Detection Techniques for Neutrinos and High Energy Astrophysics

"Low Temperature Detectors at the Astroparticle Cutting Edges"

Flavio Gatti

University and INFN of Genova, Italy

Vulcano Workshop 2014, May 21st

Outline

- Low Temperature Detectors
- How they work and applications
- Neutrino mass project HOLMES
- TES Microcalorimeter for Space X-Ray Observatory ATHENA
- Hints on Italian TES bolometers for CMB polarisation

LTD zero musketeers

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1st Low Temperature Detector Workshop-1987

1st Low Temperature Detector Workshop-1987

Update on Neutrinos, Dark Matter, and Cryogenic Detection.
By L. Stodolsky

New Results on the Basic Properties of Superheated Granules Detectors.
By L. Gonzales-Mestres and D. Perret-Gallix

Investigation of Superconducting Tin Granules for a Low-Energy Neutrino or Dark Matter Detector.
By K. Pretzl

SQUID Detection of Superheated Granules.
By A. Kotlicki

VLSI Superconducting Particle Detectors.
By 0. Liengme

"Minicylinder" Design for Solar Neutrino Detection (A naive proposal).
By G.Vesztergombi

Electron Beam Detection with Superheated Superconducting Grains.
By A. de Bellefon

Monte Carlo Simulation of a Double-Beta Decay Experiment with Superconducting-Superheated Tin Granules.
By A.F. Pacheco

Solar Neutrino Indium Detector Using Superheated Granules.
By G. Waysand

An Indium Solar Neutrino Experiment.
By N.E. Booth

Cryogenic Detection of Particles, Development Effort in the United States.
By B. Sadoulet

Calorimetric Detectors at Low Temperatures.
By F.v. Feilitzsch, F. Probst, and W, Seidel

The Possible Impact of Thermal Detectors in Nuclear and Subnuclear Physics.
By E. Fiorini

Considerations on Front End Electronics for Bolometric Detectors with Resistive Readout.
By D.V. Camin

Coherent Neutrino-Nucleus Elastic Scattering in Ultralow-Temperatures Calorimetric Detectors.
By T.O. Niinikoski

Data Acquisition and Analysis of Calorimetric Signals.
By A. Rijllart

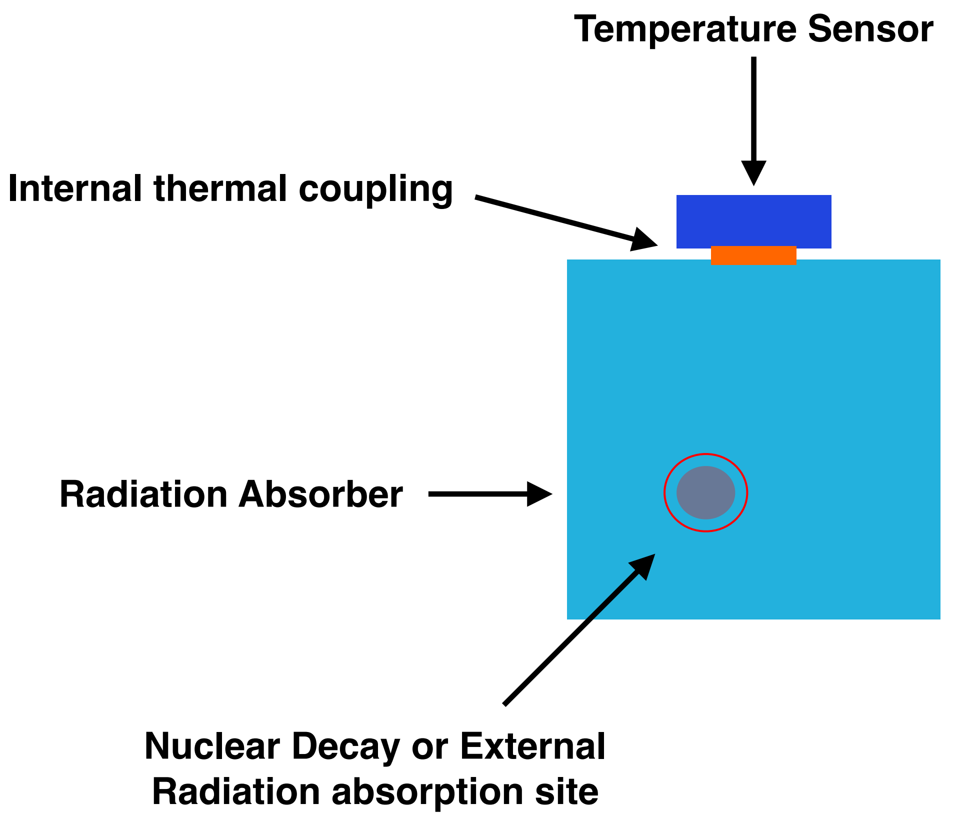
The Use of Rotons in Liquid Helium to Detect Neutrinos
By G.M. Seidel

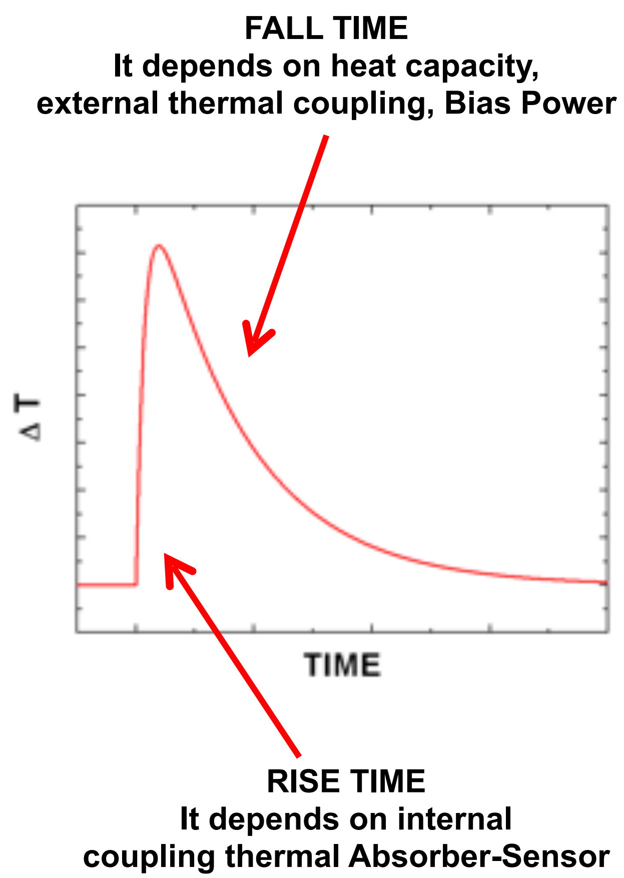
15th International Conference on Low Temperature Detectors

LTD15

Pasadena, California June 24 - 28, 2013

What is a cryogenic μ-calorimeter?





- It's ideally an Energy Dispersive Spectroscopical Detector
- It's a fast true thermal calorimeter
- Energy Sensitivity at the eV scale needs very low heat capacity at the scale less than pJ/K
- The Energy Resolution Intrinsic is ultimately limited by the thermal fluctuation noise:

$$\sim \sqrt{kT^2C}$$

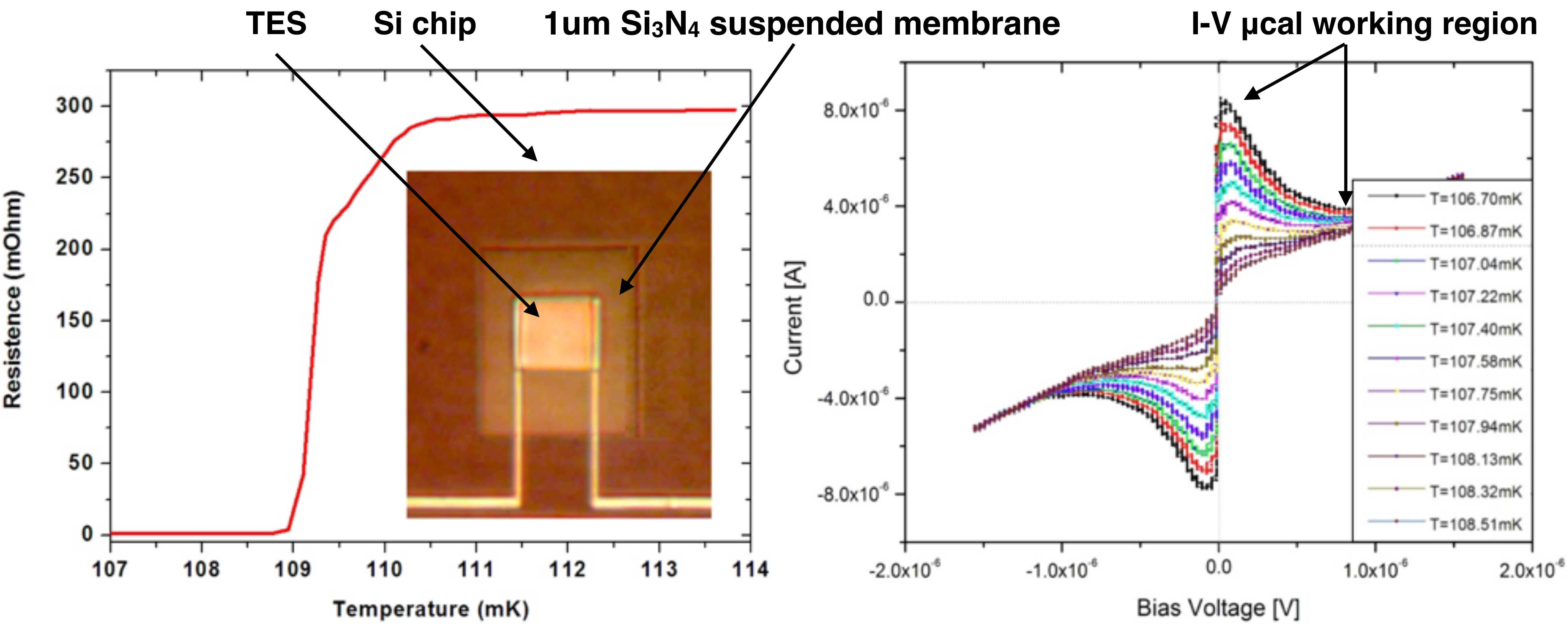
- Sub-K operating temperatures are needed (0.01-0.1 K) to reach eV resolutions

How they work?

- Many possible temperature sensors: semiconducting thermistors (Ge NTD, Si doped), metal films at the superconducting to normal transition (commonly called TES), paramagnetic sensors, kinetic inductance sensors, superconducting-insulating-normal junctions (SIN), ….

- I will stick on the TESs - Transition Edge Sensors - that are presently one of the most performing technology.

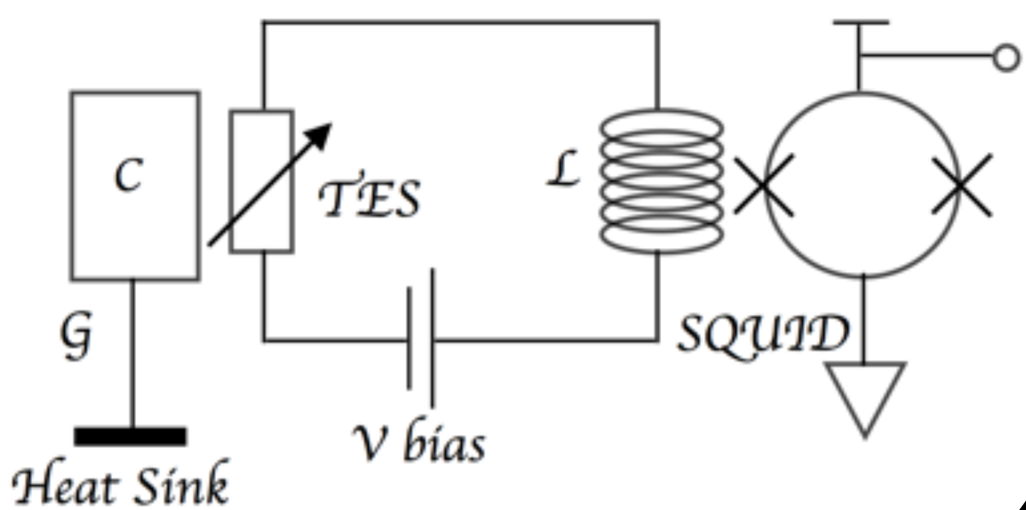
- The simplest microcalorimeter is a metal film that acts as TES and absorber on a Si_3N_4 suspended membrane on a silicon Chip

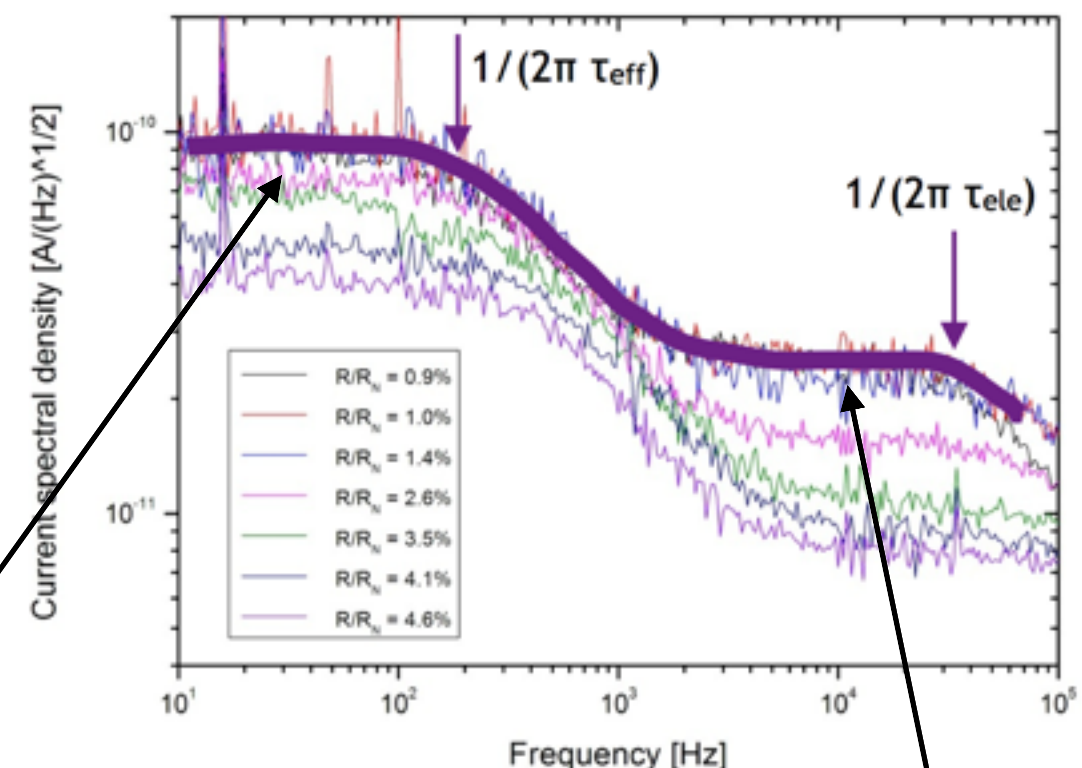


How they work?

The temperature increases in the micro calorimeter moves the TES to higher resistances, reducing the current. This is readout by a SQUID in galvanometer configuration.

The intrinsic noise has the following features: at high frequencies the plateau of the Johnson noise is limited by the electronic cut-off, at lower frequencies the high responsivity $S(\omega)$ of the micro calorimeter provides enough gain to clearly see the thermal noise plateau, which is limited by the thermal cut-off.



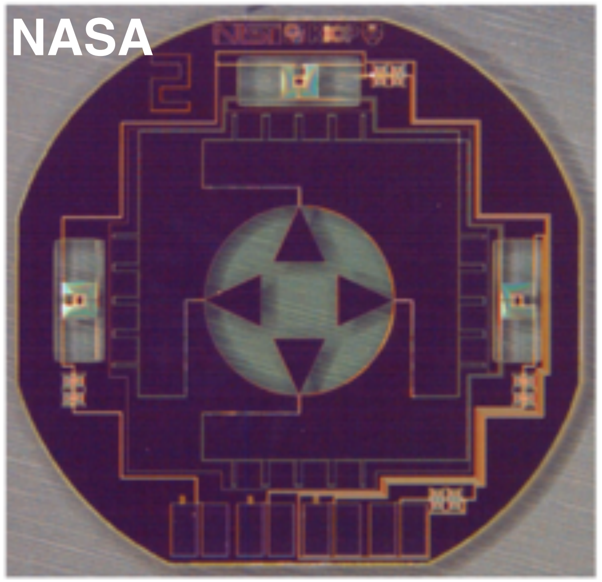


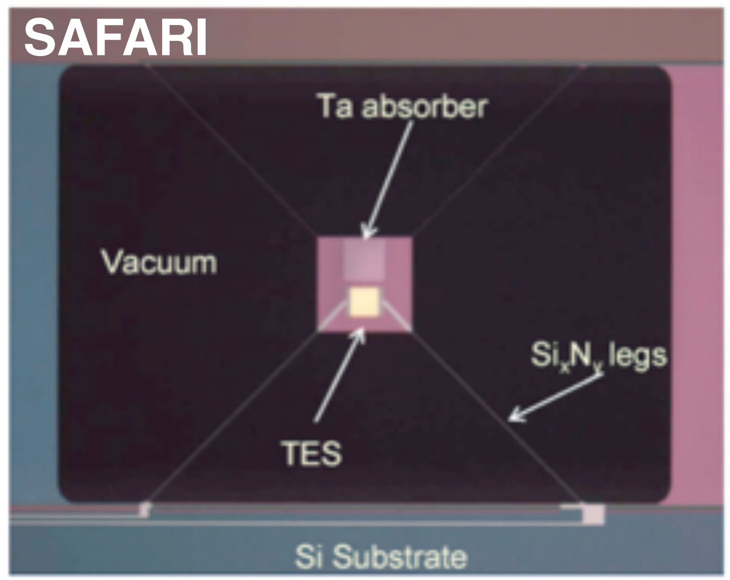
This is the thermal fluctuation noise!

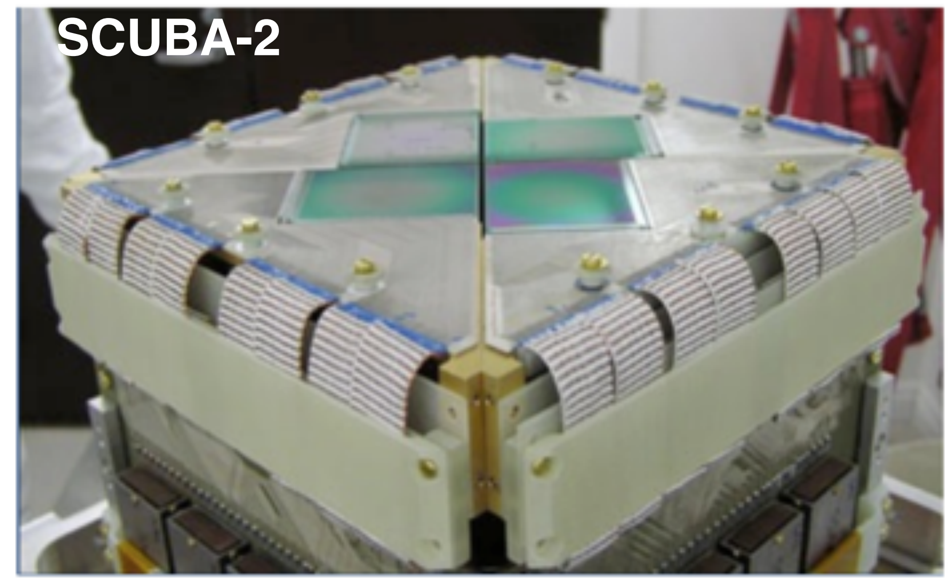
Johson Noise

Applications

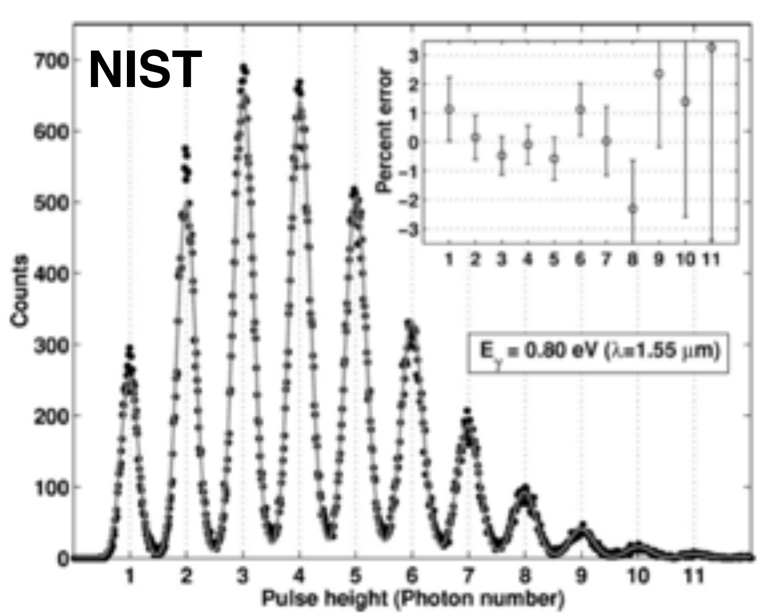
Low Power Level. **Cosmic Microwave background (CMB) and IR astronomy are the most intriguing applications that take the advantage of the very low power sensitivity of TES based bolometers. Since the CMB brightness is not a concern for the actual power level, after WMAP and PLANK CMB missions, the next goal is the search for polarisation features that requires NEP dow to 10^{-19}-10^{-18} W/(Hz)$^{1/2}$ with the detector in the figures.**

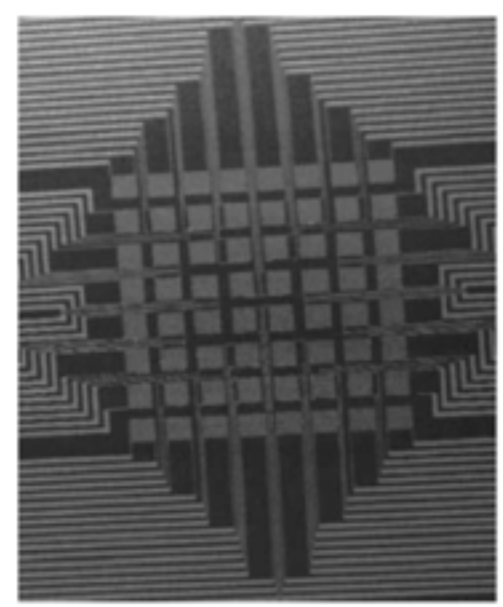




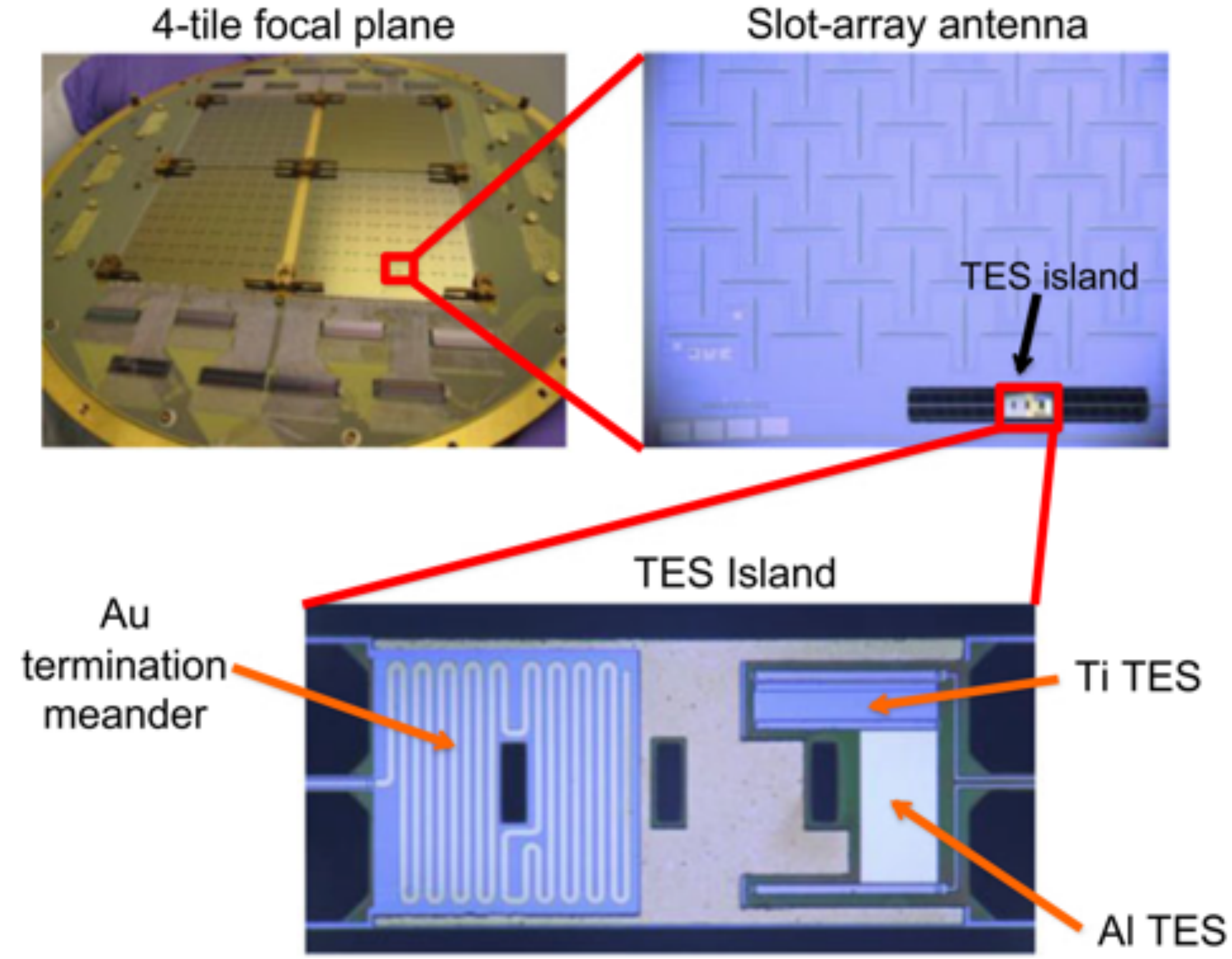


Linear Response. **TES micro calorimeters have been also investigated for detecting single photons in the visible and IR band with excellent efficiency up to 95%. Because TESs have linear response, i.e., proportional to the photon energy and a resolution of about 0.1 eV FWHM, it means that at a fixed wavelength the response is also proportional to the photon number. Photon Number Resolving power (PNR) is very important in Quantum Information due to the non ideality of the available single photon source.**

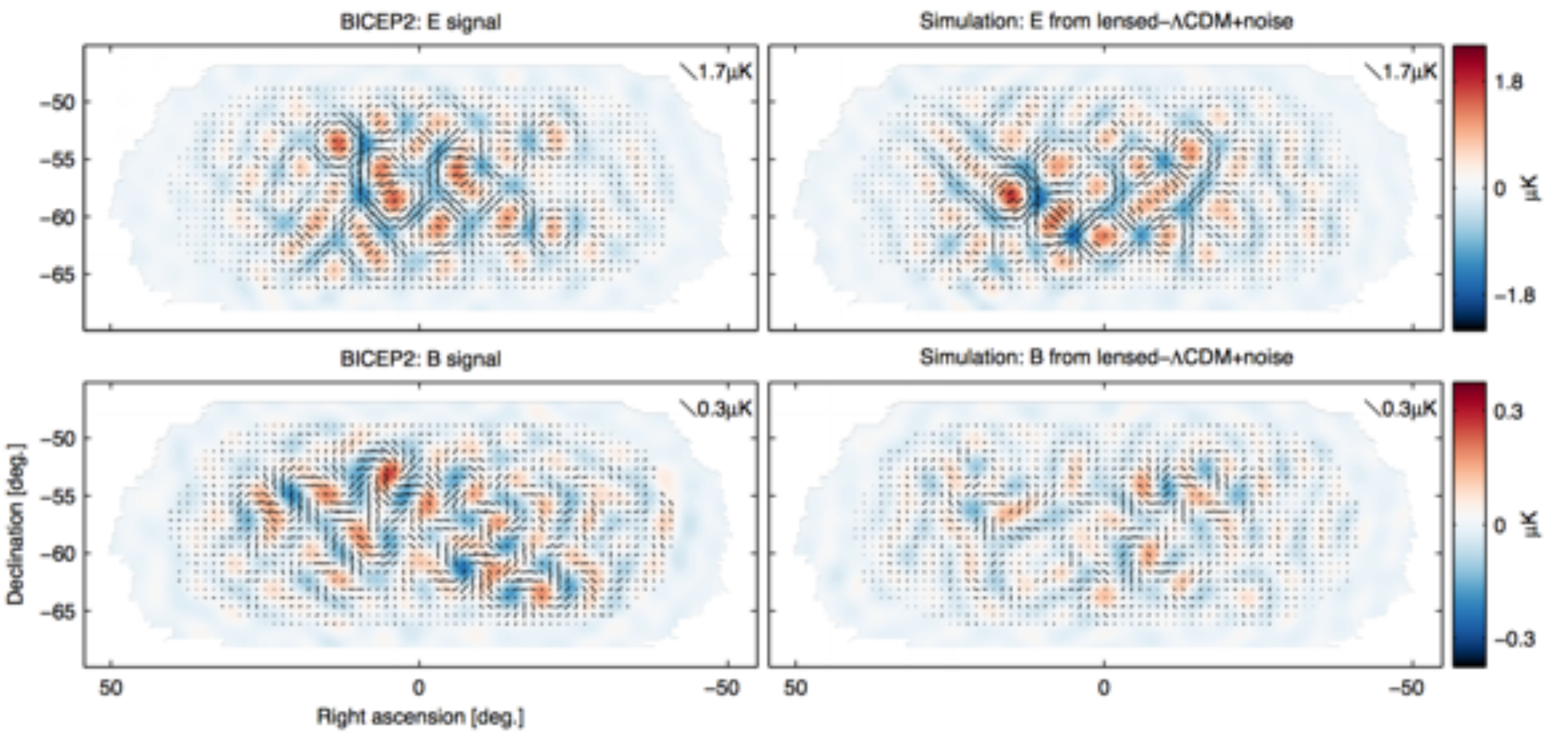




BICEP2-Keck-Array



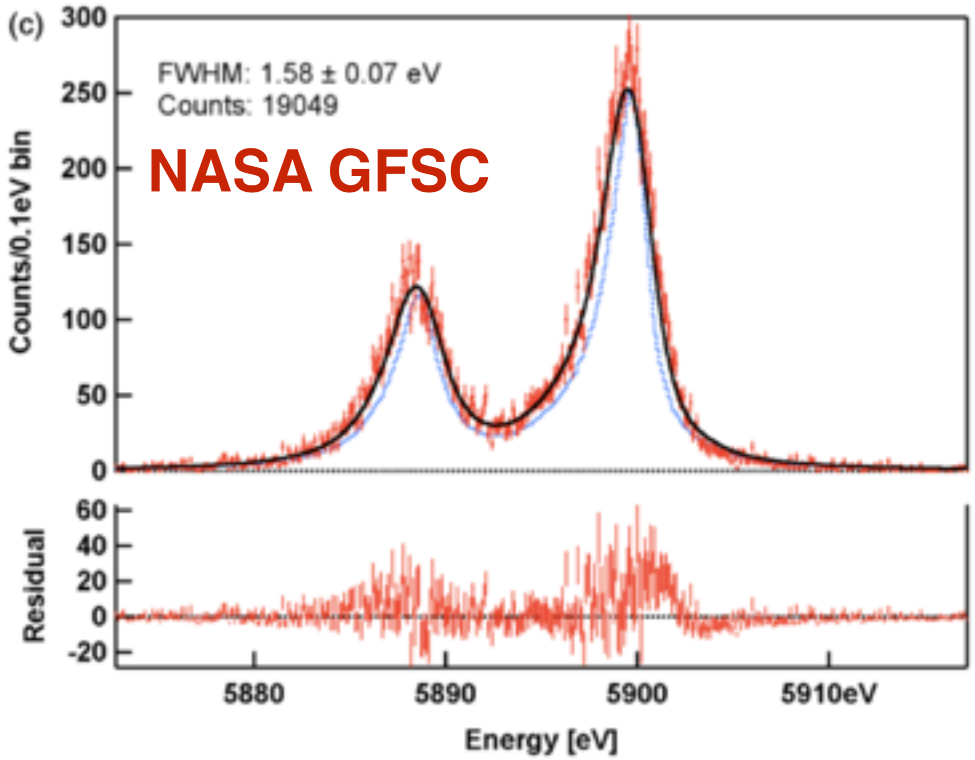
TES-antenna coupled bolometer

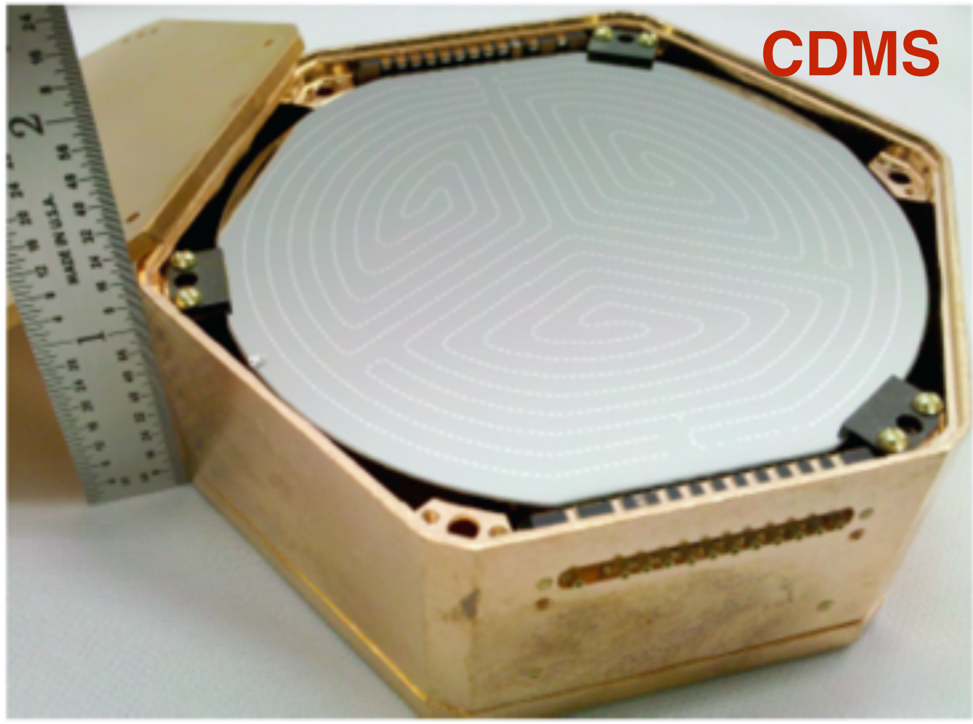


arXiv:1403.3985v2

Applications

***High energy resolution*.** Sub-eV and eV energy resolution in the 1-10 keV X-ray band is one of the most appealing feature of TES micro-calorimeters. Energy Dispersive Spectroscopy (EDS) is presently based on semiconducting charge detectors that can reach 120 eV at 6 keV and 400 eV in the hard X-ray band at 100 keV. Best performing TES micro-calorimeters built at Goddard Space Flight Center have instead shown 1.6 eV at 6 keV and at Los Alamos National Laboratory and National Institute of Standard and Technology-Boulder 22 eV at 97 keV. Others laboratories in USA, Europe and Japan have attained 3-5 eV resolution FWHM with TES.

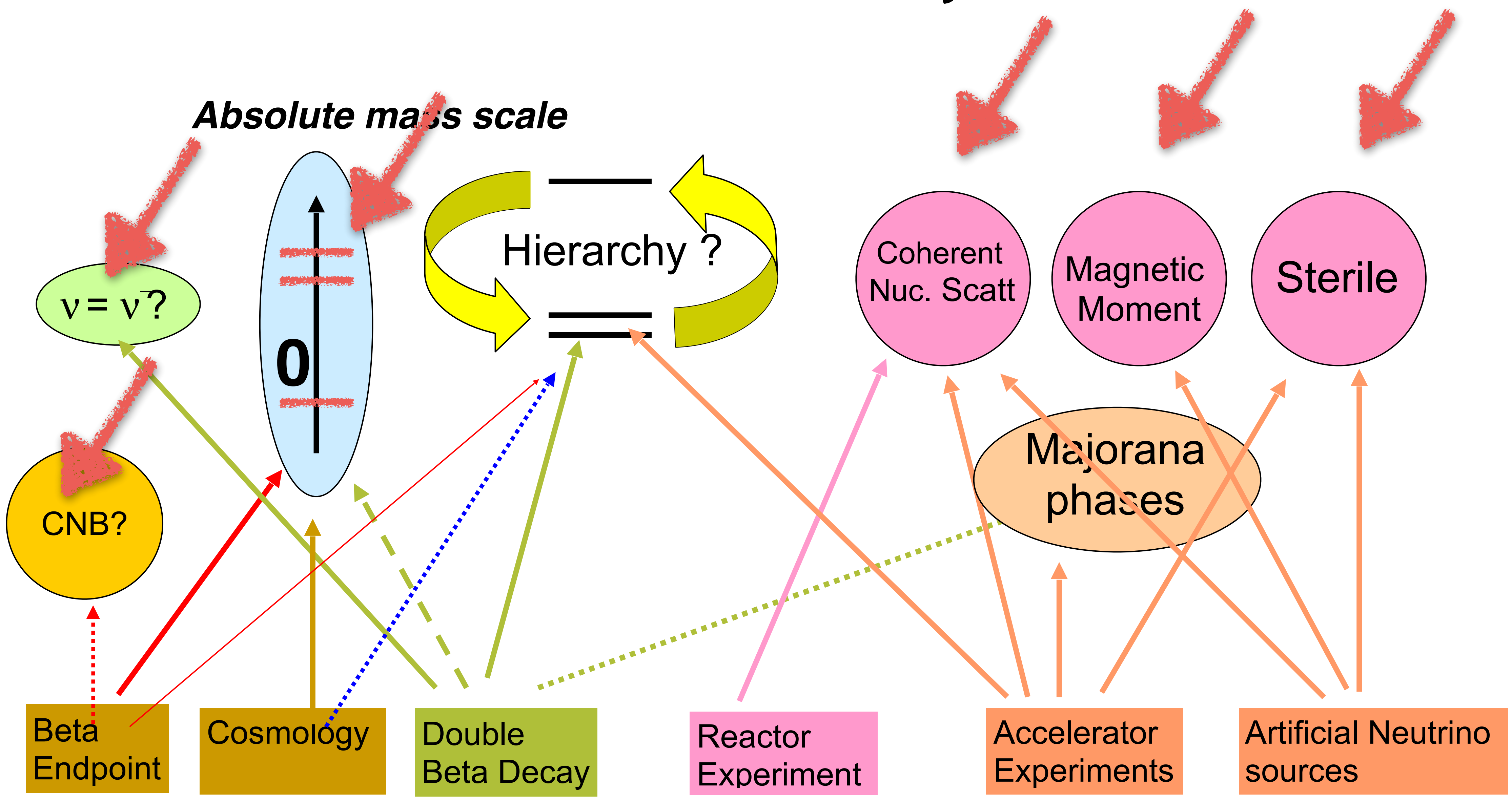




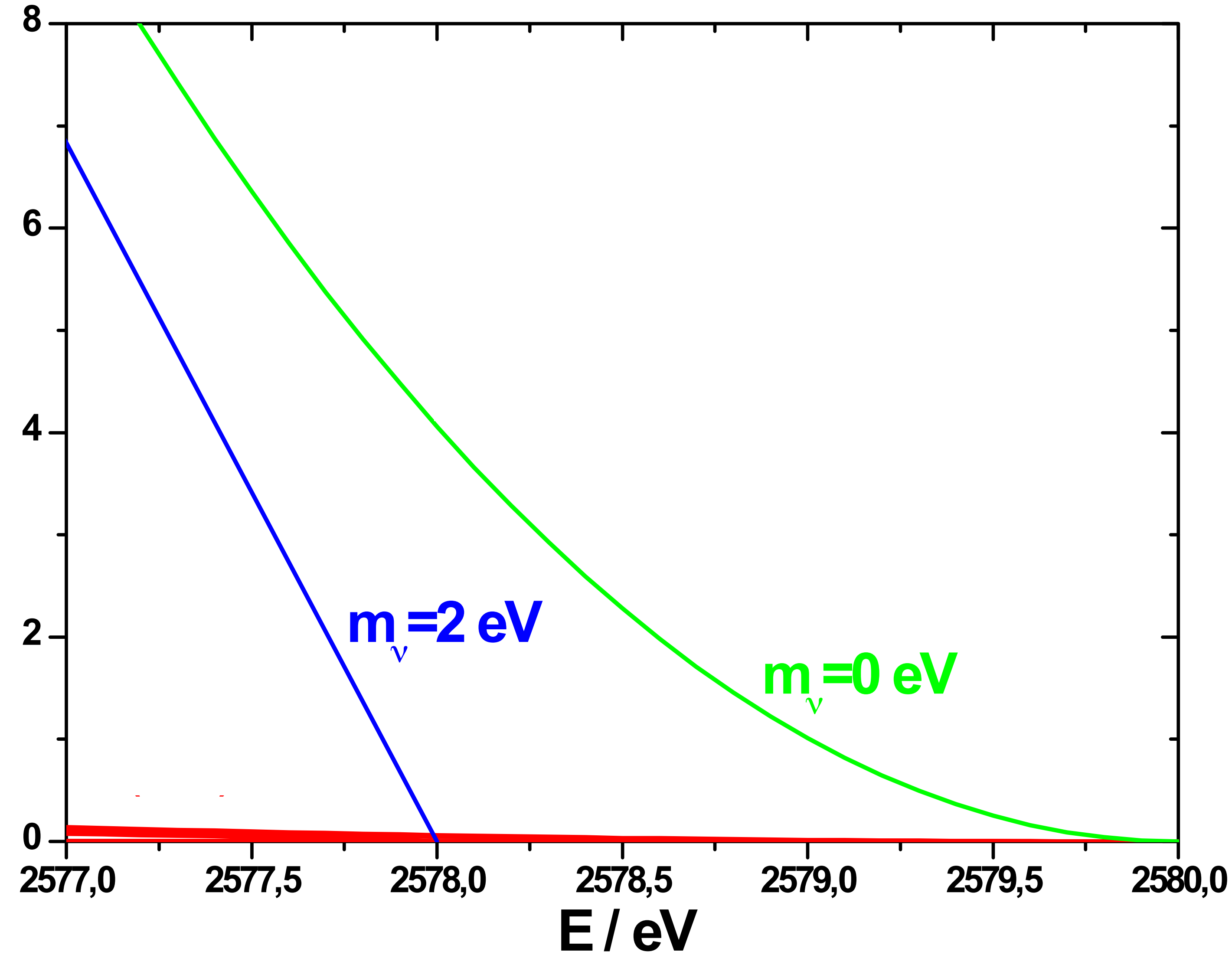
***Low Threshold and Calorimetry*.** The accurate determination of energy lines and absolute radioactivity measurements can be done respectively with TES micro-calorimeters with an external radioactive source and embedding itself in the absorbers itself. They are made of arrays of Sn crystals coupled with TES. Unprecedented performance have been obtained with alpha spectroscopy, i.e., 1 KeV FWHM at 5.3 MeV (8 keV about in semiconducting detector).

In case or rare and low energy event like the recoil from the Dark Matter particles, that are supposed overlapping the barionic matter distribution in our galaxy, a very low threshold energy for Kg size detectors is required. The Cryogenic Dark Matter Search (CDMS) experiment is searching for Weakly Interacting Massive Particles (WIMPs) using detectors with the ability to discriminate between candidate (nuclear recoil) and background (electron recoil) events by measuring both phonon and ionization signals from recoils in the detector crystals. The Phonon readout is mediated by the quasiparticles generation in Al films that then diffuse in to a TES. Direct Dark Matter searches with W TES is also performed by the CRESST experiment. Double beta decay, CUORE, will be discussed by A. Nucciotti.

Neutrino Physics Open Questions
and contributions of LTD

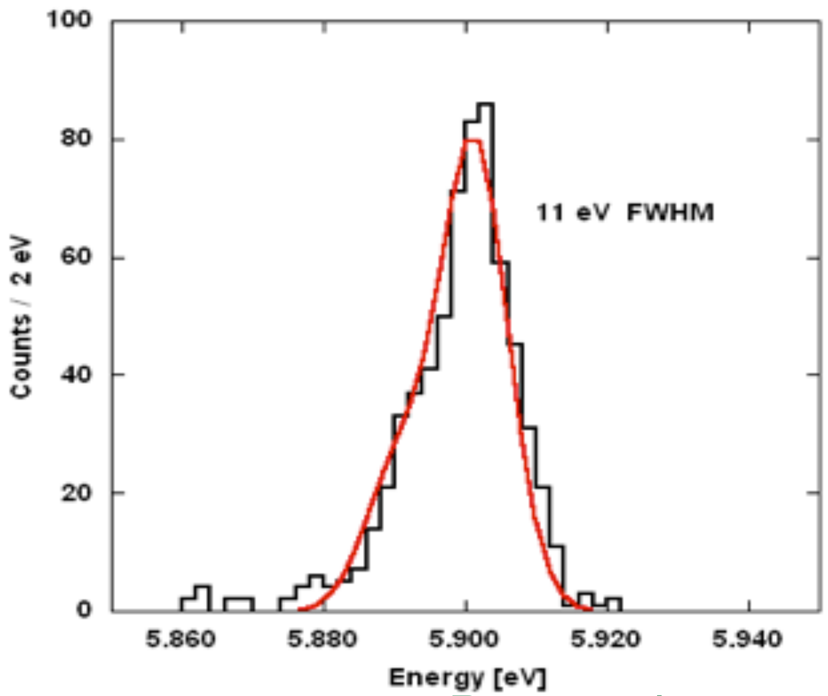


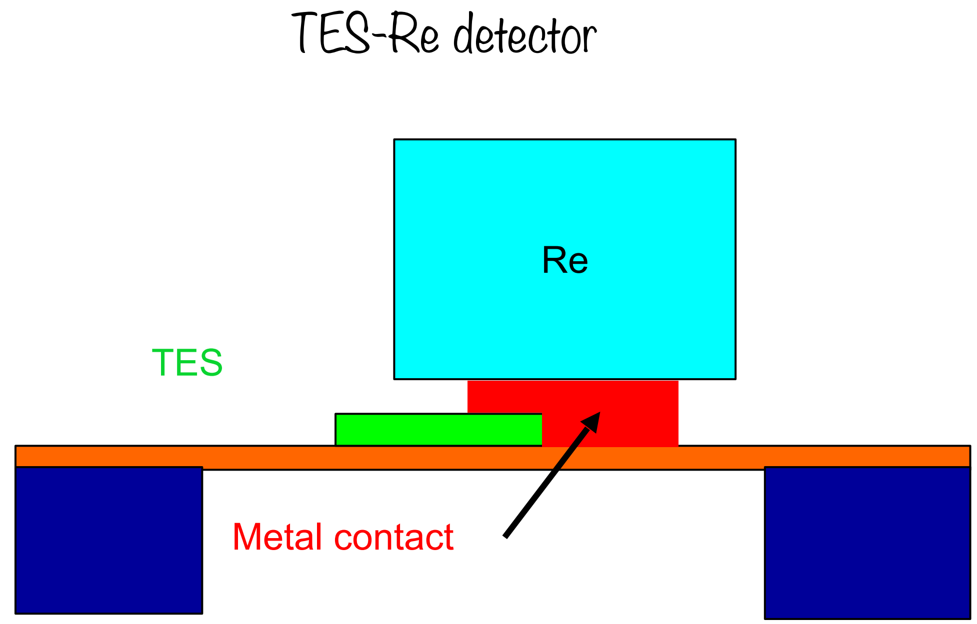
Testing Neutrino Absolute Mass scale with Direct Calorimetric Methods in Laboratory



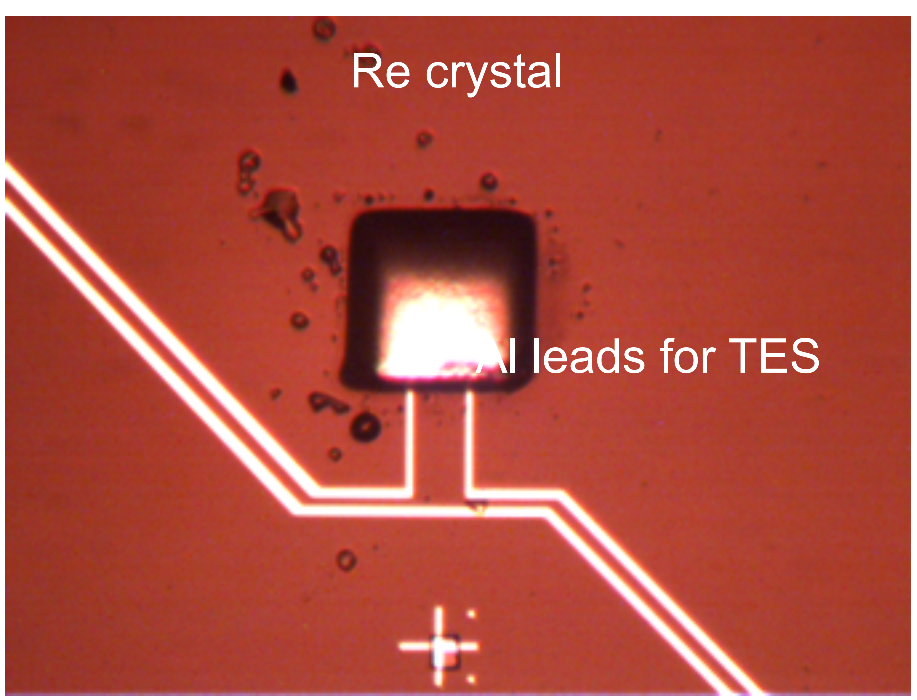
the pioneering Project MARE (INFN)

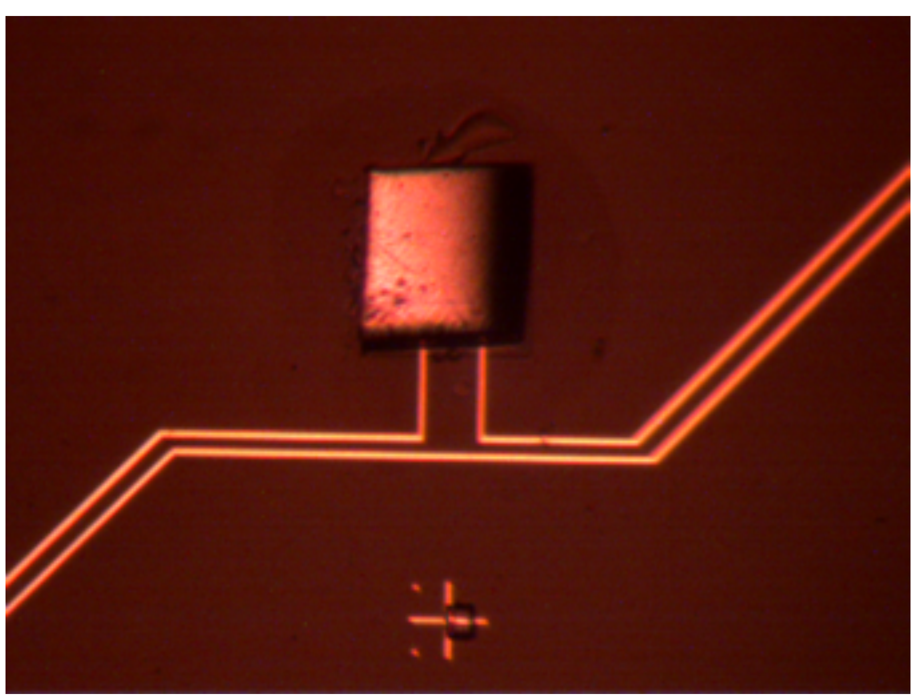
MARE Project was based on Re-187 beta decay, about 60% Isotopic Ab. in natural Rhenium. Intrinsic limitation has been found: resolution limited at 10 eV. The source of an expected excess noise is relates to to the complex process of thermalisation of the primary energy in the superconducting Rhenium.





Re-crystal on epoxy-post / Ir-TES / SiN-membrane





the project HOLMES

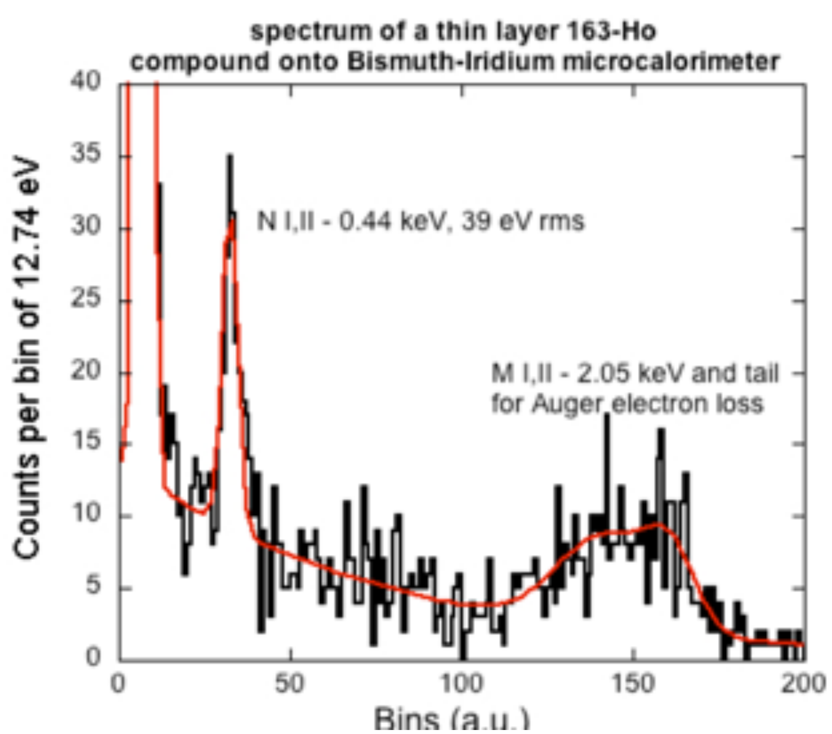
- 5 years project funded by the European Research Council (PI: Stefano Ragazzi - MiB and LNGS)
- Officially started in Feb. 2014
- Based on the Technology Developments and Expertise of MARE
- Laboratories and groups (Genova, Milano Bicocca, LNGS)
- Collaborative support by: NIST and Univ. Lisboa
- Aims:
  - perform a pilot and “sensitive”experiment with the state of the art of the micro calorimetric technology.
  - fix the technology for future large scale project: production and purification of the Ho-163 source, use of large arrays of detectors, GHz multiplexing electronics, study of background and pile-up.

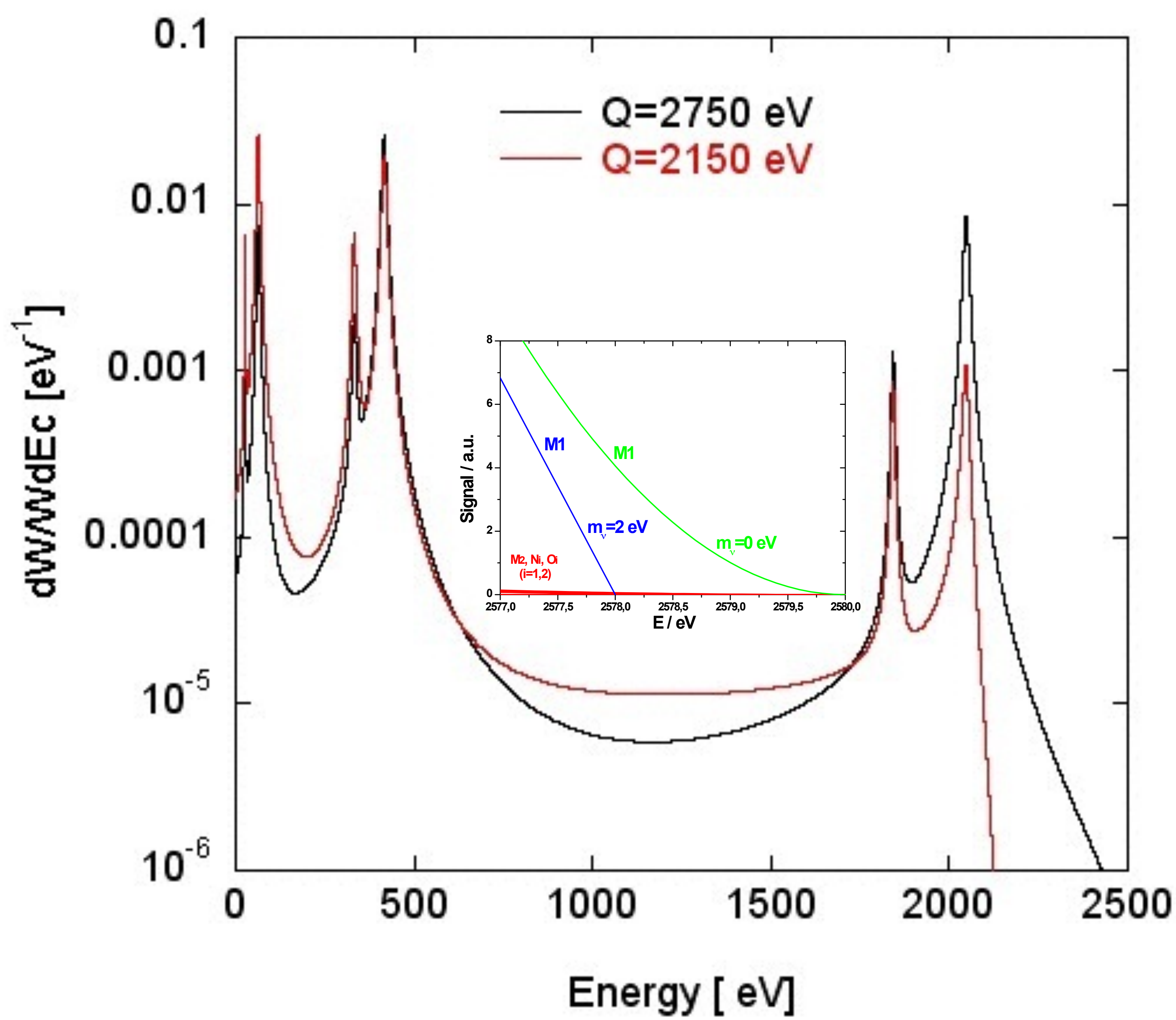
the project HOLMES

$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$ electron capture decay

(A. De Rujula and M.Lusignoli, Phys. Lett. 9 (1982)

- First calorimetric measurement of ^{163}Ho endpoint energy: Q = 2.80 ± 0.05 keV (F. Gatti, et al, Physics Letters B, 1997) with Ho-oxide embedded in Sn absorber
- Present production of ^{163}Ho made with neutron irradiation of ^{162}Er enriched of pure Er oxide sample.
- A first spectrum has been acquired for demonstrating the production capability





the project HOLMES - reference numbers

exposure required for 0.2 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	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}
10	1	1	4.6×10^{13}	1.5×10^{5}

exposure required for 0.1 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	0.1	0.3	1.2×10^{14}	3.9×10^{6}
100	0.1	0.3	6.4×10^{14}	2.0×10^{5}
100	0.1	1	7.4×10^{14}	2.4×10^{5}
10	0.1	1	4.5×10^{14}	1.5×10^{6}
10	1	1	7.4×10^{14}	2.4×10^{6}

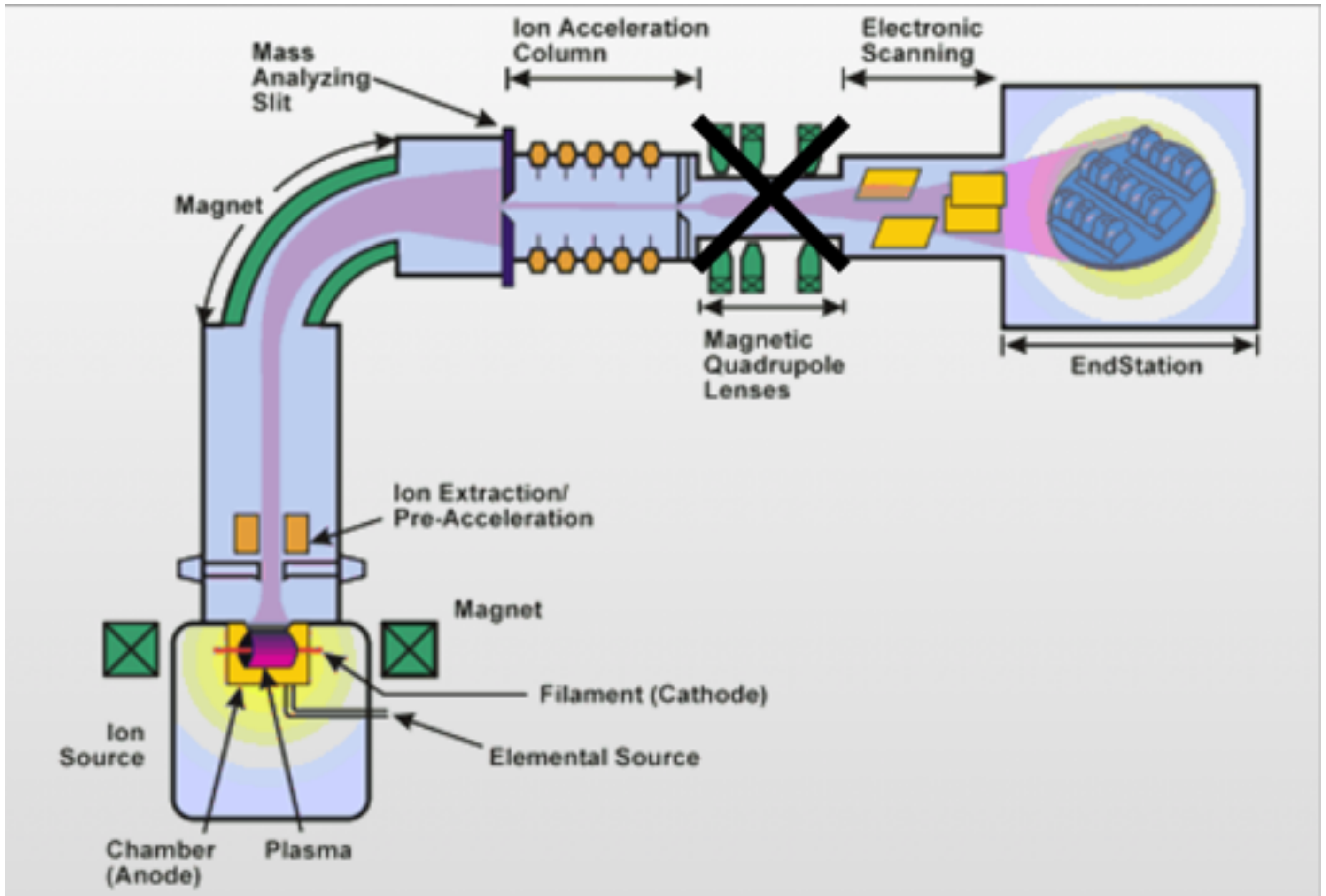
Q_{EC} **= 2200 eV**
bkg **= 0**

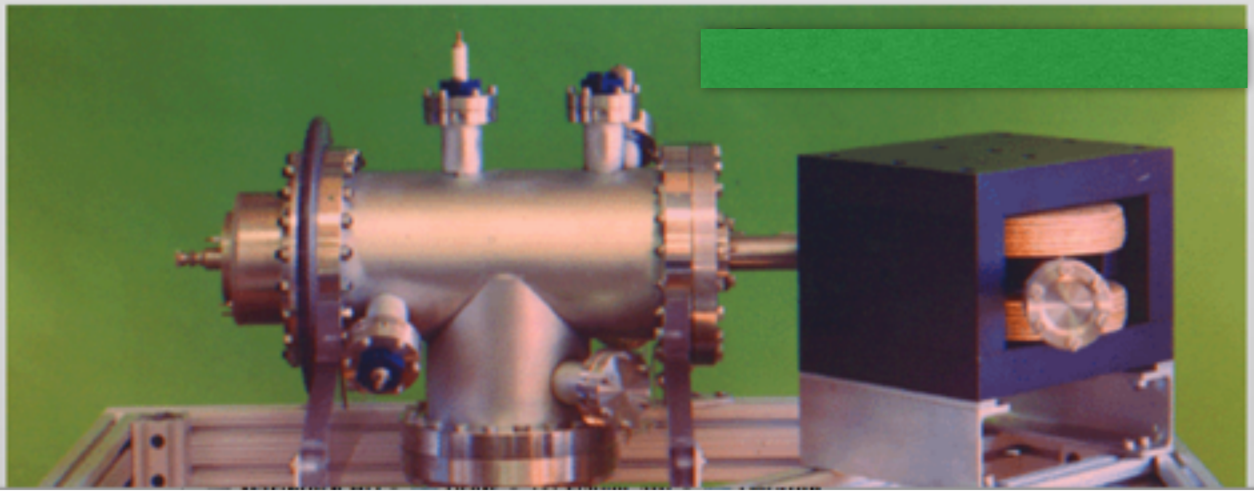
5000 pixels/array
3 arrays
1 year
$\approx 2\times10^{17}$ ^{163}Ho nuclei

5000 pixels/array
4 arrays
10 years
$\approx 3\times10^{17}$ ^{163}Ho nuclei

Inside HOLMES-isotope separation and detector implantation

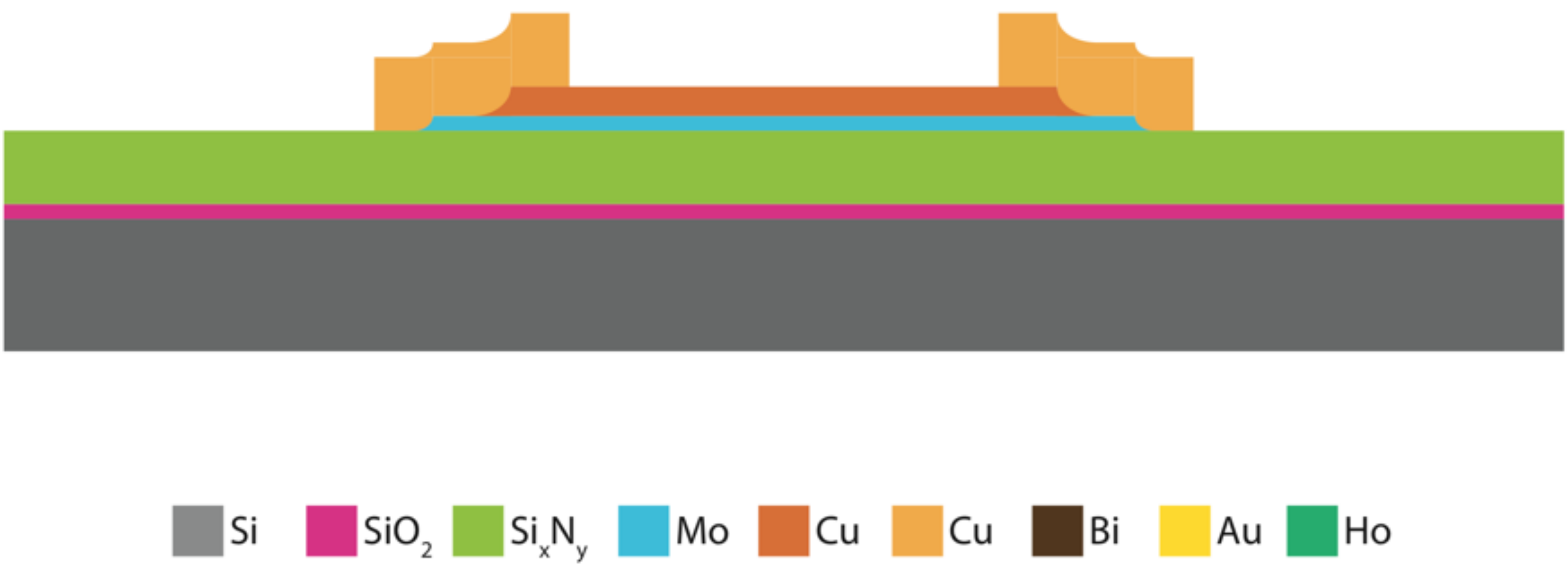
- Especially designed isotope separator and low energy implanter (10-20 keV) for handling very low amount of material and with high mass separation around 163.
- High efficiency ion source
- UHV compatible
- Beam is generated from a metal target with Ho-163 with MBq activity.
- Integrated metal evaporation source and beam analysis tools





Inside HOLMES - detector fab

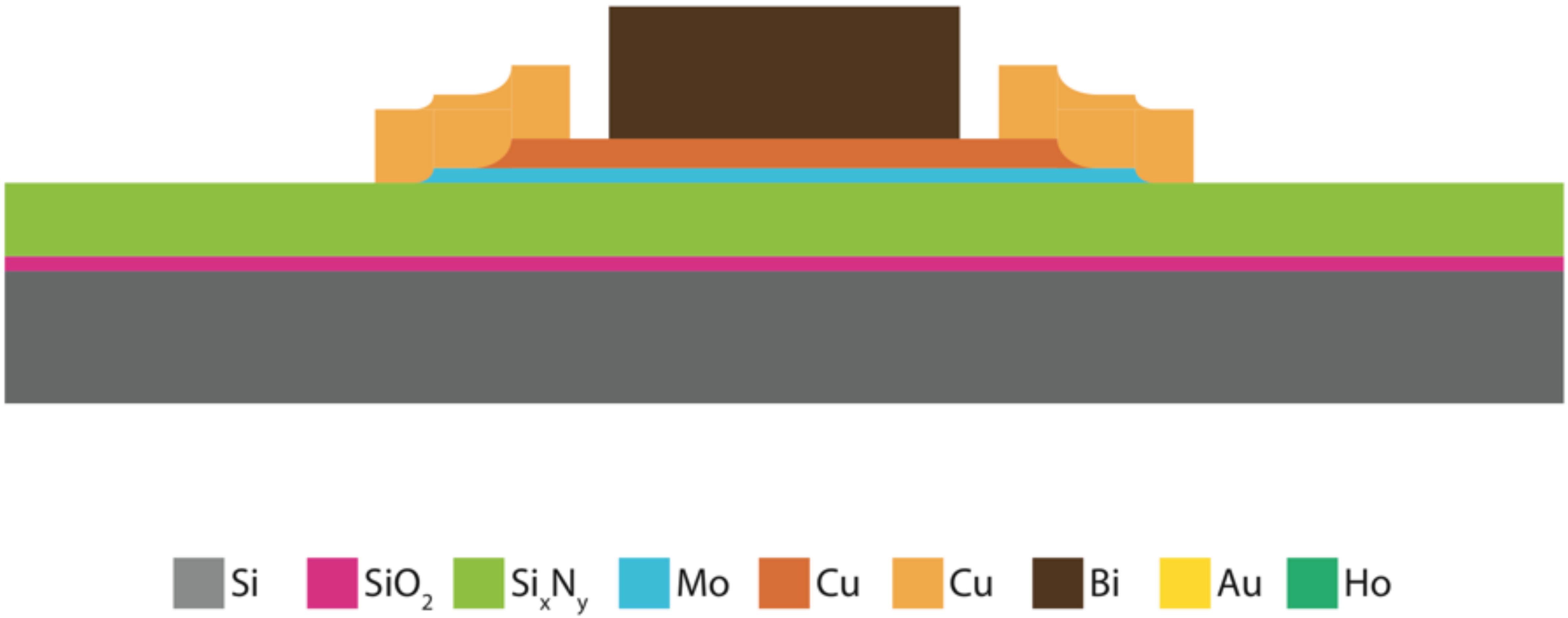
NIST-Boulder/Genova cross-fab



completed Mo/Cu TES on $Si/SiO_2/SiN$

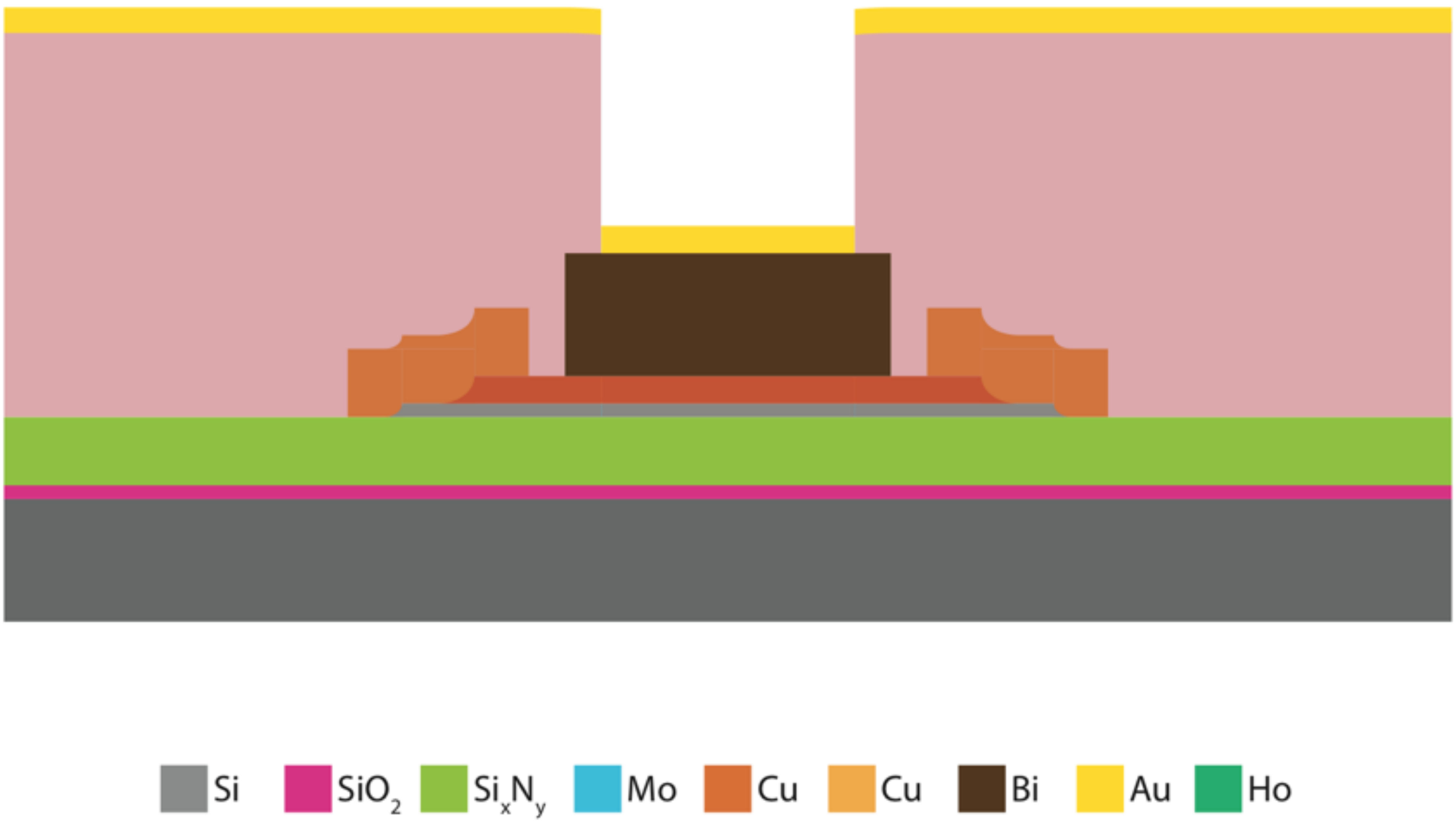
Inside HOLMES - detector fab

NIST-Boulder/Genova cross-fab



Inside HOLMES - detector fab

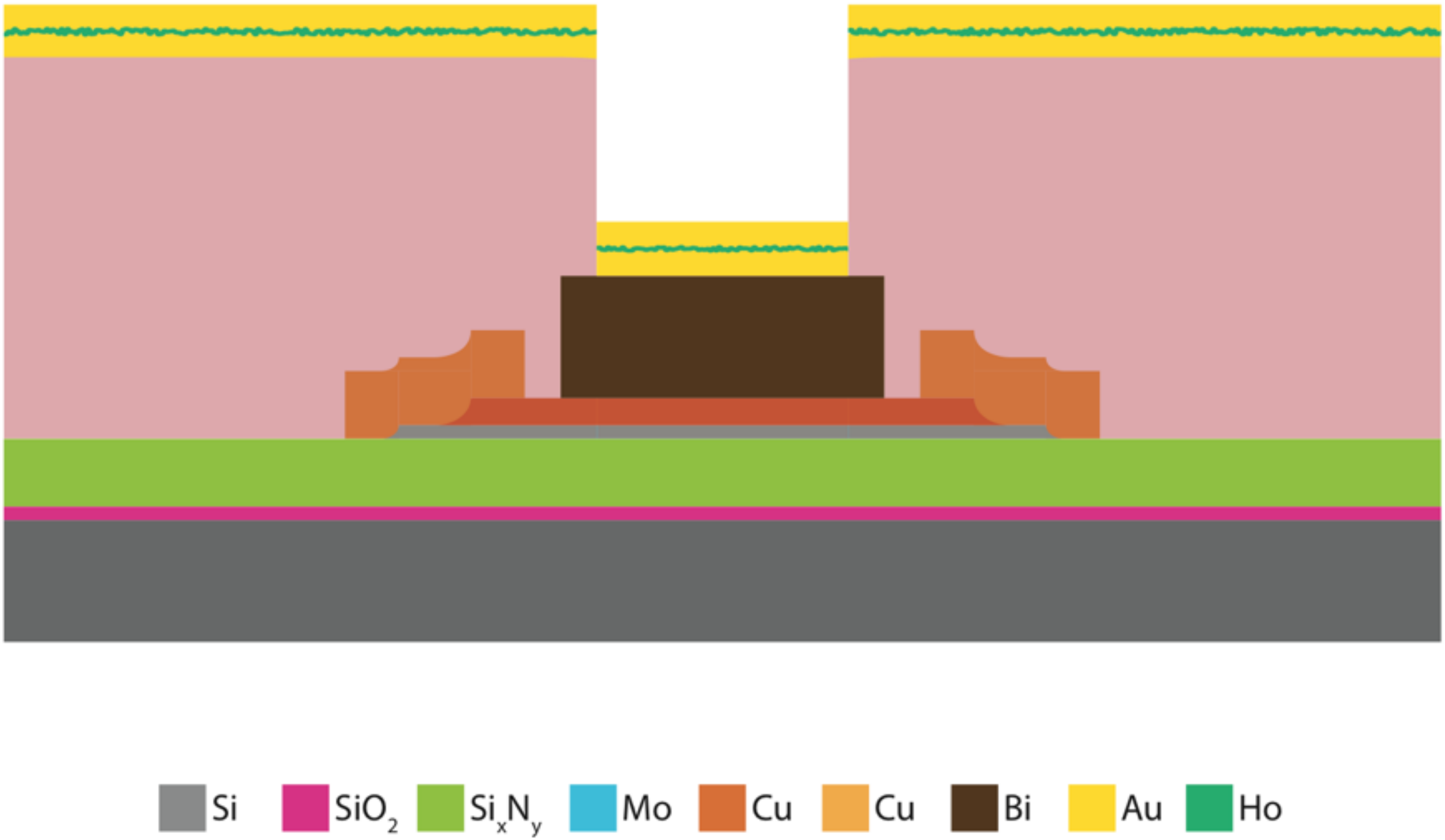
NIST-Boulder/Genova cross-fab



evaporate first gold layer (0.1-0.2 µm), do not finish liftoff, ship

Inside HOLMES - detector fab

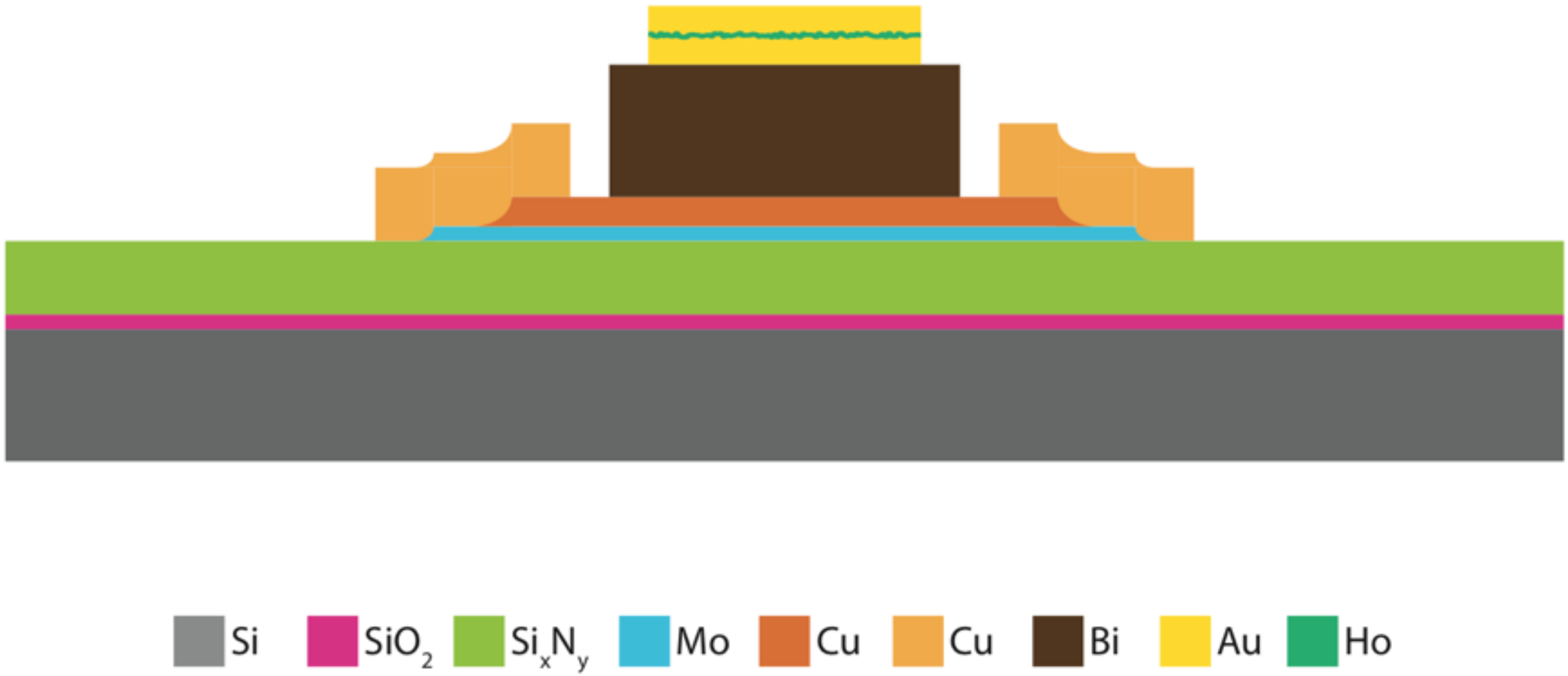
NIST-Boulder/Genova cross-fab



cap Ho with thin Au (0.1-0.2 μm)

Inside HOLMES - detector fab

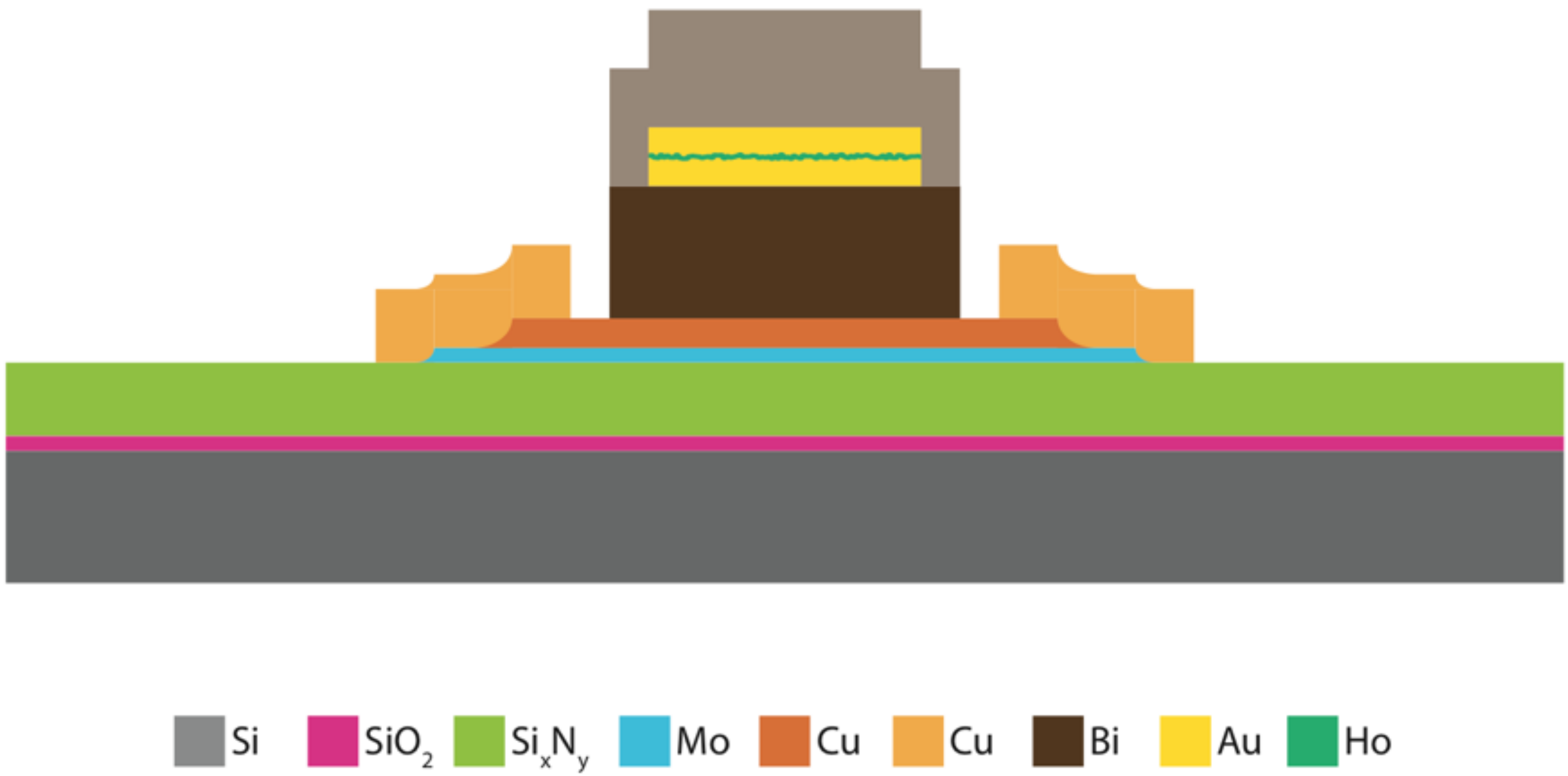
NIST-Boulder/Genova cross-fab



liftoff Au:Ho:Au layer

Inside HOLMES - detector fab

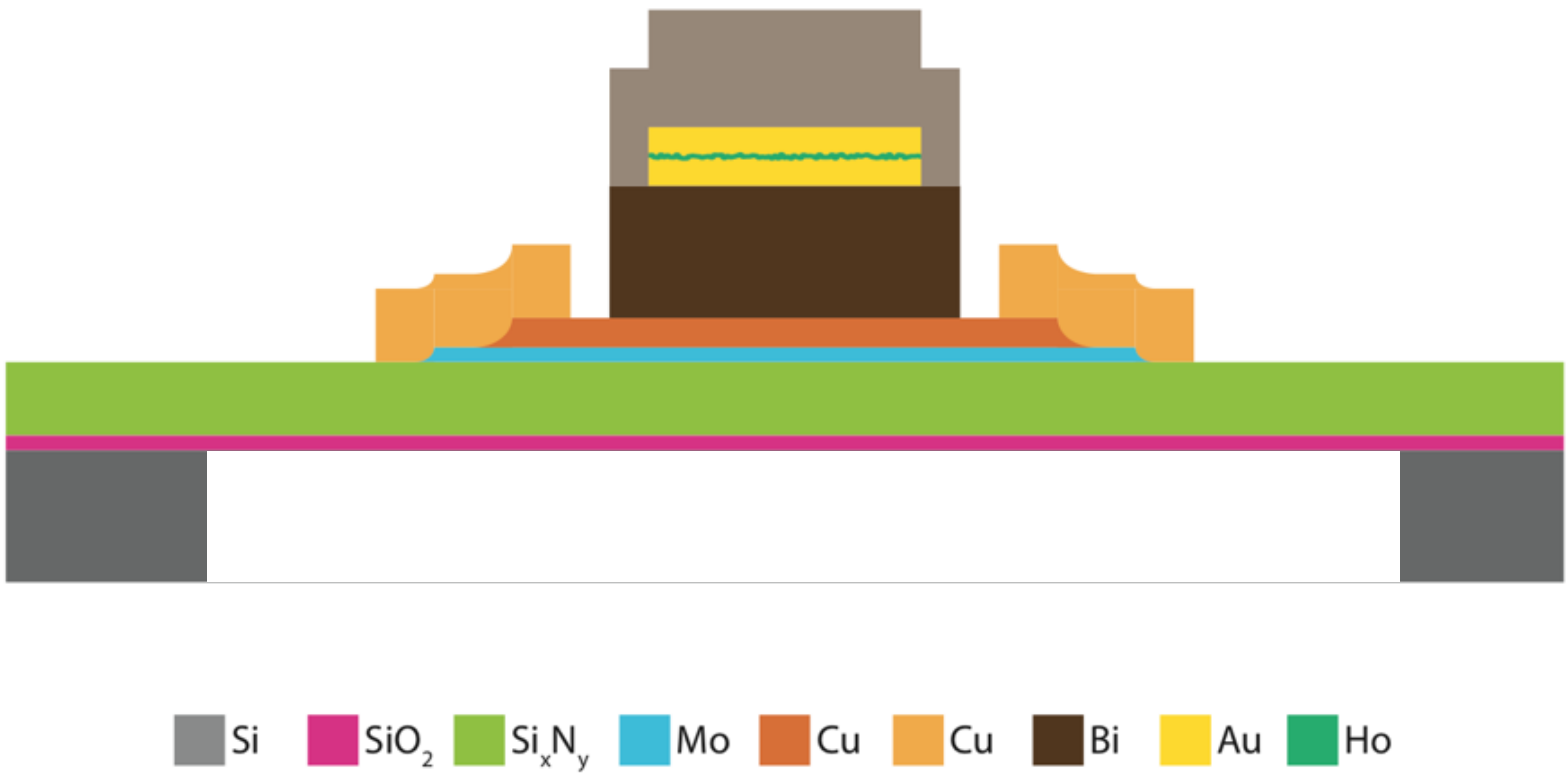
NIST-Boulder/Genova cross-fab



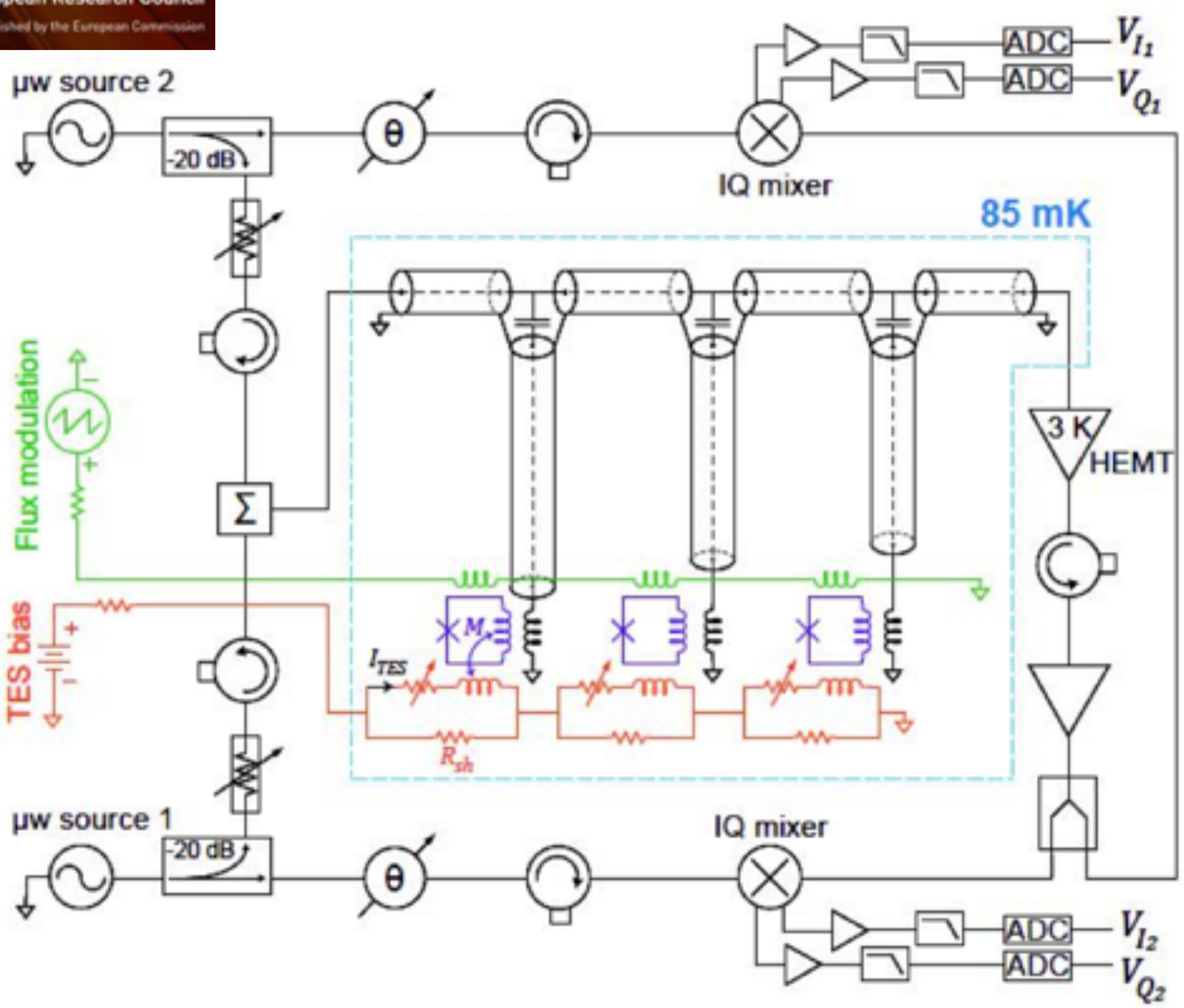
second Bi absorber layer (2-4 μm)
Bi fully encapsulates Au:Ho

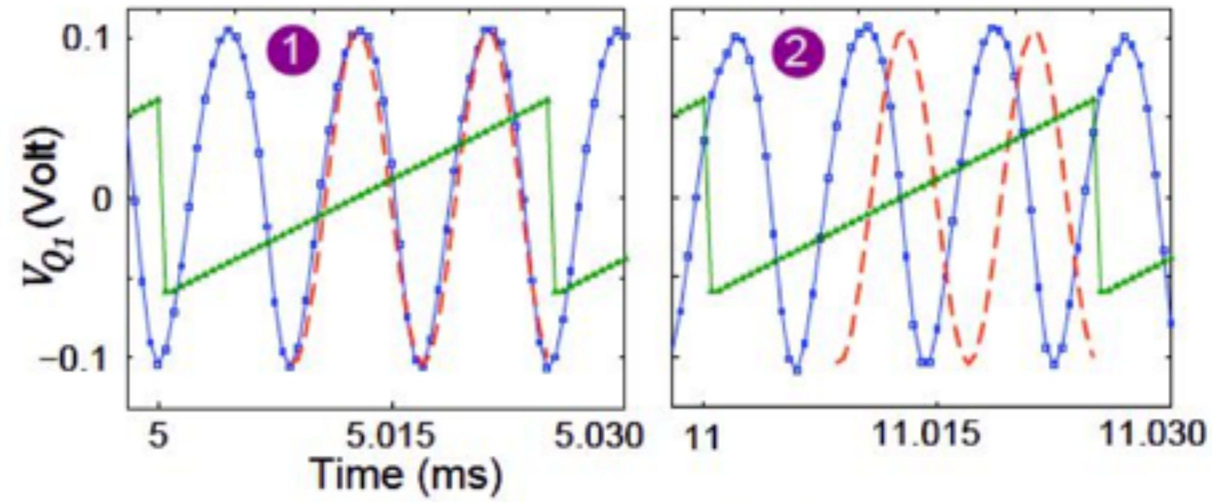
Inside HOLMES - detector fab

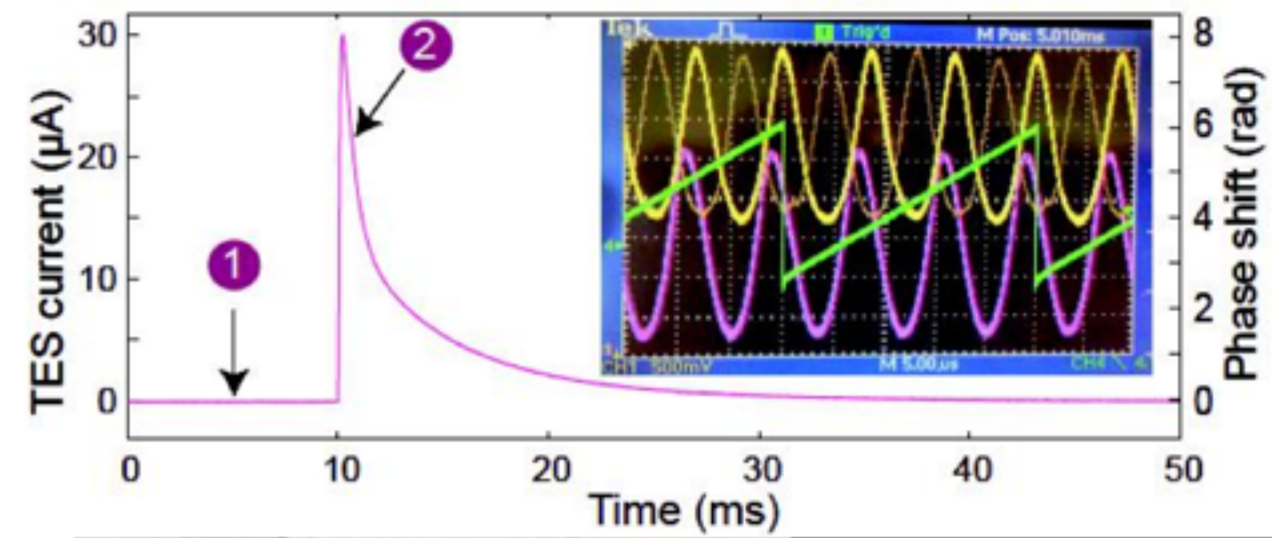
NIST-Boulder/Genova cross-fab



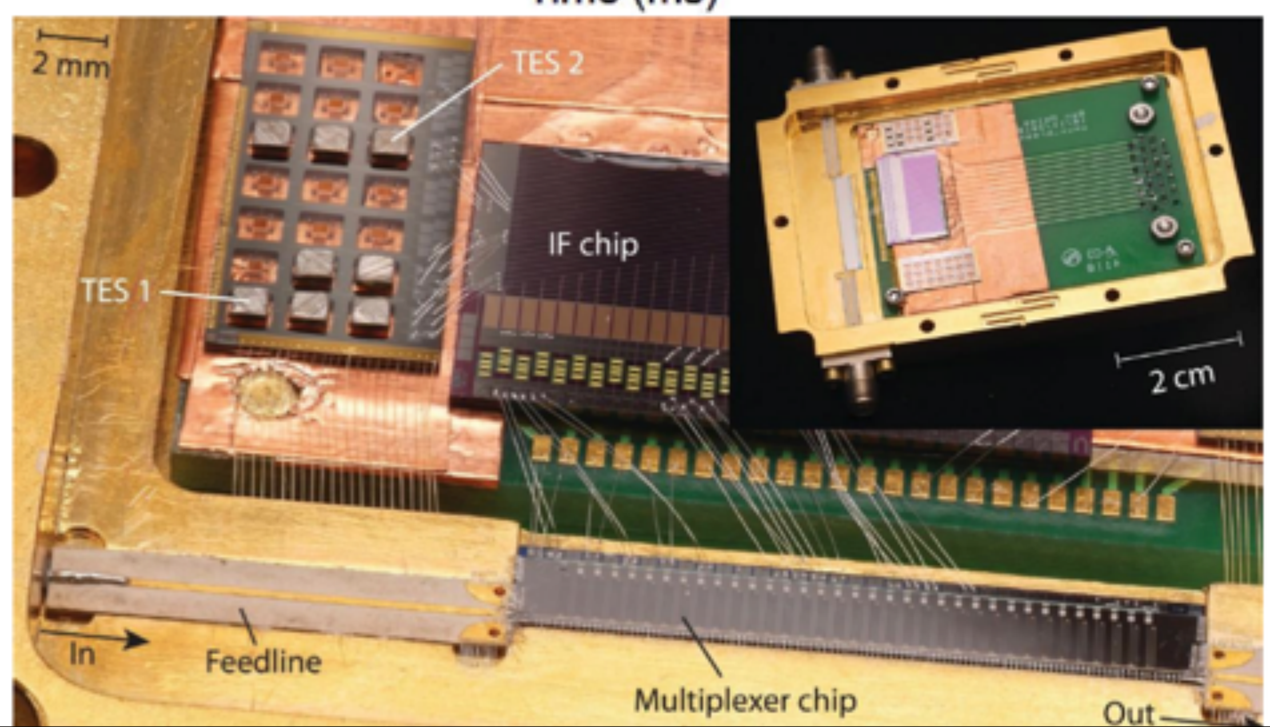
Inside HOLMES - electronics





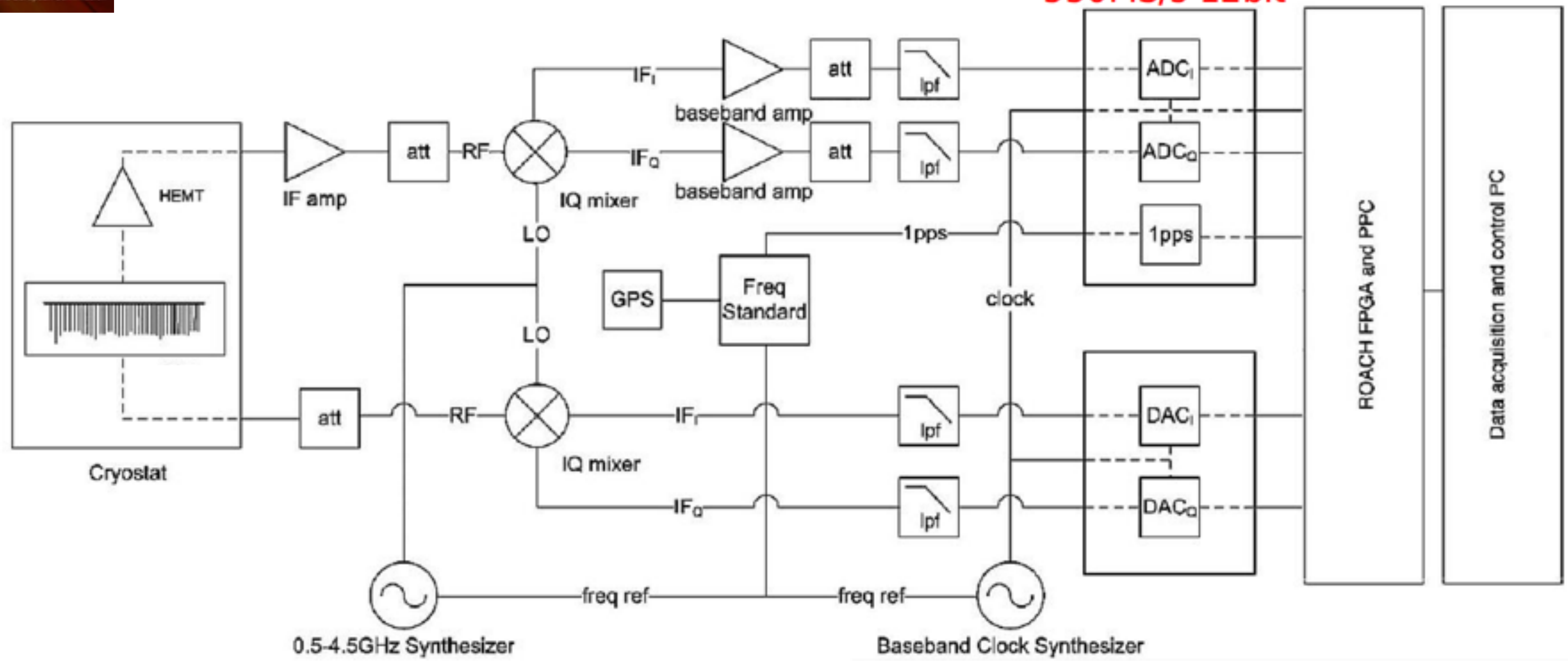


2 channel μmux



Microwave multiplexing
with RF SQUIDs (NIST-Boulder)

Inside HOLMES - electronics

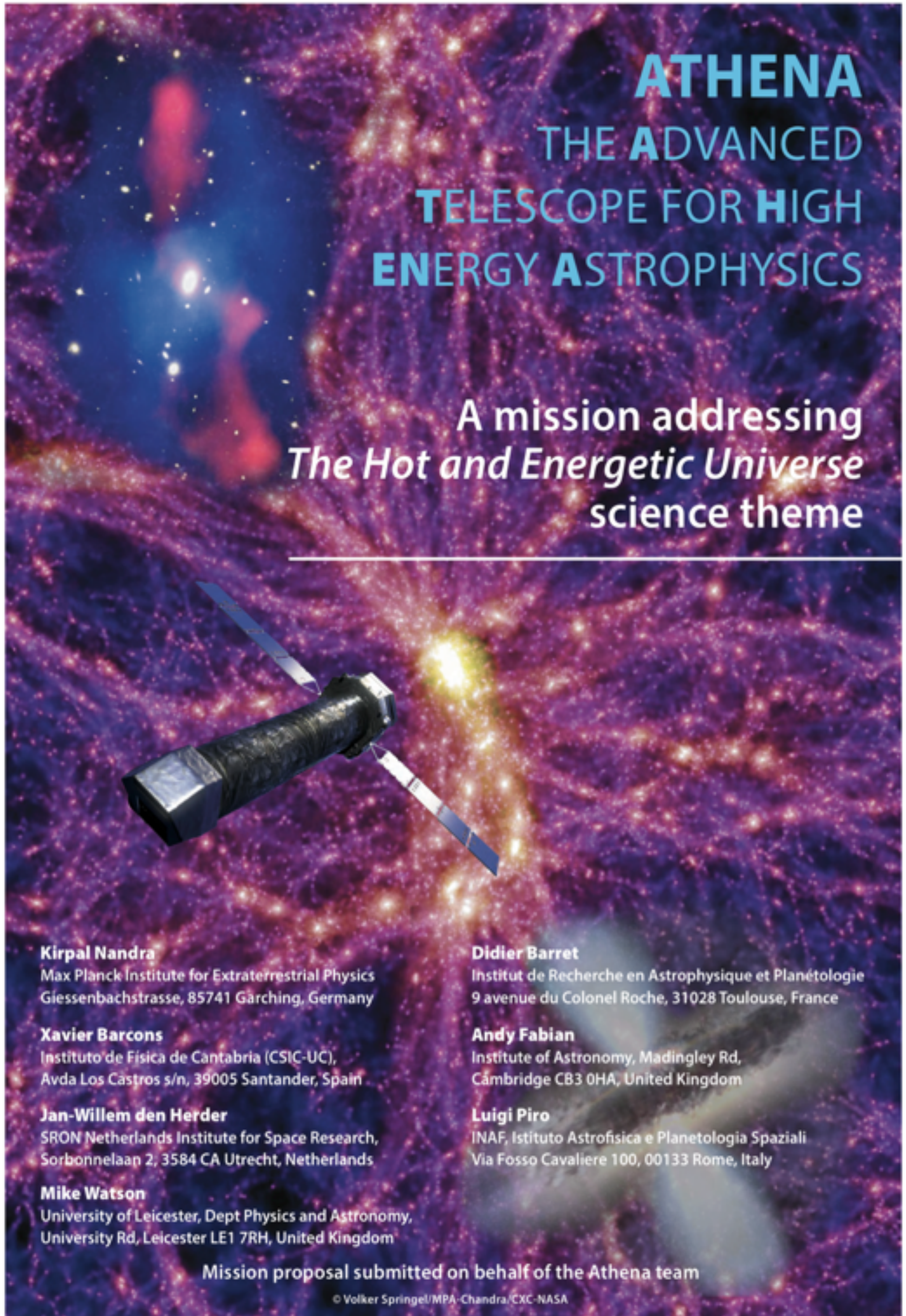


NIST-Boulder/Milano Bicocca cross-fab

bandwidth/pixel 10MHz
→ 50 resonances beteween 0 and 500MHz
→ up-conversion → 5-5.5GHz
→ down-conversion → 0-500MHz → demux

Other projects in Neutrino Physics (not a full list)

- ECHO: Holmium neutrino mass experiment in Heidelberg & possible project from Los Alamos-Stanford ("rumors")
- Double beta decay with large mass "Macro-calorimeter" CUORE
- Neutrino Nucleus Coherent Scattering (RICOCHET-MIT)
- Neutrino Magnetic Moment (MAMONT)
- Cosmic Neutrino Background (PTOLEMY)



ATHENA
THE ADVANCED TELESCOPE FOR HIGH ENERGY ASTROPHYSICS

A mission addressing
The Hot and Energetic Universe
science theme

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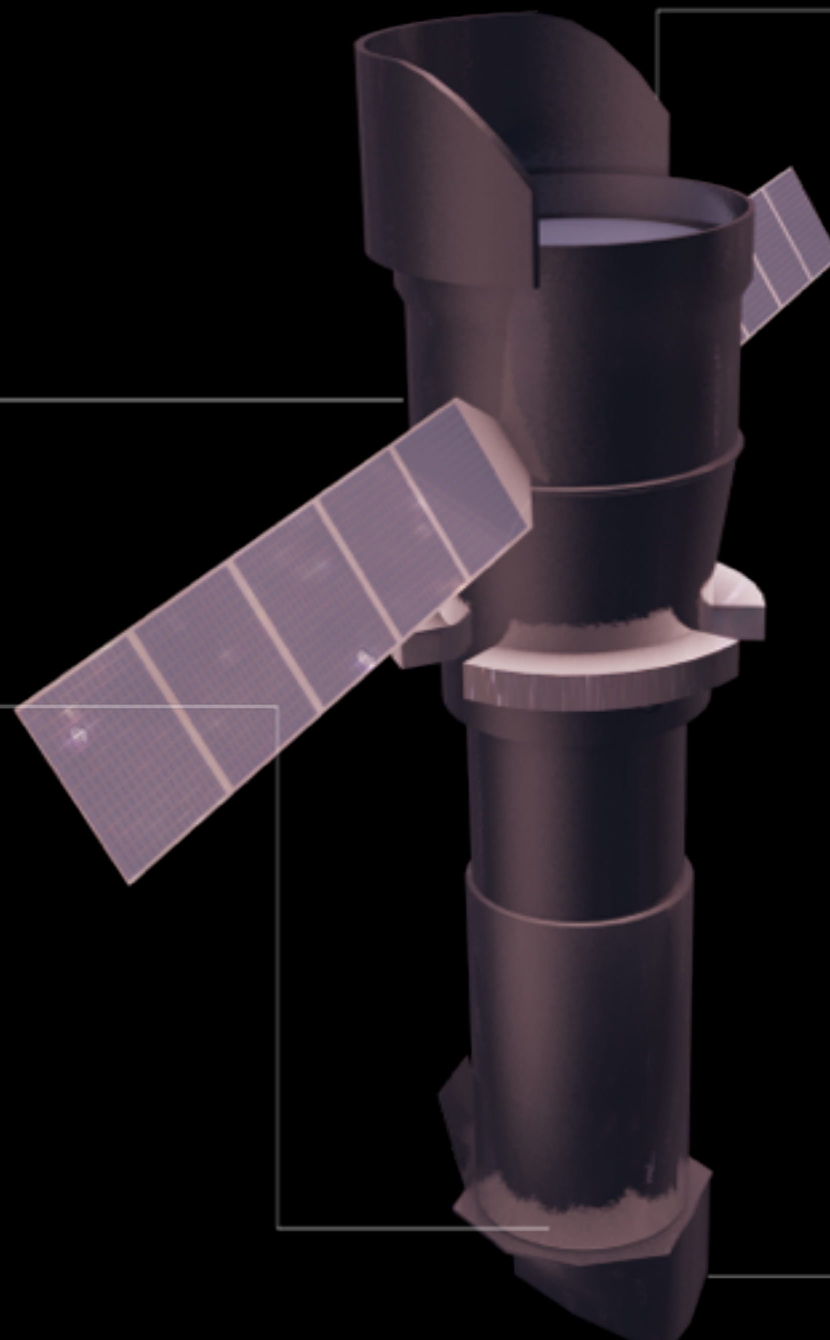
Mission proposal submitted on behalf of the Athena team

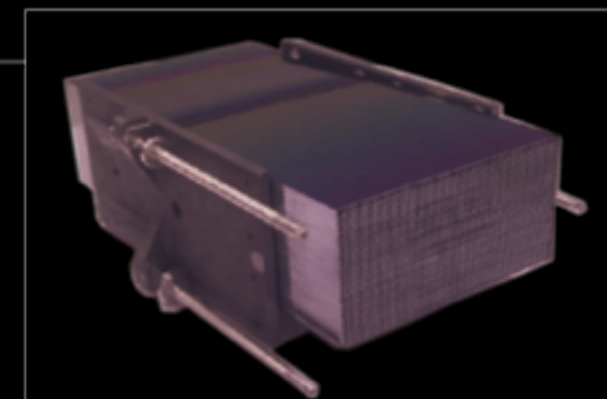
ATHENA

The Athena Observatory

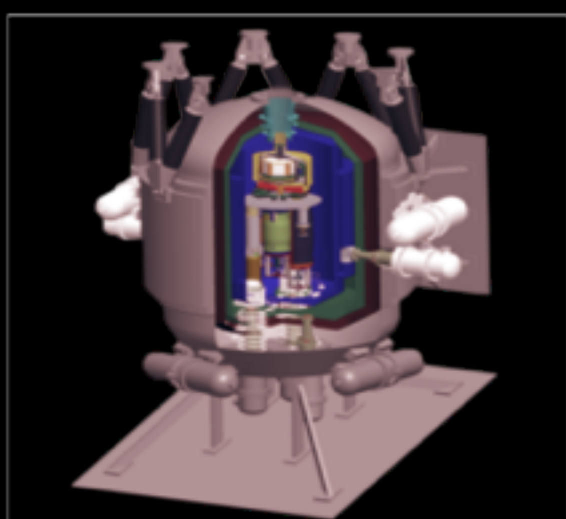
Willingale et al, 2013
arXiv1308.6785

L2 orbit Ariane V
<5100 kg
power 2500 w
5 year mission



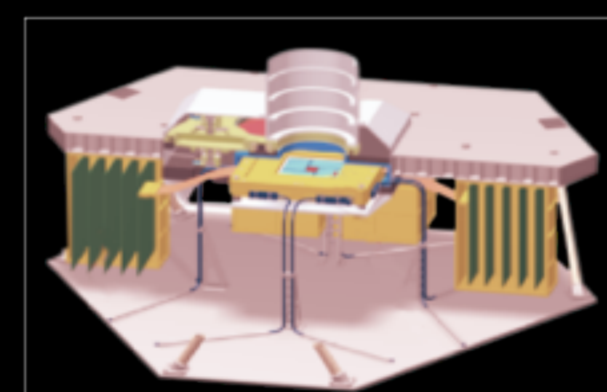


Silicon Pore Optics:
$2\ m^2$ at 1 keV
5 arcsec HEW
Focal length: 12m
Sensitivity: $3\ 10^{-17}$ erg $cm^{-2}\ s^{-1}$



X-ray Integral Field Unit:
ΔE: 2.5 eV
Field of View: 5 arcmin
Operating temp: 50 mk

Barret et al., 2013 arXiv:1308.6784

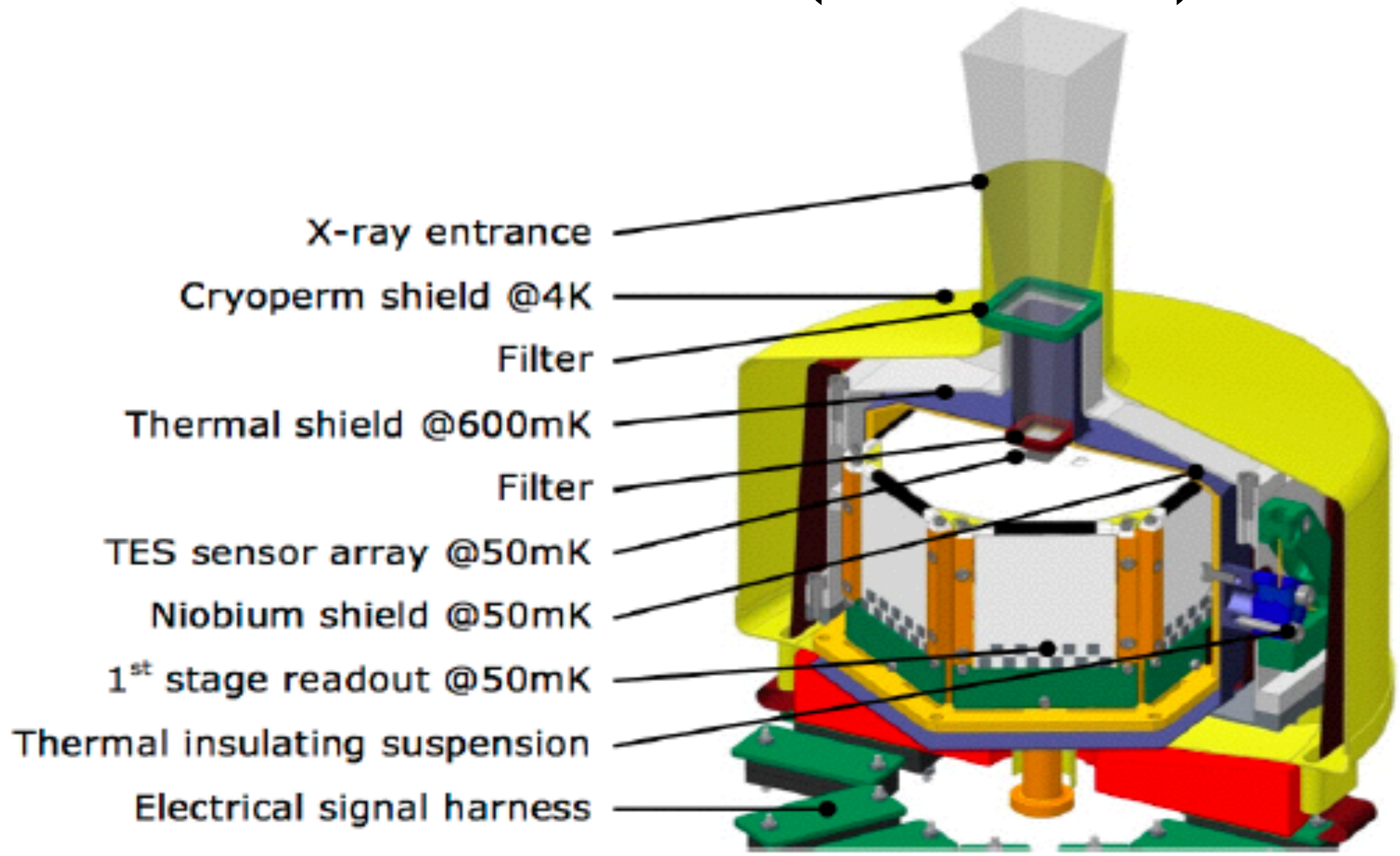


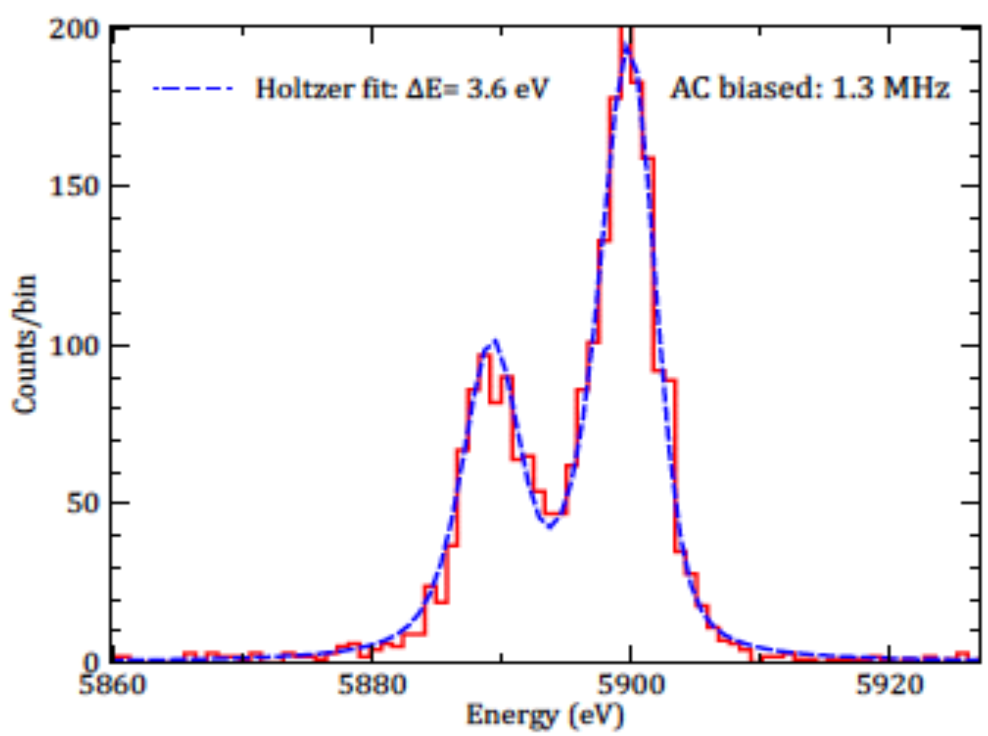
Wide Field Imager:
ΔE: 125 eV
Field of View: 40 arcmin
High countrate capability

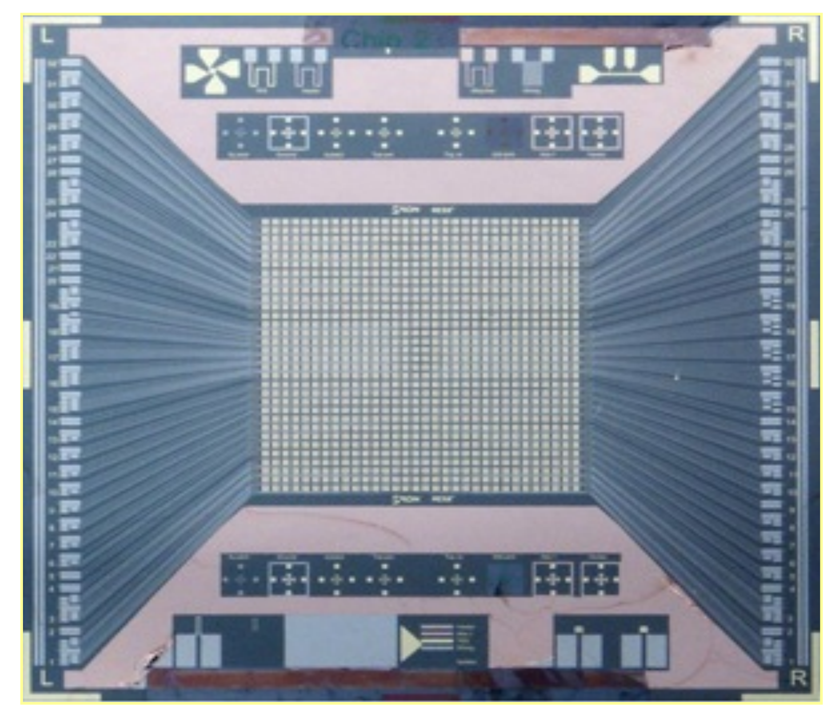
Rau et al. 2013 arXiv1307.1709

X-Ray Integral Field Unit (X-IFU)

- Transition Edge Sensor microcalorimeter in a cryostat @ 50 mK
- 4-kpixel array + CryoAC
- Read-out: FDM multiplexing
- Low instrumental background
- Detector with 32 x 32 array size build
- Cooling system various options







ATHENA - XIFU
the Italian Consortium

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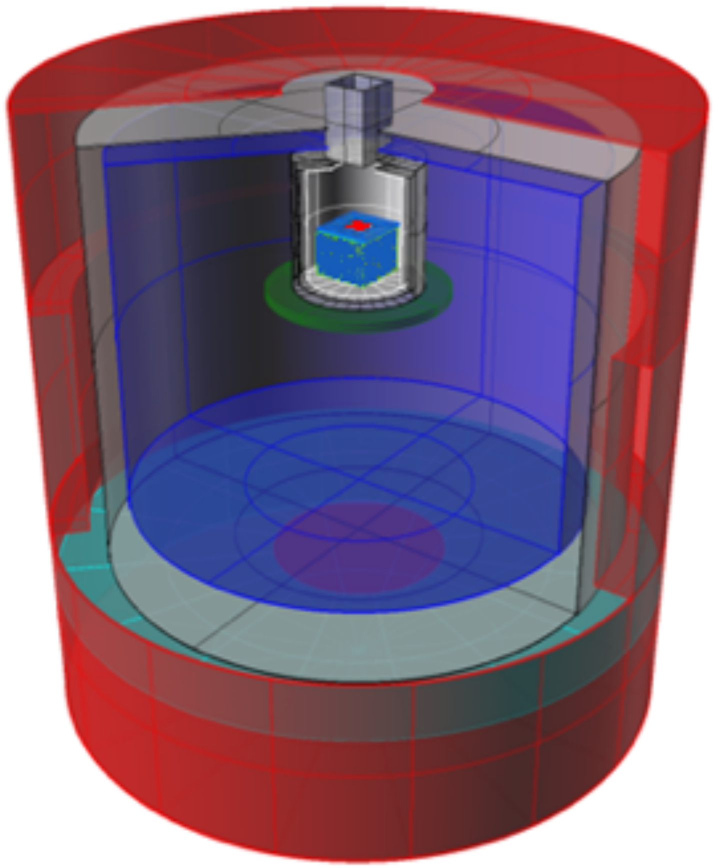
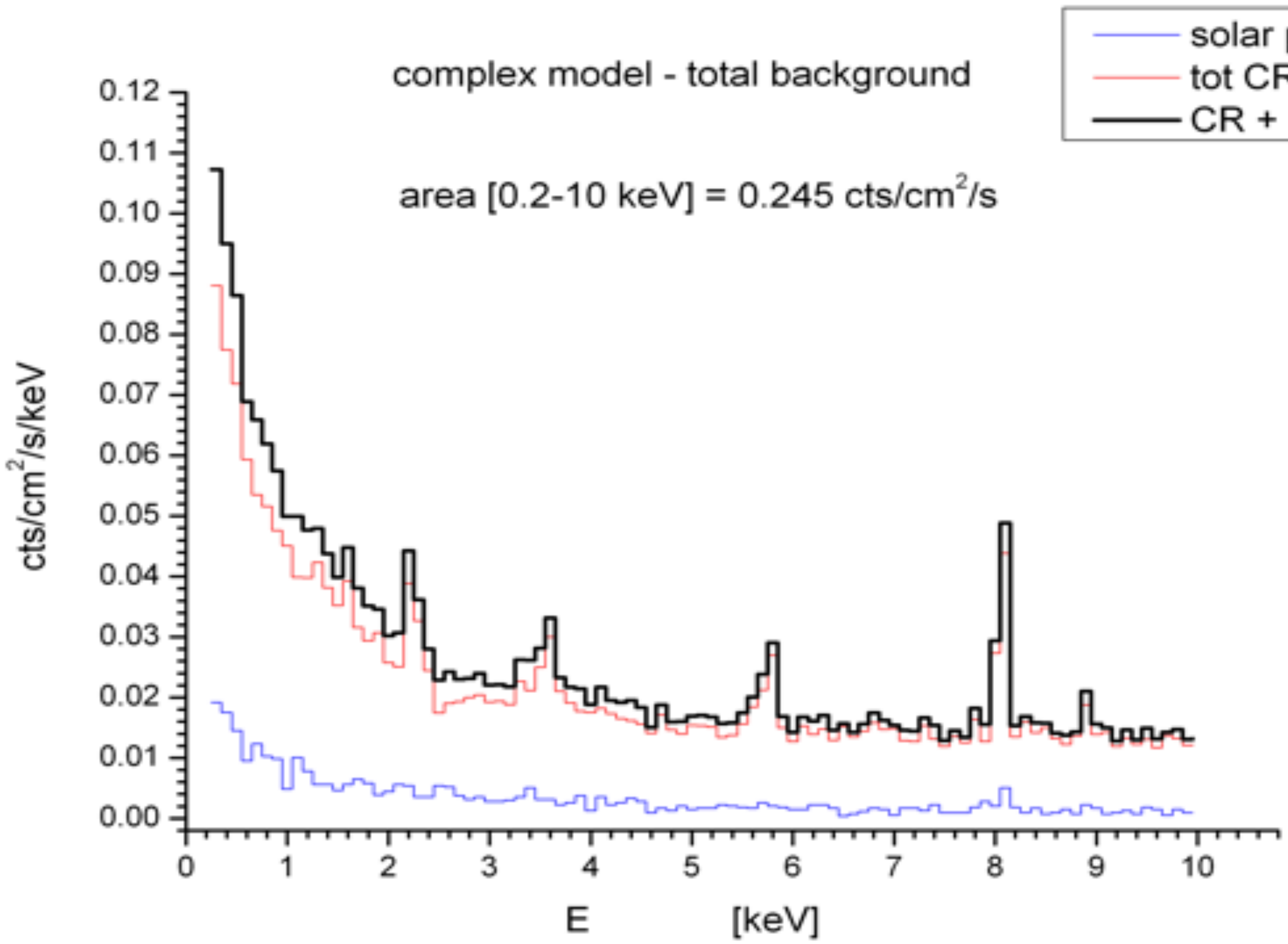
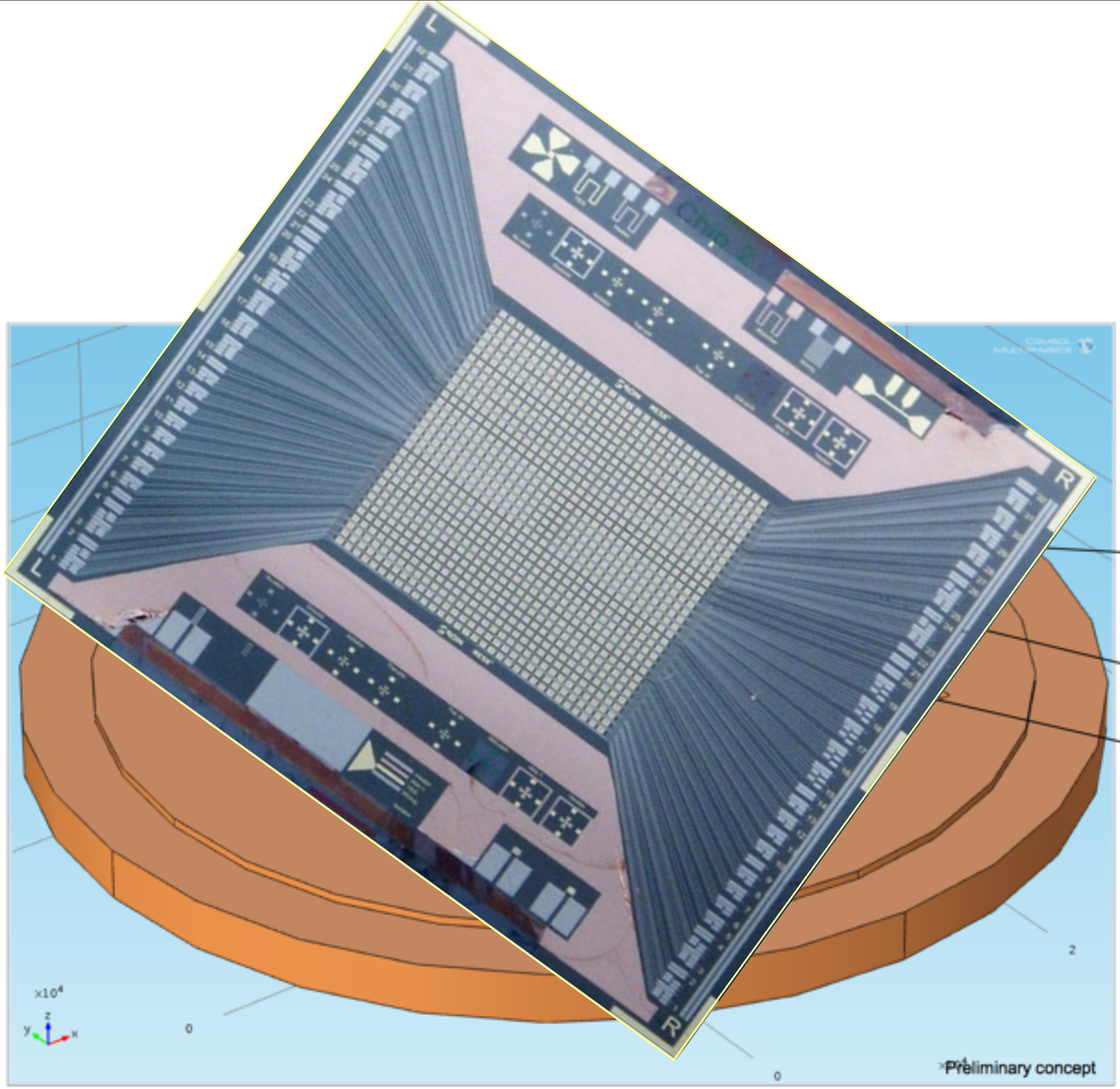
Background simulations and instrument design

- L2 environment (solar+CR)
- Soft protons focussed by mirrors (ray-tracing)
- Primary and secondary particles interacting with structures & detector (GEANT4)
- Present assessment compatible with requirements
- Residual background is dominated by secondary e- produced close to detector => substantial improvement possible with upgraded design & materials







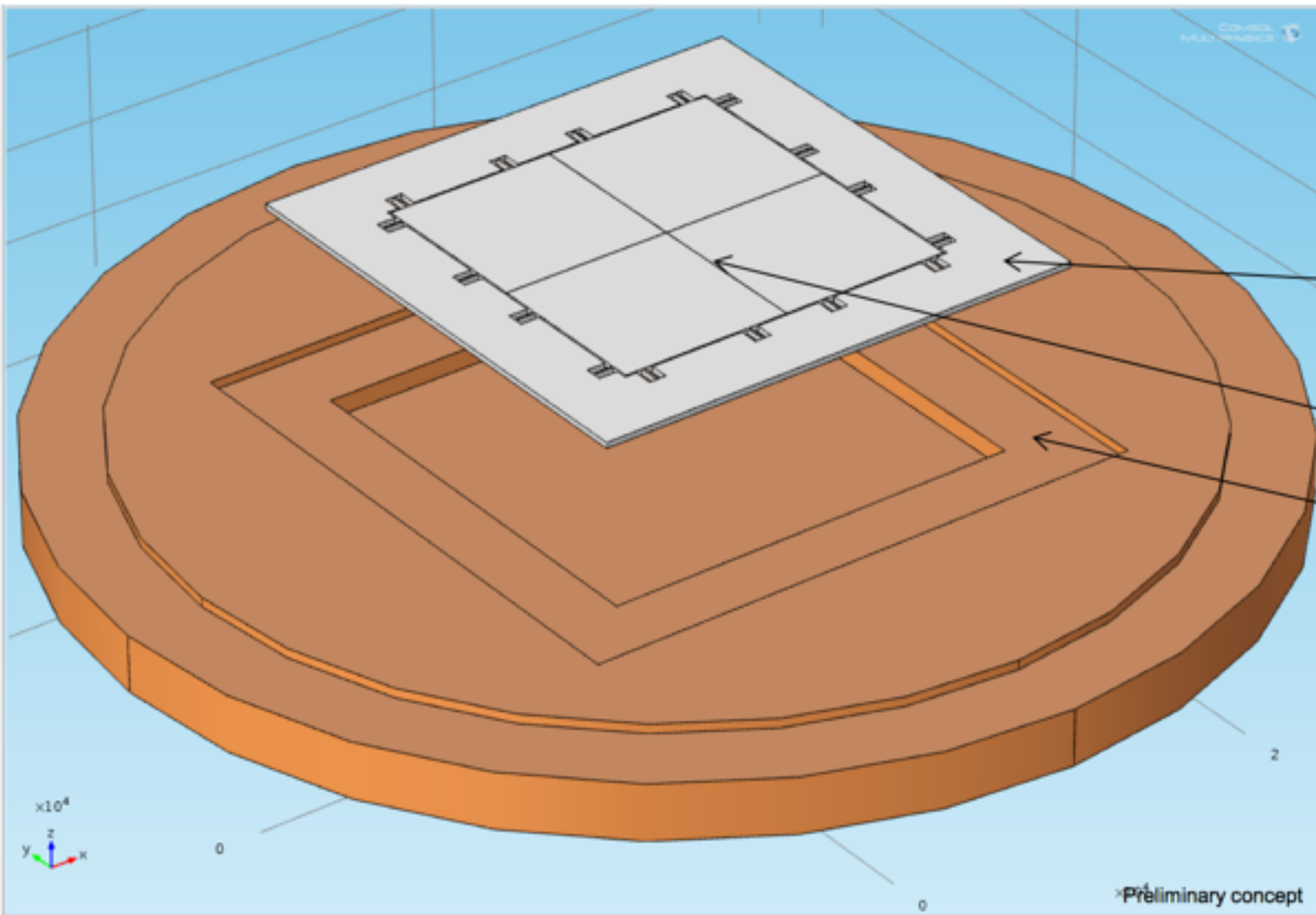
Exploded view

-Unique-process micromachined composite detector suspended by bridges

-Space between detectors: cross 20μm wide

-Copper buffer

A 4 1 cm^2 pixels with TES sensors will be placed
1-2 mm below the X-ray detector at 50 mK



Exploded view

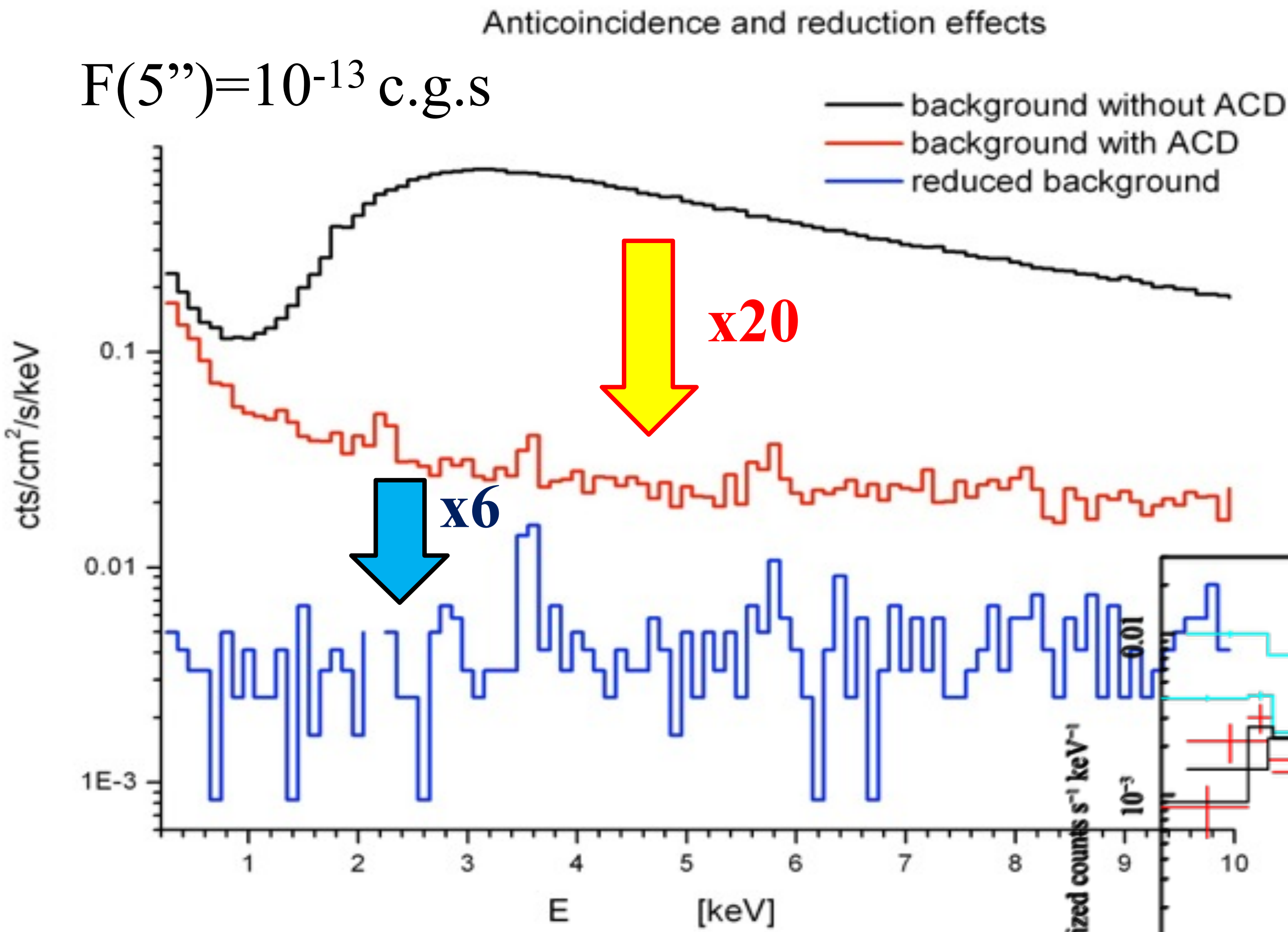
-Unique-process micromachined composite detector suspended by bridges

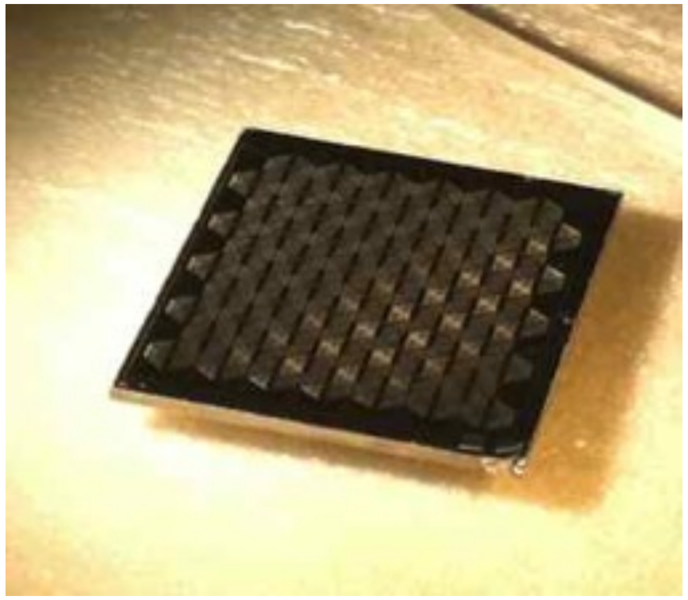
-Space between detectors: cross 20μm wide

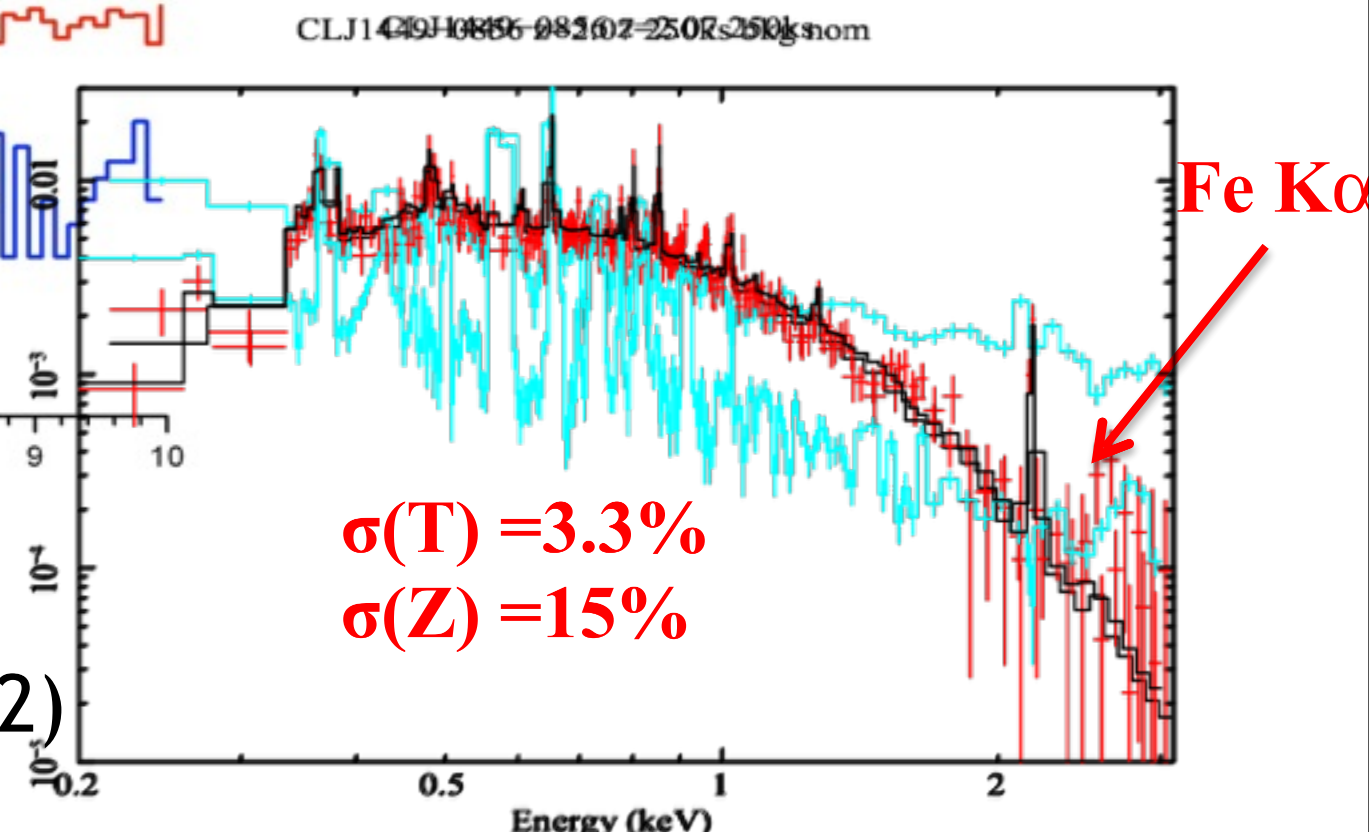
-Copper buffer

Background reduction

$F(5'')=10^{-13}$ c.g.s







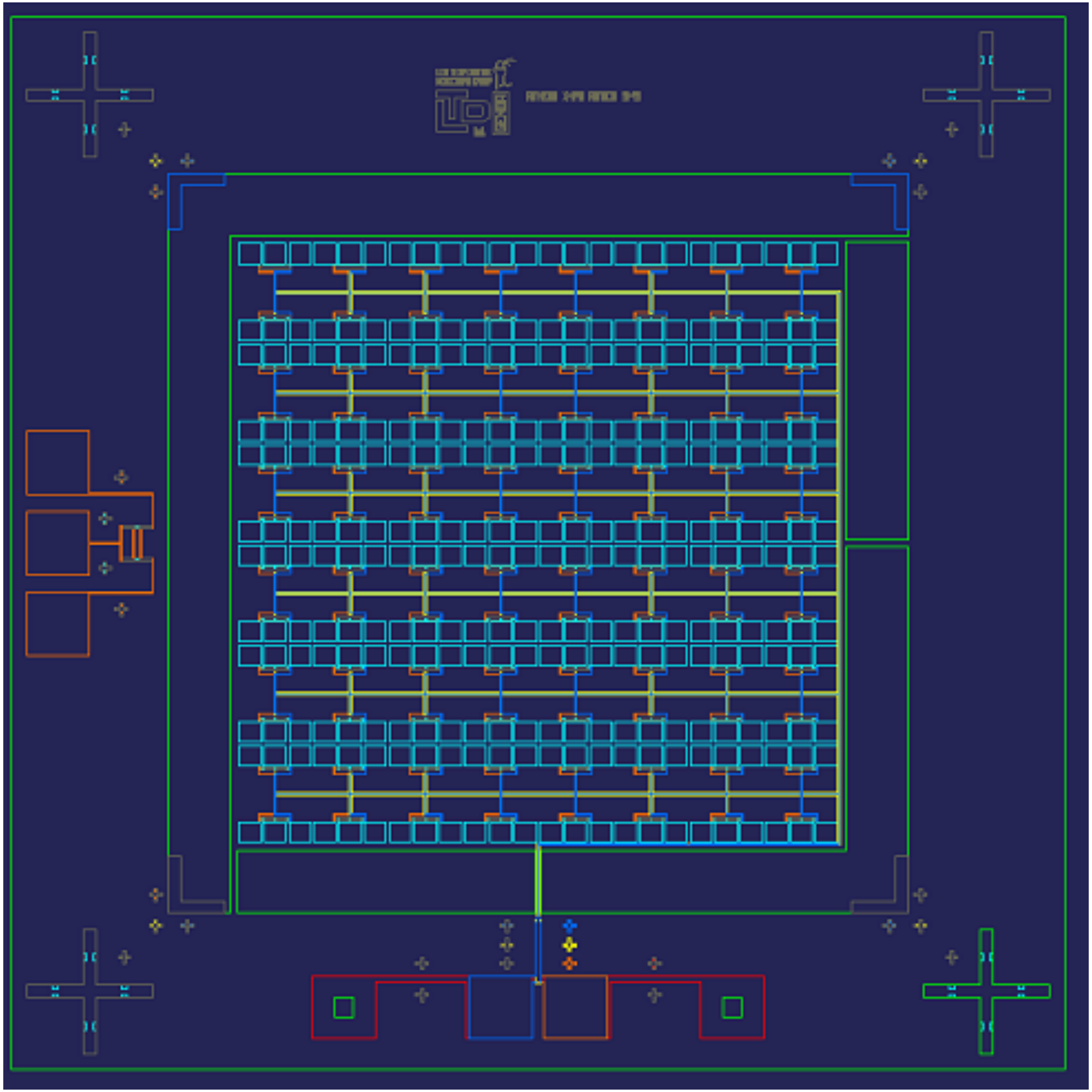
Cluster at the formation epoch (z=2)

$F=10^{-15}$ erg/cm²/s,

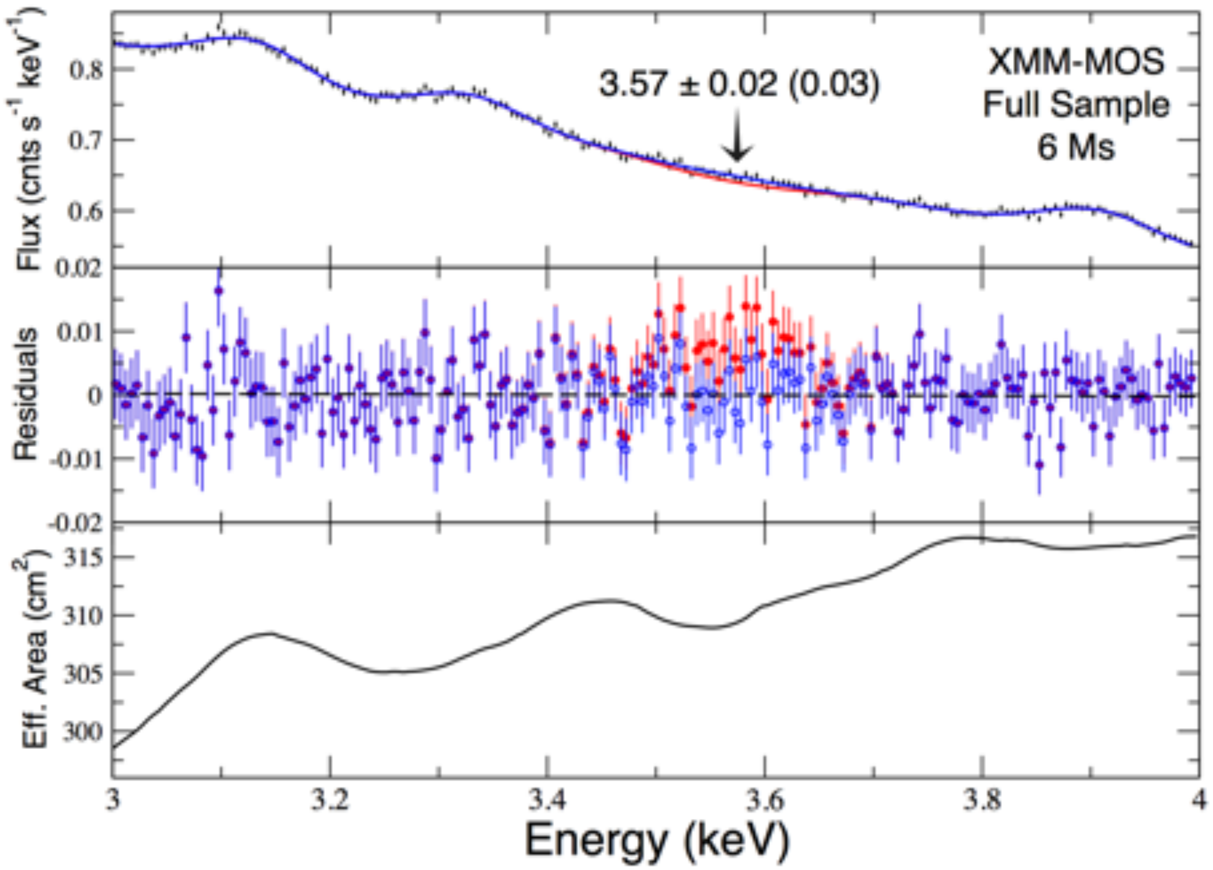
$A=0.2$ arcmin², kT=2.0 keV,

Abundance 0.3, area=1m2,f/l=12m

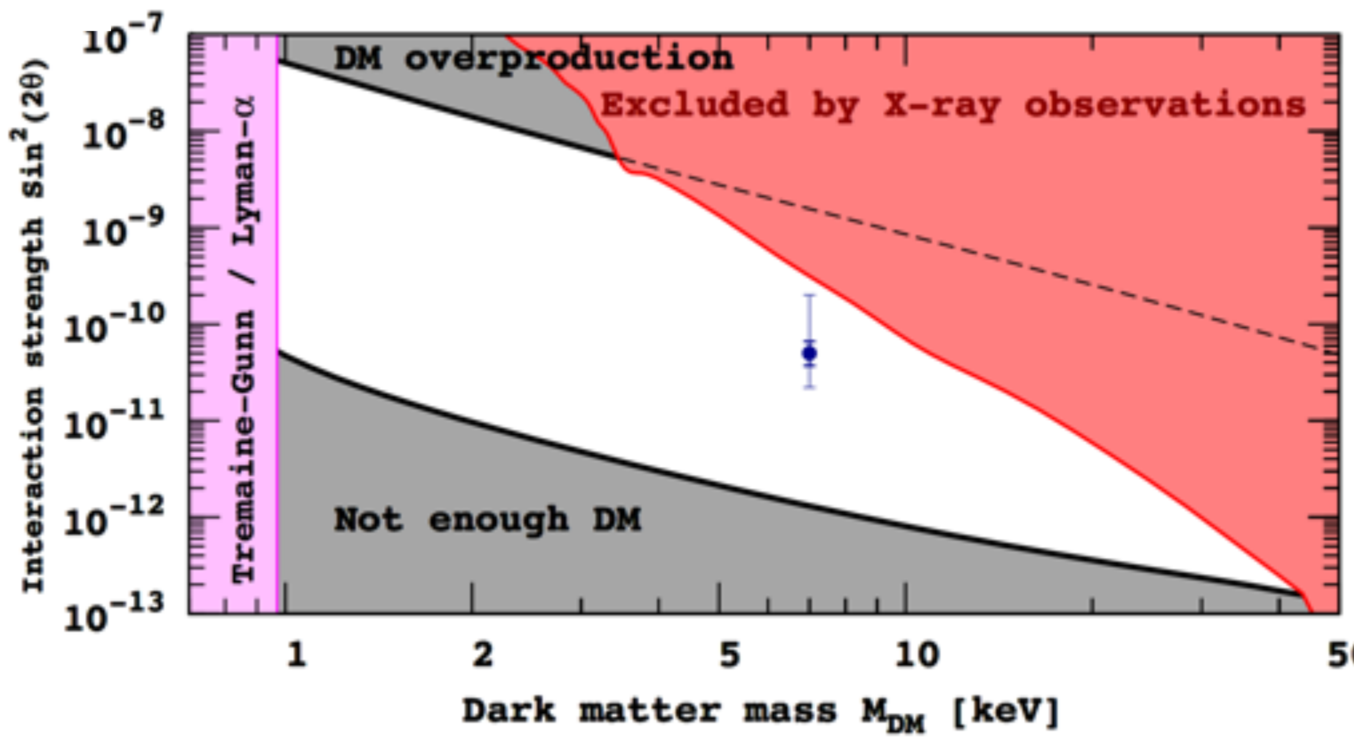
Next Prototype to be released by Genova



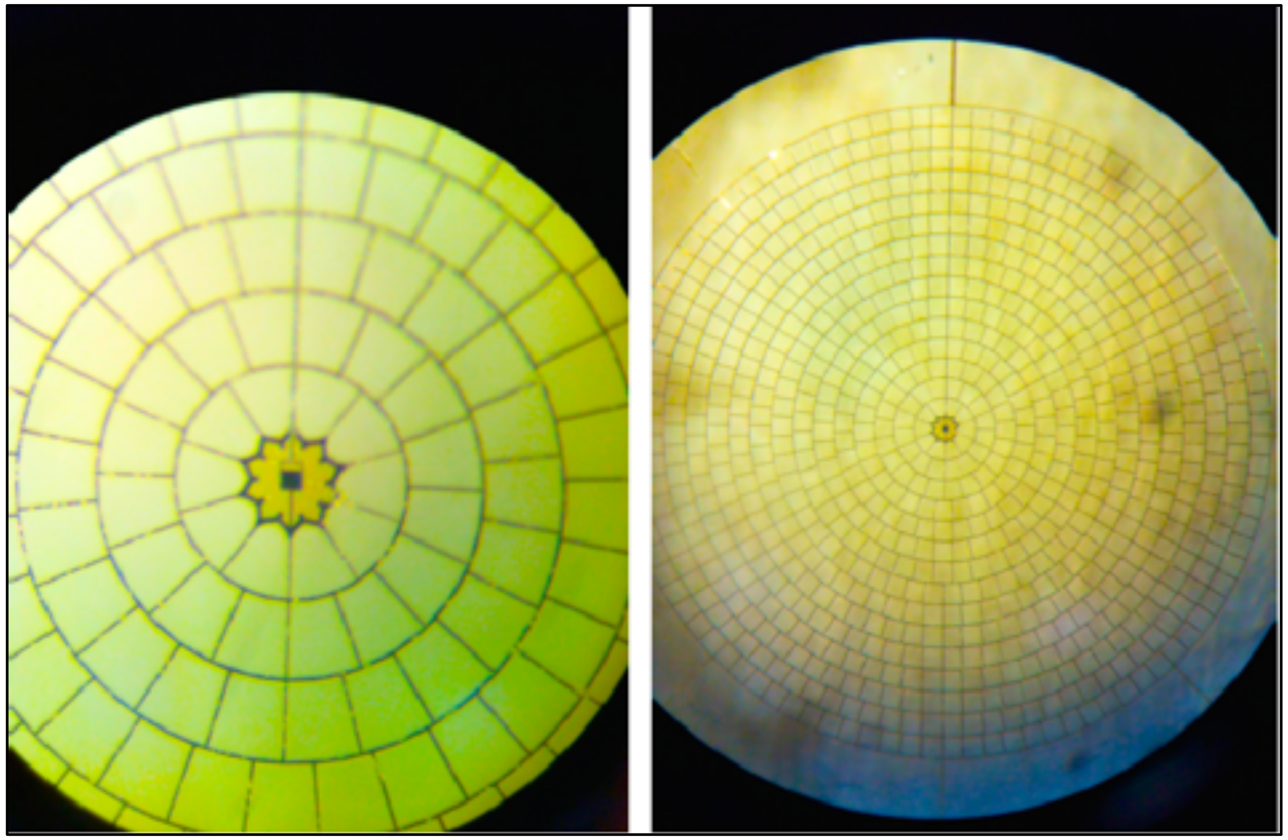
Signal from keV sterile neutrino ?

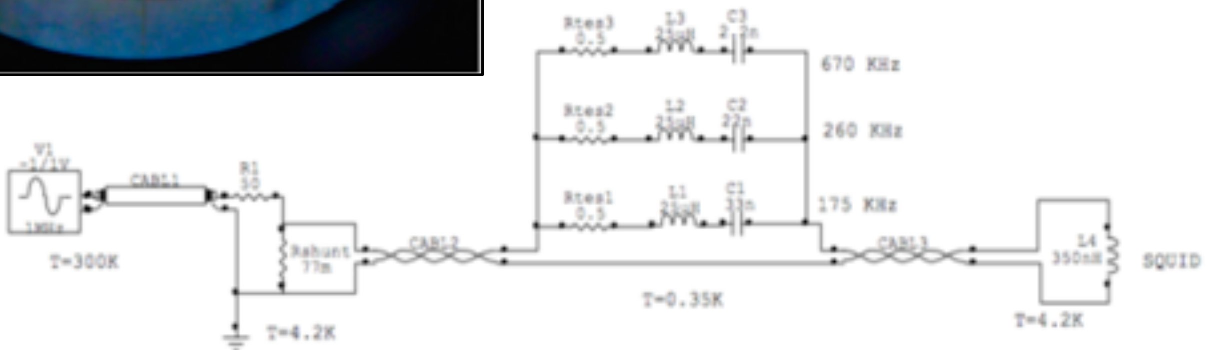


- μcalorimeter in the space will test this signal tanks to the excellent resolutions
- Direct laboratory measurements searching for kink in the β spectra are difficult.



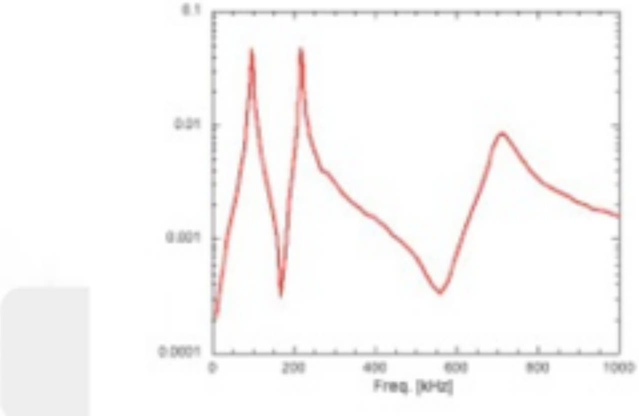
TES for cosmology in Italy

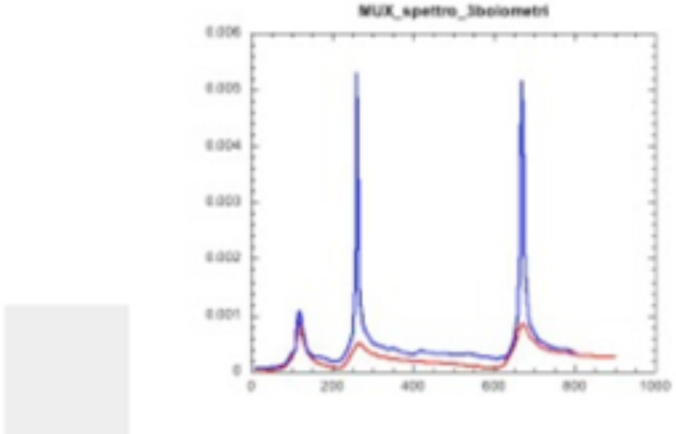




- First Spider Web Bolometer ever fabricated and tested in Italy

- Largest area bolometers for multimode high sensitivity pol.CMB measurement





Conclusions

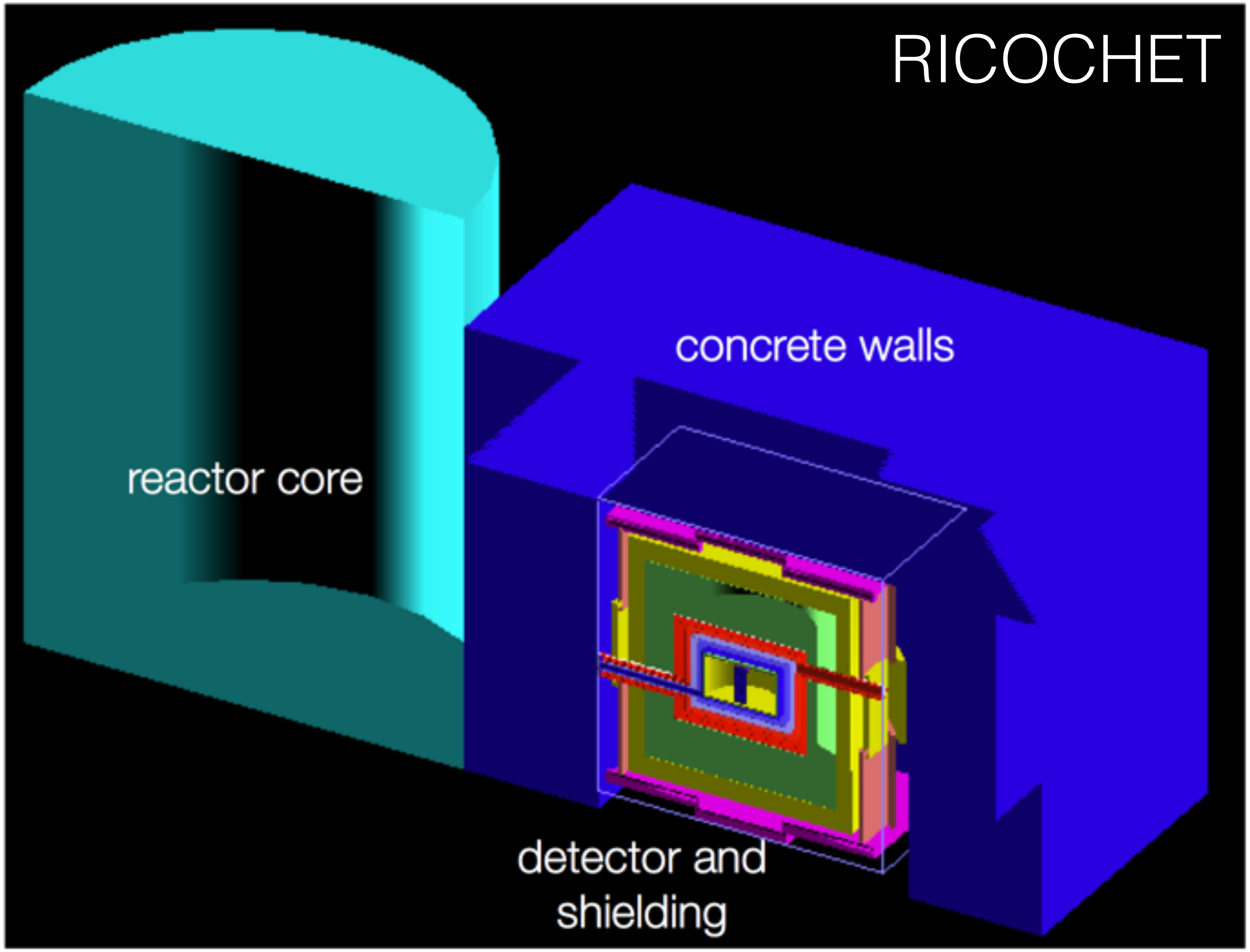
- *Calorimetric detectors provide high resolution tool for full absorption spectroscopy that apply to neutrino single and double beta decay*

- *The HOLMES project for direct search of neutrino mass with Ho-163 just started: A sensitive pilot experiment is foreseen in 5 years from now. Fully funded by the ERC.*

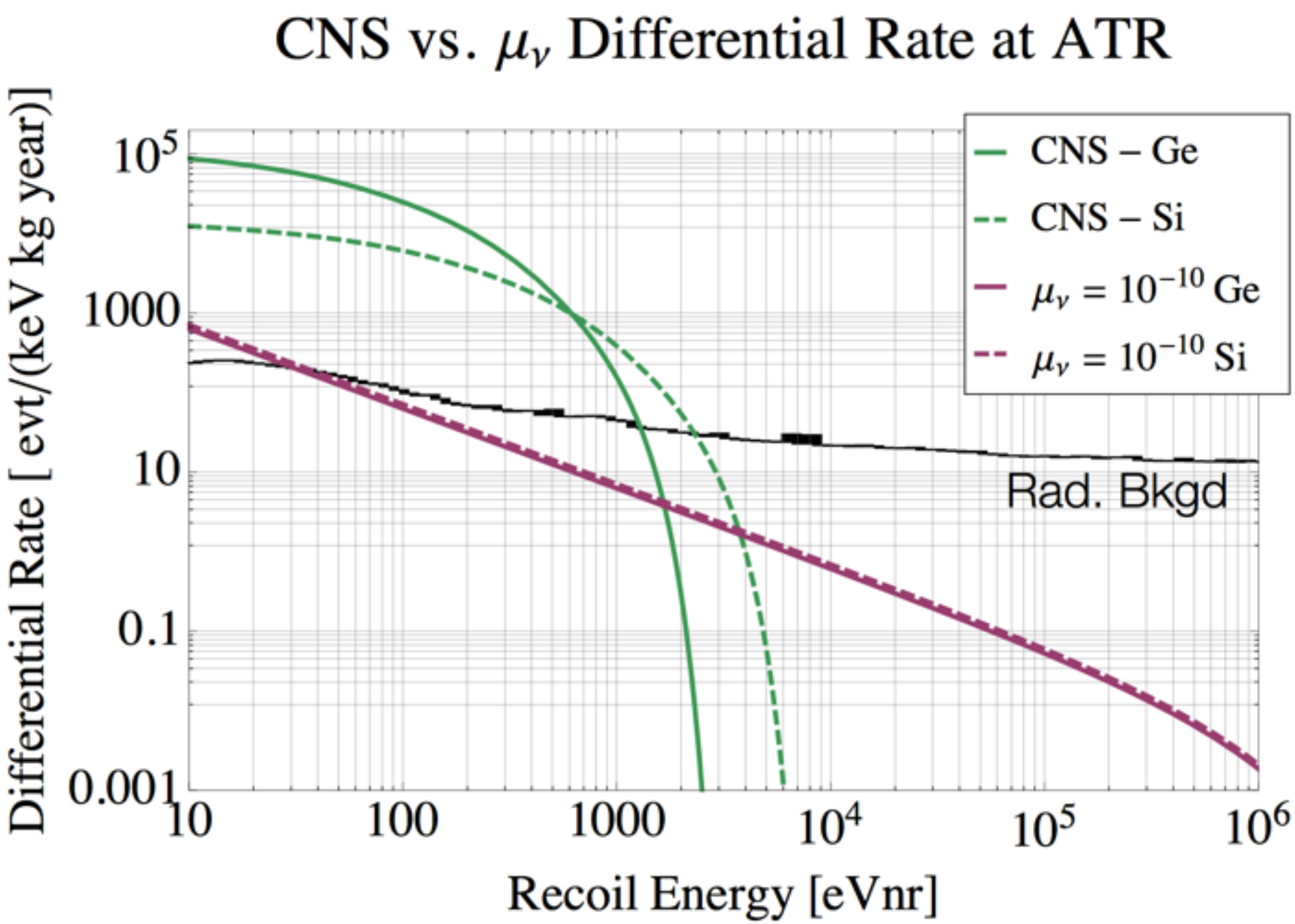
- *X-IFU of the ATHENA mission will be hopefully the first large observatory with array of 2 eV μcalorimeter for 2030 decade*

- *Possible Ballon borne missions based on large area multimode spiderweb bolometers can provide higher sensitivity instrument to the polarisation signal in respect to the single mode detection.*

Coherent neutrino scattering



CNS and Mag. Moment signal



Enectali Figueroa Feliciano - MIT