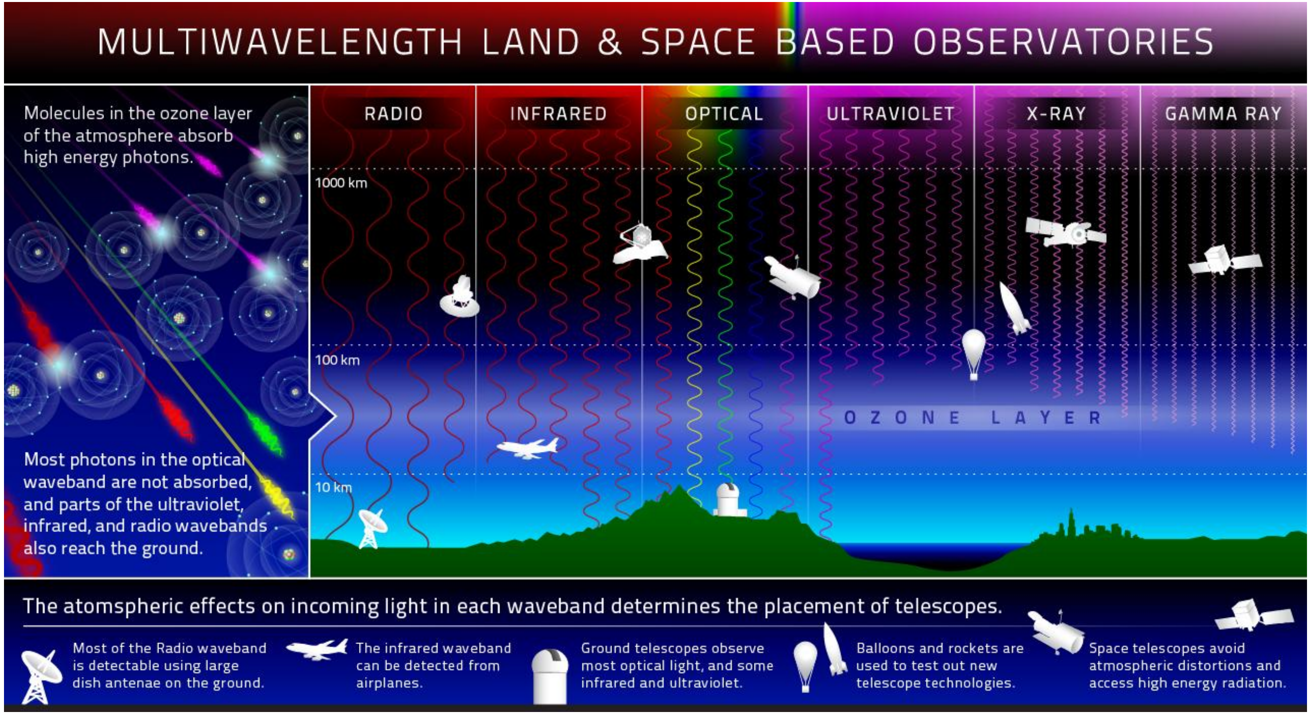
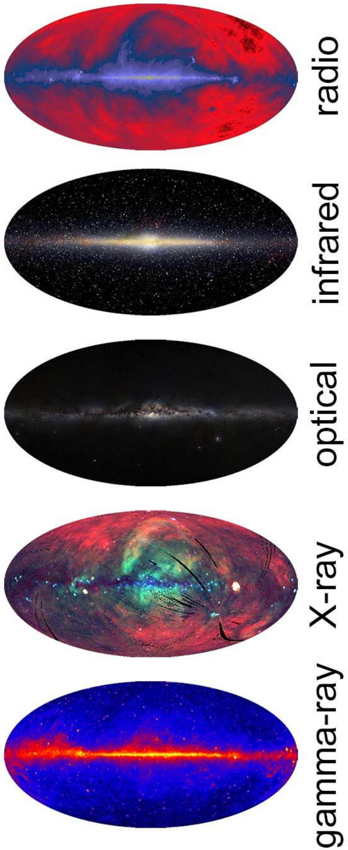
LTDs for cosmology and astrophysics

Manuel Gonzalez - DRTBT 2024
Aussois France

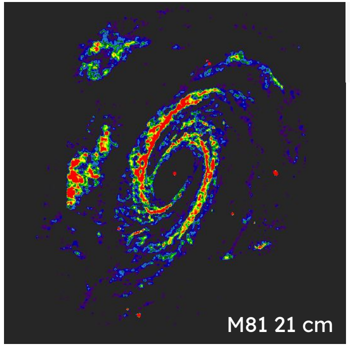
Multiwavelength astronomy

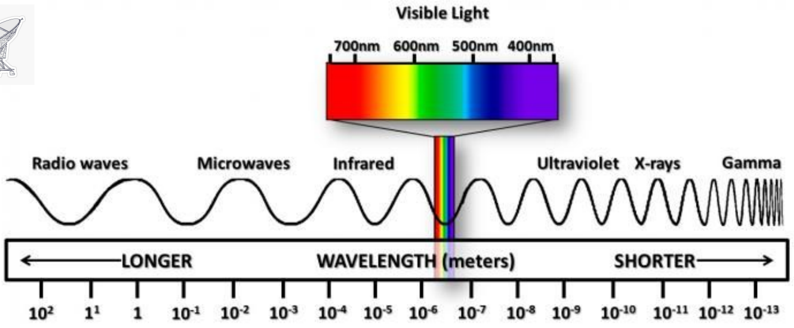


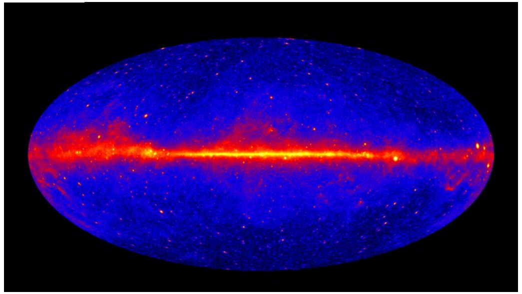


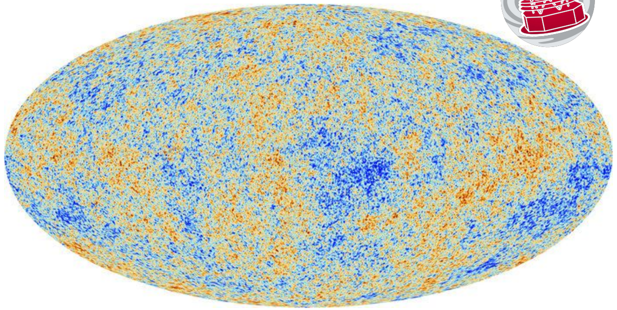
https://ecuip.lib.uchicago.edu/multiwavelength-astronomy/

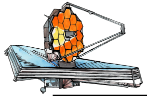
Multiwavelength astronomy

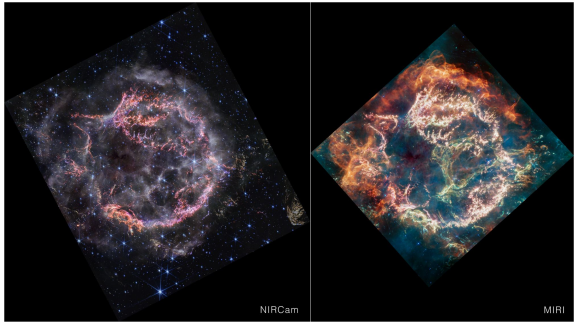


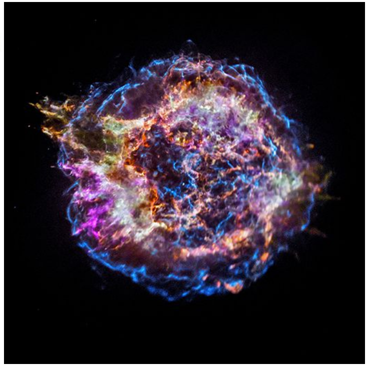




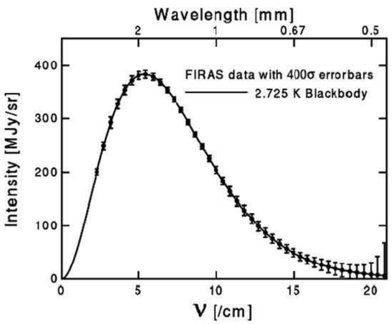


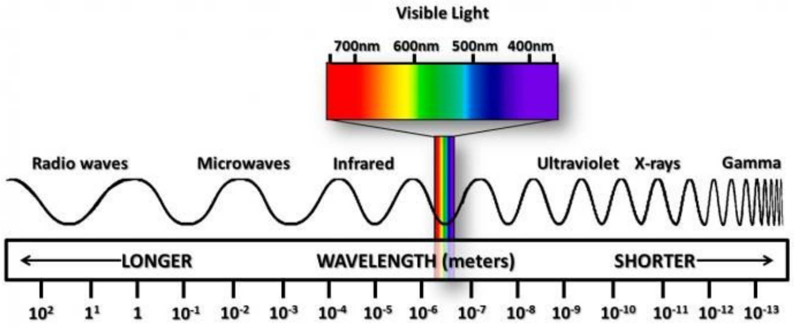


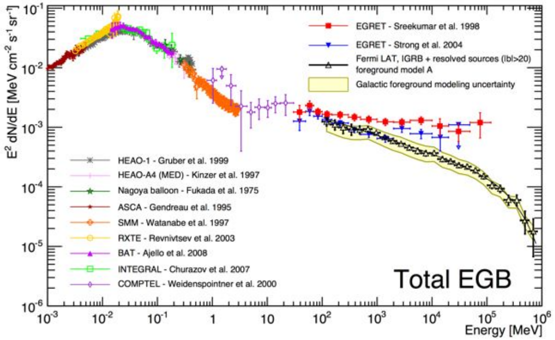


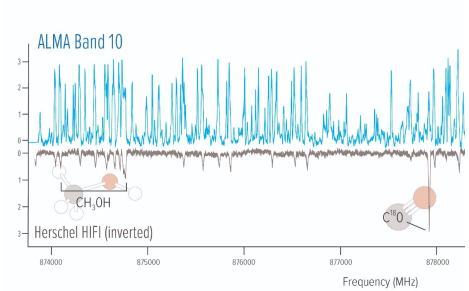


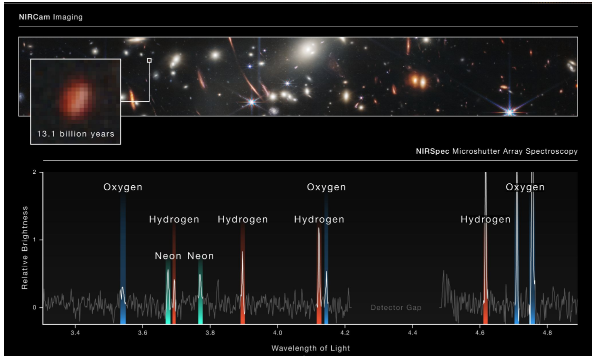
Multiwavelength astronomy - spectral measurements

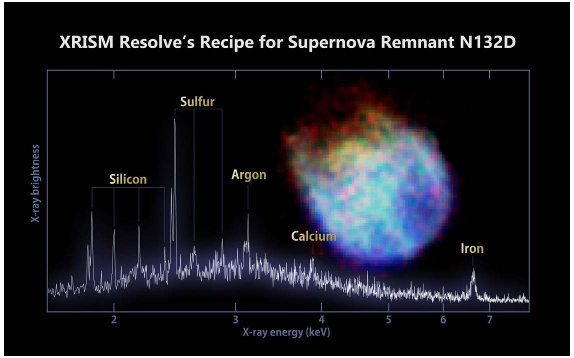








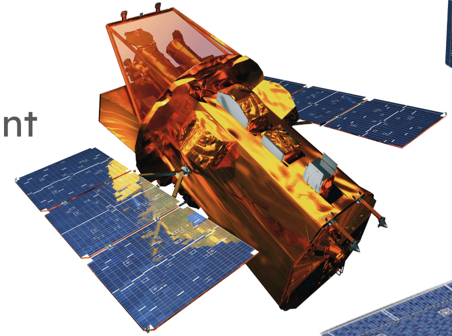




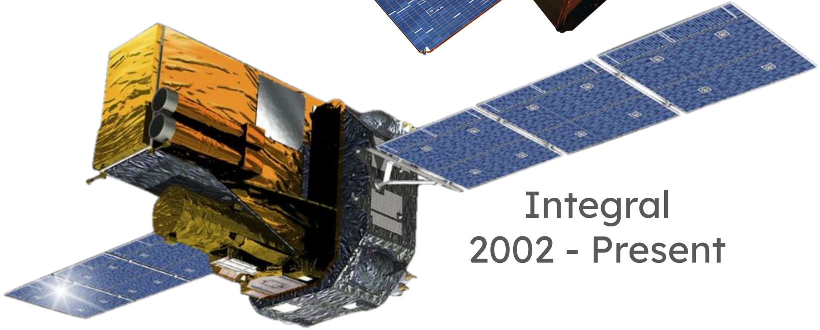
Gamma-ray instruments

Up to very high energies, gamma astronomy is done from space.

SWIFT
2004 - Present

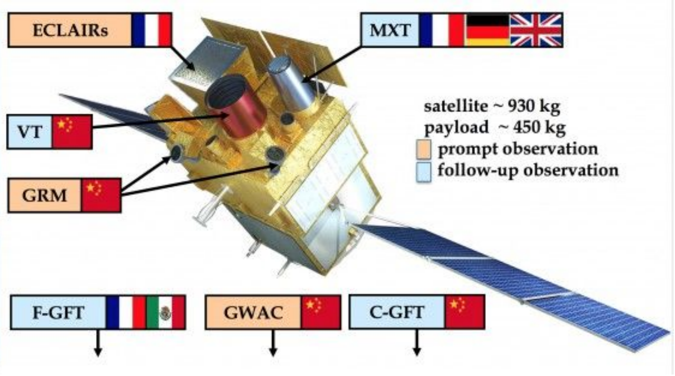


Fermi
2008 - Present



Integral
2002 - Present

SVOM
2024

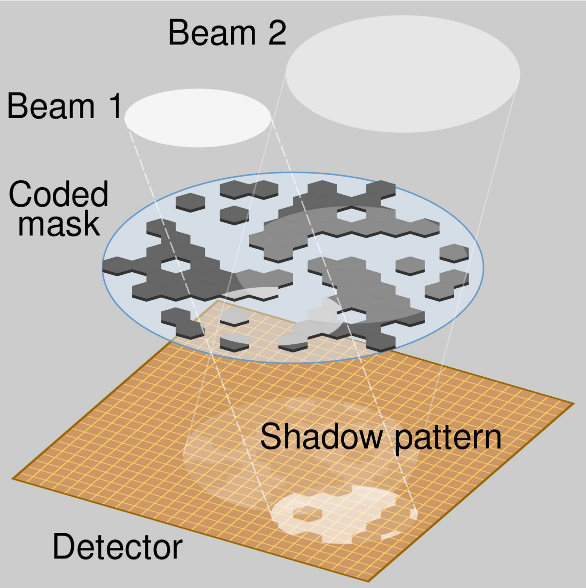


No cryogenic detectors!

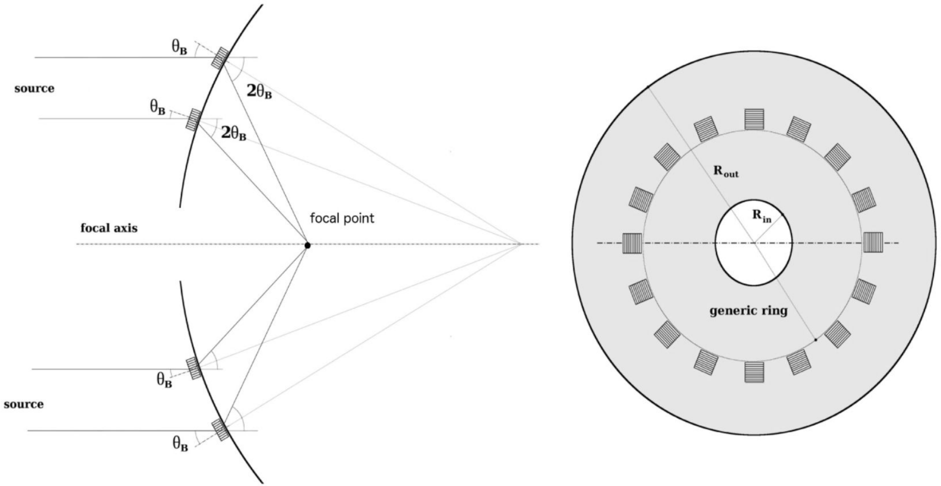
Gamma ray optics

Current instruments don't use focusing optics. Maybe in the future…

Current approach, coded mask (SVOM)



LAUE lens concept of focusing optics

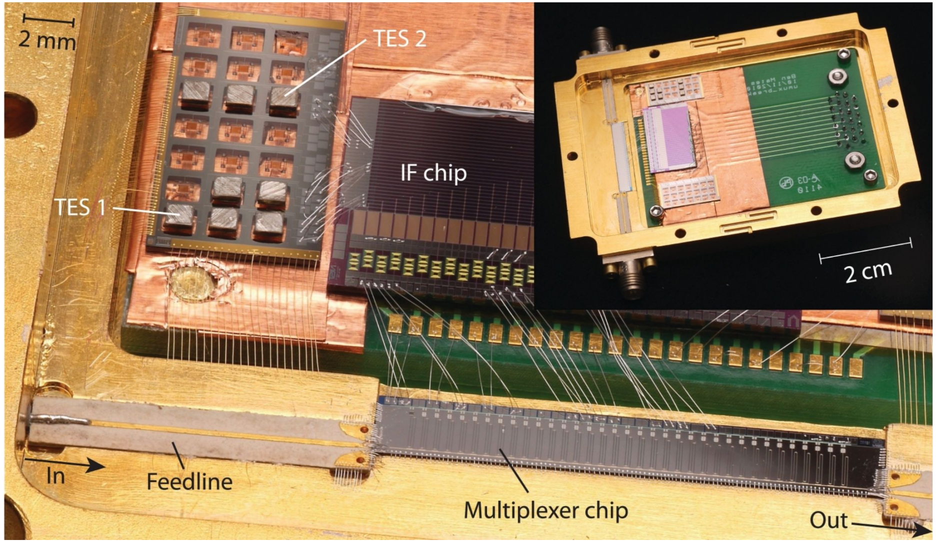


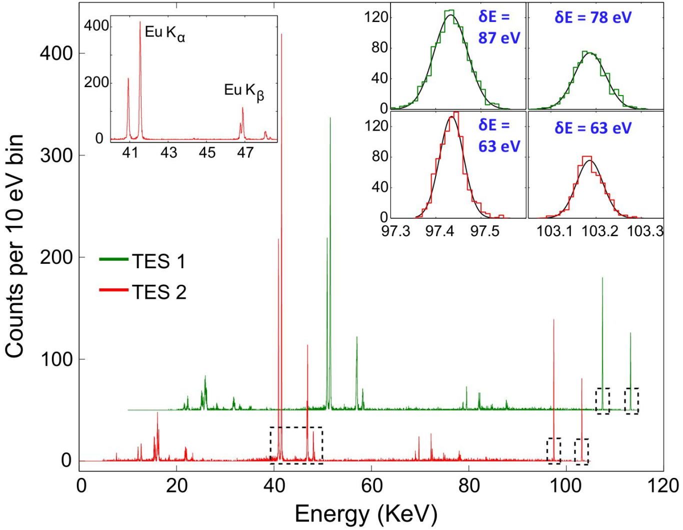
Gamma-ray detectors

E>20 keV

Currently, no LTD based instruments: no focusing optics ➡ large focal planes (~2500cm^2)

However, development of detectors have been made (TES and MMC).





arXiv:1310.7287 **[physics.ins-det]**

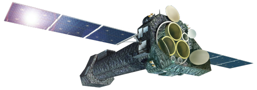
X-ray astronomy

X-ray sources, highly ionized hot plasmas (10^6 to 10^9 K)

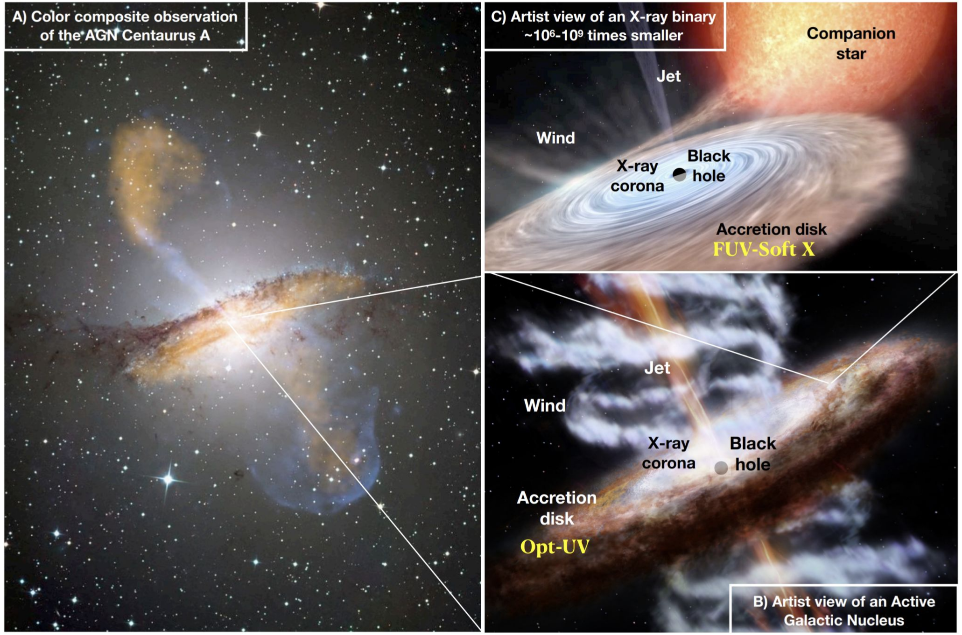
- The energetic Universe (compact objects, harder spectrum)
  - Black Holes
  - Binary systems
  - AGN
  - Gamma-Ray Bursts
- The hot Universe (extended sources, softer spectrum)
  - Supernovae remnants
  - Circumgalactic Medium (CGM)
  - Intergalactic Medium (IGM)

Continuous spectrum (Thermal Bremsstrahlung and Synchrotron) + **narrow emission lines**

Current instruments: Chandra (1999), XMM-Newton (1999), eROSITA (2019), **XRISM** (2023)



The energetic universe



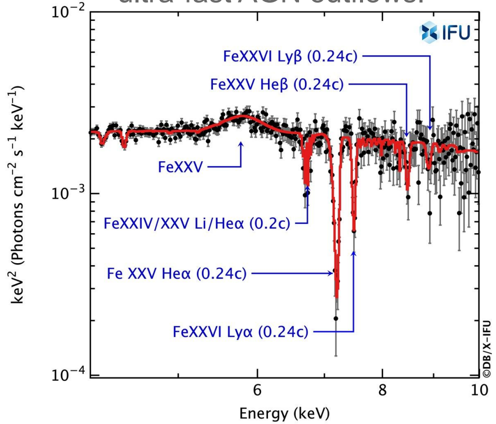
Accretion disk - corona geometry

AGN feedback mechanism

High resolution spectroscopy of absorption and emission lines:

- Composition
- Temperature
- Velocity
- Density

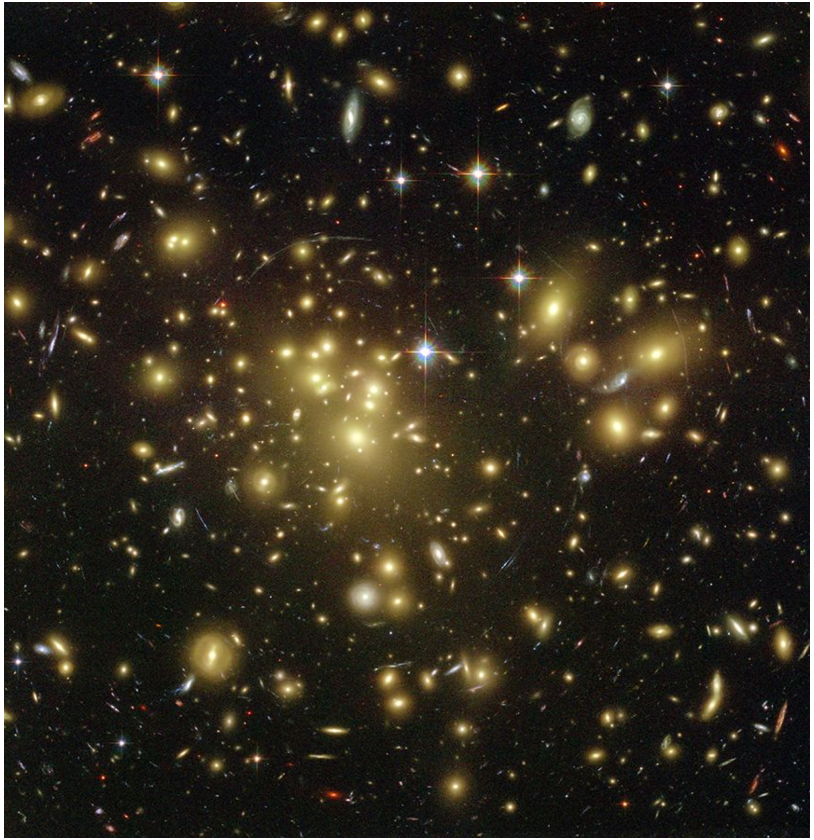
ultra-fast AGN outflows.



Point sources → large mirror

The hot universe (ICM)

Hubble

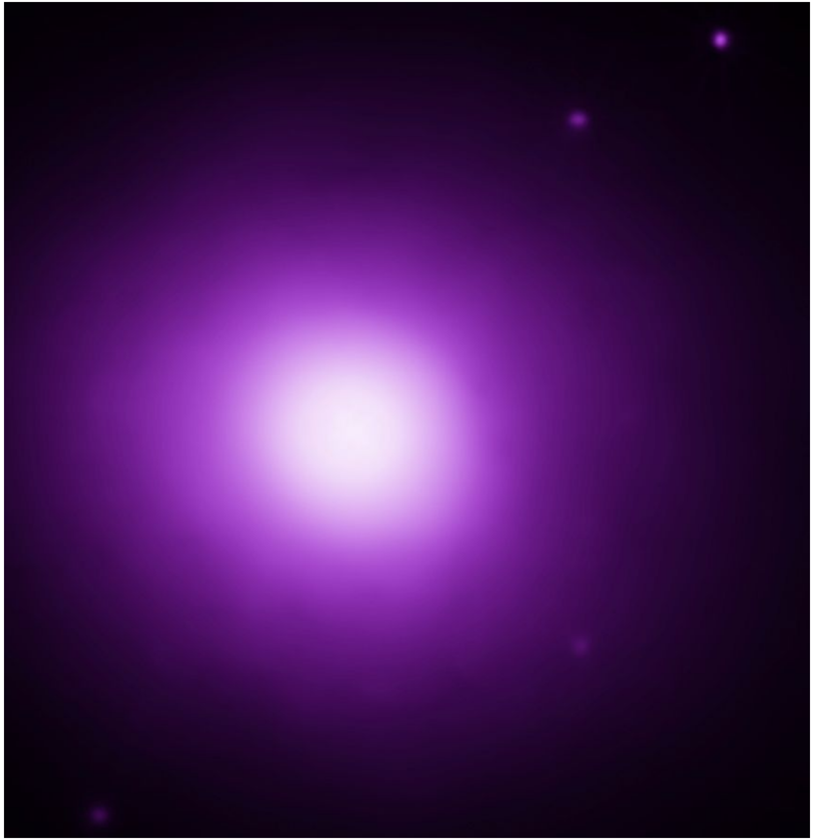


Galaxy cluster
Abel 1689

Extended sources

The hot universe (ICM)

Chandra

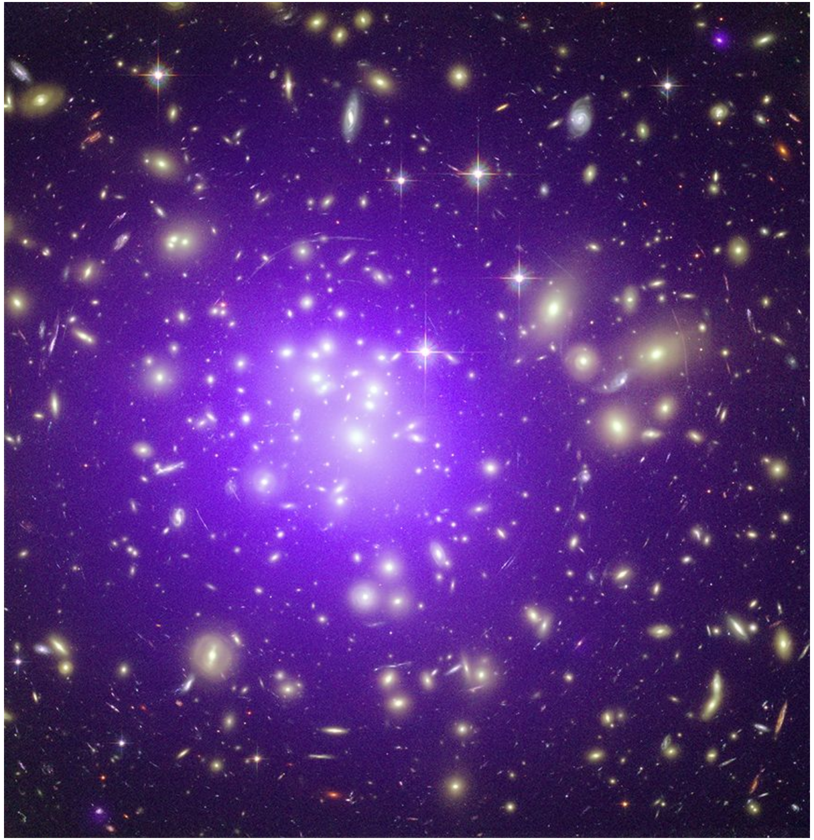


Galaxy cluster
Abel 1689

Extended sources

The hot universe (ICM)

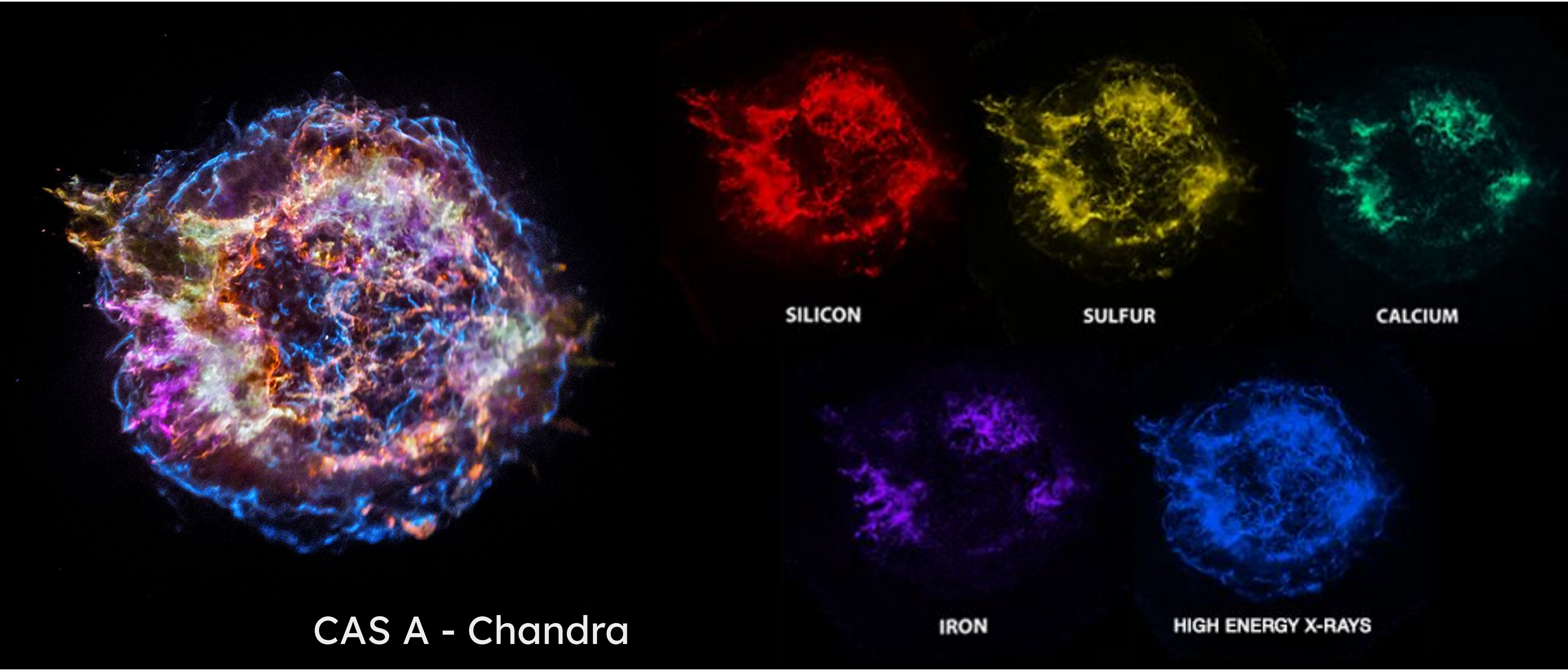
Hubble + Chandra



Galaxy cluster
Abel 1689

Extended sources

The hot universe - supernova remnant

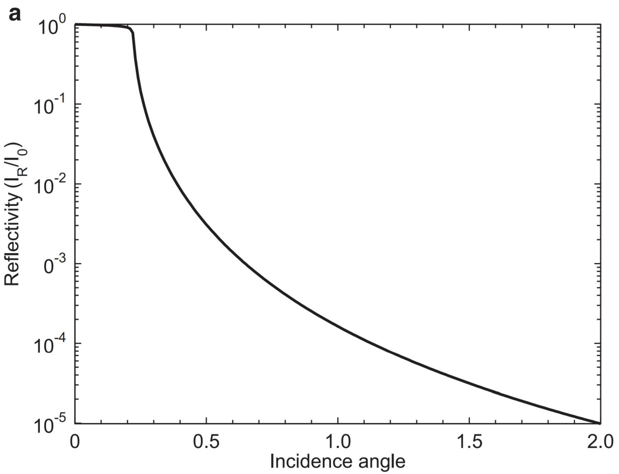


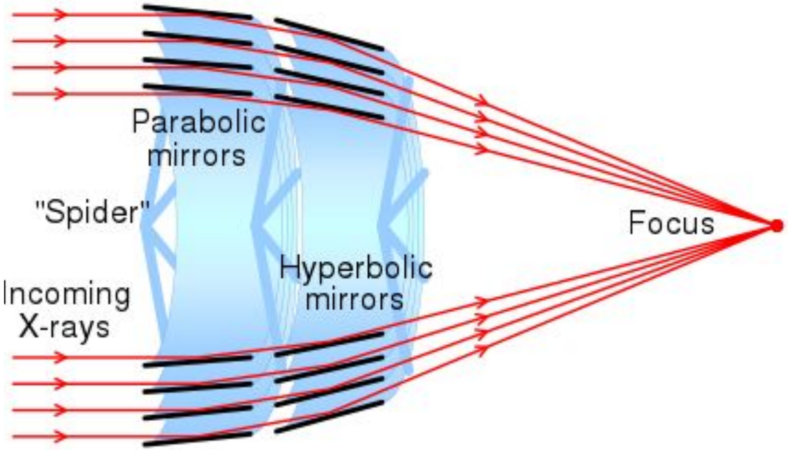
X-Ray instruments

We are limited to observe from space

- Orbit : balloon, low orbit, highly eccentric, L1, L2

X-ray optics: total internal reflection at grazing incidence angle → long focal distances





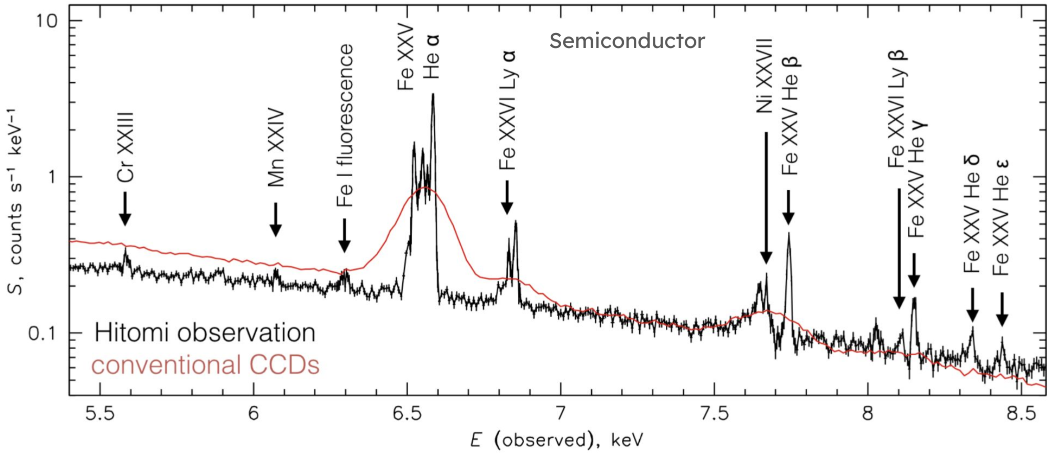
X-ray Spectroimaging

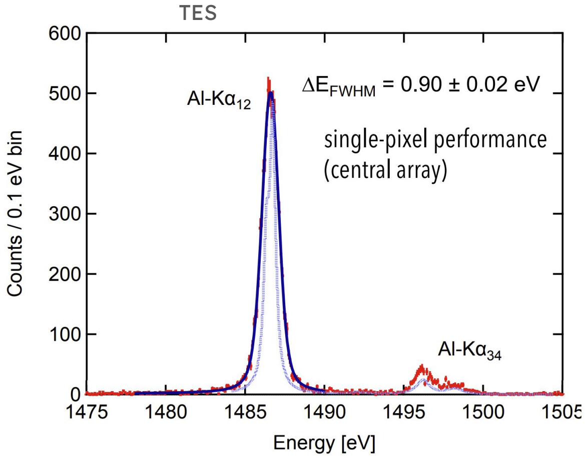
The goal is to determine the arrival **direction** and **time** as well as the **energy** of each photon

Nondispersive imaging spectrometry is required for extended sources

Best **CCD** based detectors provide energy resolution of (**~100 eV @ 7 keV**)

LTDs can do at least 50 times better (**~ 2eV @ 7keV**)





X-ray instruments using LTDs - past and present

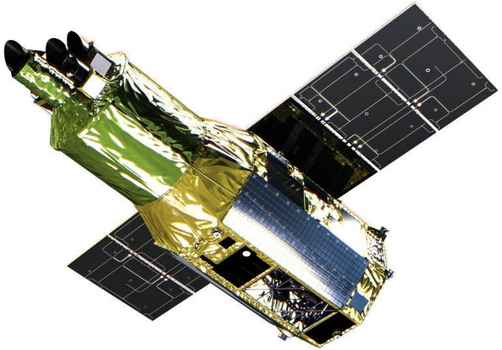
Series of Japanese missions

Astro E (2000)
Launch failure

Suzaku (2005)
Cooling failure

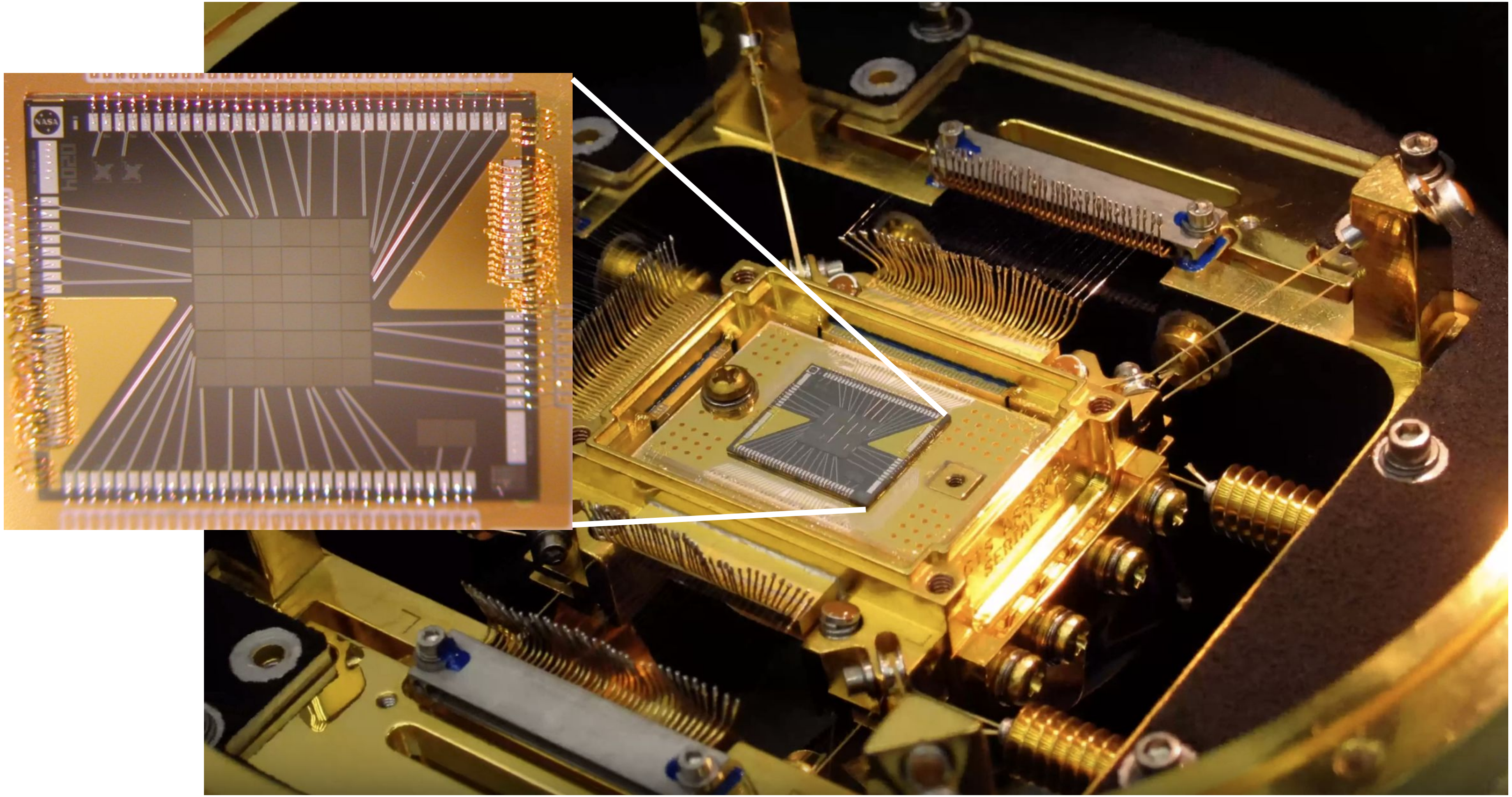
Hitomi (2016)
Attitude control

XRISM (2023)
Success! But...

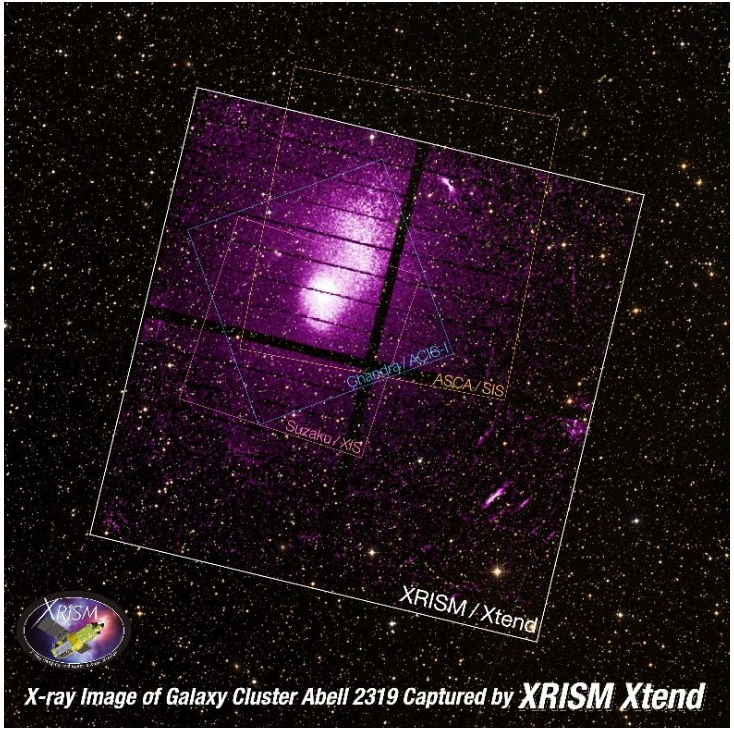


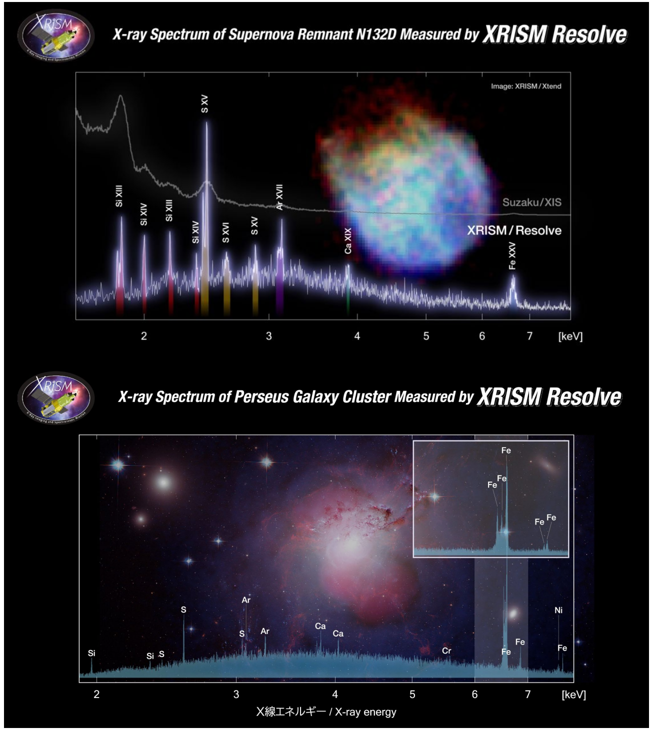
All of these missions had instruments based on cryogenic micro-calorimeters using semiconductor thermistors

XRISM Resolve - Detectors



XRISM - First results, more to come!





January 10, 2024

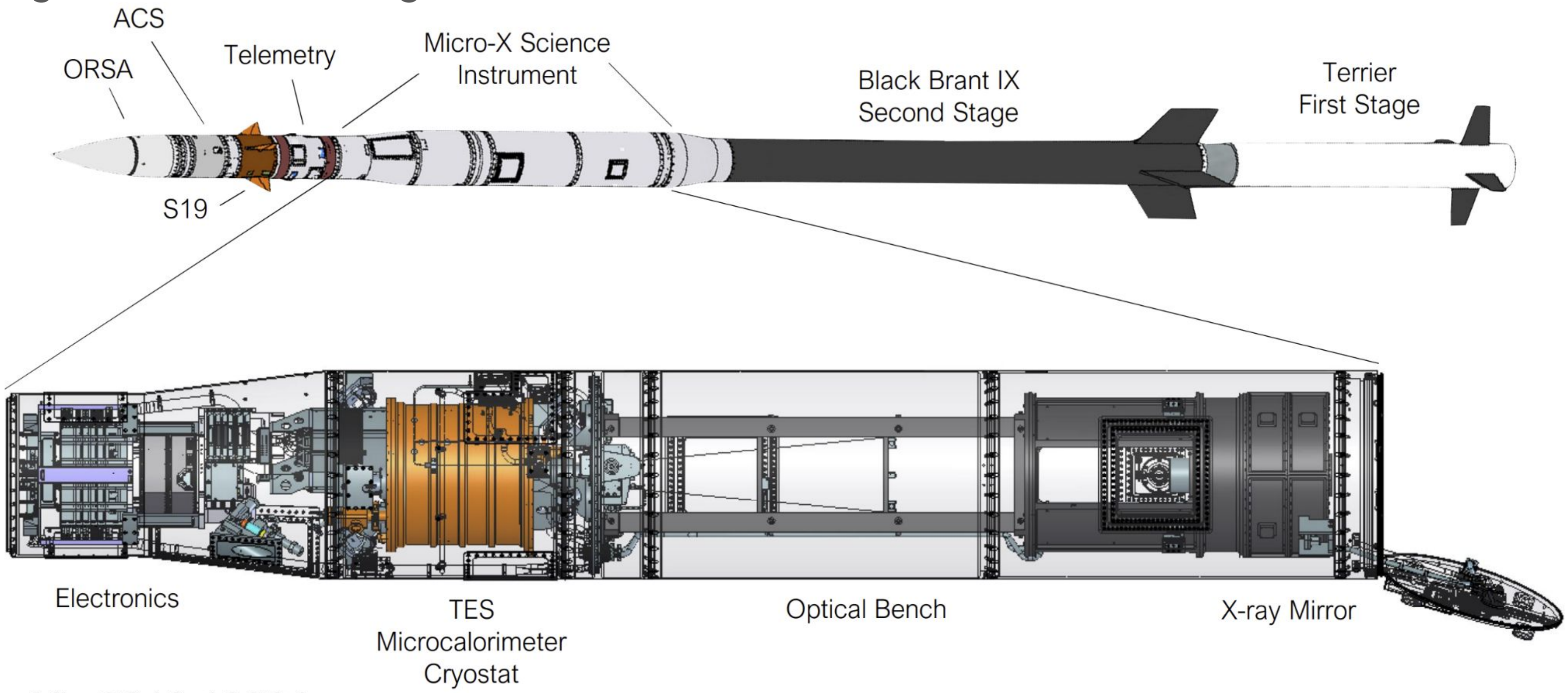
The Resolve aperture door status and a request for the proposals for the guest observer program cycle-1

The XRISM Resolve instrument's Gate Valve (X-ray aperture door) has not opened on multiple attempts. The Gate Valve blocks soft X-rays, shifting Resolve's energy band from 0.3 - 12 keV to 1.7 - 12 keV. While the XRISM team will continue

Micro X - TES in space

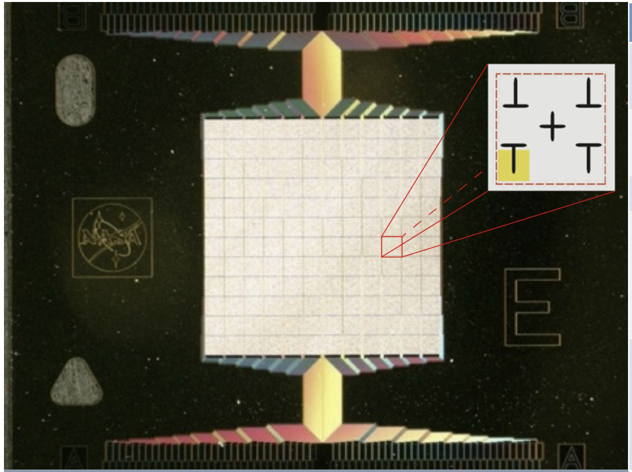
The High-resolution Microcalorimeter X-ray Imaging Sounding Rocket

First flight 2018 - Second flight 2022 - Altitude: 160 km

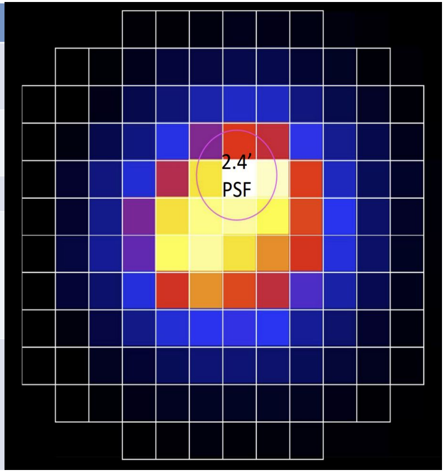


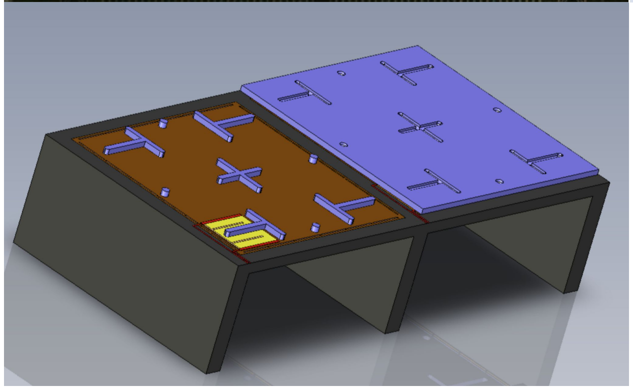
arXiv:2212.12064

Micro X - Detectors and results



The Micro-X Instrument	
Science Observation Time (time above 160 km)	~300 sec
Bandpass	0.2 – 2.5 keV (but will see some bright lines at higher energy)
Field of View	11.8 arcmin
X-Ray Optics	Conical approximated Wolter optics Collecting area ~ 300 cm² @ 1 keV Focal Length: 2.1 m 2.4' Point Spread Function
Microcalorimeter Array	128 pixels read out by 2 parallel TDM SQUID MUX (2 x 8 columns x 16 rows) Pixel pitch: 600 um = 59 arcsec/pixel 5 - 10 eV energy resolution @ 1 keV





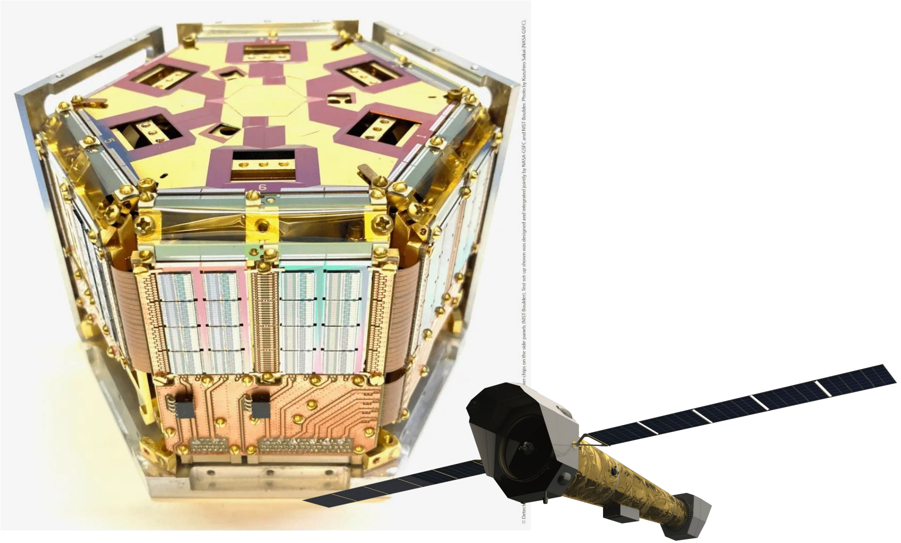
- They pointed CAS A
- They observed around 17000 science photons
- The mean energy resolution was ~10 eV
- First use of TESs in space

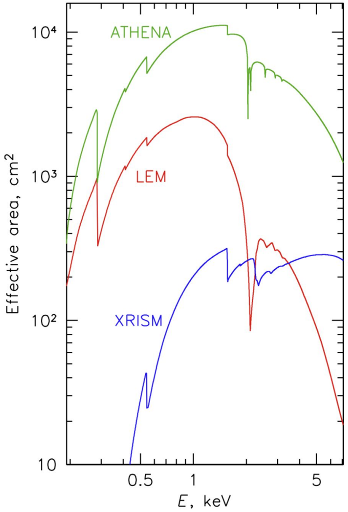
Future instruments

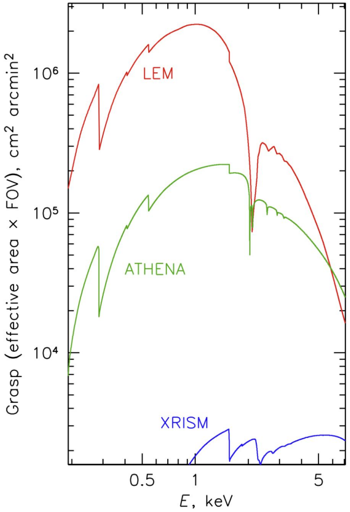
ATHENA X-IFU (~2037) ESA large mission - large French contribution (CNES, IRAP, APC)

LEM (~2032) ? American probe class mission proposal

Lynx (~2050) - American flagship mission concept



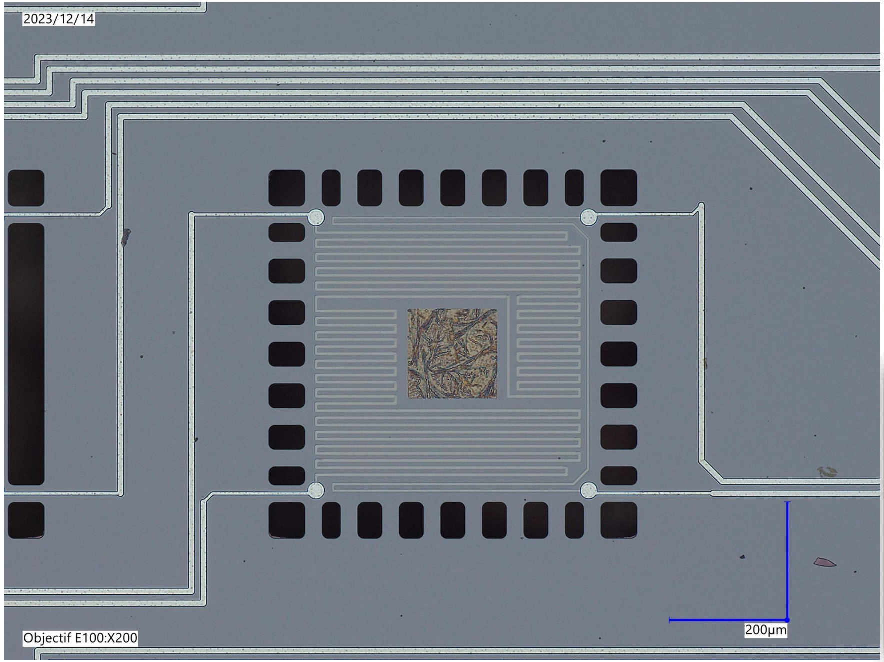




P. Peille's lecture later this week

High resistivity TES for X-rays

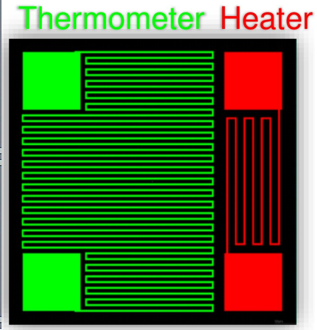
Development of high resistivity TES microcalorimeters for X-rays. Based on NbSi alloy (IJCLAB)

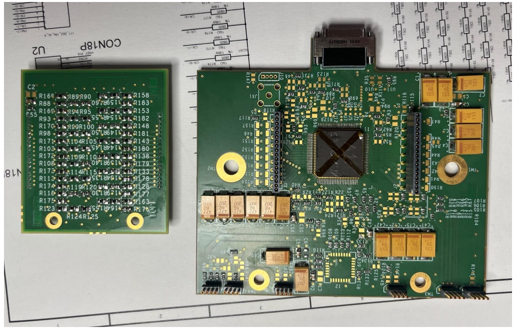


Credit: B Criton, JL Sauvageot

Hybrid between TES and Semiconductor

- ➕ Doesn't require SQUIDs
- ➖ Requires external heater for ETF





ASIC for readout and multiplexing @ 50 mK

Optical - IR astronomy

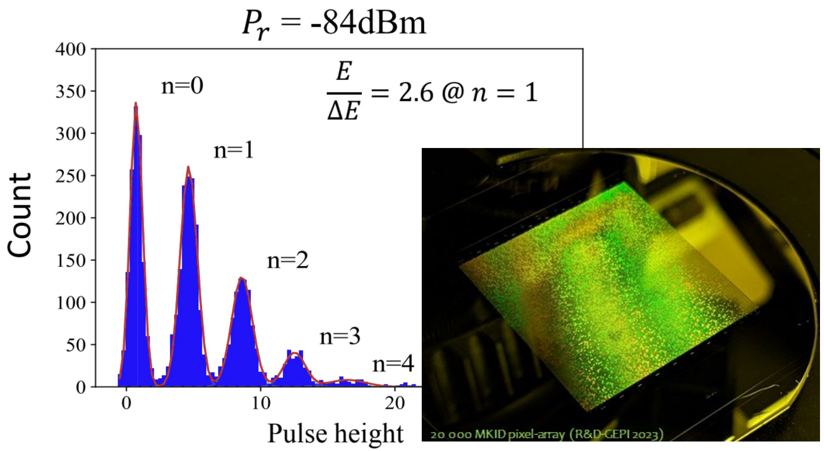
SPIAKID - SpectroPhotometric Imaging in Astronomy with **Kinetic Inductance Detectors**

Observation of Ultra Faint Dwarf (UFD) galaxies in the local group

- Lowest luminosity in the local group.
- Low metallicity.
- Spectroscopy only in few stars for each galaxy.

Spectral range (0.40 µm to 1.6 µm)

2 TiN/Ti/TiN **MKIDs** arrays of 20 kpixels



Credit: J Hu, F Boussaha

Developed by **Observatoire de Paris** in collaboration with APC

Demonstrated **single photon response @ 400 nm** with energy resolution of 2.6

Other applications include direct imaging of exoplantes (B Mazin)

Submillimeter astronomy

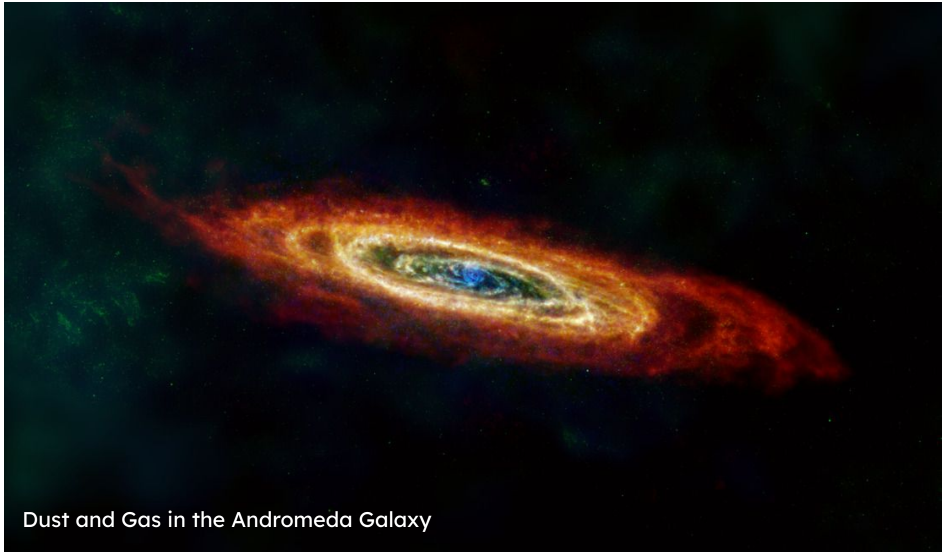
In far-infrared (~30 μm to 1 mm) astronomy we can study the cold parts of the universe.

Main astronomical sources at these wavelengths:

- Interstellar Medium (ISM)
- Star-forming Regions
- Protostellar and Protoplanetary Disks

Among main science drivers:

- Stars and planetary systems formation
- Galaxies formation and evolution



Dust and Gas in the Andromeda Galaxy

Herschel Space Observatory

In operation from 2009-2013

Three scientific instruments (all using LTDs):

- Heterodyne Instrument for the Far-Infrared (**HIFI**)

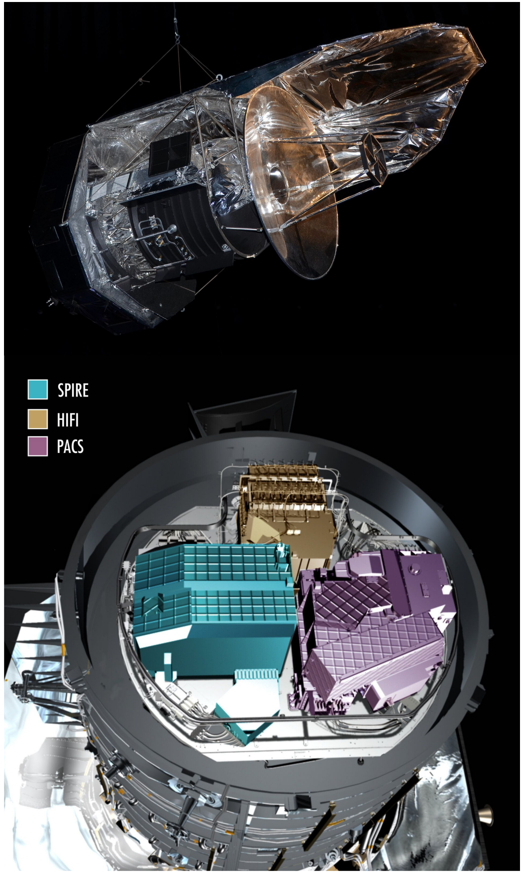
  High res spectrometer **SIS mixers and HEB** (~150 to 600 μm)
- Spectral and Photometric Imaging receiver (**SPIRE**)

  326 **spiderweb NTD Ge bolometers**

  250, 350 and 500 μm + FTS 200 to 600 um
- Photodetector Array Camera and Spectrometer (**PACS**)

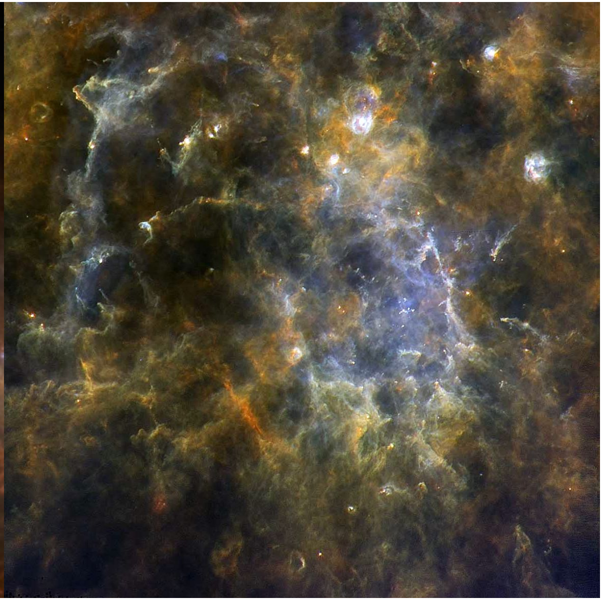
  2048 + 512 **Si:P:B semiconductor bolometers**

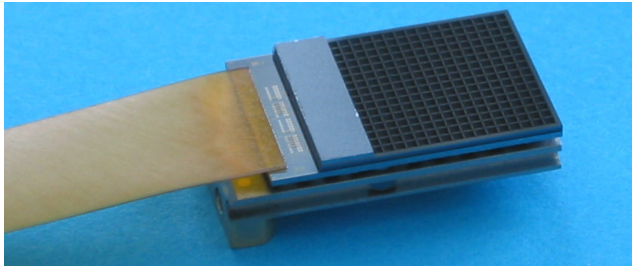
  60 - 130 μm and 130 - 210 μm

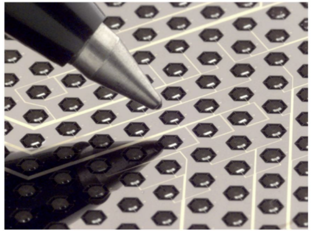


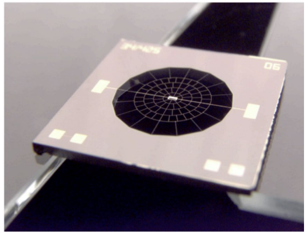
Herschel Space Observatory

Herschel view of the galactic center and galactic plane using PACS and SPIRE

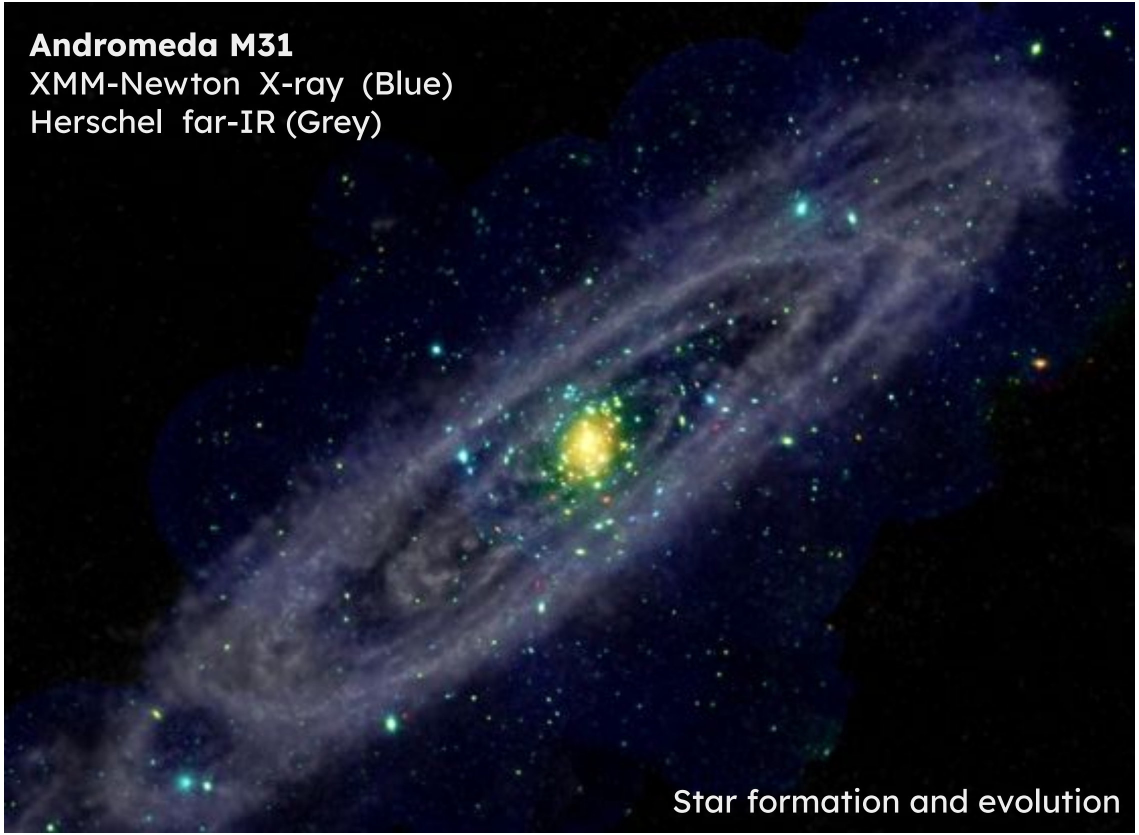




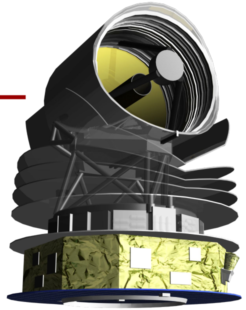




The power of multiwavelength!



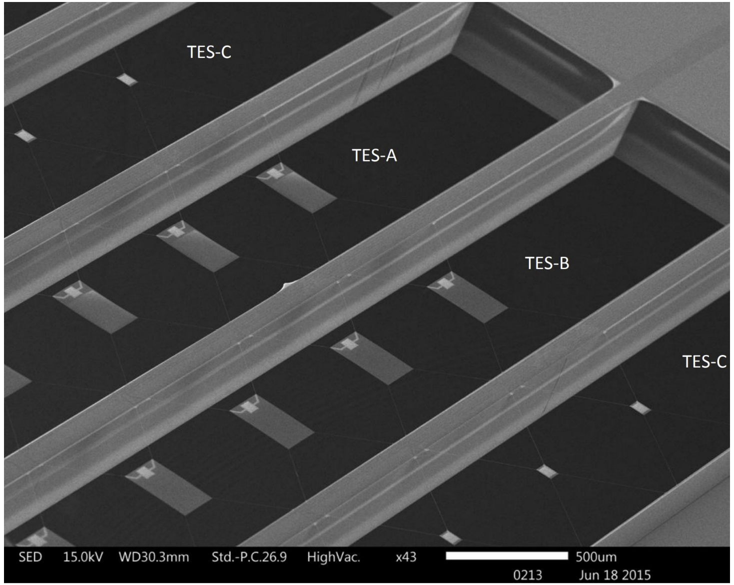
SPICA - SAFARI and B-BOP

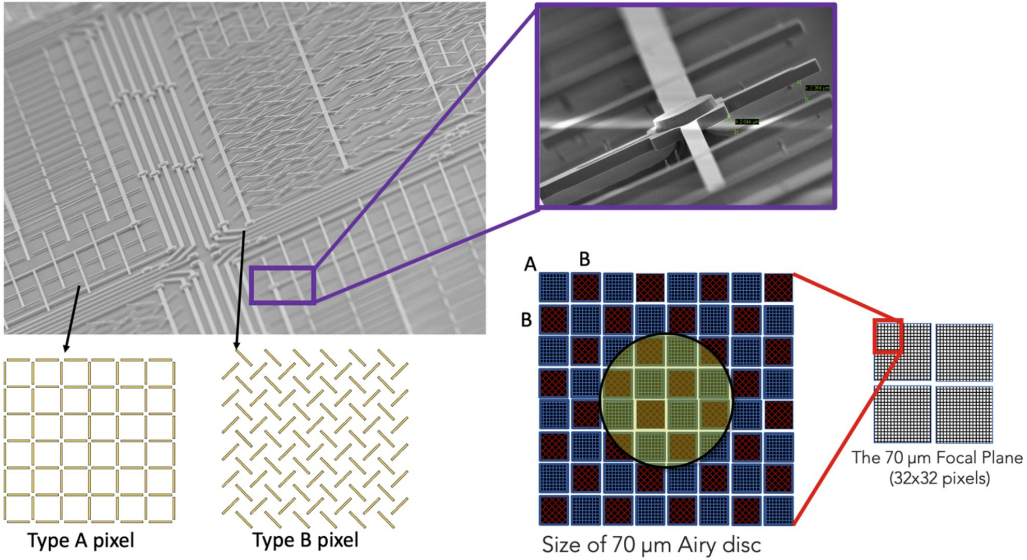


SPace **I**nfrared telescope for **C**osmology and **A**strophysics

Proposed as Herschel's successor, but stopped in 2020

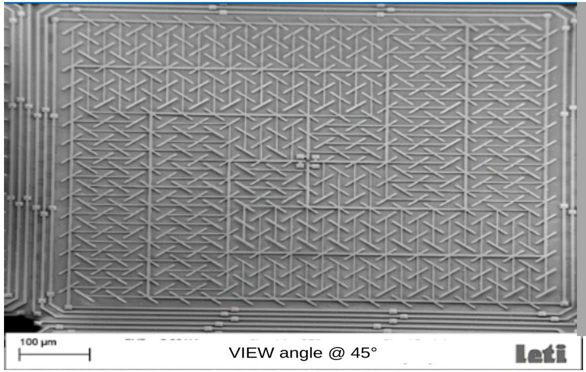
Two cryogenic instruments: **SAFARI** (TES) and **B-BOP** (Semiconductor + polarization)

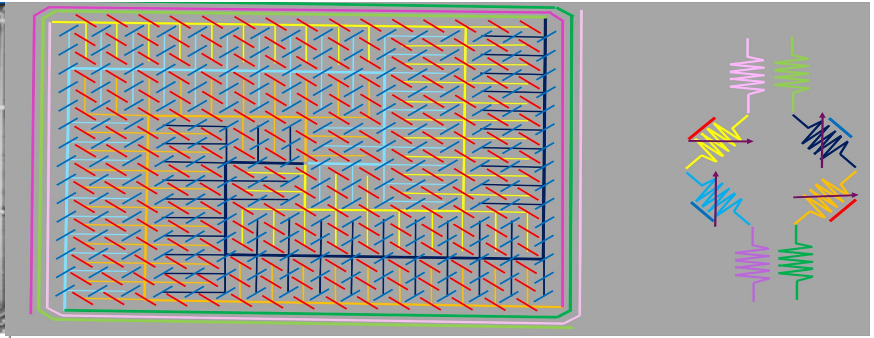


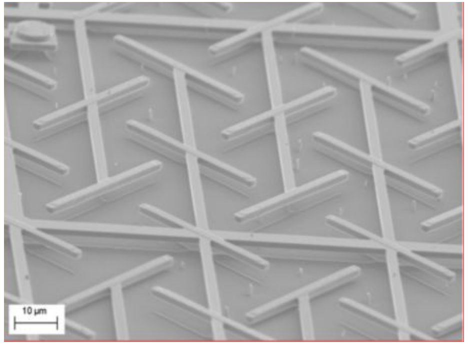


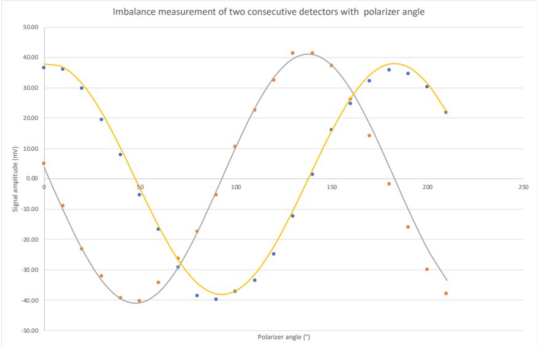
SPICA B-BOP detector developments

Detectors hybridized with CMOS readout with the addition of polarimetry



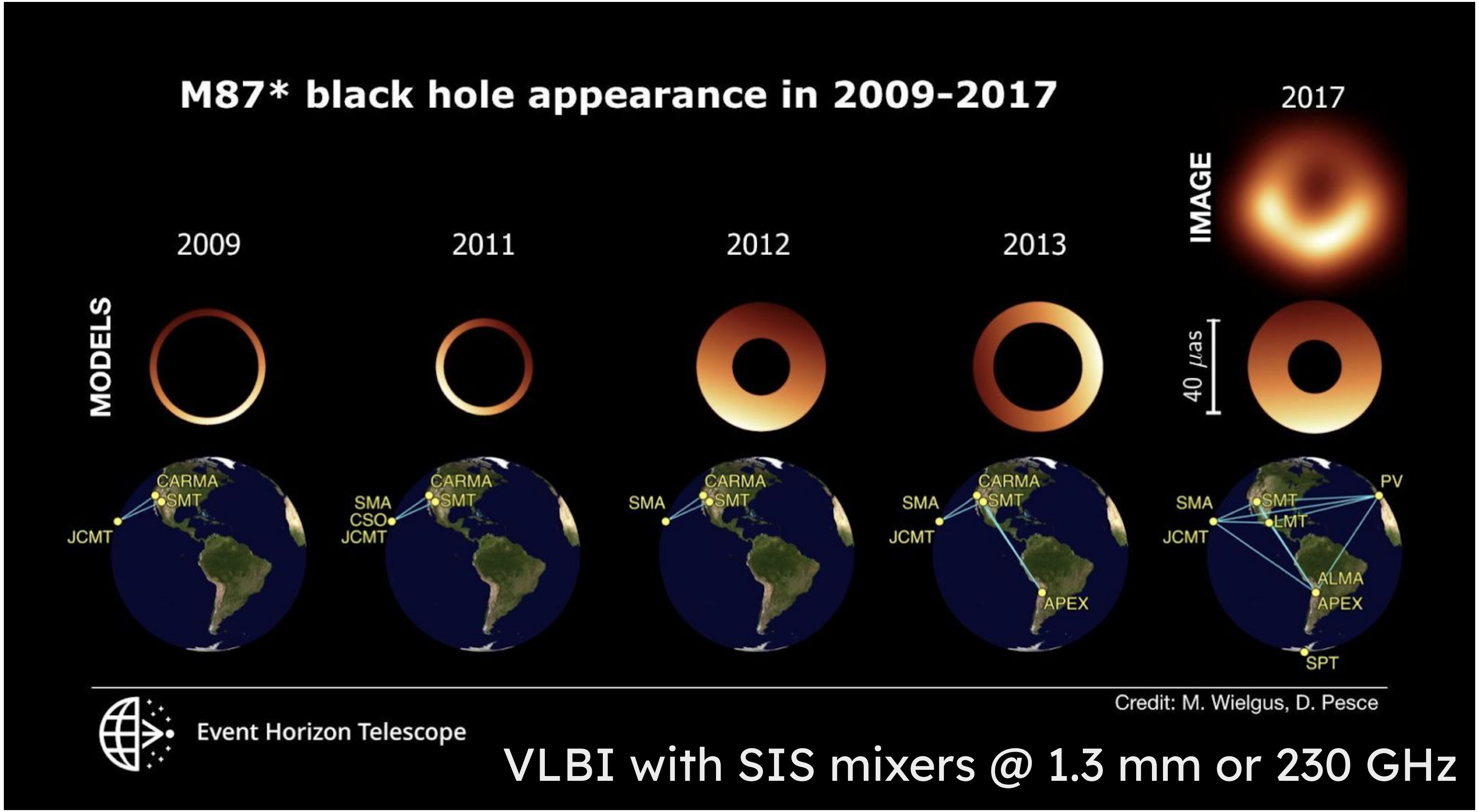






Credit: L. Rodriguez

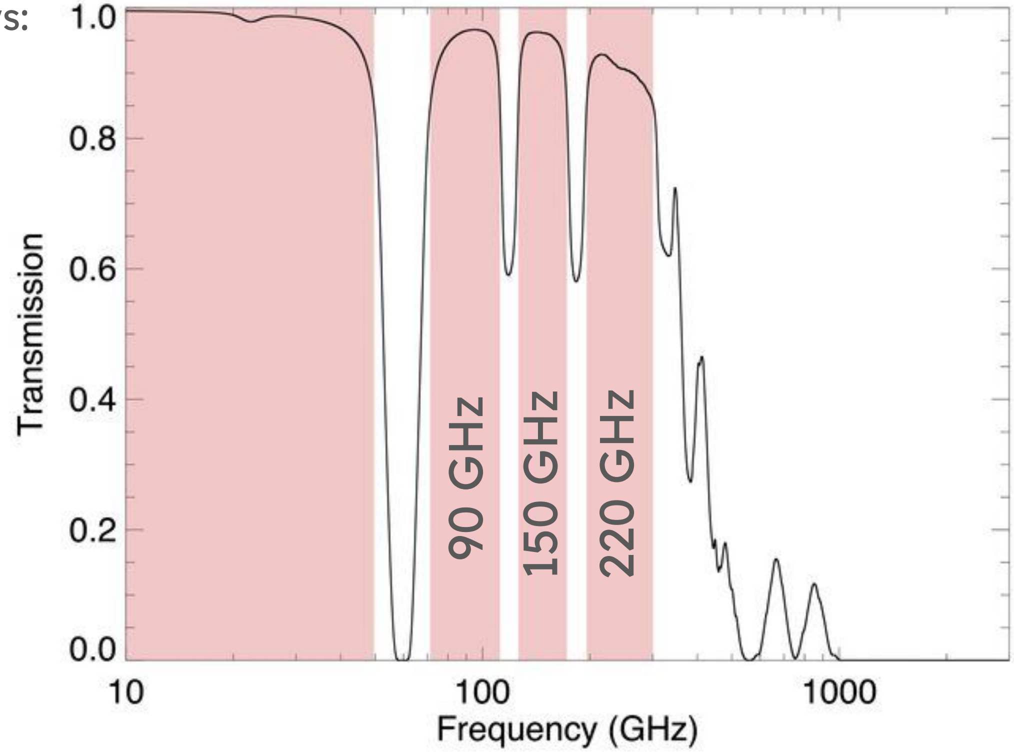
Event Horizon Telescope



mm astronomy from ground

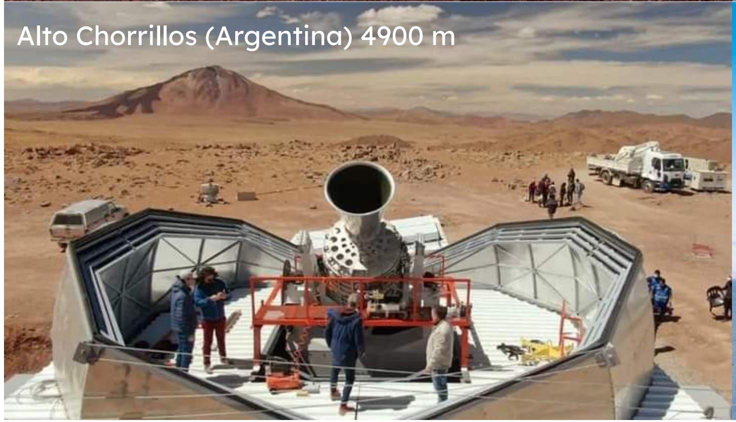
The atmosphere (specially water vapor) will absorb (then it will also emit) at mm wavelength. **High and dry** sites are required.

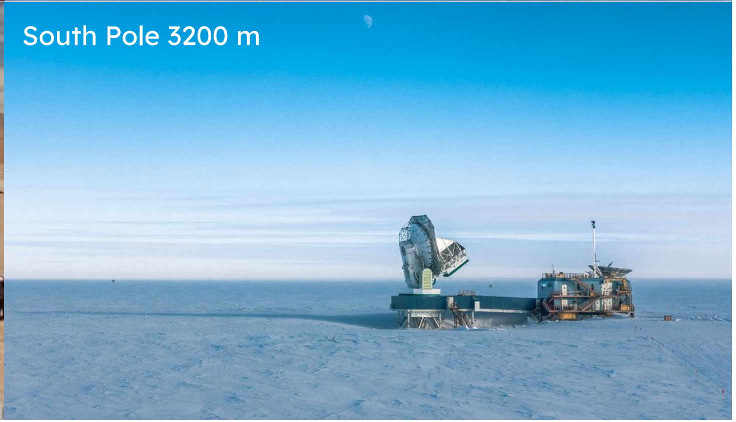
Atmospheric windows:



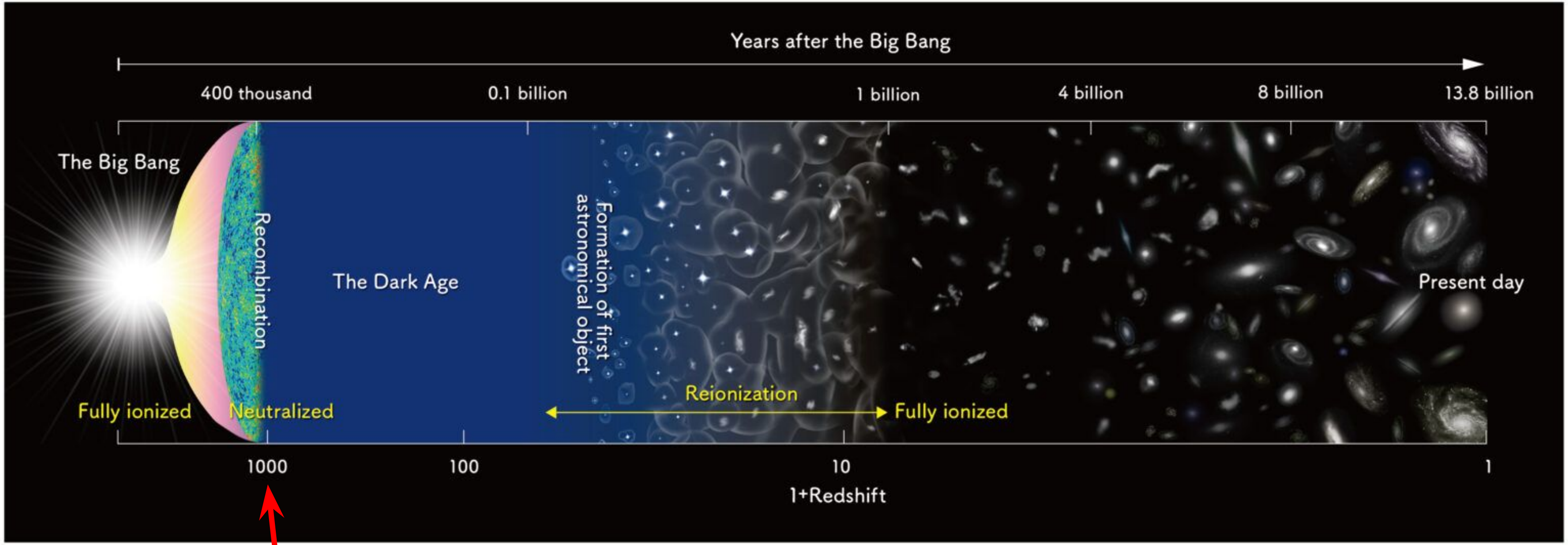
arXiv:1908.01907 [astro-ph.CO]

mm astronomy sites





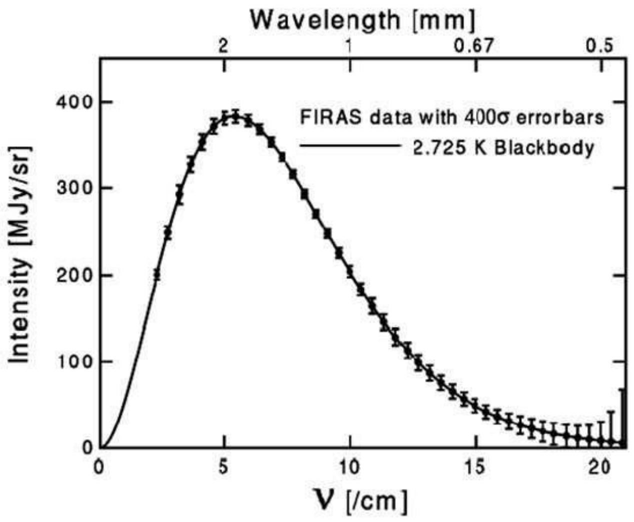
mm astronomy - Cosmic Microwave Background



CMB emission: when Universe became transparent e and p combined in H atoms

CMB Temperature

Almost perfect blackbody radiation

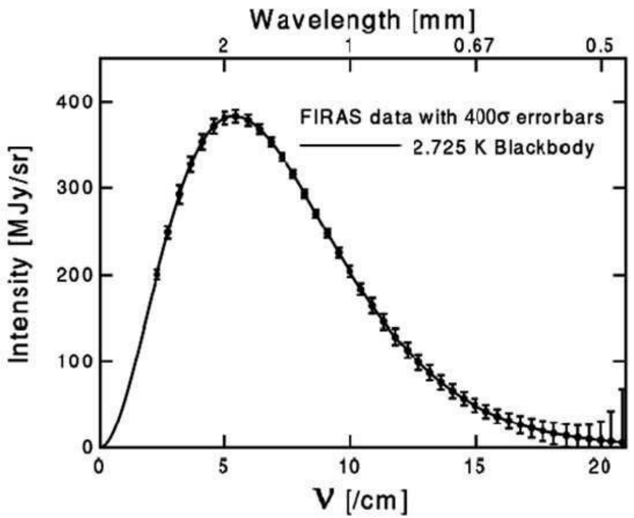


Spectral distortions, less than 1 in 10^5

COBE/DMR website

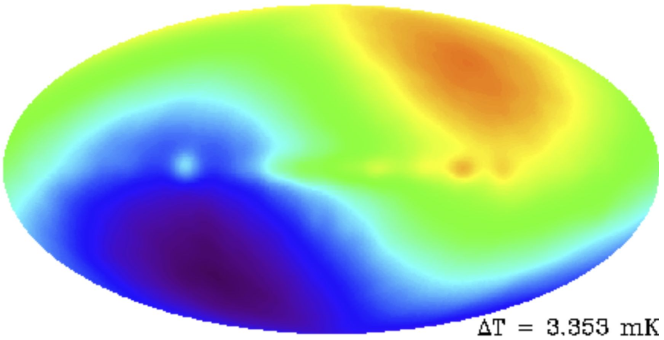
CMB Temperature

Almost perfect blackbody radiation



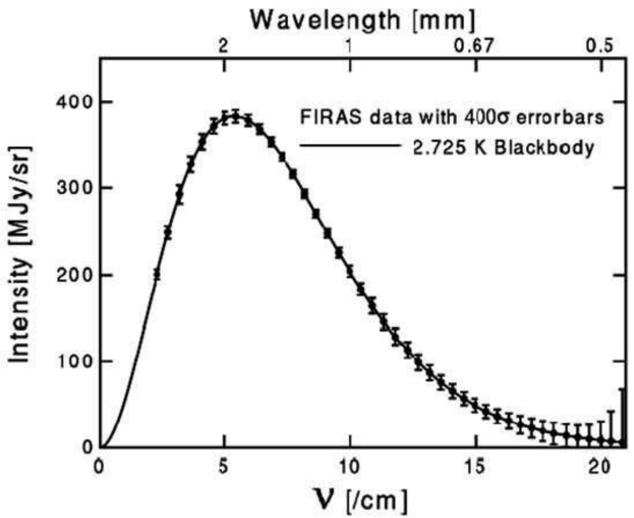
Spectral distortions, less than 1 in 10^5

COBE/DMR website



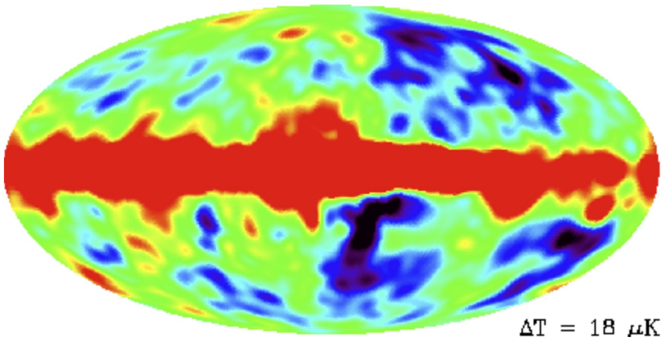
CMB Temperature

Almost perfect blackbody radiation



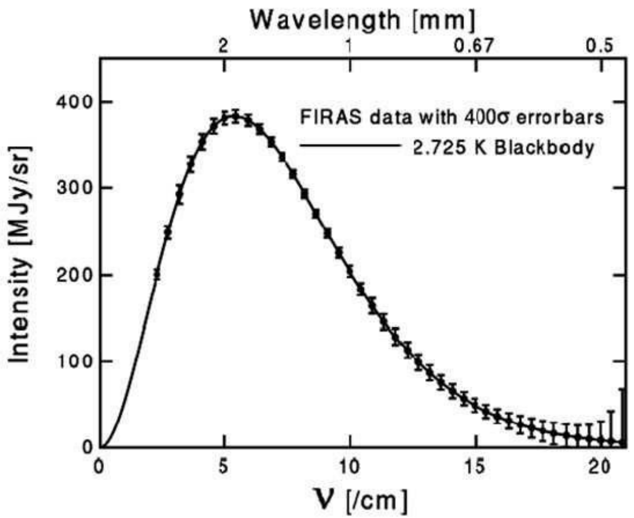
Spectral distortions, less than 1 in 10^5

COBE/DMR website



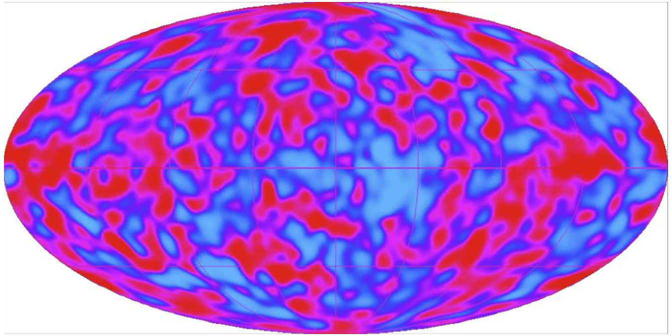
CMB Temperature

Almost perfect blackbody radiation



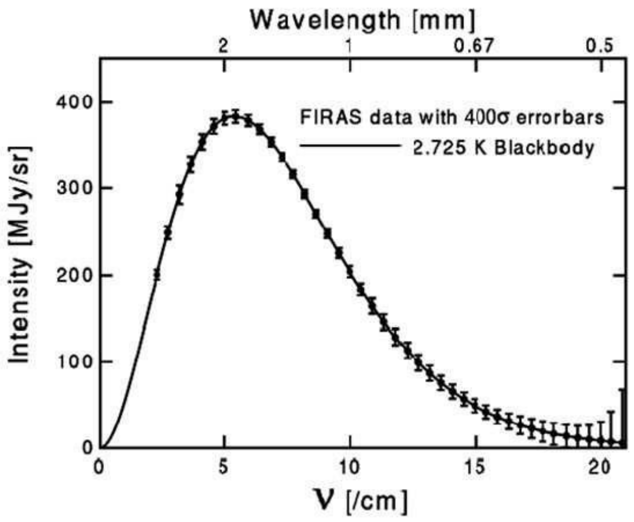
Spectral distortions, less than 1 in 10^5

COBE/DMR website



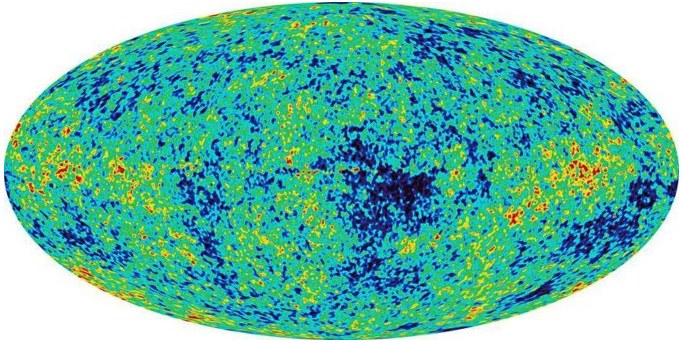
CMB Temperature

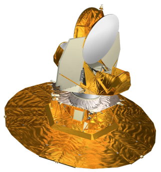
Almost perfect blackbody radiation



Spectral distortions, less than 1 in 10^5

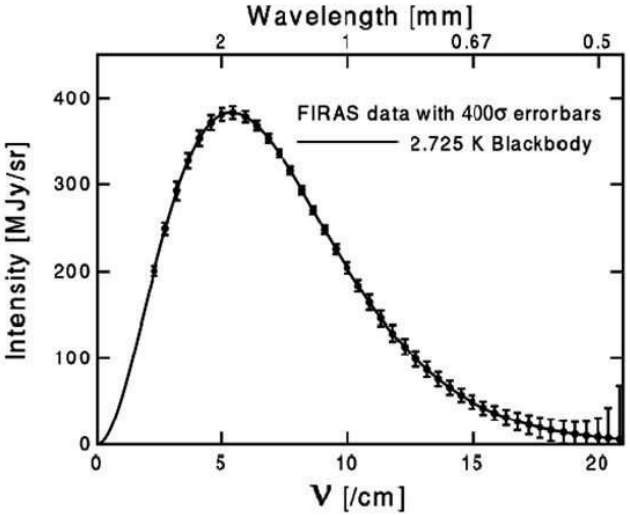
WMAP





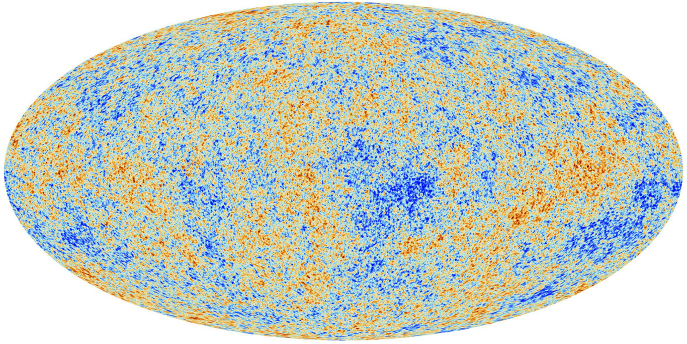
CMB Temperature

Almost perfect blackbody radiation

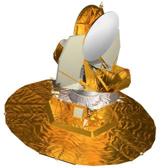


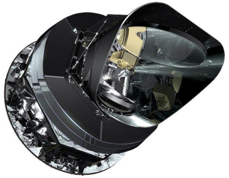
Spectral distortions, less than 1 in 10^5

Planck



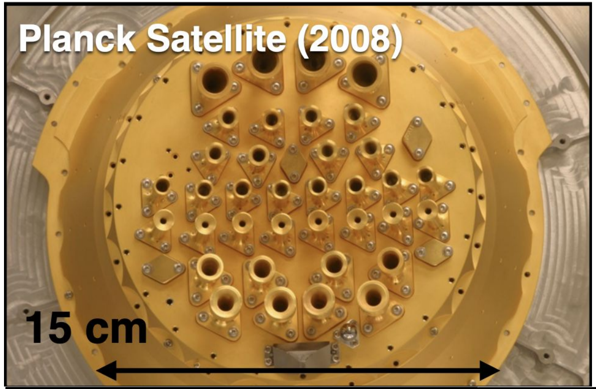
RMS ~30 μK

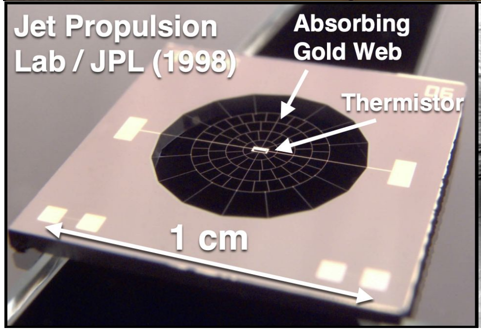


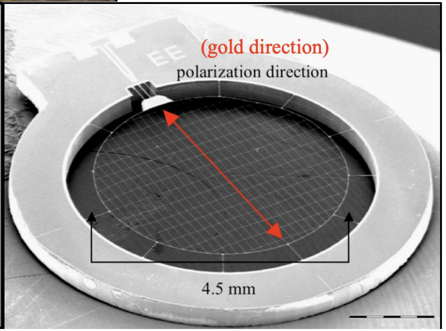


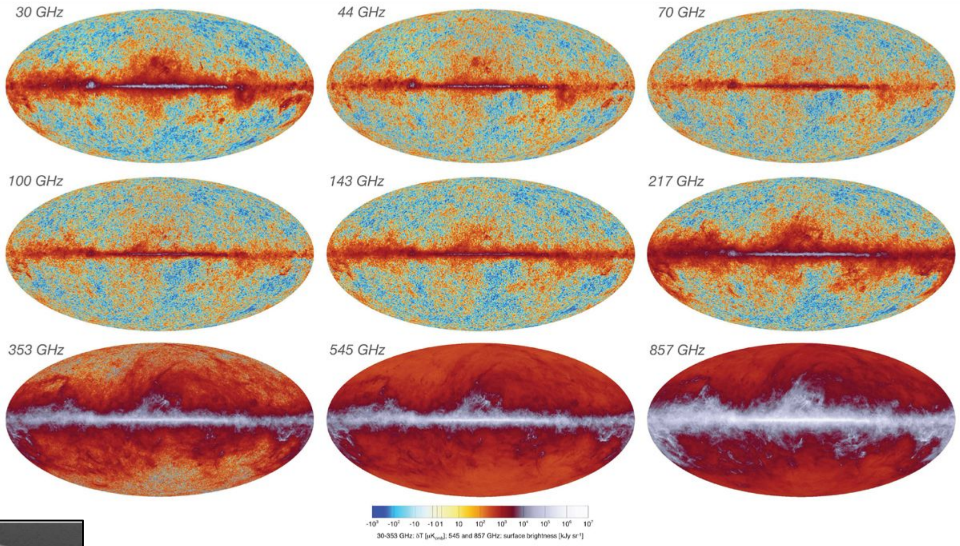
Planck - 2009 - 2013

The HFI instrument was based on NTD Ge bolometers









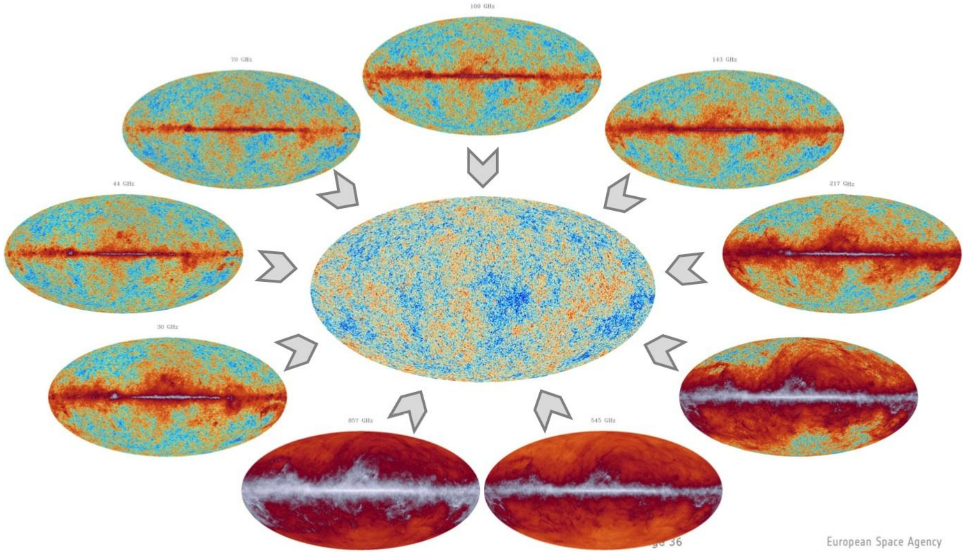
52 bolometers across 6 frequency bands (+2 dark)

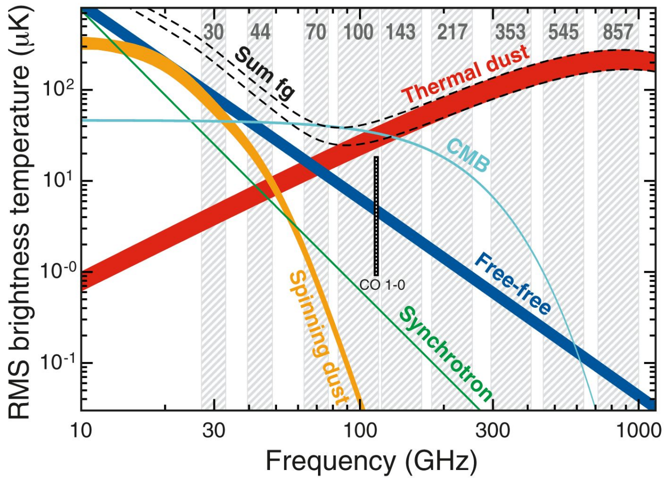
20 spiderweb bolometers

32 polarization sensitive bolometers

CMB component separation

By exploiting their spectral behavior, we can separate the different components



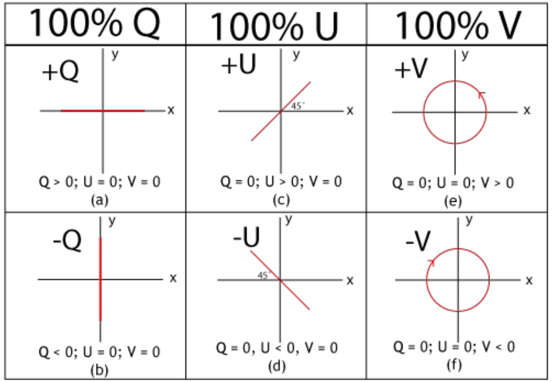


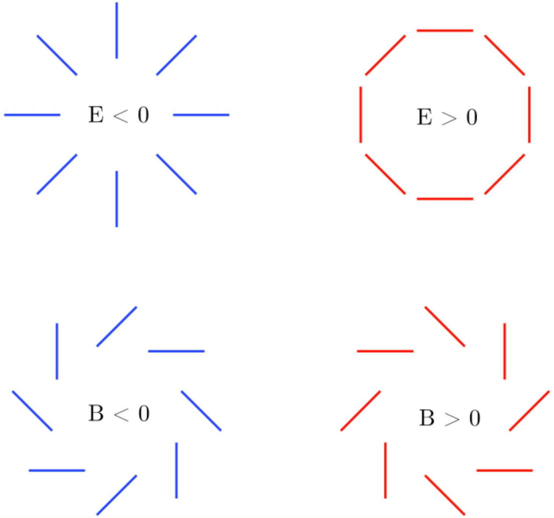
CMB polarization

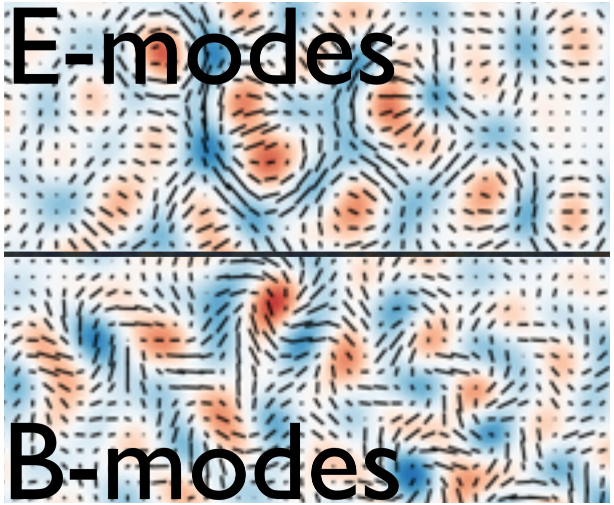
CMB is few % (linearly) polarized by Thomson scattering

Stokes parameters:

- I total intensity
- Q hor/vert linear pol
- U +-45° linear pol
- ~~V left/rigth circ pol~~

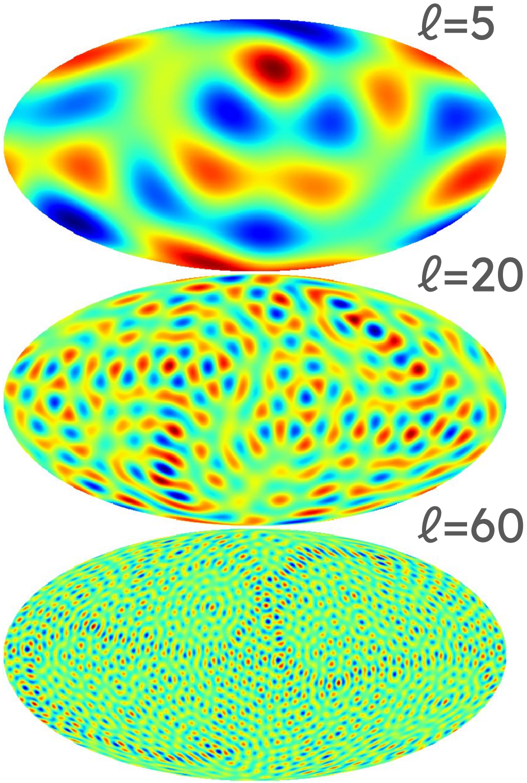


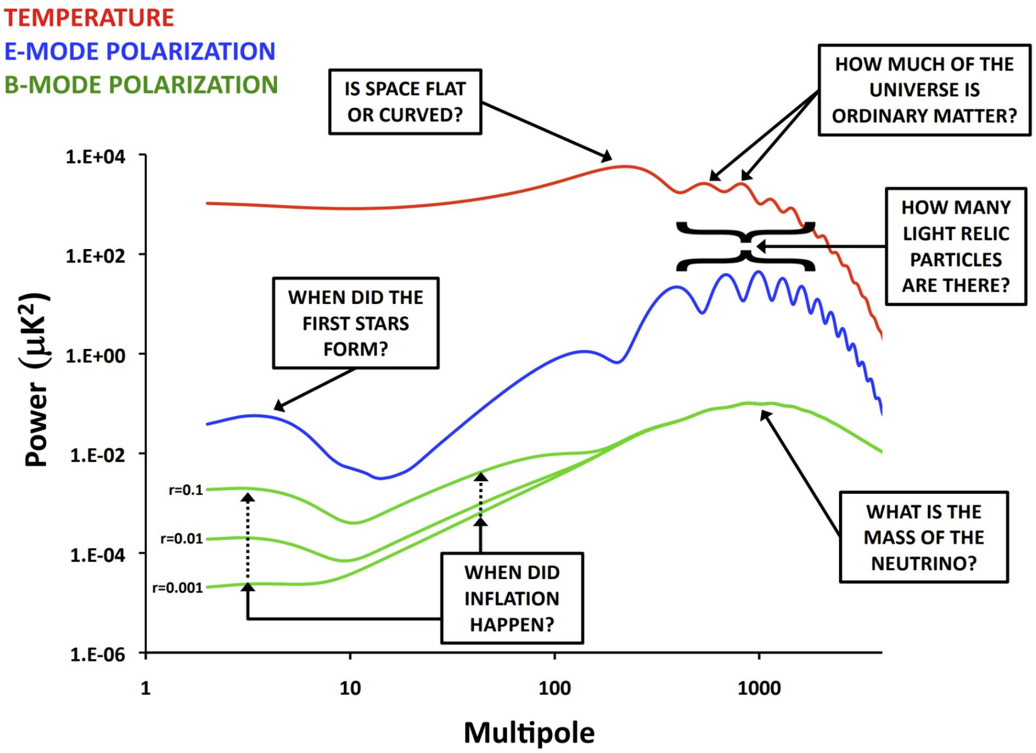




Any linear polarization field can be decomposed into the two scalar fields E and B.
Primordial B-modes are a specific prediction from inflation

Physics with CMB

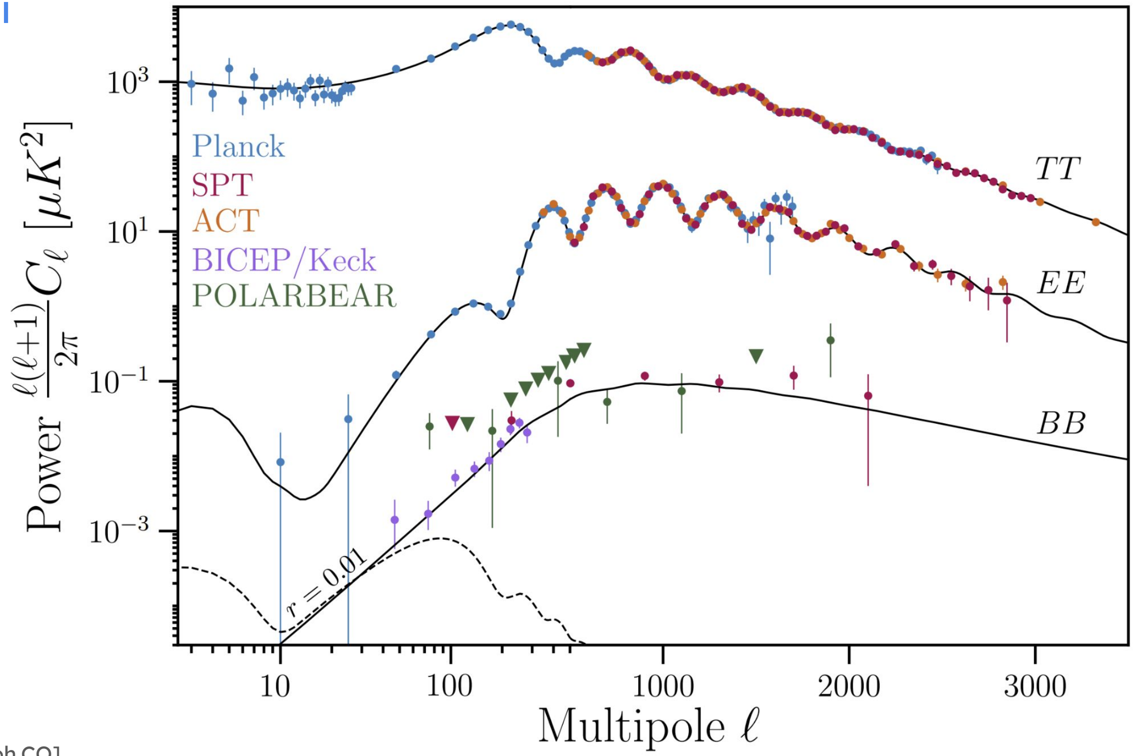




arXiv:2203.07638 [astro-ph.CO]

Current measurements

Bolo Semi Space



TES + future: KIDs South pole

TES Atacama

TES South Pole

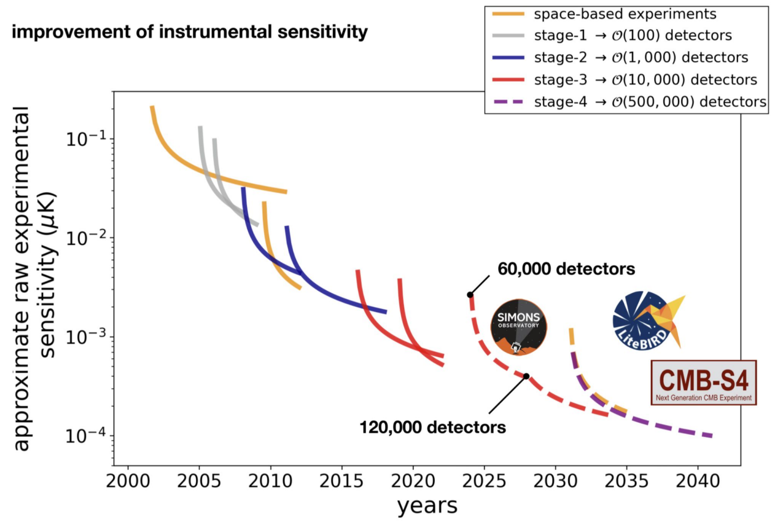
TES Atacama

arXiv:2203.07638 [astro-ph.CO]

The quest to B-modes, future instruments

There are currently three major future CMB instruments being developed:

- Simons observatory (Atacama)
- LiteBIRD (Space)
- CMB-S4 (Atacama + South pole)



Simons observatory (SO)

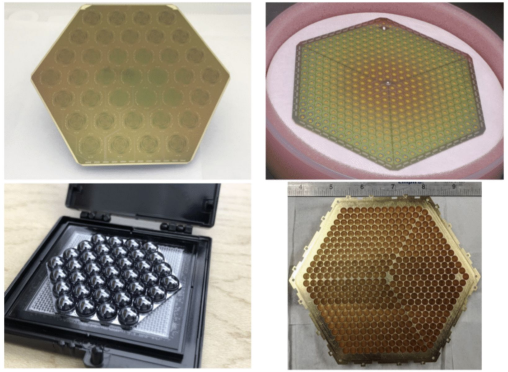
SO is in commissioning and will evolve to more than 120000 pixels by 2028.

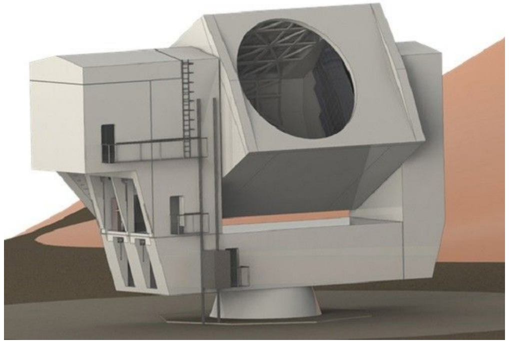
The American instruments are based on TES that are dual polarization sensitive and dichroic.

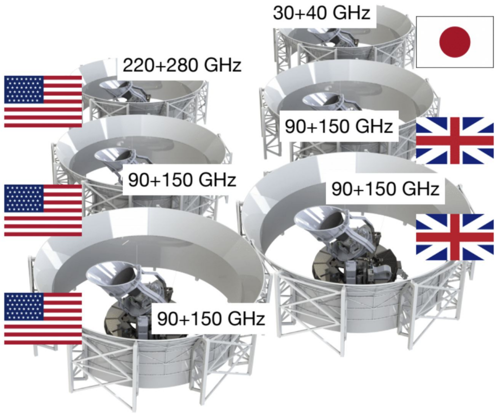
Two British KIDs based SATs and potentially one French.

Low frequency (LF) detector arrays & lenslets

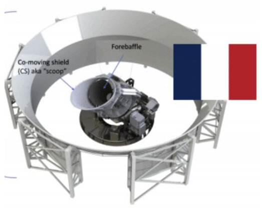
Mid frequency (MF) and ultra-high frequency (UHF) detector & horn arrays







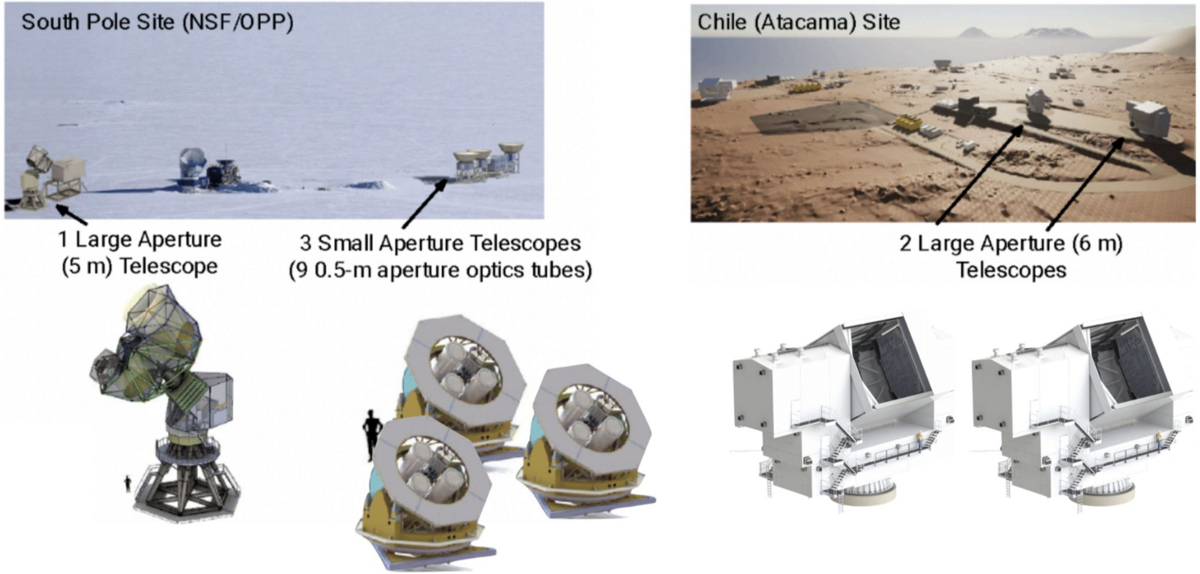
+

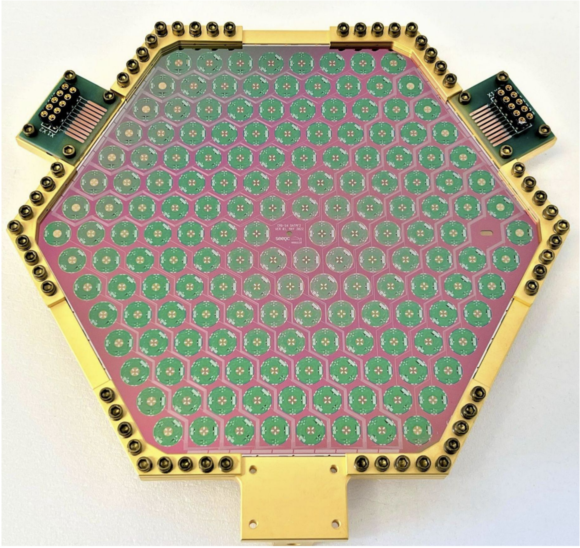


?

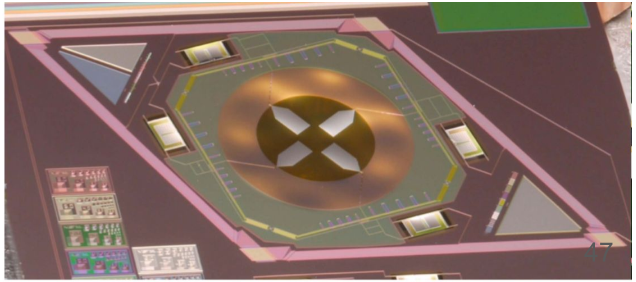
>220 GHz

CMB-S4





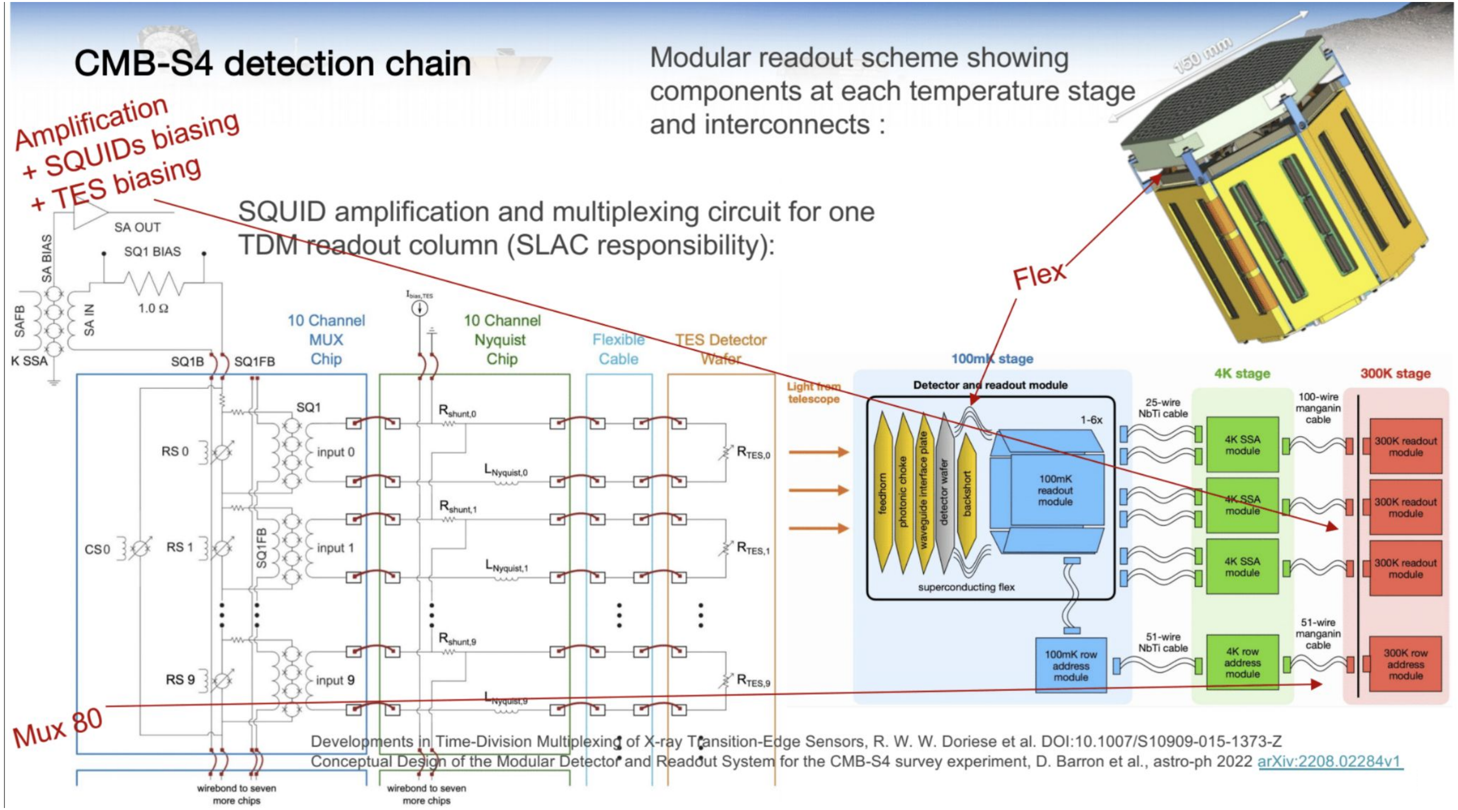
Credit: LBNL



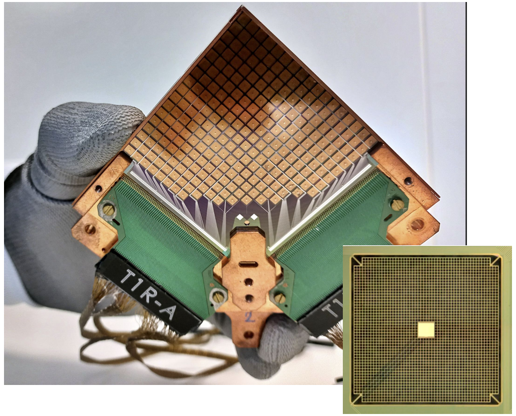
South Pole:
- 1-3% of the sky
- 1 Large (5m) Aperture Telescope
  @ 20, 25, 40, 90, 150, 220, 280 GHz
- 3 (3 tubes each) Small Aperture Telescopes
  @ 20, 40, 85, 145, 90, 150, 220, 280 GHz
- Operations: up to 10 years

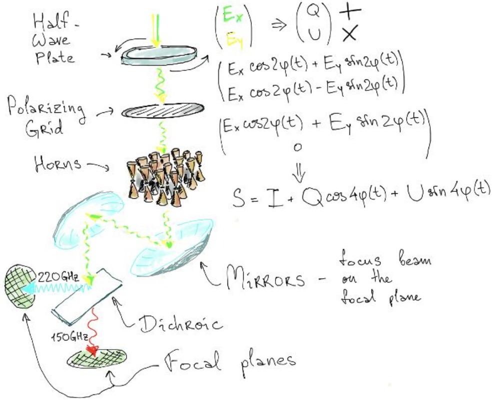
Atacama:
- 40-60% of the sky
- 2 Large Aperture (6m) Telescopes
  @ 25, 40, 90, 150, 220, 280 GHz
- Operations: 7 years

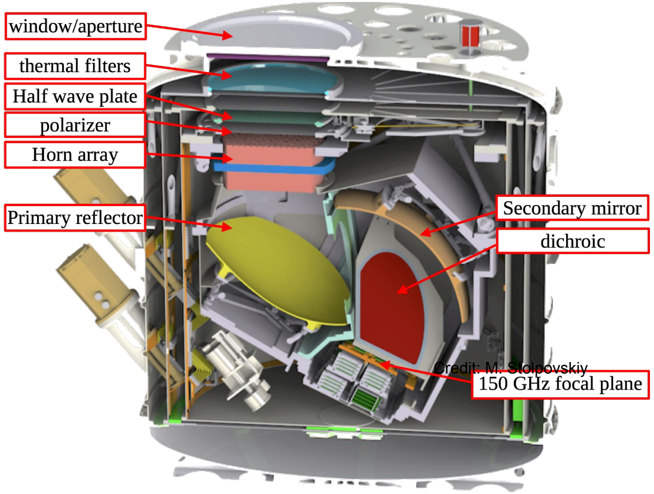
CMB-S4 readout

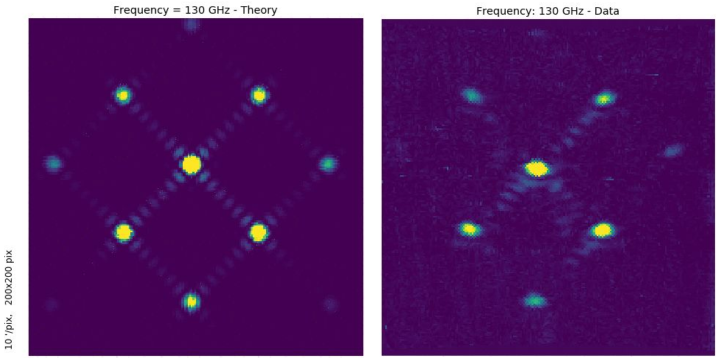


QUBIC - Bolometric interferometry



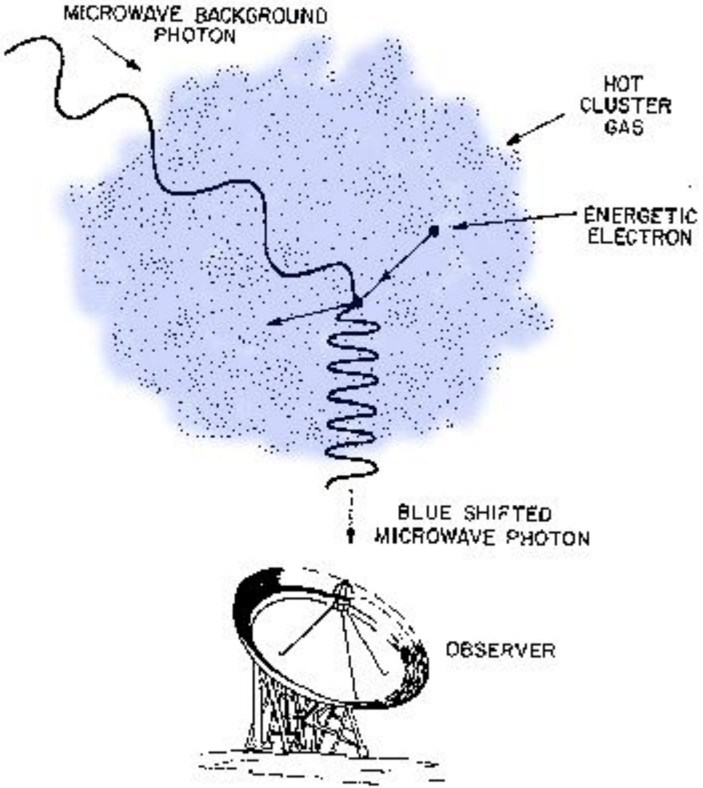


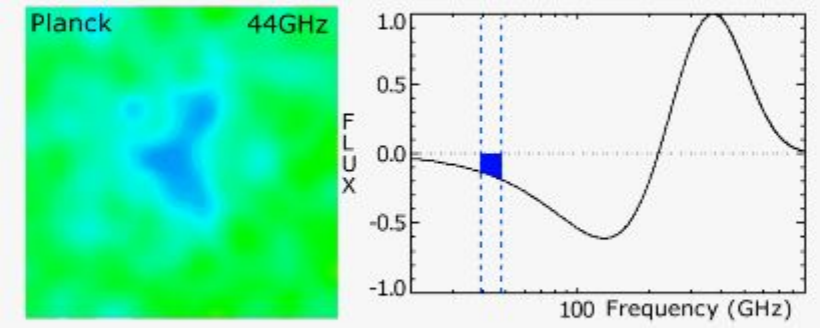


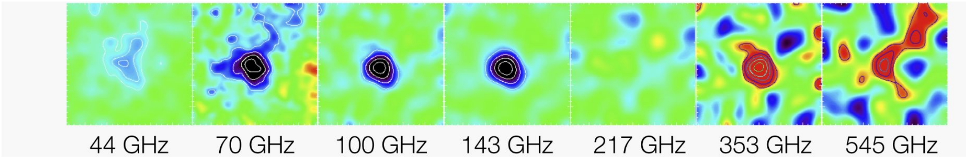


Sunyaev–Zeldovich effect

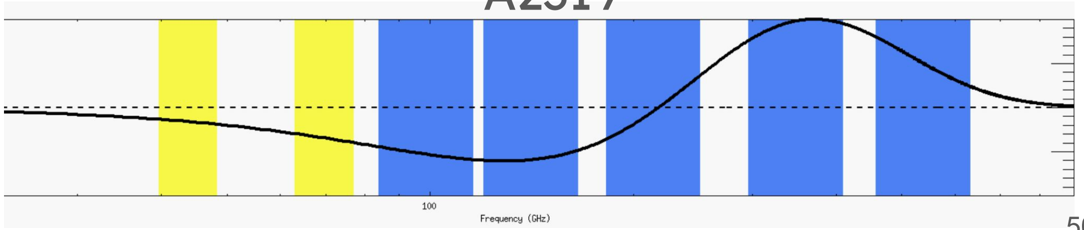
The CMB illuminates galaxy clusters and we see the effect of the scattering





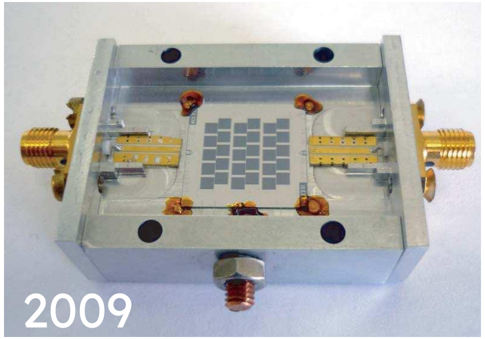


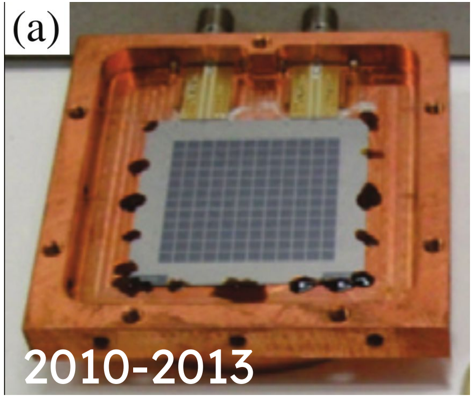
A2319

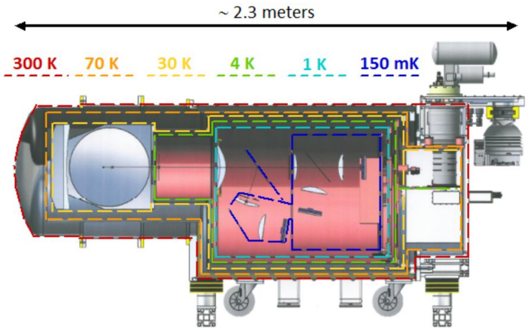


NIKA0, NIKA1, NIKA2

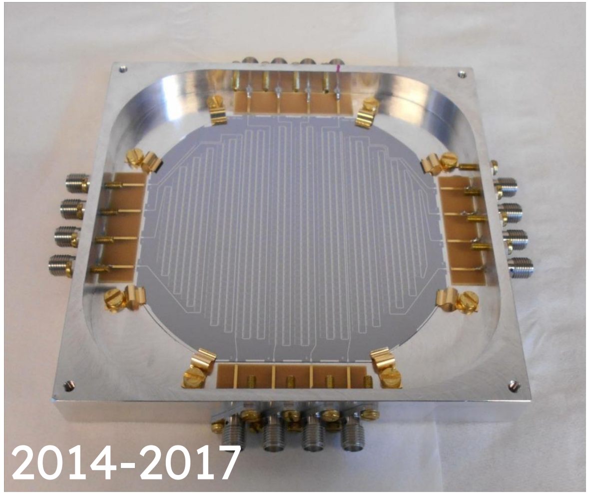
KIDs based instruments @ IRAM 30 m telescope







One of the first KIDs arrays on the sky
~30 pixels (~150 GHz)
~400 pixels (150 and 220 GHz)
~3000 pixels (150 and 260 GHz x 2 Pol)

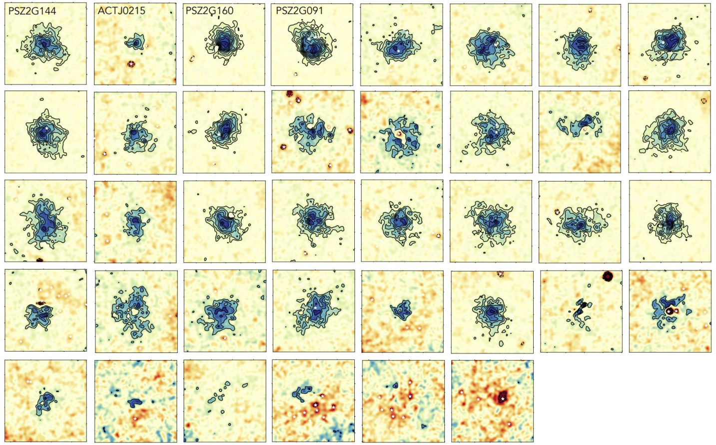


Astronomy & Astrophysics 521, A29 (2010)
The Astrophysical Journal Suppl. 194 (2011)
Astronomy & Astrophysics, 609, A115 (2018)

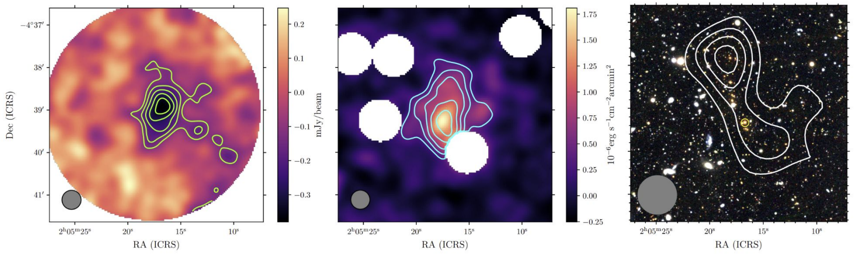
Credit: A. Monfardini

NIKA Science

Sunyaev-Zel'dovich (SZ) Large Program of NIKA2



ID (—)	R.A. (deg)	Dec. (deg)	z (—)	$T_{300\ \mathrm{kpc}}$ (keV)	$\lambda_{0.5\mathrm{Mpc}}$ (—)	$M^{\mathrm{XXL}}_{500,\mathrm{scal}}$ (10^{14} $M_\odot$)	$M^{\mathrm{XXL}}_{500,\mathrm{MT}\star}$ (10^{14} $M_\odot$)	$M^{\mathrm{XXL}}_{500,\mathrm{MT}\star,\star}$ (10^{14} $M_\odot$)	$M^{\mathrm{ACT,UPP}}_{500c}$ (10^{14} $M_\odot$)	$M^{\mathrm{ACT,cal}}_{500c}$ (10^{14} $M_\odot$)
XLSSC 102	31.322	−4.652	0.969	$3.9^{+0.8}_{-0.8}$	25 ± 8	2.6 ± 1.1	1.9 ± 1.1	$1.17^{+1.16}_{-0.60}$	$3.1^{+0.5}_{-0.4}$	$4.6^{+1.1}_{-1.0}$



150 GHz surface brightness maps of 38 clusters
Redshifts from 0.5 to 0.9
Public data release to come in 2025.

arXiv:2310.04553 [astro-ph.CO]

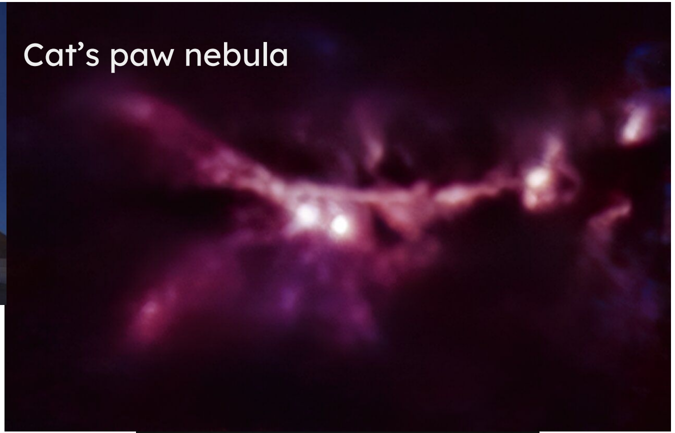
Concerto

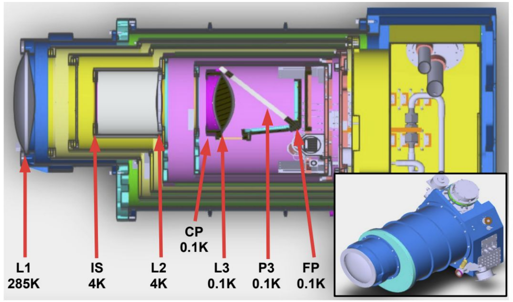
Main science goals:

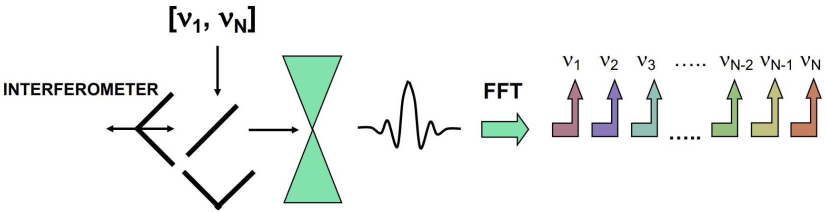
- [CII]-emission line
- Galaxy clusters SZ

Installed in APEX telescope 2021-2023

~4000 KIDs







Credit: I. Neel, LPSC, IPAG

Conclusions

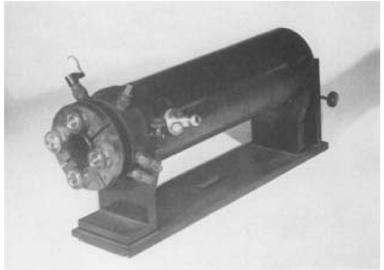
Cryogenic detectors allow for the most challenging observations across a wide spectrum

They are key to answer some of the fundamental questions in cosmology and astrophysics

There is a strong involvement of the French community

- Detectors
- Instruments
- Readout

History



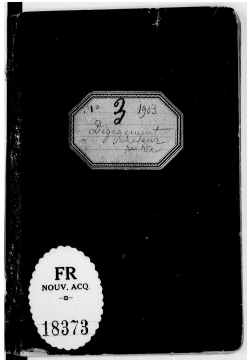
- ~1880 Langley First bolometer for IR

Langley’s bolometers were constructed by the instrument maker William Grunow.

Letter to Langley in 1893:

“I feel sorry to perceive my inability to follow up the making of bolometers, on account of the circumstances of my situation, the bad effect on my health (eyes and nerves) caused by the anxiety which the making of bolometers always creates on me, and [by the knowledge] that I should give up the making of them, rather than continue without being able to improve or perfect them…”*

- 1903 Curie/Laborte Calorimetic detection of radioactivity



- 1935 Simon Low temperature enhances performance

“The sensitivity [] can be increased by many orders of magnitude by working at very low temperatures”

- ~1940 Andrews Superconducting transition detector

*Samuel Pierpont Langley and his Contributions to the Empirical Basis of Black-Body Radiation