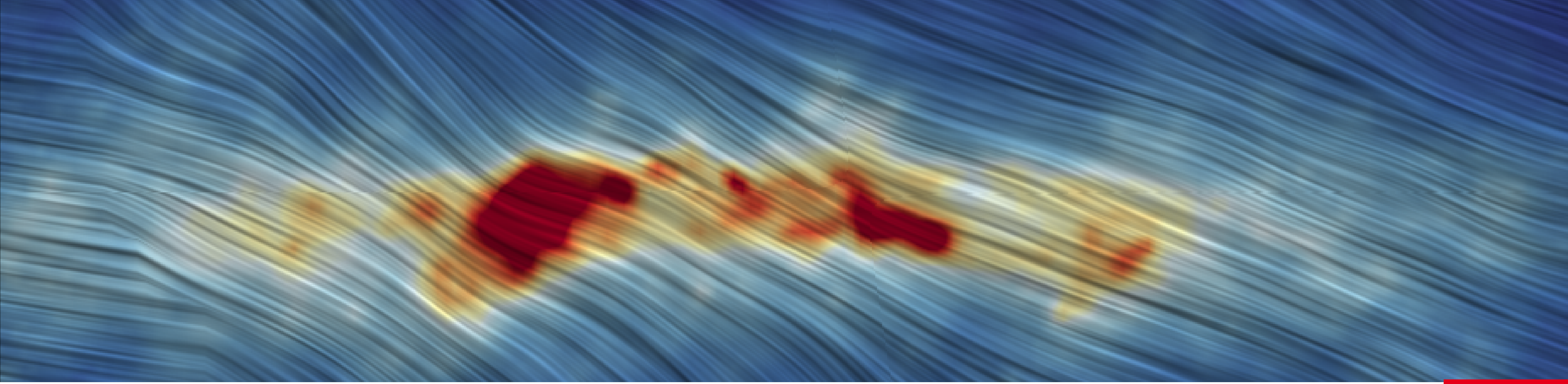
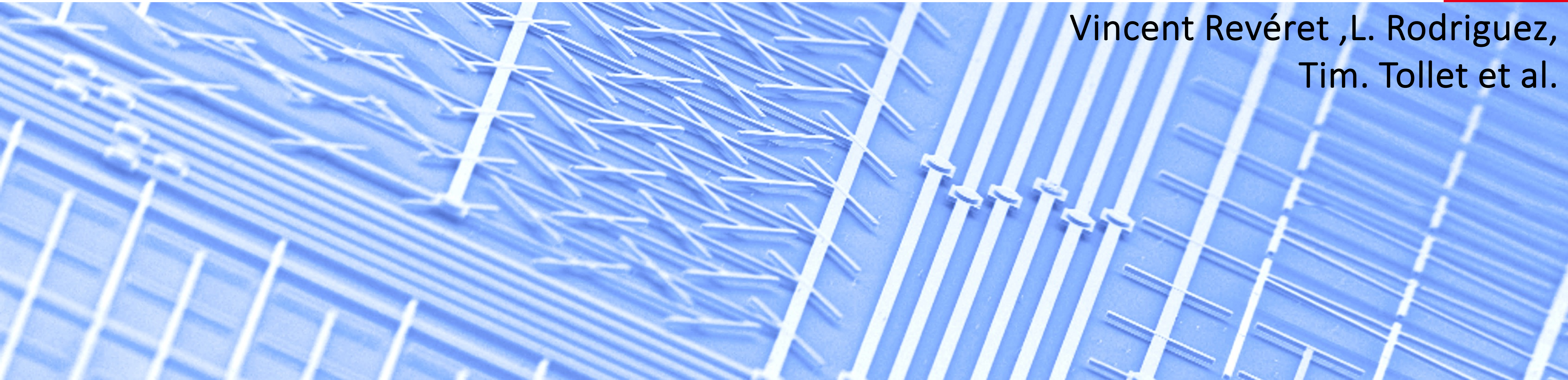


Les bolomètres submillimétriques du CEA : imagerie, polarimétrie et spectroscopie.



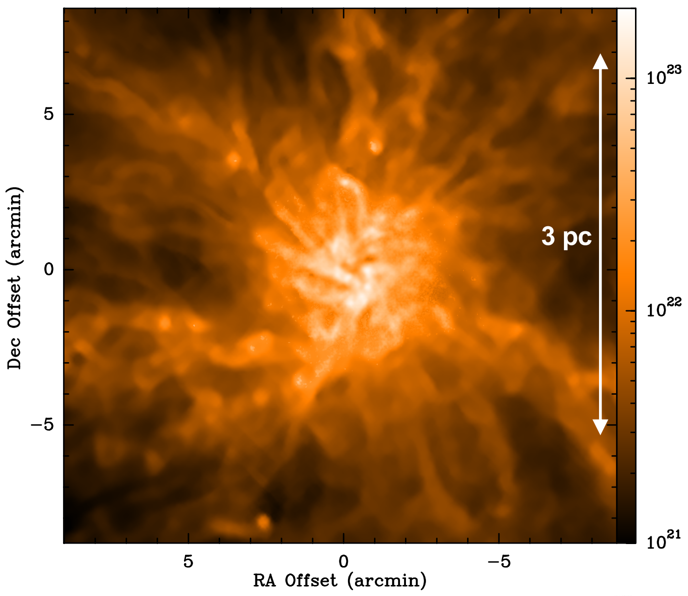
Vincent Revéret ,L. Rodriguez,
Tim. Tollet et al.

Submillimeter science for the coming decades

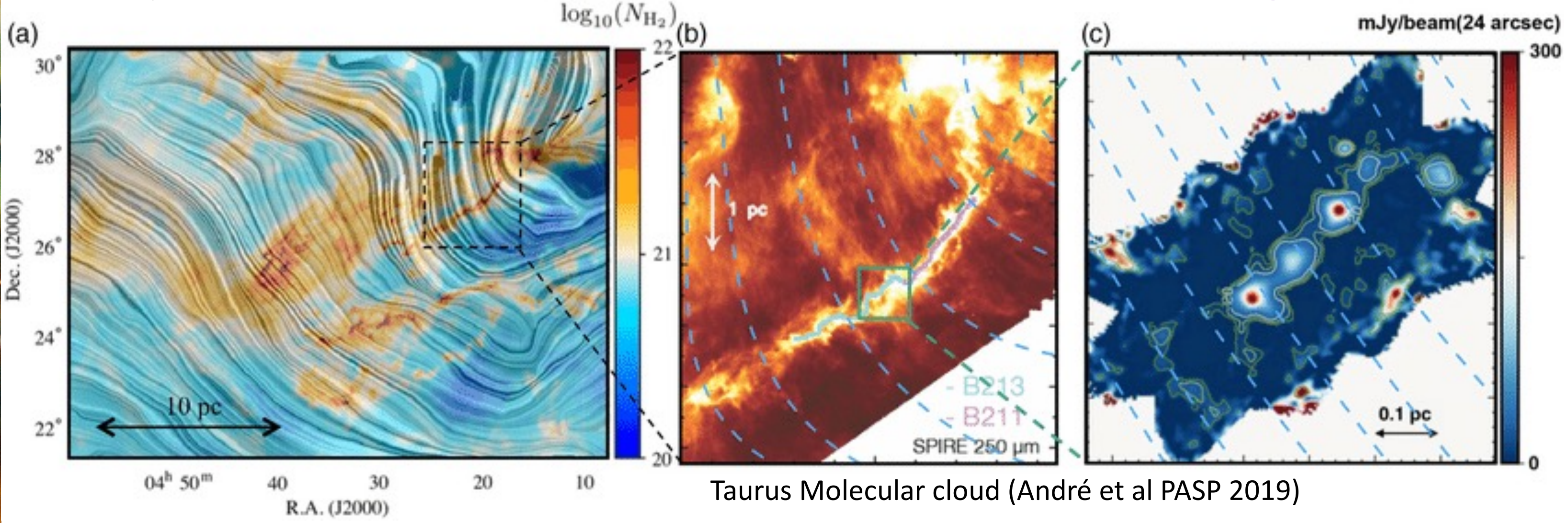
Common ESA and NASA Science themes for the future (not exhaustive) :

- Galaxy evolution, dust and heavy elements through history
- **Star formation in the Milky Way** and in nearby galaxies
- Formation of planetary disks, exoplanets, study of their chemical properties

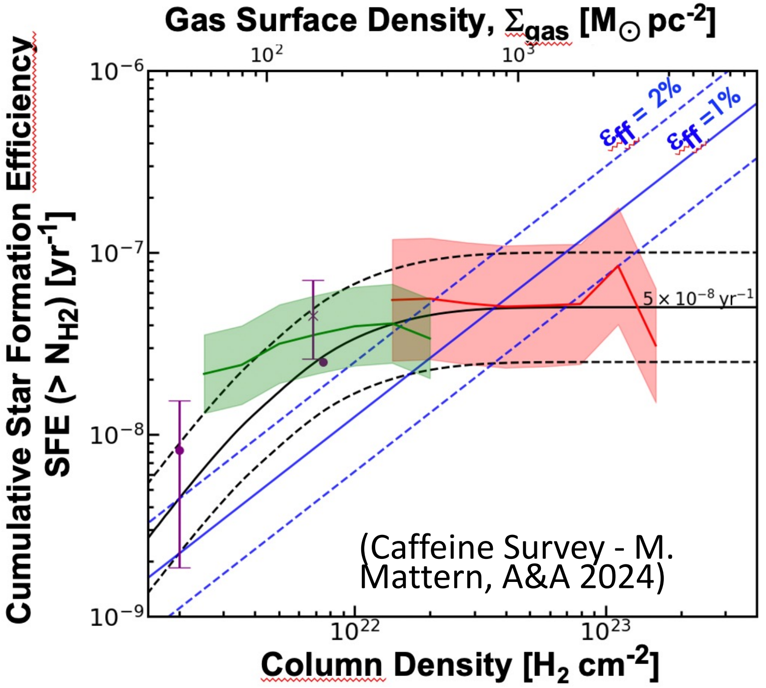
MonR2: ArTéMiS + *Herschel* N_{H2} map (8" resolution)



The particular science case of **star formation and the role of magnetic field**



Taurus Molecular cloud (André et al PASP 2019)

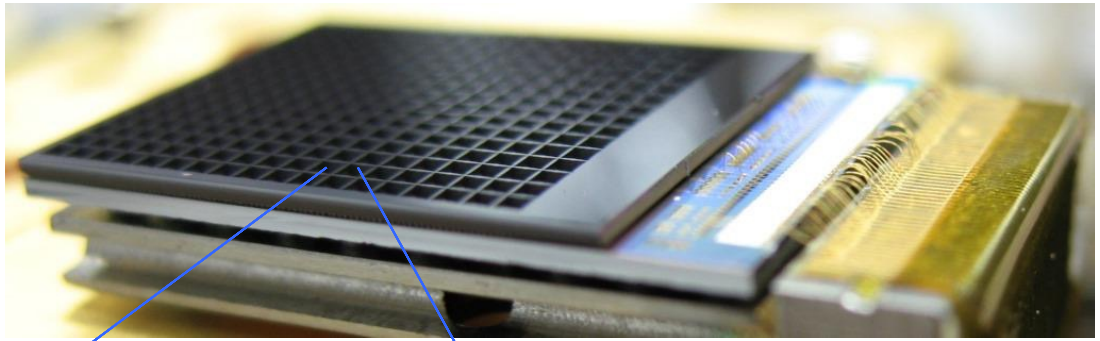


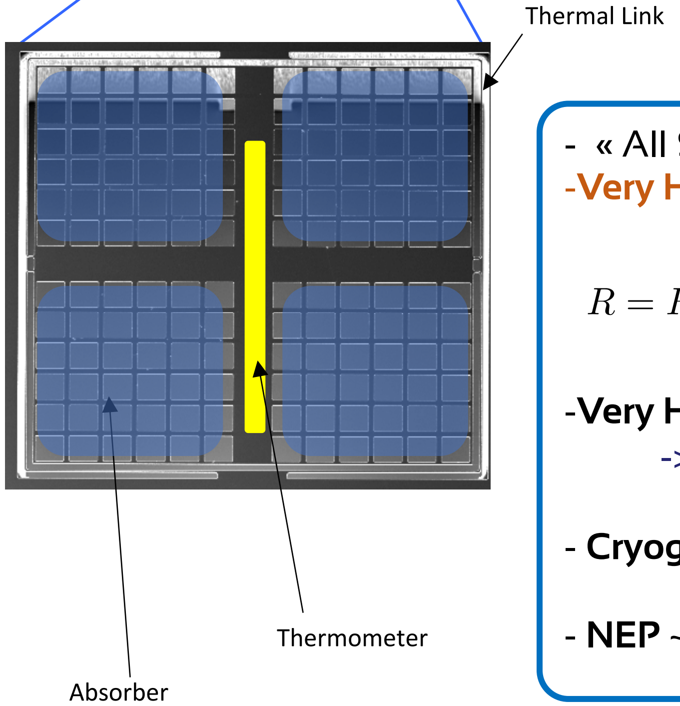
-> Needs for a high sensitivity polarimeter camera in the submm

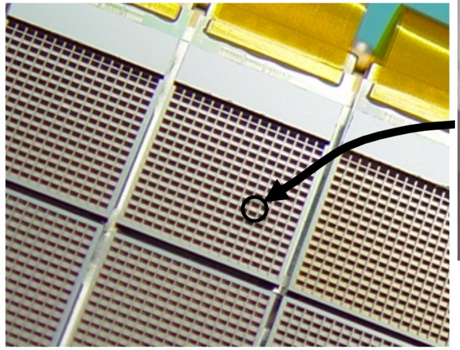
Our starting point : Herschel / PACS Silicon Resistive Bolometers in the 2000's

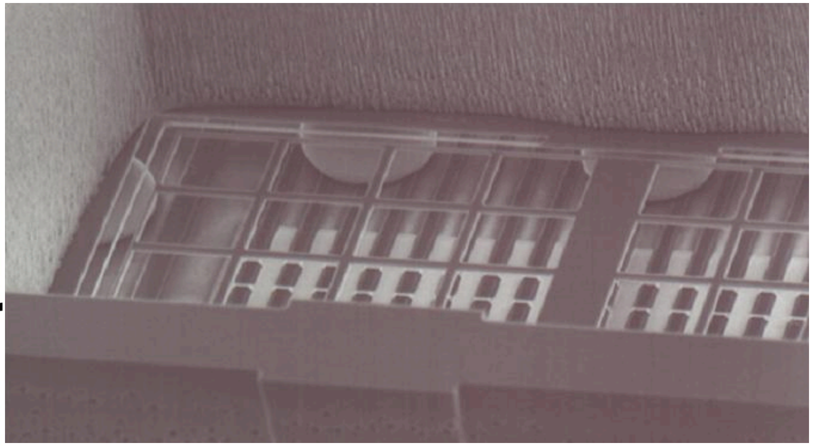
The goal : large format high sensitivity detectors in the 50 – 200 µm range.

CEA's choice : 16x16 Silicon array of bolometers working at 300 mK







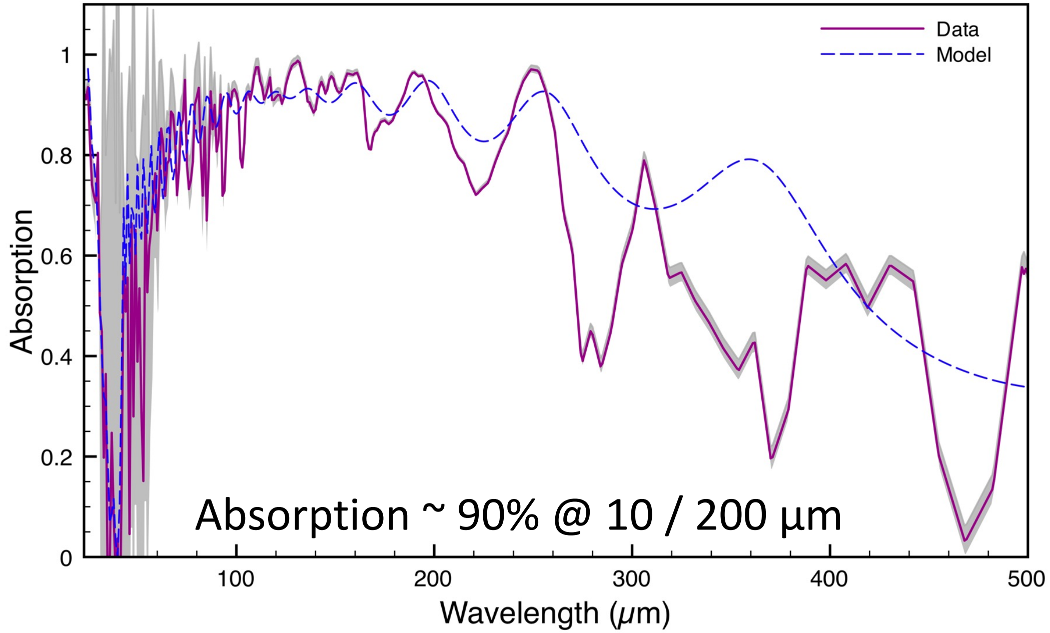


¼ Wave Cavity

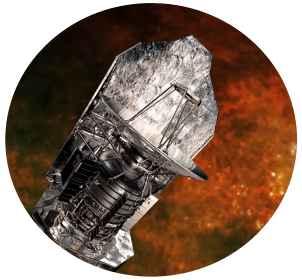
- « All Silicon » design
- **Very High impedance (~ GOhm)**

$$R = R_0 \exp\left(\sqrt{\frac{T_0}{T}}\right) \exp\left(-\frac{qL_{(T)}E}{kT}\right)$$

- **Very High Response**
  -> 2.10^{10} V/W
- **Cryogenic Multiplexing (MOS)** : 16 to 1
- **NEP** ~ 2.10^{-16} W/√Hz at 300 mK

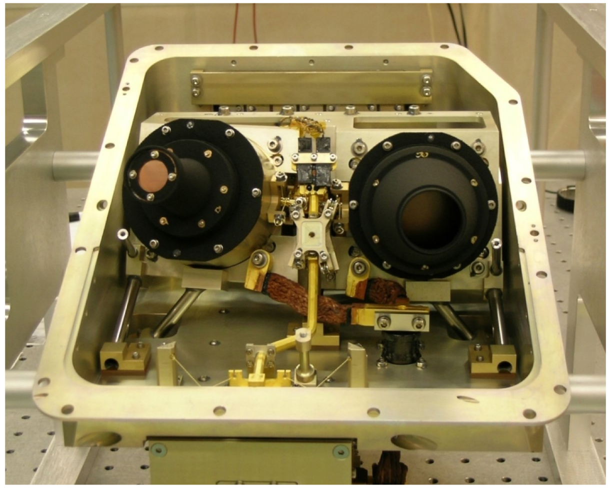


Herschel / PACS Legacy (2009– 2013)

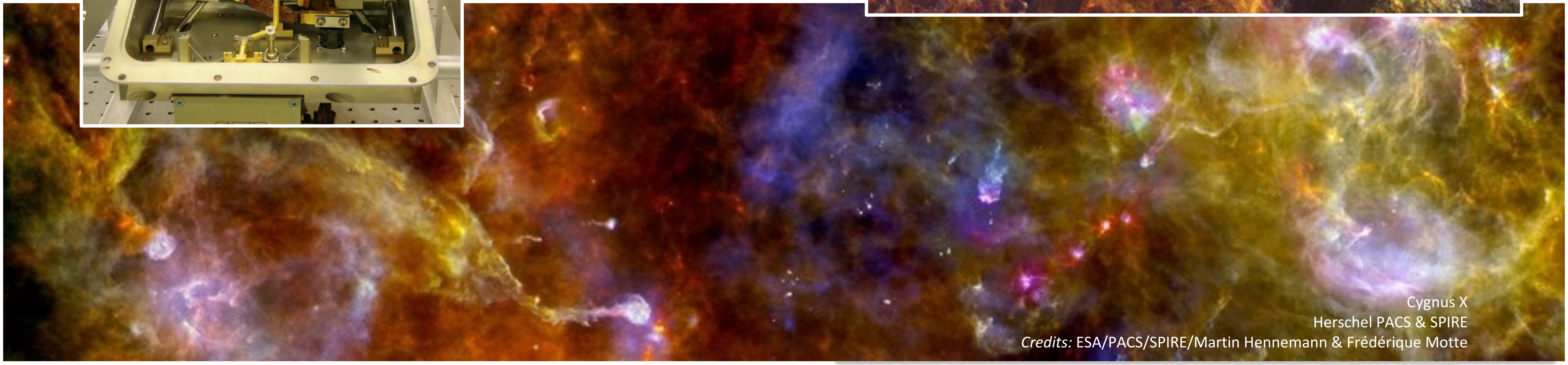


PACS Photometer

- 2560 pixels, 3 bands (70, 100, 160 µm)
- 30% of observing time, most used instrument
- (40 % if parallel mode included)

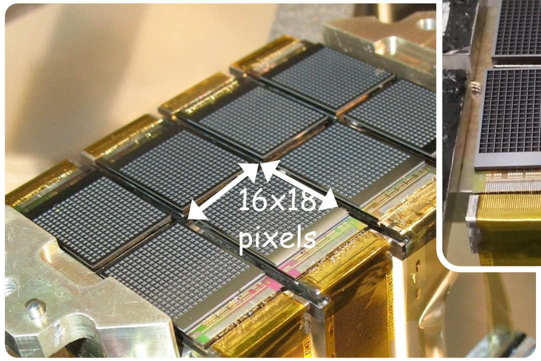


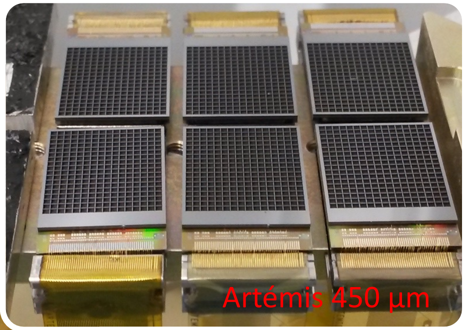
Horsehead Nebula (André et al)



Cygnus X
Herschel PACS & SPIRE
Credits: ESA/PACS/SPIRE/Martin Hennemann & Frédérique Motte

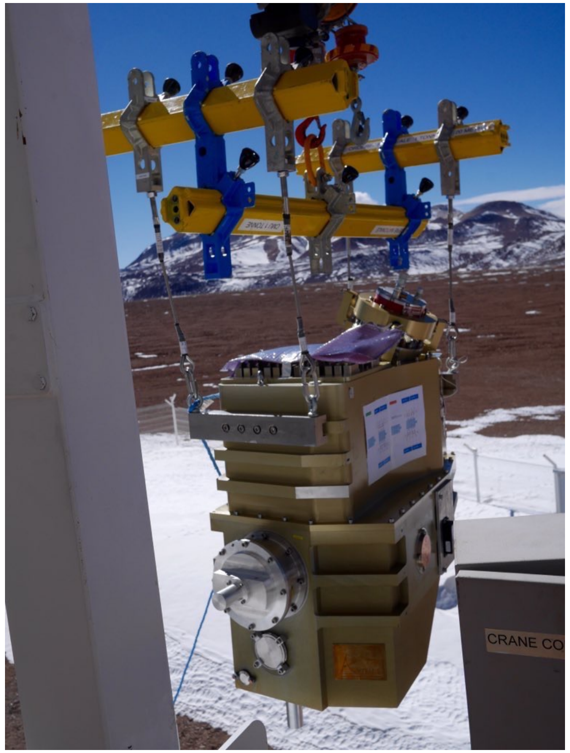
ArTéMiS on APEX : A Dual Band camera (**350 & 450 µm**) since 2013, still operating



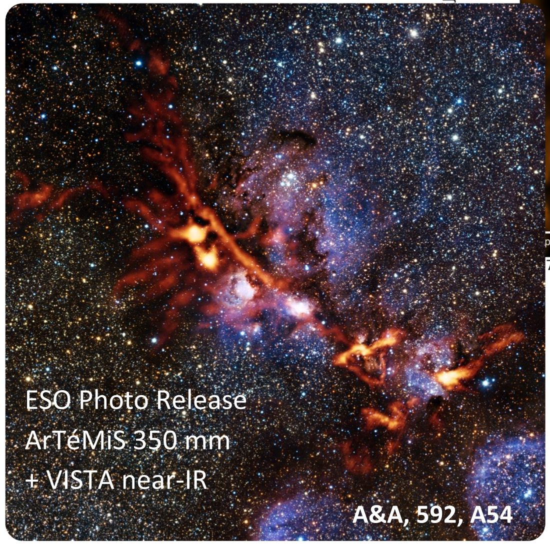


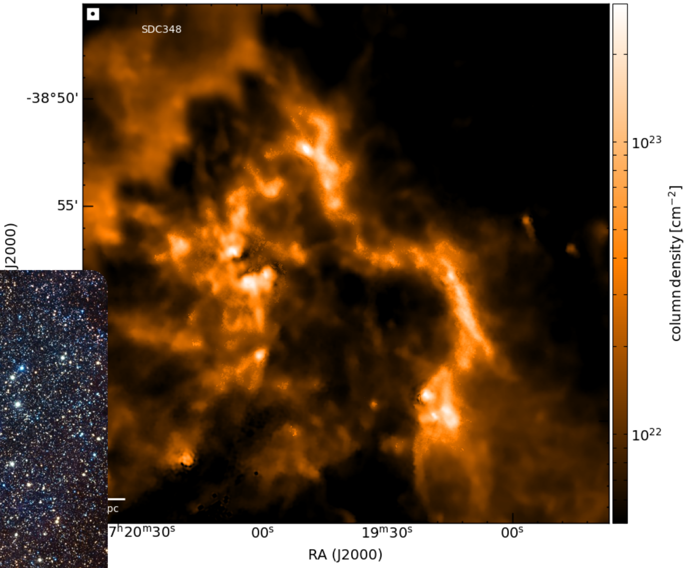
Artémis 350 µm focal plane

- The only 350 /450 µm camera open to the community (CEA/OSO/Chile).
- Complementary to Herschel Data at 350 µm (extended emission + spatial resolution)
- **Another Observation run in August this year**



Number of operational pixels	2400
Spatial Resolution **350 µm** **450 µm**	 8’’ 10.5’’
FOV (350µm)	4,7 x 2,3 arcmin^2
Median NEFD	580 mJy.s$^{1/2}$
Best NEFD	~ 300 mJy.s$^{1/2}$
Mapping speed @ 350 µm (relatively to Saboca)	~ x 5

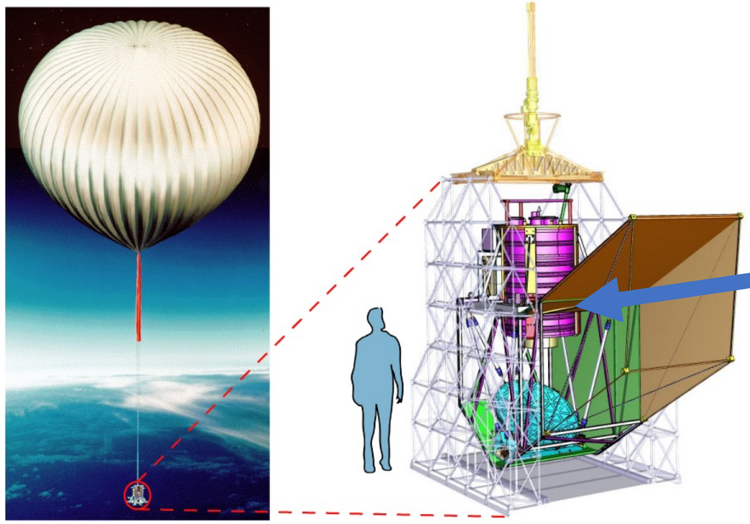


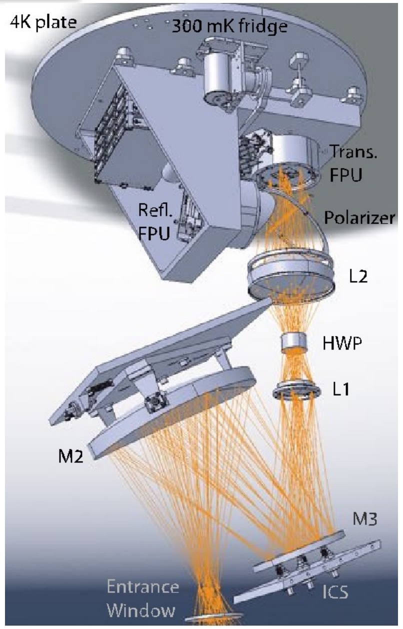


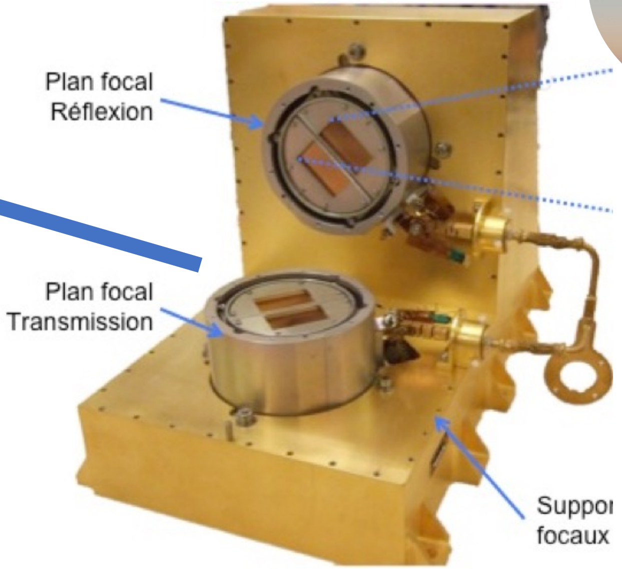
Column density map of the cloud SDC348

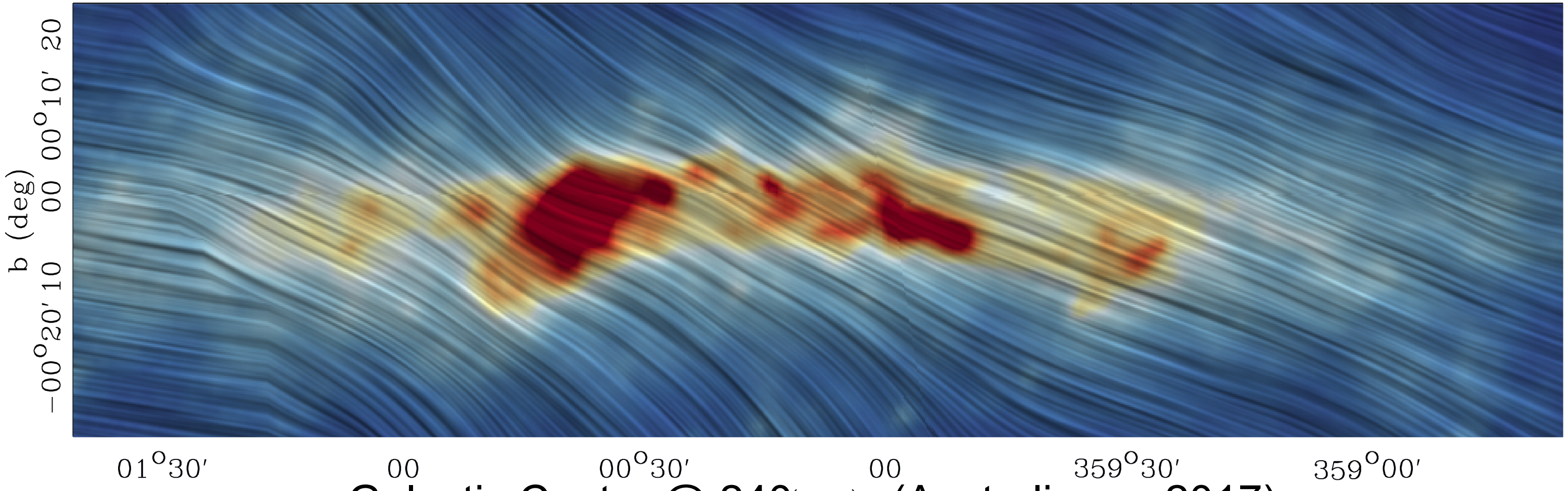
(M. Mattern, A&A 2024)

PILOT : Polarimetry with 1st generation bolometers







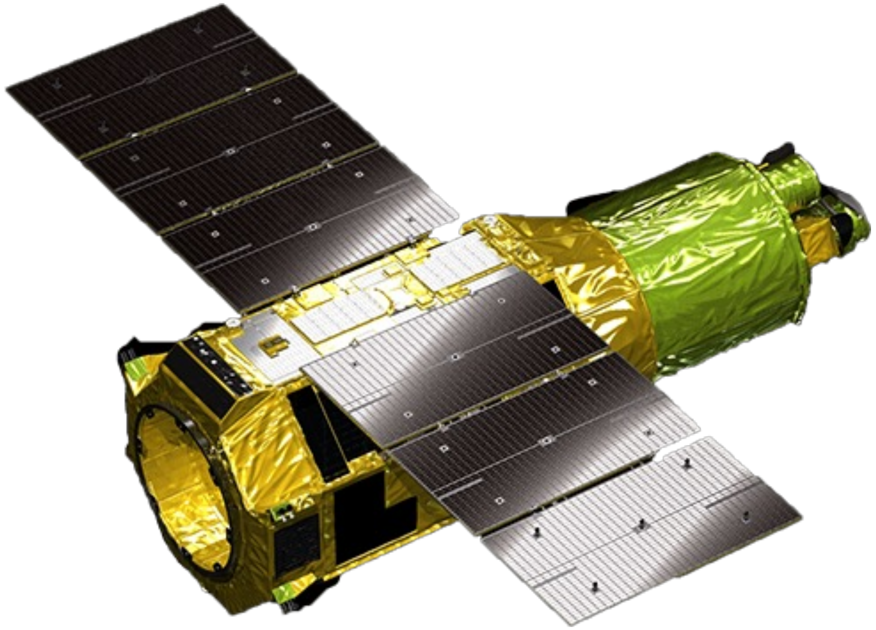


Galactic Center @ 240 µm (Australia run 2017)

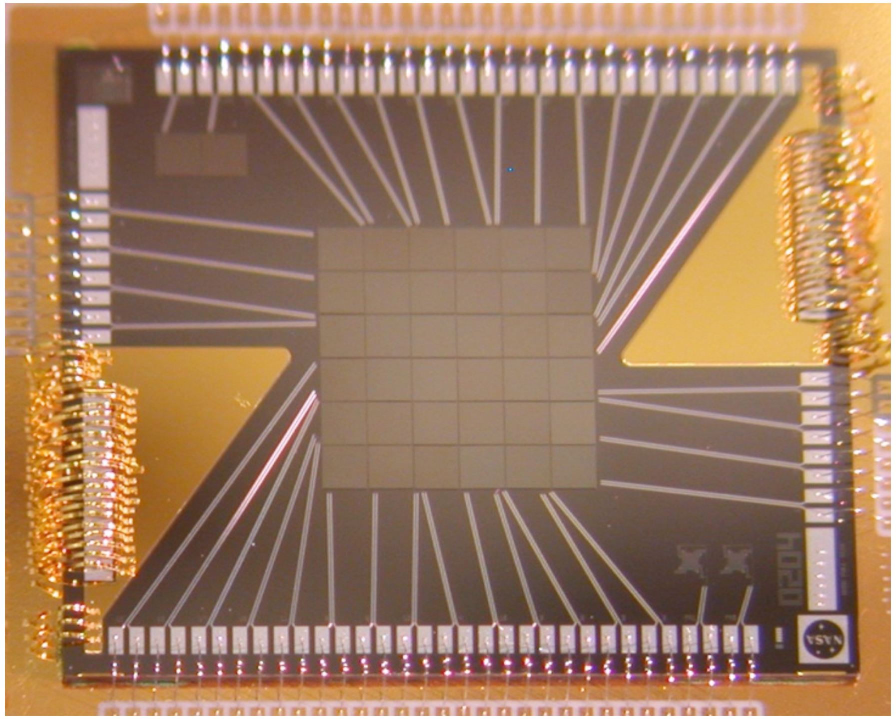
Why Silicon bolometers?

« Si Technology is not (completely) dead…! »

RESOLVE onboard the JAXA-NASA **XRISM Mission**



Launch in 2023



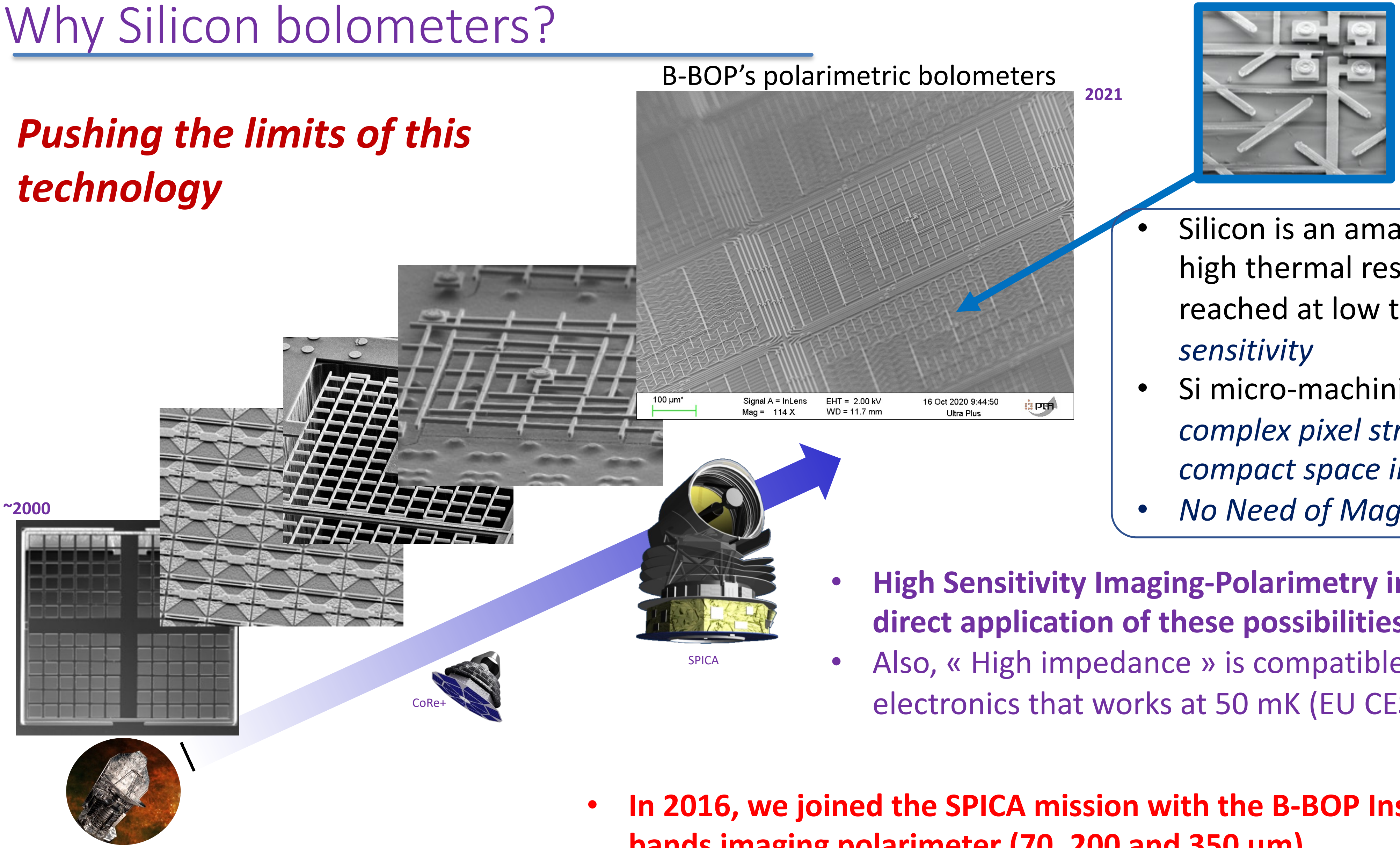
6x6 Silicon µ-Calorimeters from NASA Goddard working at 50 mK

(with ESA participation)

Why Silicon bolometers?

Pushing the limits of this technology

B-BOP's polarimetric bolometers

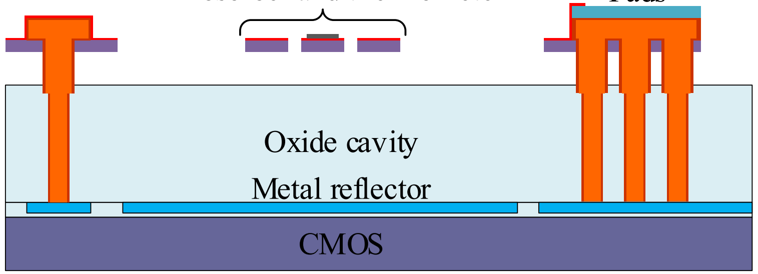


- Silicon is an amazing material : very high thermal resistance can be reached at low temperature => *high sensitivity*
- Si micro-machining enables to design *complex pixel structures to build compact space instruments*
- *No Need of Magn. shielding*

- **High Sensitivity Imaging-Polarimetry inside the pixel is a direct application of these possibilities**
- Also, « High impedance » is compatible with CMOS classical electronics that works at 50 mK (EU CESAR project).

- **In 2016, we joined the SPICA mission with the B-BOP Instrument : a 3 bands imaging polarimeter (70, 200 and 350 µm)**
- **Science Case : Magnetic Field in the ISM**

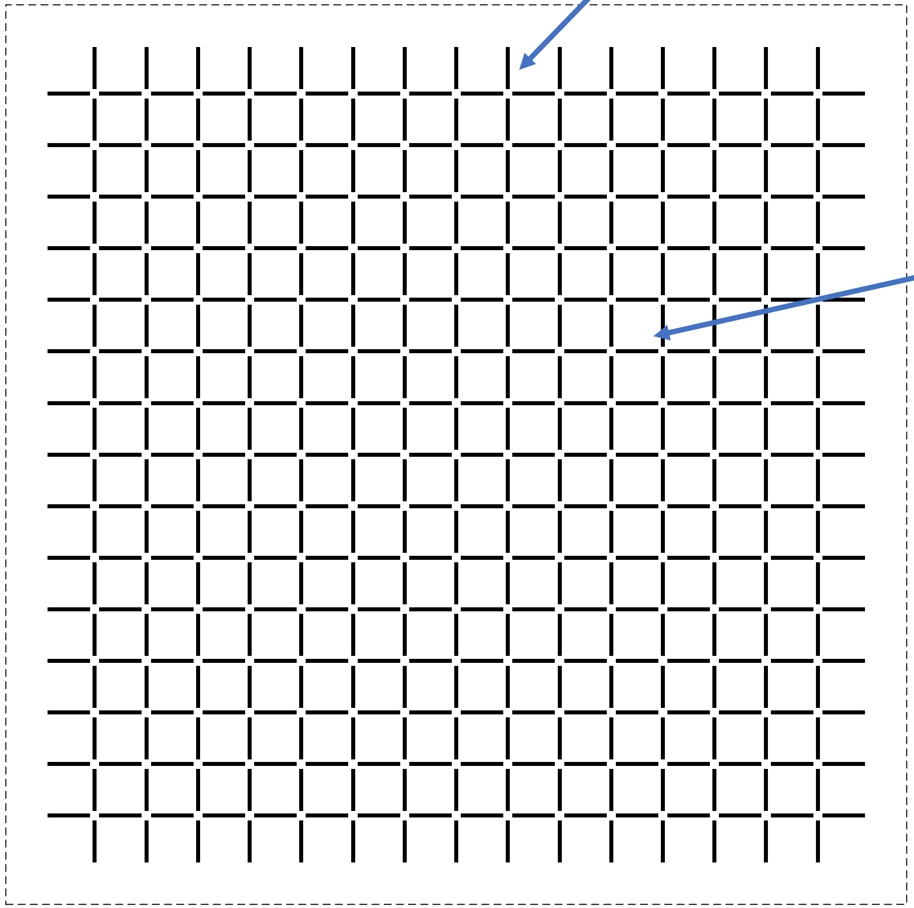
The B-BOP Detectors



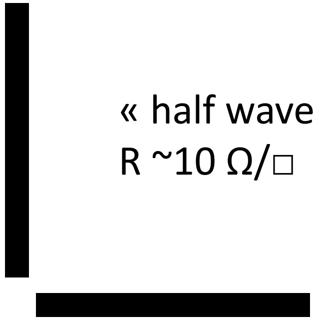
Each Pixel detects dual polarization. How ?

16x15 H dipoles
15x16 V dipoles

This is one Pixel
750x750 µm



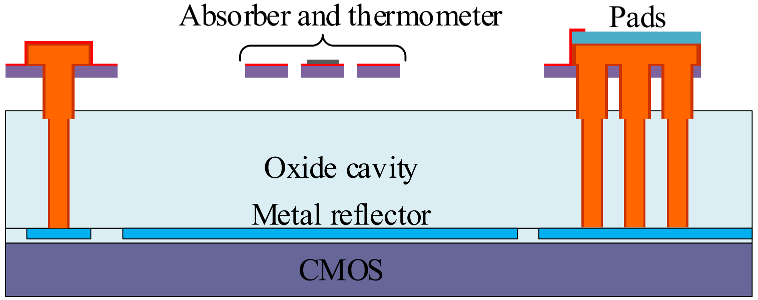
This is not a phased array antenna.



« half wave » dipoles (1.6 x 34.6 µm)
R ~10 Ω/□

The B-BOP Detectors

Each Pixel detects dual polarization. How ?



16x15 H dipoles
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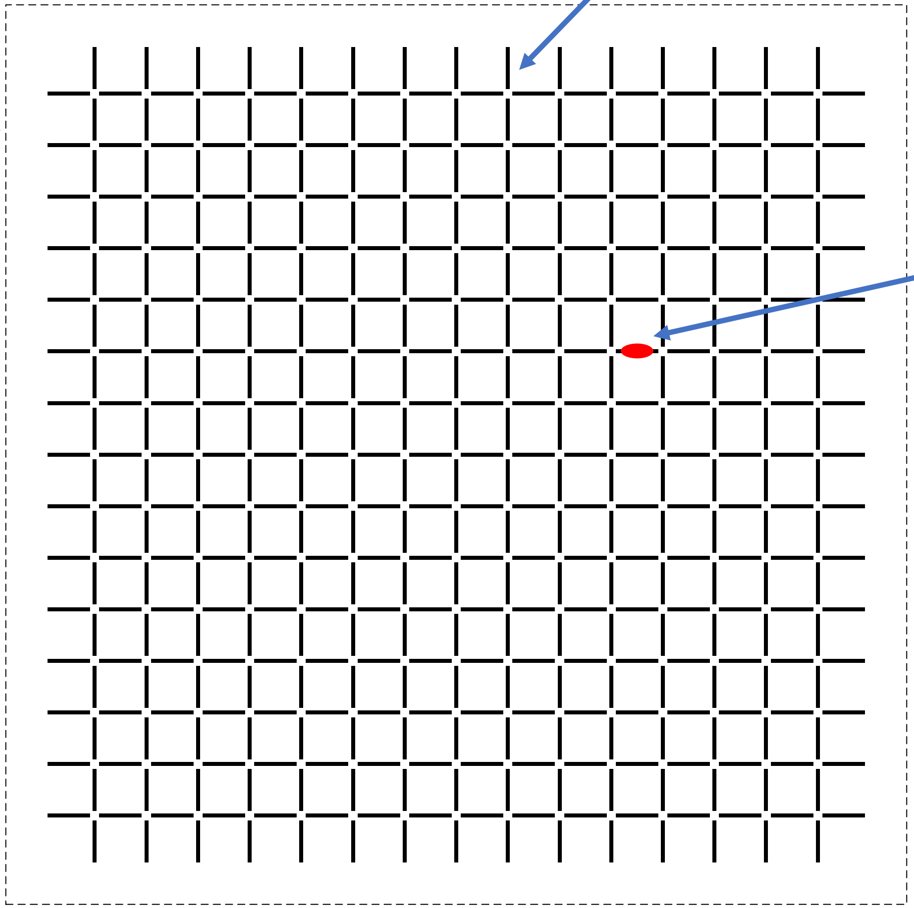
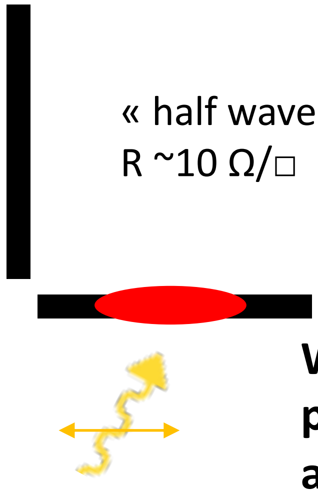
This is one Pixel
750x750 µm



This is not a phased array antenna.

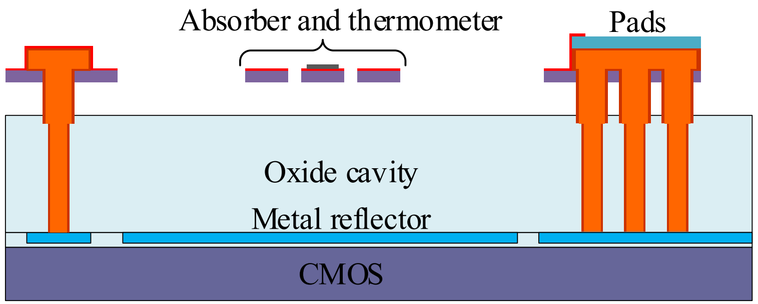


« half wave » dipoles (1.6 x 34.6 µm)
R ~10 Ω/□

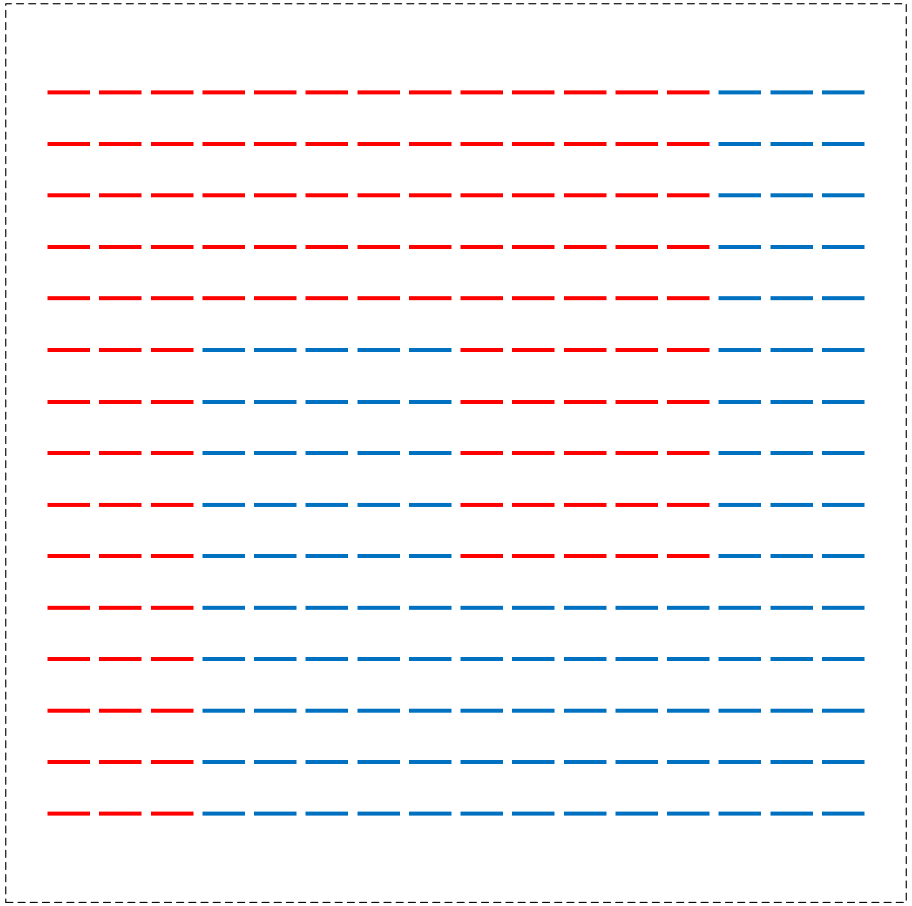
When a linearly polarized photon couples to the resistive antenna, its temperature rises.

A (sensitive) thermometer measures this rise.

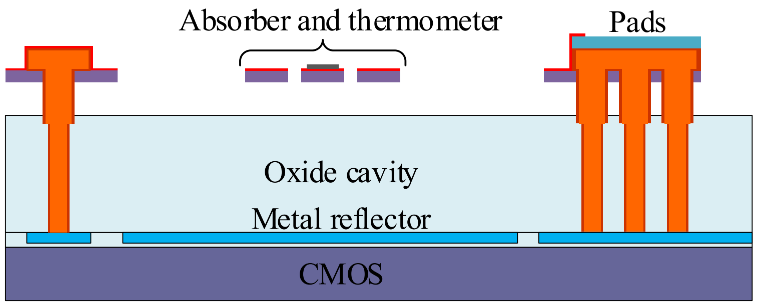
Electro-thermal scheme of the pixel

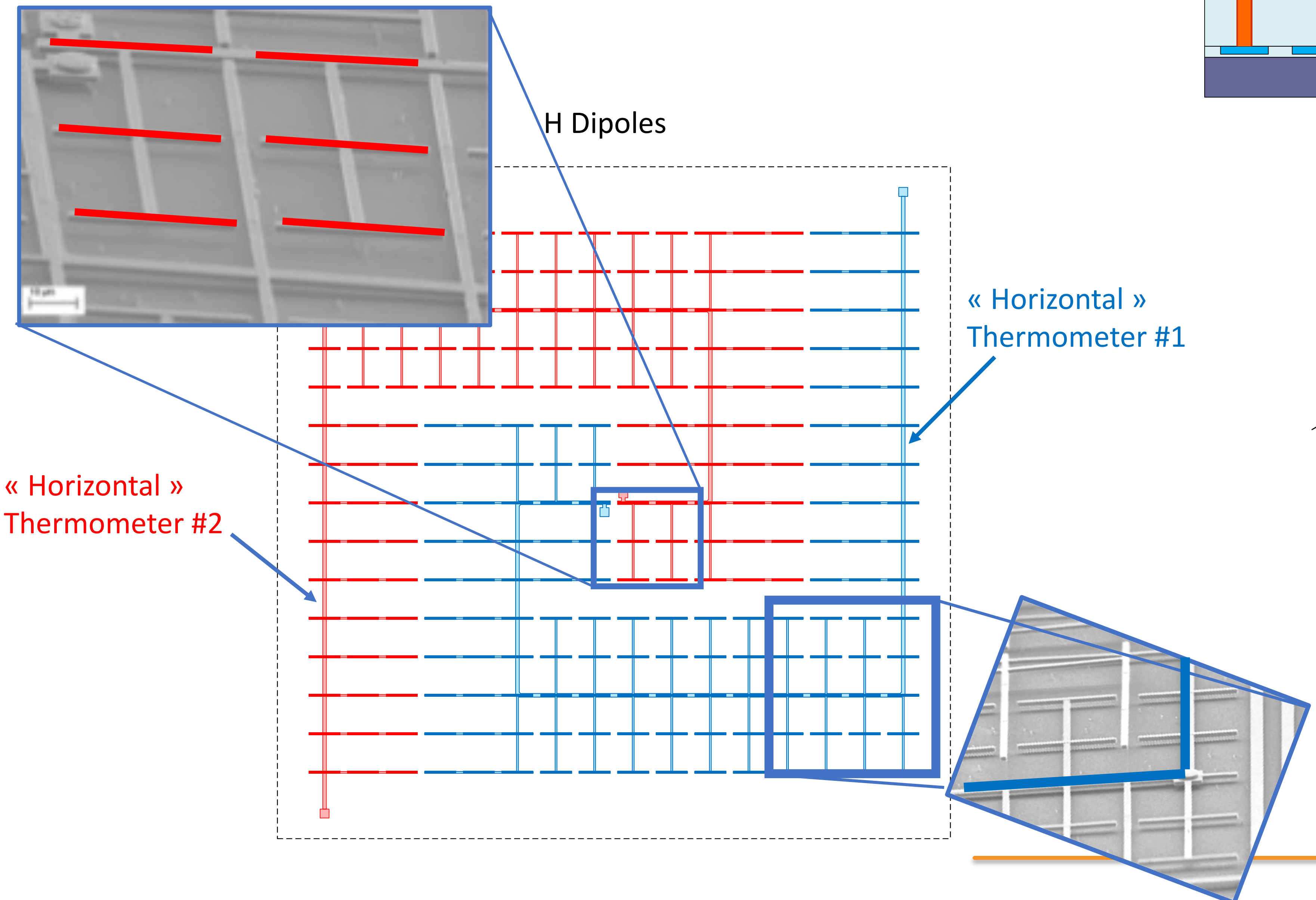


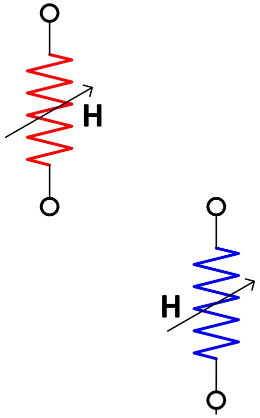
H Dipoles



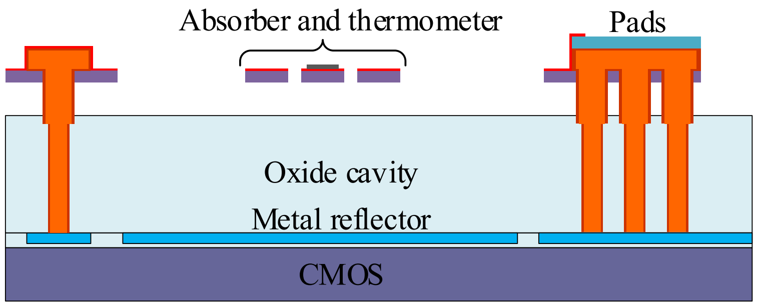
Electro-thermal scheme of the pixel

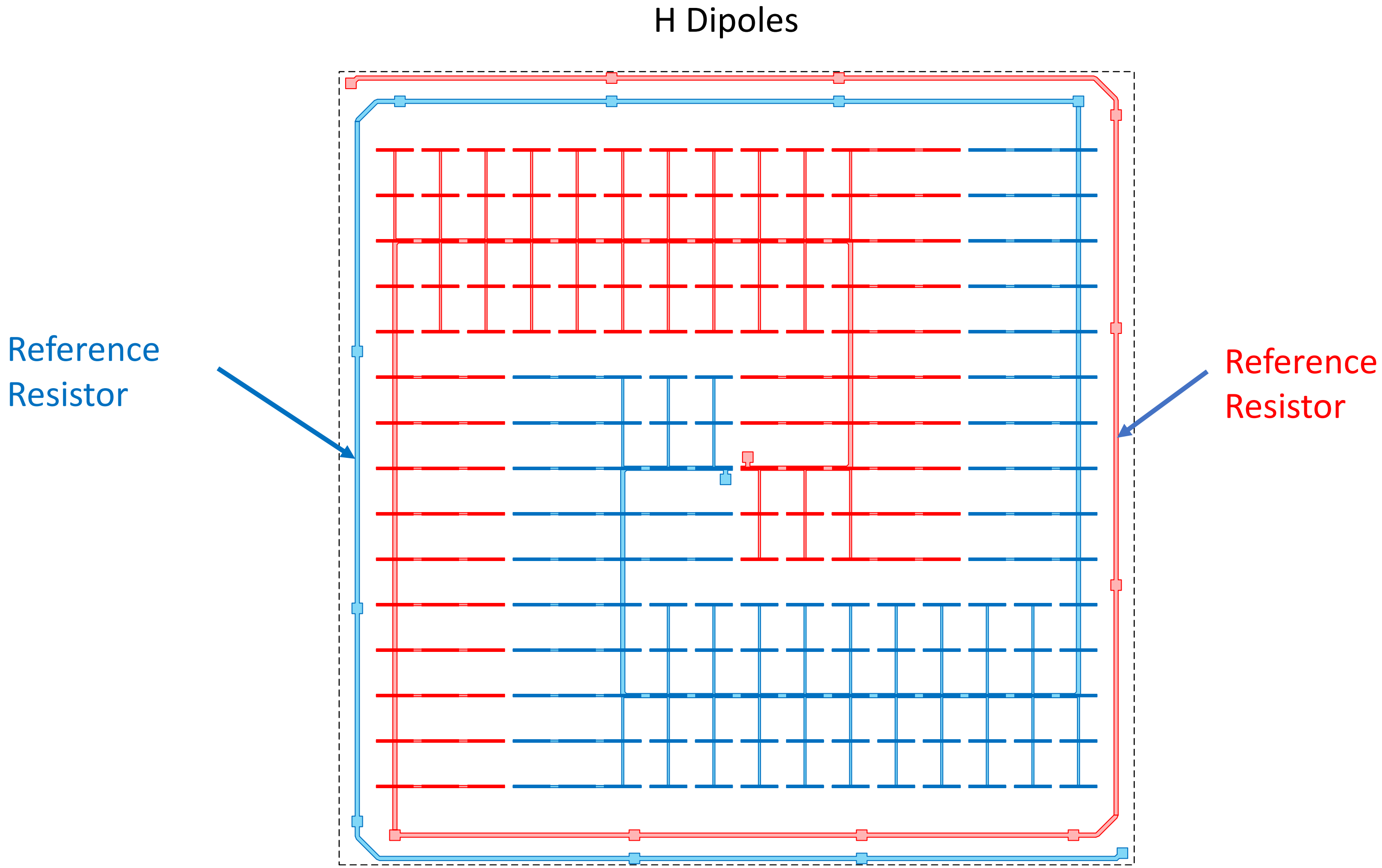


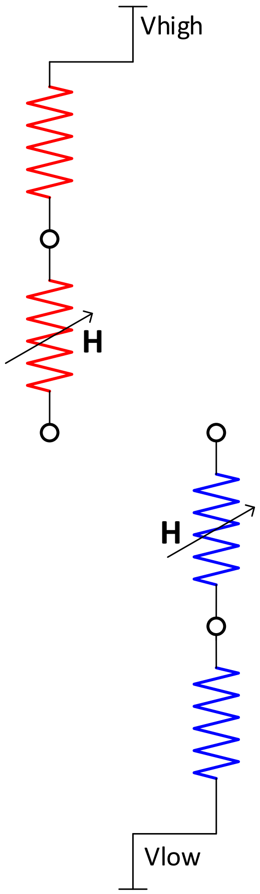




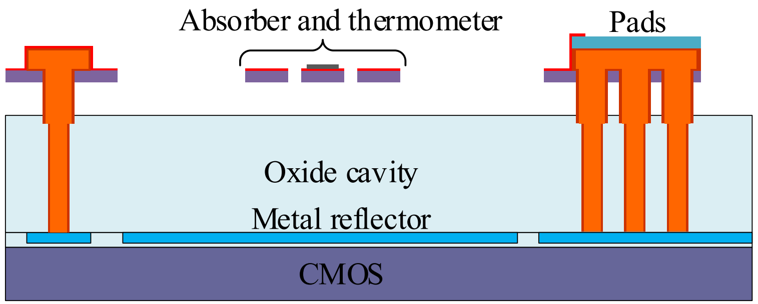
Electro-thermal scheme of the pixel



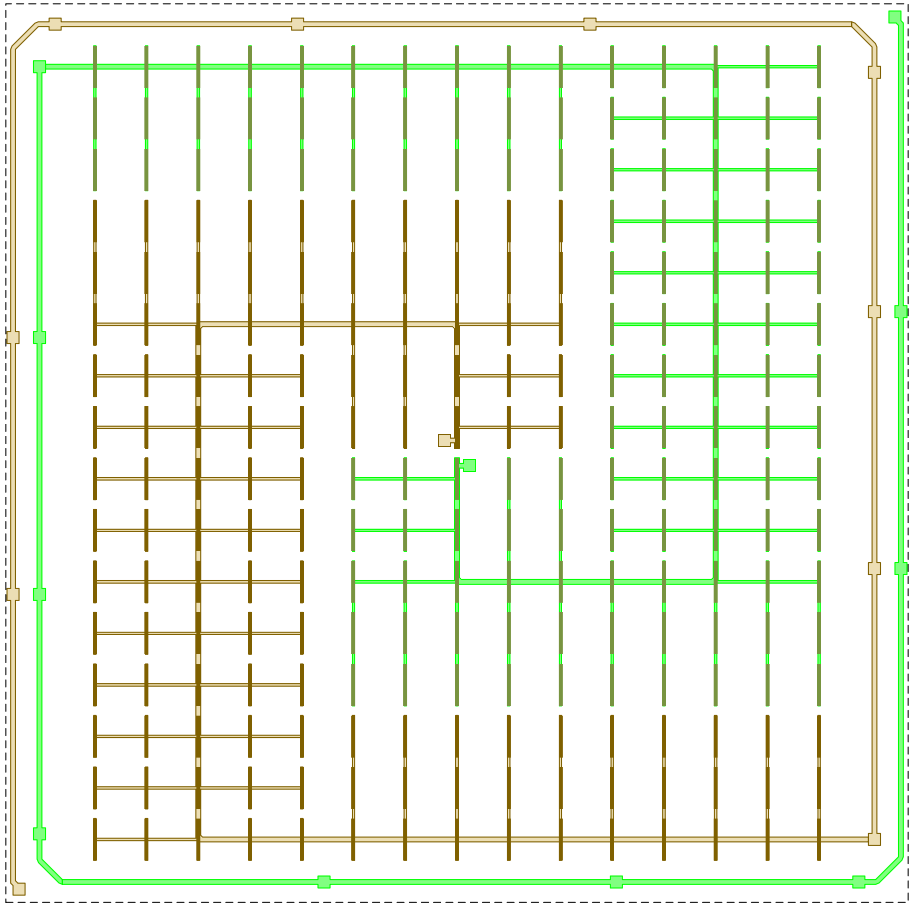


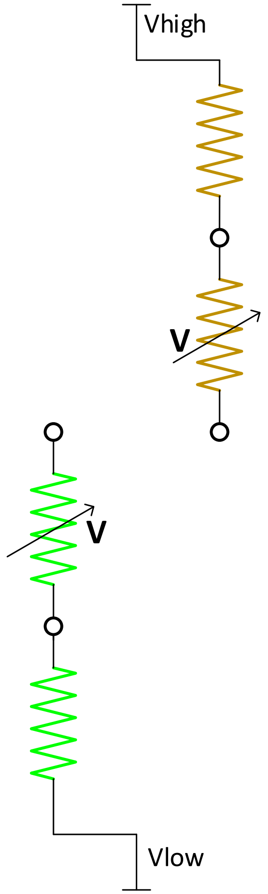


Electro-thermal scheme of the pixel

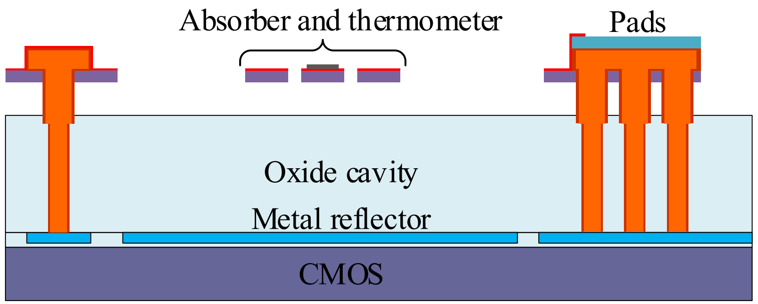


V Dipoles

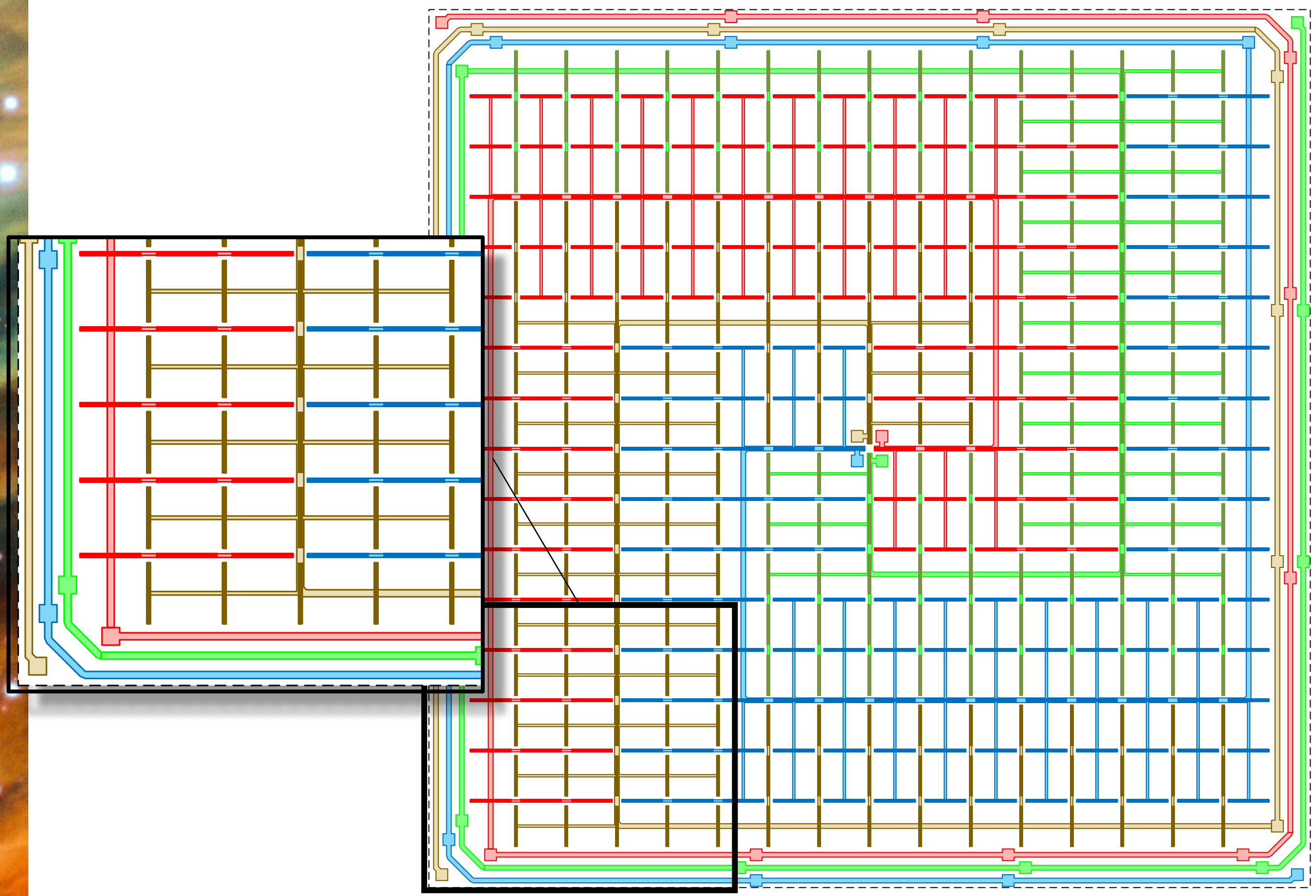


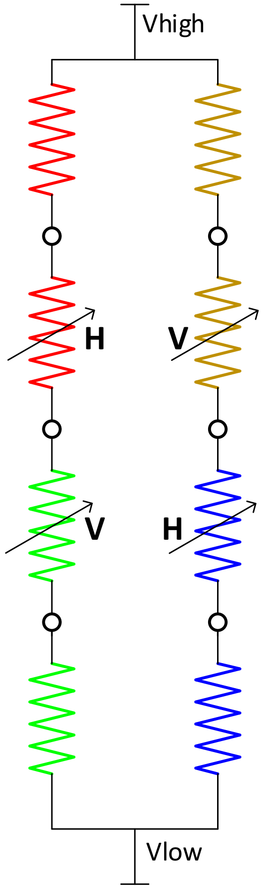


Electro-thermal scheme of the pixel

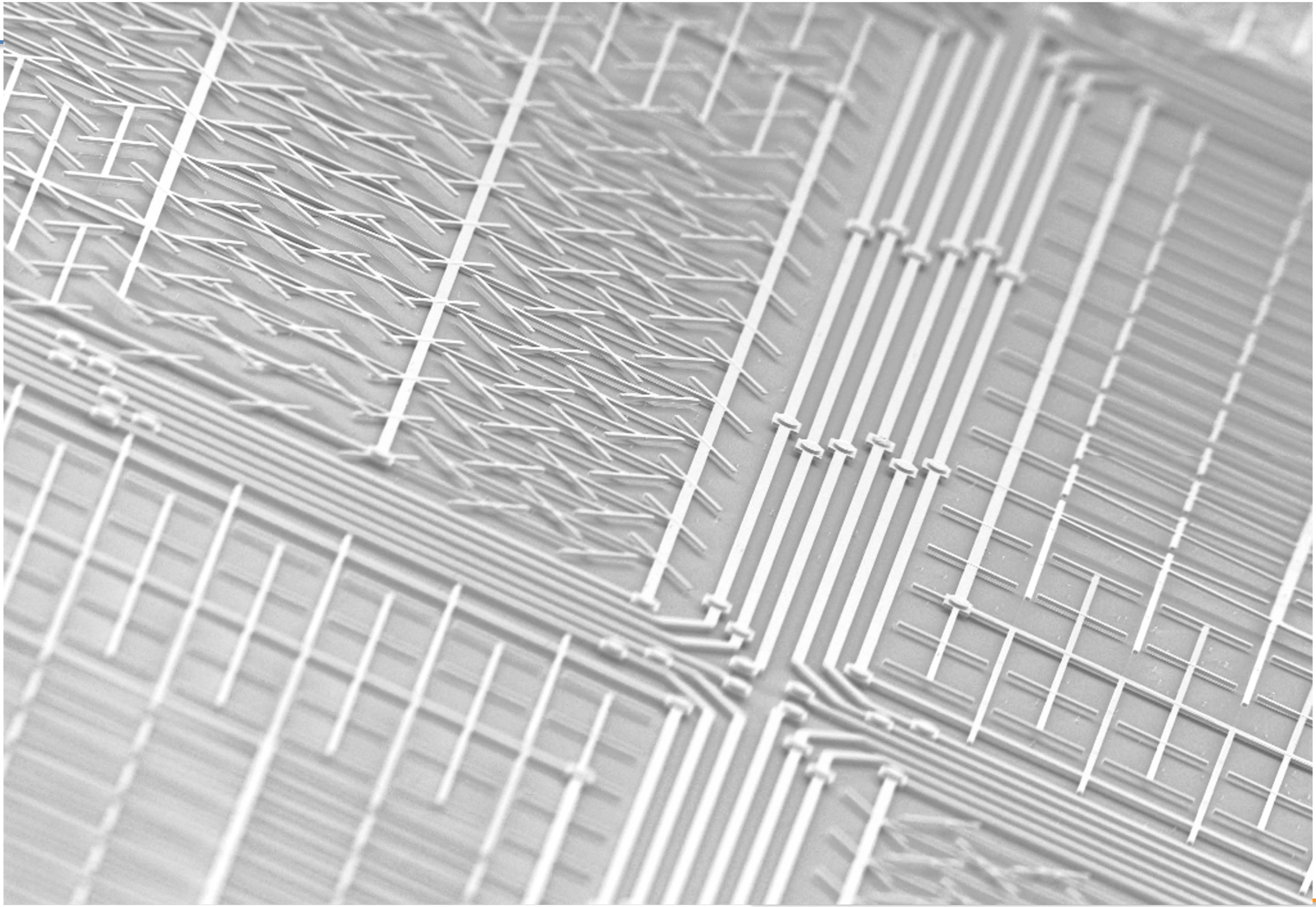


H+V Dipoles



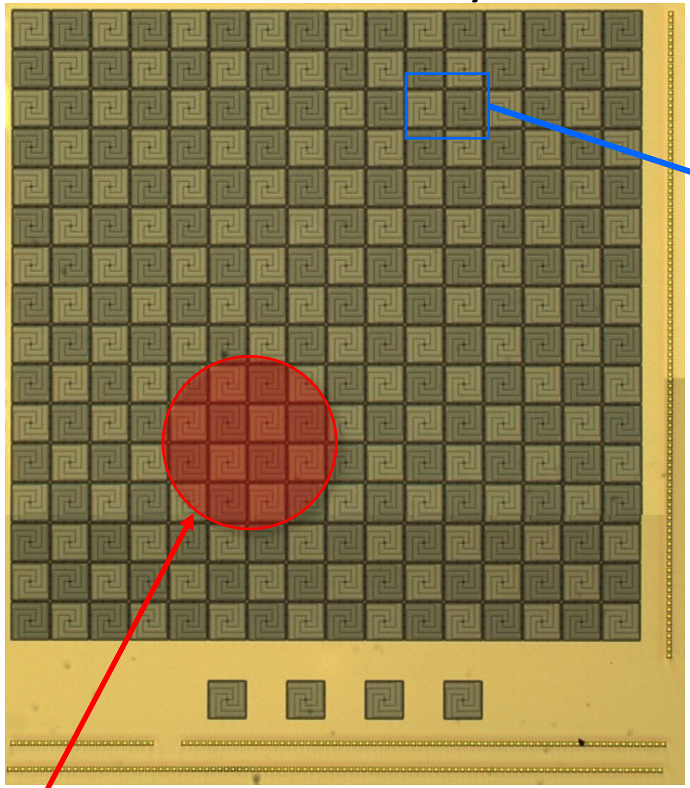


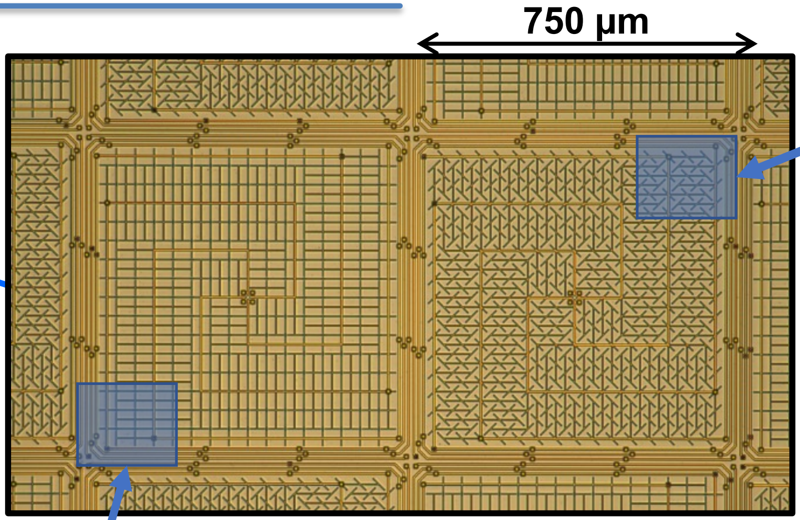
- Classical Wheatstone Bridge
- 6 points of measurement for the prototypes (will be optimized in future versions)

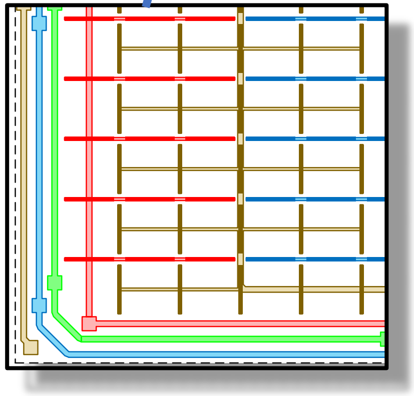


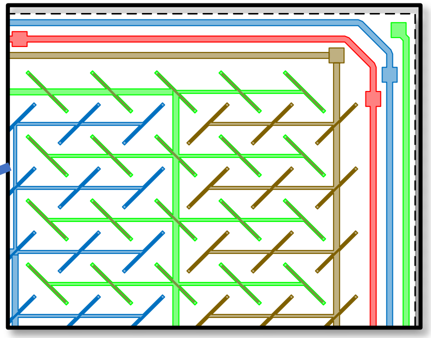
The SPICA BBOP test arrays (for the 100 µm band)

16x16 Bolometer Array









Orthogonal dipoles network

Airy Disc @ 70 µm
Nyquist sampling –> we get Stokes parameters

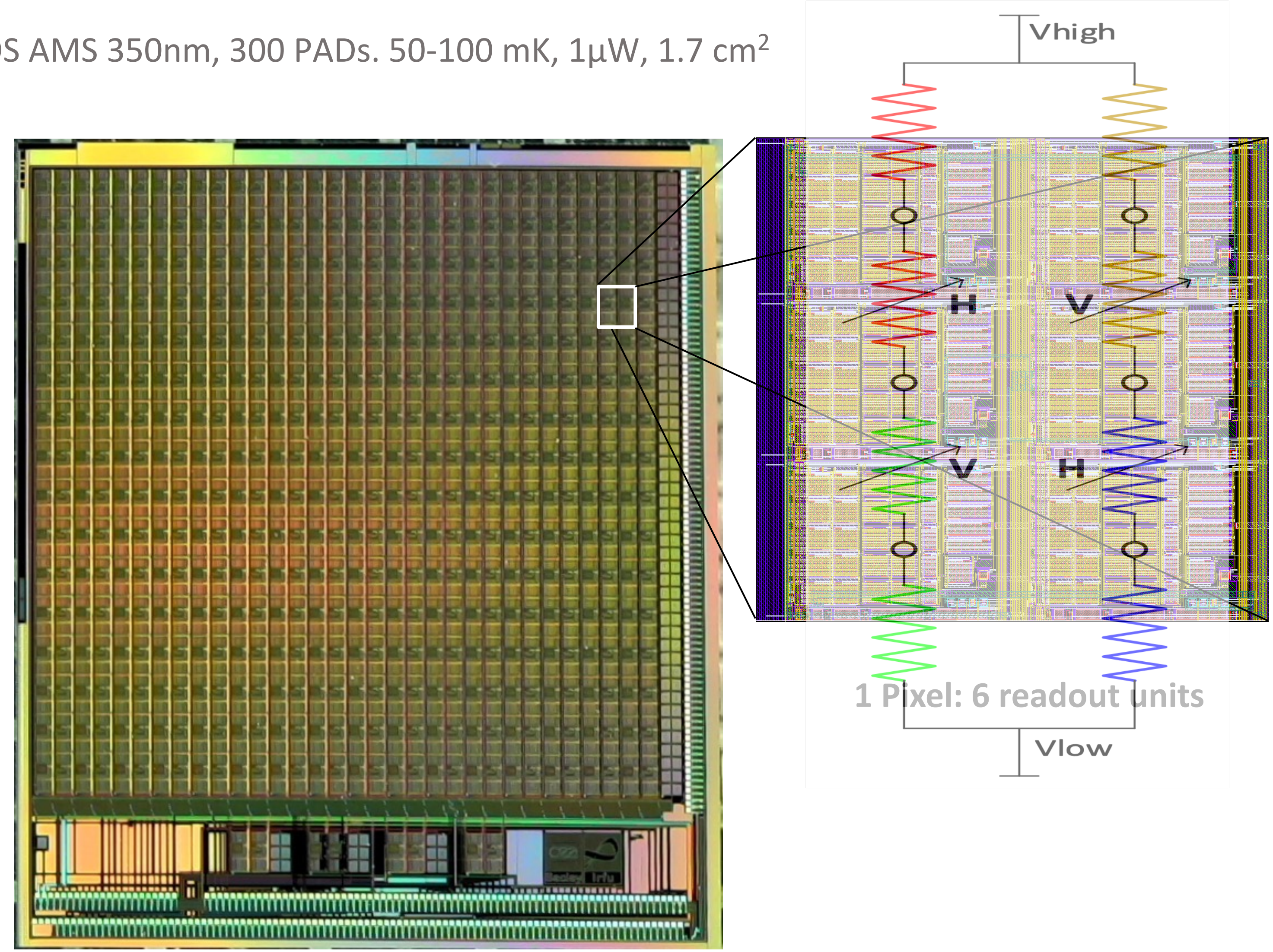
- This design enables
  - Very good optical coupling without horns or Si lenses
  - Full knowledge of Stokes parameters inside the Airy disk, without polar. modulation

FOCUS Focal Plane Array for Universe Sensing · cnes · esa · cea

« ECLIPSE » : the 50 mK readout electronics

256 pixels with 6 readout units in each pixel=>1536 readout units

CMOS AMS 350nm, 300 PADs. 50-100 mK, 1µW, 1.7 cm^2



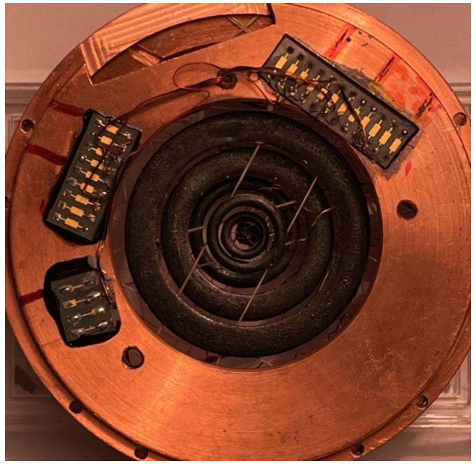
With this Wheatstone bridge circuit, for each pixel we get :

- **Differential polarization unbalance between H and V signals**
- **Differential amplitude signal**

The ADC's are optimized to adapt to the **very different dynamic ranges.**

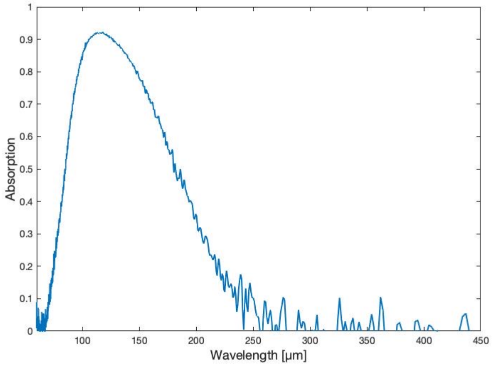
Testing the Arrays

Extreme challenge : the optical background is ~ fW/pixel



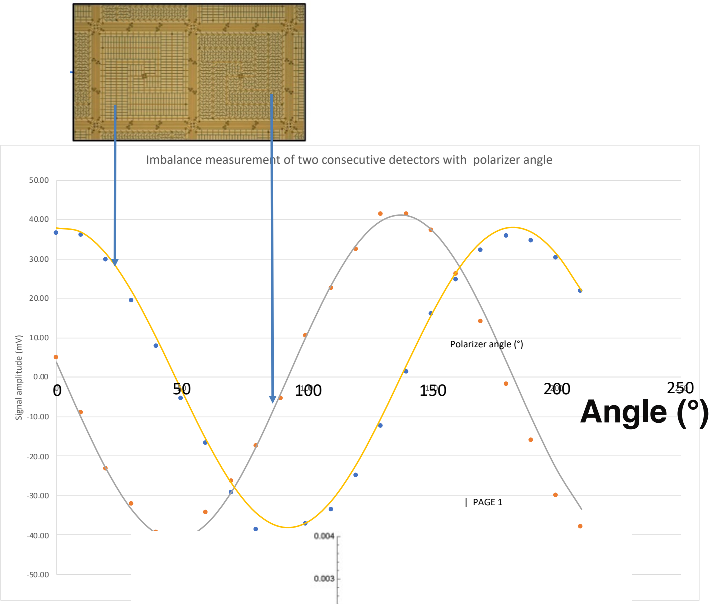
30K Optical source, using concentric emitting rings

Pixel Absorption
> 90% at 100 µm

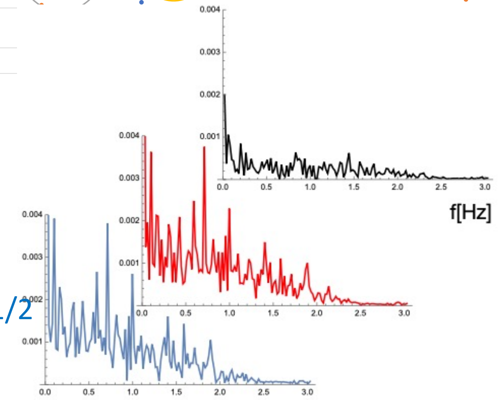


(Cryogenic FTS)

Polarimetry
Cross pol ~ 0.1%



Noise / Sensitivity
NEP = 1.4 10^{-18} W/$Hz^{1/2}$

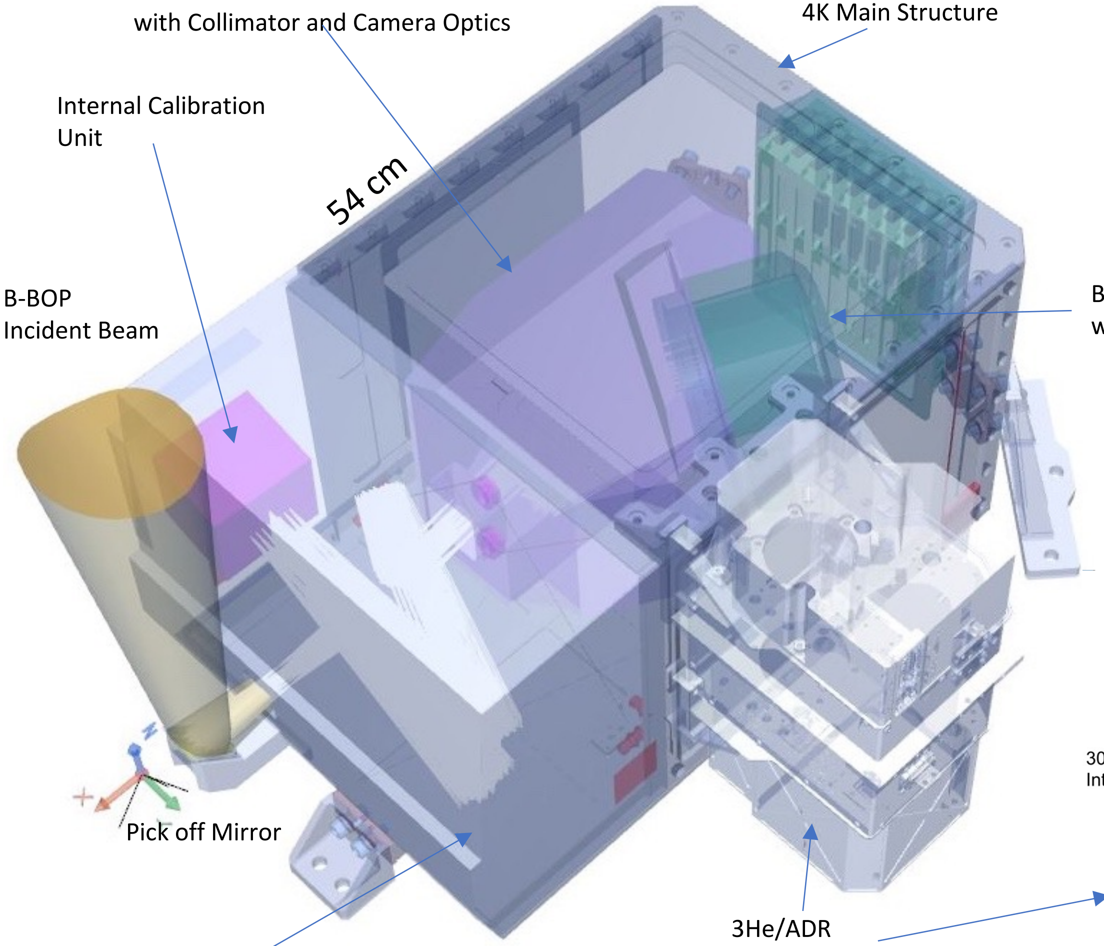


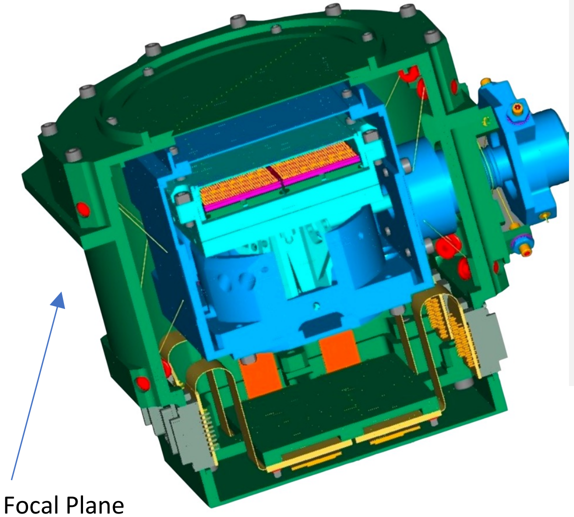
- Main parameters have been measured at cold temperature
- Very good results -> below SPICA BBOP Goal for NEP
- Challenges : thermal issues (readout currents), full MUX demonstration

B-BOP, the instrument on SPICA

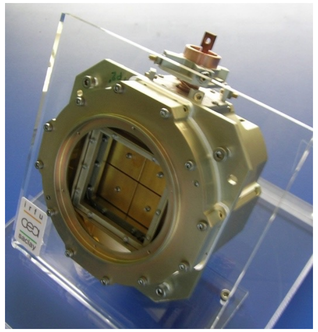
« Simple & Compact Design » : No moving part, no rotating plate (except for calibrator unit), no **Magn. Shield.**

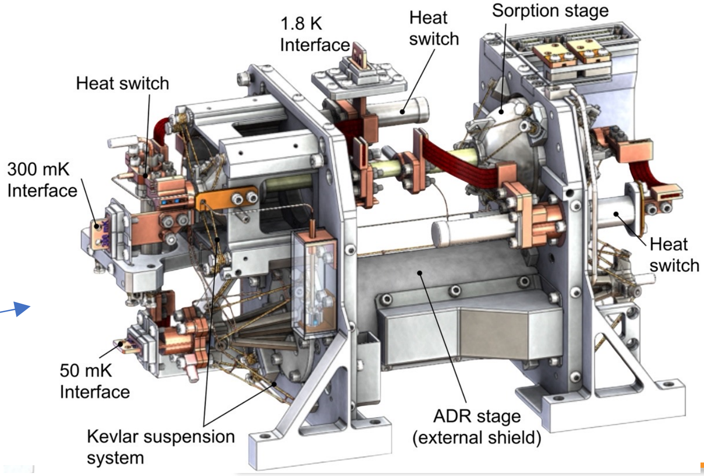
Big Advantage on the System Point of View





- The Focal Plane Assembly contains 6 bolometer modules (1344 bolometers in total).
- It is a « 3 levels » system : 2K housing, 300mK and 50mK stage (structures suspended by Kevlar wires)

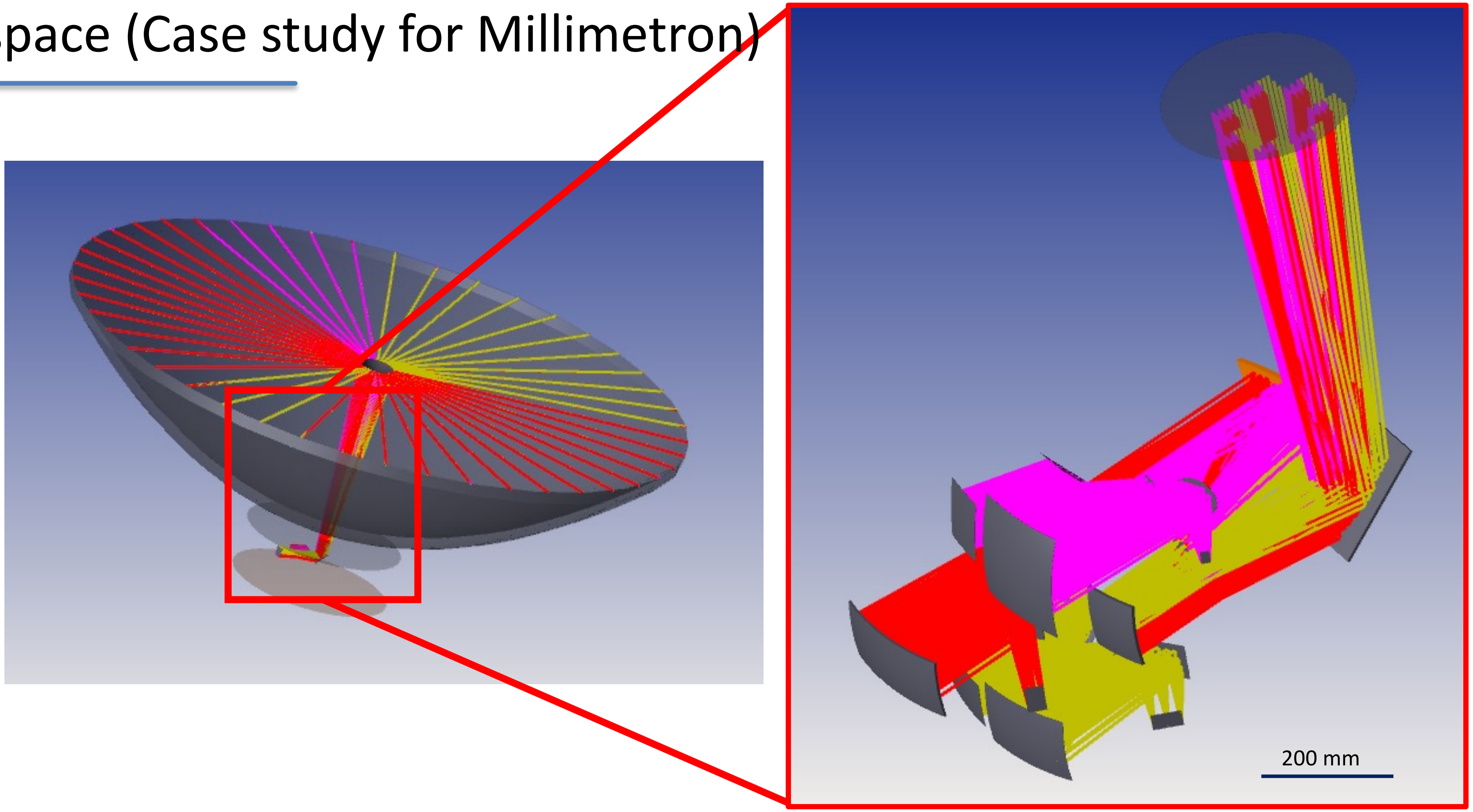




- Mass ~ 25 kg (63 kg including warm electronics)
- Power : 86 W (warm electronics)
- Power dissipation @ 50 mK ~1 µW

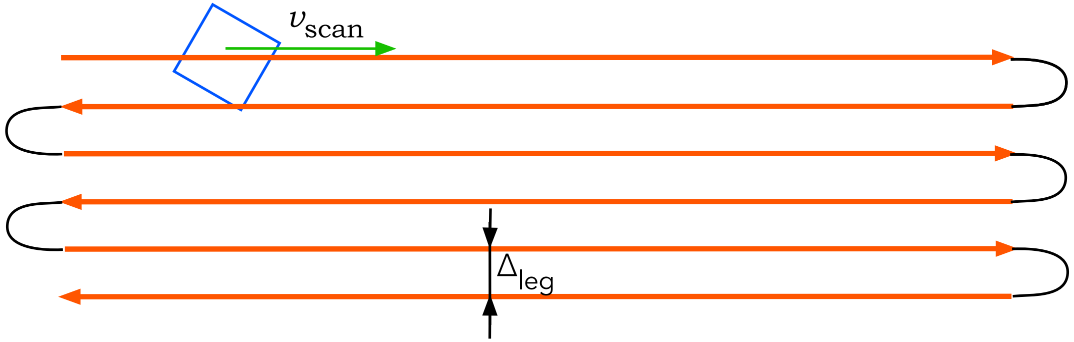
B-BOP on a 10m single dish in space (Case study for Millimetron)

- **6 broad spectral bands** (R=2) centered at **70, 100, 160, 250, 350 and 500 µm**
- No dichroic. At a given time, each band observe a different field of the sky
- Pixel size adjusted to be slightly below FWHM (except band 1)



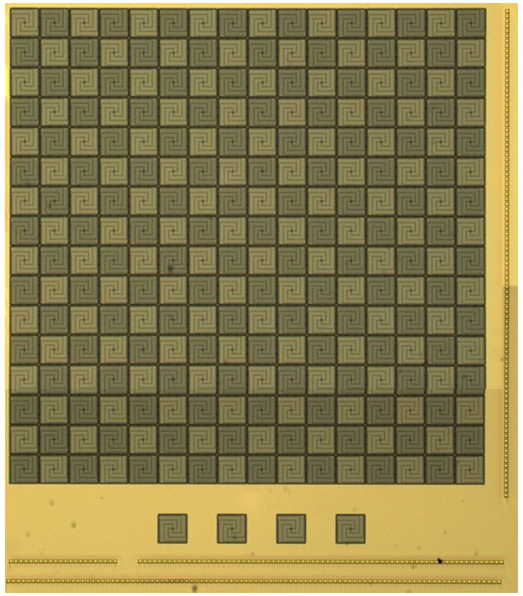
Camera optics:

- 3 optical path for the 6 bands
- “offner”-like systems: 3 mirrors (spherical or ellipsoid) to make a focal plane with a good optical quality and appropriate plate scale
- Fits in the allocated volume

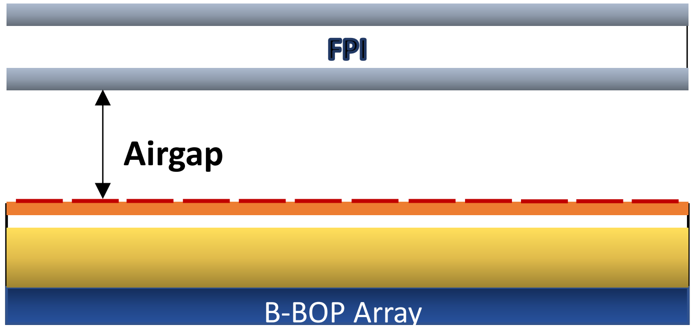


The typical observing mode for such an instrument is OTF scanning. In a « large » map, the 6 Focal Plane Arrays will cover almost the same surface on sky.

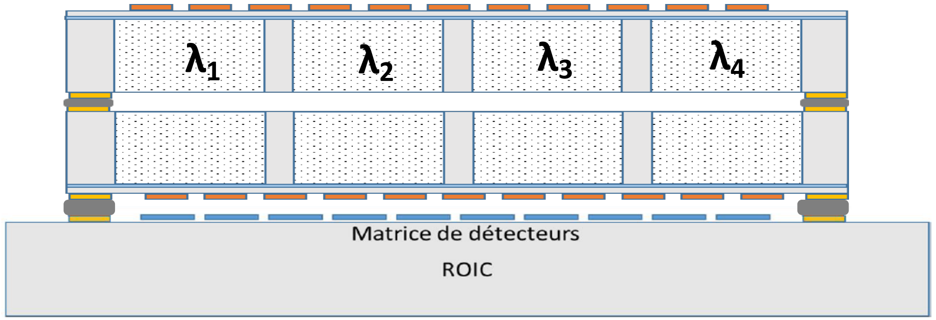
Adding (mid-R) Spectroscopy to the Array



(1) A Compact Scanning Fabry-Perot

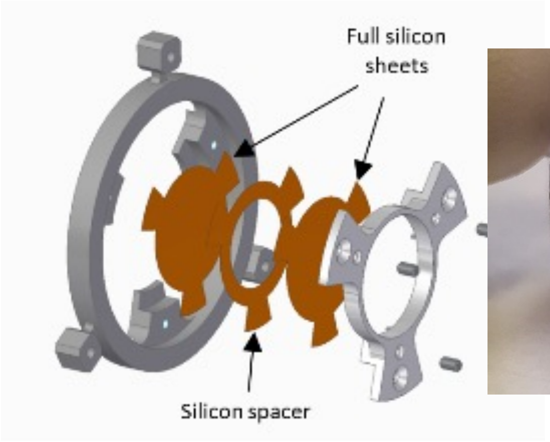


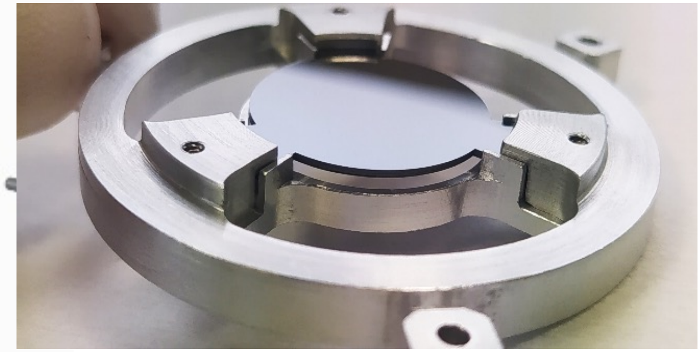
(2) A Bayer Filter Array

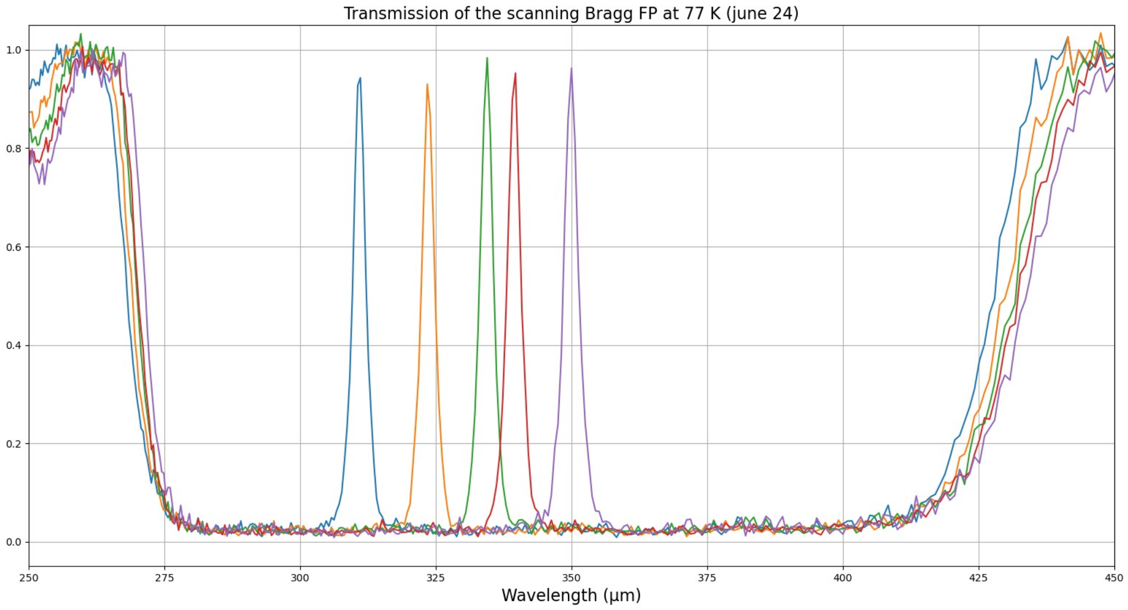


Spectroscopy – Preliminary results (R ~ 200 / 300)

Adjustable cryogenic Fabry-Perot made of Si Bragg mirrors



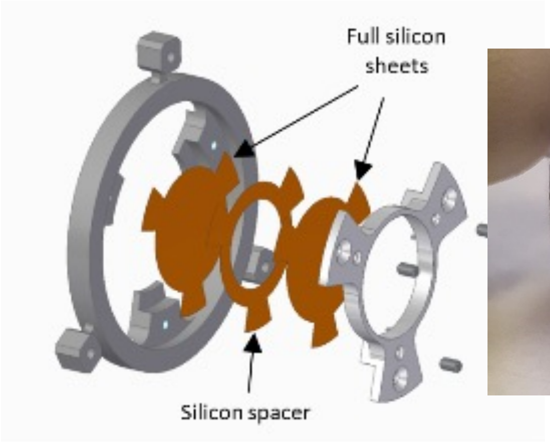


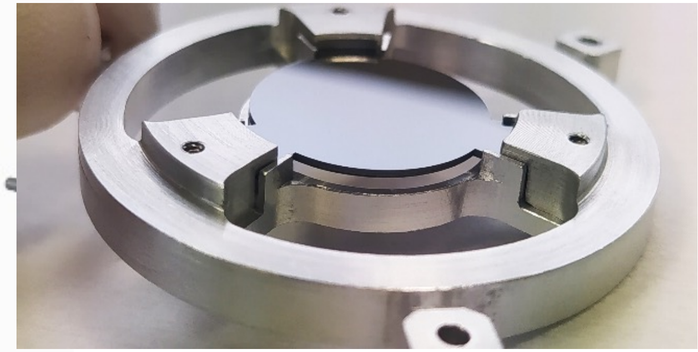


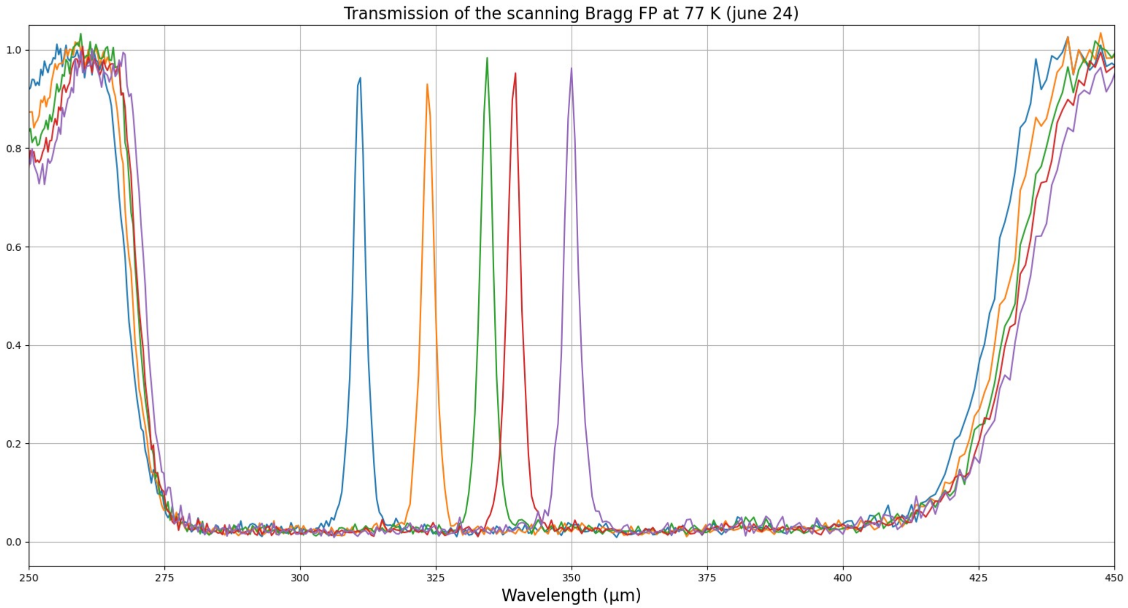
Spectroscopy – Preliminary results (R ~ 200 / 300)

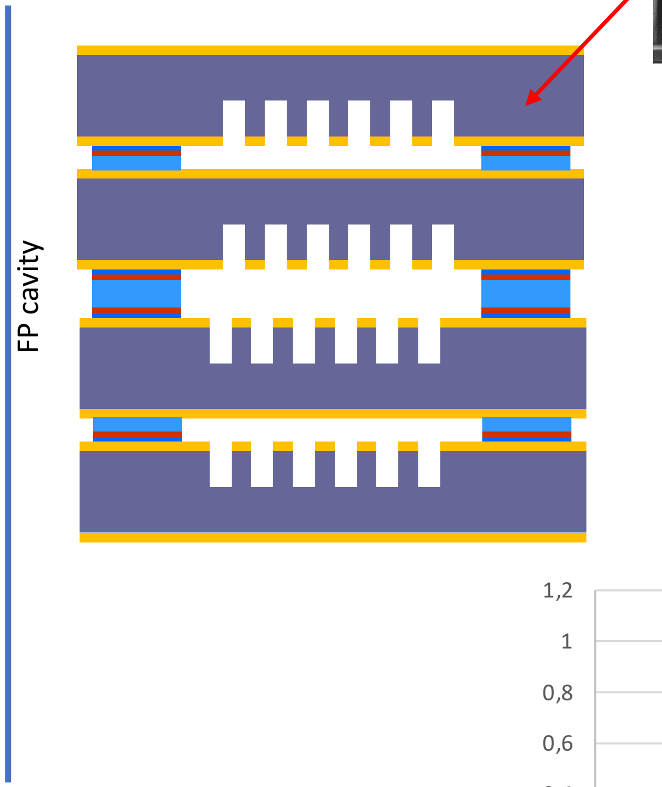
Adjustable cryogenic Fabry-Perot made of Si Bragg mirrors

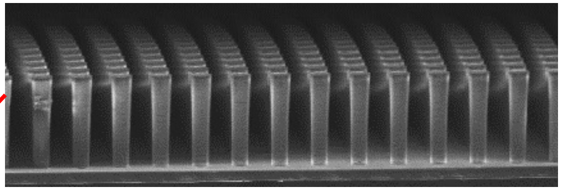
Stationary array of Fabry-Perot made of microstructures Si.

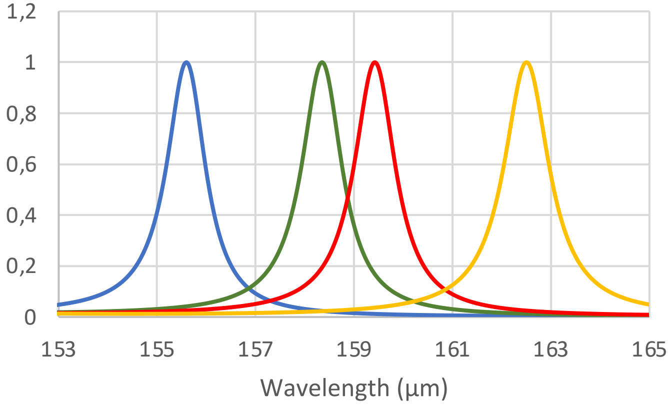






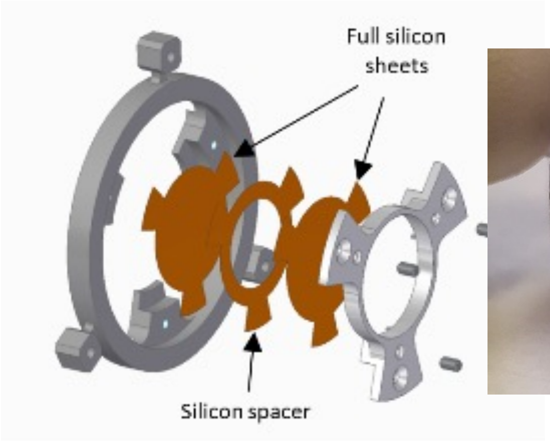


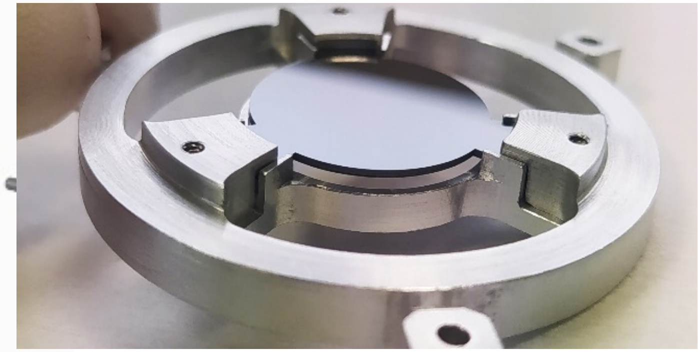


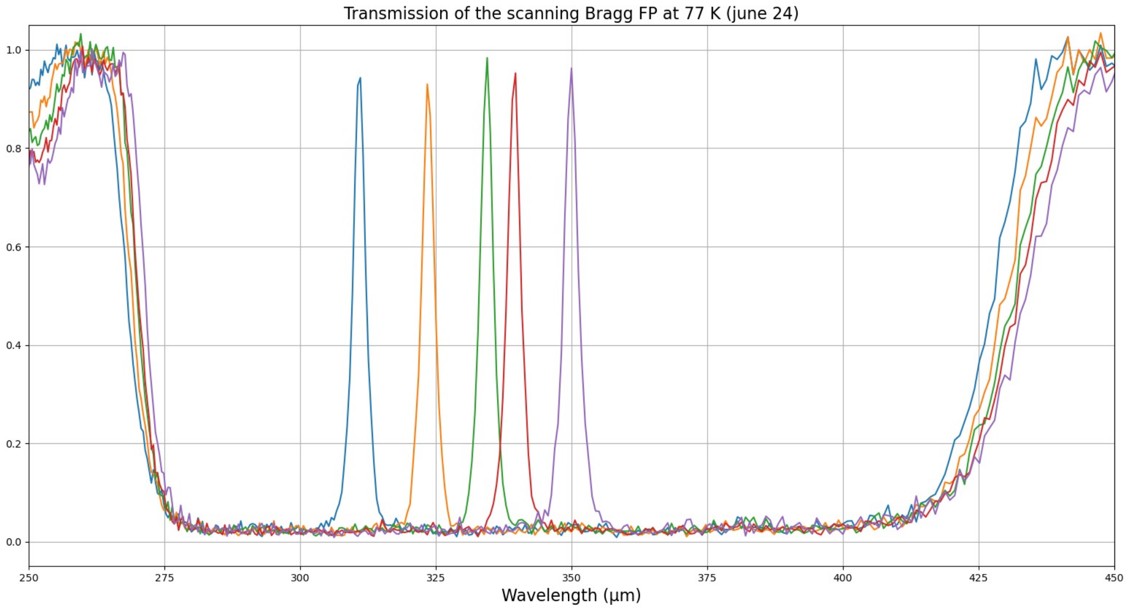


Spectroscopy – Preliminary results (R ~ 200 / 300)

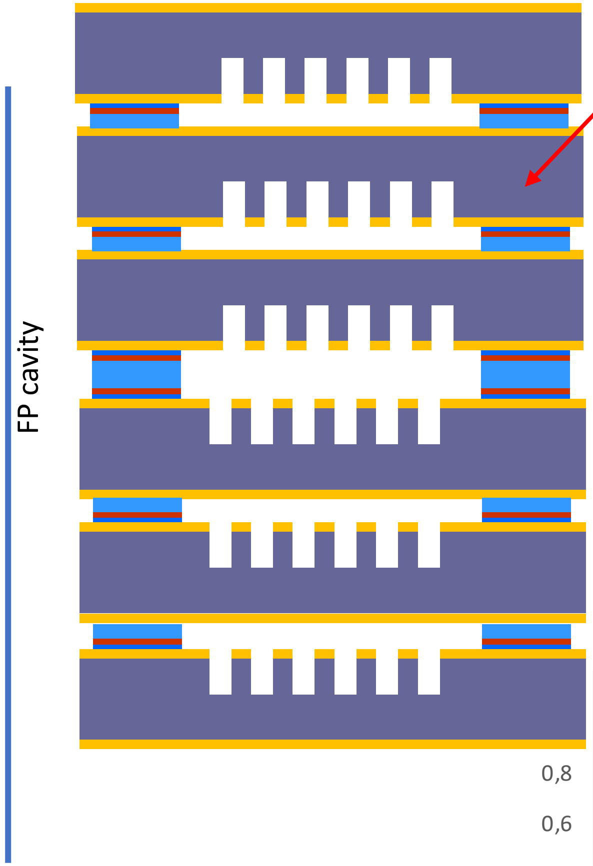
Adjustable cryogenic Fabry-Perot made of Si Bragg mirrors

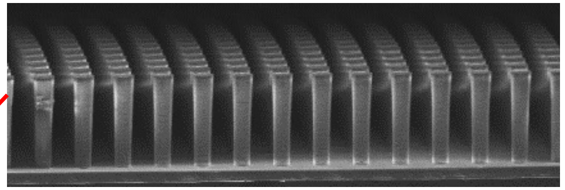


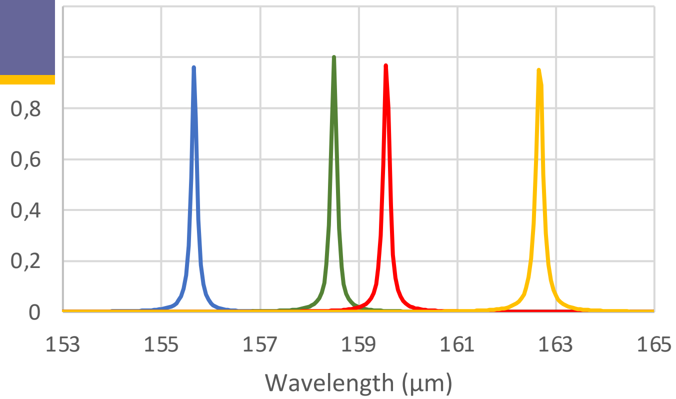




Stationary array of Fabry-Perot made of microstructures Si.



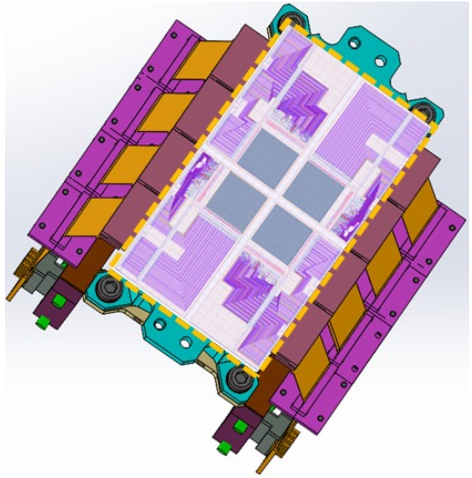




What's Next?

- CO-PILOT (?)

(C+ @ 158 µm)

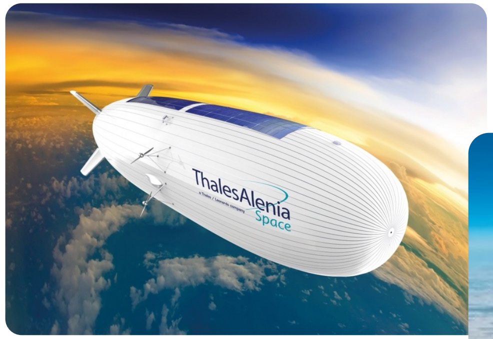


- Artémis2– Future Large ground-based telescopes

(atmospheric bands at 350 / 450 µm)

- Neostars : Very long duration flights with HAPS

(High Altitude Pseudo-Satellites – up to 1 year @ ~ 25 km)



Stratobus

CNES - Balman

- Voyage 2050 / ASTRO2020

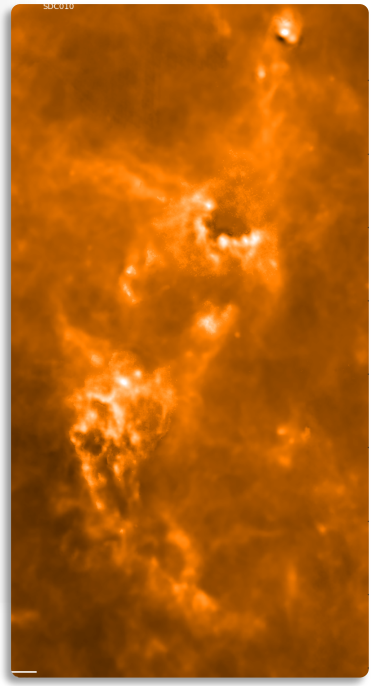
(ISM, CMB spectral distorsions, LIM)

Summary

- We push Silicon technology to its limits : high sensitivity & in-pixel functions
- The in-pixel polarimetry enables **very compact and simple instrument** (no moving part) – **Optimization of the system**
- Robust & High TRL : Herschel heritage, PhaseA study for SPICA

- Challenges on RO electronics / Detection layer on thermal aspects / MUX

- Opportunities toward Artemis2, balloon experiments



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Fundings

esa European Space Agency
cnes CENTRE NATIONAL D'ÉTUDES SPATIALES
erc European Research Council Established by the European Commission
FOCUS Focal Plane Array for Universe Sensing
ACAV+
îledeFrance
cea irfu
cea leti

B-BOP Polarization Sensitivity

Surface Brightness Sensitivity [MJy.sr^{-1}] of BBOP for polarimetric imaging.

- total surface-brightness level required to detect polarization at 7σ (p/σ=7)
- 5% fraction polarization
- NEP = 3.10^{-18} WHz$^{-1/2}$
- Background includes:
  - Zodiacal light, ISM, CIB, CMB at location typical of **low-emission Galactic** regions
  - Telescope
  - Instrument optics (transmission 50%)

70 µm Band : 1024 pixels
200 µm Band: 256 pixels
350 µm Band : 64 pixels

Instrument	Diameter [m]	Telescope Temperature [K]
SPICA	1.8	8
Millimetron	10	45
SALTUS	14	45 & 30
APEX (4096 pixels)	12	270