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https://indico.in2p3.fr/event/10777/

CMB detectors

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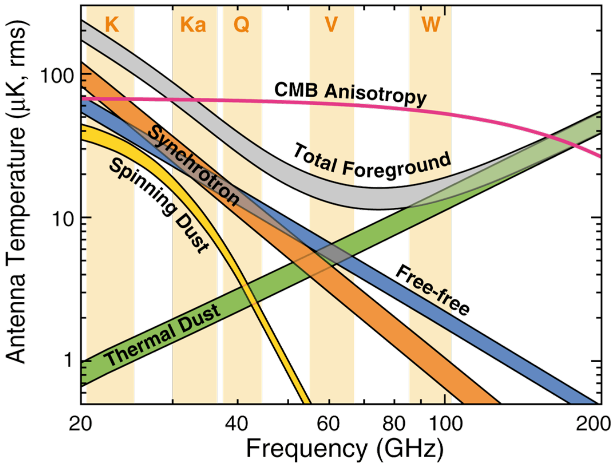
Outline

1. CMB photons and CMB instruments
2. Bolometers principle
3. System aspects
4. Development of bolometer arrays

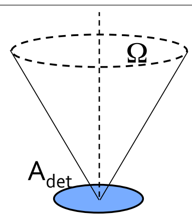
1. CMB photons

- T_{CMB} = 2.725K (COBE)
  - ➢ Max emission at ν~150GHz, λ~2mm
  - ➢ Photon energy: fraction of meV
- Monopole dominant between ~500MHz to ~800GHz
- Anisotropies dominant between ~40GHz to ~200GHz



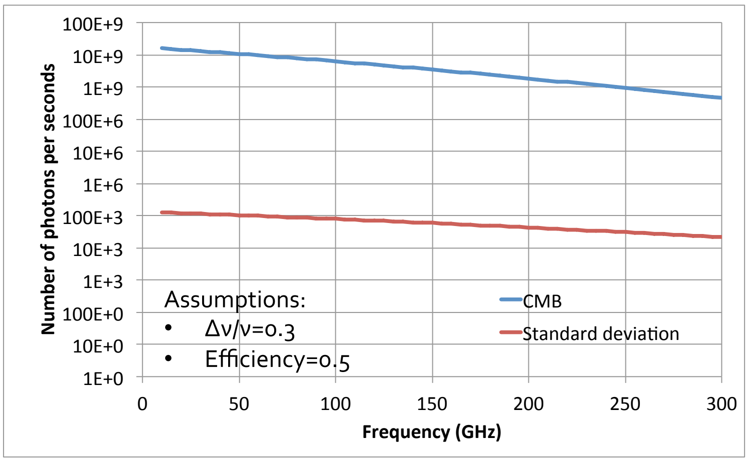
CMB photon flux

- Photon flux: $P \approx B_\nu(T_{CMB})A_{\mathrm{det}}\Omega\Delta\nu$
  - ➢ Diffraction limited: $A_{\mathrm{det}}\Omega = \lambda^2$
  - ➢ Number of photons per seconds: $N = P/(h\nu)$



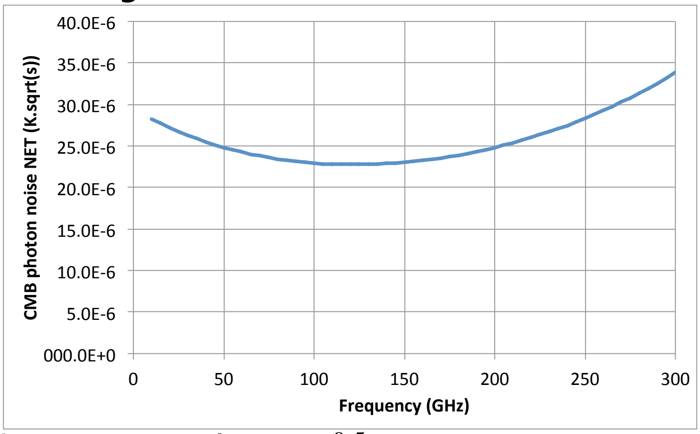
- Photon noise
  - ➢ Photon flux ≈ Poisson flux
  - ➢ Standard deviation:

$$\sigma = \sqrt{N}$$



CMB photon noise

- Noise Equivalent Temperature (NET)
  - Noise expressed as a CMB temperature fluctuation in 1 second of integration time:



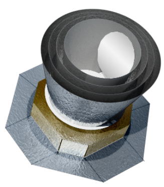
$25\mu K.s^{0.5}$

  - For N detectors, scale as $N^{-0.5}$

CMB instruments

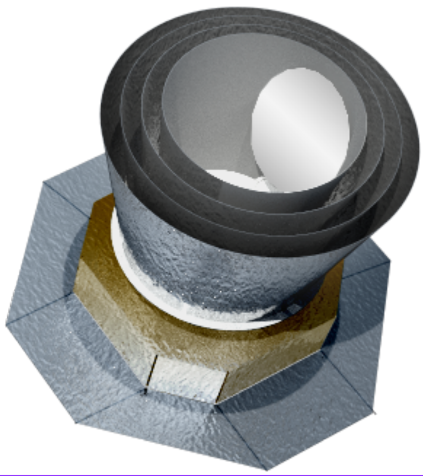
- Assuming perfect detectors, limited by the CMB photon noise:

	T anisotropies	B-modes
Required sensitivity	$6\mu K$	100nK
Angular resolution	5 arcmin	30 arcmin
Integration time per angular resolution for a 1 year mission	5s	190s
Required NET	$13\mu K$.sqrt(s)	$1.4\mu K$.sqrt(s)
Number of detection chain needed	~4	~320
Missions	Planck	COrE+



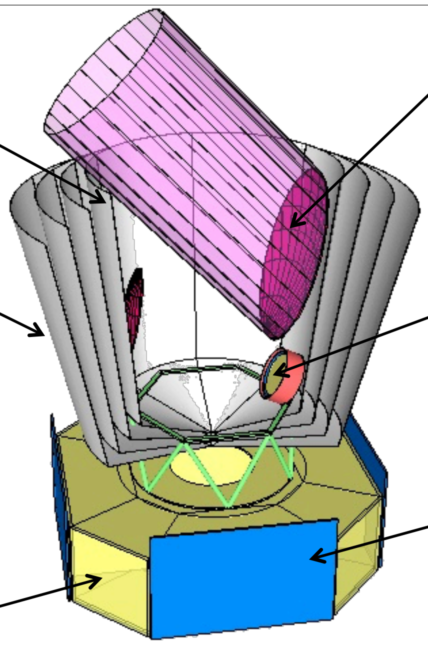
COrE+
The Cosmic Origins Explorer

- Proposal for ESA's M4 space mission (2026)
- Ultimate mission for CMB polarisation anisotropies
- Concept:
  - ➢ 15-20 frequency bands between 60GHz and 600GHz
  - ➢ Very high sensitivity (60nK$_{CMB}$ on 30 arcmin)
    - ✓ Cryogenic detectors (100mK)
  - ➢ 1.5m telescope
  - ➢ L2 orbit

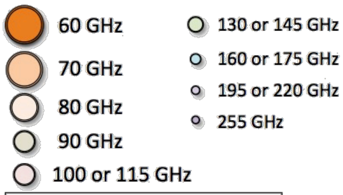


Proposal leader:
Paolo de Bernardis;
Co-leaders: *François Bouchet* & *Jacques Delabrouille*

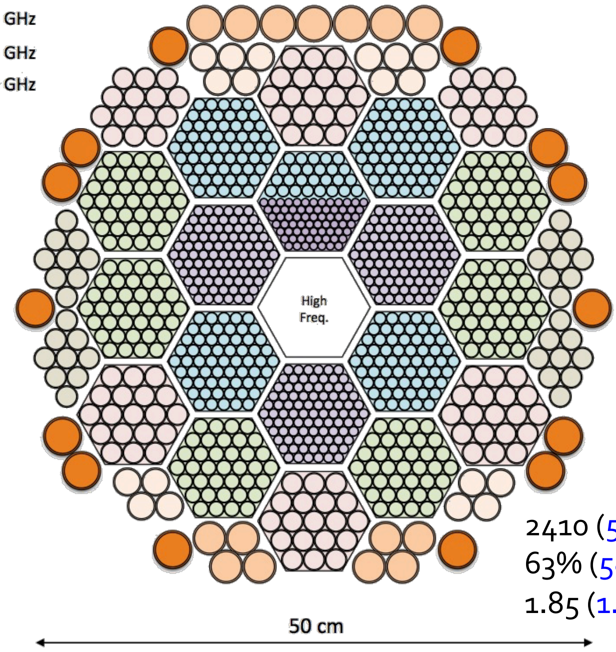
COrE+ satellite



COrE+ focal plane

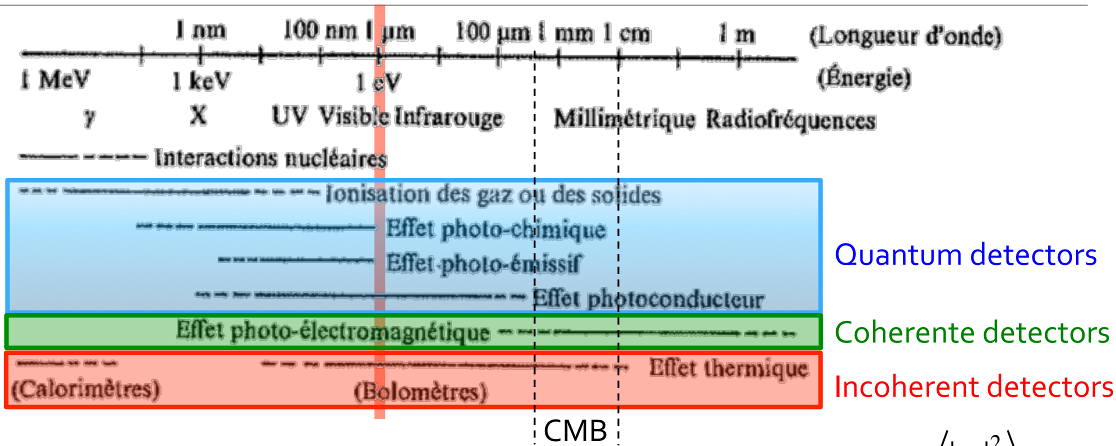


ν	$N_{det\ single}$	$N_{det\ dual}$
60	28	28
70	30	30
80	36	64
90	72	102
100	84	120
115	124	196
130	180	264
145	264	388
160	254	434
175	290	554
195	346	600
220	200	490
255	140	486
295	60	260
340	60	200
390	60	120
450	60	120
520	60	120
600	60	120
700		60
800		60



2410 (5028) detectors
63% (58%) in CMB channels
1.85 (1.2) μK.arcmin sensitivity

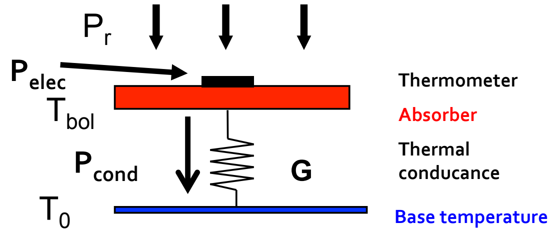
CMB detectors?

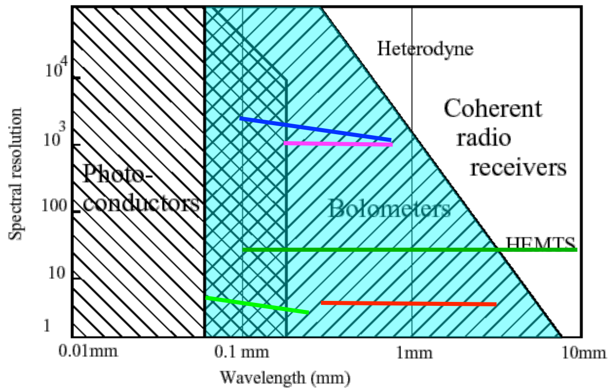


- Incoherent detectors: sensitive to the <u>average</u> EM power $P \propto \left\langle |E|^2 \right\rangle$
  - ➢ Bolometer, Kinetic Inductance Detectors
- Coherent detectors: sensitive to E field
  - ➢ Amplitude and phase
  - ➢ Intrinsically limited in sensitivity

2. Bolometer principles

- Thermal detector
  - ➢ Macroscopic system
  - ➢ Measure of the heating from the absorption of radiation
  - ➢ Thermometer = resistor R(T)
  - ➢ Readout: R=U/I
- The best detectors for <u>large bandwidth</u> detection in the wavelength range 100µm → 3mm
  - ➢ Cooled to low T < 300mK
  - ➢ Sensitivity limited by photon noise

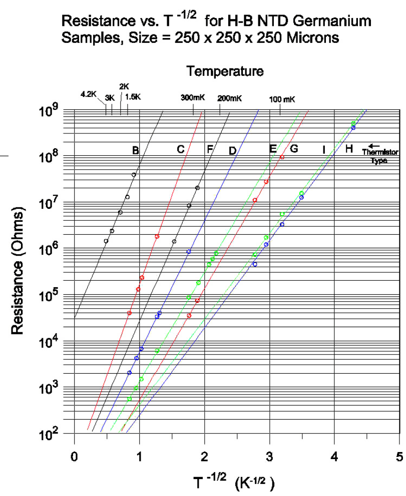


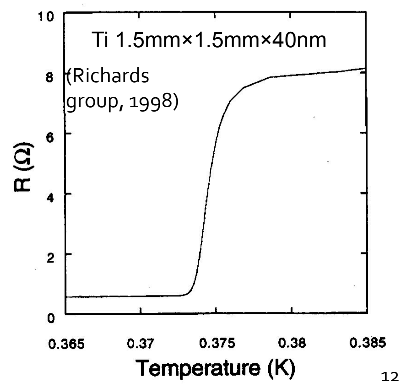


From top to bottom: SAFIRE Herschel-SPIRE COBE-FIRAS Herschel-PACS Planck-HFI

Thermometer

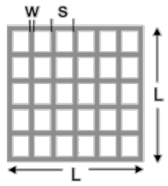
- Parameter: $\alpha = \frac{T}{R}\frac{dR}{dT}$
- Semi-conductor: α # -5→-10
  - ➢ Implanted Si
  - ➢ Ge NTD (Haller-Beeman)
  - ➢ NbSi thin film (CSNSM Orsay)
- Superconductor: α #100 → 1000 (*Transition Edge Sensor* TES)
  - ➢ Ti: T_c≈400mK
  - ➢ Mo/Cu, Mo/Au…: T_c tuning by proximity effect
  - ➢ NbSi thin film (CSNSM): T_c depends on composition Nb (>12%) vs Si

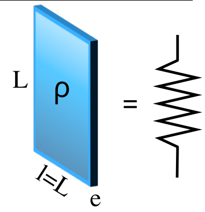




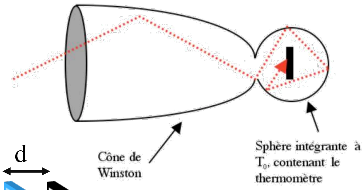
Absorber

- **Absorber = metal film**
  - Square resistance of a uniform film: $R_c = \rho/e$
  - Metal grid: $R_c = \rho/e \times s/w$
    - ✓ Equivalent to a uniform film if λ >> s and w





- In vacuum:
  - Vacuum impedance: $Z_0 = \sqrt{\mu_0/\varepsilon_0} = 377\Omega$
  - Max absorption = 50% for $R_c = Z_0/2$
  - Integrating sphere to increase absorption

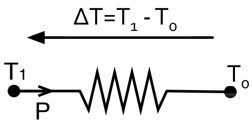


- With a reflective layer at d=λ/4 (modulo λ/2)
  - Max absorption = 100% for $R_c = Z_0$

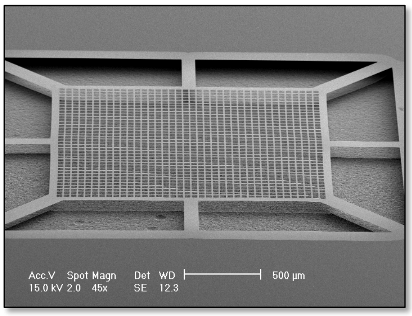
Thermal conductance

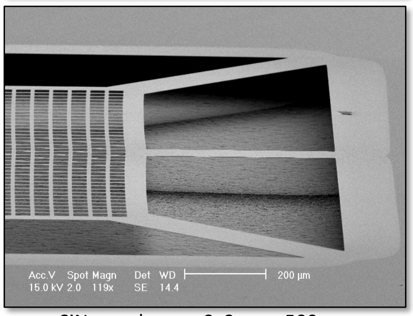
- Micro-technologies
  - Membranes in silicon nitride (SiN) or in silicon (Si)
- Thermal conduction in Si or SiN
  - Diffusive phonons transport
  - At very low temperature: diffusion on edges
    - ✓ Mean free path > sample size
    - ✓ Radiative transport
- Classical modelisation : (diffusive)

$$P = K(T_1^{\beta+1} - T_0^{\beta+1})$$



$$G_d = \left(\frac{dP}{dT_1}\right)_{T_0=cste} = (\beta+1)KT_1^{\beta}$$

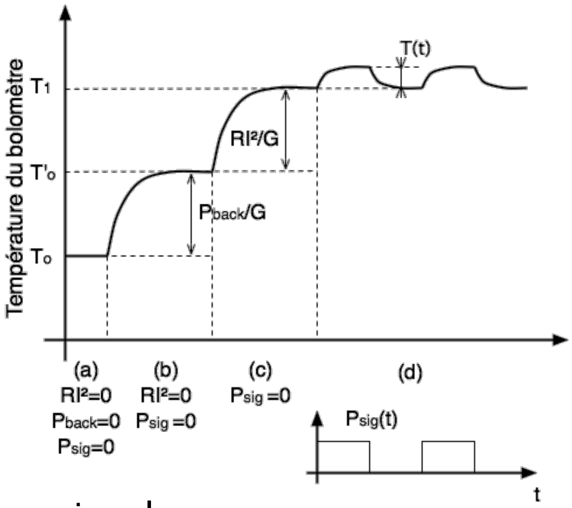




SiN membranes 3x3 mm, 500 nm thickness (IEF Orsay)

Bolometer in operation

- $P_r = P_{back} + P_{sig}(t)$
  with $P_{sig}/P_{back} << 1$
  - P_{back}: average power, *background power*
  - P_{sig}: radiative power to be measured

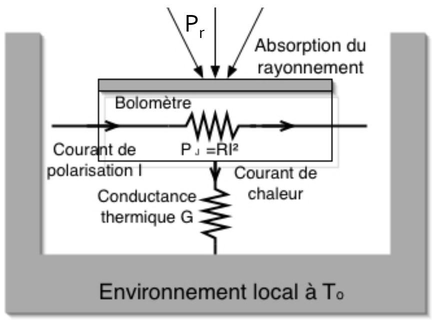


- $T_{bol} = T_1 + T(t)$ avec $T/T_1 << 1$
  - T_1: bolometer temperature with no signal
  - T: bolometer temperature fluctuations due to P_{sig}

Bolometer response in harmonic regime

- In temperature:

$$\begin{cases} \dfrac{\tilde{T}}{\tilde{P}_{sig}} = \dfrac{1}{G_{eff}\left(1 + j\omega\tau_{eff}\right)} \\ \tau_{eff} = \dfrac{C}{G_{eff}} \end{cases}$$

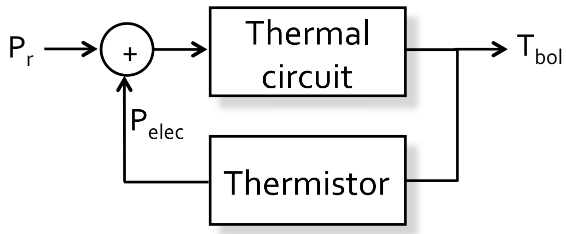


C: bolometer heat capacity [J/K]
G_{eff}: bolometer effective thermal conductance [W/K]

1. Trade-off between time constant and response
2. Low C require $\Rightarrow$ **low temperatures**

Electro Thermal Feedback (ETF)

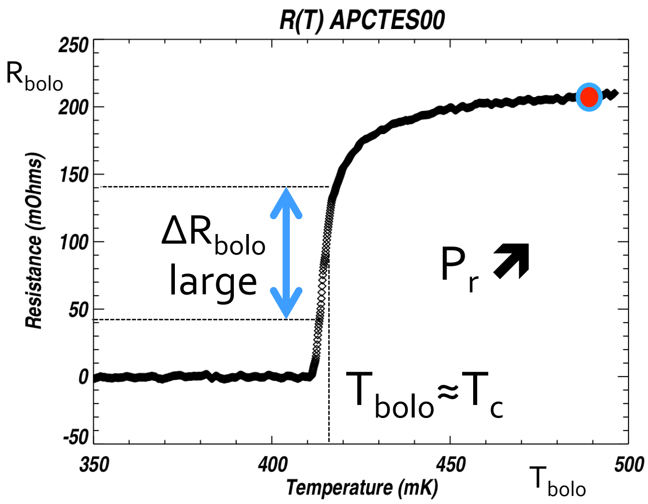
- Case α<0: semi-conducting bolometer
  - Current biasing: $T\nearrow \Rightarrow R\searrow \Rightarrow P_{elec}=RI_{bias}^2 \searrow \Rightarrow T\searrow$
- Case α>0: superconducting bolometer
  - Voltage biasing: $T\nearrow \Rightarrow R\nearrow \Rightarrow P_{elec}=V_{bias}^2/R \searrow \Rightarrow T\searrow$
- Feedback system:

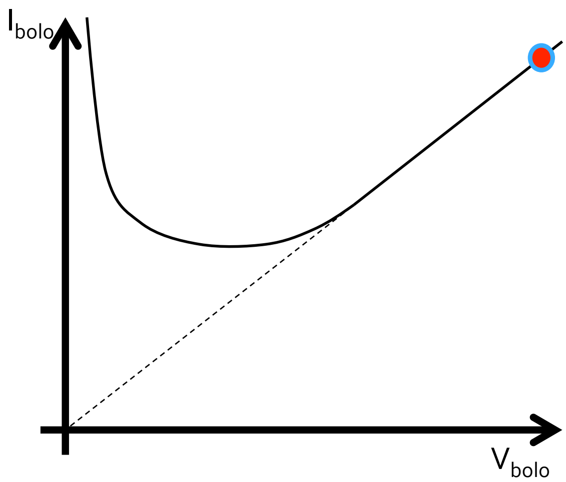


- Interesting effect if |α| is large: **superconducting bolometers**

ETF in TES

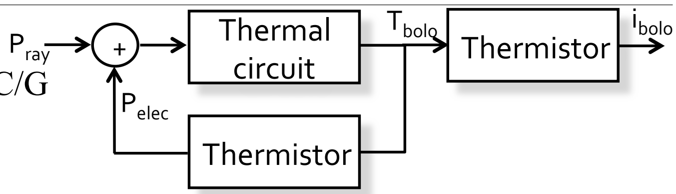
- In quasi-static: $P_r + P_{elec} = P_{cond}$





ETF effect on TES

- Feedback system:
  - 1^{st} order thermal circuit: $\tau = C/G$



- Bolometer response:

$$S_I(\omega) = -\frac{1}{V}\cdot\frac{L}{1+L}\cdot\frac{1}{1+i\cdot\omega\tau_{eff}}$$

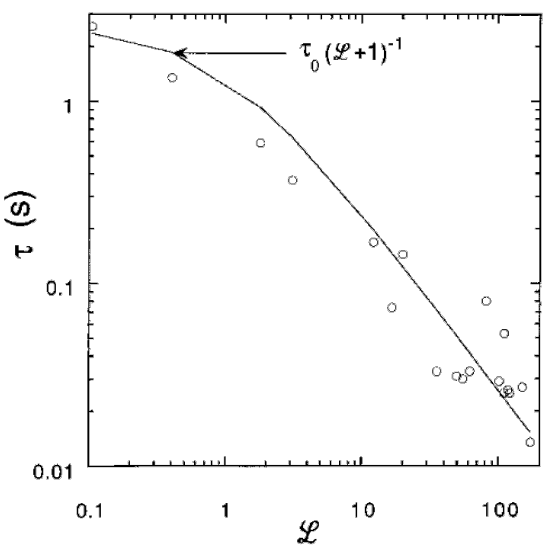
  - Time constant: $\tau_{eff} = \frac{\tau}{1+L}$
  - Open loop gain: $L = \frac{|\alpha|\cdot P_{élec}}{T_1 G_d}$ with $\alpha = \frac{T}{R}\frac{dR}{dT}$

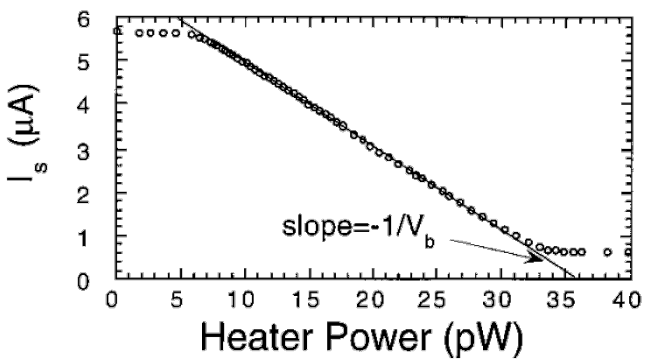
- If L>>1: (strong ETF)
  - $\tau_{eff} << \tau$
  - Static response: $\Re$=1/V
  - Natural biasing inside the transition
  - Linearisation

Superconducting bolometers
α=100-1000
L=10-100

Strong ETF in TESs

- A. Lee, P. Richards et al. 1998





Noise Equivalent Power (NEP)

- Power Spectral Density (PSD) of a noise
  - Characterise its spectral content

$$P\tilde{S}D_x(f) = \frac{2}{T}\left|\int_0^T x(t)e^{-i2\pi ft}dt\right|^2$$

- Noise expressed in photon flux input power (W):
  NEP = sqrt(PSD) [W.Hz$^{-0.5}$]
- White noise: PSD = constant
  - NEP = standard deviation of the noise, expressed in photon flux input power, for 1Hz of bandwidth (or ½ second of integration time)

$$\sigma = NEP / \sqrt{2 \times t_{obs}}$$

- Noises are generally Gaussian (central limit theorem)

TES intrinsic noise sources

Low temperatures require

- Johnson noise:
  - Electrical resistor R at temperature T

$$PSD_I = \frac{4kT}{R} \quad \left[A^2.Hz^{-1}\right] \qquad NEP_J^2 = \frac{PSD_I}{\Re^2} \quad \left[W^2.Hz^{-1}\right]$$

Responsivity [A/W]

- Phonon noise:
  - Conductance G_d at uniform temperature T

$$NEP_{Ph}^2 = 4kT^2G_d \quad \left[W^2.Hz^{-1}\right]$$

  - Bolometer: not at thermal equilibrium
    - ✓ Overestimation of NEP_{ph} by about 30% [Mather]
- Bolometer total intrinsic noise:

$$NEP_{bol}^2 = NEP_J^2 + NEP_{Ph}^2$$

TES optimisation

- Requirements:
  - No saturation: $P_{cond} = [3-6] \times P_{back}$
  - Strong ETF: $L = \frac{|\alpha| \cdot P_{elec}}{T_1 G_d} >> 1$ (Reminder: $P_{elec} = P_{cond} - P_{back}$)
    - ✓ Phonon noise dominant
  - Reasonable bolometer temperature: $T_1 - T_0 = [0.3-1] \times T_0$
- In this case:
  - With reasonable assumptions : $G_d = \frac{dP_{cond}}{dT} \approx [3-20] \frac{P_{back}}{T_0}$
  - NEP:

$$NEP_{bol}^2 \approx [3-20] \times 4kT_0 P_{back}$$

Bolometer limited by photon noise (BLIP)

- NEP of photons noise:
  - With a radiative input power P_{back} in $\nu \pm \Delta\nu/2$:

$$NEP_{h\nu}^2 \approx 2h\nu P_{back}$$

- Background limited performances (BLIP):

$$NEP_{bol}^2 \leq NEP_{h\nu}^2$$

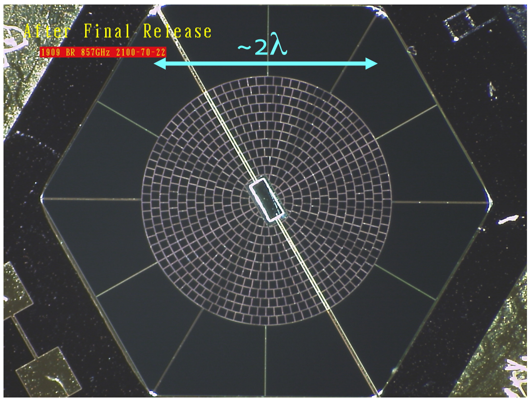
  - With an optimised bolometer: $T_0 \leq 350mK \times \frac{1mm}{\lambda}$

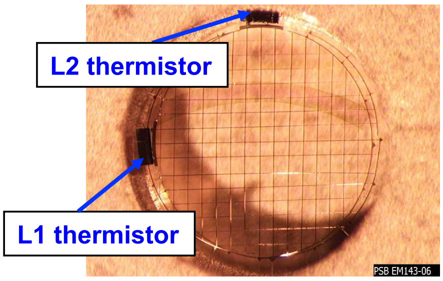
Very low T needed

Planck bolometers
Spider web bolometers (Caltech-JPL)

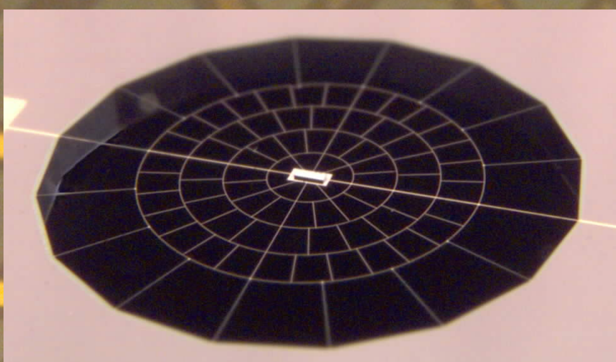
- Absorber: Si_3N_4
  - e~1μm, l~5μm, cell~100μm
  - Metallization Au
- Ge NTD thermometer
- Polarisation Sensitive Bolometer (PSB)
  - 2 bolometers in 1 module
  - Metallization in one direction

Detectors of
- **Boomerang**
- **QUAD**
- **BICEP1**
- **Planck-HFI**

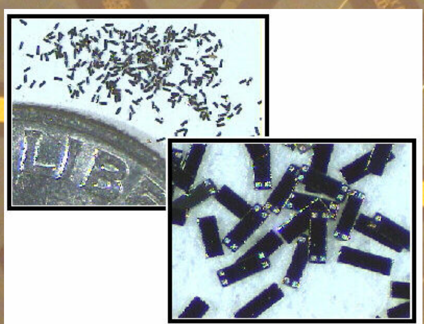


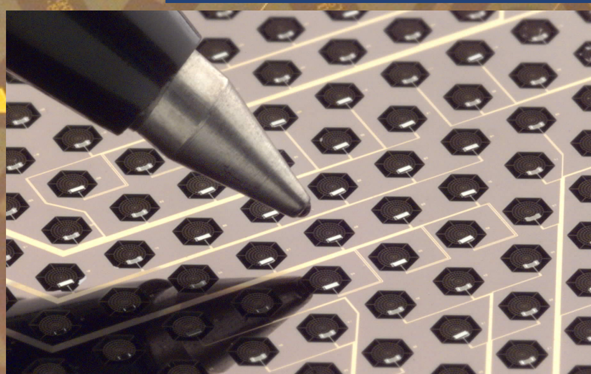


NTD Bolometers for Planck & Herschel


143 GHz Spider-web Bolometer

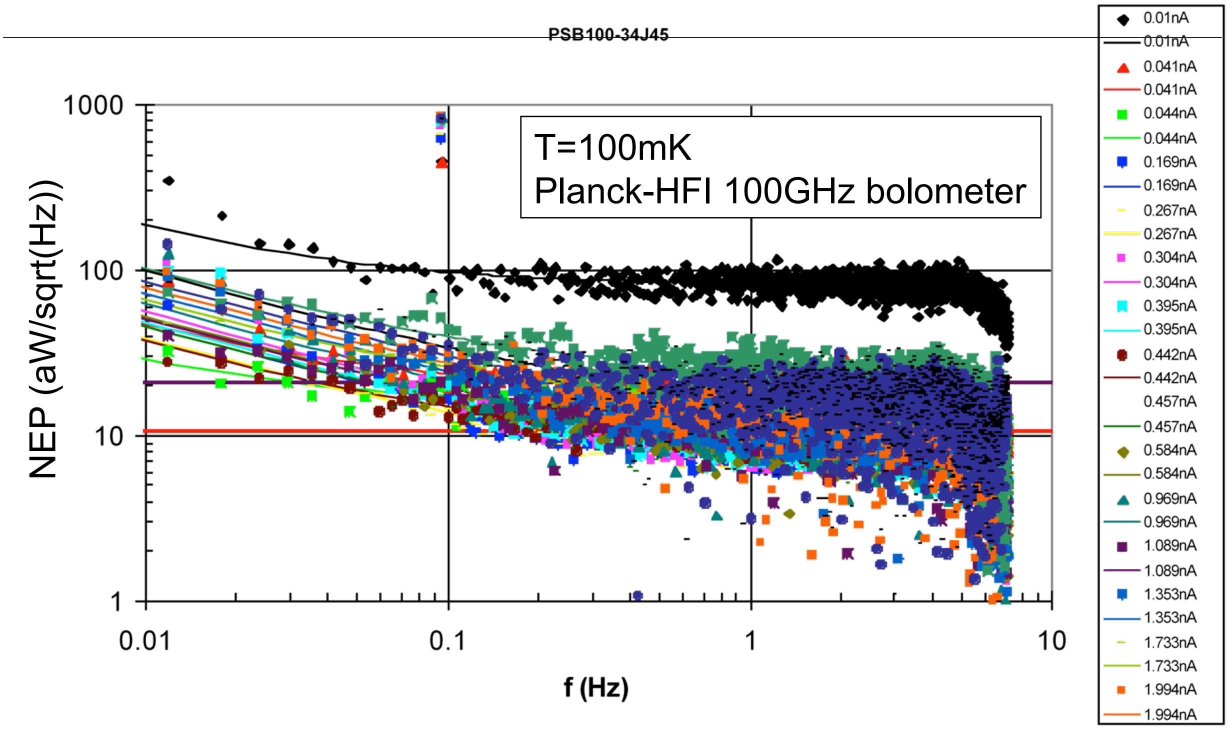

Planck/HFI focal plane (52 bolometers)


NTD Germanium


Herschel/SPIRE Bolometer Array

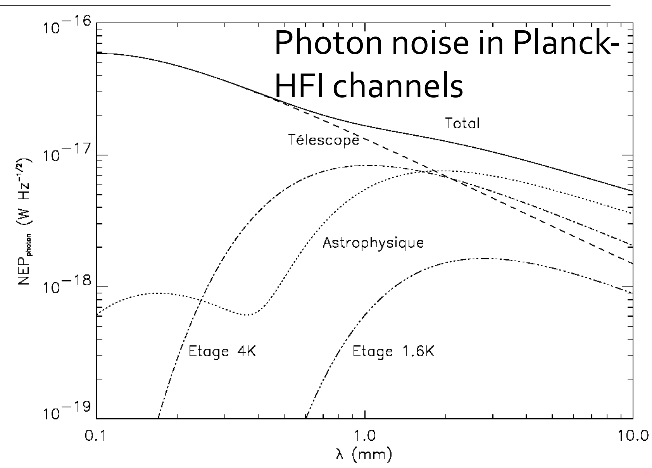
(From J. Bock, JPL)

Planck bolometers NEP



Spider web bolometer performances

- at 300mK
  - NEP = 1,5.10^{-17} W/Hz$^{1/2}$
  - τ = 11ms
  - C = 1pJ/K
- at 100mK:
  - NEP = 1,5.10^{-18} W/Hz$^{1/2}$
  - τ = 1,5ms
  - C = 0,4pJ/K



CMB photon noise limited detectors!

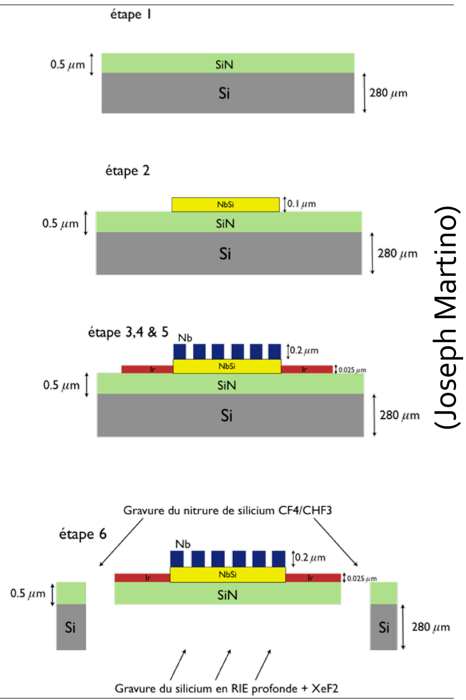
Sensitivity improvement ⇒ increase of bolometer number

Bolometers array

Bolometer production

- Based on microtechnologies
- Absorber: photolithography
- Metallisation
- Thermal sensor:
  - ➢ Planck bolo: NTD Ge by hand
  - ➢ Deposited during the process

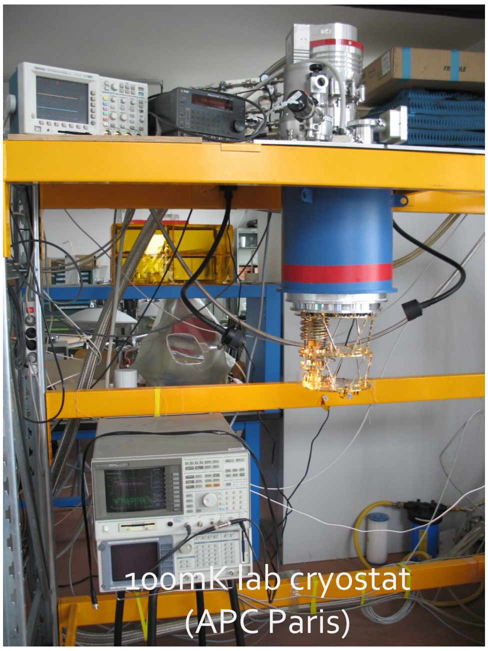
Micro fabrication facility required



(Joseph Martino)

3. System aspects

- Bolometer sensitivity ~ 10^{-17}W to 10^{-18}W
- Instrumental design
  - ➢ Risk of sensitivity degradation
- The whole system has to be designed carefully!
  - ➢ System approach
  - ➢ Bolometer to be tested with their subsystems



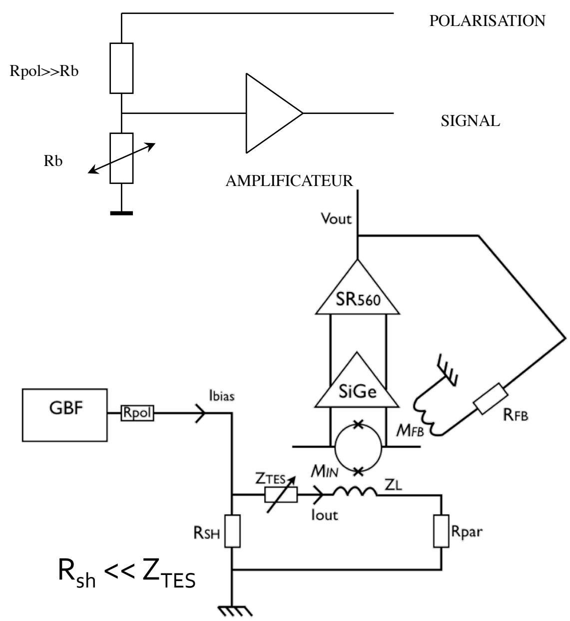
100mK lab cryostat (APC Paris)

Extra noise sources

- Readout electronics noise
- 1/f noise
- Straylight
- Temperature fluctuations
- Microphonics
- Cross-talk
- Electro-magnetic interferences
- Cosmic rays effects
- …

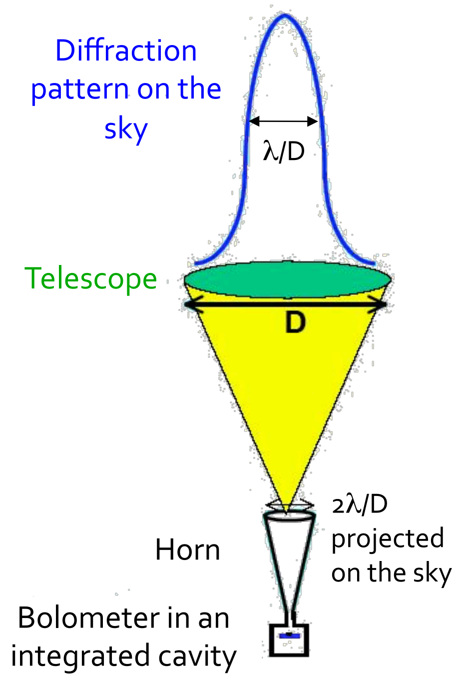
Readout electronics

- Semi-conducting bolometers:
  - R_b # MΩ
  - Impedance matching : JFET at ~120K as a follower
- Superconducting bolometers:
  - R_b # 100mΩ
  - SQUID: *Superconducting QUantum Interference Device*
    - ✓ Current readout
    - ✓ Multiplexing possible



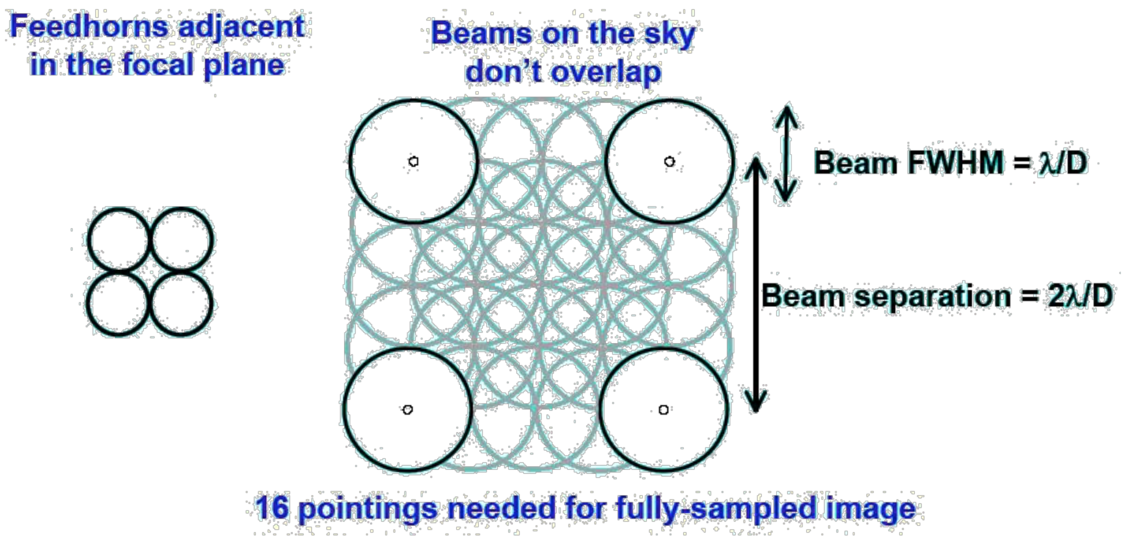
Bolometer optical coupling: horns

- Define the beam pattern
- Singlemoded ($A\Omega=\lambda^2$) or multimoded ($A\Omega=N_{modes}\times\lambda^2$)
- Singlemoded:
  - Quasi-gaussian beam pattern
  - Maximum efficiency for a horn diameter of $2\lambda/D$ (on the sky)
  - Beam pattern given by diffraction limit λ/D

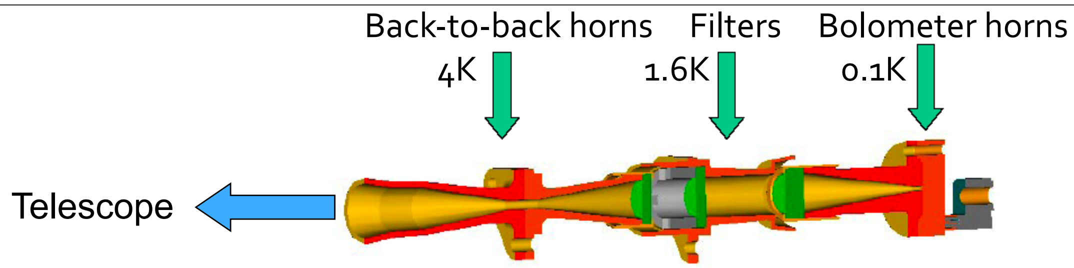


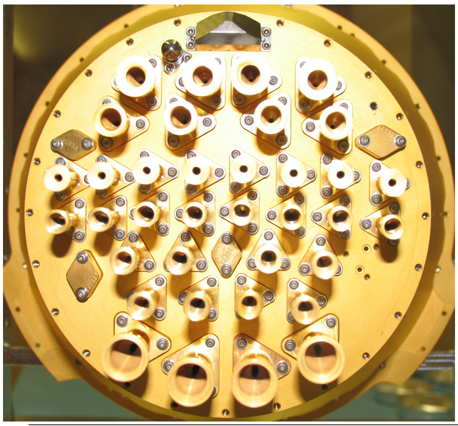
Mapping with horns

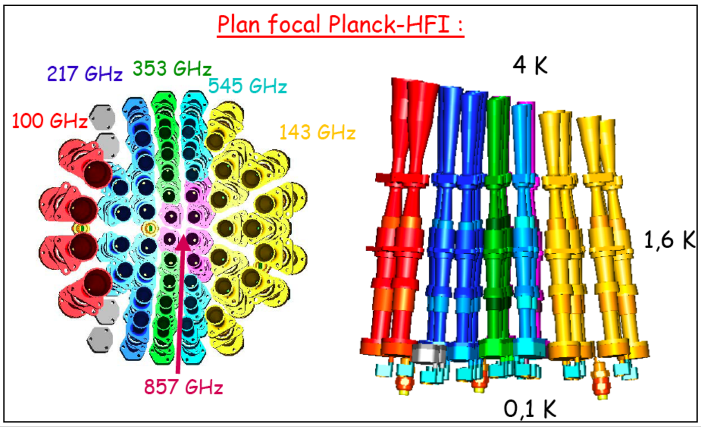
- Beam patterns do not overlap in the sky
- Requires pointing change to sample the sky (Nyquist criteria)



Example: Planck-HFI

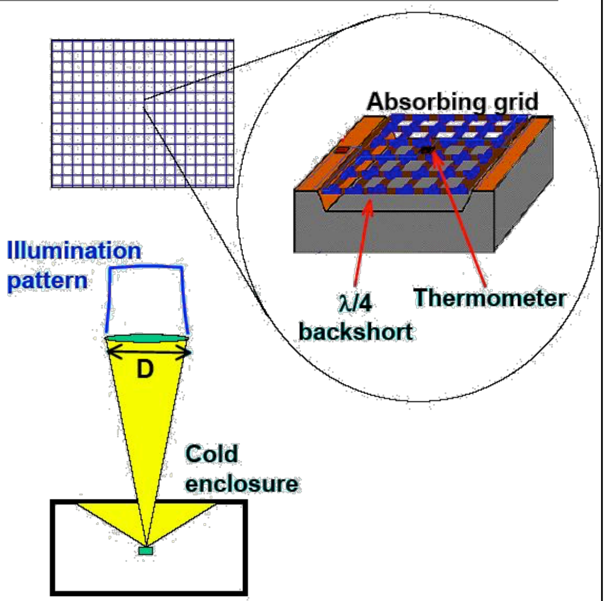






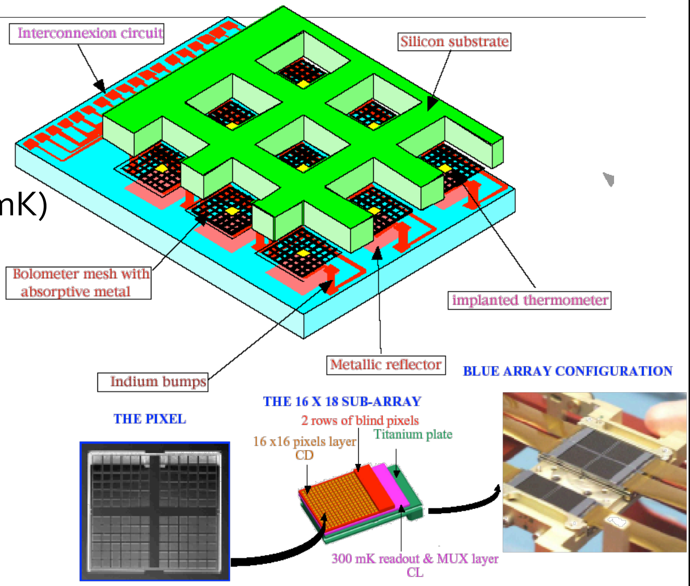
Bolometer optical coupling: filled array

- CCD-like
- Pixel size on the sky= $0.5\times\lambda/D$
  - Correct sampling of the sky
- The bolometer sees about π sr!
  - Requires a cold enclosure
  - Background power: has to be estimated from all sources in the bolometer solid angle



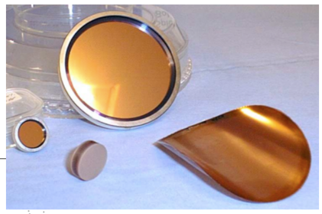
Example: CEA/LETI bolometers for Herschel/PACS

- 2 Si wafers
  - Bolometers and readout
  - Connected by indium bumps
- Thermometer: implanted Si (300mK)
- Photon absorption
  - Metallisation
  - $\lambda/4$ cavity
- Impedance matchin in CMOS technology on the second wafer
  - Operate at 300mK
  - Very close to the detector
  - TDM with 8 detectors
  - High redaout voltage noise ⇒ thermometer R ~ 10GΩ

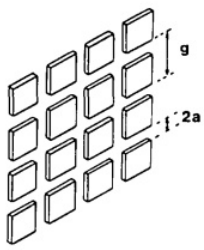


Herschel/PACS array:
32×64=2048 detectors at 300mK
Channels: 100µm and 170µm, NEP<10^{-16}W.Hz$^{-0.5}$

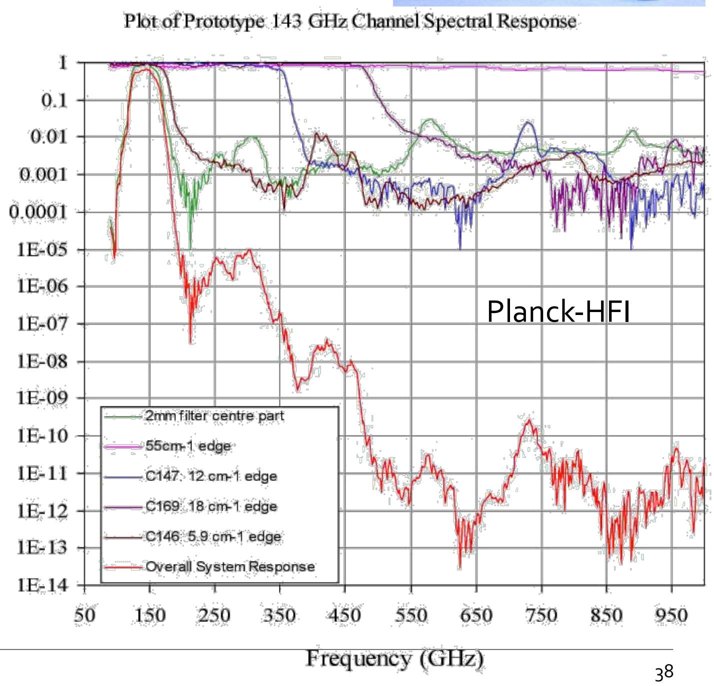
Filtering



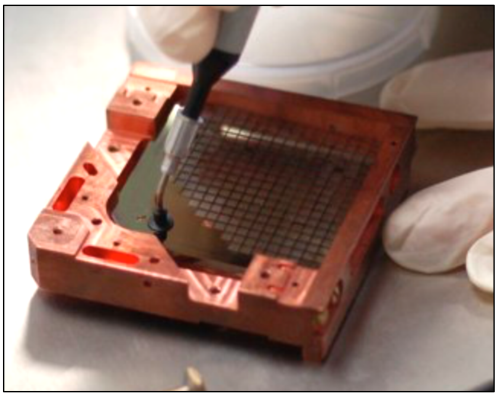
- High IR rejection needed
  - Cold optics, telescope
- Use of capacitive grid filters:
  - Low pass



- Waveguide cut-off
  - High pass



4. Development of bolometer arrays



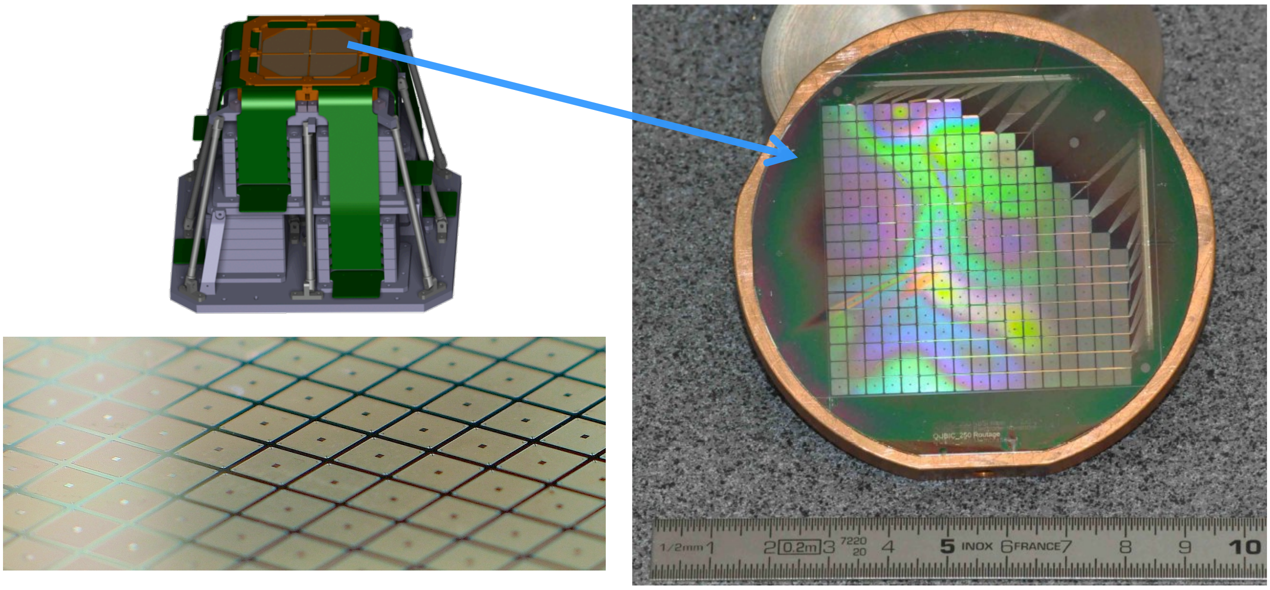
- Motivations:
  - ➢ Increase of the mapping speed
  - ➢ Increase of the sensitivity
- Requirements:
  - ➢ Sensitivity (limited by photon noise)
  - ➢ Time constant
  - ➢ Array size (from 10^2 to 10^4 pixels)
  - ➢ Filling factor
  - ➢ Optical coupling
- Constraints
  - ➢ Cryogenics: limited cooling power, multiplexing required
  - ➢ Readout electronics: close to the detectors

Multiplexing?

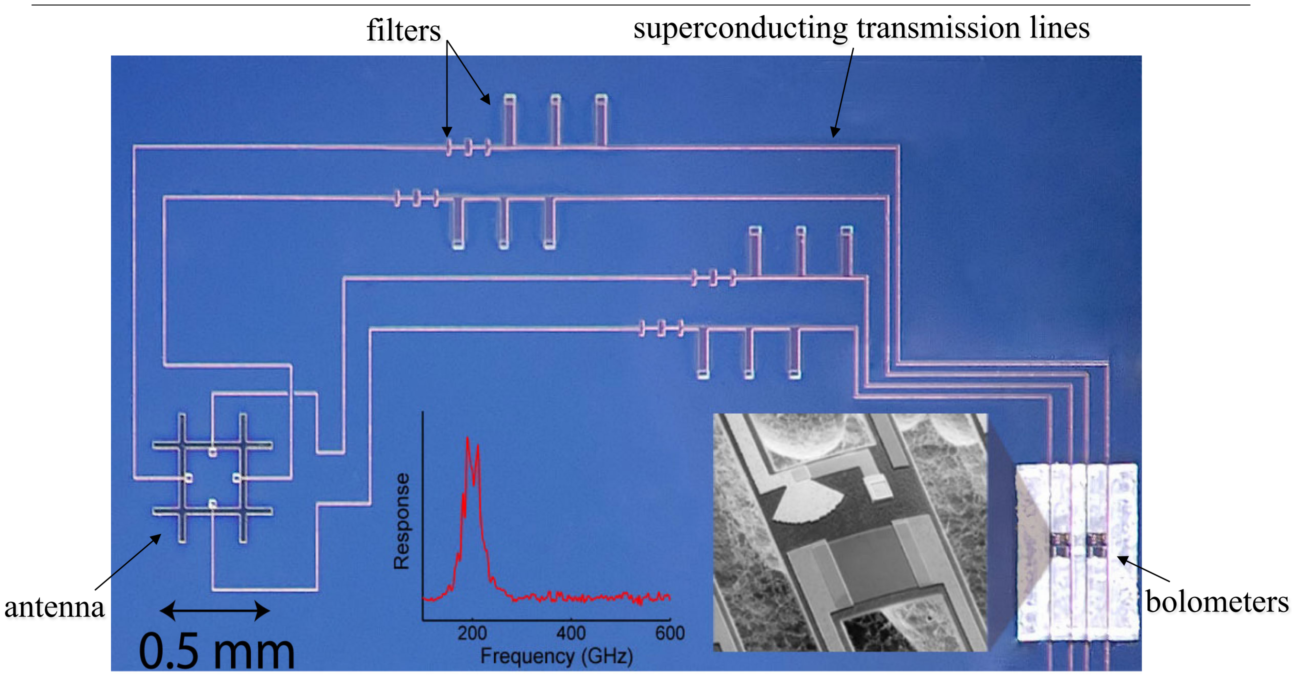
- Readout of N detectors with <u>a single</u> amplifier
- Time Domain Multiplexing (TDM)
  - ➢ Successive readout of each detector
  - ➢ Required an amplifier noise level lower by a factor ~$N^{0.5}$
- Frequency Domain Multiplexing (FDM)
  - ➢ Readout of all detector at all time
  - ➢ Each detector is modulated at a given frequency
  - ➢ Multiple lock-in detection to recover the signal
  - ➢ Require an amplifier dynamic higher by a factor ~$N^{0.5}$

Example:
248 TES QUBIC (France)

- Superconducting NbSi (CSNSM, IEF, APC)

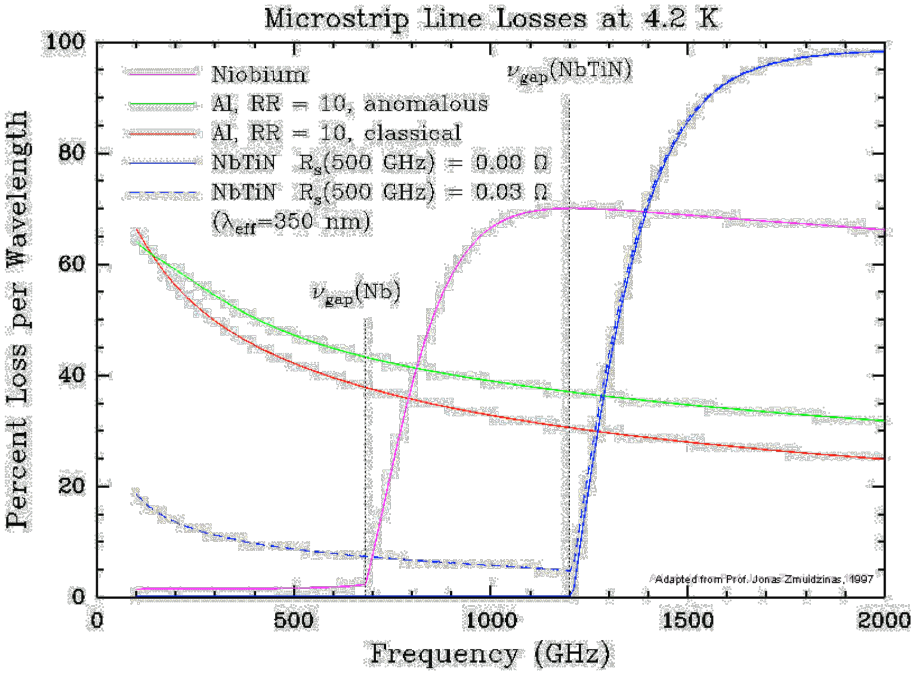


Antenna coupled bolometers
(Polarbear, UCB/LBNL)

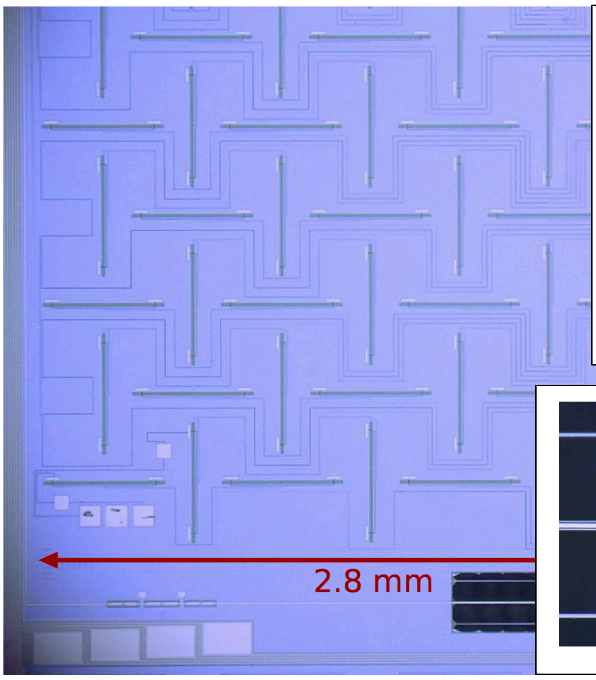


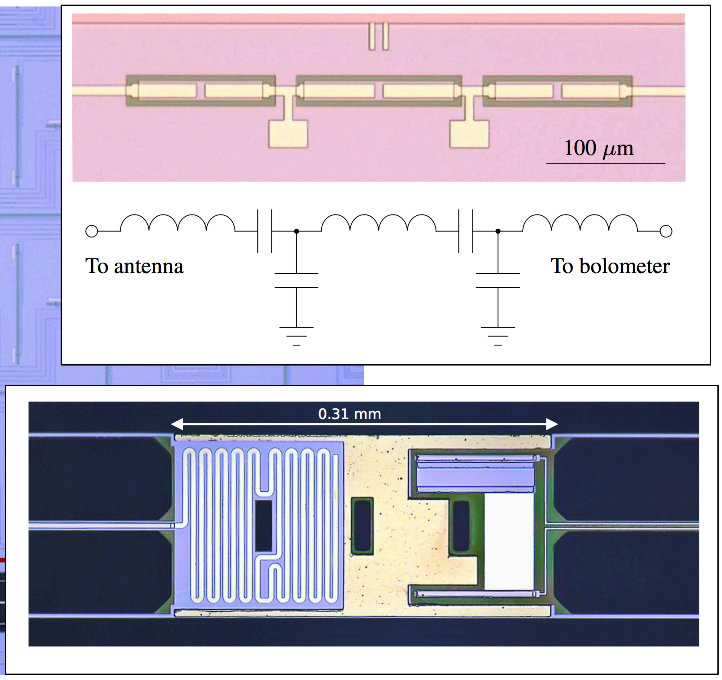
Superconducting microstrip line

- Supercond. Niobium: low losses up to 700GHz
- Nb: T_c=9.2K



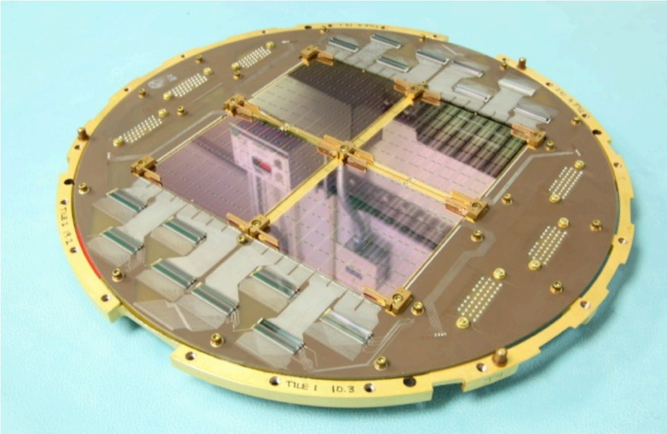
BICEP2 detectors





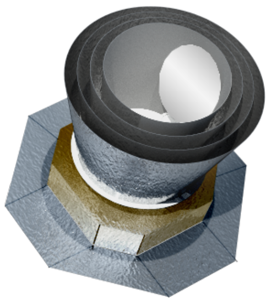
BICEP2 detectors

- 1 pixel:
  - 2 orthogonal 12x12 slot antenna phased array
  - Bandpass filter on stripline
  - 2 small TESs (Ti and Al)
- 8x8 pixels per tiles, 4 tiles
- Total of 256 pixels and 512 TESs
  - Time Domain Multiplexing
  - MUX factor = 33



Conclusions

- Requirements for next generation CMB space mission:
  - Thousands detectors
  - NEP # 10^{-17} à 10^{-18} $W.Hz^{-0.5}$ per pixel
  - τ # ms



- Complex technology
  - Heavy cryogenics
  - Importance of system aspects
  - Solid state physics, thermal physics, micro-technology, low noise electronics, cryogenics…
- TESs are a mature technology for a space mission