The CMB from A to Z: Promises and challenges of the CMB as cosmological probe

Nov 13 - 17, 2017

CMB instruments 1/3

Michel Piat

piat@apc.univ-paris7.fr

Building a (CMB) instrument

Science goals

CMB polarisation primordial B-modes, lensing…

Instrument system specifications:

Sensitivity, angular resolution, frequency bands

Sub-systems requirements

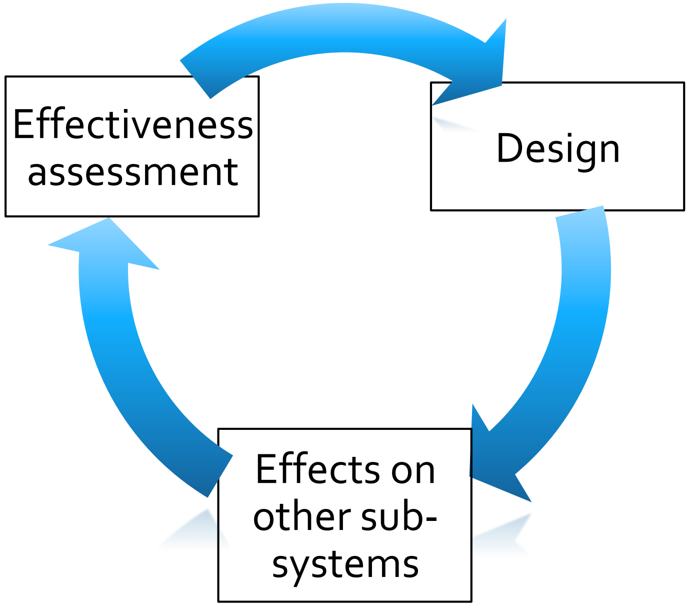
Telescope diameter, cross polarisation, detector number, temperature, speed response, scanning strategy…

Solutions

Reflective or refractive optics, coherent or incoherent detector, readout technique, orbit…

Instrumental trade-offs

- Choice of the best global solution
  - ➢ Iterative process for each sub-system



- Effectiveness criteria:
  - ➢ Performances
    - ✓ Scientist: best performances
    - ✓ Engineer: meet the specifications
  - ➢ Technical aspects: mass, volume, power consumption, data rate
  - ➢ Other important criteria: cost, schedule, available resources (human, technical), risks

Building a (CMB) instrument in the real life

Science goals

CMB polarisation primordial B-modes, lensing…

Instrument system specifications:

Sensitivity, angular resolution, frequency bands

Sub-systems requirements

Telescope diameter, optics architecture, Detector number, temperature, speed response, scanning strategy…

Solutions

Reflective or refractive optics, coherent or incoherent detector, orbit…

Designing a CMB experiment

1. CMB photons

2. CMB detectors

    2.1 Coherent detection techniques

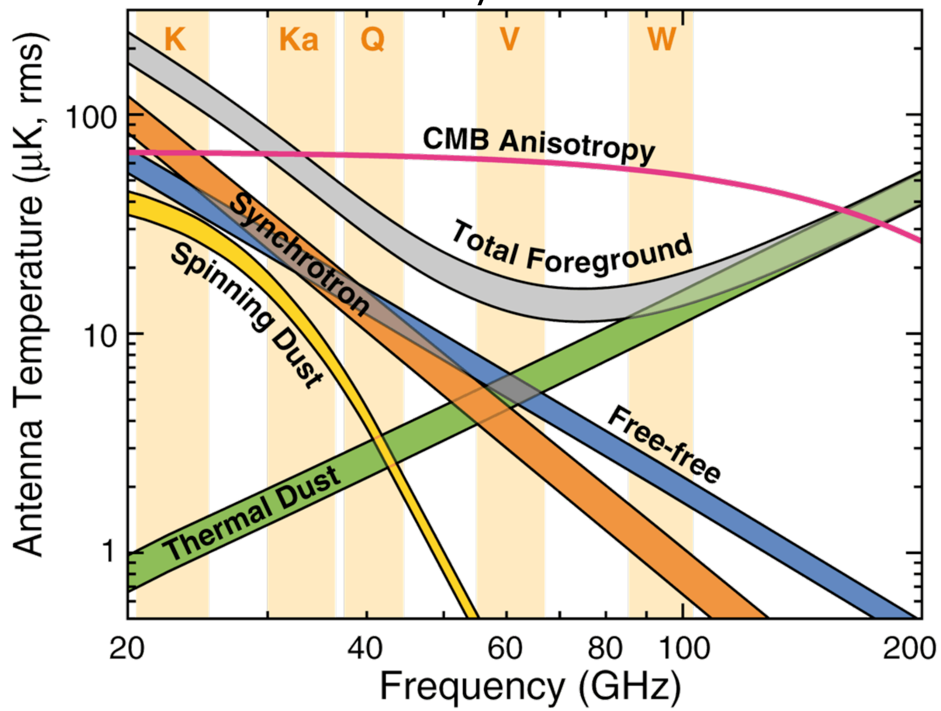
    2.2 Incoherent detectors: TESs, KIDs

3. CMB instruments design

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

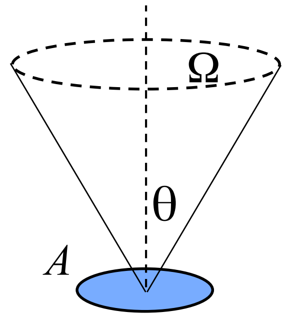
Intensity fluctuations



- **No spectral features**: we need to build a **photometer**
  - ➢ Measure of CMB power in a large bandwidth Δν: Δν/ν=20-30%

CMB photon flux

- Photon flux: $P = \eta B_\nu(T_{CMB})\, A\Omega\Delta\nu$
  - ➢ $B_\nu(T_{CMB})$: Planck's law
    - ✓ in W.m^{-2}.Hz^{-1}.sr^{-1}
  - ➢ η: overall quantum efficiency
    - ✓ Losses from detector, filters, optics
  - ➢ $A\Omega$: beam throughput (or étendue)
    - ✓ Constant in an optical system

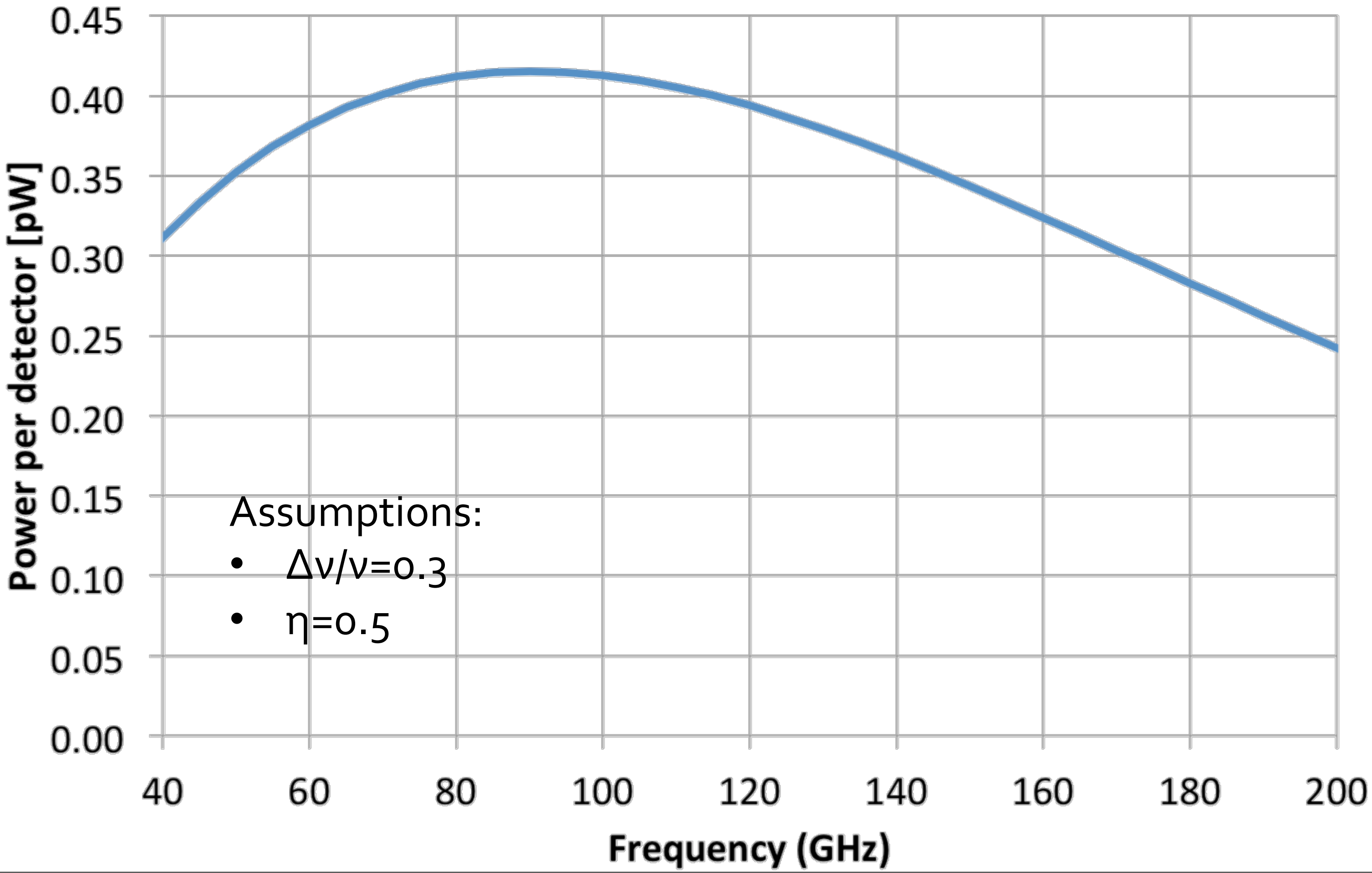


- Diffraction limited detection:
  - ➢ Diffraction limit with a telescope of diameter D: $\theta=1.22\lambda/D$

$$\left.\begin{aligned} A &= \pi\frac{D^2}{4} \\ \Omega &\approx \pi\frac{\theta^2}{4} \end{aligned}\right\} \Rightarrow A\Omega = \lambda^2$$

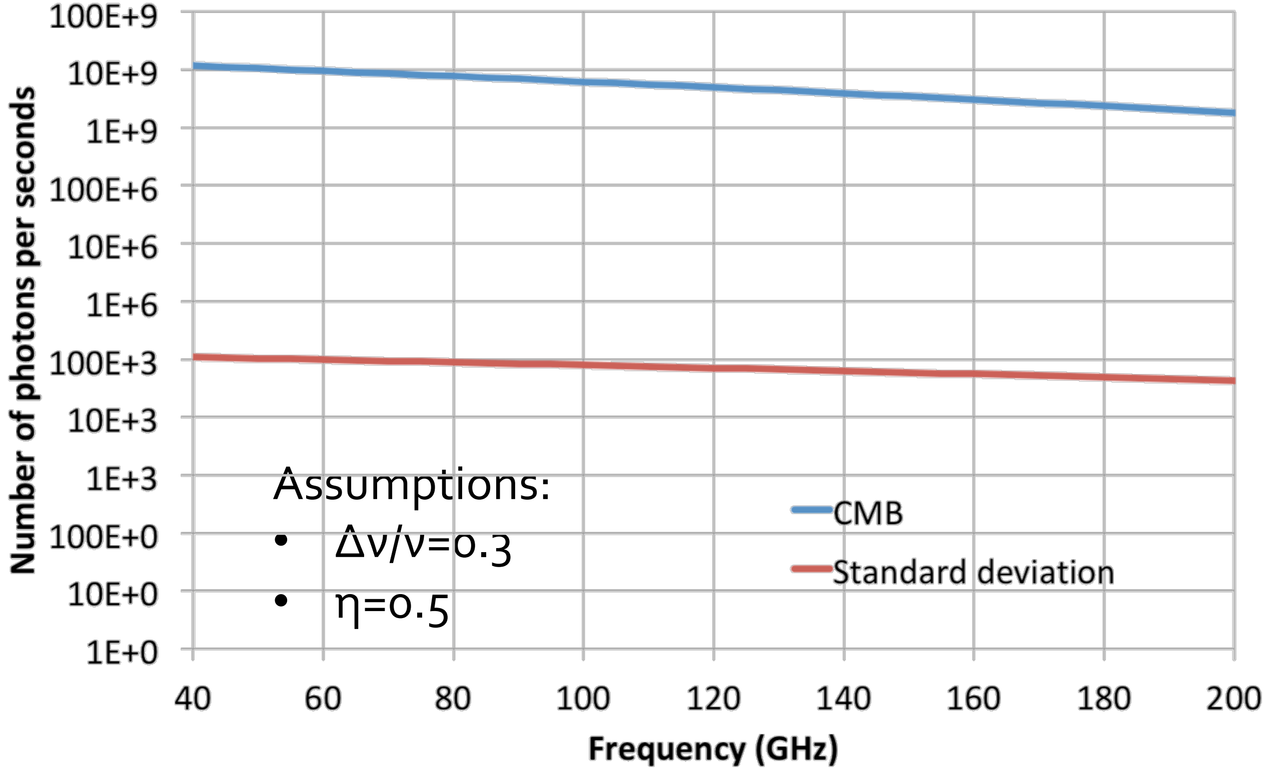
CMB power on one detector

- In a diffraction limited detector:



CMB photon noise

- Number of photons per seconds: $N = P/(h\nu)$
  - ➢ Photon flux ≈ Poisson flux
  - ➢ Standard deviation: $\sigma = \sqrt{N}$



CMB photon noise NEP

- Noise Equivalent Power (NEP):
  - **NEP = standard deviation of the photon noise, expressed in photon flux power P, for 1Hz of bandwidth (or ½ second of integration time)**

$$NEP = \sigma_P\left(t_{\text{int}} = 0.5s\right) \quad \Leftrightarrow \quad \sigma_P = NEP \Big/ \sqrt{2 \times t_{\text{int}}}$$

  - NEP unit: $[W.Hz^{-0.5}]$
  - Could also be applied to other noise sources (detector, readout…)

CMB photon noise NEP

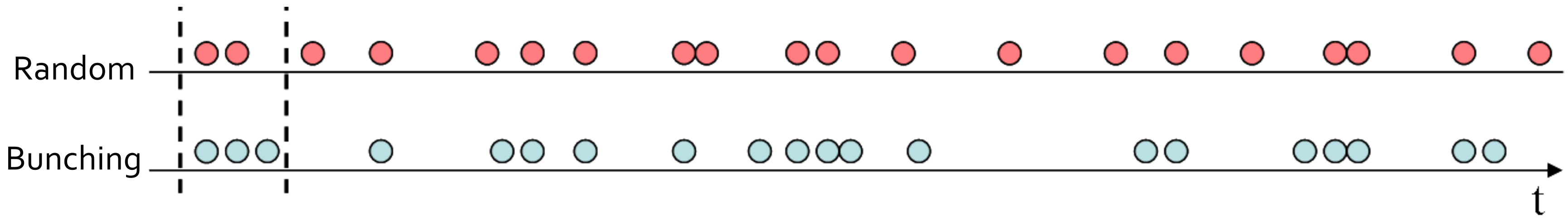
- Noise Equivalent Power (NEP):
  - **NEP = standard deviation of the photon noise, expressed in photon flux power P, for 1Hz of bandwidth (or ½ second of integration time)**

$$NEP_{h\nu}^2 = 2h\nu P + \frac{2P^2}{m\Delta\nu}$$

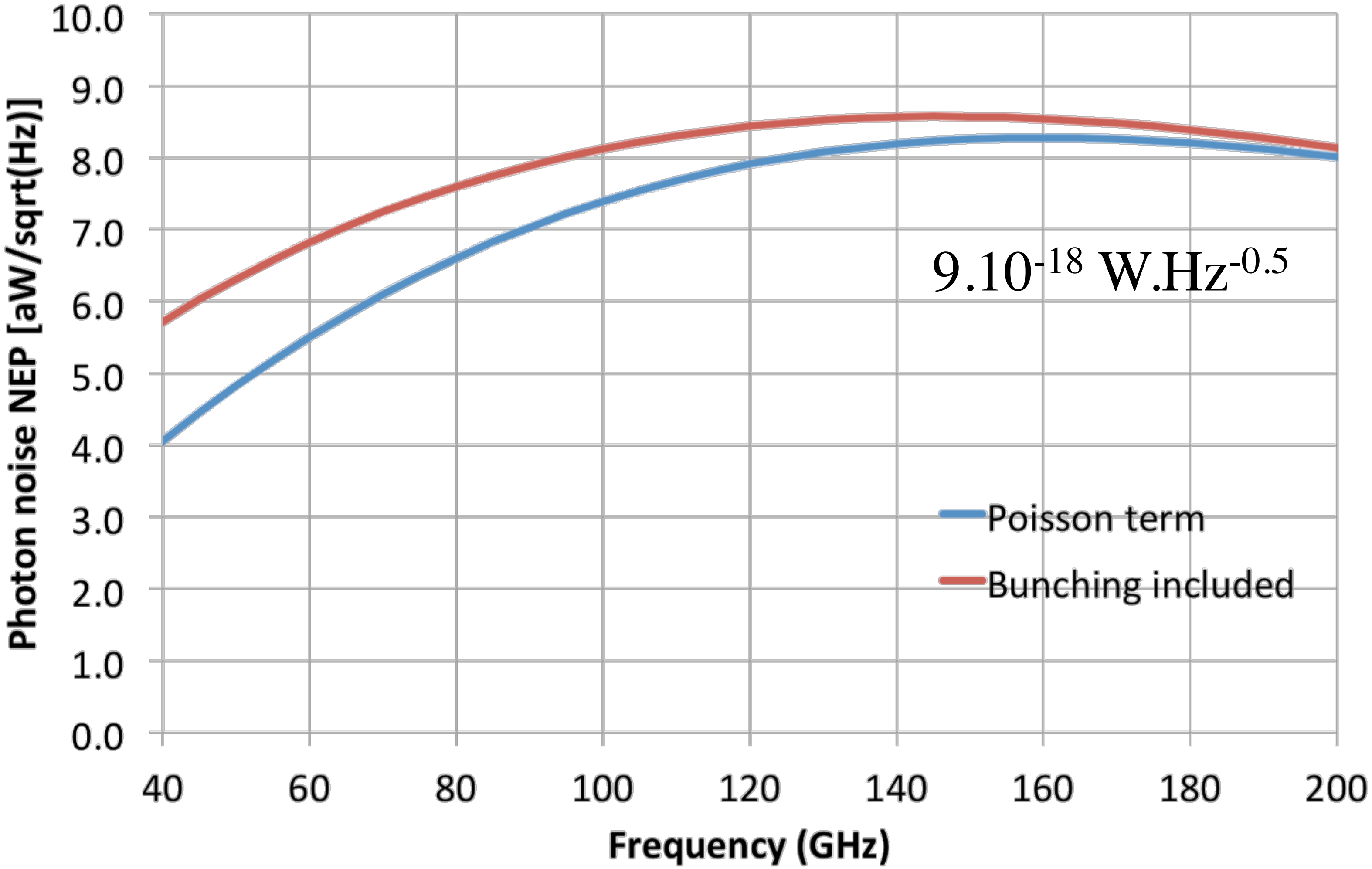
(m = 1 if polarised detector, 2 otherwise)

Poisson term

Bunching term
Bose-Einstein statistics

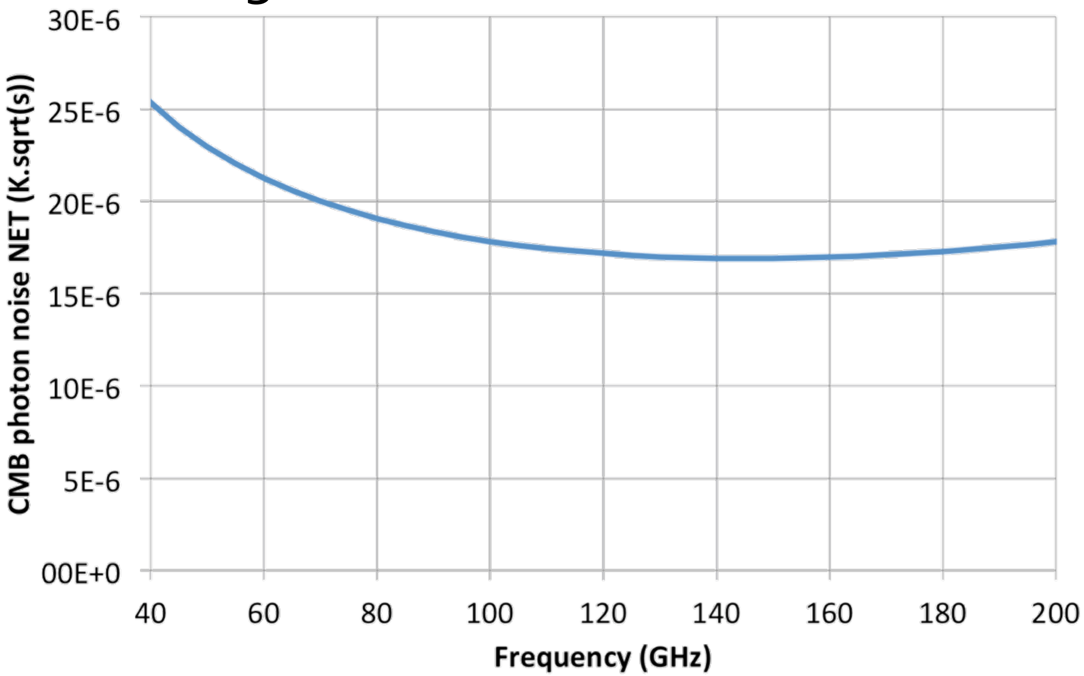


CMB photon noise NEP



CMB photon noise NET

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



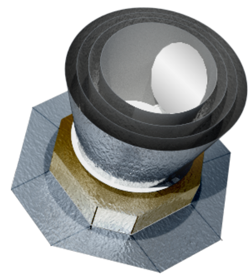
$$20\mu K.s^{0.5}$$

  - ➢ For N_{det} detectors, scale as sqrt(N_{det})

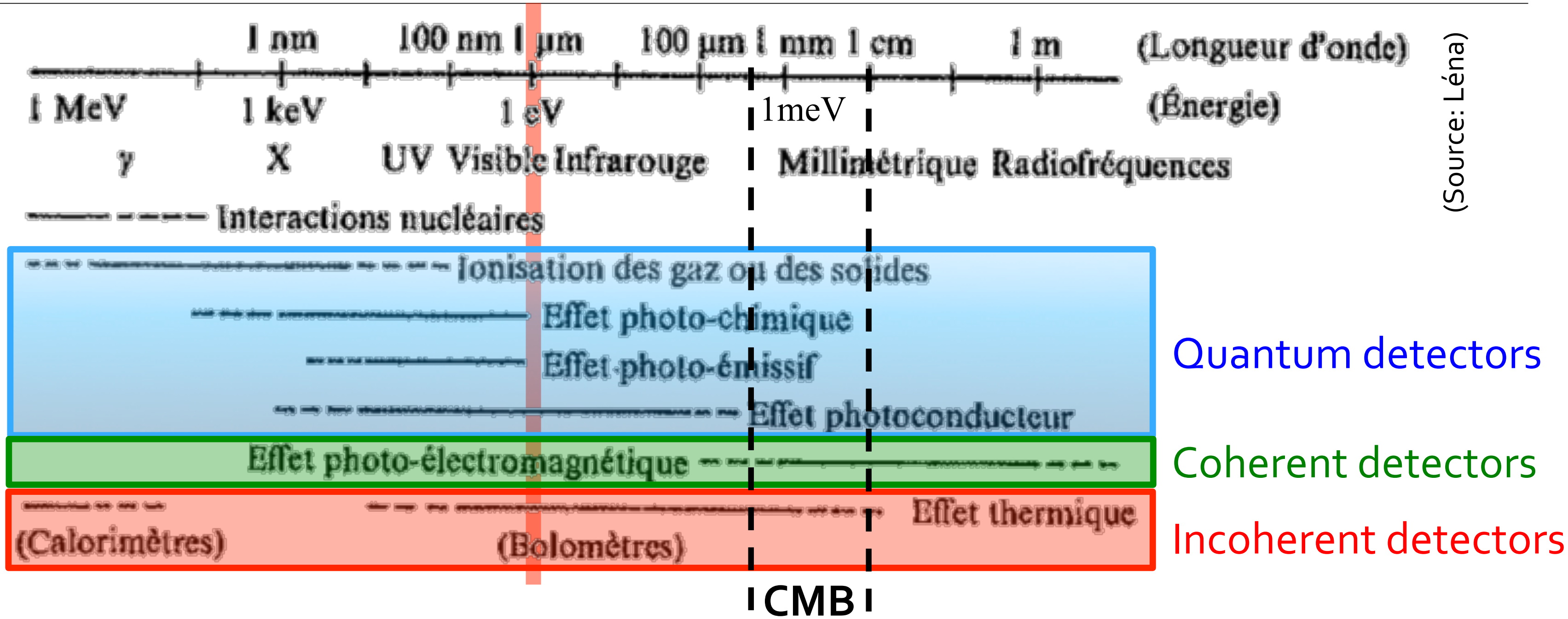
CMB instruments

Assuming perfect detectors, limited by the CMB photon noise:

	T anisotropies	B-modes
Required sensitivity	$6\mu K$	90nK
Angular resolution	5 arcmin	15 arcmin
Integration time per angular resolution for a 1 year mission	5s	50s
Required NET	$13\mu K.sqrt(s)$	$0.6\mu K.sqrt(s)$
Number of detection chain needed	~4	~1100
Missions	Planck	COrE like



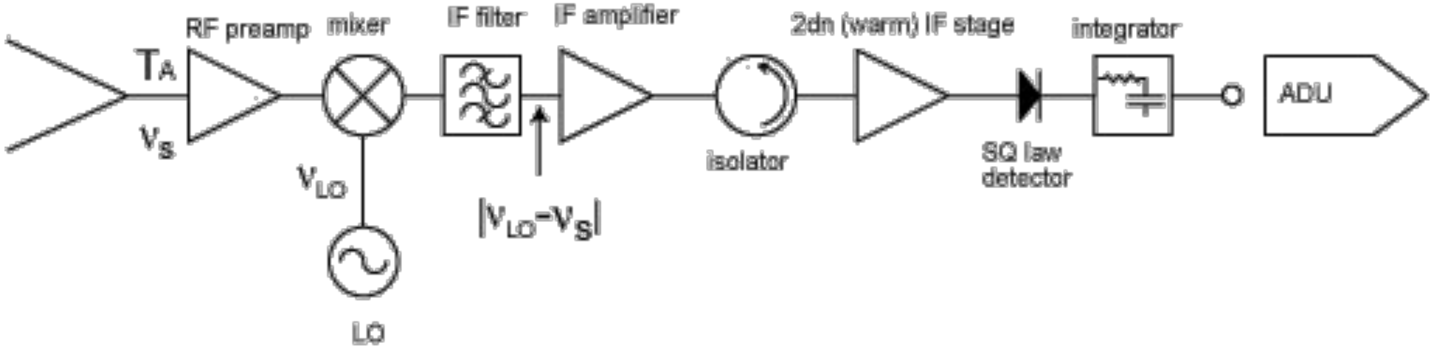
2. CMB detectors?



- Coherent detectors: sensitive to EM field (amplitude and phase)
  - ➢ Intrinsically limited in sensitivity
- Incoherent detectors: sensitive to the average EM power $P \propto \langle |E|^2 \rangle$
  - ➢ **Bolometers, Kinetic Inductance Detectors**

2.1 Coherent detection techniques

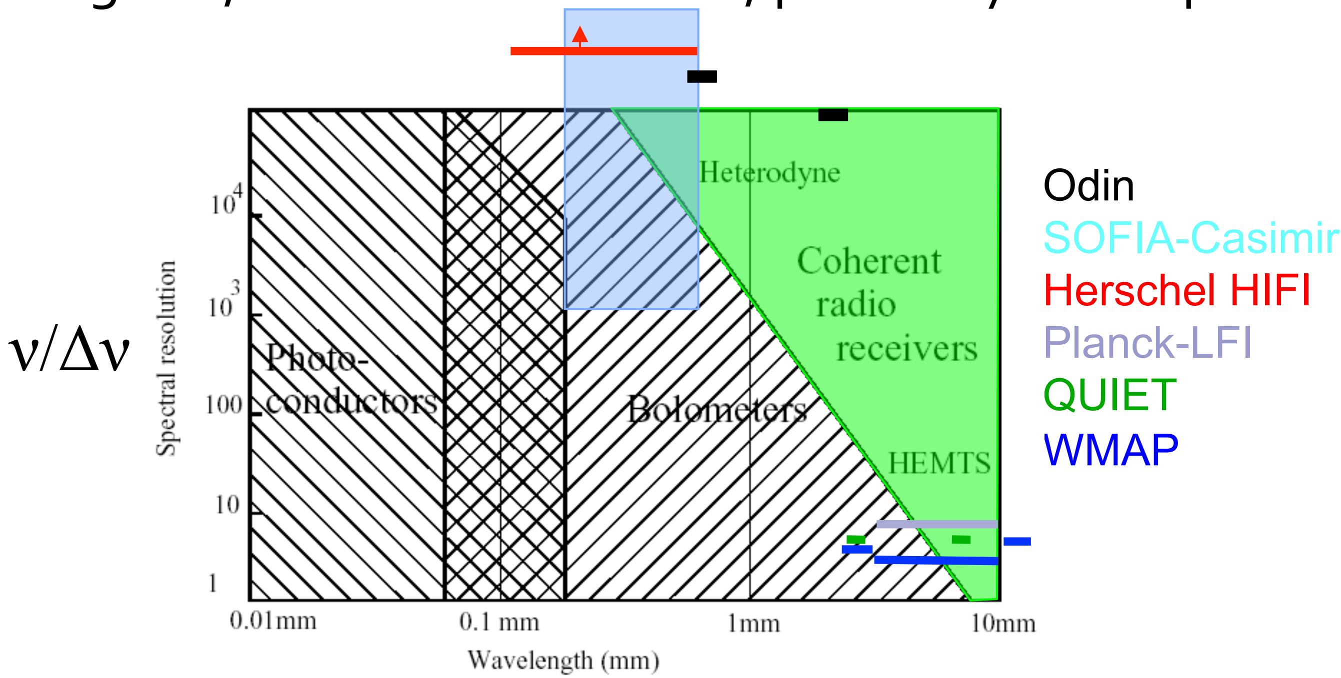
- Heterodyne power detection:



  - ➢ Use of very high frequency electronics
    - ✓ Antenna
    - ✓ High Electron Mobility Transistors (HEMTs) amplifier cooled down to 4K
    - ✓ Non-linear elements for mixing (Schottky diode, SIS mixers, HEB)
    - ✓ Diode used as square law detector
  - ➢ Conservation of phase information

Heterodyne detection technique

- Widely used for spectroscopy in the mm and sub-mm:
  - Spectral lines of atomic and molecular gas: star forming regions, interstellar medium, planetary atmospheres



Coherent receiver: signal and noise

- Signal measured in RJ limit: $P = kT_a \Delta\nu$
  - T_a: antenna temperature
  - Include source, atmosphere, ground signals…
- Noise temperature: $P_{noise} = kT_{noise}\Delta\nu$
  - Include amplifier noise, mixer losses, detector noise…
- Power measured: $P_{tot} = P + P_{noise}$
- System temperature: $T_{sys} = T_a + T_{noise}$
- Smallest detectable signal:
  - Integration time τ

$$\Delta T \approx \frac{T_{sys}}{\sqrt{\tau\Delta\nu}}$$

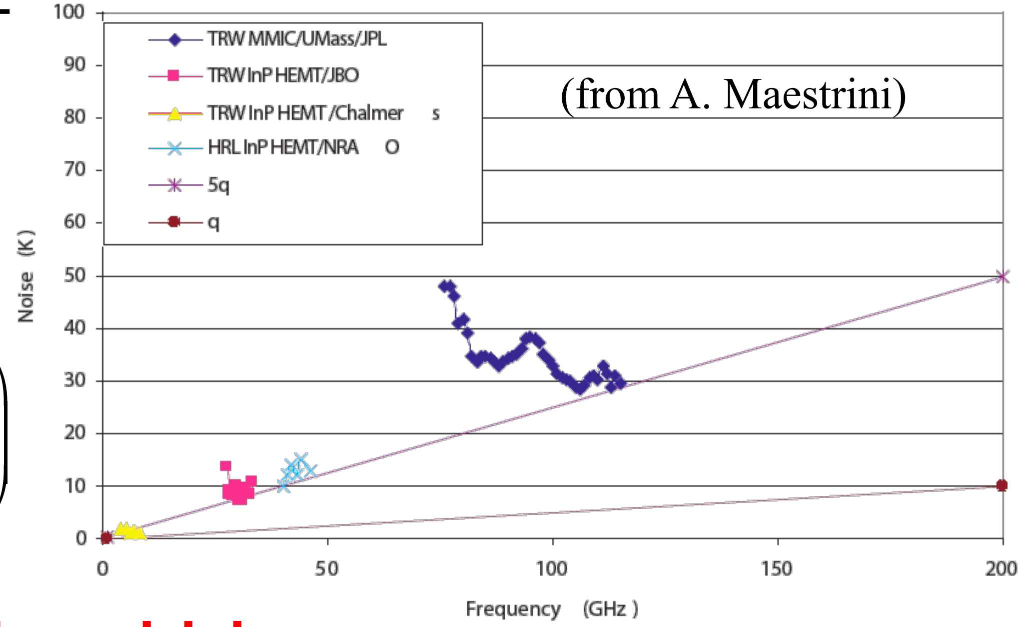
Dicke equation (1946)

The quantum tax

- Minimum noise temperature given by quantum limit:

$$T_{noise} \geq \frac{h\nu}{k} = 5K \times \left(\frac{\nu}{100GHz} \right)$$

- Best performances : ~5×QL
  - ➢ InP HEMT amplifier cooled to ~20K



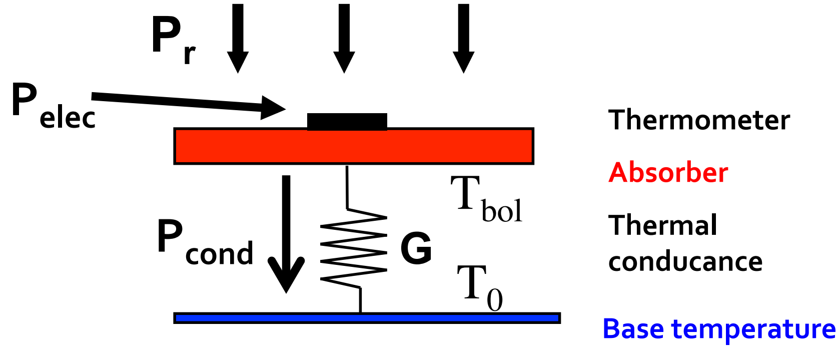
- Equivalent NEP:

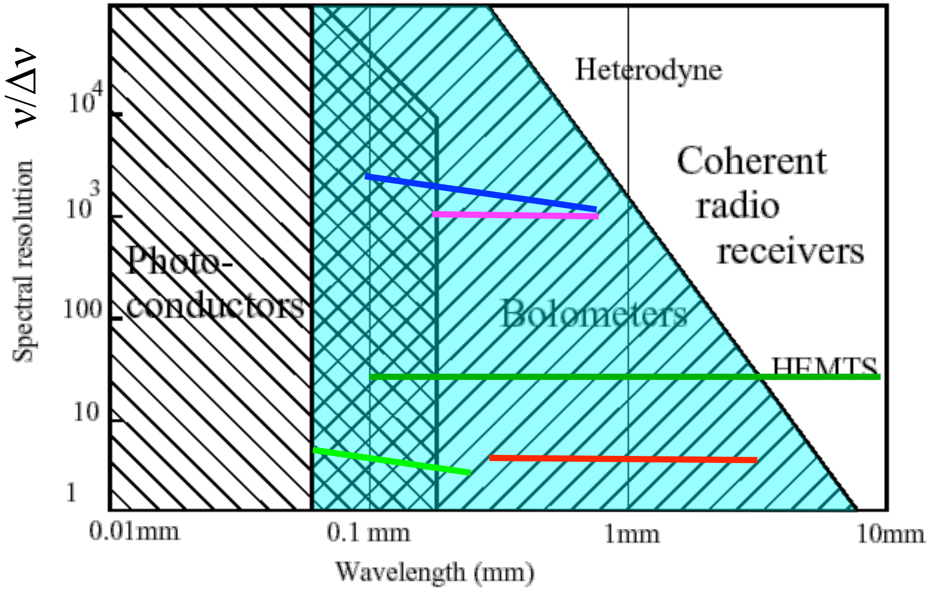
$$NEP \geq 1.7\,10^{-17}\,\mathrm{W.Hz}^{-0.5} \times \left(\frac{T_{noise}}{5K} \right) \times \left(\sqrt{\frac{\Delta\nu}{30GHz}} \right)$$

Intrinsic limitation in terms of sensitivity

2.2 Incoherent detection techniques: Bolometers

- Thermal detector
  - Measure of the heating from the absorption of radiation
  - Macroscopic system
  - 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

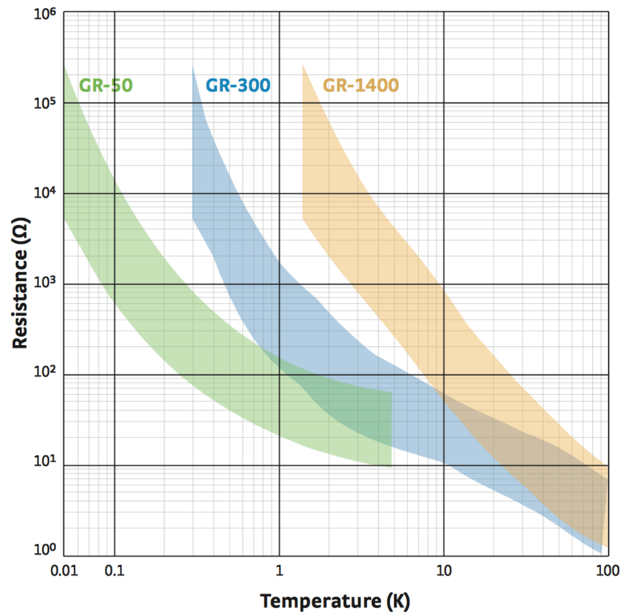




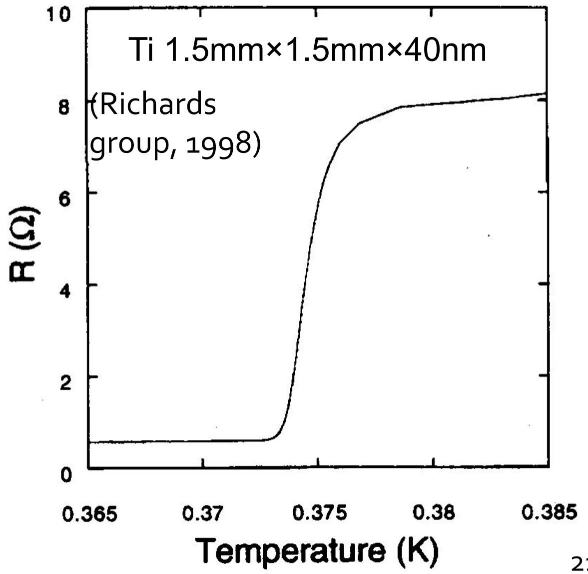
From top to bottom: SAFIRE Herschel-SPIRE COBE-FIRAS Herschel-PACS Planck-HFI

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)

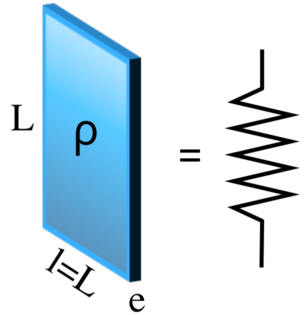


- Superconductor: α #100 → 1000 (***Transition Edge Sensor*** TES)
  - ➢ Ti: T_c≈400mK
  - ➢ Mo/Cu, Mo/Au…: T_c tuning by proximity effect
  - ➢ NbSi thin film (CSNSM): T_c depends on composition Nb (>12%) vs Si

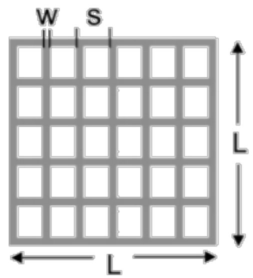


Absorber

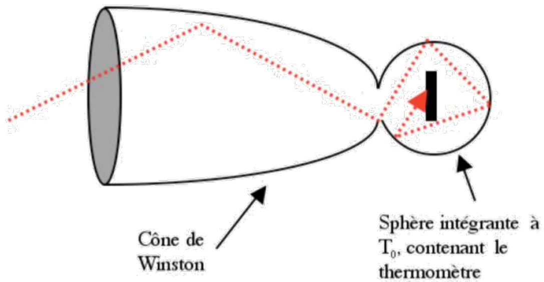
- **Absorber = metal film**
  - Square resistance of a uniform film: $R_c = \rho/e$



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



- In vacuum:
  - Max absorption = 50% for $R_c = Z_0/2$
    - ✓ Integrating sphere to increase absorption



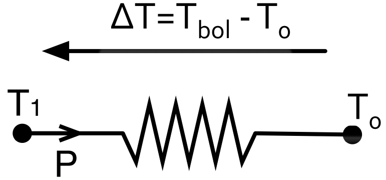
  - Max absorption = 100% for $R_c = Z_0$ <u>with a reflective layer at d=λ/4</u> (modulo λ/2)

Vacuum impedance:
$$Z_0 = \sqrt{\mu_0/\varepsilon_0} = 377\Omega$$

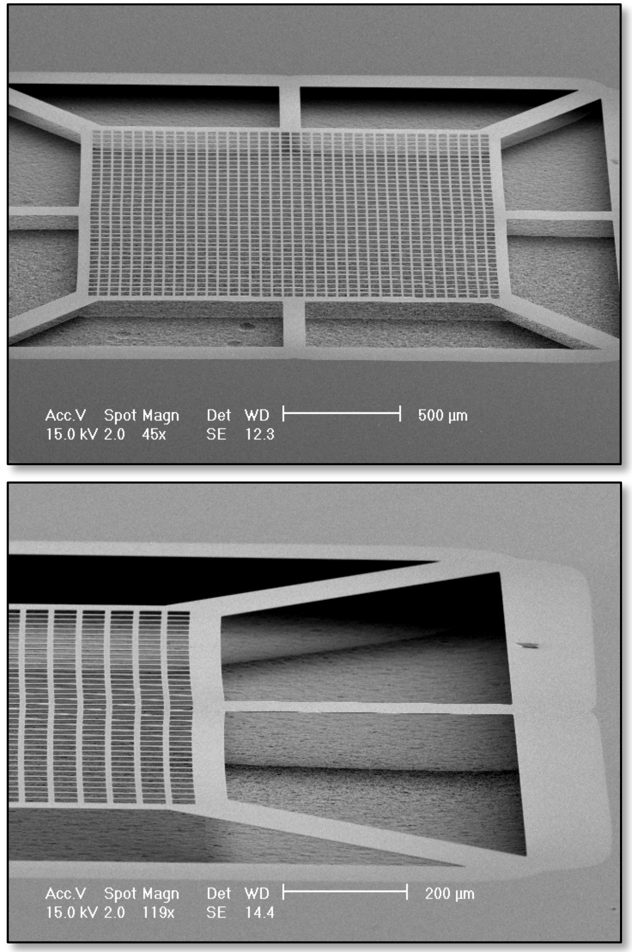
Thermal conductance

- 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)

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



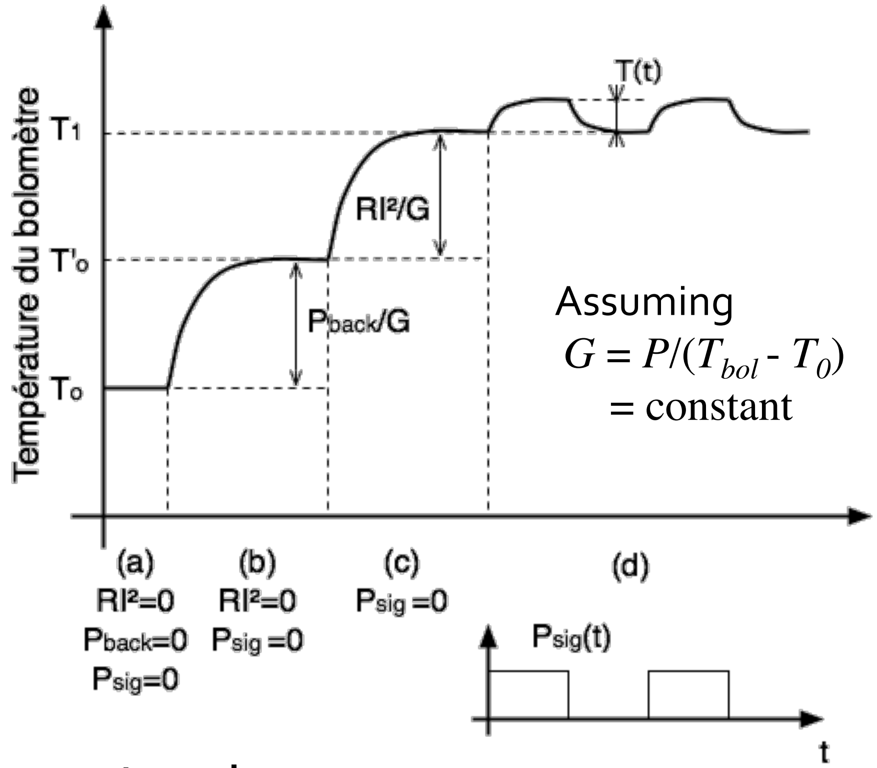
$$G_d = \left(\frac{dP}{dT_{bol}}\right)_{T_0=cst} = (\beta+1)KT_{bol}^{\beta}$$



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

A bolometer in operation

- $P_r = P_{back} + P_{sig}(\mathrm{t})$ with $P_{sig}/P_{back} << 1$
  - ➢ P_{back}: average power, *background power*
    - ✓ Thermal emission of all components in front of detectors
  - ➢ P_{sig}: radiative power to be measured



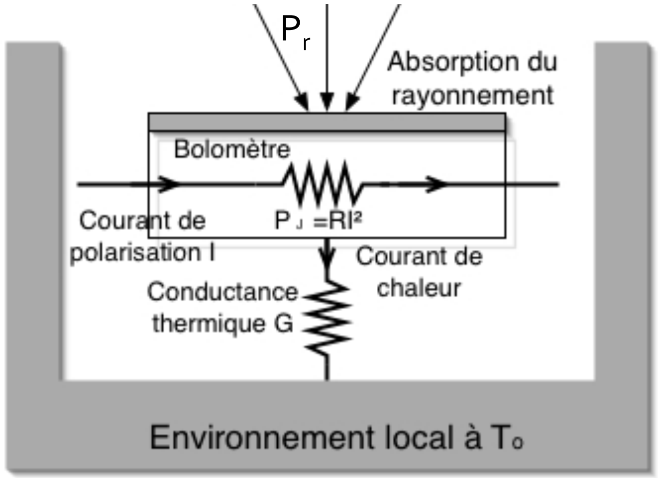
Assuming
$G = P/(T_{bol} - T_0)$
$= \mathrm{constant}$

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

Bolometer response in harmonic regime

- In temperature:

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

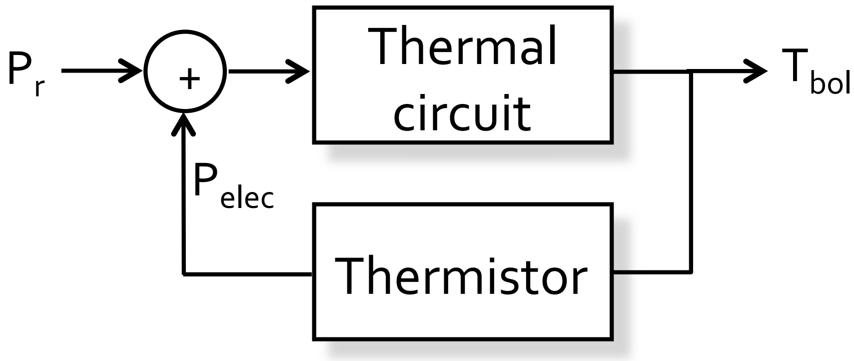


C: bolometer heat capacity [J/K]
G_{eff}: bolometer effective thermal conductance [W/K]

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

Electro Thermal Feedback (ETF)

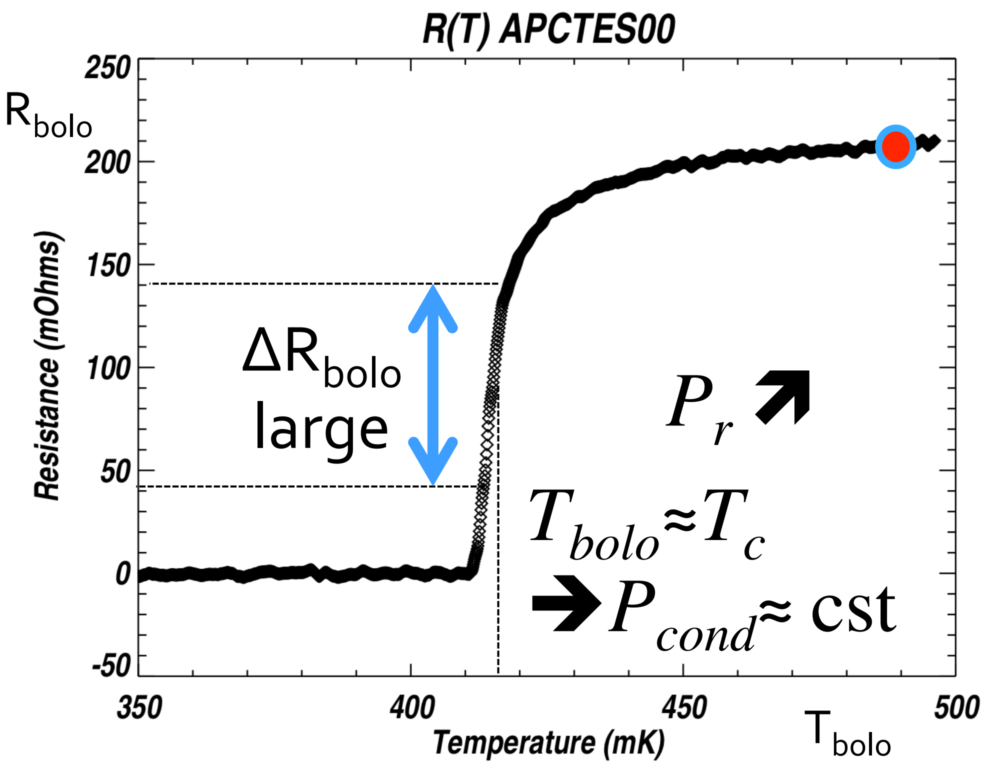
- Case α<0: semi-conducting bolometer
  - Current biasing: $T\nearrow \Rightarrow R\searrow \Rightarrow P_{elec}=RI_{bias}^2 \searrow \Rightarrow T\searrow$
- Case α>0: superconducting bolometer
  - Voltage biasing: $T\nearrow \Rightarrow R\nearrow \Rightarrow P_{elec}=V_{bias}^2/R \searrow \Rightarrow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

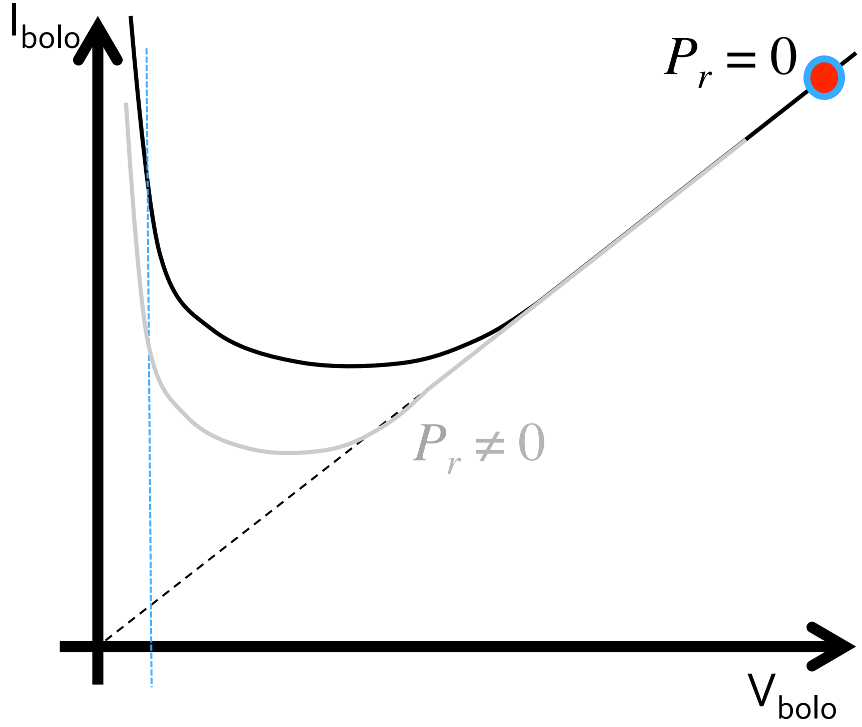


- Interesting effect if |α| is large: **superconducting bolometers**

ETF in TES

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

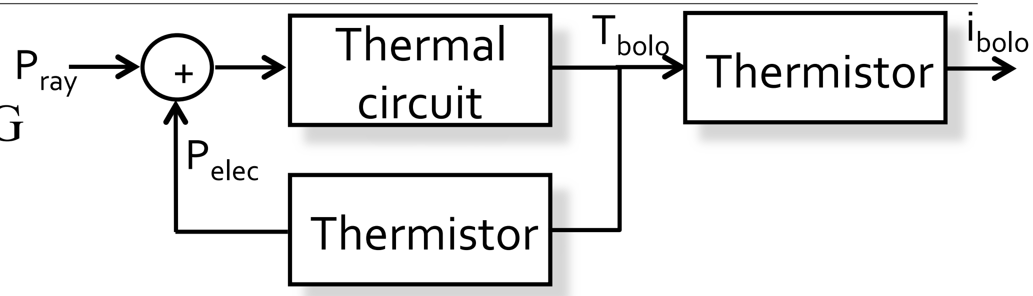




Fluctuations in P_r compensated by P_{elec}

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

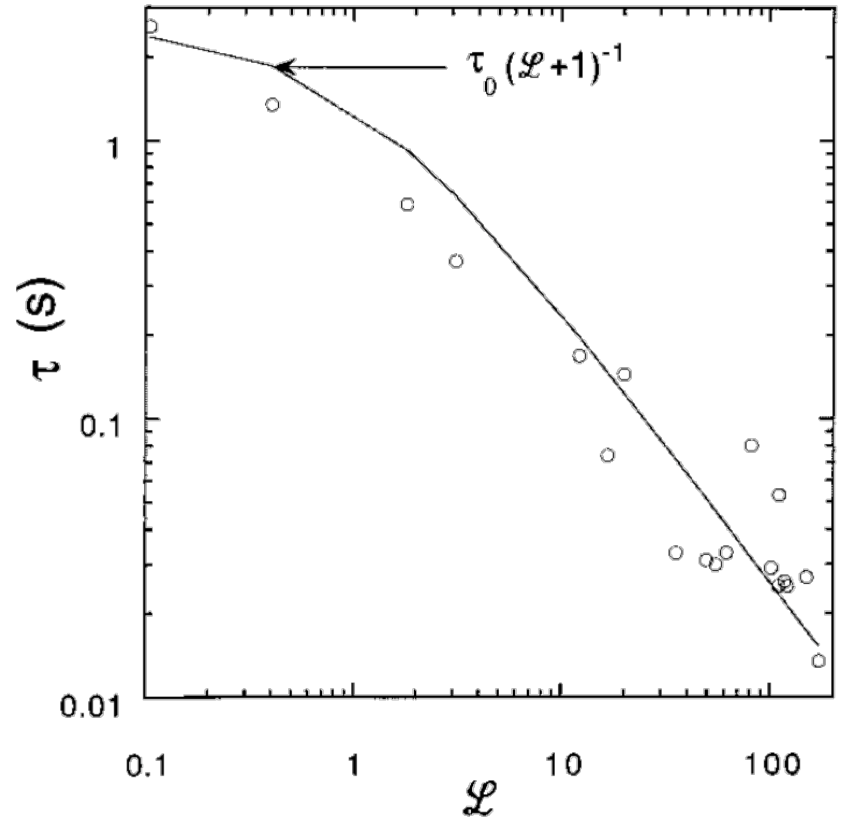
Superconducting bolometers

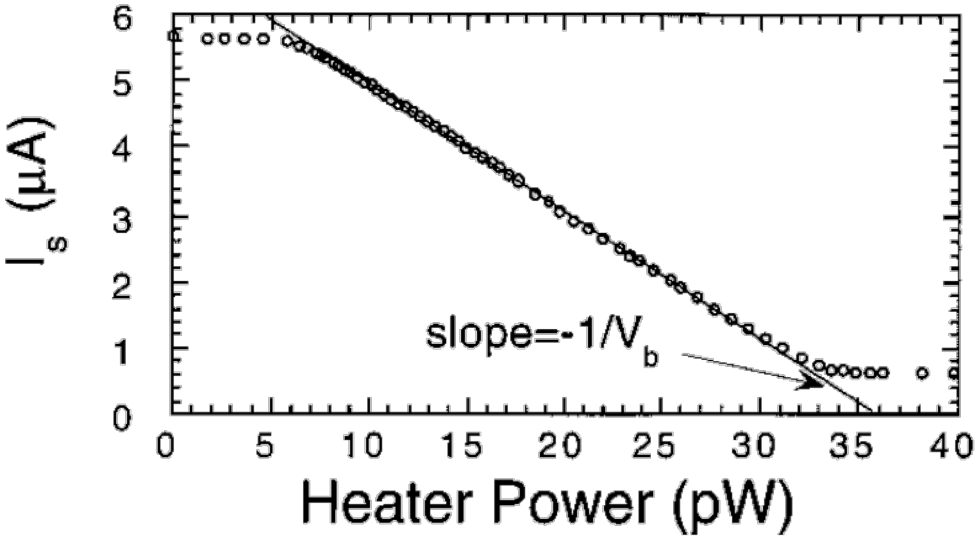
α=100-1000

L=10-100

Strong ETF in TESs

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





TES intrinsic noise sources

- Johnson noise:
  - Electrical resistor R at temperature T

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

Low temperatures require

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: $L = \dfrac{|\alpha| \cdot P_{elec}}{T_1 G_d} >> 1$ (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 : $G_d = \dfrac{dP_{cond}}{dT} \approx [3-20] \dfrac{P_{back}}{T_0}$
  - NEP:

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

Bolometer limited by photon noise (BLIP)

- NEP of photon 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):

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

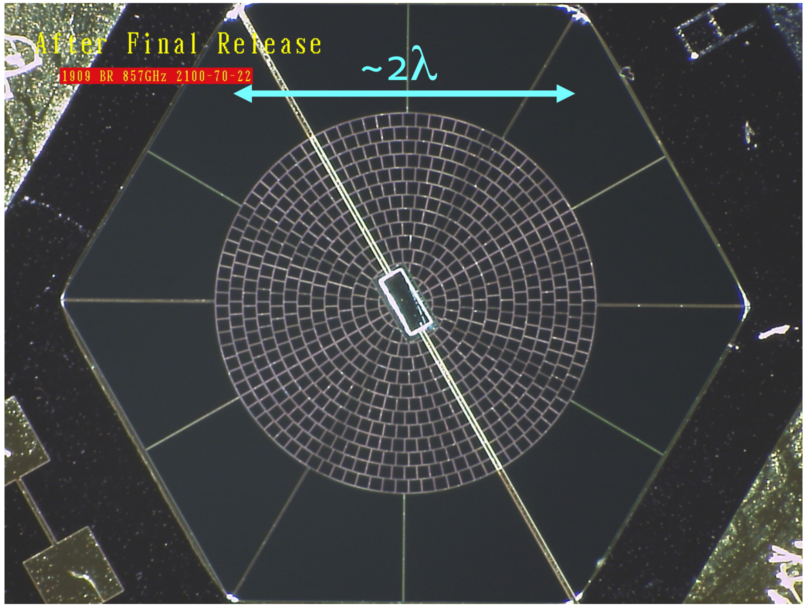
  - With an optimised bolometer: $$T_0 \leq 350mK \times \frac{1mm}{\lambda}$$

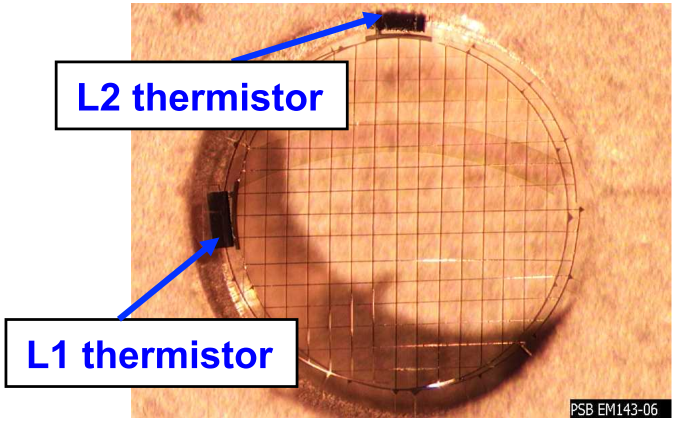
Very low T needed

Planck bolometers
Spider web bolometers (Caltech-JPL)

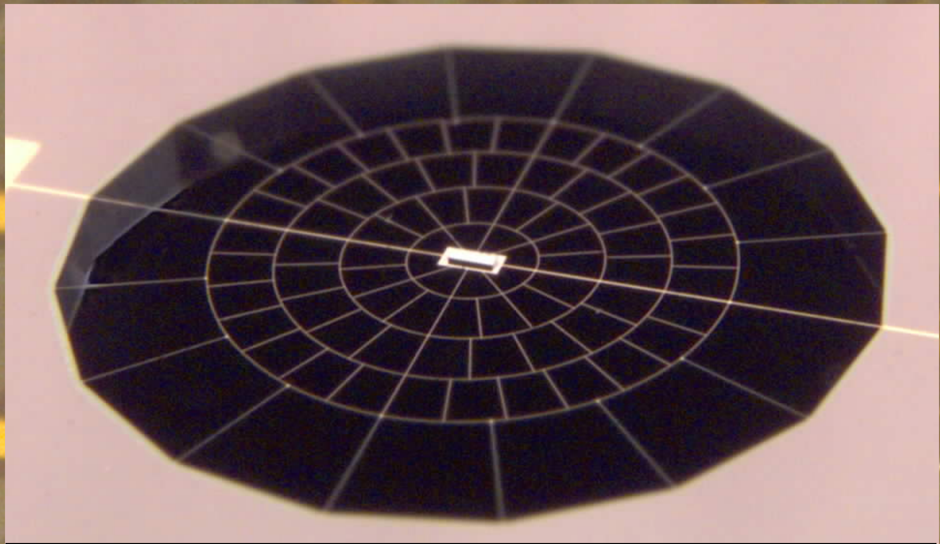
- Absorber: Si_3N_4
  - e~1µm, l~5µm, cell~100µm
  - Metallization Au
- Ge NTD thermometer
- Polarisation Sensitive Bolometer (PSB)
  - 2 bolometers in 1 module
  - Metallization in one direction

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

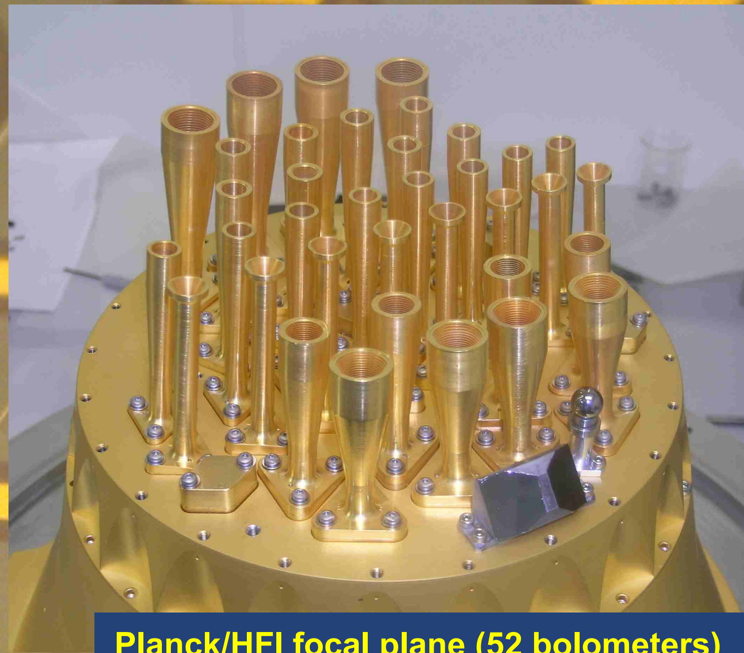




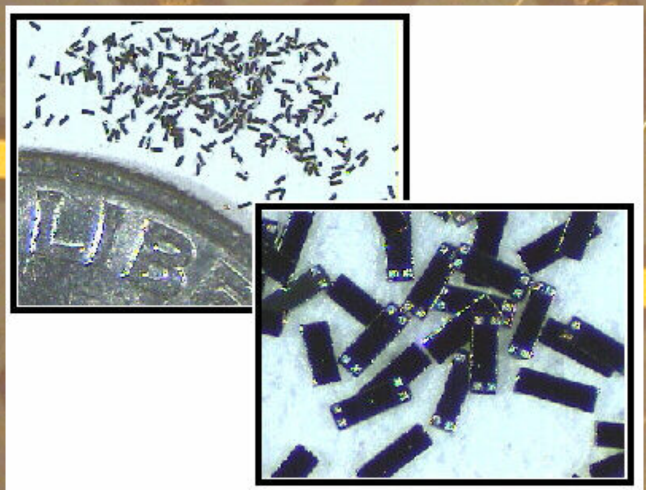
NTD Bolometers for Planck & Herschel



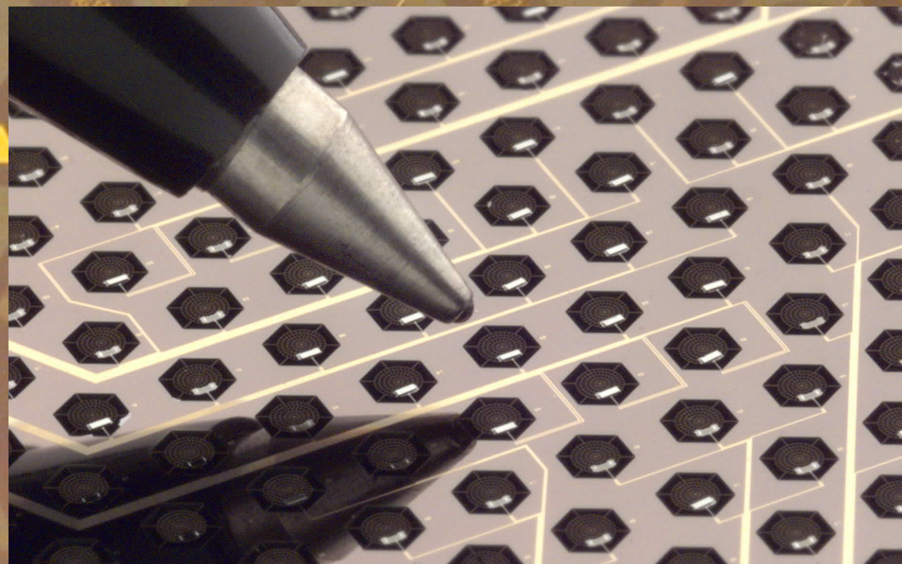
143 GHz Spider-web Bolometer



Planck/HFI focal plane (52 bolometers)



NTD Germanium



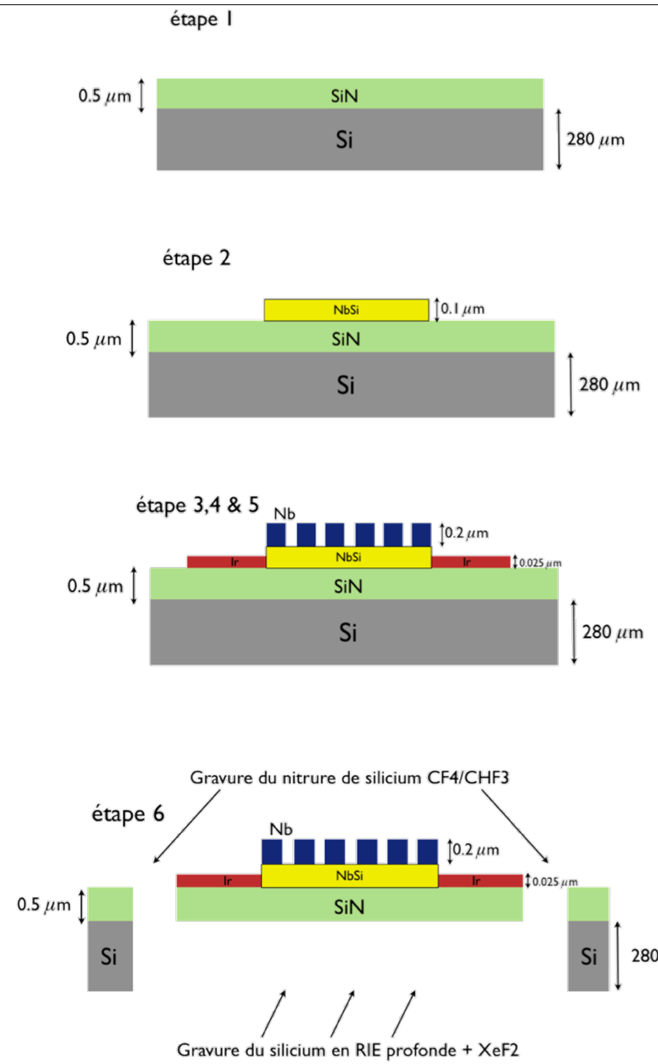
Herschel/SPIRE Bolometer Array

(From J. Bock, JPL)

Bolometer production

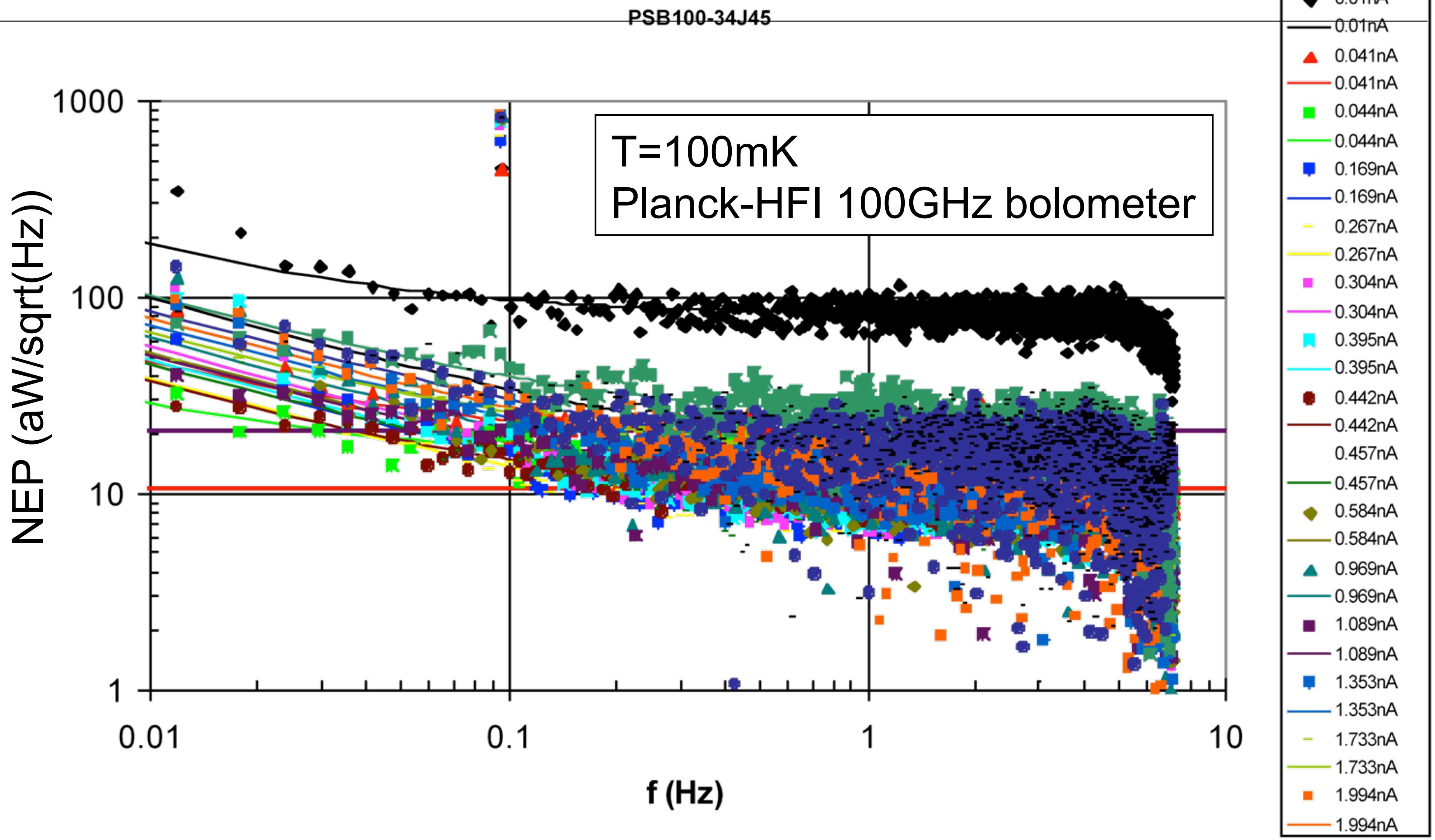
- Based on microtechnologies
- Absorber: photolithography
- Metallisation
- Thermal sensor:
  - Planck bolo: NTD Ge by hand
  - Deposited during the process

Micro fabrication facility required



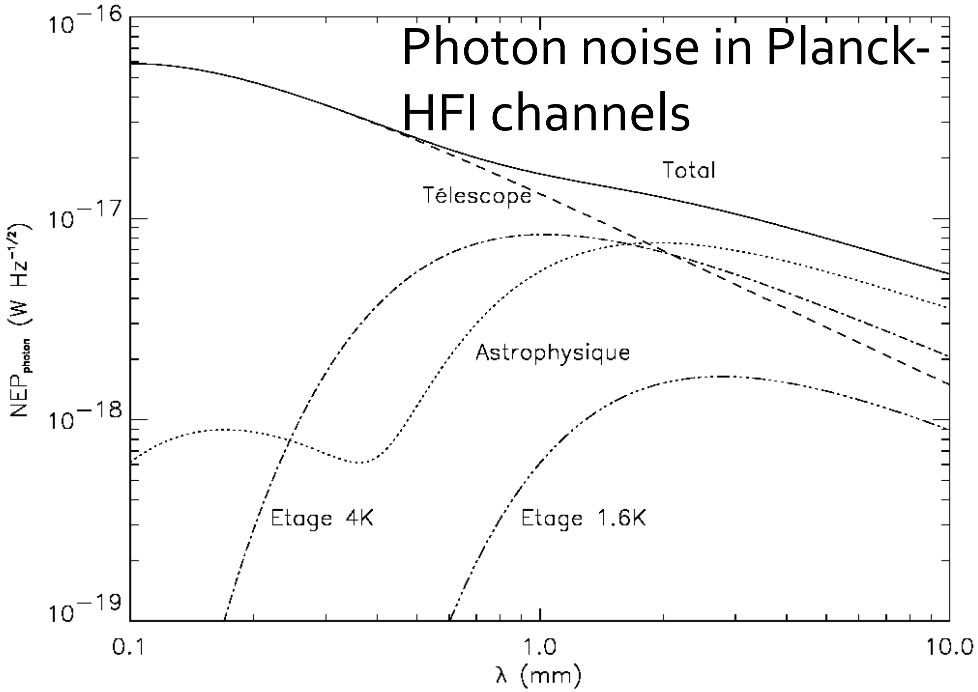
(Joseph Martino)

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



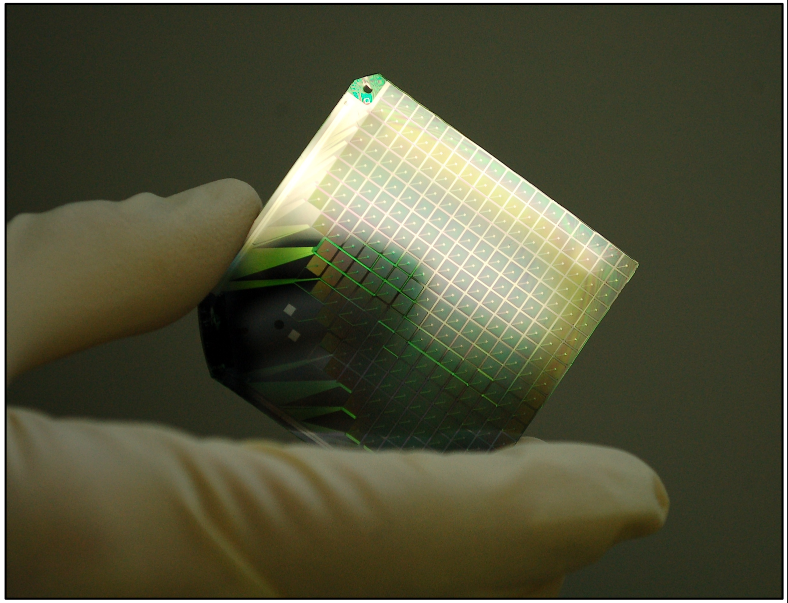
CMB photon noise limited detectors!

Sensitivity improvement ⇒ increase of detector number

Bolometer arrays

Development of bolometer arrays

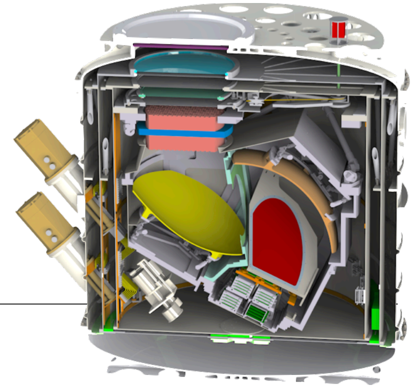
- Motivations:
  - Increase of the mapping speed
  - Increase of the sensitivity
- Requirements:
  - Sensitivity (limited by photon noise)
  - Time constant
  - Array size (from 10^2 to 10^4 pixels)
  - Filling factor
  - Optical coupling
  - Sensitivity to polarisation
- Constraints
  - Cryogenics: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



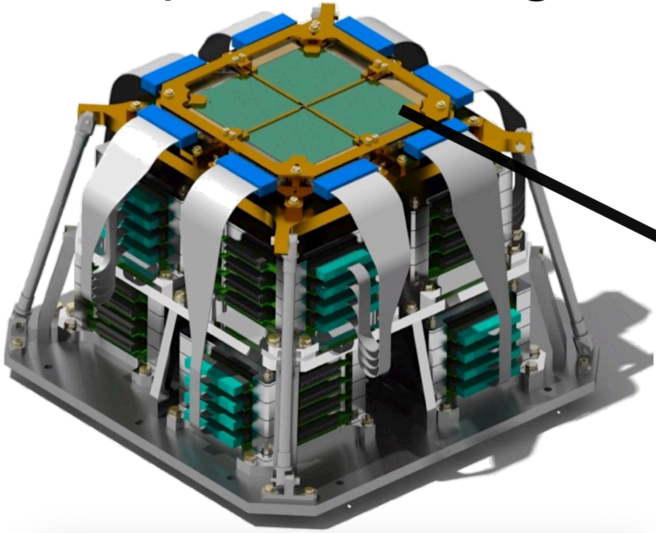
Multiplexing?

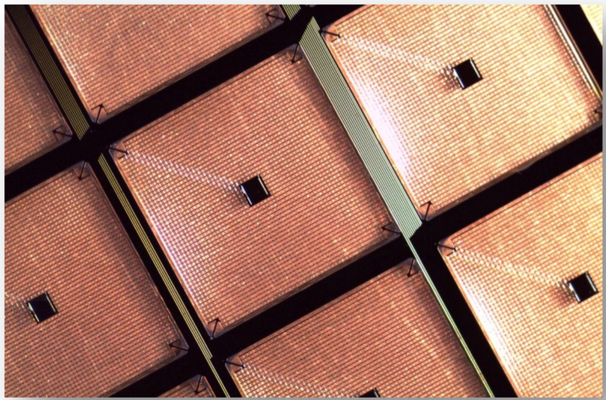
- Readout of N detectors with a single amplifier
- Time Domain Multiplexing (TDM)
  - Successive readout of each detector
  - Required an amplifier noise level lower by a factor ~$N^{0.5}$
- Frequency Domain Multiplexing (FDM)
  - Readout of all detector at all time
  - Each detector is modulated at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

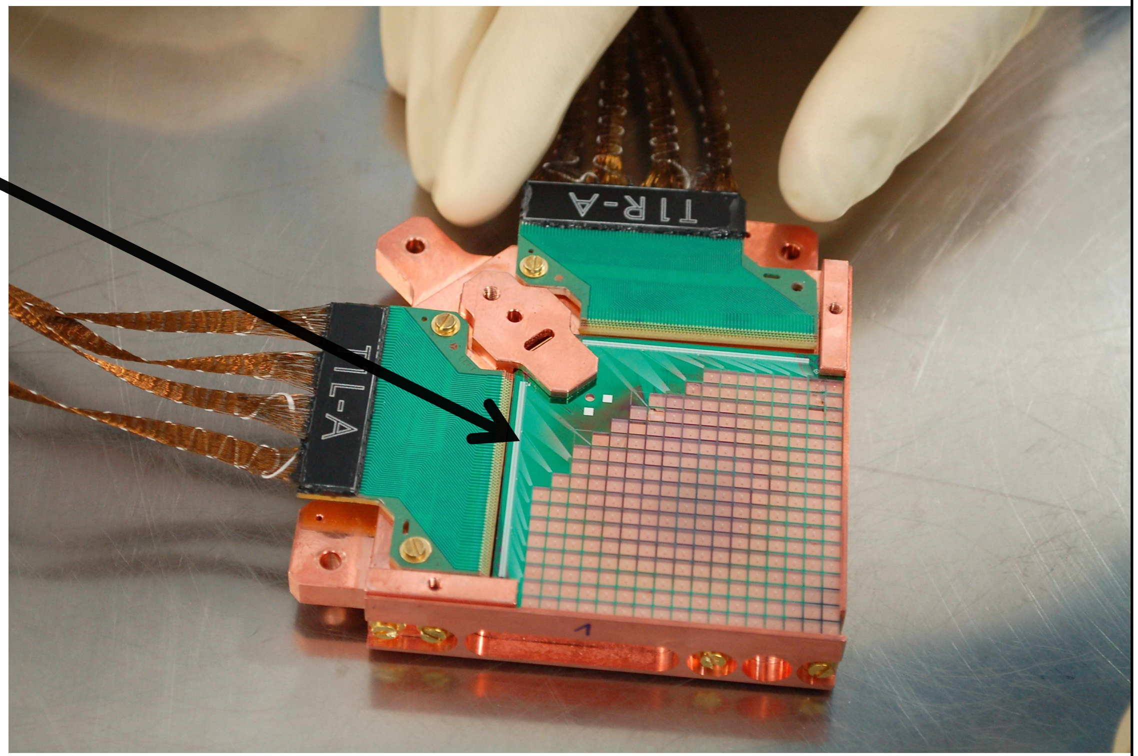
Example:
248 TES QUBIC (France)



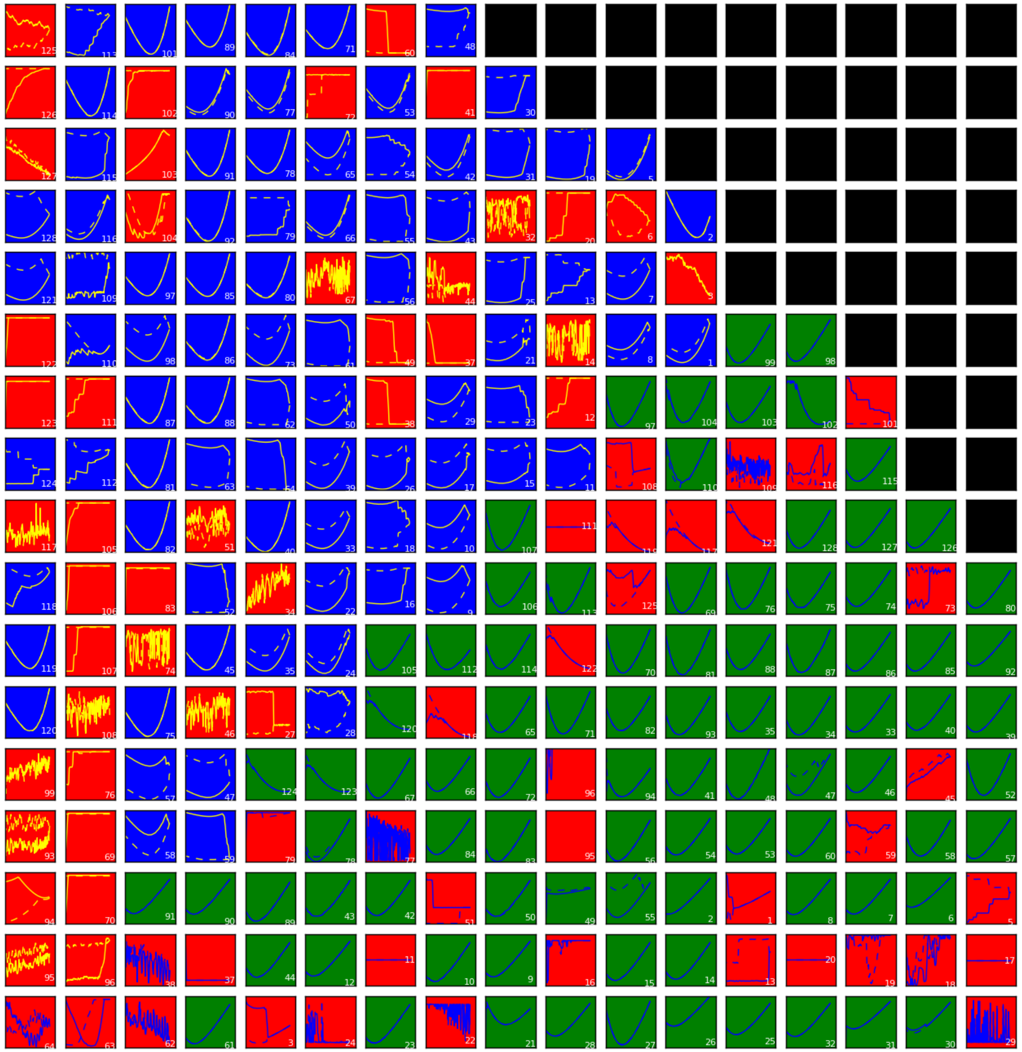
- Superconducting NbSi (CSNSM, C2N, APC)





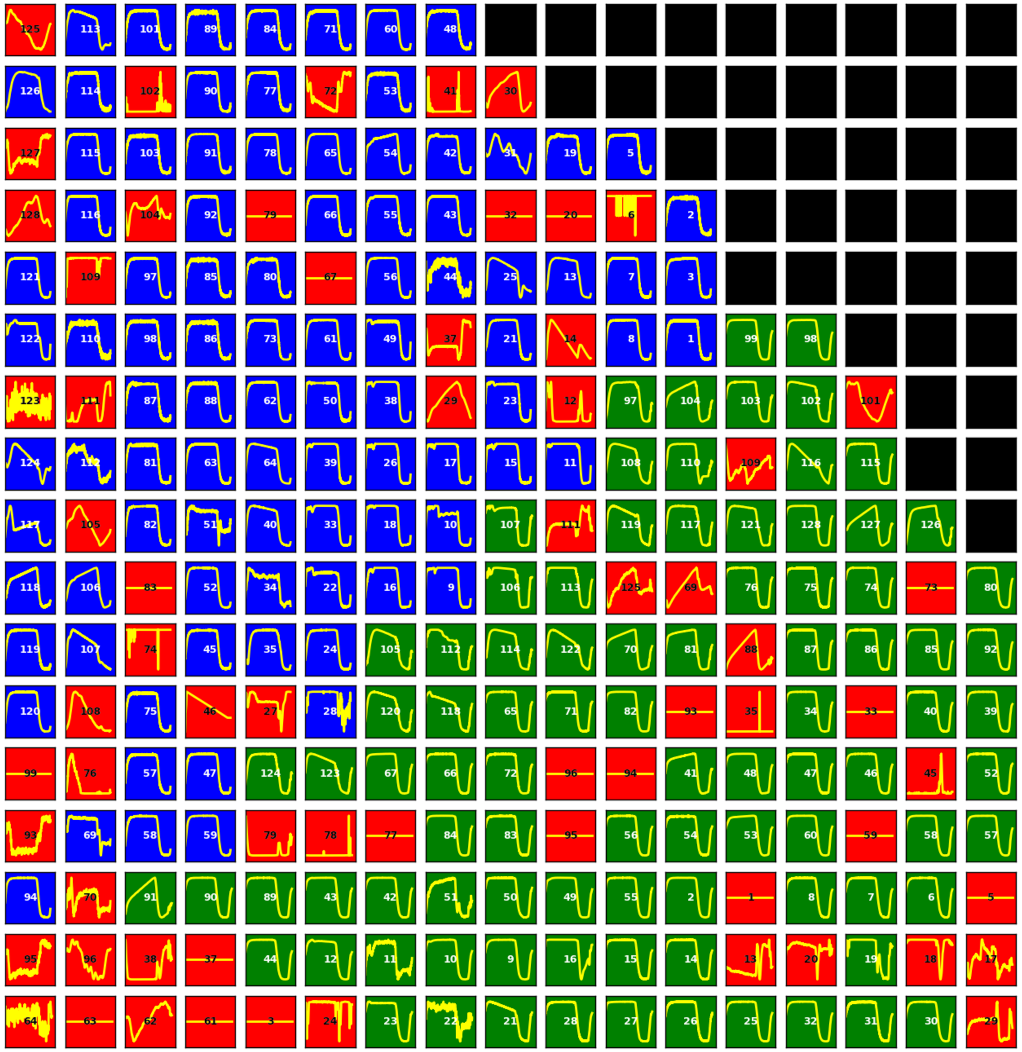


QUBIC TESs: I-V measurements



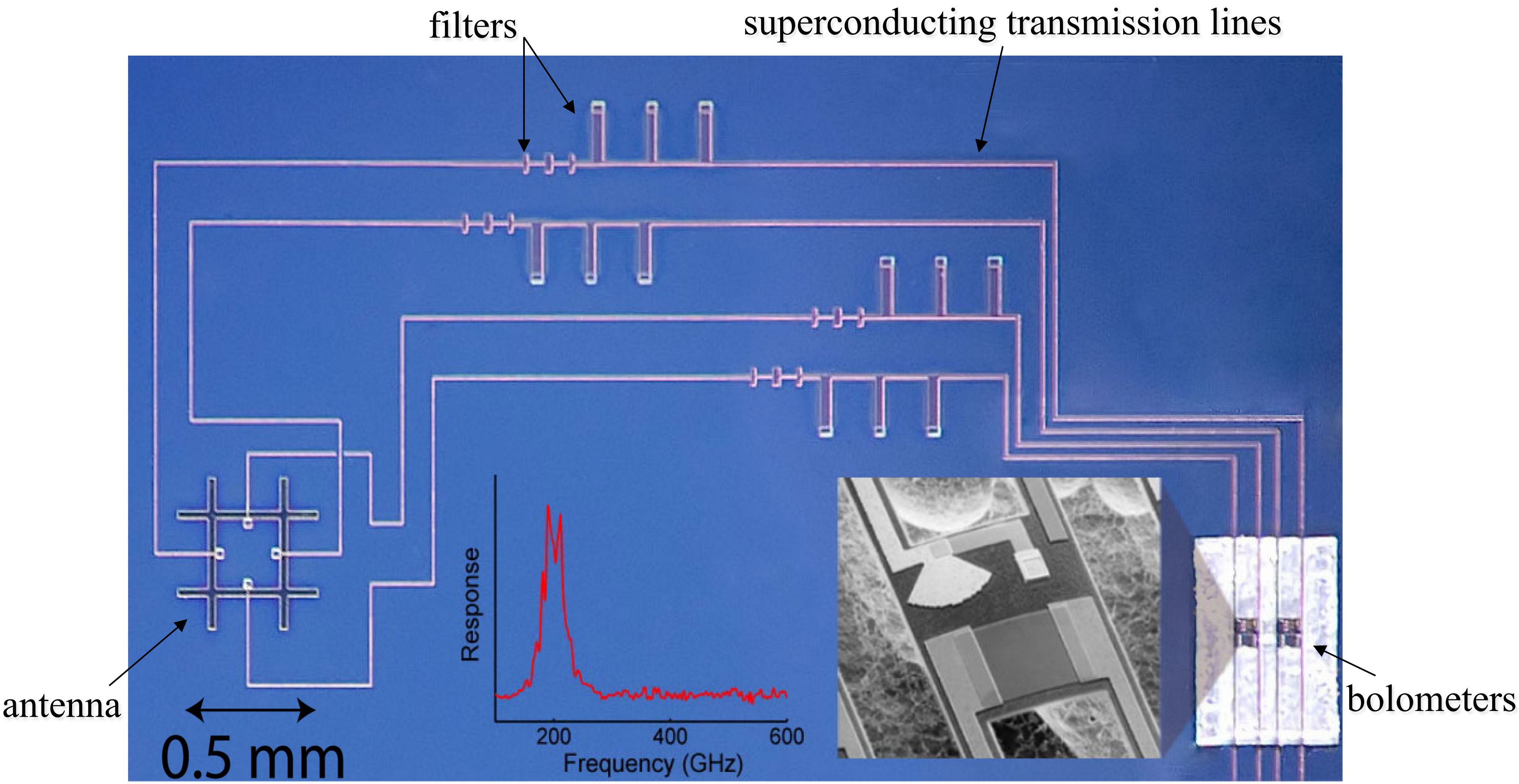
- I-V at 300mK
  - ASIC 1
  - ASIC 2
- TDM MUX factor = 128
- Yield: ~70% (array ref P73)
  - ~20% fabrication
  - ~10% readout

QUBIC TESs: optical signal



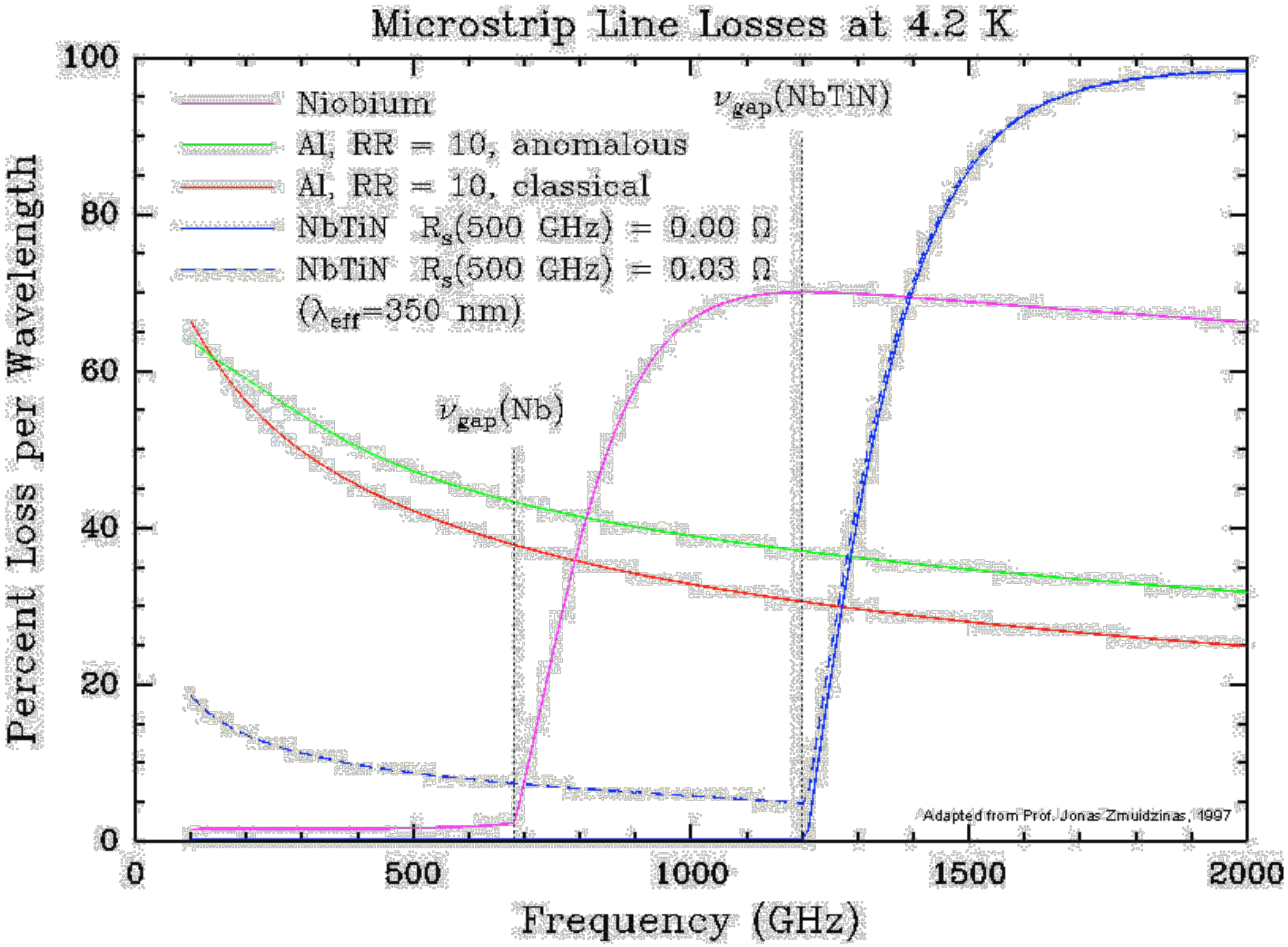
- Thermal source:
  - C fiber on 1K stage (LAL)
  - Heated by Joule effect
- Pulses on detectors
  - ASIC 1
  - ASIC 2
- Other measurements: radioactive sources

Antenna coupled bolometers (Polarbear, UCB/LBNL)

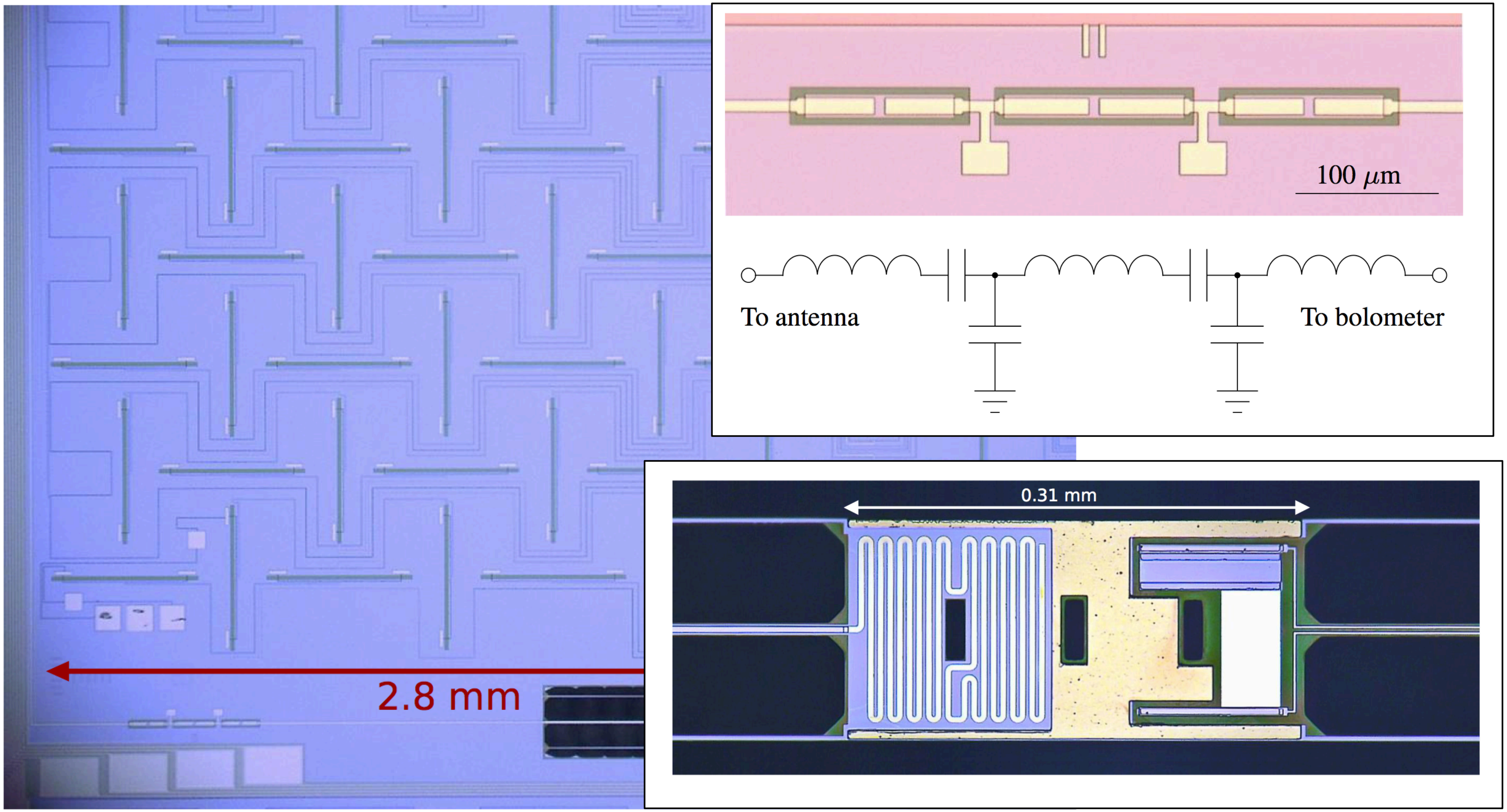


Superconducting microstrip line

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

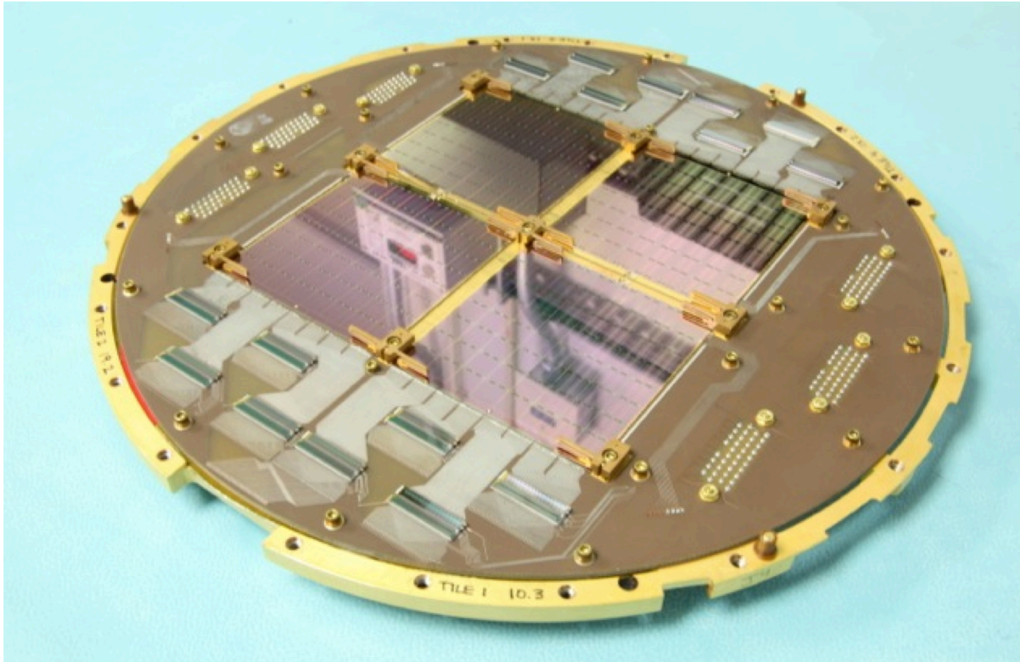


BICEP2 detectors



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

Bolometers: conclusions

- TESs: Strong Electro-Thermal Feedback
  - ➢ Increase speed response
  - ➢ Response linearization
- Advantages:
  - ➢ Sensitivity
  - ➢ High Technology Readiness Level (mainly in USA)
- Difficulties:
  - ➢ Fabrication complexity
  - ➢ Multiplexed readout