The CMB from A to Z: Promises and challenges of the CMB as cosmological probe
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# CMB instruments 3/3

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# Designing a CMB experiment

1. CMB photons

2. CMB detectors

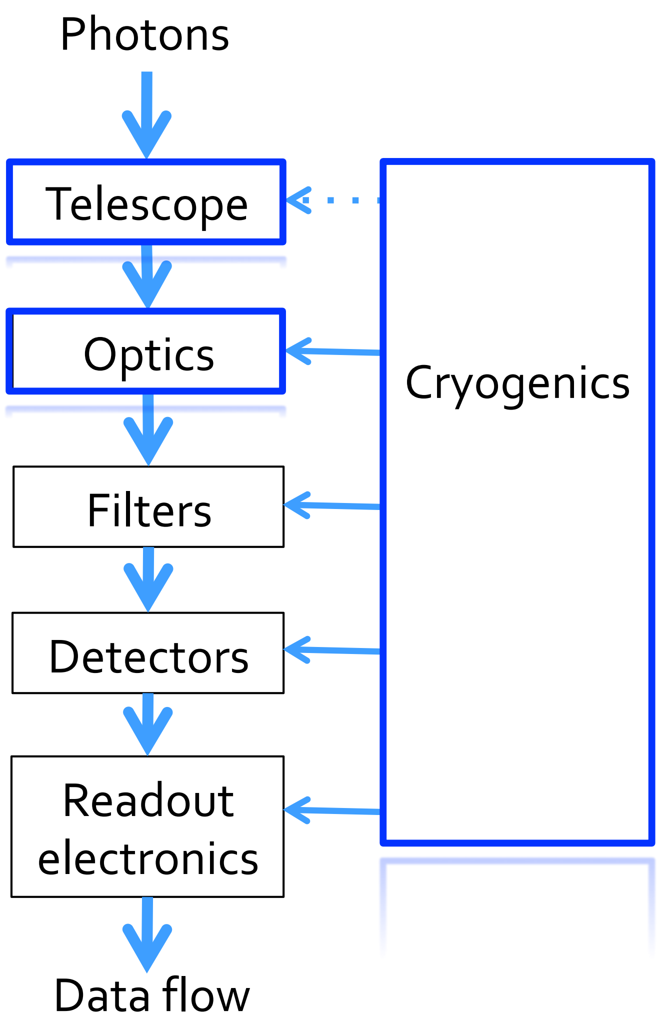
   2.1 Coherent detection techniques

   2.2 Incoherent detectors: TESs, KIDs

3. **CMB instruments design**

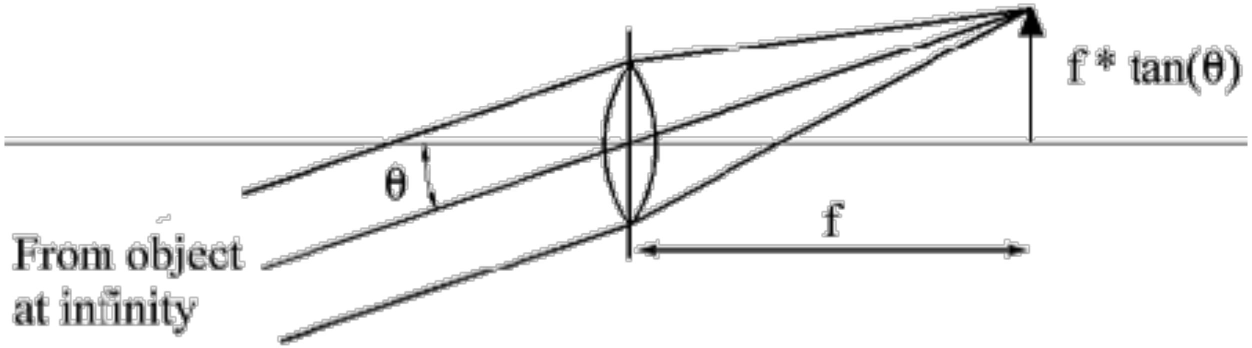
# A CMB instrument

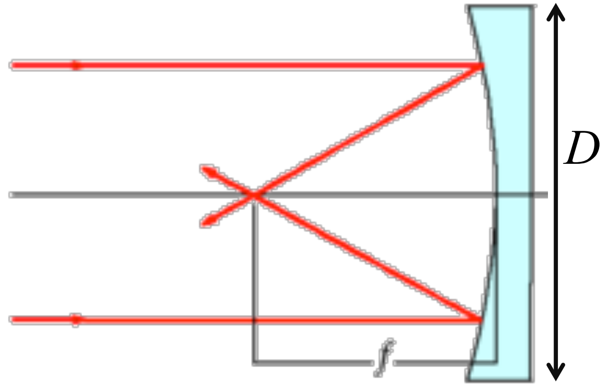
- Detectors:
  - Incoherent detectors: TESs or KIDs
  - 1000's detectors needed to increase sensitivity
  - T<300mK: cryogenics needed!



# Telescope

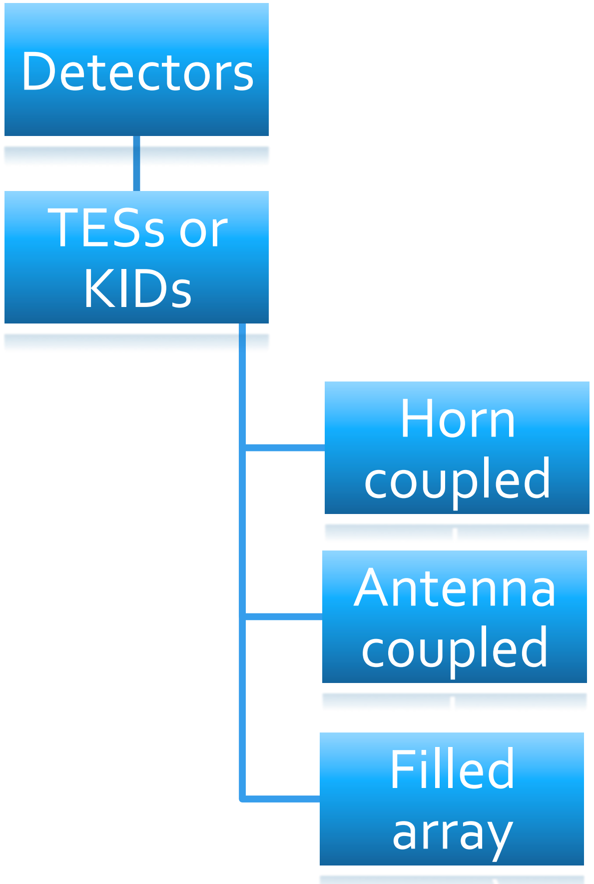
- Goal: to produce an image of the sky on the detectors
  - Refractive or reflective (or combinaison):



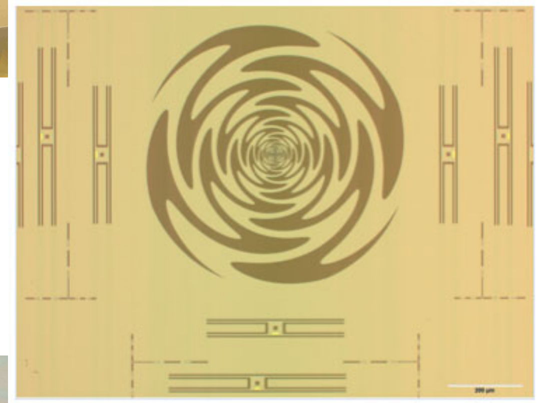




  - f: equivalent focal length
- f number: $f_{\#} = \frac{f}{D}$

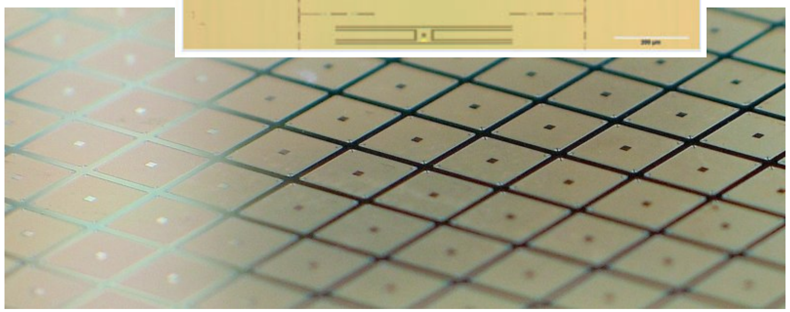
# Detectors coupling with the telescope




Planck-HFI horns



PolarBear 2 antenna coupled TESs



QUBIC TESs filled array

# Beam on the sky?

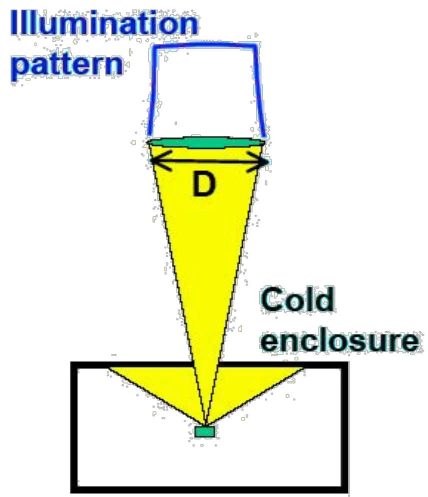
- Fraunhoffer diffraction:
  - Point Spread Function: $PSF \propto \left| TF\left[ E_a(x,y) \right] \right|^2$
    - ✓ Response of the optics to a point source
    - ✓ $E_a(x,y)$: scalar E field in the aperture (the primary optical element)

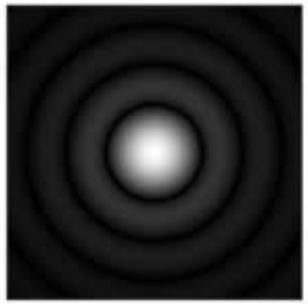
- Analysis method: use of time reversal
  - Photon source in place of the detector
  - Illumination of the telescope: $E_a(x,y)$
    - ✓ Depends on the detector radiation coupling method
  - PSF estimation

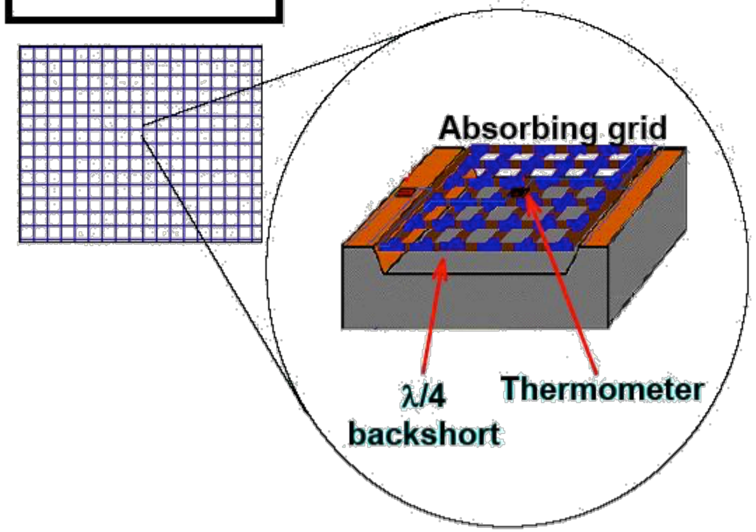
# Detector optical coupling: filled array

- ~Uniform illumination:
  - PSF=Airy disc
  - $\theta = \lambda/D$ or $f_{\#}\lambda$ on focal plane
- CCD-like: pixel size ≤ $0.5 \times f_{\#}\lambda$
  - Correct sampling of the sky
    - ✓ Imply $f_{\#} \approx 2$ since pixel size ~λ
  - Fast mapping speed
  - Large number of detectors
  - High sensitivity needed
    - ✓ **Diffraction limited: sum of all pixels covering the Airy disc**
- The detector sees about π sr!
  - Requires a cold enclosure (less than 1K)
  - Background power to be controlled in order to reduce photon noise

[Griffin et al., *Applied Optics*,41, 6543, 2002]

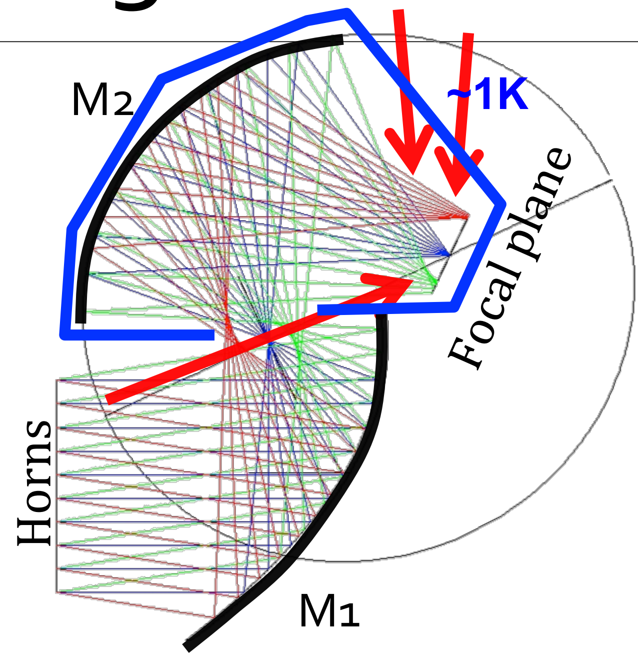




Airy disc



# The need to control the total detector solid angle

- Example of QUBIC
  - Focal plane detectors: filled array
    - ✓ Bolometric « CCD »
    - ✓ Detectors are sensitive to π sr

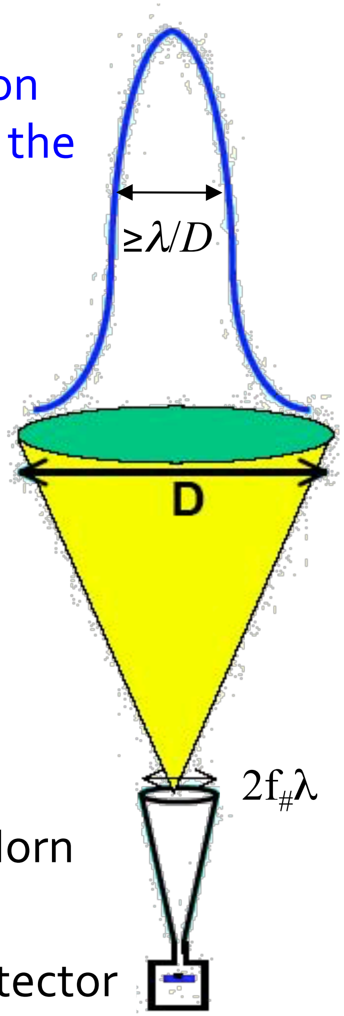



- Estimated power background:

| Environment T | Power from the sky | Power increase without cold stop | Power increase with cold stop |
|---|---|---|---|
| 4K | 6.5pW | 2pW | 0.2pW |
| 6K | 6.6pW | 4.5pW | 0.5pW |
| 10K | 6.7pW | 10pW | 1pW |

# Detector optical coupling: horns

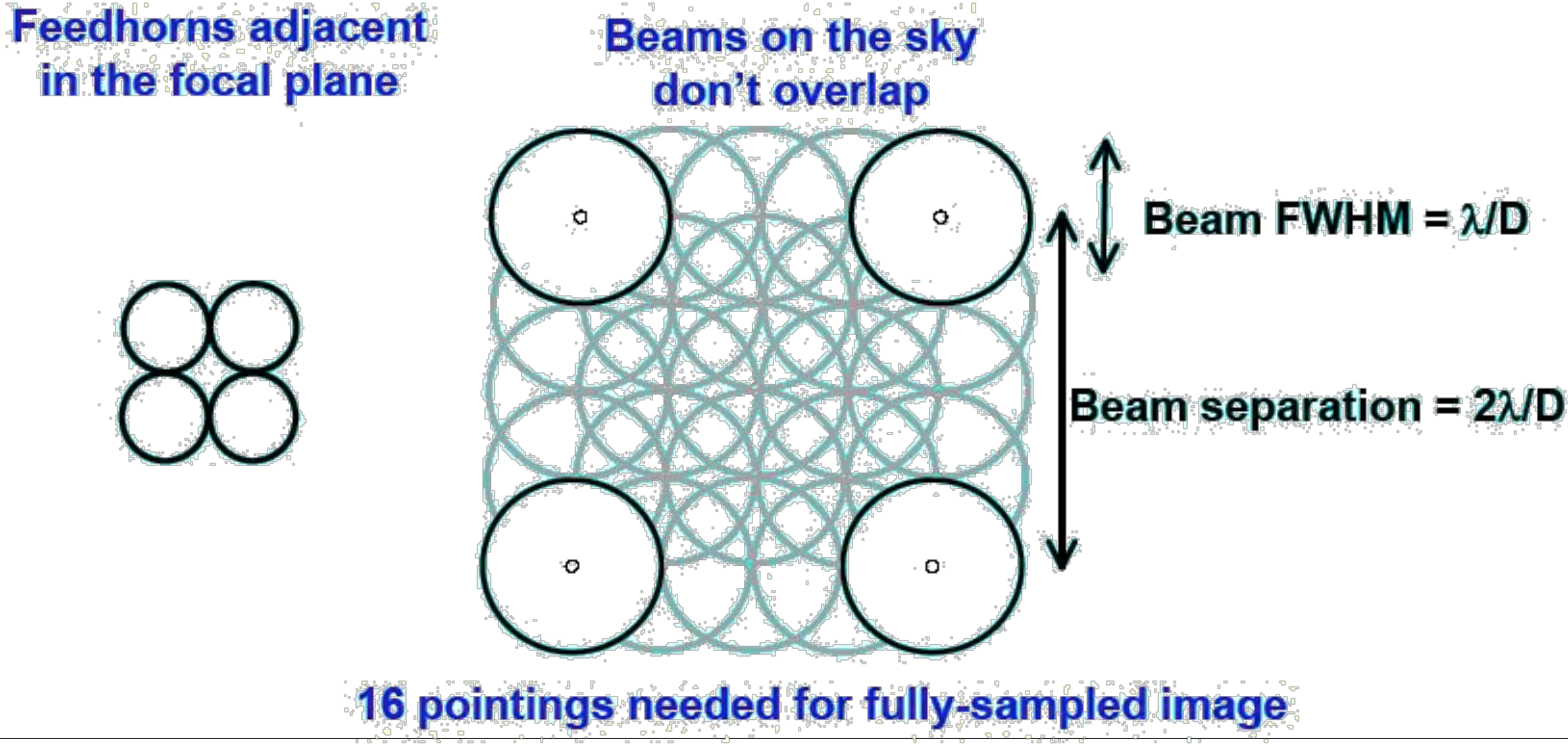
- Horn+telescope define the beam pattern on the sky
- Singlemoded horn: $A\Omega=\lambda^2$
  - Quasi-gaussian beam pattern
  - Optimal horn diameter of about $2f_{\#}\lambda$
  - Beam pattern given by diffraction limit: $\geq\lambda/D$
    - ✓ Depends on edge taper
  - **Controlled detector solid angle**
    - ✓ Horn cooled to <4K



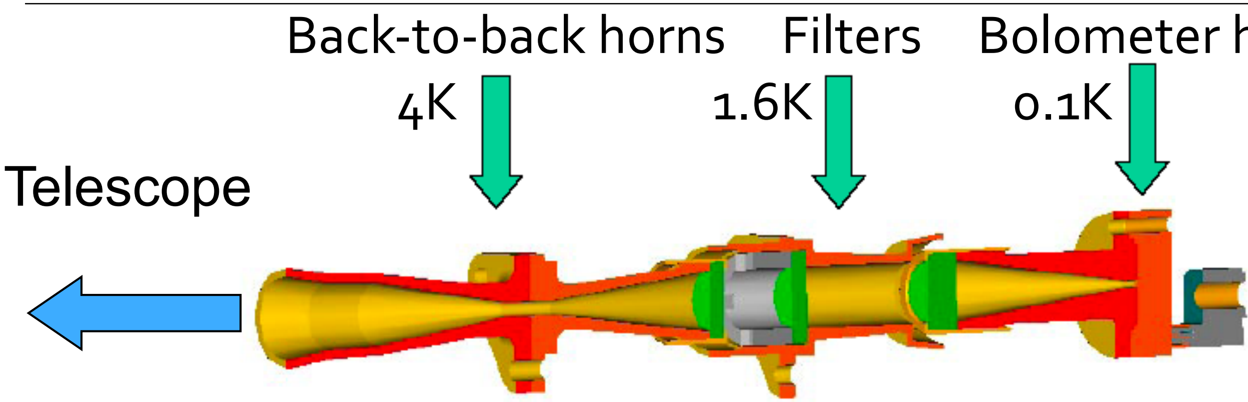

[Griffin et al., *Applied Optics*,41, 6543, 2002]

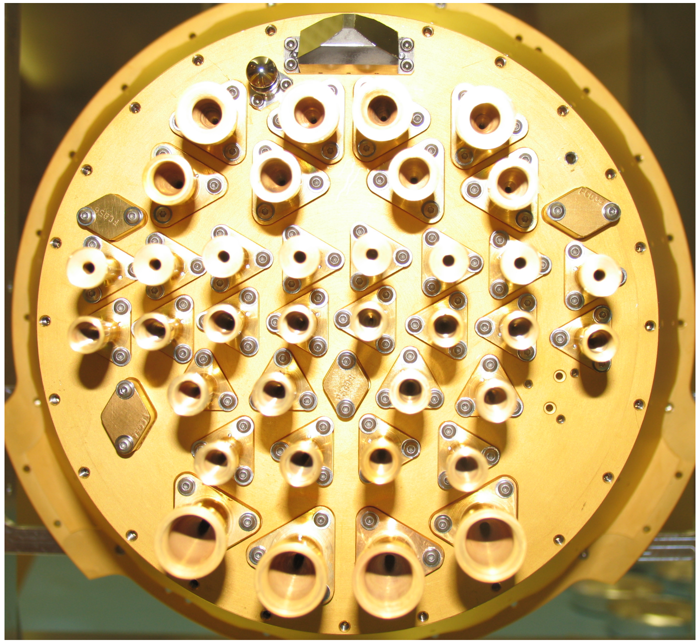
# Mapping with horns

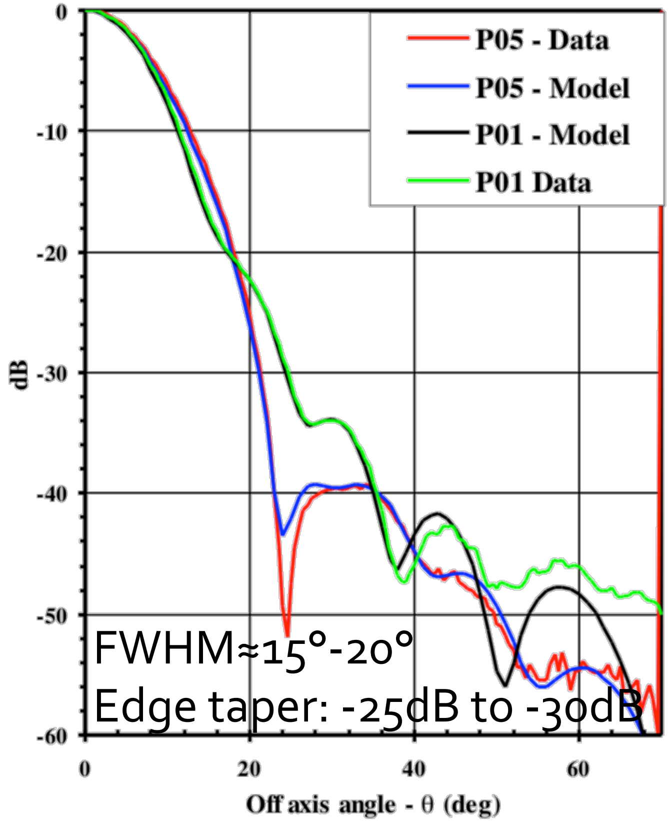
- Beam patterns do not overlap in the sky
  - Requires pointing change to sample the sky (Nyquist criteria)
  - **Reduced mapping speed**



# Example: Planck-HFI

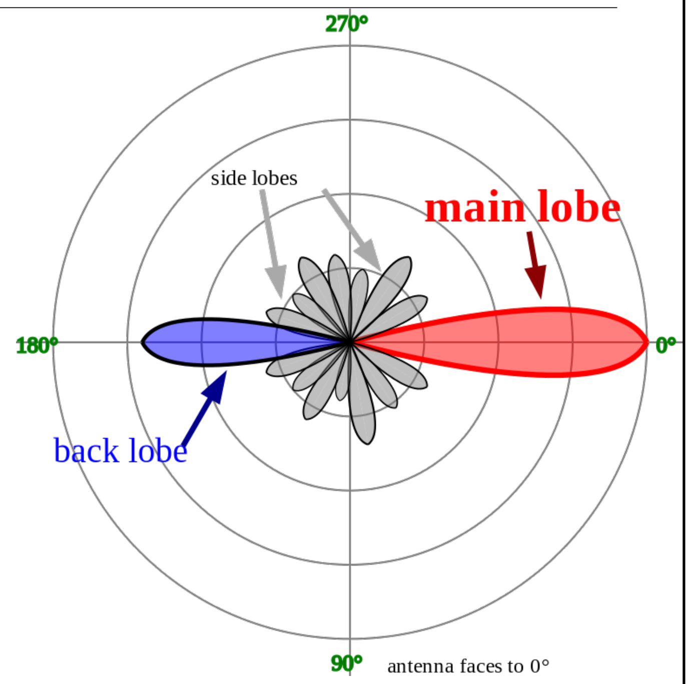




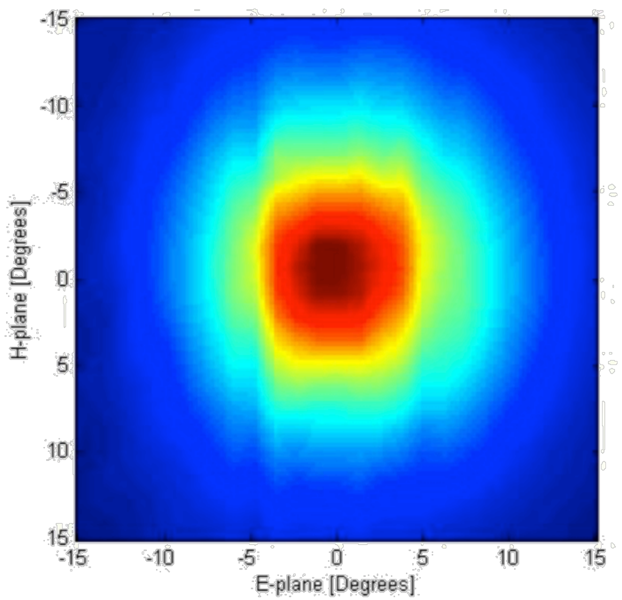
# Antenna coupled detectors

- Antenna directivity = degree to which the radiation received (or emitted) is concentrated in a single direction
  - ➢ Importance of controlling the total antenna solid angle
- Use of lenslet or phased-array to increase directivity
  - ➢ Situation similar to horns
  - ➢ Sidelobes less well controlled
  - ➢ Need of a cold enclosure or a stop

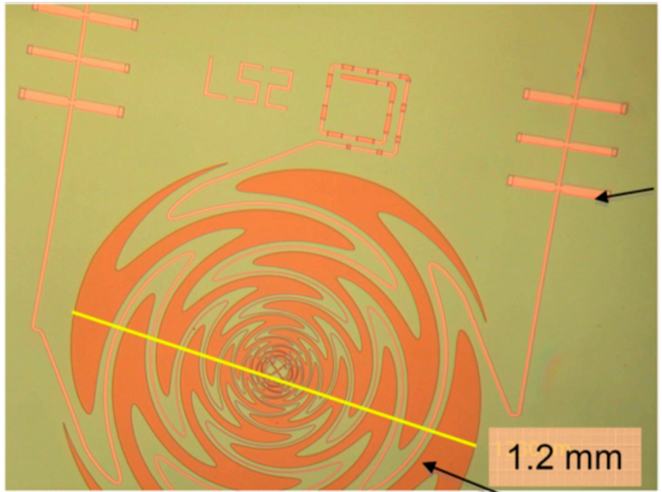


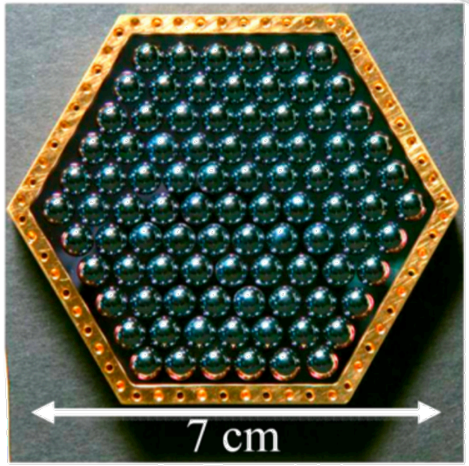
# Telescope coupling with lenslet

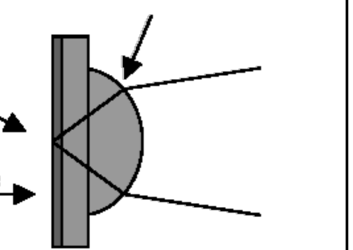
- Use of a lenslet to increase the antenna directivity
  - ➢ PolarBear design (Berkeley)




110 GHz



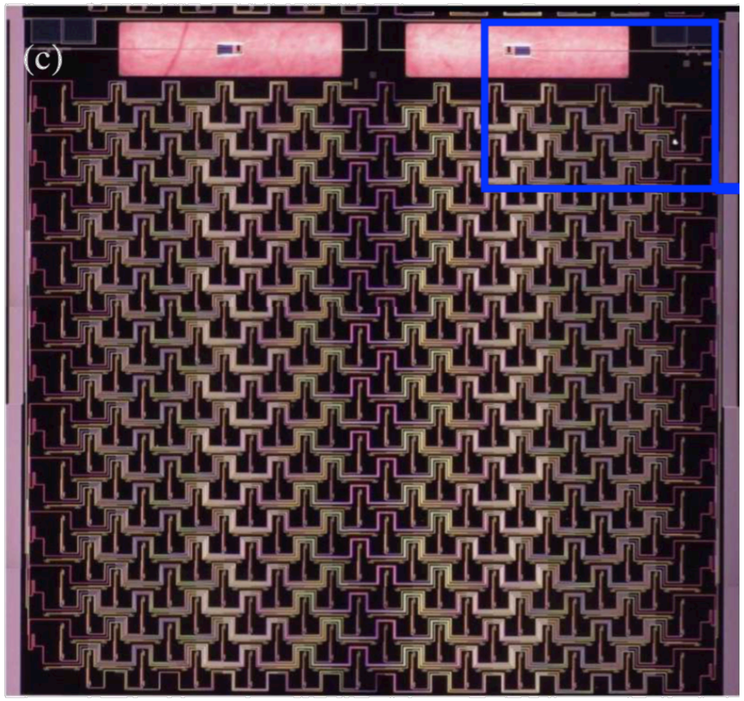



# Telescope coupling with a phased array

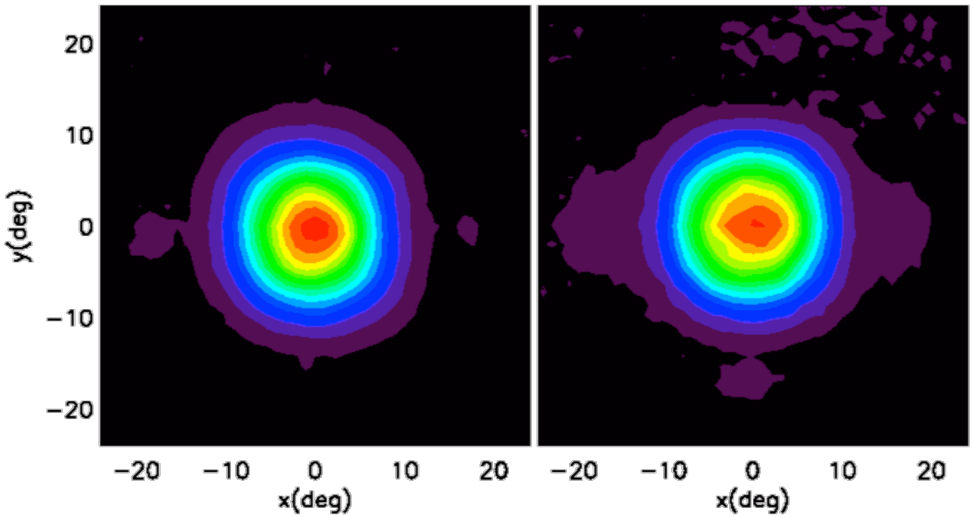
- In phase combination of all parallel antennnas
  - ➢ Increase of overall directivity

8 mm



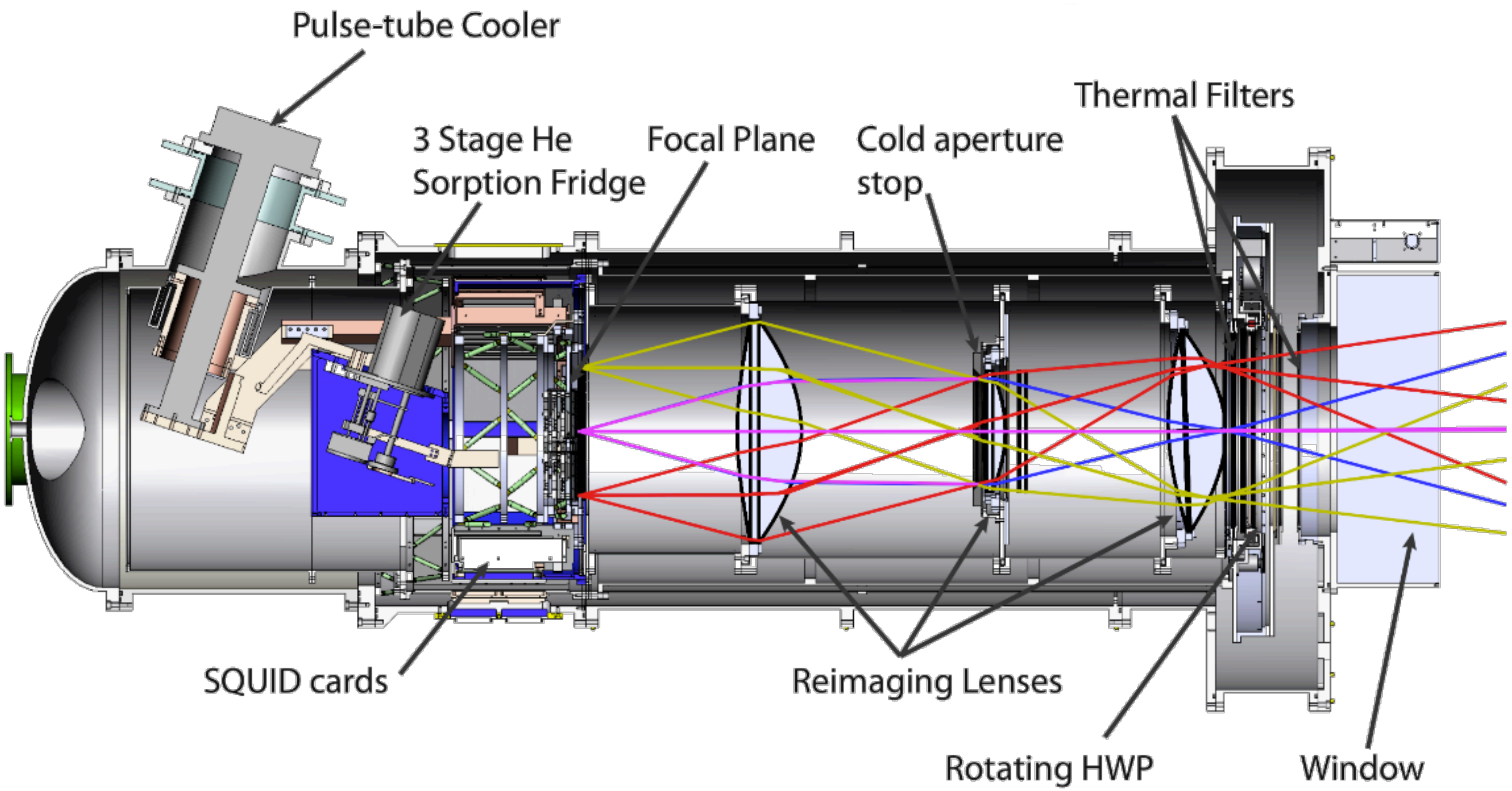

Single Pixel – Dual Pol at 145 GHz (JPL/CIT)

**Measured Beam Patterns**



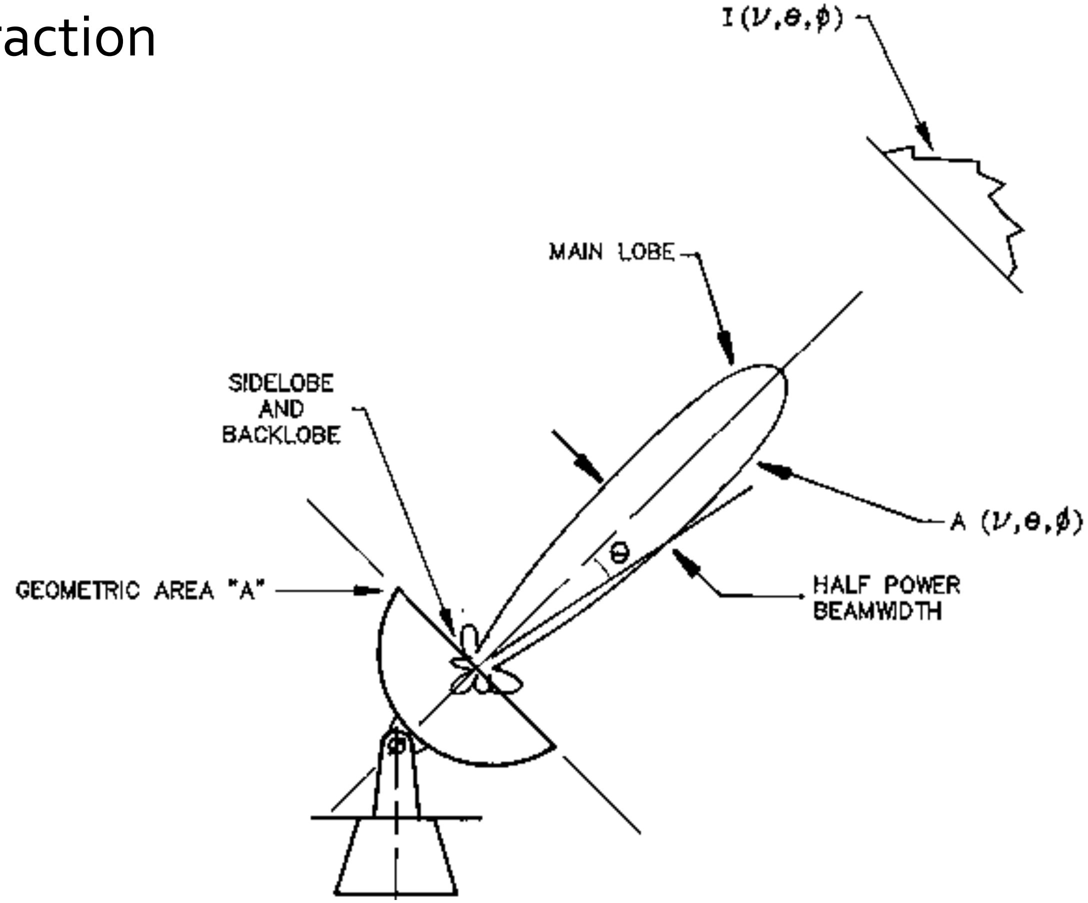
# Use of a cold aperture stop with antenna coupled detectors

- Example of PolarBear instrument:



# Far sidelobes

- Sensitivity of your instrument to unwanted directions
  - Diffraction



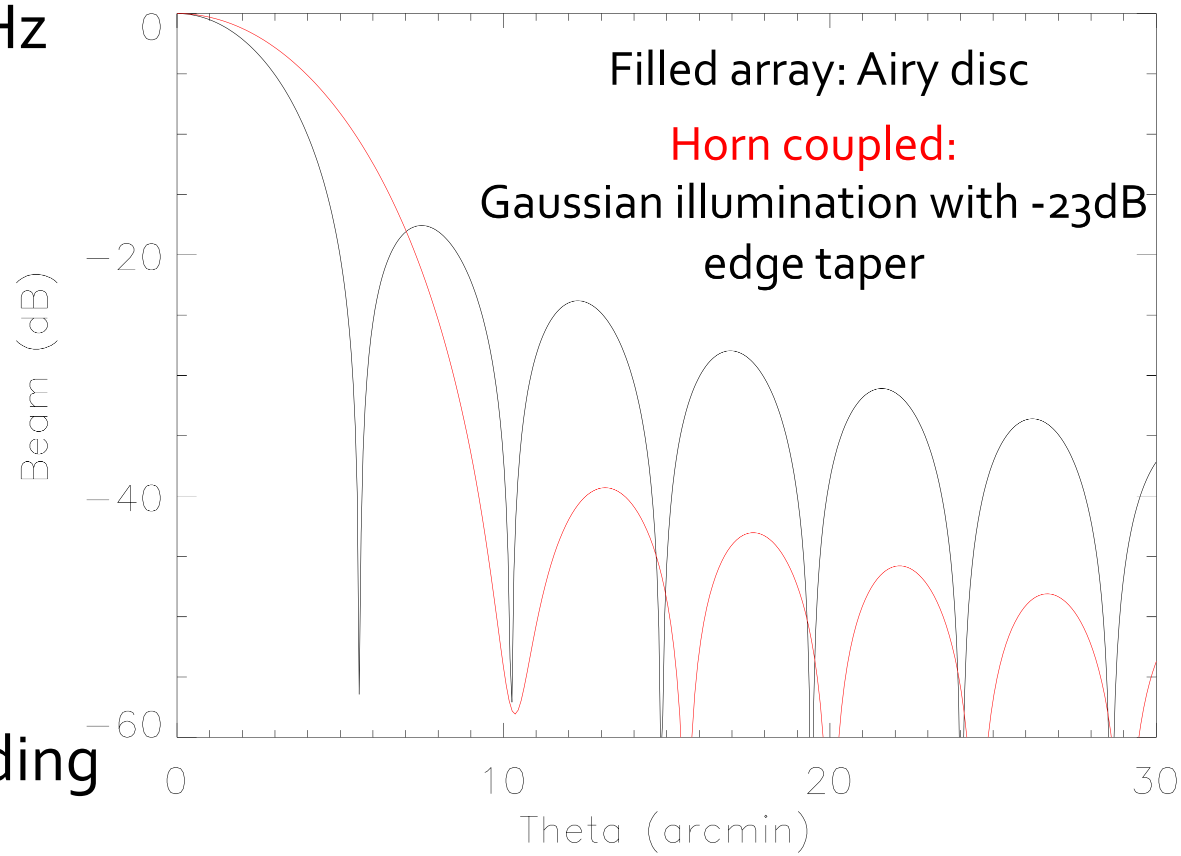
# Far sidelobes requirements

- Sidelobe rejection needed to induce a parasitic signal lower than 60nK$_{CMB}$ (assuming 30 arcmin resolution):
  - Ground-based experiment at 150GHz: ground rejection $\sim 10^{-15}$
  - Space instrument at 150GHz:

| Orbit | Source | Max normalised side lobe level |
|---|---|---|
| **L2** | Earth | -99dB |
| | Moon | -89dB |
| | Sun | -113dB |
| **LEO** | Earth | -150dB |
| | Moon | -98dB |
| | Sun | -113dB |

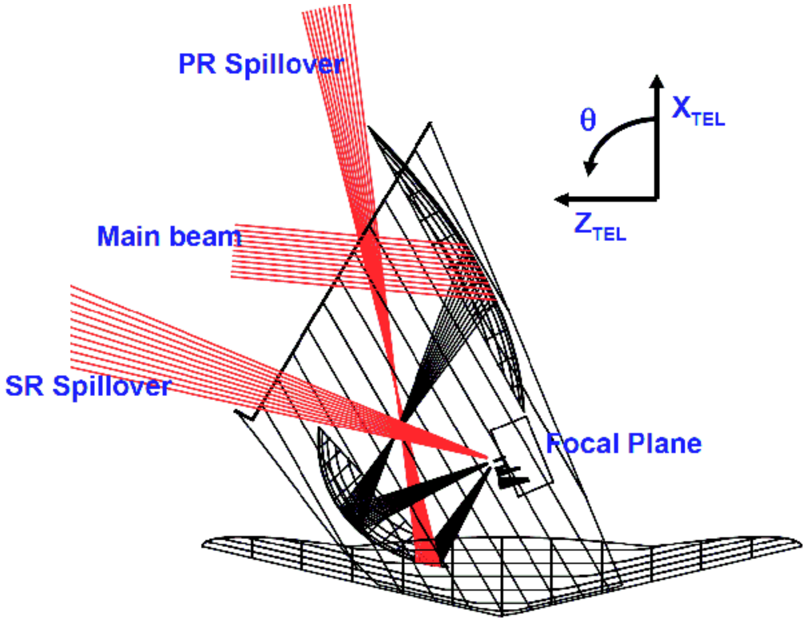
# Far sidelobes

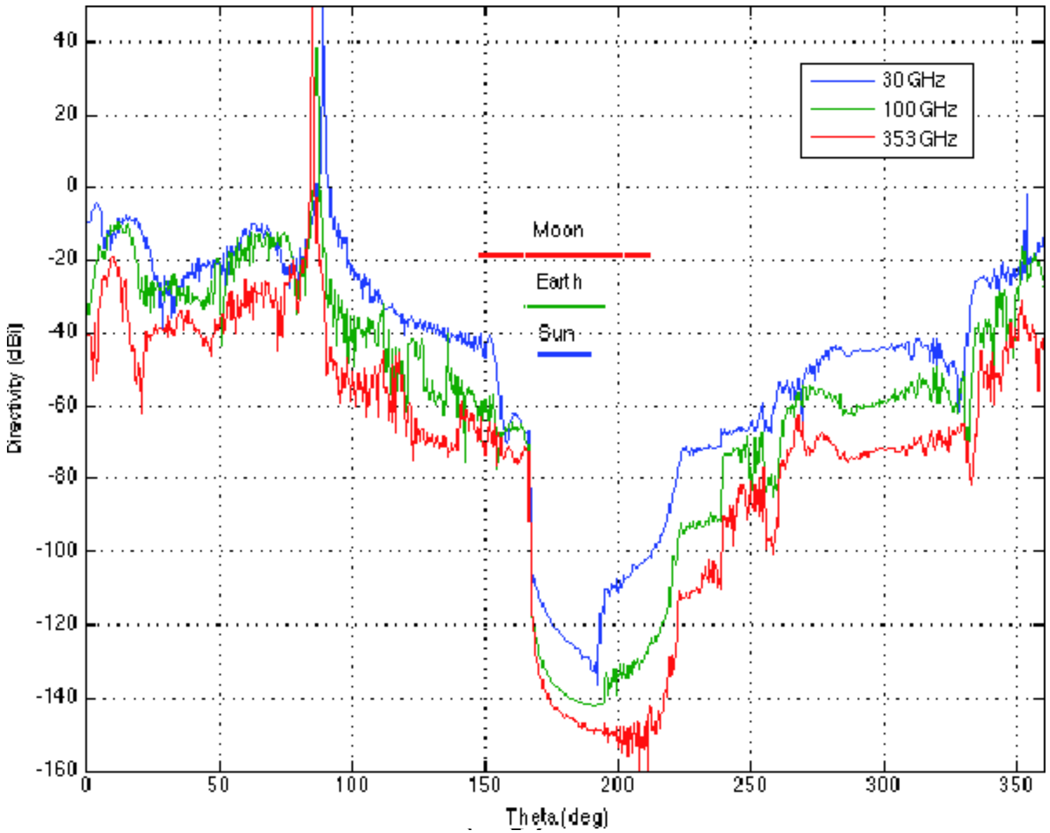
- Calculation at 150GHz
  - 1.5m telescope
- Better angular resolution: Filled array
- Lower sidelobes: Horn coupled
- Need for extra shielding



# Shielding sidelobes

- Planck simulation at 100GHz:



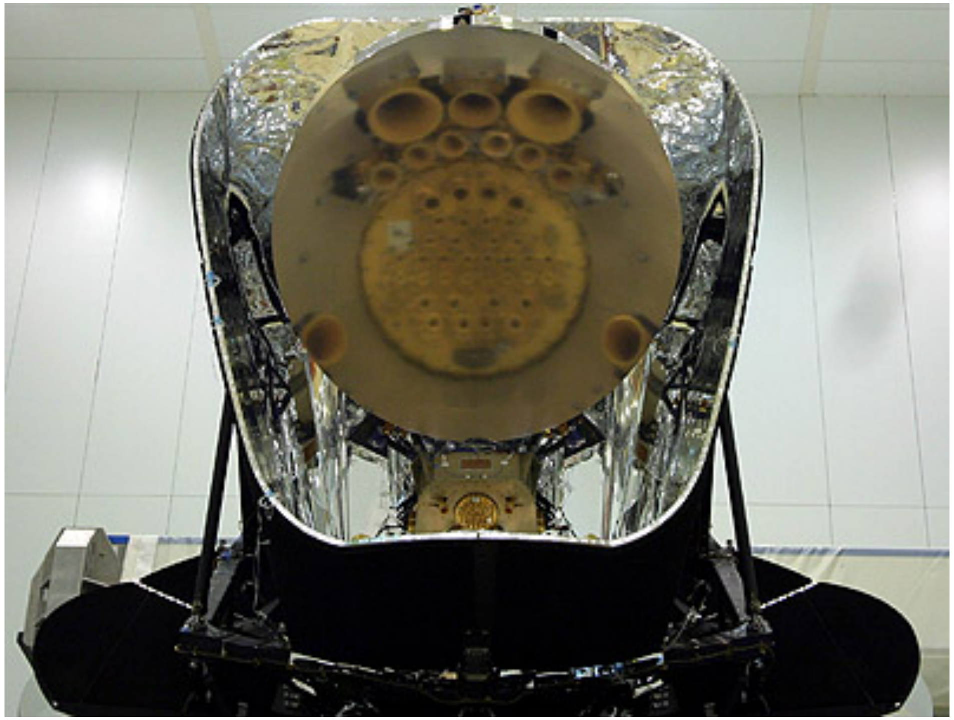
# Detector coupling trade-offs

Color code: Meet specs Limitation Critical

| | Horn coupled | Antenna coupled | Filled array |
|---|---|---|---|
| Angular resolution | Need a larger telescope (edge taper) | | |
| Bandwidth | | Di or tri-chroic | |
| Mapping speed | | | |
| Detector number | | | |
| $\Omega_{det}$ control | | Need of a cold aperture stop | |
| Far sidelobes control | Gain from edge taper | | |
| Weight | | | |
| TRL | 9 (Planck) | 5 | 9 (Herschel-PACS) |

# Reflecting optics

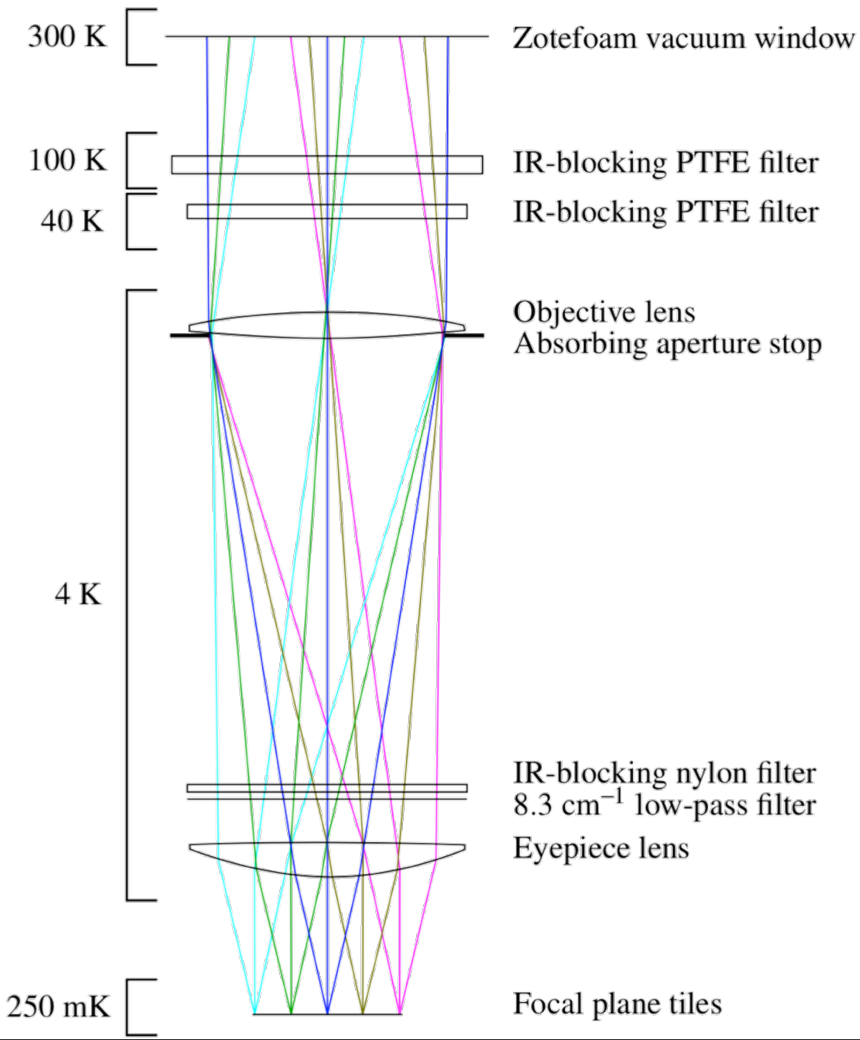
- Example of Planck
- **Pro:**
  - Light
  - Compactness
  - No chromatic aberrations
  - High TRL (Planck, WMAP)



- **Cons:**
  - Difficult to get low f-number
  - Difficult to design a proper re-imaging optics
  - High beam ellipticity due to off-axis and large FOV

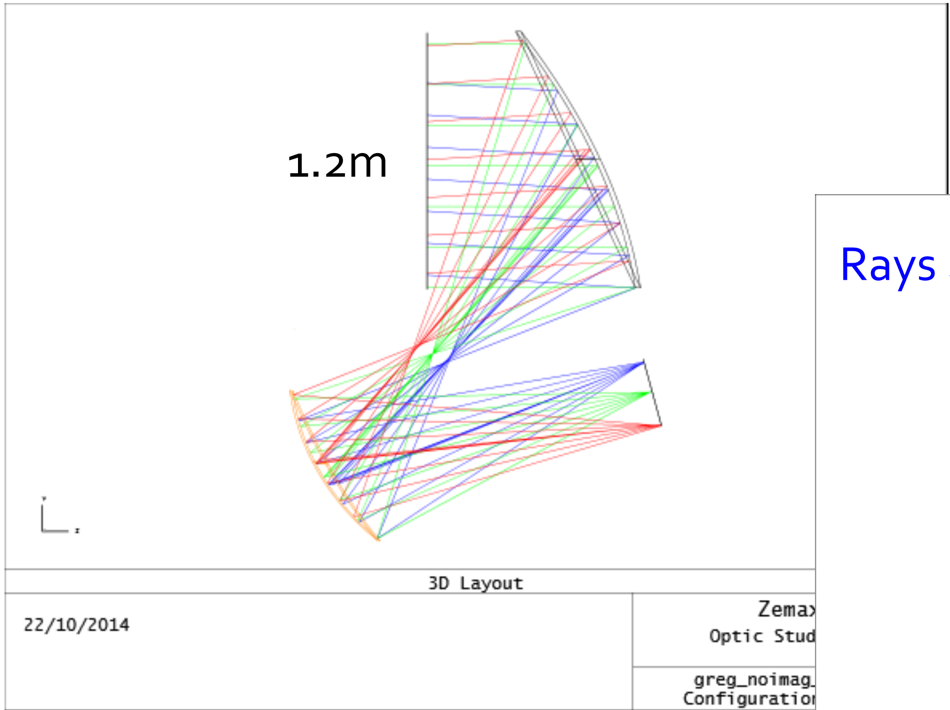
# Refractive telescope

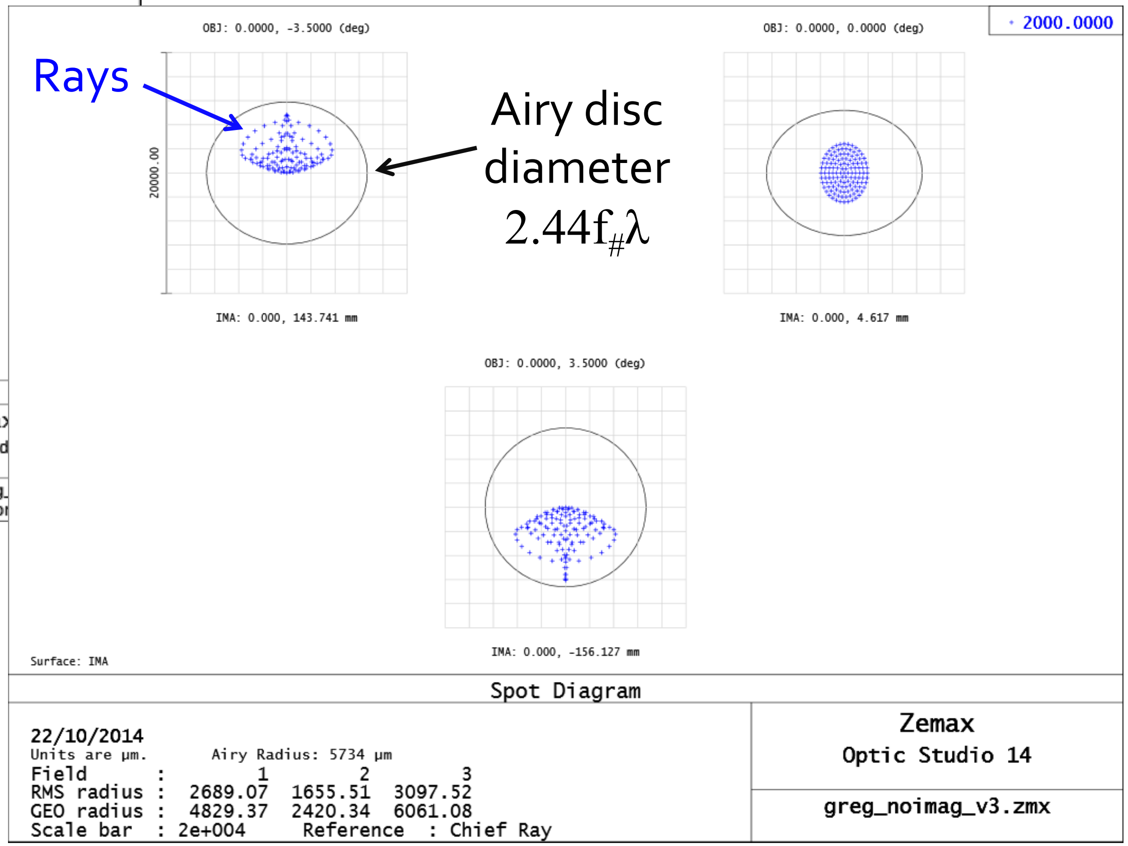
- Example of BICEP2:
  - ➢ High Density Polyethylene (HDPE) lenses
- **Pro:**
  - ➢ On axis system
    - ✓ Lower beam ellipticity
    - ✓ Lower aberrations
  - ➢ Low f-number feasible
- **Cons:**
  - ➢ AR coating needed
  - ➢ Chromatic aberrations
  - ➢ Difficult to produce large lenses
  - ➢ Weight (thick lens needed)



# Example of aberrations simulation: Gregorian F/2

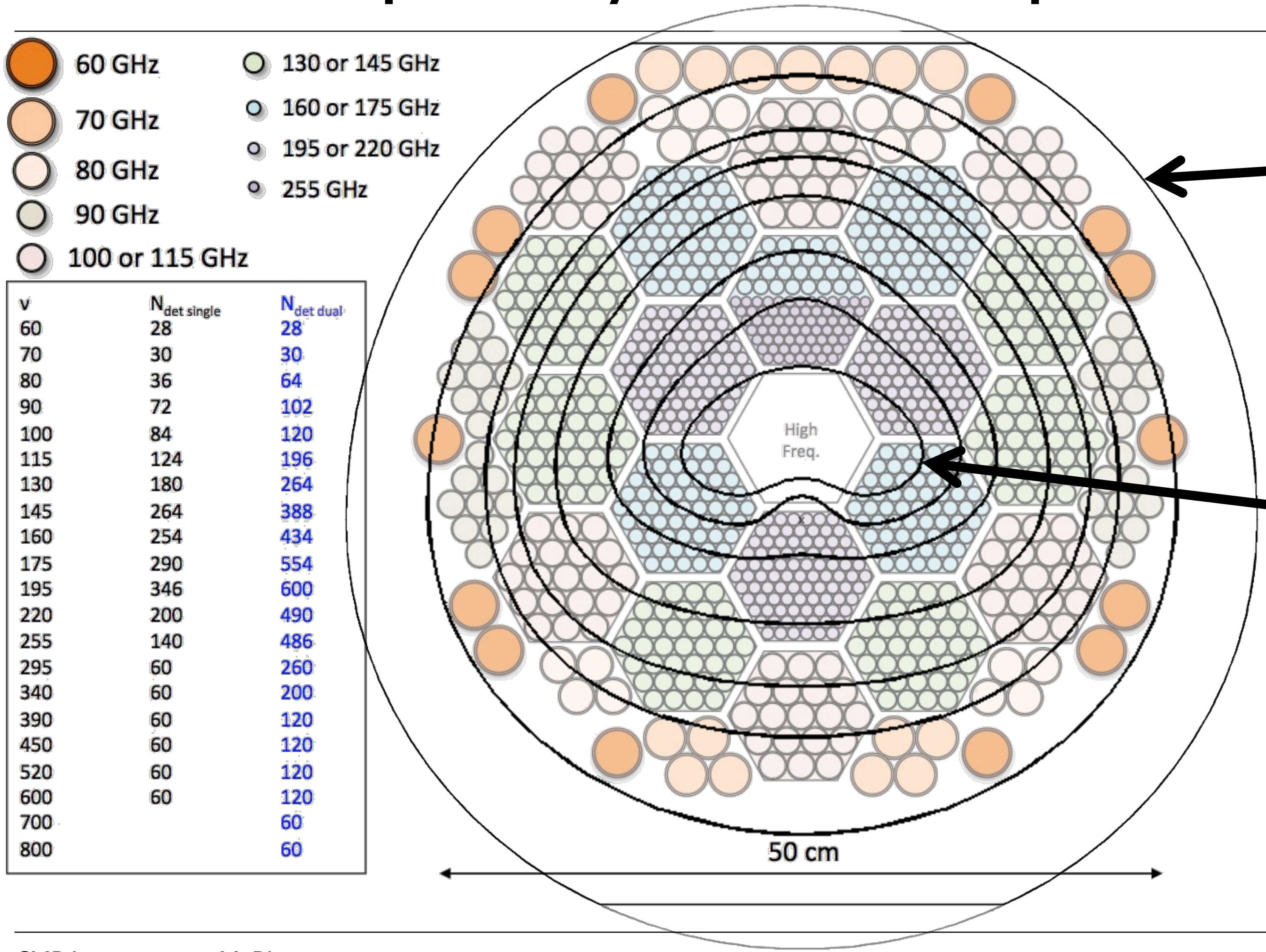
(From N. Trappe, NUIM)




**Less aberrations at the center of the focal plane**

# Consequences of aberrations: frequency bands repartition




| 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 |

Contours Strehl ratio >0.8:
60GHz
90GHz
130GHz
160GHz
220GHz
340GHz
450GHz
600GHz

Example of CORE+

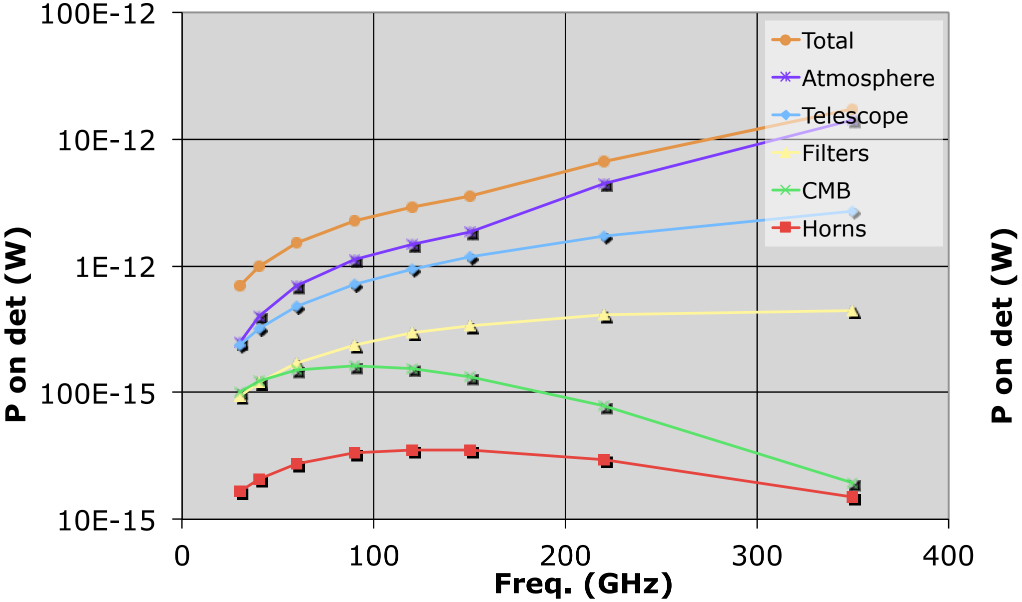
# Telescope temperature?

- Assumptions:

| Characteristics | Ground-based | Space |
|---|---|---|
| Atmosphere | 250K, ε=2%-10% | NA |
| Telescope | 240K, ε=2% | 50K, ε=1% |
| Filters | 10K, ε=10% | 4K, ε=10% |
| Horns | 4K, ε=10% | |
| Detector NEP | $10^{-17}$W.Hz$^{-0.5}$ | 3.$10^{-18}$W.Hz$^{-0.5}$ |
| Global efficiency | 40% | |
| Bandwidth Δν/ν | 30% | |

# Telescope temperature? power background

**Ground-based:** $T_{Tel=}$=240K, ε=2%

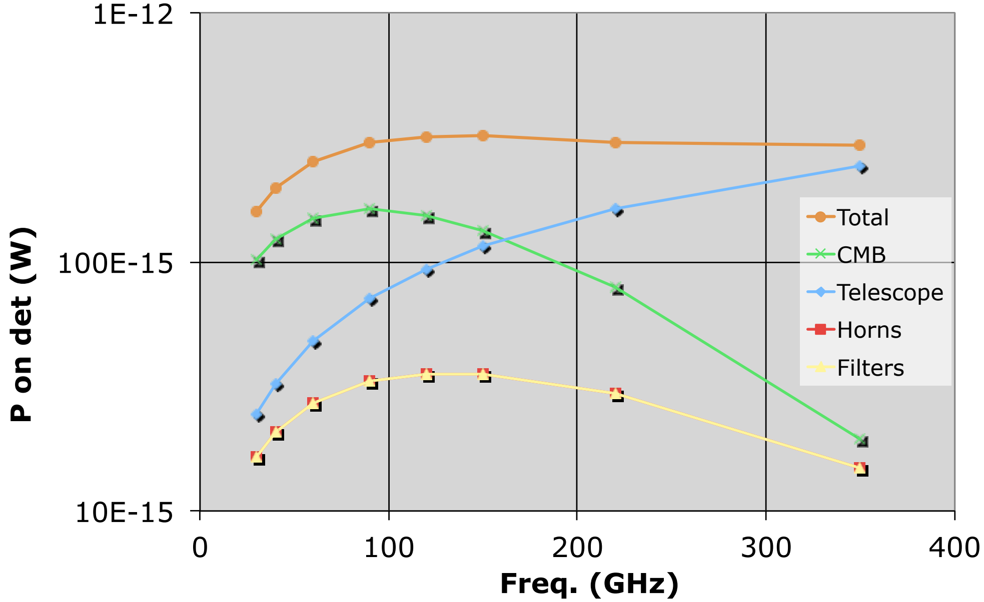



$NEP_{h\nu}=10^{-16}-10^{-17}\ W.Hz^{-0.5}$

$NEP_{det}=10^{-17}\ W.Hz^{-0.5}$

Background limited performances

**Space:** $T_{Tel=}$=50K, ε=1%




$NEP_{h\nu}=4.10^{-18}-2.10^{-17}\ W.Hz^{-0.5}$

$NEP_{det}=3.10^{-18}\ W.Hz^{-0.5}$

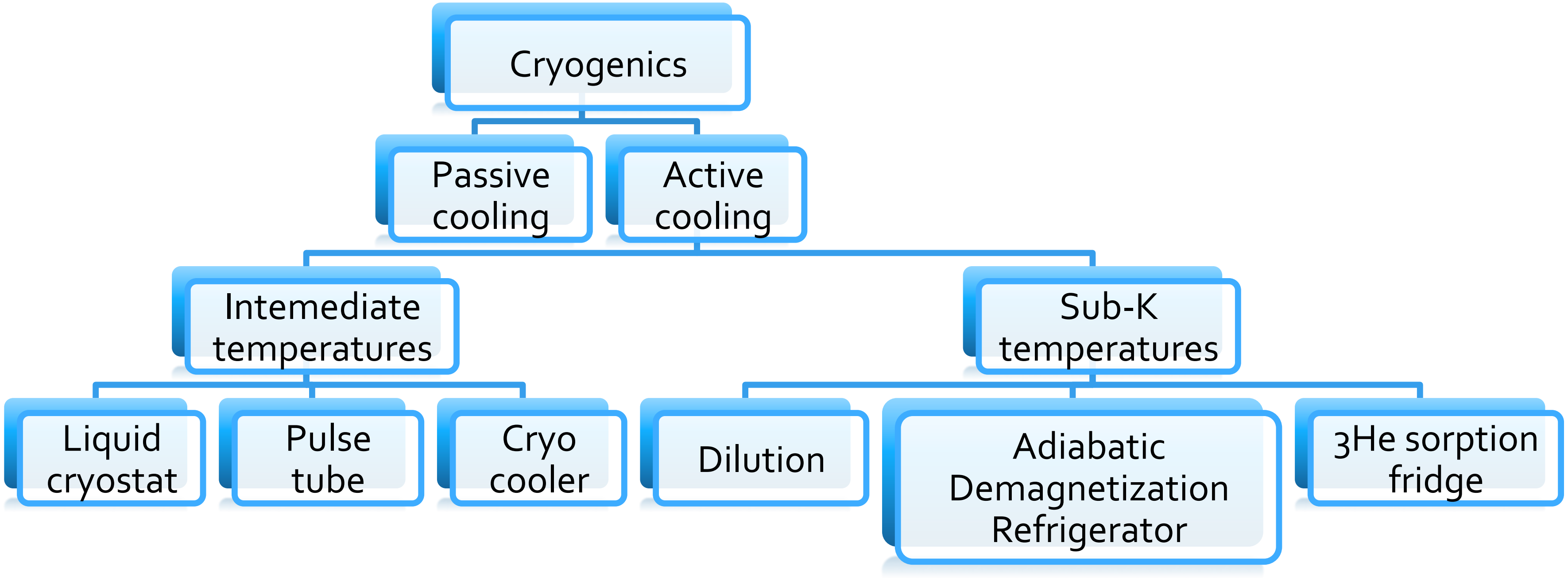
**CMB** Background limited performances

# Telescope trade-offs

Color code: Meet specs Limitation Critical

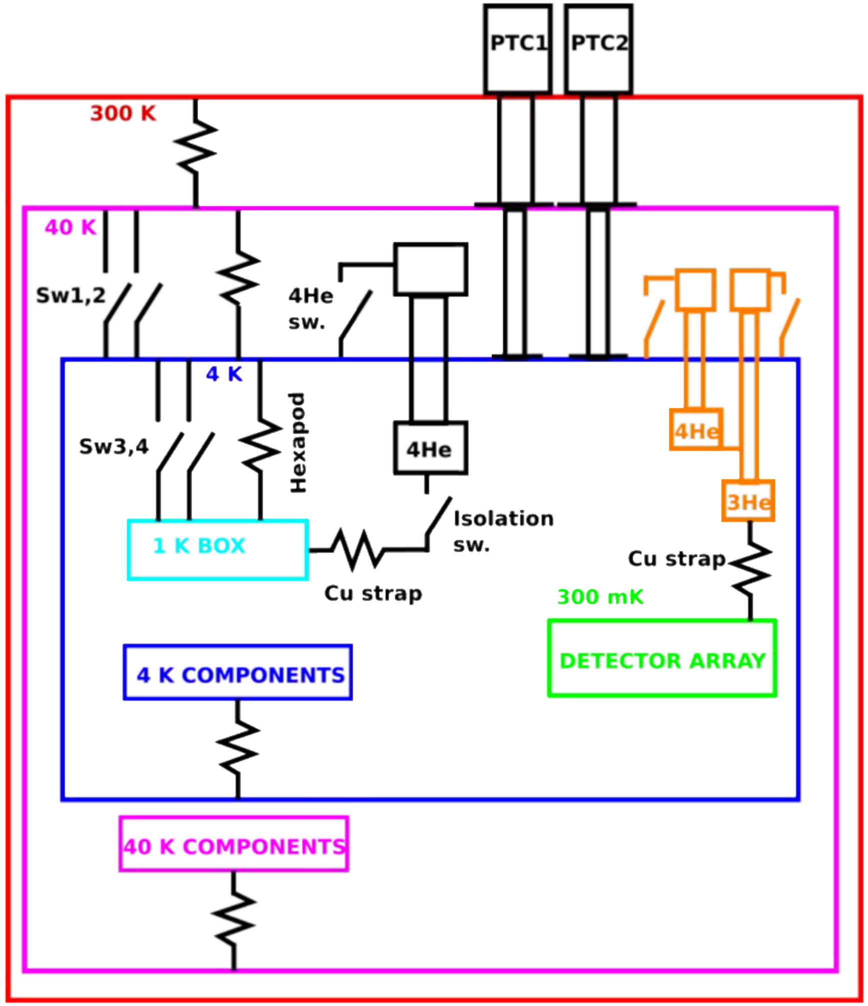
| | Reflective | Refractive |
|---|---|---|
| Aberrations | Off-axis, beam ellipticity, could be corrected with extra optics if volume | On-axis |
| Bandwidth | | AR coating needed |
| Low f-number | | |
| Re-imaging optics | Depends on available volume | |
| Size | | Limited to ~ 30cm |
| Weight | | For cryogenics T |
| Losses | | Depends on material |
| Modelling | GRASP | |
| TRL | 9 (Planck, Herschel) | 5 |

# Thermal architecture and cryogenics



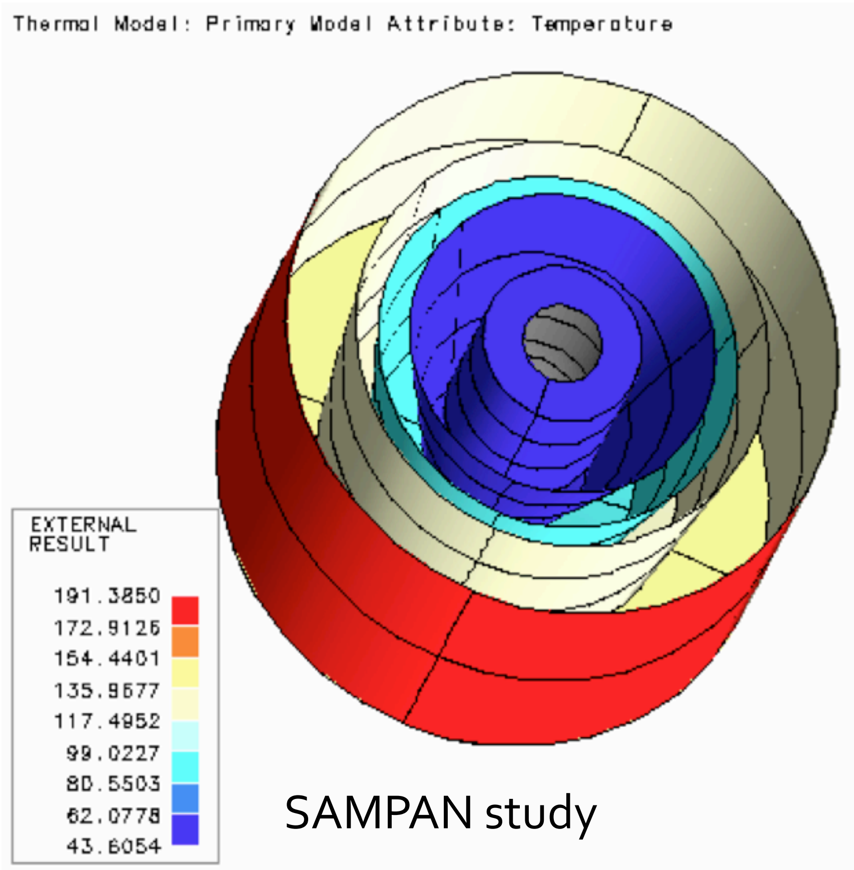
# Thermal architecture and cryogenics: ground-based version

- QUBIC example
  - 300mK sufficient for TES ground based experiment
    - ✓ Atmosphere dominate power background
  - Fully electrical control of cryogenics
  - Hold time: 24h



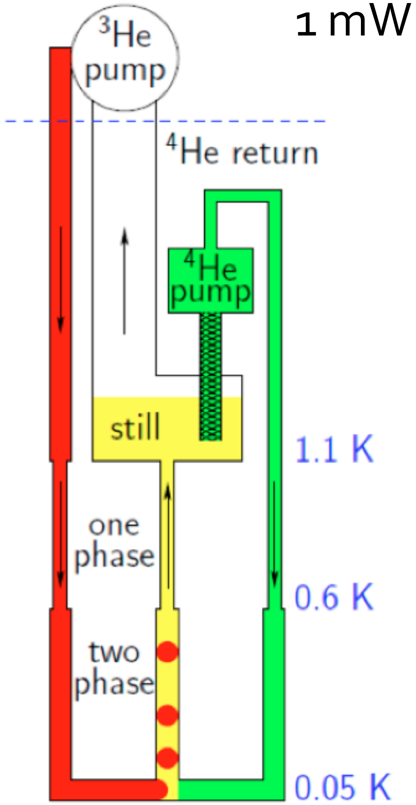
# Thermal architecture and cryogenics: space version

- Passive + active cooling




SAMPAN study

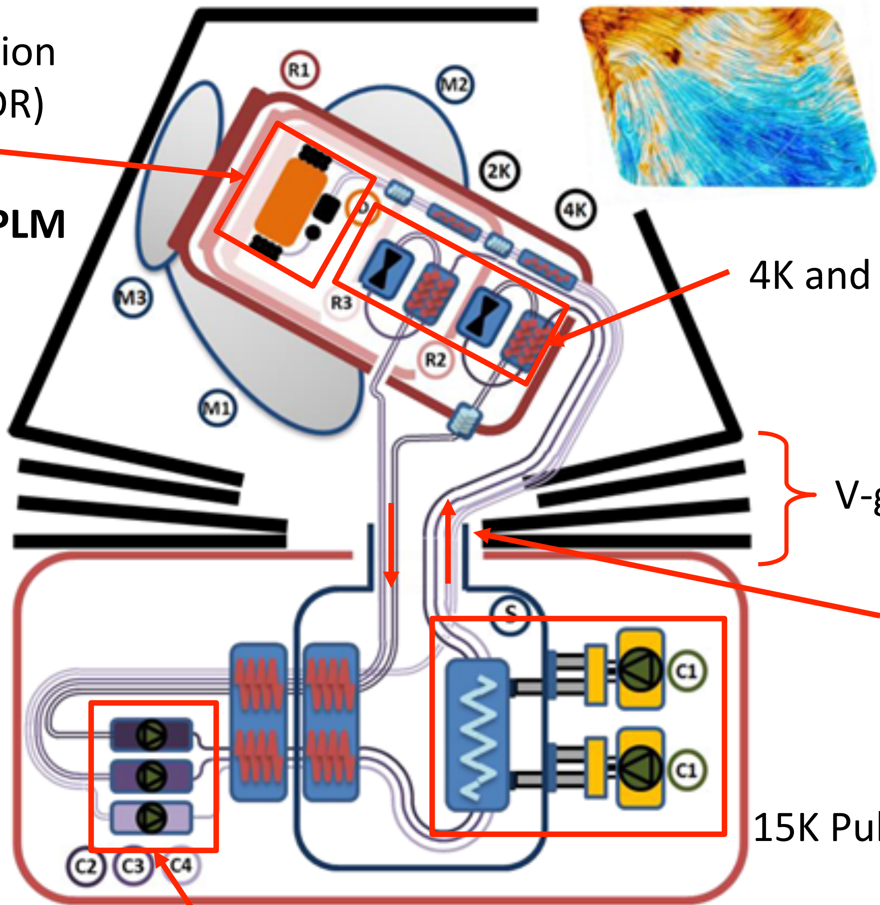
Closed Cycle Dilution Refrigerator
(R&T CNES + ITI ESA)
1 mW@50mK



# Thermal architecture and cryogenics: example of CORE

Closed Cycle Dilution Refrigerator (CCDR)

PLM




4K and 1.7K Joule Thomson cold end

V-grooves <40 K

Cold loop

SVM

15K Pulse Tube

CCDR and Joule Thomson compressors

Study made by: INAC/SBT, I. Néel, Air Liquide, Thalès, RAL, CNES, APC

# Sub-K cryogenic trade-offs

Color code: Meet specs Limitation Critical

| | Sorption fridge | CCDR | ADR |
|---|---|---|---|
| Operating T | 300mK | 100mK | 100mK |
| Continuous op | Not available | | R&D |
| Heat sink | 1.5K ($^3He$)<br>4K ($^4He/^3He$) | 1.7K | 1.8K |
| Power consumption | | | |
| Size | | | |
| Weight | | | |
| Complexity | | | |
| TRL | 9 ($^3He$ Herschel)<br>6 ($^4He/^3He$) | 3-4 (R&D) | 9 (Astro-H)<br>3-4 (continuous) |

# Conclusions

- Complexity of CMB instrument
  - ➢ Very sensitive detectors
  - ➢ Complexe optics
  - ➢ Heavy cryogenics
- Not discussed:
  - ➢ Filters
  - ➢ Polarisation modulator
  - ➢ Orbit
  - ➢ Scanning strategy
  - ➢ Calibration
  - ➢ Telemetry
  - ➢ Spectroscopy…

**Trade-offs are everywhere!**