The EPIC-IM Mission Concept

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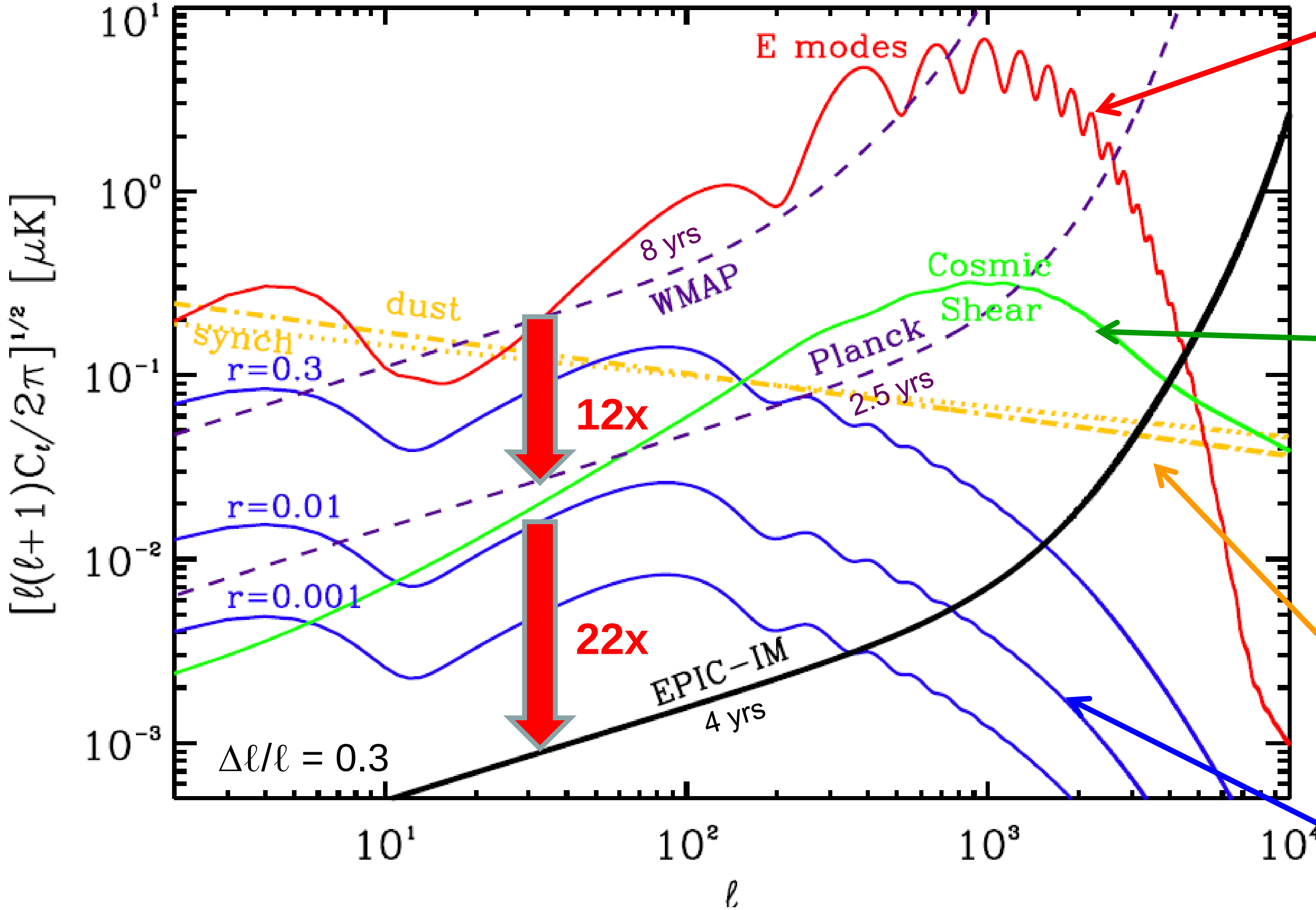
Science Objectives for a Space Mission



Measure E-mode spectrum to cosmic variance to damping tail

- Precision cosmology
- Departure from scale inv.
- Reionization history

Measure B-mode cosmic shear spectrum to cosmic limits

- Neutrino mass hierarchy
- Dark energy at z > 2

Map Galactic magnetic fields via dust polarization

- SF and large-scale B-field

Measure Inflationary B-mode spectrum at r = 0.01 to astrophysical limits

- GUT energy scale
- Large field inflation
- n_t / r consistency test

Design for Maximum Cosmology:

Get all the cosmology from CMB polarization

High sensitivity, ~5 arcminute resolution

We will be lucky to get one CMB mission after *Planck*

The EPIC-IM Concept: Main Features

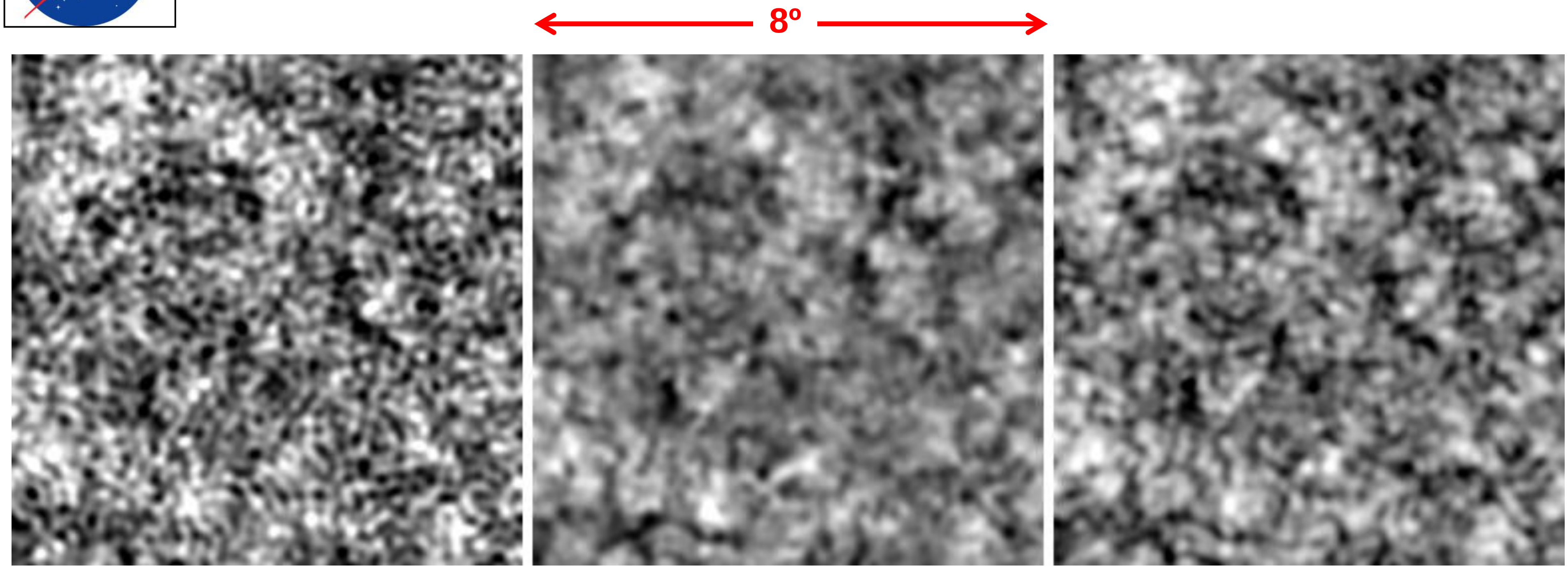
- **Maximum Cosmology**
  - high sensitivity to measure CMB polarization to cosmological (or astrophysical) limits
  - 5 arcminute resolution to map CMB lensing polarization
  - 1 arcminute resolution for Galactic science

- **Sensitive**
  - large background-limited focal plane arrays

- **Simple**
  - no cold moving parts
  - simplified Planck cooling chain to 100 mK
  - single technology covering all spectral bands

- **Systematic Error Control**
  - simple pair differencing like Planck
  - optics have excellent beam matching and good off-axis performance
  - scan strategy: perfectly isotropized scan angles, daily ½ sky maps

All Sky Maps of Projected Gravitational Potential



Theoretical projected potential

Optimal Quadratic *(Hu 2001)*

Likelihood *(Hirata & Seljak 2003)*

Gravitational potential determined from CMB polarization and temperature maps

Potential sensitive to

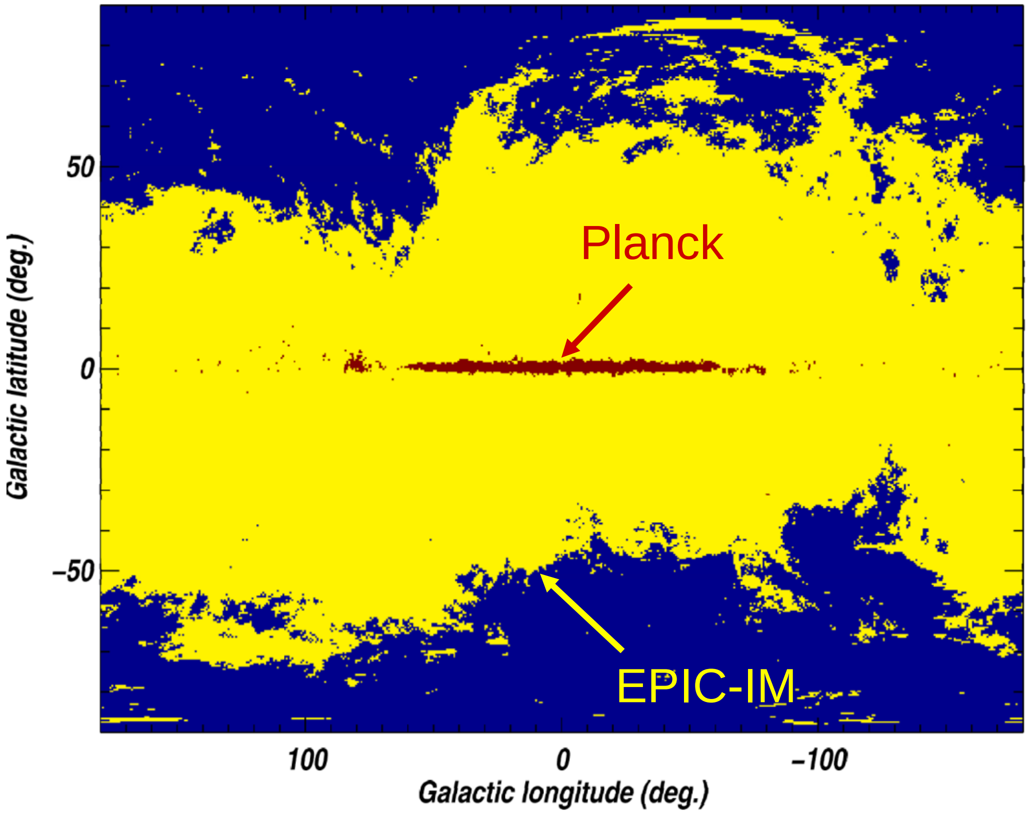
- neutrino masses
- late dark energy

All-sky potential map: 600 of these maps on the whole sky!

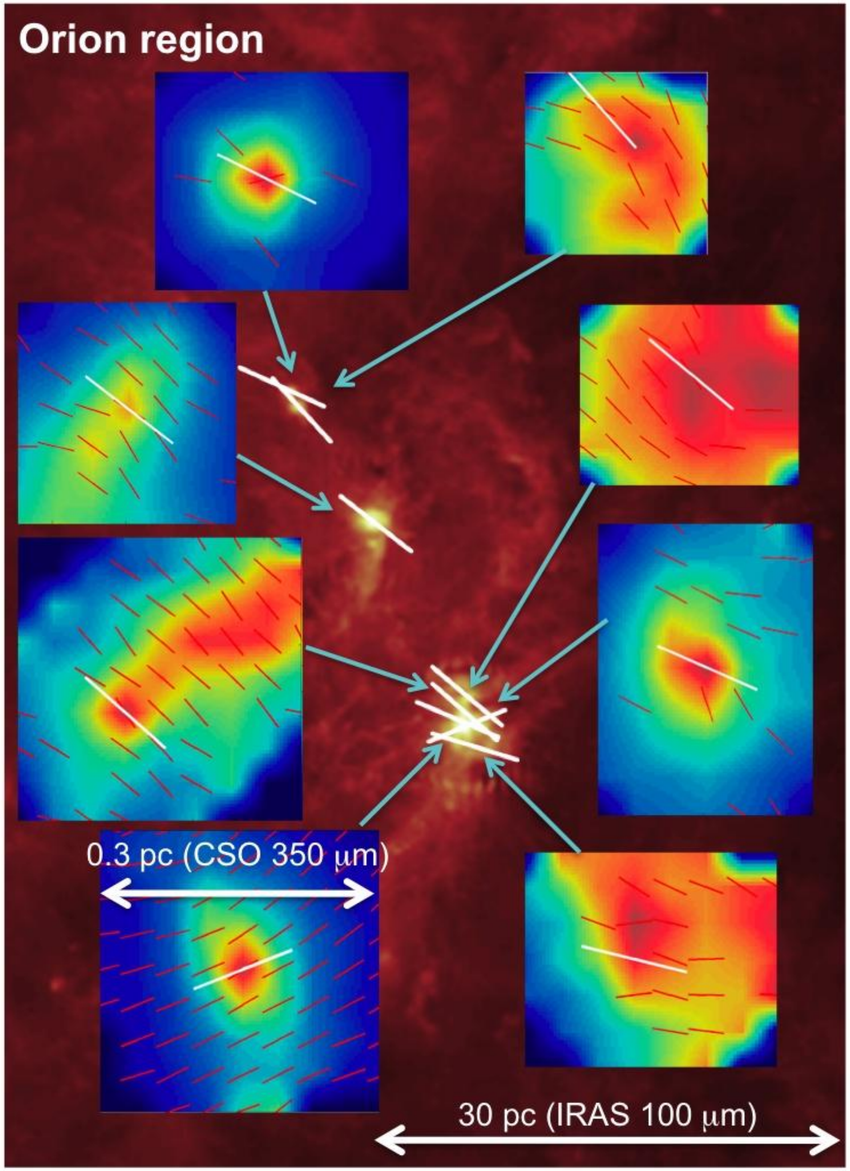
- a legacy for every future study of structure formation

Mapping Galactic Magnetic Fields over the Whole Sky

Map of full sky with $\sigma_P < 0.3$ %



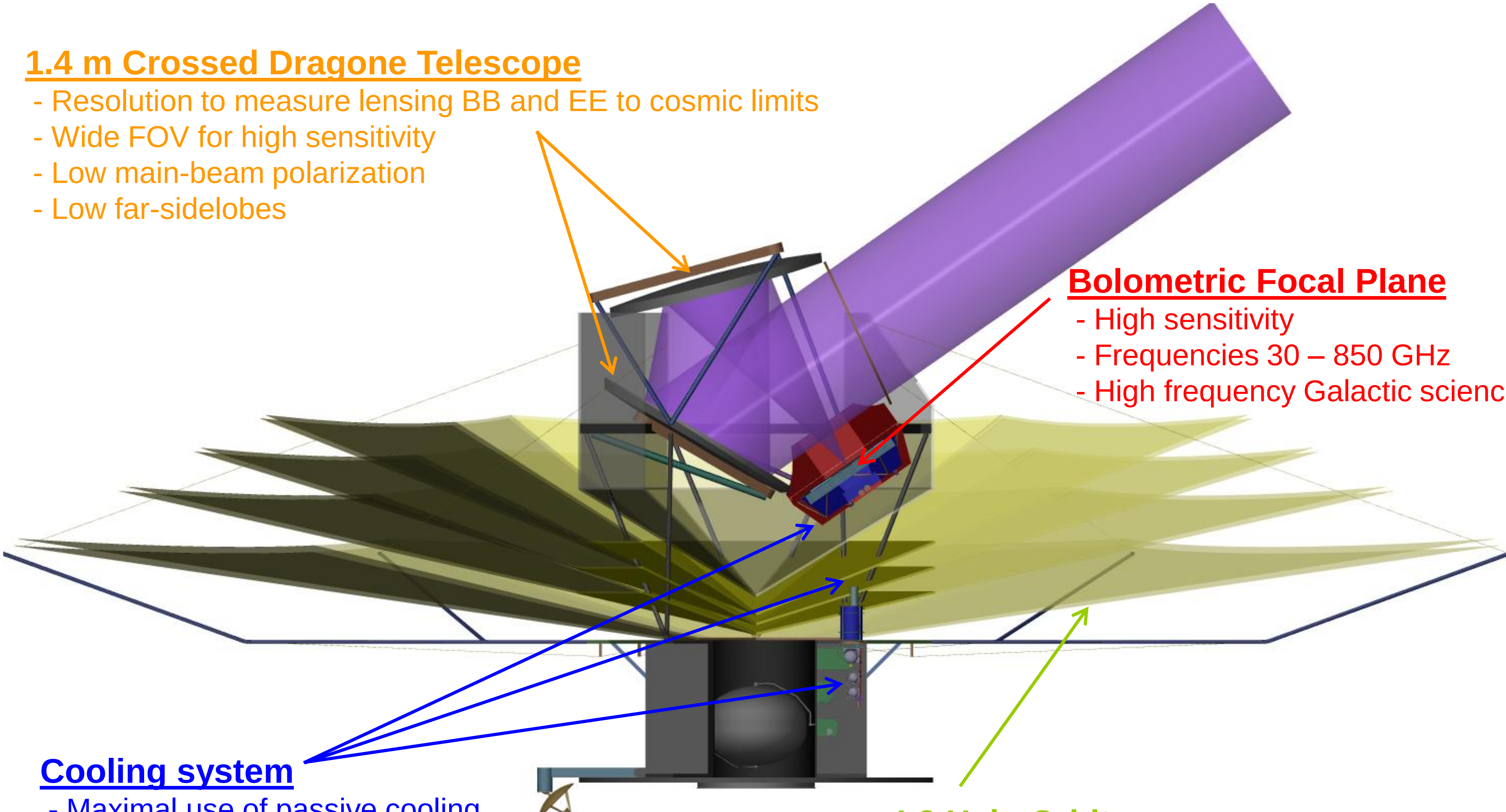
Mission	Band GHz	FWHM arcmin	σ(Q) kJy/sr/beam	Pol. depth A_V
Planck	350	5	24	4
EPIC	500	2	0.9	0.06
	850	1	0.7	0.01



How does large-scale Galactic field related to field in embedded star-forming regions?

The EPIC-IM Concept in a Nutshell

Experimental Probe of Inflationary Cosmology – Intermediate Mission



1.4 m Crossed Dragone Telescope

- Resolution to measure lensing BB and EE to cosmic limits
- Wide FOV for high sensitivity
- Low main-beam polarization
- Low far-sidelobes

Bolometric Focal Plane

- High sensitivity
- Frequencies 30 – 850 GHz
- High frequency Galactic science

Cooling system

- Maximal use of passive cooling
- Efficient 4 K cryocooler (~MIRI) cools telescope
- Continuous 100 mK cooler (~Planck) cools focal plane

L2 Halo Orbit

- Ideal scan strategy for polarization
- Extremely stable thermal environment
- Simple operations, conventional spacecraft

EPIC-IM Bands and Sensitivities

Table 3.2 EPIC-IM Bands and Sensitivities

Freq [GHz]	θ_{FWHM} [']	4 K Telescope Option					30 K Telescope Option				
		N_{bol}[a] [#]	NET [$\mu K\sqrt{s}$] bolo[b]	NET [$\mu K\sqrt{s}$] band[c]	$w_p^{-1/2}$ [μK-']^d	δT_{pix}[e] [nK]	N_{bol}[a] [#]	NET [$\mu K\sqrt{s}$] bolo[b]	NET [$\mu K\sqrt{s}$] band[c]	$w_p^{-1/2}$ [μK-']^d	δT_{pix}[e] [nK]
30	28	84	84	9.2	14	83	24	83	17	26	150
45	19	364	71	3.7	5.7	34	84	70	8	12	69
70	12	1332	60	1.6	2.5	15	208	60	4.1	6.4	37
100	8.4	2196	54	1.1	1.8	10	444	55	2.6	4.0	24
150	5.6	3048	52	0.9	1.4	8	516	57	2.5	3.8	23
220	3.8	1296	59	1.6	2.5	15	408	77	3.8	5.8	34
340	2.5	744	100	3.7	5.6	33	120	220	20	30	180
500	1.7	1092	350	10	16 (140)[f]	8[g]	108	1500	170	260 (2000)[f]	140[g]
850	1.0	938	15000	280	740 (70)[f]	7[g]	110	250k	24k	40k (3000)[f]	340[g]
Total[h]		**11094**		**0.6**	**0.9**	**5.4**	**2022**		**1.5**	**2.3**	**13**

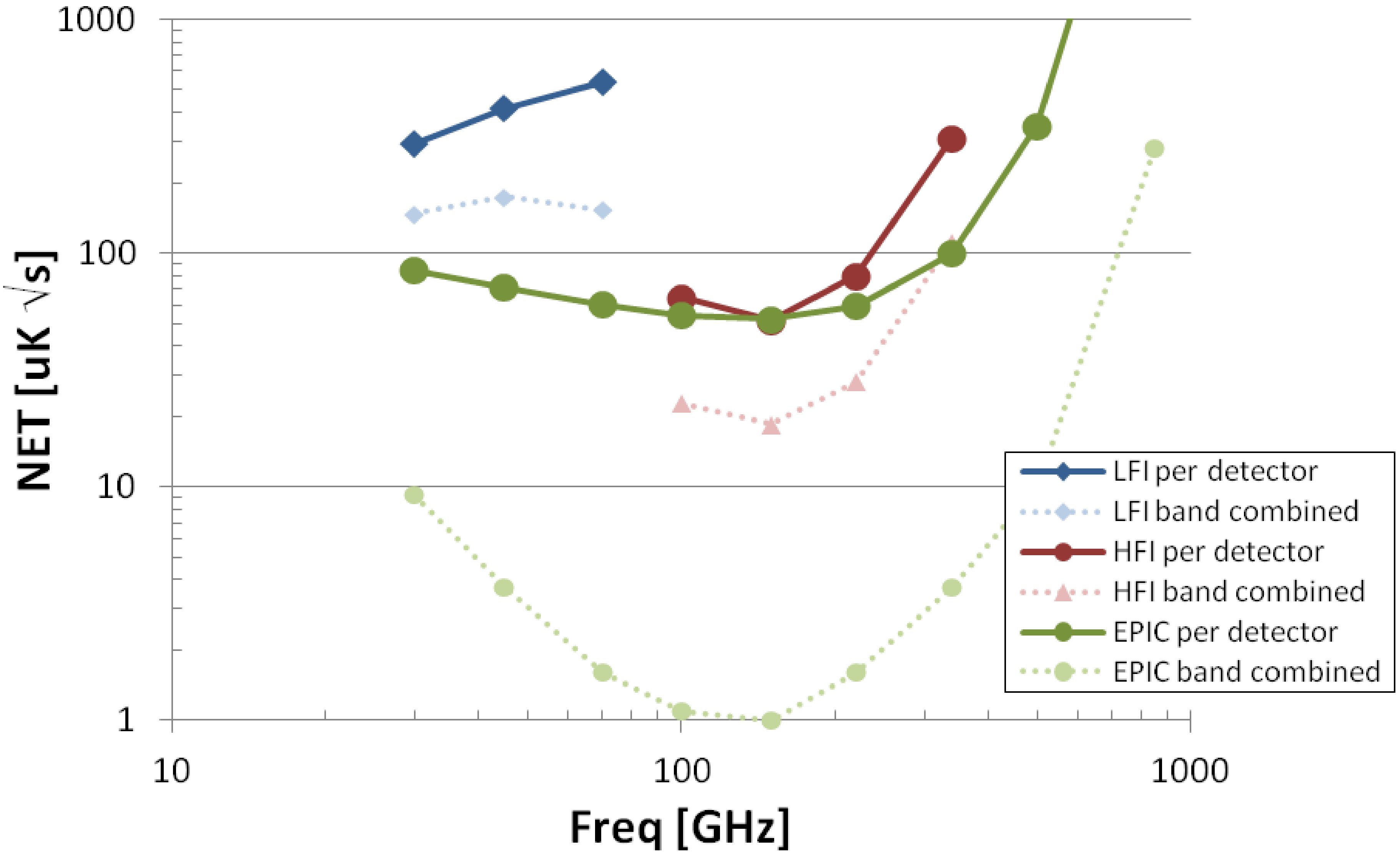
[a]Two bolometers per focal plane pixel
[b]Sensitivity for a single bolometer to CMB temperature
[c]Sensitivity combining all bolometers in a band
[d]$[8\pi\ NET_{bolo}^2/(T_{mis}\ N_{bol})]^{1/2}(10800/\pi)$
[e]Sensitivity δT_{CMB} in a 2° x 2° pixel
[f]Point source sensitivity in μJy (1σ) per beam without confusion
[g]Surface brightness sensitivity in Jy/sr in a 2° x 2° pixel (1σ)
[h]Combining all bands together

Table 3.3 Sensitivity Model Input Assumptions

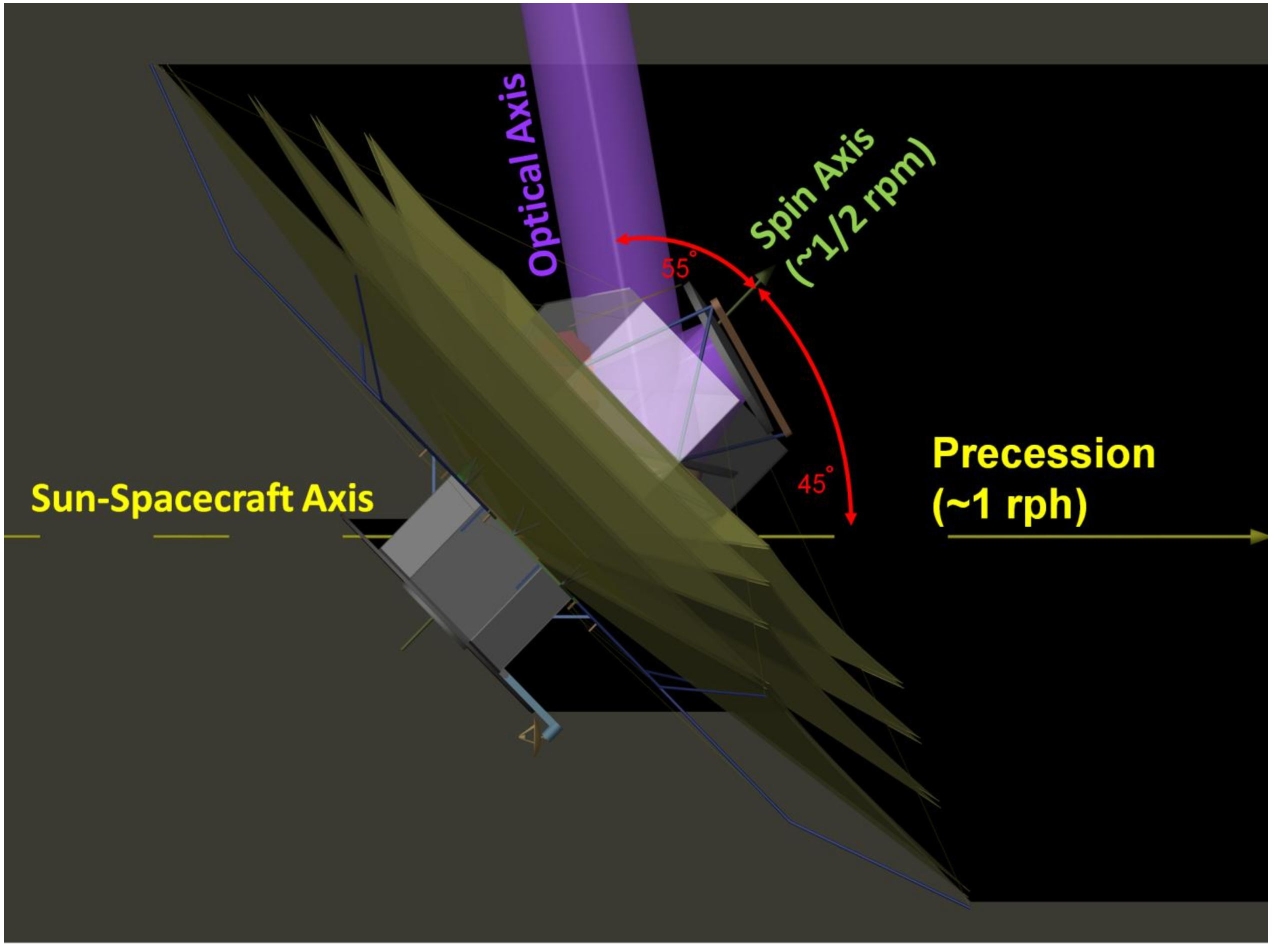
Focal plane temperature	T_o	100 mK	Optical efficiency	η_{opt}	40 %
Blocker temperature	T_{blkr}	4 K	Fractional bandwidth	$\Delta\nu/\nu$	30 %
Optics temperature	T_{opt}	4 K / 30 K*	Noise margin†		1.414
Mirror emissivity at 1 mm	ε	1 %	Mission lifetime	T_{life}	4 years
Coupling to 4 K / 30 K stop		10 % / 0.5 %*	Heat capacity	C_0	0.15 pJ/K
Coupling to 4 K baffle		5 %	$\alpha = d\ln(R)/d\ln(T)$		100
Bolometer pitch	$d/f\lambda$	2 / 3.25*	TES safety factor‡	P_{sat}/Q	5

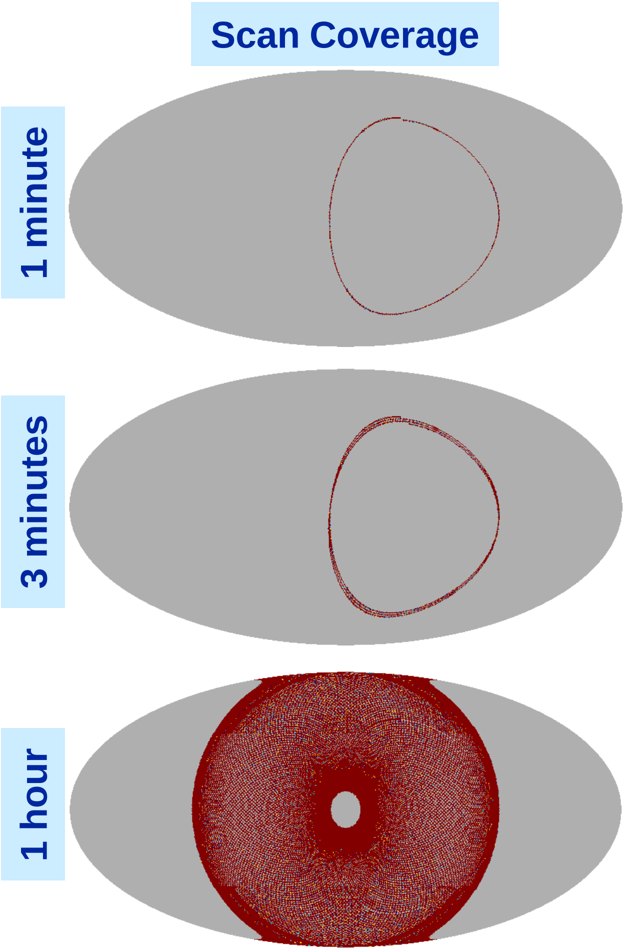
*Parameter for 4 K option / 30 K option †The total calculated sensitivity is multiplied by a safety factor of $\sqrt{2}$
‡The factors of safety are 20 for 500 GHz and 200 for 850 GHz (4 K) and 20 for 500 & 850 GHz (30 K)

EPIC-IM vs. Planck Flight Sensitivities

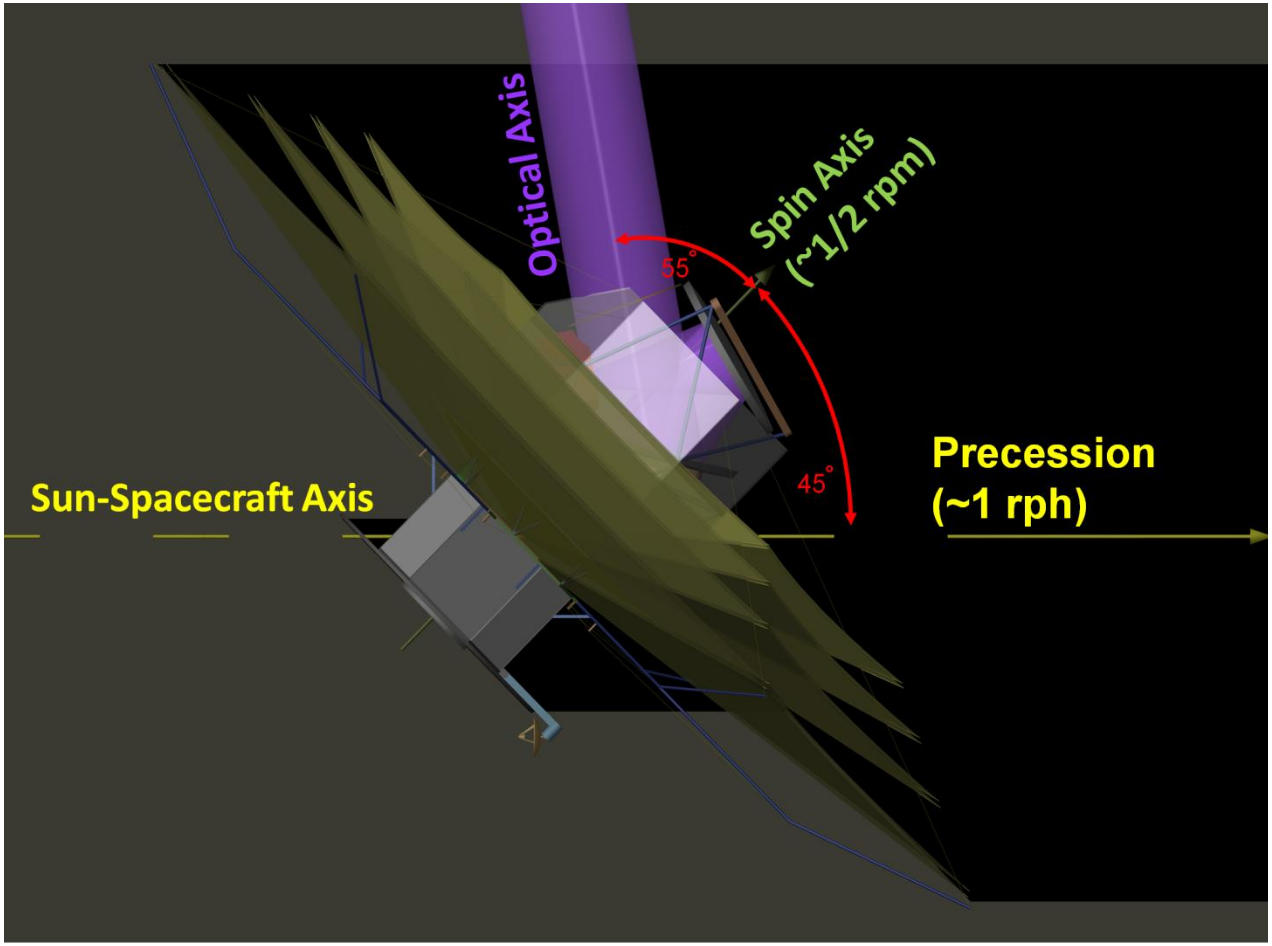


Measuring Low Multipoles in Space-Borne Observation

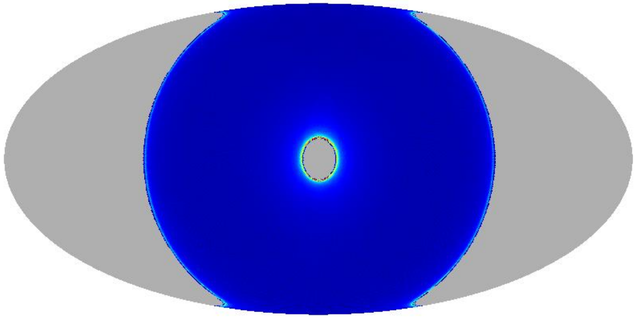




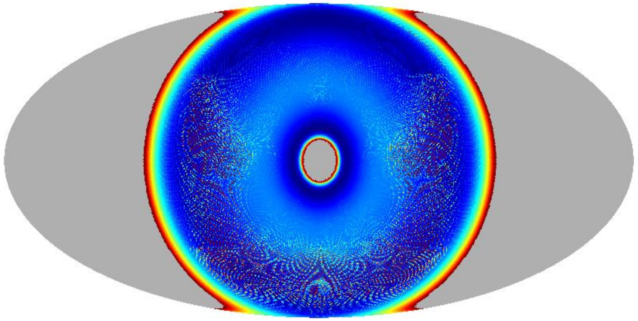
Measuring Low Multipoles in Space-Borne Observation



1 Day Maps



Spatial Coverage



Angular Uniformity

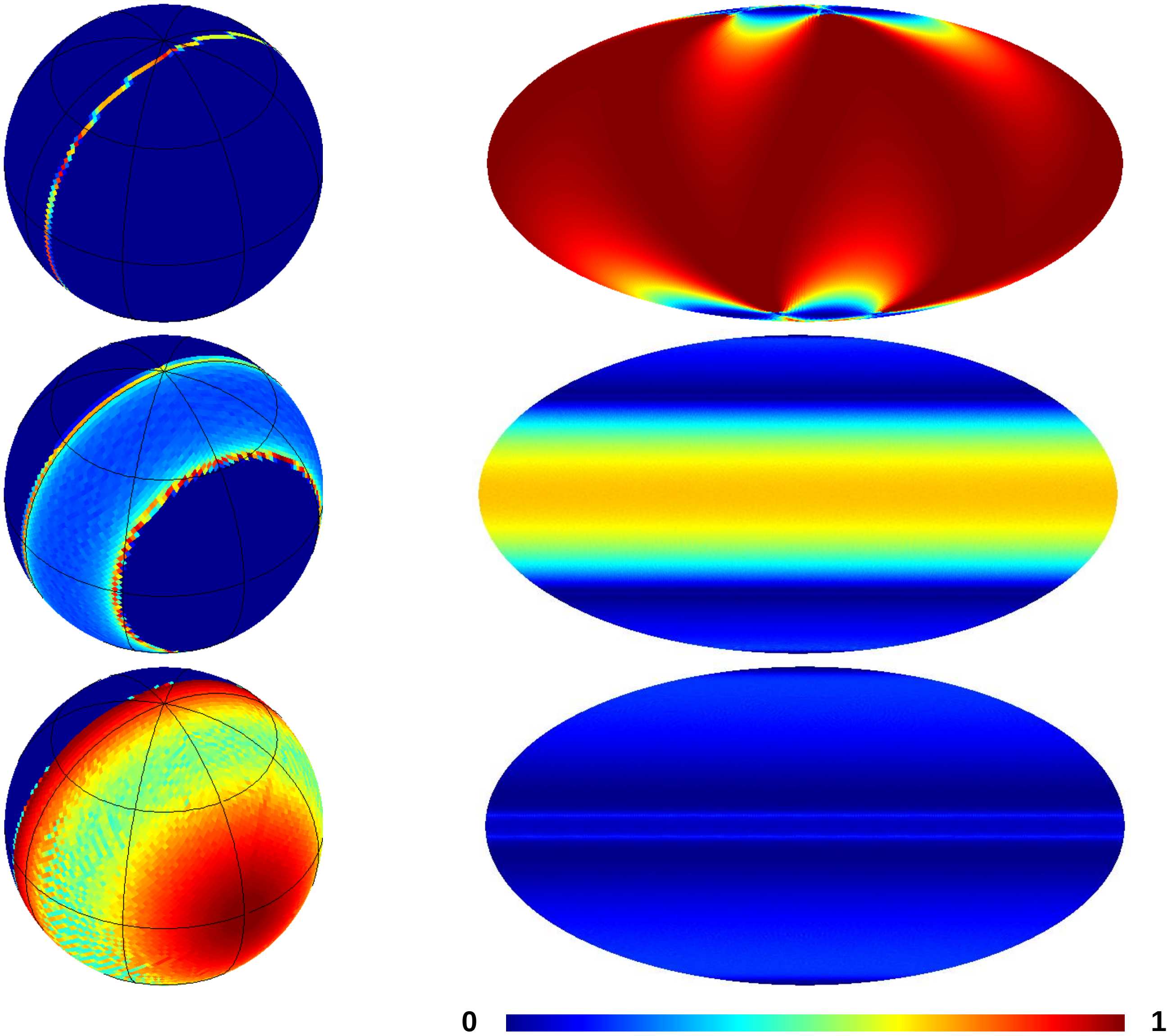
Ideal Scan Strategy for All-Sky Polarization Measurement

N-hits (1-day) | Angular Uniformity* (6-months)

Planck

WMAP

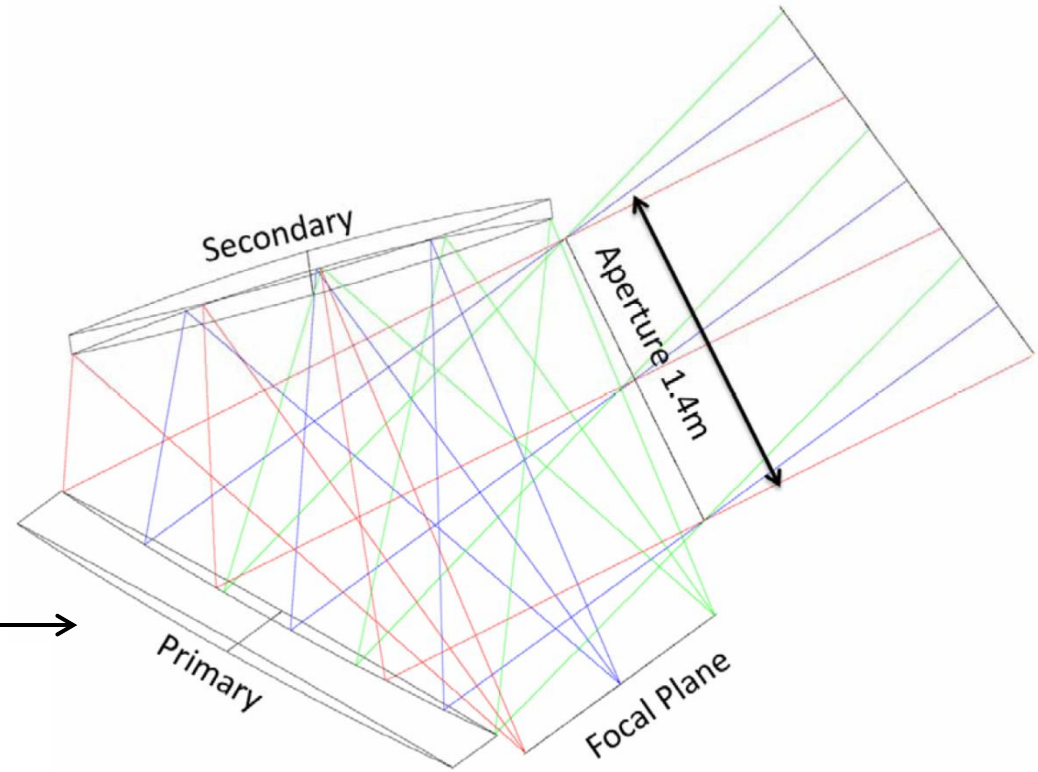
EPIC

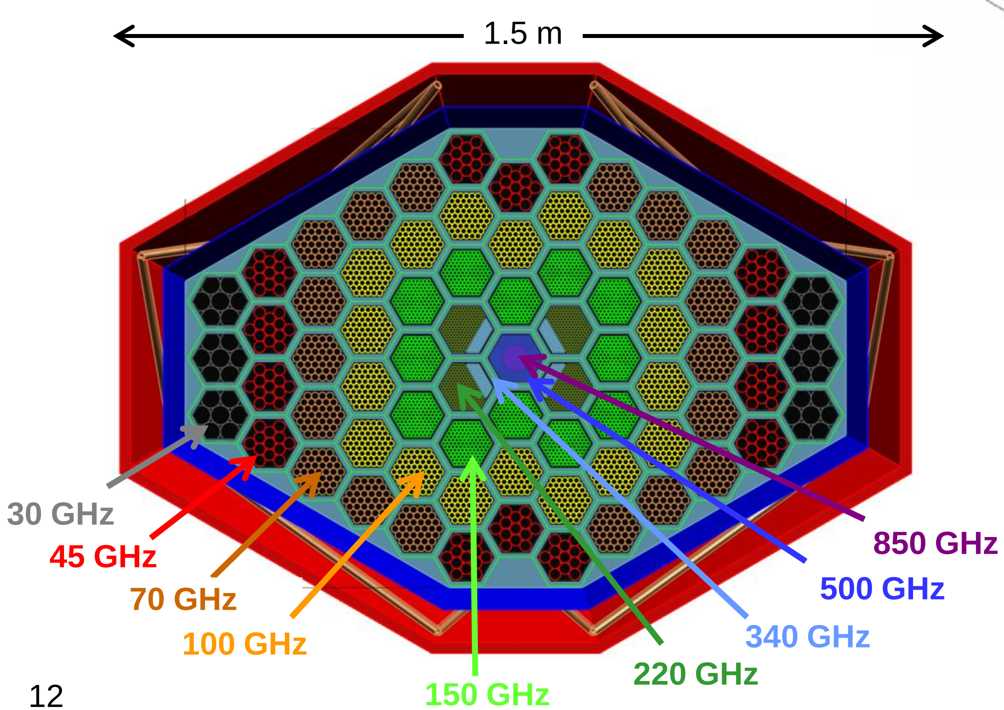


*$\langle \cos 2\beta \rangle^2 + \langle \sin 2\beta \rangle^2$

Optical Design Requirements

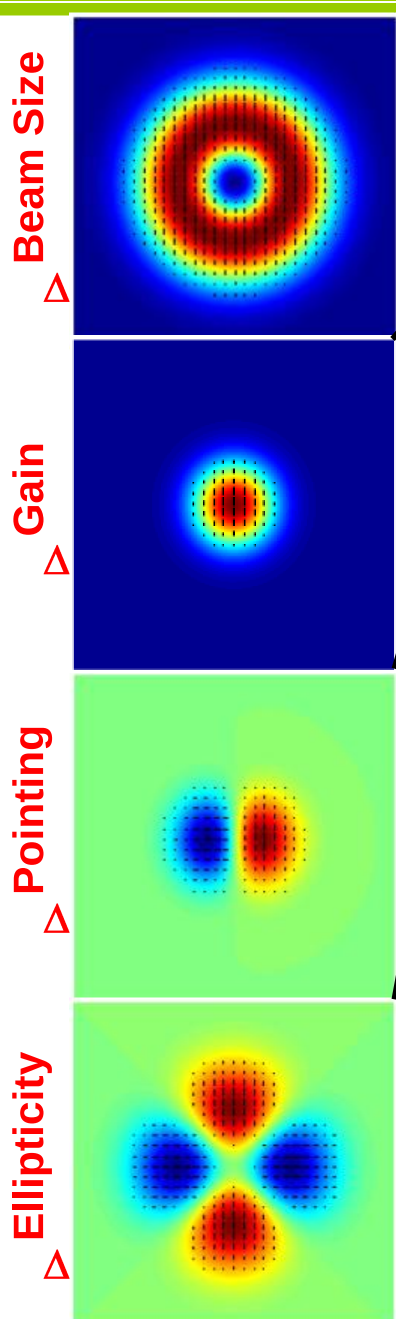
Design
1.4 m "Crossed-Dragone" telescope
Supports 1.5 x 1.0 m focal plane
Oversized primary and secondary mirrors
Cryogenic absorbing aperture stop
Cold baffles possible but not included





Requirements
Fill large field of view required for sensitivity
Fit into available space in shroud
Meet main beam polarization requirement
Meet far sidelobe requirement

Systematics: Main Beam Effects



Systematic Error	Description	Potential Effect	Mitigation
Main Beam Effects – Instrumental Polarization			
Δ Beam Size (Δμ)	$FWHM_V \neq FWHM_H$	$\nabla^2 T \rightarrow B$	Telescope design[b] In-flight beam measurements[a] Orbit-modulated dipole[a] Scan crossings[a]
Δ Gain (Δg)	Mismatched gains	$T \rightarrow B$	
Δ Beam Offset (Δρ/σ)	Pointing V ≠ Pointing H	$\nabla T \rightarrow B$	
Δ Ellipticity (Δe)	$E_V \neq e_H$	$\nabla^2 T \rightarrow B$	
Satellite Pointing	Q and U beams offset	$\nabla E \rightarrow B$	Dual analyzers[b] Pointing specification[a]
Main Beam Effects – Cross Polarization			
Δ Rotation	V & H not orthogonal	$E \rightarrow B$	In-flight measurements on polarized sources[a]
Pixel Rotation (ε)	V ⊥ H but rotated w.r.t. beam's major axis		
Scan Synchronous Signals			
Far Sidelobes	Diffraction, scattering	Pickup from sun, earth, moon and Galactic plane	Optical baffling[c] In-flight measurements on moon, 6-month jackknives[a]
Thermal Variations	Solar power variations	Temperature variation in optics, detectors	Passive thermal design[a]
Magnetic Pickup	Susceptibility in readouts and detectors	Residual signal from ambient B field	Focal plane shielding[c]
Thermal Stability			
Optics Temperature	Varying optical power from thermal emission	Residual signals from temperature variations	Dual analyzers[b] Temperature control[a]
Focal Plane Temperature	Thermal signal induced in detectors		
Other			
1/f Noise	Detector and readout drift	Striping in map	Stable detectors and readouts[b]
Passband Mismatch	Variation in filters	Differential response to foregrounds	Measure to the required level[b]
Δ Speed of Response	Different time response between bolometers	$\nabla T \rightarrow B$	Measure to the required level[b], Scan crossings[a]

Main Beam Requirements

Table 5.4 Summary of Main Beam Requirements and Goals

ν [GHz]	θ_{FWHM} [arcmin]	δT (ℓ=100) $[nK_{CMB}]^b$		Δg $[10^{-4}]$		Δμ $[10^{-3}]$		Δρ/σ $[10^{-3}]^c$		Δe $[10^{-3}]^d$		ε [']	
30	28		4.2		5.2		4		2.3		0.6		7.8
45	19		2.0		2.5		5		1.6		0.7		3.8
70	12	1.6	1.1	1.9	1.4	9	7	2.3	1.3	1.3	0.9	2.9	2.1
100	8.4	1.6	0.8	1.9	1.0	18	9	3.2	1.4	2.6	1.3	2.9	1.4
150	5.6	1.6	0.7	1.9	0.8	40	18	4.9	2.1	5.8	2.5	2.9	1.3
220	3.8	1.6	0.9	1.9	1.1	90	50	7.3	4.2	13	7.2	2.9	1.6
340	2.5		2.3		2.9		300		14		43		4.3

Requirements on: Differential gain $\Delta g \equiv (g_1 - g_2)/g$

Differential beam size $\Delta\mu \equiv (\sigma_1 - \sigma_2)/\sigma$ where $\sigma = (\sigma_1 + \sigma_2)/2$

Differential beam offset $\Delta\rho/\sigma \equiv (\theta_1 - \theta_2)/\sigma$

Differential ellipticity $\Delta e = (e_1 - e_2) / 2$ where $e = (\sigma_x - \sigma_y) / (\sigma_x + \sigma_y)$

Pixel rotation ε in arcmin

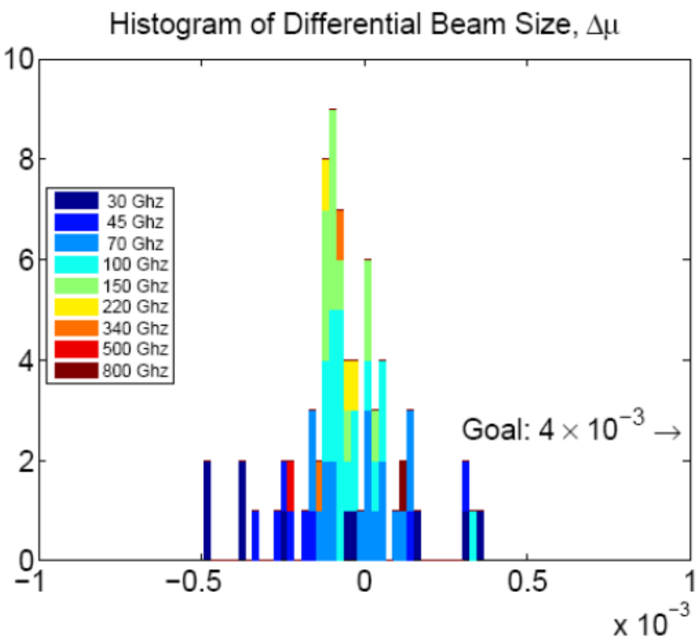
[a]Requirement (blue) and goal (red) levels are referred to band-averaged beams.

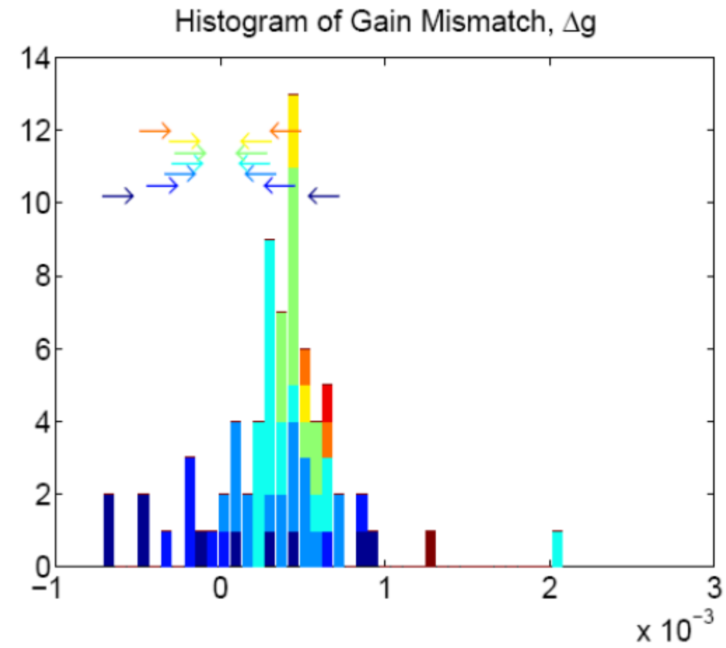
[b]Required and goal level $[\ell(\ell+1) C_\ell/2\pi]^{1/2}$ at ℓ = 100 for EPIC-IM 4 K for a 4-year mission.

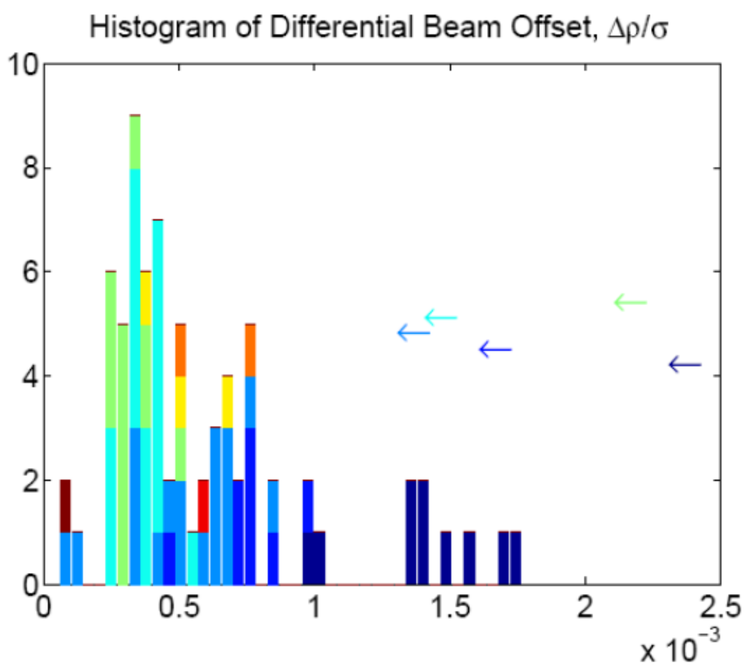
[c]Differential beam offset assumes the raw scan pattern. Scan symmetrization relaxes this requirement by approximately a factor of 100.

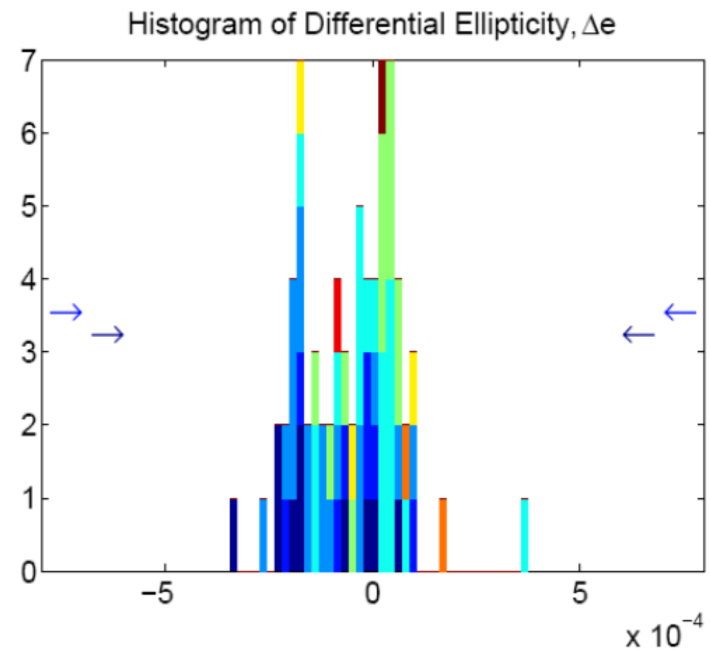
[d]Differential ellipticity calculated for the worst-case ψ = 45°. EPIC-IM is ~100x less prone to the more typical optical effect at ψ = 0° which to first order converts T → E.

Main Beam Polarization Results









Main Beam Knowledge on Planets

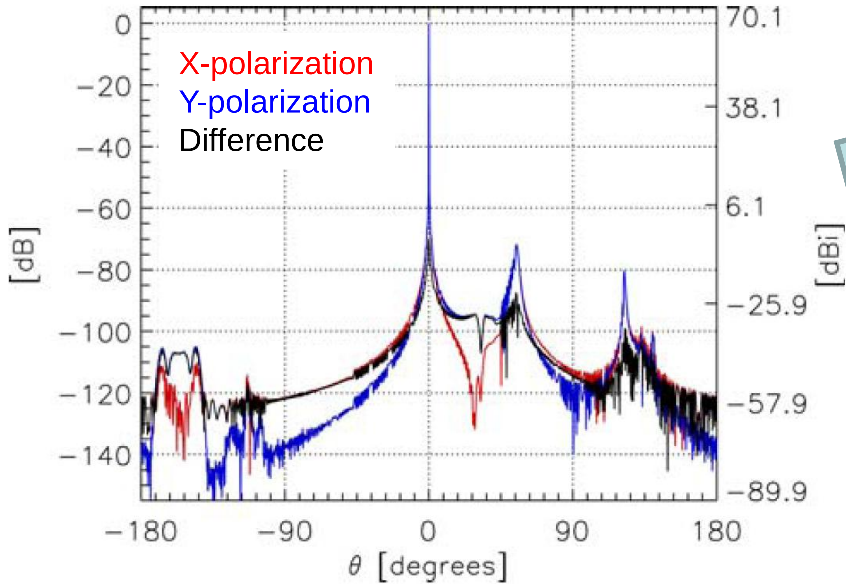
Table 5.6 In-Flight Measurements of Band-Averaged Beams on Jupiter

ν [GHz]	θ_{FWHM} [arcmin]	Δ [10^{-3}]	$\Delta\mu$ [10^{-3}]		$\Delta\rho/\sigma$ [10^{-3}]		Δe [10^{-3}]	
30	28	0.9		4		2.3		0.6
45	19	0.5		5		1.6		0.7
70	12	0.3	9	7	2.3	1.3	1.3	0.9
100	8.4	0.2	18	9	3.2	1.4	2.6	1.3
150	5.6	0.2	40	18	4.9	2.1	5.8	2.5
220	3.8	0.2	90	50	7.3	4.2	13	7.2
340	2.5	0.5		300		14		43

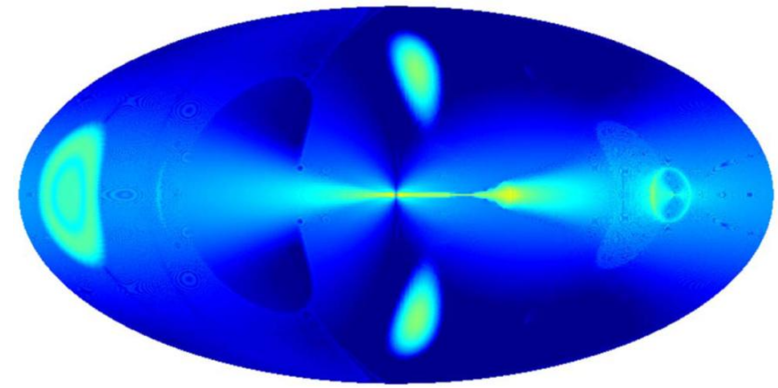
Note: Following Table 5.4, requirements are shown in blue text; goals are shown in red text on differential beam size ($\Delta\mu$), beam offset ($\Delta\rho/\sigma$), and ellipticity (Δe).
Jupiter assumed to be 170 K and 50" in apparent diameter.
Cells are shaded red where measurement Δ does not achieve the required accuracy.

Systematics: Far-Sidelobe Performance

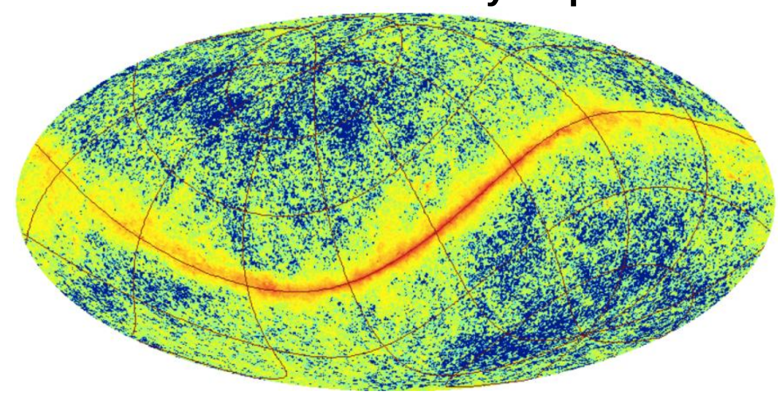
Far Sidelobes (3.25 fλ feed at 150 GHz)



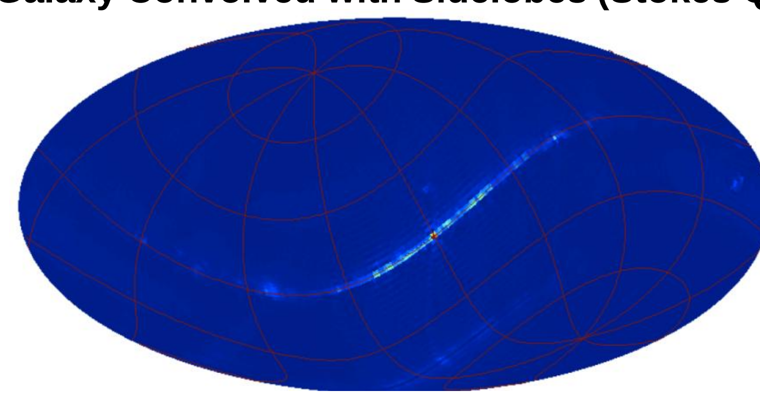
Polarized Far Sidelobe Map



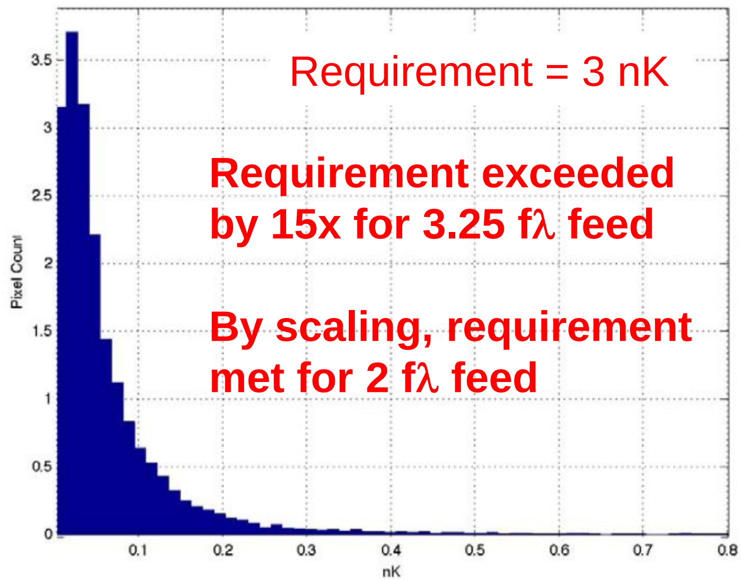
Galactic Intensity Map



Galaxy Convolved with Sidelobes (Stokes Q)

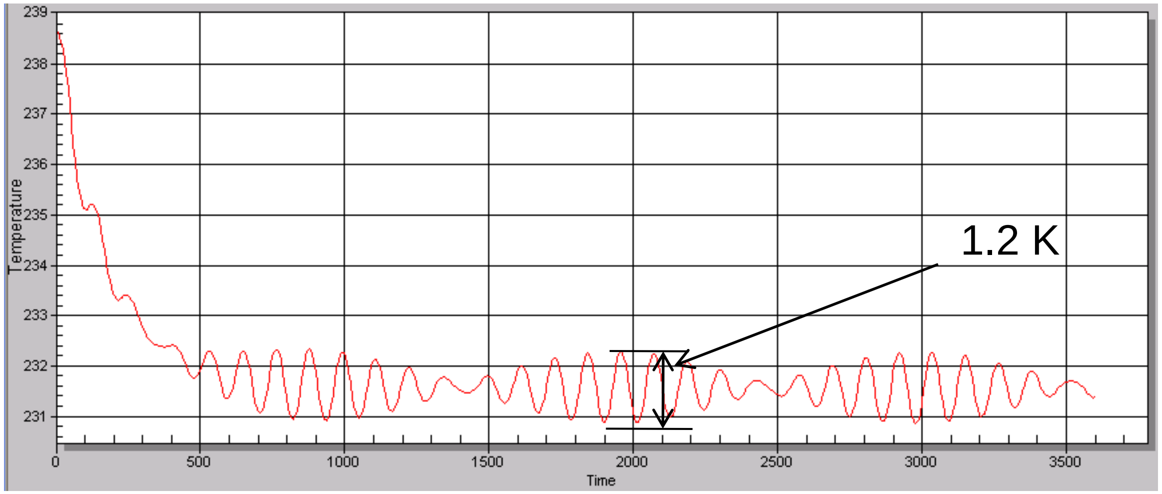


Pixel Distribution in Convolved Map



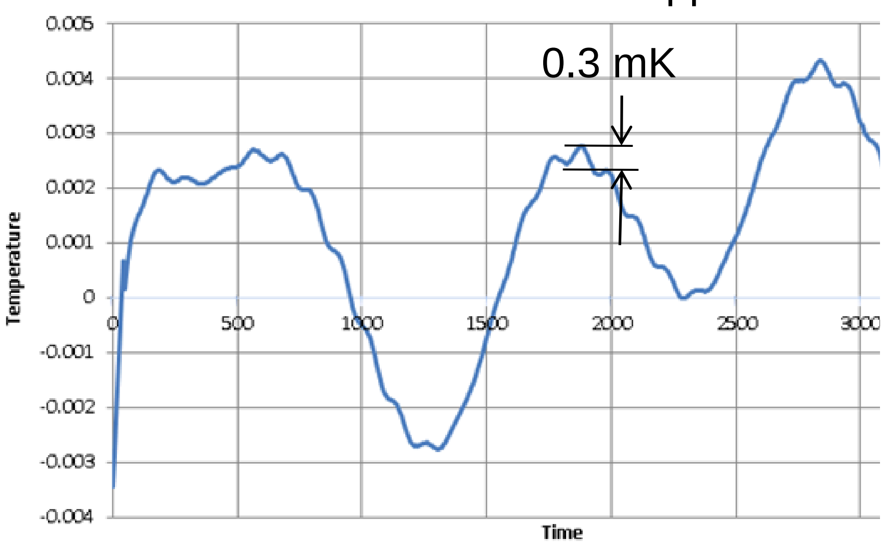
Systematics: Scan-Synchronous Thermal Variations

1st Shield ΔT = 1.2 K pp

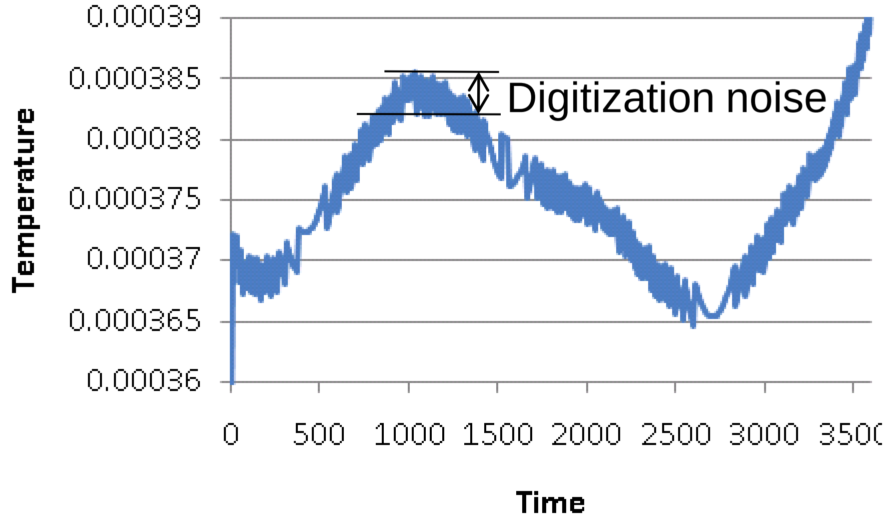


- Thermal isolation 4000 per stage.
- Implies **19 pico K variation at 4th shield.**

2nd Shield ΔT = 0.3 mK pp



3rd Shield ΔT not observable at 3 μK level



The EPIC-IM Concept: Descopes

- **Reduced Sunshield**
  - Flat design was for thermal stability, but thermal ripple is tiny
  - Shields can be canted forward

- **Smaller Focal Plane**
  - simple trade of cost vs. science
  - multi-color pixels can also reduce focal plane area

- **30 K Optics**
  - relaxed requirements on 4 K cooler
  - can remove one level of radiation shielding
  - mostly affects sensitivity in high-frequency channels

- **300 mK**
  - only modest loss in sensitivity vs. 100 mK

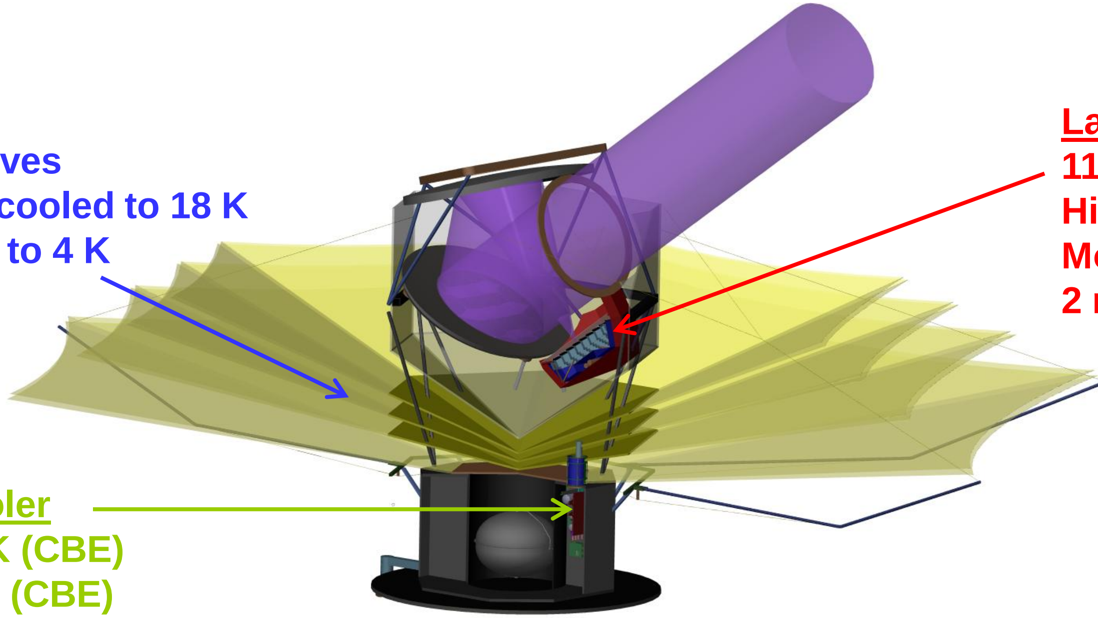
- **Earth Polar Orbit?**
  - We’re forced into this for a Taurus-class launch

Descope Option: 30 K Telescope

Larger passive cooler
4 sunshields, 3 V-grooves
Optics shield actively cooled to 18 K
Optics actively cooled to 4 K

Larger focal plane
11094 detectors
Higher pixel density
More spillover
2 radiation shields

Larger 4 K cooler
21 mW @ 4.4 K (CBE)
67 mW @ 18 K (CBE)
2x design margin

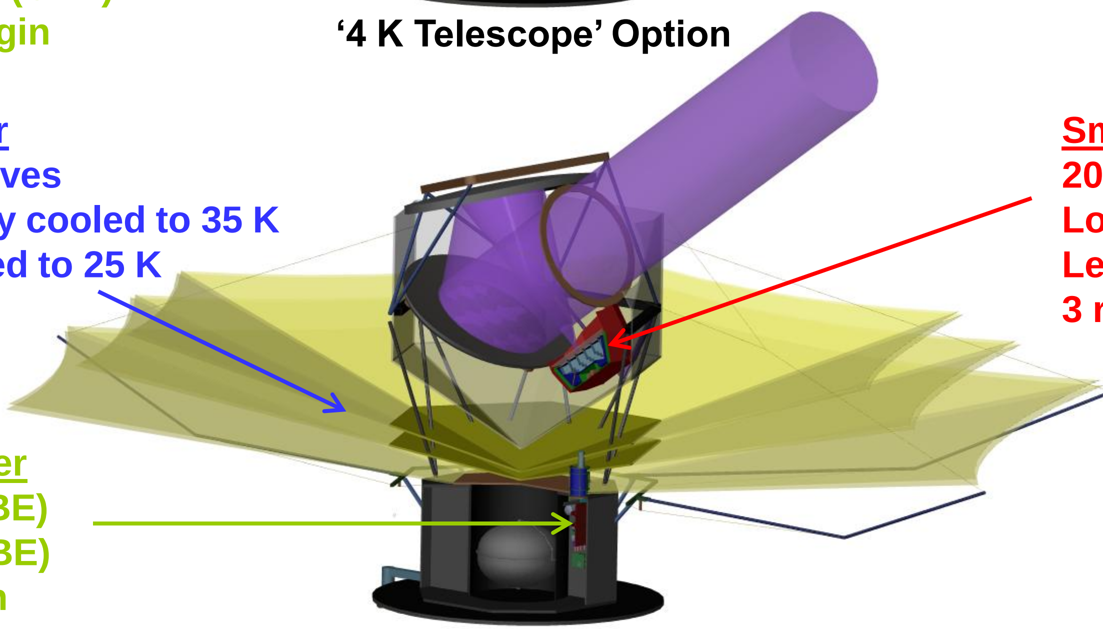


'4 K Telescope' Option

Smaller passive cooler
3 sunshields, 2 V-grooves
Optics shield passively cooled to 35 K
Optics passively cooled to 25 K

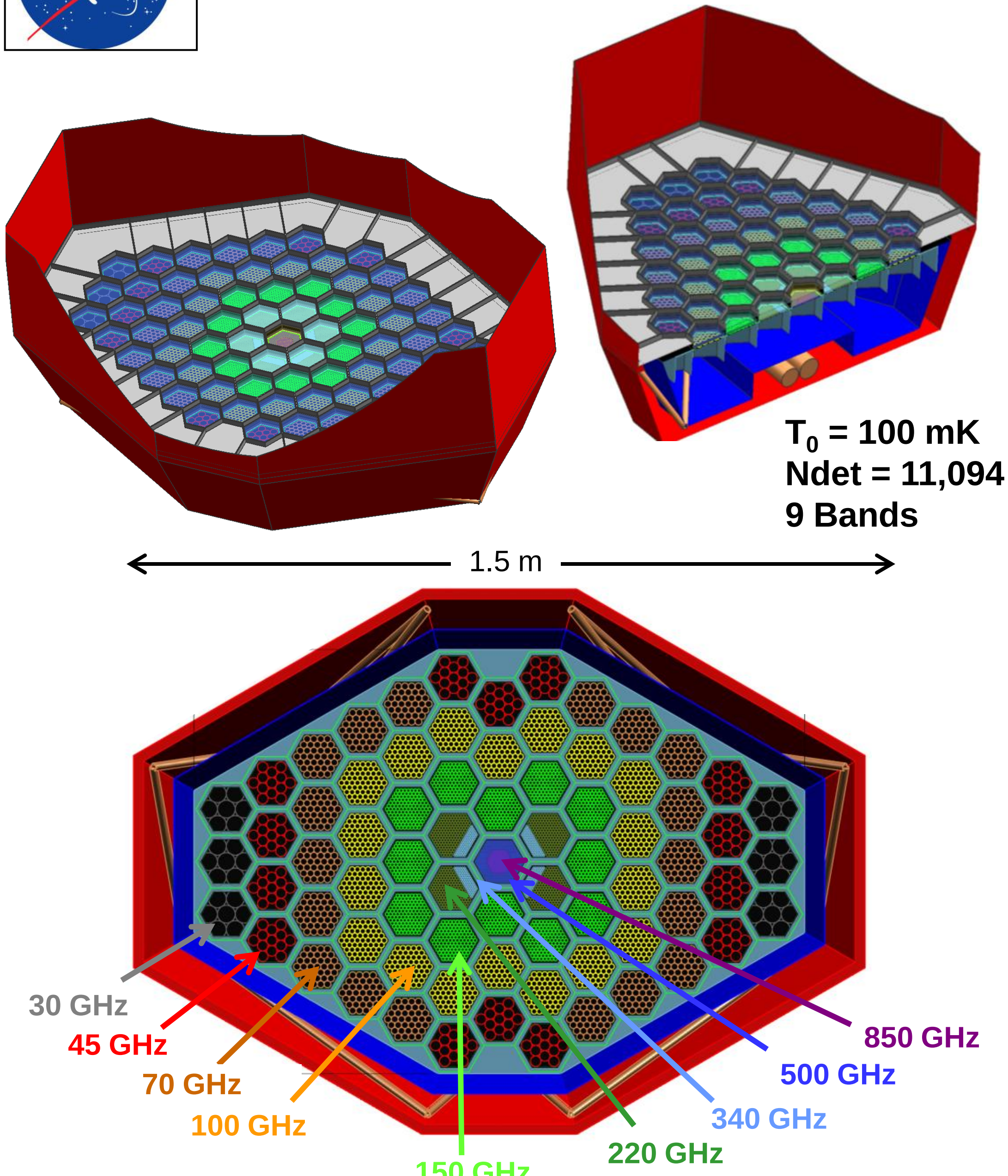
Smaller focal plane
2022 detectors
Lower pixel density
Less spillover
3 radiation shields

Smaller 4 K cooler
11 mW @ 4 K (CBE)
8 mW @ 18 K (CBE)
2x design margin



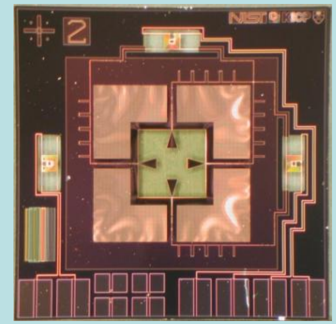
'30 K Telescope' Option

Sub-Orbital Predecessors to EPIC-IM Focal Plane

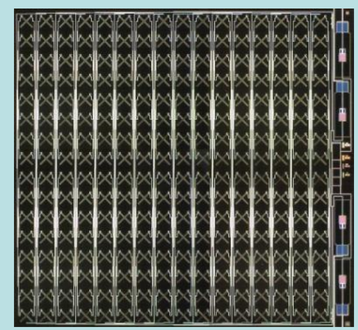


Detector Technology Options

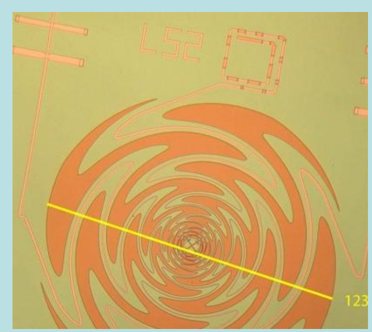
Optical Coupling



Feed Coupled

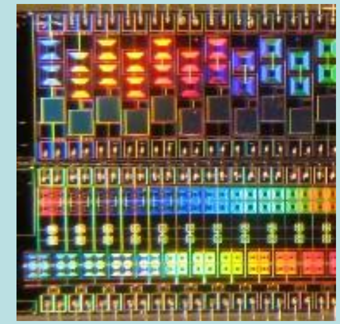


Planar Antennas

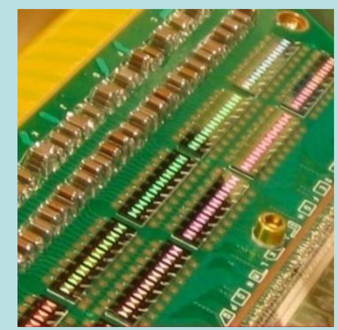


Lens-Coupled Antennas

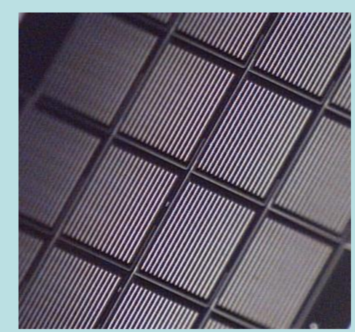
Detector / Readout



Time-Domain SQUID



Freq-Domain SQUID



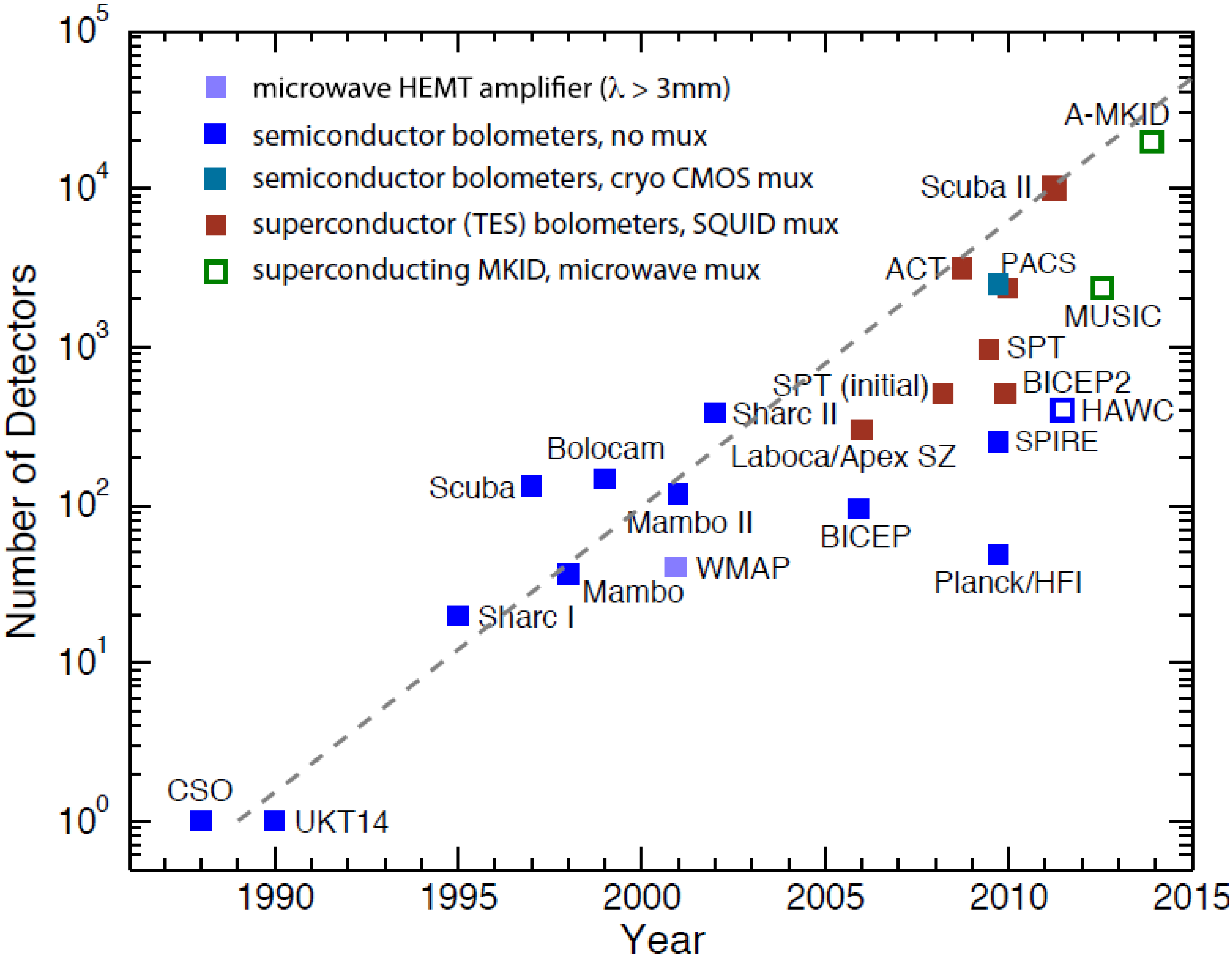
RF-Muxed MKID

Conclusions

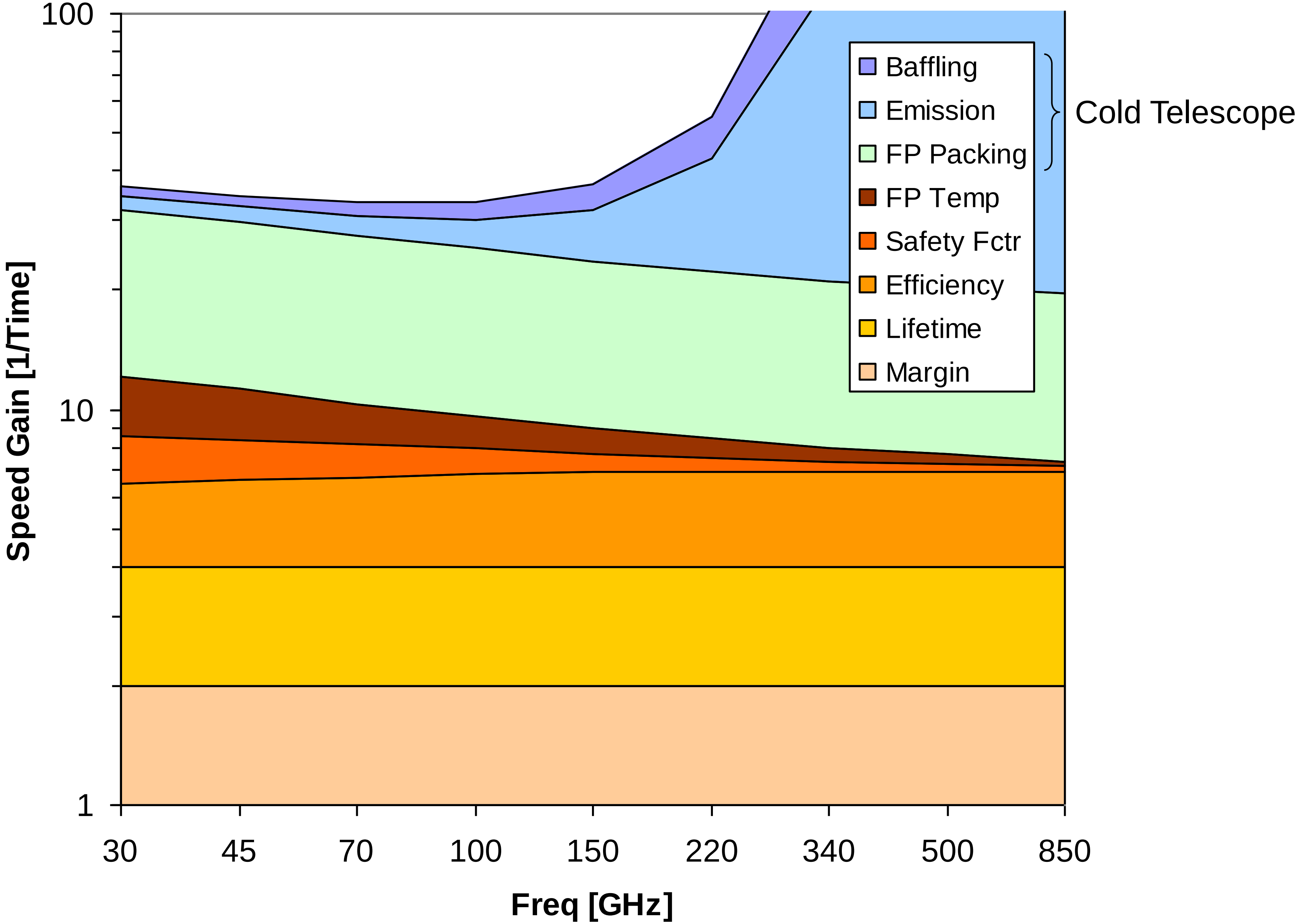
- **EPIC-IM**
  - Measures Inflationary polarization to fundamental limits
  - Measures lensing polarization to fundamental limits
  - Returns all-sky Galactic maps to map B-fields
  - Represents a major sensitivity improvement over *Planck*
- **Technology Development**
  - Need multi-color background-limited detector arrays
  - Compatible with the multiple approaches being developed by the CMB community
  - Some development programs reduce mission cost if successful
- **Avenues for Further Study**
  - Systematic error analysis encouraging but needs more work
  - Need to explore options for simplification and reduced cost
  - Is an Explorer configuration possible?

Backup

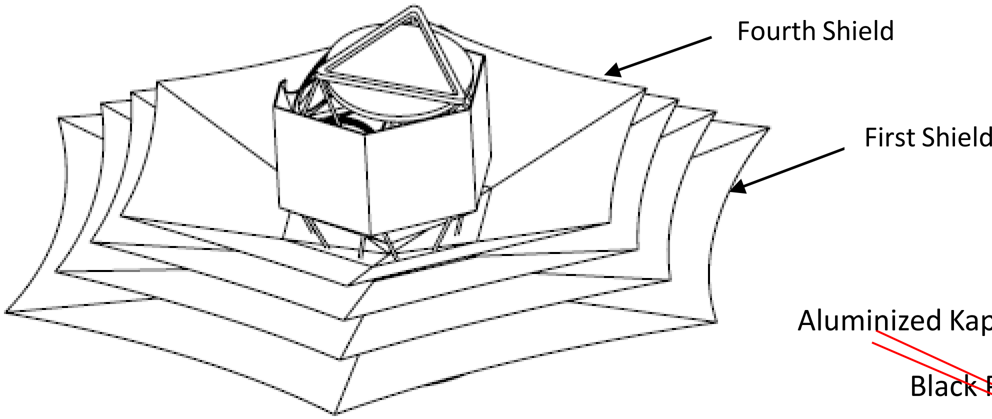
Focal Plane Technologies

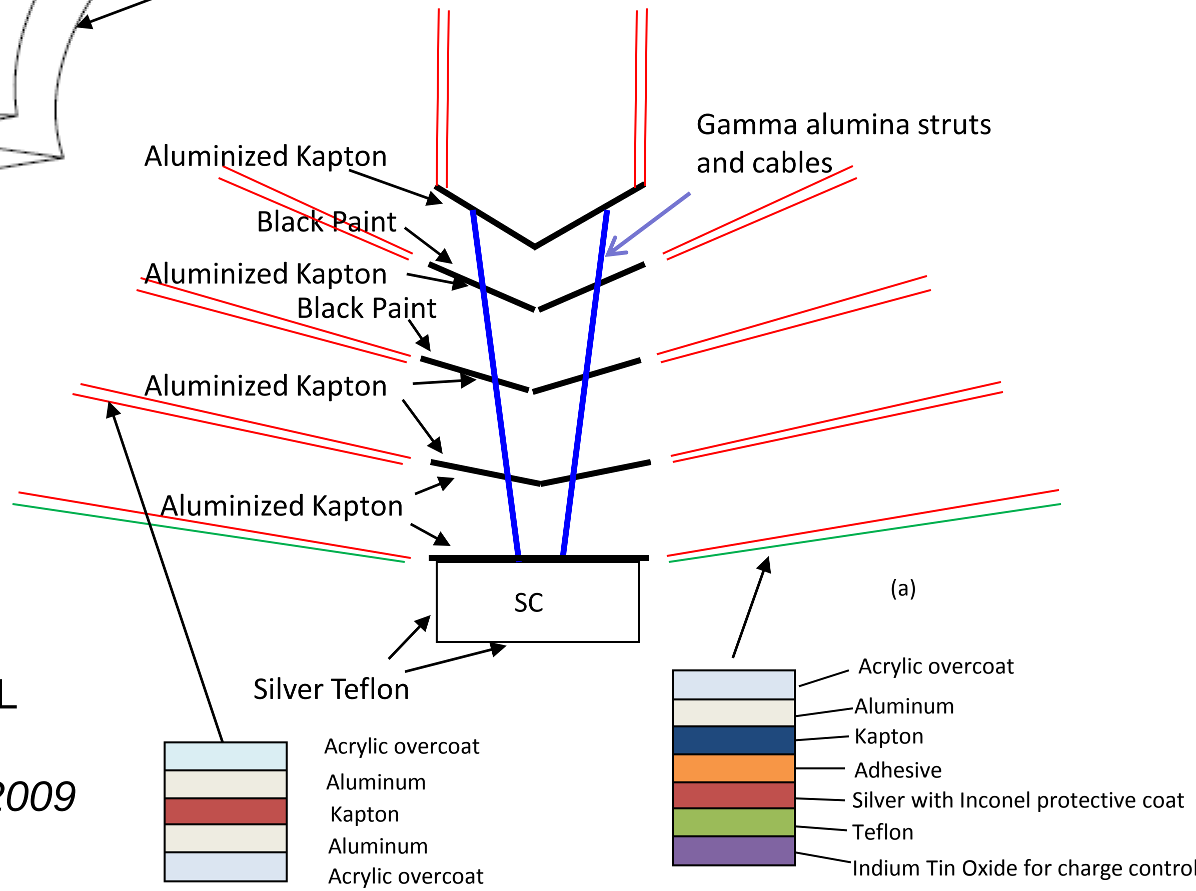


Options to Gain System Sensitivity



Thermal Design





(b) Doubled Aluminized Kapton film (red)

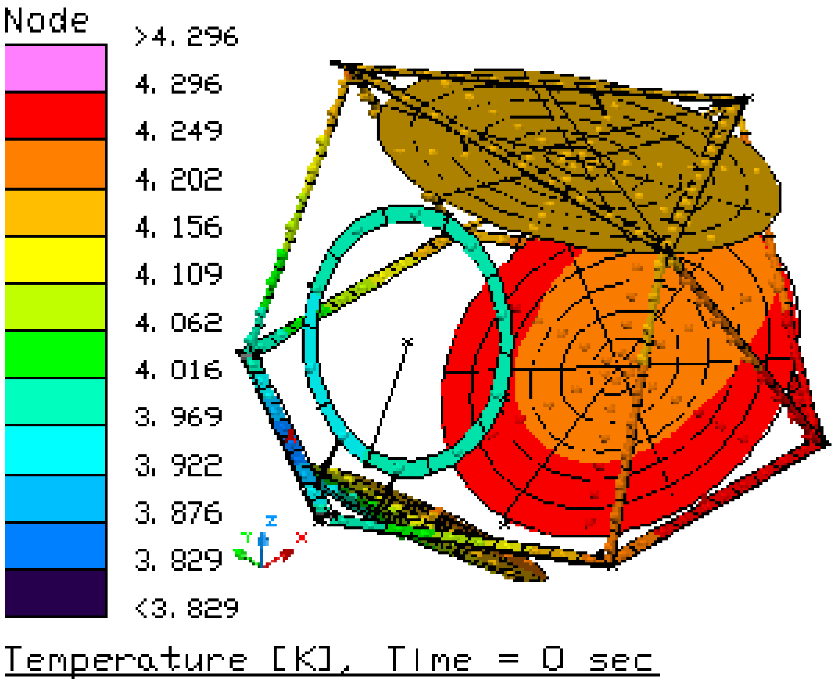
(c) Silver Teflon film (green)

Talso Chui & Warren Holmes, JPL
Jeff Raab, NGAS

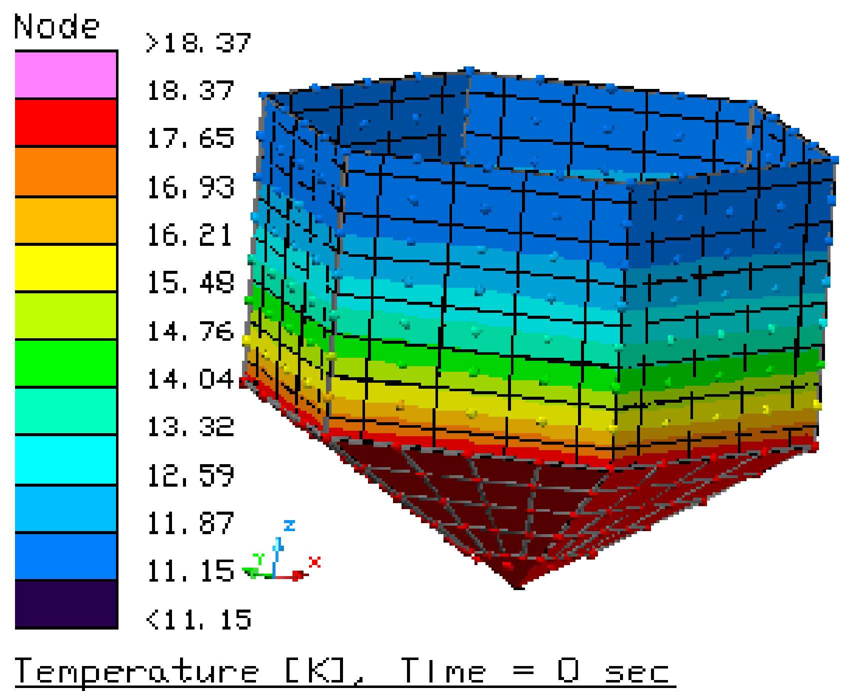
Proceedings Space Cryogenics 2009

Option #1: Cool Telescope and Baffles to 4 K

Telescope actively cooled to 4 K



Optics shield tied to cooler 18 K stage

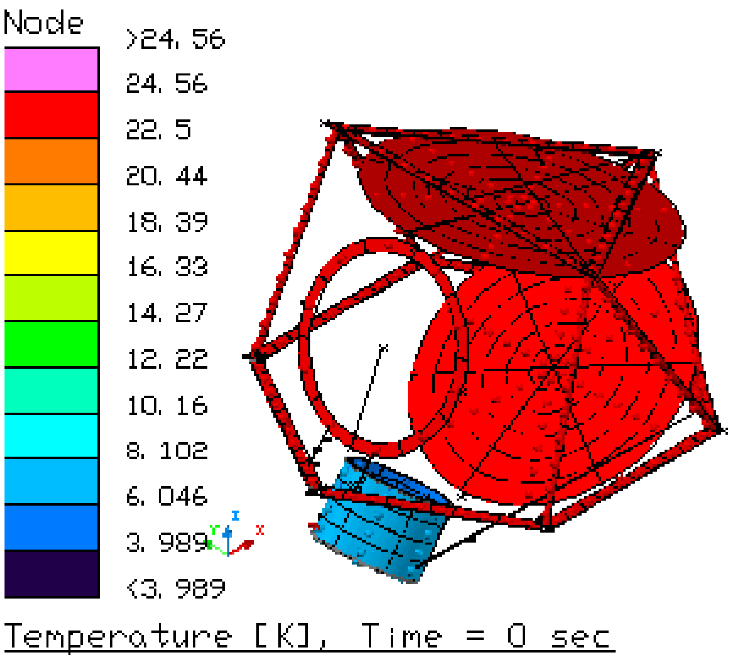


Temperature of Telescope versus cooling power

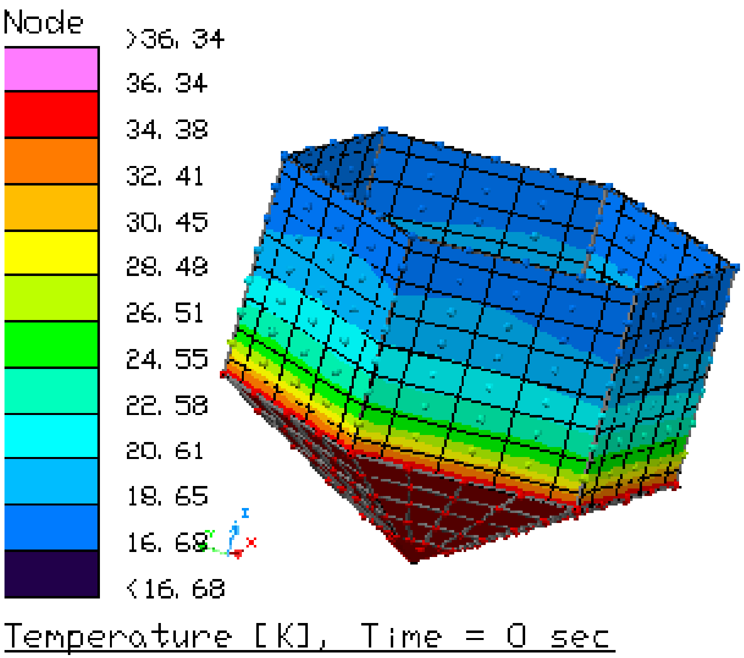
Cooling power (mW)	0	10	15	18.5	20	20.25	20.5	21
Optical Bench (telescope) T (K)	17.35	13.86	11.02	7.62	4.83	4.02	3.23	1.43
Optics Box Bottom cooling power (mW) to keep it at 18 K	78.2	74.0	71.4	69.1	68.0	67.8	67.5	67.0

Option #2: Cool Focal Plane Enclosure to 4 K

Focal plane actively cooled



Optical shield cools radiatively



Temperature Inner Focal Plane Box versus cooling power

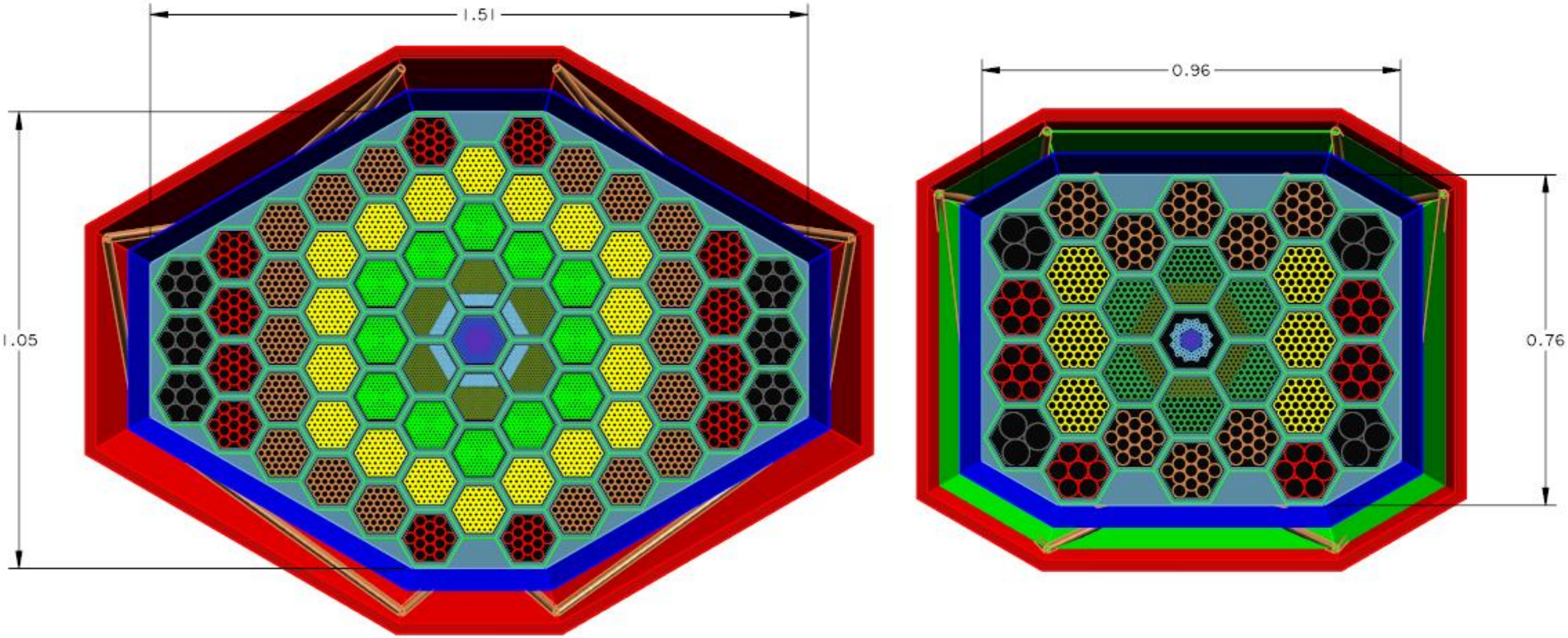
Inner FP Box Cooling power (mW)	0	4	8	10	10.5	10.55	10.58	10.6
Inner FP Box T (K)	24.96	21.53	17.49	11.41	5.28	4.81	4.24	3.12
Outer FP Box P (mW) and T(K)	7.09 18	4.13 18	0.88 18	0 13.96	0 8.30	0 7.89	0 7.28	0 6.16

Trade summary:

Remove 1 shield saves 90 kg
Reduce cooler power saves 72 W

Lower sensitivity due to photon noise and larger pixels

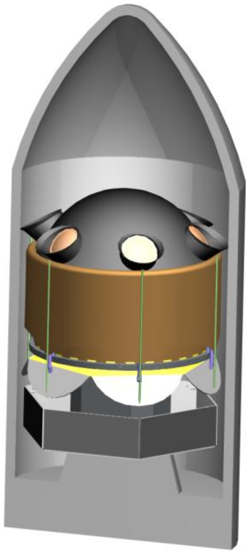
Descoped Focal Plane for 30 K Telescope

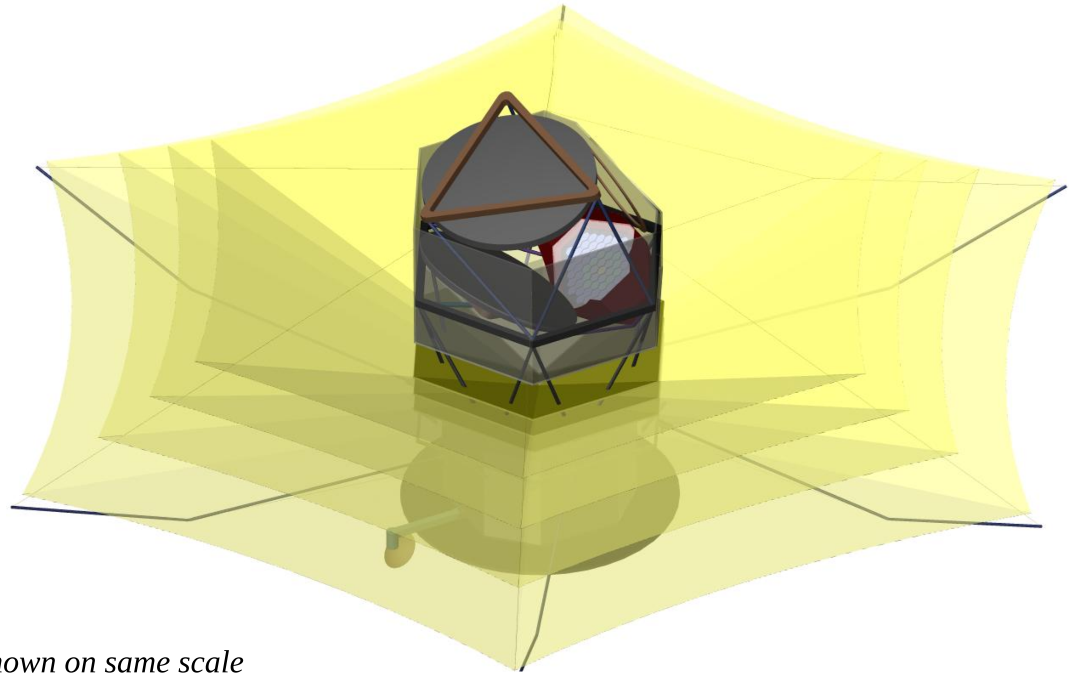


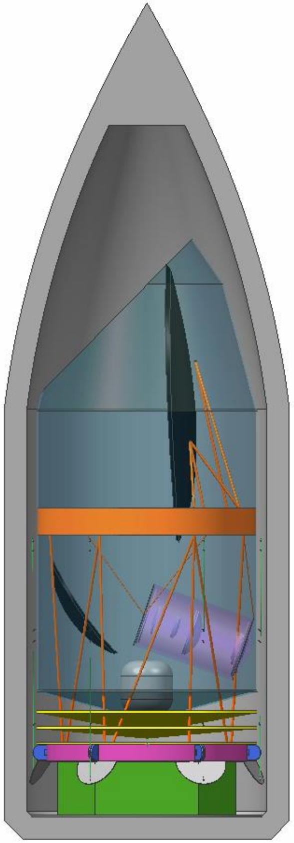
'4 K Telescope' Option **'30 K Telescope' Option**

- Focal plane reduced by 2.3x in mass
- Detectors become larger for 30 K telescope due to edge spillover
- Total detectors reduced from 11094 to 2022

The EPIC-IM Design



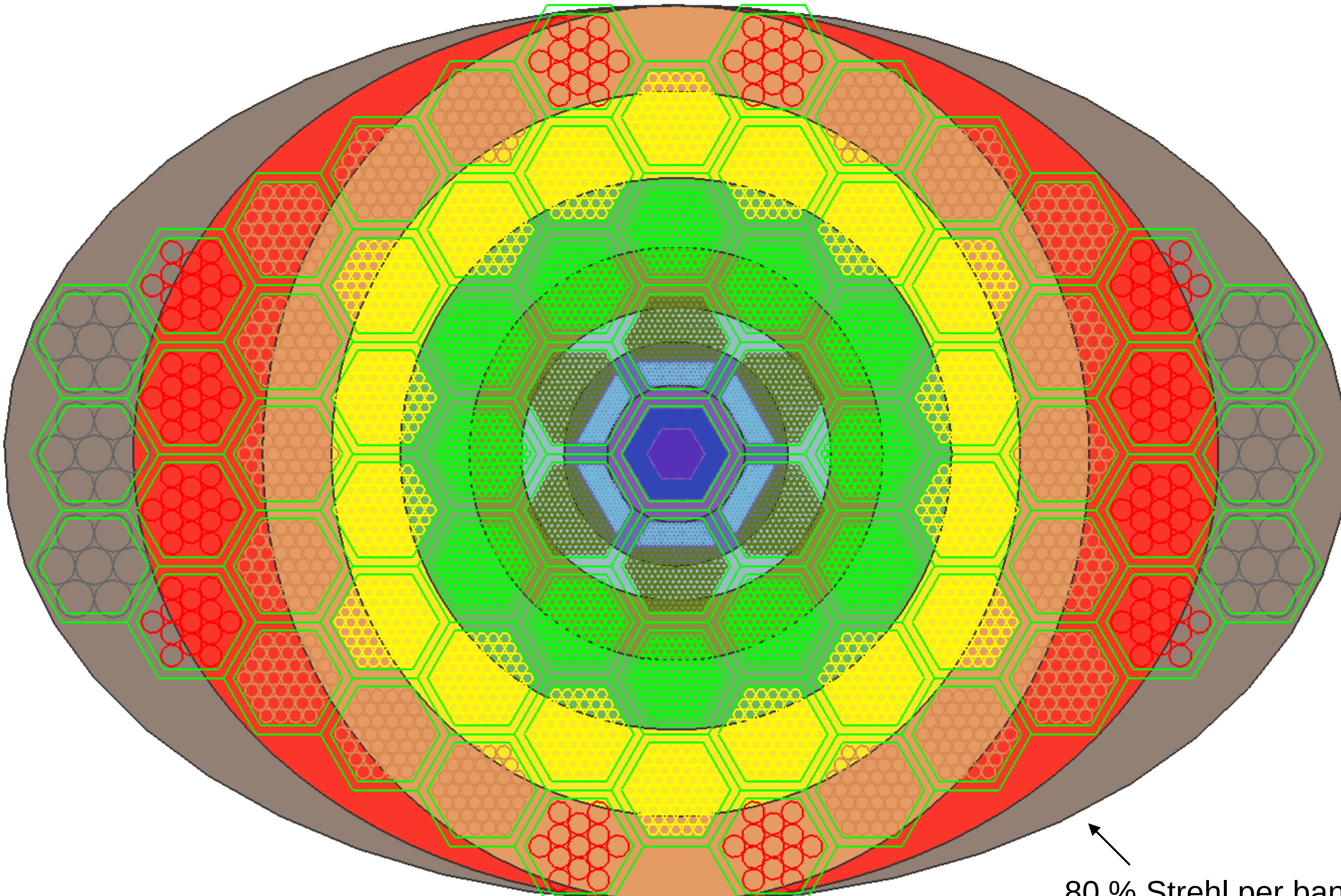




Note: Configurations not shown on same scale
Planck based on flight sensitivity and mission duration

EPIC-	*Low Cost*	*Intermediate Mission 4 K Option*	*Comprehensive Science*
Science	Inflationary B-mode polarization only	Inflationary B-modes, E-modes to cosmic variance, gravitational lensing to cosmic limits, neutrino mass, dark energy, Galactic astronomy	Inflationary B-modes, E-modes to cosmic variance, gravitational lensing, neutrino mass, dark energy, Galactic astronomy
Speed	140 Plancks	1000 Plancks	70 Plancks
Detectors	2400	11,000 (TES bolometer or MKID)	1500
Aperture	Six 30 cm refractors	1.4 m Crossed Dragone telescope	3 m Gregorian Dragone
Bands	30 – 300 GHz	30 – 300 GHz + 500 & 850 GHz	30 – 300 GHz
Cooling	LHe cryostat + ADR	4 K Cryo-cooler + ADR	TBD
Mass	1320 kg CBE	1670 kg CBE	3500 kg CBE
Publication	ArXiv 0805.4207 (192 pages)	ArXiv 0906.1188 (157 pages)	ArXiv 0805.4207 (192 pages)
Cost	$660M (FY07)	$920M (FY09)	No cost assessed

Detectors Fill Out Available FOV

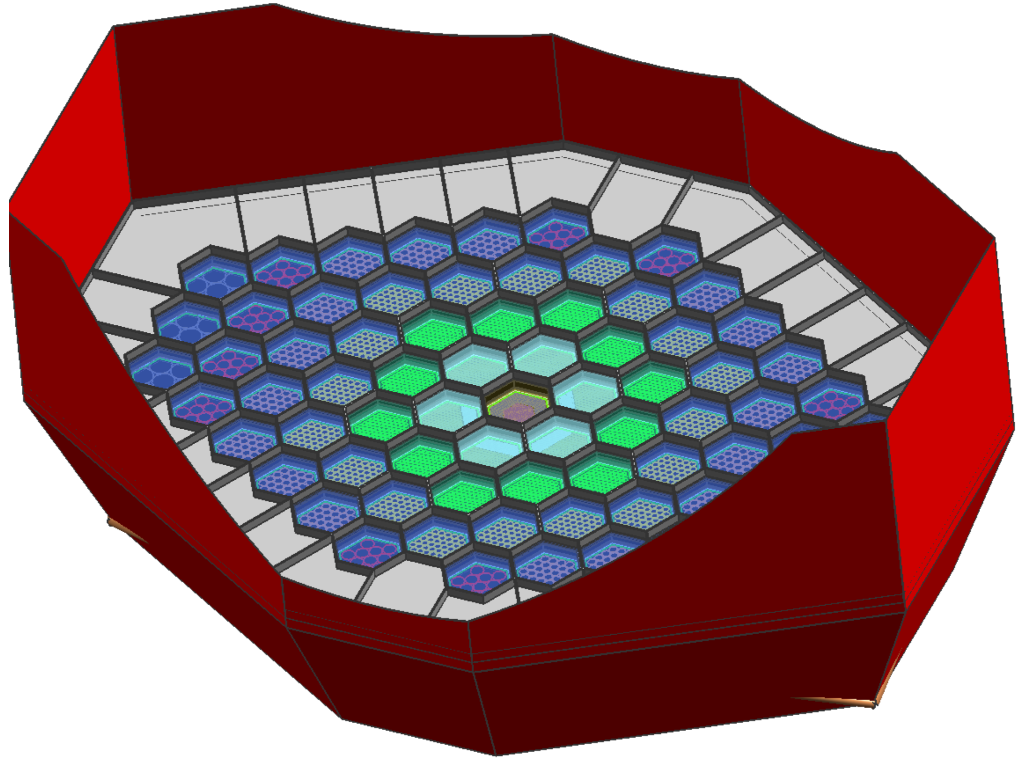


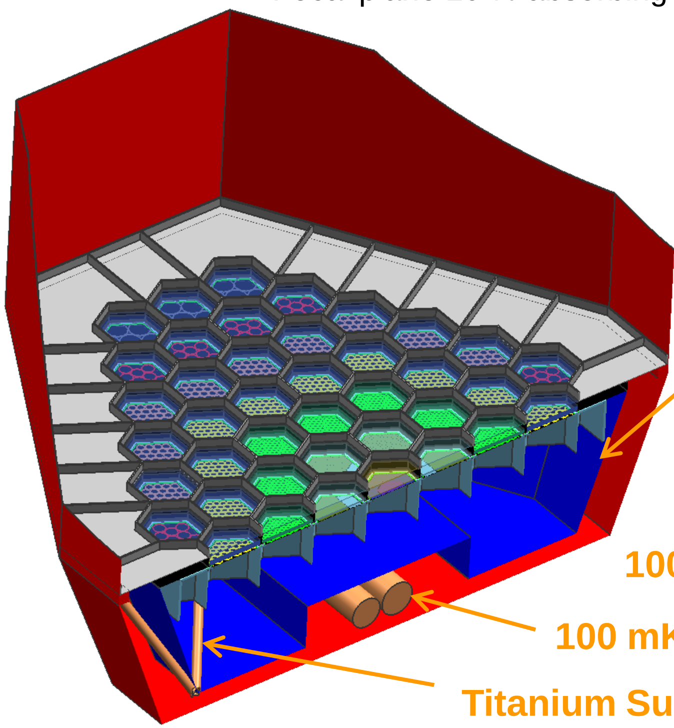
Focal Plane Structure

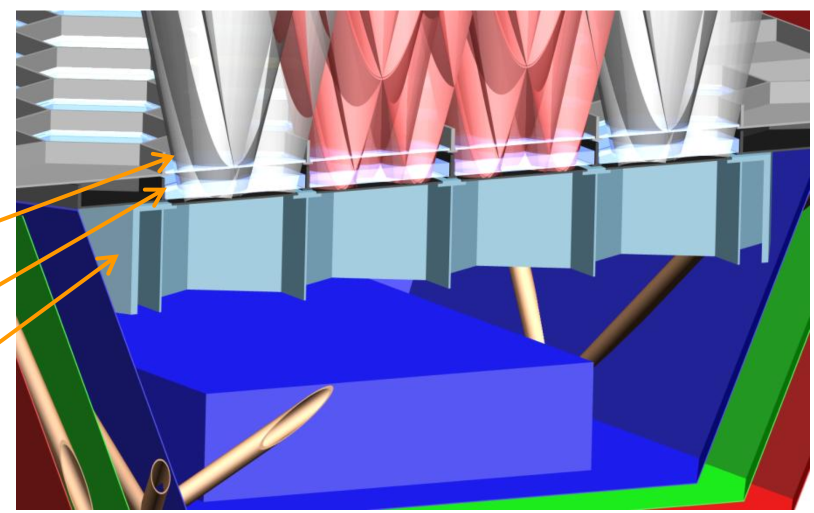
Heat Load Summary (μW)

Freq (GHz)	IR	Readout
850	0.8	0.18
500	0.6	0.15
350	0.4	0.12
220	0.3	0.22
150	0.5	0.48
100	0.2	0.36
70	0.1	0.27
45	0.0	0.07
30	0.0	0.03
Total	2.8	1.9 μW

18 K surround at ε = 100 %
Focal plane 10 % absorbing







Systematic Error Mitigation

Systematic	Description	Goal	Mitigation
	Polarized main beam effects		
Δ Beam Size	$FWHM_E \neq FWHM_H$	$< 4 \times 10^{-5}$	Optical design
Δ Gain	$G_E \neq G_H$	$< 10^{-4}$	Smaller beams
Δ Beam Offset	$Point_E \neq Point_H$	< 0.14”	Measure beams in flight
Δ Ellipticity	$e_E \neq e_H$	$< 6 \times 10^{-6}$	
Δ Rotation	E, H not orthogonal	< 4 ‘	Scan crossings
Pixel rotation	E, H rotated	< 2.4’	Orbit-modulated dipole
Optical Cross-Pol	Birefringence	$< 10^{-4}$	
Satellite Pointing	Q, U offset	< 12"	Gyro + tracker
	Scan Synchronous Signals		
Far Sidelobes	Diffraction, scattering		Optics design, cold baffles
Thermal Variations	Changing sun angle	$< 1nK_{CMB}$	Thermal design
Magnetic Pickup	Detector susceptibility		Shielding
	Thermal Stability		
40 K Baffle	Varying optical power	5 mK/√Hz	
2 K Optics		500 uK/√Hz	Temperature control
0.1 K Focal Plane	Varying thermal signal	200 nK/√Hz	
	Other		
1/f noise	Detector, readout drift	16 mHz	Stabilize focal plane
Passband mismatch	Variation in filters	$\Delta\nu/\nu < 10^{-4}$	Measure

Demonstrated in space or used in Planck (green)

Space required (blue)

Demonstrated in sub-orbital experiments (orange)

Planned sub-orbital demonstration (pink)