Experimental Probe of Inflationary Cosmology (EPIC)

Jamie Bock

JPL / Caltech

The EPIC Consortium

JPL
Peter Day
Clive Dickenson
Darren Dowell
Mark Dragovan
Todd Gaier
Krzysztof Gorski
Warren Holmes
Jeff Jewell
Bob Kinsey
Charles Lawrence
Rick LeDuc
Erik Leitch
Steven Levin
Mark Lysek
Sara MacLellan
Hien Nguyen
Ron Ross
Celeste Satter
Mike Seiffert
Hemali Vyas
Brett Williams

Caltech/IPAC
Charles Beichman
Sunil Golwala
Marc Kamionkowski
Andrew Lange
Tim Pearson
Anthony Readhead
Jonas Zmuidzinas

UC Berkeley/LBNL
Adrian Lee
Carl Heiles
Bill Holzapfel
Paul Richards
Helmut Spieler
Huan Tran
Martin White

Cardiff
Walter Gear

Carnegie Mellon
Jeff Peterson

U Chicago
John Carlstrom
Clem Pryke

U Colorado
Jason Glenn

UC Davis
Lloyd Knox

Dartmouth
Robert Caldwell

Fermilab
Scott Dodelson

IAP
Ken Ganga
Eric Hivon

IAS
Jean-Loup Puget
Nicolas Ponthieu

UC Irvine
Alex Amblard
Asantha Cooray
Manoj Kaplinghat

U Minnesota
Shaul Hanany
Tomotake Matsumura
Michael Milligan

NIST
Kent Irwin

UC San Diego
Brian Keating
Tom Renbarger

Stanford
Sarah Church

Swales Aerospace
Dustin Crumb

TC Technology
Terry Cafferty

USC
Aluizio Prata

CMB: The Most Powerful Tool in Cosmology

… Which Remains Largely Unexplored

Relic from the Early Universe

Discovery by Penzias & Wilson
- A revolution in cosmology
- Strong evidence for Big Bang model

BB Spectrum & anisotropies by COBE
- Big Bang model unassailable
- Support for Inflation

Precision Cosmology

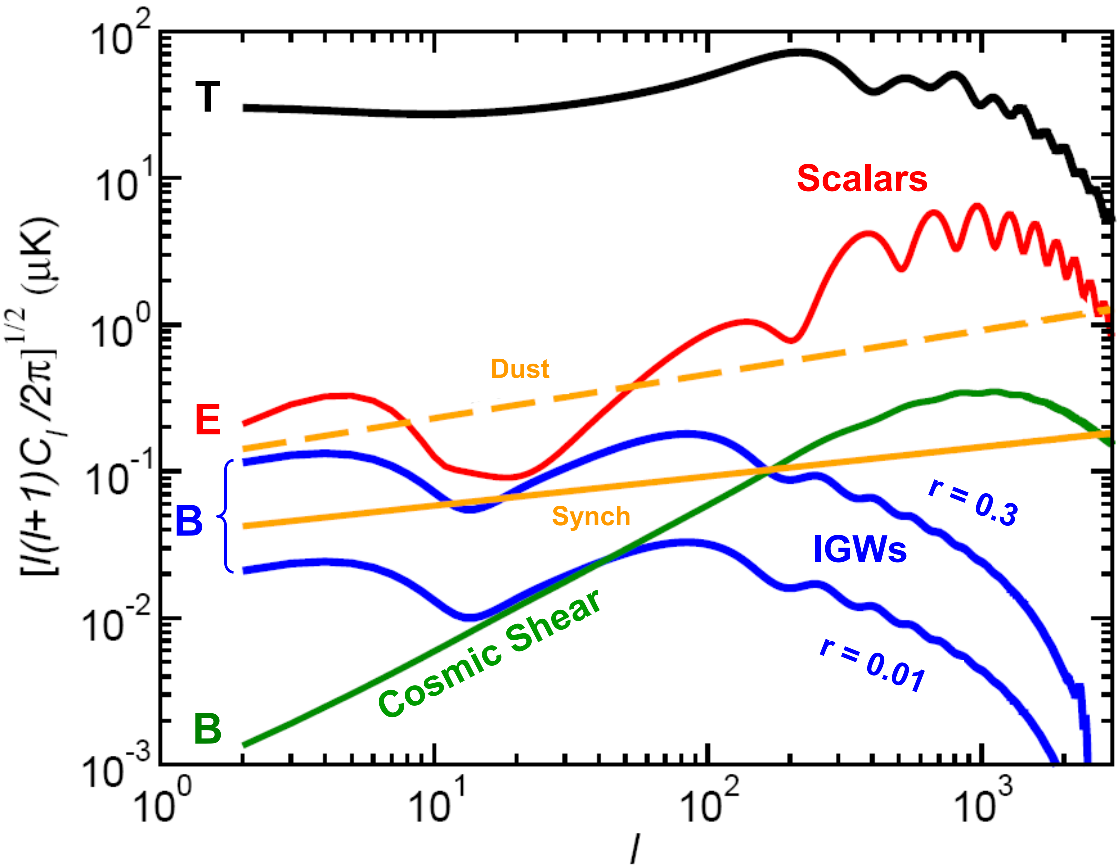
Discovery of first acoustic peak
- Flat universe – confirms Inflation

Temperature power spectrum, WMAP
- Energy/matter content of Universe

Enter Polarization

Gravitational Wave Polarization
- Best probe of Inflationary physics

A Wealth of Cosmology
- Reionization, Gravitational Lensing



EPIC is a Scan-Imaging Polarimeter

Scan detectors across sky to build CMB map
- Simple technique. Established history in CMB.
- Scaling to higher sensitivity → Better arrays
- Adapt this technique for precision polarimetry

EPIC mission concept
- High-TRL, simple, & flexible architecture
- High sensitivity, wide band coverage, low angular resolution*

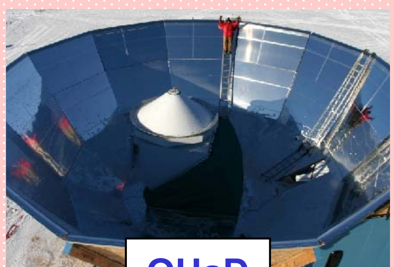
**See Weiss Committee TFCR Report: astro-ph 0604101*


Boomerang


Maxipol

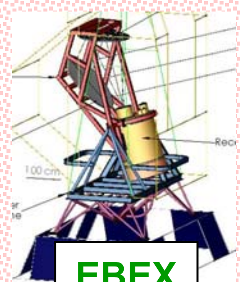
PAST


BICEP

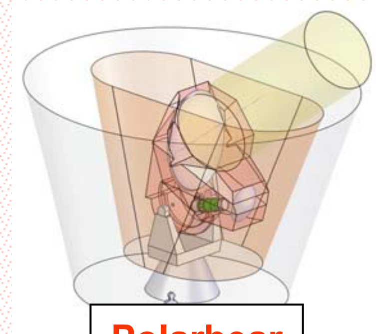

QUaD

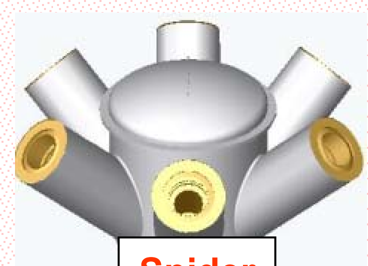
ACTIVE


Planck

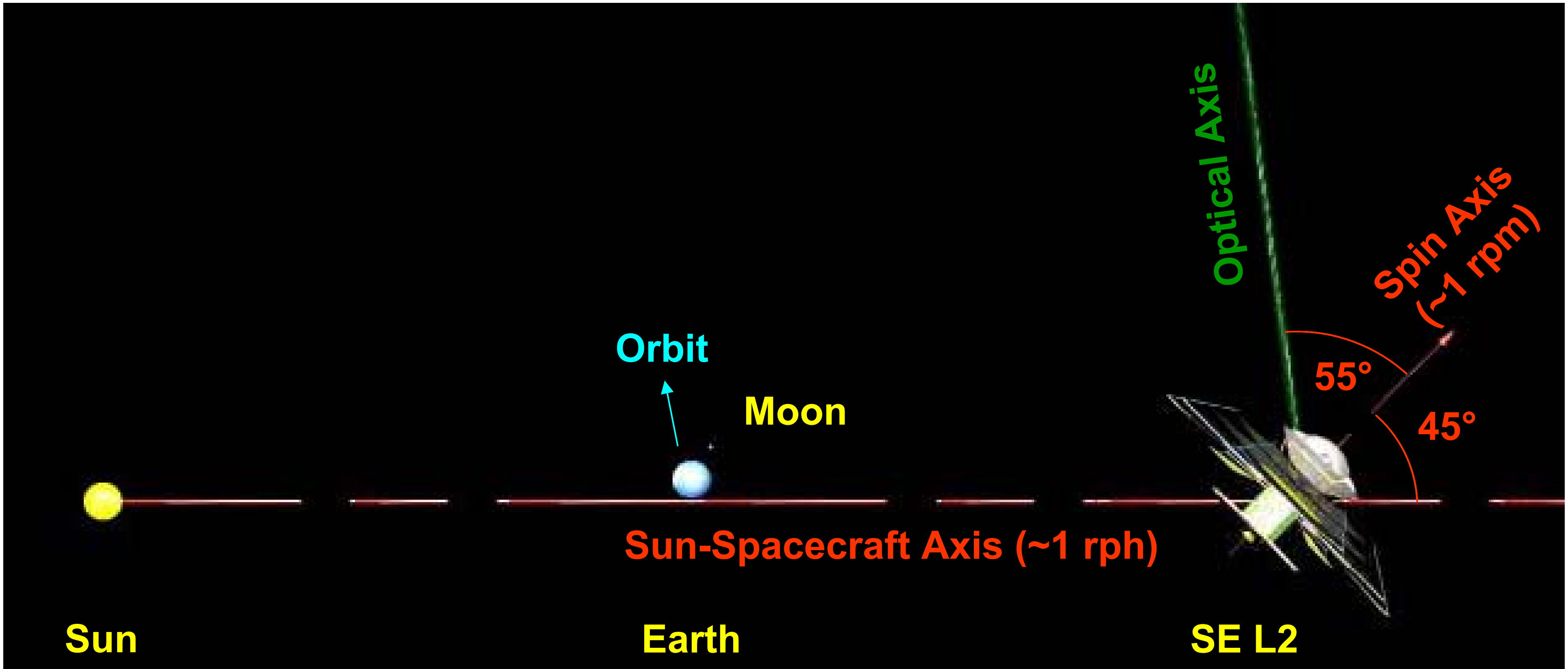

EBEX

PLANNED


Polarbear

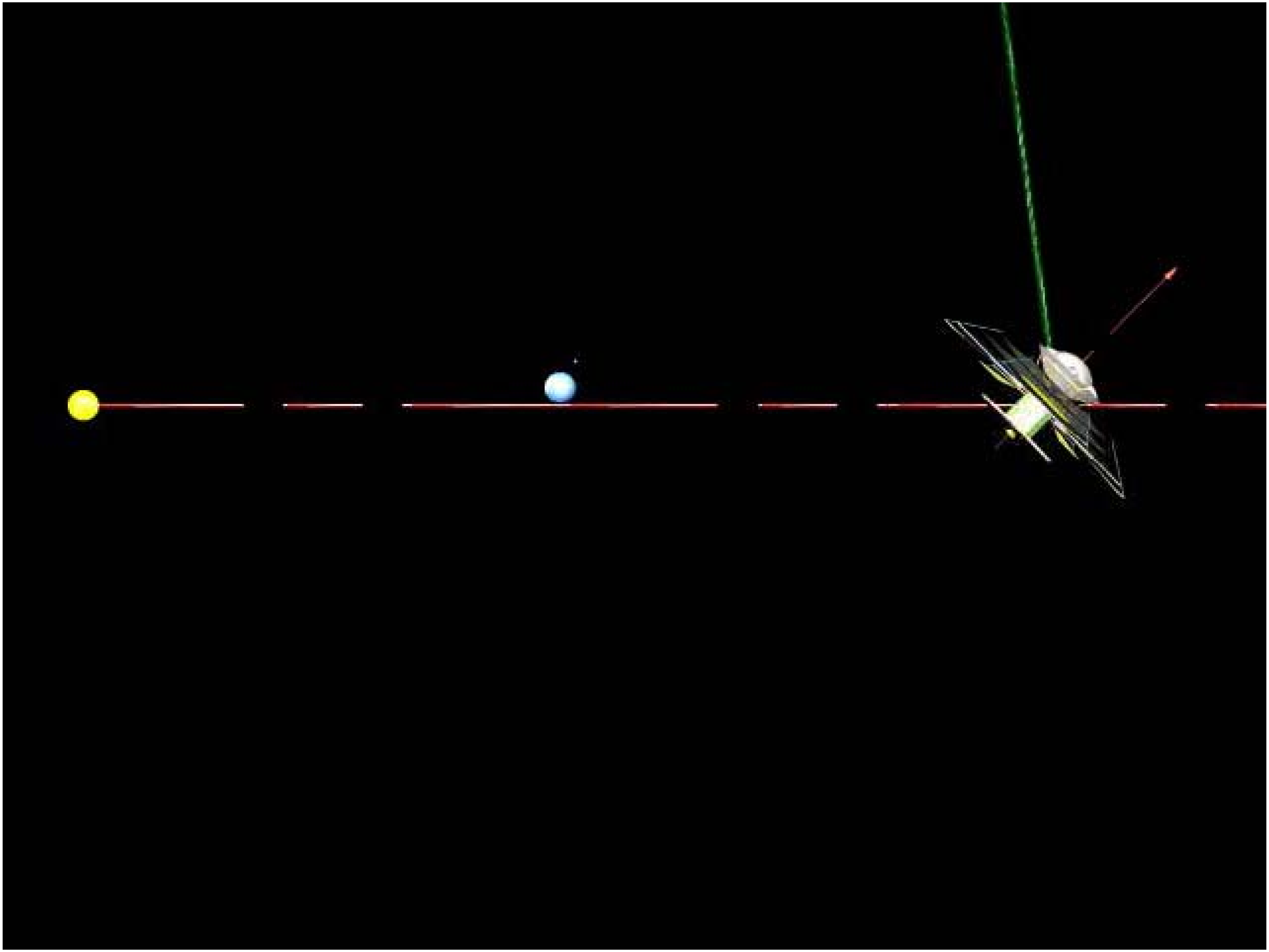

Spider

FUTURE

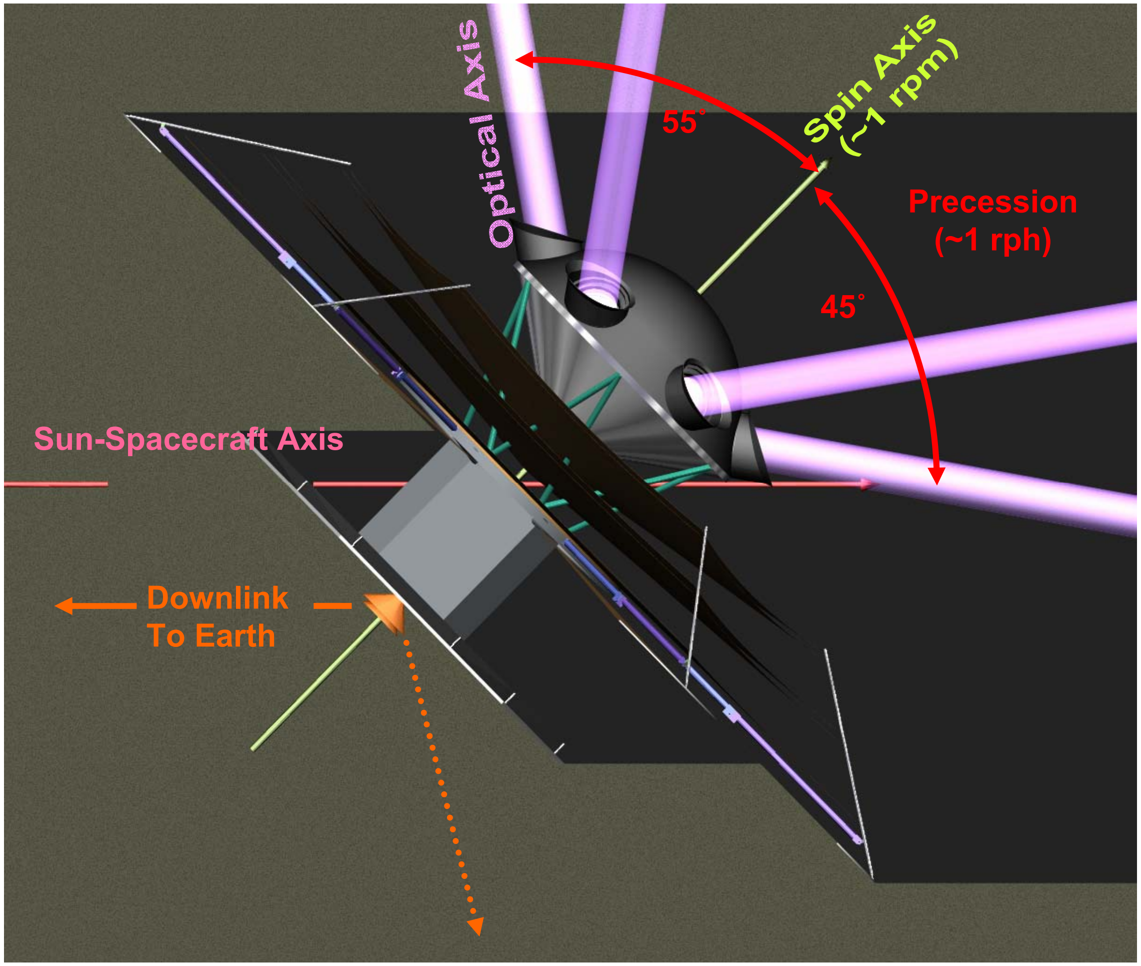


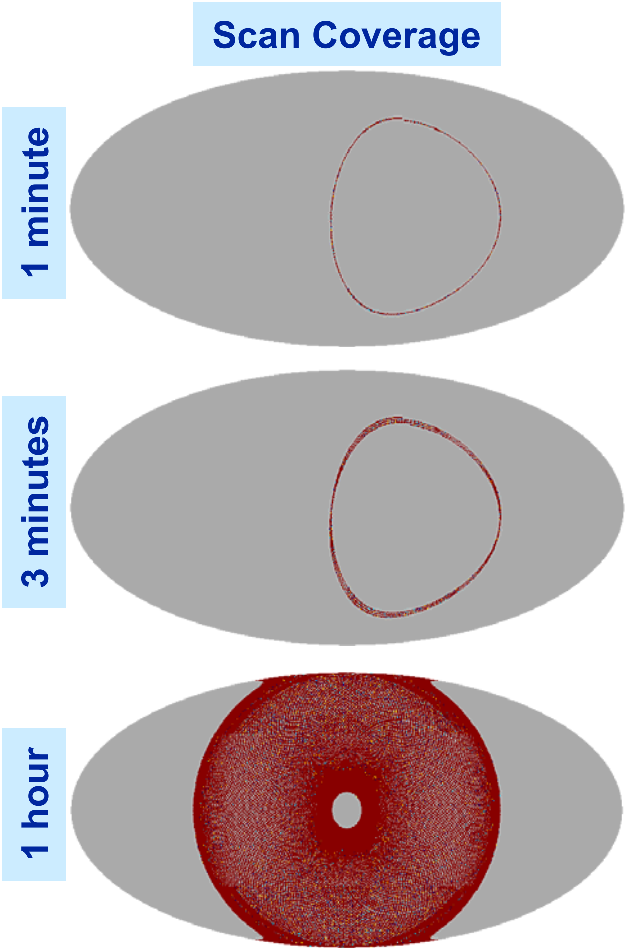
<u>Why Space?</u>

- All-Sky Coverage
- High Sensitivity
- Systematic Error Control
- Broad Frequency Coverage

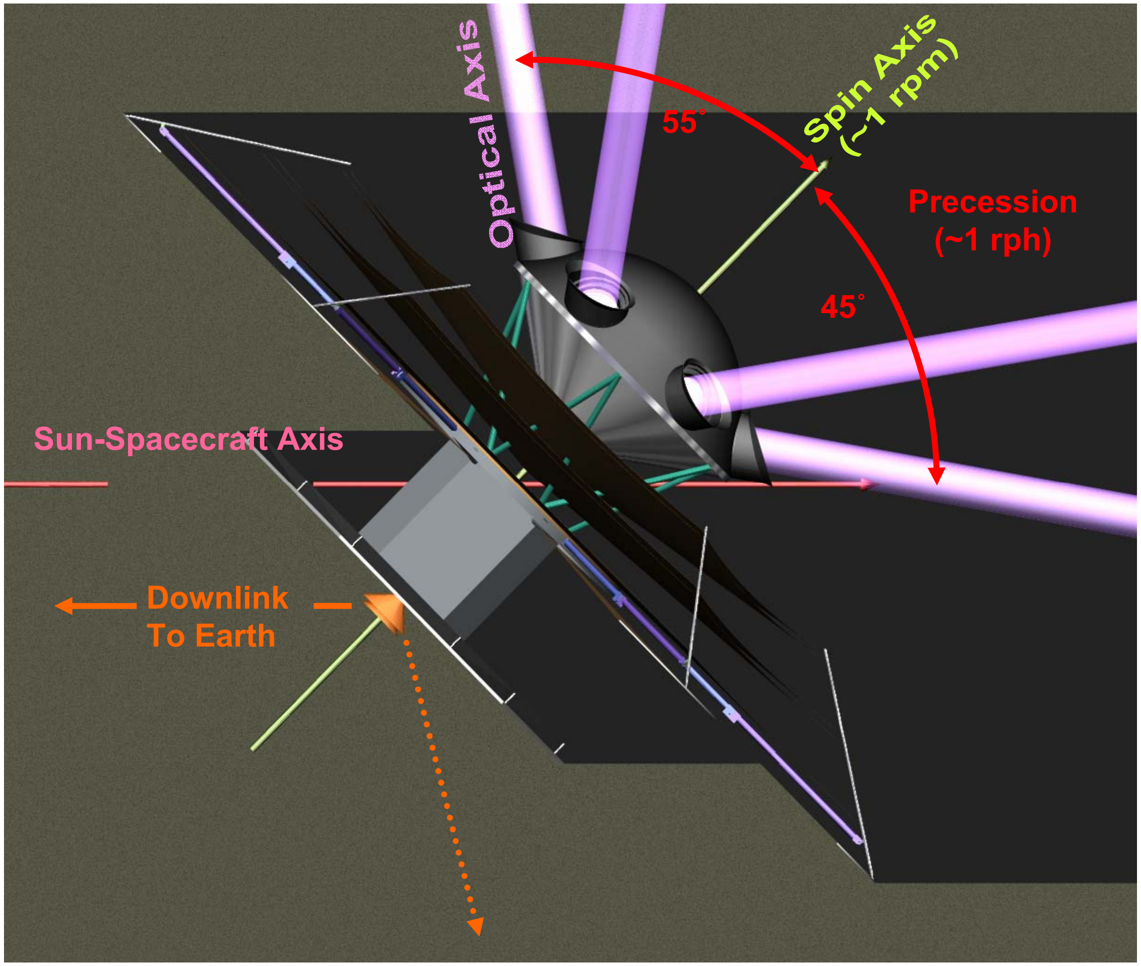


Scan Strategy

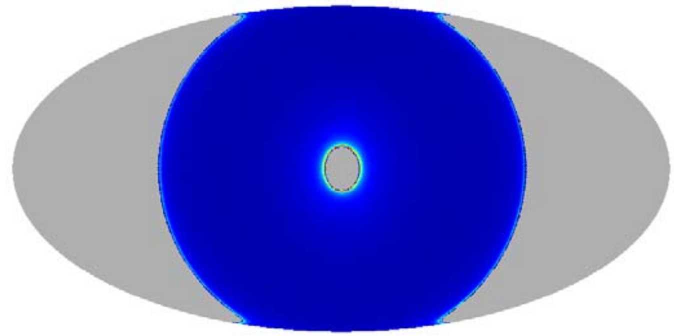




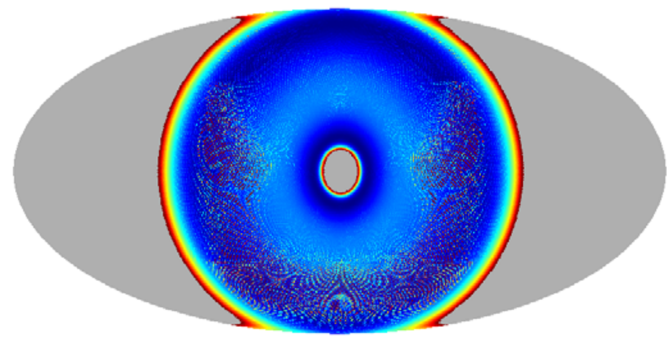
Scan Strategy



1 Day Maps



Spatial Coverage



Angular Uniformity

More than half the sky in a single day!

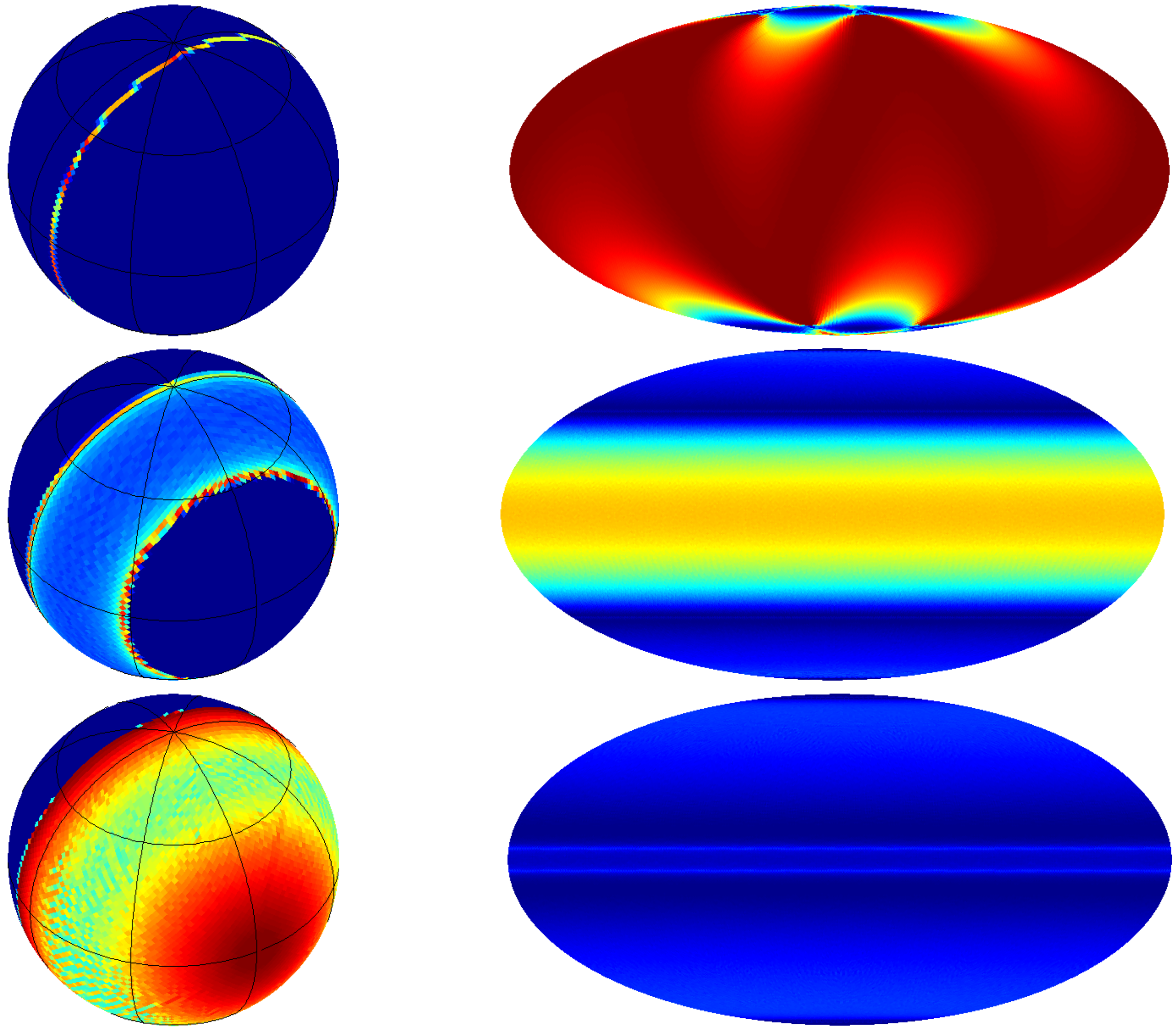
Redundant & Uniform Scan Coverage

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

Planck

WMAP

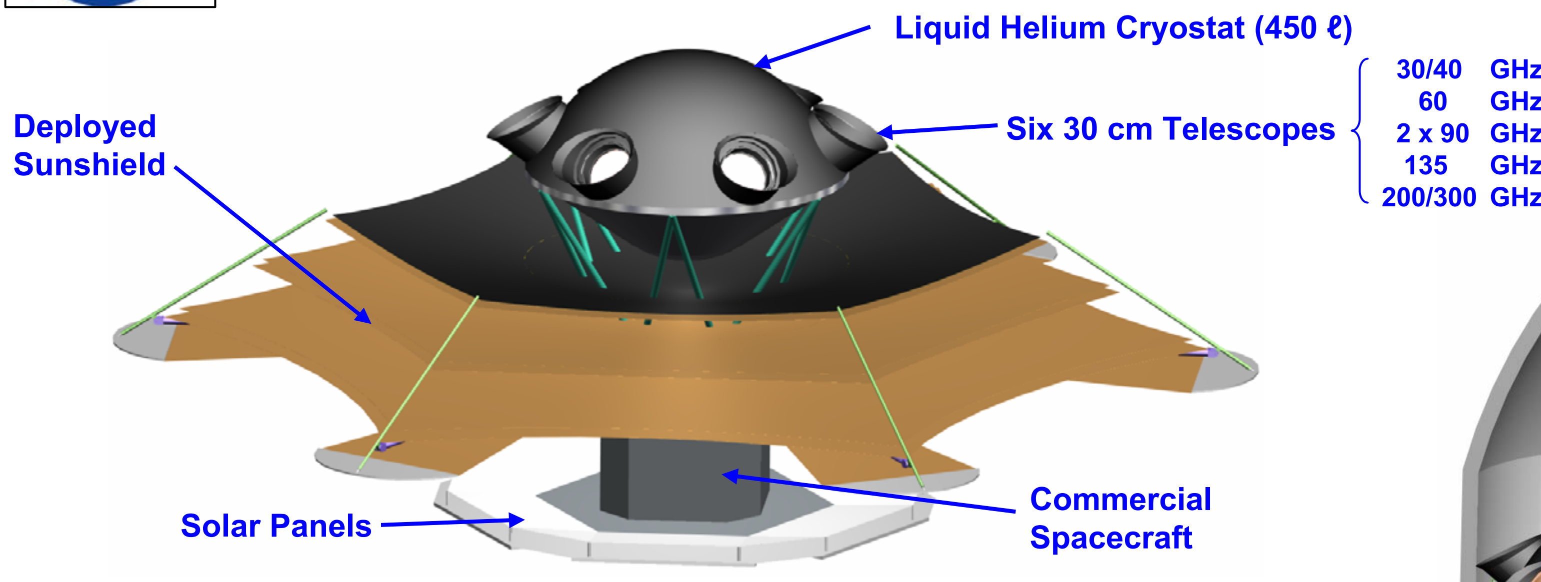
EPIC

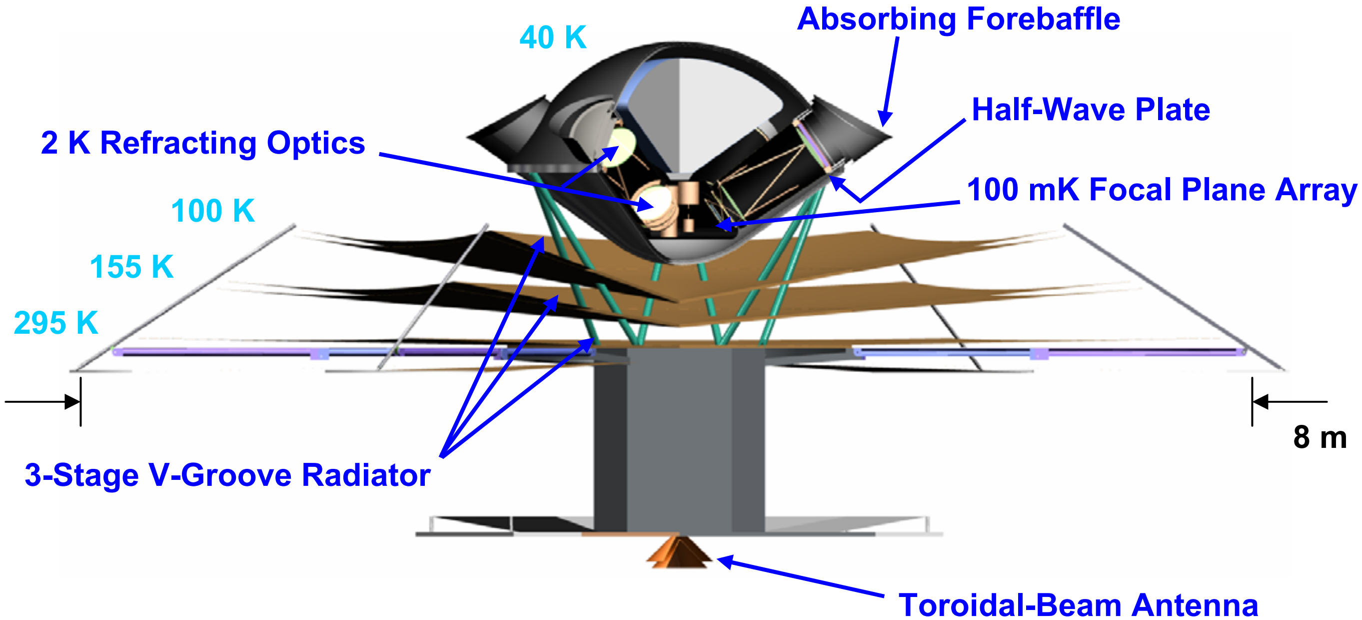


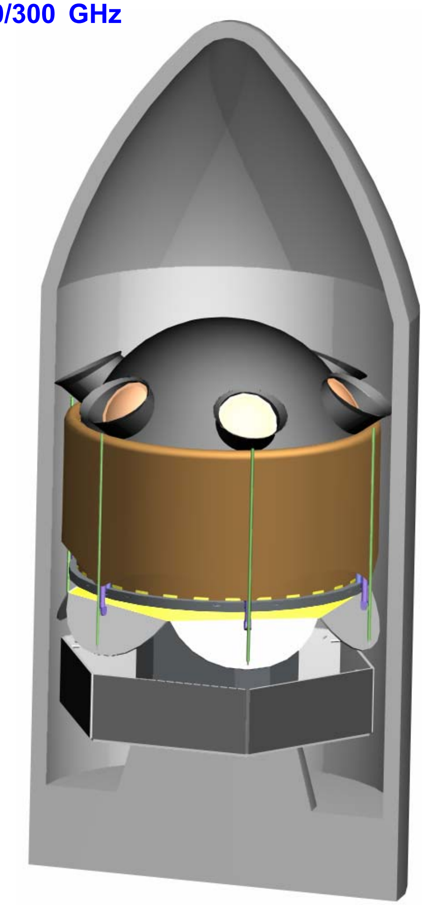
*$\langle \cos 2\beta \rangle^2 + \langle \sin 2\beta \rangle^2$

0  1

EPIC Mission Architecture

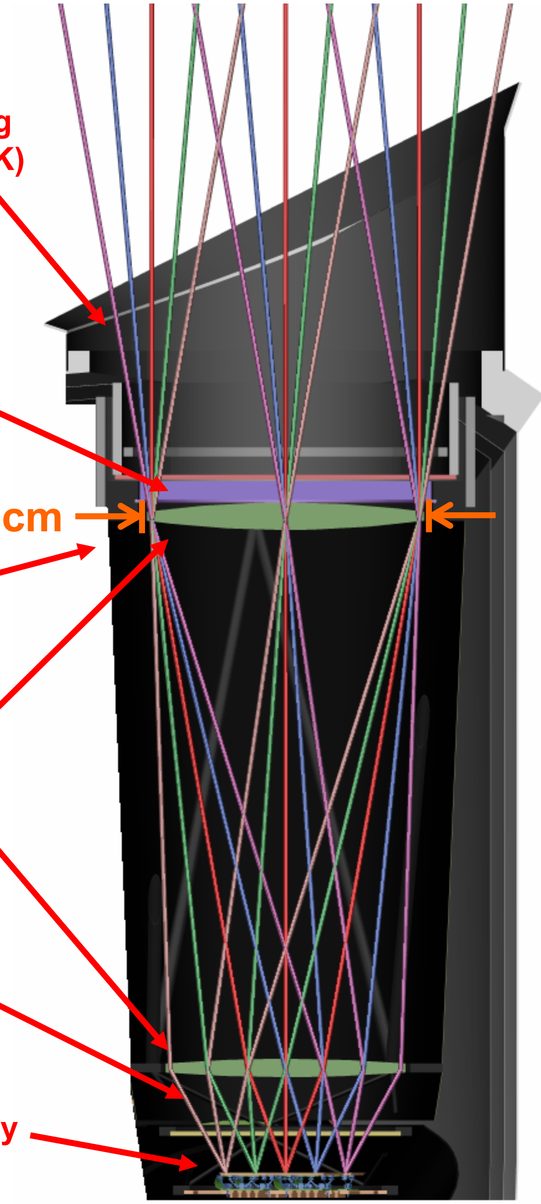






Delta 2925H 3-m

High Sensitivity with High-TRL Focal Planes



EPIC Projected Bands and Sensitivities

Freq [GHz]	FWHM [arcmin]	NTD Ge Bolometers # [det's]	NTD Ge Bolometers NET/det* [μK√s]	NTD Ge Bolometers NET* [μK√s]	*Planck* *NET/det*† *[μK √s]*
30	155	8	69	24.5	
40	116	54	60	8.2	
60	77	128	49	4.4	
90	52	256	42	2.6	*102*
135	34	256	38	2.4	*83*
200	23	64	41	5.1	*134*
300	16	64	95	11.8	*404*
Total		**830**		**1.5**	

*Design Sensitivity †Goal Sensitivity

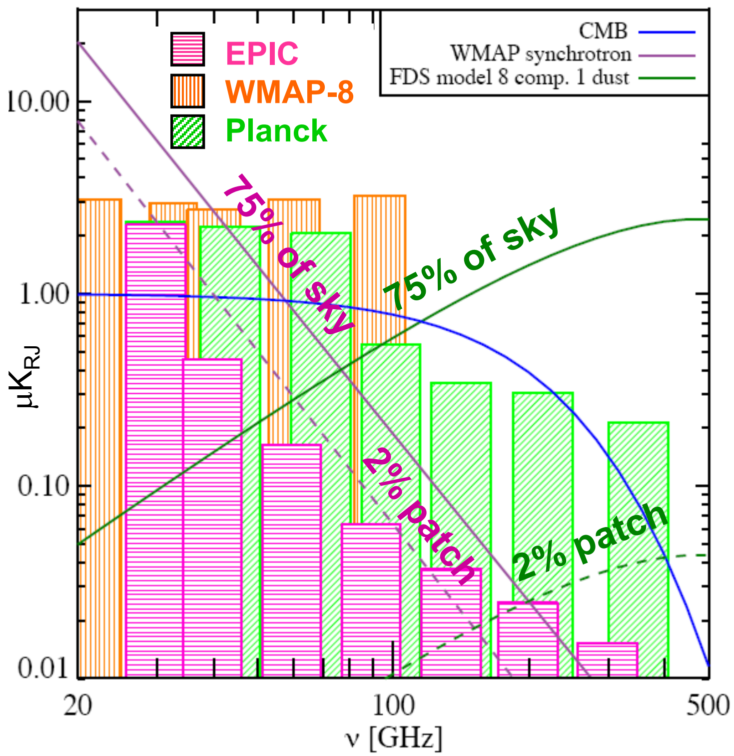
Note modest detector improvement over Planck due to relaxed time constant specification & 2 K optics

Planck Projected Sensitivities

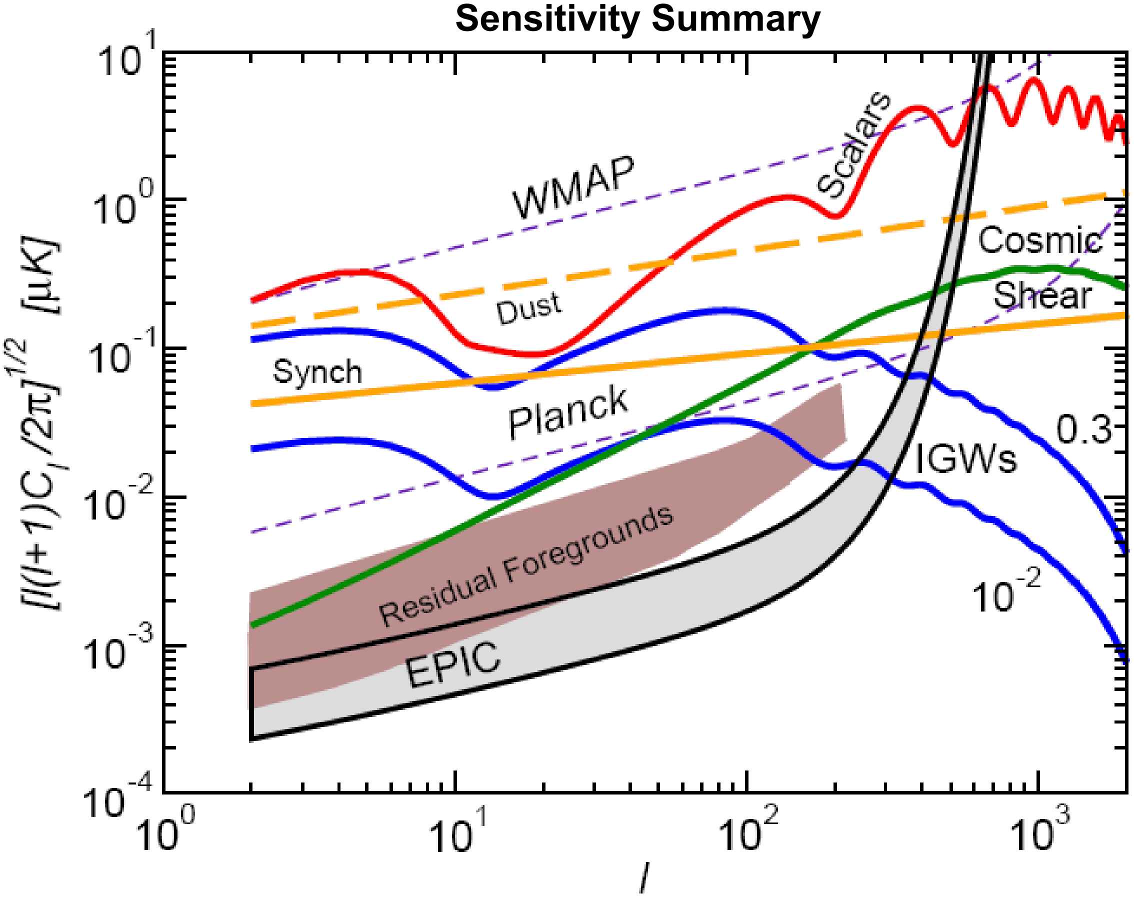
Instrument	Technology	NET [μK√s]	Value
HFI 100 – 850 GHz	NTD Ge Bolometer	20.3	Design Goal
		< 16.7	Measured
LFI 30 – 70 GHz	HEMT	68.9	Req't

Measuring B-Polarization to Lensing Limit

Multi-Band Foreground Monitoring



Sensitivity Summary



1. Input Sky Model

- Synchrotron
- Thermal dust
- Free-free
- Spinning dust

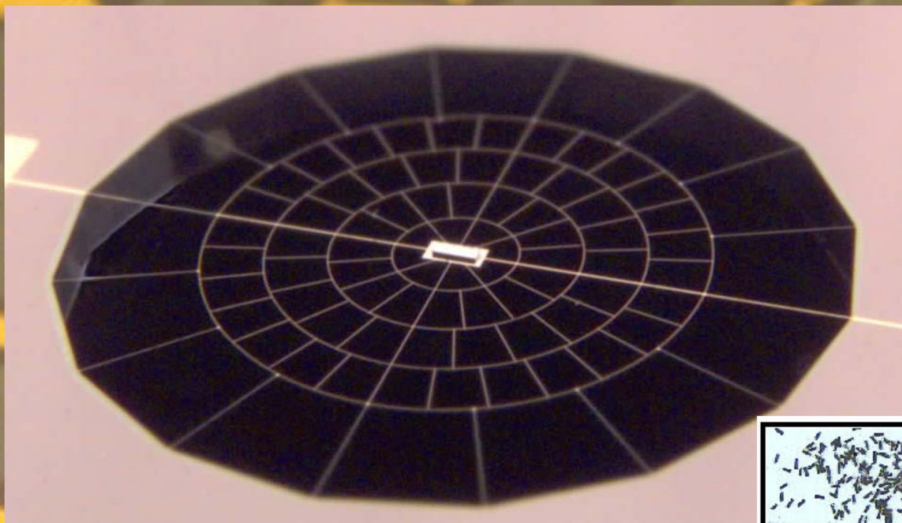
2. Multi-band Removal

- Fit components spectrally
- Let indicies float spatially

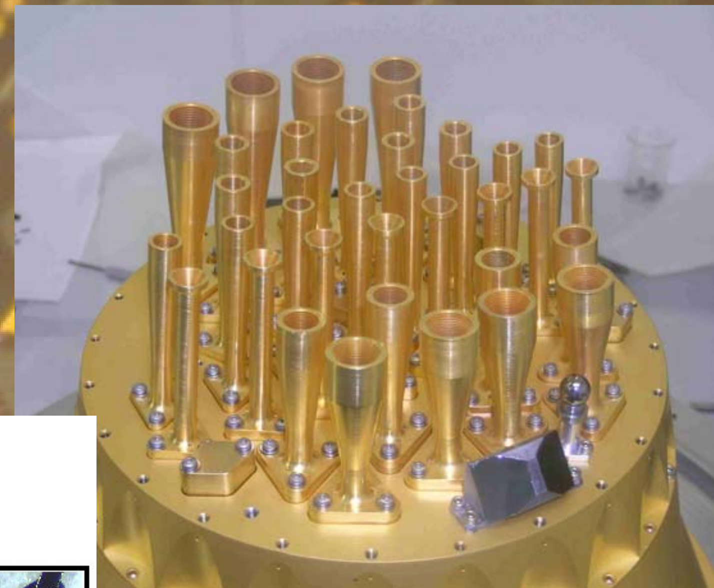
3. Results

- Removal gives a *modest* sensitivity loss
- Better sensitivity gives better subtraction

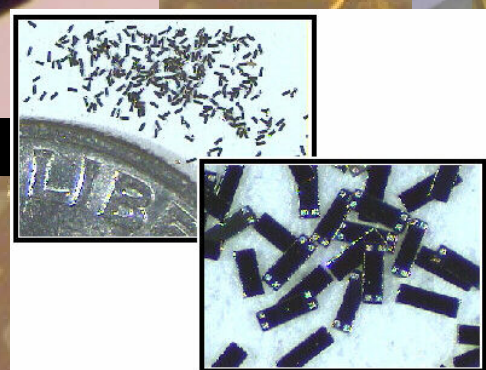
NTD Bolometers for Planck & Herschel



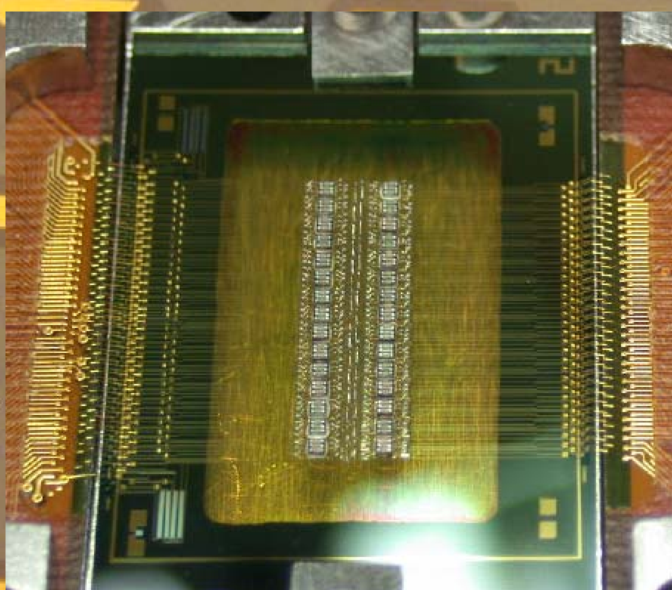
143 GHz Spider-web Bolometer



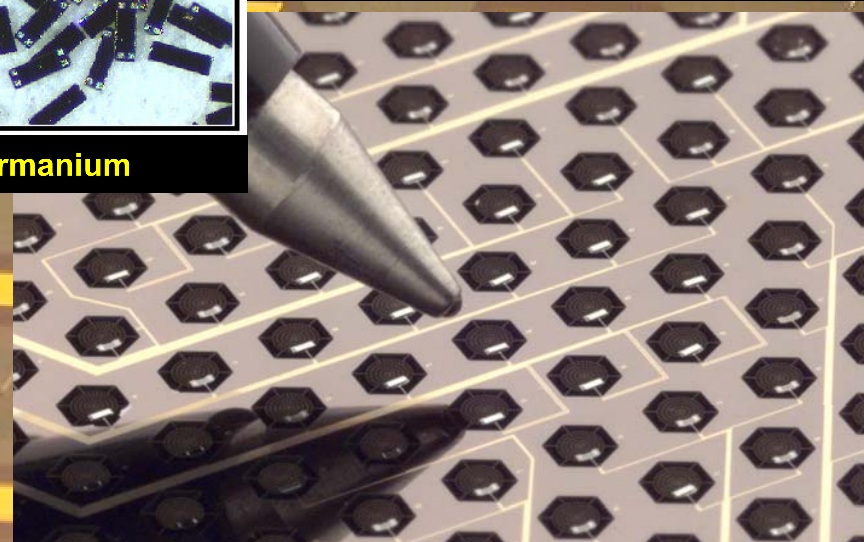
Planck/HFI focal plane (52 bolometers)



NTD Germanium



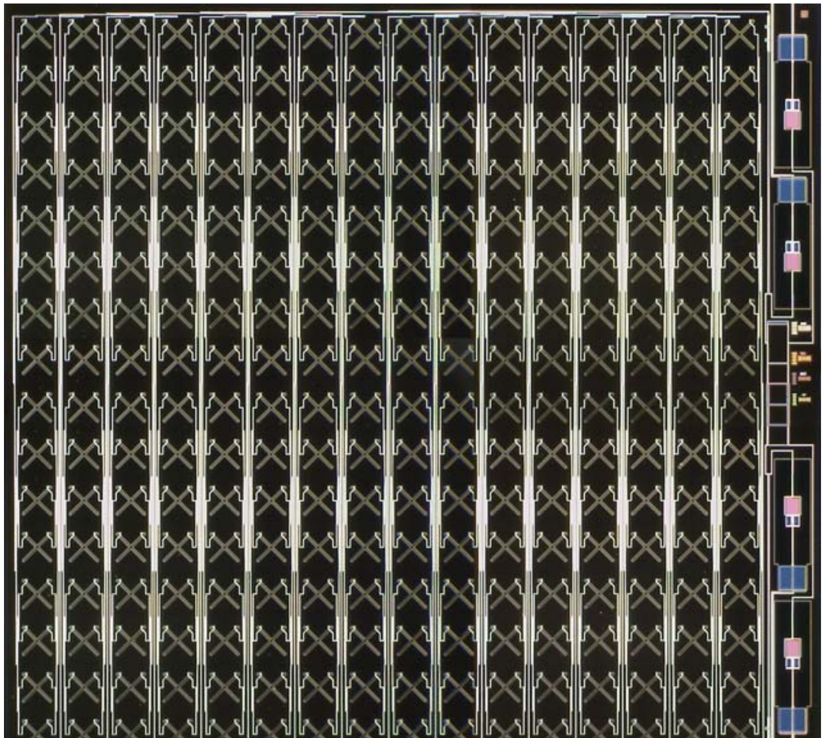
SPIRE Low-power JFETs



Herschel/SPIRE Bolometer Array

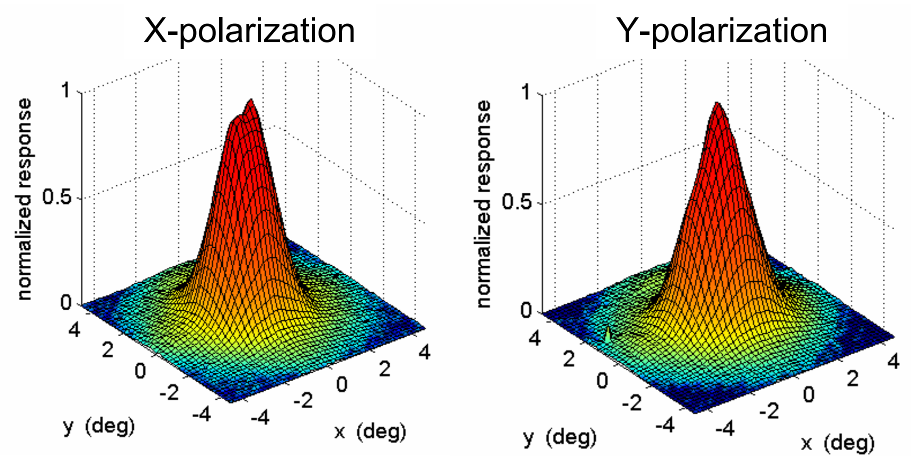
Antenna-Coupled Bolometers for EPIC

8 mm

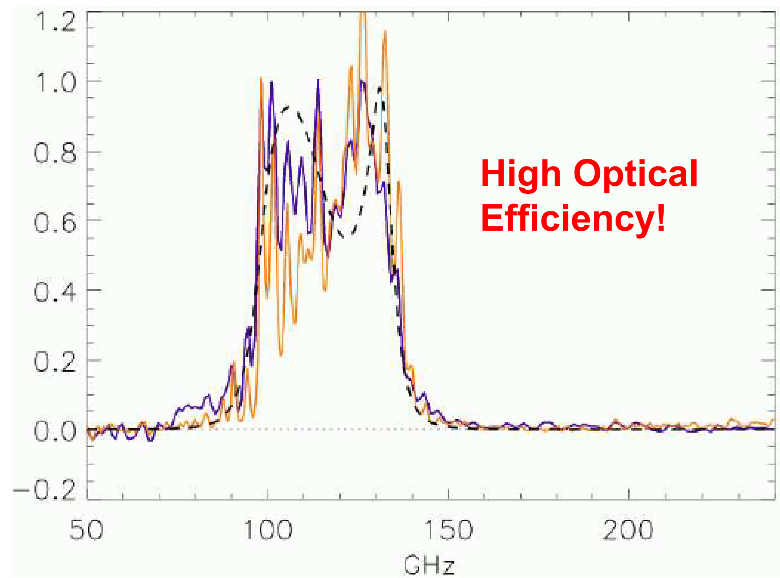


Single Pixel – Dual Polarization at 150 GHz

Measured Beam Patterns



Measured Spectral Response



Kuo *et al*. SPIE 2006

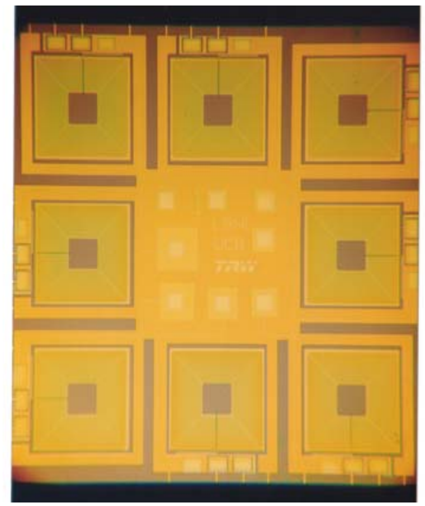
Advantages

Small active volume.. 30 – 300 GHz operation
Beam collimation…... Eliminates discrete feeds
Reduced focal plane mass
Intrinsic filters…….... No discrete components

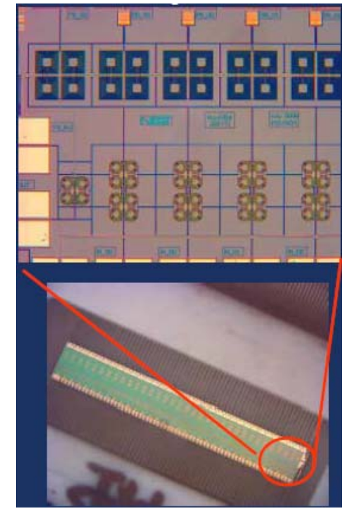
TES Bolometer Arrays

Advantages	
Multiplexing…….	Larger array formats
	Higher sensitivity
	Fewer wires to 100 mK
	Low cryogenic power disp.
Faster response...	Useful for larger aperture

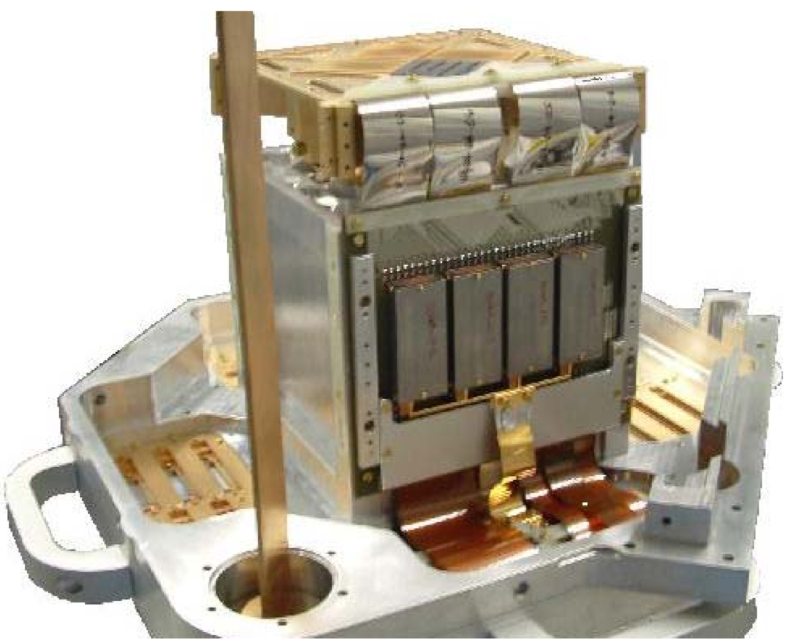
SQUID Multiplexing



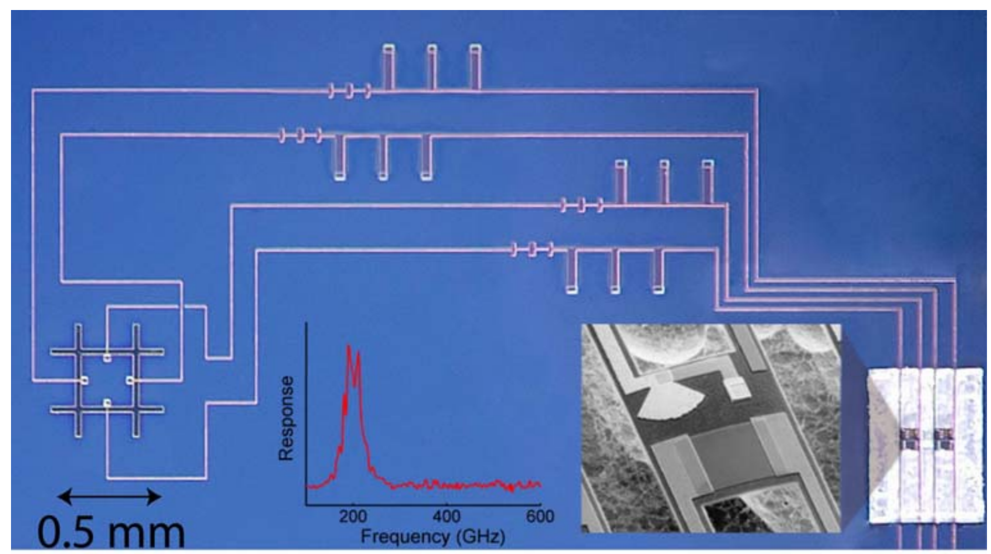
Freq. Domain (UCB/LBNL)



Time Domain (NIST)



SCUBA2 Focal Plane (10,000 TES Bolometers)



Antenna-Coupled TES Bolometers (UCB/LBNL)

EPIC Employs High-TRL Technologies

Technology	TRL	Heritage
Focal Plane Arrays (NTD Ge bolometers)		
NTD thermistors and readouts	8	Planck & Herschel
Antennas	4	
Wide-Field Refractor	6	BICEP
Waveplate (stepped every 24 hours)		
Optical configuration	6	SCUBA, HERTZ, etc.
Cryogenic stepper drive	9	Spitzer
LHe Cryostat	9	Spitzer, ISO, Herschel
Sub-K Cooler: Single-shot ADR	9	ASTRO-E2 (single-shot)
Deployable Sunshield	4-5	TRL=9 components
Toroidal-Beam Downlink Antenna	4-5	TRL=9 components

New technologies bring enhanced capabilities…

Antenna-Coupled TES / MKID detectors → Higher sensitivity, less mass & power
Continuously rotating waveplate → Better beam control
Continuous ADR → Less mass, no interruptions

…but we have the technology to do this mission today.

<u>We need technology *evolution* not *revolution*</u>

Systematic Error Mitigation Strategy

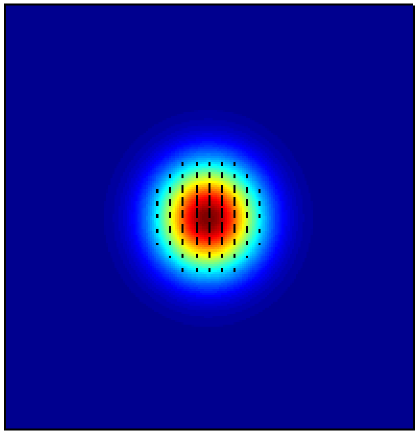
Instrument Design Goal	Instrument Requirement
Suppress *raw* systematic effect below statistical noise level	Suppress systematic errors below r = 0.01 *after correction*

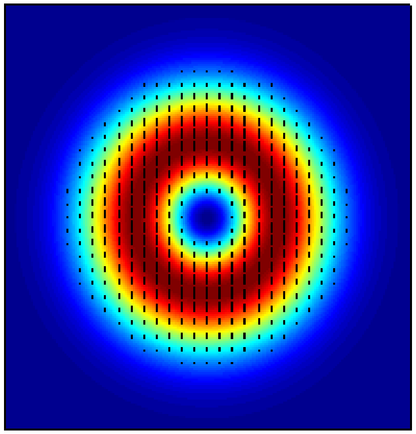
Systematic Effect		Design Goal	Mitigations	Heritage
Main Beam Effects	ΔBeamsize	1e-4	• Refracting telescope • Waveplate before telescope • Scan crossings & CMB dipole	BICEP† SPIDER‡ ---
	ΔGain	8e-5		
	ΔBeam Offset	5e-5		
	ΔEllipticity	1e-3		
	Pol. Beam Rot'n	3e-4		
Polarized Sidelobes		1 nKrms	• Refractor + baffle	BICEP*
1/f Noise		16 mHz	• Drift-scanned NTD bolometers • (TES + modulator) • Scan crossings	BOOMERANG* EBEX/SPIDER/ POLARBEAR‡ ---
Scan-Synch Signals		1 nKrms	• Scan redundancy	---
Optics Temp. Stability		10 μKrms s/s 300 μK/√Hz	• Dual analyzers	Planck*
Focal Plane Temp. Stability		3nKrms s/s 150 nK/√Hz	• Temperature monitoring & control of all critical stages	Planck*

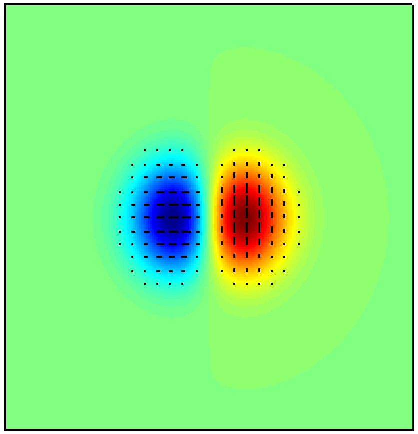
* = Already demonstrated to EPIC requirement
† = Proof of operation but needs improvement
‡ = Planned demonstration to EPIC requirement

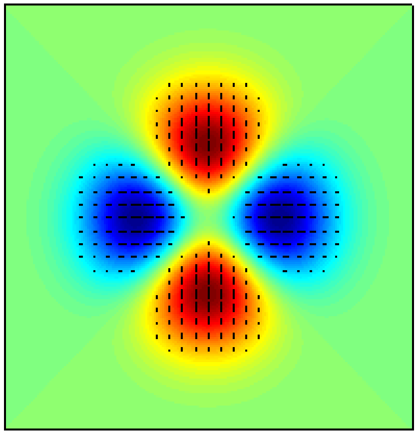
Polarization Systematics: Main Beams

Main Beam Instrumental Polarization Effects


Differential Gain, Rotation


Differential FWHM

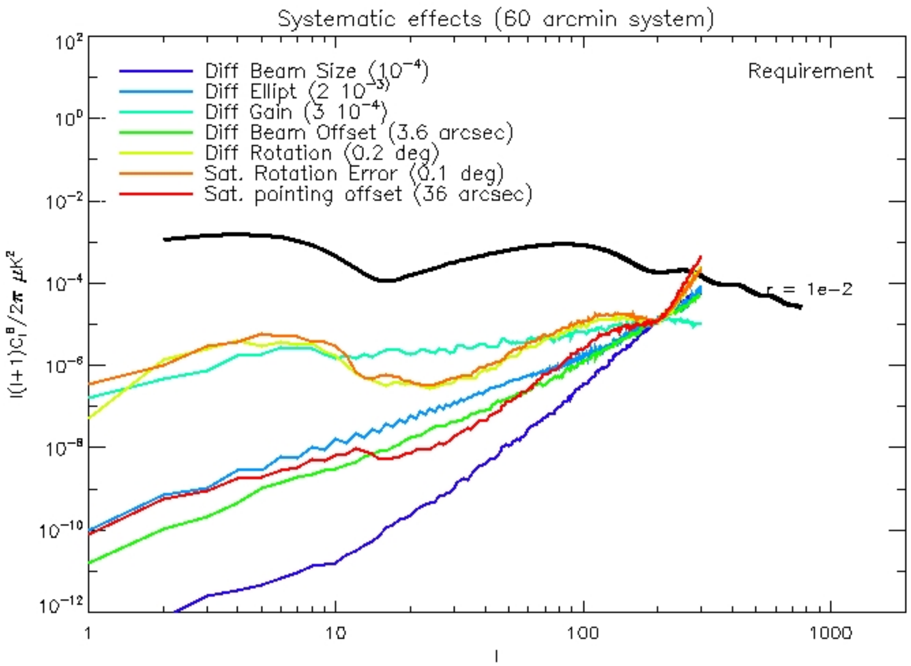

Differential Beam Offset


Differential Ellipticity

Calculation
- Difference PSB beam pairs
- Parameterize main beam effects
- Convolve w/ scan pattern
- Calculate resulting power spectrum

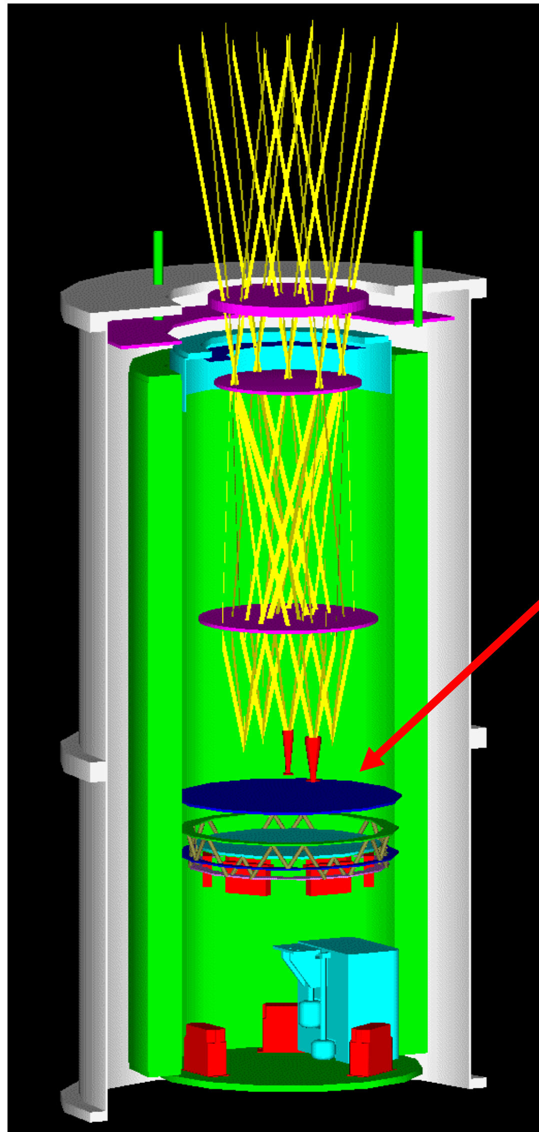
Result
- Calculated telescope performance meets or exceeds requirements

Caveats
- Calculation is conservative
- We can always apply *post facto* correction
- Waveplate virtually *eliminates* these effects



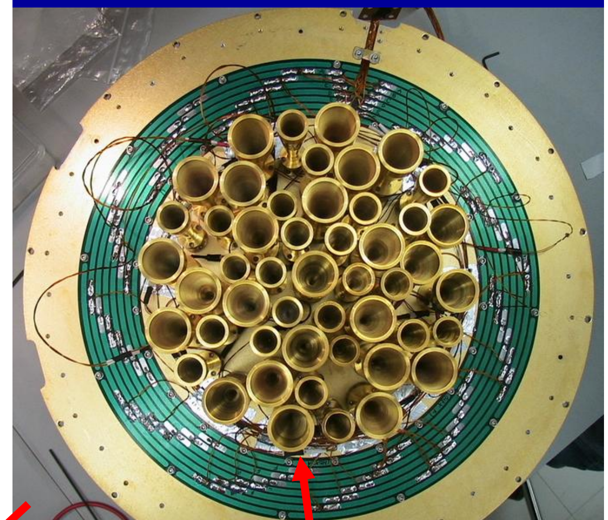
Demonstration of EPIC Technologies

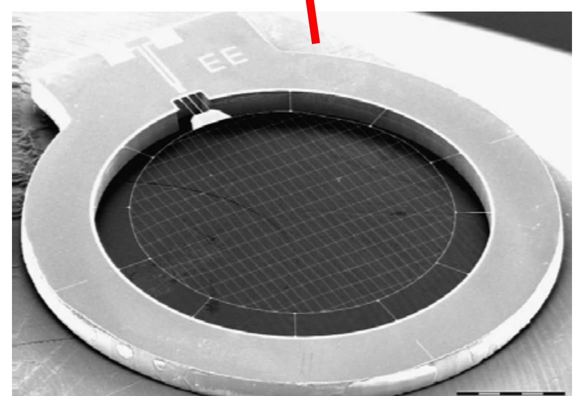
BICEP



Refracting Optics

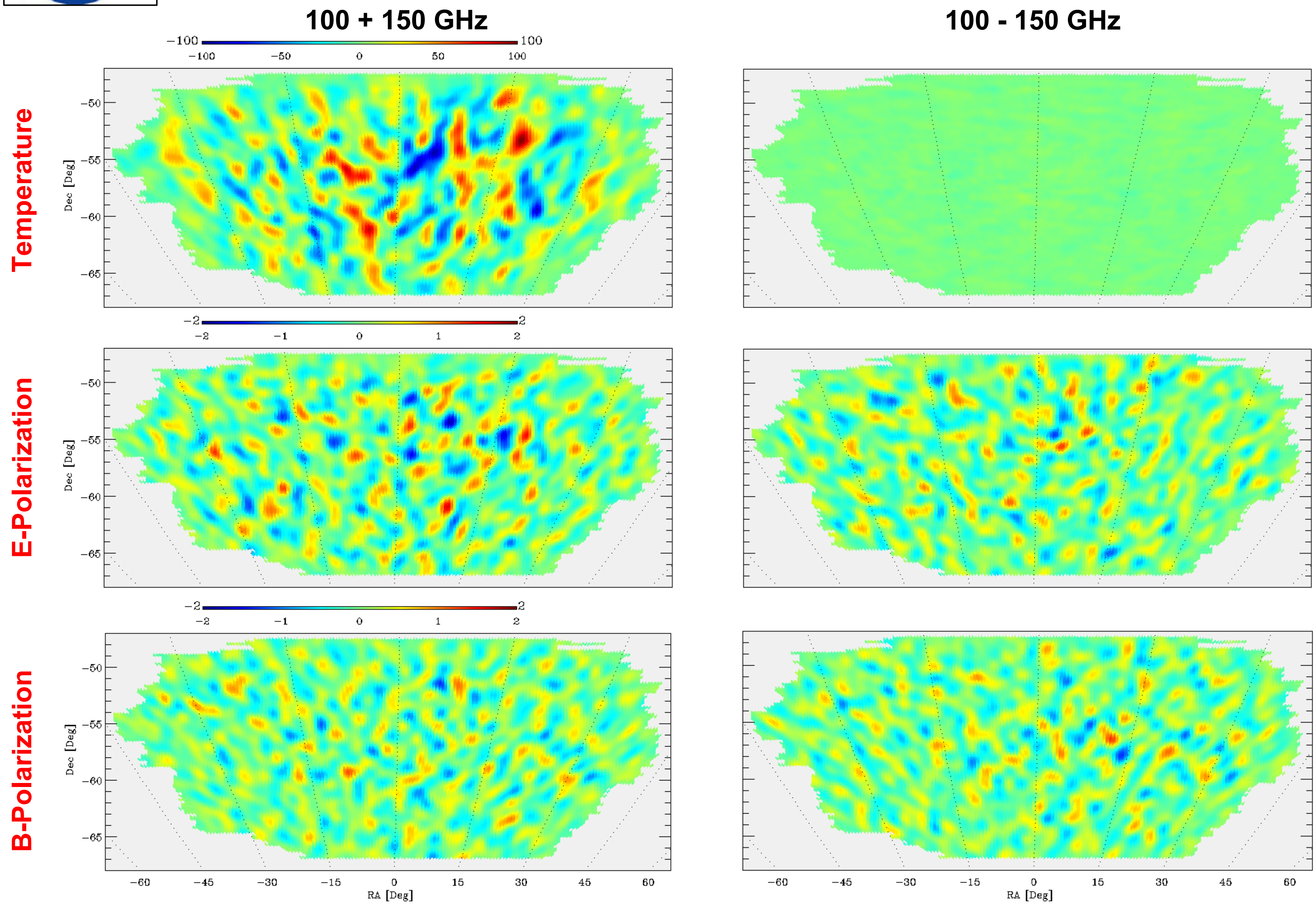
Focal Plane (98 NTD bolos)





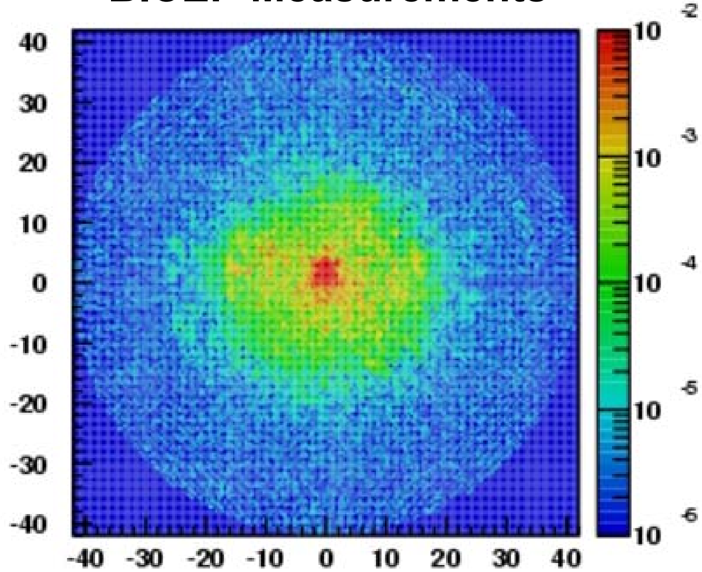
Pol. Sensitive Bolometer

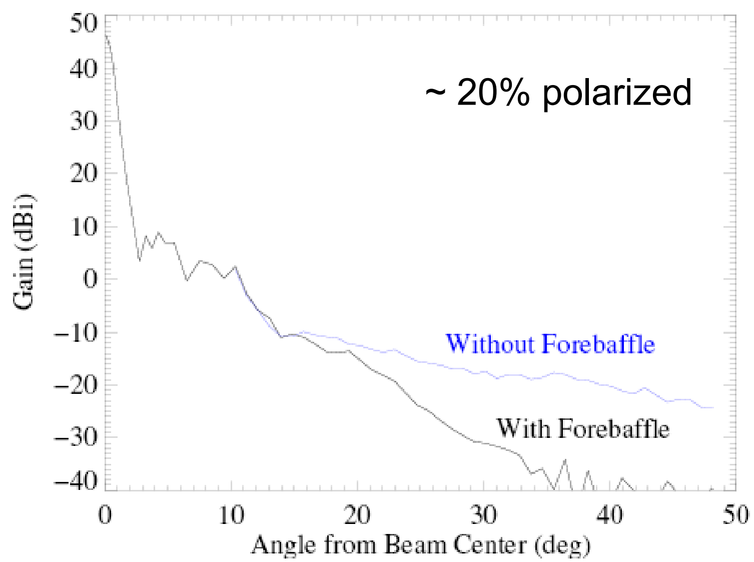
First-Season Maps from BICEP



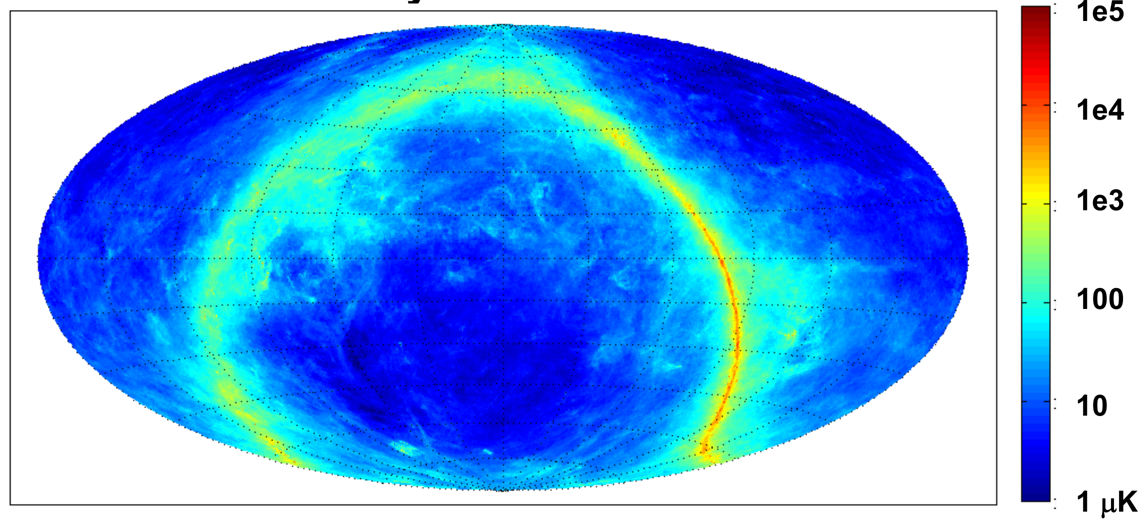
Far-Sidelobe Performance

BICEP Measurements

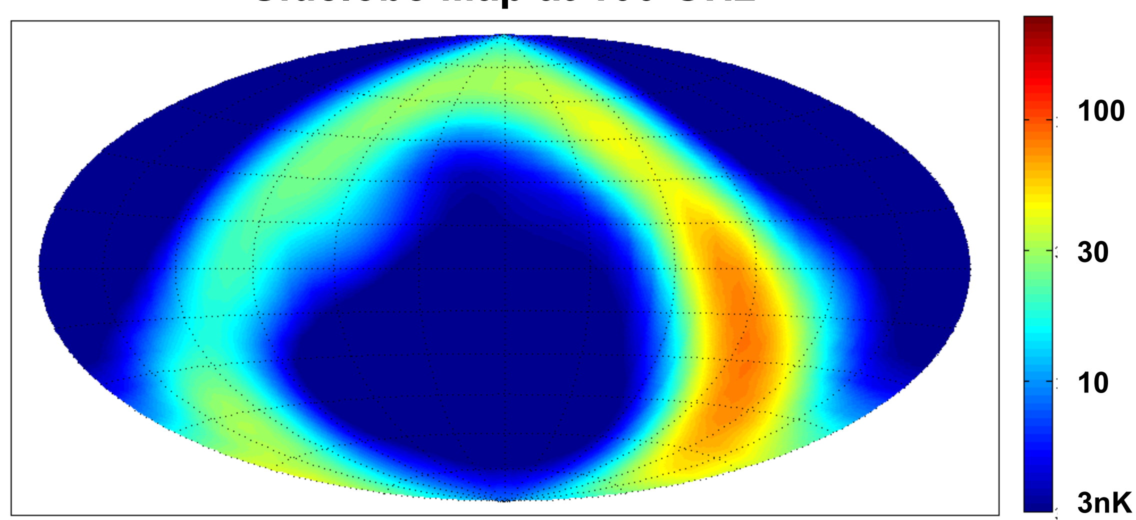




Sky at 100 GHz



Sidelobe Map at 100 GHz



Levels below 3 nK for most of the sky!

Conclusions

CMB is the most powerful tool in cosmology today

- Planck will still leave the most exciting CMB observable unexplored
- Clear role for a space-borne polarization mission

Imaging polarimeter approach

- Technically and scientifically feasible
- Simple technique. Established history.
- EPIC is high-TRL, and meets *TFCR* requirements for IGW science
- Extensive control of systematics designed in from the beginning

Foregrounds

- What we know today about polarized foreground shows they can be subtracted below r = 0.01

Technology Readiness

- We can build a very capable mission *today* with *existing technology*
- New technologies improve the mission & reduce technical risk

Backup Materials from EPIC Mission Study Report

Science Requirements Flowdown

<table>
<tr><th>NASA Objective</th><th>EPIC Objective</th><th>Measurement Criteria</th><th>Instrument Criteria</th></tr>
<tr><td rowspan="5">Discover what powered the Big Bang… search for gravitational waves from the earliest moments of the Big Bang
Discover the origin, structure, evolution, and destiny of the universe (NASA 2006 Strategic Plan)</td><td rowspan="5">Test Inflationary paradigm at GUT energy scales by probing Inflationary Gravitational Wave B-mode polarization signal to r = 0.01.</td><td rowspan="3">Detect BB signal at r = 0.01* after foreground removal</td><td>High sensitivity</td></tr>
<tr><td>30 – 300 GHz†</td></tr>
<tr><td>Control systematics to negligible levels</td></tr>
<tr><td rowspan="2">Positively detect both the ℓ = 5 and ℓ = 100 BB peaks</td><td>All-sky coverage</td></tr>
<tr><td>Low angular resolution (< 1˚)</td></tr>
<tr><td>Understand how the first stars and galaxies formed</td><td rowspan="2">Distinguish models of reionization history
Extract all available EE cosmology</td><td rowspan="2">Measure EE to cosmic variance</td><td rowspan="6">Parameters above</td></tr>
<tr><td>Determine the size, shape, and matter-energy content of the Universe</td></tr>
<tr><td rowspan="2">Measure the cosmic evolution of the dark energy, which controls the destiny of the universe</td><td>Measure lensing BB to determine neutrino mass and dark energy equation of state</td><td rowspan="2">Measure lensing BB to ~cosmic variance</td></tr>
<tr><td>Remove lensing BB using shear map</td></tr>
<tr><td>…Trace the flows of energy and magnetic fields… between stars, dust, and gas</td><td>Map Galactic magnetic fields</td><td>Measure synch and dust polarization</td></tr>
</table>

Primary Objective (red)

Secondary Objective (green)

*Sensitivity goal stated by Weiss Committee TFCR

†Frequency range stated by Weiss Committee TFCR

EPIC Mission Requirements and Goals

Instrument Criteria	Requirements	Design Goals
High sensitivity	NET = 2 μK√s	NET = 1 μK√s
Subtract foreground signals to negligible levels	Technological capability to cover 30 – 300 GHz. Remove foregrounds to below r = 0.01 science goal	Optimize bands for foreground removal based on best knowledge
Control systematic errors to negligible levels	Suppress systematic errors to < 10 % of r = 0.01 signal, after correction 1-year required life for 2 complete maps for error checks	Suppress raw systematic effects to < 10 % of statistical noise level 2-year design life for multiple error checks at higher sensitivity
Maintain sensitivity on large angular scales	All-sky coverage with redundant interleaved scan strategy	
Angular resolution	1° at 100 GHz	

EPIC Mission Parameters

Mission Parameters		
Orbit	L2 Halo	
Mission Life	1-year (Required)	2-year (Design)
Bands	40 – 300 GHz	
Sensitivity	2 $\mu K_{CMB}\sqrt{s}$ (Required)	1.5 $\mu K_{CMB}\sqrt{s}$ (Design)
Resolution	16 – 155 arcmin (FWHM)	
Focal Plane	Antenna-Coupled NTD Bolometers	
Readout	Si JFETs mounted at 40 K	
Pol. Modulation	Half-wave Plate before Telescope Stepped 45° every 24 hours	
Optics	Six 30-cm Wide-Field Refractors	
Cryogenics	Passive to 40 K / LHe Cryostat to 2 K / Continuous ADR to 0.1 K	

Focal Plane Options

Input Assumptions

Fractional bandwidth $\Delta\nu/\nu$ = 30 %
Focal plane temperature = 100 mK
Waveplate temperature = 20 K, with 2 % coupling
P_{sat}/Q = 5 for TES bolometers

Optical efficiency η = 40 %
Optics temperature = 2 K, with 10 % coupling
Baffle at 40 K with 0.3 % coupling (measured)
G_0 = 10 Q / T_0 for NTD bolometers

NTD Bolometer Option

Freq [GHz]	θ_{FWHM} [′]	Nbol[3] [#]	Required Sensitivity[1] NET[4] [μK√s] bolo	Required Sensitivity[1] NET[4] [μK√s] band	Required Sensitivity[1] δT-θ[5] [μK ′]	Required Sensitivity[1] δTpix[6] [nK]	Design Sensitivity[2] NET[4] [μK√s] bolo	Design Sensitivity[2] NET[4] [μK√s] band	Design Sensitivity[2] δT-θ[5] [μK ′]	Design Sensitivity[2] δTpix[6] [nK]
30	155	8	98	34.6	106	630	69	24.5	53.1	315
40	116	54	85	11.5	35.4	210	60	8.2	17.7	105
60	77	128	70	6.2	18.9	110	49	4.4	9.5	56
90	52	256	59	3.7	11.3	67	42	2.6	5.6	34
135	34	256	53	3.3	10.2	61	38	2.4	5.1	30
200	23	64	58	7.2	22.1	130	41	5.1	11.0	66
300	16	64	135	16.7	51.4	310	95	11.8	25.7	150
Total[7]		**830**		**2.1**	**6.5**	**39**		**1.5**	**3.3**	**19**

TES Bolometer Option

Freq [GHz]	θ_{FWHM} [′]	Nbol[3] [#]	Required Sensitivity[1] NET[4] [μK√s] bolo	Required Sensitivity[1] NET[4] [μK√s] band	Required Sensitivity[1] δT-θ[5] [μK ′]	Required Sensitivity[1] δTpix[6] [nK]	Design Sensitivity[2] NET[4] [μK√s] bolo	Design Sensitivity[2] NET[4] [μK√s] band	Design Sensitivity[2] δT-θ[5] [μK ′]	Design Sensitivity[2] δTpix[6] [nK]
30	155	8	87	30.8	66.7	560	62	22	33.4	280
40	116	54	77	10.4	22.7	190	54	7.4	11.3	95
60	77	128	66	5.8	12.7	107	47	4.1	6.3	53
90	52	512	59	2.6	5.6	47	41	1.8	2.8	24
135	34	512	59	2.6	5.7	48	42	1.9	2.8	24
200	23	576	72	3.0	6.5	55	51	2.1	3.2	27
300	16	576	145	6.0	13.0	110	100	4.2	6.5	55
Total[7]		**2366**		**1.5**	**3.2**	**27**		**1.0**	**1.6**	**13**

[1] Sensitivity with √2 noise margin in a 1-year mission
[2] Calculated sensitivity in 2-year design life
[3] Two bolometers per focal plane pixel
[4] Sensitivity of one bolometer in a focal plane pixel
[5] Sensitivity δT in a pixel θ_{FWHM} x θ_{FWHM} times θ_{FWHM}
[6] Sensitivity δT in a 120′ x 120′ pixel
[7] Combining all bands together

Risk Mitigation Strategy

Low Cost Mission Option Design Approach		
Instrument Requirements	**Mitigation Approach**	**Mitigations**
Sensitivity	NTD Ge detectors	Requirement includes √2 noise margin Upscope to TES bolometers when fully demonstrated
Subtract foreground signals below r = 0.01	Antenna-coupled bolometers	Technology covers full 30 – 300 GHz spectral band
	Single-color refracting telescopes	Optimized AR coatings and waveplate modulation for operation over full 30 – 300 GHz spectral band
Suppress systematic errors to < 10 % of r = 0.01 signal, after correction	Spinning/precessing scans	Uniform angular coverage over entire sky
	Highly redundant scan strategy, Step waveplate every 24 hours	Redundant daily maps with each pixel of 50 % of sky allow comprehensive jackknife tests.
		Immunity to data interruptions, bad pixels, bad arrays
		Two full maps in 1-year for systematic error testing
		Upscope to continuous waveplate with fully demonstrated
	Dual-polarization detector	Suppresses common-mode temperature signals, thermal drifts
	Waveplate modulator in front of telescope	Suppresses main beam systematics by rotating polarization without altering beam shapes
		Suppresses 1/f noise by signal modulation if continuous
		Suppresses gain and temperature drifts if continuous
	Small aperture monochromatic refracting telescope	Large throughput
		Low instrument- and cross- polarization
		Low main beam asymmetries
		Optimized low-reflection coatings
		Low far-sidelobe response
All-sky coverage	1-year required lifetime	Cryostat spec has 100 % margin
Minimize cost and risk	30 cm monochromatic refracting telescope	Low-cost polyethylene lenses with simple AR coatings Already demonstrated in BICEP
	LHe cryostat	Low technology risk
		Low integration risk - no microphonic, EMI or B-field disturbances
		Readily allows systems-level testing
	Commercial spacecraft	Low-cost standardized spacecraft with modifications
	Fixed downlink antenna	Eliminates risk of gimballed antenna

Mass Summary

Mass Summary: Low-Cost Option				
Sub-Assembly		Mass (CBE) [kg]	Contingency [%]	Allocated Mass [kg]
Focal Planes	Mass at 0.1 K per unit	0.9	35	1.2
	Mass at 0.4 K per unit	1.0	35	1.4
	Mass at 2 K per unit	0.5	35	0.7
	Total Focal Plane Assemblies (6)	**14.2**	**35**	**19.2**
Tele-scopes	Lenses at 2 K per unit	2.1	35	2.8
	Supports per unit	1.6	35	2.2
	Shields per unit	0.9	35	1.2
	Total Telescope Assemblies (6)	**27.8**	**35**	**37.5**
Wave-Plates	Waveplate 3-stack ave per unit	3.0	35	4.0
	Suspended bearing/motor per unit	1.5	35	2.0
	Non-suspended mass	2.5	35	3.4
	Total Waveplates (6)	**41.7**	**35**	**56.3**
Adiabatic Demagnetization Refrigerator		**5.7**	**35**	**7.7**
Ejectable Telescope Covers (6)		**6.0**	**35**	**8.1**
Cryostat and Shell	Liquid Helium	62.9	0	62.9
	Helium Tank	29.5	35	39.8
	Vapor-Cooled Shields	57.5	35	77.6
	Vacuum shell	185.0	35	249.8
	MLI	12.7	35	17.1
	Fill/vent lines, valves, ports	16.0	35	21.6
	Total Cryostat and Shell	**363.6**		**468.8**
Cabling		**7.0**	**35**	**9.4**
Warm Electronics		**40.0**	**35**	**54.0**
V-groove Radiators		**51.3**	**35**	**69.3**
Deployed Sunshield		**74.1**	**35**	**100.0**
Struts from S/C to Instrument		**15.5**	**35**	**20.9**
Spacecraft (based on SA200HP bus)		**354.0**	**15**	**407.1**
X-band Antenna and Transmitter		**12.7**	**35**	**17.1**
Propellant [ΔV = 160 m/s]		**122.0**	**0**	**122.0**
Total		**1149**		**1398**

Launch Vehicle Maximum Payload Mass to L2 (C3 = -0.6)			
Vehicle	**Mass**	**Margin [%]**	**Margin [kg]**
Delta 2925H-9.5 Star 48	**1440**	**3**	**42**
Delta IV 4040	**2773**	**98**	**1375**
Atlas V 401	**3485**	**150**	**2087**

Power Summary

Power Summary: Low-Cost Option			
Item	**Power (CBE) [W]**	**Contingency [%]**	**Allocated [W]**
X-band TWTA	200	30	260
ADR Electronics	40	30	50
Bolometer Readout Electronics	150	30	195
Spacecraft	355	30	460
Total	**935**	**30**	**965**
GaAs Triple Junction Solar Panels			
Panel Area	**Power [W]**	**Margin [%]**	**Margin [W]**
4.0 m^2 Fixed at 45° Incidence	710		
3.8 m^2 Deployed at 45° Incidence	670		
Total	**1380**	**43**	**415**

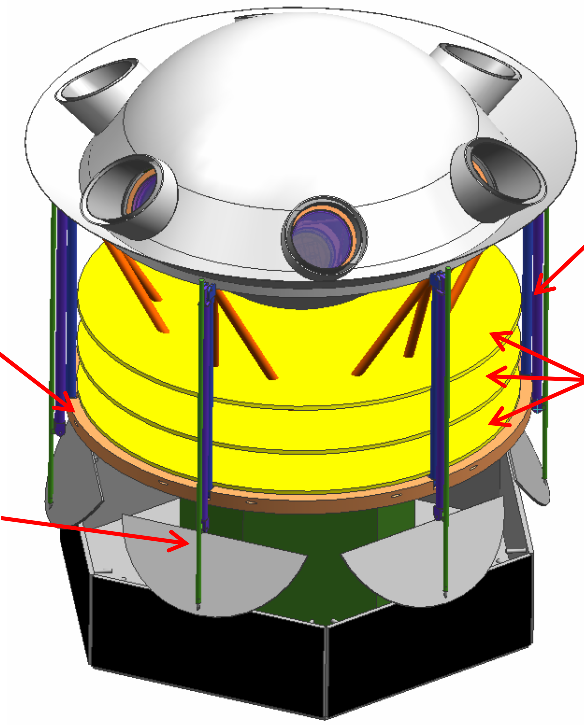
Telemetry Budget

Antenna BW [deg]	Antenna Gain [dBi]	SC-Amp [W]	Gnd Station [m]	Gnd Gain [dBi]	Downlink Rate [Mbps]
2	9.0	100	12	58.65	0.5
2	9.0	90	34	68.29	4

Option	Spin rate [rpm]	Waveplate rate	Input Rate[1] [kbps]	Downlink time per day [hrs]	
				12-m GS	34-m GS
Scan-modulated NTD bolometers[2]	1.0	1 rev / day	87	4.2	0.5
Waveplate-modulated TES bolos[3]	0.1	40 – 300 rpm	480	-	2.8
Scan-modulated TES bolometers[4]	3.0	1 rev / day	1260	-	7.4

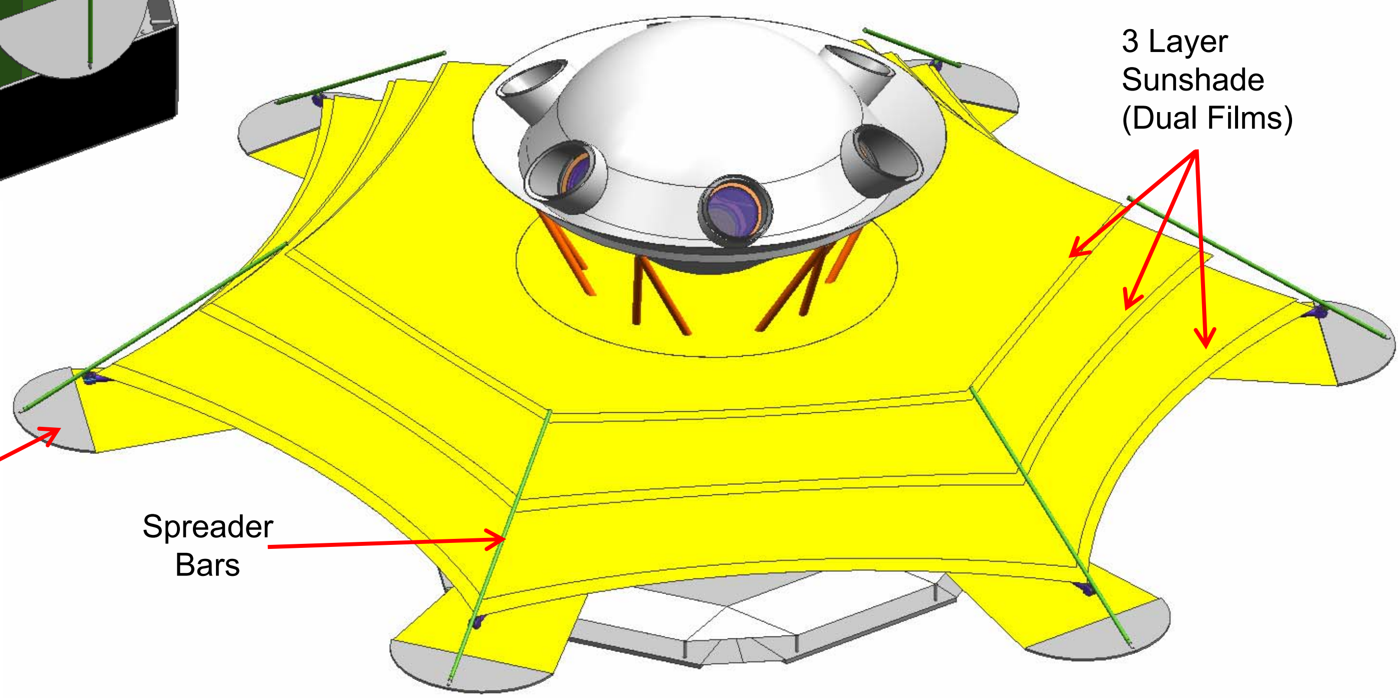
[1]Assumes 4 bits per sample per detector (Planck compression ratio), and 2x Nyquist sampling.
[2]Requires a 1/f knee < 16 mHz (already demonstrated for NTD bolometers).
[3]Assumes 10 polarization cycles per beam crossing for each band. Requires 1/f knee < 2.5 Hz.
[4]Requires a 1/f knee < 50 mHz (near state-of-the-art for TES bolometers)

Deployable Sunshield Design (1)

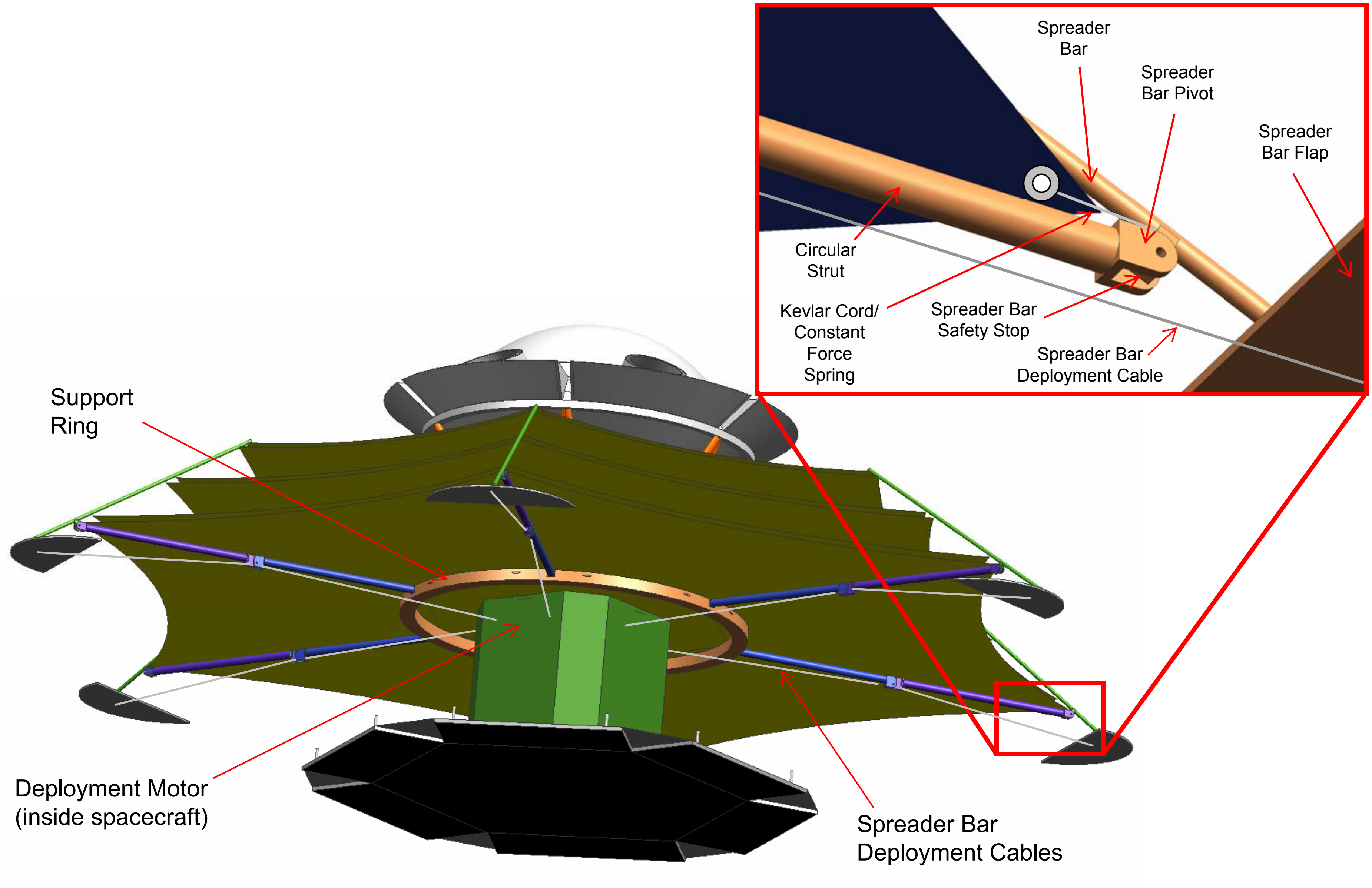


Sunshade Parameters

Shade largest diameter	8 m
Fairing	Delta II 2925 3-m
Fundamental frequency	> 0.17 Hz
Strut safety factor	> 6
Spreader bar safety factor	> 3
Sunshield layers	3, double layered
Sunshade and deployment hardware mass	74 kg

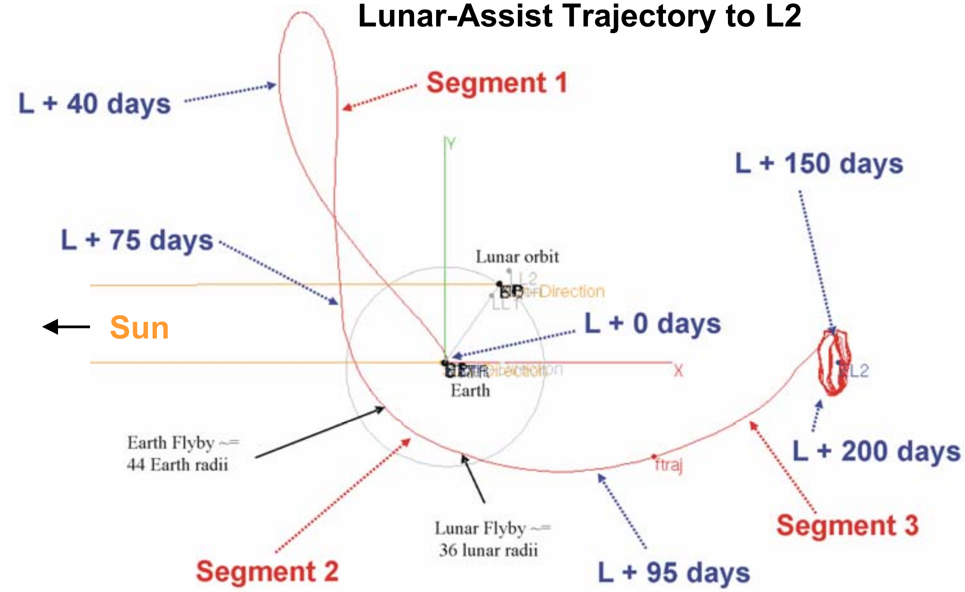


Deployable Sunshield Design (2)



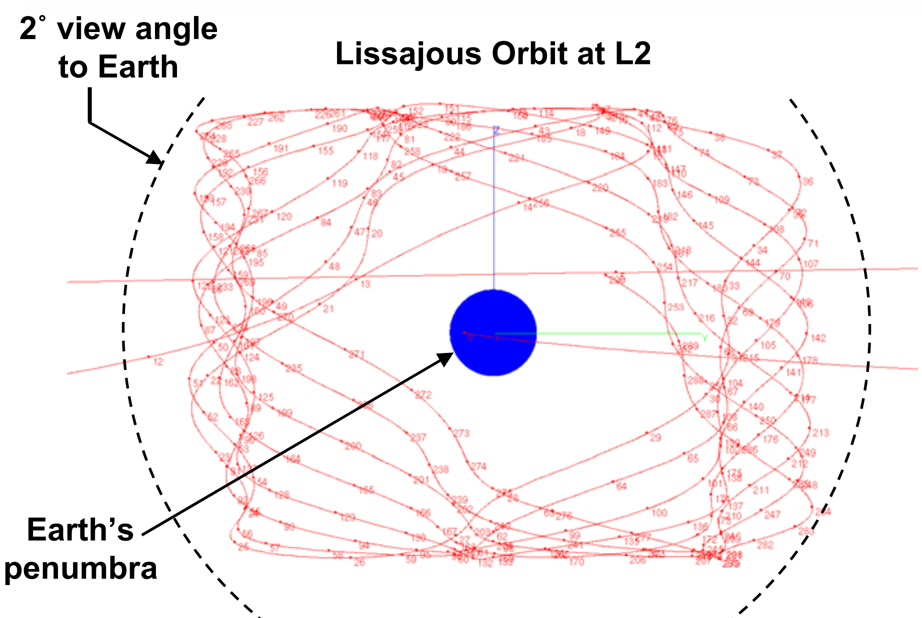
L2 Halo Orbit Parameters

Lunar-Assist Trajectory to L2



Nominal Orbital Parameters	
Transfer Time	~170 Days
Halo Dimensions	24,000 × 46,000 × 33,000 km
Max Earth-view Angle	2°
Partial Eclipses	None over 4 years
Lunar Fly-by Distance	64,000 km
C3	$-0.45\ km^2/s^2$
Deterministic ΔV	0 m/s

Lissajous Orbit at L2



Summary of EPIC ΔV Budget (4 years)

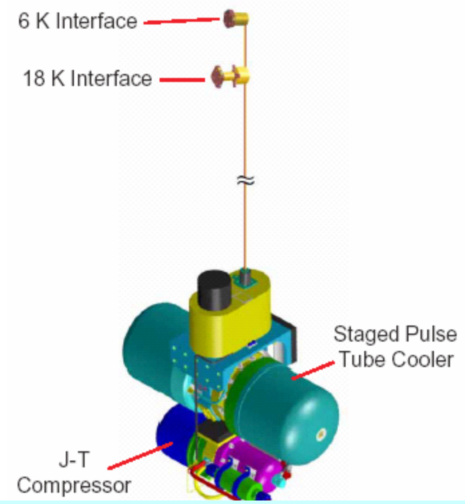
Event / Function	Very Conservative		Semi Conservative	
	Mean	Sigma	Mean	Sigma
Injection Cleanup	64	45	58	34
Post-Injection up to Lissajous Insertion (L + 200 days)	7	3	7	3
Sub Total	72	45	65	34
Lissajous per Rev	4	1	4	1
4-Years Sub Total	31	10	31	10
Grand Total	103	46	96	35
Total 95% Probability	195		166	
Margin	10		10	
Total Budget	215		176	

Available Cooler Options to 100 mK

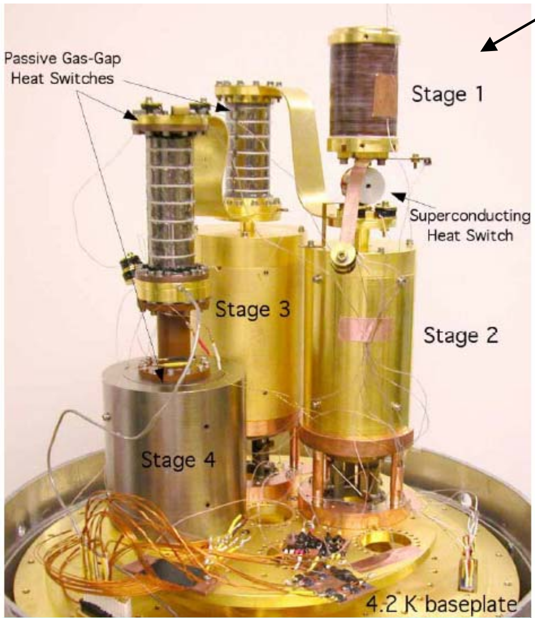
High-TRL Baseline Approach

1. Passive cooling to 40 K
   - Temperatures are extremely stable
2. Simple 450 ℓ liquid helium cryostat to 2 K
3. Single-shot ADR to 100 mK
   - We can tolerate data interruptions

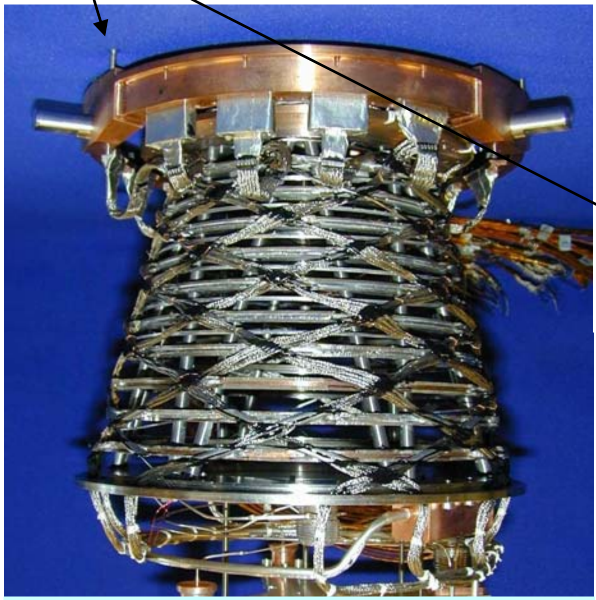
Other Available Options



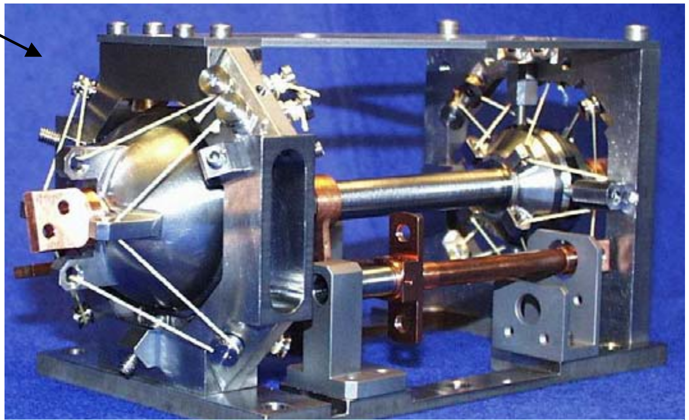
Mechanical Coolers to 2-4 K
+ Long life, low mass, JWST dev.
- T stability, μ-phonics, B-fields?



Continuous ADR
+ Continuous, low mass
- Low-TRL, T stability

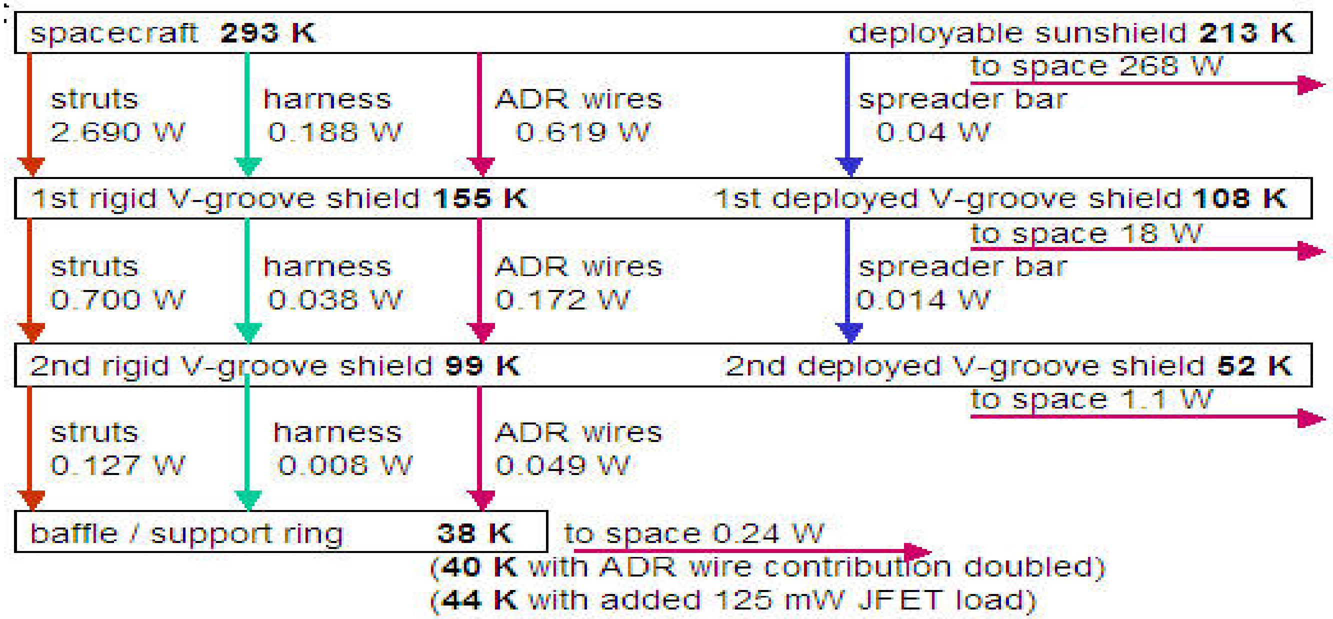


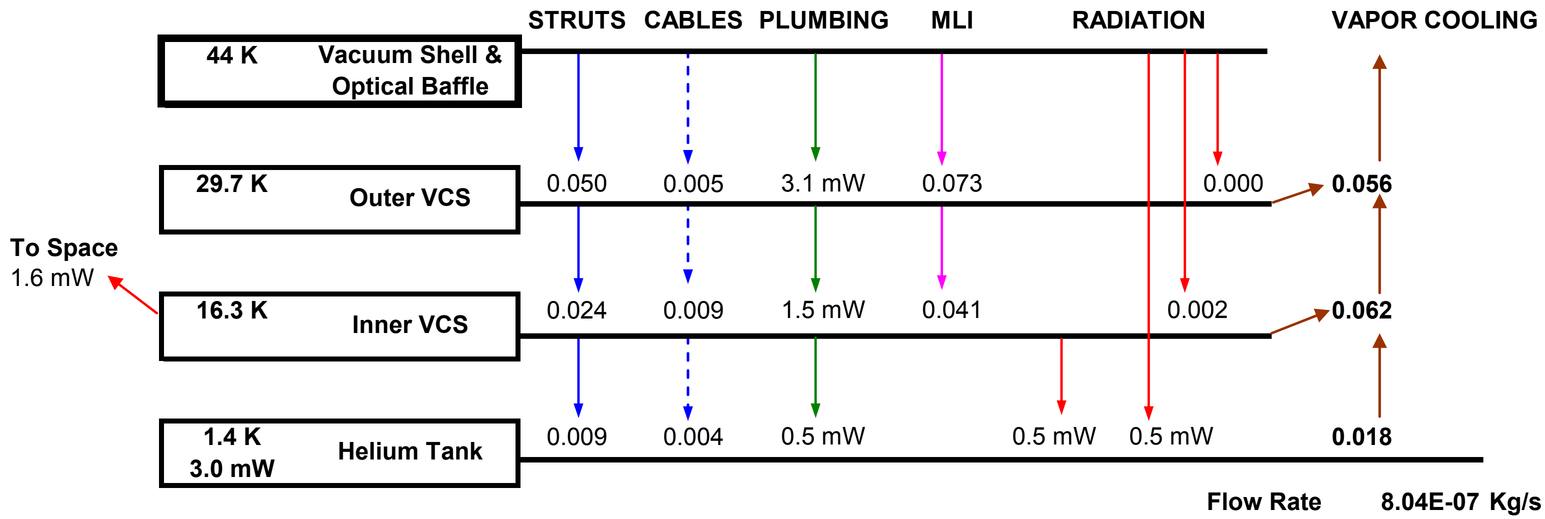
Continuous OC Dilution Fridge
+ Flight-qualified, highly stable
- Low cooling power



^3He Sorption Cooler
+ Flight-proven, highly stable
- 300 mK, not continuous

Thermal Heat Flow Analysis

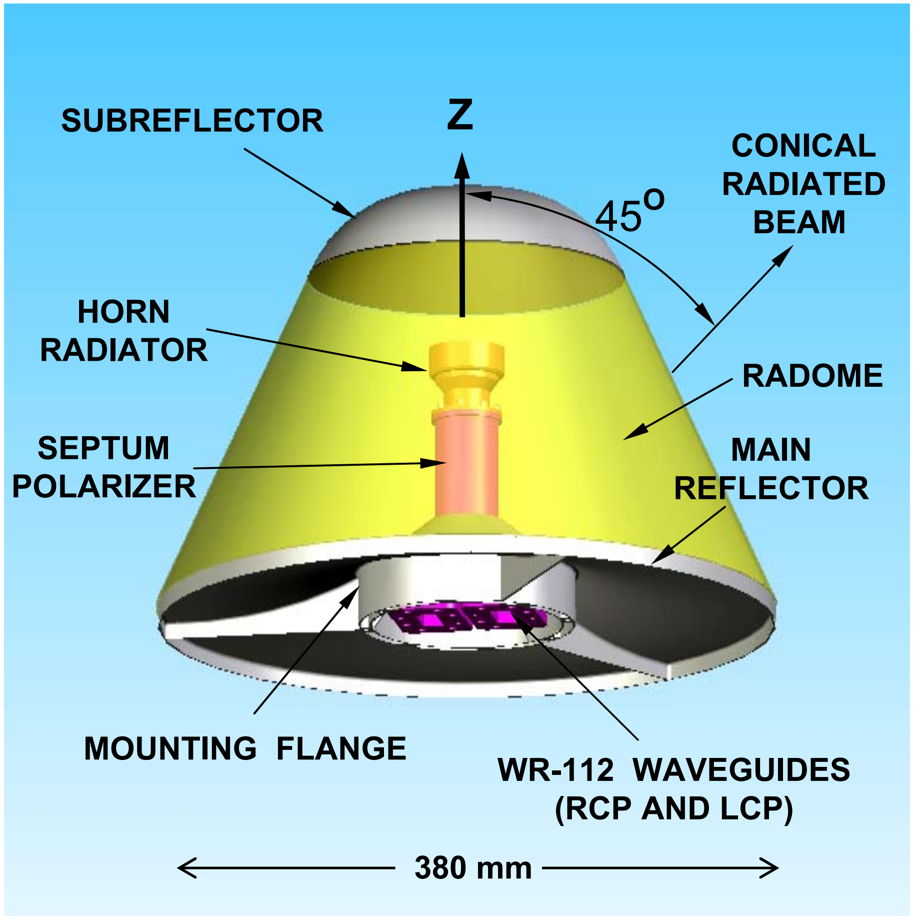


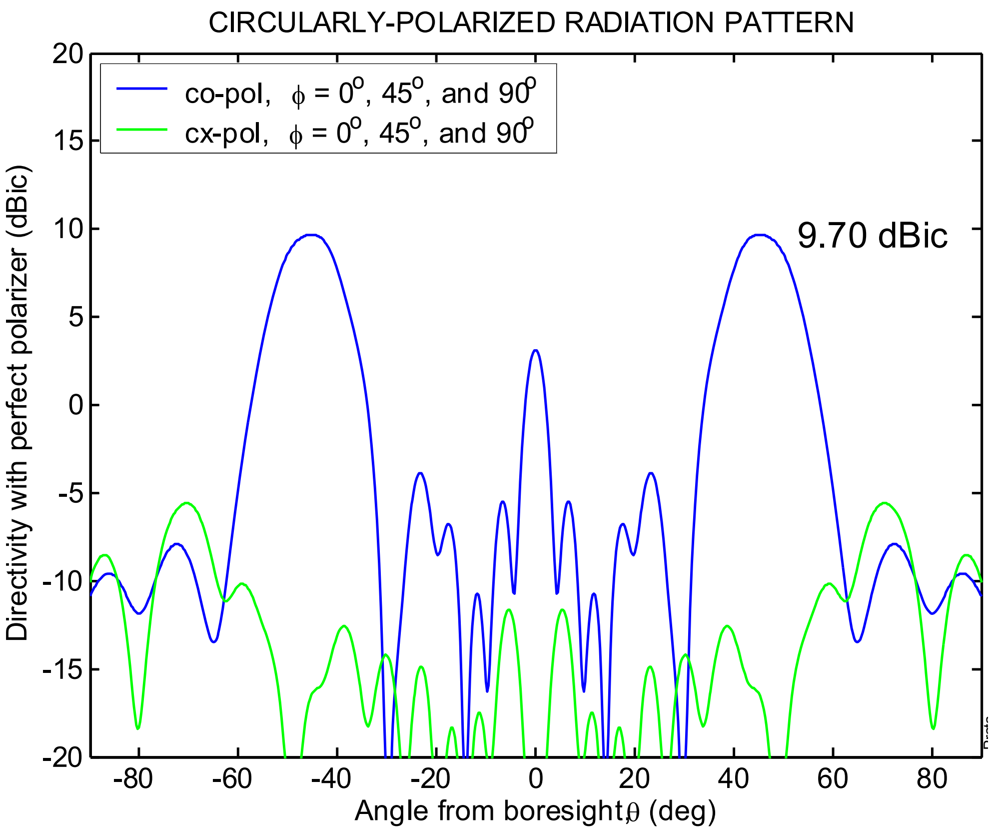


30.2 Month Primary Cryogen Lifetime
433 liter Primary Cryogen tank

Heat flow in Watts unless noted

Toroidal Beam Antenna





Aluizio Prata, USC/JPL