Experimental Probe of Inflationary Cosmology (EPIC)

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Some Background

NASA funded 3 mission studies for the Einstein "Inflation Probe"

- **Envisioned as $350-$500M mission launch 2010 & every 3 years**
- **2 year study & not much money**
- **In the meantime, some programmatic changes at NASA…**

These results are the work of a small group of dedicated individuals

Asantha Cooray	Warren Holmes	Mark Lysek	Tom Renbarger
Dustin Crumb	Brian Keating	Michael Milligan	Celeste Satter
Shaul Hanany	Adrian Lee	Nicolas Ponthieu	Huan Tran

What did we study?

- **2 point designs responding to the Weiss committee roadmap**
- **Selected mission tradeoffs**
- **Key technical challenges for imaging polarimeters**

What are we still working on?

- **Foreground subtraction model**
- **Complete systematic error analysis**
- **Complete optical analysis incl. sidelobes**

What is outside of our study plans?

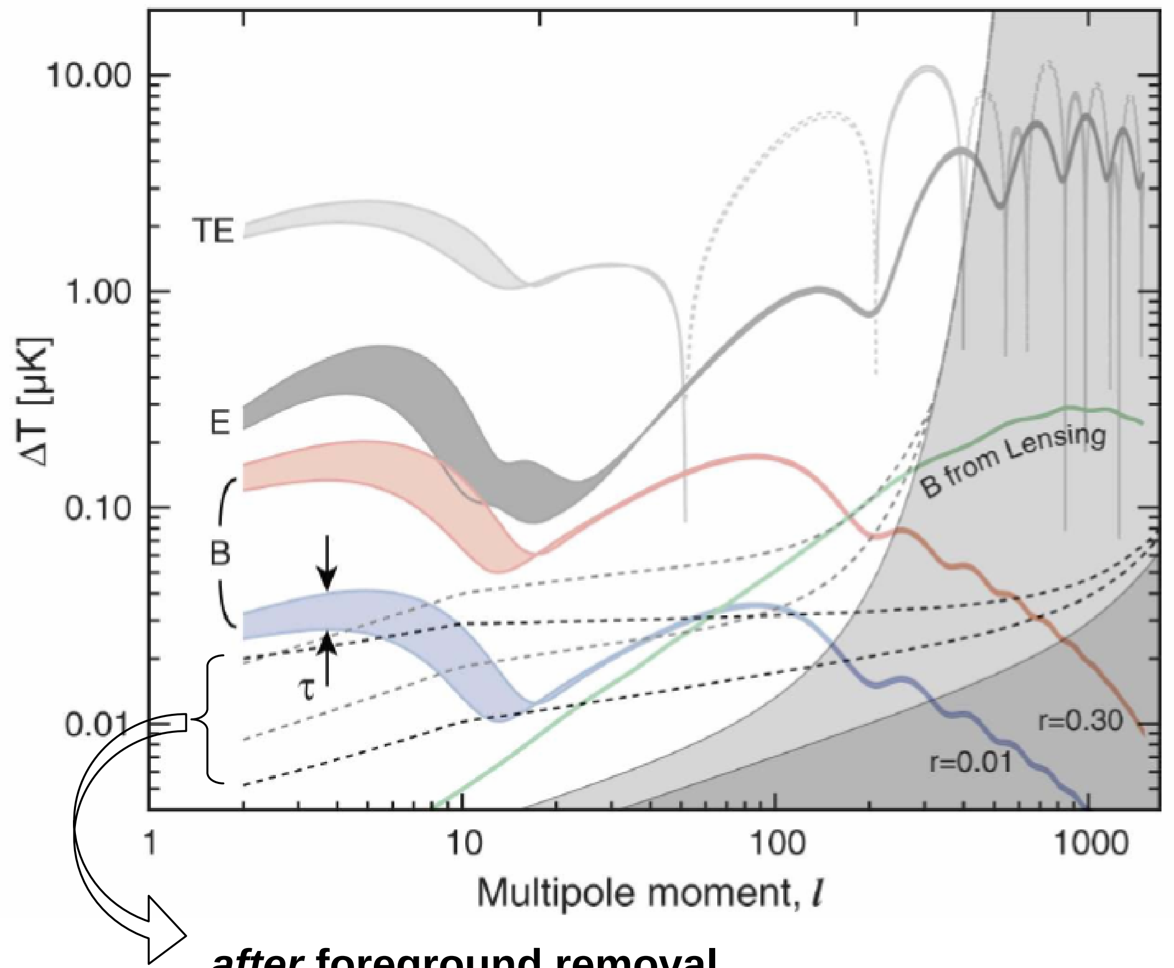
- **Other design options (interferometry, HEMTs)**
- **Cost analysis**

Recommendations from the Weiss Committee

Two missions
- **1º beams: 1.6 μK√s @ 1-yr**
- **0.1º beams: 1.1 μK√s @ 1-yr**

GW polarization science
- **goal is r = 0.01**
- **note two peaks**

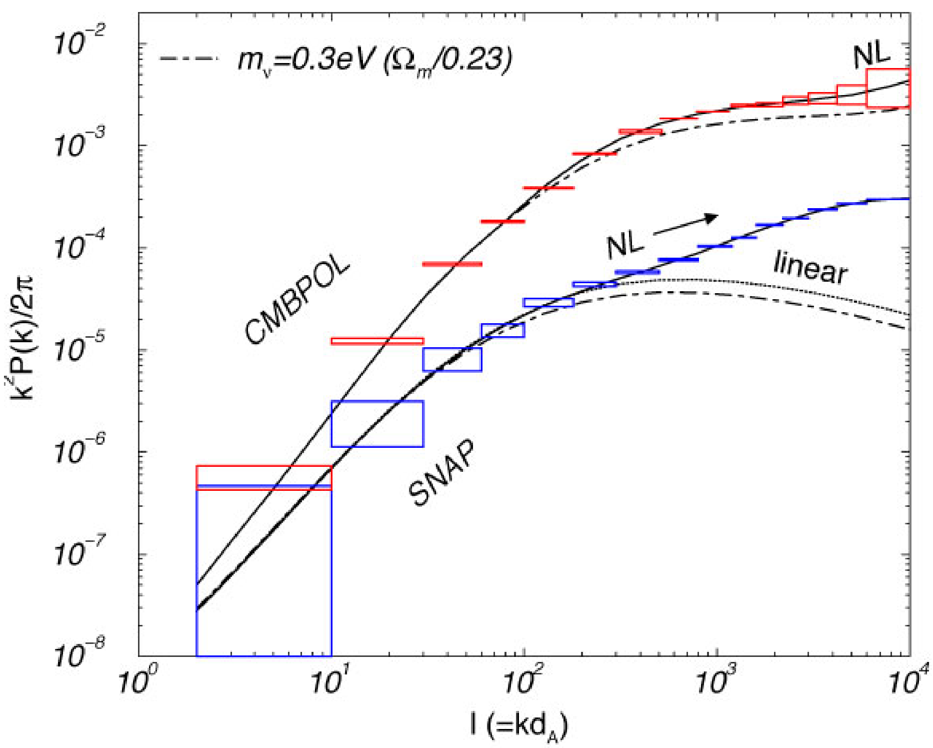
Foreground subtraction is key
- **recommends 30 – 300 GHz**



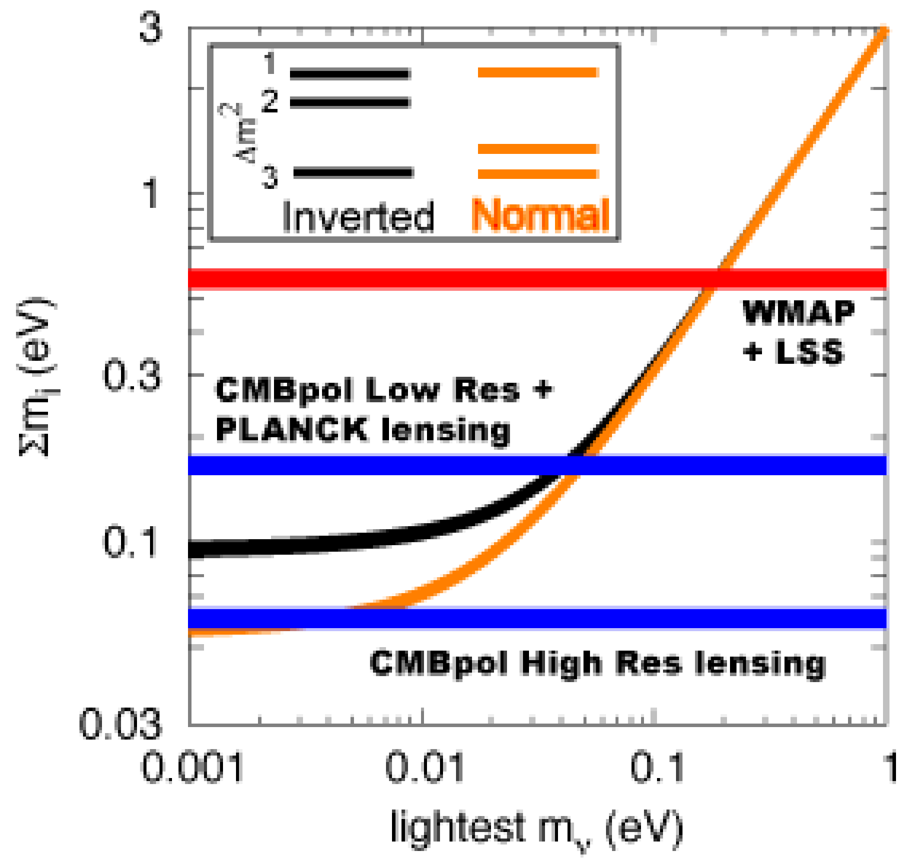
***after* foreground removal**

What Do You Get for Higher Resolution? (One Example)

CMBPOL Measures P(k) in Linear Regime



Constraints on Neutrino Mass



A. Cooray
M. Kaplinghat

Science Inputs to EPIC Mission Study

Low-Cost Option		
Science	Science Requirements	Instrument
GW <BB>	Detect *both* l = 5 & l = 100 <BB> bumps at r = 0.01 *after Galactic foreground removal*	1º FWHM @100 GHz All sky 2 $\mu K\sqrt{s}$ 2 years 30 – 300 GHz

Comprehensive Science Option		
Science	Science Requirements	Instrument
GW <BB>	Detect *both* l = 5 & l = 100 <BB> bumps at r = 0.01 *after Galactic foreground removal*	5' FWHM @100 GHz All sky 2 $\mu K\sqrt{s}$ 2 years 30 – 300 GHz
Lensing <BB>	Measure lensing <BB> to cosmic variance to l = 1000 *Potential to subtract lensing <BB>*	
<EE>	Measure <EE> to cosmic variance into the damping tail	

Drift-Scanned Imaging Polarimeters

Team encompasses many PIs in imaging polarimetry

Instruments scaleable to higher sensitivity
- “only” requires better detector arrays

Do the optics have large enough throughput?

Can we control systematic errors to < 10 nK?
- currently demonstrated to < 1 μK


Boomerang


Maxipol

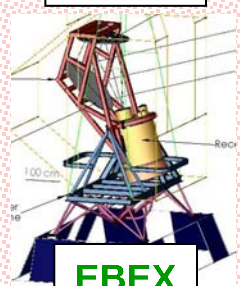
PAST


BICEP

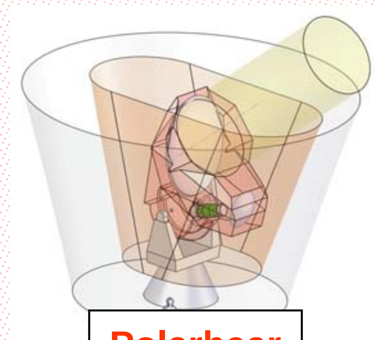

QUaD

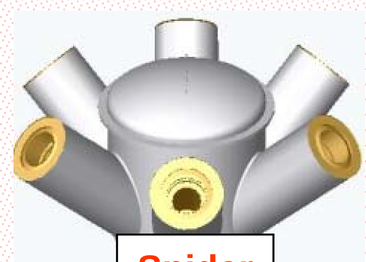
ACTIVE


Planck


EBEX

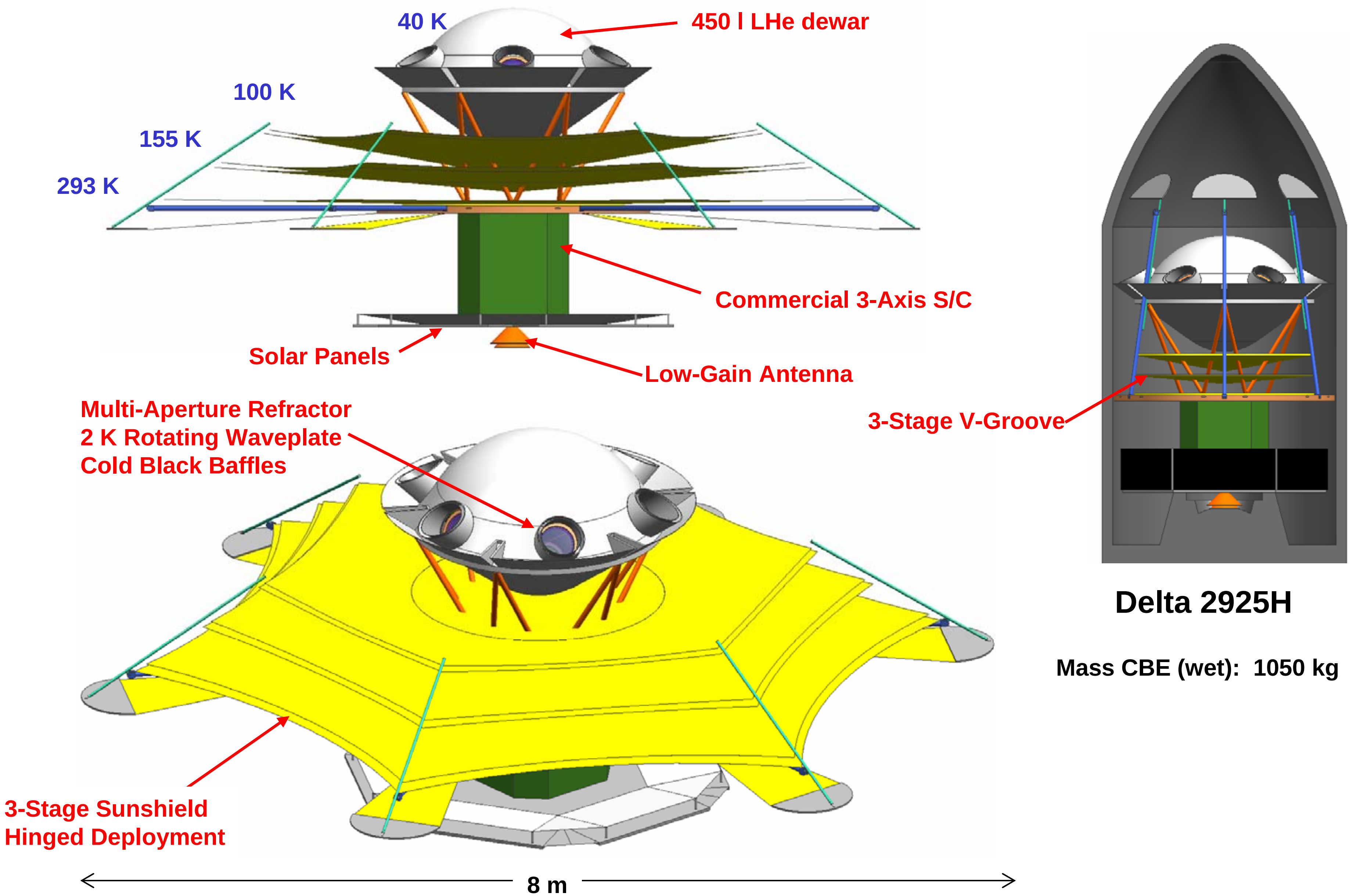
PLANNED


Polarbear


Spider

FUTURE

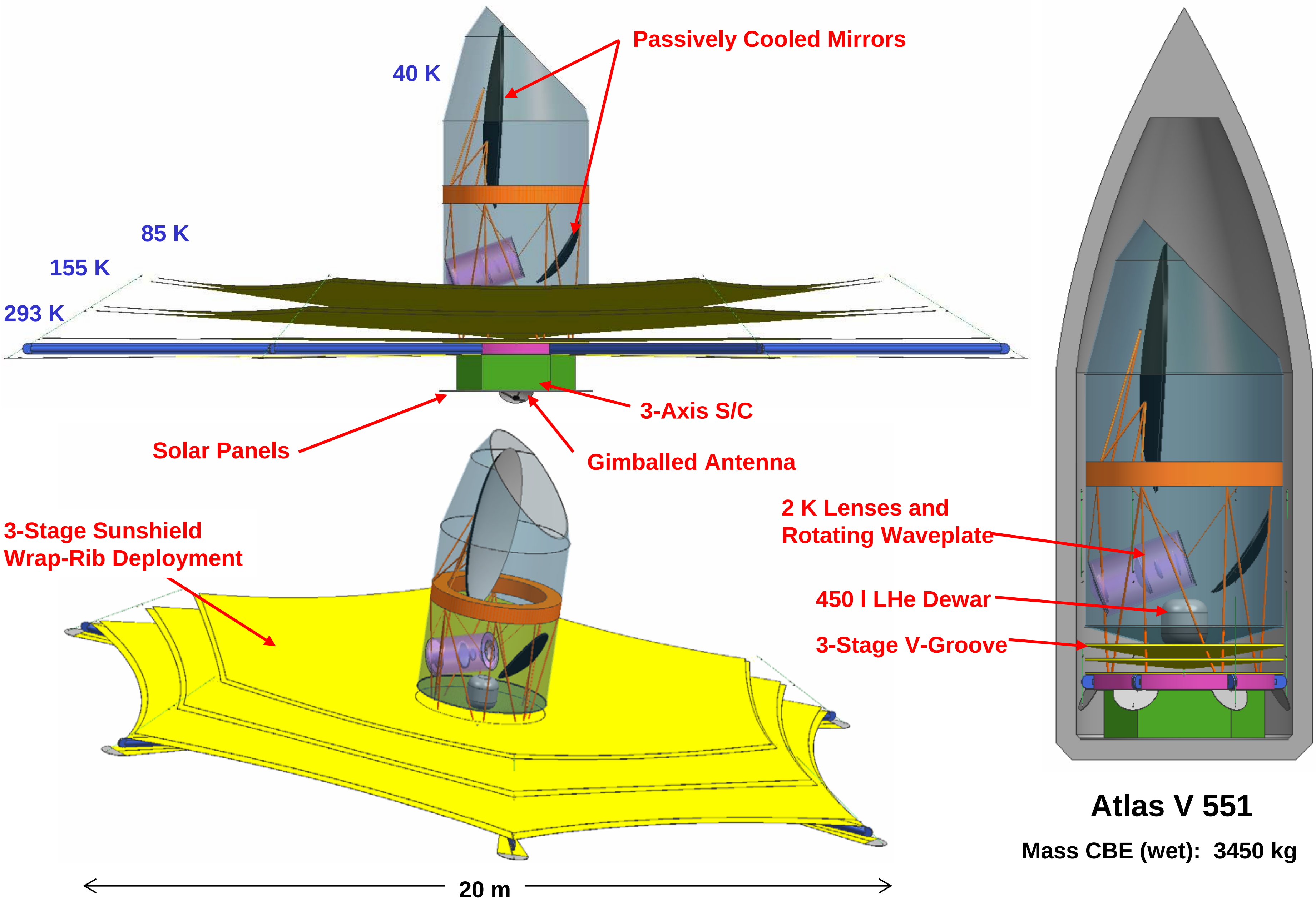
Low-Cost Mission Architecture



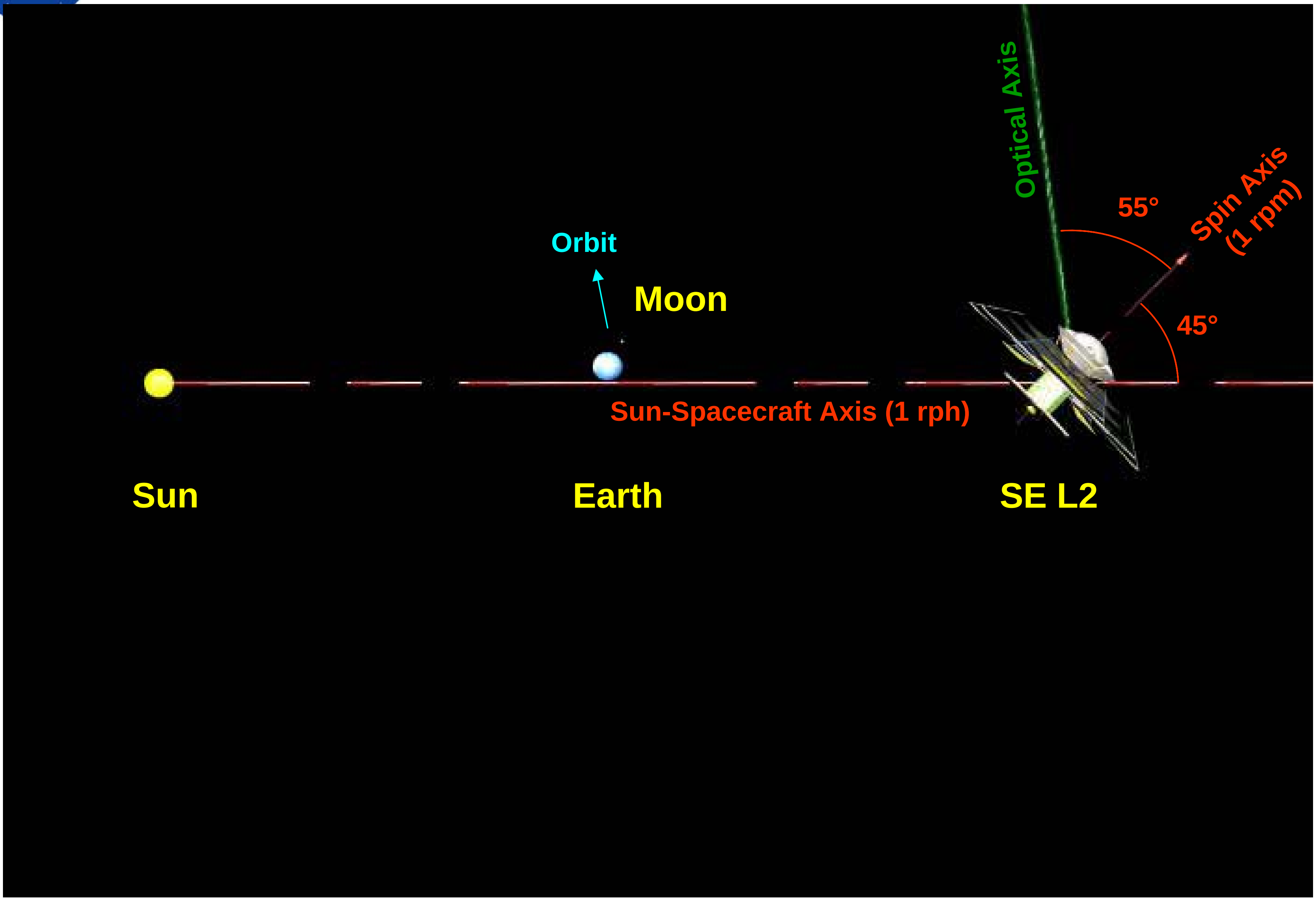
Delta 2925H

Mass CBE (wet): 1050 kg

Comprehensive Mission Architecture



Scan Strategy



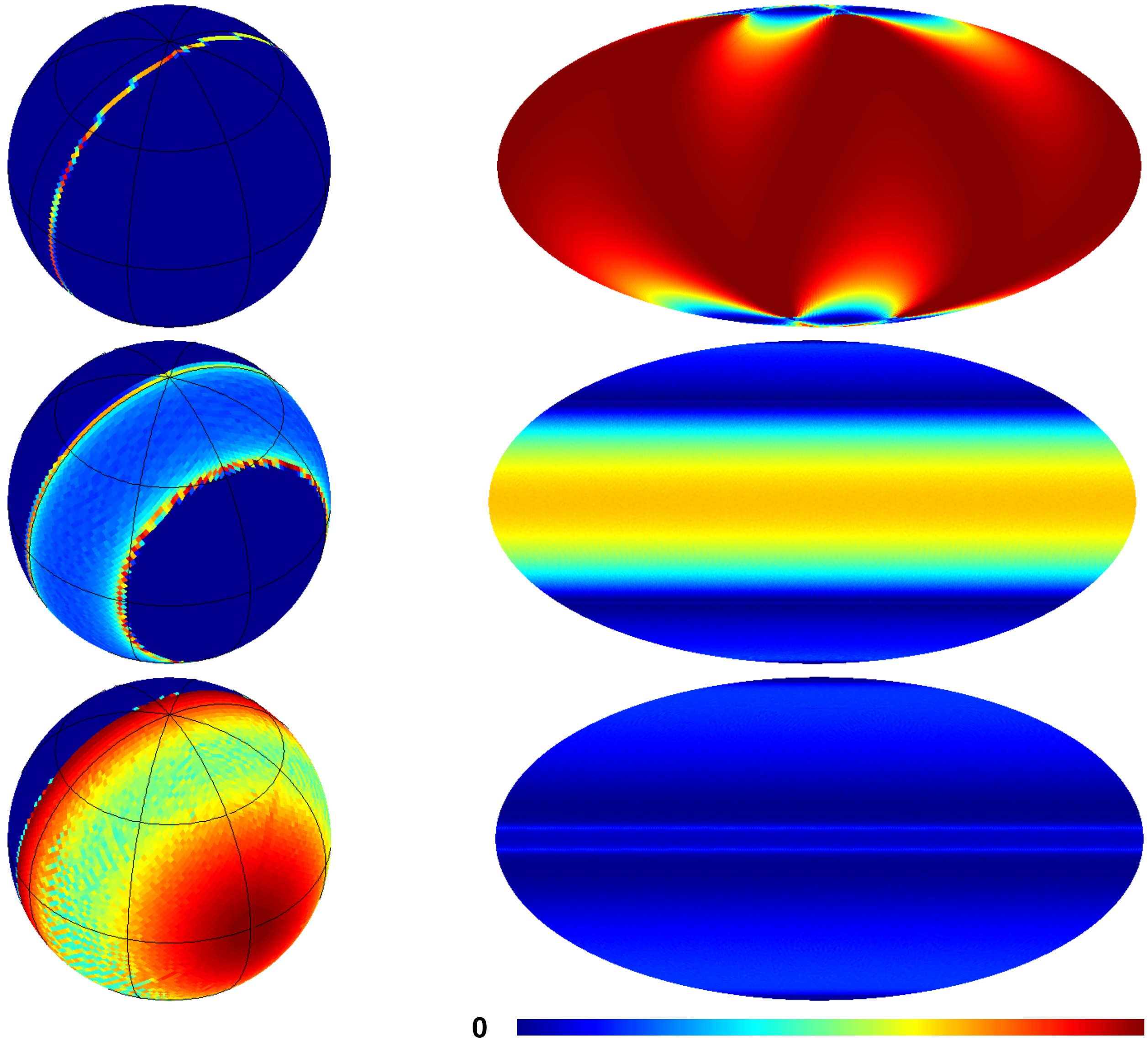
Highly Redundant & Uniform Scan Coverage

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

Planck

WMAP

EPIC



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

Optical Design Methodology

Requirements:

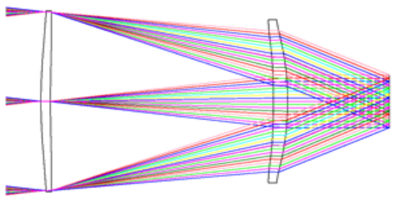
- **Large Throughput**
  - **Small - 20° FOV at 100 GHz**
  - **Large - 3° FOV at 100 GHz**
  - **5° FOV at 30 GHz**
- **Flat and Telecentric Focal Plane**
- **Cold Pupil Stop**
- **Low Sidelobes**

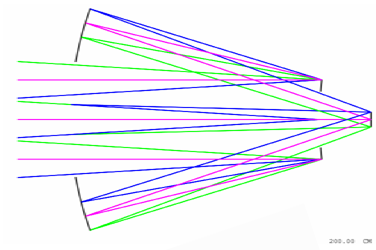
Metrics:

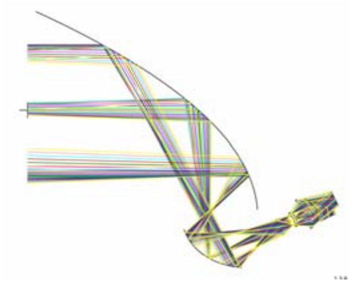
- **Strehl ratios**
- **Mueller matrices**
- **E/H and co/cross beam differences**

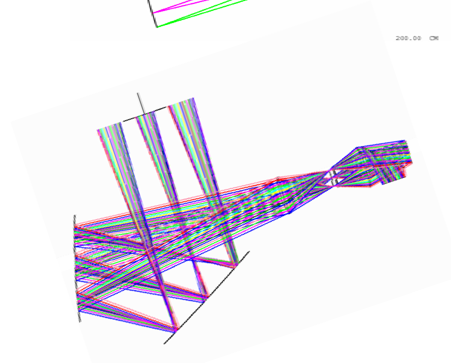
Tools:

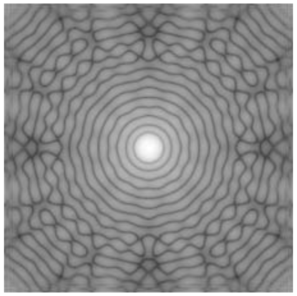
- **Code5**
  - **main beam + Mueller matrices**
- **Grasp9**
  - **main beam**
  - **sidelobes**
  - **polarization**
- **Zemax**
  - **main beam**
  - **physical optics (lenses)**
- **Analytical calculations**

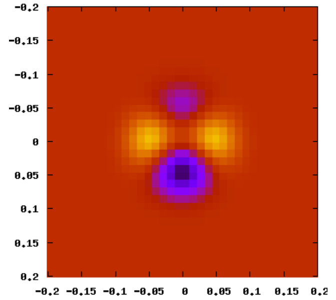


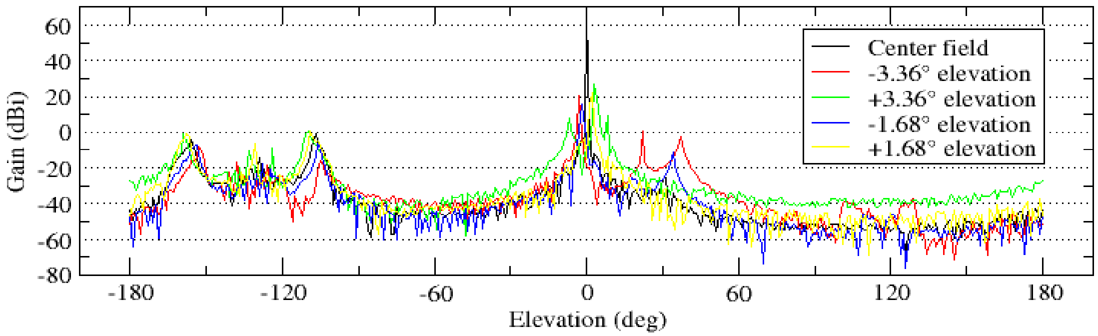








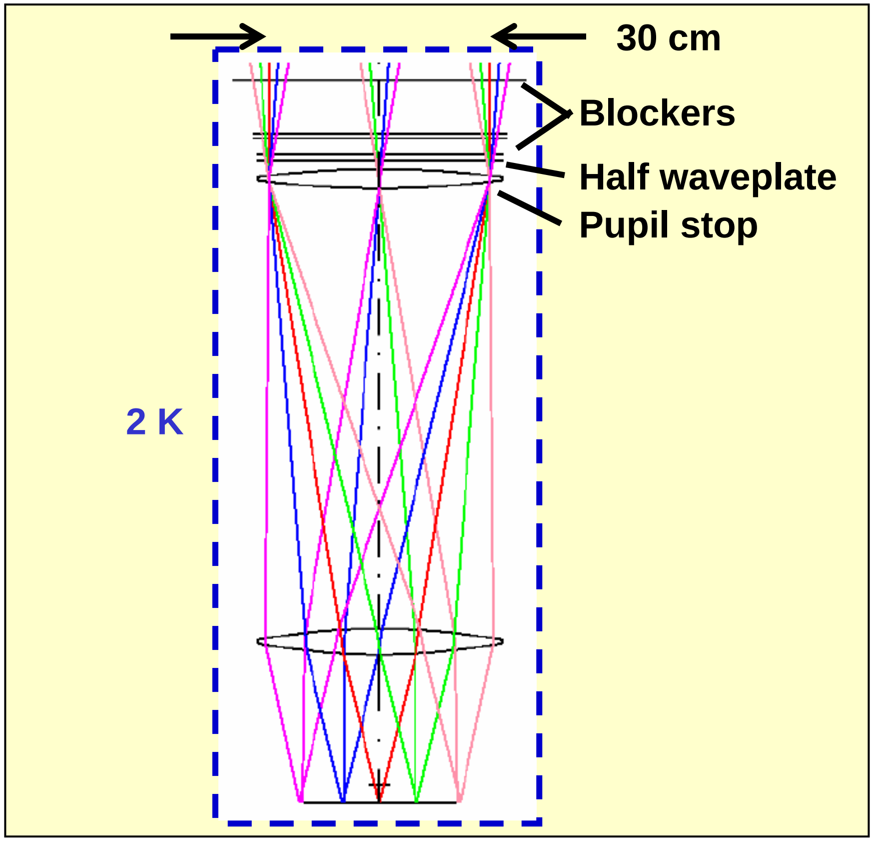




S. Hanany *M. Milligan*
T. Renbarger *H. Tran*

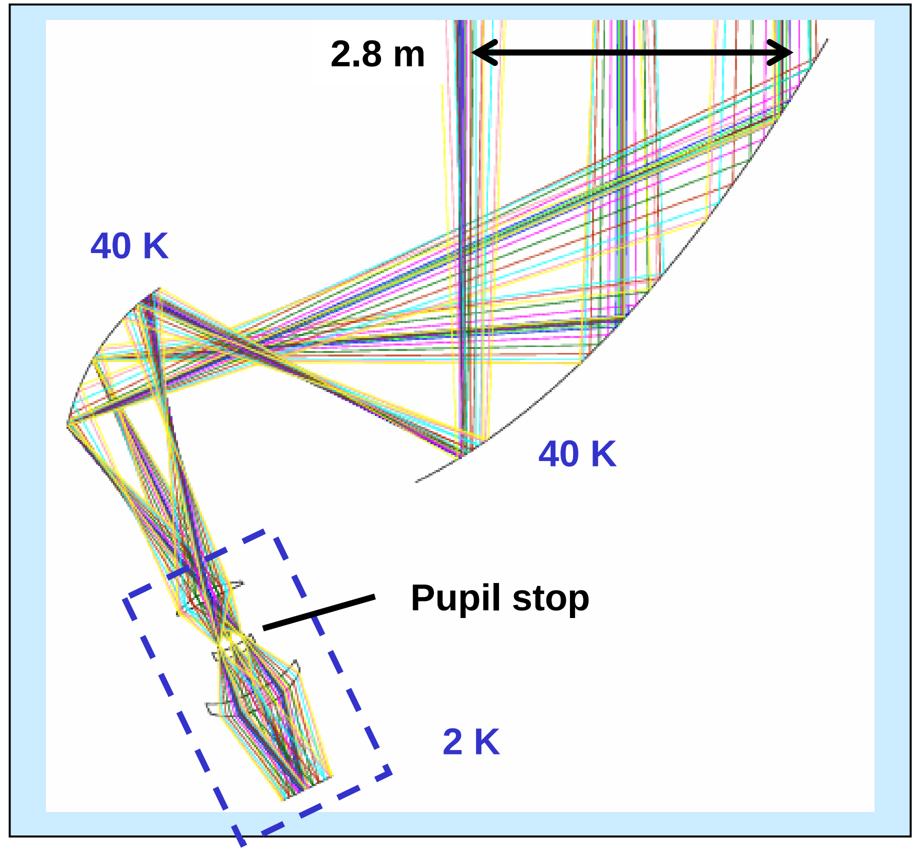
Optical Systems Study

Refractor



FWHM @ 100 GHz	0.8º
FOV @ 100 GHz	20º
Strehl ratio*	> 0.96
I-Pol.*	0.02 % (ideal AR)
	0.5 % (poor AR)
X-pol.*	< 5e-6

Gregorian Dragone

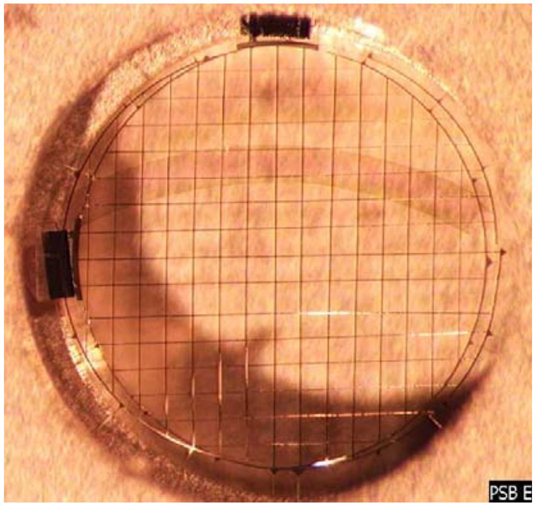


FWHM @ 100 GHz	4'
FOV @ 100 GHz	3º
Strehl ratio*	> 0.94
I-Pol.*	0.14 % (ideal AR)
	1.0 % (poor AR)
X-pol.*	18 %

*evaluated at edge of FOV at 100 GHz

Main Beam Polarization Systematics

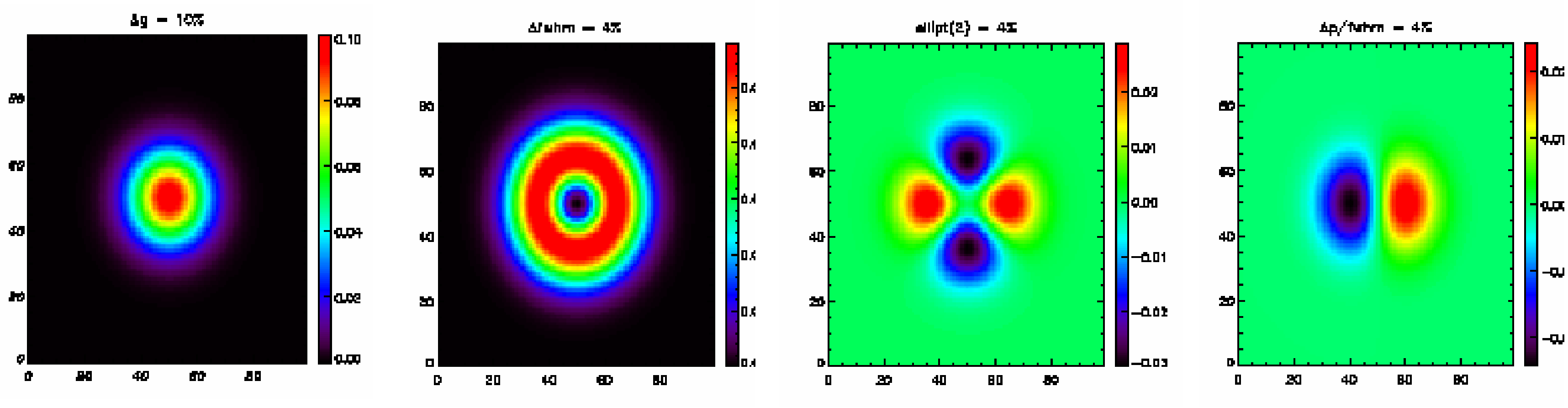
- Instrument polarization converts T to Q & U
- Cross-polarization converts Q to U
- Goal is to keep raw effect below science goal
- Effects can be measured and removed, and/or mitigated by a waveplate



Assumptions:

- take difference between x & y PSB
- parameterize main beam effect
- convolve with scan strategy
- calculate resulting power spectrum

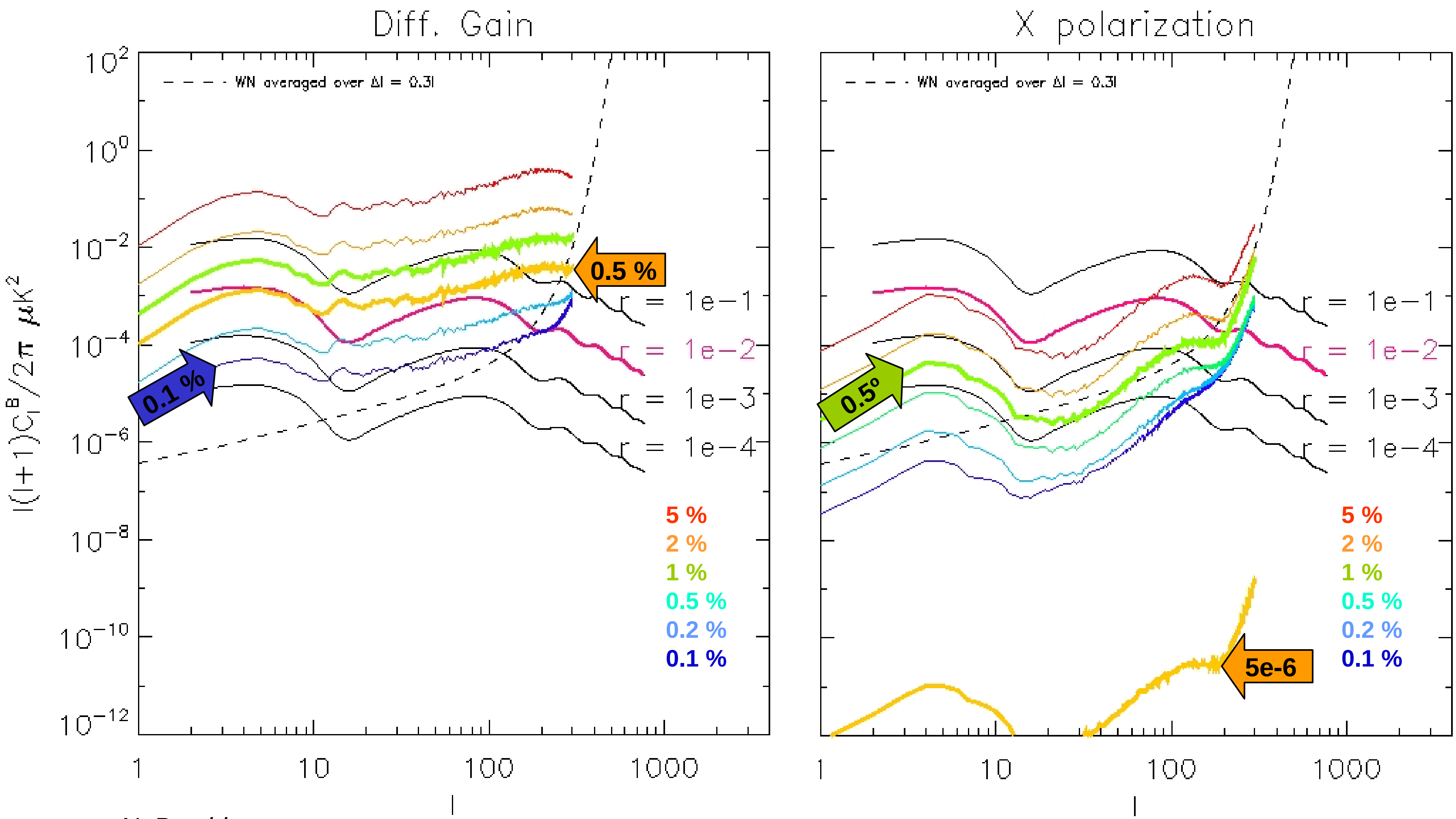
Main Beam Instrumental Polarization Effects



Inst-Pol (differential gain) Cross-Pol (rotation)	Differential FWHM	Differential Ellipticity	Differential Offset

Effects of Uncorrected Polarization

Refractor with 1º FWHM at 100 GHz

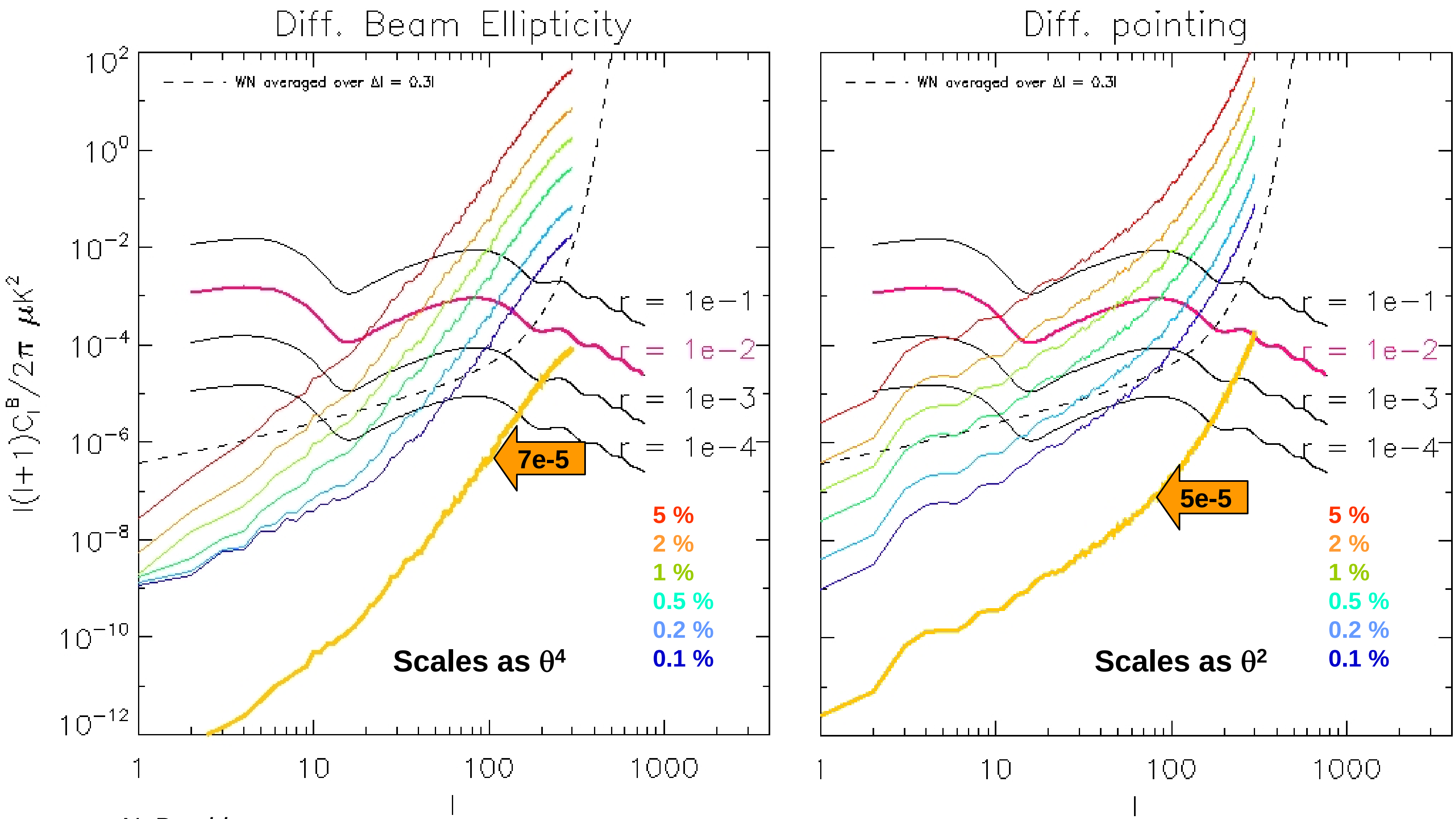


N. Ponthieu
E. Hivon
B. Keating

Arrows indicate the level achieved by optical analysis using Code V
100 GHz, 10° radius

Effects of Uncorrected Polarization

Refractor with 1º FWHM at 100 GHz



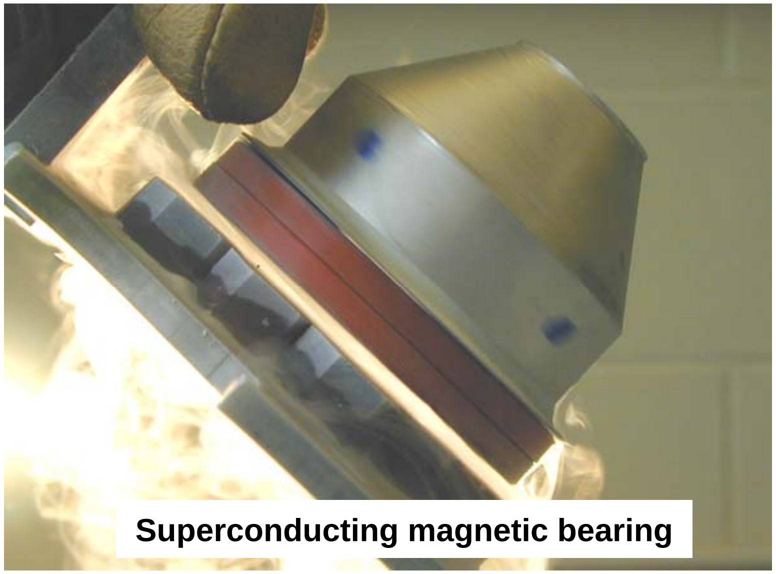
N. Ponthieu
E. Hivon
B. Keating

Arrows indicate the level achieved by optical analysis using Zemax PO
100 GHz, 10° radius

Polarization Modulators

+ Removes polarization of downstream optics
+ High frequency chop

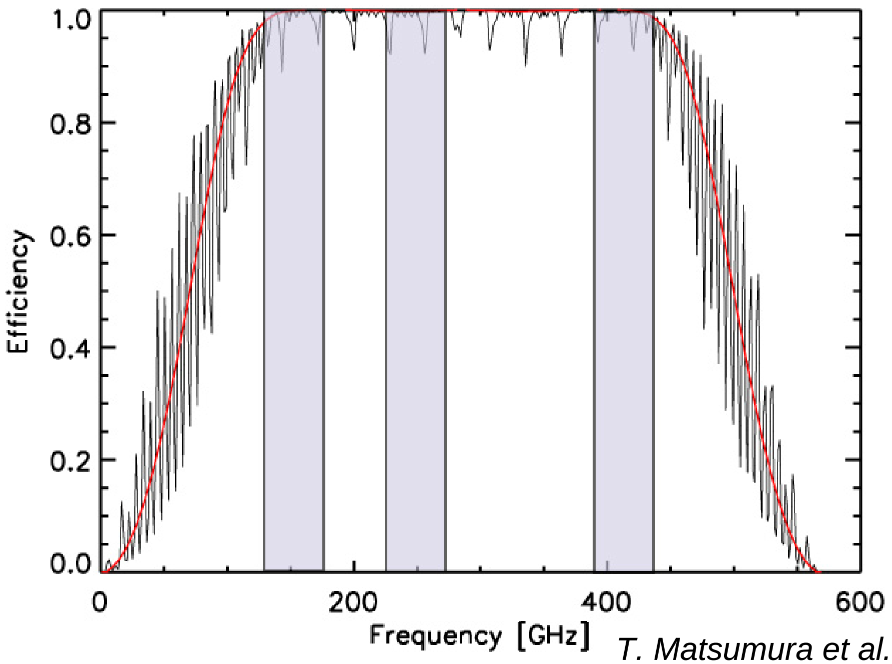
- Can introduce own polarization effects
- Bandwidth a problem



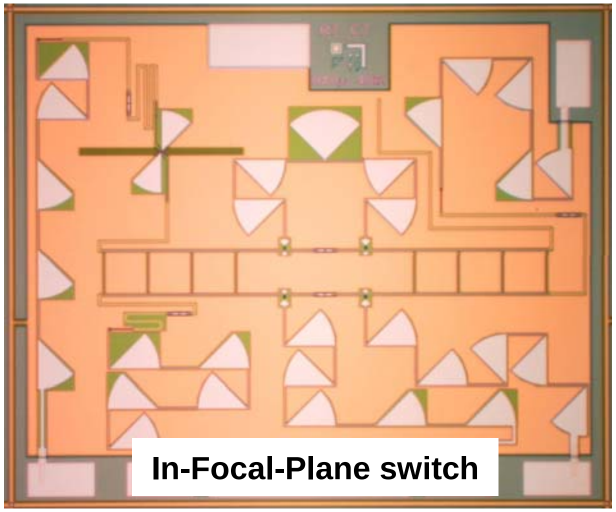
Superconducting magnetic bearing

S. Hanany et al.

Broadband 5-stack waveplate



T. Matsumura et al.



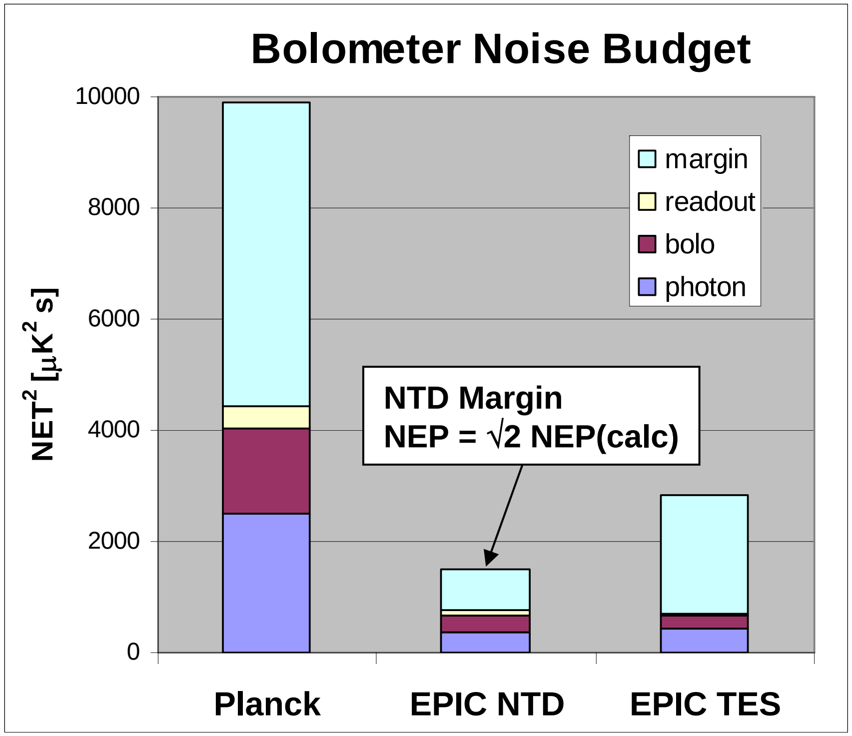
In-Focal-Plane switch

Faraday Modulator

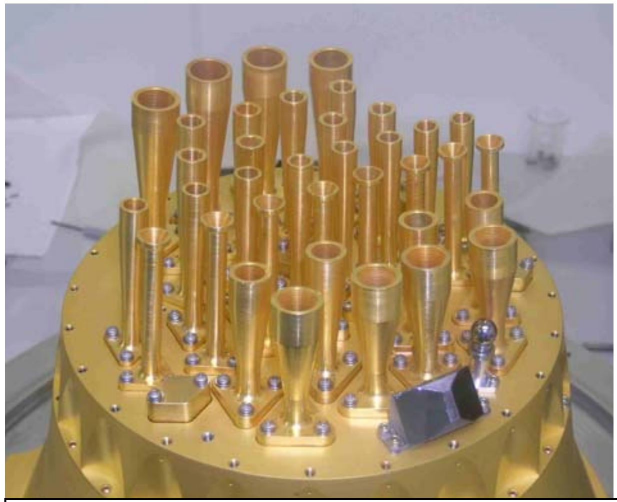
B. Keating et al.

Focal Planes – Existing Technology

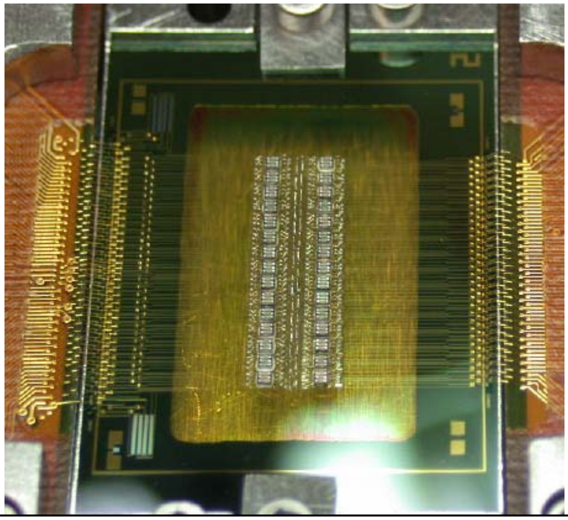
Freq. coverage	[GHz]	60 – 300
# bolo		700
NEP	[W/√Hz]	~6e-18
System NET	[μK√s]	2.4
τ	[ms]	25
Wires to 0.1 K		1500
Focal plane mass at 0.1 K	[kg]	20
JFET power to 40 K	[mW]	130 mW



Absorber-Coupled NTD Bolometers



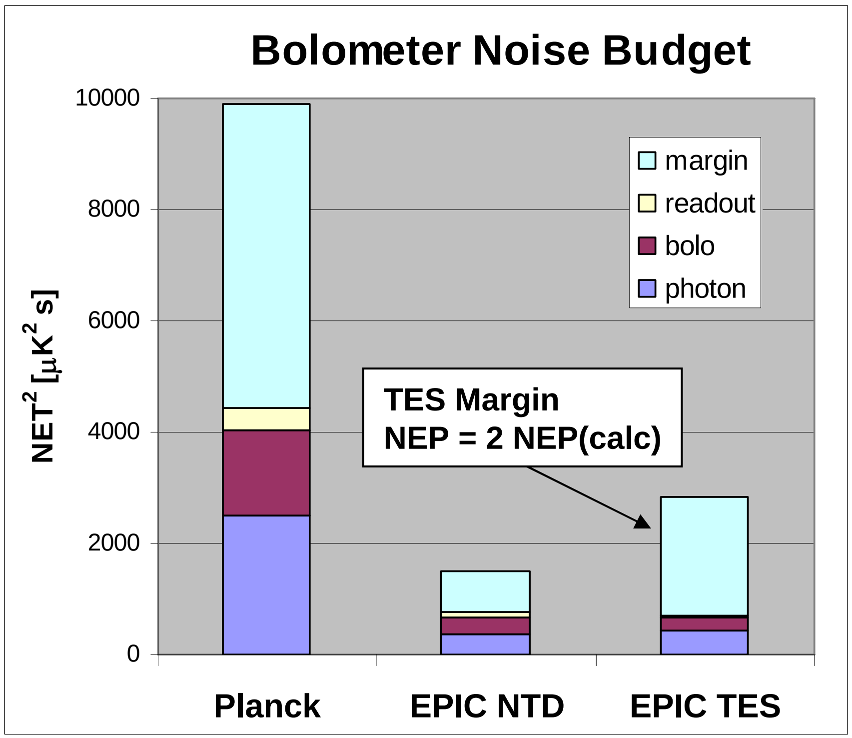
Planck/HFI focal plane (52 bolometers)



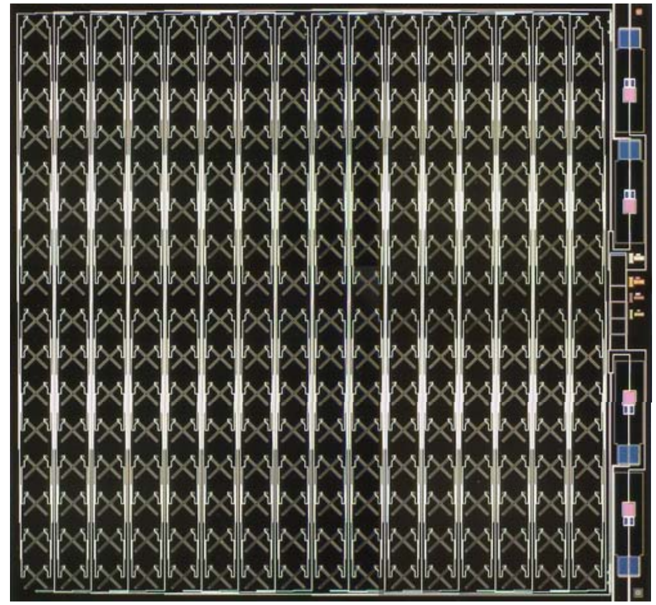
Low-power SPIRE JFETs (360 channels)

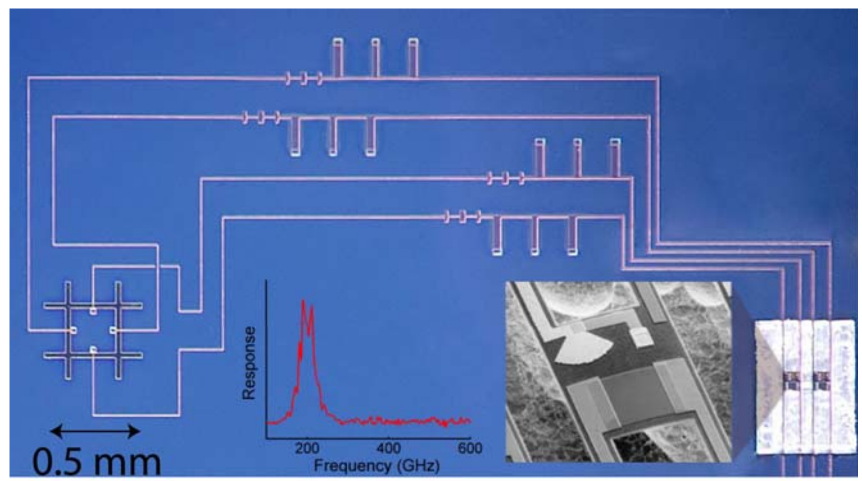
Focal Planes – Future Capabilities

Freq. coverage	[GHz]	30 – 300
# bolo		2200
NEP	[W/√Hz]	~6e-18
System NET	[μK√s]	1.6
τ	[ms]	1
Wires to 0.1 K (32:1 mux/band)		600
Focal plane mass at 0.1 K	[kg]	5
SQUID power to 0.1 K	[μW]	1



Antenna-Coupled TES Bolometers





Irvine Workshop 23-25 March 2006

A. Lee et al.

Conclusions

Scientific case for space

- **All-sky space mission needed**
- **Political landscape is currently unfavorable**
- **… we need to stick together as a community**

Imaging polarimeter approach

- **Optical design feasible**
- **Main beam effects are encouraging**
- **Systematics study still in progress**

Foregrounds

- **Need to know their amplitude**
- **Need to know how well they subtract**
- **… especially for ν > 90 GHz**

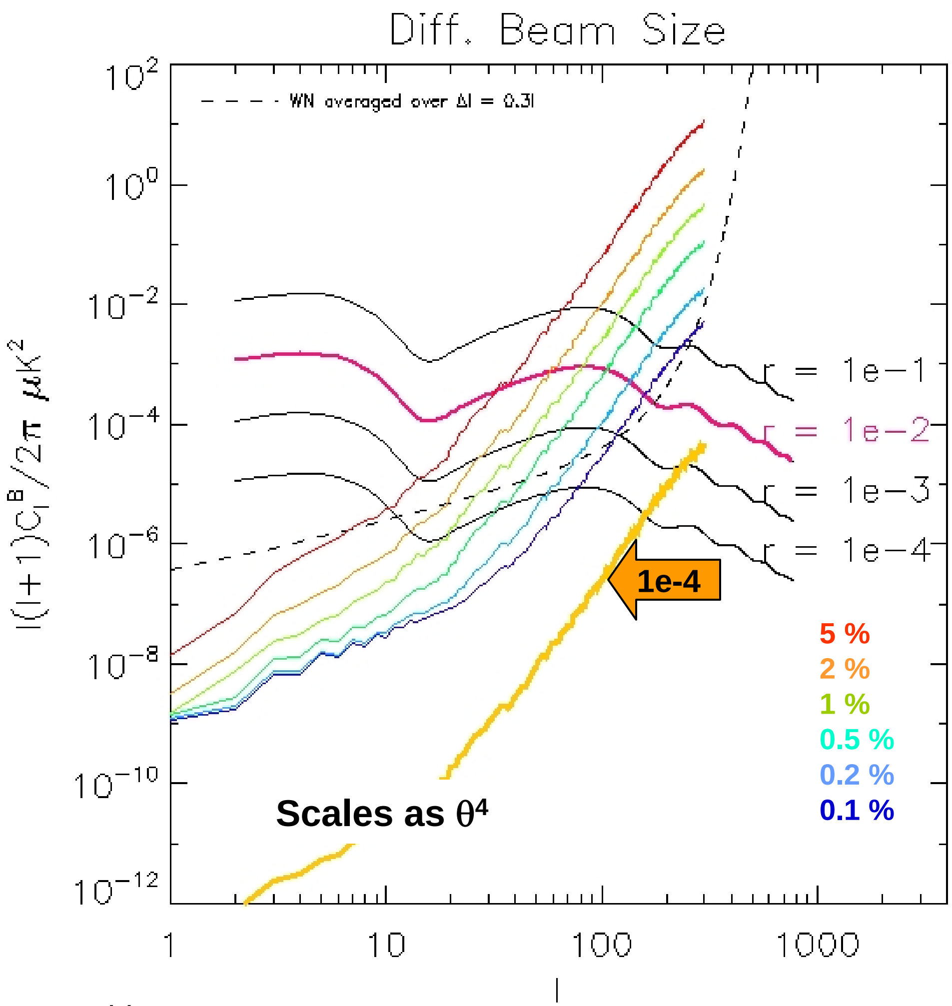
Technologies

- **We could build a very capable mission right now**
- **Clear path forward: improve focal plane sensitivities**
- **Antenna-coupled bolometers *reduce* cost & complexity**
- **System demos of new technologies**

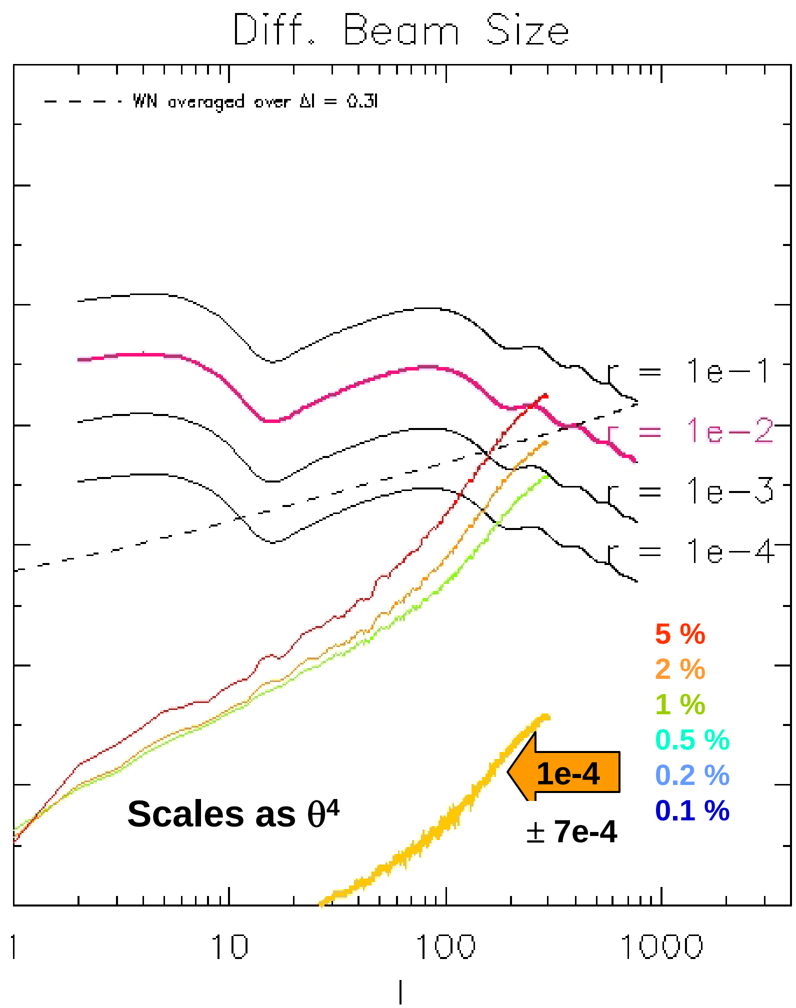
Backup Materials

Effects of Uncorrected Polarization

1º Refractor



5' Gregorian Dragone



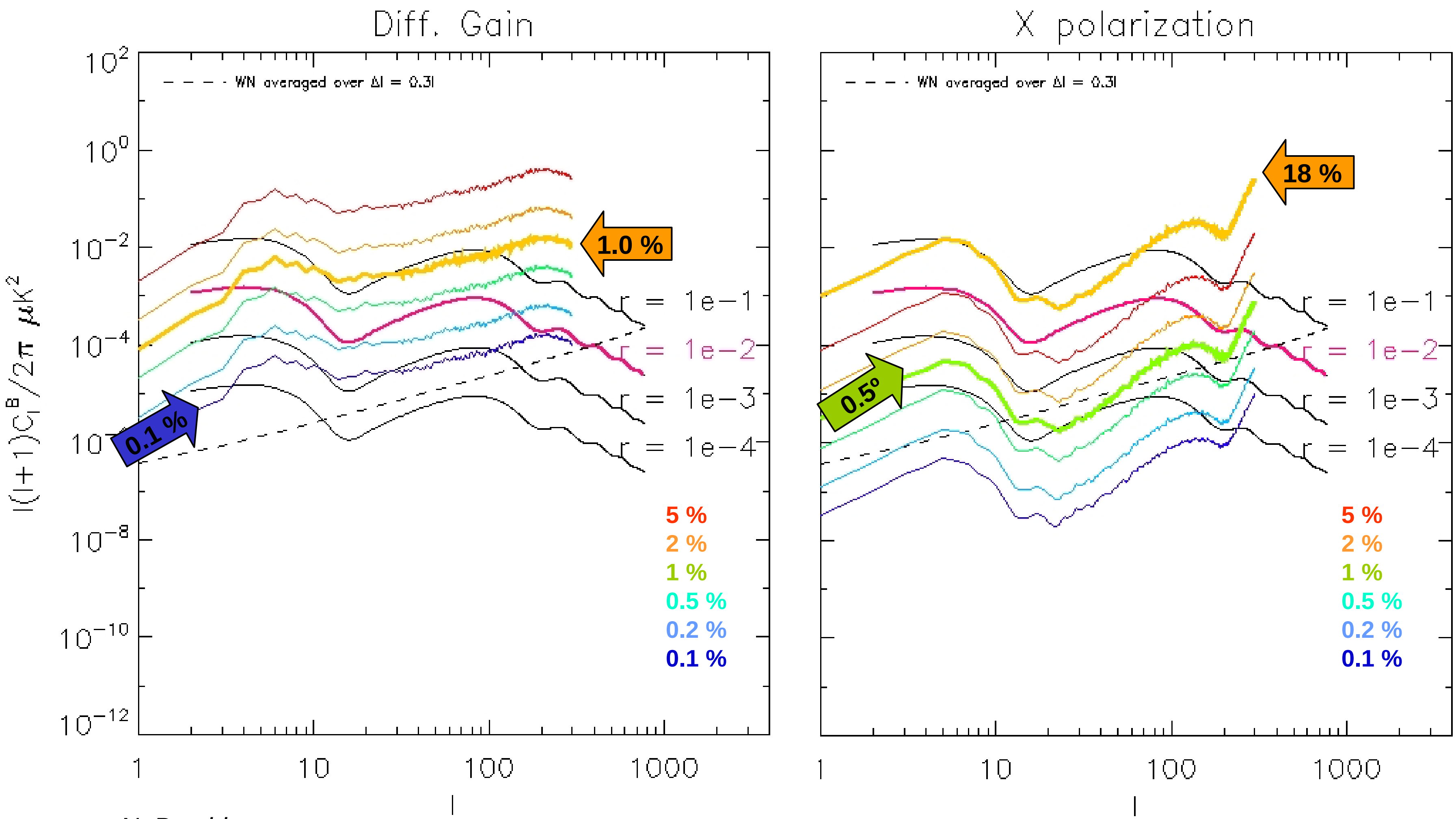
N. Ponthieu
E. Hivon
B. Keating

Arrow indicates the level achieved by optical analysis using Zemax PO

Arrow indicates the level achieved by optical analysis using Grasp9, *for mirrors only*

Effects of Uncorrected Polarization

Gregorian Dragone with 5' FWHM at 100 GHz



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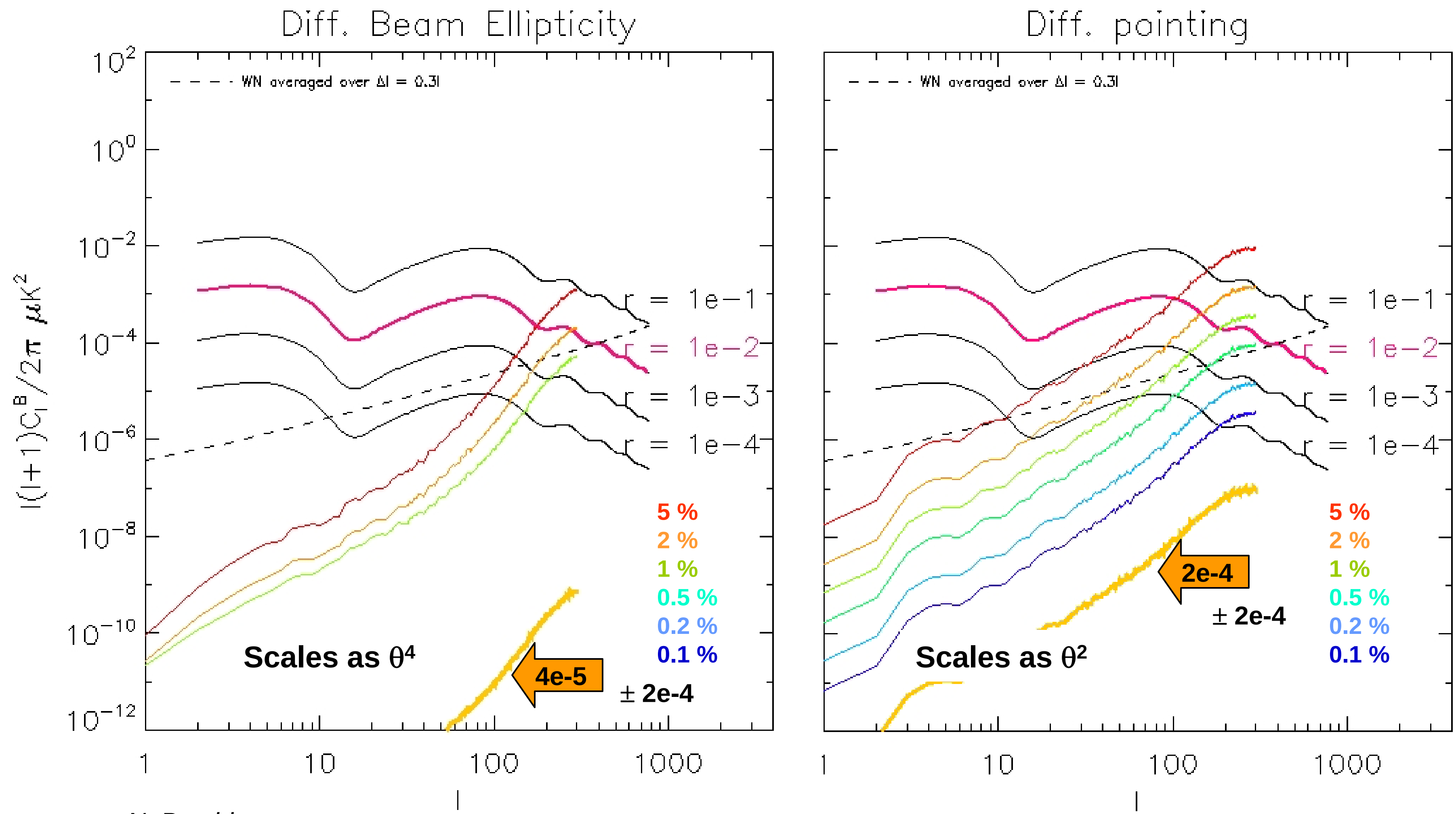
Arrows indicate the level achieved by optical analysis using Code-V
100 GHz, 1.5° radius

Effects of Uncorrected Polarization

Gregorian Dragone with 5' FWHM at 100 GHz



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Arrows indicate the level achieved by optical analysis using Grasp9, *for mirrors only*