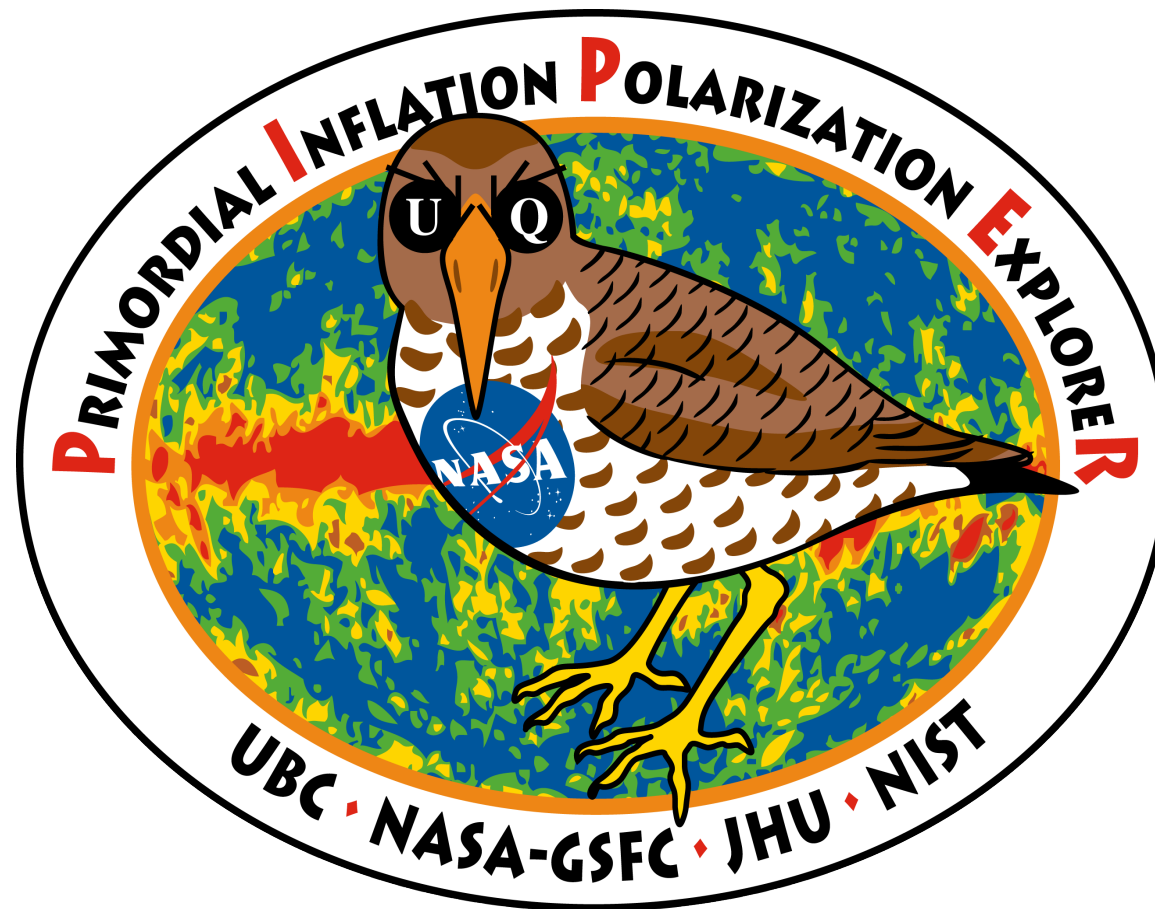


Goddard Space Flight Center

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# Primordial Inflation Polarization Explorer



Al Kogut  
Goddard Space Flight Center



Goddard Space Flight Center

# Primordial Inflation Polarization Explorer

## NASA/GSFC

A. Kogut (PI)  
D. Benford  
D. Chuss  
D. Fixsen  
J. Hinderks  
C. Jhabvala  
T. Miller  
P. Mirel  
H. Moseley  
E. Sharp  
J. Staguhn  
E. Switzer  
E. Wollack

## Johns Hopkins

C. Bennett  
J. Lazear  
J. Eimer

## Cardiff

P. Ade  
C. Tucker

## NIST

G. Hilton

## NASA/Ames

J. Dotson

## Stanford

K. Irwin

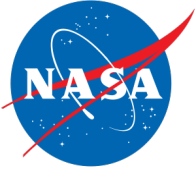
## UBC

M. Halpern  
G. Hinshaw

## Michigan

J. McMahon

*Detect Inflationary Gravity Waves  
on Largest Angular Scales*



# PIPER Overview

## Sensitivity

- 5120 TES bolometers
- 1.5 K Optics with no warm window
- Background-limited ( $NEQ < 2 \mu\text{K s}^{1/2}$ )

## Systematics

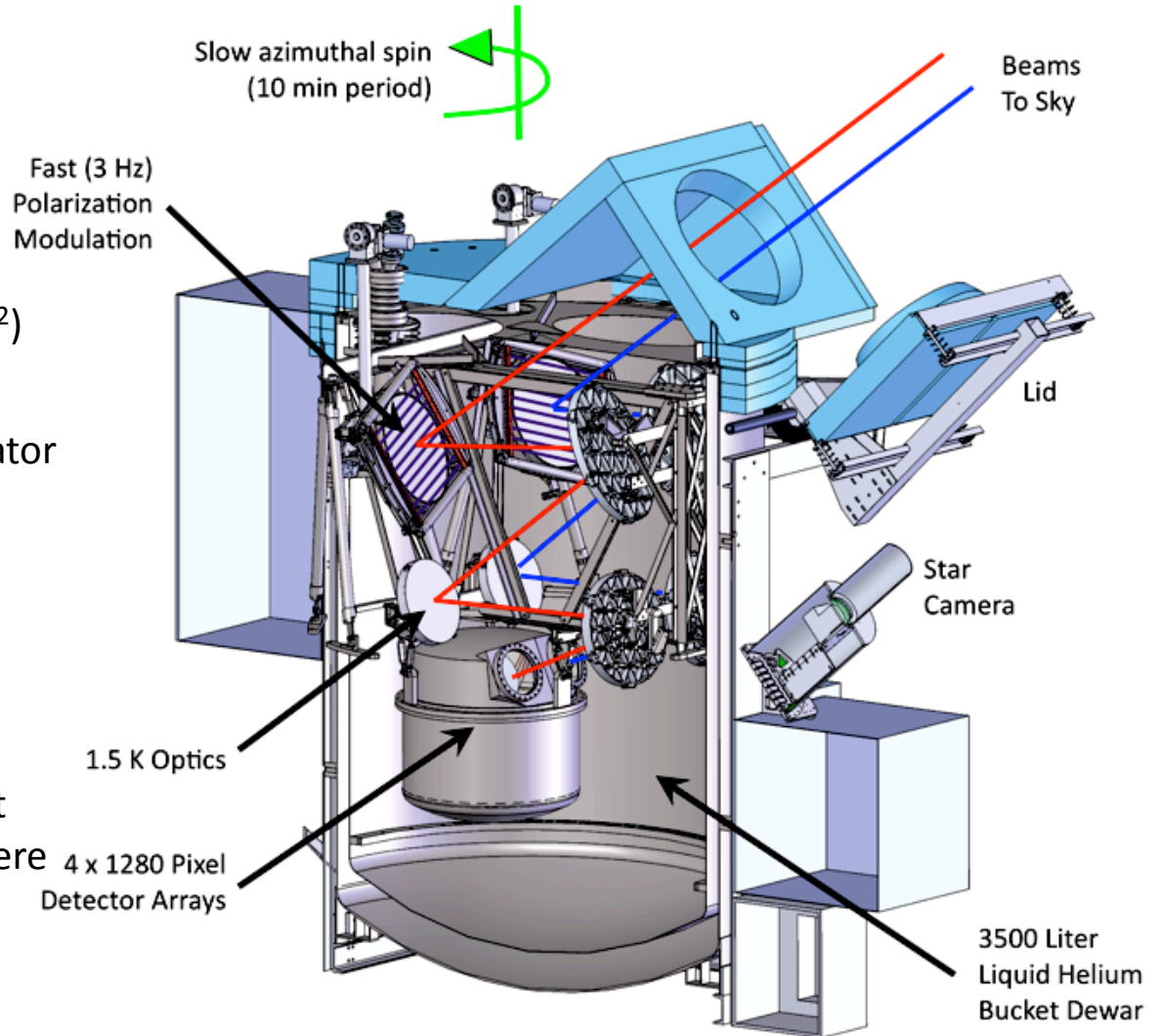
- Front-End VPM polarization modulator
- Twin cryogenic telescopes

## Foregrounds

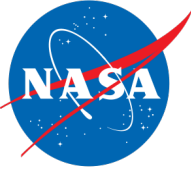
- 200, 270, 350, and 600 GHz
- Cleanly separate dust from CMB

## Sky Coverage

- Balloon payload, conventional flight
- 8 flights, North and South hemisphere



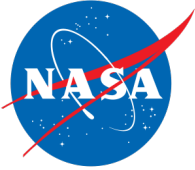
See the sky, the whole sky, and nothing but the sky



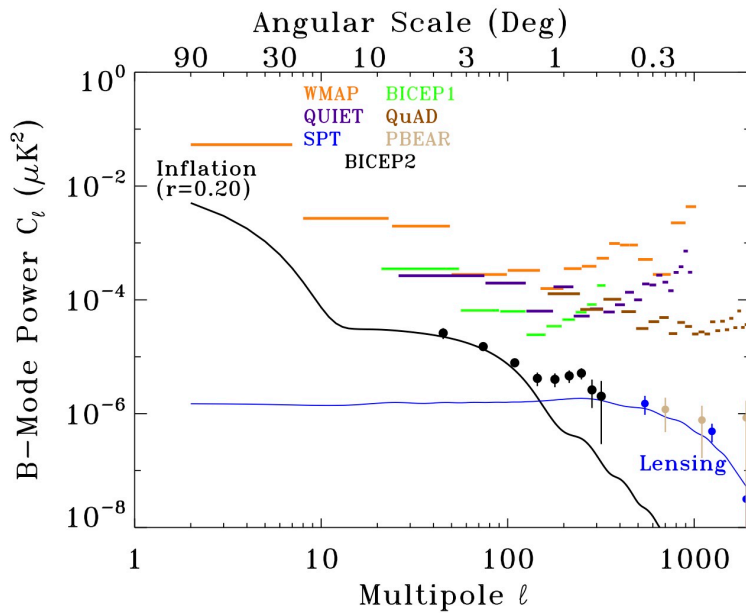
# Why Balloons?



*The problem with ground-based cosmology*



# Designing for B-Modes



## Sensitivity

- Photon noise limit
- Near-space sensitivity

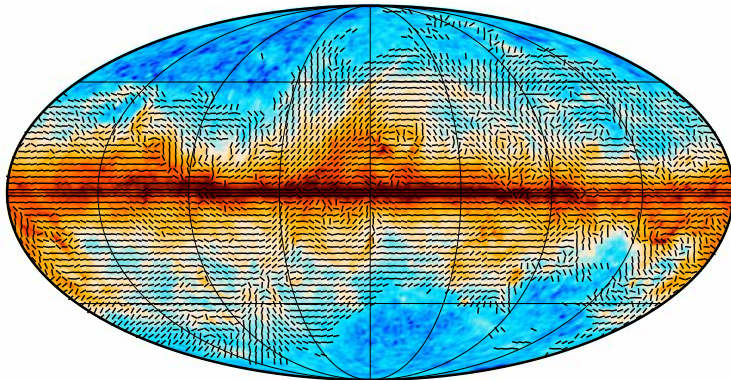
## Sky Coverage

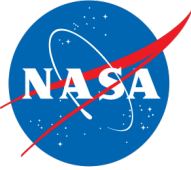
- Low  $l \rightarrow$  Large angular scales
- Map polarization over most of sky

## Foregrounds

- Multiple frequency bands
- Dust  $\rightarrow$  Access to high frequencies

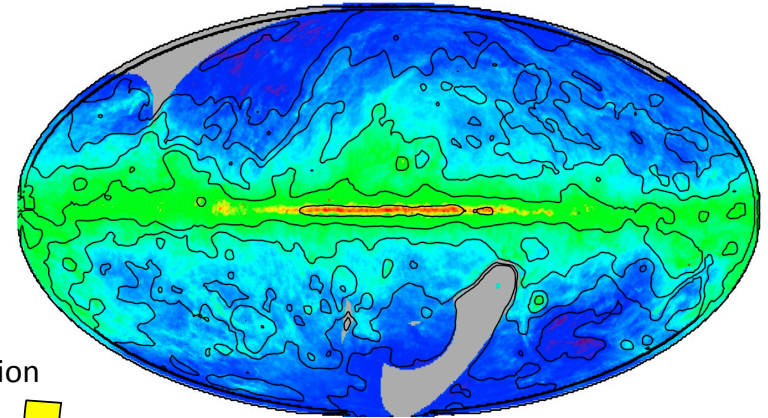
**Balloons!**





# PIPER in a Nutshell

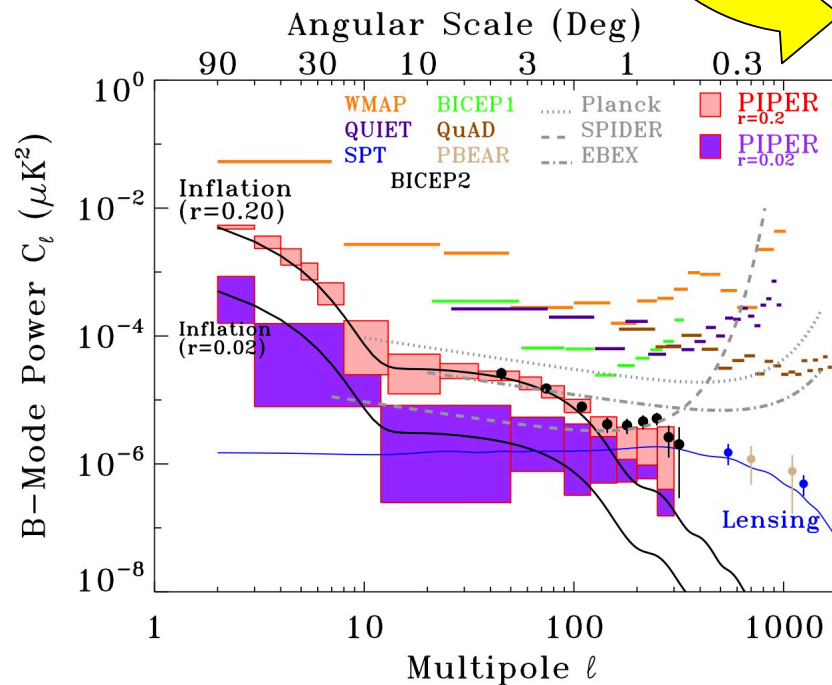
Cold optics improve mapping speed by a factor of 10 ...



PIPER Sky Coverage

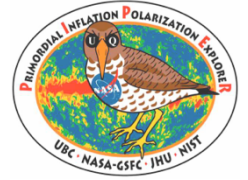
Which allows overnight flights instead of Antarctic long duration flights ...

Which allows scans over the full  $2\pi$  steradians of the night sky



Sensitivity  $r < 0.007$  ( $2\sigma$ )  
First flight planned for Sept 2015

PIPER observes both the **inflationary signal** on large angular scales and the **lensing foreground** on small scales and will map the **polarized dust foreground**

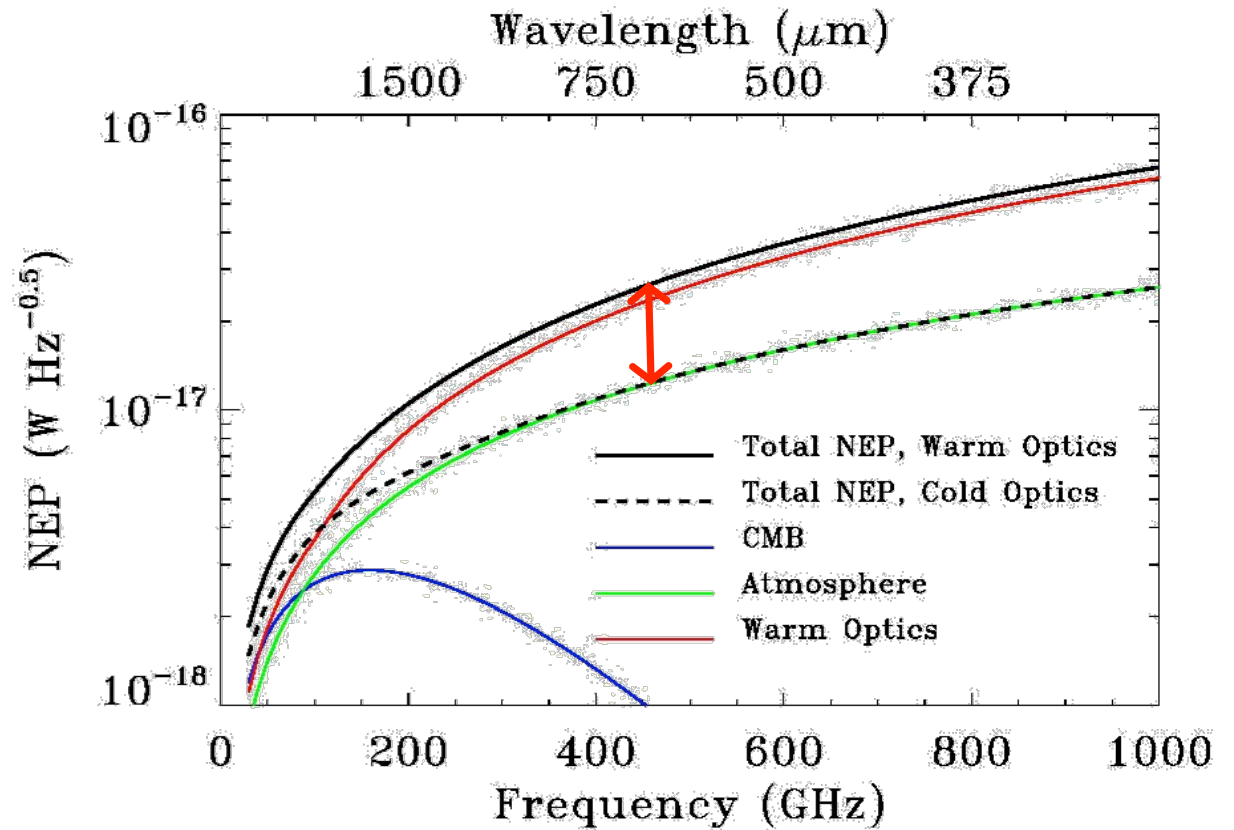


# Cold Optics for Fast Mapping

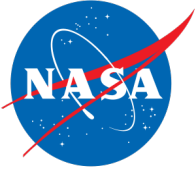


*No Warm Surfaces = No Unwanted Photons*

Improve NEP x 3  
Improve speed x 10

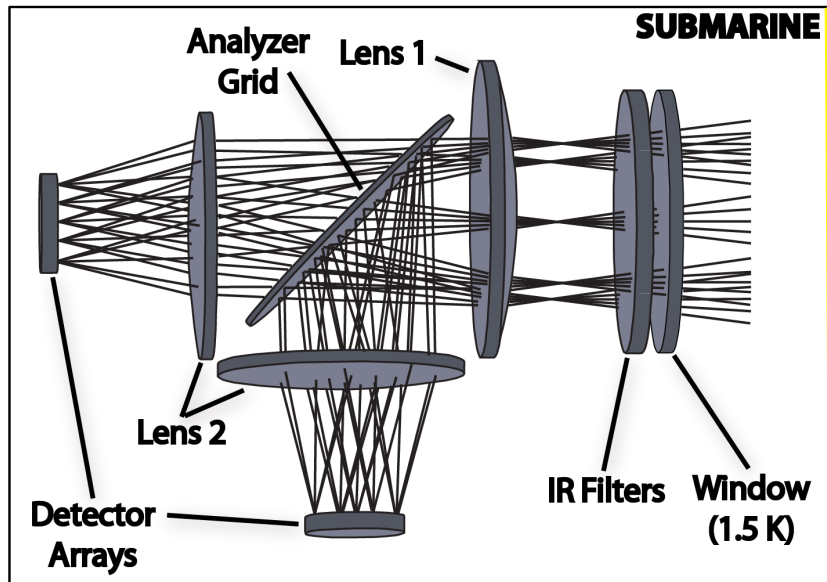
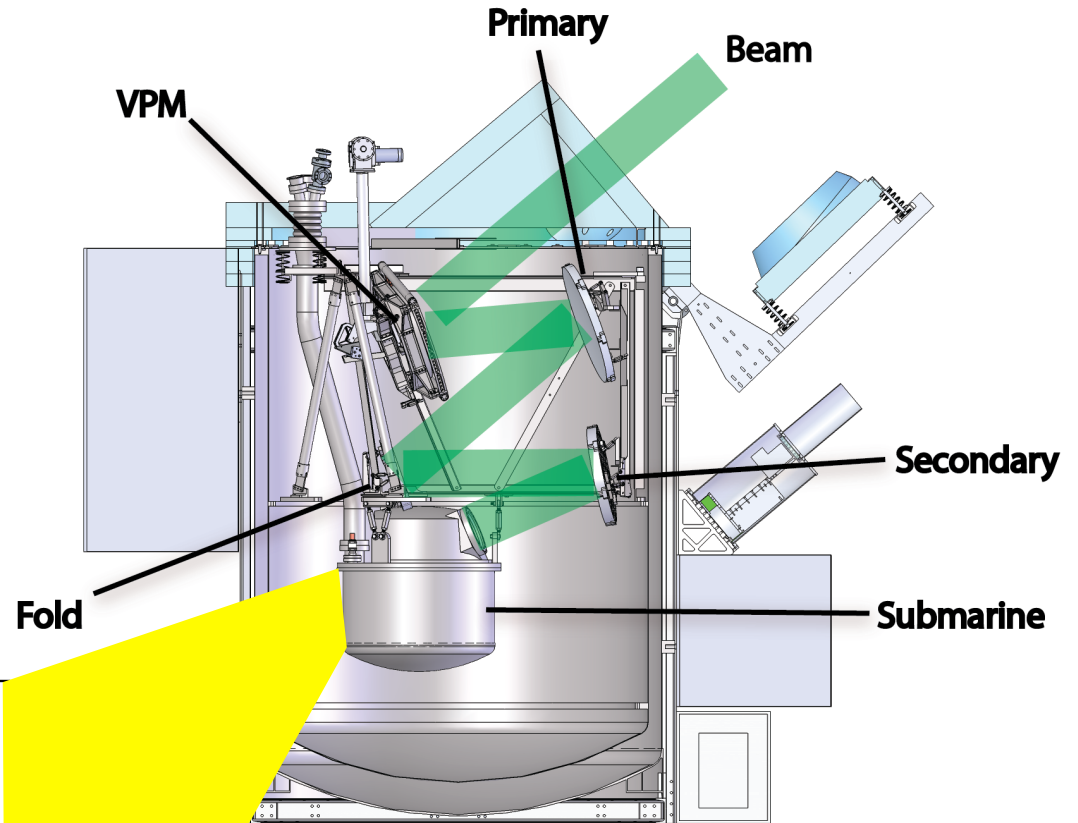


*Warm surfaces = Throw away 90% of your detectors!*



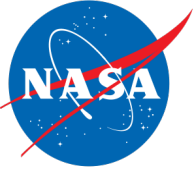
# Telescope

- All optical elements at 1.5 K using proven ARCADE design
- Metamaterial AR coating (Jeff McMahon, U Mich)
- One telescope measures IQV, the other measures IUUV



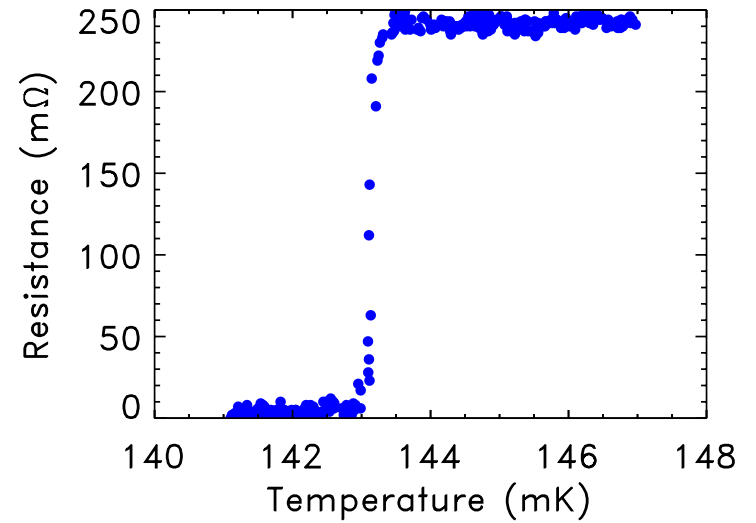
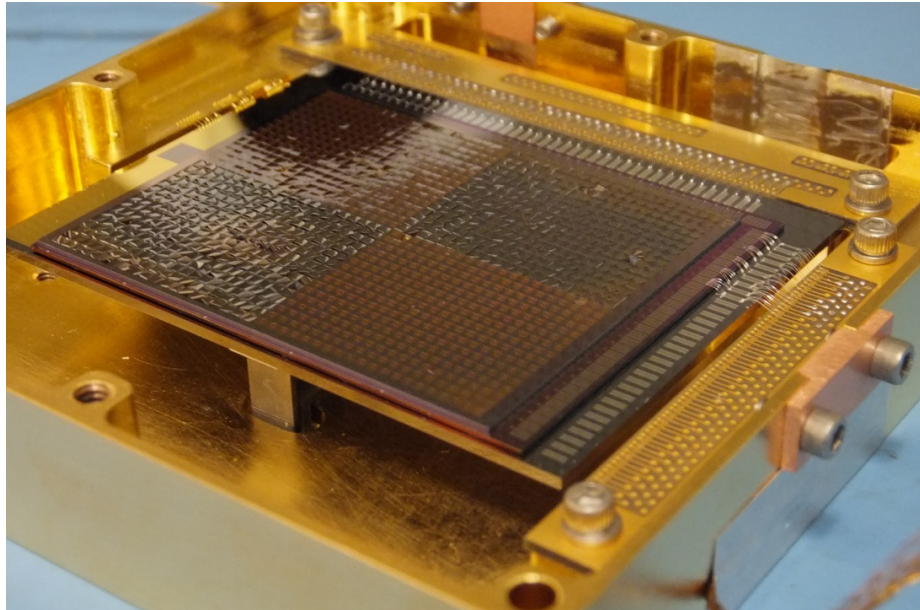
- 5° x 7° field of view
- 20 arc-min beam
- Four 32x40 detector arrays



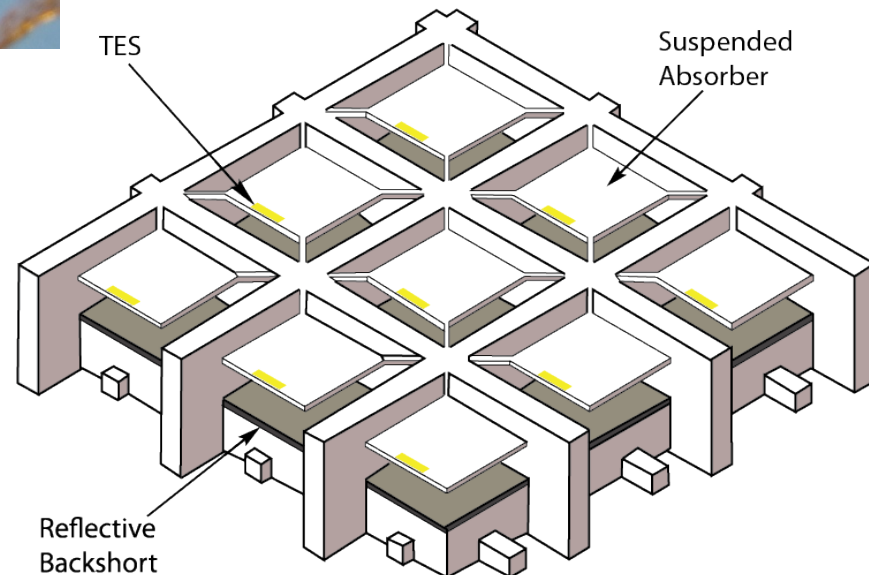


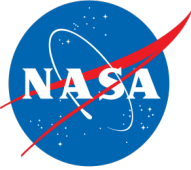
# Detectors

## Four 32x40 TES Bolometer Arrays



Pixel Pitch	1135 $\mu\text{m}$
Base Temperature	100 mK
Absorber Temperature	140 mK
Power Loading	0.5 $\mu\text{W}$
Thermal Conductance	29 $\mu\text{W}/\text{K}$
NEP	$3.8 \times 10^{-18} \text{ W Hz}^{-0.5}$





# Detector Arrays

Parameter	Band 1	Band 2	Band 3	Band 4
Frequency (GHz)	200	270	350	600
Wavelength ( $\mu\text{m}$ )	1500	1100	850	500
Bandwidth $\delta\nu/\nu$	0.30	0.30	0.16	0.10
Beam Width (arc-min)	19	15	13	10
Optical Efficiency to Detector	0.55	0.52	0.50	0.42
Detector Absorption Efficiency	0.90	0.90	0.70	0.50
CMB Power (fW)	120	70	20	<1
Atmospheric Power (fW) <sup>a</sup>	20	90	150	230
Total Absorbed Power (fW)	200	190	190	250
Saturation Power (fW)	1200	1200	1200	1200
Photon NEP ( $\text{W Hz}^{-1/2}$ )	$7 \times 10^{-18}$	$8 \times 10^{-18}$	$11 \times 10^{-18}$	$13 \times 10^{-18}$
Phonon NEP ( $\text{W Hz}^{-1/2}$ )	$4 \times 10^{-18}$	$4 \times 10^{-18}$	$4 \times 10^{-18}$	$4 \times 10^{-18}$
Single-Detector NEQ ( $\mu\text{K } \sqrt{\text{s}}$ )	44	70	320	3800
Number of Detectors (phonon)	5120	5120	5120	5120
Number of Detectors (photon)	945	1550	2270	3760
Instrument NEQ ( $\mu\text{K } \sqrt{\text{s}}$ )	1.3	1.9	6.7	110
Instrument NEQ ( $\text{mJy} \sqrt{\text{s}}$ )	13	9	17	30

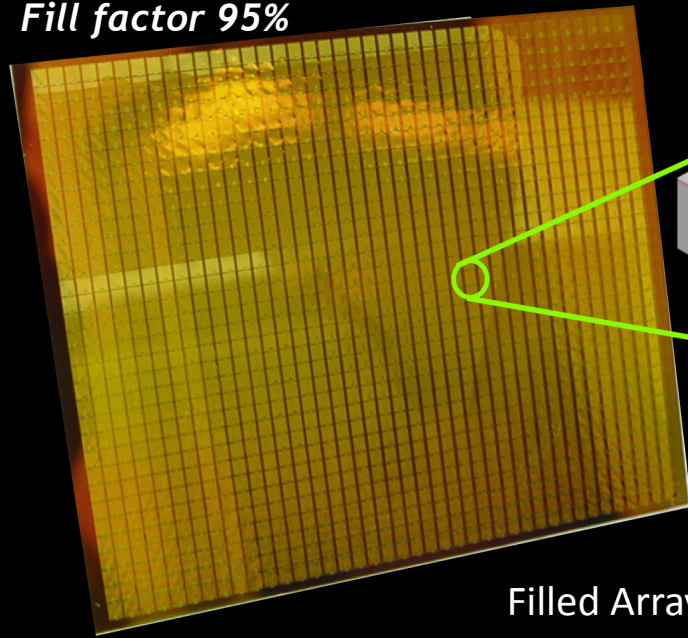
<sup>a</sup>Atmospheric values shown for float altitude 35 km

- Absorber-coupled TES bolometers at 100 mK
- 4 arrays each 32 x 40 pixels (5120 total)
- Backshort-Under-Grid (BUG) architecture
- Bump-bond to NIST 32x40 tMUX chip

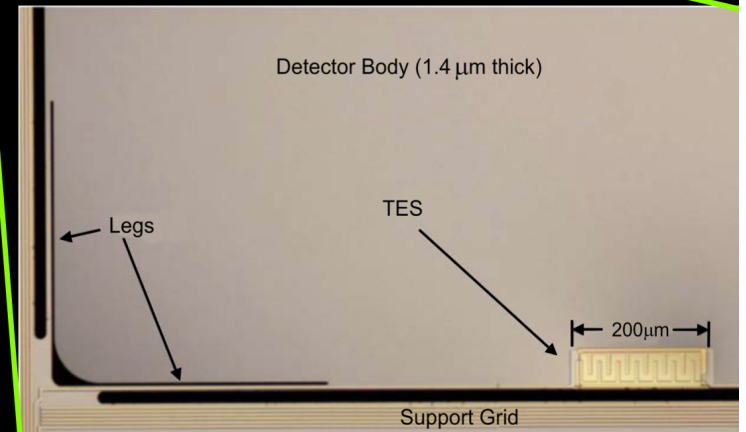
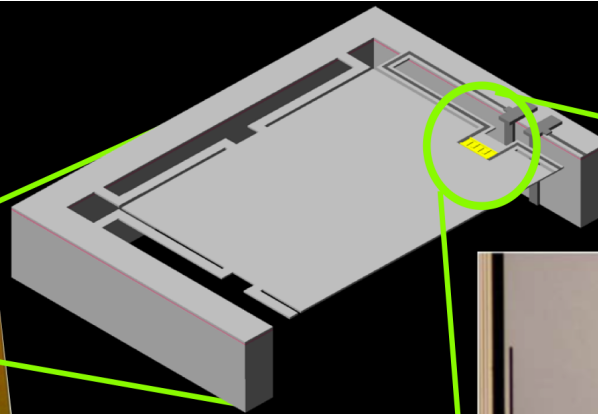
*Fly With Near-Space Power Loading*

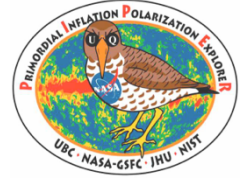
*NEQ < 2  $\mu\text{K } \text{s}^{1/2}$  in both CMB bands*

Fill factor 95%

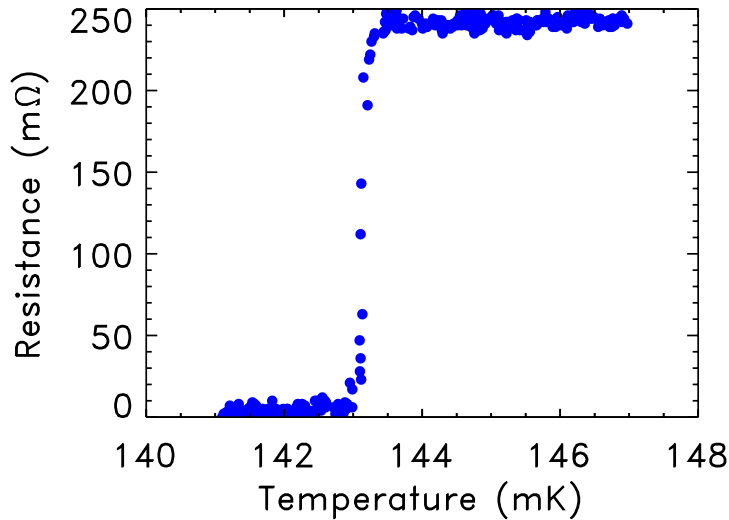


Filled Array 32 x 40 pixels





# Detector Characterization



### Demonstrated design parameters

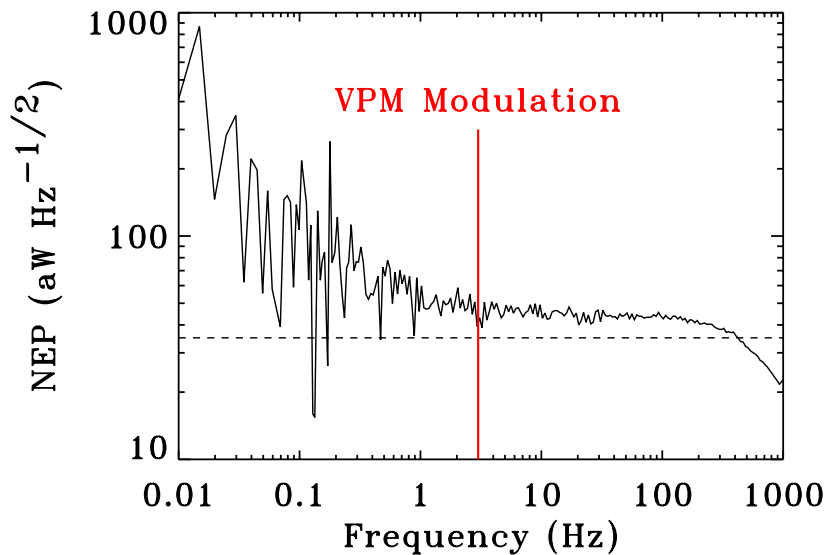
- $T_c$ ,  $G$  for flight signal levels and noise
- Thru-wafer vias, indium bump bonds for signal routing
- VPM greatly relaxes  $1/f$  requirements

### Pathfinder to demonstrate 32 x 40 array

- Wafer and pixel yields
- Flight-like signal path through MCE readout
- Demonstrate superfluid plumbing

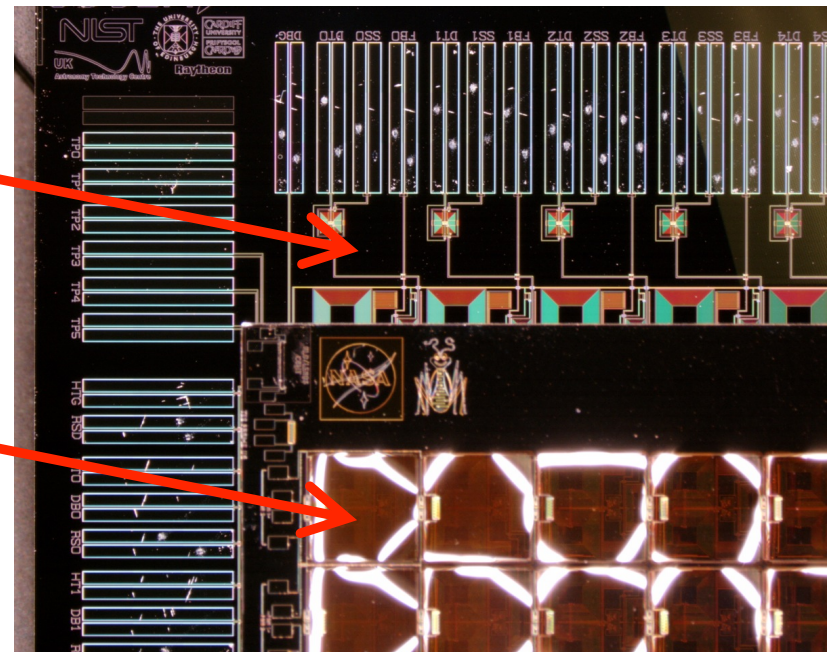
### Flight array delivery early 2015

- Final sensitivity,  $1/f$  knee
- Flight code for autonomous array optimization

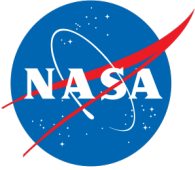


NIST  
tMUX

BUG  
Array

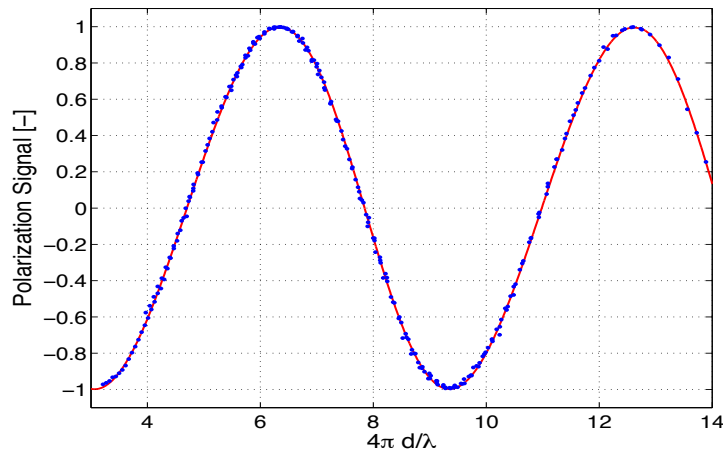
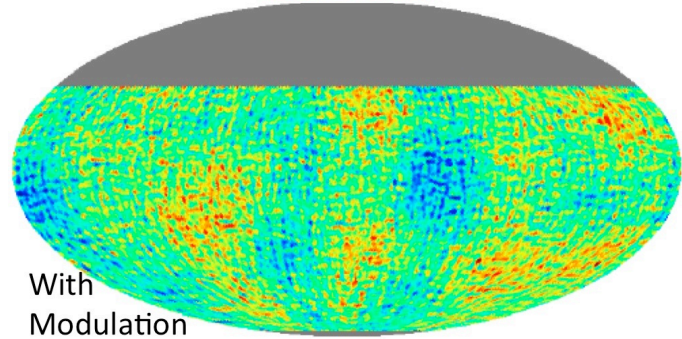
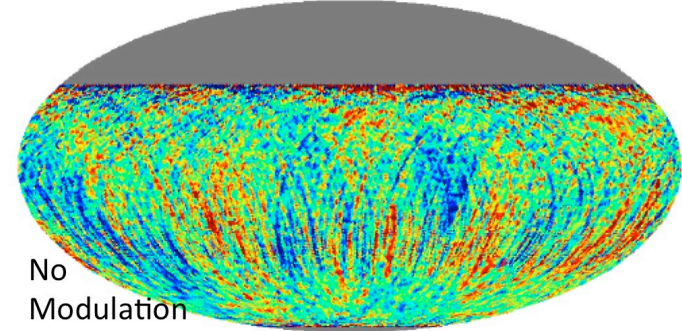
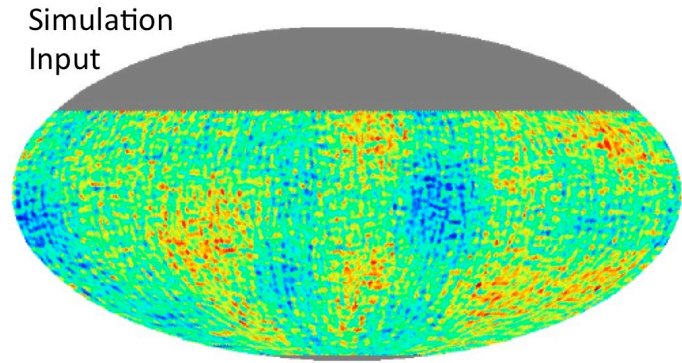
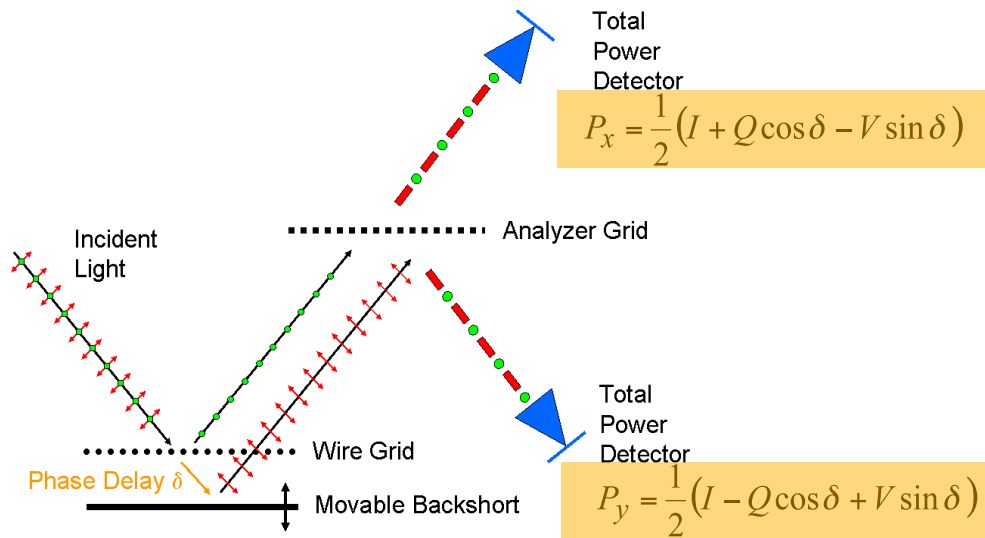


32 x 40 array hybridized to MUX



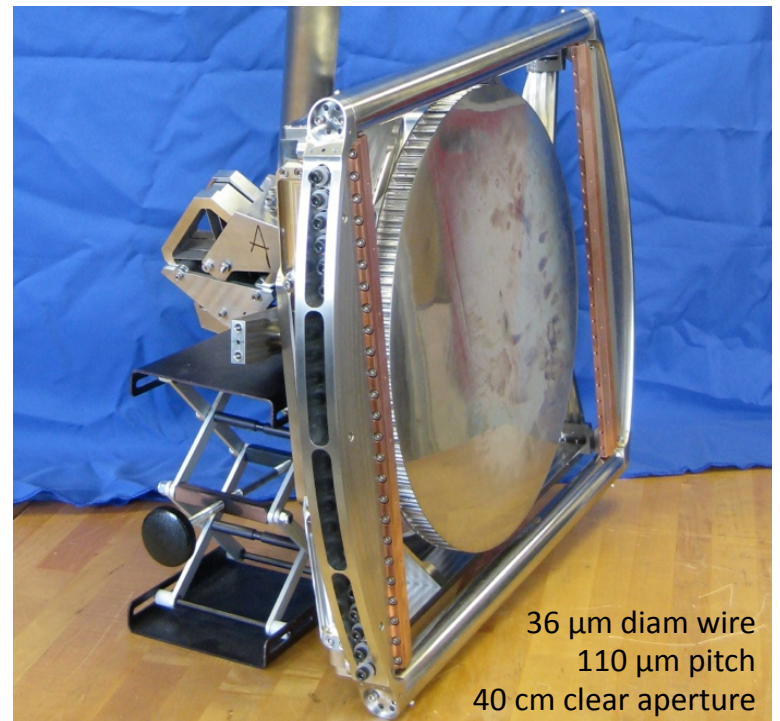
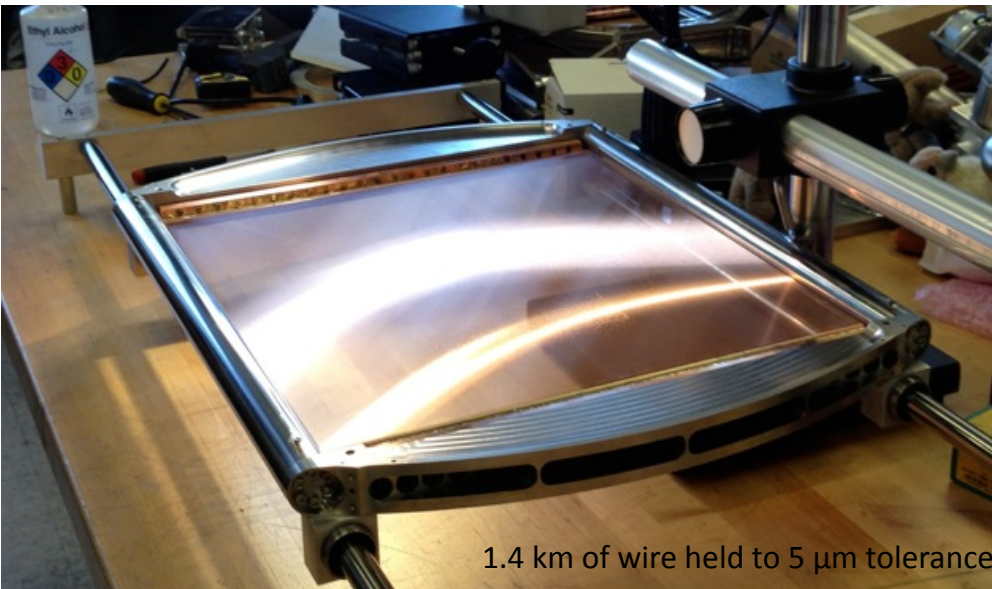
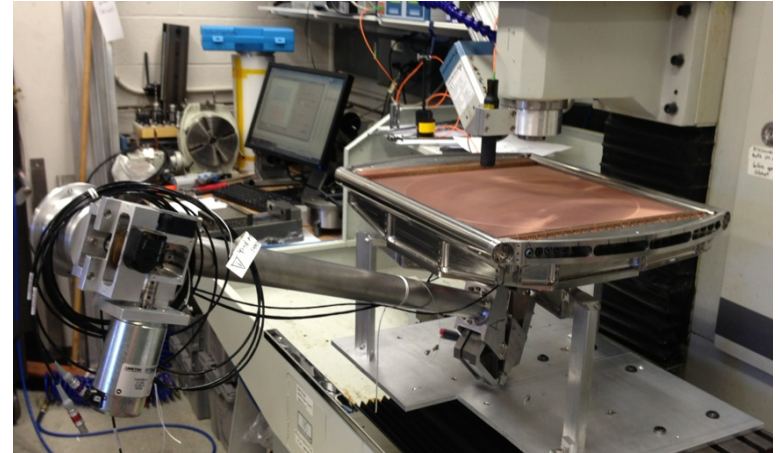
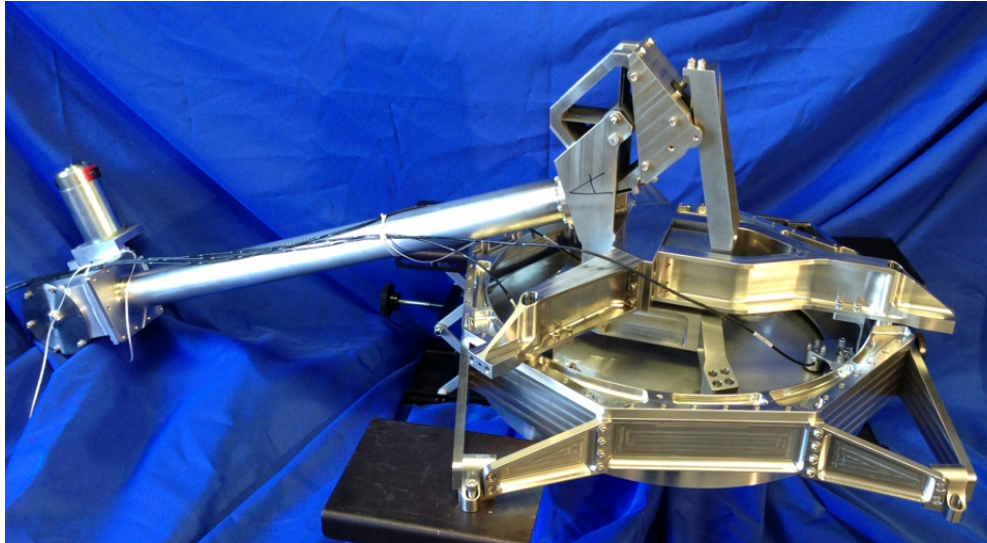
# Variable-Delay Polarization Modulator (VPM)

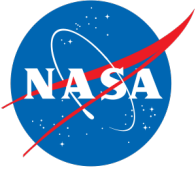
Measure linear and circular polarization!



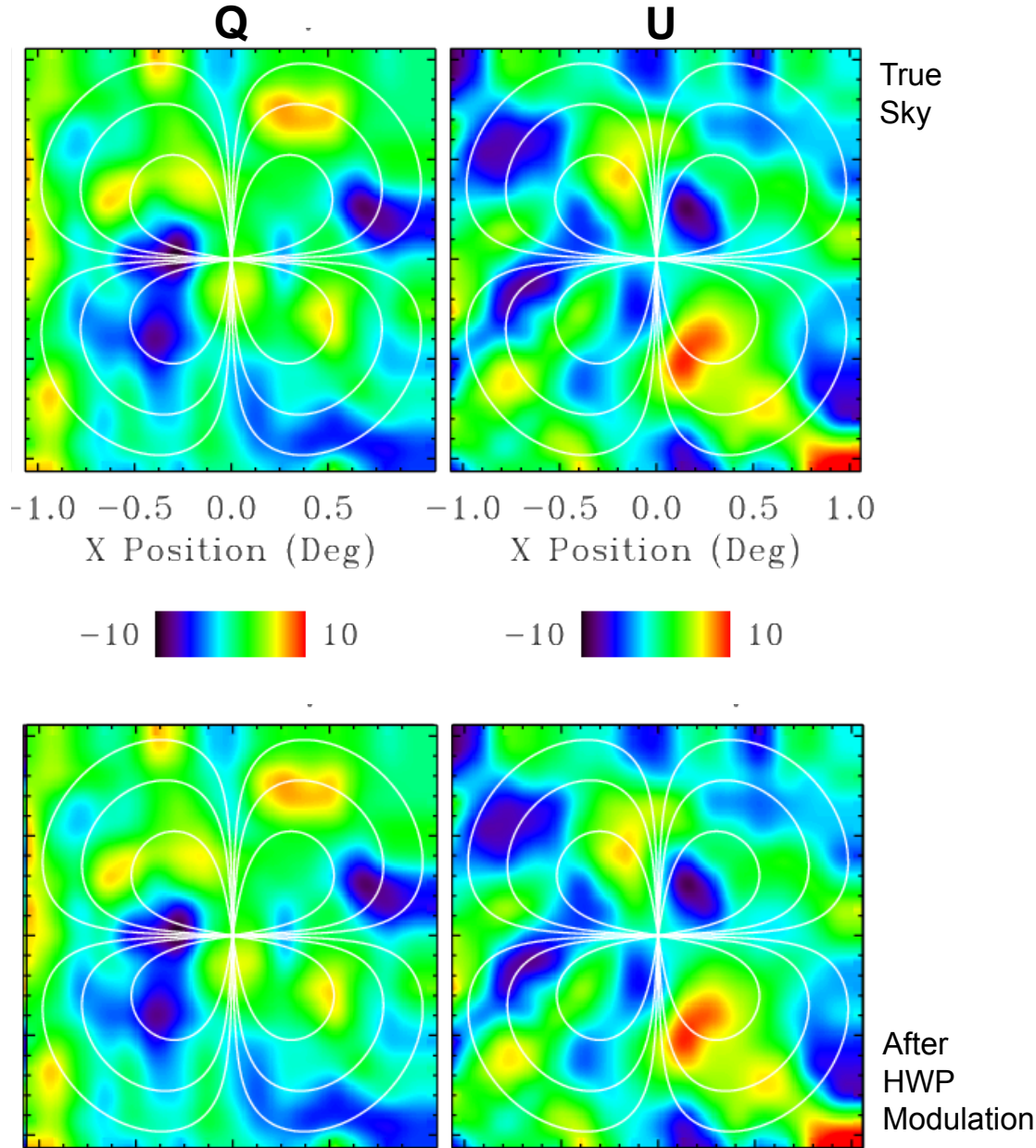


# Polarization Modulator

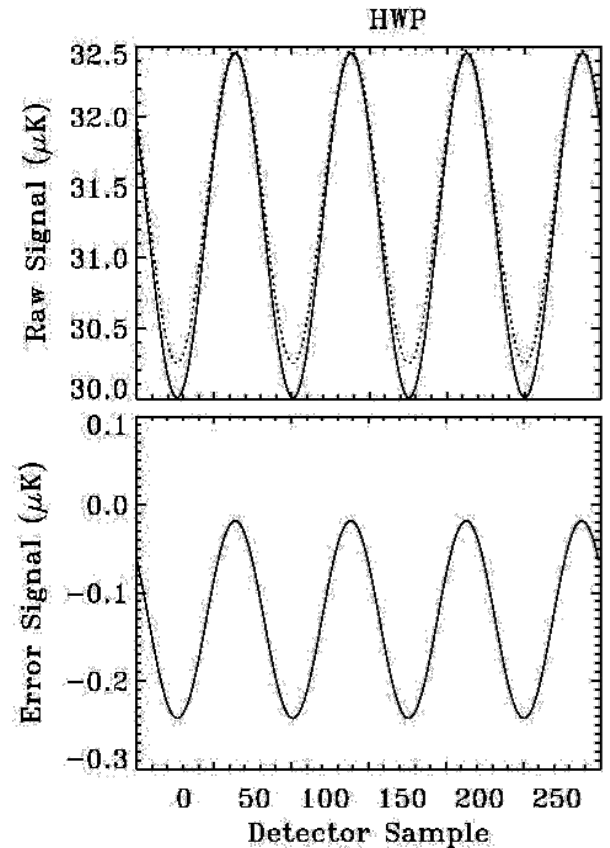


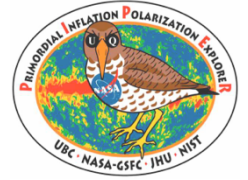


# Cross-Polar Beam Systematics

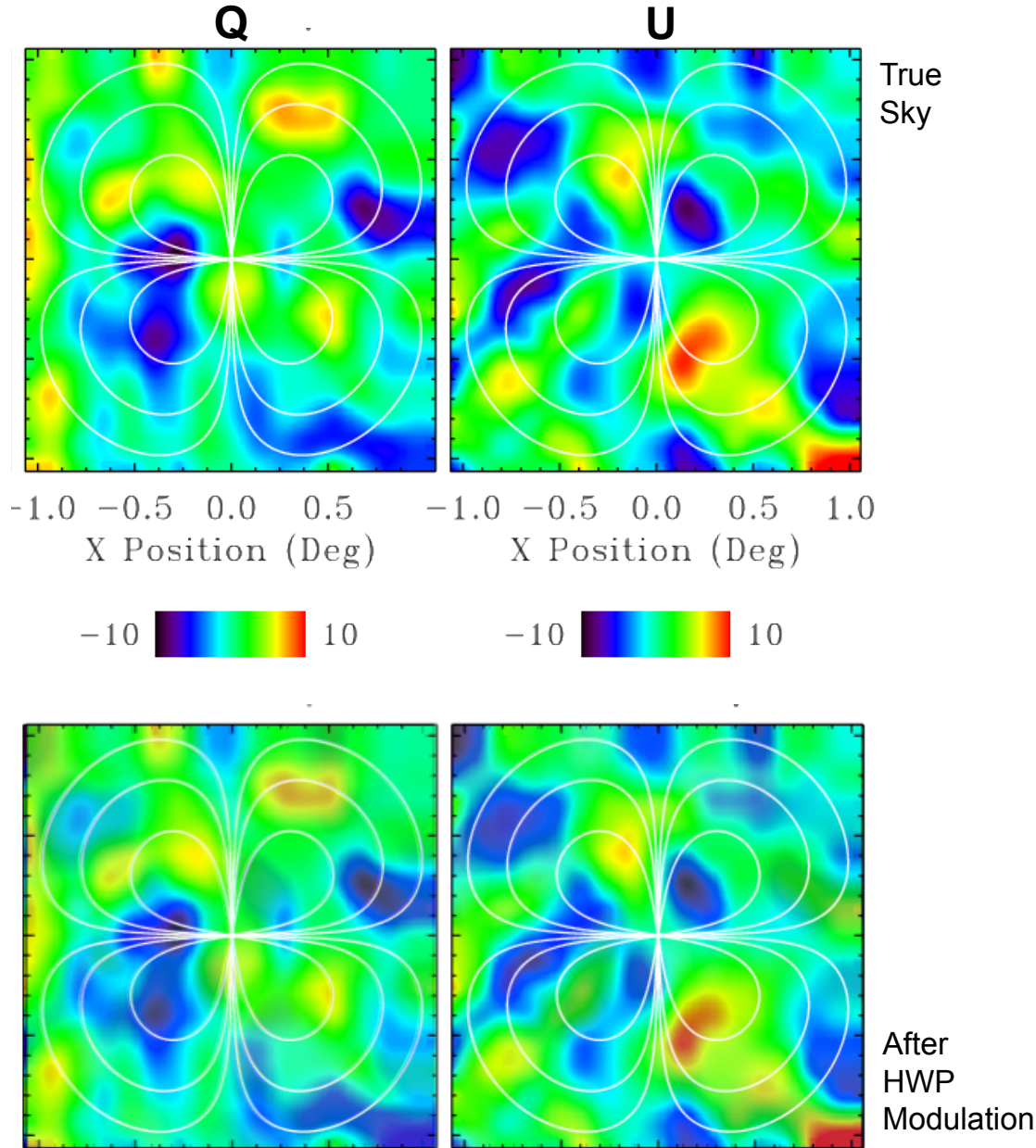


Wave Plate:  
Q/U mixing  
plus  
Q/U modulation

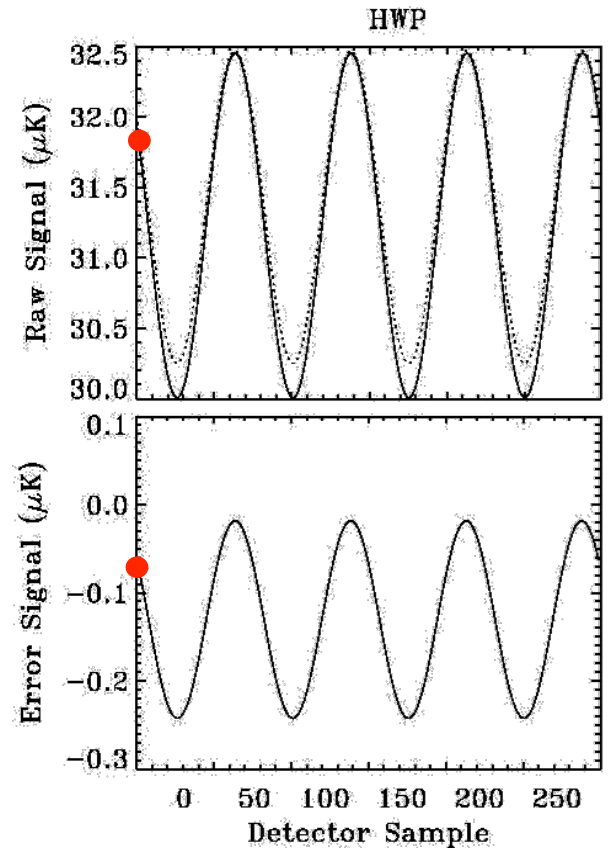




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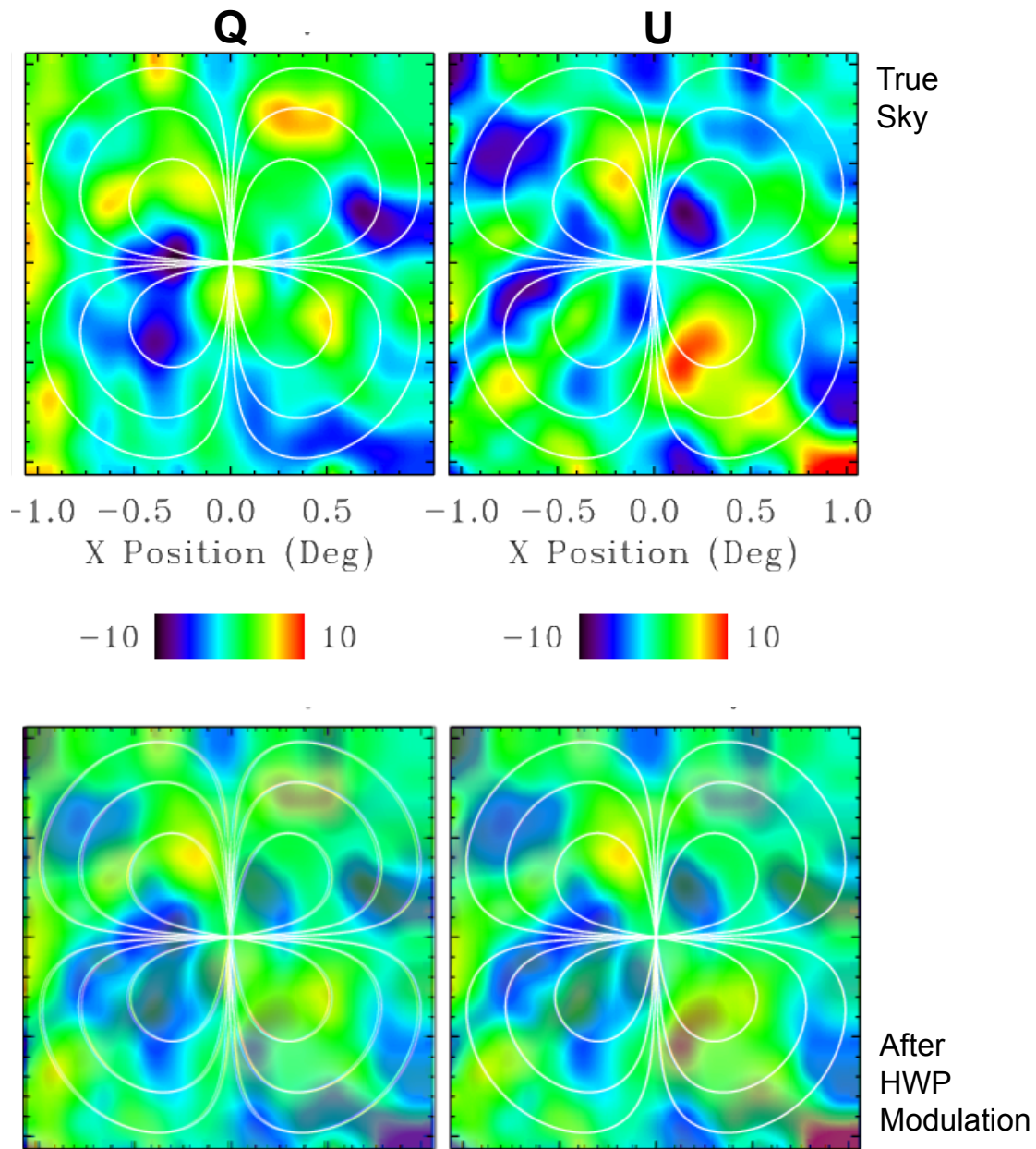


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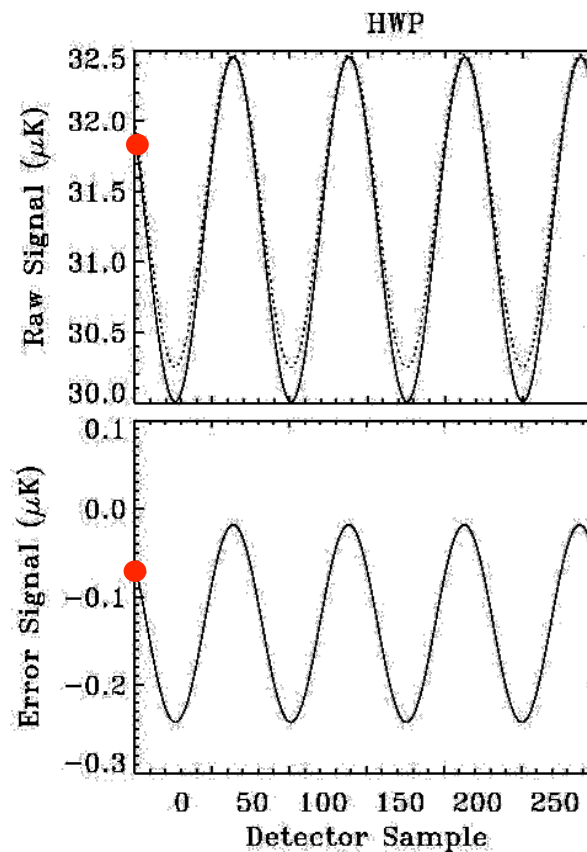




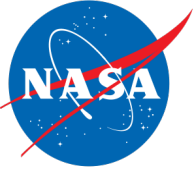
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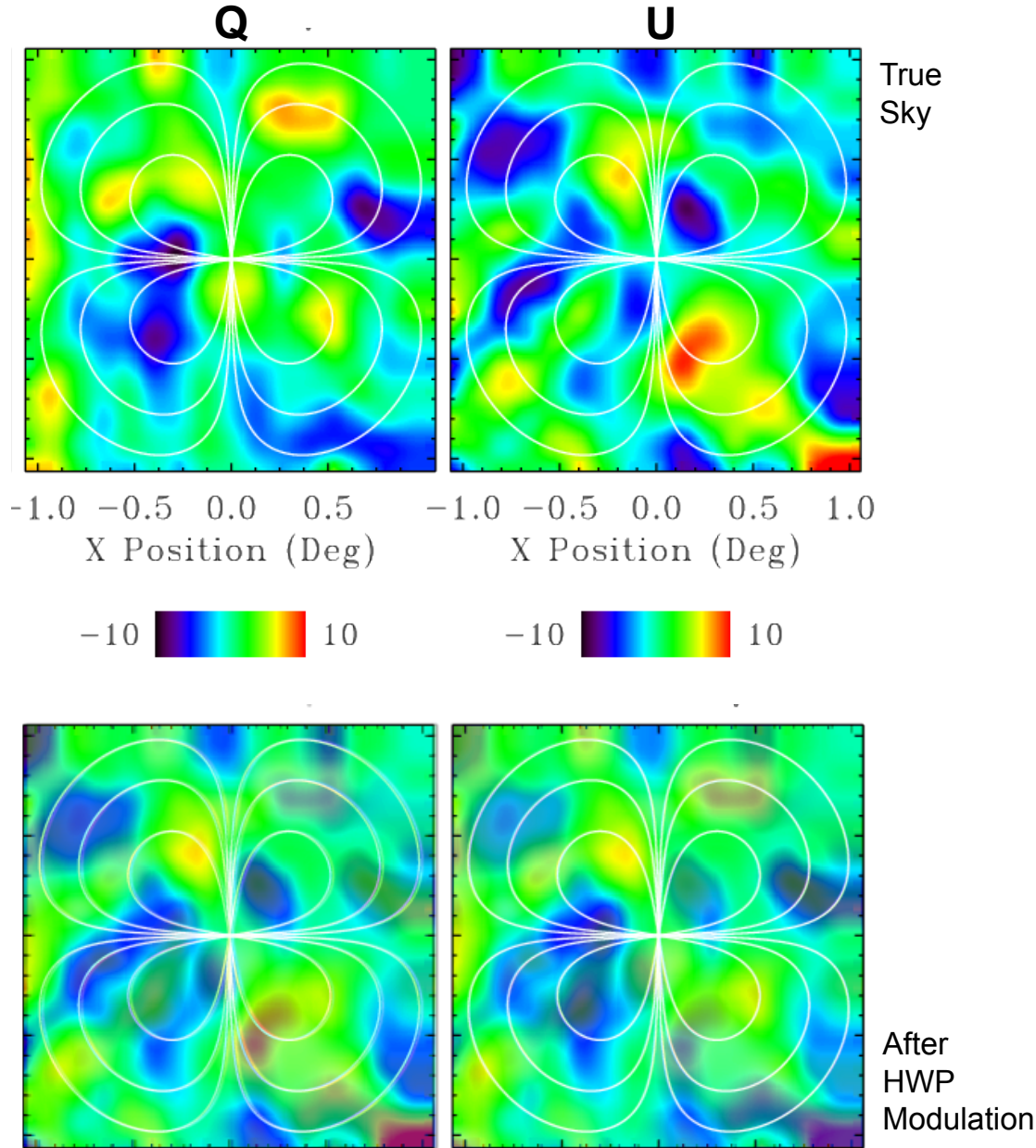
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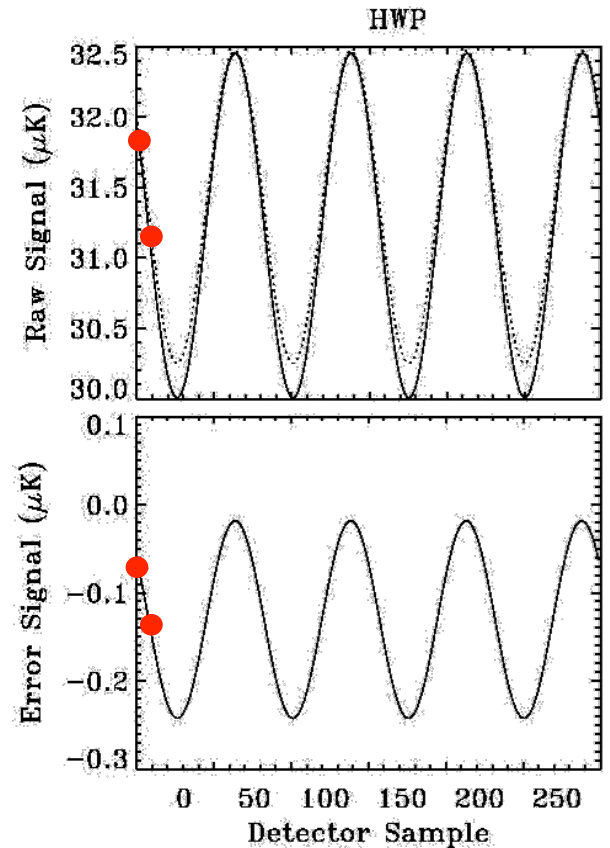


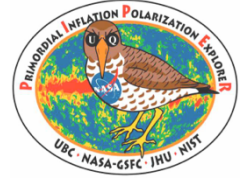
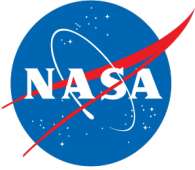


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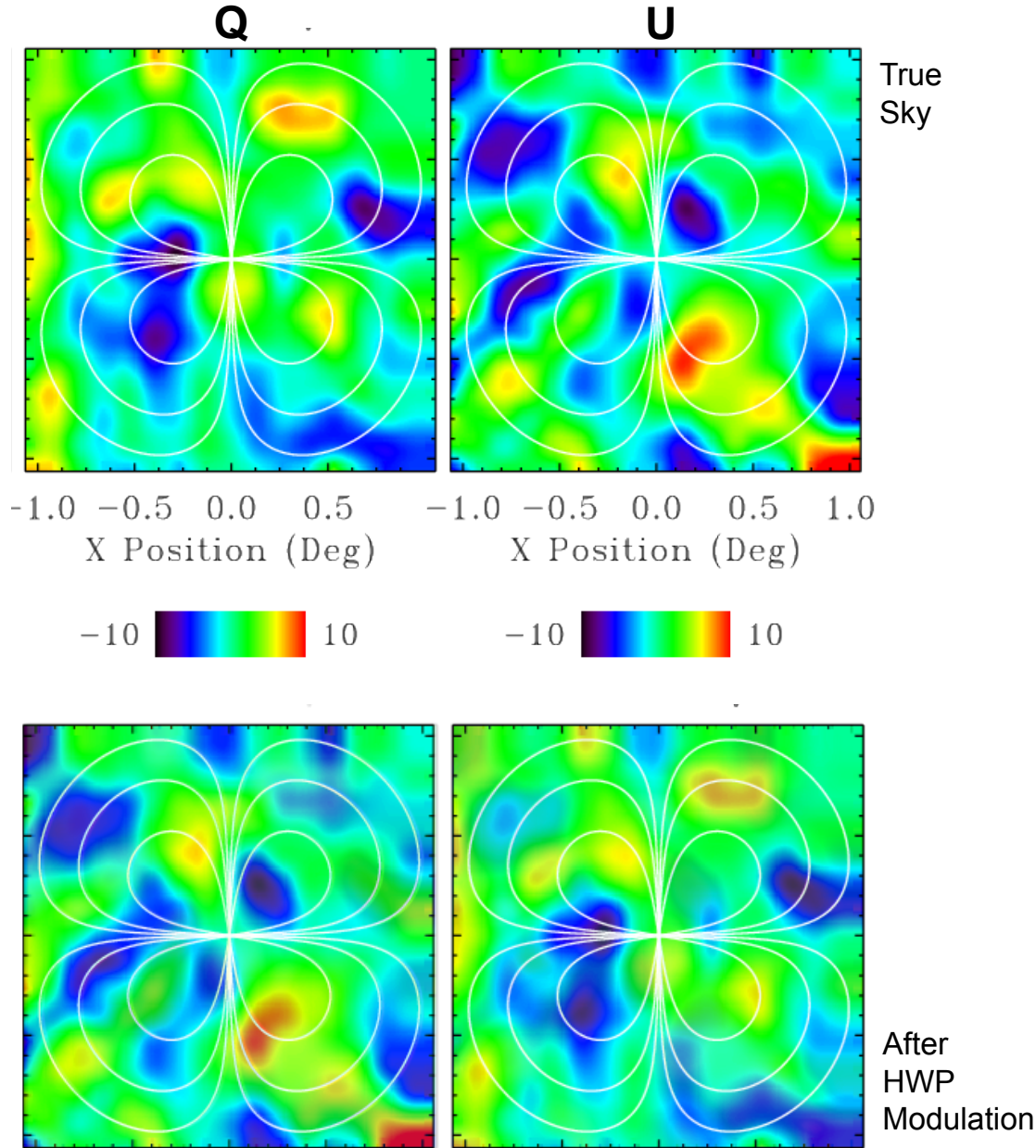


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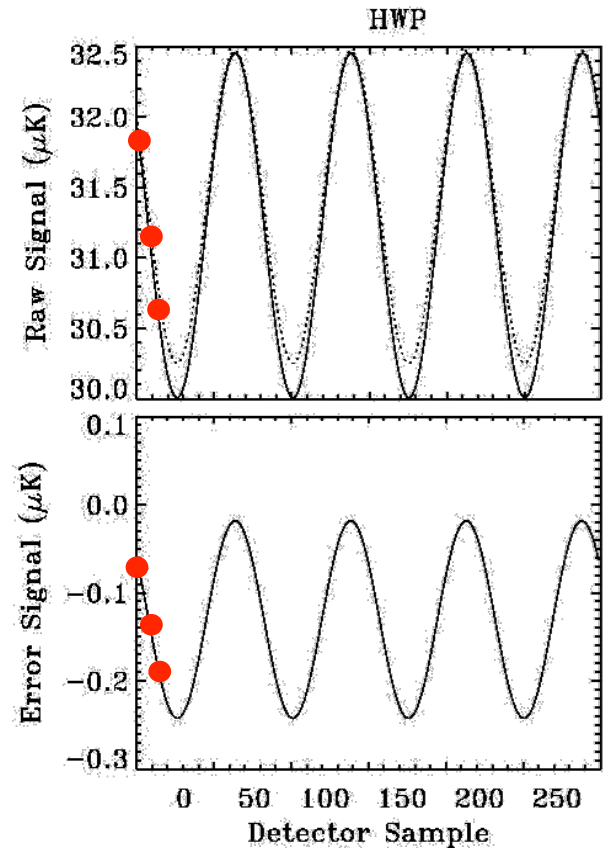


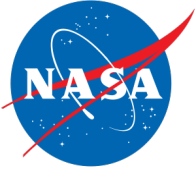


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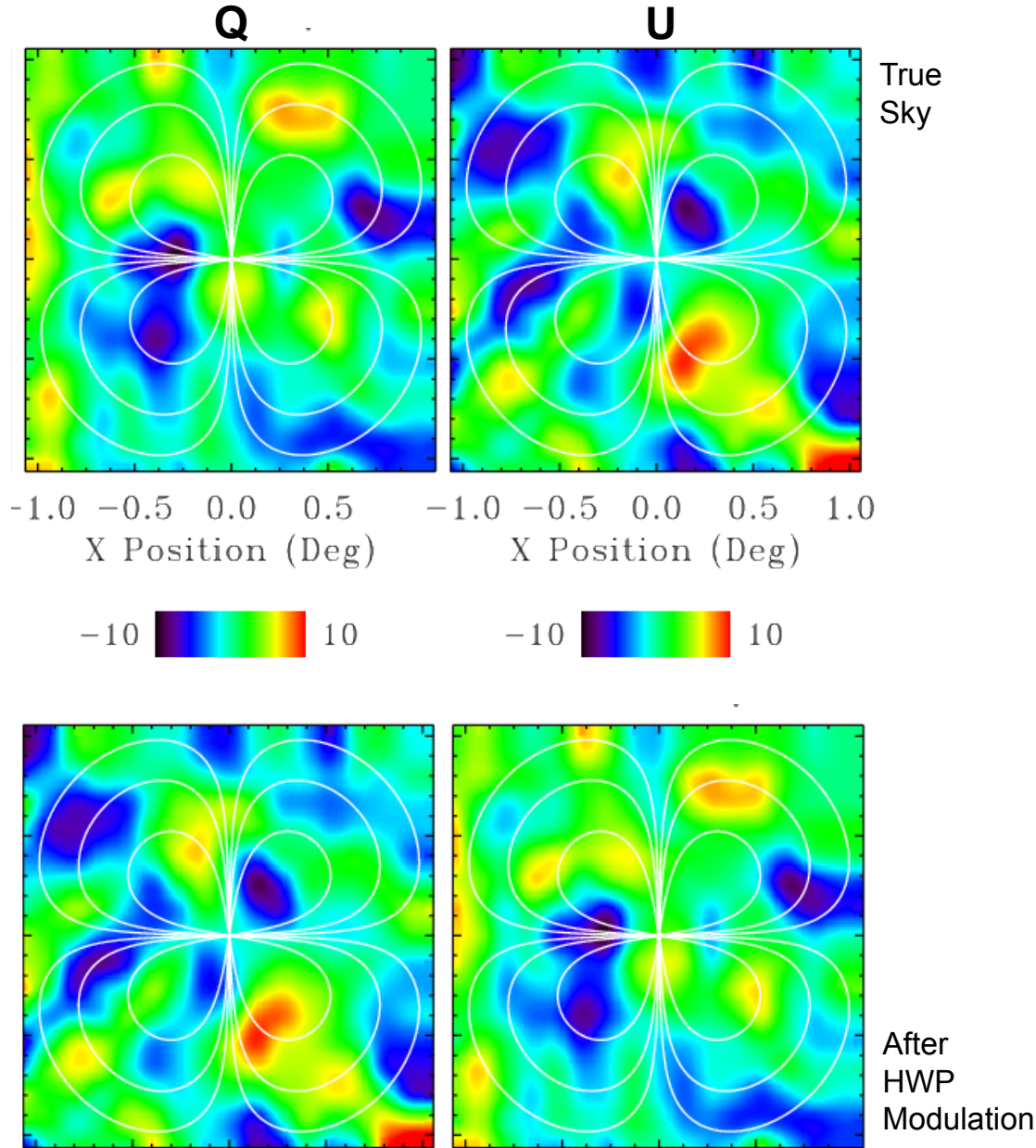


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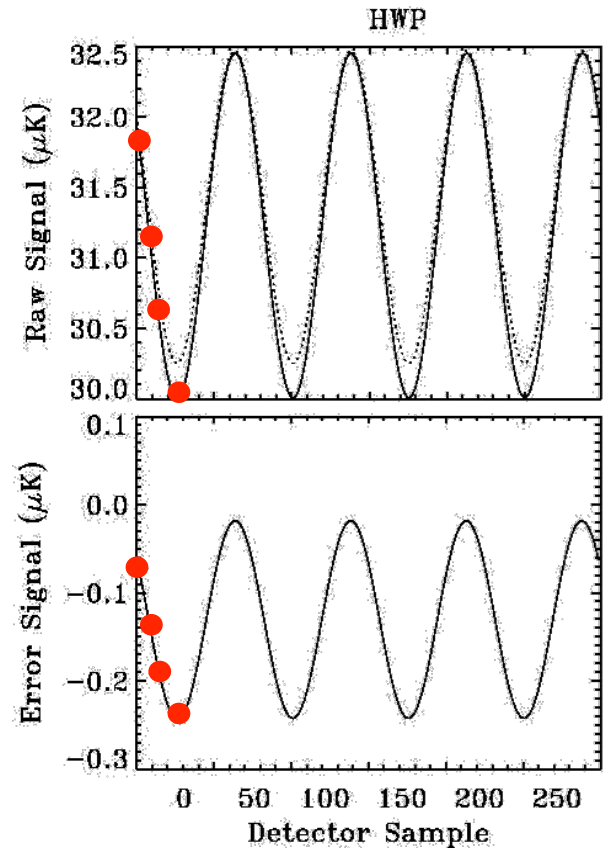


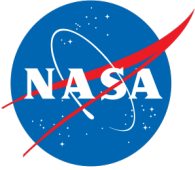


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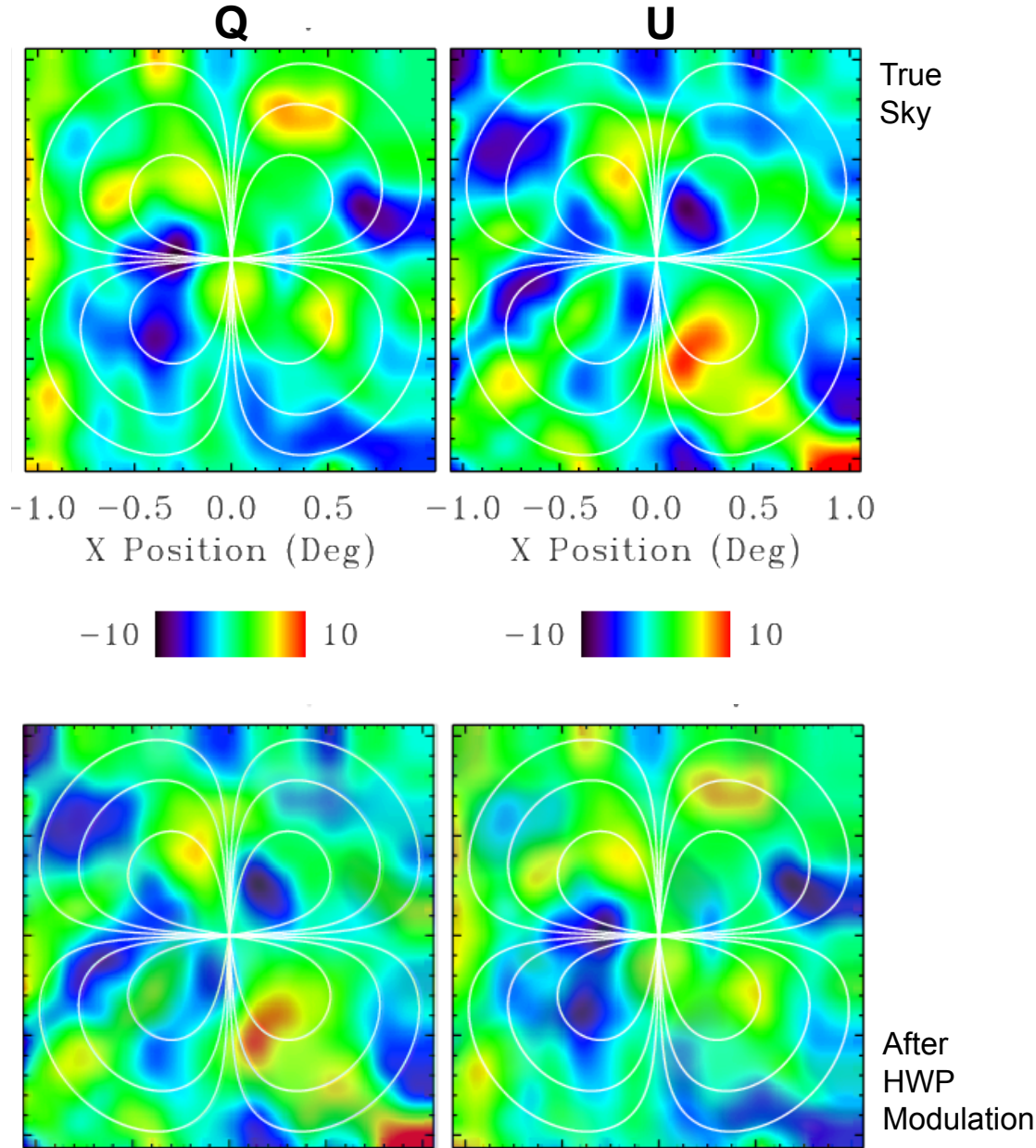


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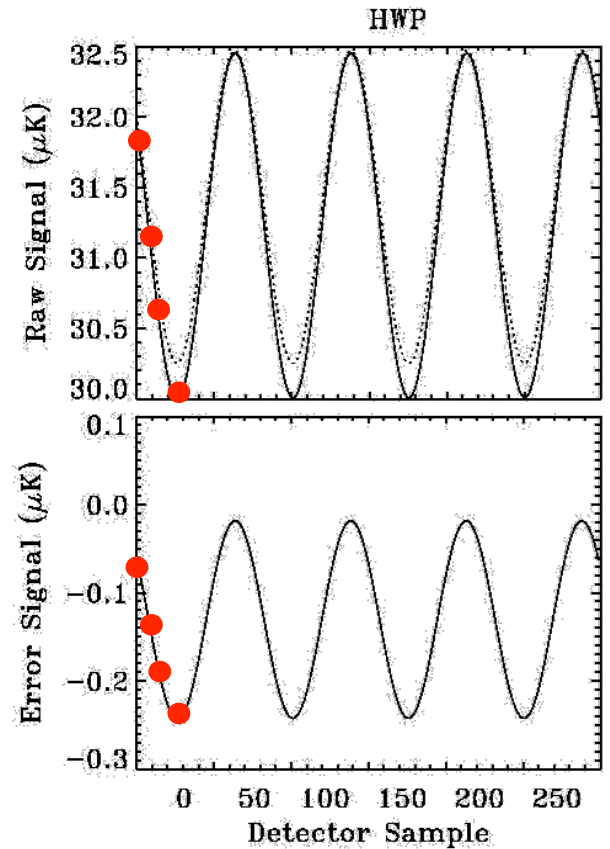




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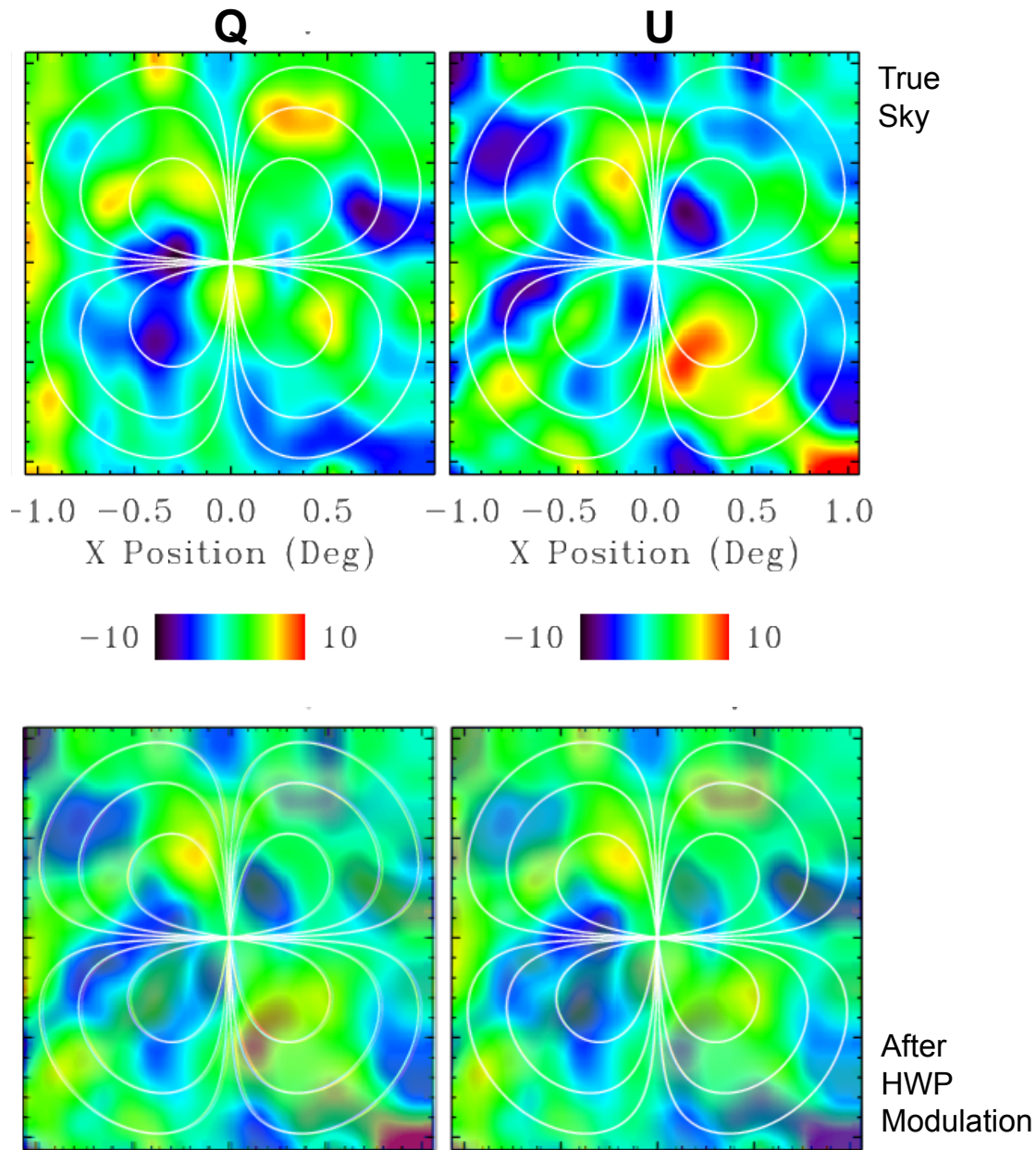


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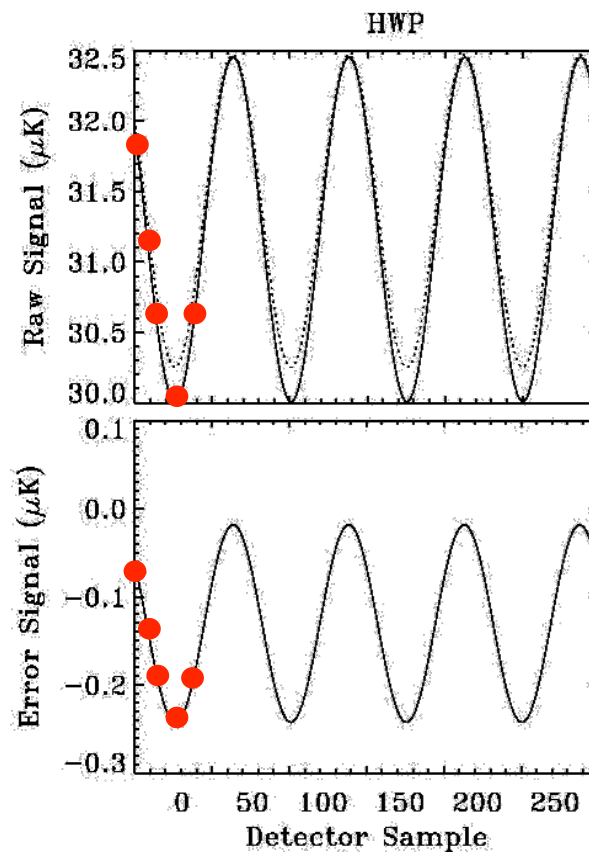


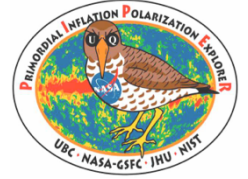


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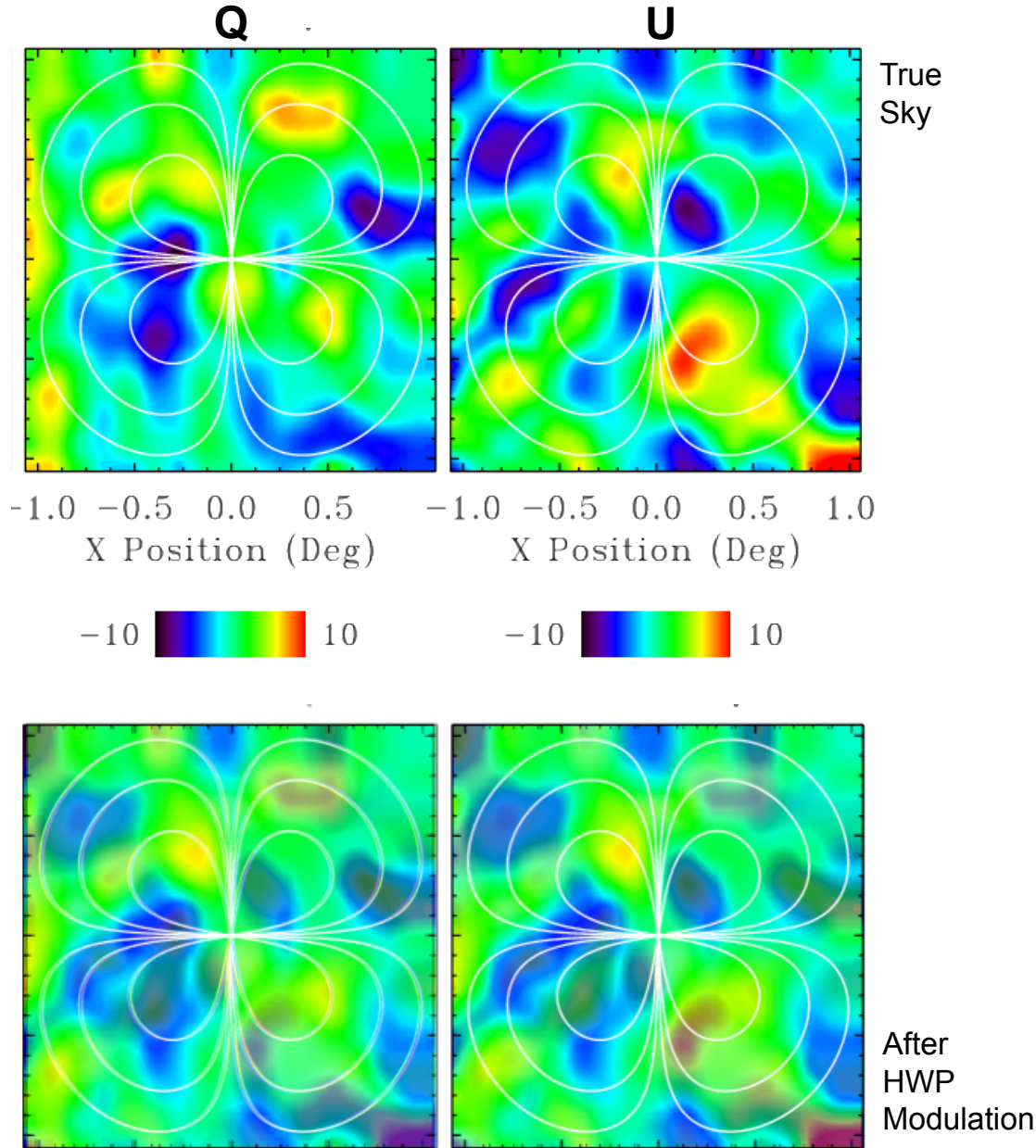


Wave Plate:  
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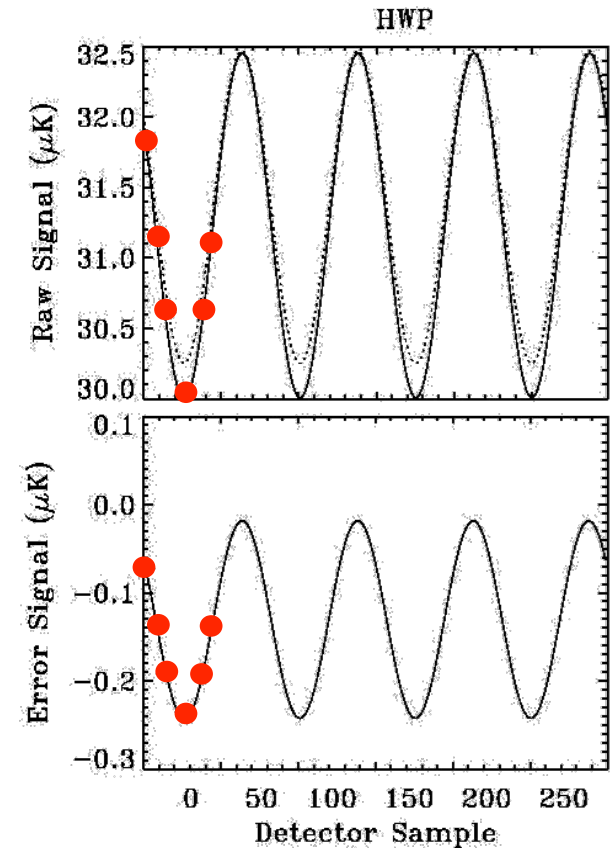




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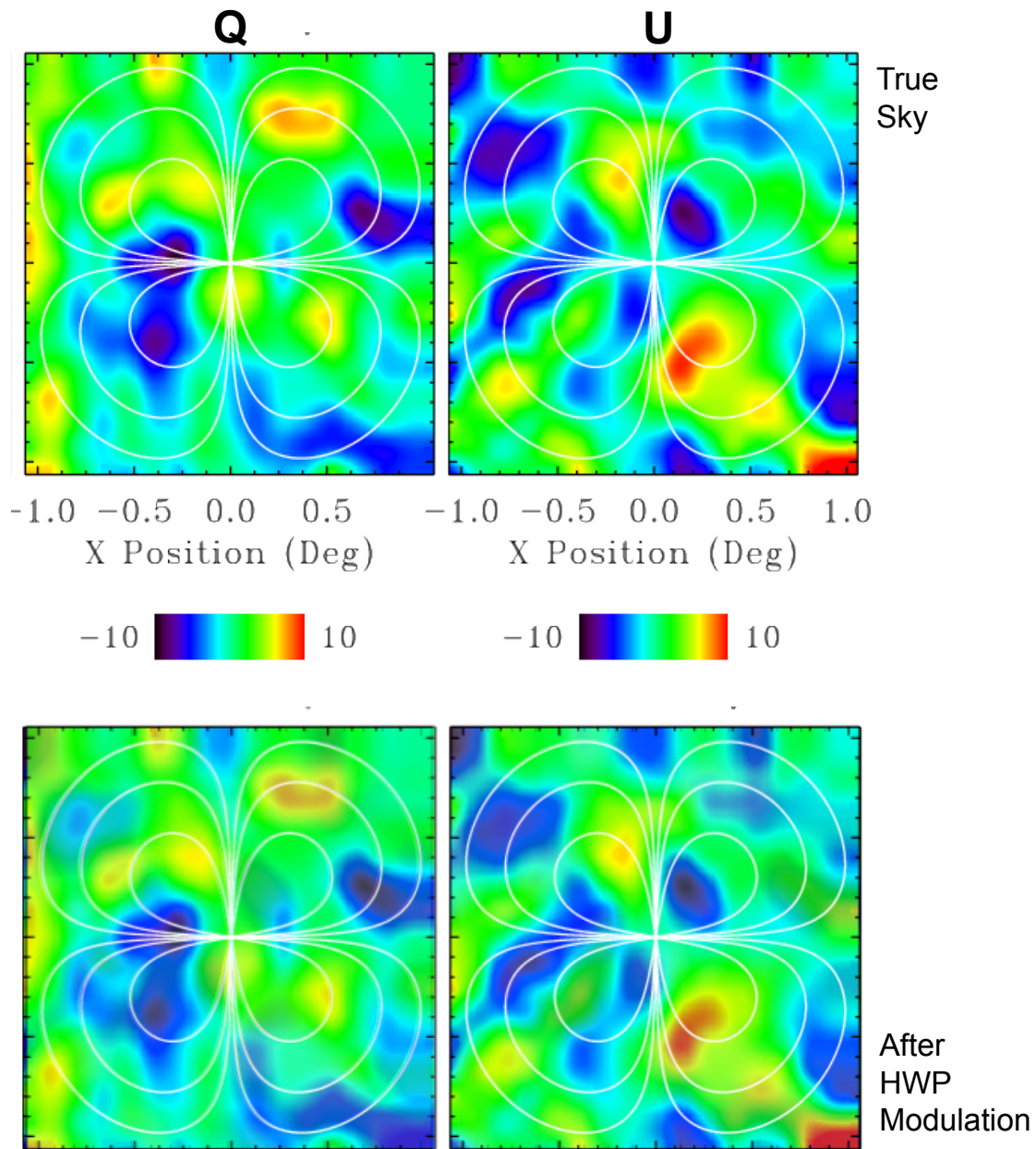


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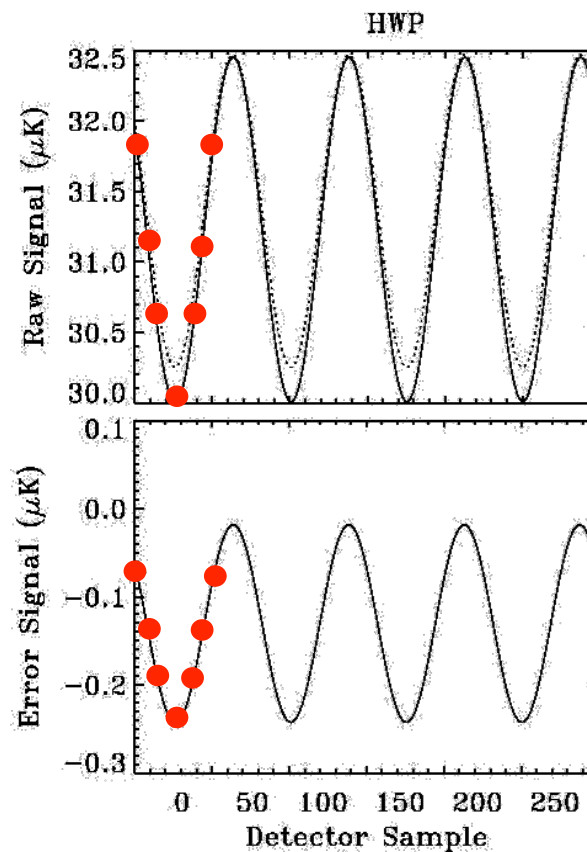


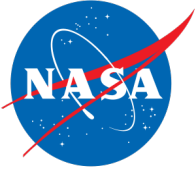


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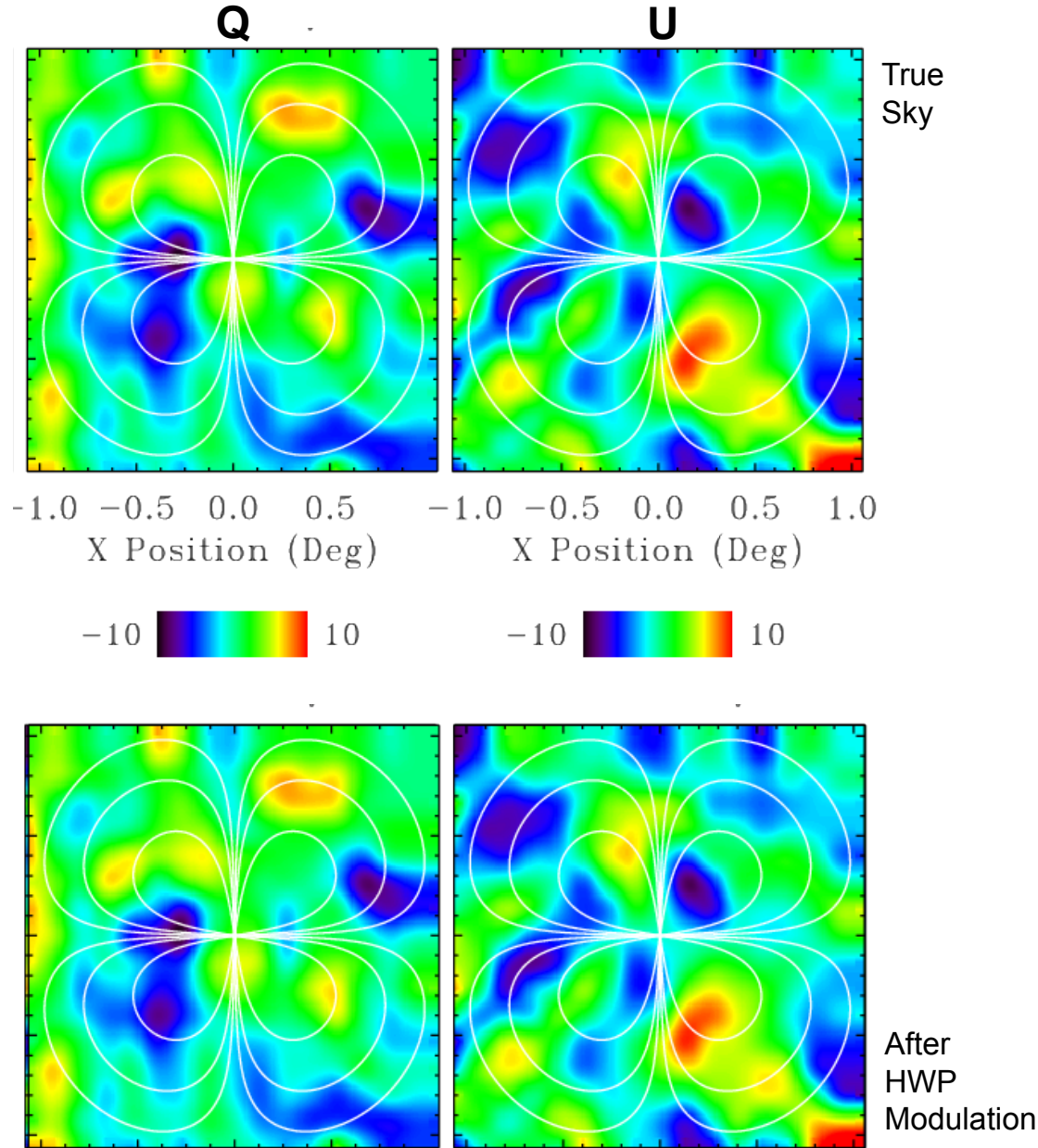


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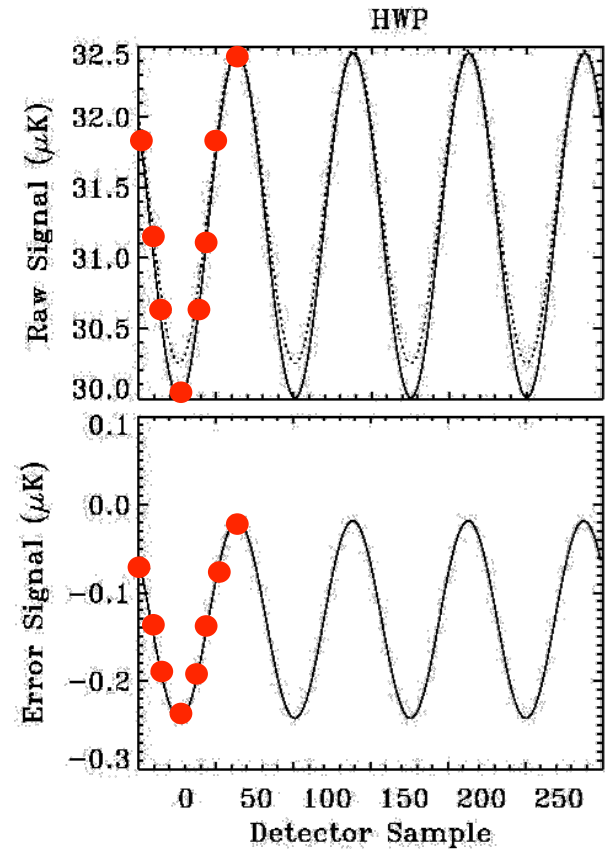




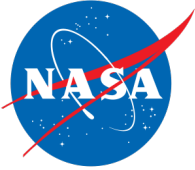
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Wave Plate:  
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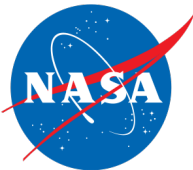




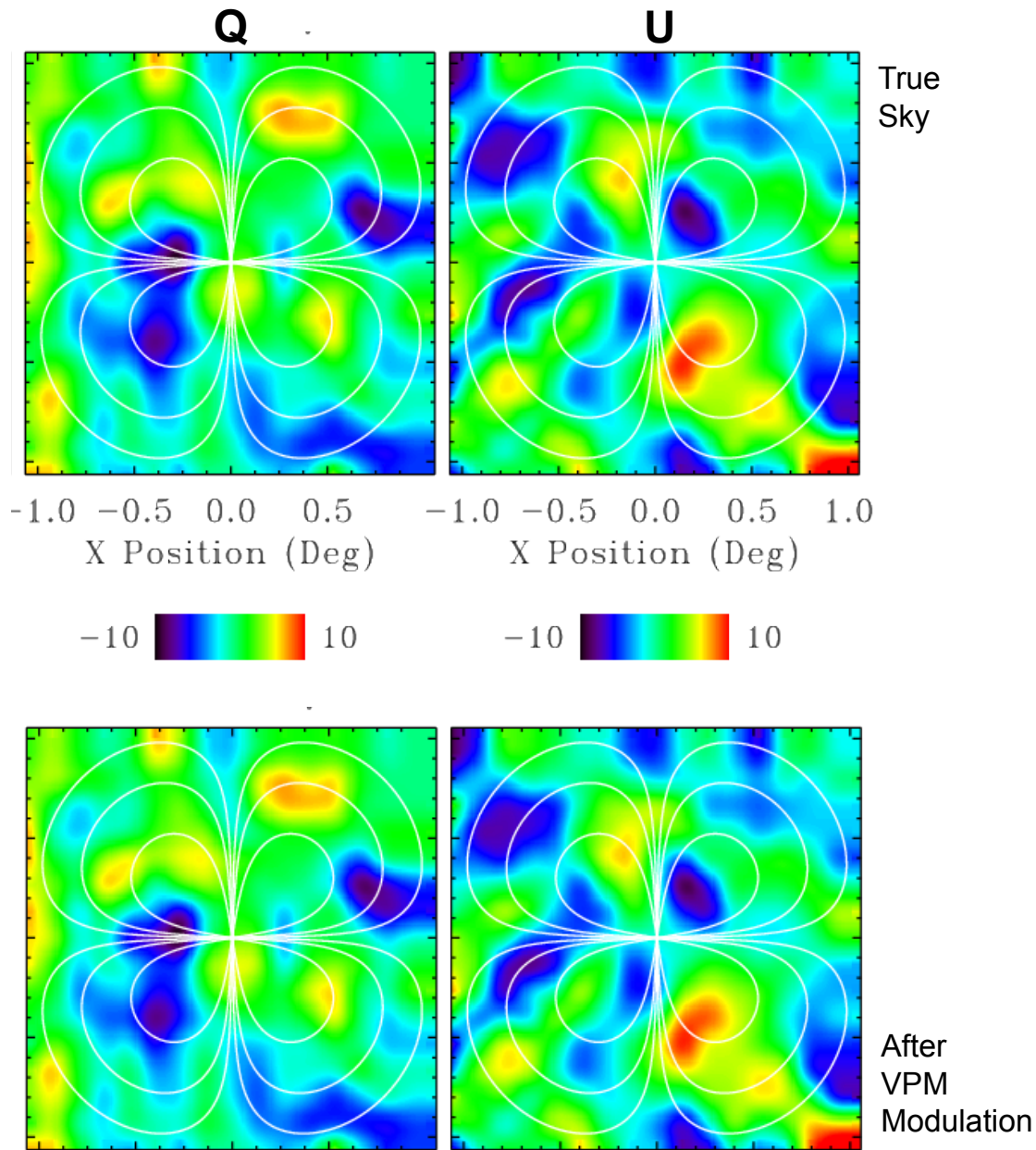
**Goddard Space Flight Center**

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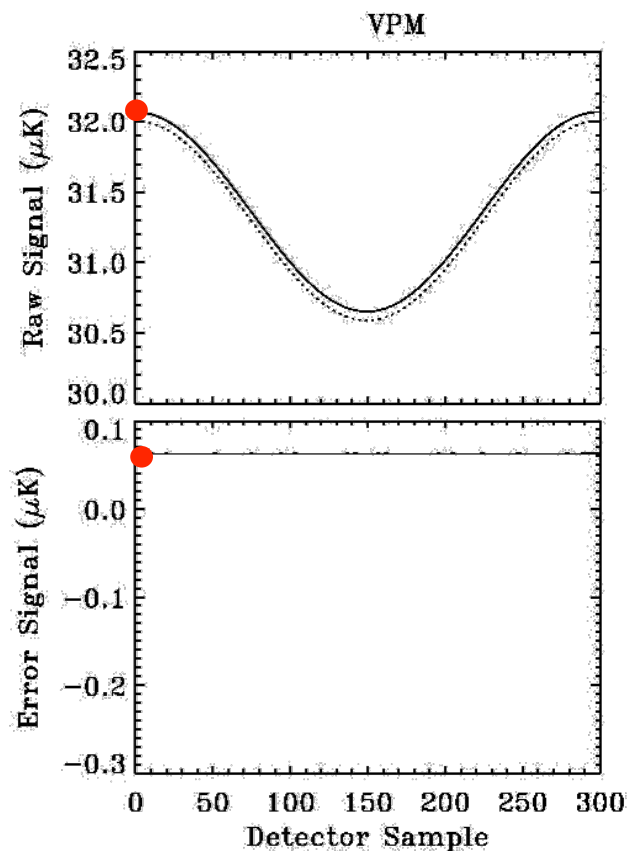


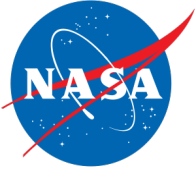


# Cross-Polar Beam Systematics

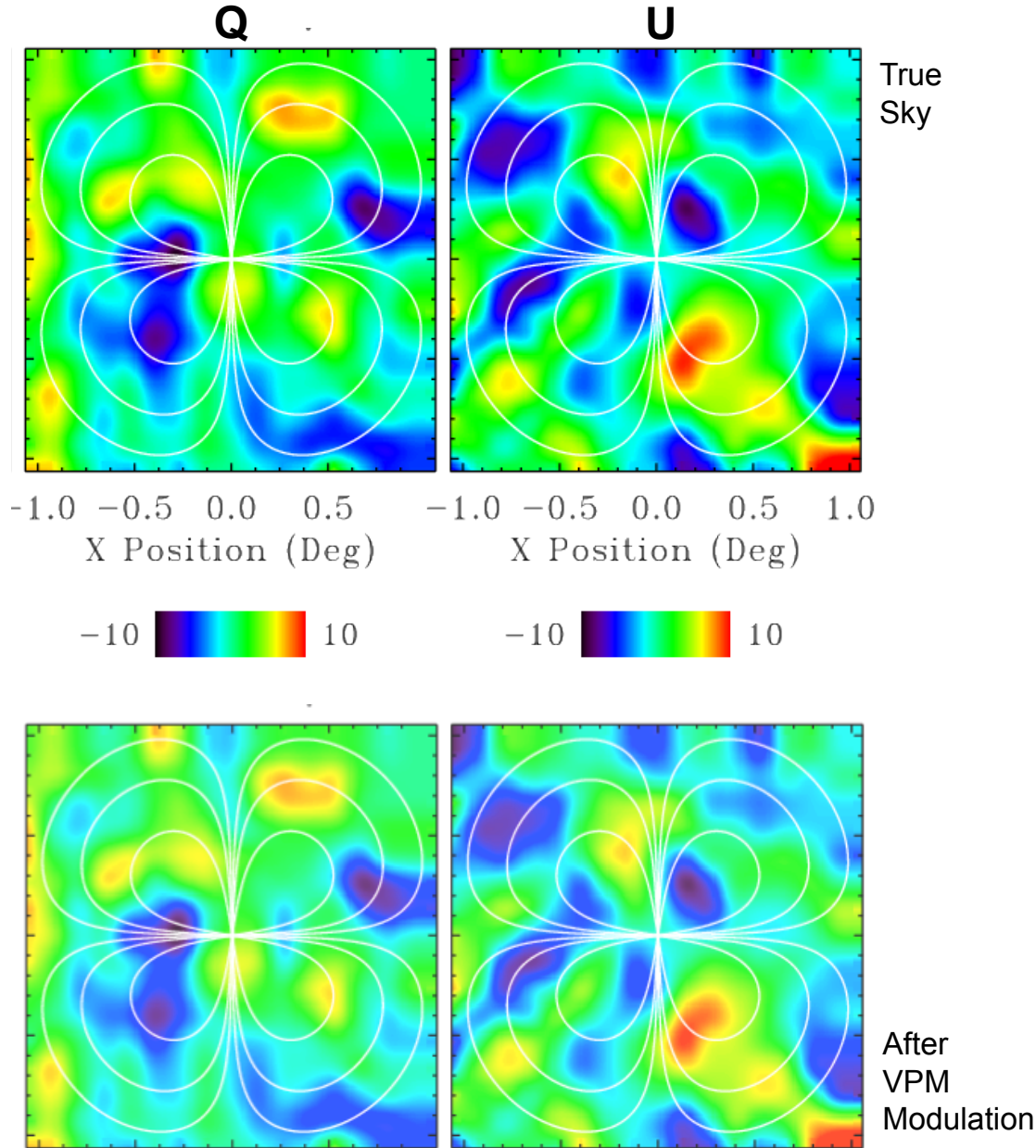


VPM:  
Q/U mixing  
but  
Q/V modulation

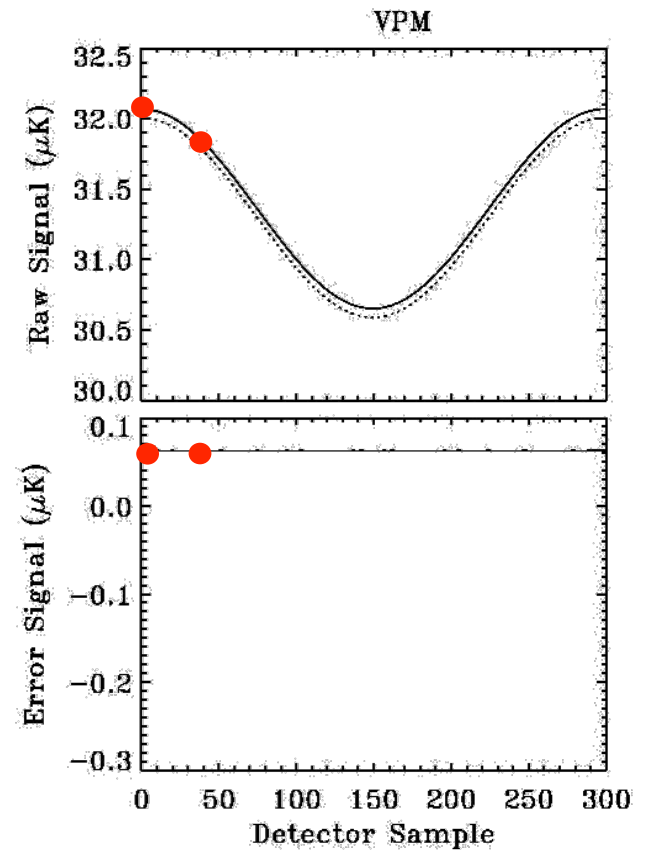


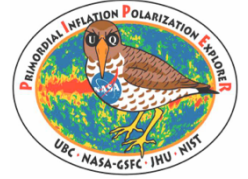
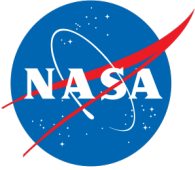


# Cross-Polar Beam Systematics

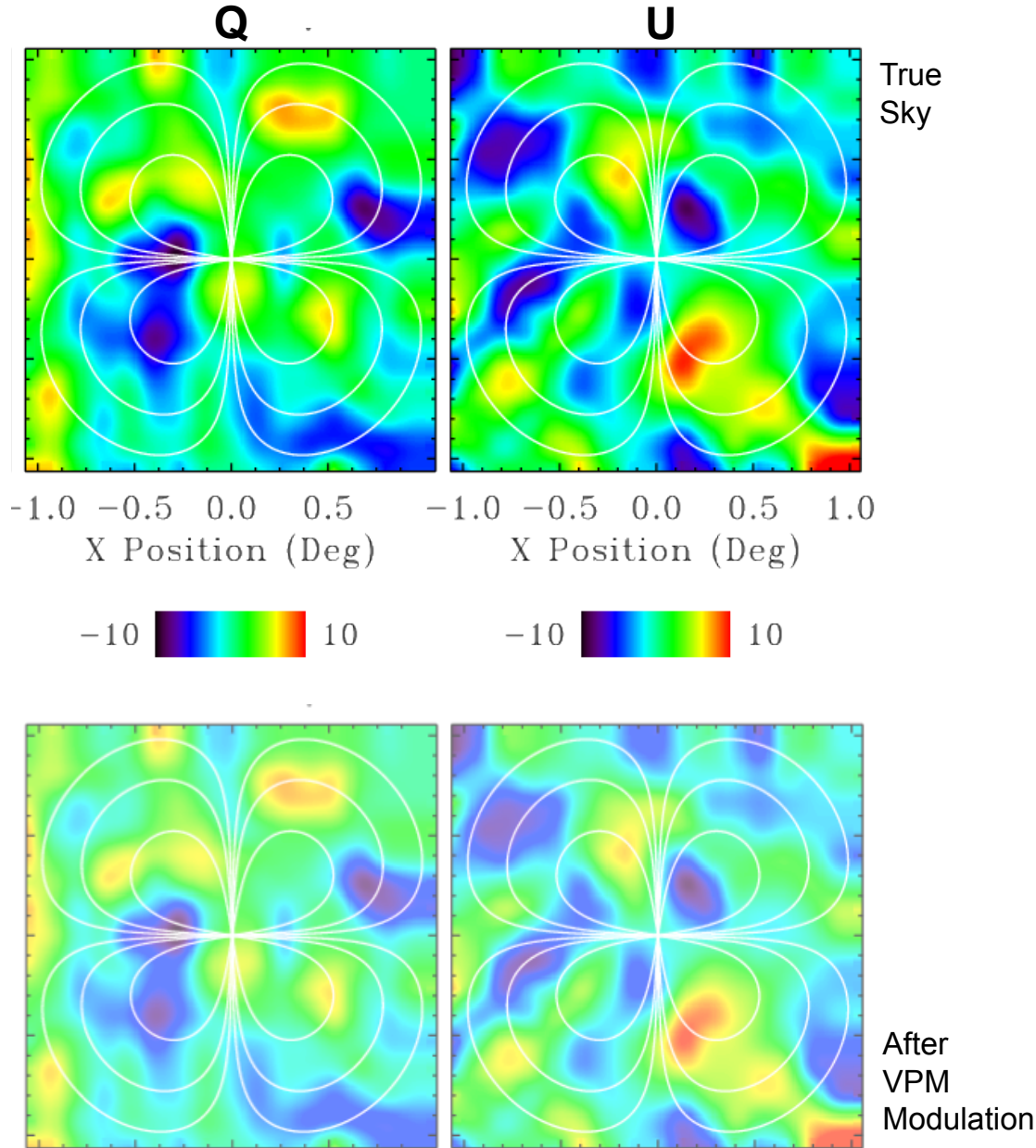


VPM:  
Q/U mixing  
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Q/V modulation

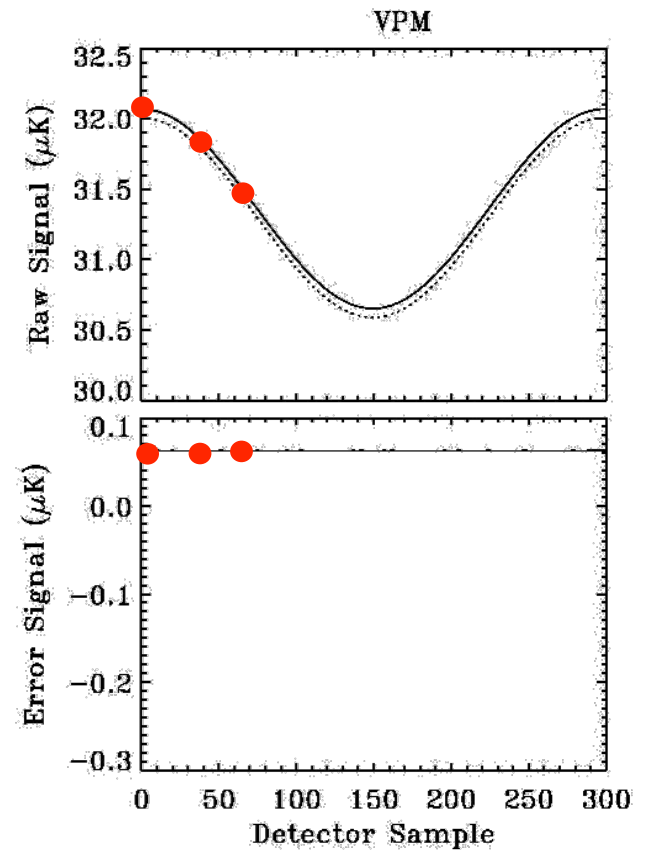


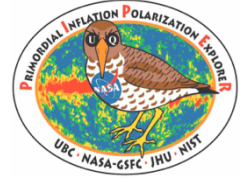
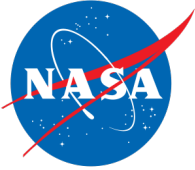


# Cross-Polar Beam Systematics

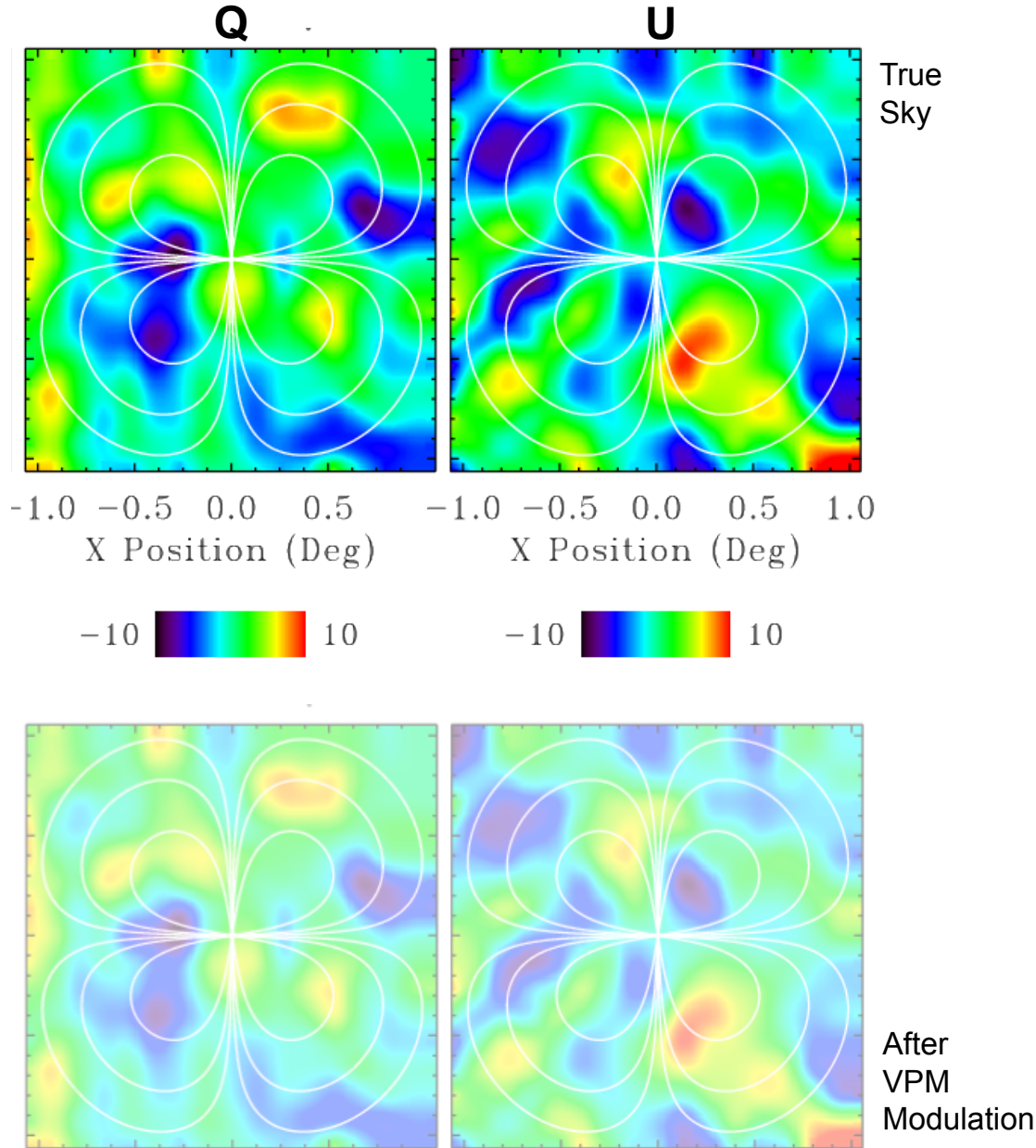


VPM:  
Q/U mixing  
but  
Q/V modulation

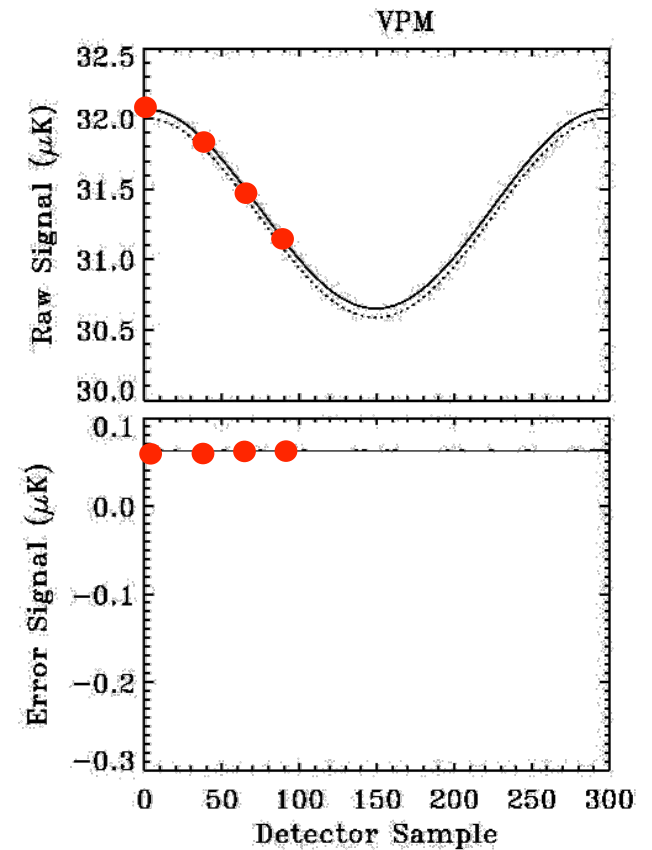


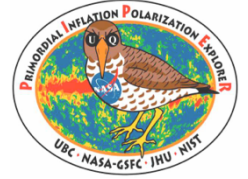
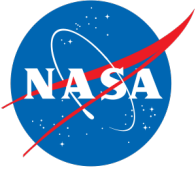


# Cross-Polar Beam Systematics

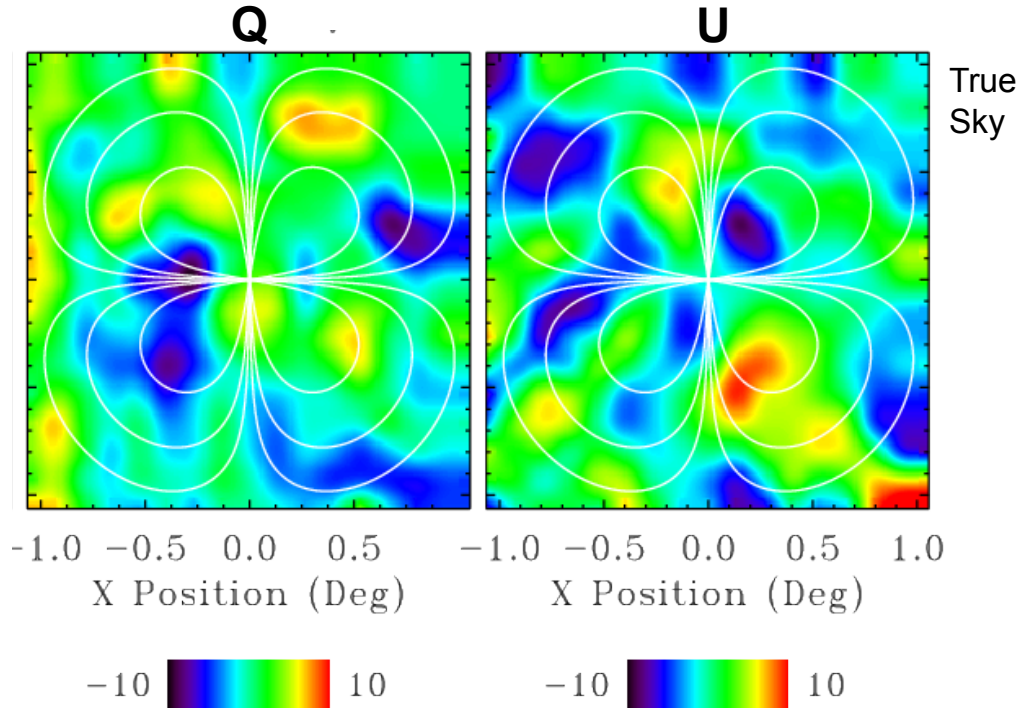


VPM:  
Q/U mixing  
but  
Q/V modulation

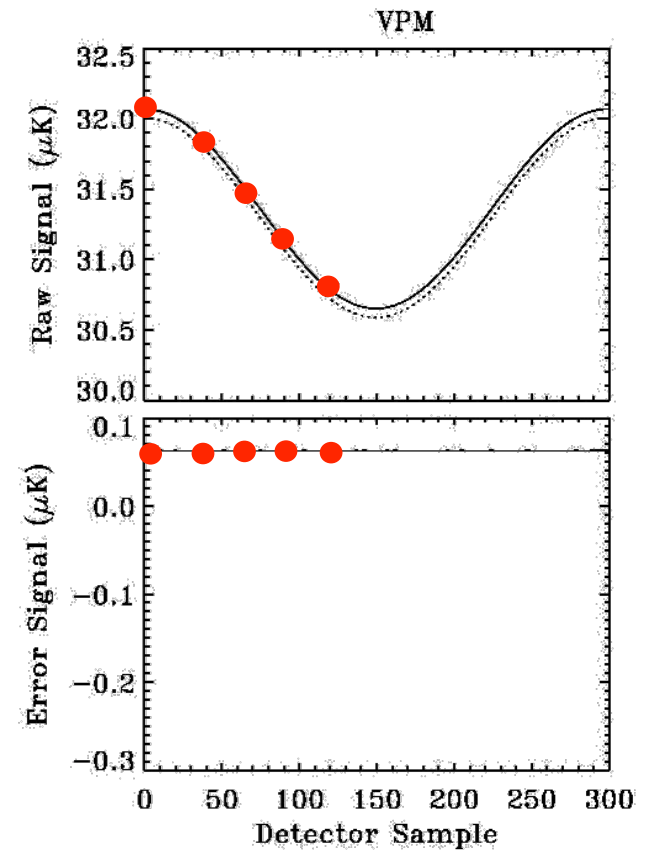
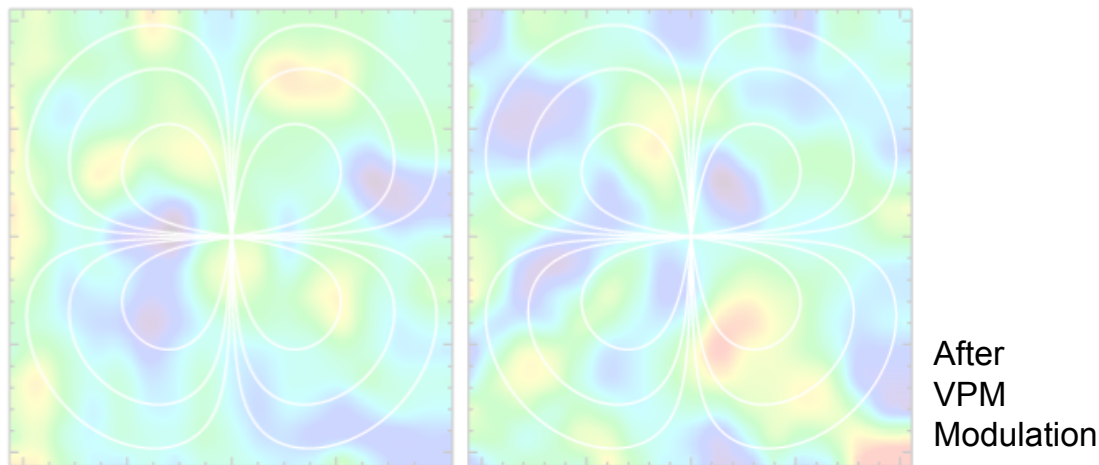


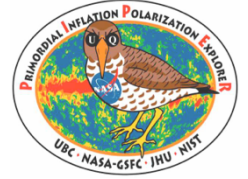


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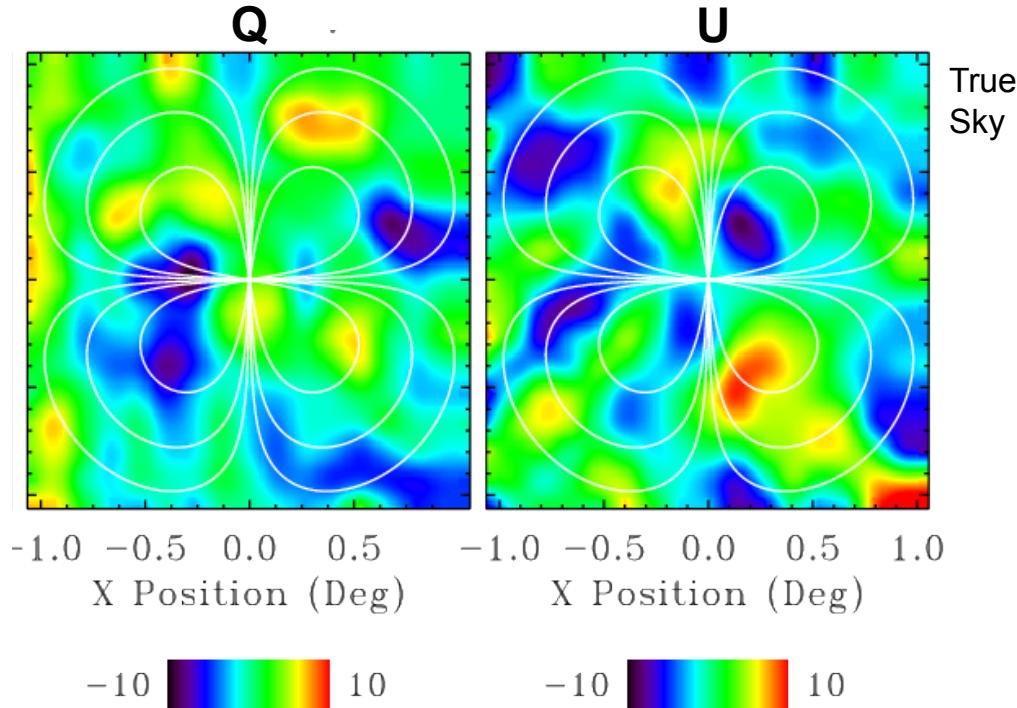


VPM:  
Q/U mixing  
but  
Q/V modulation



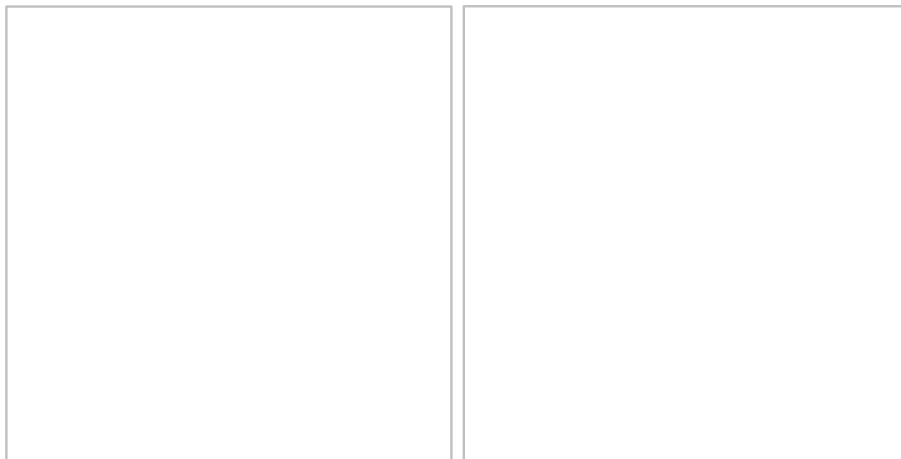


# Cross-Polar Beam Systematics

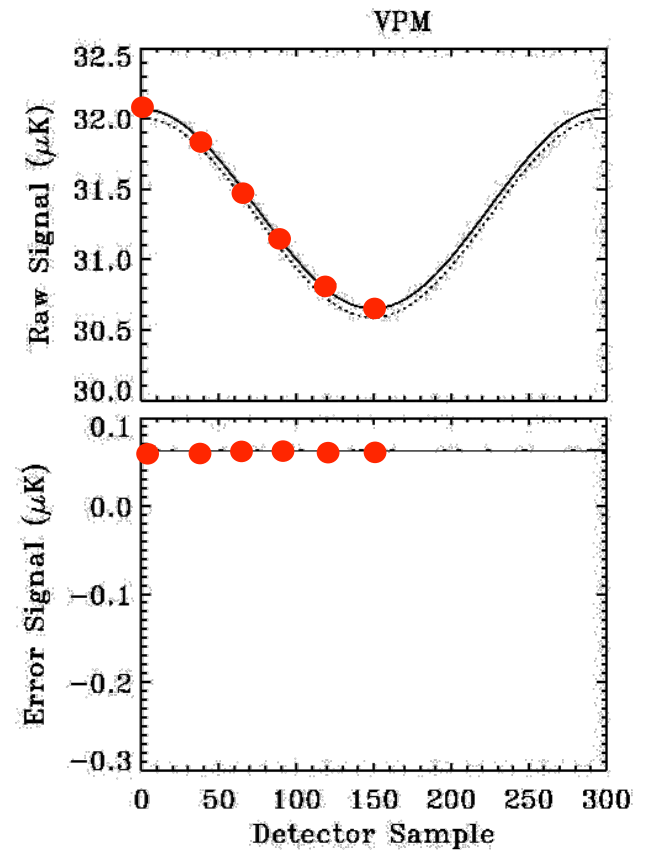


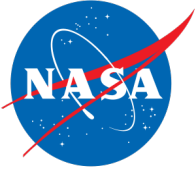
True Sky

VPM:  
Q/U mixing  
but  
Q/V modulation

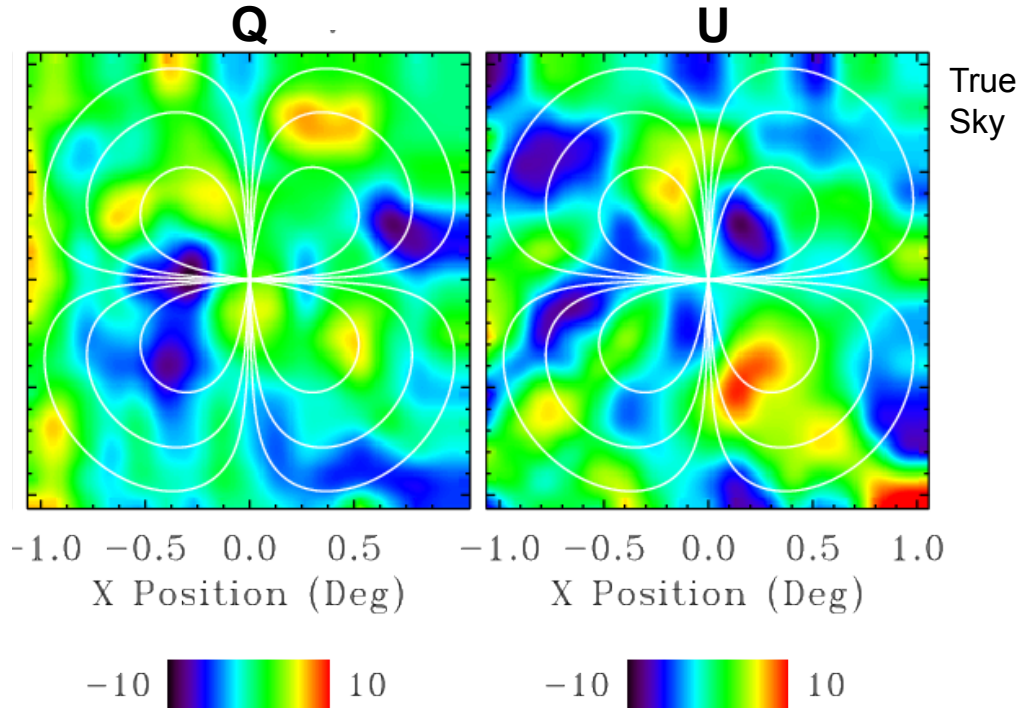


After  
VPM  
Modulation

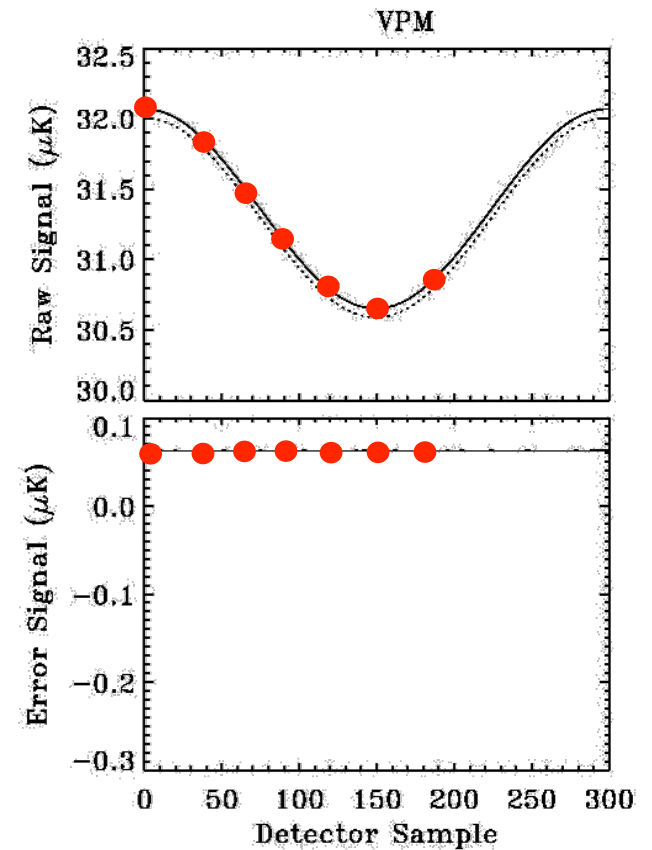
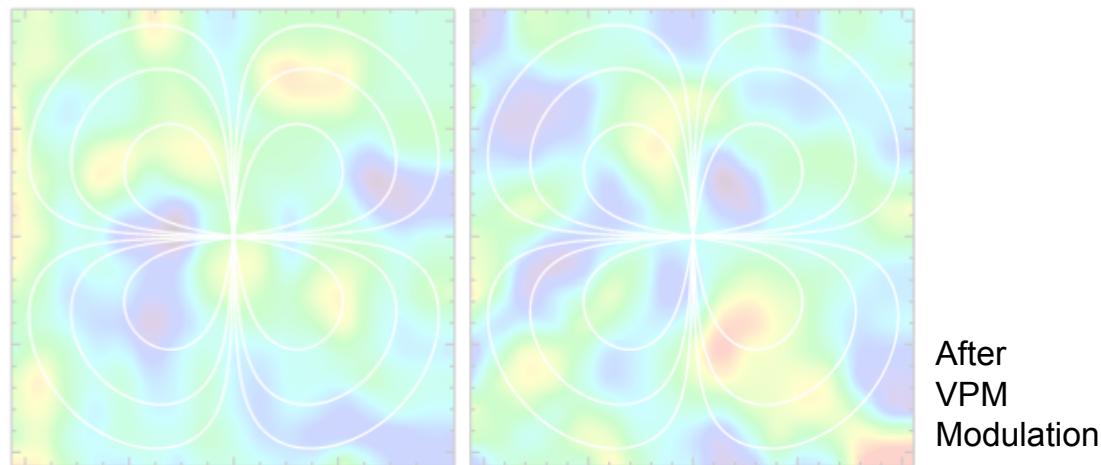




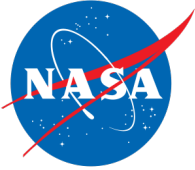
# Cross-Polar Beam Systematics



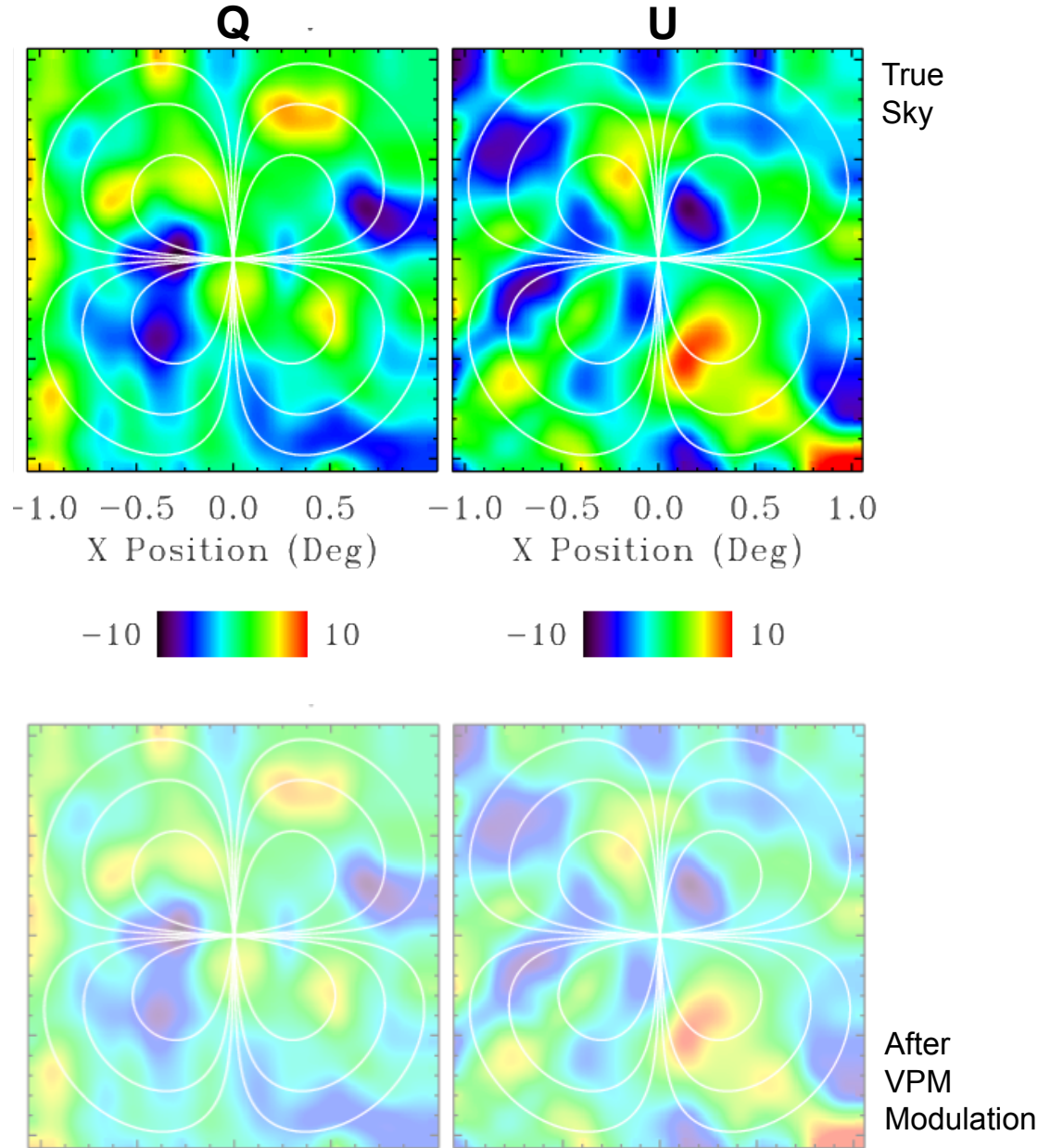
VPM:  
Q/U mixing  
but  
Q/V modulation



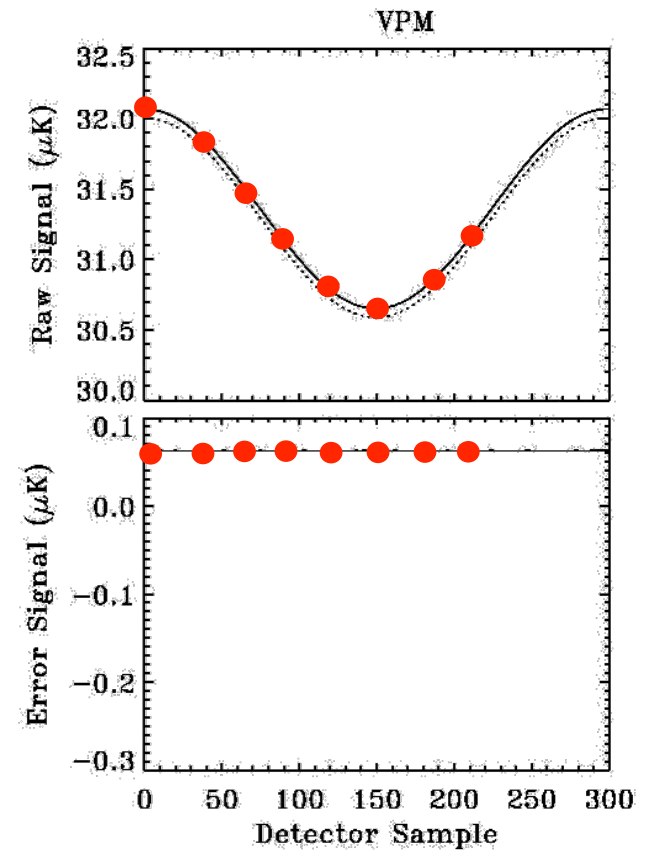


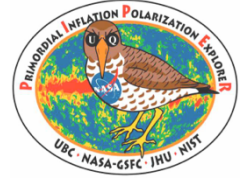


# Cross-Polar Beam Systematics

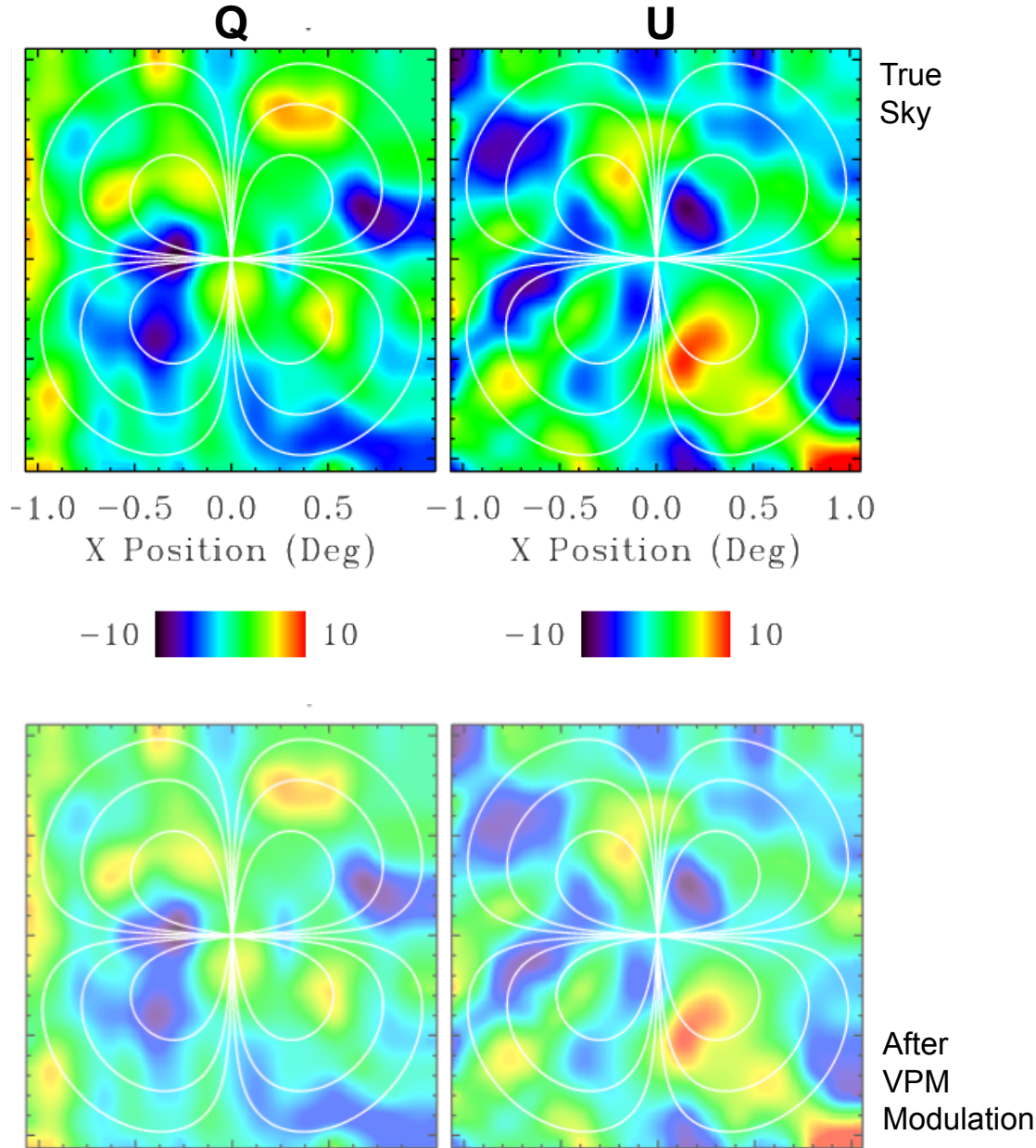


VPM:  
Q/U mixing  
but  
Q/V modulation

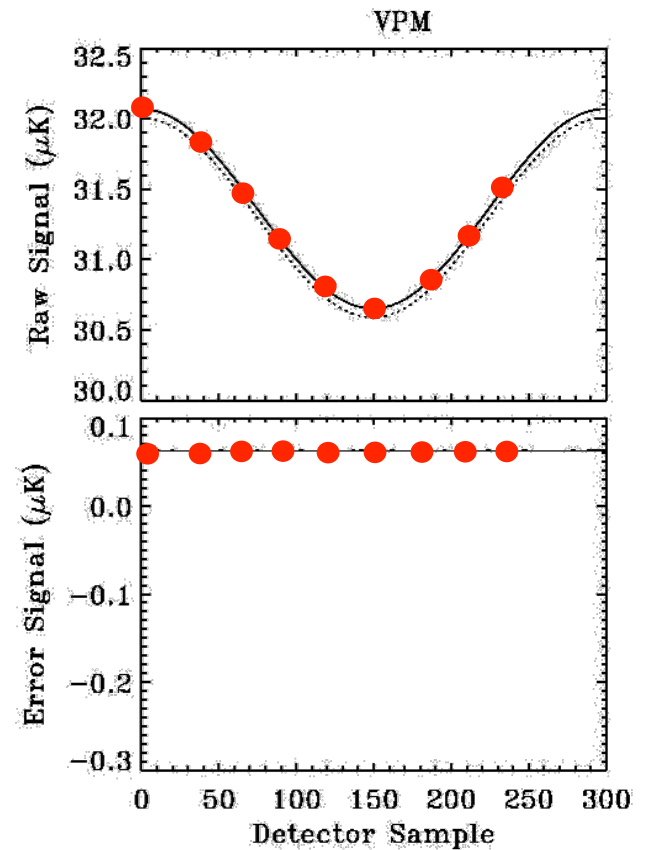


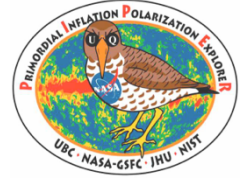
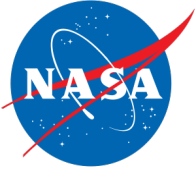


# Cross-Polar Beam Systematics

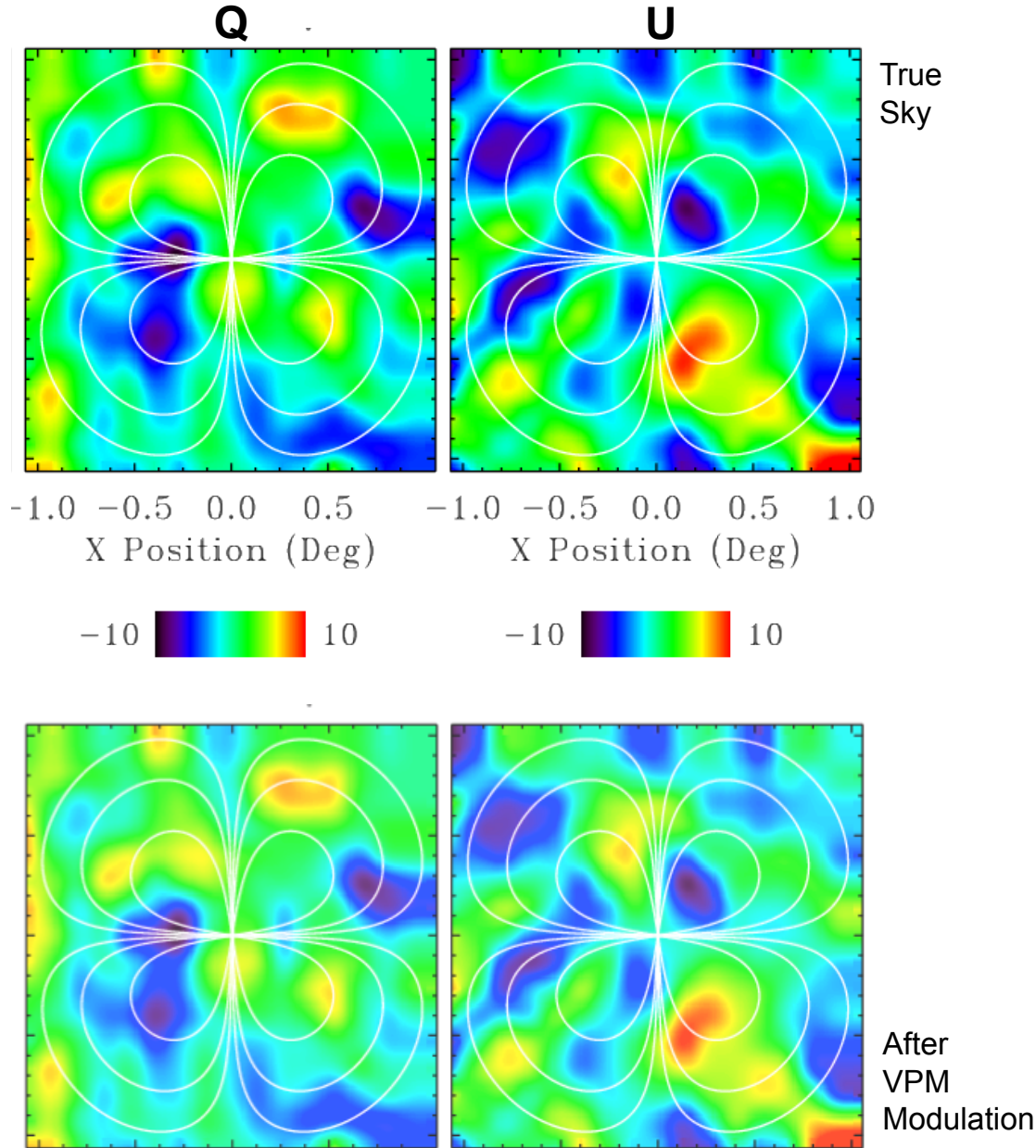


VPM:  
Q/U mixing  
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Q/V modulation

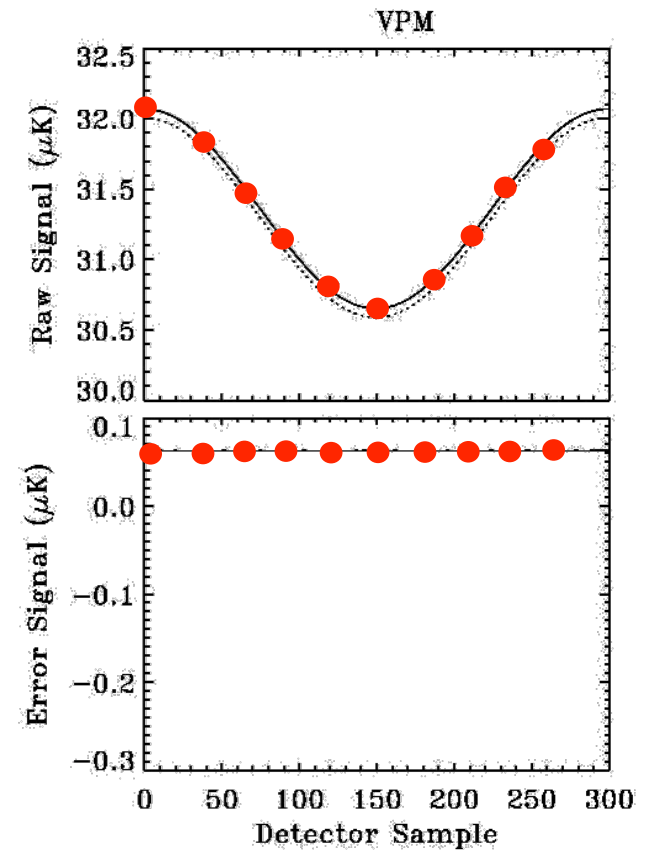


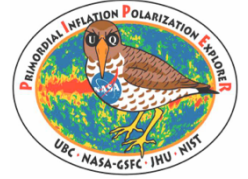


# Cross-Polar Beam Systematics

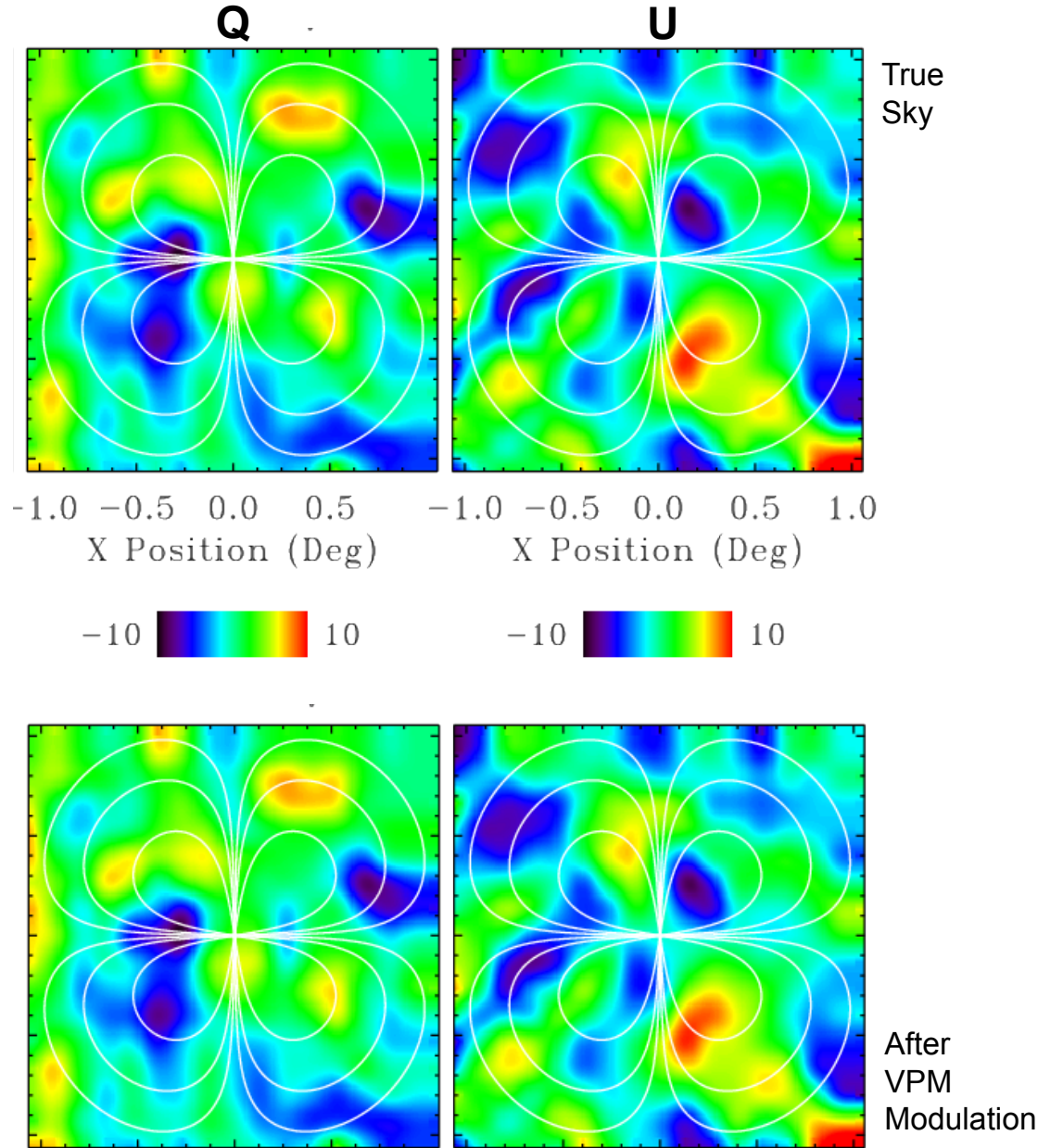


VPM:  
Q/U mixing  
but  
Q/V modulation

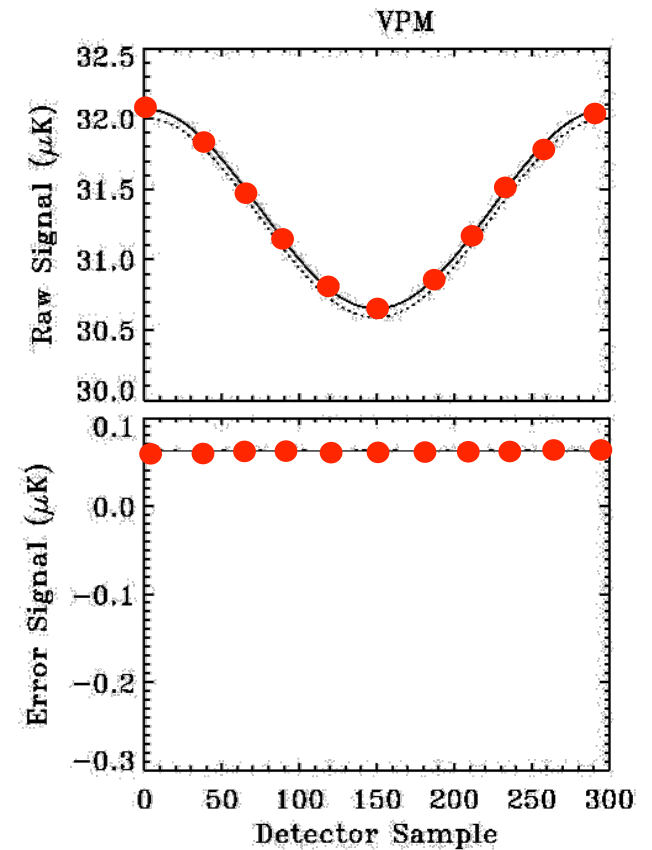


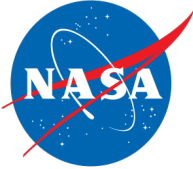


# Cross-Polar Beam Systematics



VPM:  
Q/U mixing  
but  
Q/V modulation





## VPM Advantages



### Minimizes a whole range of systematic errors

- $Q \leftrightarrow V$  modulation distinct from  $Q \leftrightarrow U$  ( $E \leftrightarrow B$ ) mixing
- Take advantage of  $V=0$  for sky

### Decouples polarization from scan strategy

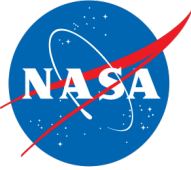
- Diagonal pixel covariance matrix
- No degradation at large angular separations/low  $\ell$

### Simple cryogenic implementation

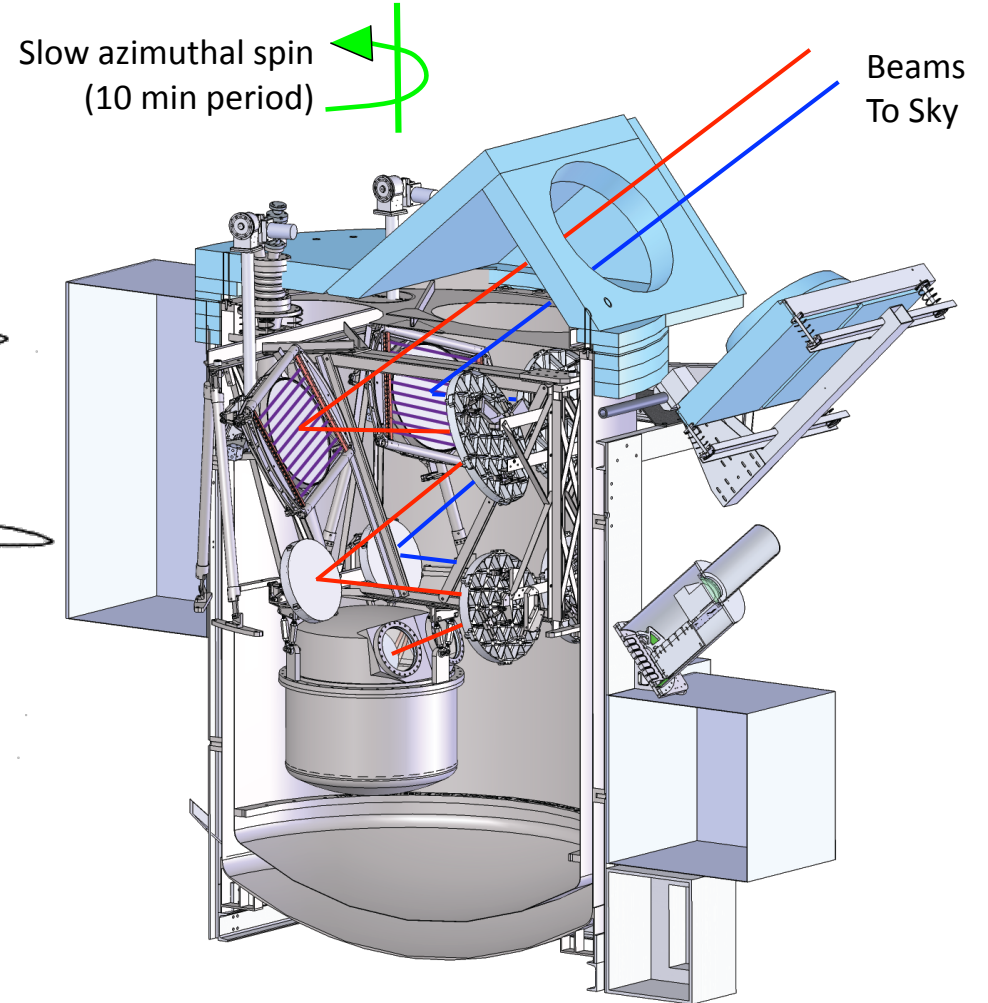
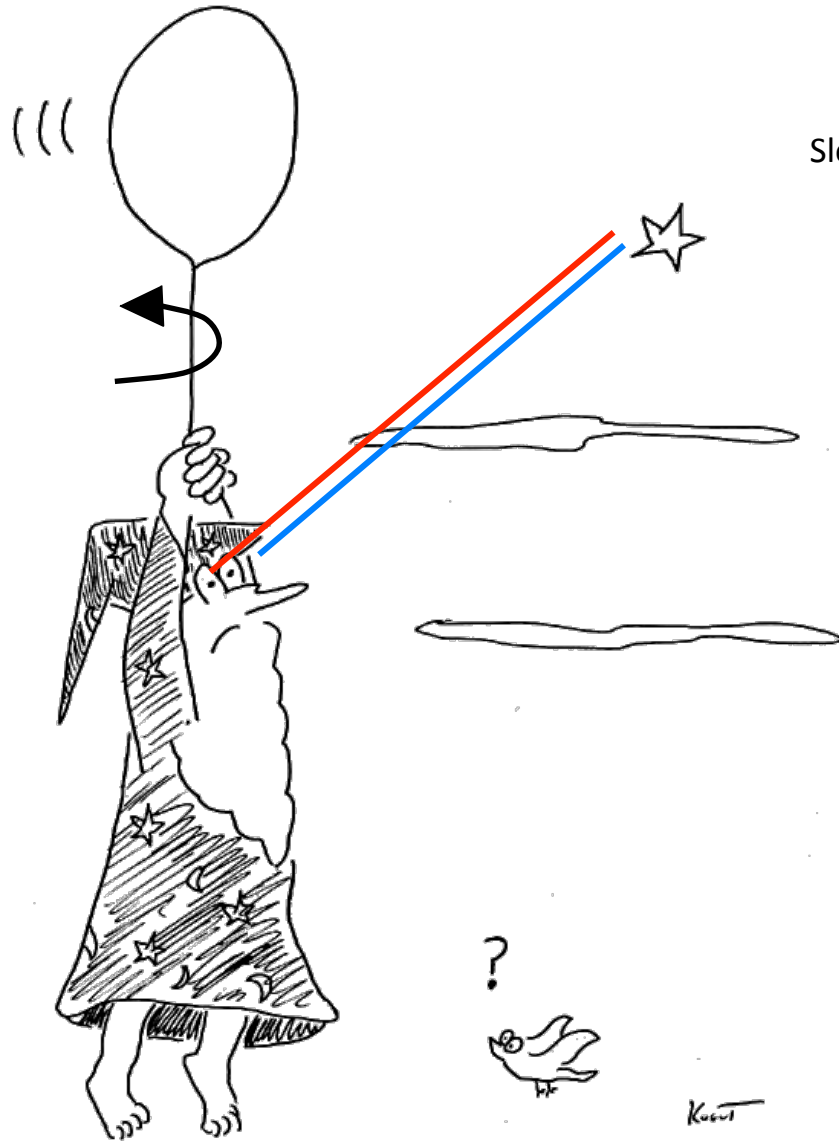
- Small linear translation instead of large angular rotation
- Simple cooling path to grating and mirror
- Vary mirror sweep to vary  $Q/V$  sampling
- Non-ideal effects are computable from first principles

Plus: Get full-sky map of Stokes V  
*Four orders-of-magnitude improvement!*

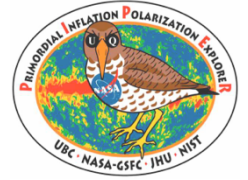
***Yow! Fun With Circular Polarization***



# Sky Coverage: Looking All Around



Kuort

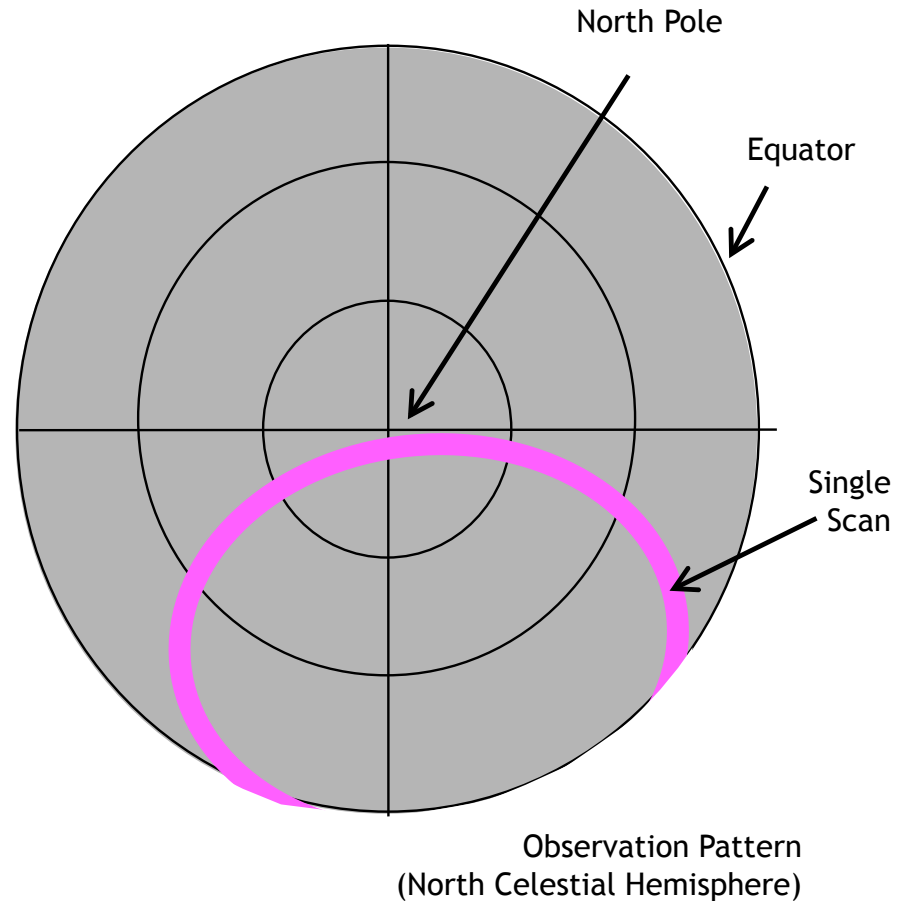


# Single-Flight Sky Coverage

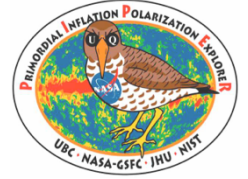
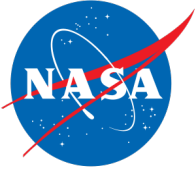
Fast Mapping Speed Enables Conventional Balloon Flights

## Night Observations

- Beams pointed  $55^\circ$  from zenith
- Slowly spin gondola (600 sec period)
- Observe 55% of the sky per night



*Simple Operations From Conventional Balloon Payload*

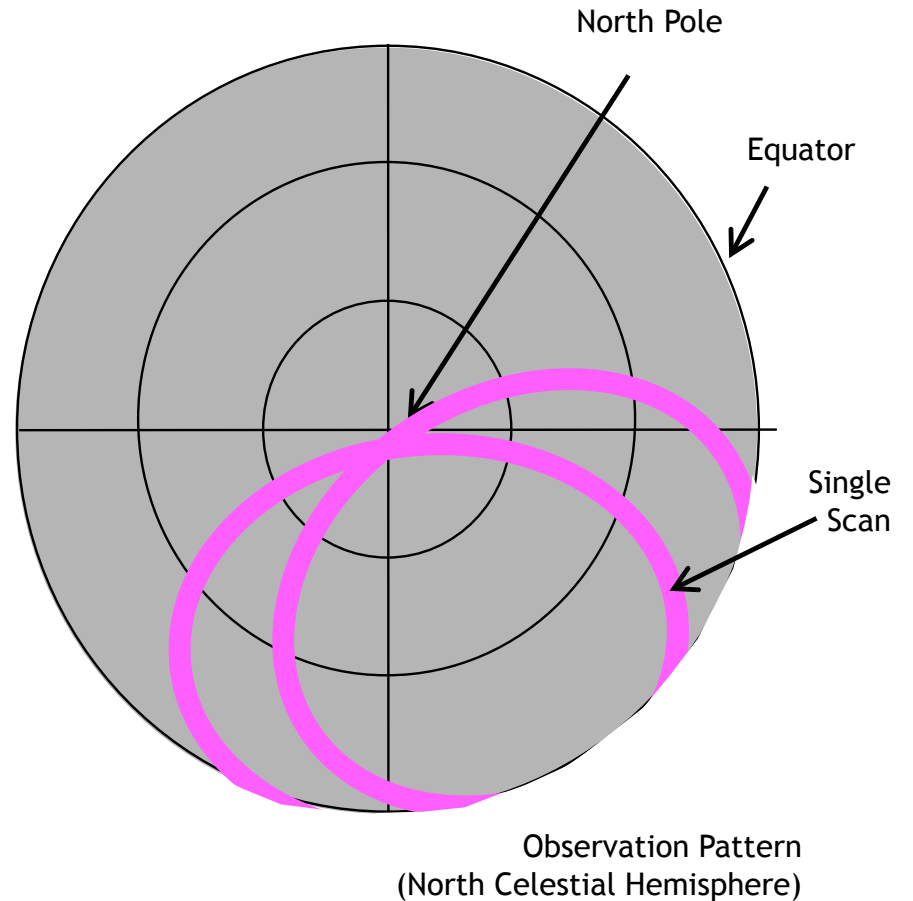


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Fast Mapping Speed Enables Conventional Balloon Flights

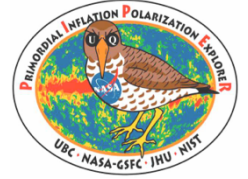
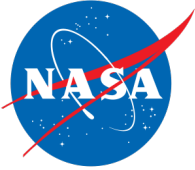
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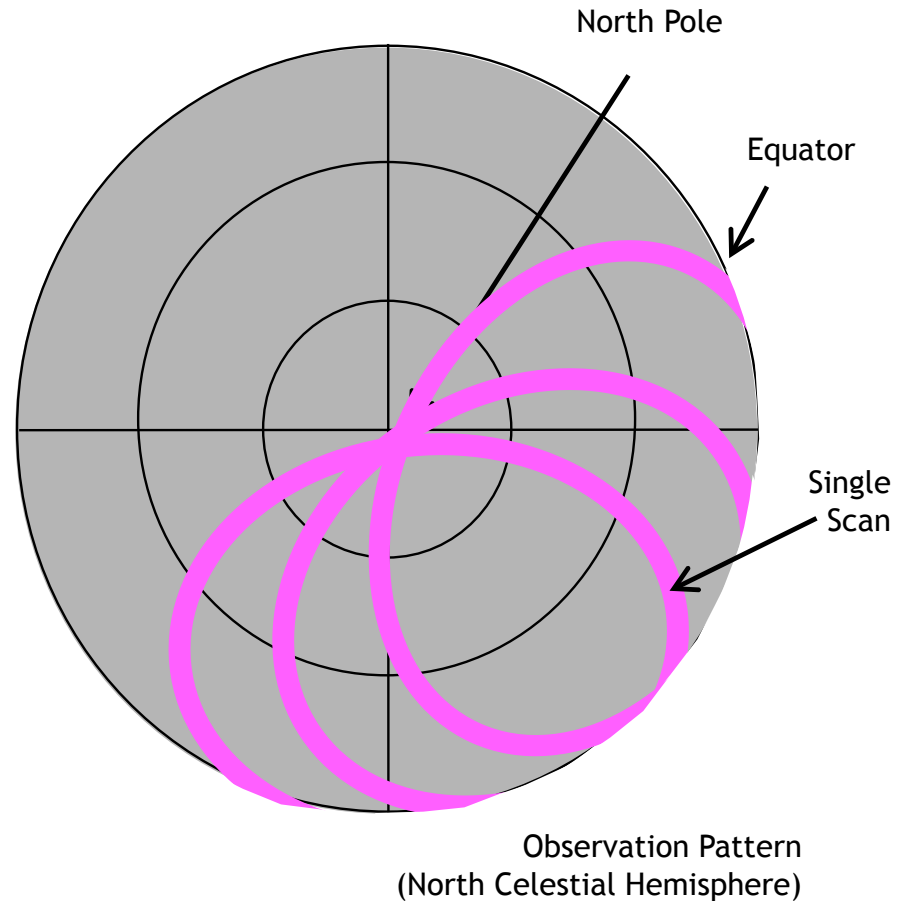


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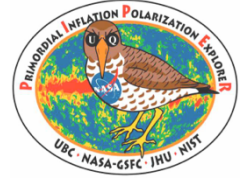
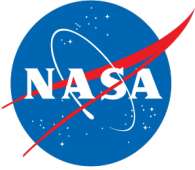
Fast Mapping Speed Enables Conventional Balloon Flights

## Night Observations

- Beams pointed  $55^\circ$  from zenith
- Slowly spin gondola (600 sec period)
- Observe 55% of the sky per night



*Simple Operations From Conventional Balloon Payload*



# “Butt Crack” Scan Pattern

Fast Mapping Speed Enables  
Conventional Balloon Flights

## Night Observations

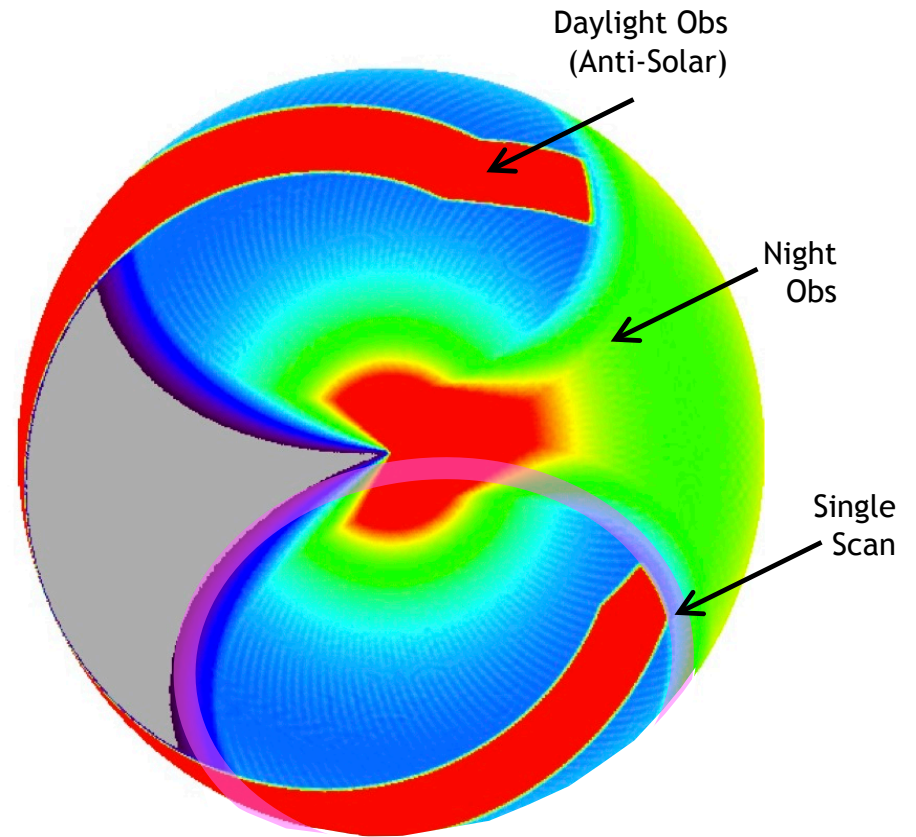
Beams pointed  $55^\circ$  from zenith  
Slowly spin gondola (600 sec period)

## Day Observations

Scan anti-solar strip

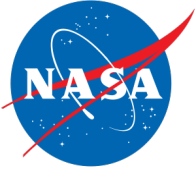
**Single Flight: Observe 55% of sky**

**Two Flights: Observe 85% of sky**



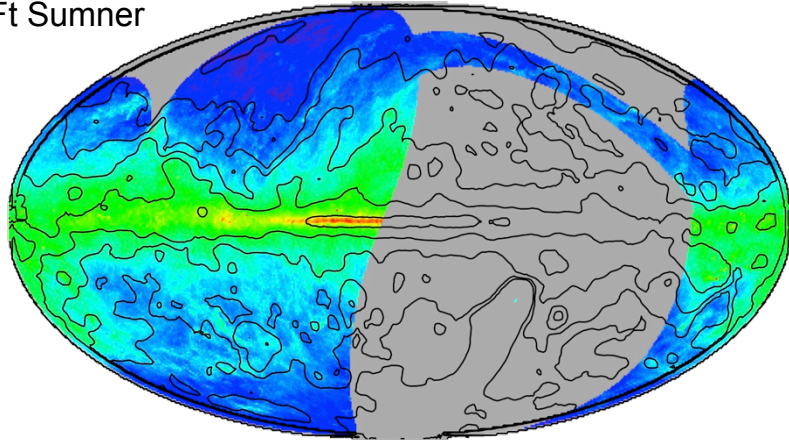
Observation Pattern  
(North Celestial Hemisphere)

*Simple Operations From Conventional Balloon Payload*

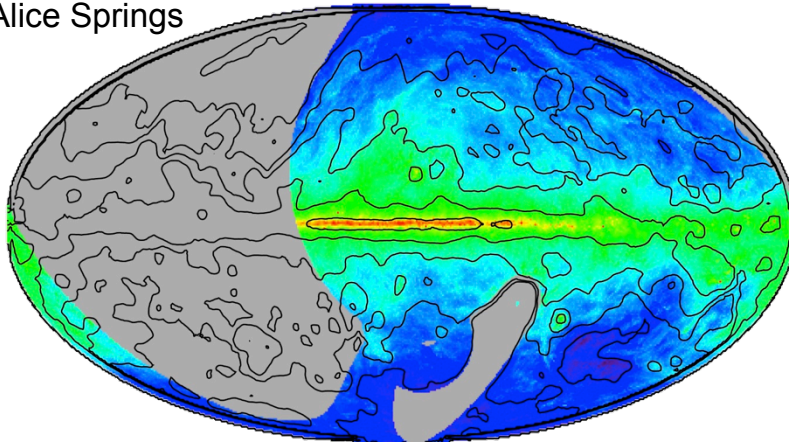


# Combined Sky Coverage

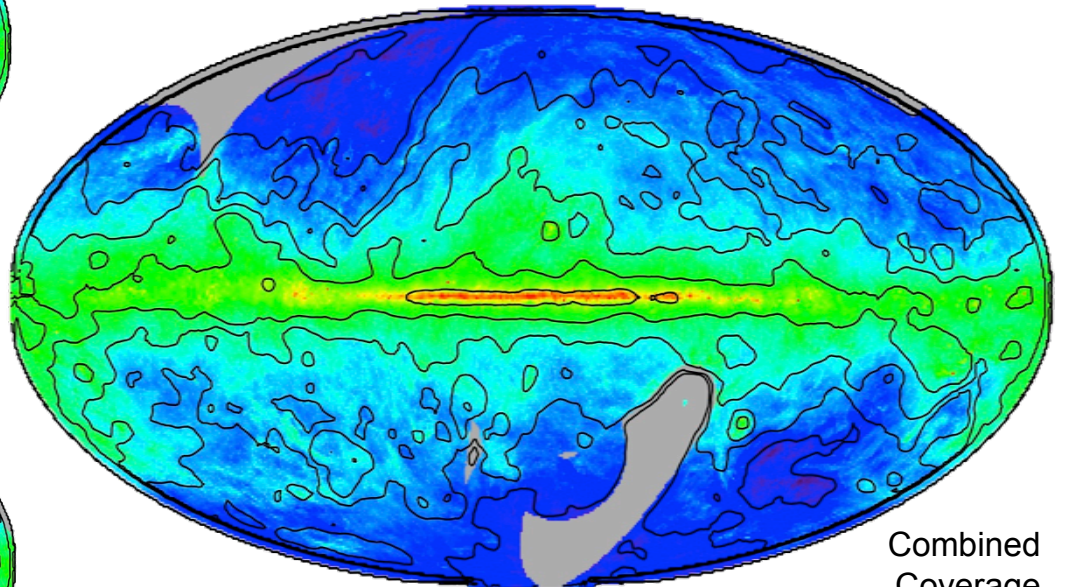
Northern Hemisphere  
Ft Sumner



Southern Hemisphere  
Alice Springs



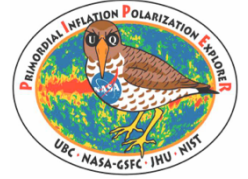
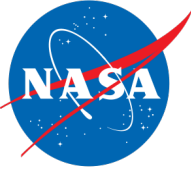
85% of sky  
 $2 < \ell < 400$



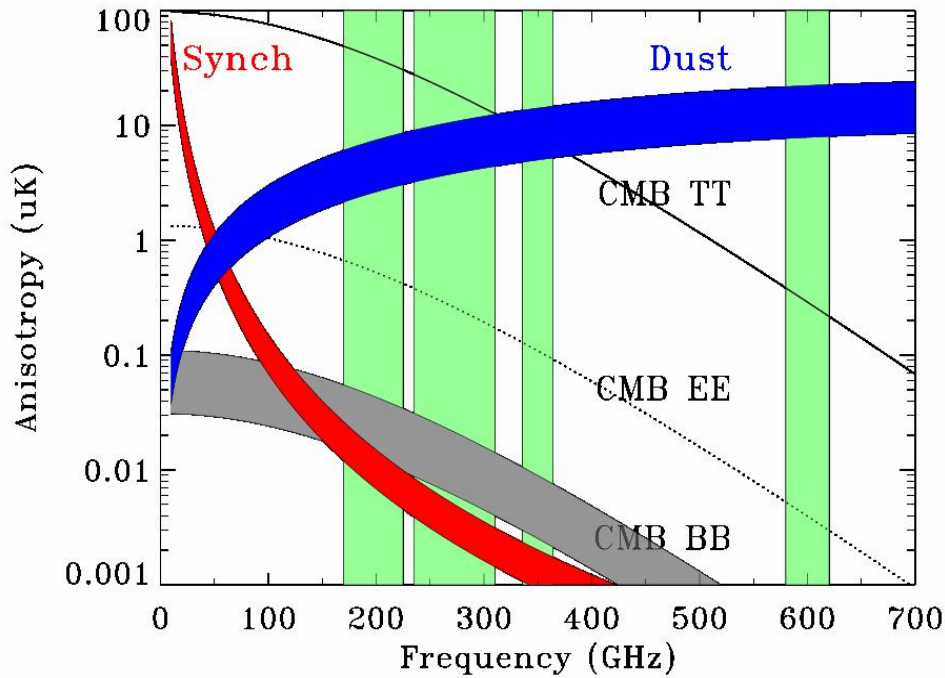
Combined  
Coverage

0.01  300  
Intensity (Jy)

See the sky, the whole sky, and nothing but the sky



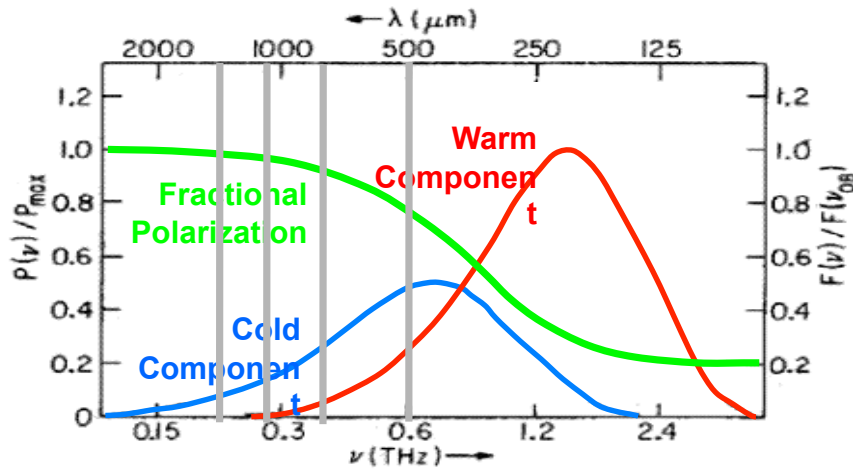
# Foregrounds



Re-fly optics and detectors  
Swap out bandpass filters

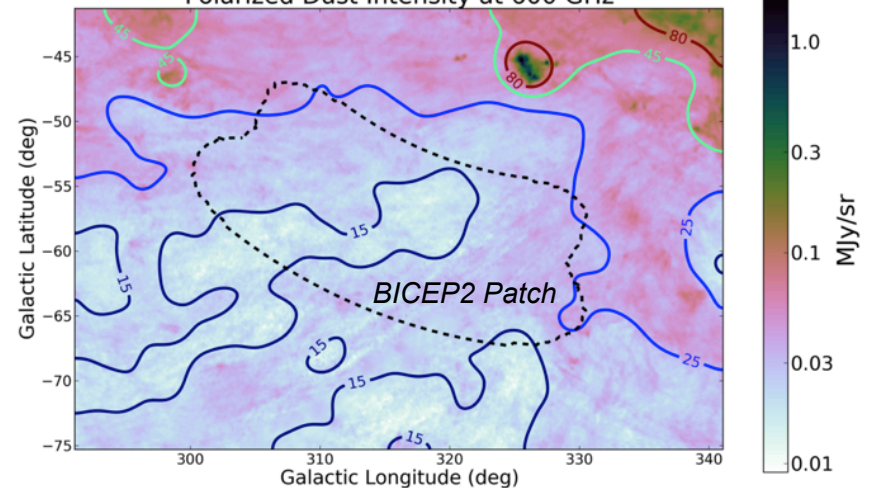


*Flexibility to add/change bands!*



***S/N > 10 even in low-dust patches***

Polarized Dust Intensity at 600 GHz





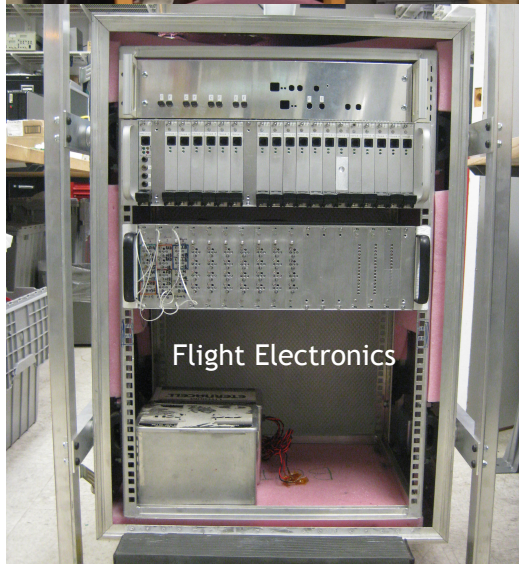
# Current Status



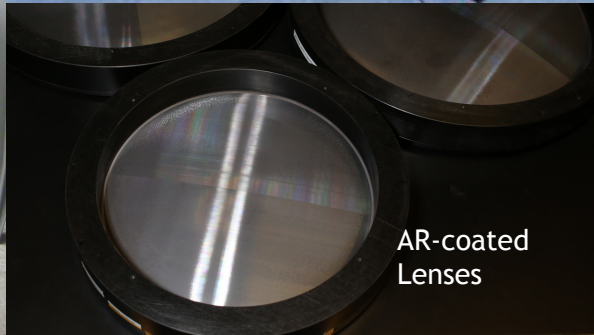
Detector Testing



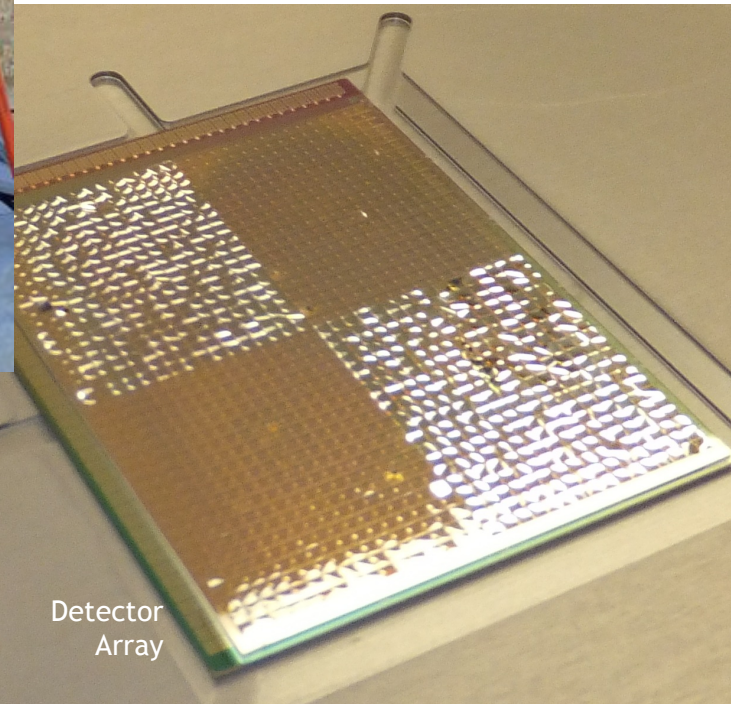
Flight Dewar



Flight Electronics



AR-coated Lenses



Detector Array

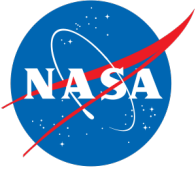
## Payload Integration Underway

- VPM / Optics
- “Superfluid Submarine”
- Flight Electronics

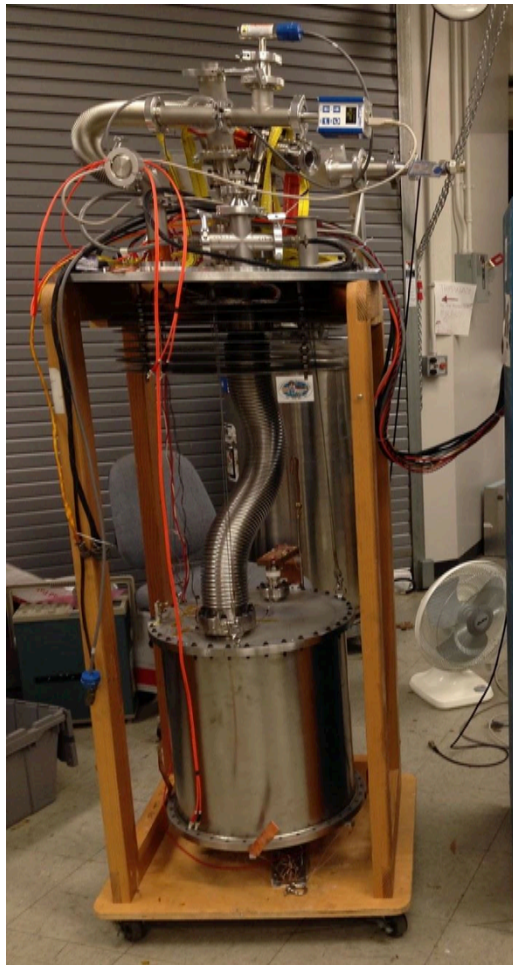
## Pacing Item is Flight Detectors

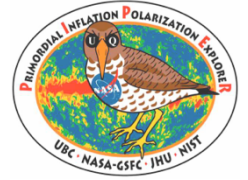
- Pathfinder array under test
- Flight arrays in production

**First Flight: Sept 2015**



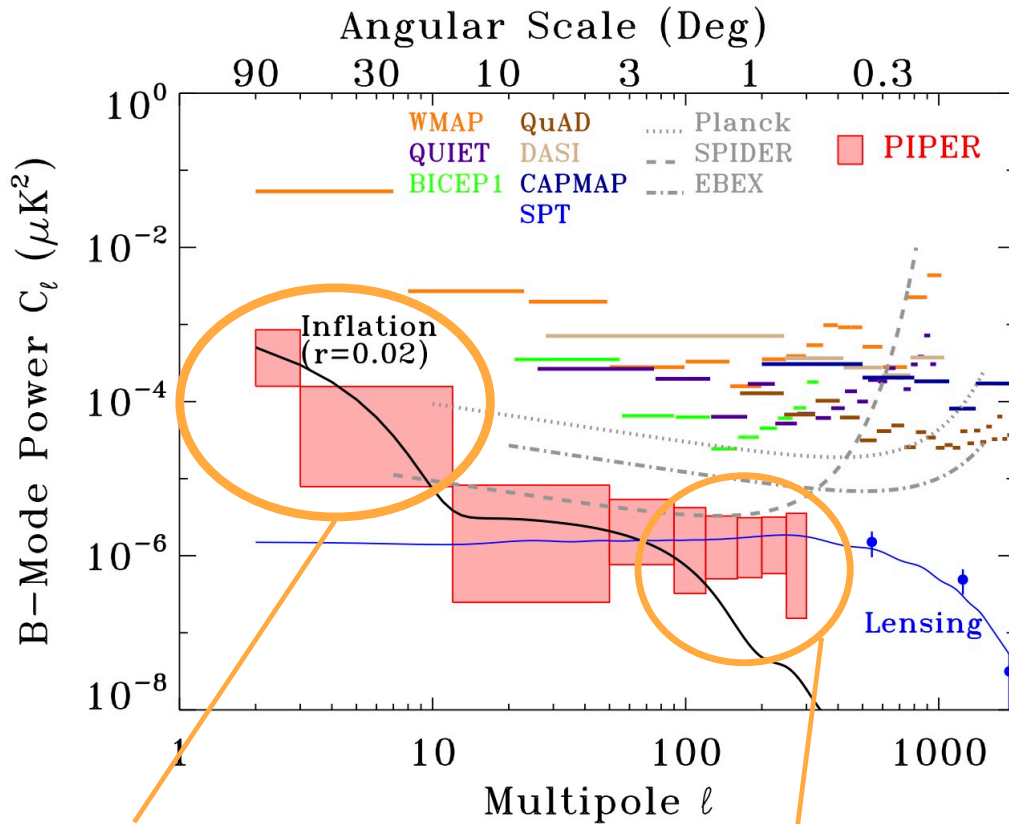
# Payload Testing





# PIPER Science

**Detect signal on largest scales using conventional ballooning**



Large angular scales:  
Amplitude of primordial  
signal

Small angular scales:  
Amplitude of lensing  
foreground

**Limits  $r < 0.03$  (one flight)  
 $r < 0.007$  (8 flights)**



**Detect primordial B-mode signal  
Characterize low- $l$  E-mode  
Map circular polarization**