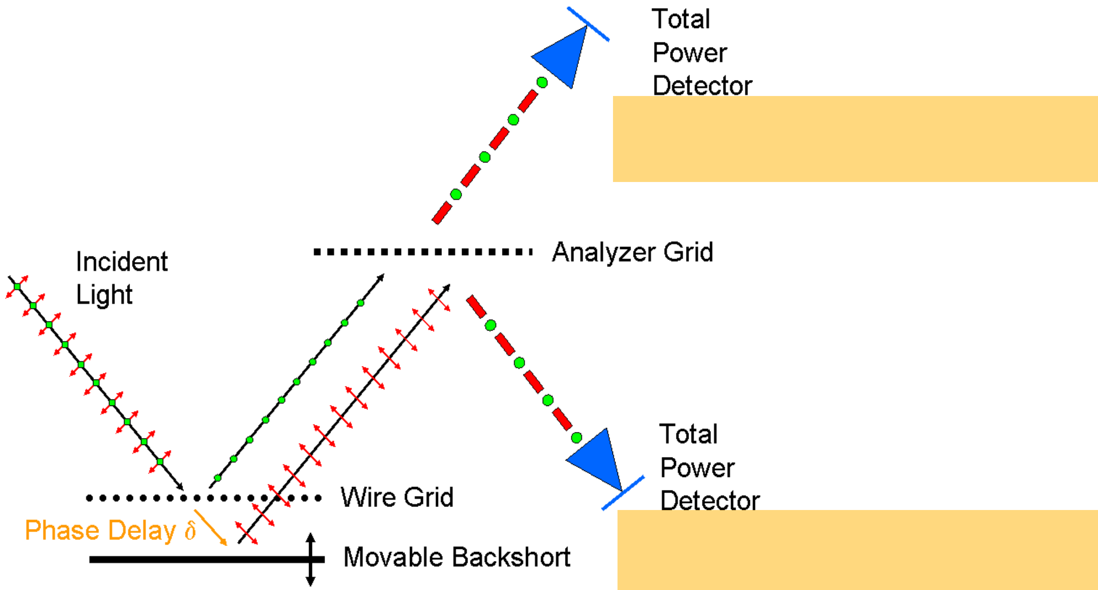
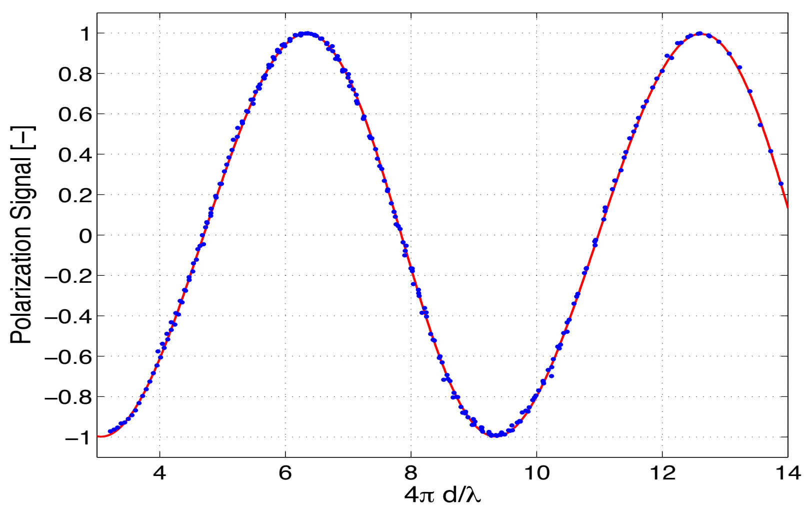
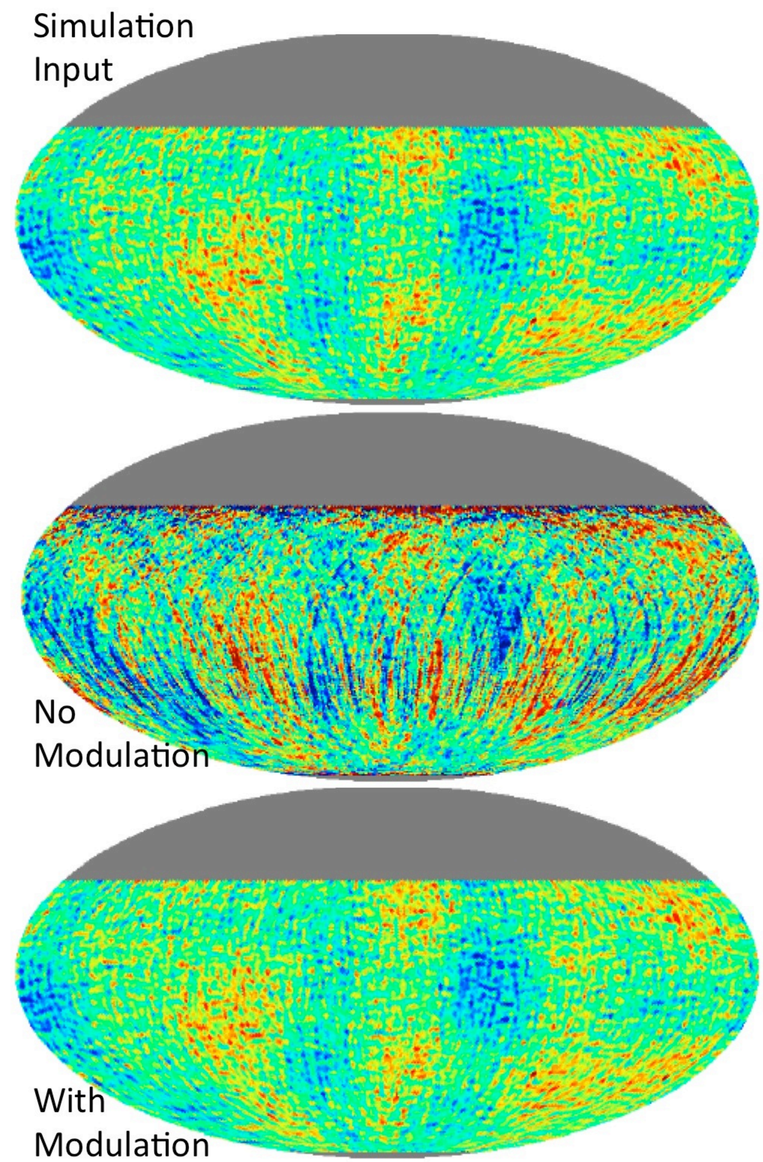
# *Variable-Delay Polarization Modulator (VPM)*

*Measure linear and circular polarization*

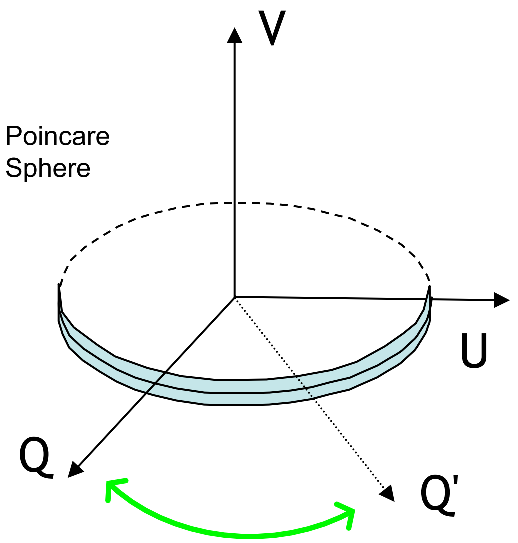



Miller et al 2018

# VPM Mitigates Cross-Polar Beam Mixing



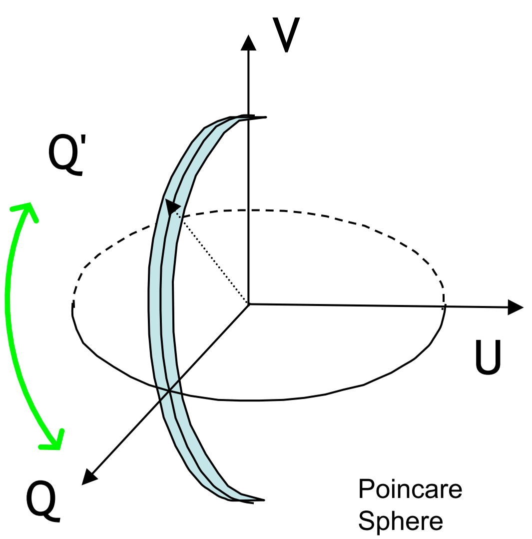

**Modulation in same direction as mixing: Systematics!**

HWP rotates Q↔U

$$\begin{bmatrix} I' \\ Q' \\ U' \\ V' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\alpha & \sin 2\alpha & 0 \\ 0 & -\sin 2\alpha & \cos 2\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

Problem: Sky is bright in Q and U

Any other QU mixing (e.g. cross-pol) can then project bright [QU] foregrounds into false B-mode signal




**Modulation orthogonal to mixing: Efficiency!**

VPM rotates Q↔V

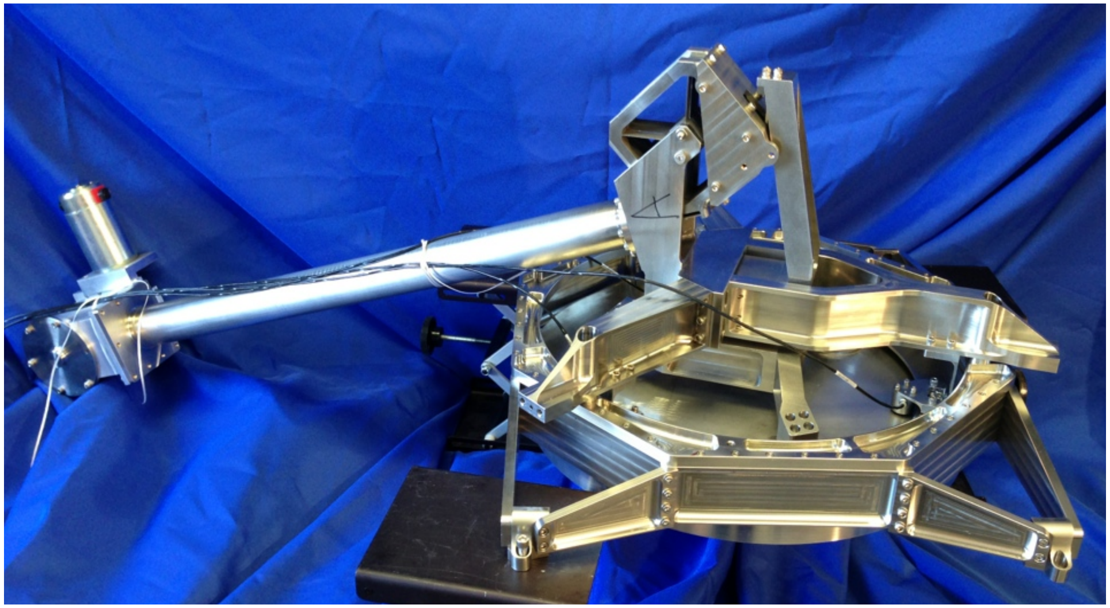
$$\begin{bmatrix} I' \\ Q' \\ U' \\ V' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\delta & 0 & \sin\delta \\ 0 & 0 & 1 & 0 \\ 0 & -\sin\delta & 0 & \cos\delta \end{bmatrix} \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

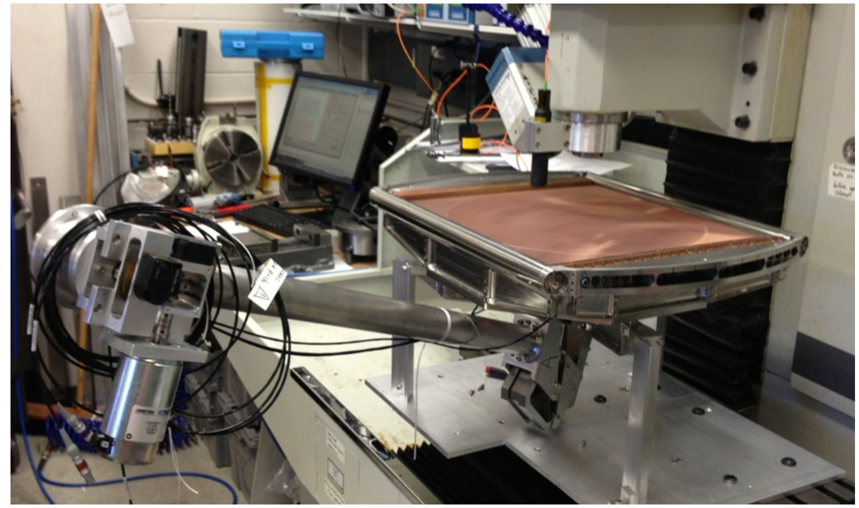
Solution: Modulate Q↔V instead!

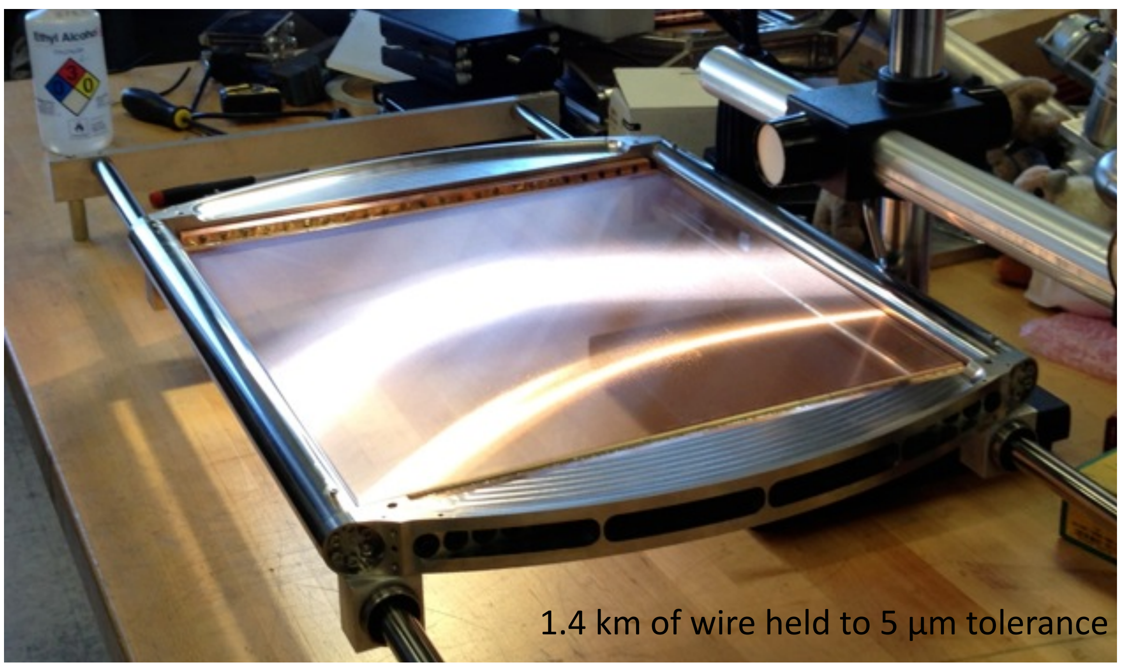
No celestial signal in V, so Q↔V mixing simply reduces amplitude of detected Q modulation.

Efficiency, not systematic error!

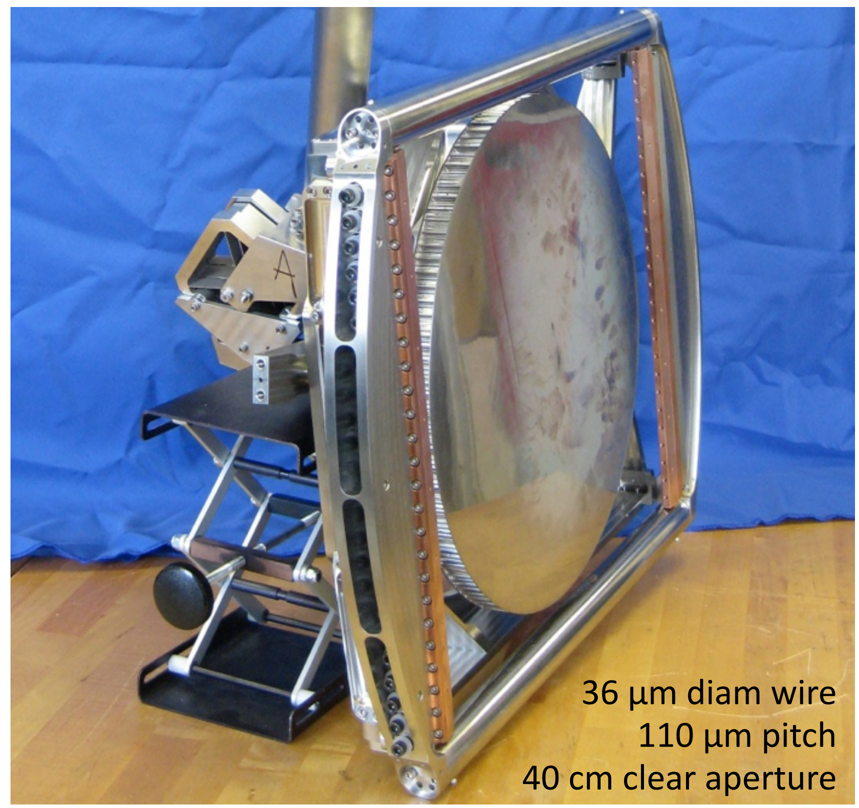
# Polarization Modulator





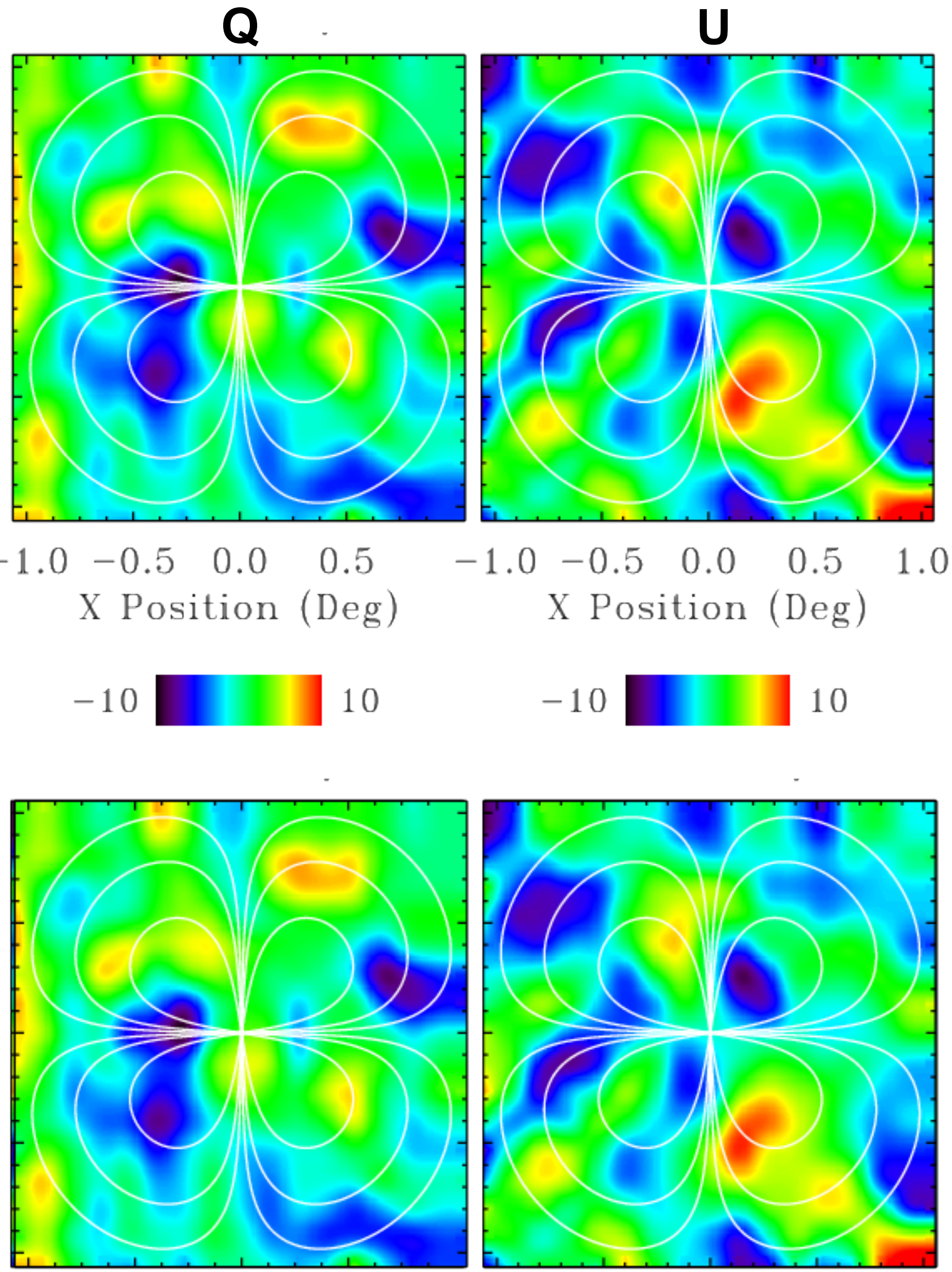


1.4 km of wire held to 5 μm tolerance



36 μm diam wire
110 μm pitch
40 cm clear aperture

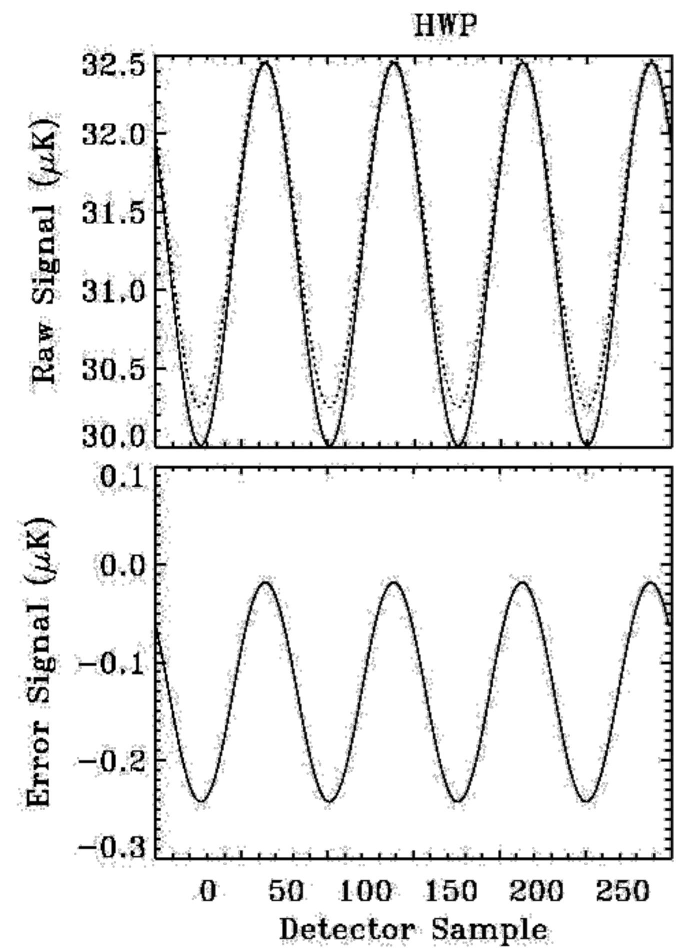
# Cross-Polar Beam Systematics




True Sky

After HWP Modulation

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



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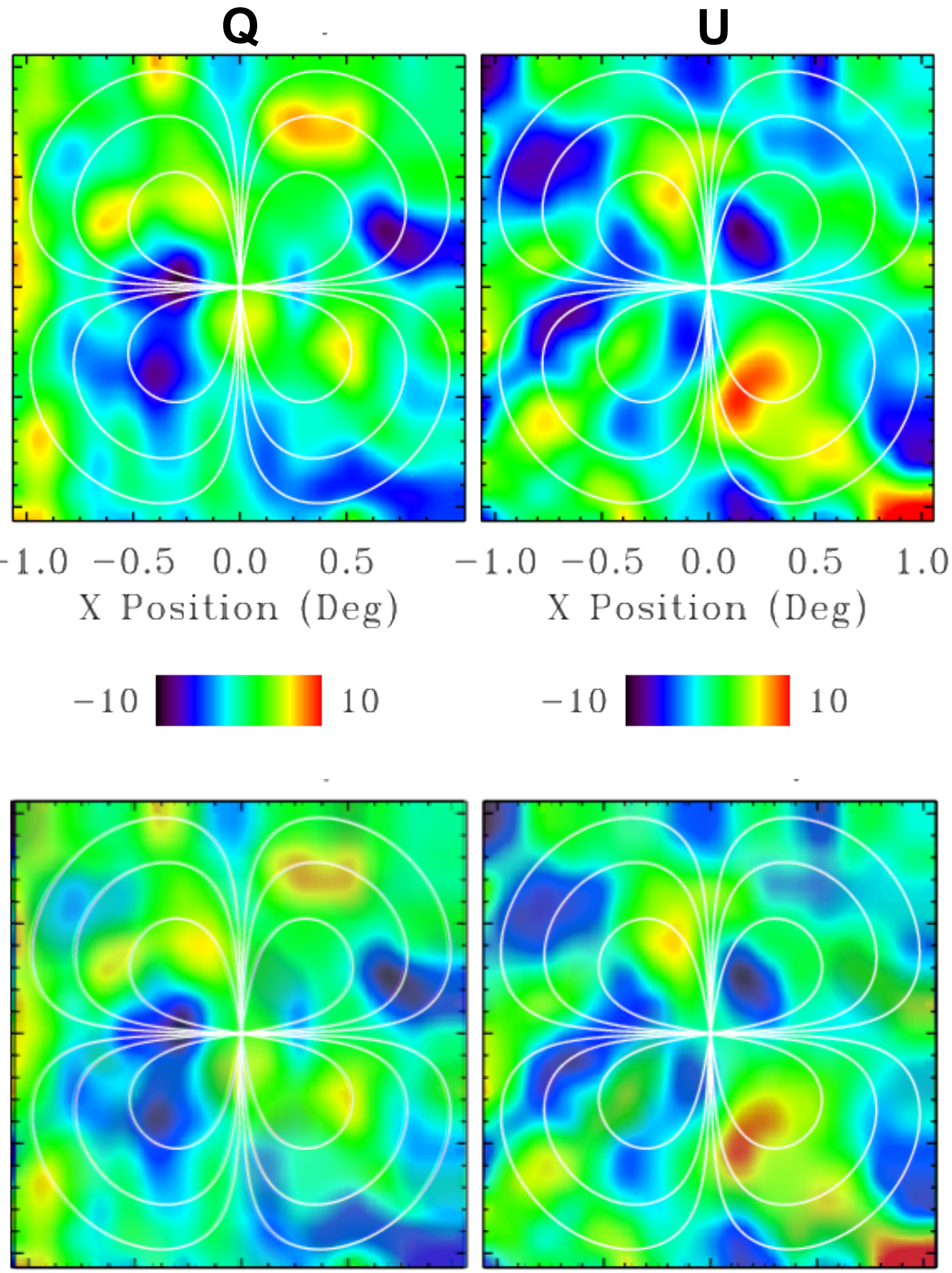


True Sky

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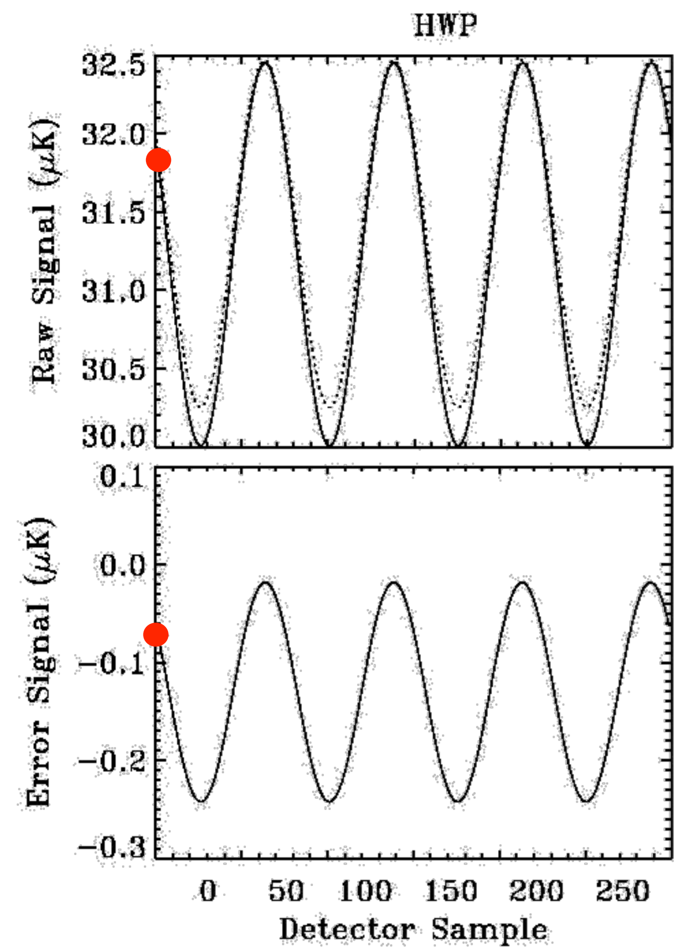

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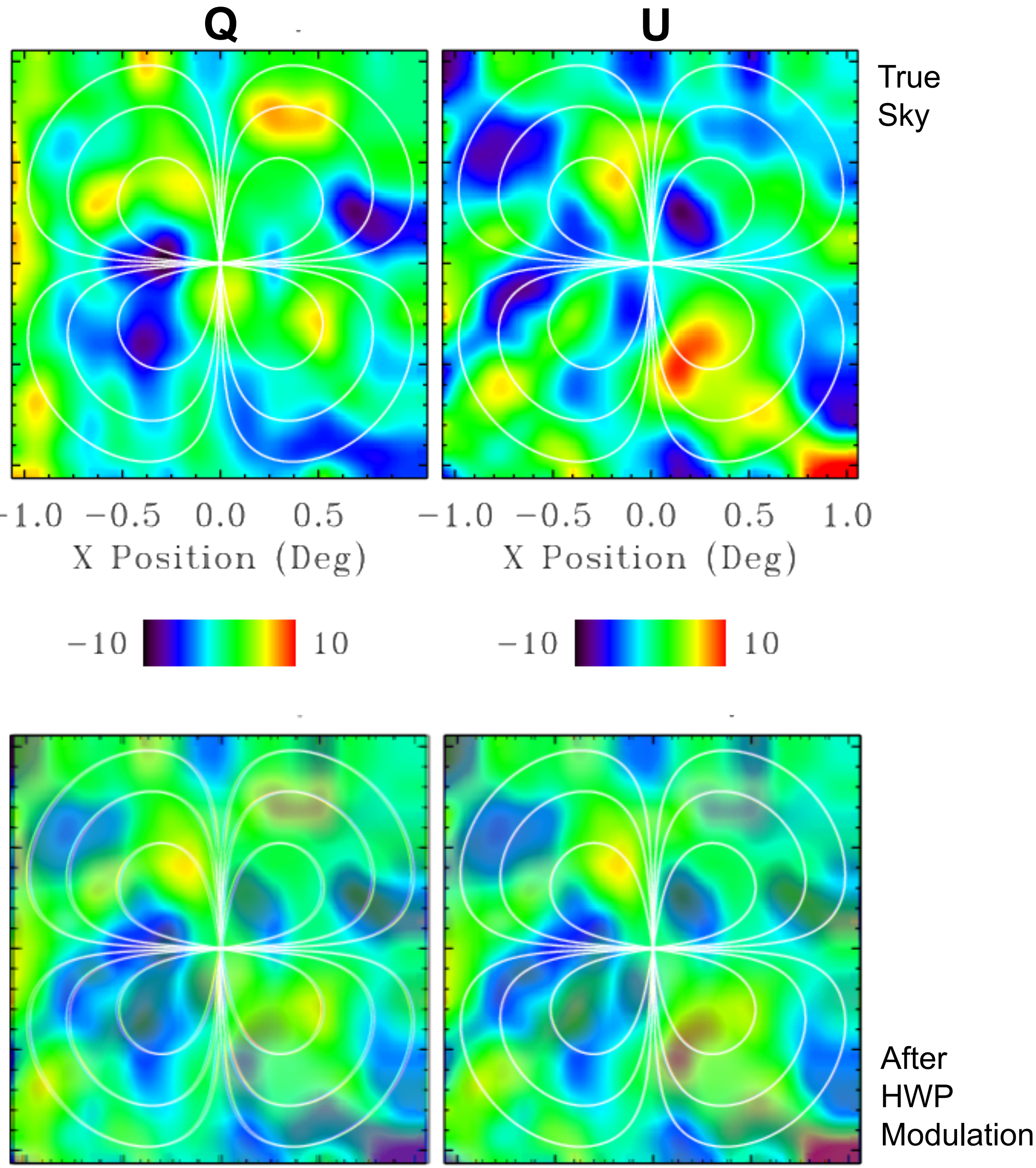


Wave Plate:
Q/U mixing
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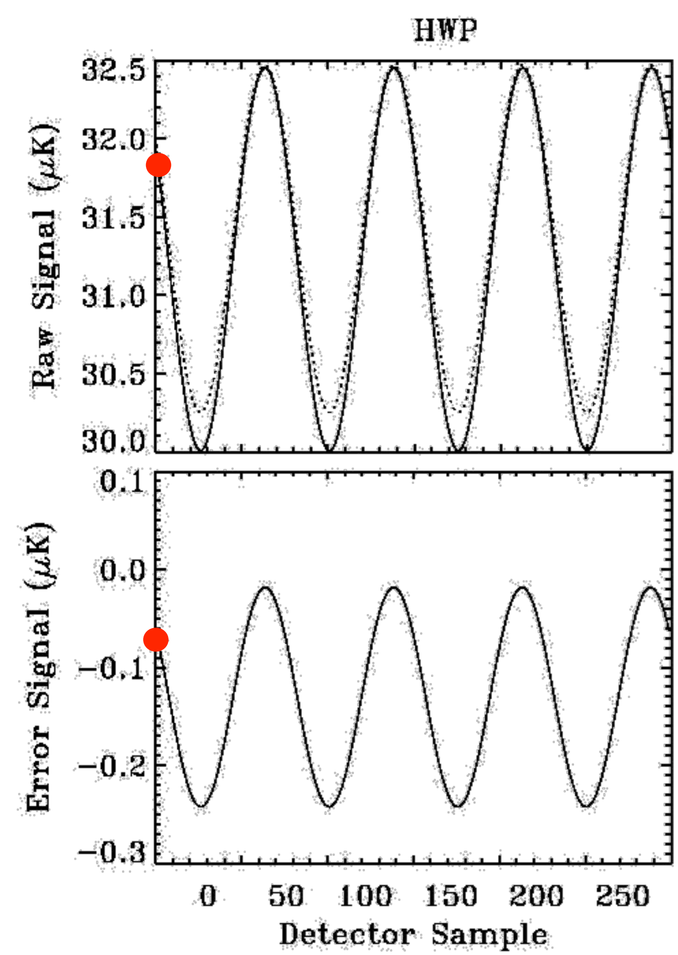

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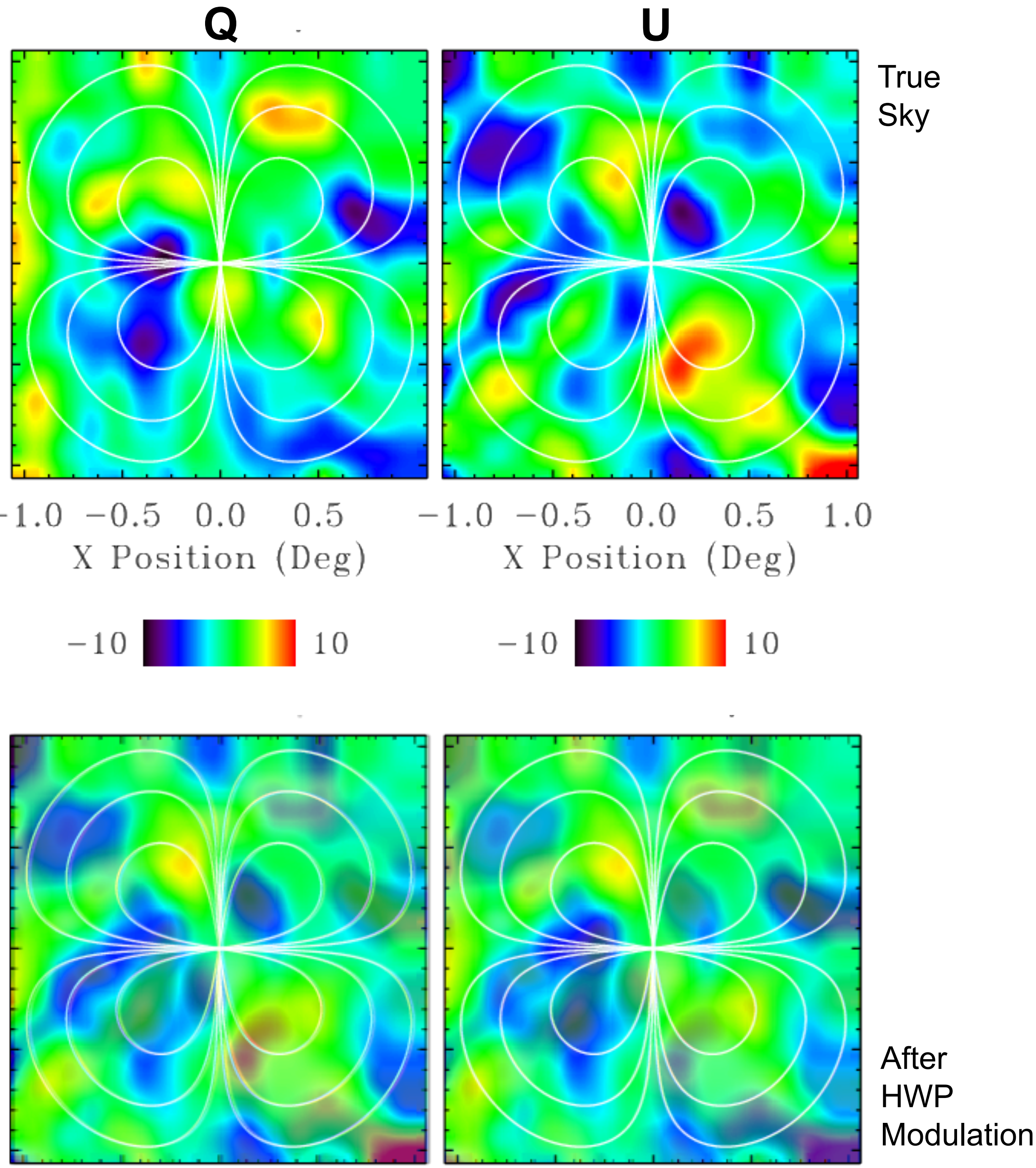
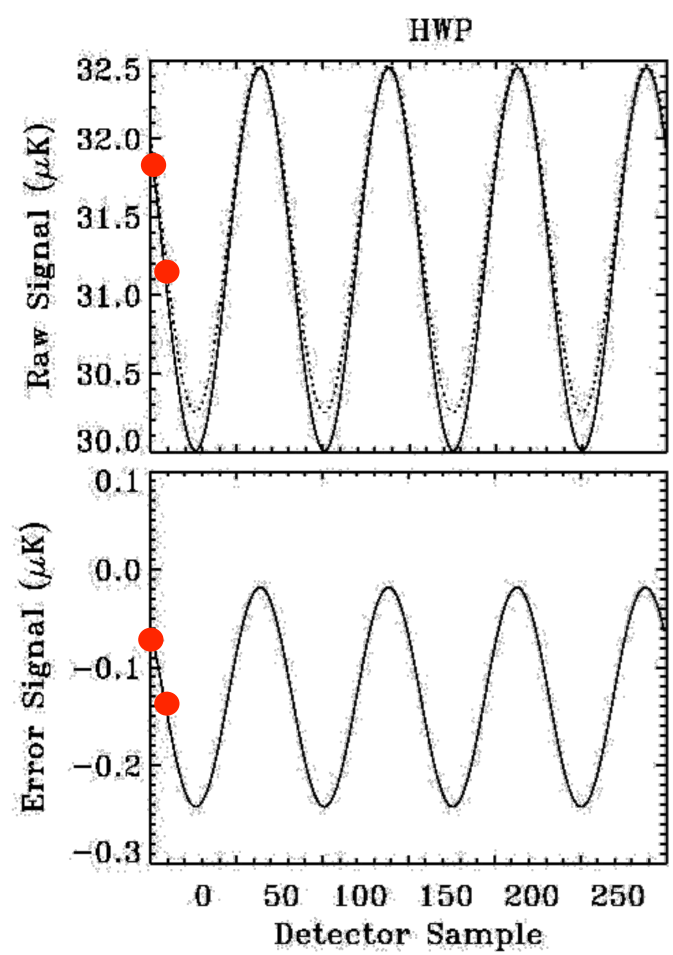
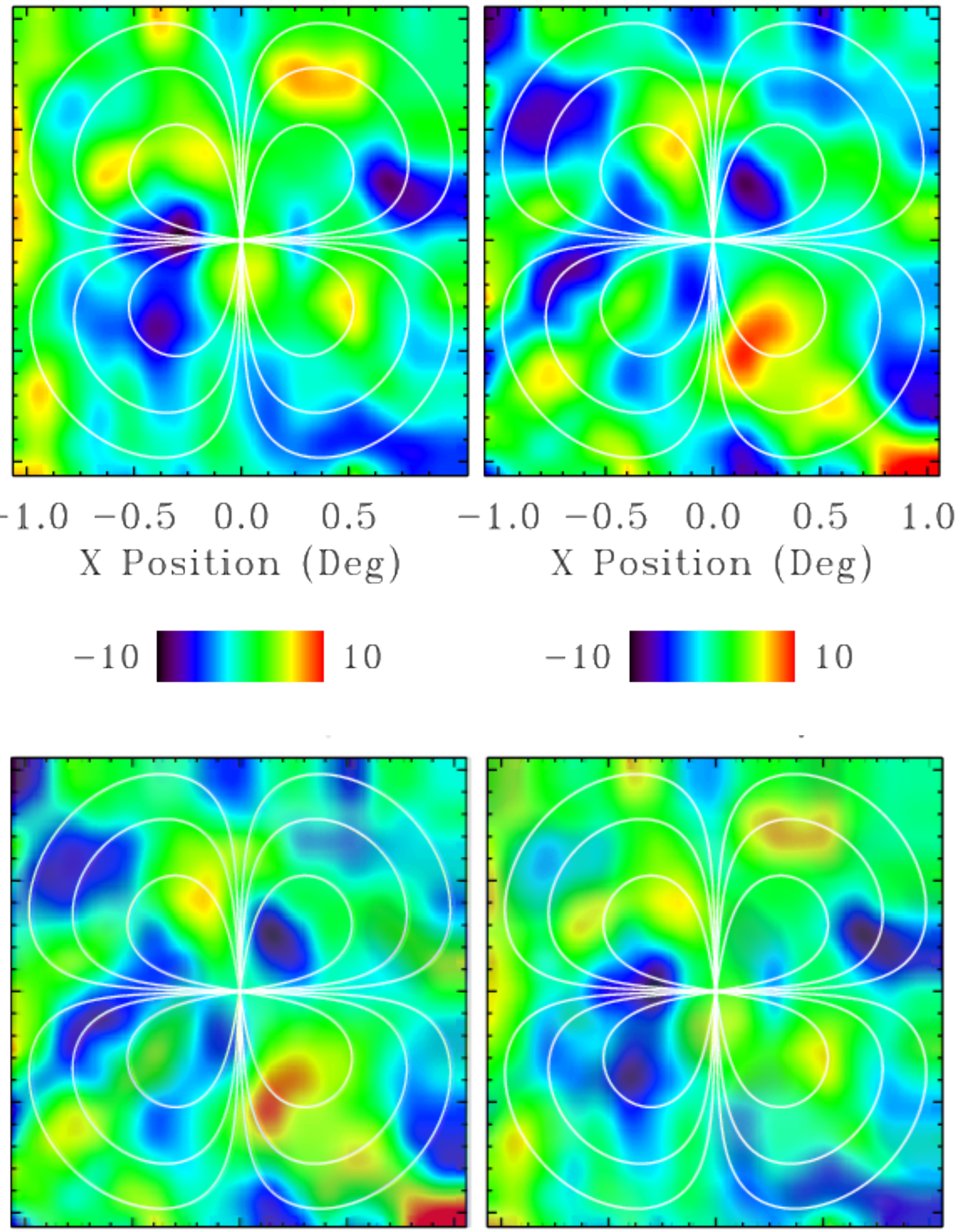



Wave Plate:
Q/U mixing
plus
Q/U modulation



# Cross-Polar Beam Systematics

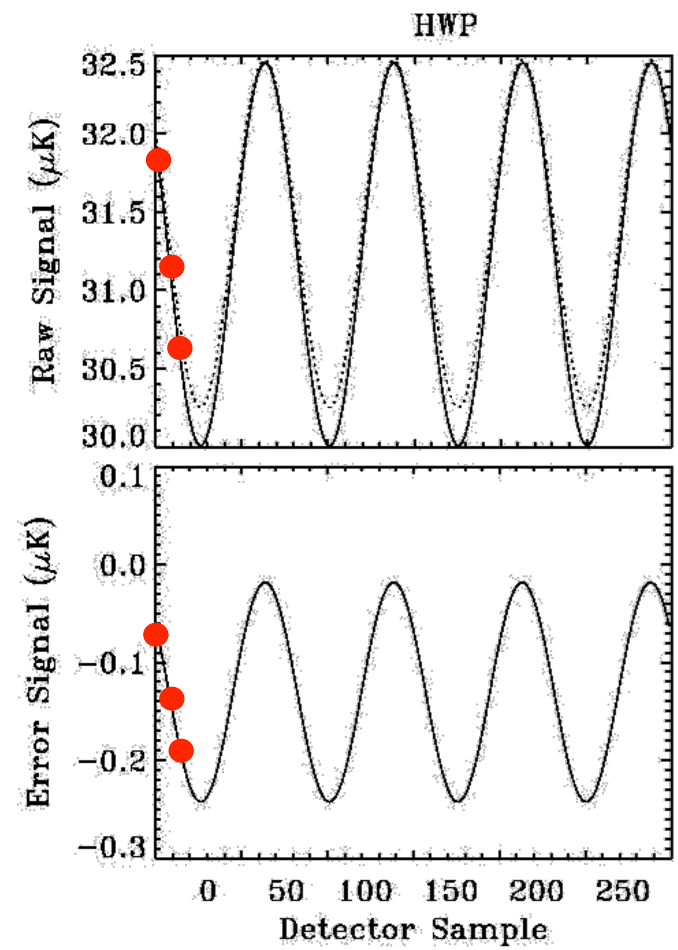
**Q** **U**




True Sky

After HWP Modulation

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



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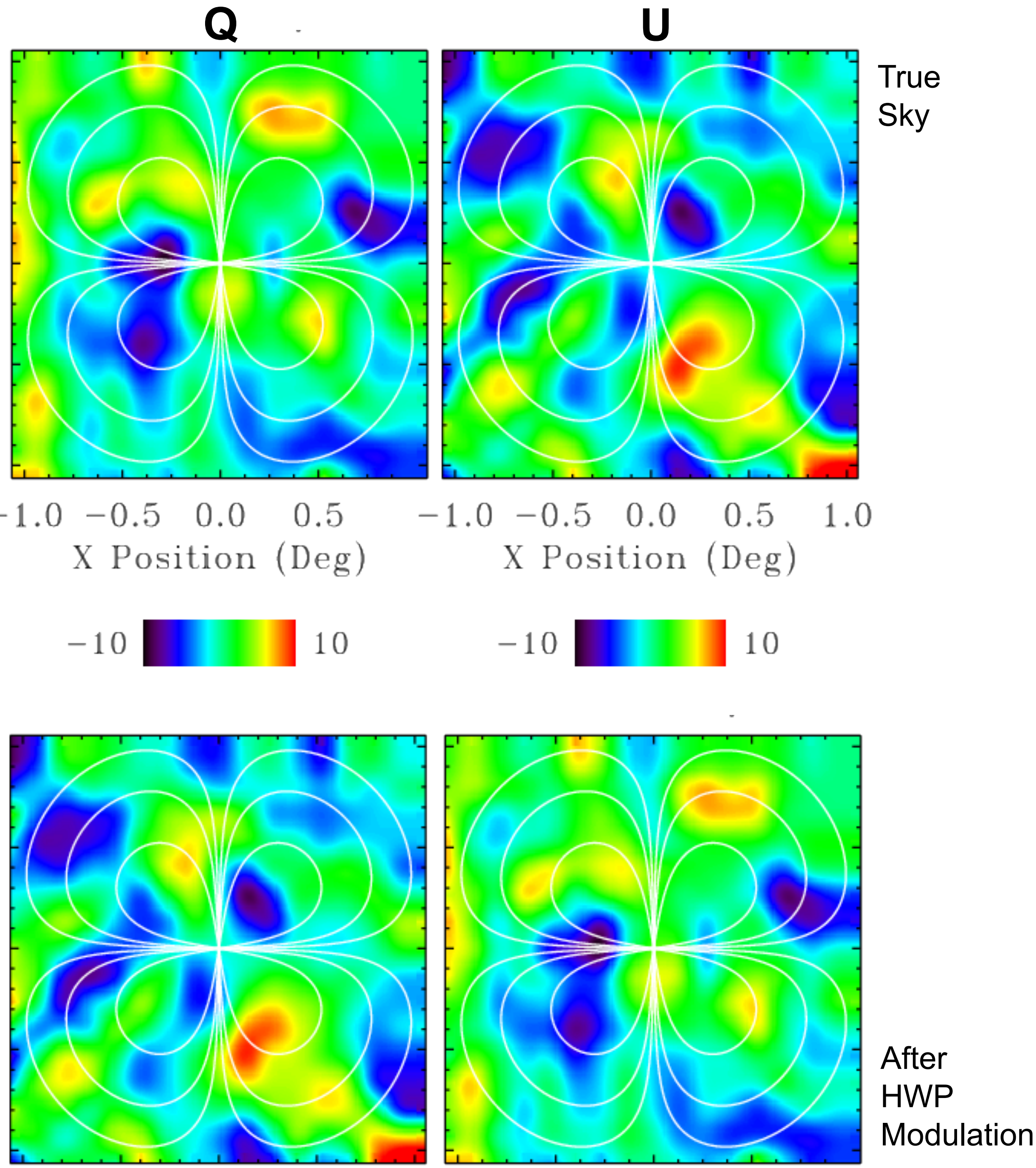
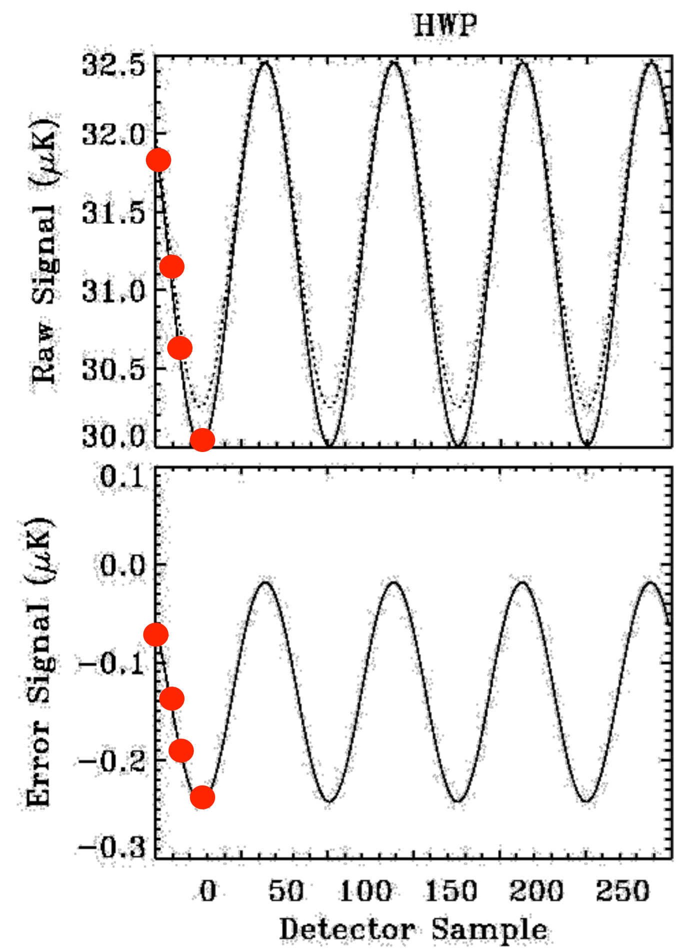



Wave Plate:
Q/U mixing
plus
Q/U modulation



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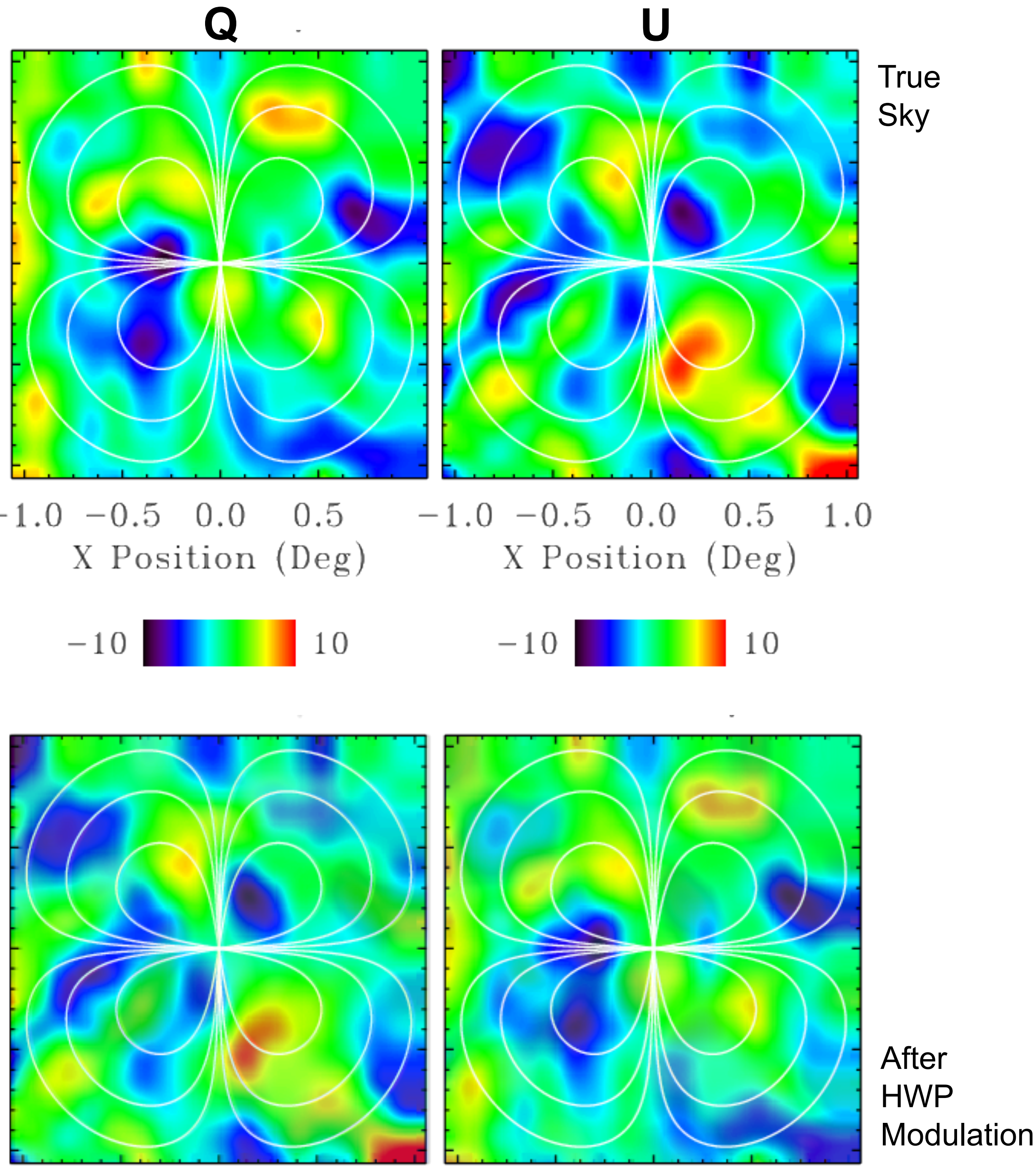
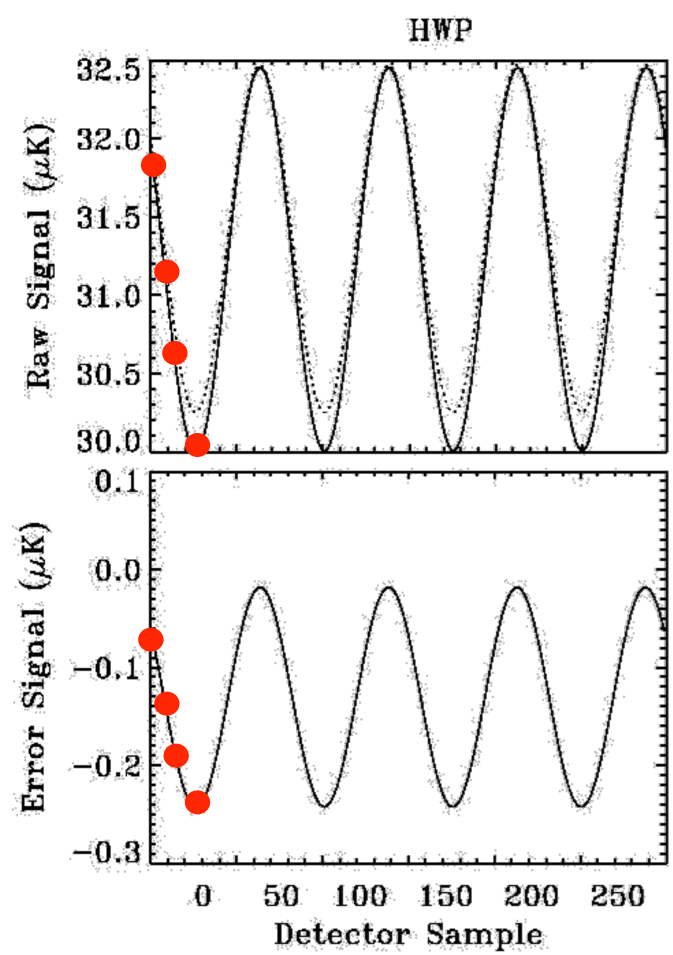



Wave Plate:
Q/U mixing
plus
Q/U modulation



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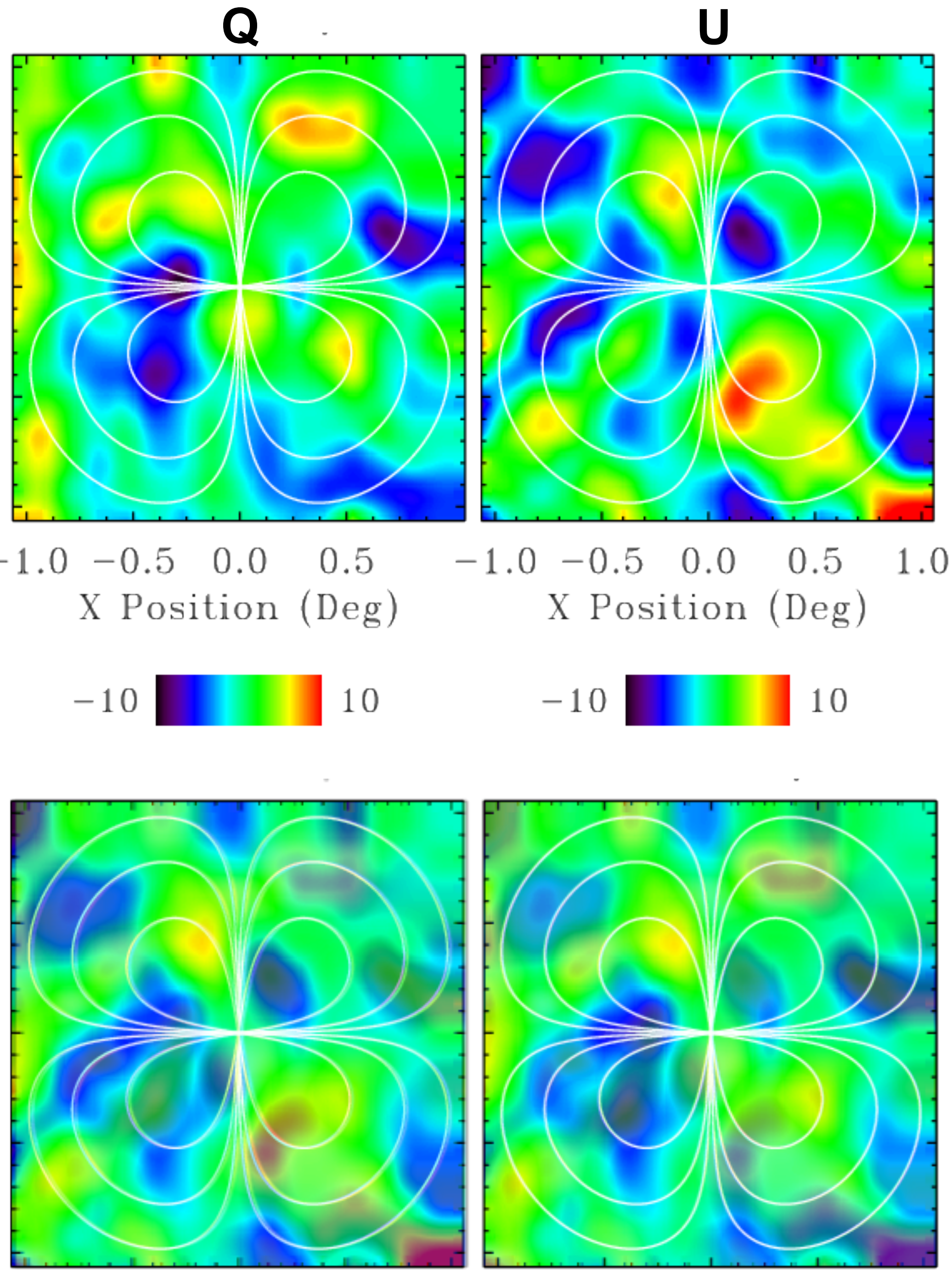
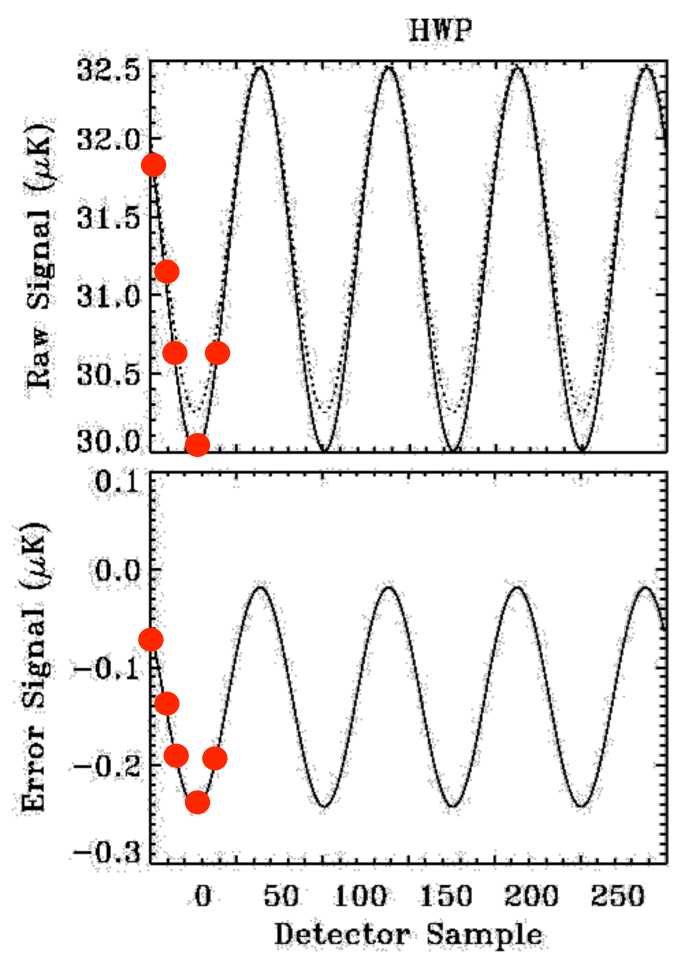



True Sky

After HWP Modulation

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



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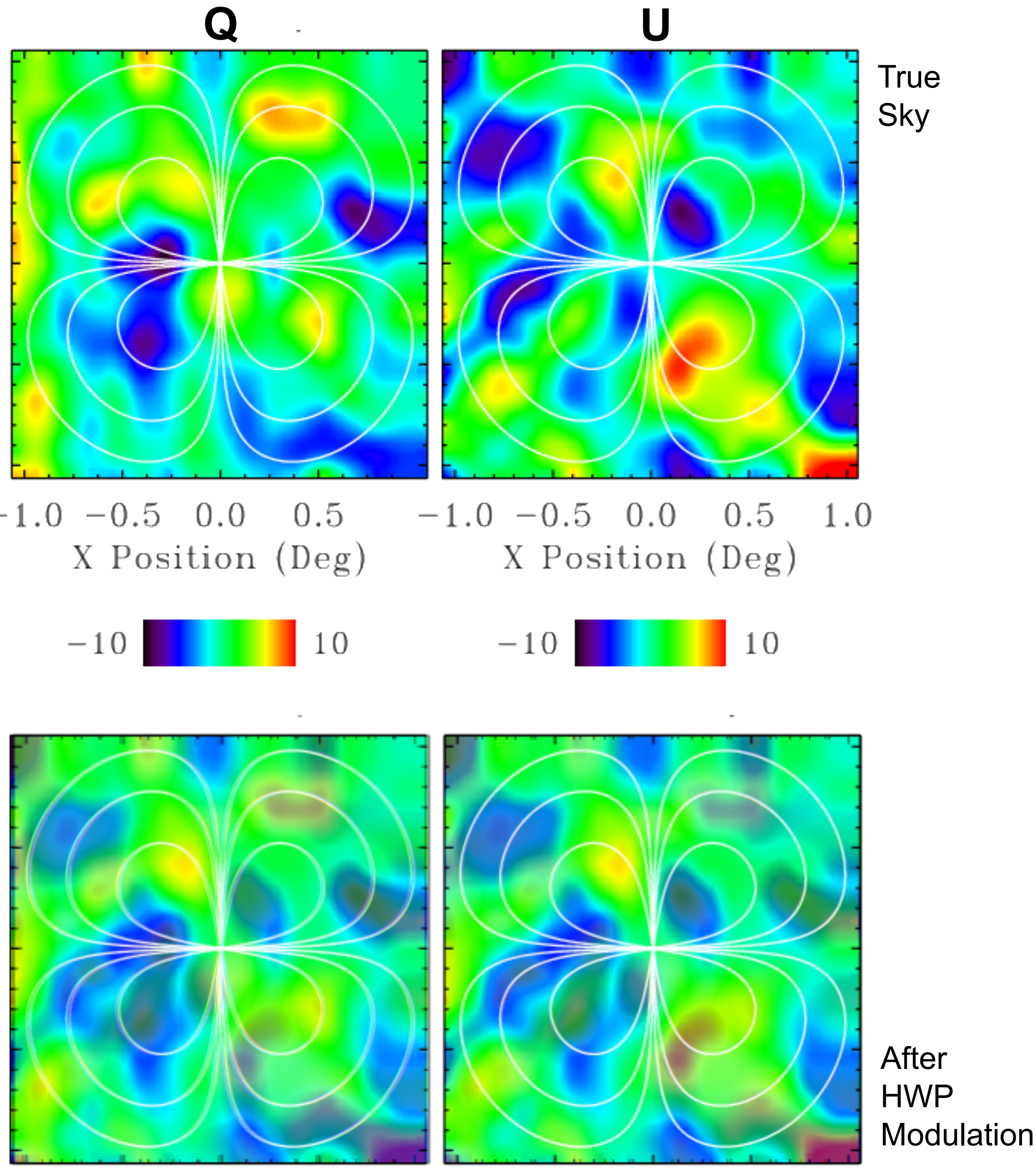
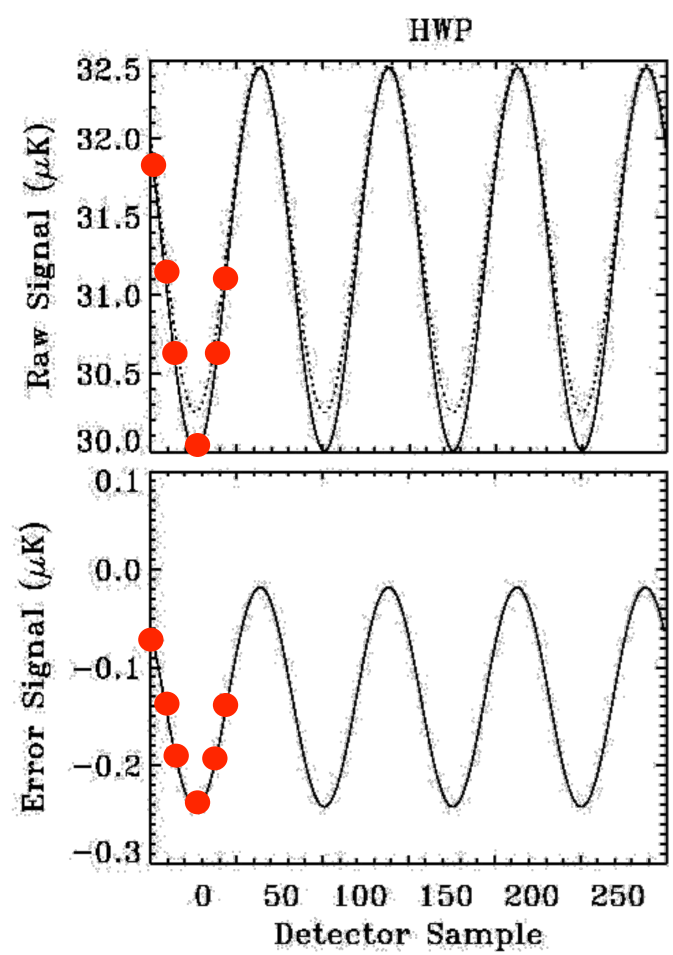



Wave Plate:
Q/U mixing
plus
Q/U modulation



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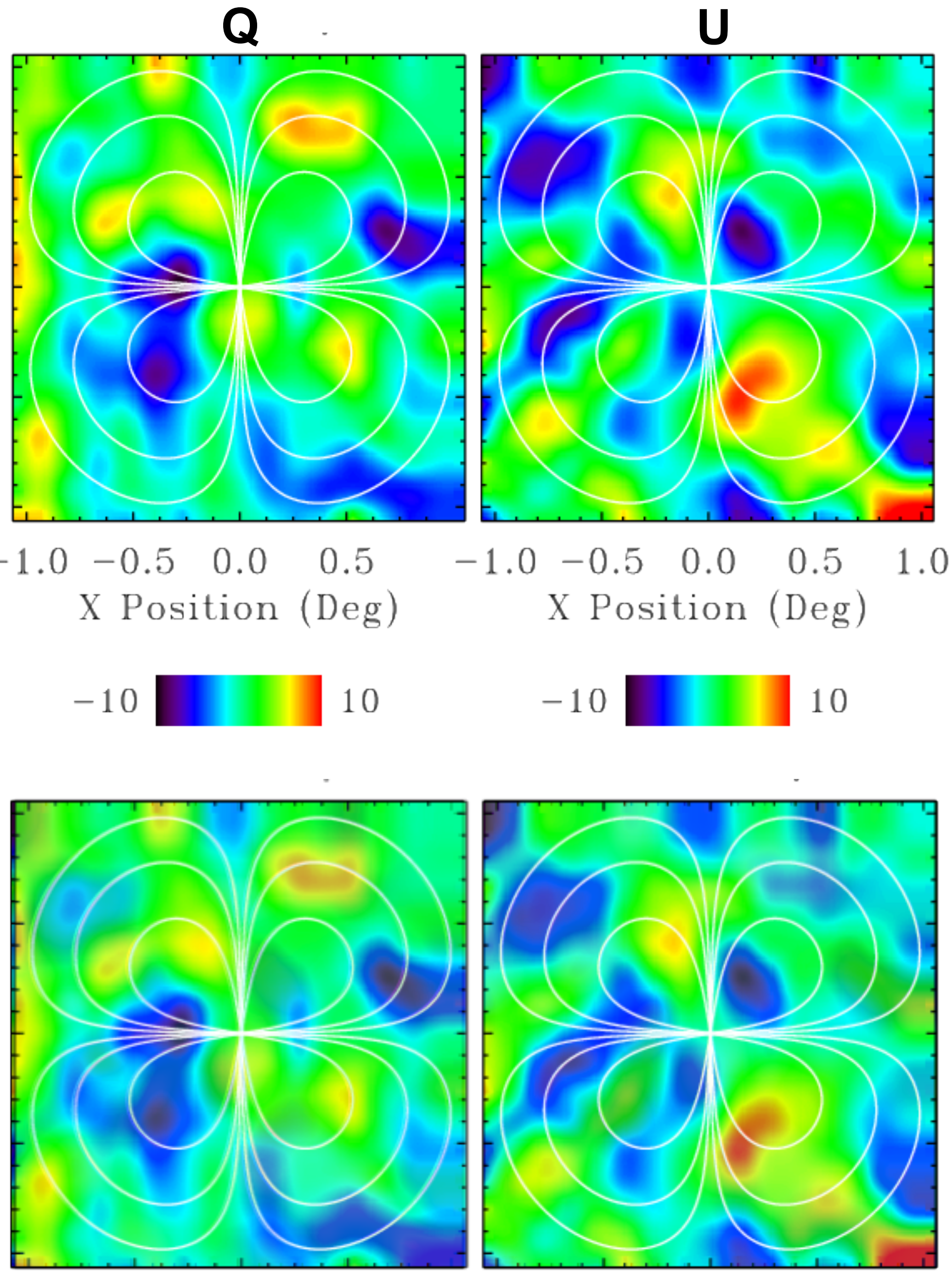
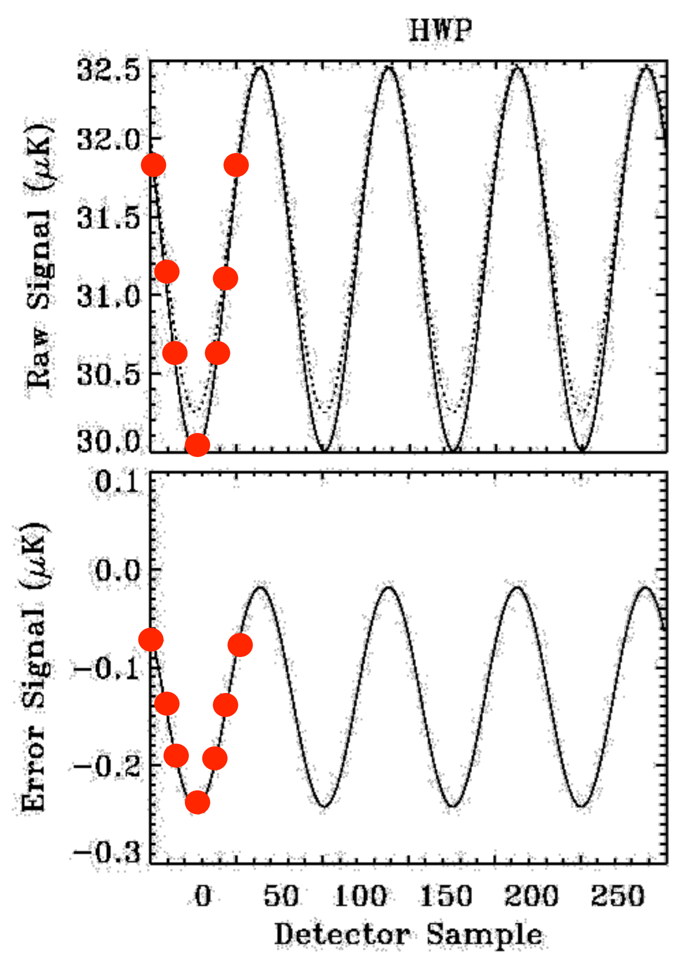



True Sky

After HWP Modulation

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



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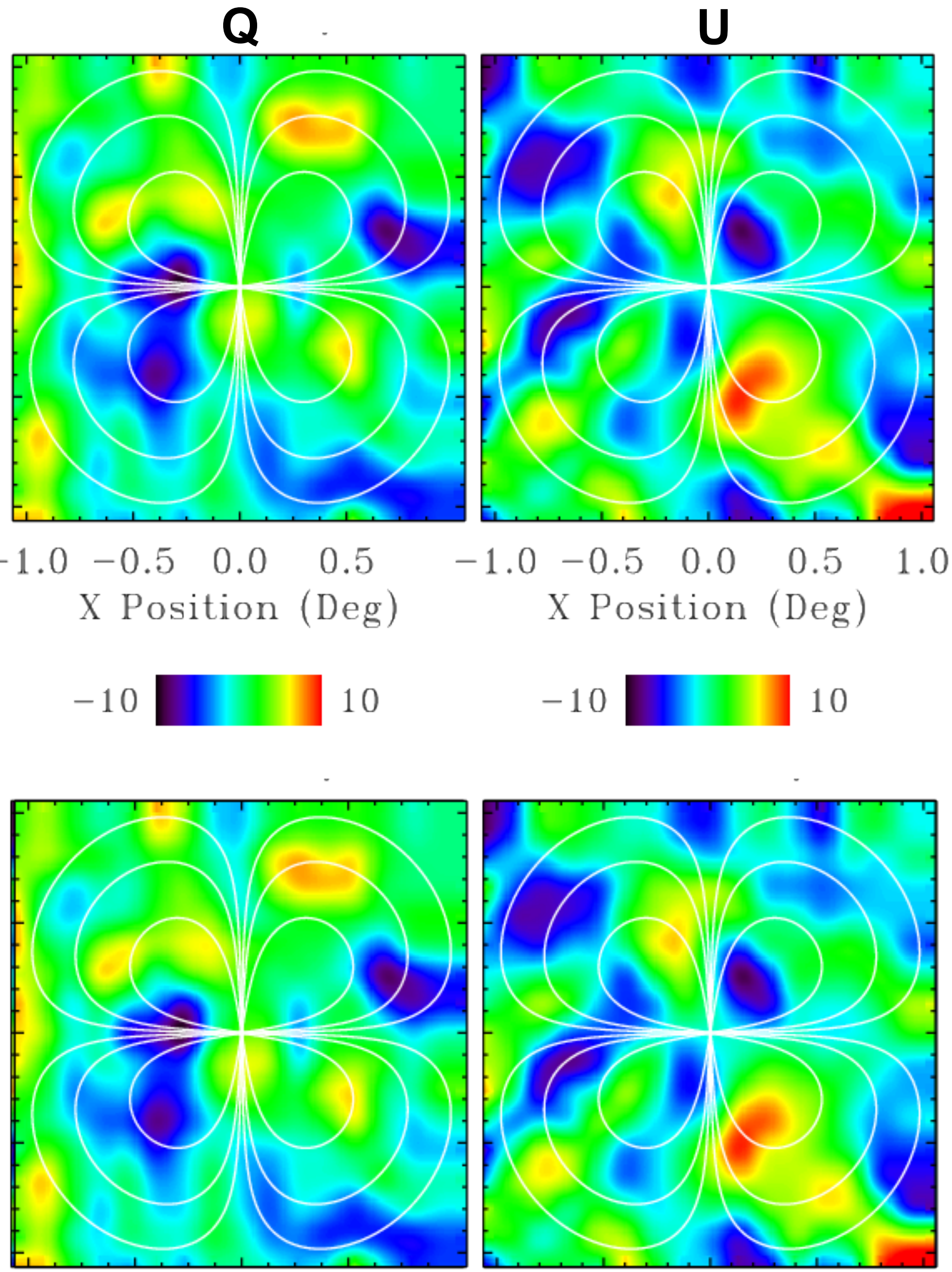
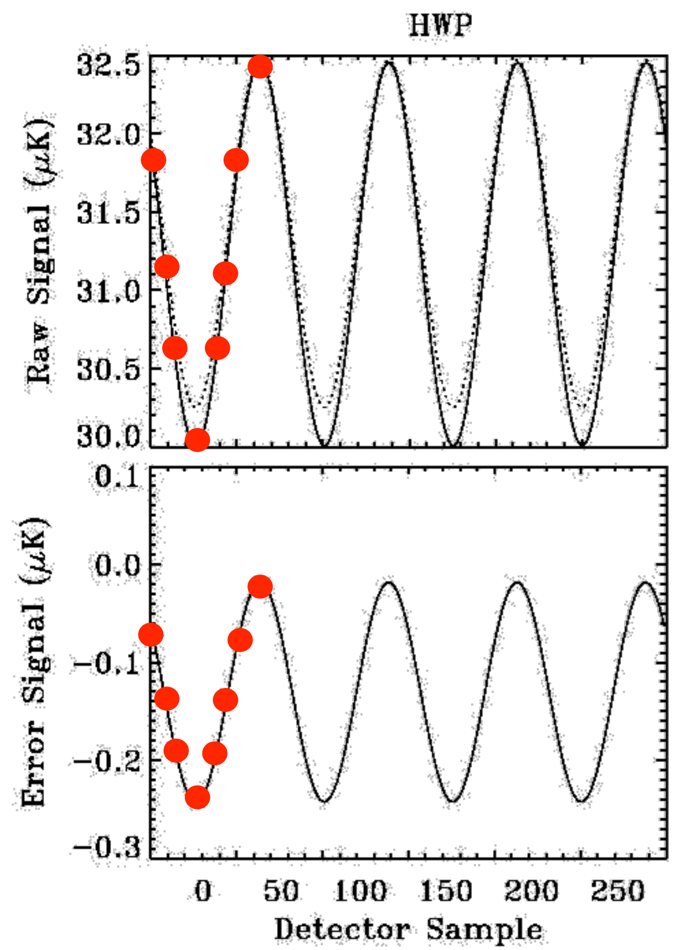


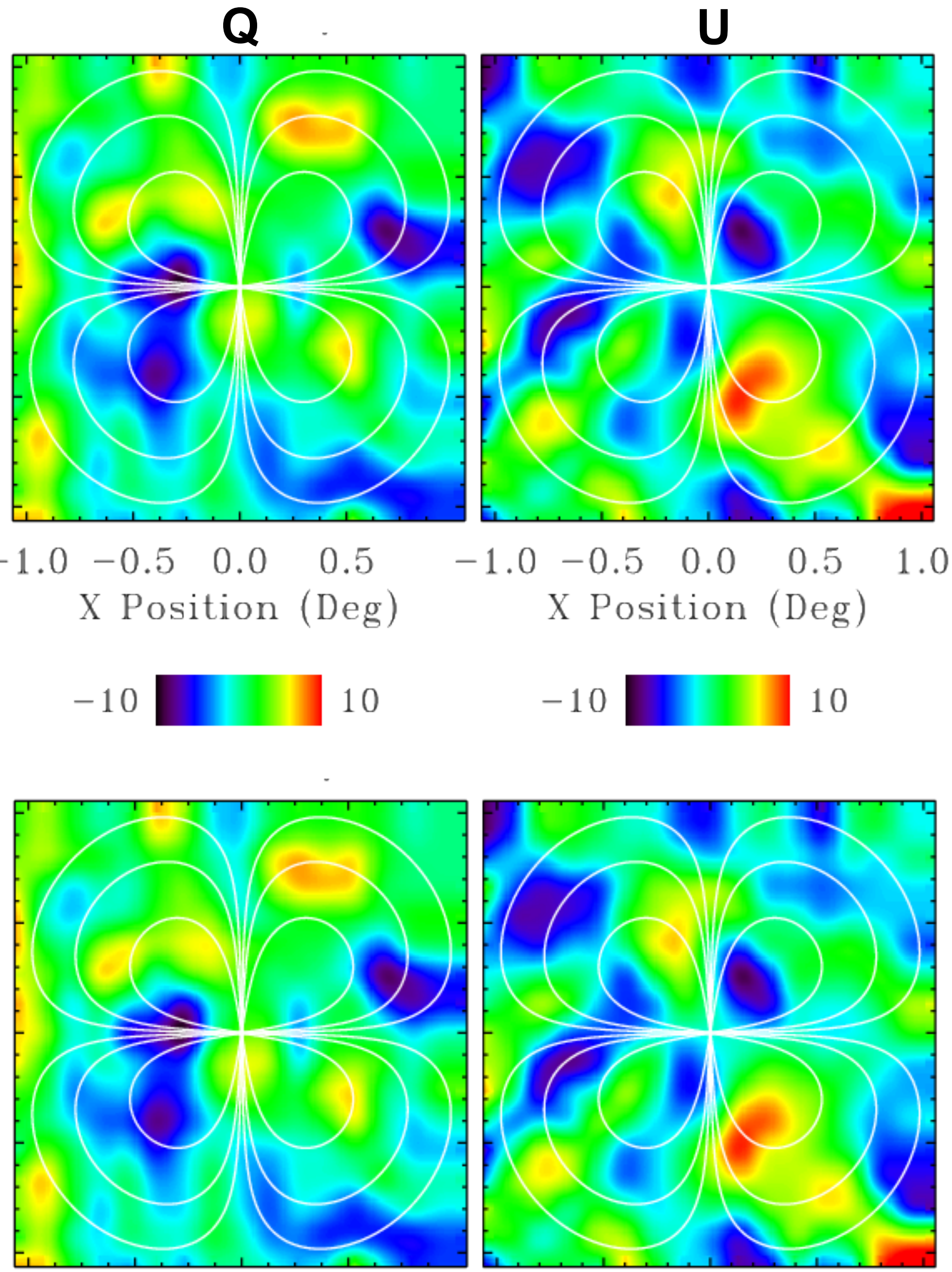

True Sky

After HWP Modulation

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



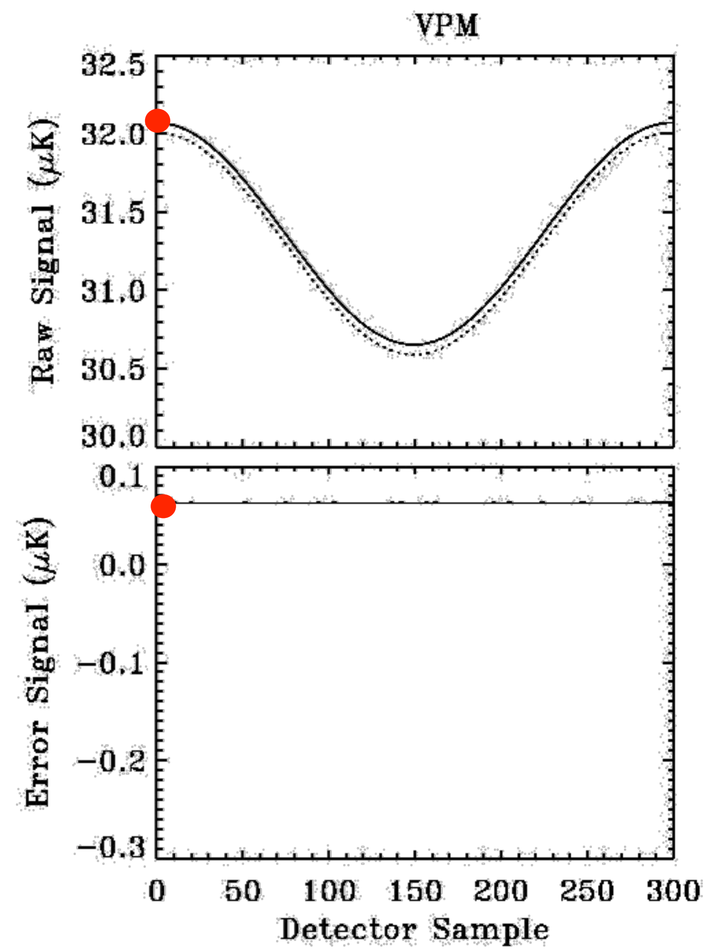
# Cross-Polar Beam Systematics




True Sky

After VPM Modulation

VPM:
Q/U mixing
but
Q/V modulation



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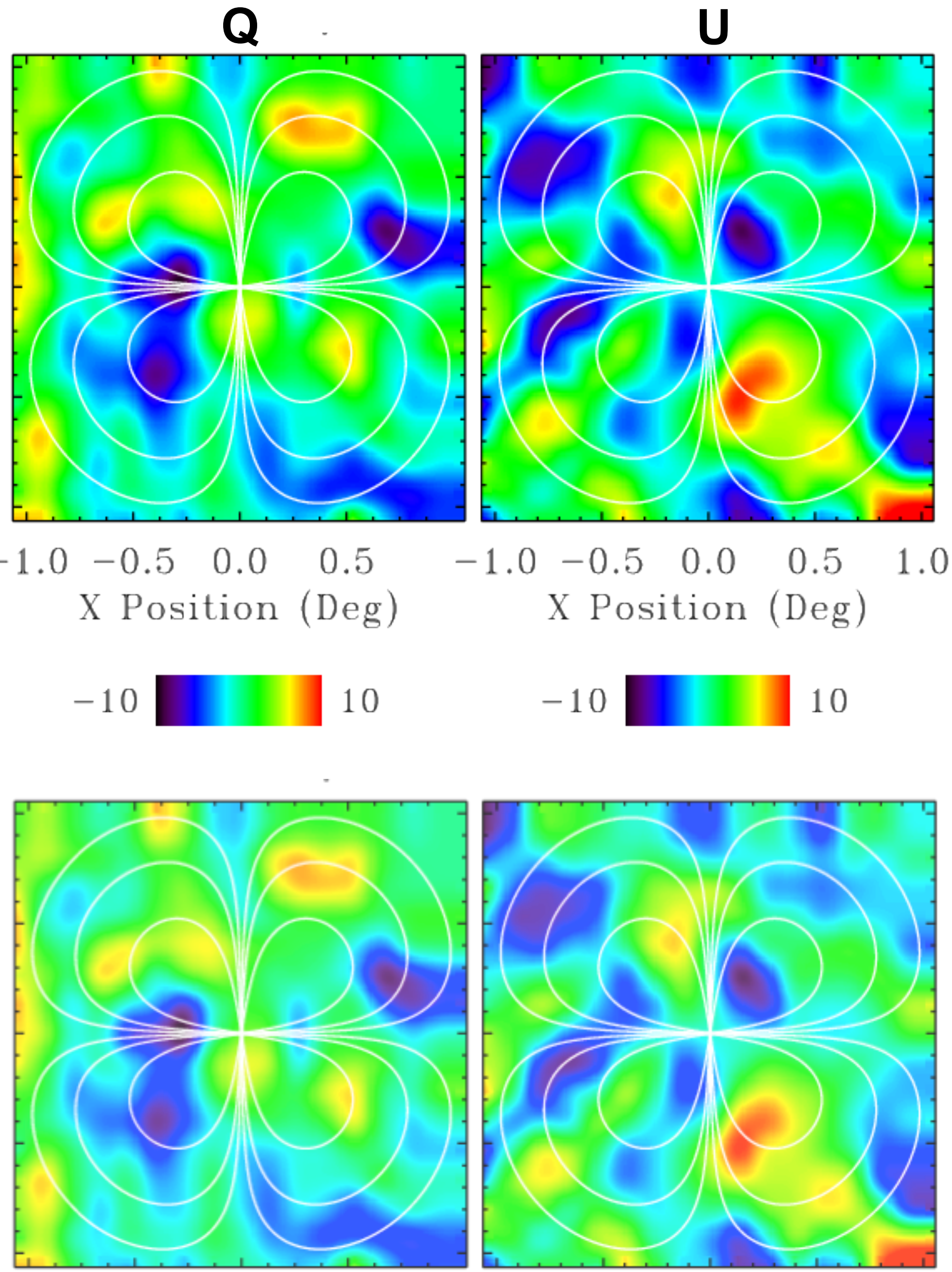
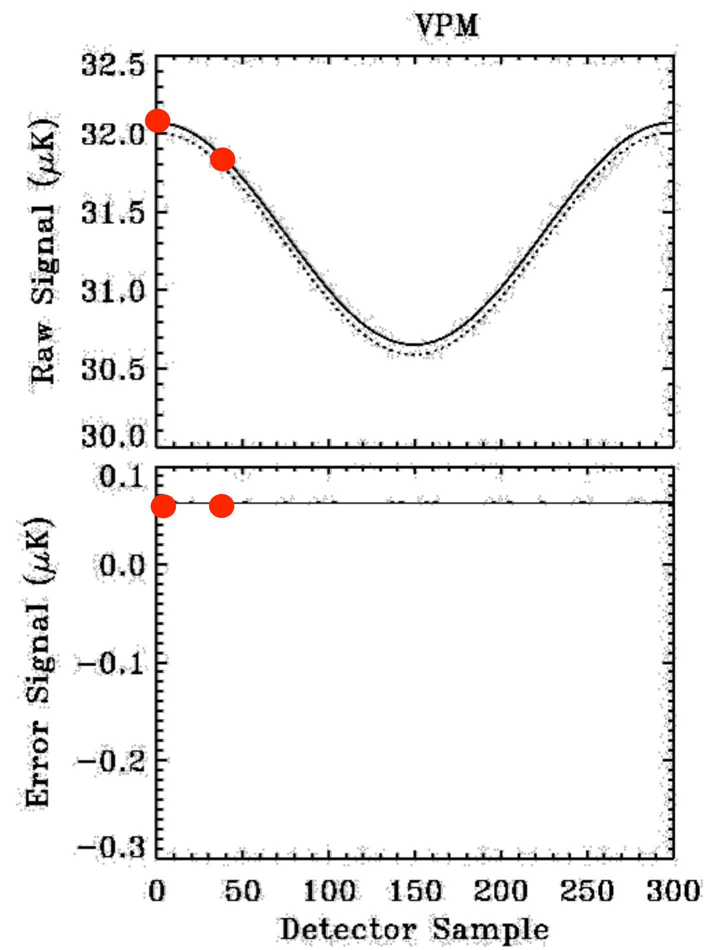



True Sky

After VPM Modulation

VPM:
Q/U mixing
but
Q/V modulation



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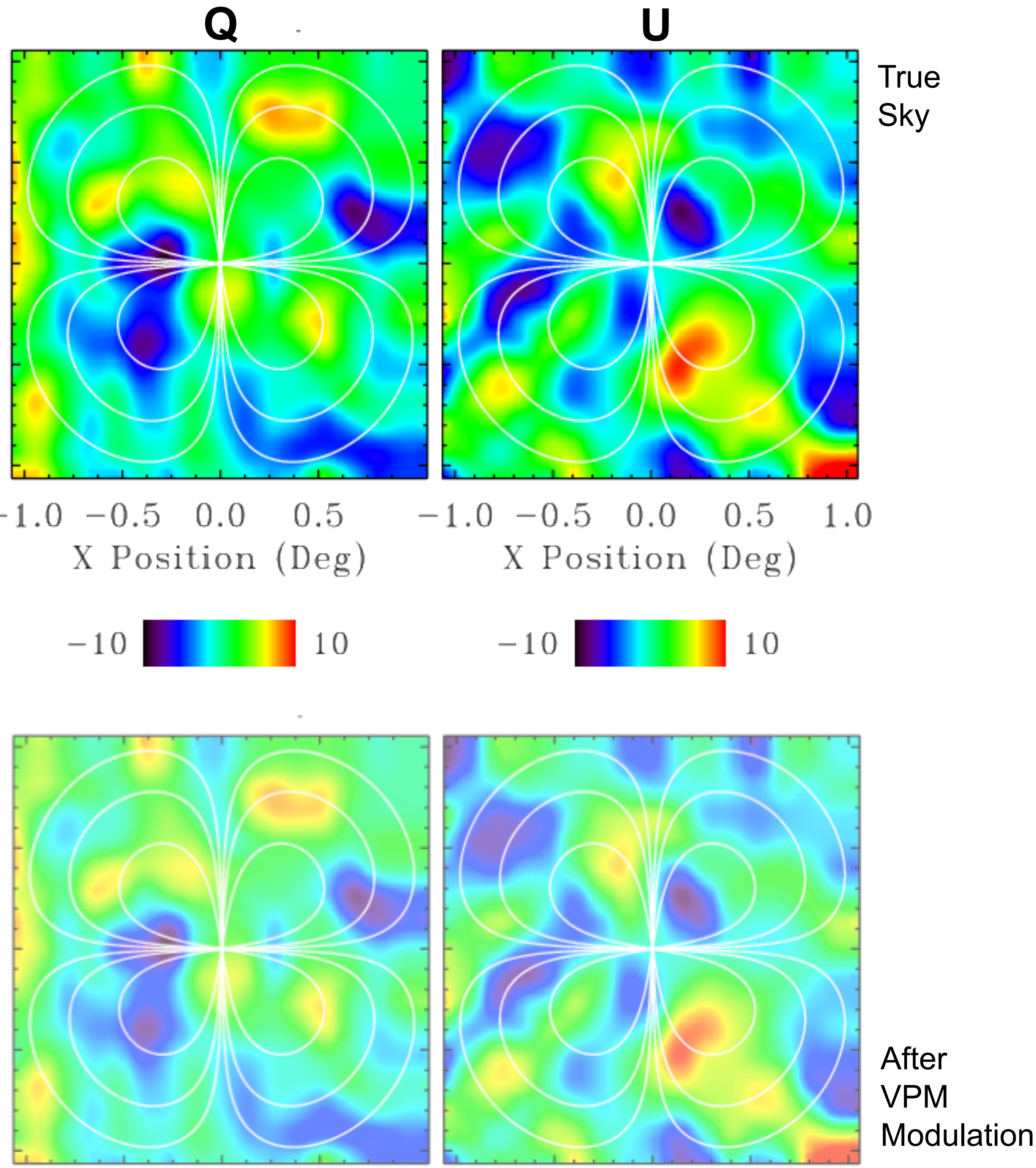


VPM:
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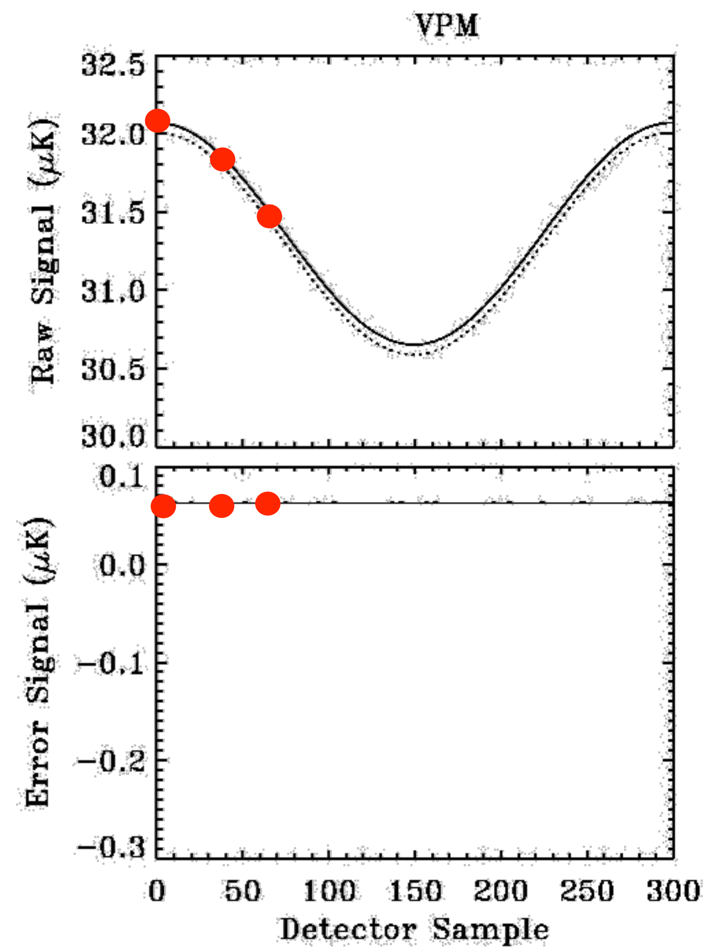

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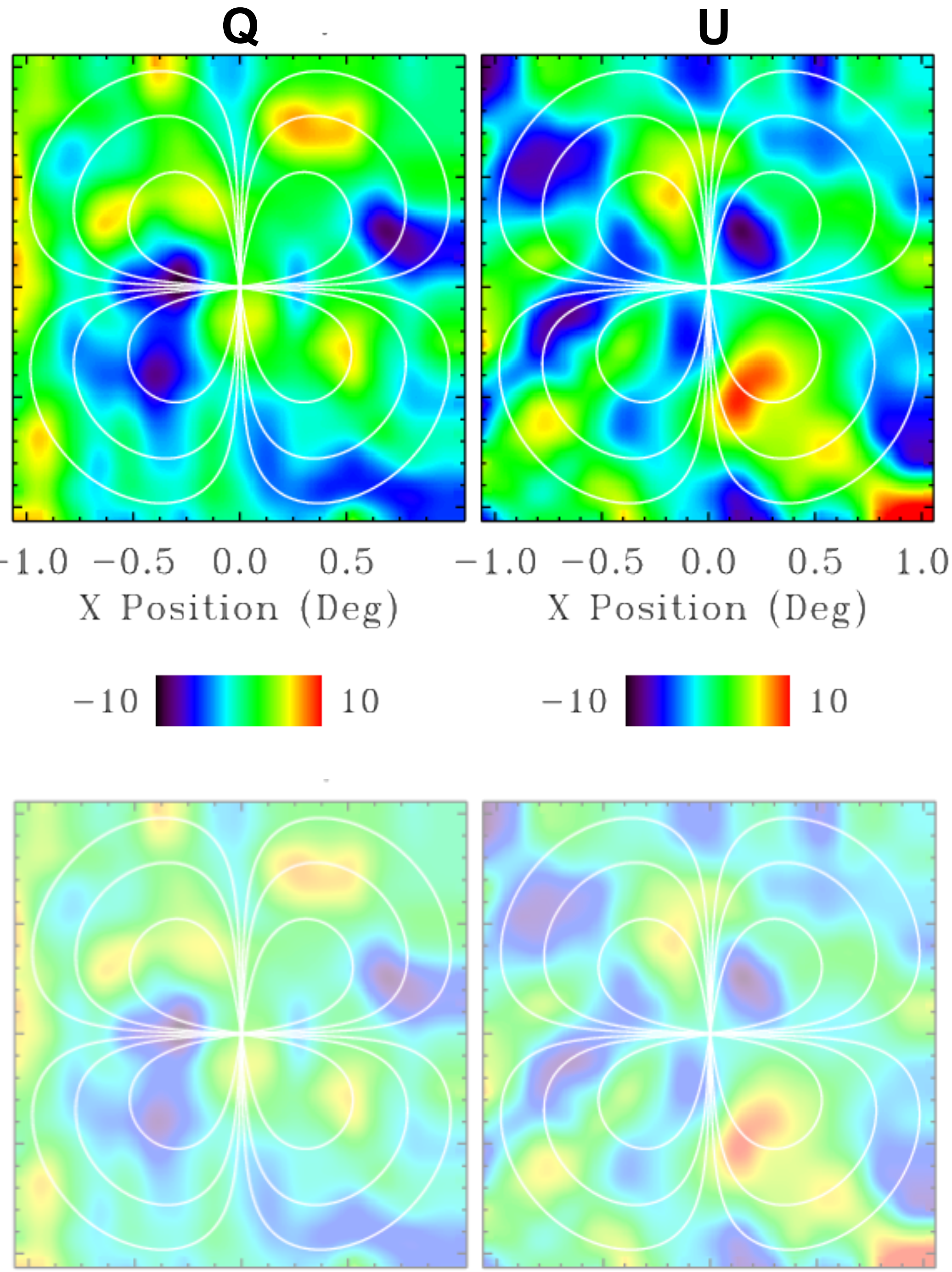
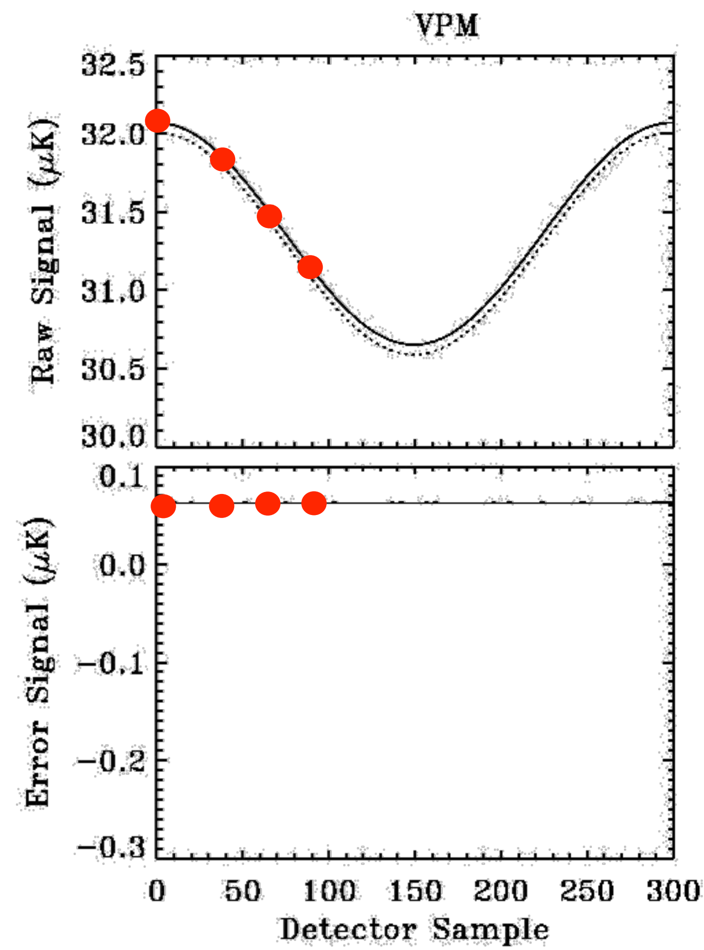



True Sky

After VPM Modulation



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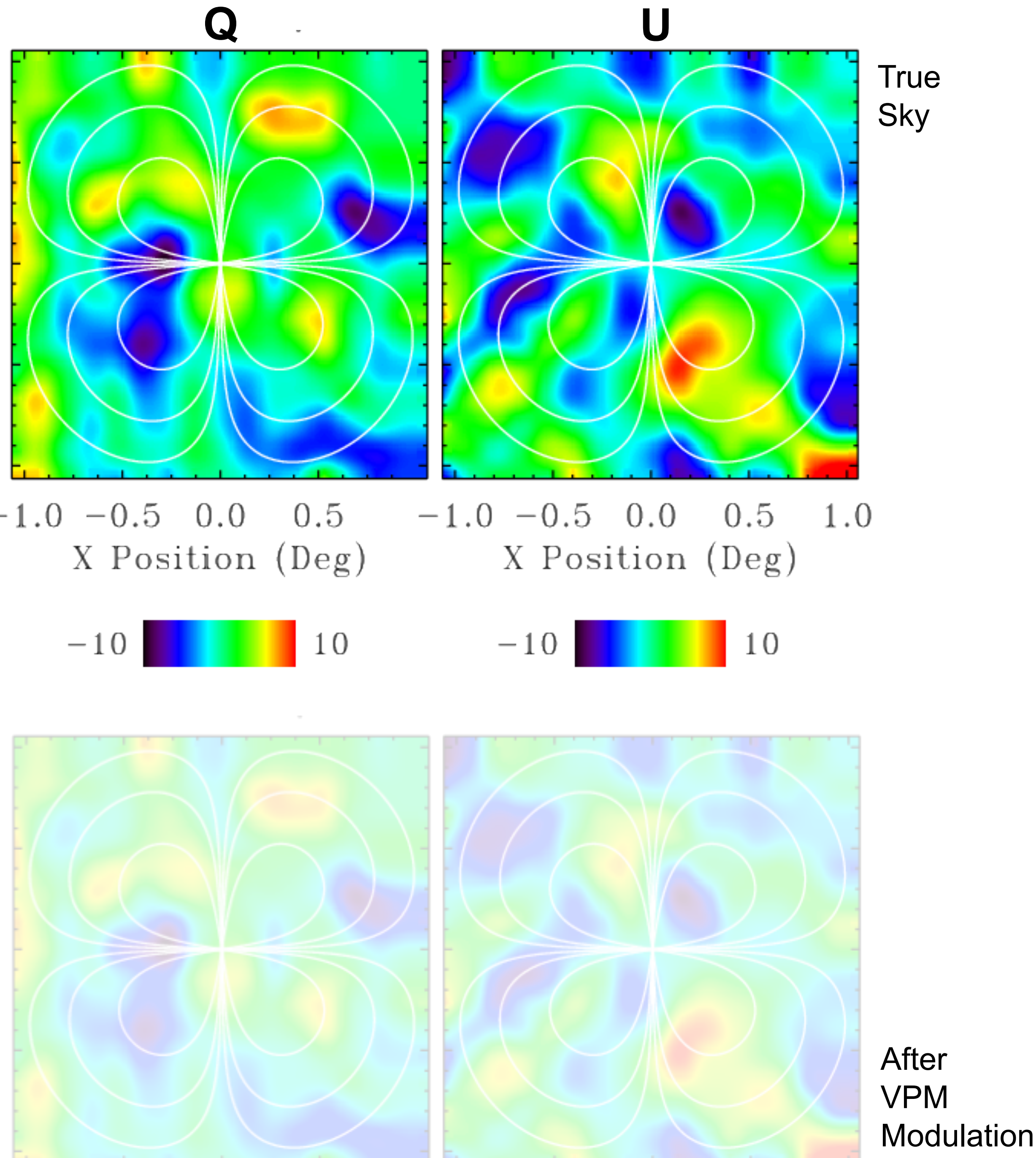
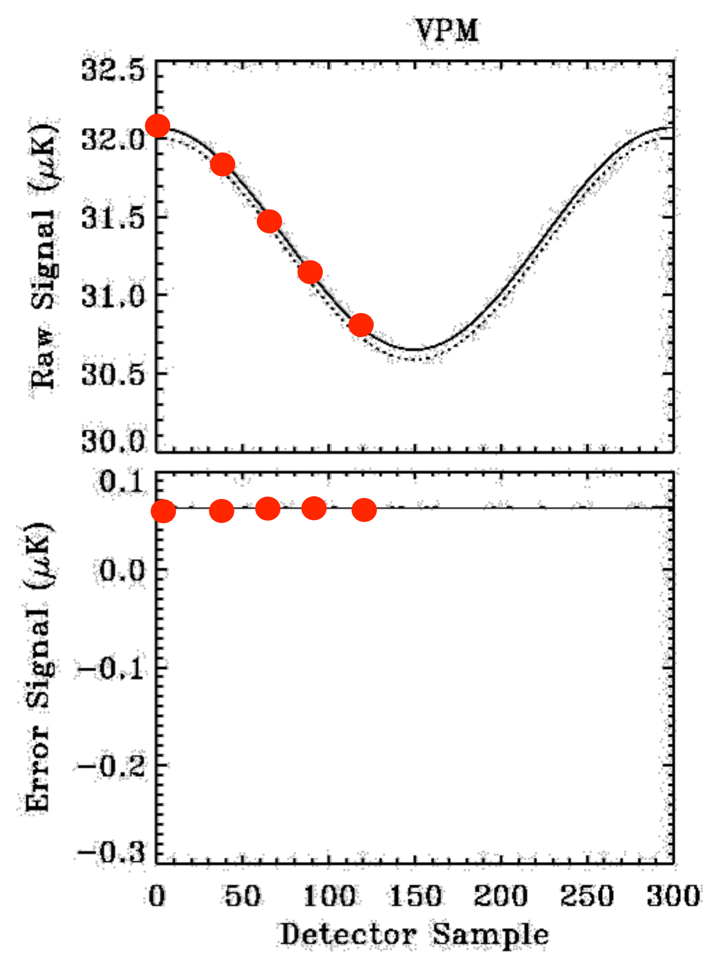



VPM:
Q/U mixing
but
Q/V modulation



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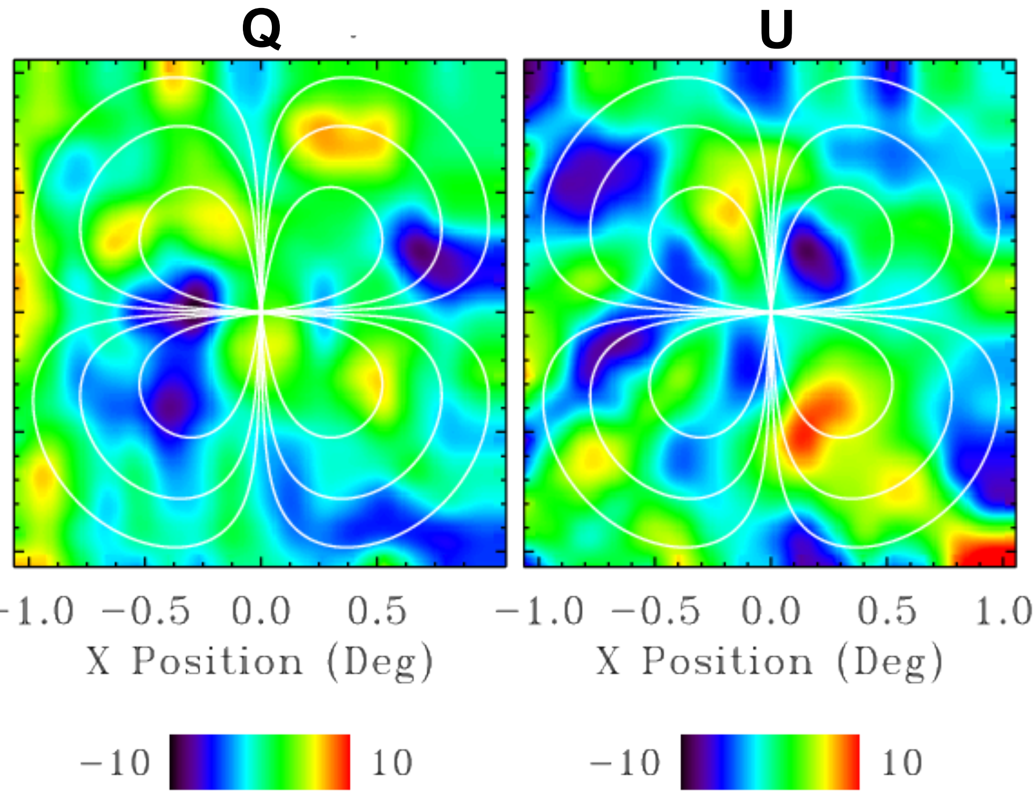


True Sky

After VPM Modulation

VPM:
Q/U mixing
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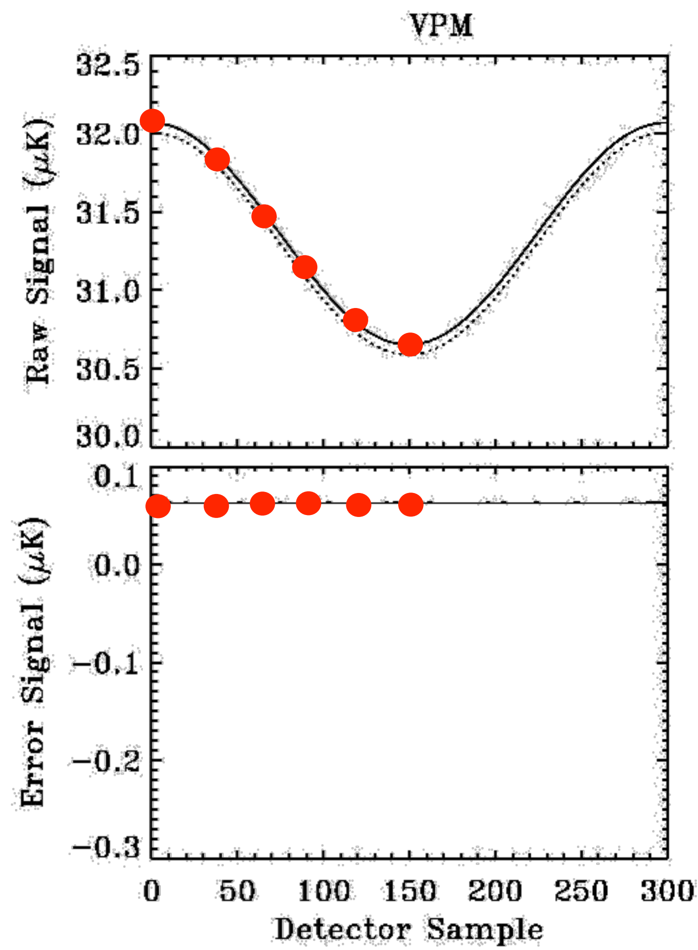

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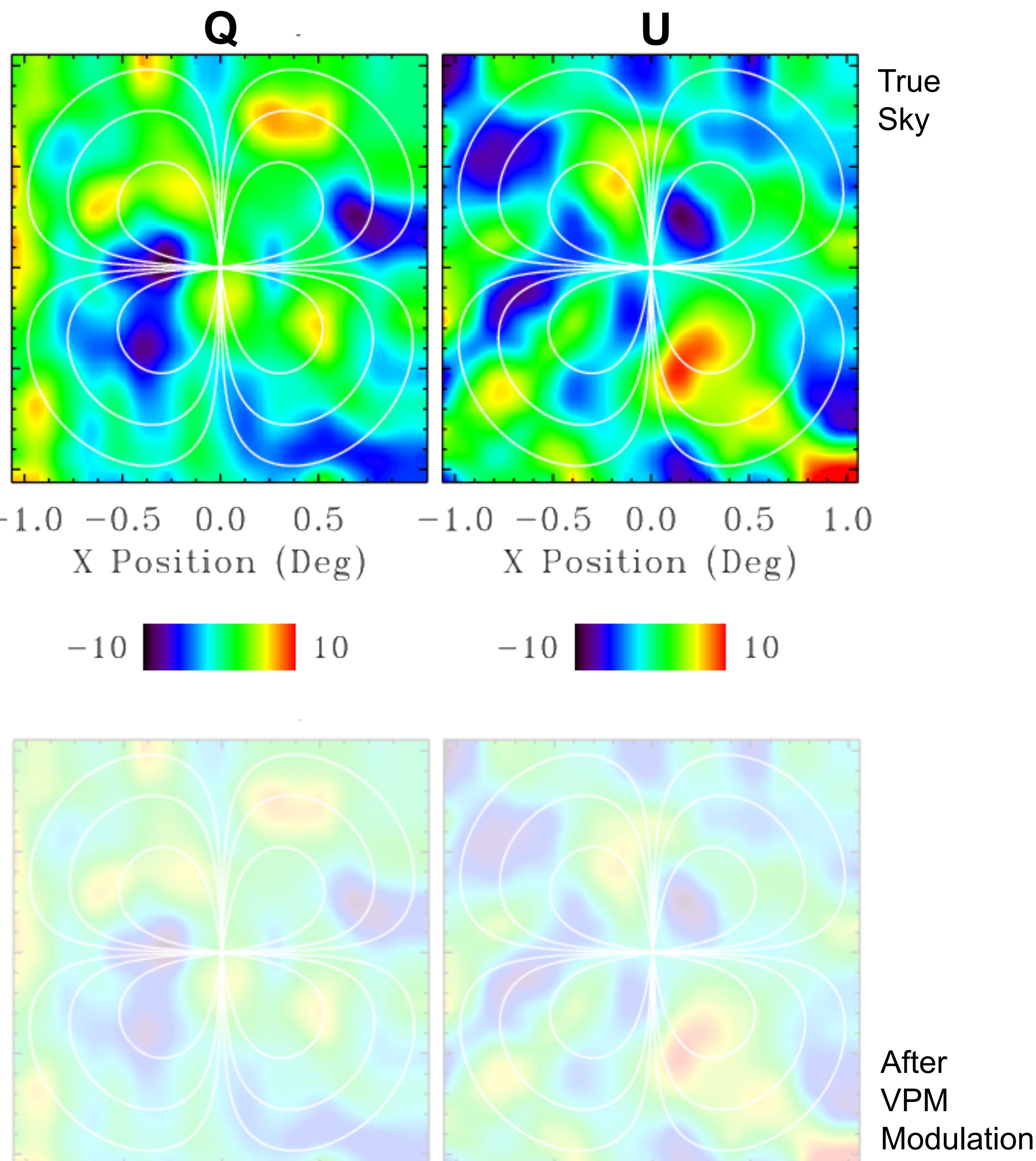


VPM:
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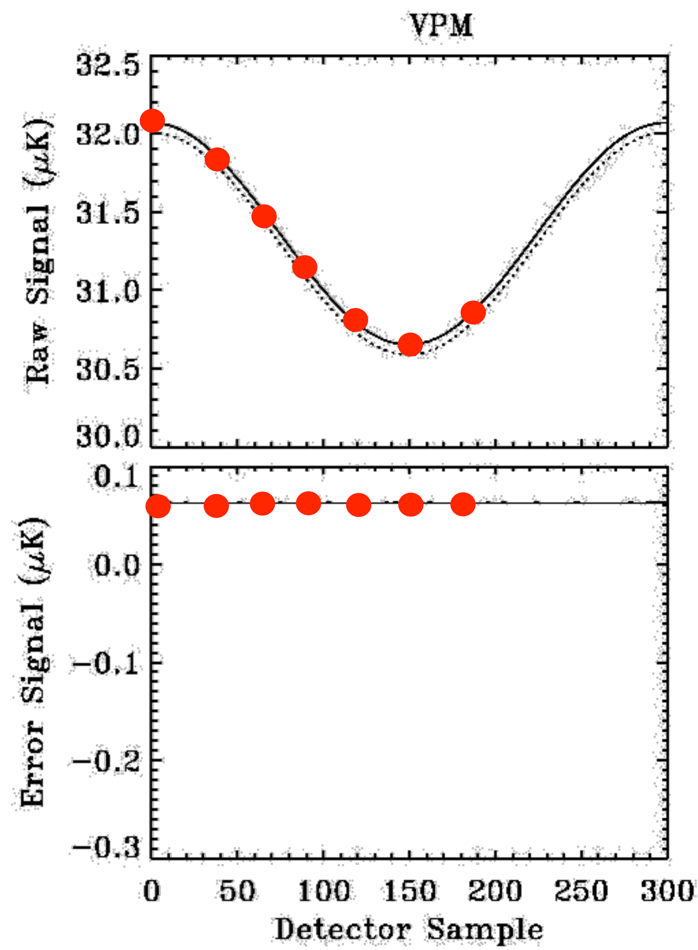

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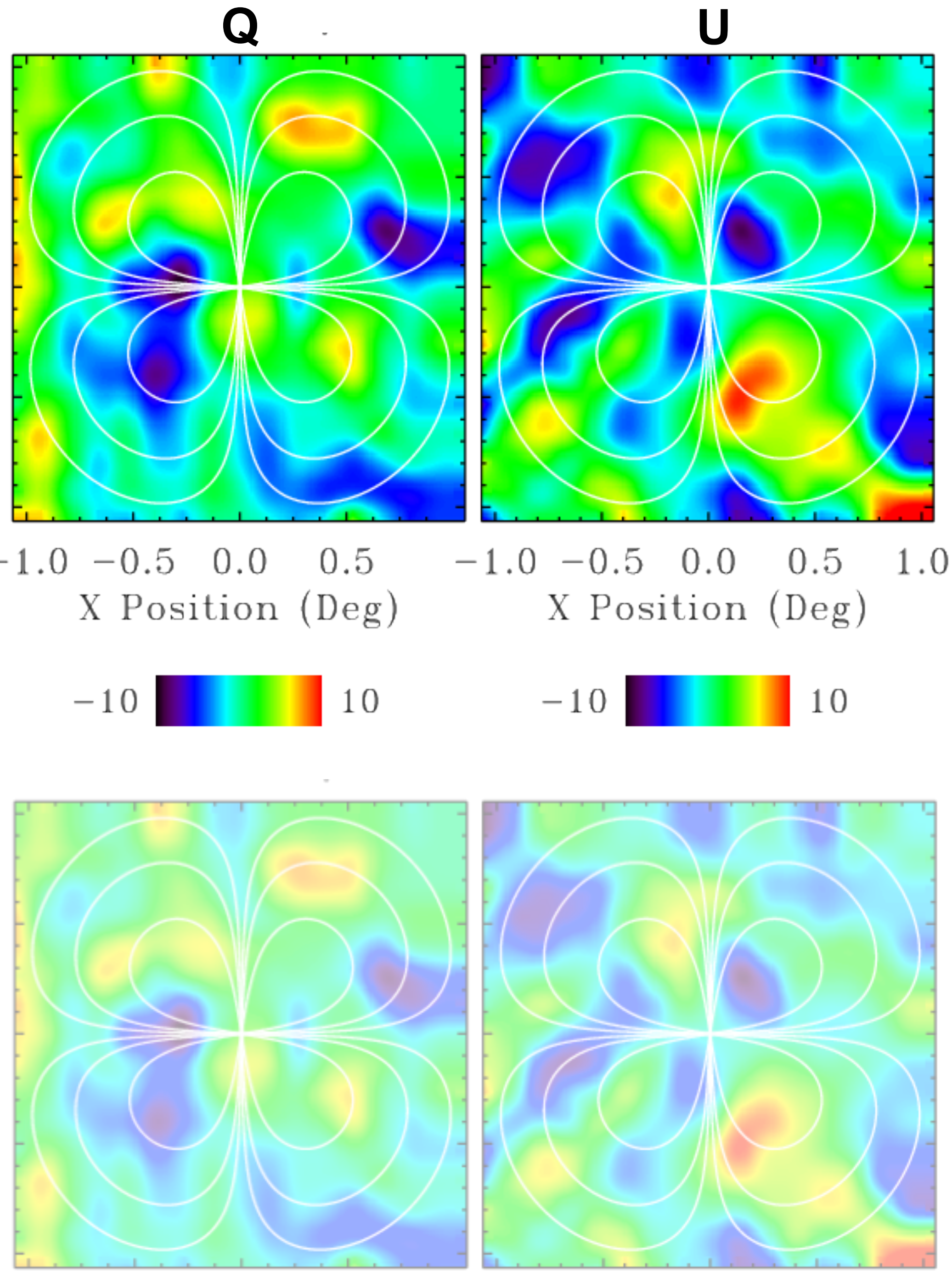
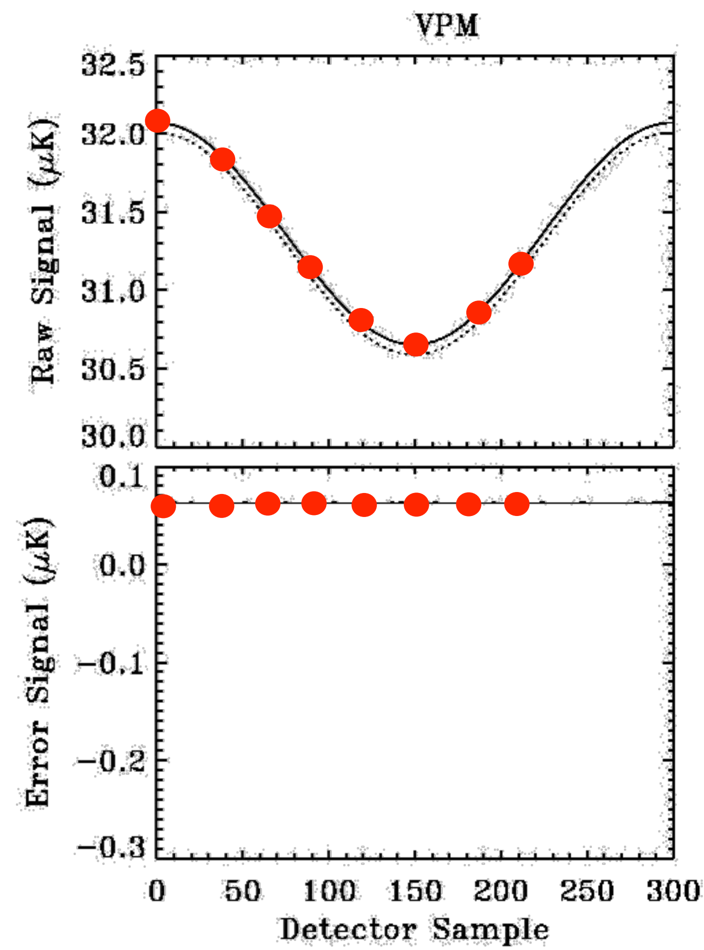



True Sky

After VPM Modulation

## VPM:
## Q/U mixing
## but
## Q/V modulation



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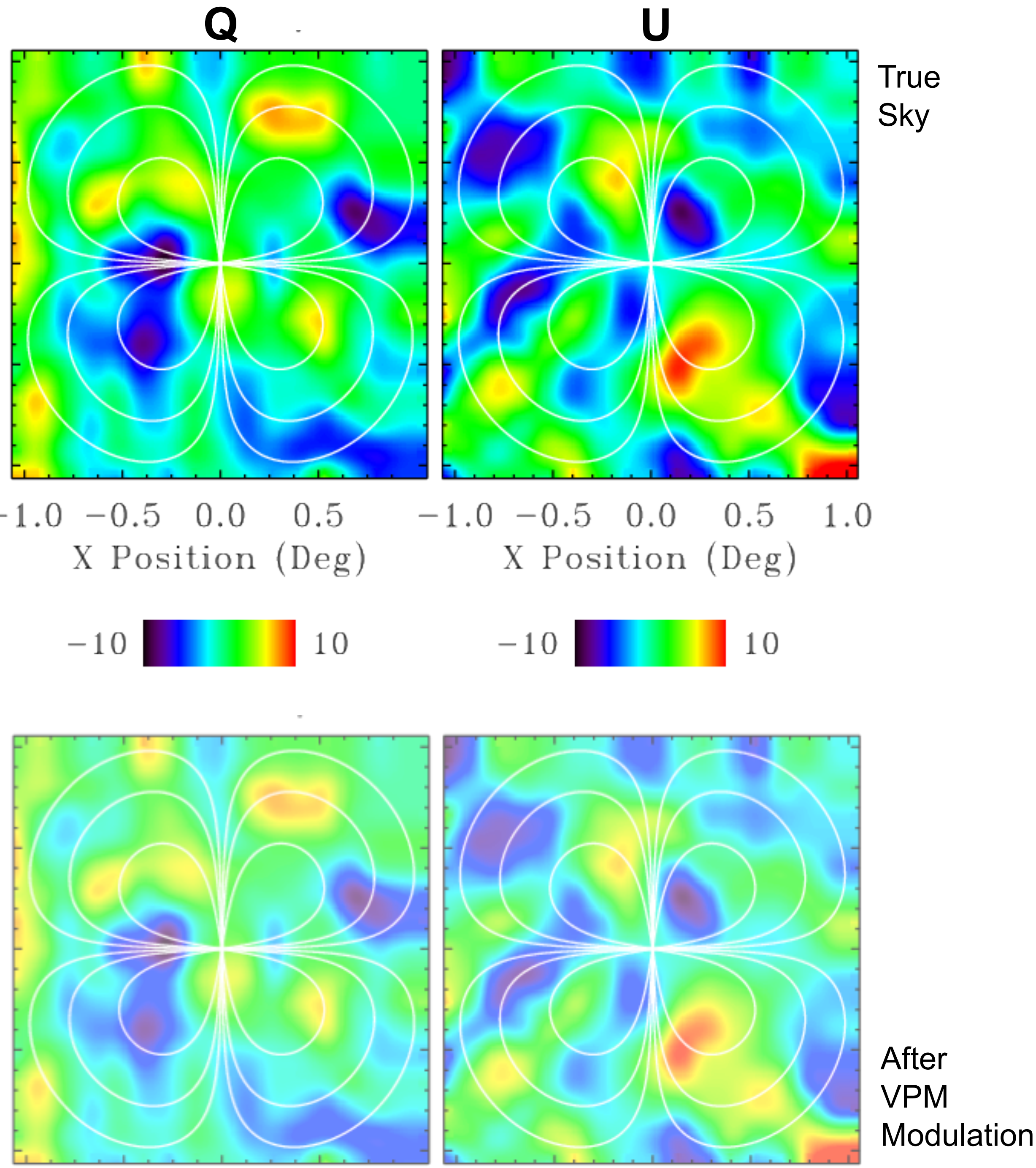


VPM:
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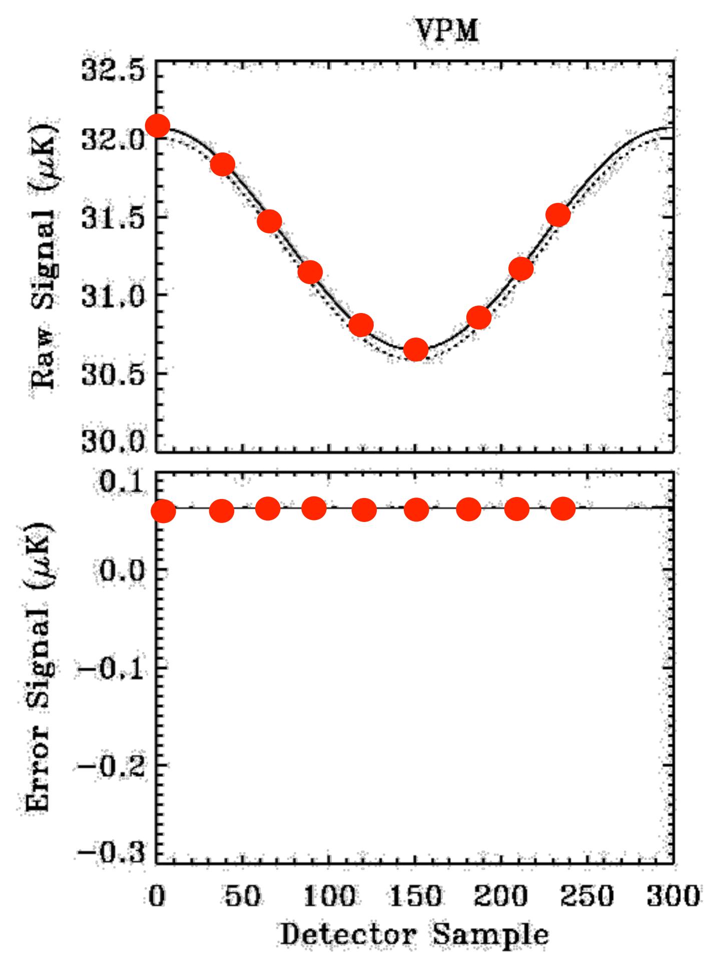

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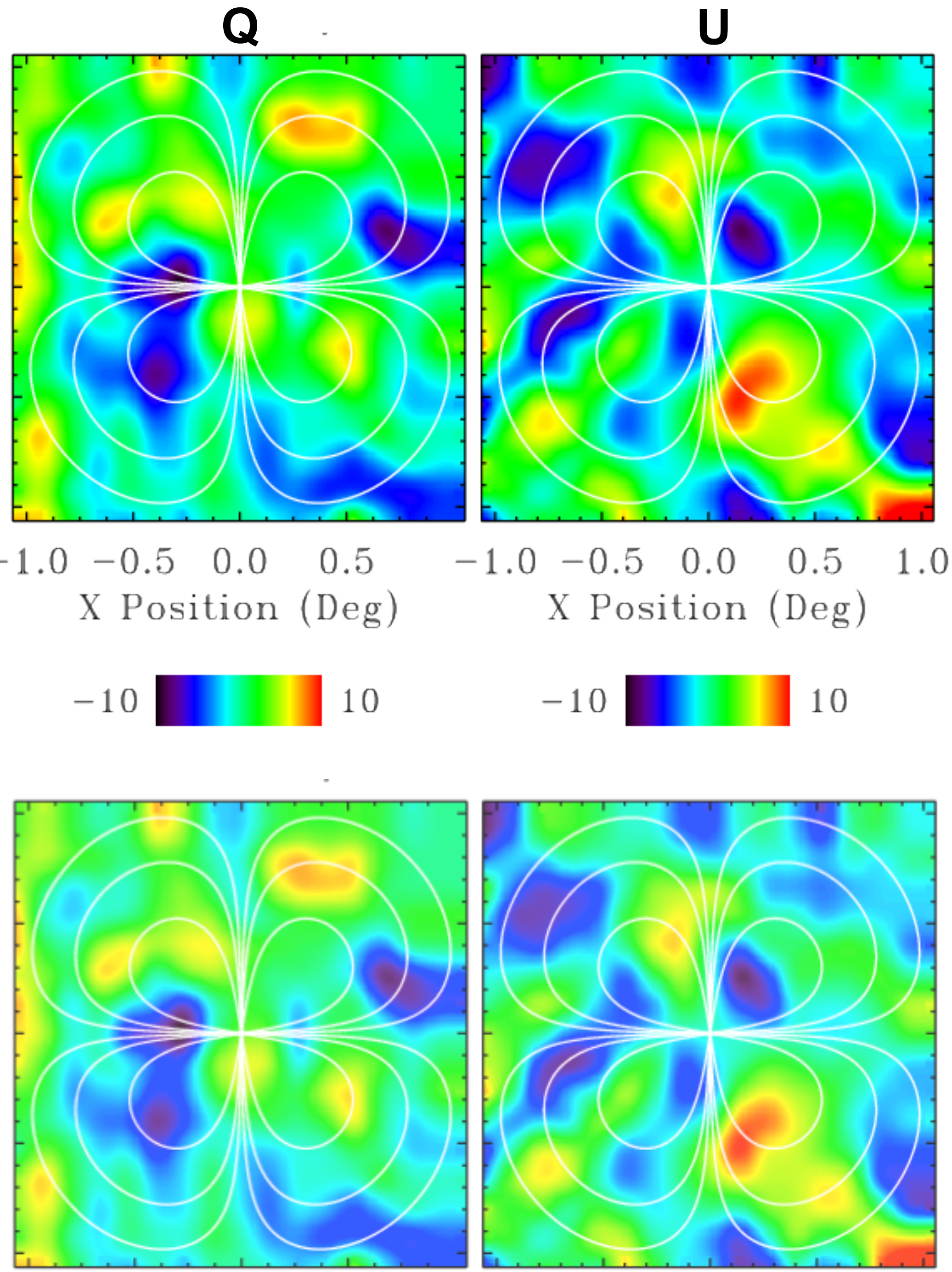


True Sky

After VPM Modulation

VPM:
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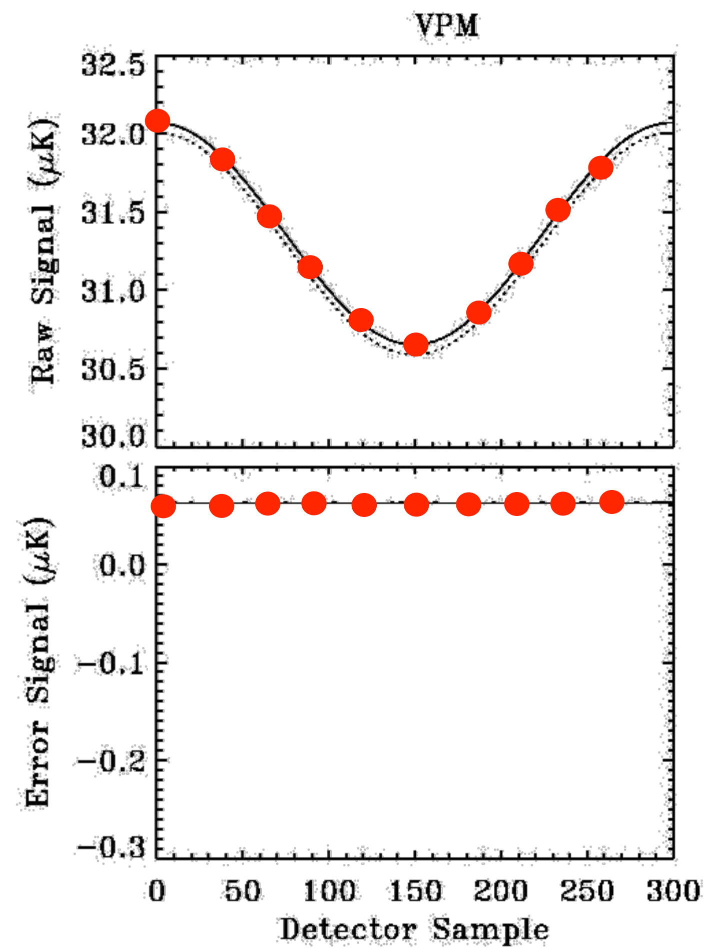

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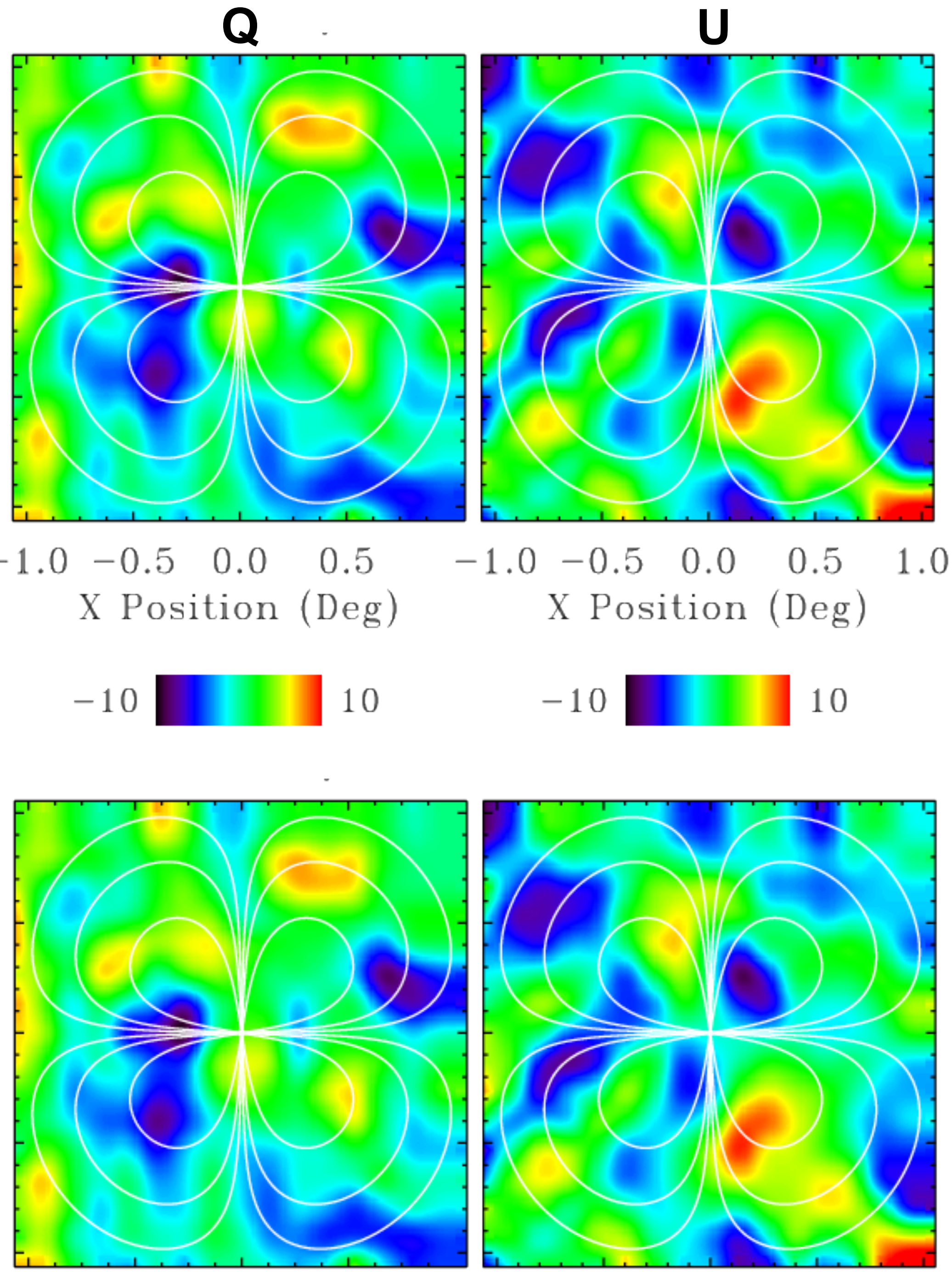


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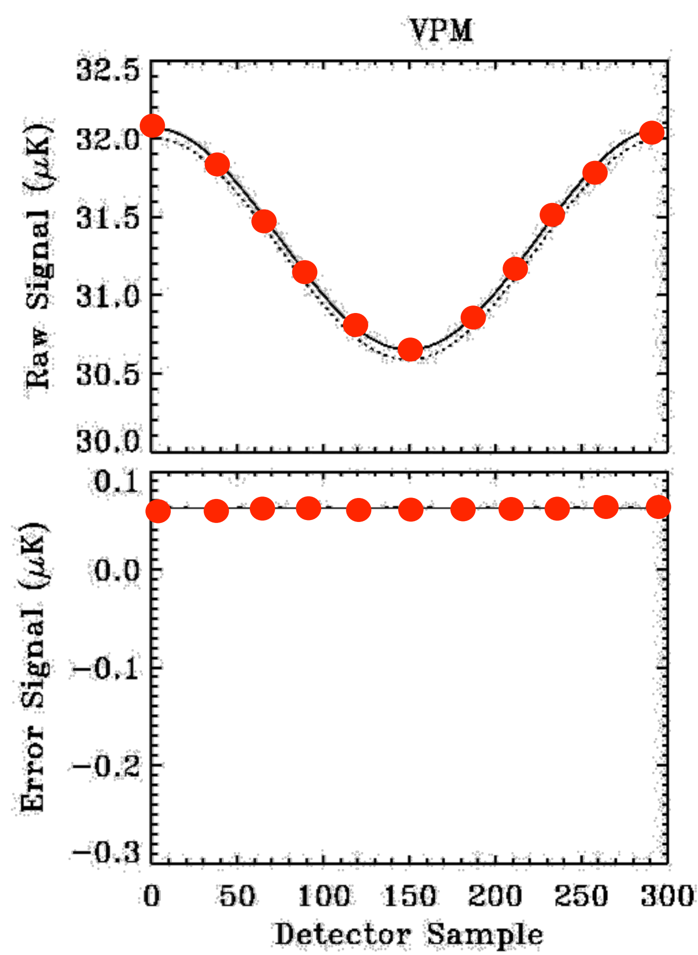


# VPM Advantages


**Minimizes a whole range of systematic errors**

- Q↔V modulation distinct from Q↔U (E↔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**

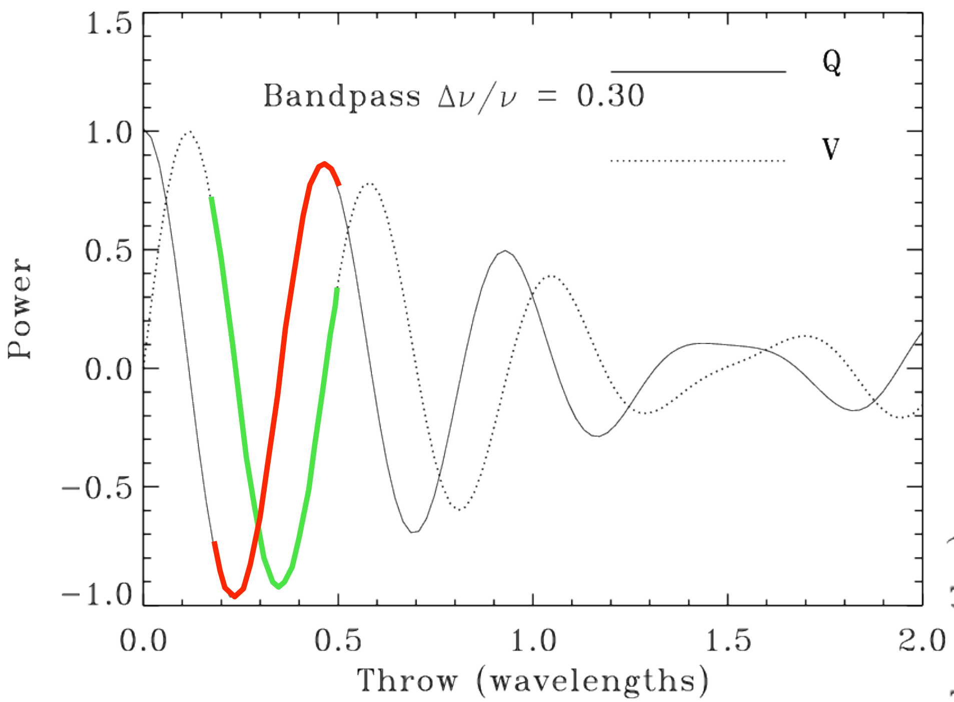
- Small linear translation instead of large angular rotation
- Simple cooling path to grating and mirror
- Vary mirror sweep to vary Q/V sampling
- Non-ideal effects are computable from first principles

Plus: Get full-sky map of Stokes V

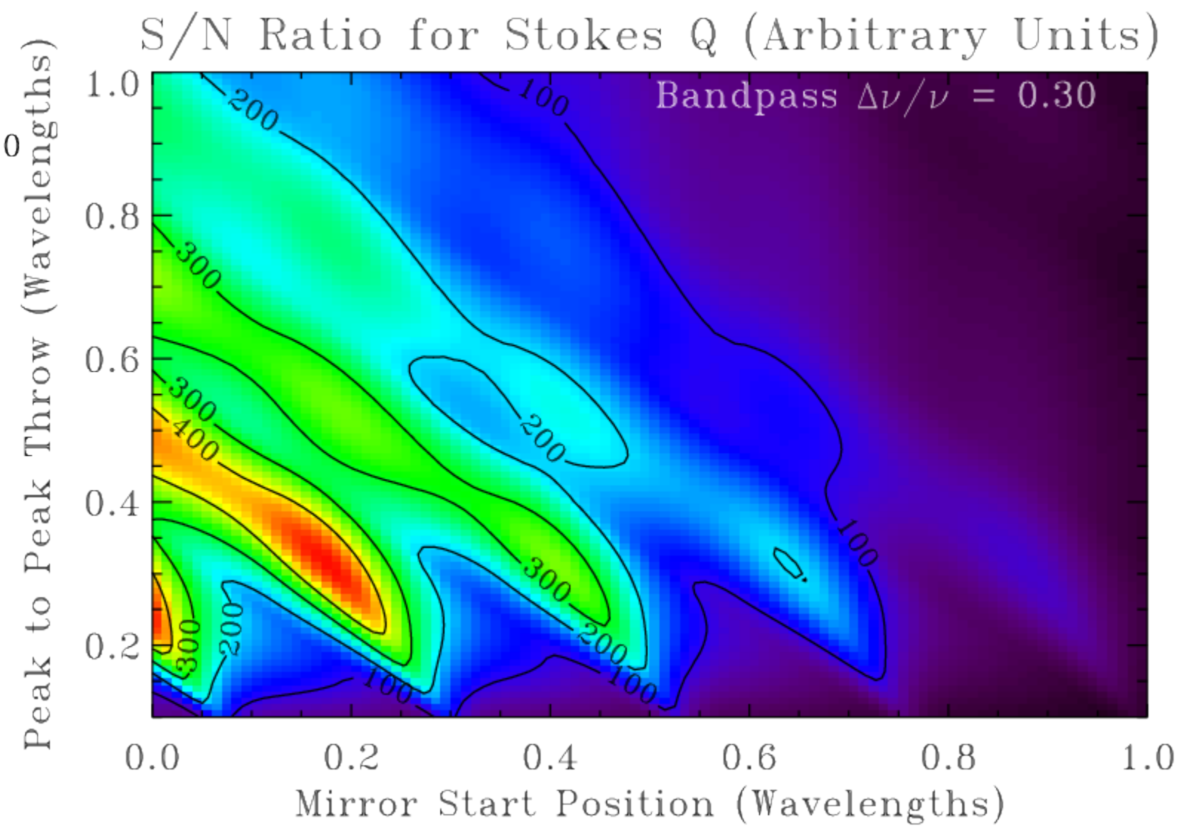
***Four orders-of-magnitude improvement!***

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

# VPM Stroke vs Efficiency




Sine sweep from –Q to +Q
70% Q
30% V




Full-sky maps in Q, U, and V
- Clean test for systematics
- Limit non-standard physics