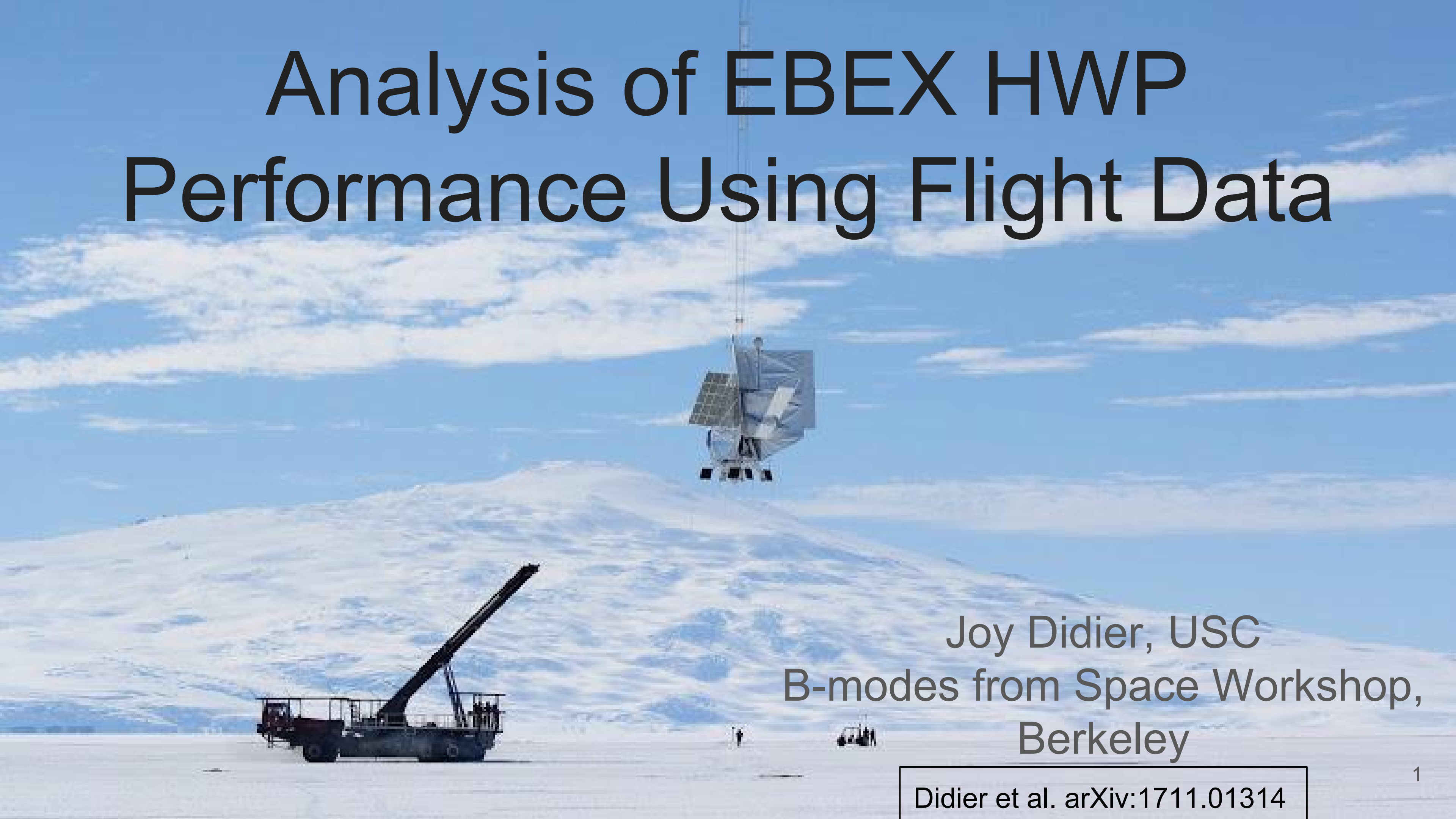
Analysis of EBEX HWP Performance Using Flight Data



Joy Didier, USC

B-modes from Space Workshop, Berkeley

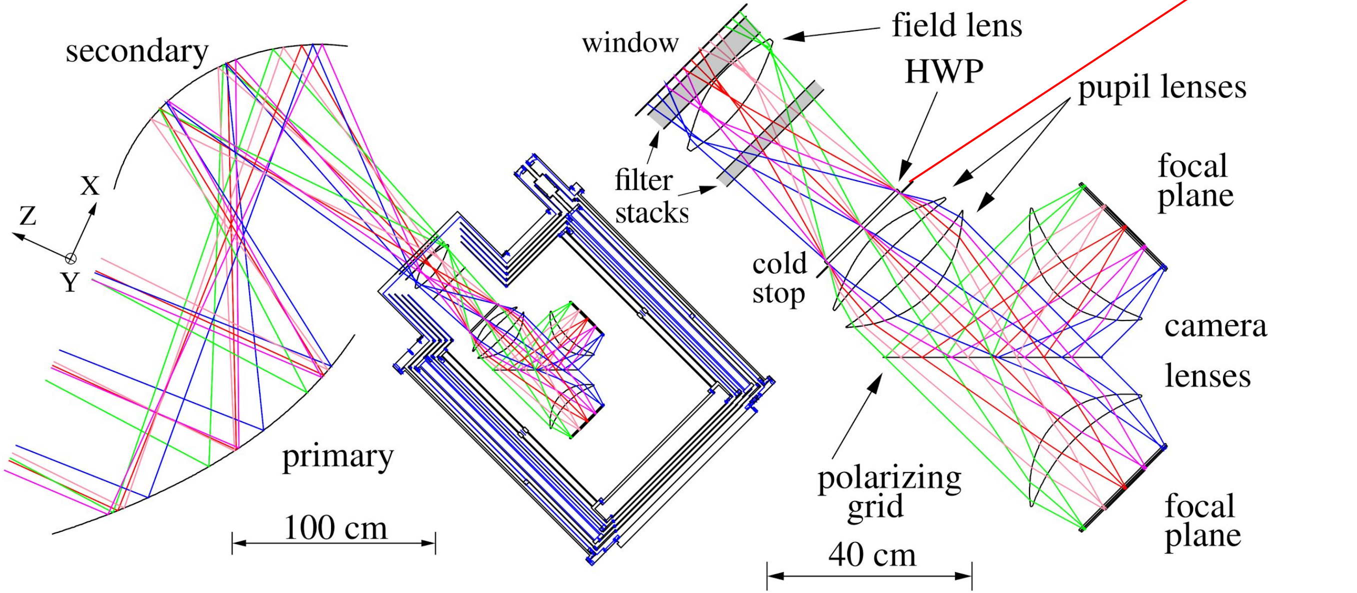
Didier et al. arXiv:1711.01314

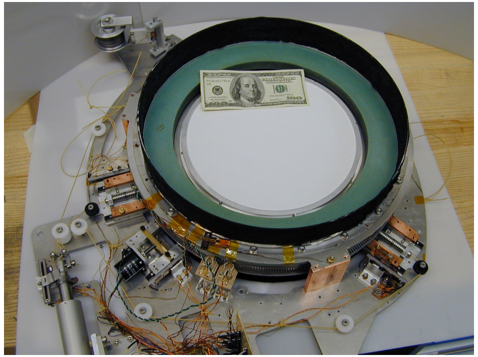
Why use a continuously rotating HWP?

- Modulate polarization signal → away from low frequency noise
- Single detector measures Q & U simultaneously → avoid pair differencing systematics
  - differential beam ellipticity
  - differential gain
  - differential pointing
- Increase coverage of parallactic angle
- Minimize Instrumental Polarization if HWP early in optical chain
- But…
  - LARGE HWP Synchronous Signal (HWPSS) at harmonics of the rotation frequency
  - Other systematic effects such as SED dependant polarization rotation angle, excess load if warm, polarization modulation efficiency, other...

Today's talk

The EBEX Polarimeter





24 cm diameter HWP

EBEX Optics, Receiver and Polarimetry
arXiv:1703.03847

- 5 stack Sapphire broadband HWP @ 4 K aperture stop continuously rotating at 1.24 Hz
- EBEX was the first CMB experiment to use an achromatic stack for the HWP
- First use of a superconducting magnetic bearing (SMB) at 4K

Data Model with a HWP

HWP Angle

$$D_t = \frac{1}{2}\left(I_t^{sky} + \epsilon Q_t^{sky}\cos(4\gamma_t - \Phi_t) + \epsilon U_t^{sky}\sin(4\gamma_t - \Phi_t)\right)$$

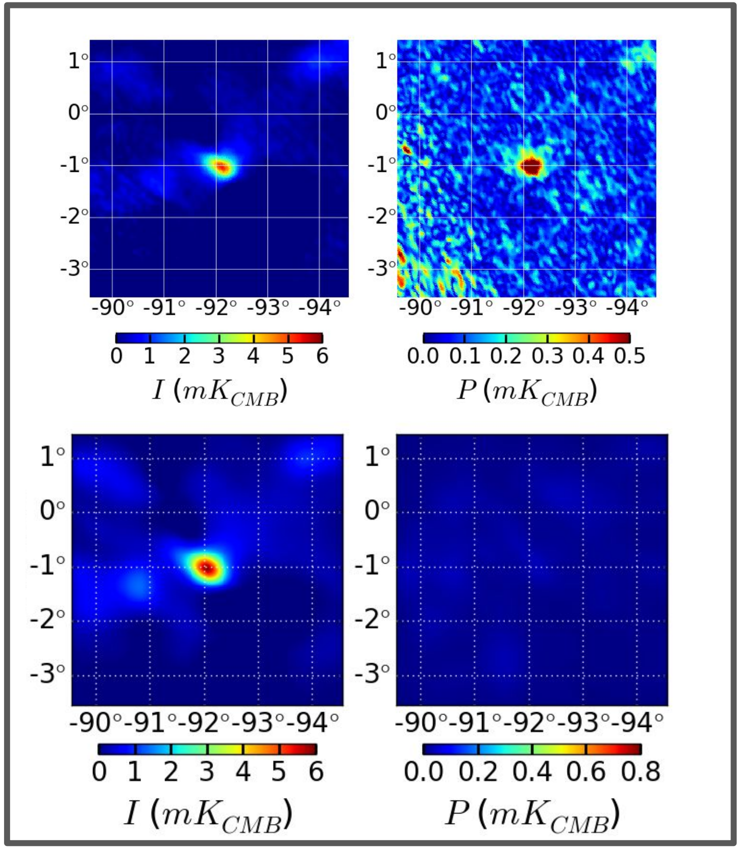
$$+ A(\gamma_t) + n_t$$

$$A(\gamma_t) = \sum_{j=0}^{j=\infty} \underbrace{A_j \cos(j\gamma_t - 2\alpha_j)}_{\text{stationary}} + \underbrace{A'_j I_t^{sky} \cos(j\gamma_t - 2\alpha'_j)}_{\text{scan modulated}}$$

- $A(\gamma)$ = HWP Synchronous Signal (HWPSS)
- A_4:
  - from optics sky side of HWP:
    - polarized emissions (ex: mirror)
    - Optics unpolarized emission * instrumental polarization
  - Polarized 1/f noise if A_4 varies with time (ex: temperature changes, gain variations)
- A'_4: Intensity Coupled Polarization (ICP)

Intensity Coupled Polarization (ICP) in EBEX Maps

RCW 38



EBEX

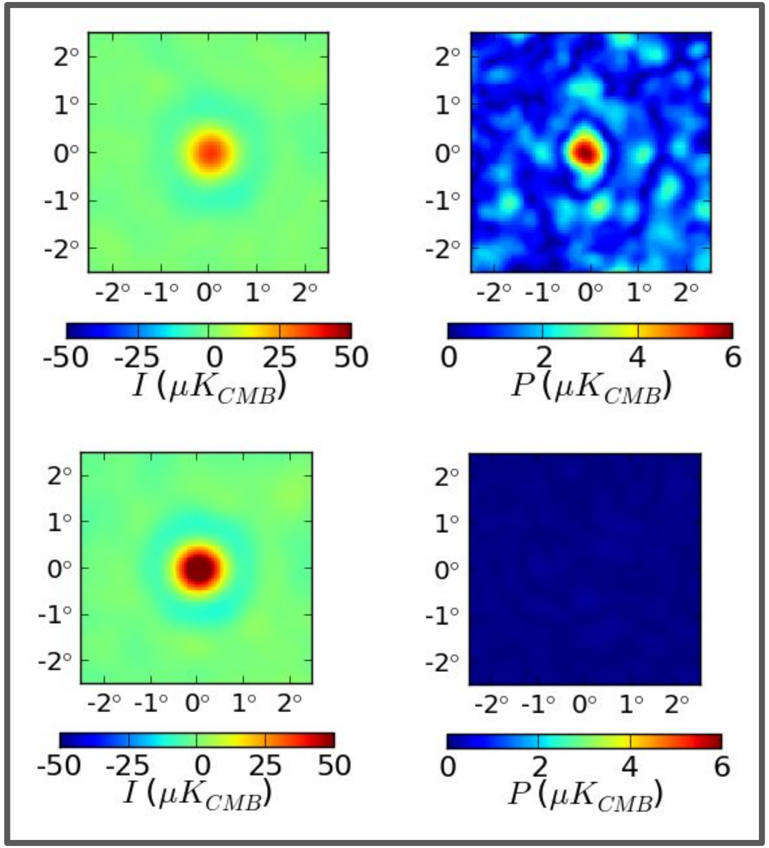
↔

~ 10% ICP

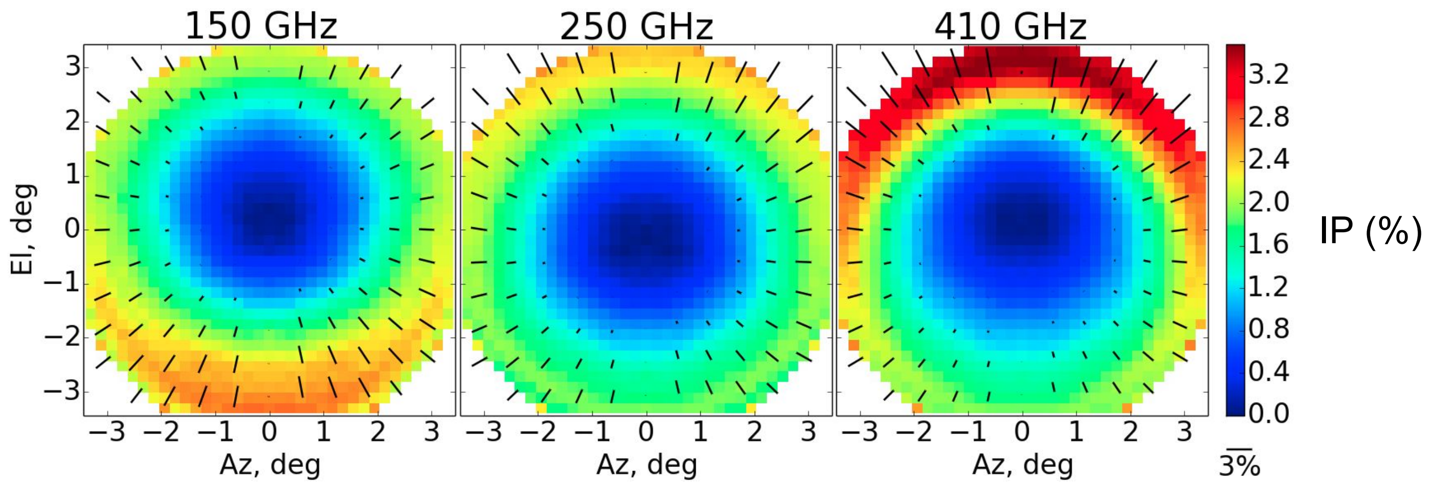
Planck

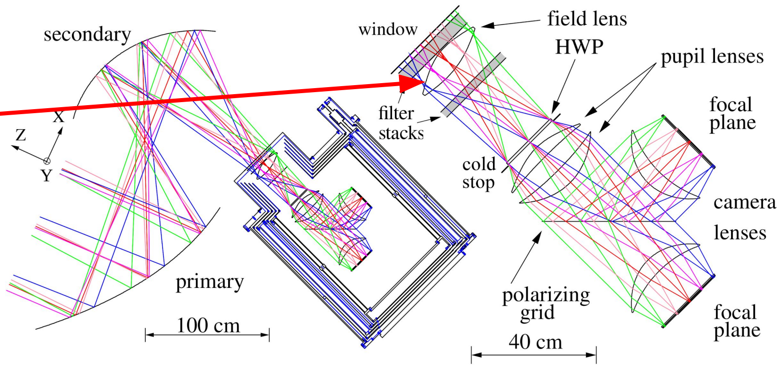
↔

CMB Stacked Hot Spots



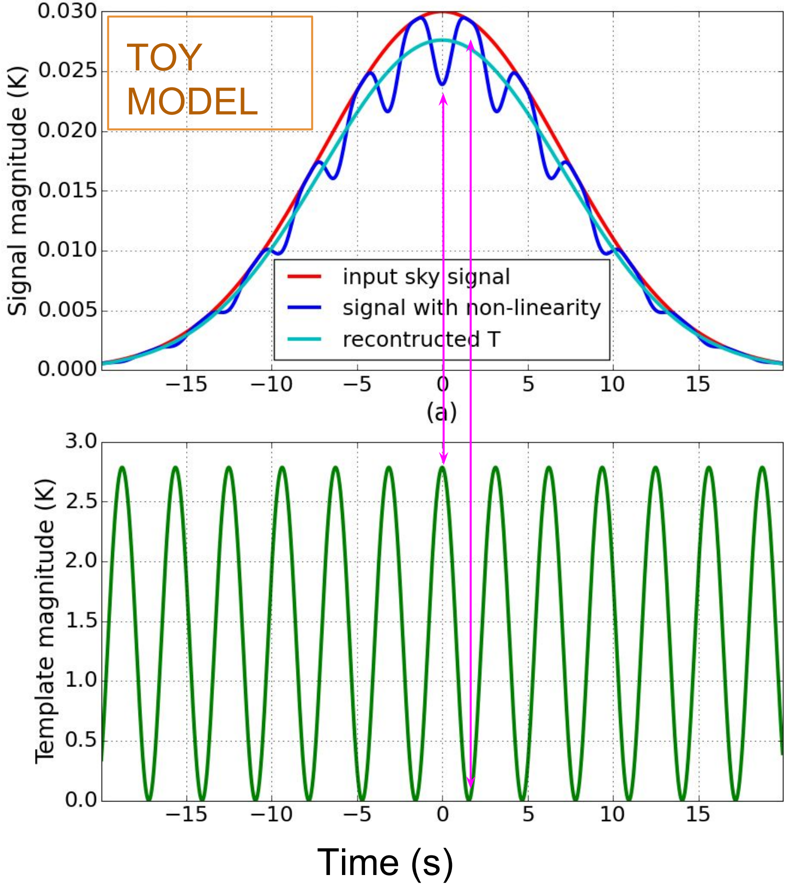
Sources of ICP: Instrumental Polarization (IP)





- Code V EBEX model
- IP dominated by field lens
  - Max IP of 2.7% at 150 GHz
  - Radial pattern, larger IP at edge of focal plane (FP)
- Note that radial IP doesn't average down with boresight rotation!

Sources of ICP: A4 & Detector Non-Linearity



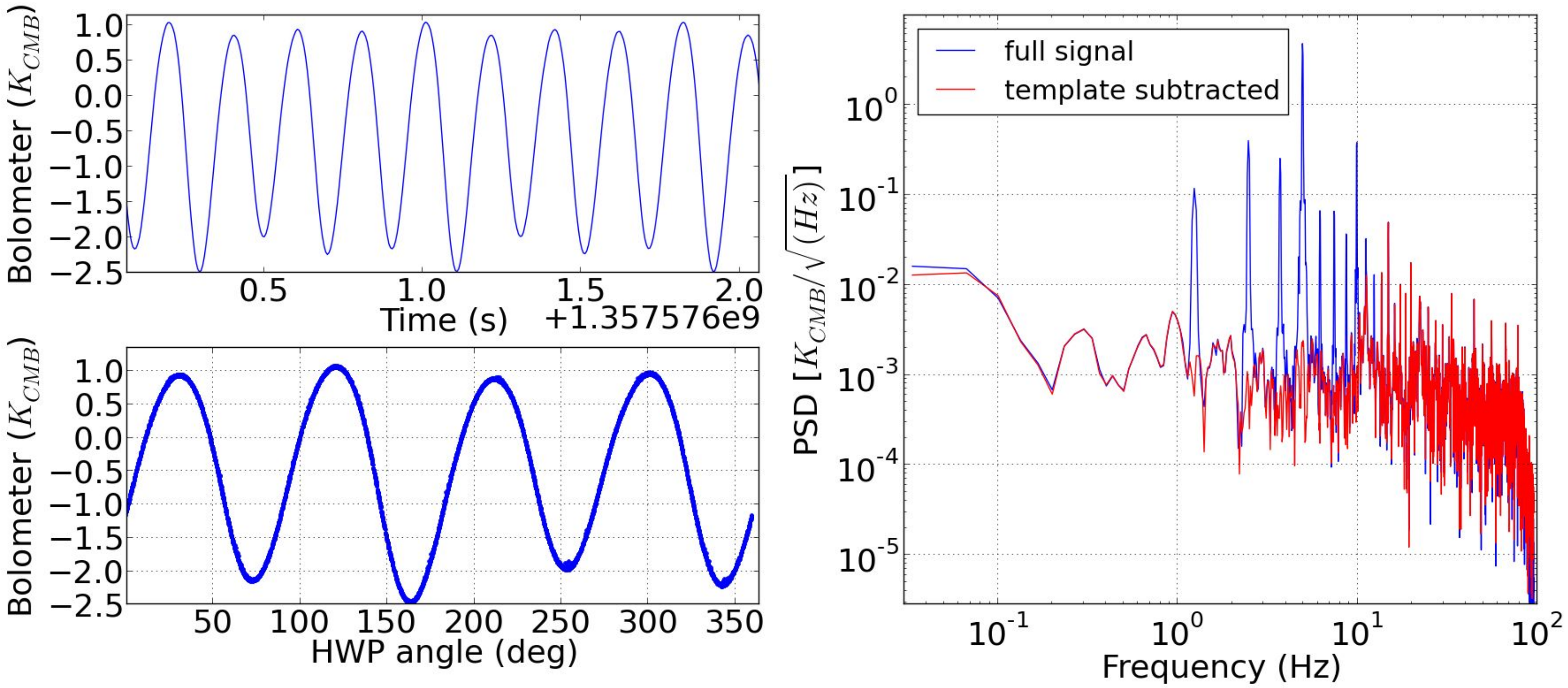
TOY MODEL:

$$D_t = I_t^{sky} + A_4 \cos(4\gamma_t - 2\alpha_4).$$

$$D_t^{NL} = f^{NL}(D_t) = D_t - K D_t^2$$

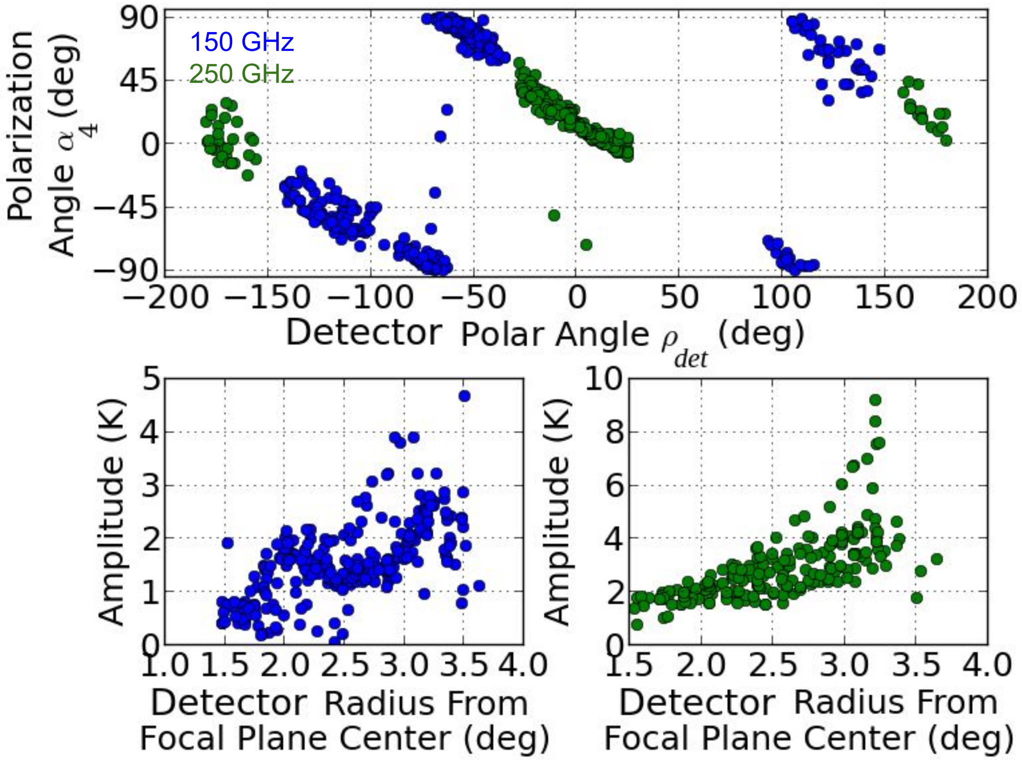
- NL decreases incoming I by (1 - K*I)
- NL creates ICP with
  - polarization fraction 2 A_4*K
  - polarization angle = $\alpha_4 + \pi/2$
- NL creates higher harmonics in the HWPSS

Flight Data



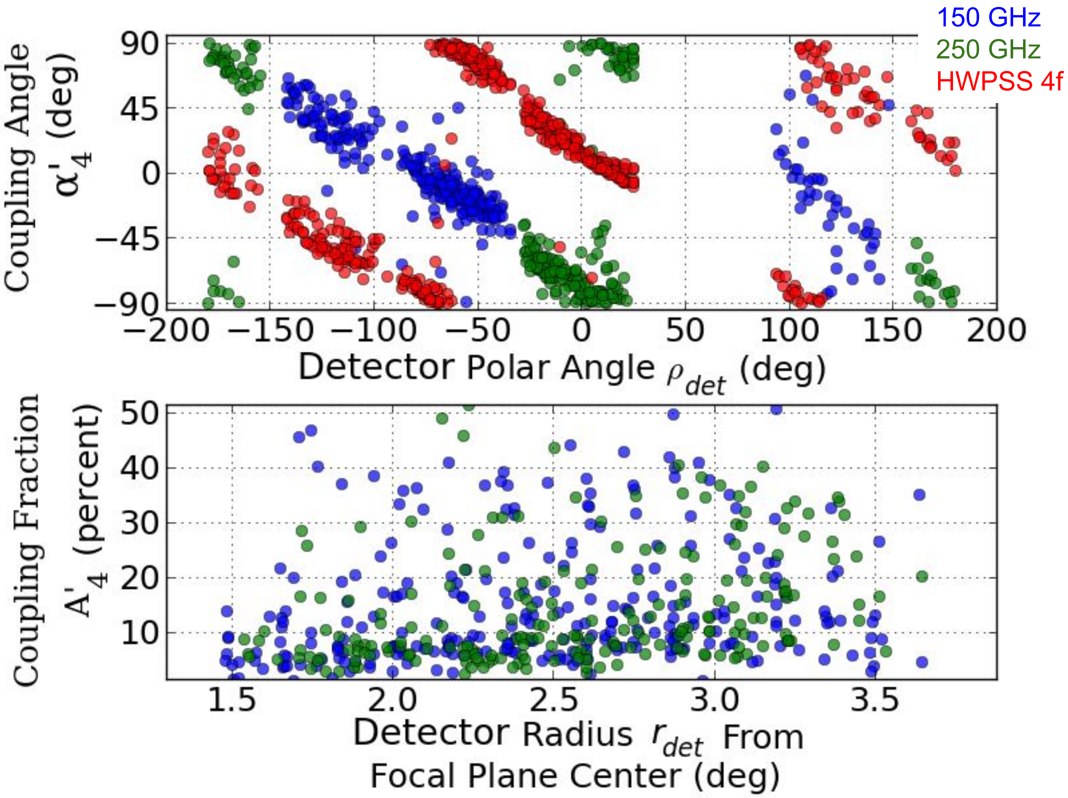
- Conversion @150GHz: 3.24 mK_CMB/ fW power incident on telescope (A4 ~ 0.6 pW)

EBEX Stationary 4f HWPSS: FP dependance



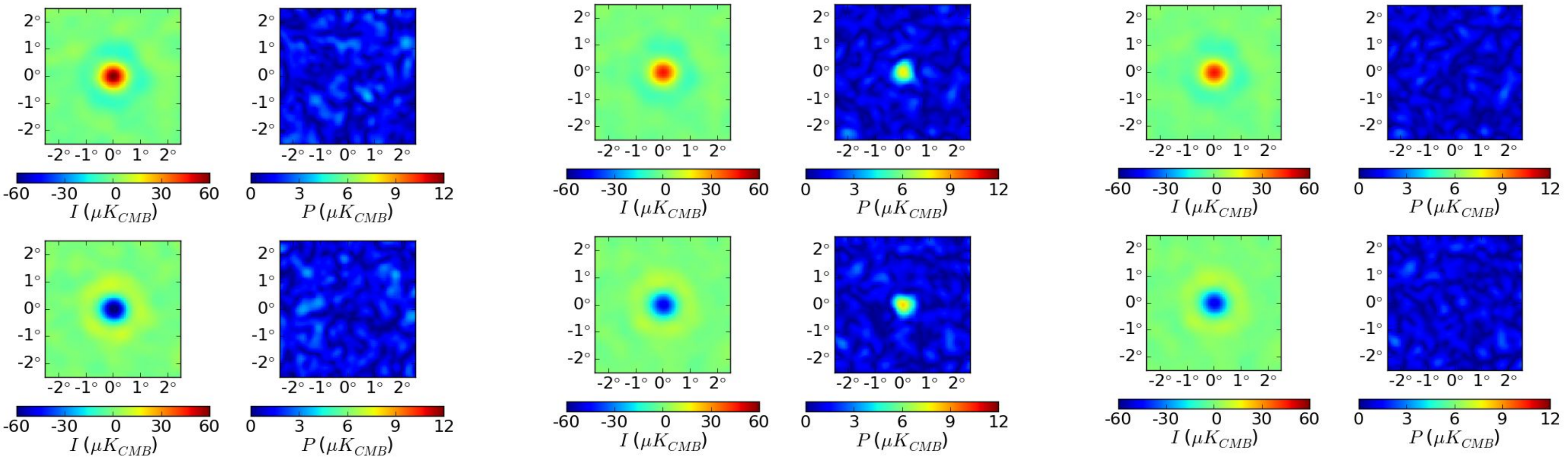
- A4 measured 570 fW
- A4 has two sources:
  - Polarized mirror emissions:
    - Polarization along Q
    - Estimated 85 fW
  - Field lense IP
    - Radial Polarization
    - Estimated 370 fW (with measured excess load)
- A4 variation with FP position shows field lens IP dominates.
- ICP:
  - if originate from IP, same polarization angle as A_4
  - if originate from NL, polarization angle offset by pi/2

Measuring ICP per detector



- <u>Single detector maps</u> used to calculate ICP fraction and angle, using Galaxy
- Other sources can be used, CMB too (but need single detector maps)
- Polarization angle of ICP offset from HWPSS A_4 angle by pi/2: this is from NL
- ICP fraction mode 7%, std 5.7% (larger than predicted IP)

Removing ICP: Simulations with noise (inst frame)



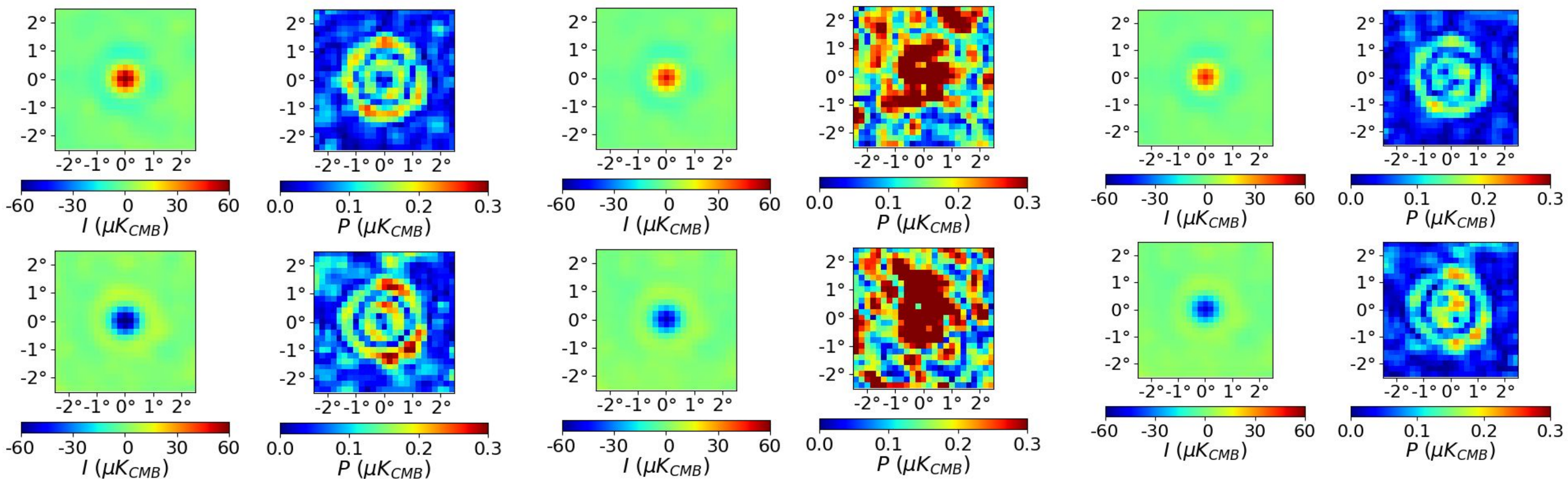
Reference: no NL

NL added

ICP removed

- Note: NL function used to simulate measured from ratio of A8 to A4 provides similar leakage (10%) to what observed in data
- 95% ICP removed
- Note ICP removed is different than correcting for NL (cf dimmed I and P)

Removing ICP: Simulations (sky frame)



Reference: no NL

NL added

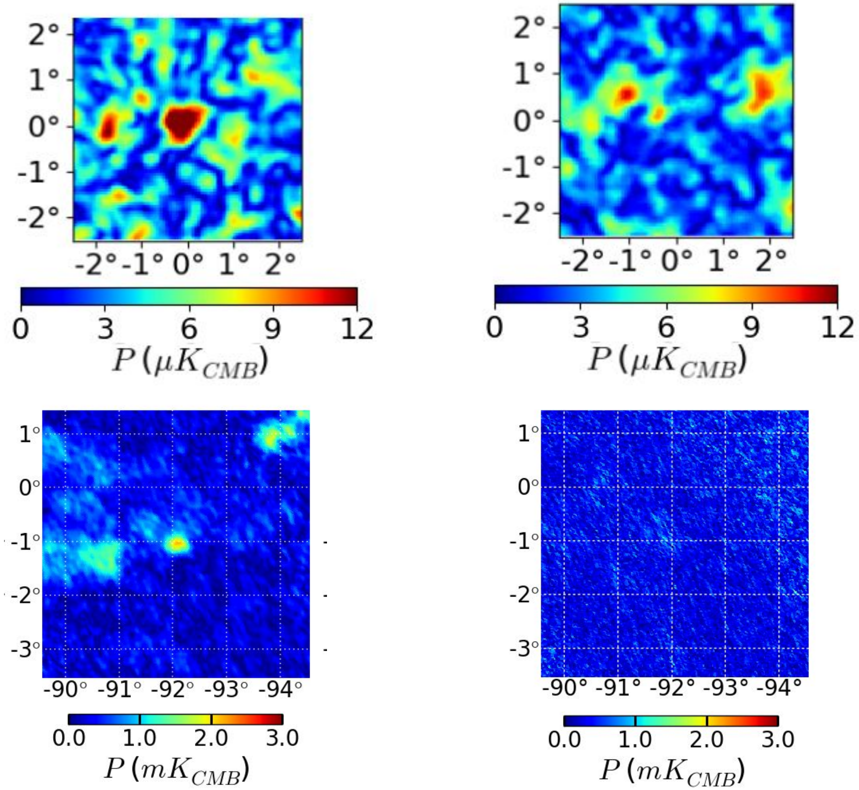
ICP removed

- Noiseless simulations, stacked maps in sky frame
- ICP removed, but not all effects of NL, cf dimmer I and P
- RMS between input-output E-modes is 0.01 uK

Removing ICP: EBEX 250 GHz (instrument frame)

Hot Spots P
92 % ICP
removed

RCW 38:
98% ICP removed



Before Removal

After Removal

Conclusion / Lessons Learned

- HWPSS pushed EBEX detector in NL regime which coupled with 4f produced 10% ICP. This effect can be minimized by:
  - making detectors more linear (see model in Takakura et al., 2017)
  - reducing HWPSS
- HWP early in the optical chain minimizes both IP and HWPSS A4
  - EBEX HWPSS dominated by 4f from field lens IP & excess load
- Stability of temperatures in the instrument important for polarization 1/f noise
- In EBEX, lens IP dominates contribution to A4 hence radial polarization pattern in HWPSS & IP (this doesn't average out with boresight rotation)
- Map based method to correlate and remove ICP in the time domain removes 92% of excess polarization. This can be used for future missions (particularly spaced-based).
  - This only removes ICP, doesn't correct for NL!!

EBEX /Acknowledgements

- NASA
- Canada Space Agency
- National Science Foundation
- Canada Research Chairs Program
- Natural Sciences and Engineering Research Council of Canada
- Canadian Institute for Advanced Research
- Science and Technology Facilities Council (UK)
- Minnesota Supercomputing Institute
- National Energy Research Scientific Computing Center
- Minnesota and Rhode Island Space Grant Consortia
- Funding from Collaborating Institutions
- Sigma Xi
- Private Donations

EBEX Collaboration

APC Paris
Jacques Delabrouille
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Berkeley Lab
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Ted Kisner

Brown University
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LAL-Orsay
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NIST
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Hannes Hubmayr
Carl Reintsema

SISSA-Trieste
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UC Berkeley
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Ben Westbrook

University of Minnesota/ Twin Cities
Francois Aubin
Christopher Geach
Ben Gold
Shaul Hanany (PI)
Terry Jones
Michael Milligan
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Qi Wen
Karl Young

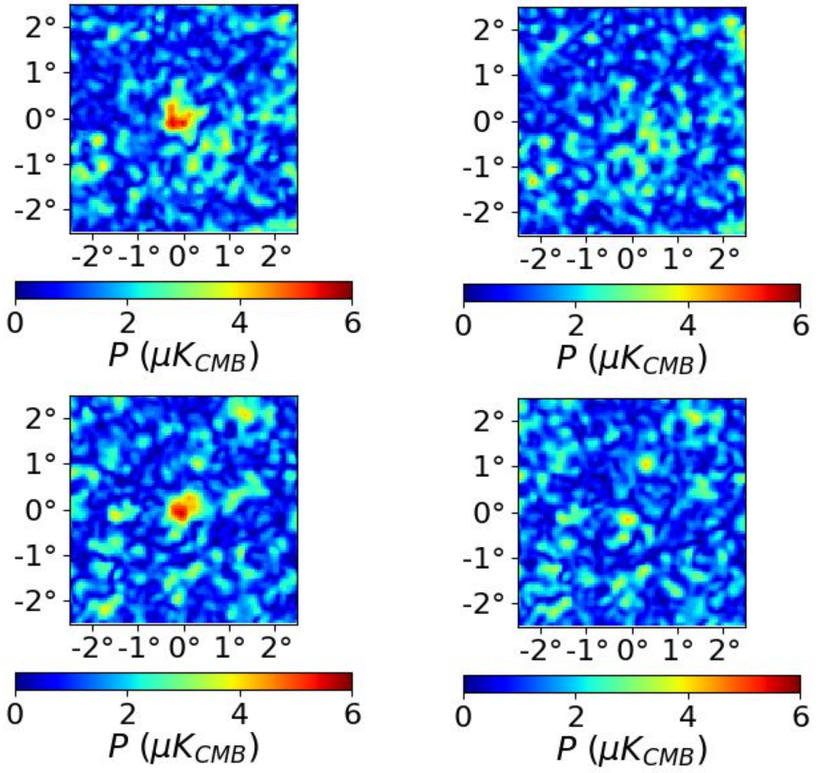
University of Southern California
Joy Didier
Amber Miller

Extra Slides

Removing ICP: EBEX 150 GHz (instrument frame)

Hot Spots

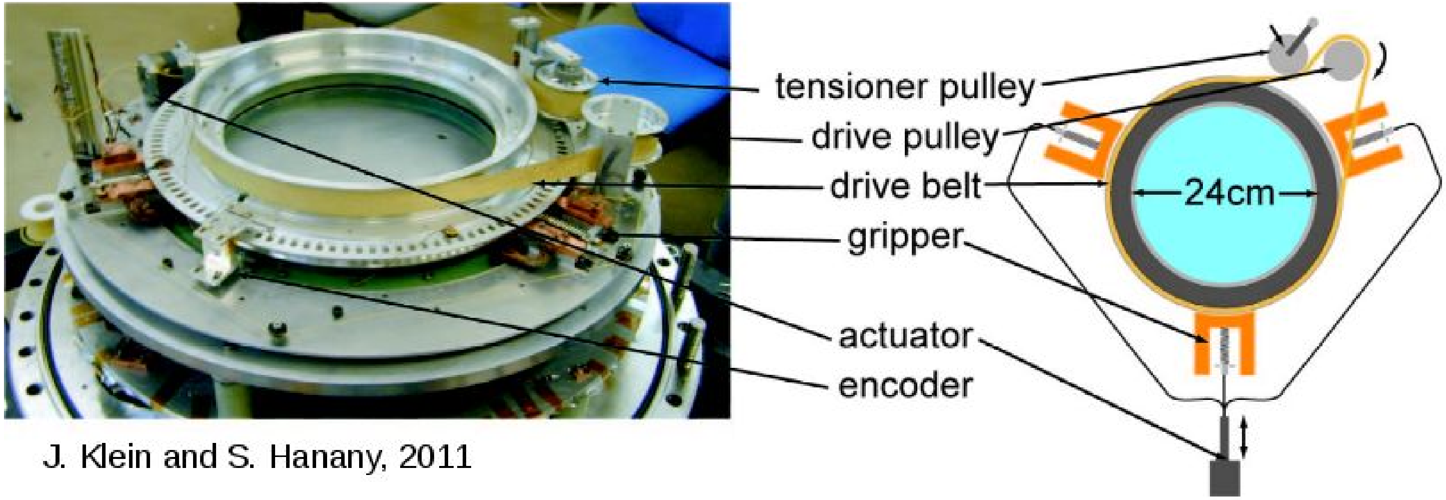
Cold Spots



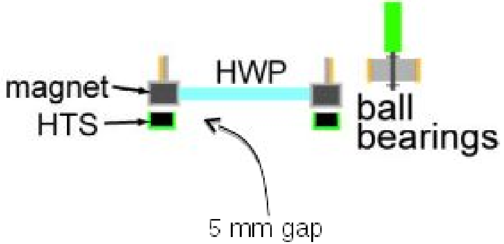
Before Removal

After Removal

Instrument / Polarimetry



J. Klein and S. Hanany, 2011



- Continuous 1.24 Hz rotation at 4 K
- 645,000 rotations during 2012 flight
- Estimated 15 mWatt power dissipation