EBEX

The EBEX AHWP

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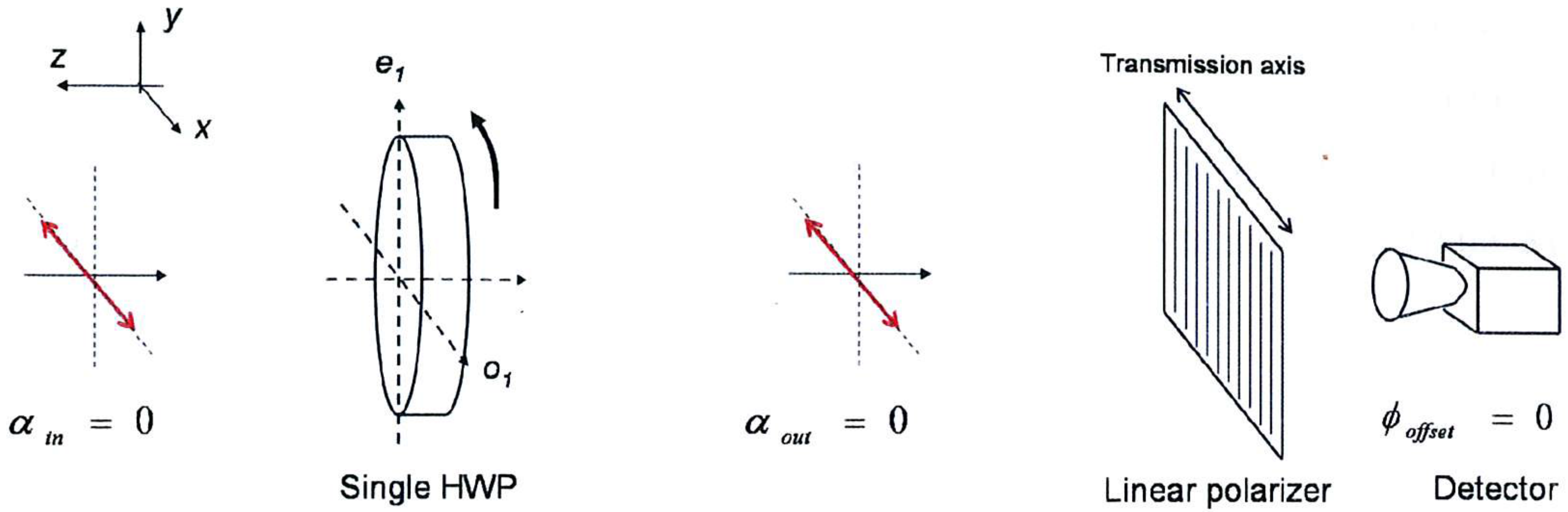
SISSA

Single HWP Model



$$I_{measured} = \frac{1}{2}\left[I_{in} + I_{Pin}\cos(4\omega_{hwp}t - 2\alpha_{in})\right]$$

Scanning modulates intensity and polarized intensity

$$I_{in} \rightarrow I_{in}(t), \quad I_{Pin} = I_{P0} + \Sigma I_{pj}\cos\omega_j t$$

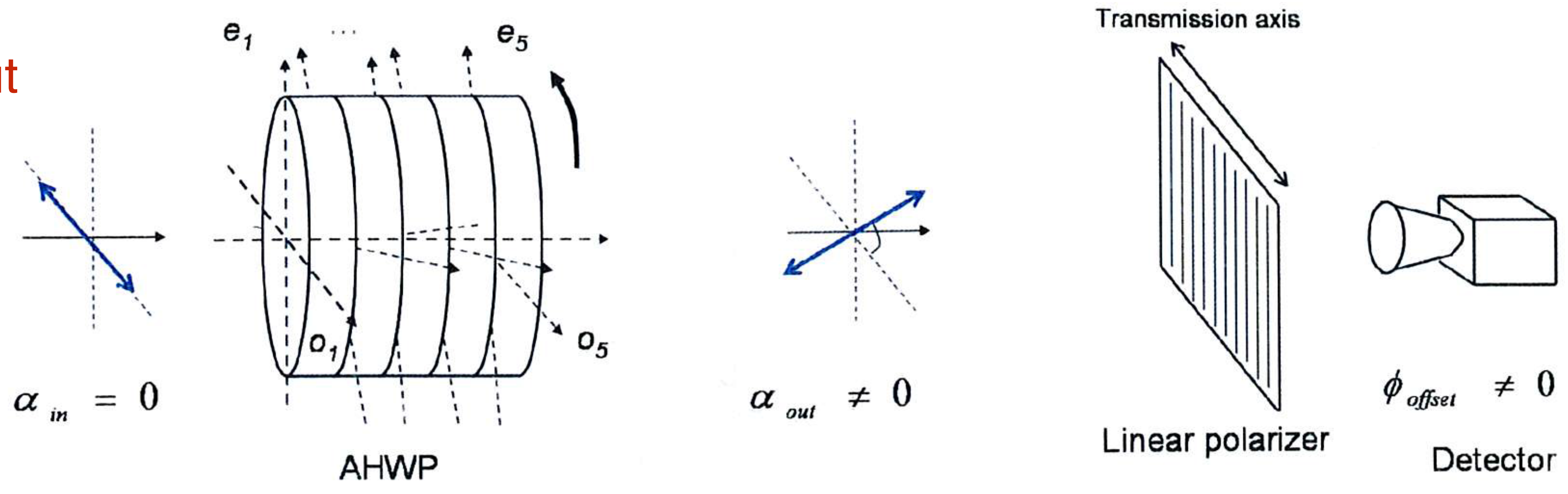
$$I_{measured} = \frac{1}{2}\left[I_{in}(t) + I_{P0}\cos(4\omega_{hwp}t - 2\alpha_{in}) + \Sigma I_{pj}\cos\omega_j t\cos(4\omega_{hwp}t - 2\alpha_{in})\right]$$

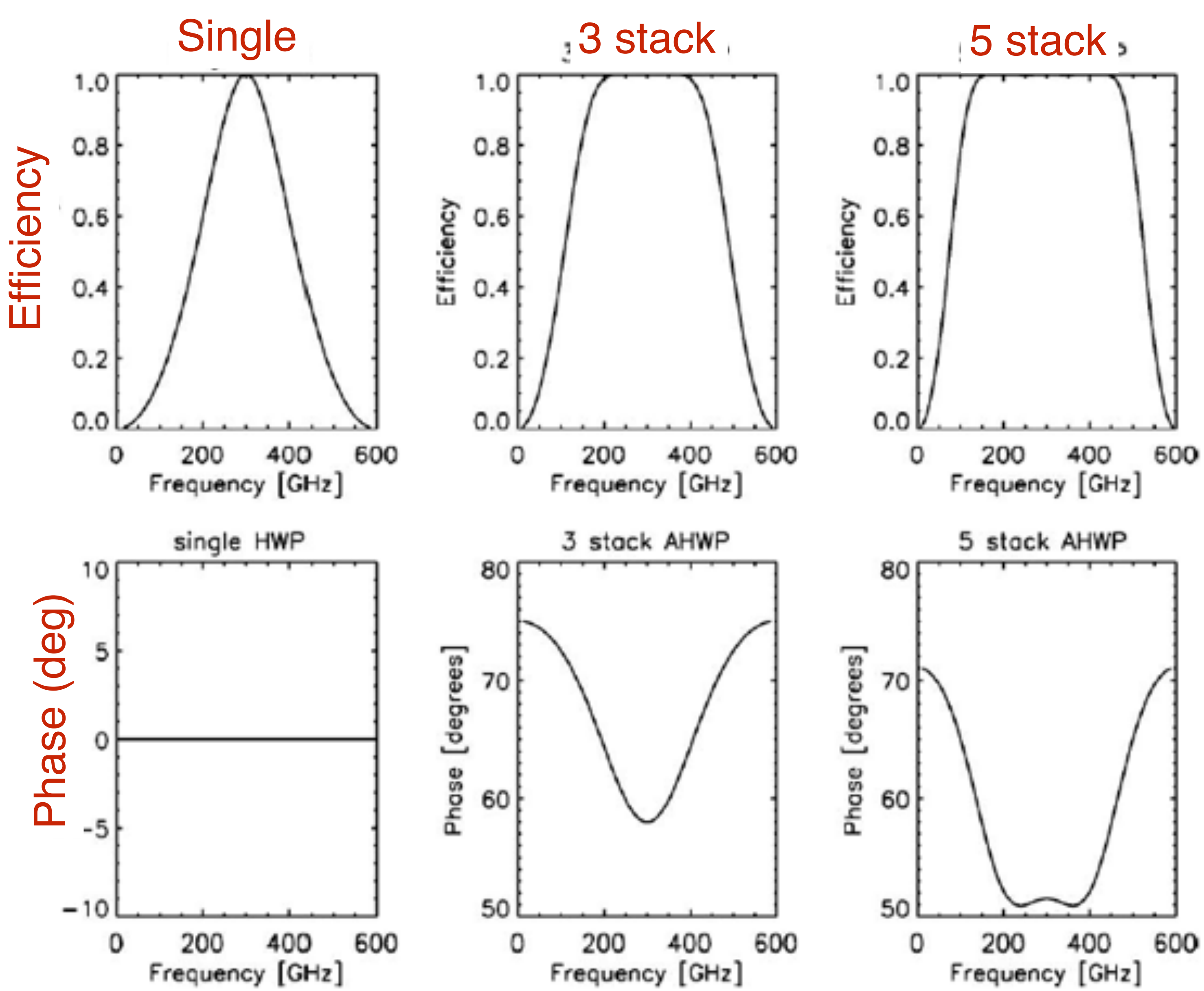
Stable polarization is at 4th harmonic

Sky synchronous is at both side-bands of 4th

Single vs AHWP Model

Flat Spectrum Input





matsumura et al. 2009

MAXIPOL: Continuous Rotation in CMB

MAXIPOL: COSMIC MICROWAVE BACKGROUND POLARIMETRY USING A ROTATING HALF-WAVE PLATE

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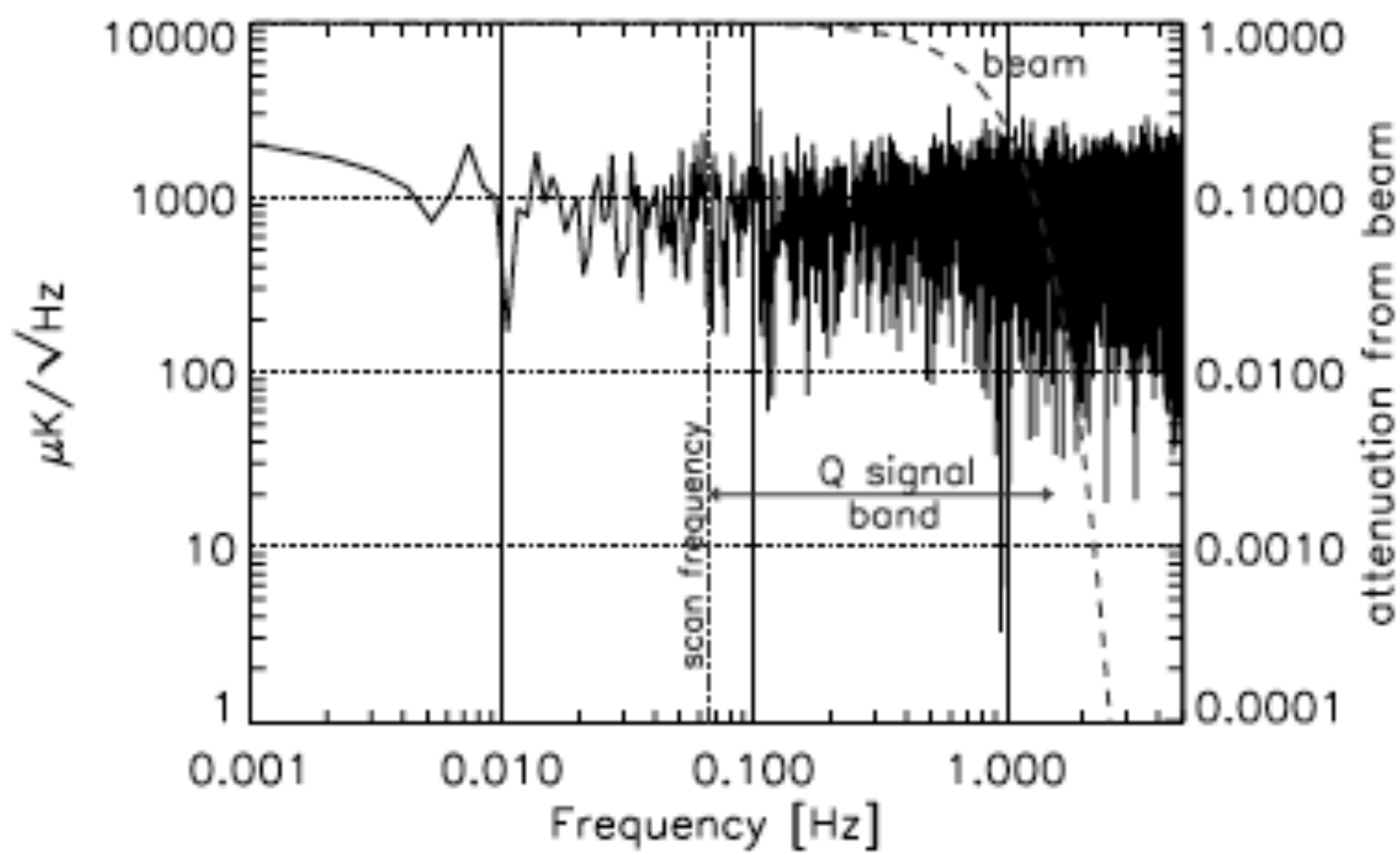
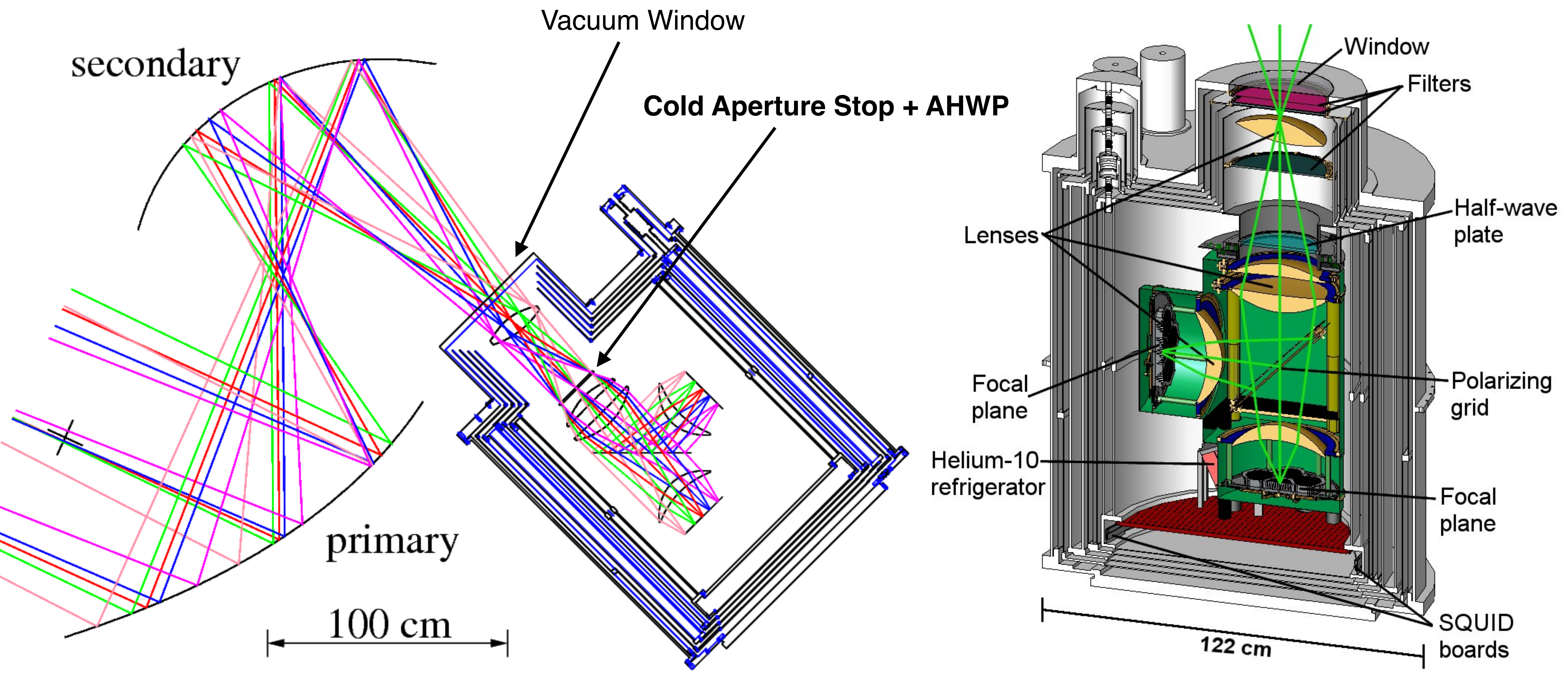
- Detection of EE

- Stability to 1 mHz post-demodulation



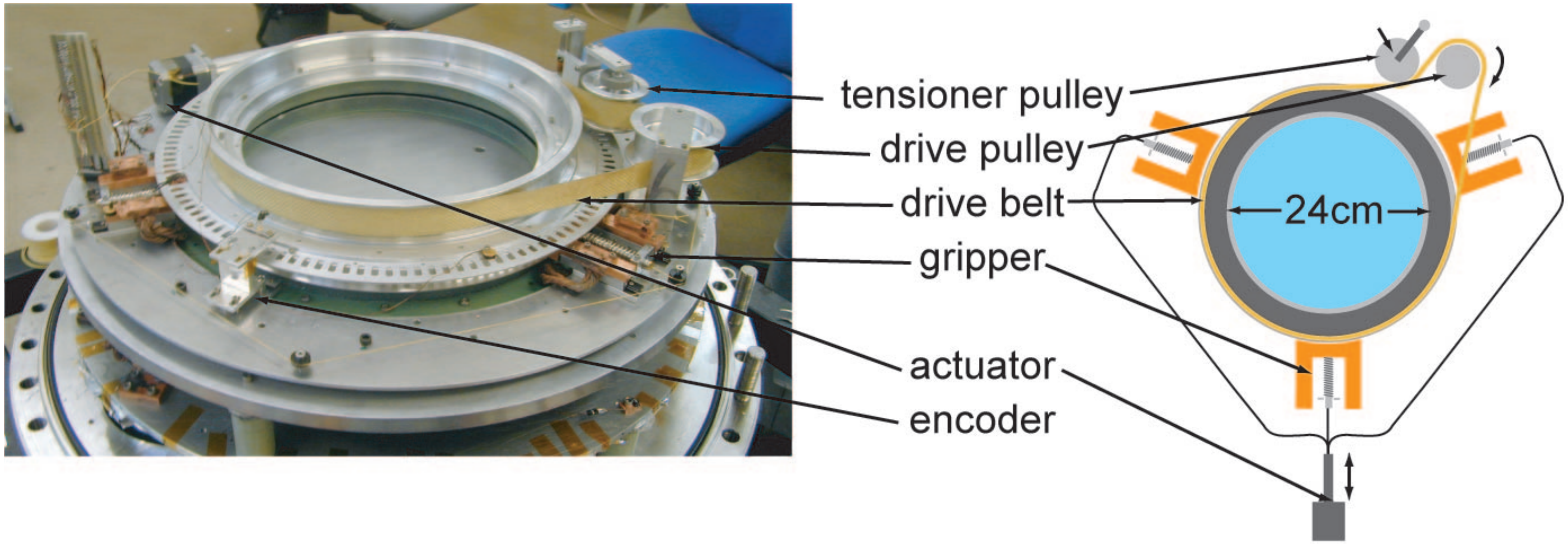
EBEX Optical Path and AHWP



AHWP

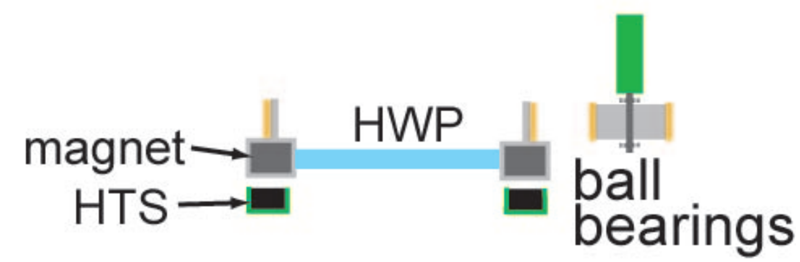
- is an aperture stop
- not the first element in the path; behind the field lens
- operated at 4 K (to reduce emission)
- must be achromatic to serve all focal plane

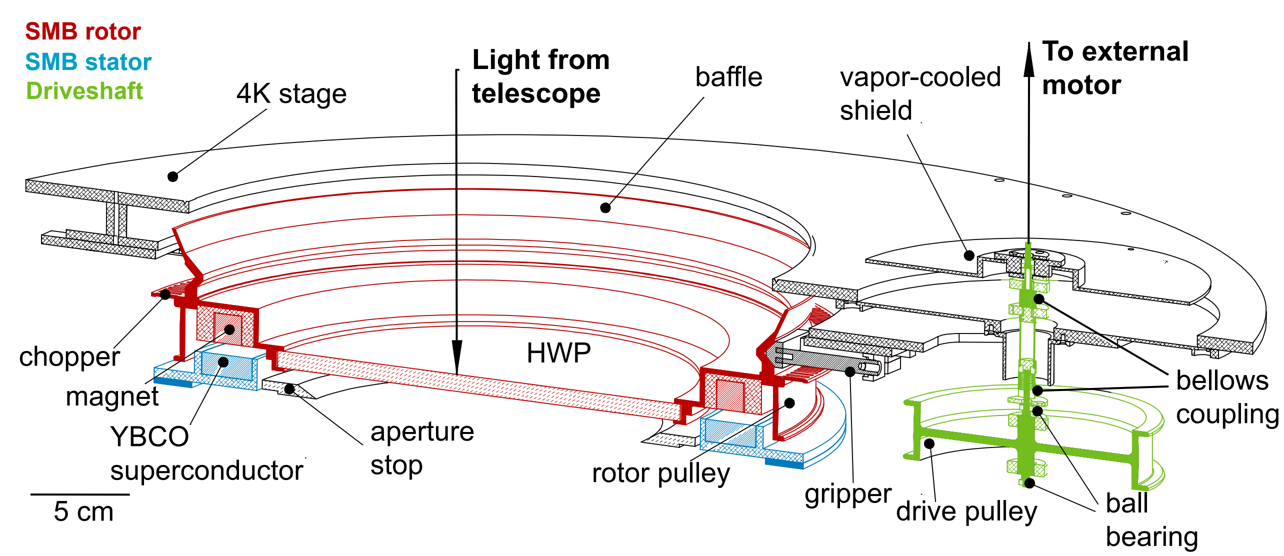
Construction + Drive



- Based on a superconducting magnetic bearing
- Stator = YBCO, Tc = 95 K; Rotor = NdFeB
- Drive = DC brushless motor @300 K,

  MoS_2 coated SS ball bearings at 4 and 20 K
- Kevlar belt + tensioner pulley
- 3 Spring-loaded grippers actuated with linear actuator + kevlar wire
- No step functionality

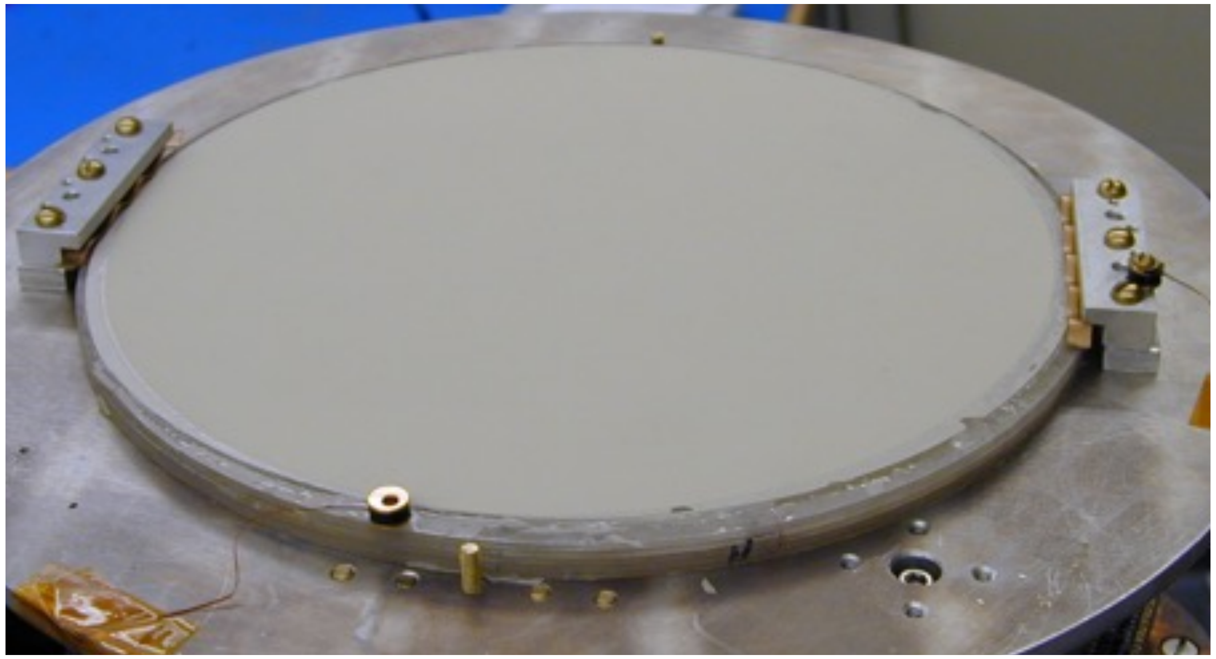


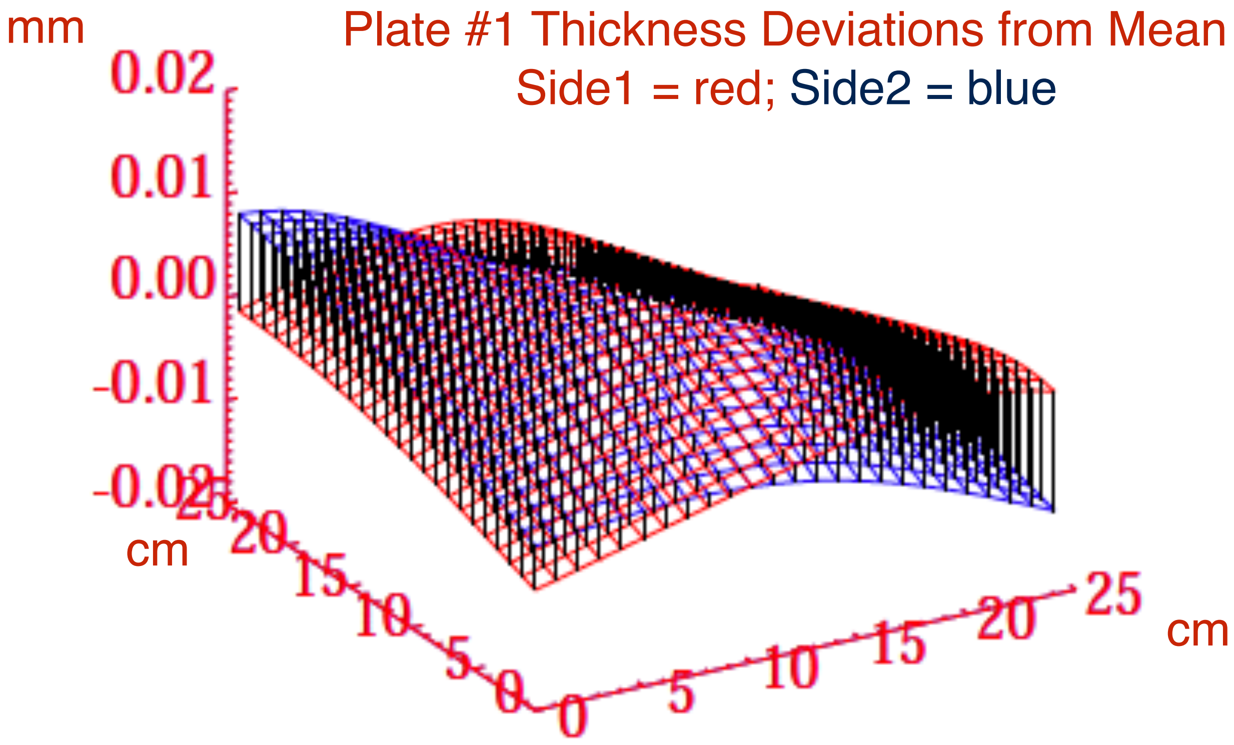


HWP and ARC

- 5 stack sapphire
- 24 cm diameter, 22 cm ARC,

  19 cm diameter optically active.
- ~1.66 mm thick each
- glued with polyethylene
- 5 layer ARC (including glue)
  - stycast 1266 (40 μm)
  - TMM6 (125 μm)
  - stycast 1266 (40 μm)
  - TMM3 (150 μm)
  - perforated teflon (220 μm)



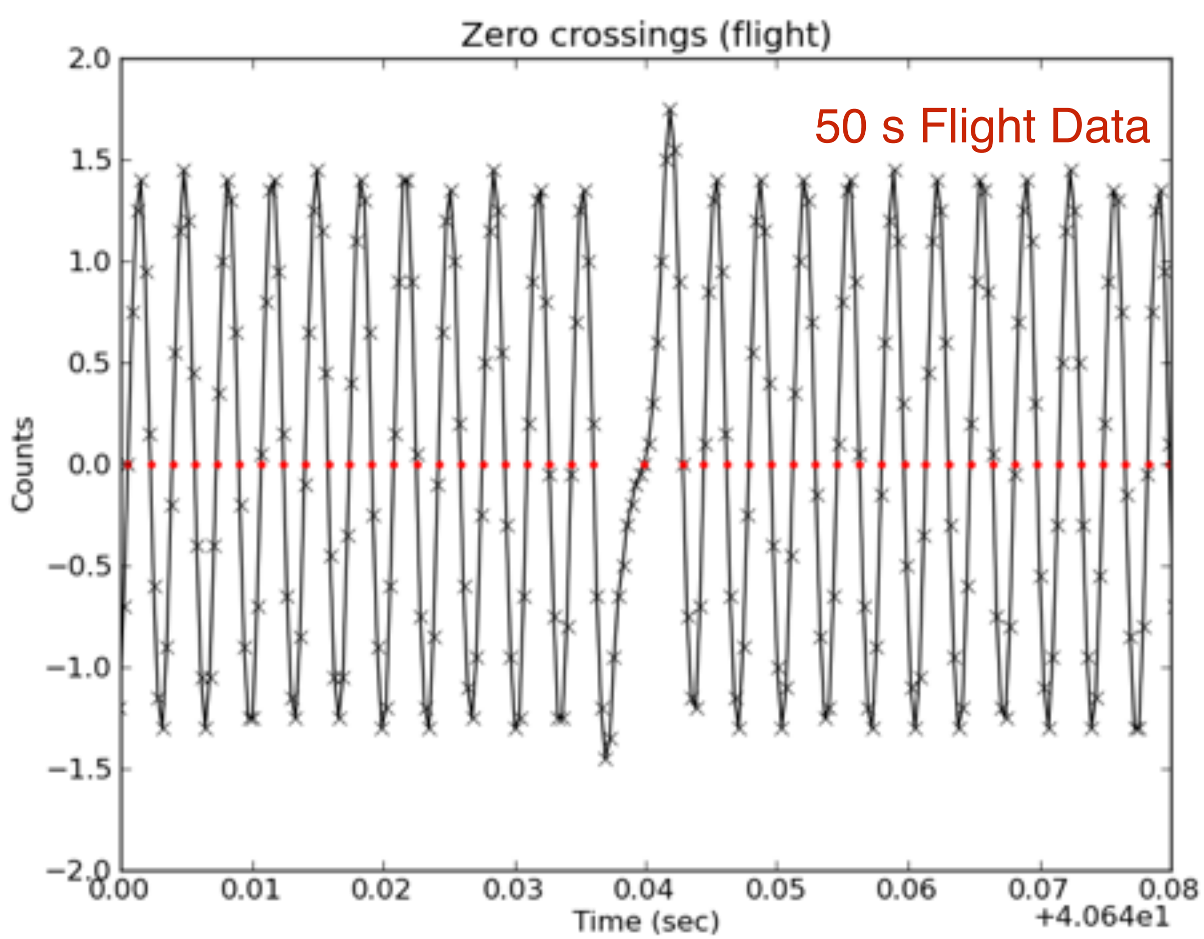


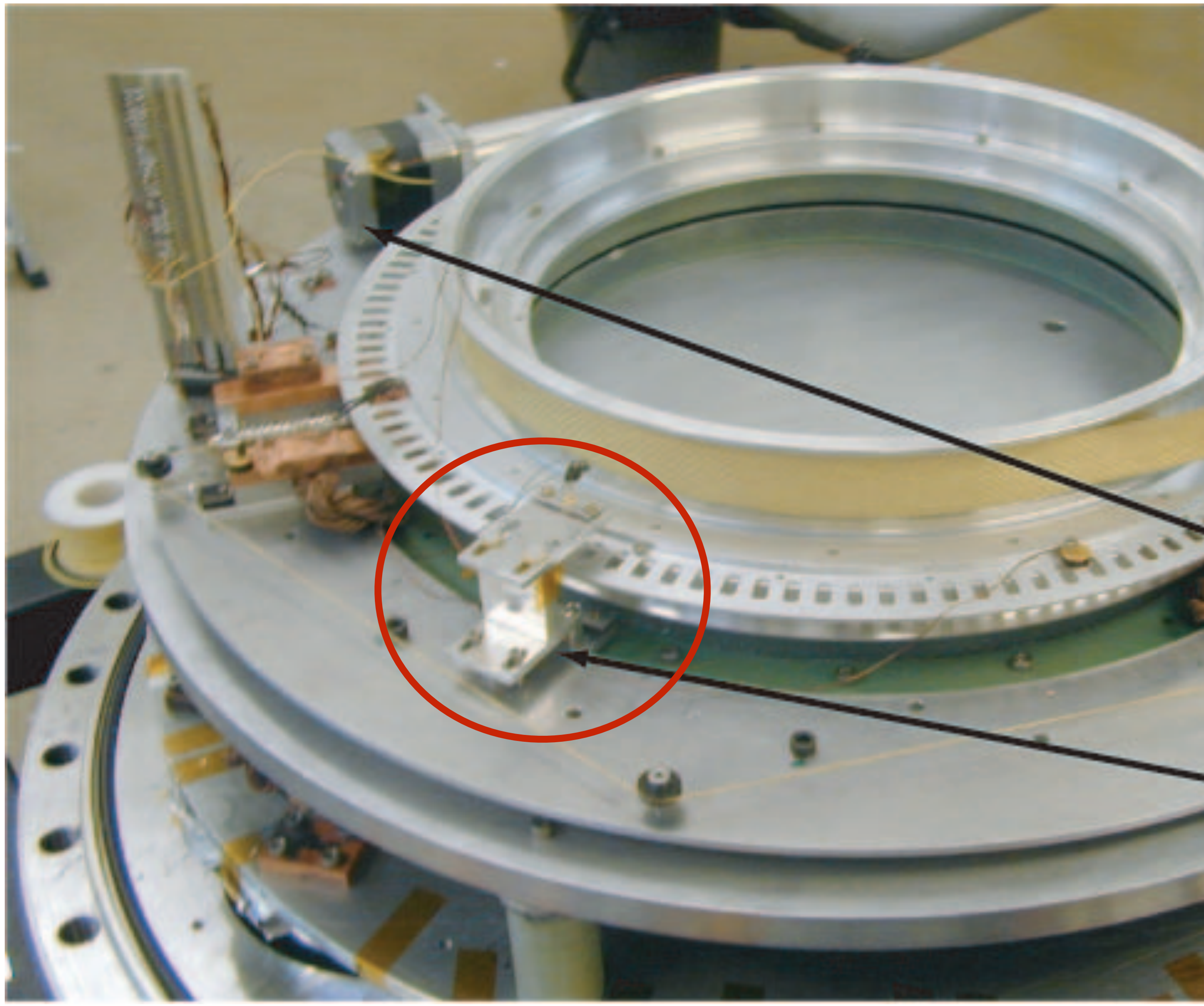
Angular Encoding

- Based on chopper,

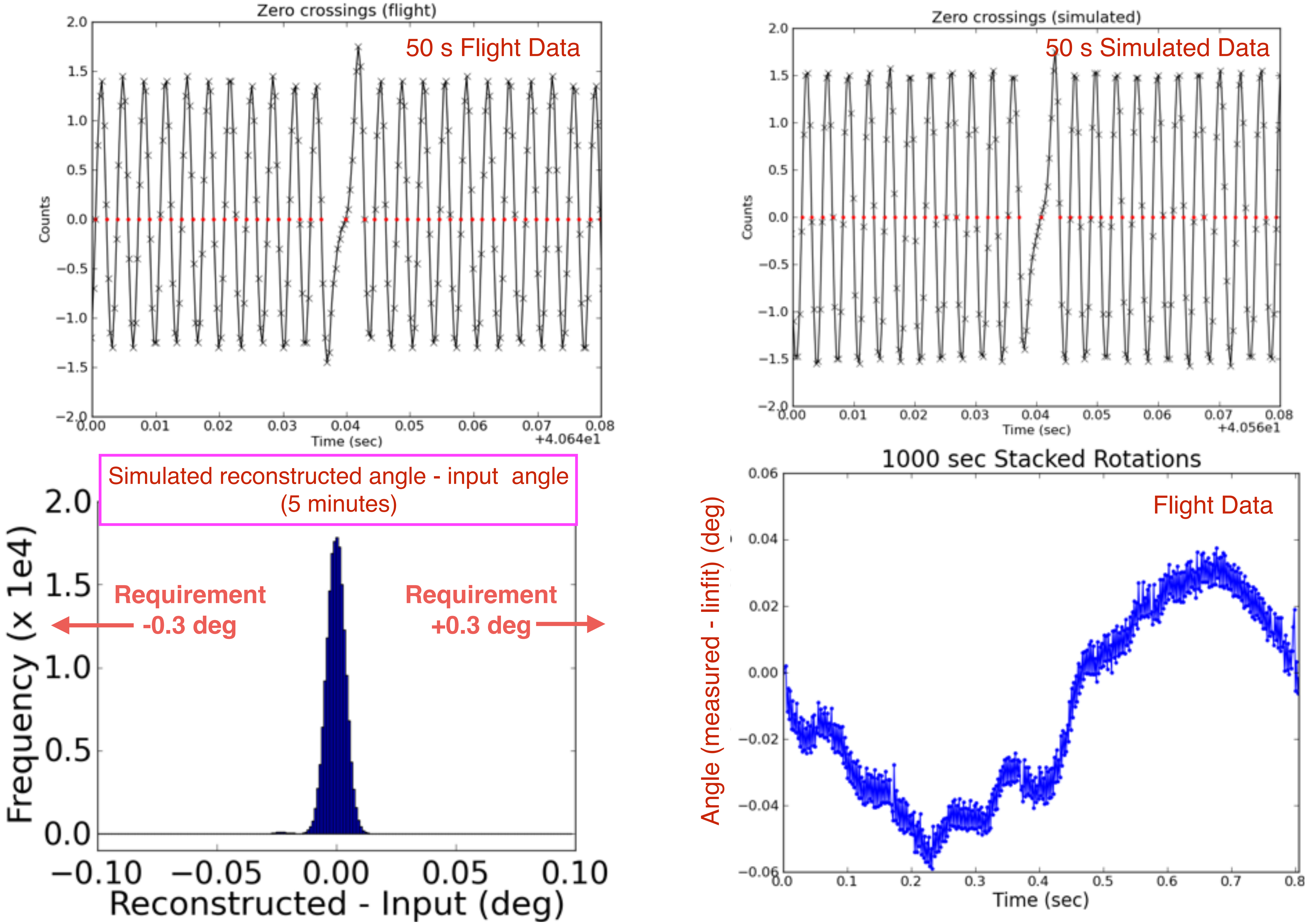
  240 slots (=1.5 deg period)

- Cryogenic LED and Photodiode





HWP - Flight Angle Reconstruction



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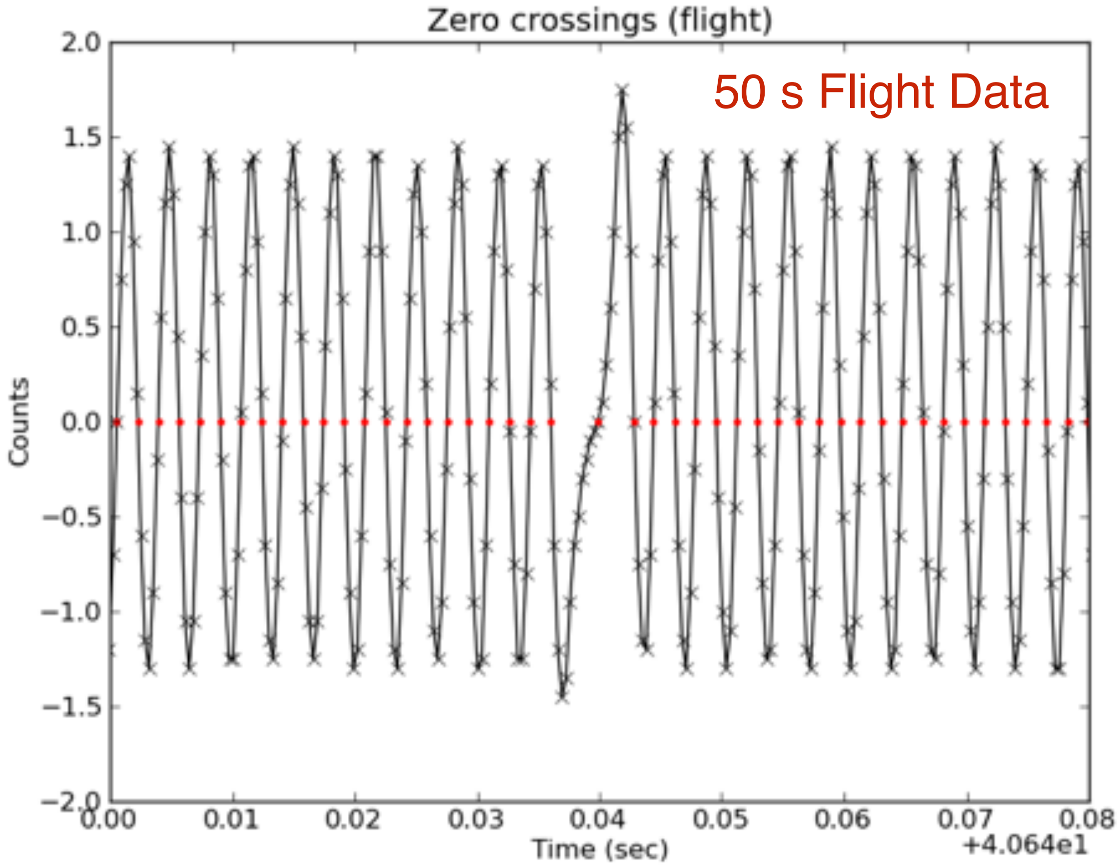
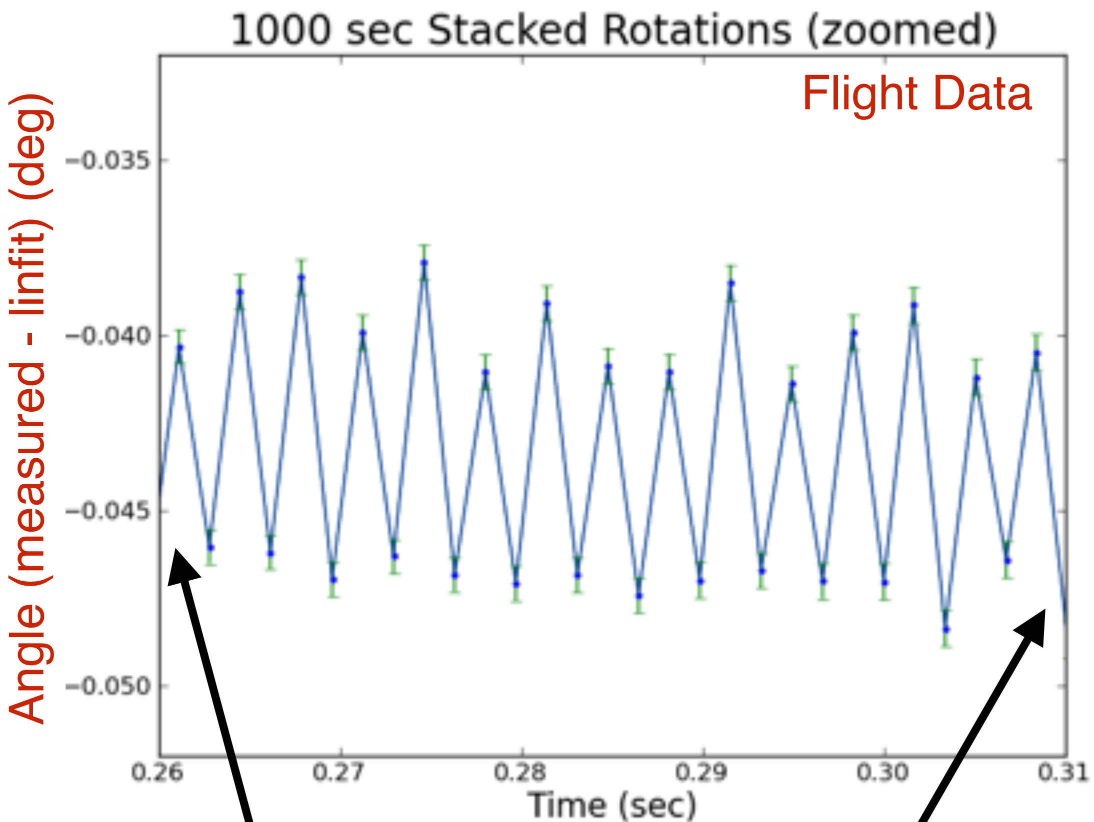
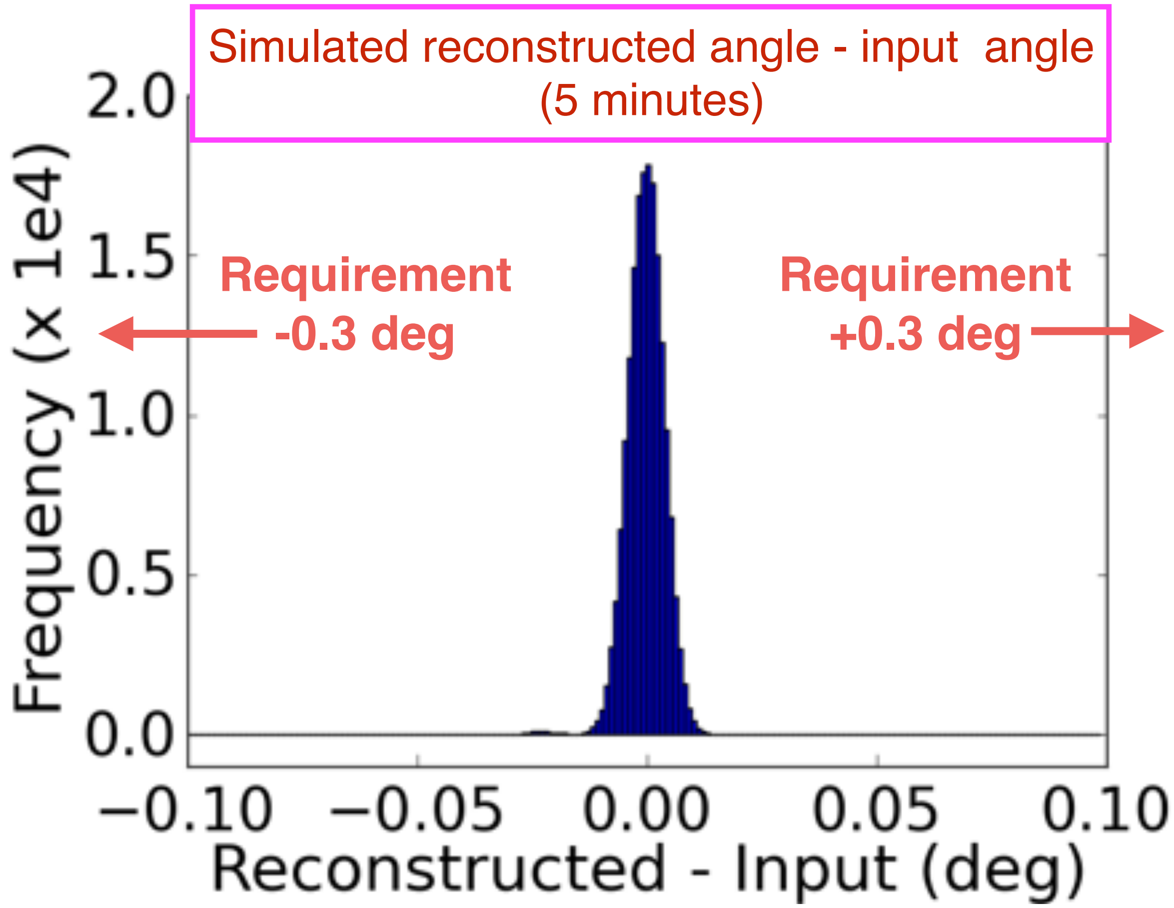
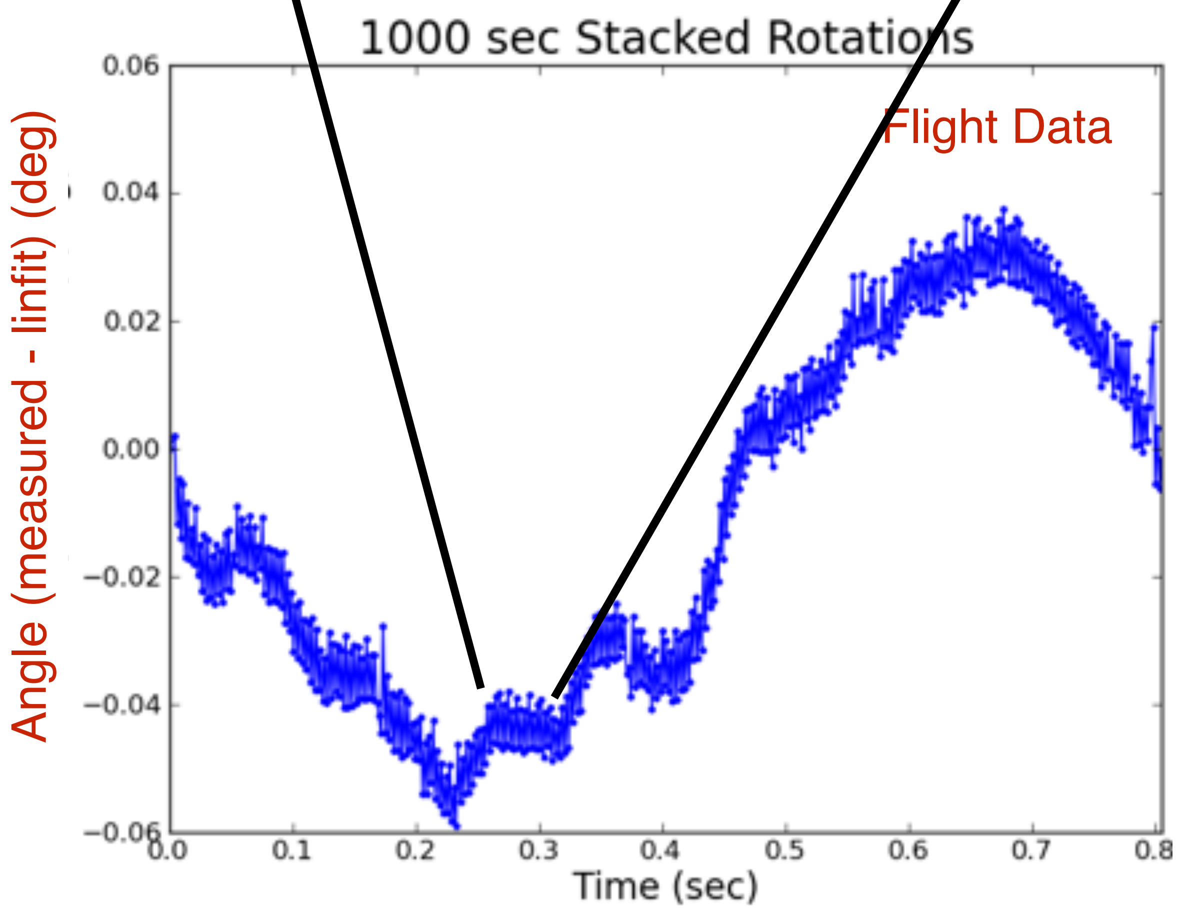




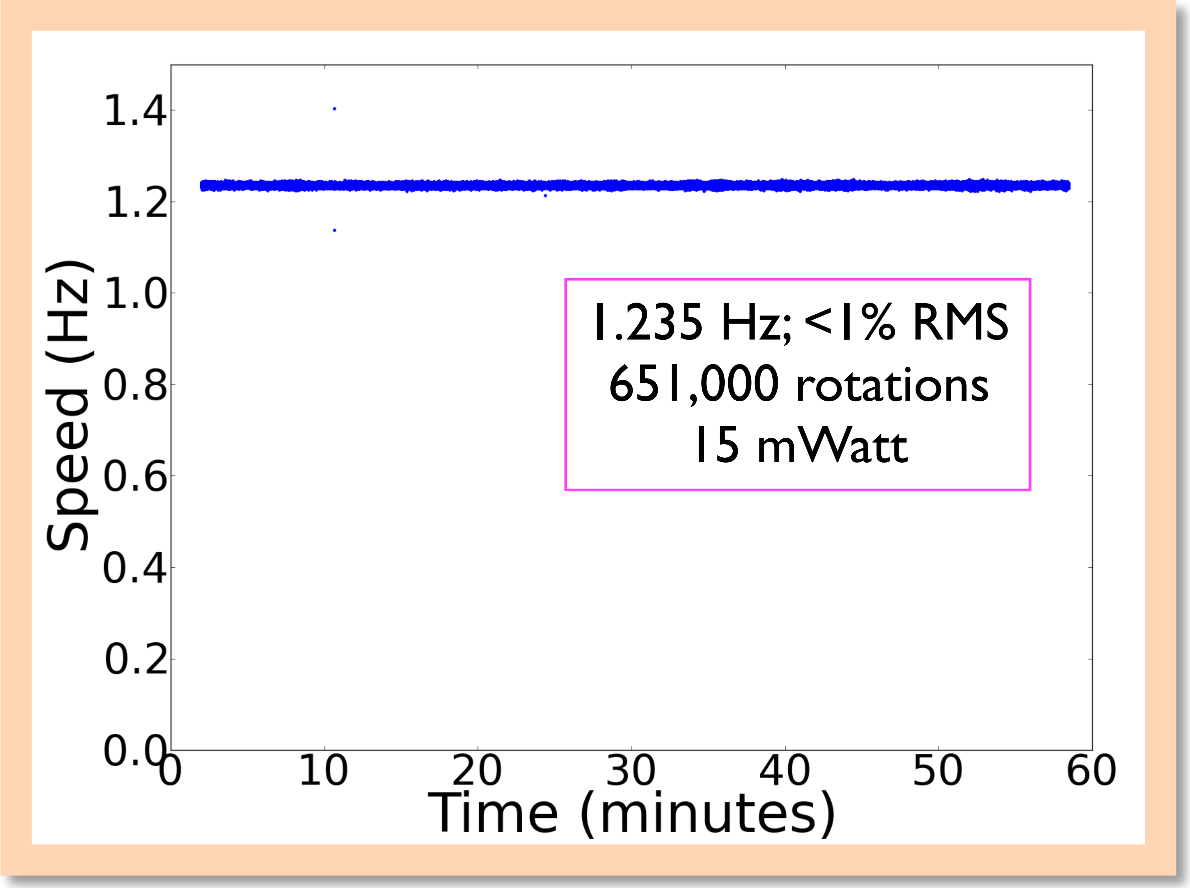




Rotation Performance

Flight Statistics:

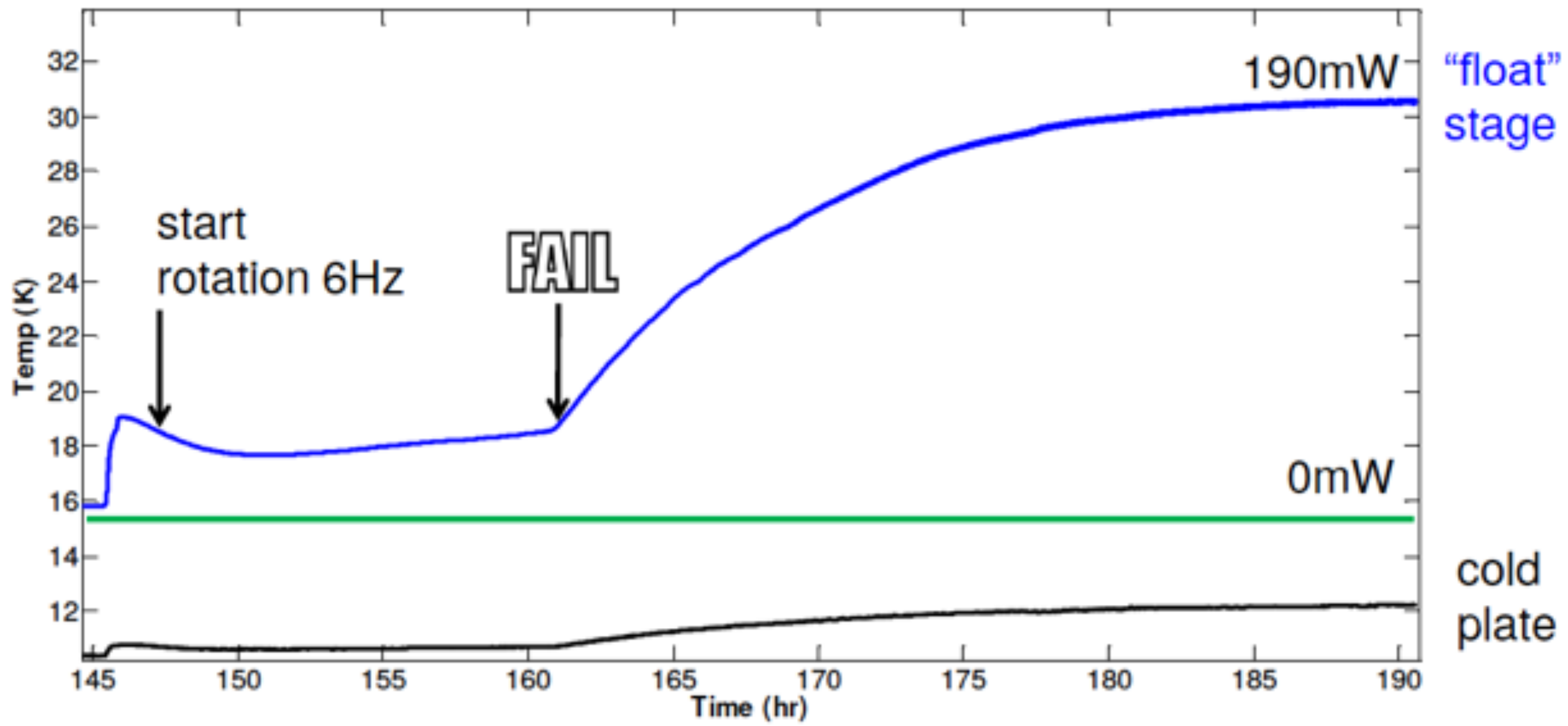
- Rotation speed 1.235 Hz
- 6.1 days; 651,000 rotation
- 9 stop/start cycles
- One 'ungrip' operation (on the ground)
- 15 mW = 5% of total power on LHe

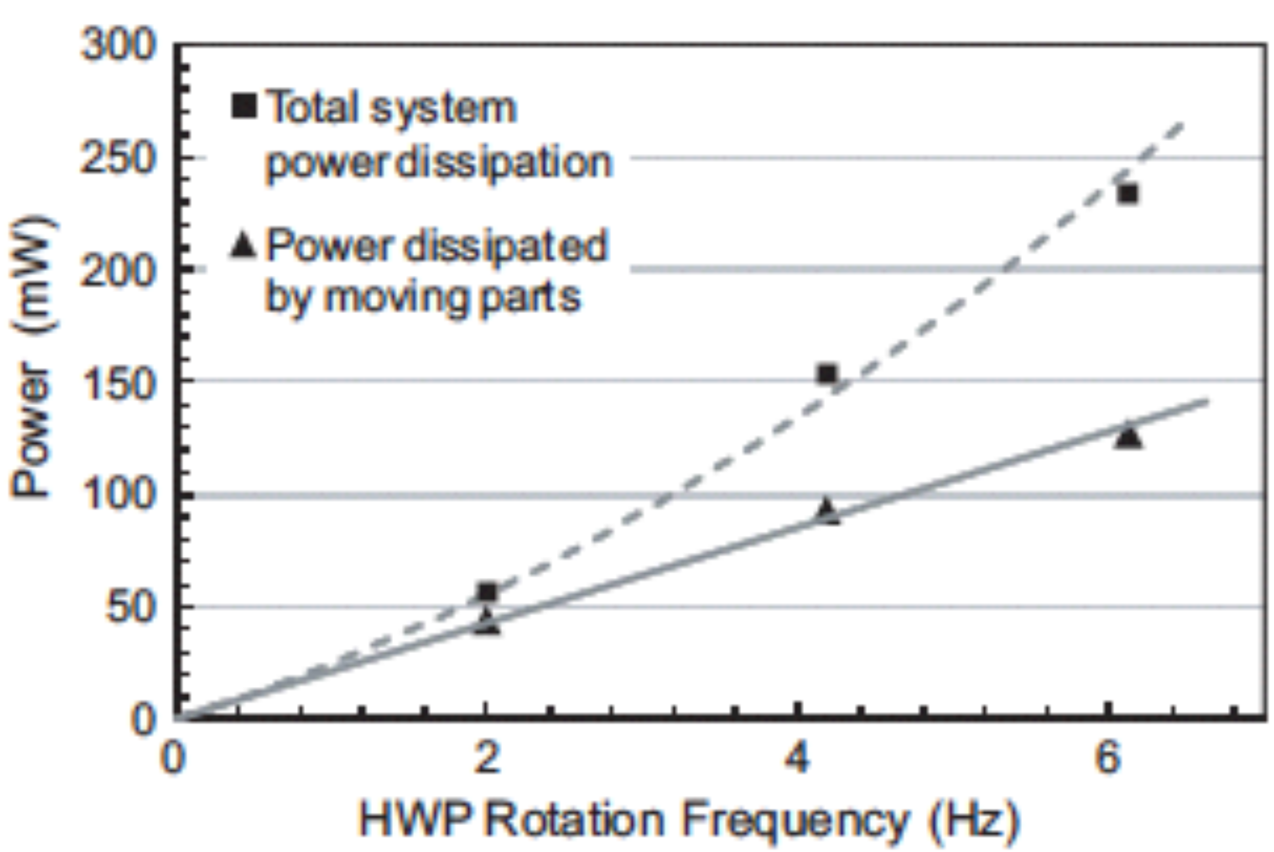


Power Dissipation

Sources

- Moving parts = friction: bearings, belt => ~Linear with speed
- Stationary parts = Eddy Currents (magnet inhomogeneity) => quadratic with speed
- Bearing friction dominant at low speed, eddy currents at higher speeds

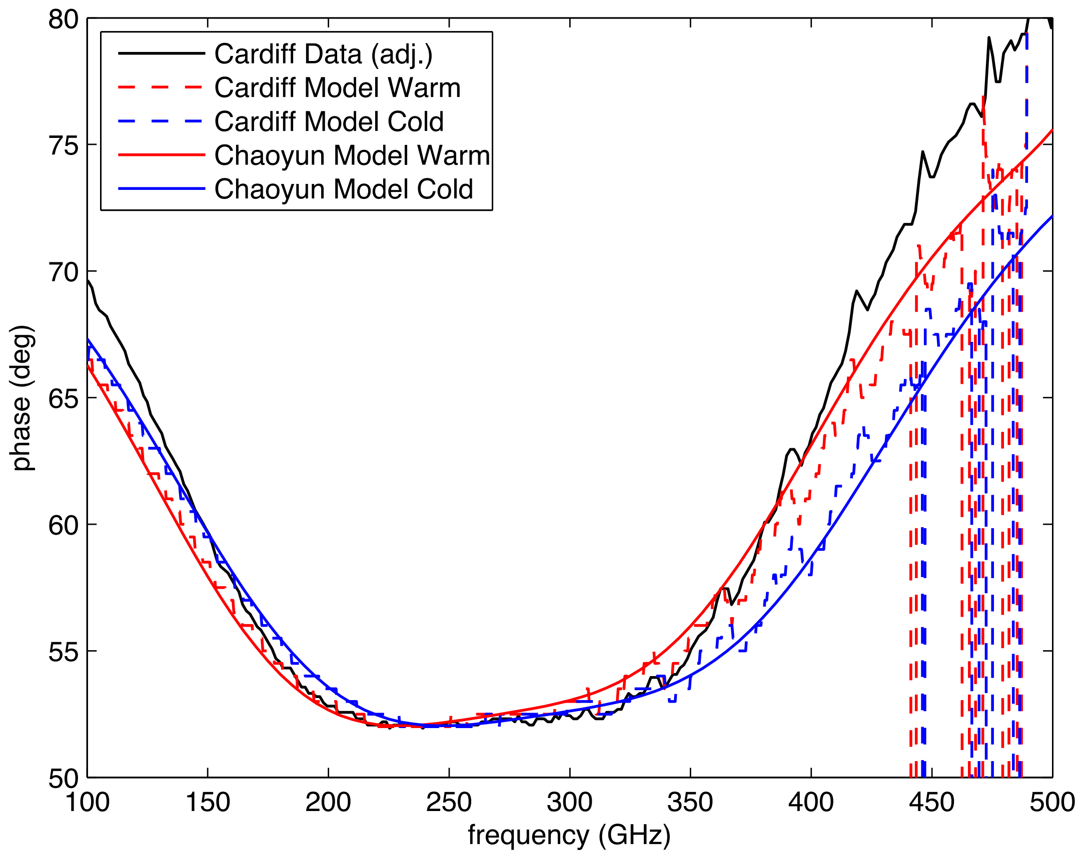


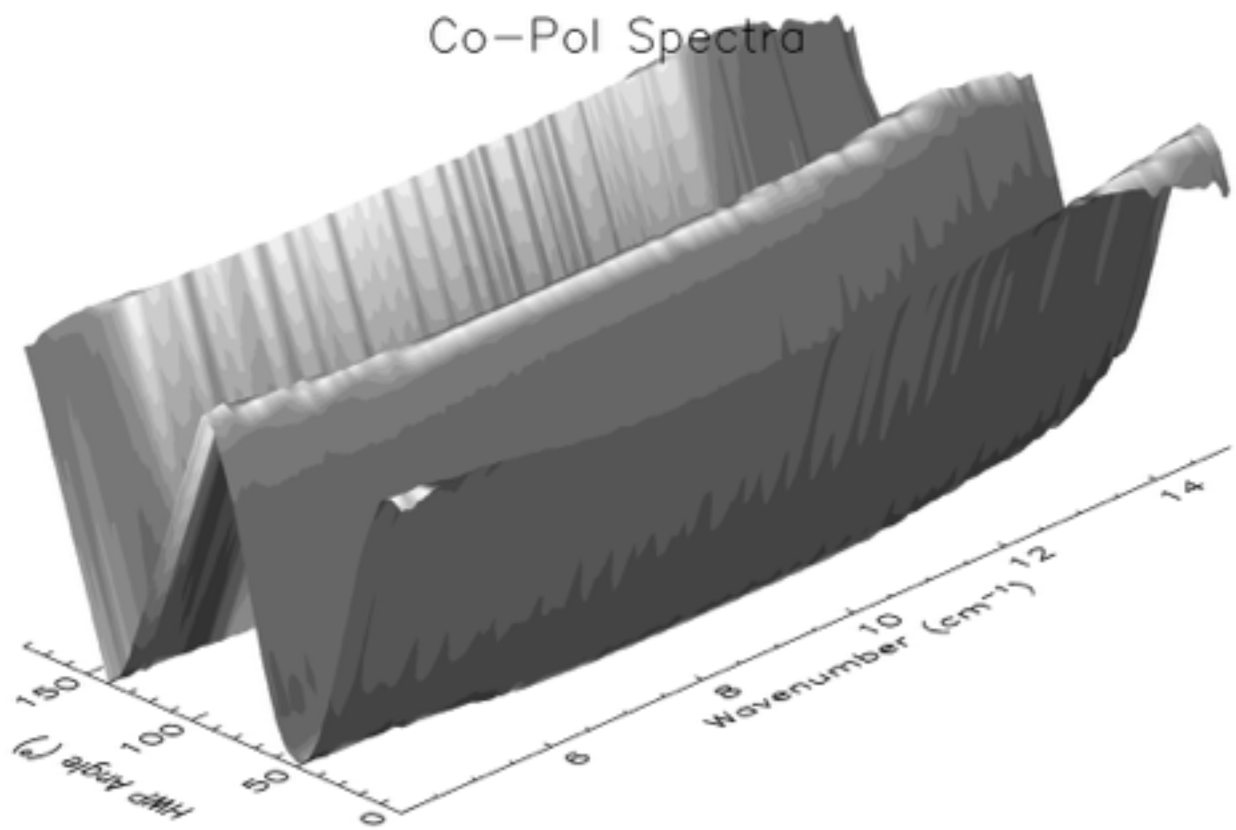


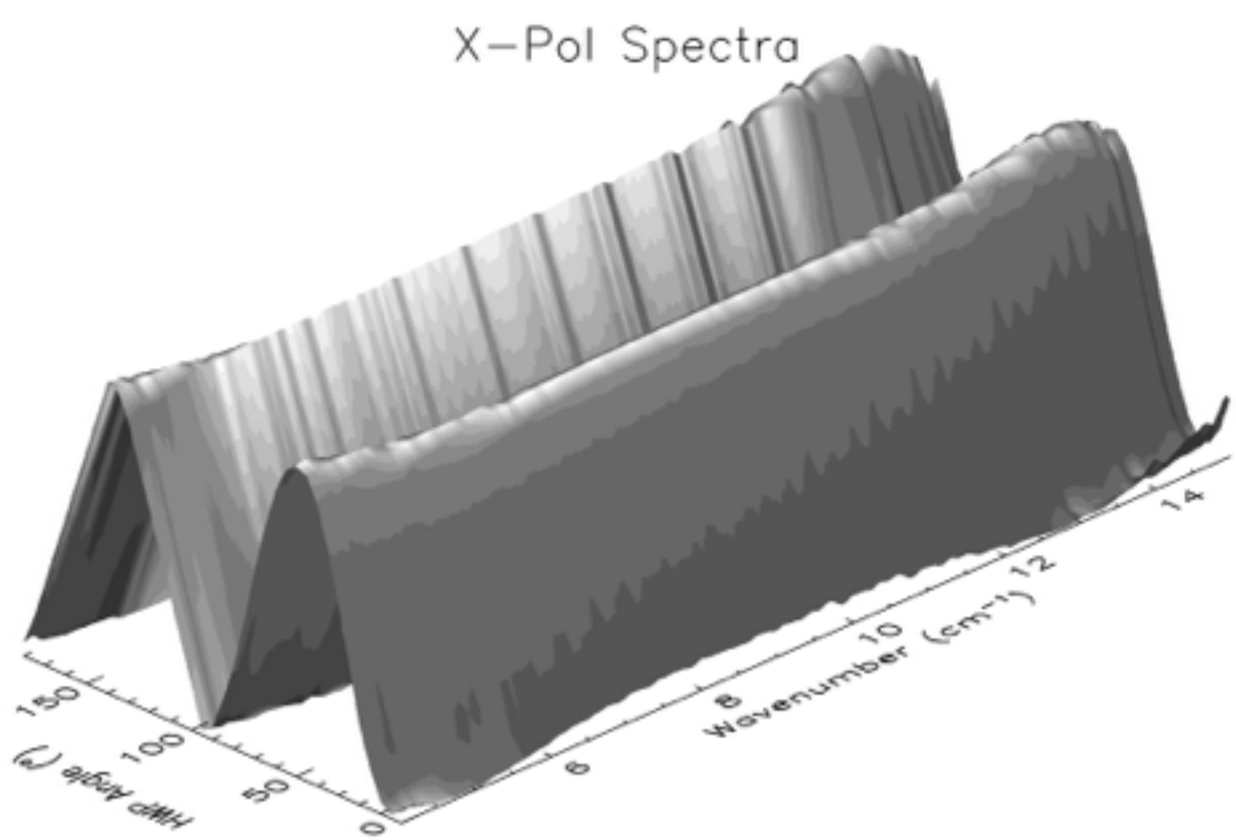
Optical Properties

Cardiff:

- Transmission vs. HWP angle vs. frequency
- Extract polarization modulation efficiency and phase response







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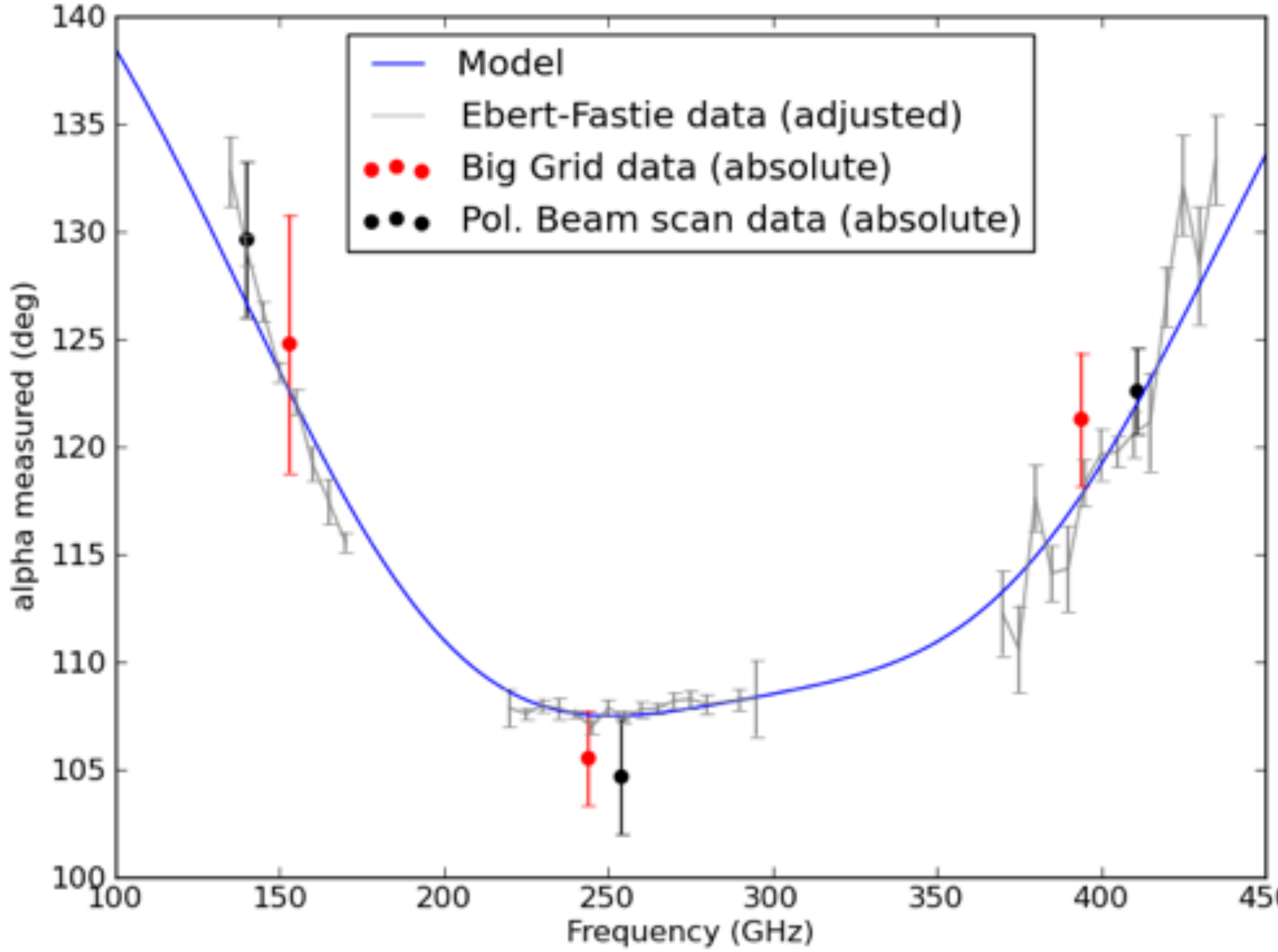
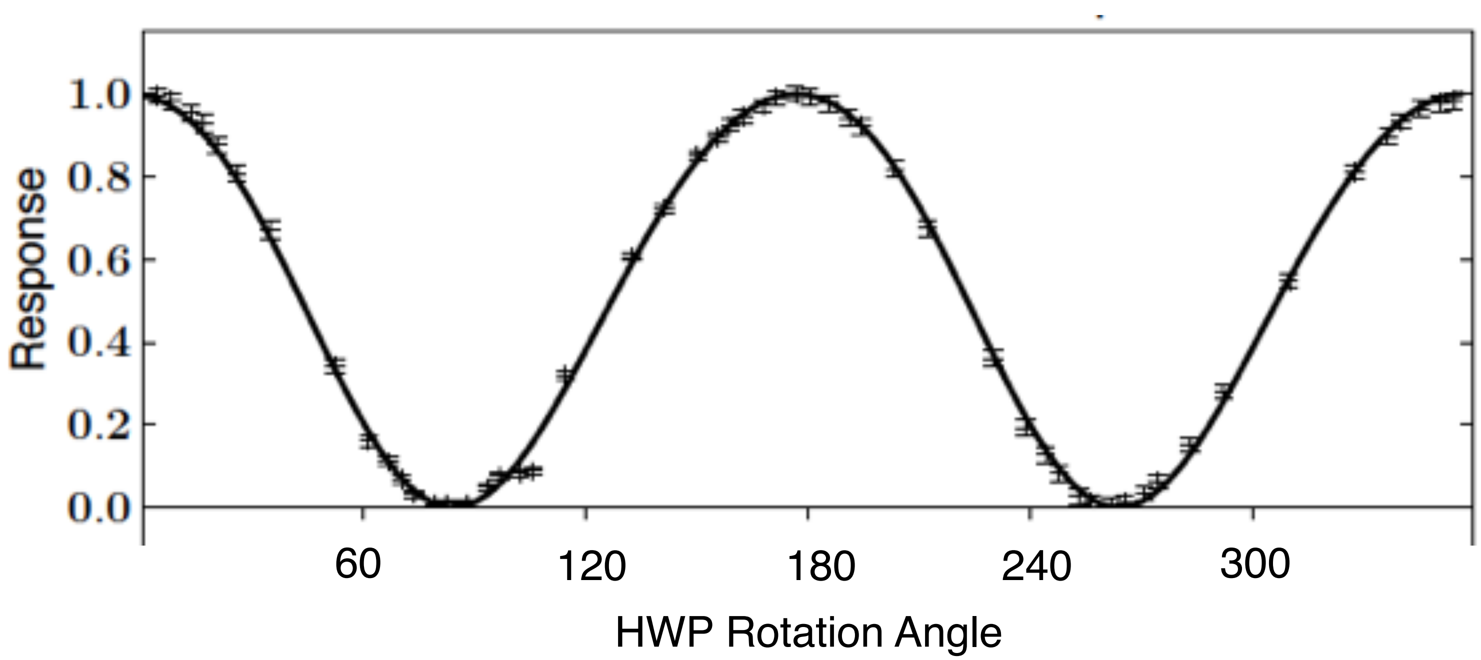
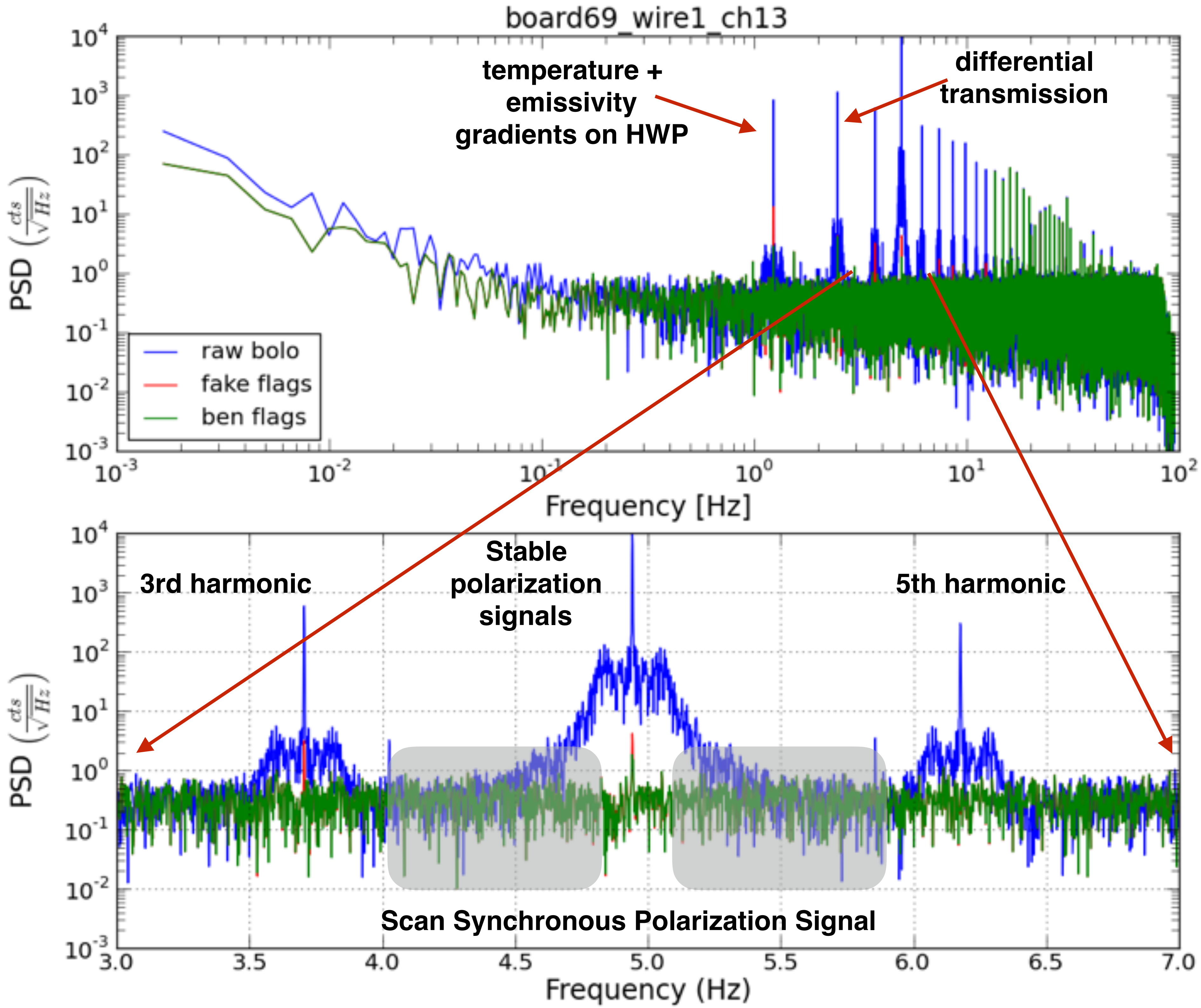


Frequency (GHz)	Modulation Efficiency (%)
150	98±6
250	98±2
410	92±6



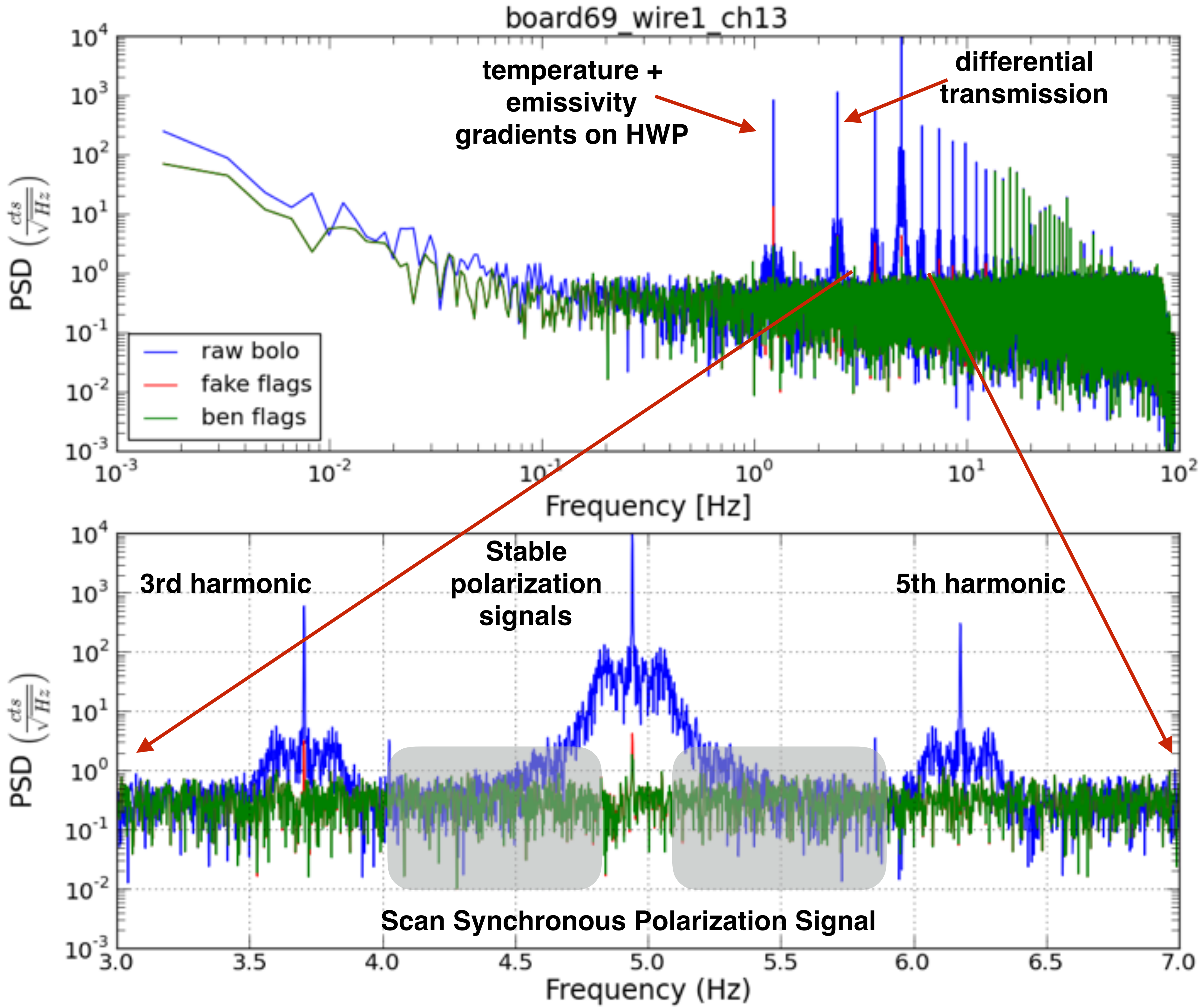
Time Domain Data

- Strong rotation synchronous Signal
- Mostly removed upon fitting a template locked to encoder angle



Time Domain Data

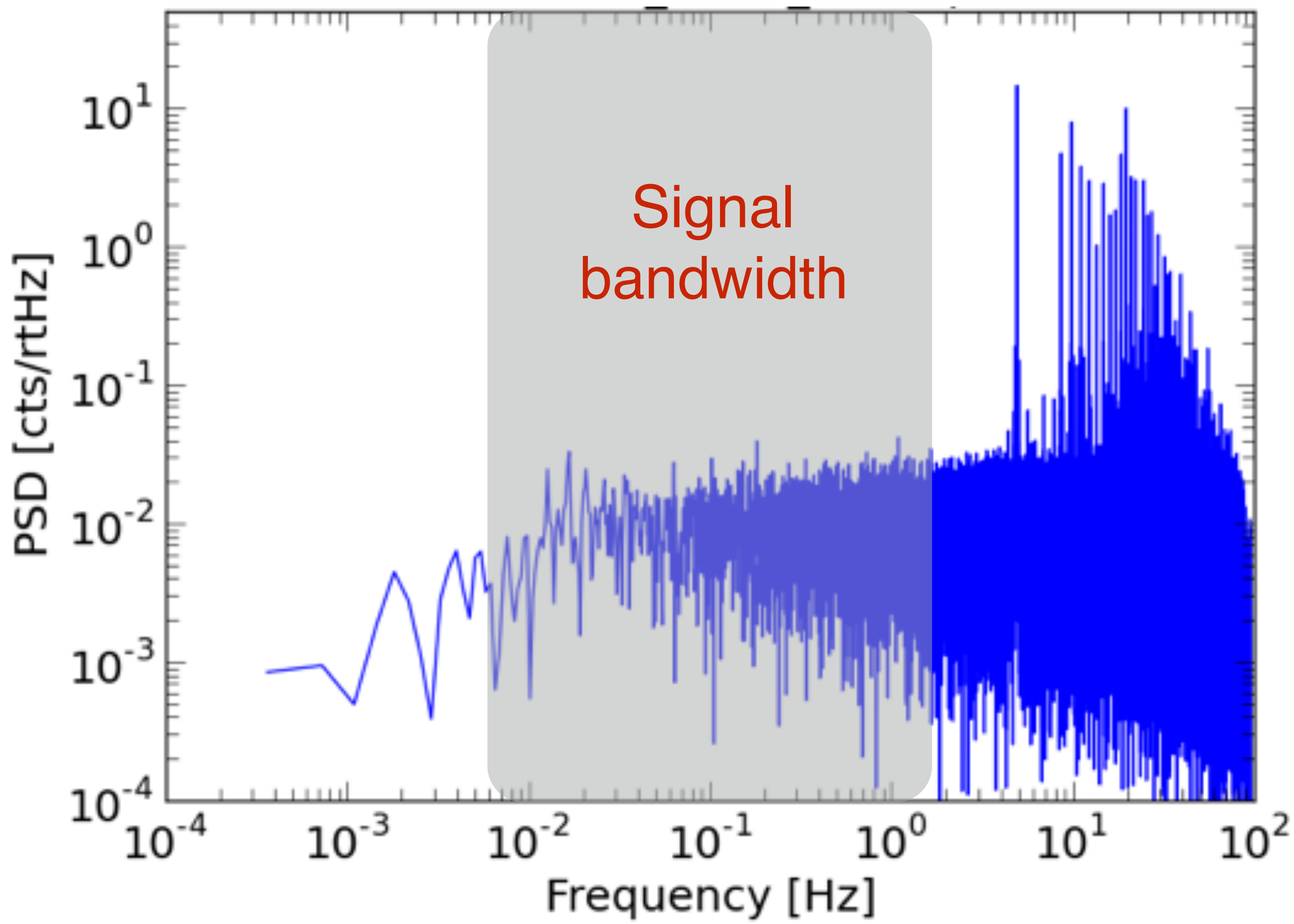
- Strong rotation synchronous Signal
- Mostly removed upon fitting a template locked to encoder angle
- 4th harmonic size consistent with mirror emission and instrumental polarization by field lens



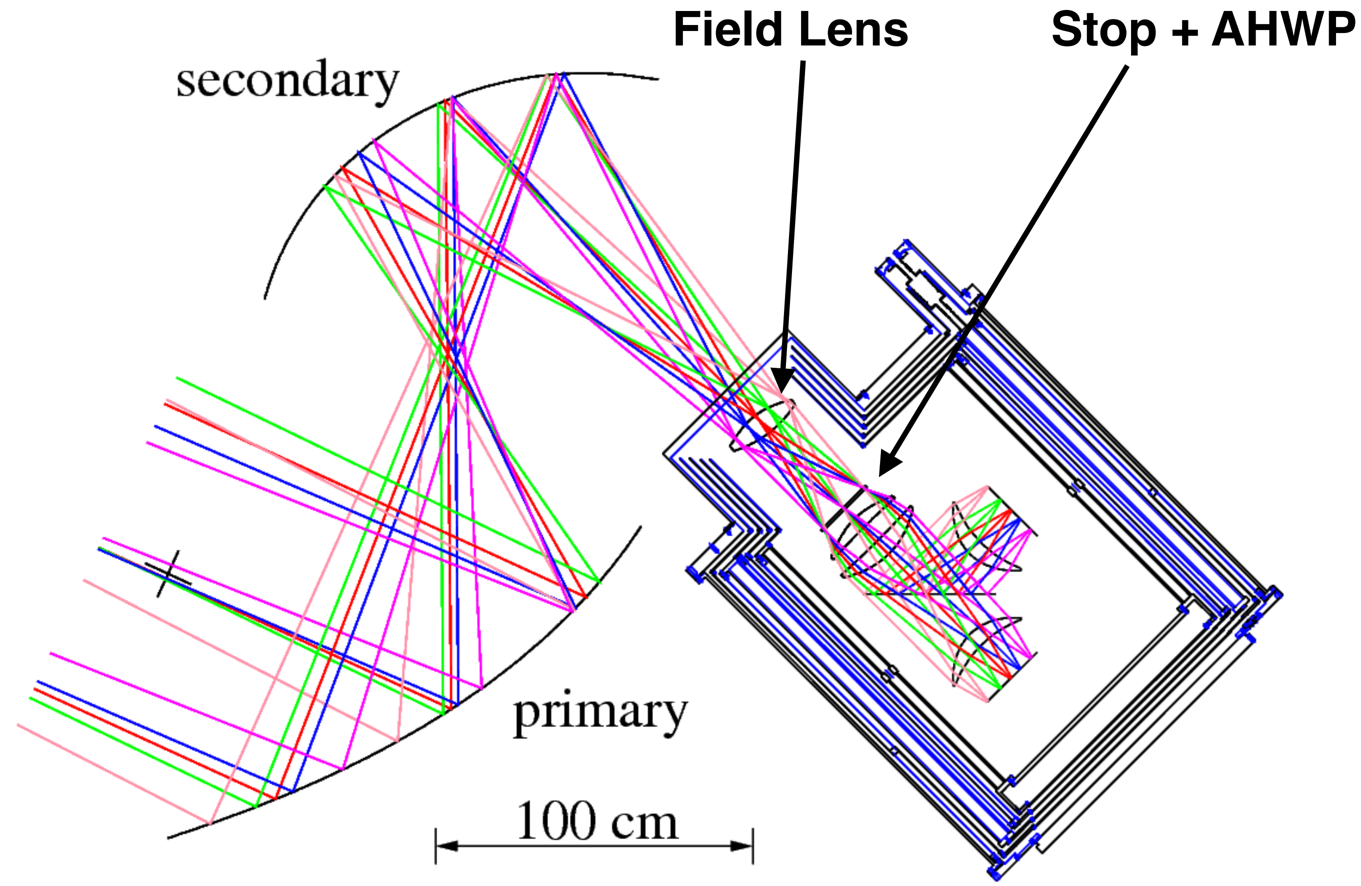
Time Domain Data

- Post demodulation signal is white to low frequencies

Sample Q power spectrum

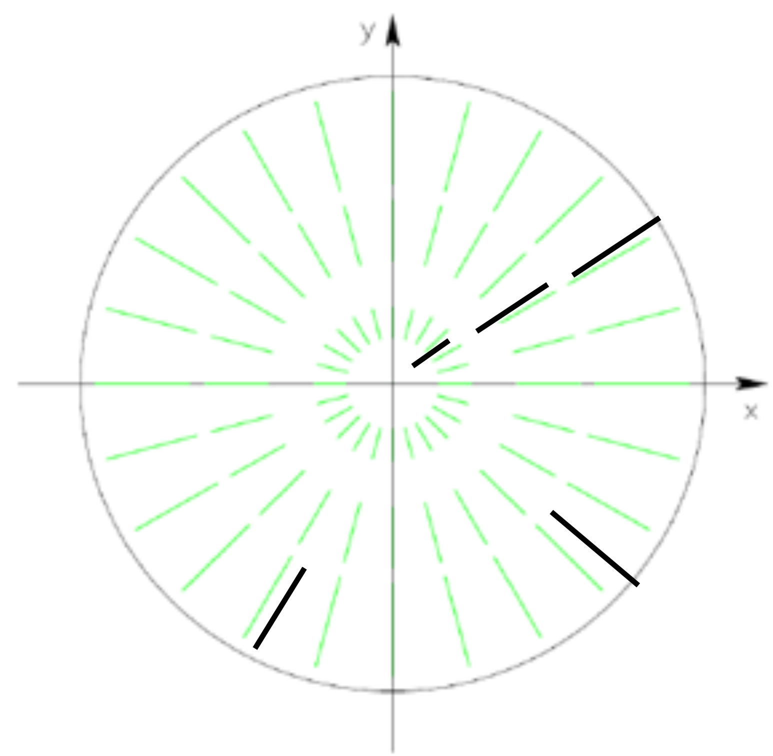


Instrumental Polarization by Field Lens



4th harmonic

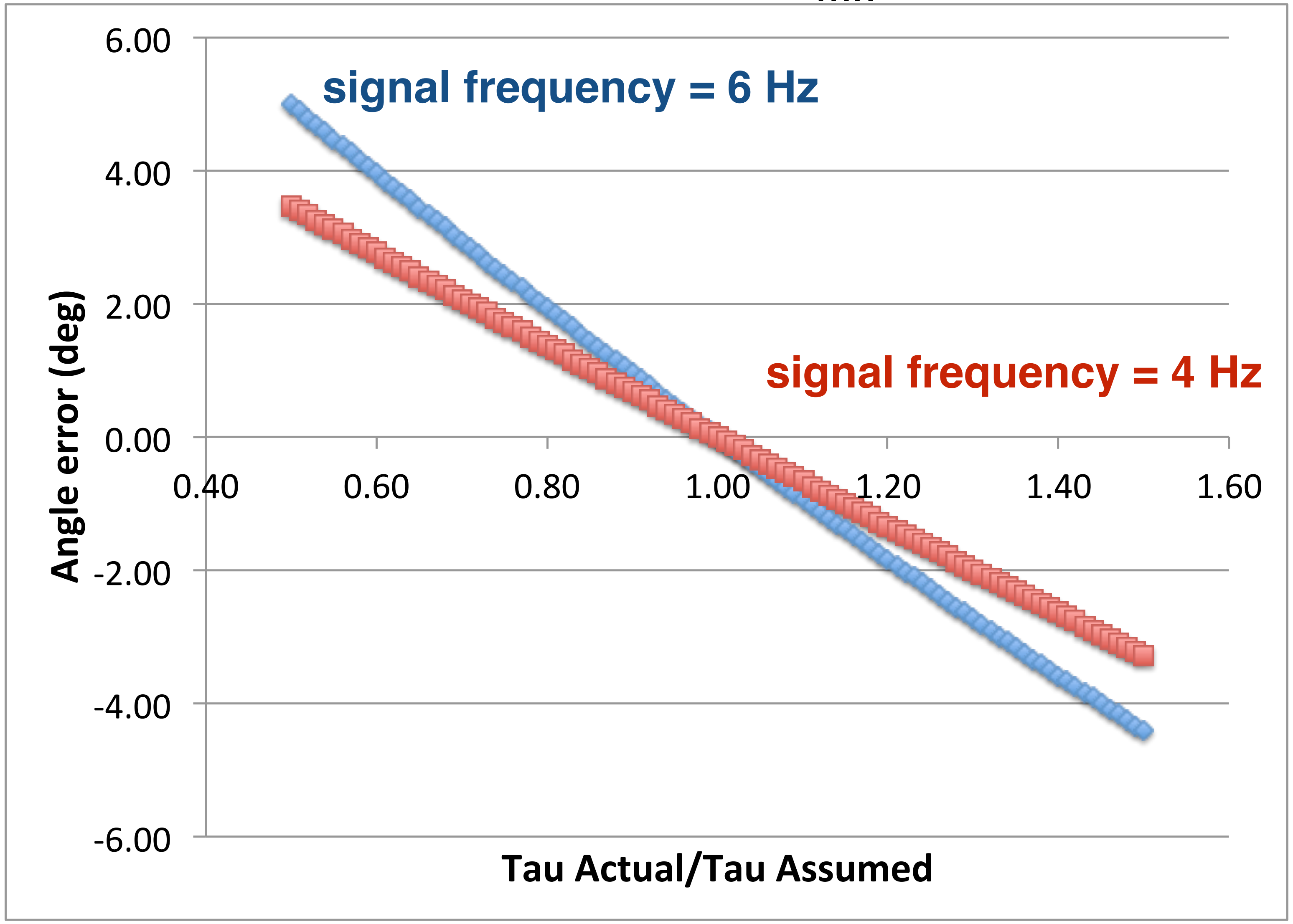
- Differential transmission through field lens polarizes mirror emission
- radially larger vectors
- phase rotates with azimuthal angle; expect slope=2



Transfer Function Uncertainty

- The bolometer time constant is a complex filter that phase shifts Q,U signals relative to nominal HWP angle
- Uncertainty in the time constant is a conversion of Q<=>U and E<=>B.
- Sources for time constant uncertainty:
  - measurement uncertainty
  - changes in loading, bias point, bath temperature
- Currently largest source of uncertainty in the EBEX polarization calibration.

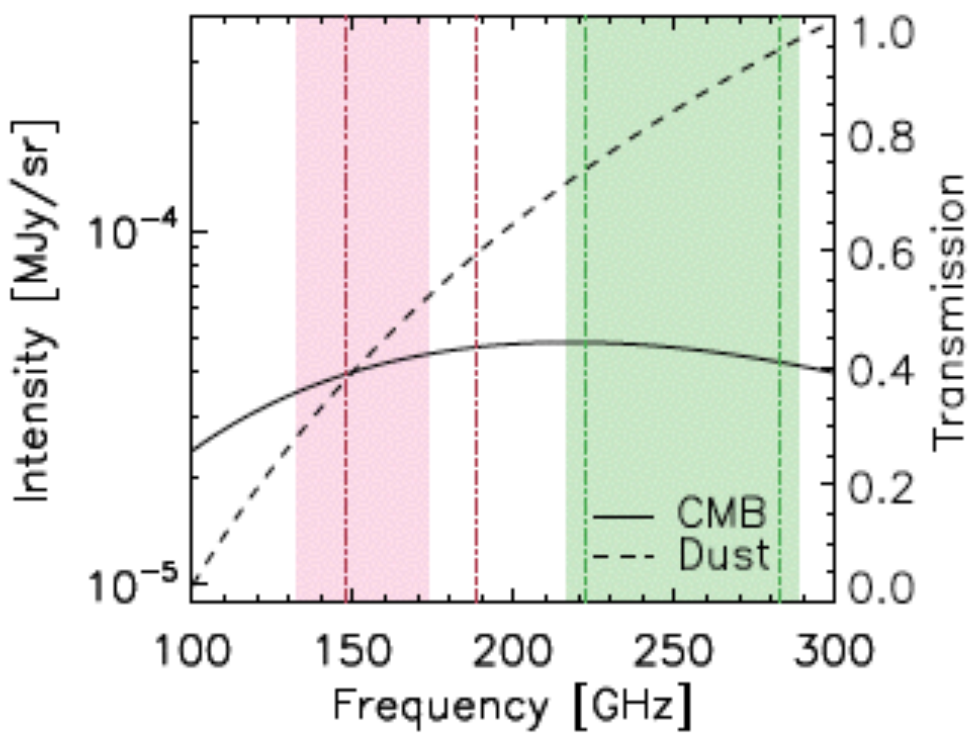
Tau assumed = 10 ms
$4f_{HWP}$ = 5Hz



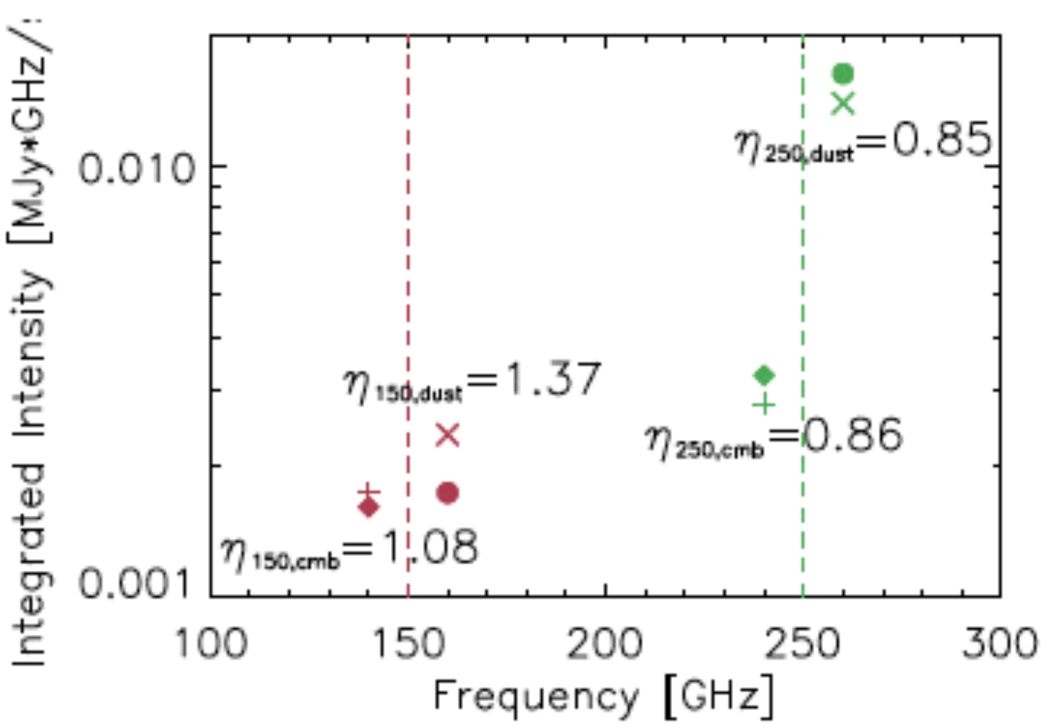
Is the AHWP Phase Variability a Surmountable Issue?

Bao et al. 2015

- The phase output of an AHWP depends on the only-partially-known
  - spectrum of the dust
  - instrumental frequency bands
  - AHWP properties (plates' thickness, indices, rotations)



- Define 'scaling coefficient' per band, per source
  - ratio: (assumed power)/(real power)



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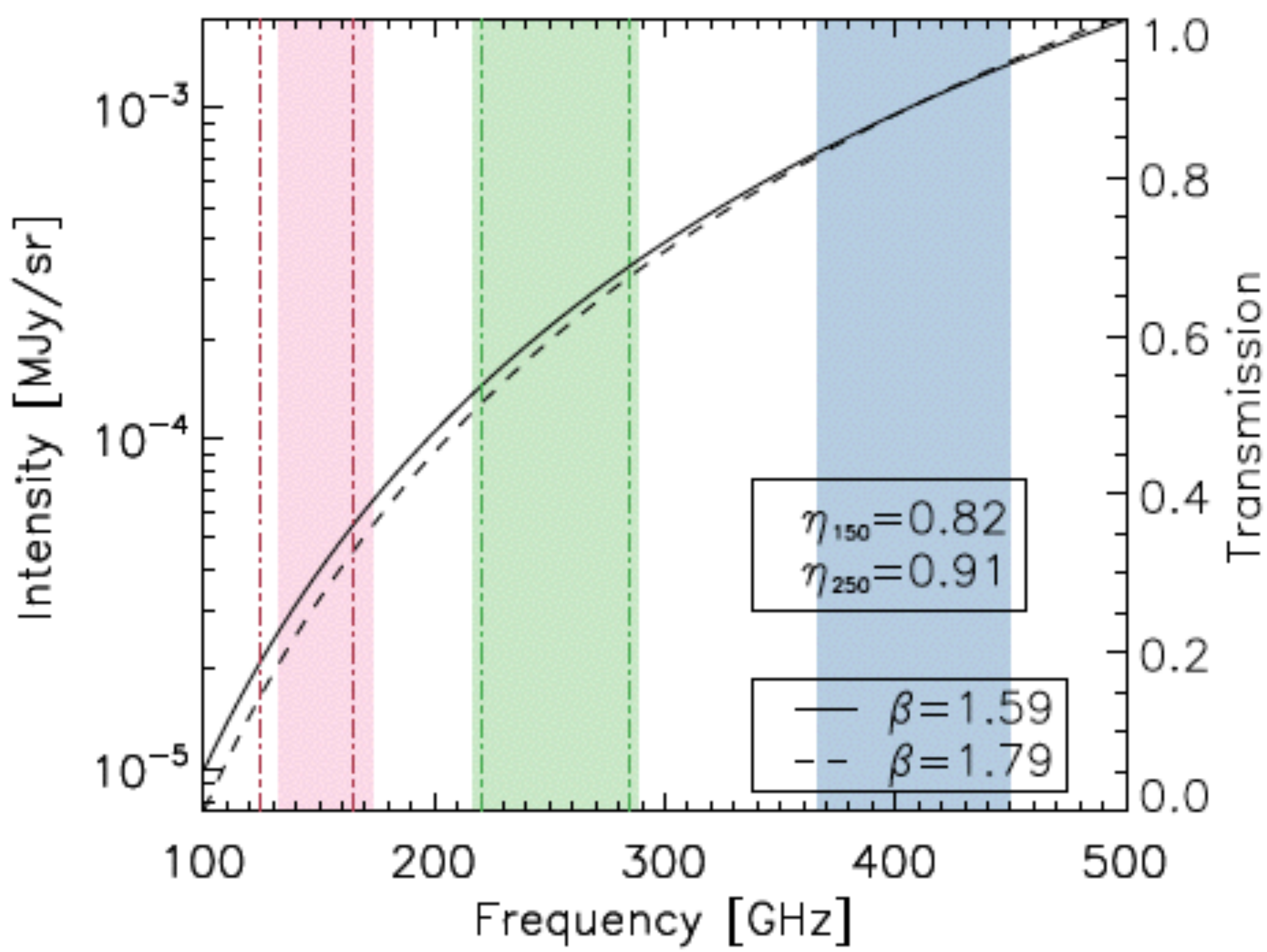
Example Degeneracy

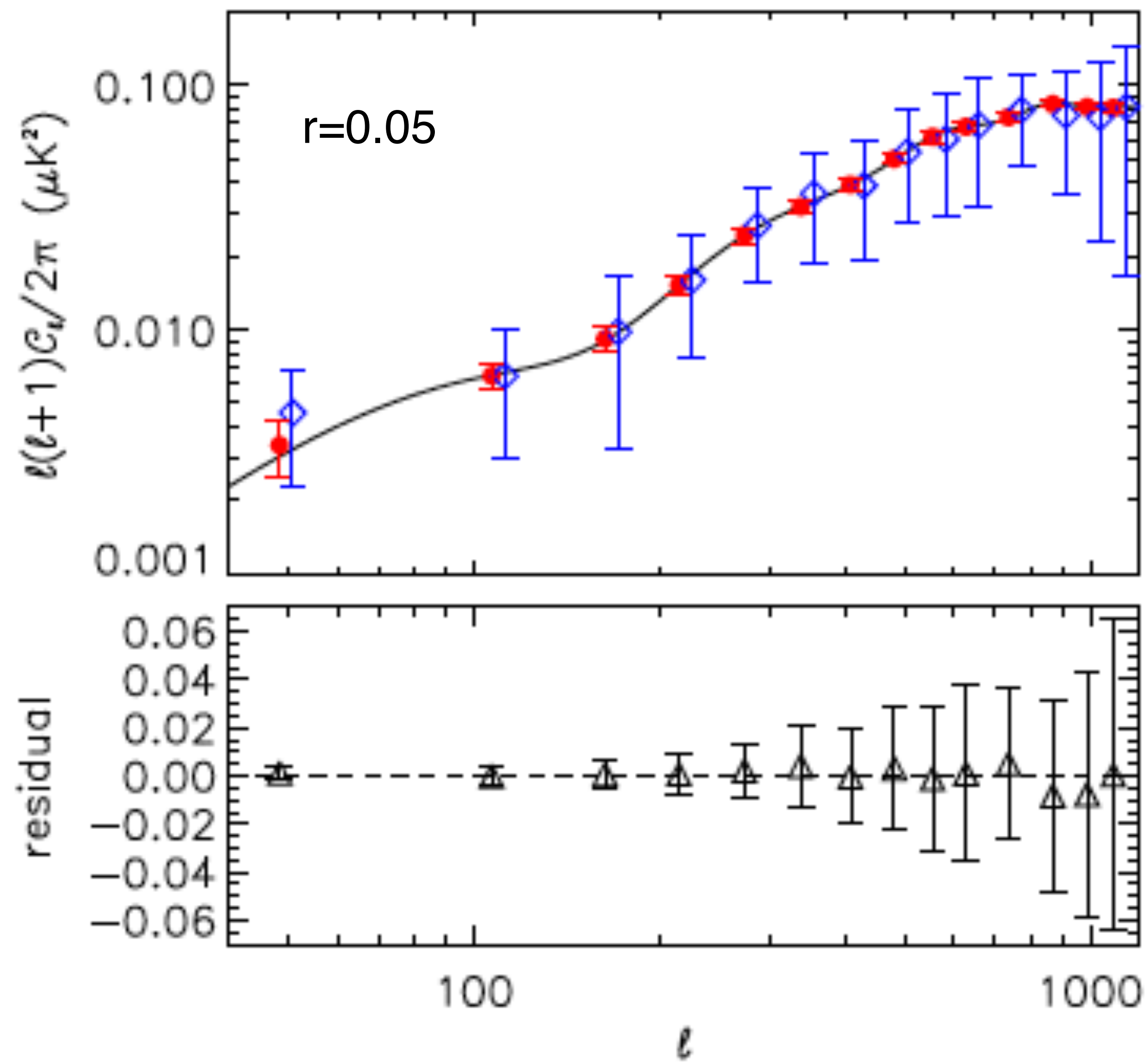


- Define 'scaling coefficient' per band, per source
  - ratio: (assumed power)/(real power)

Is the AHWP Phase Variability a Surmountable Issue?

Bao et al. 2015

- Use maximum likelihood parametric fitting (Stompor et al. 2009)
- Solve simultaneously for the foregrounds AND for the instrumental parameters:
  - band center + width
  - band averaged rotation angle
- Use priors to constrain fitting parameters
- Prior = measurement errors
- Conclusion: not an issue for EBEX2013



5% Gaussian Priors on scaling coefficients
4 deg Gaussian priors on rotation angles

EBEX2013 Modulator

- SMB worked well
- 651,000 rotation for the small SS ball bearings
- Angular encoding x10 better than required
- Signals are near 5 Hz, away from 1/f noise
- Noise is white post-demodulation
- If LiteBIRD uses a modulator:
    - have it as the first element in the light path (as you already do)
    - have a good plan for accounting for uncertainties in the transfer function (bolo tau)

Extra Slides