# Optical designs and performance of LiteBIRD

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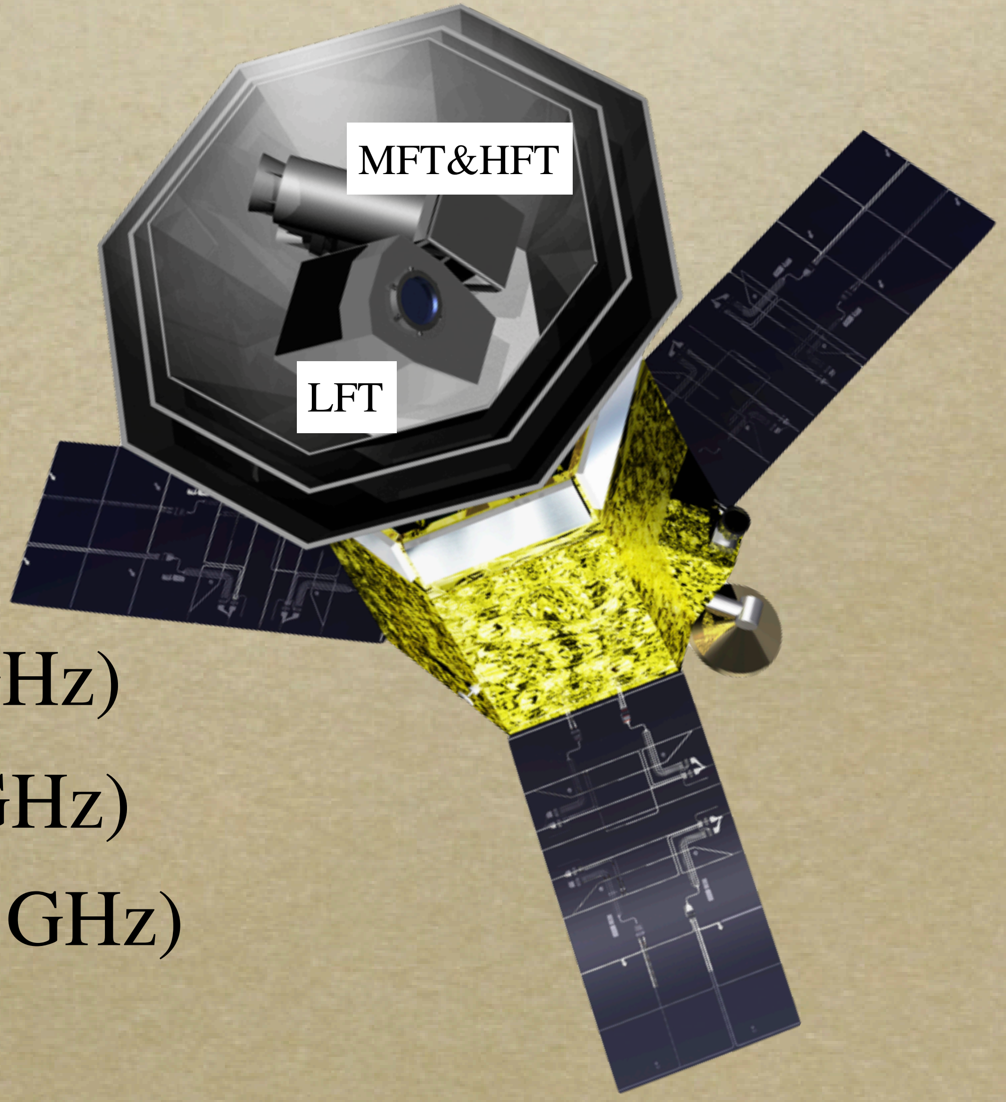
LiteBIRD collaboration

17 Feb. 2020

# Introduction

- LiteBIRD — **Lite** satellite for the studies of **B**-mode polarization and **I**nflation from cosmic background **R**adiation **D**etection
  - CMB B-mode polarization by the primordial gravitational wave
- Mission goal: $\delta r < 0.001$ (for $r$=0)
- Mission requirements (regarding an optical performance)
  - angular multipole: $2 \leq l \leq 200$
    - ➡ telescope beam size
  - observing frequency: 34 — 448 GHz
    - ➡ three telescopes
- Telescopes
  - Low Frequency Telescope (LFT, 34 — 161 GHz)
  - Mid Frequency Telescope (MFT, 88 — 224 GHz)
  - High Frequency Telescope (HFT, 166 — 448 GHz)

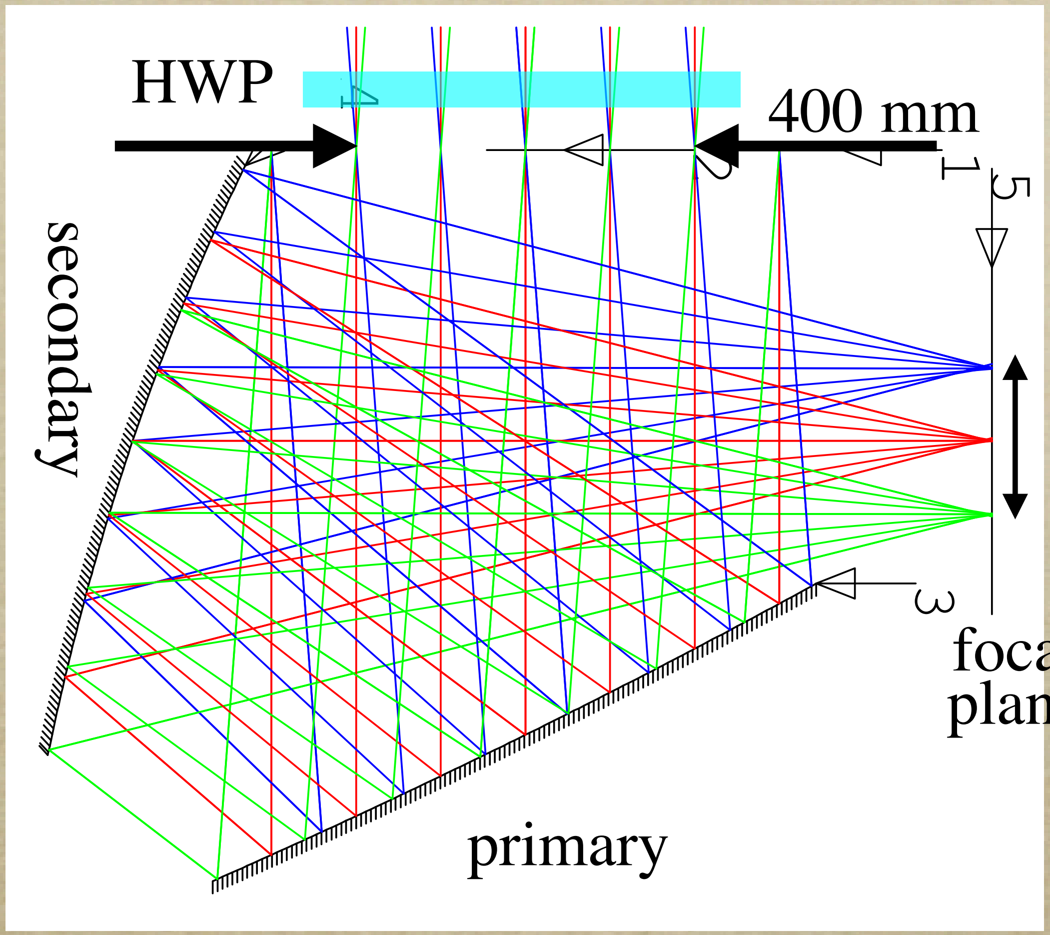


# Optical Configuration

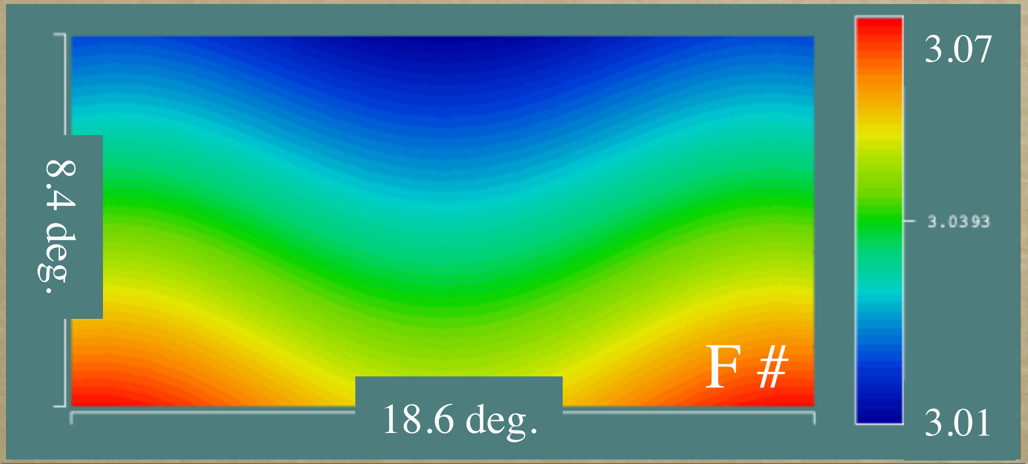
- ❖ Basic configuration
  - polarization modulator
    - ✓ birefringent-based half wave plate (HWP) or meta-material-based one
  - telescope
    - ✓ reflective or refractive
  - detector array
    - ✓ dielectric lens or feed horn (with TES)
- ❖ LFT (which this talk focuses on)
  - sapphire-based HWP, reflective (crossed Dragone telescope), silicon lenslet + sinuous antenna
- ❖ MFT
  - metal-mesh-based HWP, refractive (two lenses), silicon lenslet + sinuous antenna
- ❖ HFT
  - metal-mesh-based HWP, refractive (two lenses), feed horn

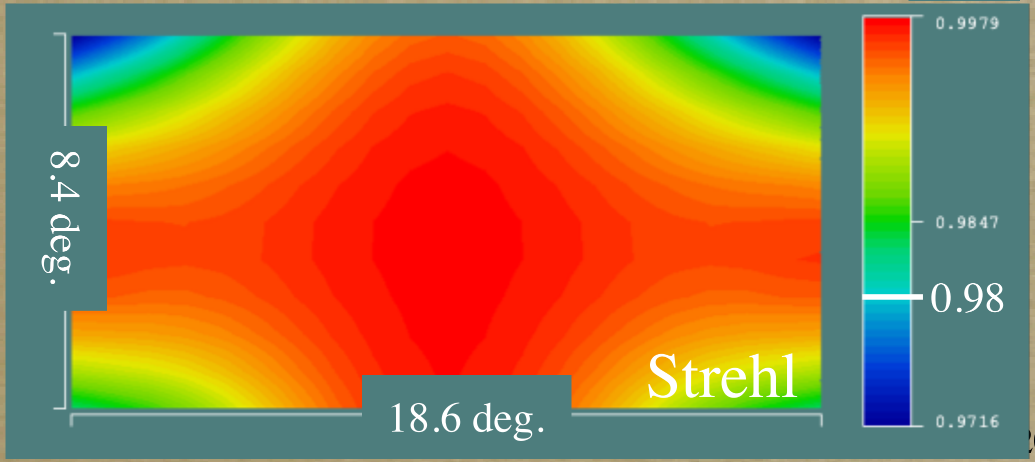
# Optical Design (LFT)

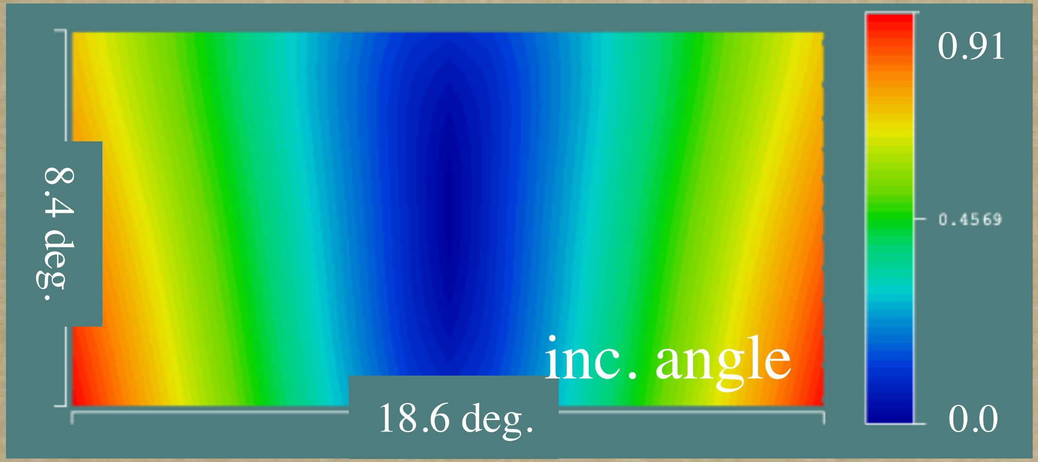
❖ Specifications
- 400-mm aperture
  - ✓ spatial resolution 20 ~ 70 arcmin.
- F number: ~ 3
- Strehl ratio: > 0.98 @ 150 GHz
- field of view: ~ 20° x 10°
- incident angle to focal plane < 0.5°




provided by S. Kashima

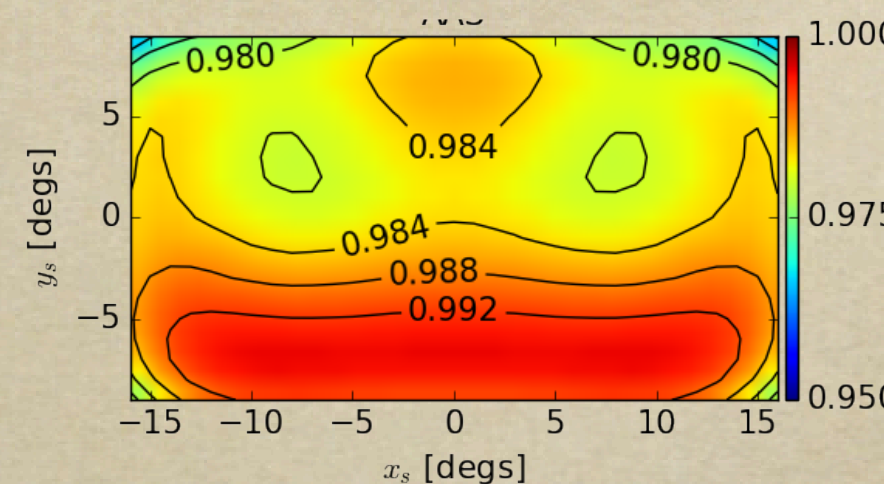


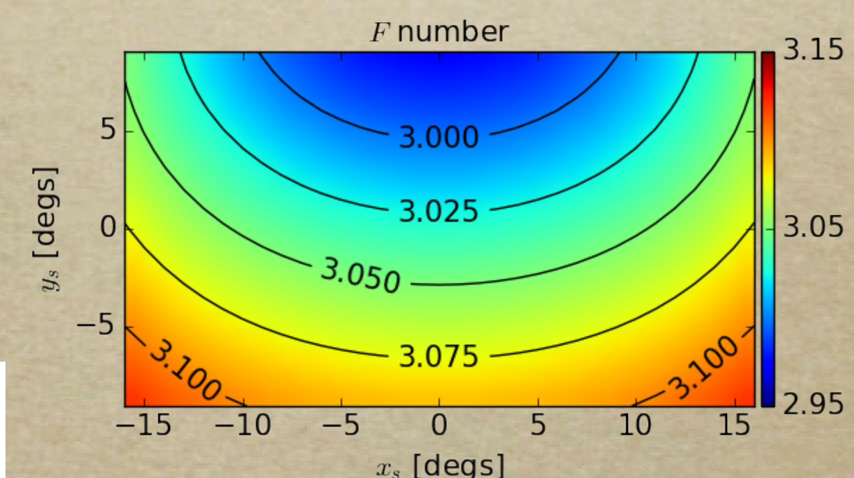



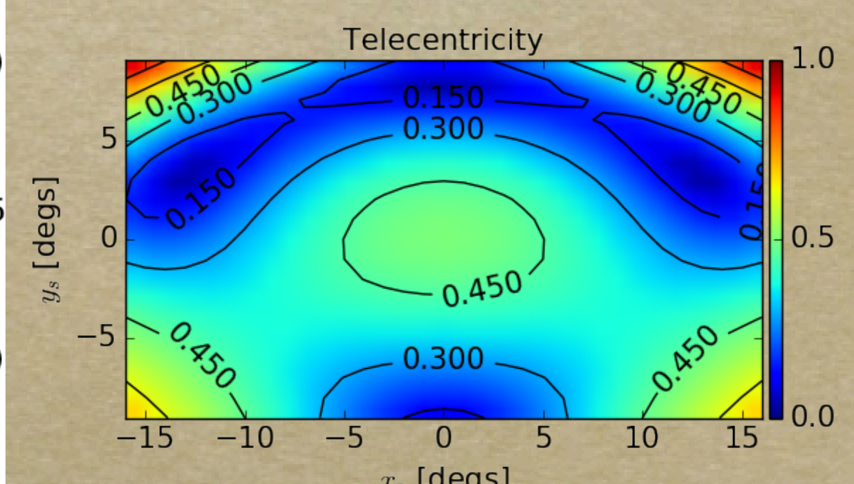



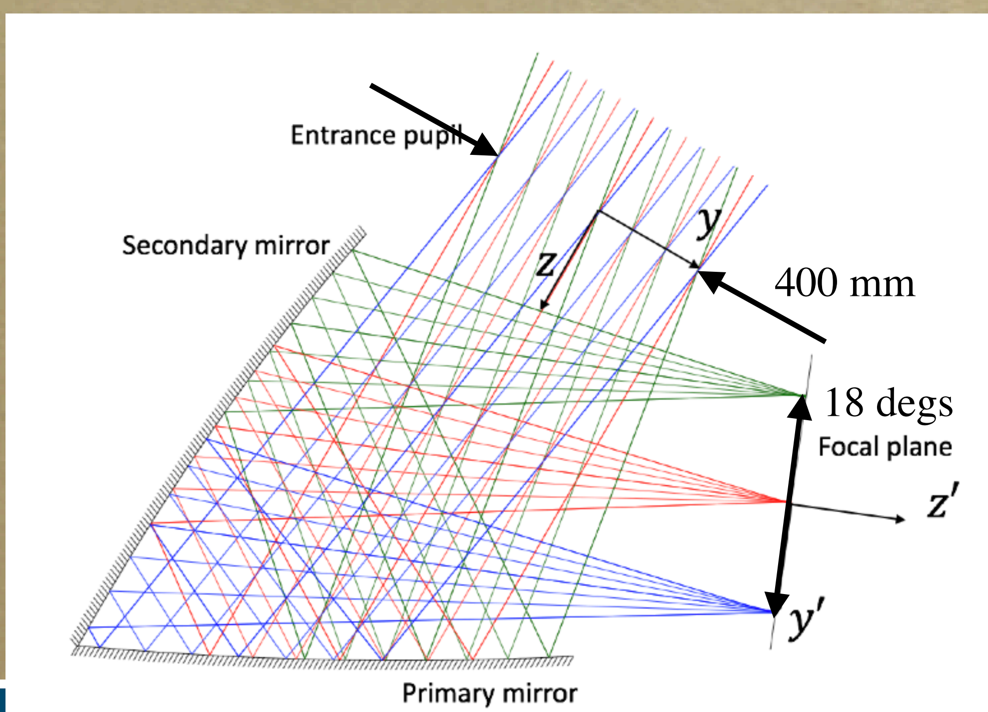
# Wide Field of View System

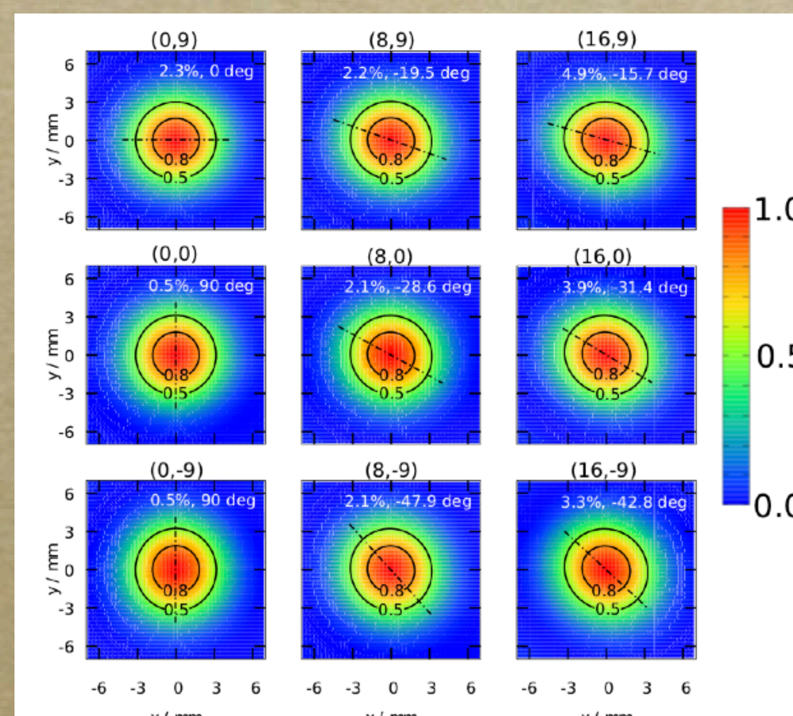
- ❖ Crossed Dragone telescope has great potential !!
  - 400-mm aperture
  - F number of 3
  - Strehl ratio: 0.98 @ 150 GHz
  - incident angle to focal plane: < 1°
- ❖ Telescope with 36°x18° FoV was obtained
  - Kashima et al. Applied Optics Vol. 57, Issue 15, pp. 4171-4179 (2018)



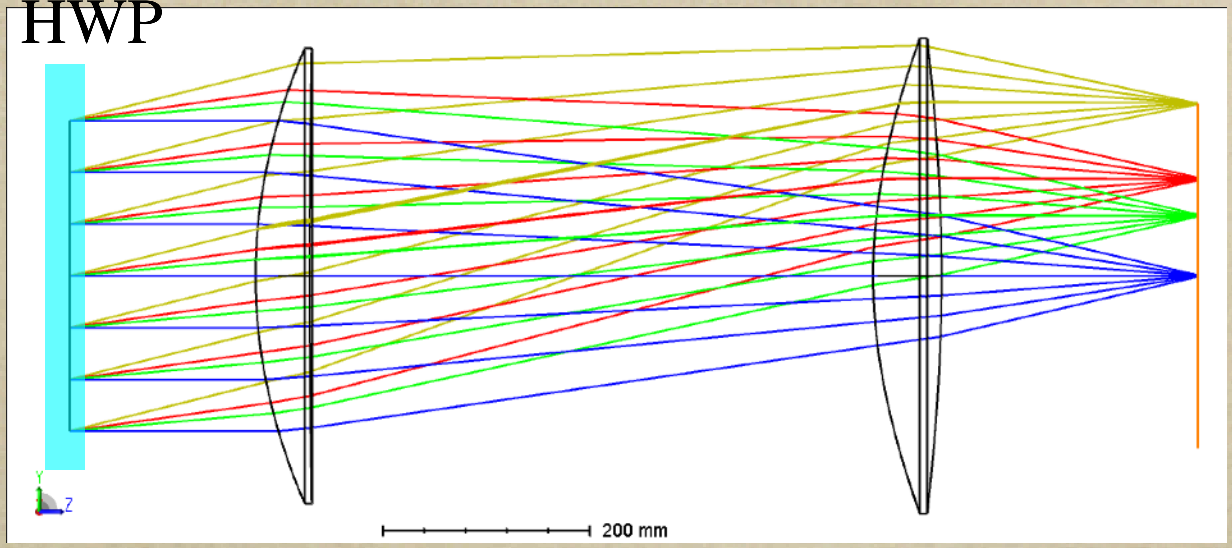



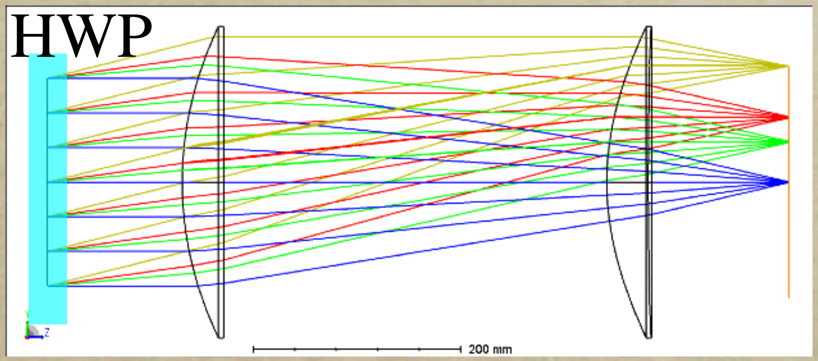



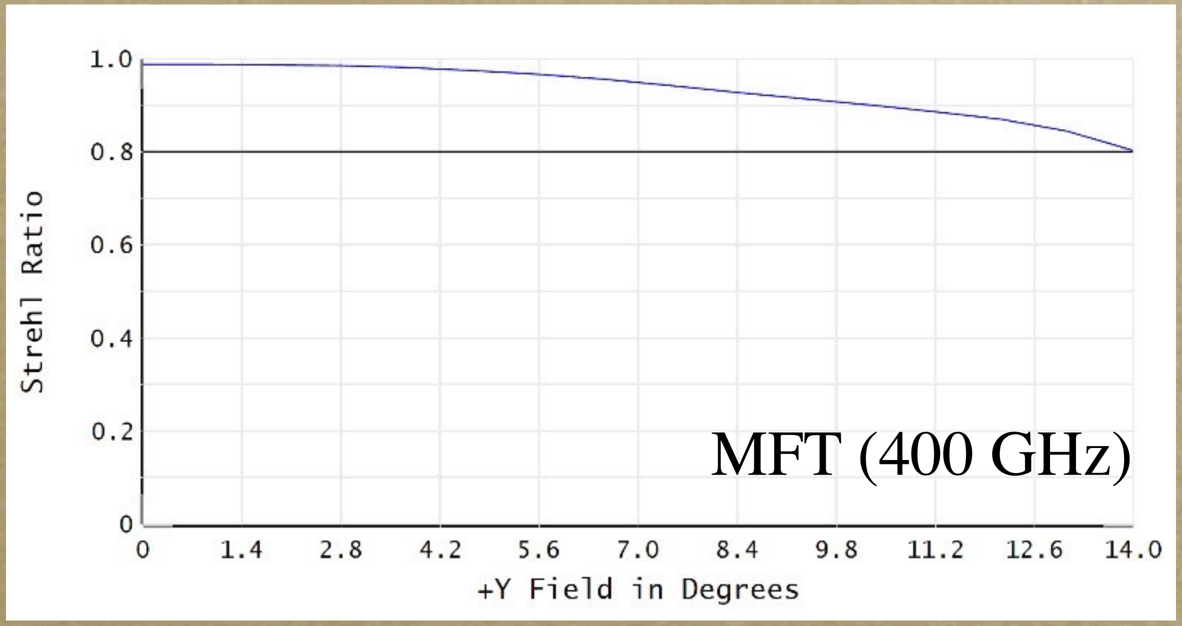
# Optical Design (MFT&HFT)

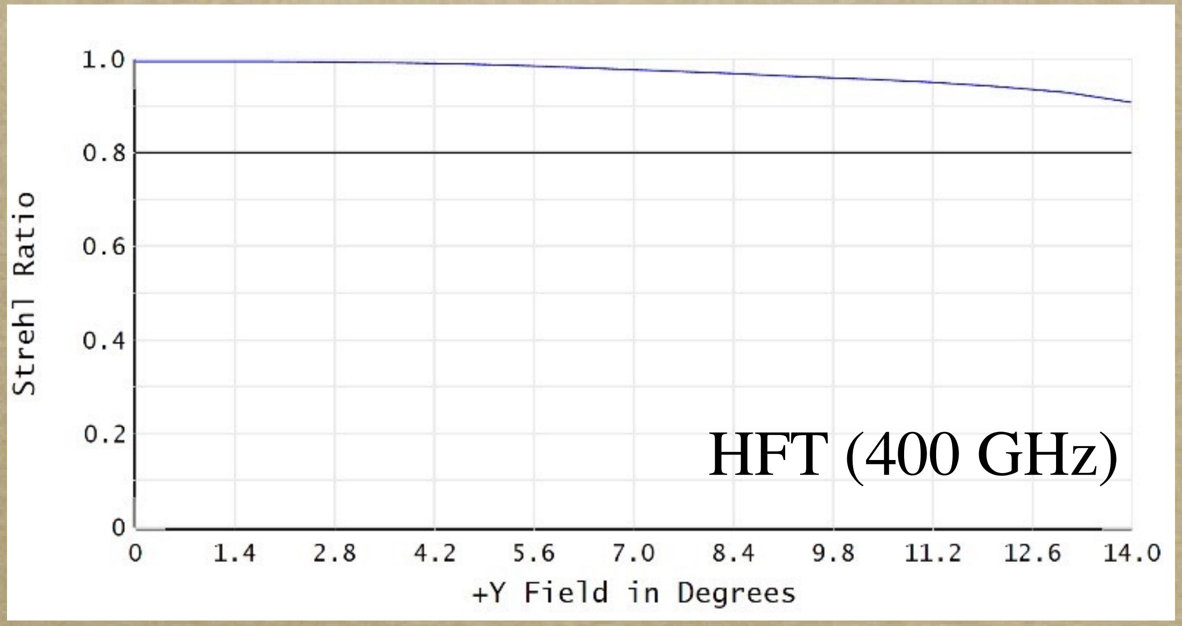
- ❖ Specifications
  - aperture
    - ✓ 300 mm for MFT, 200 mm for HFT
    - ✓ spatial resolution 20 ~ 38 arcmin.
  - F number: ~ 2.2
  - filed of view: 28° in diameter
- ❖ Still under study




MFT (top)
HFT (left)

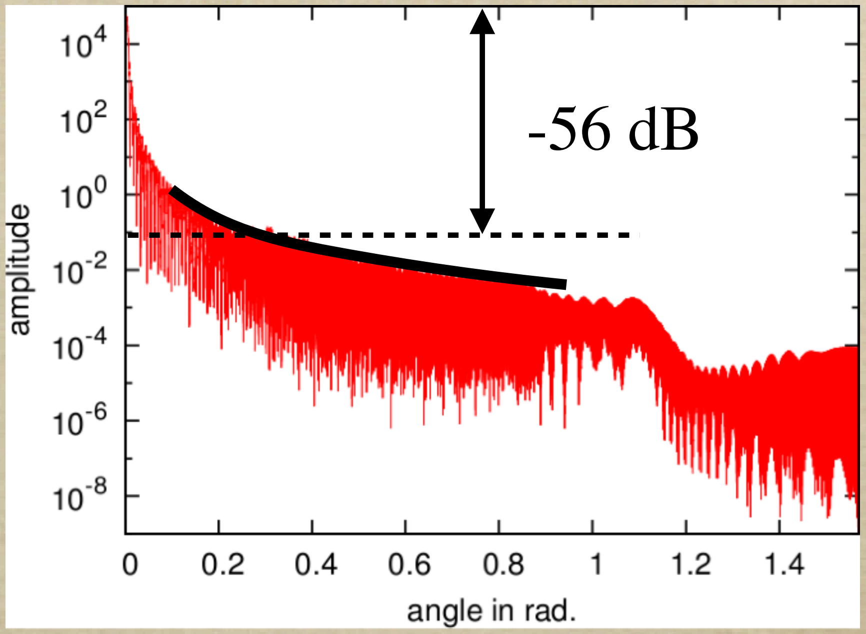


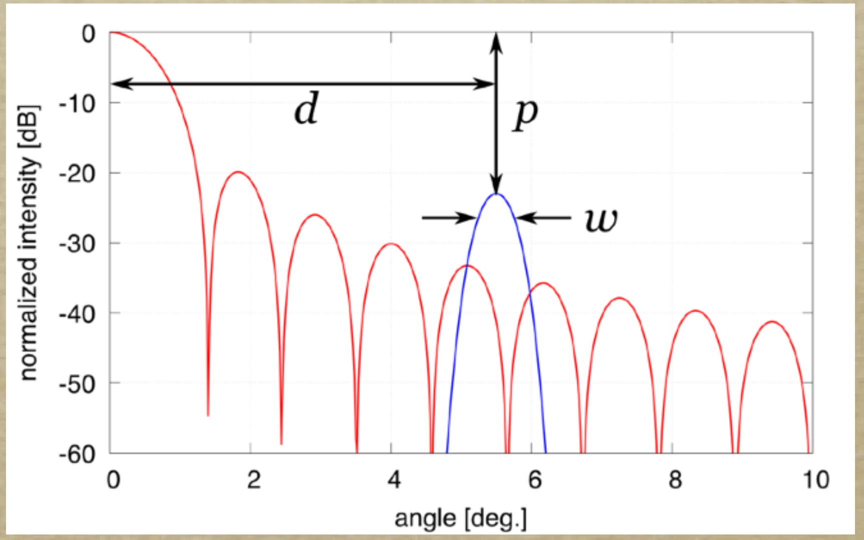




provided by P. Hargrave

# Beam Systematics

- ❖ Many items to consider
  - beam itself: main and side lobes, polarization, etc.
  - related factors: scan strategy, band pass, etc.
- ❖ Criteria on side lobe (by R. Nagata)
  - derived from the polarized foreground
    1. side lobe level (~10° far from main lobe)
       - ✓ suppress < -56 dB or calibrate > -56 dB
         - ➡ applicable to "normal" diffraction pattern (large scale) like Airy disk
    2. side lobe level
       - ✓ satisfy the inequalities or calibrate
         - ➡ applicable to small scale features like stray light, ghost etc.



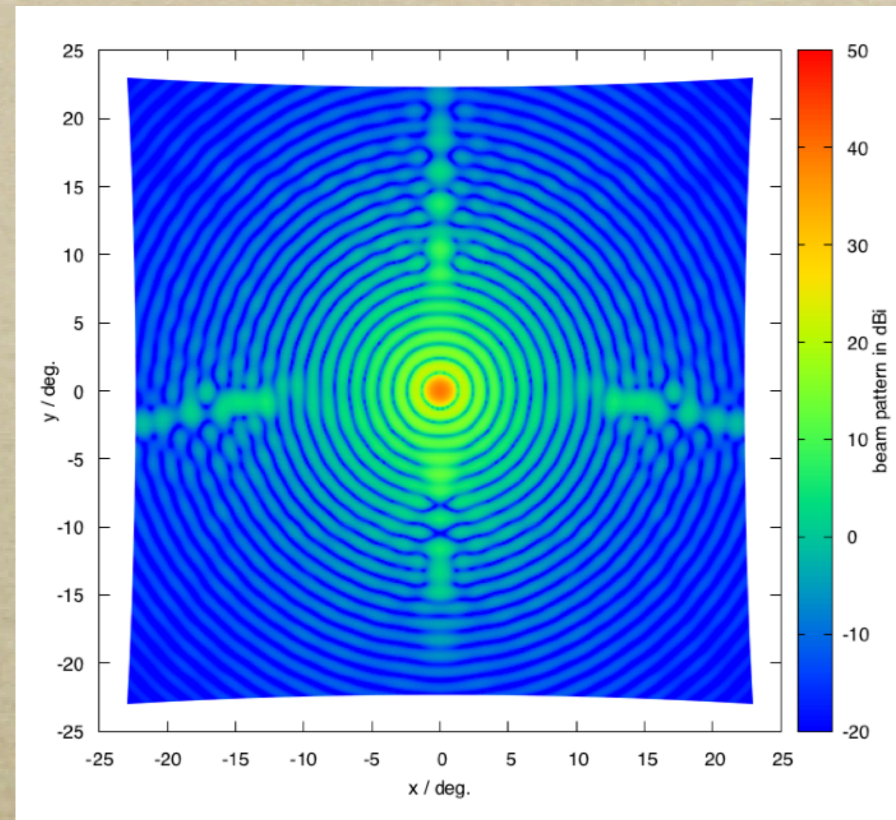




$$\left(\frac{d}{7\,\mathrm{deg.}}\right)\left(\frac{p}{0.03}\right)\left(\frac{w}{30\,\mathrm{arcmin}}\right)^2 \leq 1,$$

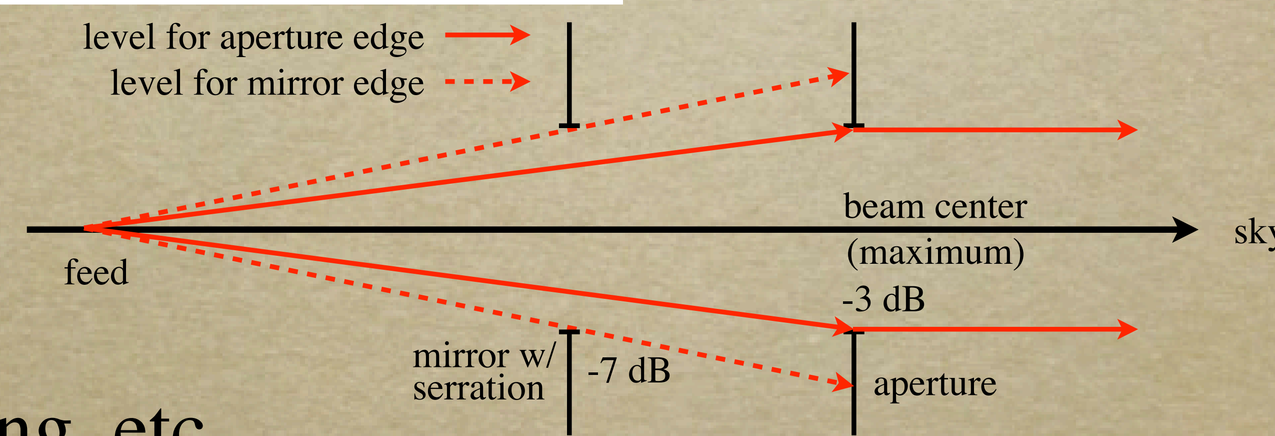
$$\left(\frac{p}{0.001}\right)\left(\frac{w}{30\,\mathrm{arcmin}}\right)^2 \leq 1$$

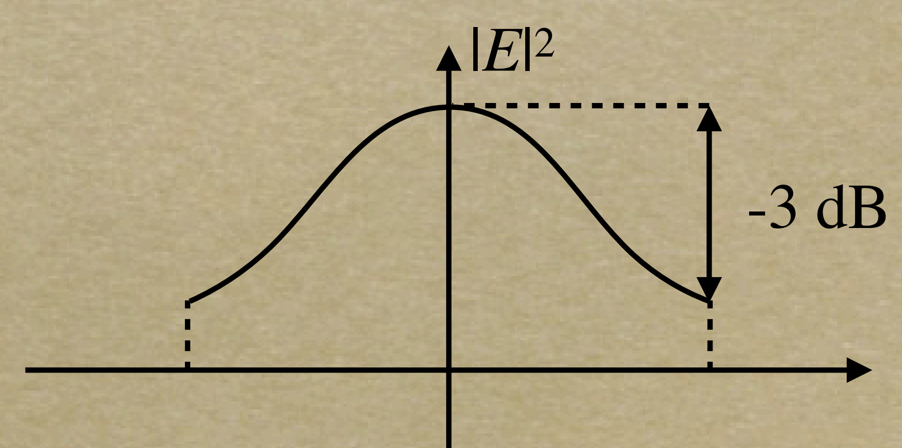
# Beam Systematics

- ❖ Additional side lobe
  - diffraction at mirror edges
    - ➡ relatively large scale
  - stray light & ghost
    - ➡ small scale
- ❖ How to mitigate
  - diffraction at mirror edges
    - ✓ serration & large mirror size
  - stray light & ghost
    - ✓ baffle, arrangement of optical components, anti-reflection coating, etc.
  - Imada et al., Proc. SPIE, 10698, 106984K (2018)




| vel at erture | level at mirrors | ratio of beam size |
|---|---|---|
| .5 dB | -5 dB | 1.83 |
| 3 dB | -7 dB | 1.53 |
| 4 dB | -9 dB | 1.50 |
| 6 dB | -12 dB | 1.41 |
| 8 dB | -14 dB | 1.32 |
| 0 dB | -16 dB | 1.26 |




e.g. energy distribution on aperture

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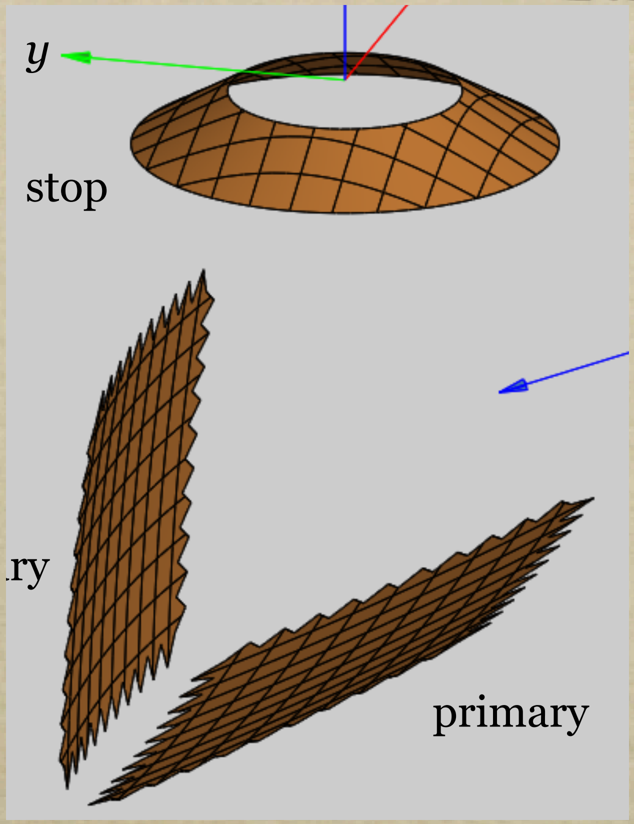


| level at aperture | level at mirrors | ratio of beam size |
|---|---|---|
| -1.5 dB | -5 dB | 1.83 |
| -3 dB | -7 dB | 1.53 |
| -4 dB | -9 dB | 1.50 |
| -6 dB | -12 dB | 1.41 |
| -8 dB | -14 dB | 1.32 |
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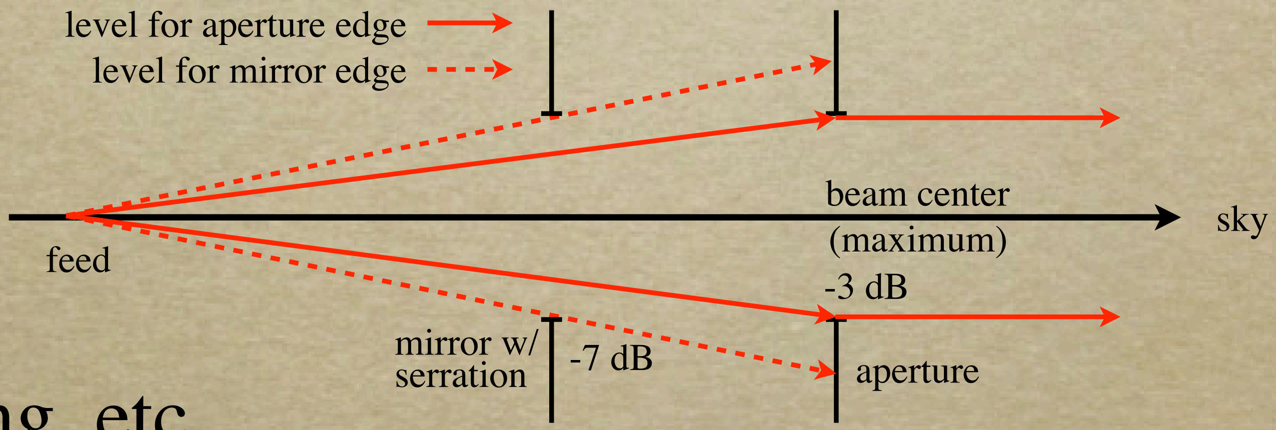
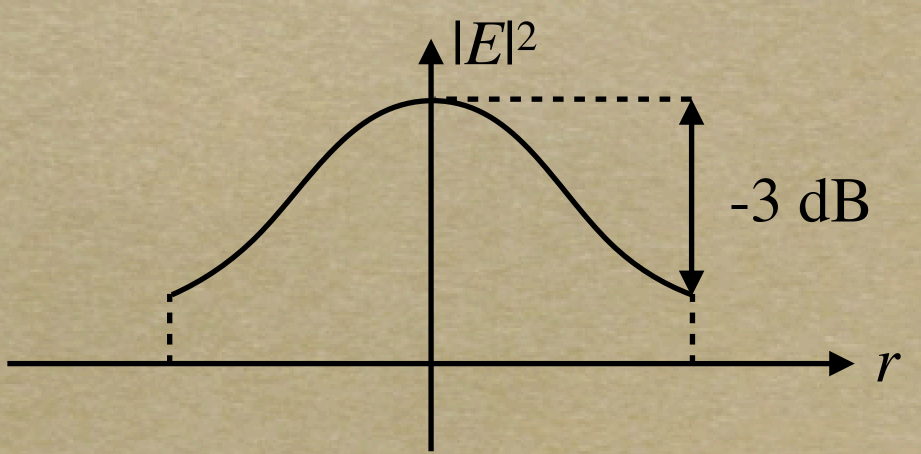
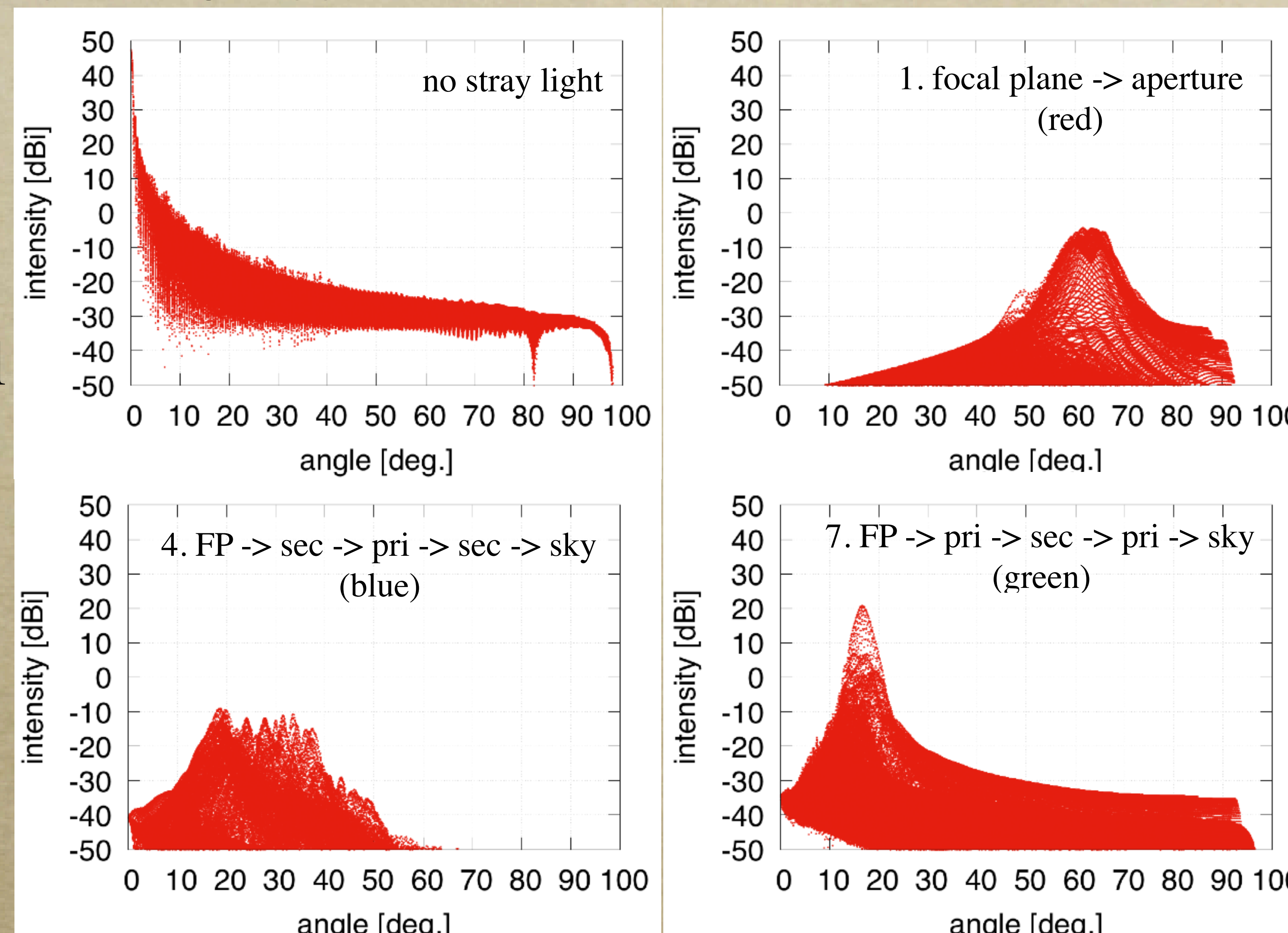


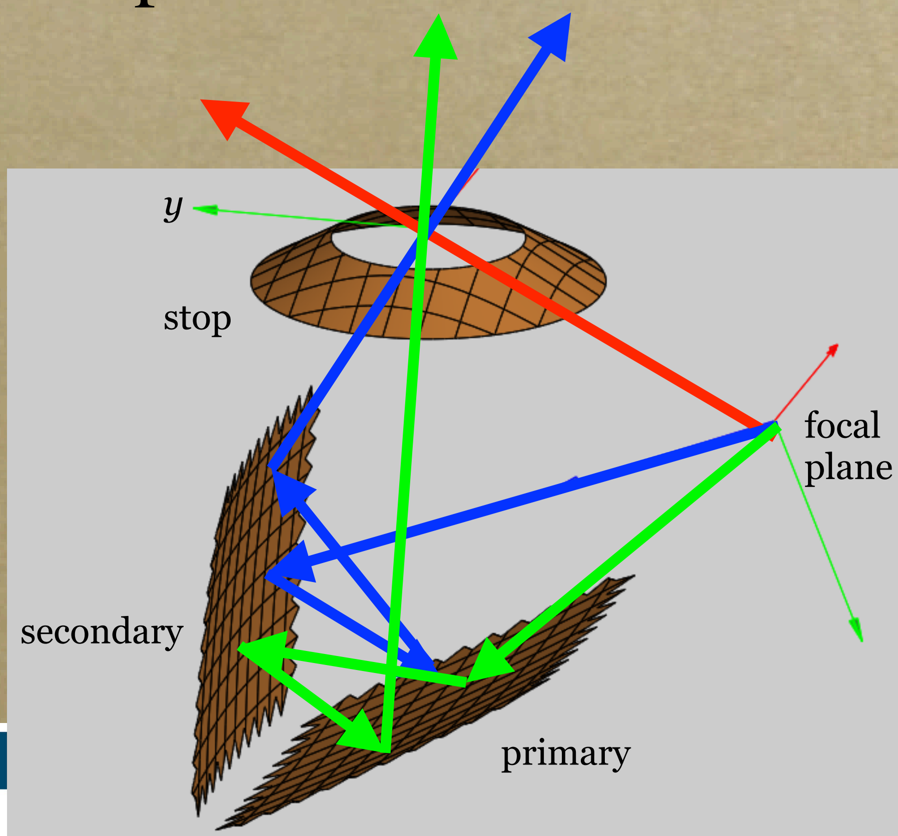




e.g. energy distribution on aperture

# Beam Systematics

- Stray light in LFT
  - silicon lenslet + sinuous antenna for feed
  - 3 significant paths
- Results
  - blue: negligible
  - red&green: baffles at focal plane and aperture stop, position of FP & mirrors

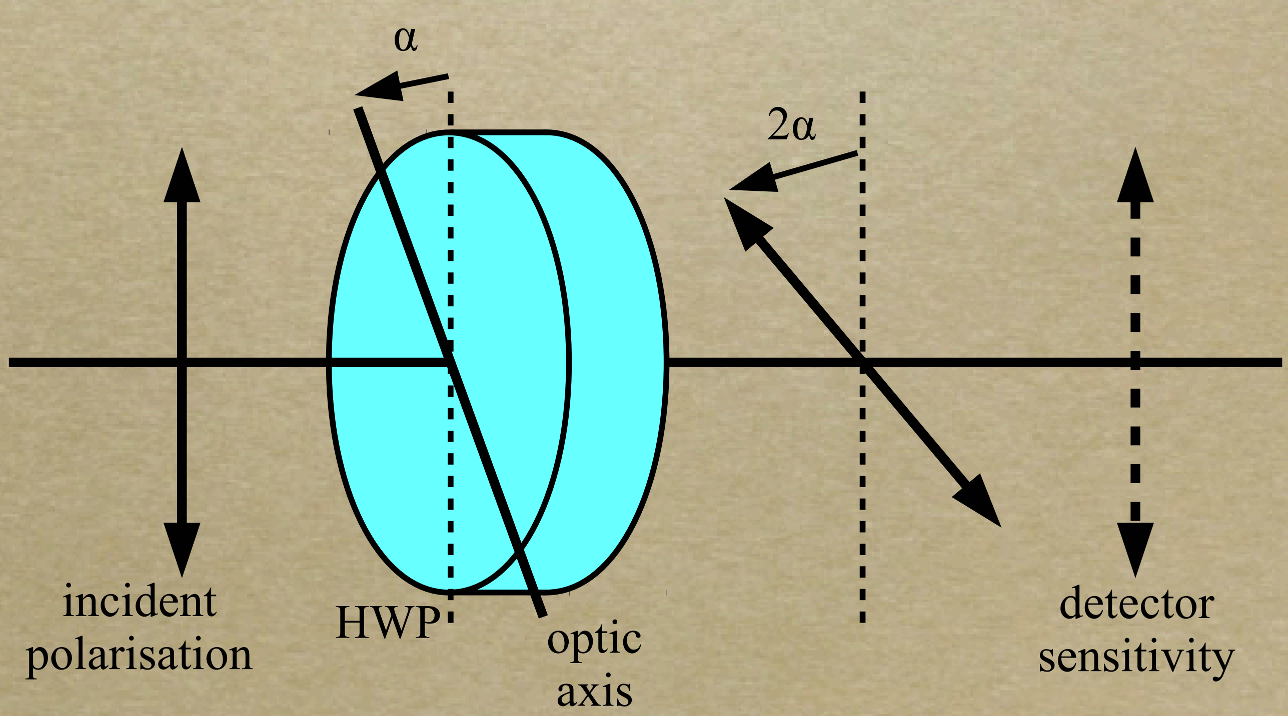



| path ID | $\left(\frac{d}{7\,\mathrm{deg.}}\right)\left(\frac{p}{0.03}\right)\left(\frac{w}{30\,\mathrm{arcmin}}\right)^2$ | $\left(\frac{p}{0.001}\right)\left(\frac{w}{30\,\mathrm{arcmin}}\right)^2$ |
|---|---|---|
| 1 | 0.4 | 1.3 |
| 4 | $4 \times 10^{-3}$ | 0.05 |
| 7 | 2.7 | 33.7 |

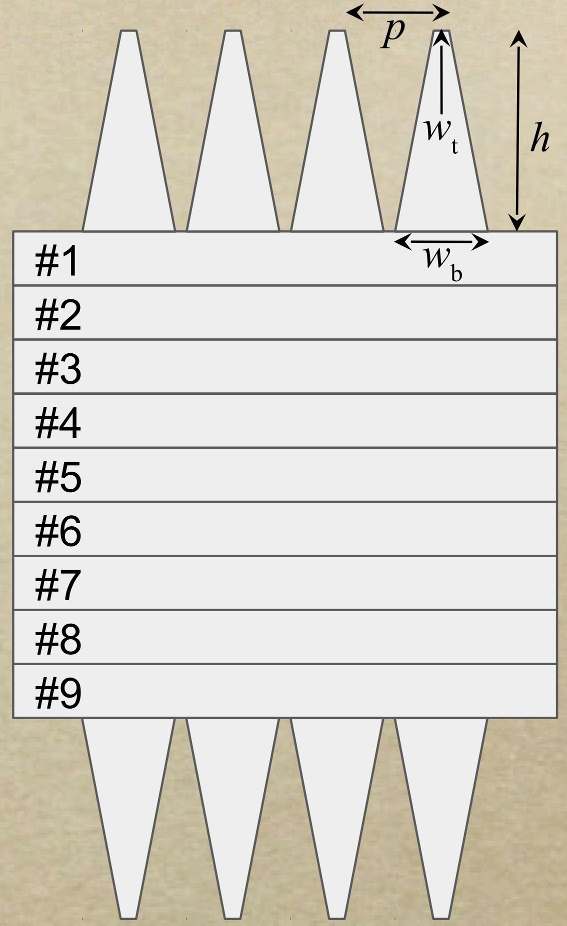
# Polarization modulator

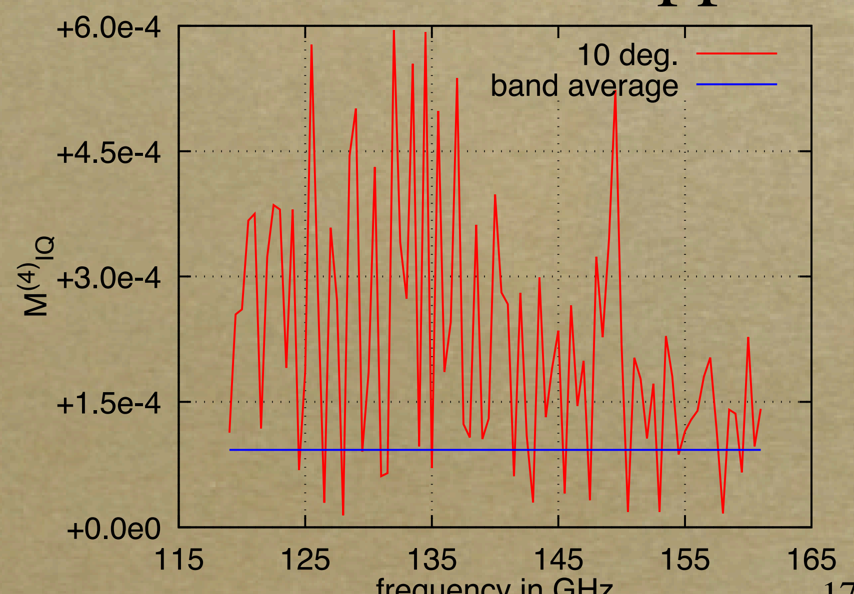
- Key component of telescopes on LiteBIRD
  - to mitigate the effects of 1/*f* noise, mismatches between detectors
- How to work
  - HWP rotates linear polarization: twice as the angle b/w incoming polarization and optic axis of HWP
  - every time HWP rotates by 90 degs. the outgoing polarisation and detector sensitivity are parallel
    - ➡ detector output oscillates at 4 times higher frequency of rotation when a linear polarization enters the HWP
- Systematics
  - birefringence-based HWP generates false polarization
    - ✓ oblique incidence is one of the causes

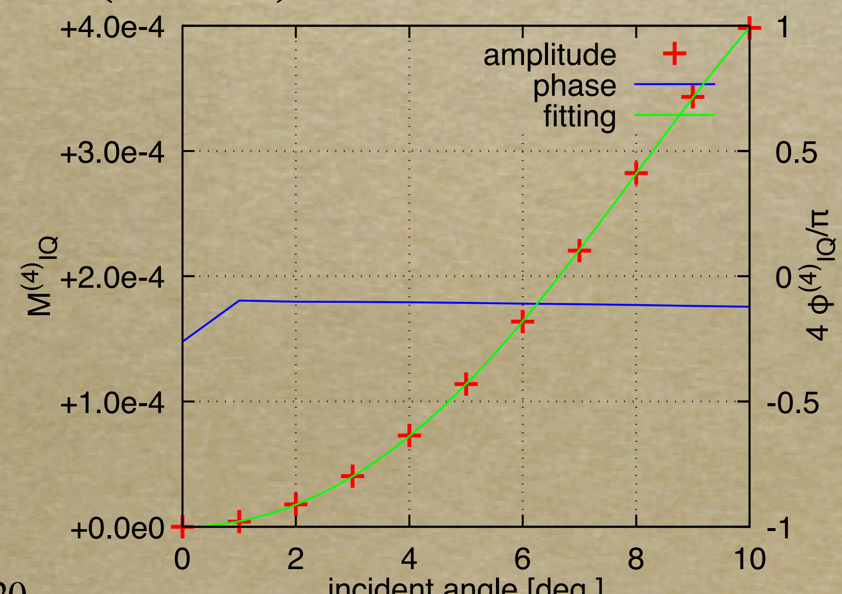


# Instrumental Polarization by HWP

- ❖ Electromagnetic simulation
  - Pancharatnam-type HWP made of 9 Sapphire plates
    - ✓ with subwavelength structure for antireflection
  - linearly polarized plane wave
  - in the 140-GHz band with 0.5-GHz intervals at 10-deg. incidence
  - at 140 GHz with an incident angle of 0-10 degs.
- ❖ Conversion of unpolarized light to linear polarization
  - at 4 times higher frequency of HWP rotation
  - Imada et al., ISSTT 2018, pp. 61 — 67 (2018)



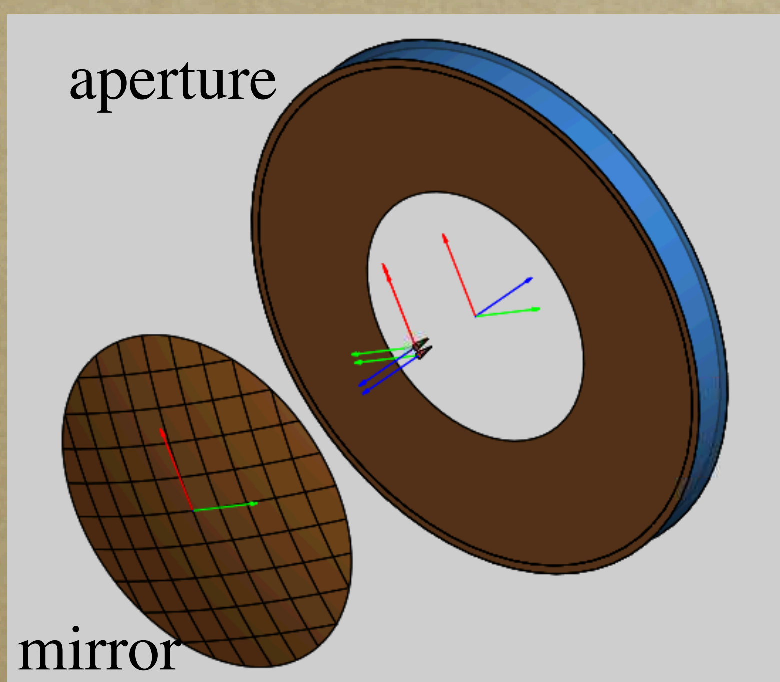



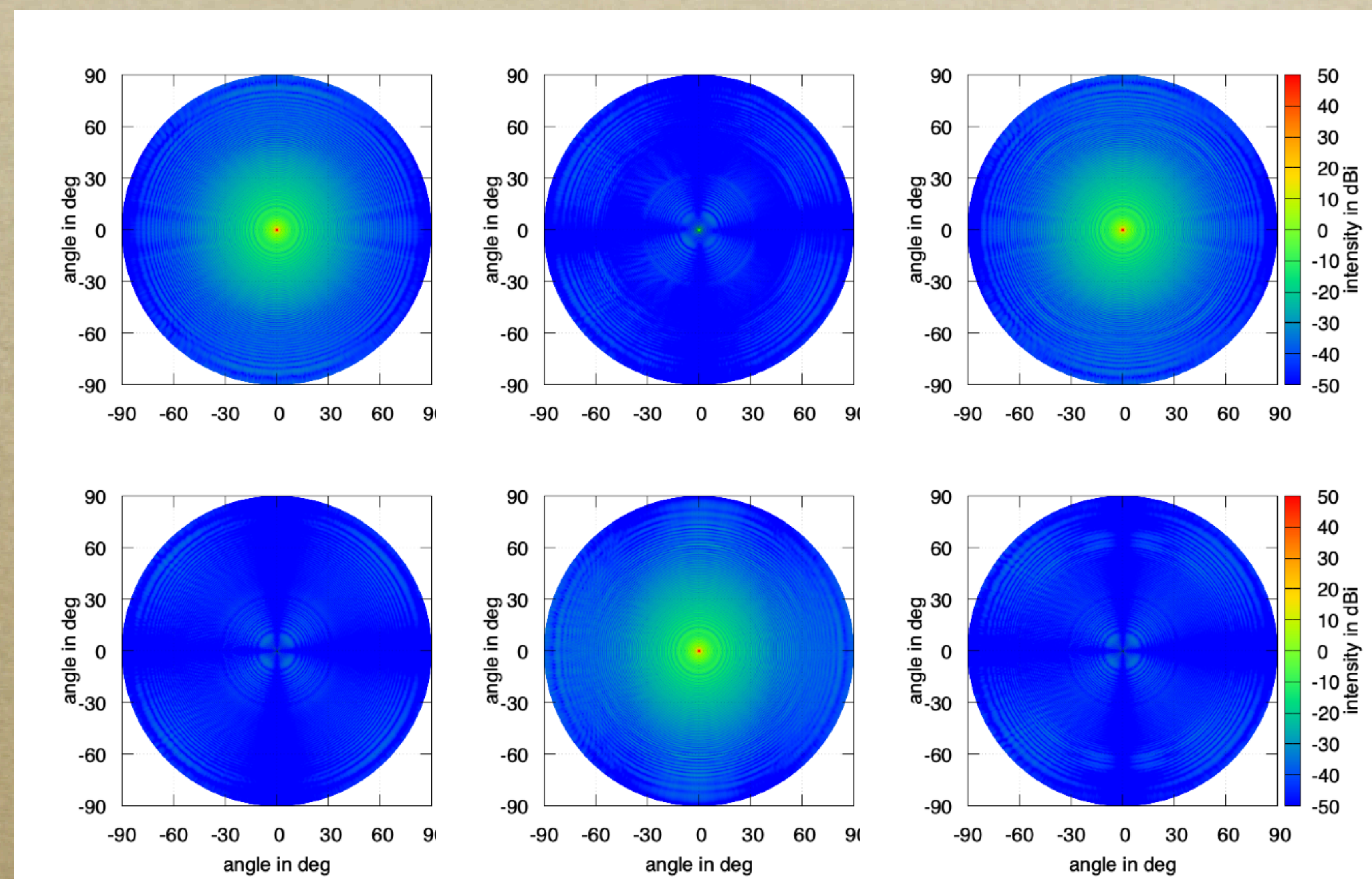
# Beam Simulation with HWP

❖ Developing simulation tool

- one mirror + 300-mm aperture + HWP at aperture
- refractive indices of HWP: $n_o$ = 3.0 & $n_e$ = 3.3 (close to Sapphire ones)
- Gaussian beam
- 88 GHz

❖ Still under study




**0 degs** **45 degs** **90 degs**

Beam pattern on the sky

upper: |$E_1$|^2, lower: |$E_2$|^2 (following the Ludwig's 3rd def.)

# Summary

- LiteBIRD has three telescopes
  - LFT (reflective), MFT & HFT (refractive)
  - a reflective system with 36°x18° FoV was achieved
  - all telescopes have a good performance: Strehl ratio, beam size, telecentricity, etc.
- Beam systematics
  - severe criteria for side lobe
  - diffraction at mirror edges made additional side lobe and affected systematics
    - ✓ the relation b/w beam size and mirror size was revealed (w/ serration)
  - stray light was identified
    - ✓ baffles and adjustment the position of mirror and focal plane
- HWP systematics
  - Pancharatnam-type HWP makes instrumental polarization
    - ✓ conversion of unpolarized to linear polarization: ~ $10^{-4}$
- References

Kashima et al. Applied Optics Vol. 57, Issue 15, pp. 4171-4179 (2018), Imada et al., Proc. SPIE, 10698, 106984K (2018), Imada et al., ISSTT 2018, pp. 61 — 67 (2018)