Optical Design Considerations in the mm/submm

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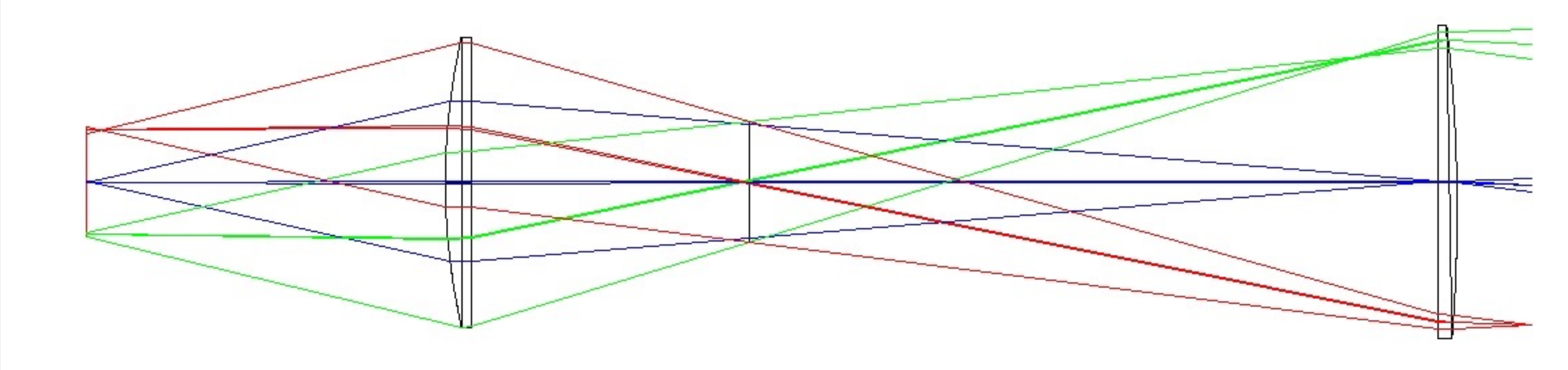


General Outline

- A detailed discussion of design considerations regarding pixel spacing
  - Don’t stress about the details, the intention is to provide context regarding the range of design considerations that are relevant for what seems like a minor attribute
  - This is based on a talk I originally gave in 2011
- Design drivers and performance of the MUSIC optics
- Design drivers for the CCAT-LWCAM optics
- Design drivers for the SKIPR optics

fλ – The Question of Pixel Spacing on the Focal Plane

- References
- Defintions
- Consequences of various spacings
- Optimal choice for various scenarios
- Some examples
- Closing thoughts

Useful References

- Bock, J., et al., *Silicon nitride micromesh bolometer arrays for SPIRE,* 1998, Proc. SPIE, 3357, 297
  - Goes over tradeoffs and considerations that went into choosing the focal planes architecture for SPIRE. Fig. 3 is particularly useful (and I'll show it during this talk)
  - See also Turner, A., et al., *Silicon nitride micromesh bolometer array for submillimeter astrophysics*, 2001, Appl. Opt., 40, 28
- Griffin, M. et al., *Relative performance of filled and feedhorn-coupled focal-plane architectures*, 2002, Appl. Opt. 41, 31
  - This is a more general treatment that covers a range of geometries, but it does lack a discussion of filled arrays using a directed coupling element
- Goldsmith, P., *Quasioptical Systems*

Definitions

- $f/\# = F_{lens}/D_{lens}$, where F_{lens} is the focal length of the final lens in the system and D_{lens} is the aperture diameter of that lens
  - Large f/# is "slow", small f/# is "fast"
  - Think of the path length between the aperture and the focus position
- Telescope plate scale = $\dfrac{206265}{D_p * (f/\#)}$ (arcsec/mm)
  - As an example, consider the MUSIC camera on the Caltech Submm Observatory
    - The primary diameter D_p is 10400 mm, but a Lyot stop reduces this to an effective $D_p = 9000$ mm
    - The final f/# of the optics is 3.5
    - So the platescale is 6.5 arcsec/mm
- $f\lambda$ (also known as $(f/\#)\lambda$) describes the center-to-center pixel spacing δ of the detectors on the focal plane (i.e., the size of the pixels)
  - For MUSIC, $\delta = 5$ mm
  - For the MUSIC band at $\lambda = 2$ mm, the pixel spacing is thus equal to $0.71f\lambda$
    - i.e., $f\lambda = 3.5 * 2$ mm = 7 mm, so $0.71f\lambda = 5$ mm

Definitions (Continued)

- With optics, it's often useful to think about the system in both the time-forward sense and the time-reverse sense
- In particular, the optical coupling element for the detector can take two basic forms
  - A "bare absorber" that couples efficiently to incoming light from any incidence angle
    - Think of a time-reverse beam subtending 2π steradians
  - A forward-coupling element such as a feedhorn, lens, or phased array of antennas
    - The time-reverse beam subtends an angle roughly equal to λ/δ (diffraction)
- fλ-sized forward coupling elements approximately match the time-forward f/# from the telescope with the time-reverse f/#
  - Although note that the time-reverse beam is approximately Gaussian due to diffraction, which means there is still significant coupling outside of the time-forward ray bundle from the telescope
- In order to Nyquist sample the sky, 0.5fλ spacing is required

What are the Optical Consequences of Your Pixel Spacing?

- For Nyquist $0.5f\lambda$ spacing most of the time-reverse beam does not couple to the telescope
  - i.e., 12% couples to the telescope while 88% "spills over" outside of the primary mirror
  - This spillover needs to be coupled to a controlled surface to avoid significant excess noise and systematics
  - The time-reverse primary mirror illumination is approximately a top-hat, maximizing angular resolution
    - i.e., you obtain close to the full λ/D

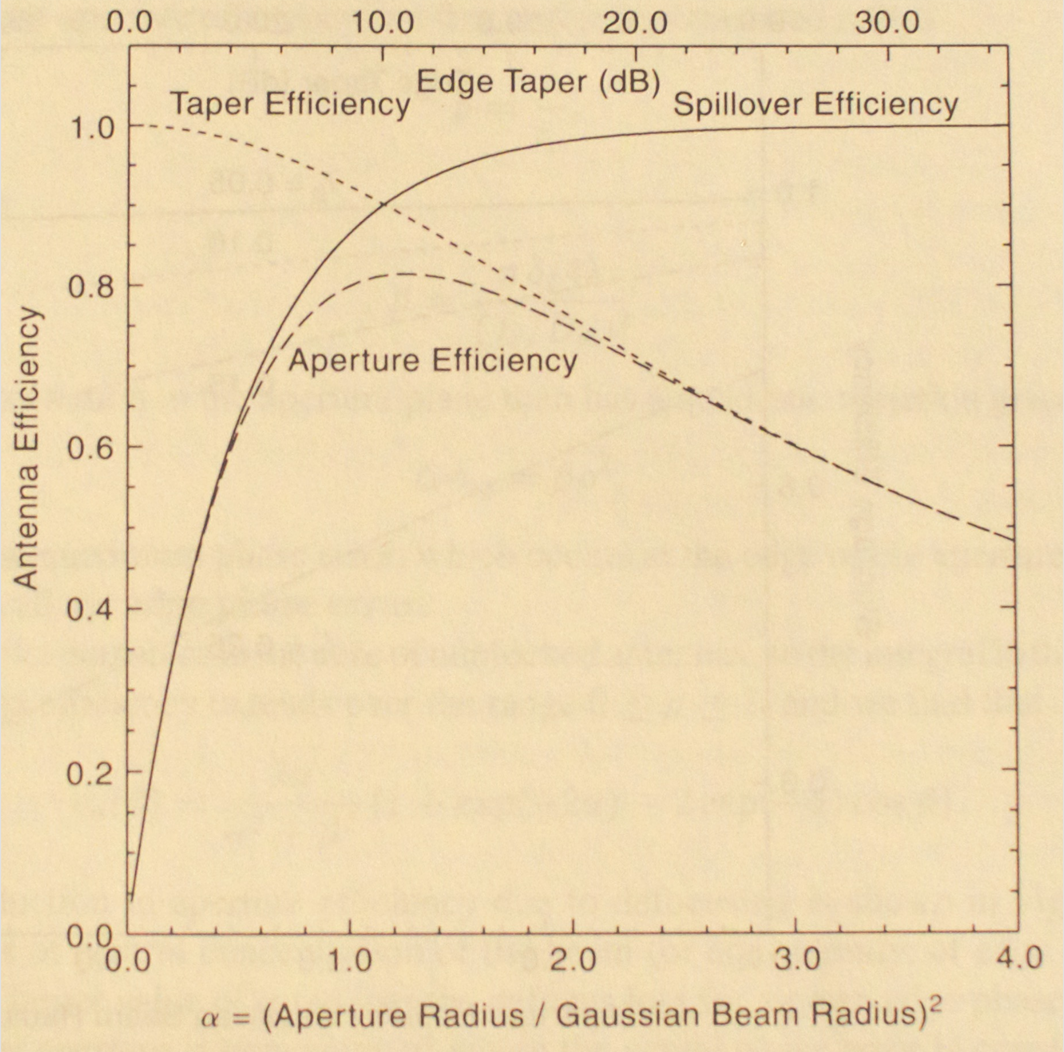


Figure from Goldsmith

What are the Optical Consequences of Your Pixel Spacing?

- For 2fλ most of the beam does couple to the telescope
  - i.e., 87% couples to the telescope while 13% “spills over” outside of the primary mirror
  - This significantly mitigates the need to have controlled surfaces for the spillover
  - However, now the primary mirror is illuminated in the time-reverse sense by a Gaussian
    - i.e., the resolution is worse than λ/D

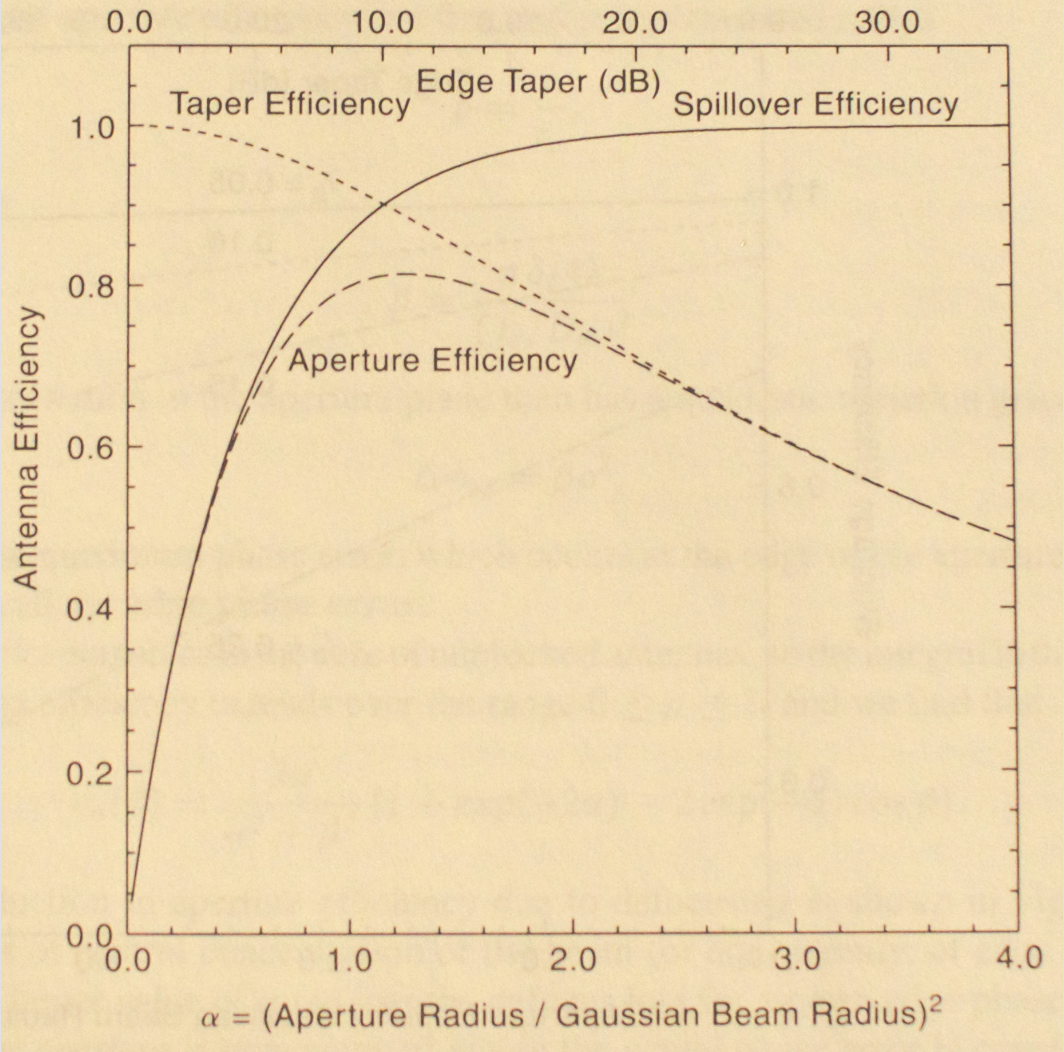
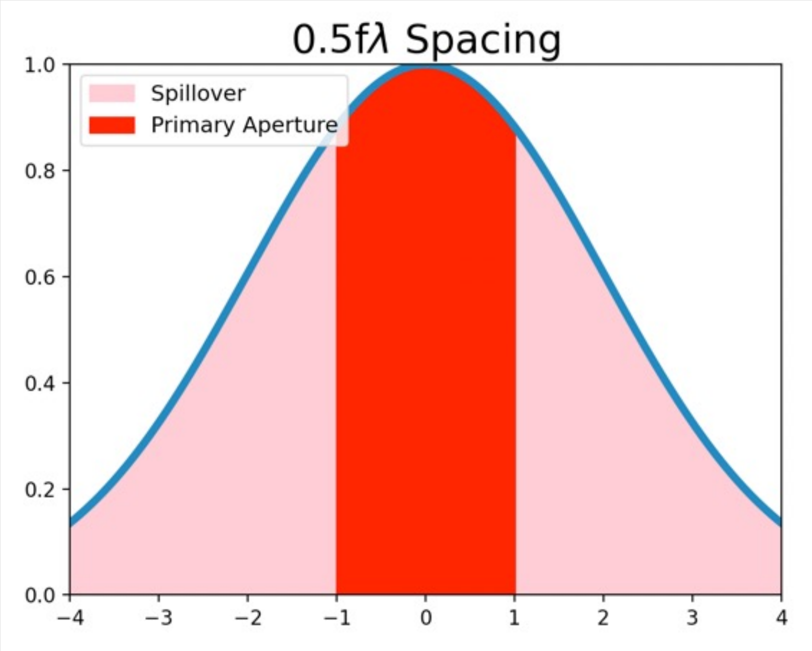
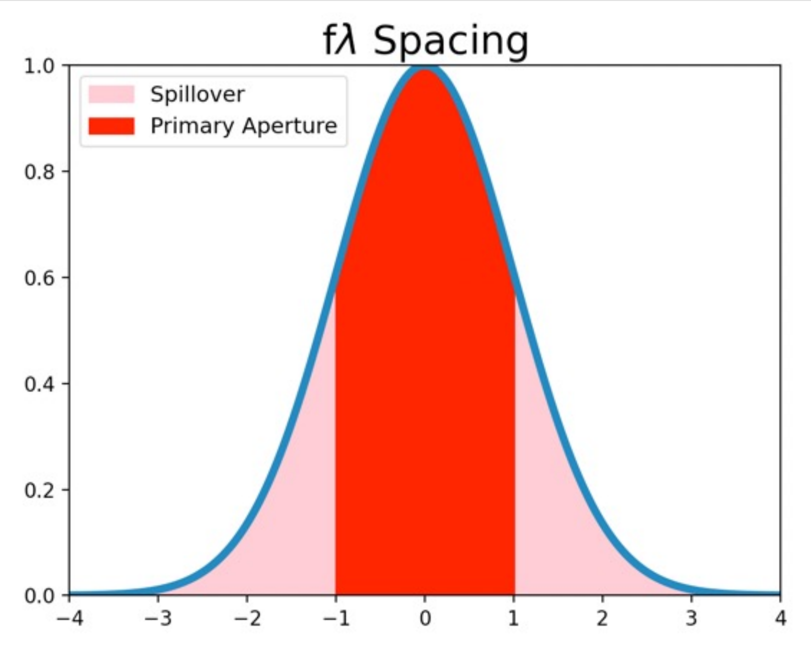
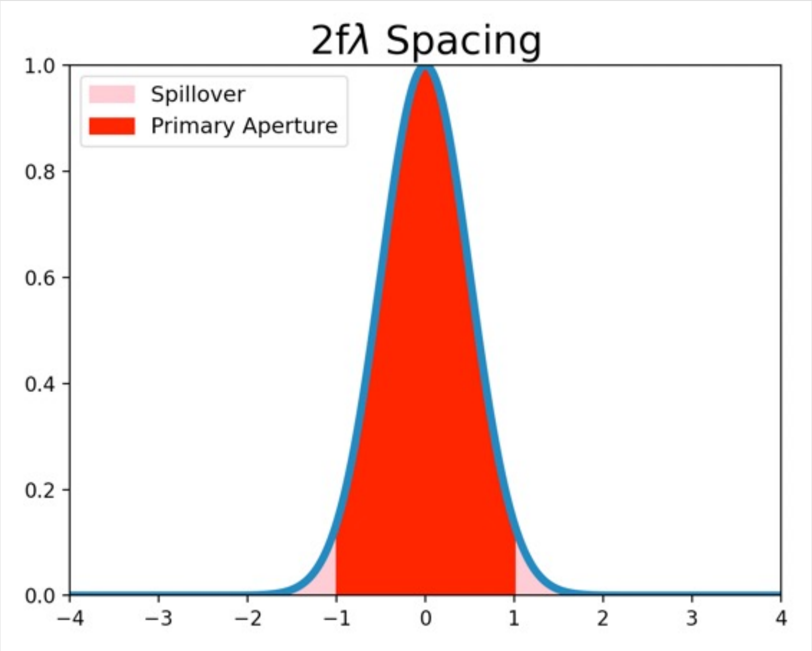


Figure from Goldsmith

Primary Illumination and Spillover







- The primary illumination is close to a top-hat for $0.5f\lambda$
- The spillover is very small for $2f\lambda$

What are the Optical Consequences of Your Pixel Spacing?

- With a Nyquist sampled focal plane you could in principle stare at a given target while obtaining a fully sampled image
- For 2fλ you need a minimum of 16 different dither positions in order to fully reconstruct the image
- In practice, all mm/submm detectors require dithering
  - The detectors, electronics, and atmosphere have significant fluctuations on long timescales, making it inefficient to “stare”
- It is generally possible to choose dithering parameters that efficiently sample the image for any detector spacing
  - Easy for large maps (i.e., surveys), can be more challenging for compact objects

What are the Camera (System-Level) Consequences of Your Pixel Spacing?

- The background optical load sets the optimal photon-noise limit for the system
  - You want your system to perform at this limit!
  - The total power on the detector will be $Q_{opt} \sim \eta$ (for coupling efficiency η)
- mm/submm photometric imagers are generally close to the shot noise limit (i.e., low number of photon arrivals)
  - Photon noise equivalent power (NEP) thus scales like $\sqrt{\eta}$
  - $\eta_{Nyquist} = 0.15 \ * \ \eta_{2f\lambda}$
  - This means $\mathrm{NEP}_{\mathrm{Nyquist}} = 0.4 \ * \mathrm{NEP}_{2f\lambda}$
- The NEP of the detector and readout electronics tends to be independent of (or weakly dependent on) η
  - Thus, the noise performance of your detectors+electronics needs to be 2.5 times better for optimal performance for Nyquist spacing compared with 2fλ spacing

What are the Camera (System-Level) Consequences of Your Pixel Spacing?

- However, NEP is not what we really care about
  - What matters is the noise referenced to astronomical surface brightness (i.e., NESB)
  - The NESB also depends on η!
  - For lower optical efficiency you have lower photon arrival rates, which means the fractional Poisson noise will increase as $\sqrt{\eta}$
- So, even if you do have a good enough detector+electronics to reach the fundamental photon noise limit in the Nyquist case, the NESB of this fundamental limit will be a factor of 2.5 higher than for 2fλ spacing
- But! For a given focal plane size, you can fit 16 times more Nyquist pixels than 2fλ pixels
  - The net result is that, for unit focal plane area, the Nyquist focal plane will be a factor of $\frac{\sqrt{Npix}}{\sqrt{\eta}} = \frac{4}{2.5} = 1.6$ times more sensitive
- However, in practice, this generally doesn't hold
  - It is more difficult to reach the photon noise limit with Nyquist sampling
  - There is also excess noise and systematics from the larger spillover fraction

Some Additional Considerations

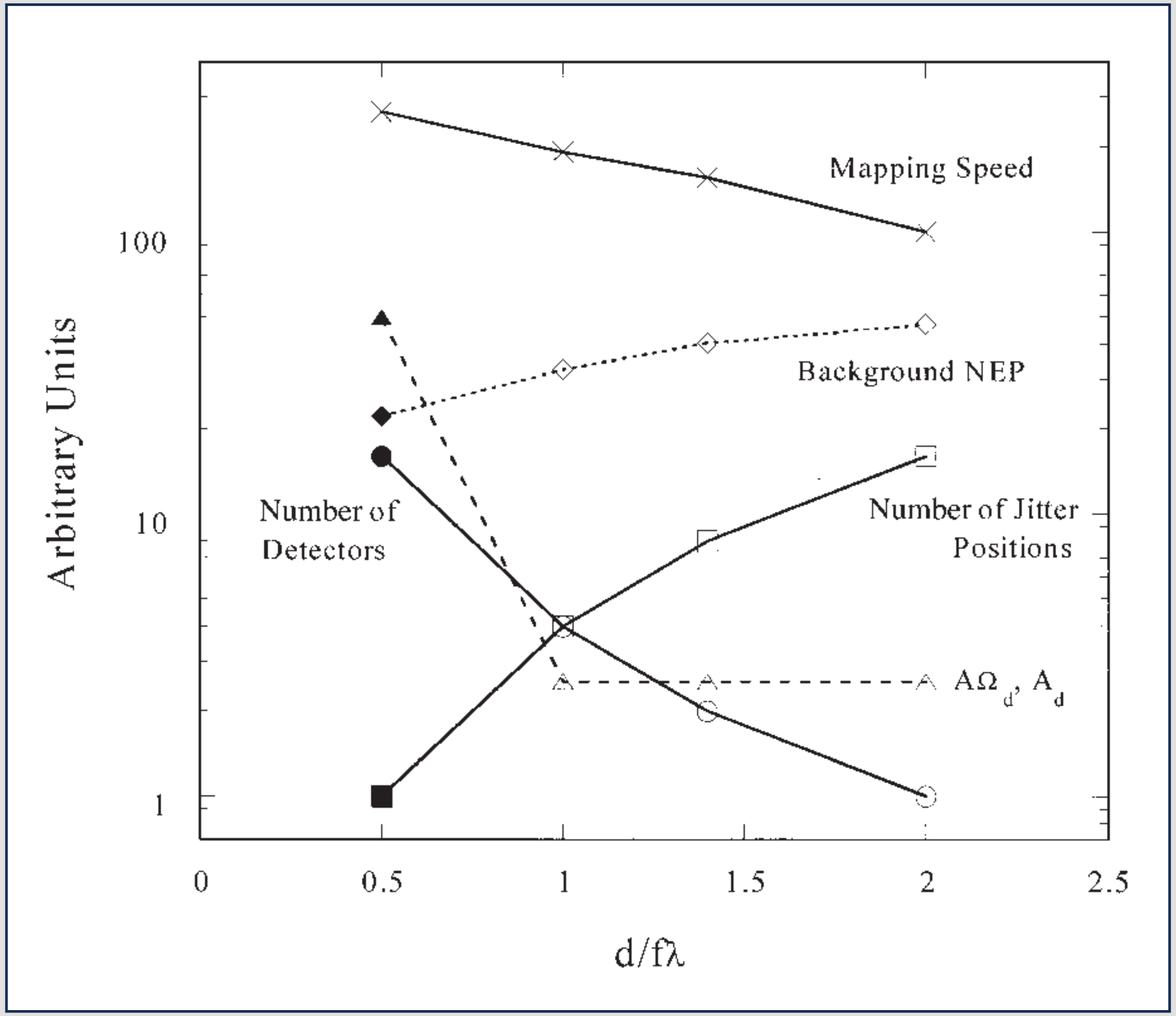
- Even if you can reach the photon noise limit, and fully control the spillover, there are other "penalties" associated with a Nyquist sampled focal plane
  - 16 times more detectors, readout lines, data volume, etc.
  - The costs associated are often significant, in terms of hardware and computing, but also in terms of person effort
- Note that there are penalties associated with $2f\lambda$ spacing as well
  - The width of the point spread function is 10-15% larger
  - The dithering required to fully sample the image can be inefficient
- Many modern instruments have settled on an "optimum" near $1f\lambda$ spacing

Some Additional Considerations

- Note that there is little motivation to having pixels smaller than Nyquist (0.5fλ)
  - The image is already “fully sampled”, and so the smaller pixels only result in lower values of η and larger spillover fractions
- Note that there is little motivation to having pixels larger than 2fλ
  - Spillover and η are already close to optimal
  - Larger pixels will reduce the time-reverse primary illumination, resulting in significant degradations in angular resolution
- There are very few examples of mm/submm instruments that have operated outside of the range 0.5fλ - 2fλ

How Do You Optimize for Your Science?

- Can you afford to have a larger number of detectors?
- Are your detectors sensitive enough for Nyquist spacing?
- Do you need to maximize angular resolution?
- How critical is stray light (spillover) control?
- How efficiently can you dither your focal plane?



What Would Motivate $2f\lambda$?

- Each detector is expensive
  - You can only afford a “small” number of detectors, and so it is critical to make each of those detectors as sensitive as possible
- Your detector (and/or electronics) noise is not good enough for background-limited operation
- Your telescope optics are good enough to provide a large field of view
  - i.e., for a given number of detectors, you have enough space to move them further apart from each other
- Systematics from stray light may strongly impact your science
  - e.g., large-angle response can be very challenging for CMB measurements

What Would Motivate (0.5fλ)?

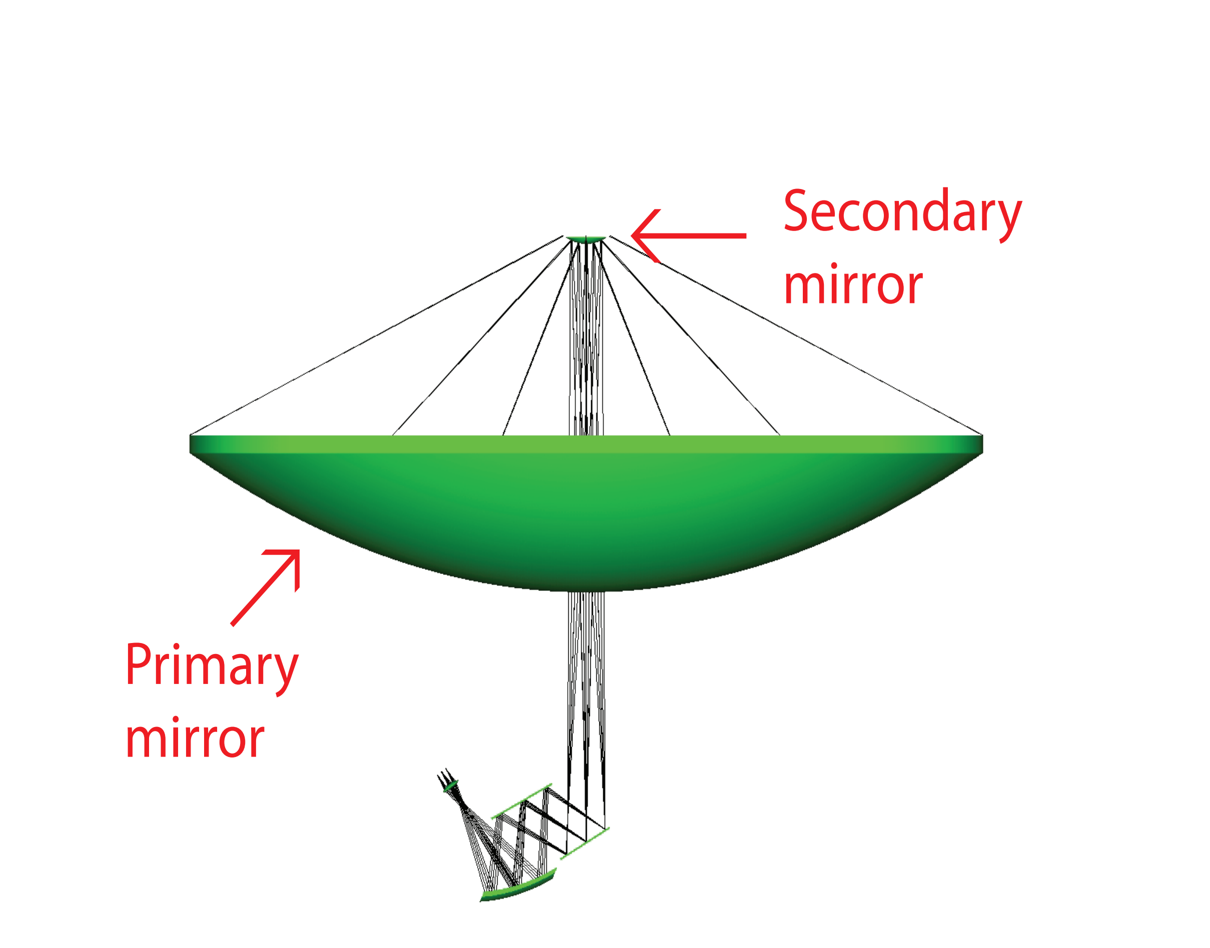
- Each detector is cheap
  - You can afford as many detectors as you wish to populate your focal plane
- Your detector (and/or electronics) noise is good enough for background-limited operation in the Nyquist case
- Your telescope optics are not good enough to provide a large field of view
  - i.e., you have a limited amount of space to populate with detectors
- Maximum angular resolution is critical to your science
- Stray light (spillover) is unlikely to strongly impact your science
  - e.g., you are studying bright compact objects

Case Study – The MUSIC Camera on the CSO

- We developed MUSIC in circa 2008 to be the long-wavelength facility camera on the Caltech Submm Observatory
  - I was a postdoc for Hien working on this!
- Our budget was set by total detector count – with a total of 2400
- The primary science driver was large-sky surveys
  - We thus desired to maximize the per-detector sensitivity (i.e., toward $2f\lambda$)
  - The field of view of the CSO is limited by the opening in the primary mirror to an approximate diameter of 14 arcmin
  - MUSIC had bands at 150, 220, 290, and 350 GHz
  - For these bands the pixel sizes filling a 14 arcmin field of view are $0.7f\lambda$ – $1.6f\lambda$

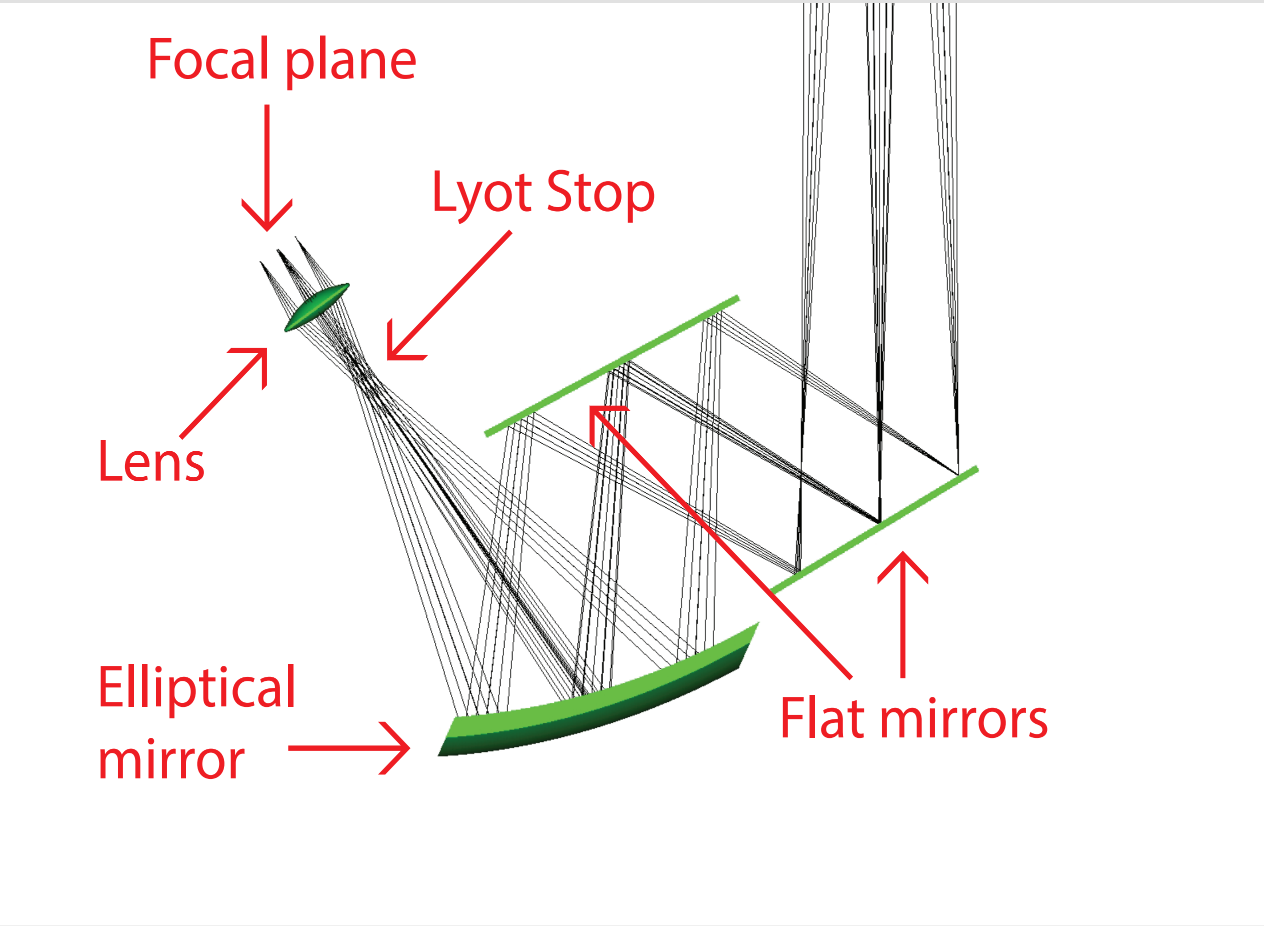
How Do We Couple MUSIC to the CSO?

- The CSO is a 10.4 m diameter Cassegrain telescope
- We require re-imaging optics to form a pupil for stray light control
- Due to limited space near the telescope prime focus, we first need to “fold” the optical path



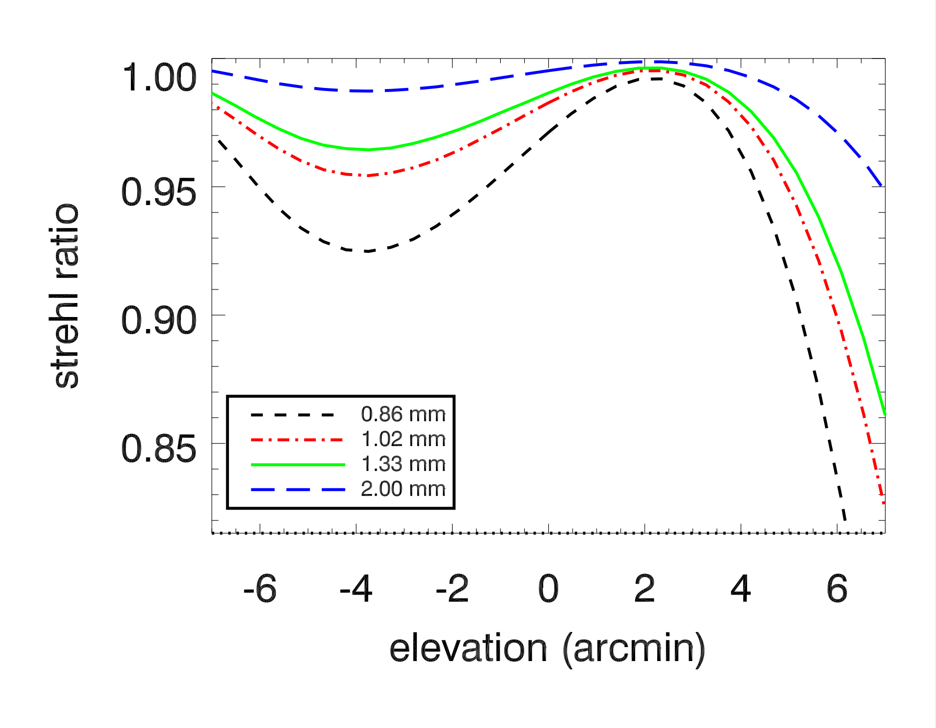
How Do We Couple MUSIC to the CSO?

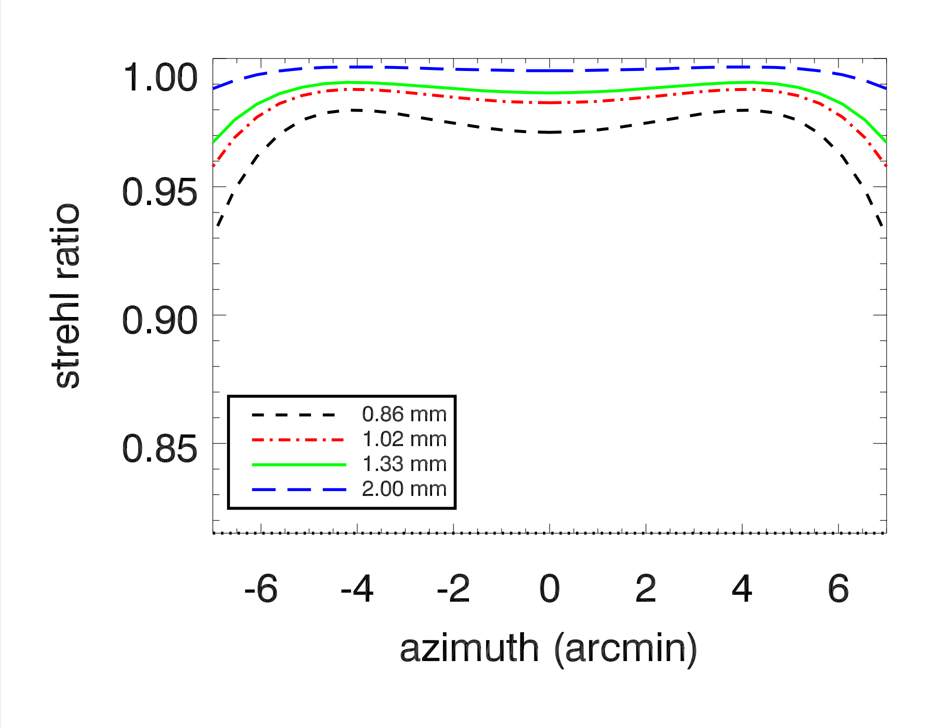
- Given this off-axis folding, the best way to re-image is with an elliptical mirror
- We optimized the profile of the mirror to obtain the best possible pupil
  - i.e., within the 14 arcmin field of view the pupil should be at the same location and with the same projected diameter
- A lens is also required behind the pupil
  - It was optimized for telecentricity and aberrations



Quantify the Aberrations

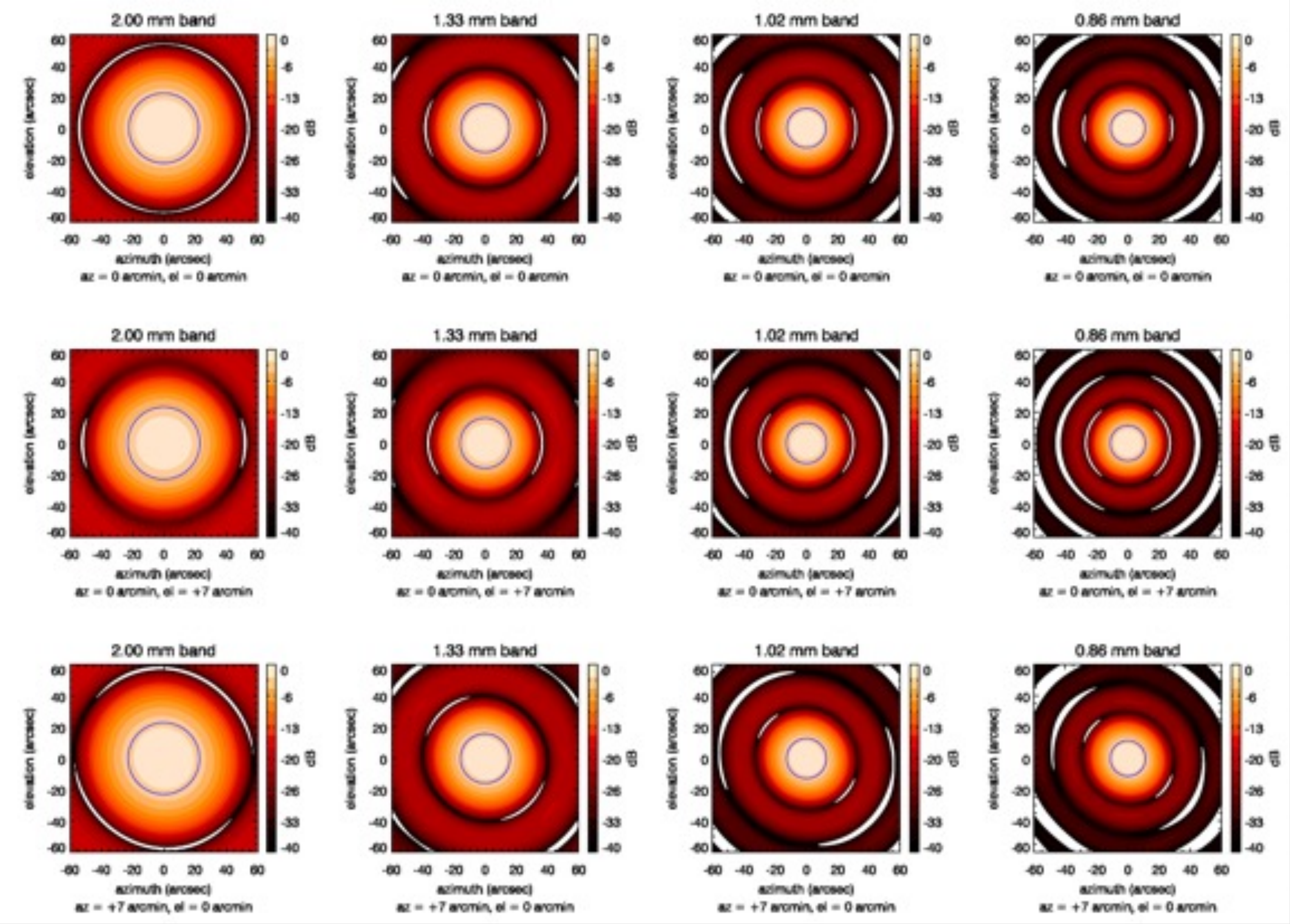
- The "diffraction" limit corresponds to a Strehl ratio of 0.8
- We thus desired better than this over the entire field of view





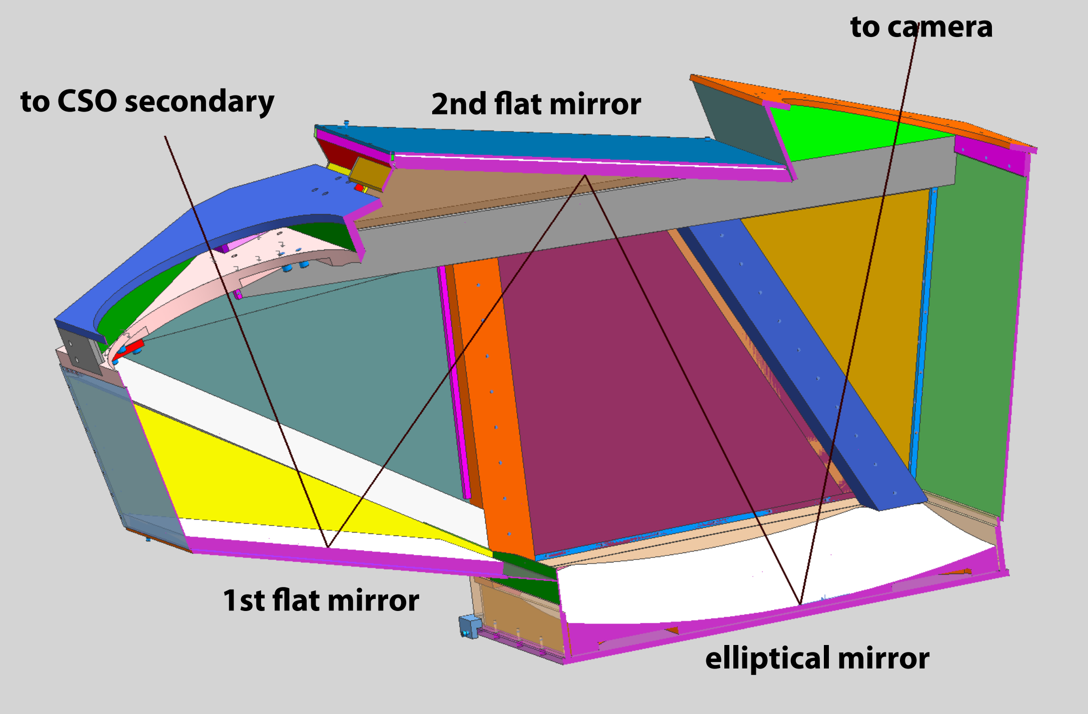
PSF Shapes

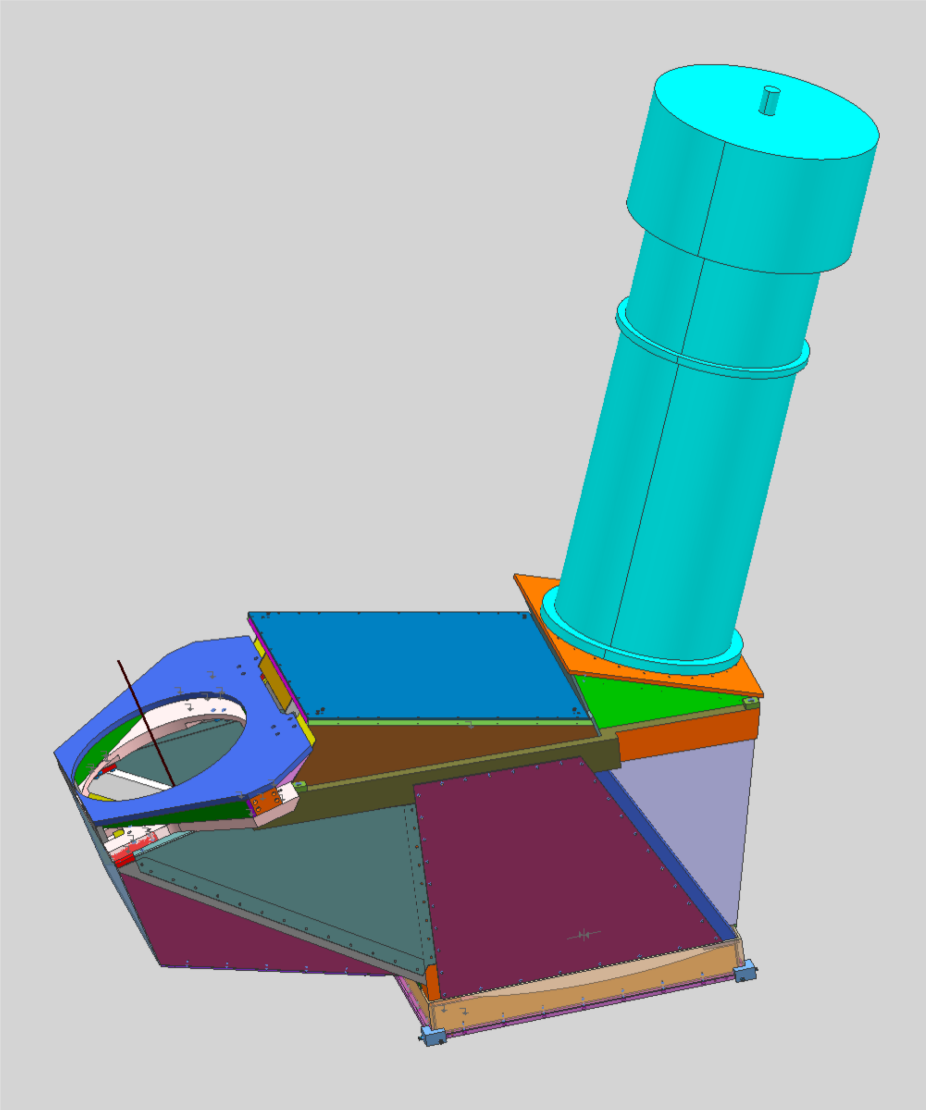
- MUSIC planned large surveys to detect unresolved galaxies
- A uniform PSF shape over the field of view was thus desired
- To good approximation this was achieved



Mechanical Design

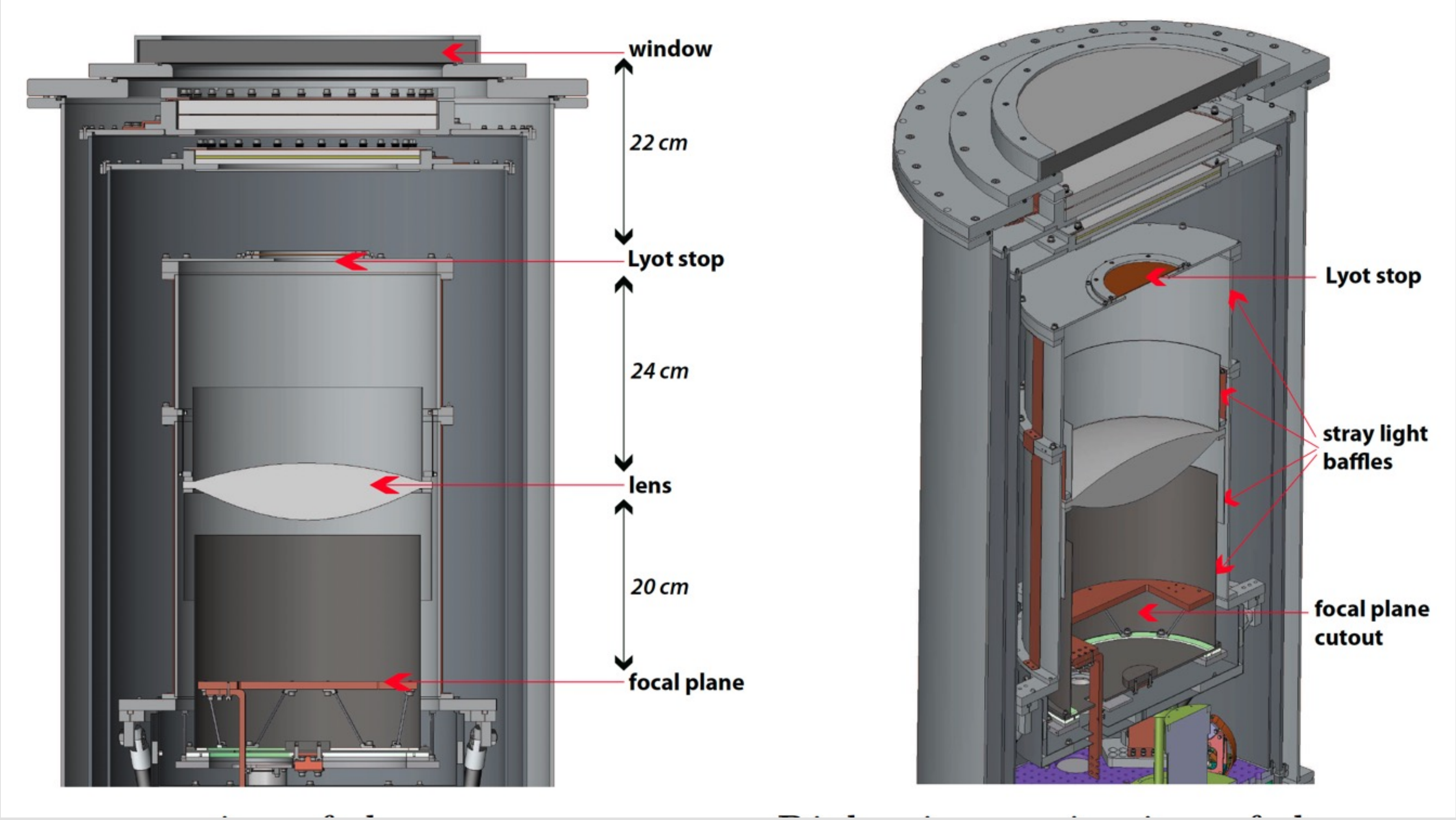
- Once an optical design was in place, we then needed a mechanical design
- The structure must be stiff enough to avoid degrading performance





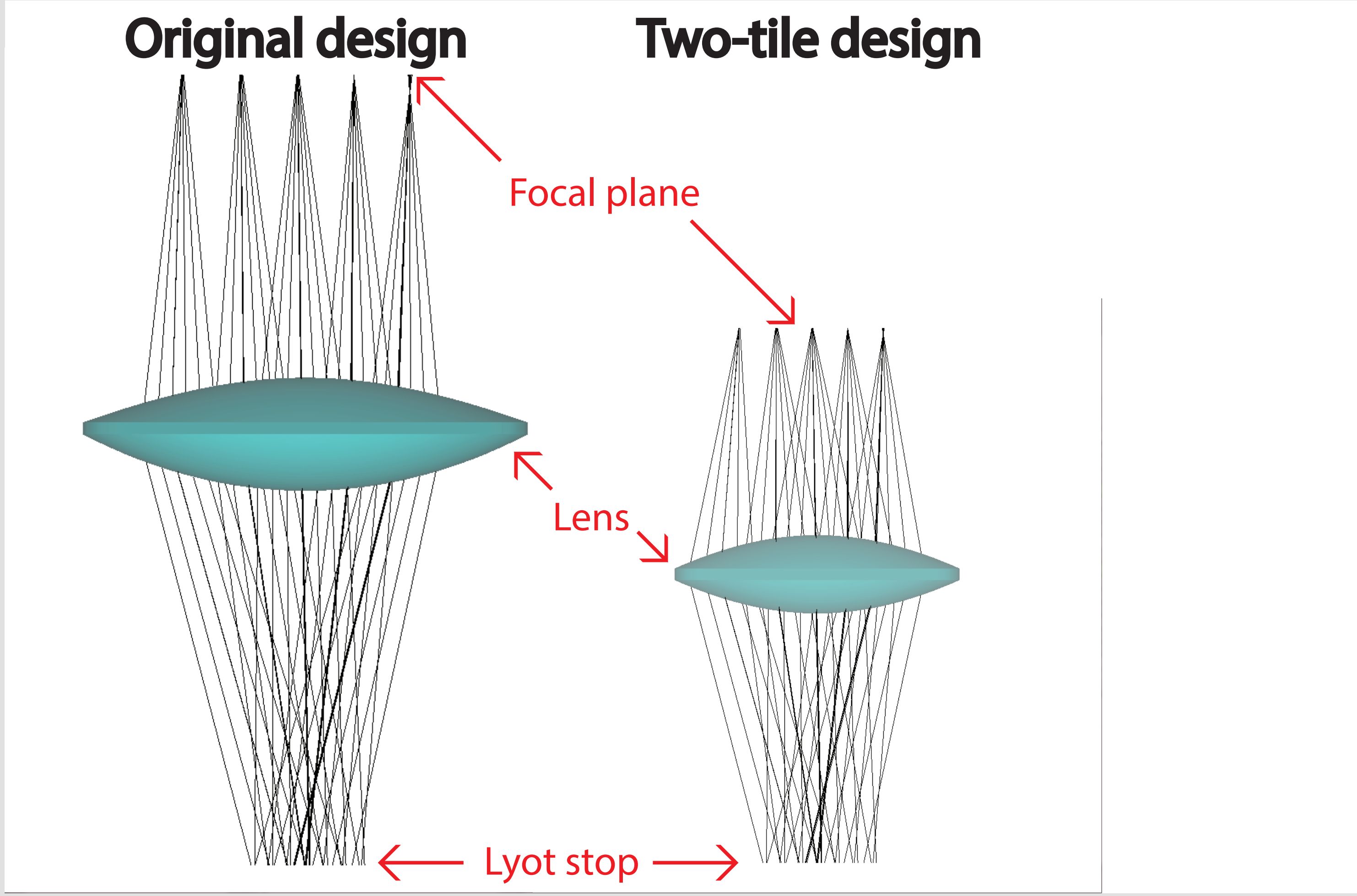
Mechanical Design

- A full mechanical design for the optics within the instrument cryostat is also needed



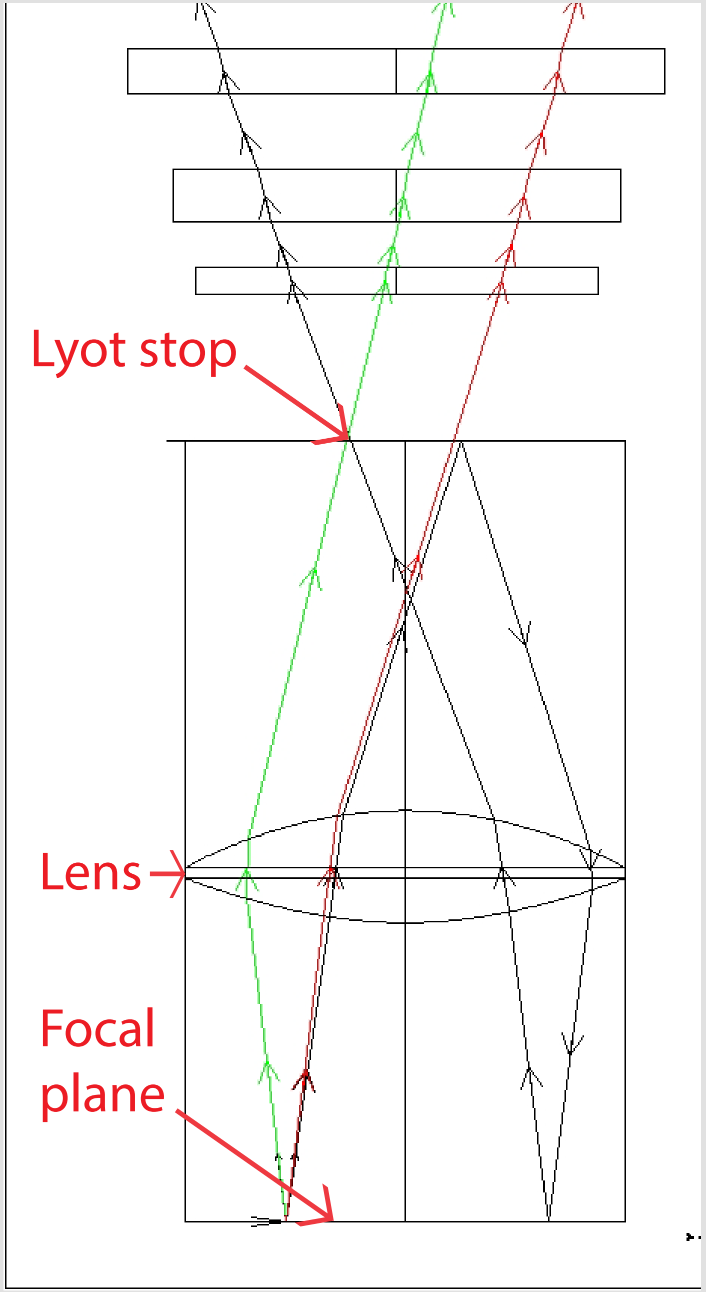
A Change!

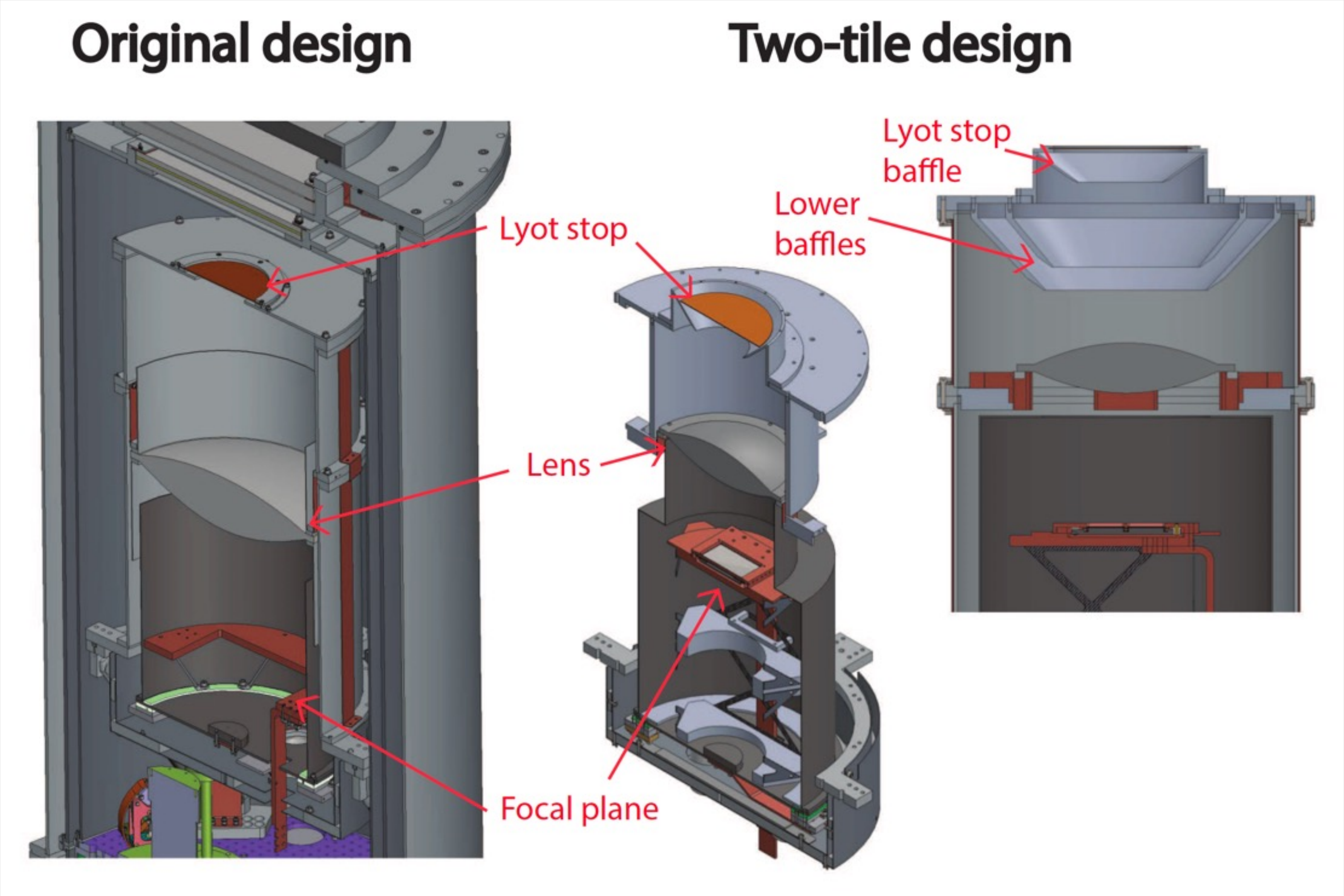
- Due to manufacturing challenges, we only had 2 of the planned 8 detector tiles
- We therefore changed the optics
    - Old 0.7fλ – 1.6fλ
    - New 1.0fλ – 2.0fλ
    - Improved per-detector sensitivity



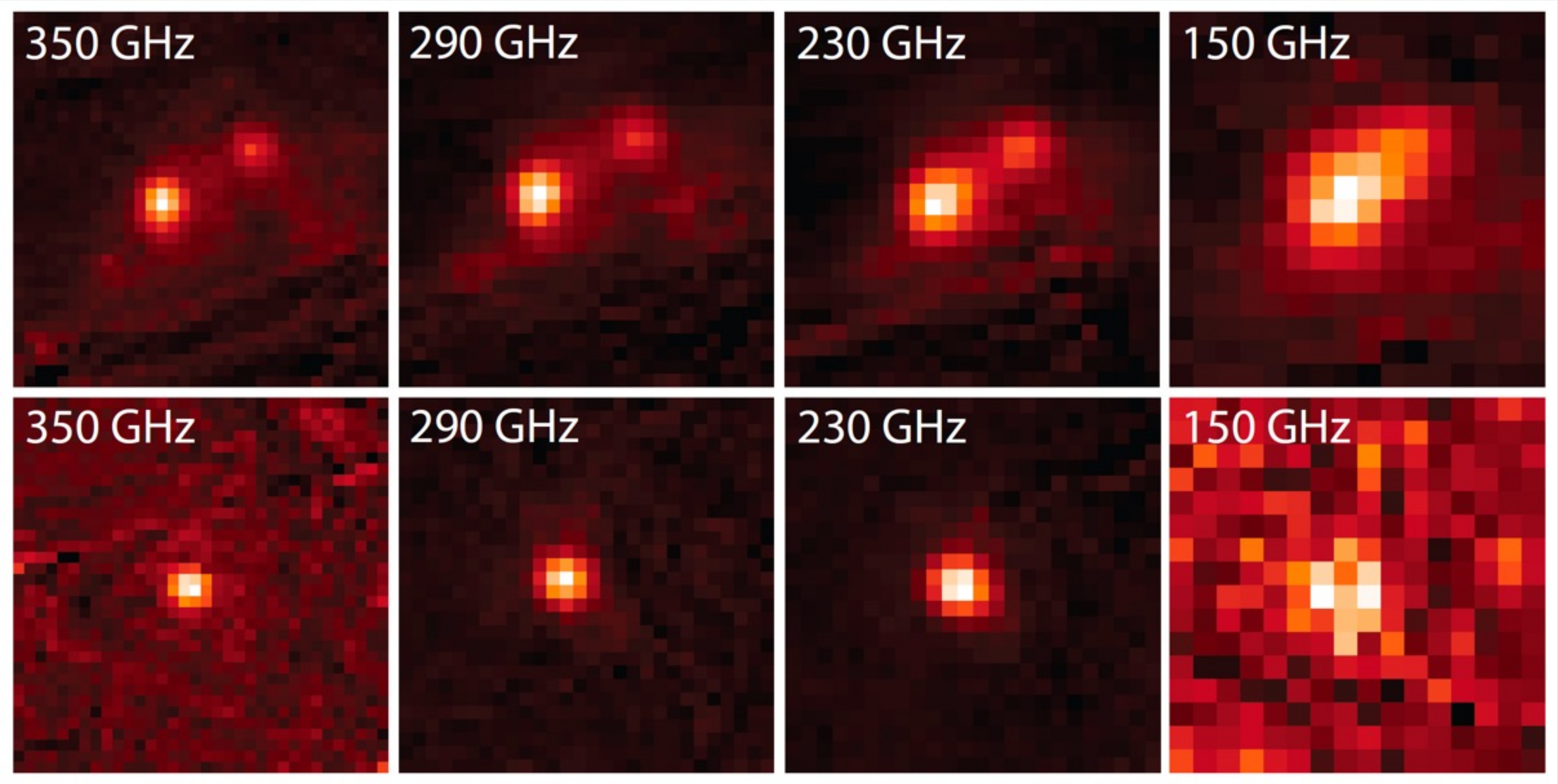
Stray Light

- We found significant stray light pickup from large angles
- We modeled the system to determine the cause
- Red and green show the desired telescope coupling from a detector
- Black shows a ray that reflects within the optics and exists at a large angle
    - We need to eliminate these reflections!



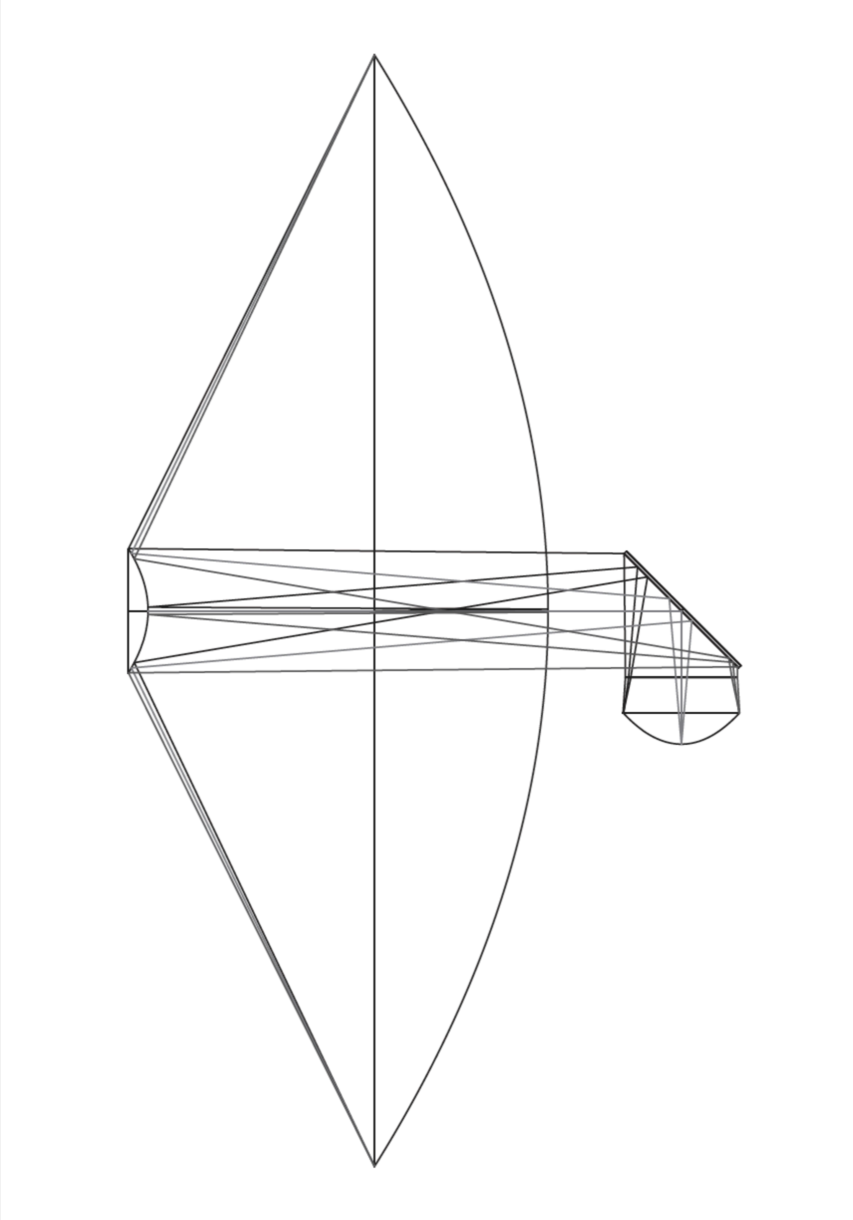

Original design
Two-tile design
Lyot stop
baffle
Lower
baffles
Lyot stop
Lens
Focal plane

Point Spread Function and Diffraction



Case Study – CCAT 25 m

- While no longer an active project, Caltech was heavily involved with the CCAT 25 m telescope concept
- The science goals required a very large field of view
- To achieve this field of view, the telescope design resulted in a highly curved focal surface
  - The plan was to place a large number of sub-cameras within this field of view so that the focal surface was close to being locally flat for each sub-camera

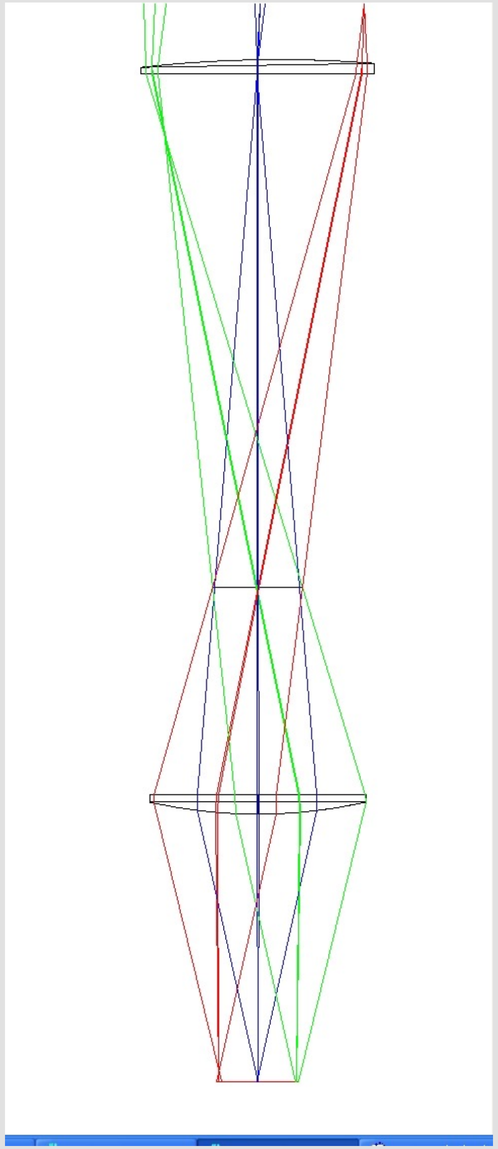


CCAT LWCam Optics

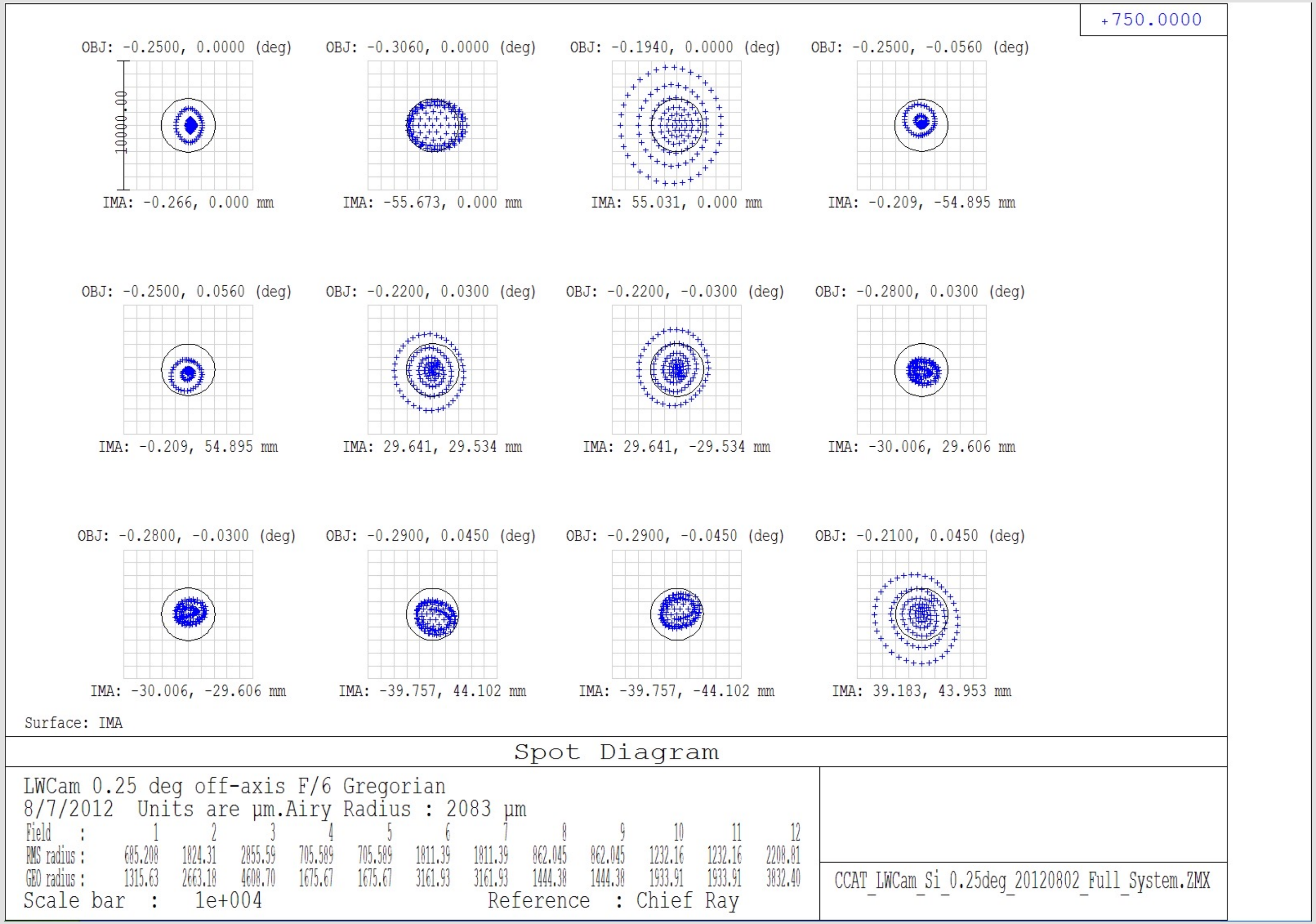
- I worked on concepts for the long wavelength camera (LWCam)
- We decided to split the full 1 deg field of view into 7 arcmin sub-fields
- How did we go about optimizing the optical design for these fields?
- I decided to “keep it simple”
  - Using 2-lens systems with Si lenses
  - All lens surfaces were convex or planar
  - The lenses could be tilted and decentered
  - The lens surfaces could be aspheric
- In order of importance, the design goals were
  - Telecentricity
  - Contain a high quality pupil
  - Minimize aberrations

Design for 0.25 Degree Off-Axis Sub-Camera

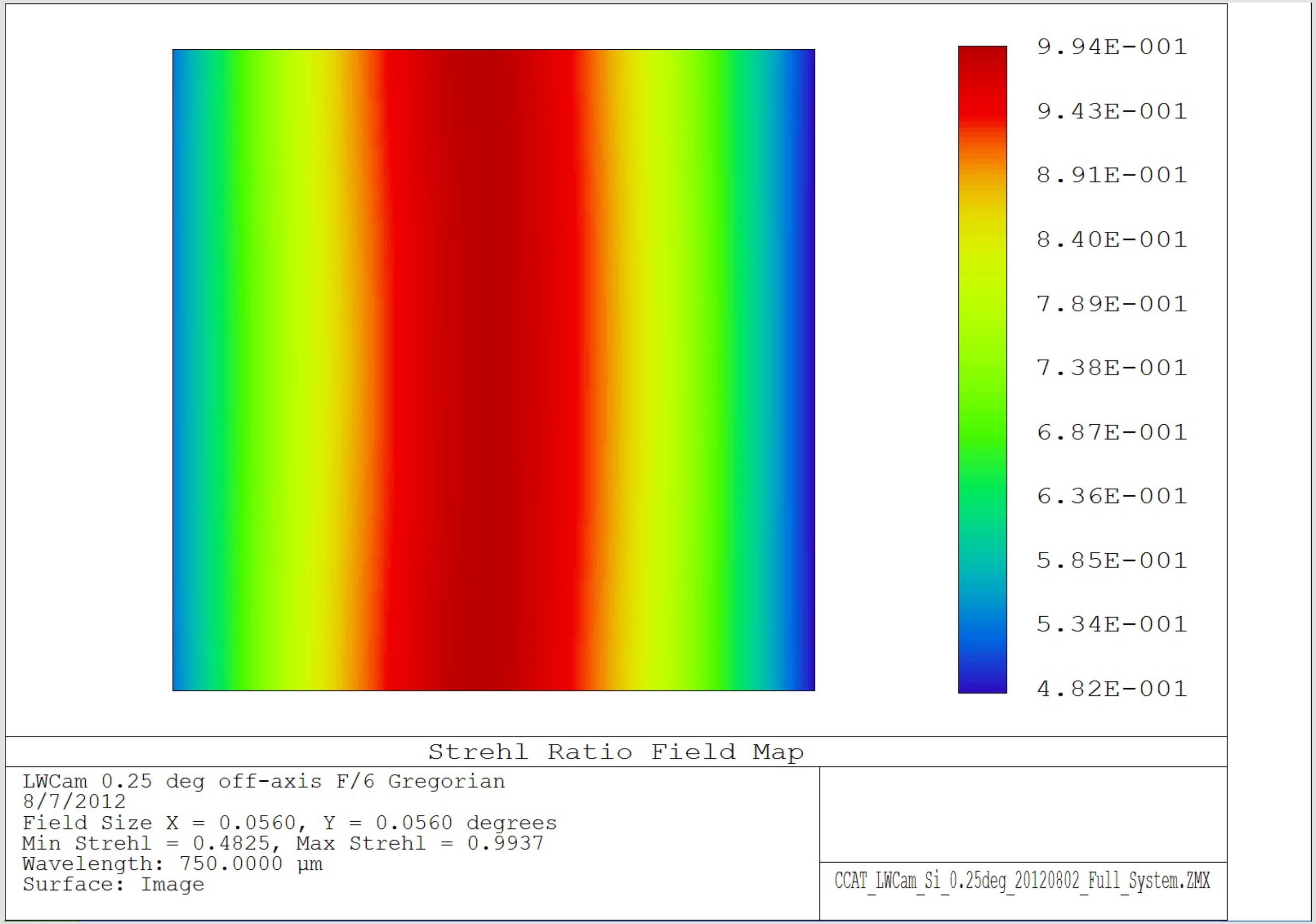
- Found that the first lens must be slightly decentered to produce the best pupil quality
  - Decentering distance of 2.5 cm
- Found that the second lens needs to have an aspheric surface to optimize image quality
- The most compact design possible had a total length of 150 cm
- With this simple design, it is impossible to fully correct for the curved focal surface of the telescope



Design for 0.25 Degree Off-Axis Sub-Camera



Design for 0.25 Degree Off-Axis Sub-Camera



Summary of 0.25 Degree Off-Axis Design

- With a simple 2 lens Si design we can achieve
  - A system with good pupil quality
  - A highly telecentric system
  - Diffraction limited performance over the entire field of view for $\lambda \geq 1$ mm
  - Diffraction limited performance over a 4 x 7 arcmin field of view for $\lambda \geq 0.75$ mm
- The lenses were not tilted
  - Designs with tilted lenses did now show improved performance
- It is possible to obtain VERY good image quality with a tilted focal plane
  - This comes at the expense of losing telecentricity