Maunakea Spectroscopic Explorer

Details of the Baseline Quad Mirror (QM) Telescope Proposed for MSE

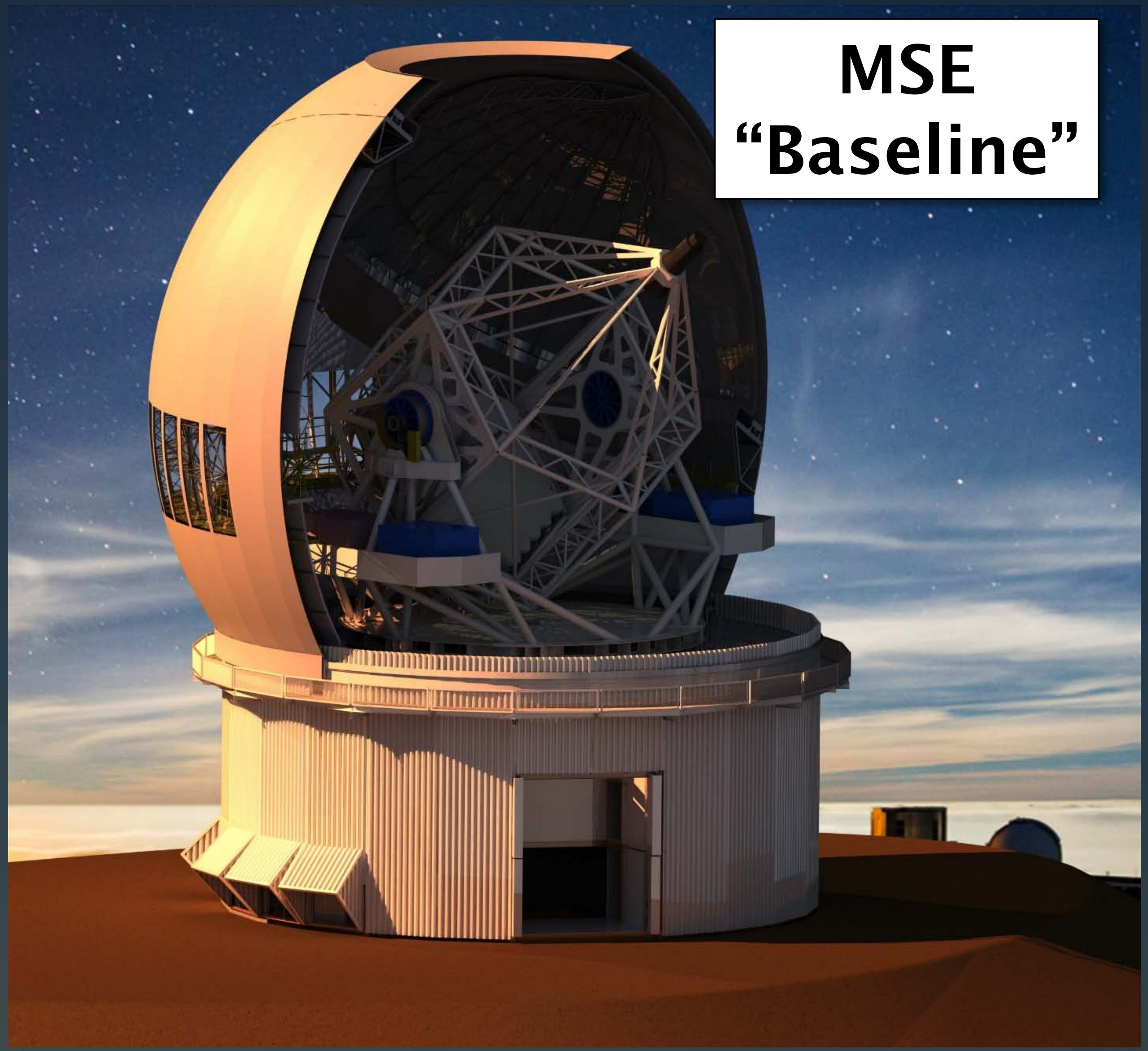
Workshop on New Generation Twin Spectroscopic Telescope Initiative
Beijing China, July 2023

Marc Baril presenting on behalf of Sam Barden

Canada France Hawaii Telescope / Maunakea Spectroscopic Explorer

Maunakea Spectroscopic Explorer (MSE)

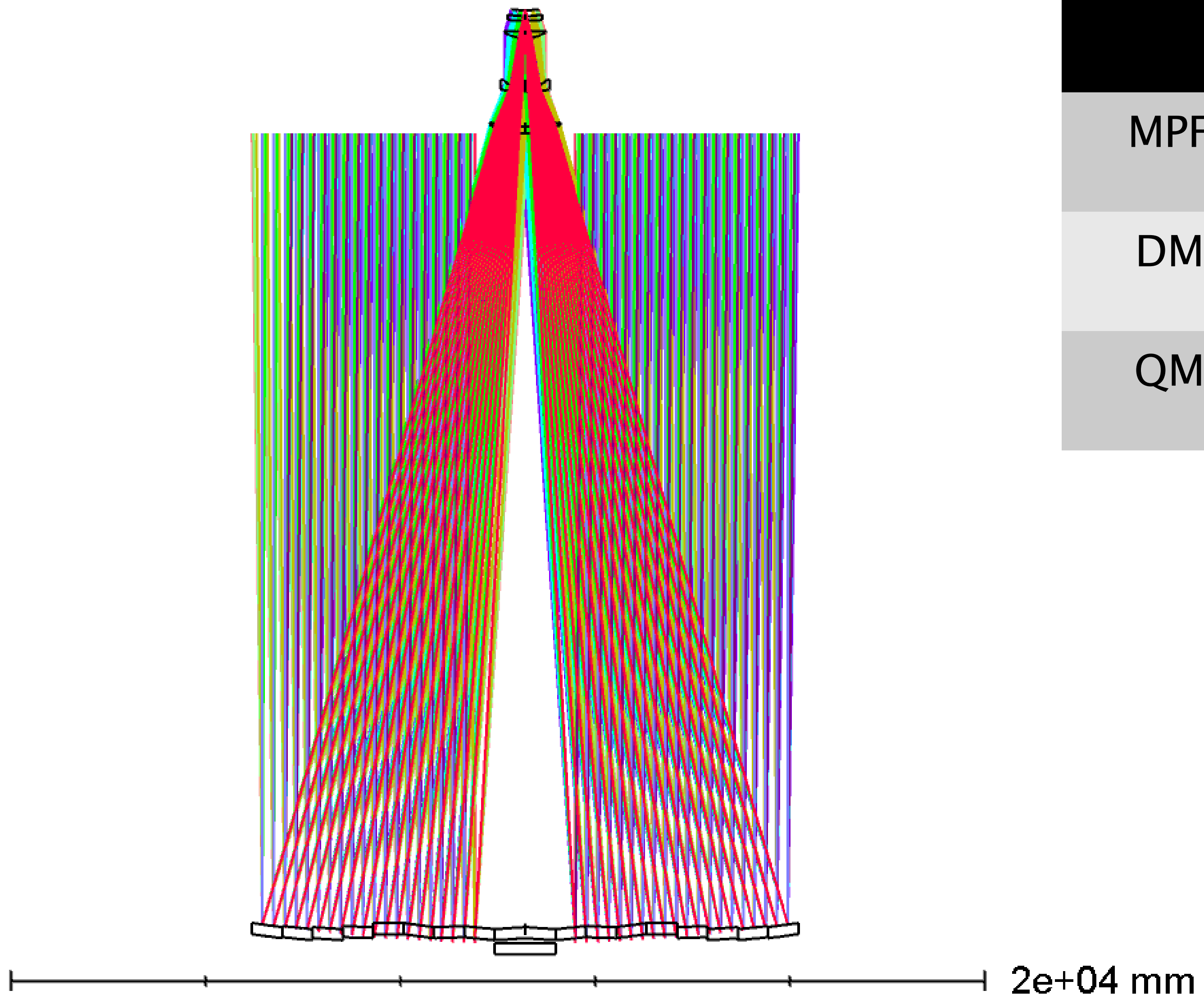
MSE will transform the Canada France Hawaii observatory into a large aperture spectroscopic survey facility



- Baseline has ~4000 fibers, ¾ feeding low-medium resolution spectrographs, ¼ feeding high resolution spectrographs operating between 350 - 1800 nm
- MSE sets a challenging sensitivity requirement, m_{AB} = 24 with SNR of 2 in one hour of integration. ***Both optical ghosts and scattering must be carefully controlled.***

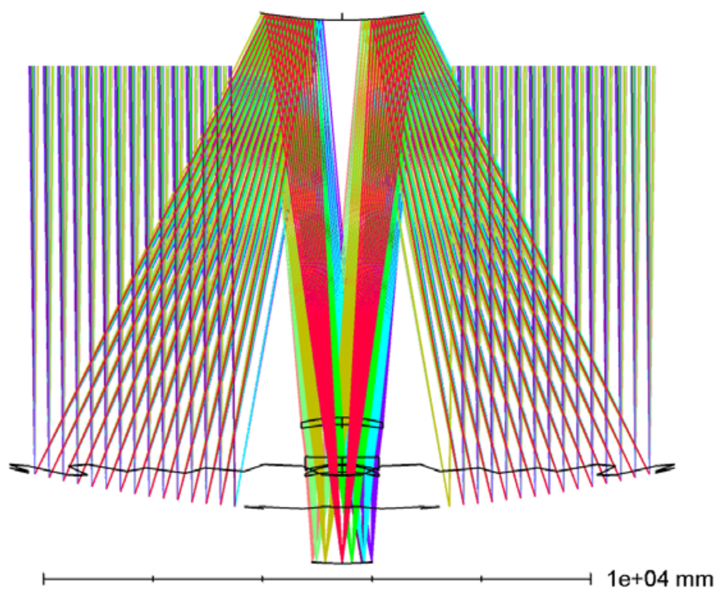
3 Possible MSE Variants

Prime-Focus Design - PF

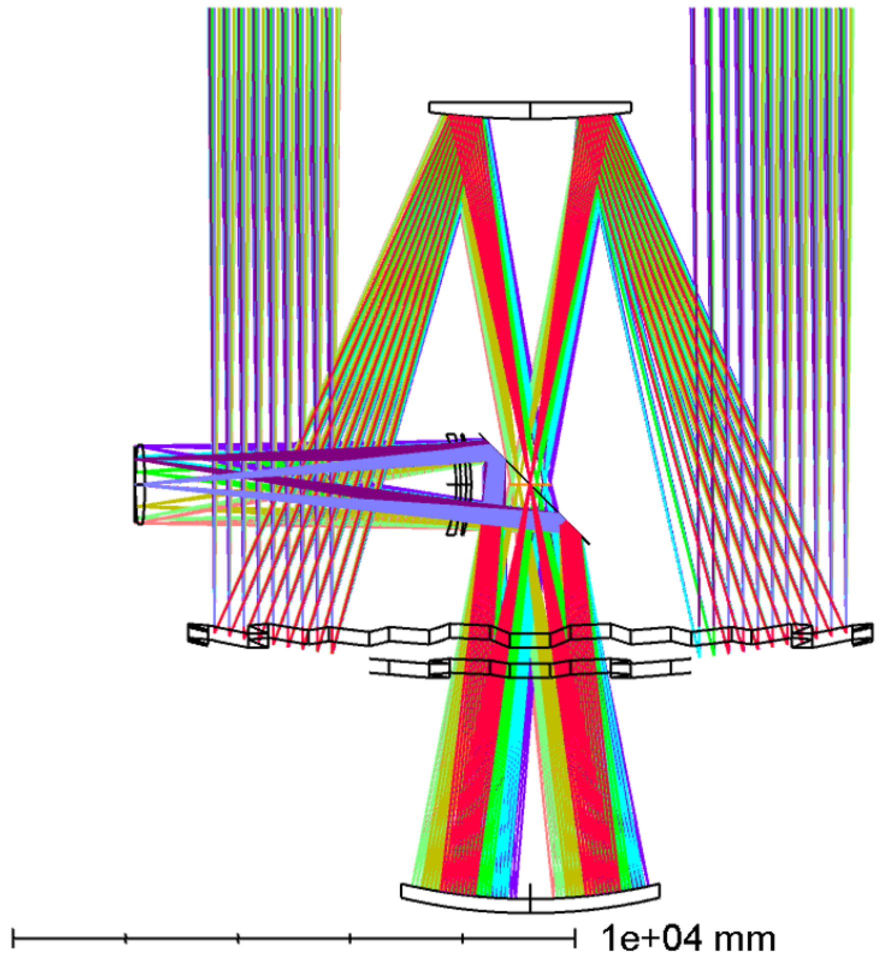


Design	f/#	Normalized 1.5° physical area	Approx fiber count
MPF	1.93	1.00	4330
DM	3.20	2.75	11900
QM	3.99	4.27	18490

Dual-Mirror Design - DM

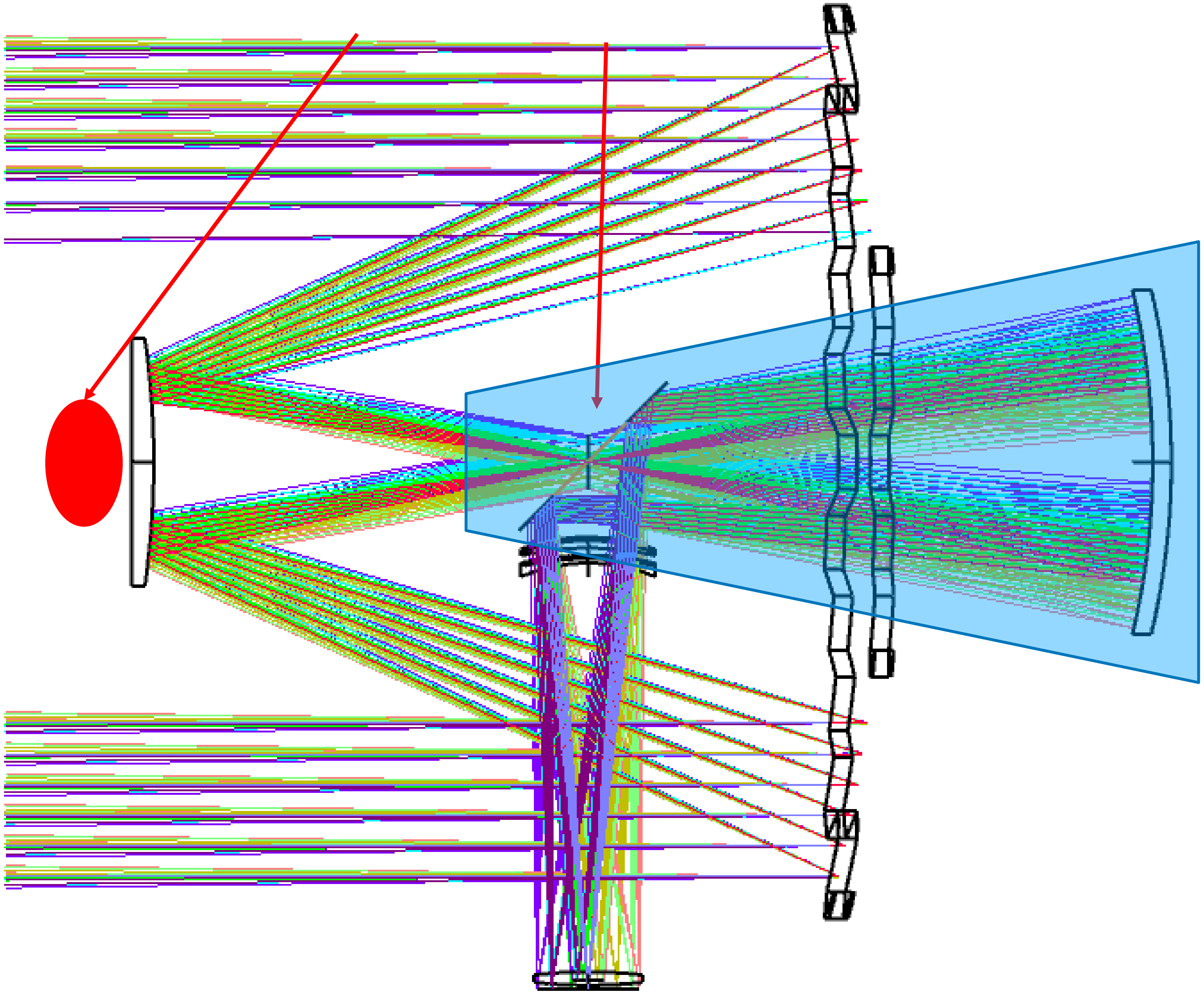


Quad-Mirror Design - QM



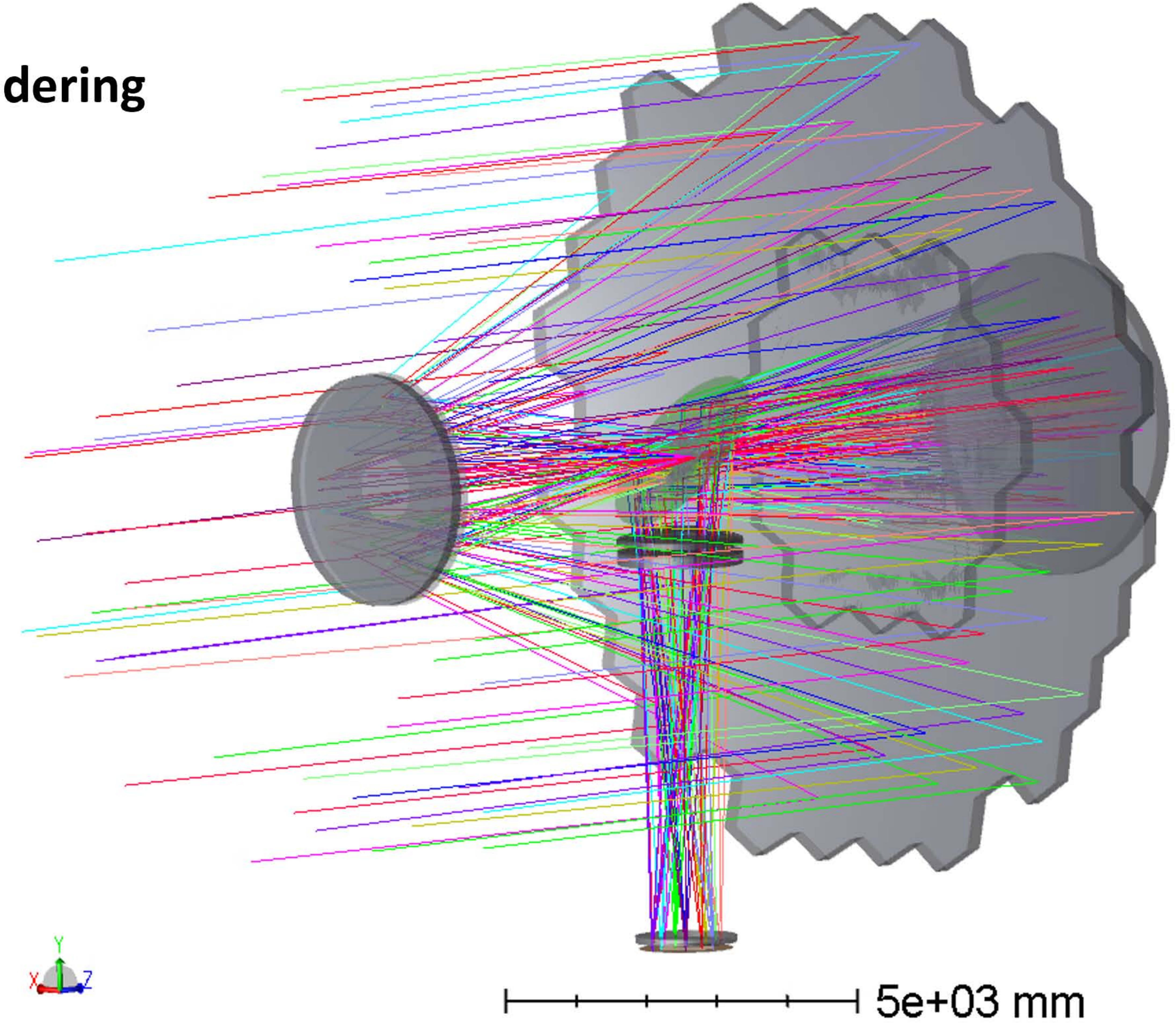
The DM option provides the most compact telescope.

The QM option provides most versatility with multiple focal stations possible, plus reduced gravitational variability.



- Light baffle for M3 and M4 could provide a quasi-sealed environment for M3 and M4 as well as the ADC.
- M1is segmented to allow easier and superior reflective coatings. M3 could be segmented if segments are feasible. LAMOST experience validates feasibility.
- Ease of access to the focal surface allows versatility for instrumentation. *e.g.* alternative spectrograph interfaces, imagers, etc.
- Minimal chromatism can allow extensions further to the IR and UV.
- Plate scale allows high density of fiber probes over field of view (20,000 “echidna” FPs).
- Nasmyth arrangement allows for shorter fibers.

Shaded model rendering

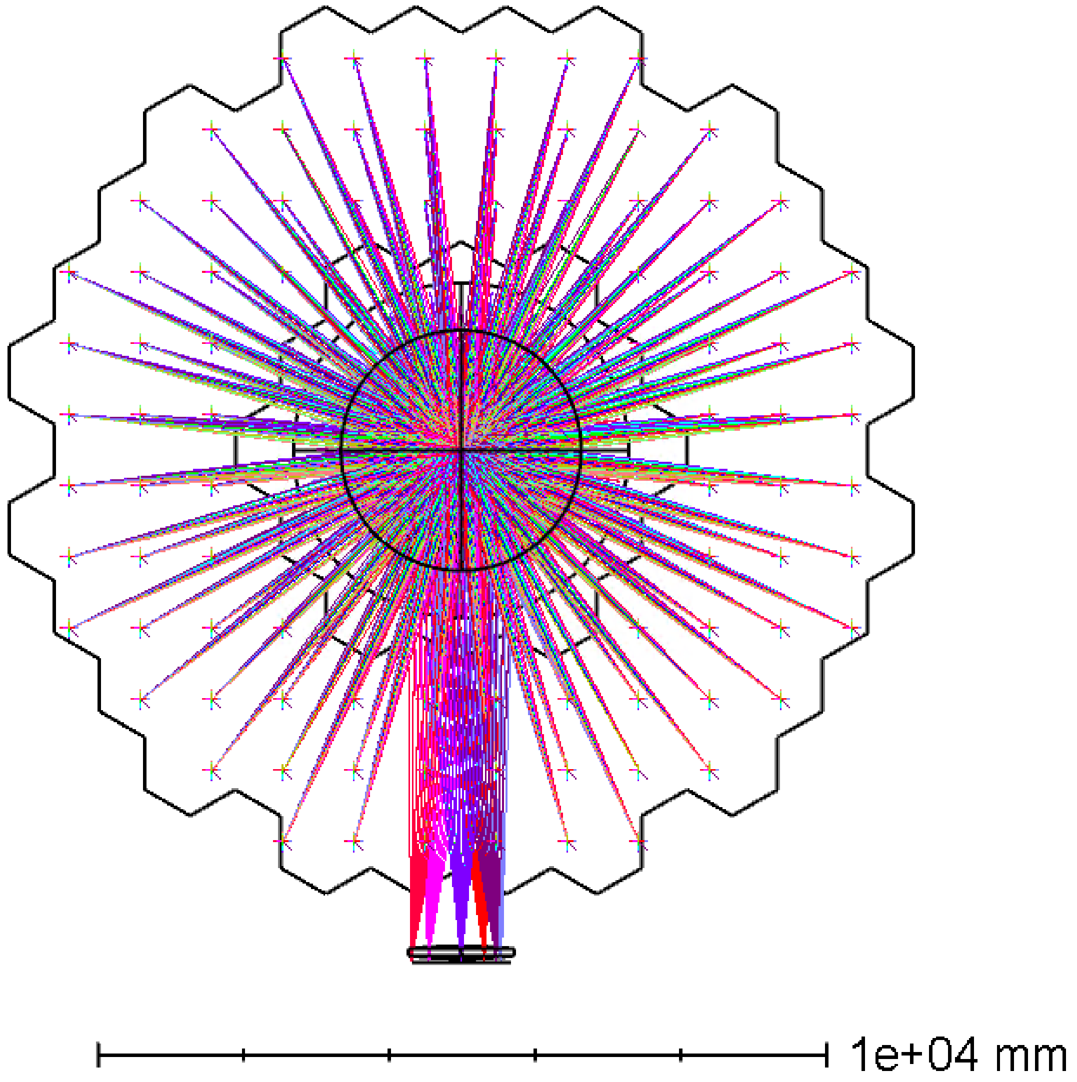


Maunakea Spectroscopic Explorer

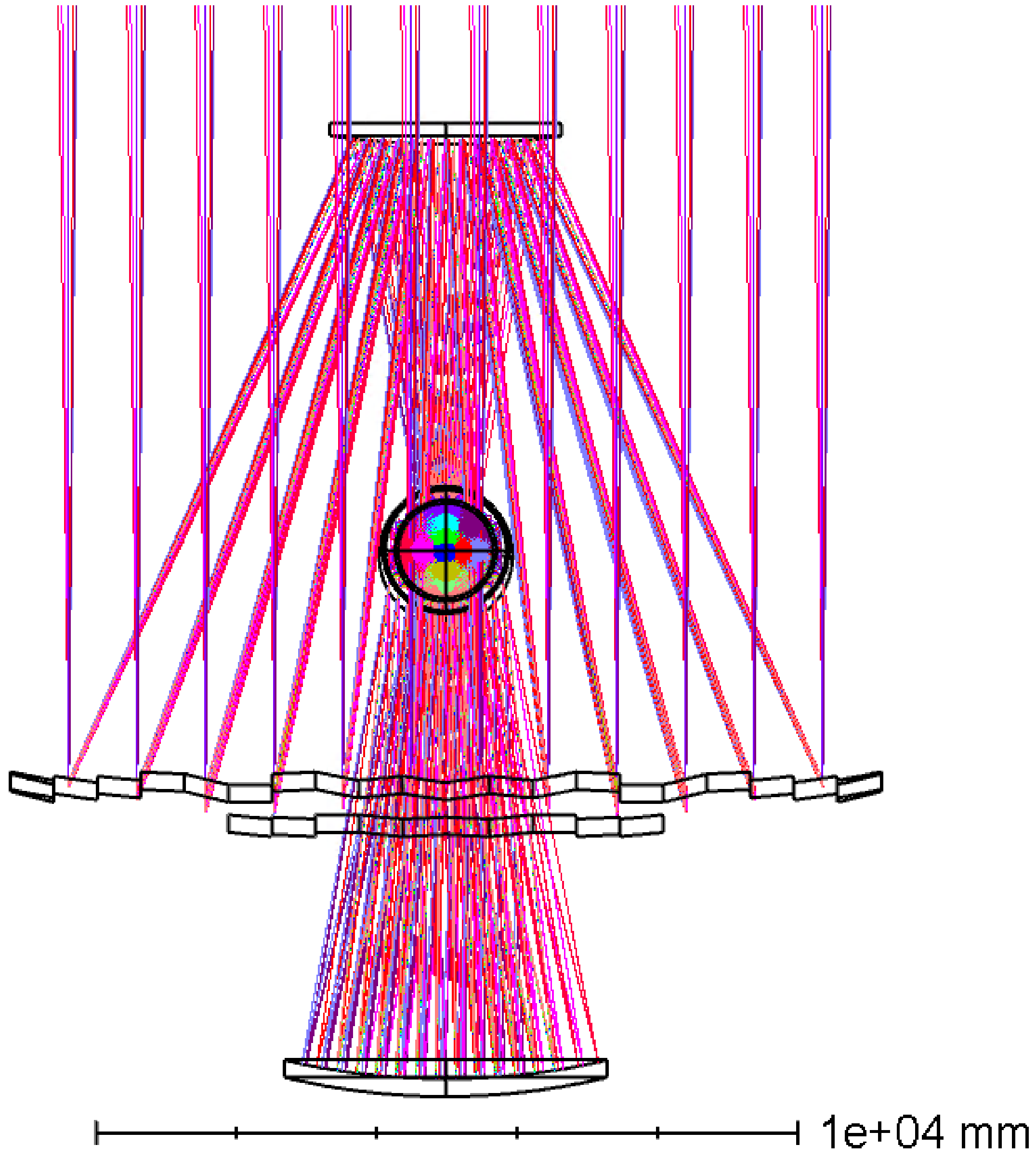
QM: Basic Parameters

- Based upon concept originally from Barden, Harmer, Claver, Dey, 2000, SPIE, 4004, 397B
- Expanded upon in Barden, McGrath, Gillingham, Harmer, 2004, SPIE, 5489, 454B
- All derivatives of the Paul-Baker 3-mirror anastigmat (e.g., LSST)
- **Also, independently studied by the CAS – as presented here at AOPC2023 by Cui, Xiangqun (NIAOT)**

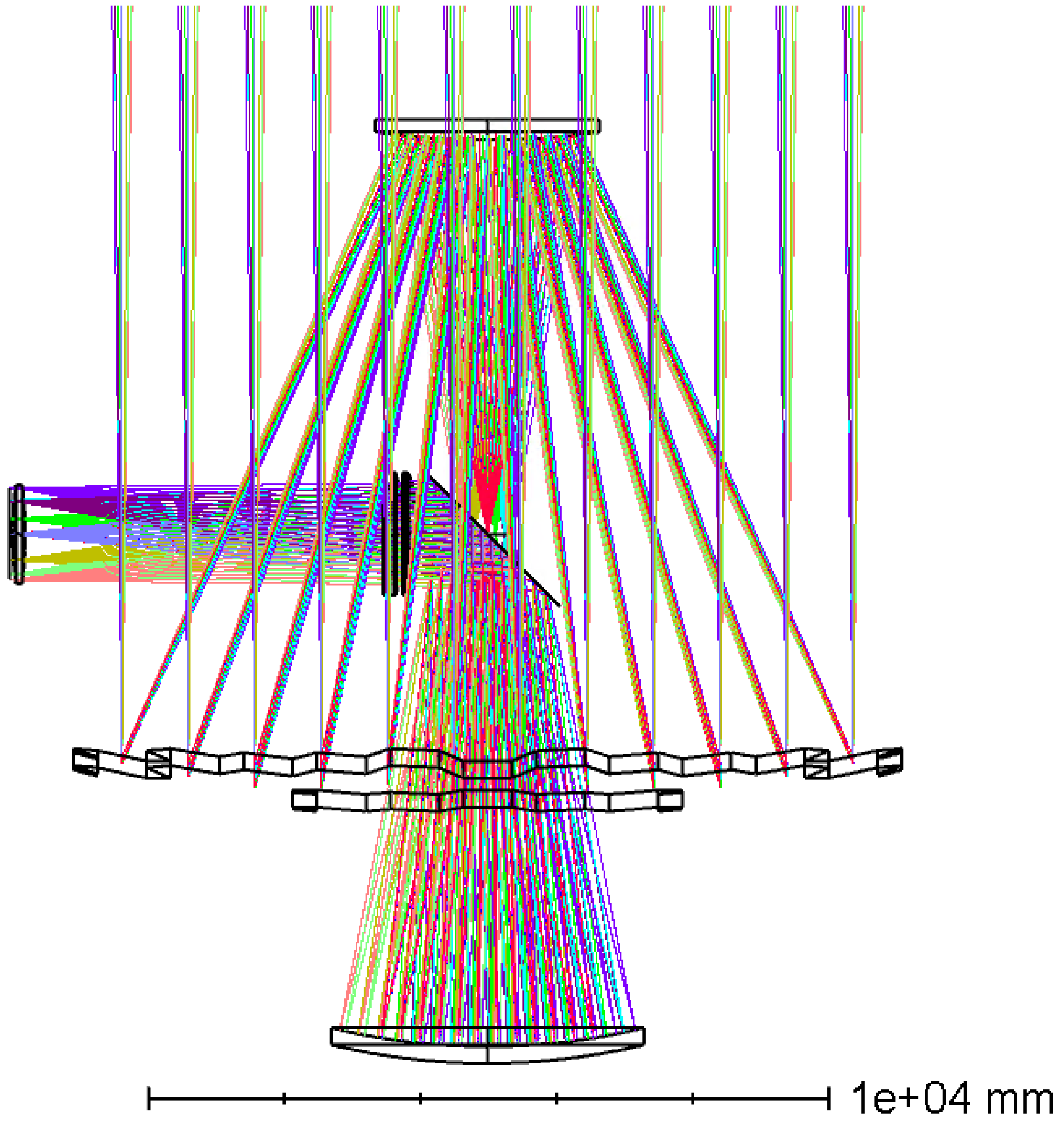
	Radius (mm)	Diameter (mm)	Comments
Aperture	6350	12700	
M1			Segmented, E-ELT compliant
M2	1650	3300	
M3	~2300	~4600	Constrained to fit through CFHT hatchway
M4 Hole	420x690		40mm Offset
Prime Focus	~650	~1300	Field of view 1.5°



<u>View from front of telescope</u>



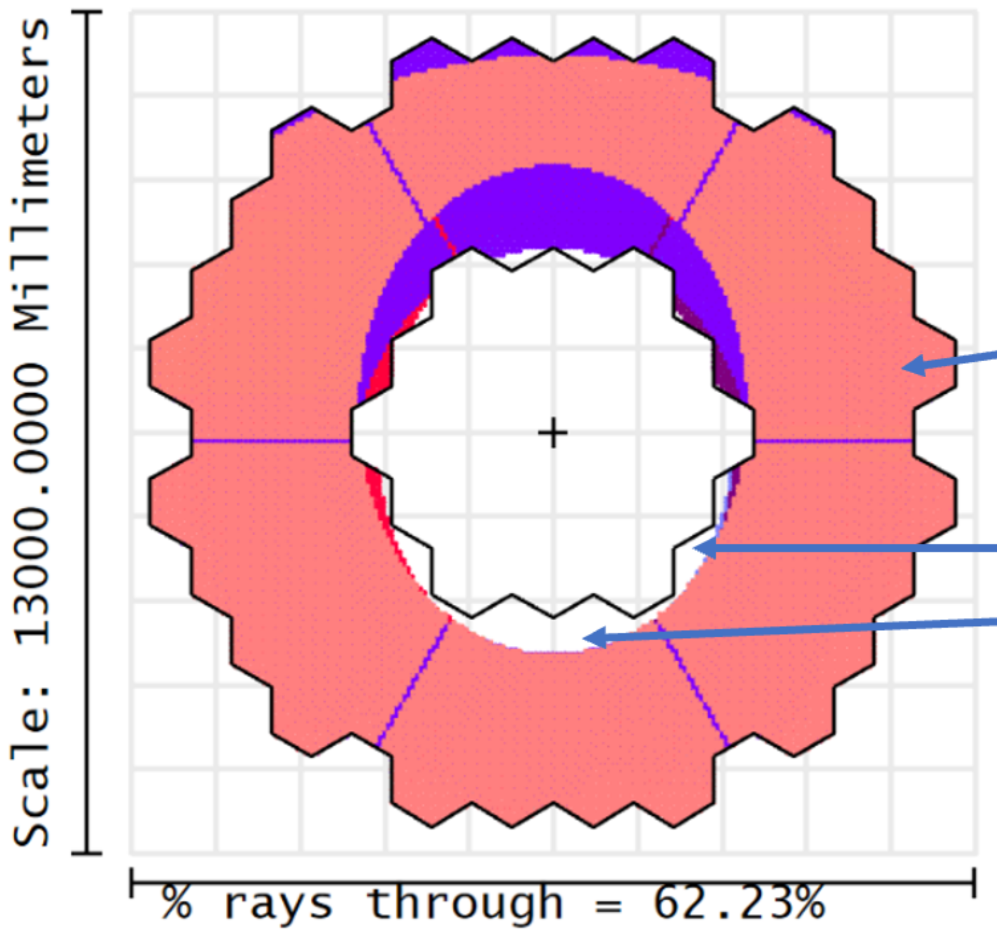
<u>Side view of telescope, down O.A.</u>

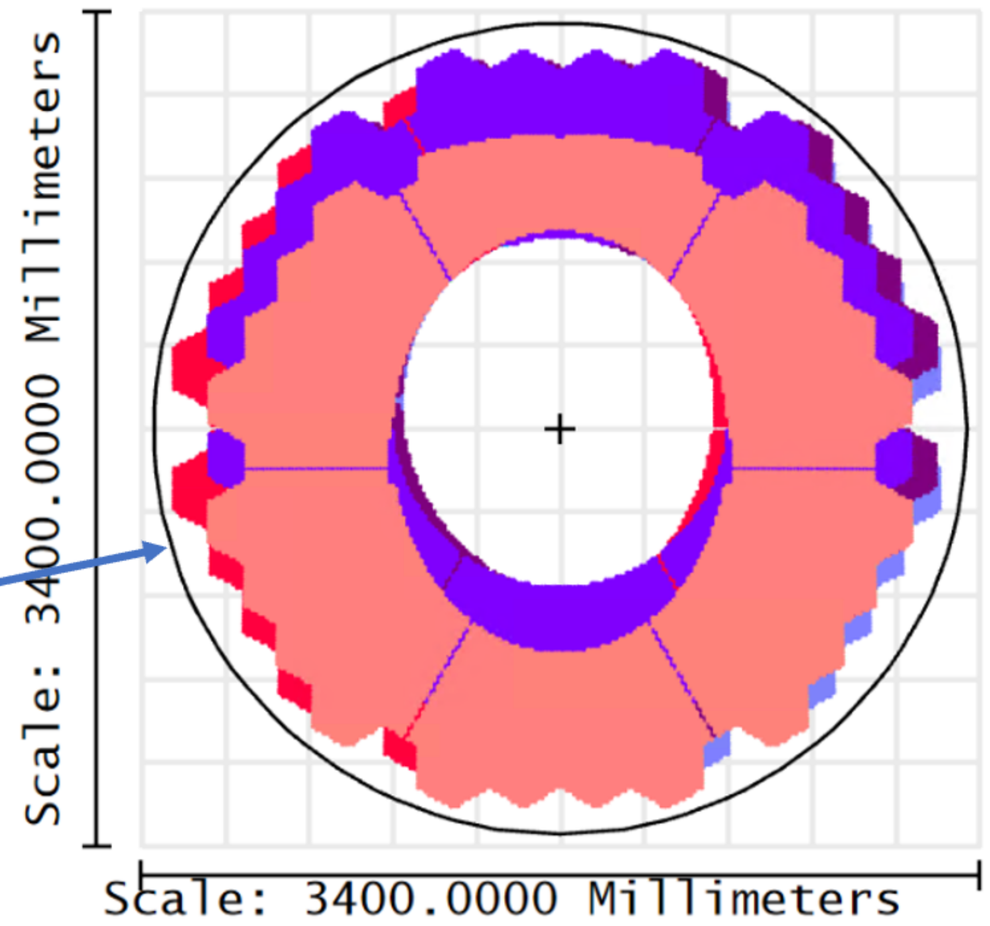


<u>Side view of telescope</u>

- 3 conic mirrors
- 1flat mirror
- 2 element Fused Silica ADC
- 1element Fused Silica pupil centration lens
- M1segmented with 144 meter segments

- 12.7 meter circumscribed diameter segmented Primary
- f/4 focus
- EFFL = 50722 mm
- 152 deg diam field = 15 square degree science FOV
- 246 microns/arc-second plate scale





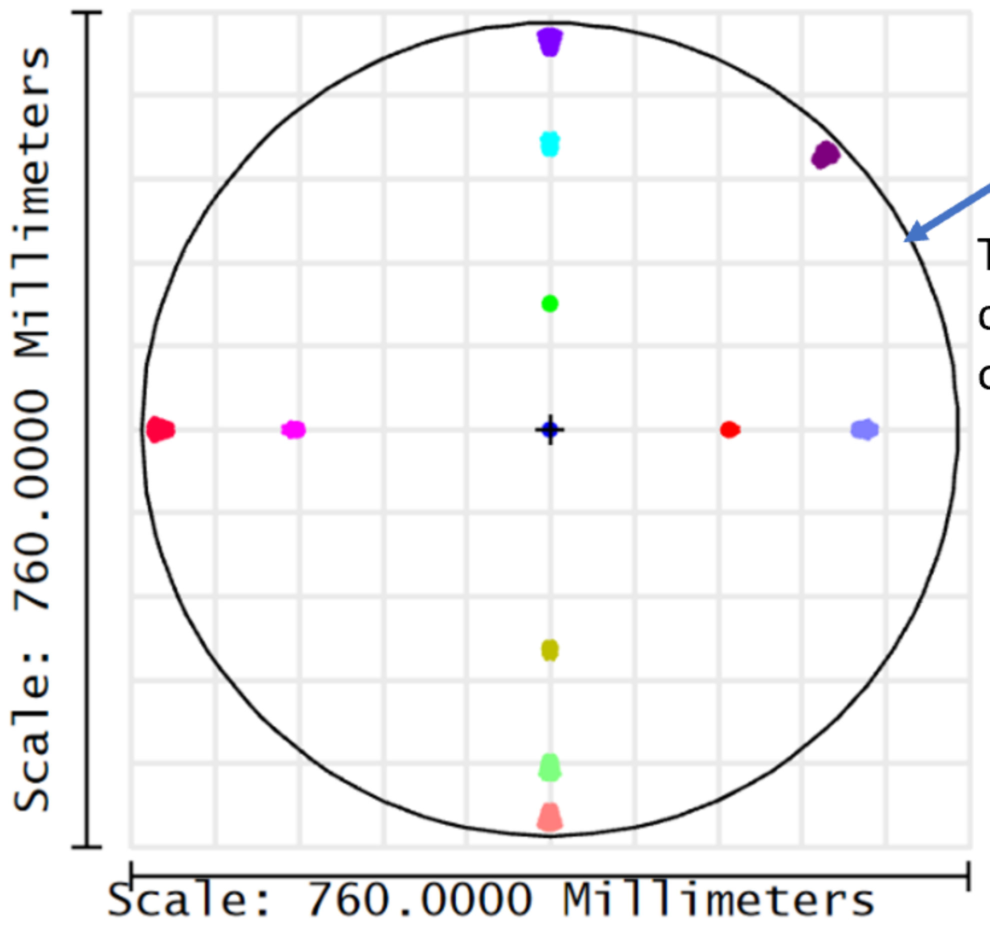
Optical Footprints

M1 Primary (segmented)
Circumscribed
Diam 12.7 m with
6.2 m central hole

Central Shadow

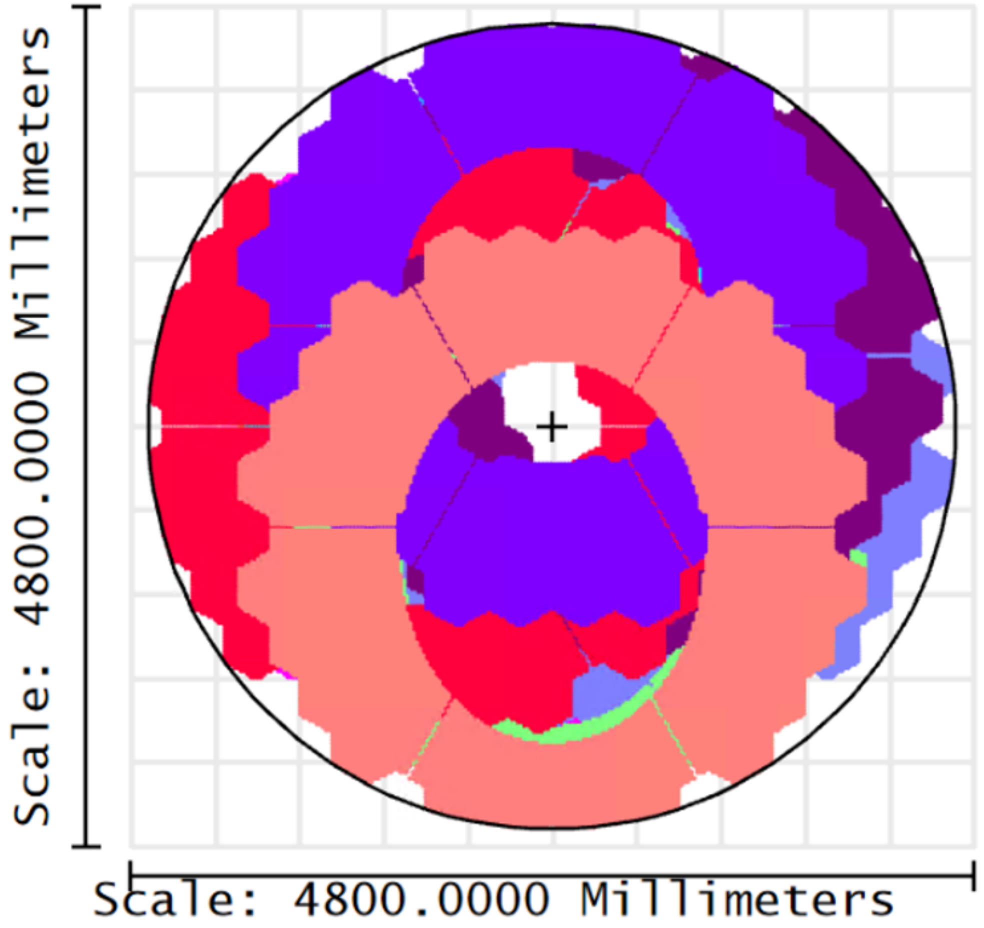
M2 Secondary
Diam 3.3 m

Prime Focus
Diam 0.740 m

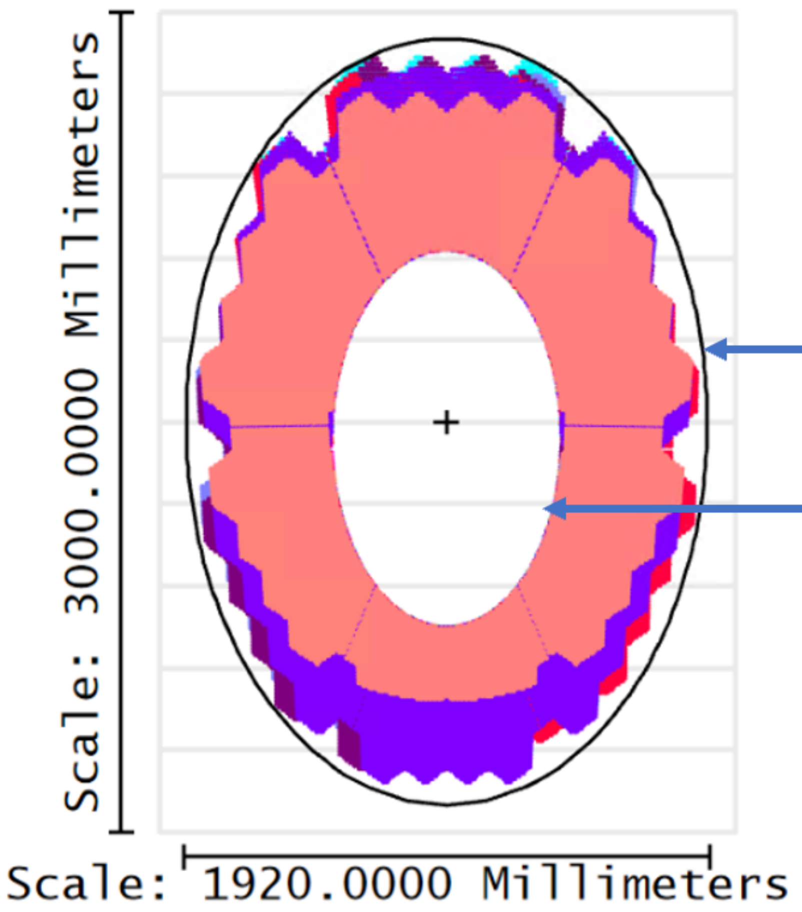


This sets the central obstruction

M3 Tertiary
Diam 4.6 m
Size limited by existing CFHT infrastructure and imposes some vignetting in the outer fields.

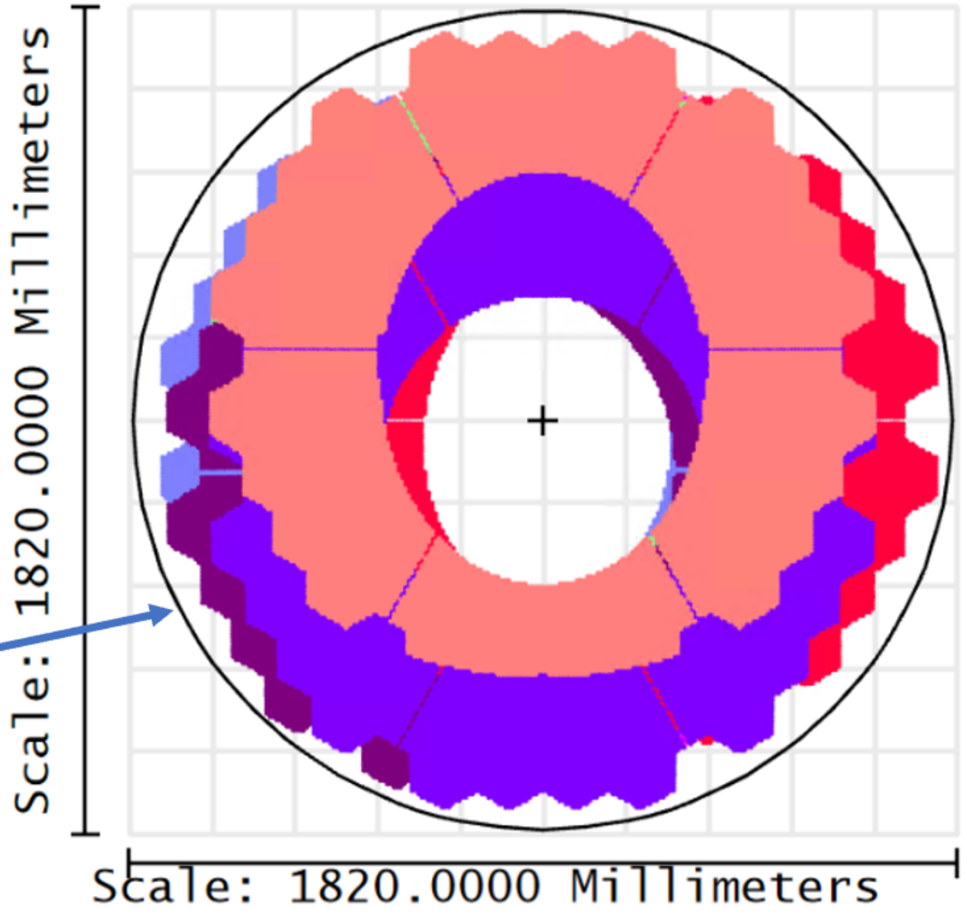


M2 and M3 are not illuminated at their centers. The mirrors could have center holes useful for support, handling, and alignment.

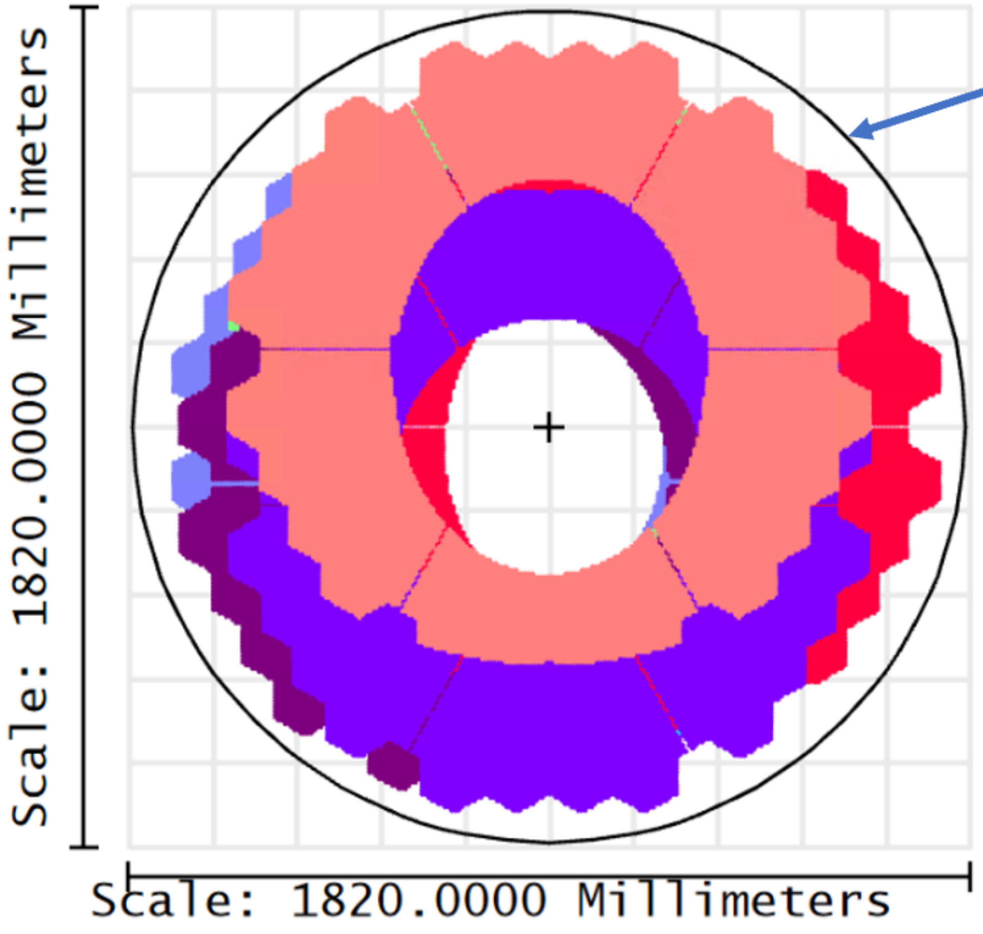


Optical Footprints

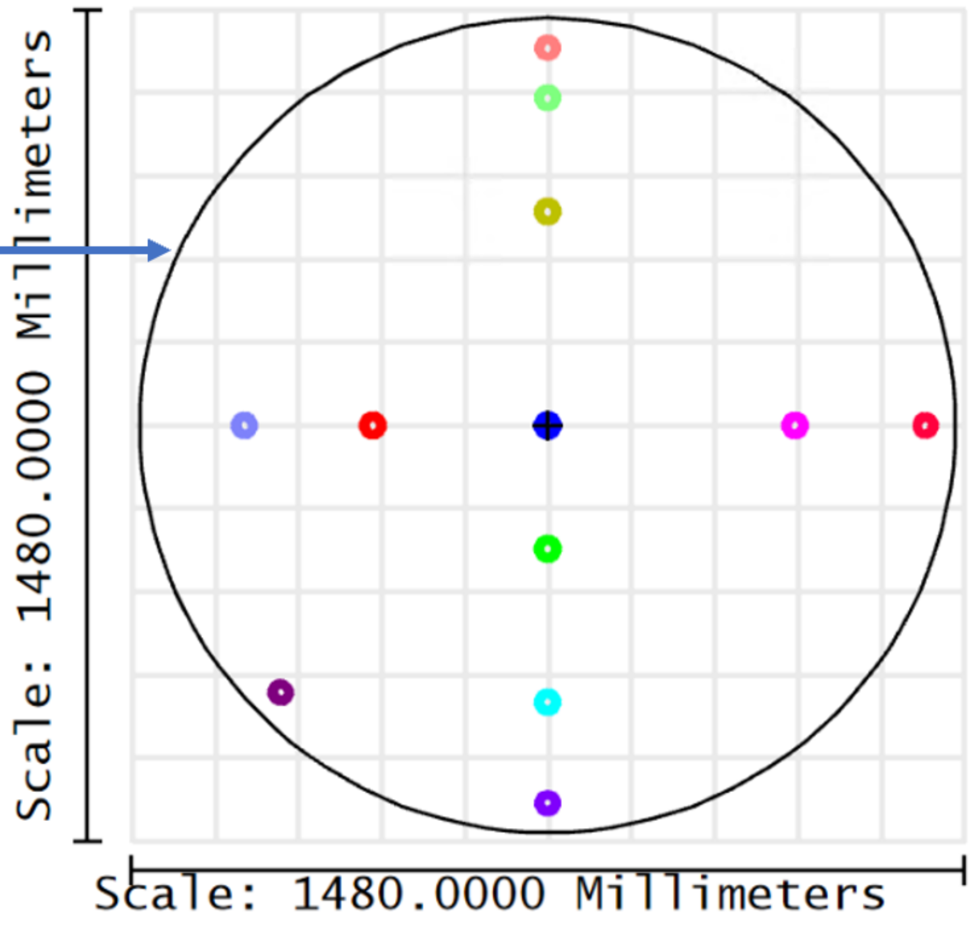
M4 Quaternary Fold
1.9 x 2.8 m
with 0.84 x 1.38 m hole
(assumes elliptical hole)



ADC Lens 1 (Fused Silica)
Diam 1.80 m



ADC Lens 2 (Fused Silica)
Diam 1.80 m

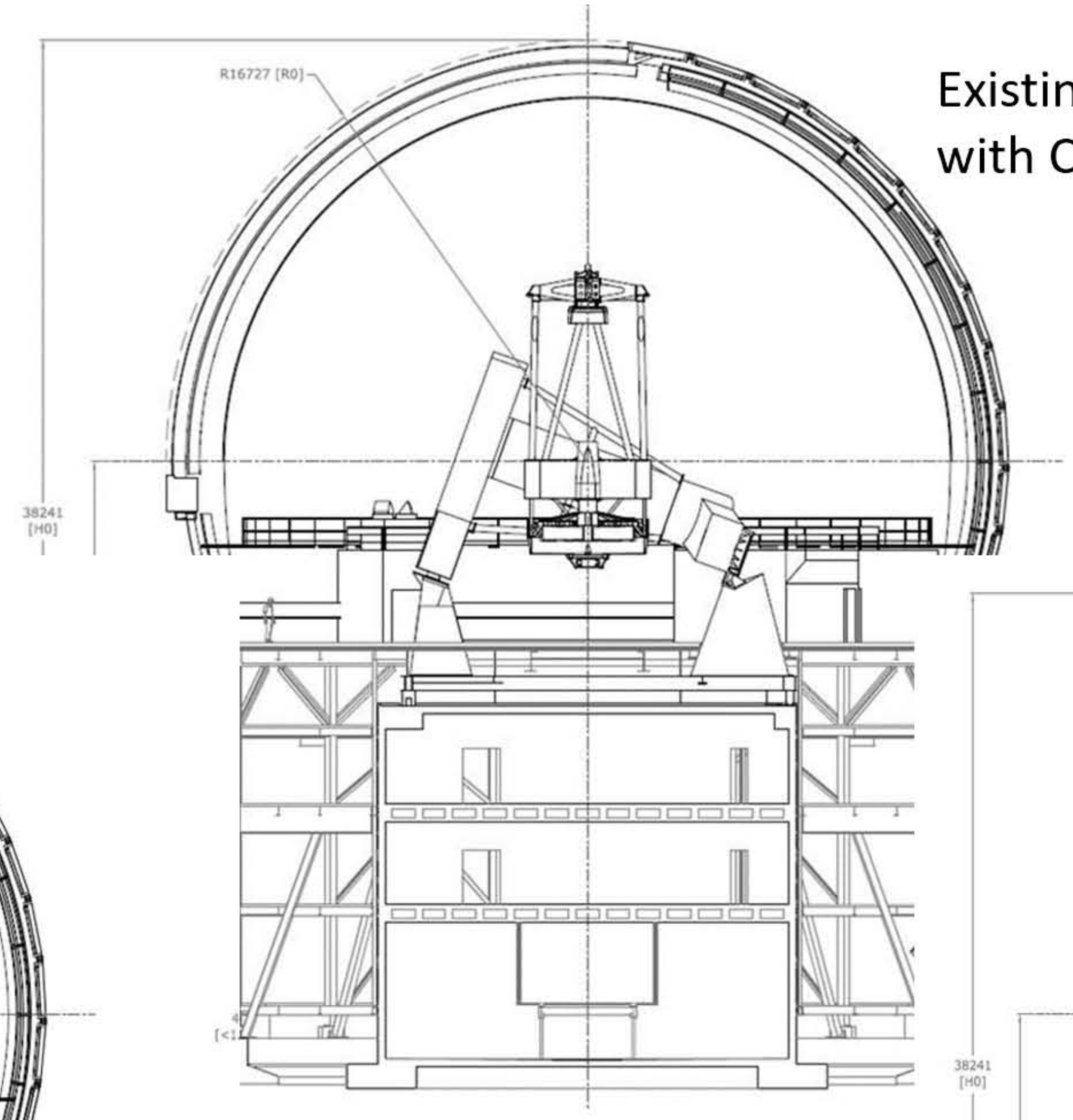


Field Lens (Fused Silica)
Diam 1.45 m

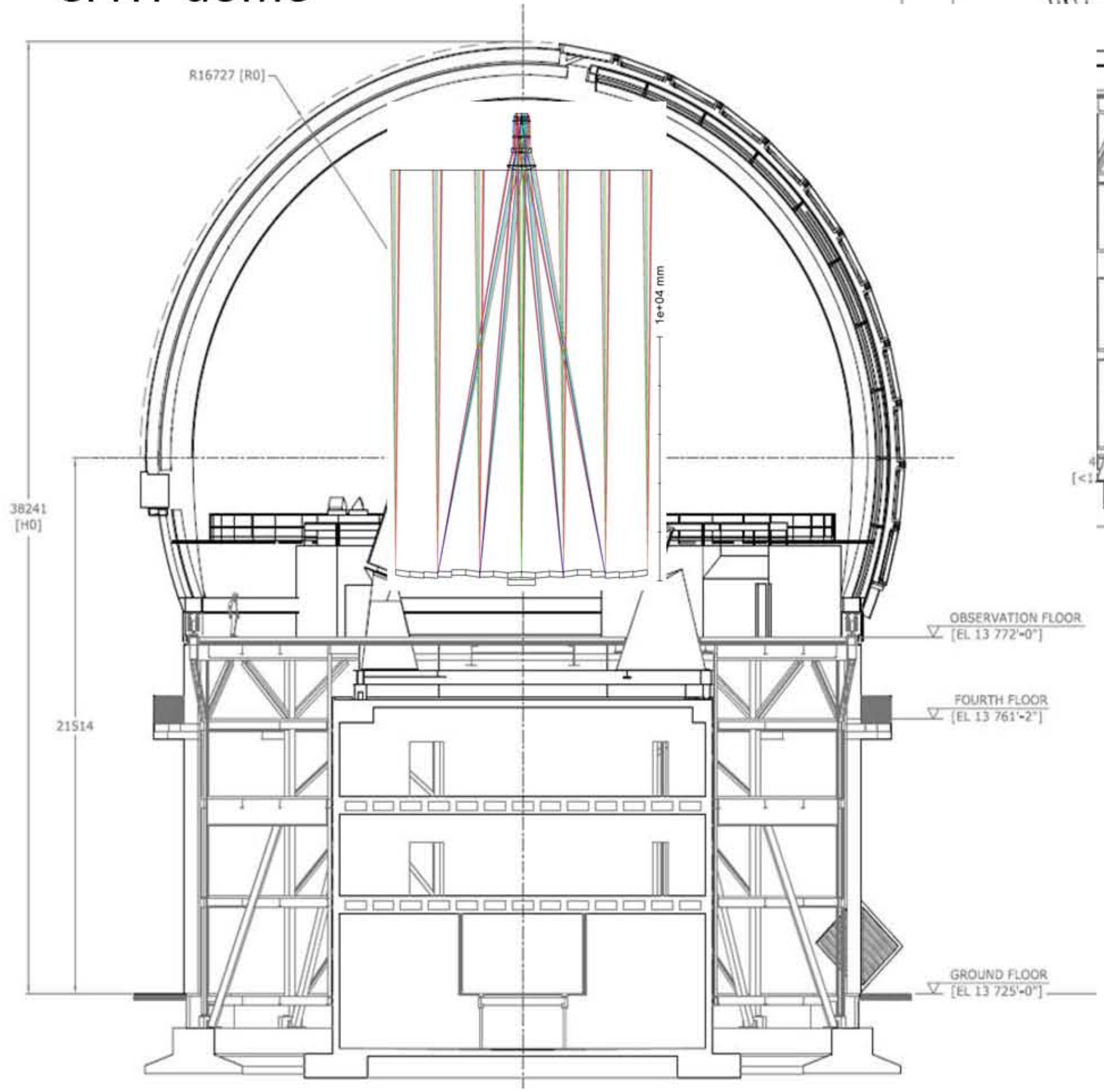
All lens surfaces are spherical.

Both ADC lenses are not illuminated at their centers. The optics could have center fixtures useful for support, handling, and alignment.

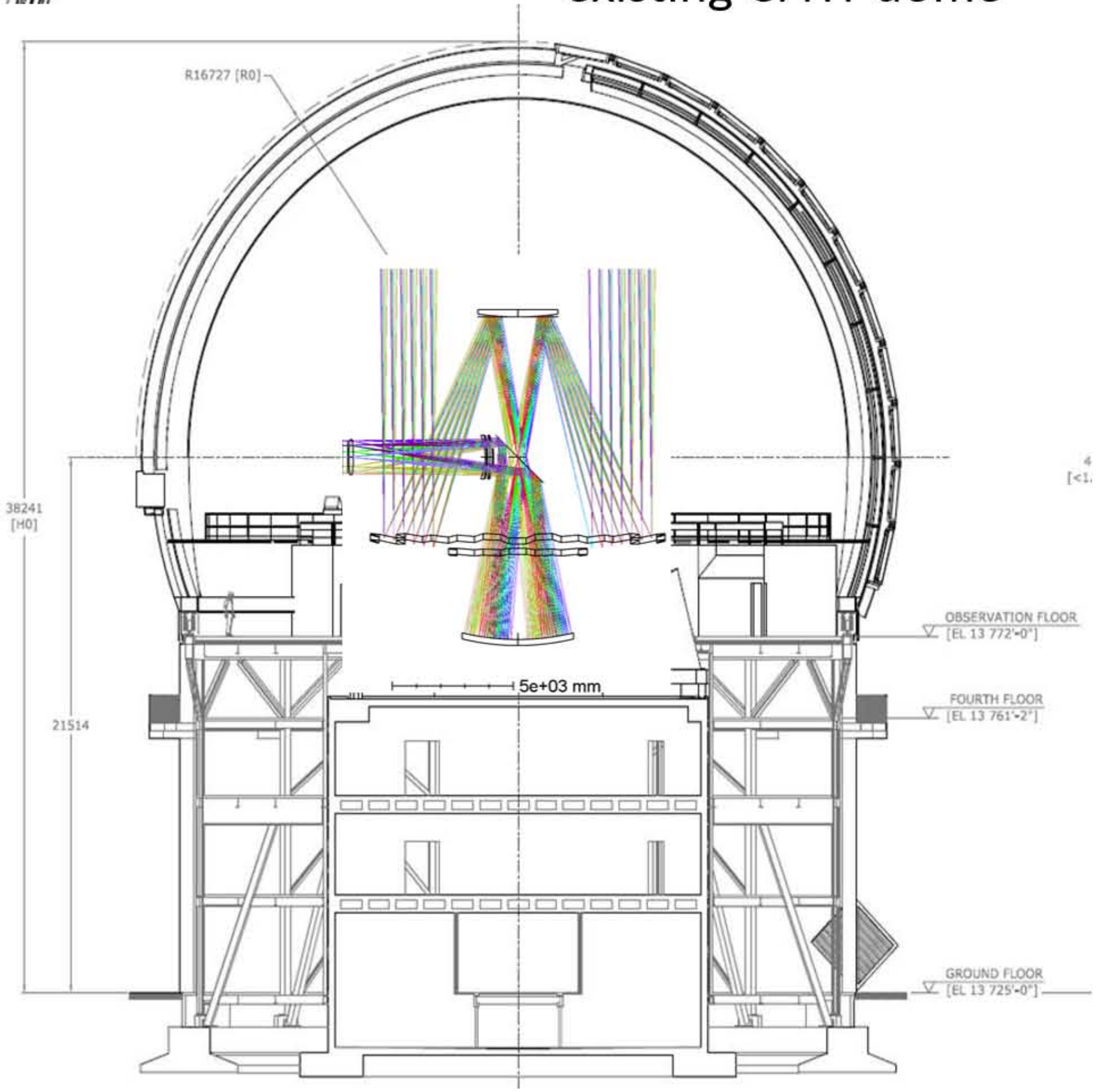
Existing CFHT dome with CFH Telescope



6w6 MSE in existing CFHT dome

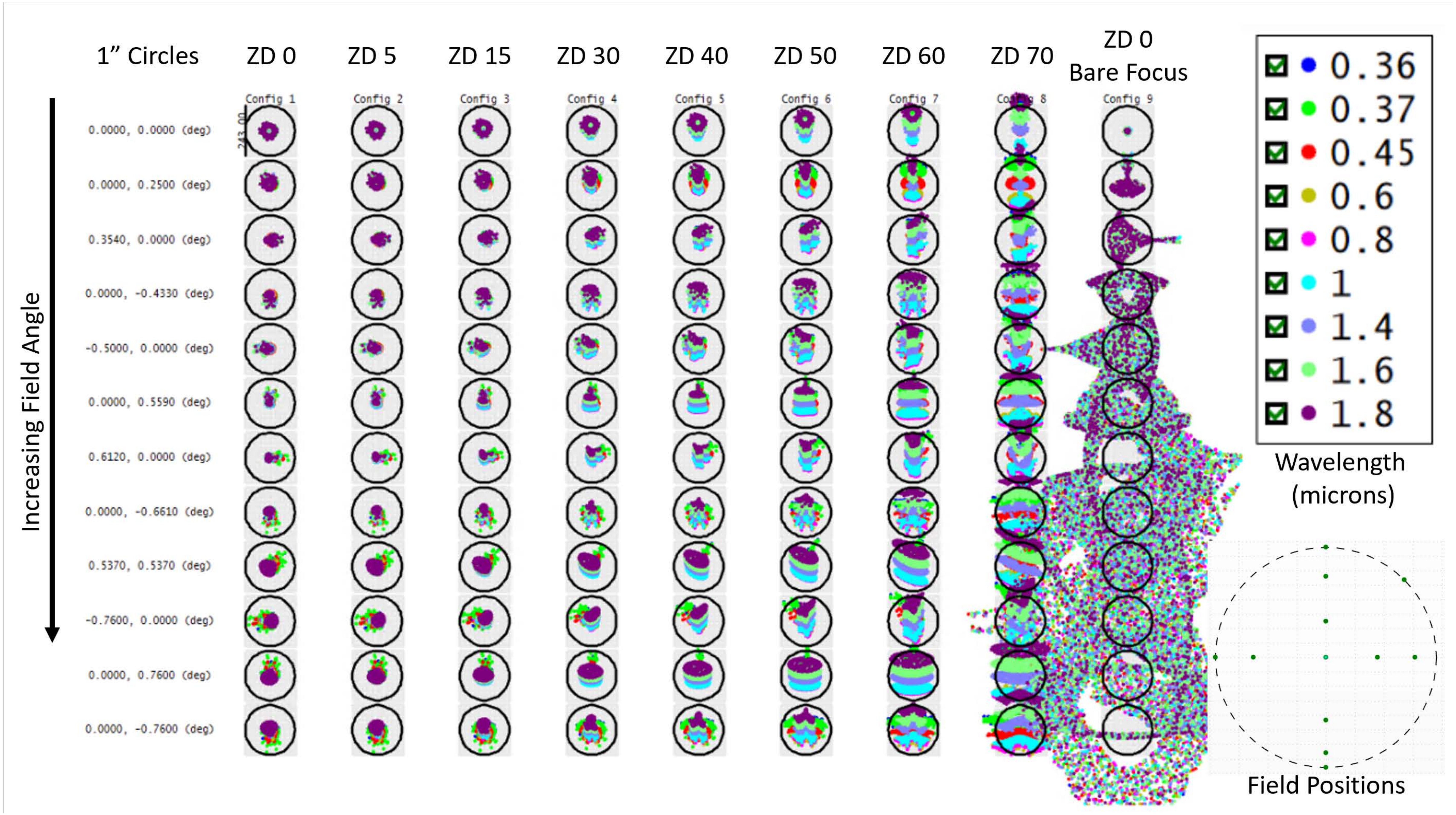


Quad-Mirror MSE in existing CFHT dome



The 6w6 design does not fit within the existing dome envelope. The QM design likely can fit within the existing envelope.

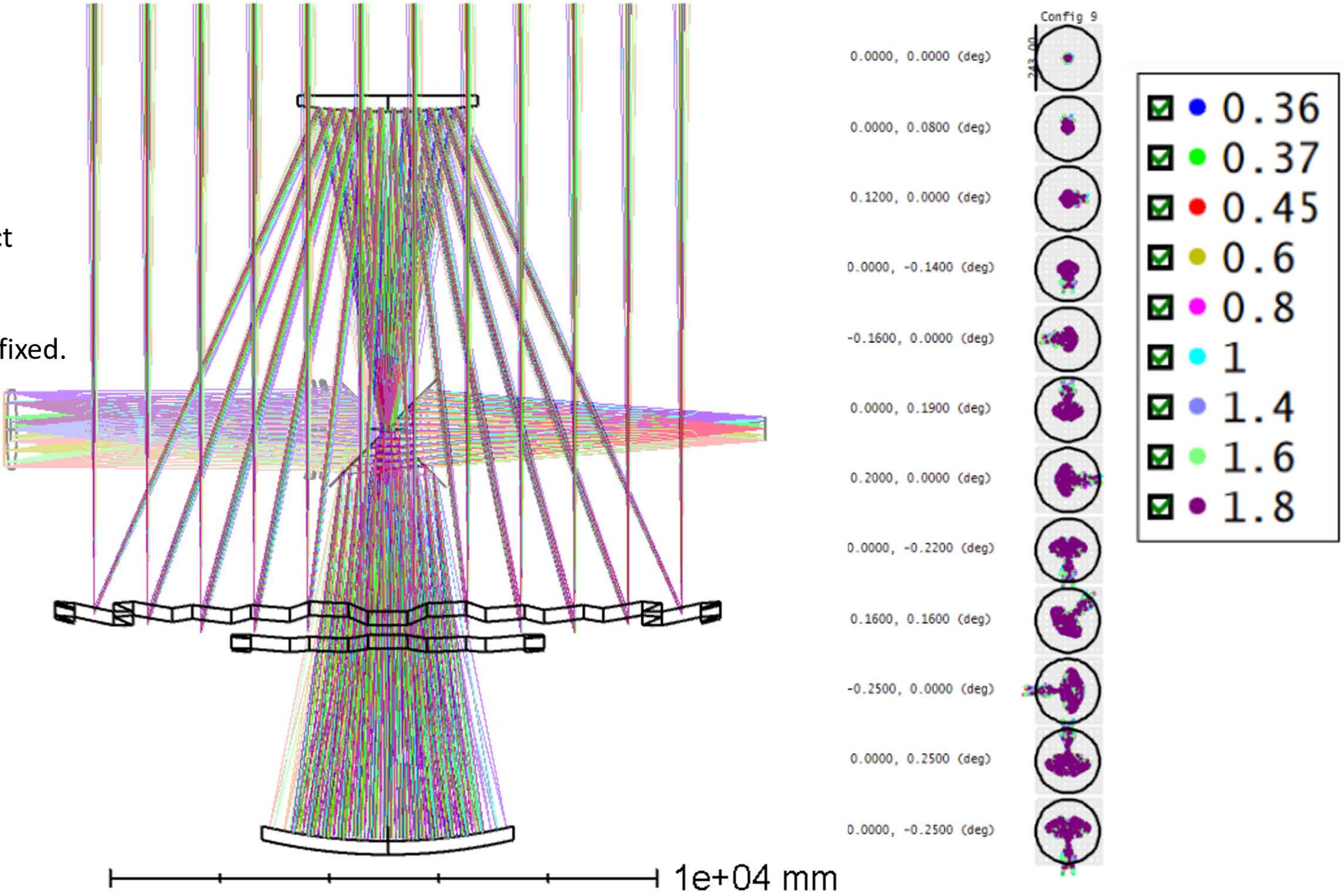
A new dome/shutter is required in either case due to the larger aperture of the telescope compared to CFHT.

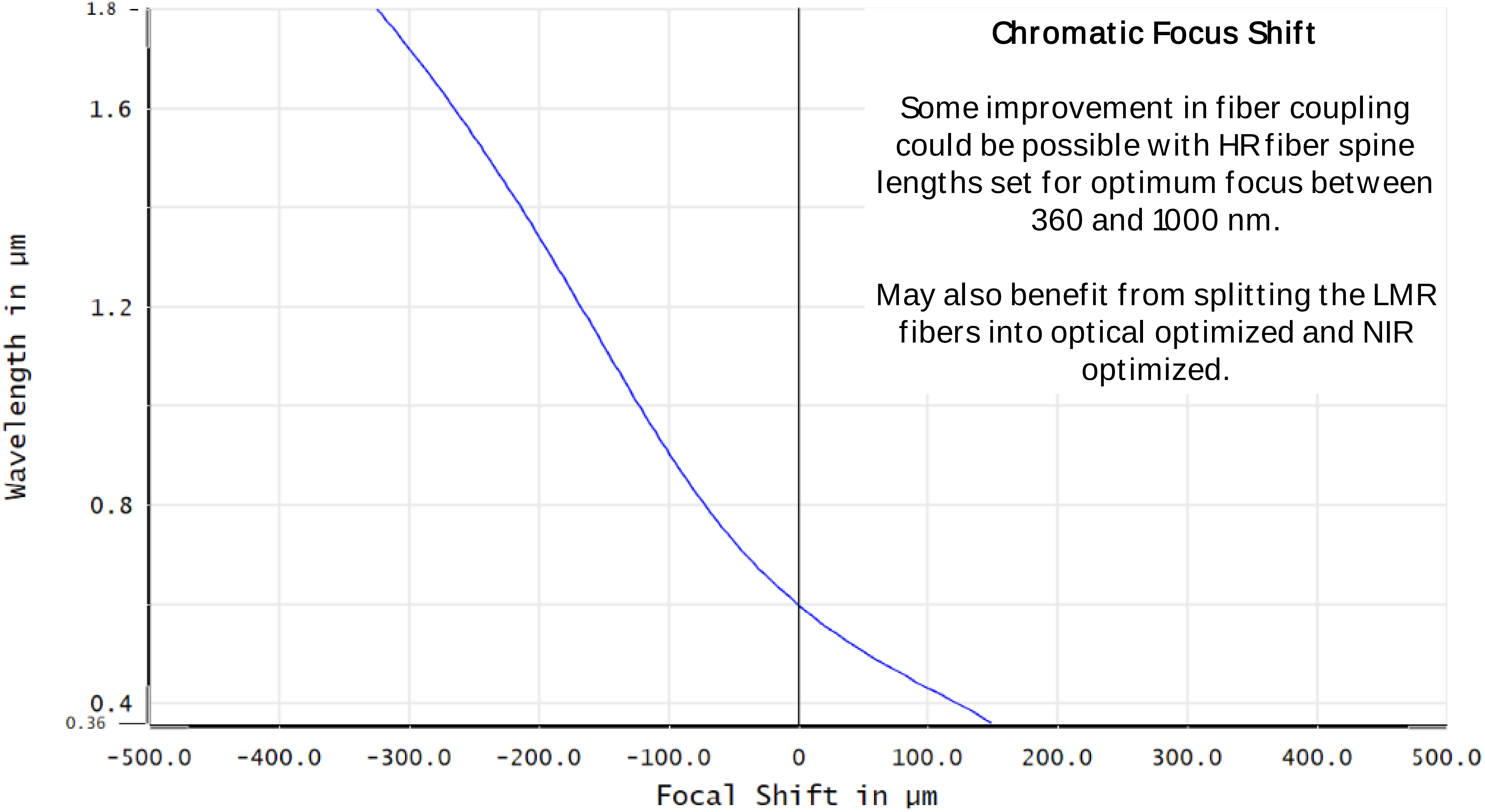

1” Circles
ZD 0
ZD 5
ZD 15
ZD 30
ZD 40
ZD 50
ZD 60
ZD 70
ZD 0 Bare Focus
Config 1
Config 2
Config 3
Config 4
Config 5
Config 6
Config 7
Config 8
Config 9
Increasing Field Angle
0.0000, 0.0000 (deg)
0.0000, 0.2500 (deg)
0.3540, 0.0000 (deg)
0.0000, -0.4330 (deg)
-0.5000, 0.0000 (deg)
0.0000, 0.5590 (deg)
0.6120, 0.0000 (deg)
0.0000, -0.6610 (deg)
0.5370, 0.5370 (deg)
-0.7600, 0.0000 (deg)
0.0000, 0.7600 (deg)
0.0000, -0.7600 (deg)
0.36
0.37
0.45
0.6
0.8
1
1.4
1.6
1.8
Wavelength (microns)
Field Positions

MOS and Bare Nasmyth Foci

M4 rotates to select port.

MOS ADC remains fixed.



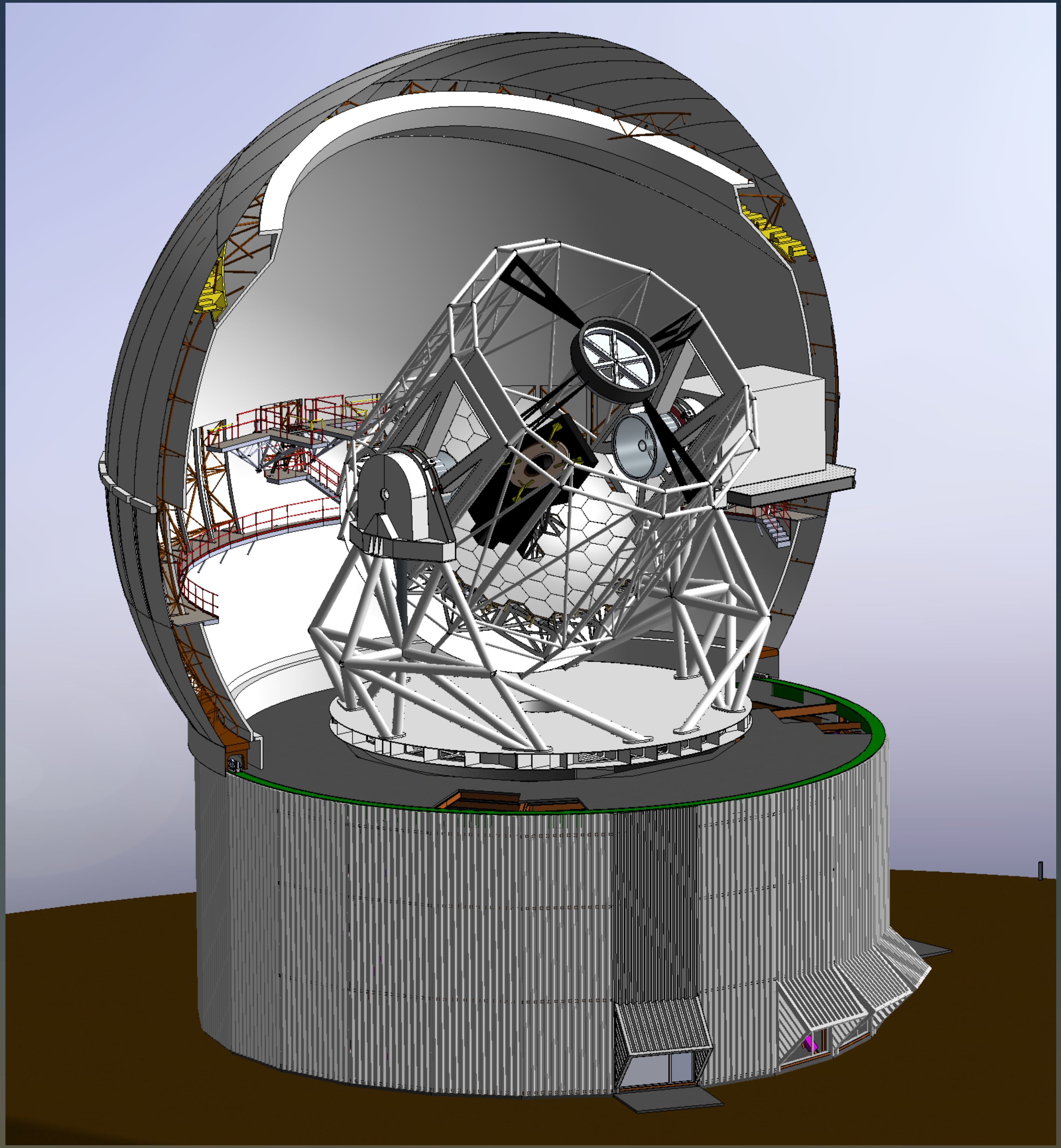


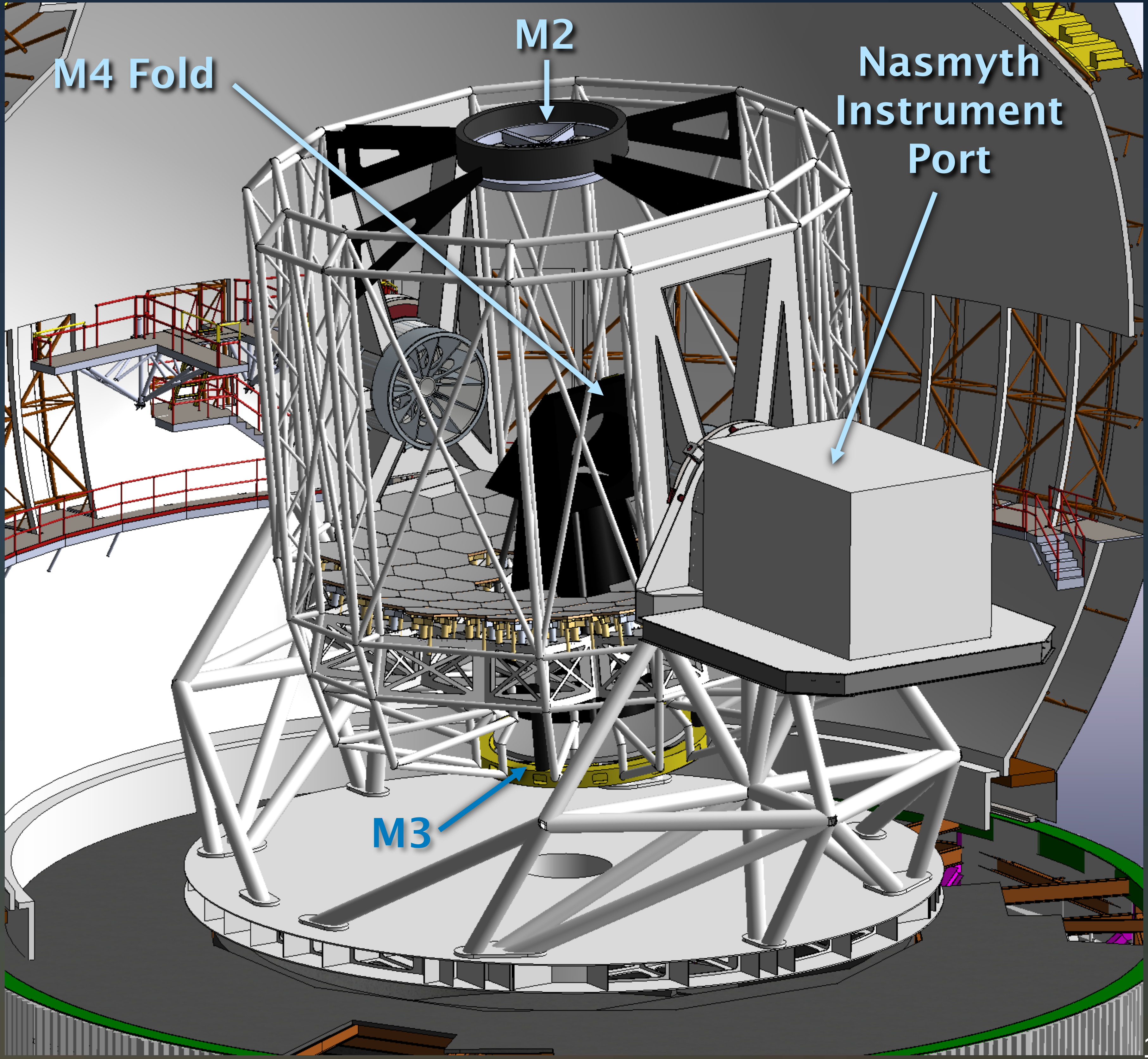
Chromatic Focus Shift

Some improvement in fiber coupling could be possible with HR fiber spine lengths set for optimum focus between 360 and 1000 nm.

May also benefit from splitting the LMR fibers into optical optimized and NIR optimized.

MSE QM – Mechanical design cartoon





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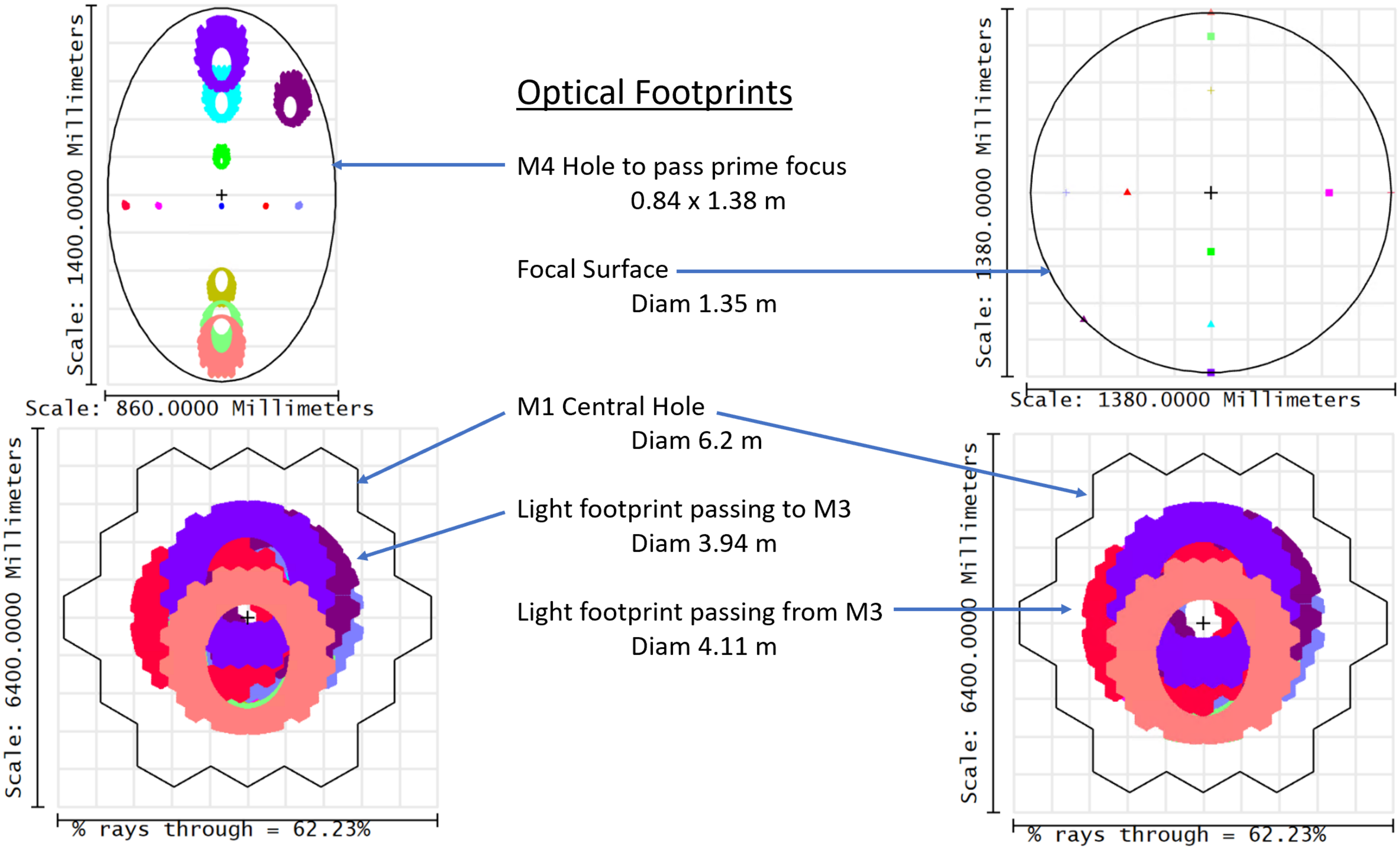
Feasibility - Next steps

- ADC fused silica sourcing or alternative approaches?
- Optical surface figure tolerances
- Telescope structure, mass estimate
- Throughput, coatings

- Parallel work needed:
  - Realignment of science case to current/upcoming spectroscopic facility landscape
  - Refine concept for spectrographs – wavelength splitting, pupil slicing, power budget?
  - Are the constraints being applied too specific to the CFHT site in the context of a partnership with twin north/south facilities?

Optical Footprints



QM increases multiplexing 5x from baseline

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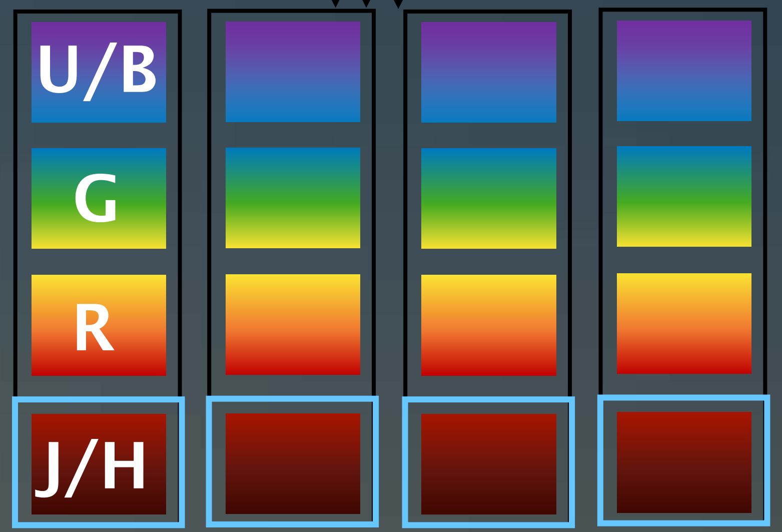
Baseline Concept

10 m Segmented M1

Low/Medium Res. (R = 4500 - 6000): ~3,000 Fibers, 3.6 – 1.8 μm

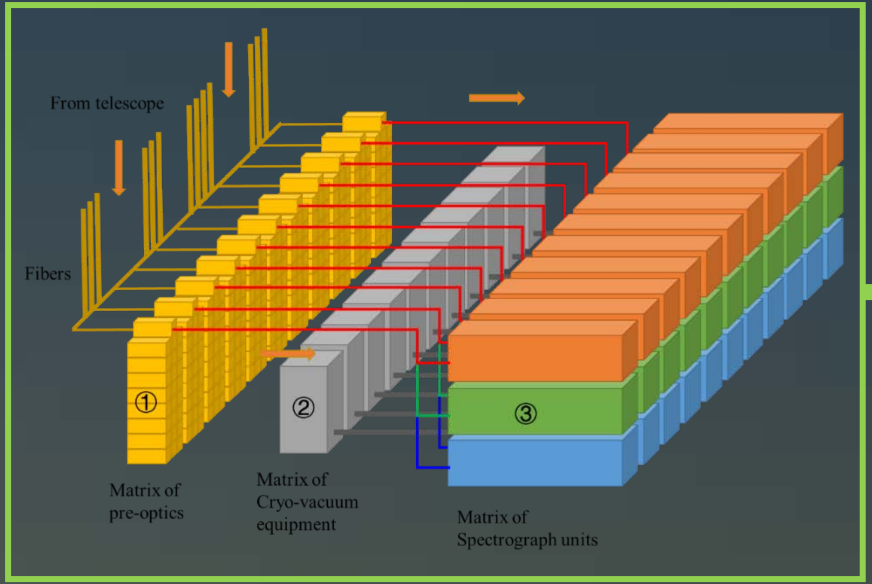
High Res (R = 30,000 – 40,000): ~1,000 Fibers, 3.6 – 1.0 μm



Cryo optics for J & H Bands

4 x MOONs style spectrographs x 4 wavelength bands, 16 total dispersers/cameras (4 collimators)

Kai Zhang concept, 2022



Split wavelength channels before the spectrograph, 11 x 3 bands for a total of 33 spectrographs

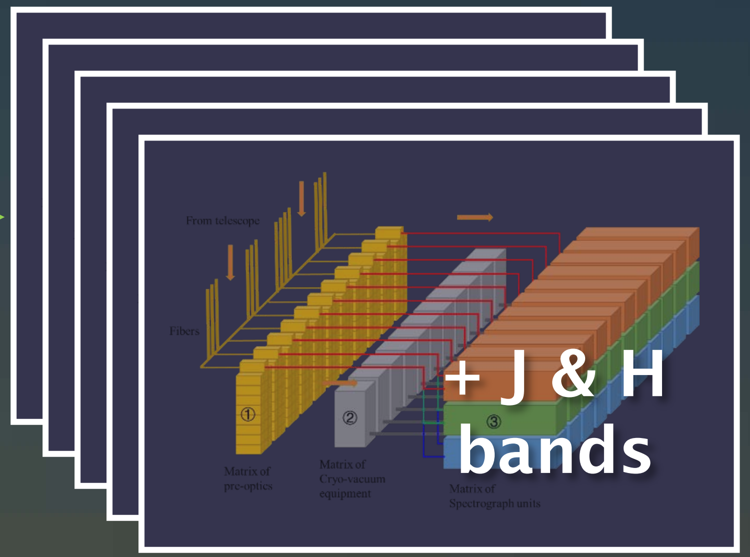
Same 1.5° Field of View, 2.3x Baseline Plate Scale

Quad Mirror

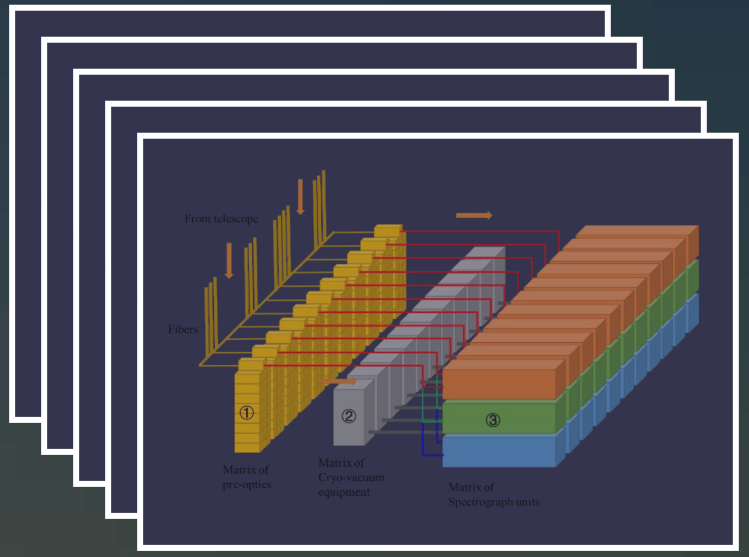
12.5 m Segmented M1

Low/Medium Res. 15,000 Fibers

High Res. 5,000 fibers



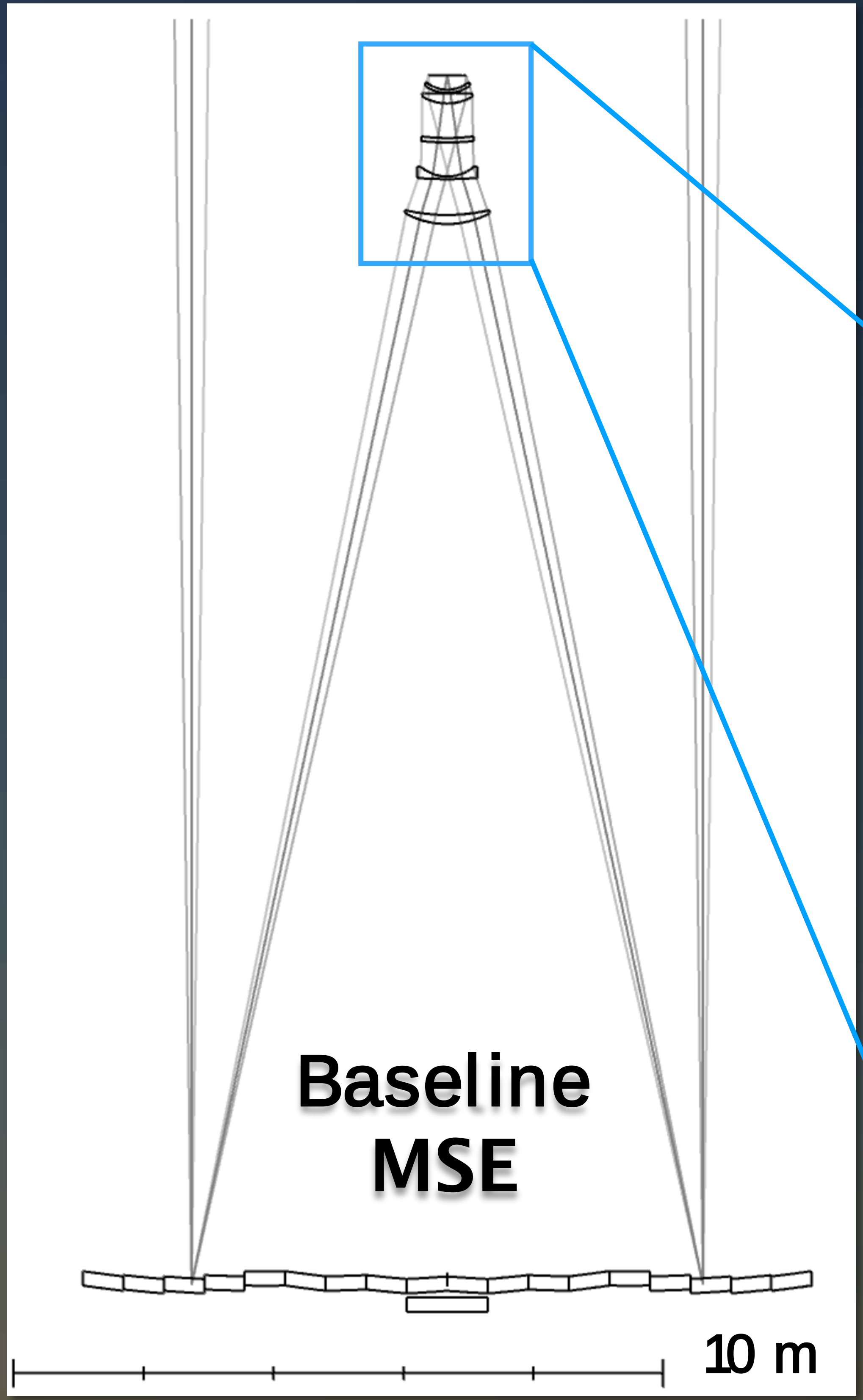
Similar concept as Zhang, 2022: 36 per band, for a total of 180 spectrographs

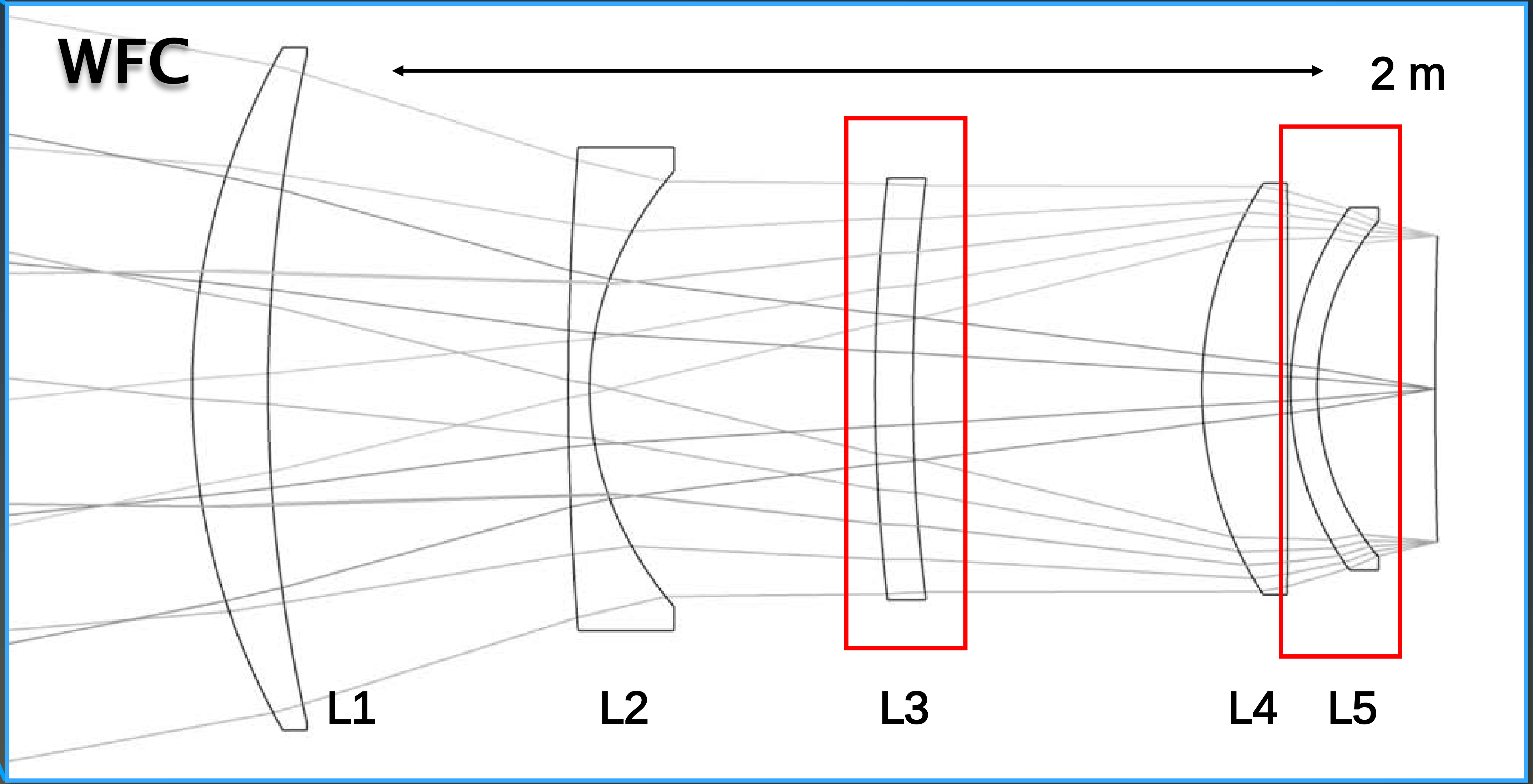


20 per band for a total of 60 spectrographs

Optical ghosts in the MSE Baseline

- Zero-power "bent plates" (menisci) are particularly problematic because a well focused ghost is likely.
- L3 and L5 in the baseline wide-field-corrector (WFC), circled in red
- L3 and L5 are PBM2Y, remainder are fused silica.

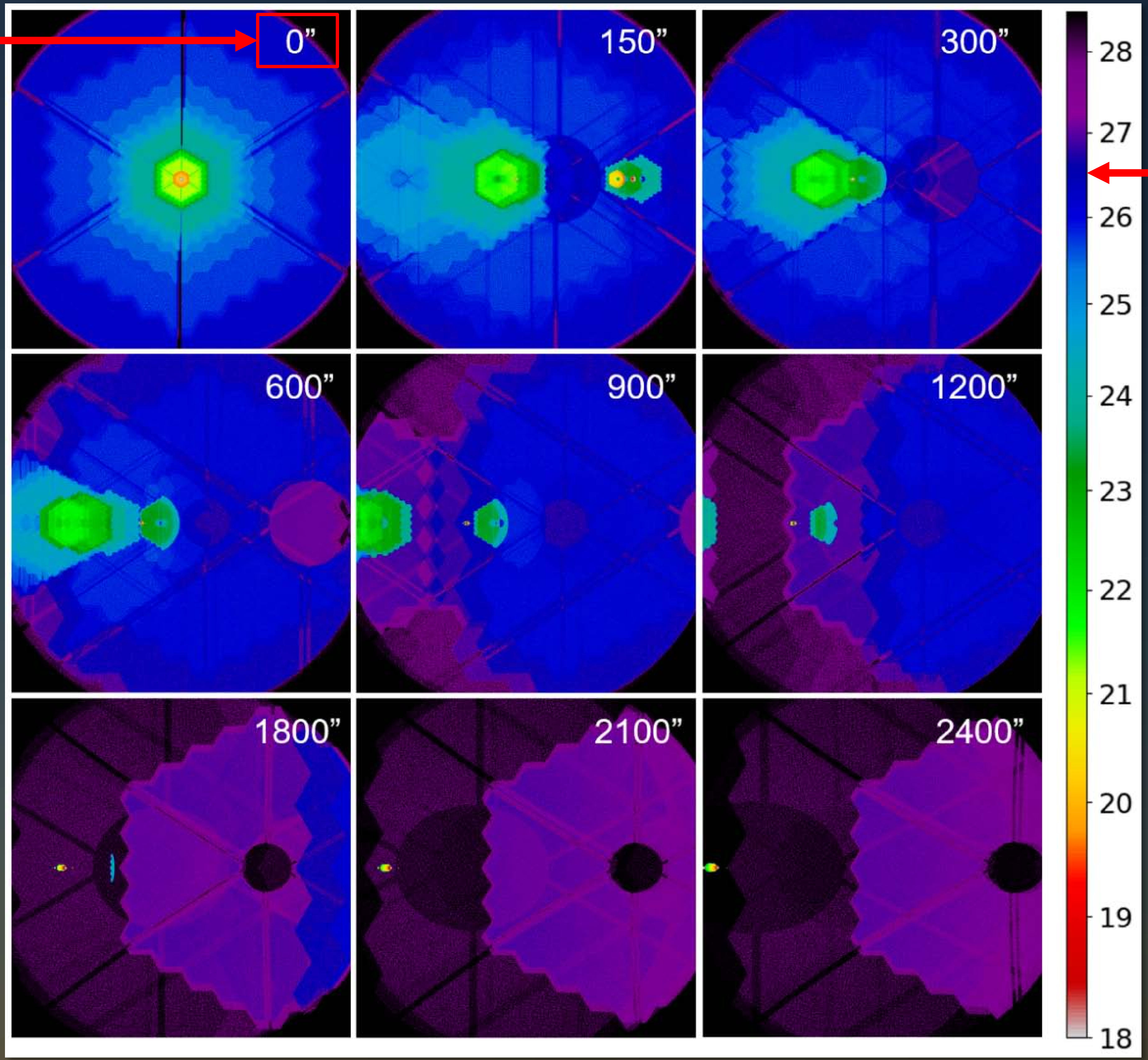




Ghost irradiance for the MSE baseline

Source position in arc-sec

Ghosts this bright require complicated mitigation strategies that limit sky coverage, especially along the galactic plane.



Ghost Threshold M = 26.5 "-2

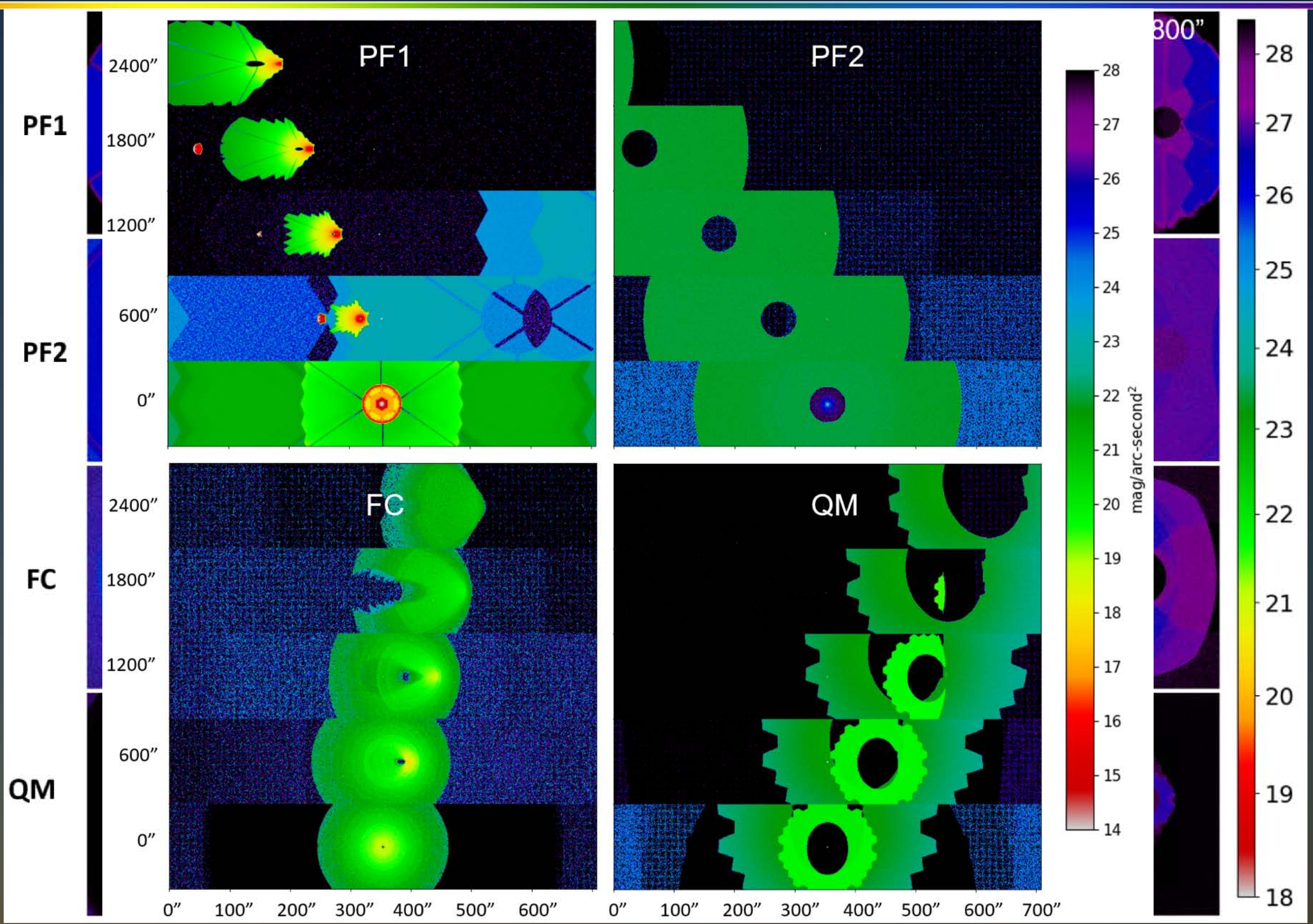
Ghost comparison between telescopes

PF1: Original prime focus

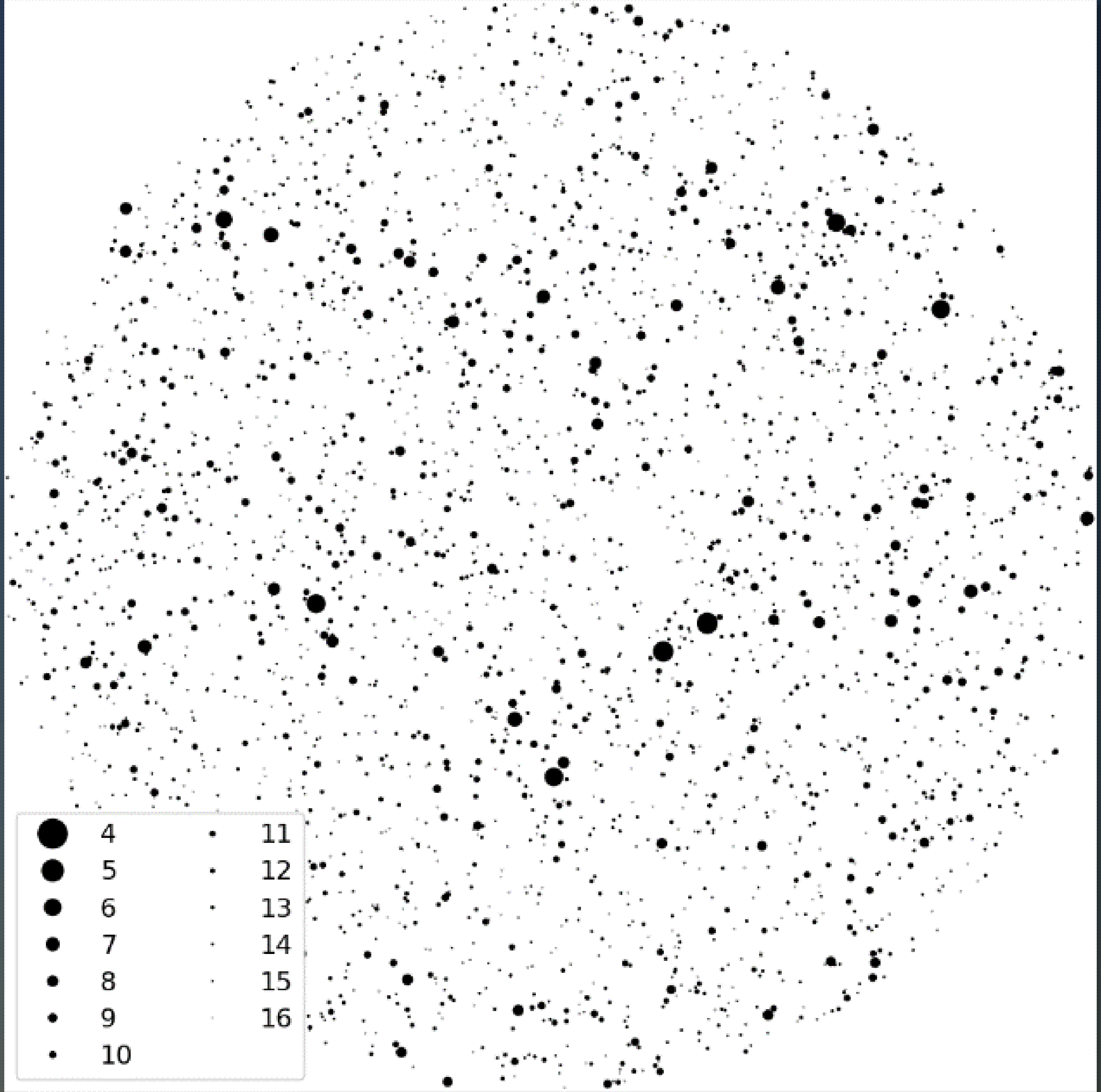
PF2: Ghost Optimized prime focus

FC: Cassegrain

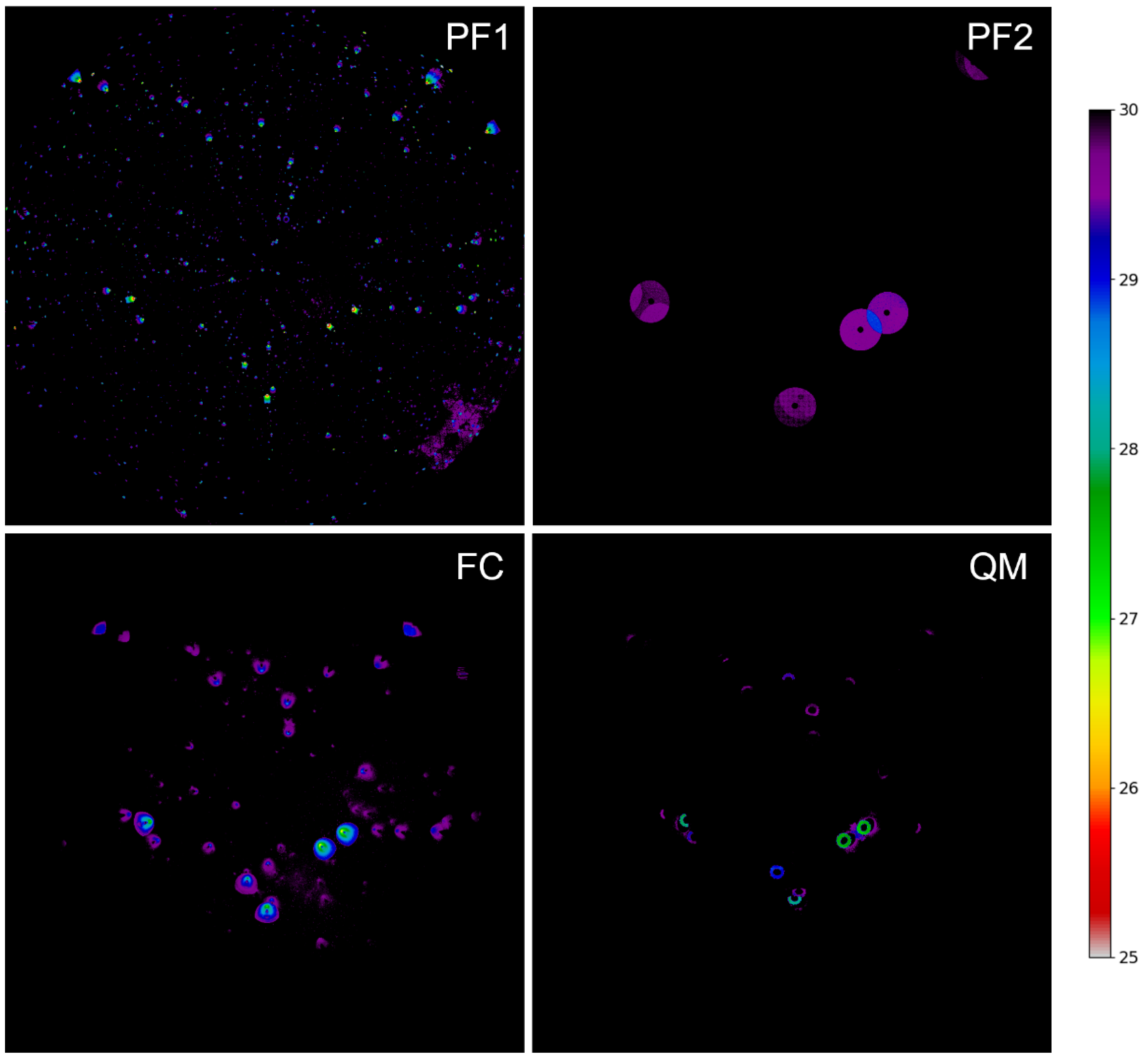
QM: Quad mirror



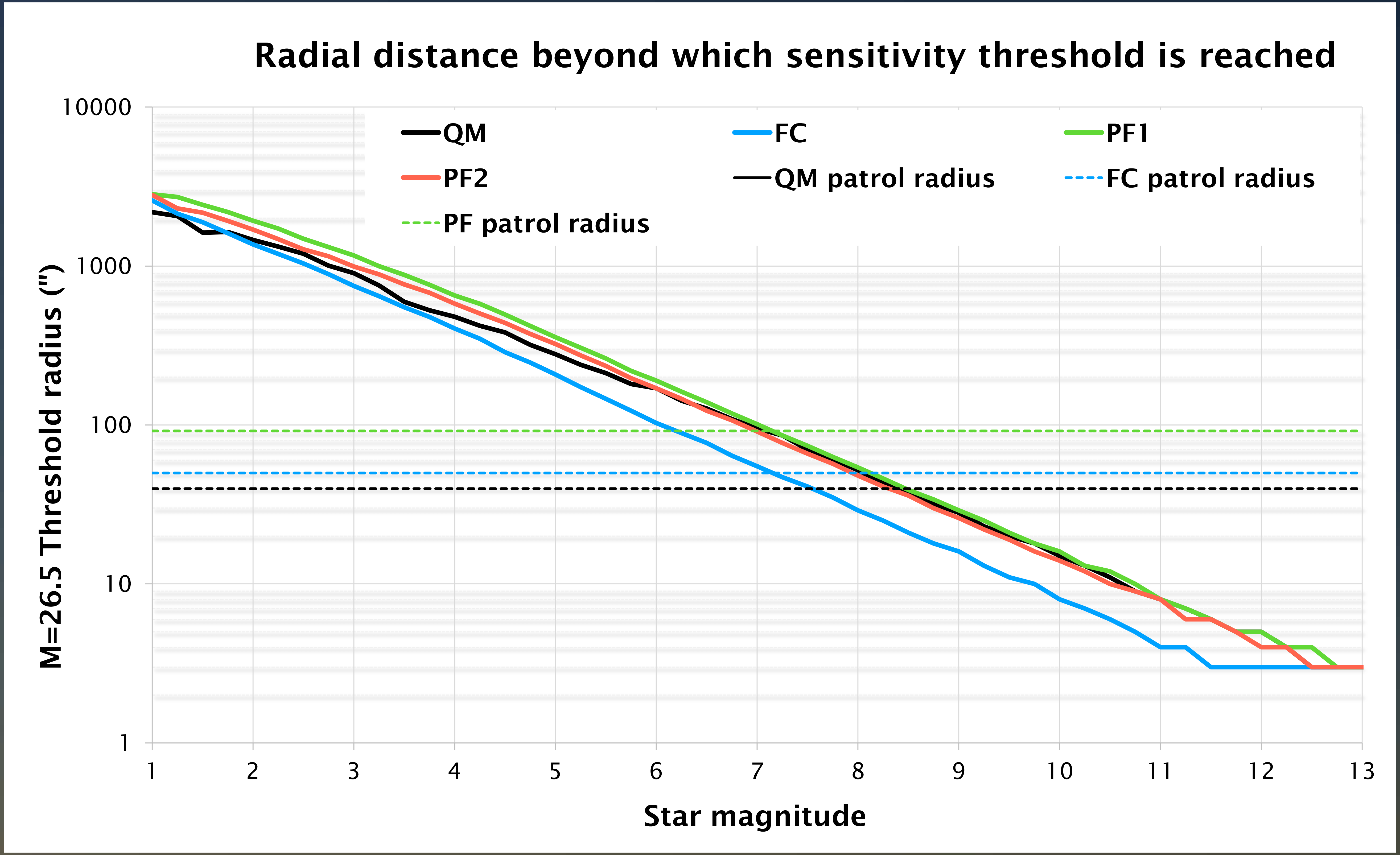
Dense star field ghost simulation



Star field centered on HD187750, including stars down to m_R=18



Scattering comparison



The sum of the solid angle of the sky that will be above threshold due to stars down to 10th magnitude:

- PF1: 0.45%
- PF2: 0.35%
- FC: 0.2%
- QM: 0.3%

Scattering will not drive the telescope design selection.

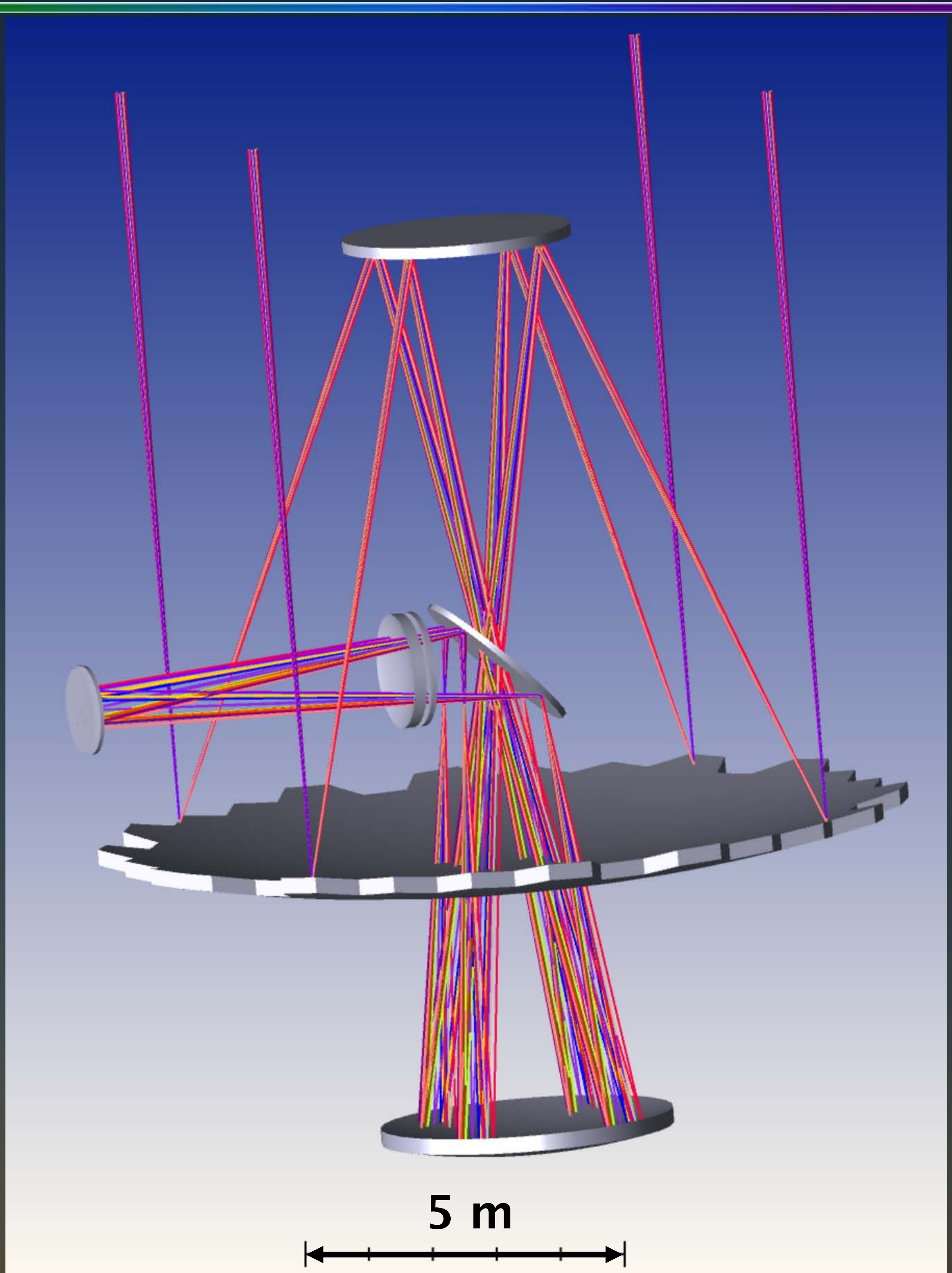
QM – Constraints

The variant here is due to Sam Barden (2022, SPIE Vol. 12182 121822I-4), it is compatible with REOSC's ELT segment fabrication facility and CFHTs current observatory building.

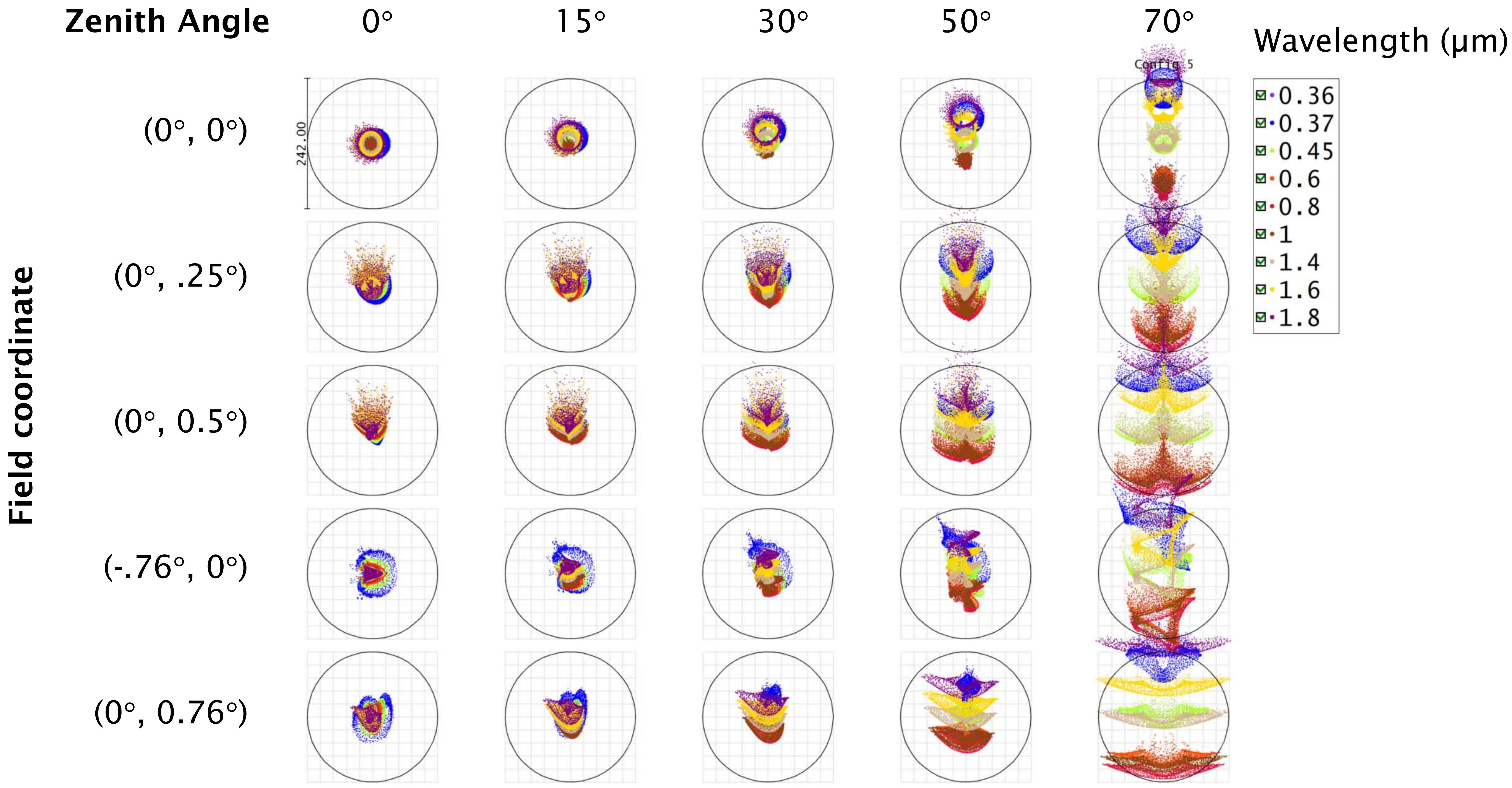
- M3 constrained to be no more than 4.65 m (design = 4.6 m) to fit through CFHTs current hatchway.
- The M1 asphericity of PV = 390 μm slightly exceeds the testing limit with the REOSC ELT tools (379 μm) but is workable.
- M1 has 1.43 m circumscribed diameter segments (same as ELT)
- M1 segment radius of curvature 26 m will work with ELT warping harness (20 m minimum).

Comments about optimizing this configuration:

- Solutions exist with the conic constant for M2, -6 < k < 6, including the spherical case. However, the hyperbolic solution is preferred since it allow spherical ADC surfaces.
- The ADC placement sets the lens size to ~1.8 m diameter.
- A field lens is required near the focal plane to ensure the pupil-centric or telecentric beam required for efficient fiber injection.
- Field diameter of 1.5° is near practical limit for 1" size fibers given above constraints.
- Limited success has been had placing the ADC near the focal plane.

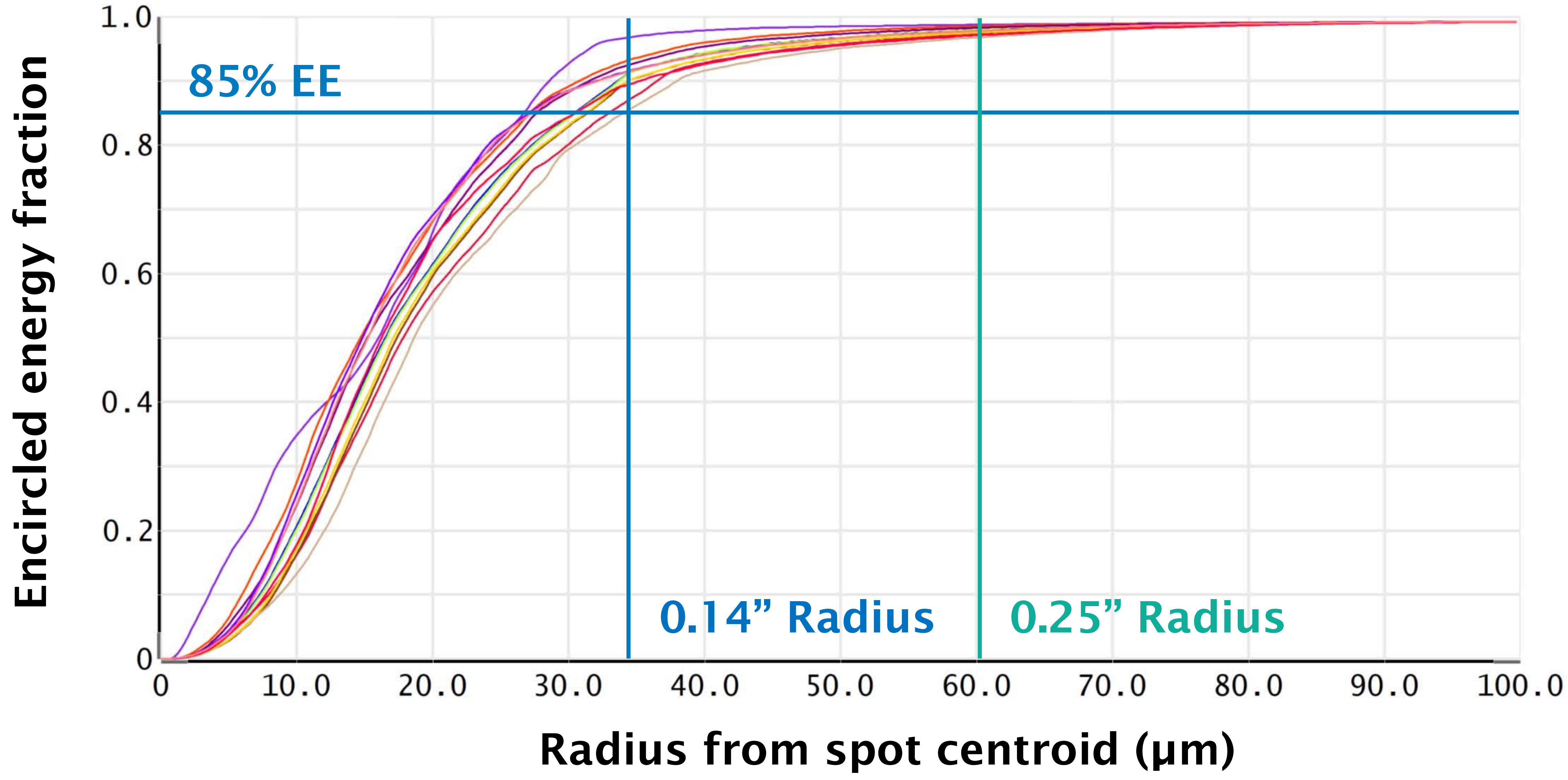


QM – Spot diagram

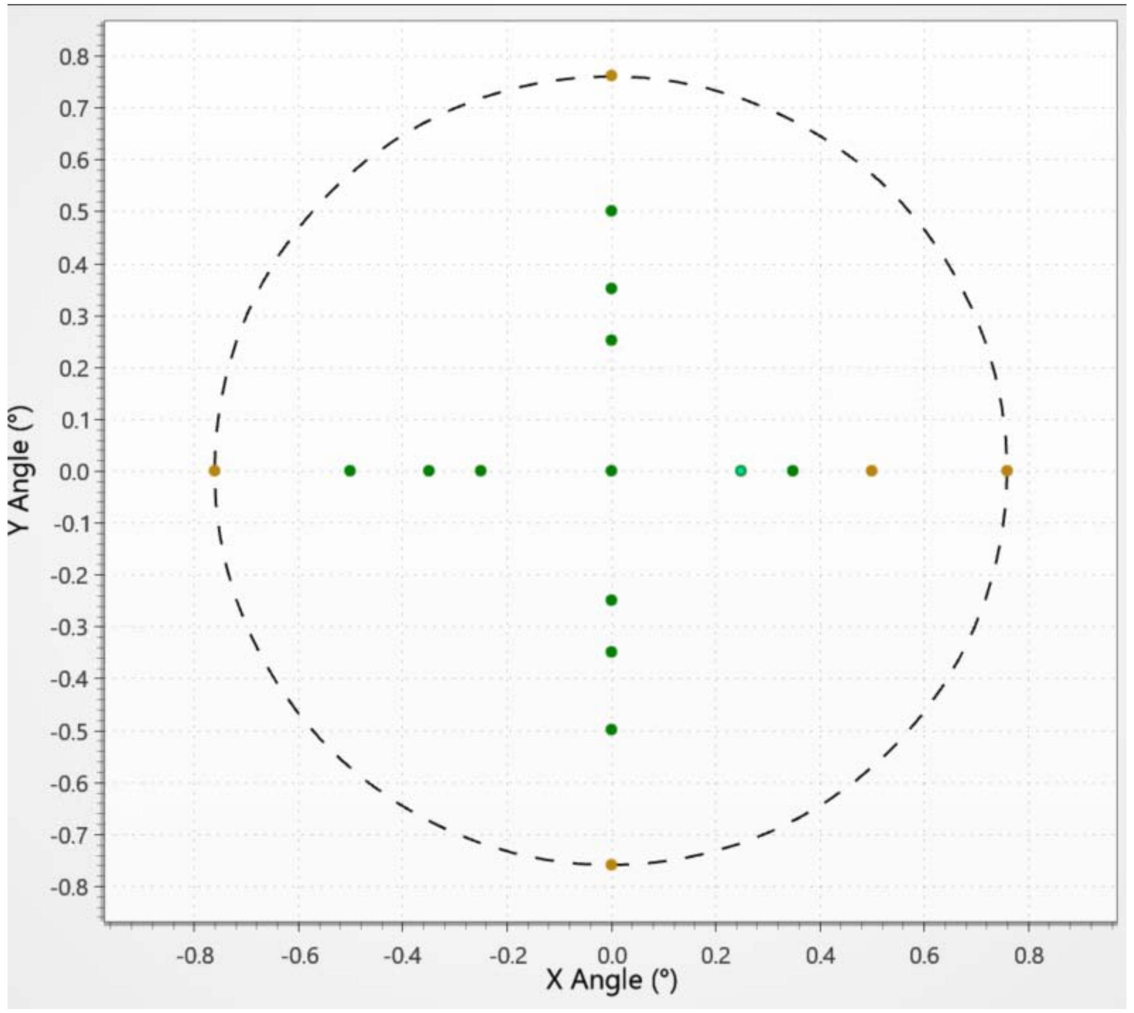


Circle diameter 1” (242 μm)

QM – Polychromatic Geometric encircled energy: 0.36–1.8 μm, At zenith

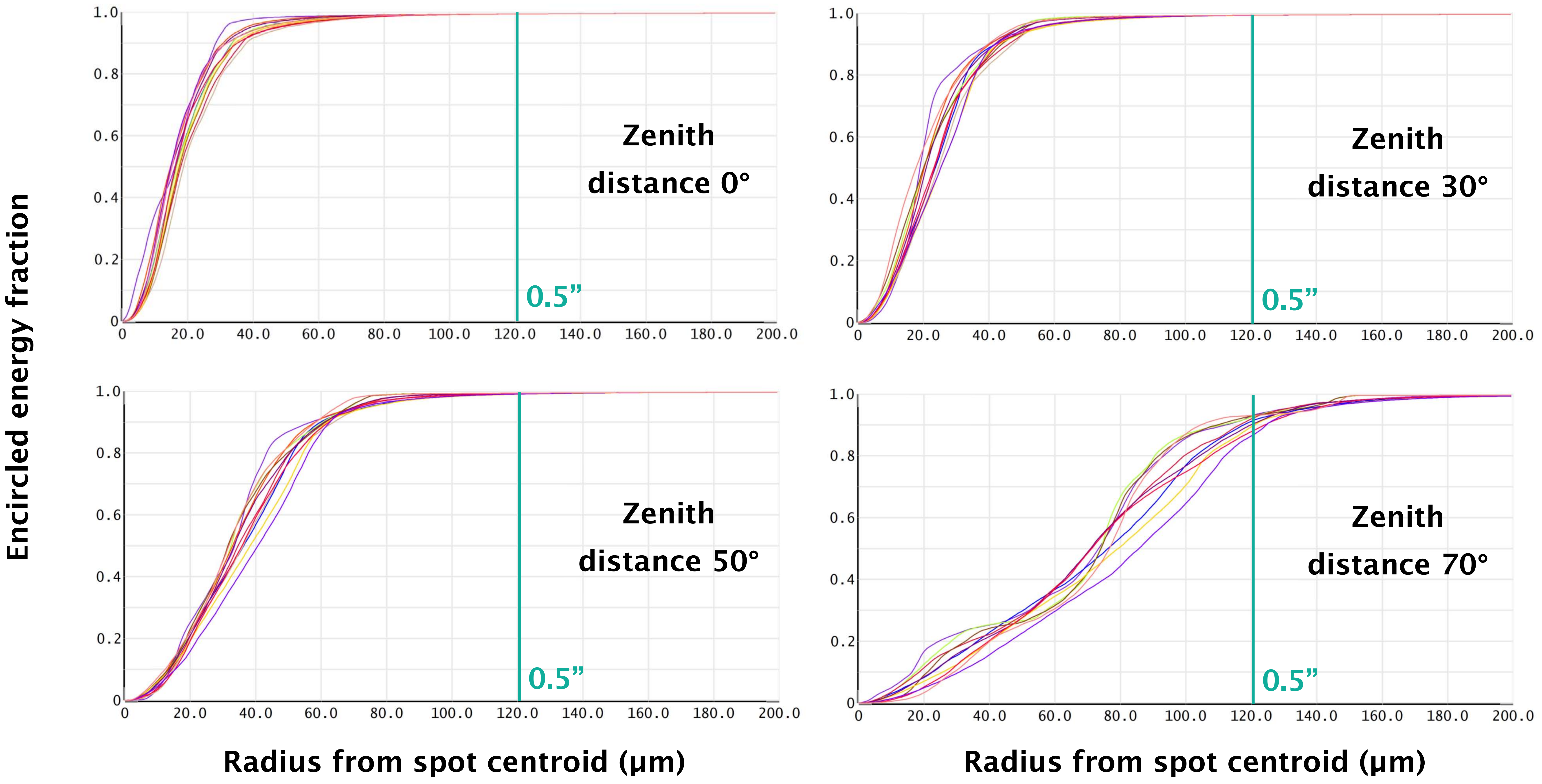


Fields used in EE plot

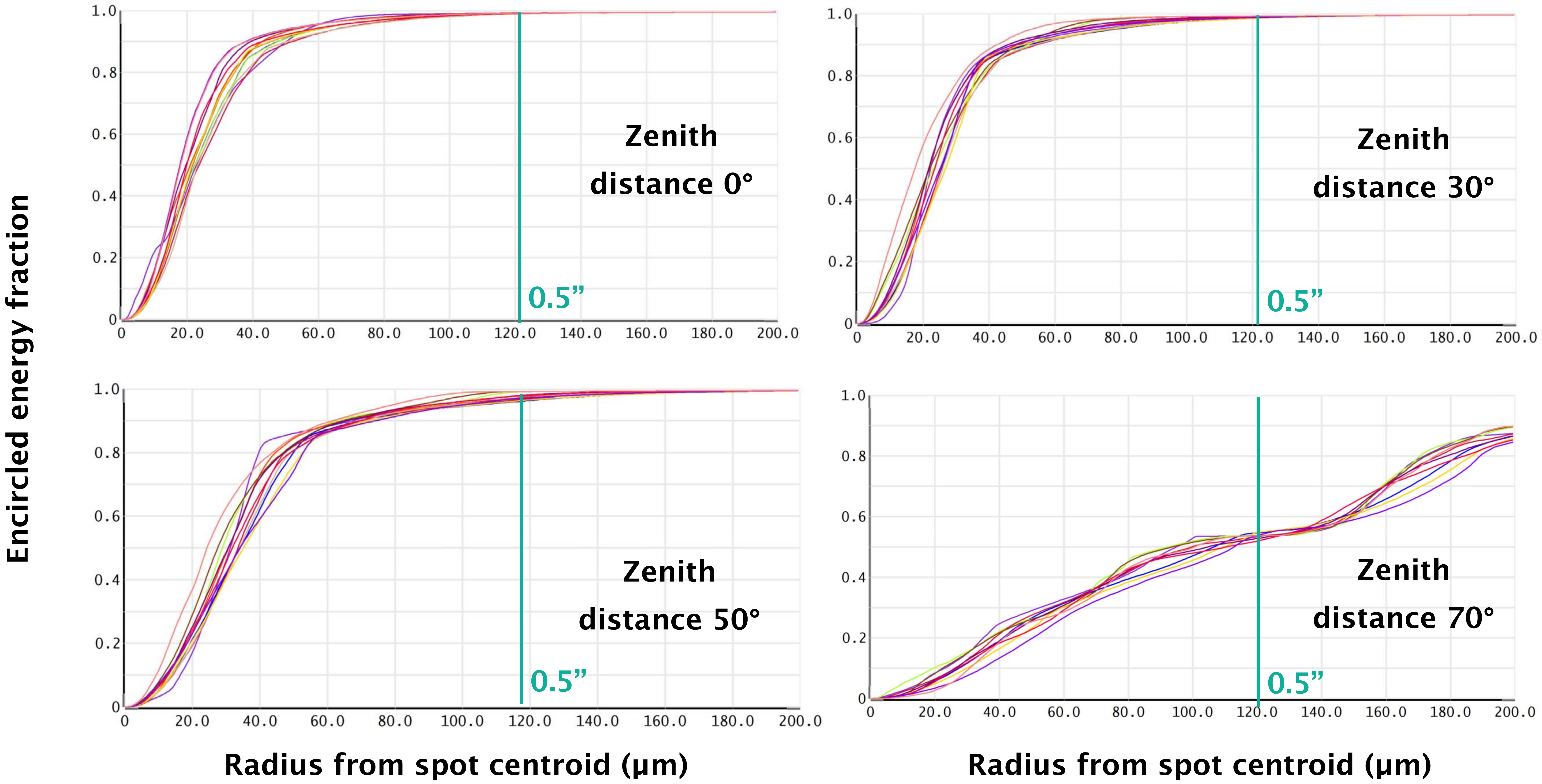


Note: MSE Fiber diameter is 1”, optimized for Maunakea seeing (0.65” median seeing)

QM – Polychromatic Geometric encircled energy: 0.36–1.8 µm, ADC performance



QM – Polychromatic Geometric encircled energy: 0.36–2.5 μm, ADC performance



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MSE QM feasibility

- **Optical tolerances and alignment**
  - M1 phasing is assumed (no phasing leads to 15% loss in efficiency).
  - The TMT approach to alignment and phasing will be used.
  - Ellipsoidal M3 allows its surface to be adjusted using independent metrology from the global alignment and phasing optics.
  - Modeling of the PSF, including estimates surface irregularities from the support print-through for the M2, M3 and M4 is needed to ensure feasibility of the concept.

- **Optics manufacturability / coatings**
  - Goal is to leverage off existing segmented mirror fabrication facilities (*e.g.* REOSC ELT fab).
  - The atmospheric dispersion corrector (ADC) has two 1.8 m diameter fused silica elements. Material this large may be challenging to source.
  - M2, M3 and M4, although large and thin, are similar in size to existing projects (*e.g.* LSST) and could employ similar mounting methods.
  - High reflectivity, wide bandpass coatings need to be developed for the mirrors

- **Telescope size and weight**
  - QM fits within the current MSE baseline envelope.
  - **Telescope weight will be the same or less than the baseline MSE.**

MSE QM feasibility - spectrographs

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The QM allows extreme multiplexing compared to existing and proposed facilities. How will 20,000 source targets be accommodated?

- Number of spectrographs:
  - Low-mid-resolution (LMR: R=3,000 – 5,000): Estimate is 36 each in the B, G, R, J & H bands (**180 total**) with no pupil slicing.
  - High resolution (HR: R>=20,000): Estimate is 20 each in the B, G & R bands, with a 2x2 sliced pupil (**60 total**).
  - **Spectrograph designs must be simple and amenable to industrial scale duplication**
- We assume that the pupil of the HR spectrographs is sliced to, (1) slow down the optics, (2) obviate the need for large echelle gratings and beam splitters.
- Wavelength splitting external to the spectrographs is assumed. An ATI proposal to prototype these is in process.
- How are 240 spectrographs accommodated within the existing CFHT footprint?
- Initial estimate indicates between 260-420 kW of power required to cool the detectors and optics for the spectrographs. Our current capacity is 300 kVA.
- Half of the cooling power is driven by H band, where it is assumed that the entire spectrograph optics must be cooled to near 80K. Scale back this band?

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Conclusion

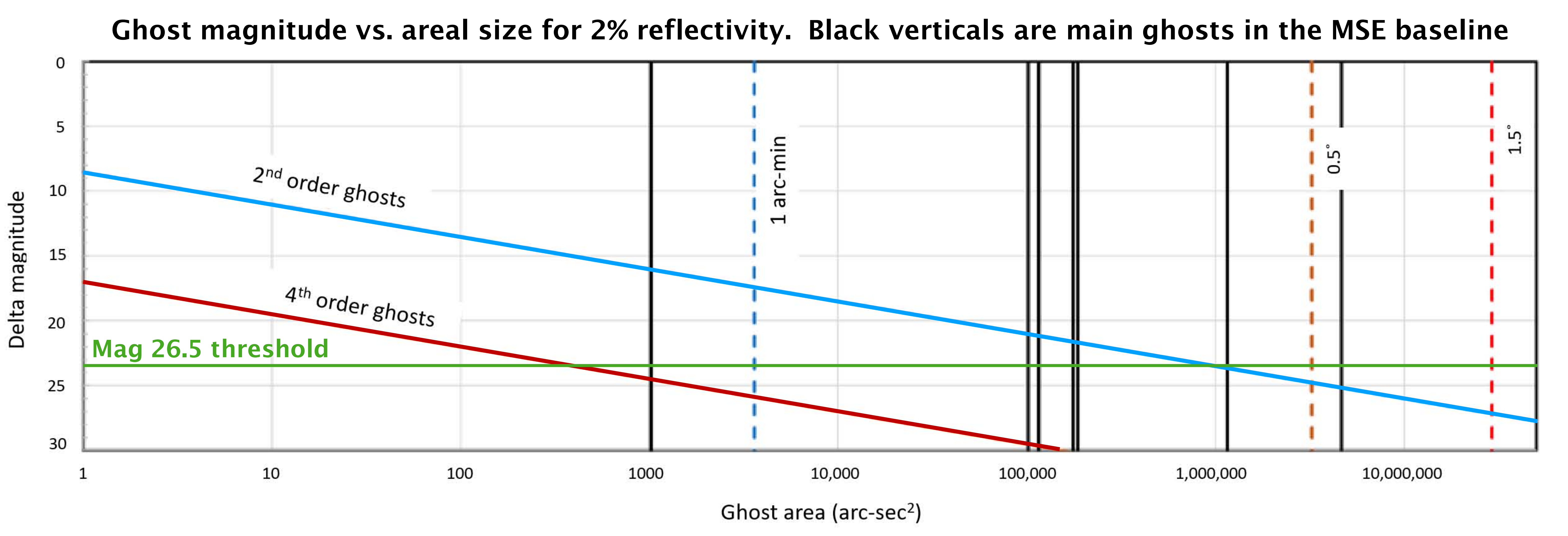
MSE has several workable telescope design options on the table that could meet the sensitivity requirements in terms of contamination from ghosts, including a design whose configuration is close to the current baseline.

The quad-mirror provides the key advantages of (1) a more accessible focal plane, better suited to repurposing decades in the future, and (2) multiplexing at a scale that places MSE squarely beyond the current generation of multiplexed spectroscopic instruments.

Key work needed to complete the feasibility study:

- Define mechanical tolerances to maintain optical alignment and surface figures.
- Define plan to achieve alignment of the optics.
- Confirm weight estimates of the telescope structure with the view of reusing the CFHT pier.
- Identify source for the large transmissive elements, investigate feasibility of high reflectivity coatings for the monolithic mirrors (M2, M3, M4).
- Continue to refine power profile for the observatory.

Optical ghosts – effect on sensitivity



- One can estimate the ghost intensity relative to the source (delta mag) using the product of the reflectivities and the relative area subtended by the ghost to the collection area of the fiber.
- For convenience use 1”^{2} for the fiber area.
- Vertical black lines are the main ghosts in the MSE baseline. To meet the m=24 sensitivity requirement, ghosts should be ~10x fainter, at a threshold of m=26.5 1”$^{-2}$ for a 0th magnitude ghost source.
- **There are many 2nd order ghosts above this threshold in the MSE baseline.**

Scattering estimate

The scattering contribution from dust was estimated using the Mie polydisperse sphere model implemented in NIST's MIST (Modeled Integrated Scatter Tool) package, as follows:

- Starting point was Robert Hubbard's analysis for DKIST.
- A Harvey model was used to describe the BSDF of the scattering from surface imperfections:
  - λ=600nm
  - exponent s = 1.5
  - RMS surface roughness of 20 Å
  - scattering roll-off at an angle of ~0.1 milli-rad → b ≈ 9.8×10^{-7}
  - Harvey model converted to an ABg model for direct use in OpticStudio™, with A=1.4×10^{-4}, B=10^{-6}, g = 1.5
  - Total integrated scatter (TIS) = 0.17%
- The scattering contribution from dust was estimated using the Mie polydisperse sphere model implemented in NIST's MIST (Modeled Integrated Scatter Tool) package, as follows:
  - BRDF with CL=500 for upward facing mirrors. Total integrated scatter (TIS) at 0° incidence = 1.4%
  - BRDF with CL=240 for downward or side facing mirrors. TIS (as above) = 0.045%
  - BTDF with CL=240 for the case of light entering exposed lens surfaces. TIS = 0.017%
  - BTDF with CL=240 for the case of light exiting exposed lens surfaces. TIS = 0.015%

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Scattering – broad conclusions

- The FC presents a ~1 mag advantage over the other designs from this analysis, primarily as a combination of its longer focal length compared to the PF, and the assumption that the QM's M3 will be as hard to keep clean as its M1 (almost certainly too conservative).
- Aside from this difference, scattering is not seen as a major discriminator in terms of design selection.
- The sum of the solid angle of the sky that will be above threshold due to stars down to 10^{th} magnitude:
  - PF1: 0.45%
  - PF2: 0.35%
  - FC: 0.2%
  - QM: 0.3%
- Along the galactic plane, or in bright clusters, these numbers will be larger.
- For the PF2, FC and QM designs, the target sky avoidance algorithm due to scattering will largely overlap what is required from ghosting.
- **The largest limitation is that the results indicate that stars brighter than m=3 cannot be accommodated in the field, or even some distance from the field.**

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Maunakea Acknowledgment

Maunakea is a mountain at once steeped in history and natural beauty, central to the Hawaiian tradition and revered throughout the island chain. Maunakea is also greatly valued as the foremost astronomical site in the northern hemisphere.

CFHT acknowledges its thankfulness for the privilege of observing from this unique portal into our cosmos. As heirs to CFHT's legacy, the Maunakea Spectroscopic Explorer team pledges to foster CFHT's culture of respect for the mauna, while giving back to its island community.

Maunakea Spectroscopic Explorer

Summary

- Technical overview of the Maunakea Spectroscopic Explorer (MSE)
- Motivations for looking at alternative designs to the baseline MSE telescope design
  - Optical ghosts: Meeting a challenging sensitivity requirement
  - Extending the science: Increased the field of view and fiber count.
  - “Future proofing” the facility: Avoidance of the size limitations imposed by an instrument mounted along the telescope optical axis (prime-focus or Cassegrain).
- First look performance of the modified Paul-Baker quad mirror (QM)
- Feasibility study, salient questions