# High-transmittance UVOIR space telescope prime focus concepts & technologies

J. B. Breckinridge[a] and M. Flannery[b]

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a. Breckinridge associates, Pasadena, CA.
b. Northrop Grumman Aerospace Systems, Redondo Beach, CA.

R. Polidan, J. Breckinridge, C. Lillie, H. MacEwen, et. al. (2015) **An evolvable space telescope for future astronomical missions** Proc. SPIE 9602-6

# Background

- 21st century space astronomy needs twelve to twenty meter class space telescopes
- Requirements
  - Cost less than JWST
  - Performance to 100 nm UV wavelength
  - Coronagraph for imaging spectrometry @ $10^{-11}$
  - Polarization preserving (0.01%)
  - ~4-arc minute FOV (or larger)

$$N = \left[ \frac{FOV}{1.2\lambda / d} \right]^2 = 8.4 \cdot 10^8 \approx 4 \text{ giga-pixels}\Big|_{\text{nyquist}}$$

# How to

- Reduce cost
  - Minimize # of reflections (precision mechanical structures)
  - Implement the Evolvable Space Telescope (EST)
  - Prime focus
- Increase UV-Vis performance
  - Innovative optical design (imagers & spectrometers) – wide FOV with fewer reflections
  - Polarization preserving configurations & coatings

# How important is mirror count?
# Cost to recover mirror losses

- To fit our optical instruments into the telescopes of today, designers use lots of fold mirrors which absorb and scatter valuable radiation.
- Calculate the cost of light lost because of reflections.
  – Reflection losses reduce aperture
  – Cost to recover aperture to compensate losses

# How important is mirror count?
## Cost to recover mirror losses

**Unnecessary reflections are expensive**

$A_e$ = the effective aperture

$d_e$ = diameter of the effective aperture

$A_T$ = telescope aperture

$d_T$ = telescope diameter

$\tau$ = transmittance or reflectance

$$A_e = \tau A_T$$

$$\pi \frac{d_e^2}{4} = \tau \cdot \pi \frac{d_T^2}{4}$$

$$d_e = d_T \sqrt{\tau}$$

# Reflection losses reduce the effective aperture of a telescope

| # of normal incidence reflections to detector | Tau for R=0.95 | A 10-m aperture is effectively | A 2.4-m aperture is effectively |
|---|---|---|---|
| 1 | 0.95 | 9.7 | 2.3 |
| 4 | 0.81 | 8.8 | 2.1 |
| 8 | 0.66 | 7.8 | 1.9 |
| 12 | 0.54 | 6.9 | 1.7 |
| 16 | 0.44 | 6.1 | 1.5 |
| 20 | 0.36 | 6.0 | 1.4 |
| 24 | 0.29 | 4.8 | 1.1 |
| 28 | 0.24 | 4.2 | 1 |

# Assume a 10 meter telescope can be built for ~$3B. What is the cost to recover the losses ?

| # of normal incidence reflections to detector | Tau for R=0.95 | Increase the 10m diameter to maintain SNR | Mission cost assuming cost=d^2.0 |
|---|---|---|---|
| 1 | 0.95 | 10.3 | 3.2 |
| 4 | 0.81 | 11.1 | 3.7 |
| 8 | 0.66 | 12.3 | 4.5 |
| 12 | 0.54 | 13.6 | 5.6 |
| 16 | 0.44 | 15.1 | 6.8 |
| 20 | 0.36 | 16.7 | 8.4 |
| 24 | 0.29 | 18.5 | 10.3 |
| 28 | 0.24 | 20.5 | 12.6 |

***Eight reflections cost > $1B***

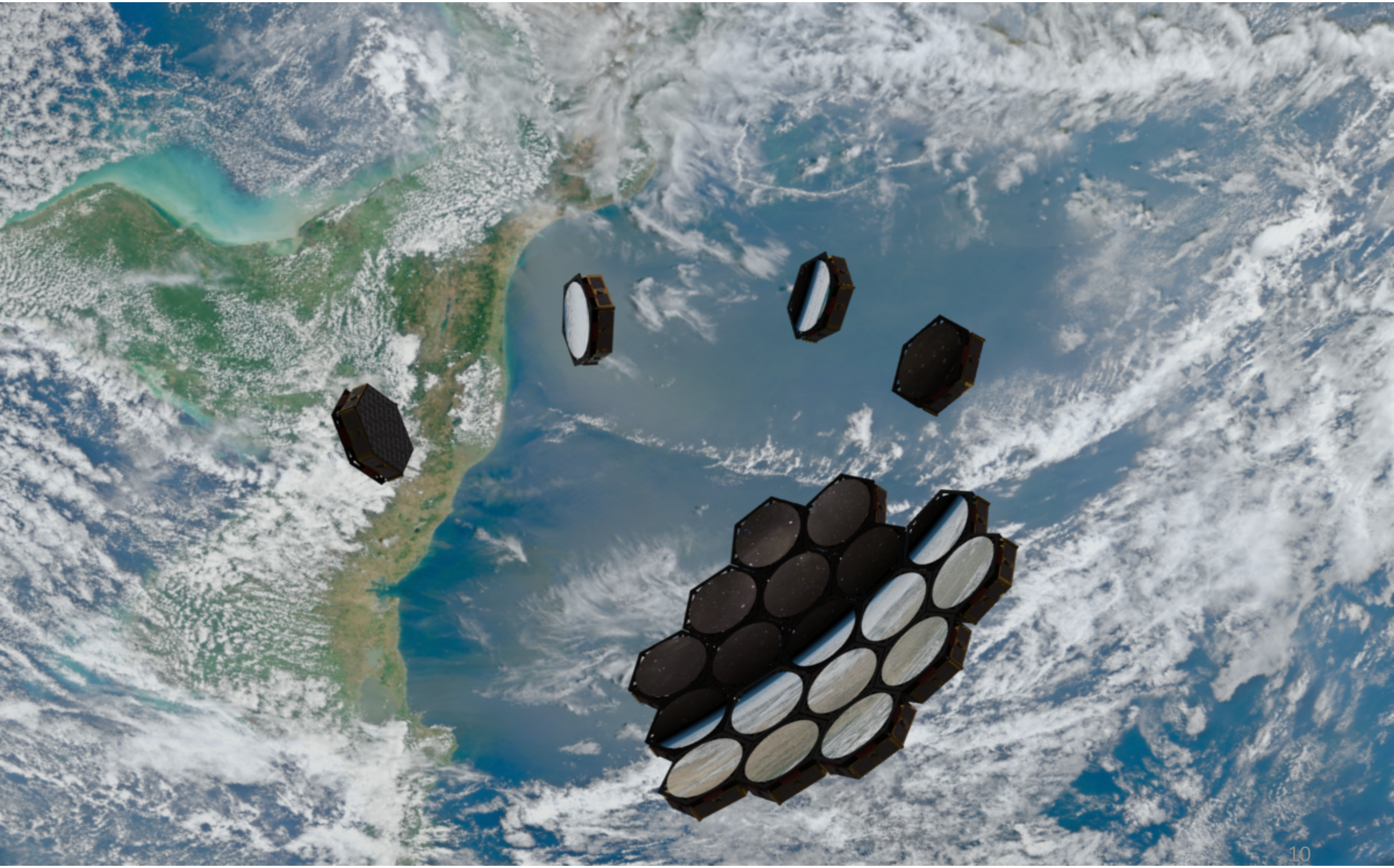
# EST Plan

- By launching the telescope in segments and reuse in-space structural elements =>
- Many of the constraints on
  - Mass,
  - Deployment mechanisms
  - Packaging
  - **are removed**

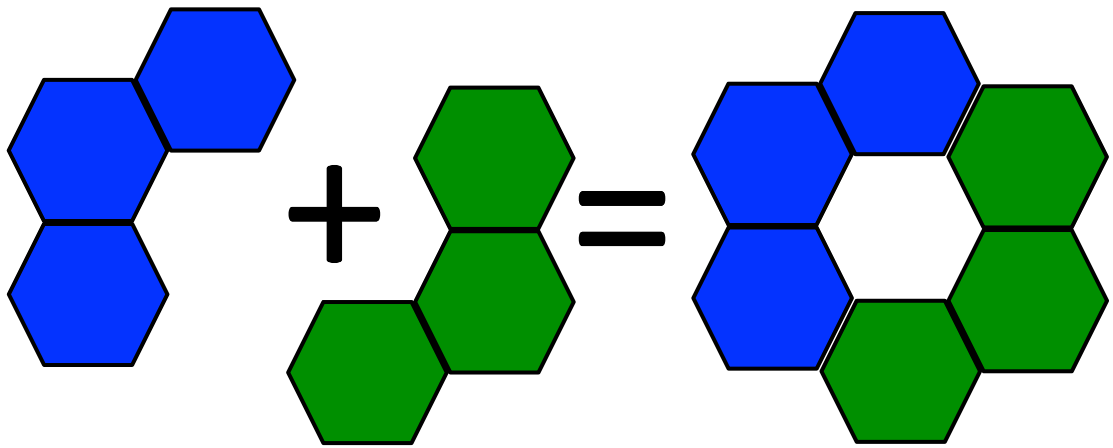
# New paradigm to break cost curve

- **Partition the telescope into segments**
- **Launch segments separately**
- **In space assembly in stages**
- **Choose stages so each one is astronomically productive**
- **Today discuss**
  - **An architecture to do this**
  - **Optical design & issues**
- **MacEwen: infrastructure**
- **Lillie: on-orbit assembly & servicing**

# The Evolvable Space Telescope Vision



# Phase 1 and 2 of EST
# 4-m class segments



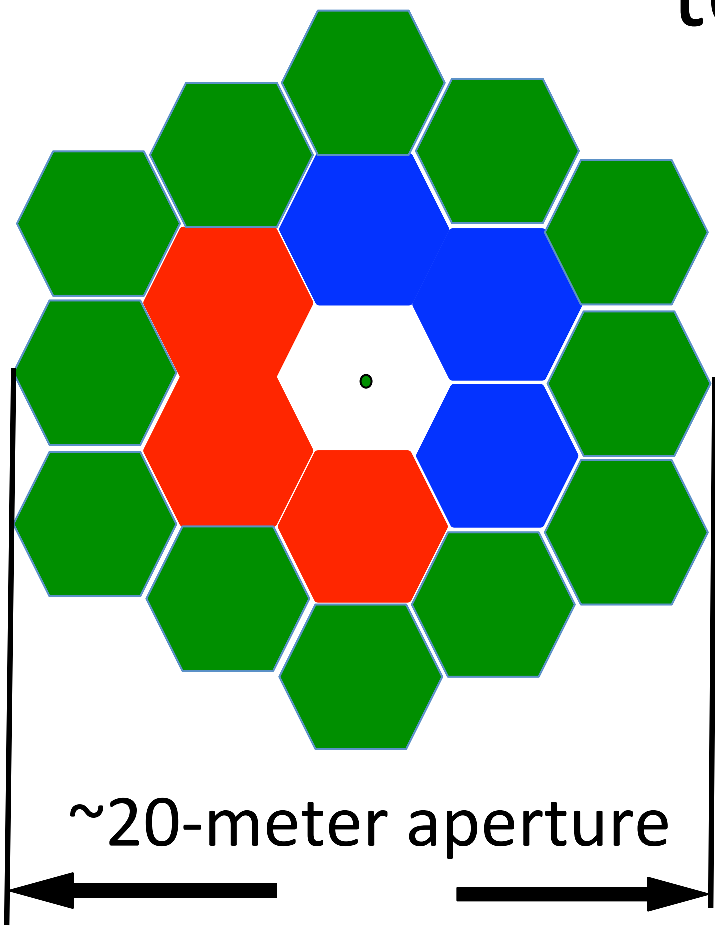
| $\Phi_1$ | $\Phi_1^{'}$ | $\Phi_2$ |
|---|---|---|
| 6x12-m | 6x12-m | 12-m |

# Evolvable Space Telescope (EST)

1. **Stage 1**: **First, build, launch, and conduct high value science with a fully functional three 4m segment telescope complete with instruments.**
2. **Stage 2: Some years later add a mirror, instrument, and service package to the in-space Stage 1 telescope to create an 8 – 12 meter aperture.**
3. **Stage 3**: **Some years after that add to the in-space Stage 2 telescope, more mirror segments, to make a 14 – 20 meter aperture with new instruments and additional support systems.**

- <u>Science data is obtained continuously beginning with Stage 1 commissioning with only HST-like servicing gaps in the science return</u>

# UVOIR built using EST processes & technology



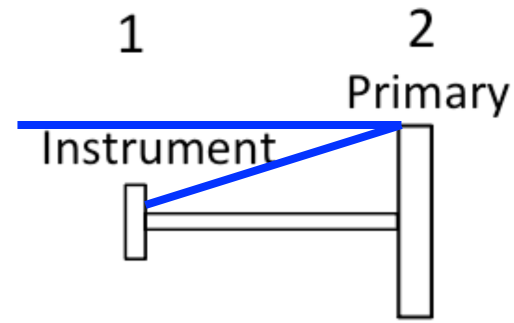

Phases to a 20-meter

1. 3 segments
2. 3 more segments
3. 12 more segments added at edge

***Is Prime focus an advantage? . . . .***

# Pointing stability is a big issue
# Prime focus may be more stable

Prime focus telescope is a 2 body problem

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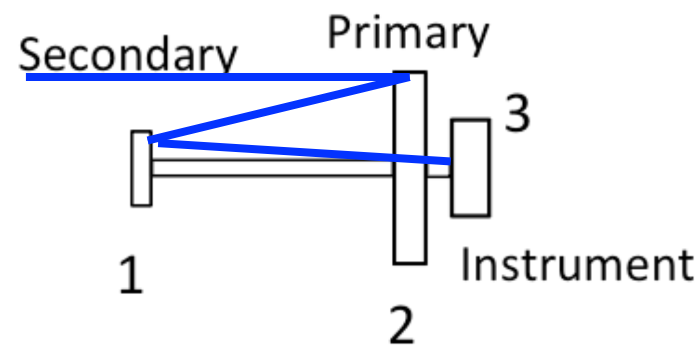
Cassegrain telescope is a 3 body problem

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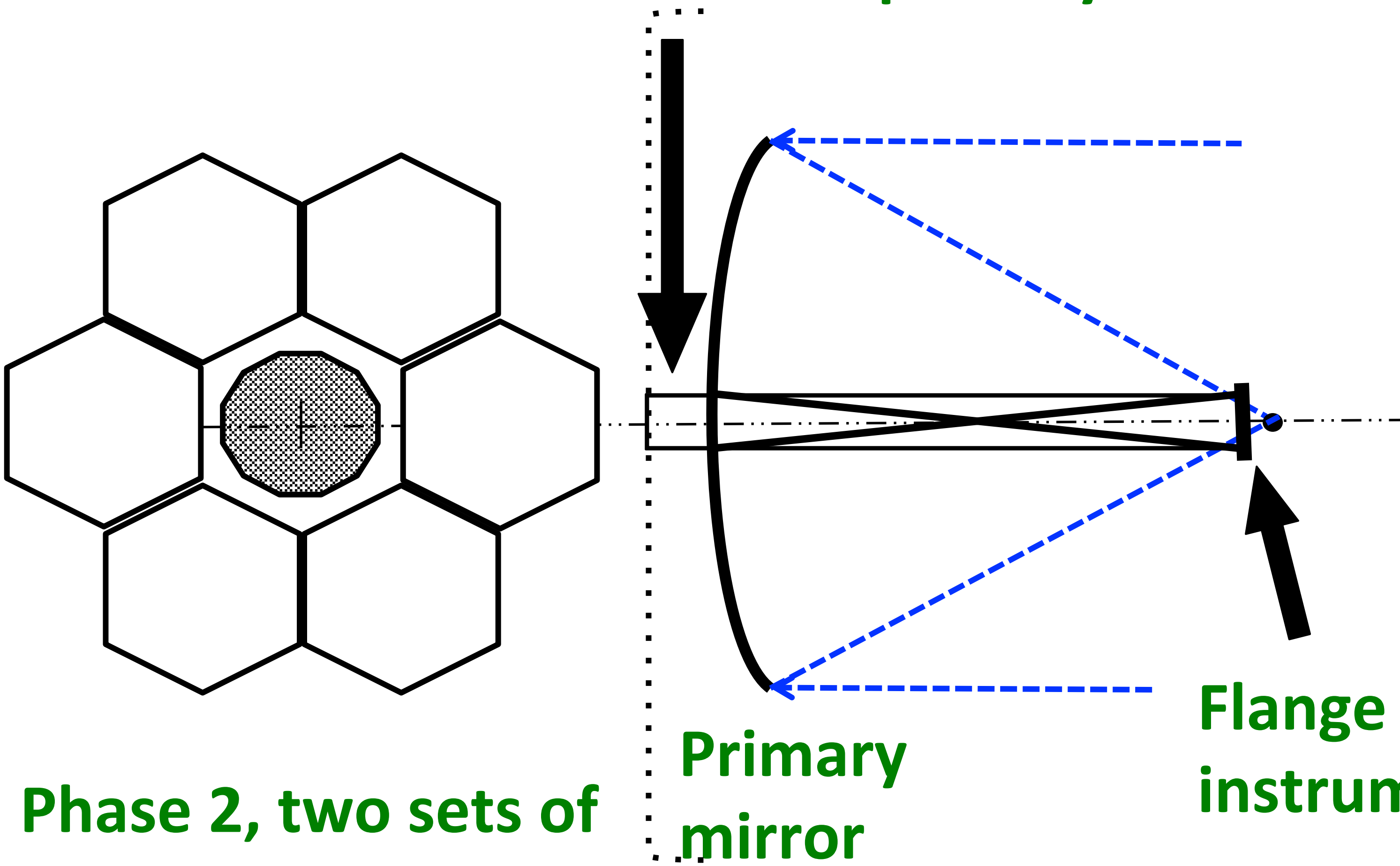
**The thermal induced piston error in a Cassegrain telescope Is twice (2x) that for a prime focus system**

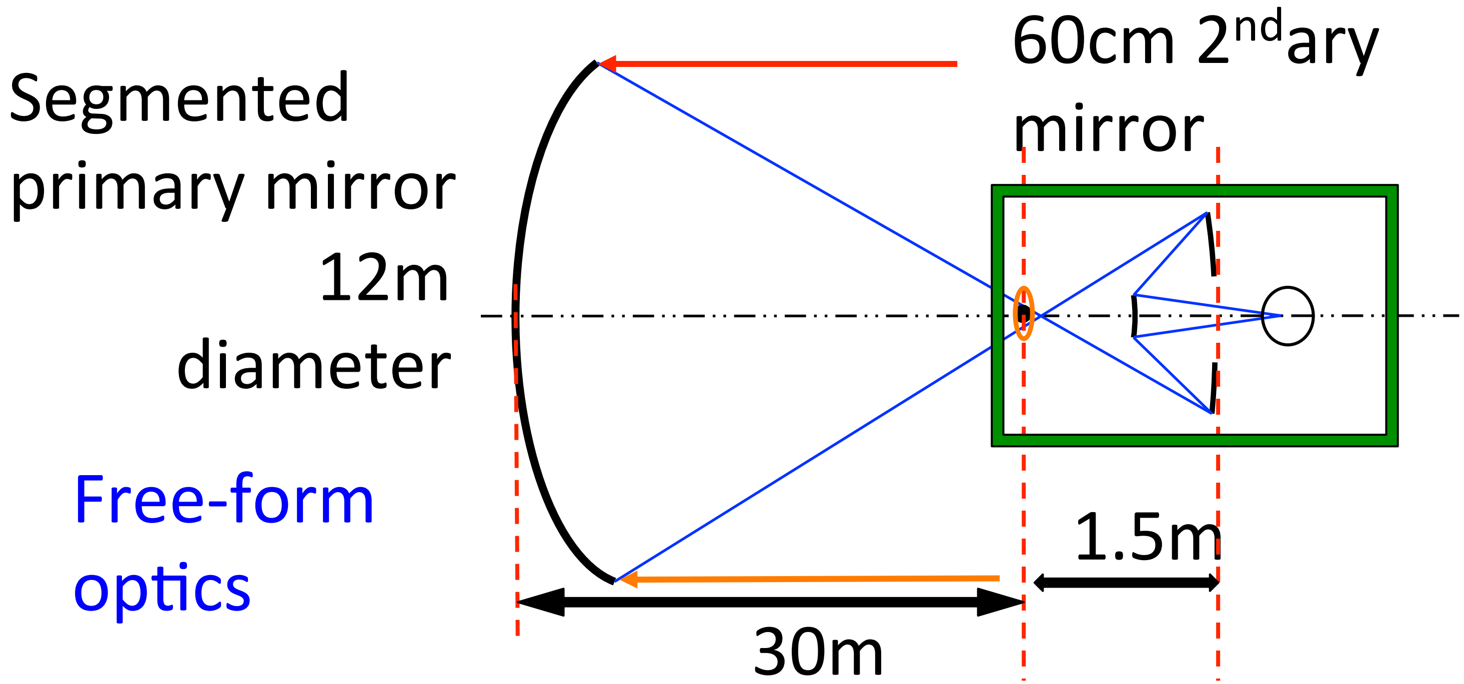
# Prime focus 12-m EST

**Metering structure**
**Between vertex of the primary & the flange**




**Phase 2, two sets of Three segments=6.**

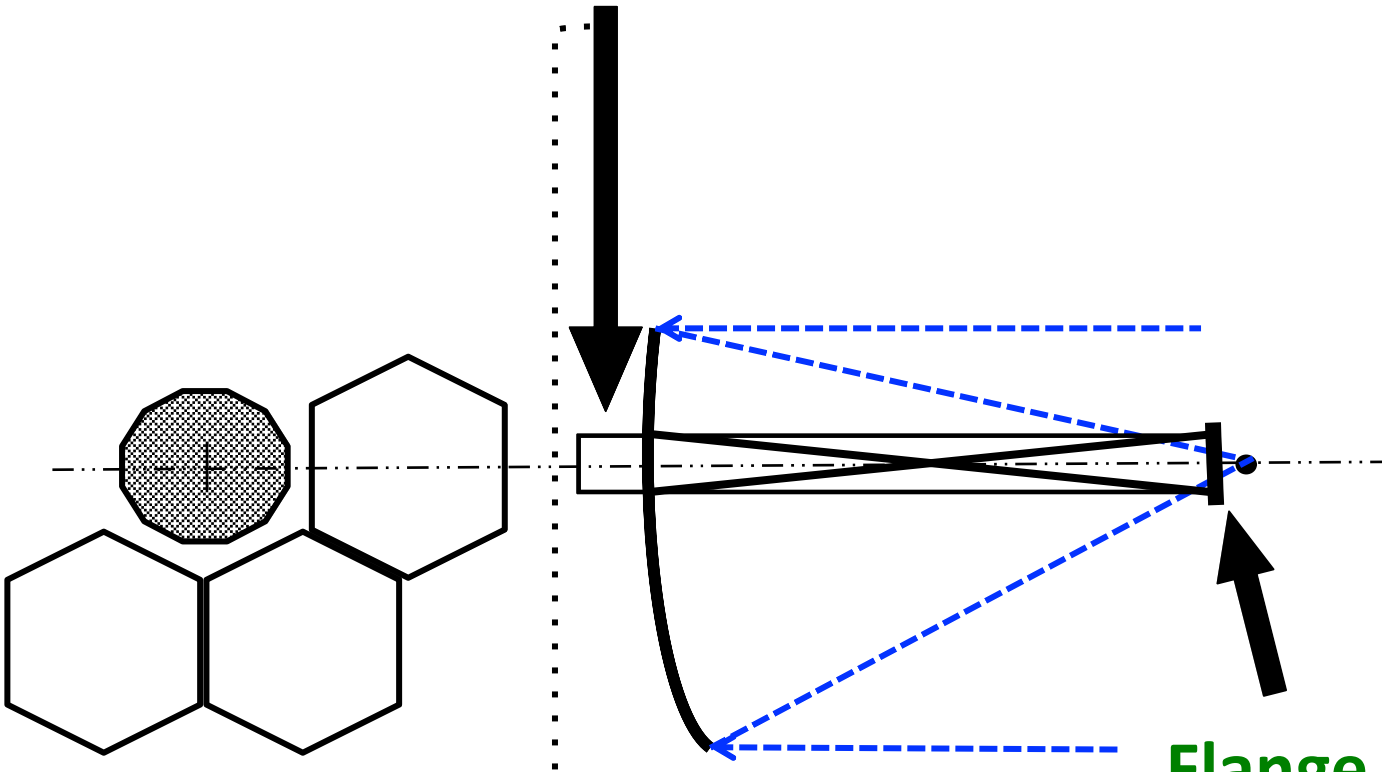
# Concept for prime focus UVOIR imager




- Low polarization (no fold mirrors)
- High transmittance (few reflections)
- UV transmitting refractive correctors
- Wide field

# Prime focus 6 x 12 m EST

**Metering structure**
**Between vertex of the primary & the flange**



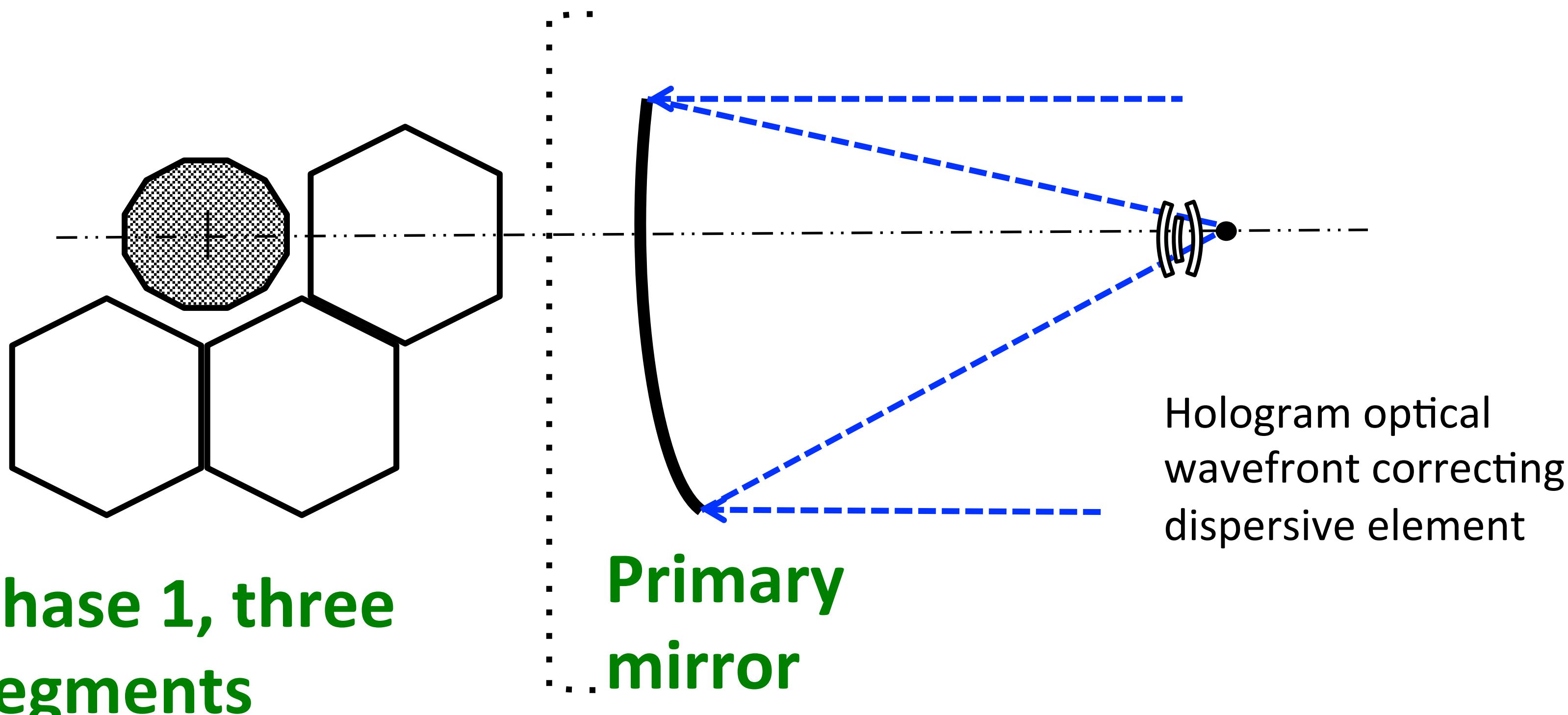
**Phase 1, three segments**

**Primary mirror**

**Flange for docking instruments or Cassegrain 2nd ary**

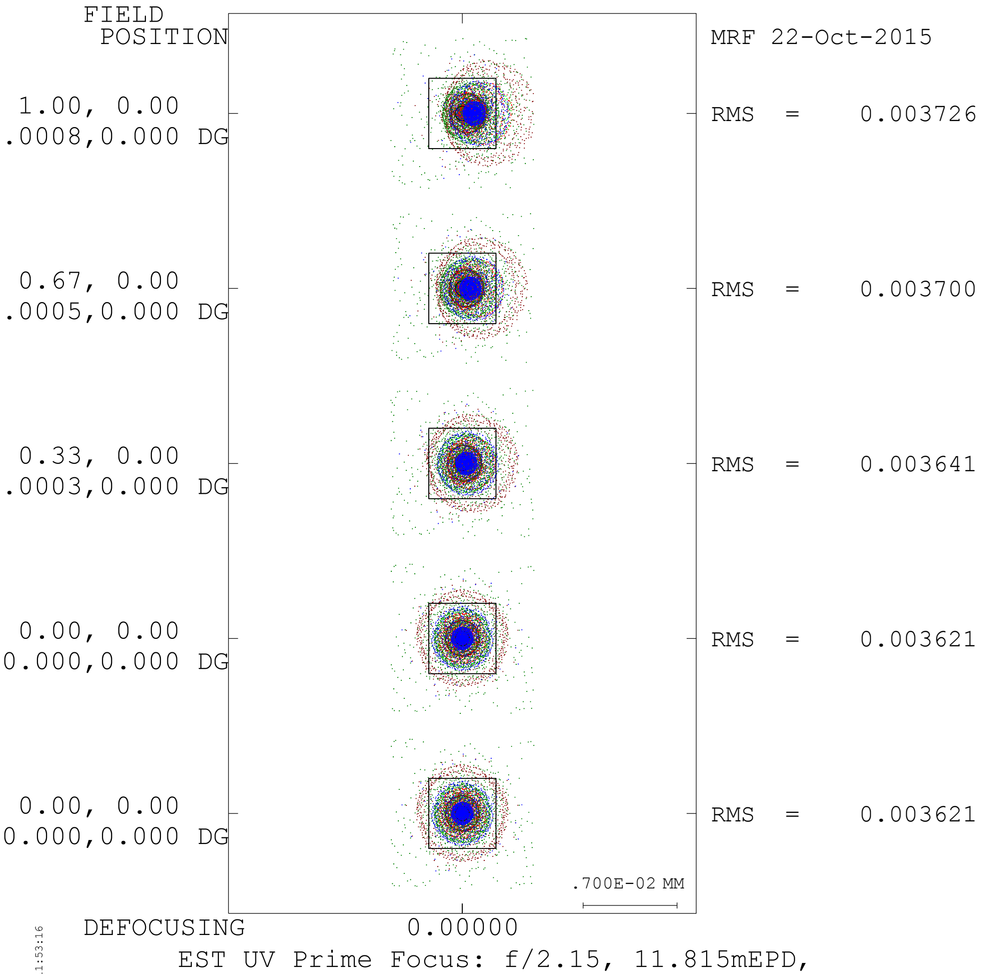
# Prime focus 6 x 12 m EST

## Shows the UV imaging spectrometer correctors at prime focus



# Ray-trace quick look at single reflection filled aperture

- 2 Corrector glasses: LiF & $CaF_2$ @ f/2.15
- Wavelength range: 150-250 nm
- Spot diagrams over 7.8 arc sec FOV

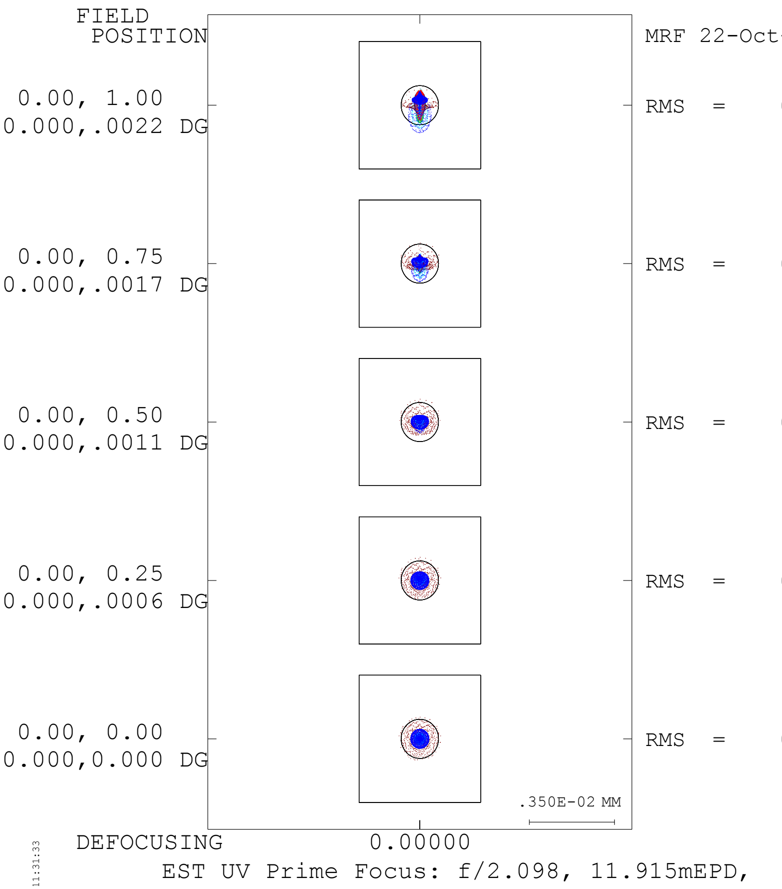



5 micron pixels

# Ray-trace quick look at single reflection filled aperture

- 2 Corrector glasses: LiF & $CaF_2$ @ f/2.098 at image plane
- Wavelength range: 250-350 nm
- Spot diagrams over 16.2 arc sec FOV

5 micron pixels; circle is diffraction limited



# Lyot coronagraph system for prime focus EST

System minification is 20:1

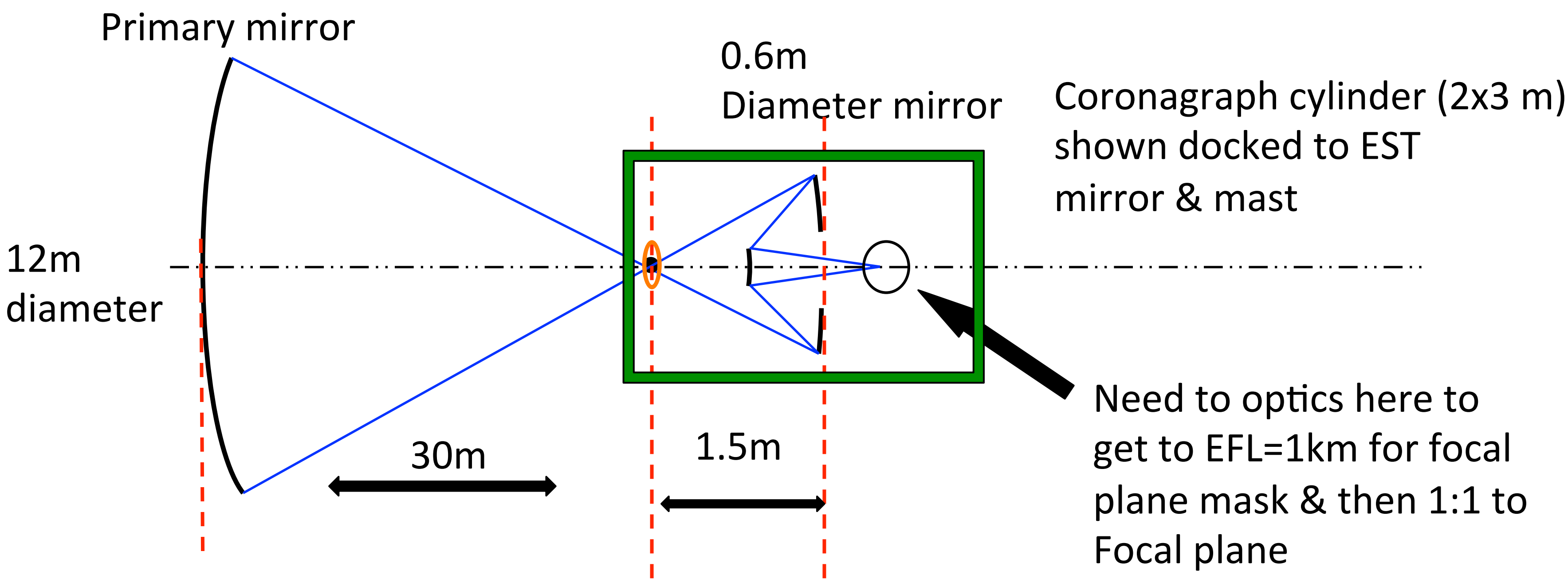
**Drawing below is not to scale**

- Segmented active secondary

0.6 meters diameter

To image 1:1 the primary segments

- Solid tertiary
- Refractive correctors
- Stop at prime focus controls scattered light




Breckinridge, Lam & Chipman (2015) Polarization aberrations in astronomical telescopes PASP **127**, 445 = > fold mirrors are bad for coronagraphs => EST gives potential to build a Lyot coronagraph with no fold mirrors – only powered optical elements

# Lyot coronagraph system for prime focus 6x12-m EST

Pupil =>

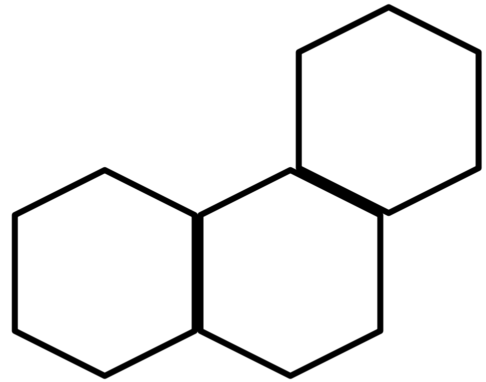
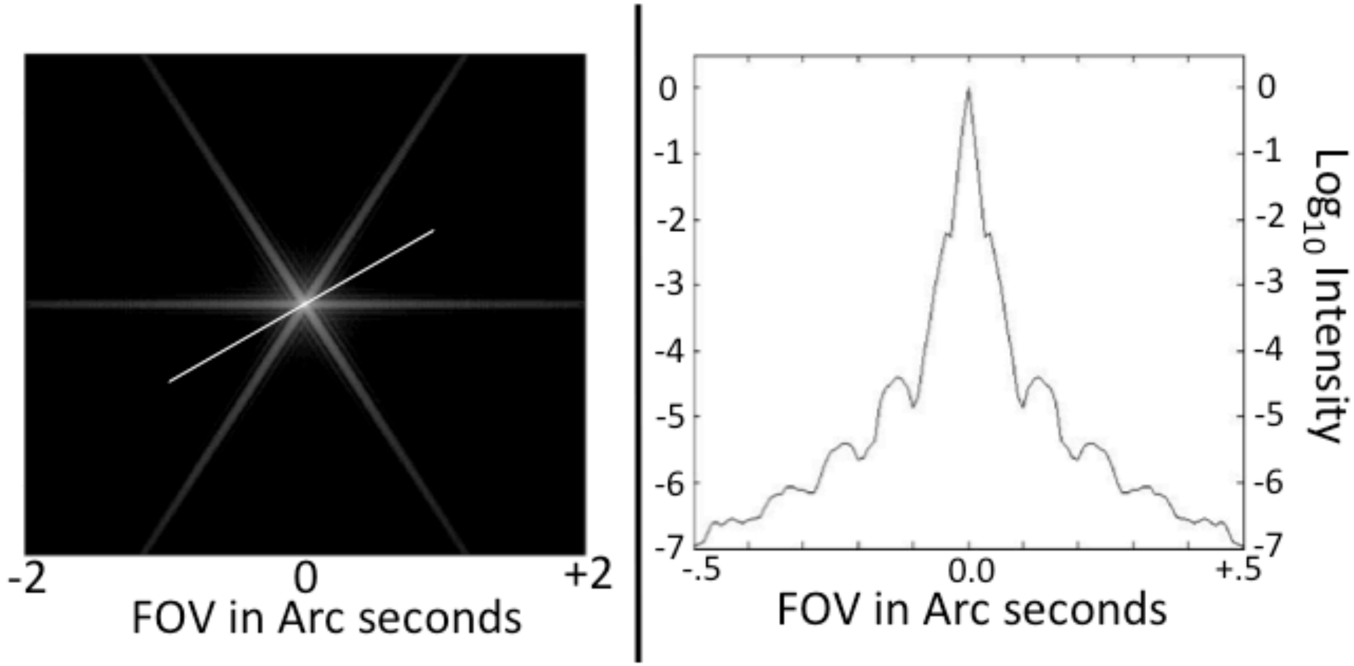


Image plane =>



# Prime focus advantages over Cassegrain

- Science applications
  - UV imaging spectroscopy (75 to 250 nm)
  - High contrast exoplanet coronagraphy ( $C_T \approx 10^{-11}$ )
  - Deep field imaging & spectroscopy astrophysics $(m_V \approx 35, \text{ for 12-m})$
- Prime focus design advantages
  - Low scattered light – less complicated to baffle than Cassegrain
  - One metal/dielectric reflection to UV focal plane
  - One metal/dielectric reflection to a coronagraph mask
  - Thermally induced structural distortion: ½ Cassegrain
  - Two-reflections to an A/O in an imager
  - Minimum polarization aberrations
  - Fewer sources of polarization anisotropy

# For next year

- Identify requirements & design solutions for
  - UV imaging [75 to 300 nm] spectroscopy
  - Terrestrial exoplanet coronagraphy
  - Deep field astrophysics [$35^{th}$ $m_v$; >4 arcmin]
  - Precision photo-polarimetry [0.01%]
- Optimize geometric & polarization aberrations
- Calculate the PSF across FOV
- SNR calculations

# References


- Polidan, Breckinridge, Lillie, MacEwen, et. al.

An Evolvable Space Telescope for Future Astronomical Missions: 2015 update. Proc. SPIE **9602**-6

- Breckinridge, Lam and Chipman, Polarization Aberrations in Astronomical Telescopes: The Point Spread Function, (2015) PASP, **127:**445–468
- Scowan et. al. Recommendations to the COPAG Executive Committee by the SIG #2, (2016) in press


*See me for .pdf's of these papers*

*jbreckin@earthlink.net*

# Thank you

# Why is polarization important?

- Hardware
  - Transmittance
  - Image Quality
- Exoplanet science
  - Atmospheric aerosols
  - Size of solid particles & dust envelopes
  - Orbital mechanics
- Astrophysics
  - High energy phenomena
  - Interstellar matter

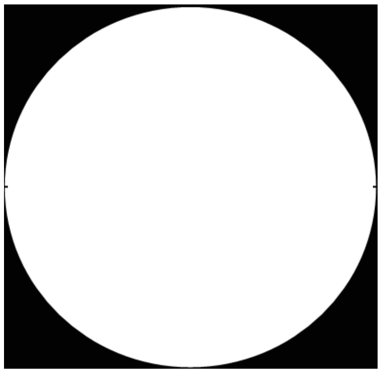
# Proof: polarization role in image formation

For zero OPD error $W(x,y)$=0.0

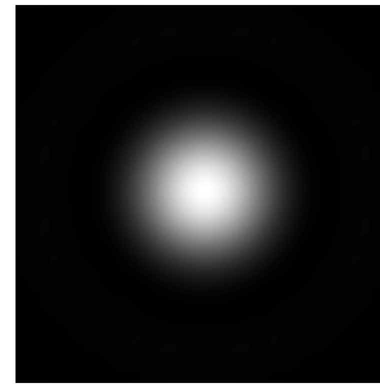
**Exit pupil**

**Image plane PSF**

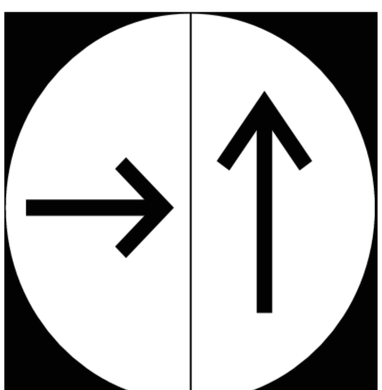
*No Polarizer*



Resolution is position angle **<u>in</u>**dependent



To represent internal polarization in the extreme we add two perpendicular linear polarizers



Resolution is position angle **<u>de</u>**pendent

The PSF is the incoherent sum of two "D" apertures

# Observations

- Orthogonally polarized light does not interfere to to contribute to an image.
- The shape of the point spread function depends on how polarization changes across the exit pupil.

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# Questions?

- What are the sources of instrument polarization in astronomical telescopes?
- What is the magnitude of the effect?
- What is the impact?