Candidate concepts for exoplanet detection and characterization

ExoPAG-COPAG meeting
26 April 2011

Charley Noecker
Ball Aerospace & Technologies Corp.

Agenda

- Menagerie of exoplanet direct detection options
  - High level description of each concept
  - Impacts on telescope requirements
- Overview of constraints on synergy

Vis-UV Exoplanet Concepts In Consideration

Internal coronagraphs

- Lyot coronagraph
- PIAA or pupil remapping
- Shaped pupil
- Visible nulling (VNC)
- Optical Vortex Coronagraph (OVC)

External coronagraphs

a.k.a. external occulters

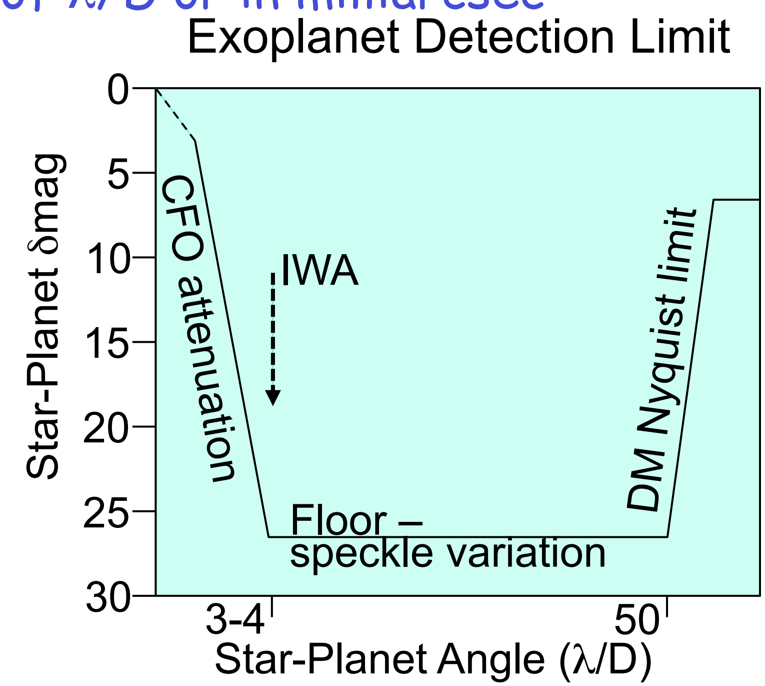
- Hypergaussian petal
- Optimized petal

Superb UV opt Astrophysics Telescope → Choice of method for exoplanet detection & characterization →

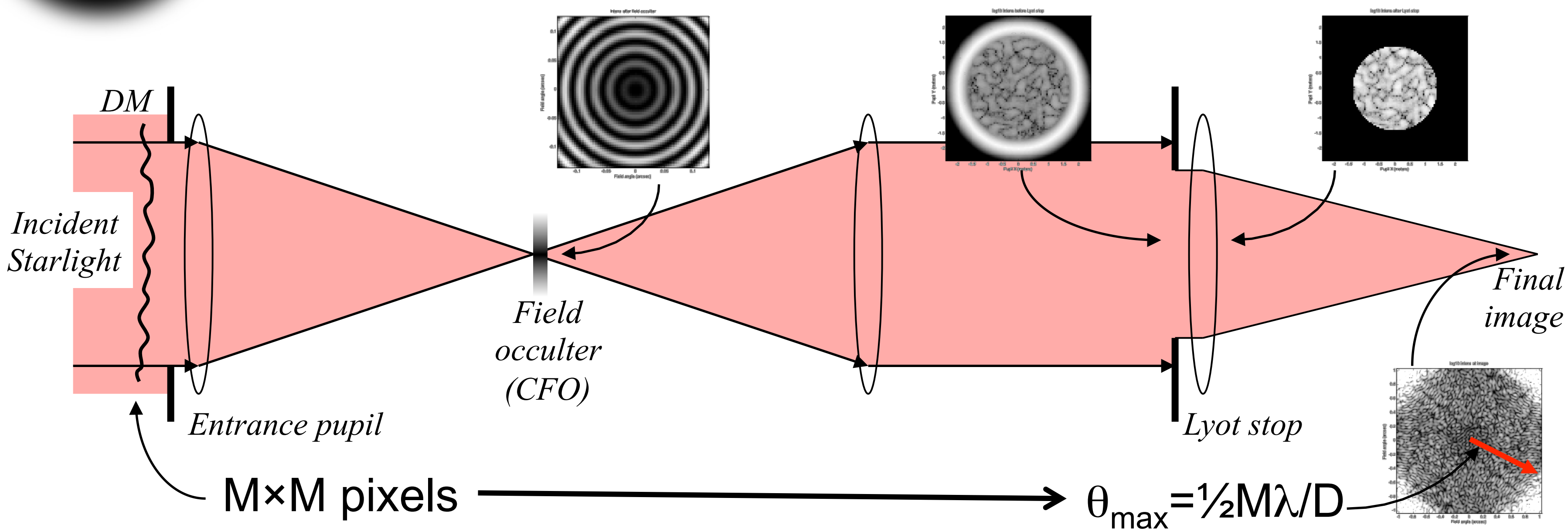
- On-axis vs. off-axis
- Segmented vs. monolithic
- Optical quality & stability
- Coatings
- Instrument volume
- Fraction of mission time

Exoplanet Acronyms and Terminology

- TXP terrestrial exoplanet (roughly 0.5–10 $M_{\oplus}$, rocky)
- HZ habitable zone: range of orbital semi-major axis for which liquid water can exist on the surface of a TXP
- δmag star-planet brightness ratio expressed in stellar magnitudes. Earth-Sun δmag≈25 at quadrature
- IWA Inner working angle = smallest angle from star at which a TXP can be detected. Given in multiples of λ/D or in milliarcsec
- Speckles — faint variations of brightness in the image, or the optical fields giving rise to them, caused by residual wavefront errors
- DM Deformable mirror, used for real-time wavefront correction to minimize speckles
- Sensitivity floor — minimum detectable exoplanet brightness, even for very large integration times, limited by speckle variations



Coronagraph features using Lyot coronagraph as an example



- Image plane "field occulter", followed by pupil plane "Lyot stop"
  - Blocks ordinary Fraunhofer diffraction from pupil edges
- Residual wavefront amplitude and phase errors cause speckles that can obscure exoplanets
- Deformable mirror enables optimized wavefront correction to drive down these speckles, and create a dark region in image plane

Rules of thumb for Internal Coronagraphs

- Wavefront sensing and control is paramount
  - Faint planets → faint speckles
    ➔ long integration times for wavefront sensing
    ➔ long times for passive stability
    - Wavefront correction <0.1nm rms
    - Wavefront stability ~0.003nm rms passively for ~hours
- Throughput and image sharpness for exoplanets are key drivers
  - Background-limited detection
  - Need to resolve exoplanet from exozodi dust clouds
    ➔ large telescope diameter, narrow PSF, high throughput
- Trying to get smaller IWA with same telescope (fewer λ/D) makes requirements harder
  - Severely tightens wavefront tolerances
  - Most coronagraphs suffer in throughput, PSF width, & integration time
- Must minimize number of edges in the pupil
  - Pupil mask blocks a substantial area around each gap in pupil
  - More segments, smaller IWA drive <u>sharply</u> lower throughput and fatter PSF

$$\left.\begin{array}{r}\text{\# segments} \uparrow \\ \text{IWA} \downarrow\end{array}\right\} \Rightarrow \left\{\begin{array}{l}\downarrow \text{Throughput} \\ \uparrow \text{PSF width}\end{array}\right.$$

Most internal coronagraphs demand a monolithic unobscured aperture

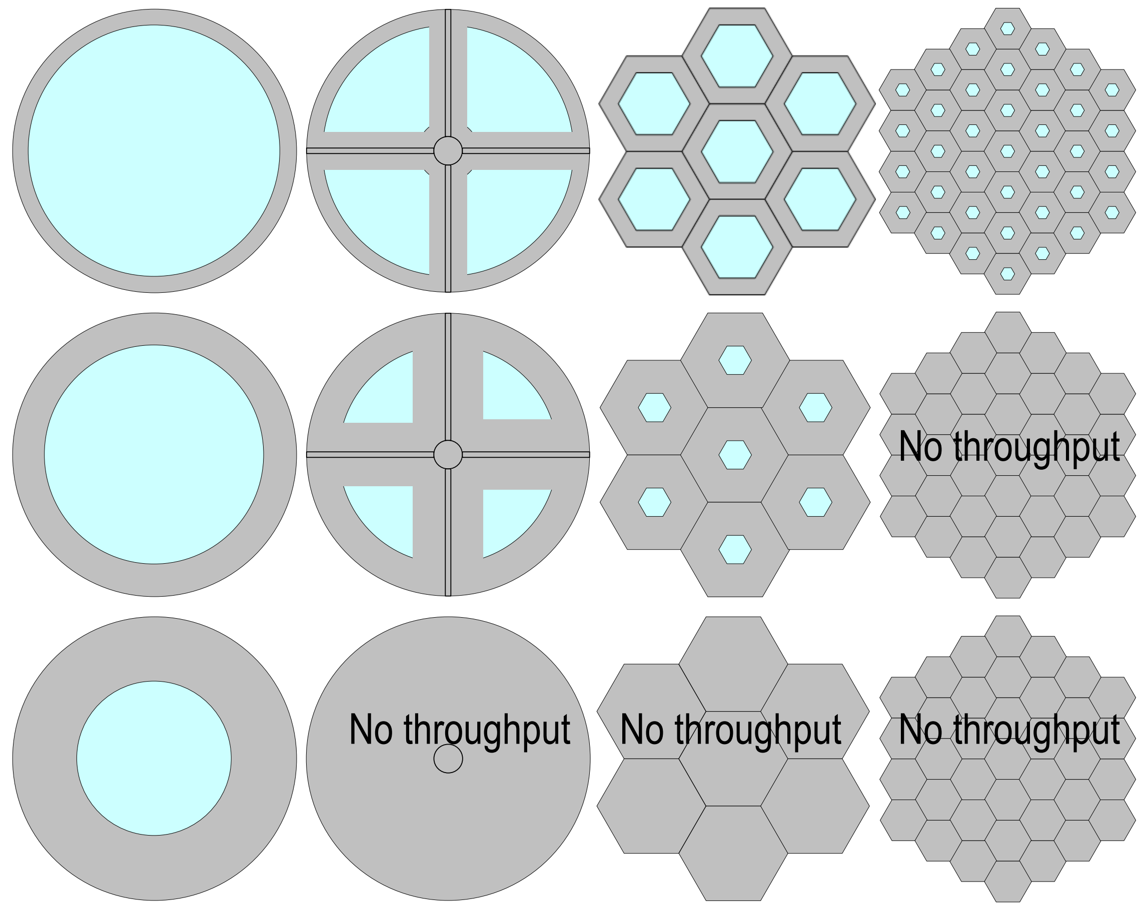
- Pupil mask blocks a substantial swath around each gap in pupil
- If IWA= $N\lambda/D$ for some (small) N, then half-swath $\propto \lambda/\text{IWA} = D/N$
- For N=3 (aggressive), we must block ~1/3 of width, 43% of area

Masking in Lyot stop for various obscurations and segmentations

IWA= 12 λ/D

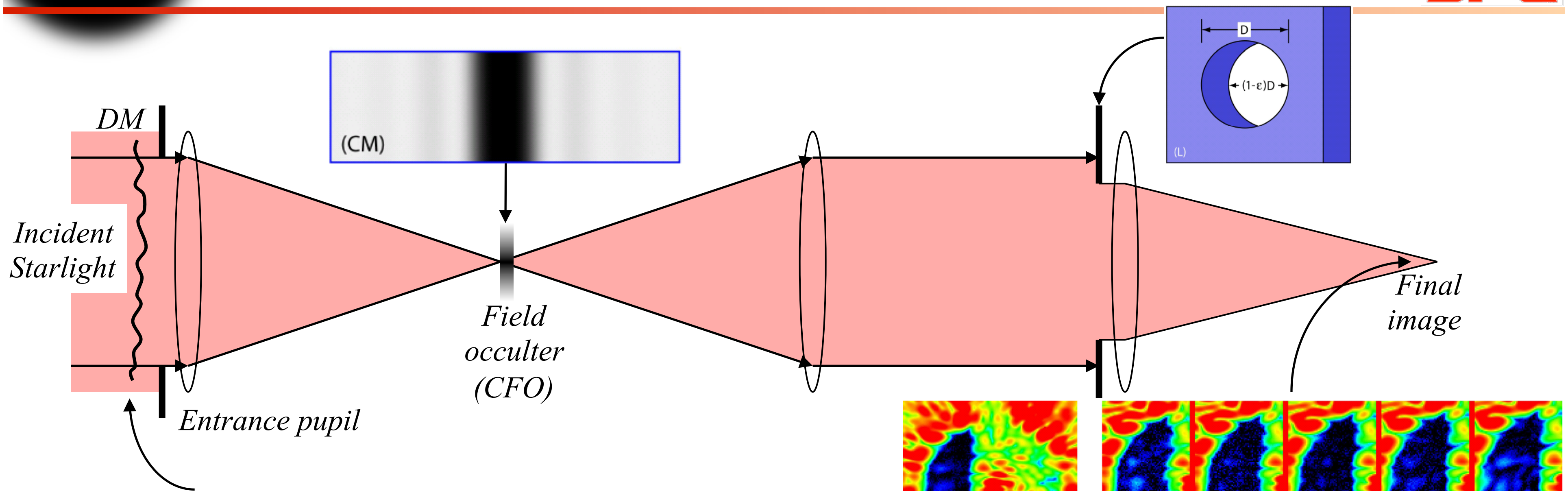
6 λ/D

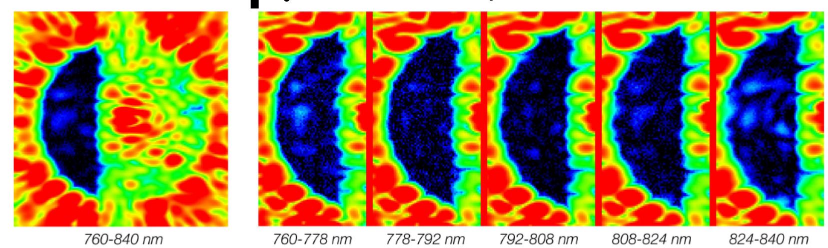
3 λ/D



For Lyot coronagraph, as for **<u>most</u>** (not all) kinds of internal coronagraph, a monolithic unobscured aperture is ~<u>required:</u> the only practical option

Lyot Coronagraph

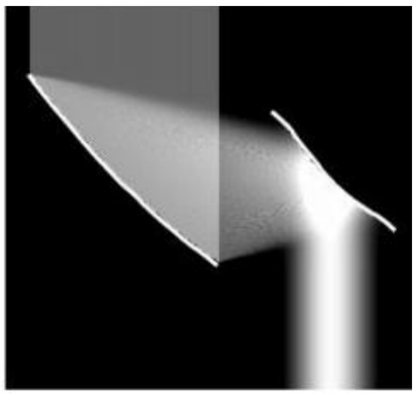


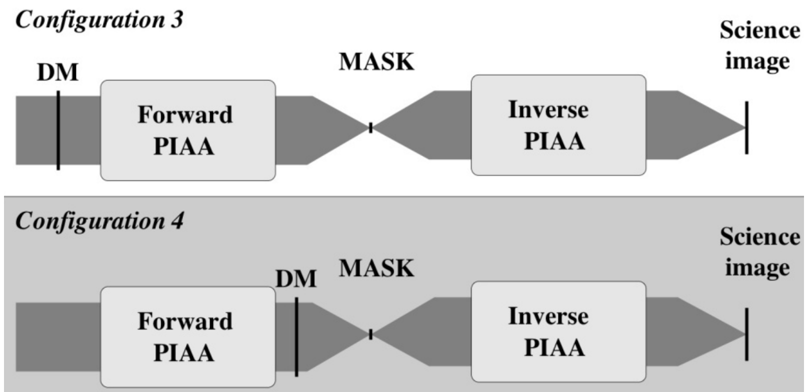


- Band-limited 4th-order CFO is used for IWA < 4λ/D
- First-tier technical maturity – ahead of the others
  - Current performance ~5e-10 in 10% passband
  - Instrument stability demonstration ~ meets requirement for TXPs
- Monolithic unobscured telescope with picometer stability for hours
- 15-20 mirror path → silver coatings in exoplanet channel

PIAA or Pupil Remapping Coronagraph

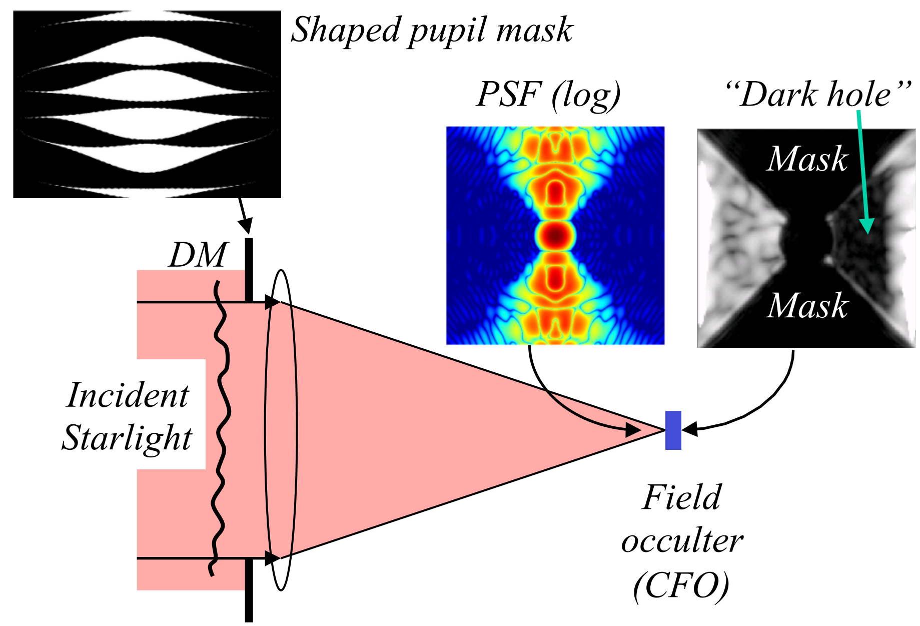
- Highly aspheric optics remap the uniform top-hat pupil into an apodized beam
  - Focuses to an optimally compact amplitude profile
  - Blocked with hard-edge CFO
  - No Lyot stop needed
- Followed by similar optics to undo remapping and restore the original PSF with wide FOV
- Preserves high mask throughput and narrow PSF even for very small IWA (< 2λ/D)
- Still demands
  - monolithic unobscured pupil
  - picometer stability for (fewer) hours
  - silver coatings in exoplanet channel
- 2nd-tier technology maturity





Shaped pupil coronagraph

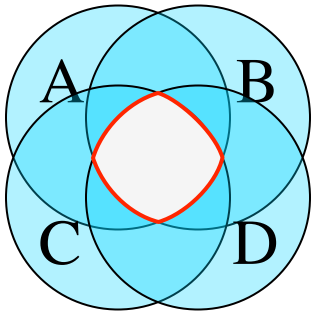
- Uses carefully tapered binary pupil mask to construct a compact PSF, then binary field mask to block star
  - Pupil mask is applied after secondary mirror
  - PSF is butterfly-shaped — sacrifices north & south while clearing east & west
- No Lyot stop, but significant loss of throughput at pupil mask
- Some designs compatible with obscuration and a few gaps across primary (chord folds)
- Successful designs at 4λ/D
- 2nd-tier technology maturity



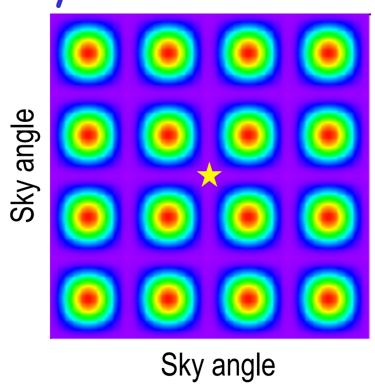
Visible Nulling Coronagraph (VNC)

- Achromatic nulling interferometer prepares destructive interference of 2 or 4 copies of telescope pupil, with relative lateral shear

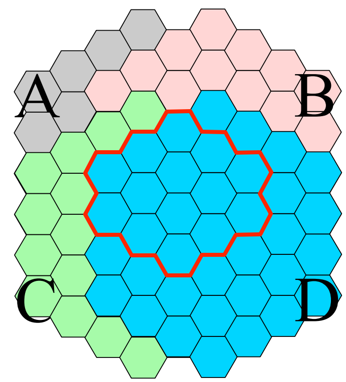
Exit pupil:



- Re-imaging 4-beam exit pupil (red) yields an image of exoplanet system multiplied by sine × sine function:



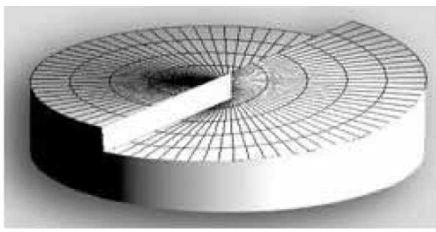
- The only candidate compatible with segmented telescope — when shear = segment spacing

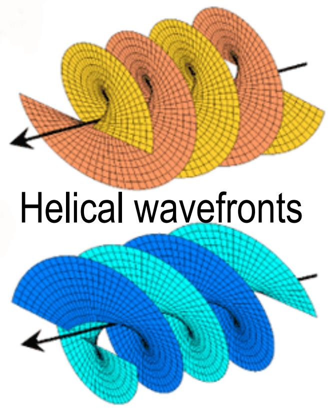


- Bright-port control at 15 Hz
- IWA ~2λ/D in some cases
- 2nd-tier technology maturity

Optical Vortex Coronagraph

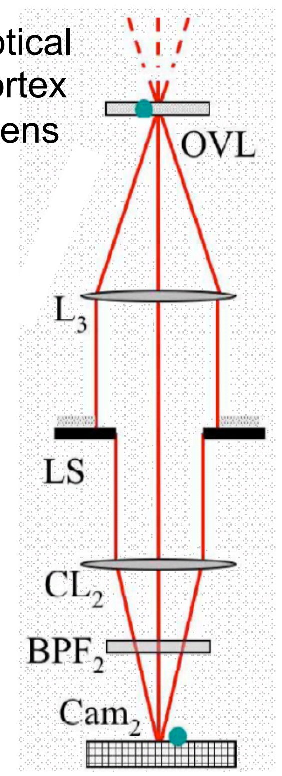
- Uses photon orbital angular momentum (POAM) – vaguely like polarization





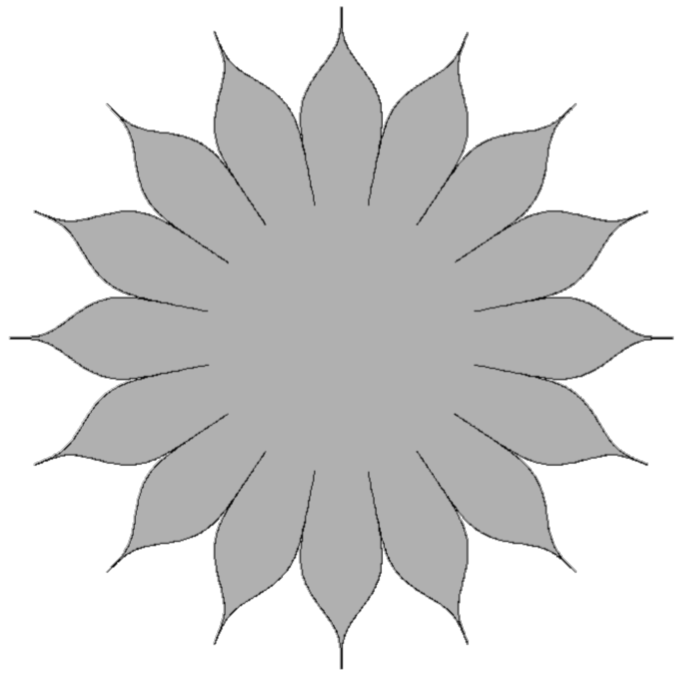
- Also polarization methods
- Mask excludes zero-POAM light on-axis, transmits it off-axis
- Lyot stop traps excluded light ➔ this is a Lyot coronagraph but Lyot mask throughput is almost 100%

- Recent demos on binary stars
  - Great strength is IWA ~2λ/D
  - Still achieving modest contrast
- 2nd-tier technology maturity



External Coronagraphs

- Large occulting mask between star and telescope
  - Typically 50-80m diam and 50-100 Mm from telescope
    - Mm = 1000 km
  - Size driven by small IWA and diffraction
- Compatible with any telescope: obscured, segmented, etc.
- Only need telescope to be diffraction limited
- Petal is tapered to suppress diffraction into shadow
- 2^{+}-week slews
  - Lots of astrophysics time
  - Limited agility for exoplanet studies
- Telescope must carry instruments and inter-spacecraft telemetry to help maintain alignment
- Most petal tolerances > cm, some ~0.1mm, a few ~0.01mm
- 2^{nd}-tier maturity, with all issues on occulter



Other issues

UV coated optics

- Internal coronagraphs have 15-25 mirrors to the exoplanet FPA
  ➔ If throughput is low, we don't want to lose another 50% of exoplanet light to aluminum/ MgFl coatings

- Occulter system could have only 4-5 mirrors to the exoplanet FPA ➔ can afford more loss at UV-coated mirrors
  ➔ might allow UV observations of exoplanets

Instrument volume

- Internal coronagraphs require multiple relay mirrors
  - Volume for folded coronagraph instruments
  - Multiple spectral & polarization channels
  - Competes with wide-field imaging instruments
- Occulter only needs camera with filters, spectrometer with modest spectral resolution

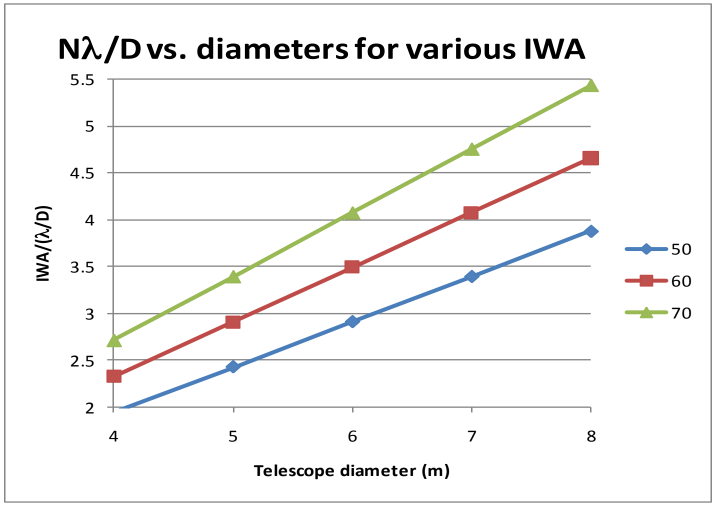
Summary

	Lyot or OVC	PIAA	VNC	Occulter
Obscuration	No	No	Yes	Yes
Folding /segments	No	No	Yes	Yes
Telescope stability	<~3 pm 1-10 hr	<~3 pm/ 1-10 hr	<~3 pm/ 0.1 sec	<40 nm
# mirrors UV coated	≤ 2	≤ 2	≤ 2	more
Planet throughput	10-15%	60-80%	10-15%	80-90%
Smallest IWA	3λ/D	1-2λ/D	2-3λ/D	1-2λ/D
Astrophysics time	50%	50%	50%	70-80%

Flowdown from exoplanet science to telescope properties

Starting assumption: we must have 60 mas IWA to find enough TXPs

- 4m diam coronagraph ➔ very aggressive 2.4 λ/D instrument
  ➔ monolithic unobscured, few-picometer wavefront stability
  if Lyot ➔ severe cut in throughput, much longer integration times
- 8m diam coronagraph ➔ comparatively modest 4.5 λ/D instrument
  ➔ monolithic unobscured, 0.5-0.8 nm wavefront stability
  if Lyot ➔ ~40-60% cut in throughput, longer integration times
- Any size with occulter ➔ all tough requirements on occulter
  ➔ any diffraction-limited telescope, 20-40 nm wavefront stability



Controlled WF accuracy and stability

	8m	4m
Focus	2.1 nm	0.016 nm
Astigmatism	2.9 nm	0.022 nm
Coma	0.55 nm	0.003 nm
Trefoil	1.3 nm	0.009 nm
Spherical	0.019 nm	0.003 nm