Phase-Induced Amplitude Apodization Complex Mask Coronagraph (PIACMC)

Pros and Cons of considering a high efficiency coronagraph option

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Summary

SCIENTIFIC MOTIVATION: **With a full efficiency* coronagraph, a 2.4m telescope could potentially directly image and acquire low-resolution spectra of rocky planets in the habitable zones of nearby stars. (significant part of TPF-C goal) → Can this goal be reached ?**

(*) Full efficiency coronagraph: fully removes starlight while preserving the angular resolution and sensitivity of the telescope with inner working angle ~ 1 l/D

PIAACMC (described in this presentation) is one example of a coronagraph that approaches full efficiency – used in this presentation to illustrate scientific opportunities and also technical challenges associated with an "aggressive" coronagraph option.

PIAACMC technology (and probably any other high efficiency coronagraph) is less mature and more demanding (wavefront control, pointing) than more conservative options.

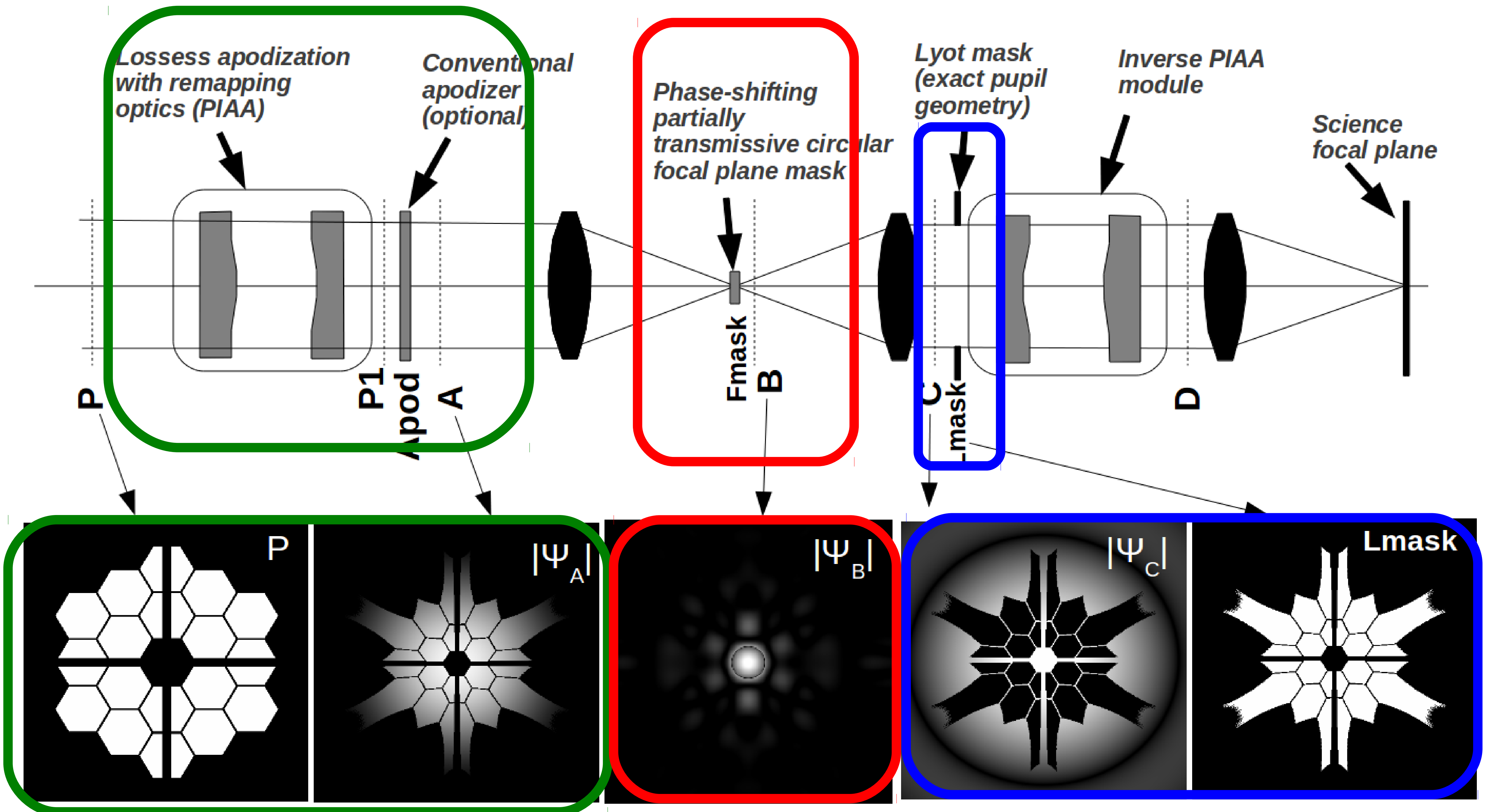
Implementation on 2.4-m telescope would require further technology development and study (schedule, R&D cost ?).

How does PIAACMC work ?

Combines 3 techniques :

- **Lossless apodization with PIAA optics (beam shaping)**
- **Phase mask coronagraphy (focal plane mask is phase-shifting)**
- **Lyot coronagraphy (Pupil plane Lyot mask removes starlight)**

→ starlight rejection achieved by **destructive interference** between light that passes through the focal plane mask and light that passes outside the focal plane mask



PIAACMC vs PIAA

PIAA: lossless apodization + opaque focal plane mask

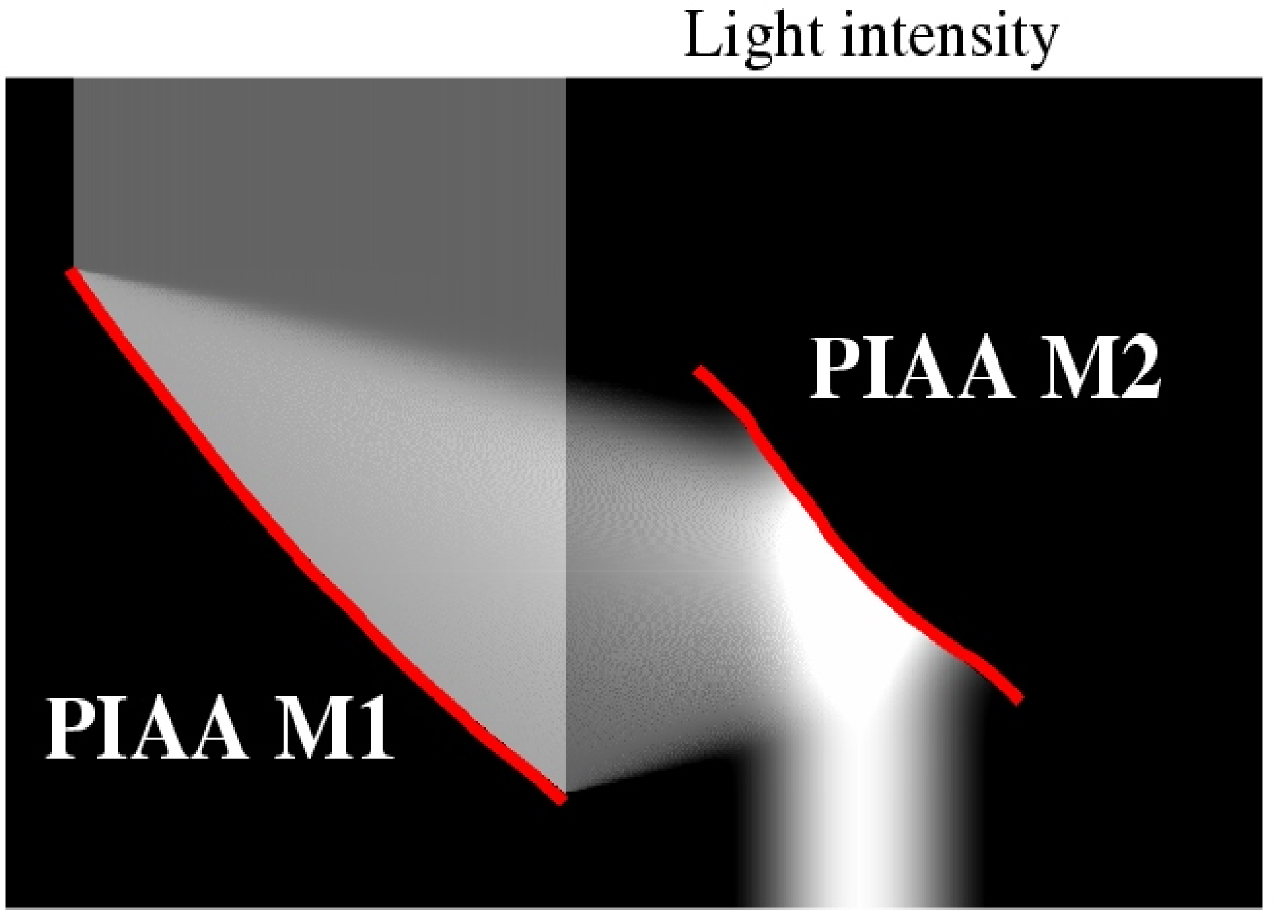
PIAACMC is an evolution of the PIAA coronagraph, which does use a phase shifting focal plane mask.

Gains / advantages:

(1) **Lower IWA than PIAA** (~0.7 l/D, vs. ~2 l/D for PIAA), preserving full efficiency
(2) Can work on **centrally obscured or segmented apertures** with no loss in performance
(3) Uses **milder apodization** (PIAA optics easy to manufacture for PIAACMC)
(4) Offers degrees of freedom for **achromatization** not available in PIAA

Challenges:

(1) Extreme sensitivity to tip/tilt error (needs to be <mas) and stellar angular size
(2) Sensitivity to low order aberrations
(3) Chromaticity

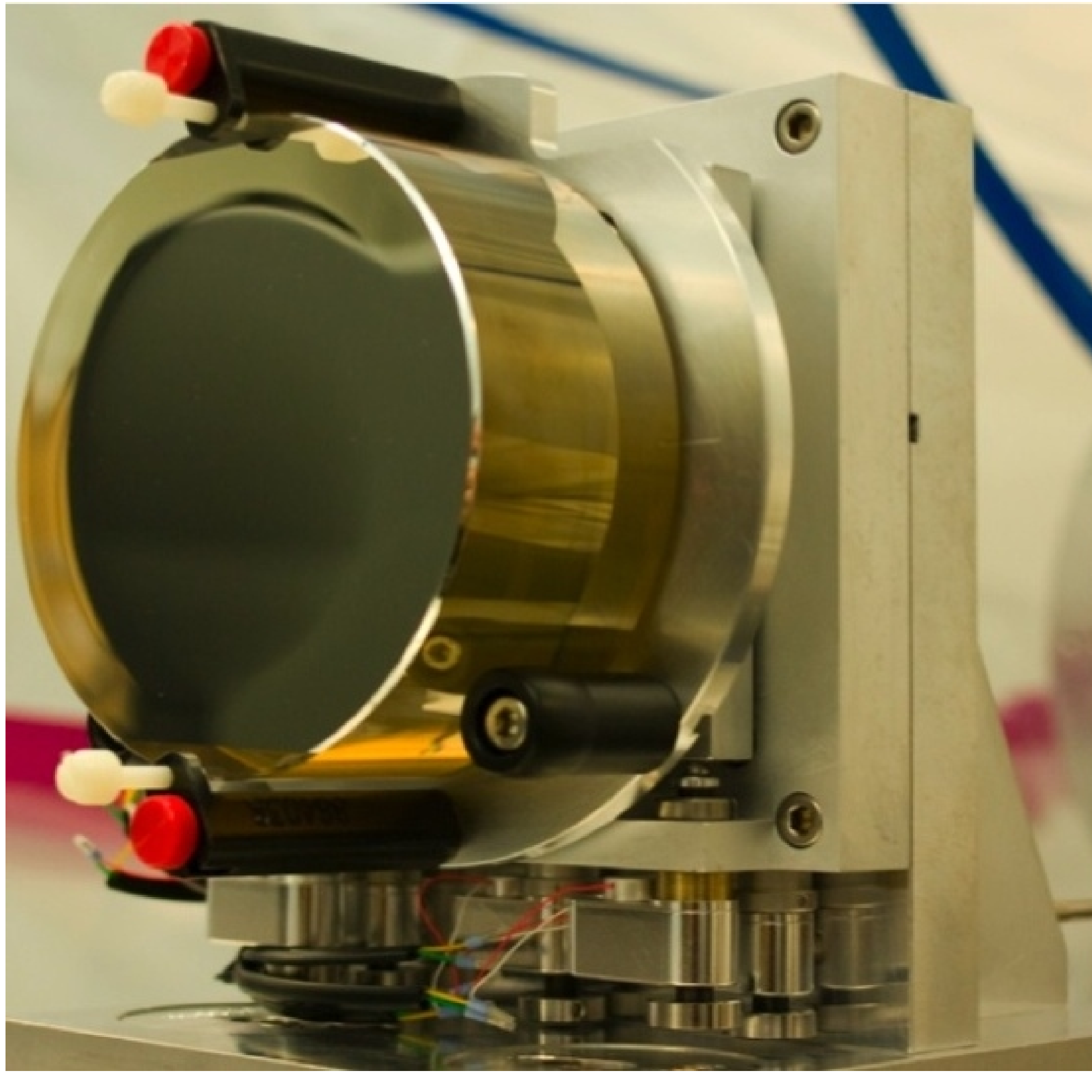


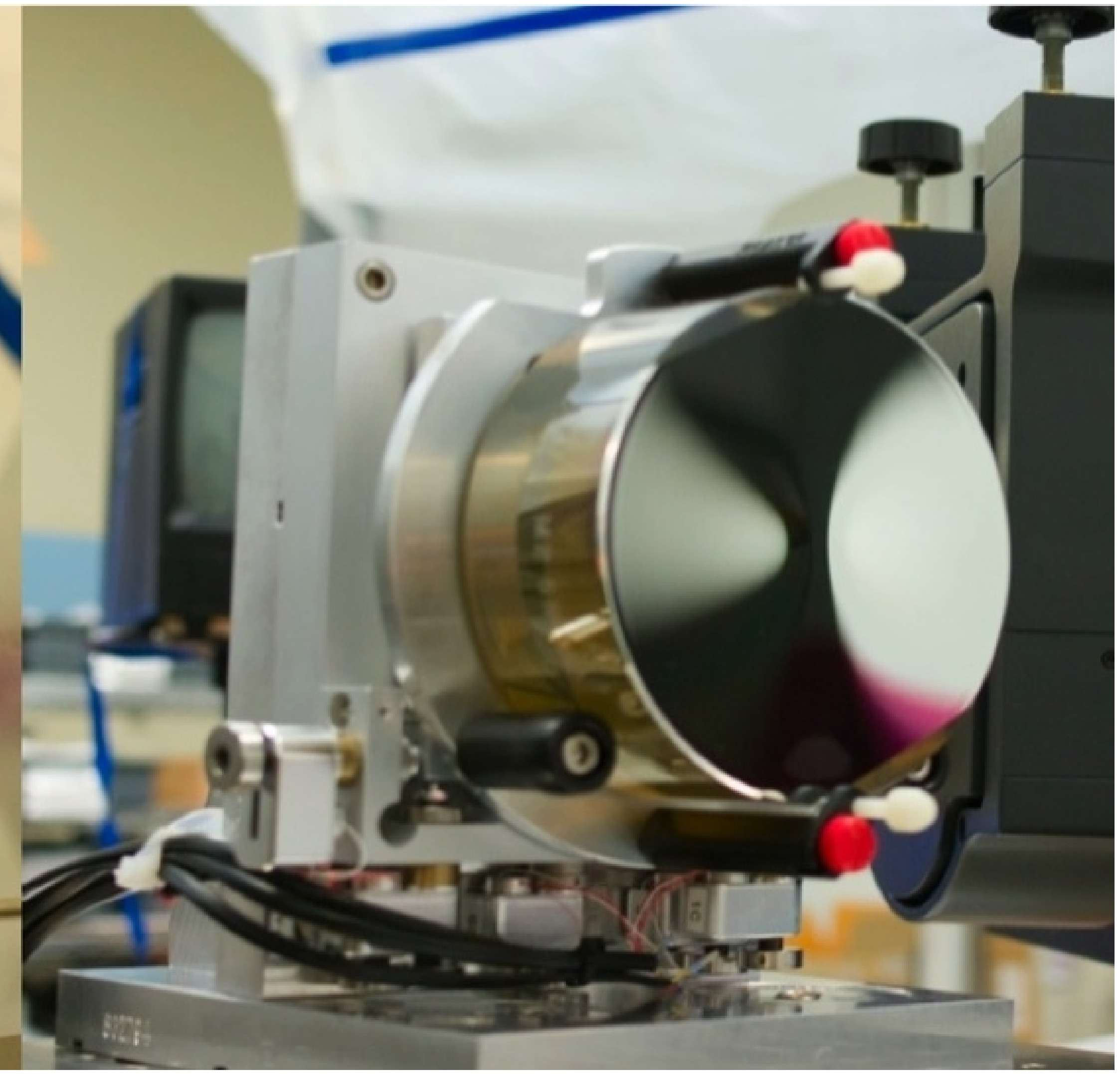
Existing PIAA systems:
JPL (HCIT)
NASA Ames
Subaru Telescope (validated on-sky)

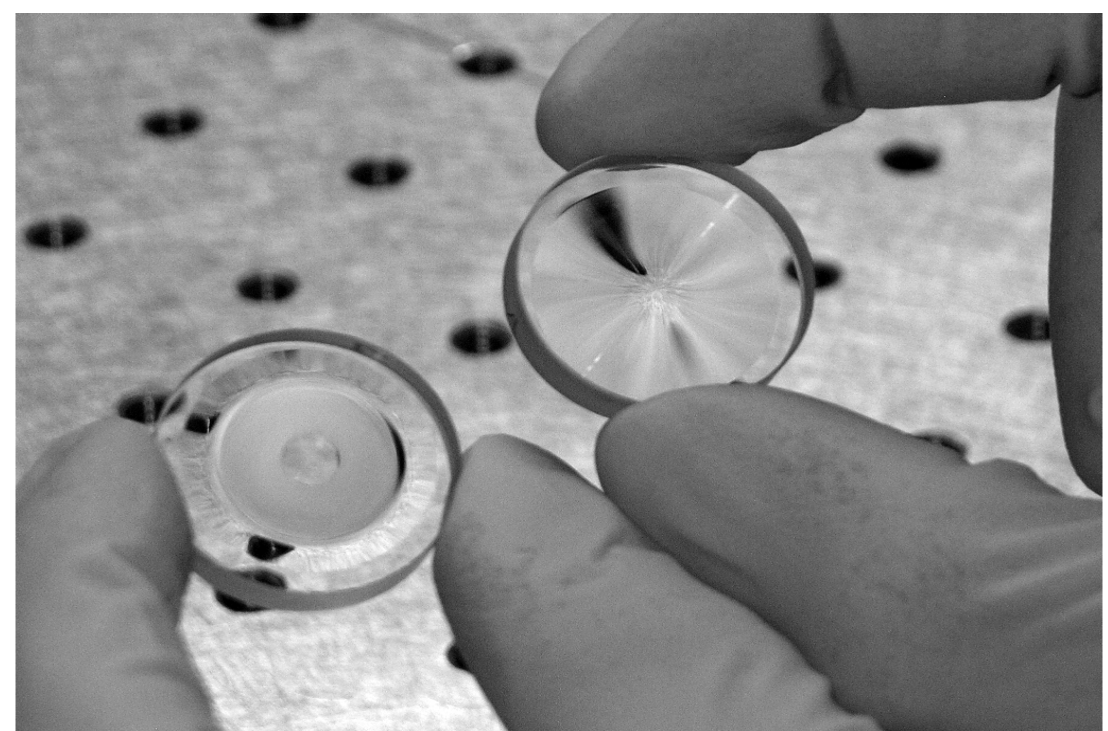
Under study:
EXCEDE (NASA Explorer program)

Guyon, Belikov, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present

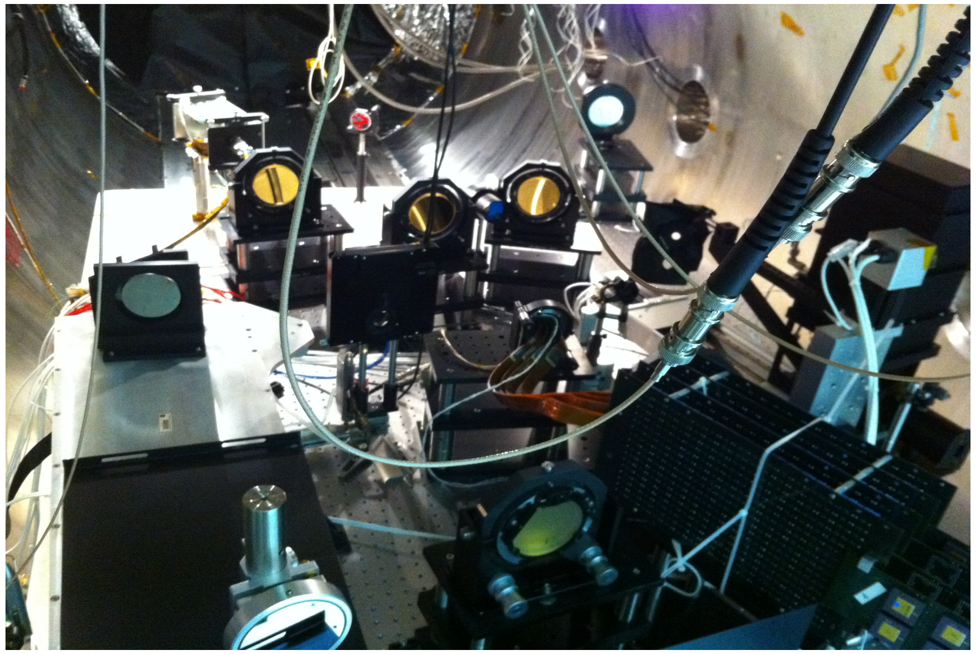
PIAA optics

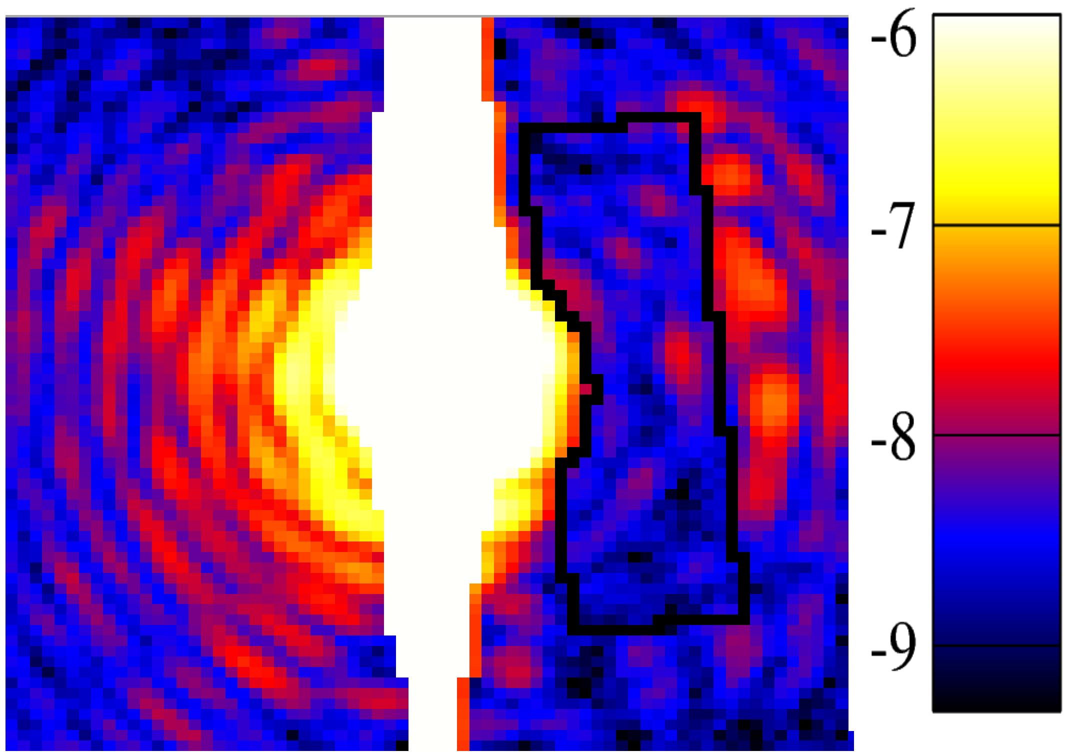






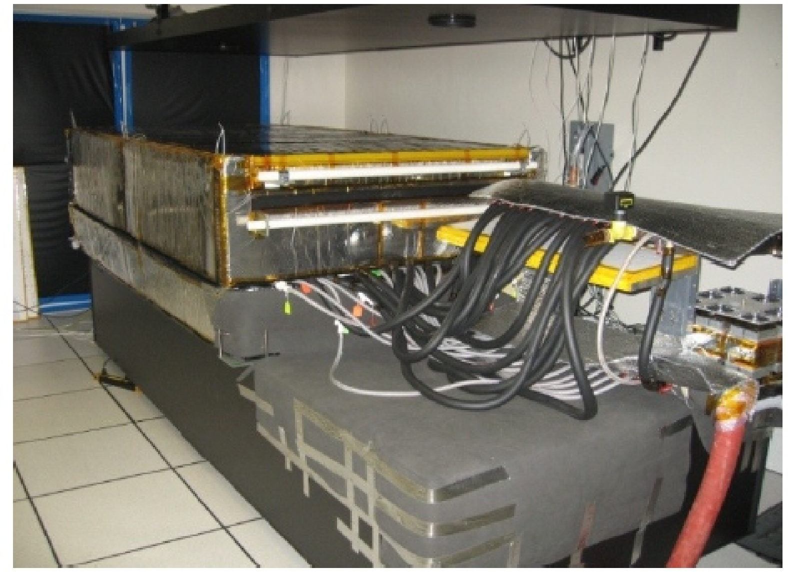
NASA JPL vacuum testbed

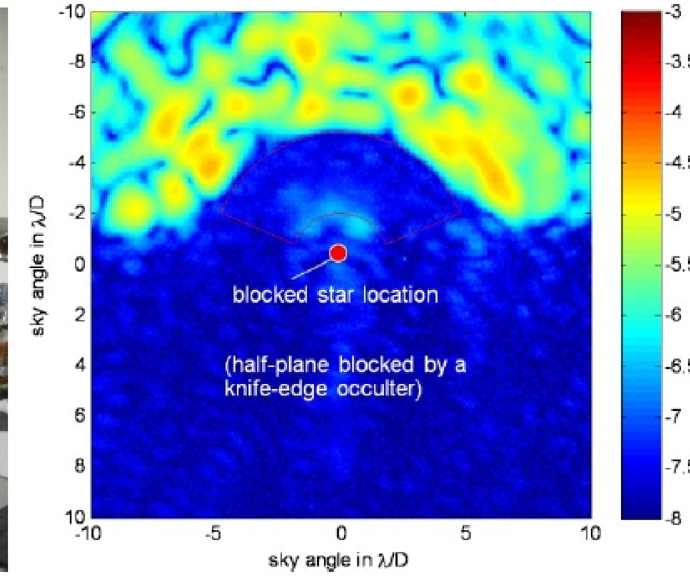




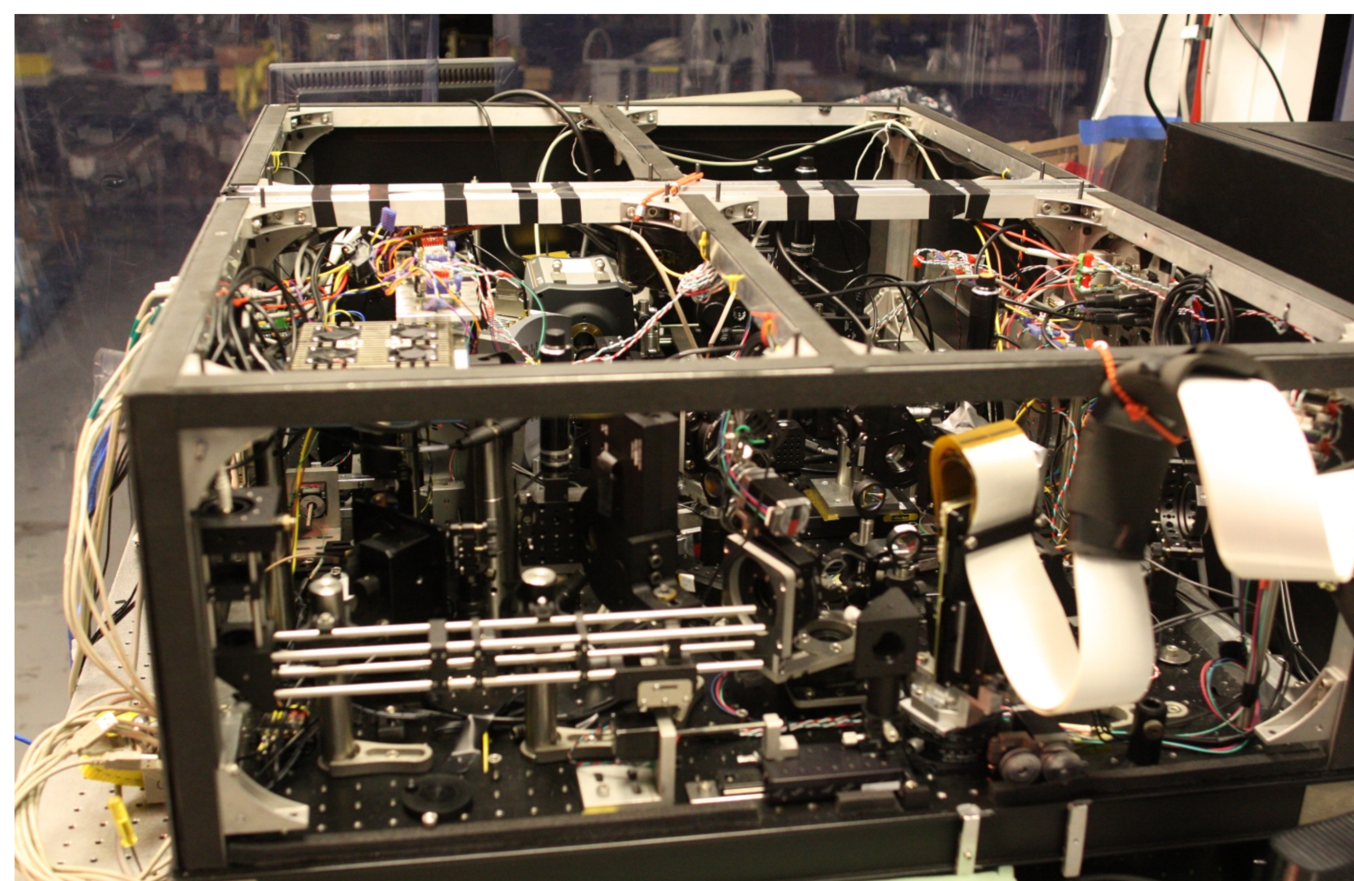
PIAA is reaching 1e-9 contrast at 2 to 5 lambda/D separation

NASA Ames

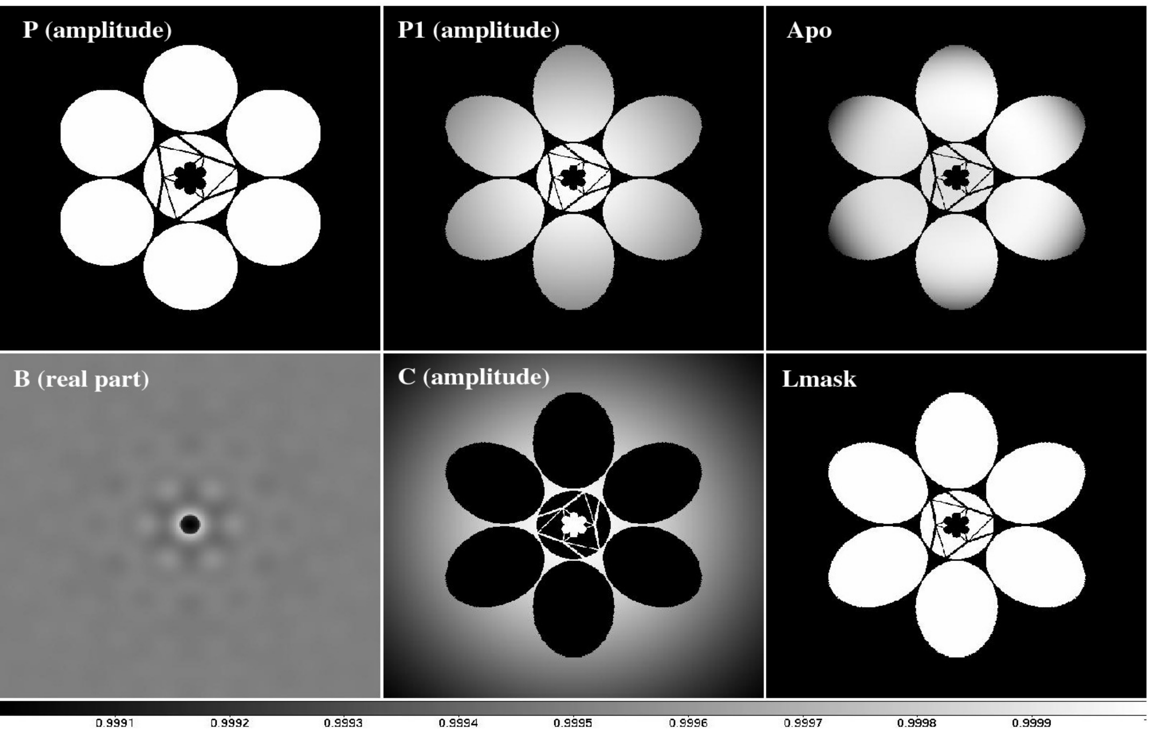




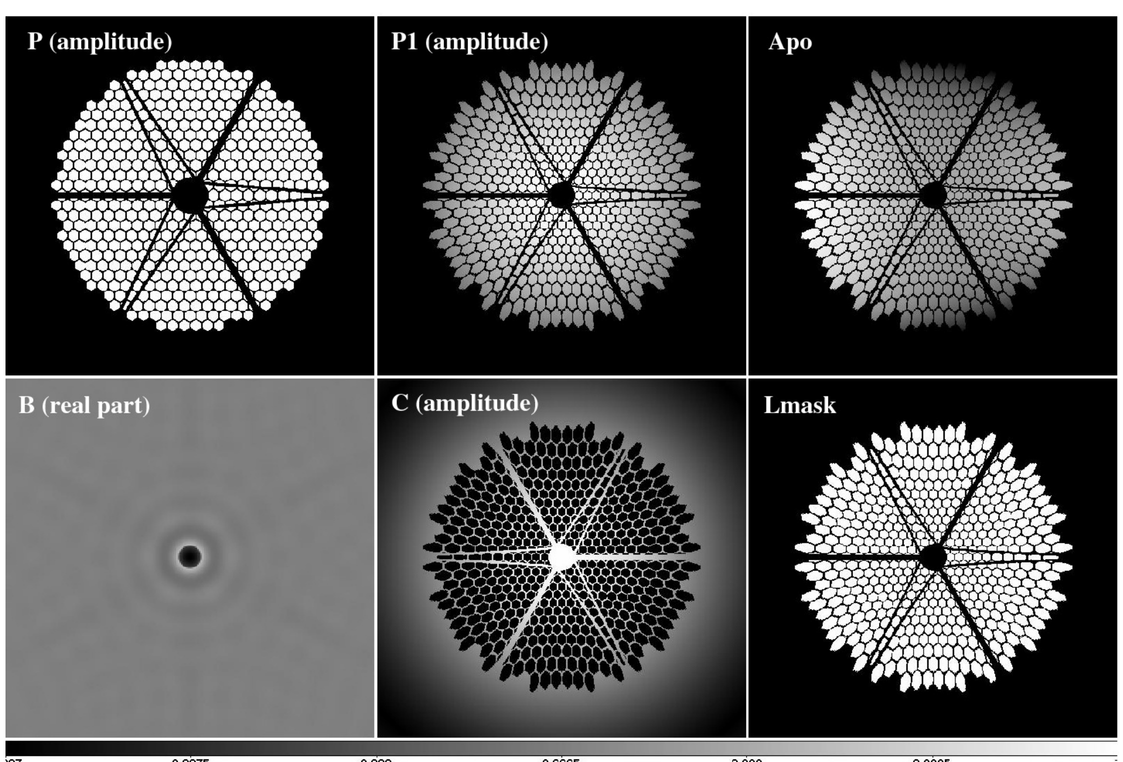
Subaru Telescope

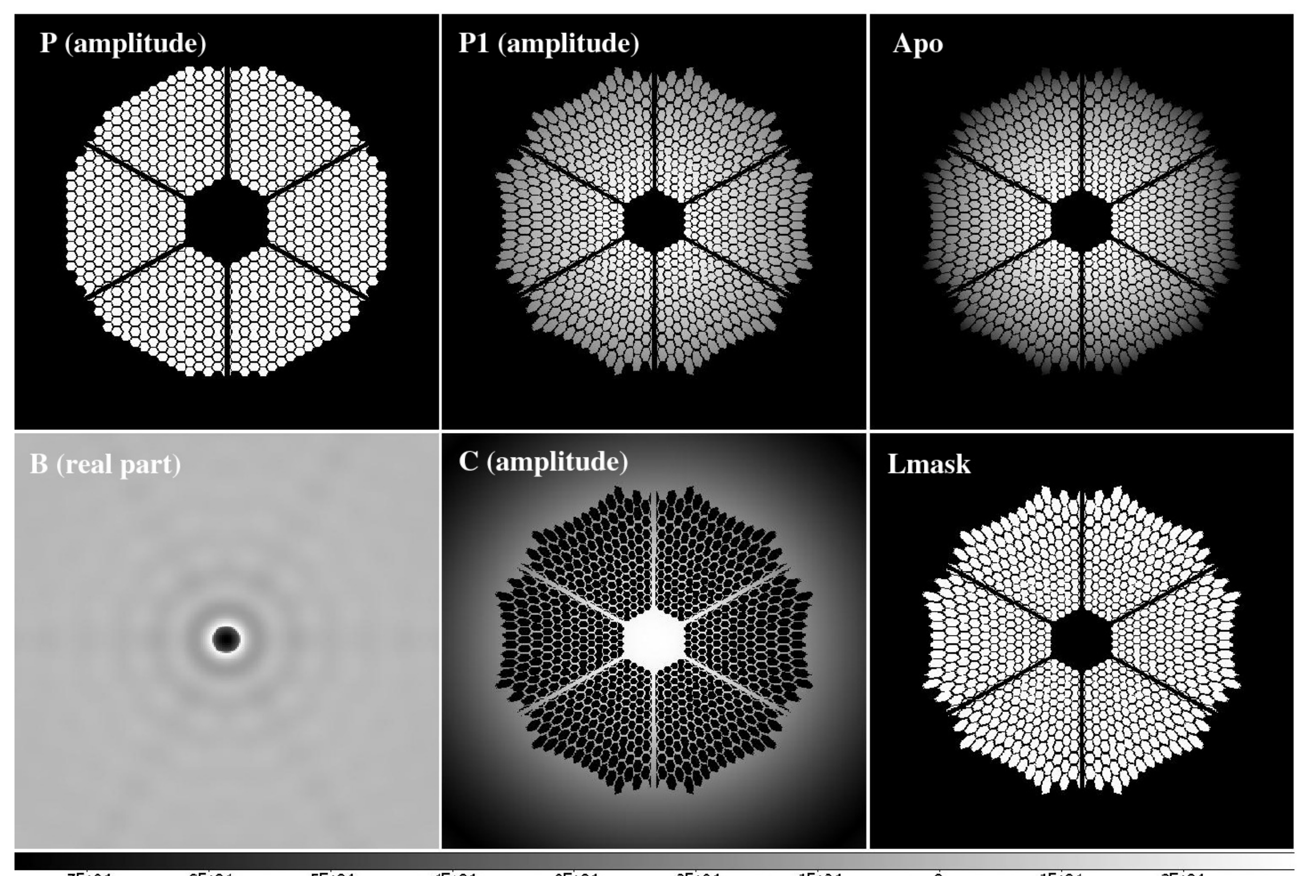


PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit



<u>Pupil shape does not matter</u>





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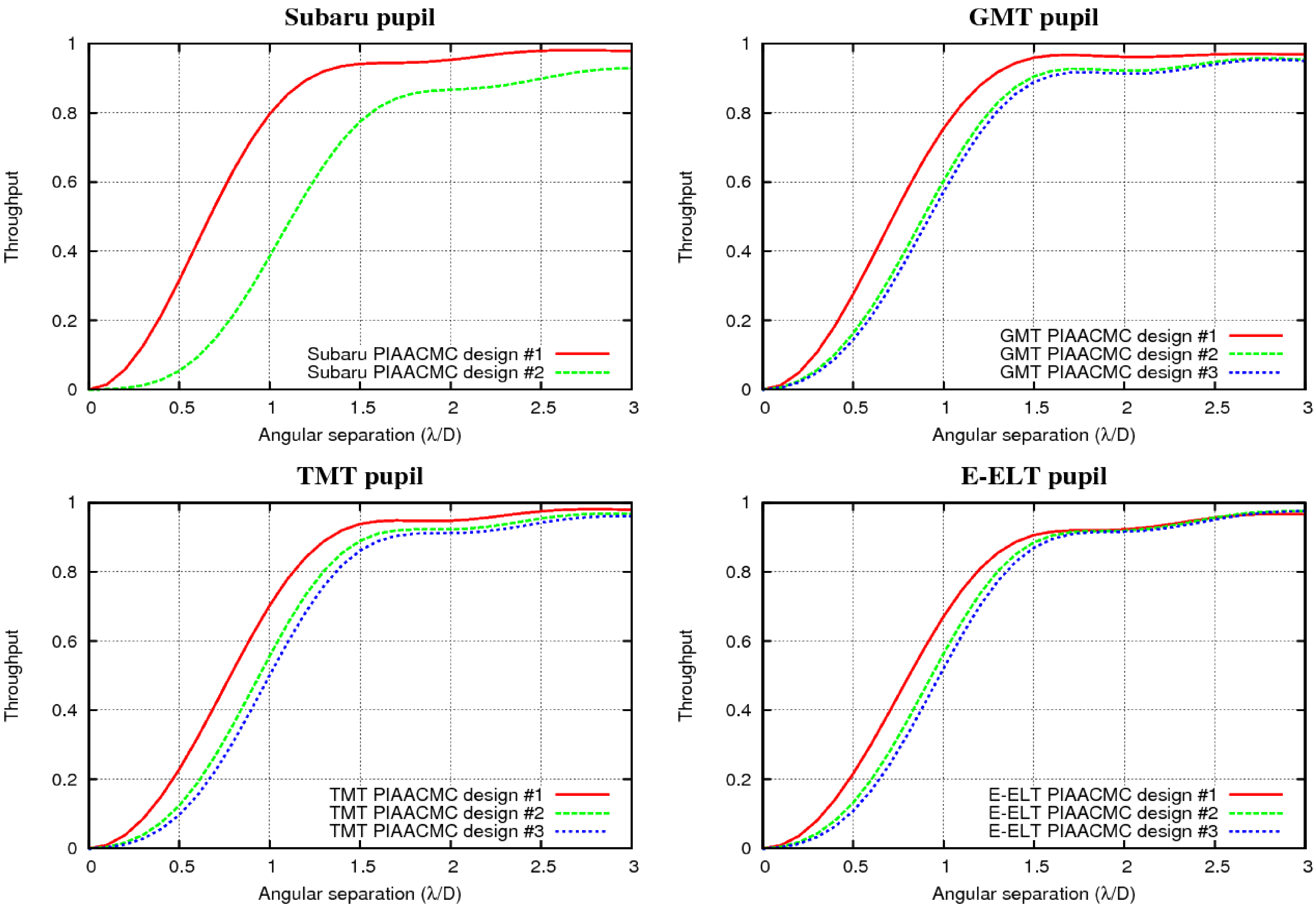


PIAACMC achromatization: diffractive focal plane mask

Challenges:

focal plane mask size needs to scale with lambda
focal plane mask transmission needs to be achromatic
focal plane mask phase shift needs to be achromatic

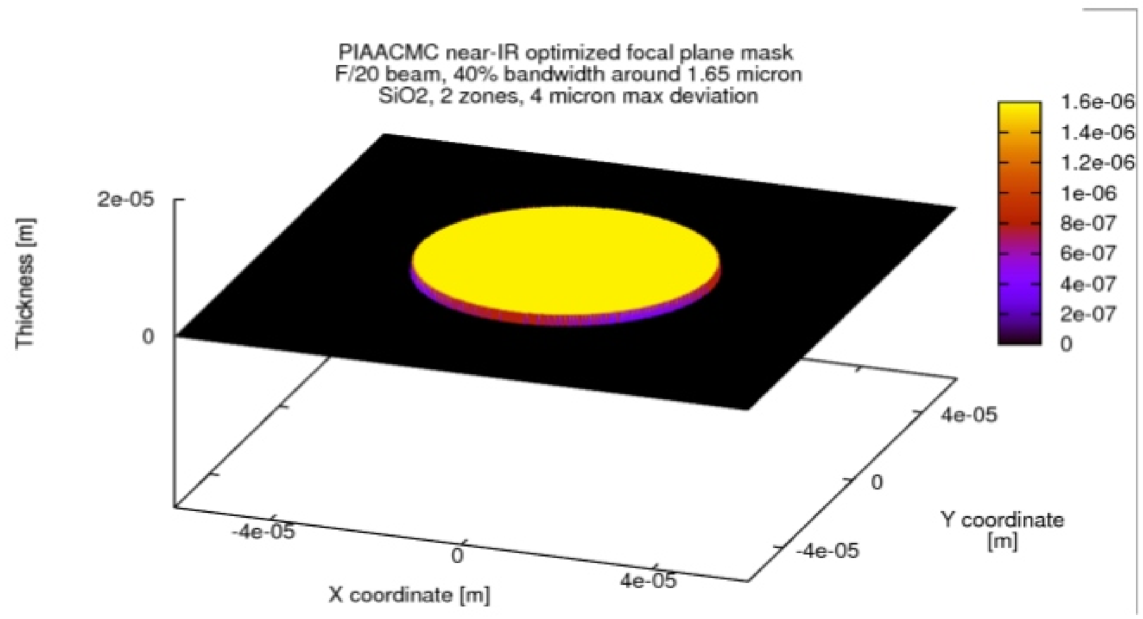
Solution:

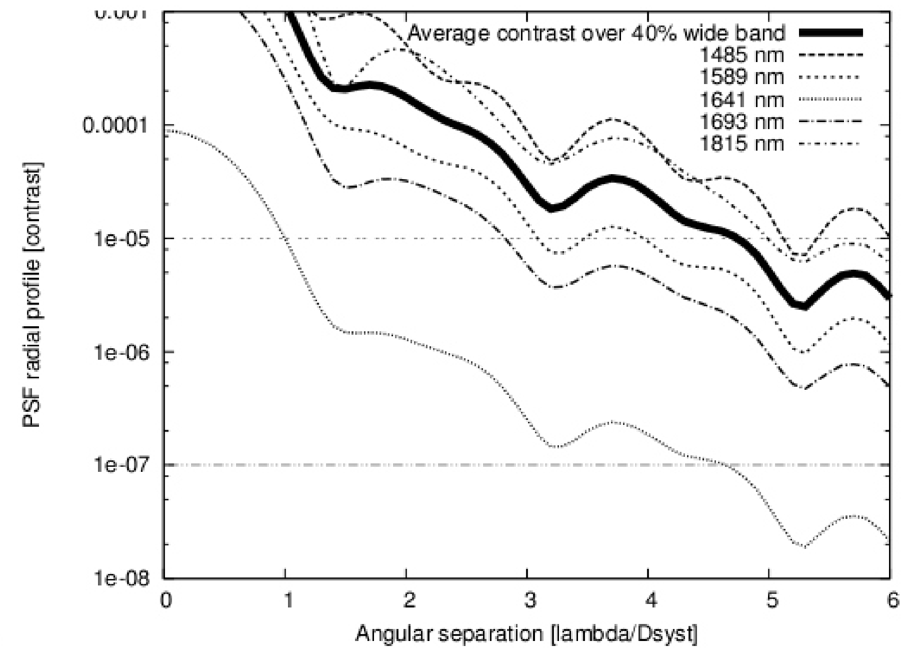
Design focal plane mask as a diffraction grating that offers the correct transmission as a function of wavelength, as seen through the Lyot stop.

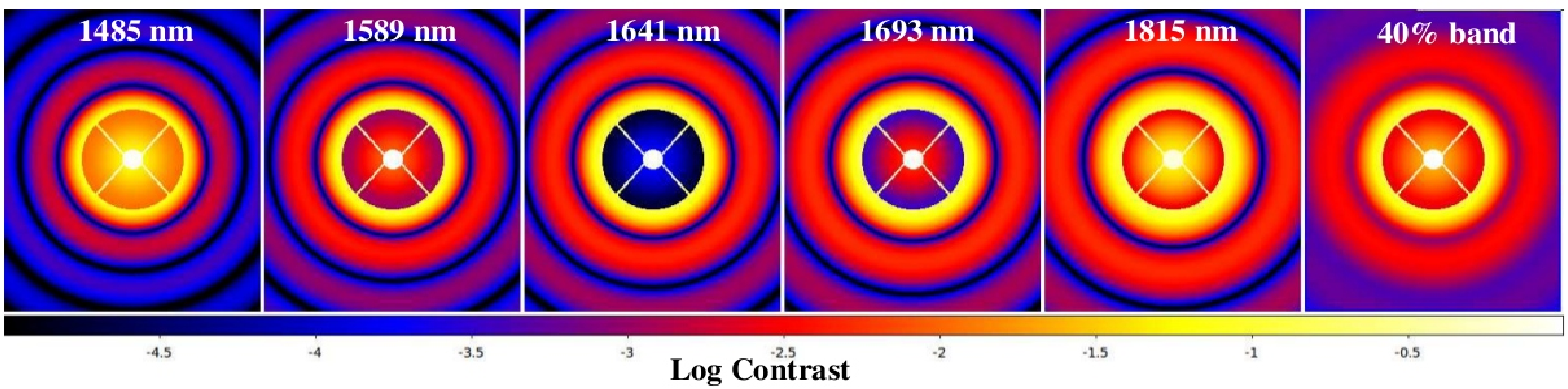
In most high contrast systems, the coronagraph should be designed to be achromatic at the ~1e-7 level without wavefront control. Wavefront control then pushes further the contrast in polychromatic light.

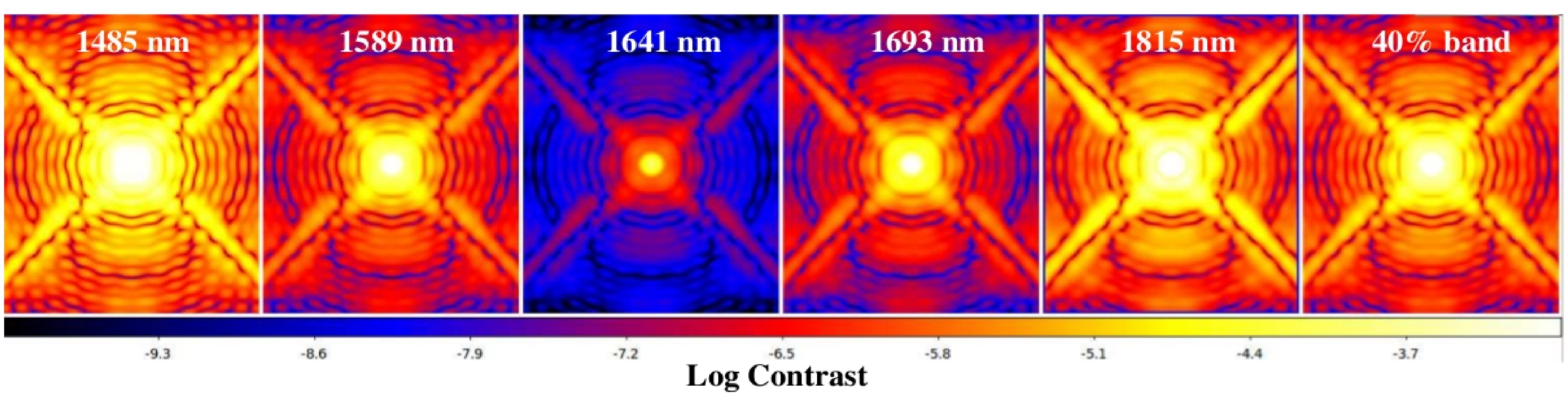
With a diffractive mask, the number of zones (and their phase shifts) in the mask can be increased to reach better achromatic performance. Next 2 slides show that 20 zones are sufficient to reach 1e-7 raw contrast in 40% wide band without wavefront control.

PIAACMC contrast without achromatization: 1e-4 raw contrast across 40% band

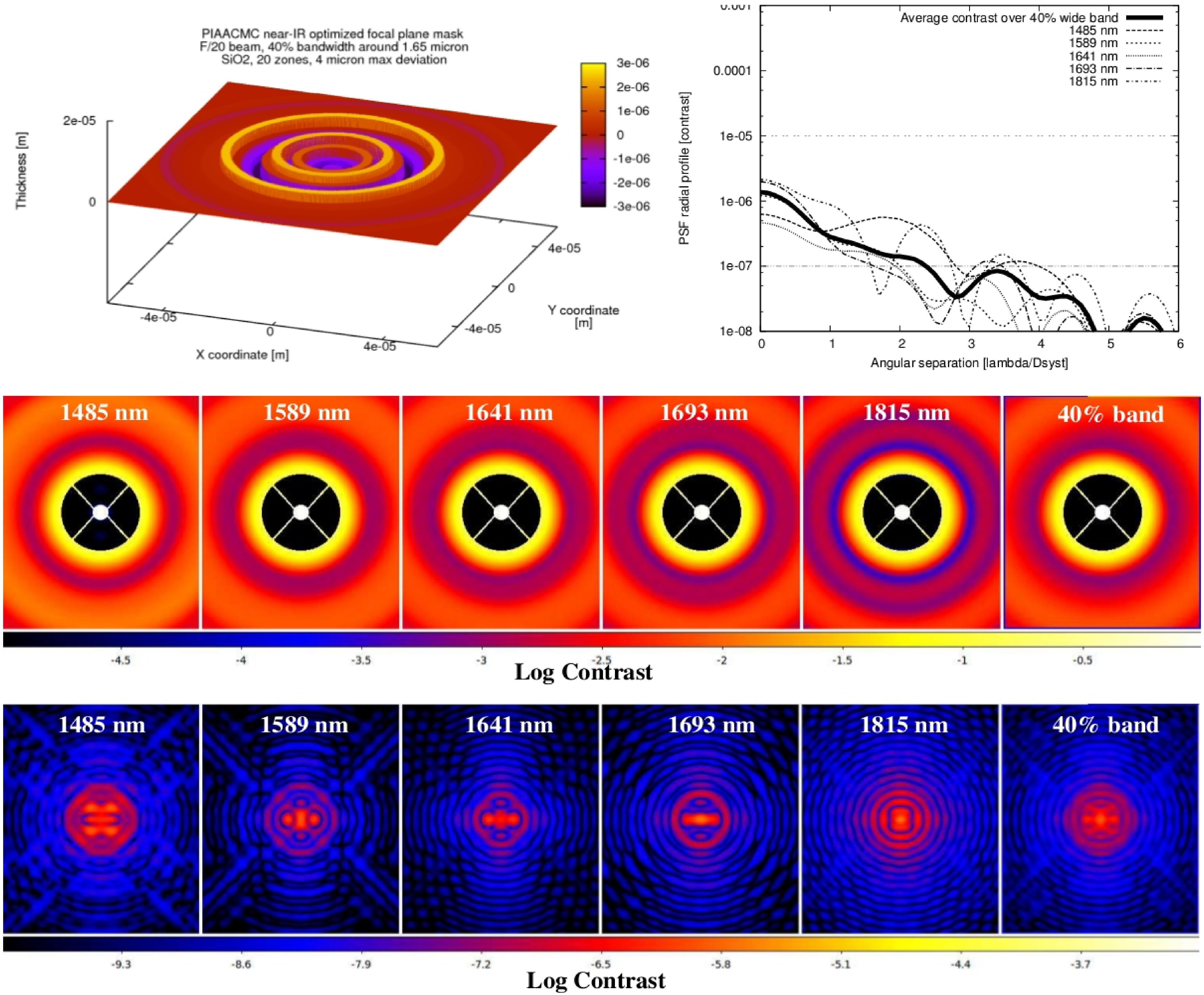








Example: PIAACMC designed for 1e-7 raw contrast across 40% band → 20 zones required



Comparative study of coronagraph systems for direct imaging of Earth analogs (1 Earth radius, Earth albedo, 1 AU equivalent distance)

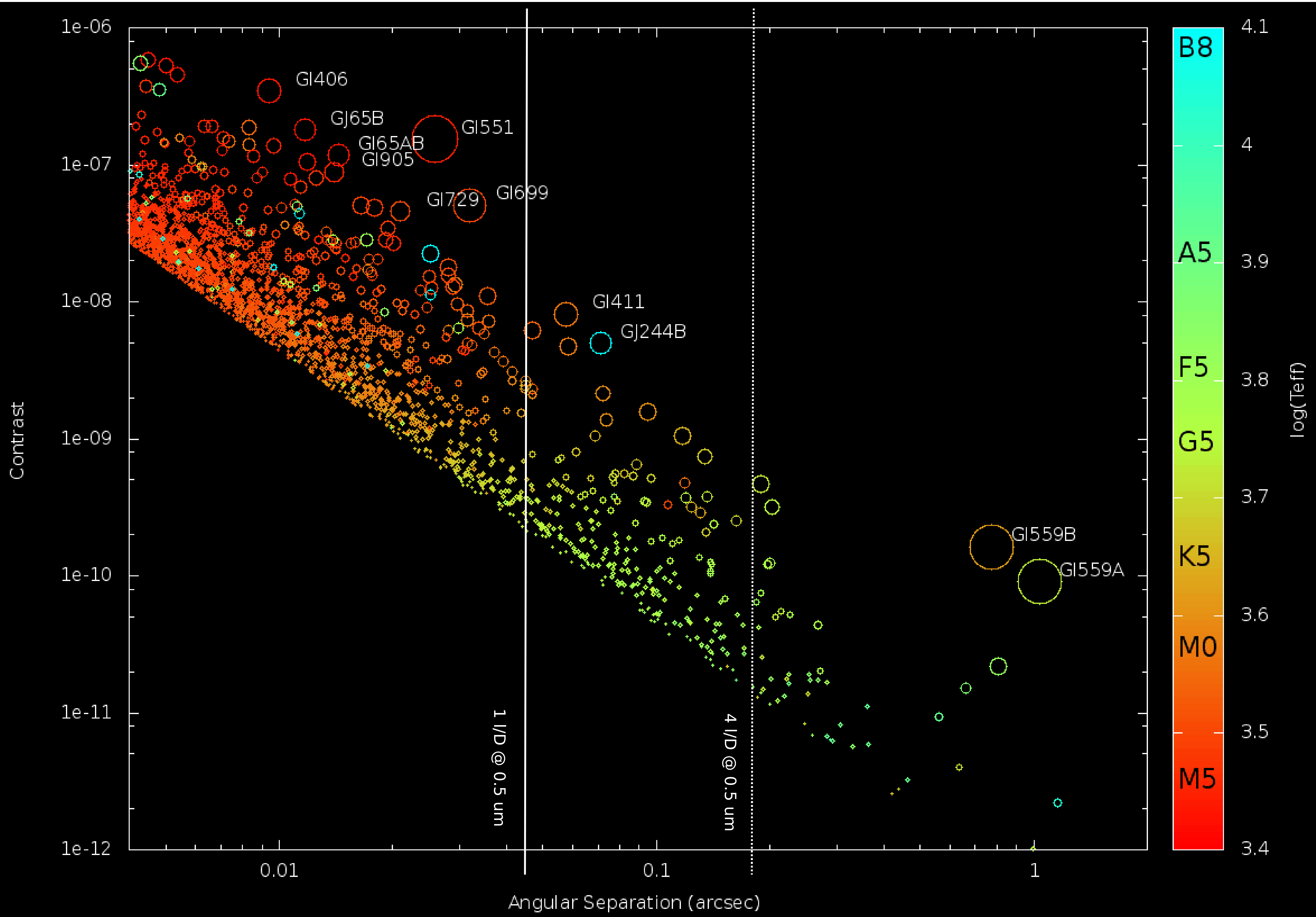
	Baseline 2.4	PIAACMC 2.4	TPF FB1	Notes
Telescope diameter	2.4 m		8 x 3.5 m	
Efficiency	20%			coatings, detector
Wavelength	0.5 um			
Spectral bandwidth	0.1 um (R=5)			
Zodi background	m_V=22 arcsec^{-2}			
Exozodi	2x zodi			
IWA	3 l/D	1.0 l/D	4 l/D	PIAACMC IWA increased to 1l/D due to stellar angular size
Throughput	20%	100%	30%	
Airy efficiency	50%	100%	50%	affects sensitivity due to background (zodi+exozodi)
PSF size	2 l/D	1 l/D	3 l/D (2x4.6 l/D)	
Discovery space	100%	100%	100%	

Assuming detection limit is set by both calibration limit and photon noise:
- If planet is 1000x fainter than raw contrast, or if inside IWA, SNR = 0
- otherwise, SNR driven by photon noise (zodi + exozodi + instrument contrast + planet)

Contrast = 1.74e-10 for Earth analog around Sun

Using catalog produced by merging Hipparcos, SUPERBLINK, Gliese, RECONS and 2MASS
→ 2581 stars within 20pc (most of them M type)

Earth analogs (1 Earth radius, Earth albedo, 1-AU equivalent distance)



Earth analogs (1 Earth radius, Earth albedo, 1-AU equivalent distance)

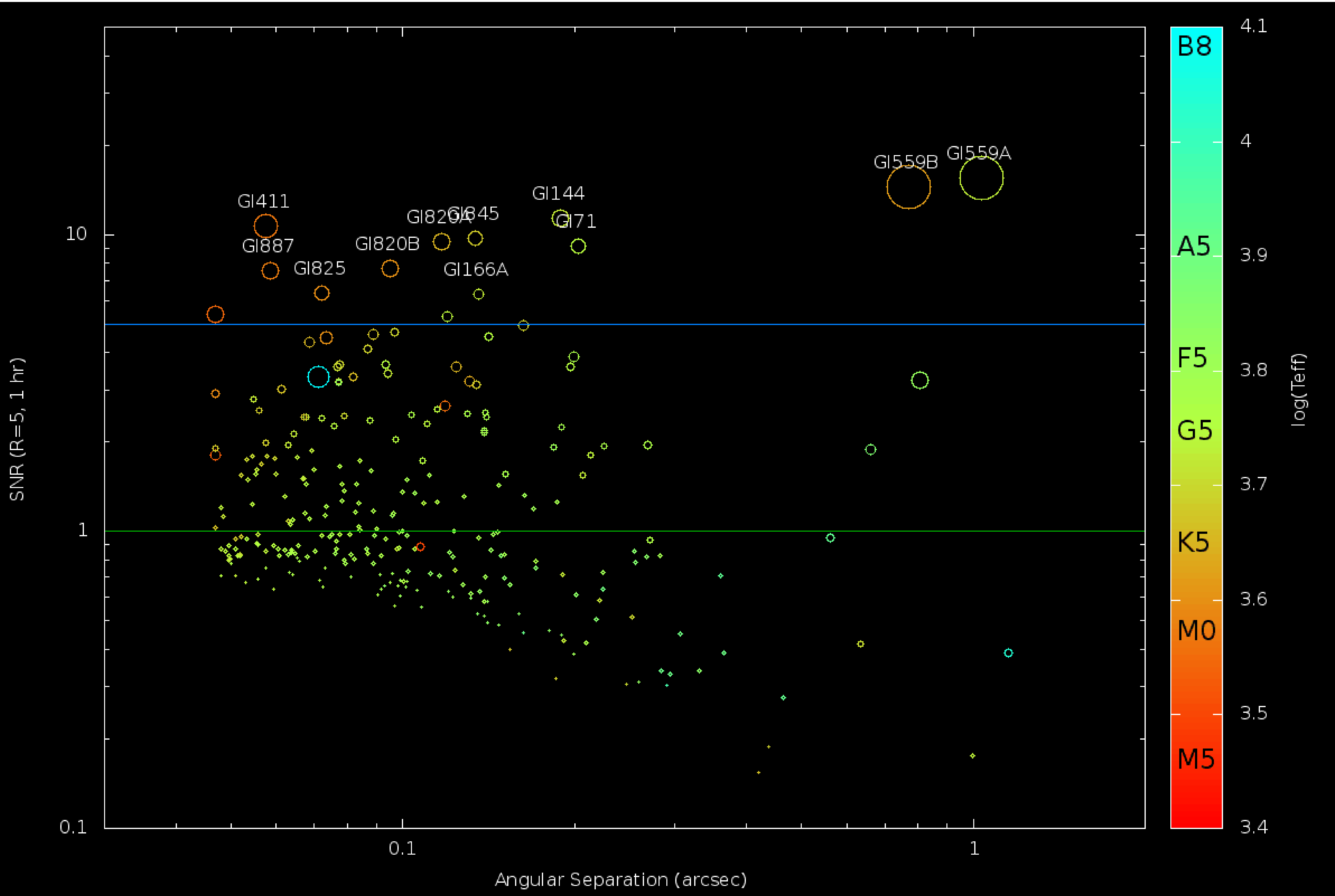
The next slides show SNR for 1hr observation at R=5 for various coronagraph configurations and raw contrast level

The size of each circle is inverse proportional to system distance. The color shows the star spectral type.

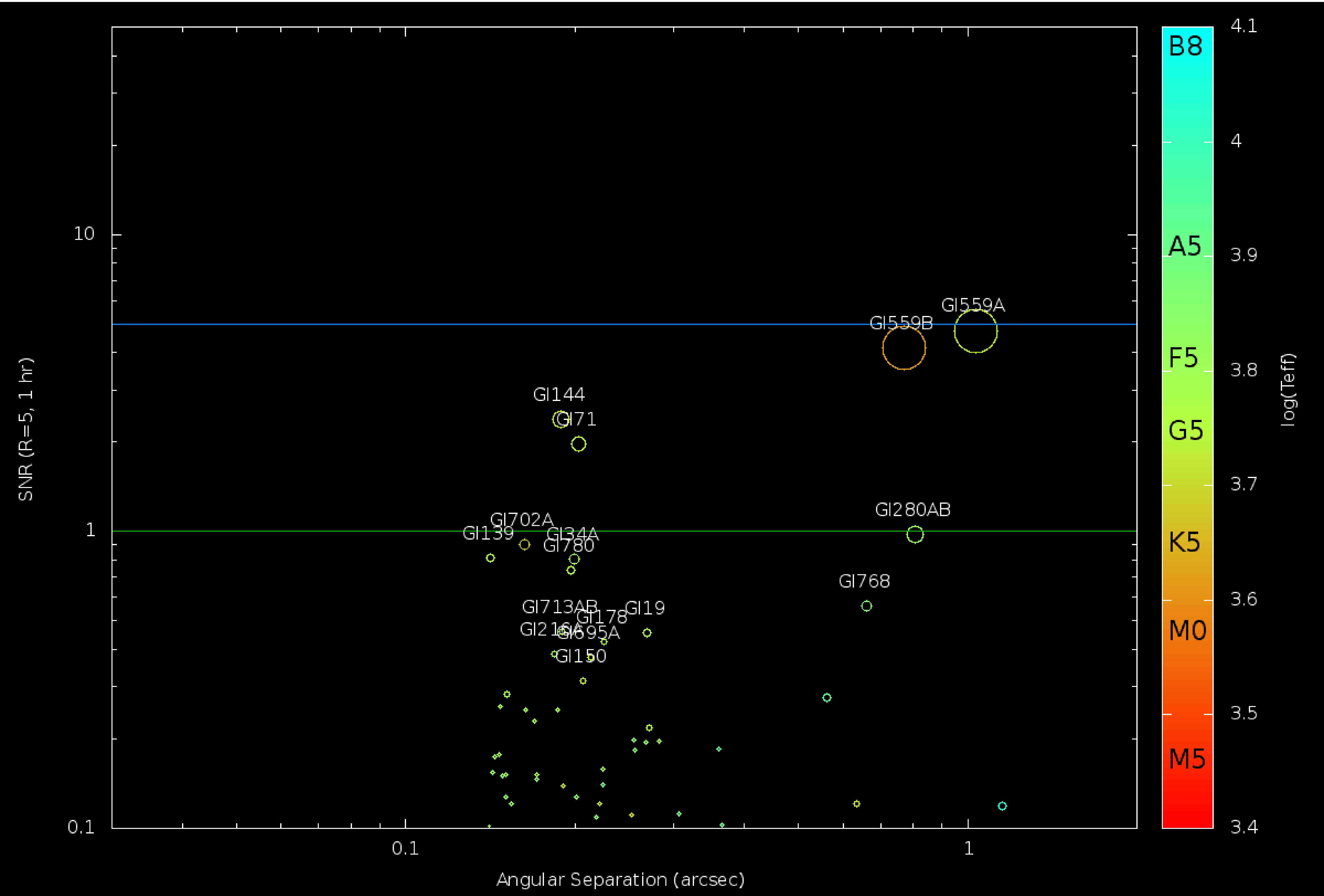
Targets above the horizontal green line (SNR = 1) can be detected and their colors identified with 1 day observation.
SNR=1, R=5 in 1hr corresponds to SNR=5 @ R=5 in 1 day.

Targets above the horizontal blue line (SNR = 5) can be characterized in 1 day.
SNR=5, R=5 in 1hr corresponds to SNR=5 @ R=120 in 1 day.

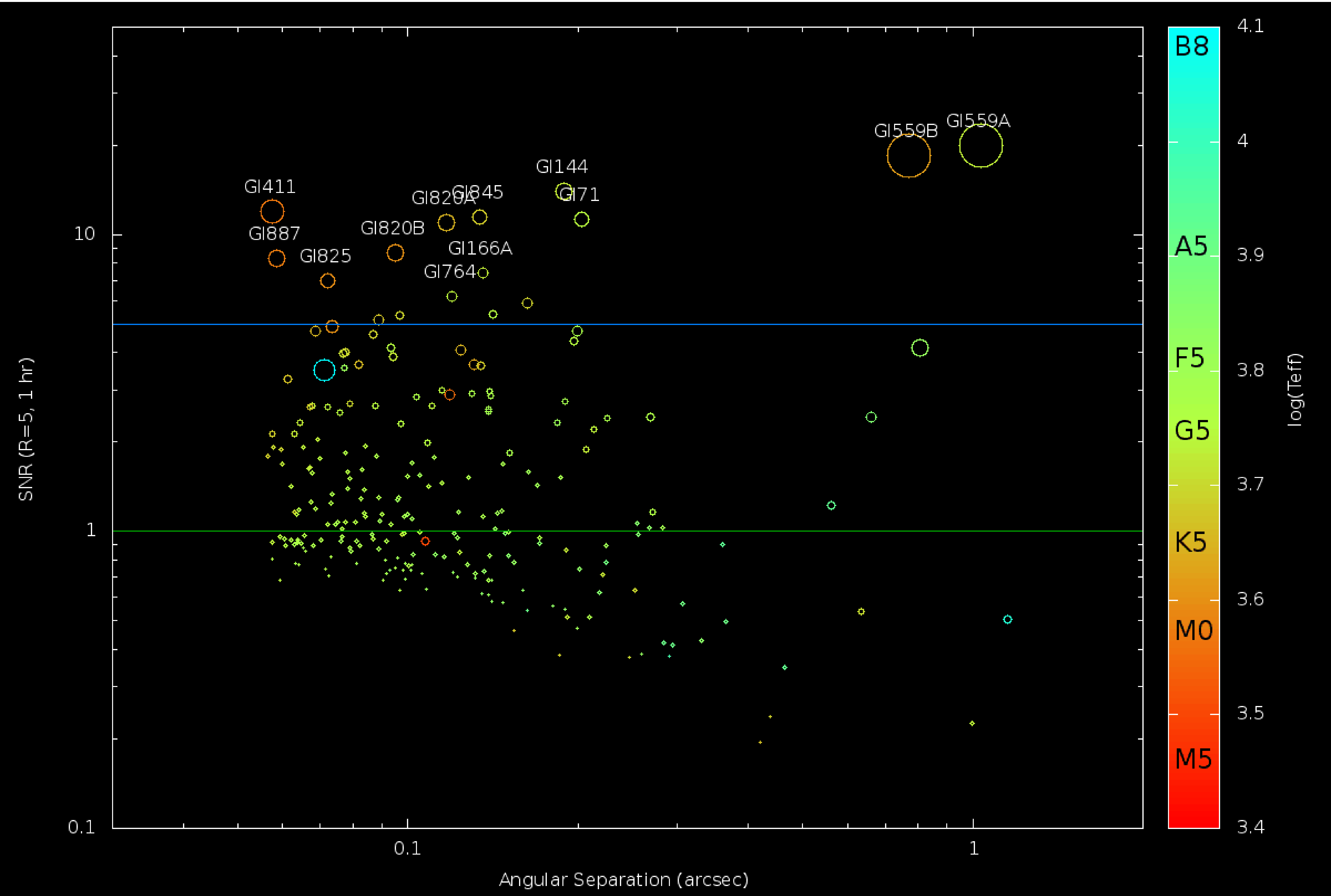
PIAACMC, 1e-9 RAW instrument contrast



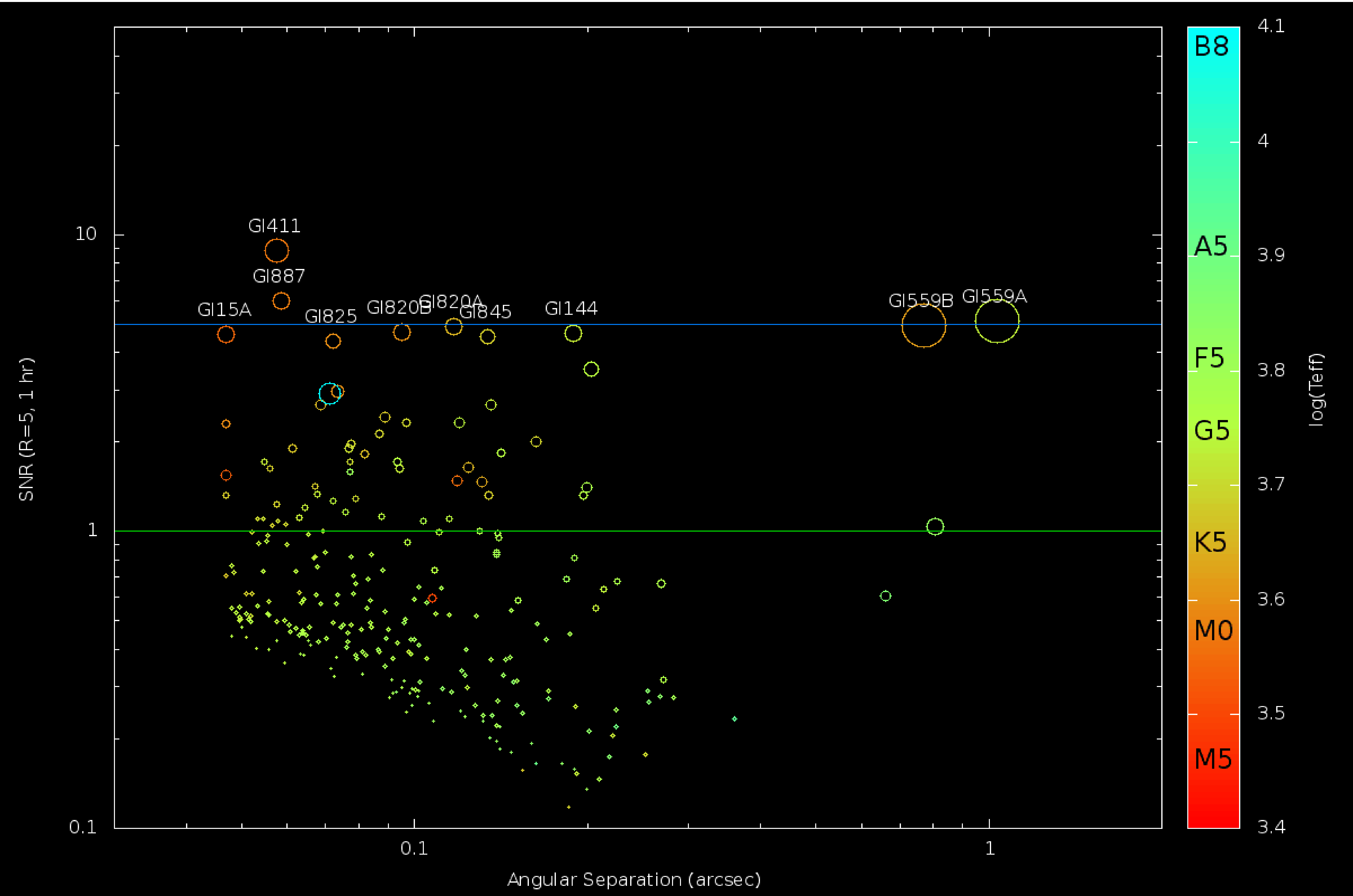
Baseline, 1e-9 RAW instrument contrast



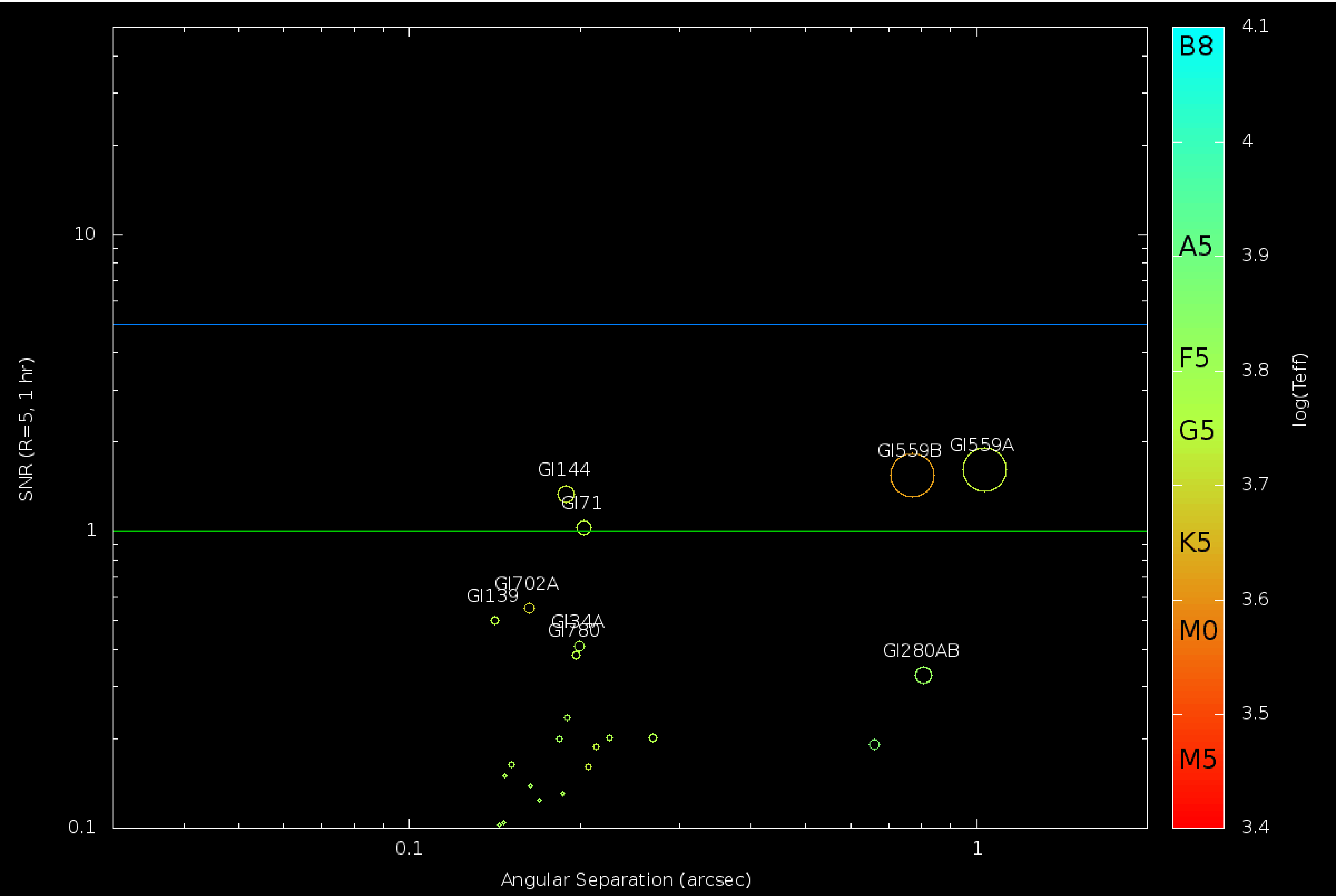
TPF-C FB1, 1e-9 RAW instrument contrast



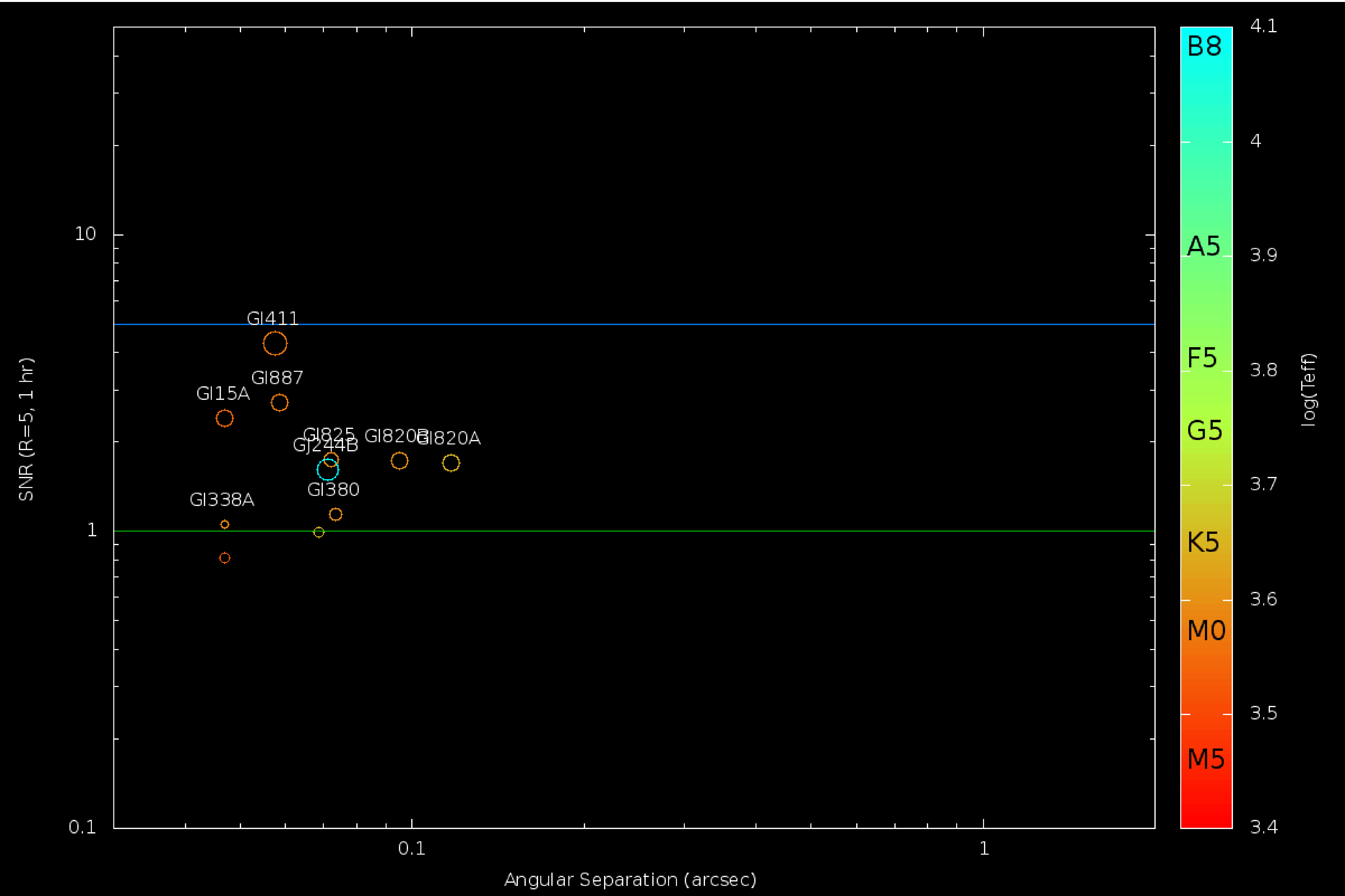
PIAACMC, 1e-8 RAW instrument contrast



Baseline, 1e-8 RAW instrument contrast



PIAACMC, 1e-7 RAW instrument contrast, 1% calibration limit



Important findings

With full efficiency coronagraph, 2.4-m telescope could potentially detect and characterize habitable Earth-like planets around ~10 to 20 stars
requires instrument contrast ~1e-7 at 1-3 l/D, and ~1e-8 at 3-30 l/D
requires calibration to ~1e-8 contrast at 1-3 l/D, and to ~1e-9 / 1e-10 at 3-30 l/D

Performance gain comes both from lower IWA (access to more planets, brighter and at more moderate contrast) and higher efficiency
For planets that are outside the IWA of both baseline and PIAACMC, the PIAACMC is 50x more efficient (same SNR with 50x less exposure time) than baseline

The PIAACMC, even if working at only 1e-7 raw contrast would detect more Earth-like planets (around 9 stars) than the baseline coronagraph would if working at 1e-9 contrast (around 3 stars). Note that the stars sampled are different (no overlap in target list).

PIAACMC on 2.4m telescope: scientific return is potentially comparable to TPFC-FB1, on a sample ~1/2 the size

Important findings

BUT, more work/study is needed:

Accurately take into account stellar angular size for each target
Establish requirements for telescope stability
Design work and lab testing for PIAACMC, with special attention to chromaticity
Model exozodi & its impact

What will tell us if a high efficiency coronagraph option is feasible ?

(1) Lab raw contrast demonstration needs to reach at least ~1e-7 at 1-3 l/D, and ~1e-8 at 3-30 l/D in polychromatic light

(2) Need to demonstrate that telescope stability is sufficiently good to reach and maintain this contrast

(3) Need to understand and demonstrate detection contrast

Coronagraph choice and contrast
(we need to become quantitative...)

Low IWA coronagraph comes with high sensitivity to low order aberrations.
In a passive system, it is considerably harder to maintain high contrast at small IWA than at large angular separation.

However:

Small IWA coronagraph does not require as good a contrast as a large IWA system.
Raw contrast can be relaxed by >100x by adopting a high efficiency coronagraph (compare slides 15 and 19)
PIAACMC can do R~100 spectroscopy of Earth analogs around a few stars in 1 day with a 1e-8 raw instrumental contrast (slide 17)

In an active system, efficient coronagraph means efficient wavefront sensing and control → telescope stability can be relaxed
mid and high spatial frequencies: PIAACMC is 50x more efficient than baseline for detecting faint sources (background-limited regime), and 10x more efficient than baseline for bright sources → at the same contrast level, telescope wavefront drift can be 10x to 50x faster if a high efficiency coronagraph is used.
low order aberrations can be sensed efficiently using all starlight with a low-order WFS