Considerations Between Coronagraph Robustness and Telescope Stability

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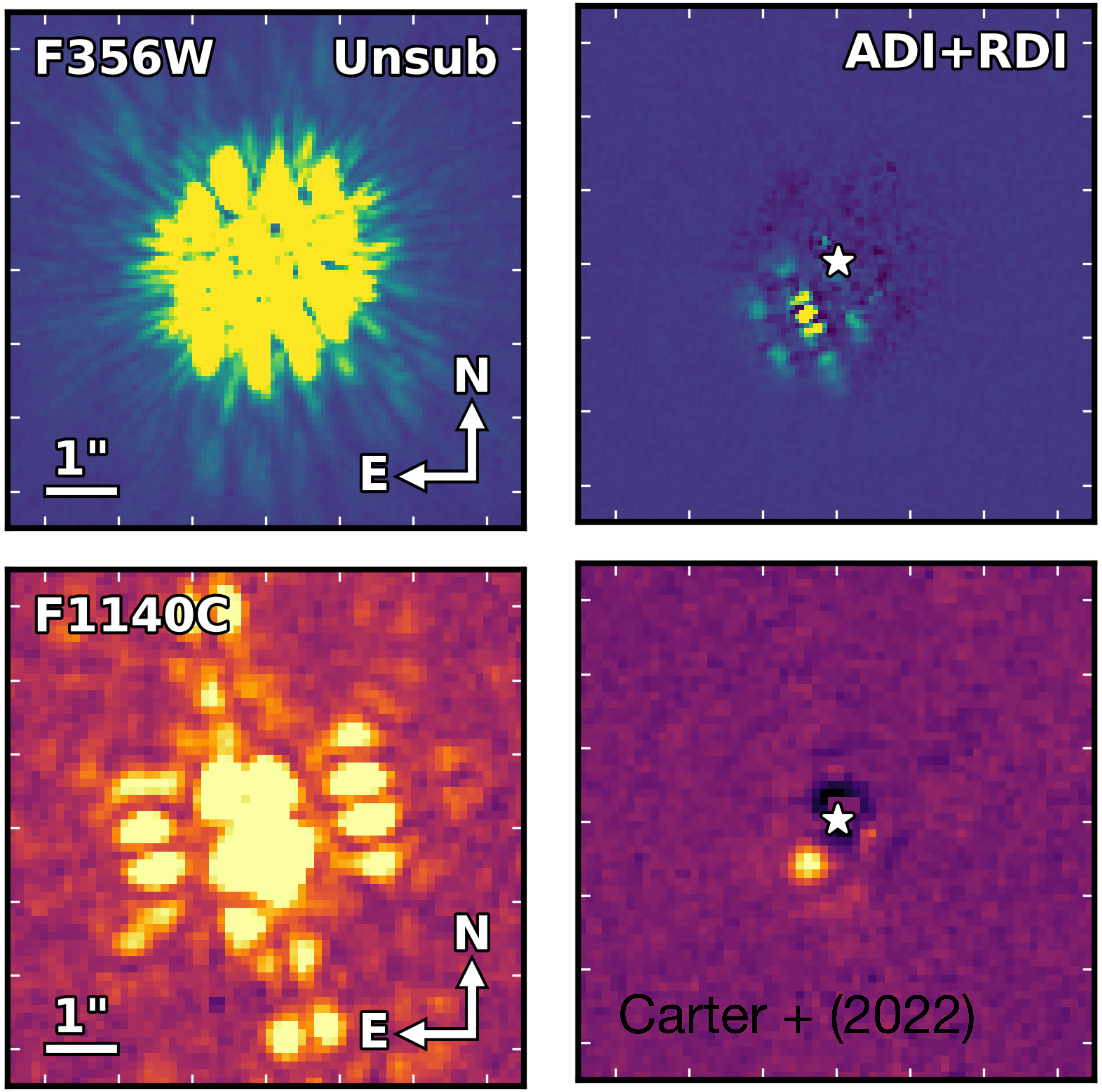
Example of JWST coronagraphs

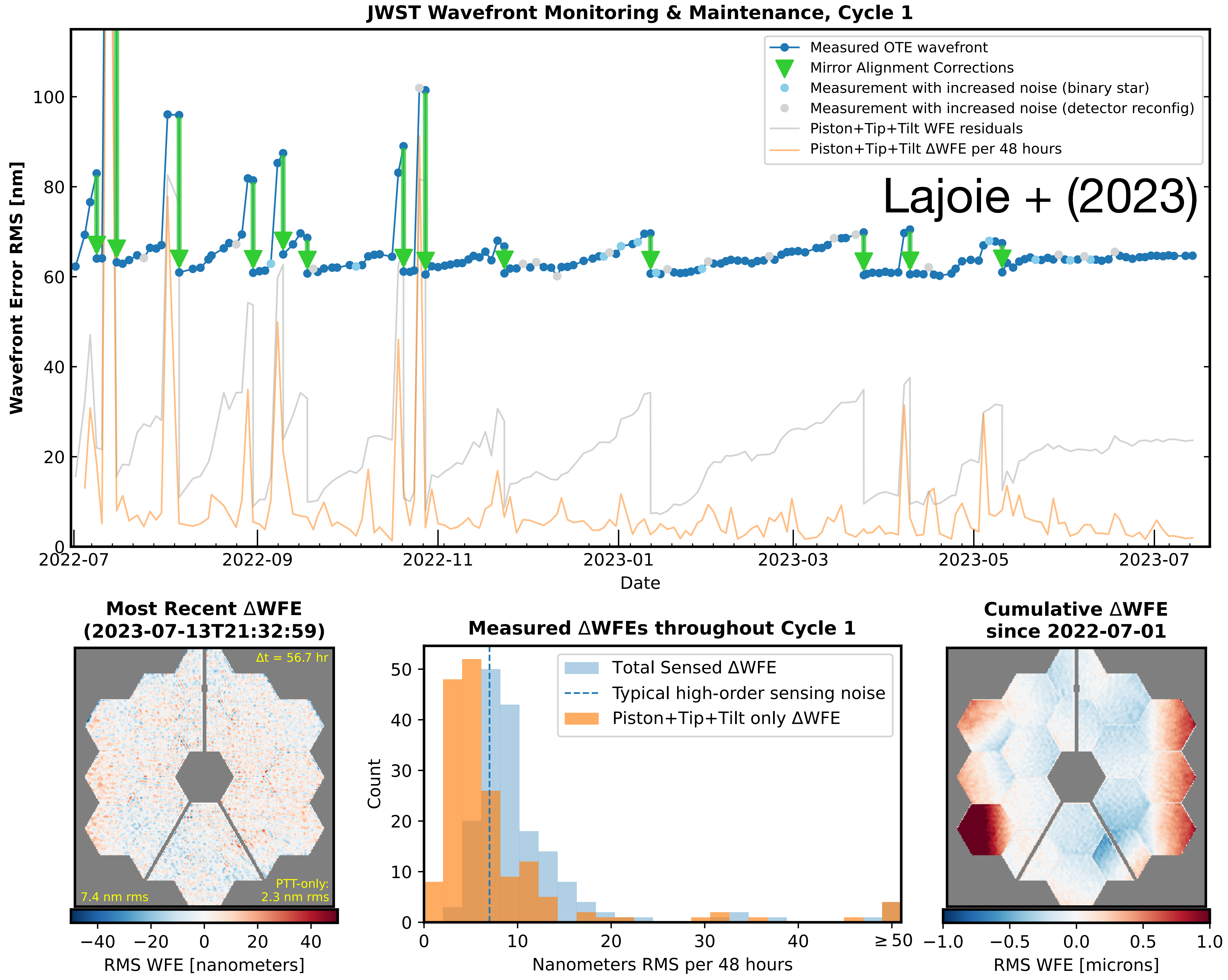
NIRCam and MIRI observe exo solar systems with similar orbital scales

At 11 microns coronagraph needs to operate “closer” in units of wavelength/aperture.

2-4 microns: robust coronagraph.

10-15 microns: less robust coronagraph.

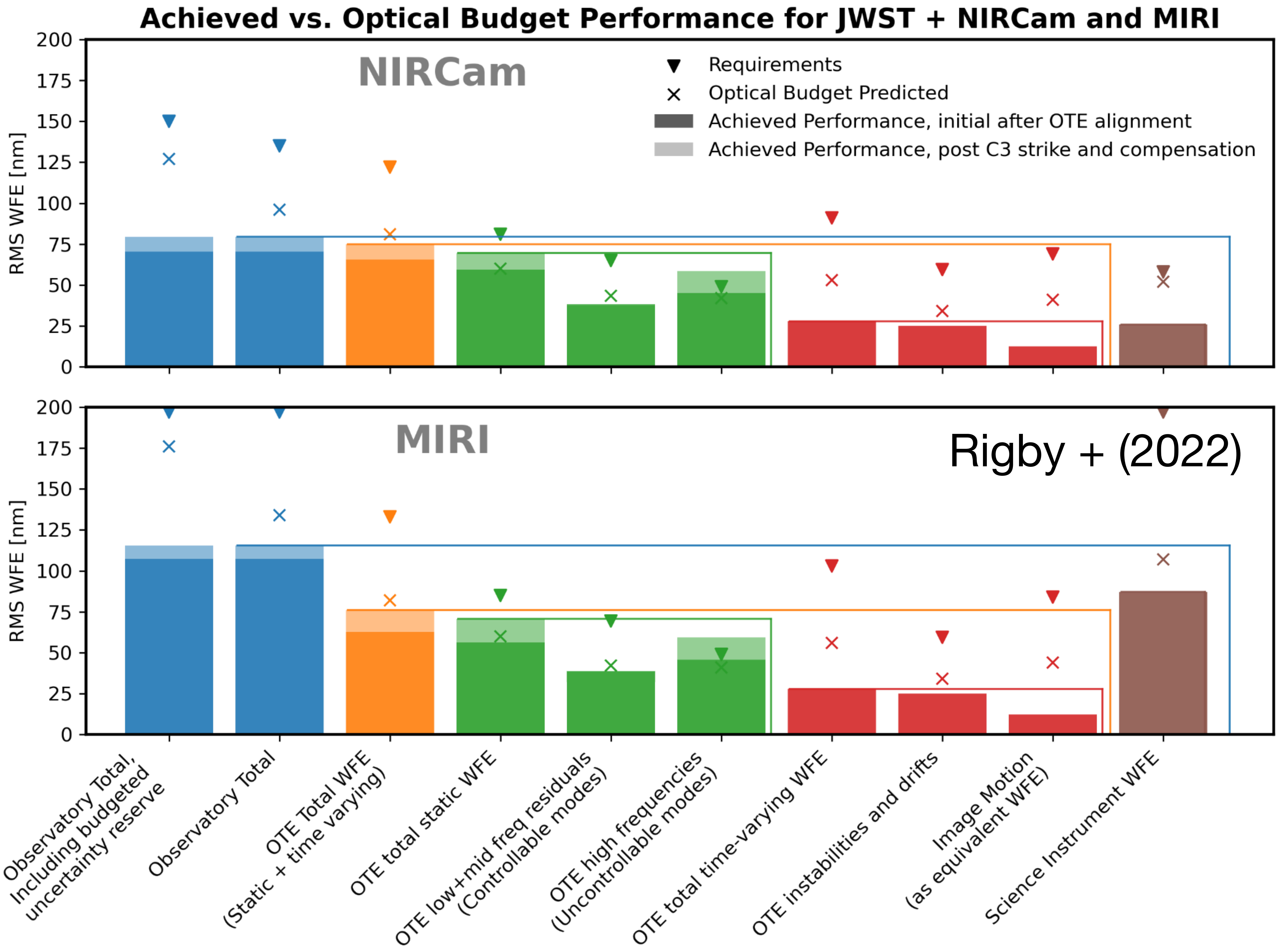




JWST is more stable than requirements.

Frequency and amplitude of tilt events getting smaller.

Line of sight jitter more than 5 times better than requirements.



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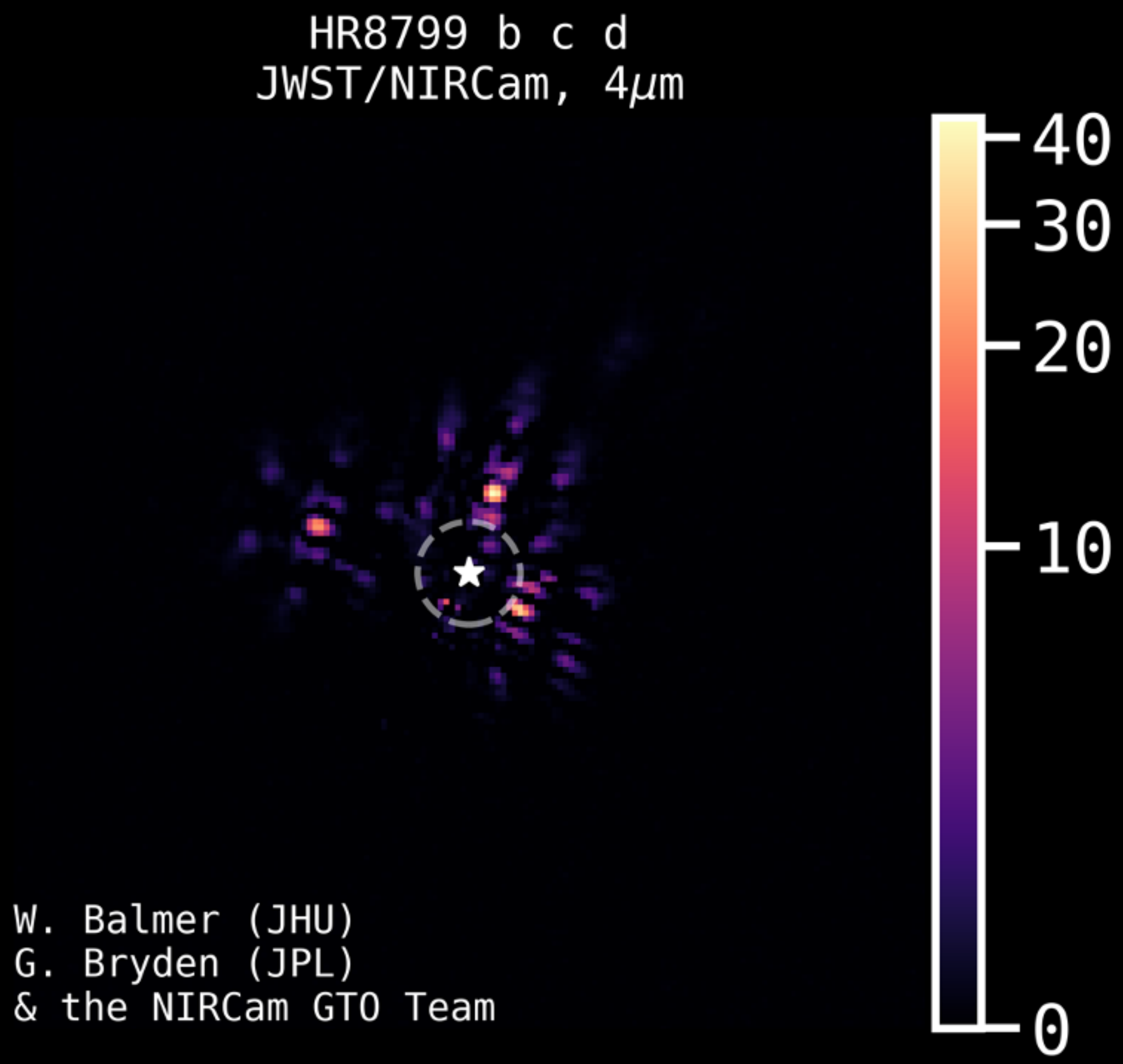
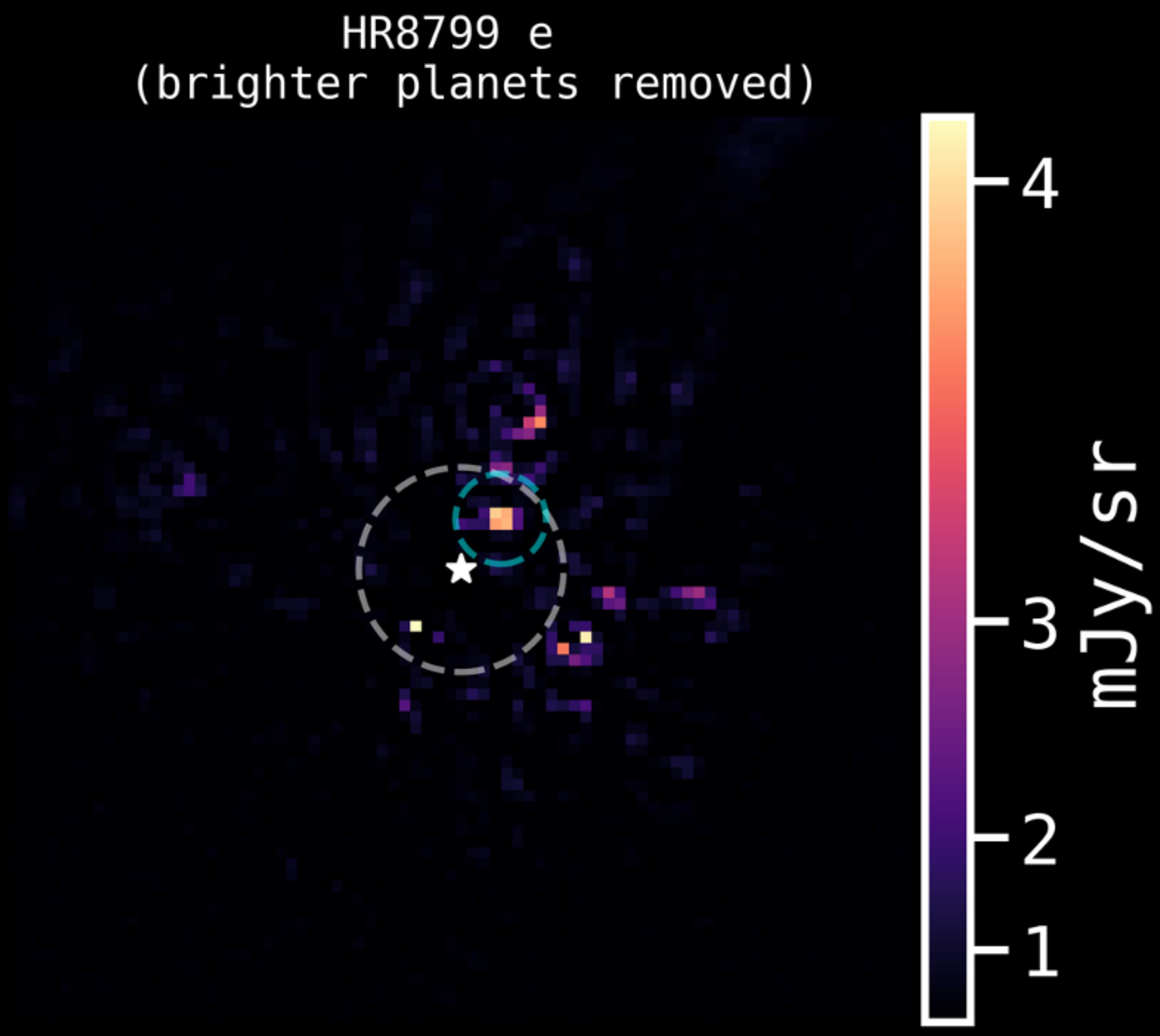
Frequency and amplitude of tilt events getting smaller.

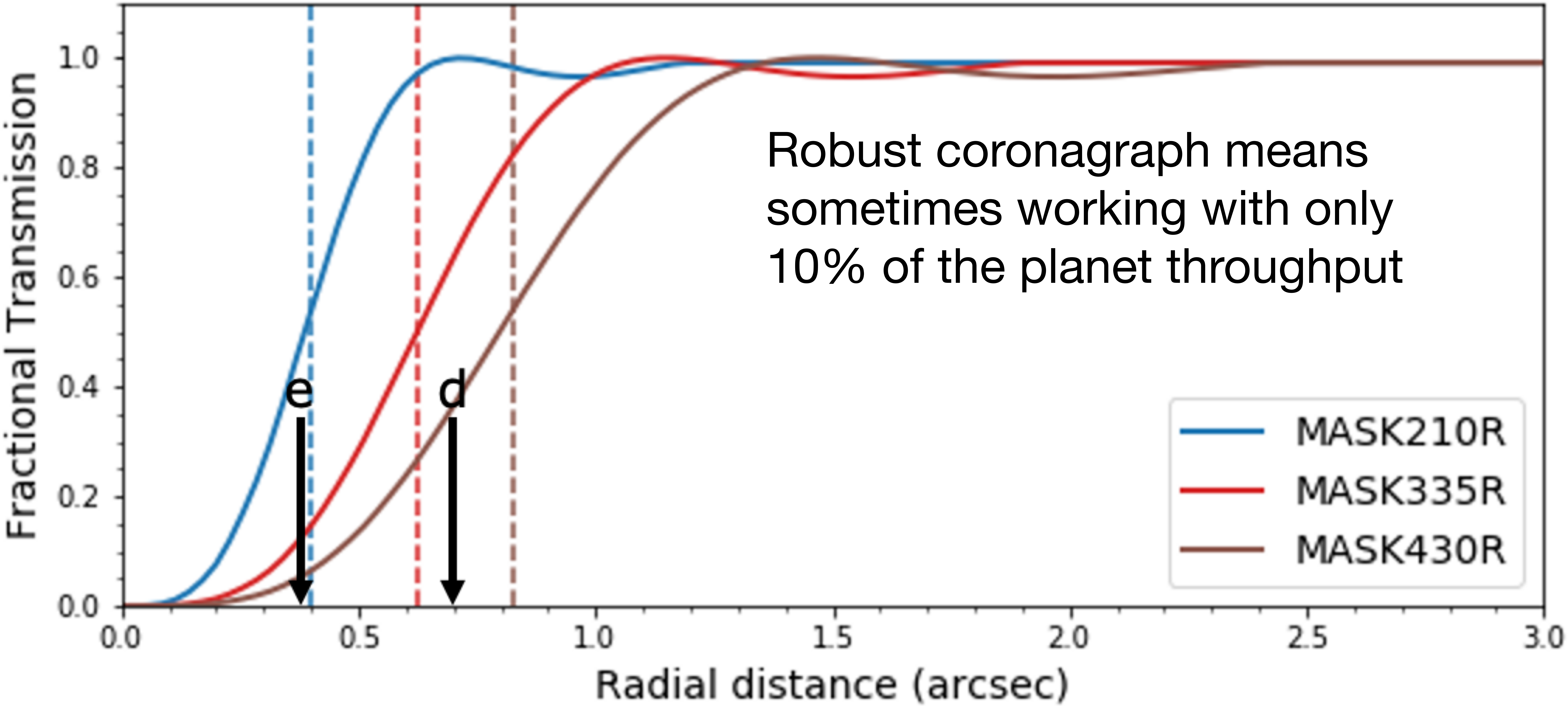
Line of sight jitter more than 5 times better than requirements.

What does it means for exoplanet observations?





JWST GTO 1194



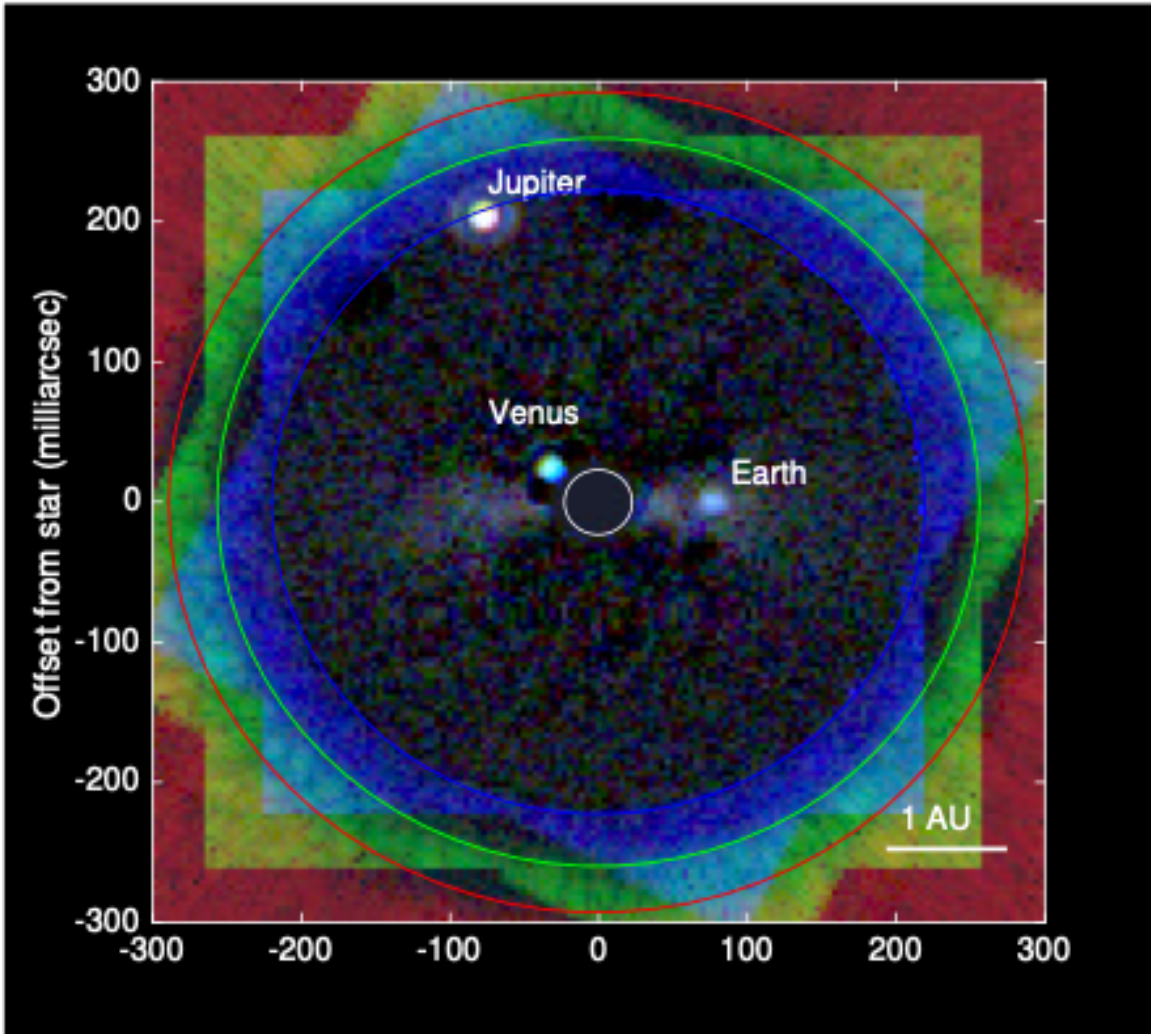
With a more aggressive coronagraph - had we known about superb stability- more planets might be accessible.

Broken power law
Cumming et al. (2008)
Fernandes et al. (2019)
Wittenmyer et al. (2020)
Δln(a) = 0.63
Fulton + (2021)
N_P / 100 stars / Δln(a) (30 - 6000 M⊕)
Semi-major axis (au)
0.1
0.3
1.0
3.0
10.0
30.0
0
2
4
6
8
10
12
14
16
Nielsen et al. (2019)
this work
Bowler et al. (2015)
Posterior Probability Density
Number of planets per 100 stars between 5-13 MJ and 10-100 au
0.00
0.05
0.10
0.15
0.20
0.0
2.5
5.0
7.5
10.0
12.5
15.0

Hab Worlds will be the first mission for which interface between coronagraph and observatory will be key to meet science requirements.

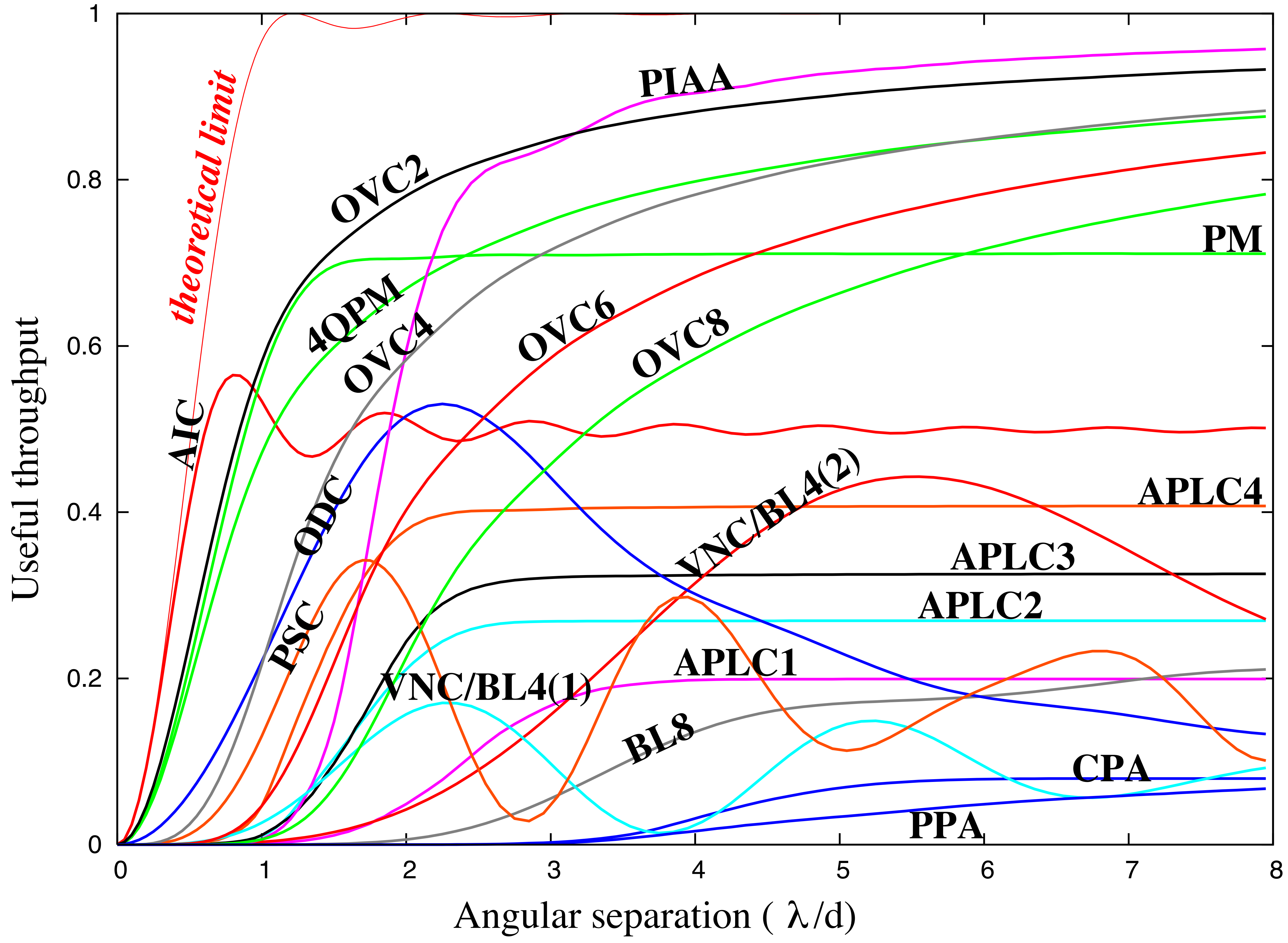
Hab Worlds will be the second mission to fly Deformable Mirrors with a high contrast coronagraph (after Roman). Those mirrors can be used to maintain exoplanet detectability while telescope “alignment” varies.

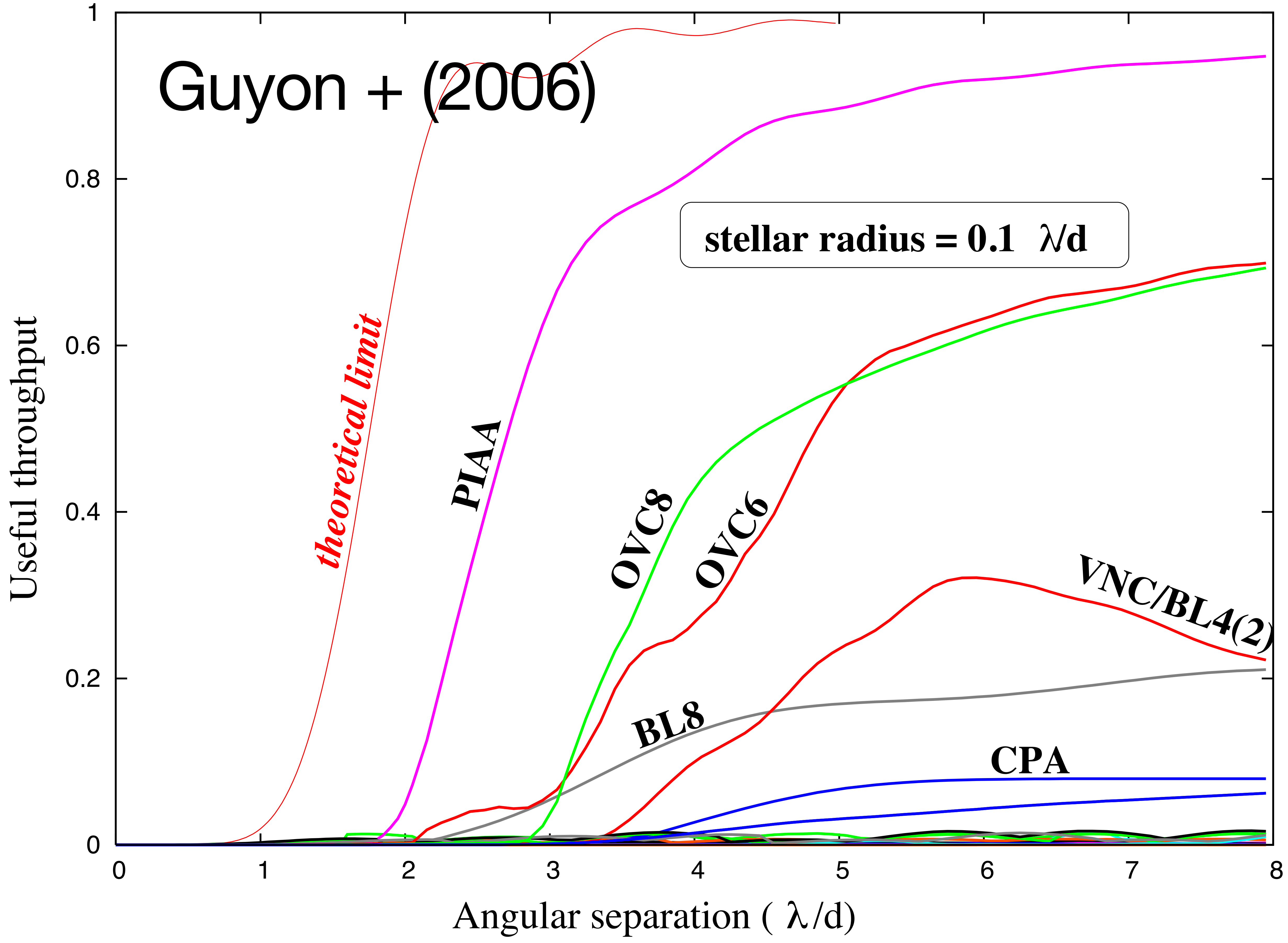
We need to formalize this interplay between observatory stability, coronagraph masks and Deformable Mirrors.



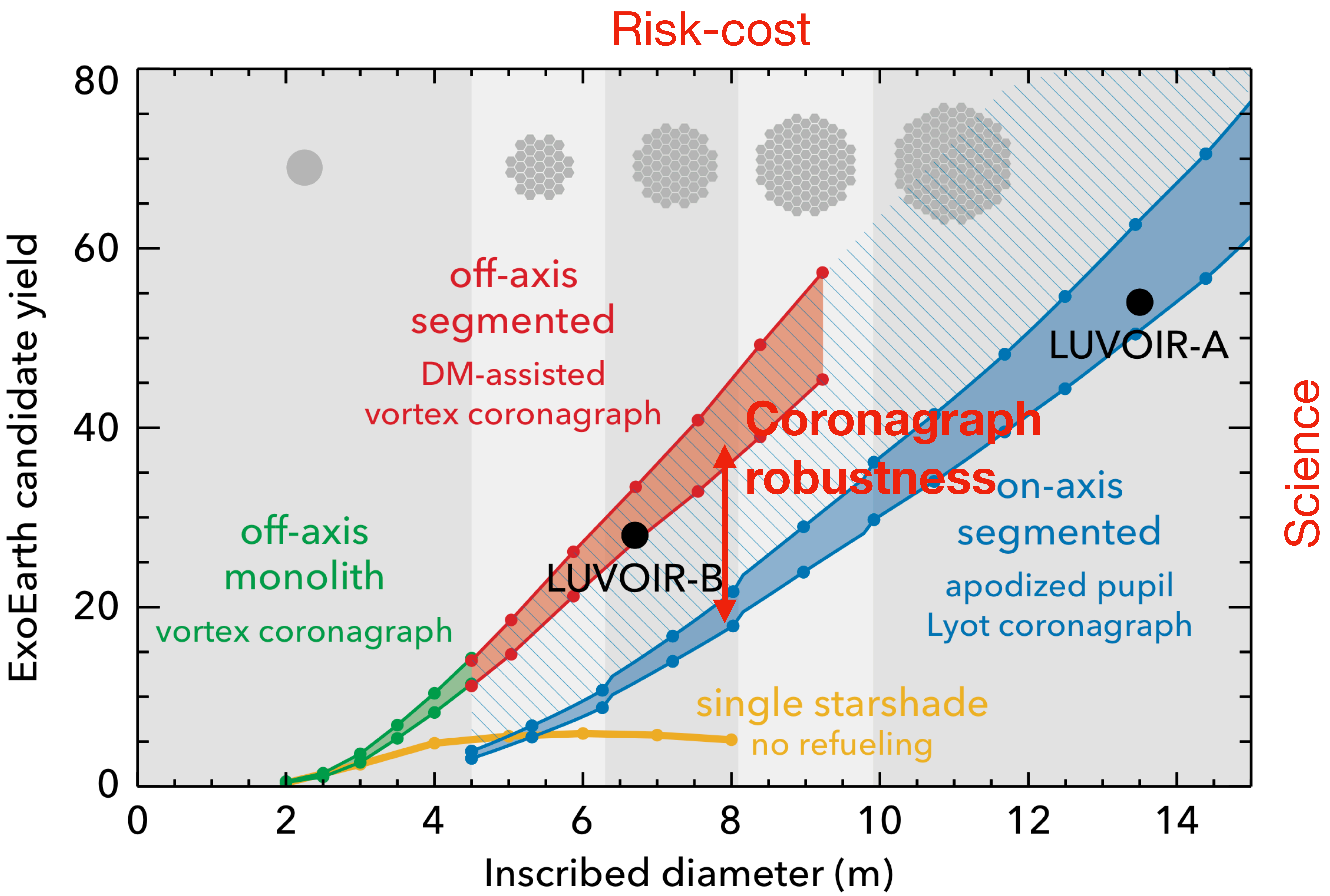
An example more relevant to Hab Worlds.

Sensitivity to exoplanets decreases once we take into account stellar angular size

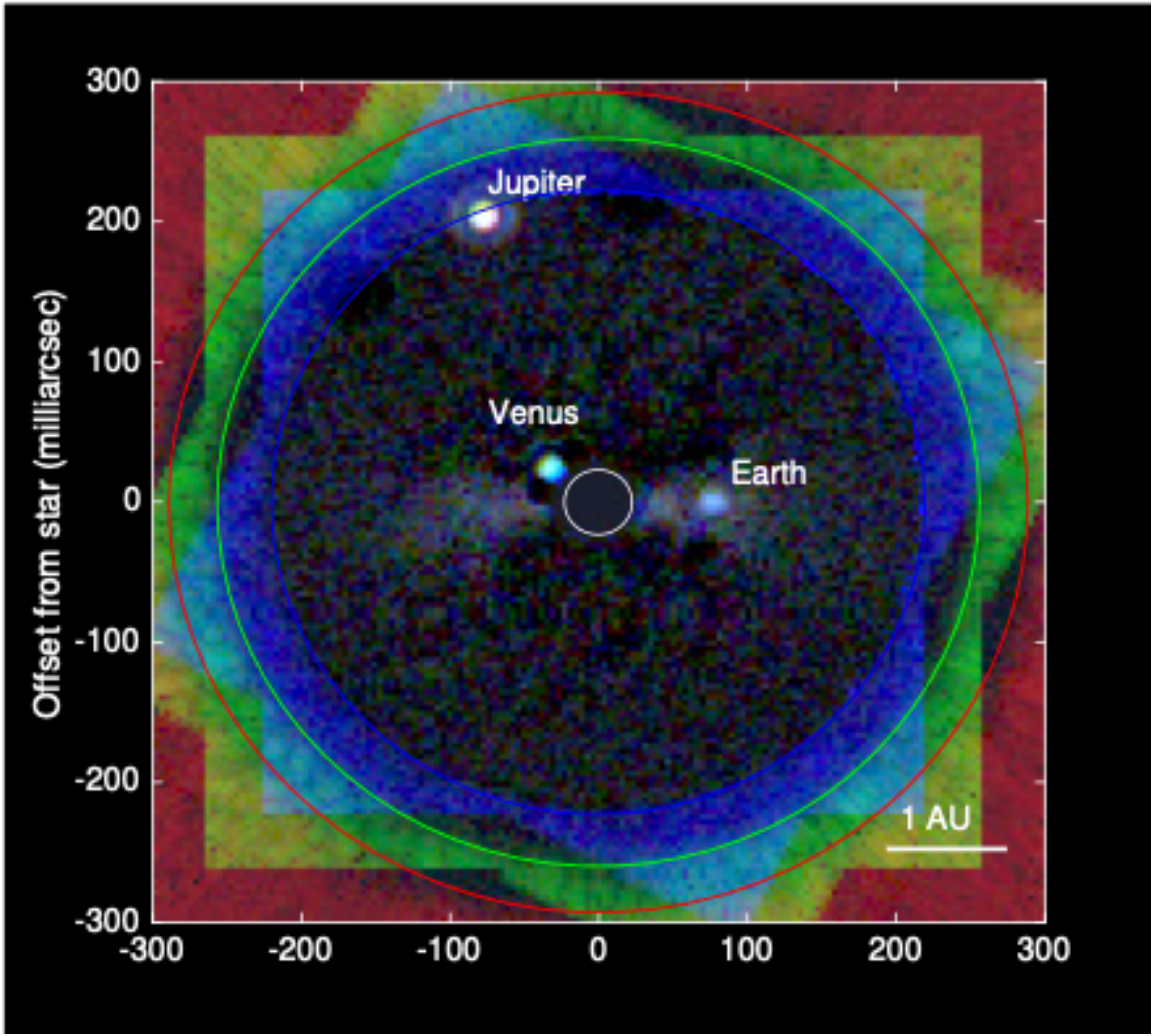




The number of options to pick from also decreases!

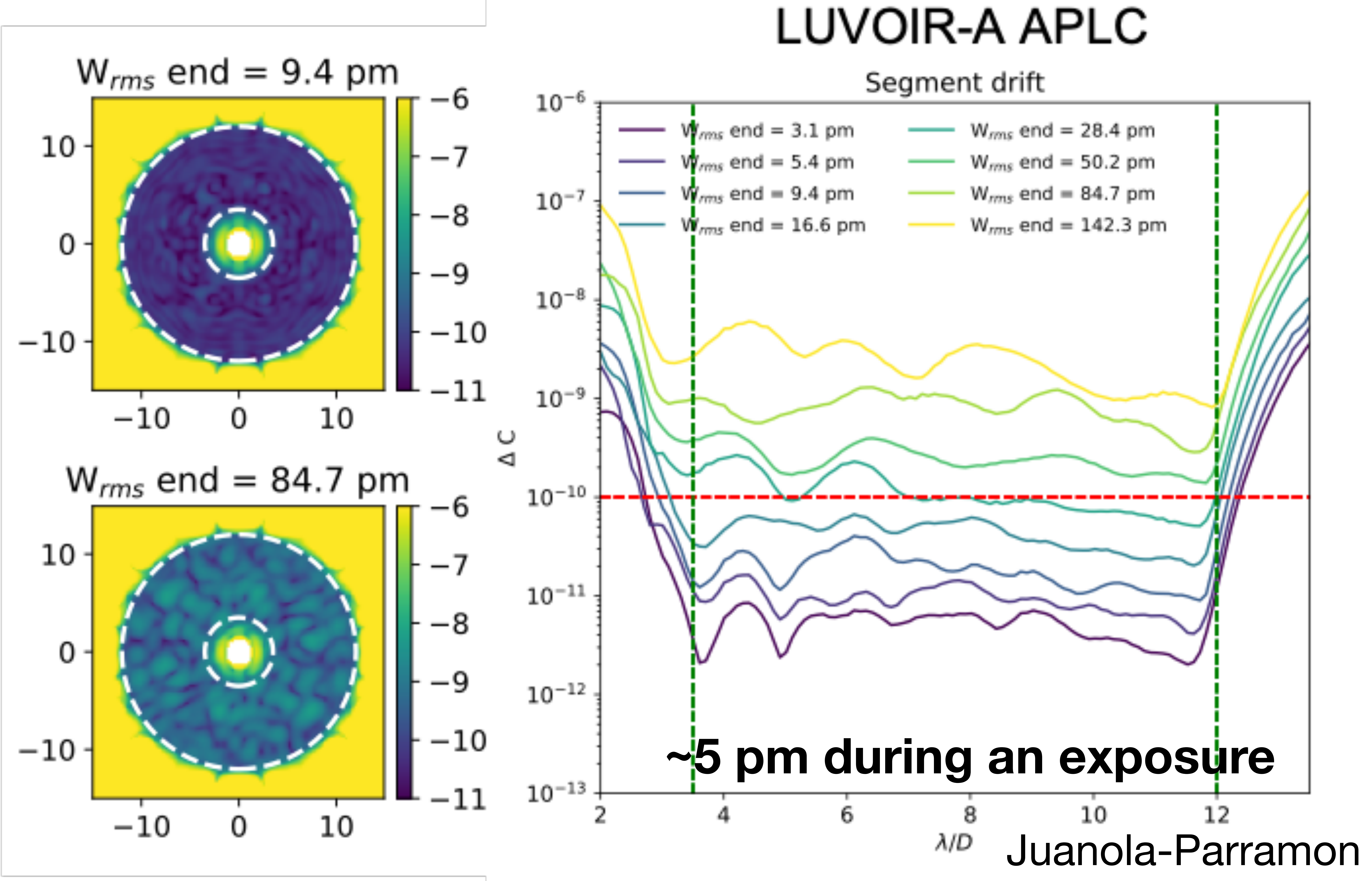


Risk-cost
Science
ExoEarth candidate yield
Inscribed diameter (m)
0
20
40
60
80
0
2
4
6
8
10
12
14
off-axis
segmented
DM-assisted
vortex coronagraph
off-axis
monolith
vortex coronagraph
LUVOIR-B
LUVOIR-A
Coronagraph
robustness
on-axis
segmented
apodized pupil
Lyot coronagraph
single starshade
no refueling



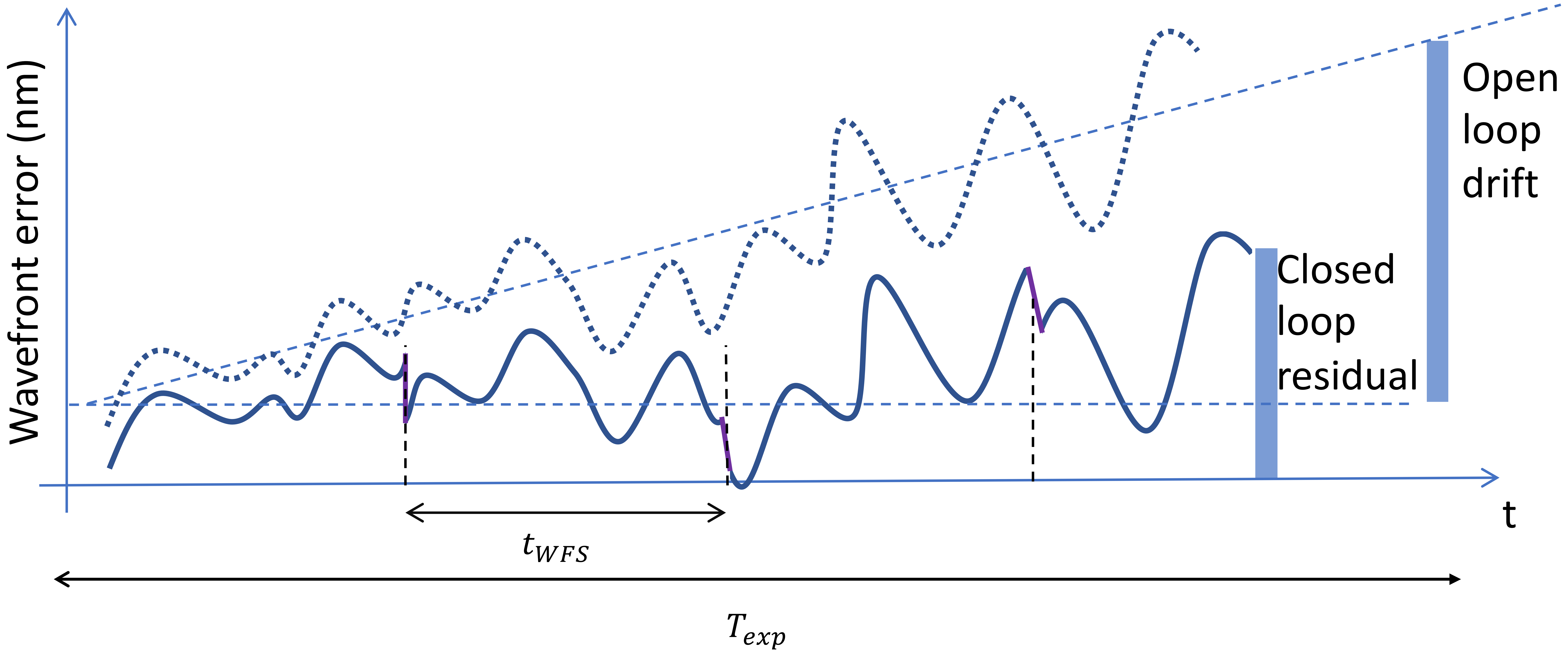
So how do we go about this?

Change in contrast due to thermal drifts



Juanola-Parramon + (2019)

Difference between Open loop and closed loop.



Shorten the time scales of wavefront drifts from a science exposure time (~10 hours) to a wavefront sensing exposure time (minutes, seconds, milliseconds?).

Scaling laws for stability requirements in open loop

$$d_{OL} \sim \frac{1}{(S/N)_P^3} \frac{\dot{N}_S F_R^{3/2}}{2\alpha^3 \Lambda}$$

Stellar flux

Planet to star flux ratio

Desired planet SNR

Raw contrast

Coronagraph robustness

Pueyo + (2022), Pogoreluyk +(2022)

Scaling laws for stability requirements in closed loop

Planet to star flux ratio

Stellar flux

$$d_{CL} \sim \frac{1}{(S/N)_P^2} \frac{\dot{N}_S F_R^{3/2}}{2\beta^2 \alpha \Lambda^3}.$$

Desired planet SNR

Coronagraph robustness

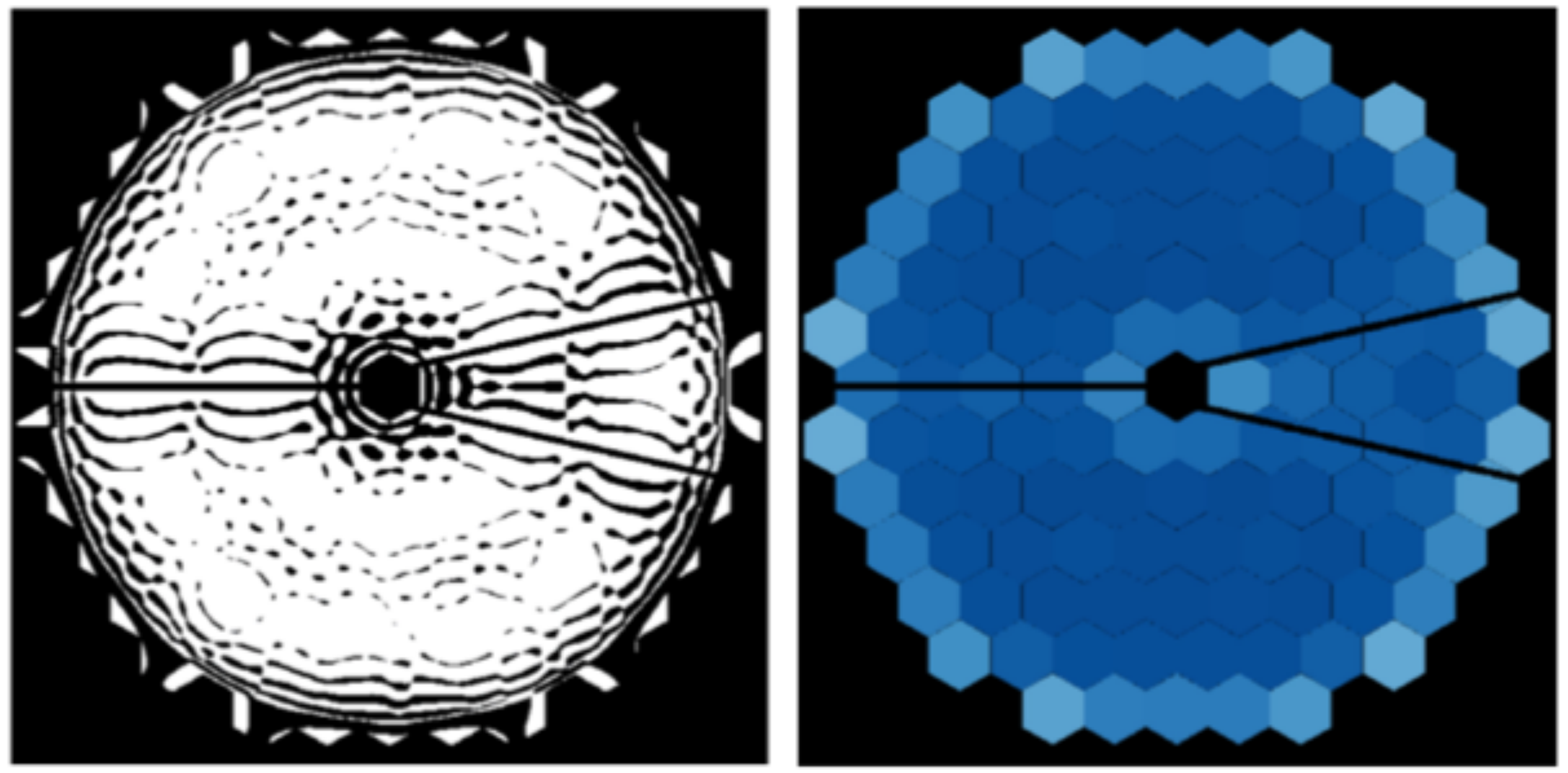
Sensing efficiency

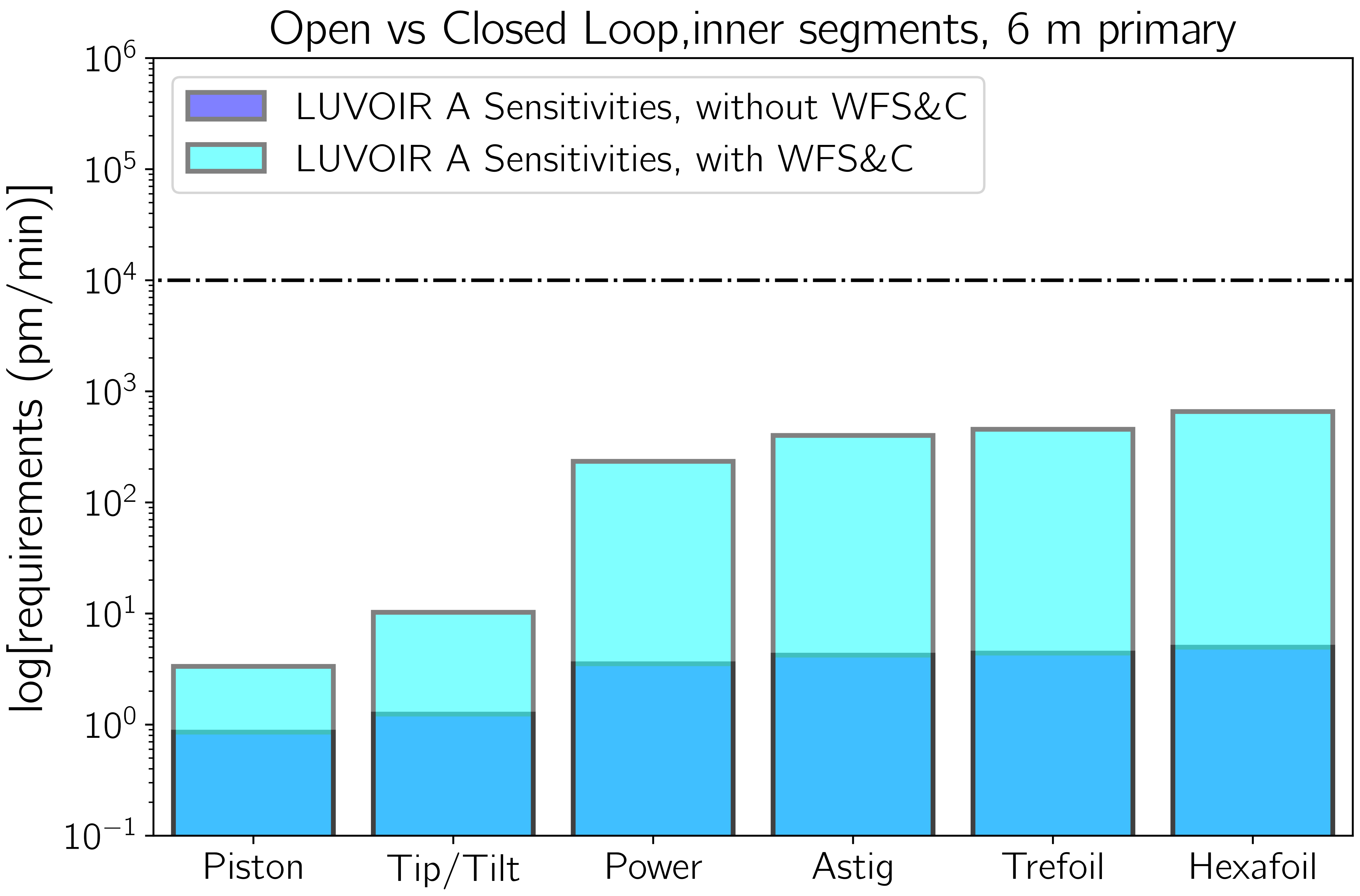
Raw contrast

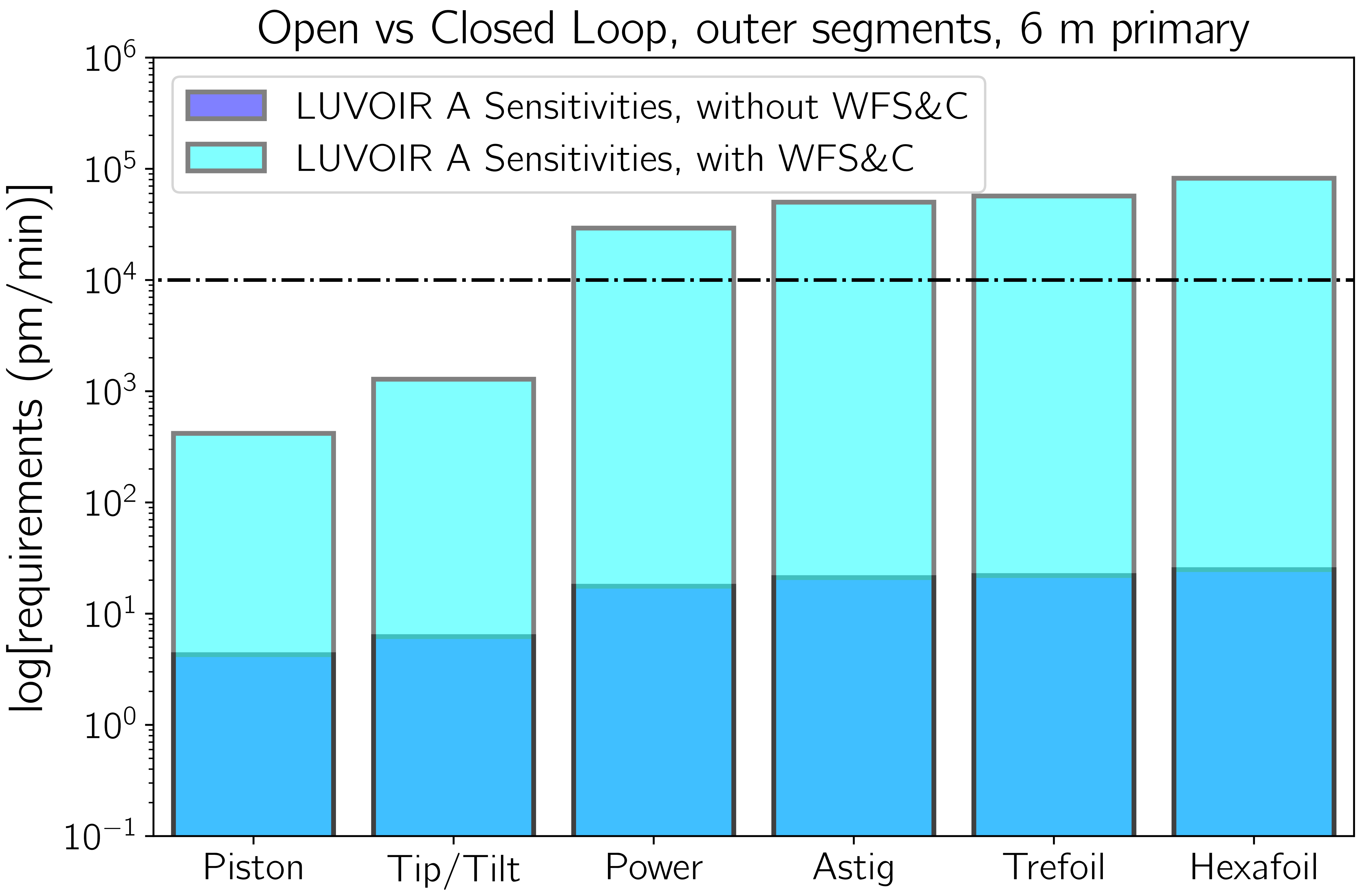
Pueyo + (2022), Pogoreluyk +(2022)

Results with a ~6 m segmented aperture

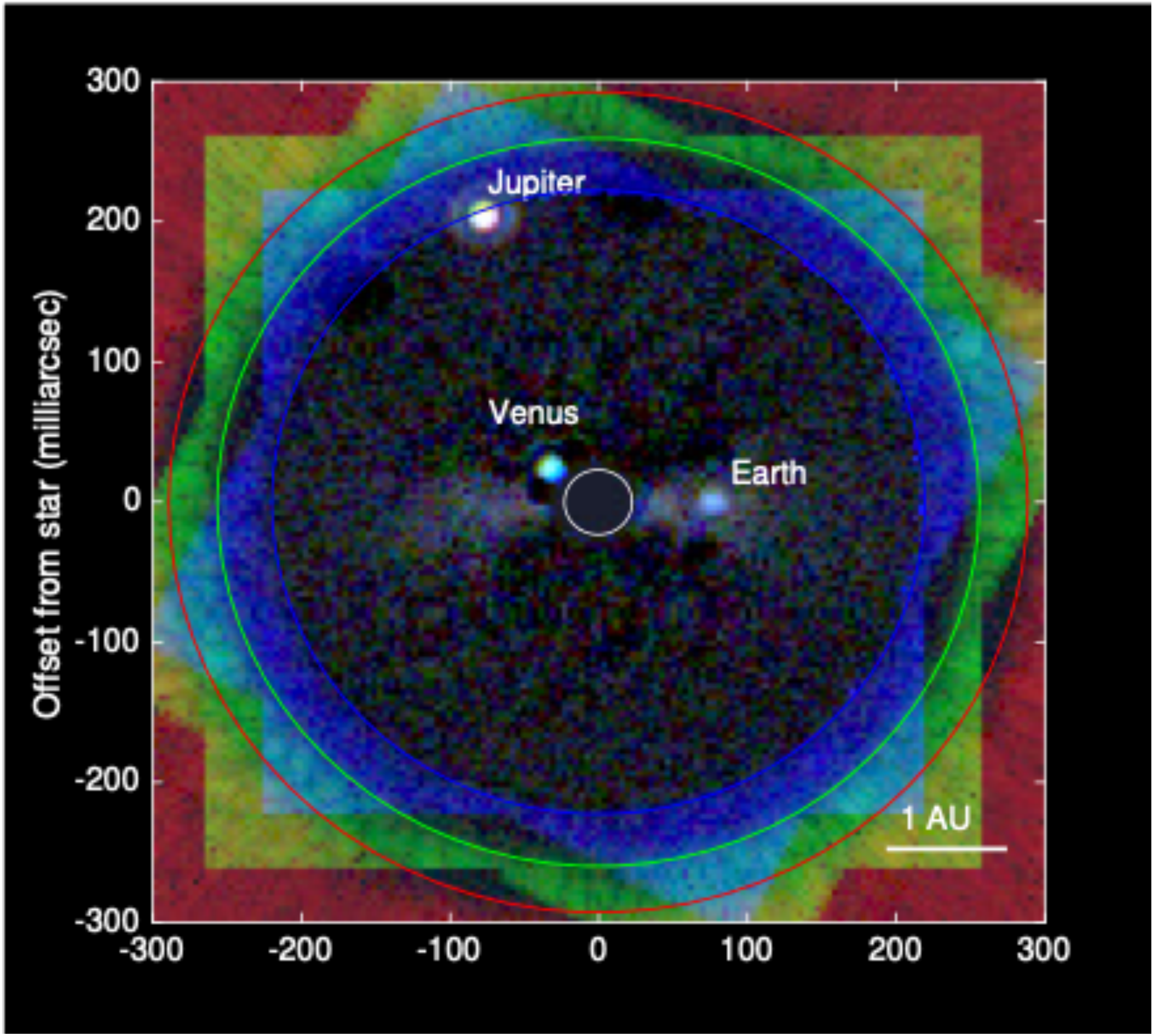
Requirements are much more relaxed in closed-loop for robust segments





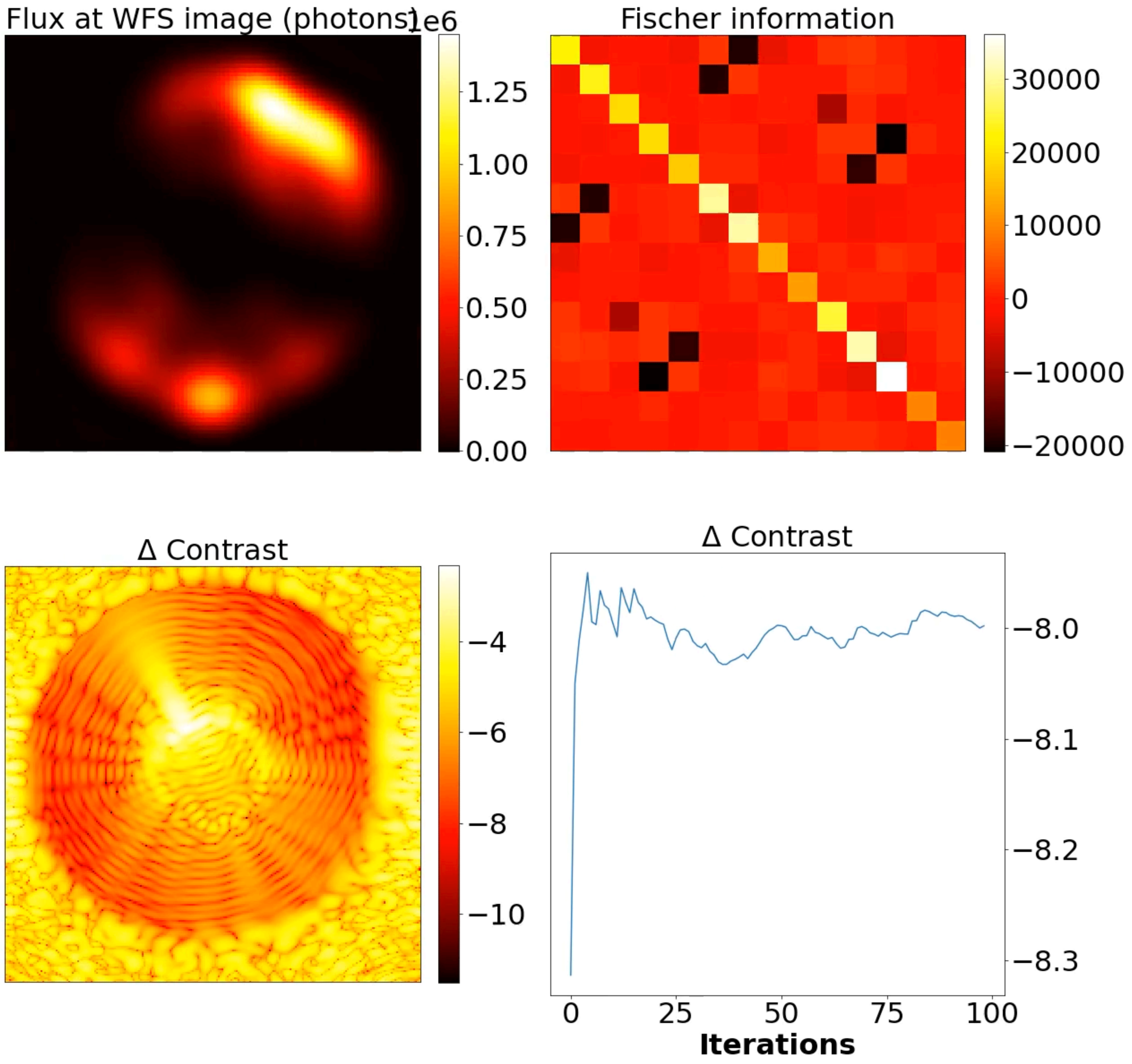


Pueyo + (2022), Laginja + (2022), Pogoreluyk +(2022)

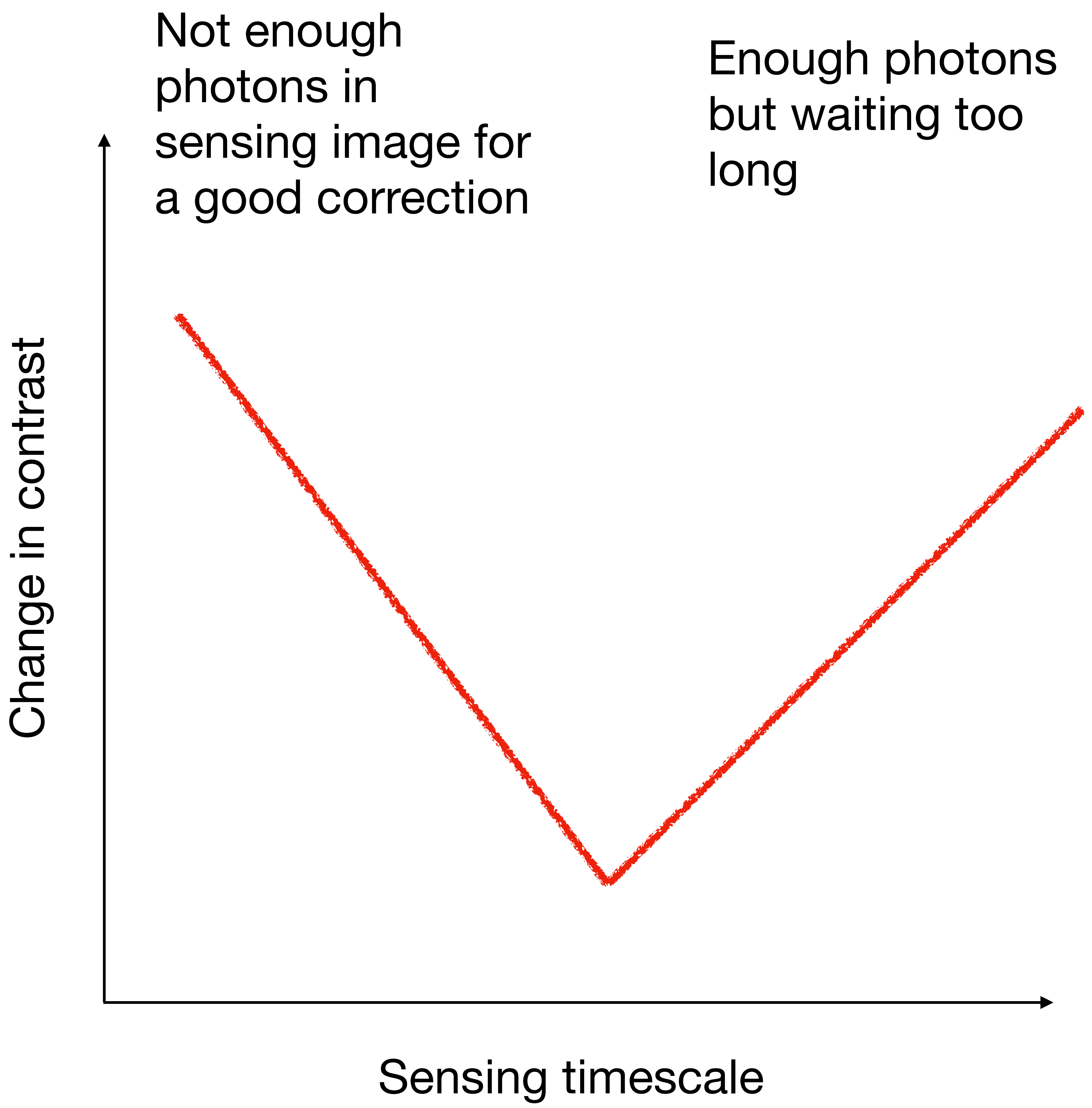


Devil is in the details… how do we get rid of the "~"?

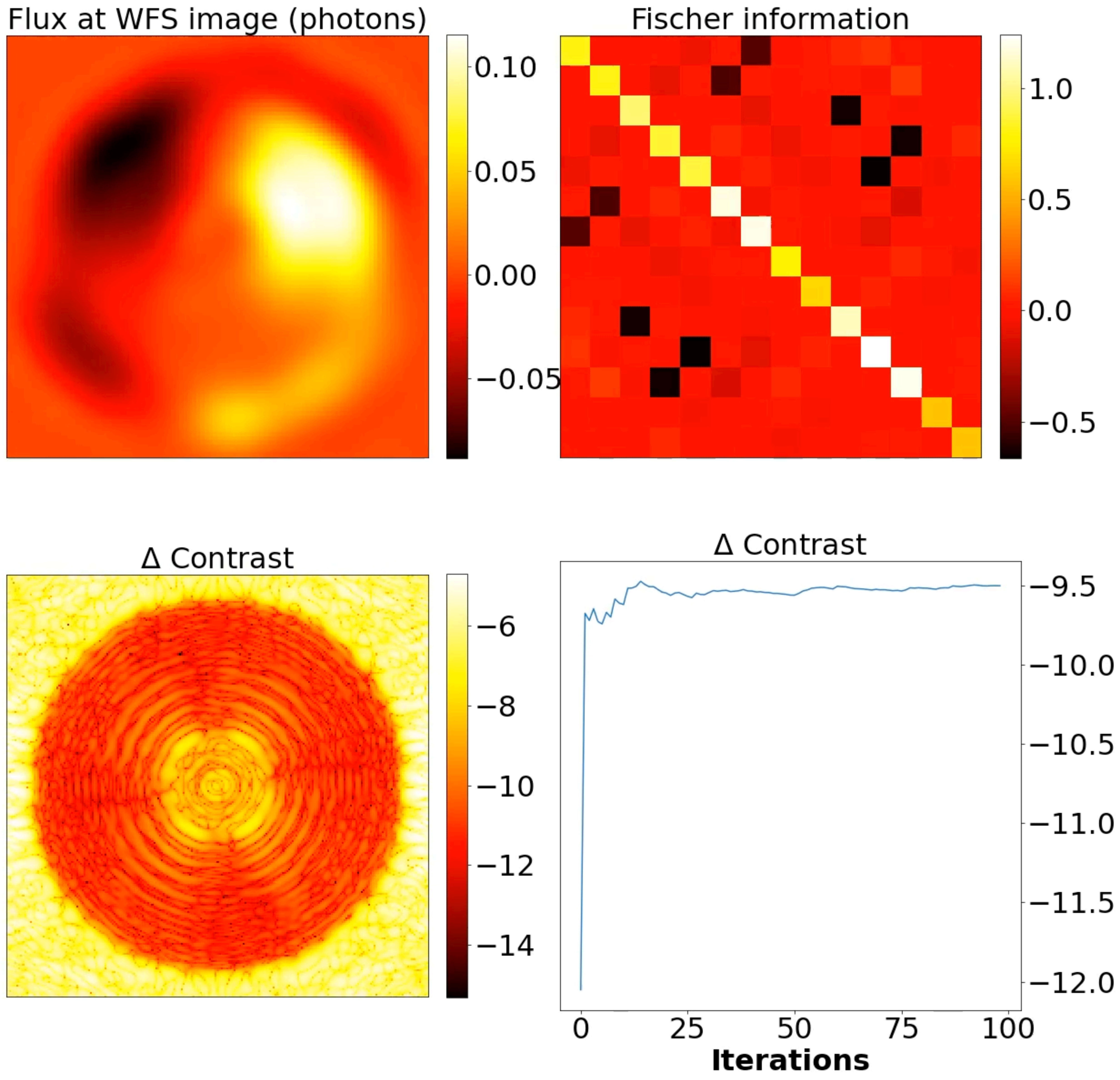
Same calculation with realistic simulations



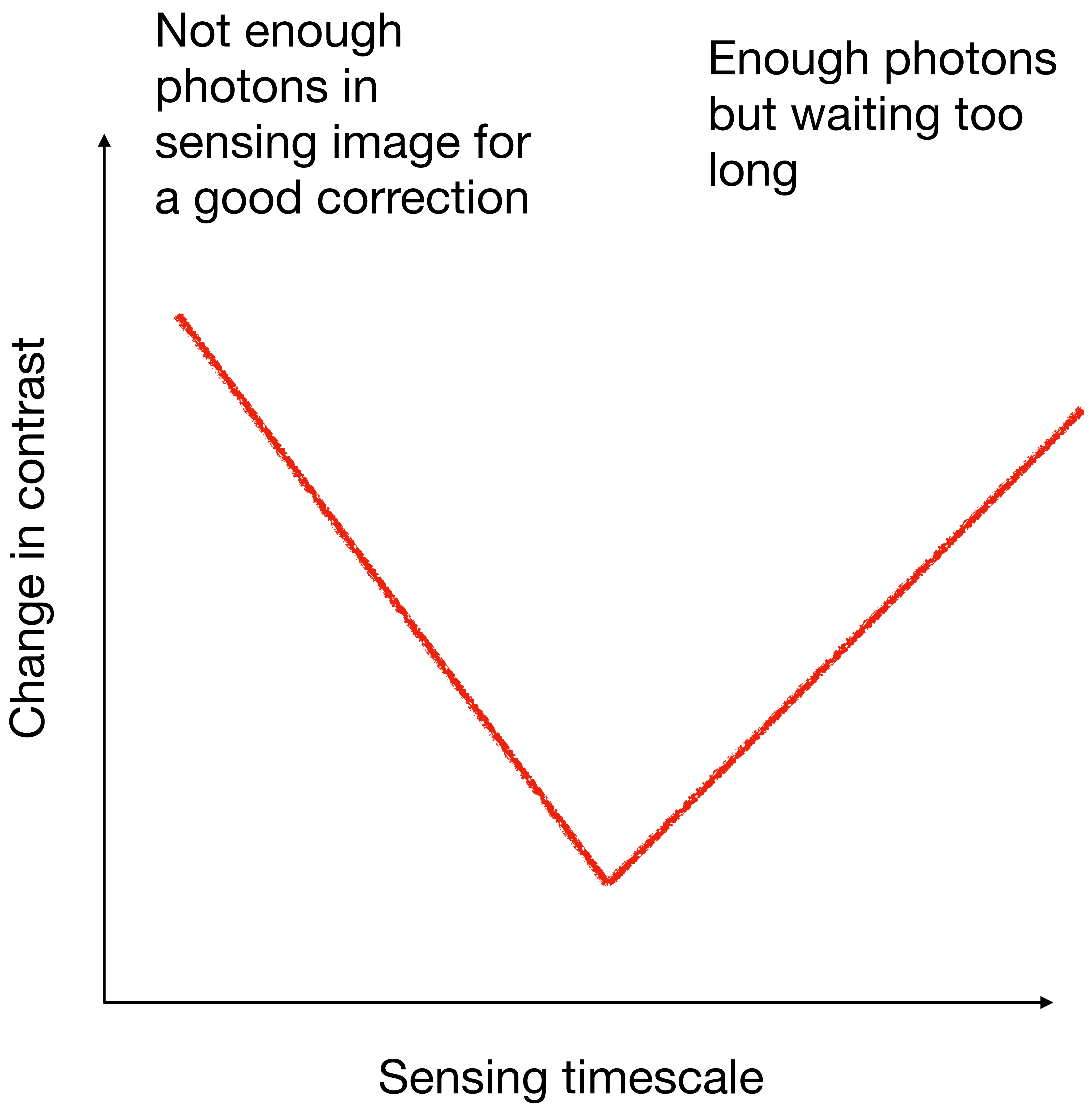
10 seconds exposure



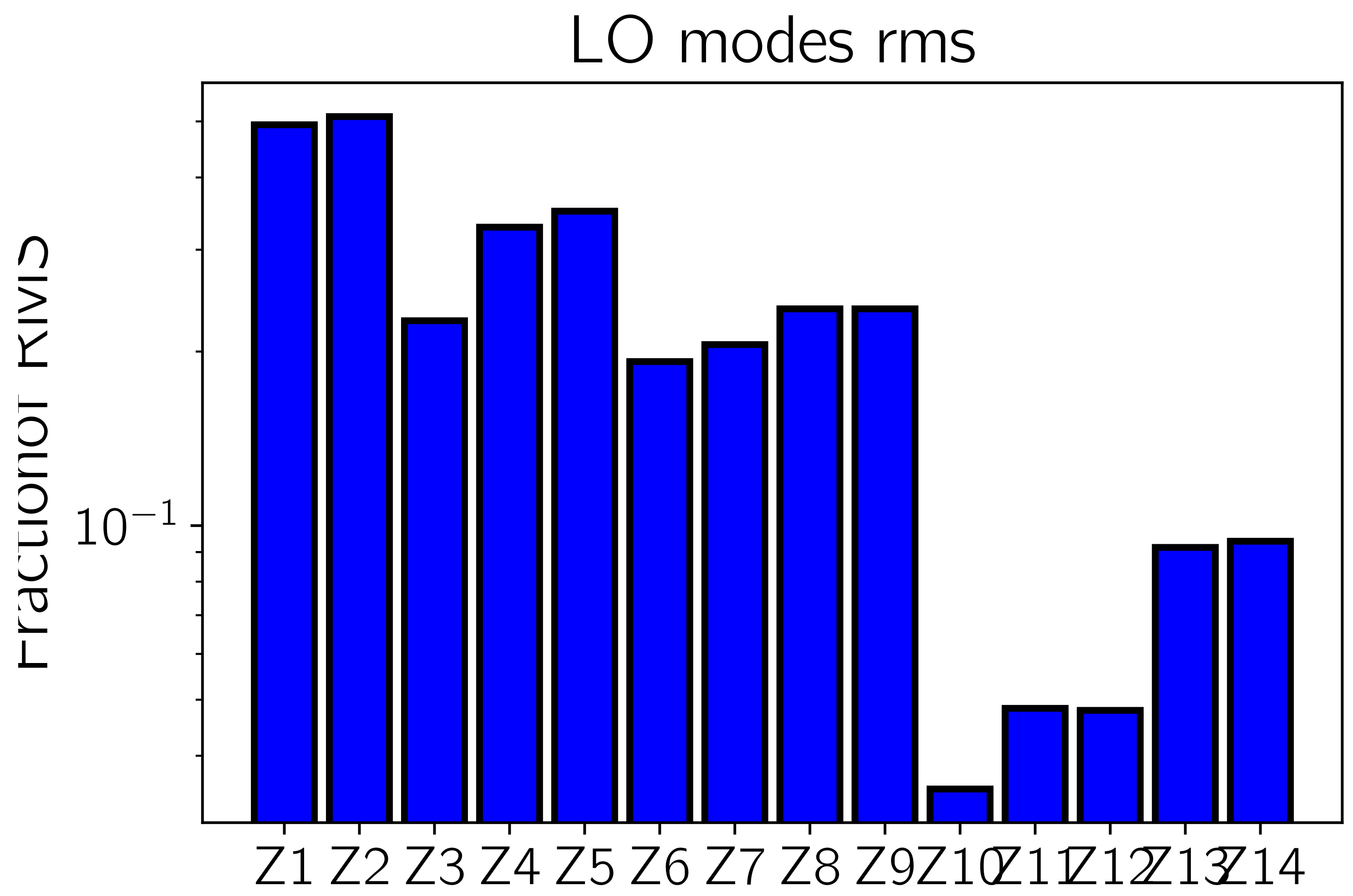
Same calculation with realistic simulations



10 milli-seconds exposure



Relative Contribution of each mode.

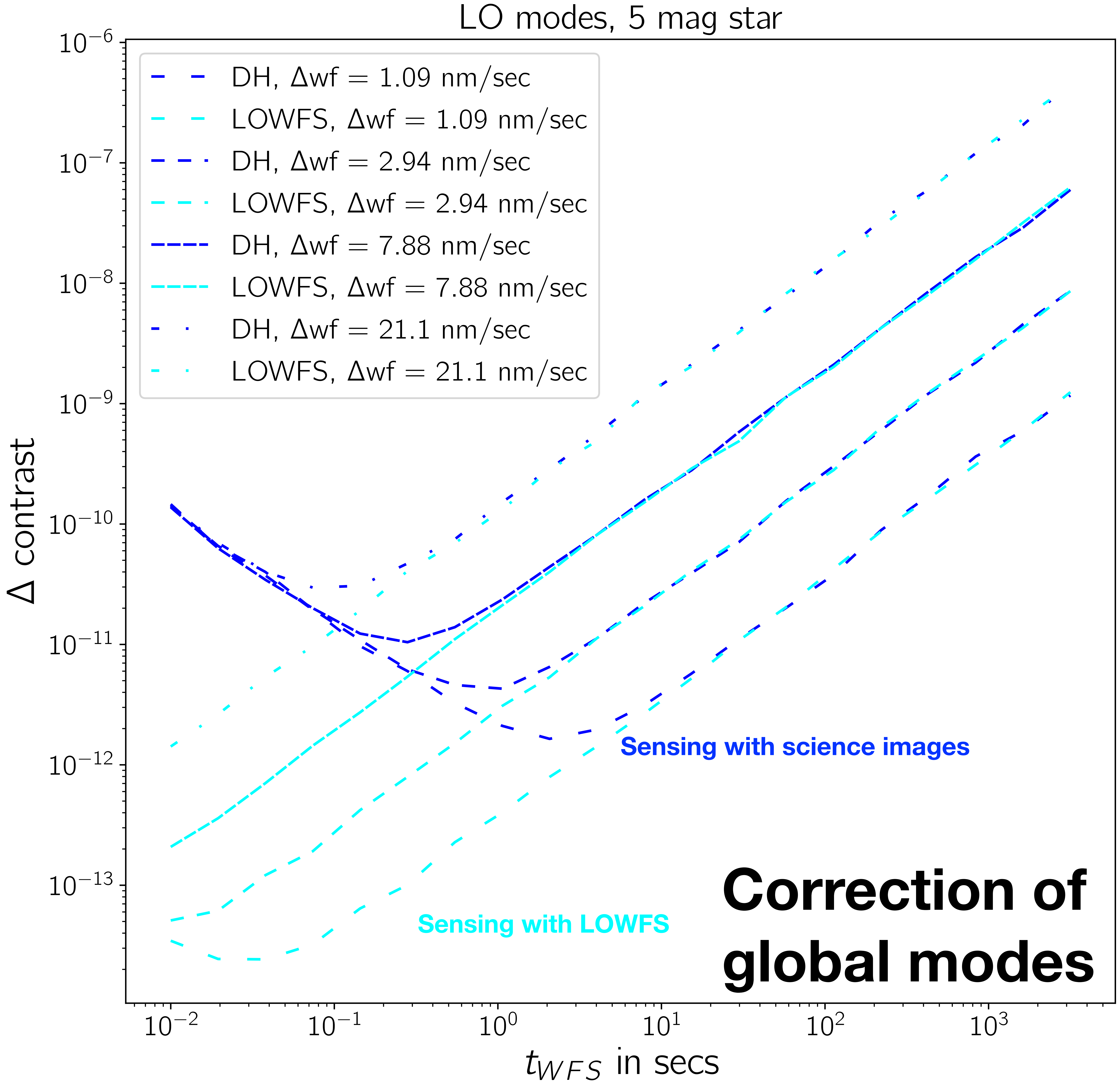


LO modes requirements with DH

Mag 0 star, < 20 nm/sec, $t_{WFS} > 0.03$ sec.

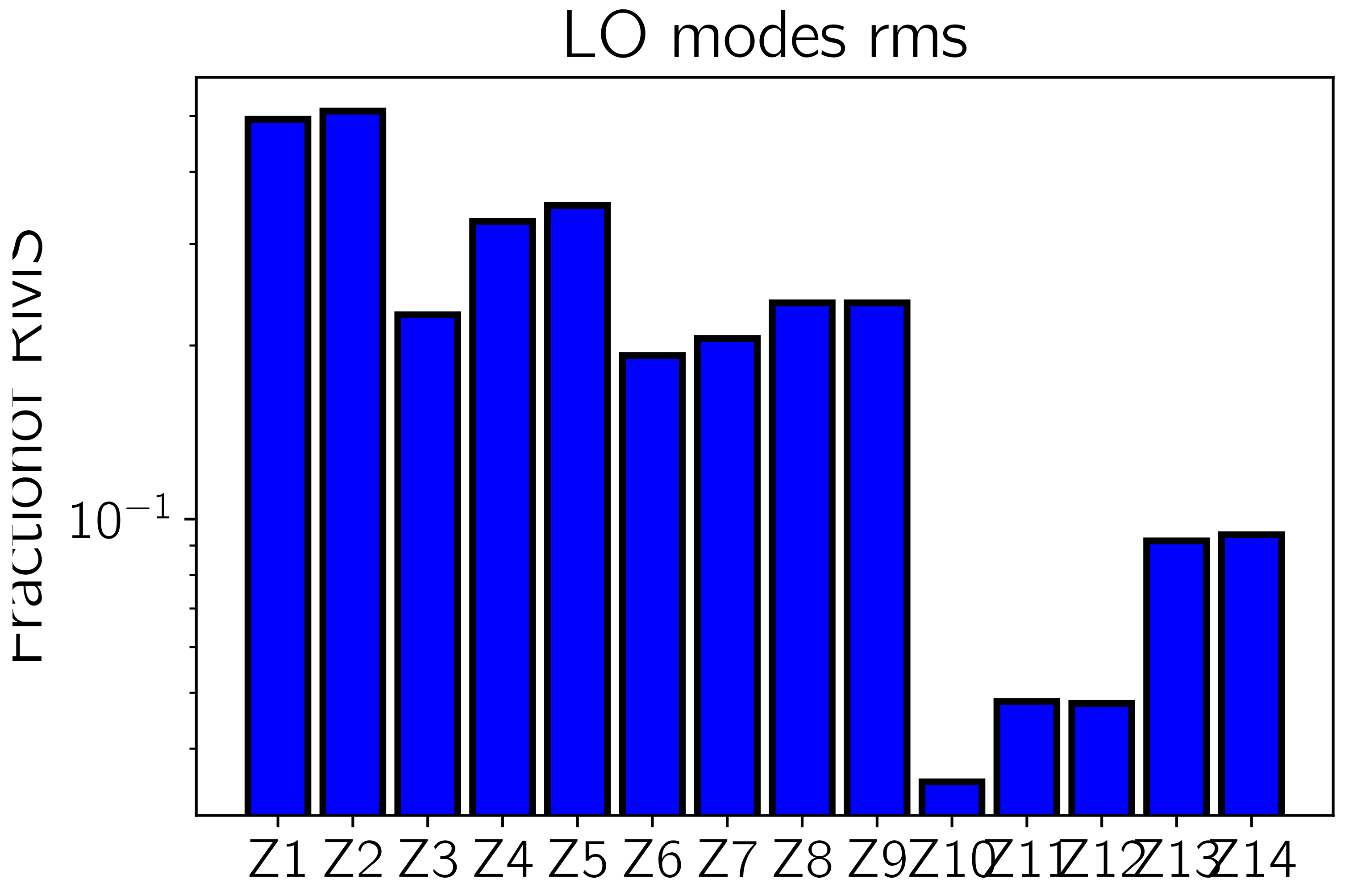
Mag 5 star, < 8 nm/sec, $t_{WFS} > 0.5$ sec.

Mag 10 star, < 3 nm/sec, $t_{WFS} > 7$ sec.



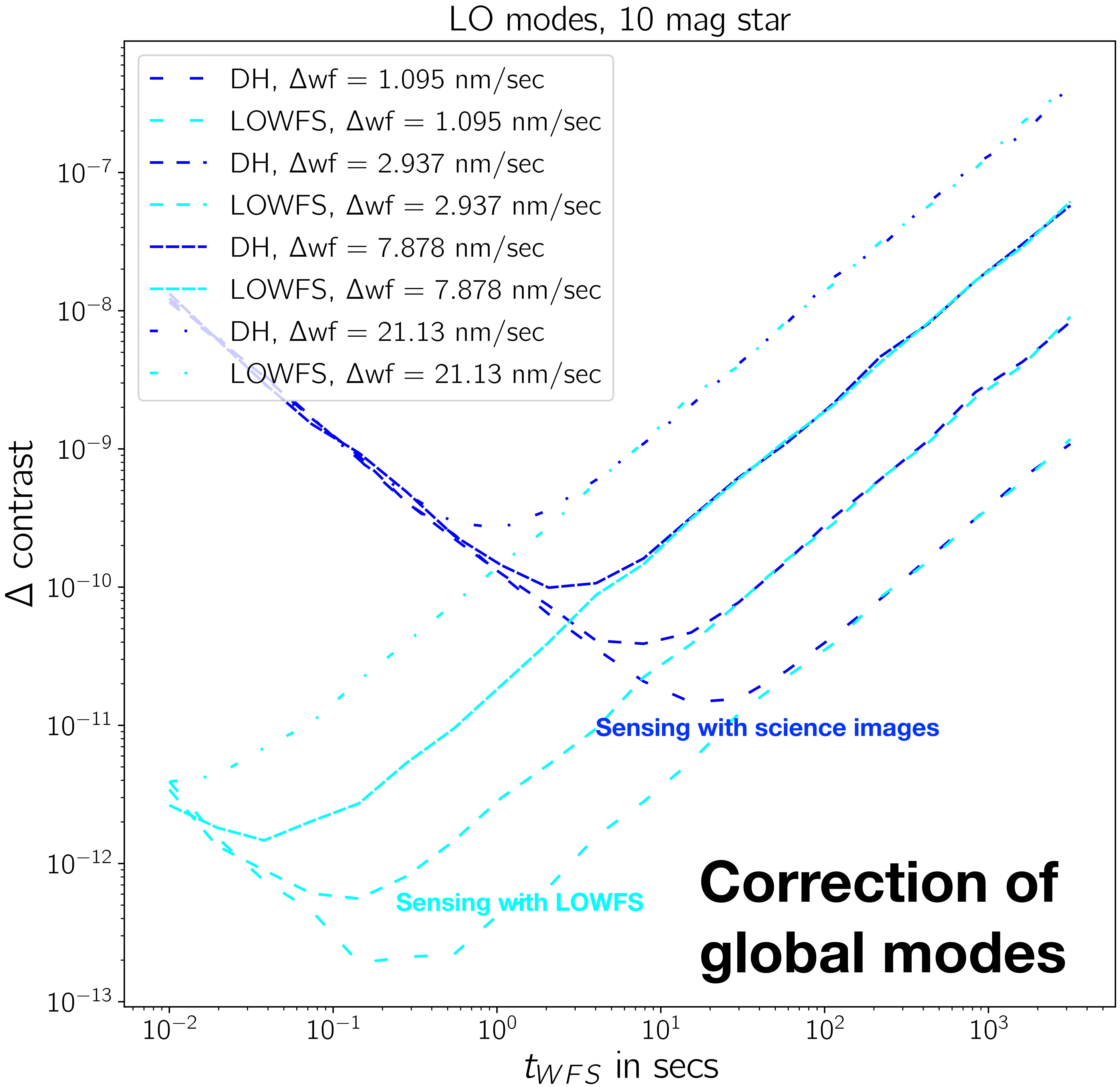
Correction of global modes

Relative Contribution of each mode.

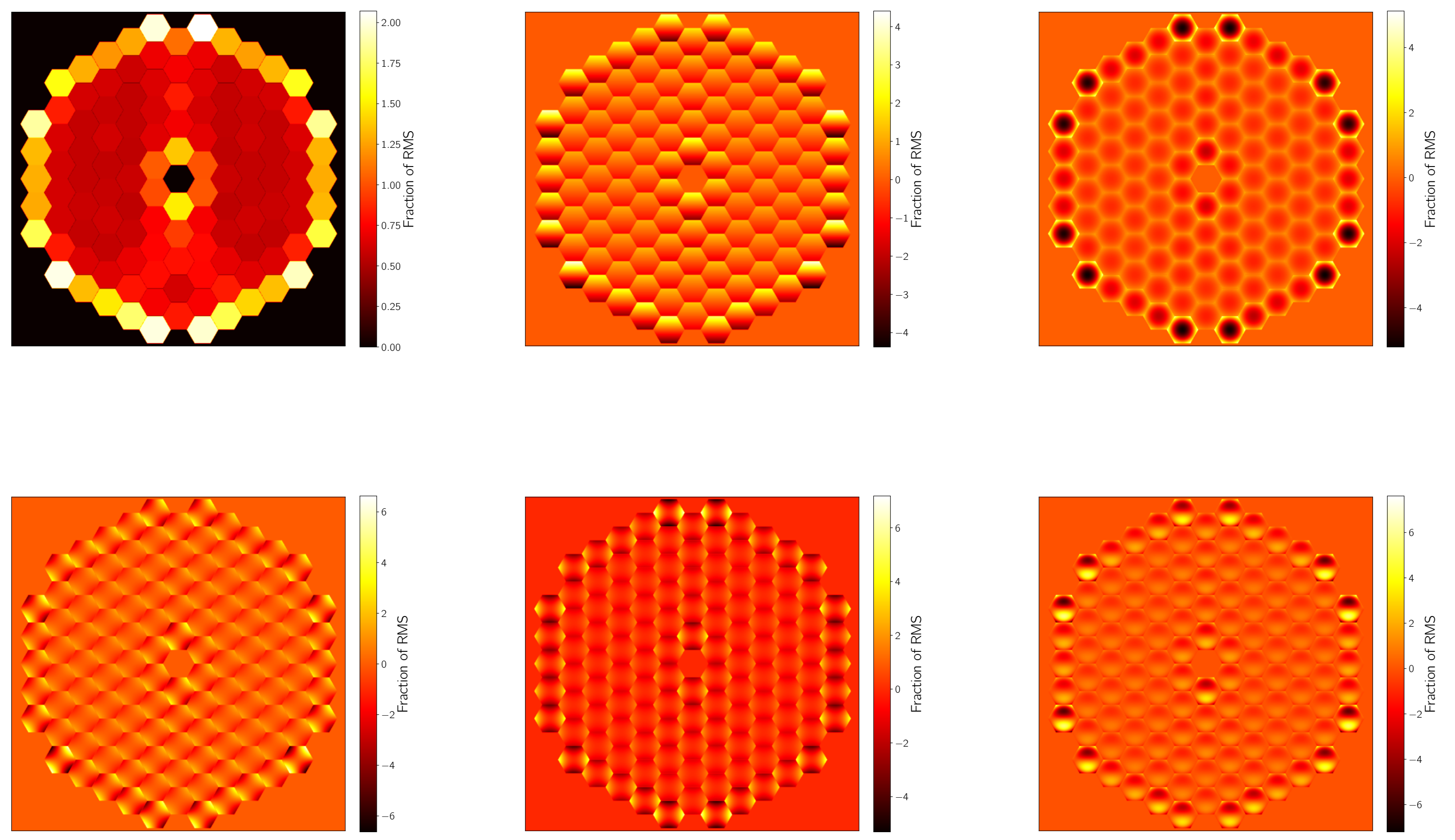


LO modes requirements with LOWFS

Mag 10 star, < 20 nm/sec, $t_{WFS} > 0.03$ sec.



Relative Contribution of each mode.

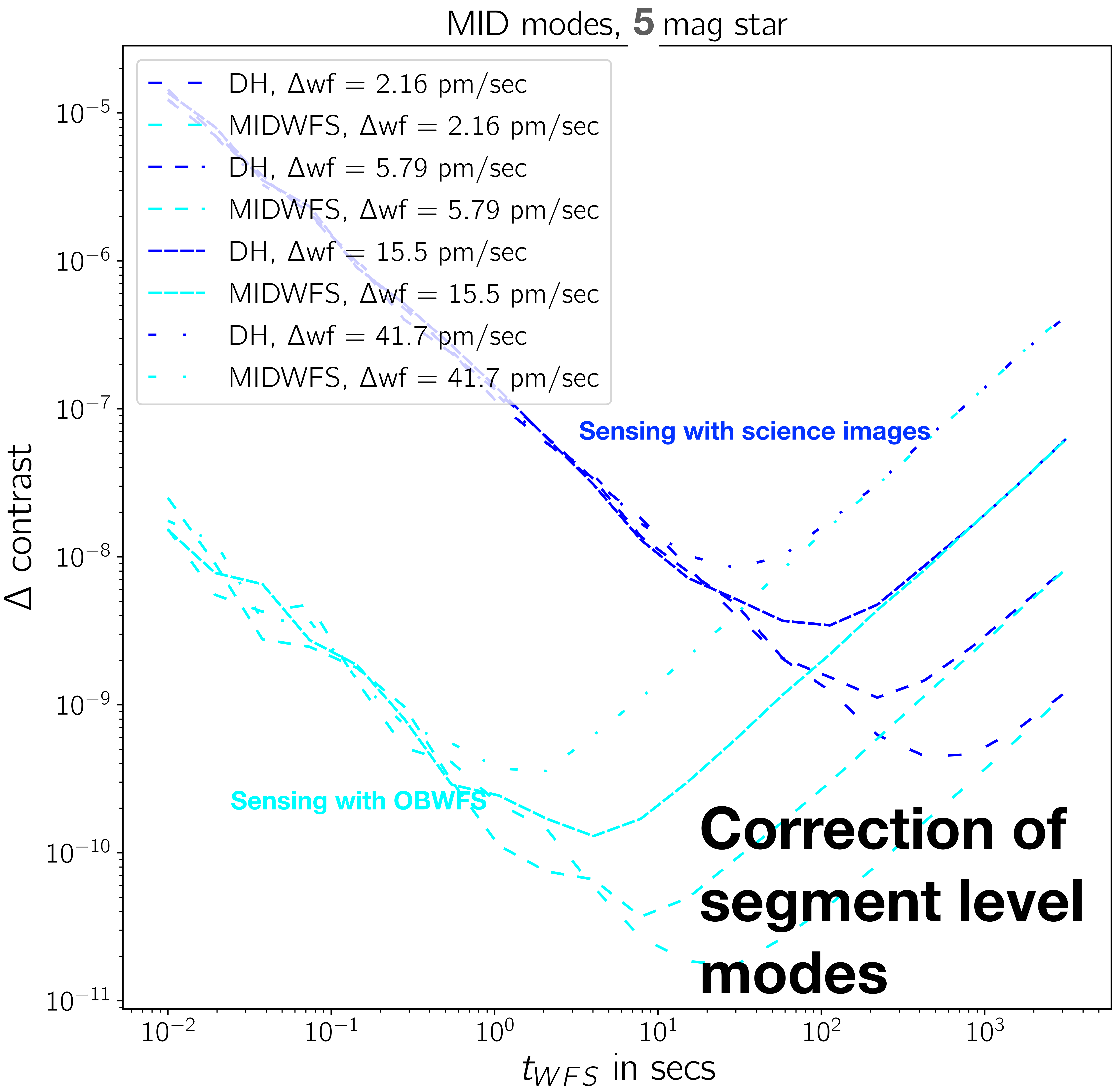


MID modes requirements with MIDWFS

Mag 0 star, < 15 pm/sec, $t_{WFS} > 0.5$ sec.

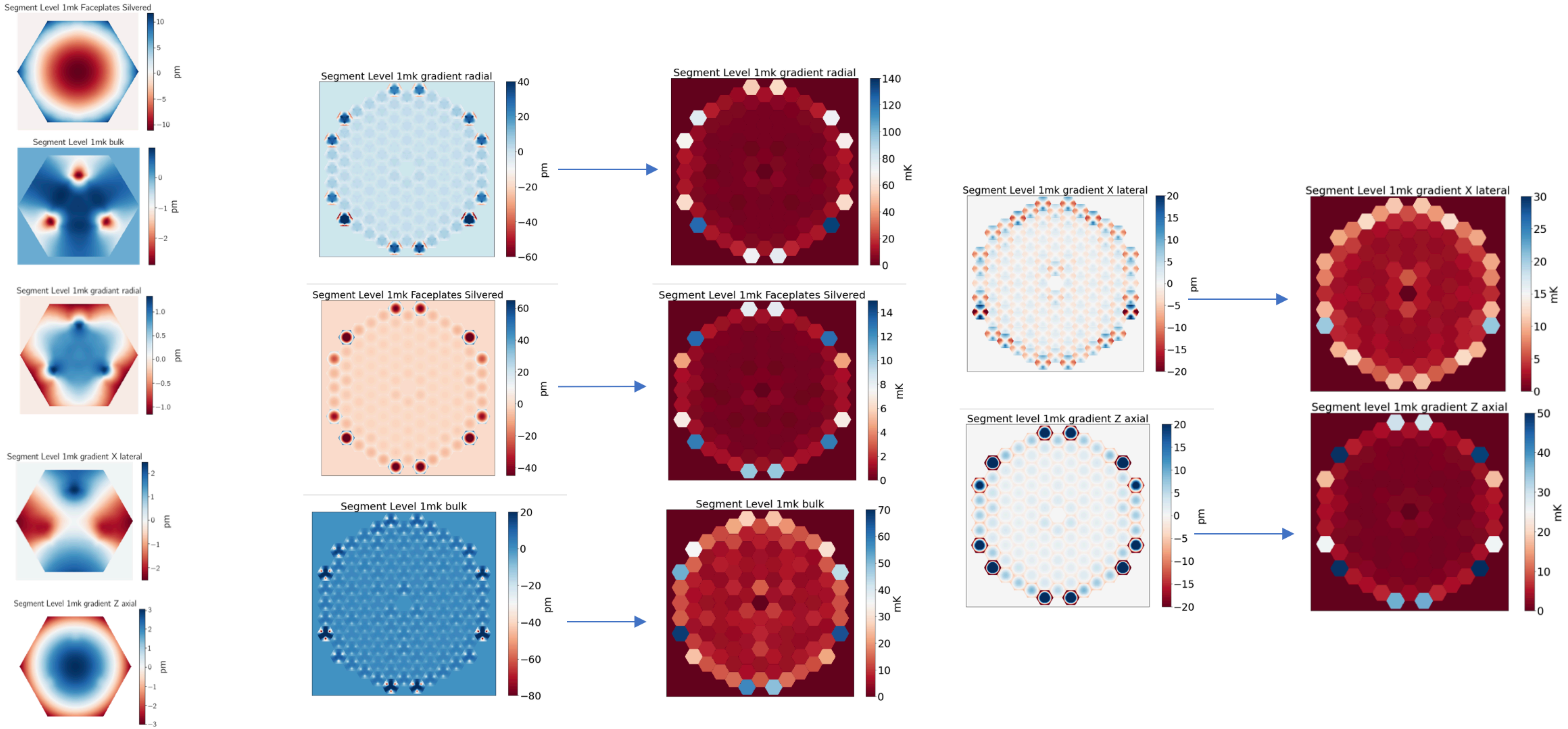
Mag 5 star, < 2 pm/sec, $t_{WFS} > 20$ sec.

Mag 10 star, < 0.5 pm/sec, $t_{WFS} > 2000$ sec.



Representation of segment level errors

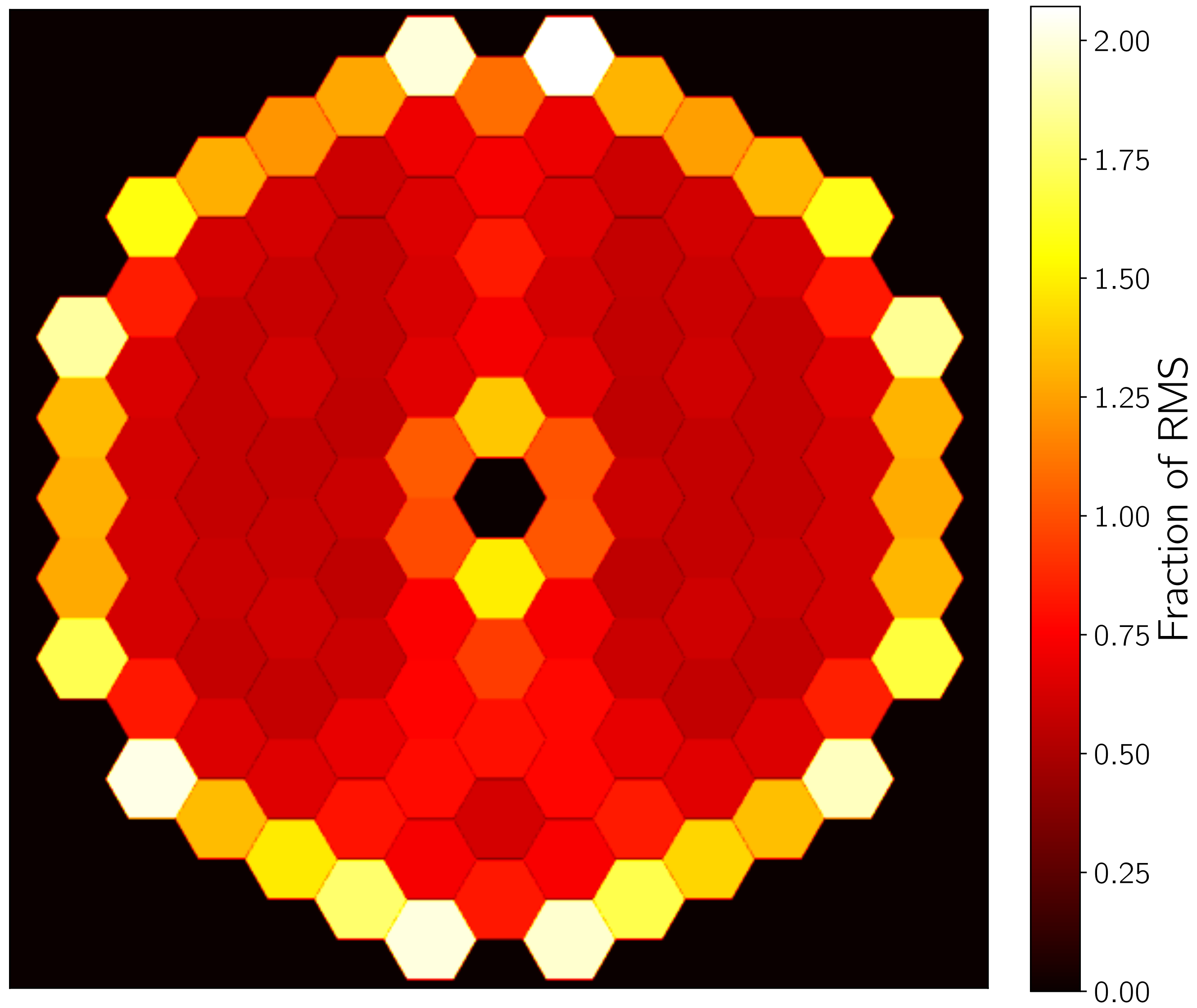
Sahoo + (2022)



We find that thermal drifts requirements are of ~5 mK over timescales of 10s of seconds to minutes (depending on architecture)

Recursive wavefront sensing

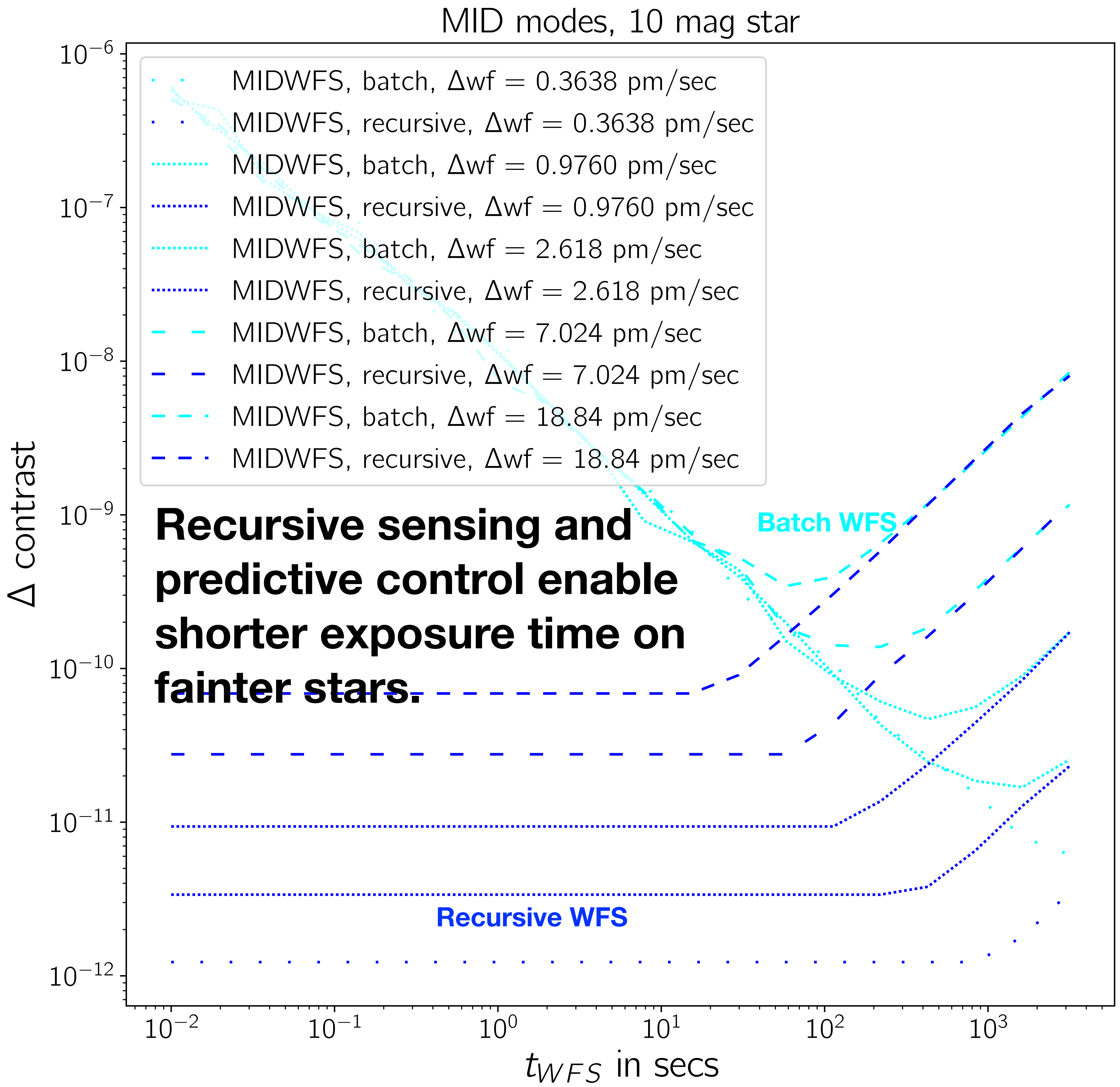
Relative Contribution of each mode.



MID modes requirements with MIDWFS

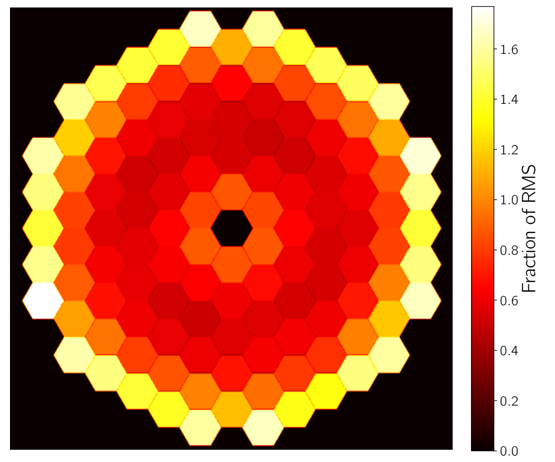
Mag 5 star, < 25 pm/sec, $t_{WFS} > 0.1$ sec.

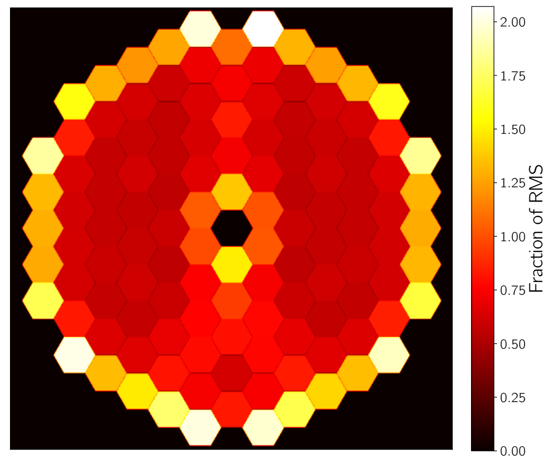
Mag 10 star, < 8 pm/sec, $t_{WFS} > 0.1$ sec.

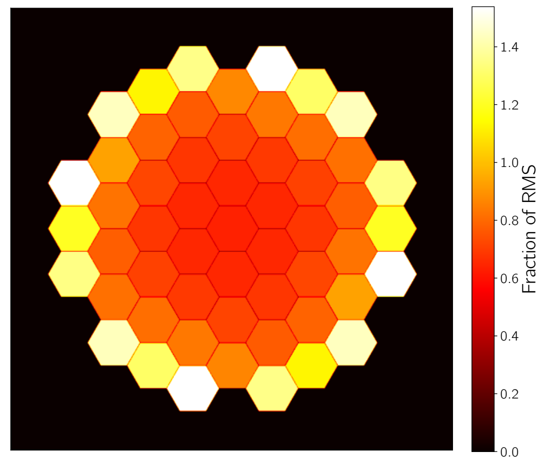


Changing the coronagraph and telescope

Relative Contribution of each mode.





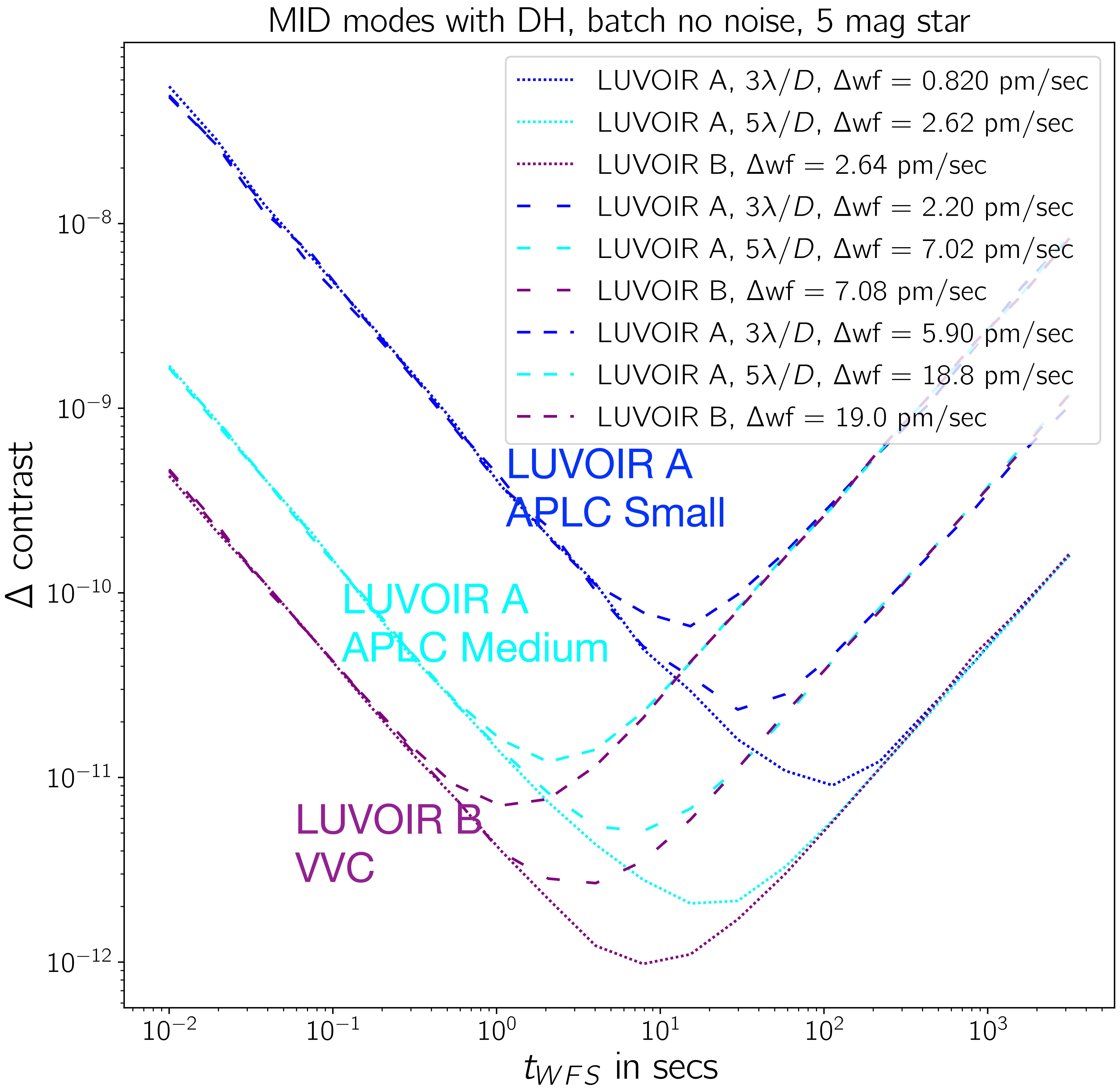


MID modes requirements

LUVOIR A $5\lambda/D$, < 15 pm/sec, $t_{WFS} > 10$ sec.

LUVOIR A $3\lambda/D$, < 0.9 pm/sec, $t_{WFS} > 100$ sec.

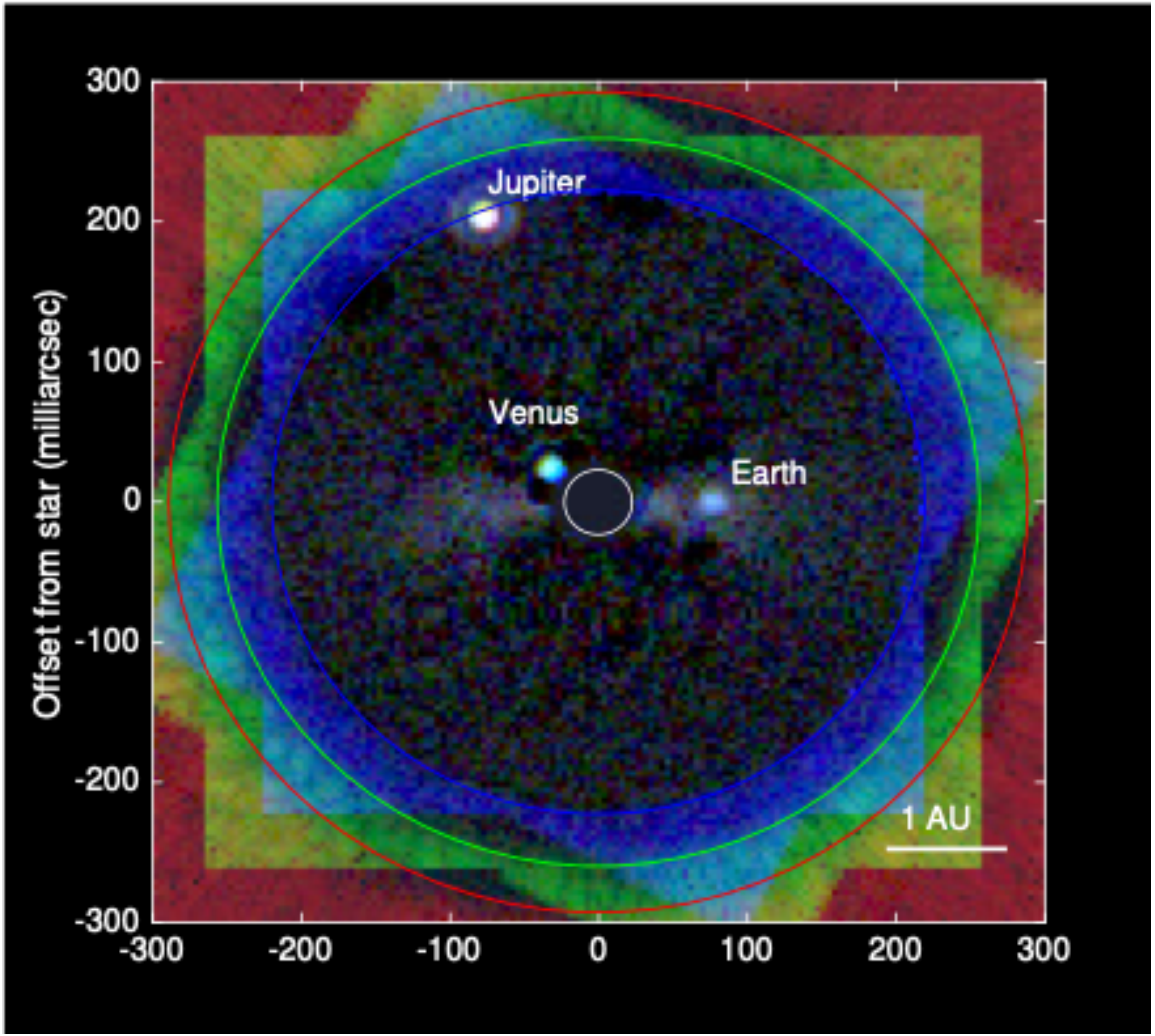
LUVOIR B, < 20 pm/sec, $t_{WFS} > 1$ sec.



Main takeaway from initial - albeit very incomplete- analysis:

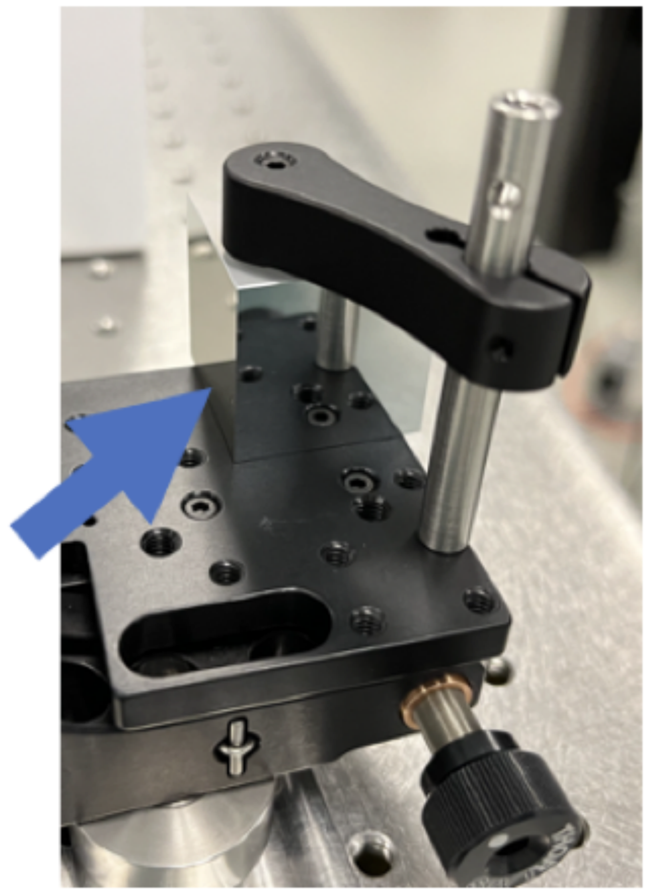
The scaling factor in front of requirement equation depends on

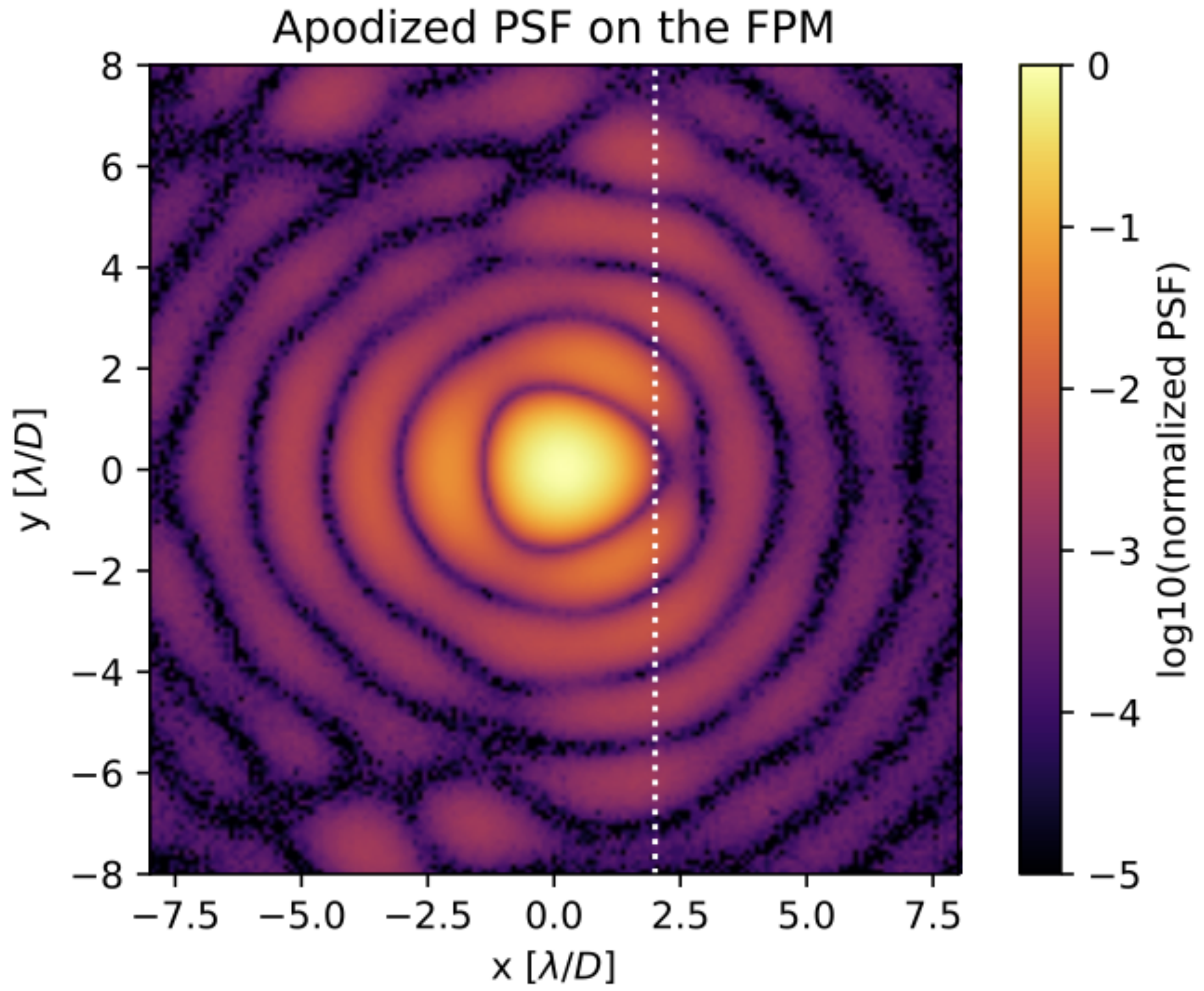
1) wavefront sensing architecture
2) coronagraph robustness
3) telescope geometry (e.g. number of segments)

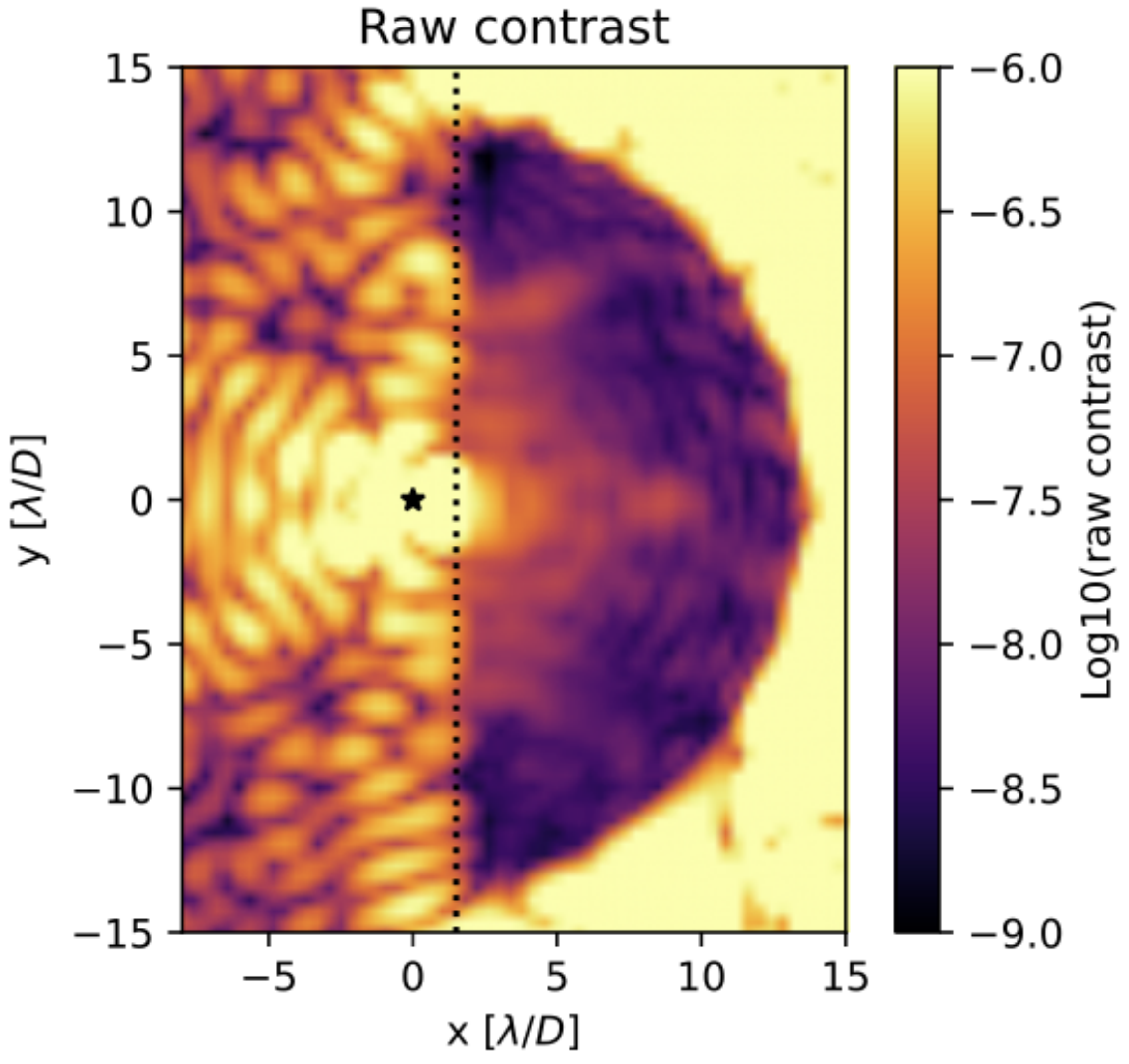


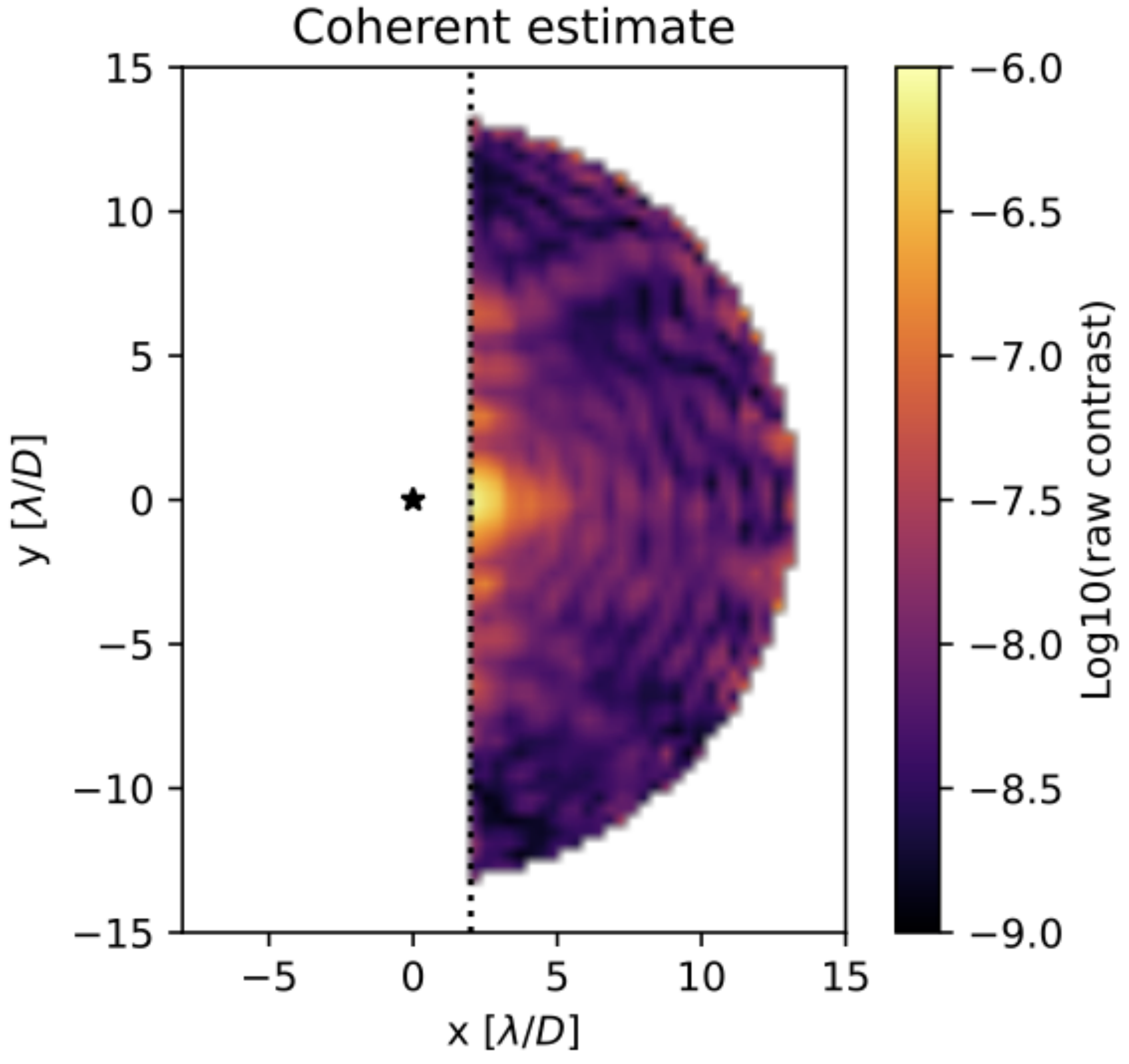
Next we will have to verify these calculation with laboratory data.

Static contrast (broadband)

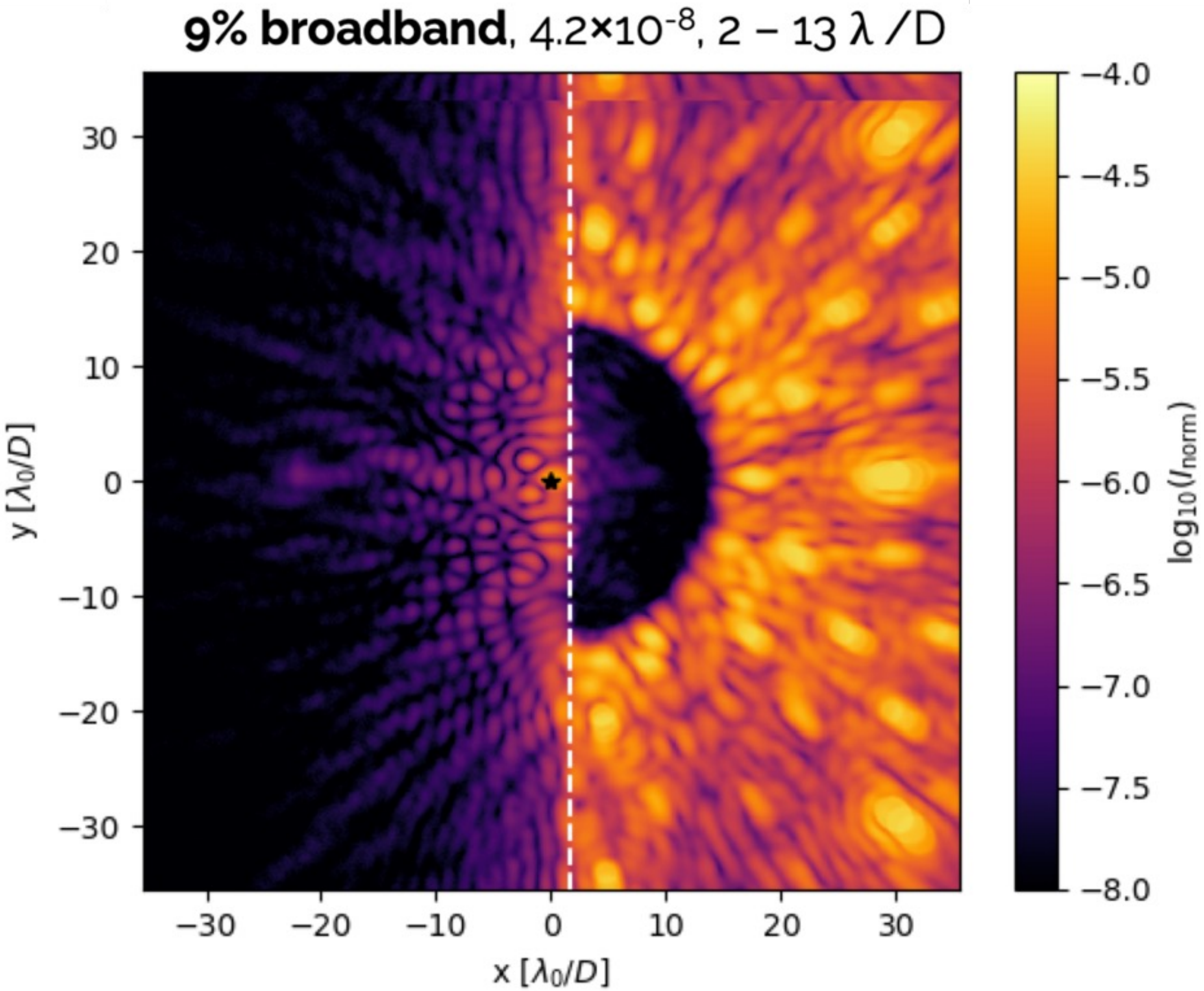






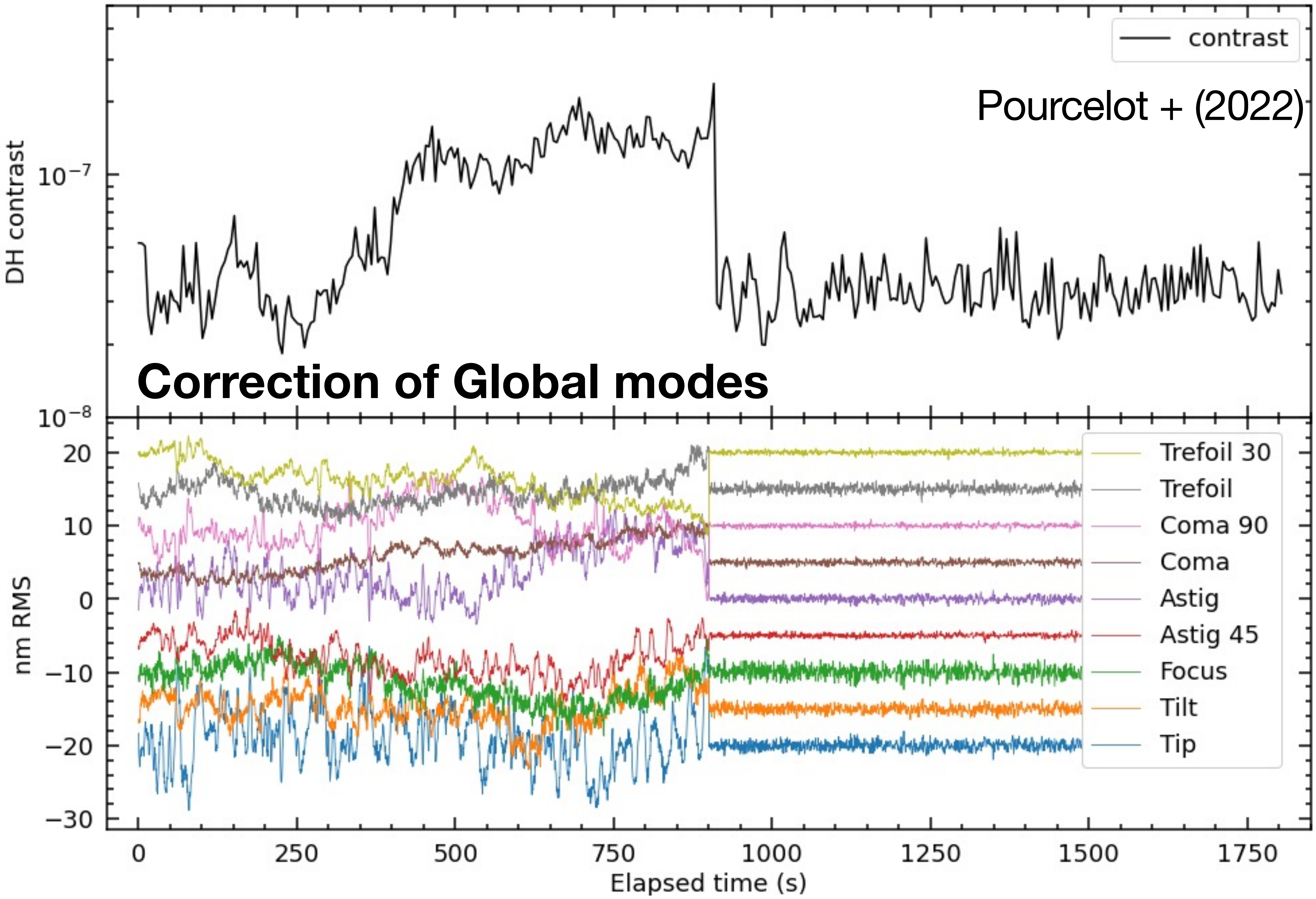


PAPLC recent results on HiCAT testbed (Emiel Por)

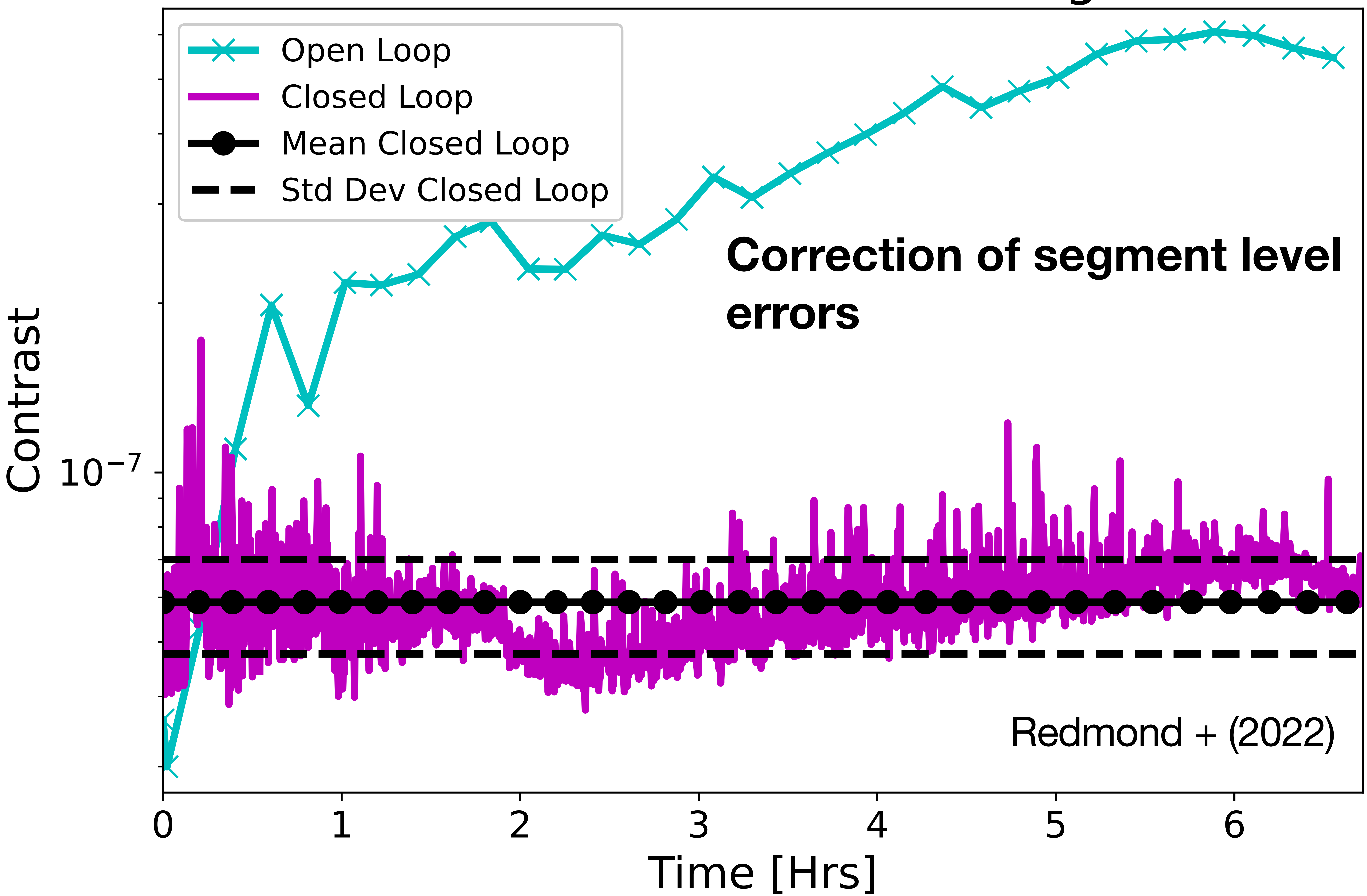


Por + (2022)

PAPLC: monochromatic 2e-8 (2-13 lambda/D), 8e-9 (5-13 lambda/D)

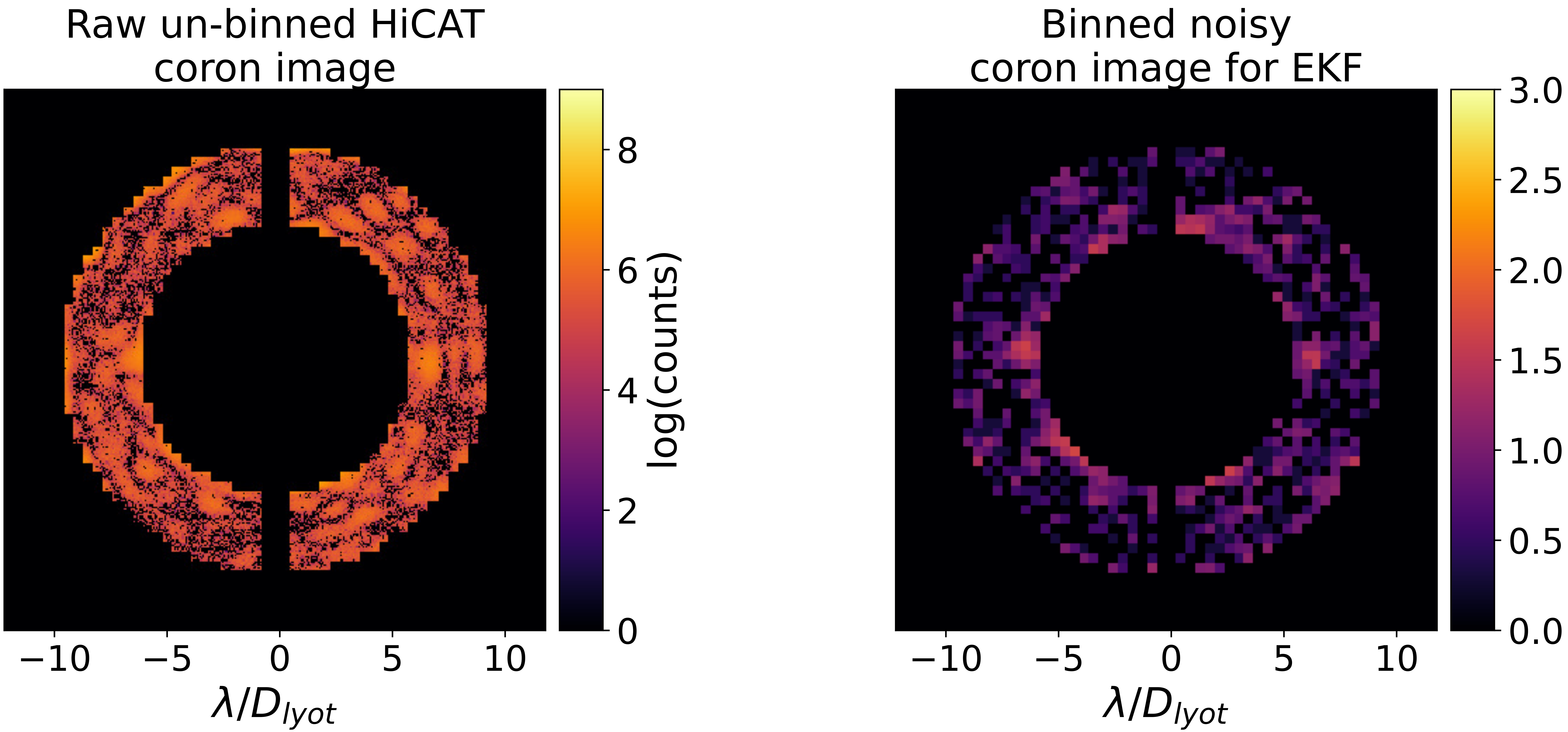


Pourcelot + (2022)
Correction of Global modes
contrast
DH contrast
10−7
10−8
nm RMS
20
10
0
−10
−20
−30
Trefoil 30
Trefoil
Coma 90
Coma
Astig
Astig 45
Focus
Tilt
Tip
0
250
500
750
1000
1250
1500
1750
Elapsed time (s)



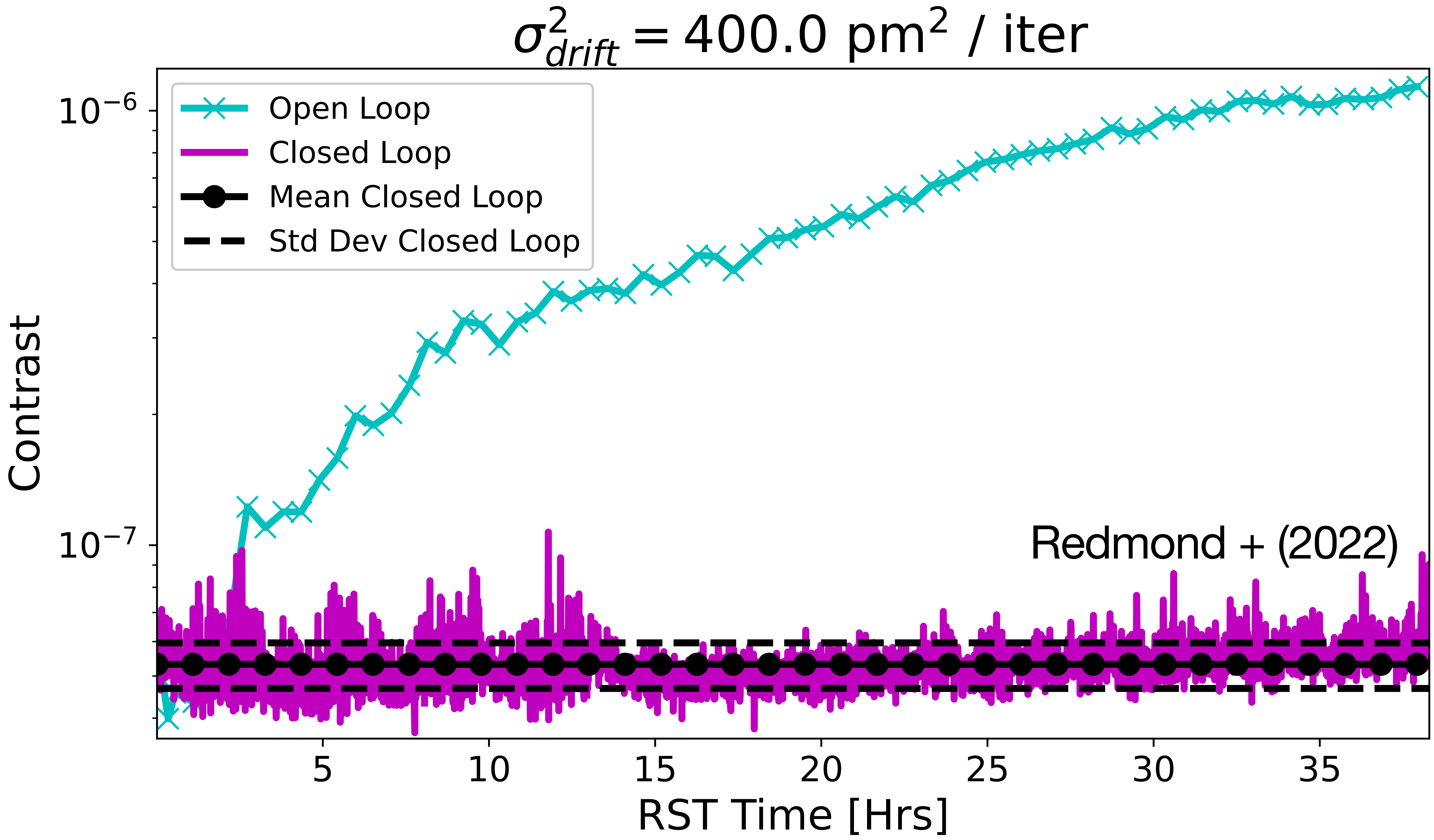
Open Loop
Closed Loop
Mean Closed Loop
Std Dev Closed Loop
Correction of segment level errors
Redmond + (2022)
Contrast
10^{-7}
0
1
2
3
4
5
6
Time [Hrs]

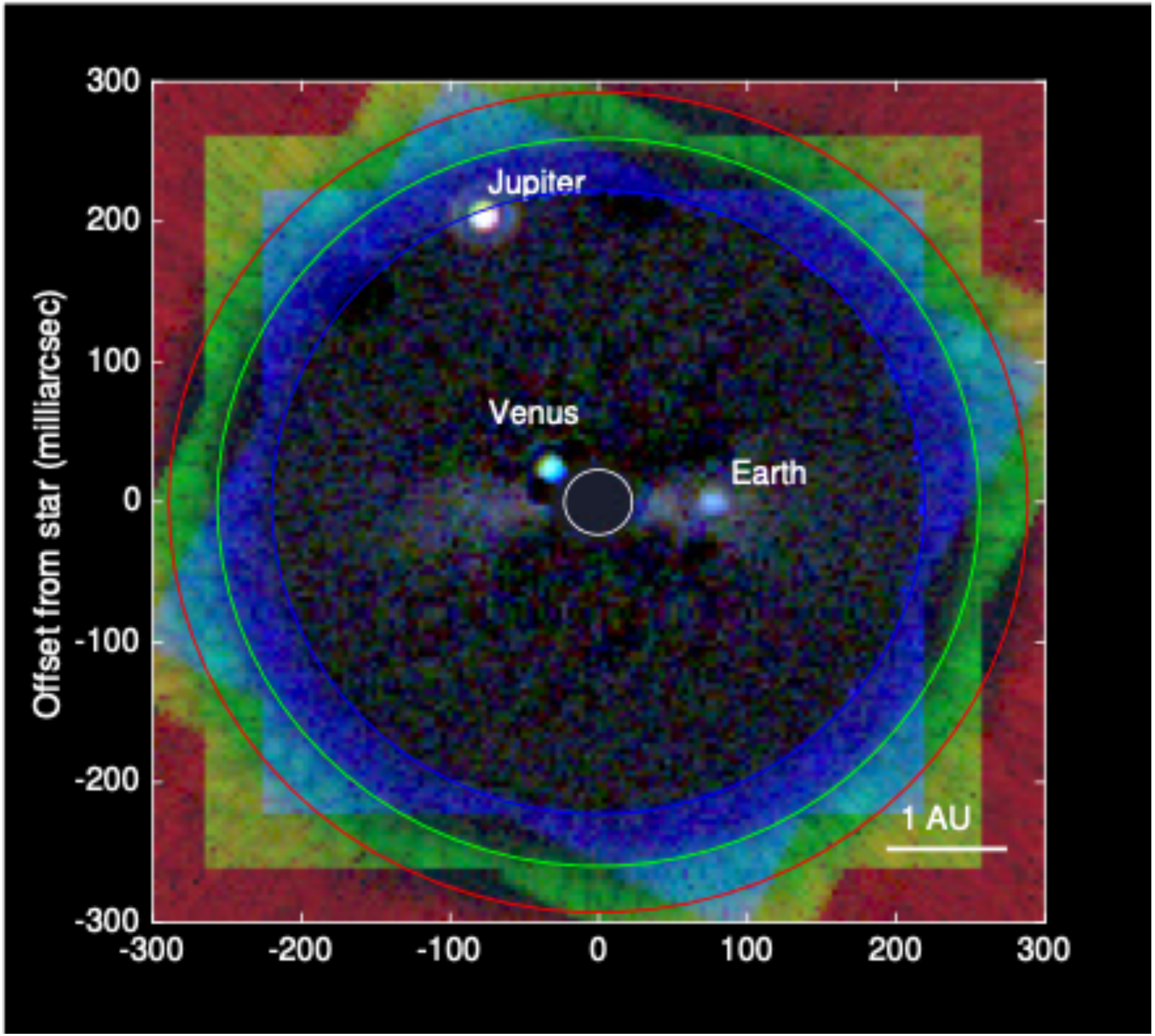
Correction of high order errors with low photon counts



Redmond + (2022)

Correction of high order errors with low photon counts




Jupiter
Venus
Earth
1 AU
Offset from star (milliarcsec)
300
200
100
0
-100
-200
-300
-300
-200
-100
0
100
200
300

Conclusion

The scaling factor in front of requirement equation depends on

1) wavefront sensing architecture
2) **coronagraph robustness, this impacts yield!**
3) telescope geometry (eg number of segments)

We need to develop a technology maturation plan that will:

1) Measure coronagraph robustness and validate models in open loop (this might be hard).
2) And/or verify if closed loop performances match model predictions.