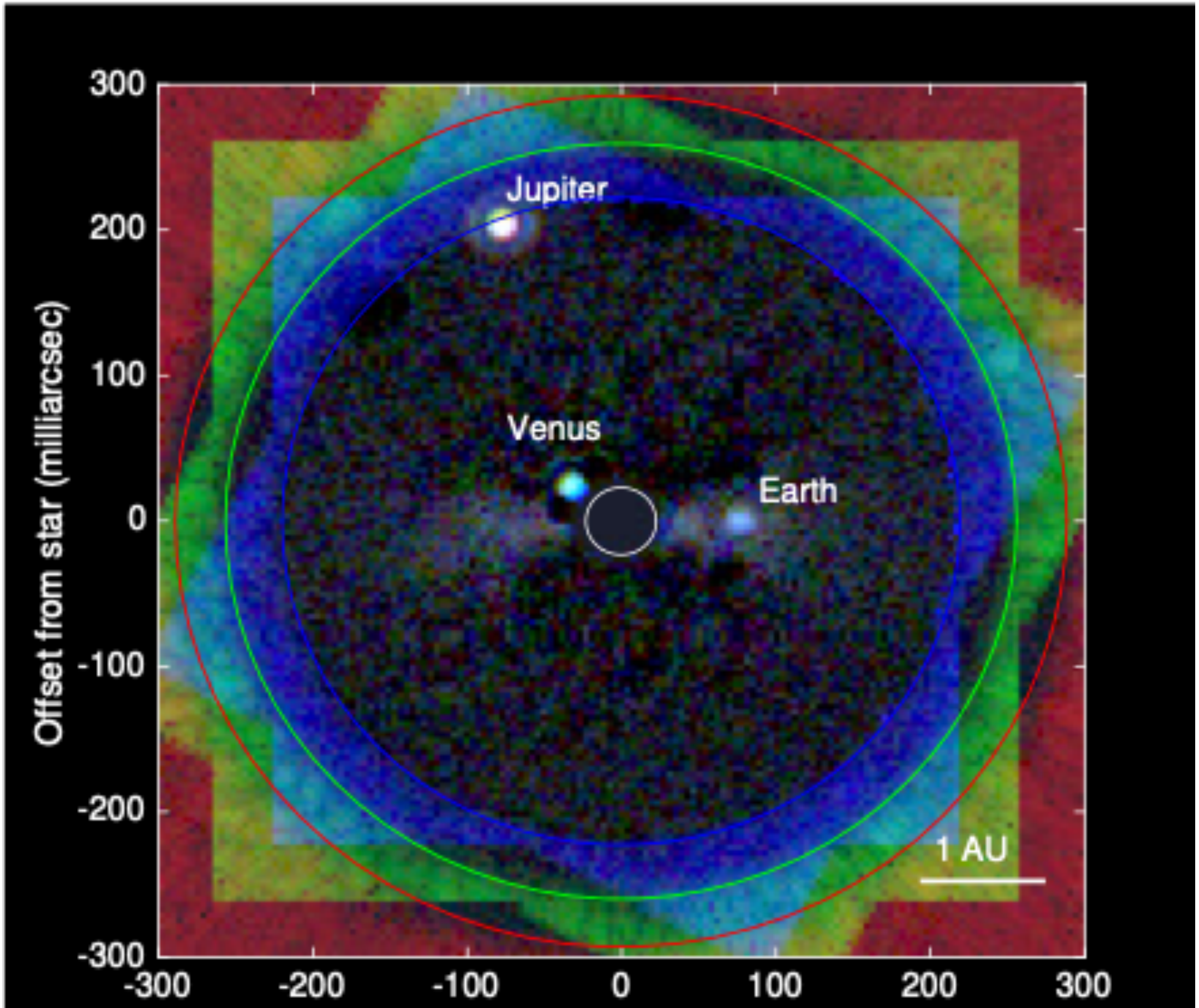
Architecture trades to optimize wavefront stability requirements for exoplanet imaging in space

Laurent Pueyo, Leonid Pogorelyuk, Iva Laginja, Remi Soummer, Ananya Sahoo, Emiel Por, Kerri Cahoy, Laura Coyle, Scott Knight

ExEP Technology colloquium
09/27/2022

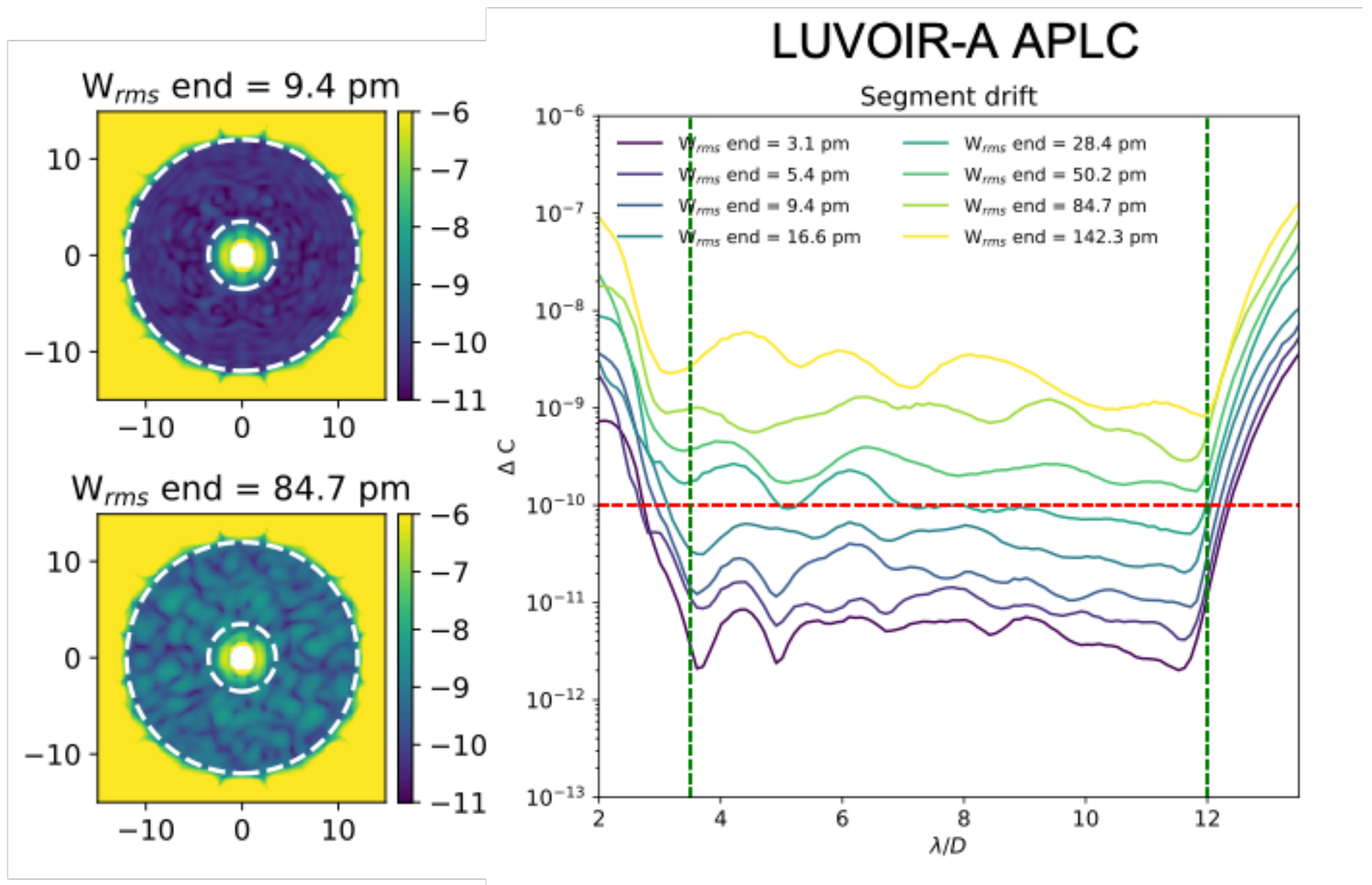
Statement of the problem



~10 pm during an exposure

We can design coronagraph masks that will make these images.

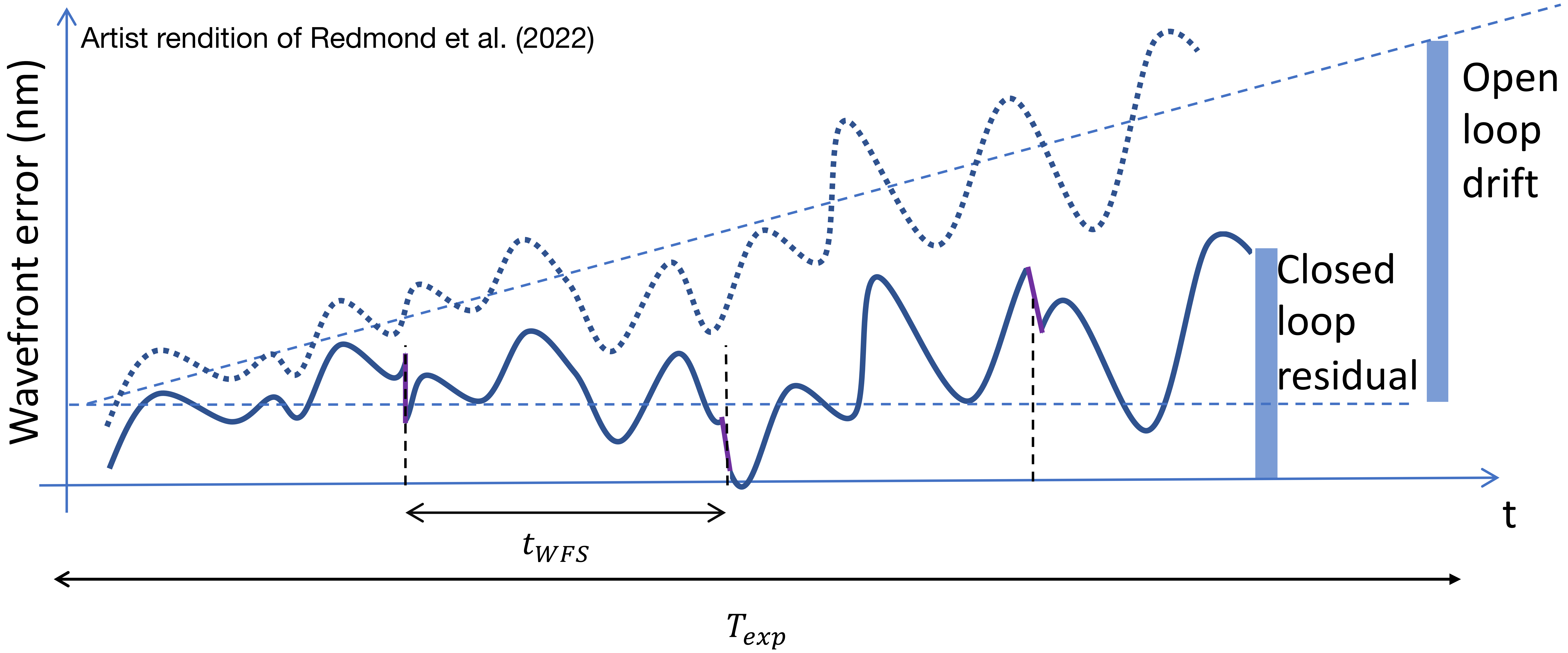
How do we keep the optics stable enough so the contrast does not change during science exposures?



Juanola-Parramon et al. (2019)

Methods

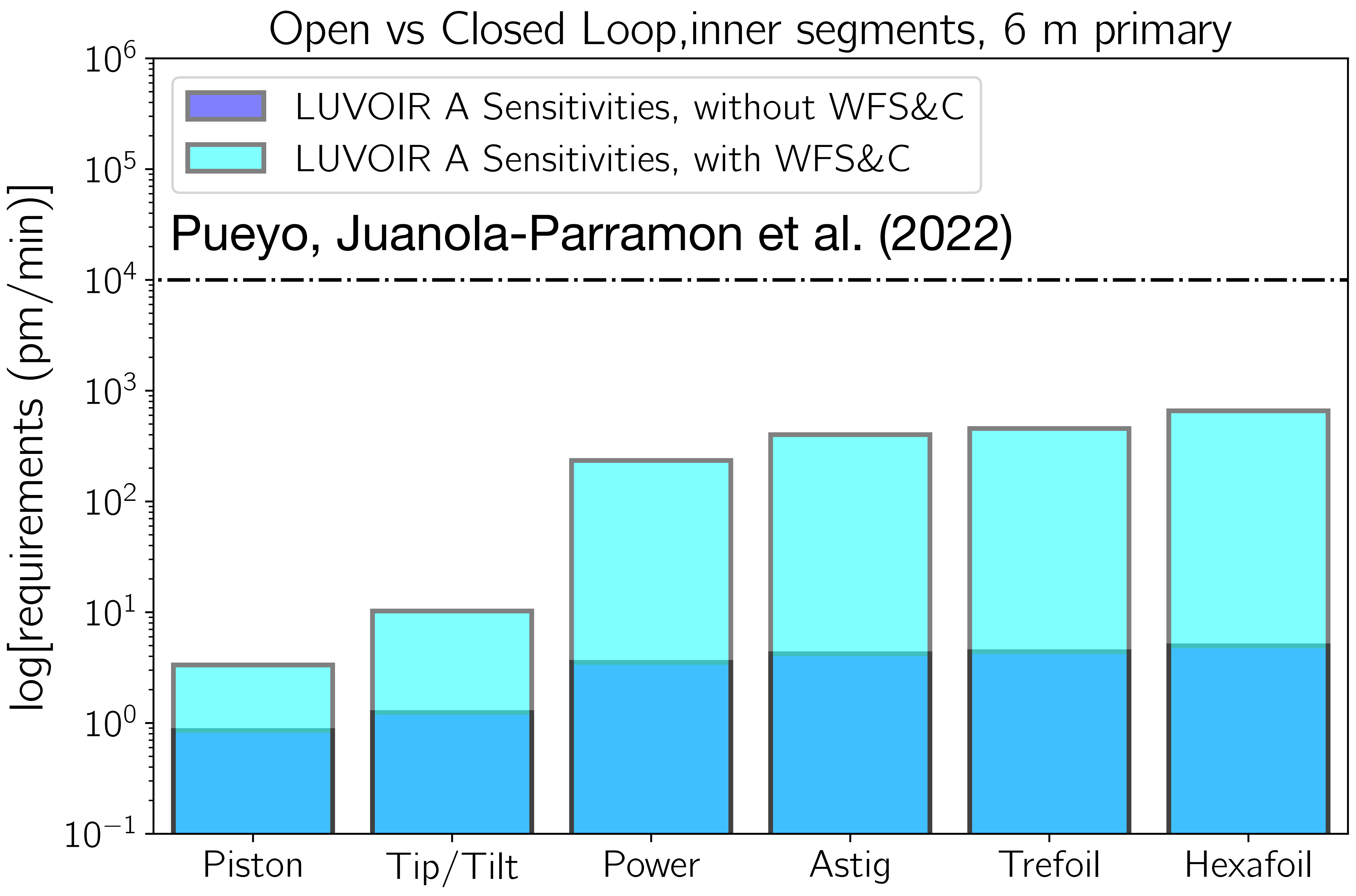
Why wavefront control/maintenance?

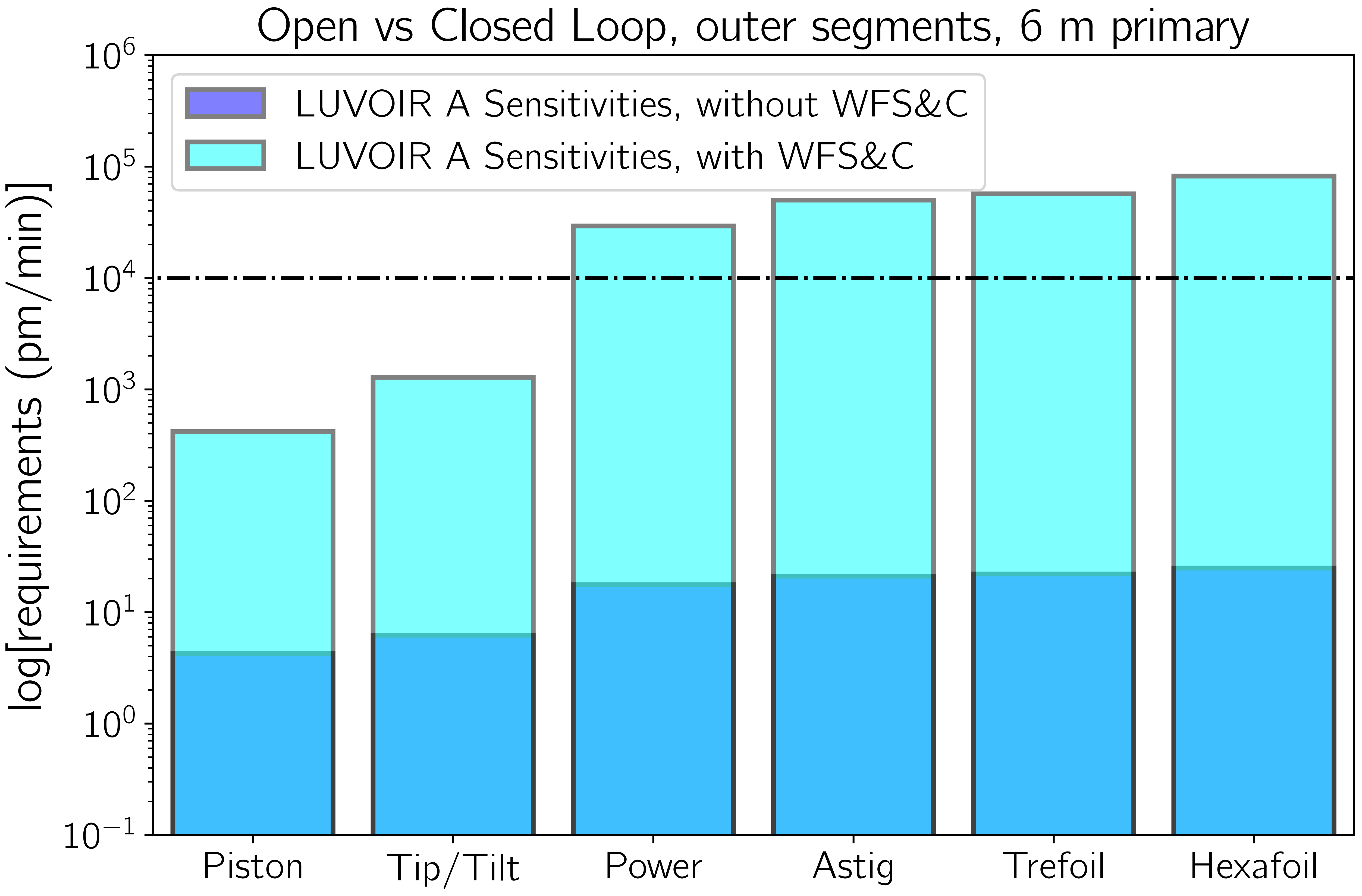


Shorten the time scales of wavefront drifts from a science exposure time (~10 hours) to a wavefront sensing exposure time (minutes, seconds, milliseconds?).

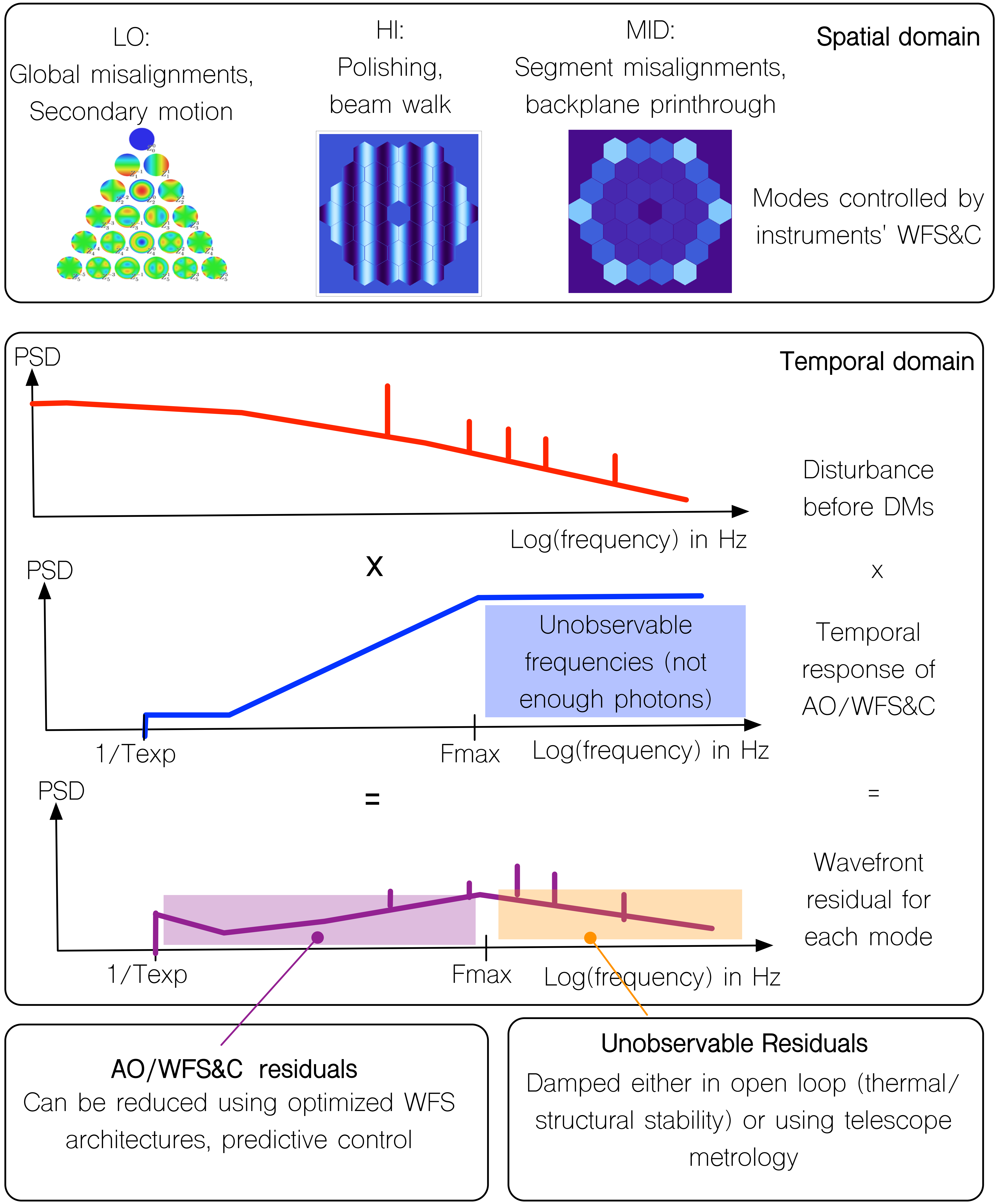
Zeroth order analysis of gain associated with WF Maintenance

Maintenance Gain = Sensor efficiency / (raw contrast * coronagraph sensitivity)





Coronagraphs robust at the segment level: Leboulleux et al. (2022)



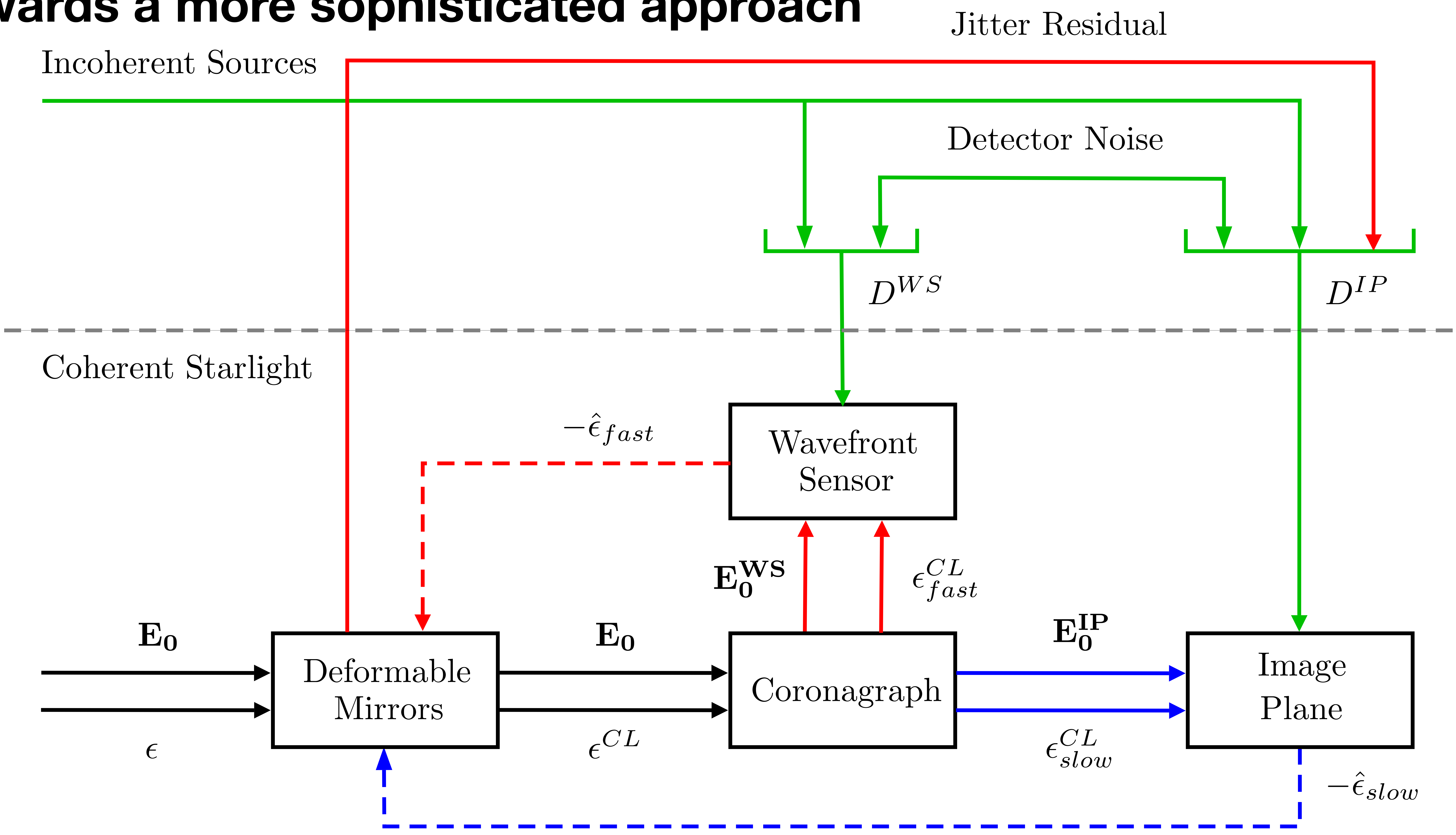
Towards a more sophisticated approach

- we assume that the instrument Wavefront Sensing and Control can reject some of the observatory disturbances.

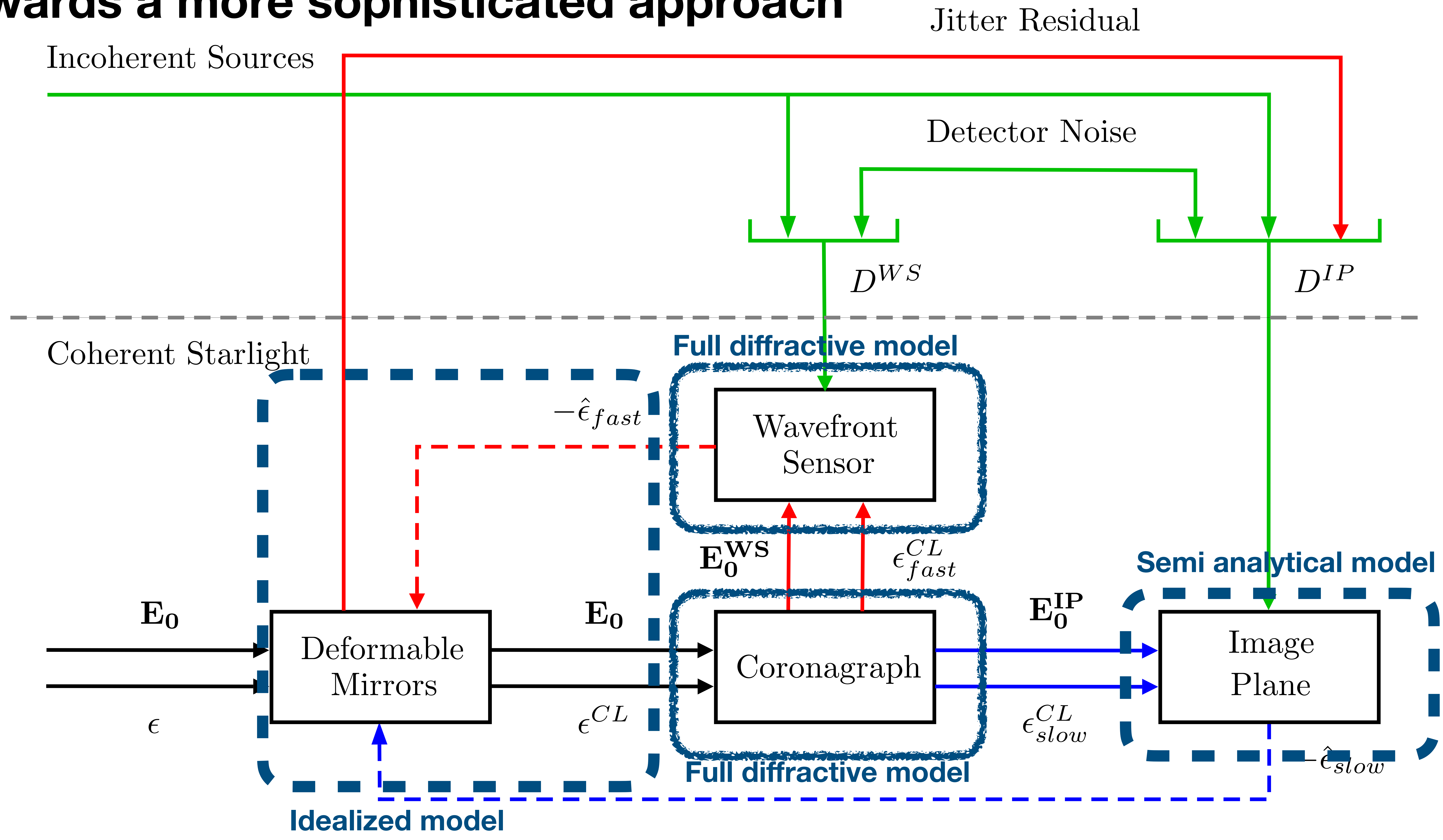
- what is left has to be corrected actively or passively at the observatory level.

This talk: what is required from observatory if we have WFS&C ?

Towards a more sophisticated approach



Towards a more sophisticated approach



The long form version

1. We pick an open loop wavefront variance.
2. We draw a random wavefront.
3. We use a **diffractive linear optical model of the WFS** to simulate sensing images as a function of wavefront.
4. Assuming that there exists an **unbiased estimator** for this given WFS, we use the Fischer information matrix as a proxy for the **SNR in these sensing images** (changes with detector noise, exposure time, stellar magnitude).
5. Assuming that there exists a **perfect control algorithm**, we use the Cramer Rao bound to **convert sensing SNR into wavefront variance** associated with measurement uncertainty.
6. We use two version of the Cramer Rao bound: one that only used the last WFS measurement (**batch**), and one that takes into account the full WFS history (**recursive**).
7. Closed loop wavefront variance = open loop wavefront variance + WFS measurement uncertainty
8. We use a **diffractive linear optical model of the coronagraph** to convert closed loop wavefront variance into contrast.
9. We go back to step 2 but this time draw a random wavefront from the closed loop variance.
10. We iterate.

Laginja et al. (2020), https://arxiv.org/abs/2103.06288

Pogorelyuk et al. (2021), https://arxiv.org/abs/2108.03269

PASTIS

- For any basis set for ε, the contrast change integrated over the Dark Hole is given by:

$$\Delta C = tr\left(GG^T Q\right) \quad (8)$$

- We build G numerically by poking each mode in the basis set.
- We pick $\Delta C = 10^{-11}$
- We invert Eq. 8 assuming the modes are uncorrelated to derive the open loop variance Q

Fisher information

$$\mathscr{I} = \sum_i \frac{4\dot{N}_S t_s}{\left\|G_i \varepsilon^{CL} + \mathbf{E}_{0,i}\right\|^2 + \dot{N}_S^{-1} D_i} G_i^T \left(G_i \varepsilon^{CL} + \mathbf{E}_{0,i}\right)\left(G_i \varepsilon^{CL} + \mathbf{E}_{0,i}\right)^T G_i \quad (3)$$

Cramer Rao bound

- When using a single WFS image (batch estimator), the wavefront estimation covariance cannot be smaller than the inverse of the Fischer information:

$$P_k \geq (\mathscr{I}_{k+1})^{-1} \quad (4)$$

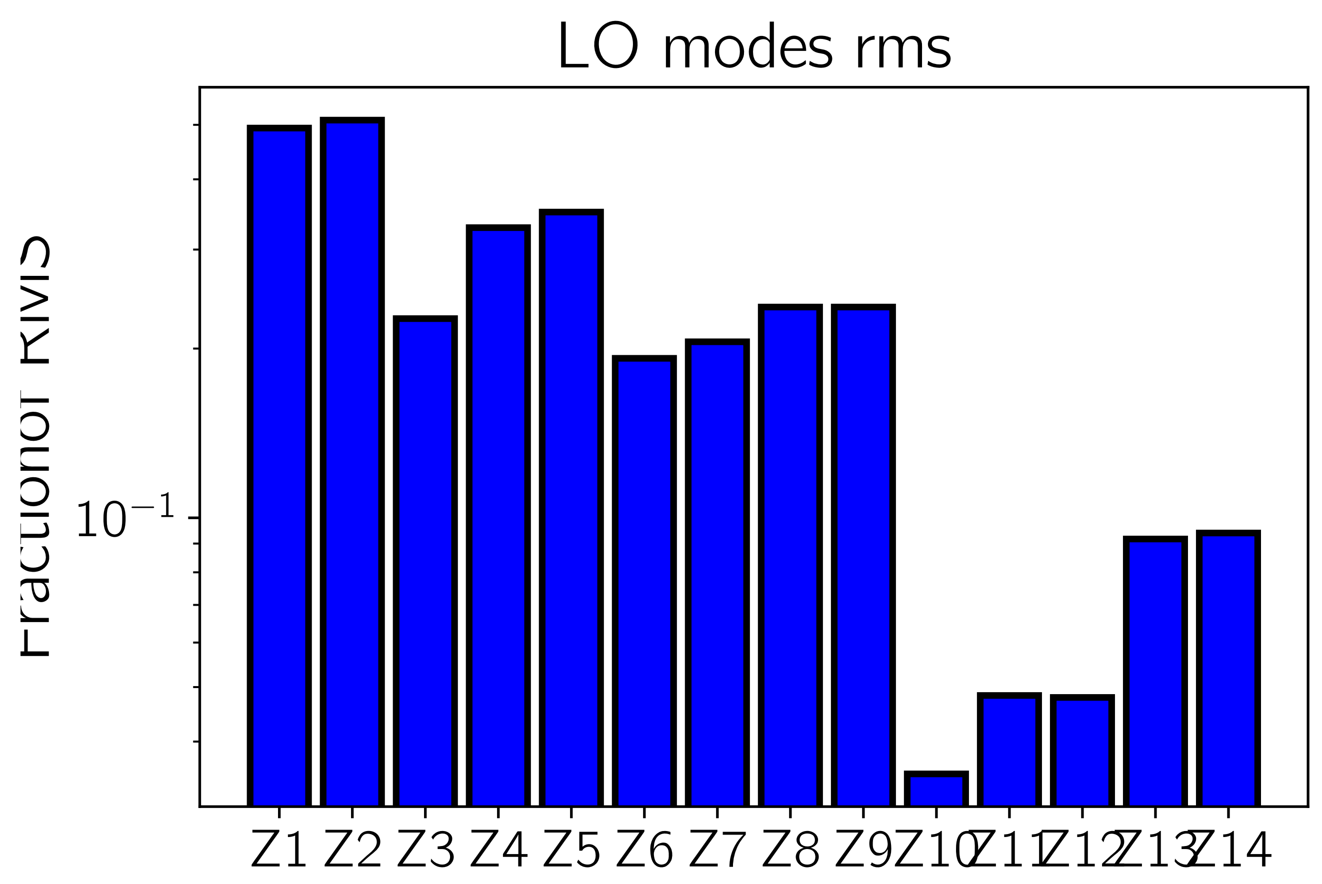
- When WFS history (recursive estimator), the difference in wavefront estimation covariance cannot be smaller than the inverse of the Fischer information:

$$P_{k+1} \geq \left(\mathscr{I}_{k+1} + (P_k + Q)^{-1}\right)^{-1} \quad (5)$$

Example of trades

Trade 1: LOWFS or focal plane maintenance with LUVOIR A

Relative Contribution of each mode.

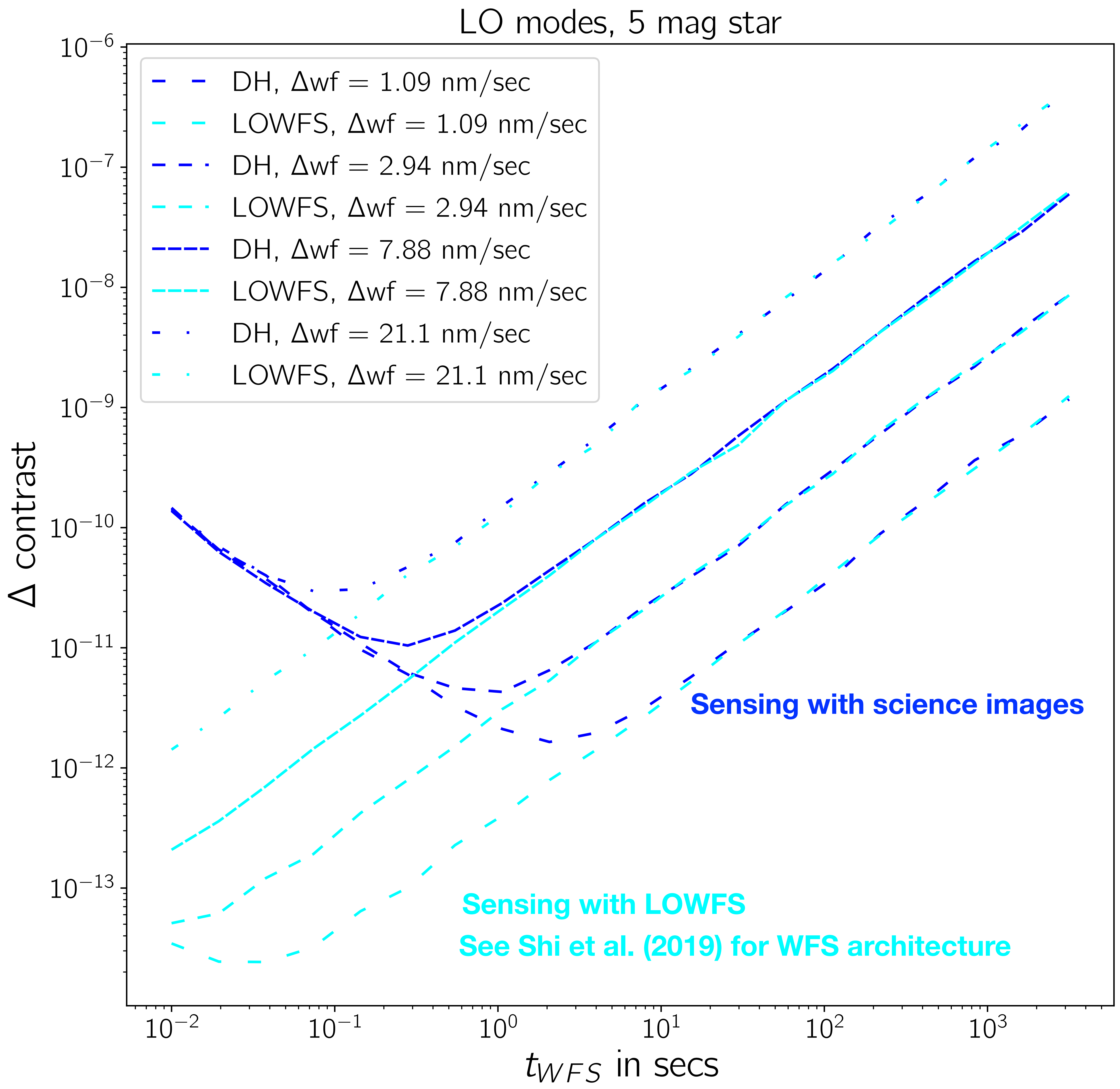


LO modes requirements with DH

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

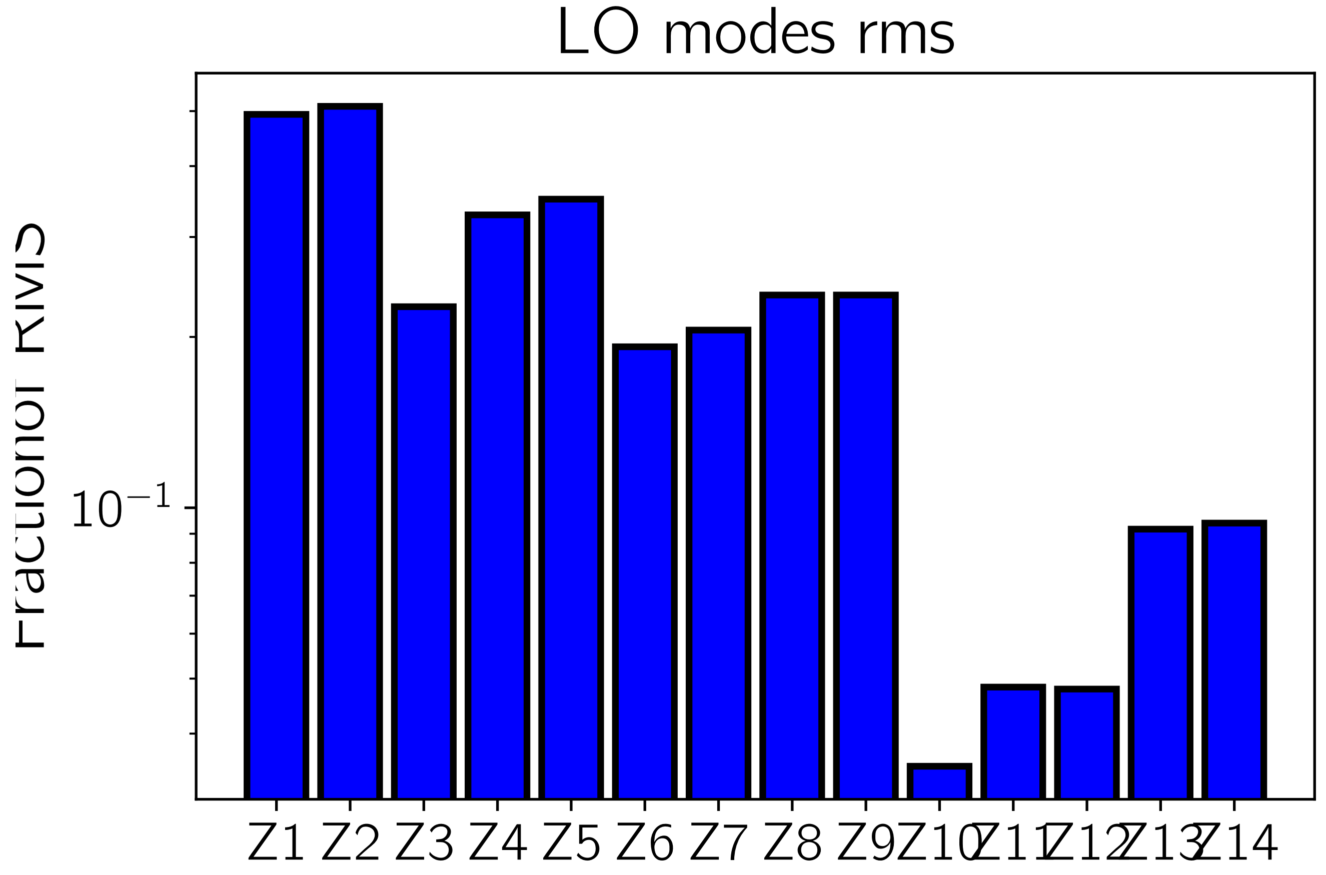
Mag 5 star, < 8 nm/sec, $t_{WFS} > 0.5$ sec.

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



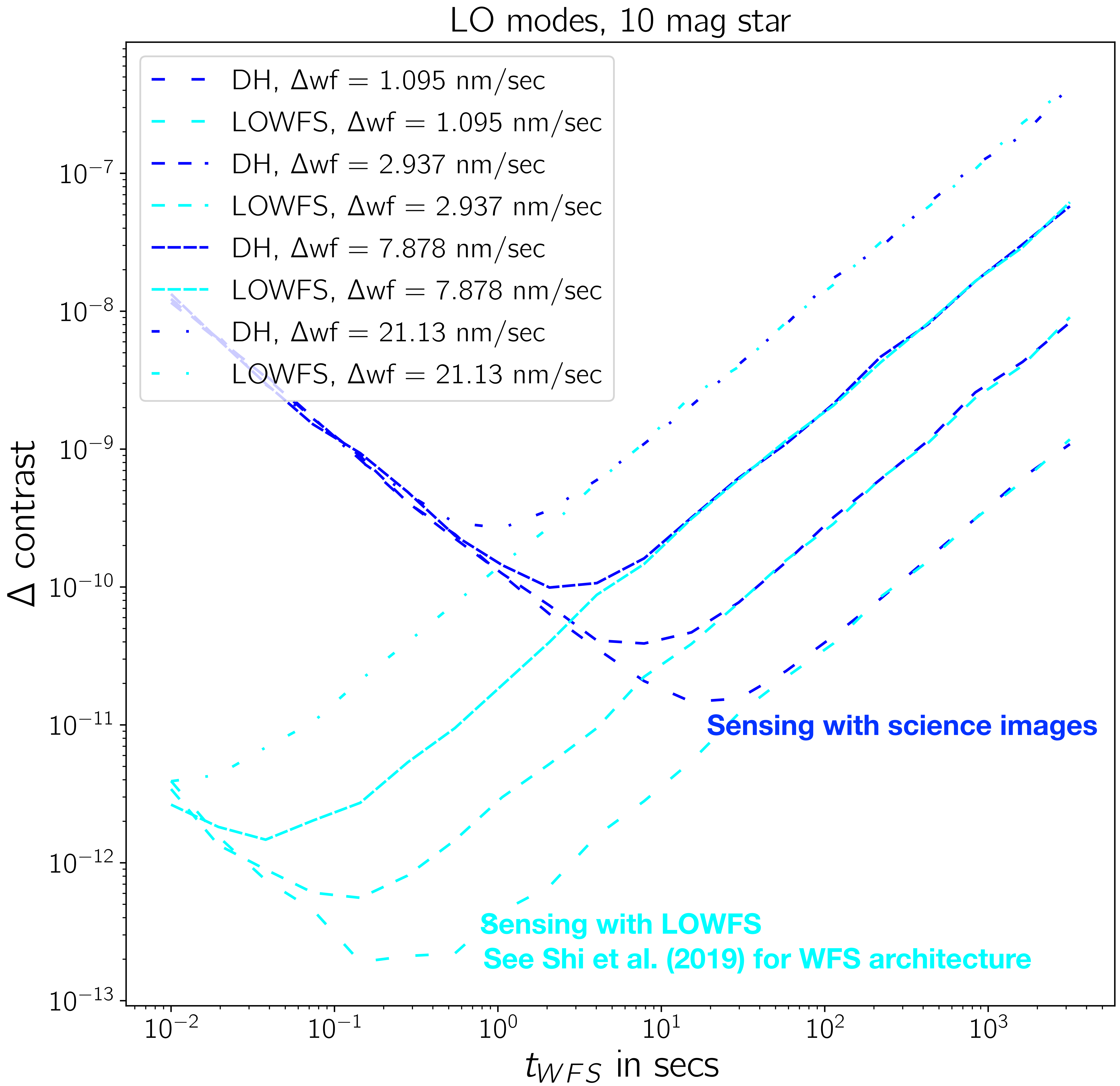
Trade 1: LOWFS or focal plane maintenance with LUVOIR A

Relative Contribution of each mode.



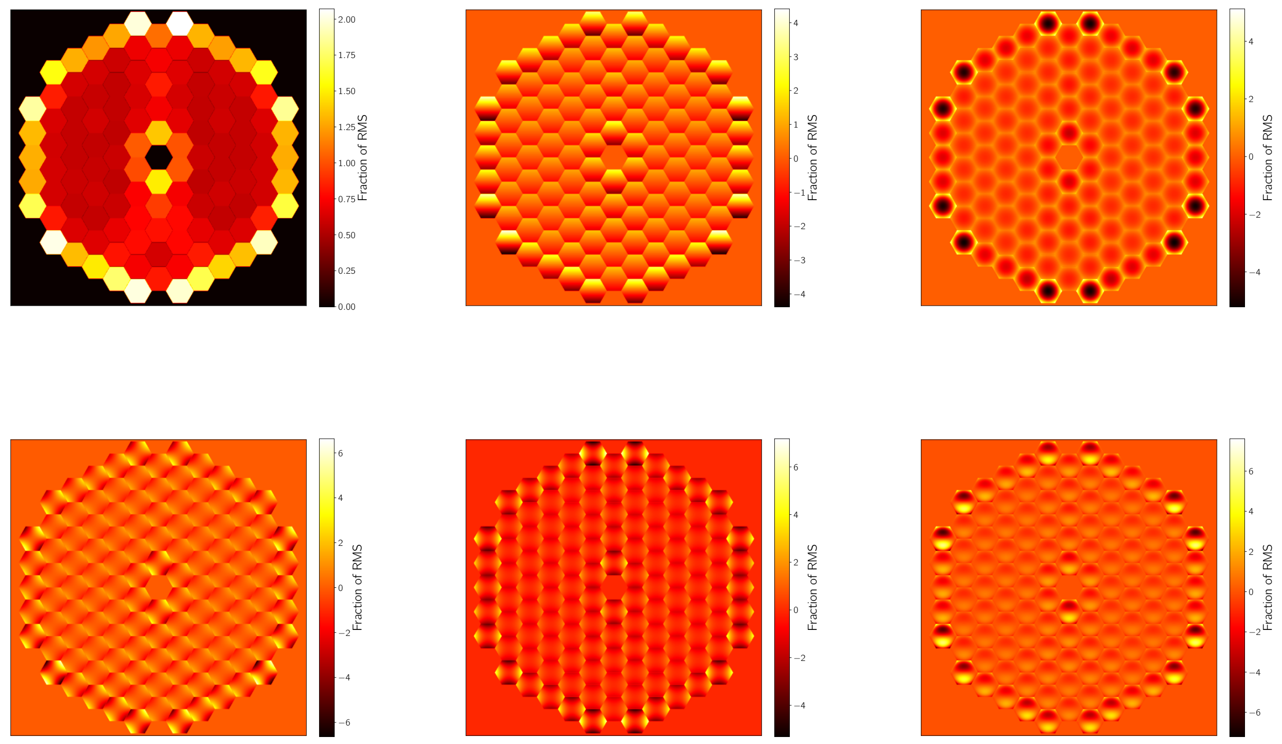
LO modes requirements with LOWFS

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



Trade 2: MIDWFS or focal plane maintenance for segment level errors

Relative Contribution of each mode.

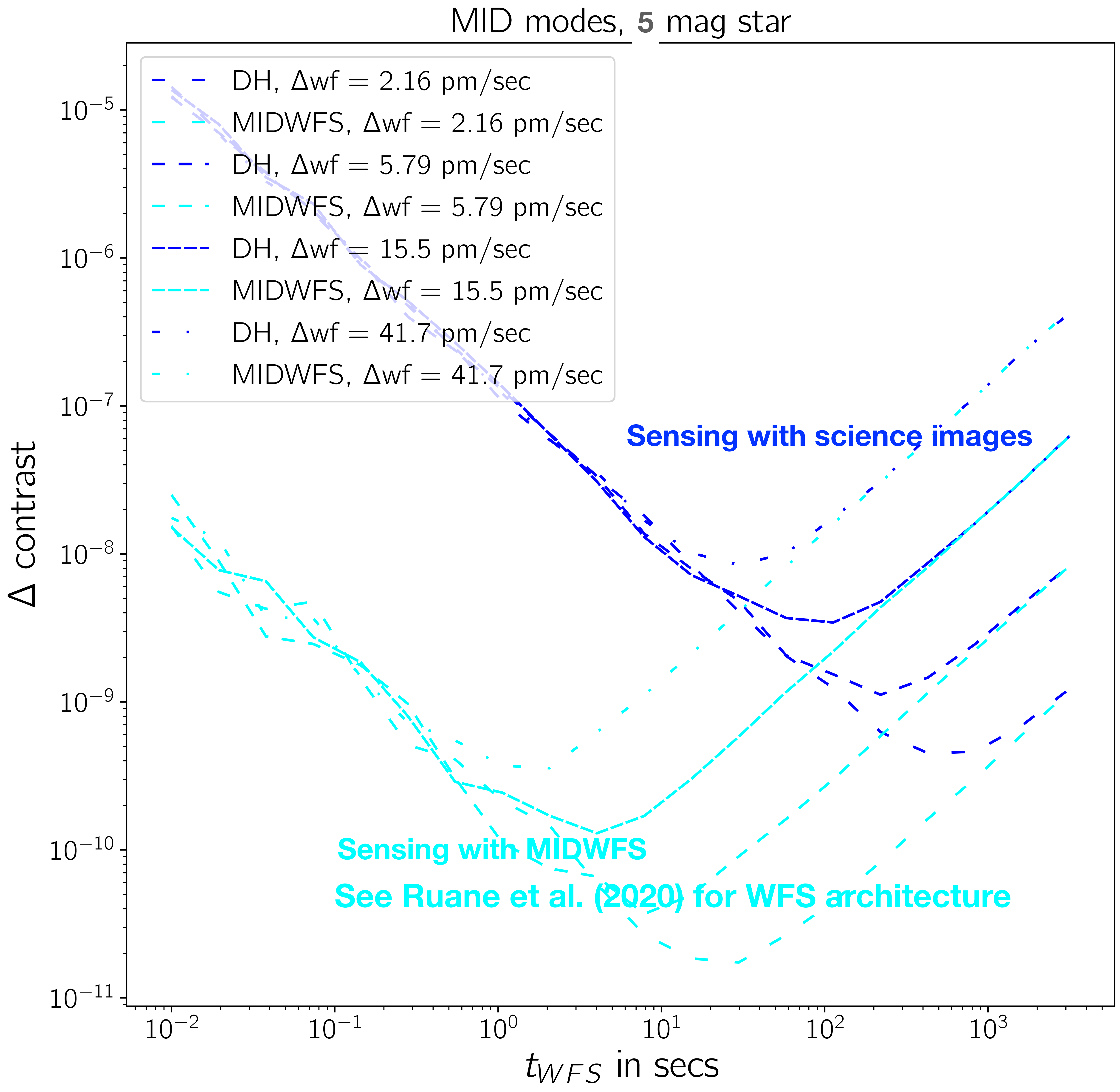


MID modes requirements with MIDWFS

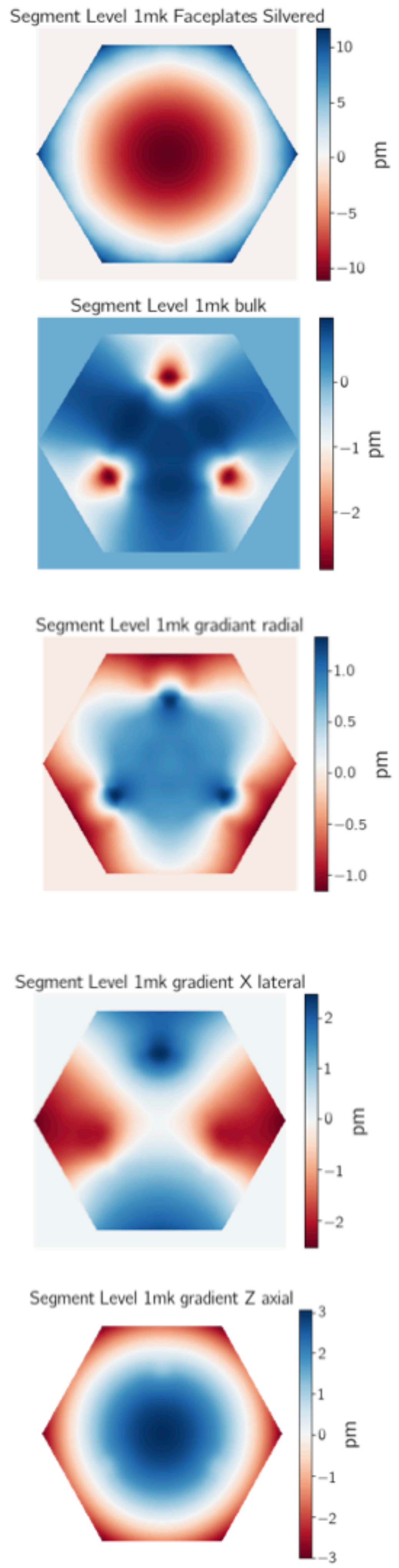
Mag 0 star, < 15 pm/sec, $t_{WFS} > 0.5$ sec.

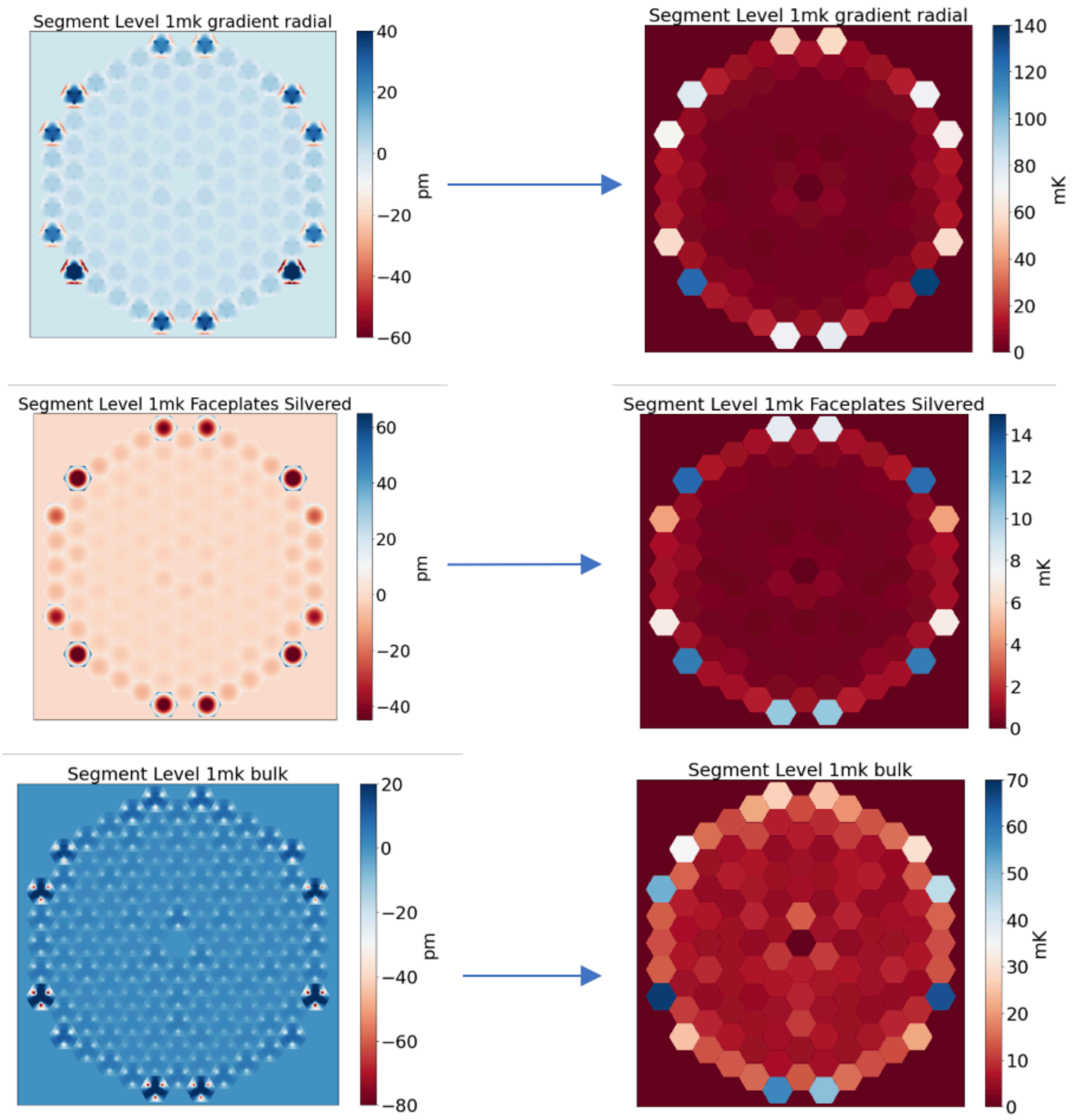
Mag 5 star, < 2 pm/sec, $t_{WFS} > 20$ sec.

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

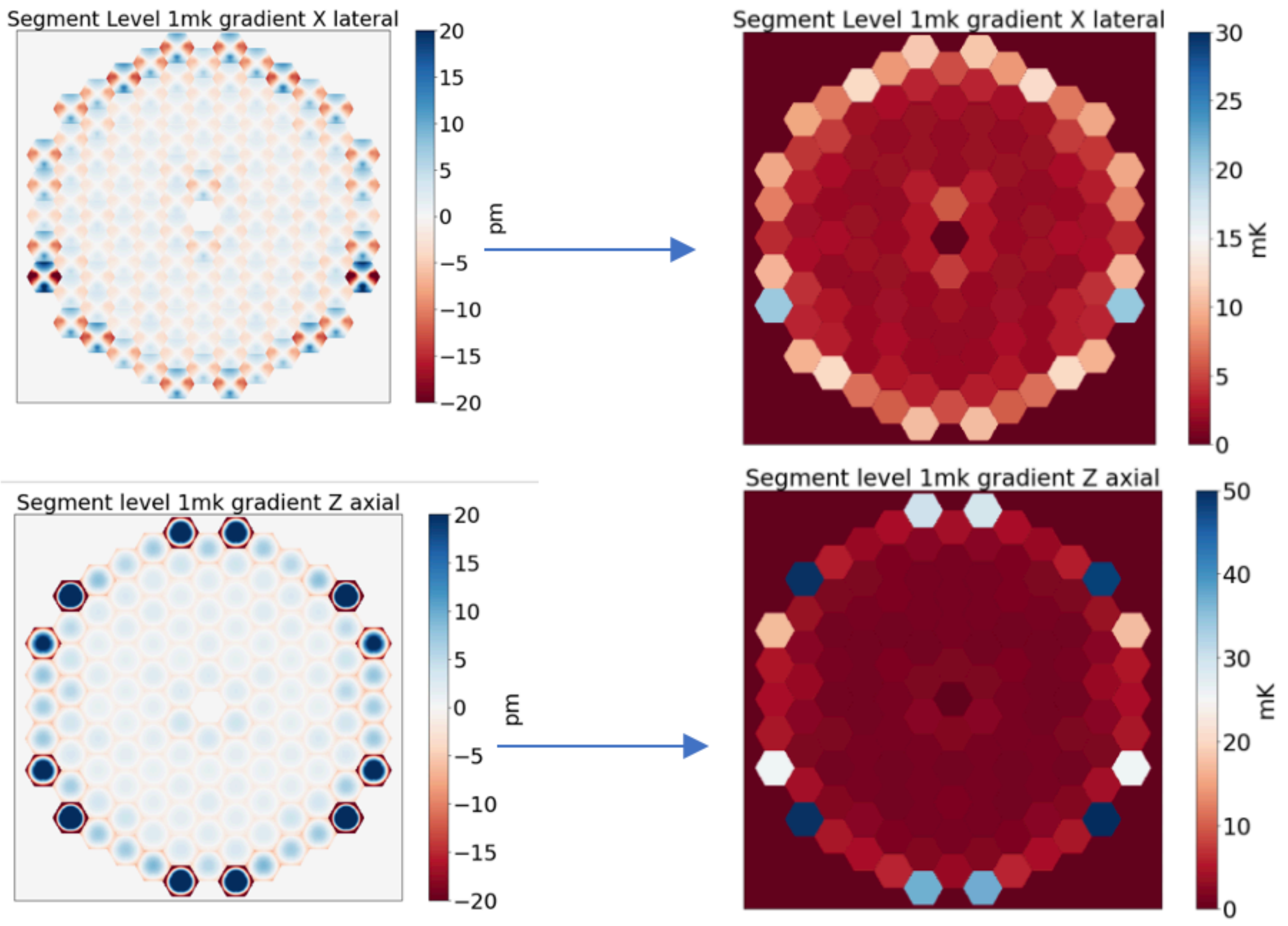


Trade 3: Representation of segment level errors



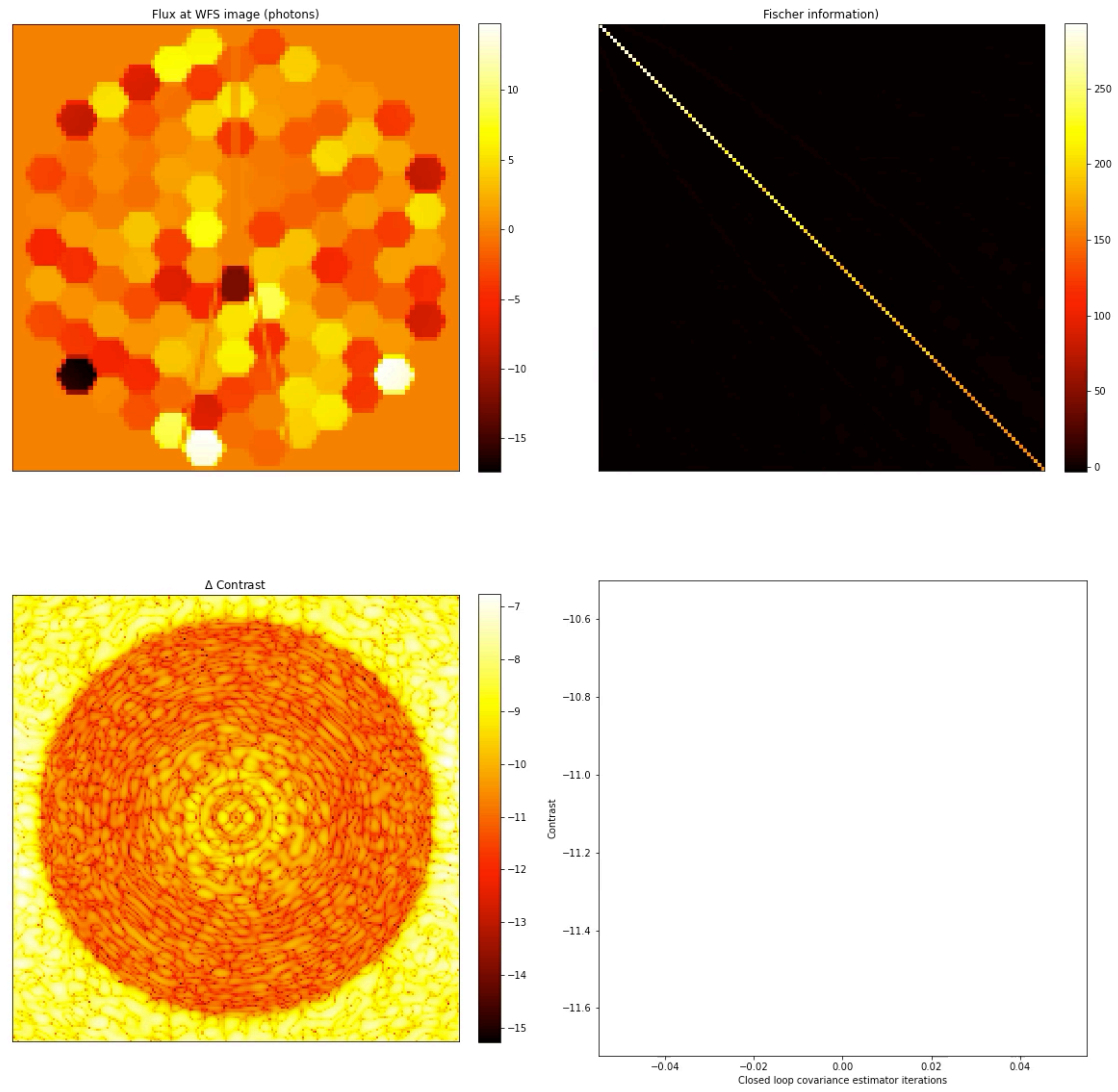


Sahoo et al. (2022)

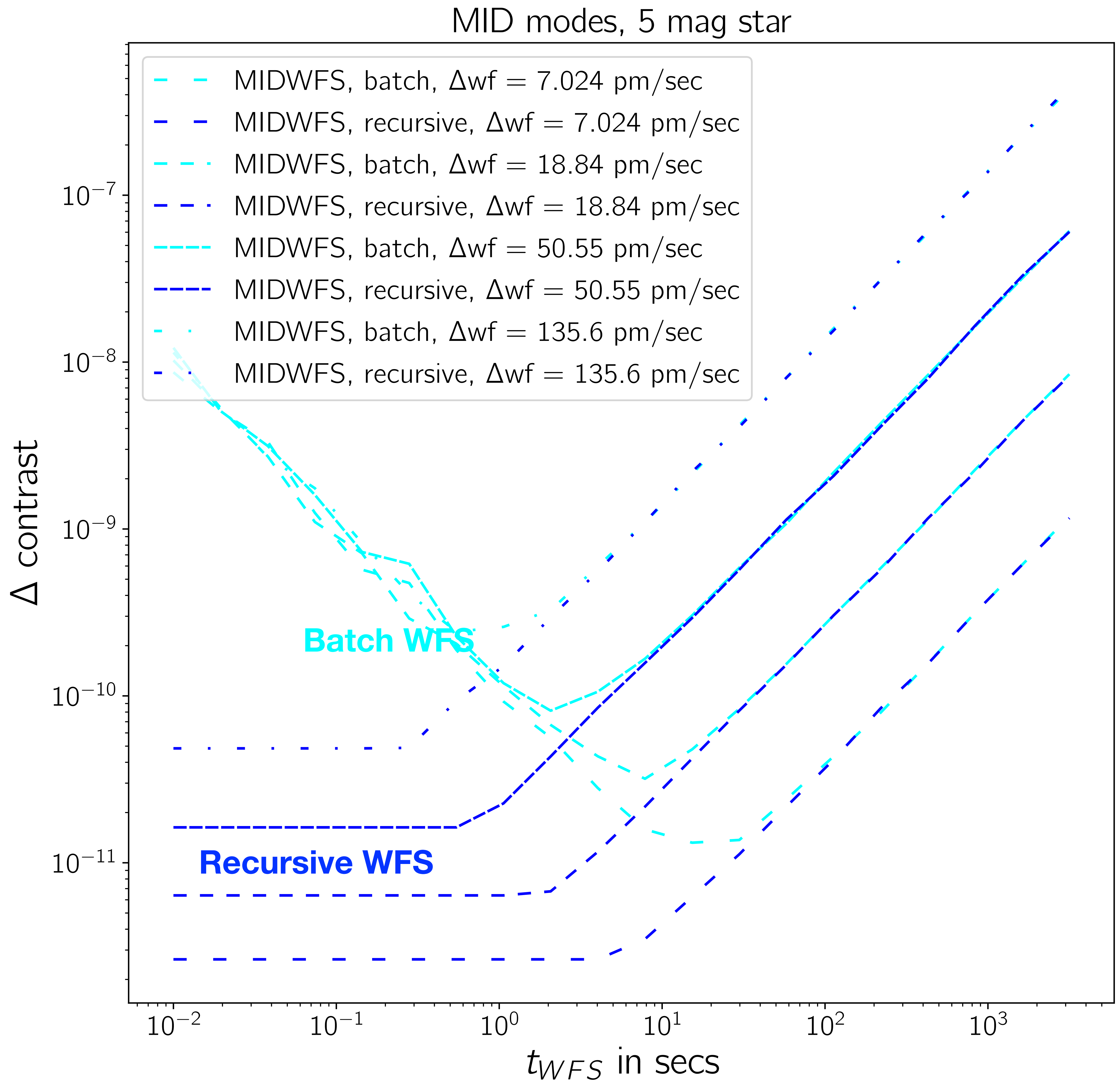


We find that thermal drifts requirements are of ~5 mK over timescales of 10s of seconds to minutes

Trade 4: OBWFS maintenance for segment pistons with LUVOIR A, changing sensing algorithm



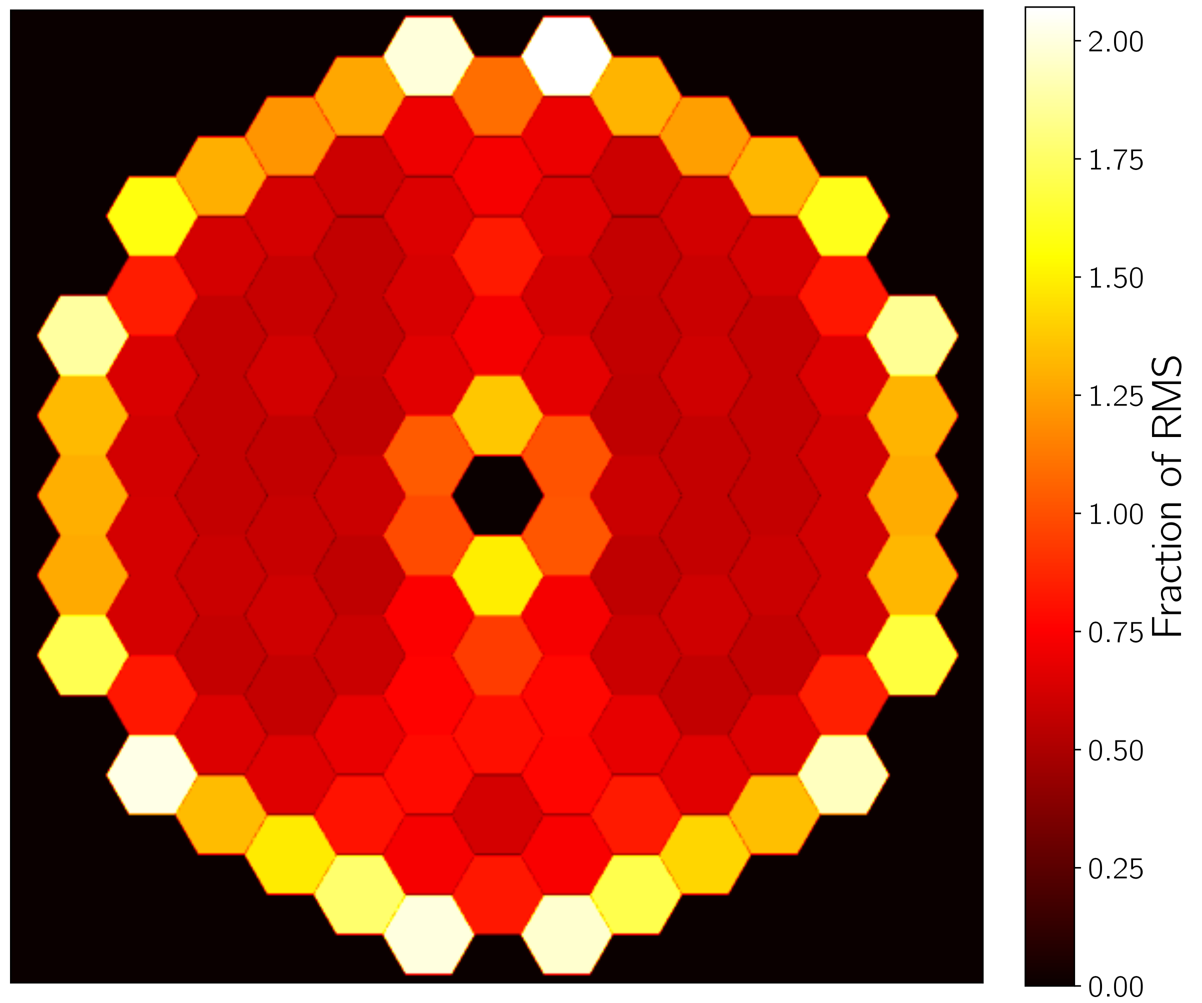
10 milli-seconds exposure



Recursive sensing and predictive control enable shorter exposure time on fainter stars.

Trade 4: OBWFS maintenance for segment pistons with LUVOIR A, changing sensing algorithm

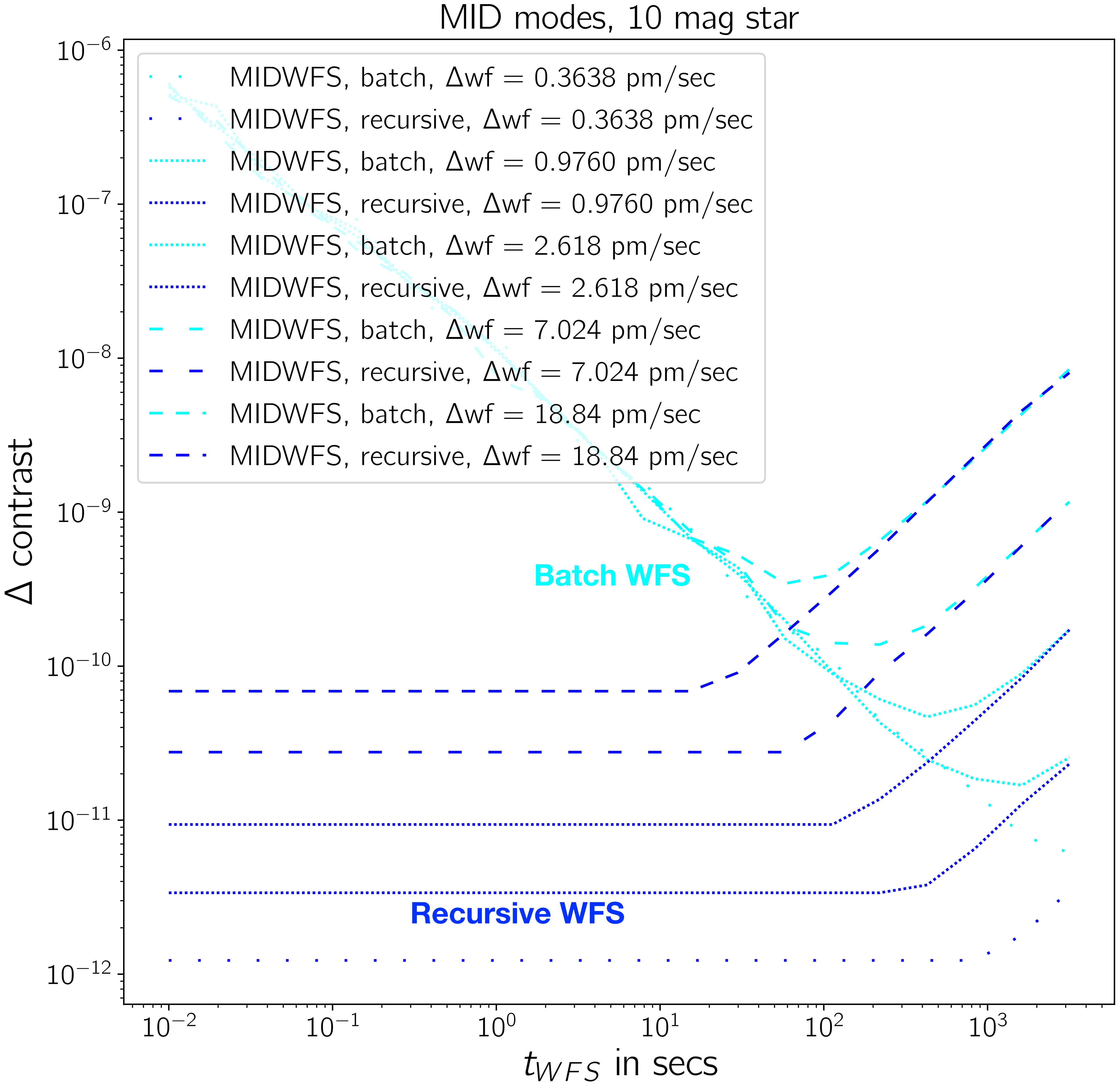
Relative Contribution of each mode.



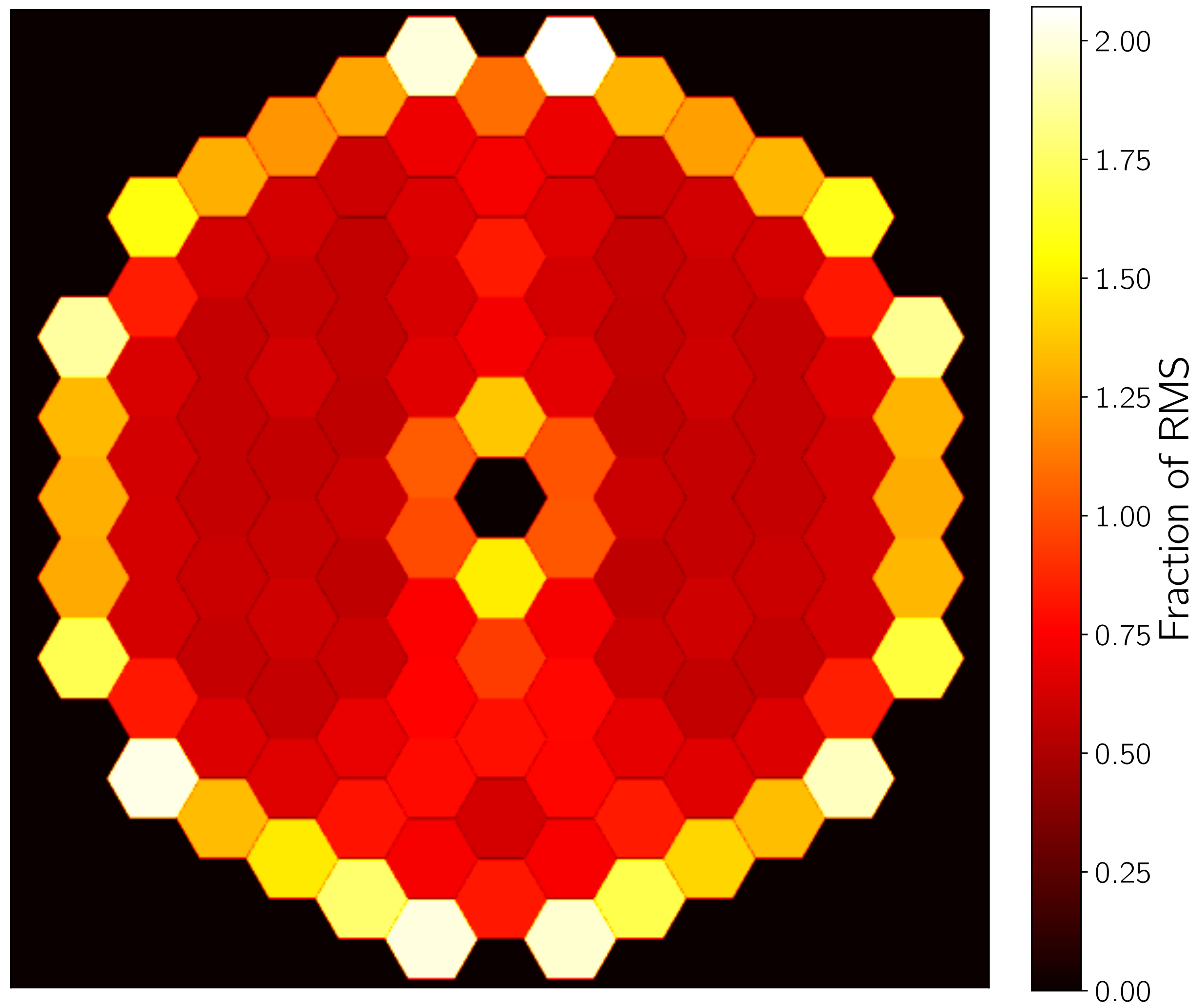
MID modes requirements with MIDWFS

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

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



Trade 5: Influence of detector noise

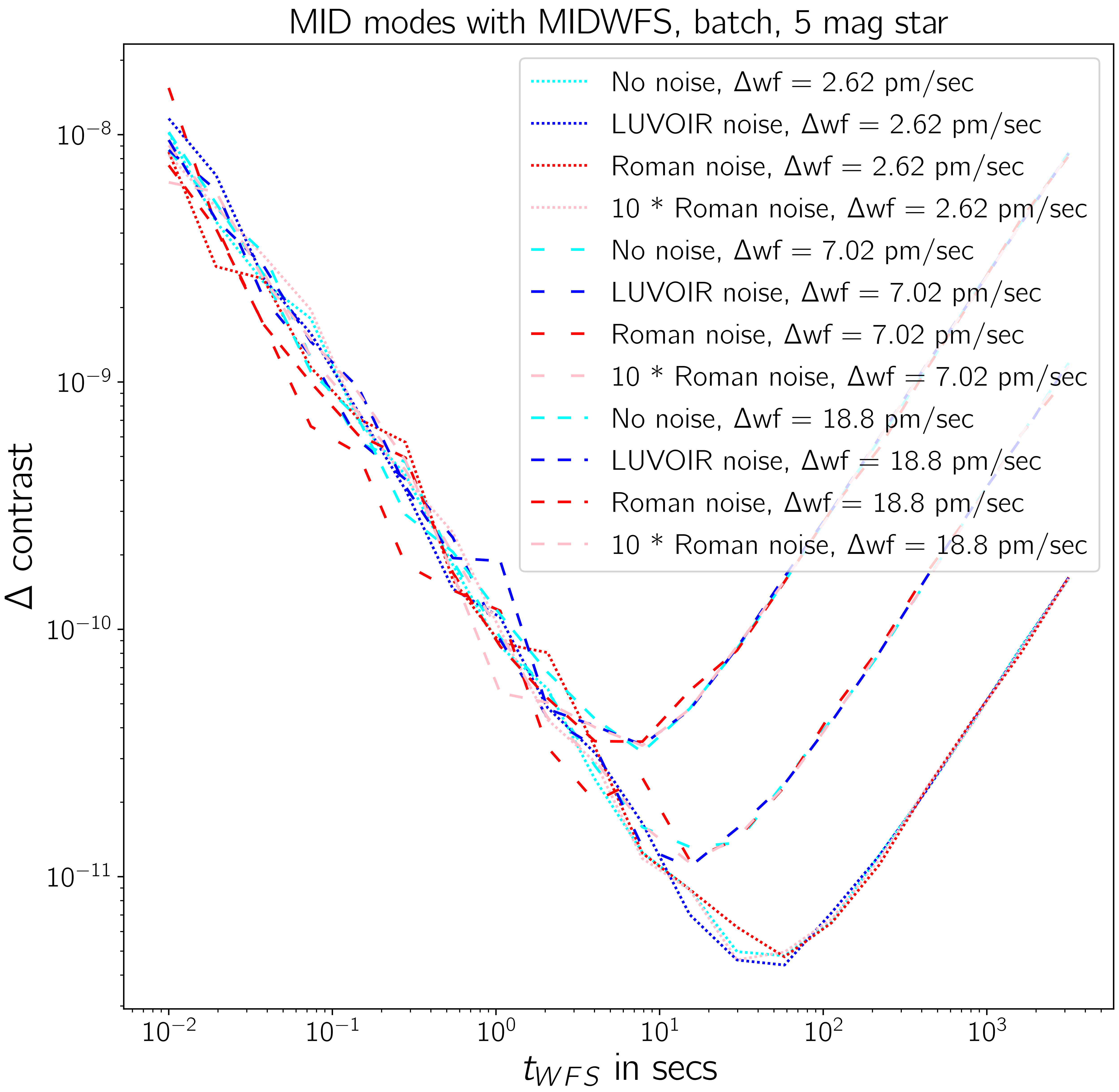


Detector noise does not affect MIDWFS.

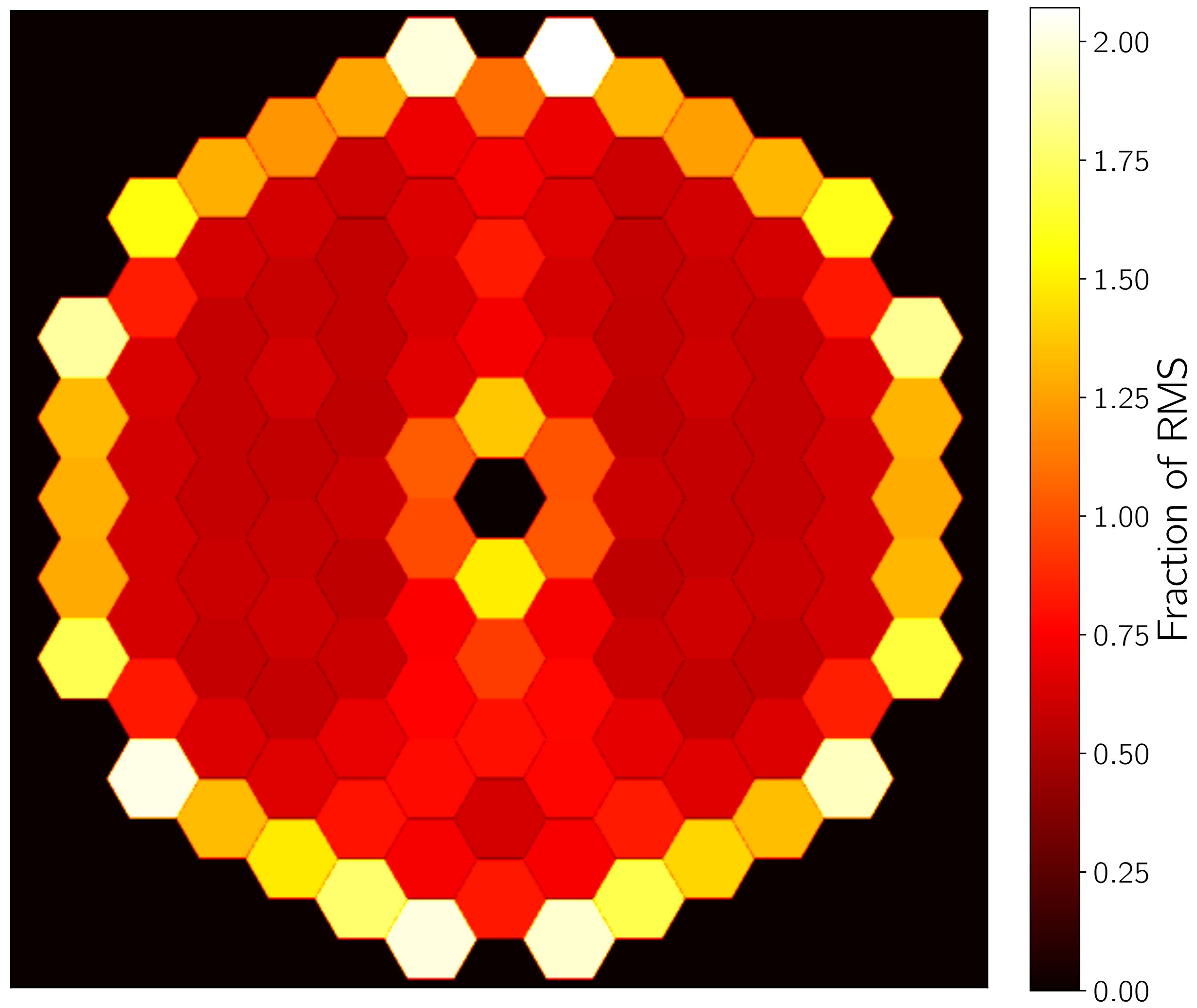
Detector noise affects Dark Hole maintenance with science images.

MID modes requirements with MIDWFS

Mag 5 star, < 15 pm/sec, $t_{WFS} > 10$ sec.



Trade 5: Influence of detector noise

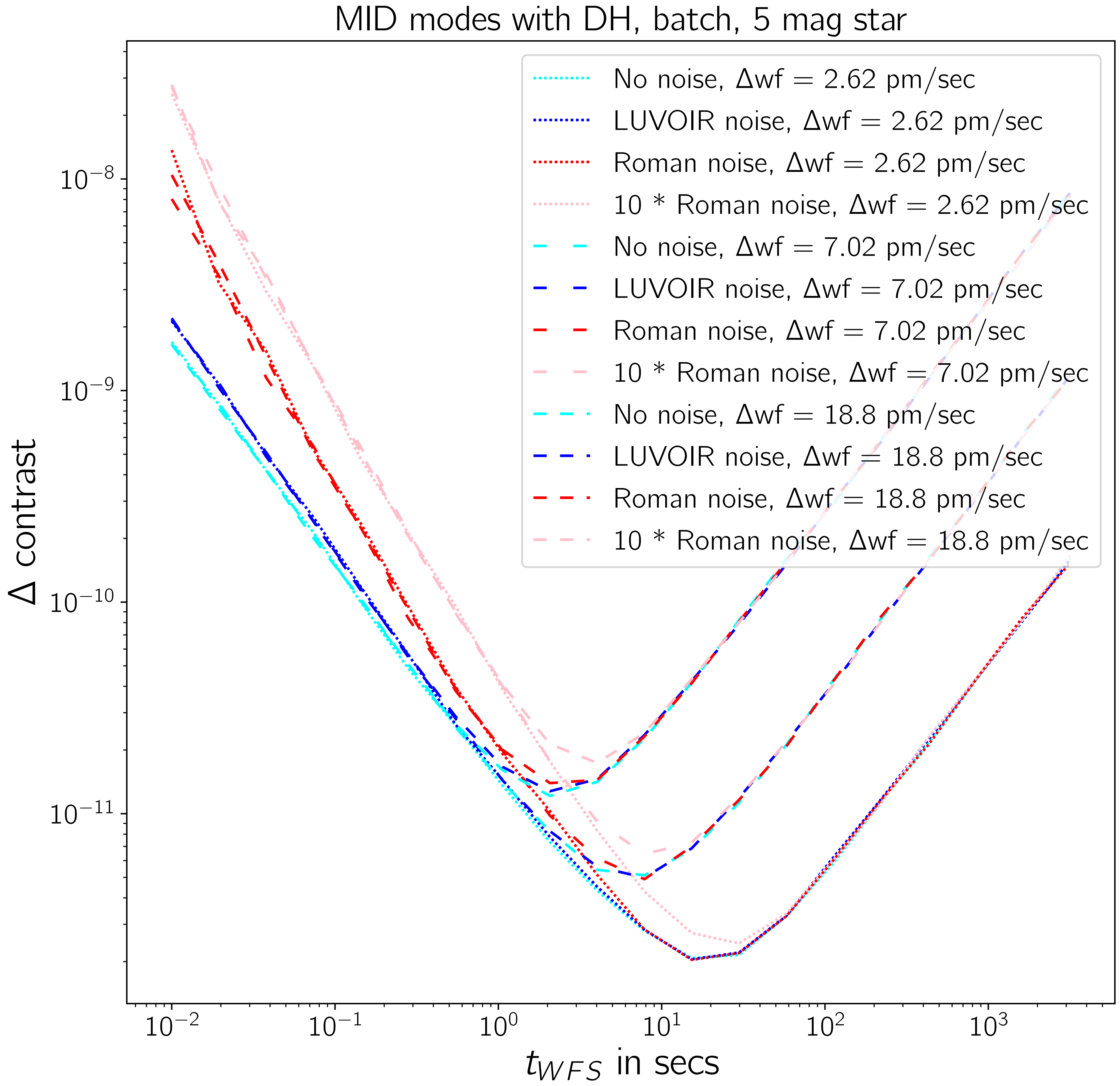


Detector noise does not affect MIDWFS.

Detector noise affects Dark Hole maintenance with science images.

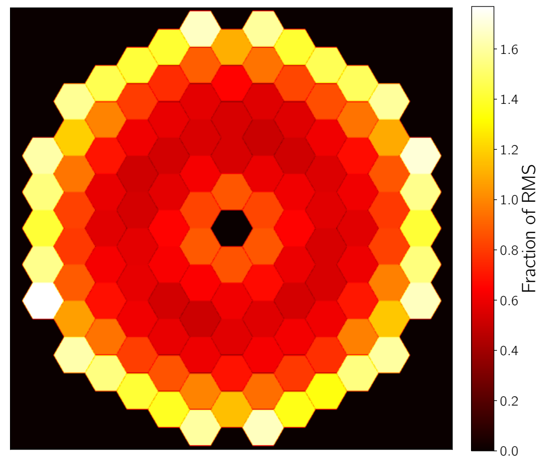
MID modes requirements with MIDWFS

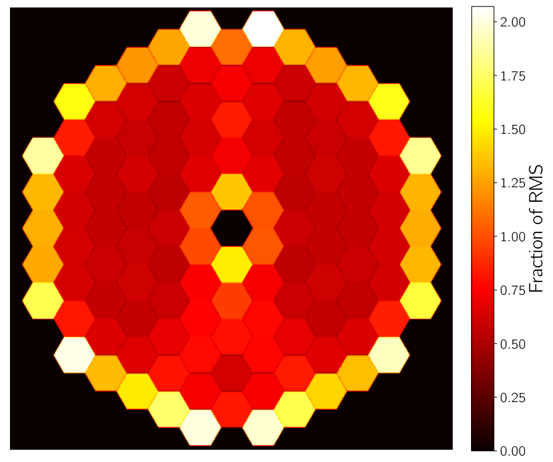
Mag 5 star, < 15 pm/sec, $t_{WFS} > 10$ sec.

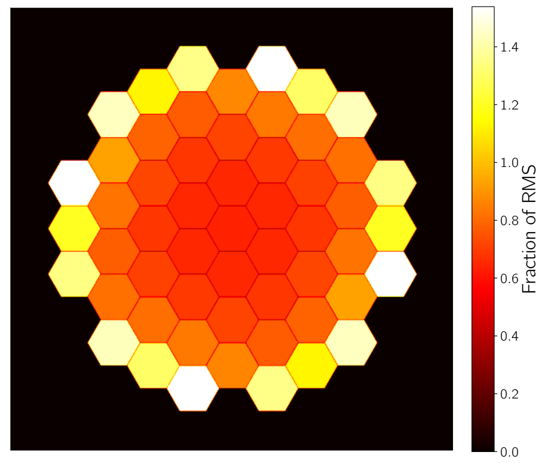


Trade 6: Changing the coronagraph and telescope

Relative Contribution of each mode.





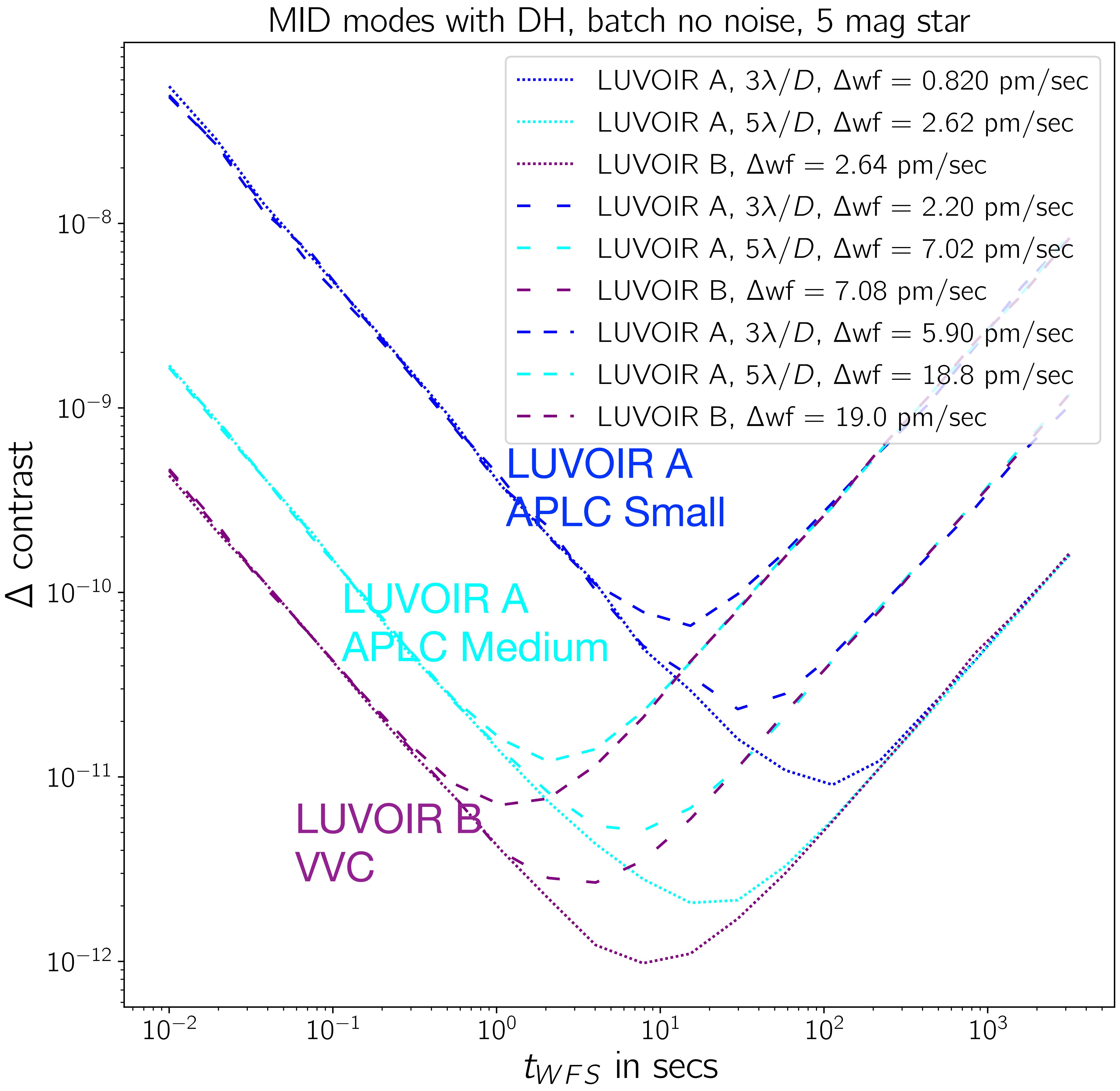


MID modes requirements

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

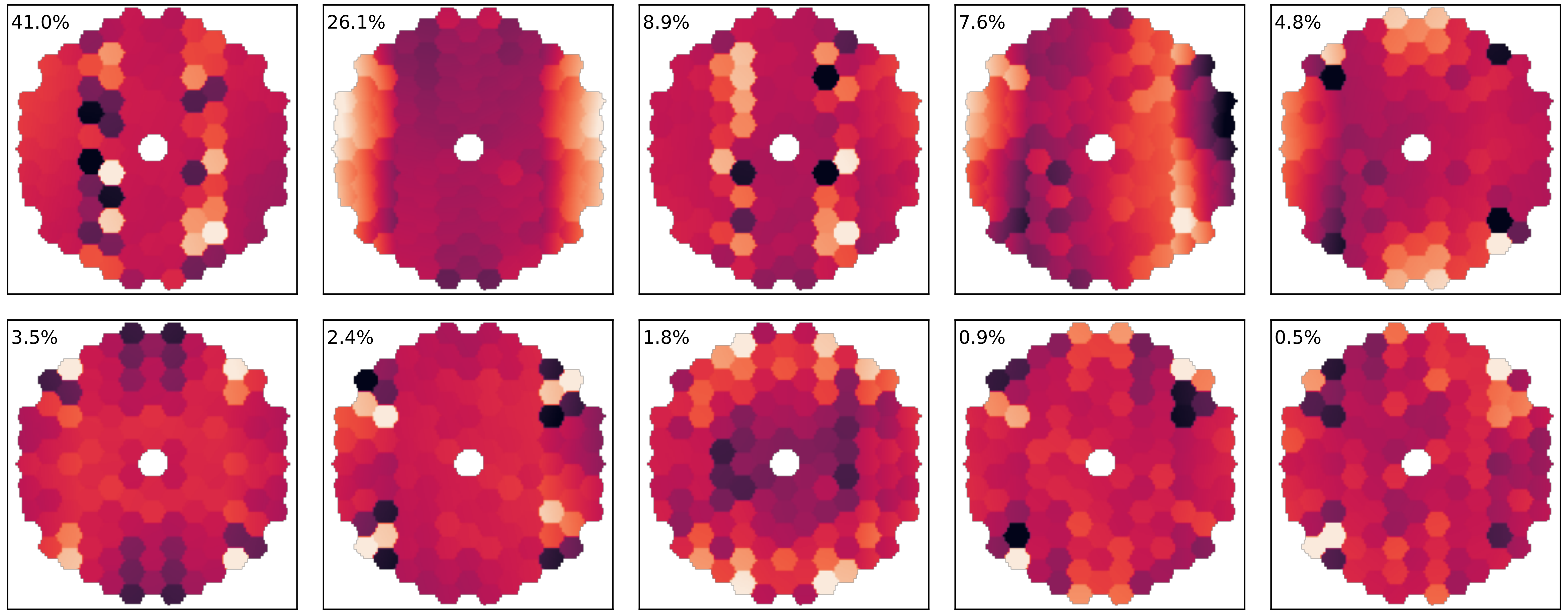
LUVOIR A $3\lambda/D$, < 0.9 pm/sec, $t_{WFS} > 100$ sec.

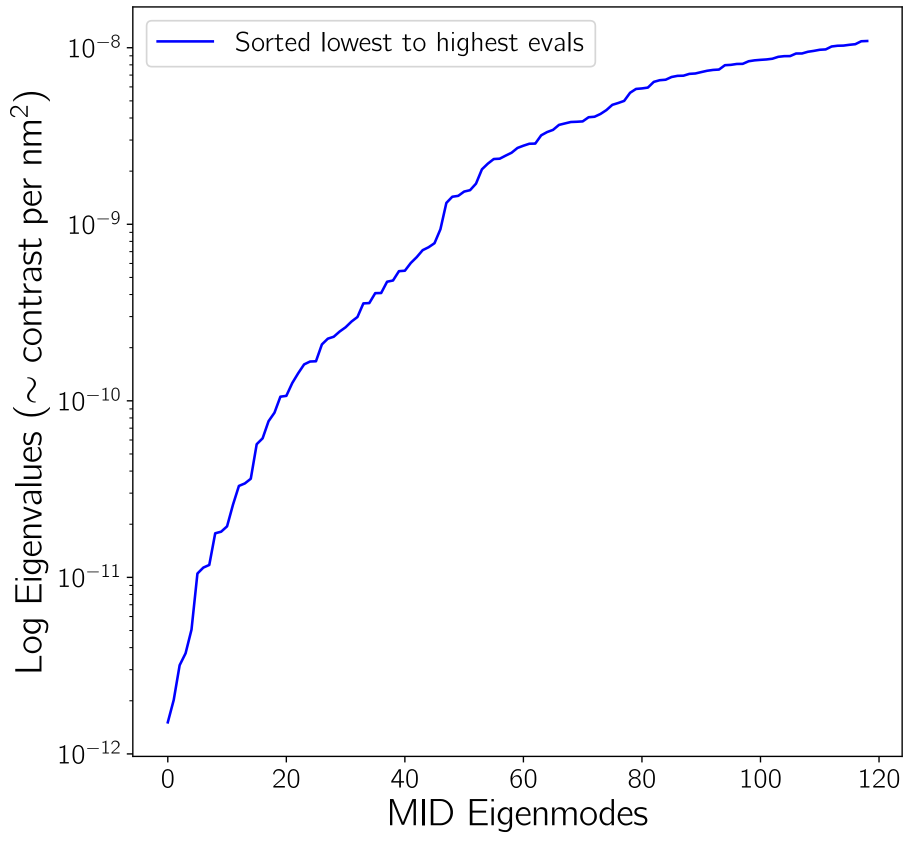
LUVOIR B, < 20 pm/sec, $t_{WFS} > 1$ sec.



Trade 7: Looking at vibrations (short time scales)

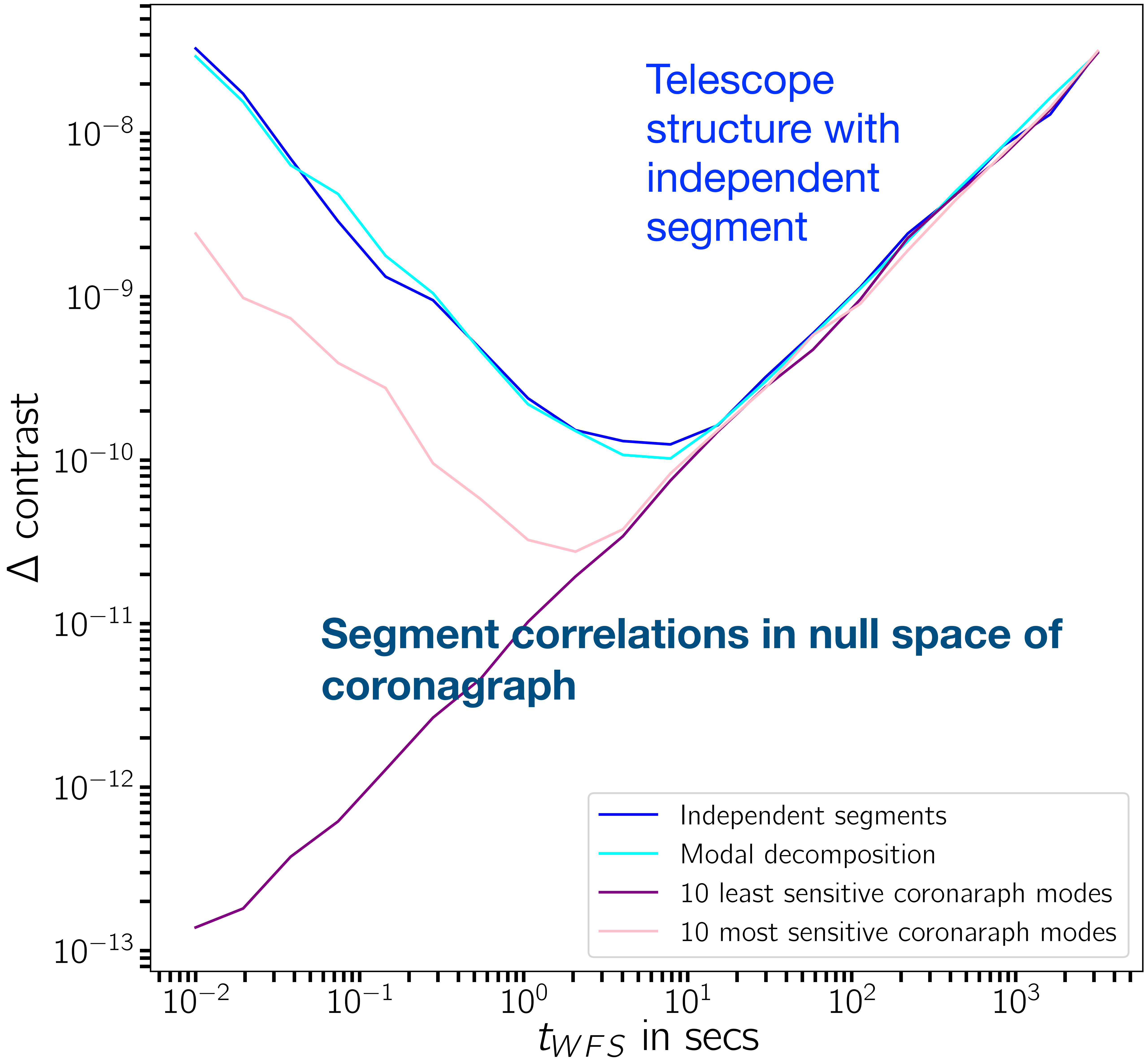
When vibrating, segments are not independent

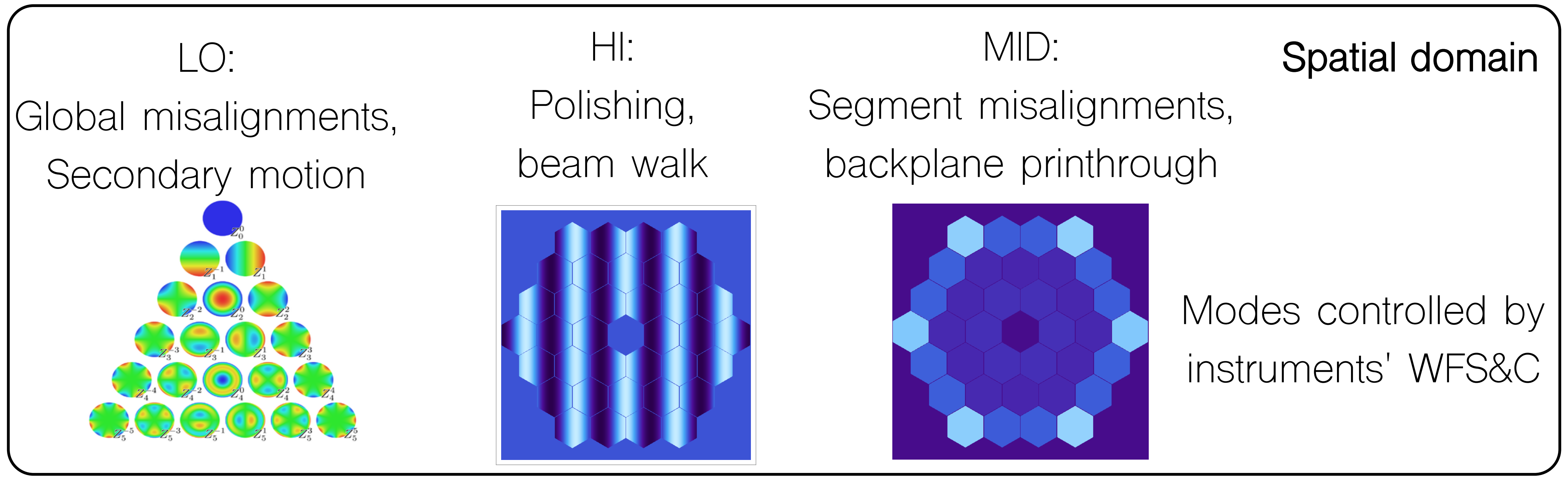


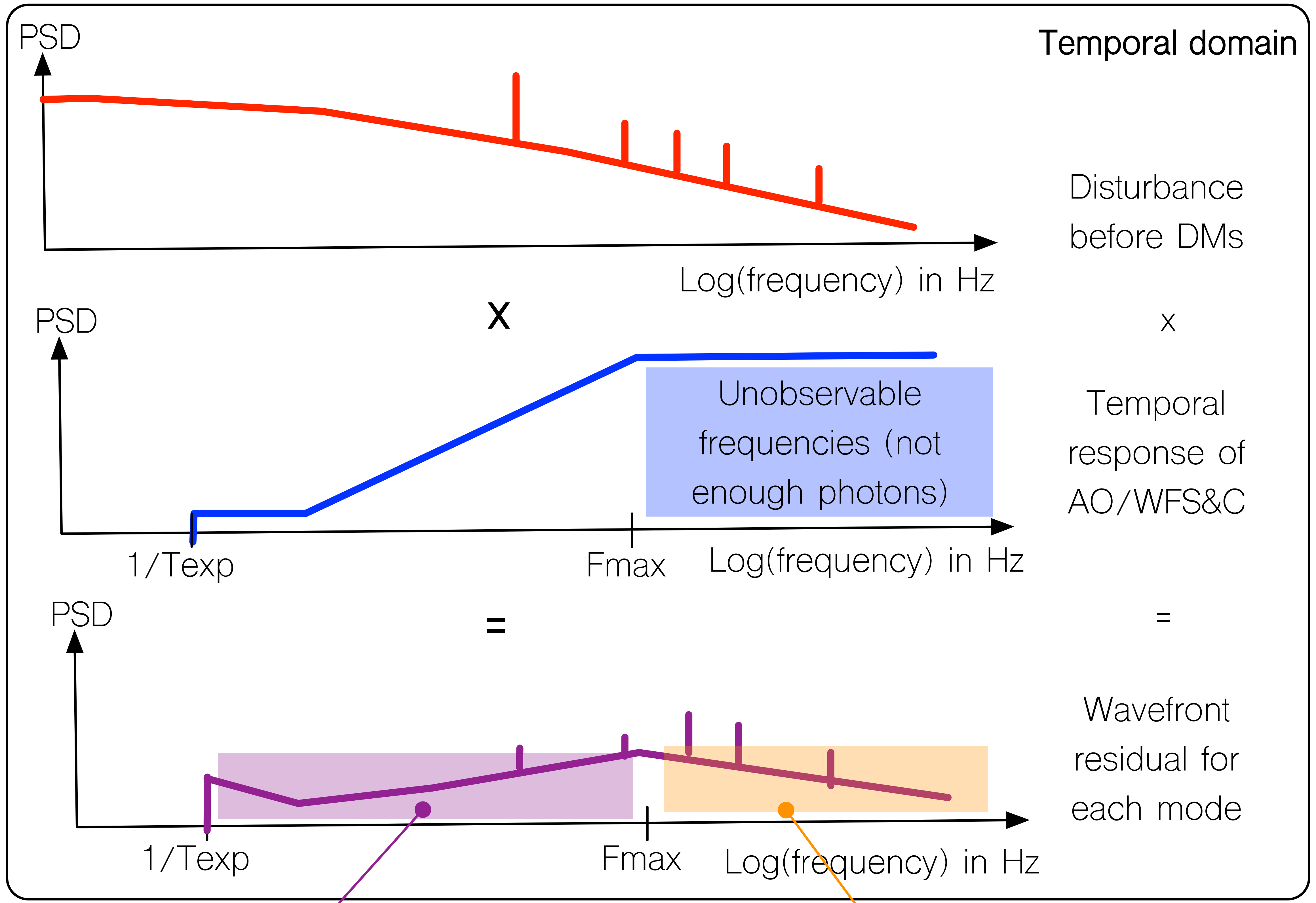


Potier et al. (2021

- **This means that we can use the full telescope for sensing, not just each segment.**
- **Depending on their morphology, correlated structures at primary leak more or less through the coronagraph**







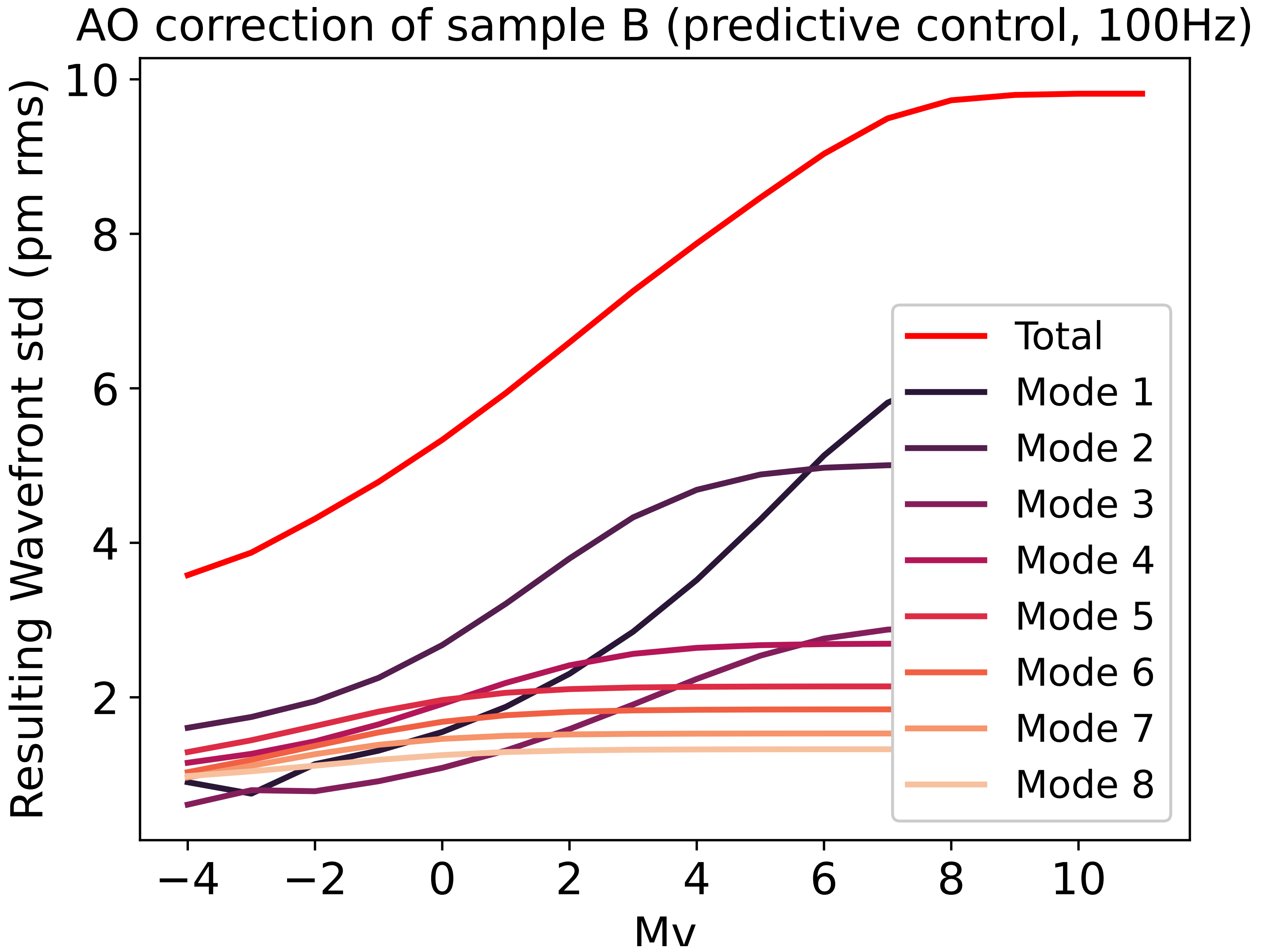
AO/WFS&C residuals

Can be reduced using optimized WFS architectures, predictive control

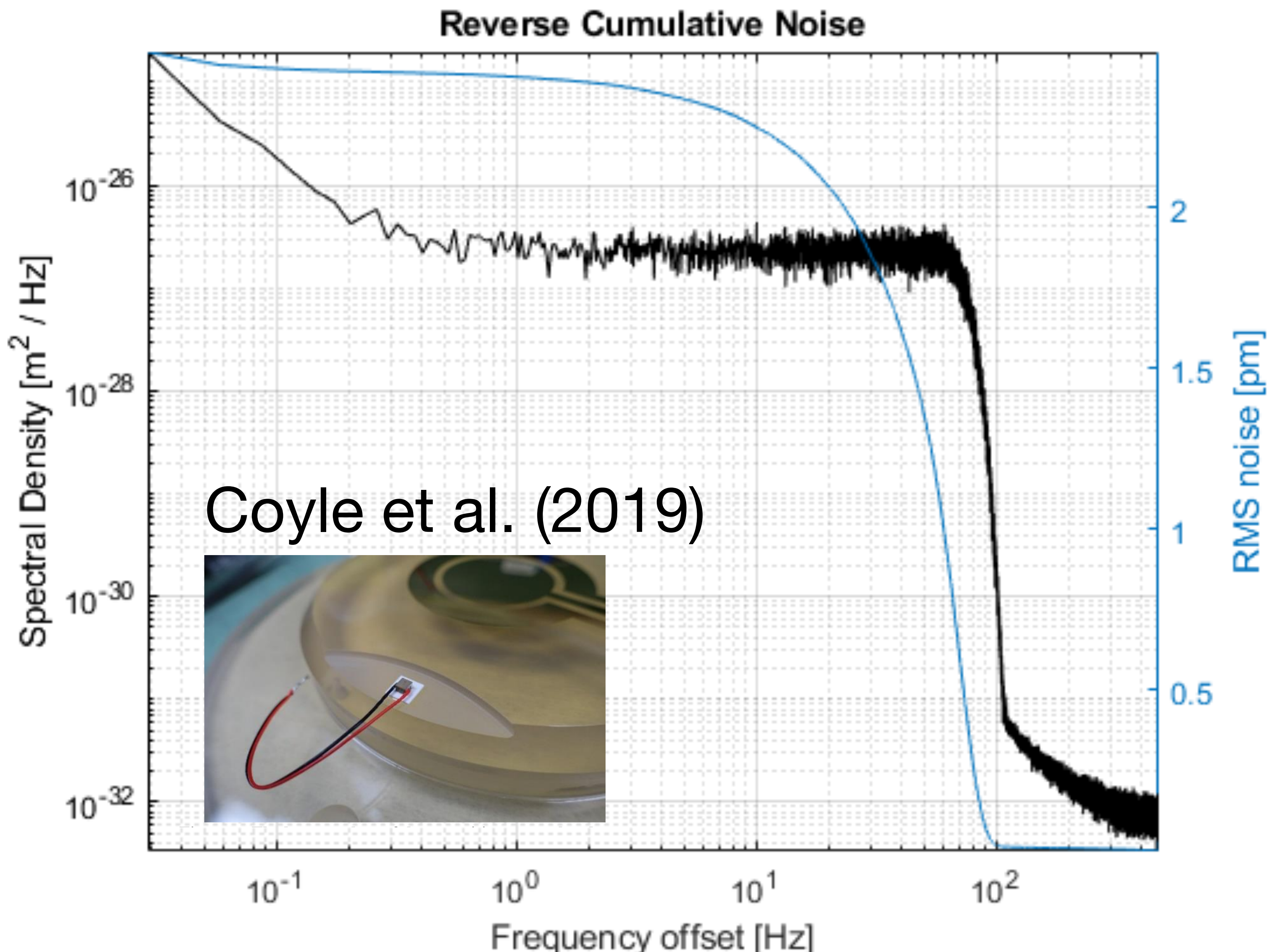
Unobservable Residuals

Damped either in open loop (thermal/ structural stability) or using telescope metrology

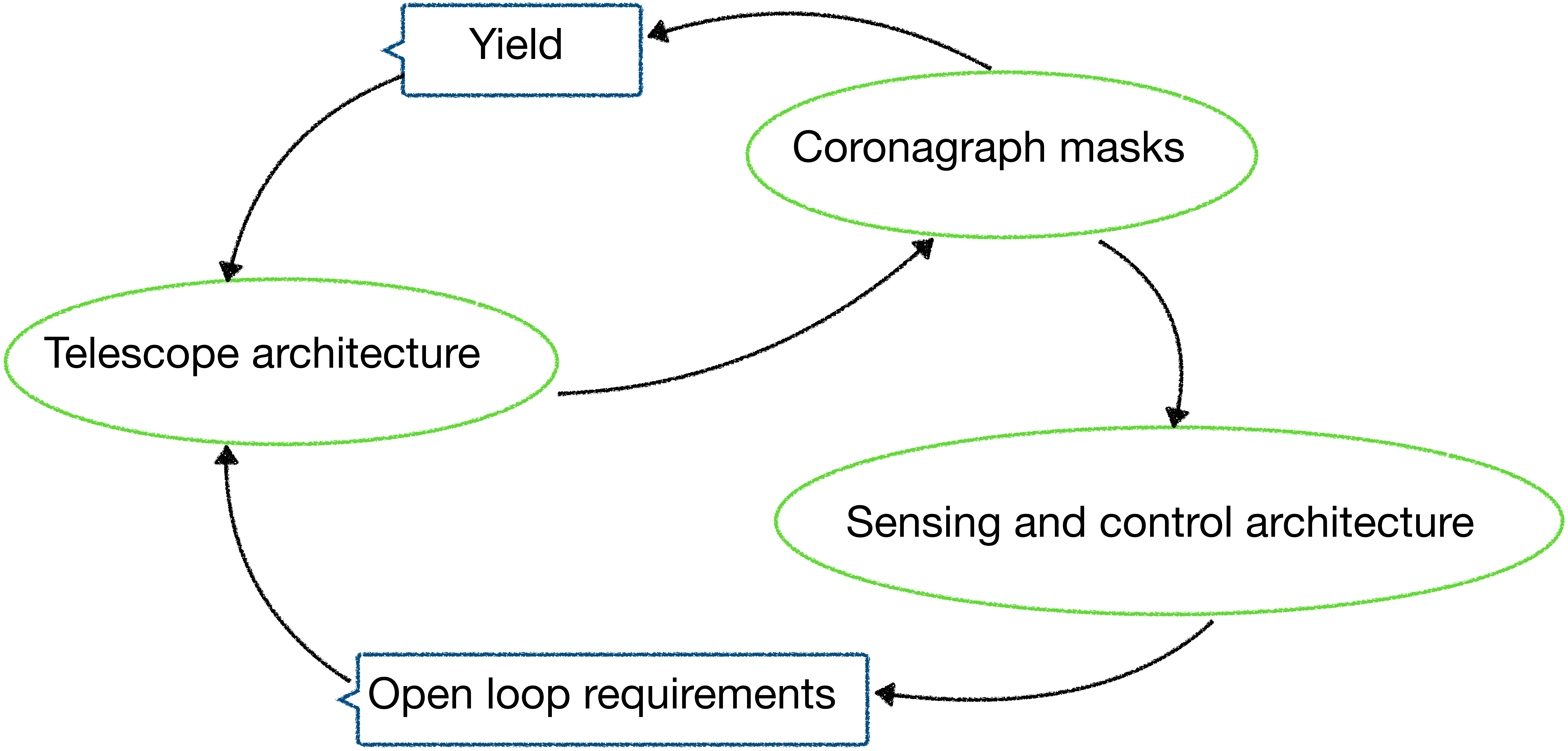
Laser or natural guide star metrology



Edge sensor metrology



Conclusion: we are not breaking any laws of physics ….



…. but we need to optimize a complex system