Wavefront sensing and control for future missions

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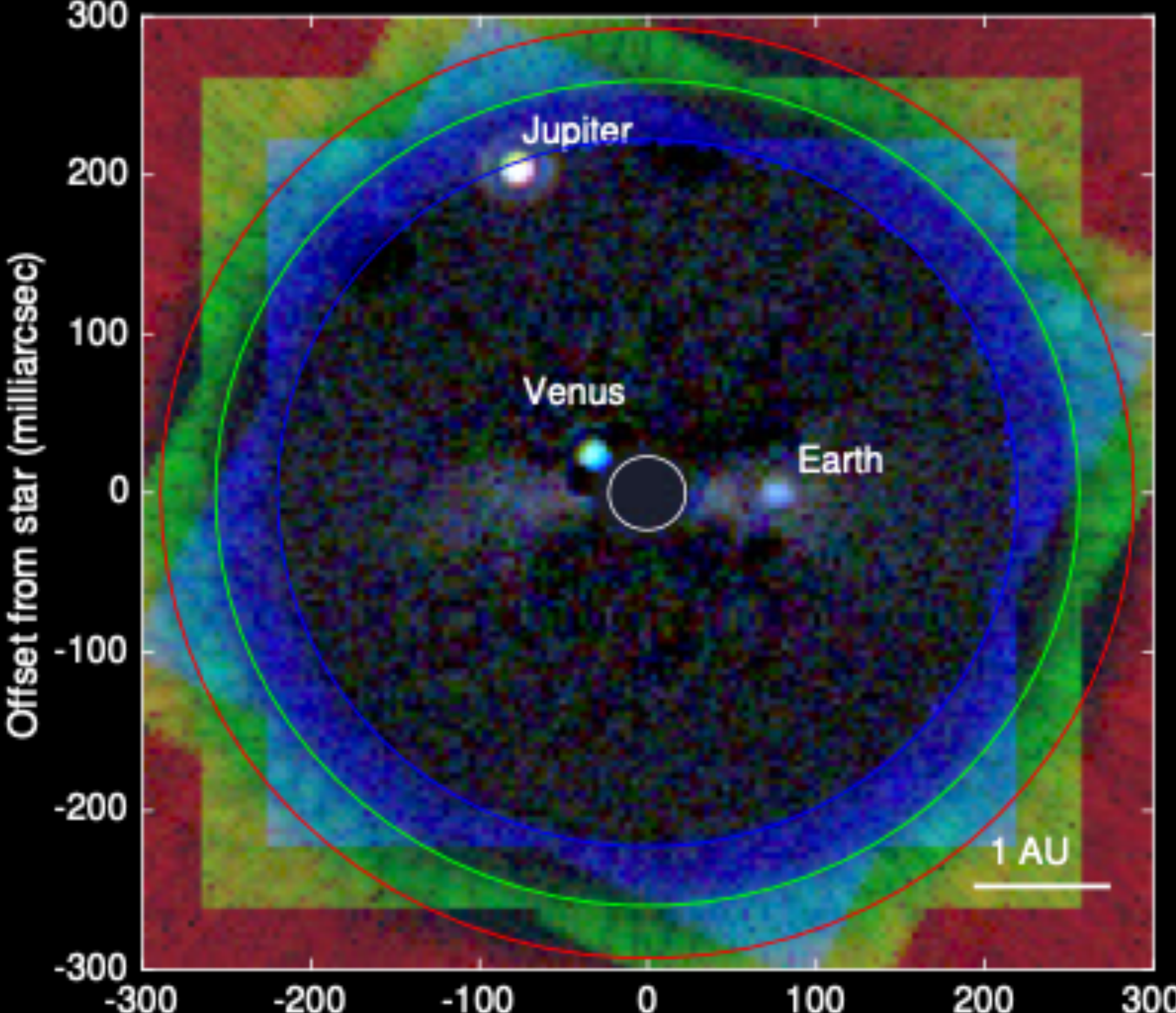
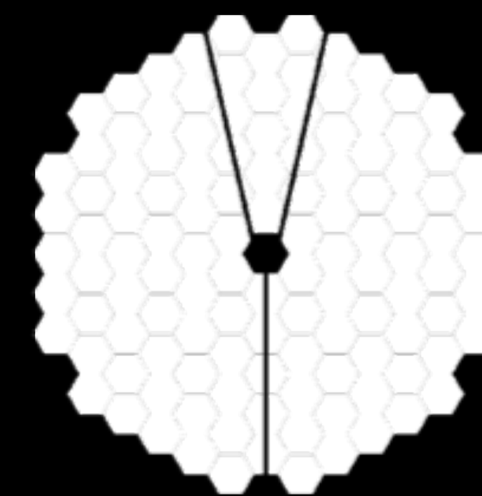
5/1/2020

Why doing this?

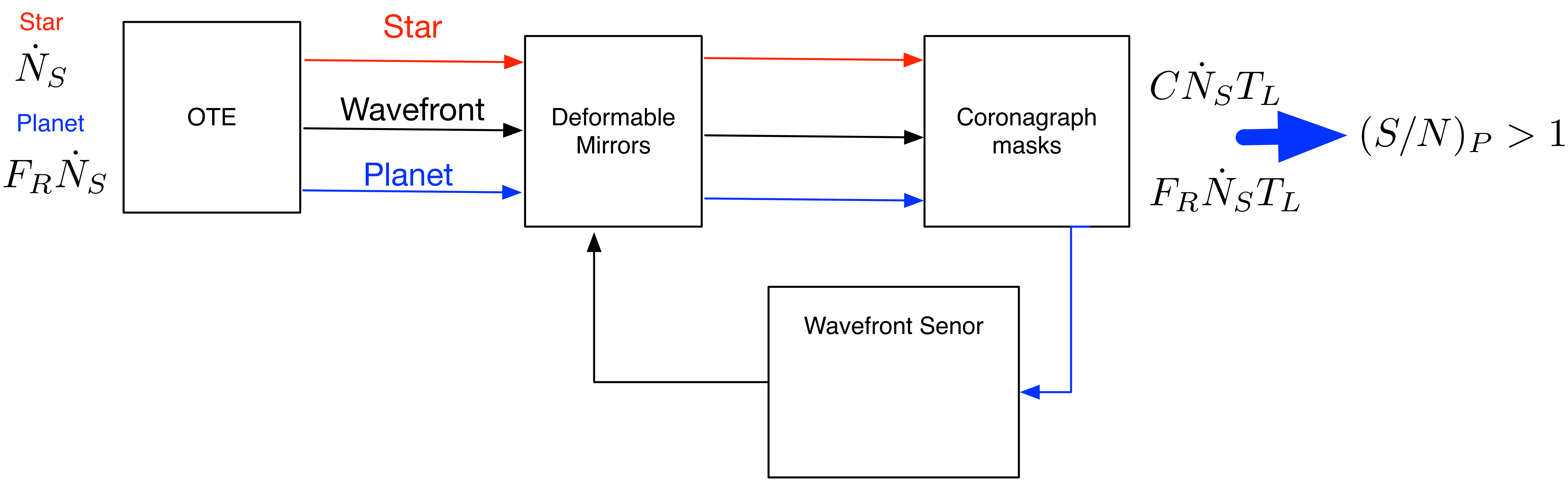


Juanola-Parramon et al. (2019)



- 0.75 mas star
- 10 pm segment piston/tip/tilt jitter
- 0.2 mas los jitter

How are we modeling this?

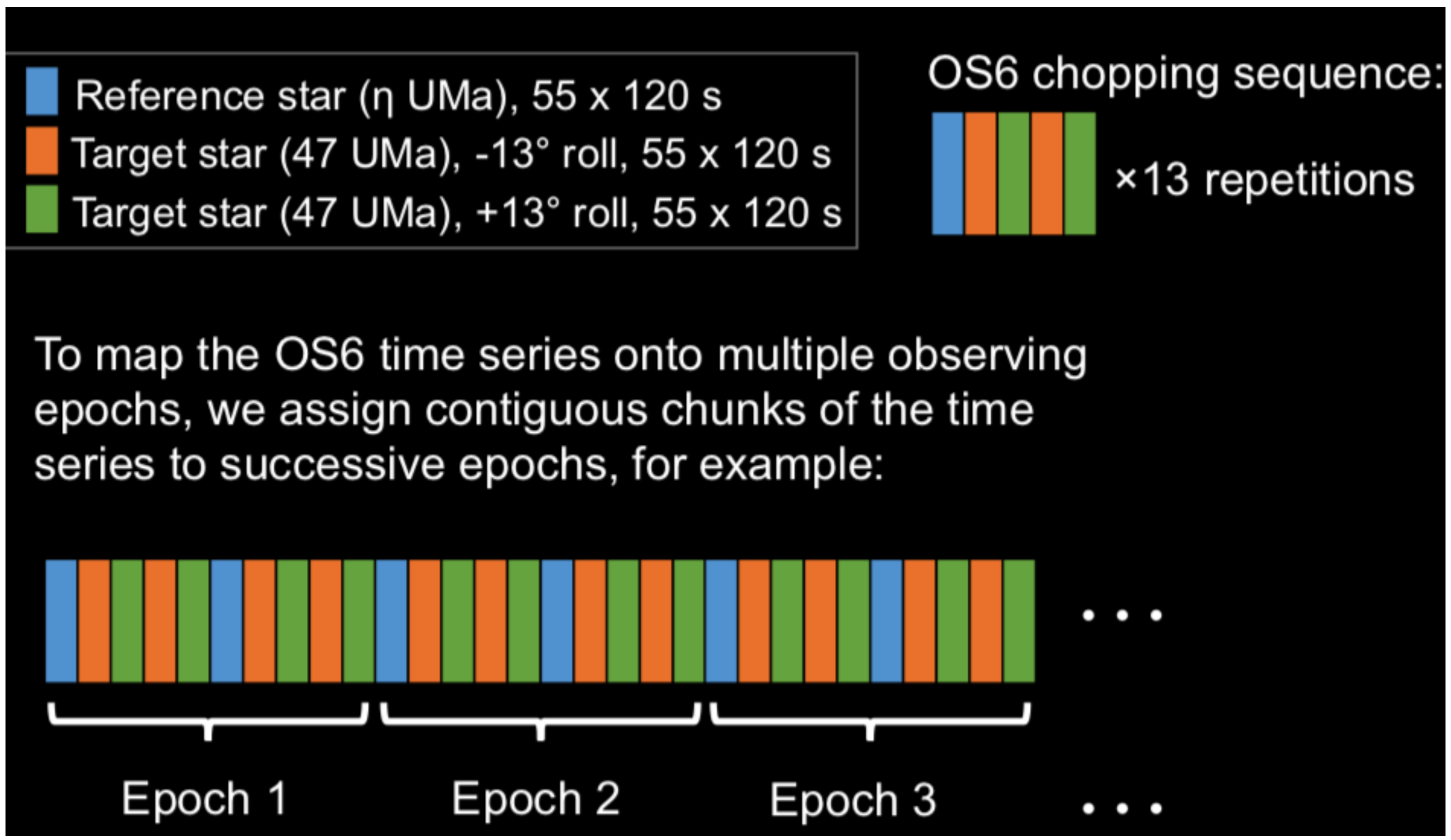


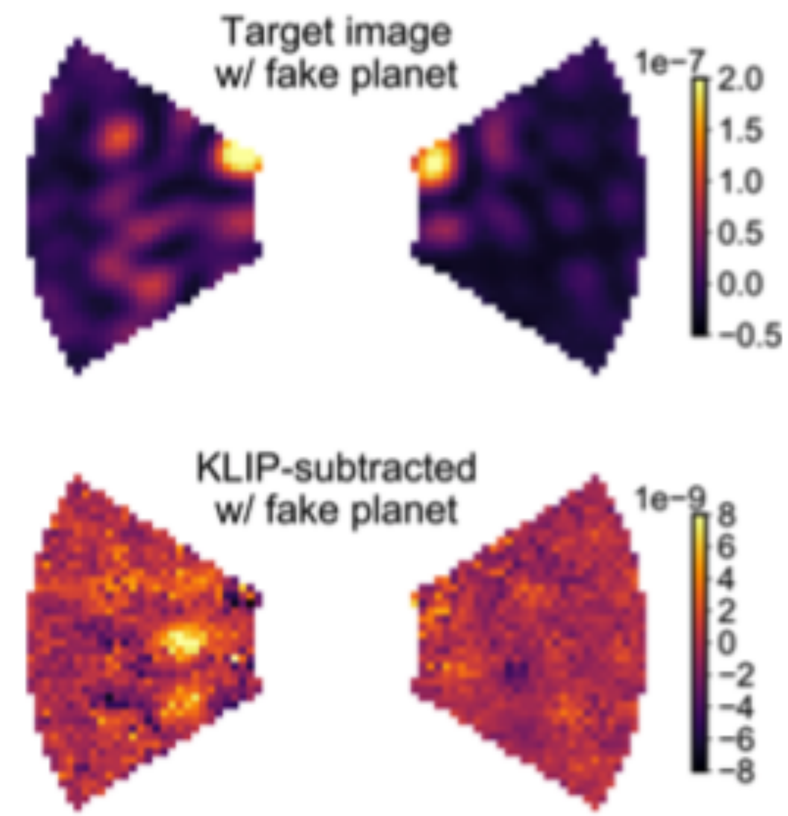
- We make a distinction between flux ratio (astrophysical) and contrast (instrument).
- We assume a sum of orthogonal modes.

- The coronagraph turns picometer into photons.
- The WFS&C system turns photons into picometer at the DM.

Raw contrast (alpha)

We only need stability if the raw contrast is larger than the planet/star flux ratio.
We are assuming the reference/roll subtraction.



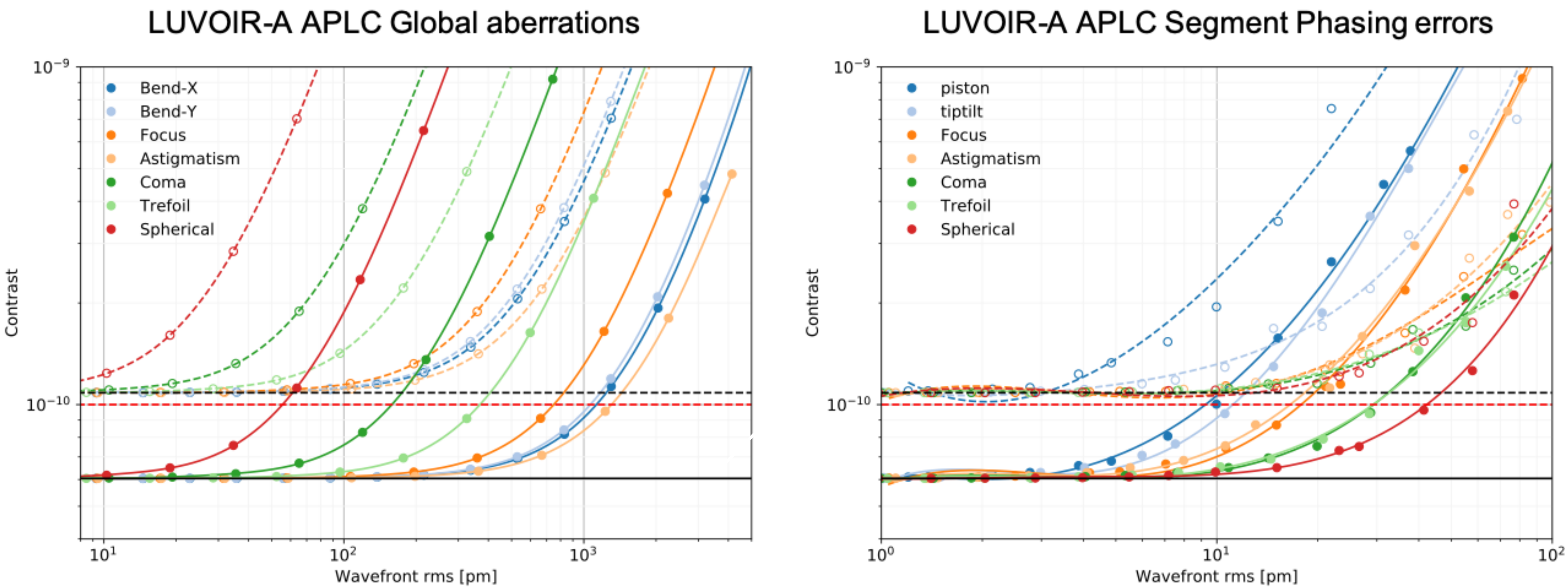


Courtesy of N. Zimmermann

“Alpha” measures show far away the static wavefront is from what it would need to be to see the planet at desired SNR without PSF subtraction.

Coronagraph sensitivity (Lambda)

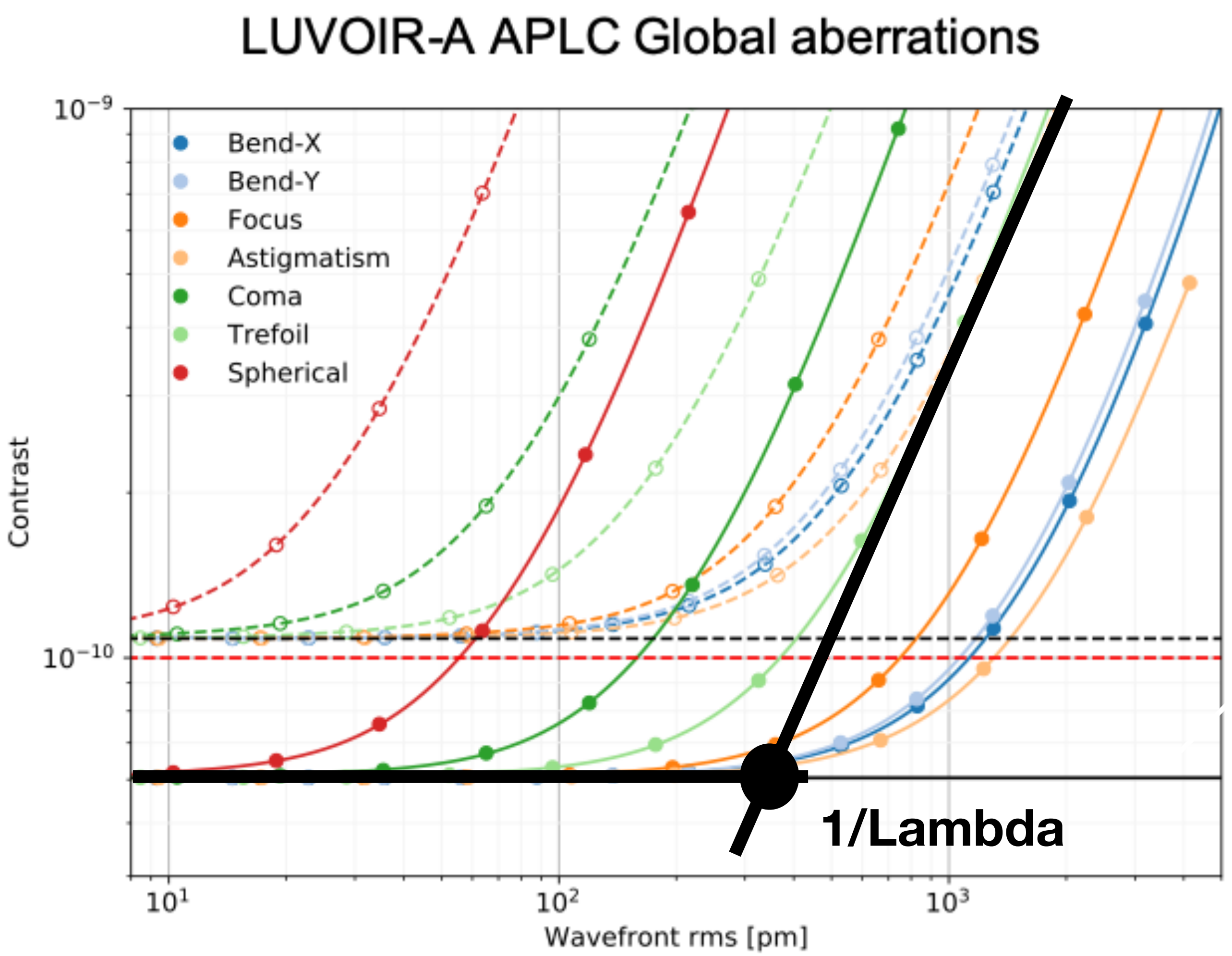
Juanola-Parramon et al. (2019)

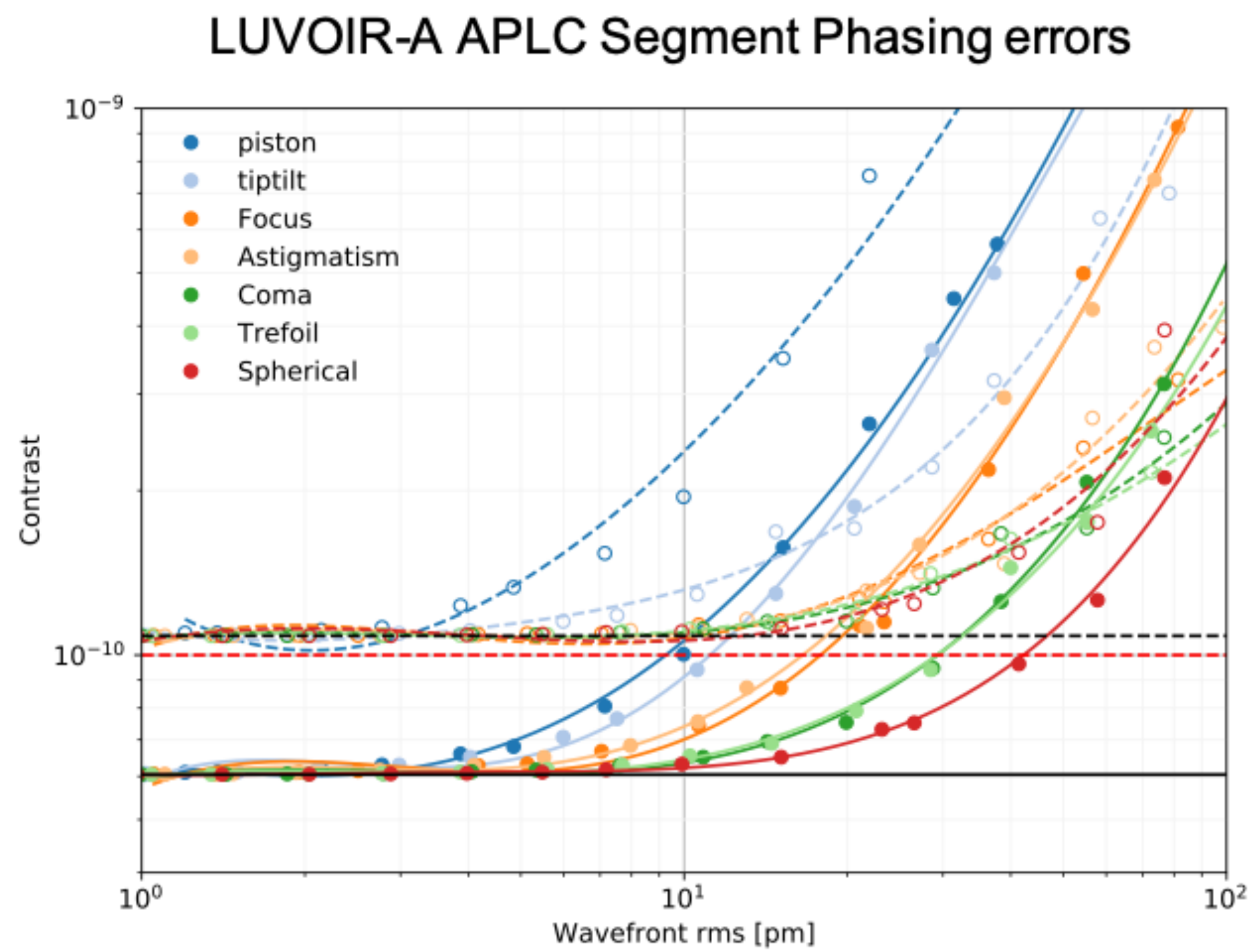


- “Lambda” measures how efficient the coronagraph is at suppressing a given mode of wavefront errors. Also called robustness.
- Small is better (except when it significantly degrades throughput)

Coronagraph sensitivity (Lambda)

Juanola-Parramon et al. (2019)





- “Lambda” measures how efficient the coronagraph is at suppressing a given mode of wavefront errors. Also called robustness.
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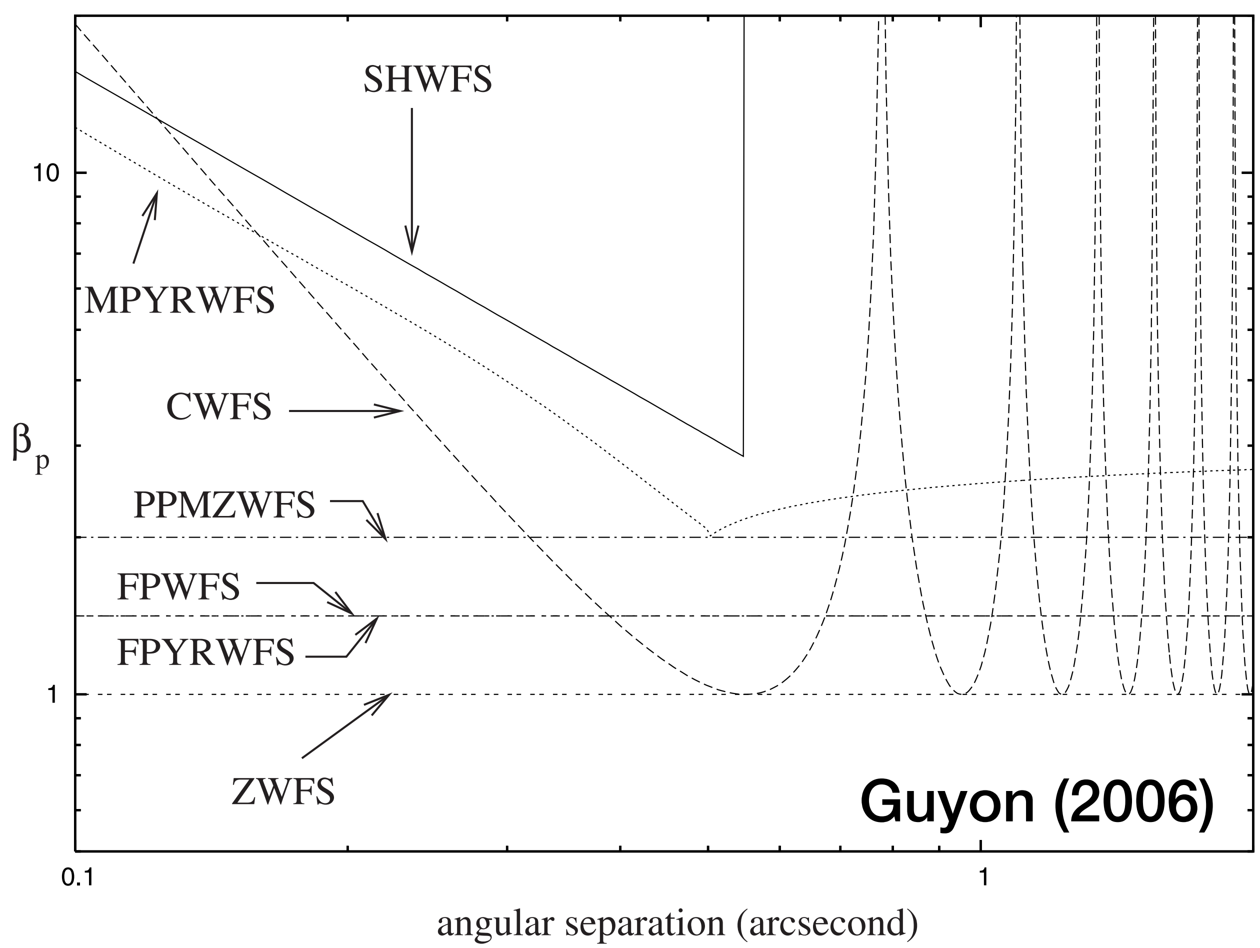
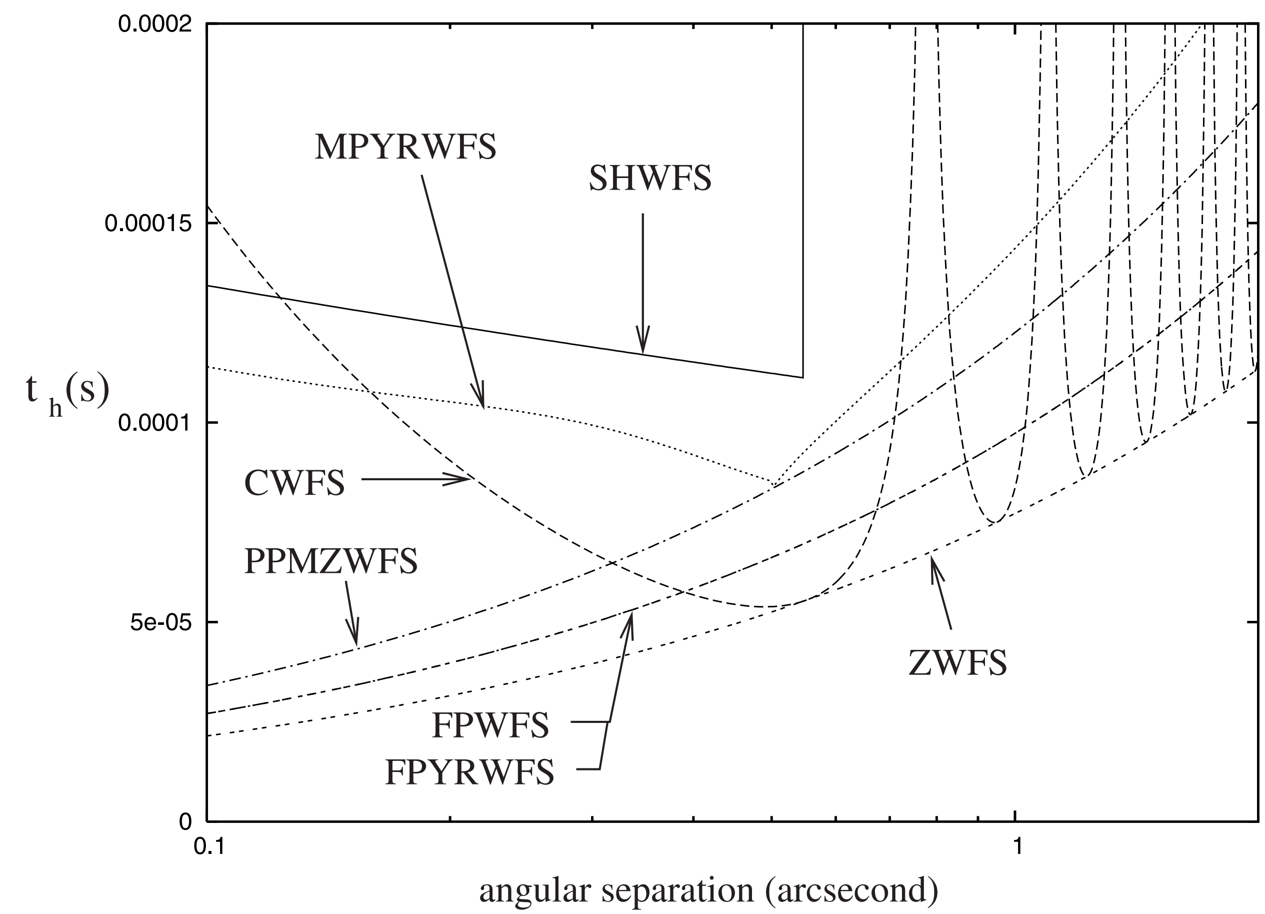
WFS&C sensitivity (beta)

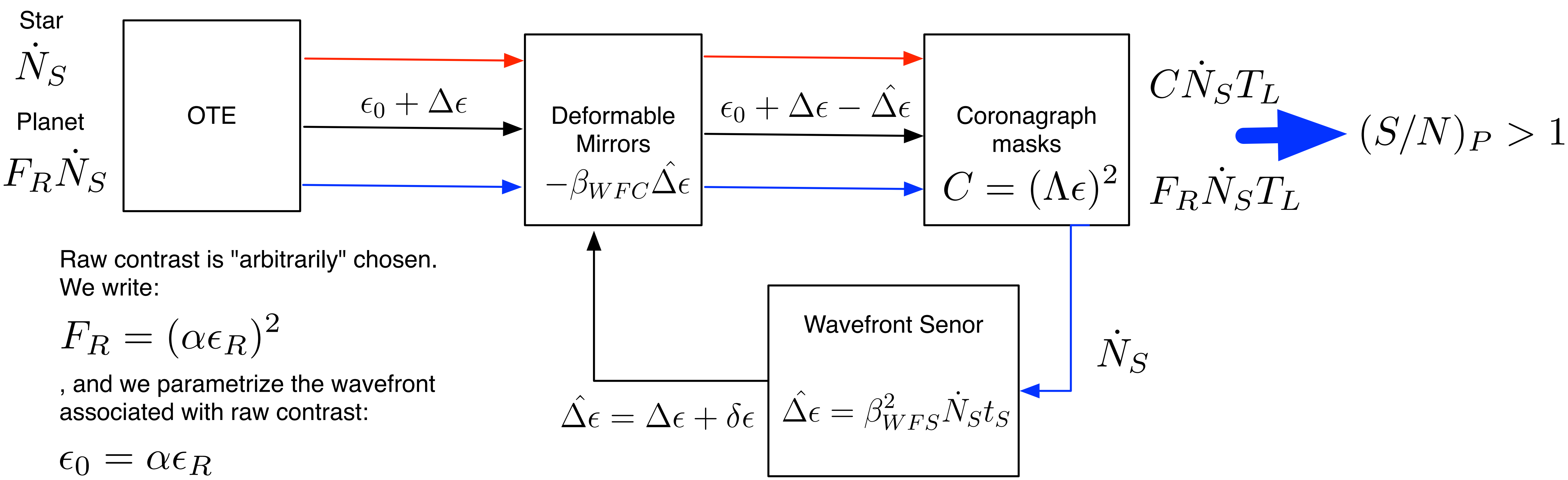
Control law gain x WFS sensitivity





- How efficient is the WFS&C at converting the photons associated with a given mode into picometer at the DM.
- Closer to 1 is better (cannot “create photons” unless predictive control is used)

How are we modeling this?



Raw contrast is "arbitrarily" chosen.
We write:

$$F_R = (\alpha\epsilon_R)^2$$

, and we parametrize the wavefront associated with raw contrast:

$$\epsilon_0 = \alpha\epsilon_R$$

We work in the regime for which we need PSF subtraction: alpha >1.

The coronagraph turns picometer into photons.

The WFS&C system turns photons into picometer at the DM.

Wavefront drift requirements

Assuming an astrophysical flux ratio.
Assuming a stellar magnitude.
Assuming a raw contrast (either set by coronagraph limitations of Dark Hole digging).
Assuming that WFS&C is only limited by the photon noise in the wavefront sensor (perfect “gain 1” controller).

What are the requirements (in pm/mnts) for the stability of each mode **without** WFS&C?
What are the requirements (in pm/mnts) for the stability of each mode **with** WFS&C?
What is the gain associated with WFS&C?

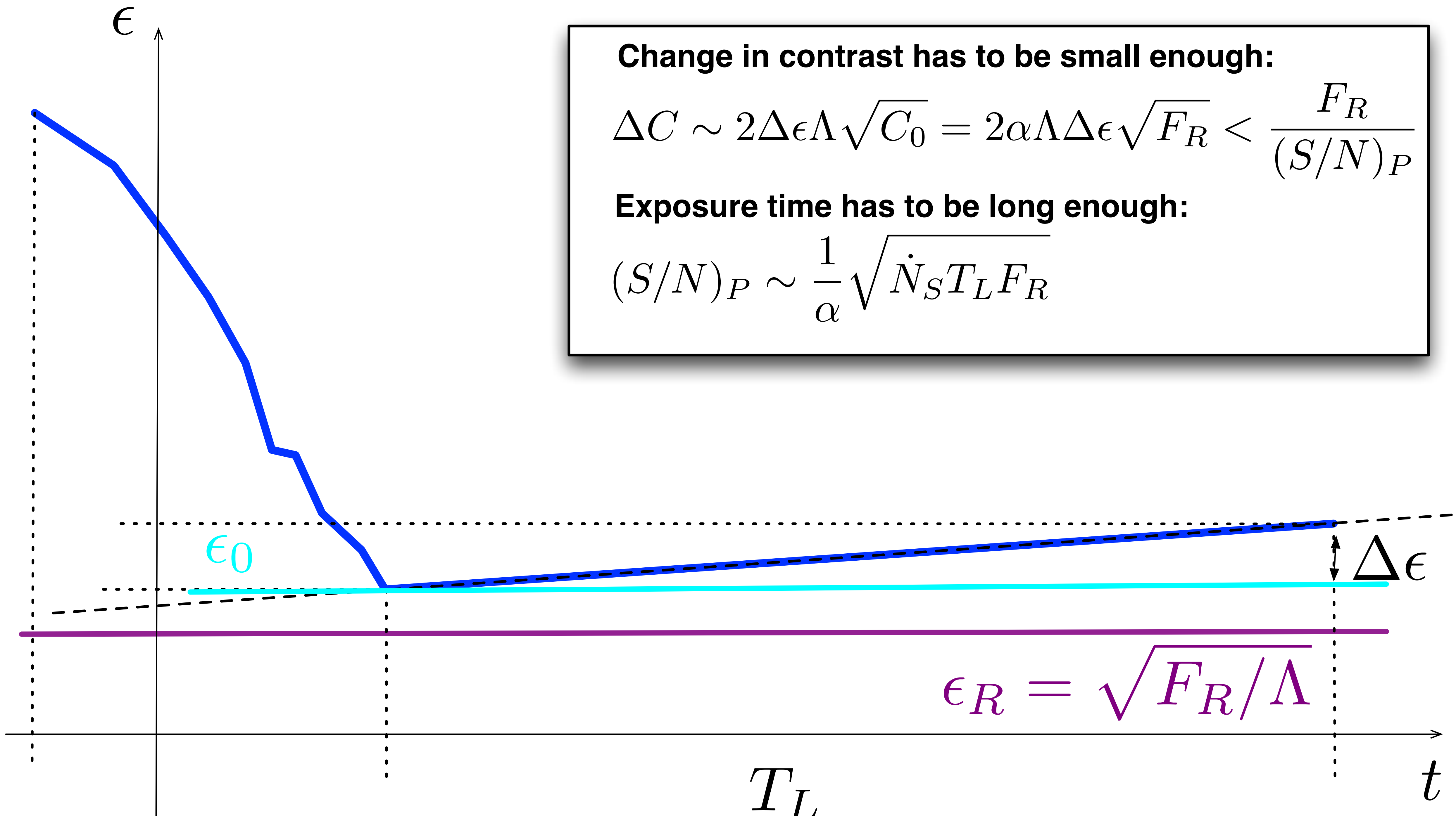
Classical PSF subtraction

Change in contrast has to be small enough:

$$\Delta C \sim 2\Delta\epsilon\Lambda\sqrt{C_0} = 2\alpha\Lambda\Delta\epsilon\sqrt{F_R} < \frac{F_R}{(S/N)_P}$$

Exposure time has to be long enough:

$$(S/N)_P \sim \frac{1}{\alpha}\sqrt{\dot{N}_S T_L F_R}$$



The wavefront cannot change during the course of an exposure (and a slew/roll)

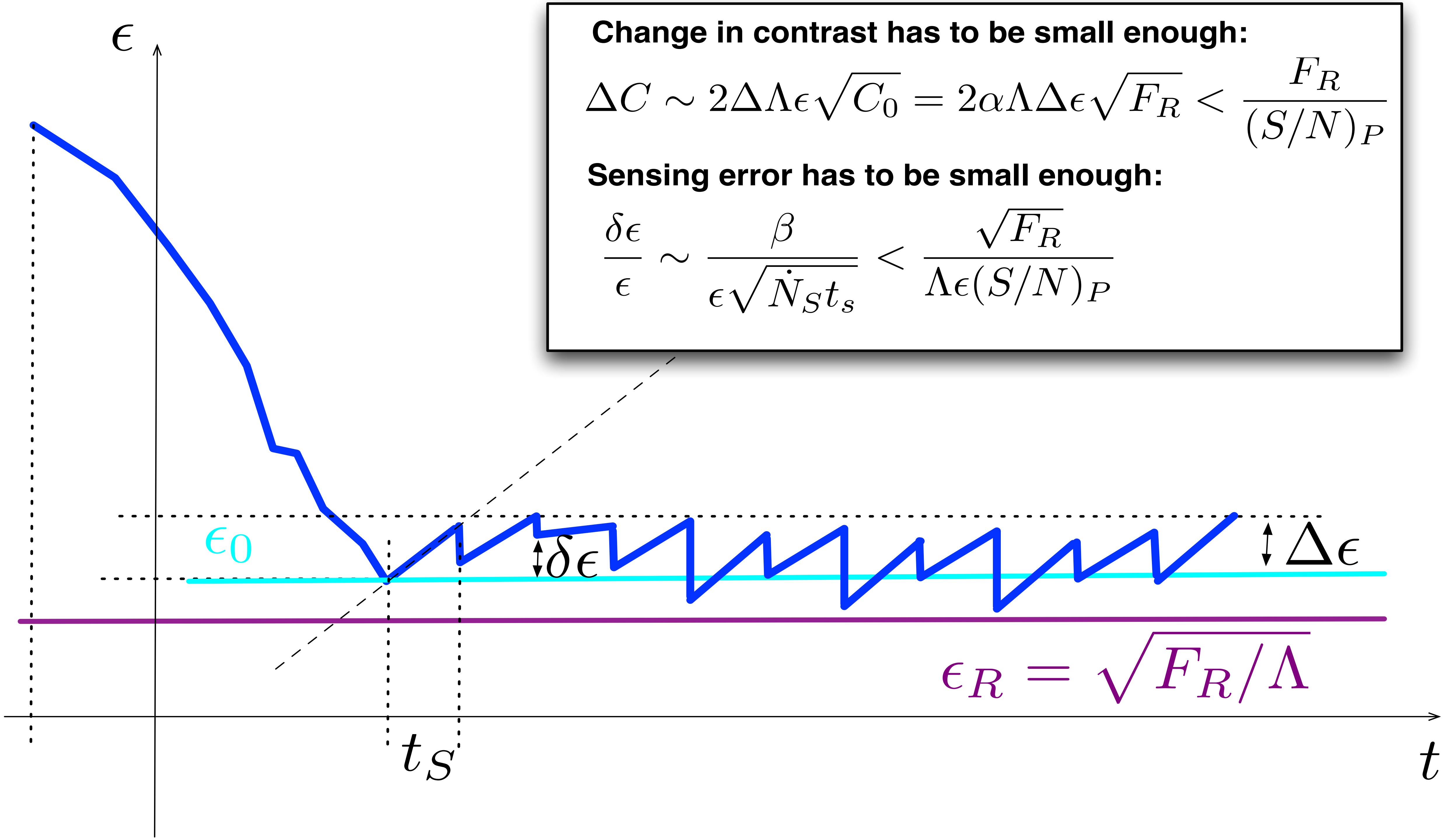
Continuous WFS&C

Change in contrast has to be small enough:

$$\Delta C \sim 2\Delta\Lambda\epsilon\sqrt{C_0} = 2\alpha\Lambda\Delta\epsilon\sqrt{F_R} < \frac{F_R}{(S/N)_P}$$

Sensing error has to be small enough:

$$\frac{\delta\epsilon}{\epsilon} \sim \frac{\beta}{\epsilon\sqrt{\dot{N}_S t_s}} < \frac{\sqrt{F_R}}{\Lambda\epsilon(S/N)_P}$$



The wavefront can wiggle during the course of an exposure (and a slew/roll)

Requirements on drifts

Set and Forget

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

WFS&C

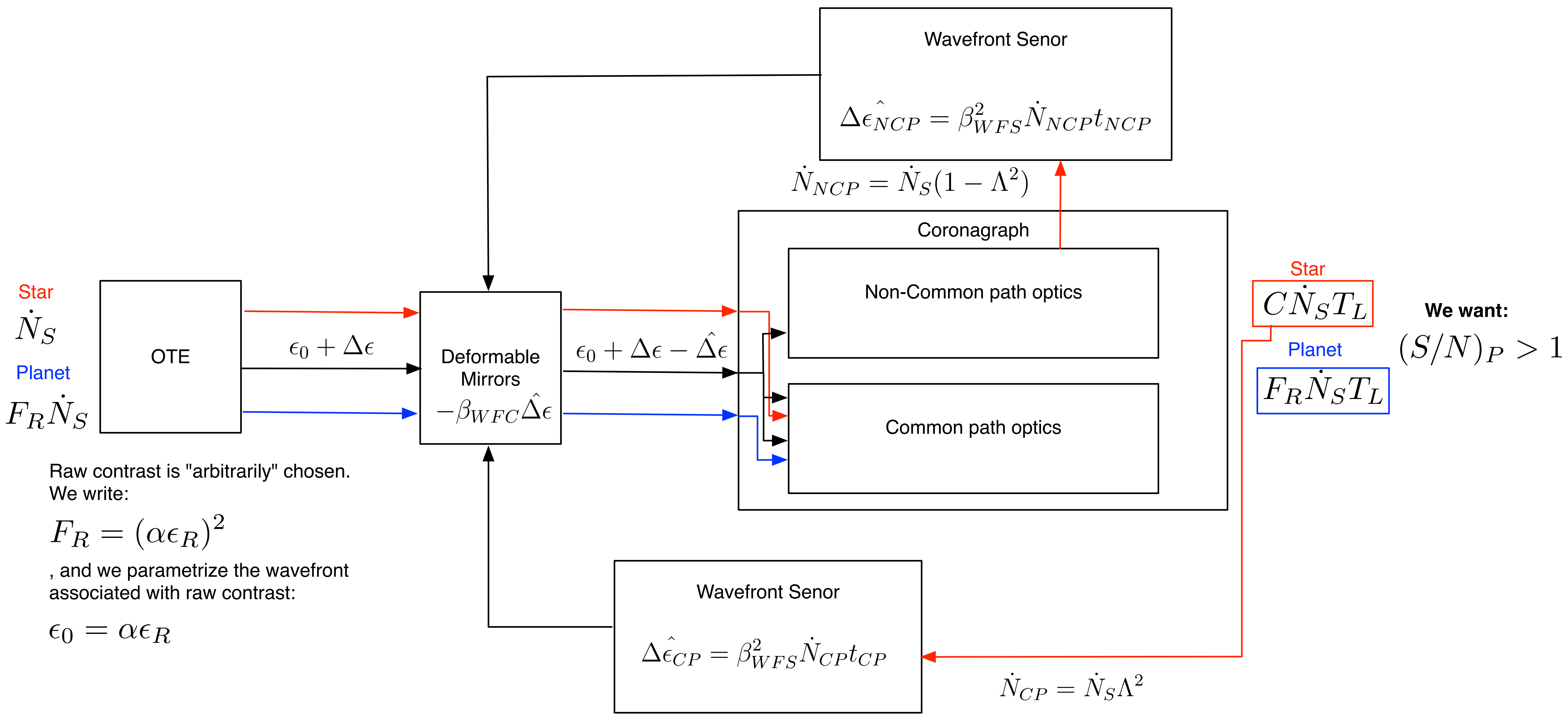
$$d_{WFSC} = \frac{1}{(S/N)_P^3} \frac{\dot{N}_S F_R^{3/2}}{2\beta^2 \alpha \Lambda^3}$$

WFS&C GAIN

$$\frac{d_{WFSC}}{d_{SF}} = \left(\frac{\beta\alpha}{\Lambda}\right)^2$$

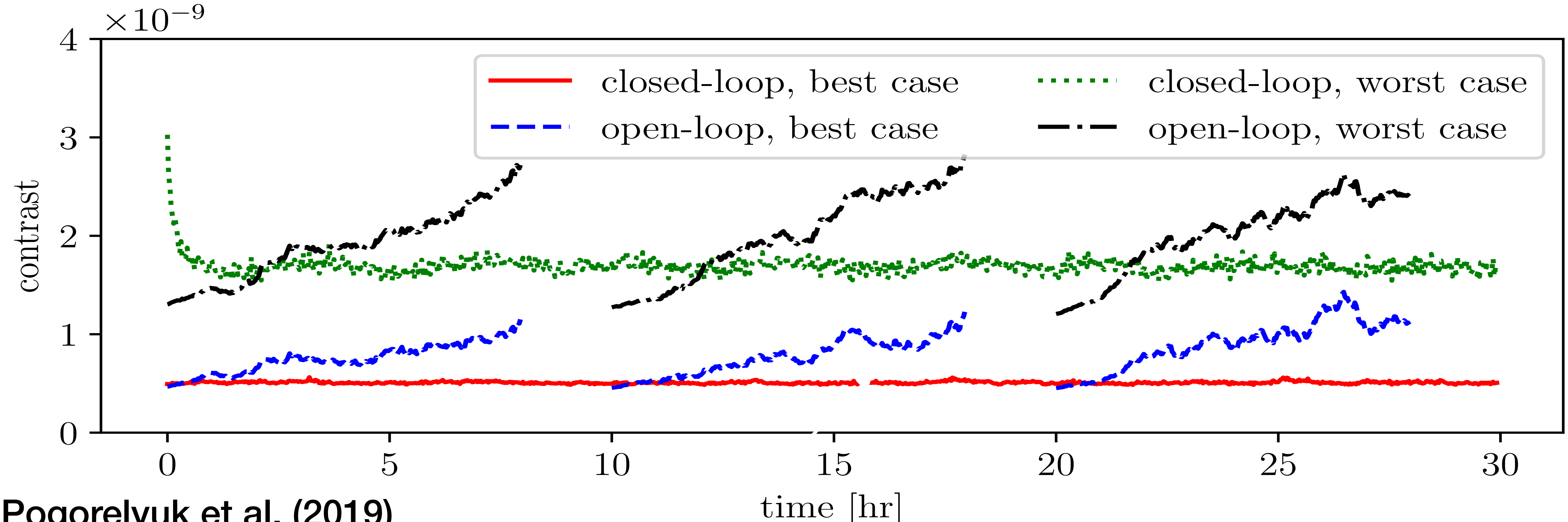
- **WFS&C "pointless" if raw contrast good enough.**
- **WFS&C yields a larger gain with robust coronagraphs.**
- **WFS&C yields a larger gain with optimal architecture/algorithms**

WFS&C Architecture



We need to optimize architectures as close as possible to the (1-Lambda^2) - Lambda ^2 regime.

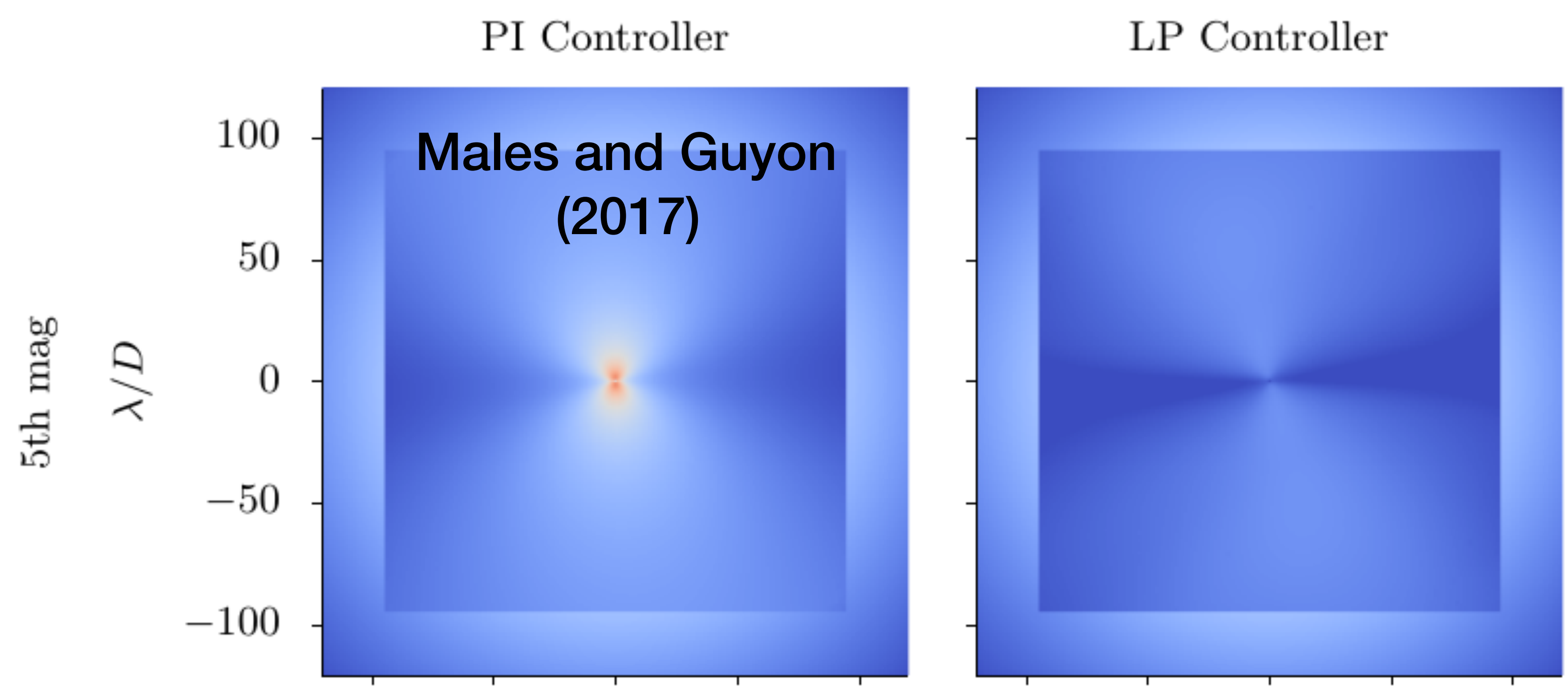
Beyond unity WFS&C gain



Pogorelyuk et al. (2019)

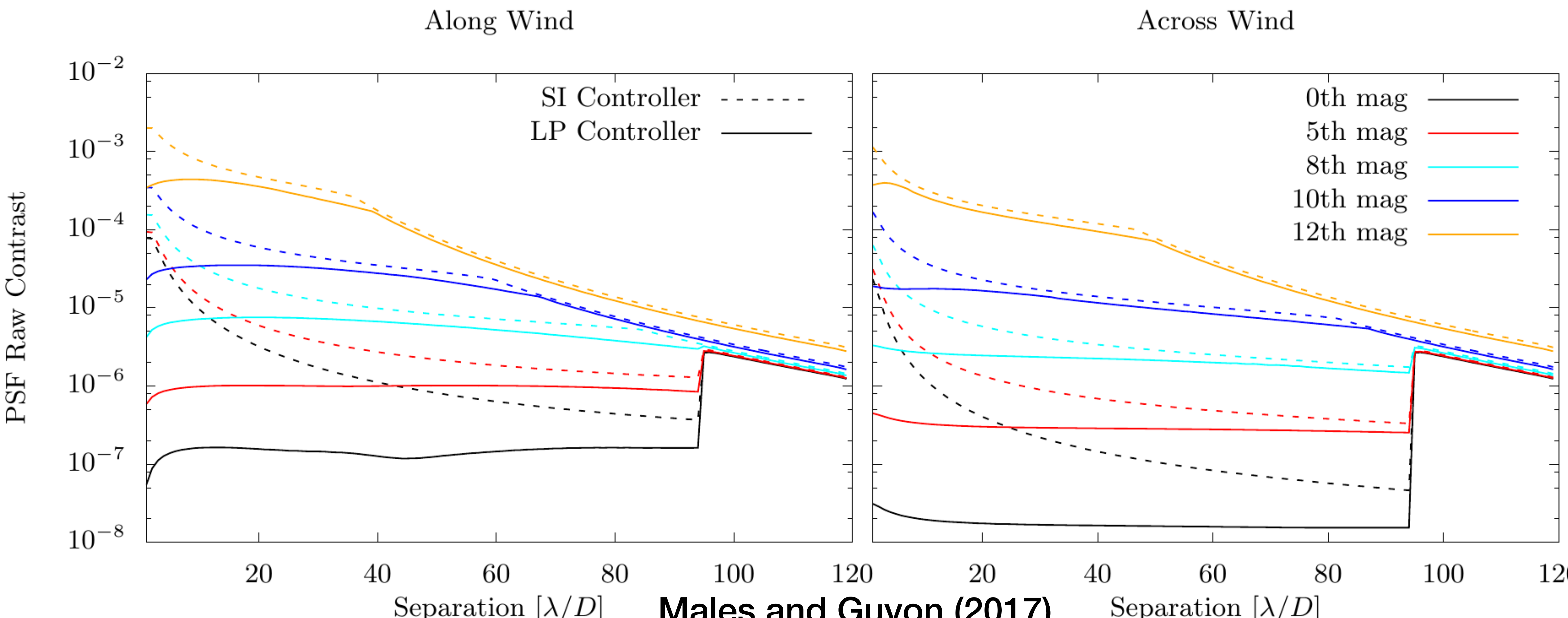
Common path (slow, photon poor)

Non-Common Path (fast, photon rich)



Synergies with ground based AO

Non-Common Path (fast, photon rich) component follows the architecture of ground based AO system.



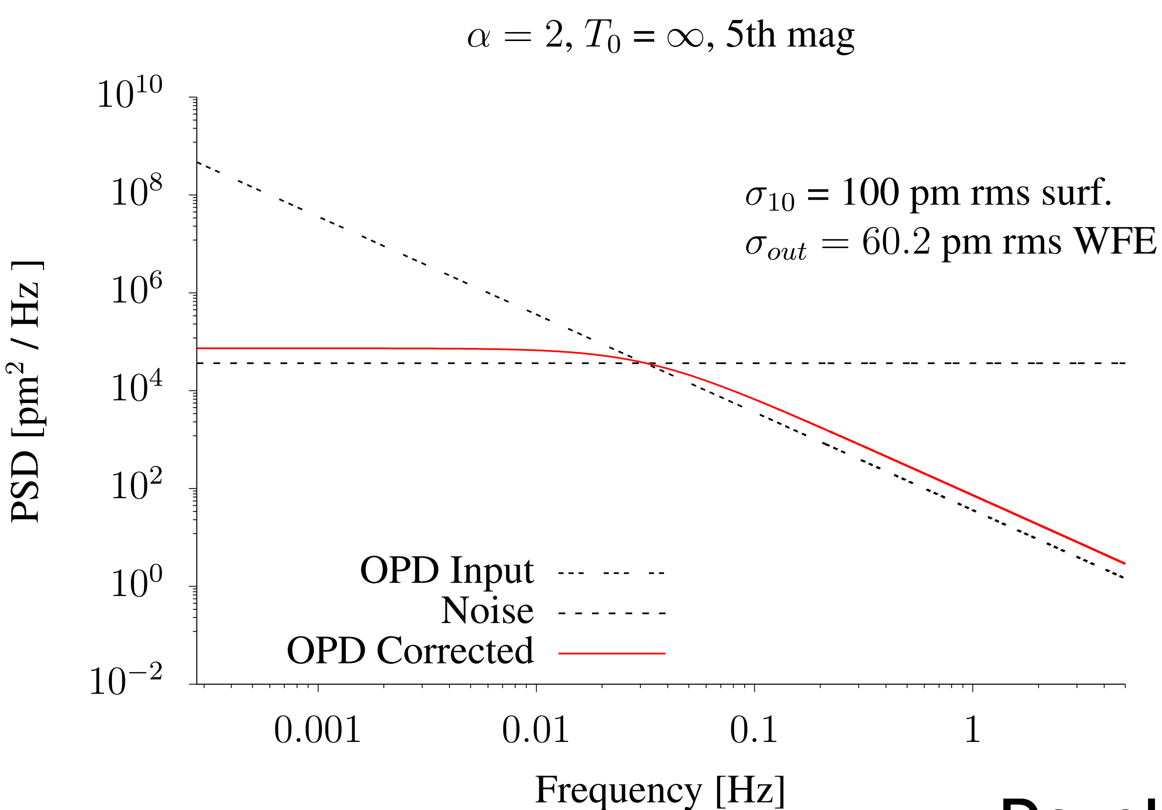
Males and Guyon (2017)

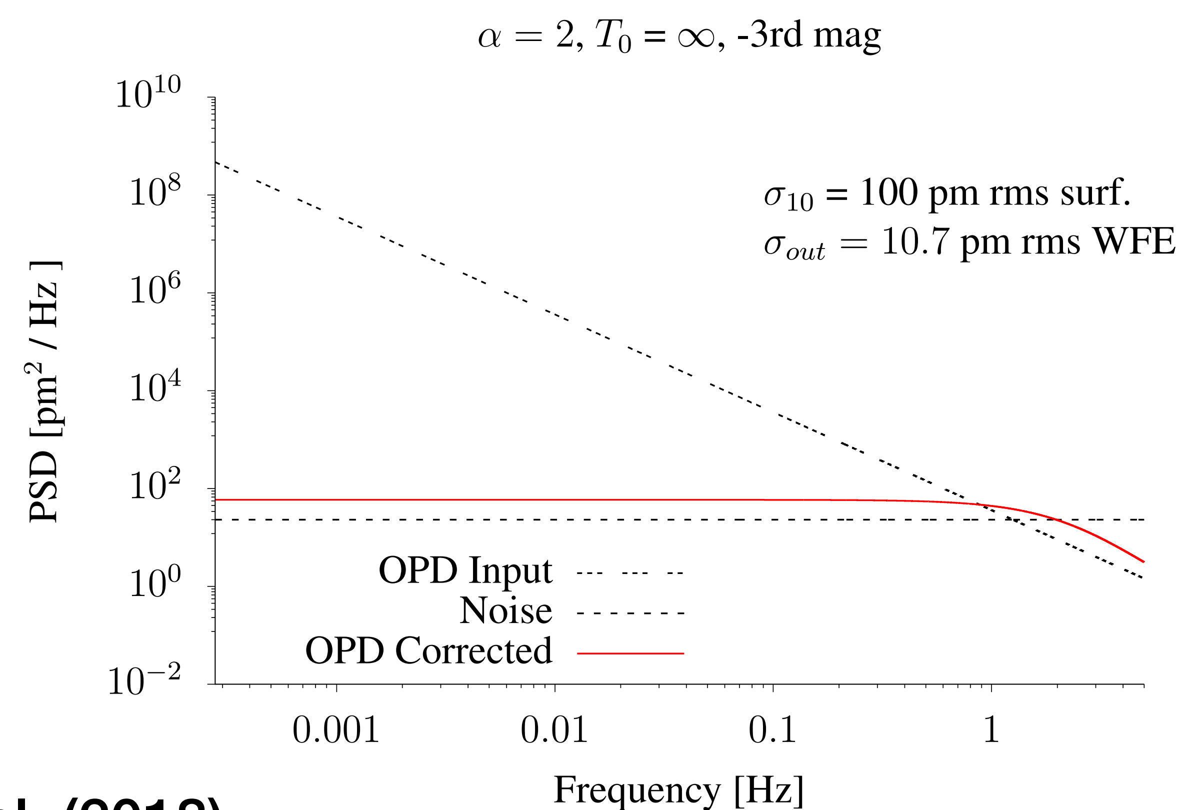
Ground based AO system need to maximize beta to get to close separation:

- For 8 m class: Giant planet peak at 5-20 AU
- For ELTs: habitable zone planets around low mass stars

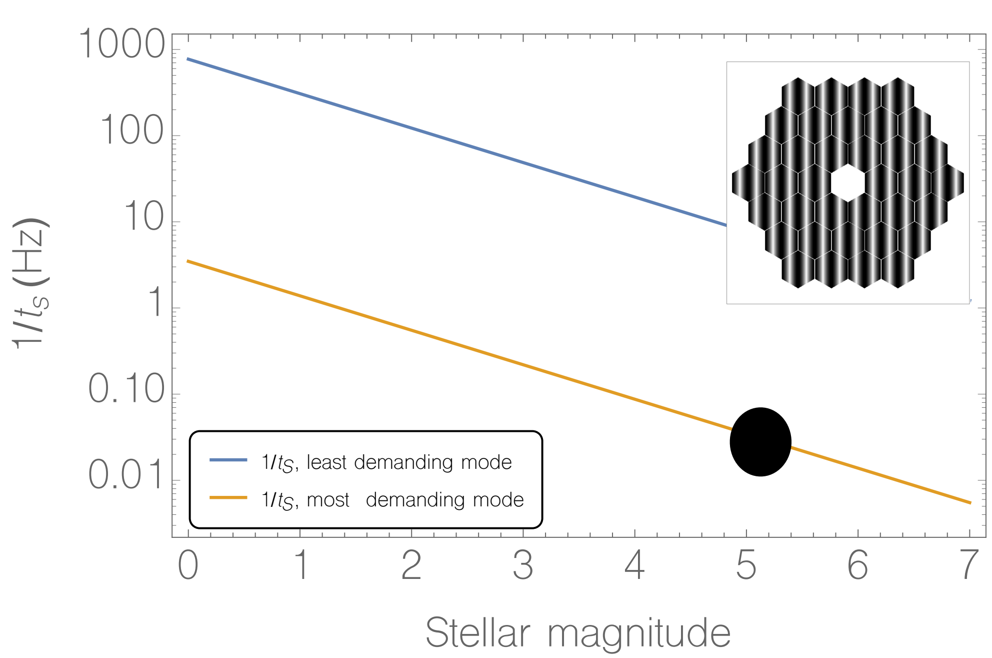
Next: use temporal PSDs

Drift "toy model" is instructive but not really realistic.





Douglas et al. (2018)



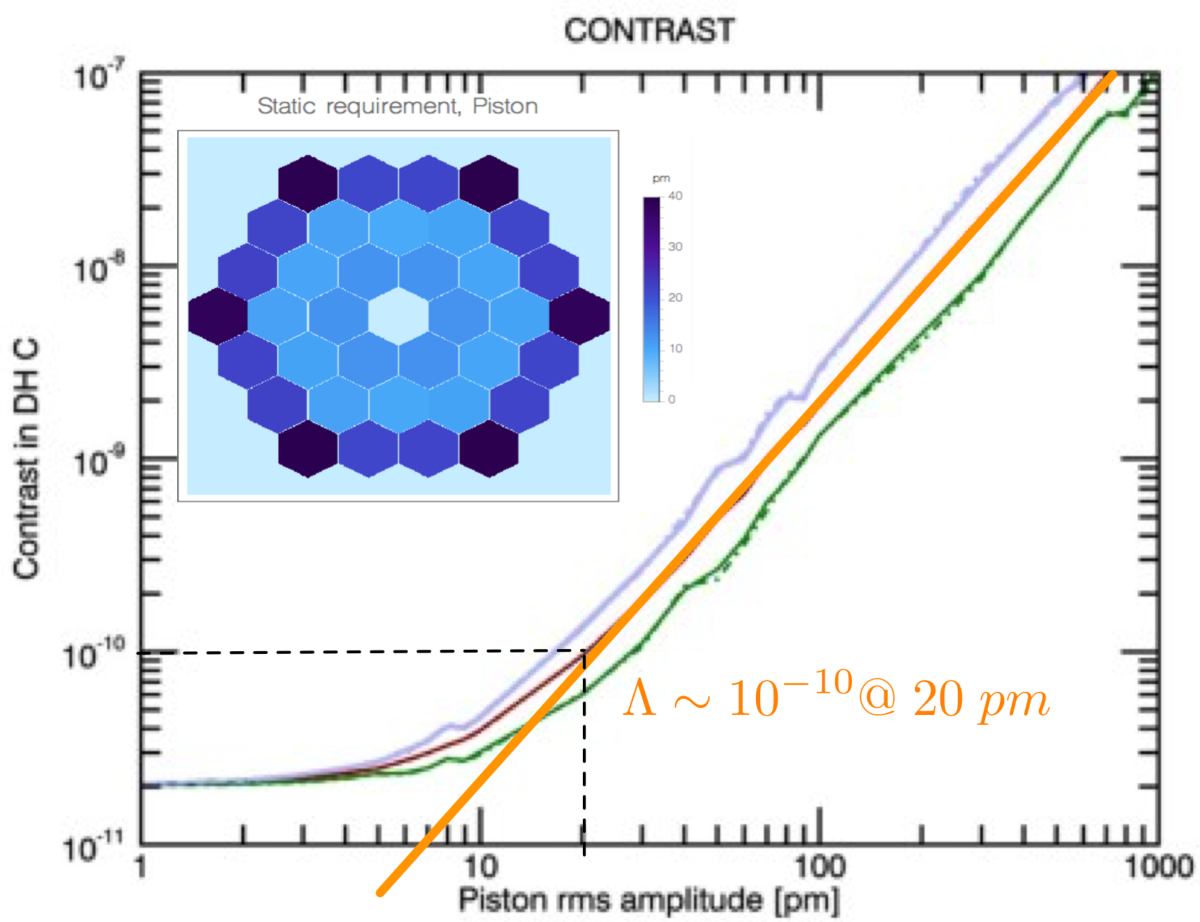
For high frequency ripples the timescales are unforgiving….

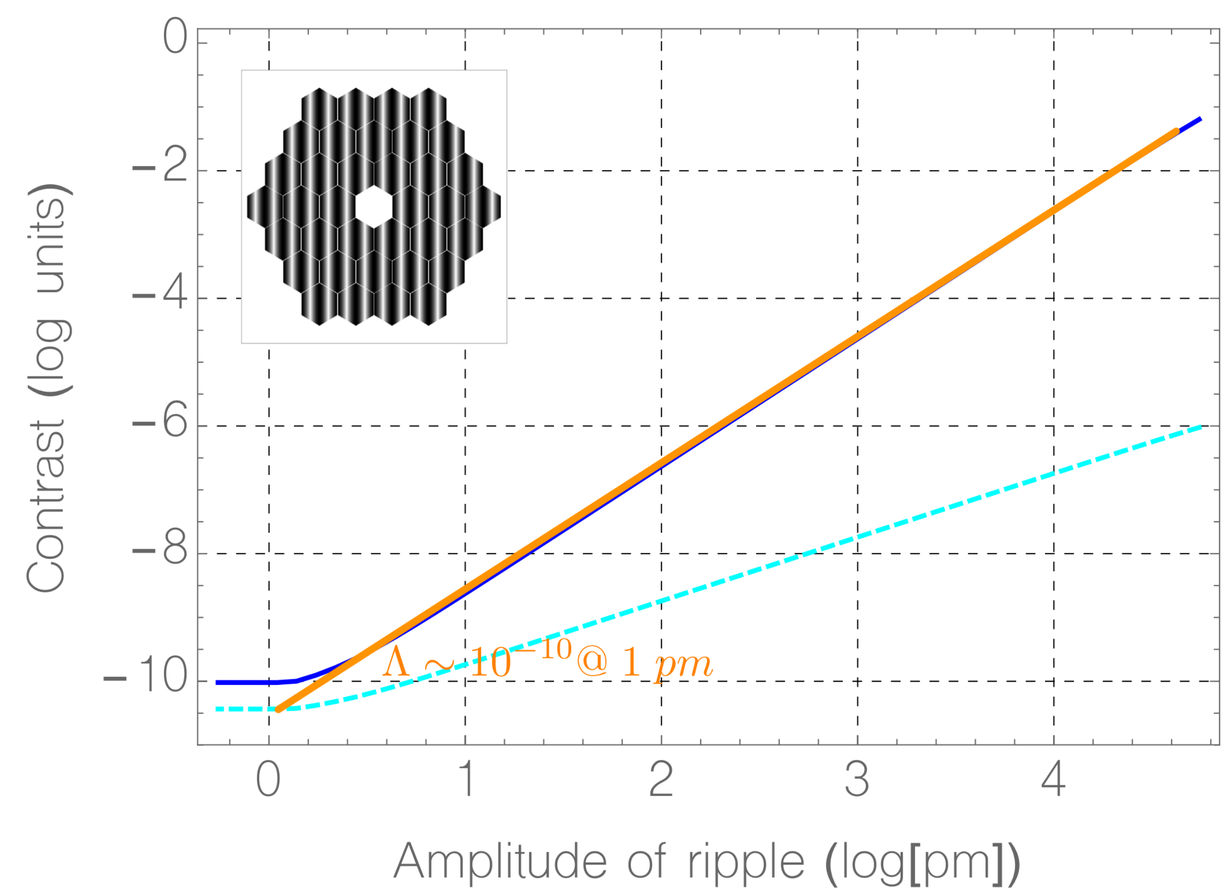
…shall we give up?

Next: Proper modes for segments

Ripples do not capture the all the information associated with a segmented aperture.

Leboulleux et al (2018)





$$\frac{d_{WFSC}}{d_{SF}} = \left(\frac{\beta\alpha}{\Lambda}\right)^2$$

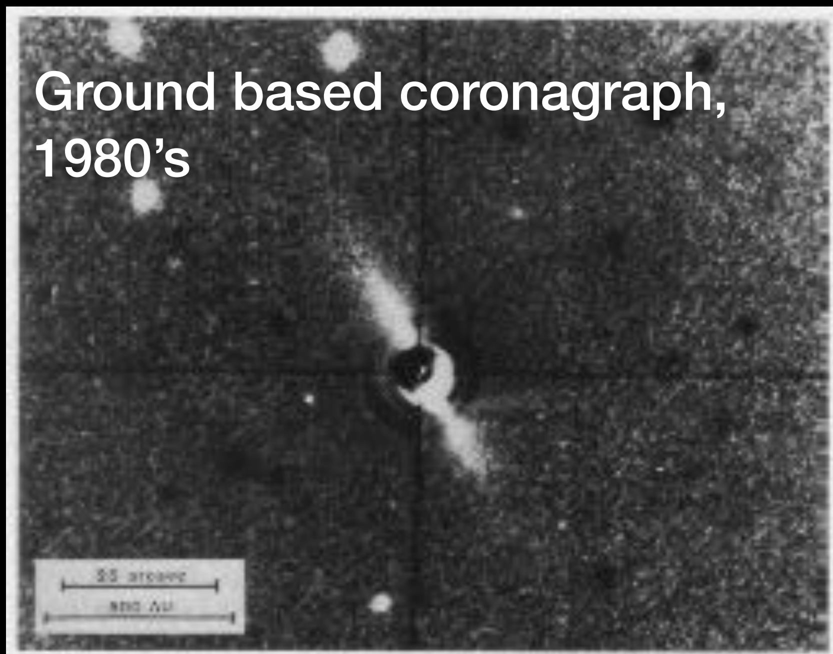
A factor of 20 in robustness means that WFS&C will relax drift requirements by a factor of 400.

Conclusion (with words)

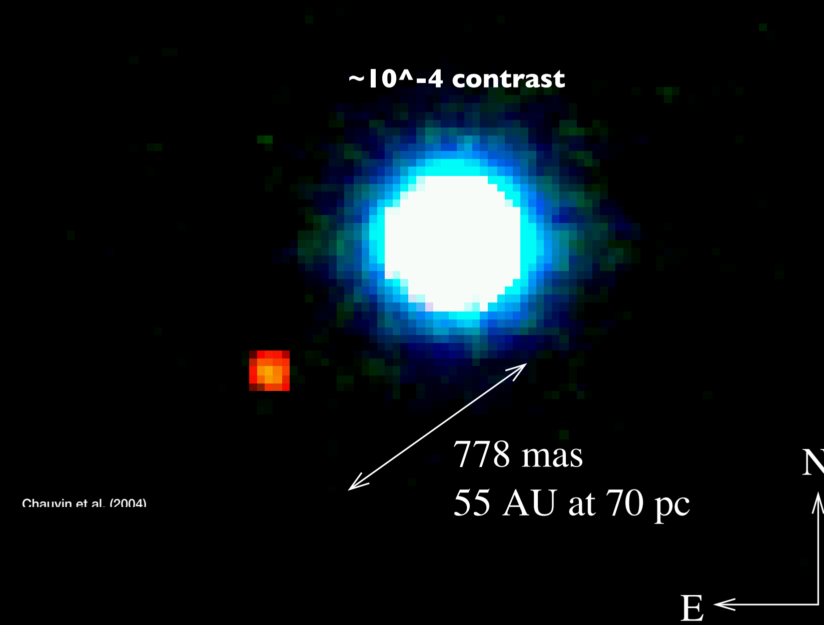
- **Raw contrast** is not the full story. We have focused on this for years but two other quantities matter.
- **Minimizing Coronagraph Wavefront Sensitivity** (without killing throughput). WFIRST (testbed and flight) provides unique opportunities to measure these sensitivities at "TRL9".

- **Maximizing WFS&C efficiency.** This involves optimizing architectures and algorithms to take advantage of each photon to infer "best" DM commands. This will minimize stability requirements at the telescope level.
- **Maximizing WFS&C efficiency** is also key to ground based exoplanet science. We should aggressively pursue synergistic plans.

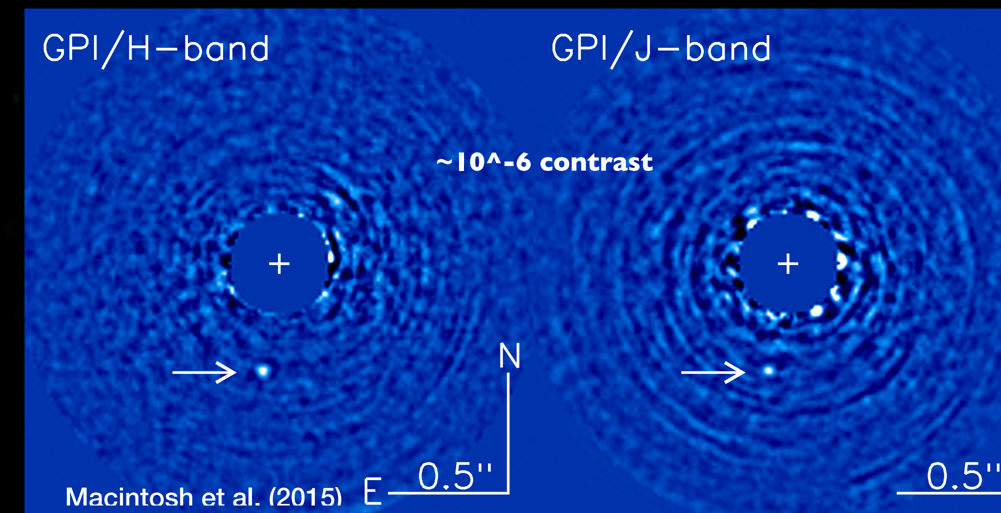
Conclusion (with pictures)



Ground based AO in 2004



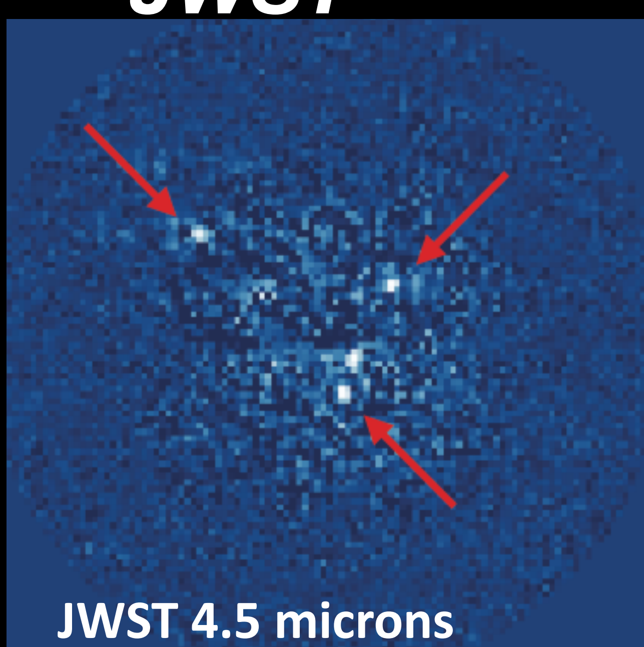
Ground based AO in 2015



1/1000 gain with AO

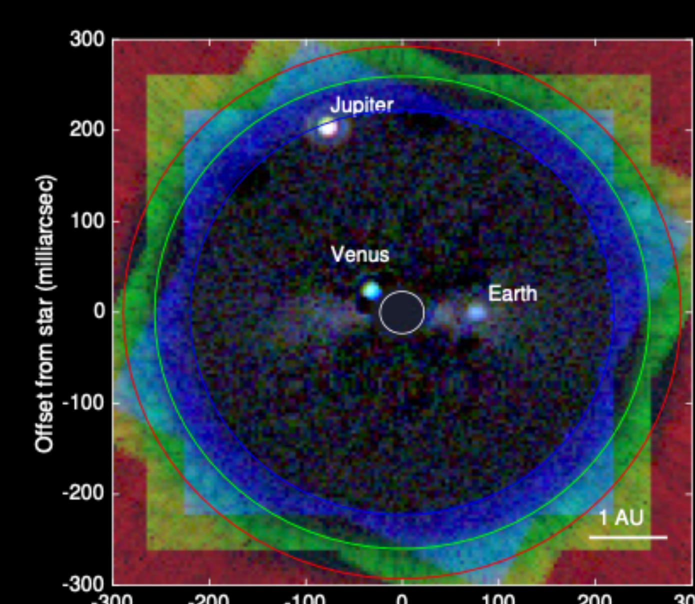
1/100 gain ExAO+ coronagraph

JWST



WFIRST

HabEx-LUVOIR



Back up

Requirements on drifts with PP

Set and Forget

WFS&C

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