High-contrast imaging with E-ELT/HARMONI

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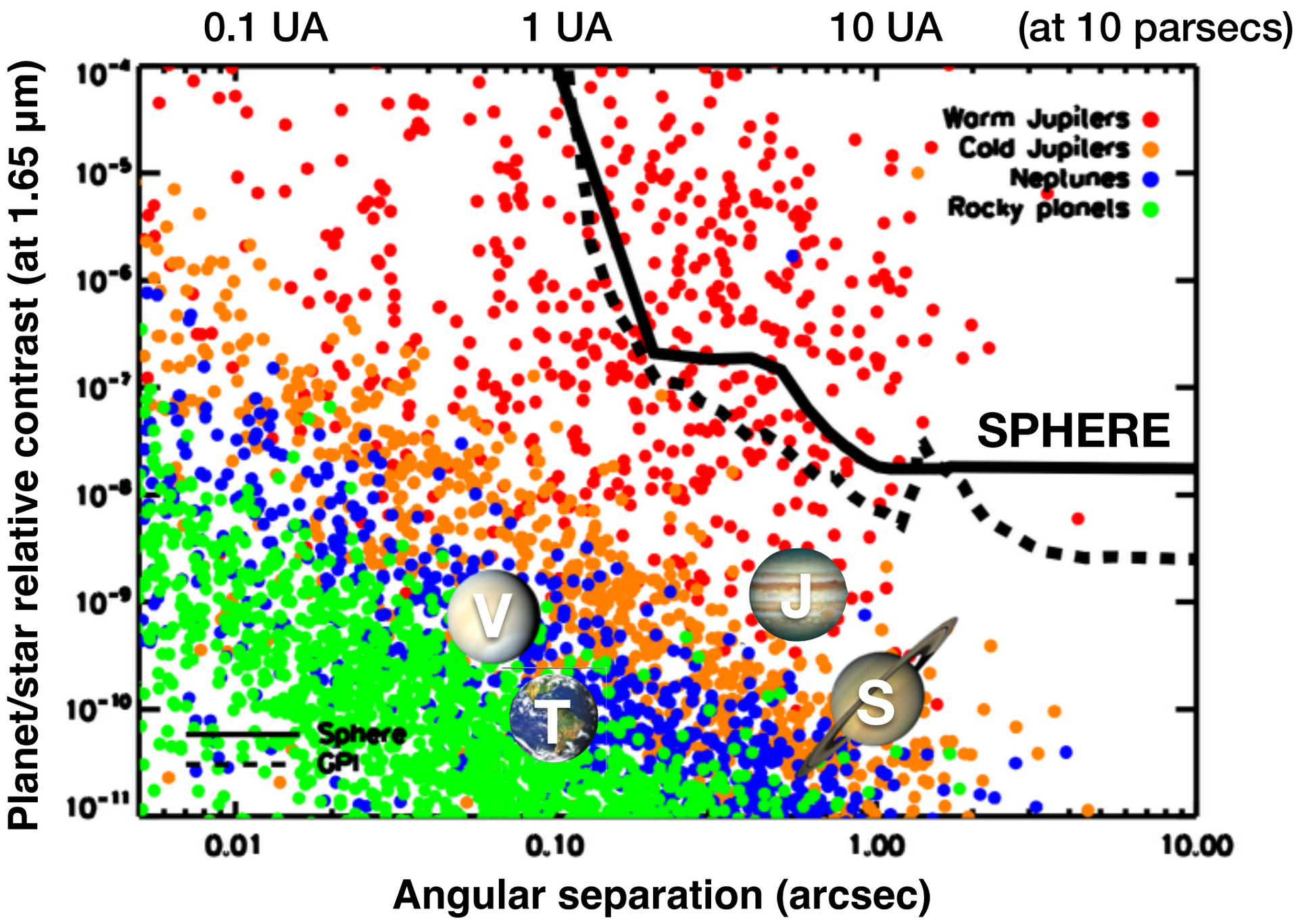
Imaging young giant planets

Planetary population model for young stars



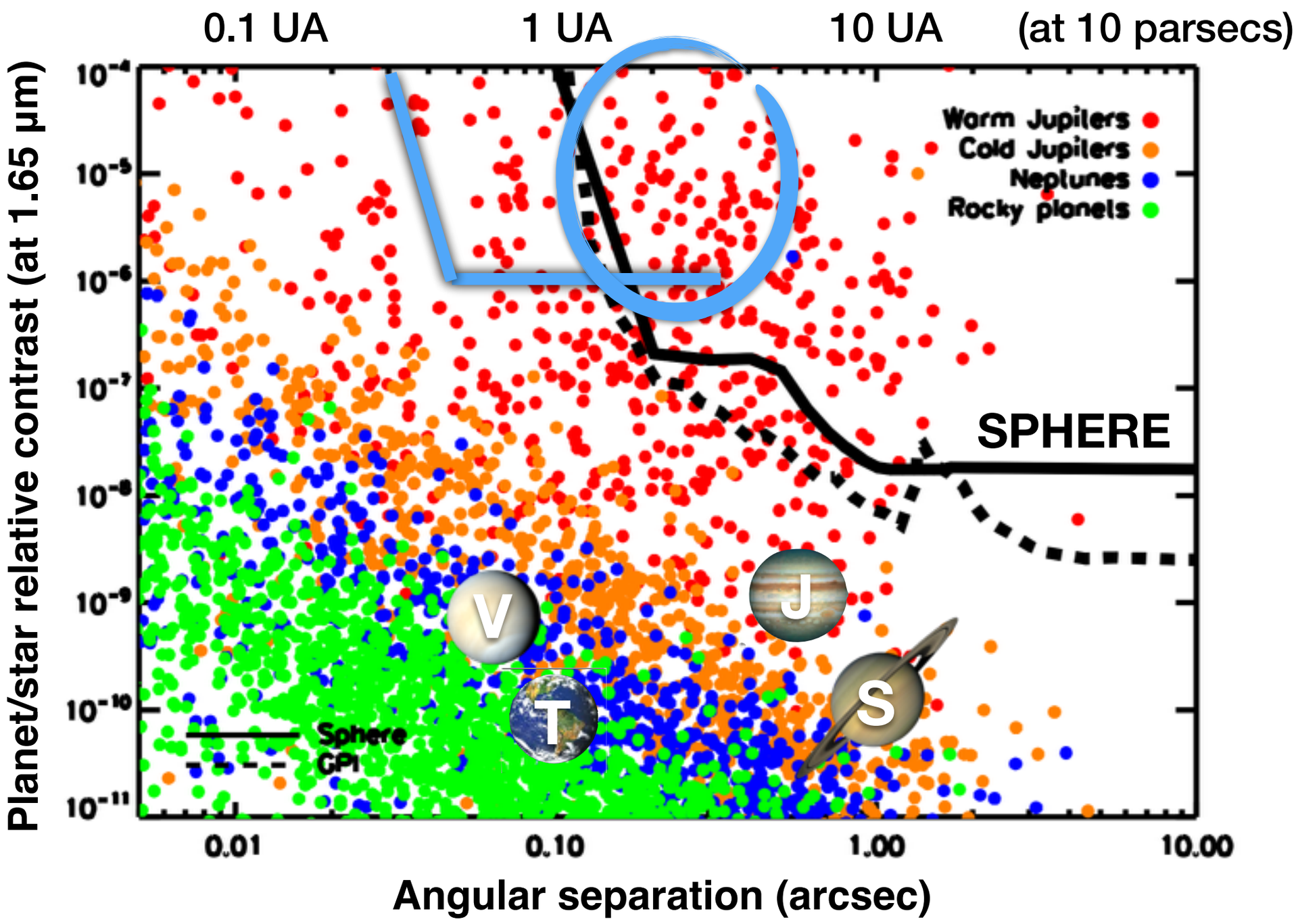
Gratton, 2014 (from Bonavita et al. 2012)

What contrast for HARMONI?

- HARMONI is not specifically optimized for high-contrast
- Single component vs. dedicated high-contrast arm
- Spec: 10^{-6} at 200mas ; Goal: 10^{-5}-10^{-6} at 40mas
  - Follow-up of SPHERE, GPI, and other targets ; Medium spectral resolution makes possible observation of K & CO lines.
  - Characterization of planets around M dwarves.
  - Observation of the inner edge of debris disks & associated planetary or substellar companions.

Imaging young giant planets

Planetary population model for young stars

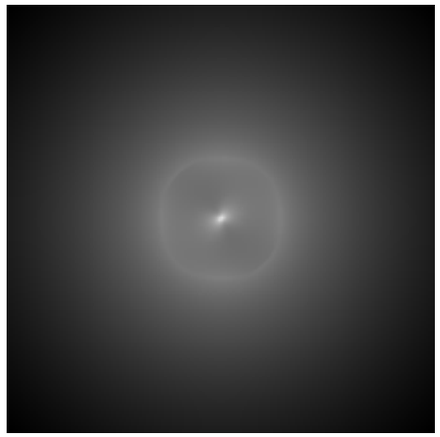


Gratton, 2014 (from Bonavita et al. 2012)

Limitations on contrast

- Telescope AO (M4 has ~74 actuators across pupil)
- Telescope aperture (segments discontinuities, obscuration)
- Instrument stability:
  - temporal & chromatic NCPA
  - thermal drift, chromatic pupil shift, …
- Instrument limitations:
  - *non-corrected* atmospheric dispersion
  - limited access to pupil & image planes
  - cross-talk & diffusion in the IFS

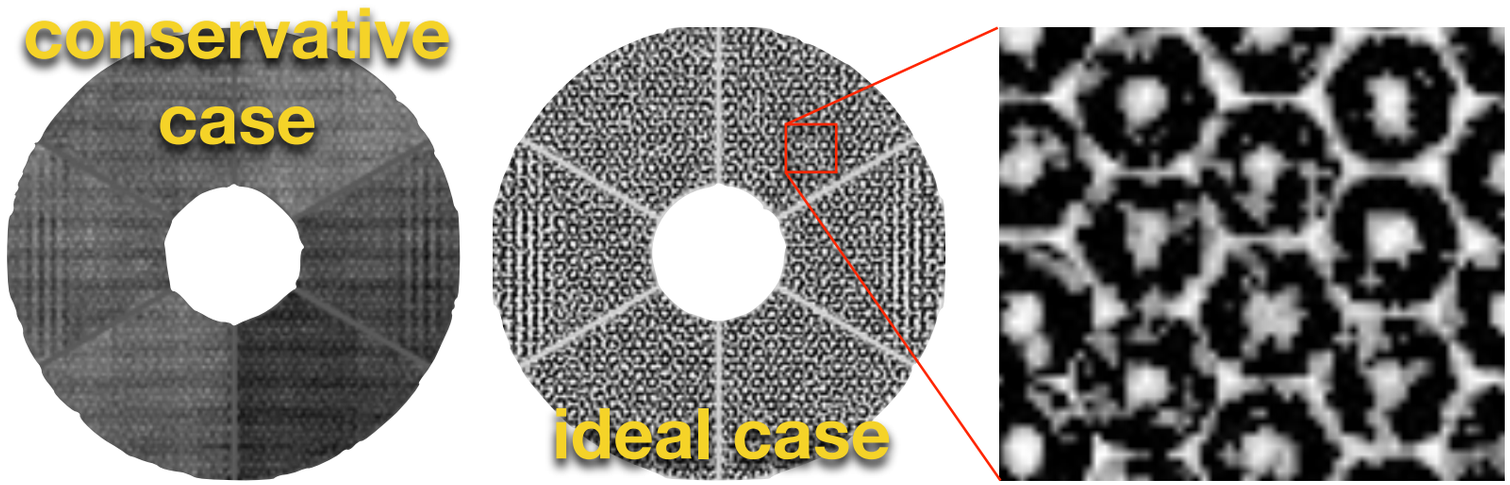
AO: semi-analytical approach



1 - Analytic 2D power spectrum of atmospheric residuals
(after SCAO ; ~180nm RMS)

2 - Best fit of M1 by M4:

Aberrations on each segment create ~60nm RMS global wavefront error.

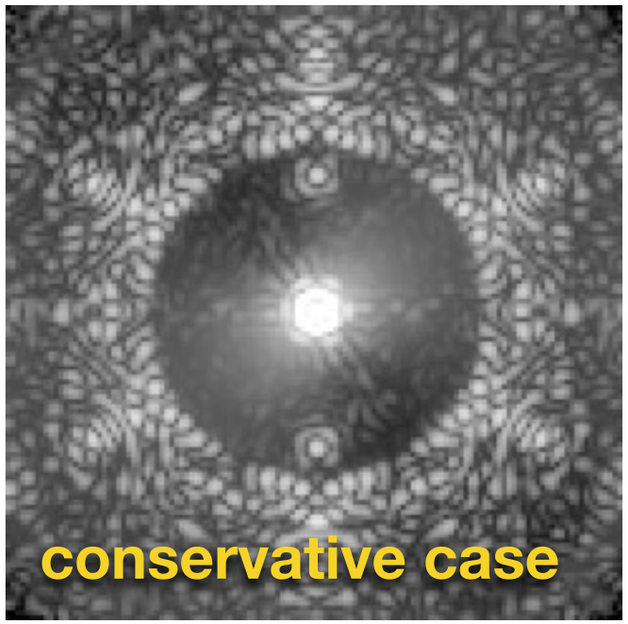


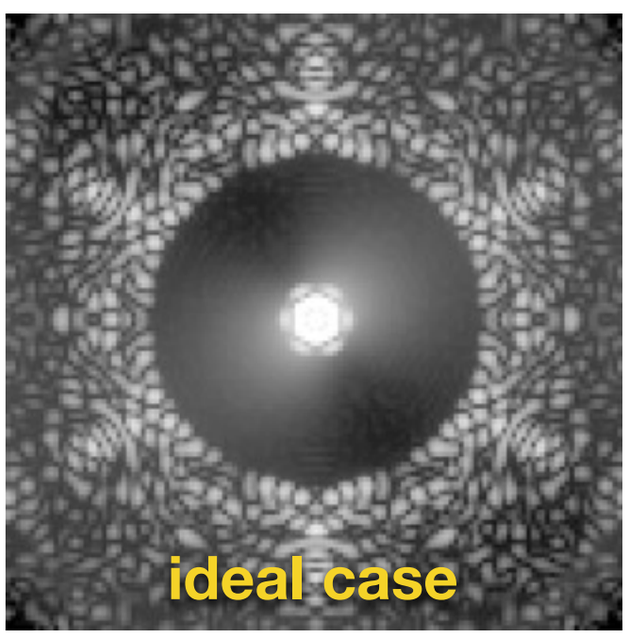
3 - Non common path estimation/calibration error

- 5nm RMS in this example.
- Exhaustive system analysis required.

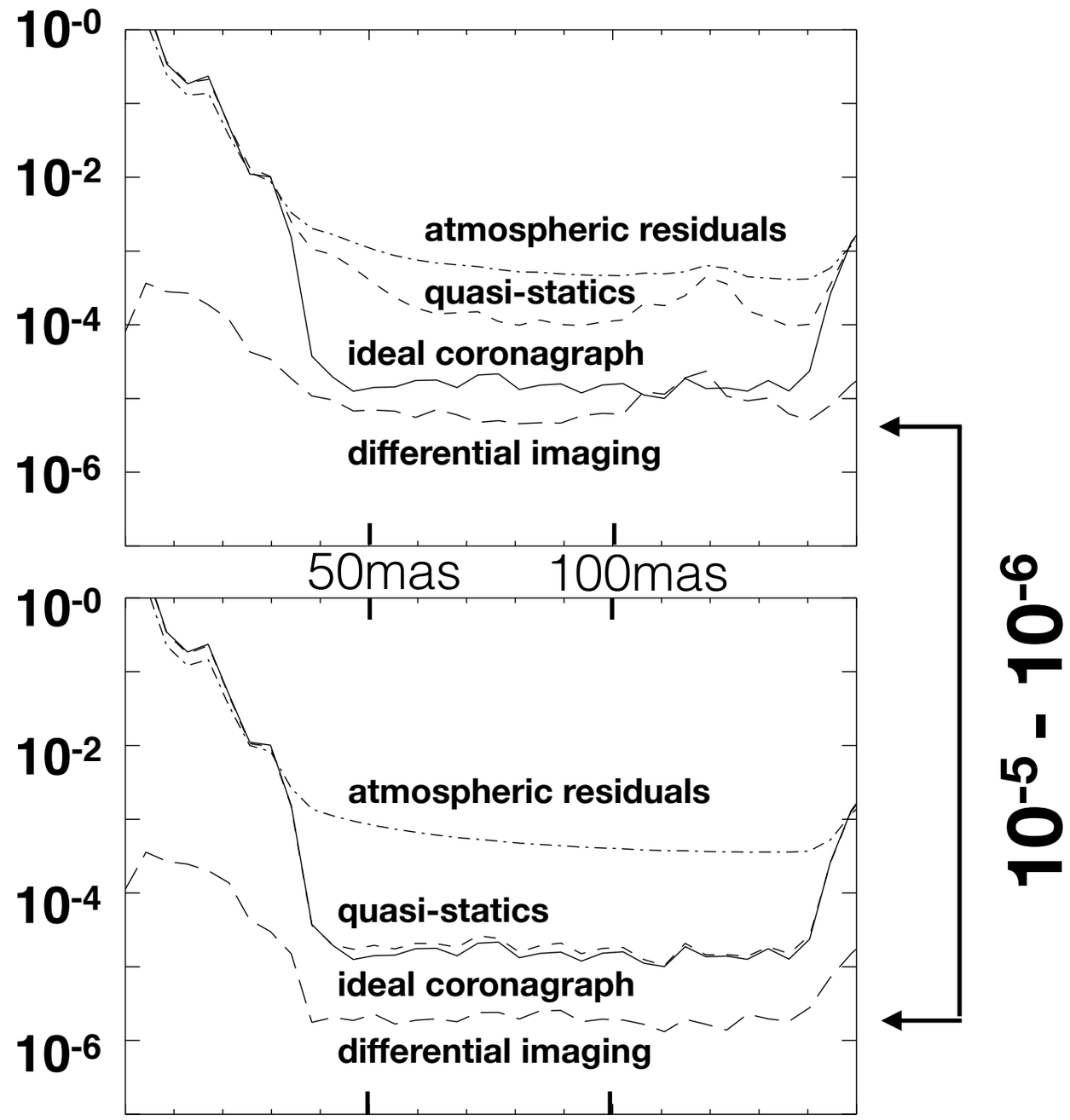
AO: semi-analytical approach

Infinitely long exposure
(no photon noise)





PSF cross-section
(5-sigma detection limits)



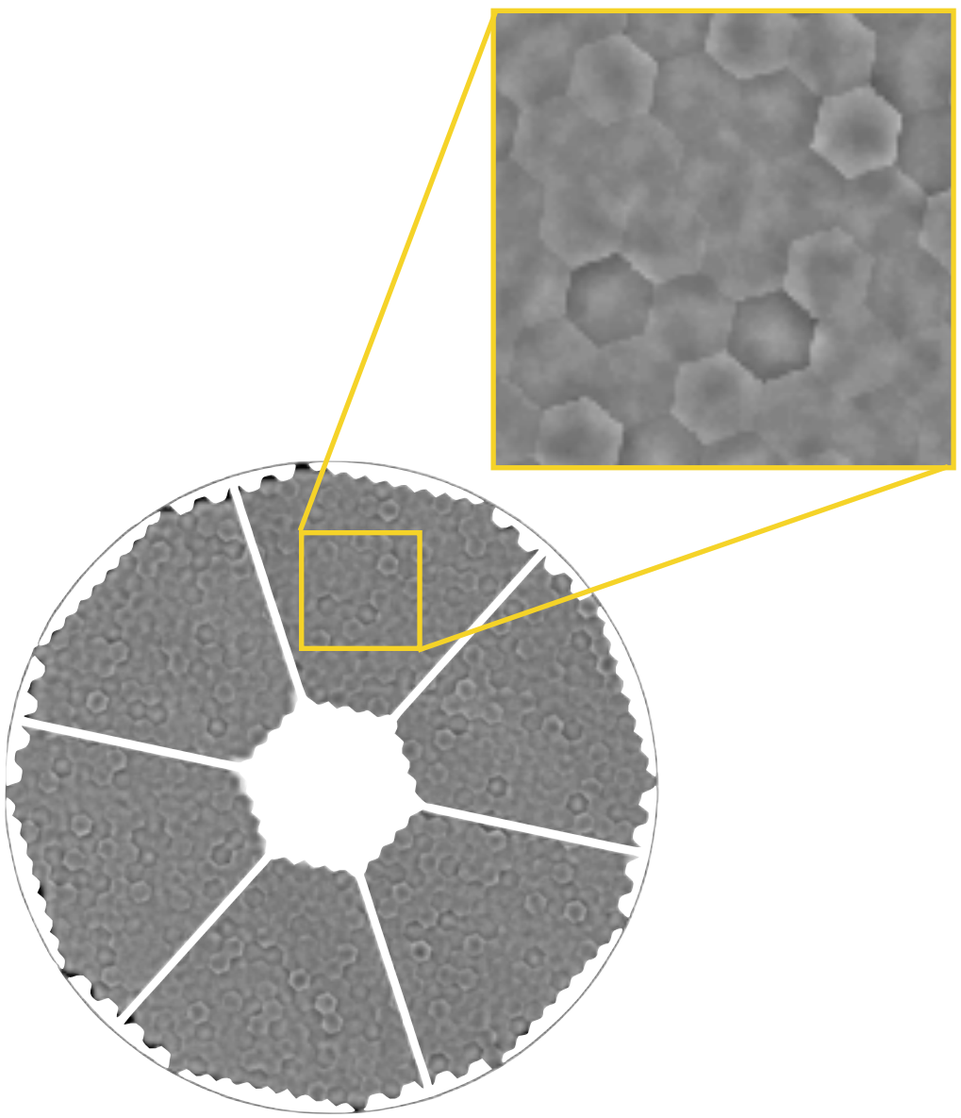
AO: end-to-end model

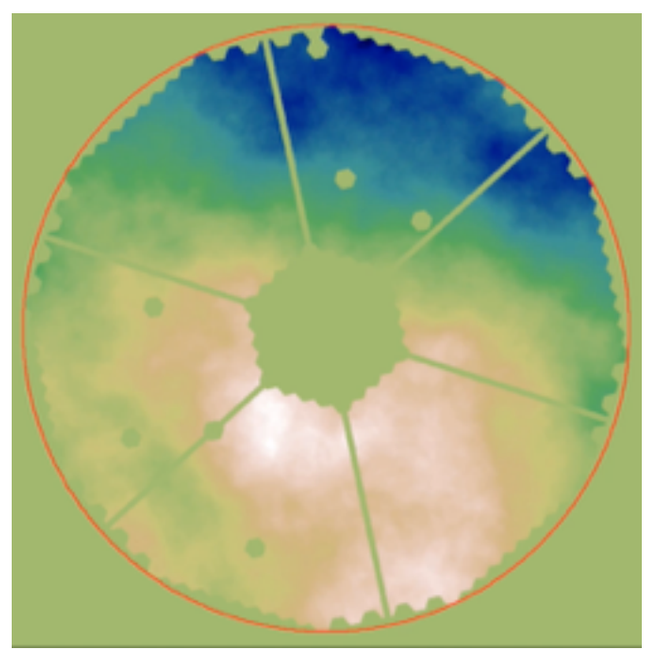
GPU-based COMPASS platform (Gratadour et al. 2014, Carlotti et al., 2014)

Open-source, freely distributed code ; Uses Nvidia's CUDA software & hardware.

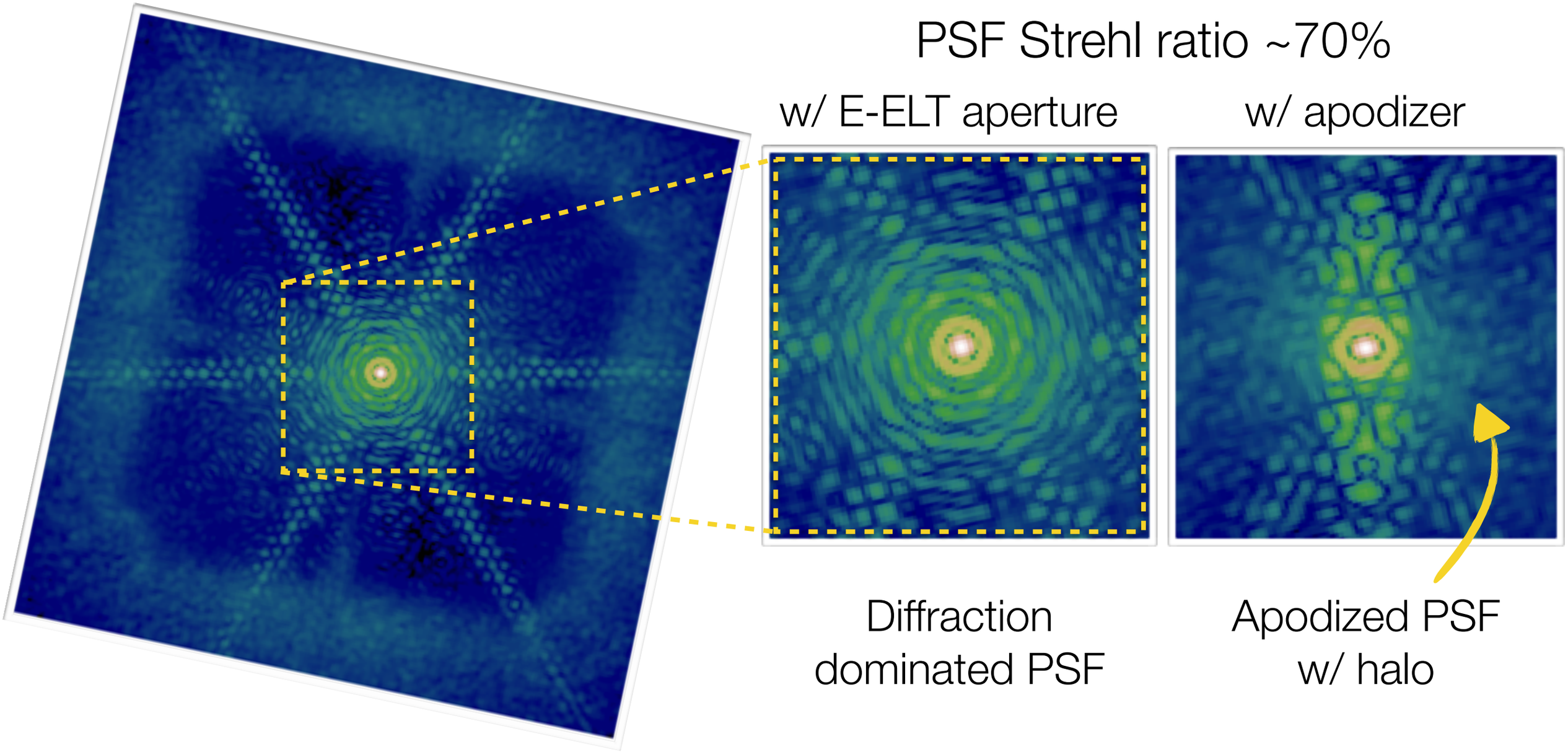
Segments introduce phase & amplitude discontinuities:

1% reflectivity ; 50nm piston ; 50nm TT ; 50nm defocus w/ 10nm mean





AO: end-to-end model



Development of a COMPASS extension for high-contrast imaging.

Compatible coronagraphs

Baseline constraints:

- atmospheric dispersion *not* corrected => No focal plane mask.
- Pupil plane masks are the only option here.

Pupil

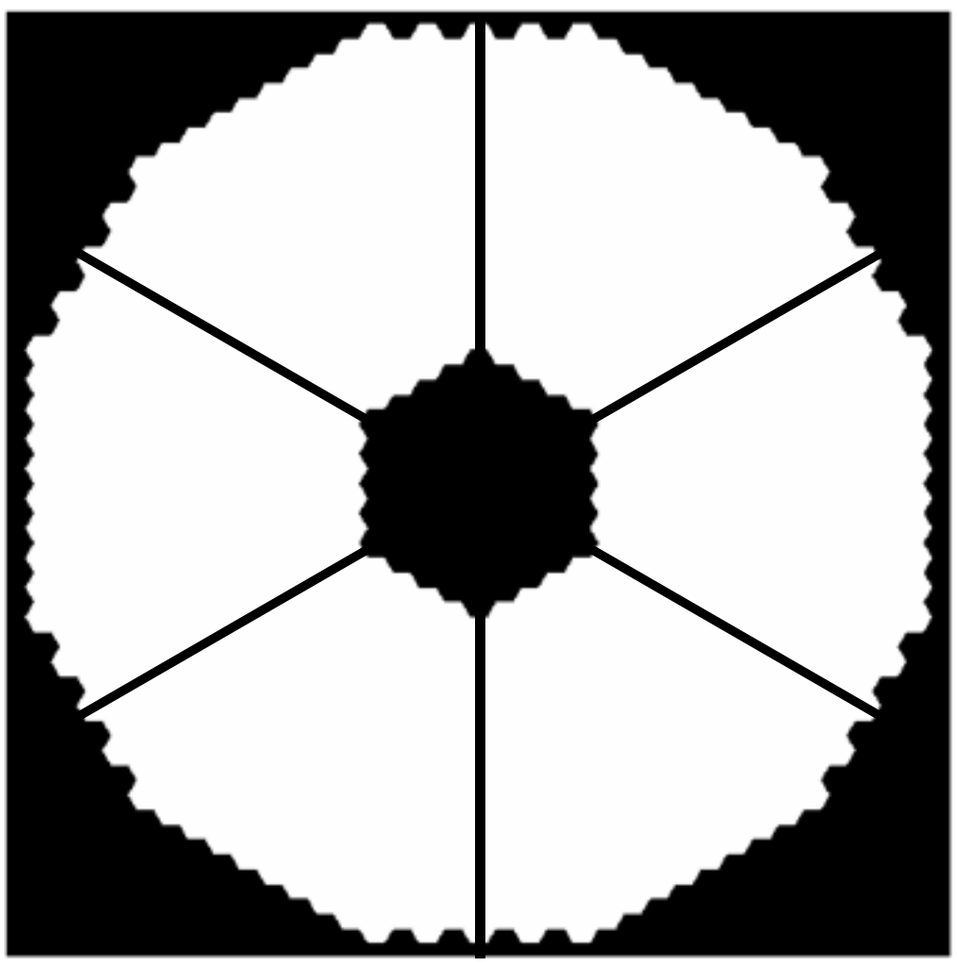
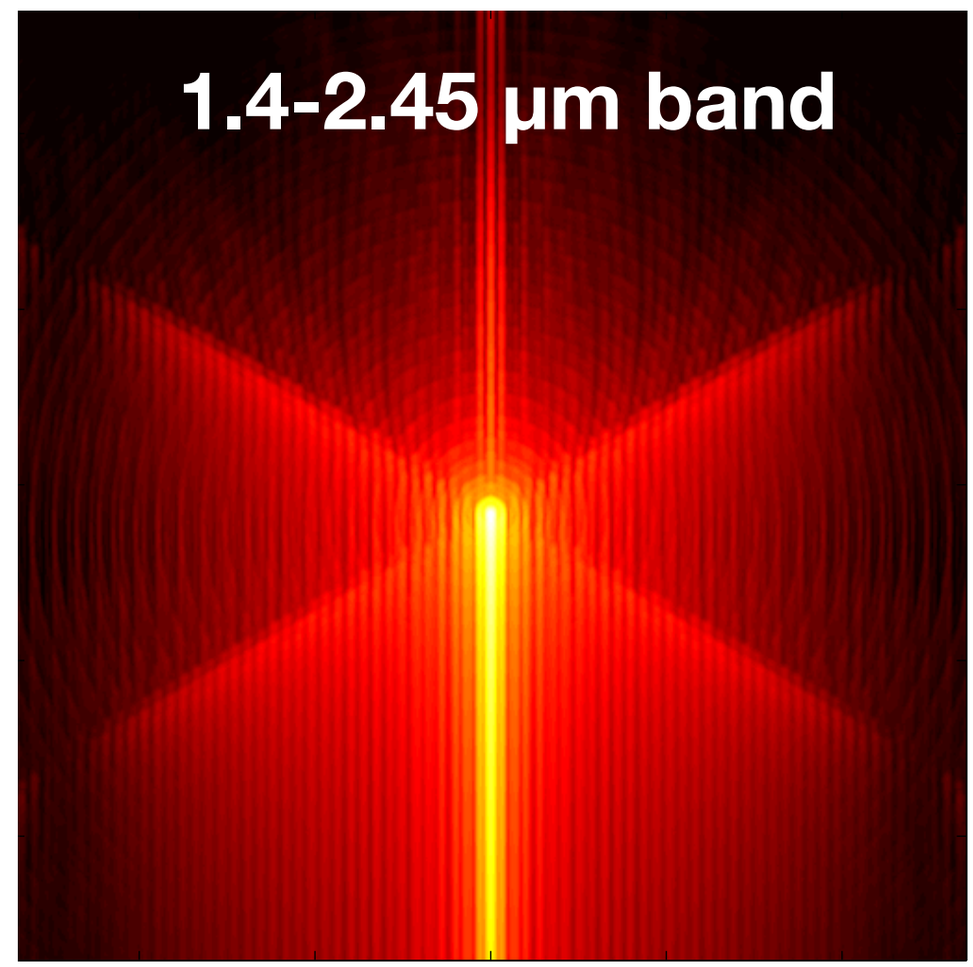


Image (log scale)

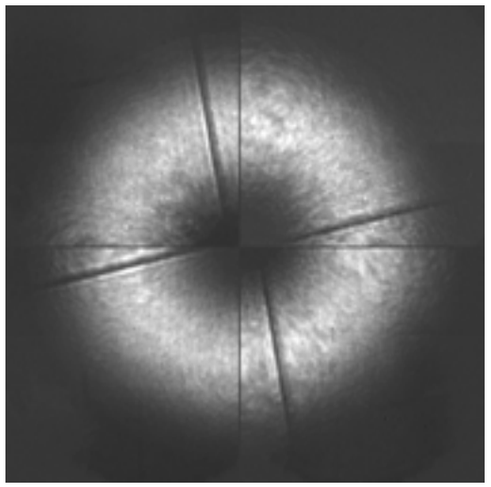


Apodizing the aperture

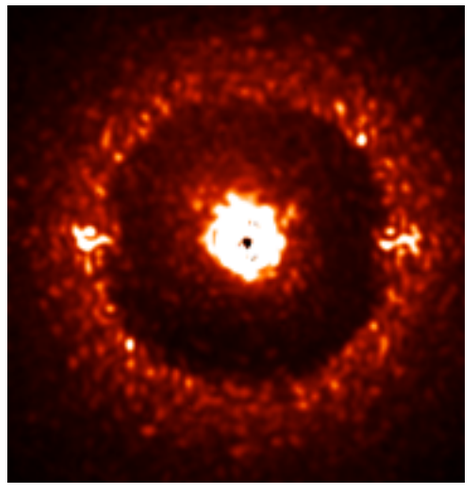
see Aime & Soummer 2001, Vanderbei et al. 2003, Carlotti et al. 2011

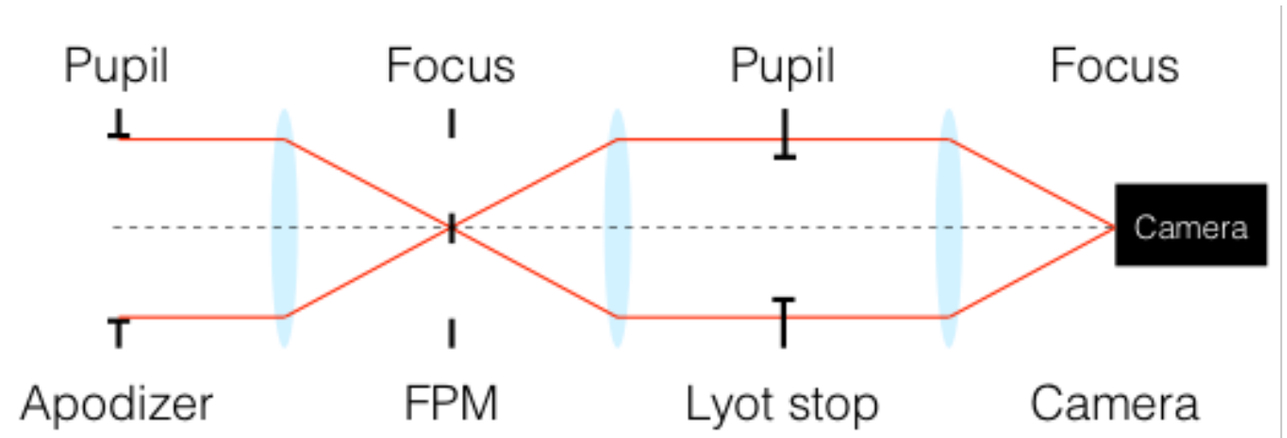
Apodized Lyot coronagraph (as used in VLT/SPHERE & Gemini/GPI):

Apodized aperture

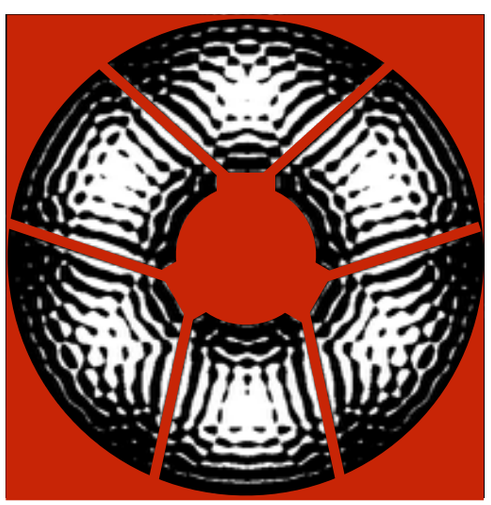


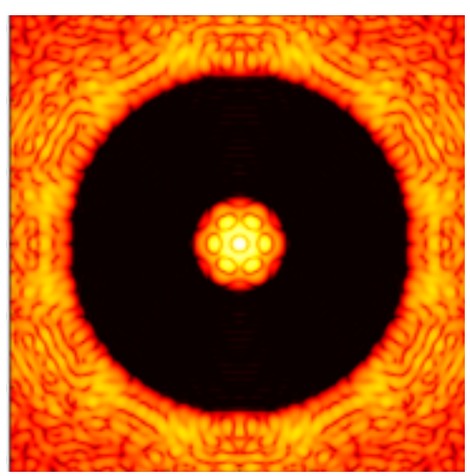
Apodized PSF

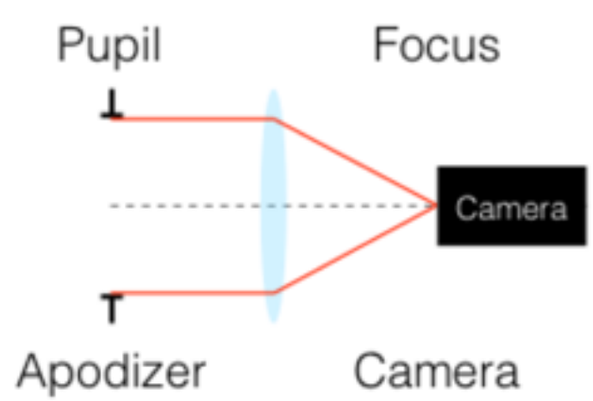




Shaped pupil coronagraph (as used in WFIRST-AFTA and in SUBARU/SCExAO):





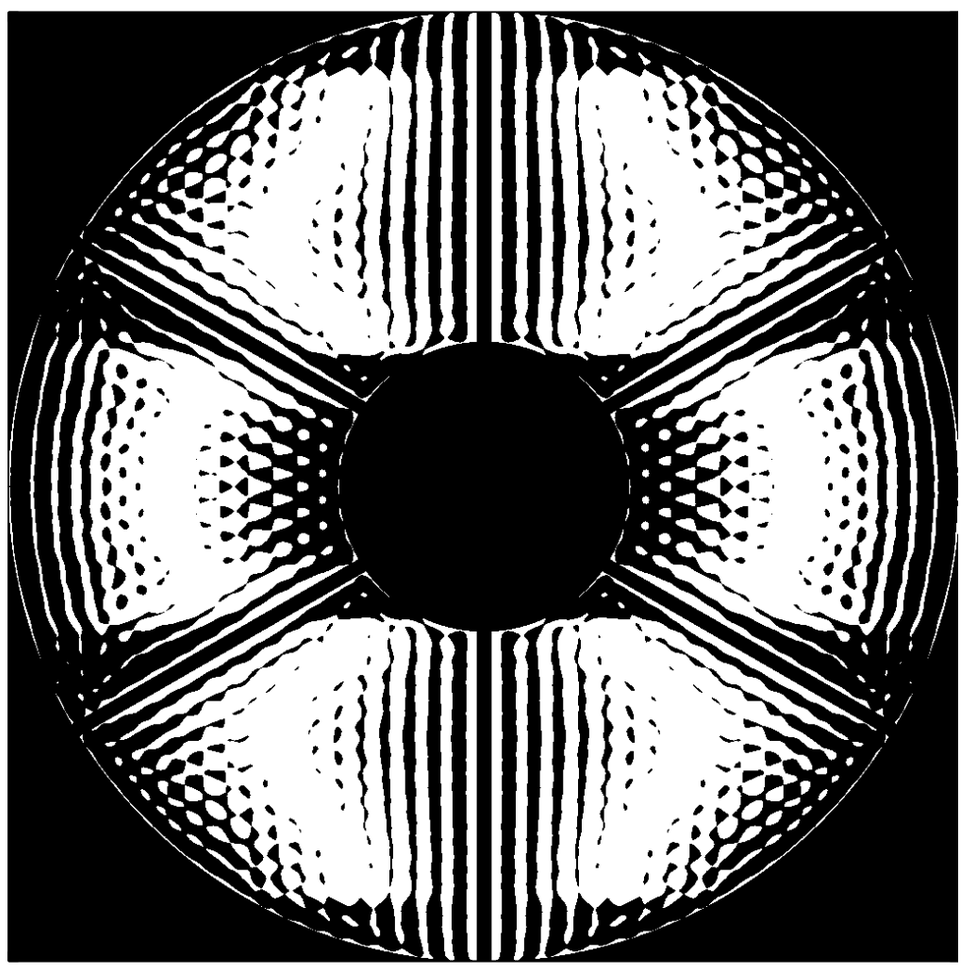


Compatible coronagraphs

Solution to satisfy constraints:

- direct apodization, i.e., Shaped Pupils, APP, still compatible.
- pupil tracking mode enables angular differential imaging.

Pupil



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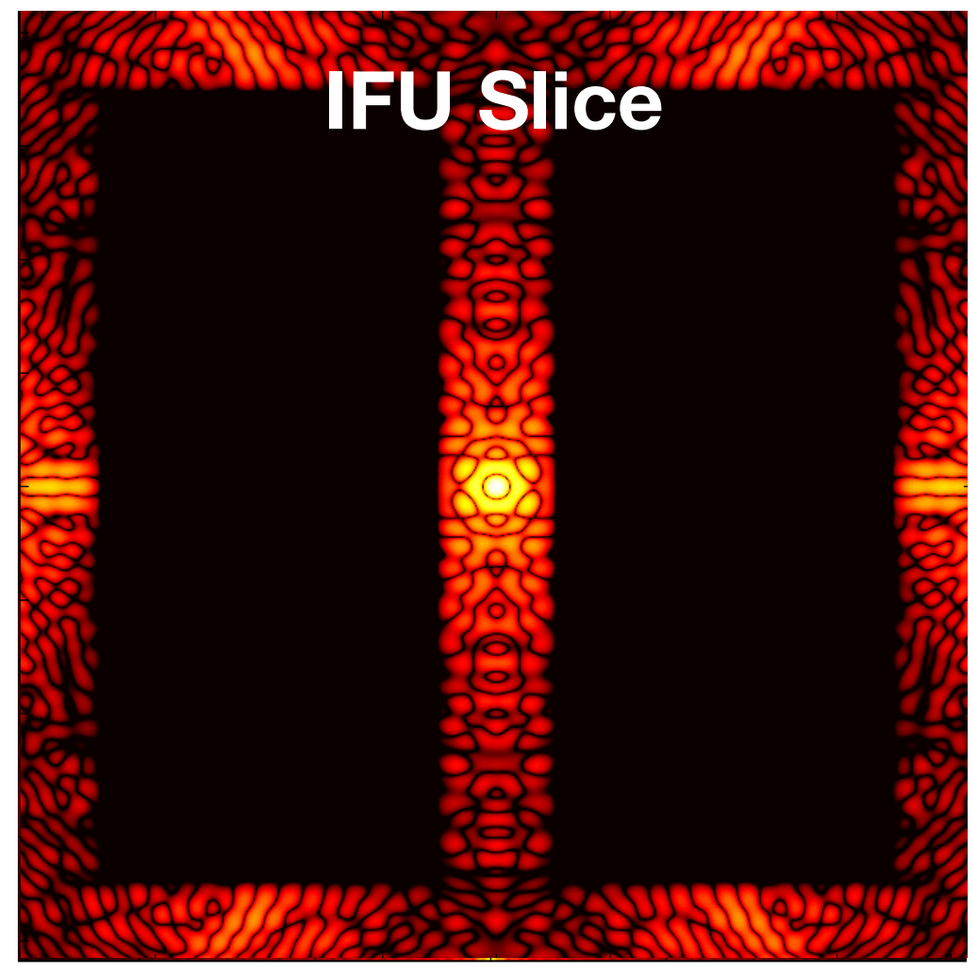
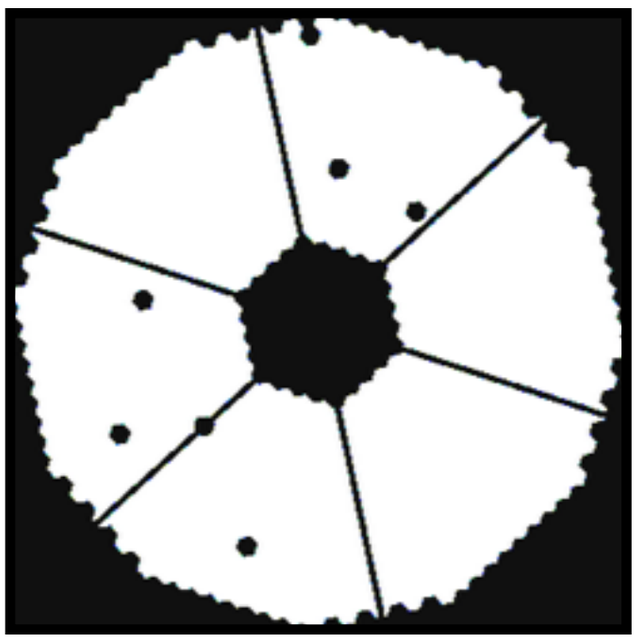


Aperture constraints

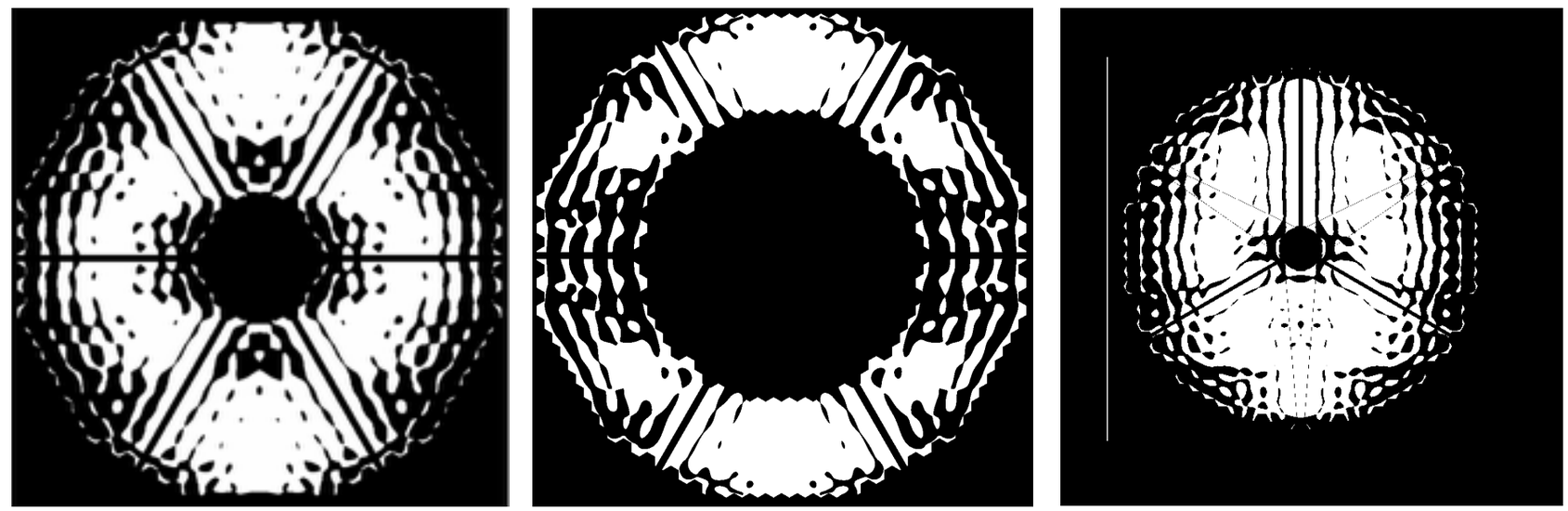
Missing segments



Not a decisive problem for 1st light instruments…

Central obscuration constrains the coronagraph

Nominal E-ELT **E-ELT -5 rings** **TMT**



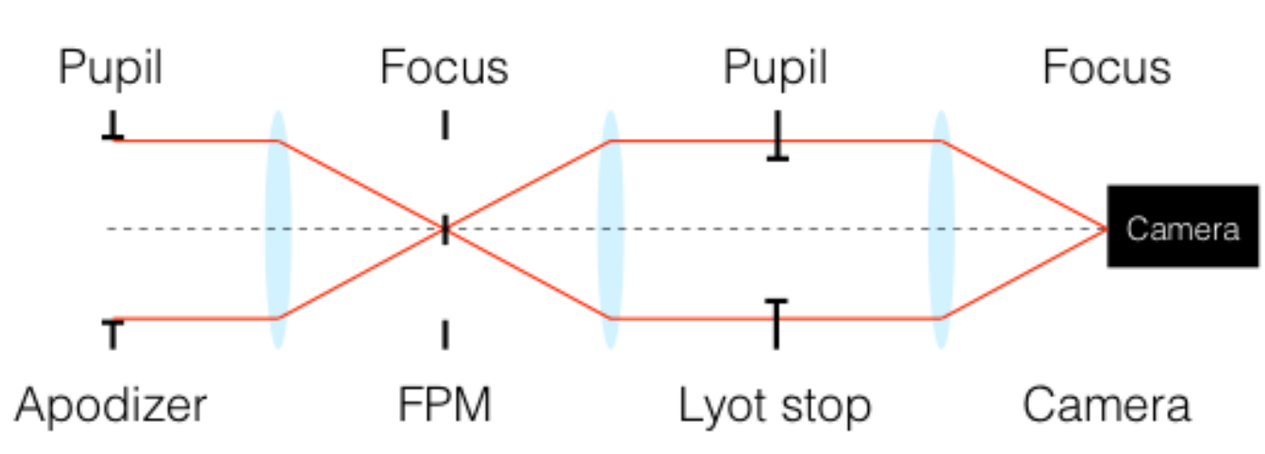
Δmag=12.5 detection, i.e., 10^{-5} contrast & same # of photons in the PSF core:

Nominal E-ELT: 30% obsc.: 36 mas

E-ELT -5 rings: 63% obsc.: 54 mas

TMT: 14% obsc.: 37 mas

Advantages of a dedicated arm



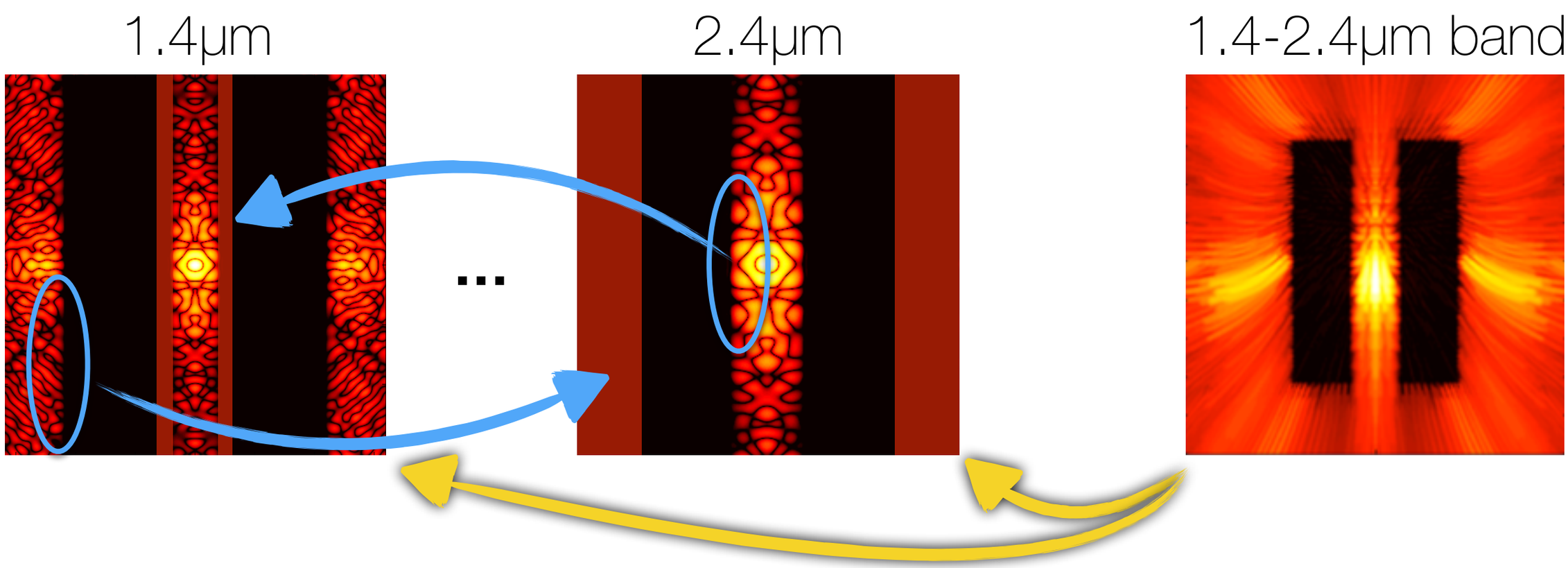
- Simplest option: 1 apodizer & 1 focal plane mask
  - reduces diffusion, dynamical range on camera

- w/ a (simple) ADC to allow APLC-like configuration:
  - smaller angular separation ~30mas w/ same contrast
  - weaker chromatic variations of NCPA => better stability

IFS: cross-talk & diffusion

Local contamination from spectral & spatial cross-talks

Global contamination due to 0.5% diffusion

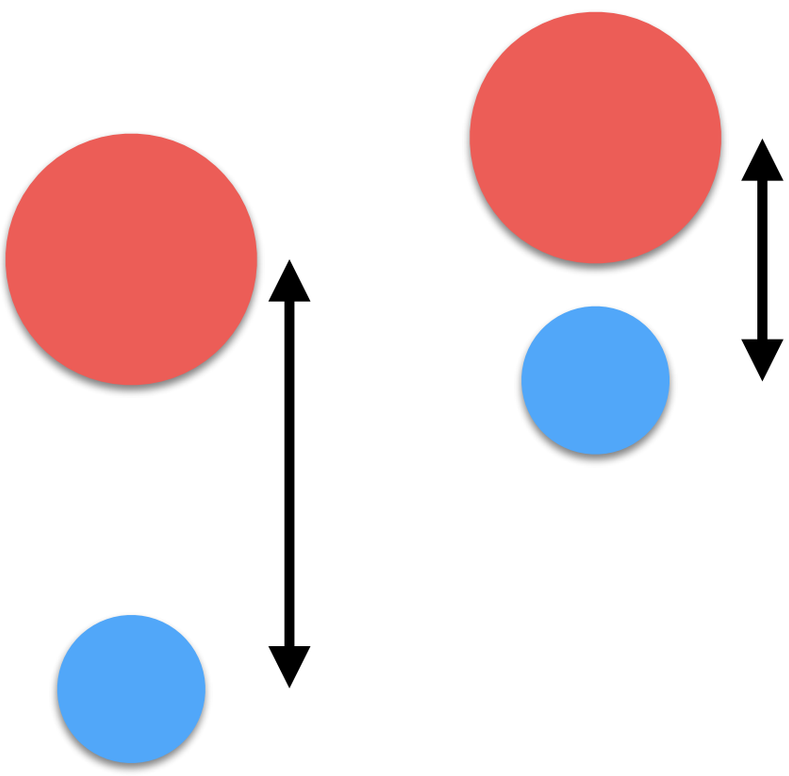


PSF spreads during exposure

Conservative example with a star 5h from meridian, 63° from zenith
1min exposure leads to 6.4mas dispersion.

Relative positions for two epochs:

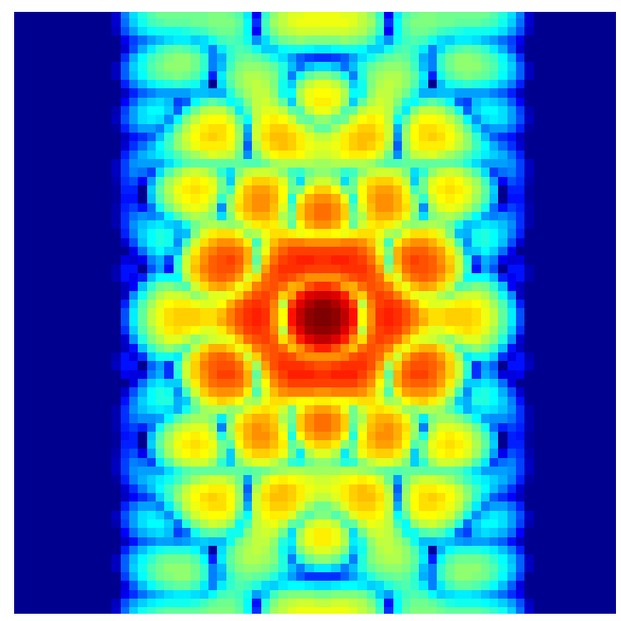
T_0, Z_0 $T_0+\Delta t$, $Z_1 > Z_0$



PSF blur is minimized by targeting blue star:

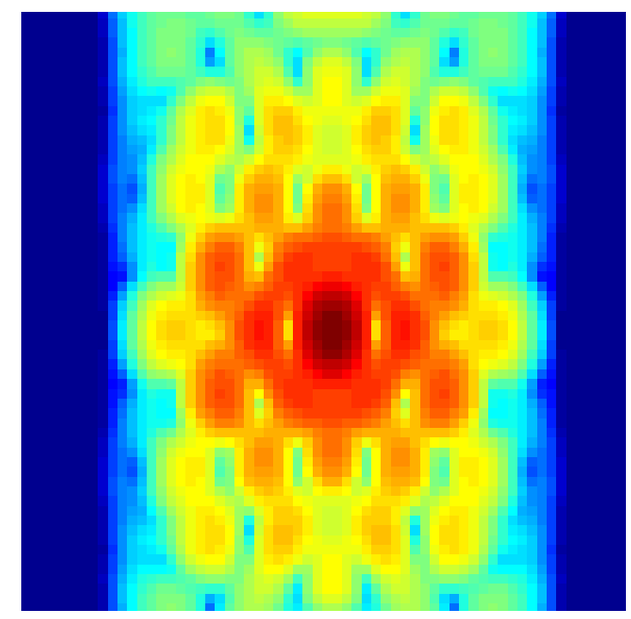
worst blur if blue star is targeted:

(2.45μm observation)



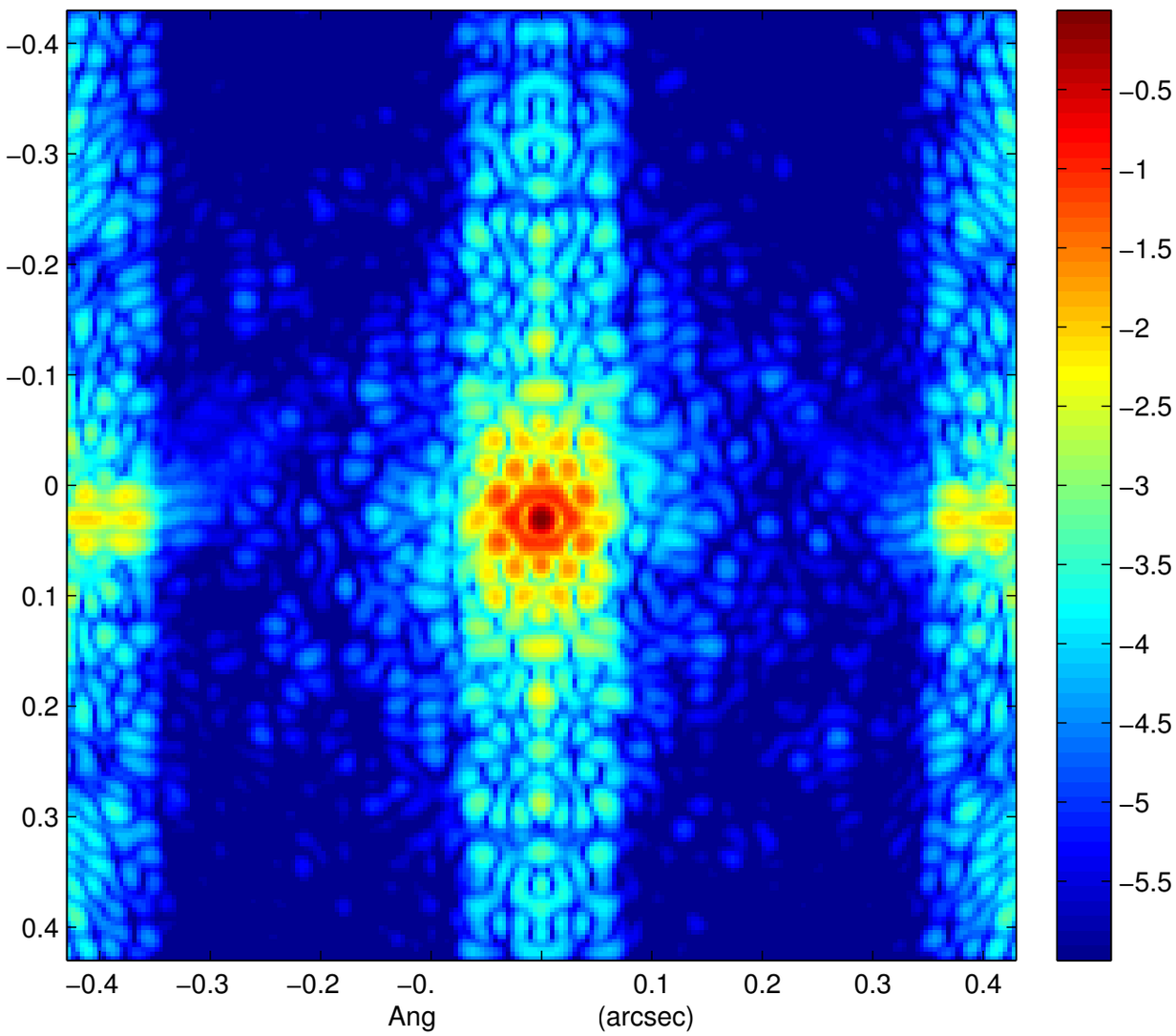
worst blur if red star is targeted:

(0.8μm observation) rescaled



Quasi-static aberrations

PSF w/ cross-talk & diffusion



100nm RMS residual aberrations.

- temporal evolution? Only one surface rotates wrt. instrument.
- chromatic evolution? Fresnel effects to be modeled.

Diffusion produces 10^{-5} plumes artefacts.

PSF is blurred vertically due to cross-talk, dispersion

Summary

- HARMONI has great potential for planet characterization:
  - 10-100 times the spectral resolution of SPHERE
  - down to 40 mas angular sep. (5 times smaller than at VLT)
  - Robust coronagraphic solutions exist.
- Next steps for the preliminary design phase:
  - Detailed system analysis required for NCPA.
  - What to expect from post-processing algorithms?
  - Development of a GPU-based coronagraphic module