Performance evaluation of mid-IR vortex coronagraphs with centrally obscured segmented pupils

B. Carlomagno[1], O. Absil[1], G. J. Ruane[2], D. Mawet[3], M. Feldt[4], S. Hippler[4], C. Delacroix[5], P. Forsberg[6], S. Habraken[1], E. Huby[1], M. Karlsson[6], J. Surdej[1], E. Vargas Catalan[6]

[1]Département d'Astrophysique, Géophysique & Océanographie, Université de Liège, Belgium
[2]Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology, USA
[3] California Institute of Technology / NASA Jet Propulsion Laboratory, USA
[4] MPIA, Heidelberg, Germany
[5]Centre de Recherche Astrophysique de Lyon, France
[6] Angstrom Laboratory, Uppsala University, Sweden

erc VORTEX Université de Liège UPPSALA UNIVERSITET

1. Objective and simulation setup

In its original design, the E-ELT/METIS mid-infrared imager and spectrograph incorporates a vortex coronagraph for the detection and characterization of exoplanets, with a required 5-sigma L-band contrast of 3e-5 (goal: 1e-6) at 5 lambda/D (goal: 2 lambda/D), with lambda/D~20 mas at L band. The AGPM (Annular Groove Phase Mask) is a vortex phase mask with impressive characteristics (small inner working angle, high throughput, achromaticity) and theoretically achieves perfect starlight cancellation for a circular pupil. However, a non-circular or obstructed pupil and non-flat input wavefront result in a starlight leakage, which degrades the performance of the vortex coronagraph.

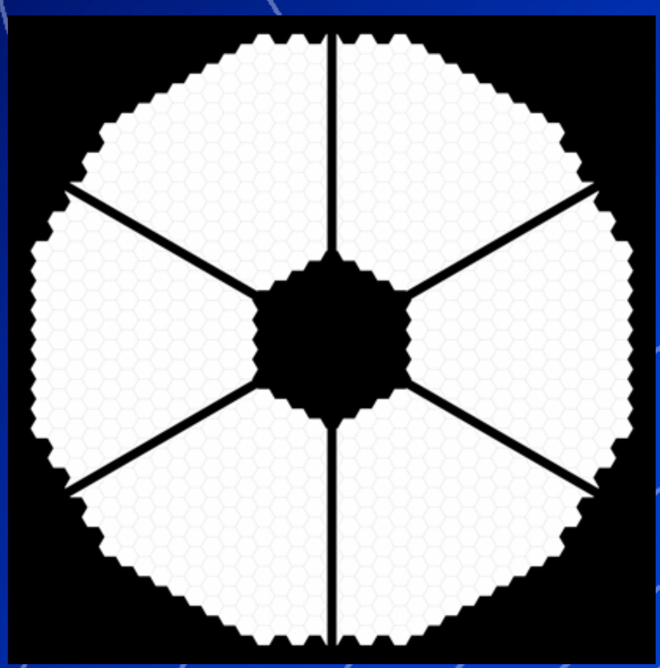

Fig. 1: E-ELT pupil.

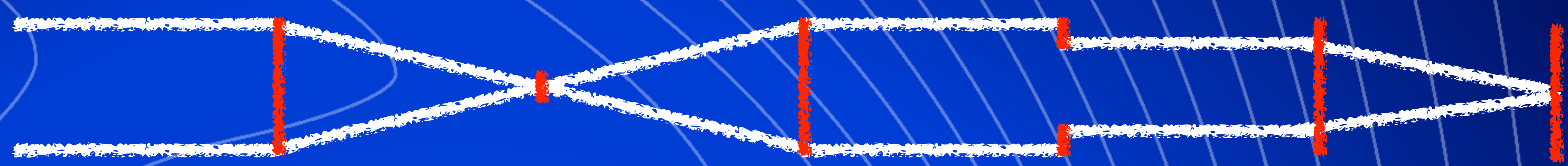

Fig. 2: System Design.

The system design for the simulations is very simple: from the pupil, the wavefront goes through the charge-2 vortex, then through the Lyot stop, up to the final detector.

2. Raw contrast for a perfect input wave front

Our model of the E-ELT includes the central obstruction, spiders and segmented aperture. We assume a perfect vortex coronagraph. In order to compensate for the non-circular pupil, several solutions have been analyzed. The **Lyot Phase Mask** (Ruane et al., 2015) is a phase-only optical element, placed at the Lyot stop, that can improve the performance of the vortex coronagraph in a defined area of the focal plane (here, 4 to 19 lambda/D). The **Double Vortex** (Mawet et al., 2011) is a multi-stage vortex coronagraph, with two focal plane vortex phase masks and two Lyot stops, that can reduce the residual light leakage without loosing in throughput. The **Ring-Apodized Vortex Coronagraph** (Mawet et al., 2013) combines the vortex coronagraph with an amplitude ring apodizer in order to compensate for the central obstruction.

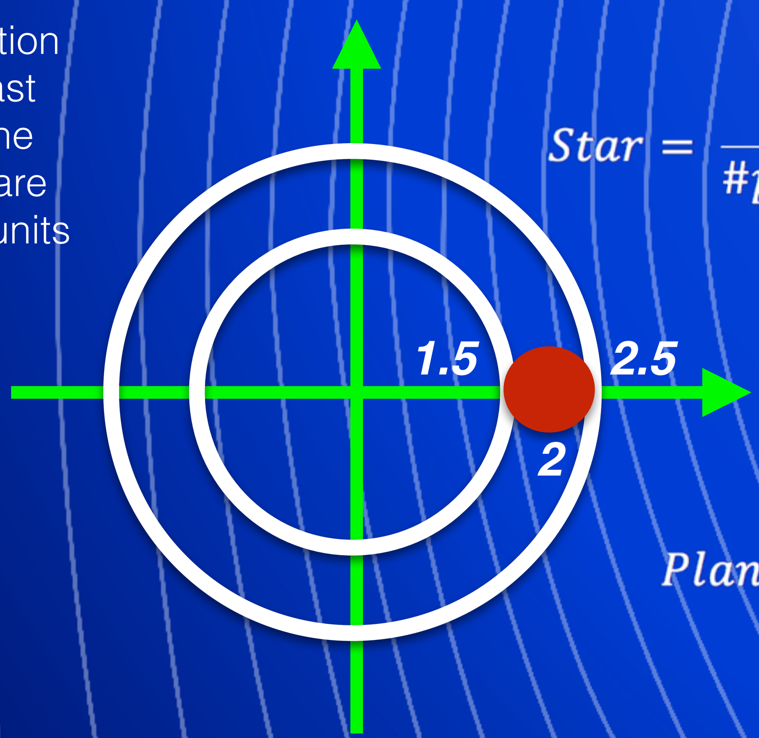

Fig. 3: Illustration of the contrast definition. The coordinates are expressed in units of of λ/D.

$$Star = \frac{EE(2.5) - EE(1.5)}{\#pixels(2.5) - \#pixels(1.5)}$$

$$Planet = \frac{EE\,(1\ at\ 2)}{\#pixels\ (1\ at2)}$$

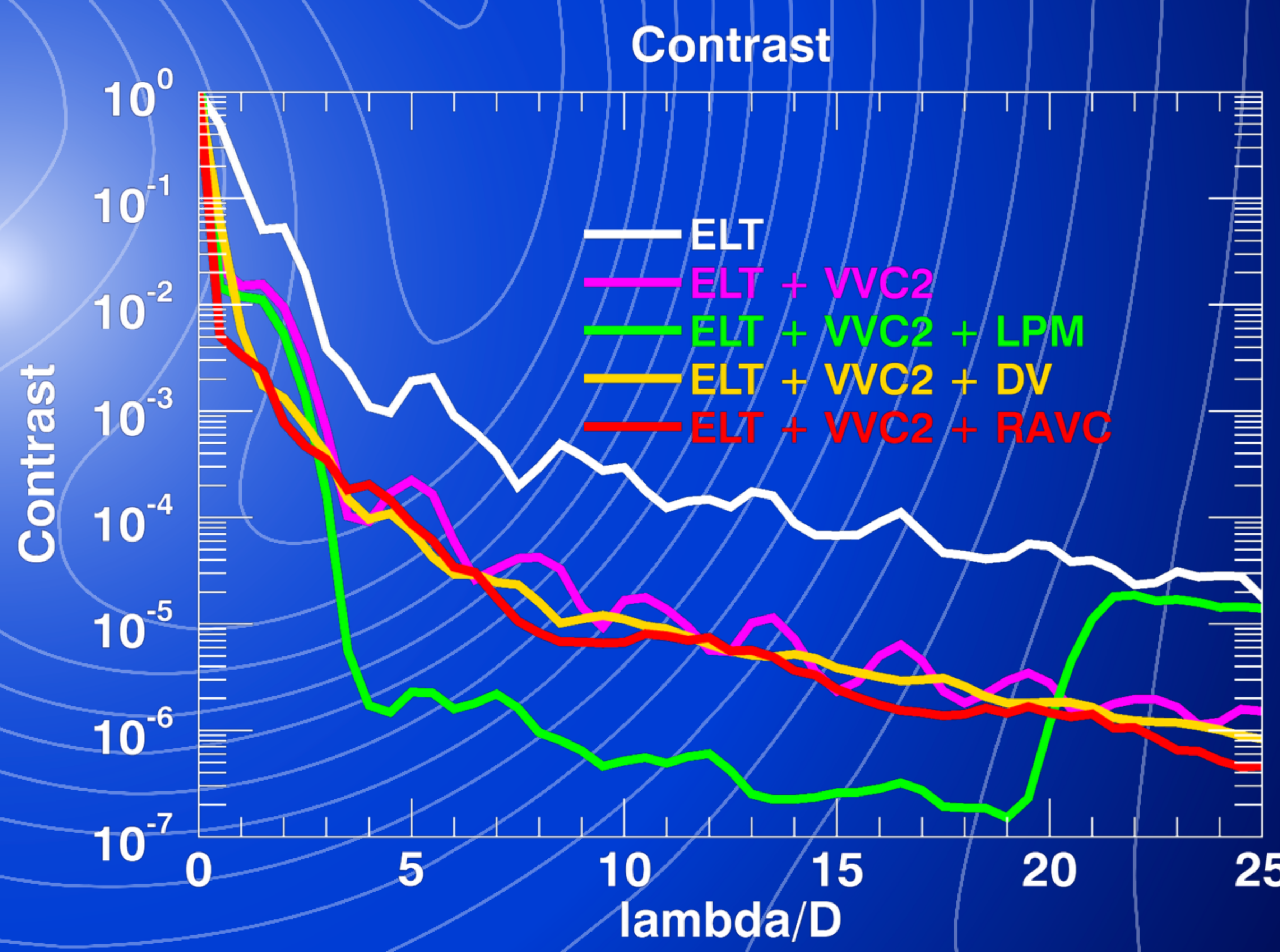

Fig. 4: Raw contrast in absence of wave front aberrations.

3. Raw contrast for SCAO-corrected phase screens

Natural guide star single-conjugated adaptive optics simulations under YAO have been used to estimate the residual turbulence at the entrance of the METIS instrument (Feldt & Hippler, personal communication). We have used these screens to evaluate the performance degradation of the vortex coronagraph and the proposed solutions under typical observing conditions. Our simulations suggest that all concepts will deliver similar raw contrasts in presence of atmospheric turbulence, except for very small angles where some differences can be noticed. Final contrasts taking into account post-processing still need to be computed and may show more differences.

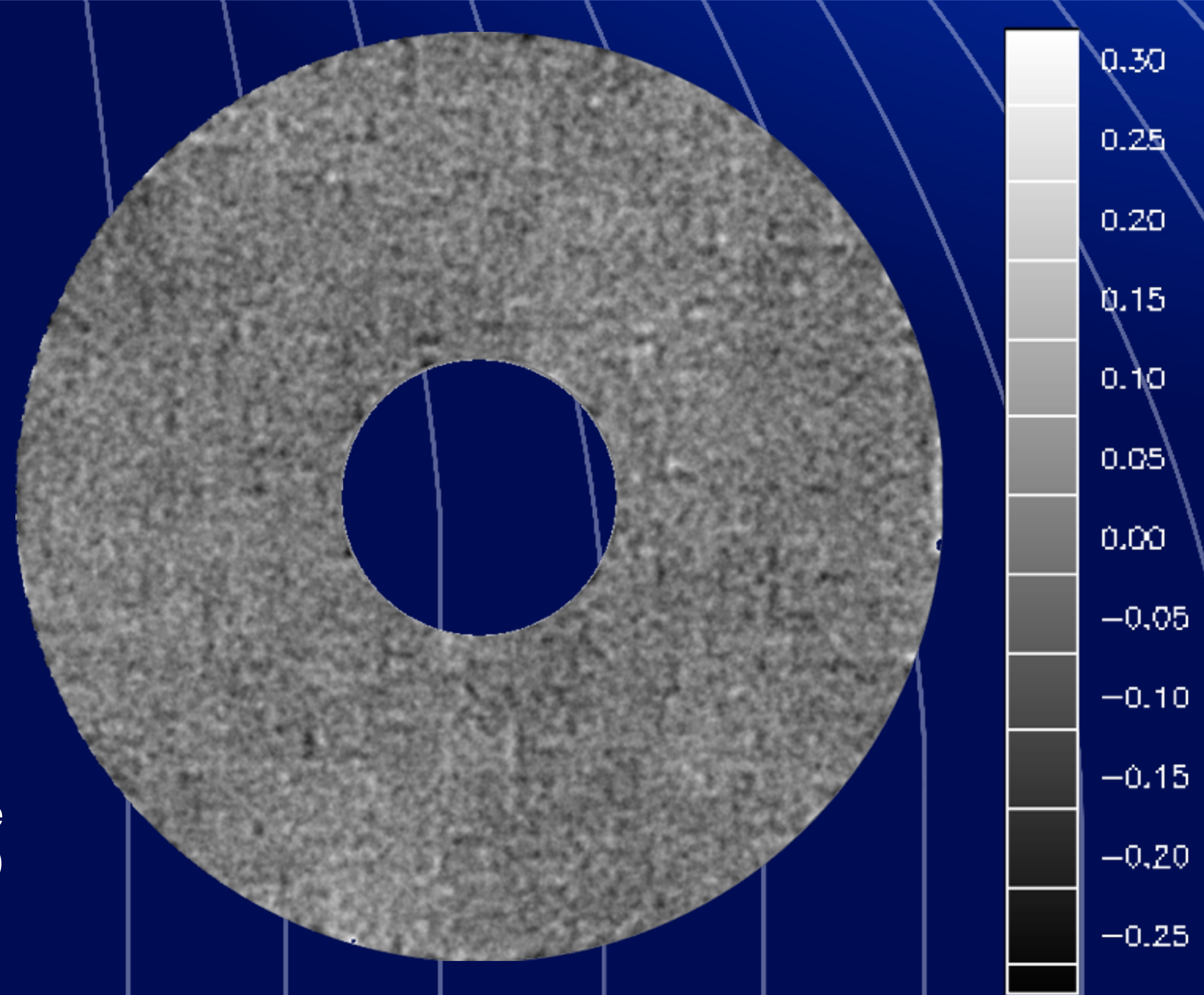

Fig. 5: Post-AO Residual phase screens (in μm) obtained with YAO.

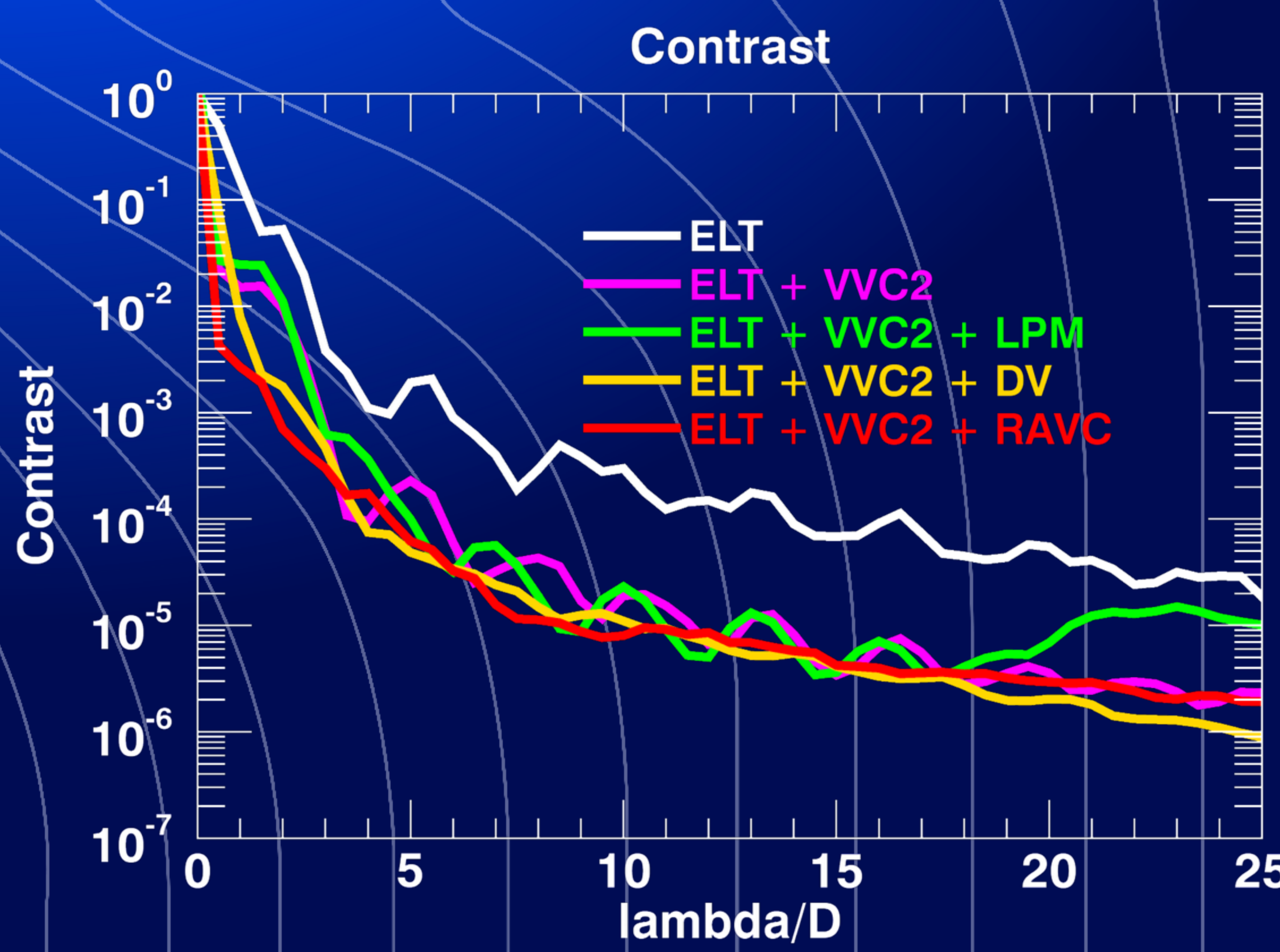

Fig. 6: Raw contrast with post-AO residual phase screens.