Knowing your limits

How close & how deep can we go? Is it efficient?

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Journées SF2A 2026 - Grenoble (sorry about the low temperatures, next year will be warmer!)

Exoplanet Adaptive Characterization with the ELT

European Research Council
Established by the European Commission

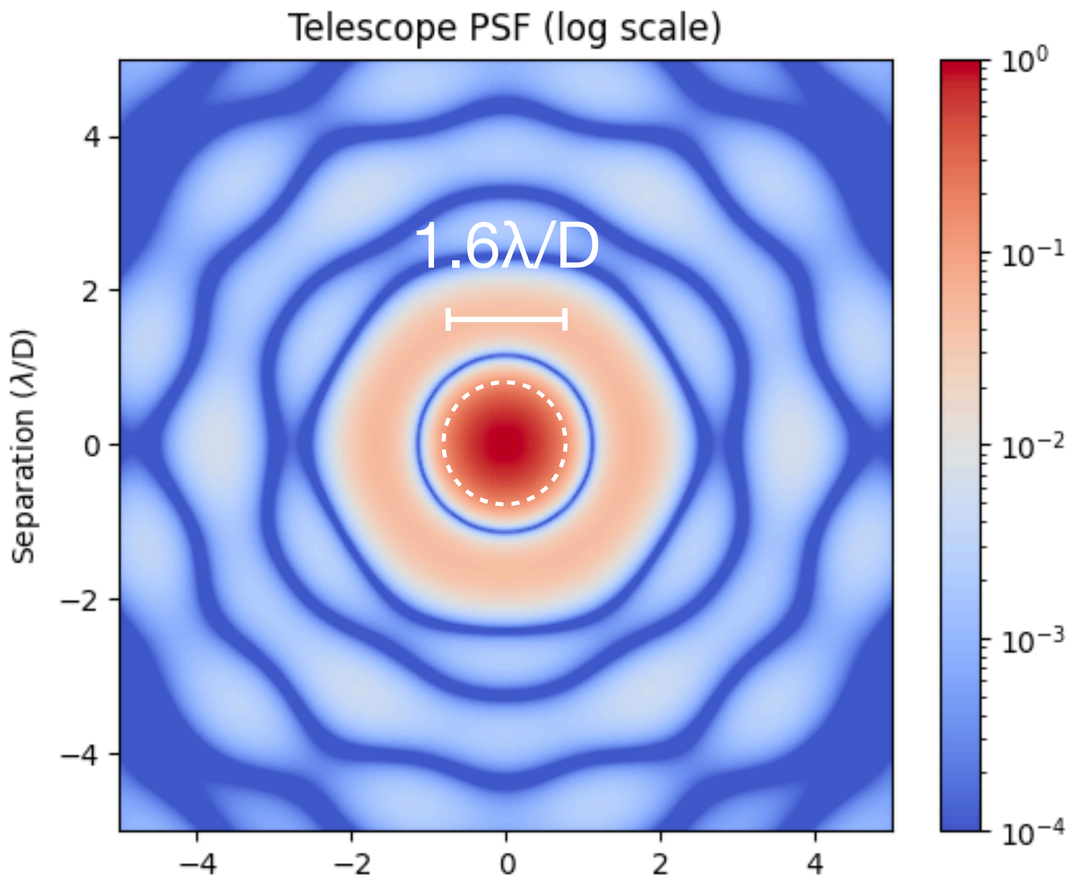
This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme, grant agreement No. 866001 (EXACT)

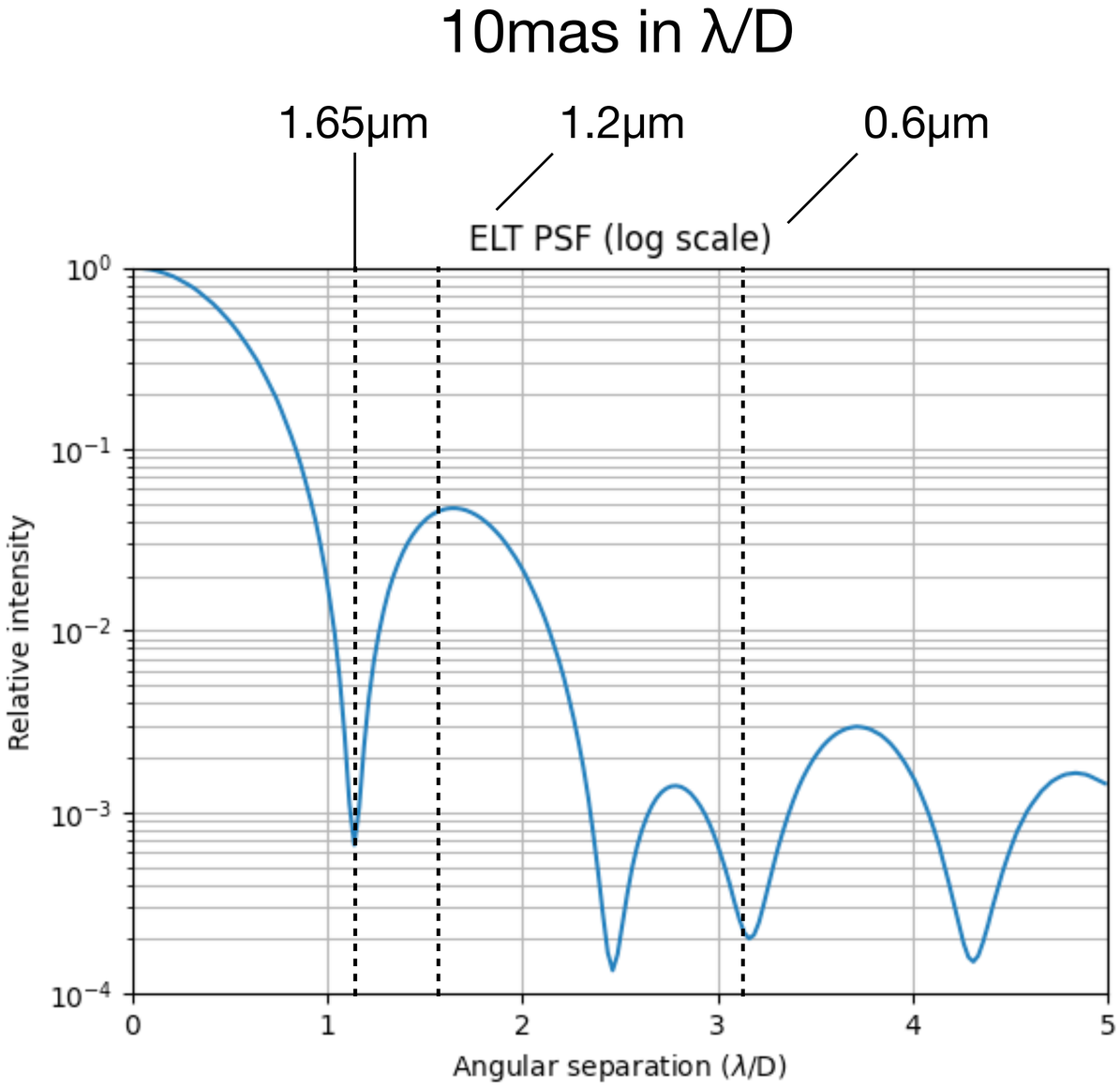
A few assumptions, and a question

- Known planet position, thanks to GAIA or other means
- Mid/High resolution spectra acquired with an IFU or a fiber-fed spectrometer
- No non-ideal effects related to detector & spectrograph at this point
- Star / planet spectral diversity leveraged for characterization:
  high-pass filtering & forward modeling through cross-correlation with models

In the best case scenario, what is the detection limit?

The ELT PSF


Telescope PSF (log scale)
1.6λ/D
Separation (λ/D)
4
2
0
−2
−4
−4
−2
0
2
4
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}


10mas in λ/D
1.65μm
1.2μm
0.6μm
ELT PSF (log scale)
Relative intensity
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5
Angular separation (λ/D)

The many ways of lowering the starlight

- Direct phase or amplitude pupil masking:
  - apodized phase plates (APP, V-APP) & dark hole creation w/ an AO system
  - shaped pupils
- Apodized coronagraphs:
  - w/ an amplitude mask: APLC
  - w/ a phase mask: Roddier&Roddier, FQPM, Vortex
  - w/ loseless apodization: PIAA, PIAA-CMC

Also, constraints can be set:

- on the intensity, *or*
- on the electric field coupling into a fiber

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in this talk

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Photon noise limited SNR as ultimate floor

From **Ruane+ 2018**: $$\mathrm{SNR} = \frac{\eta_p}{\sqrt{\eta_s}} \epsilon \sqrt{N_\star} = \epsilon \sqrt{\frac{\eta_p N_\star}{C}}.$$

η_p : planet throughput

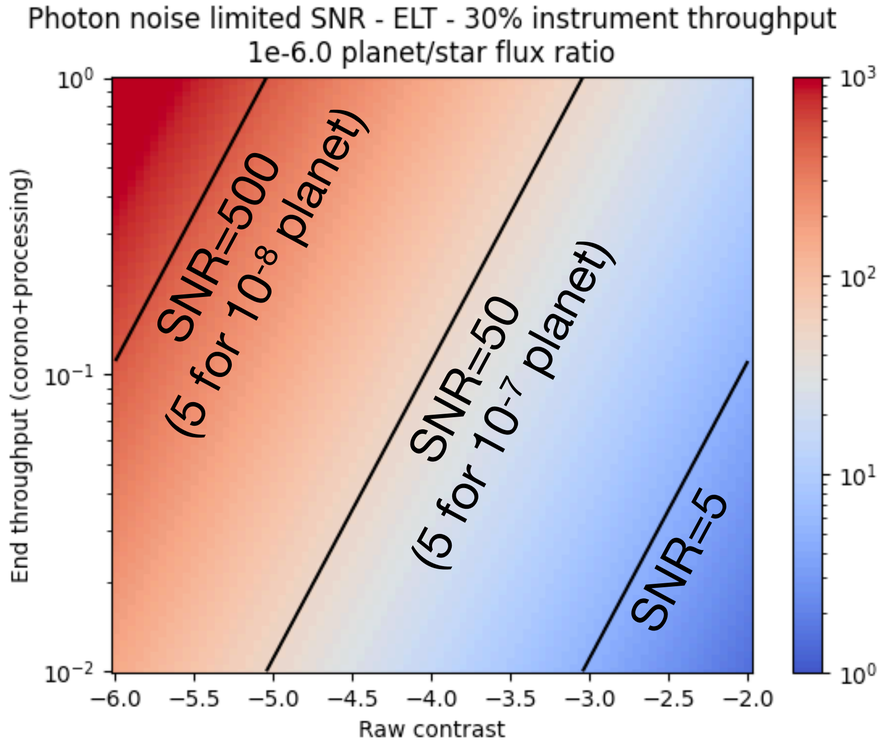
C : raw contrast

$N_\star$: total star photons (before coronagraph)

ϵ : planet/star flux ratio (<< 1)

ELT example: K star, H=8, 1h exposure, 30% base throughput (excl. coronagraph)
End throughput takes into account coronagraph & post-processing contributions

Caveat: the end throughput should effectively depend on the planet spectra (not considered here).



SNR gain

t: total planet transmission

C_{tel}: raw contrast* at planet location w/o the coronagraph

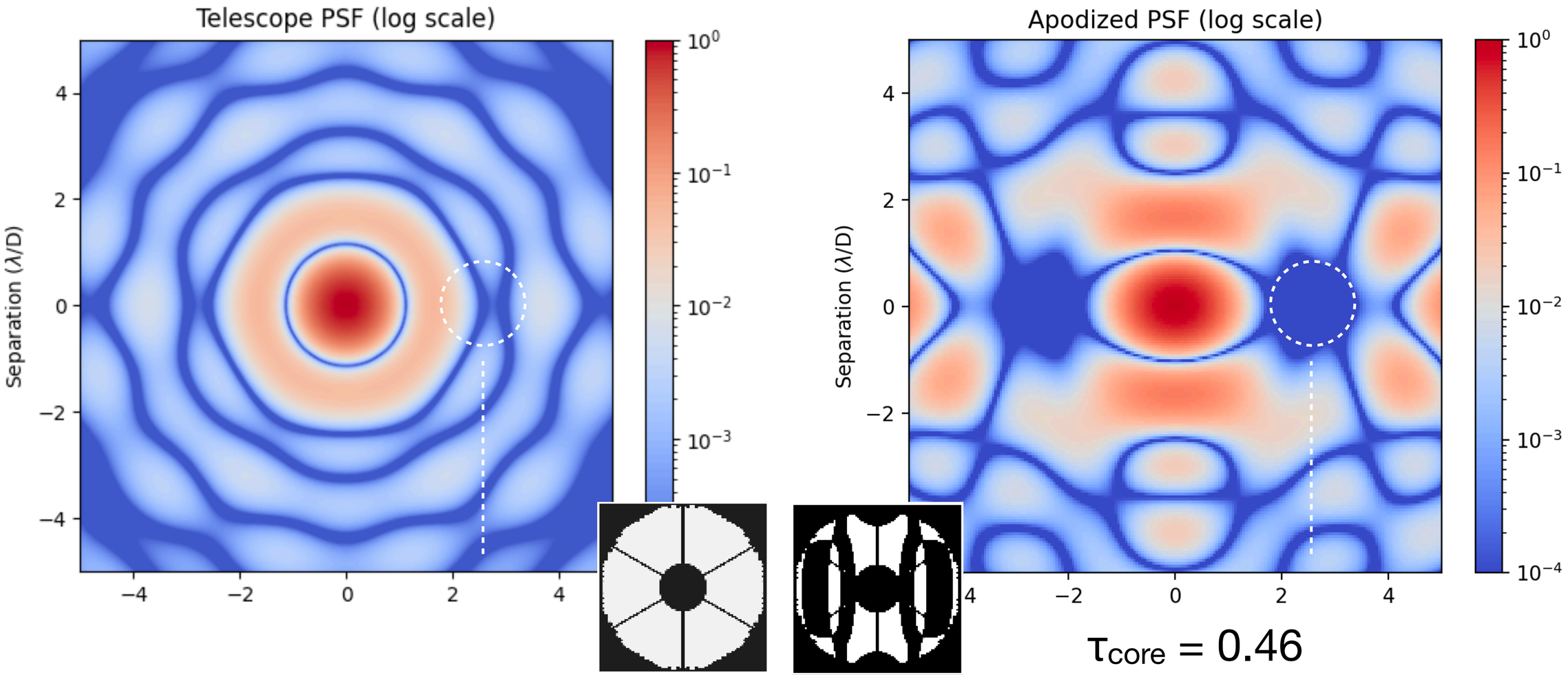
$$\mathrm{SNR}_{\mathrm{gain}} = \frac{\sum_{\mathrm{PA}} I_{apod}}{\sum_{\mathrm{PA}} I_{\mathrm{tel}}} \cdot \sqrt{\frac{\sum_{\mathrm{PA}} I_{\mathrm{tel}}}{\sum_{\mathrm{PA}} I_{\mathrm{apod}}}} = \tau_{\mathrm{core}} \sqrt{t \frac{C_{\mathrm{tel}}}{C_{\mathrm{apod}}}}$$

C_{apod}: raw contrast* at planet location with the coronagraph

τ_{core}: core energy fraction, i.e., relative concentration of light within the photometric aperture with and without the apodizer

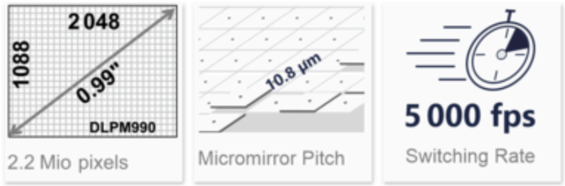
* The raw contrast can be considered in an ideal case, or in the presence of aberrations

One example: 2.4 λ/D, t=0.45, SNR_{gain}~11



Achromatic amplitude and phase control

Recent advances to provide high spatial resolution control!



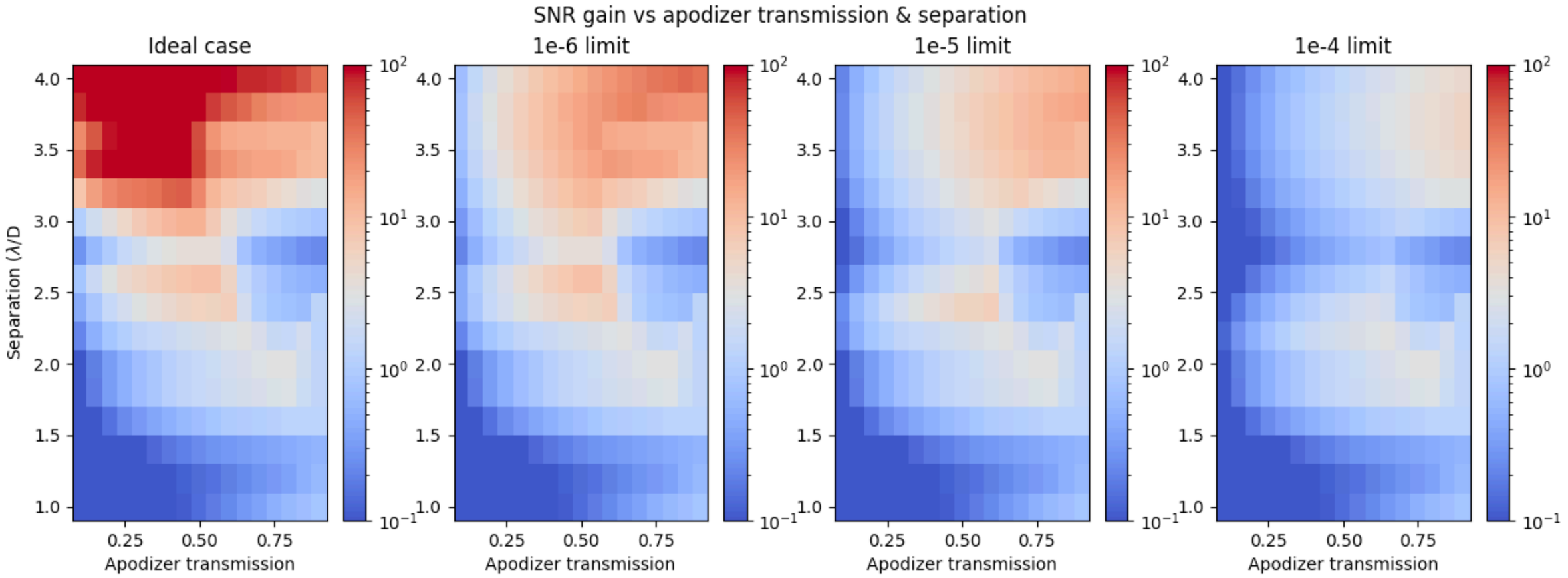
Texas Instruments phase light modulator available later this year
Segmented DM with > 1K actuator across, ~1 λ phase in VIS (NIR: expected)
Important caveat: 4bits control only (16 phase levels, non-linear)

Equivalent technology from the Fraunhofer Institute (IPMS, Dresden) with 8bits (256 levels) - Project RealHolo, low TRL

Achromatic amplitude control with ~300 actuators across from the Fraunhofer Institute (IPMS, Dresden) - Prototype to be tested at IPAG 2026-2027

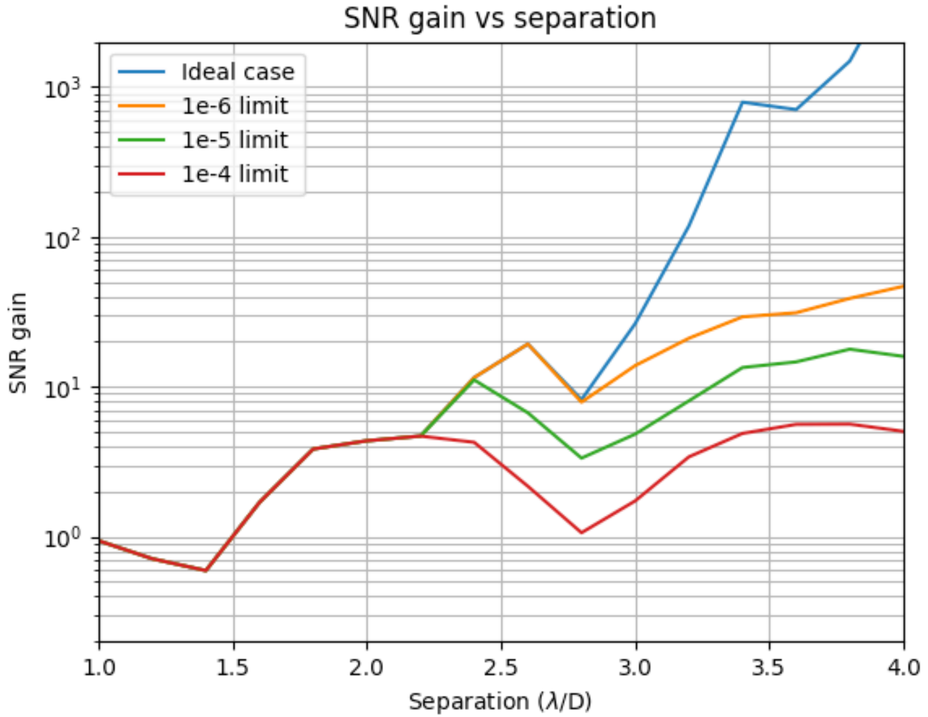
A more exhaustive look

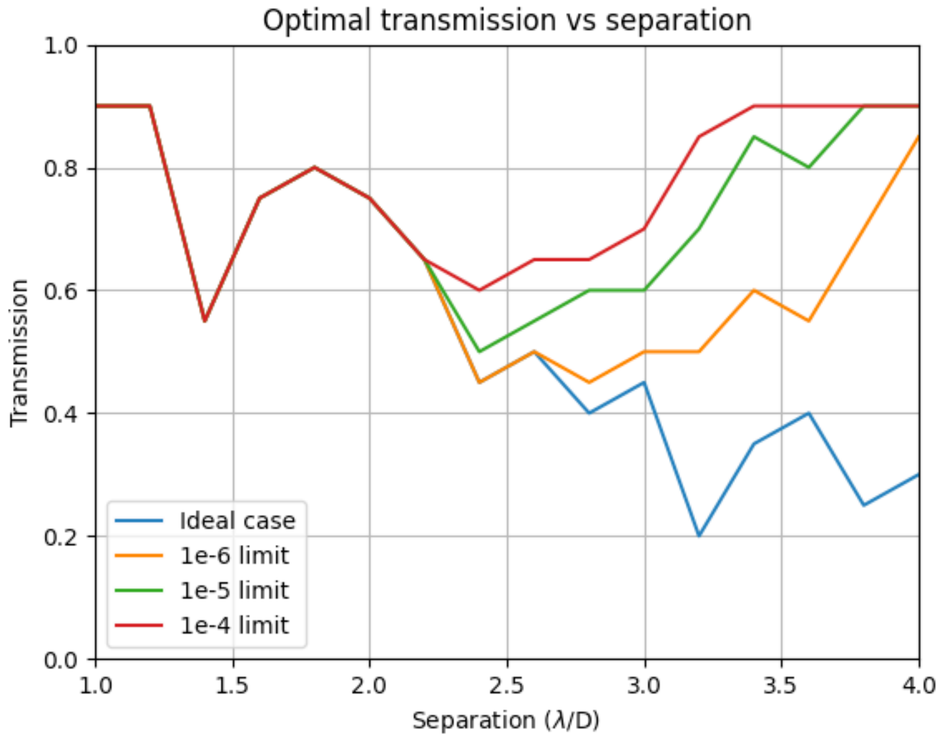
Illustrating the difficulty of lowering the intensity very close to the star



Optimal throughput set by contrast limit

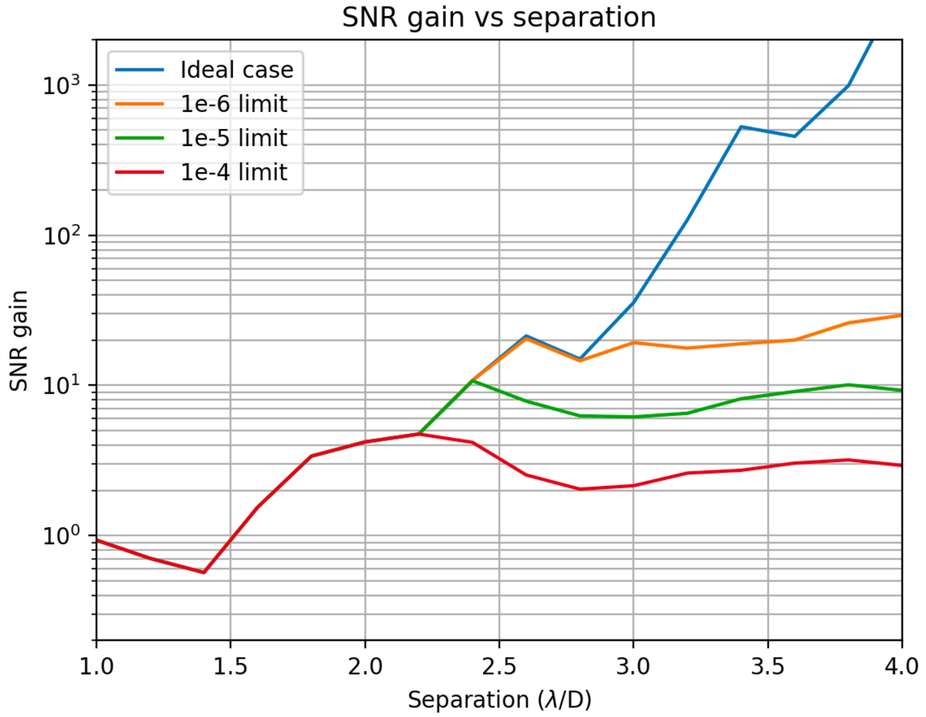
Specific case of HC regions created along the x-axis

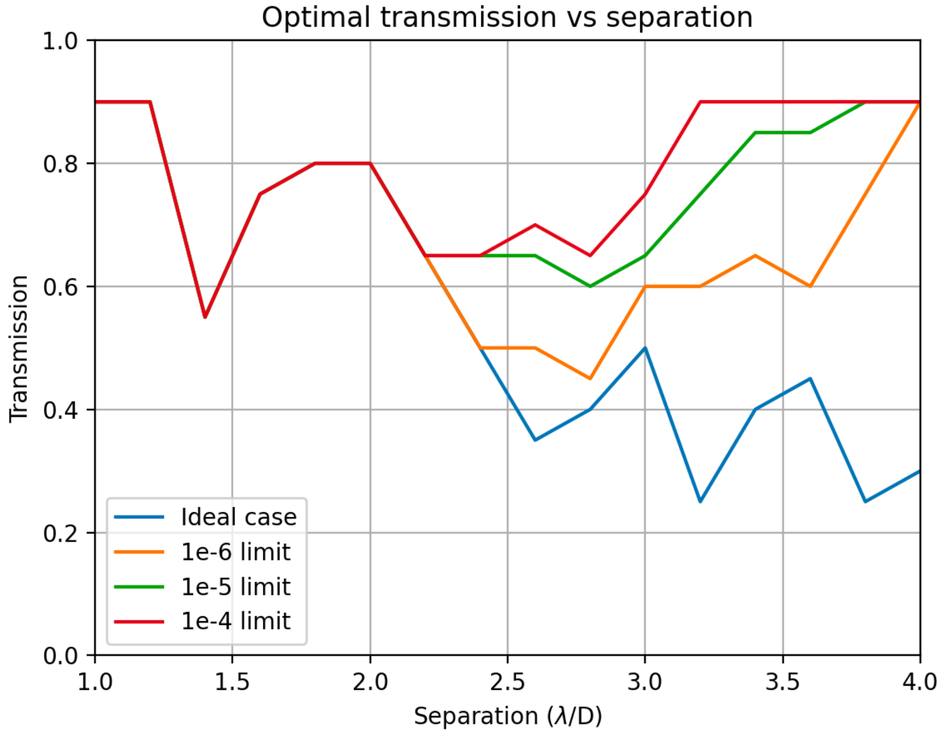




Optimal throughput set by contrast limit

Specific case of HC regions created along the y-axis





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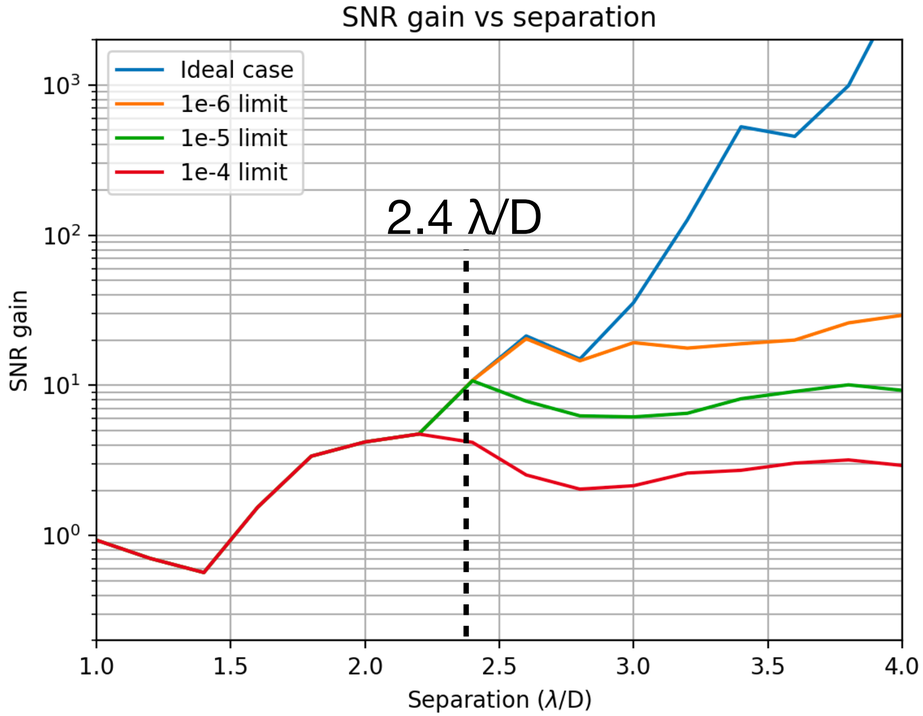


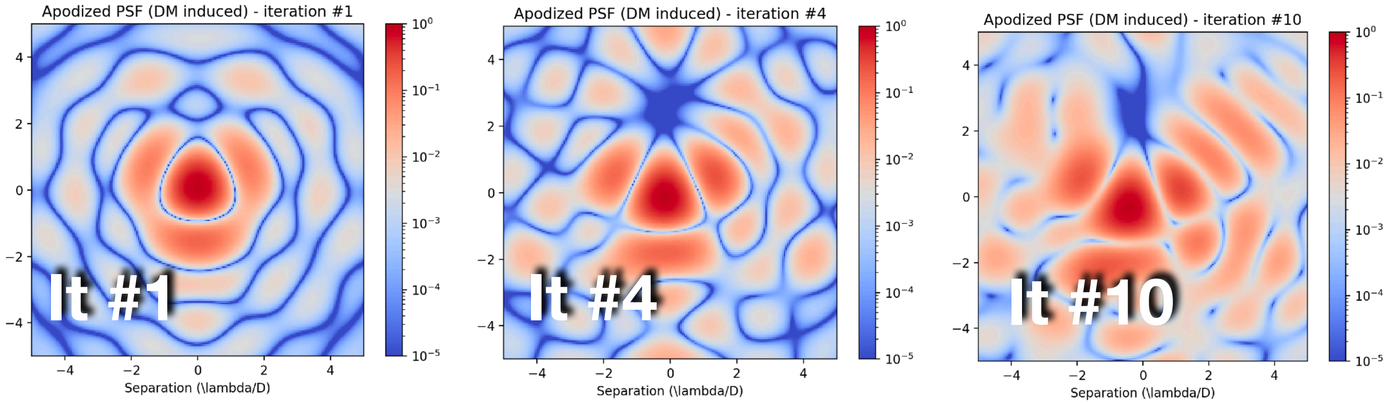
SNR gain ~ 4 at 2.4 λ/D for an effective **1e-4** raw contrast

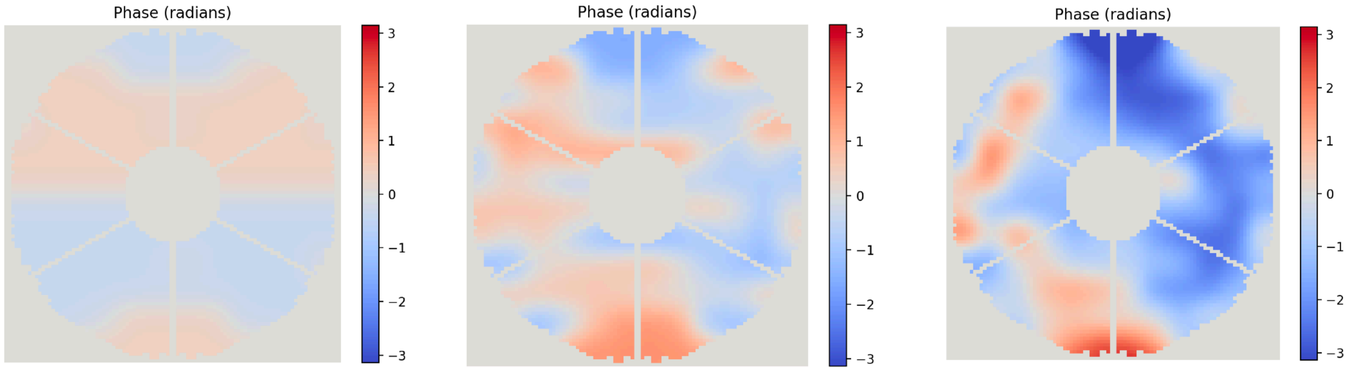
SNR gain ~ 10 at 2.4 λ/D for an effective **1e-5** raw contrast (or lower)

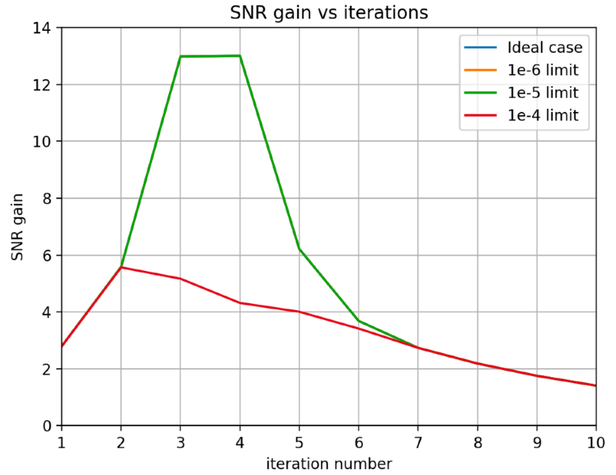
Phase apodization - 12x12 actuators DM

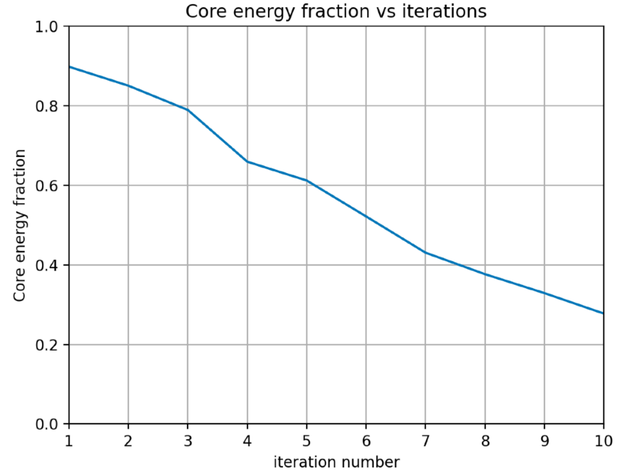
Iterative phase optimization algorithm

Maximum SNR gain ~ 5.5 & 13 (1e-4 & 1e-5 effective raw contrasts)







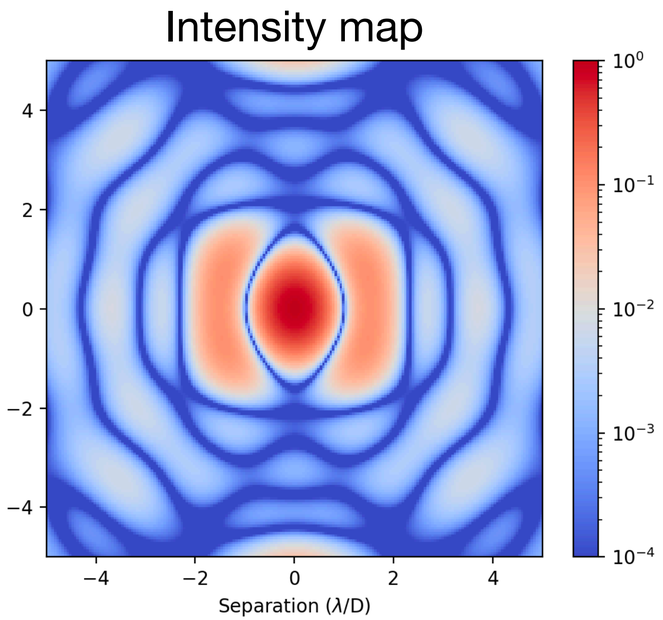


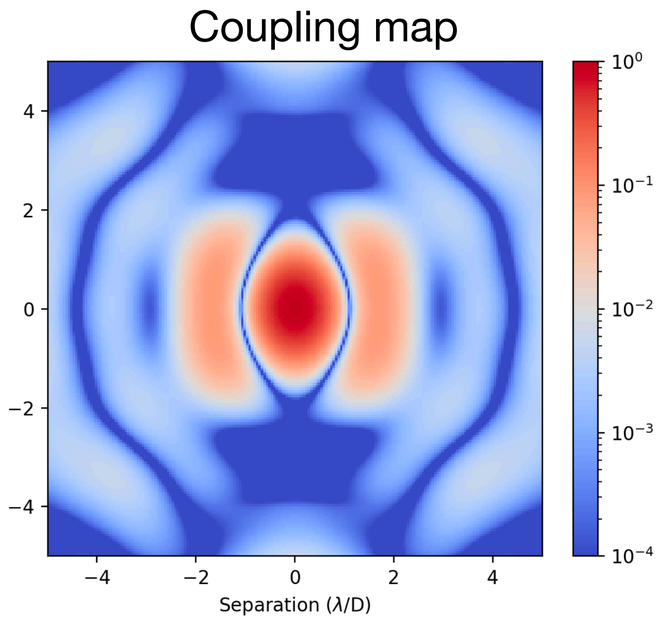
Single-mode fiber case - shaped pupils

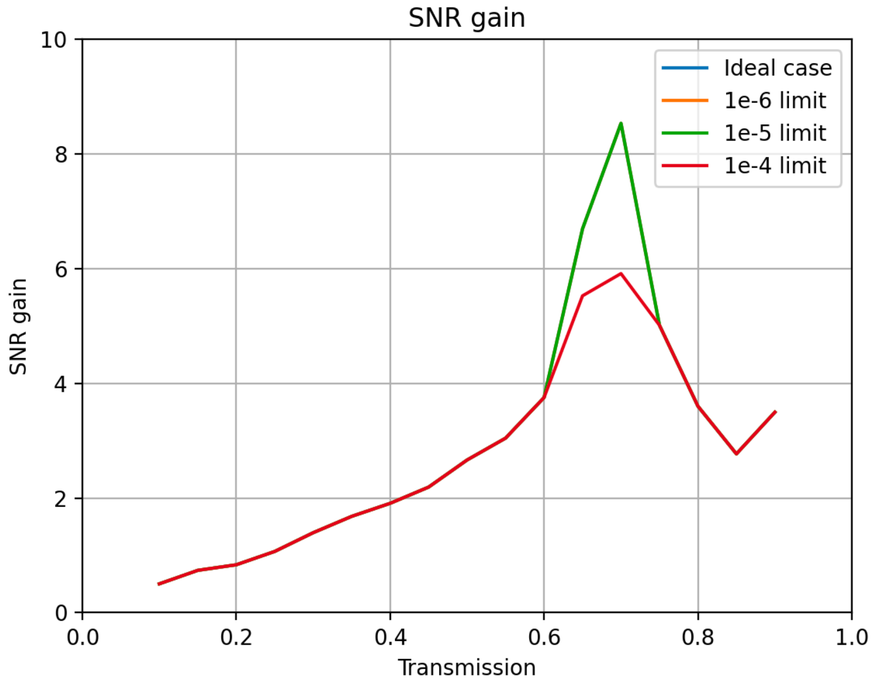
Similar to the SCAR concept (Por & Haffert, 2020)

Theoretically more efficient, but current results are not very encouraging

SNR_{gain} values should be taken with a (big) grain of salt, though.







Conclusions & perspectives

Removing the star light at close separation is tough.

~2.5 λ/D seems like a starting point with ELT

Who would have thought?

A common metric to compare various high-contrast techniques is essential

Photon noise limited SNR may be a convenient way when post-processing relies on high-resolution spectral diversity

Phase and amplitude apodizations may offer comparable performance

A closer, more exhaustive look is required to say more