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Optimal wavefront control for coronagraphy on faint exoplanets

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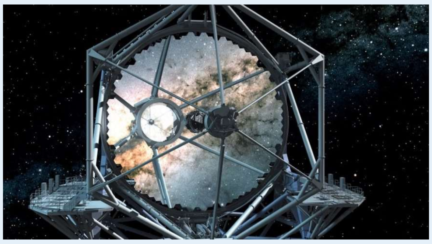
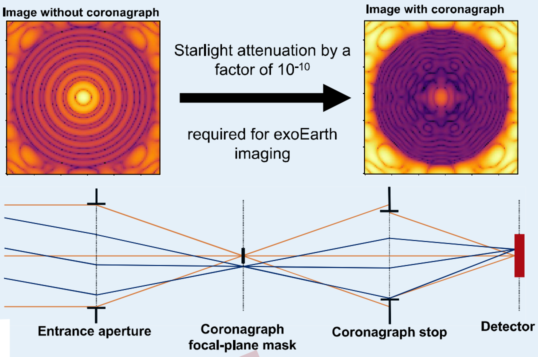


Large primary mirror diameters

These science goals require a **high angular resolution** to separate the exoplanet from its host star, which we will achieve with large telescopes from space and the ground (*left*). And they require an **efficient starlight suppression** system with “coronagraphs” and wavefront sensing and control (WFS&C) to gain access to the dim planet light (*right*).

A “Luvex”-type space telescope, at least 6 m in diameter and launched in the 2040s, will be able to image an exoEarth. The imminent ground-based extremely large telescopes (ELT, TMT, GMT) will push us closer to this goal.

Coronagraph

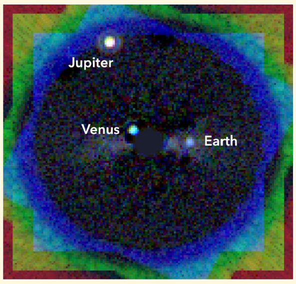


Starlight attenuation by a factor of 10^{-10}

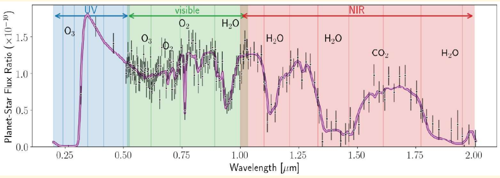
required for exoEarth imaging

Science goals

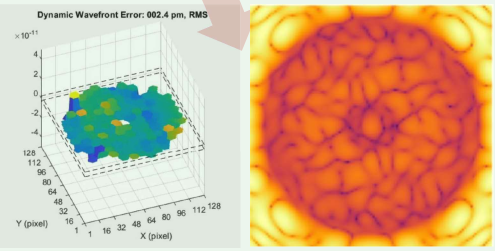
Directly capturing the light of faint, rocky exoplanets will allow us to spectrally analyze their atmospheres, with the hope to eventually find signs of life outside our own solar system.



*Top: **Simulated solar system** at a distance of 12.5 parsec as seen with a 15 m space telescope.*
*Bottom: **Simulated spectrum of an exoEarth**, identifying molecular signatures.*

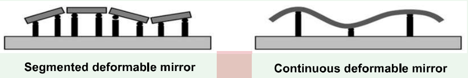


Laginja et al. 2022, A&A
Laginja et al. 2021, JATIS
Laginja et al. 2020, SPIE
Laginja et al. 2019, SPIE



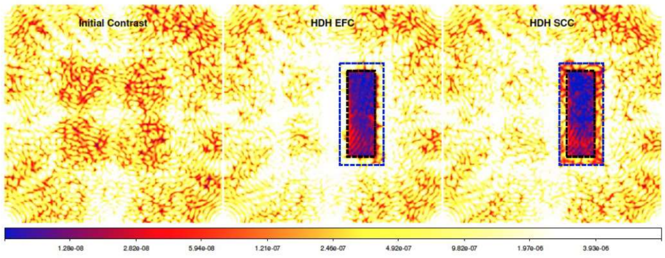
Ultra-stable wavefront control

Optical systems, and in particular large, segmented primary mirrors, experience **dynamic agitations** (*top left*) that lead to a contamination of the coronagraph detector with light (*top right*). To minimize this effect, active control with **deformable mirrors** (DMs, *below*) is of utmost importance in order to keep telescopes ultra stable, to the order of 10 pm over 10 minutes.



Extending models from segmented to continuous DMs

Going beyond the piston-only case on a segmented mirror, sensitivity studies can be valuable tools to learn how to improve the overall WFS&C architecture of a space-based exoEarth mission. Optimizing these control techniques will allow us to exploit the continuous DMs currently contained in every future high-contrast mission and establish a stable coronagraphic image with less aberrations and less time. This would minimize the time for setting up coronagraphic observations and maximize observing time.



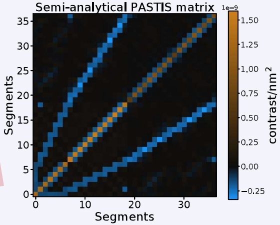
Left: Images from the THD testbed with a coronagraph. The three images show the initial image (far left) and two different control algorithms. Tuning our wavefront controllers to the particular coronagraph in use aims to speed up this process and make it more robust to aberrations in the system.

Modeling stability sensitivity

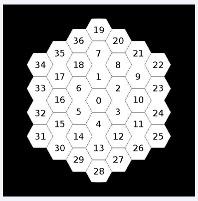
mean contrast contrast variance

$$\langle c\rangle = c_0 + tr(MC_a) \qquad Var(c) = 2\,tr[(MC_a)^2]$$

contrast sensitivity matrix segment covariance



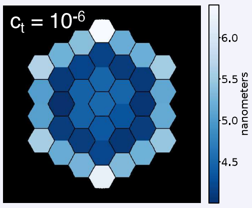
*An **eigendecomposition** of the matrix yields the **PASTIS modes**, encoding the sensitivity of the coronagraph to instabilities.*



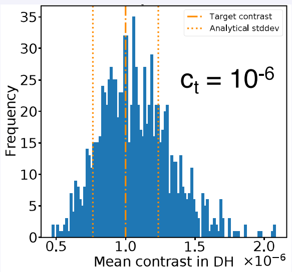
*Top: **Segmented mirror on HiCAT** with its numbered segments and Lyot stop outline.*

Experimental demonstrations

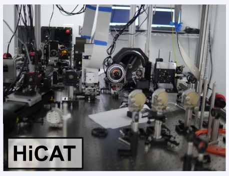
Modeling as shown on the right allows us to derive the per-segment limit of piston aberrations which we can allow before the coronagraphic image gets too contaminated with spurious light for the envisioned observations. Below are experimental results confirming the correctness of this model on HICAT.

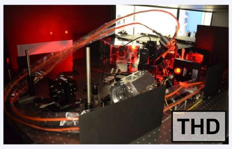


1000 random samples →



*Top: **Segment-level piston requirement map** for HiCAT, for a target contrast of c_t=10^{-6}*





Optical testbeds as pathfinders

Laboratory testbeds are an integral part of conducting research and developing technology for high-contrast imaging. They allow us to develop and test new observing methods and algorithms in a controlled environment. Two testbeds are part of this project, the HiCAT testbed (*top left*) and the THD testbed (*bottom left*).

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