Jet Propulsion Laboratory
California Institute of Technology

SEEING CLEARLY - OBSERVING THROUGH EARTH'S ATMOSPHERE

Ahmed Soliman

NASA Jet Propulsion Laboratory
California Institute of Technology

Keck Institute for Space Science Short Course
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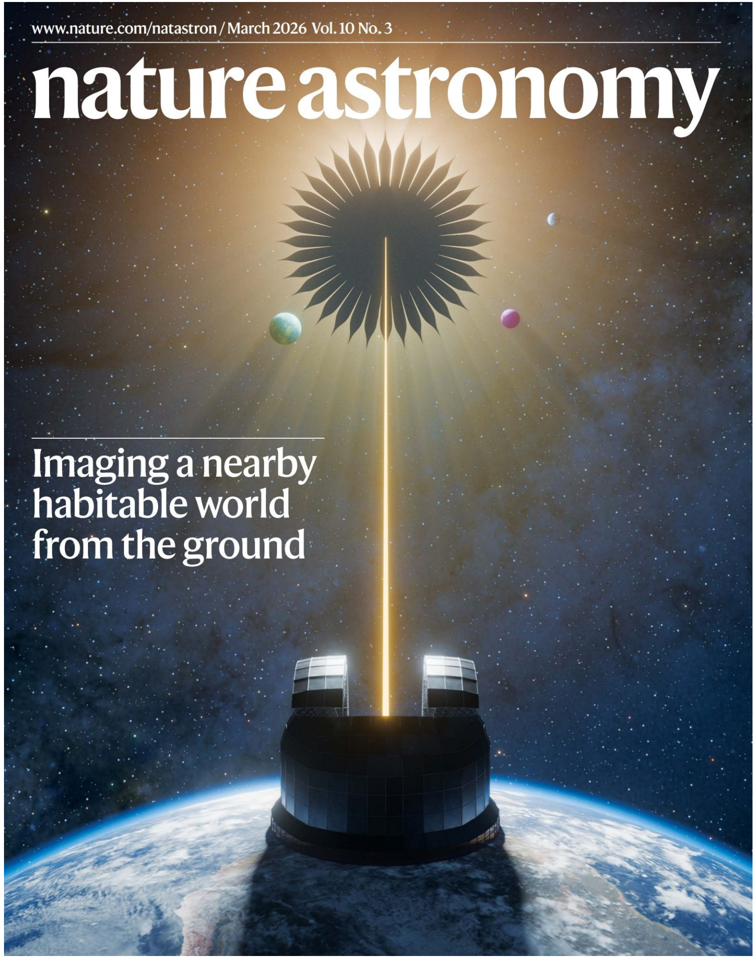

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Short Course Outline

- ❑ Understanding the challenges and discoveries (details to cover this study week).
- ❑ Expected performance of hybrid Ground Telescopes with Starshade (NASA NIAC HOEE – KISS Topic).
- ❑ The atmospheric turbulence & AO mitigation (the actual ELT AO PSF incorporated).
  - Imaging contrast with various Strehl Ratios (SRs)
  - Full solar system observation
  - Spectroscopy
- ❑ Summary and future work.

Atmospheric Effects on Ground-Based Astronomical Observations

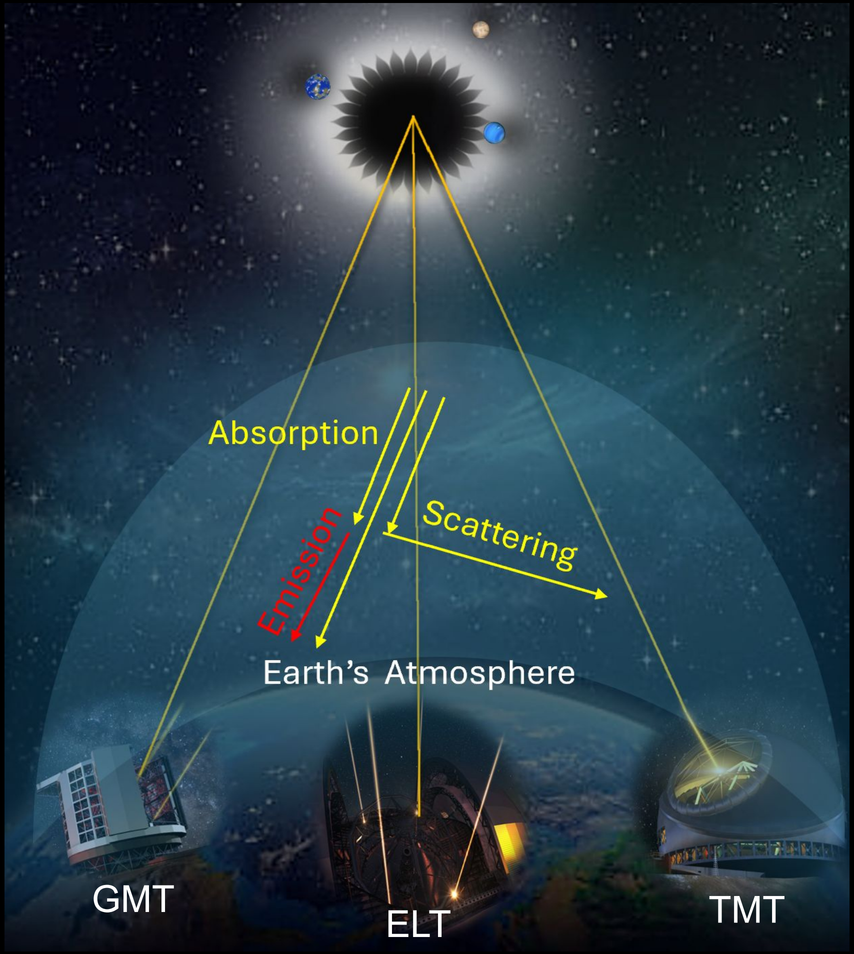
- ❑ Light should pass through Earth's atmosphere, which affects the observation. Key atmospheric effects -

1. Sky emission and telluric Interference (Absorption Lines): molecules with strong absorption lines that overlap with the spectra of exoplanets (mask the spectral signatures of the same molecules)

2. Chromatic effects of the atmosphere A- Refraction leads to chromatic anisoplanatism in AO and B- The refractive index itself is a bit chromatic.

3. Atmospheric Turbulence (Seeing) - creating a "seeing" limit that blurs images.

Corrections are therefore required to see clearly see and recover astronomical spectra for observations with ELTs.



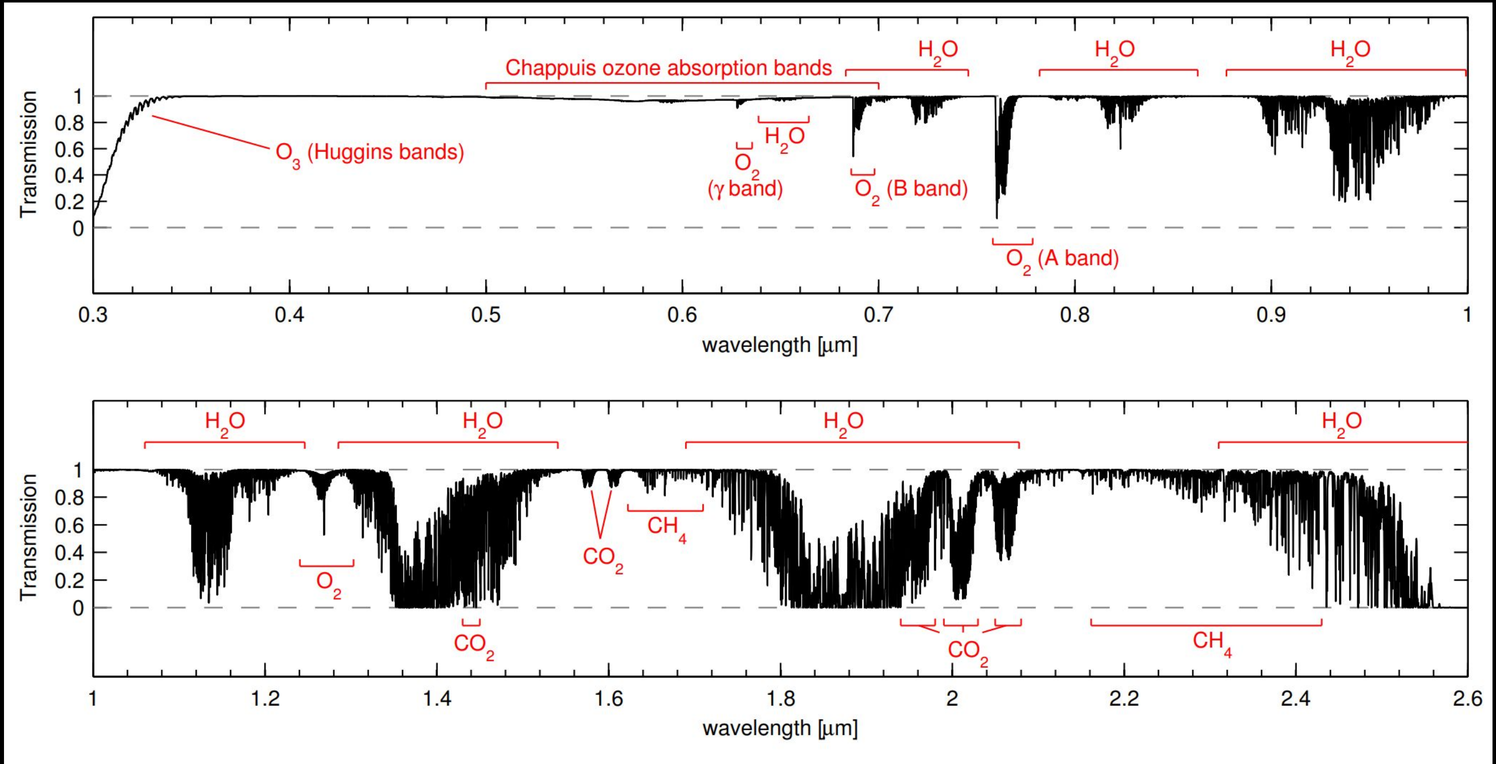
1- Sky Emission and Telluric Absorption Lines - spectroscopic observations

A - Atmospheric Absorption: Optical + NIR (credit: Smette et al. 2015, A&A, 576, A77)

The eight main molecules O_2, O_3, H_2O, CO, CO_2, CH_4, OCS, and N_2O contribute more than 5% to the absorption in some wavelength regimes.

The red regions mark the ranges where they mainly affect the transmission.

ESO's Skycalc tool (https://www.eso.org/observing/etc/bin/gen/form?INS.MODE=swspectr+INS.NAME=SKYCALC) is very useful and easy to use for studying atmospheric emission and absorption for different wavelengths and spectral resolution.



Synthetic absorption spectrum of the sky between 0.3 and 2.6 μm

1- Sky Emission and Telluric Absorption Lines - spectroscopic observations

B- Atmospheric Emission – Ex: Airglow (OI, Oxygen , Hydroxyllight) emission by chemiluminescence

Airglow occurs when atoms and molecules in the upper atmosphere, excited by sunlight, emit light to shed their excess energy.

Credit: NASA

C- High variability of the Earth's atmosphere transmission (KISS topic: WMO Greenhouse Gas Bulletin No. 10, 6 Nov 2014)

How can we get rid of this ?

Plan 1 - Go to space ☺ : High risk, costly, limited payload, short lifetime, no upgrades.

Plan 2 - ELT uses telluric correction software tools (Molecfit and Skycorr) to remove atmospheric absorption and emission lines from the data (https://www.eso.org/sci/software/pipelines/skytools/). At the instrument level, ELT uses High-Resolution Spectroscopy for Spectroscopic Calibration. Q: how can this fit in the HOEE specifications ? (KISS study topic this week).

2- Chromatic effects of the atmosphere

- Refraction leads to chromatic anisoplanatism in AO - A. the refractive index of a medium depends on wavelength (dispersive). B. the laser guide star (LGS) is at a different wavelength to the science observation.

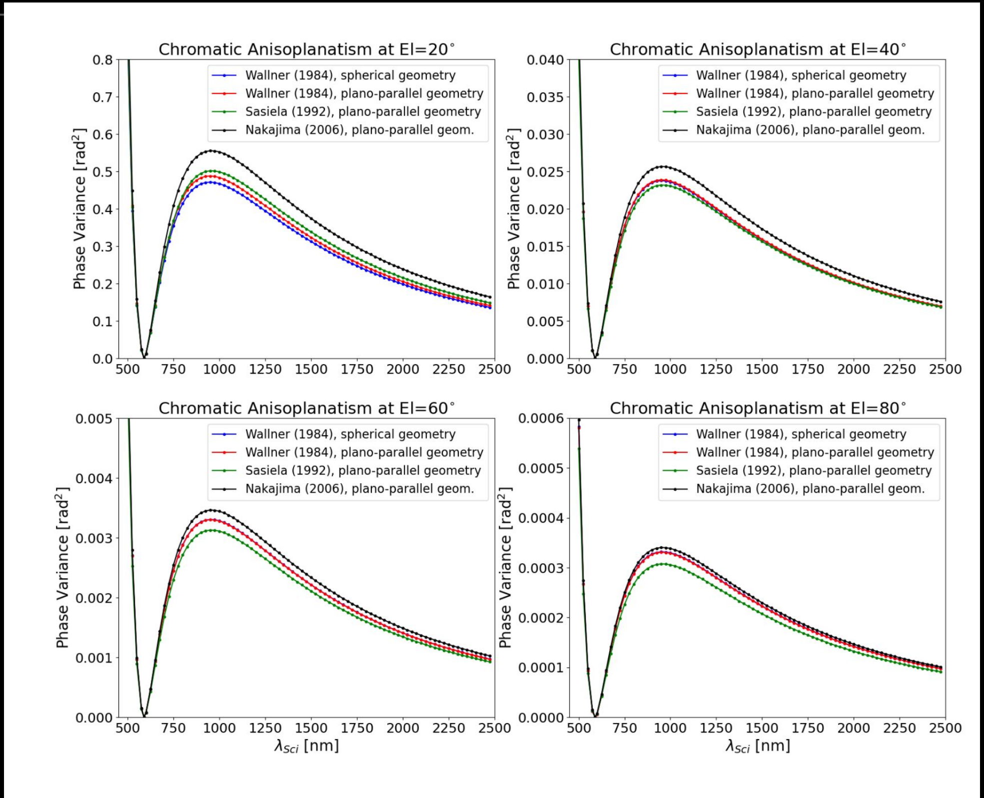
- Refractive chromatic errors are of two types:

A. Chromatic path length errors – changes in optical path length between different wavelengths traveling through the same turbulence.

B. Chromatic anisoplanatism – wavelength-dependent bending (Snell's law) that makes different wavelengths pass through different turbulent regions.

- These effects are negligible for 8-m telescope but start to limit performance at a 39-m ELT (see the impact here: Devaney & Femenía-Castellá (2024)).

- **How can we get rid of this ?** Bring λ (AO LGS) close to science observation –can be done with an orbiting artificial guide star.



Comparison of the phase variance on the ELT due to chromatic anisoplanatism from the models in Wallner - plane parallel (1984), Sasiela (1992) and Nakajima (2006), and Wallner using the Labriji spherical atmosphere model (Devaney & Femenía-Castellá (2024).

3- Atmospheric Turbulence (Seeing)

- ELT Planetary Camera & Spectrograph (PCS) and ExAO uses thousands of actuators on deformable mirrors to correct wavefront distortions in real-time, with Laser Guide Stars (NGS) or multi-wavelength laser for diffraction-limited imaging (AO error budget)
- ELT performs atmospheric calibration through multi-layered AO system combined with Atmospheric Dispersion Correctors (ADCs) and specialized calibration units to manage optical distortions.
- ADC to fix the splitting of light into spectra (chromatic aberration) caused by the atmosphere.
- Post-processing techniques (PSF modelling, ADC, Calibration) aim to reduce residual distortions that remain after AO correction, including effects from atmospheric turbulence, chromatic beam wander, and speckle noise.
- See Markus's Short course for more details.

Without AO (Seeing-Limited) to With AO (Diffraction-Limited)

Credit: ESO – shows the effect of AO on the observed image.

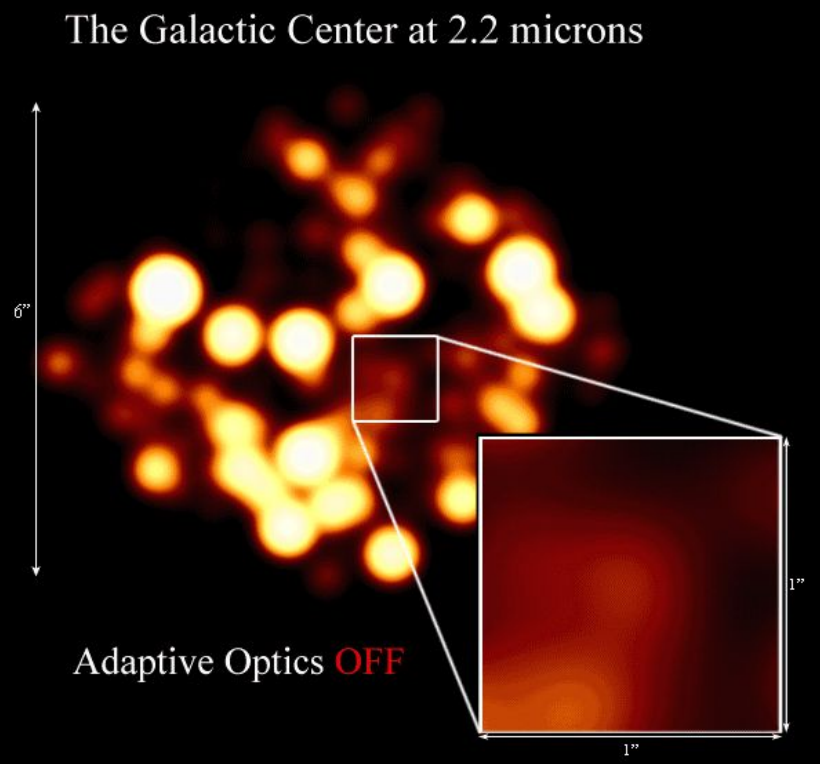
Reference: Goncharov, A, et al," Atmospheric dispersion compensation for extremely large telescopes", Optics Express, vol. 15, Issue 4, pp.1534-1542, 2007.

Seeing Clearly through Adaptive Optics (Ex: Keck and VLT)

(making the images obtained almost as sharp as those taken in space)

Ex 1: Keck Telescope

Galactic Center with and without Adaptive Optics – sharpen the image to the diffraction limit.



Credit: W.M. Keck Observatory Laser Team

Ex 2: ESO's Very Large Telescope VLT

- This sequence starts with a wide view of the Milky Way and zooms in on the globular star cluster NGC 6388 in the constellation of Scorpius (The Scorpion).
- The final images are first from MUSE (the Multi-Unit Spectroscopic Explorer) on ESO's VLT in Wide Field Mode and then the last, very sharp, image shows part of the cluster using the MUSE Narrow Field Mode with adaptive optics turned on (imaging res comparable to space).

Credit: ESO/S. Kammann (LJMU)/ N. Risinger (skysurvey.org)

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- ❑ The atmospheric turbulence & AO mitigation (the actual ELT AO PSF incorporated).
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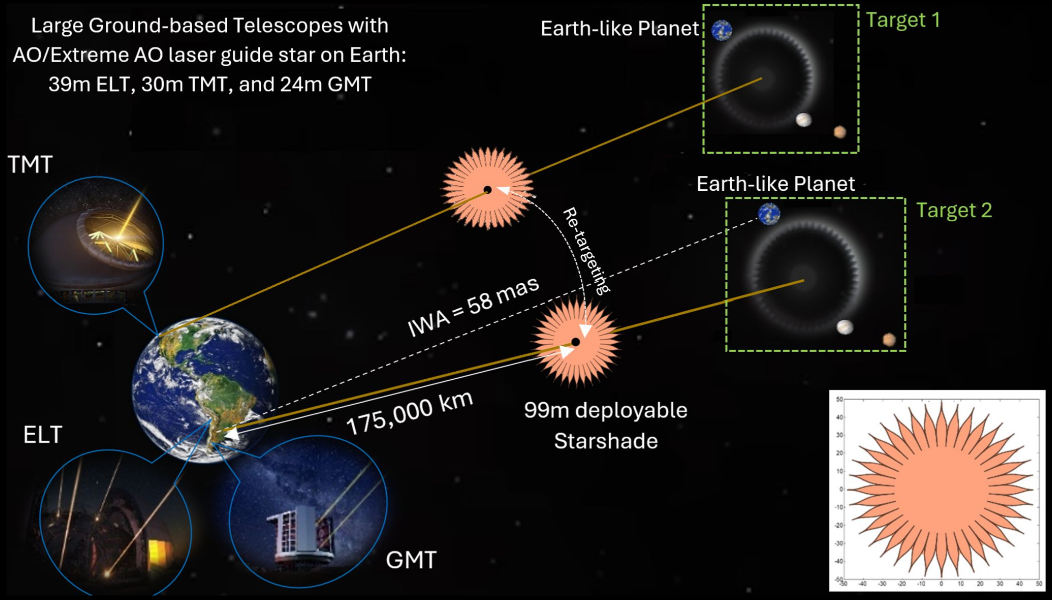
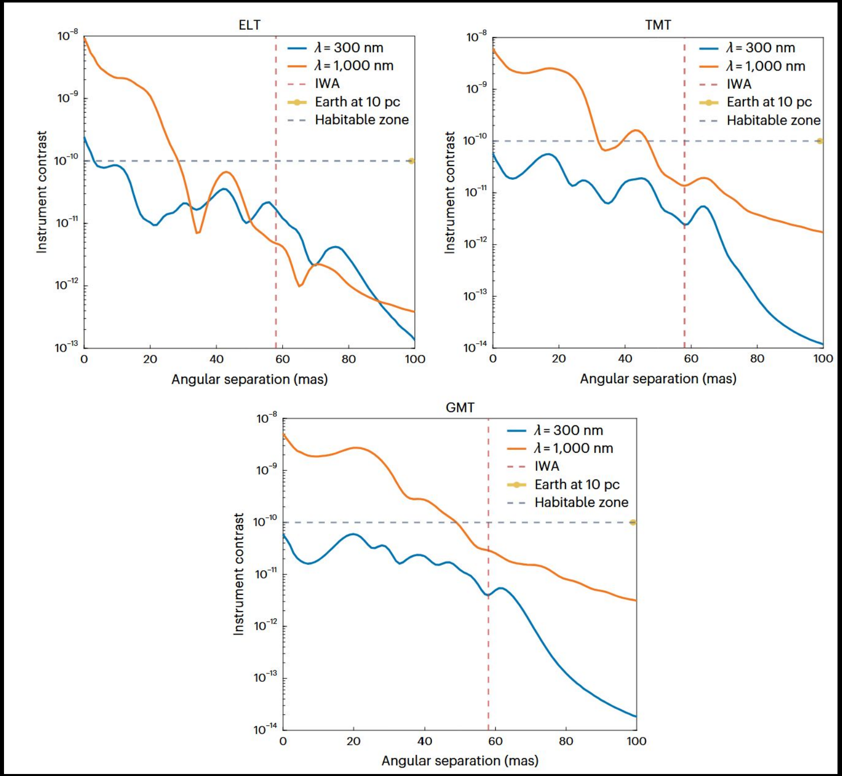
KISS topic - Hybrid ground telescopes-starshade (No Earth’s Atmosphere & ELT AO)





NASA NIAC - HOEE, Mather, et. al.

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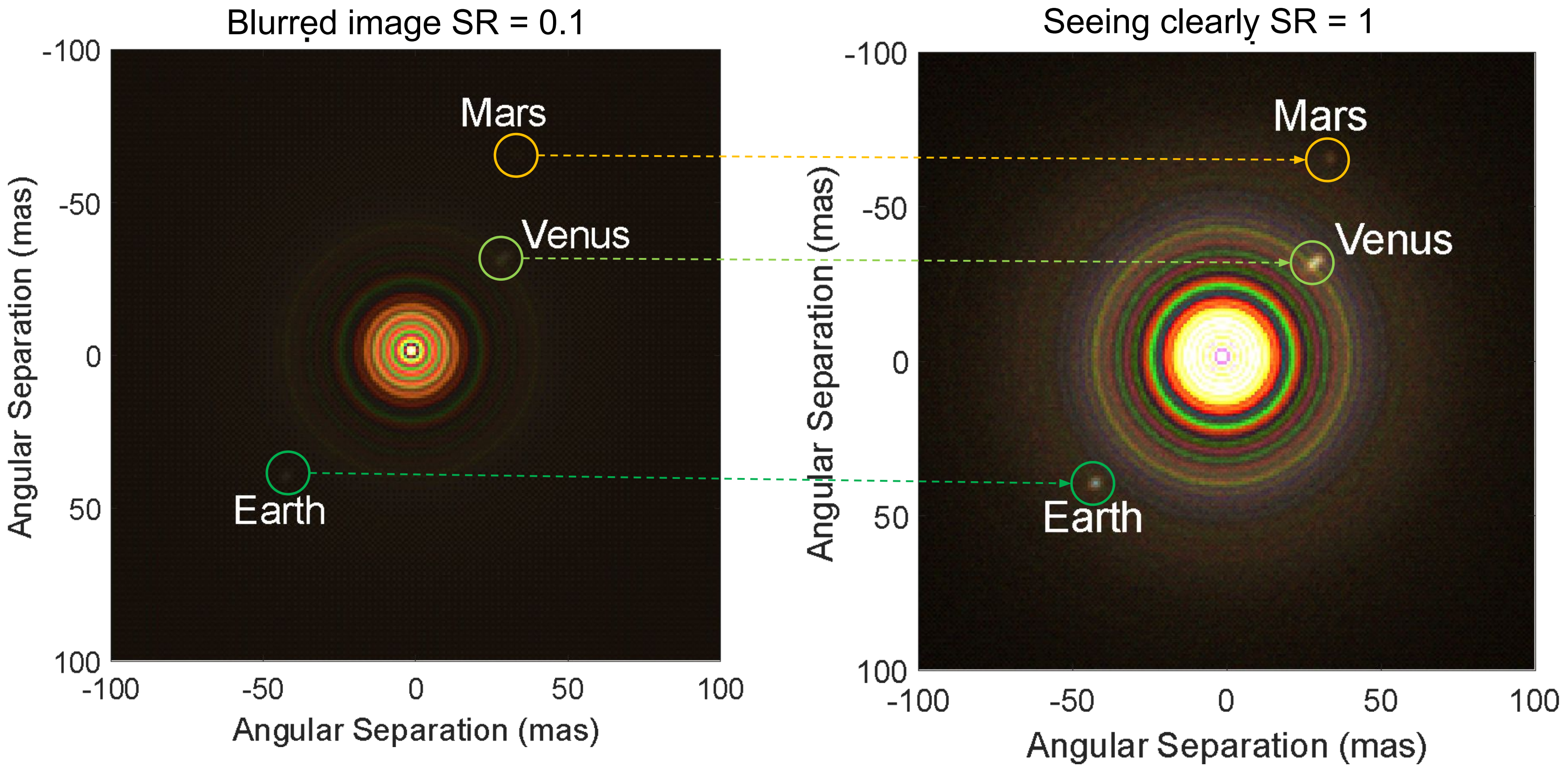
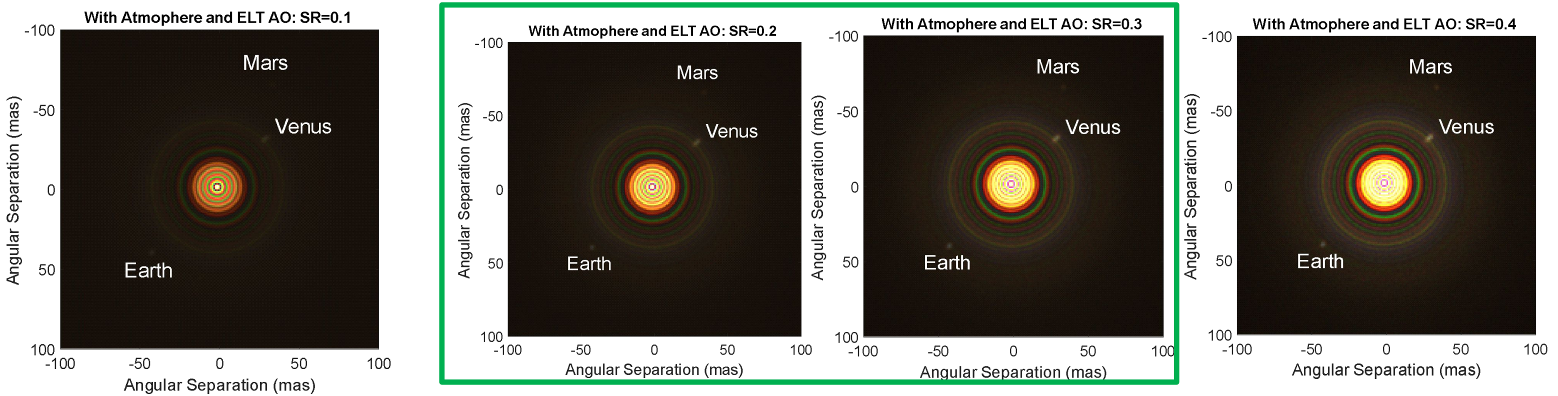
- Ahmed Soliman, Stuart Shaklan, John C. Mather, Eliad Peretz, Dylan McKeithen, "Optical performance of Hybrid Observatory for Earth-like Exoplanets," J. Astron. Telesc. Instrum. Syst. 11(1) 014002 (8 March 2025) https://doi.org/10.1117/1.JATIS.11.1.014002

Actual ELT AO PSF incorporated

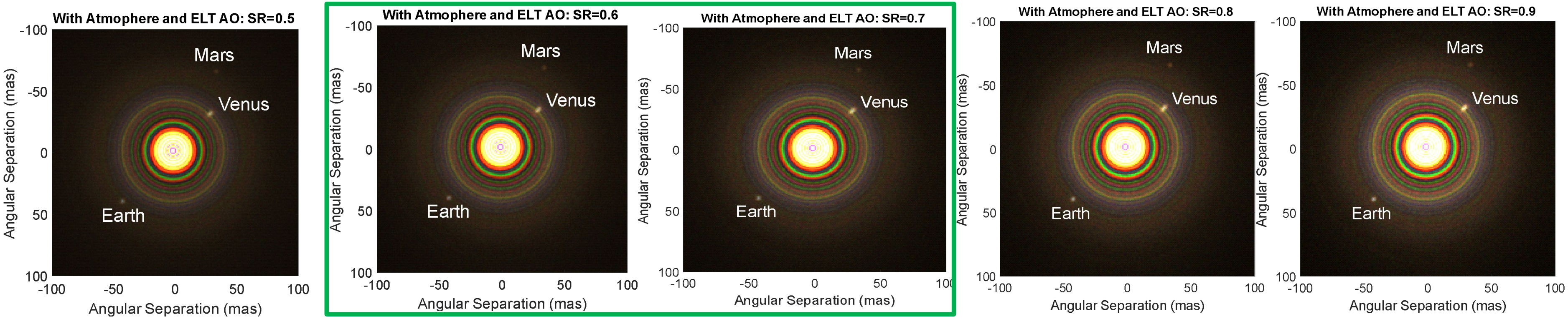
With Earth's Atmosphere –AnisoCADO Realistic ELT AO PSF - 20 mins exposure time - Solar type star 17 pc, Strehl Ratio (SR) 0.1 & 1, and medium weather conditions.



Seeing Clearly with actual ELT AO incorporated: Earth-like Exoplanet



Gen-1 ELT 750nm, depend on the seeing.



Gen-2 ELT Instrument (PCS) 750 nm, depend on the seeing.

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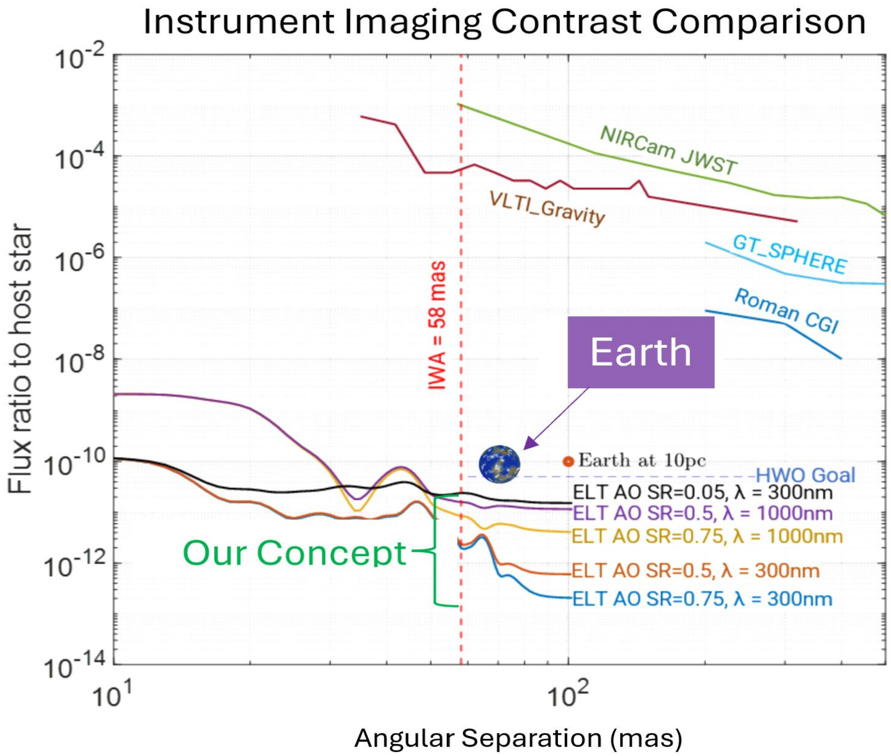
Seeing Clearly with actual ELT AO incorporated: Imaging Contrast

- Our model predicts an imaging contrast of ~ 3×10^{-12} , sufficient to detect the Earth-like Exoplanets at ~ $1\times\ 10^{-10}$ under moderate conditions with Earth's Atmosphere and ELT AO system.
- We present a better imaging contrast than the current and proposed efforts – such as HWO.
- ELT AnisoCADO AO - Medium Weather conditions.



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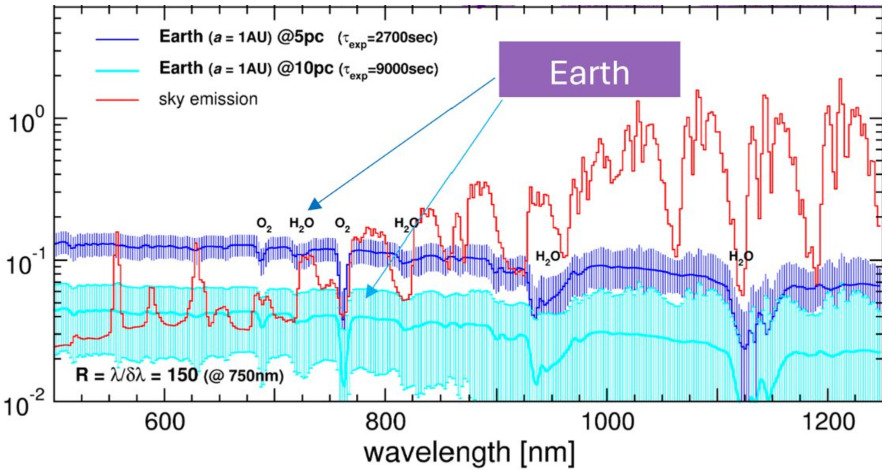
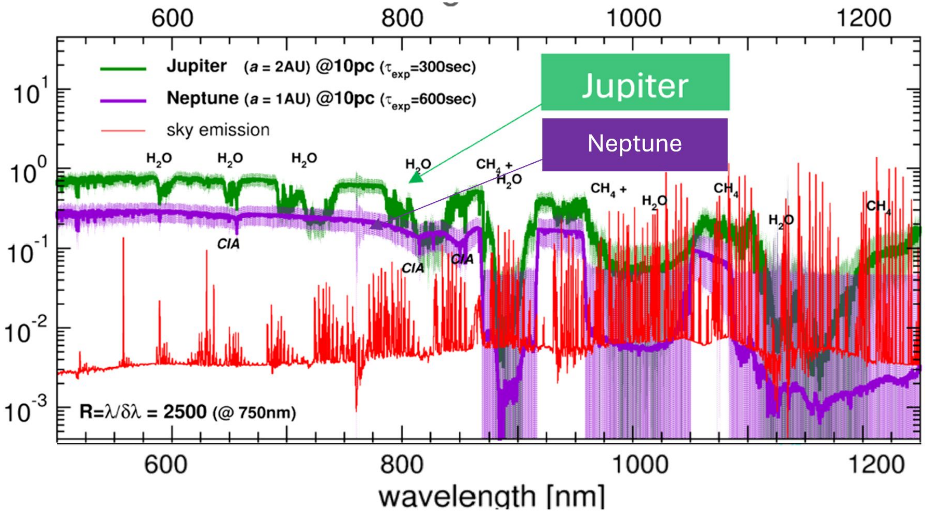
Seeing Clearly with actual ELT AO incorporated: signs of life (Oxygen and Water)

- Earth's Atmosphere with the realistic ELT AO under moderate Weather conditions.
- Our simulated spectra show that water and oxygen molecular features are clearly observable for exo-Jupiters, exo-Neptunes, and exo-Earths.
- At some wavelengths, exo-Earth at 10 pc is as faint as the sky emission. Continued advances in ground-based extreme AO instruments are expected to mitigate this limitation.





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Summary and Future Work

- Understanding the Earth's atmospheric effects and mitigation methods to enable deep observations of the universe from ground-based observatories (seeing clearly).

- This study provides a proof of concept for ELT adaptive optics (AO) in mitigating atmospheric turbulence and observing Earth-like exoplanets under moderate weather conditions.

- Our simulated spectra show that molecular features of water and oxygen are clearly detectable in exo-Jupiters, exo-Neptunes, and exo-Earths in the presence of the realistic ELT AO point spread functions (PSFs).

- Next steps to extend the analysis to other hybrid ground-based observatories, including the Giant Magellan Telescope (GMT), the Thirty Meter Telescope (TMT), and the Keck telescopes with Extreme Adaptive Optics (XAO) and artificial guide stars for further enhancement to the deep observation to the faint objects.

- Final Caltech KISS report outlining a roadmap for the remaining key steps needed toward a representative mission to enable the detection of the first Earth-like exoplanet with the NIAC HOEE concept.