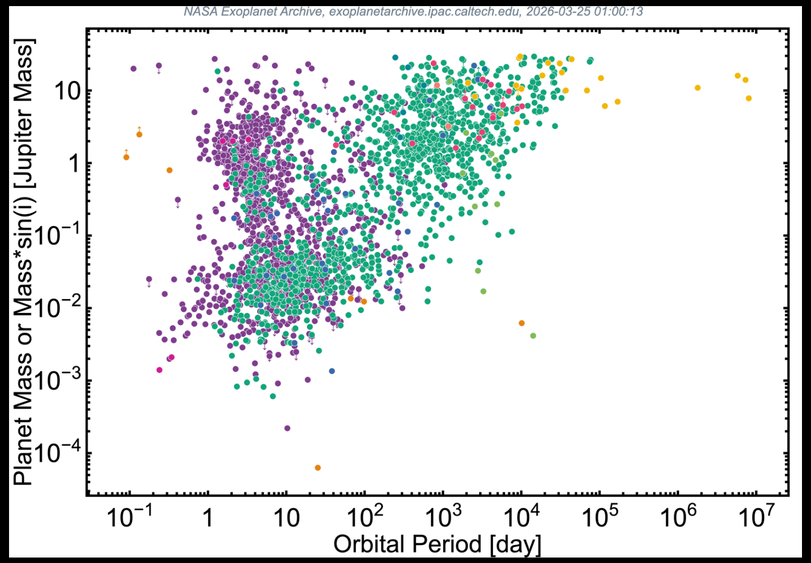
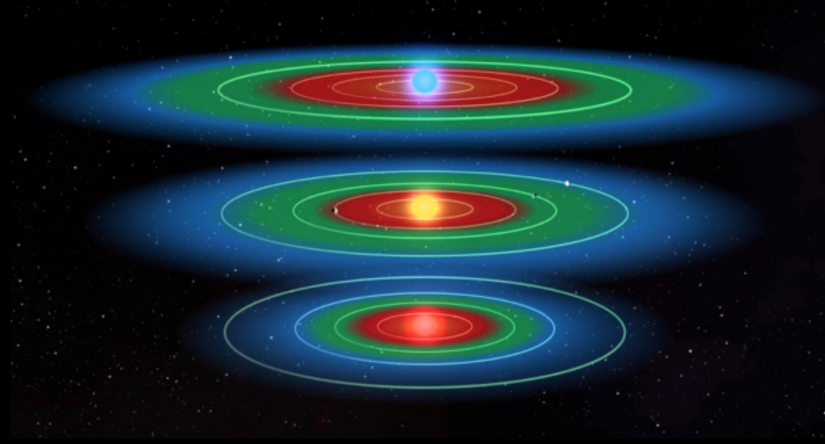
EL ESPECTROGRAFO ANDES PARA EL ELT: LA BUSQUEDA DE UNA SEGUNDA TIERRA



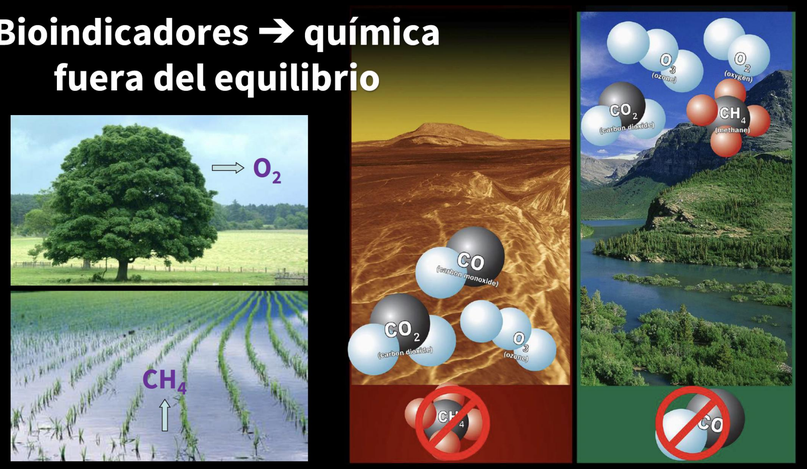
ENRIC PALLE

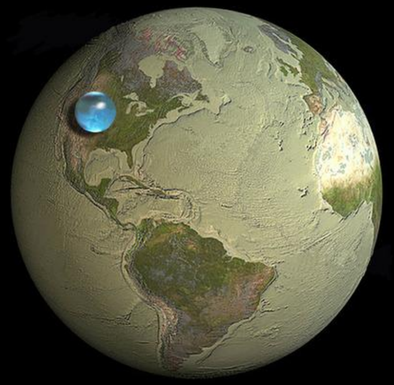






Bioindicadores ➔ química fuera del equilibrio



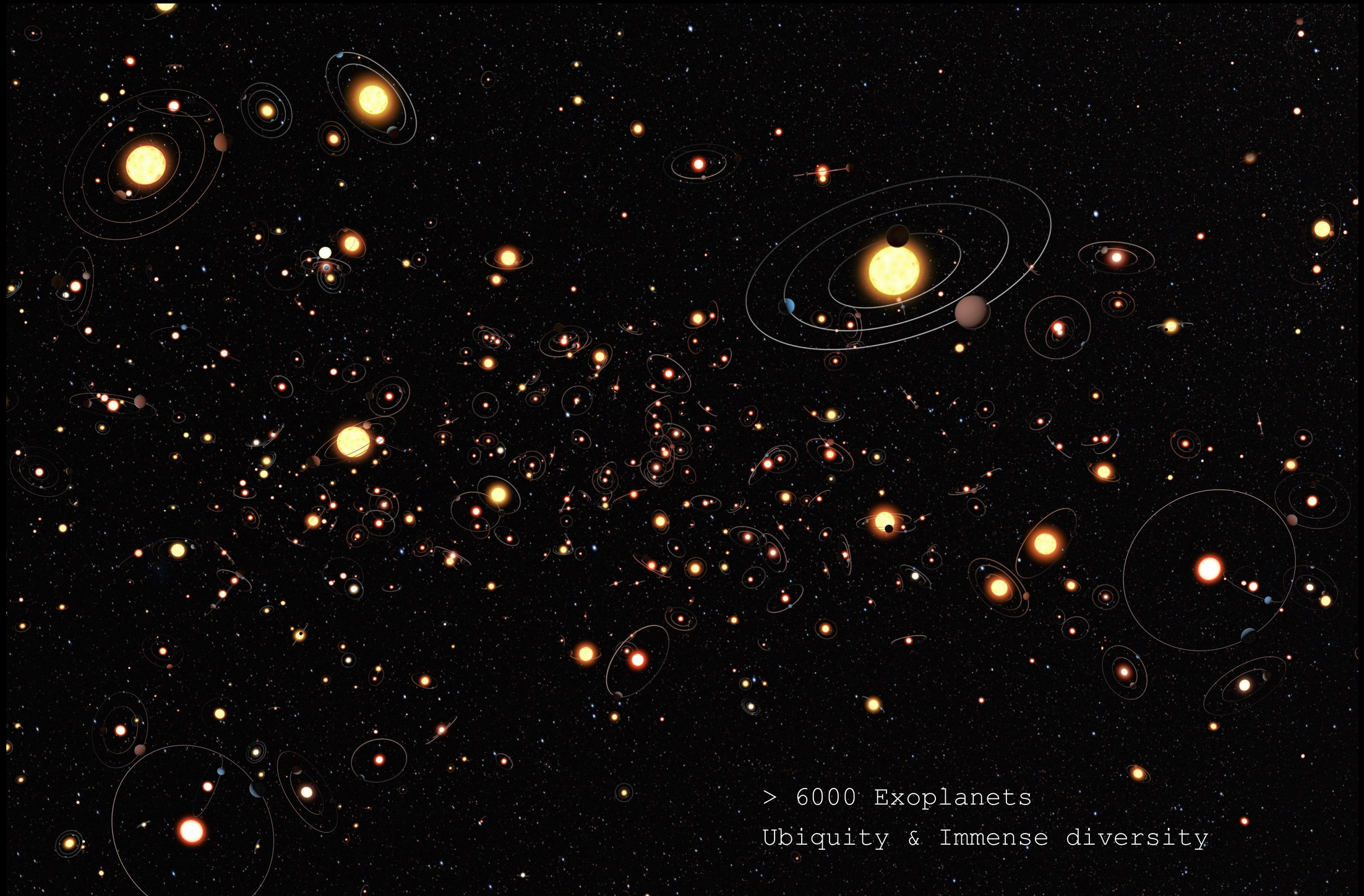


Habitable ≠ Habitado

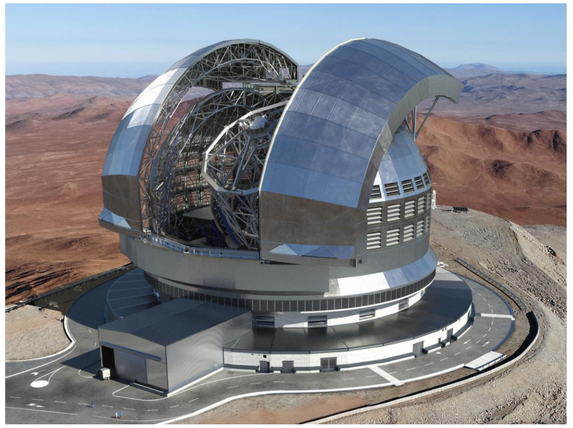


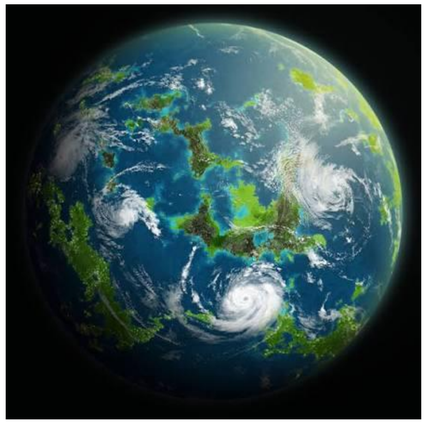
¿Como lo sabremos cuando encontremos uno?


Exoplanets ?


> 6000 Exoplanets
Ubiquity & Immense diversity

ANDES





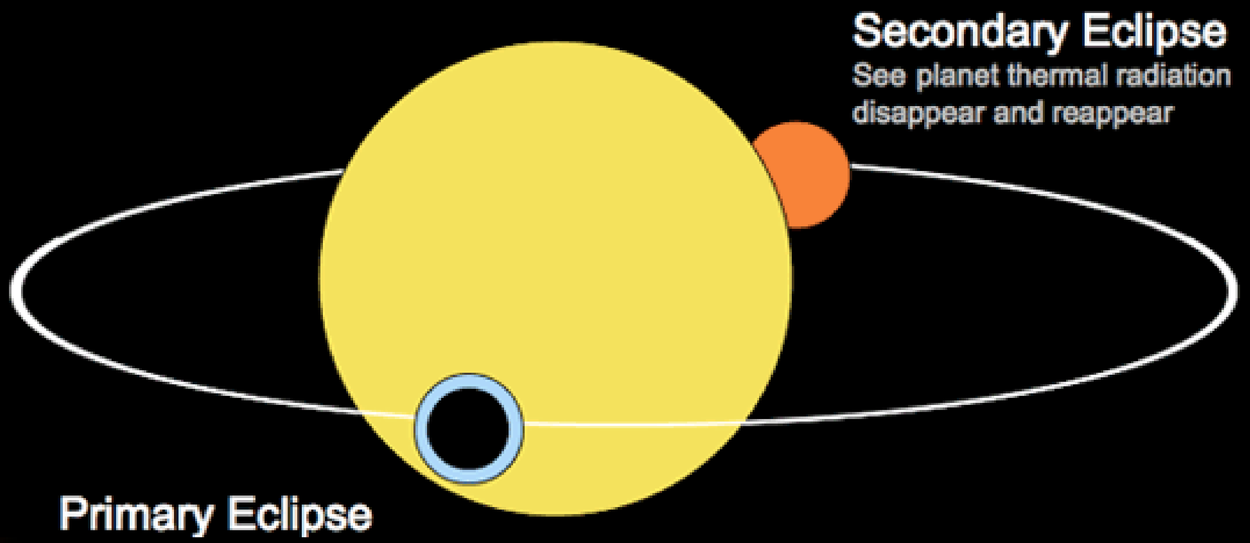
SPEAR project

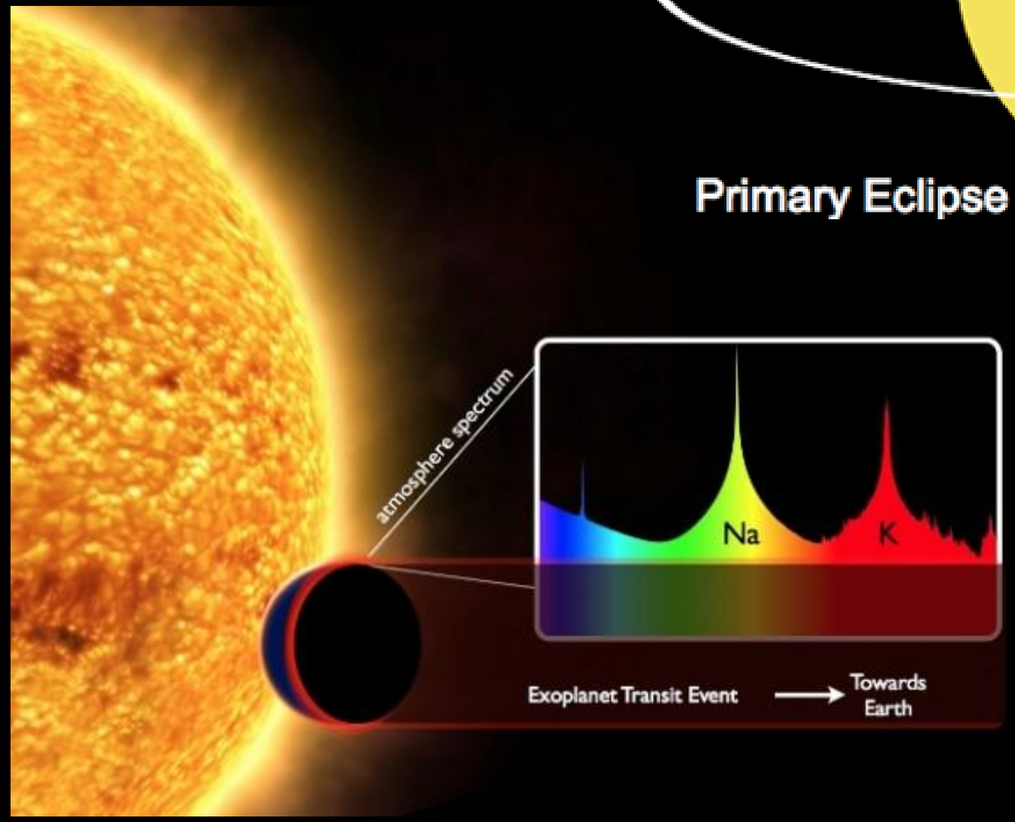
INSTITUTO DE ASTROFISICA DE CANARIAS · IAC ·

European Research Council
Established by the European Commission

EXOPLANETS & ASTROBIOLOGY

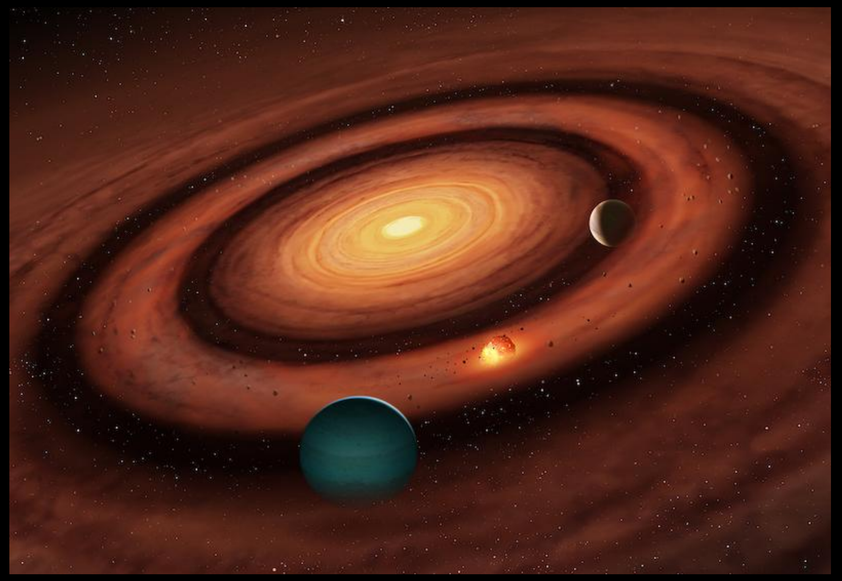
Transmission Spectroscopy: First characterization of exoplanet atmospheres



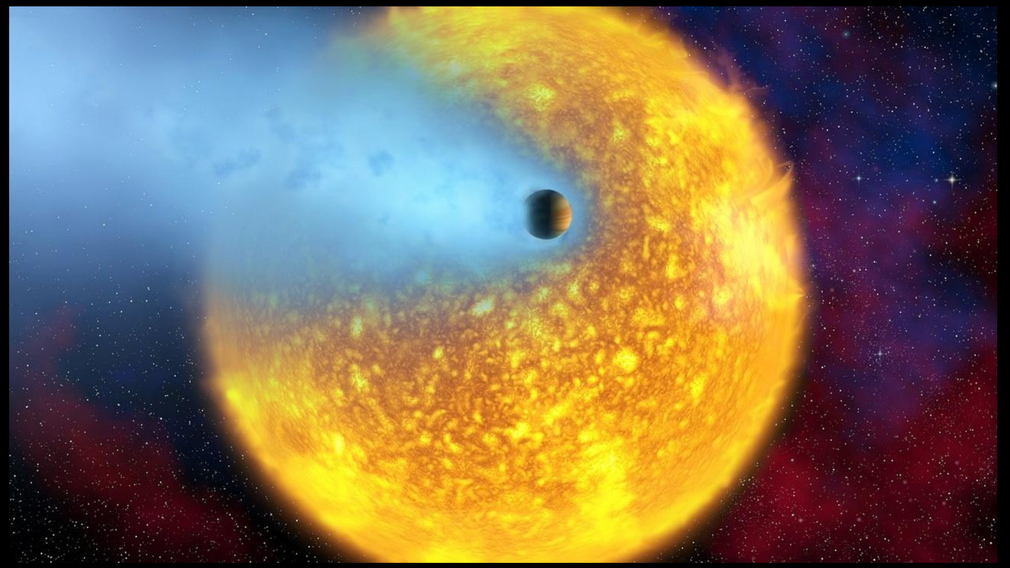


Chemical composition !!

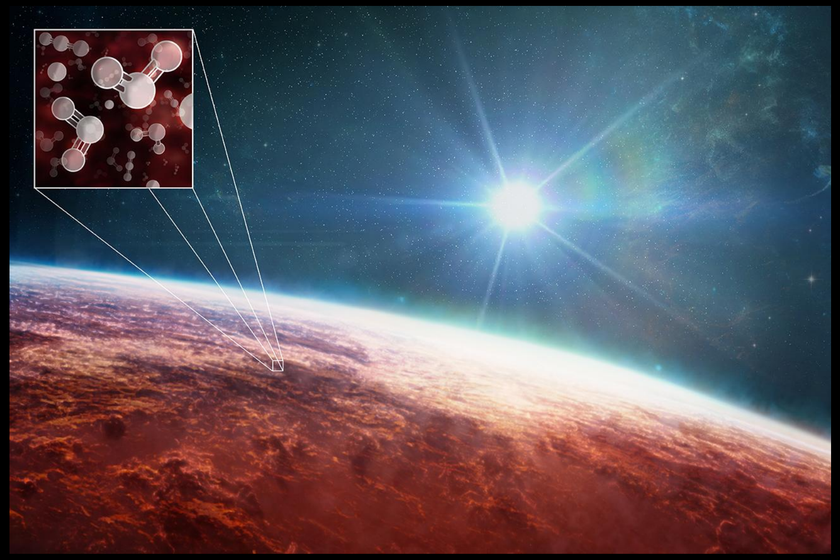
The atmosphere is the key



Metalicities are fosiles from planet formation



Evolution, atmospheric loss and secondary atmospheres



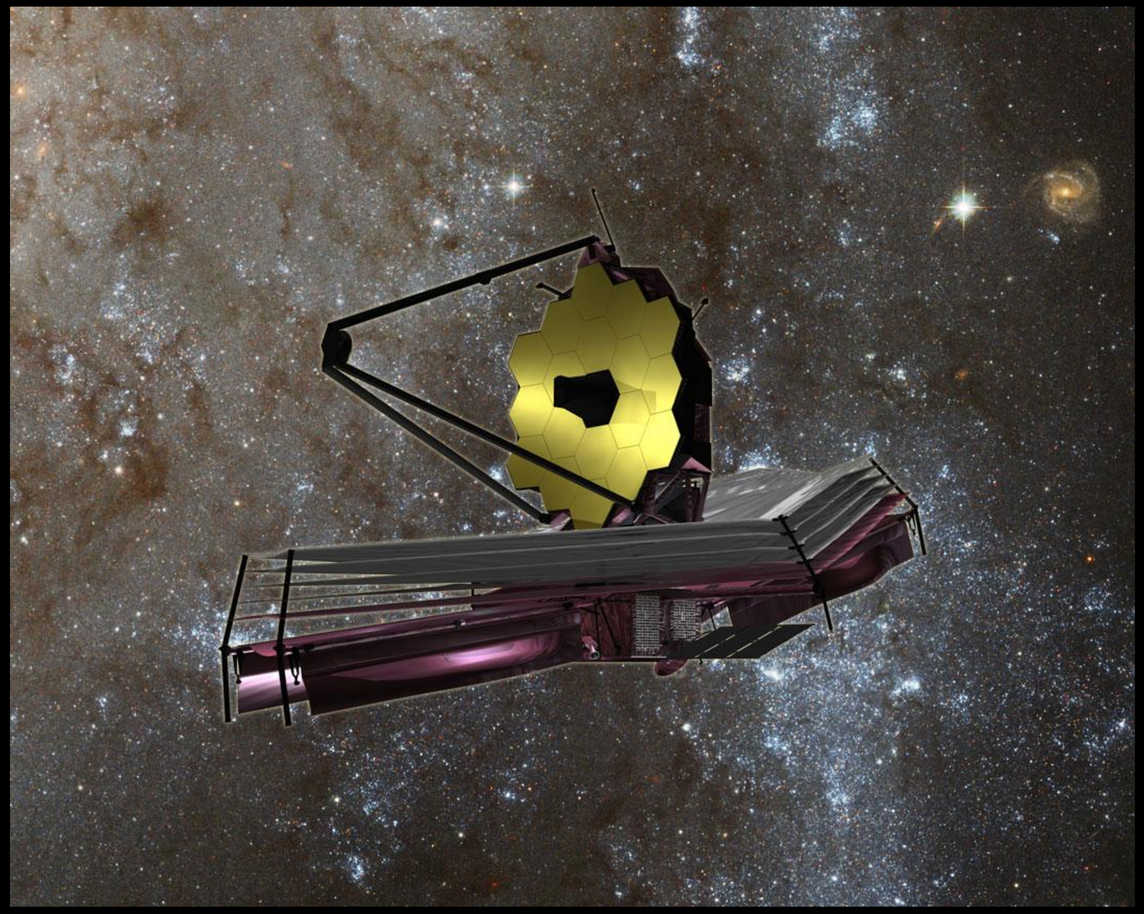
Chemical composition and habitability

I’ll skip 20 years of atmospheric research on exoplanets from ground and space, and we jump to the JWST era





JWST: a 6-m telescope in space



December 2021

Revolution in the exoplanet field

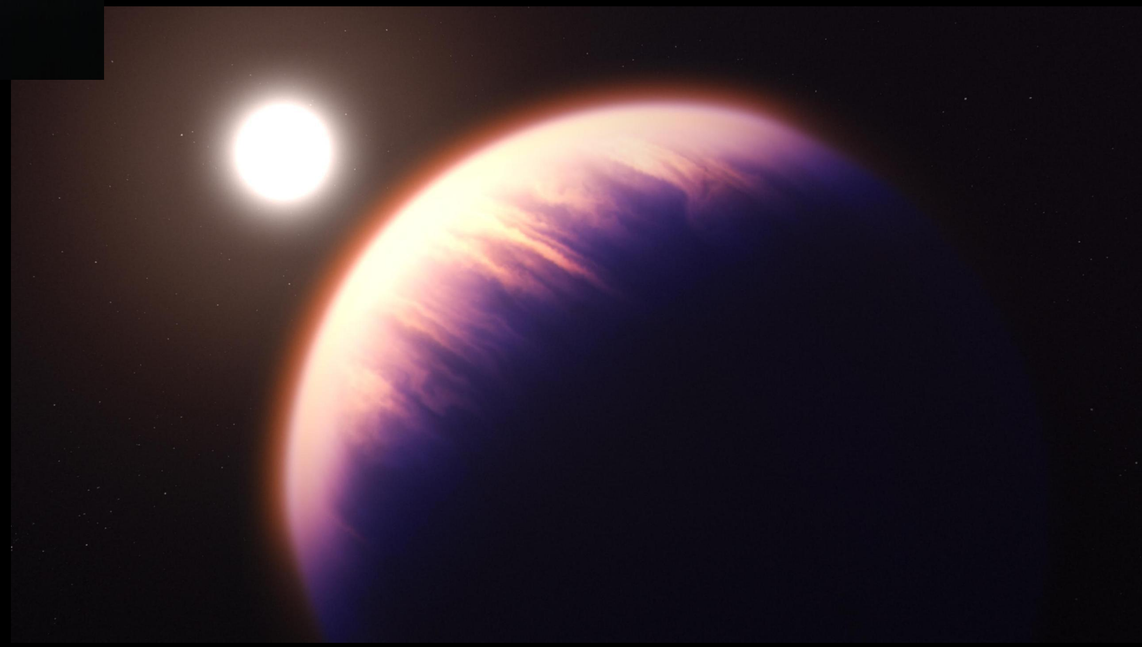


JWST ERS WASP-39 b

1.3 xRj but 0.3 x MJ

P= 4 days Teq= 900 K

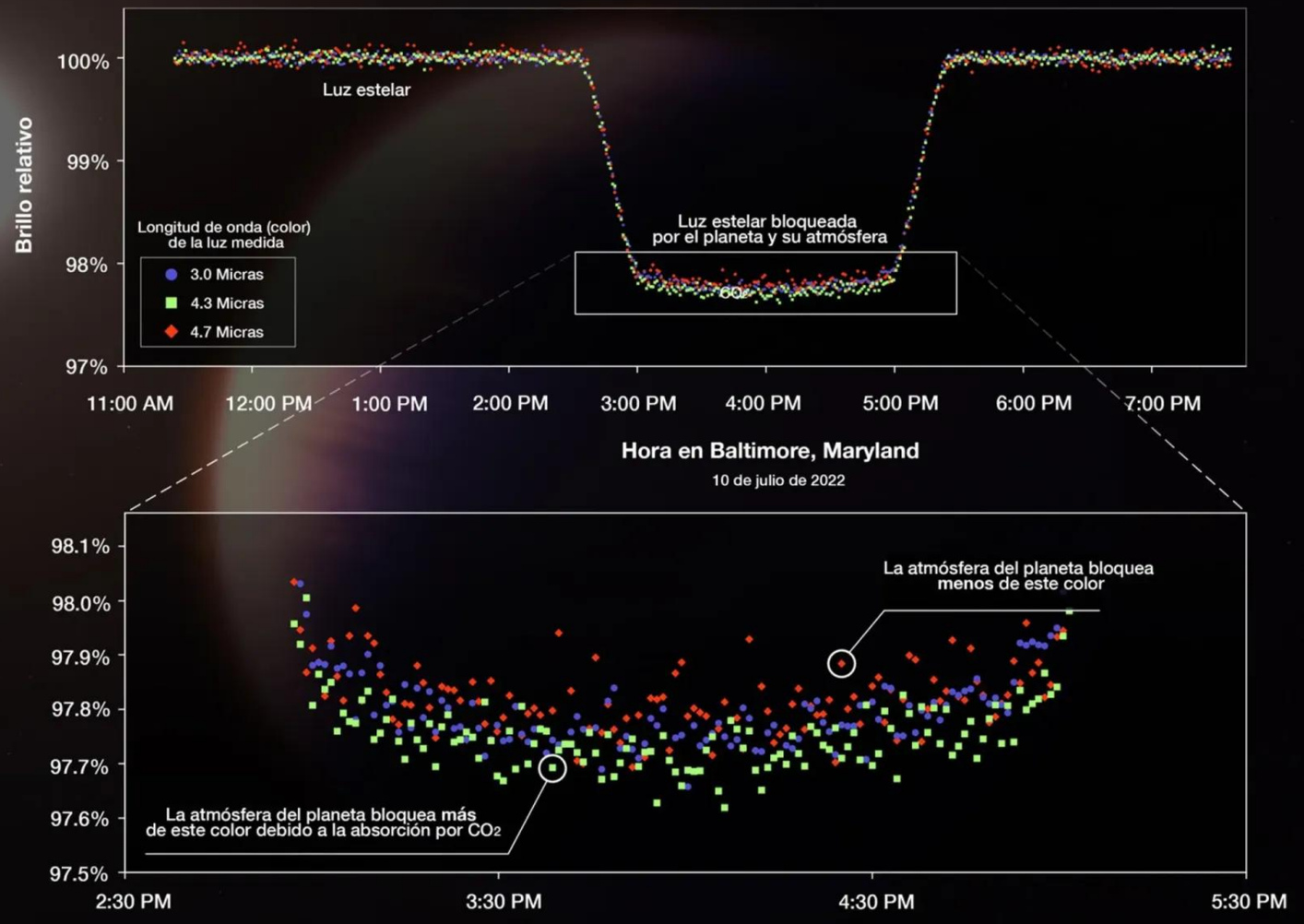
Extended atmosphere



EXOPLANETA GIGANTE DE GAS CALIENTE WASP-39 b

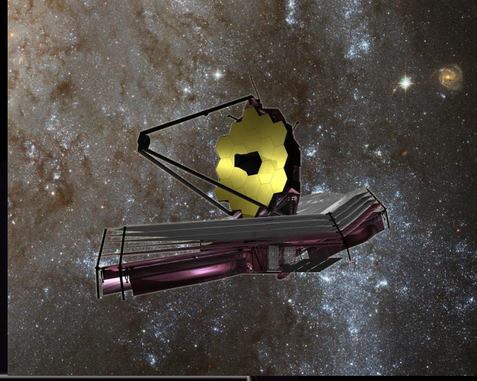
CURVA DE LUZ DEL TRÁNSITO

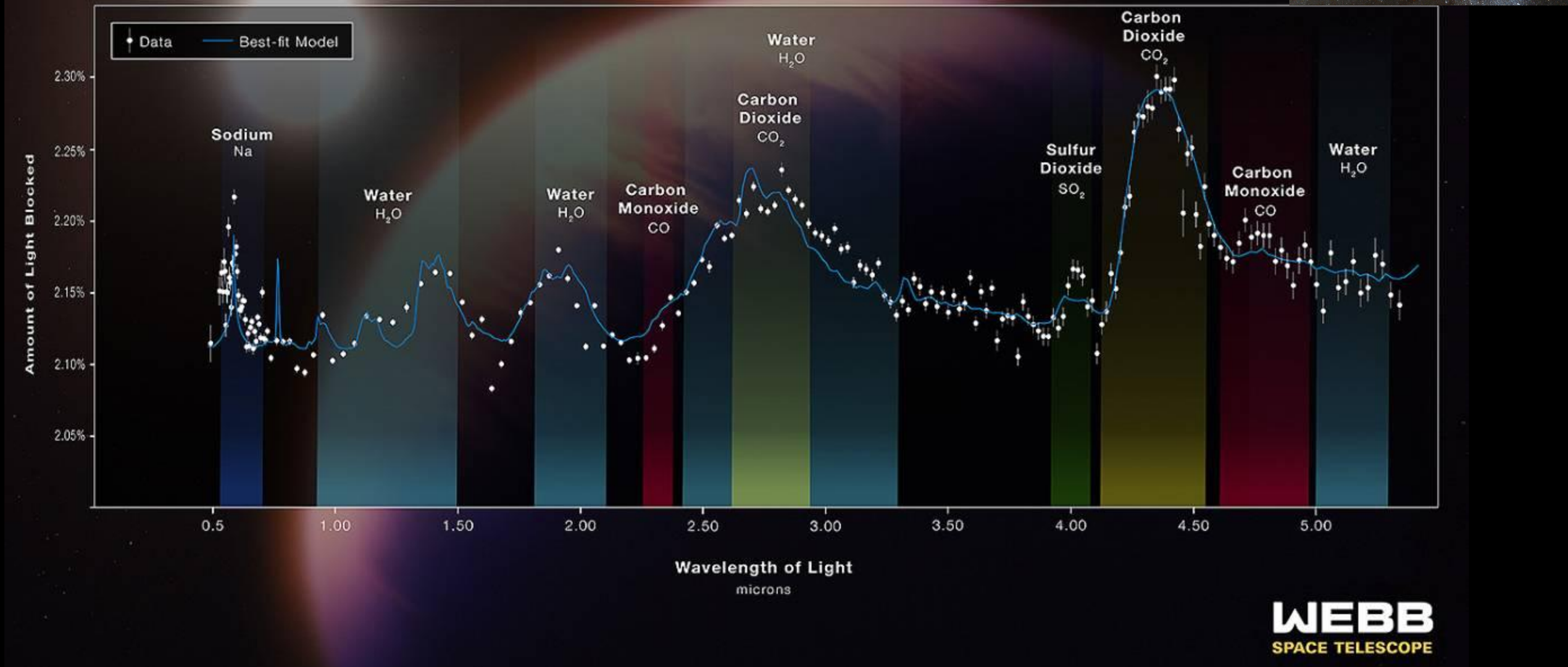
NIRSpec | ESPECTROSCOPIA DE SERIE TEMPORAL DE OBJETOS BRILLANTES



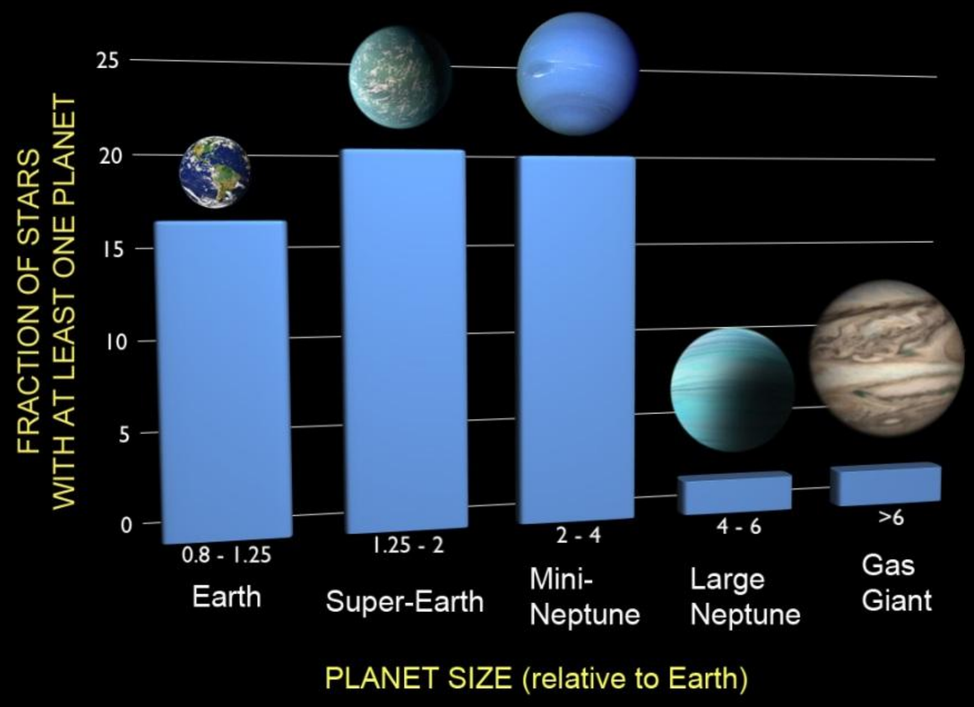
WEBB SPACE TELESCOPE

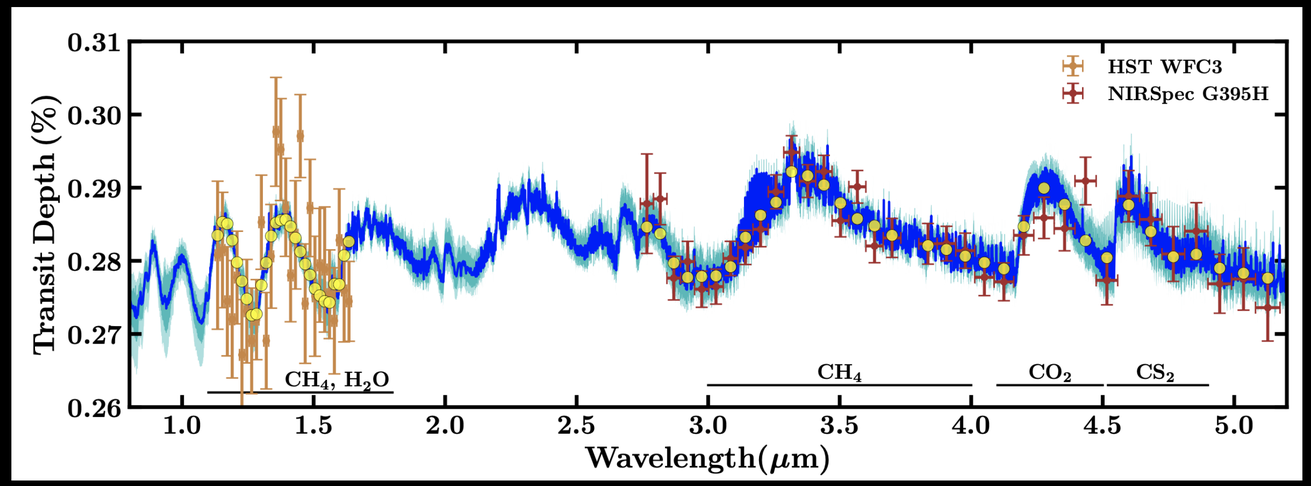
JWST ERS WASP-39 b

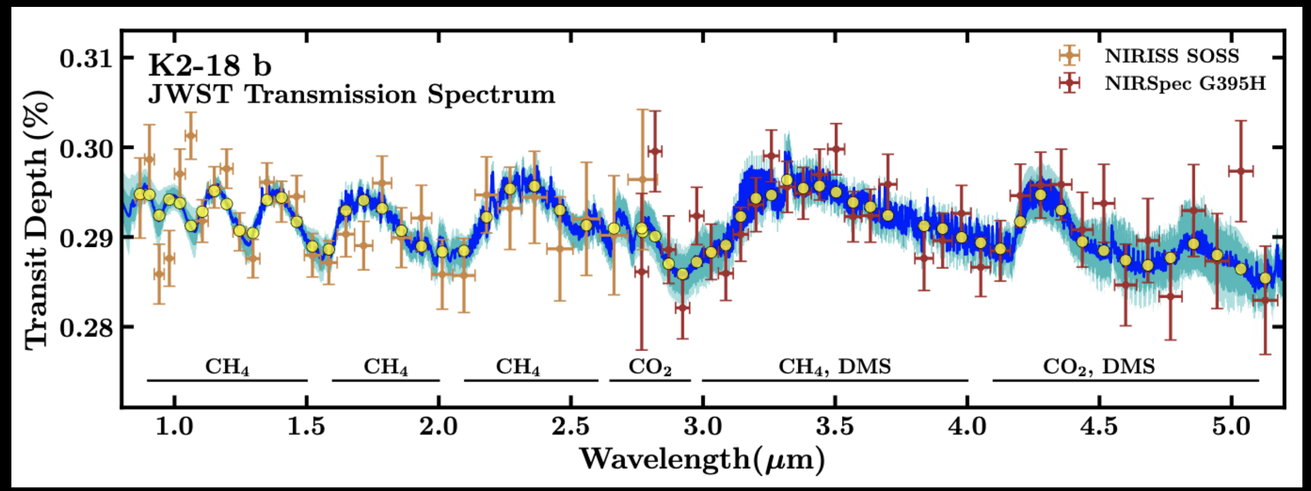




The true JWST revolution: sub-Neptune atmospheres



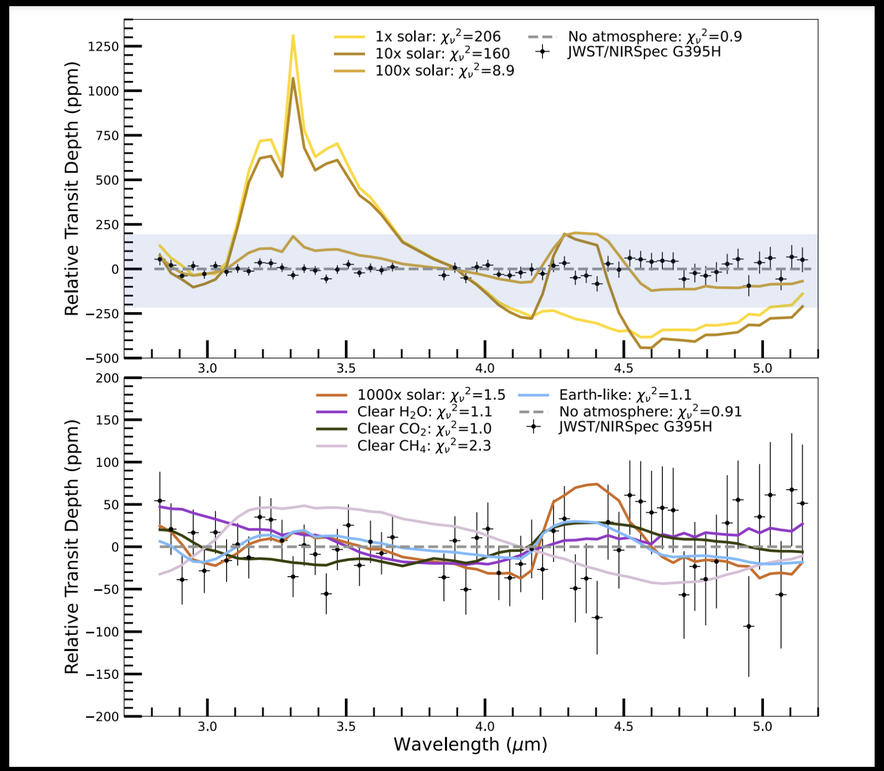




Enormous Degeneration !!!

What about rocky planets ?

LHS 457b Lustig-yaeger et al, 2023



nature
PLANETARY SCIENCE

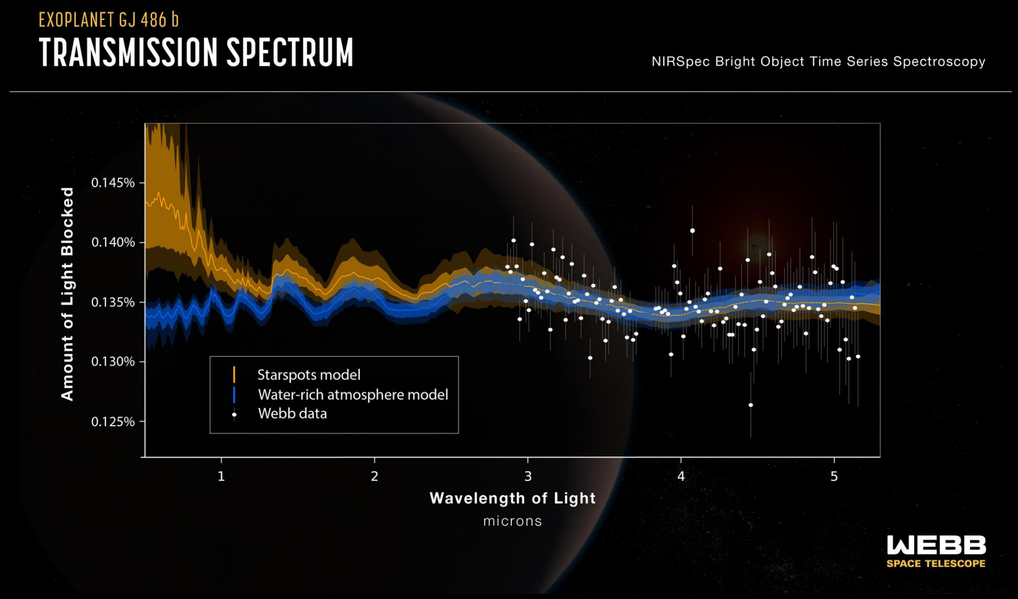
JWST Sees No Atmosphere on 'Earthlike' TRAPPIST-1 Exoplanet

TRAPPIST-1b is probably an airless rock, but the same may not be true for its six Earth-sized siblings

May 1, 2023

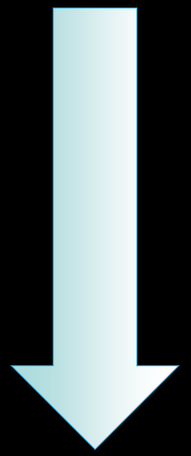
Webb Finds Water Vapor, But From a Rocky Planet or Its Star?

GJ486b Moran et al 2023



From 1,000-10,000 photons from the star, only 1 has crossed the planet atmosphere

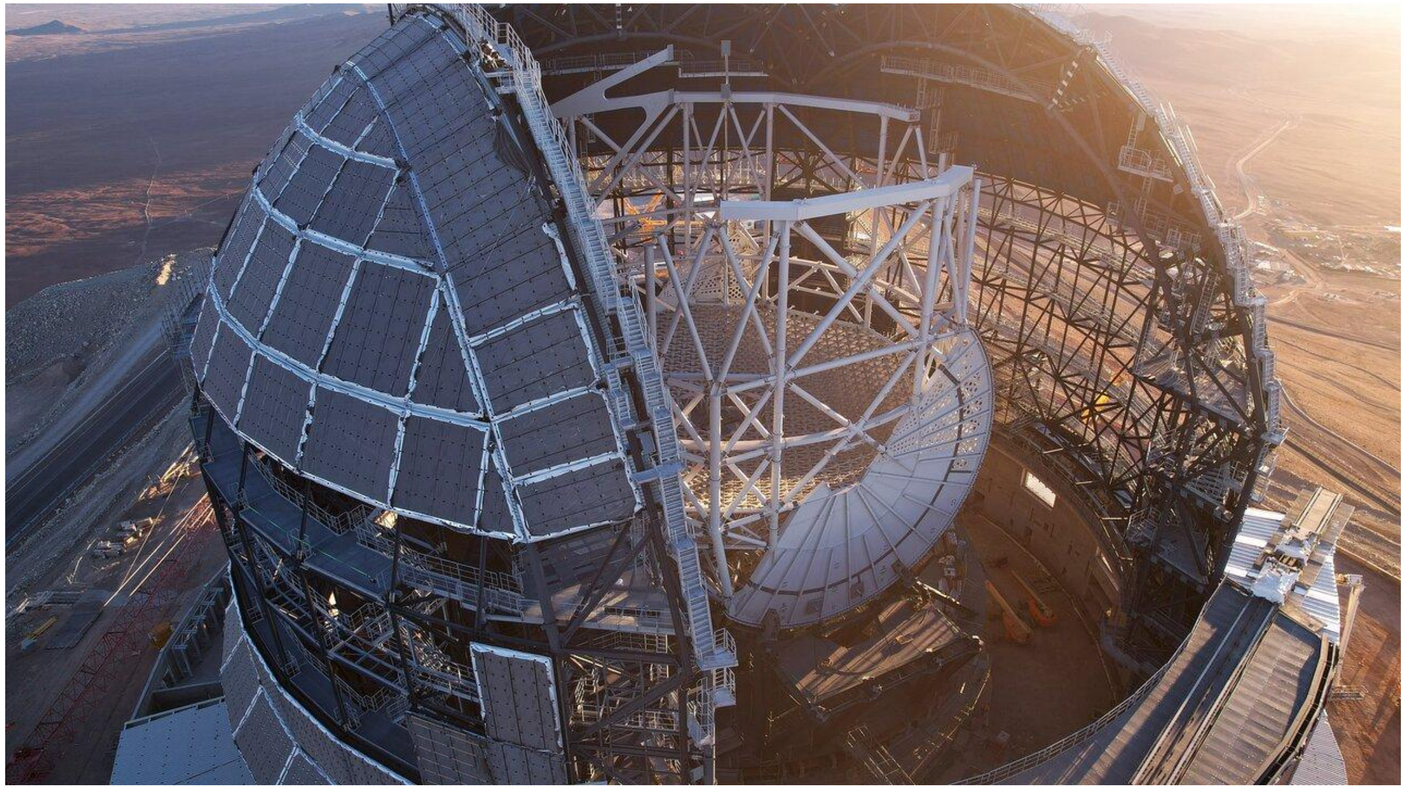






From 100,000-1,000,000 photons from the star, only 1 has crossed the planet atmosphere

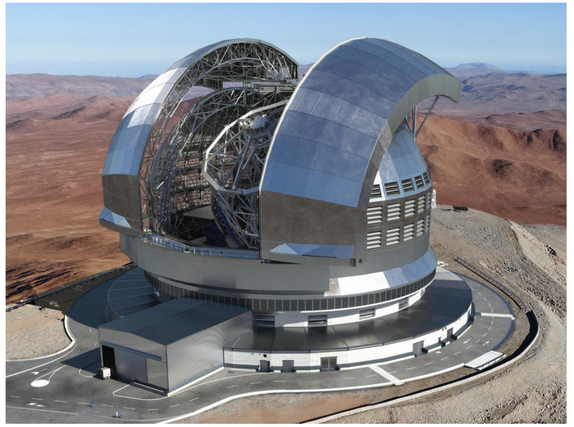
THE ELT



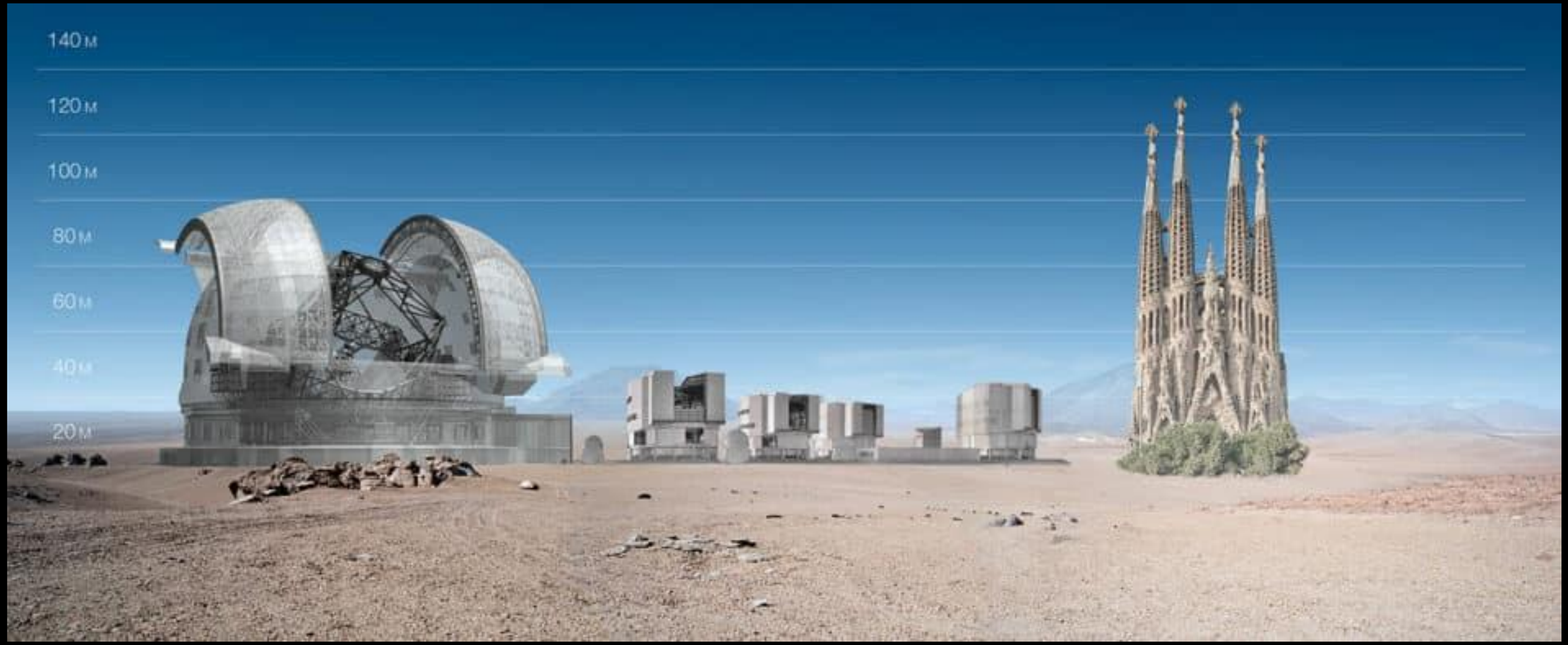
Largest optical/infrared telescope in the world: 39-m segmented primary mirror

Fully AO-assisted telescope

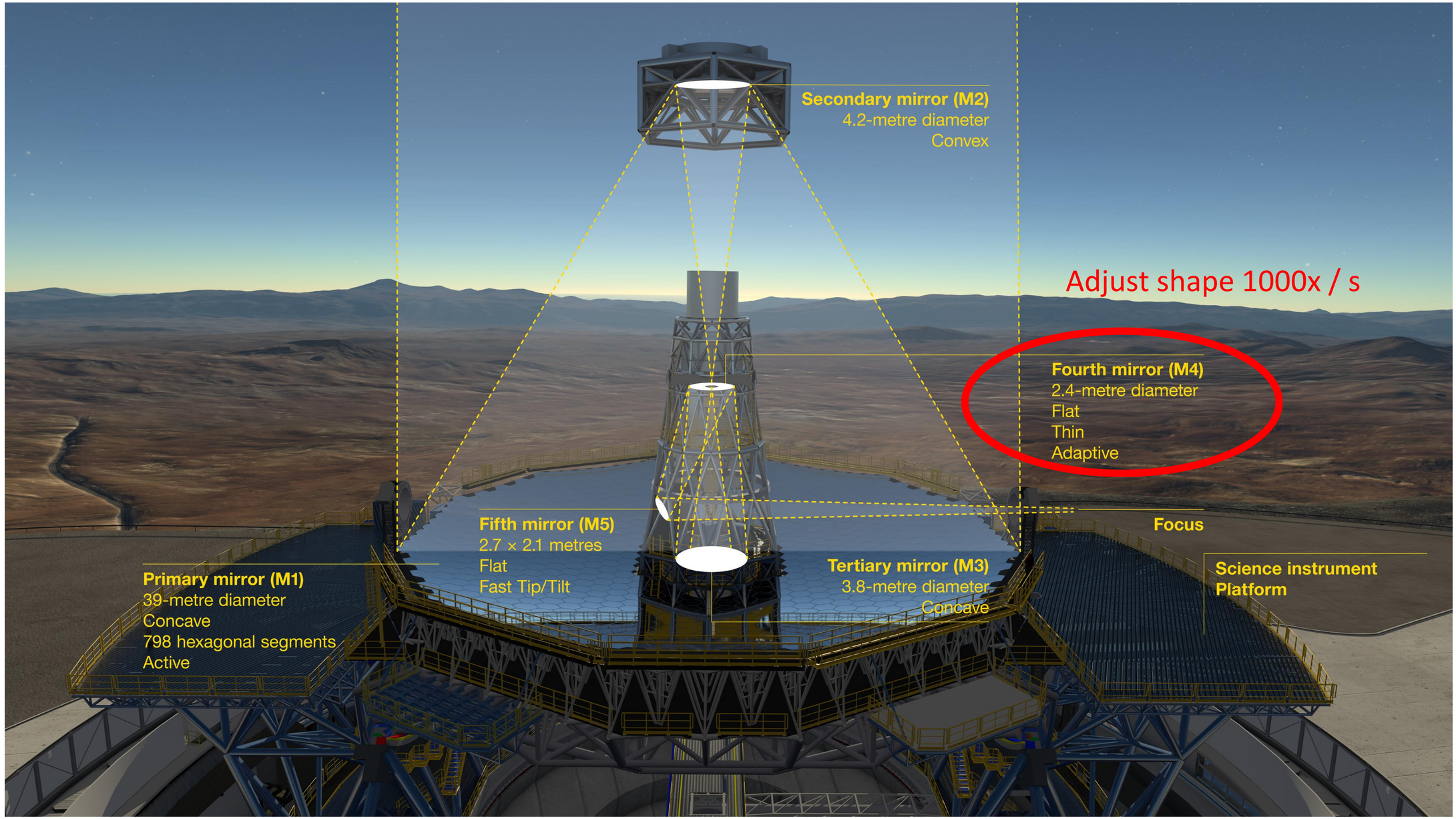
Tackle some of the most pressing issues in modern astrophyscis from Cosmology to Solar System

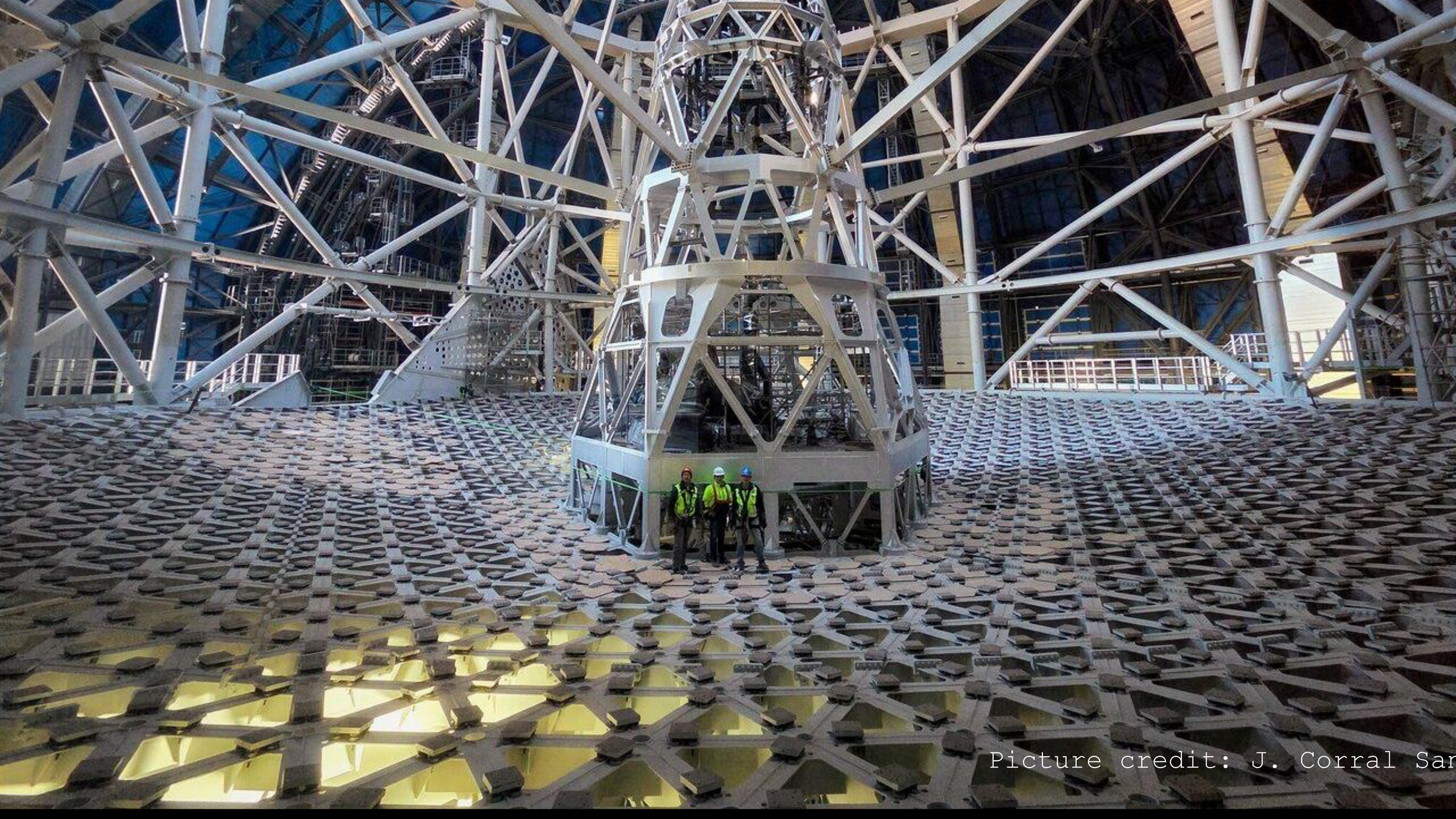


Technical first light in 2028 !!


140 M
120 M
100 M
80 M
60 M
40 M
20 M

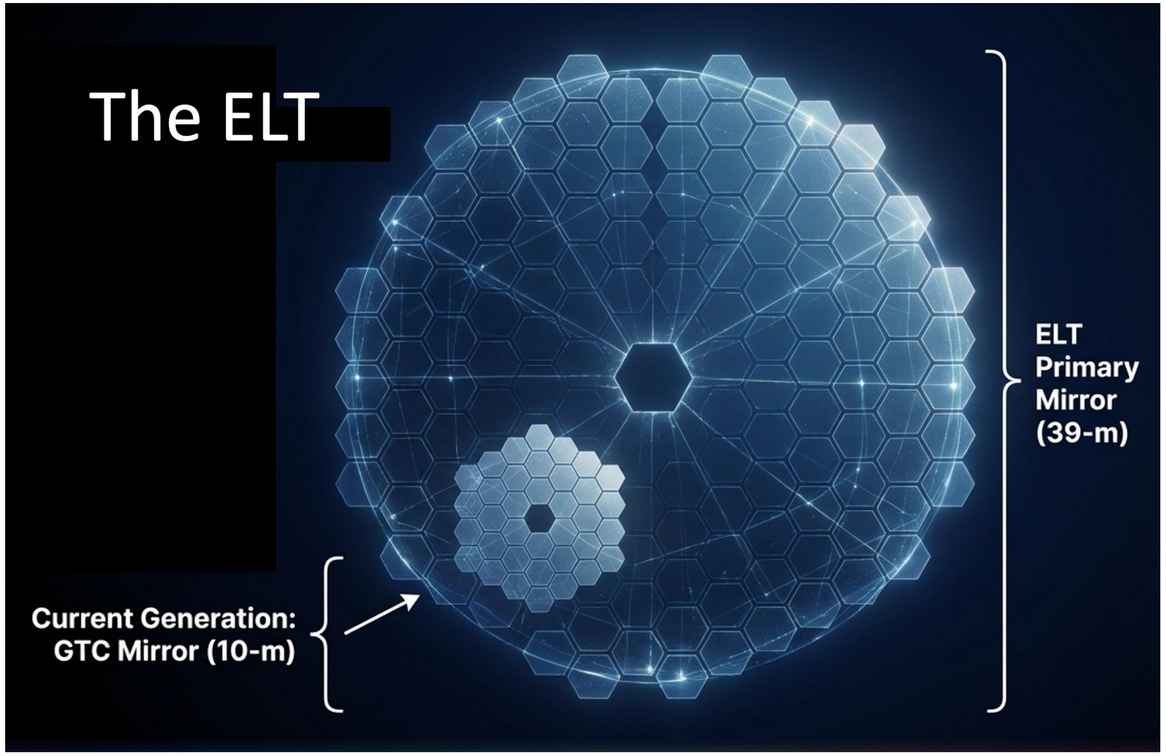
THE ELT – MIRROR SYSTEM



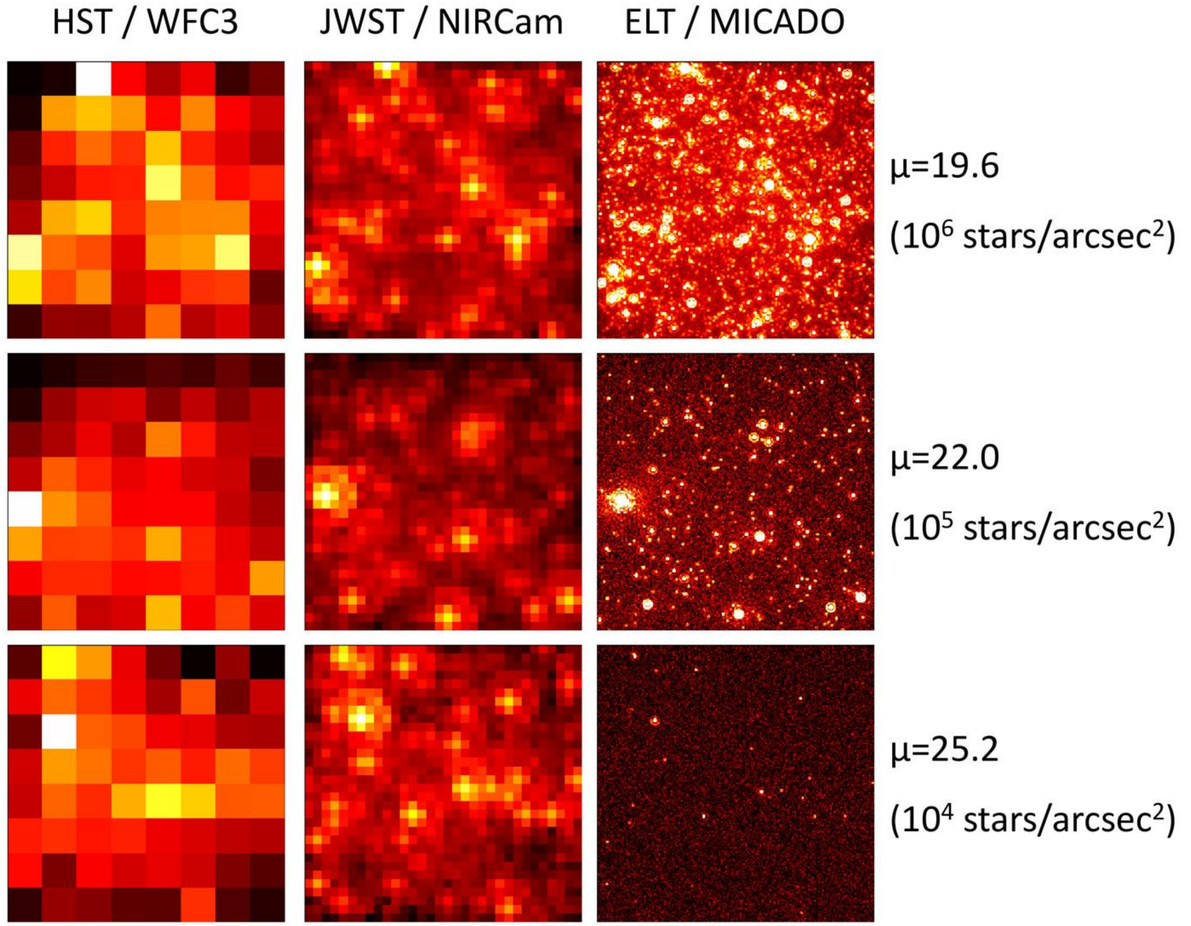


Picture credit: J. Corral San

THE ELT - COLLECTING POWER & ANGULAR RES



Unprecedented collecting power

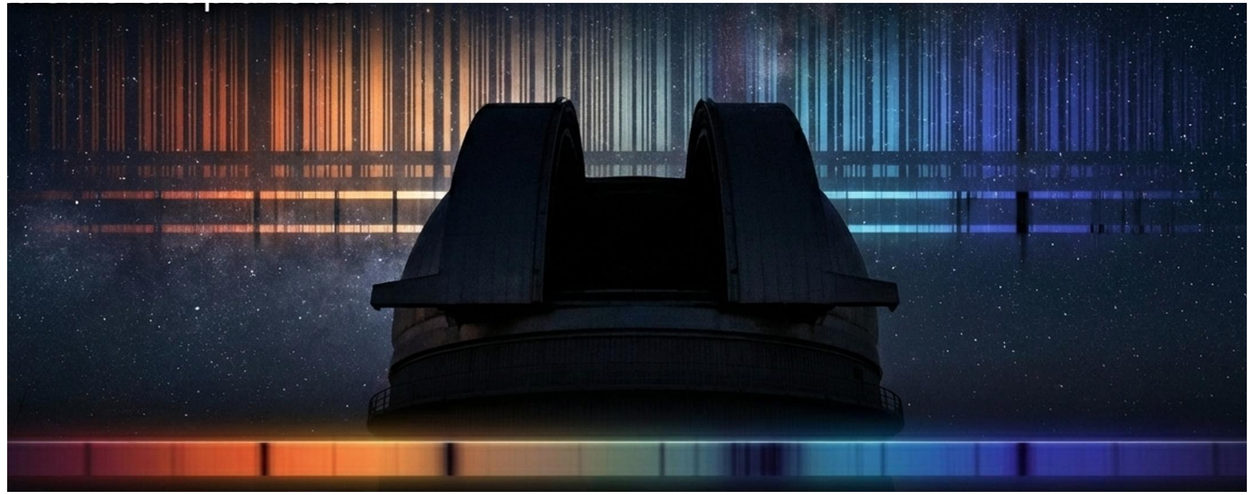


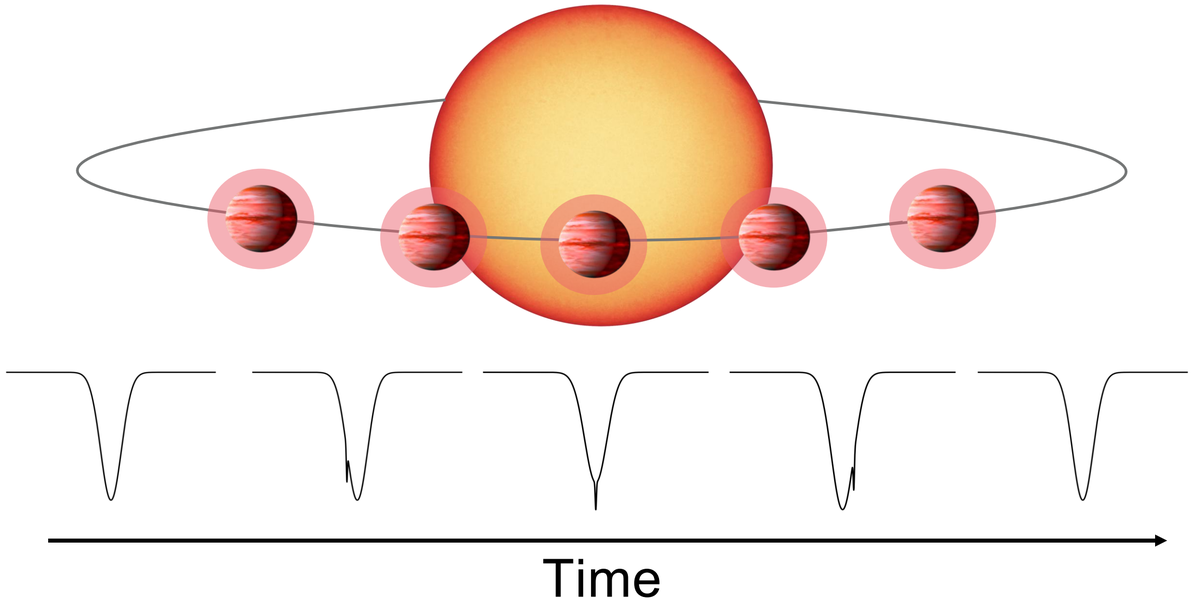
ELT diffraction limit

~ 8 mas in the J-band (λ ~ 1.2μm)

~ 14 mas in the K-band (λ ~ 2μm)

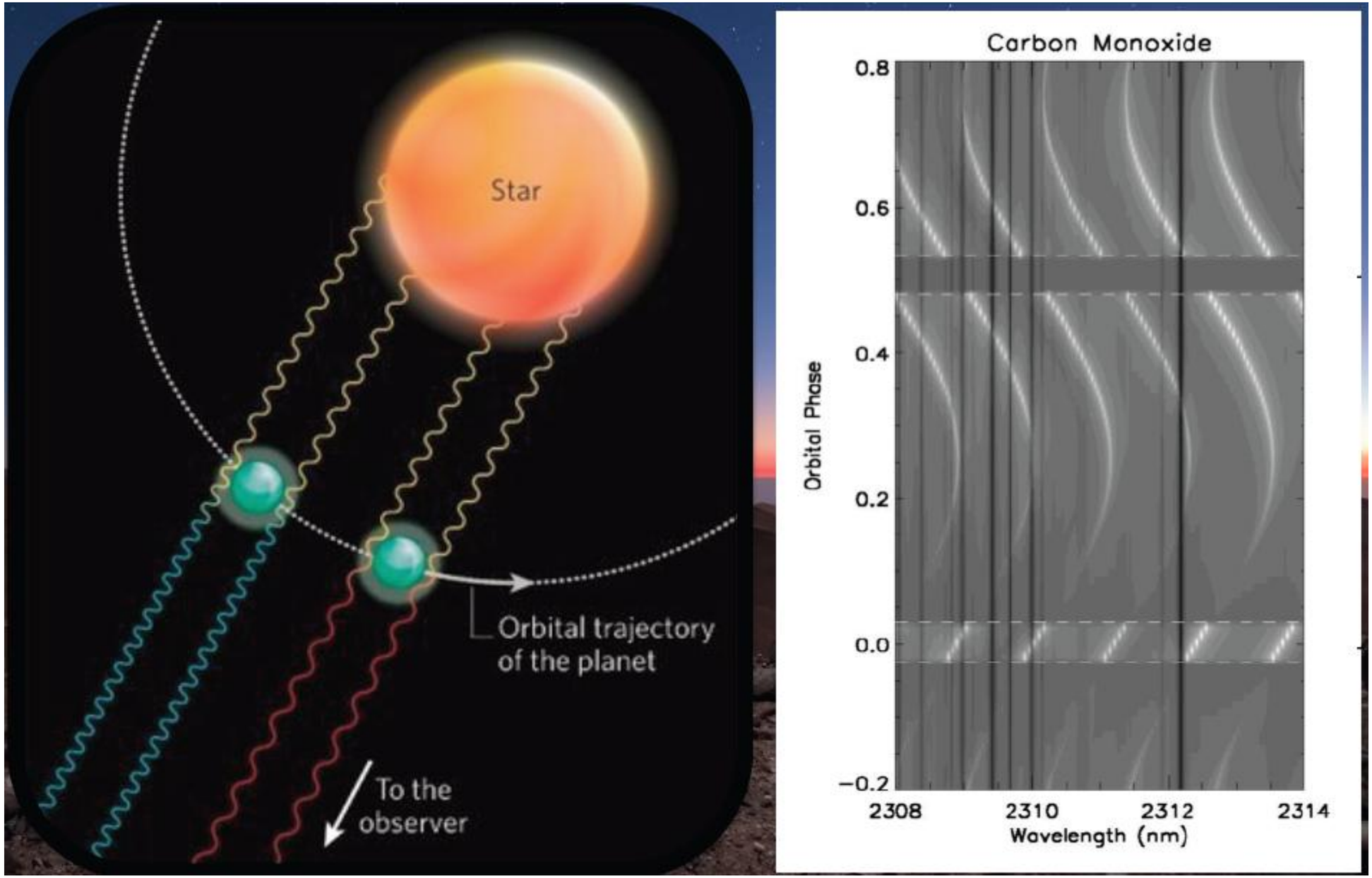
Ground-based telescopes can host high-resolution spectrographs that are used to explore exoplanet atmospheres



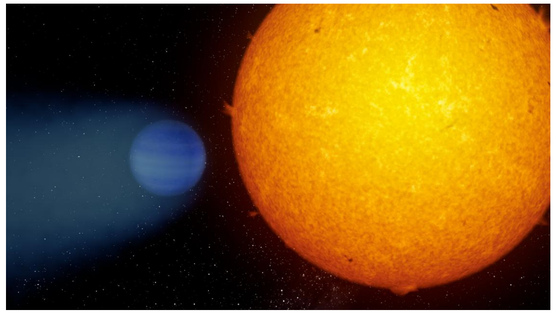


They take advantage of the different star-planet velocities

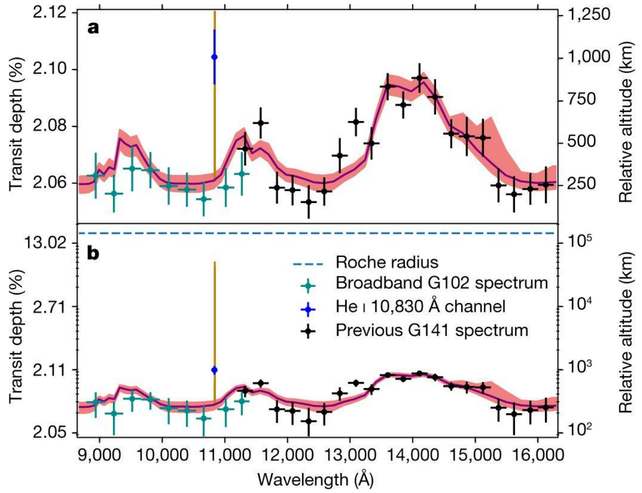
The planet moves at different velocity than the star



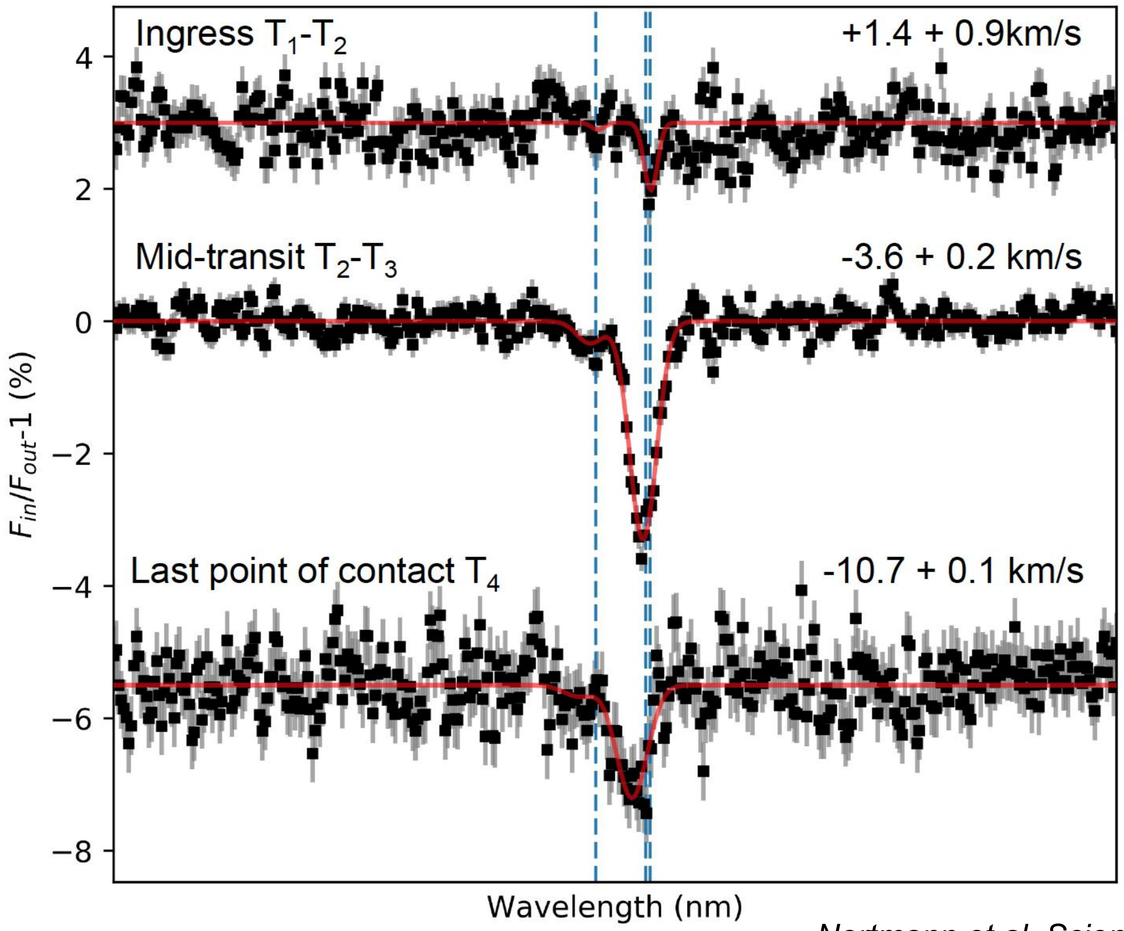
Exoplanet Atmospheres at high-resolution: Resolving the line profiles



Atmospheric loss tracer, the He I metastable triplet



Spake et al, Science, 2018



Nortmann et al, Science, 2018

Information content !!
Pressure-T profiles, Mass loss mechanisms, winds and dynamics …

But so far ***limited to gas giants*** (except extended atmospheres)


ANDES















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Faculty of Physics, Astronomy and Informatics





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Leibniz-Institut für Astrophysik Potsdam











UNIVERSITÉ DE GENÈVE

FACULTÉ DES SCIENCES
Département d'astronomie









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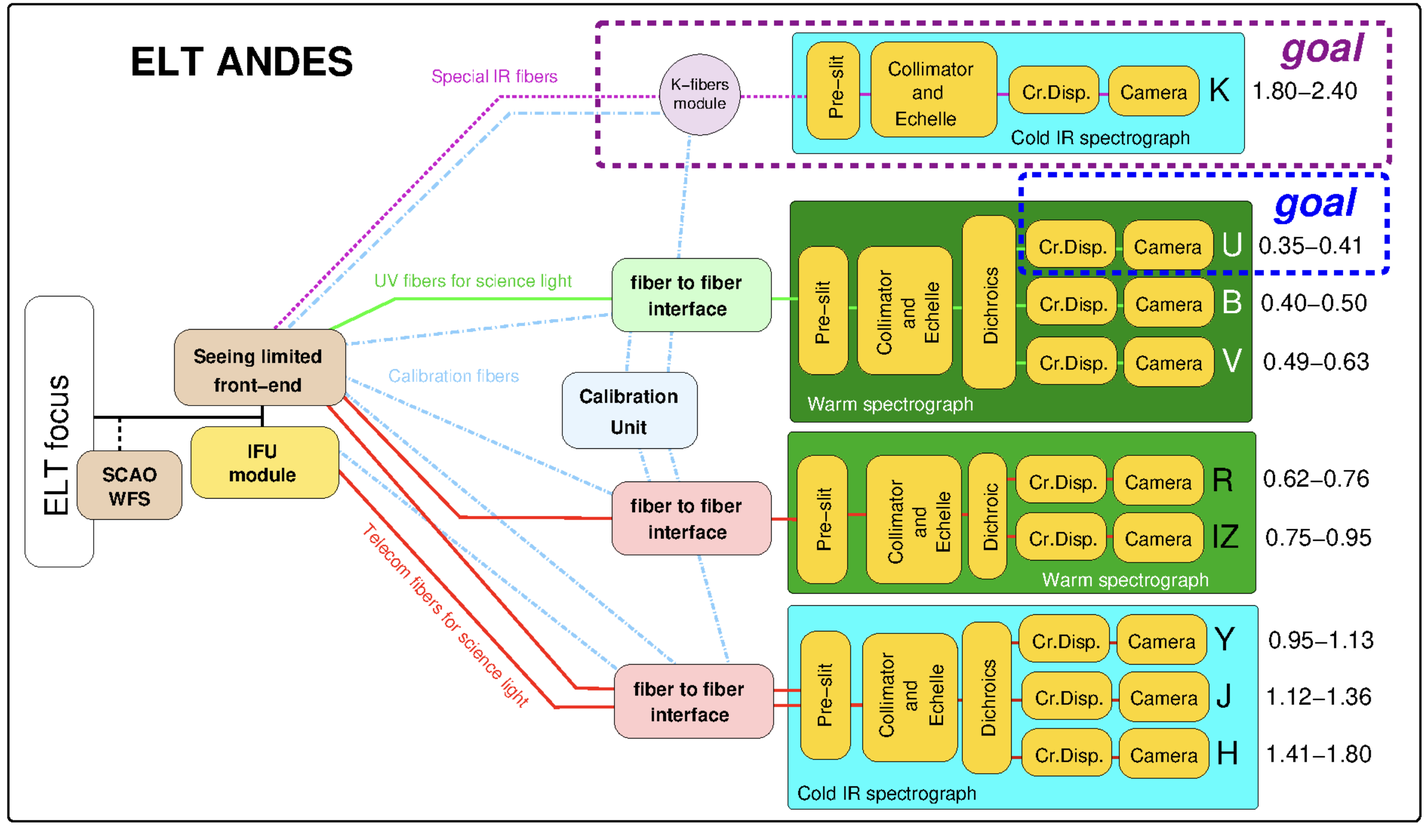
Institut de Planétologie et d'Astrophysique de Grenoble

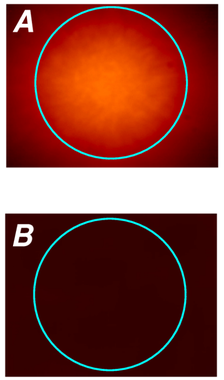
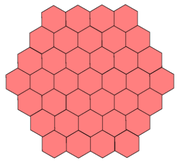
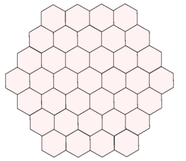
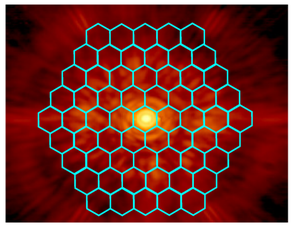
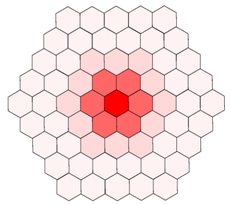


Universität Hamburg

DER FORSCHUNG | DER LEHRE | DER BILDUNG

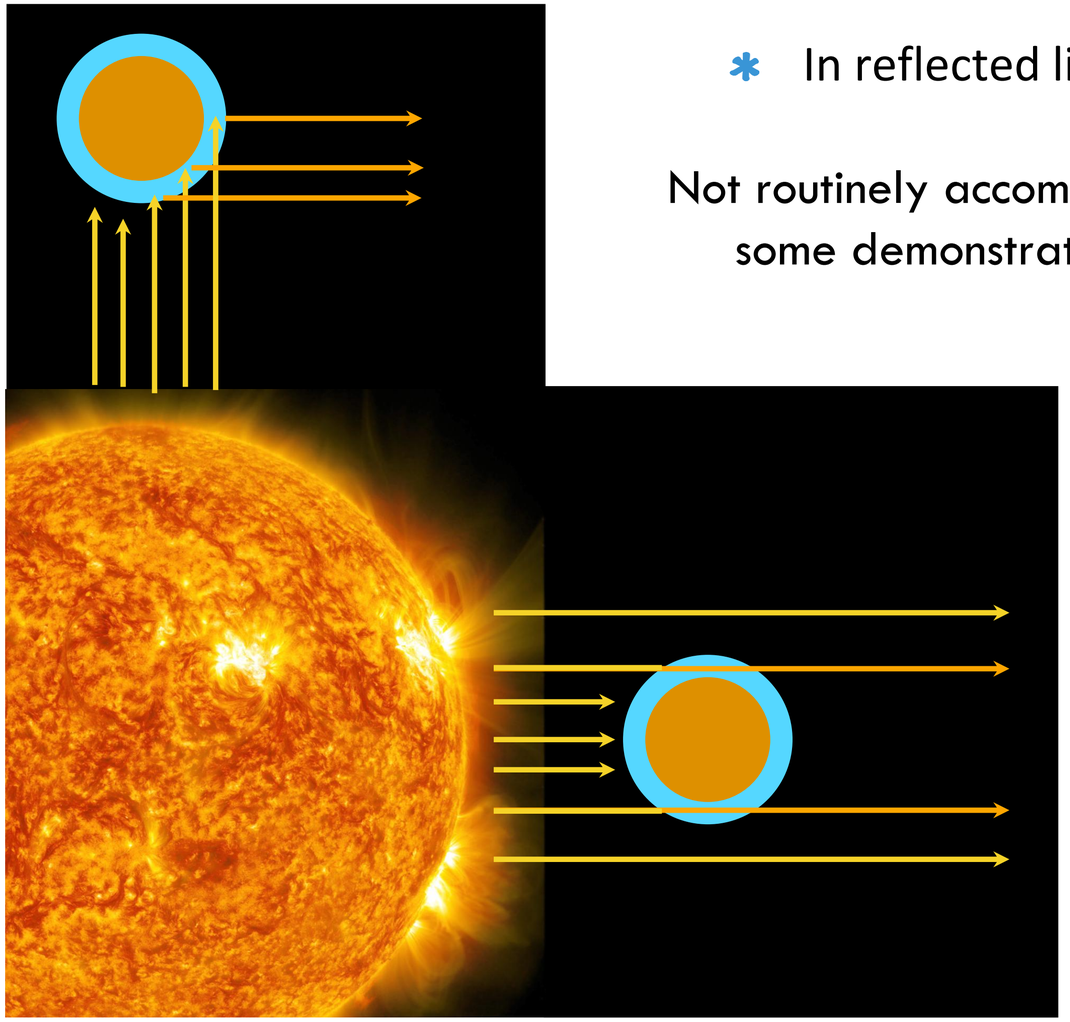
R=100,000 OPT+NIR SPECTROGRAPH



	Front–end	Fiber–to–fiber interface
Seeing limited observing mode	PSF on single large fiber 	Light distribution on fibers bundle after scrambler and slicer  
IFU–SCAO observing mode	PSF on microlenses array and fibers bundle 	Light distribution on fibers bundle after fiber to fiber couplers 

- Modular instrument
- Both **Seeing**- and **Diffraction-Limited** observations posible

EXOPLANET ATMOSPHERES – TOP SCIENCE CASE



* In reflected light

Not routinely accomplished yet some demonstrations

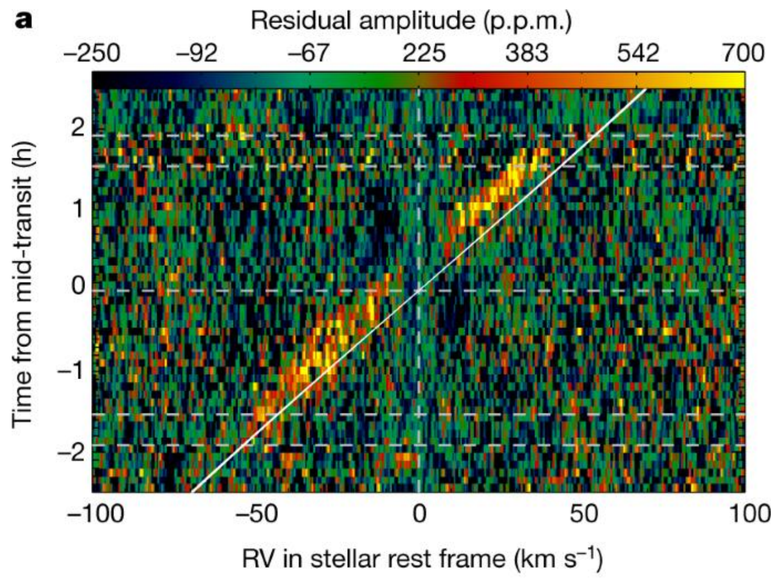
This science case involves two separate techniques

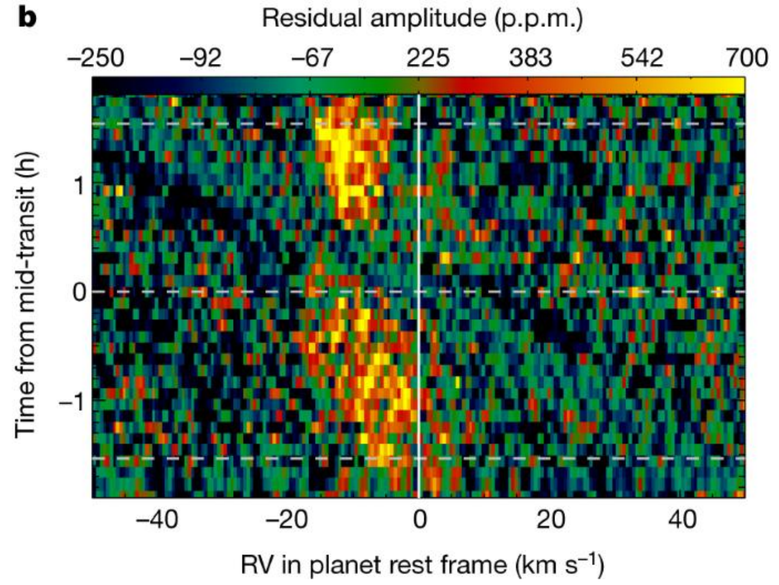
The TRLs discussed here enable both simultaneously, ***but reflected light relies on the need of an AO system***.

* In transmitted light

Technologically not challenging

GIANT EXOPLANET ATMOSPHERES

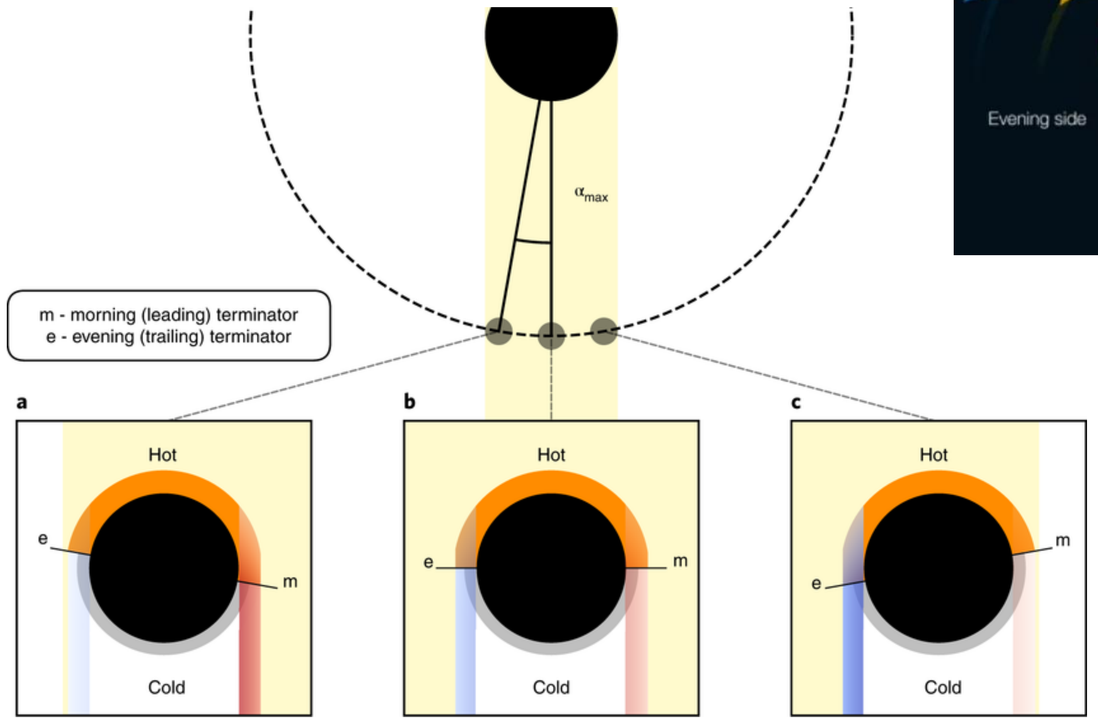


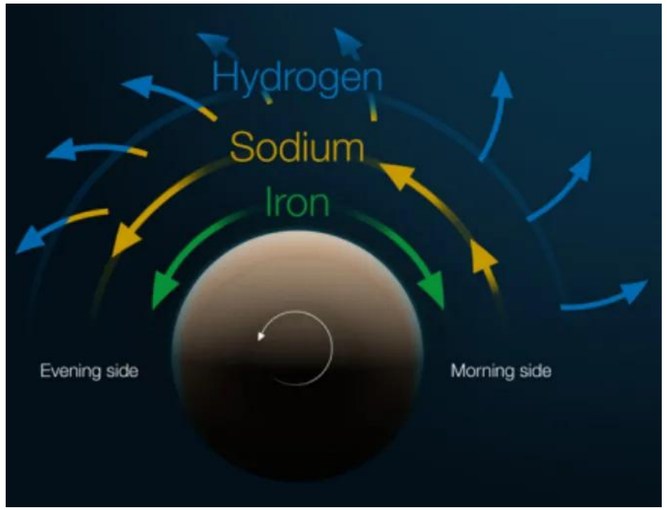


ESPRESSO **Ultra-hot Jupiter** **WASP-76b** (Ehrenreich et al 2020)

First time/spatial resolved spectroscopy and dynamics

Prinoth et al, 2022



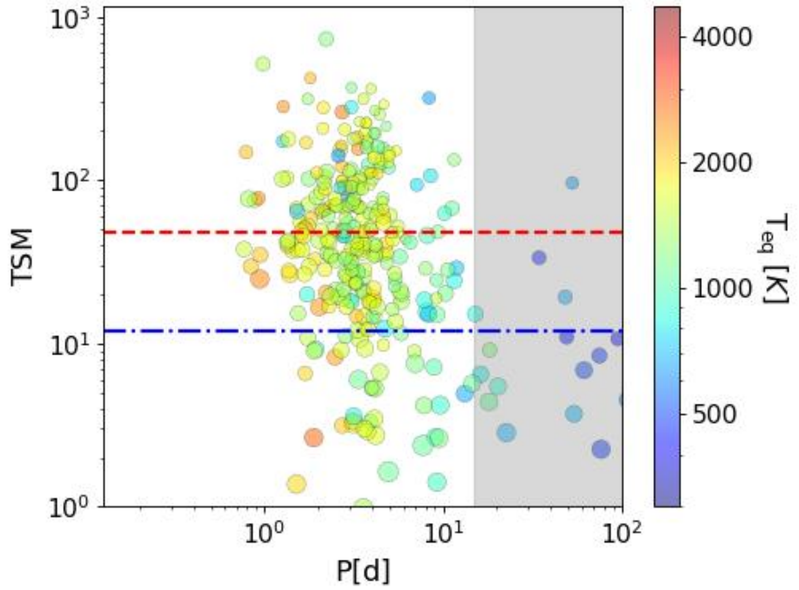


Seidel et al, 2025

GIANT EXOPLANET ATMOSPHERES

Giant exoplanet atmospheres: weather and dynamics in a single night

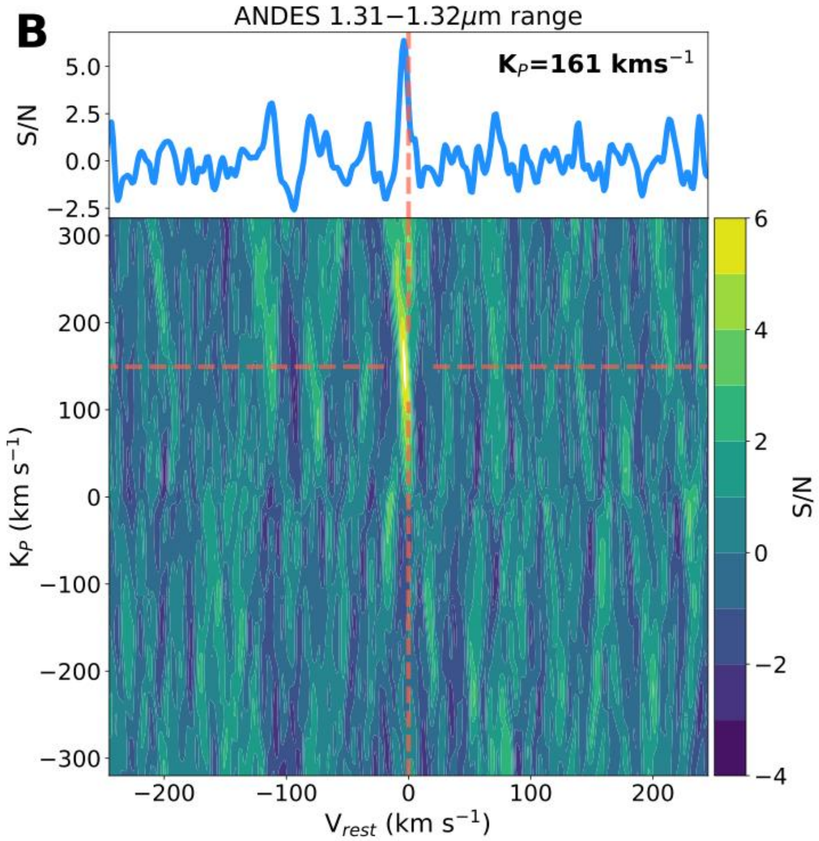
The known population of transiting gas giants

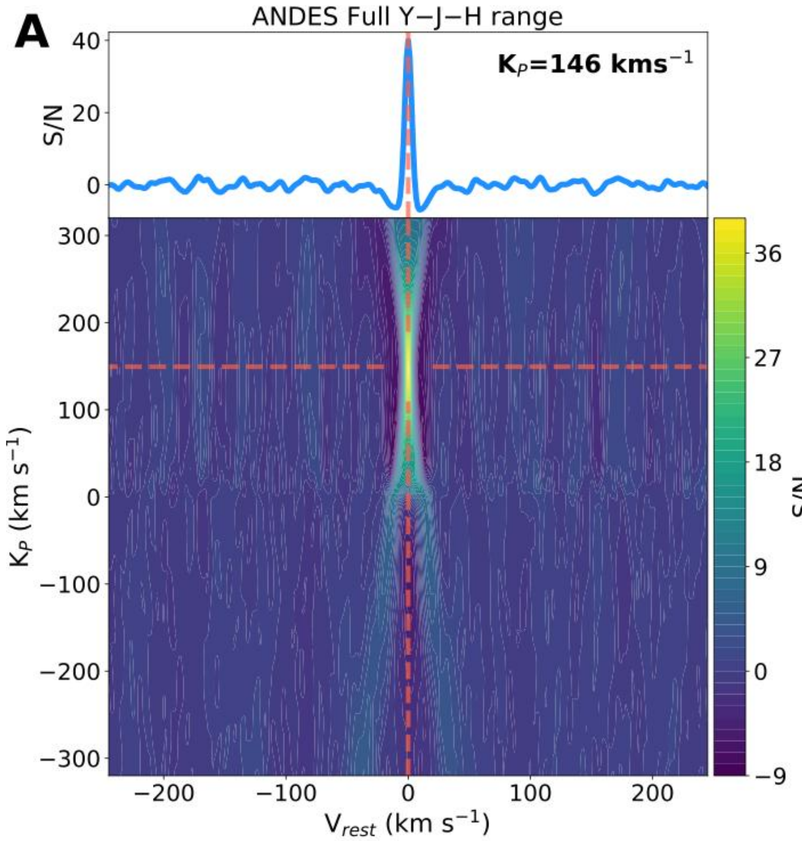


Above red line: One transit needed

Above blue line: Accessible to ANDES for time-resolved dynamical studies

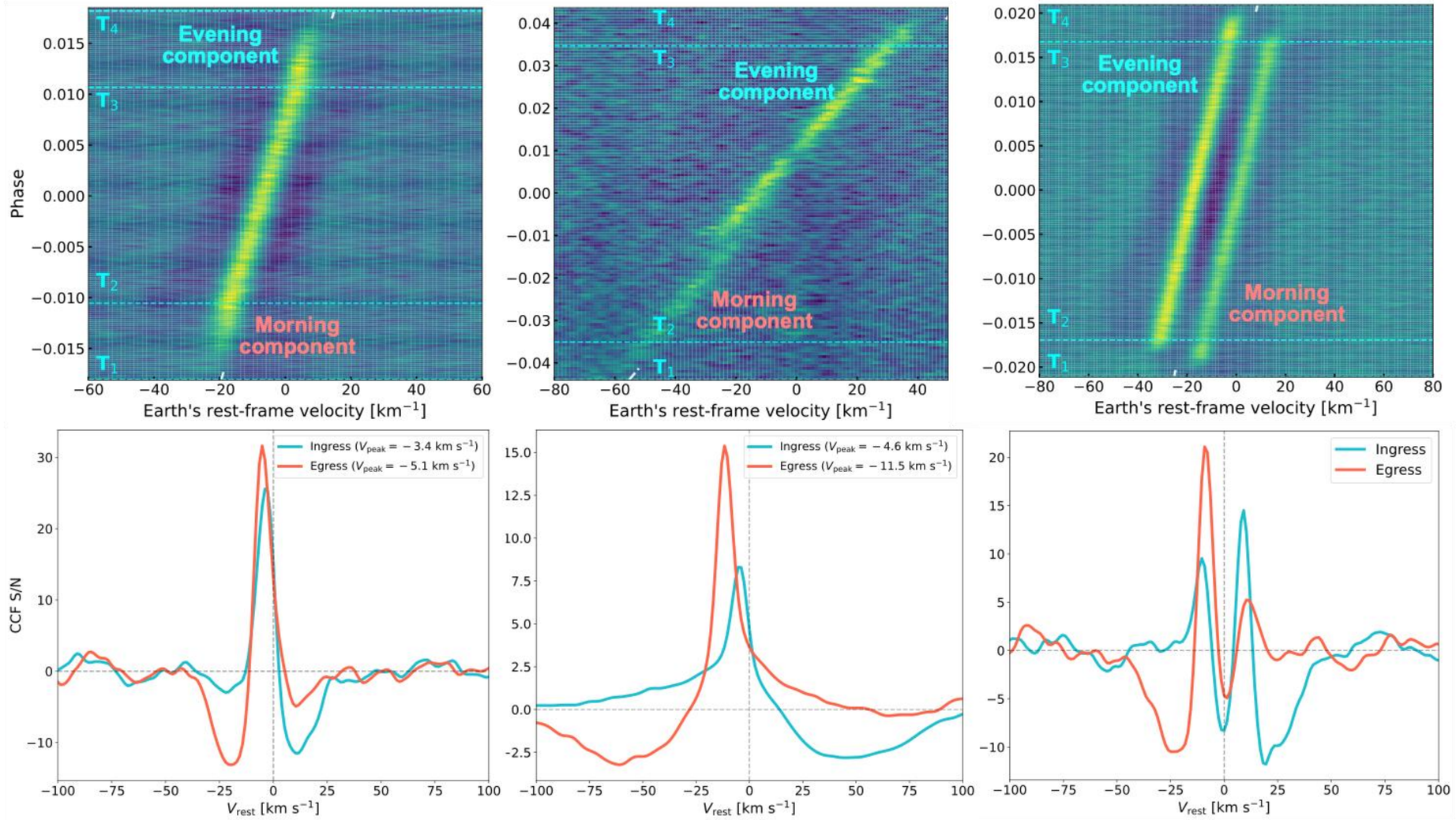
Palle et al (2025)





Sanchez-Lopez & Palle (submitted)

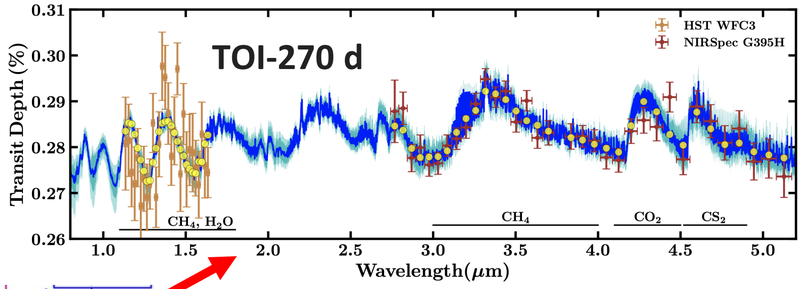
GIANT EXOPLANET ATMOSPHERES

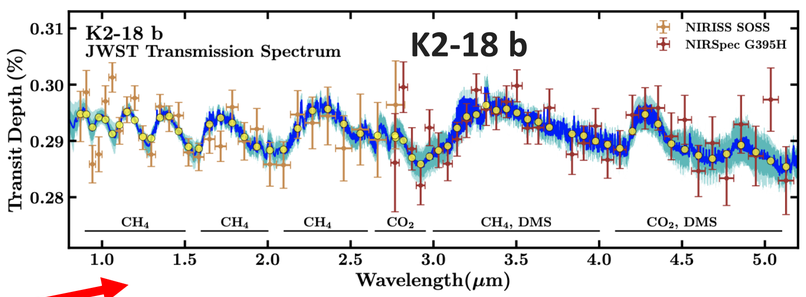


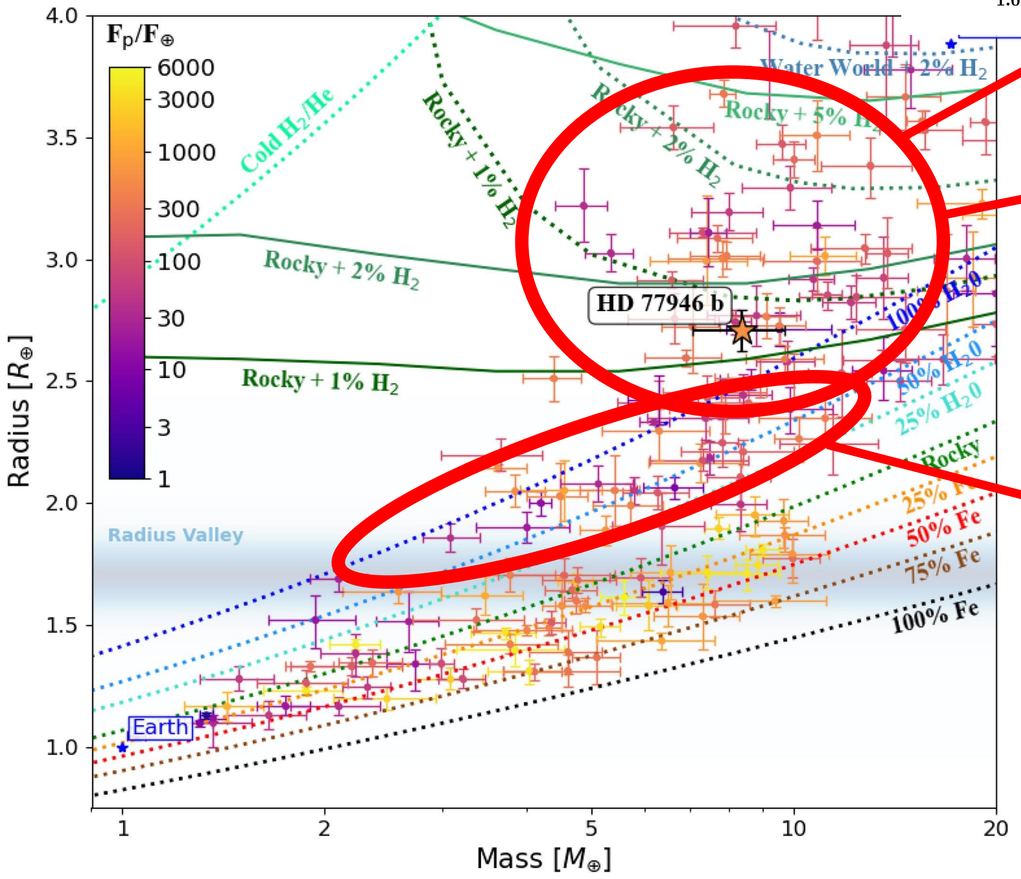
Hot Jupiter's simulation

Sanchez-Lopez & Palle (submitted)

SMALL (<4 R_E) EXOPLANET ATMOSPHERES



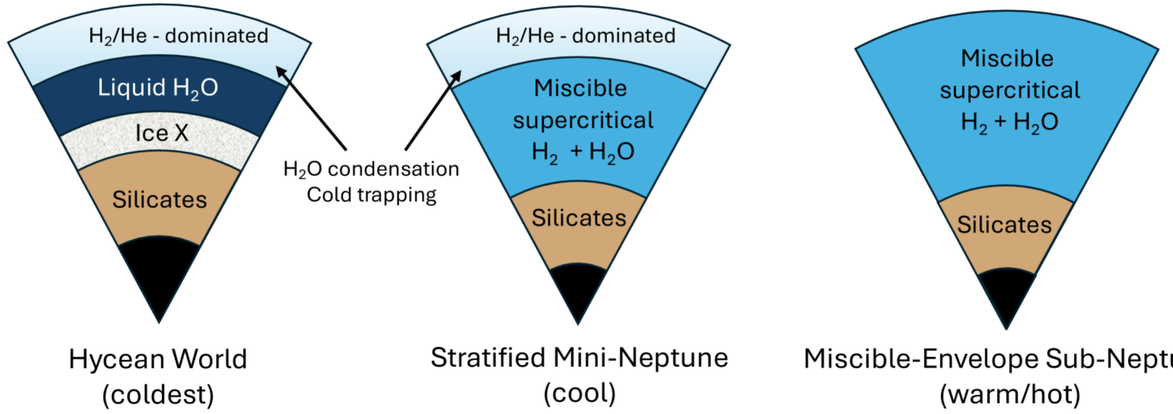




Palethorpe et al 2024

JWST is providing fabulous data, ANDES will provide synergetic observations at higher spectral resolution

Unmistaken molecular mapping



Hycean World (coldest)

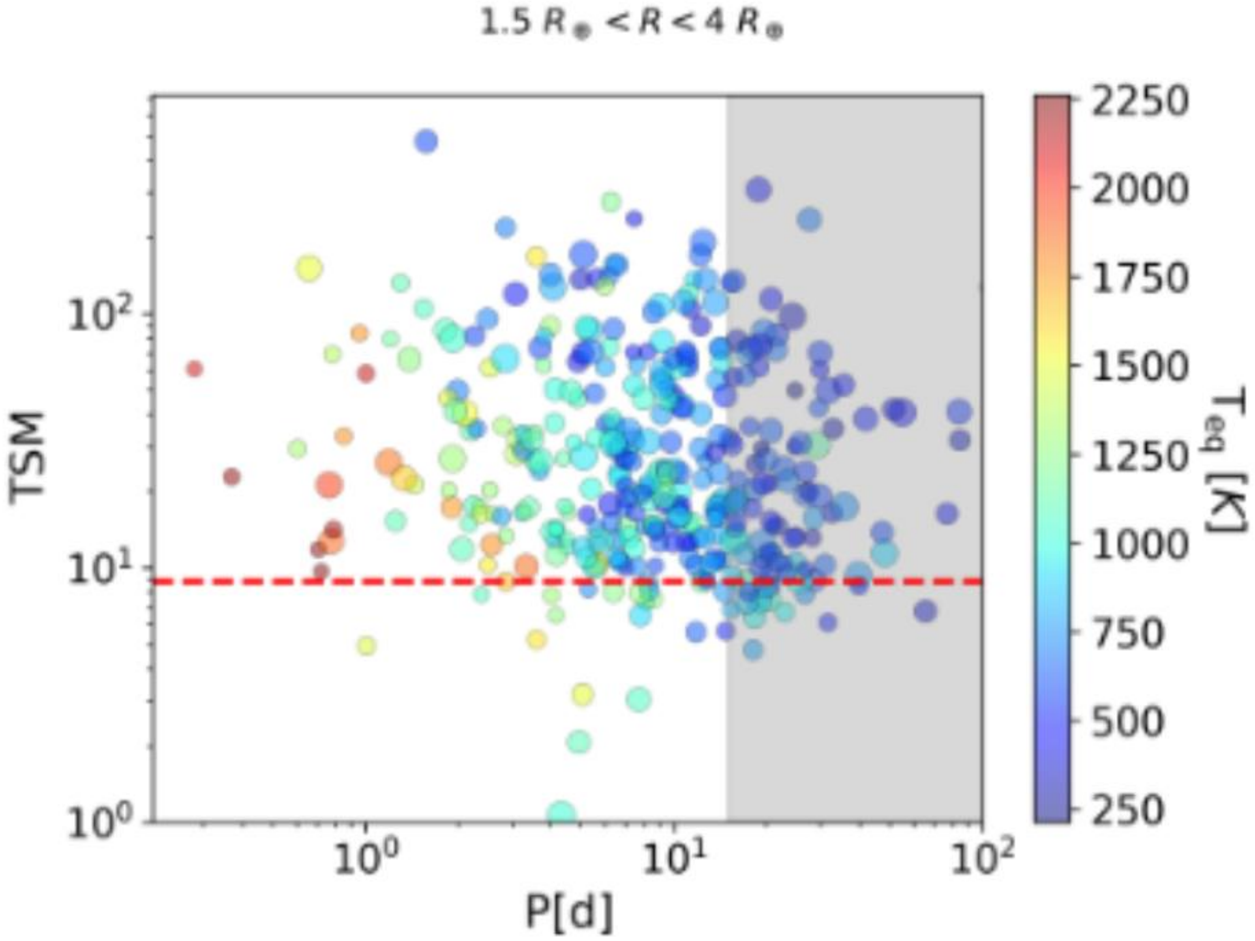
Stratified Mini-Neptune (cool)

Miscible-Envelope Sub-Neptune (warm/hot)

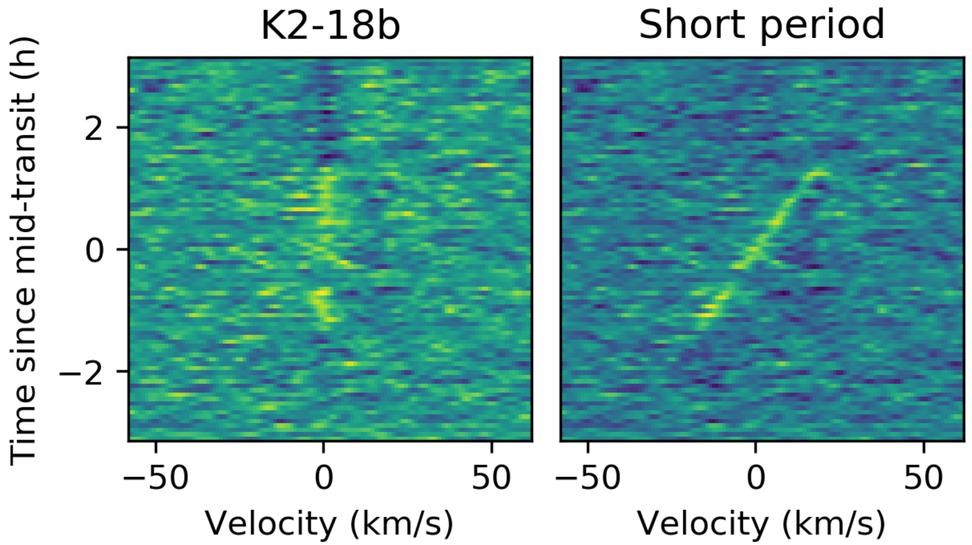
Benneke et al 2024

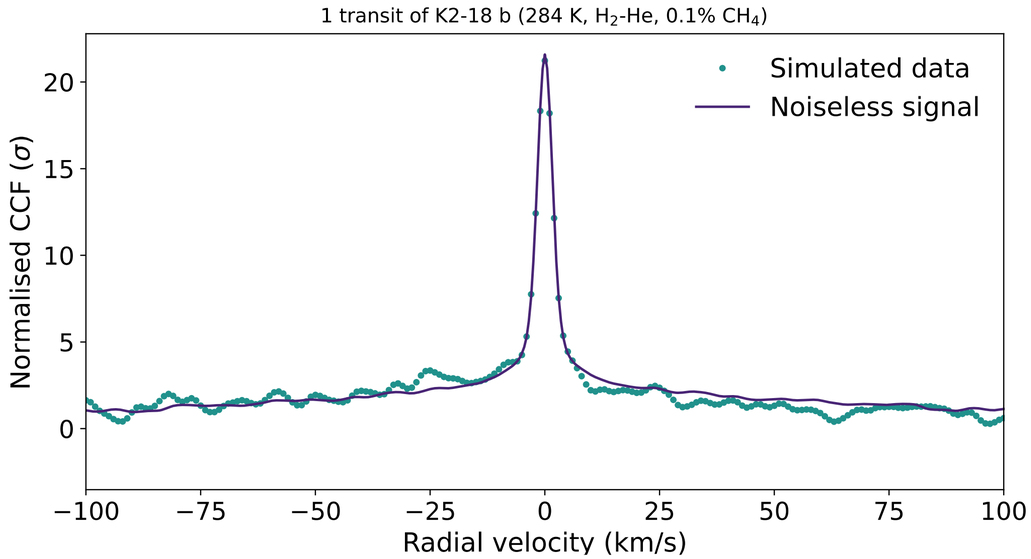
SMALL (<4 R_E) EXOPLANET ATMOSPHERES

The known population of small planets



Red line marks the 5 sigma detection in 1 transits

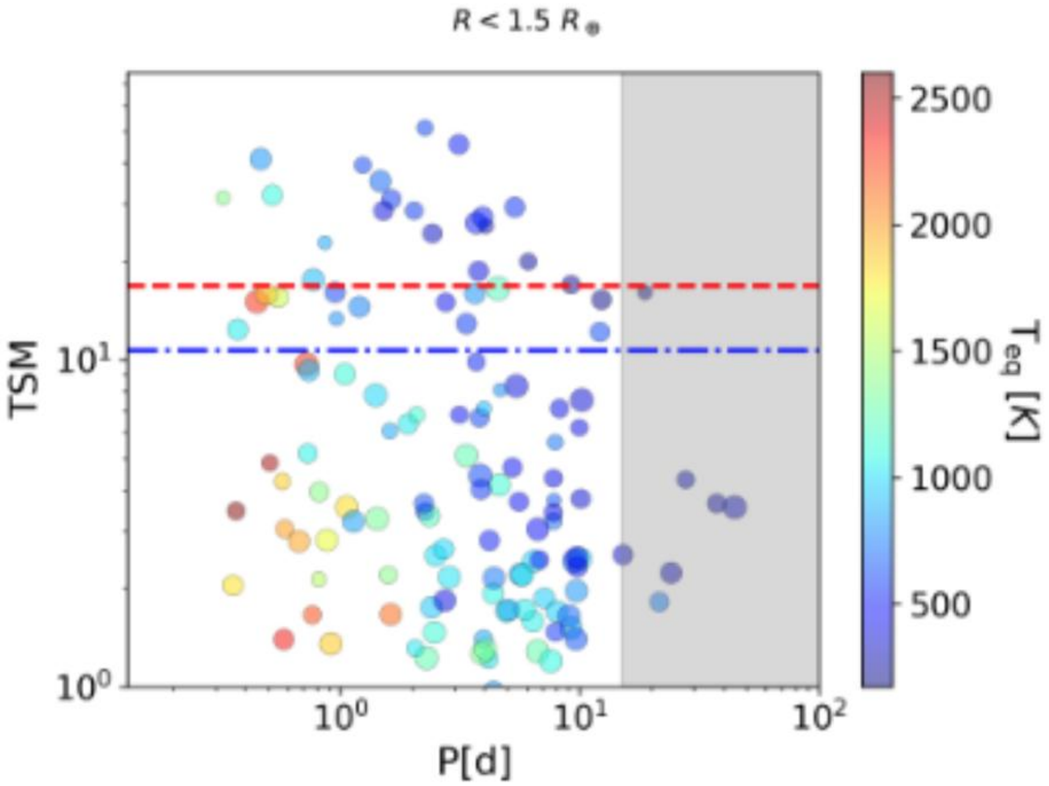




Palle et al 2025

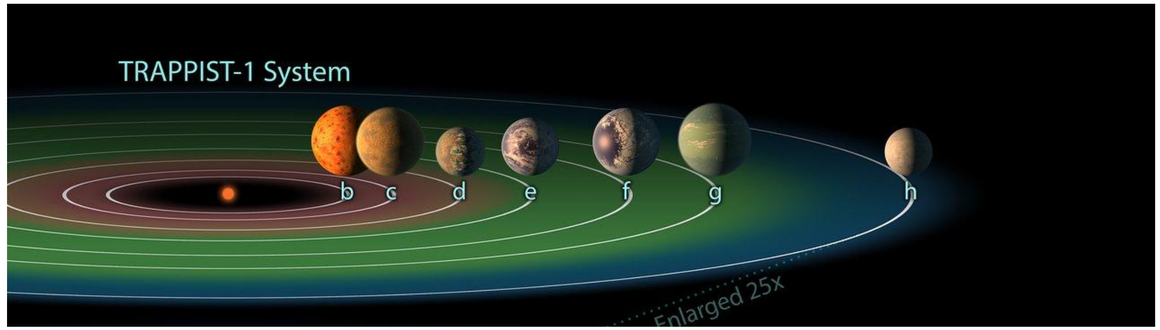
EARTH-LIKE EXOPLANET ATMOSPHERES

The known population of small planets



Broken lines mark the 5 sigma detection in 5 transits for CO_2-dominated and earth-like atmospheric compositions

Palle et al 2025



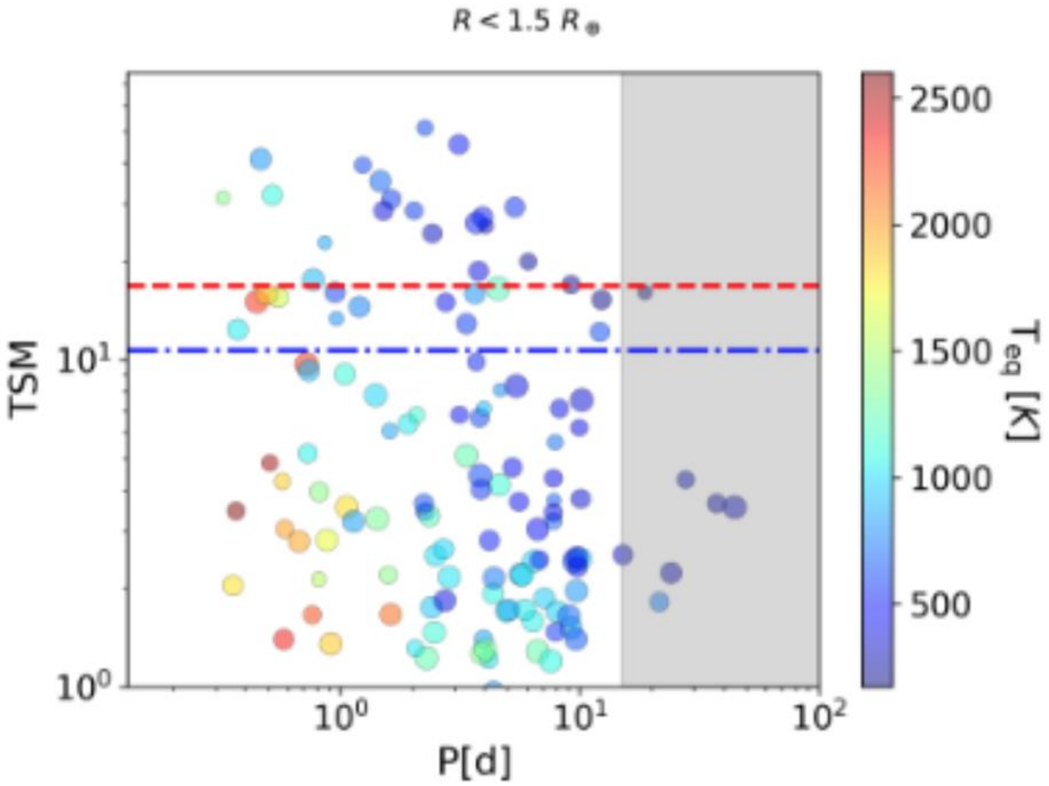
M dwarf Trappist 1 planets:

- 1.3-1.7 um H_2O band at an SNR of 6 in 2 transits
- 0.9-1.1 um H_2O band in 4 transits
- CO_2 in 4 transits.
- O_2 detected in 25 transits.

For these planets, the transit duration is <1 hour

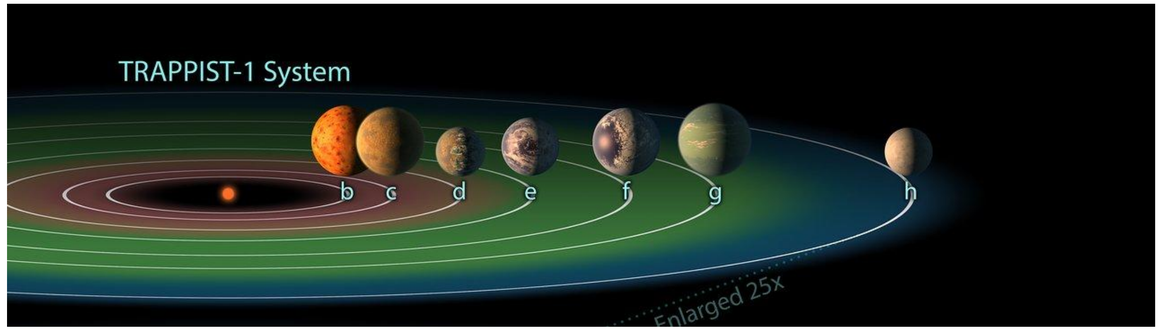
EARTH-LIKE EXOPLANET ATMOSPHERES

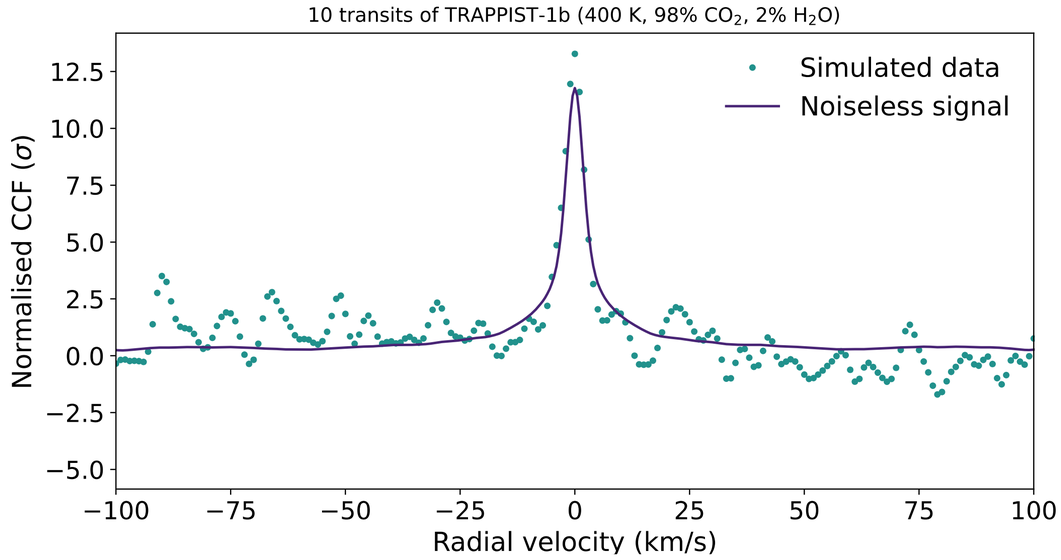
The known population of small planets



Broken lines mark the 5 sigma detection in 5 transits for CO_2-dominated and earth-like atmospheric compositions

Palle et al 2025

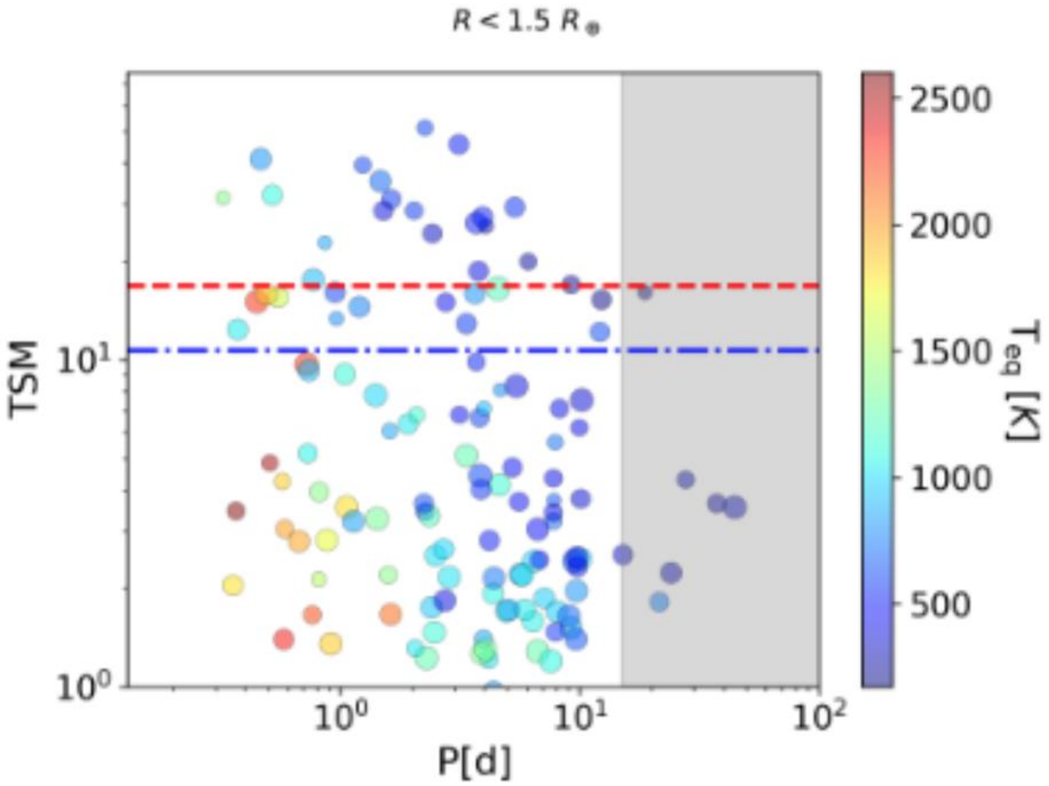


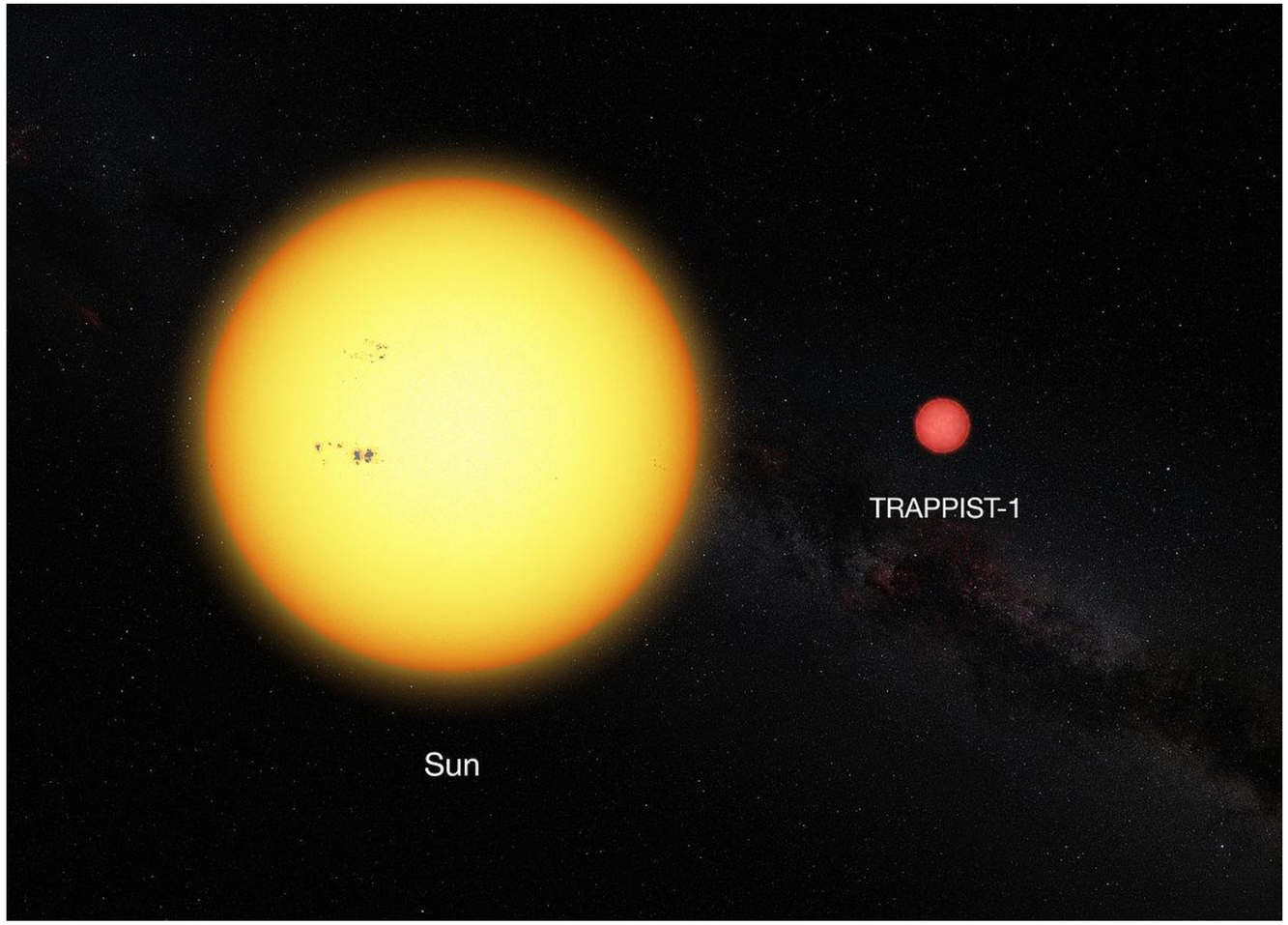


100-night (4 months with overheads) program explores the best 30 HZ transiting planets in TS at the 5 sigma level.

EARTH-LIKE EXOPLANET ATMOSPHERES

The known population of small planets





Broken lines mark the 5 sigma detection in 5 transits for CO_2-dominated and earth-like atmospheric compositions

Palle et al 2025

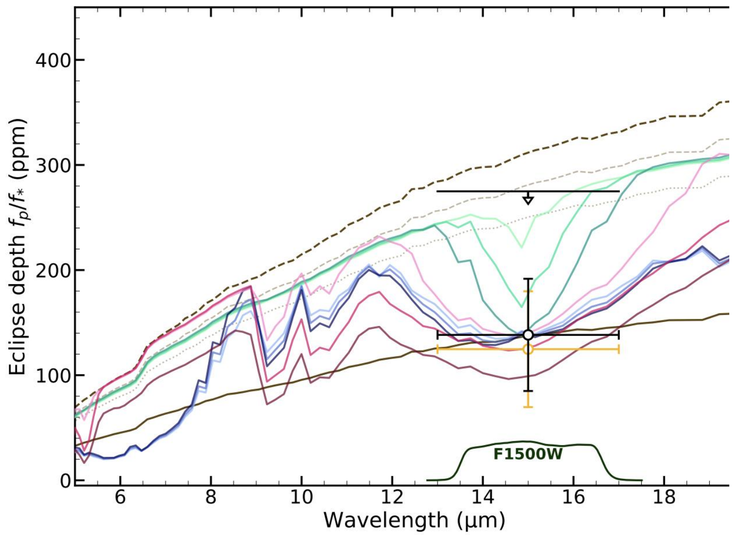
EARTH-LIKE EXOPLANET ATMOSPHERES

Is there hope to find atmospheres around M dwarf planets ?

Hot Rocks Survey I: A possible shallow eclipse for LHS 1478 b

P. C. August[1,⋆], L. A. Buchhave[1], H. Diamond-Lowe[1,2], J. M. Mendonça[1,3,4], A. Gressier[2], A. D. Rathcke[1], N. H. Allen[5], M. Fortune[6], K. D. Jones[7], E. A. Meier Valdés[7], B.-O. Demory[7,8], N. Espinoza[5,2], C. E. Fisher[9], N. P. Gibson[6], K. Heng[10,11,12], D. Kitzmann[16], B. Prinoth[17], J. D. Eastman

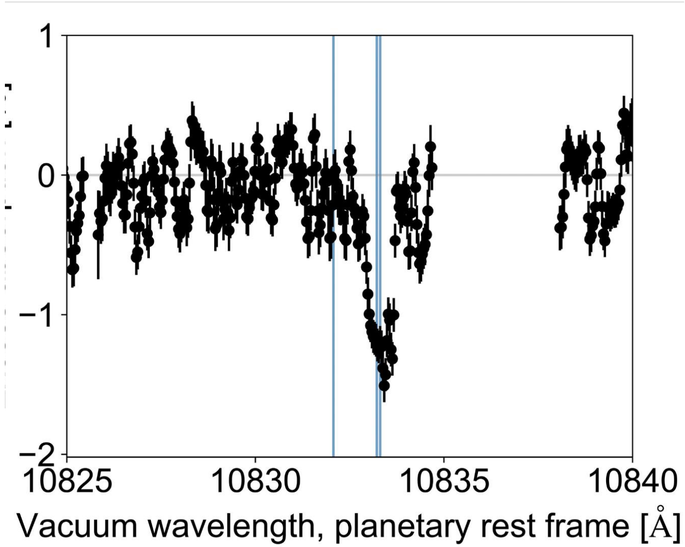
R= 1.2 Re, T= 590 K, hot rock

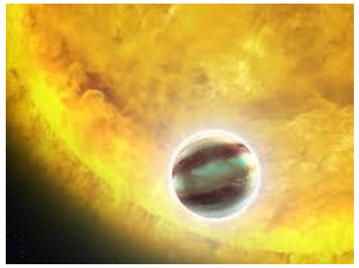


Helium escaping from the atmosphere of a nearby rocky exoplanet orbiting in a habitable zone

COLLIN CHERUBIM, SHREYAS VISSAPRAGADA, TIM CUNNINGHAM, ANNABELLA G. MEECH, DAVID CHARBONNEAU, ROBIN WORDSWORTH, TESKE, LEONARDO A. DOS SANTOS, [...], AND MERCEDES LÓPEZ-MORALES +6 authors Authors Info &

Re, T= 226 K, HZ SE/MN



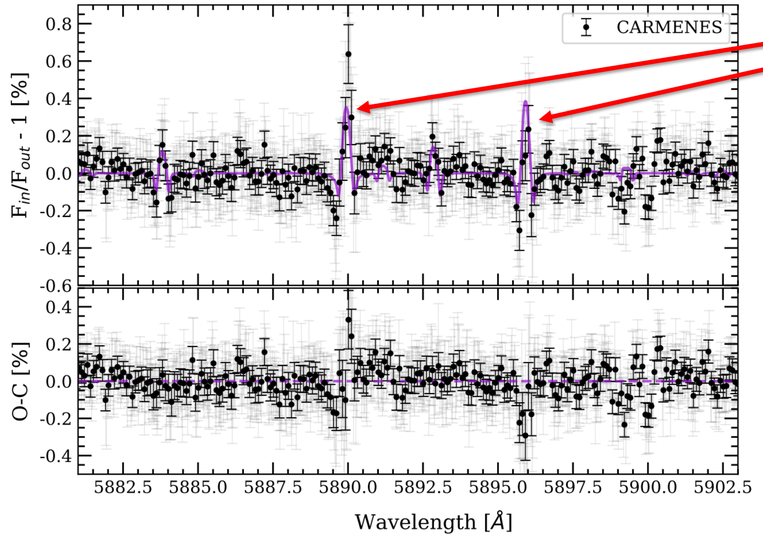


HD 209458b an important warning

Benchmark GIANT PLANET

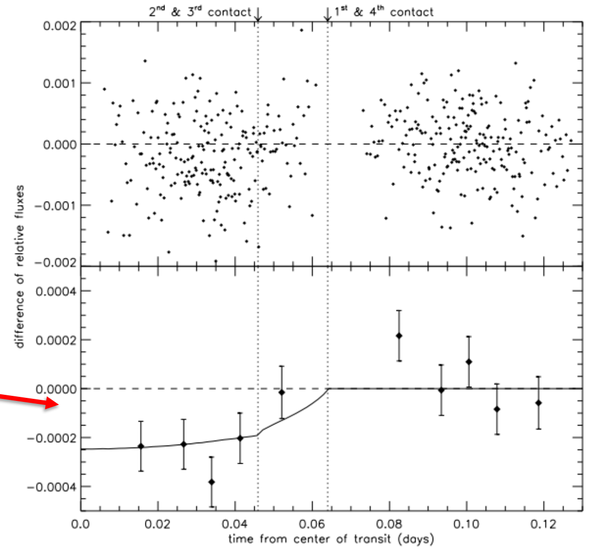
1st to transit 1st Atmospheric detection

Easiest targets for HRTS



Casasayas-Barris, Palle, et al (2020)

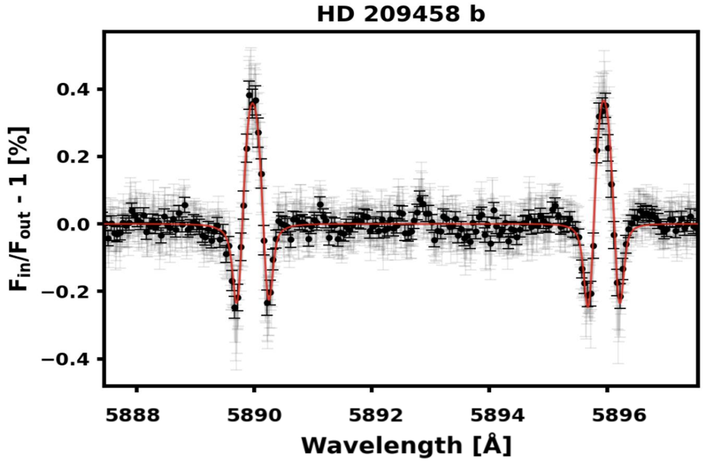
Na ¿?



Charbonneau et al (2002)

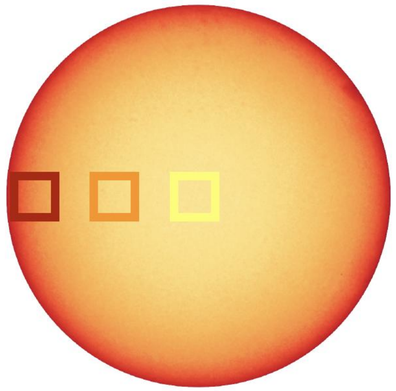
23 years after the first claim of an exoplanet atmosphere detection, we now demonstrated (thanks to better models) that that detection was *probably* spurious

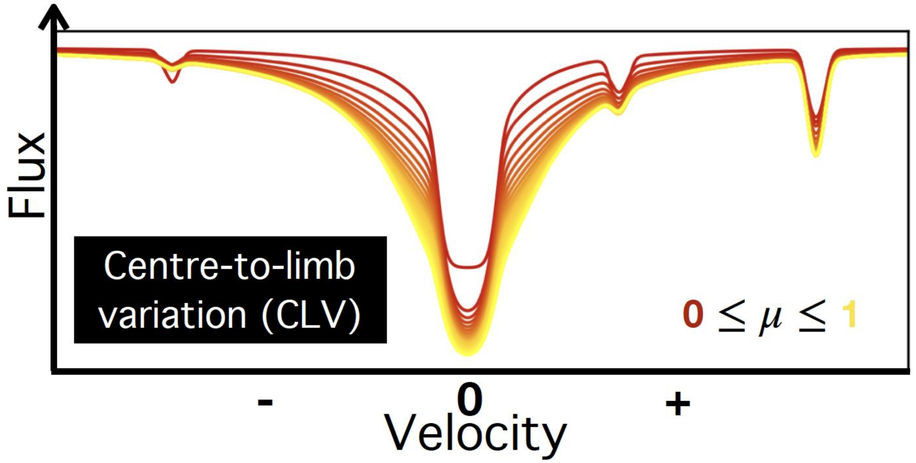
Canocchi, et al (2024) 3D, non-LTE stellar models

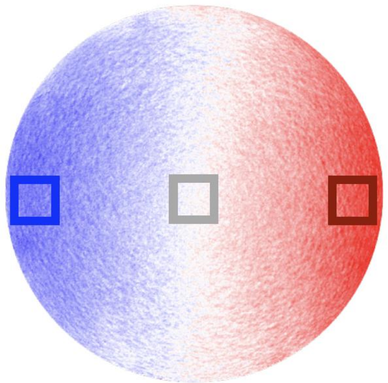


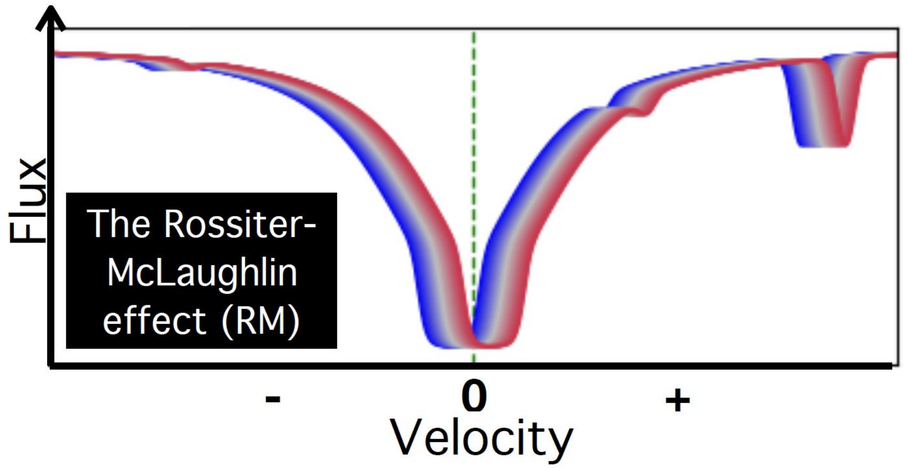
RME and CLV Effects

The Rossiter-McLaughlin effect and the centre-to-limb variation

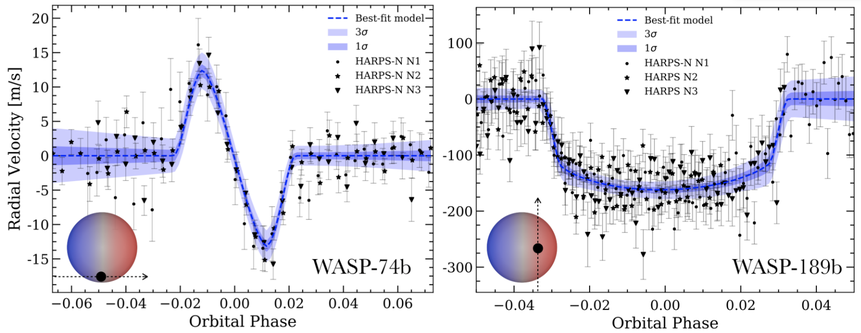


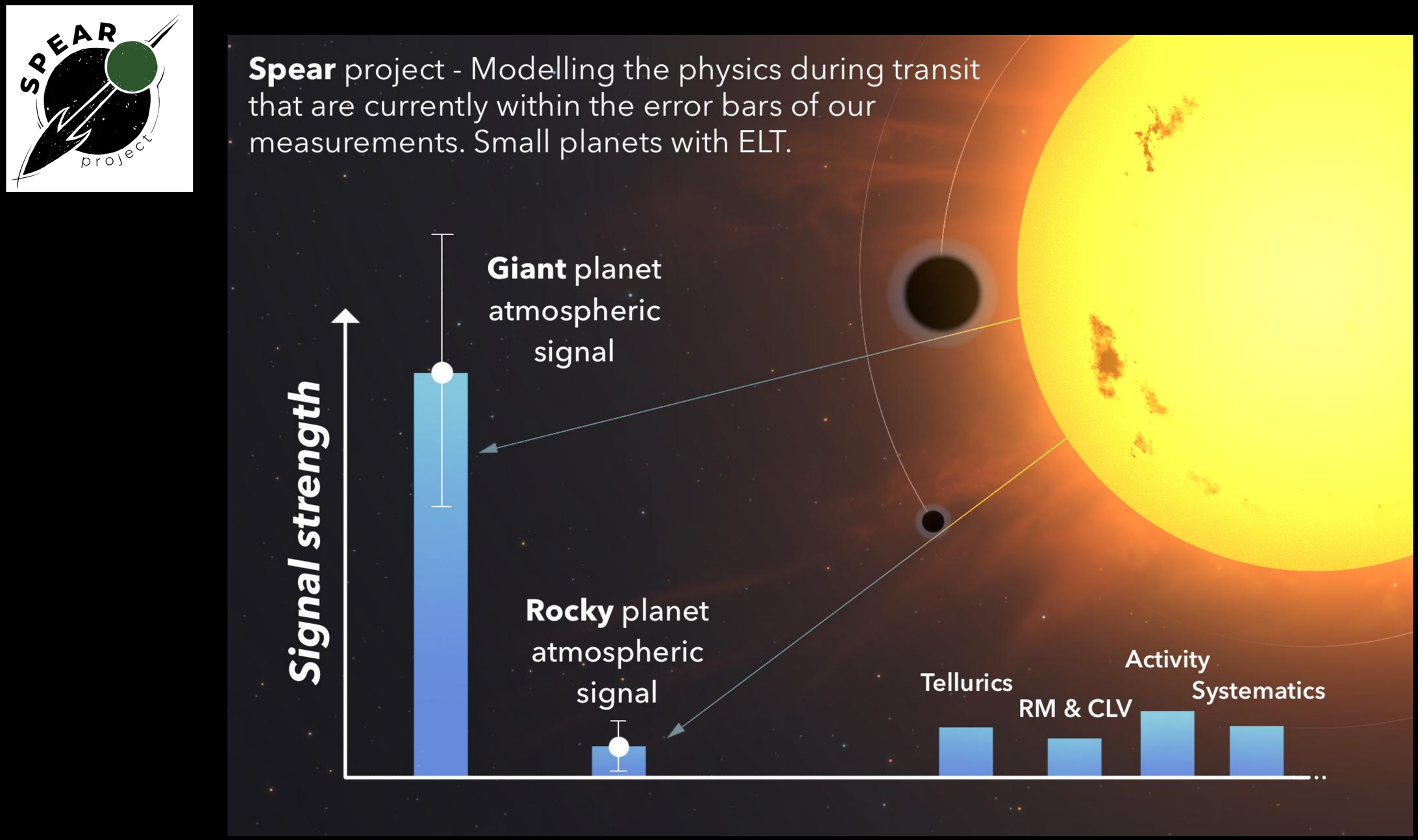


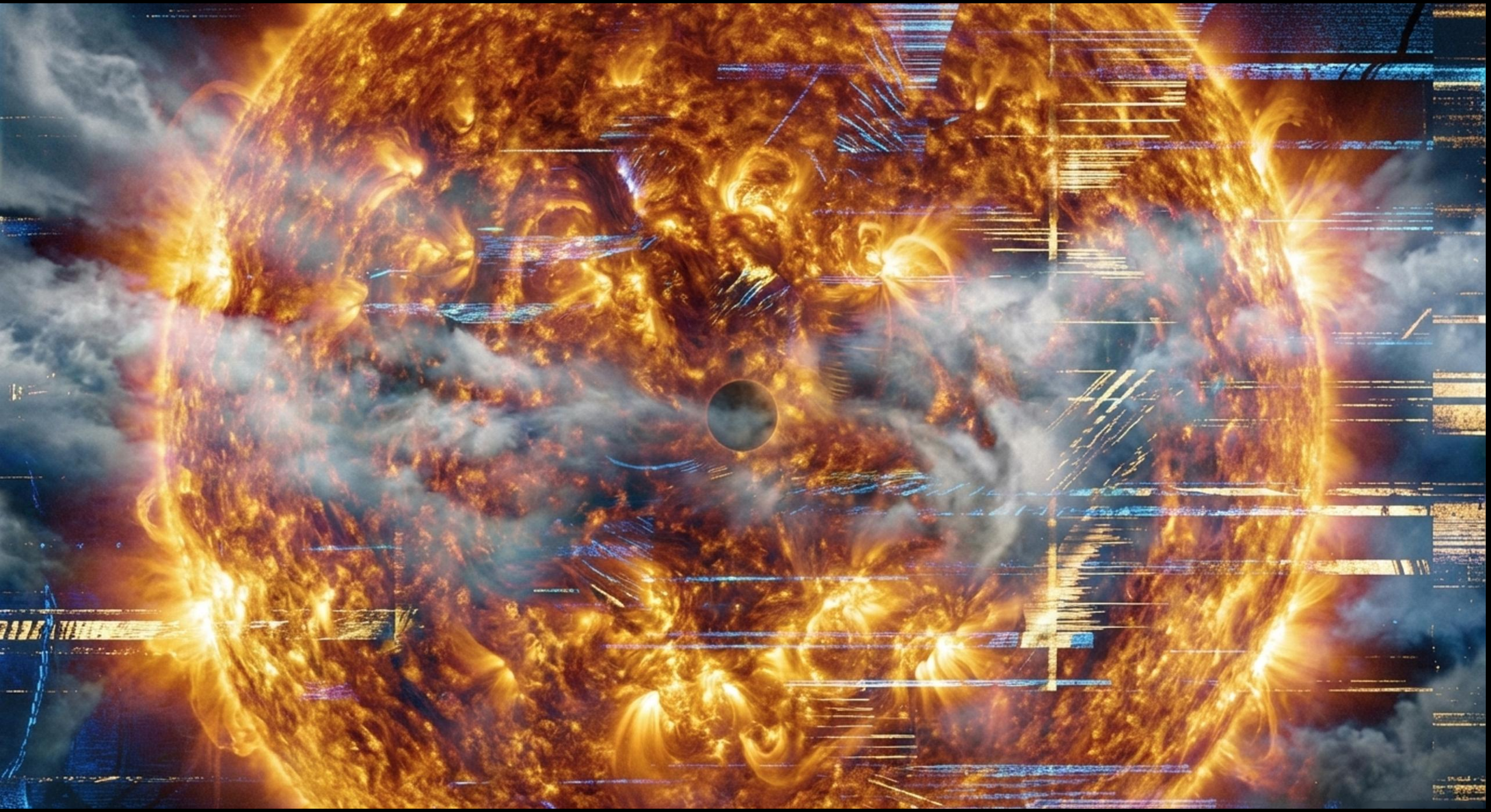




Credit: Solar Orbiter/PHI Team/ESA & NASA



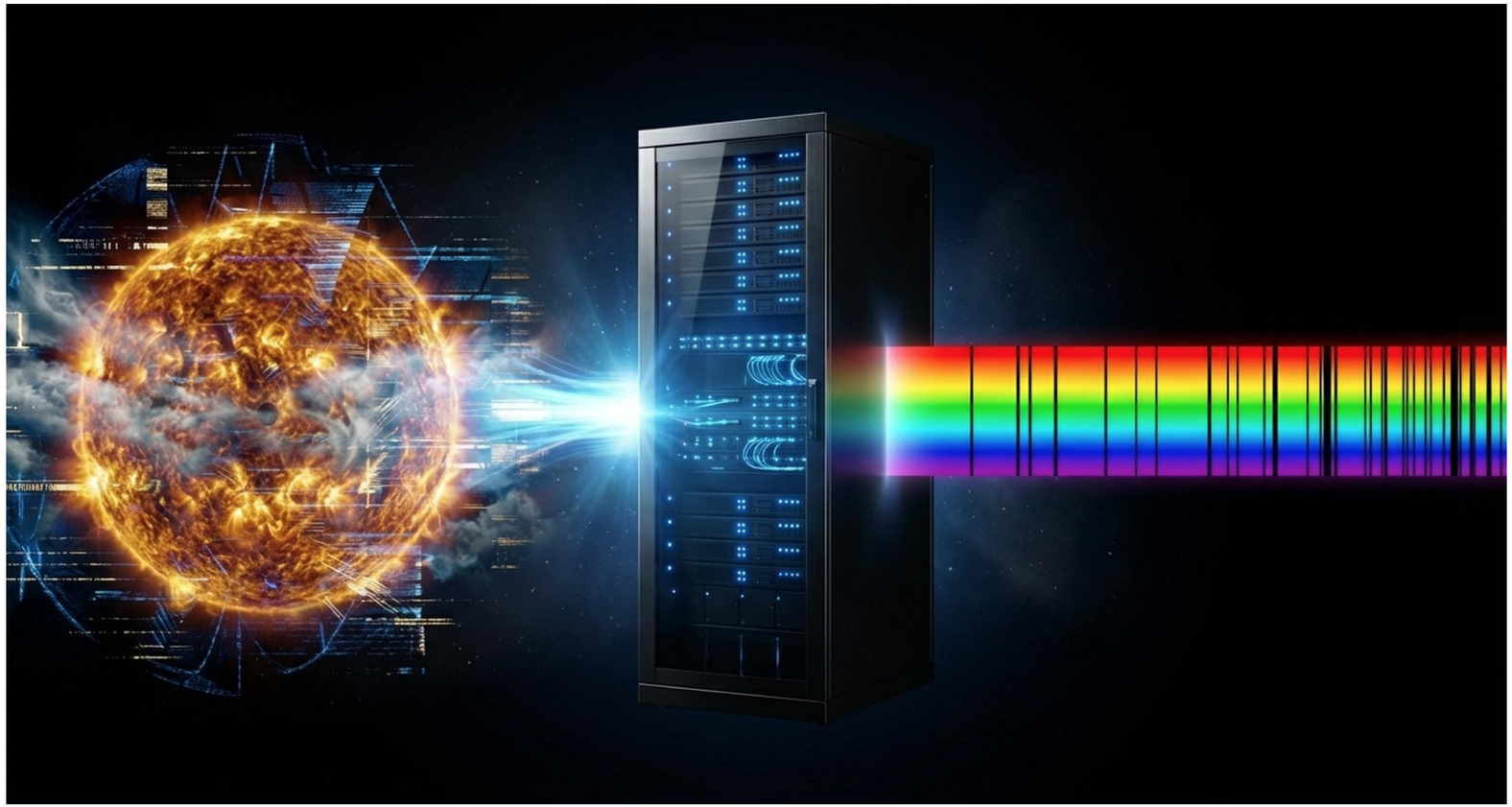

Spear project - Modelling the physics during transit that are currently within the error bars of our measurements. Small planets with ELT.
Giant planet atmospheric signal
Signal strength
Rocky planet atmospheric signal
Tellurics
RM & CLV
Activity
Systematics



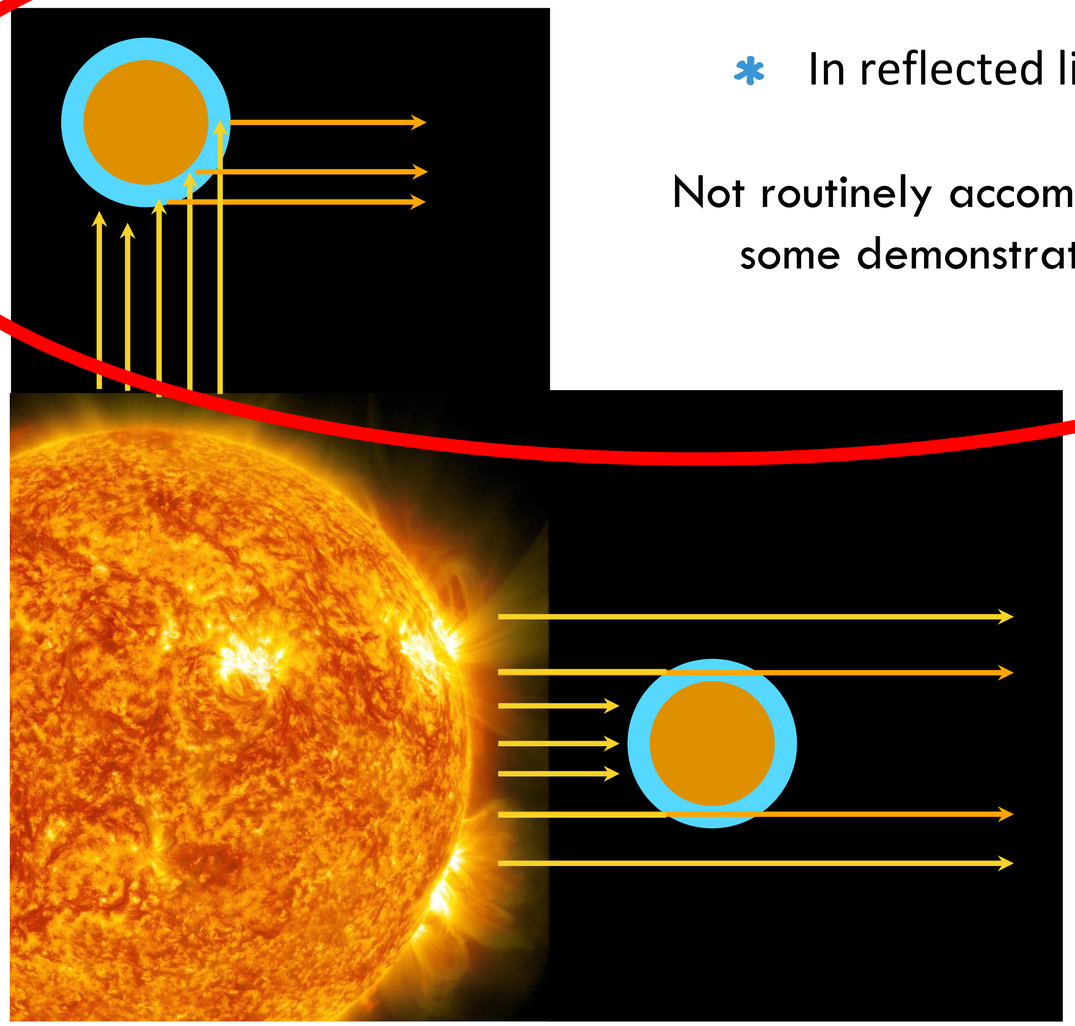
SPEAR: Accounting for the physics during transits

Make ***realistic simulations*** of the ANDES capabilities for exoplanet sciences and astrobiology

Provide a ***state-of-the-art data analysis framework*** capable of extracting the weak planetary signals of small HZ planets



EXOPLANET ATMOSPHERES



* In reflected light

Not routinely accomplished yet
some demonstrations

* In transmitted light

Technologically not challenging

EARTH-LIKE EXOPLANET ATMOSPHERES

Exoplanet Atmospheres : transmission vs direct light

Probability of transits of Earth - Sun 0.5%
Probability of transit of Earth – M star 1-2%

- We will only be able to explore in transmission 1/200 of the closest Sun-Earth twins
- We will only be able to explore in transmission 1/50 of the closest Earth-like planets around M stars
- Probabilities and distances= photons

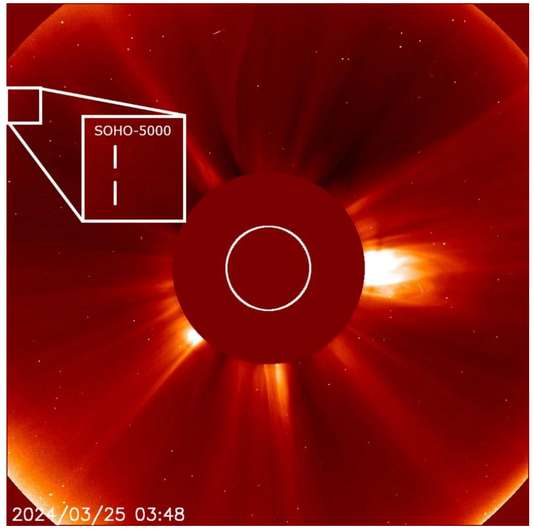
Transmission spectroscopy probes the (upper) atmosphere of the planet

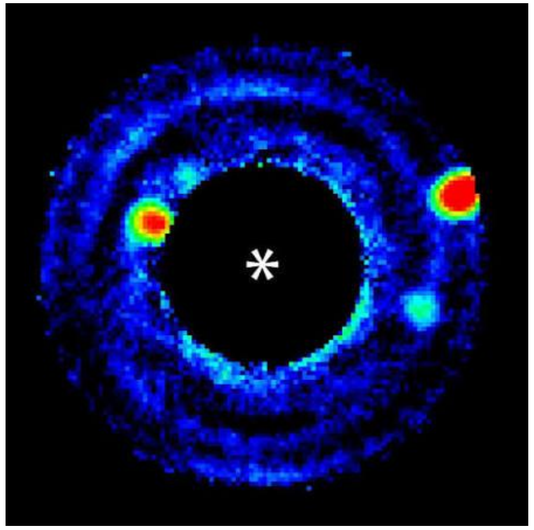
Reflected light from telluric planets probes down to the surface, including surface features (biomarkers)

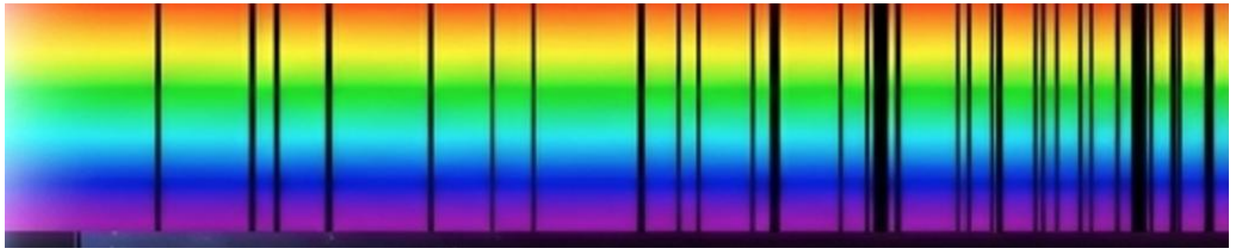


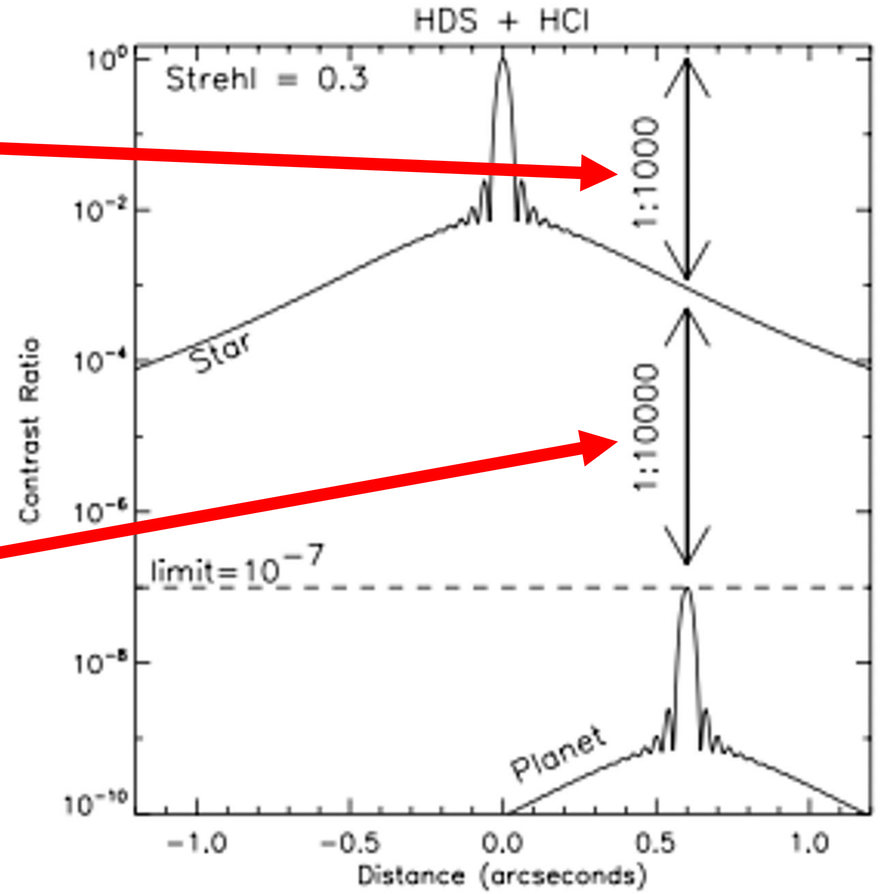
EARTH-LIKE EXOPLANET ATMOSPHERES

High **spatial resolution** combined with high **spectral resolution**









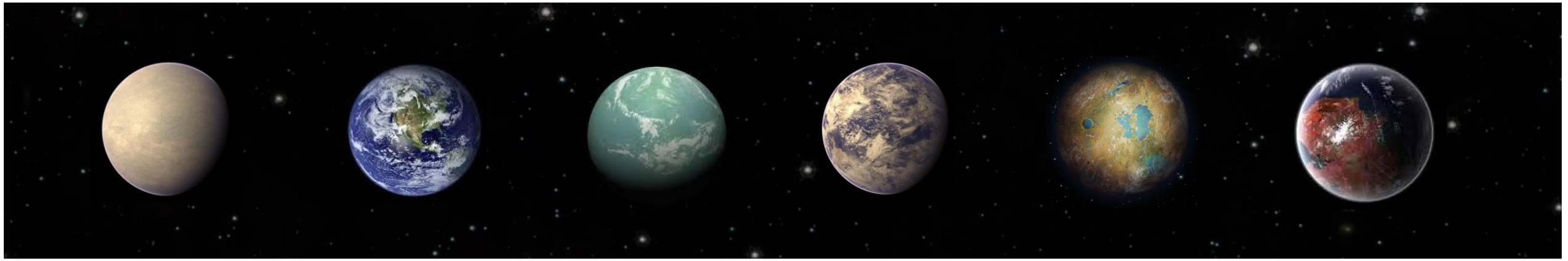
EARTH-LIKE EXOPLANET ATMOSPHERES

Direct detection of the planet's reflected light

ANDES Golden Sample:

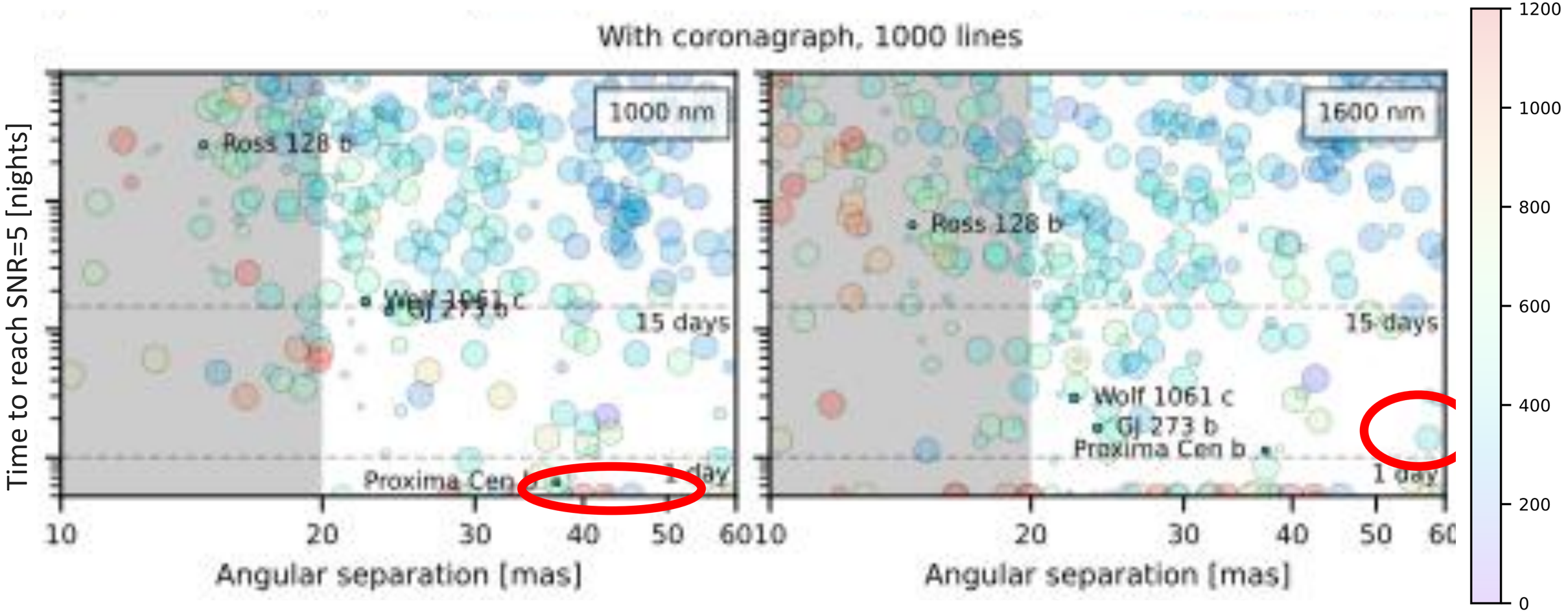
Name	SpecTyp ($T_{\rm eff}$) [K]	d [pc]	V [mag]	P [d]	$m \sin i$ [$m_\oplus$]	$R_{\rm p}$ [$R_\oplus$]	$T_{\rm eq}$ [K]	sep [mas]	contrast [10^{-8}]	nights
Proxima Cen b	M (2900 K)	1.30	11.01	11.19	1.1	1.07	217	37.3	11.2	0.67
~~Ross 128 b~~	~~M (3163 K)~~	~~3.37~~	~~11.12~~	~~9.87~~	~~1.4~~	~~1.15~~	~~283~~	~~14.7~~	~~12.5~~	~~13~~
GJ 273 b	M (3382 K)	3.80	9.84	18.65	2.9	1.64	266	24.0	7.52	6.5
Wolf 1061 c	M (3309 K)	4.31	10.10	17.87	3.4	1.81	275	20.7	9.57	5.8
~~GJ 682 b~~	~~M (3257 K)~~	~~5.01~~	~~10.94~~	~~17.48~~	~~4.4~~	~~2.11~~	~~259~~	~~16.6~~	~~16.6~~	~~7.2~~

Palle et al 2025



EARTH-LIKE EXOPLANET ATMOSPHERES

Direct detection of the planet's reflected light



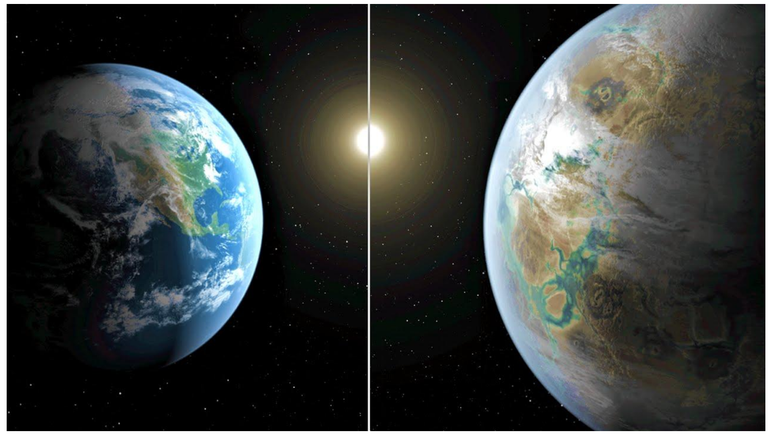
JWST can not access these targets

Palle et al 2025

The ELTS will offer both *Opportunity & Challenges*

- ✓ ANDES will provide **full atmospheric characterization** from giant gas planets to sub-Neptunes
- ✓ It will open the study of planets in reflected light at (visible?) near-IR wavelengths
- ✓ ANDES is the only instrument in design phase that is able to measure the chemical compositions of **HZ earth-like planet atmosphere**s and search for **biomarkers**
- ✓ ANDES capabilities and discovery space when combined with a occulter in space are mind-blowing.

SPEAR will build on our experience, and provide a quality jump in our star/planet modelling and data analysis methodologies, enabling us to reach rocky planet atmospheres.




Thank you
!!

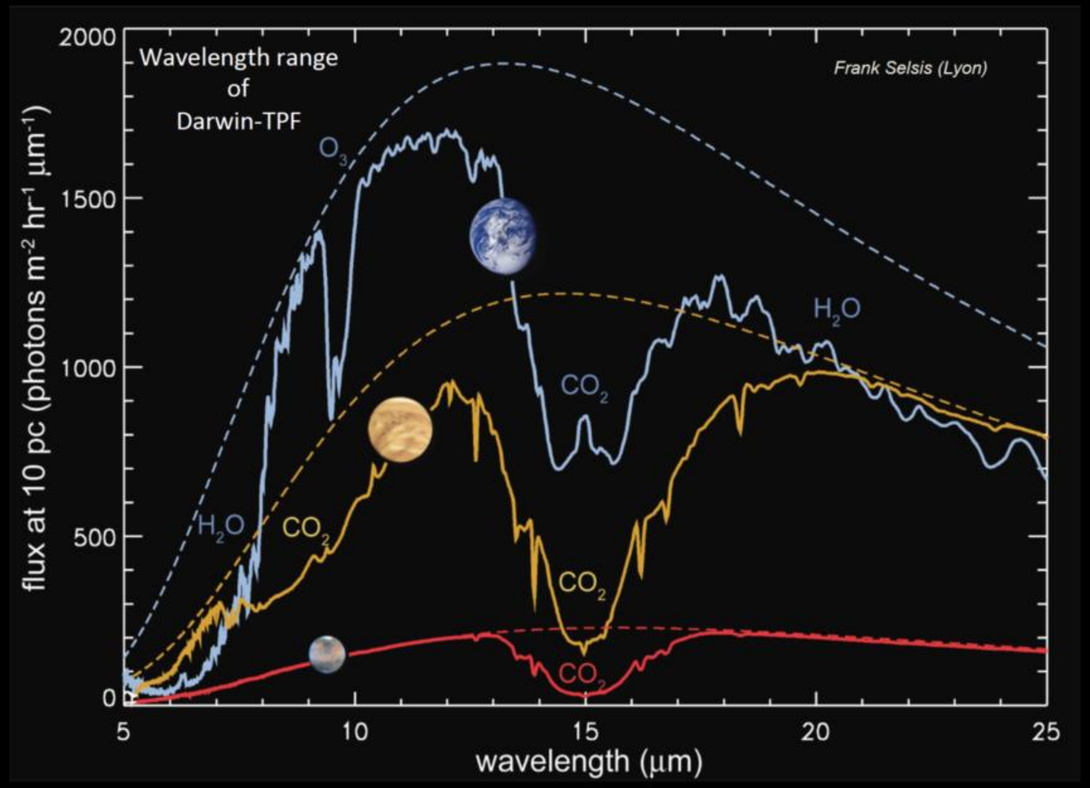
The Future

LIFE
LARGE INTERFEROMETER FOR EXOPLANETS

esa

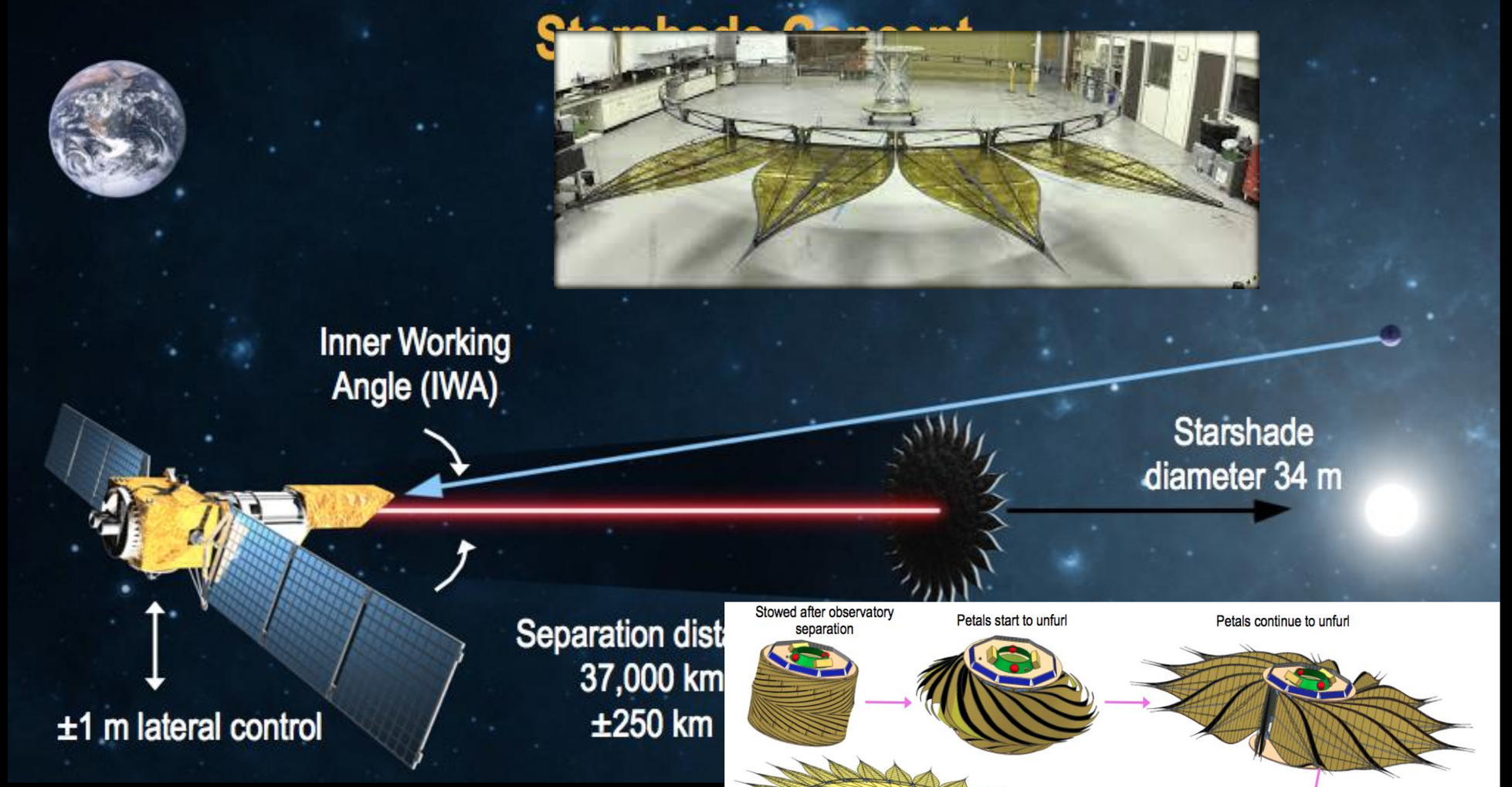
Infrared interferometry from space

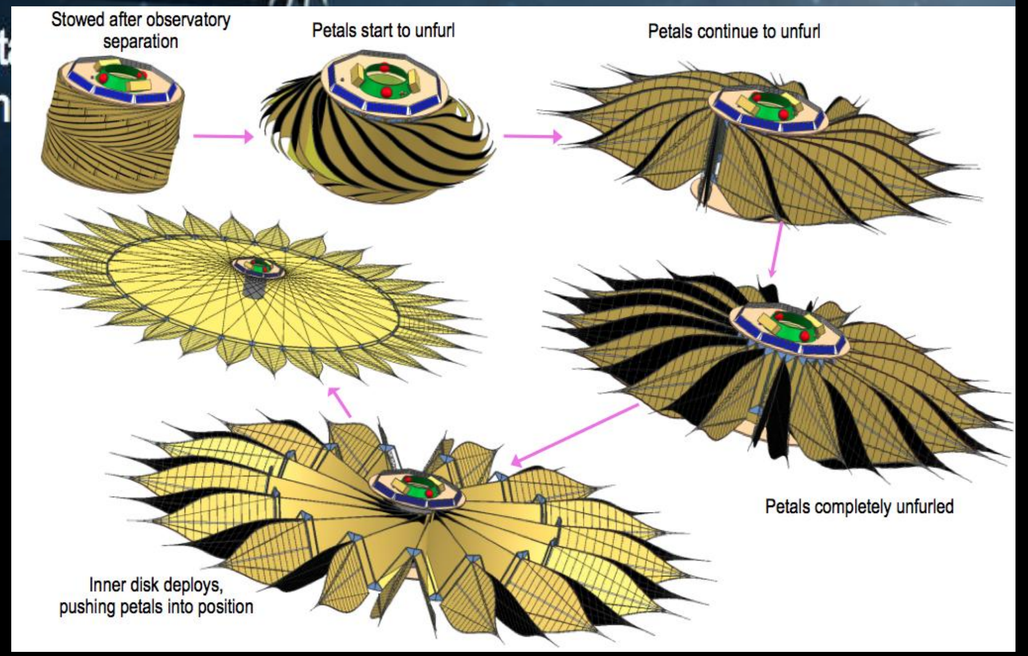




2040-2050

Habitable Worlds Observatory

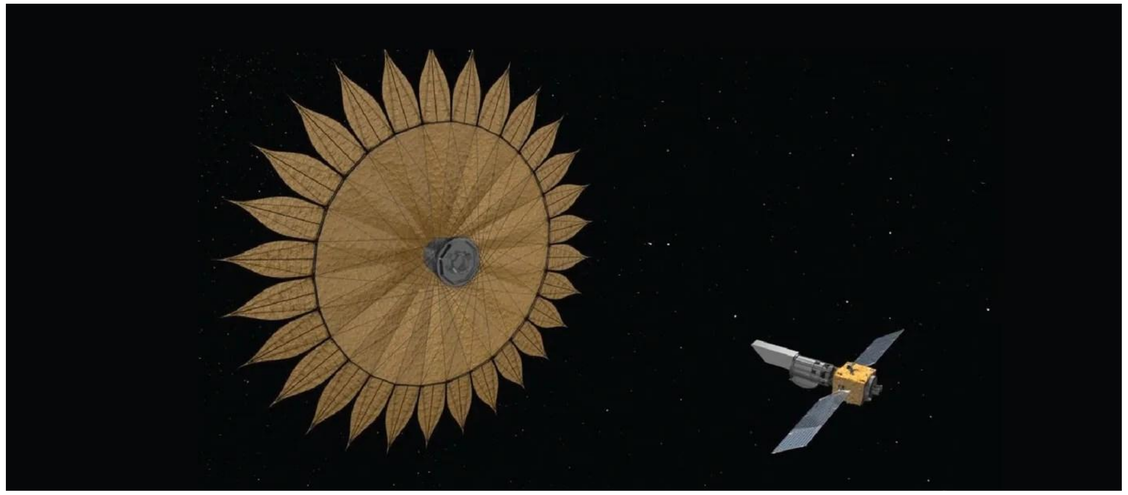




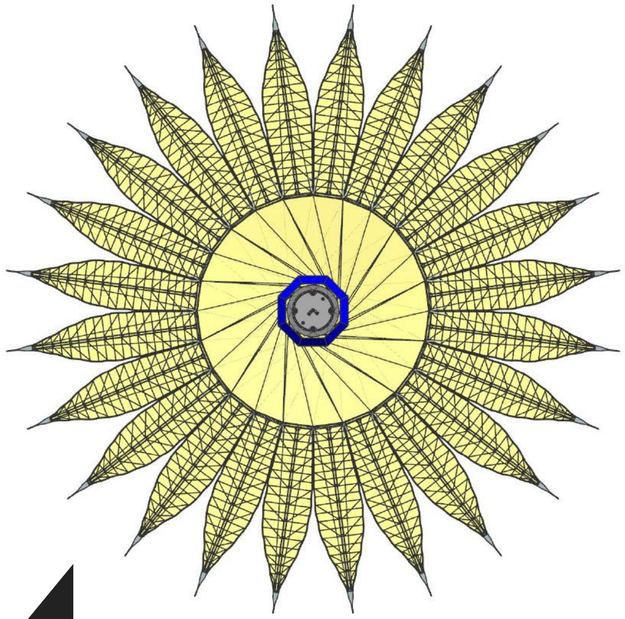
2040-2050


ALWAYS HOPE, THERE IS


THERE IS ANOTHER

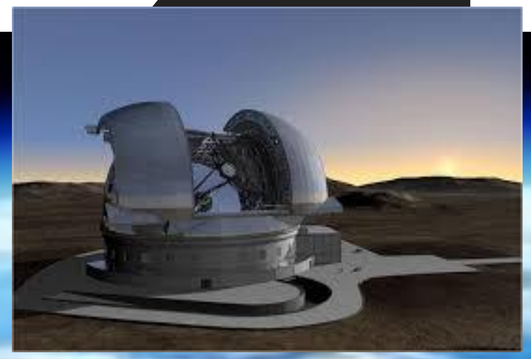


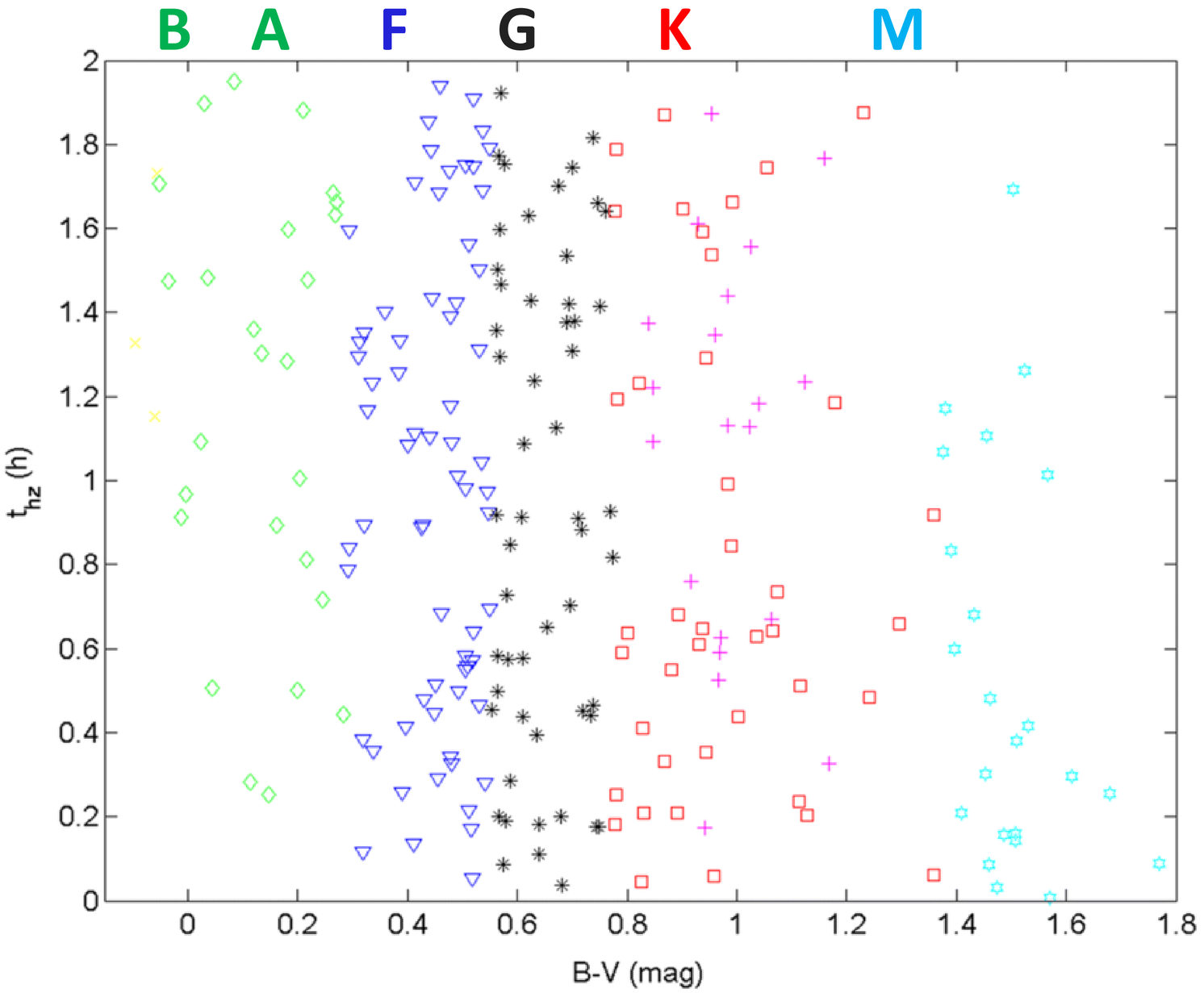
HabEx Occulter Concept

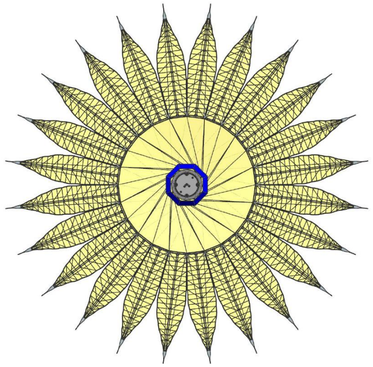


Janson (2007), Janson et al (2019)

Stockholm University



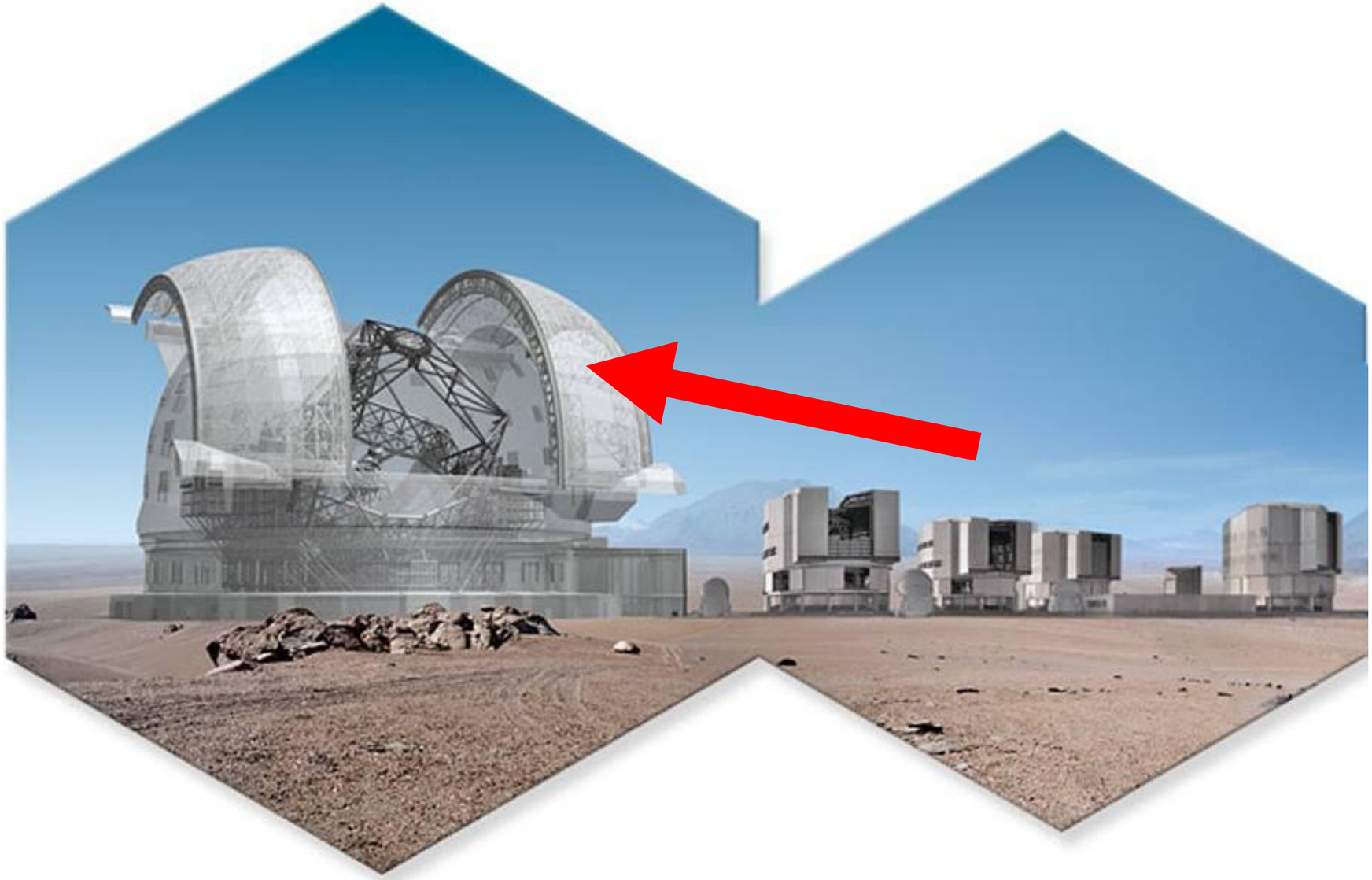




Stars for which **Earths in the HZ** *(if present)* would be detectable in less than 2 h with an **8 m-class** telescope

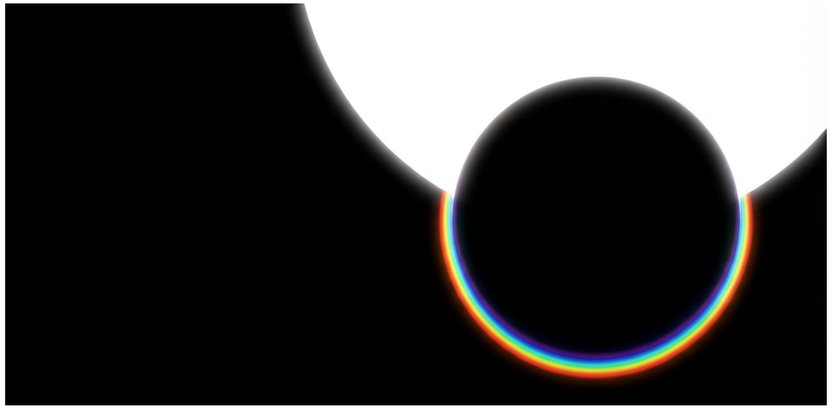
Janson et al (2019)

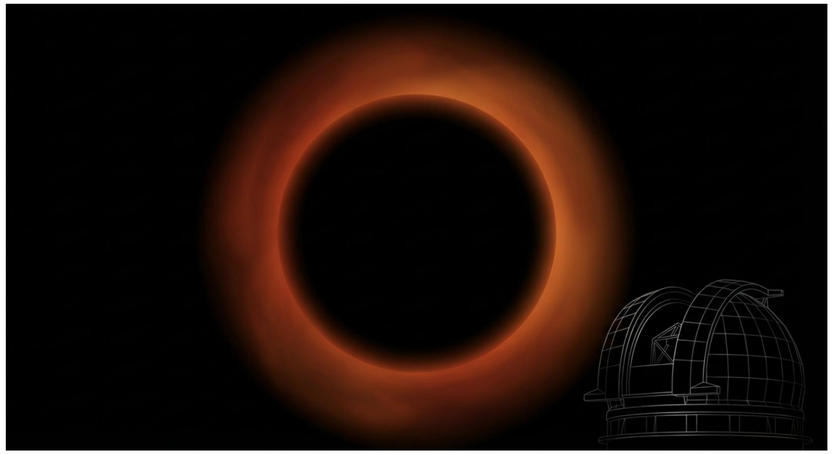
ESO expanding horizons, white papers (2025)

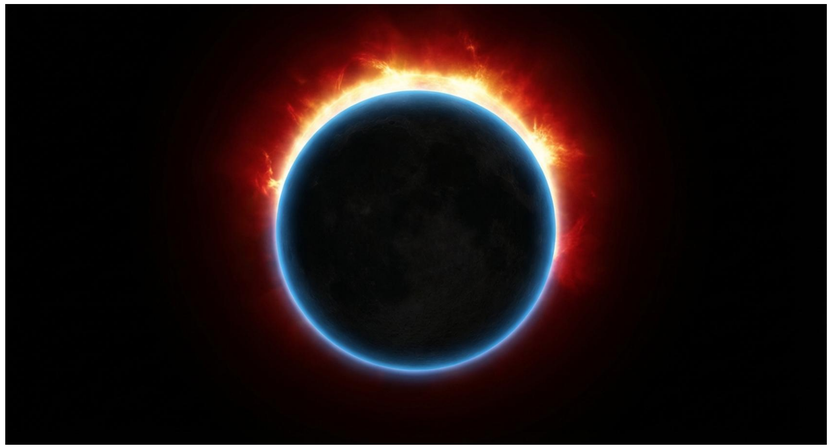


Goal: interest the community in preparing ELT instrumentation for an external occulter


Thank you
!!

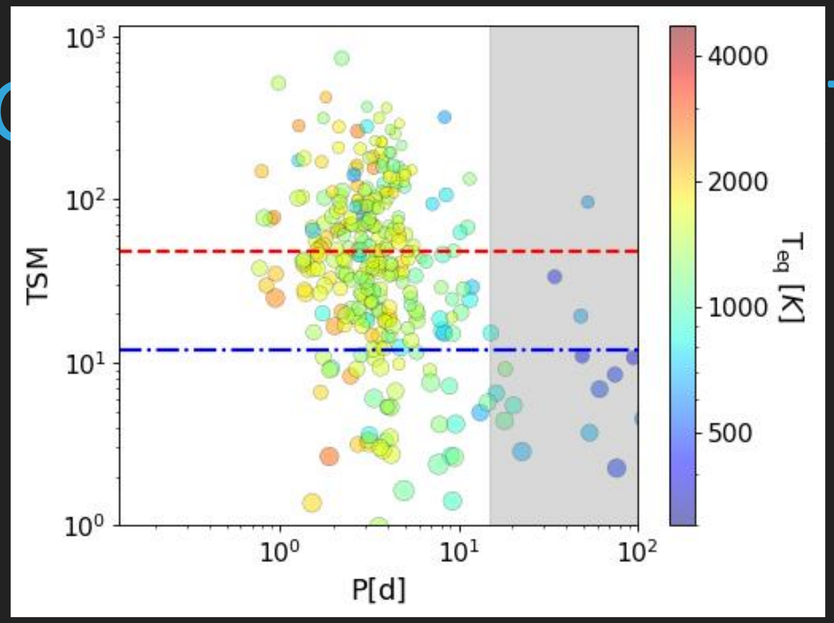






Giant exoplanet atmospheres: weather and dynamics in a single night

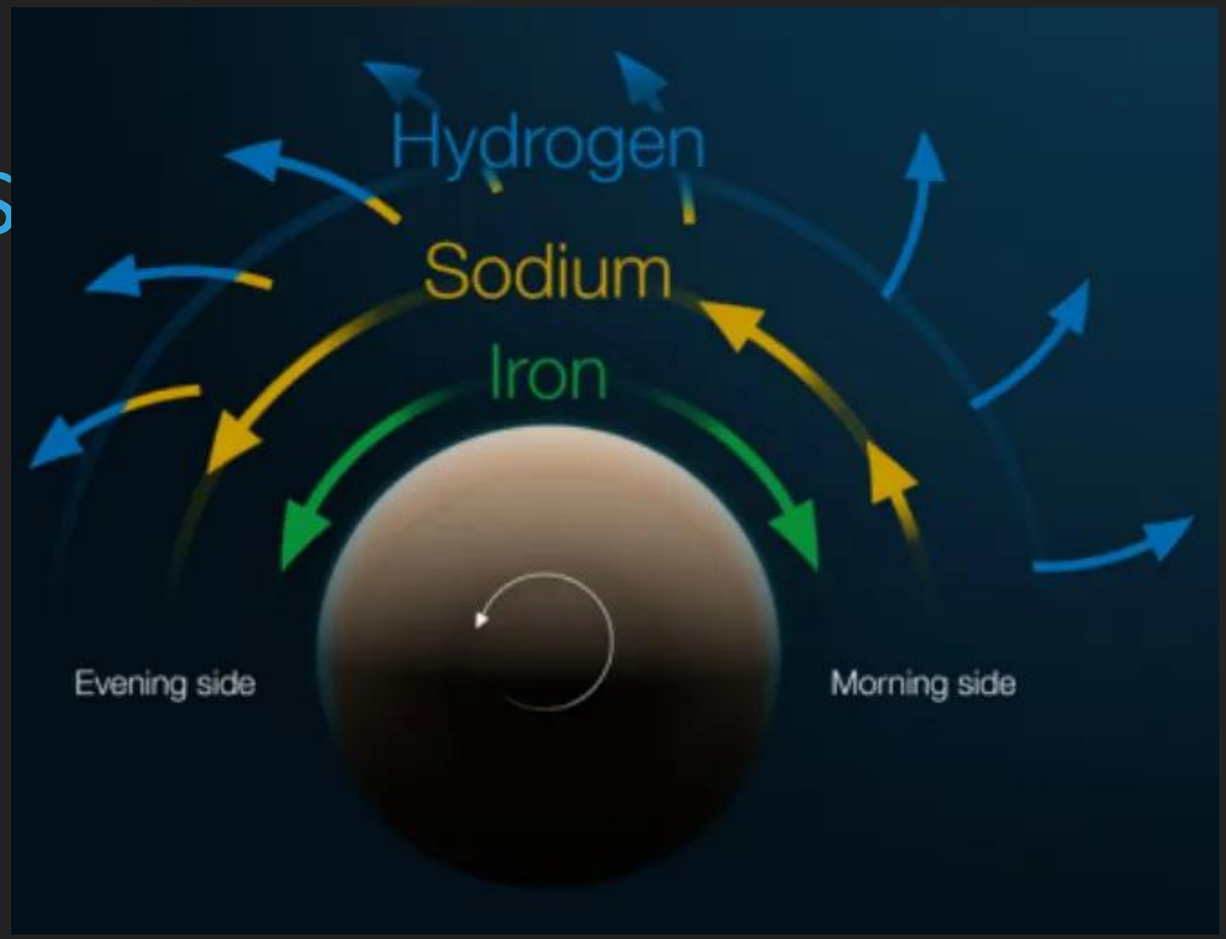
The known population of transiting gas giants



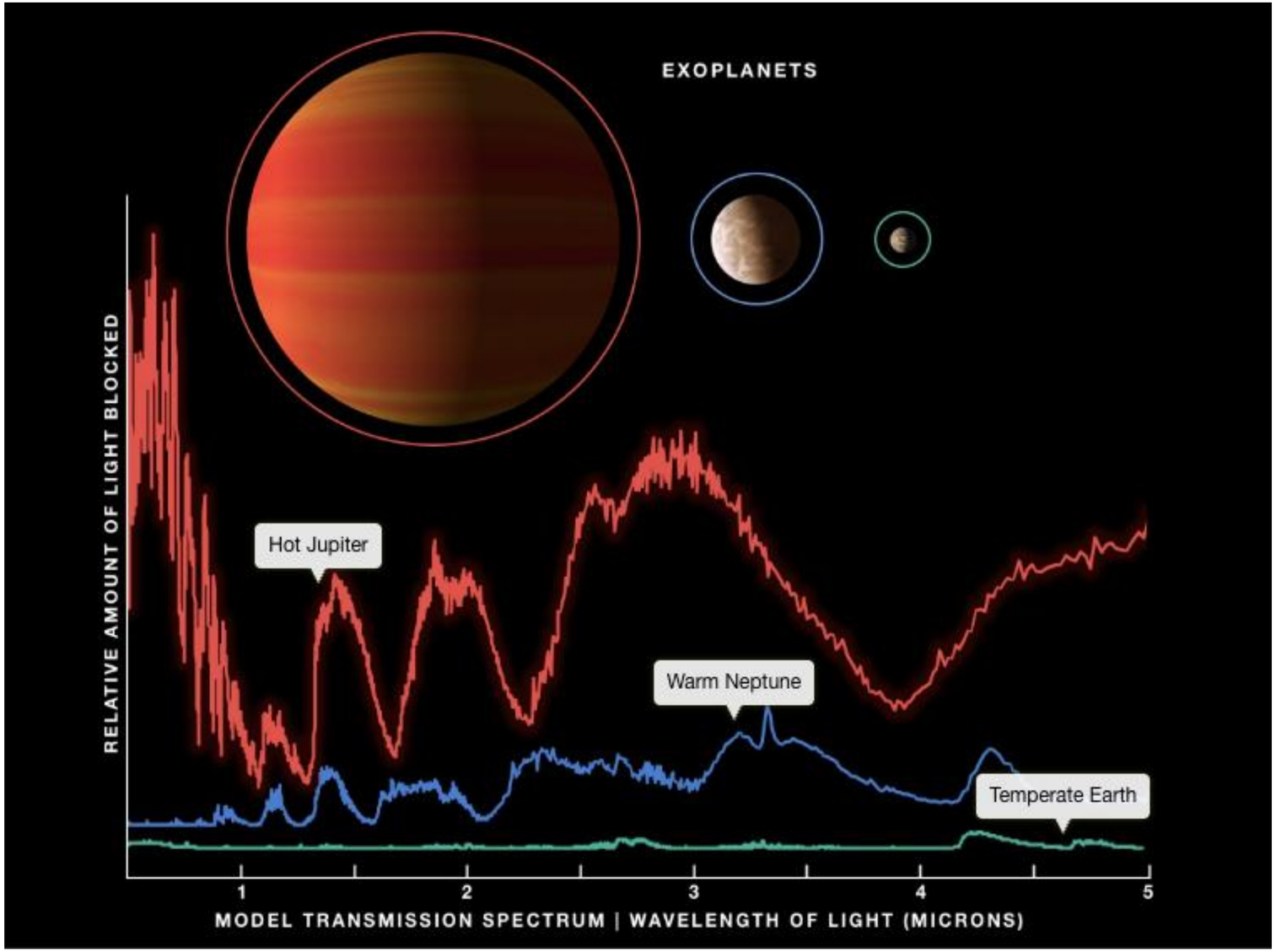
C TMOS

Above red line: One transit needed

Above blue line: Accessible to ANDES for time-resolved dynamical studies

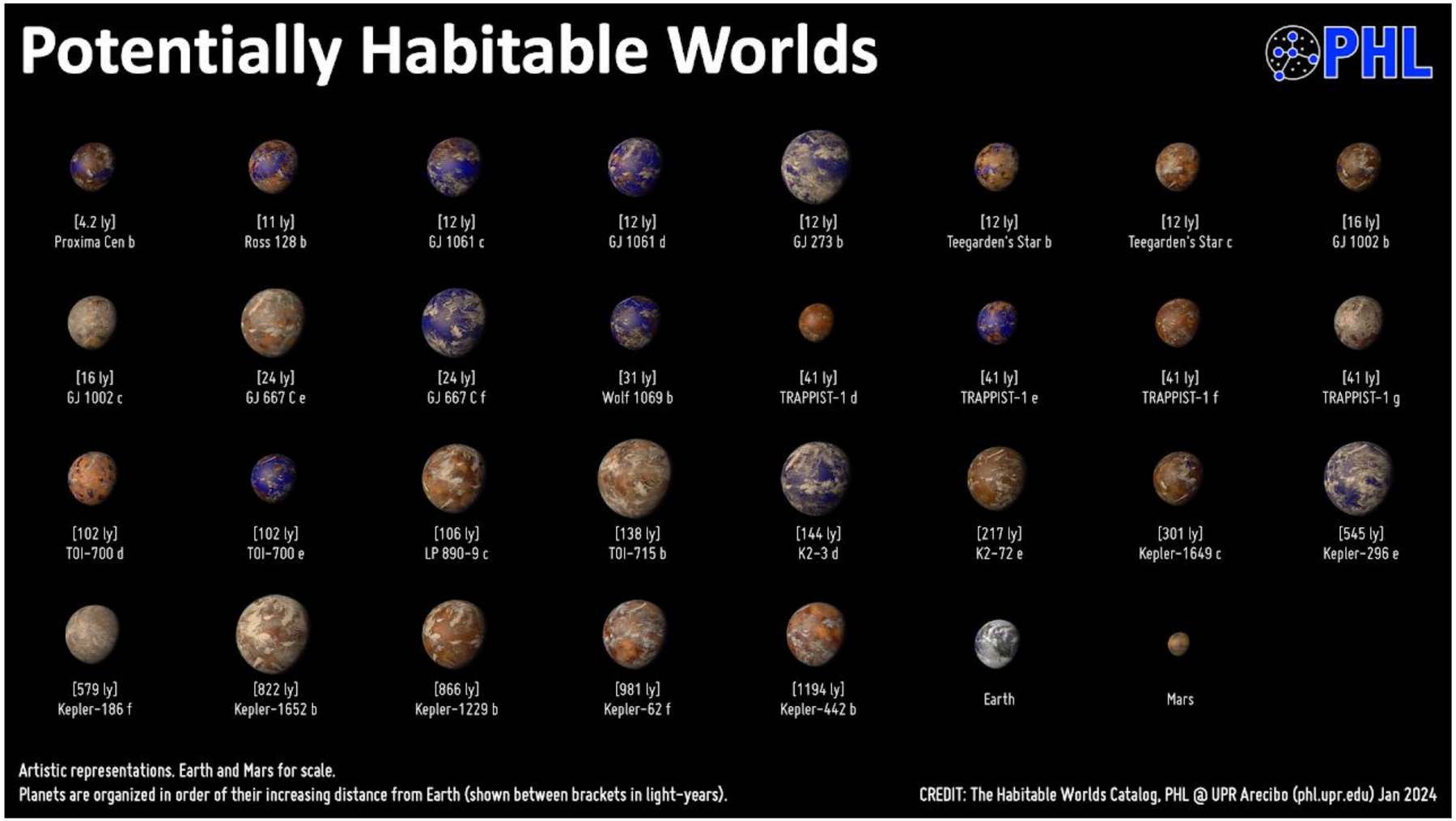


Exoplanet type transmission spectroscopy



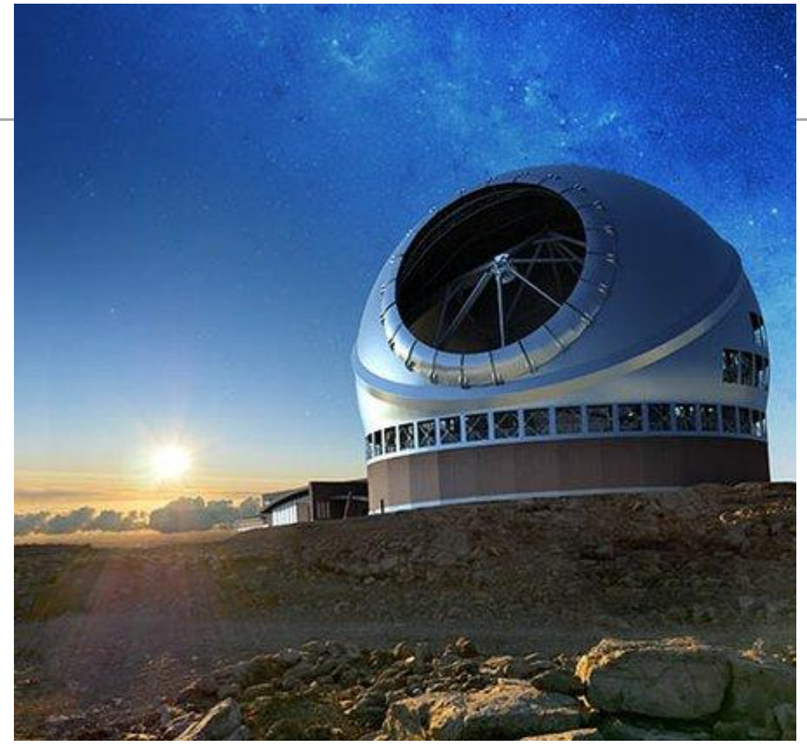
Exoplanets: Lo que mas mola

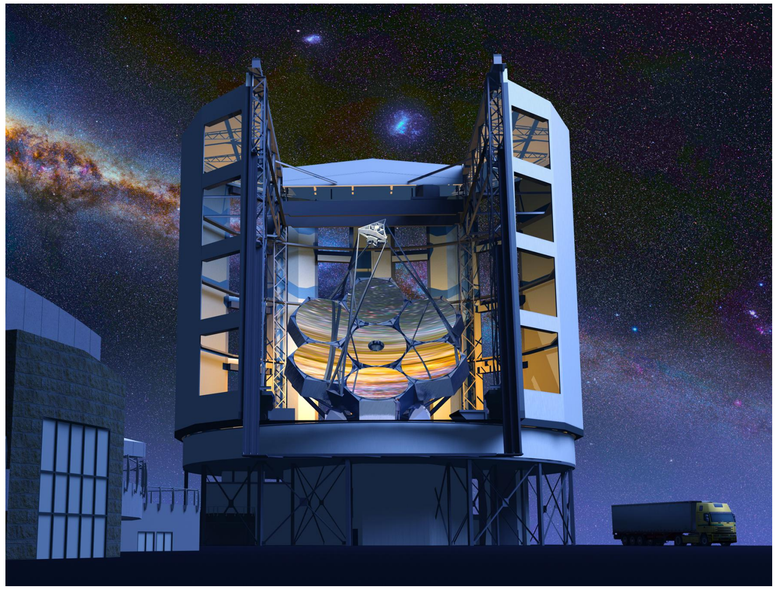
1995 – 1st planet 2025 - >7000



THE LARGE TELESCOPES FAMILY

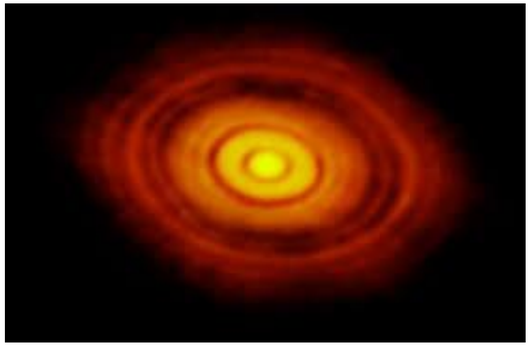
Type of Instrument	GMT	TMT	ELT
Near-IR, AO-assisted Imager + IFU	GMTIFS	IRIS	HARMONI
Wide-Field, Optical Multi-Object Spectrometer	GMACS	WFOS	MOSAIC-HMM
Near-IR Multislit Spectrometer	NIRMOS	IRMS	MOSAIC-HMM
Deployable, Multi-IFU Imaging Spectrometer		IRMOS	MOSAIC-HDM
Mid-IR, AO-assisted Echelle Spectrometer		MIRES	METIS
High-Contrast Exoplanet Imager	TIGER	PFI	ELT-PCS
Near-IR, AO-assisted Echelle Spectrometer	GMTNIRS	NIRES	ANDES
High-Resolution Optical Spectrometer	G-CLEF	HROS	ANDES
“Wide”-Field AO-assisted Imager		IRIS	MICADO

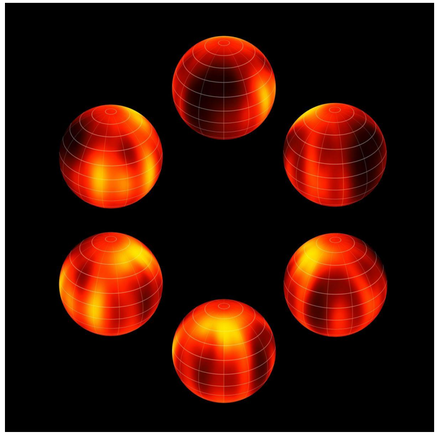




“ADDITIONAL” EXOPLANET SCIENCE

- Disk Science
  - Compositional and kinematical properties
  - The scenarios of planet formation (Gaps in disks, Planet impact formation)
- Earth-analogs Radial velocity mass measurements
  - Earth-like masses around solar analogs measured within 10%
- **Know thy star:**
  - Stellar spectra at unprecedented SNR
- Giant planets chemistry and dynamics at unprecedented detail
- Extension to K band
  - “CO machine” for gas giant planets: tracer of atmospheric dynamics.
  - Doppler tomography maps of directly-imaged exoplanets
- Extension to U band
  - Atmospheres of young habitable planets (Ozone absorption, Rayleigh slopes
  - Hot exoplanets: Calcium “atmospheres” (Mercury-like sputtering for hot rocky planets)





ExoAtmospheres

IAC community database for exoplanet atmospheric observations

So far **305** planets explored for detected atmospheres.
68 different species or properties

Submit your papers !!

ExoAtmospheres

IAC community database for exoplanet atmospheric observations

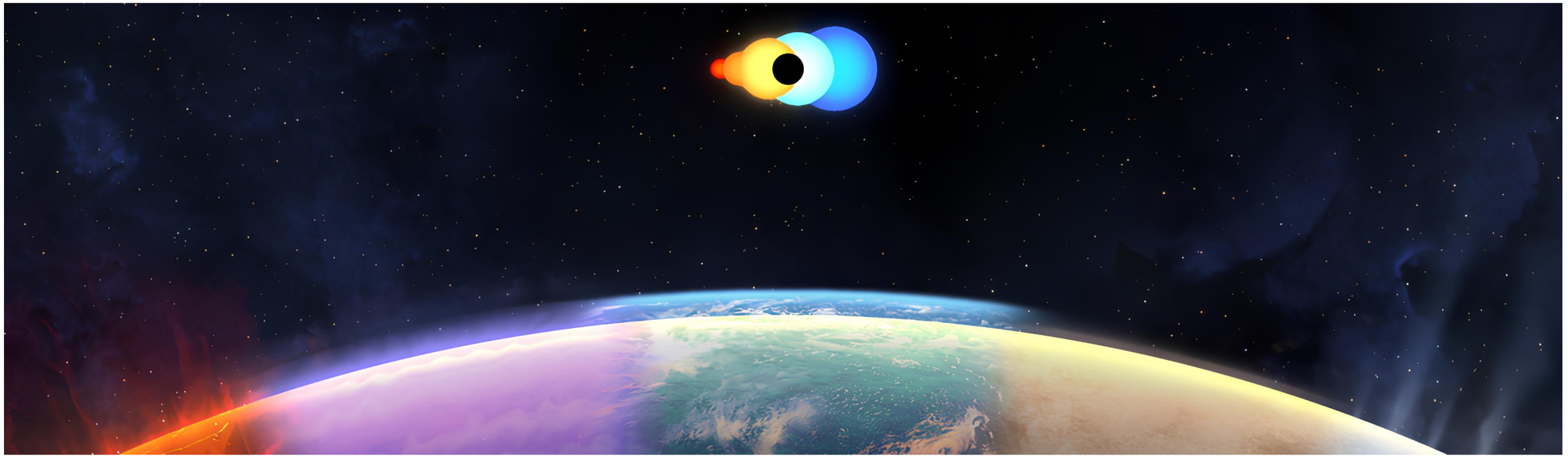
EXOPLANETS &ASTROBIOLOGY

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The **Exoplanet Atmospheres Database** is built for the community and maintained by the community. Exoplanet atmospheres is an exciting and vibrant field of research, where new discoveries and publications occur at a very fast pace, and it is easy to miss many interesting results. The main purpose of this database is to become a quick and useful repository of all available exoplanet atmospheres observations, and also to help in the gathering of useful references for a given planet or planet types.

Please help us maintain it as complete as possible by submitting your own (or anyone else's) results via the submission form above. We are a small team and we will maintain and improve this site on a best effort basis. We will be happy for any feedback you might have for us (Contact: exoatm@iac.es).



The SPEAR Project

Enric Palle

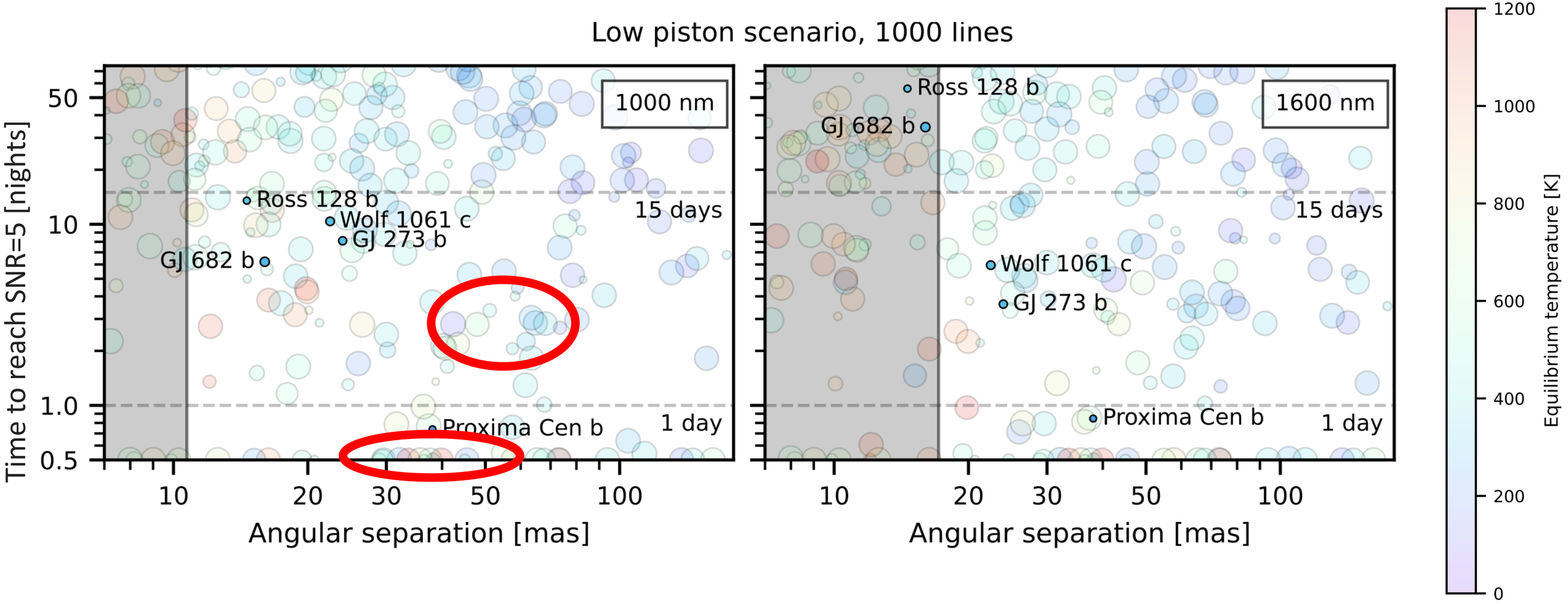
2.5 M€ 2026-2030

Funded by the European Union

European Research Council
Established by the European Commission

EARTH-LIKE EXOPLANET ATMOSPHERES

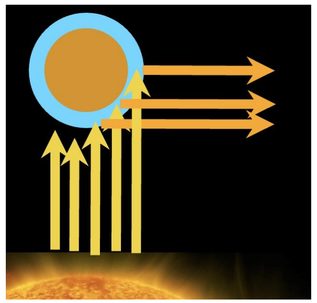
Direct detection of the planet's reflected light



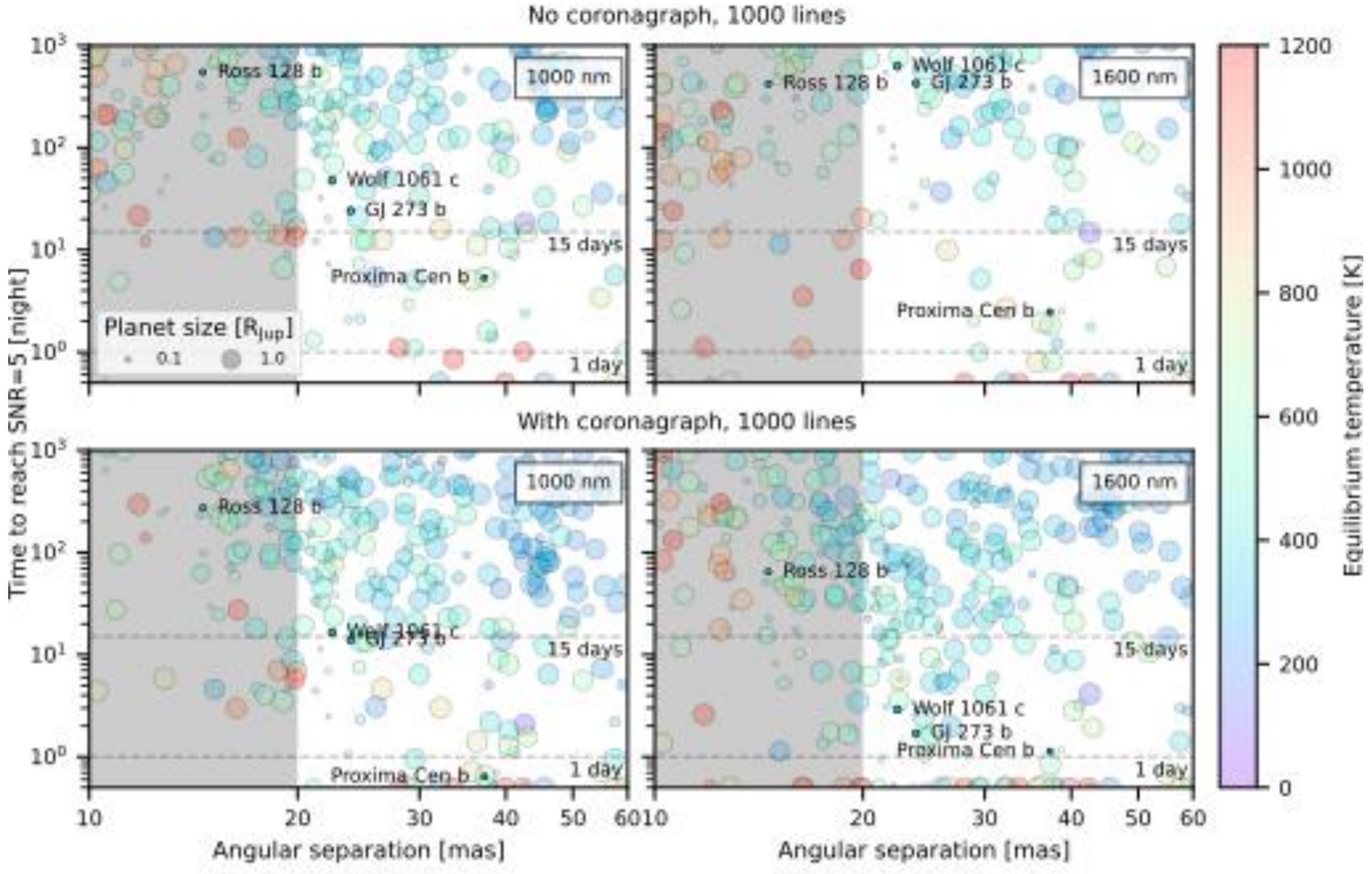
New: Coronograph inclusion to improve performance.

Palle et al 2025

Priority 1, Topic 1: Atmospheres on small rocky planets



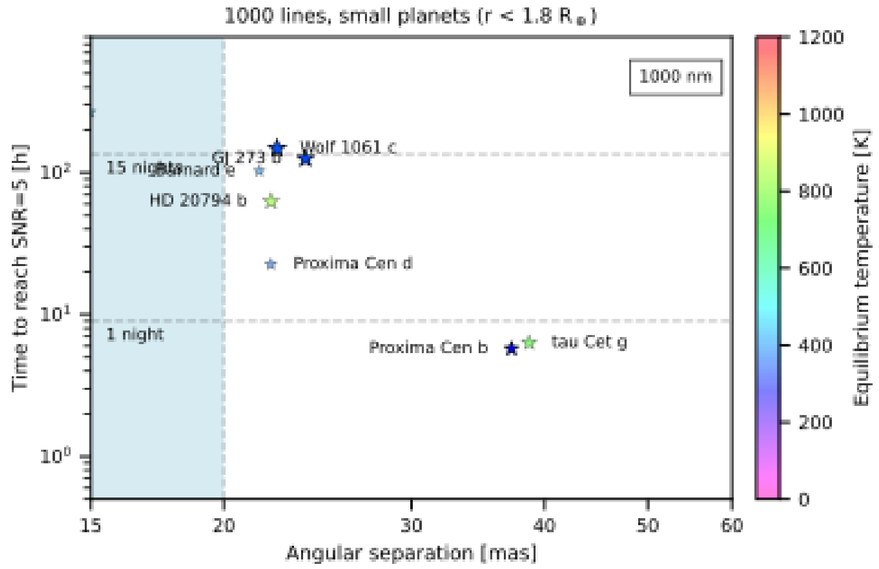
A new coronagraph is added to ANDES, to enable reaching small rocky planets in reflected light.

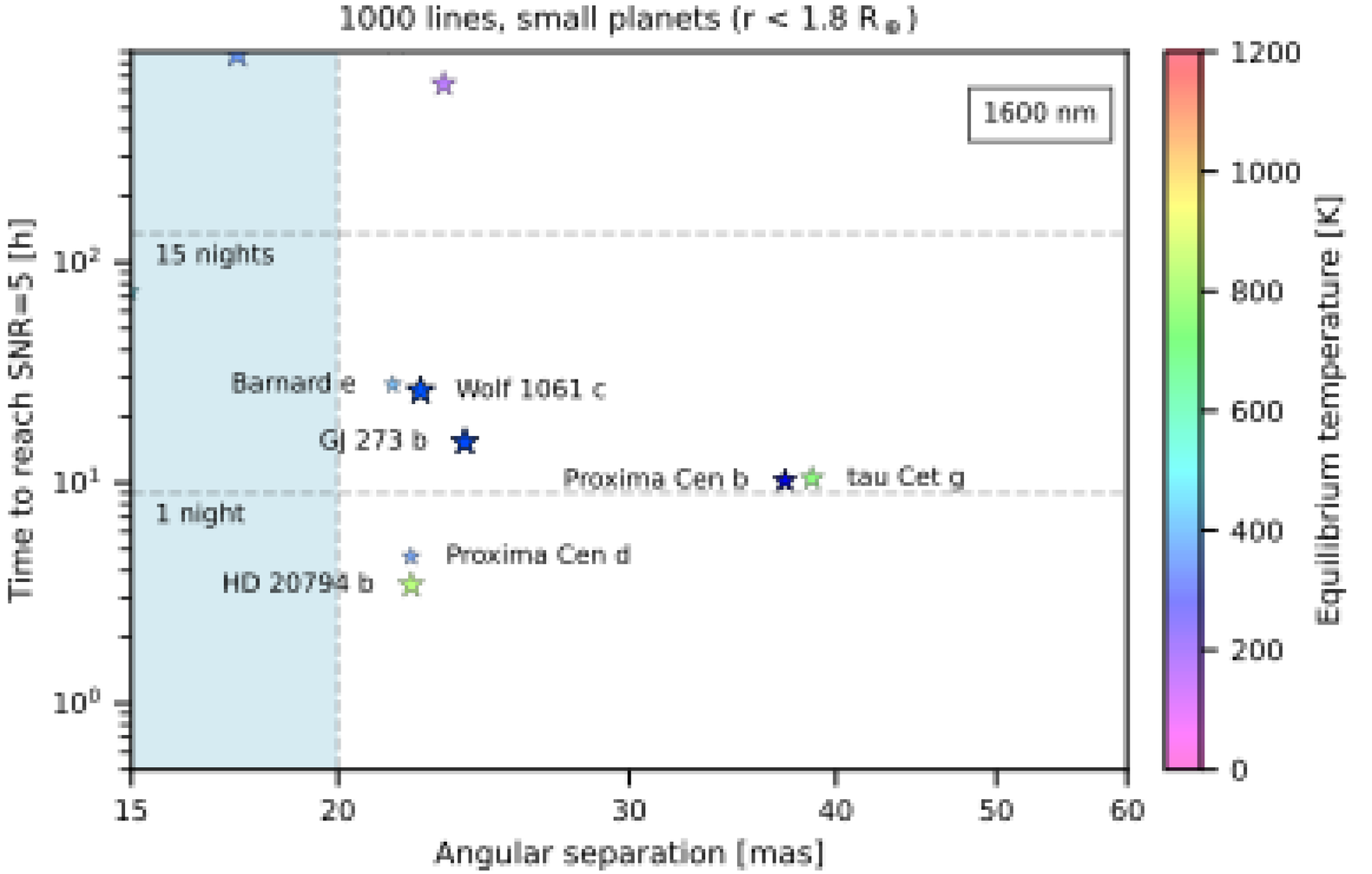


Priority 1, Topic 1: Atmospheres on small rocky planets

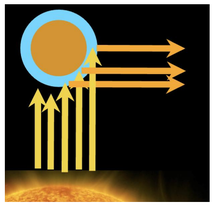
ANDES Golden Sample:

Name	SpecTyp ($T_{\rm eff}$) [K]	d [pc]	V [mag]	P [d]	$m \sin i$ [$m_\oplus$]	[
Proxima Cen b	M (2900 K)	1.30	11.01	11.19	1.1	1
~~Ross 128 b~~	~~M (3163 K)~~	~~3.37~~	~~11.12~~	~~9.87~~	~~1.4~~	~~1~~
GJ 273 b	M (3382 K)	3.80	9.84	18.65	2.9	1
Wolf 1061 c	M (3309 K)	4.31	10.10	17.87	3.4	1
~~GJ 682 b~~	~~M (3237 K)~~	~~5.01~~	~~10.94~~	~~17.48~~	~~4.4~~	~~1~~

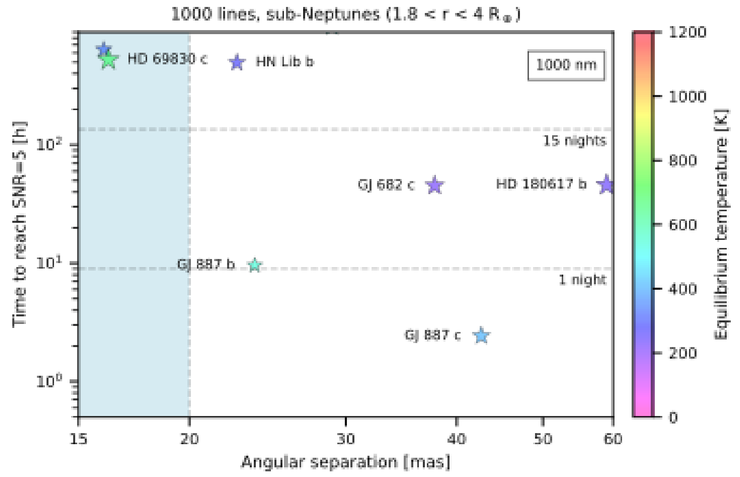




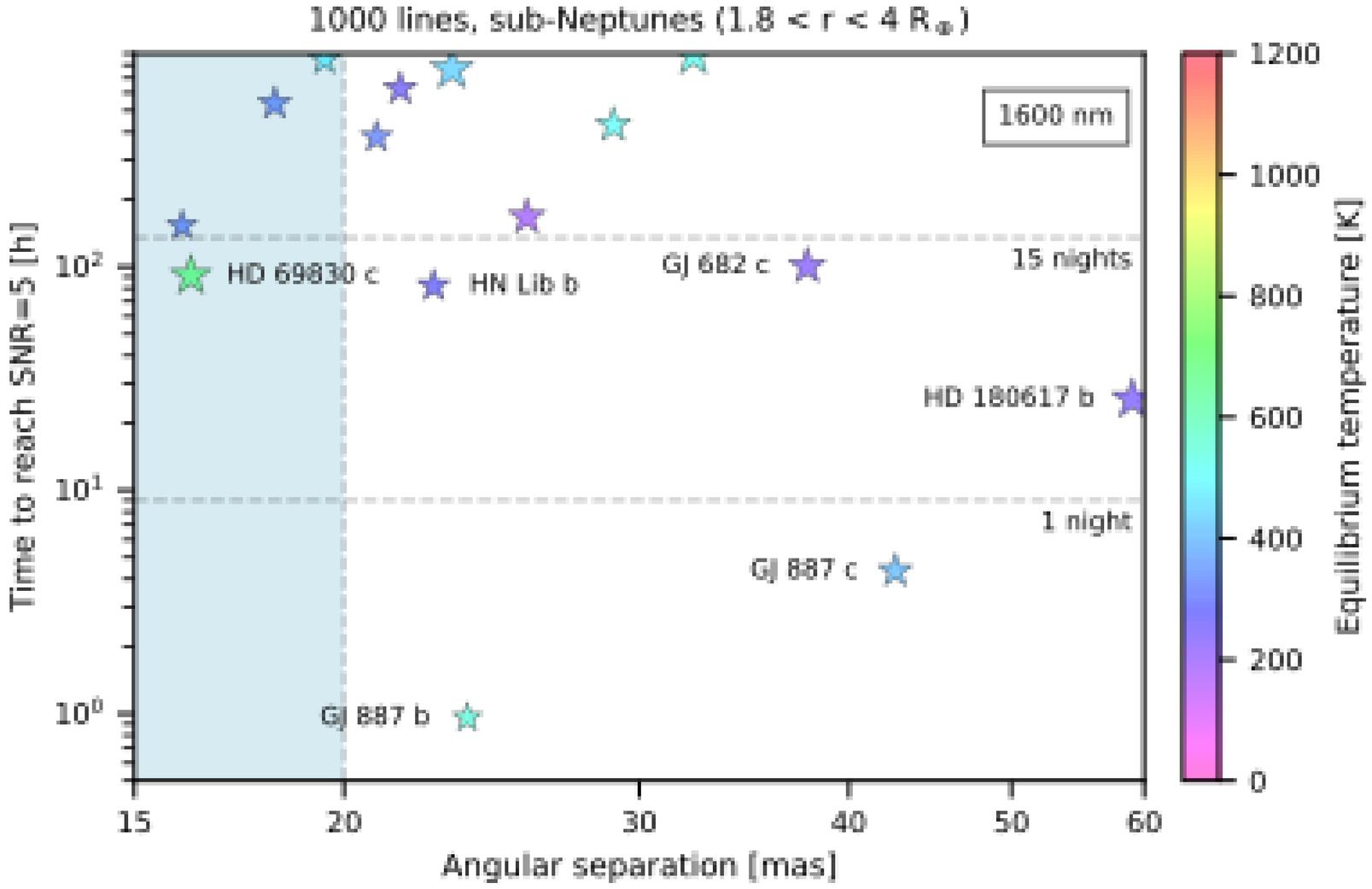
Priority 1, Topic 2: mini-Neptunes / super-Earth atmospheres



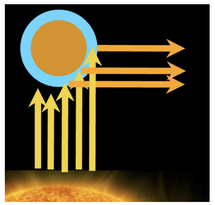
In reflected light: ***Where are our targets??***



JWST does not access these targets either

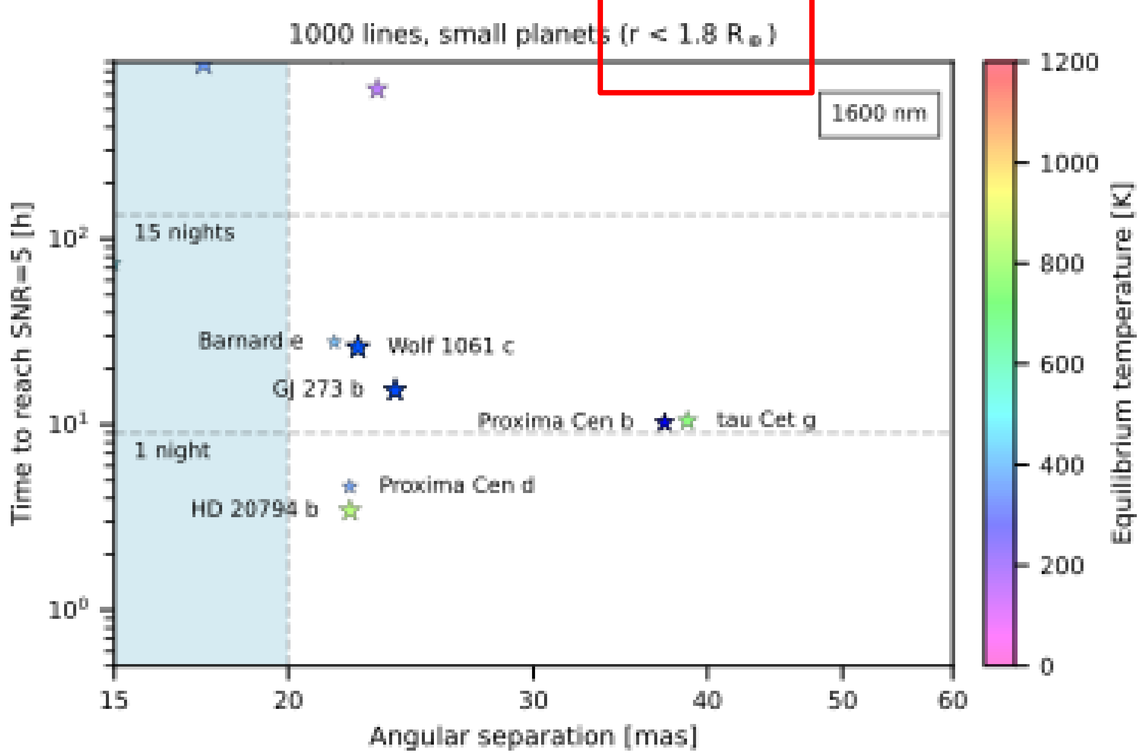


Priority 1, Topic 2: mini-Neptunes / super-Earth atmospheres



In reflected light: ***Where are our targets??***

Earths



Sub-Neptunes

