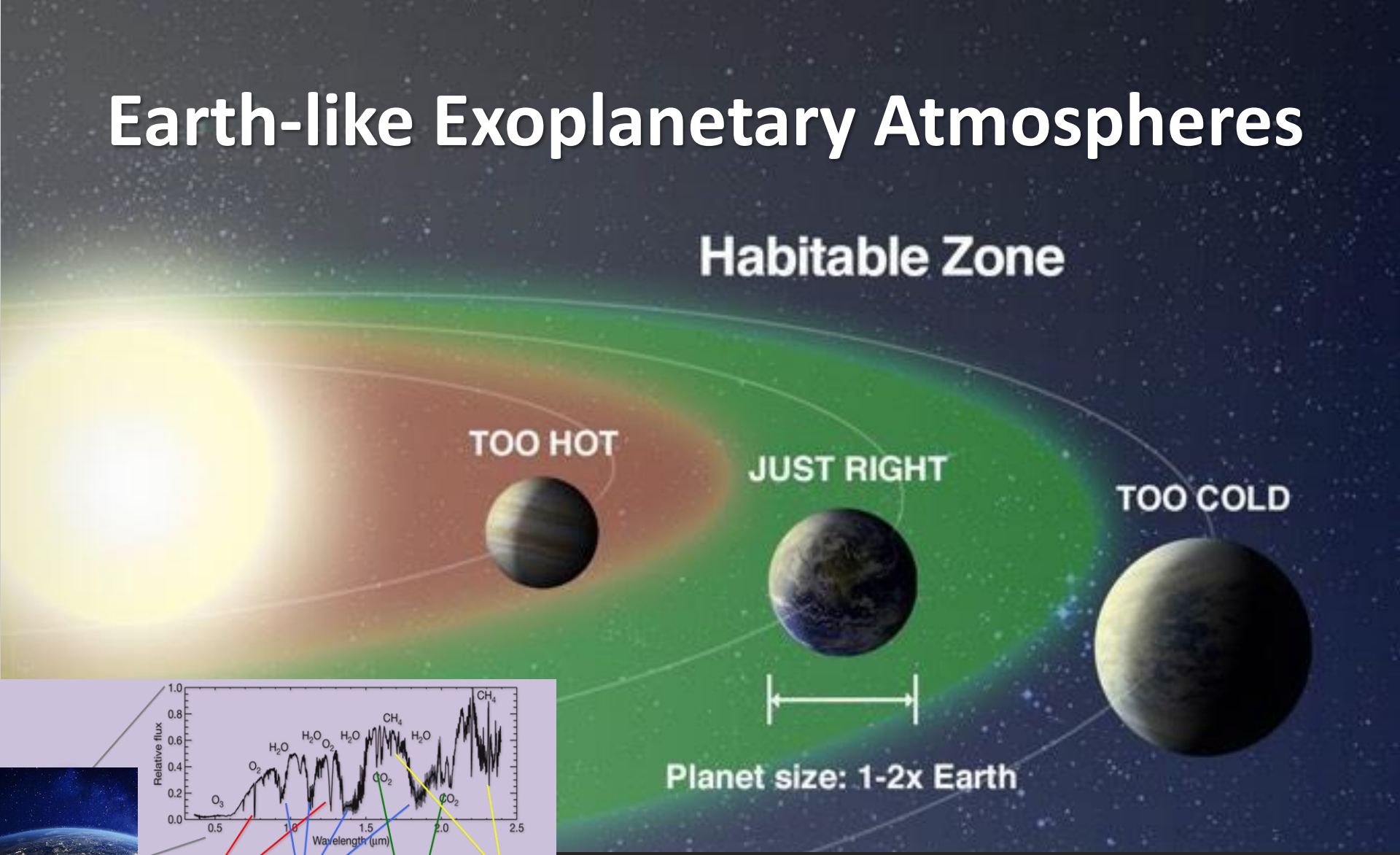
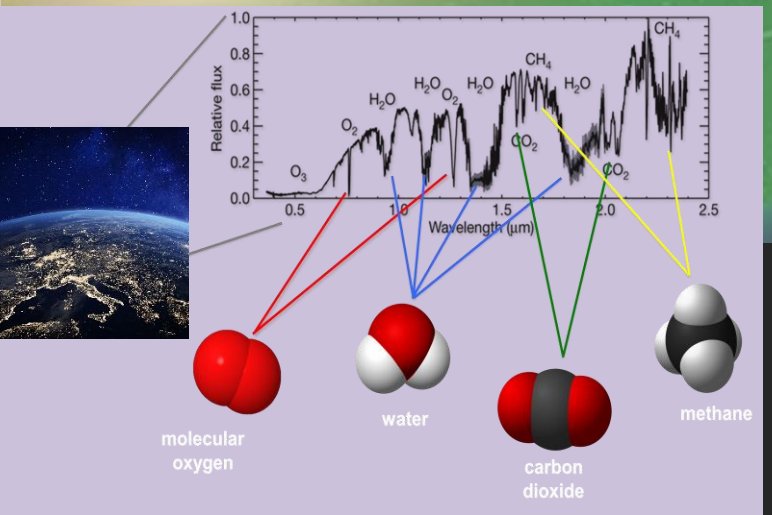
Earth-like Exoplanetary Atmospheres





Alessandro Sozzetti

(INAF – Osservatorio Astrofisico di Torino)

Overarching Questions

- **Planetary Systems Formation:**

a) How do planets and planetary systems form? b) Which features (spirals, gaps) of protoplanetary disks trace unambiguously ongoing planet formation? c) Where (which snowlines) and how (planetary accretion history) do planets grow ?

- **Planetary Systems Demographics:**

What is the diversity of planets and planetary system architectures? How common are true Solar System analogs? **Where are the nearest Earth-*like* planets?** How do the architectural and physical properties of planetary systems depend on stellar and environmental properties?

- **Planetary Systems Characterization**:

What are exoplanets made of? What is the chemistry and dynamics of their atmospheres?

Can we find evidence for biological activity? Can we understand habitability?

See also ASTRONET Roadmapping exercise final report of the Panel on Planetary Systems Formation and Evolution available at: https://www.astronet-eu.org/forums/roadmap-community-consultation

Exoplanets@INAF

Detection/Demographics:

- 21 Schede INAF (4 Programs/Schede Madri)
- Total: 121 Participants
- All INAF Institutes

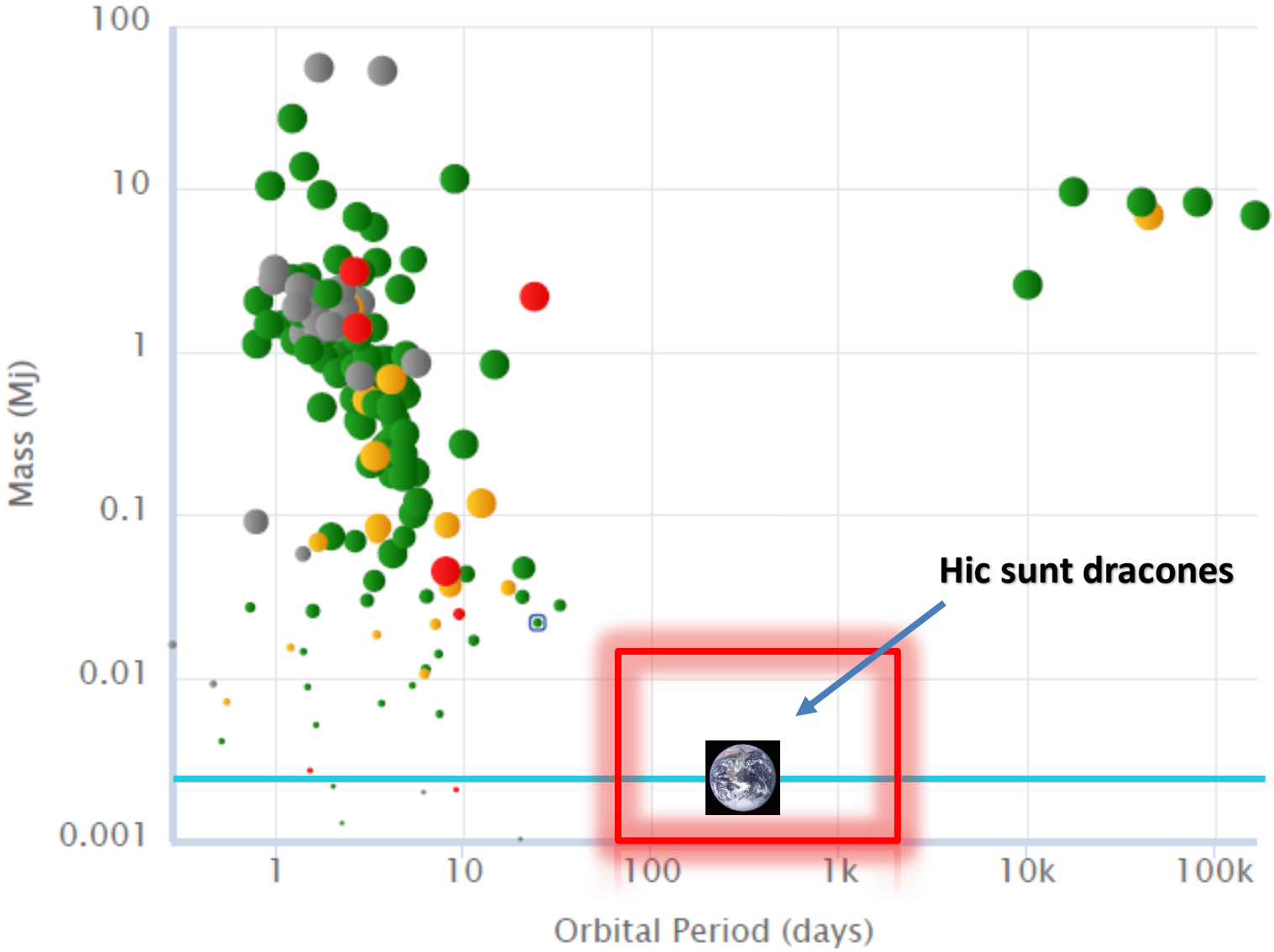
Atmospheric Characterization:

- 8 Schede INAF (1 Program/Scheda Madre)
- Total: 99 Participants
- 11 INAF Institutes

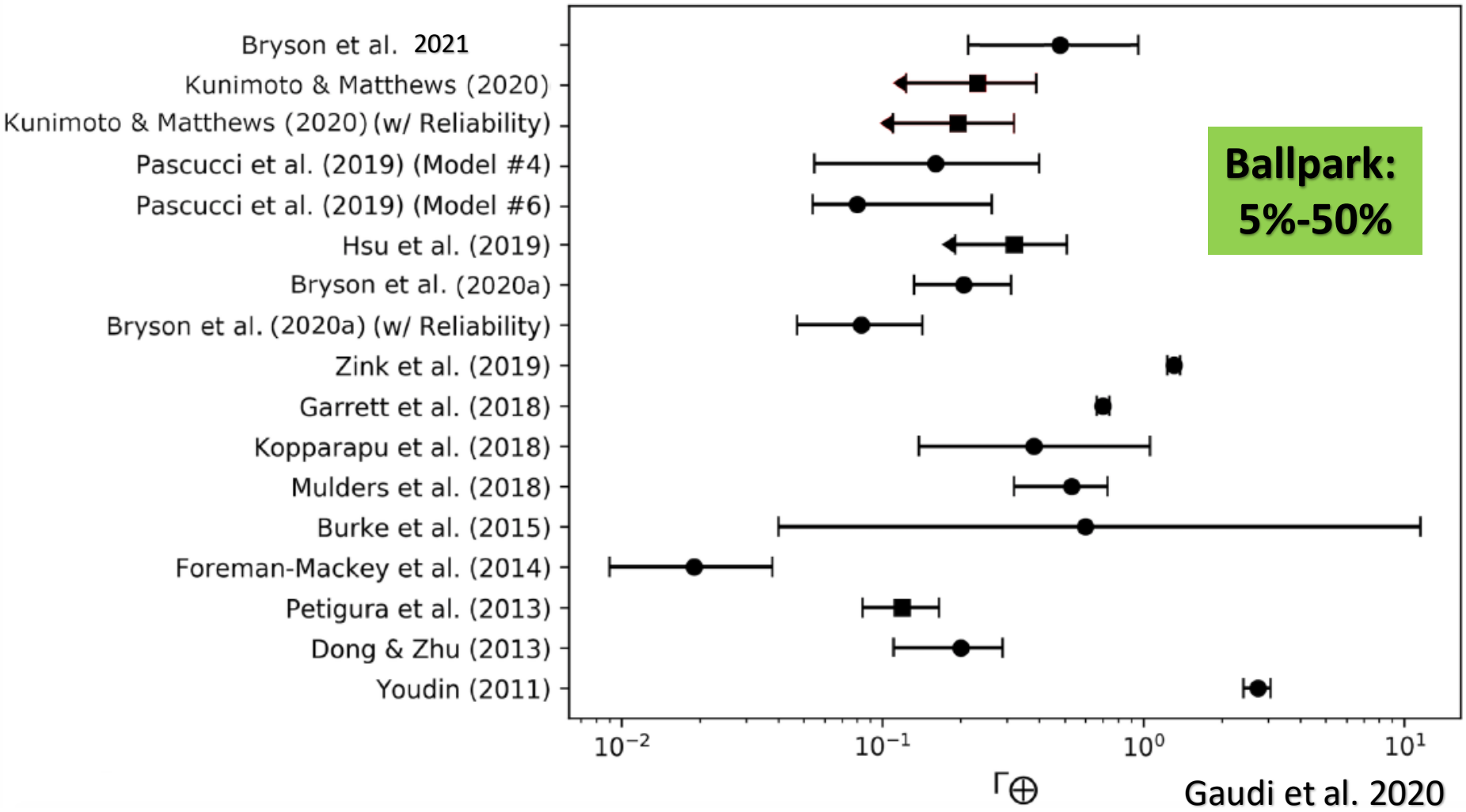
Modeling (formation, atmospheres, habitability):

- 6 Schede INAF (2 Programs/Schede Madri)
- Total: 21 Participants
- 9 INAF Institutes

Atmospheres: Atoms & Molecules



Earth Twins: Occurrence Rates



WARNING: Only extrapolations! Something PLATO should fix…

Exoplanet Missions

NGRST

JWST[2]

TESS

PLATO

Ariel

Kepler

CHEOPS

Spitzer

Gaia

Hubble[1]

CoRoT[3]

LUVEX/IROUV, LIFE?

ESPRESSO

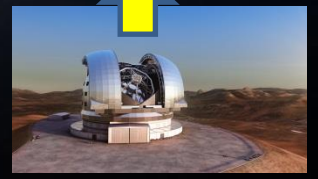
ANDES

NASA Missions

ESA/European Missions

ESO/HARPS

TNG/HARPS-N



VLT

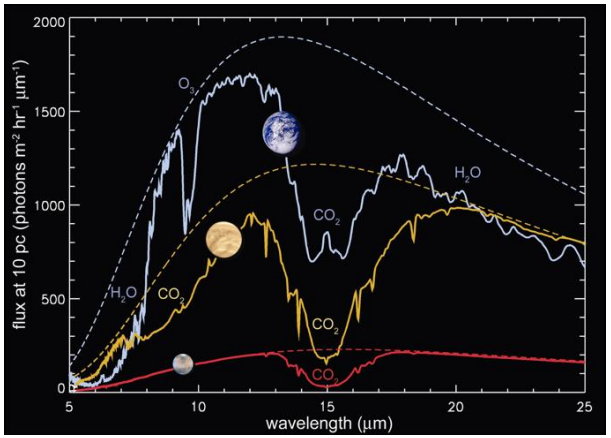
(E-)ELTs

W. M. Keck Observatory

[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA

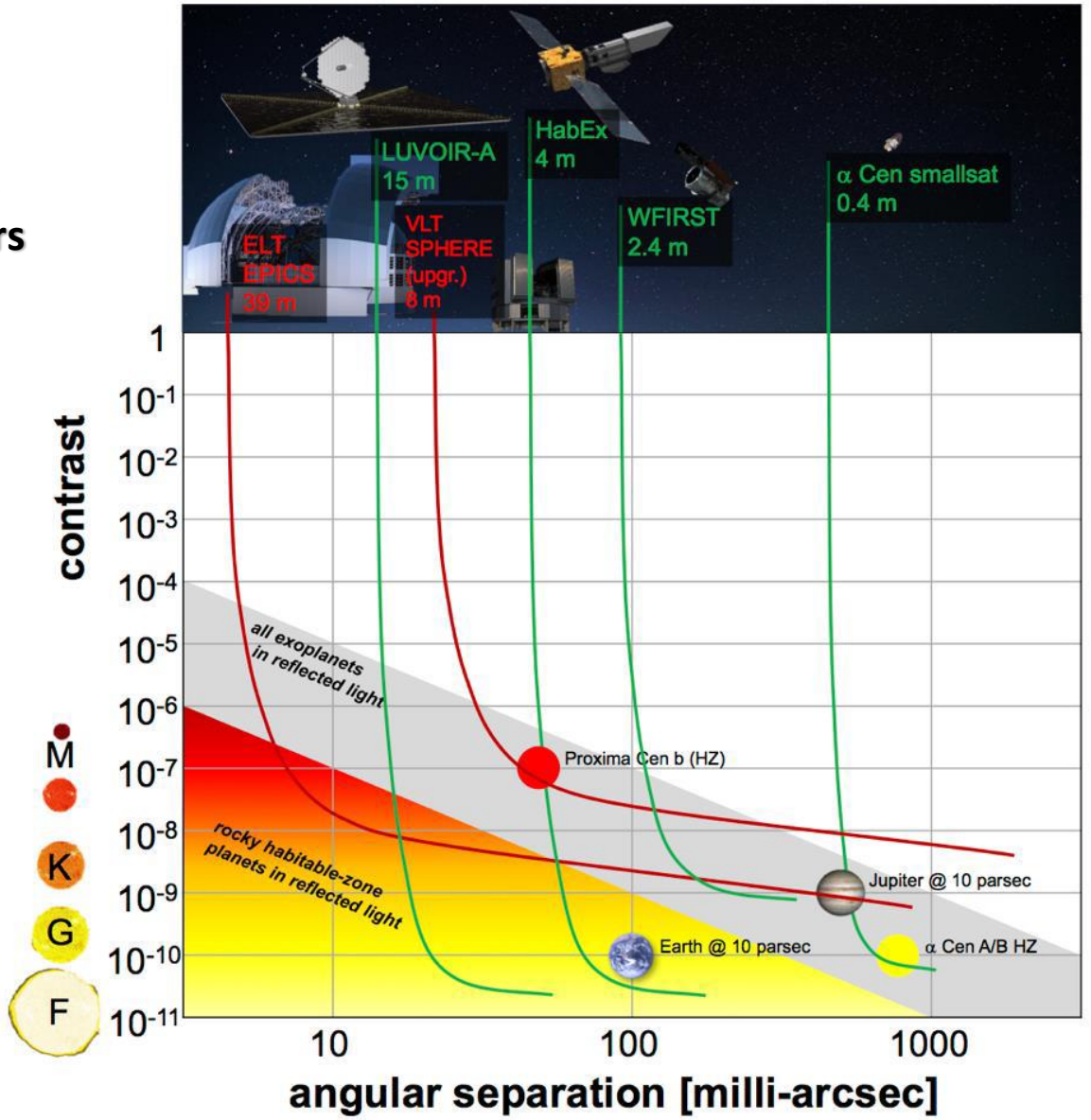
Earth-*Like* Planets: The Ultimate Frontier

Habitability and atmospheric biosignatures of temperate terrestrial exoplanets around the nearest *solar-type* stars



Finding the targets FIRST is mandatory in order to maximize science return

True Earth twin: K = 9 cm/s



Now, and Then: JWST, Ariel

Demographics of exoplanetary atmospheres:

- Low spectral resolution in space

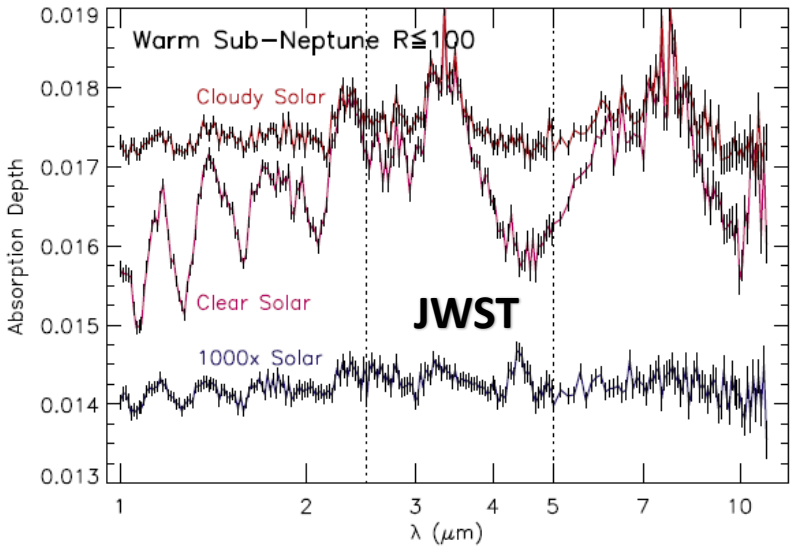
- JWST: R= 100-2,000, 1.0-11.0 μm (in chunks)
- 100s of close-in planets (ERS, GTO, etc.)

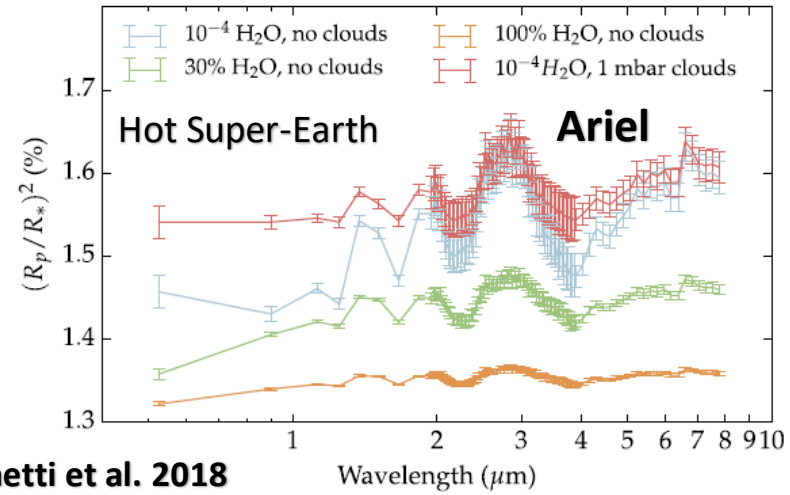
- Ariel: R=30-200, 0.5-7.8 μm (simultaneous)
- 1000s of close-in planets (3-tier program)

- Abundance ratios, chemistry, circulation, clouds…

1) Limited to transiting systems (TESS and PLATO)
2) HZ Super-Earths with JWST: <0.5 Msun hosts
3) Atmospheres of true Earth twins beyond reach

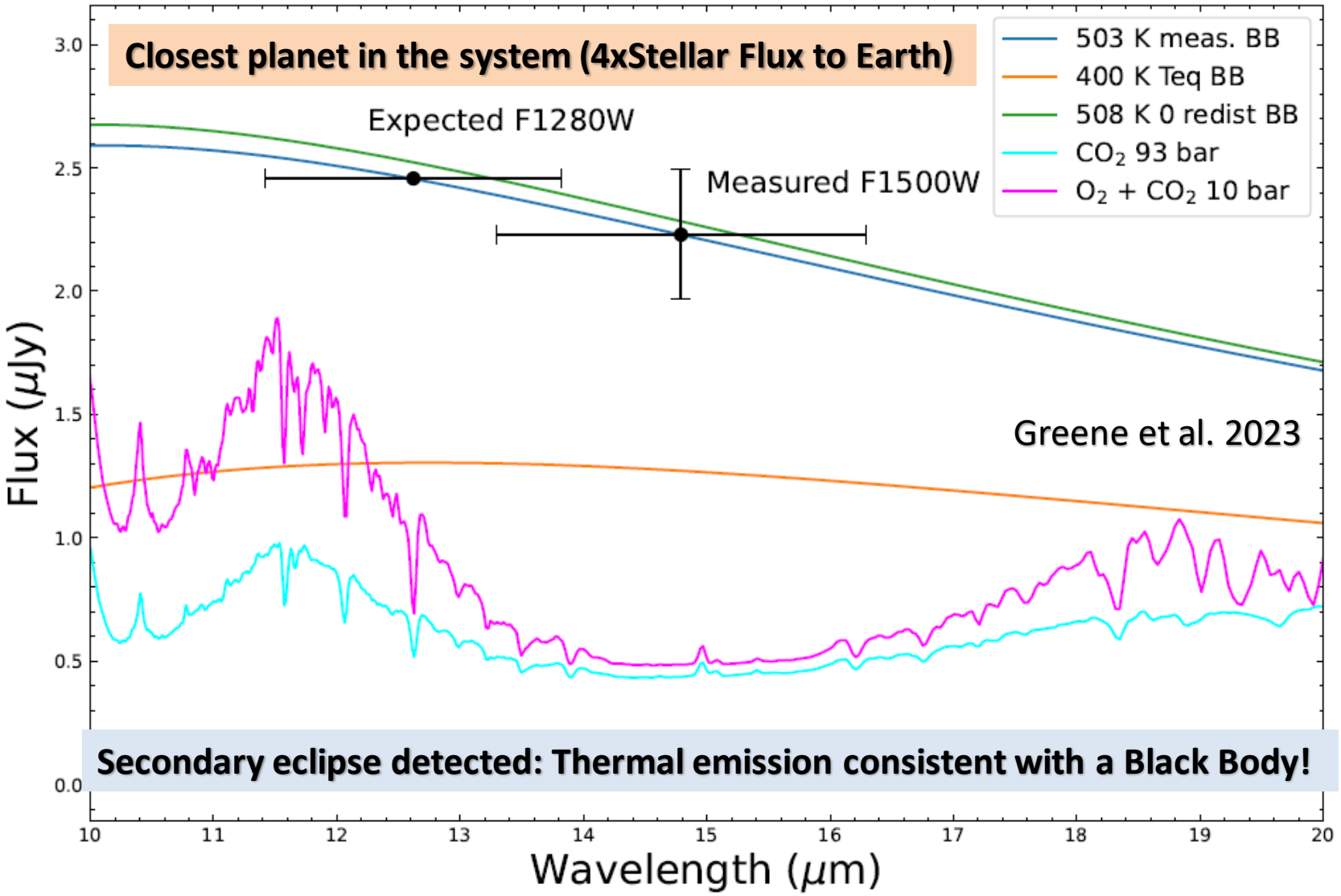
Greene et al. 2016





Tinetti et al. 2018

Trappist-1b with JWST/MIRI



The Future: EPRV Instruments

Optical:

- **HARPS (ESO 3.6m)**
- HARPS-N (TNG 3.6m)
- **ESPRESSO (ESO VLT)**
- **CARMENES (CA 3.5m)**
- EXPRESS (DCT)
- CHIRON (CTIO)
- Levy (APF)
- PSF (Magellan)
- **NEID (WIYN)**
- ....

NIR:

- **CARMENES (CA 3.5m)**
- **HPF (HET)**
- SPIRou (CFHT)
- ...

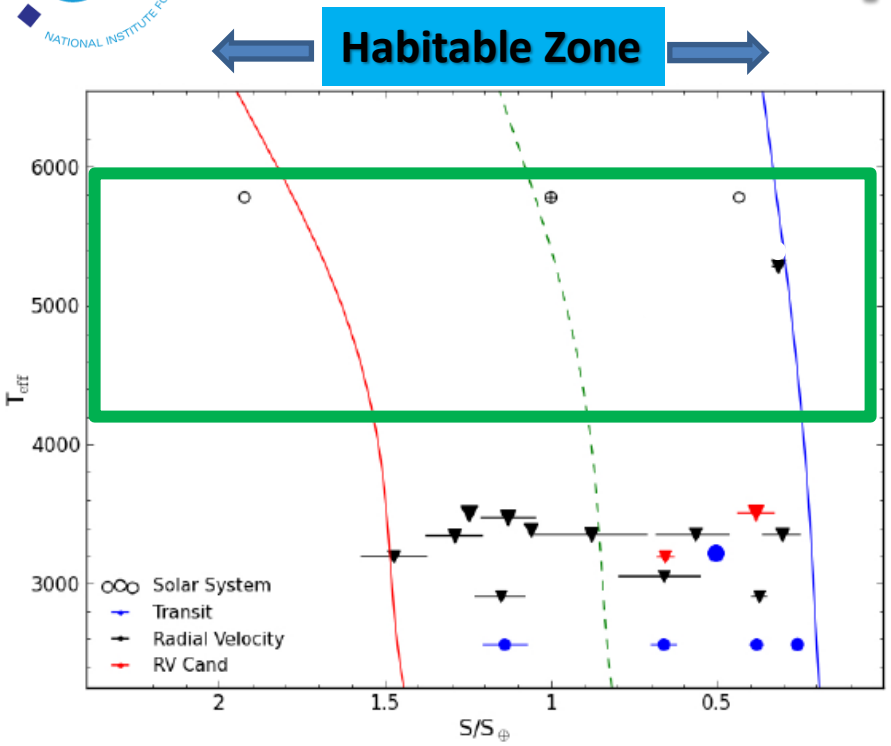
Future:

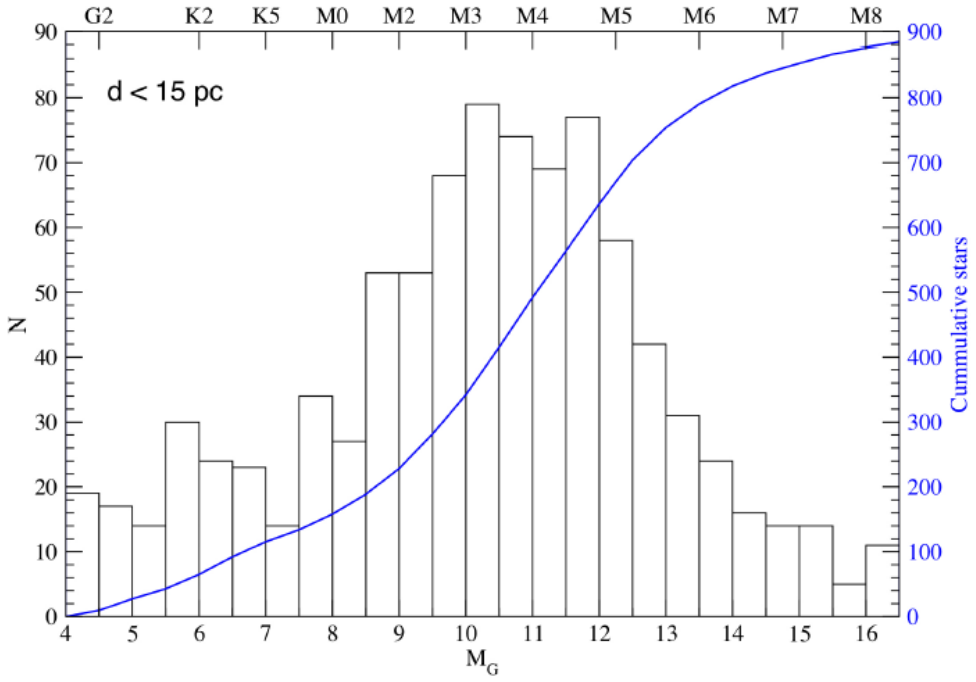
- Maroon-X (Gemini-N)
- KPF (Keck)
- HARPS3 (INT)
- GCLEF (GMT)
- MODHIS (TMT)
- ...

K = 9 cm/s:
an Earth-twin around a Sun-like star

Ultra-stable VIS/NIR high-resolution spectrographs enabling <10 cm/s precision

The Opportunity



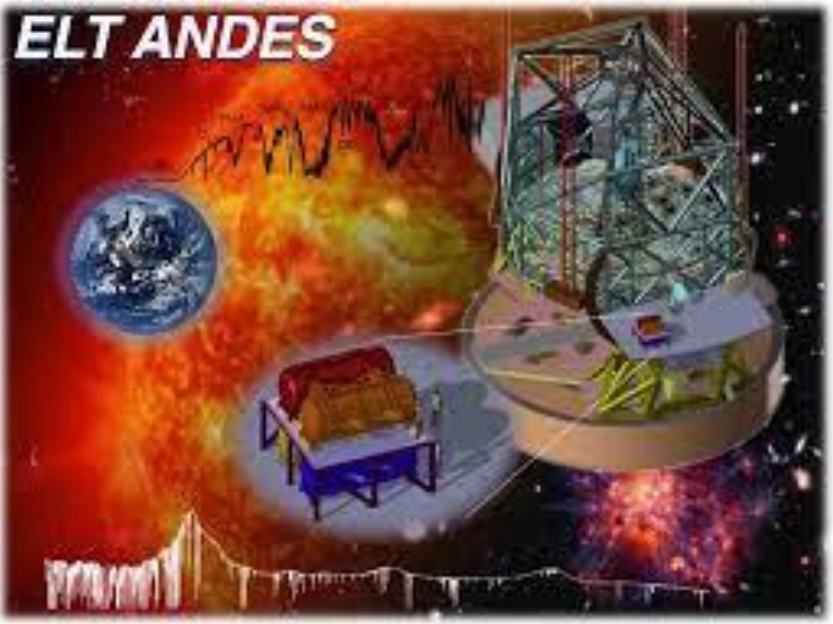


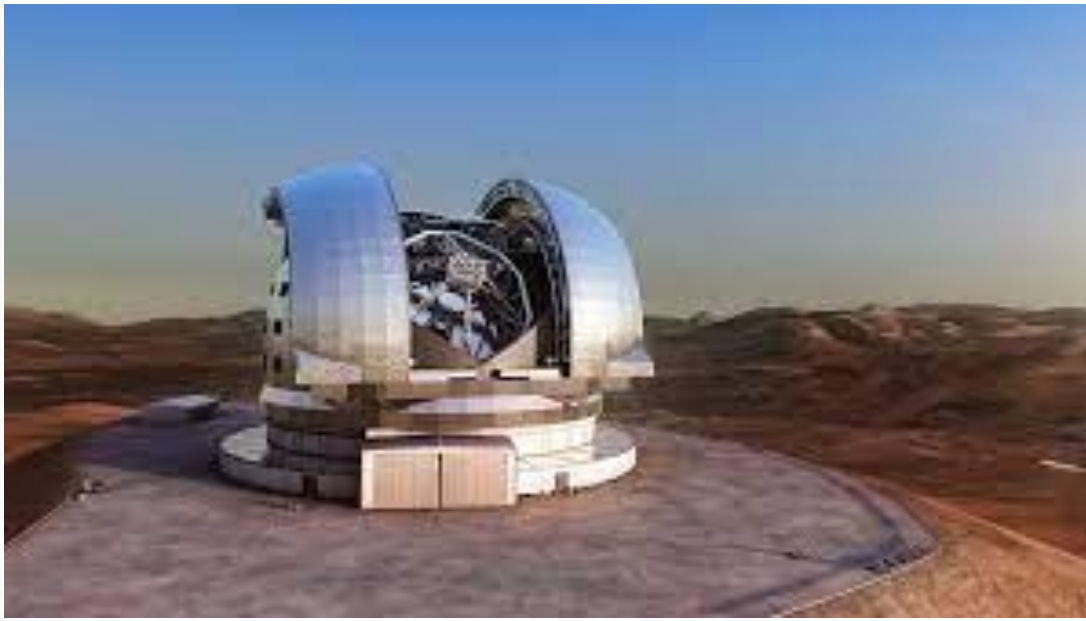
"A long-term extreme-precision RV monitoring campaign for the most nearby G-K-type stars is therefore highly recommendable" (Snellen+2019, ESA Voyage 2050 WP)

Same recommendations from the ASTRONET panel on planet formation

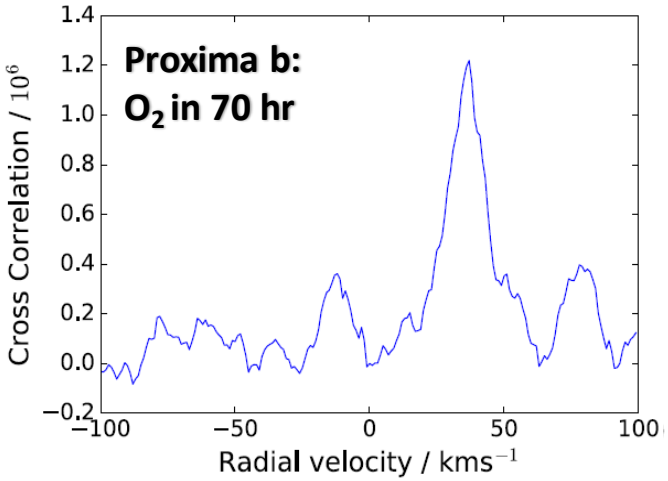
No dedicated facility for a Southern hemisphere version of the "Terra Hunting Experiment"

The Future: ANDES/ELT

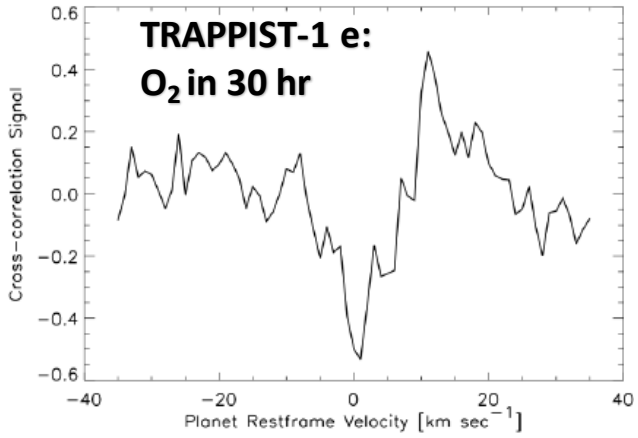




Biosignatures in the atmospheres of Earth-like planets around M dwarfs in transmission and reflected light @0.4-**2.4** micron and R=100,000



Hawker & Parry 2019



The Future: ANDES/ELT

Credits: A. Marconi

ANDES

Consortium

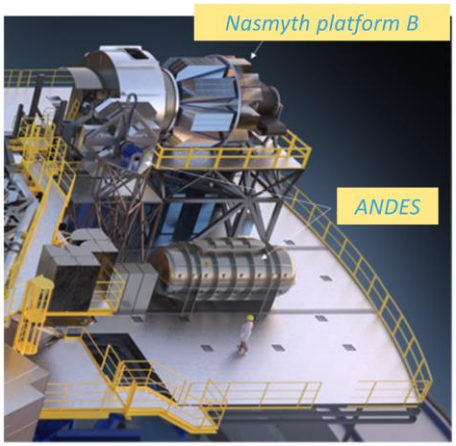
>30 institute in 13 countries (> 600 FTE):

BR CA DK FR DE IT PL PT ES SE CH GB US

>200 people
The state-of-the-art scientific and technological expertise in high-resolution spectroscopy in Europe

INAF: PI (A. Marconi)

* INAF Leads Project Office
* INAF Leads Fiber Link-IFU
* INAF Leads SCAO
* INAF Leads System AIV
* INAF Contributes to Front End

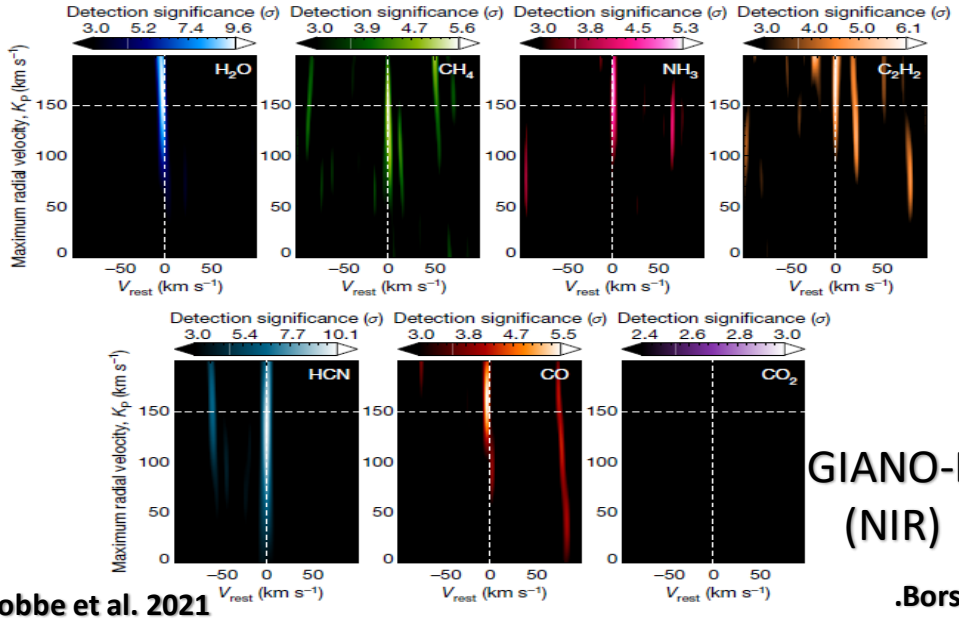


Baseline cost: 35 M€. Make it 50!

The Future: ANDES@ELT

It capitalizes on the state-of-the art expertise developed at INAF on atmospheric characterization of exoplanets at high spectral resolution

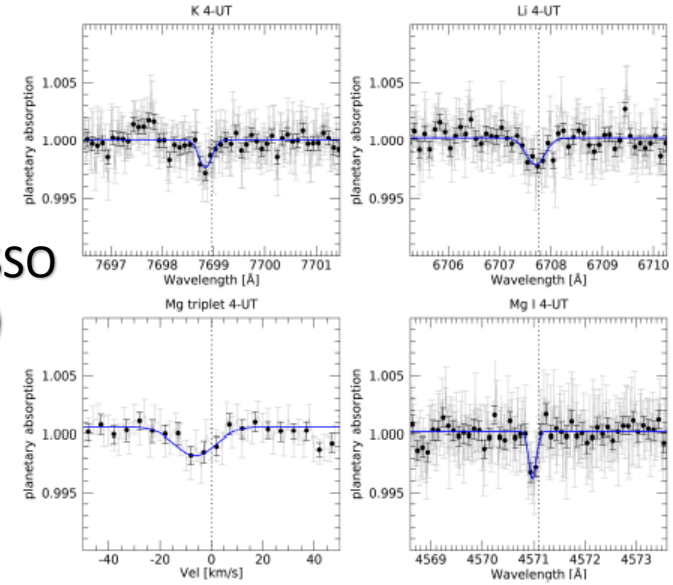
Inventories of atomic and molecular species: training on hot Jupiters!



Giacobbe et al. 2021

GIANO-B (NIR)

ESPRESSO (VIS)

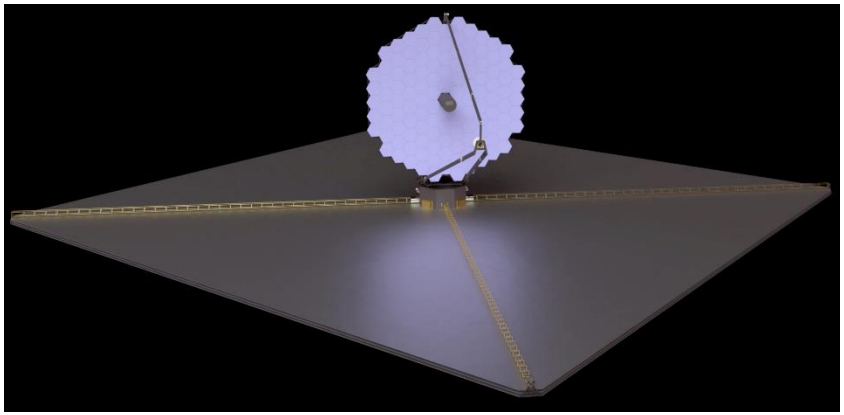


.Borsa et al. 2021

- Probes atmospheres of both transiting and non-transiting planets (with SCAO+IFU)
- Highly complementary to HCI and HDS in the thermal infrared with METIS…
- …and a spectacular complement to low-res spectroscopy with JWST!

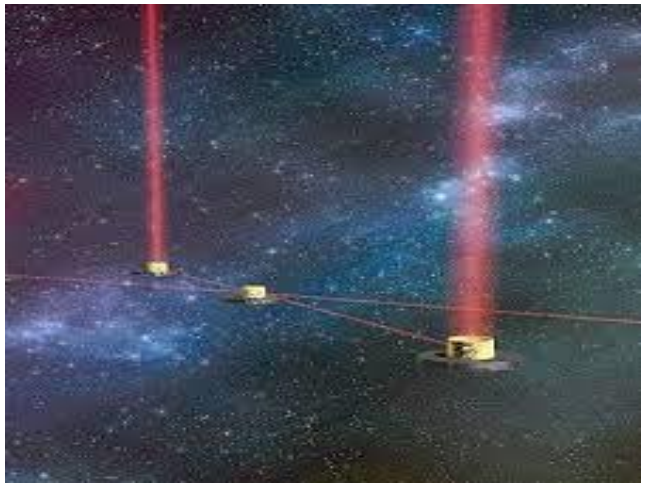
The (Distant) Future: Space

Astro2020 Decadal Survey:
Identify habitable Earth-like worlds



LuvEx, HWO (??)
Large 6-m class IR/O/UV telescope for High-contrast imaging and spectroscopy of 25 Earth-like planets around Sun-like stars

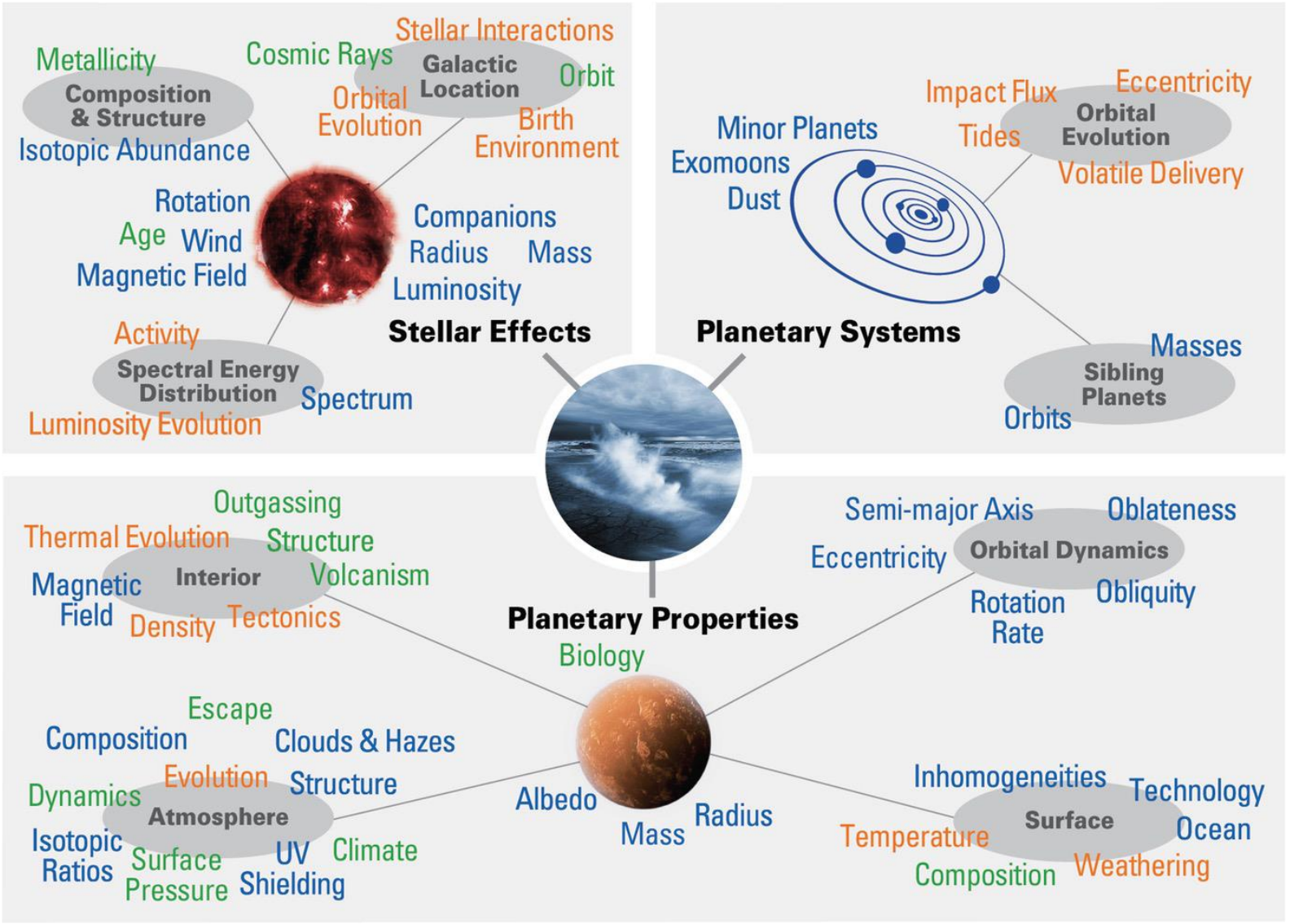
ESA Voyage 2050:
Characterisation of Temperate Exoplanets



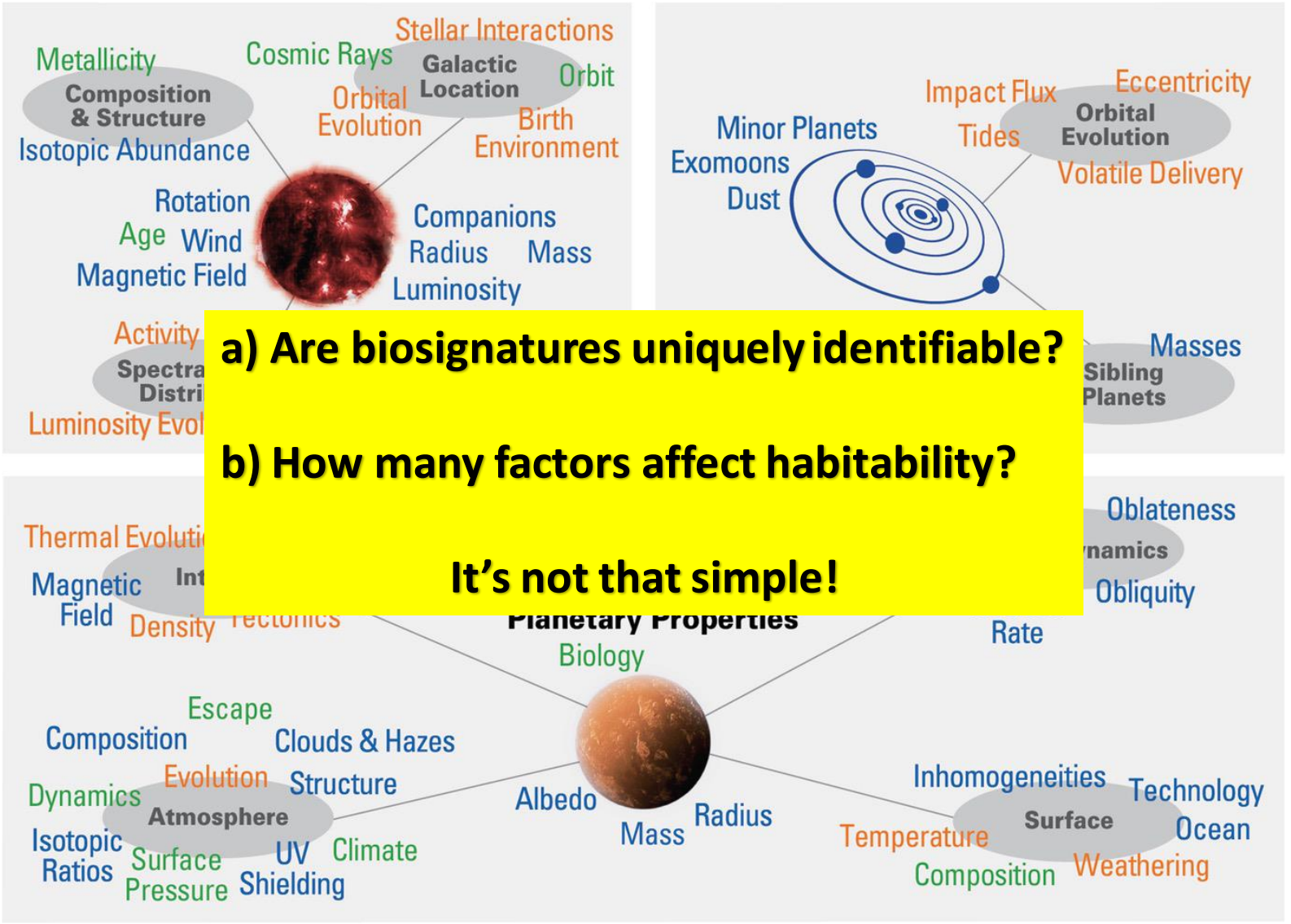
LIFE (??)
Mid-IR nulling interferometer for high-contrast direct spectroscopy of thermal emission of 30-50 Earth-like planets around M through F stars

Or an EU contribution to LuvEx/HWO?

Ultimately…


Stellar Interactions
Metallicity
Cosmic Rays
Galactic Location
Orbit
Composition & Structure
Orbital Evolution
Birth Environment
Isotopic Abundance
Rotation
Companions
Age
Wind
Radius
Mass
Magnetic Field
Luminosity
Stellar Effects
Activity
Spectral Energy Distribution
Spectrum
Luminosity Evolution
Impact Flux
Eccentricity
Minor Planets
Orbital Evolution
Tides
Exomoons
Volatile Delivery
Dust
Planetary Systems
Masses
Sibling Planets
Orbits
Outgassing
Thermal Evolution
Structure
Interior
Volcanism
Magnetic Field
Density
Tectonics
Semi-major Axis
Oblateness
Eccentricity
Orbital Dynamics
Obliquity
Rotation Rate
Planetary Properties
Biology
Escape
Composition
Clouds & Hazes
Evolution
Structure
Dynamics
Atmosphere
Albedo
Inhomogeneities
Technology
Mass
Radius
Surface
Isotopic Ratios
Surface Pressure
UV Shielding
Climate
Temperature
Ocean
Composition
Weathering

Ultimately…



a) Are biosignatures uniquely identifiable?

b) How many factors affect habitability?

It's not that simple!

Recommendations

- INAF should consider leading an EPRV program to provide Earth-like candidates to the ELT (there's a 90% INAF-owned facility next door).

- ANDES is pivotal. And make no mistake: the K-band is mandatory!

- Combining HRS & LRS will become key. It will require HPC (starting point in the PNRR-funded national center on HPC, BD, and QC)

- Further stress the interdisciplinarity of the topic: understanding the viability of biosignatures and actual habitability of Earth twins will be a HUGE effort ⟹ key components in Astrobiology

- Start thinking seriously about the next space-based opportunity, not to go amiss as it happened with JWST