LIFE
Large Interferometer For Exoplanets

Technological challenges for the Large Interferometer For Exoplanets

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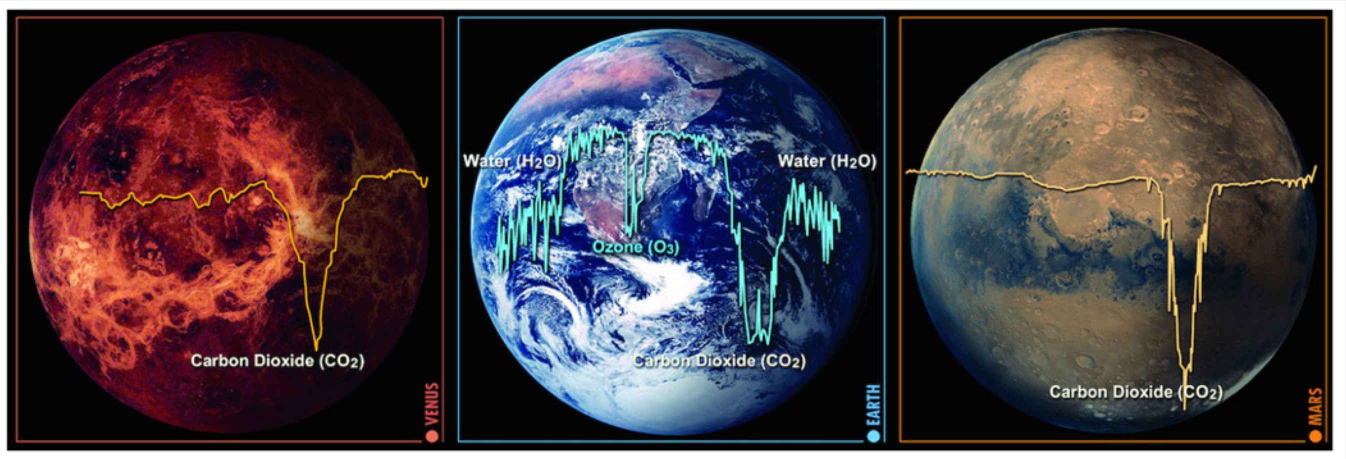
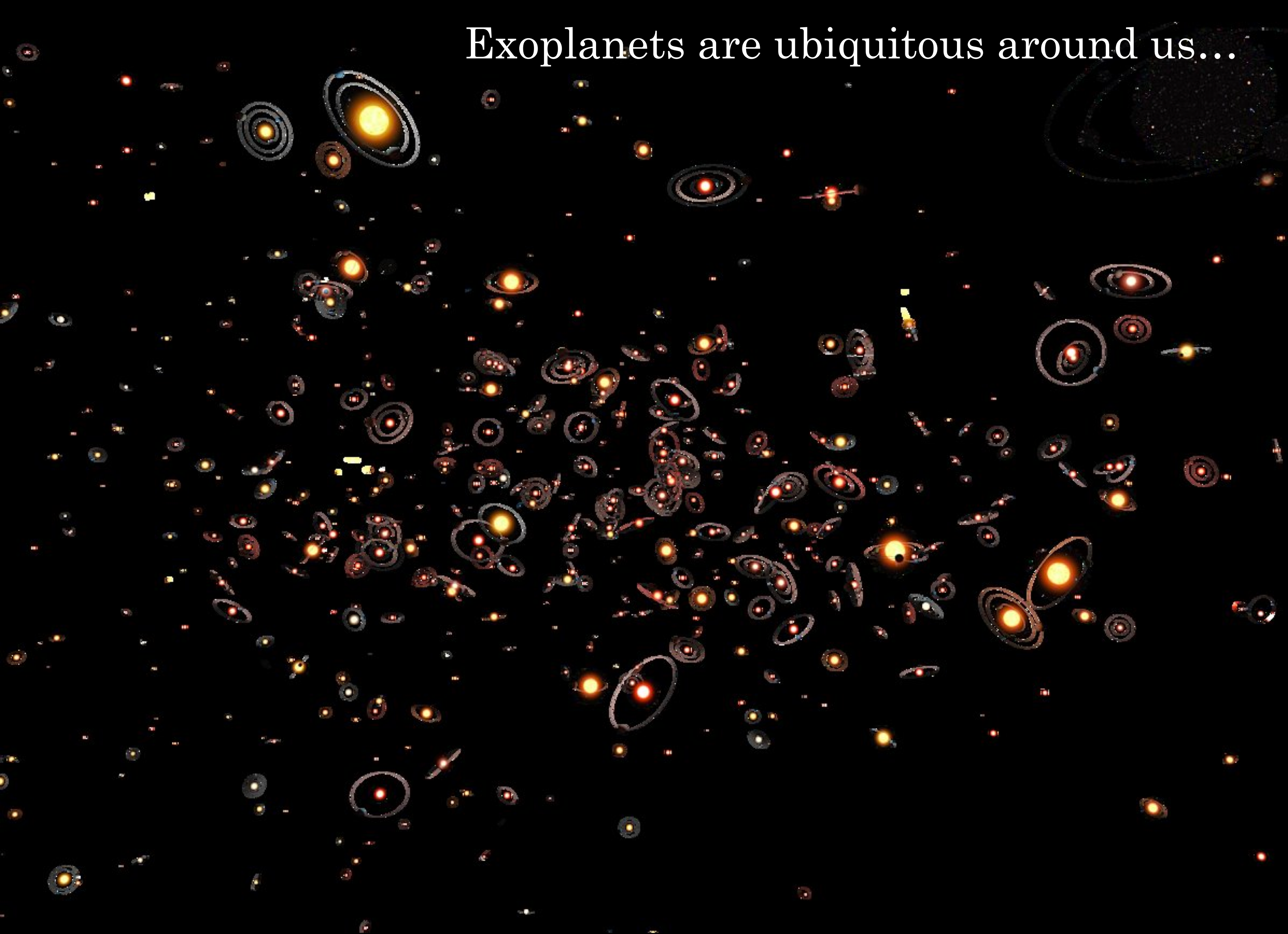


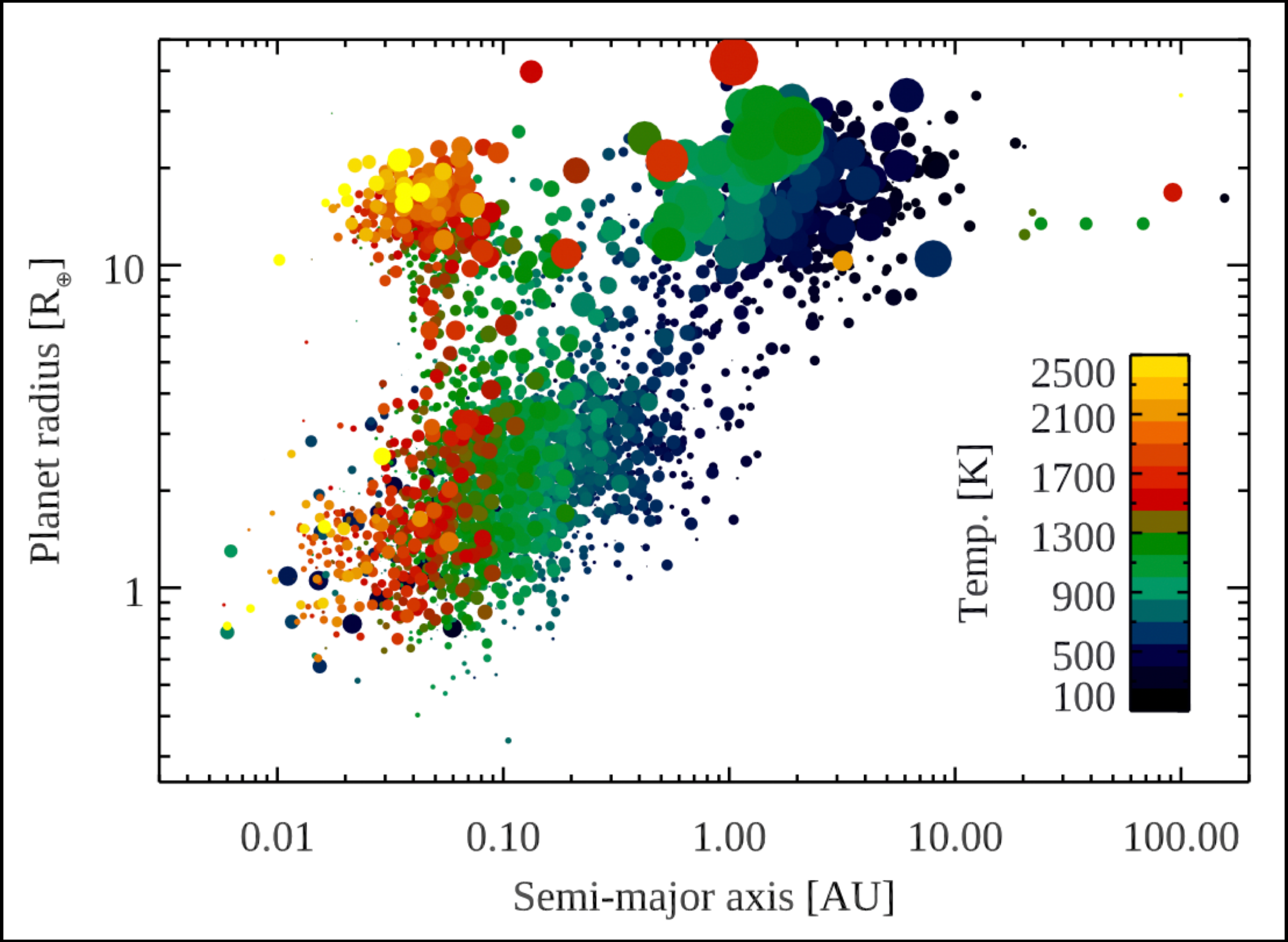
November 4th 2019 – future technology workshop @ ESA/ESTEC

Exoplanets are ubiquitous around us…



Credit: ESO/M. Kornmesser - https://www.eso.org/public/images/eso1204a/

and they show a great diversity.



Key exoplanet questions

Strong voyage2050 theme

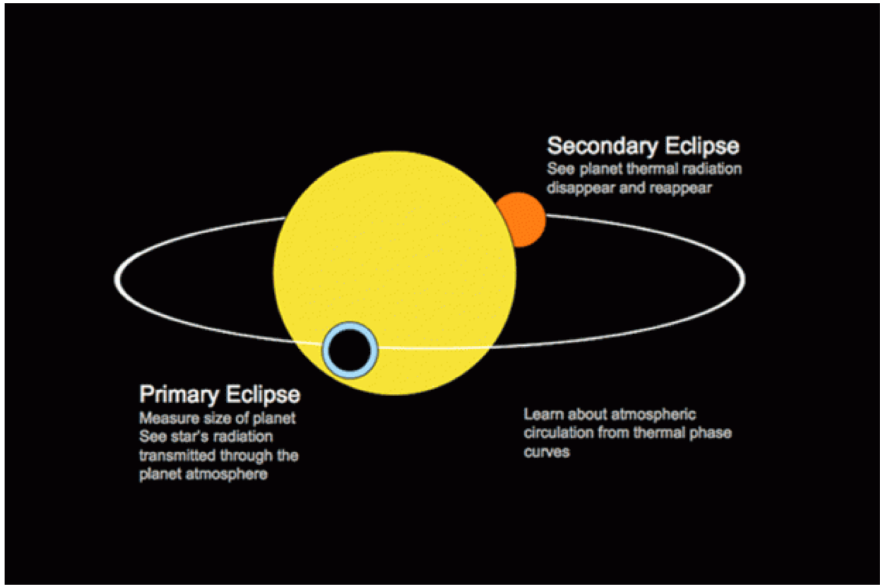
- Chemical diversity of rocky exoplanets around Sun-like stars
- Habitability and prevalence of habitable planets
- Presence of biomarker gases
- Prevalence of biological activity

Species	Information on planet
Visible and infrared continuum	Orbital parameters => dynamical mass
Infrared continuum	Combination of surface temperature, pressure, radius, and albedo
CO_2	Presence of an atmosphere
H_2O	Presence of water
O_2, O_3, CH_4	Biomarker gases

+ many others (see LIFE whitepaper)

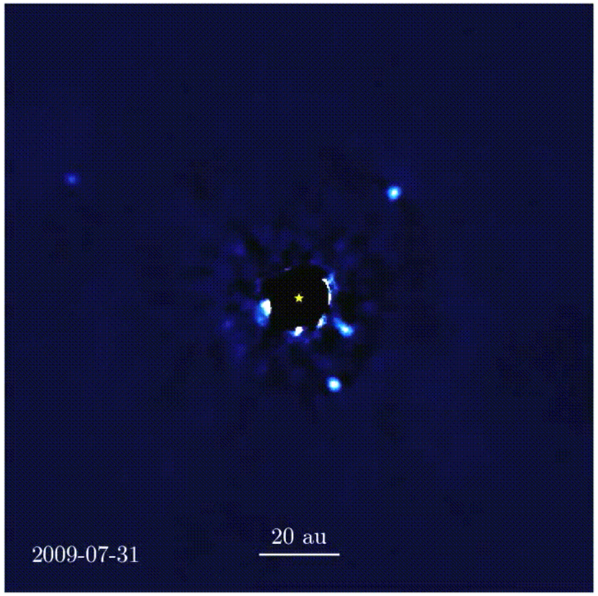
How to measure their photons?

Time differential techniques



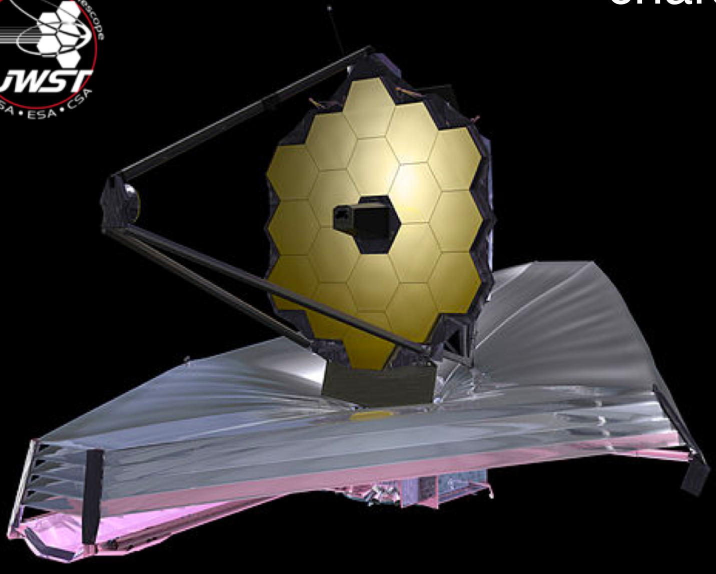
S/N ~D

Angular differential techniques



S/N ~D^2

Spectroscopy is key and upcoming MIR characterisation missions will focus on hot / warm ***transiting*** exoplanets



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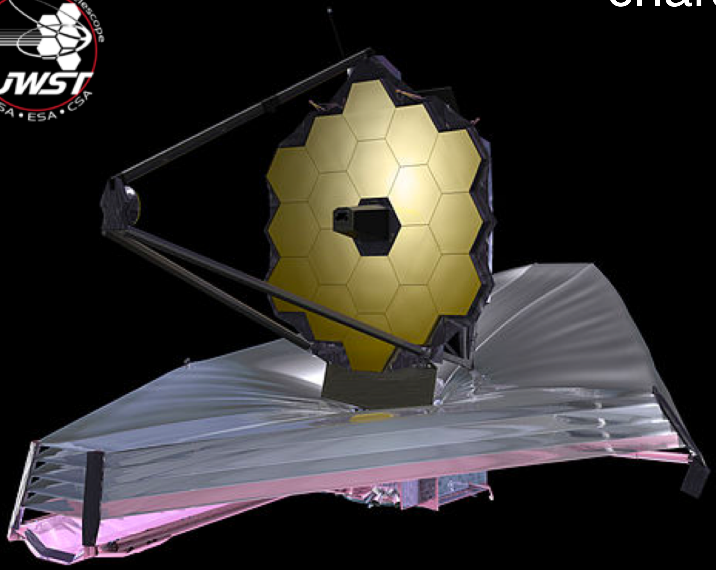
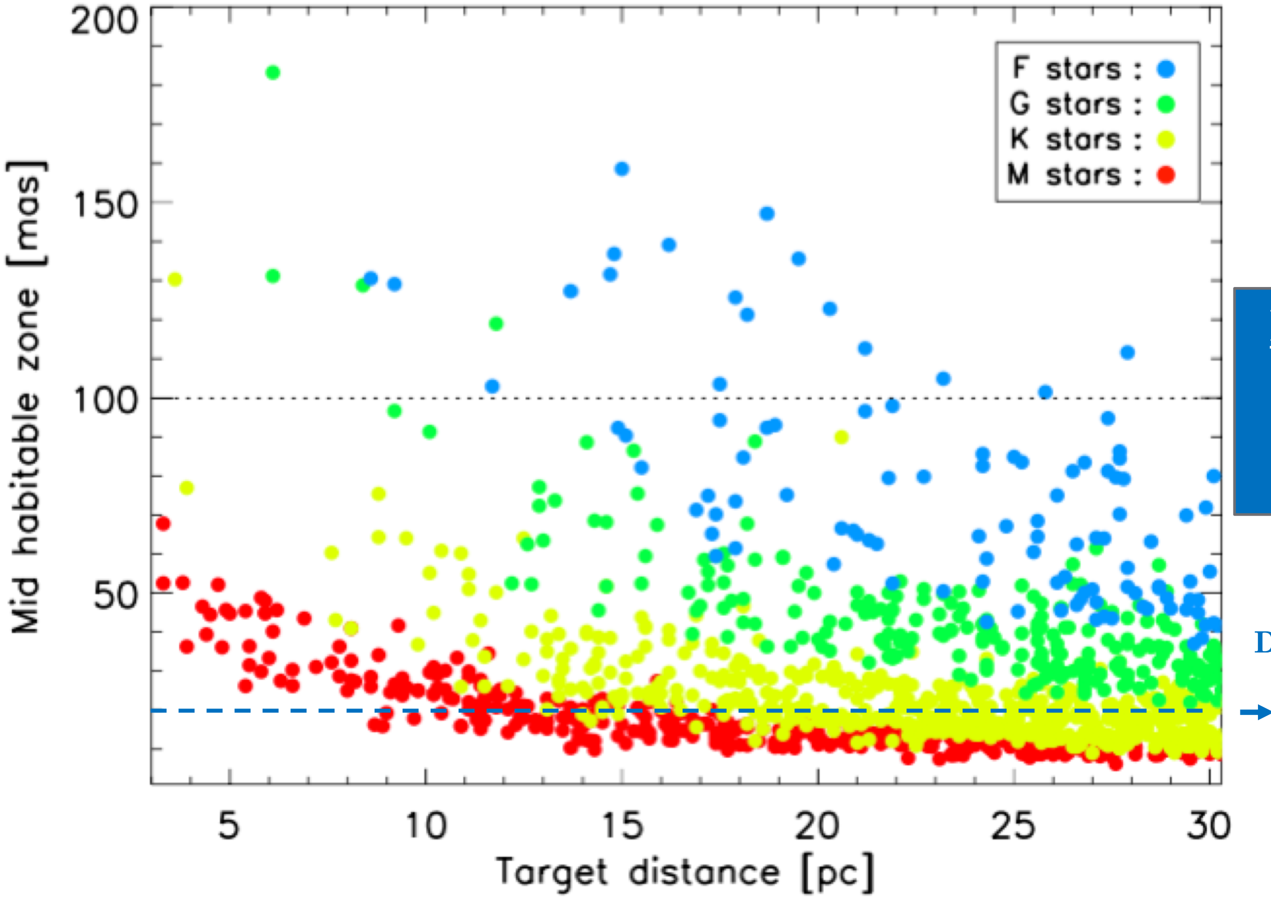


"A long term scientific objective is to characterize the whole range of exoplanets, including, of course, potentially habitable ones. ARIEL would act as a pathfinder for future, even more ambitious campaigns. " ARIEL Assessment Study Report (Yellow Book)

Imaging challenge 1: angular resolution

- Science driven: characterize at least 30-40 rocky exoplanets with $0.5R_{\mathrm{Earth}} < R_{\mathrm{planet}} < 1.5\ R_{\mathrm{earth}}$ and $0.35\ S_{\mathrm{Earth}} < S_{\mathrm{planet}} < 1.75\ S_{\mathrm{Earth}}$



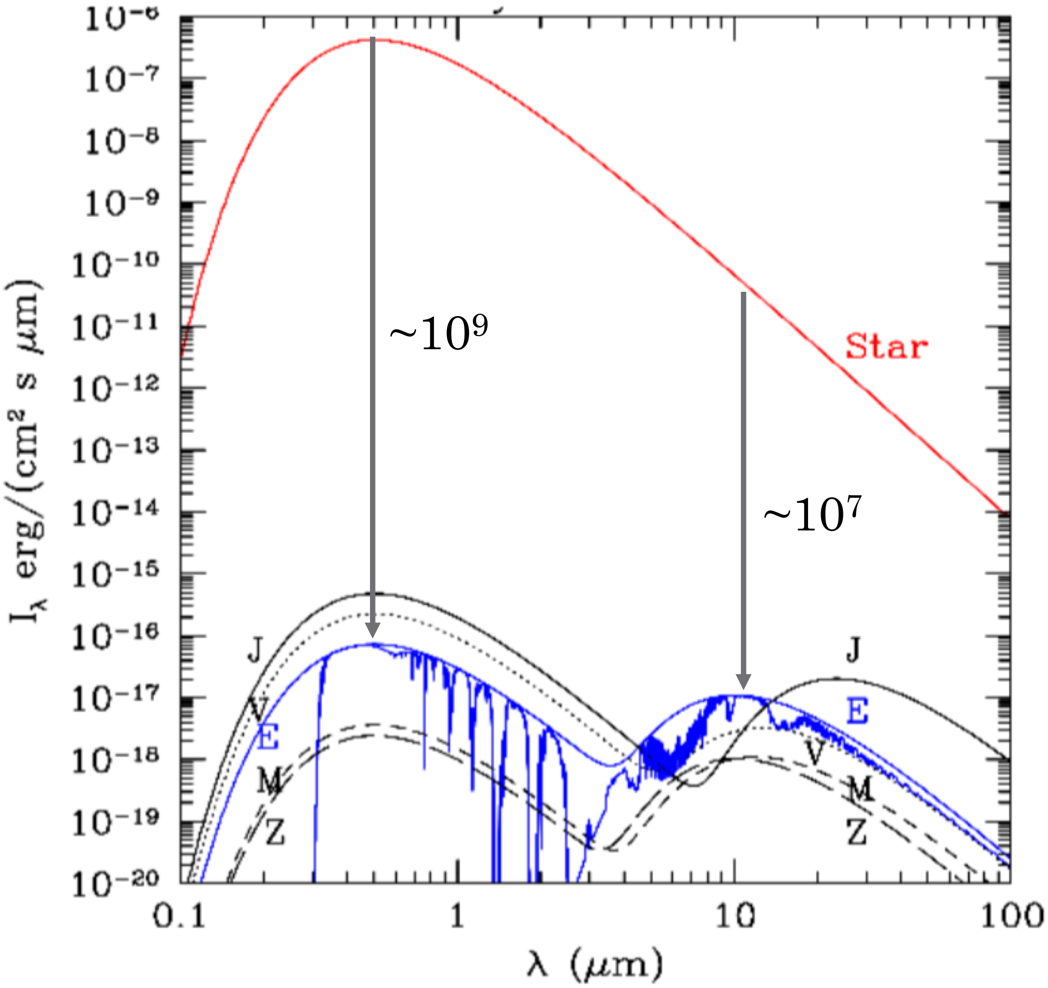
REQUIREMENT 2:
~200m primary mirror or interferometer

↑

D required for > IWA (2λ/D):

→ Visible (550nm): ~12m
Infrared (10μm): ~200m

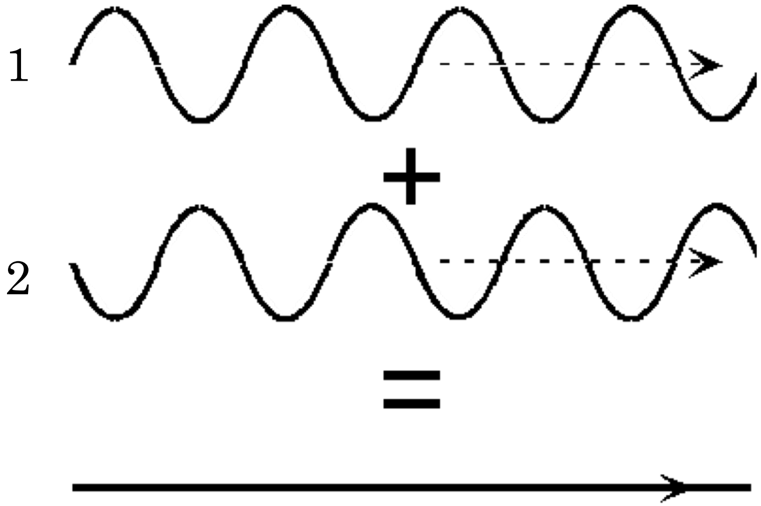
Imaging challenge 2: planet/star contrast

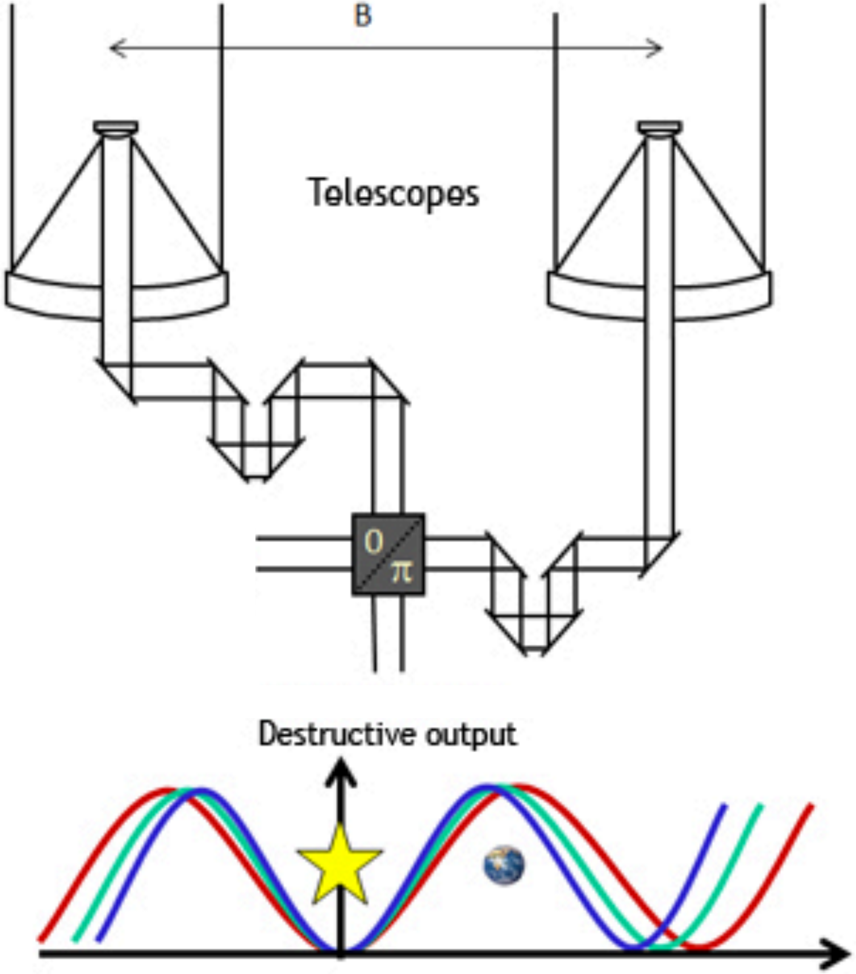


<u>REQUIREMENT 1</u>:
STARLIGHT
SUPPRESSION
TECHNIQUES

Nulling interferometry

Stellar suppression (coronagraph) + angular resolution





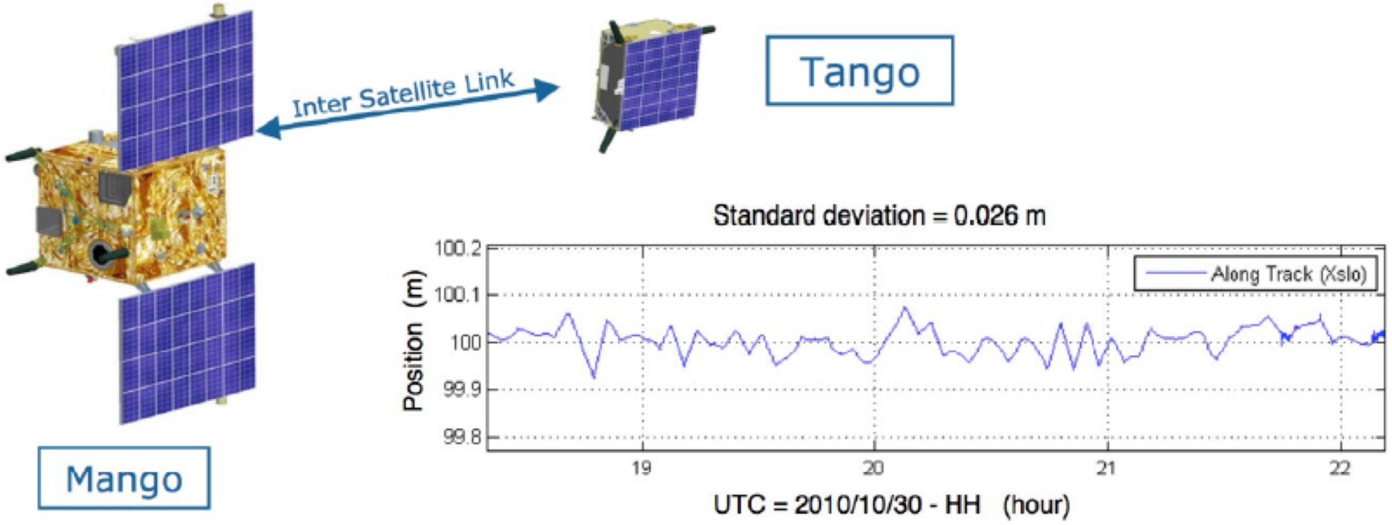
Technological challenges

- Formation flying
- Ultra-stable starlight suppression
  - Cryogenic deformable mirrors
  - Fibers and integrated optics
- Ultra-low noise mid-IR detectors
- Passive cooling and thermal noise

Formation flying

- High-level requirements and features:
    - Control: 2 cm / 20 arcsec
    - At least 4 spacecraft, rotating and with fault recovery

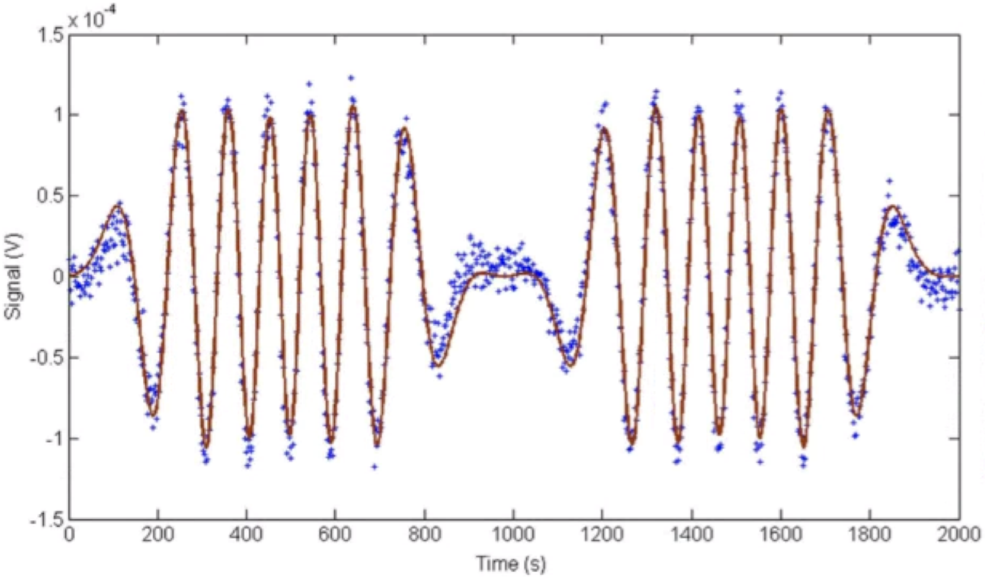
- State-of-the art:
    - Flight: PRISMA (**2 spacecraft**), RMS of a few cm, over 4 hours (limited by accuracy of radio sensor), PROBA-3 in 2020 (goal 1 mm RMS) **=> exceed LIFE’s control requirements**
    - Lab: Formation Control Testbed (3 spacecraft, 2D), rotation, 5cm/60 arcmin

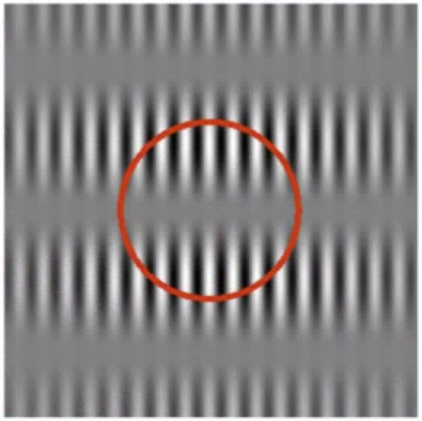


Ultra-stable starlight suppression

- High-level requirements and features:
    - Null depth 10^{-5} with stability 10^{-6} over ~50000s (5-20 microns)
    - Control: amplitude 0.05% RMS, phase: 3nm RMS (conservative, might be relaxed by post-processing)

- State-of-the-art:
    - <u>Lab</u>: null depth of 8×10^{-6}, 10^{-8} (after post-processing) @ room temperature and 10% bandwidth (Martin et al. 2012);
    - <u>On-sky</u>: null depth of $\sim10^{-2}$, stability 10^{-4} (after post-processing) with LBTI, limited by thermal background (Defrère et al. 2016)

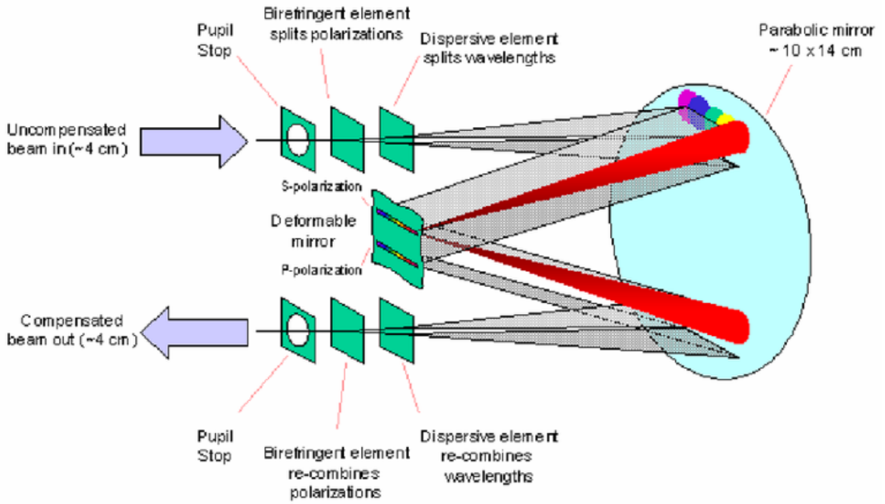




Cryogenic deformable mirror

- High-level requirements and features:
  - Actuator stroke, stroke resolution, heat dissipation, and actuator count are TBD
  - Must be **operable at cryogenic temperatures**
  - Fiber injection and/or achromatic phase shifter (Peters et al. 2009)

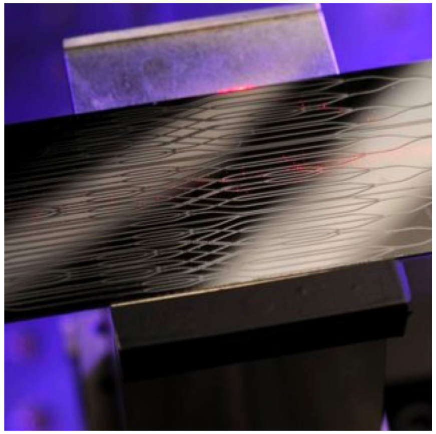
- State-of-the-art:
  - MEMS DM with 32x32 actuator count operated at 5K demonstrating 2.6 nm rms repeatability (Morgan et al. 2019)
  - Unimorph deformable mirrors operated at liquid nitrogen temperature (90K, Rausch et al. 2015)



Fibers and integrated optics

- High-level requirements and features:
  - Reduce constraints on wavefront quality;
  - Various options: single-mode fibers, photonic crystals, integrated optics;
  - Integrated optics for more compact and less risky concepts;
  - Requirements are TBD

- State-of-the-art:
  - Operating chalcogenide or silver halide single-mode fibers.
  - Photonic crystal options need to be investigated for higher throughput
  - Operating nulling I/O chip in chalcogenide glasses
  - All need to be tested over the full waveband and in cryo conditions. Throughput has to be improved.



Ultra-low noise mid-IR detectors

- High-level requirements and features:
    - Direct impact on maximum spectral resolution
    - Low readout noise, high QE
    - Requirements under study, likely ~5x better than JWST’s MIRI

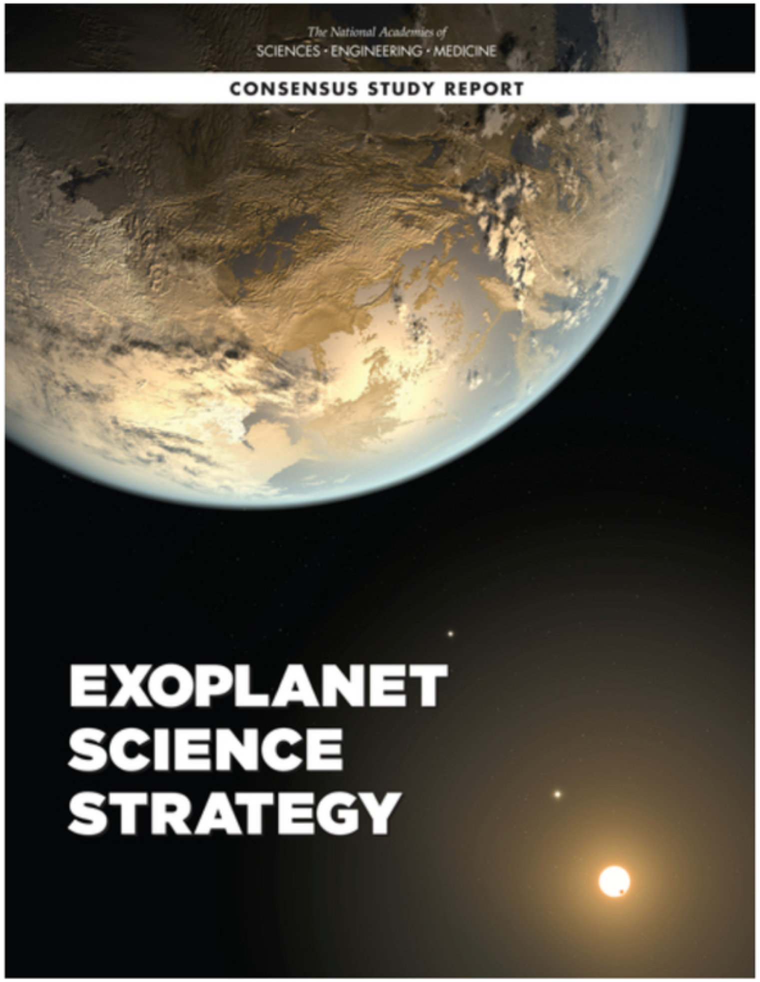
- State-of-the-art:
    - Flight: Spitzer IRAC Si:As detector
    - Lab: JWST/MIRI’s band-impurity detectors (8K, ~14 e- rms), HgCdTe detectors (28K, Cabrera et al. 2019)

Passive cooling and thermal noise

- High-level requirements and features:
  - Optics at 40K to preserve performance at 17-20 microns (CO_2);
  - Baffling, cleanliness, and surface finish requirements to mitigate scattered light (<10 ph/s/bin);
  - Thermal stability

- State-of-the-art:
  - Herschel/Planck passively cooled at 40K

The road ahead



The National Academies of
SCIENCES · ENGINEERING · MEDICINE

CONSENSUS STUDY REPORT

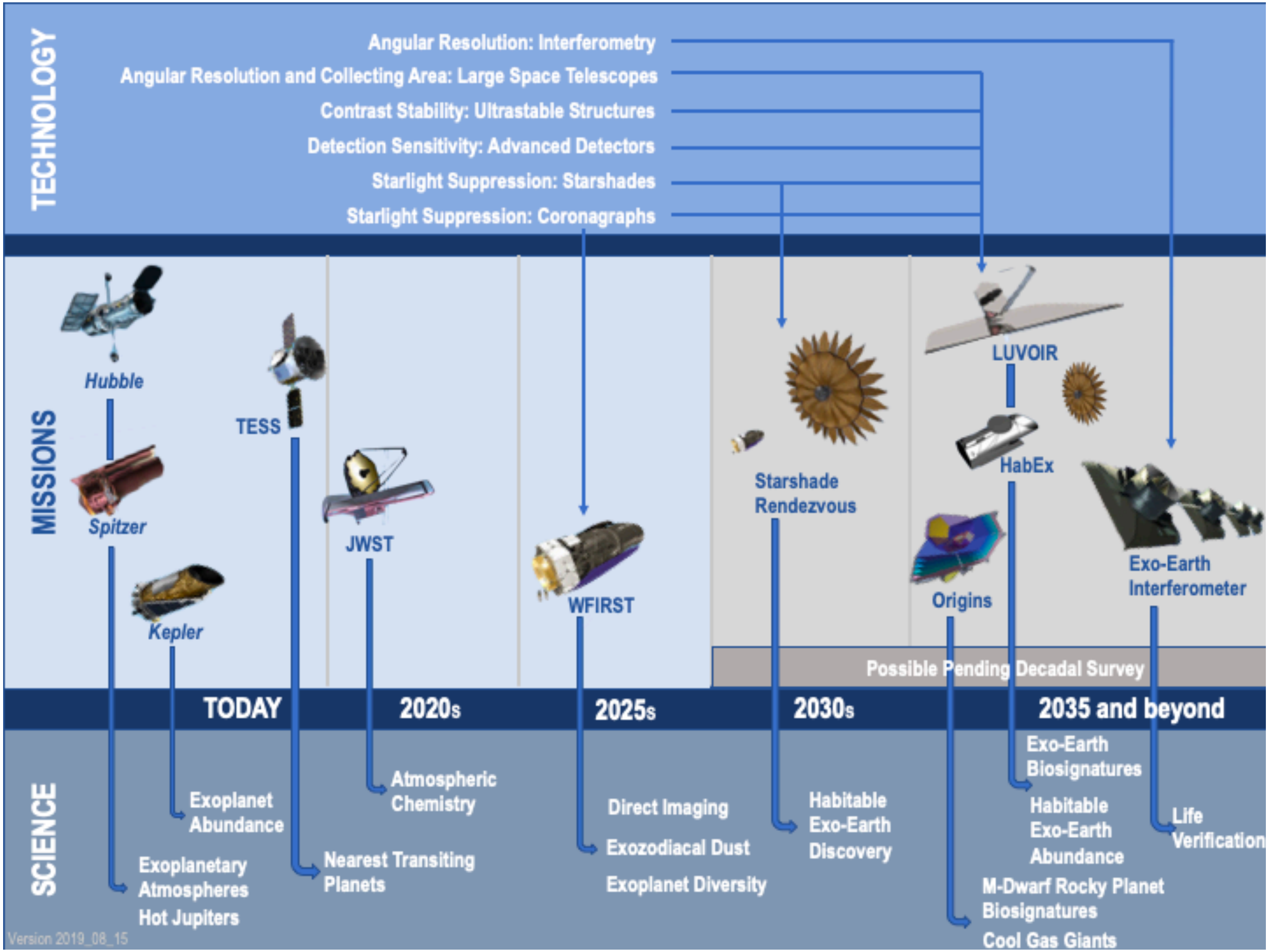
EXOPLANET
SCIENCE
STRATEGY

National Academy of Sciences (2018)

The report states: “**Technology development support in the next decade for future characterization concepts such as mid-infrared (MIR) interferometers […] will be needed to enable strategic exoplanet missions beyond 2040**.”

Even more important is the following statement: “That said, the common (although often unspoken) belief is that **such a nulling, infrared interferometer would be a necessary follow-up to any reflected light direct imaging mission, as detecting the exoplanet in thermal emission is not only required to measure the temperature of the planet, but is also needed to measure its radius**, and so (with an astrometric or radial velocity detection of [...] the mass of the planet) measure its density and thus determine if it is truly terrestrial.”

The road ahead



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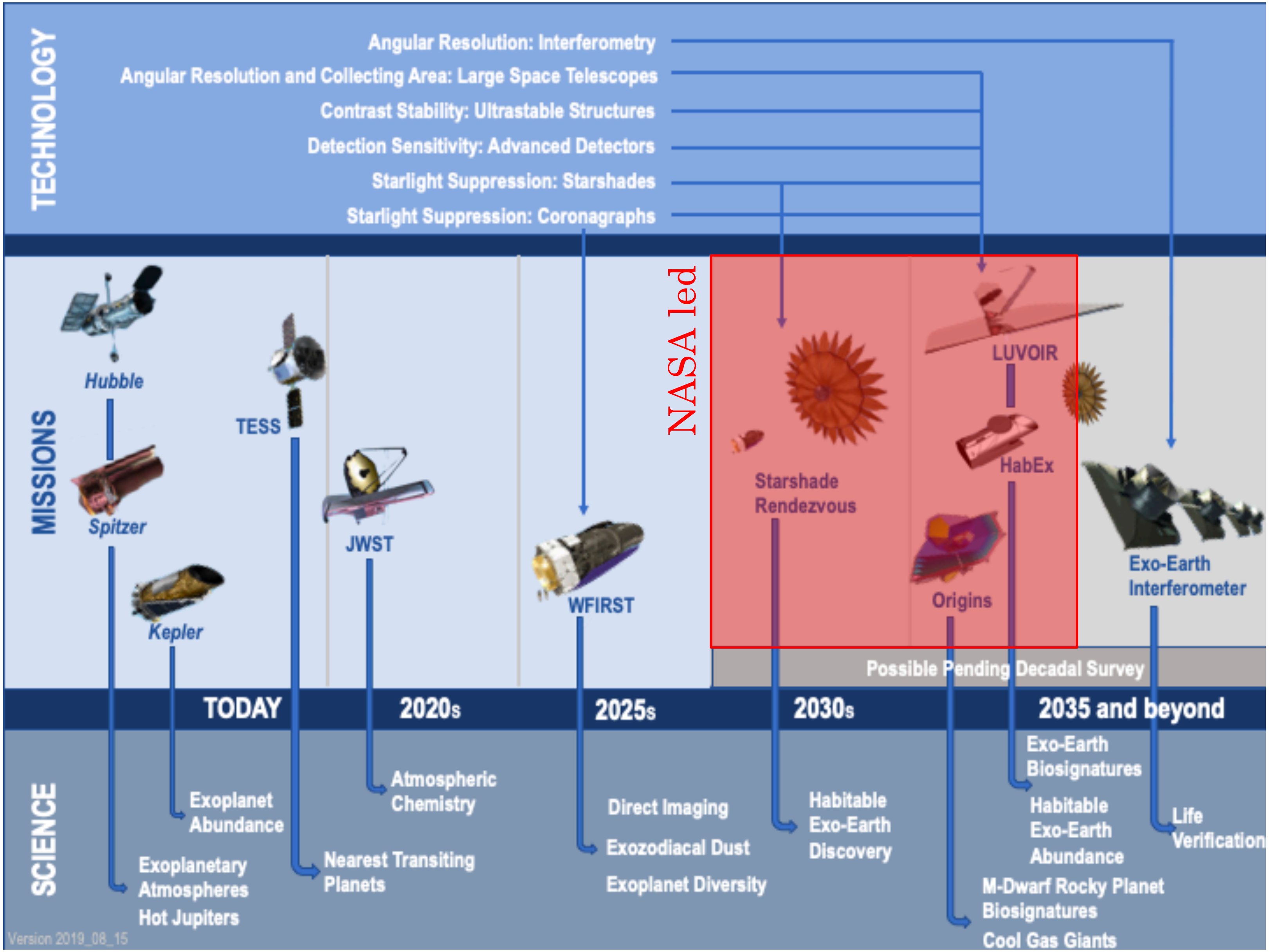


TECHNOLOGY

Angular Resolution: Interferometry

Angular Resolution and Collecting Area: Large Space Telescopes

Contrast Stability: Ultrastable Structures

Detection Sensitivity: Advanced Detectors

Starlight Suppression: Starshades

Starlight Suppression: Coronagraphs

MISSIONS

Hubble

Spitzer

Kepler

TESS

JWST

WFIRST

NASA led

Starshade Rendezvous

LUVOIR

HabEx

Origins

Exo-Earth Interferometer

Possible Pending Decadal Survey

TODAY | 2020s | 2025s | 2030s | 2035 and beyond

SCIENCE

Exoplanetary Atmospheres

Hot Jupiters

Exoplanet Abundance

Nearest Transiting Planets

Atmospheric Chemistry

Direct Imaging

Exozodiacal Dust

Exoplanet Diversity

Habitable Exo-Earth Discovery

Exo-Earth Biosignatures

Habitable Exo-Earth Abundance

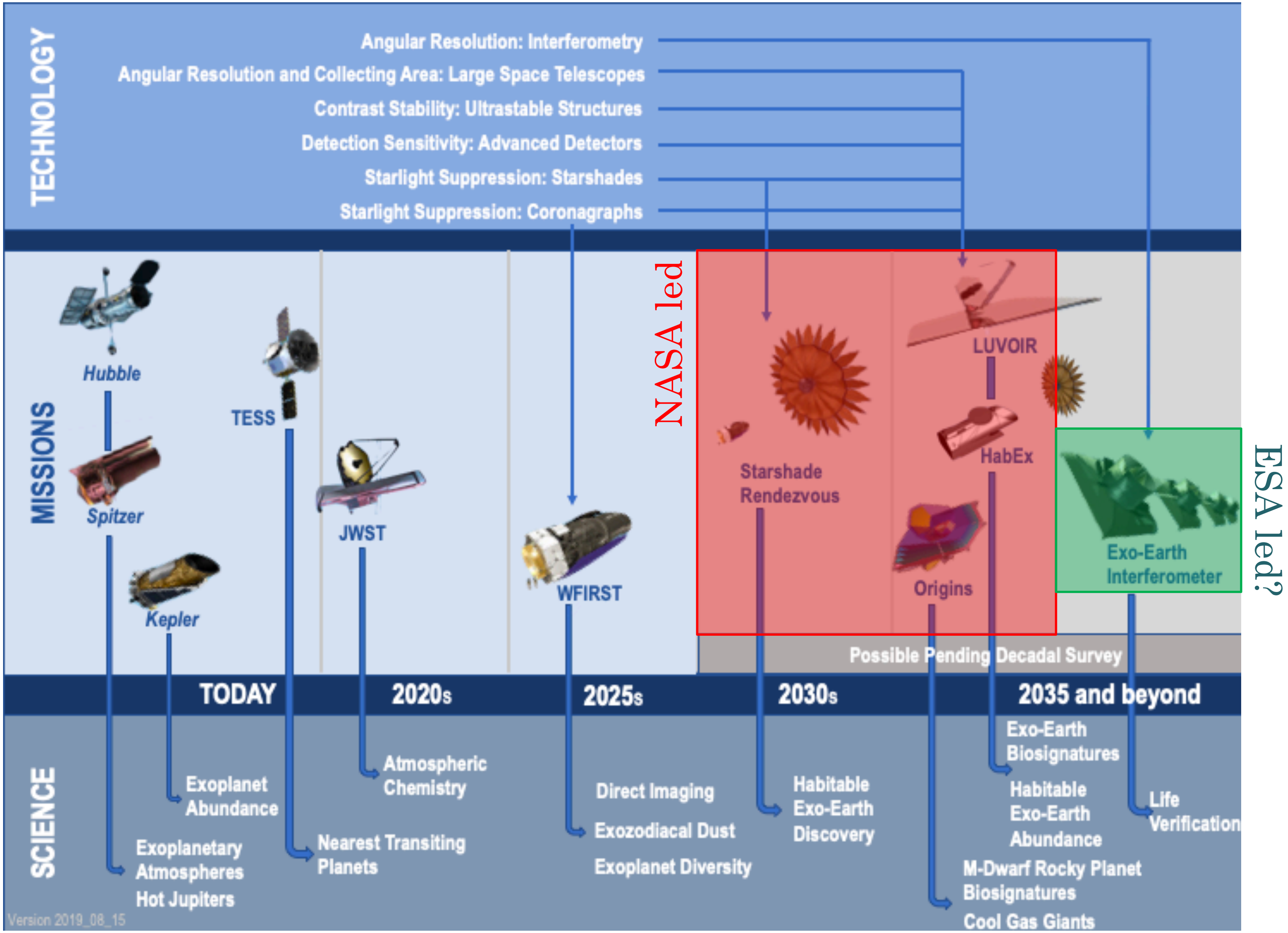
M-Dwarf Rocky Planet Biosignatures

Cool Gas Giants

Life Verification

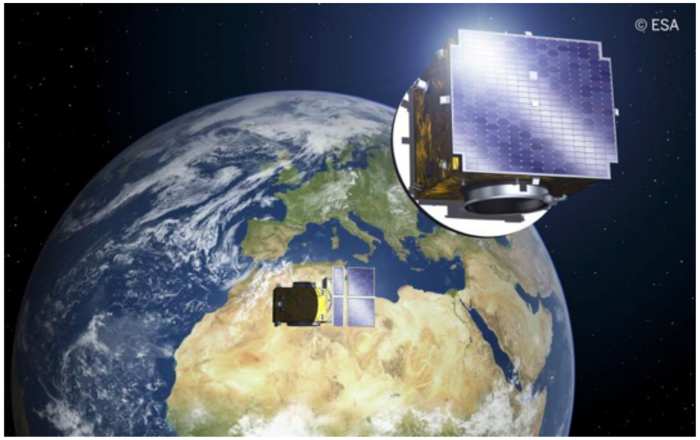
Version 2019_08_15

The road ahead

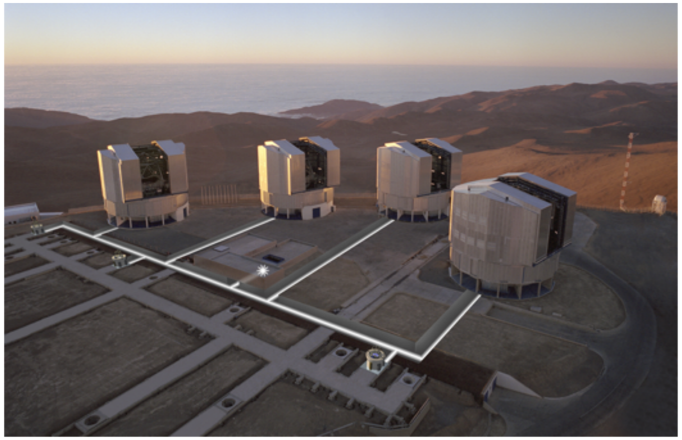


Europe is a strong position to lead this effort

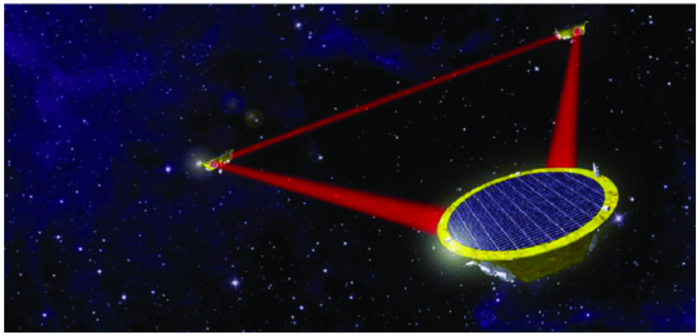
Formation flying – Proba 3



Precision interferometry (ESO's VLTI)



Space interferometry -- LISA



MIR instruments

ARIEL

James Webb Space Telescope

JWST

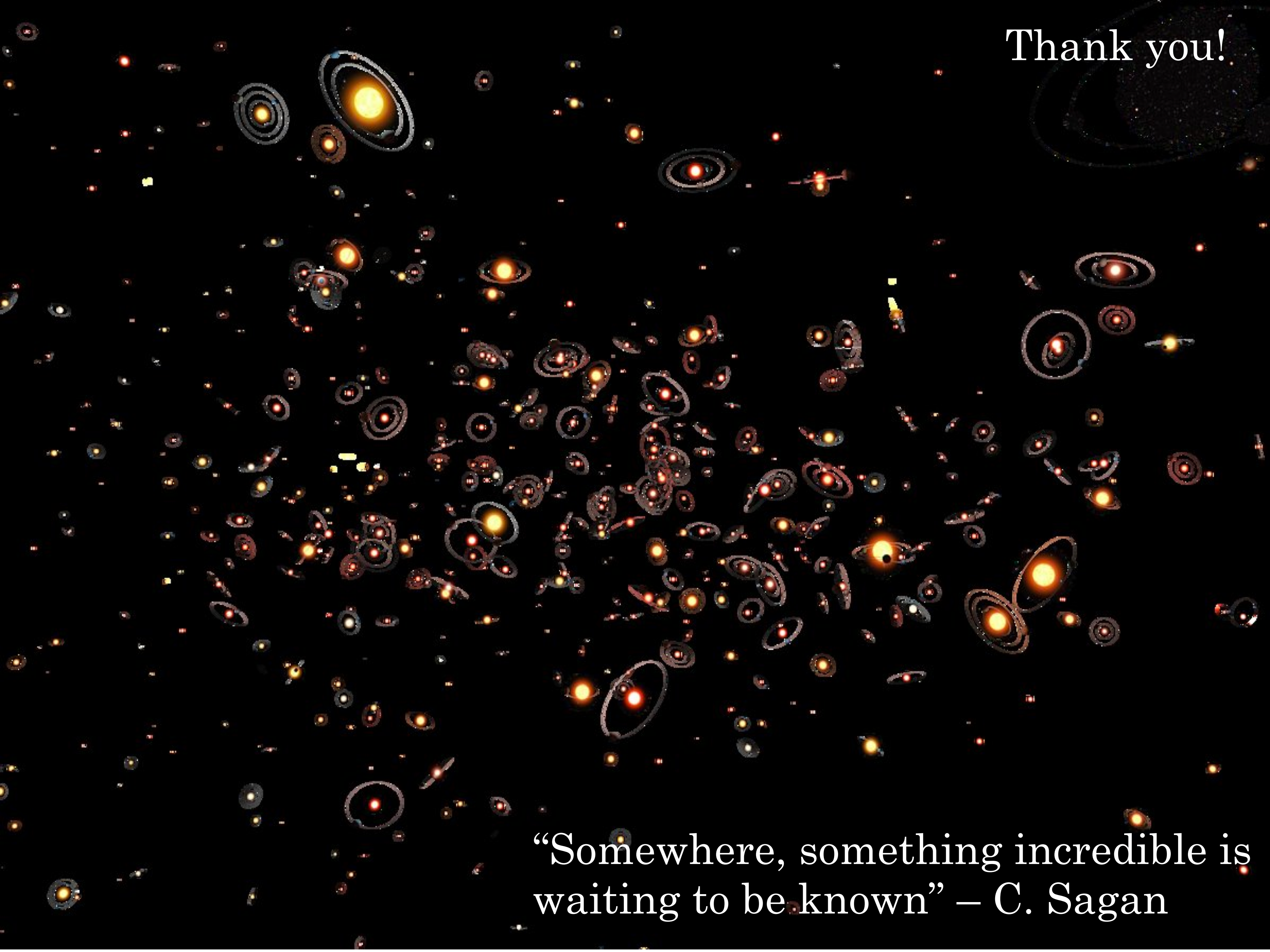
NASA • ESA • CSA

MIRI

Cryogenics (ESA's Herschel)

Summary

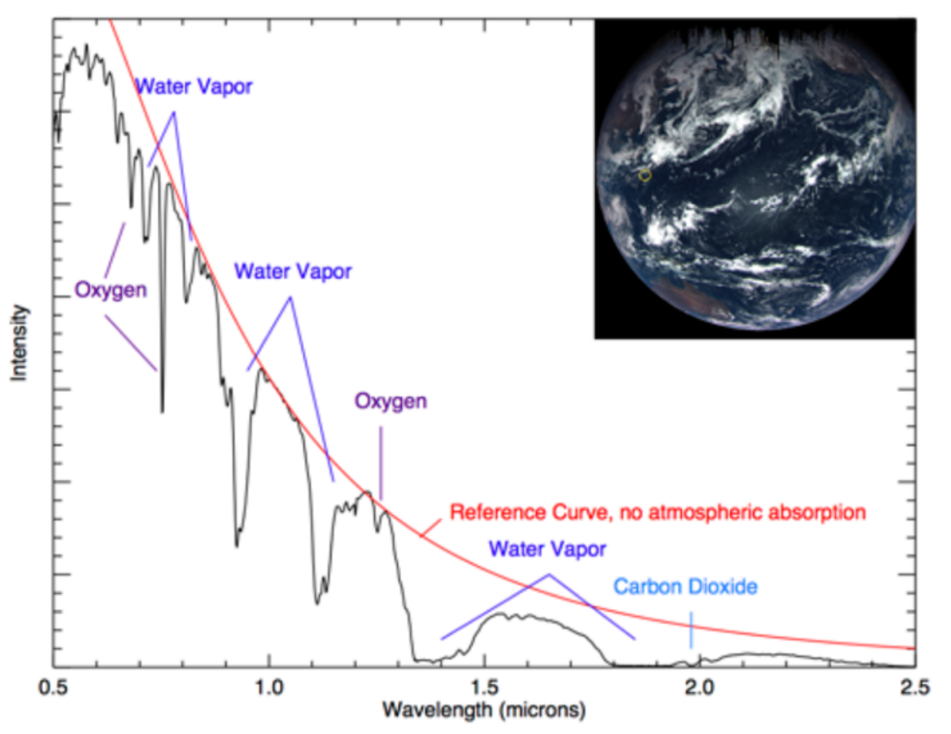
- Huge progress over the past decade in key technologies (formation flying, starlight suppression) and operation of nulling interferometers from the ground
- Instrumental requirements met in the lab
- Next step: space qualification (e.g., cryogenic deformable mirrors) and wavelength coverage expansion
- Strong science theme for ESA's voyage2050 program (see e.g., I. Snellen and S. Quanz white papers)
- Europe in strong position to take the leadership



Thank you!

“Somewhere, something incredible is waiting to be known” – C. Sagan

Backup

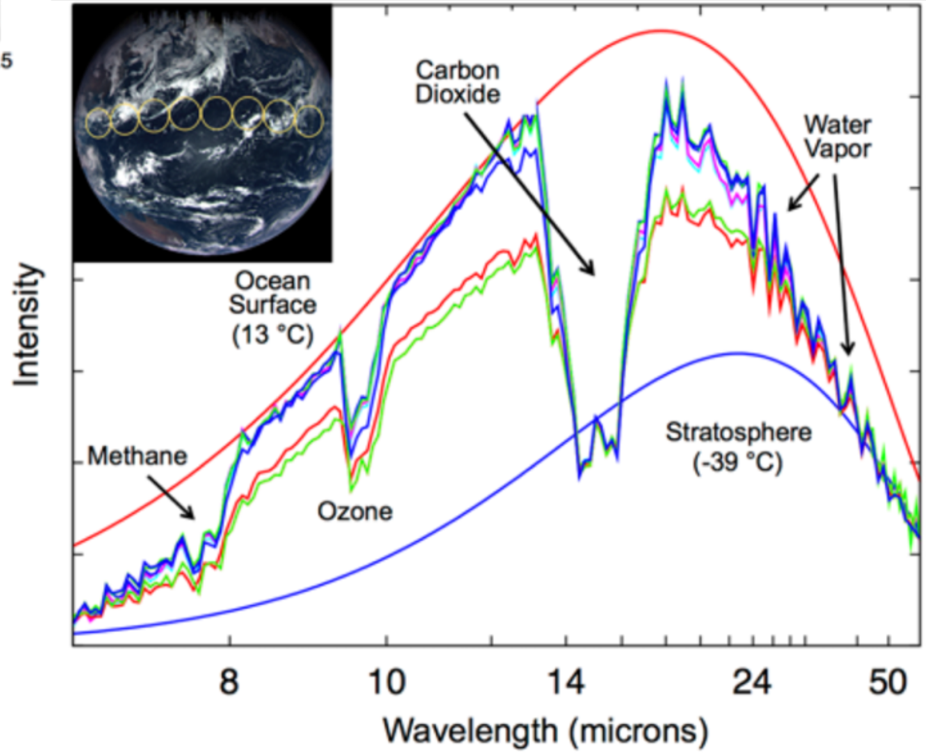


OSIRIS-Rex **optical** spectrum

- Evidence of gas-phase H_2O over the entire planet.
- Substantial concentration of O_2

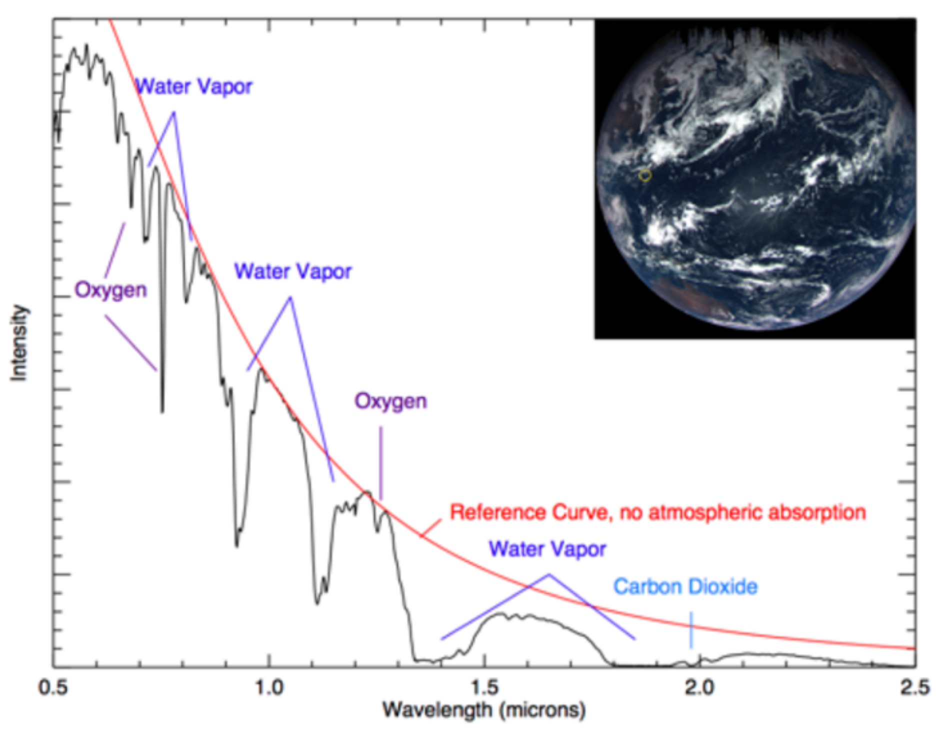
OSIRIS-Rex **infrared** spectrum

- Evidence of CO_2, O_3 , CH_4, and H_2O
- Atmosphere transparent between 8.3 and 12.5 µm (probe of surface temperatures => <u>habitability</u>)



Lauretta et al. 2018

Credit: NASA/Goddard/University of Arizona/Arizona State



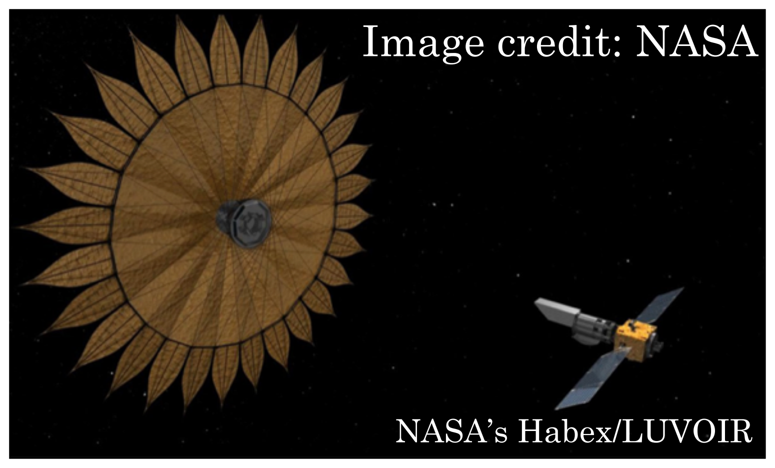
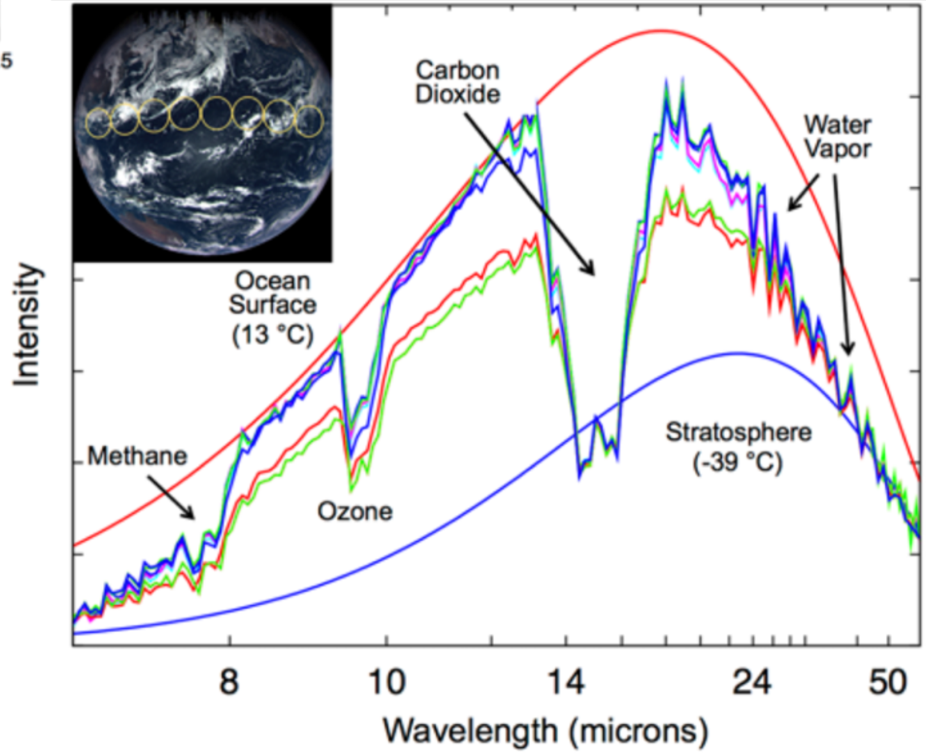


Image credit: NASA



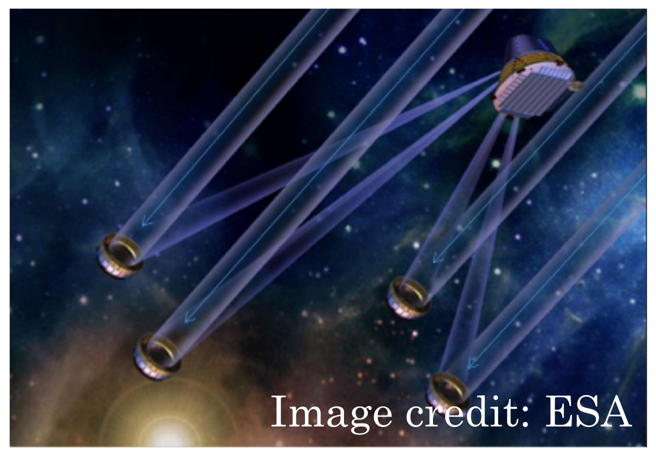
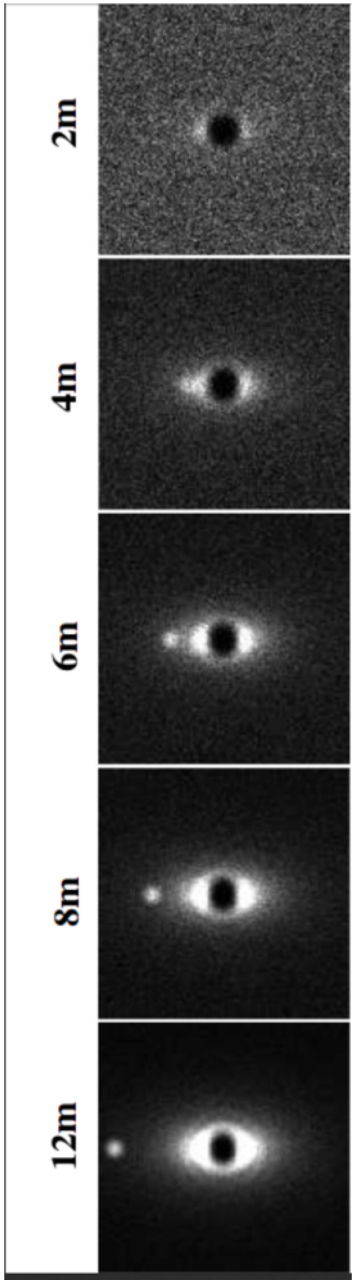


Image credit: ESA

Lauretta et al. 2018

Credit: NASA/Goddard/University of Arizona/Arizona State

Need a big aperture



Exoplanet imaging mission science return increases **very quickly** with aperture:

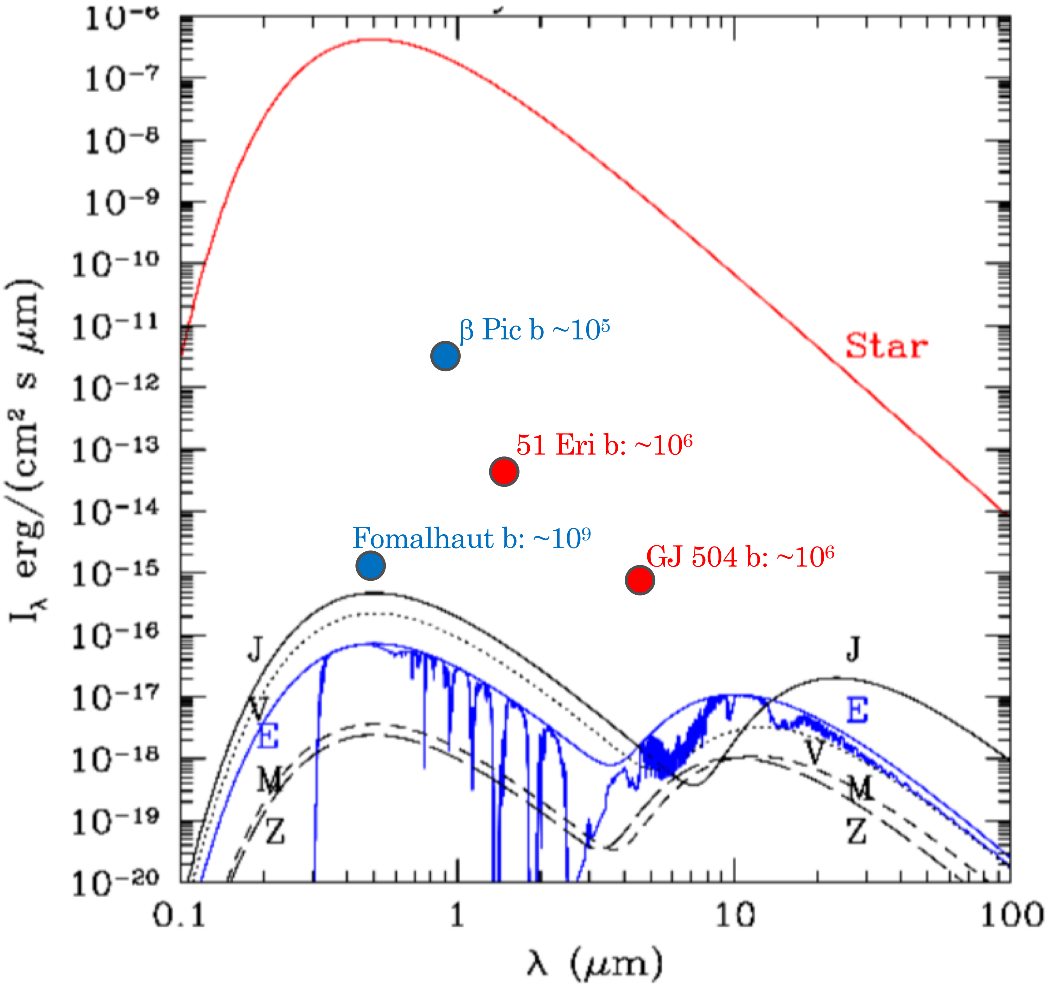
Efficiency & Yield
- Number of IWA-accessible planets goes as D^3 (Stark et al. 2015)
- Exposure time required to reach given SNR goes as D^{-4} for most low-mass planets (zodi+exozodi → background-limited detection)

Characterization
- Access to longer wavelength spectroscopy, λ_{max}~ D
- Light can be sliced in multiple bins: spectral resolution, time domain,
polarization
- Better astrometry → better orbits, dynamical masses
- Resolving (time-variable) structures in exozodi

Data quality
- Higher angular resolution → less confusion between multiple planets,
exozodi clumps
- More light → better PSF calibration

Diversity
- Larger aperture allows habitable planets to be observed around a wider range of stellar types

Imaging challenge 1: planet/star contrast



Visible:
~10^9:Fomalhaut b but 150x sep
(Kalas et al. 2008)

~10^5: β Pic b but 9x sep
(Males et al. 2014)

Infrared: ~10^6
H band: 51 Eri b but 13x sep
(Macintosh et al. 2015)

L band: GJ 504b but 40x sep
(Skemer et al. 2016)

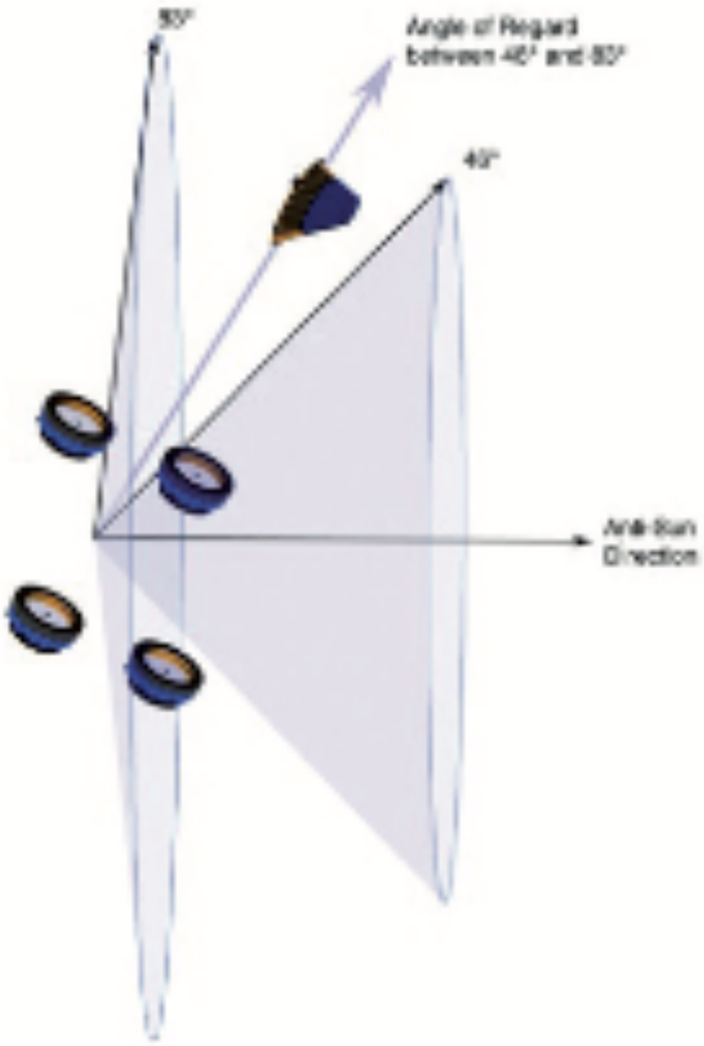
Illustrative mission concept

Science driven: characterize at least 30-40 rocky planets with

$0.5\ R_{\mathrm{Earth}} < R_{\mathrm{planet}} < 1.5\ R_{\mathrm{Earth}}$

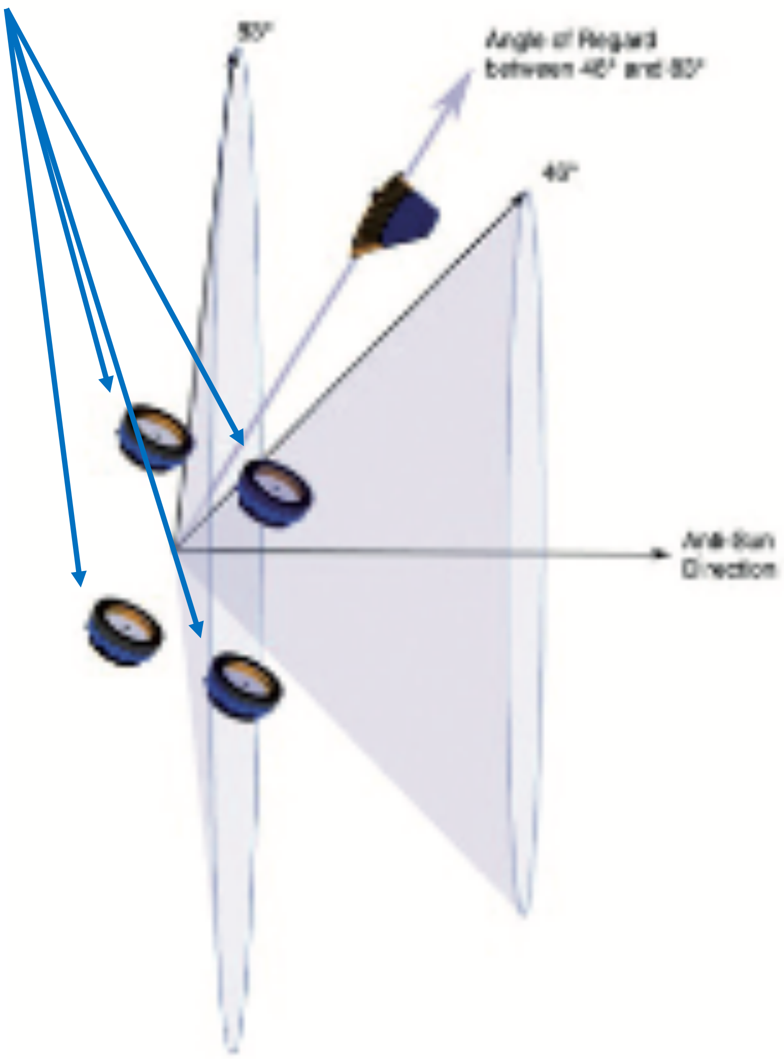
and

$0.35\ S_{\mathrm{Earth}} < S_{\mathrm{planet}} < 1.75\ S_{\mathrm{Earth}}$



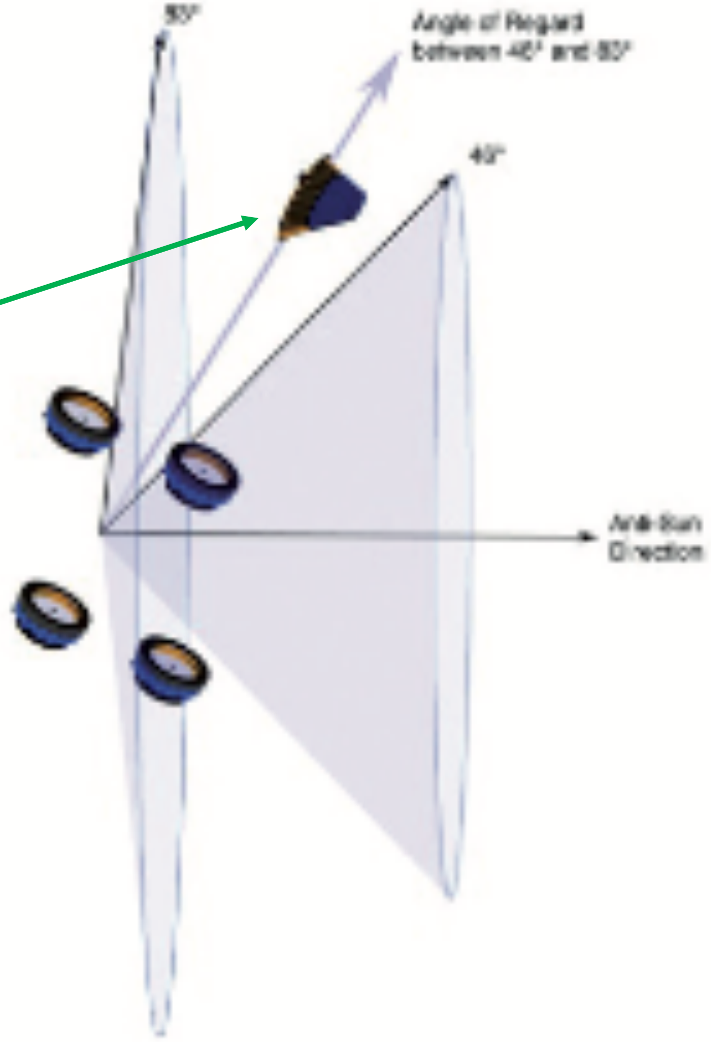
Illustrative mission concept

- At least three identical collector spacecraft:
  - At least 2m in diameter
  - Passively cooled to 40K
  - Max baselines: 60 x 400m



Illustrative mission concept

- At least three identical collector spacecraft:
    - At least 2m in diameter
    - Passively cooled to 40K
    - Max baselines: 60 x 400m
- One beam combiner spacecraft
    - Detector @ 8K
    - 5-20 microns
    - 20-100 spectral resolution
    - Modal filtering
    - Phase and amplitude control
    - ~1000m above



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- 3 years of operation (5 years if search phase is required)