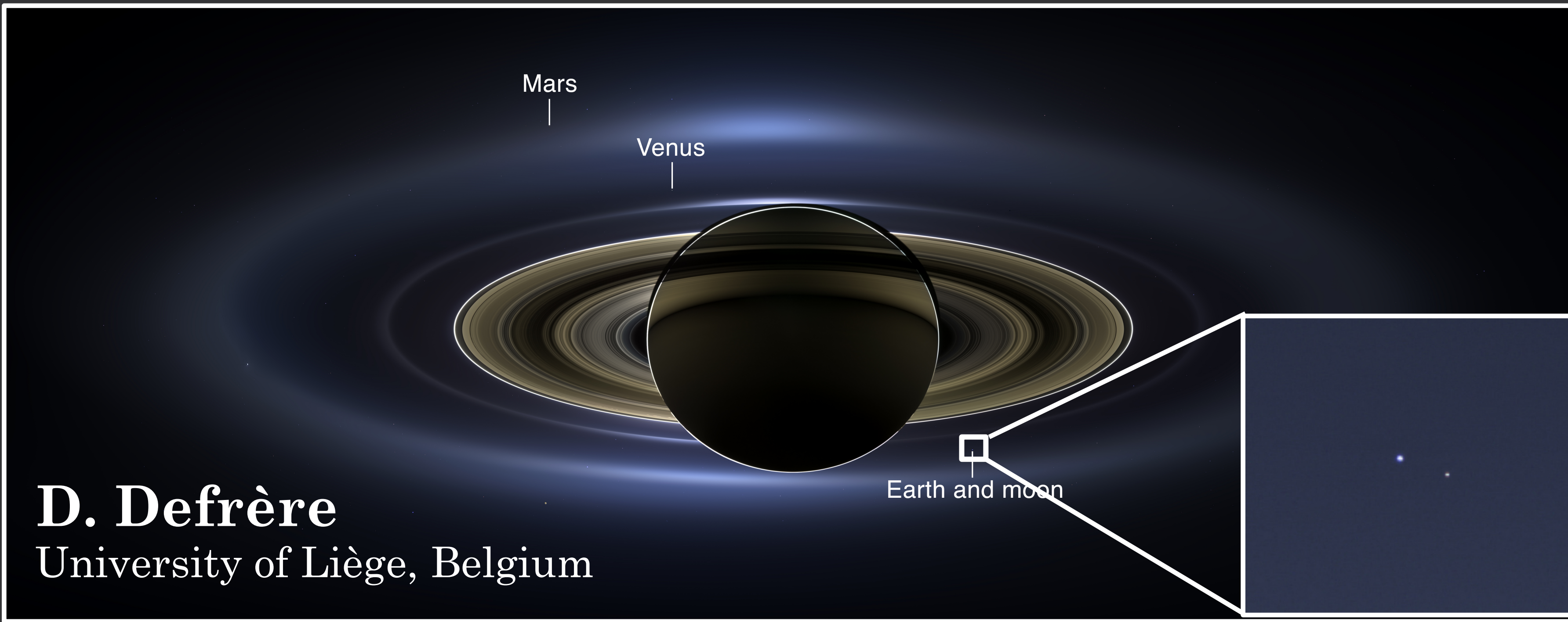
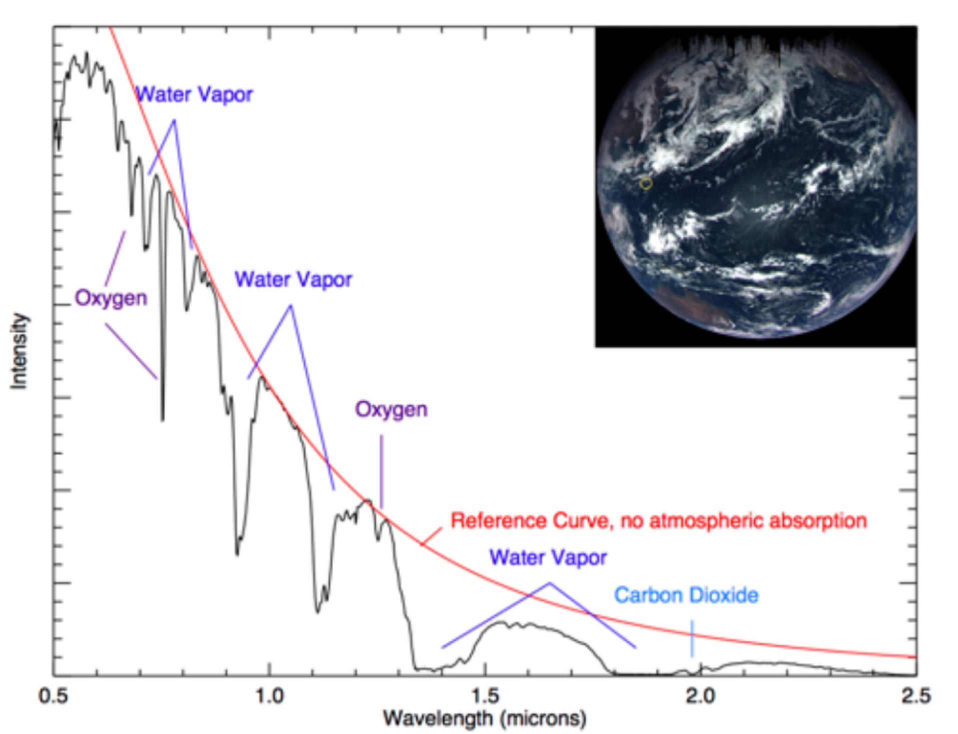
Requirements for Imaging and Spectroscopy of Habitable Earths



D. Defrère
University of Liège, Belgium

April 11st 2018 -- Caltech – Pasadena

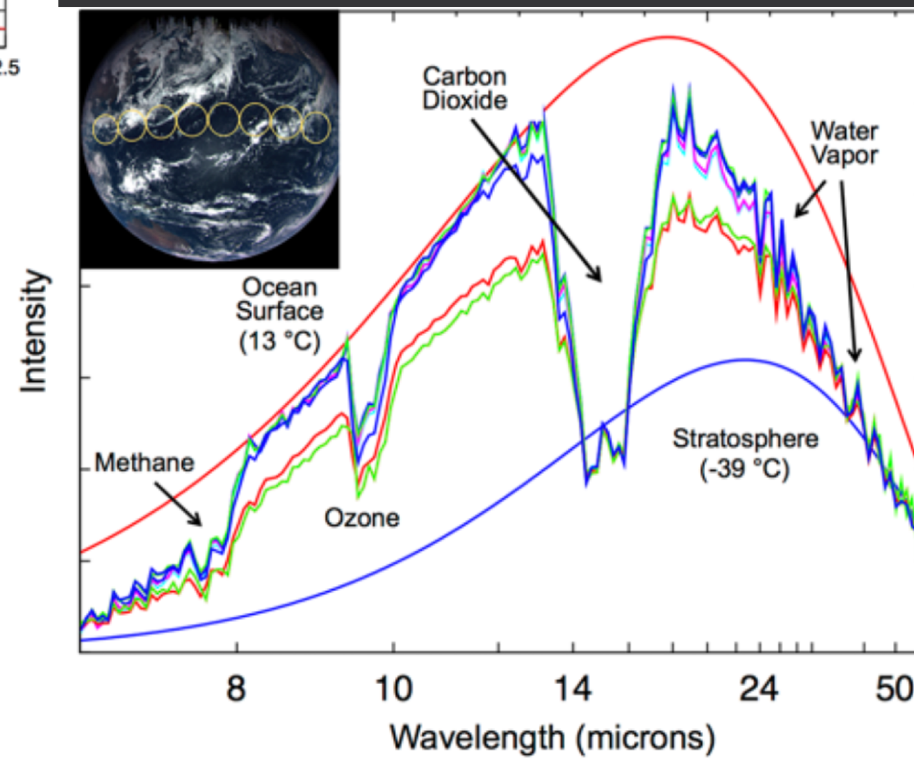


OSIRIS-Rex **optical** spectrum

- 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)



Lauretta et al. 2018

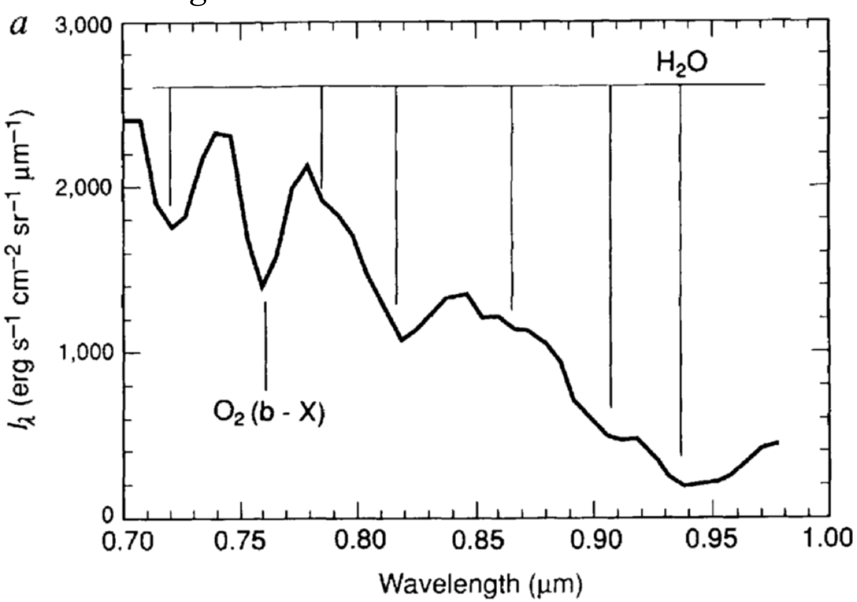
Credit: NASA/Goddard/University of Arizona/Arizona State

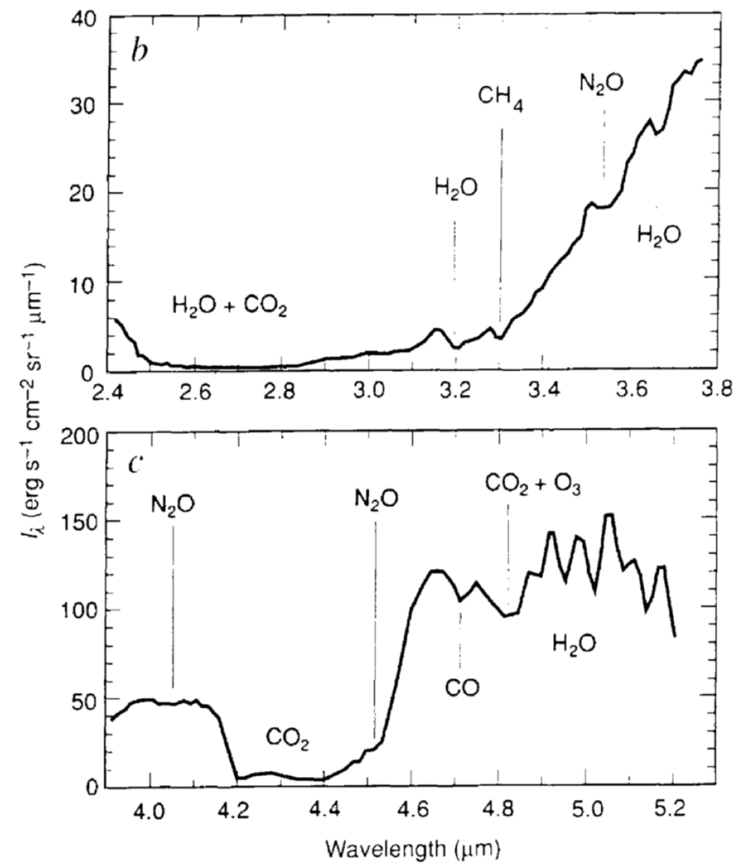
Scientific motivation

Are we alone in the Universe? Do other life-bearing planets exist? How common is Earth? Where is everyone?

Galileo observations of Earth: large amount of O_2 and traces of CH_4 considered as indicator for life (Sagan 1993)

Sagan 1993





Scientific goals

Ambitious/extraordinary endeavors can be broken in intermediate science goals:

SAG 5

Goal 1: Determine the overall architectures of a sample of **nearby** planetary systems.

Goal 2: Determine or constrain the atmospheric compositions of discovered planets.

Goal 3: Determine or constrain planetary radii and masses.

Understanding planet atmospheric processes and their evolutionary histories is crucial for unambiguously identifying extraterrestrial life

Science goals

Goal 1: Determine the overall architectures of a sample of **nearby** planetary systems. Why huge diversity? Formation and evolution processes? Interaction/correlation with star and dust belts? Typical planet architectures? How common is the solar system?

OBSERVING NEARBY STARS IS REQUIRED IN ORDER TO GET THE COMPLETE PICTURE!

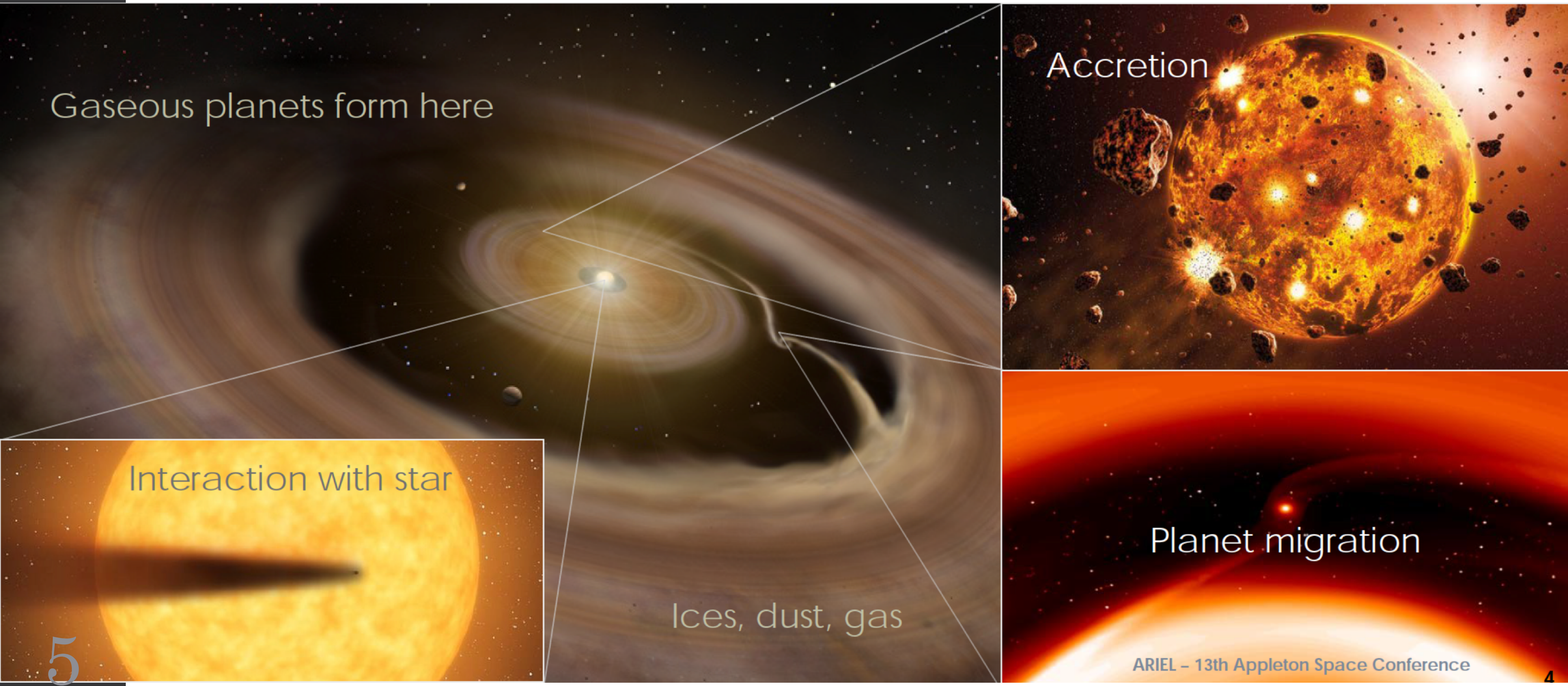
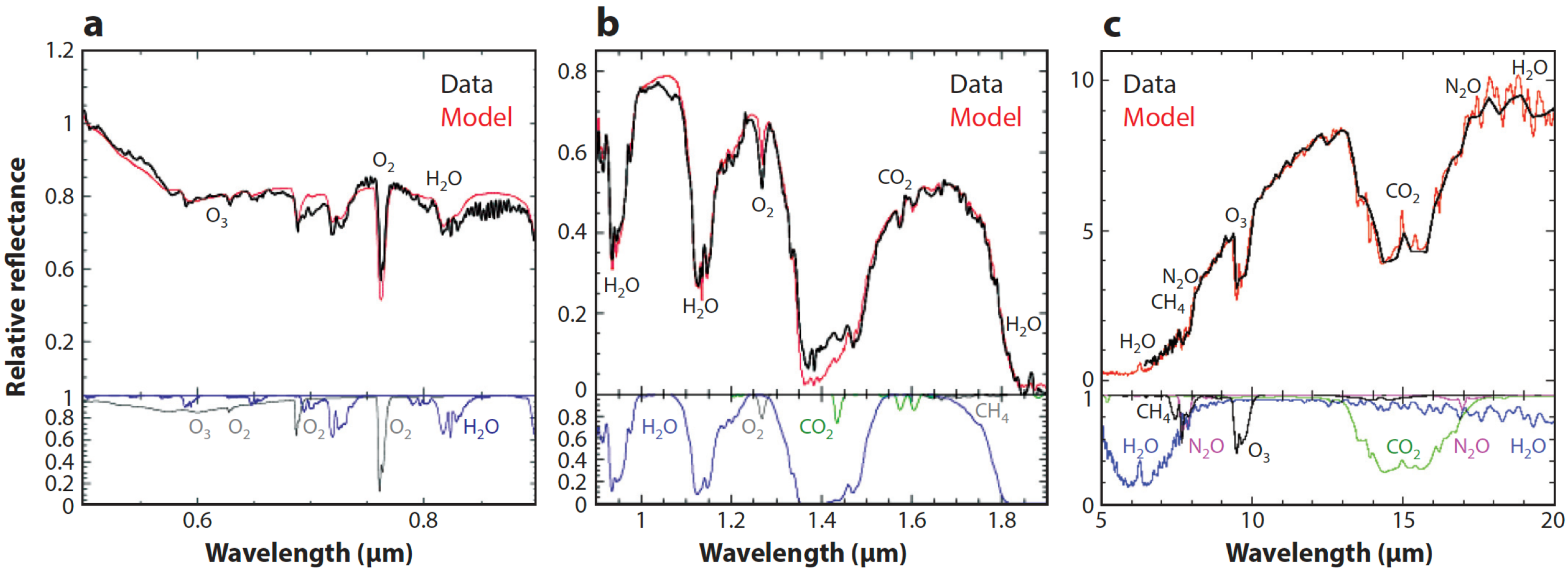


Image credit: G. Tinetti (ARIEL)

Science goals

<u>Goal 2</u>: Determine or constrain the atmospheric compositions of discovered planets. Understand chemical diversity. Which planets have an atmosphere? Which planets have water on their surface? Which planets have continents and oceans?

Visible to infrared wavelengths rich in atmospheric signatures



Kaltenegger et al. 2017

Science goals

Goal 2: Determine or constrain the atmospheric compositions of discovered planets. Understand chemical diversity. Which planets have an atmosphere? Which planets have water on their surface? Which planets have continents and oceans?

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	Suggestion of life

(see complete list with wavelength and bandwidth in SAG15 report)

Science goals

Goal 2: Determine or constrain the atmospheric compositions of discovered planets. Understand chemical diversity.

IS ELEMENTAL COMPOSITION CORRELATED
TO EXOPLANET PROVENANCE OR STELLAR METALLICITY?

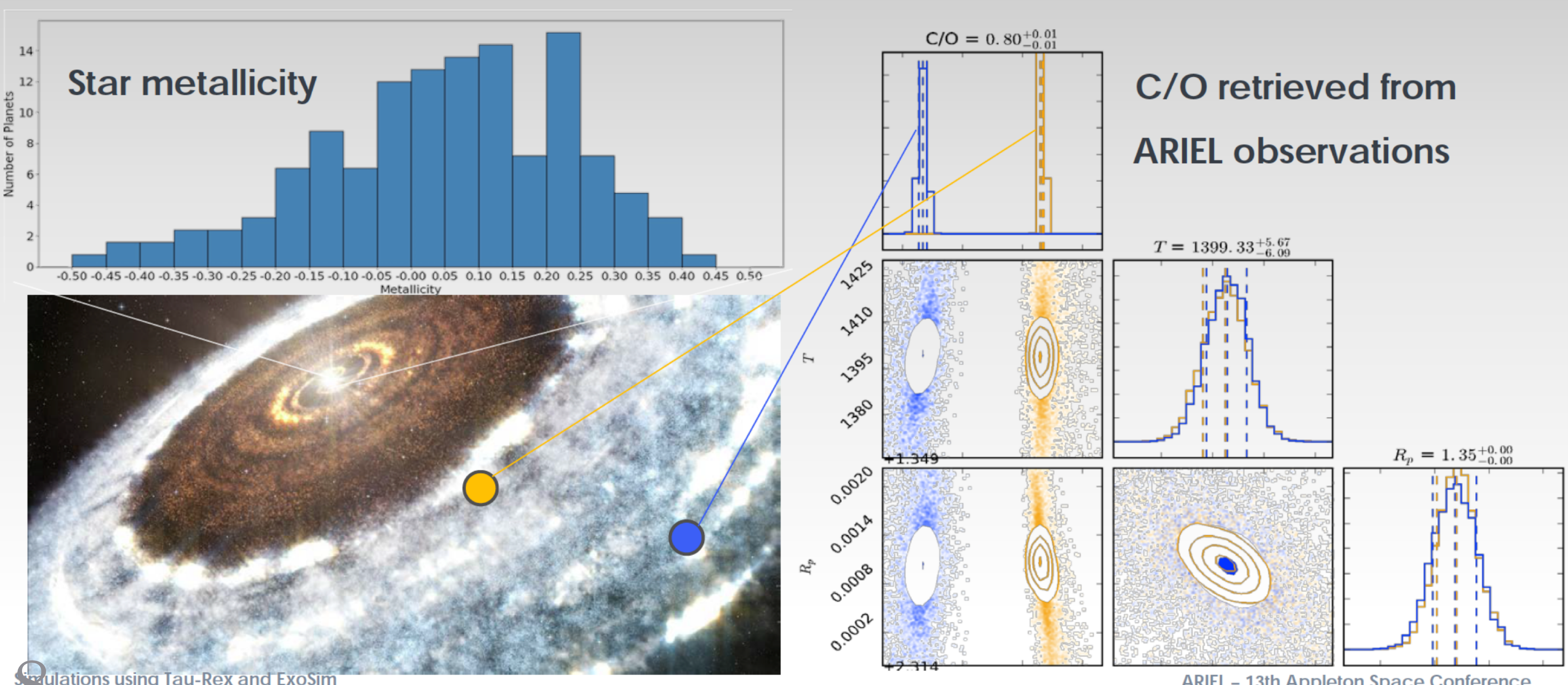
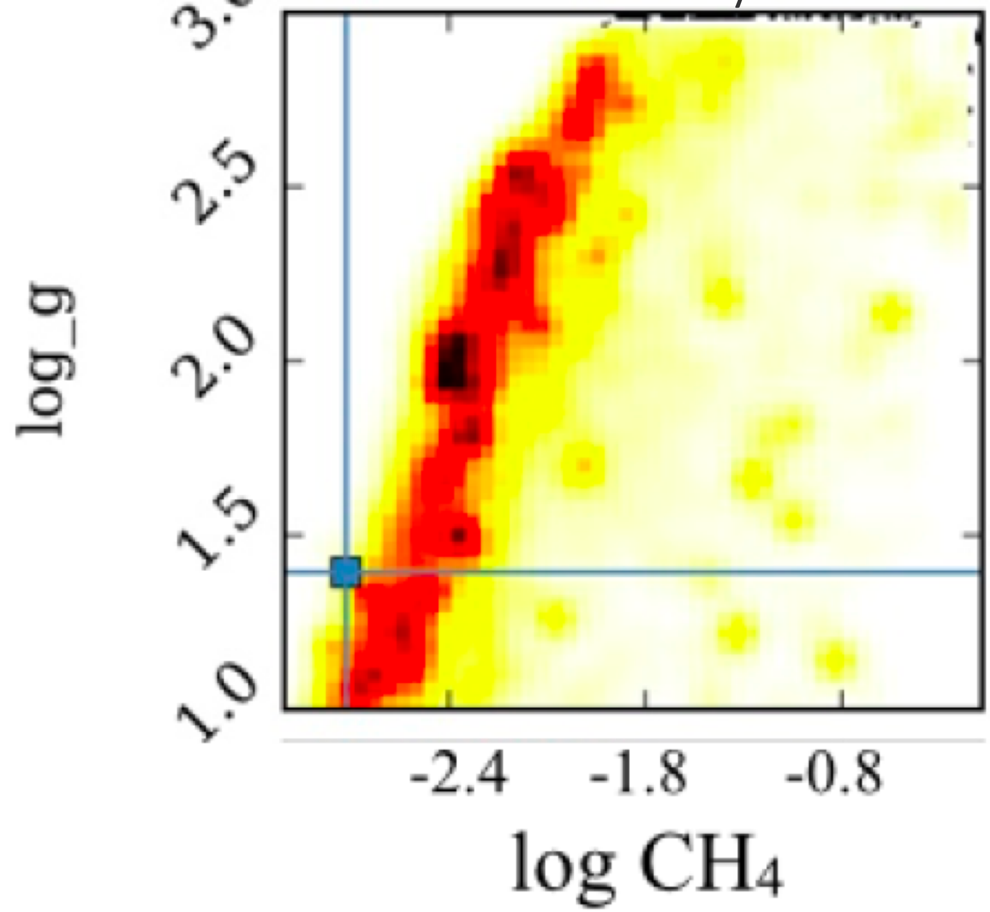


Image credit: G. Tinetti (ARIEL)

Science goals

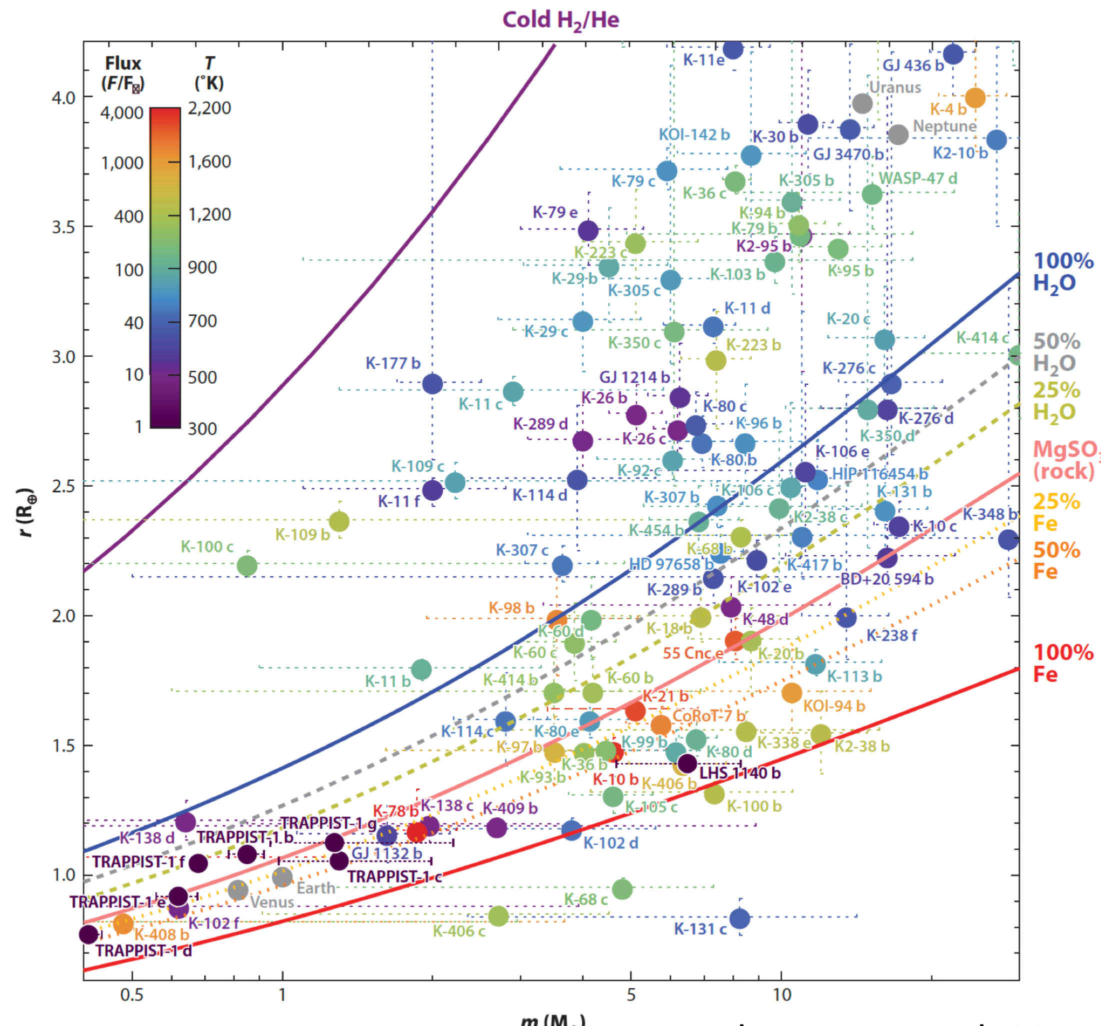
Goal 3: Determine or constrain planetary radii and masses. Required to break model degeneracies. Ex: gravity vs CH_4

Morley et al. 2014



Science goals

- <u>Goal 3</u>: Determining or constraining planetary radii and masses. Radius stronger constraint on "rockyness":



Kaltenegger et al. 2017

Summary of science goals (from SAG15)

Science Questions and Required Data for Direct Imaging Exoplanet Missions

	Science Questions	Targets	Data Type and Quality
Planetary Sys. Properties	A1 Planetary System Diversity	Statistical Studies of Planetary Systems	1) Multi-epoch Imaging: Planetary Orbits 2) Phot/Spec/RV/Astrom: Planet Masses
	A2 Planetsimal Belts, Exo-Zodi Disks, Formation of Planetary Systems?		1) O/IR Imaging: Locations of Dust Belts 2) Planet masses and orbits (RV, Astrom.)
Planet Properties	B1 Rotation and Obliquitiy	Studies of Individual Planets	1) Time-Resolved Phot/Spec 2) High-Res Spec. for Rotational Period 3) Lightcurves at Multiple Orb. Phases: Obliquity
	B2 Which Rocky Planets have Surface Liquid Water?		1) Time-Resolved Obs: Ocean Glint 2) Rotational Mapping: Oceans 3) Water Line Spectroscopy
	B3 Aerosols and Composition in Giant Planets		1) Low-res., broad range spectroscopy 2) Time-resolved Phot. for Cloud Mapping 3) Optical/Near-IR Colors
	B4 Terrestrial Planets Atmospheric Composition		1) Low-res., broad range spectroscopy 2) Optical/Near-IR colors 3) Planet masses and orbits
Planetary Processes	C1 What Processes/Properties Influence Atmospheric Circulation?	Statistical Studies of Groups of Planets	1) Multi-epoch, moderate to high-res. NIR spectroscopy
	C2 Key evolutionary pathways for rocky planets?		1) Atmospheric Characterization (B4) 2) Planet Mass
	C3 Geological Activity/Interior Processes		1) Atmospheric Characterization (B4) AND 2) Surface mapping (B2) 3) Planet Mass (RV or astrom.)

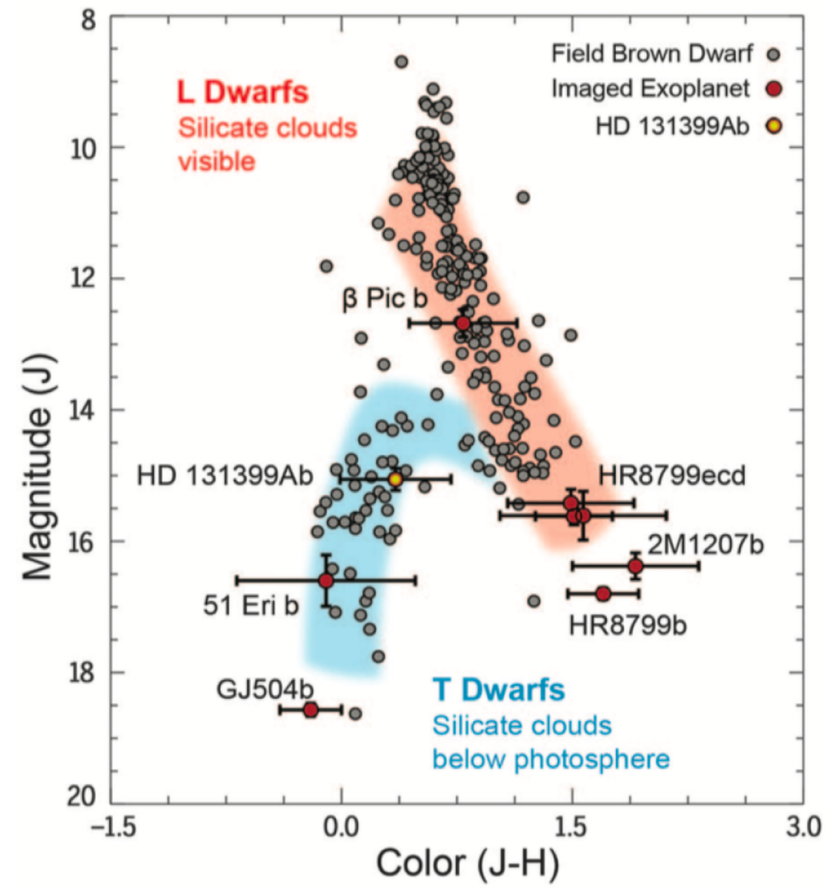
eos-nexus.org/sag15

EXOPAG/SAG15 Team and Daniel Apai / Univ. Arizona

And then? How to identify life?

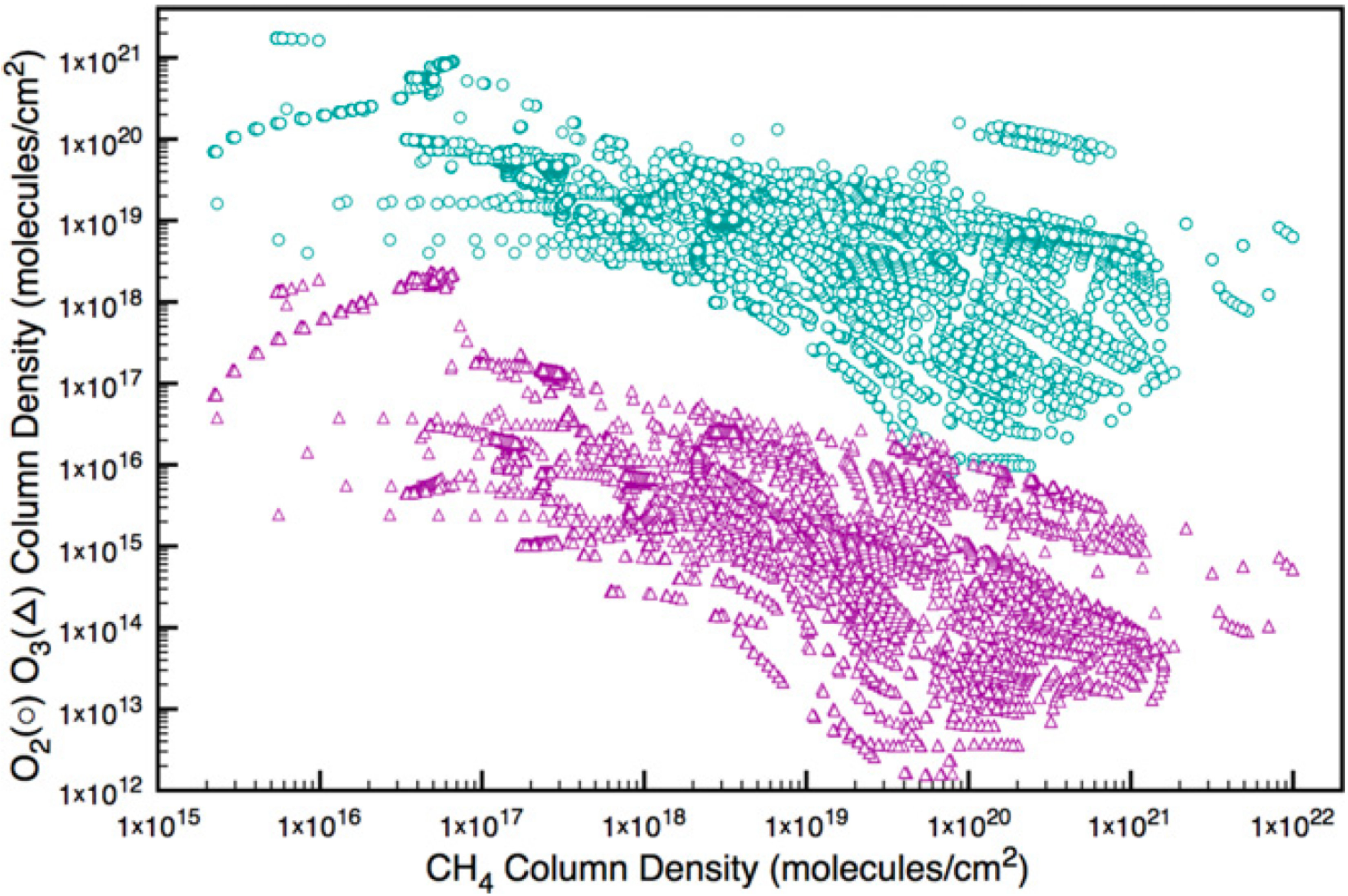
- Several important molecules to look for (ex: O_2, O_3, CH_4) but no clear/unambiguous biosignatures (false positives!)
- Necessary to better planet atmospheric processes and their evolutionary histories
- **Large sample is required**
- Population analysis:

Colour-colour or $CH_4/O_2/H_2O$ diagrams will allow to identify **families of planets** and maybe some **anomaly**



Wagner et al. 2016

And then? How to identify life?



Domagal-Goldman et al. 2014

Overview

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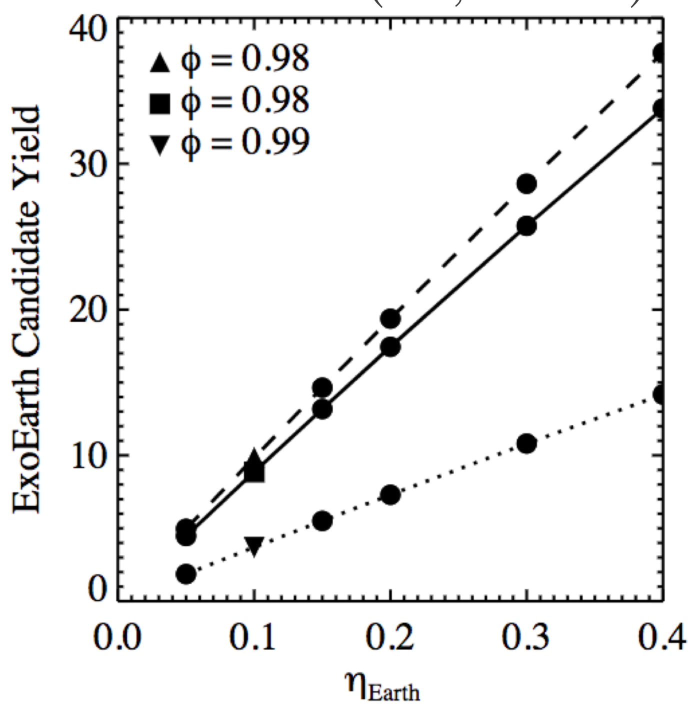
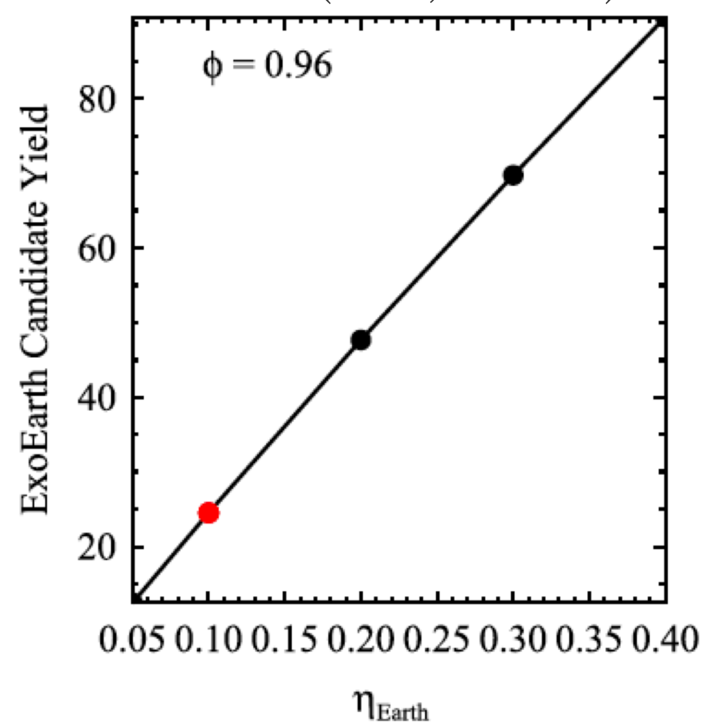
Exoplanet yield

- Obvious impact on the exoplanet yield of any mission design
- Many studies in the litterature (e.g., Stark et al. 2015 and 2016, Kammerer and Quand 2018, see Morgan's talk tomorrow)
- Ex: Stark et al. 2015 and 2016

Starshade (4m, 550nm)

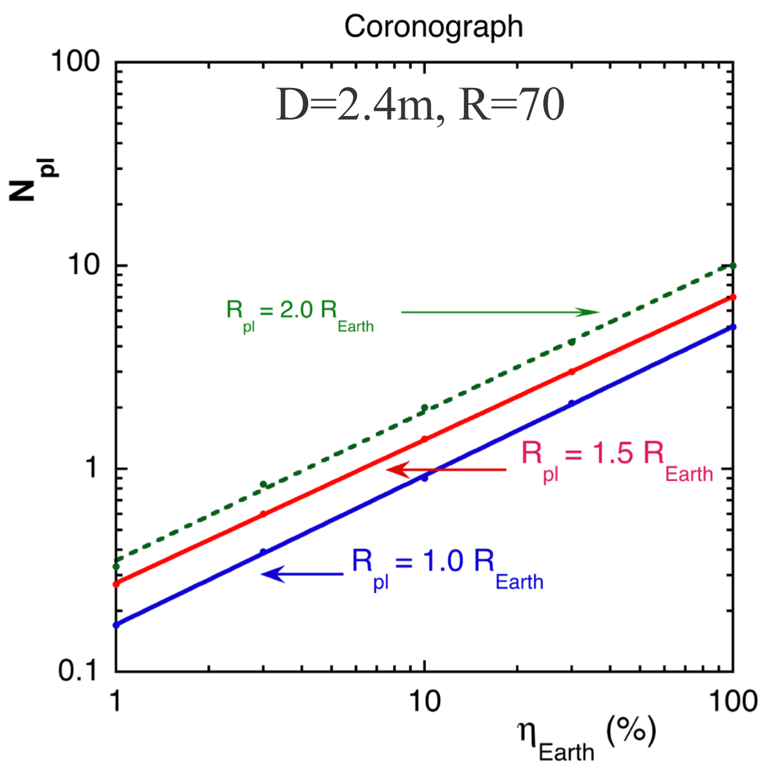


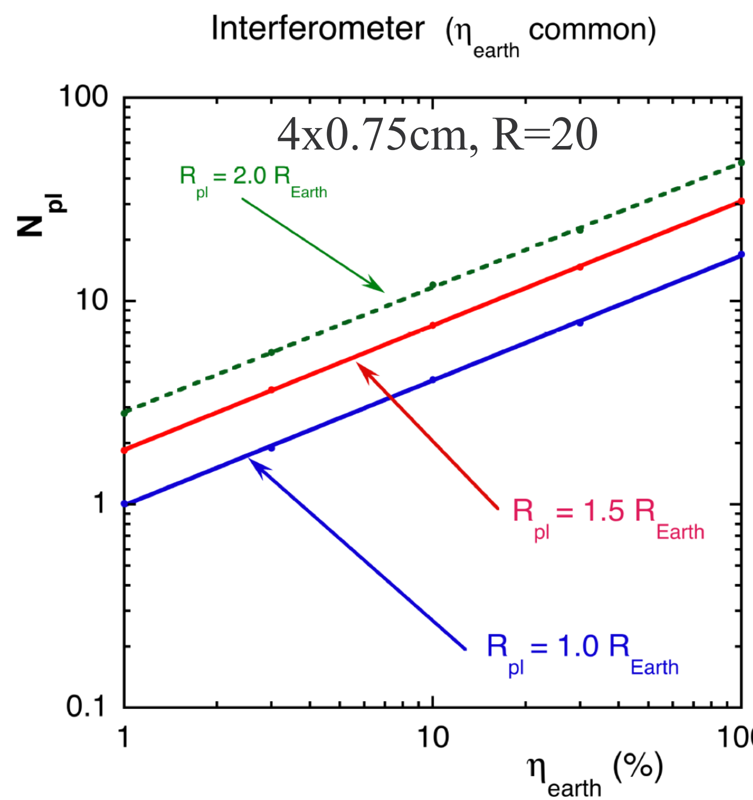
Corono (10m, 550nm)



Exoplanet yield

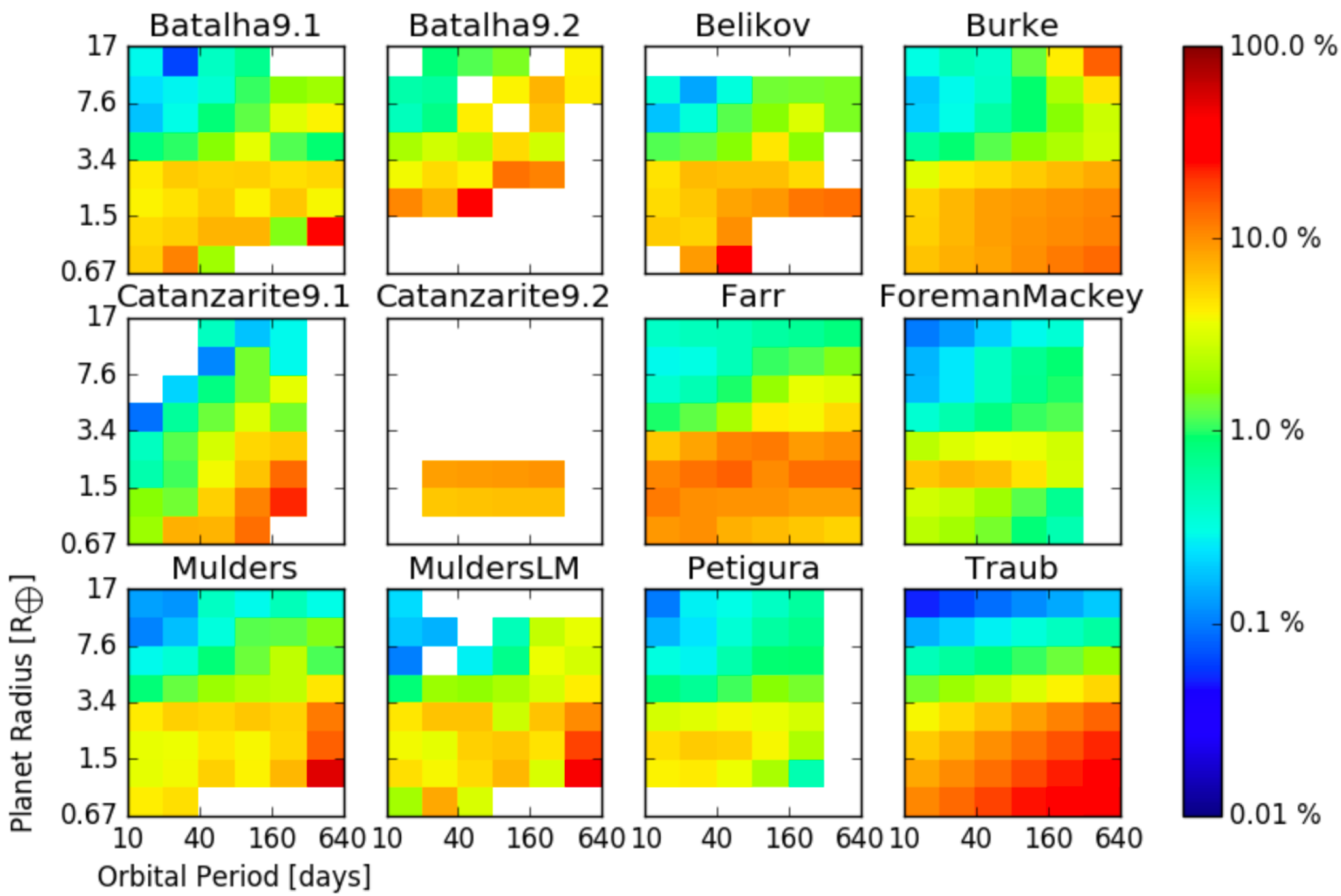
- Obvious impact on the exoplanet yield of any mission design
- Many studies in the litterature (e.g., Stark et al. 2016, Kammerer and Quand 2018, see Morgan's talk tomorrow)
- Ex 2: Léger et al. 2015





Exoplanet occurrence rate

- Vary according to authors



Source: SAG13 report

Kepler field vs nearby stars

Radius	Period	Fressin+ (2013)	Petiugra+ (2013)	Mulders+ (2015)	Fulton+ (2017)
1.4–2.8 R_E	< 100d	35%	33%	27%	44%
2–4 R_E	< 100d	24%	24%	23%	36%

	Howard+ (2012) *Kepler*	Wright+ (2012) *RV*
"Hot Jupiters" P < 10 d	0.4% R_P = 8–32 R_E	1.2% M_P = 0.1 M_J

- Multiple studies agree to ~50% level
- Hot Jupiter rate differs by ~3x
- Future surveys must plan for 2-3 variations in planet occurence rate (see SAG13 report)

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   - Spectroscopic characterization

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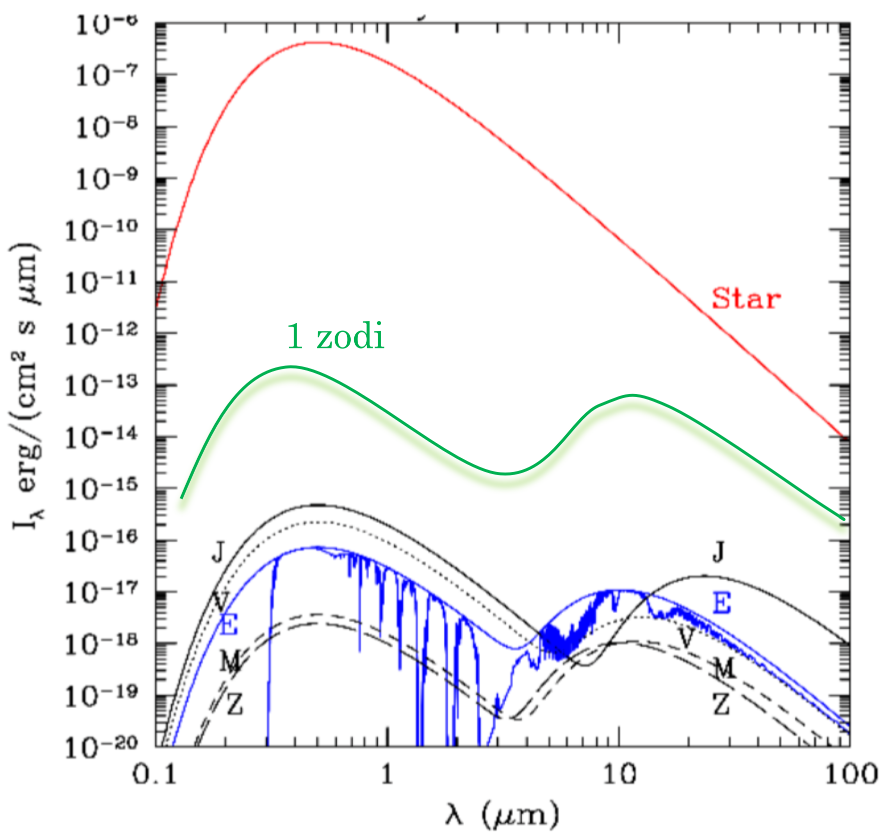
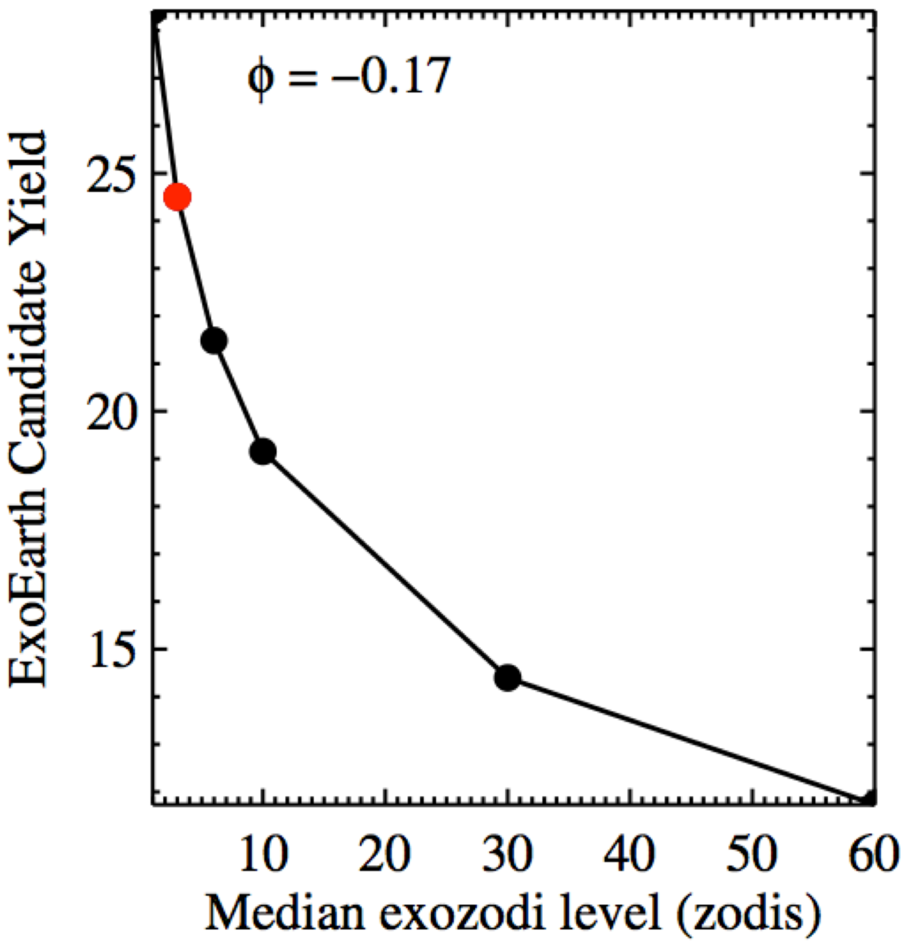
Exozodiacal dust – why do we care?

- Exozodis: dust in or near the HZ of stars
- Source of noise and confusion
  - Solar zodiacal cloud ~300 times brighter than Earth (IR and V)
  - Asymmetric features can mimic the planetary signal.



Direct impact on science yield



Reduce exozodi by 10x, increase yield by ~ 2x

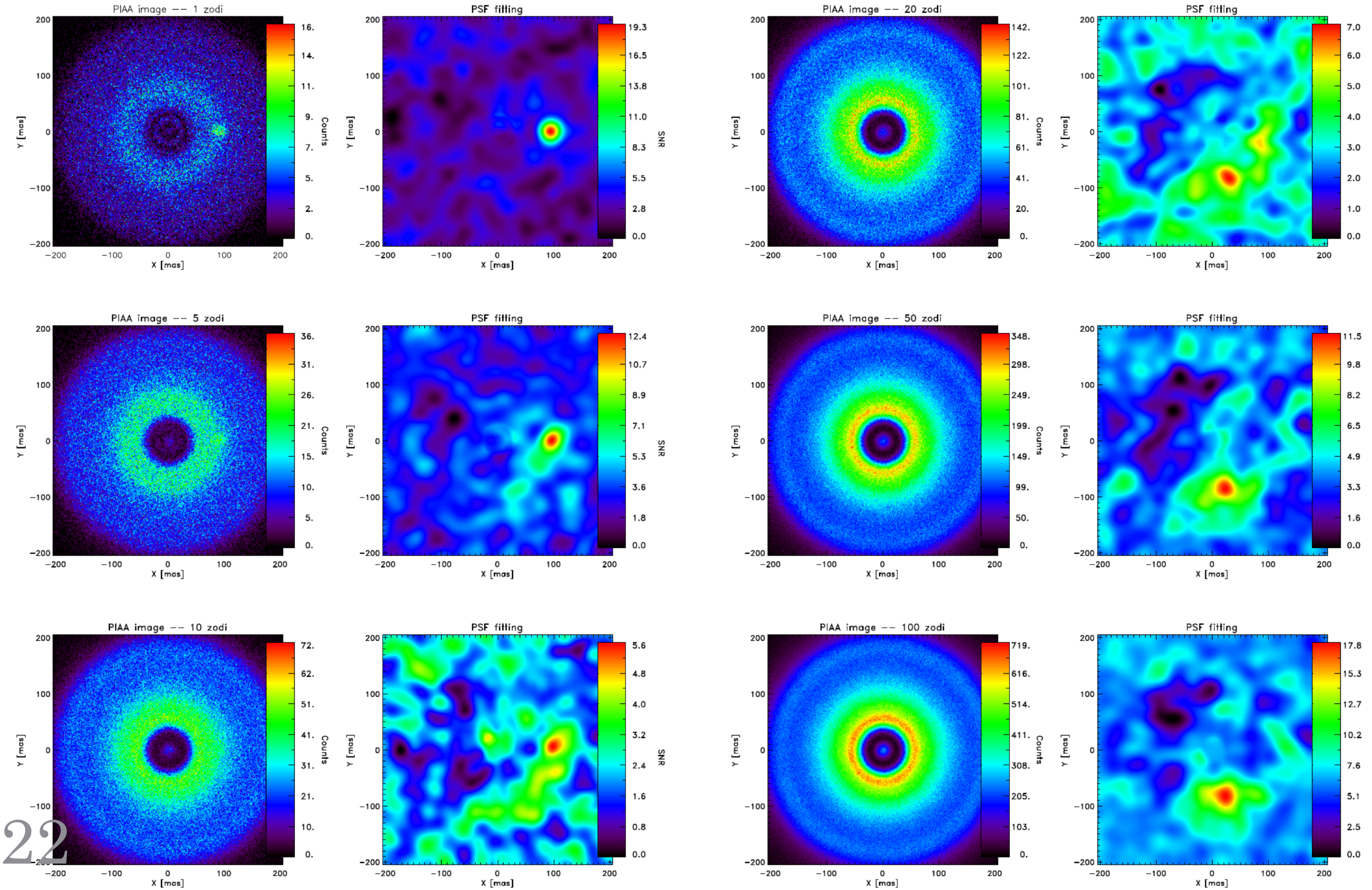
Stark et al., 2014, 2015

Tolerable dust density is ~15 zodis for IR imagers

Defrère et al. 2010

Source of confusion

Defrère et al. 2012

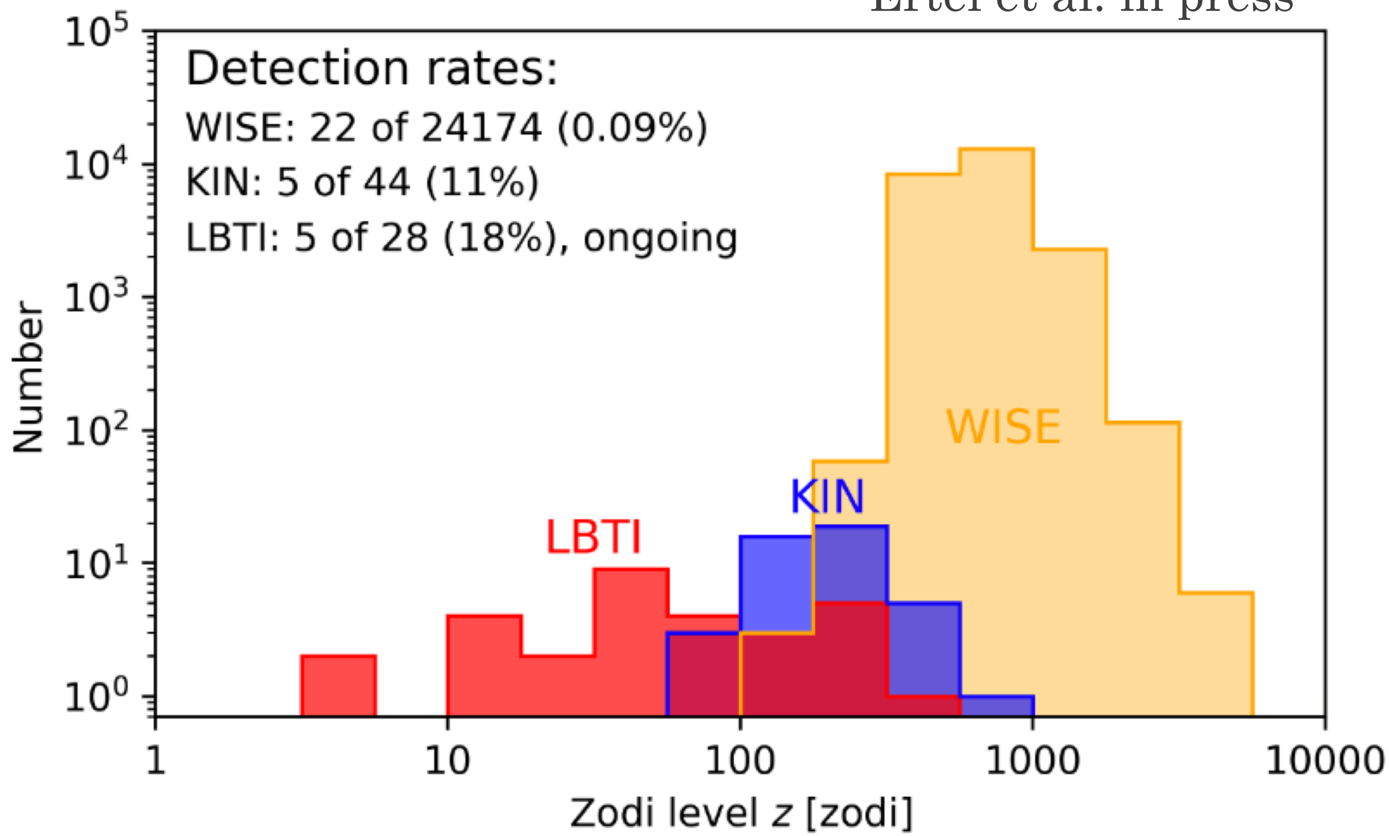


Exozodiacal dust – what do we know?

- New resuls from LBTI's HOSTS survey:

  Upper limits on the median HZ dust level of **13 zodis** (95% confidence) for a sample of stars without cold dust and 26 zodis when focusing on Sun-like stars without cold dust

Ertel et al. in press



HOSTS status

- HOSTS survey completed last week (35 total stars observed, ongoing analysis).

- More observations required:
  - Exozodi still major uncertainty in exoplanet yield predictions
  - Some high priority targets (i.e. nearest stars) not observed during baseline survey
  - To tie the phenomenon of zodiacal dust to physical models and proxy markers

- System performance and robustness will improve (new wavefront sensor, real-time water vapor seeing correction, new optimized data acquisition approach,)

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Key questions

- What are the **minimum science requirements** to justify an exoplanet direct imaging mission?
- What are the **additional science goals** that can be used as "discriminators" to evaluate science performance beyond the minimum thresholds?
- What are the possible achievements from the ground by plausible launch date, and overlapping the expected mission lifetime?

Minimum science requirements

- List from SAG3 conclusions (non exhaustive):

1. Able to detect an Earth twin at quadrature in a Solar System twin at a distance of 10 pc
2. Able to detect a Jupiter twin at quadrature in a Solar System twin at a distance of 10 pc
3. Examine at least 14 HZs to detect point sources with the sensitivity to detect terrestrial planets
4. Characterize every discovered candidate exoplanet by **R>=4** spectroscopy (0.5 µm to ~1.0 µm)
5. Able to characterize the "Earth" in a Solar System twin at 5 pc and the "Jupiter" in a Solar System twin at 10 pc **by R>70** spectroscopy (0.5 µm to ~1.0 µm)
6. …

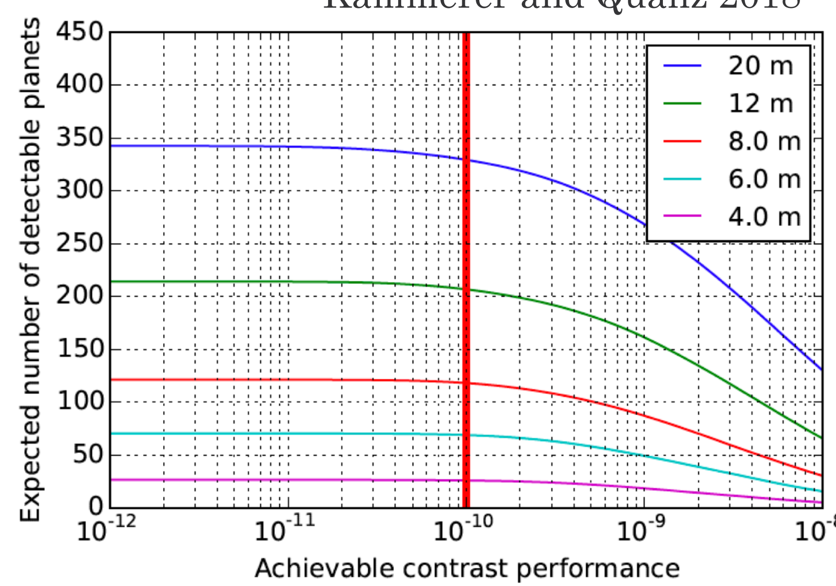
What can be done?

- Exoplanet yield based on Kepler stats:
  - 207 ($R < 6R_E$) planets observable (V band), 70 (J band), and 38 (H band)
  - No significant improvement with contrasts better than 10^{-10}
  - Improving IWA more important at this point

Table 5. Instrumental parameters for our baseline scenario for HabEx/LUVOIR.

Parameter	Value	Description
D	12 m	Aperture size
IWA	$2\ \lambda_{\mathrm{eff}}/D$	Inner working angle
C_{ref}	1e−10	Achievable contrast performance
$\lambda_{\mathrm{cen},\ V}$	554 nm	Central wavelength of V-band filter
$\lambda_{\mathrm{cen},\ J}$	1245 nm	Central wavelength of J-band filter
$\lambda_{\mathrm{cen},\ H}$	1625 nm	Central wavelength of H-band filter
$F_{\mathrm{lim},\ V}$	3.31e−10 Jy	Sensitivity limit (V-band)[a]
$F_{\mathrm{lim},\ J}$	9.12e−10 Jy	Sensitivity limit (J-band)[a]
$F_{\mathrm{lim},\ H}$	8.32e−10 Jy	Sensitivity limit (H-band)[a]

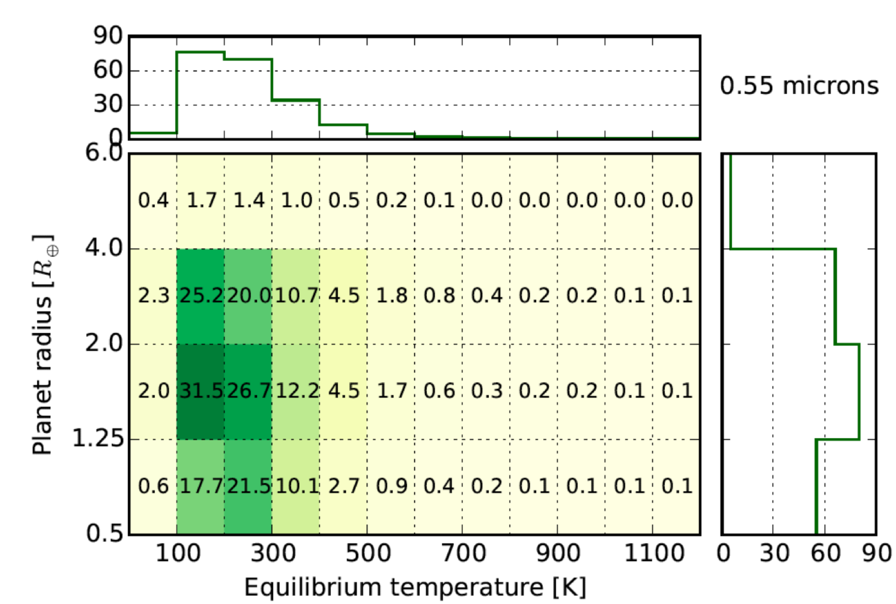
Kammerer and Quanz 2018

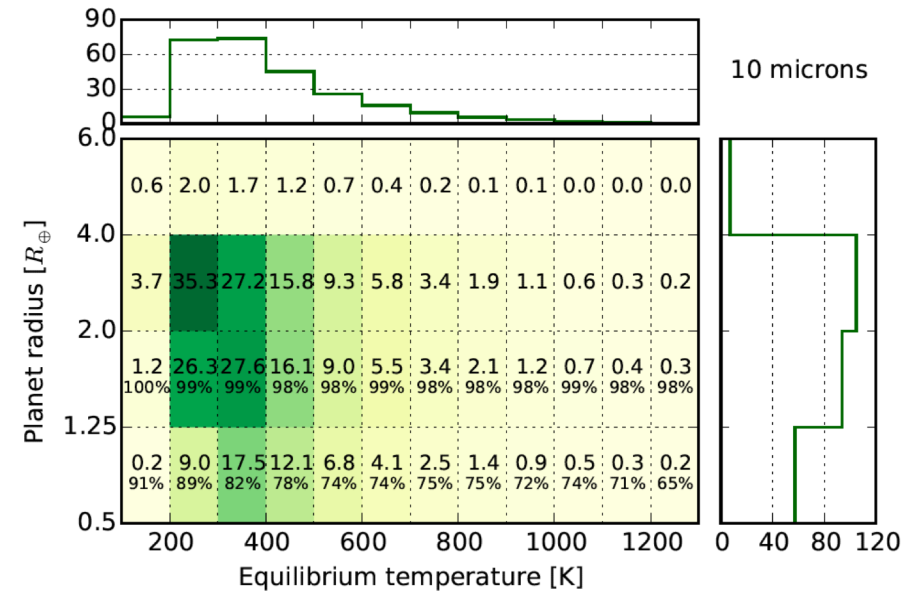


Science yield for coronagraphs and starshades (see Morgan's talk tomorrow)

Visible/mid-IR comparison

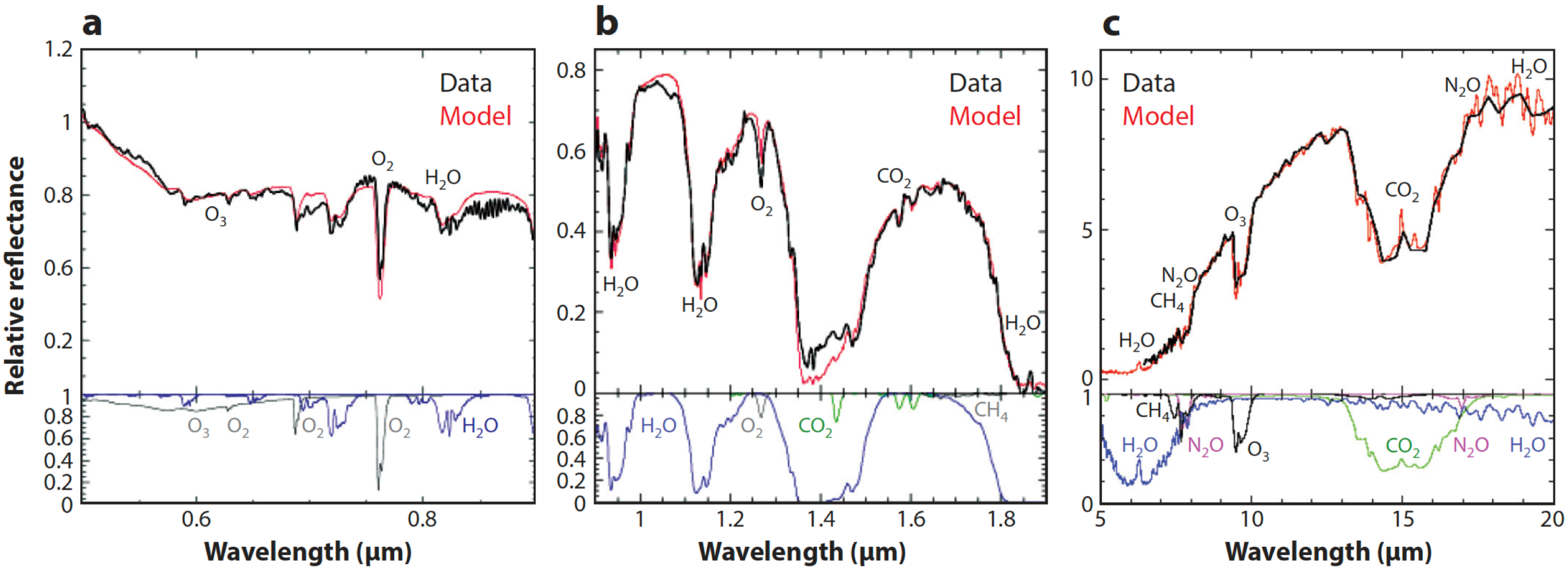
- Comparison with mid-IR nuller (4x 2-m, Darwin-like with 5 mas IWA):
  - Similar results for 200 and 450 K and radii between 0.5 and 1.75 R_{Earth} : **63 (LUVOIR) vs 85 (DARWIN/TPF-I) detections**.
  - For mid-IR nuller, 50% of observed planets are **around M stars**





Kammerer and Quanz 2018

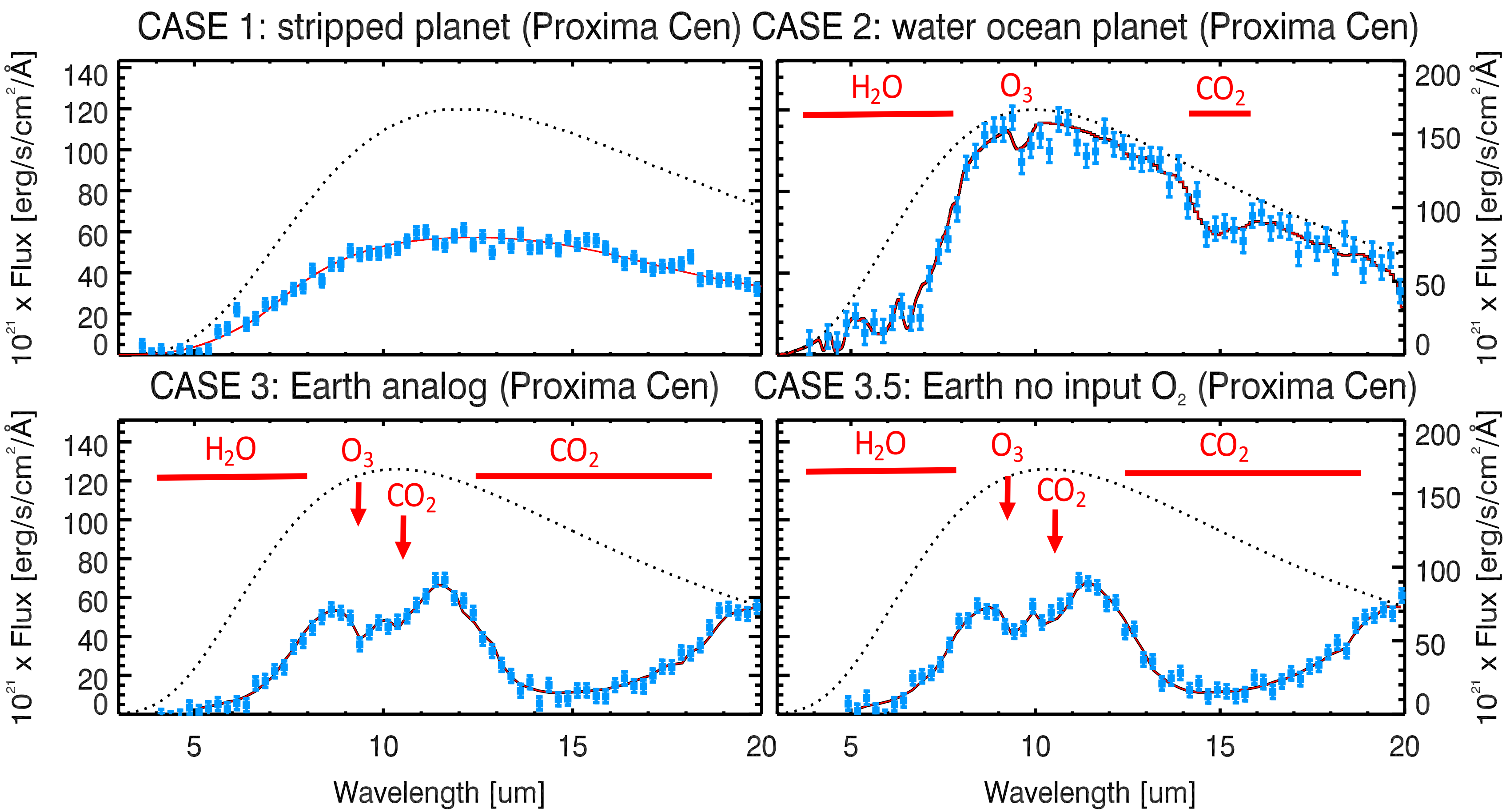
Spectroscopic resolution requirements



O_2 @ 0.76 μm: **R=70**	O_2 @ 1.26 μm: **R~70**	O_3 @ 9.4 μm: **R~20**
CO_2 @ 1.2 μm: R=35	CH_4 @ 1.6 μm: R~10	CH_4 @ 7.4 μm: R~15
O_3 @ 0.53 μm: R=5	CH_4 @ 2.2 μm: R~10	
O_3 @ 0.31 μm: R=16		

Example observations (mid-IR)

- Simulated observations (R=40, blue points) imposing a S/N of 20 on continuum detection at 10 μm (Léger et al. in prep).
- All spectral features detected in a single visit (besides O_3):



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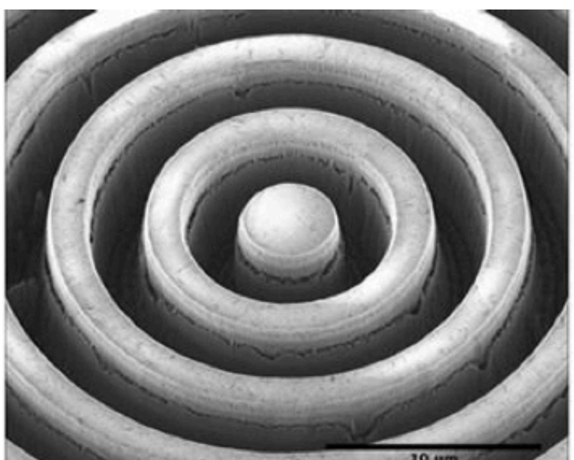
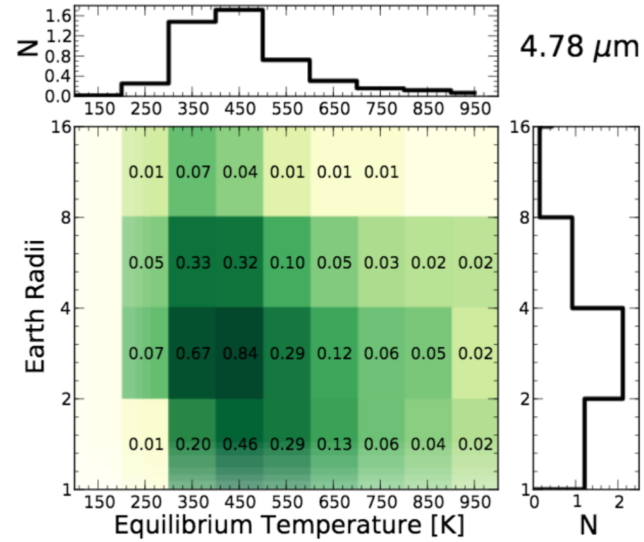
Imaging HZ planets from the ground

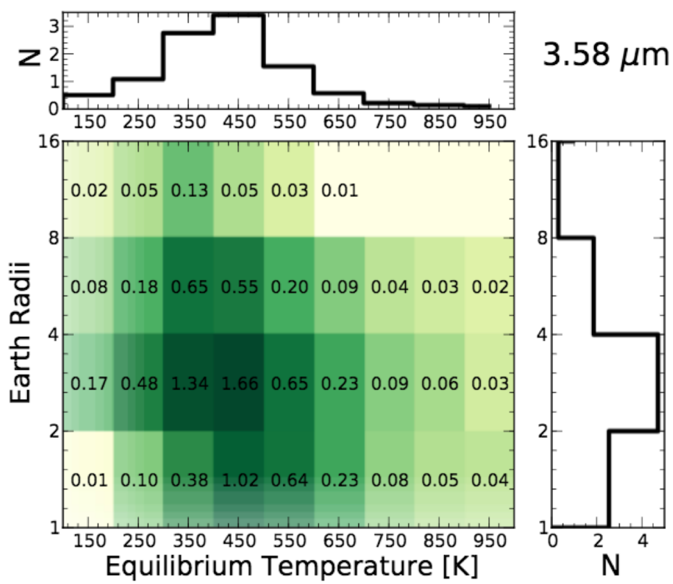
- NEAR project ("Breakthrough watch") project to detect the thermal emission (10 μm) of HZ exoplanets around α Cen A and α Cen B
- ~100 hours observations expected to begin **in 2019**
- Use a state-of-the-art Vortex coronagraph to be installed in VLT/VISIR (see Absil's talk this afternoon)

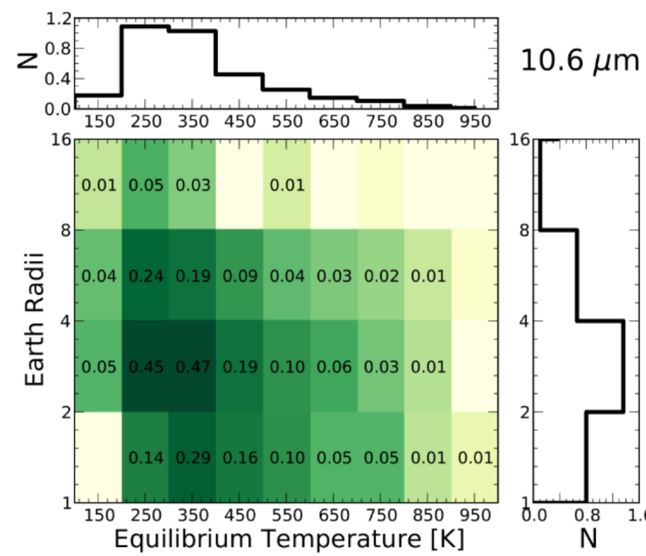


Imaging HZ planets from the ground

- ELT/METIS (2025+): mid-infrared imaging and spectroscopy (3-13 μm) of disks and exoplanets
- ~20 cool gas giants detected by RV
- ~10 rocky planets (300K - 500K)







Quanz et al. 2014

Other projects (2025+)

- ELT/PCS : optical imaging and spectroscopy (1-1.7 μm) of disks and exoplanets (see M. Kasper talk)

- PSI/TMT: instruments for exoplanets in reflected and thermal light (see Mawet's talk)

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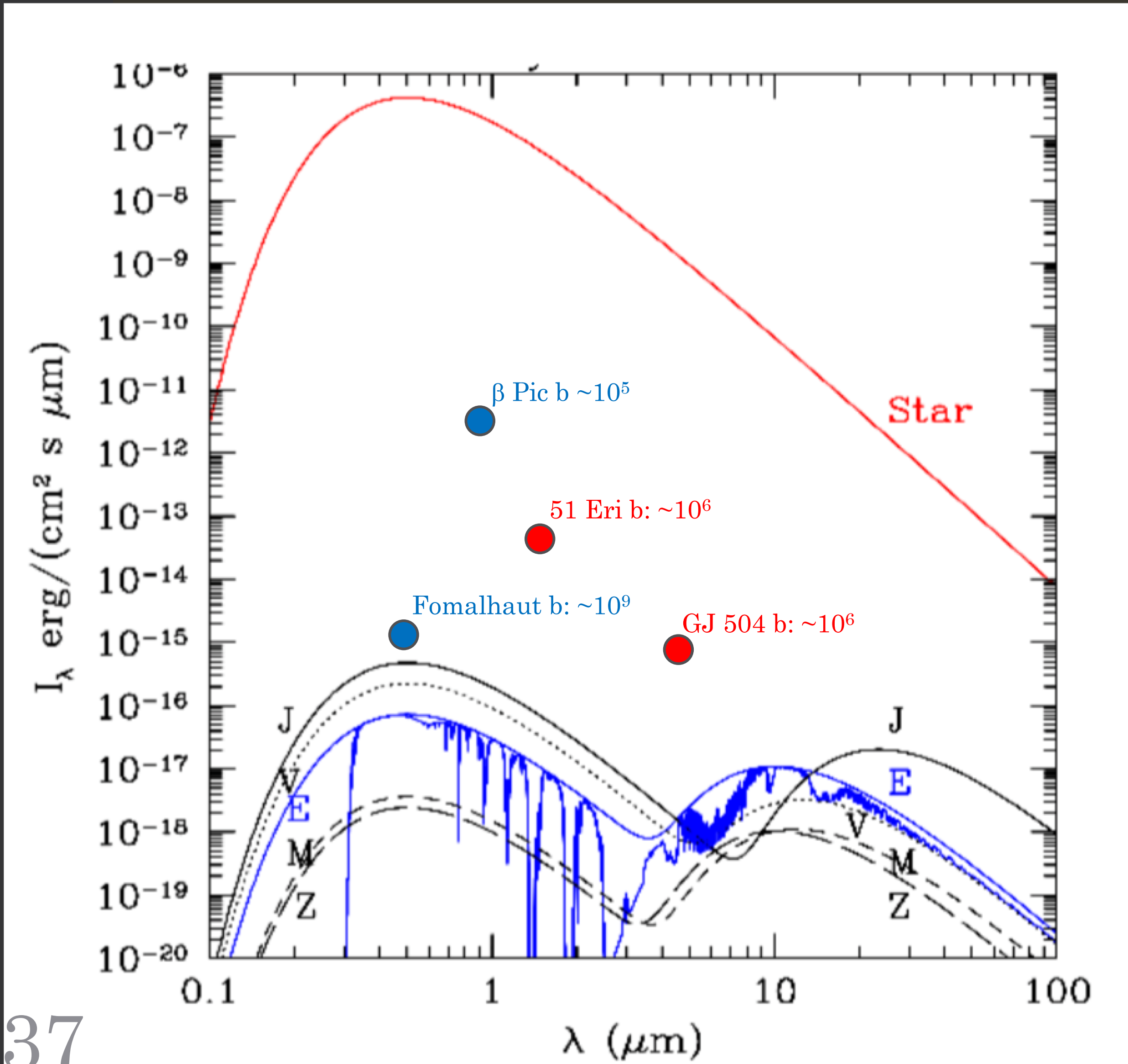
Current contrast performance



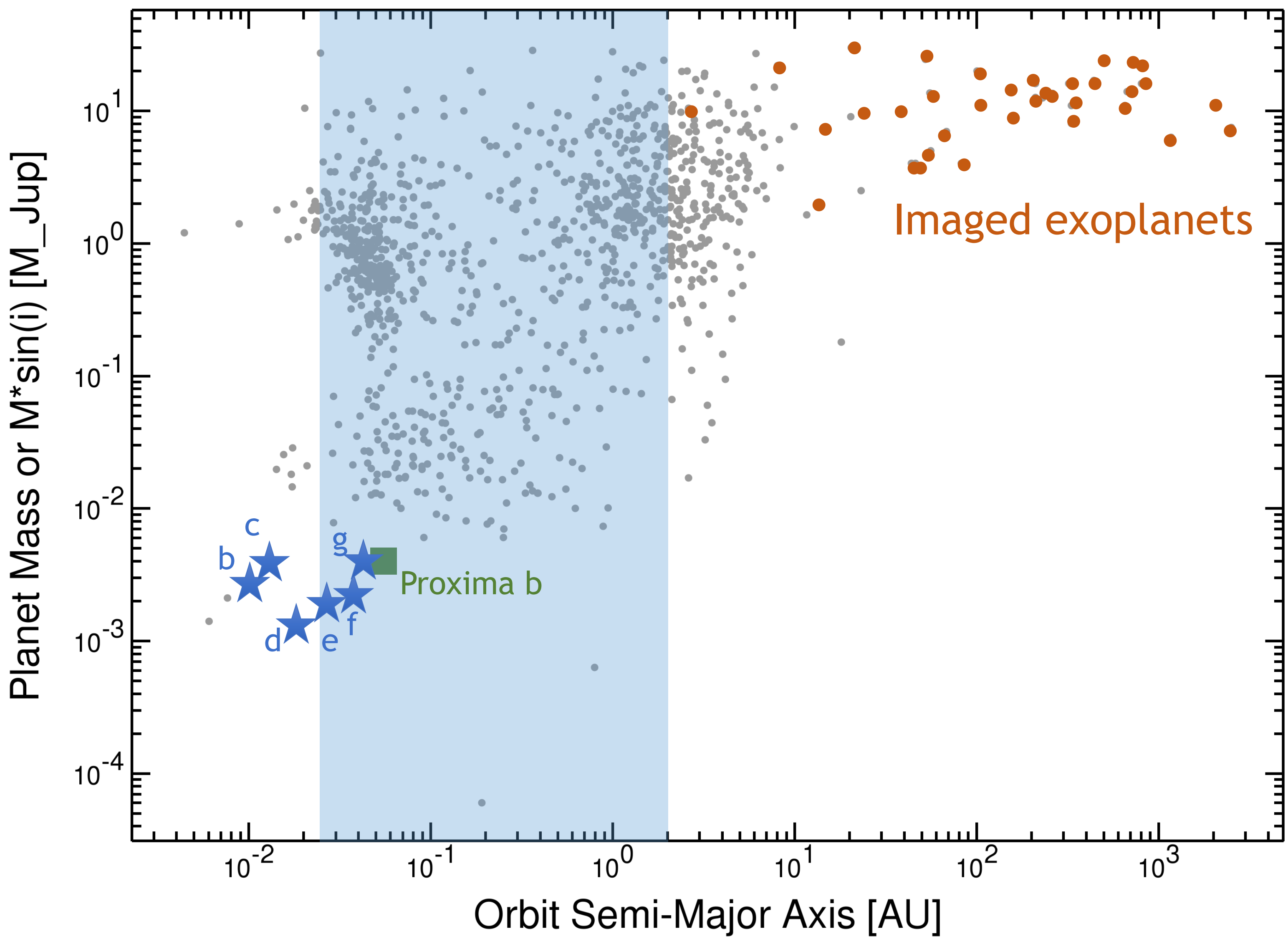
Visible:
$\sim 10^9$:Fomalhaut b but 150x sep
(Kalas et al. 2008)

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

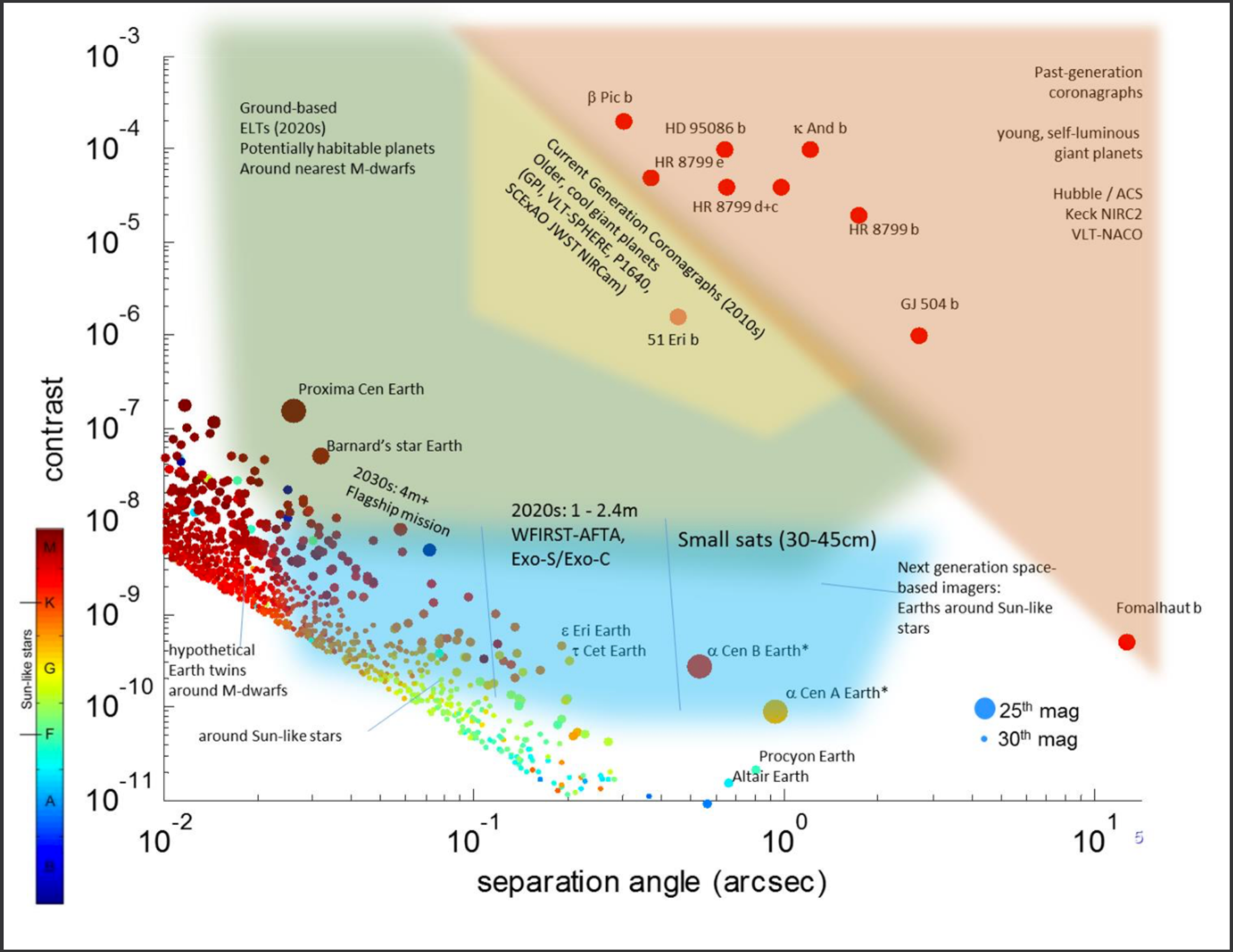
Infrared: $\sim 10^6$
H band: 51 Eri b but 13x sep
(Macintosh et al. 2015)

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

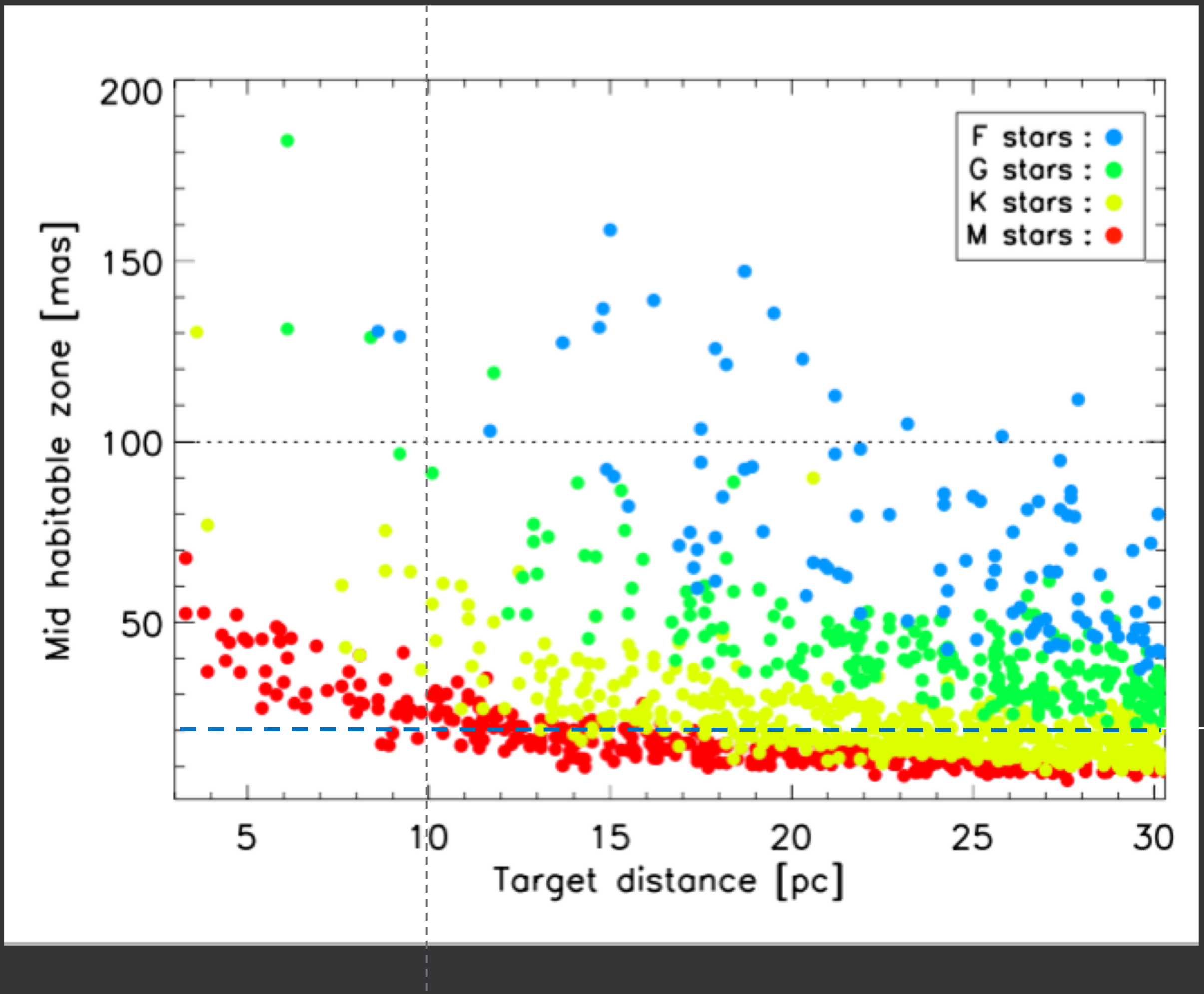
How does it compare to the HZ?



Inner working angle



Inner working angle



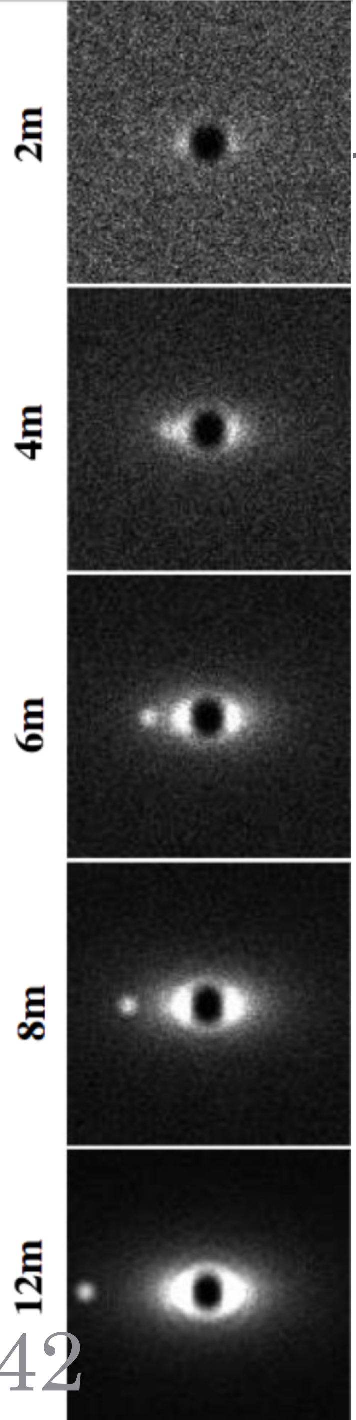
2. Angular separation:
   - ~10 to 150 mas

D required for > IWA (2λ/D):

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


Need a big aperture!

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, $\lambda_{max} \sim D$
- Light can be sliced in multiple bins: spectral resolution, time domain, polarization
- Better astrometry → better orbits, dynamical masses
- Resolving (time-variable) structures in exozodi

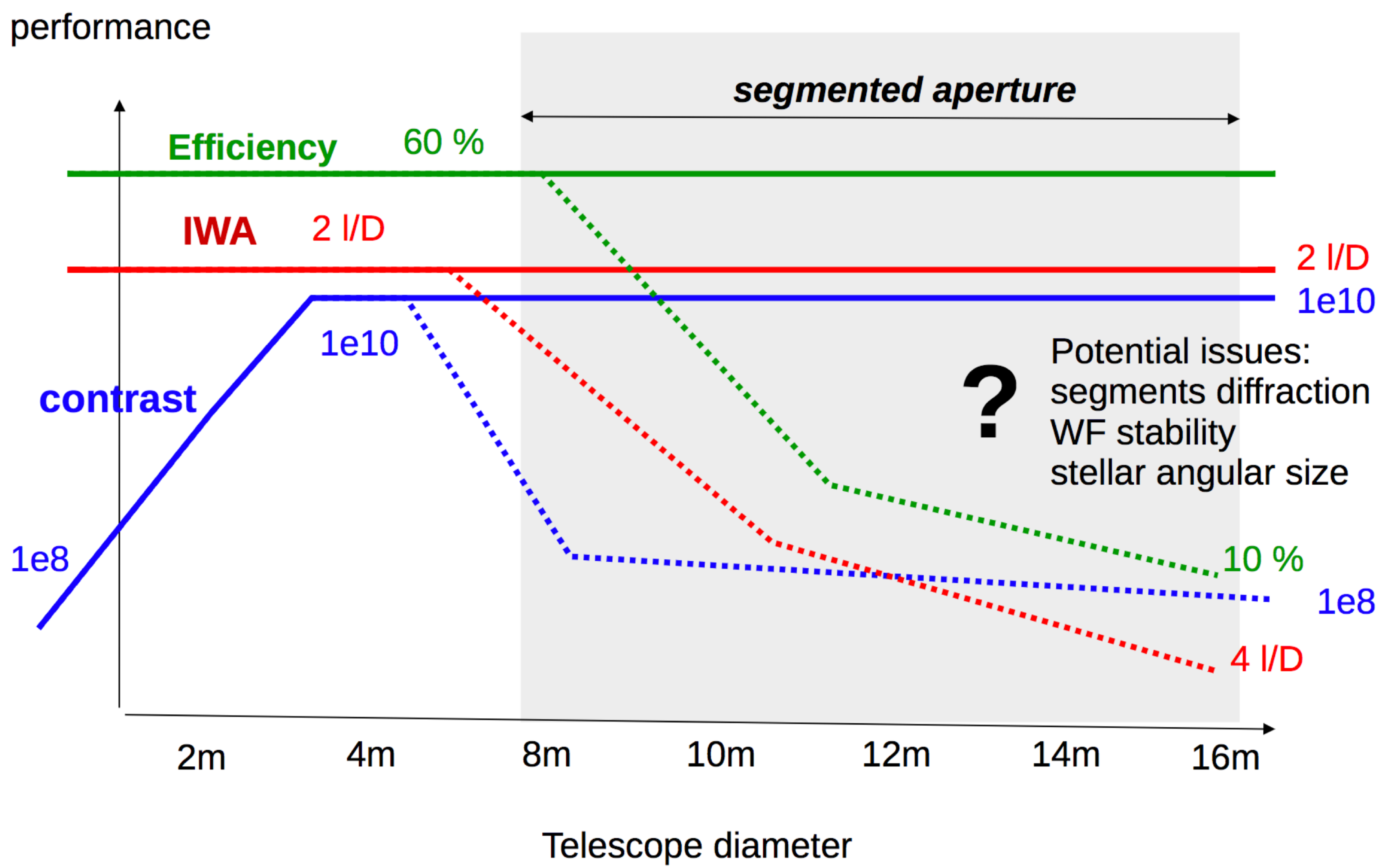
Data quality

- 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

How does perfo. scale with aperture?



(see next talk)

Image credit: O. Guyon