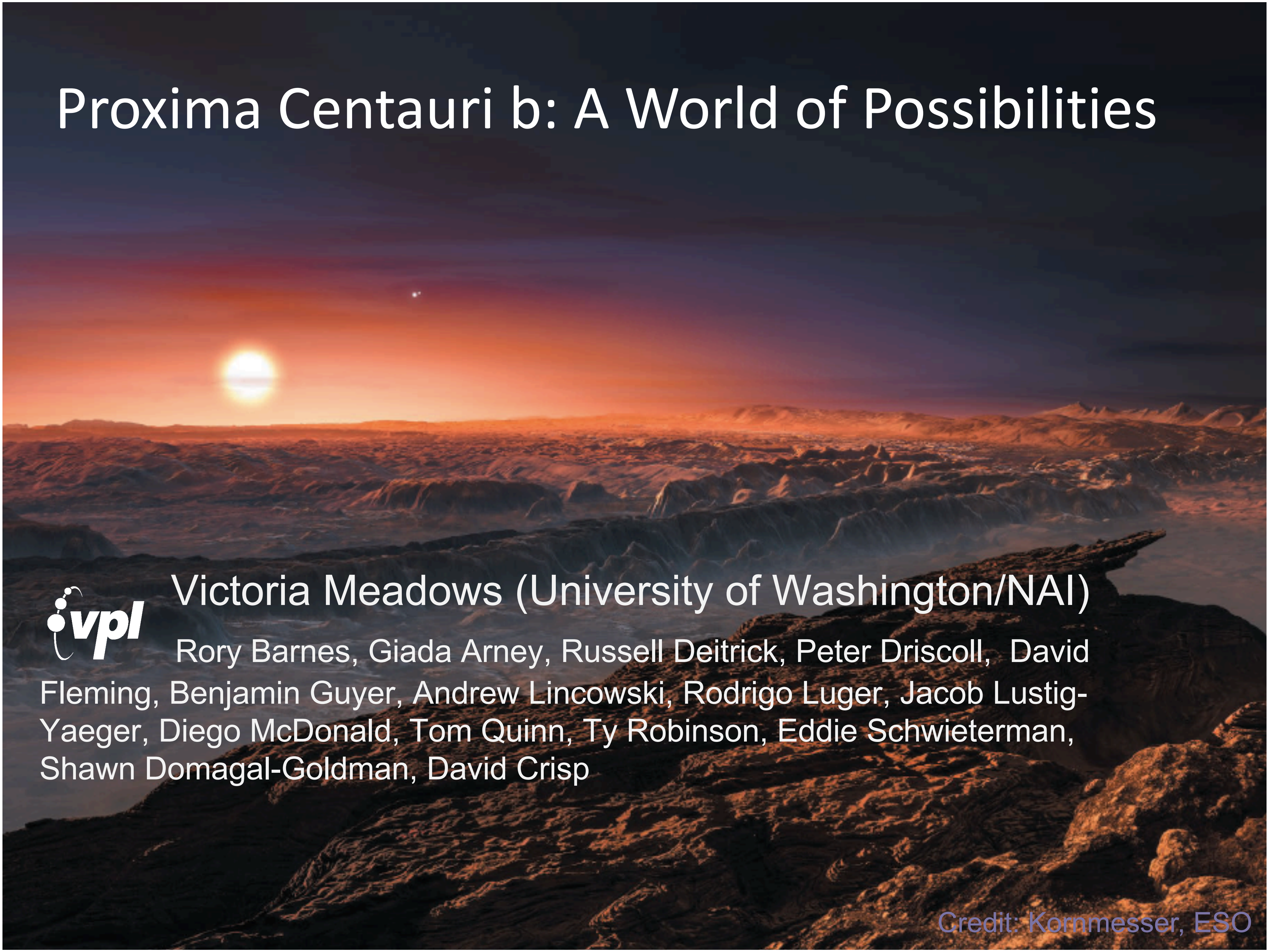
Proxima Centauri b: A World of Possibilities

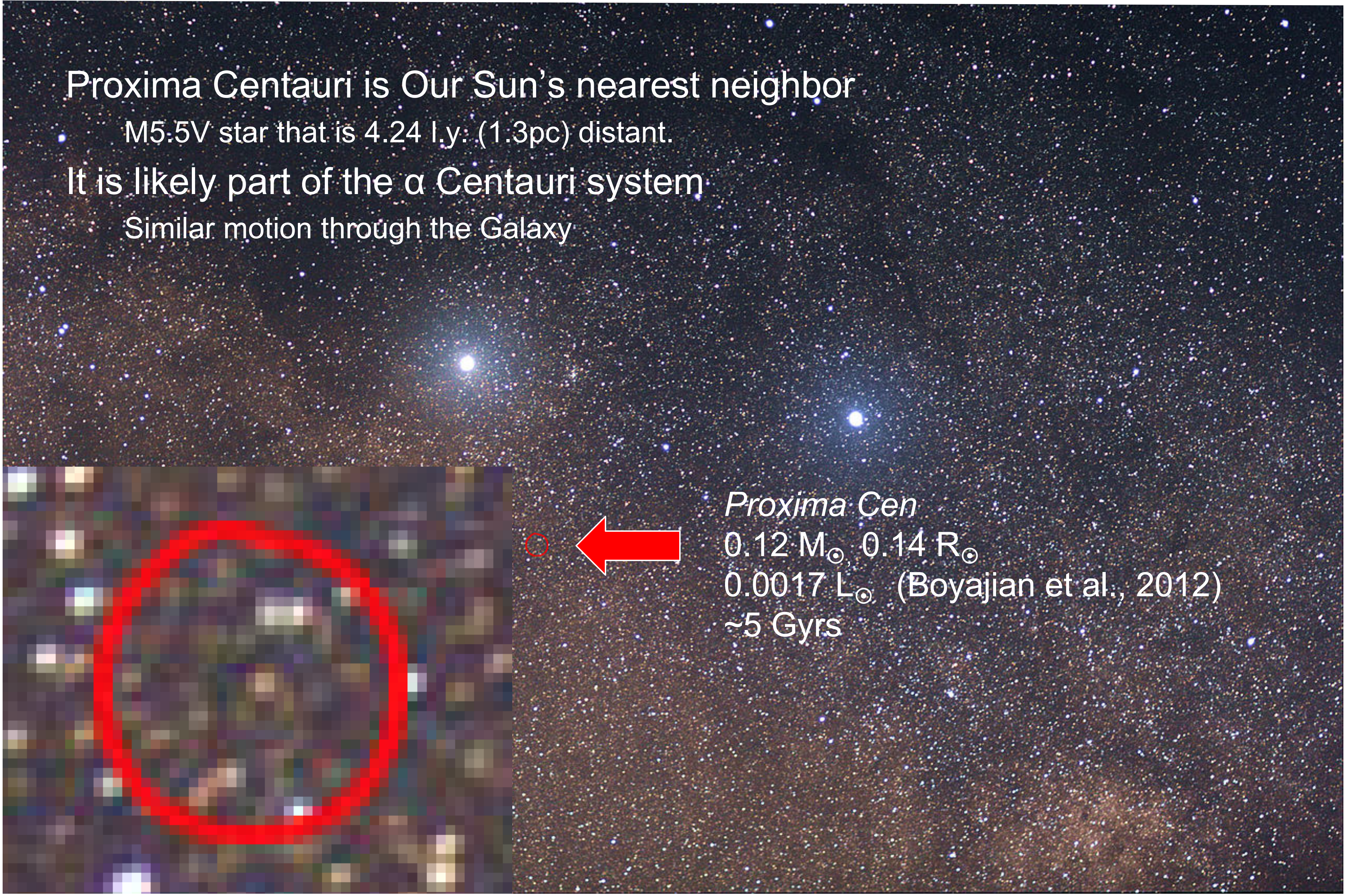


Victoria Meadows (University of Washington/NAI)

Rory Barnes, Giada Arney, Russell Deitrick, Peter Driscoll, David Fleming, Benjamin Guyer, Andrew Lincowski, Rodrigo Luger, Jacob Lustig-Yaeger, Diego McDonald, Tom Quinn, Ty Robinson, Eddie Schwieterman, Shawn Domagal-Goldman, David Crisp

Credit: Kornmesser, ESO

Proxima Centauri



- Proxima Centauri is Our Sun’s nearest neighbor
  - M5.5V star that is 4.24 l.y. (1.3pc) distant.
- It is likely part of the α Centauri system
  - Similar motion through the Galaxy

Proxima Cen

$0.12\ M_\odot$, $0.14\ R_\odot$

$0.0017\ L_\odot$ (Boyajian et al., 2012)

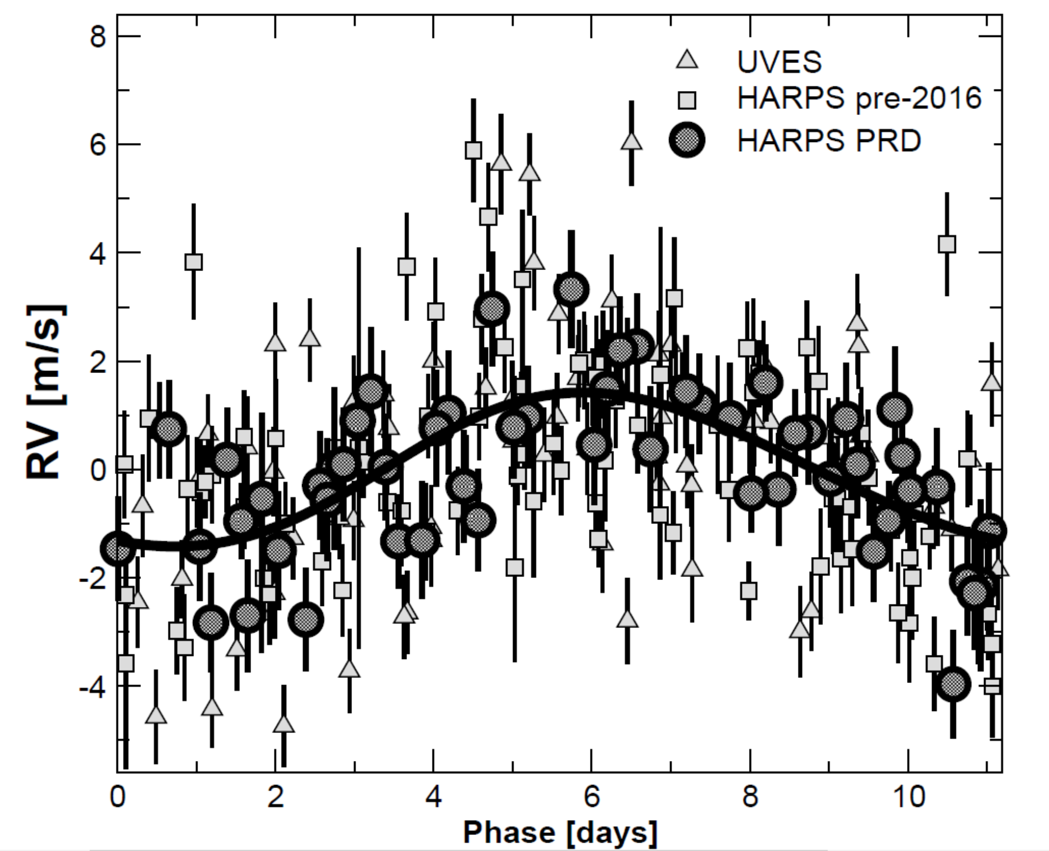
~5 Gyrs

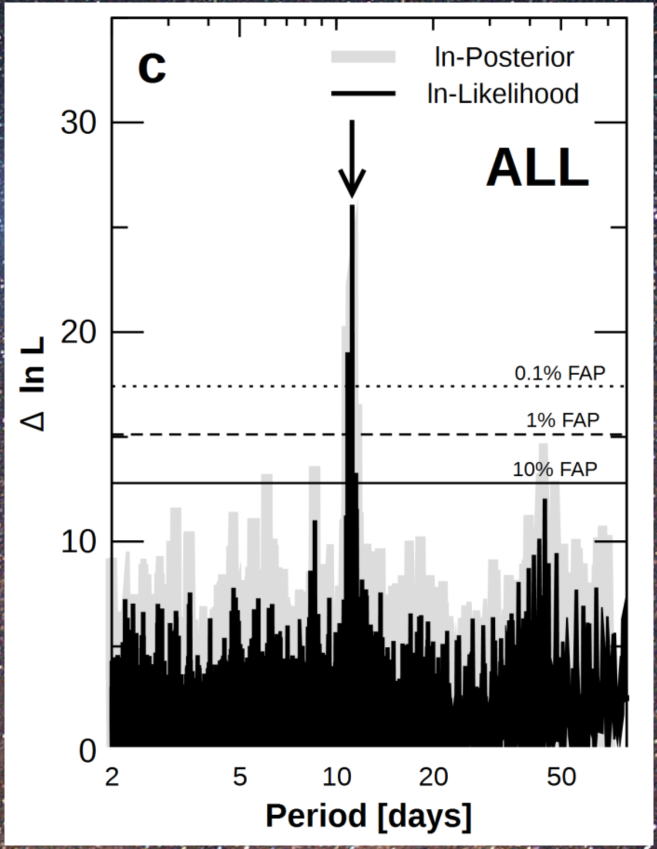
Proxima Centauri b

Proxima Centauri b was discovered by Anglada-Escude et al. (2016) using the radial velocity method, and announced on Aug 24th, 2016.

Minimum mass of 1.3 M_{Earth}, orbital period of 11.2 days, a=0.0485 AU, e < 0.35

No conclusive evidence that Proxima Cen b transits its star (Kipping et al., 2016)





Anglada-Escudé et al., 2016

Proxima Cen b orbits within the Habitable Zone

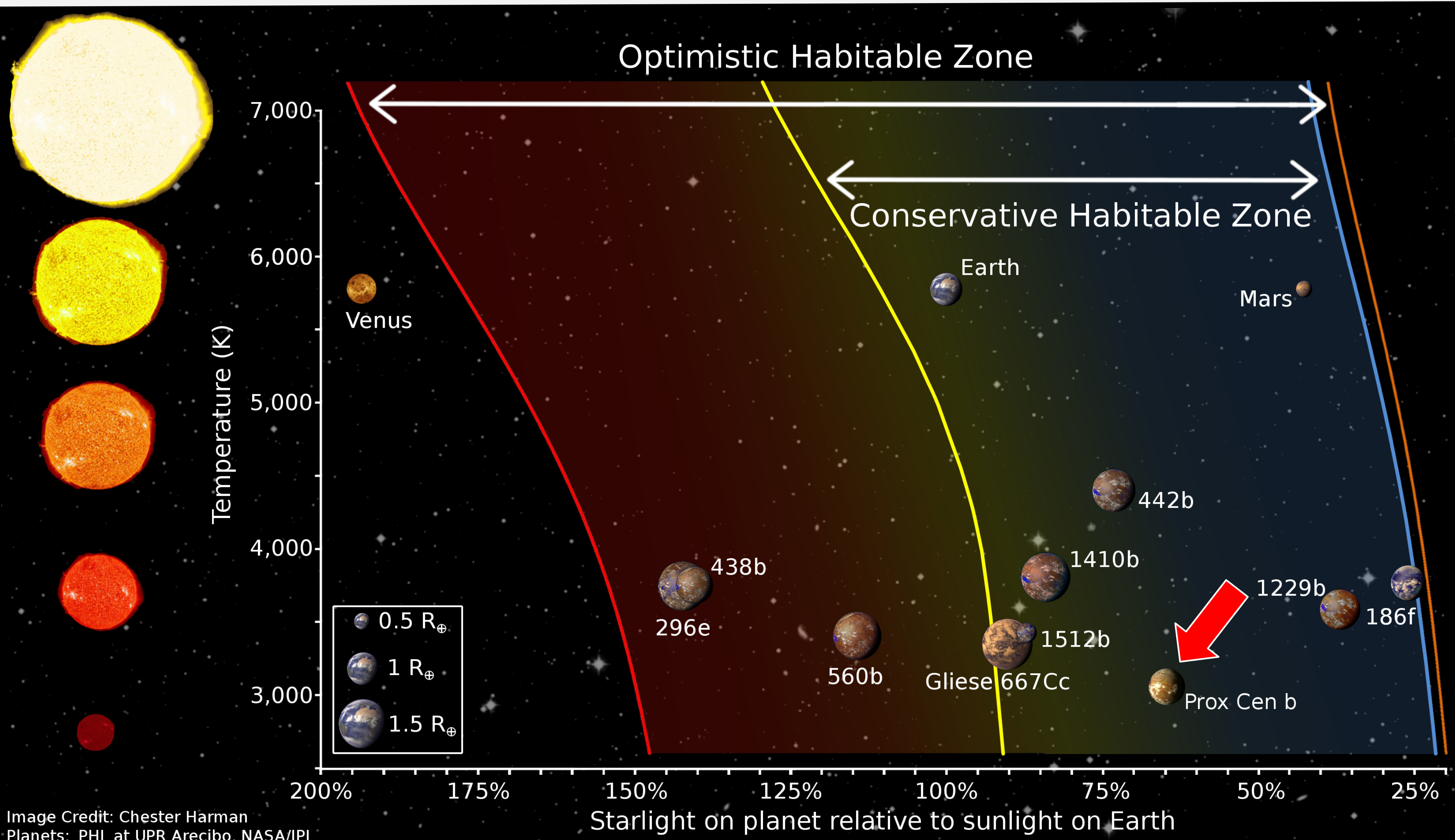
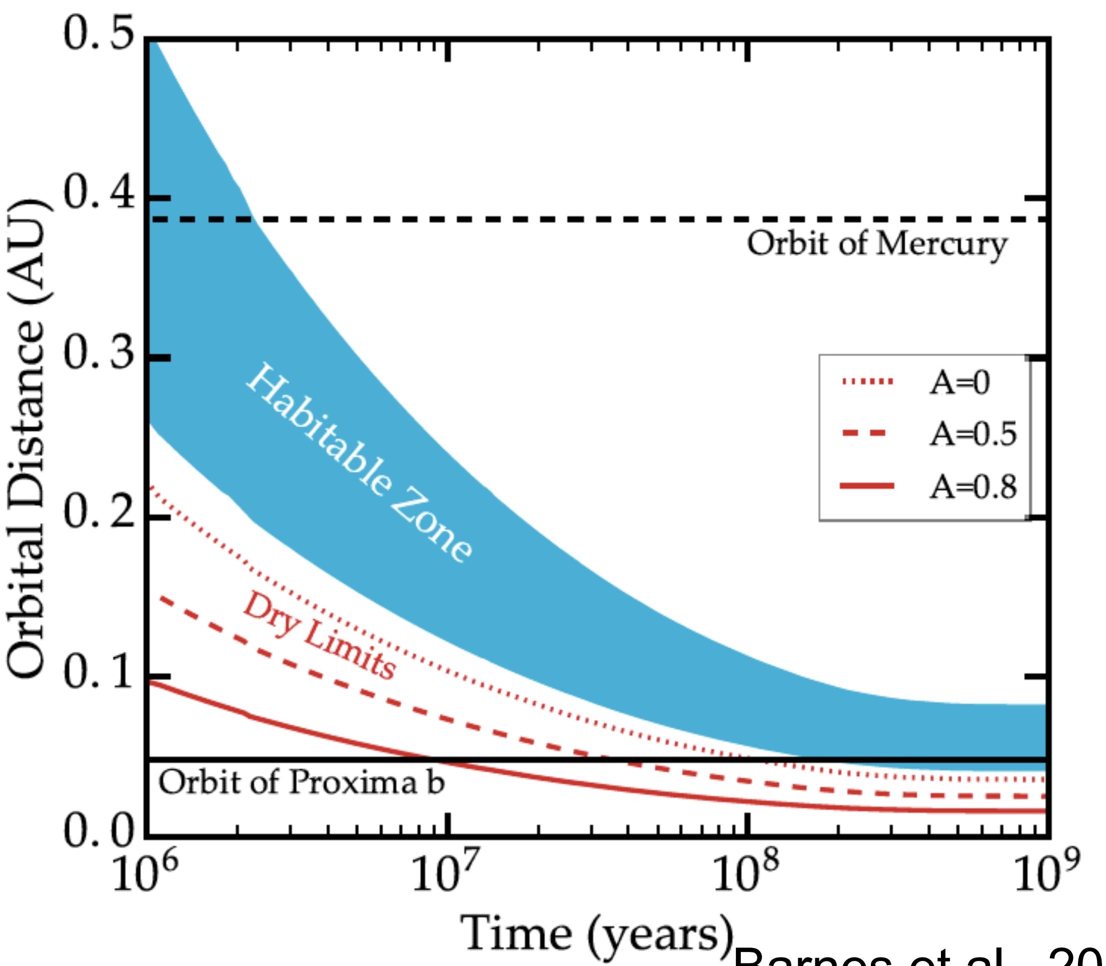


Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/JPL

Proxima Cen b receives 65% of the sunlight that the Earth receives

Proxima Cen b was not always in the Habitable Zone



Barnes et al., 2016

The star's likely luminosity evolution suggests that if Proxima Cen b had formed at its current position, then the habitable zone would not have moved in towards the star to encompass the planet until abut 160 Myrs after formation.

The Significance of Proxima Cen b

- A very nearby potentially habitable planet orbiting an M dwarf, the most common type of star in the Galaxy
  - Proximity means relatively large star-planet separation (for M dwarf)
  - Relatively bright (for a late-type M dwarf!)
  - Oh, and we could go there!!
- Contributes to two key areas of exoplanet research
  - Comparative Planetology: Understand the evolution of terrestrial planets.
  - Astrobiology: Understand the distribution of life in the Universe.

Credit: Kornmesser, ESO

M Dwarf Habitable Planets May Be The Most Common

M dwarf stars comprise 75% of the stars in our Galaxy

260 of them are within 10pc

For these stars, the HZ terrestrial planet occurrence rate may be as high as 0.8 per star ***(Morton&Swift, 2014)***

Even a more conservative estimate of 0.24 HZ terrestrials per M dwarf predicts that the nearest HZ terrestrial is **within 2.6pc (✔), and the nearest transiting one is within 10.6pc** ***(Dressing and Charbonneau, 2015)***

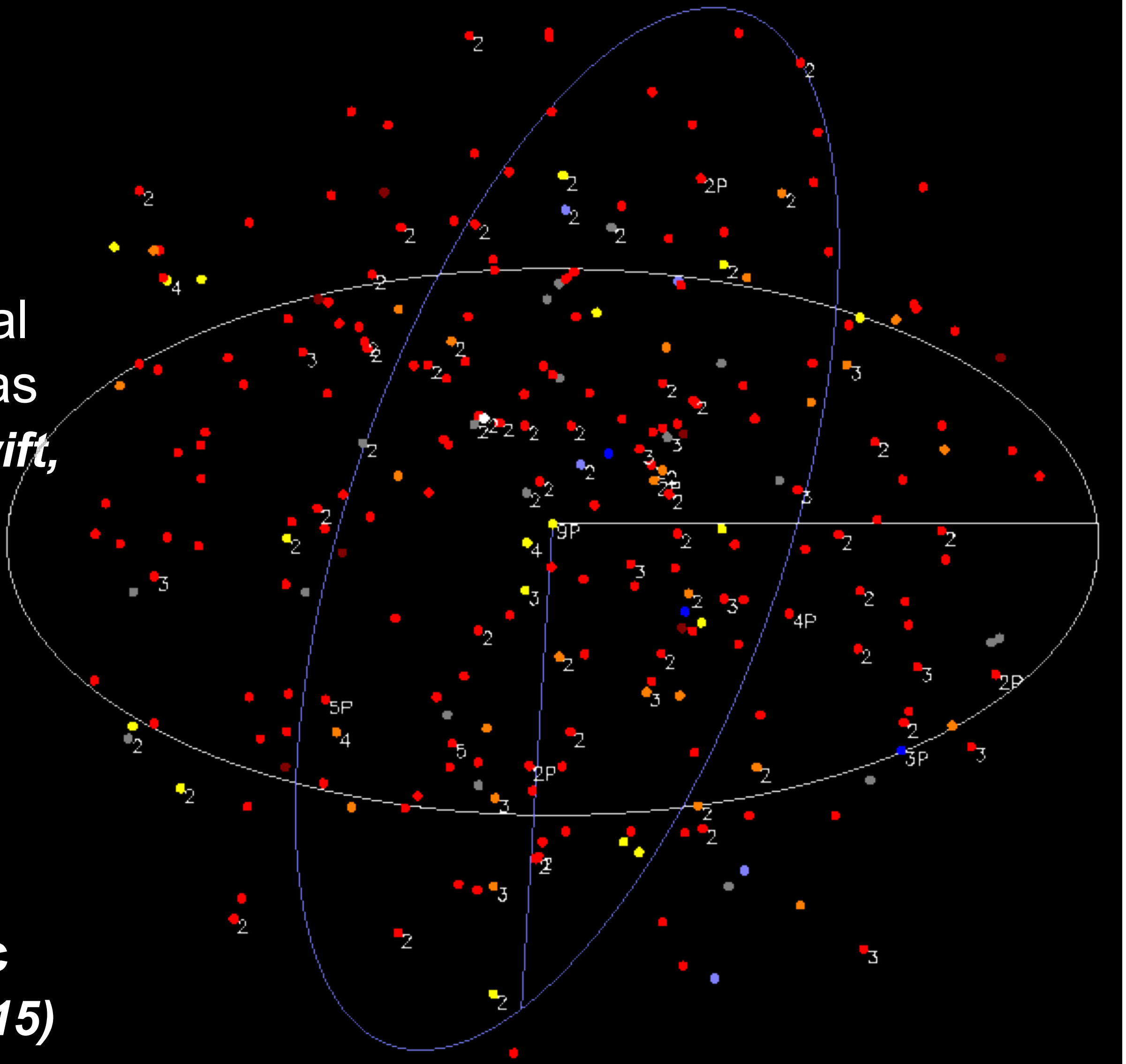
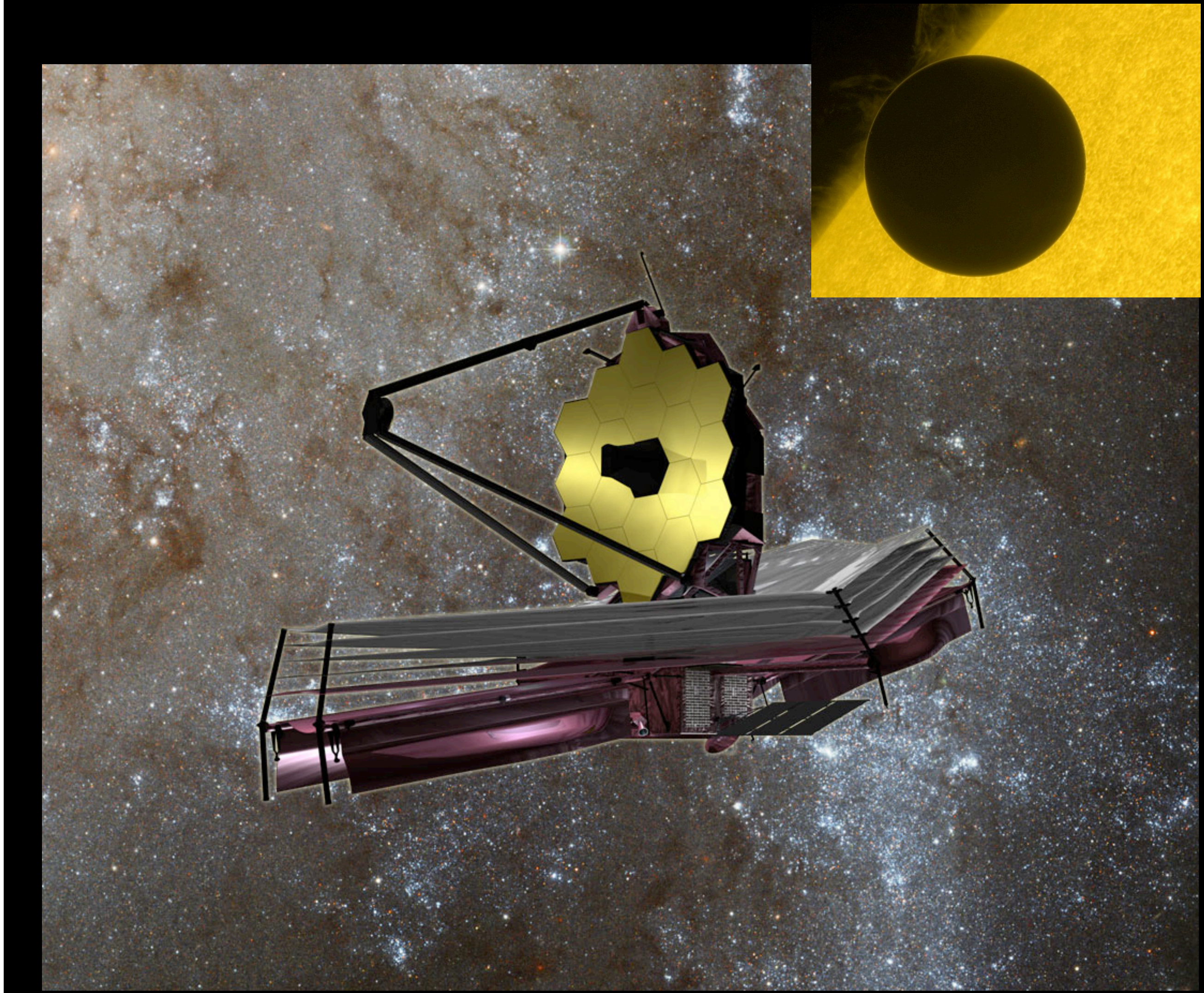


Image: Riedel, Henry, & RECONS group

M Dwarf Planets Will Be The First Searched For Life

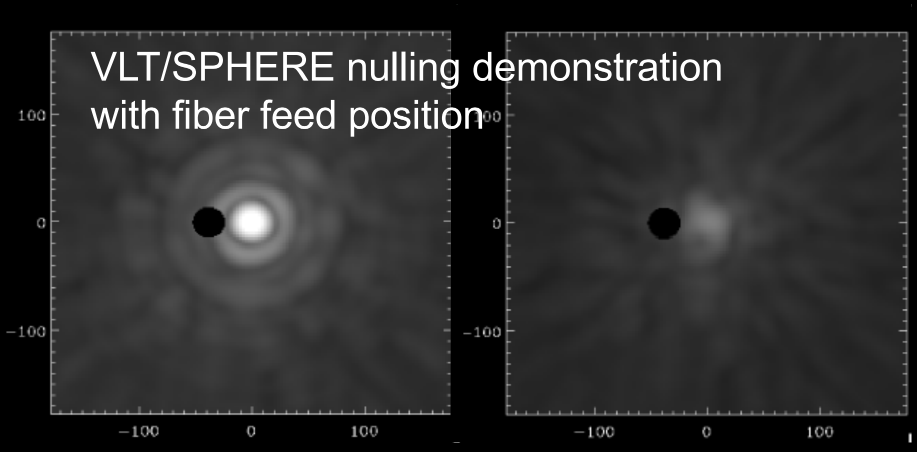


M dwarf planets are prime targets for transmission spectroscopy with JWST

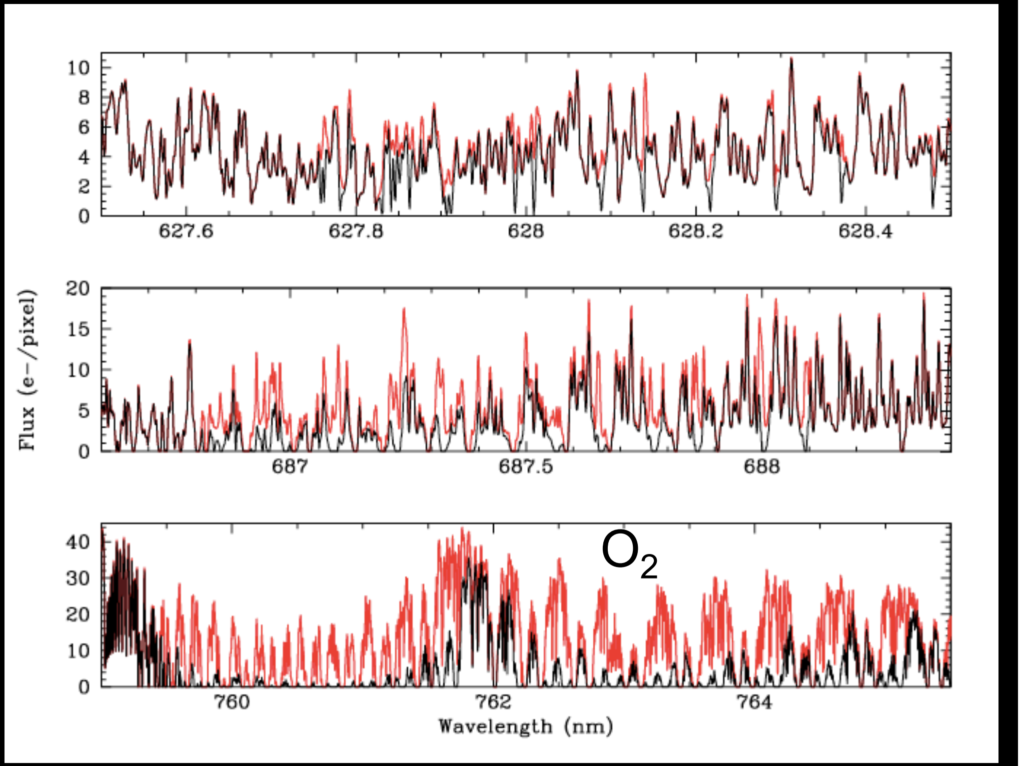
- Star/planet size ratio
- proximity of the HZ

Still challenging though! JWST may obtain spectra of 1-3 M dwarf HZ terrestrials (Cowan et al., 2015).

Possible Near-Term Ground-Based Observations

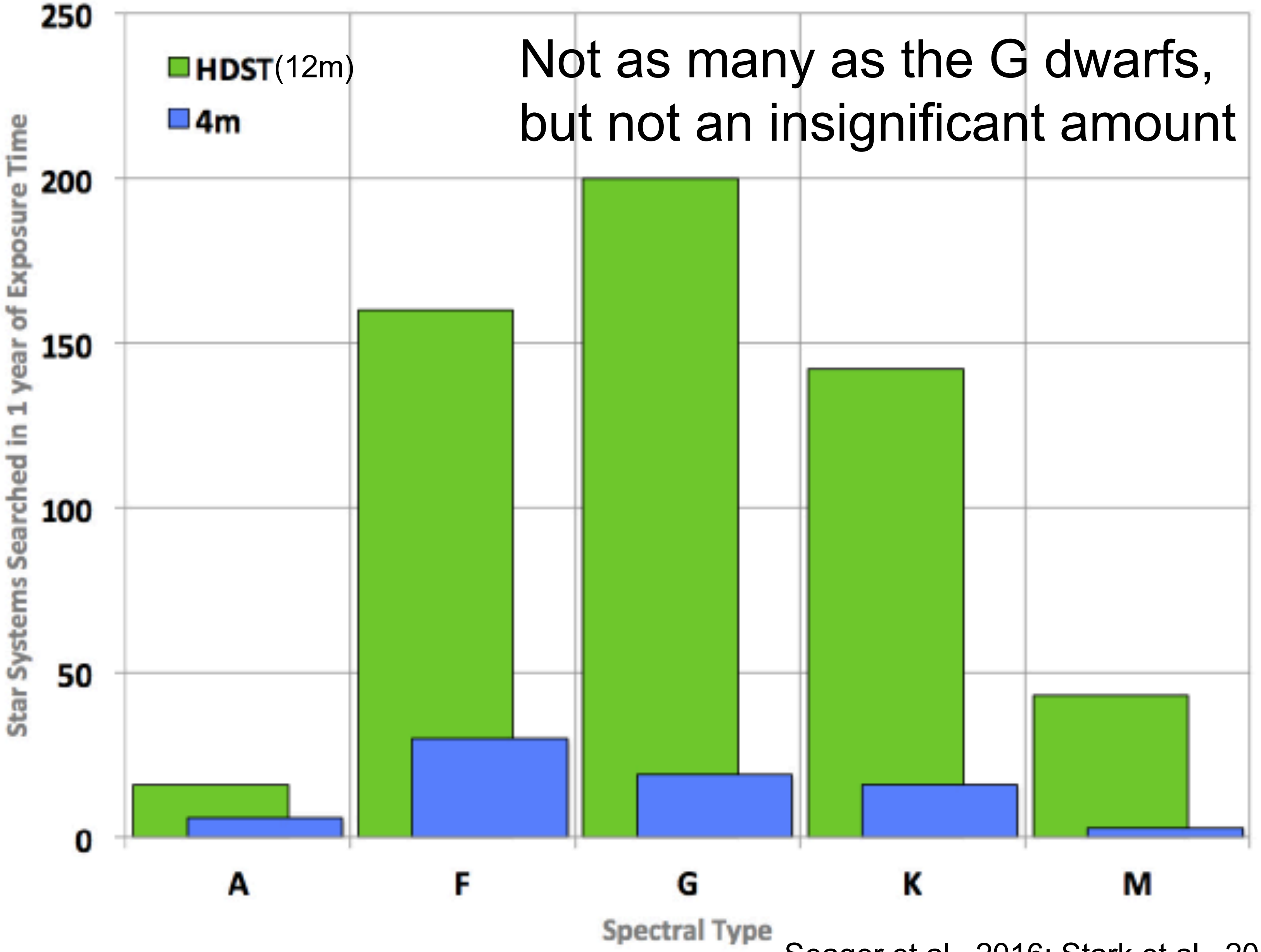

VLT/SPHERE nulling demonstration with fiber feed position

Lovis et al., 2016



- Ground-based telescopes could use direct imaging, ultra-high resolutions spectroscopy, or both to observe M dwarf planets (e.g. Snellen et al., 2013; 2014; Quanz et al., 2014)
- Proposed upgrades to the high-contrast imager SPHERE and the new ESPRESSO high-resolution spectrograph on the ESO VLT may provide “early” results.
- Planet detection and mass determination, visible $O_{2,}$ CH_4 bands.
- 3-σ O_2 detection in 60 nights of telescope time, spread over 3 years (Lovis et al., 2016).
- Ground-based and space-based observations could be combined (Brogi et al., 2016).

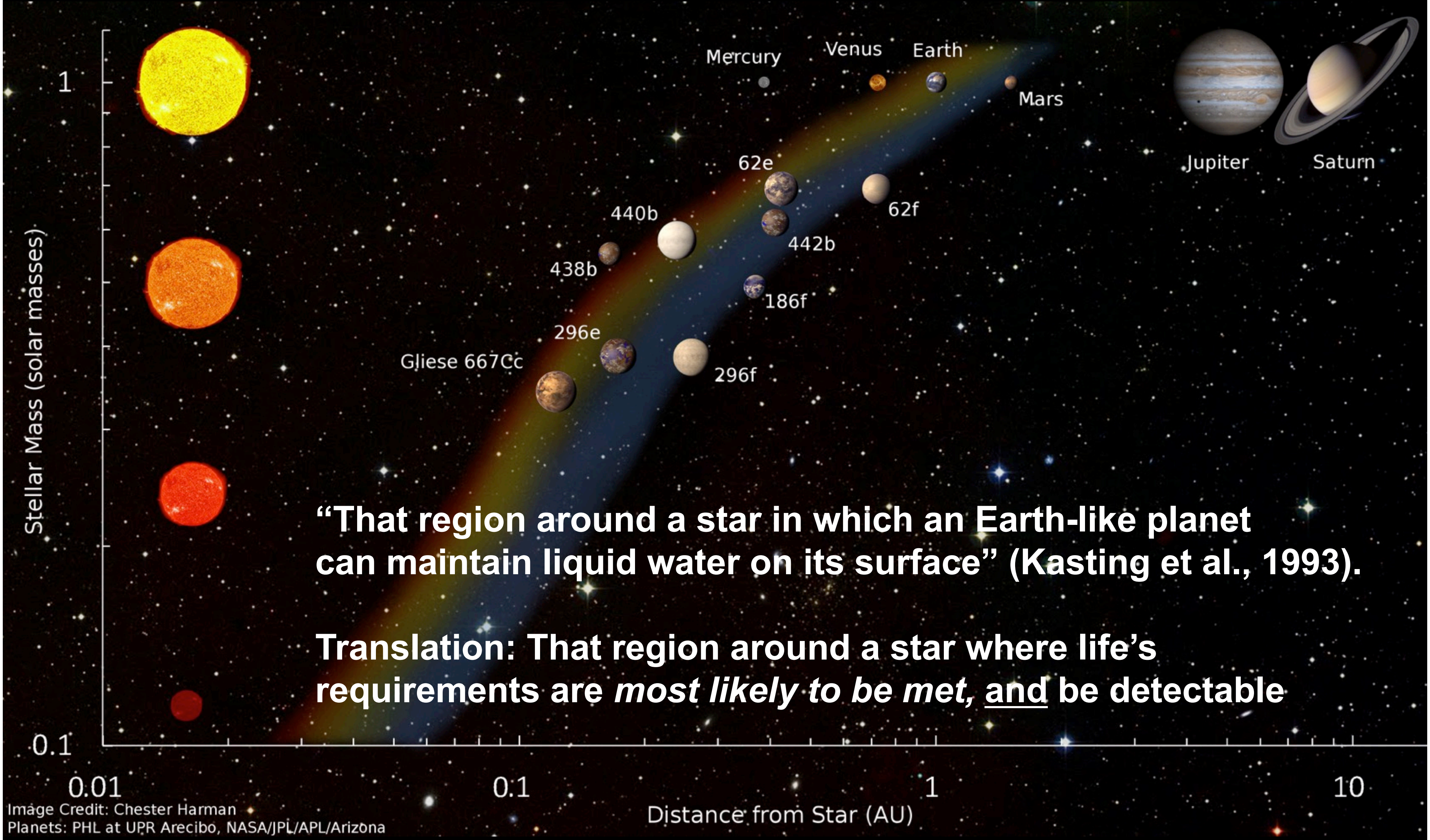
LUVOIR may also observe M dwarf planets



Not as many as the G dwarfs, but not an insignificant amount

Seager et al., 2016; Stark et al., 2015

The Surface Liquid Water Habitable Zone

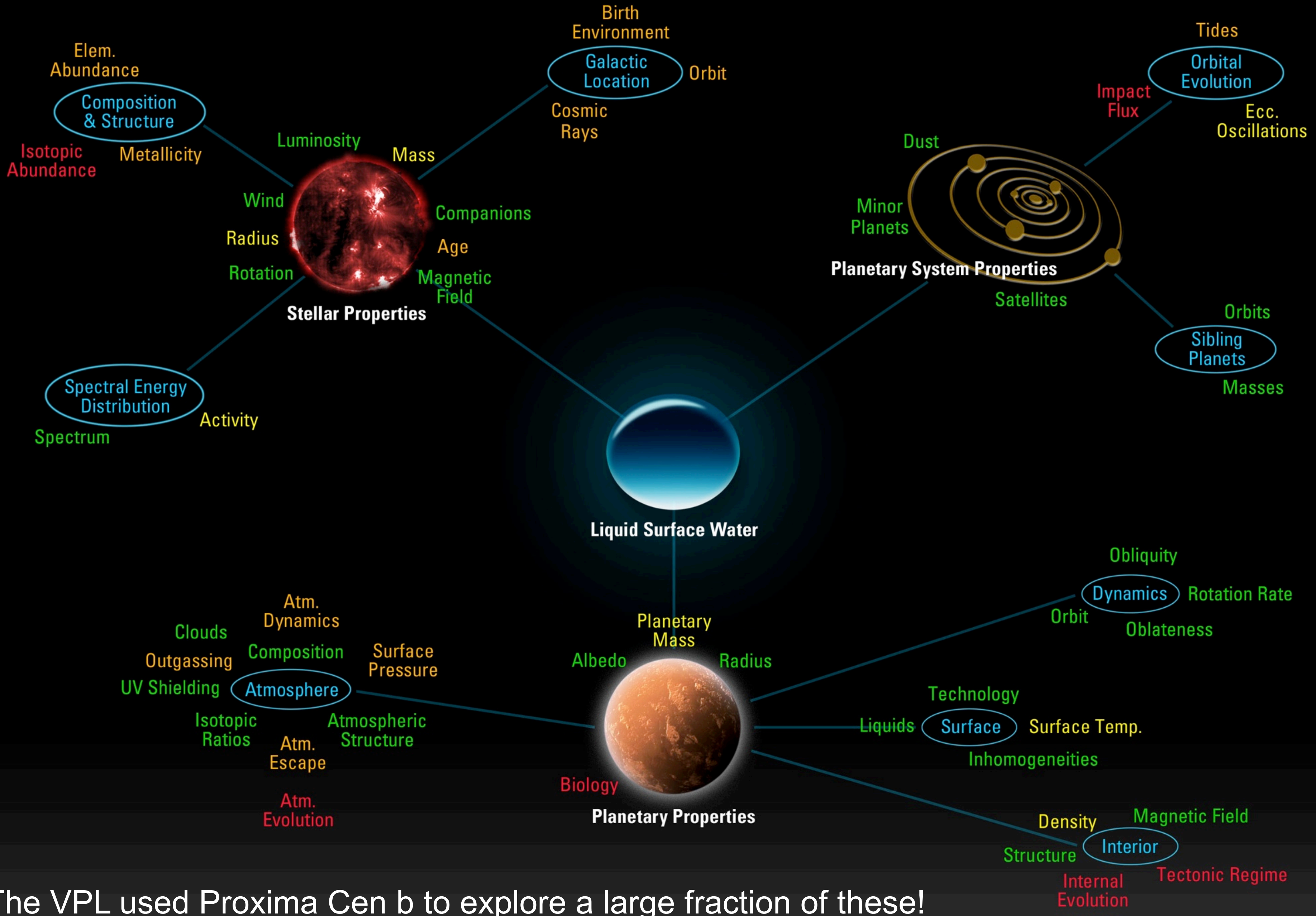


“That region around a star in which an Earth-like planet can maintain liquid water on its surface” (Kasting et al., 1993).

Translation: That region around a star where life’s requirements are *most likely to be met,* <u>and</u> be detectable

Kopparapu et al., (2013)
http://depts.washington.edu/naivpl/content/hz-calculator

Star/planet/planetary system interactions and evolution can all affect habitability



Stellar Properties

Luminosity
Mass
Wind
Radius
Rotation
Companions
Age
Magnetic Field

Composition & Structure
Elem. Abundance
Isotopic Abundance
Metallicity

Galactic Location
Birth Environment
Orbit
Cosmic Rays

Spectral Energy Distribution
Activity
Spectrum

Liquid Surface Water

Planetary System Properties

Dust
Minor Planets
Satellites

Orbital Evolution
Tides
Impact Flux
Ecc. Oscillations

Sibling Planets
Orbits
Masses

Planetary Properties

Planetary Mass
Albedo
Radius
Biology

Atmosphere
Atm. Dynamics
Clouds
Composition
Surface Pressure
Outgassing
UV Shielding
Isotopic Ratios
Atmospheric Structure
Atm. Escape
Atm. Evolution

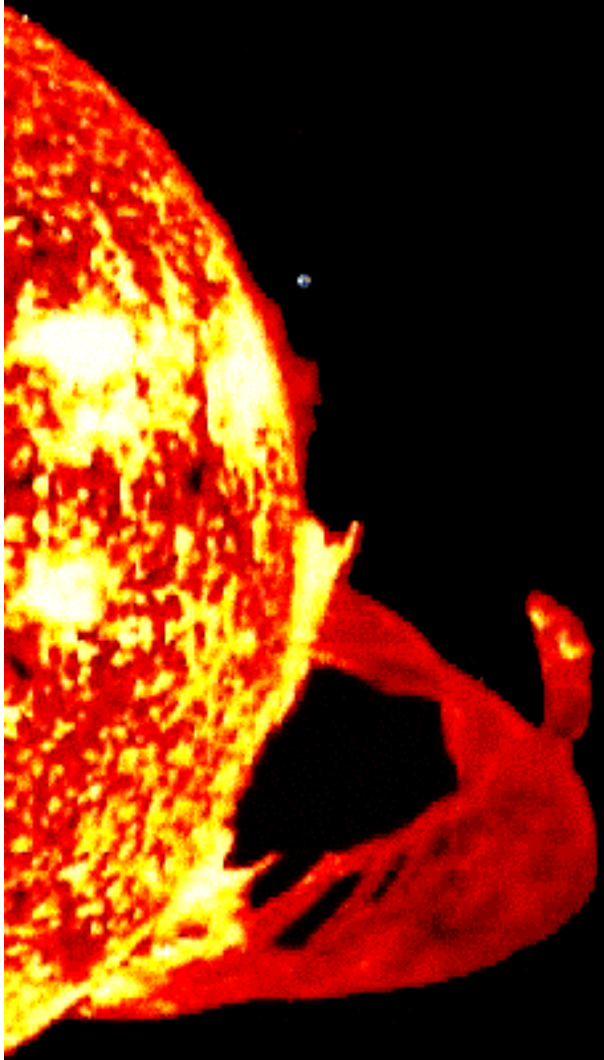
Dynamics
Obliquity
Rotation Rate
Orbit
Oblateness

Surface
Technology
Liquids
Surface Temp.
Inhomogeneities

Interior
Density
Magnetic Field
Structure
Tectonic Regime
Internal Evolution

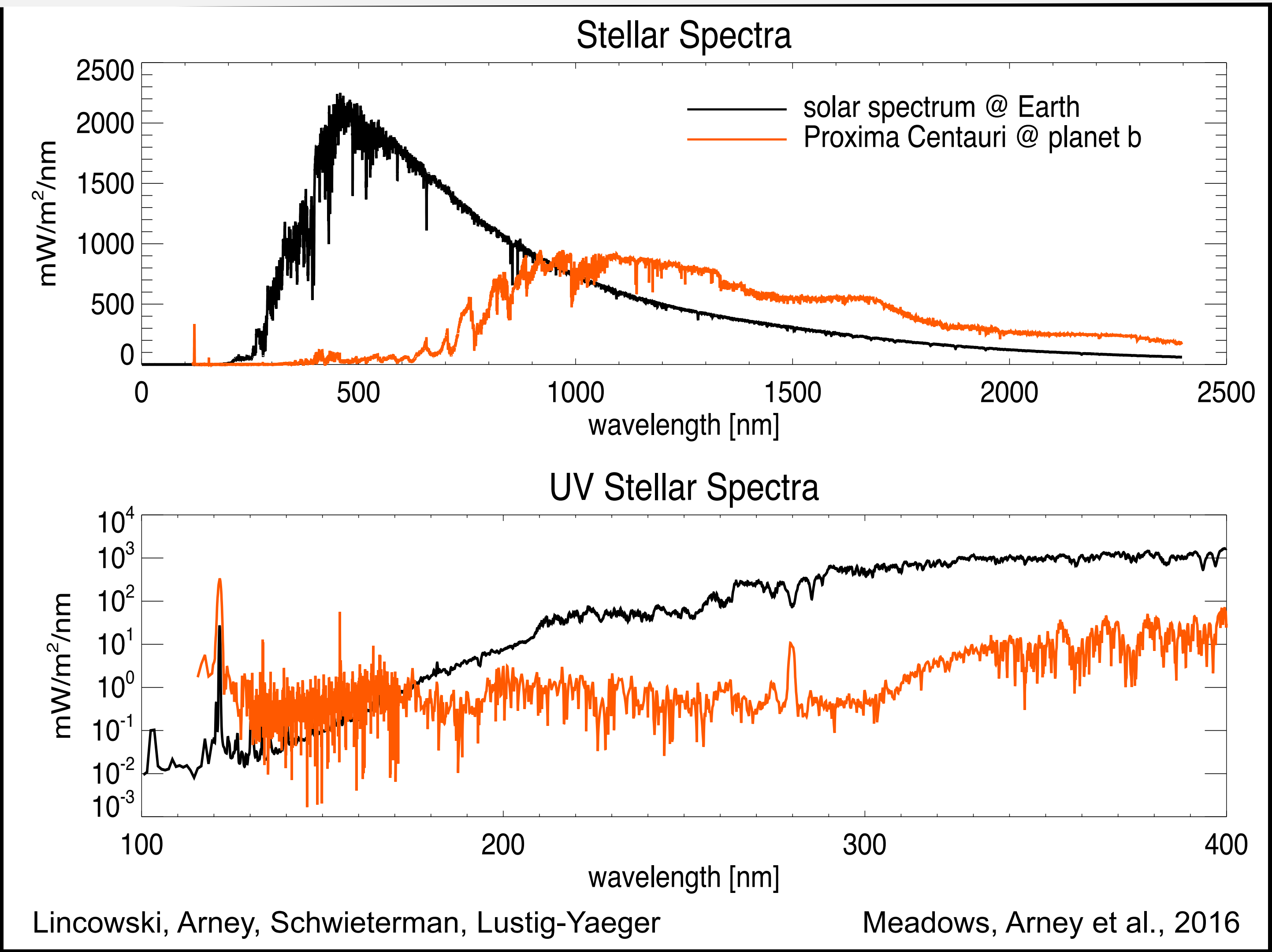
The VPL used Proxima Cen b to explore a large fraction of these!

M Dwarf Planets: Radiative Effects



- Spectrum of starlight
  - Affects climate via changes to atmospheric/surface absorption
- Stellar Activity
  - Photochemistry
  - Surface UV fluxes
- Stellar Evolution
  - Extended Pre-Main Sequence

M dwarf vs G dwarf stellar spectra



Lincowski, Arney, Schwieterman, Lustig-Yaeger

Meadows, Arney et al., 2016

- Lower stellar T produces more radiation at longer wavelengths – affects climate
- Higher activity produces more UV radiation – affects photochemistry
- *Proxima Cen spectrum available for download at https://depts.washington.edu/naivpl/*

Stellar Spectrum Affects Position in the HZ

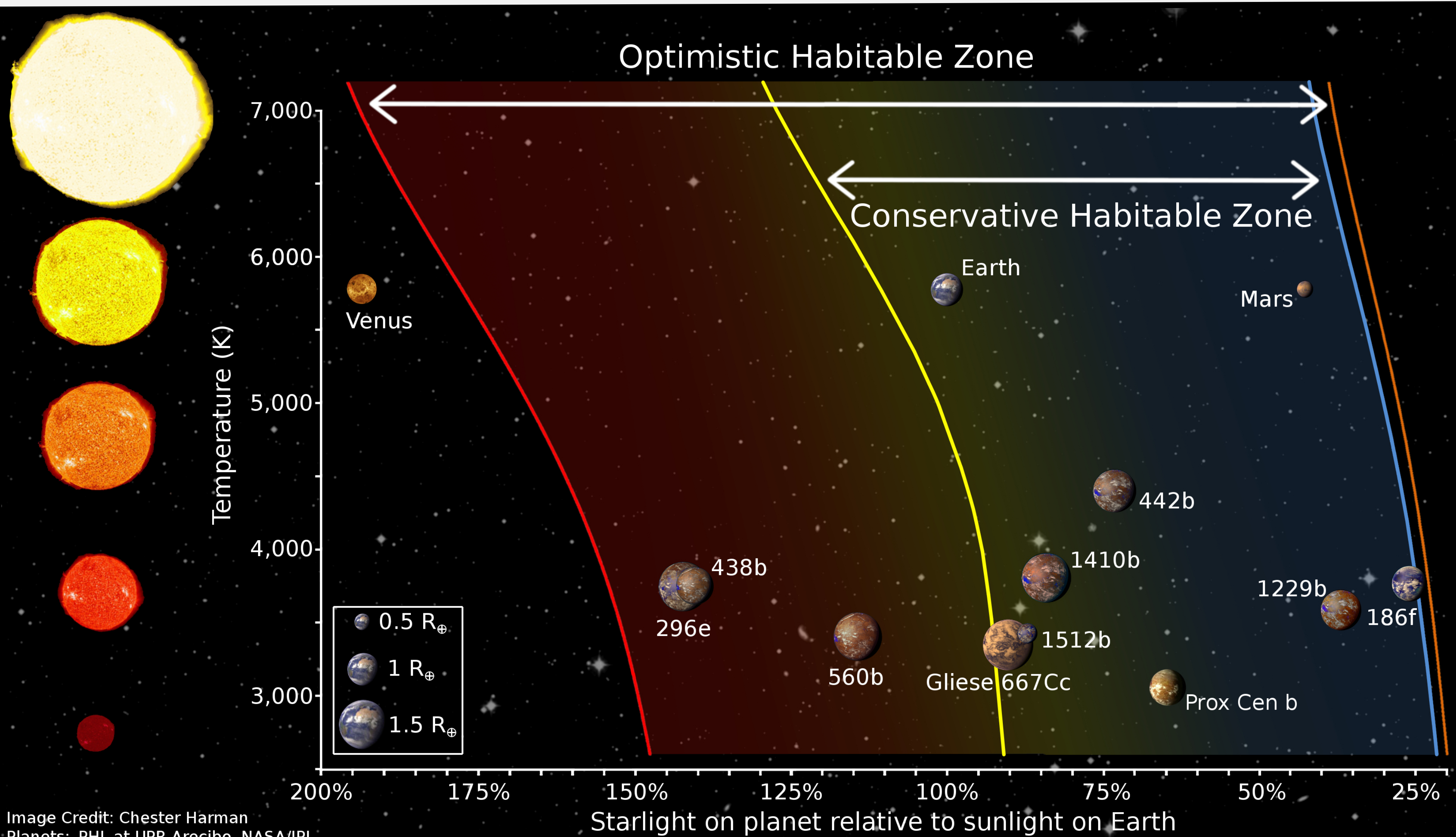
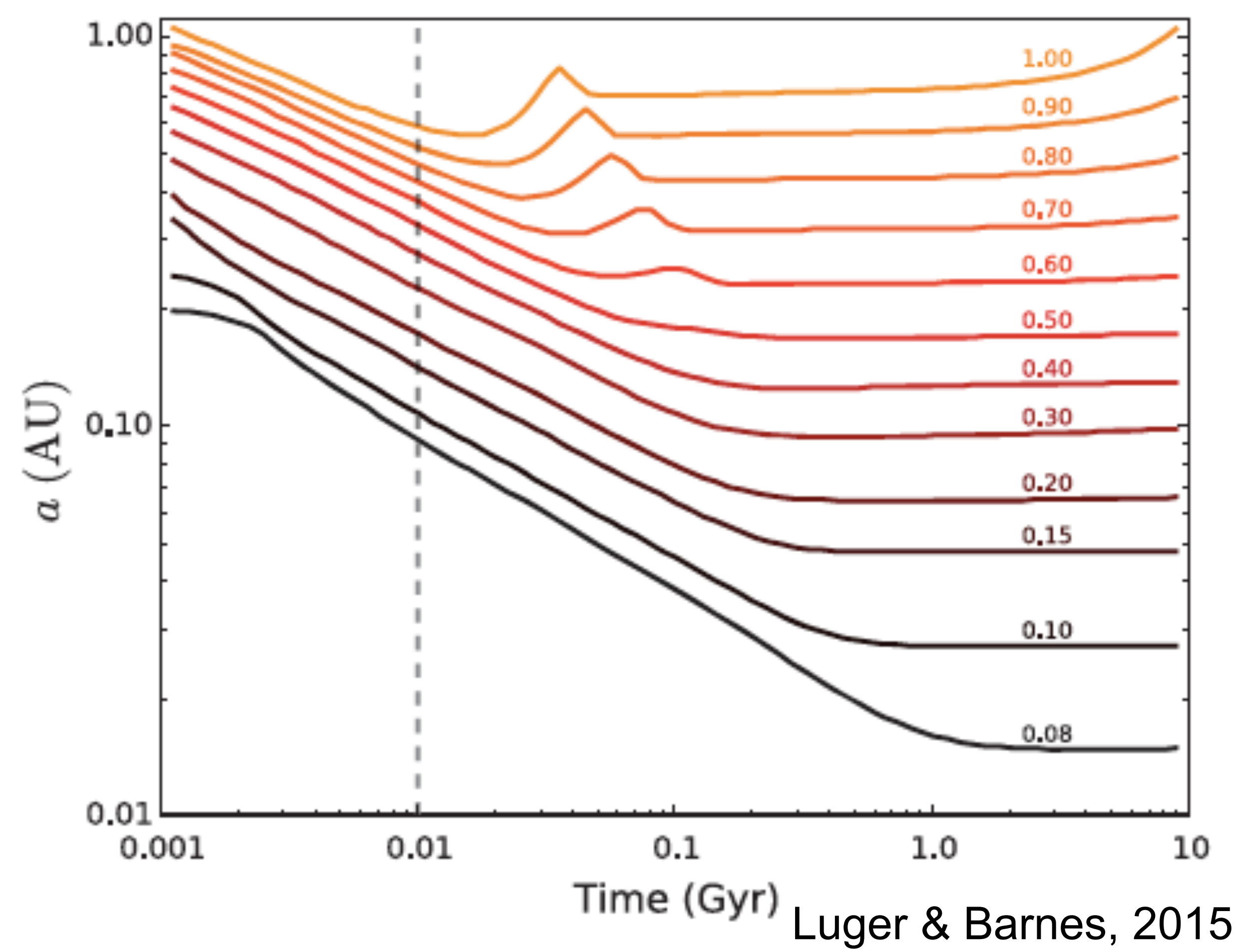


Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/JPL

Pre-Main Sequence Super Luminous Phase

Line shows the evolution of the inner edge of the HZ as a function of time

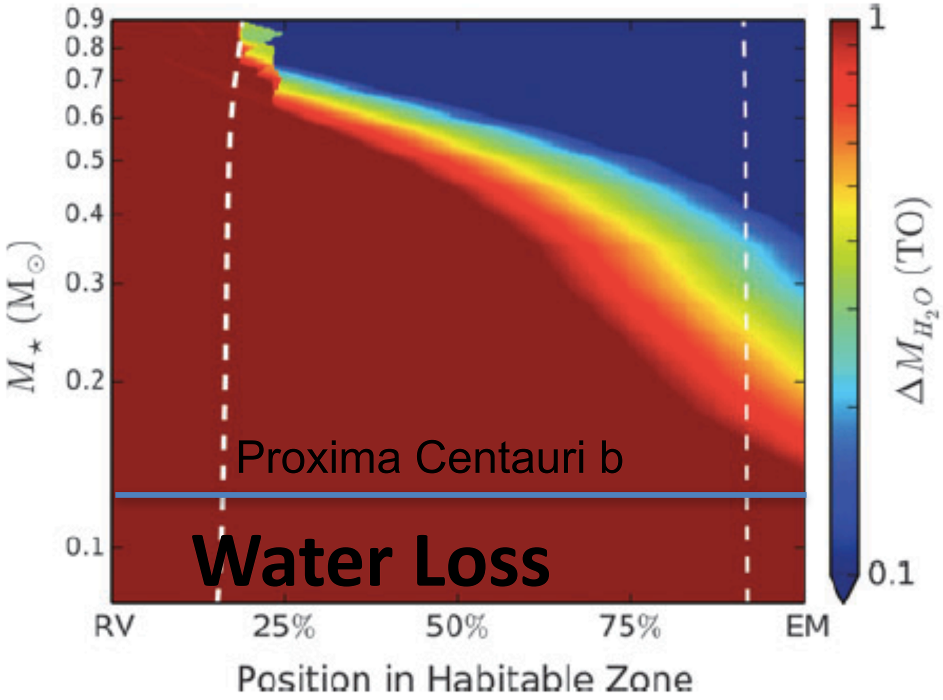


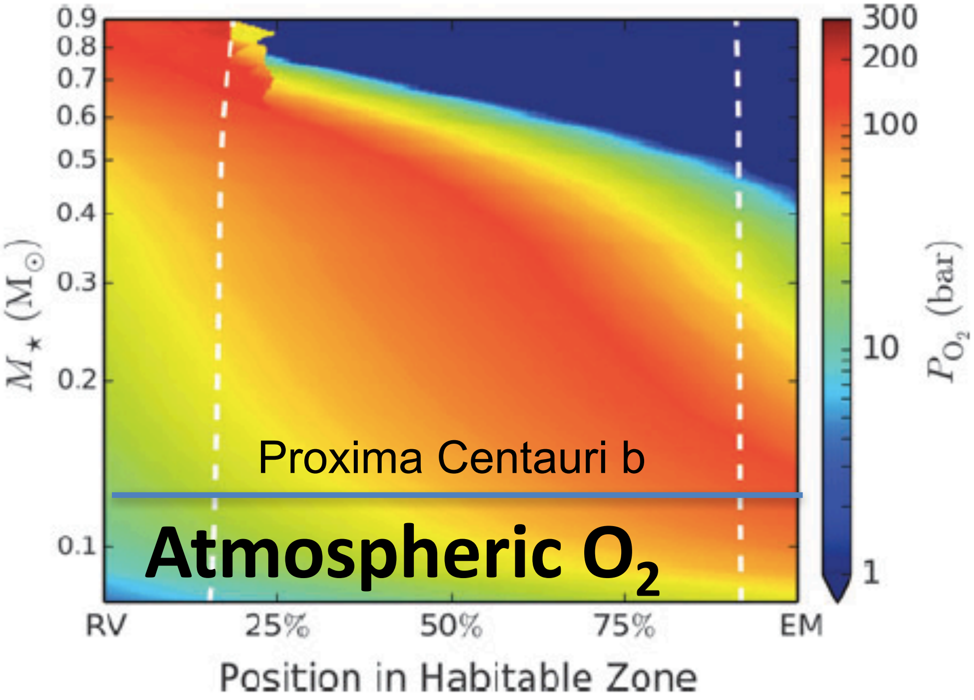
Luger & Barnes, 2015

Numbers are stellar mass in solar masses

- Late K and and all M dwarfs undergo a significant super-luminous phase as they contract down on to the main sequence.
- Any planet that forms in what will become the main sequence habitable zone of these stars can be subjected to very high levels of radiation for up to a Gyr.

Stellar Evolution, Water Loss and O_2 buildup.

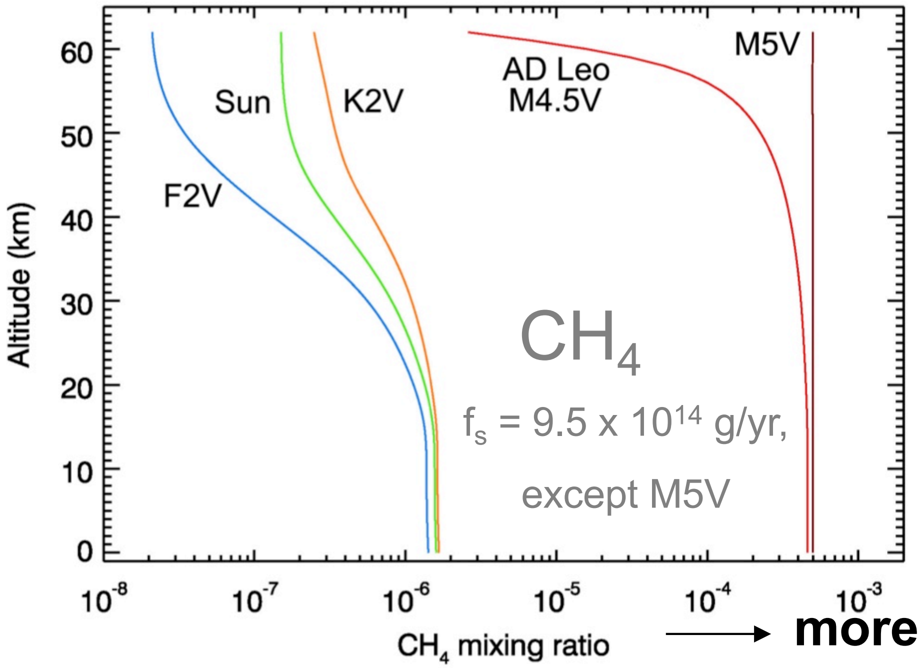




During the Pre-MS of M dwarfs terrestrial planets can lose several Earth oceans of water via hydrodynamic escape (Luger & Barnes, 2015)

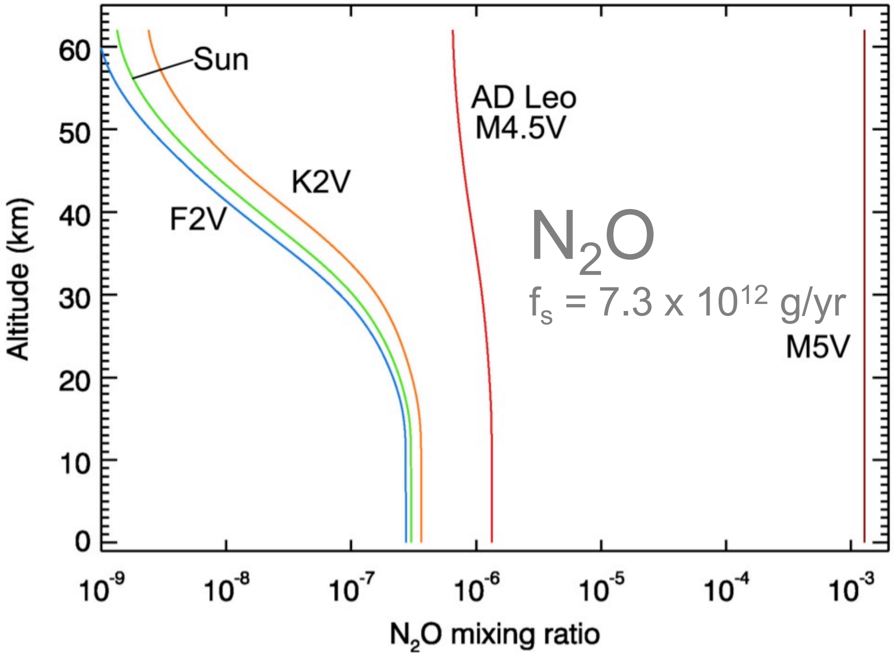
Hot Earths such as GJ1132b (Berta-Thompson et al.,2015) may undergo a similar process (Schaeffer et al., 2016). They will be excellent initial tests of the abiotic production of O_2, and the planet's ability to sequester it.

M Dwarfs May Enhance Biosignature Gases



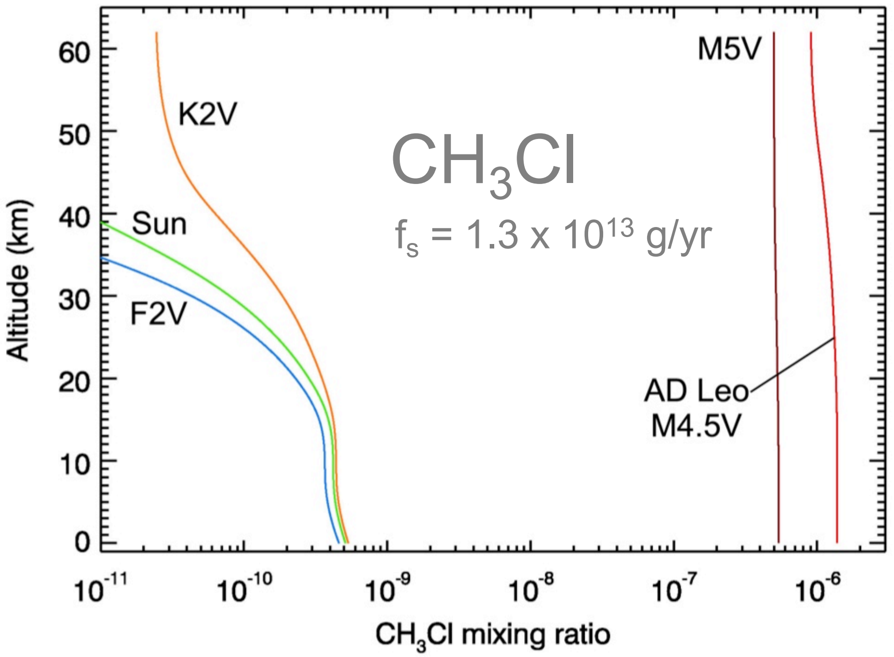
→ **more**

Segura et al., 2003, 2005



- •Earth-like planets around cooler stars show enhanced biosignature abundances (Segura et al., 2003, 2005)
  - – M stars less effective at O_3 photolysis
- •Enhancements in biosignatures, (including are *also* seen towards the outer edge of its habitable zone (Grenfell et al., 2006, 2007)

- •False positives for O_2 can be generated depending on stellar spectrum.



Several mechanisms may produce biosignature false positives for planets orbiting M dwarfs

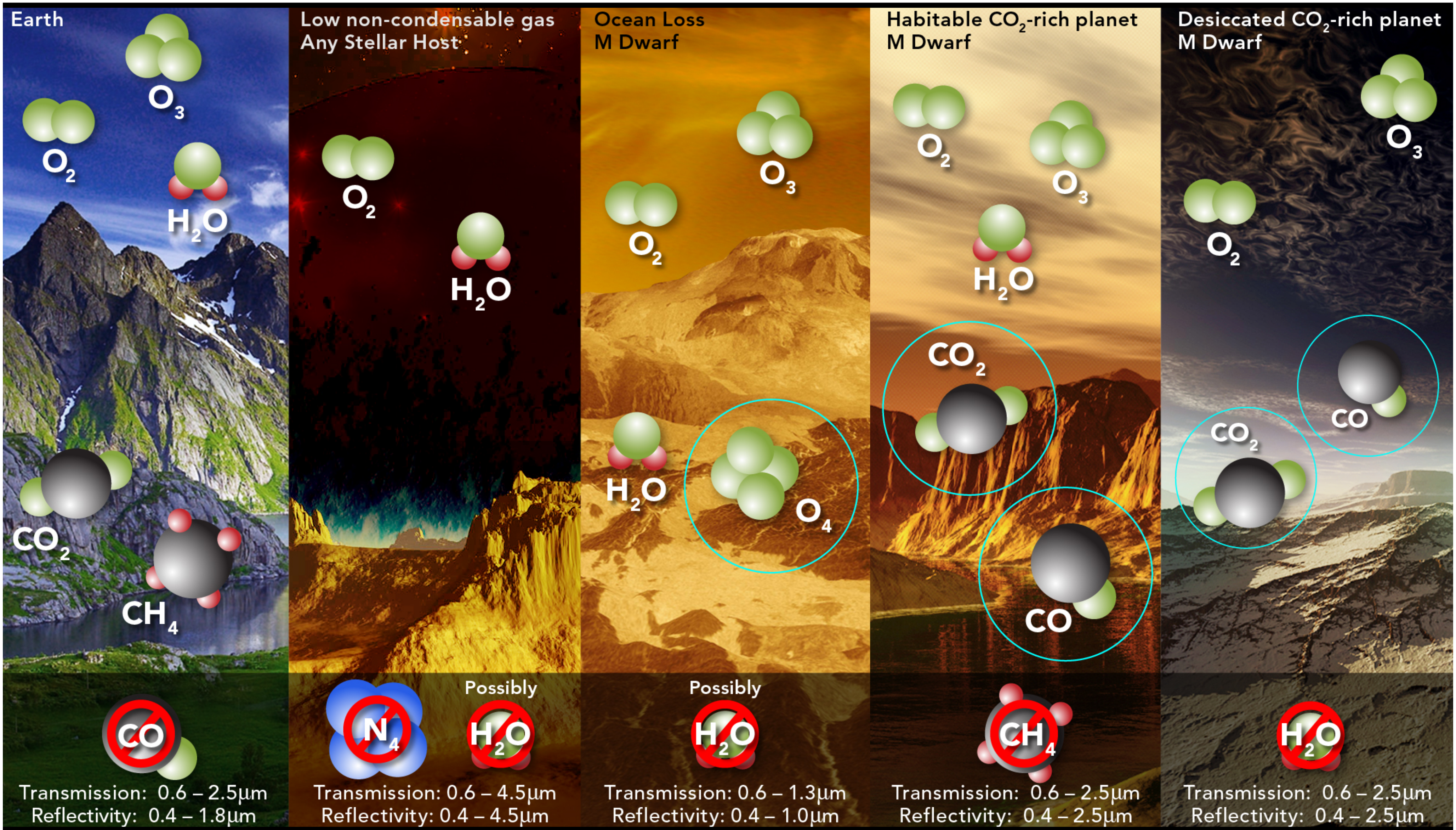
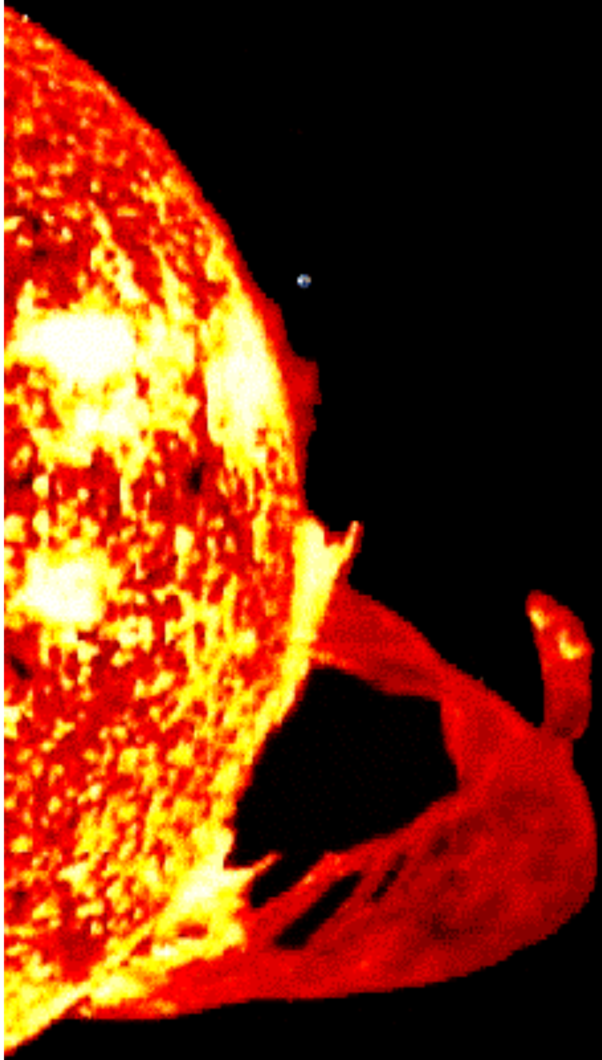


Figure Credit: Hasler/Meadows/Domagal-Goldman

Meadows, 2016, in review

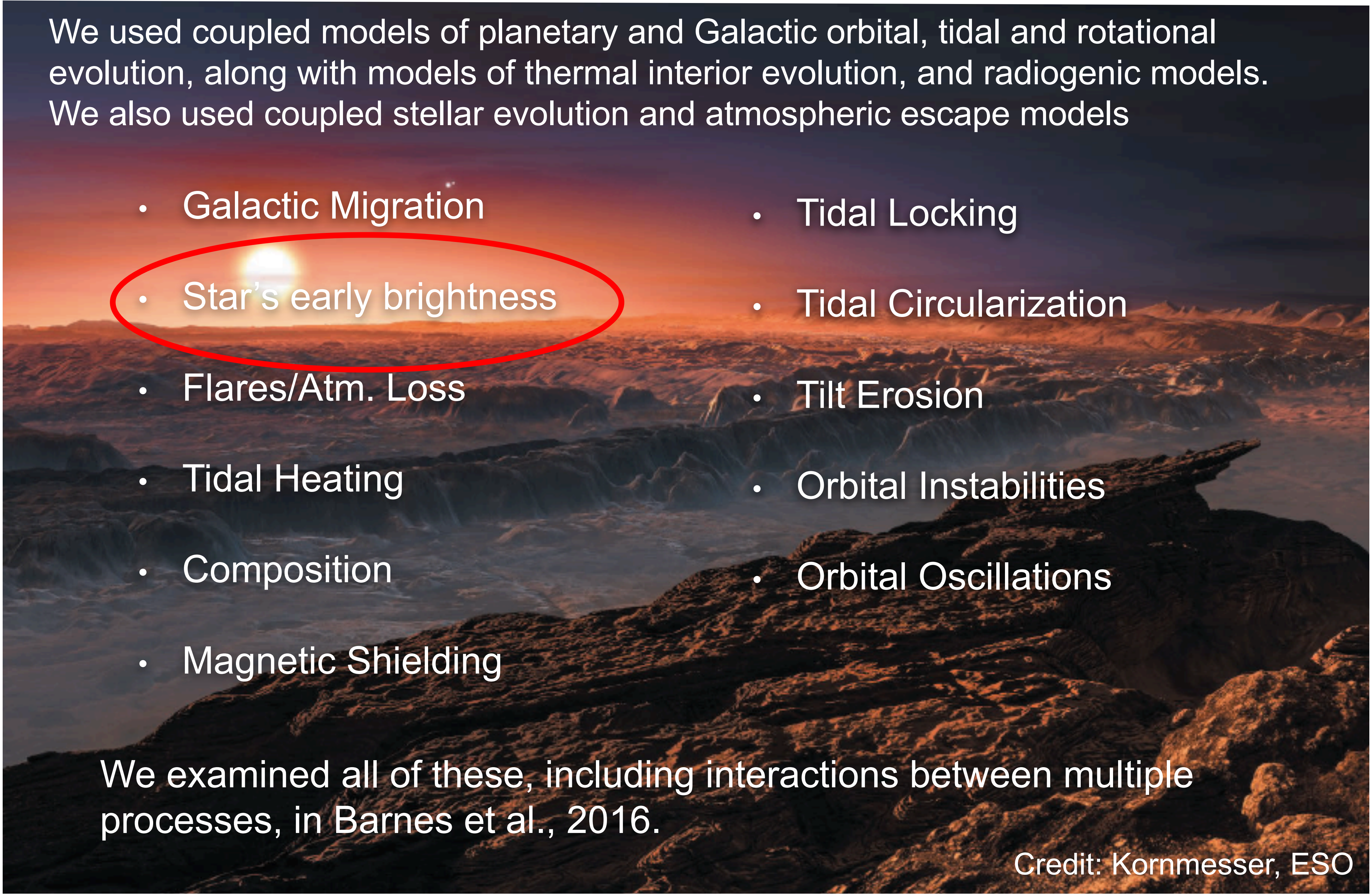
M Dwarf Planets: Gravitational Effects



- Orbital Evolution
  - Tidal Locking
  - Circularization
  - Climate effects
- Tidal Effects
  - Tidal Venuses
  - Loss of magnetic field

Proxima Centauri b: Things We Considered...

We used coupled models of planetary and Galactic orbital, tidal and rotational evolution, along with models of thermal interior evolution, and radiogenic models. We also used coupled stellar evolution and atmospheric escape models



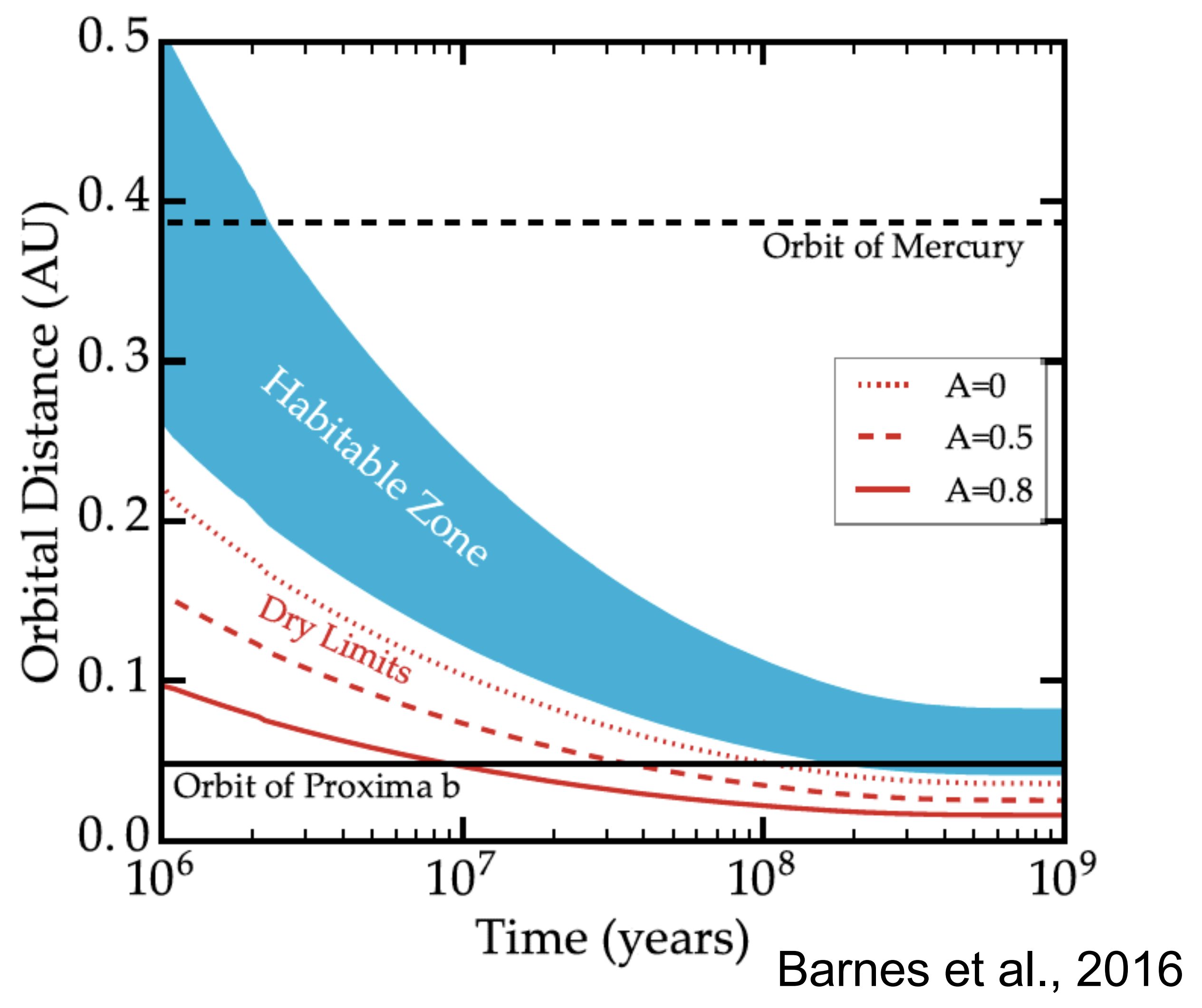
- Galactic Migration
- Star’s early brightness
- Flares/Atm. Loss
- Tidal Heating
- Composition
- Magnetic Shielding

- Tidal Locking
- Tidal Circularization
- Tilt Erosion
- Orbital Instabilities
- Orbital Oscillations

We examined all of these, including interactions between multiple processes, in Barnes et al., 2016.

Credit: Kornmesser, ESO

Proxima Cen b and Stellar Luminosity Evolution

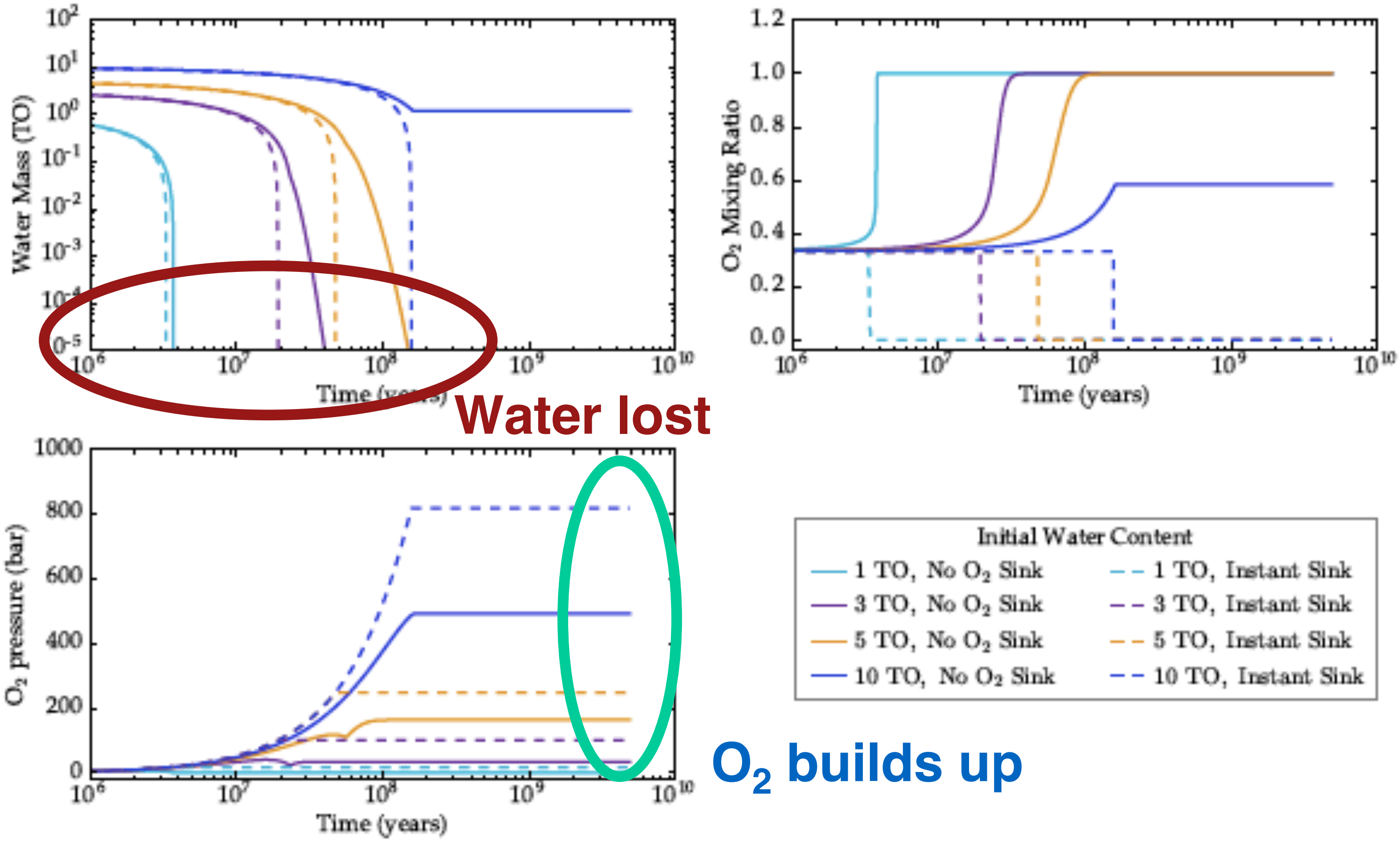


Barnes et al., 2016

The star's likely luminosity evolution suggests that if Proxima Cen b had formed at its current position, then the habitable zone would not have moved in towards the star to encompass the planet until abut 160 Myrs after formation.

Water Loss from Proxima Cen b

Abundant water but no H_2 envelope



Water lost

O_2 builds up

Coupled stellar and atmospheric evolution models

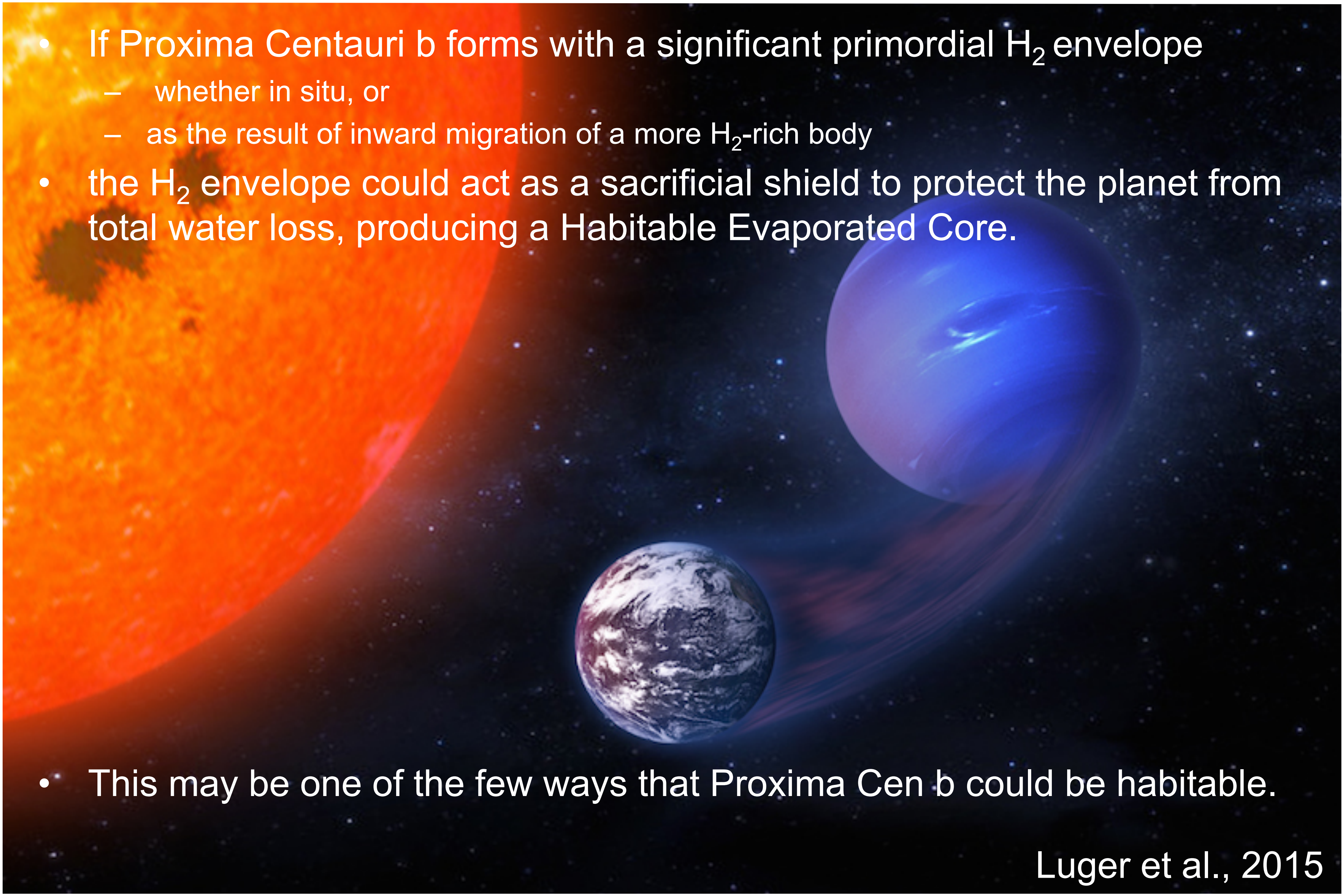
Barnes et al., 2016

Only one of the modeled scenarios (initial 10 oceans of H_2O, no O_2 sink) produced a planet that was NOT desiccated in the first 160 Myrs.

If Proxima Cen b formed at it current location, it is likely desiccated

(c.f Ribas et al., 2016 who used a significantly lower XUV flux and find that Proxima Cen b lost less than an ocean of water).

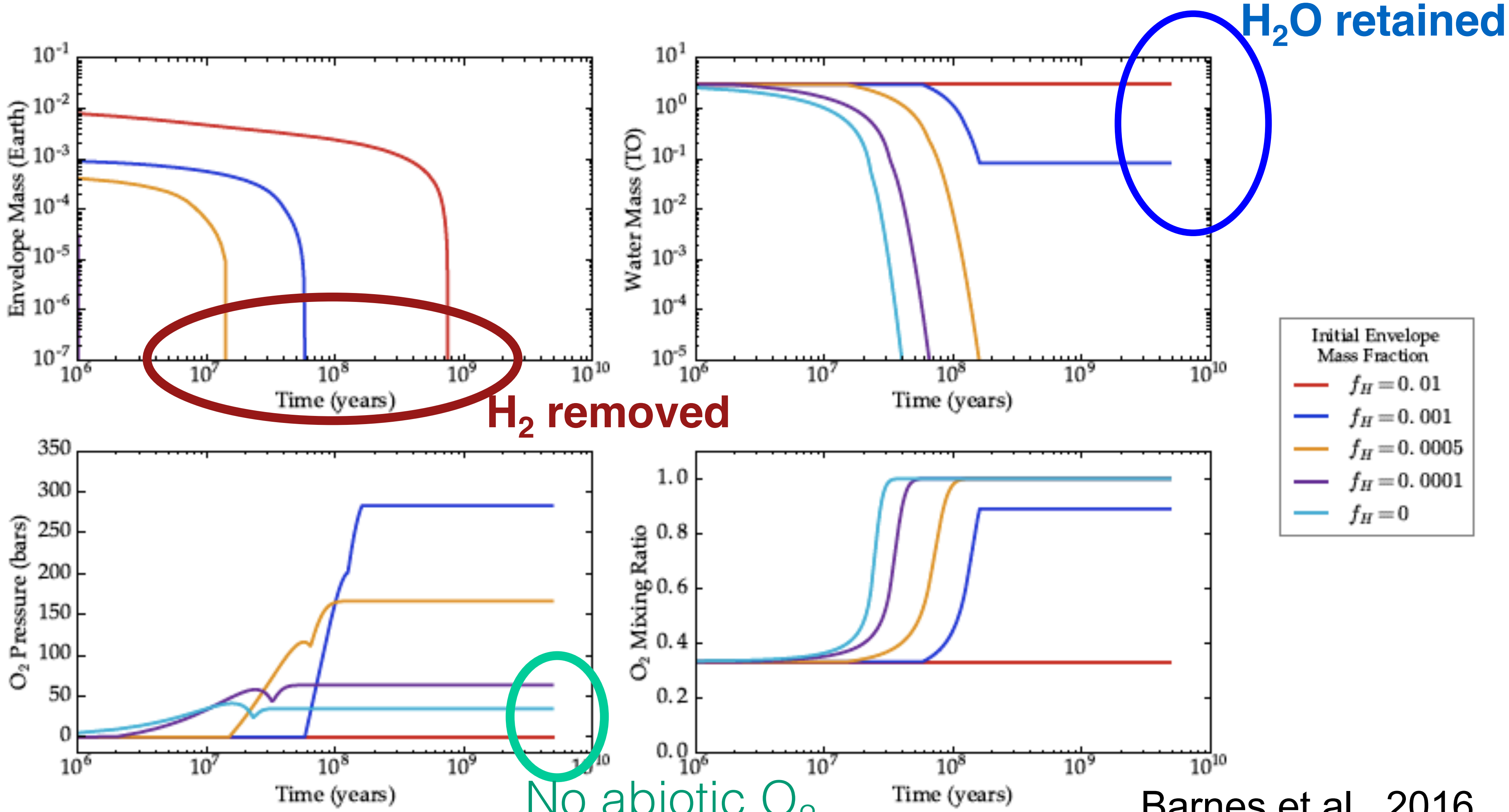
H_2 Envelope as Water Shield



- If Proxima Centauri b forms with a significant primordial H_2 envelope
  - whether in situ, or
  - as the result of inward migration of a more H_2-rich body
- the H_2 envelope could act as a sacrificial shield to protect the planet from total water loss, producing a Habitable Evaporated Core.
- This may be one of the few ways that Proxima Cen b could be habitable.

Luger et al., 2015

Loss of a H_2 envelope



H_2O retained

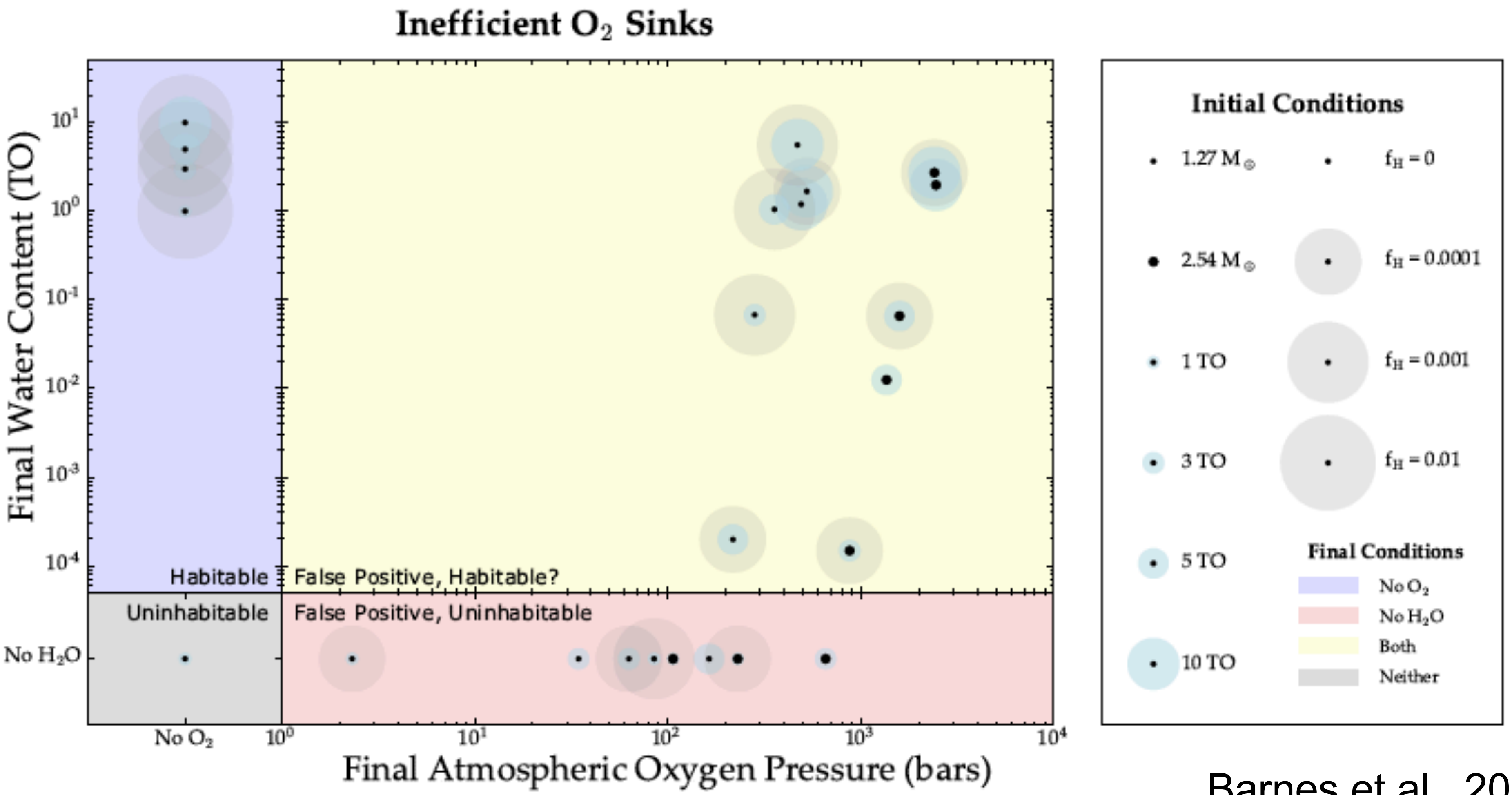
H_2 removed

No abiotic O_2

Barnes et al., 2016

- Too little H_2, and all water is lost.
- Too much (>1% or a larger mass planet), and the H_2 envelope is not lost, likely rendering the planet uninhabitable (c.f. Owen & Mohanty, 2016).

Several evolved states are possible

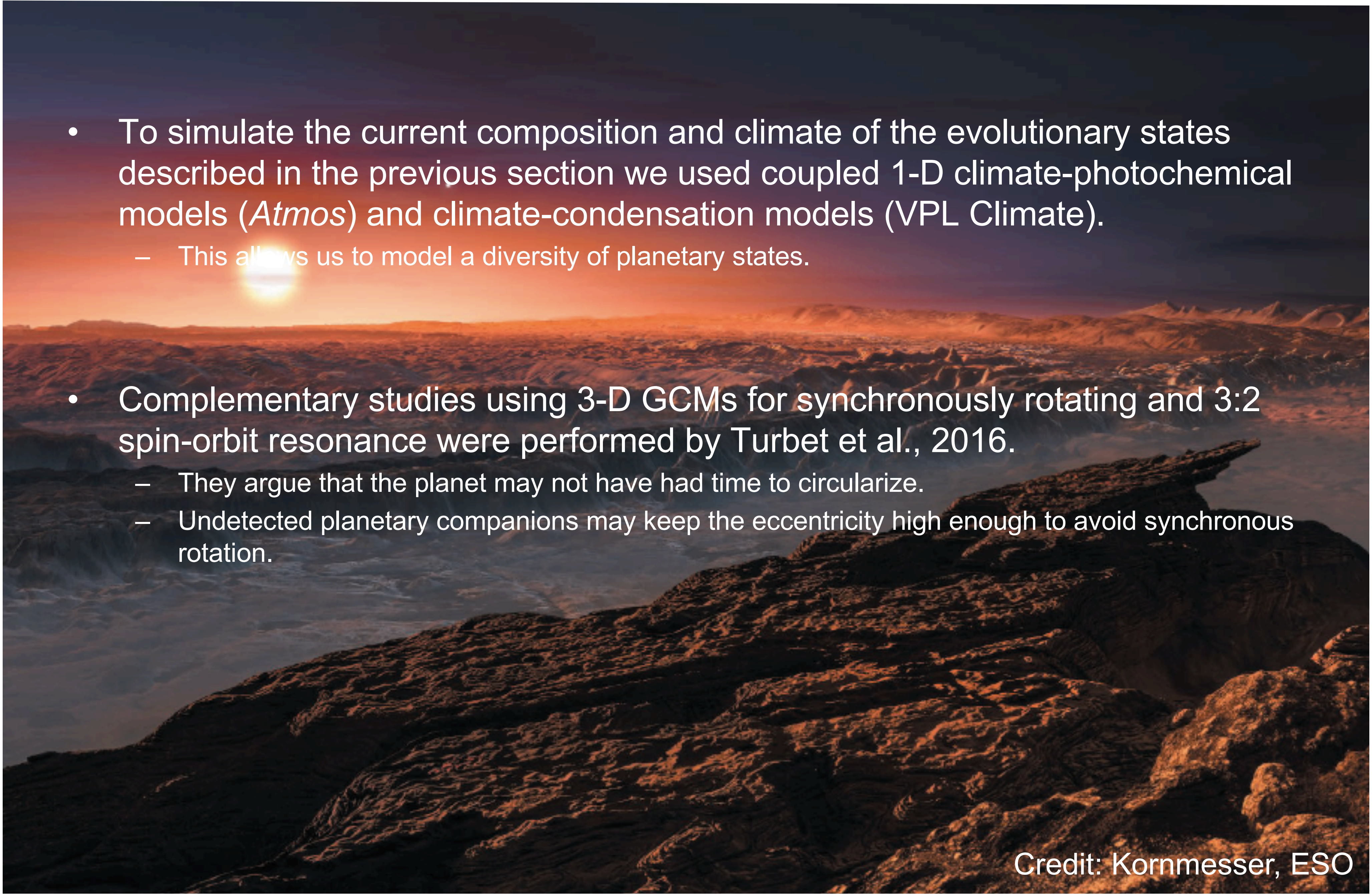


Barnes et al., 2016

Depending on H_2 envelope fraction, planet mass, and initial water inventory, planets could be habitable/uninhabitable, and have high abiotic O_2, or not.

An exact mass for Proxima Cen b could help inform the atmospheric escape history.

Proxima Centauri b: Current Atmospheric States



- To simulate the current composition and climate of the evolutionary states described in the previous section we used coupled 1-D climate-photochemical models (*Atmos*) and climate-condensation models (VPL Climate).
  - This allows us to model a diversity of planetary states.
- Complementary studies using 3-D GCMs for synchronously rotating and 3:2 spin-orbit resonance were performed by Turbet et al., 2016.
  - They argue that the planet may not have had time to circularize.
  - Undetected planetary companions may keep the eccentricity high enough to avoid synchronous rotation.

Credit: Kornmesser, ESO

1D and 3D Climate Model Comparisons

Atmosphere	VPL	Model	Comparison	Reference
1 bar CO_2	271 K	VPL Climate Meadows et al., 2016	266K (3:2) 247K (synch)	Turbet et al., 2016
4 bar CO_2	306K	VPL Climate	305K (3:2) 289K (synch)	Turbet et al., 2016
6 bar CO_2	320K	VPL Climate	324K (3:2) 309K (synch)	Turbet et al., 2016
1 bar N_2, 376ppm CO_2	247K	VPL Climate	238K (3:2) 220K (synch)	Turbet et al., 2016
2% CO_2, 0.02% CH_4, water	282K	*Atmos* Arney et al., 2016.	287K	Charnay et al., 2013
6% CO_2, water	286K	*Atmos*	288K	Wolf and Toon., 2013

For the 3:2 spin-orbit resonance cases our 1-D models agree with the 3-D GCM results to within ~10K.

Summary of Evolutionary End States Considered*

- O_2-dominated (formed in situ, ocean loss)
  - 10 bar O_2-dominated with 0.5% CO_2, desiccated
  - 10 bar O_2-dominated with 0.5% CO_2, water remaining

- CO_2/O_2-dominated (post ocean loss, CO_2 outgassed)
  - 90, 10 bar atmospheres 45% CO_2, 45% O_2, desiccated.
  - 1 bar desiccated atmosphere with $CO_2/O_2/CO$

- CO_2-dominated atmospheres (post ocean loss, O_2 lost/sequestered)
  - Venus-like 90, and 10 bar CO_2 atmosphere, 20 ppm water, self-consistent H_2SO_4 cloud formation.

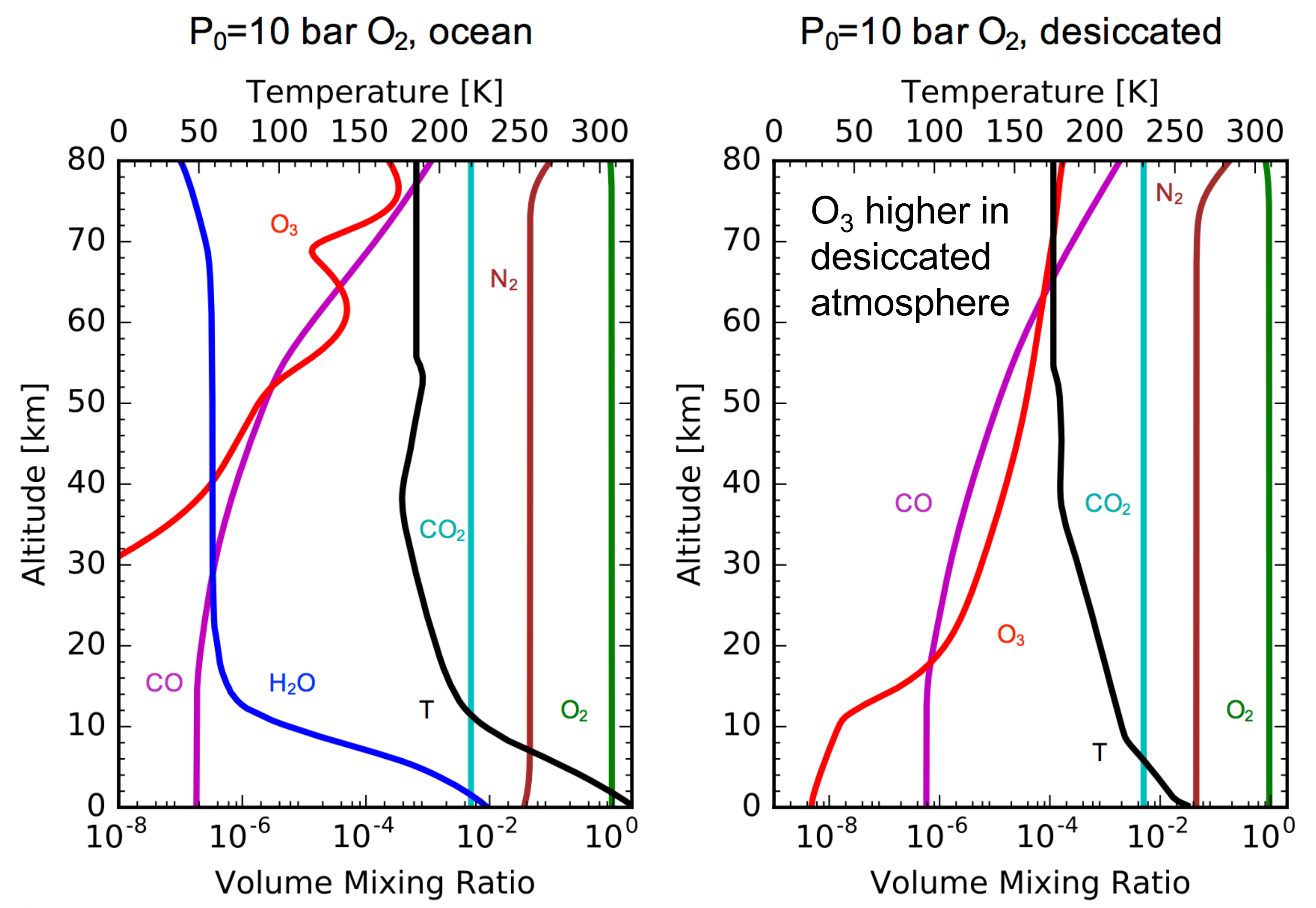
- N_2/O_2-dominated Earth-like (HEC, or planet-planet orbital evolution)
  - photochemically self-consistent with stellar UV

- $N_2/CO_2/CH_4$ anoxic early Earth-like (HEC, or orbital evolution)
  - Self consistent formation of hydrocarbon haze.

*representative, not complete!

Meadows, Arney et al., 2016

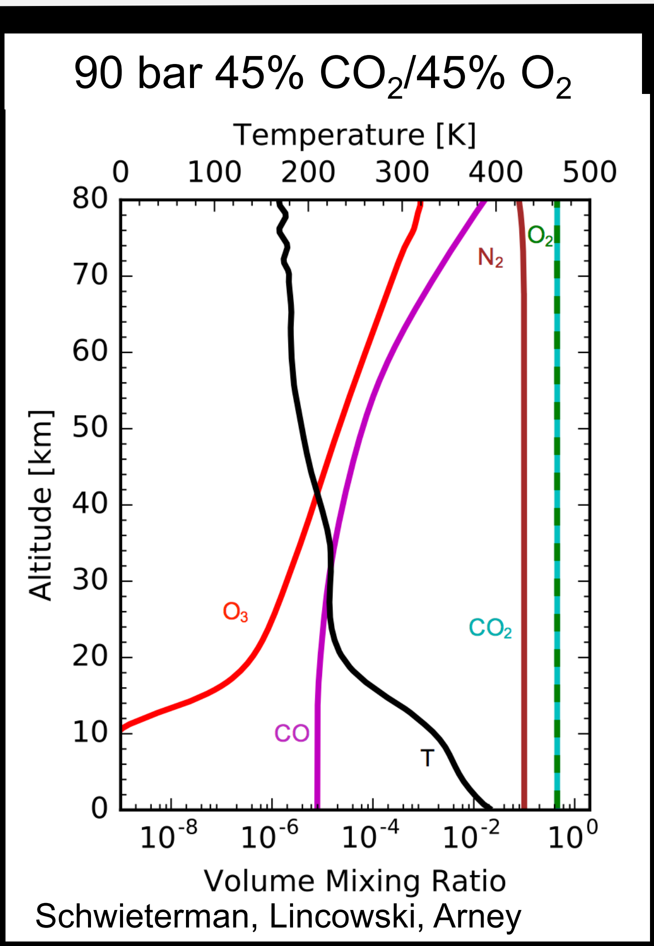
O_2-dominated, post ocean loss



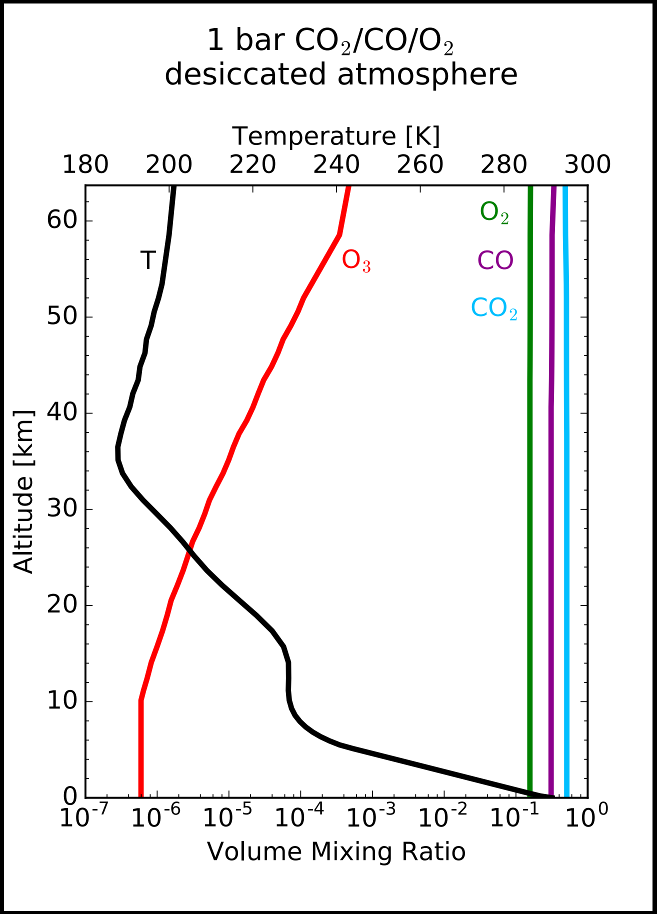
Schwieterman, Arney, Lincowski

- Self-consistent “ocean-remaining” and “desiccated” cases
- Lack of water (OH radicals) affected CO, O_3 profiles and surface temperature
- Tsurf = 320K and water present for ocean remaining (habitable?)
- Tsurf = 257K and desiccated (cold and dry - not habitable)

CO_2/O_2 and CO_2– dominated, post ocean loss

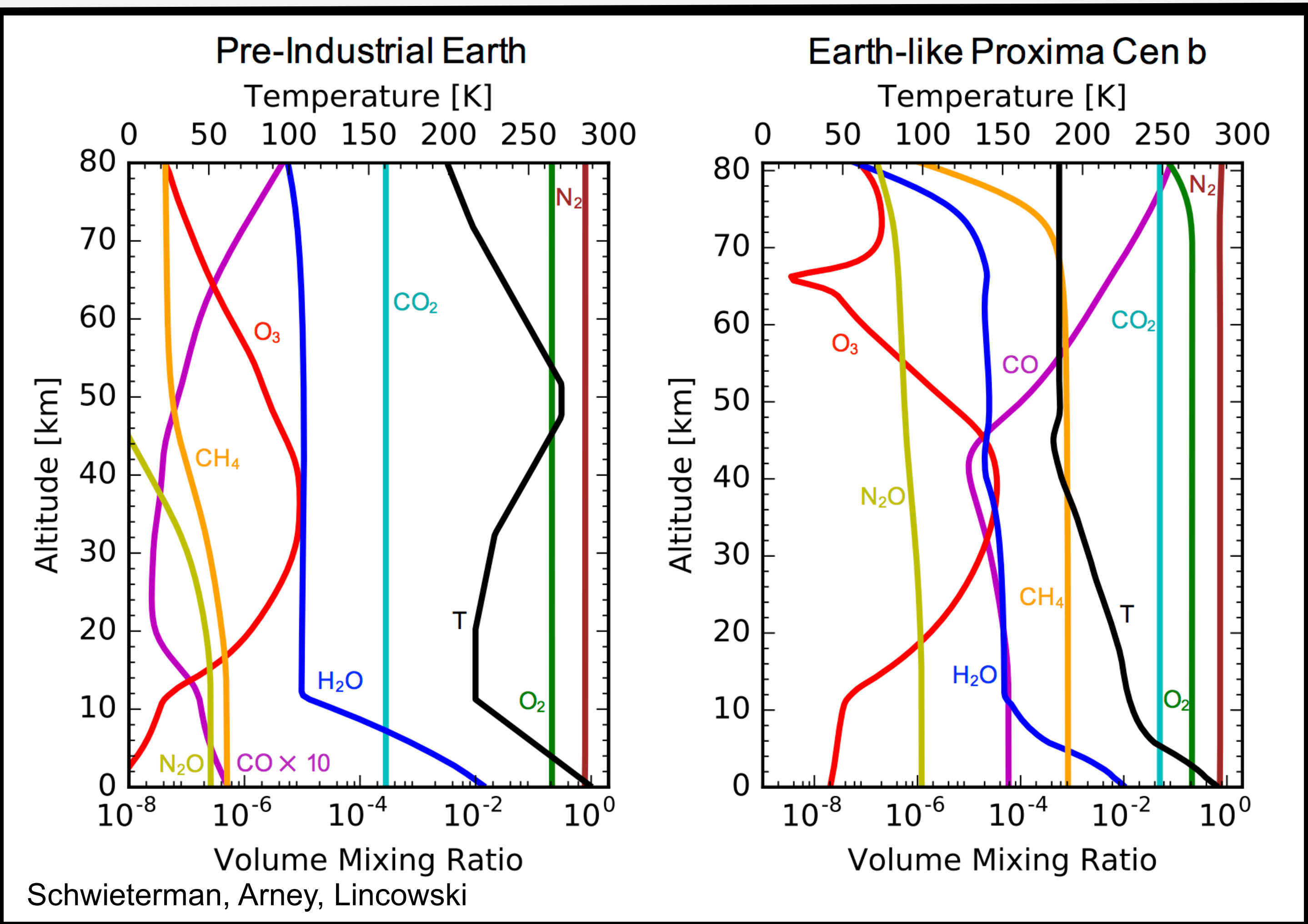

90 bar 45% CO_2/45% O_2

Schwieterman, Lincowski, Arney


1 bar CO_2/CO/O_2
desiccated atmosphere

- 10 and 90 bar 45% CO_2, 45% O_2 and ~ 10% N_2 atmosphere
- 1-bar desiccated CO_2/O_2/CO atmosphere (Gao et al., 2016)
- 90 bar Tsurf = 383K, 10 bar Tsurf=342K (dessicated – not habitable)
- 1 bar Tsurf = 297K (nice!) but desiccated (not nice)
- 10 and 90 bar Venus-like (96% CO_2, 20ppm H_2O) Tsurf = 428-568K (not habitable!)

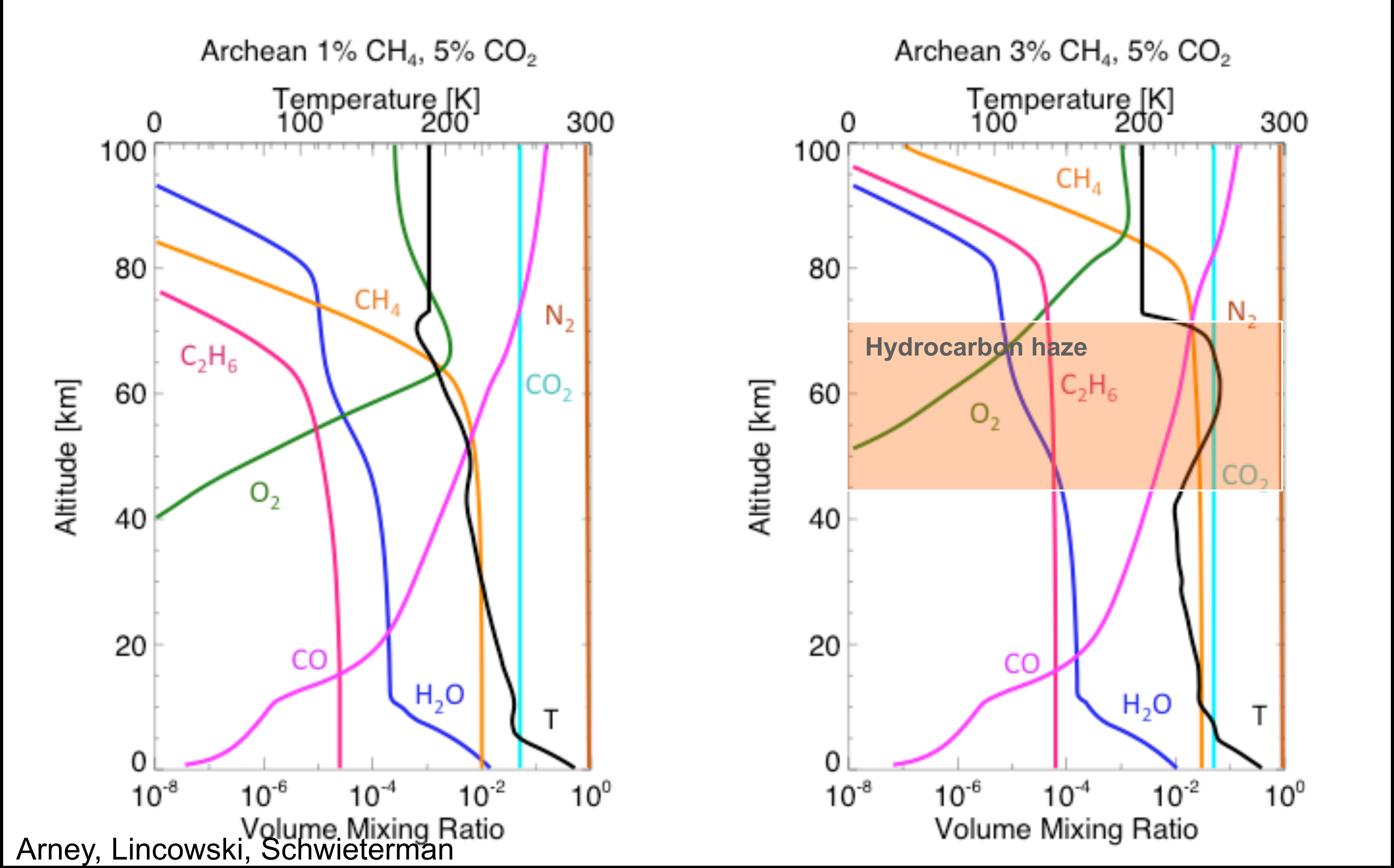
N_2/O_2-dominated, HEC or orbital evolution



Schwieterman, Arney, Lincowski

- 1-bar N_2/O_2 atmosphere with trace gases determined self-consistently with the star's UV flux Earth's pre-industrial surface fluxes.
- CH_4,N_2O are photochemically enhanced around Proxima Cen b
- With 5% CO_2, Tsurf = 283K, water present (habitable)

N_2/CO_2 dominated (early Earth), HEC or orbital evolution



Arney, Lincowski, Schwieterman

- 1-bar N_2-dominated atmosphere with 5% CO_2 and either 1% or 3% CH_4.
- The larger CH_4 abundance produces a hydrocarbon haze.
- Haze-free 1% CH_4, Tsurf = 289K (habitable)
- Hazy 3% CH4, Tsurf= 285K (habitable) Haze has little effect for M dwarfs
- Haze as a possible biosignature (Arney et al., 2016b; Guzman-Marmolejo et al., 2013)

Proxima Cen b: A World of Climate Possibilities

Case	**Tsurf**	**H_2O?**	**Notes**	**Hab?**
N_2/O_2-rich, Modern Earth-like, 1 bar, H_2O cloud.	283K	✔	5% CO_2, self-consistent w/star, HEC or orbital evolution	✔
$N_2/CO_2/CH_4$ Archean Earth-like, haze,1 bar	289K 285K	✔	5% CO_2, 1% CH_4 - 3% CH_4 for haze, HEC or orbital evolution	✔
O_2-rich, H_2O-remains, 10 bar	320K	✔	0.5% CO_2, incomplete ocean loss. O_2 may hamper life's origin	✔?
$CO_2/CO/O_2$, no-H_2O 1 bar	298K	✗	Stable mix if H < 1ppm. CO_2 recombination if H_2O/catalysts.	✗
O_2-rich, H_2O lost 10 bar	257K	✗	0.5% CO_2, ocean loss, some O_2 sequestration	✗
O_2/CO_2-rich, H_2O lost 10 and 90 bar	342K 383K	✗	Ocean loss, outgassing of CO_2, some O_2 sequestration	✗
CO_2-rich,20 ppm H_2O 10 and 90 bar	428K 567K	✗	Ocean loss, outgassed CO_2, all O_2 sequestered, Venus-like	✗

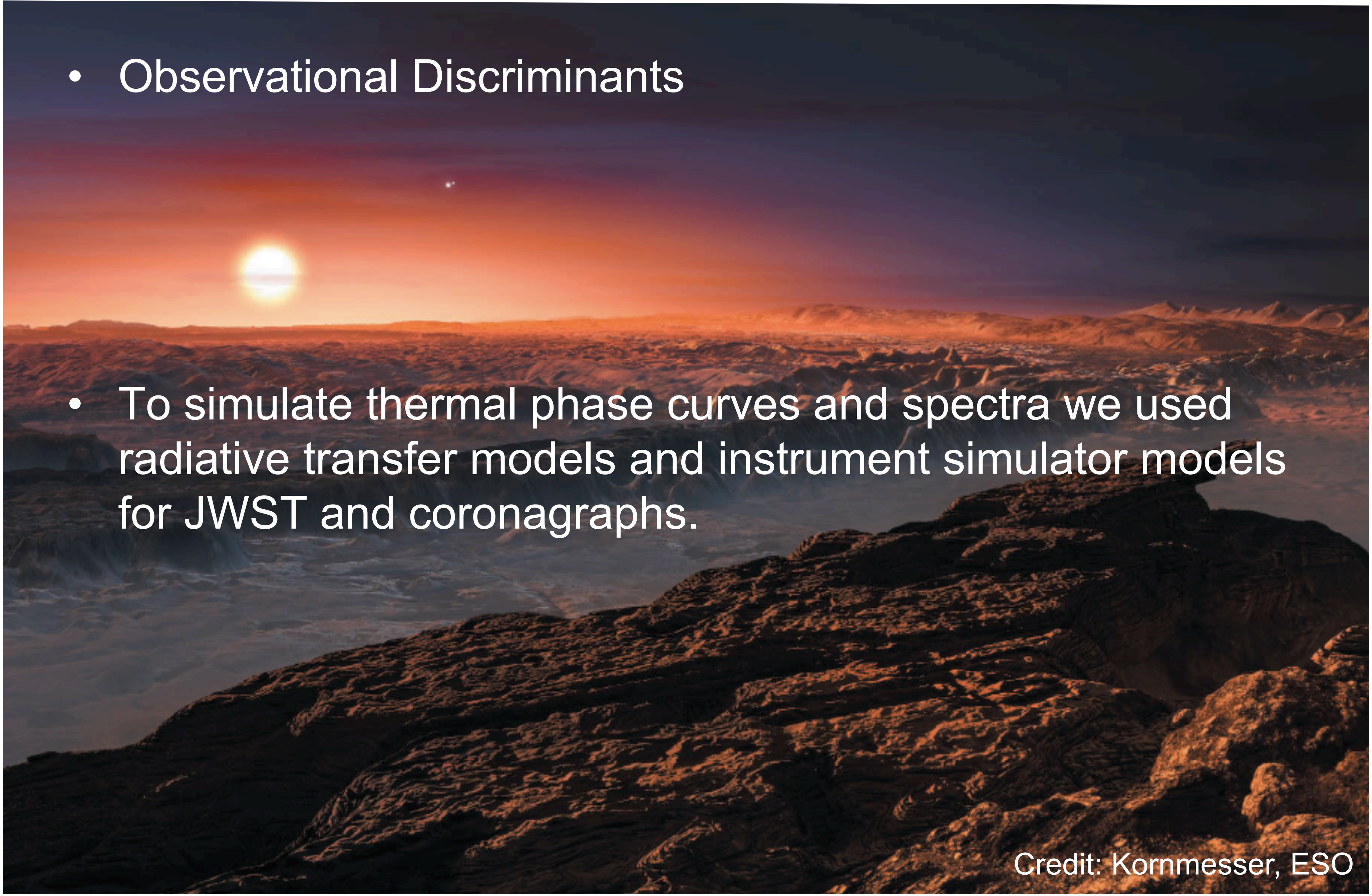
Although it sits squarely in the habitable zone, depending on the evolutionary path taken, Proxima Cen b may or may not be habitable.

What do we take away from this?

- Clearly terrestrial planet evolution, and the resulting atmosphere, matters to a planet’s habitability.
- Will observations allow us to recognize these different planetary states and the likely evolutionary path taken by the planet?

Credit: Kornmesser, ESO

Proxima Centauri b

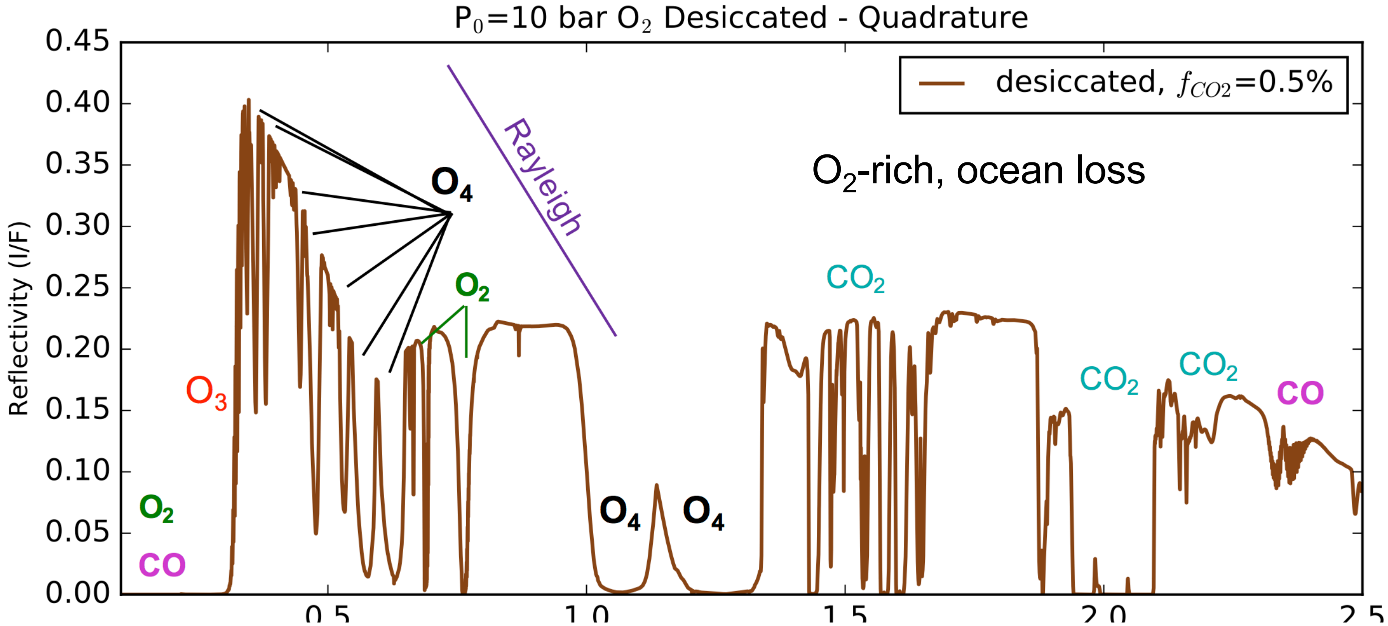


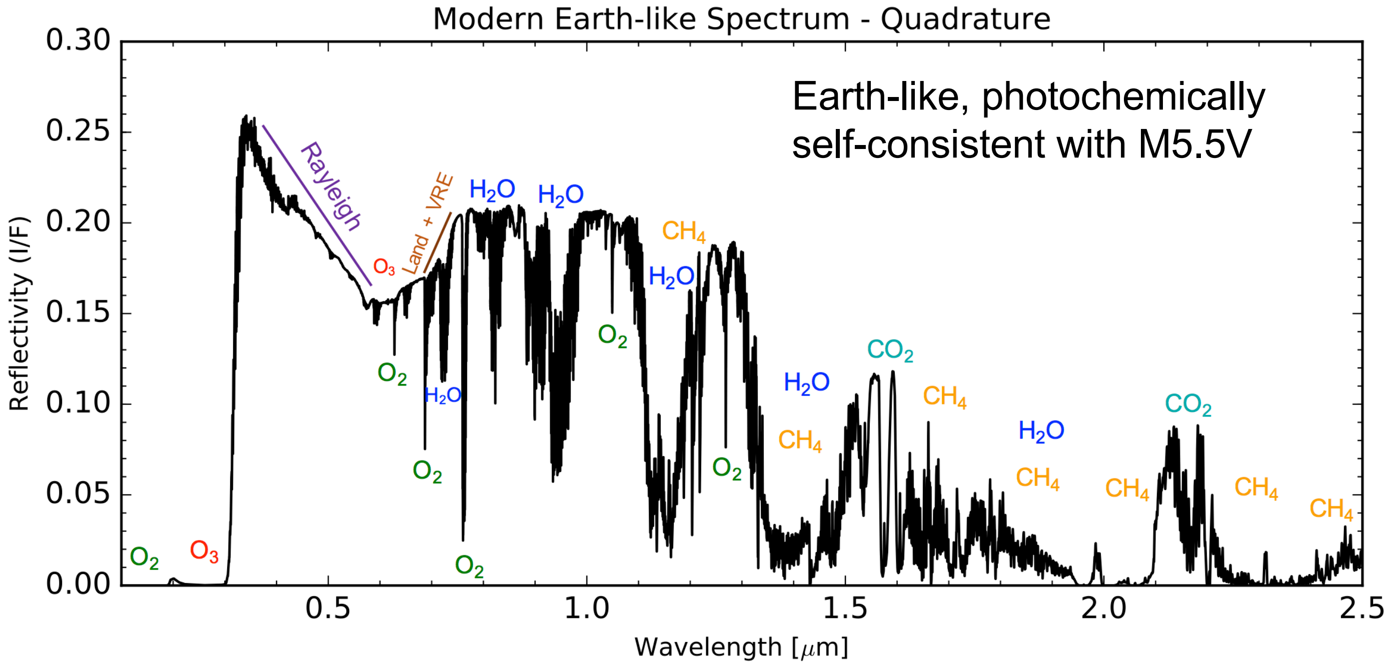
- Observational Discriminants

- To simulate thermal phase curves and spectra we used radiative transfer models and instrument simulator models for JWST and coronagraphs.

Credit: Kornmesser, ESO

O_4 Discriminates Ocean Runaway vs Inhabited Earth-Like Planets


P_0=10 bar O_2 Desiccated - Quadrature


Modern Earth-like Spectrum - Quadrature

O_2-rich, ocean lost

Strong O_2 and O_3

O_4 CIA (0.35 - 1.3μm)

H_2O weak or missing

CO_2 present

Earth-like Biosphere

Strong O_2 and O_3

No O_4 CIA

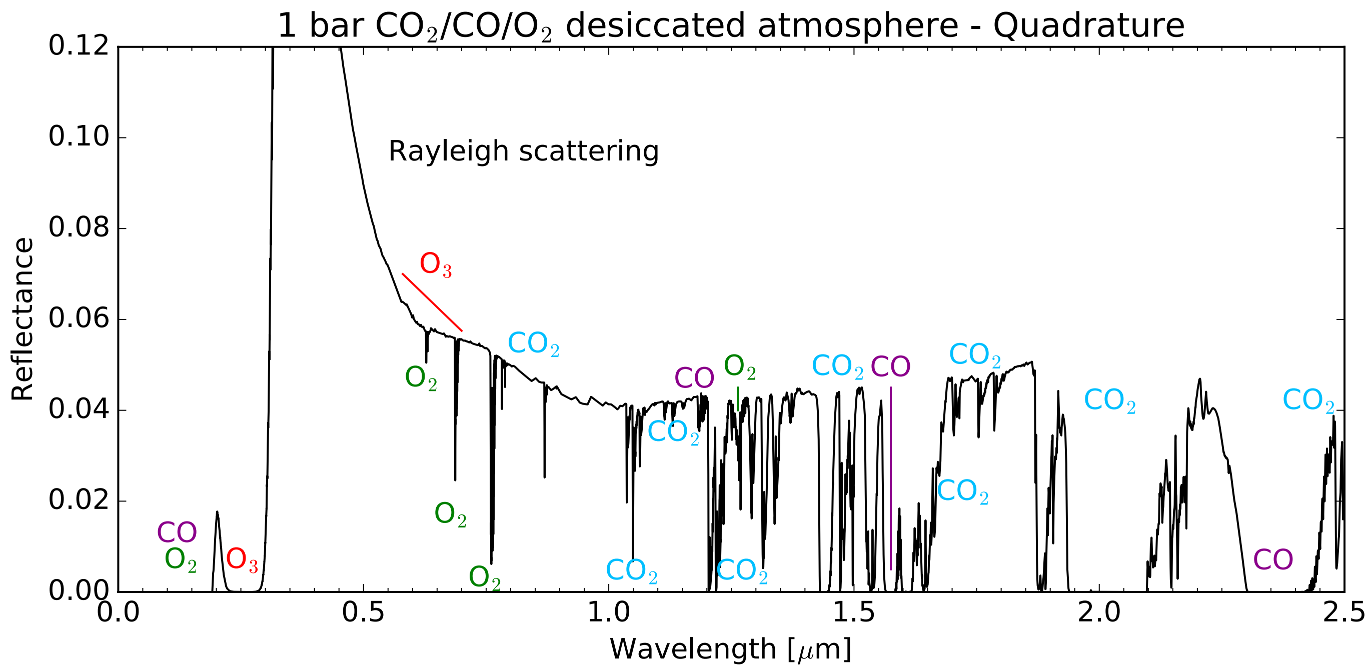
Strong H_2O

Strong CH_4

CO_2 present

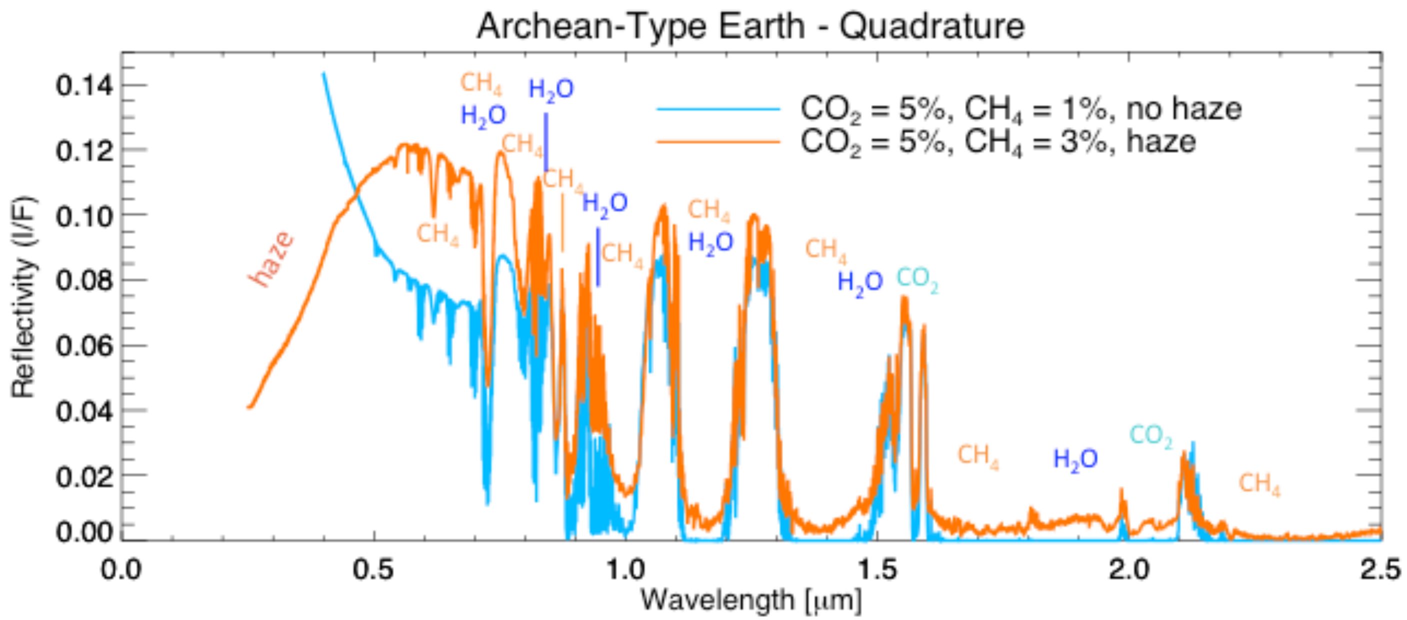
Schwieterman et al., 2016:
Meadows, Arney et al., 2016

Desiccated O_2/CO_2 Atmospheres and Archean-type



Lack of H_2O indicates that the O_2 is more likely to have an abiotic source

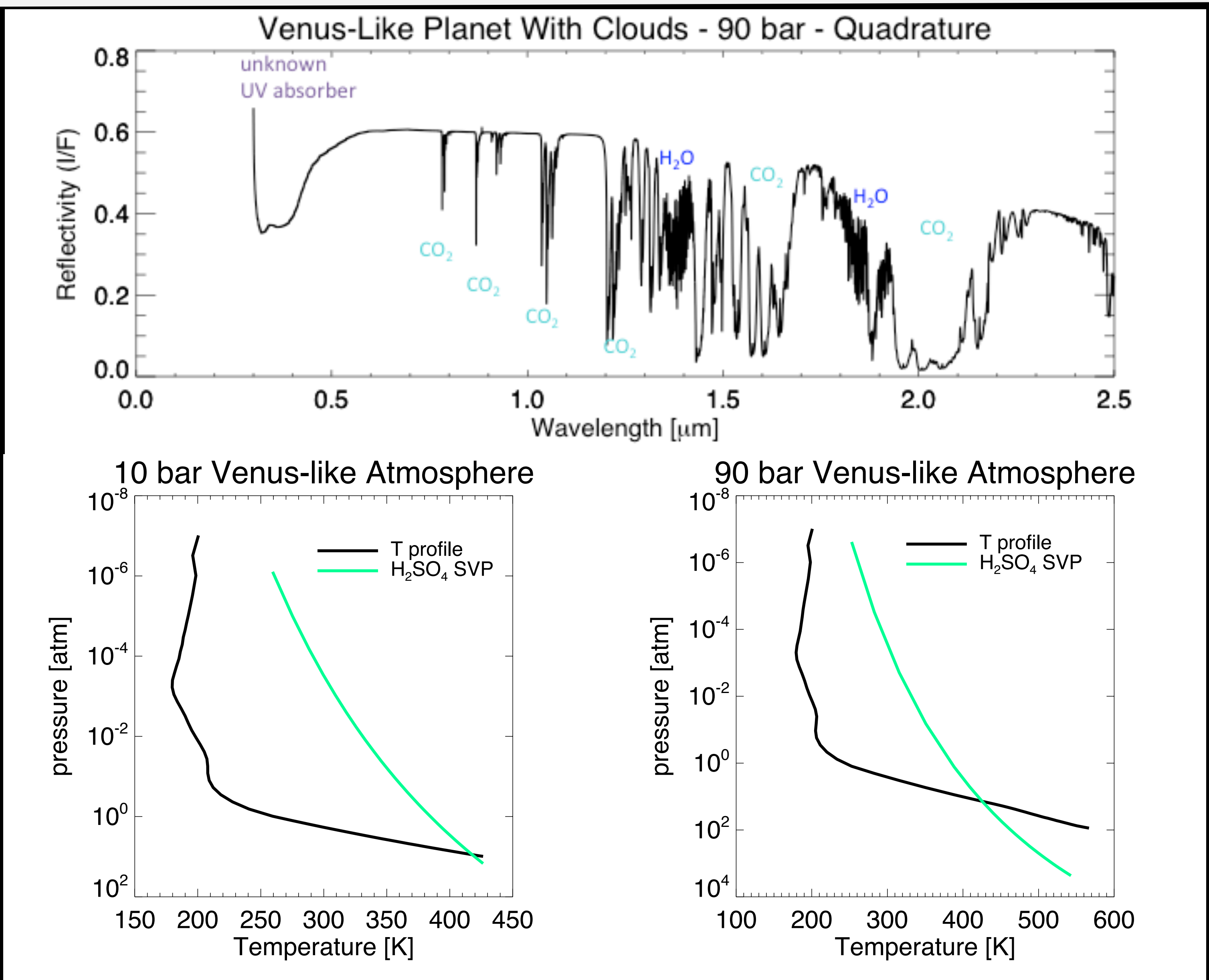
(Gao et al., 2016; Schwieterman et al., 2016)



Early Earth shows strong CO_2, CH4 and haze absorption.

(Arney et al., 2016)

Venus-like planet shows strong CO_2, and possibly H_2O



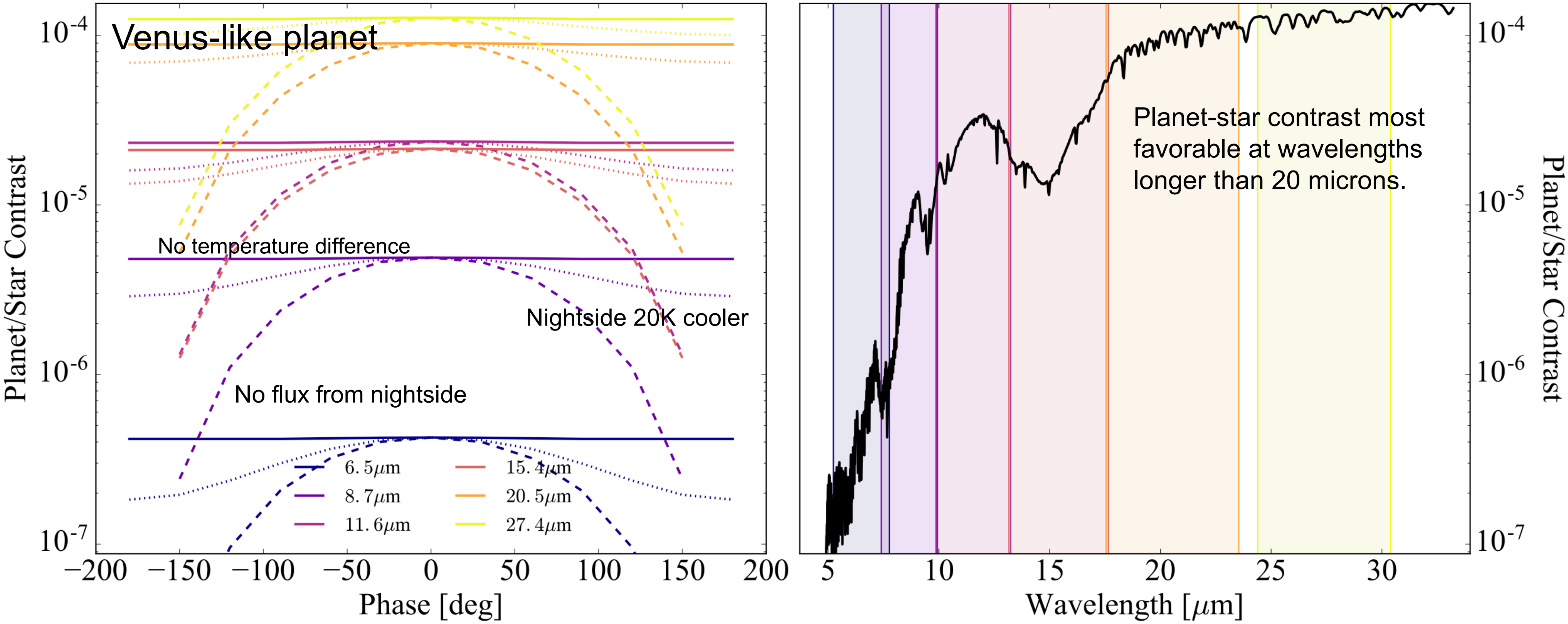
Model validated by predicting altitude of Venus cloud base at 48km

Proxima Centauri b

- Observations and Observational Capabilities

Credit: Kornmesser, ESO

Proxima Cen b - Detecting Day/Night with JWST


Venus-like planet

No temperature difference

Nightside 20K cooler

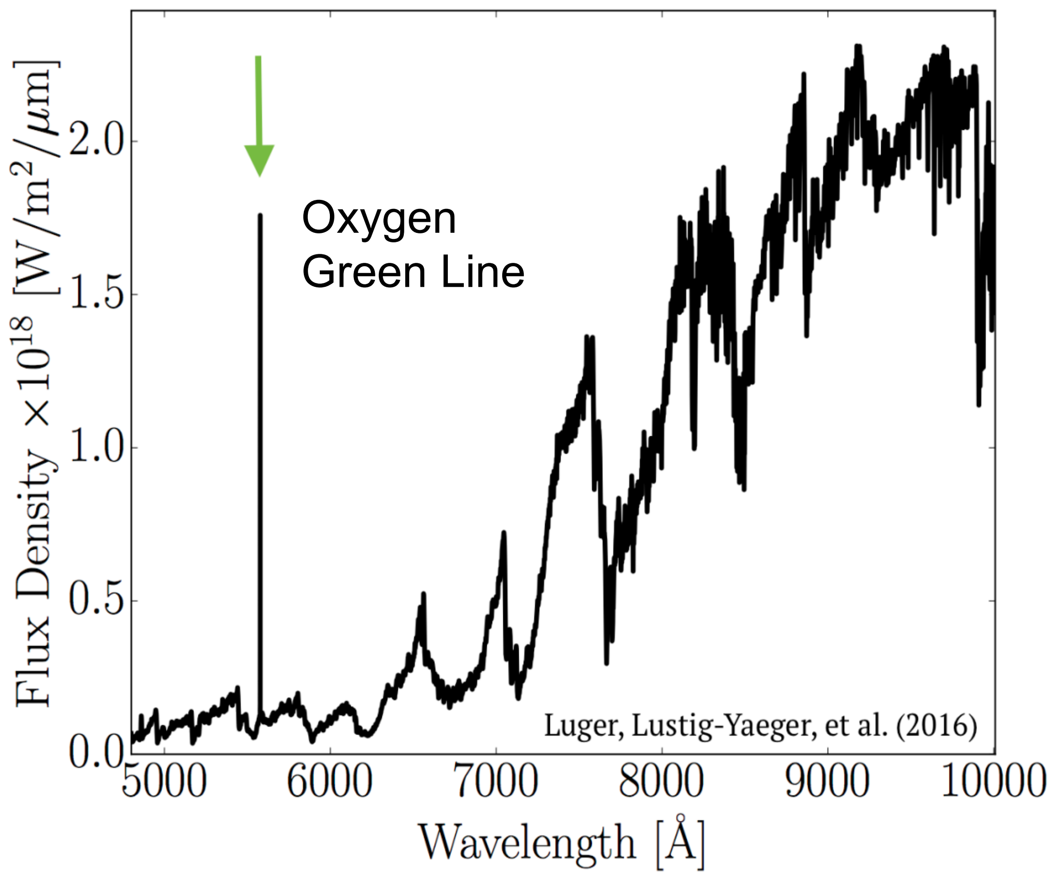
No flux from nightside

Planet-star contrast most favorable at wavelengths longer than 20 microns.

- At λ > 7μm, 20 hour exposures with JWST at two phase angles could detect the planet and search for day-night temperature differences, revealing atmospheric heat transport.
- (Meadows et al., 2016; see also Turbet et al., 2016, Kreidberg & Loeb, 2016)

- Detection of ocean glint is highly unlikely with JWST, but may be within the reach of larger aperture telescopes.
  - 2λ/D needed for LUVOIR to do glint, 3λ/D for ground-based telescopes (Meadows et al.,2017).

Exo-aurorae may reveal a planetary atmosphere



Detect in 40 hours with ground-based 30 meter telescope if it achieves a coronagraph design contrast of 10^{-7} and negligible instrumental noise

Luger, Lustig-Yaeger, et al (2016) arxiv

Direct Imaging Observations of Proxima Cen b

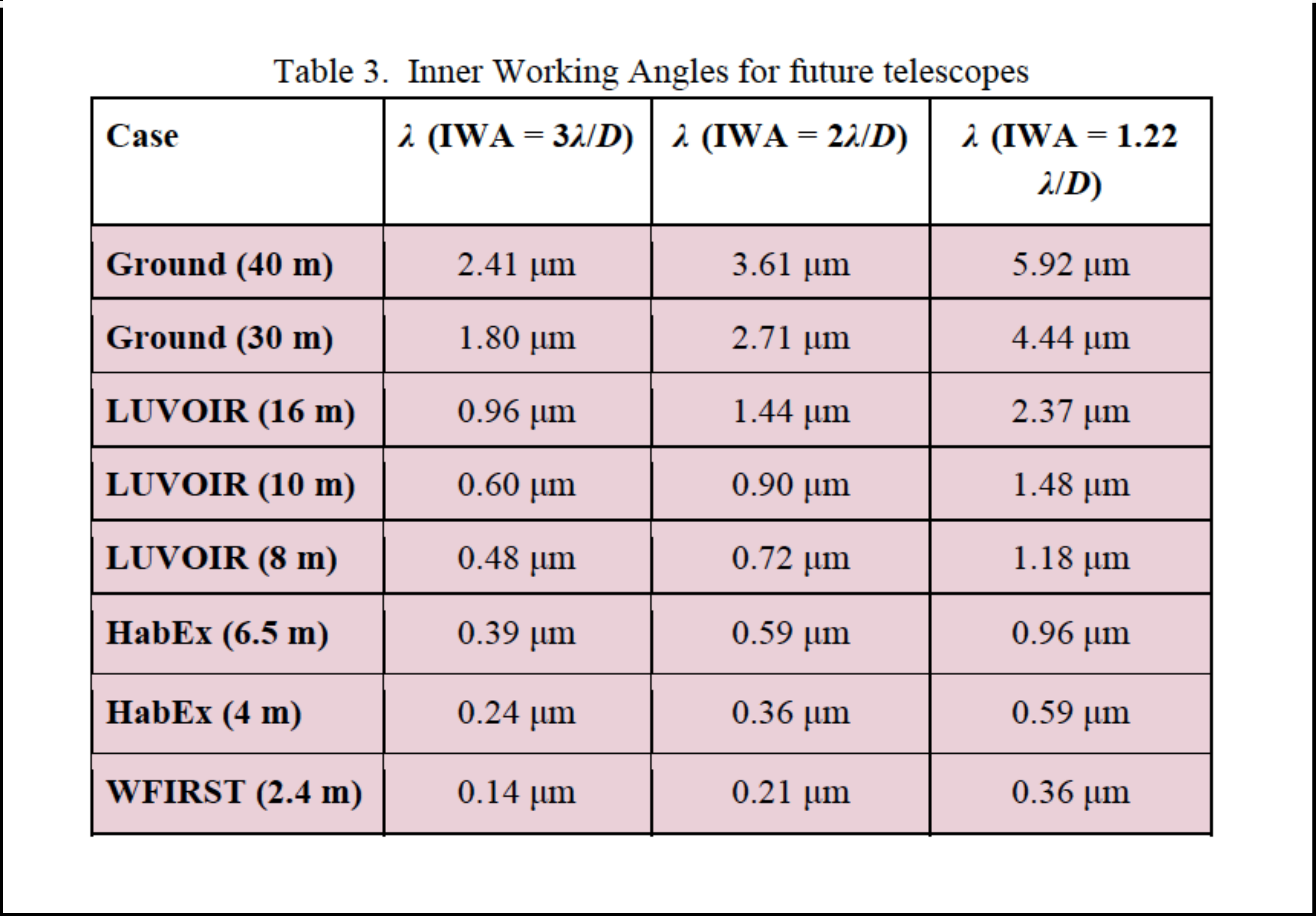
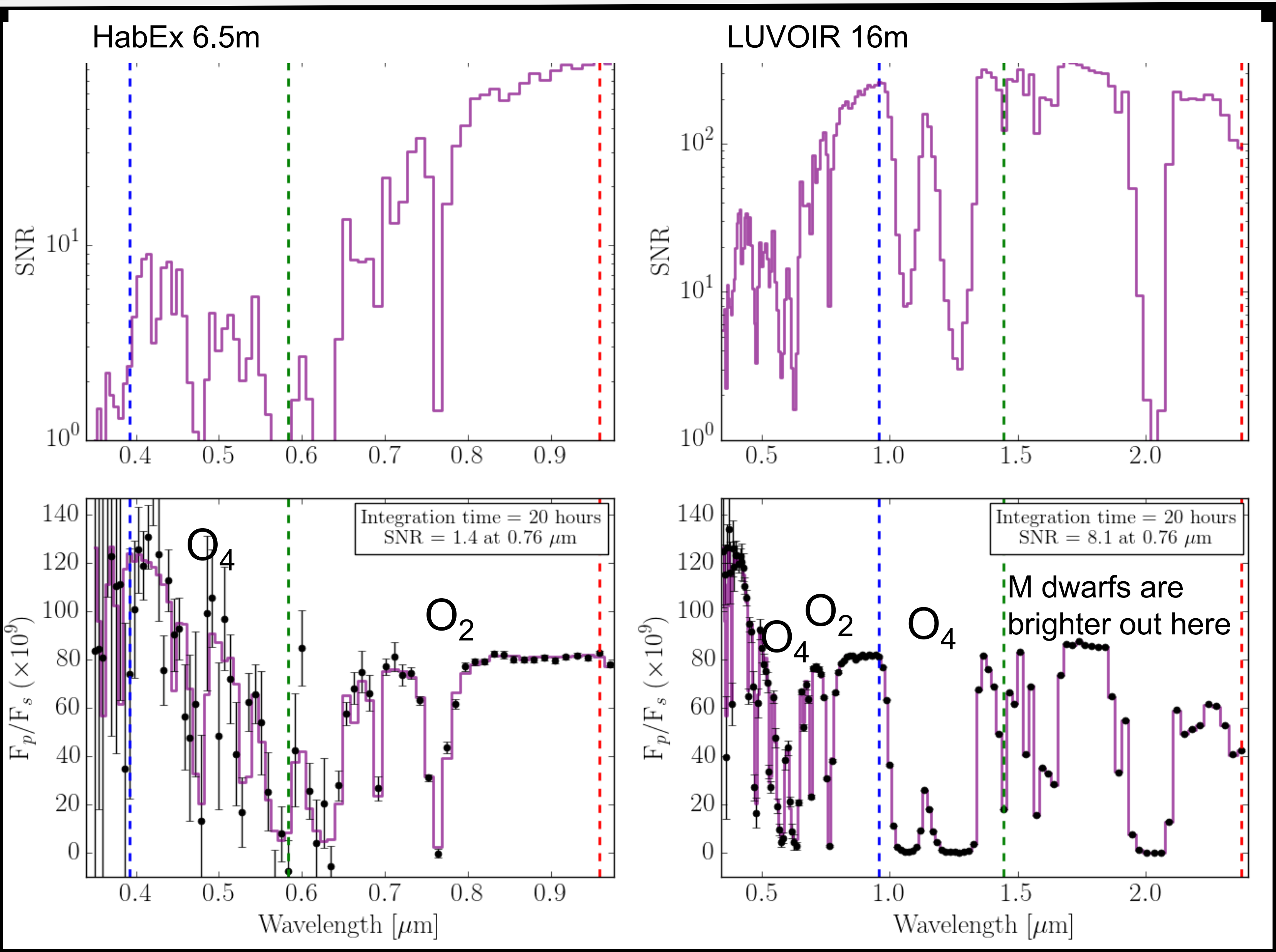


Table 3. Inner Working Angles for future telescopes

Case	**λ (IWA = $3\lambda/D$)**	**λ (IWA = $2\lambda/D$)**	**λ (IWA = $1.22\ \lambda/D$)**
Ground (40 m)	2.41 μm	3.61 μm	5.92 μm
Ground (30 m)	1.80 μm	2.71 μm	4.44 μm
LUVOIR (16 m)	0.96 μm	1.44 μm	2.37 μm
LUVOIR (10 m)	0.60 μm	0.90 μm	1.48 μm
LUVOIR (8 m)	0.48 μm	0.72 μm	1.18 μm
HabEx (6.5 m)	0.39 μm	0.59 μm	0.96 μm
HabEx (4 m)	0.24 μm	0.36 μm	0.59 μm
WFIRST (2.4 m)	0.14 μm	0.21 μm	0.36 μm

- O_4 at 0.35-0.65, 1.-6-1.27, O_3 at 0.5-0.7, O_2 at 0.76um, H_2O at 0.94um, CO_2 at 1.6um CO at 2.3um
- Need large aperture, starshade, or both.

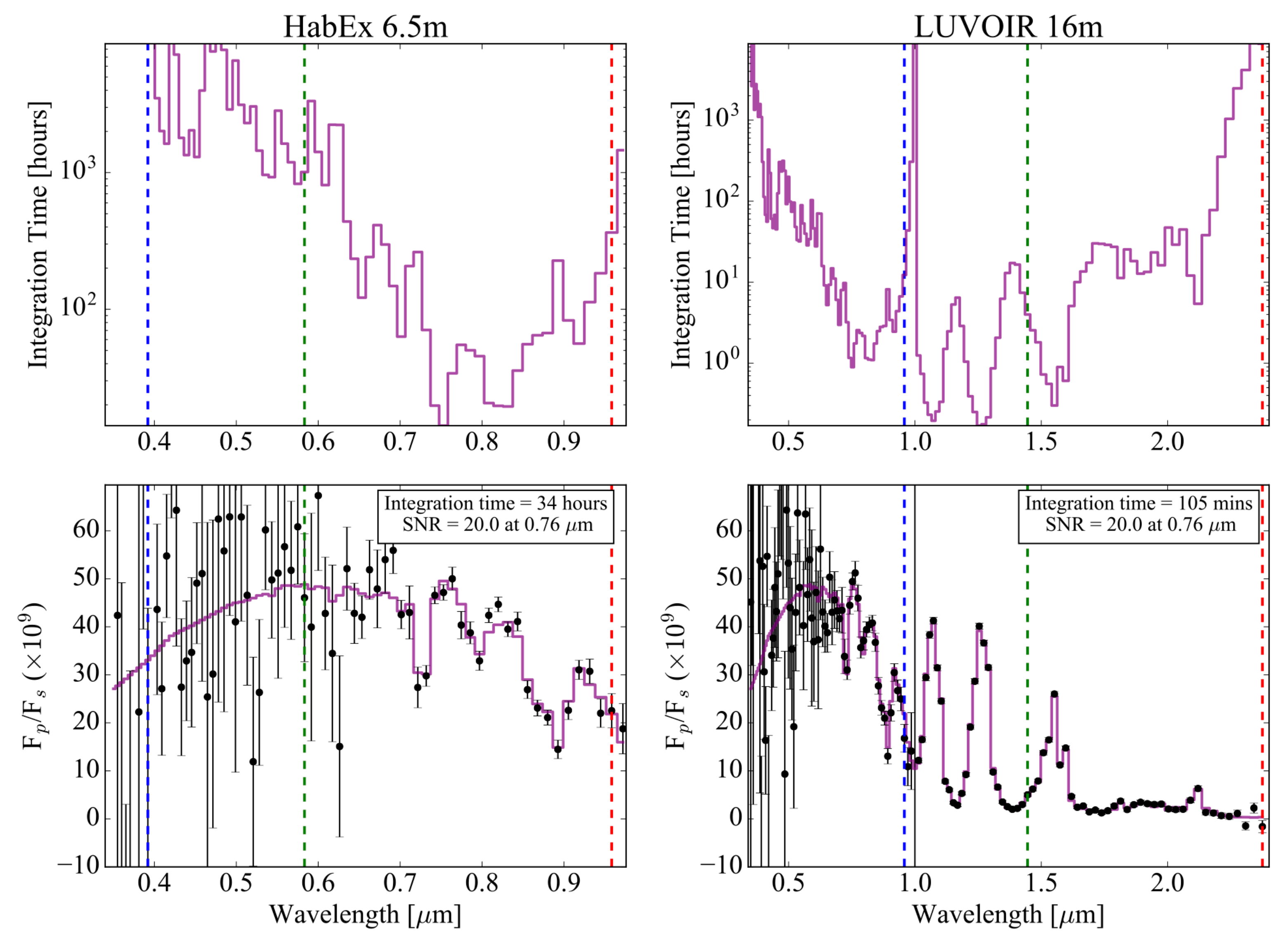
Space-based Direct Imaging Spectroscopy



M dwarfs are brighter out here

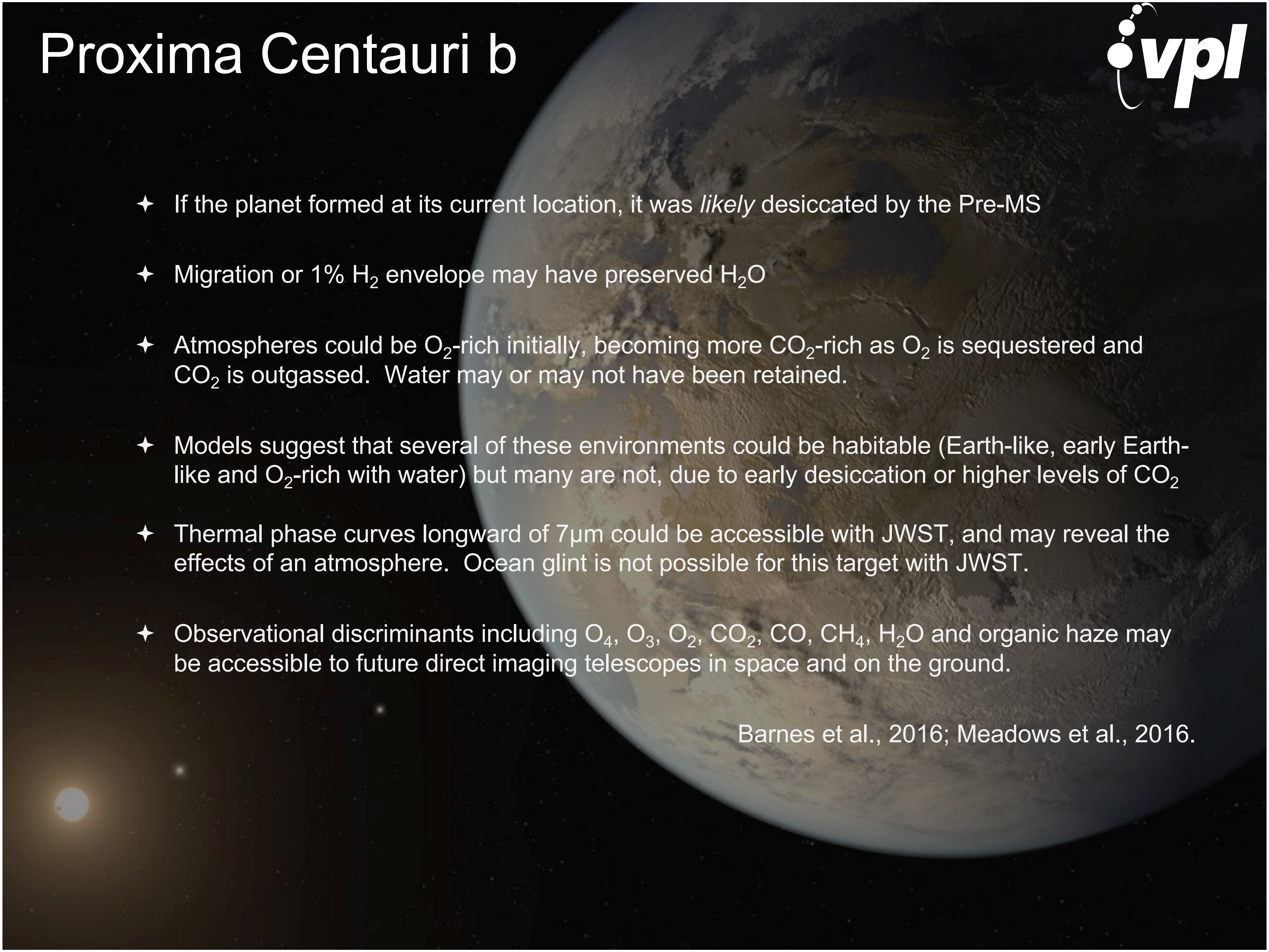
The LUVOIR (16m) simulation shows a S/N~8 at the oxygen A-band in a 20 hr exposure

Direct Imaging of Early-Earth-Type



- Haze feature difficult to observe due to low stellar flux
- Low stellar flux *and* small HZ separation conspire against small telescopes!

Proxima Centauri b

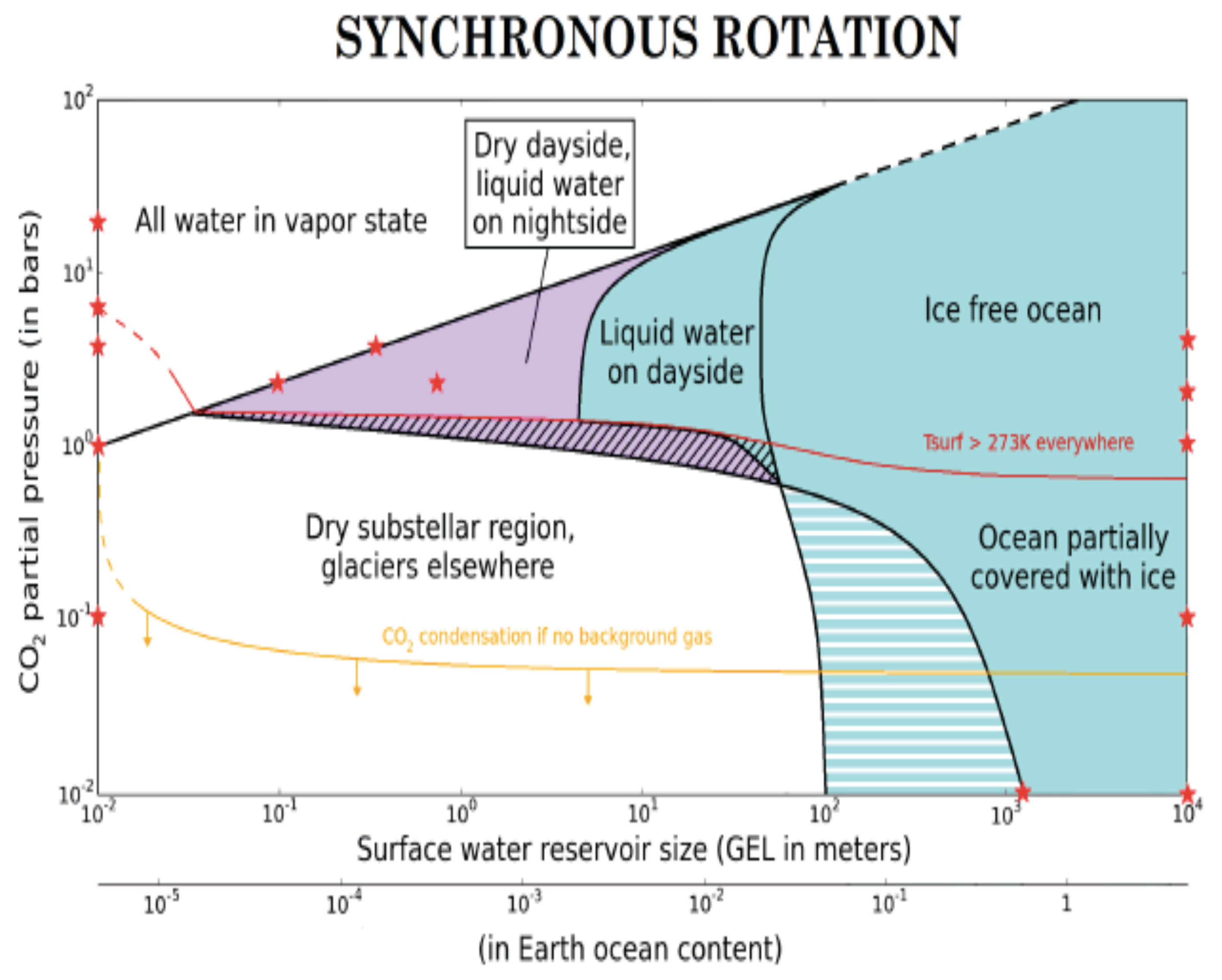


- If the planet formed at its current location, it was *likely* desiccated by the Pre-MS
- Migration or 1% H_2 envelope may have preserved H_2O
- Atmospheres could be O_2-rich initially, becoming more CO_2-rich as O_2 is sequestered and CO_2 is outgassed. Water may or may not have been retained.
- Models suggest that several of these environments could be habitable (Earth-like, early Earth-like and O_2-rich with water) but many are not, due to early desiccation or higher levels of CO_2
- Thermal phase curves longward of 7µm could be accessible with JWST, and may reveal the effects of an atmosphere. Ocean glint is not possible for this target with JWST.
- Observational discriminants including O_4, O_3, O_2, CO_2, CO, CH_4, H_2O and organic haze may be accessible to future direct imaging telescopes in space and on the ground.

Barnes et al., 2016; Meadows et al., 2016.

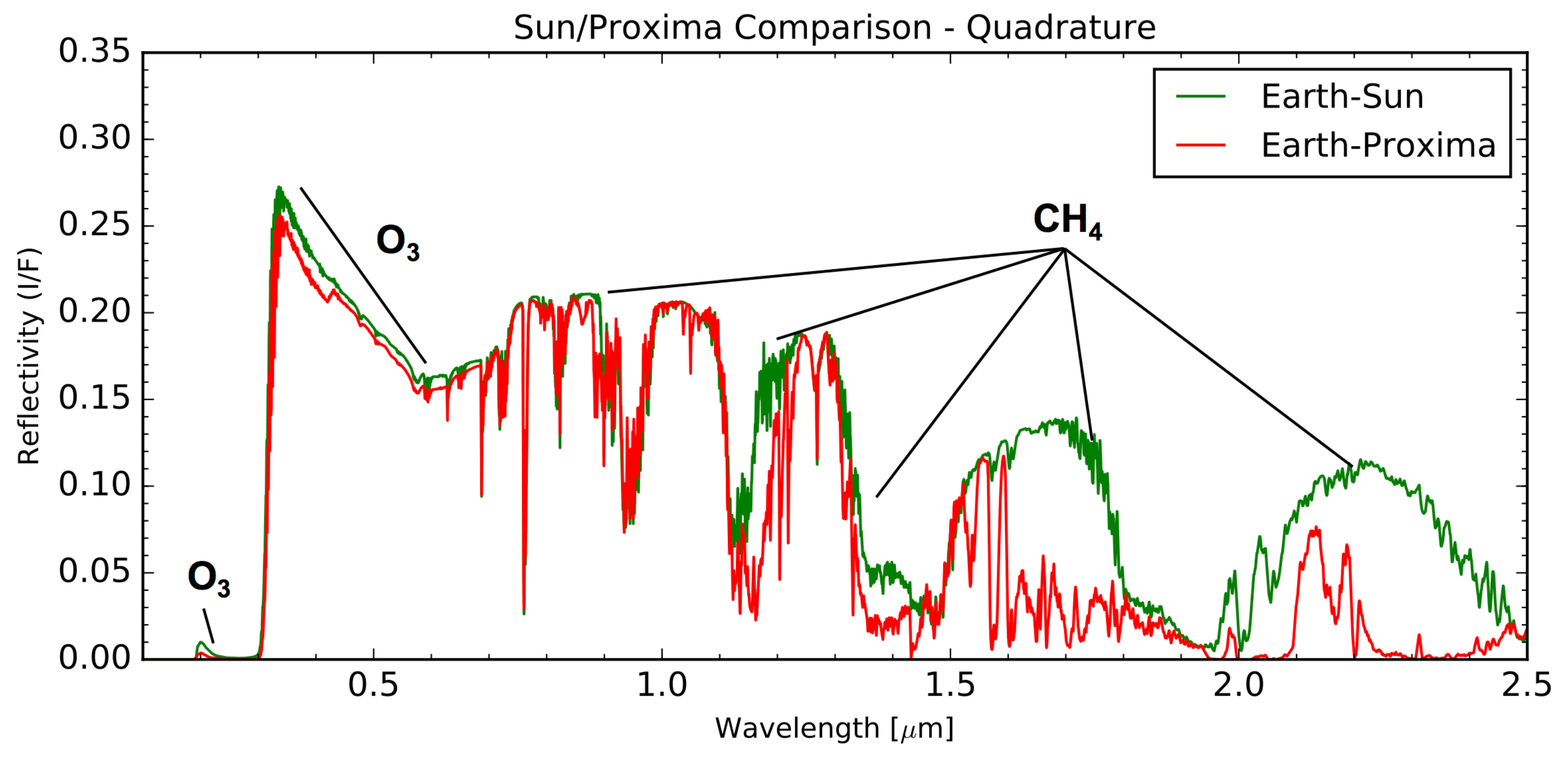
Questions?

Backup Slides



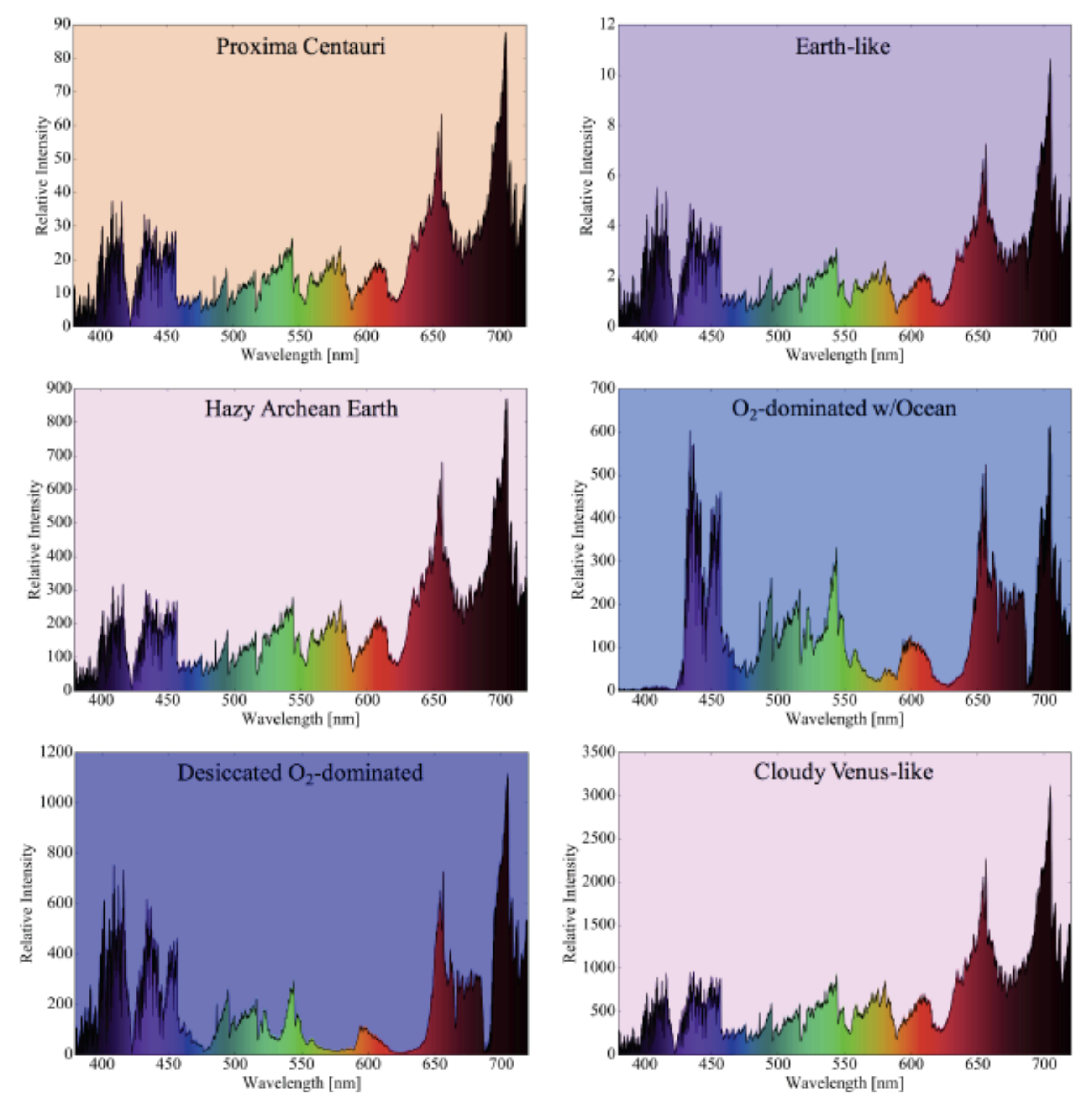
Turbet et al., 2016

Photochemistry matters! Stellar UV matters!

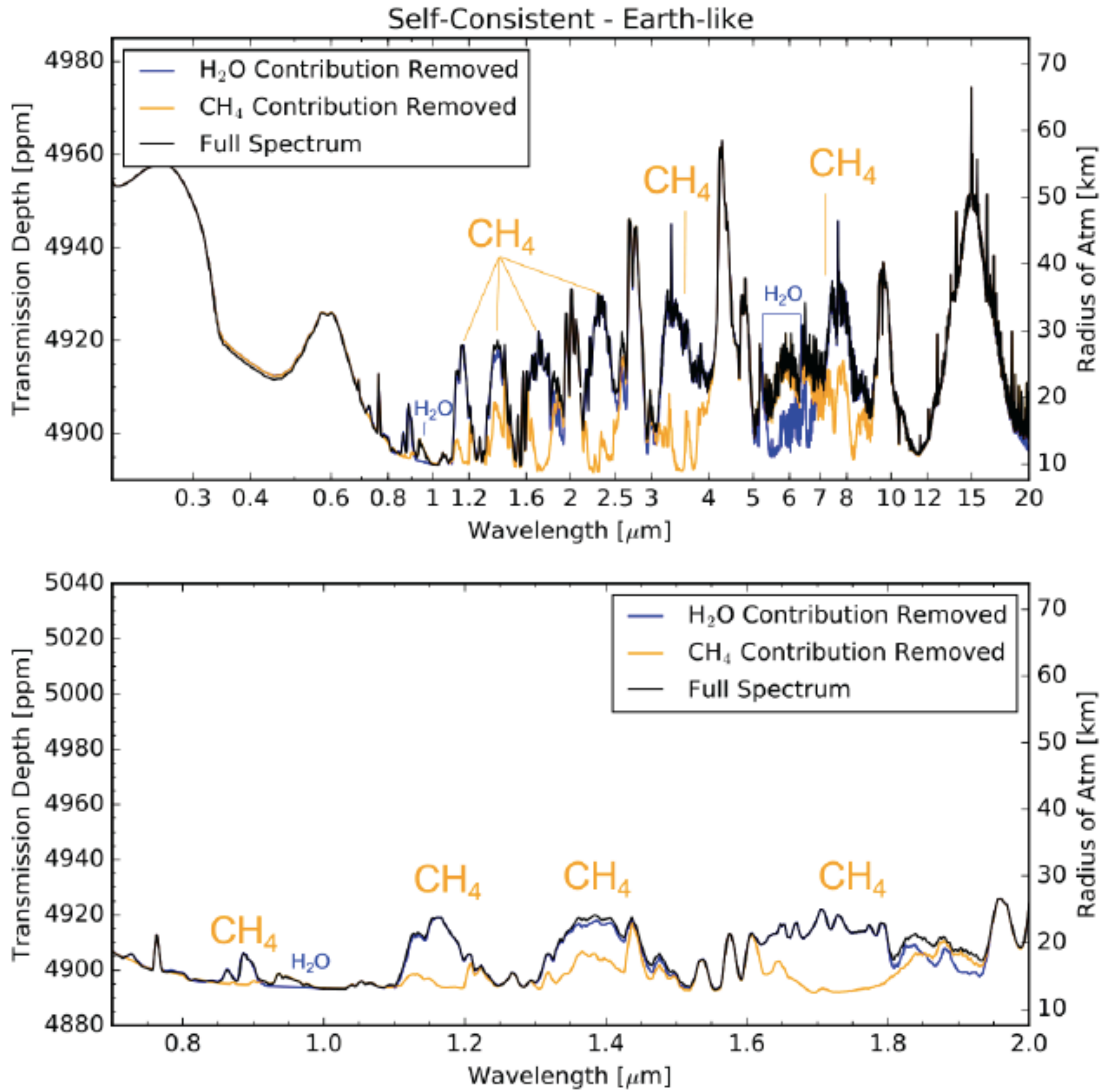


- CH_4 has a longer lifetime in the planet's atmosphere under M dwarf UV irradiation, and so has higher abundance for the same surface flux.

Proxima Cen b: The Pale Lavender Dot



Prox


Self-Consistent - Earth-like
H_2O Contribution Removed
CH_4 Contribution Removed
Full Spectrum
CH_4
CH_4
CH_4
H_2O
H_2O
Transmission Depth [ppm]
4980
4960
4940
4920
4900
Radius of Atm [km]
70
60
50
40
30
20
10
0.3
0.4
0.6
0.8
1
1.2
1.6
2
2.5
3
4
5
6
7
8
10
12
15
20
Wavelength [μm]
H_2O Contribution Removed
CH_4 Contribution Removed
Full Spectrum
CH_4
CH_4
CH_4
CH_4
H_2O
Transmission Depth [ppm]
5040
5020
5000
4980
4960
4940
4920
4900
4880
Radius of Atm [km]
70
60
50
40
30
20
10
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Wavelength [μm]

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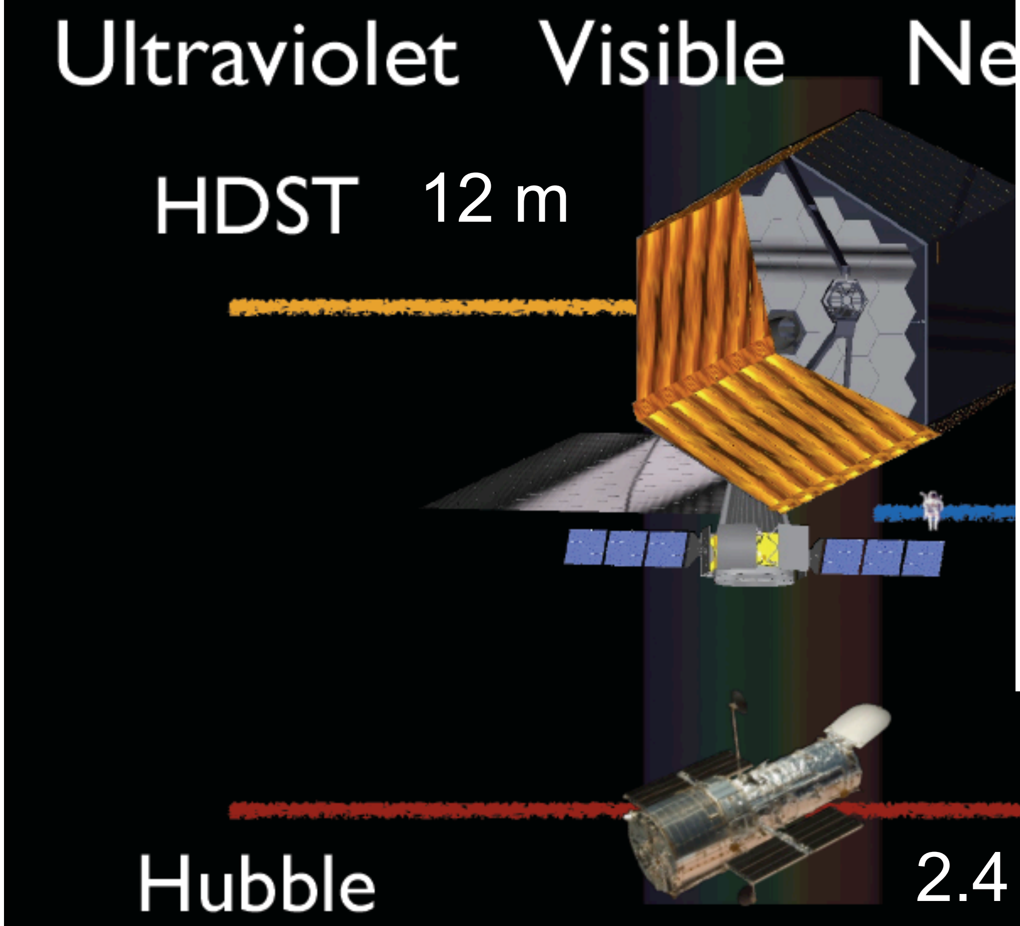
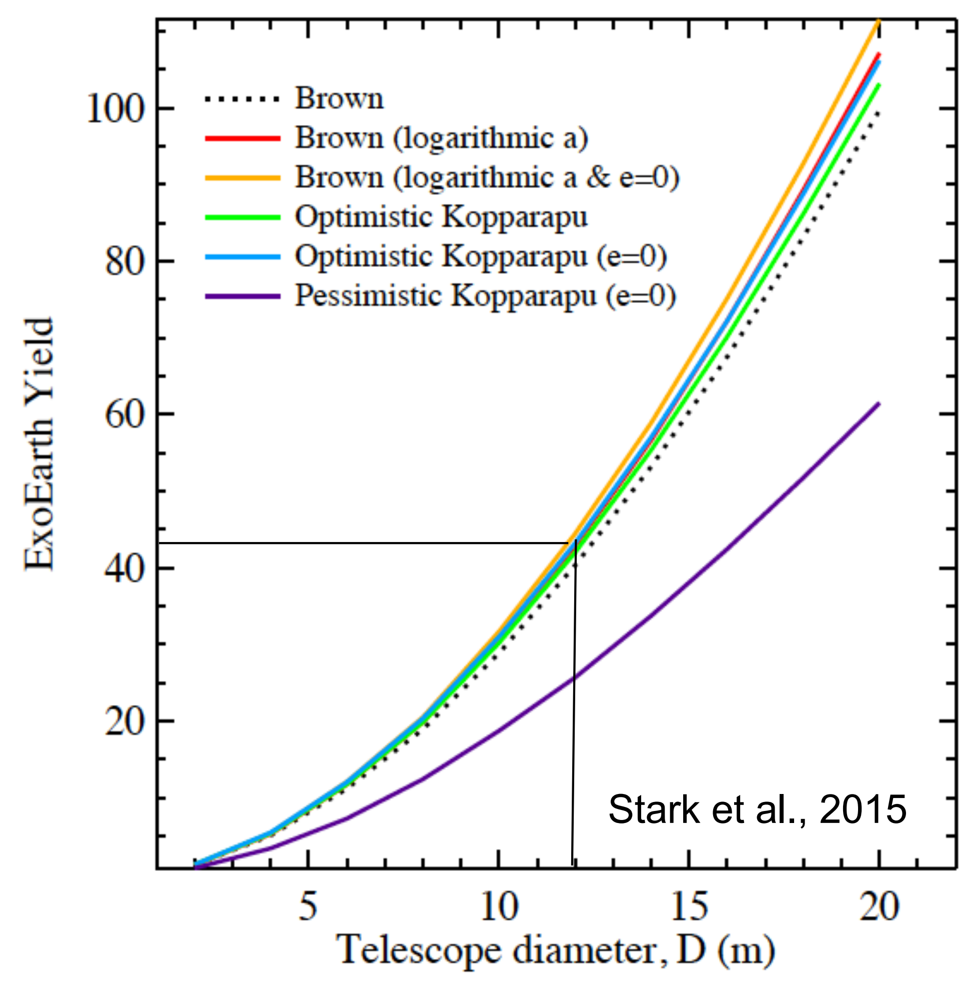
The High Definition Space Telescope Concept

Will be able to directly image tens of Earth-sized planets in the Habitable Zone. HabEx a smaller but exoplanet dedicated telescope also under consideration

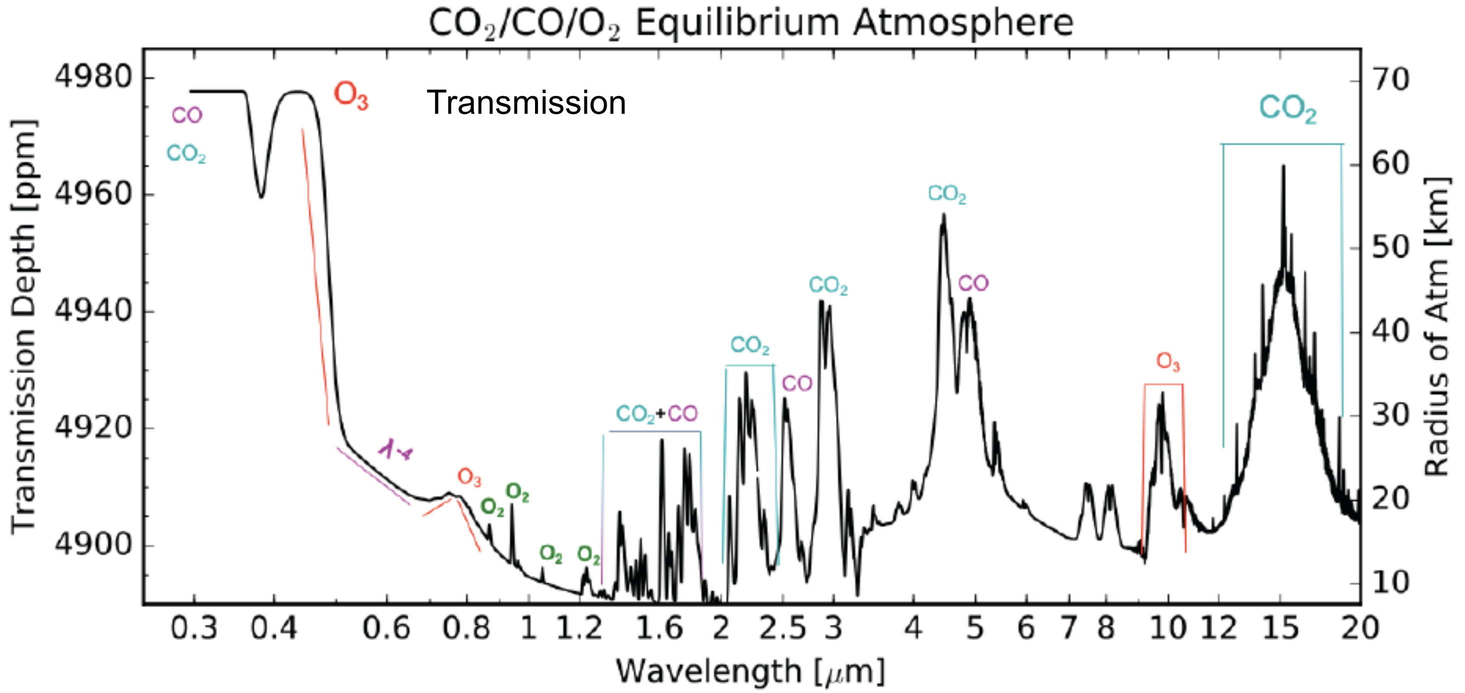


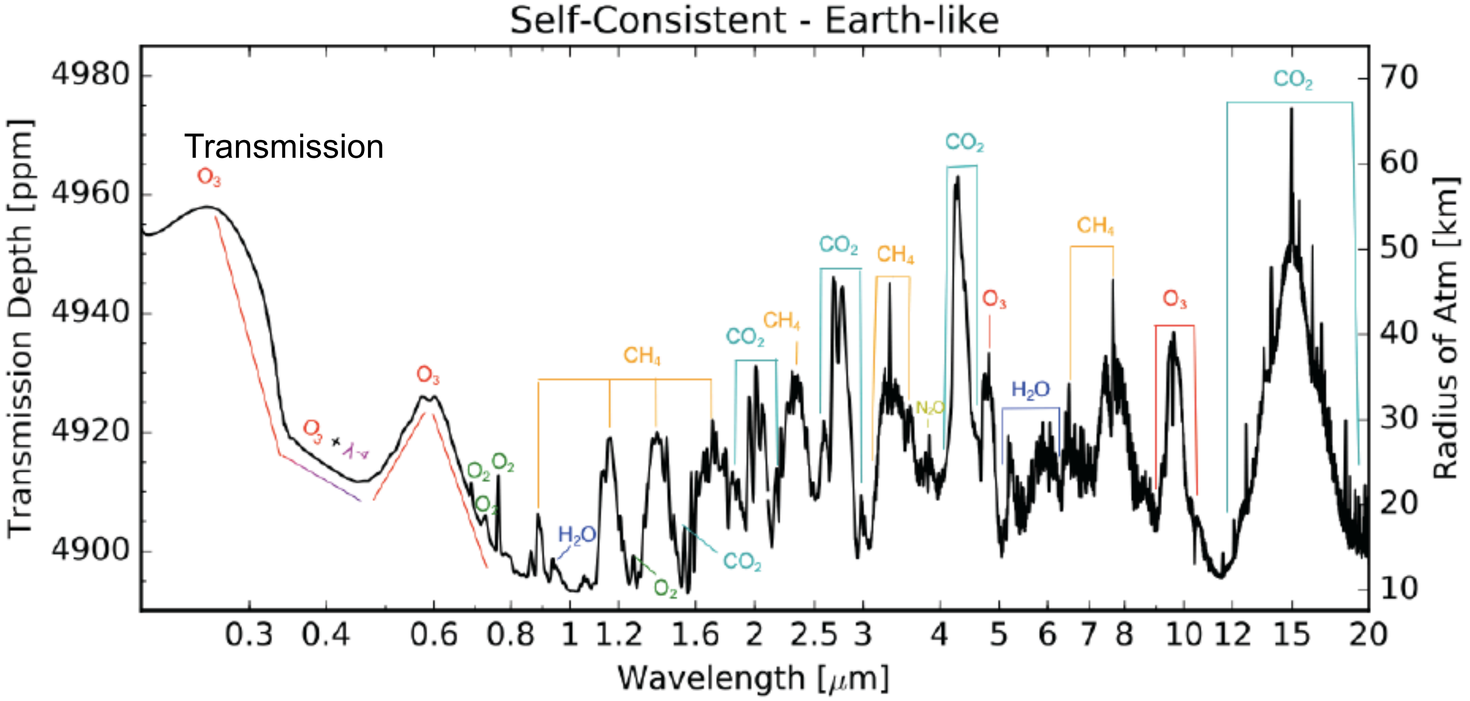


Stark et al., 2015

Dalcanton et al., 2015

Proxima Cen b simulated environments - Transmission


$CO_2/CO/O_2$ Equilibrium Atmosphere


Self-Consistent - Earth-like

Segura et al., 2005; Gao et al., 2015; Schwieterman et al., 2016: Meadows et al., 2016

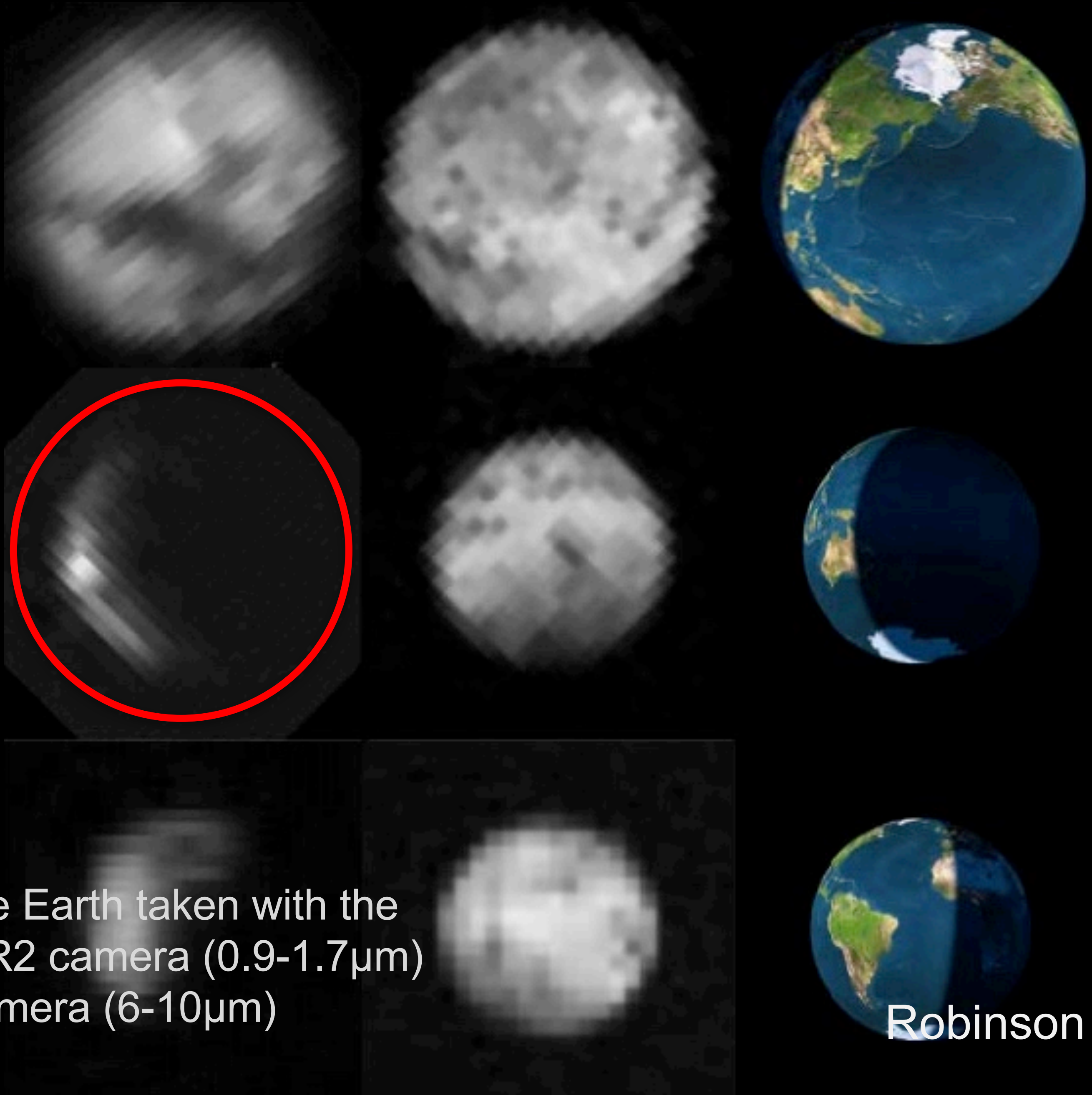
Are Terrestrial Planets Orbiting M Dwarfs Habitable?

This is a very rich area with many avenues to explore:

- How common are potentially habitable planets orbiting M dwarfs?
- How do parent stars of terrestrial planets shape habitability over long timescales?
- Can M dwarf HZ terrestrial planets produce, keep, and if necessary, get rid of atmospheres?
- What is the nature of the delivery, cycling and loss of H_2O and N_2 for terrestrial planets?
- What role does the planetary magnetic field play, if any, in retention of an atmosphere and protection from surface radiation and particles?
- What is the effect of synchronous rotation and clouds on M dwarf planet habitability?

- How do we identify the best M dwarf planets for spectroscopic follow-up?
- How do we detect signs of habitability on M dwarf planets?

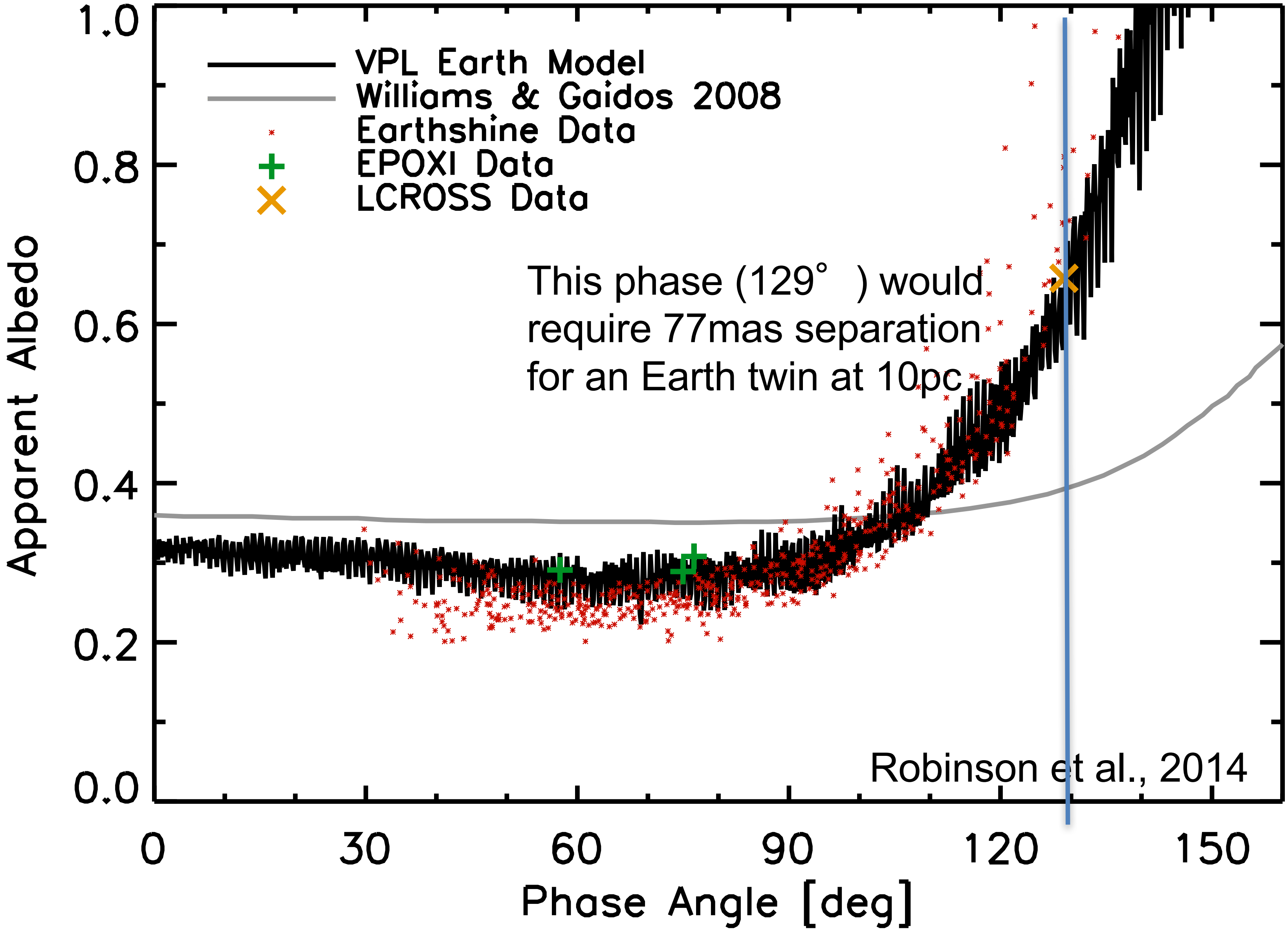
LCROSS Observations of Earth Glint



Images of the Earth taken with the LCROSS NIR2 camera (0.9-1.7μm) and MIR1 camera (6-10μm)

Robinson et al., 2014

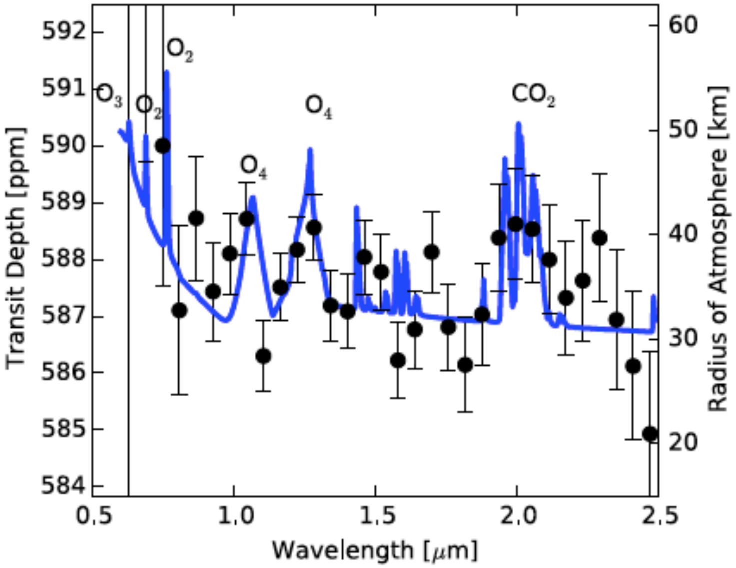
LCROSS Data Confirm VPL Glint Predictions

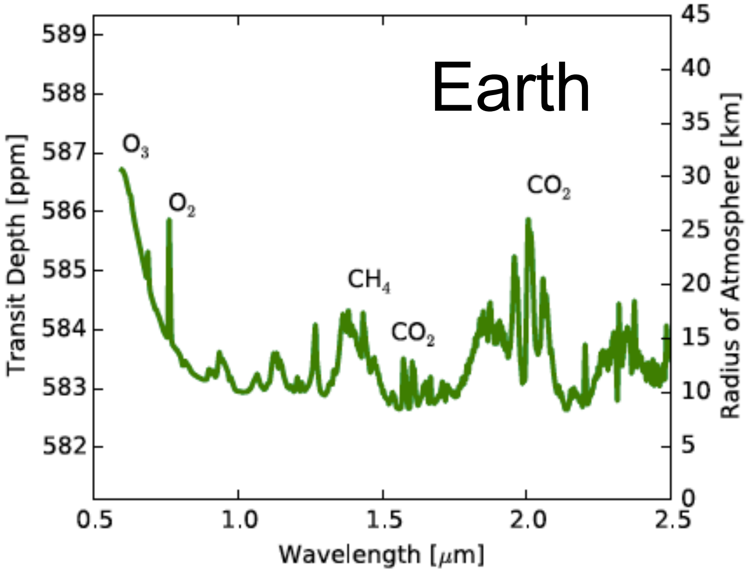


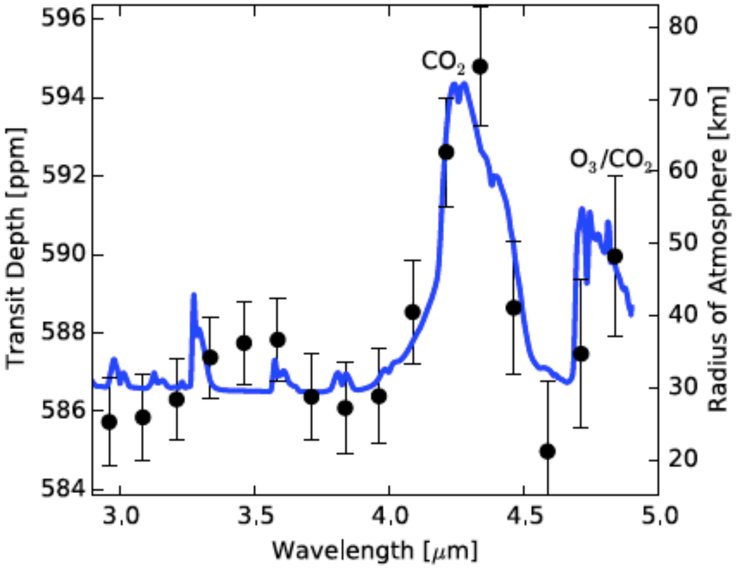
This phase (129°) would require 77mas separation for an Earth twin at 10pc

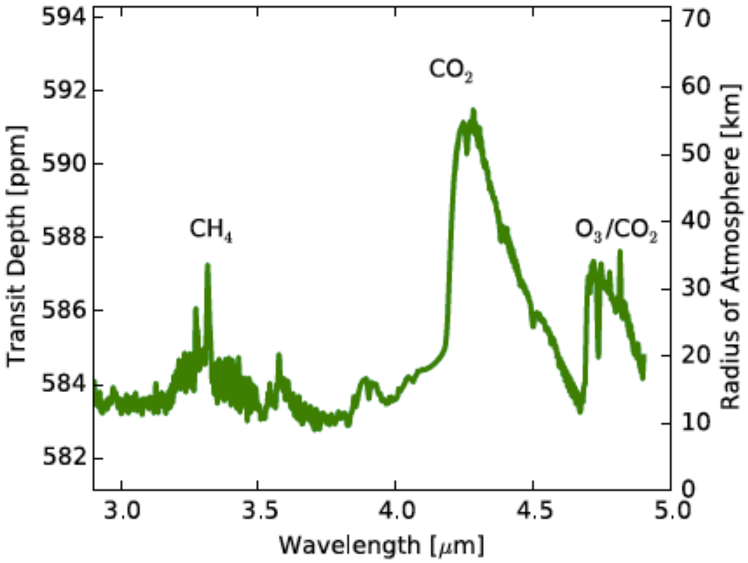
Earthshine data provided by Enric Pallé (Pallé et al., 2003);, EPOXI data provided by Tim Livengood (Livengood et al.2013; LCROSS data provided by Kimberley Ennico (Robinson et al., 2014).

Massive O_2 atmospheres will likely have O_4





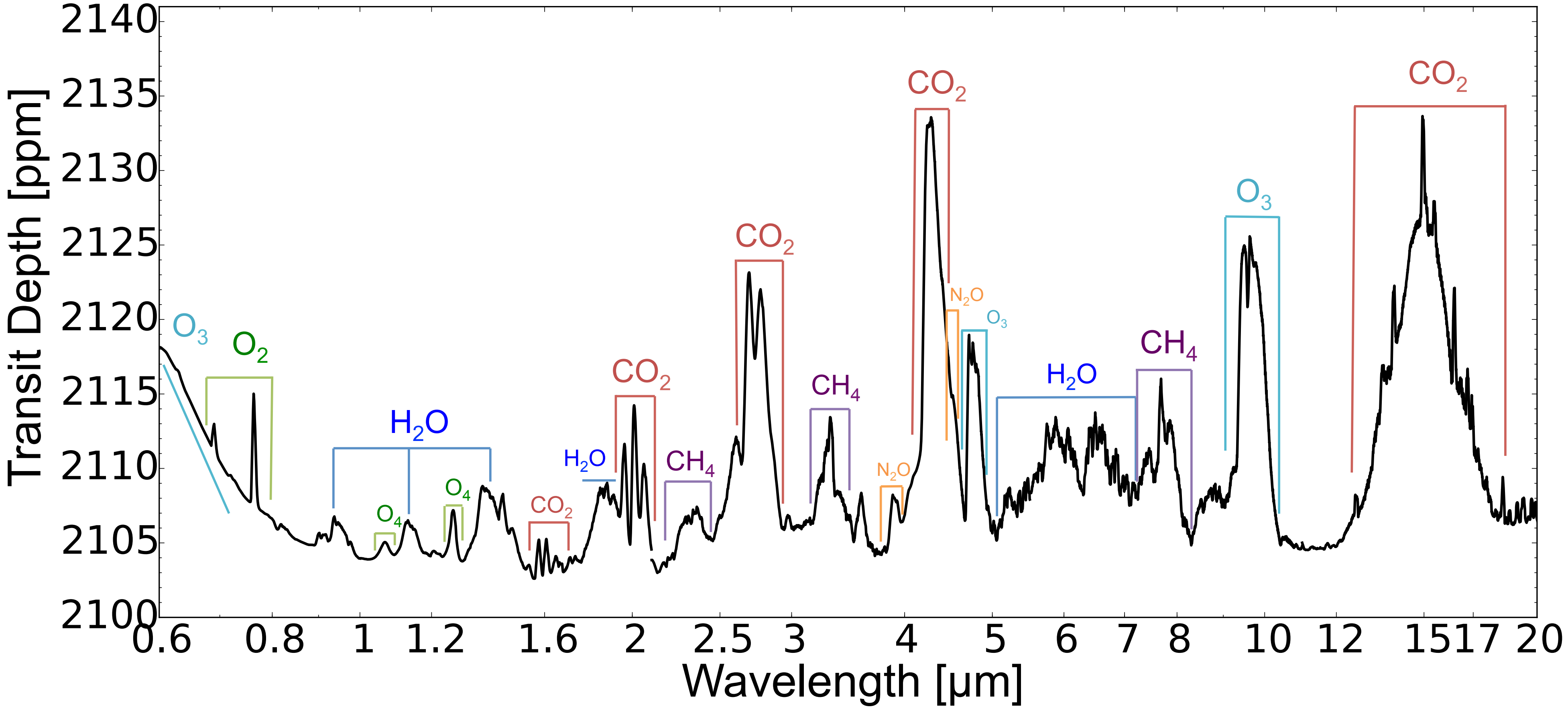




JWST transmission simulations (65 hrs)

Schwieterman et al., 2016

Modern Earth orbiting an M5V

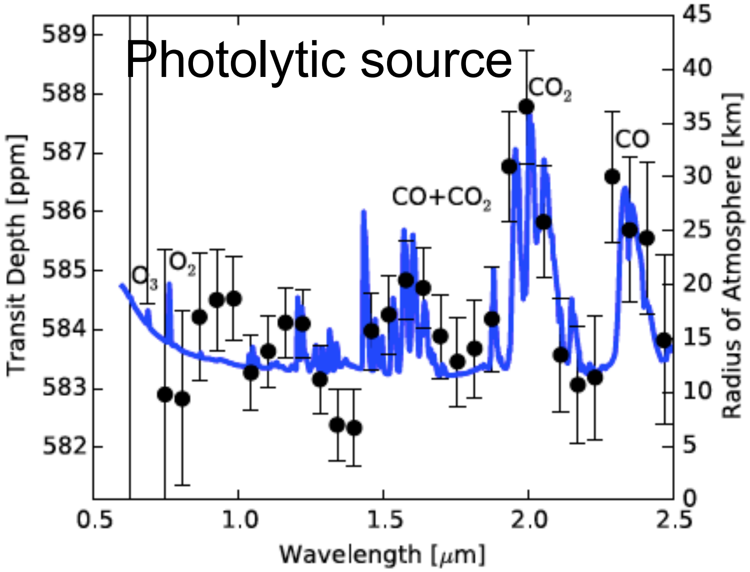


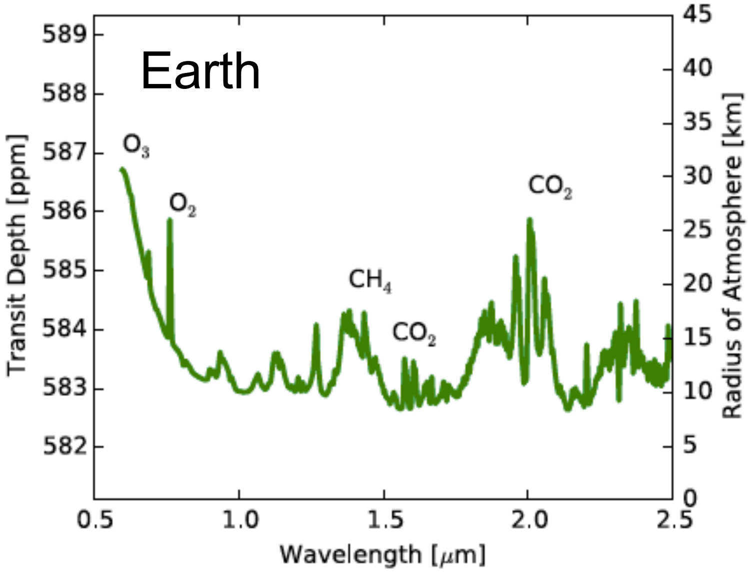
Features at 2-30 ppm.   Water vapor seen at the few ppm level.

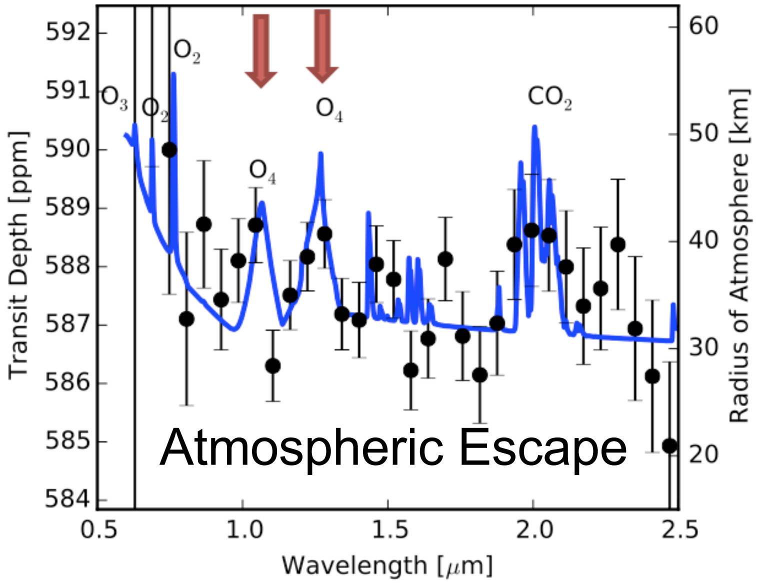
Transmission model (includes refraction) from Misra et al., (2014)

Model is cloud-free, however continuum corresponds to 8km above the planetary surface, likely above any actual cloud deck.

CO and O_4 may help identify abiotic O_2 generation







The CO and O_4 absorption is stronger *and more detectable* than the abiotic O_2

Schwieterman et al., 2016