# Super Earths:
# Reflection and Emission Spectra

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KISS Exoplanet Workshop
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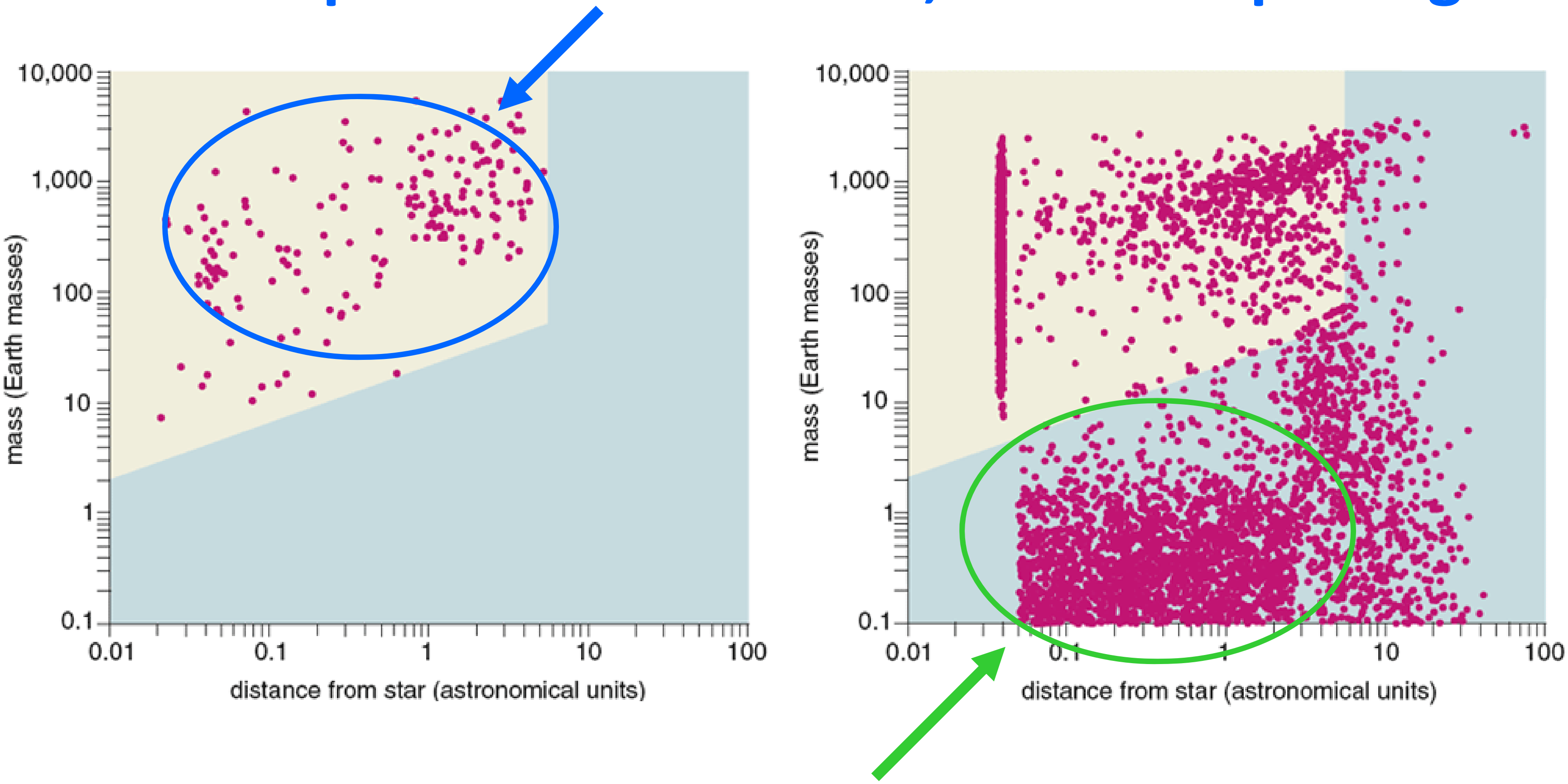
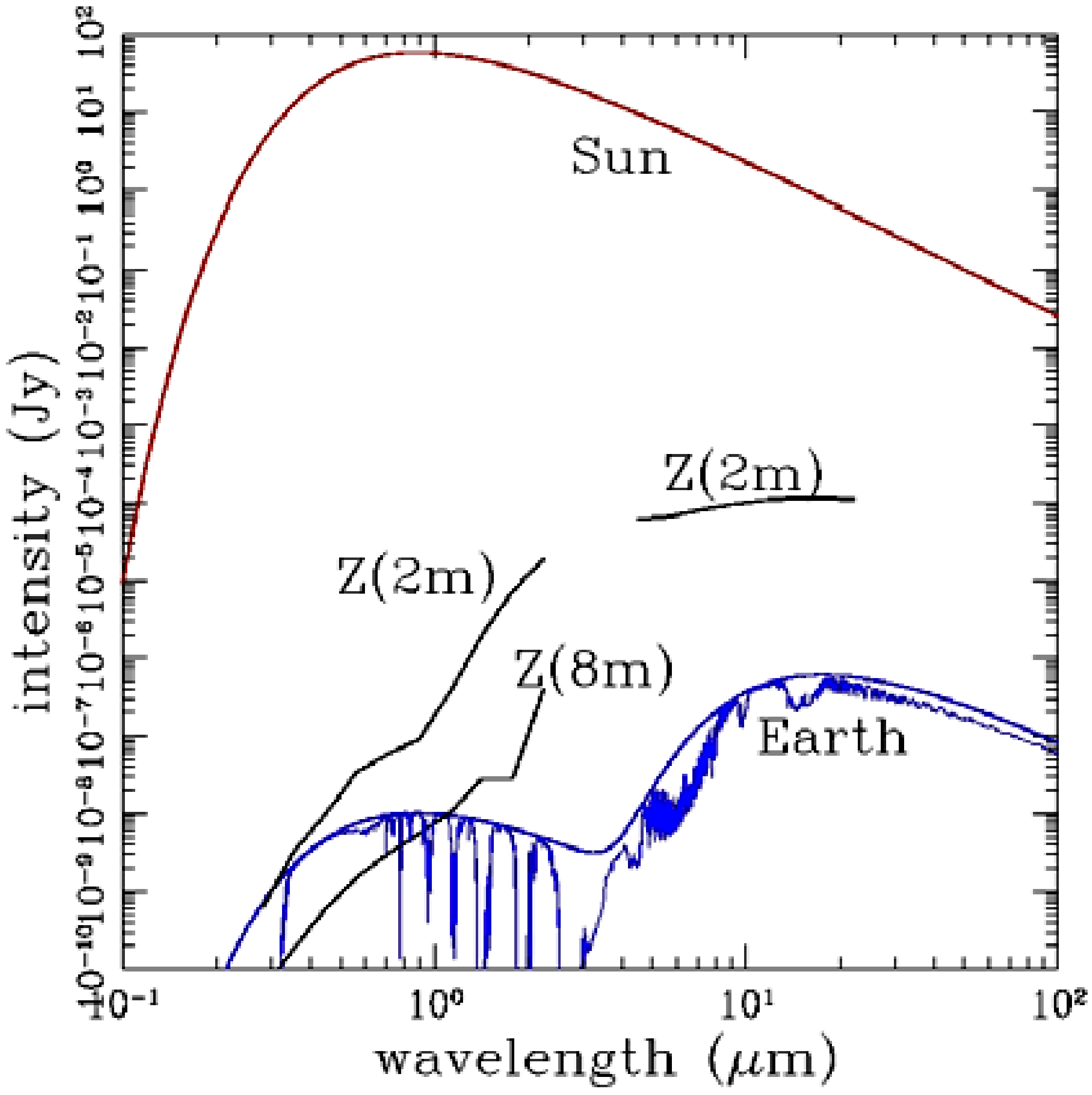
# Direct Imaging

# Giant planets found so far, Planetscope targets



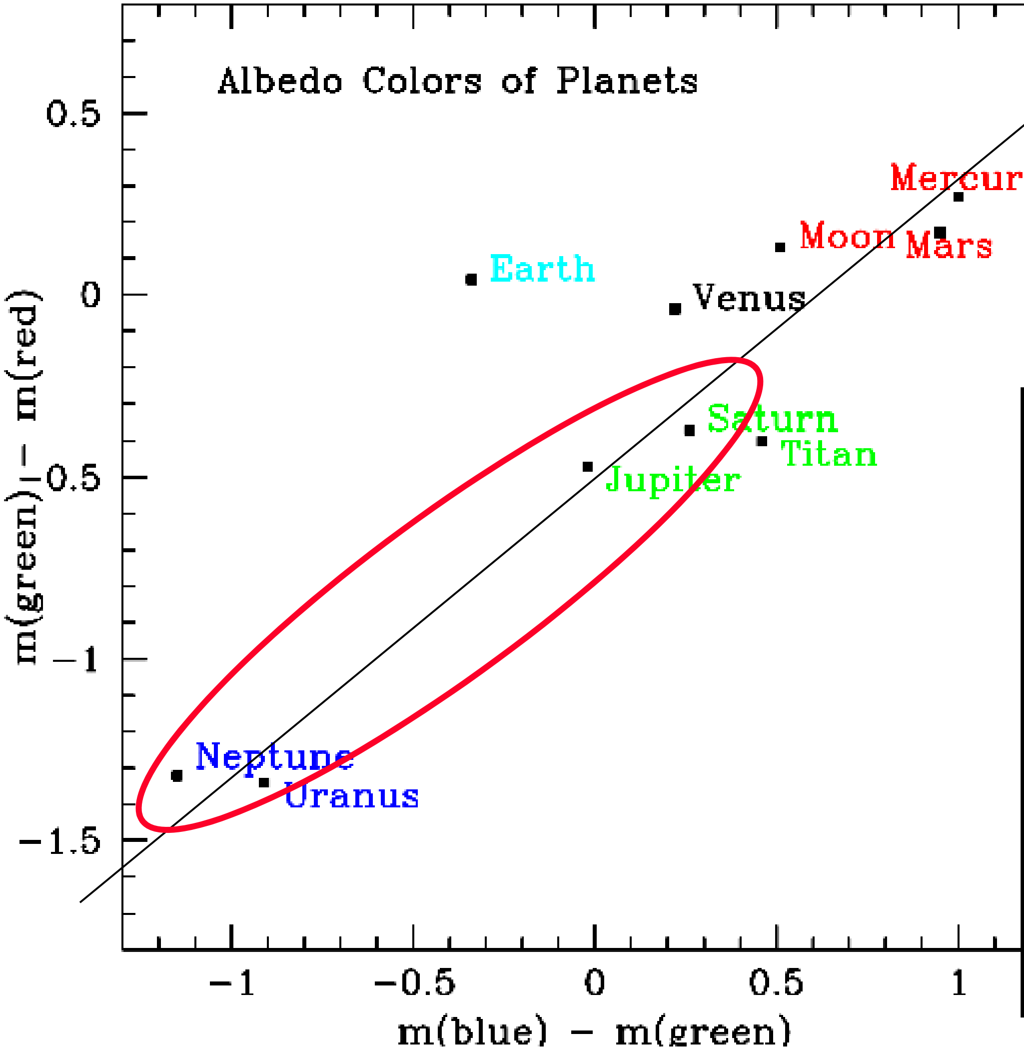
**Terrestrial planets we hope to find, in a future space mission**

# The Earth at 10 pc

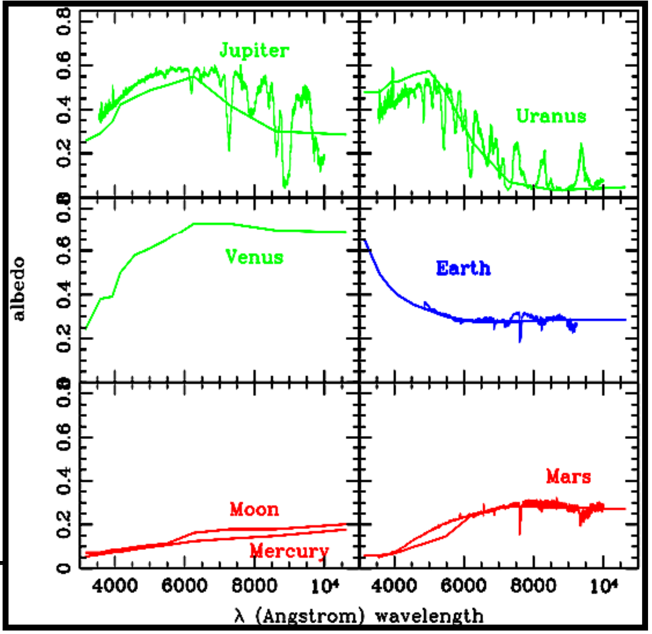


Plot: Kasting, Traub et al. 2009 (Astro2010 WP). Zodi: Kuchner 2009.

# Planetscope could measure colors of gas giants



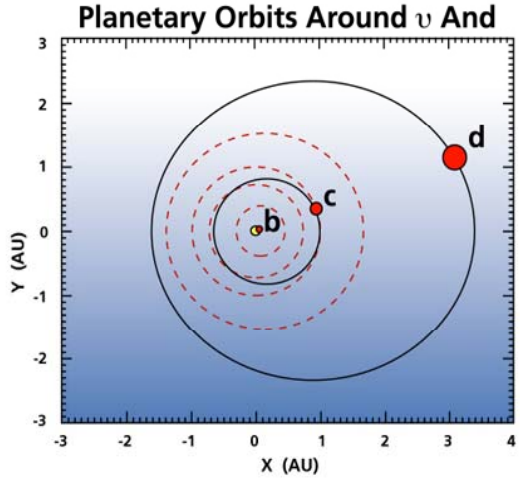
Solar system planets have colors that label them by type.



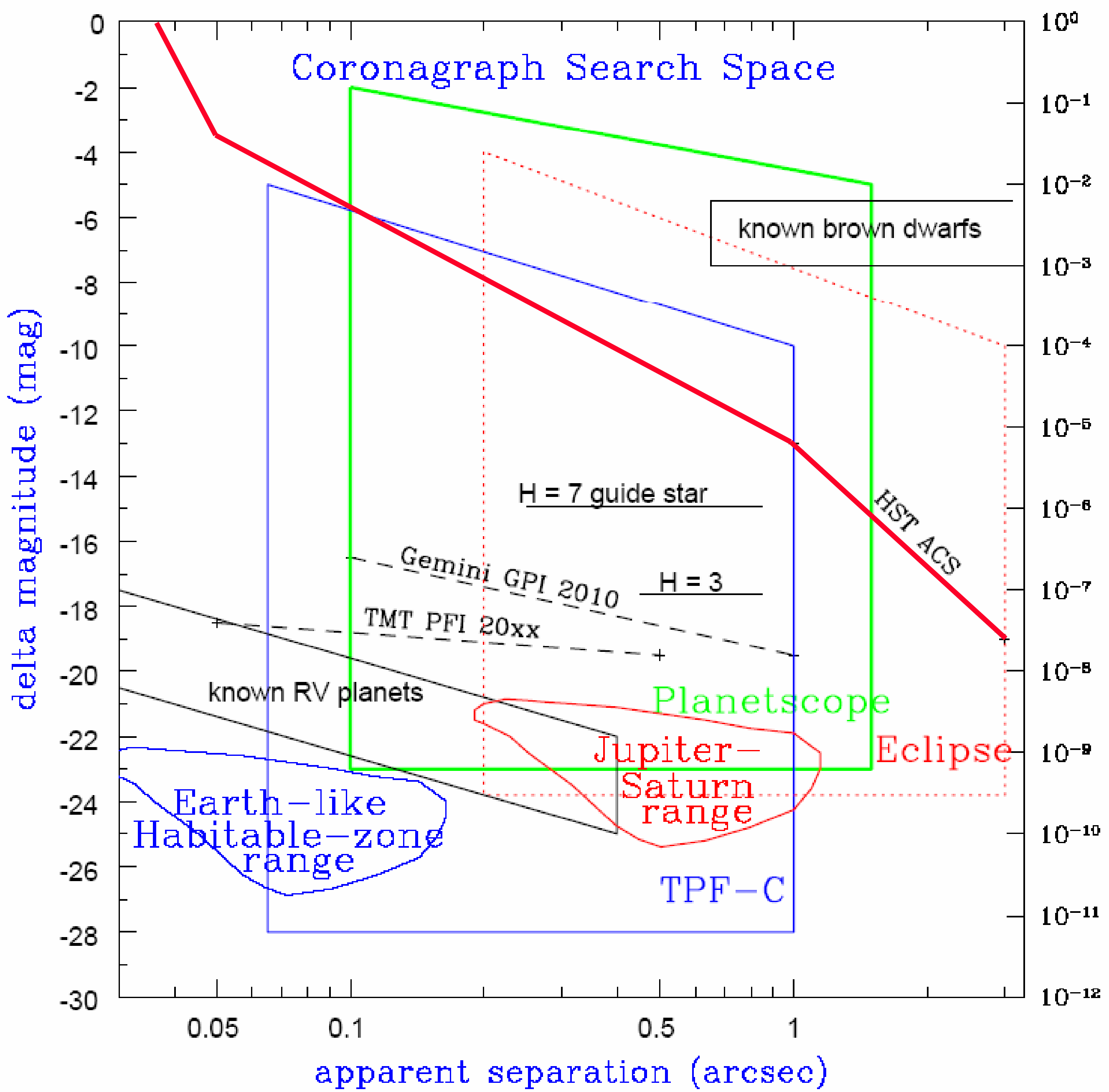
Planet spectra

**Blue (0.4-0.6 μm), Green (0.6-0.8 μm), Red (0.8-1.0 μm)**

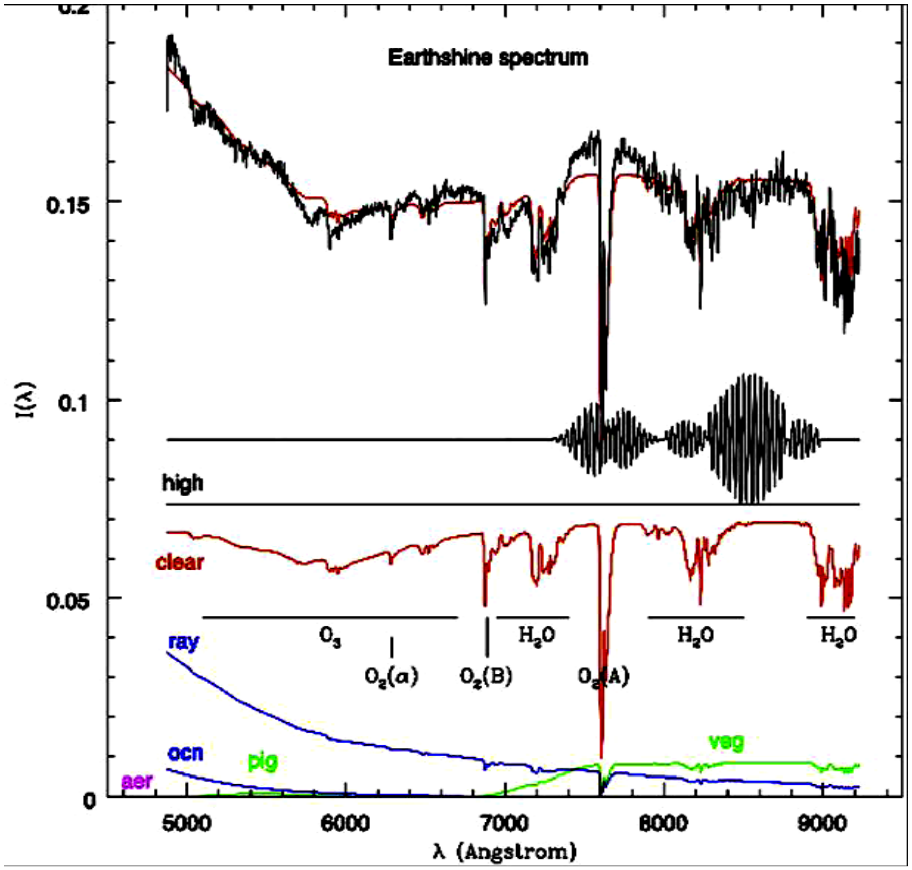
# ExoPlanet Explorati

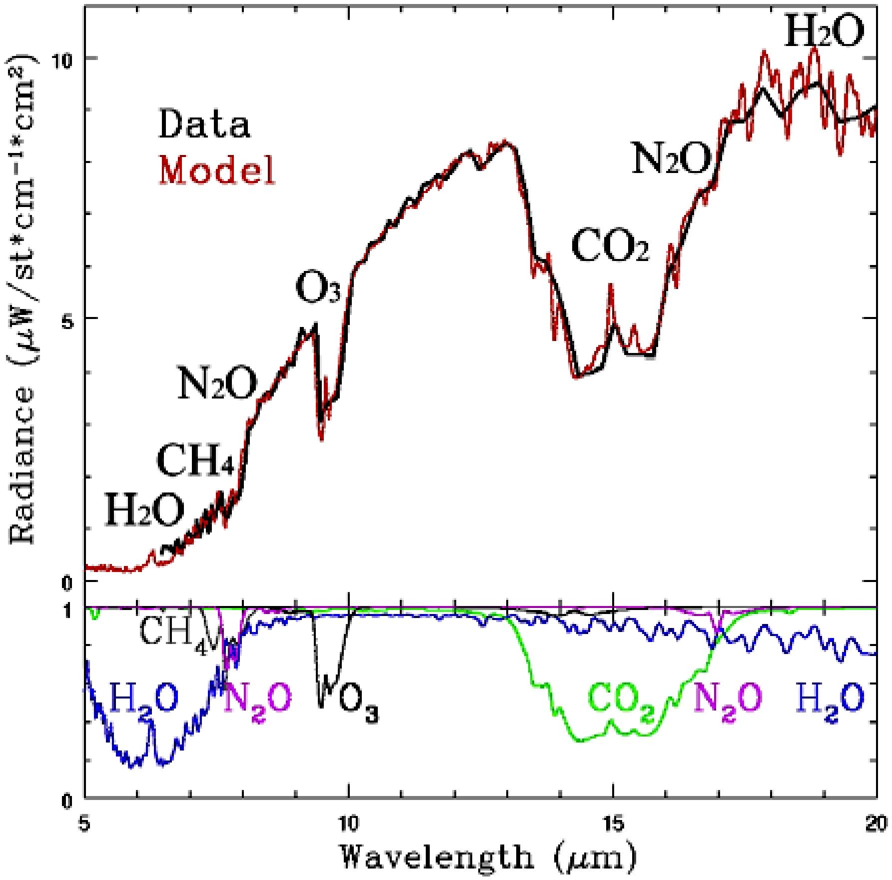


Example exoplanets.
Over 400 are known.



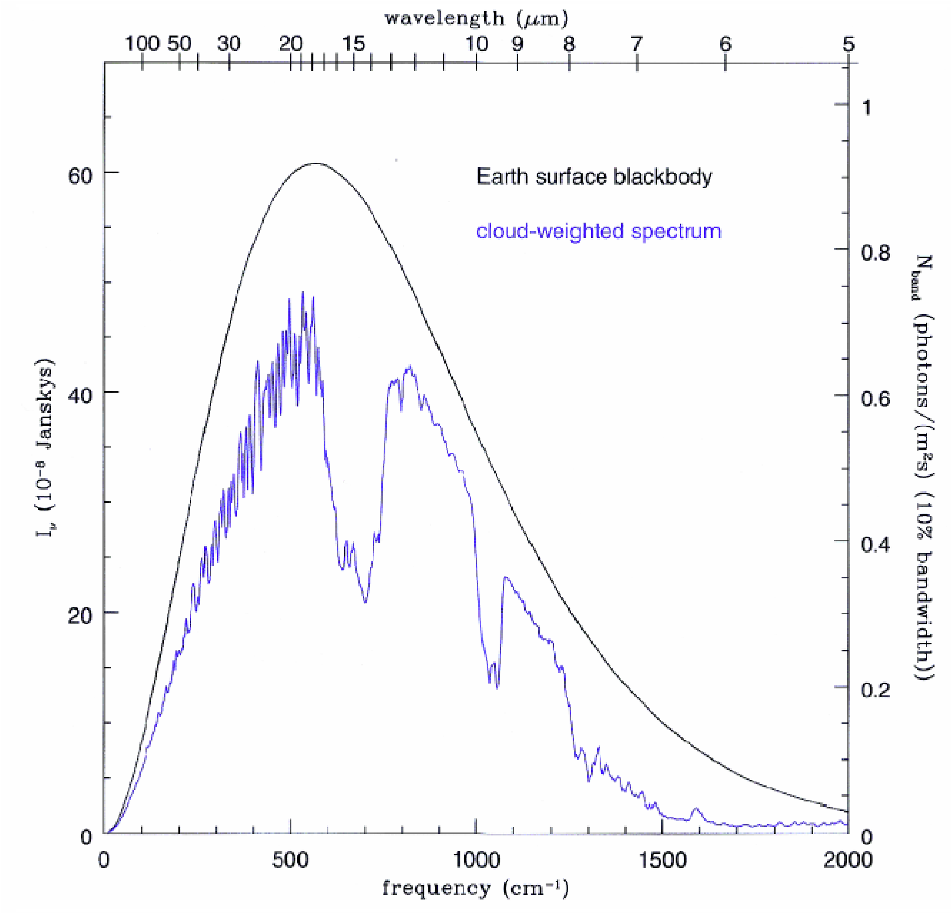
# Visible and Far-infrared Earth Spectra



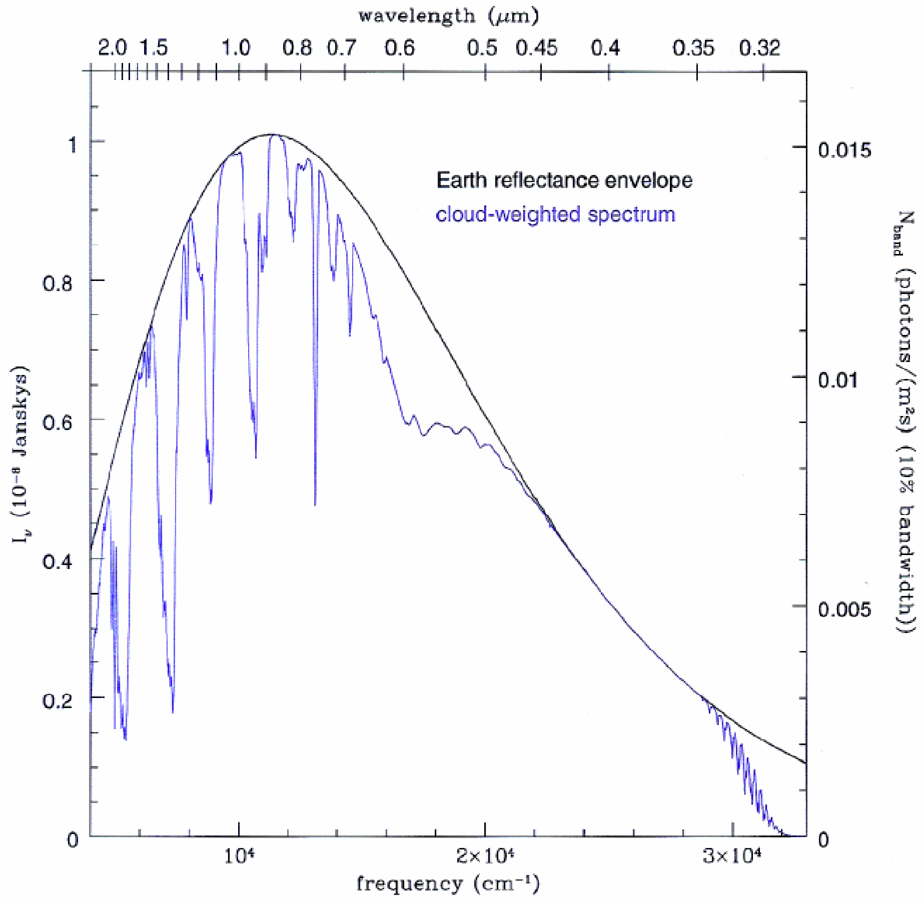


Refs.: (left) Woolf et al. 2002; (right) Kaltenegger et al. 2007, and Christensen & Pearl 1997

# Brightness of Earth at 10 pc, in photons



Thermal Infrared



Visible

Ref.: DesMarais et al., 2002

# Species SNRs for an 8-m telescope, 6 day integration

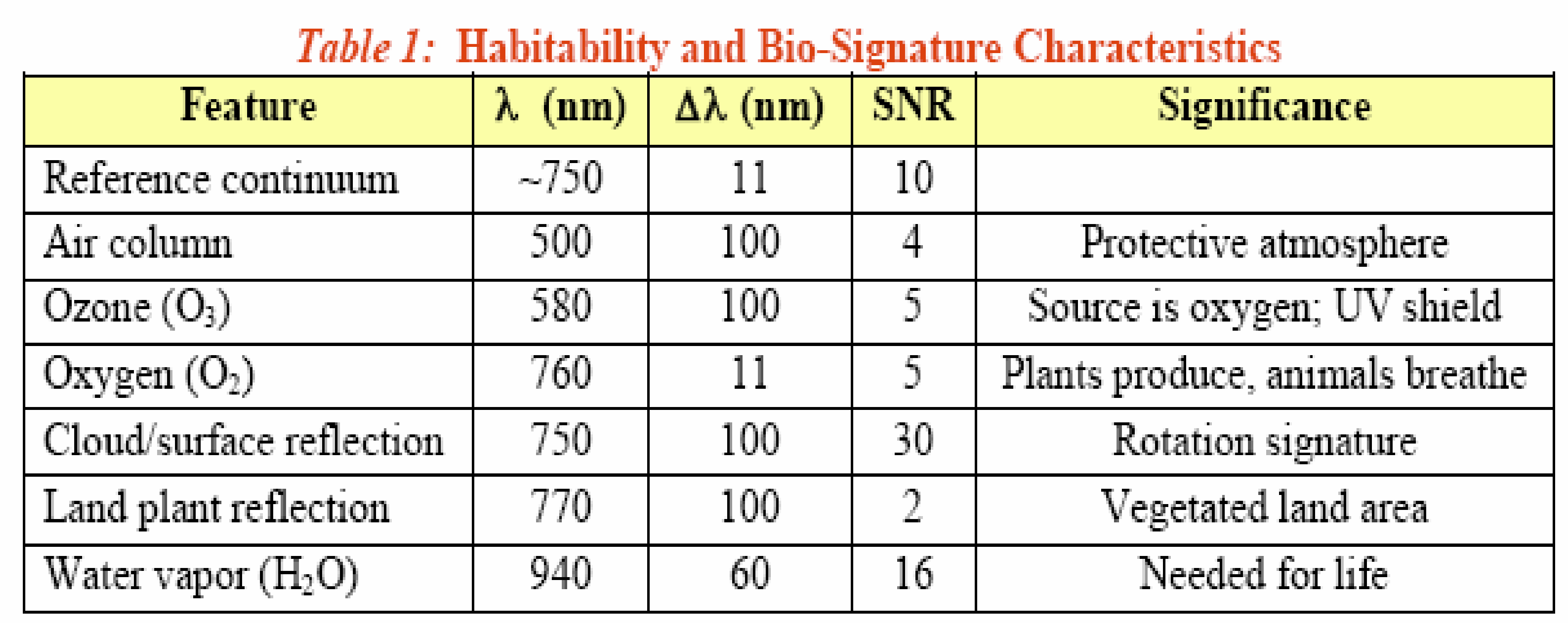


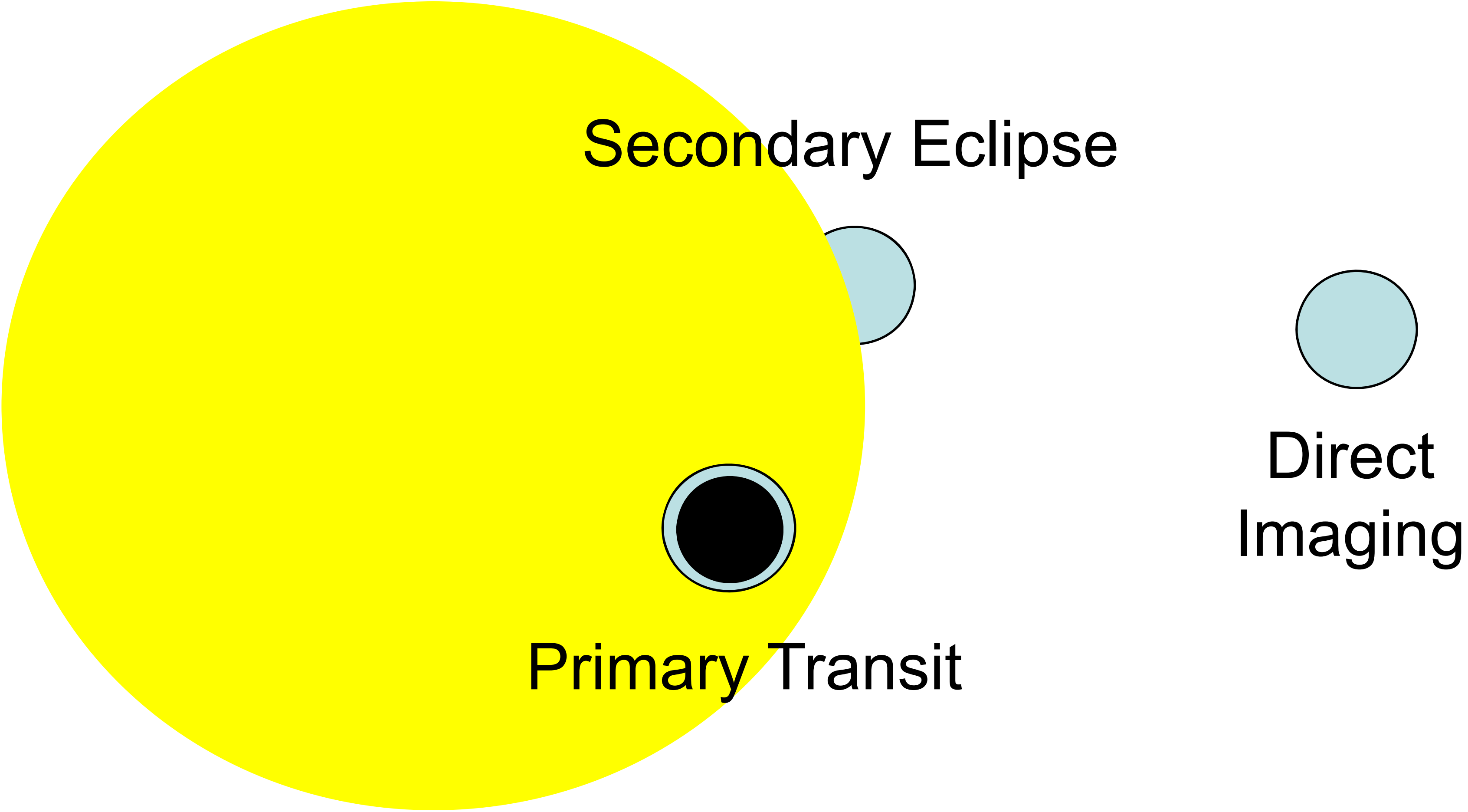
*Table 1:* **Habitability and Bio-Signature Characteristics**

| Feature | λ (nm) | Δλ (nm) | SNR | Significance |
|---|---|---|---|---|
| Reference continuum | ~750 | 11 | 10 | |
| Air column | 500 | 100 | 4 | Protective atmosphere |
| Ozone ($O_3$) | 580 | 100 | 5 | Source is oxygen; UV shield |
| Oxygen ($O_2$) | 760 | 11 | 5 | Plants produce, animals breathe |
| Cloud/surface reflection | 750 | 100 | 30 | Rotation signature |
| Land plant reflection | 770 | 100 | 2 | Vegetated land area |
| Water vapor ($H_2O$) | 940 | 60 | 16 | Needed for life |

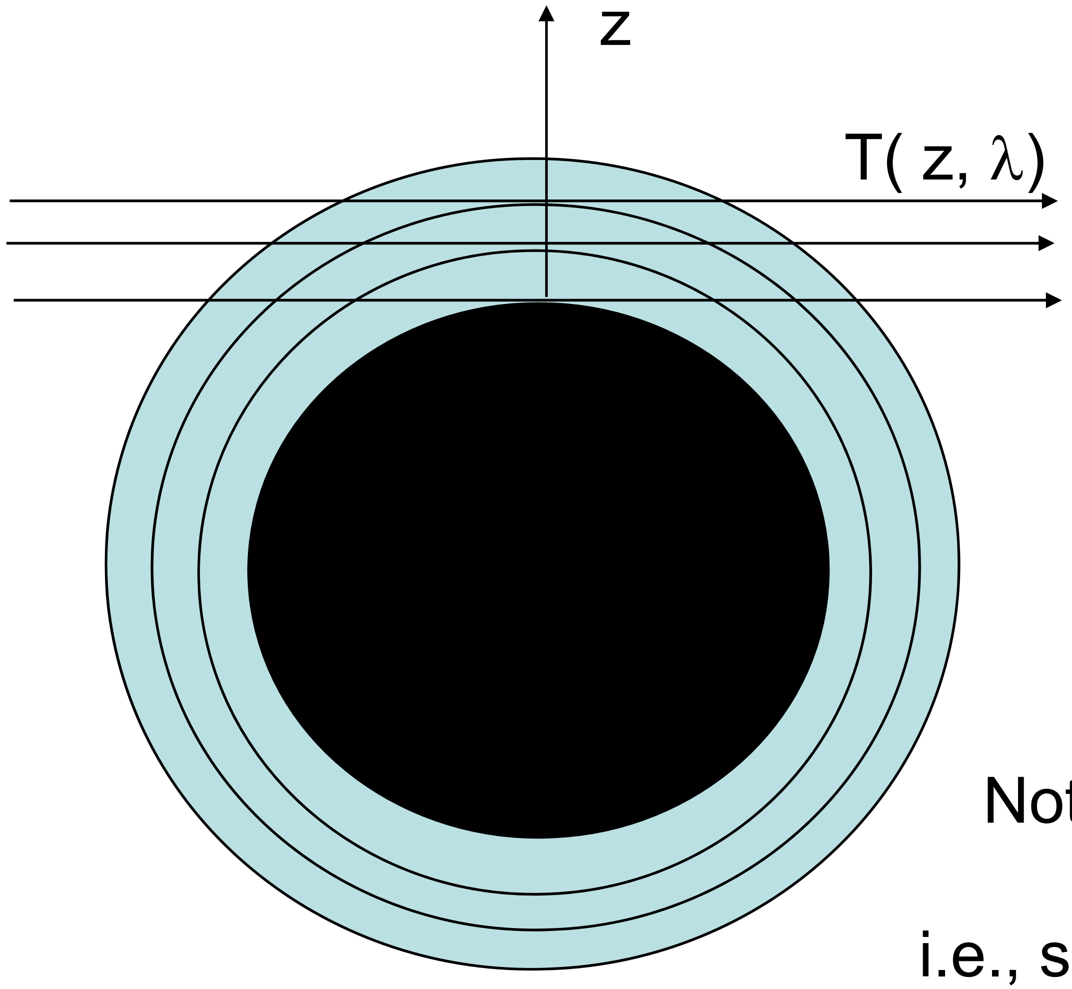
Ref.: M. Postman et al. 2009, ATLAST study.

# Characterizing Earths:  Transits

# Three Geometries



# Transit Geometry



***h*** is the effective height of an opaque atmosphere:

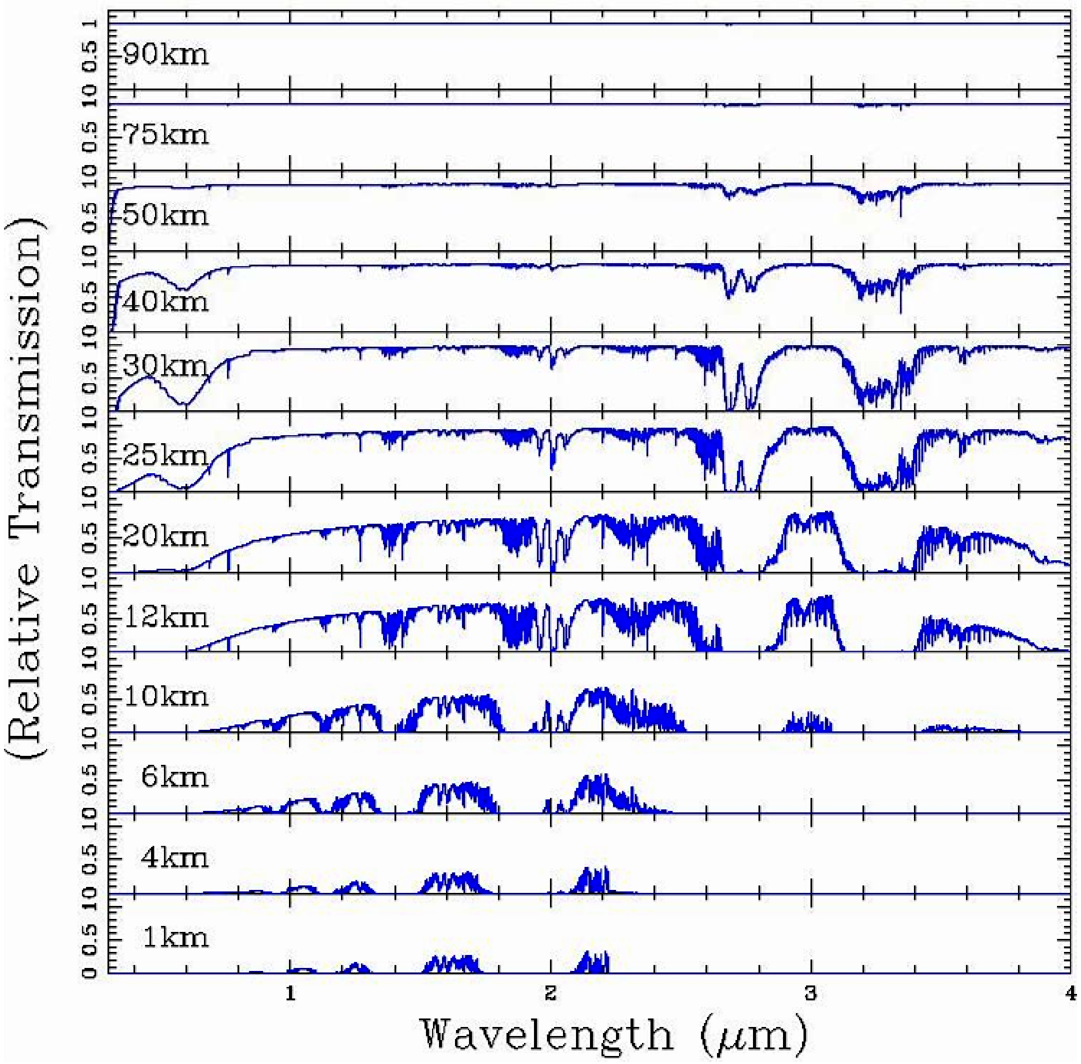
$\boldsymbol{h}(\lambda) = \int (1-T)\, dz$

So

$R(\lambda) = R_0 + h(\lambda)$

Note: The scale height is
H ~ 1/R0
i.e., smaller for Super-Earths.

# Ray-by-ray spectra, visible & near-infrared



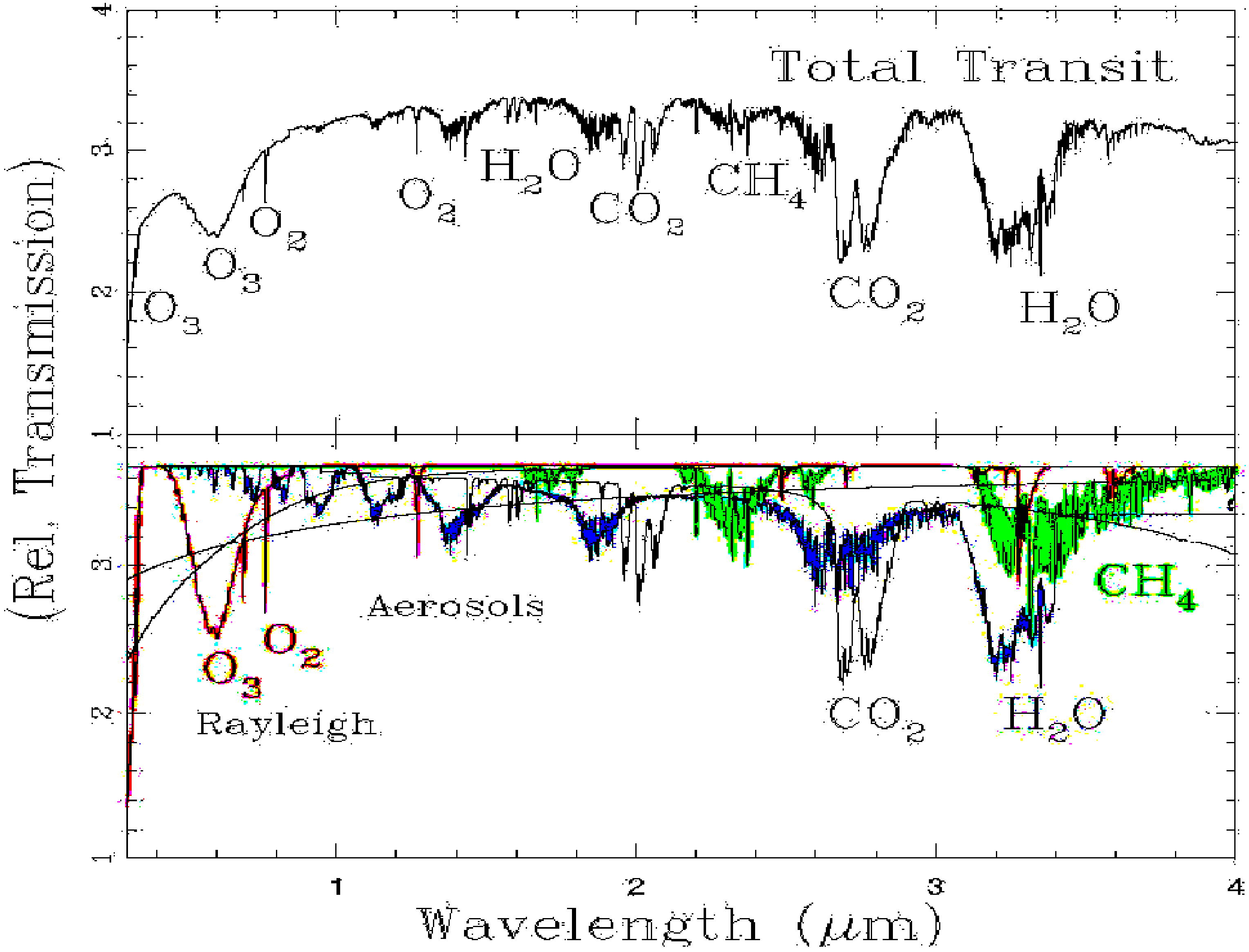
Short wavelength range of transmission spectrum.

Note:
- strong O3 bands at 0.3 & 0.6 um,
- weak H2O bands in visible,
- strong Rayleigh in blue,
-low transmission below 10 km.

Enric Palle et al. showed an observed spectrum from a lunar eclipse, but with additional dimer features.

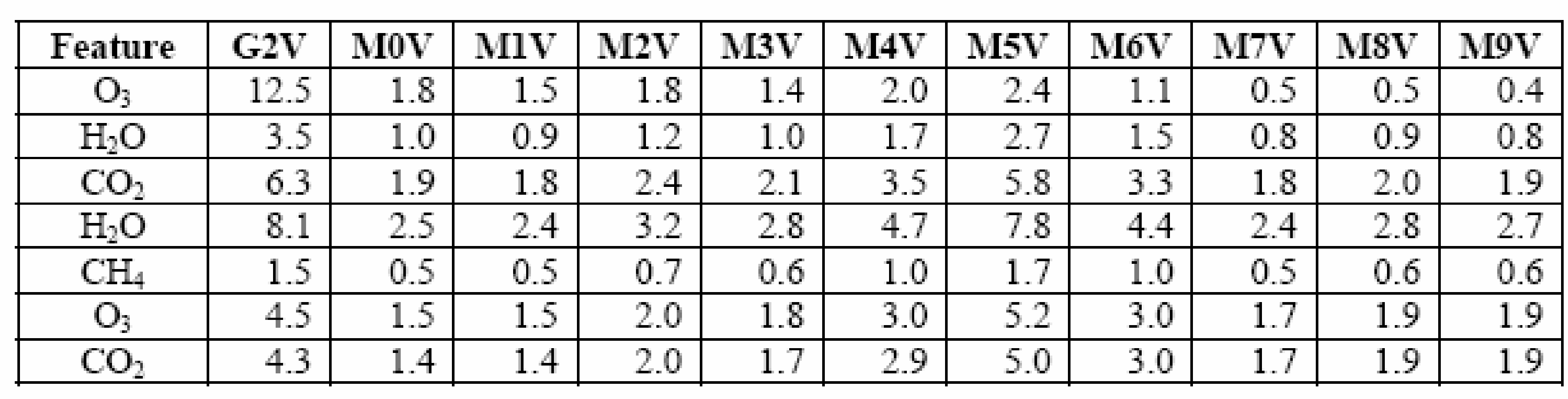
Ref.: Kaltenegger & Traub 2009

# Visible & near-infrared segment

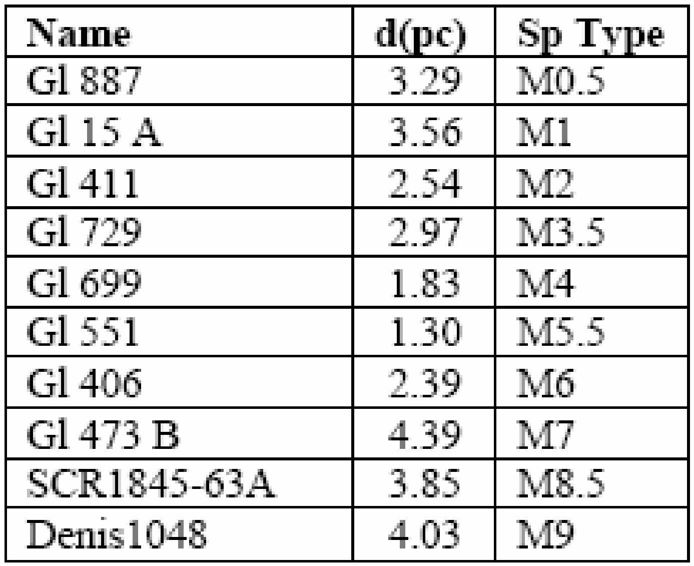


Ref.: Kaltenegger & Traub 2009

# 1-transit SNRs for ***the*** nearest star



| Feature | G2V | M0V | M1V | M2V | M3V | M4V | M5V | M6V | M7V | M8V | M9V |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $O_3$ | 12.5 | 1.8 | 1.5 | 1.8 | 1.4 | 2.0 | 2.4 | 1.1 | 0.5 | 0.5 | 0.4 |
| $H_2O$ | 3.5 | 1.0 | 0.9 | 1.2 | 1.0 | 1.7 | 2.7 | 1.5 | 0.8 | 0.9 | 0.8 |
| $CO_2$ | 6.3 | 1.9 | 1.8 | 2.4 | 2.1 | 3.5 | 5.8 | 3.3 | 1.8 | 2.0 | 1.9 |
| $H_2O$ | 8.1 | 2.5 | 2.4 | 3.2 | 2.8 | 4.7 | 7.8 | 4.4 | 2.4 | 2.8 | 2.7 |
| $CH_4$ | 1.5 | 0.5 | 0.5 | 0.7 | 0.6 | 1.0 | 1.7 | 1.0 | 0.5 | 0.6 | 0.6 |
| $O_3$ | 4.5 | 1.5 | 1.5 | 2.0 | 1.8 | 3.0 | 5.2 | 3.0 | 1.7 | 1.9 | 1.9 |
| $CO_2$ | 4.3 | 1.4 | 1.4 | 2.0 | 1.7 | 2.9 | 5.0 | 3.0 | 1.7 | 1.9 | 1.9 |



| Name | d(pc) | Sp Type |
|---|---|---|
| Gl 887 | 3.29 | M0.5 |
| Gl 15 A | 3.56 | M1 |
| Gl 411 | 2.54 | M2 |
| Gl 729 | 2.97 | M3.5 |
| Gl 699 | 1.83 | M4 |
| Gl 551 | 1.30 | M5.5 |
| Gl 406 | 2.39 | M6 |
| Gl 473 B | 4.39 | M7 |
| SCR1845-63A | 3.85 | M8.5 |
| Denis1048 | 4.03 | M9 |

Most likely transits, in each sub-spectral type, will be at 10-20 pc,
so 100 times fainter,
& 10 times smaller SNR

where SNR = $N^{1/2}(\text{total})*2hR_p/R^2_s$

Ref.: Kaltenegger & Traub 2009

# Results & Examples

SNR(sec)/SNR(pri)

| | | |
|---|---|---|
| Earth, G star, visible | 1/500 | primary best |
| Earth, M star, visible | 1/50 | primary best |
| Hot Jupiter, G star, vis. | 1 | both OK |
| | | |
| Earth, G star, infrared | 1/2000 | primary best |
| Earth, M star, infrared | 40 | secondary best |
| Hot Jupiter, G star, IR | 200 | secondary best |

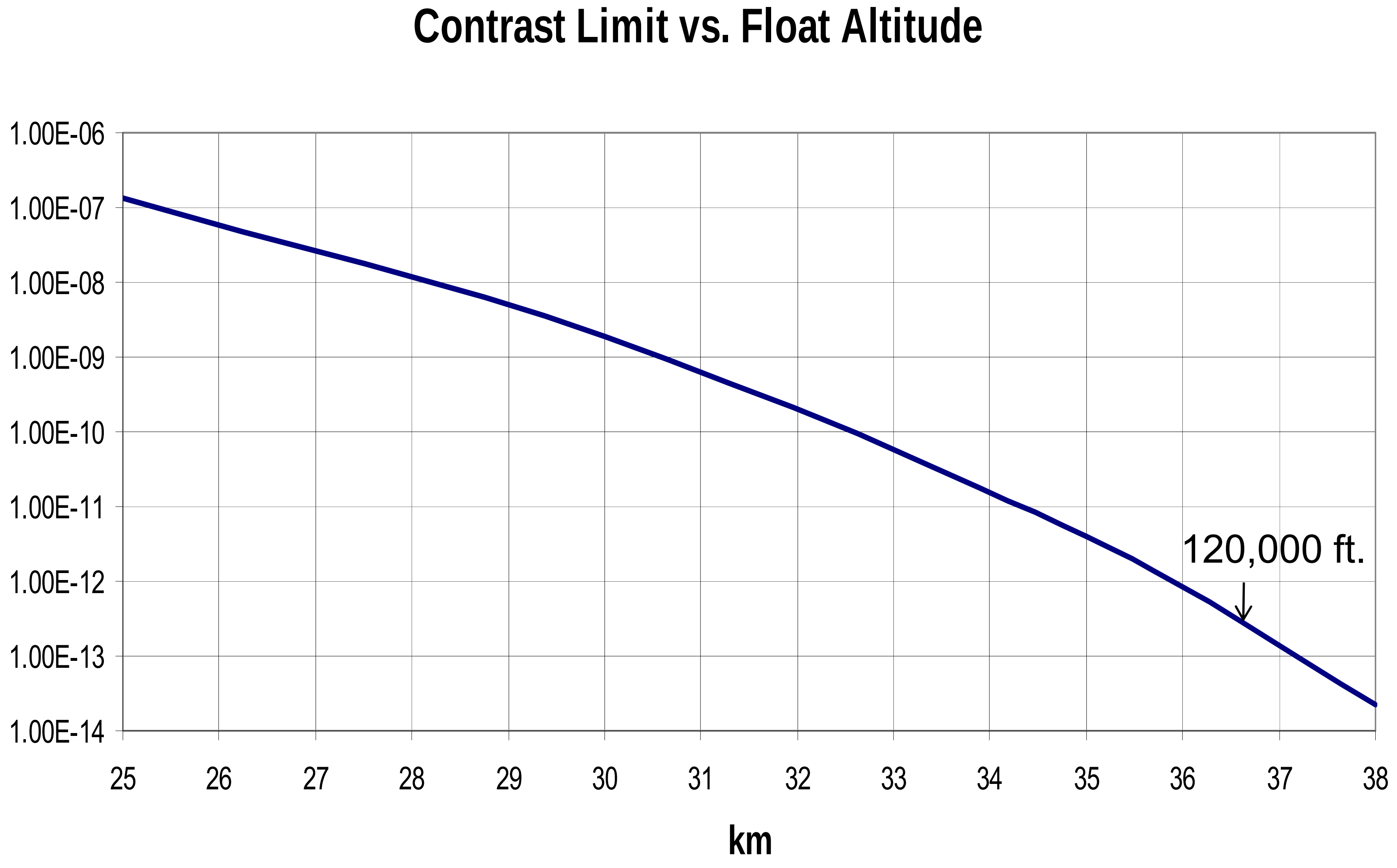
So, in the visible, for Earth around a G or M dwarf, the primary transit is best; likewise in the infrared for Earth around a G star.

So for these cases, the small SNR values for primary transits are the best we can do.

Super Earths will be similar.

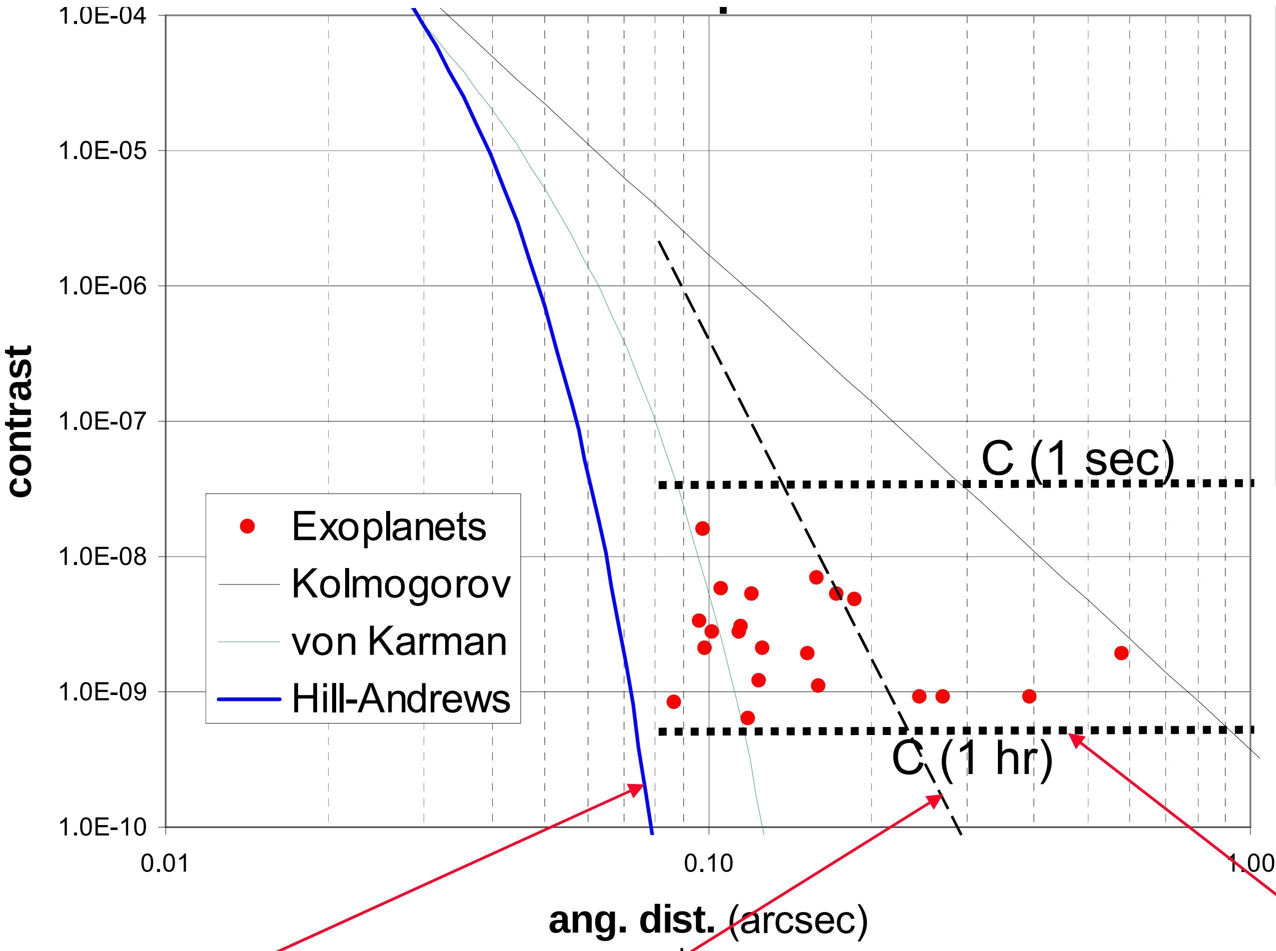
# Planetscope: A Coronagraph on a Balloon Platform or on the ISS

# Contrast level dependence on altitude



P. Chen & W. Traub, 2009

# Contrast & known RV exoplanets vs angle



**"Dome Seeing" Contribution:**
C(1 sec) assumes night best (rms = 1 nm) but only 0.1 nm of this going to speckles in the range IWA-OWA, with 0.9 nm going to piston and tilt.

C(1 hr) assumes above reduced by (1 sec / 1 hr)$^{1/2}$ , i.e., this is the uncertainty in the average background speckle level.

$C = \pi(2\pi\sigma/N\lambda)^2$
for $\sigma = \lambda/1000$
& $\sigma = \lambda/10000$
& $N = 60$

IWA-OWA = 2-30 λ/D
for 550 nm & 2.5 m

Expected free-atmosphere speckle contrast

Expected PSF from coronagraph

Expected dome-seeing contrast uncertainty in 1 hour

P. Chen &
W. Traub, 2009

# Summary

- Giant planets are accessible with a coronagraph on a balloon platform or on the ISS, with a 1-3 m telescope.
- Colors and low-resolution spectra are feasible from both cases.
- Terrestrial planets will need a larger (3-8 m) telescope.

# Thank you!