The Atmospheres of Extrasolar Super-Earths

Eliza Miller-Ricci[1]
Dimitar Sasselov[2] - Sara Seager[3] - Michael Meyer[4] - Linda Elkins-Tanton[3]

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(1) UCSC (2) Harvard (3) MIT (4) ETH

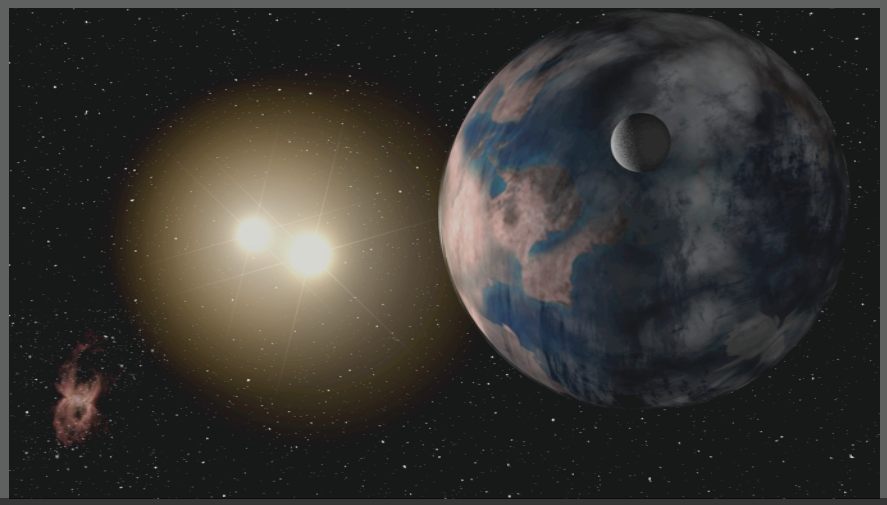
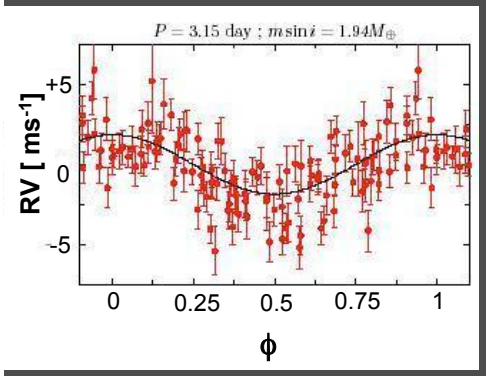
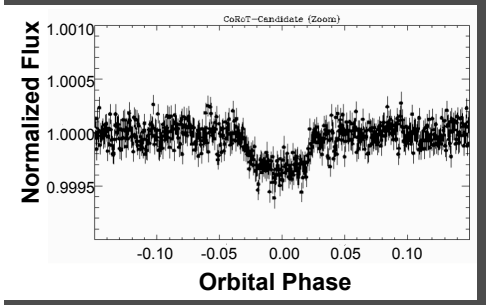
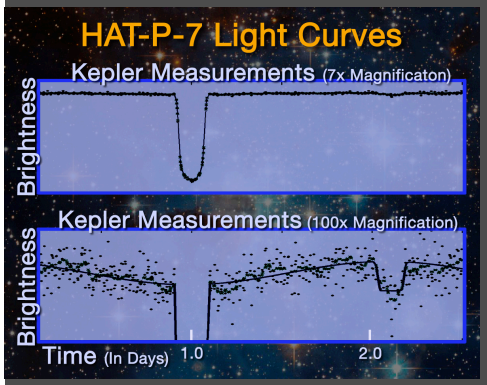


Image credit: Paul A. Kempton





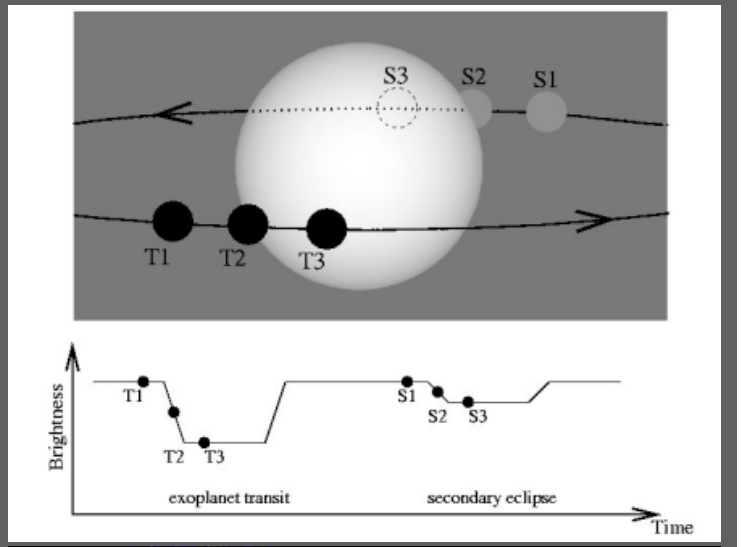


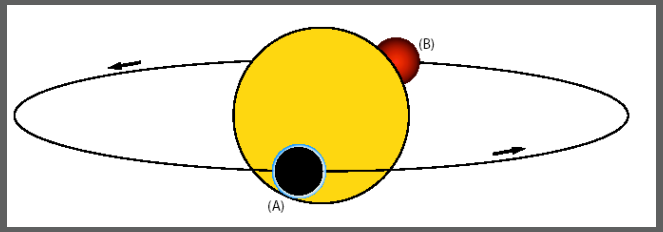
The Age of the Super Earth

- CoRoT: launched 12/27/2006
- HARPS: ~15 new super Earths with mass < 10_{Earth}
- MEarth: capable of detecting super Earths transiting M-dwarfs from the ground
- Kepler: launched successfully - March 6, 2009

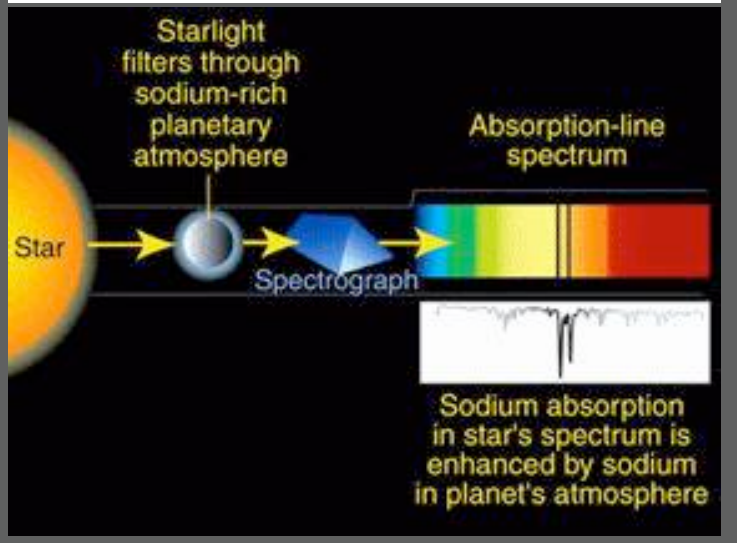
Observing Exoplanet Atmospheres

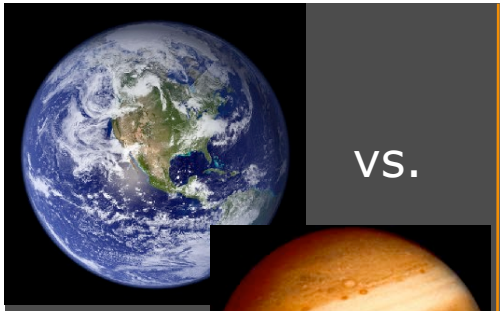
Emission

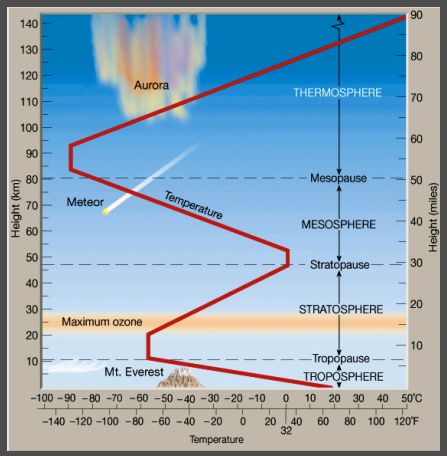




Transmission







Questions

- Do super Earths retain atmospheric hydrogen?
- Optically thin vs. optically thick?
- What are the photochemical properties?
- Outgassing history?
- Plate tectonics & cycles?
- Habitability?

Super-Earth Model Atmosphere

- 1-D plane-parallel structure
- Pressure profile: hydrostatic equilibrium
- Temperature profile: Irradiated grey atmosphere (Hansen et al.) + adiabatic convection
- Chemical equilibrium + photochemical considerations
- Molecular opacities (H_2O, CO, CO_2, CH_4, NH_3, O_2, O_3)
- Produces emission and transmission spectra

Gl 581 Exoplanet System

Planets:

e: 1.9 M_{Earth}
P = 3.15 d

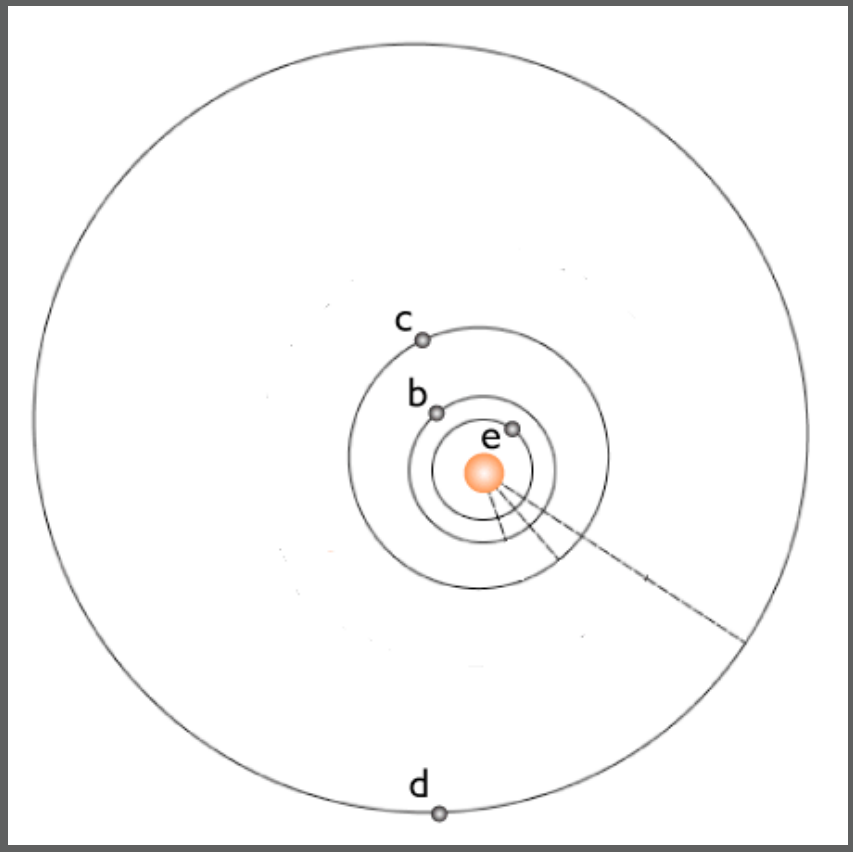
b: 15.6 M_{Earth}
P = 5.37 d

c: M = 5.4 M_{Earth}
P = 12.9 d
e = 0.16
$T_{eq} \approx 370$ K
$R_{pl} \approx 1.5\ R_{Earth}$?

d: 7.1 M_{Earth}
P = 66.8 d

Star: Gl 581

- Spectral Type: M3, V = 10.55



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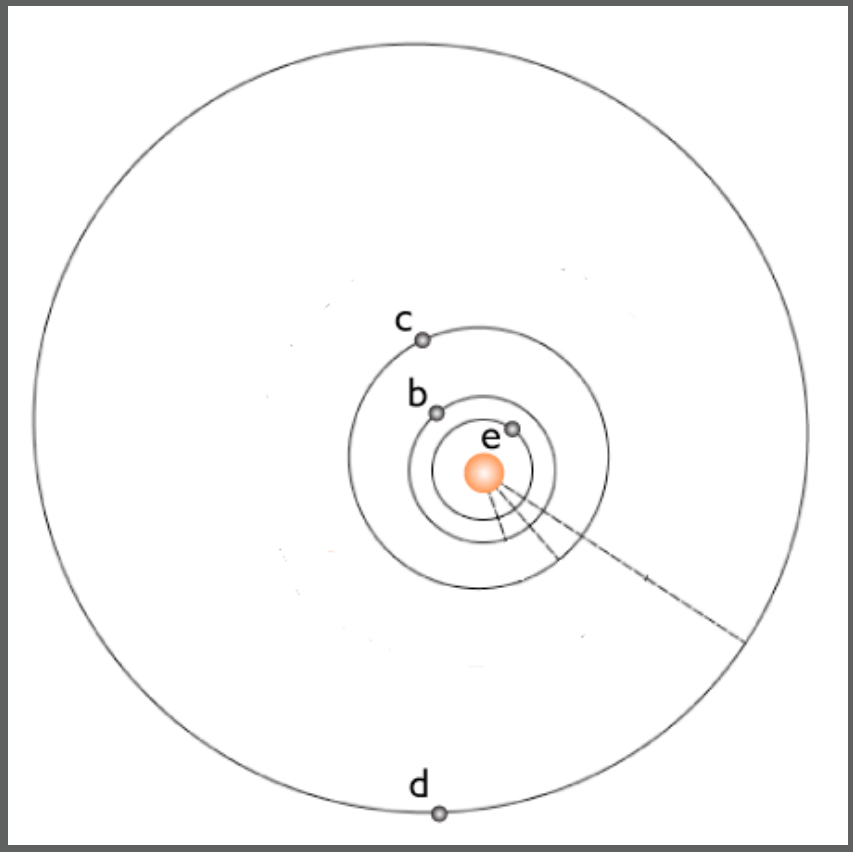
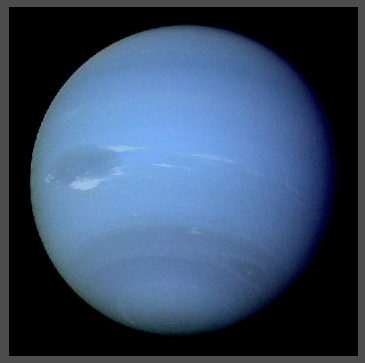
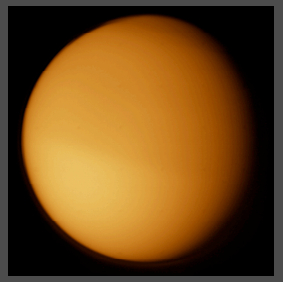






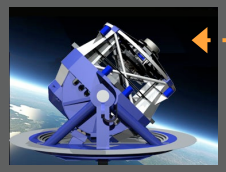
Atmosphere Scenarios

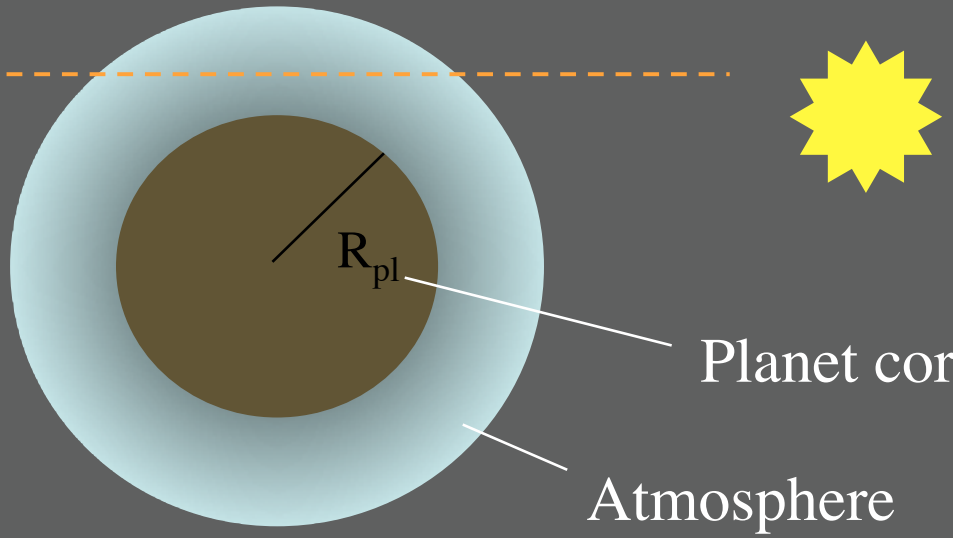
1) Hydrogen-Rich Atmosphere -
   H_2, He, + H_2O, [CH_4, NH_3]

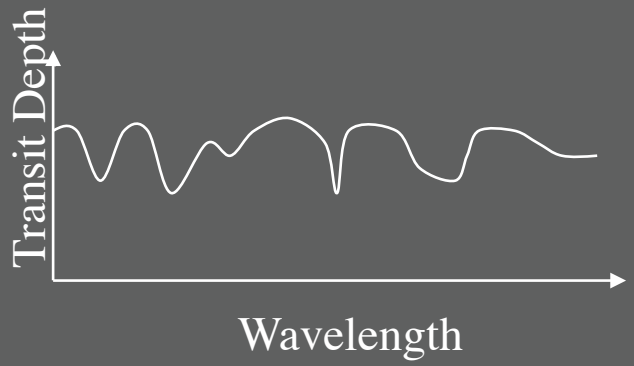
2) Intermediate Hydrogen Content Atmosphere -
   Mostly H_2O, CO_2, and [CH_4] with some H_2

3) Hydrogen-Poor Atmosphere -
   Mostly CO_2

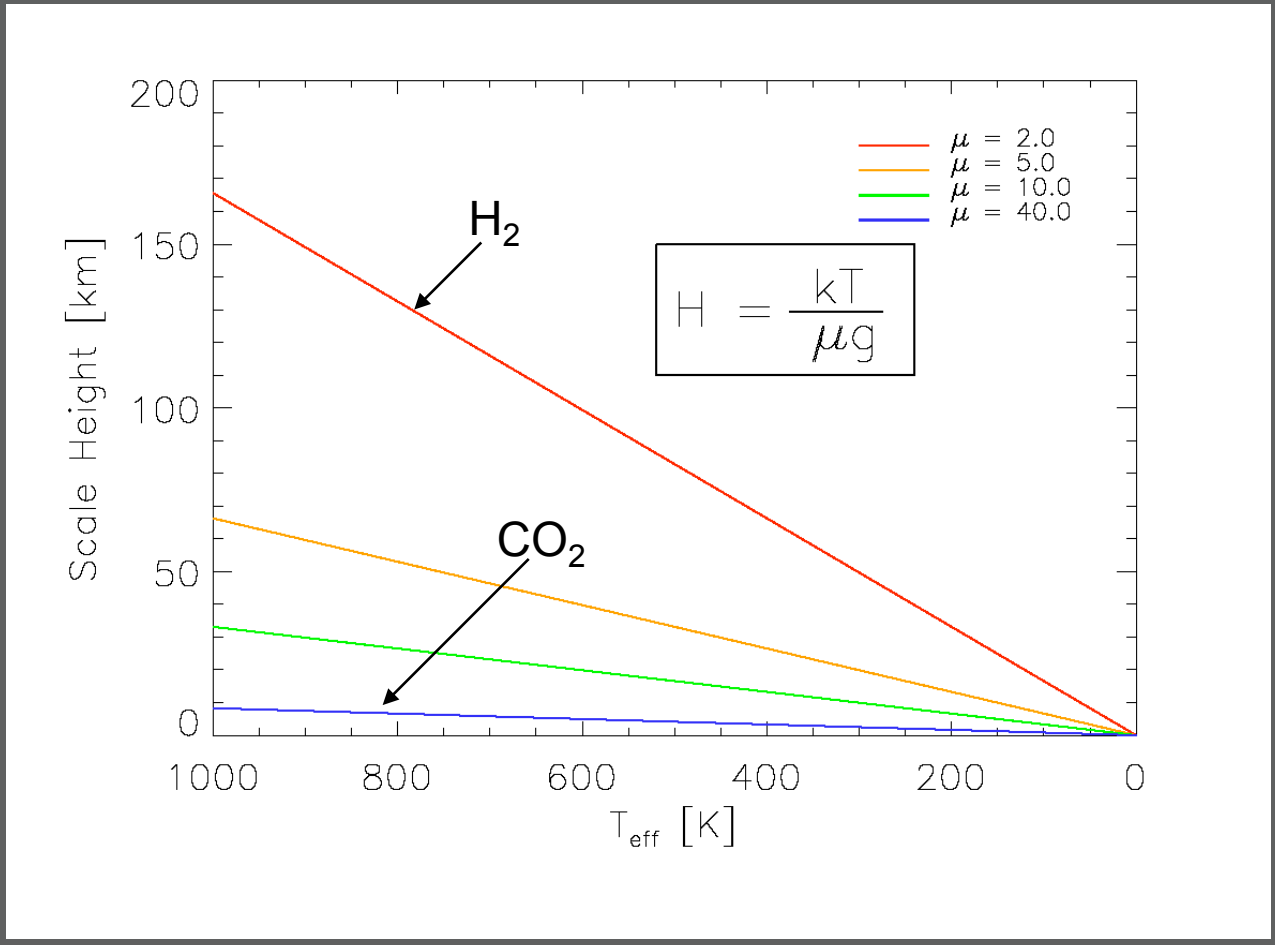
Transmission Spectroscopy







Atmospheric Scale Height

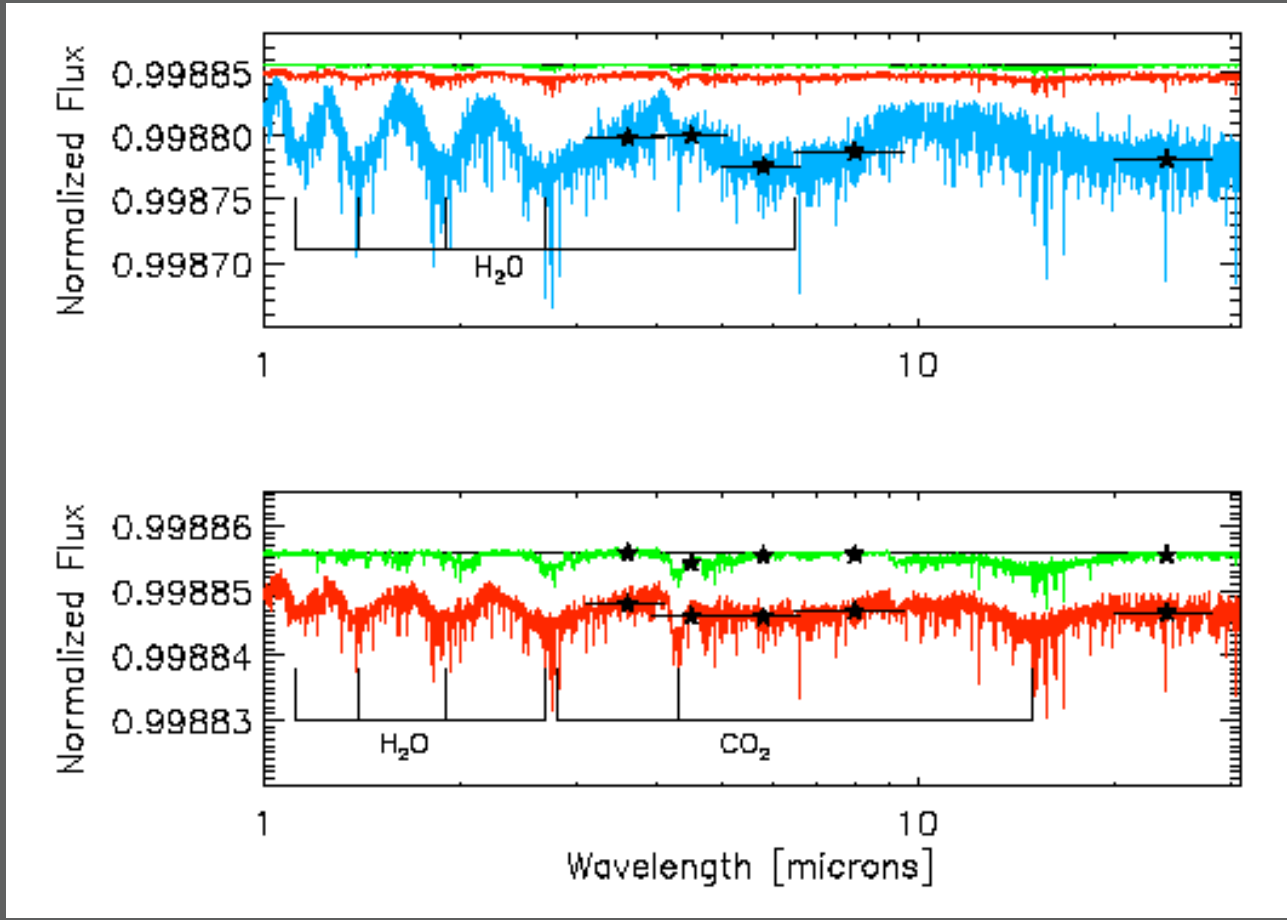


Miller-Ricci et al., 2009

Gl 581c Transmission Spectra

- ------- No atmosphere
- ------- Hydrogen-Rich
- ------- Intermediate
- ------- Hydrogen-Poor

$\Delta_{depth} \sim 20H\ R_{pl} / R_*^2$



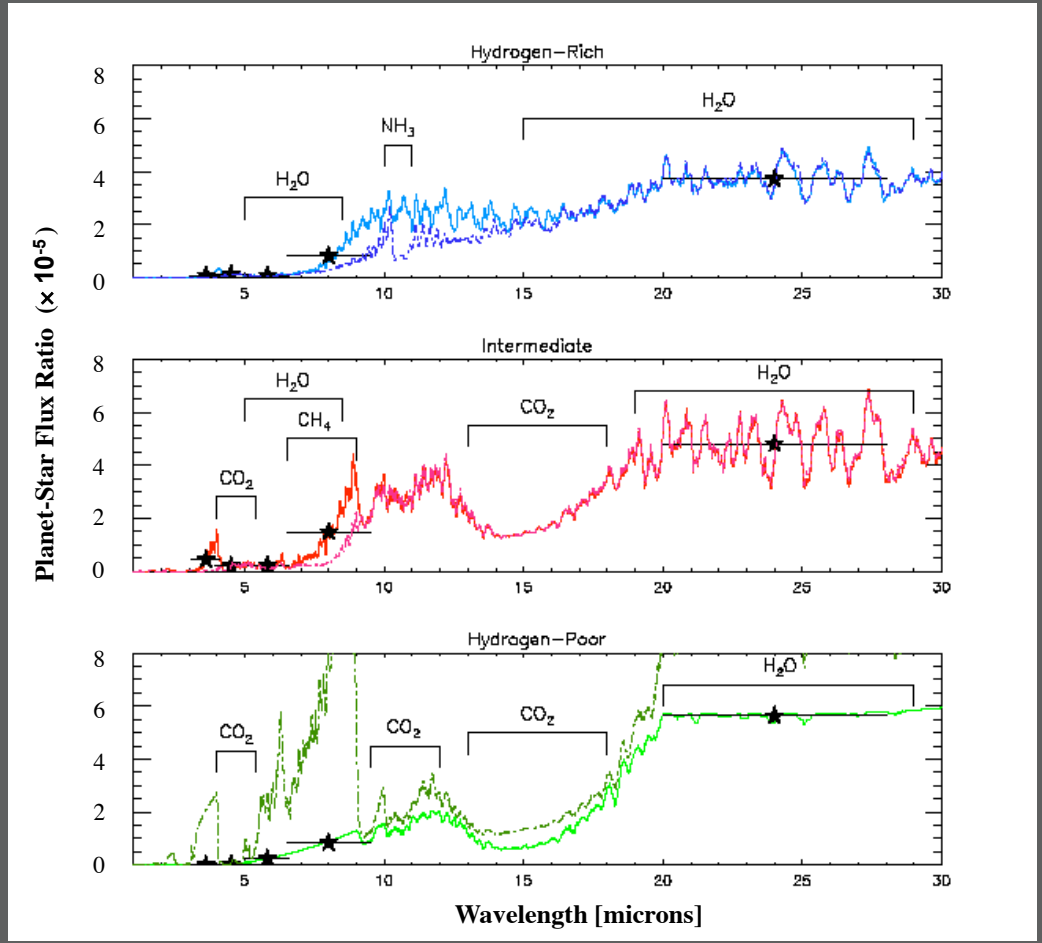
Miller-Ricci et al., 2009

Gl 582c Emission Spectra

w/o CH_4 and NH_3
w/ CH_4 and NH_3

w/o CH_4 and NH_3
w/ CH_4 and NH_3

w/ clouds
w/o clouds

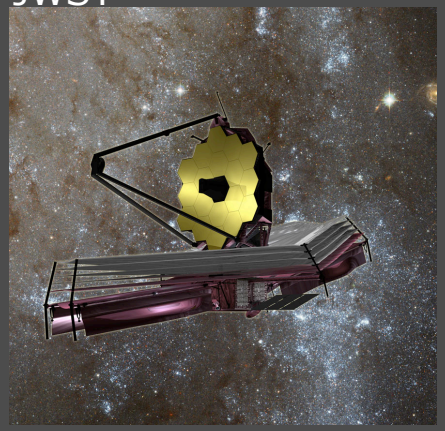


Miller-Ricci et al., 2009

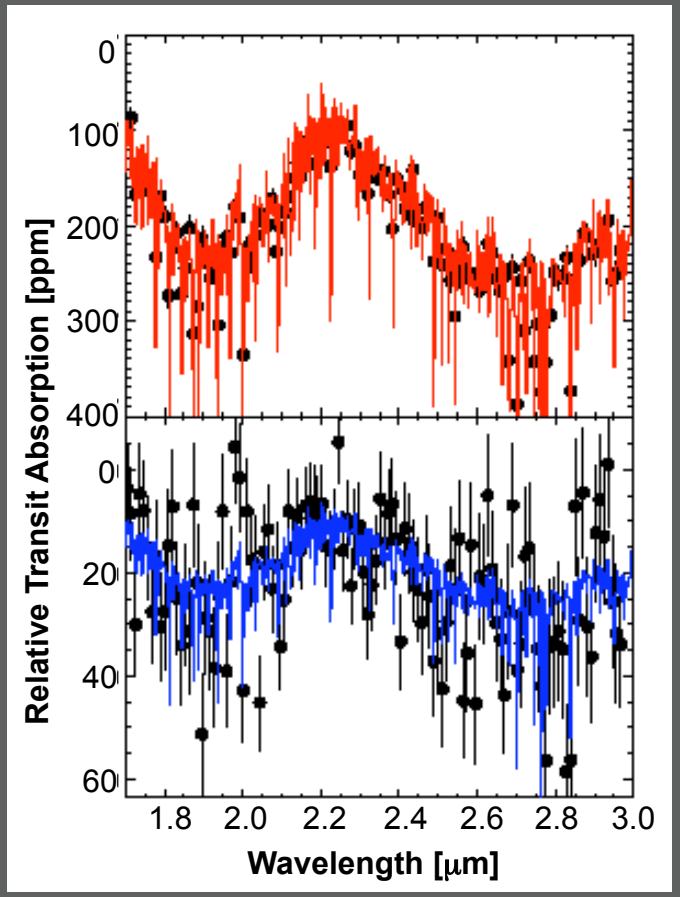
Eclipse depth ~ $(R_p/R_*)^2$ (T_p/T_*)

Observing Super-Earth Atmospheres

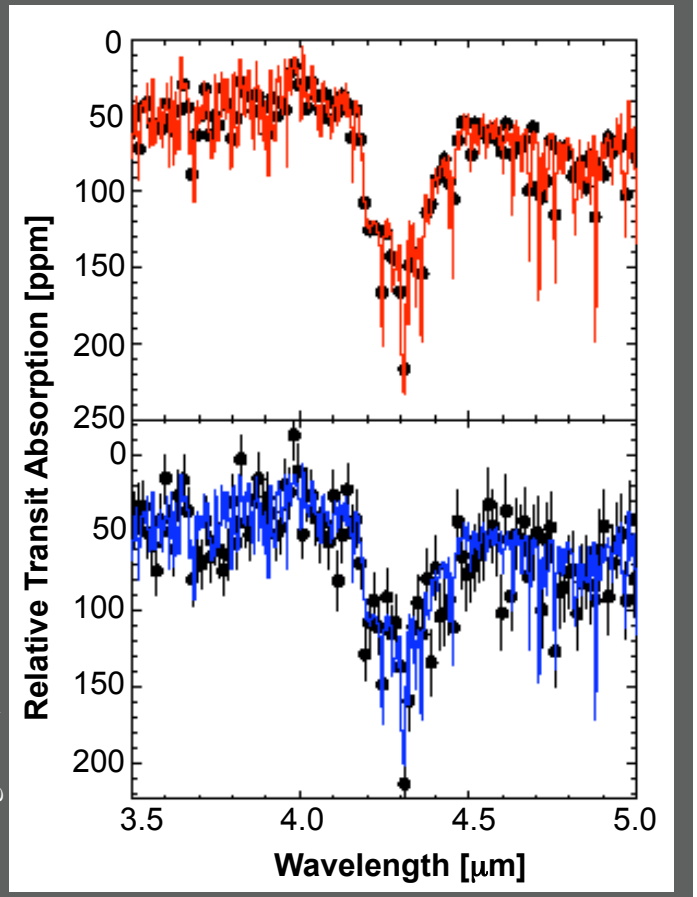
JWST



- Signals of several to 100 ppm → JWST



Deming et al., 2009

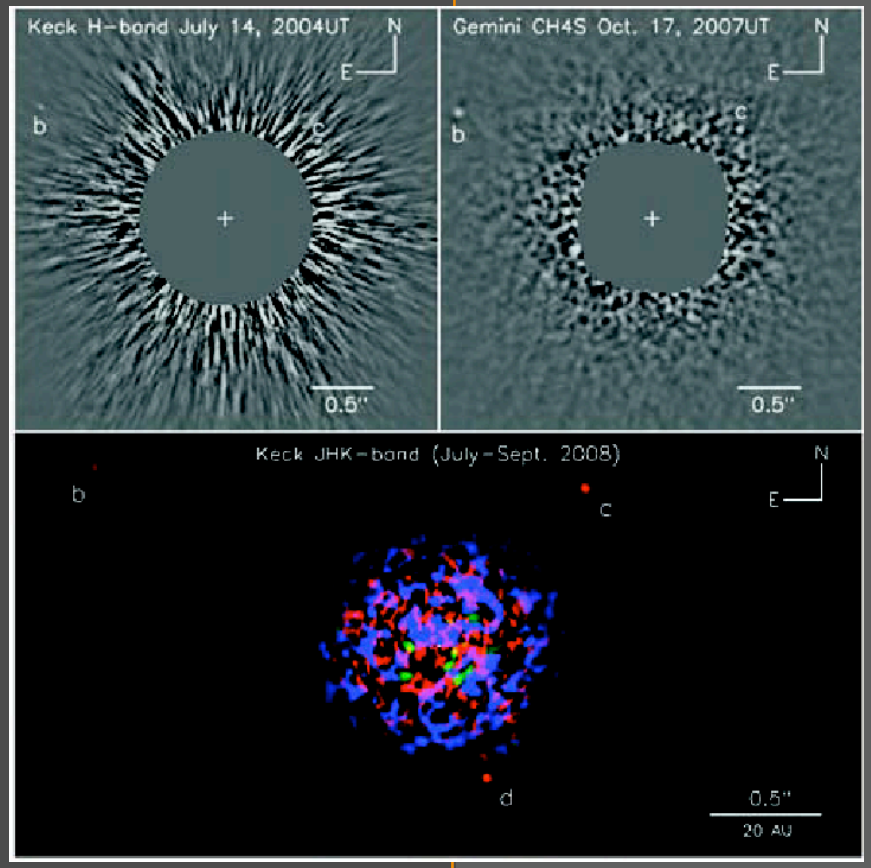


------- Hot super-Earth

------- Habitable super- Earth

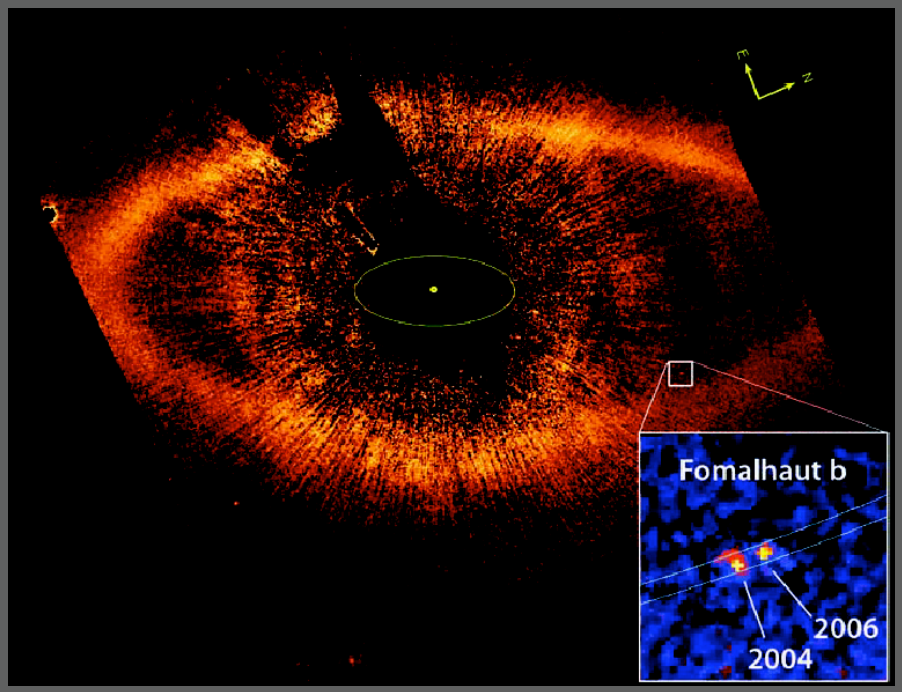
Recent Direct Imaging Results

HR 8799



Marois et al., 2008

Fomalhaut



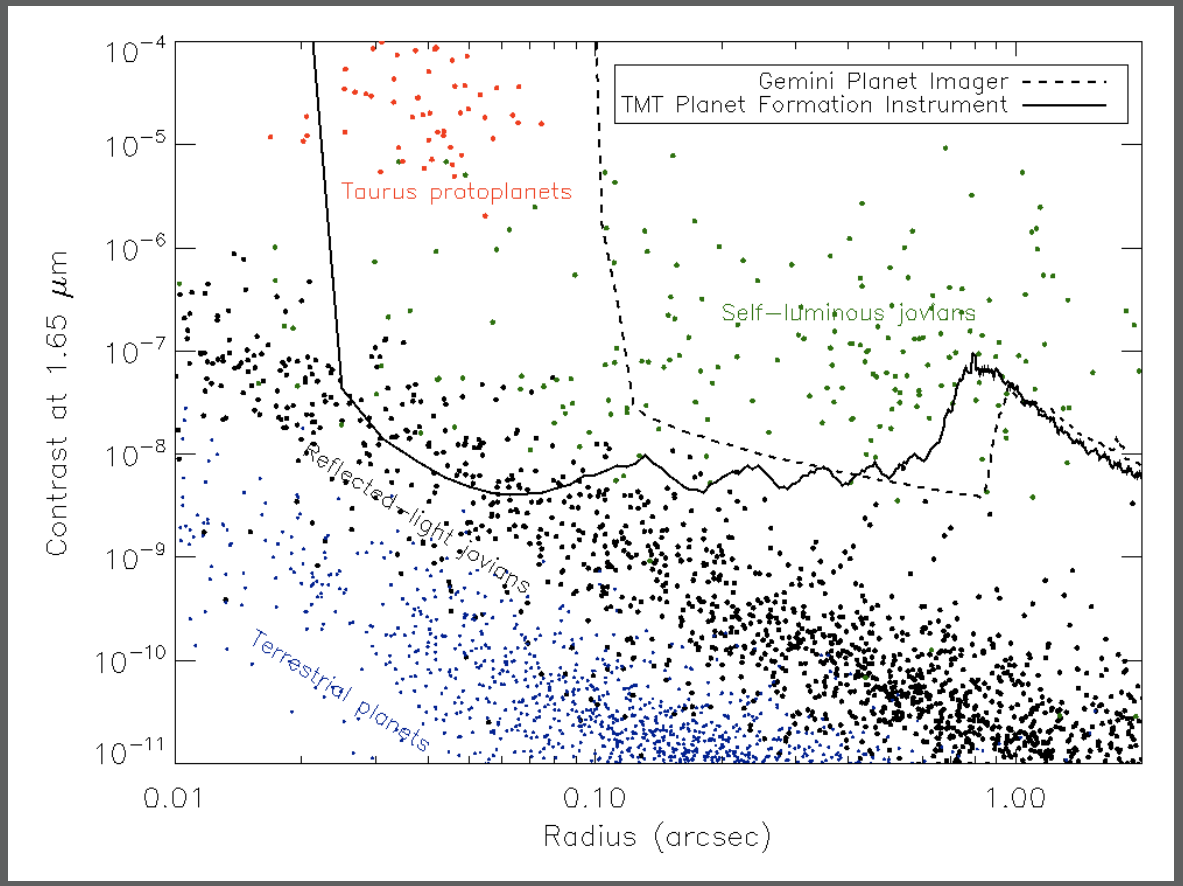
Kalas et al., 2008

Direct Imaging of Super-Earths


Image credit: http://www.eso.org


Image credit: http://www.tmt.org


Image credit: http://www.gmto.org



Macintosh et al., 2006

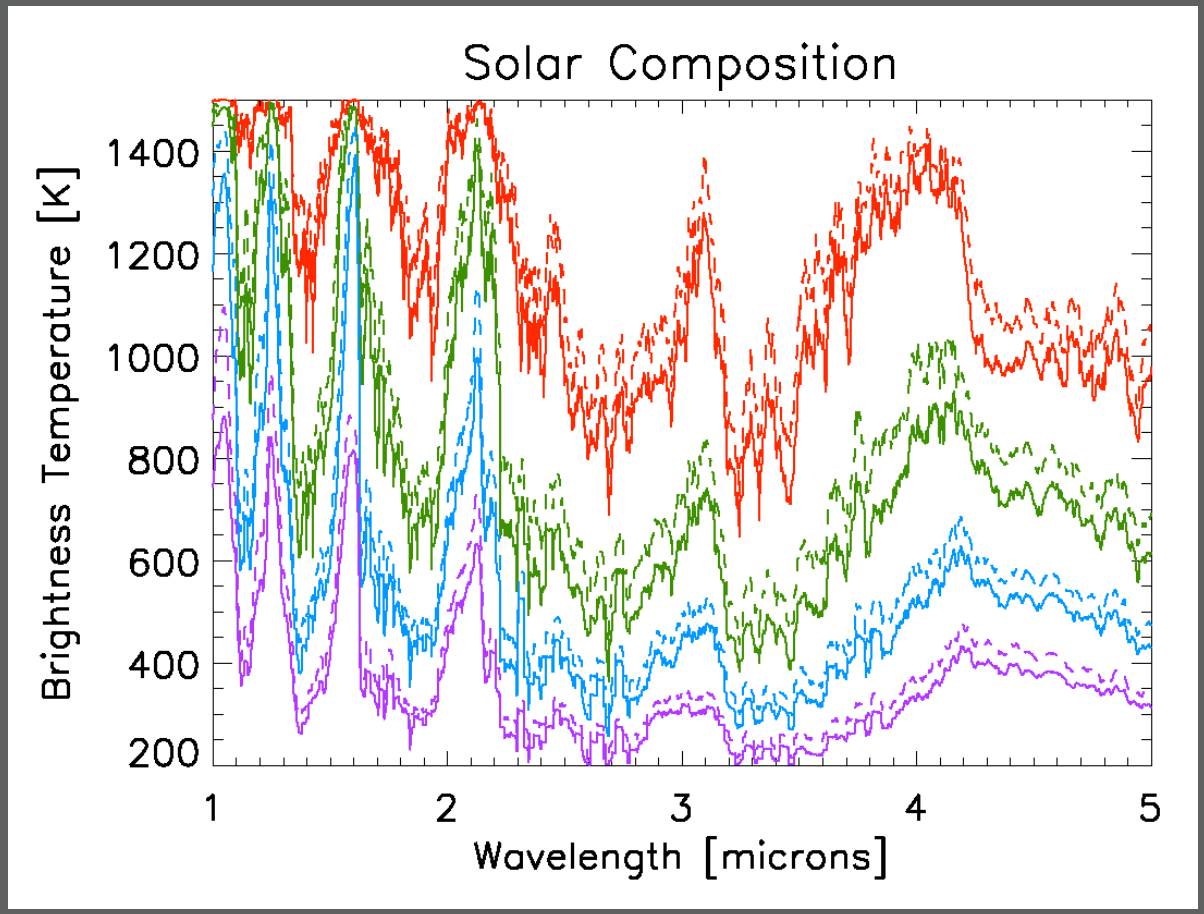
Hot Super-Earth Collision Afterglows

Image Credit: Don Davis

Surface temperature:
1,500-4,000 K
Cooling time in free space:
~100,000 yrs
Cooling time with a thick atmosphere:
~1-10 Myr

→ ~10% of young stars with a hot super-Earth afterglow at a given time

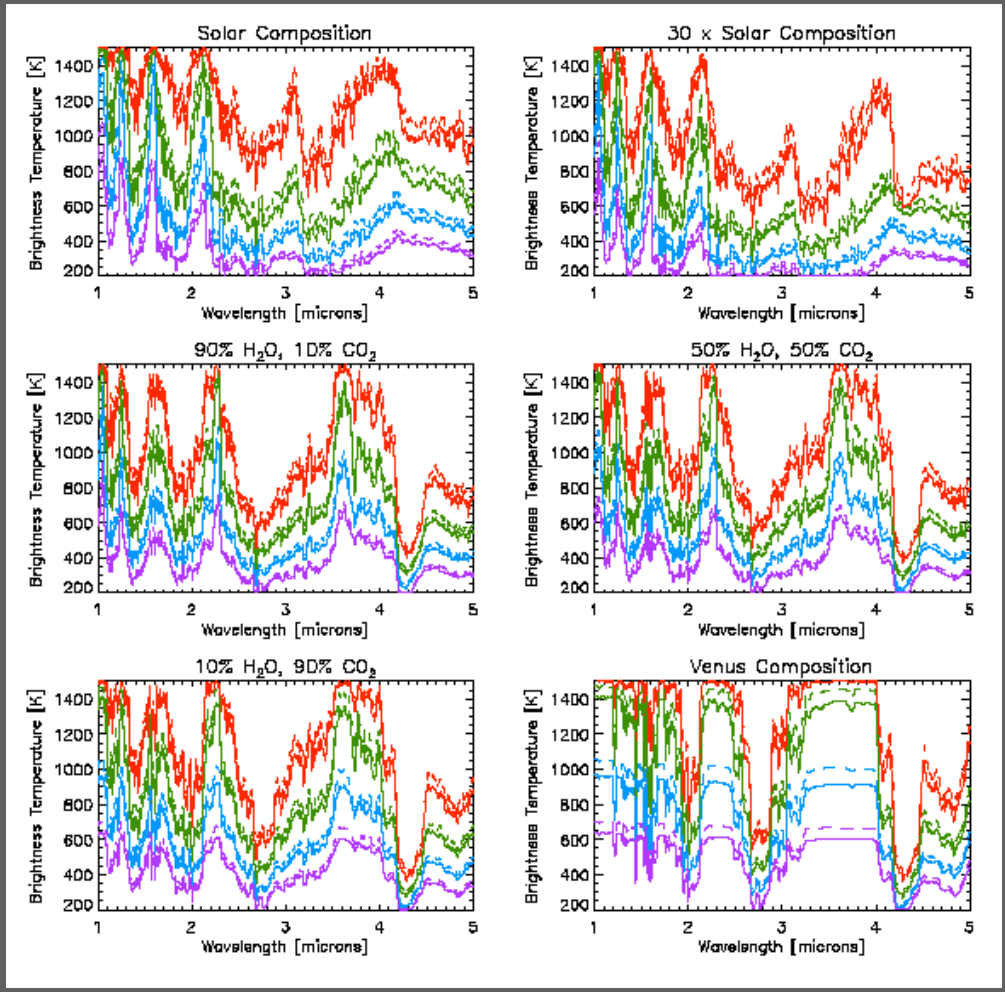
Collision Afterglow Spectra



Miller-Ricci et al., 2009

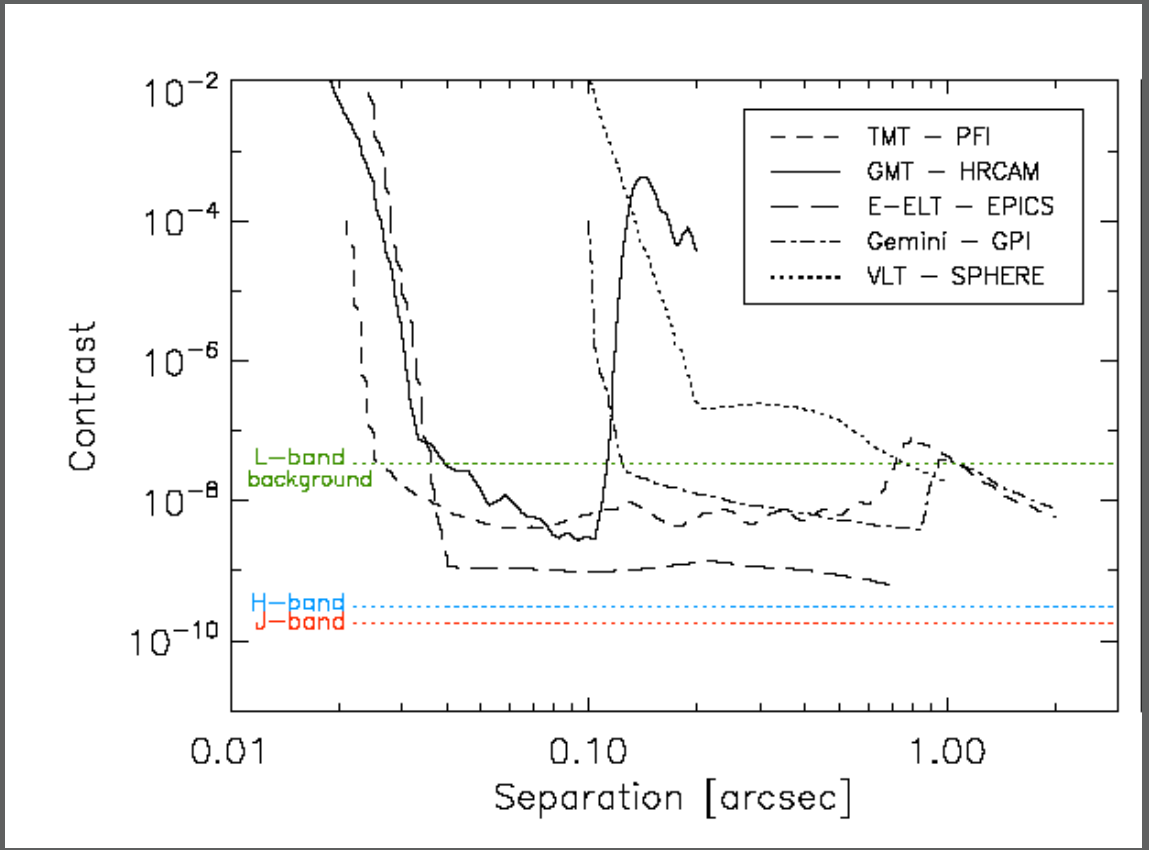
Collision Afterglow Spectra

- 1 bar
- 10 bar
- 100 bar
- 1000 bar



Miller-Ricci et al., 2009

Imaging Collision Afterglows with Future ELTs



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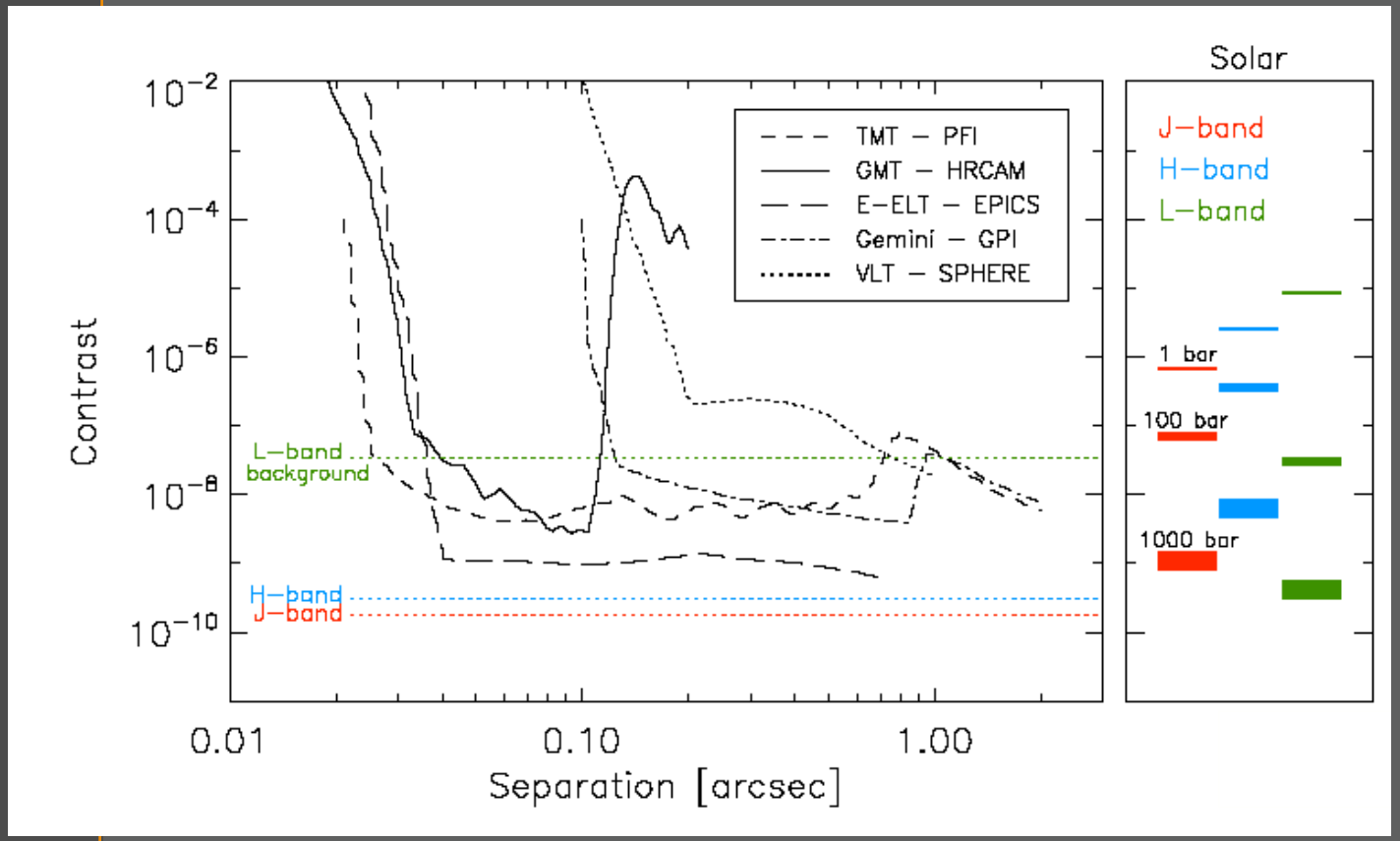
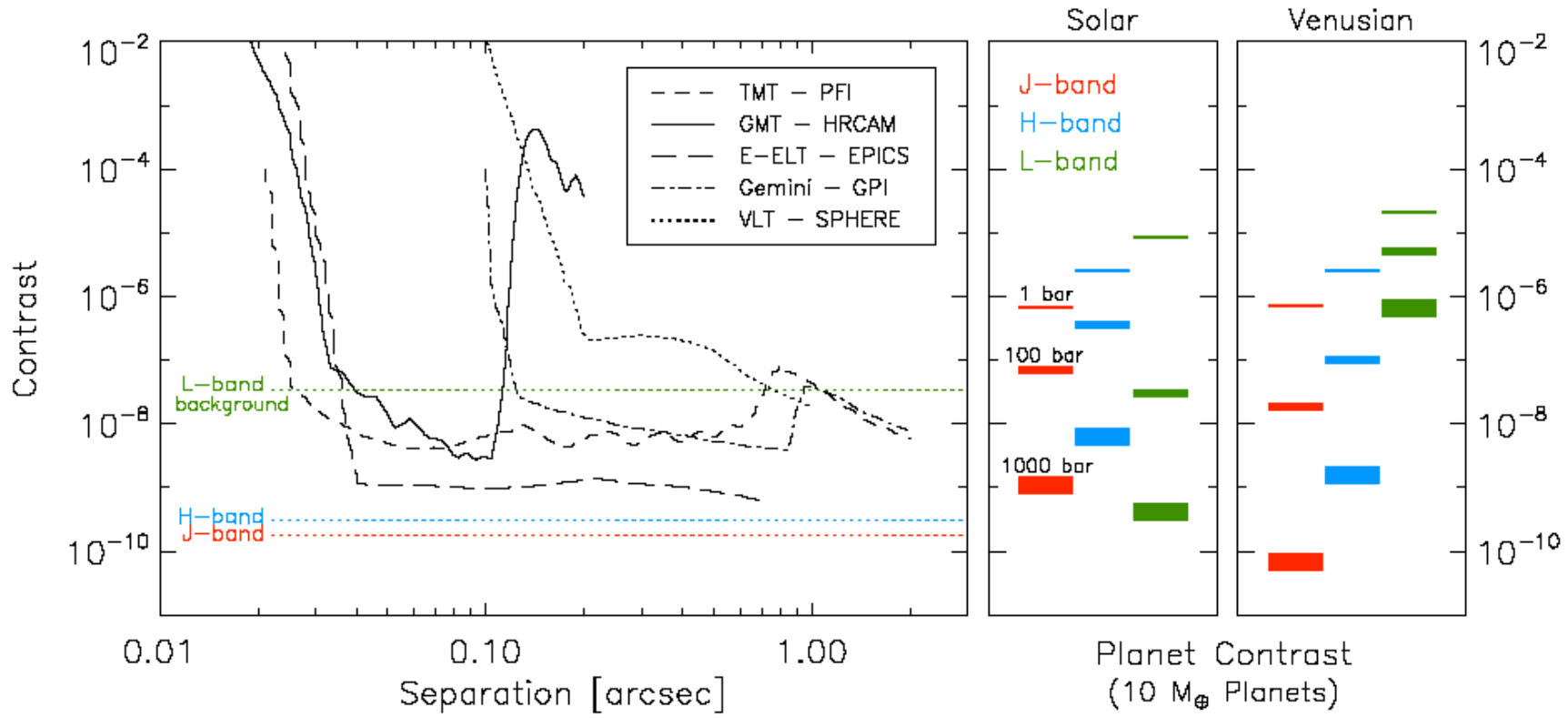


Eliza Miller-Ricci

Imaging Collision Afterglows with Future ELTs



Miller-Ricci et al., 2009

Conclusions

- Super-Earths are detectable with current instrumentation, and these planets may be quite common
- Super Earths may exhibit a wide range of atmospheres
- Transmission spectroscopy is the best way to differentiate between H-rich and H-poor atmospheres
- Super Earth atmospheres will be observable with next generation facilities such as JWST and ground-based ELTs