# Exoplanet Characterization with TMT

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# Major Categories of Questions for Exoplanets

## 1) Planet Demographics

*What is the frequency of planets as a function of separation and mass? What is the complete set of possible outcomes from the planet formation process?*

## 2) Planetary System Architectures

*What correlations exist between the locations and properties of different planets in a planetary system?*

## 3) Planet Characterization

*What are the properties of individual planets, and how do these properties vary among the full set of new and diverse worlds?*

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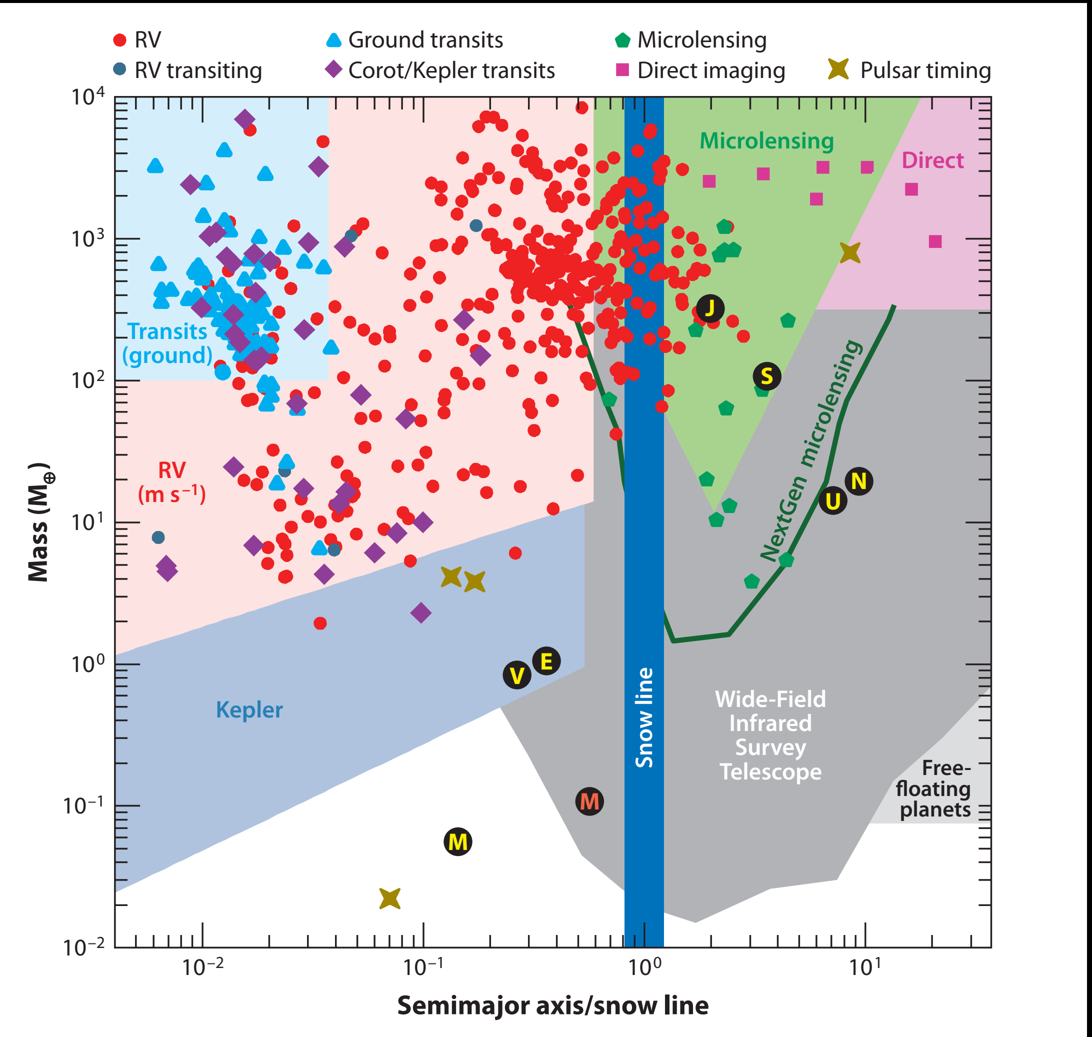


Gaudi et al. (2012)

# 2) Planetary System Architectures

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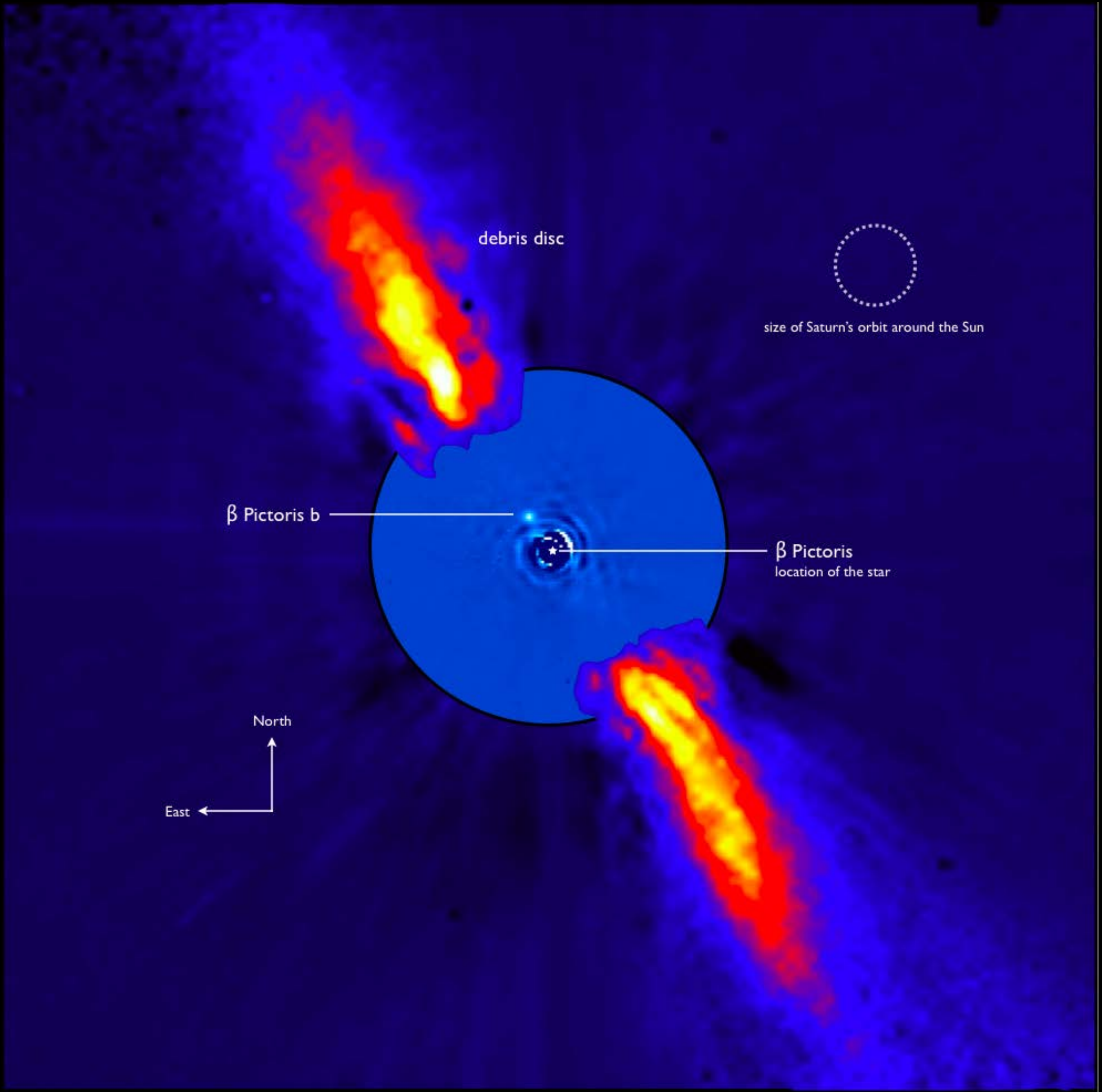

# 3) Planet Characterization

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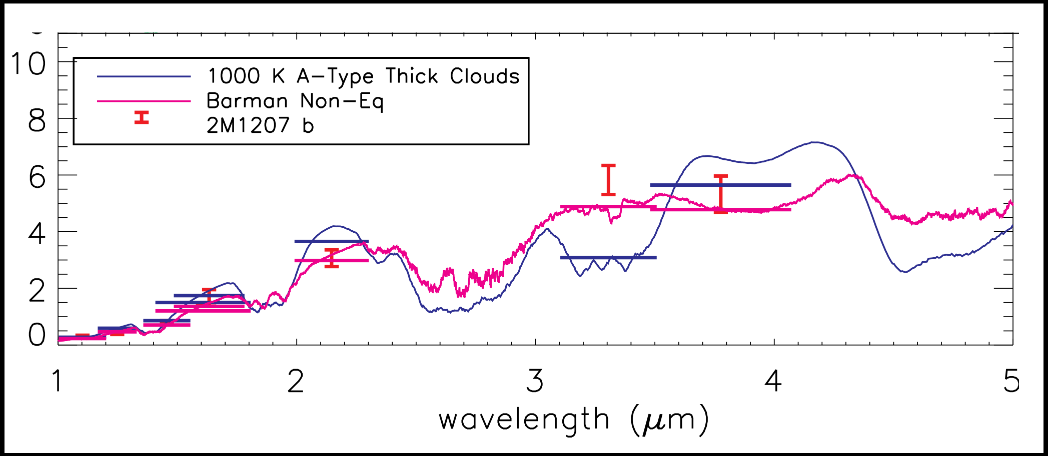
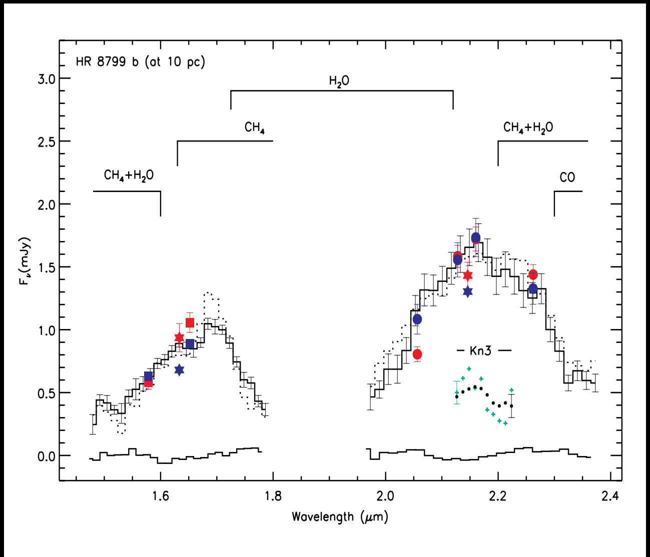
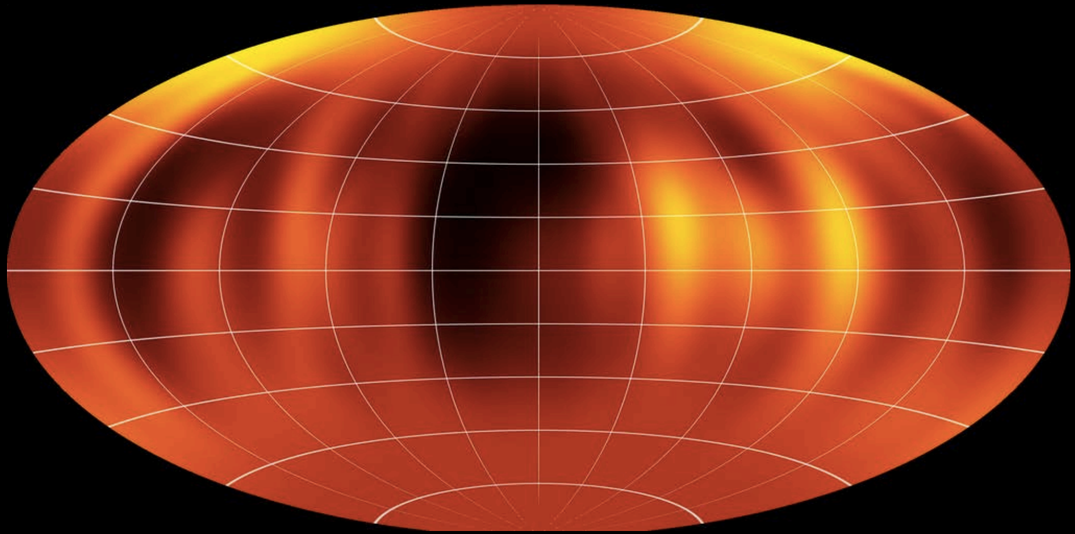


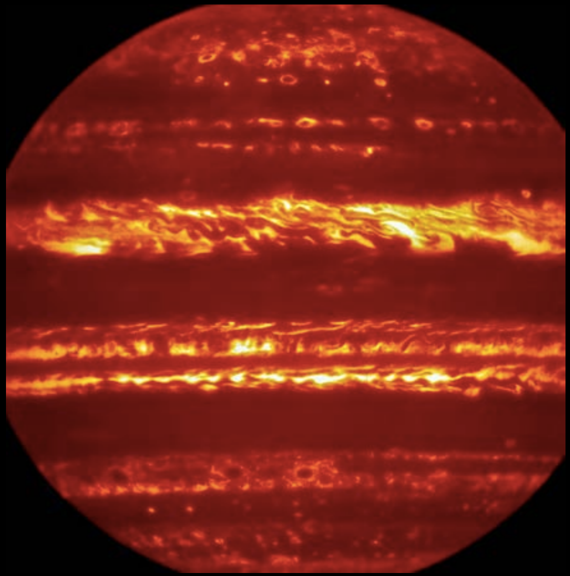



Skemer et al. (2014)
Barman et al. (2011)
Crossfield et al. (2014)

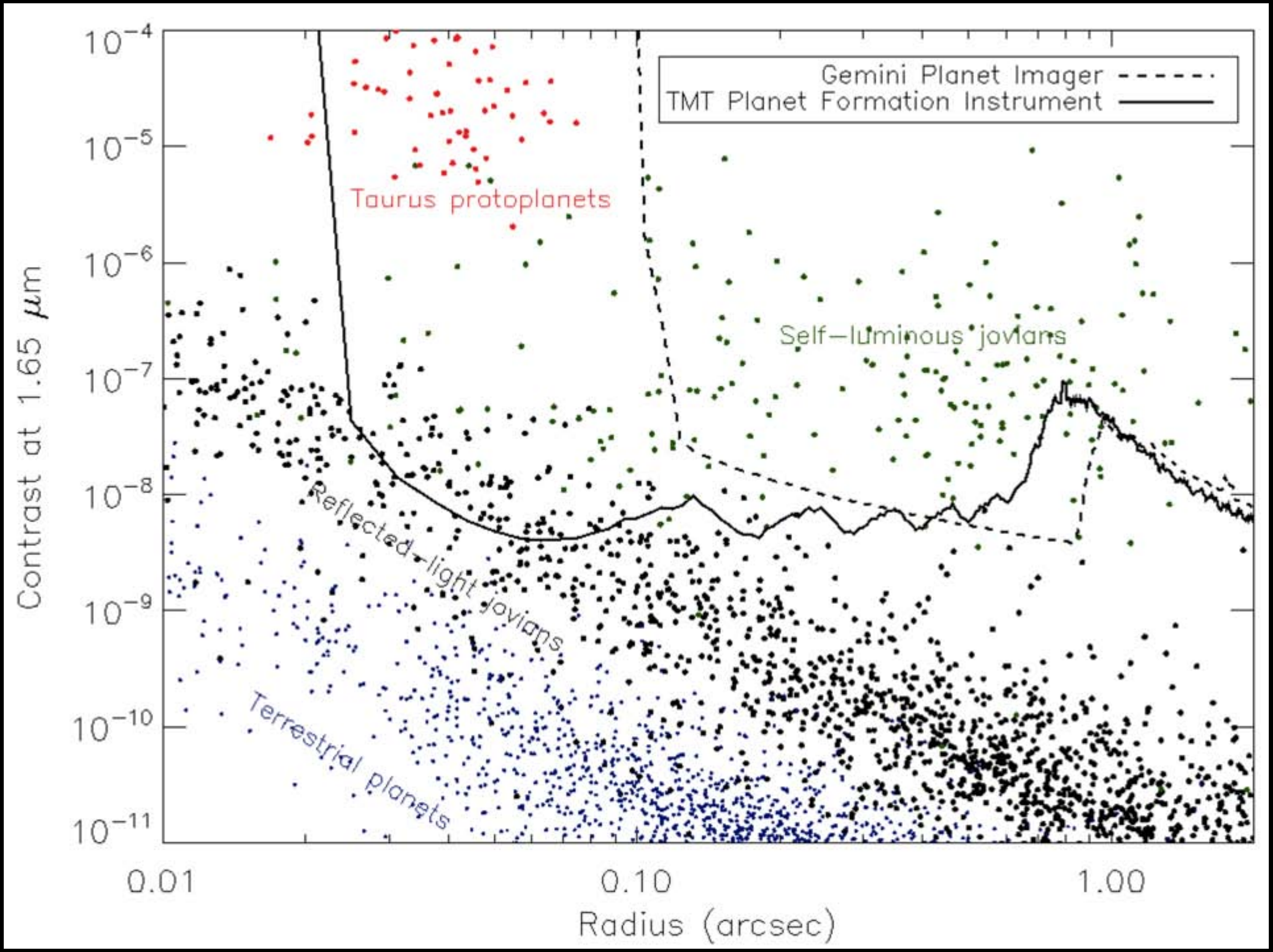
# The Promise of Direct Imaging

## Characterization

- Long-period planets
- Cold and temperate planets
- Self-luminous planets
- Planet surfaces
- Thin atmospheres
- Planets with high clouds/hazes

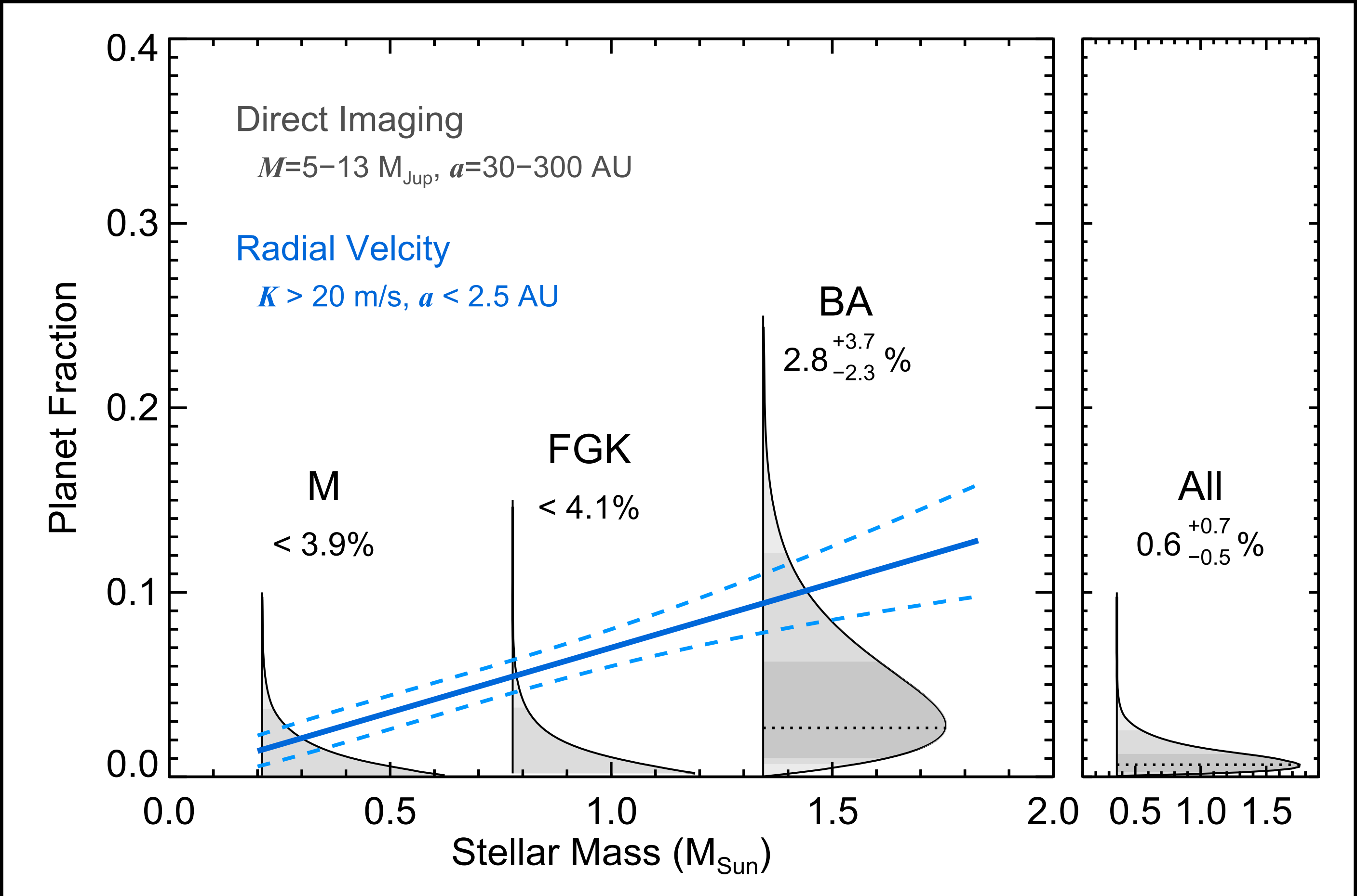


# OK, but why haven't we imaged more planets?



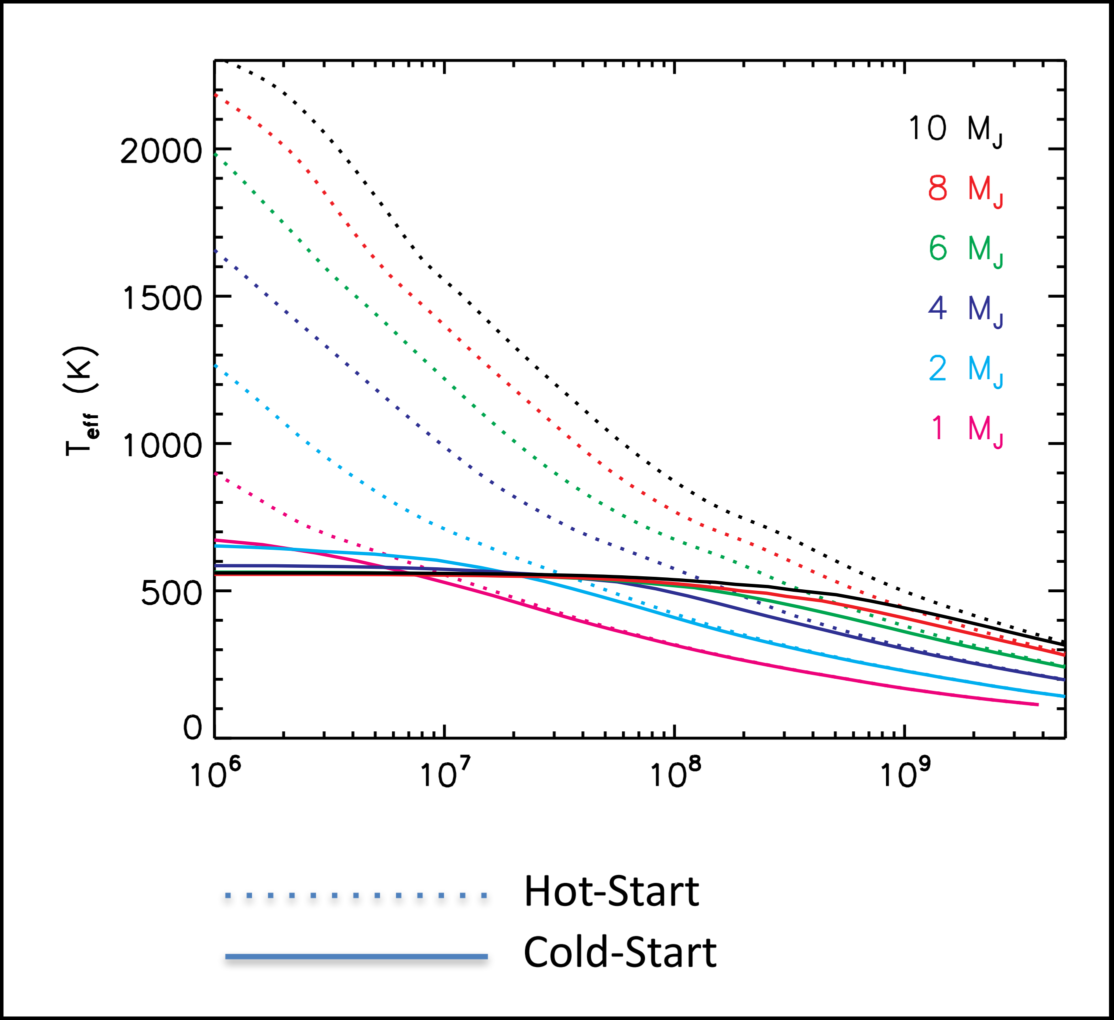

Macintosh PFI Study, 2006

# Massive Planets on Wide Orbits are Rarer than we Thought




Bowler (2016)

# Planets are Colder than we Thought




Marley et al. (2007)
Fortney et al. (2008)

# The TMT Solves Both Problems

## Not enough planets at wide separations…

-Look at smaller separations where they are more common

-Overlap with RV so we know where to look

Need bigger telescope for better resolution

## Planets are colder than we thought…

-Look at longer wavelengths where planets are more luminous

-Look at shorter wavelengths, where lambda/D gives access to reflected light planets

Need bigger telescope for better sensitivity

Need bigger telescope for better resolution

# Direct Imaging has the Most to Gain from the ELTs

| Observing Method | Integration time for a fixed S/N (background-limited) |
|---|---|
| Seeing-Limited | $D^2$ |
| Diffraction-Limited | $D^4$ |
| Direct Imaging at Small Separations | $D^\infty$ |

TMT doesn't just speed up exoplanet observations, it allows us to study whole new classes of exoplanets

# Classes of Exoplanets

**Radius**
- Earth (1 $R_{earth}$)
- Super-Earth (2-3 $R_{earth}$)
- Neptune (3-8 $R_{earth}$)
- Jupiter (>8 $R_{earth}$)

**Temperature**
- Hot (>500 K)
- Temperate (250-500 K)
- Cold (<250 K)

**Age**
- Infant (0-5 Myr)
- Young (5-500 Myr)
- Old (>500 Myr)

**Stellar Type**
- A
- F
- G
- K
- M

**Energy Source**
- Heated by Star
- Self-luminous

**Formation History**
- Binary Fragmentation
- Disk Instability
- Core-Accretion

**System Properties**
- Multiple planets
- Planets and disks
- Resonances
- Tidally locked

**Abundances**
- High [Fe/H]
- Low [Fe/H]
- High [C/O]
- Low [C/O]

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Image accreting proto-Jupiters with 2-5 micron spectroscopy

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Image Earth's around the nearest ~5 stars with 10 micron imaging

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Image tidally-locked Earth-sized planets with visible reflected light imaging

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Image Super-Earth's around K-stars in reflected light and thermal light to study energy balance.

# Ways to Characterize Exoplanets

<u>Wavelength</u>
- Reflected Light
- Thermal Emission

<u>Spectral Resolution</u>
- Low
- Medium
- High

<u>Time Domain</u>
- Photometry
- Doppler Imaging

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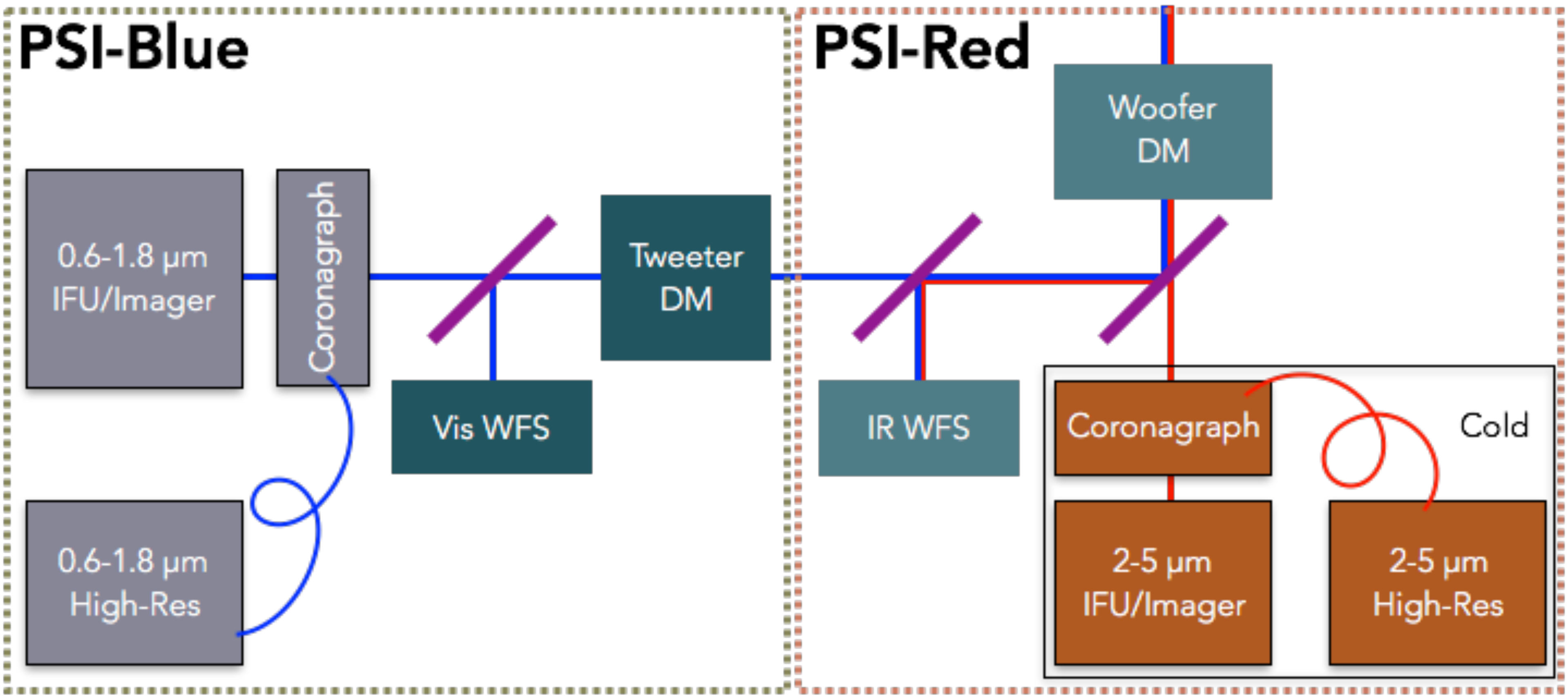
Combinations help:
- Low + high resolution gives bulk properties and molecules
- Reflected + Thermal gives energy balance

# Planetary Systems Imager



# Phase I: 2-5 micron IFS + High Res Spectrograph

- 7x7” Imager
- 1.2x1.2” IFS with R~200
- 0.1x0.1” IFS with R~5000
- Fiber-injection to R~100,000

- Follows established best practices for imaging exoplanets (coronagraphs, lenslet-based IFS, single-mode fiber for speckle-suppression, etc.)

# Conclusions

- There is an extraordinary diversity of exoplanets that can be imaged by TMT.
- The biggest exoplanet science cases for TMT involve characterization.  We need instruments that won't just find exoplanets, but will also characterize them.
- No other instrument can do this first.  Not JWST. Not GPI.