TMT High-Contrast Exoplanet Science

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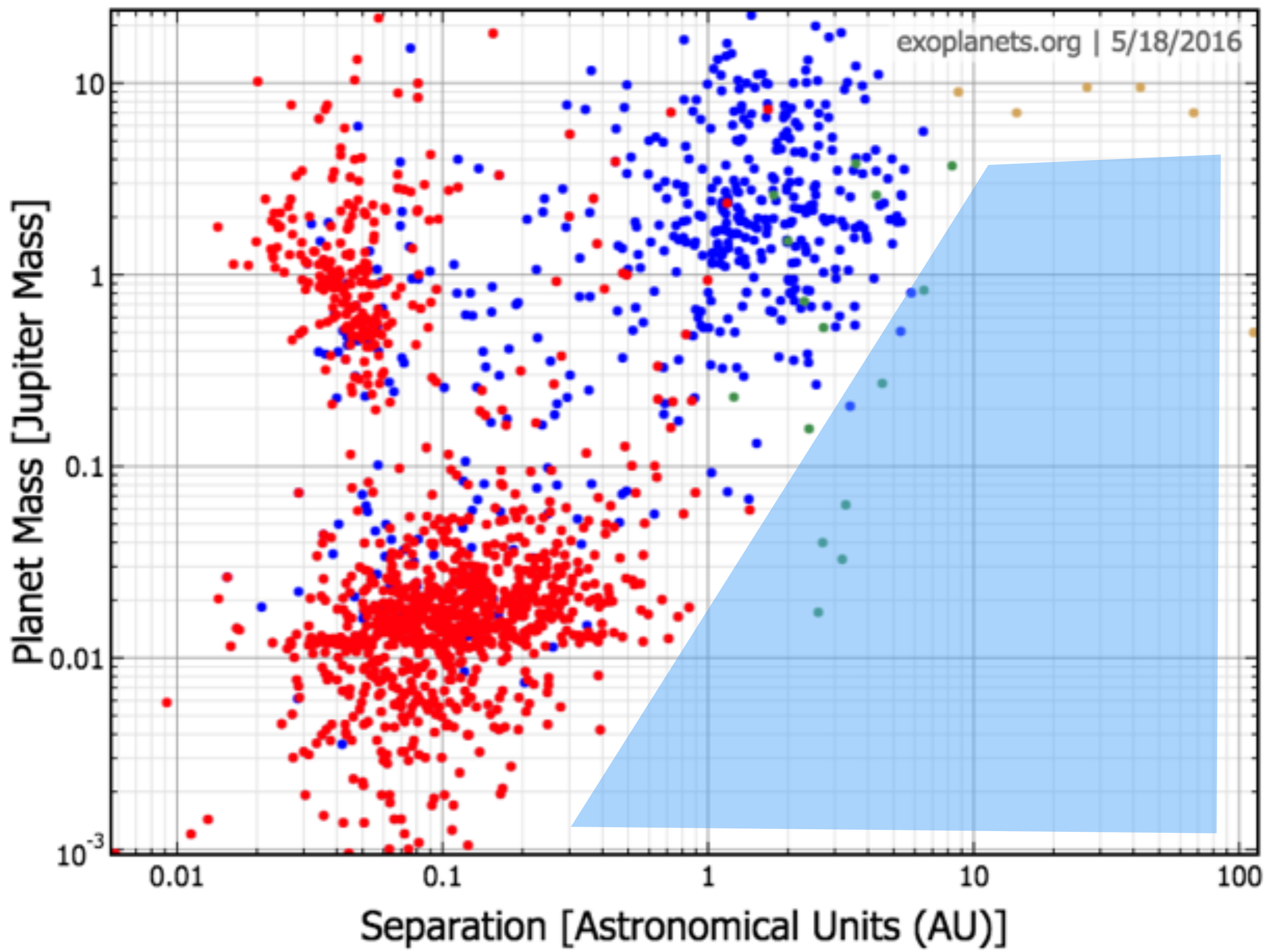
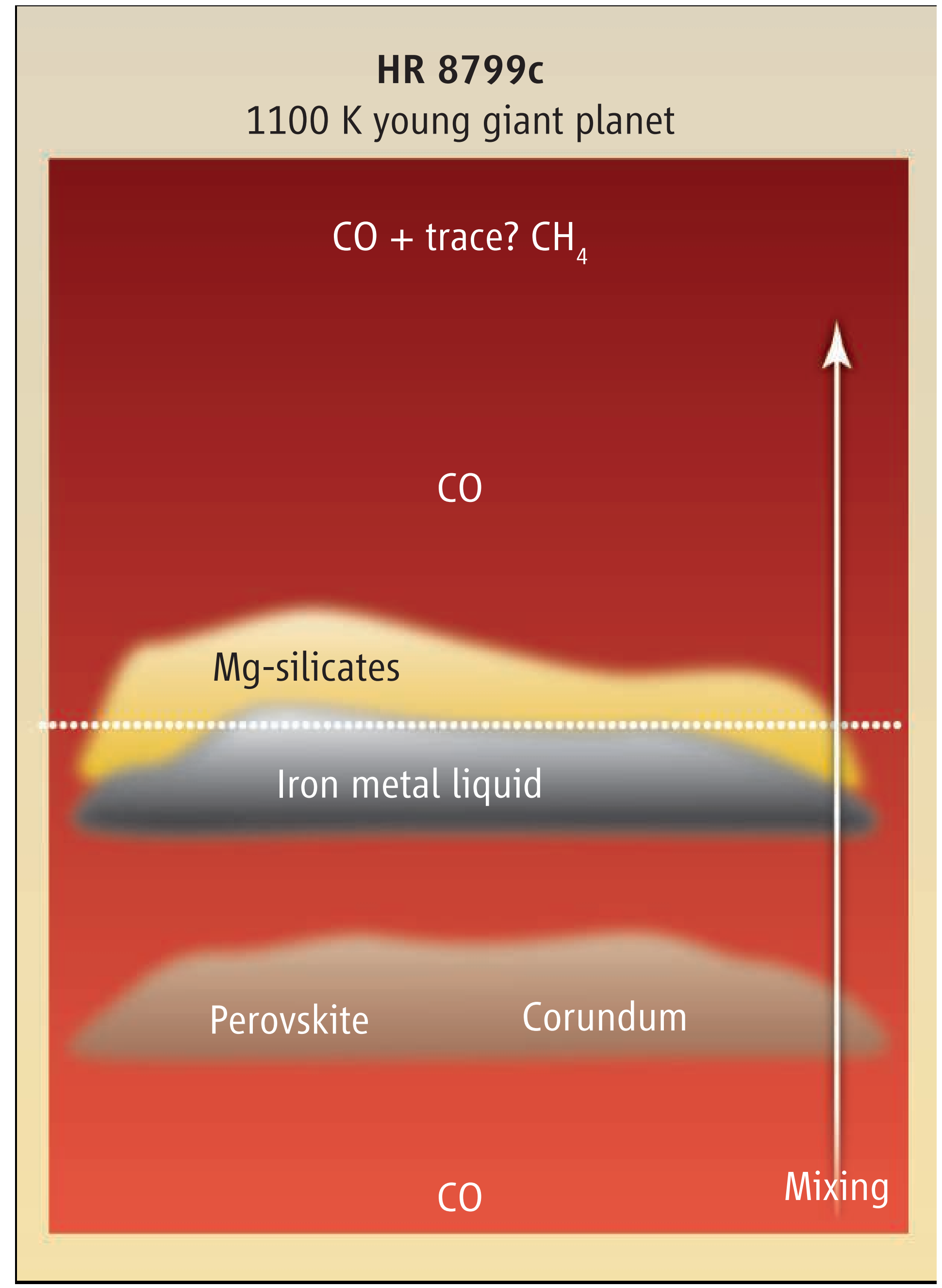
The Next Decade+

- Demographics
    - Kepler has provided rich census of radius/semimajor-axis space down to terrestrial planets
    - But at lower mass and larger separations picture is much less clear
        - Important for formation (condensation profiles)
    - Masses, densities, occurrence rates



The Next Decade+

- Atmospheric Characterization
  - Transmittance, reflectance, and thermal emission
  - Low-res IR absorption spectroscopy gives some window to H2O, CH4, CO, CO2, equilibrium chemistry status (though degeneracies exist)
  - Low-res visible absorption spectroscopy gives Na, K, TiO, clouds/hazes
  - high-resolution spectroscopy allows for more detailed characterization, C/O ratio, rotation, doppler imaging



Marley (2013)

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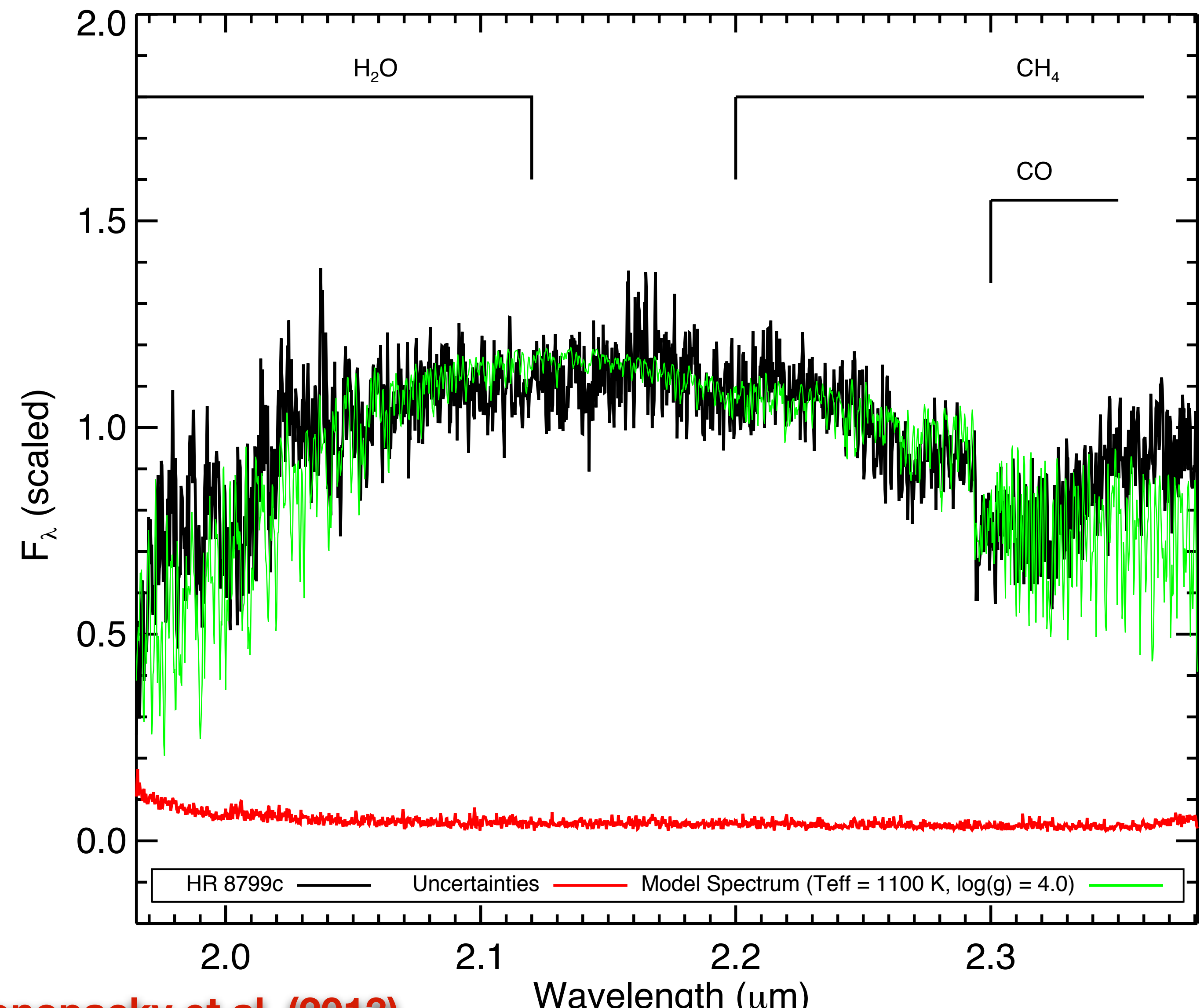

Konopacky et al. (2013)

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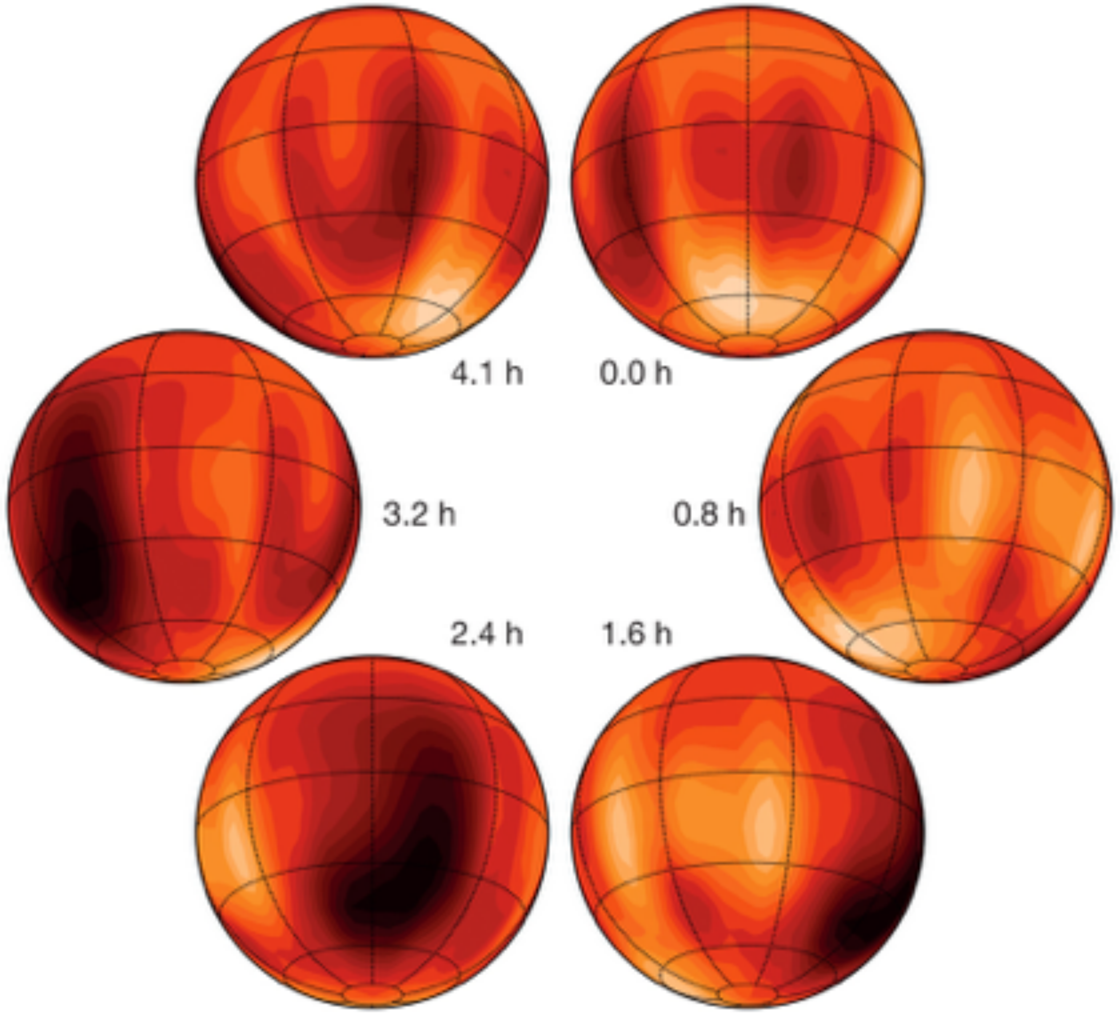

Crossfield+14

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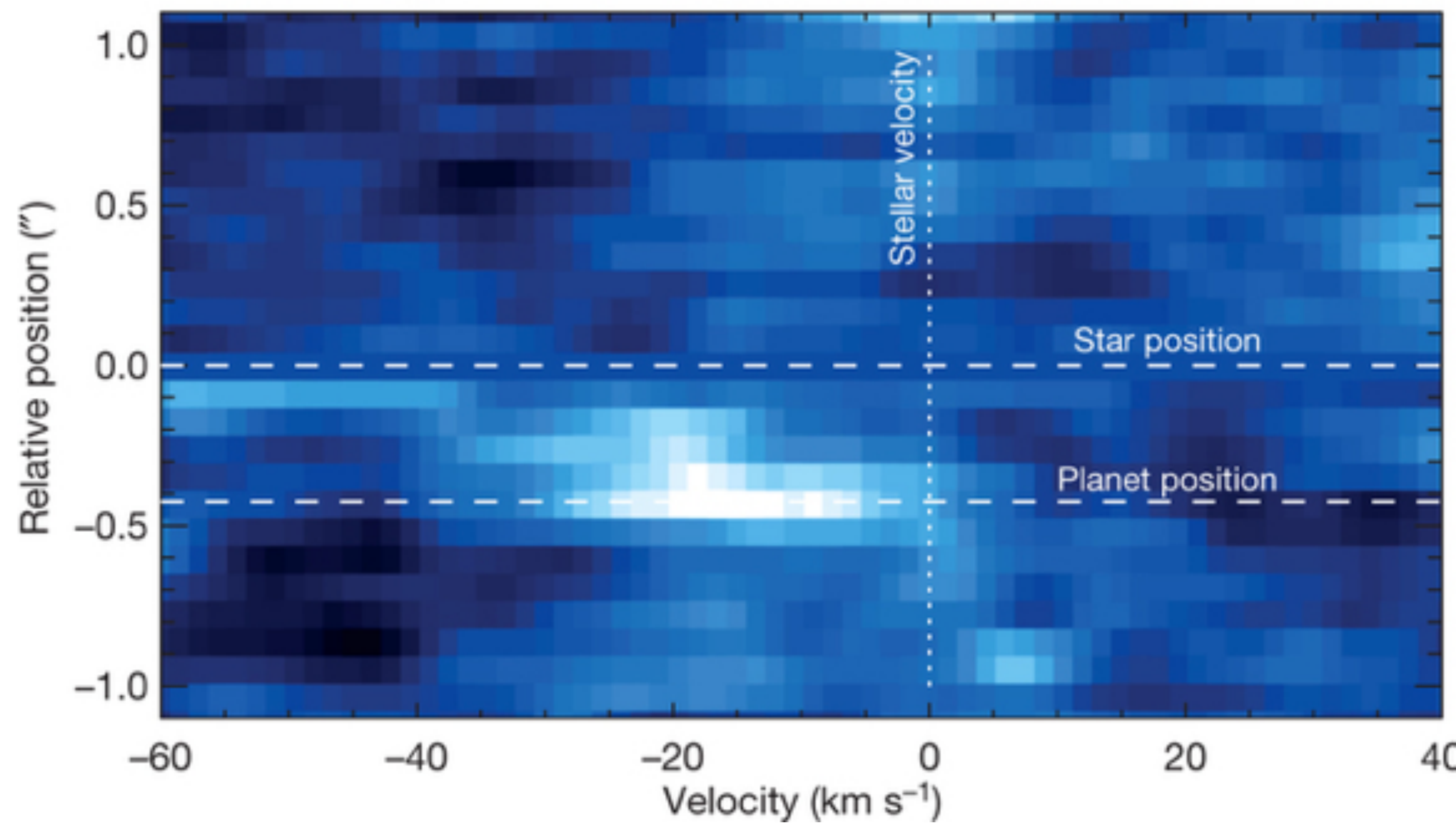
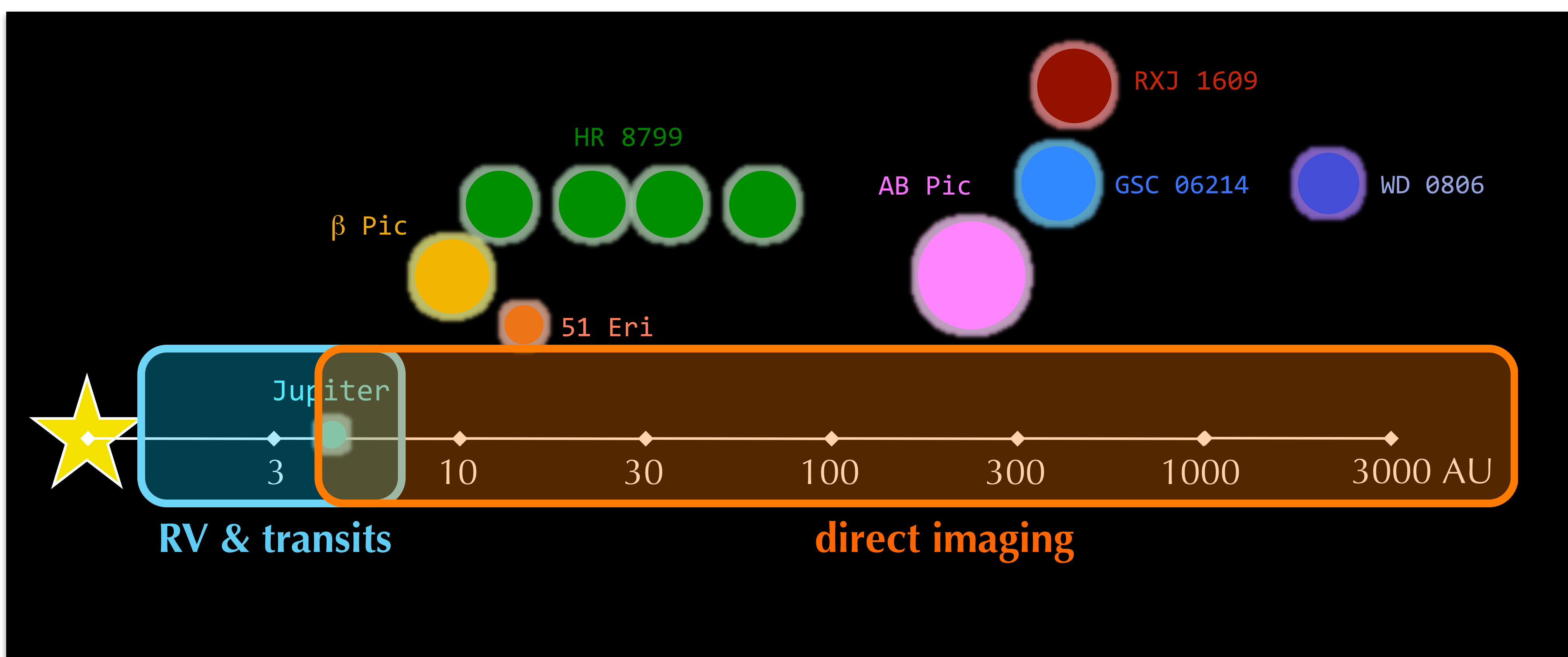


Snellen+14

More Characterization

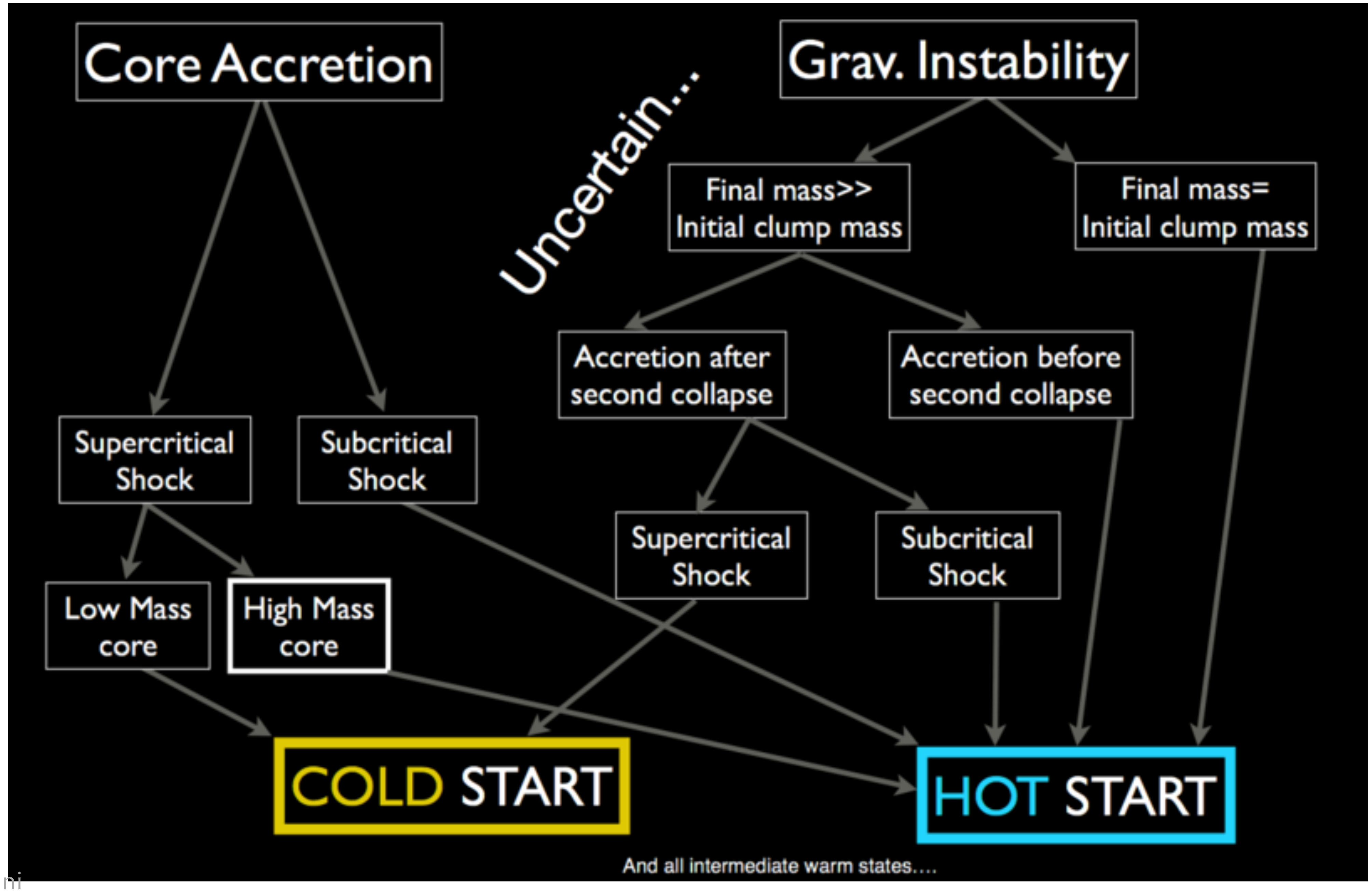
- Direct imaging results
  - Thermal emission spectroscopy of young giants
  - Comparisons with brown dwarfs



M. Liu

The Next Decade+

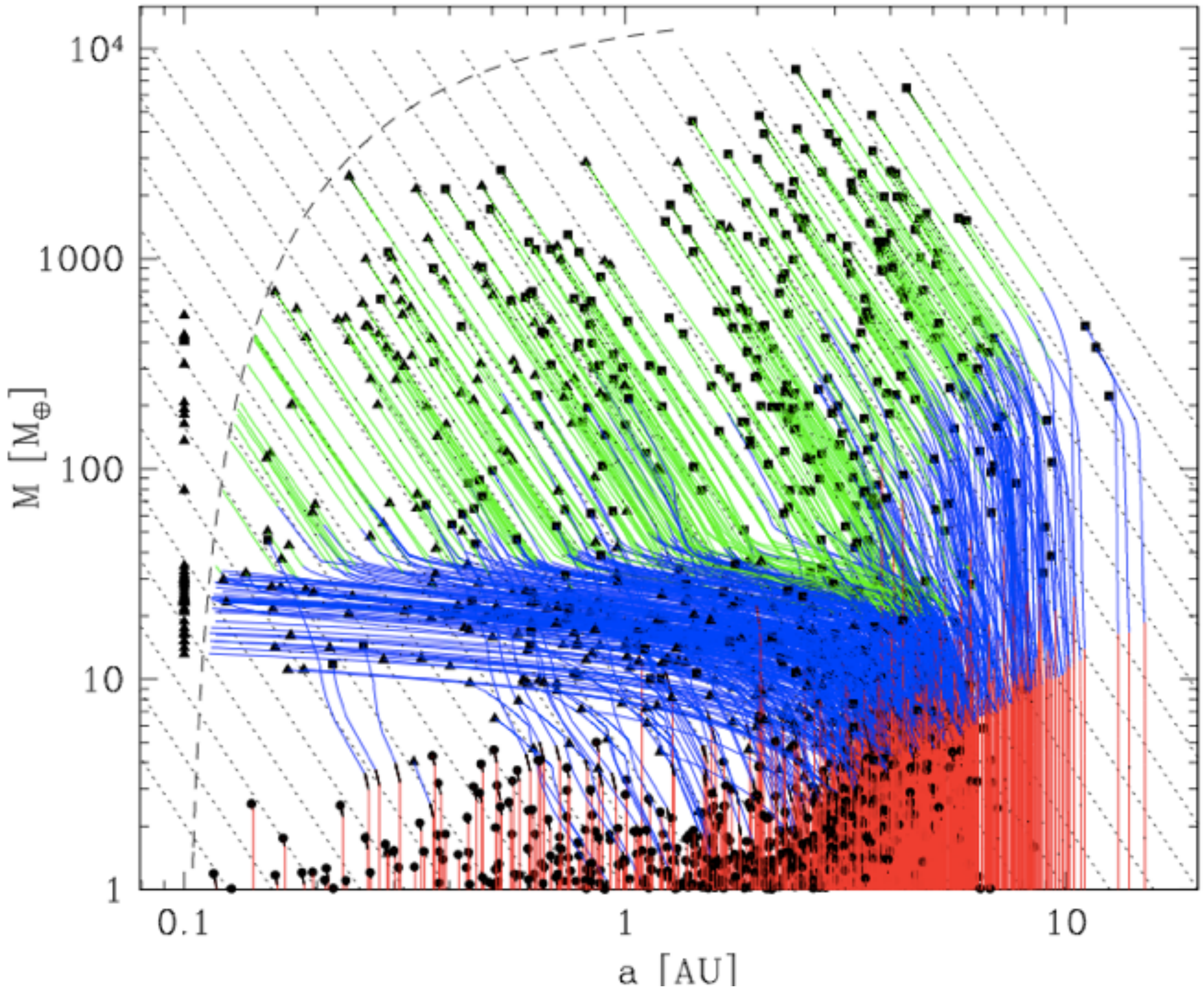
- Formation Pathways



C. Mordasini

The Next Decade+

- Formation Pathways
  - Orbital dynamics
  - Chemistry gradients



Mordasini, Alibert, Benz (2009)

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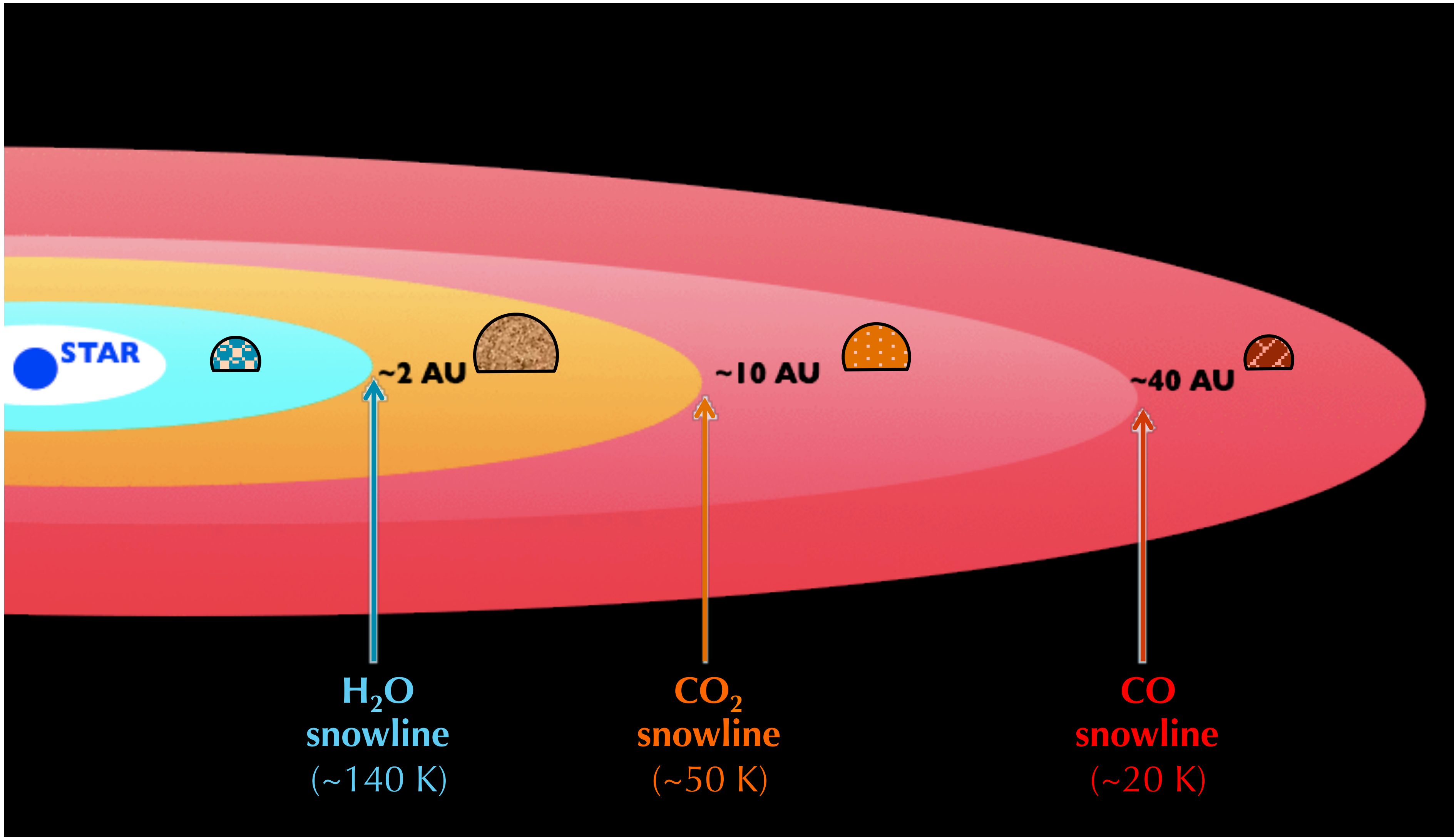
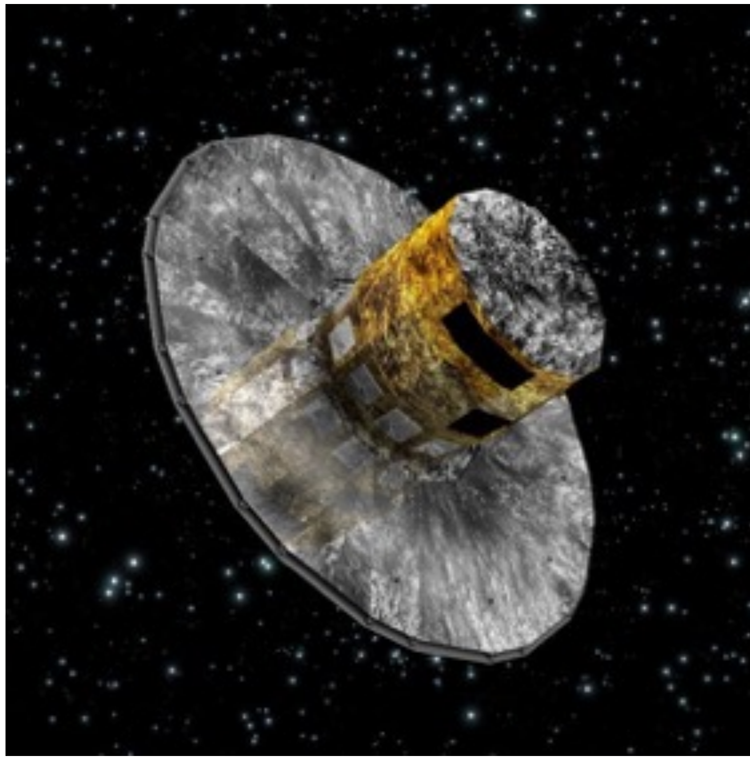
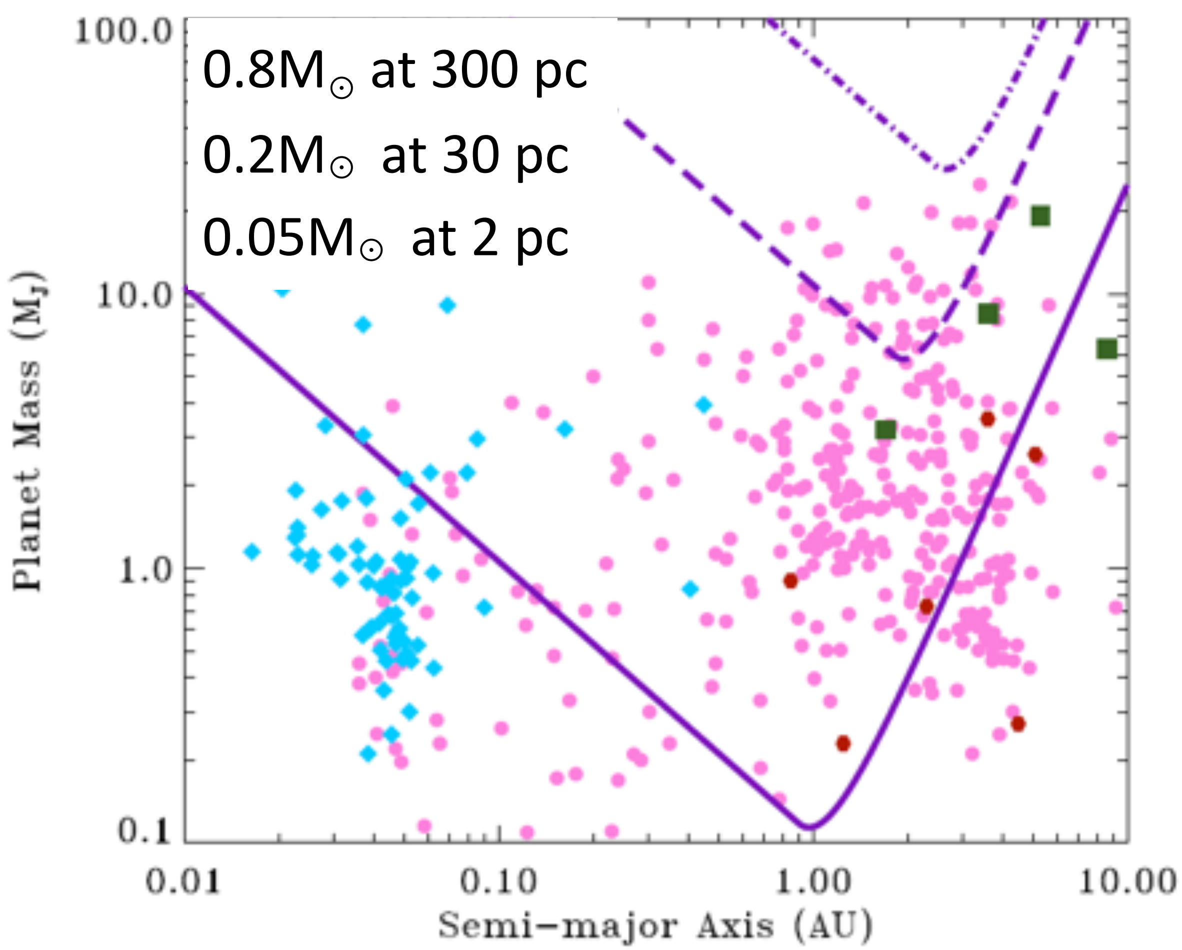


Oberg+11

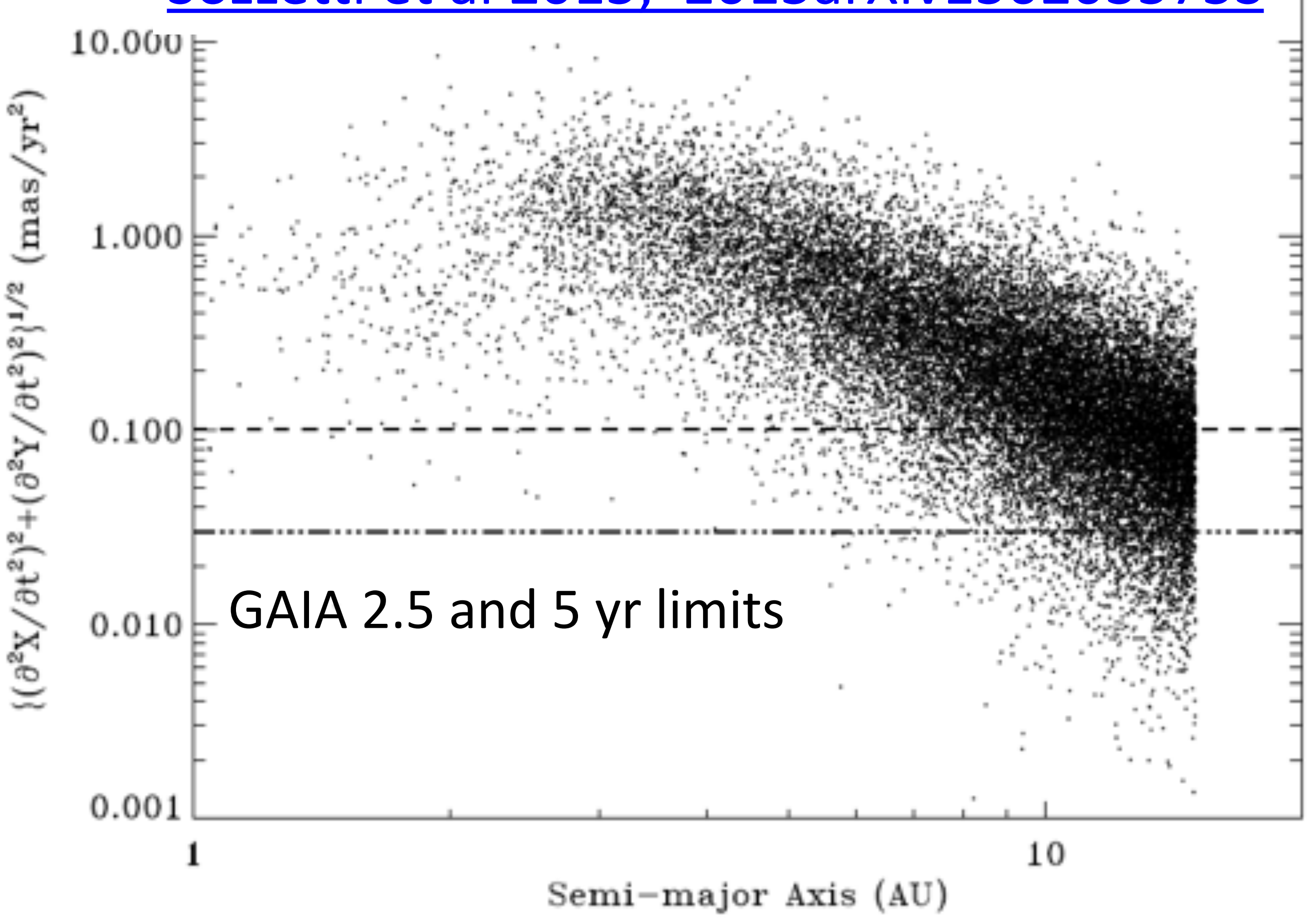
Astrometry with GAIA



- GAIA expects to find >>10,000 Jupiters orbiting FGKM and WDs <100 pc, many with orbits
- ~2,600 detections of Jupiter mass planets incl. ~500 accurate orbits (assuming η_{Jup}~3% from RV)
  - Some detectable with ELTs @ 10^{-8} contrast
- Astrometric trends from 1-70 M_{Jup} companions. BDs detectable with current ExAO

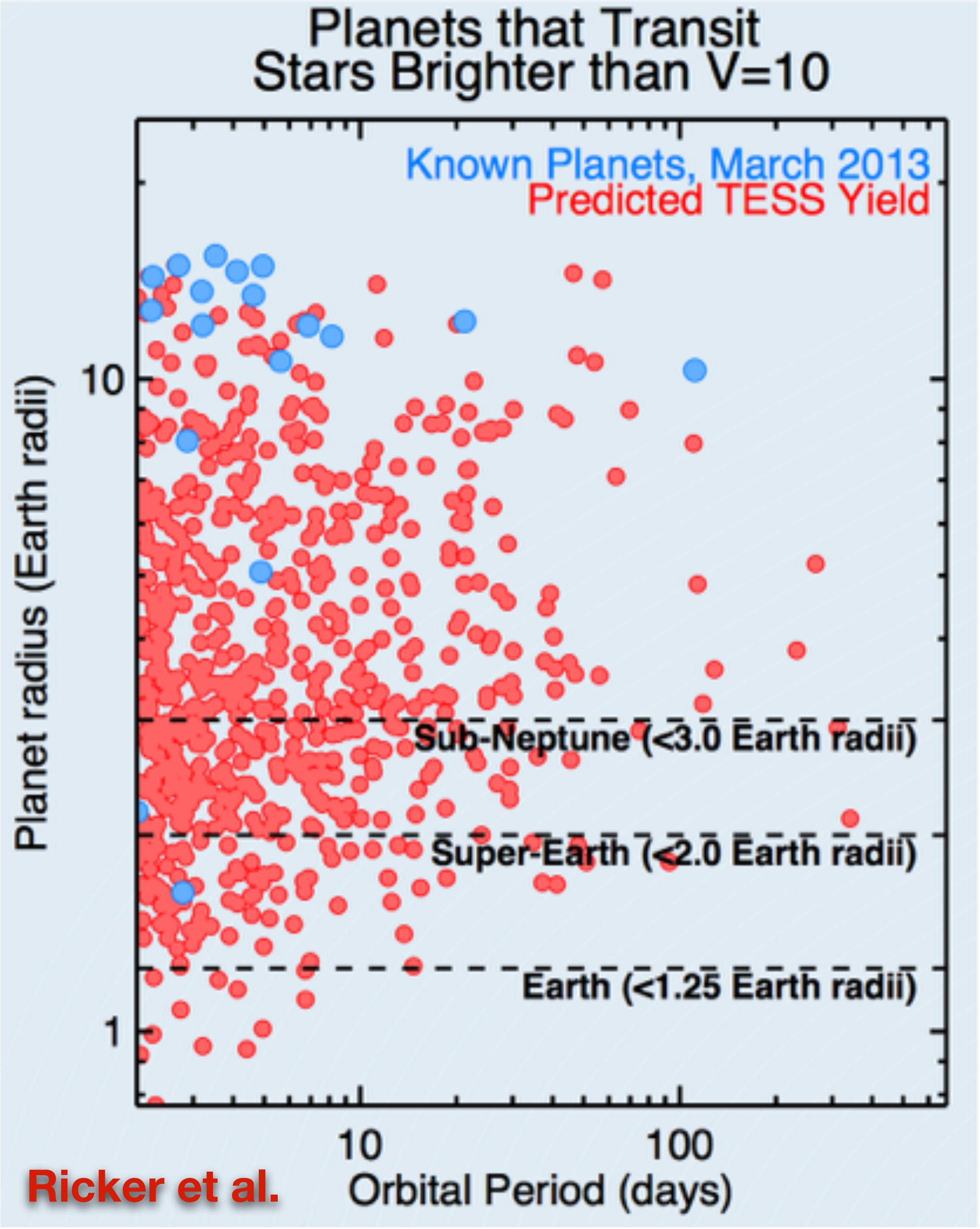


Sozzetti et al 2015, 2015arXiv150203575S



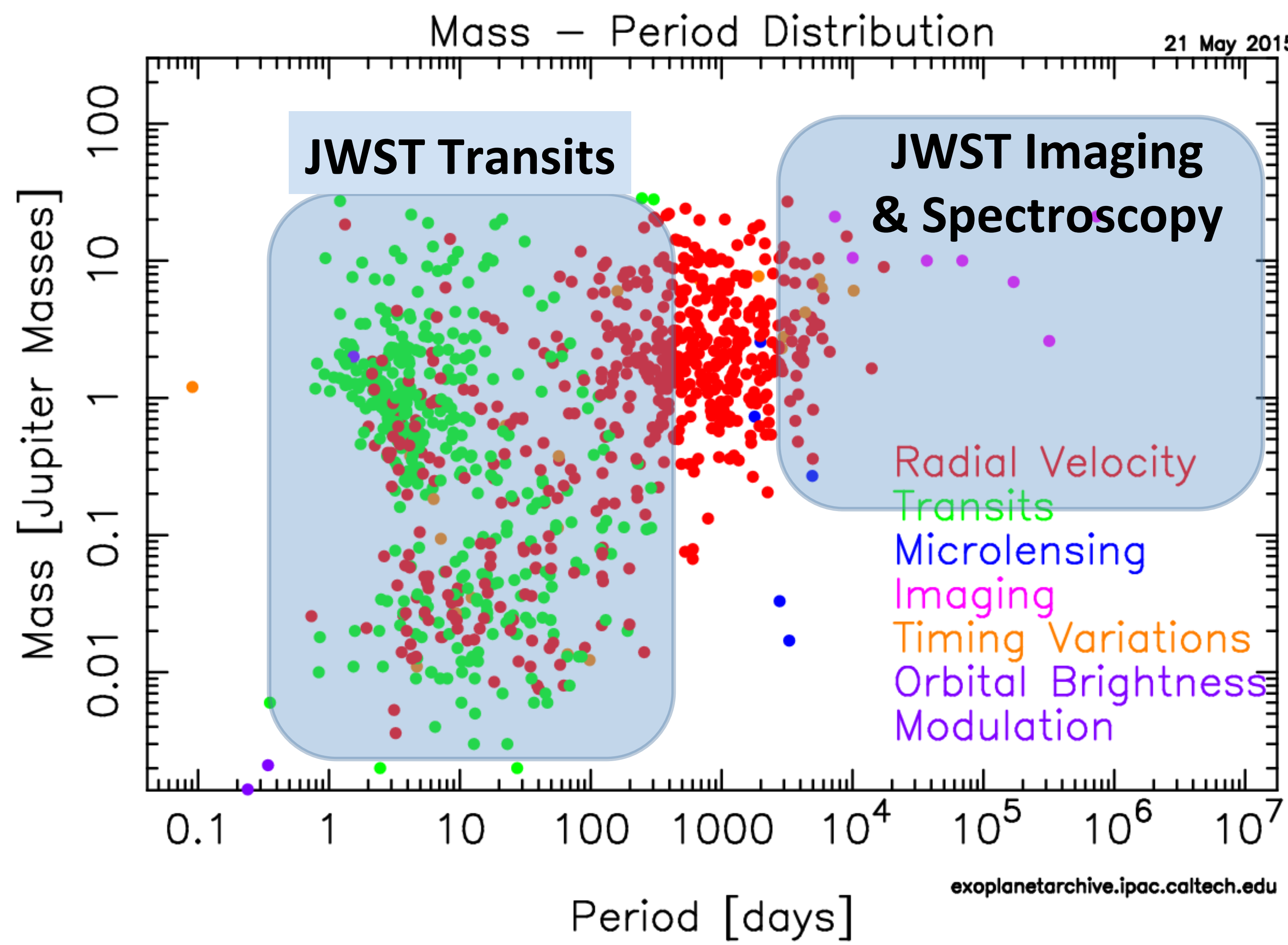
TESS

- >2017
- All-sky transit mission
- More exoplanet demographics
- Will detect a few super-Earths in 100-day orbits around nearby stars



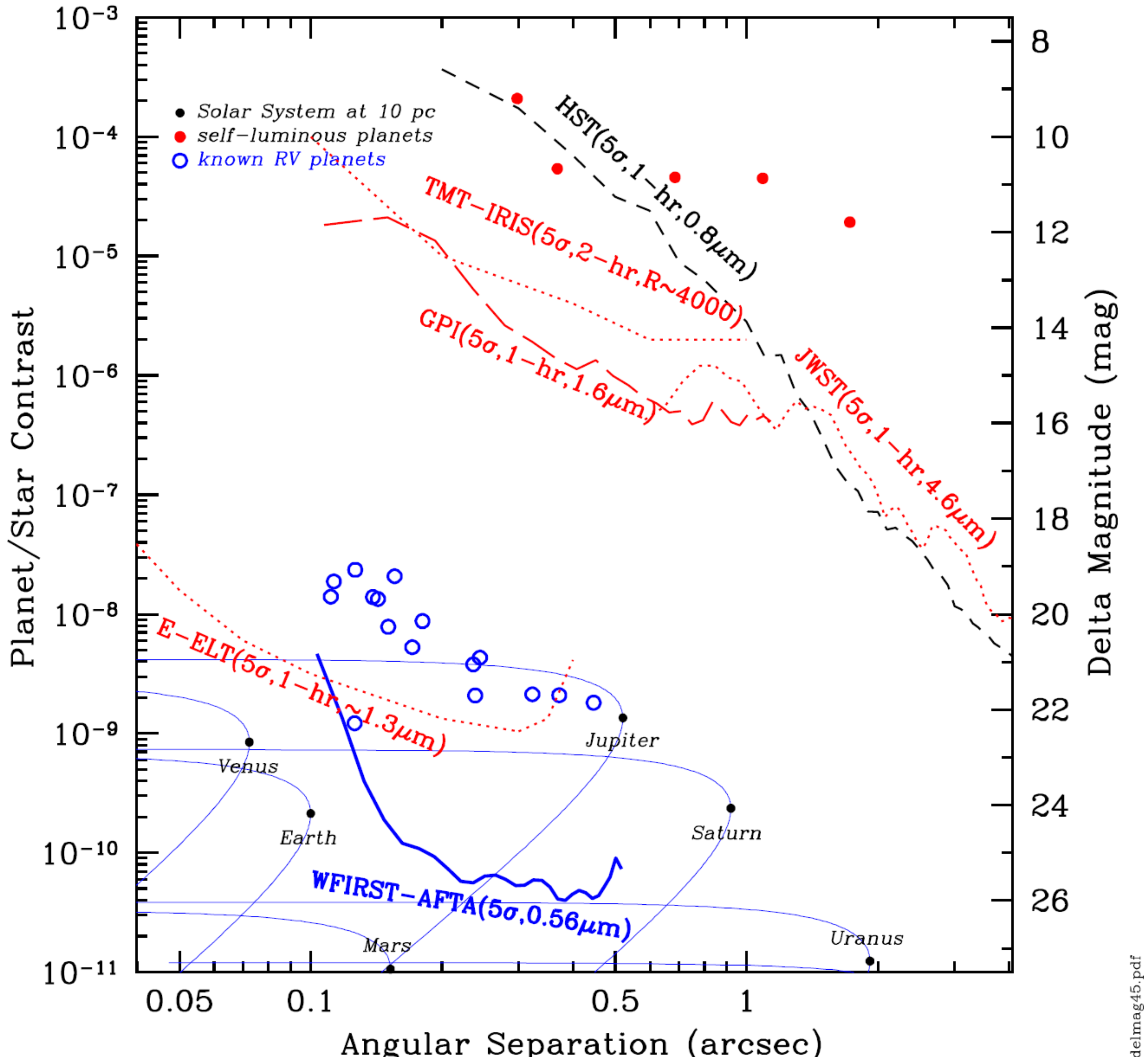
JWST

- transit spectroscopy of short-period planets
- high-contrast imaging of self-luminous planets at larger separations
    - limited low-resolution spectroscopy



WFIRST-AFTA

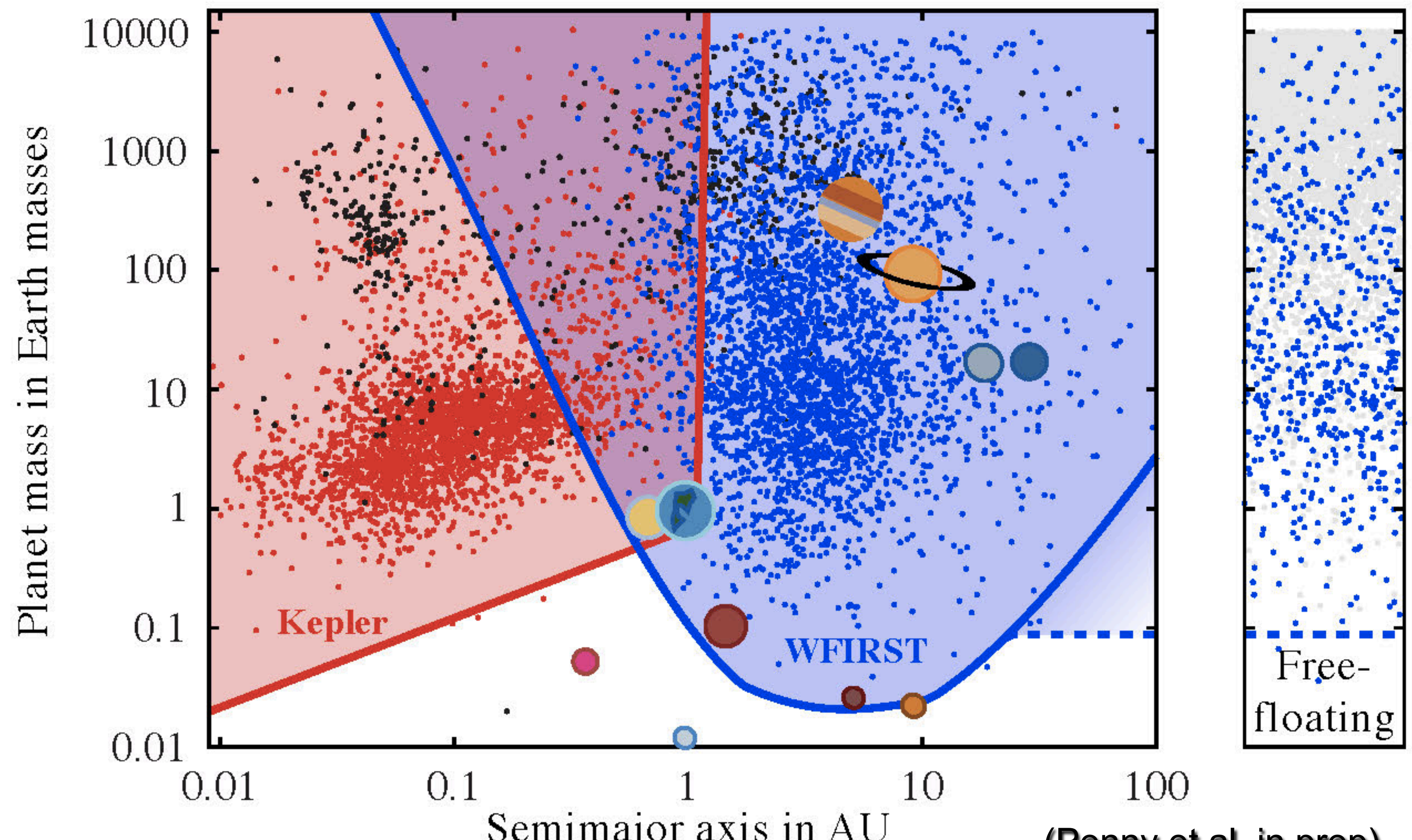
- >2024
- Visible light
- R~70 spectroscopy
- Inner working angle 0.2”
- Discovery and characterization of nearby giant planets, several Neptunes



W. Traub

WFIRST-AFTA

- Microlensing survey
  - Galactic bulge monitoring
- Detection and demographics
  - Characterize mass function for >1 M_E at a>1 AU to better than 10%/dex
  - Expected 2,800 detections
  - With 300 ~1 M_E planets
- But no spectroscopy



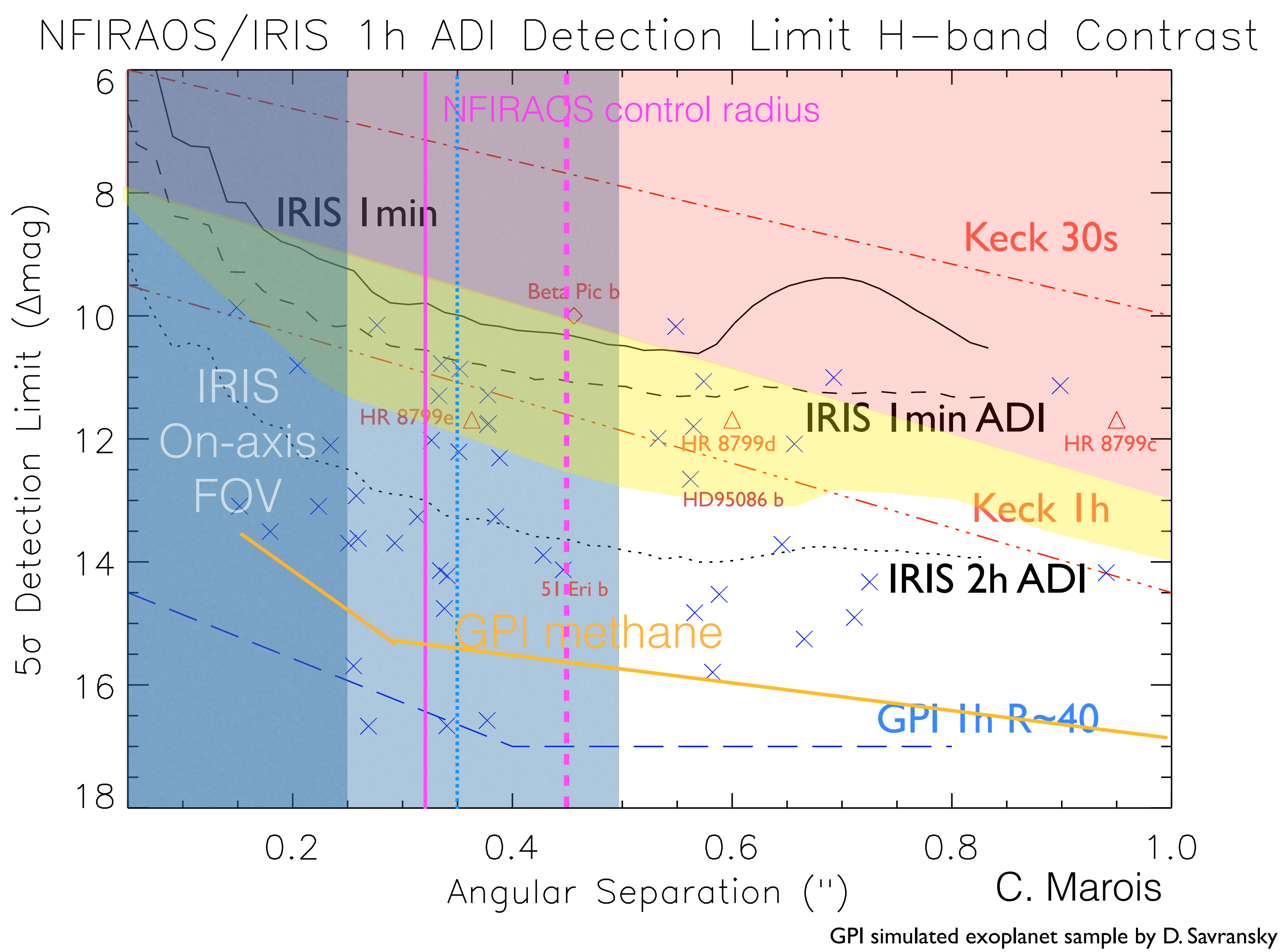
(Penny et al. in prep)

Long-Term Complementarity

- e.g. HabEx, LUVOIR
- Deeper contrast, reflected-light terrestrial exoplanets at *visible* wavelengths
- (Perhaps) longer term than first wave of TMT 2nd-generation instrumentation
- Smaller aperture than TMT (larger inner-working angle)

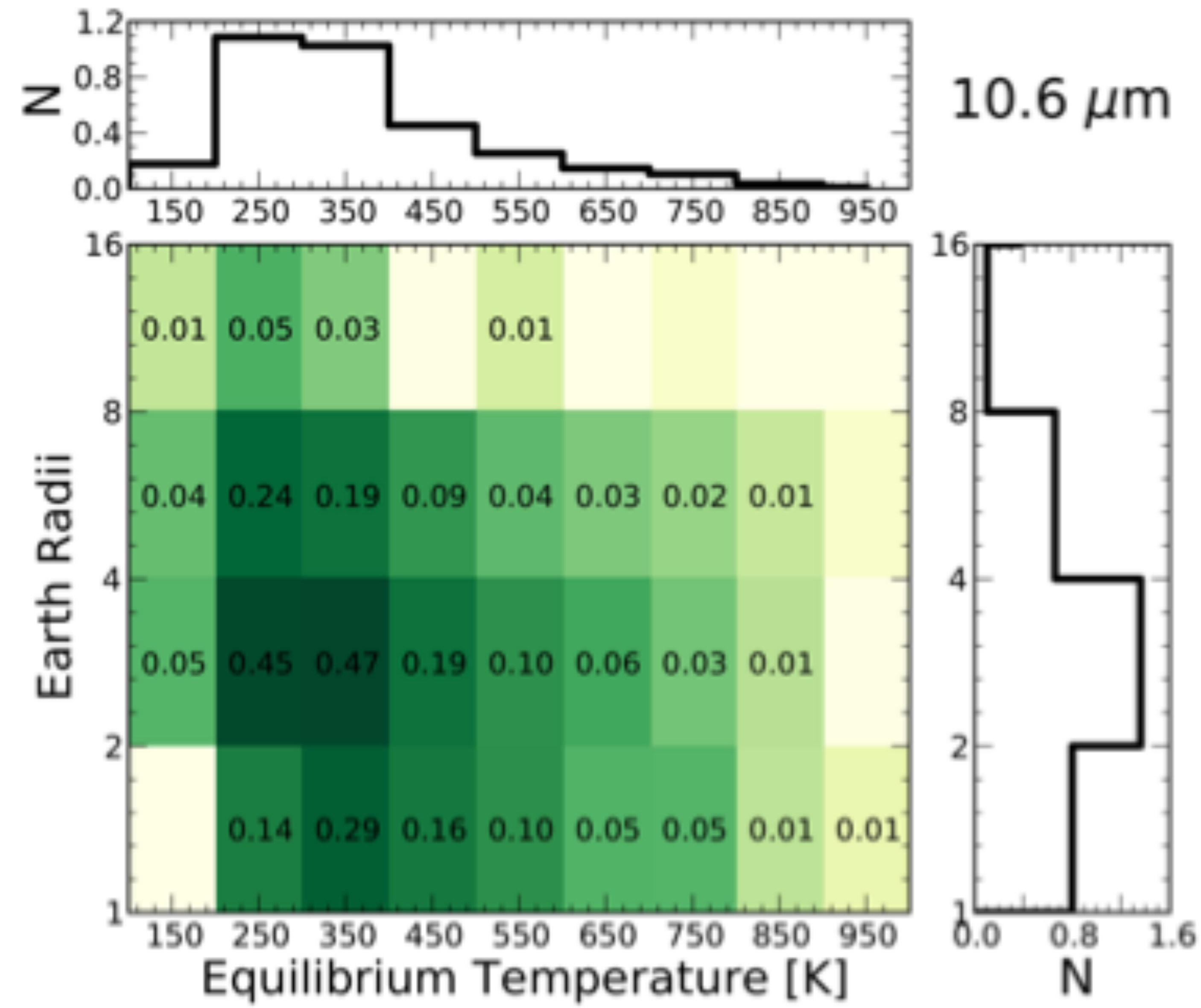
Early ELT Instruments

- For TMT/NFIRAOS/IRIS
  - Moderate contrast, moderate spectral resolution, 0.8-2.5 μm
  - 3×10^{-6} contrast at 400 mas, R=4,000-8,000 (no coronagraph)
  - Comparable to GPI, but higher spectral resolution



Early ELT Instruments

- For E-ELT/METIS
  - Also a first-light instrument
  - 3-19 μm coronagraphy
  - 3-5 μm IFS
  - characterizing luminosity, equilibrium temperature
  - complementary to scattered-light imaging

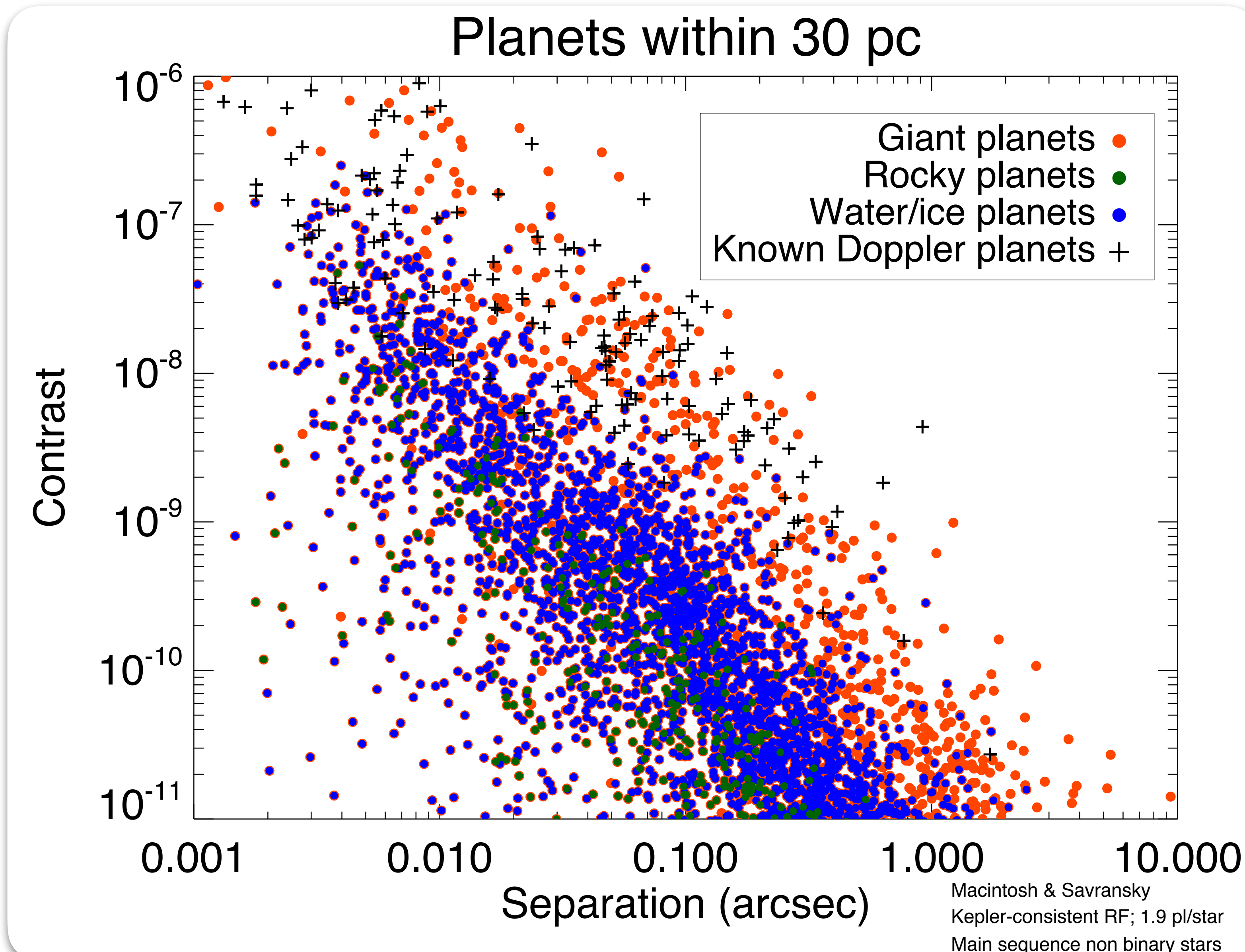


Quanz+14

Where can TMT make an impact?

Reflected Light

- Detection and Characterization
  - Enabled by angular resolution and inner-working angle
  - Opportunity for first reflectance spectroscopy of Super-Earths in NIR
  - Opportunity for first reflectance spectroscopy of cooler Earth-size planets



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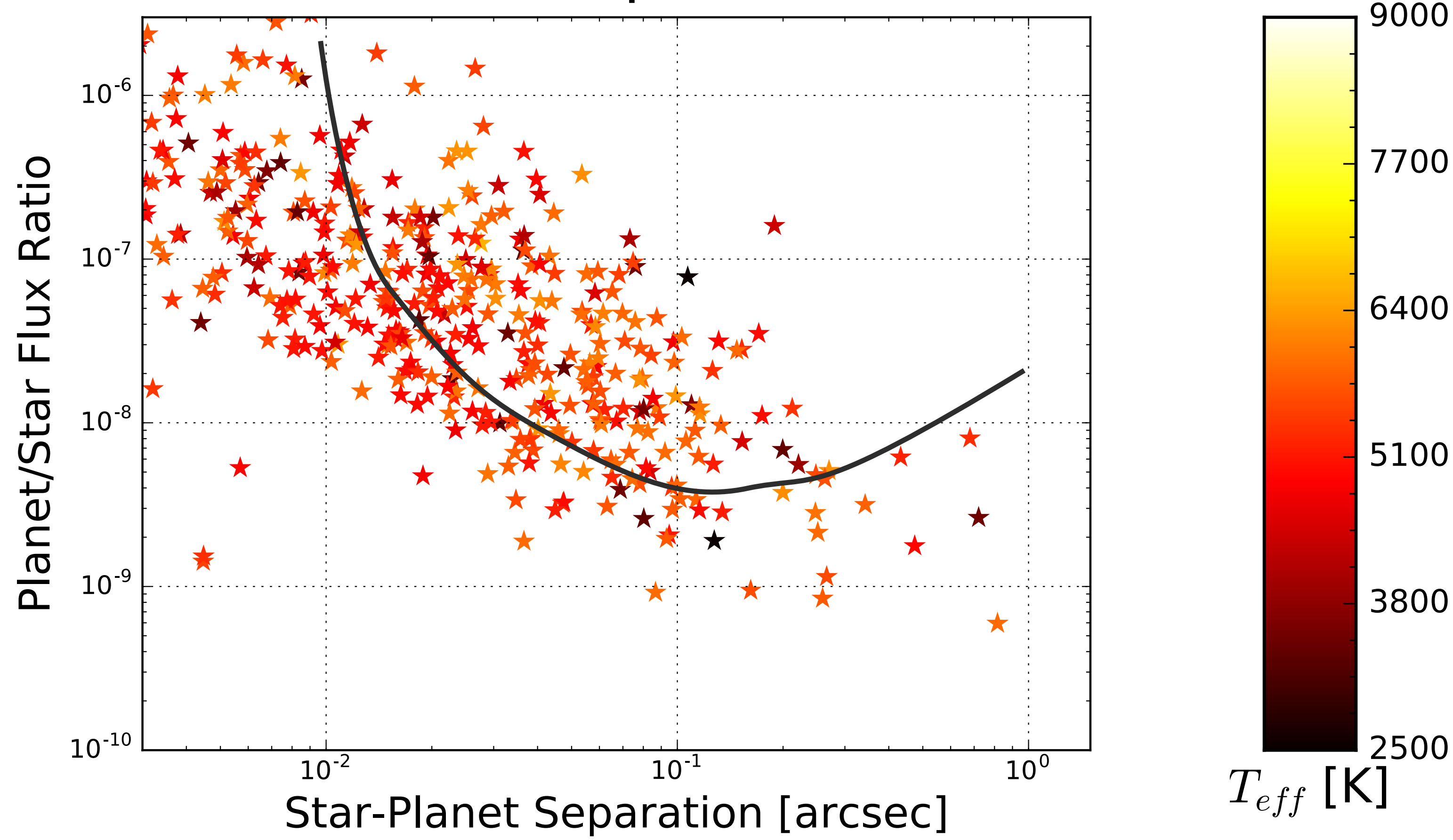
Known RV planets



Crossfield (2016)

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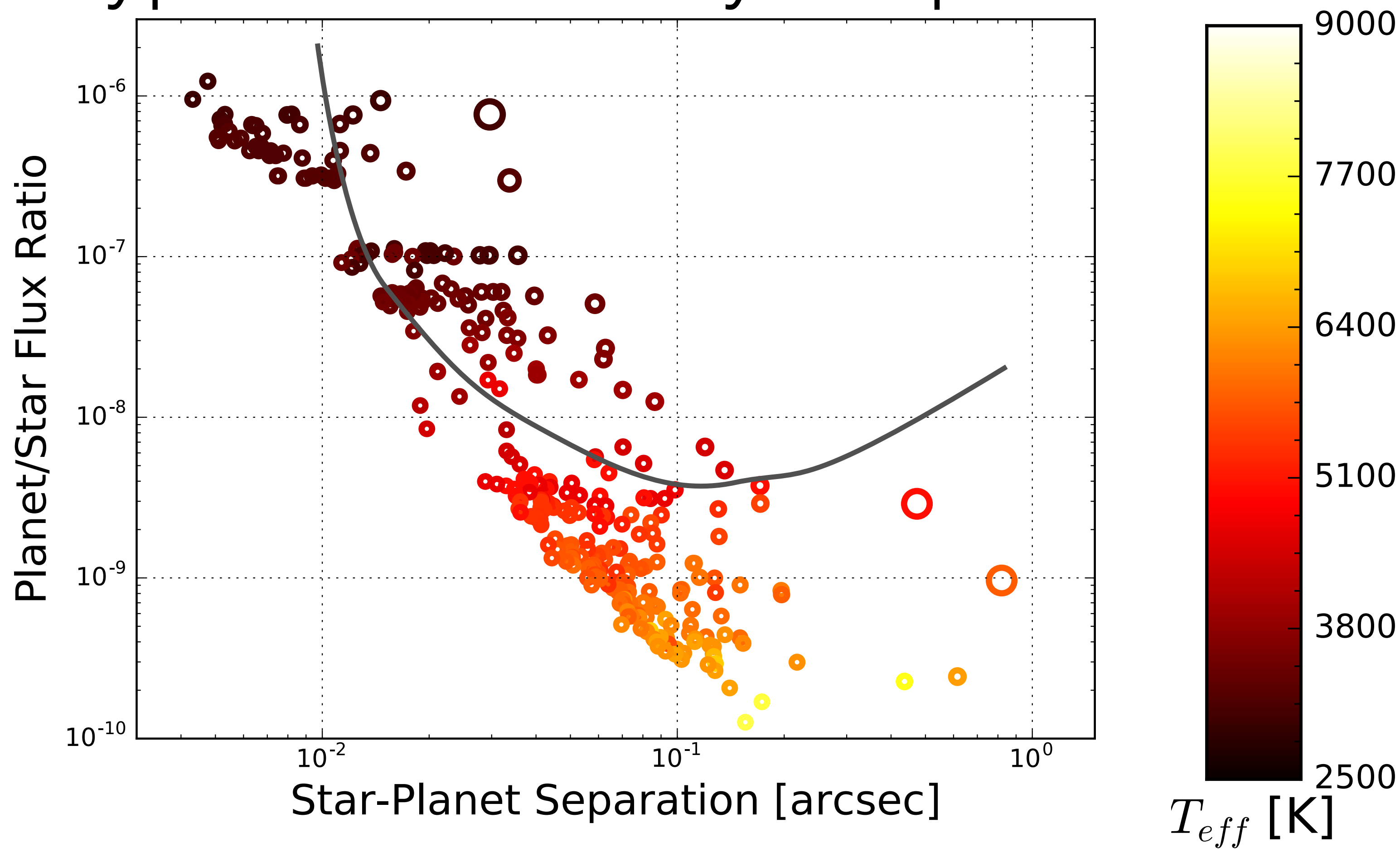
Hypothetical rocky HZ planets



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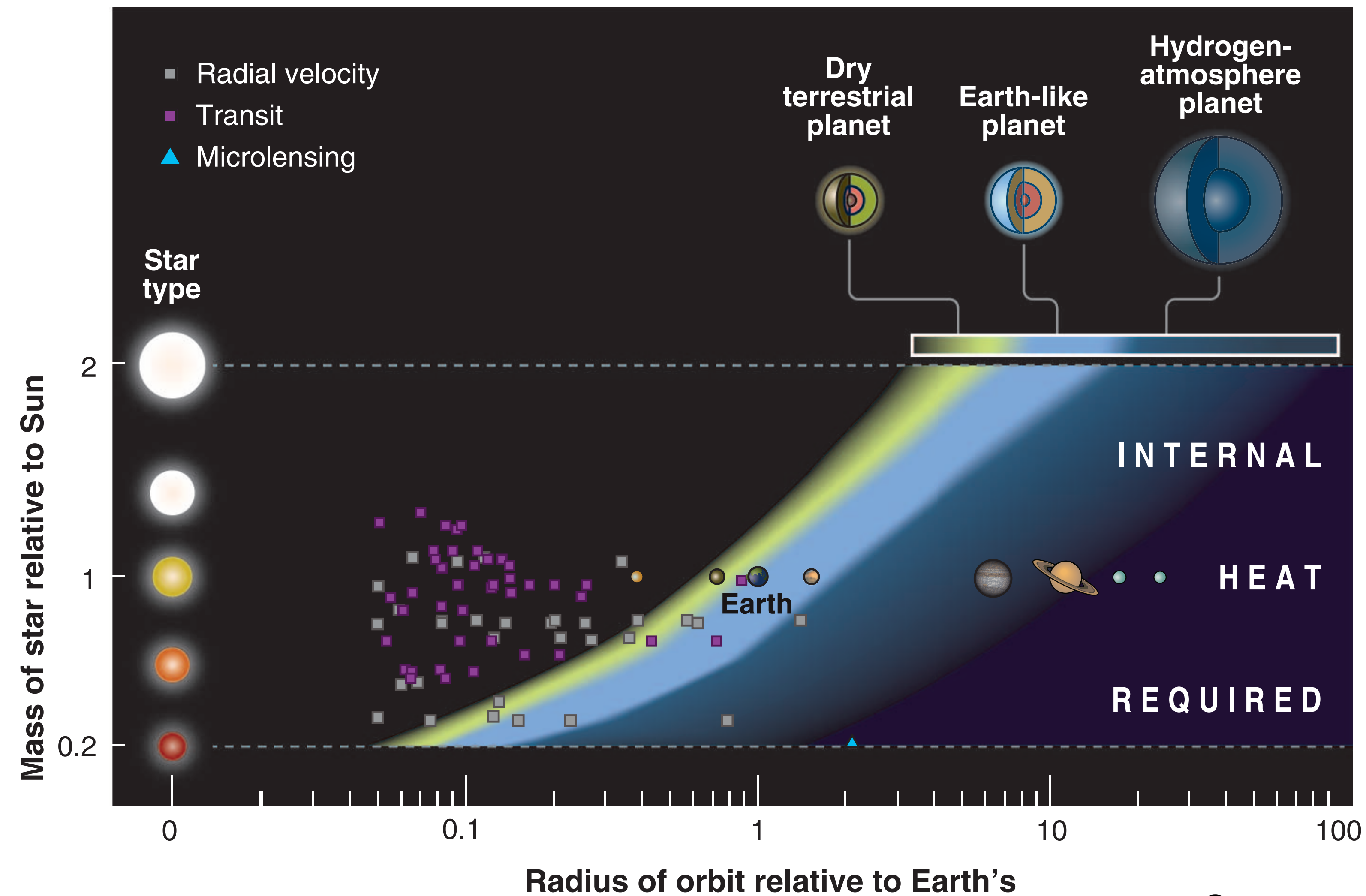
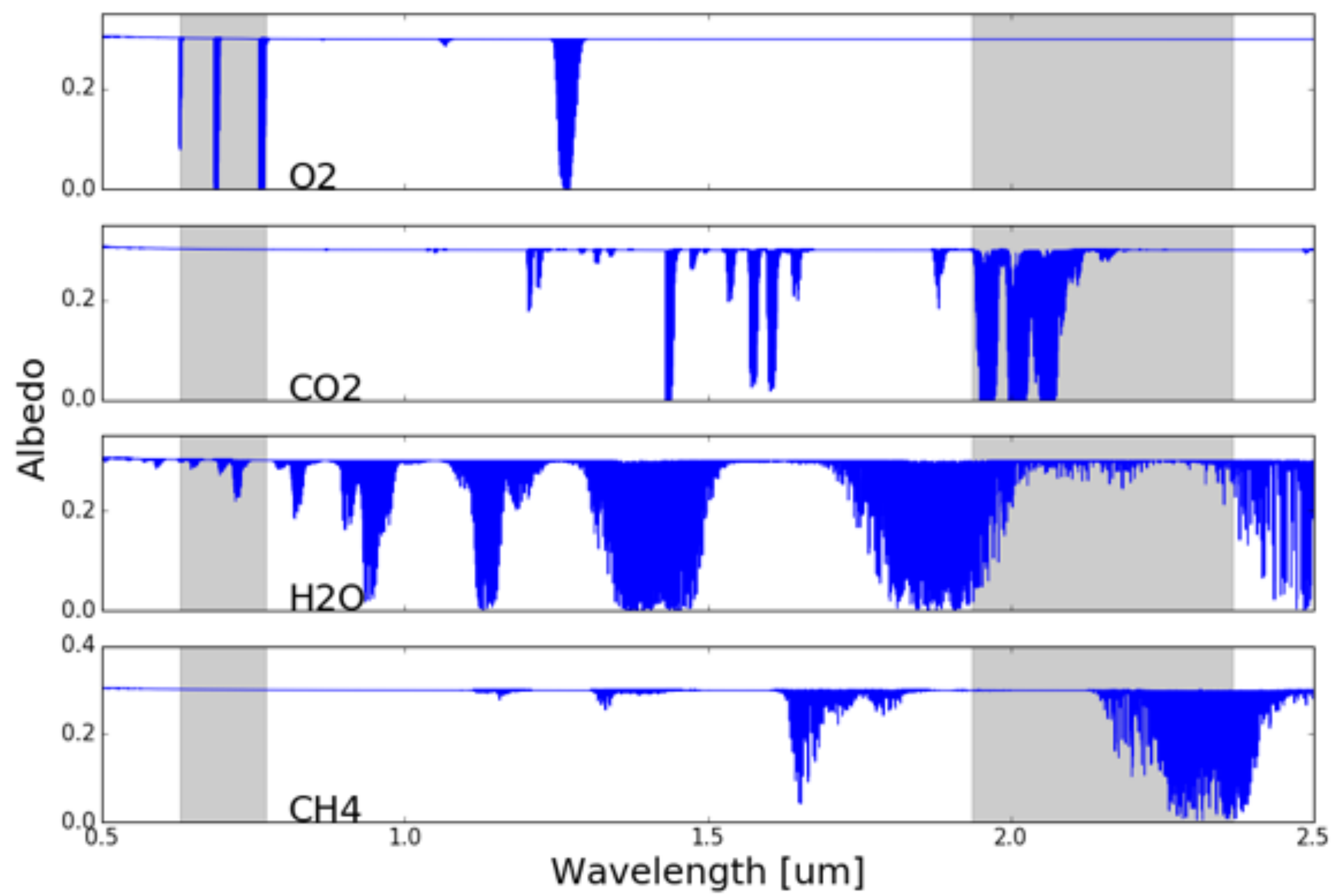


Seager

High Spectral Resolution

- Detection and detailed characterization
  - With improved R and raw contrast
    - more ability to detect molecular species via cross-correlation
    - *down to Earth-size planets*
  - O2 and H2O can only be detected with R > 10,000 with the cross-correlation method at very high levels of raw contrast
  - can detect of CO2 and CH4 at more modest raw contrast of 10^{-5}
  - characterize variability (rotation, cloud patchiness, moons)



courtesy of Ji Wang, Renyu Hu, Dimitri Mawet

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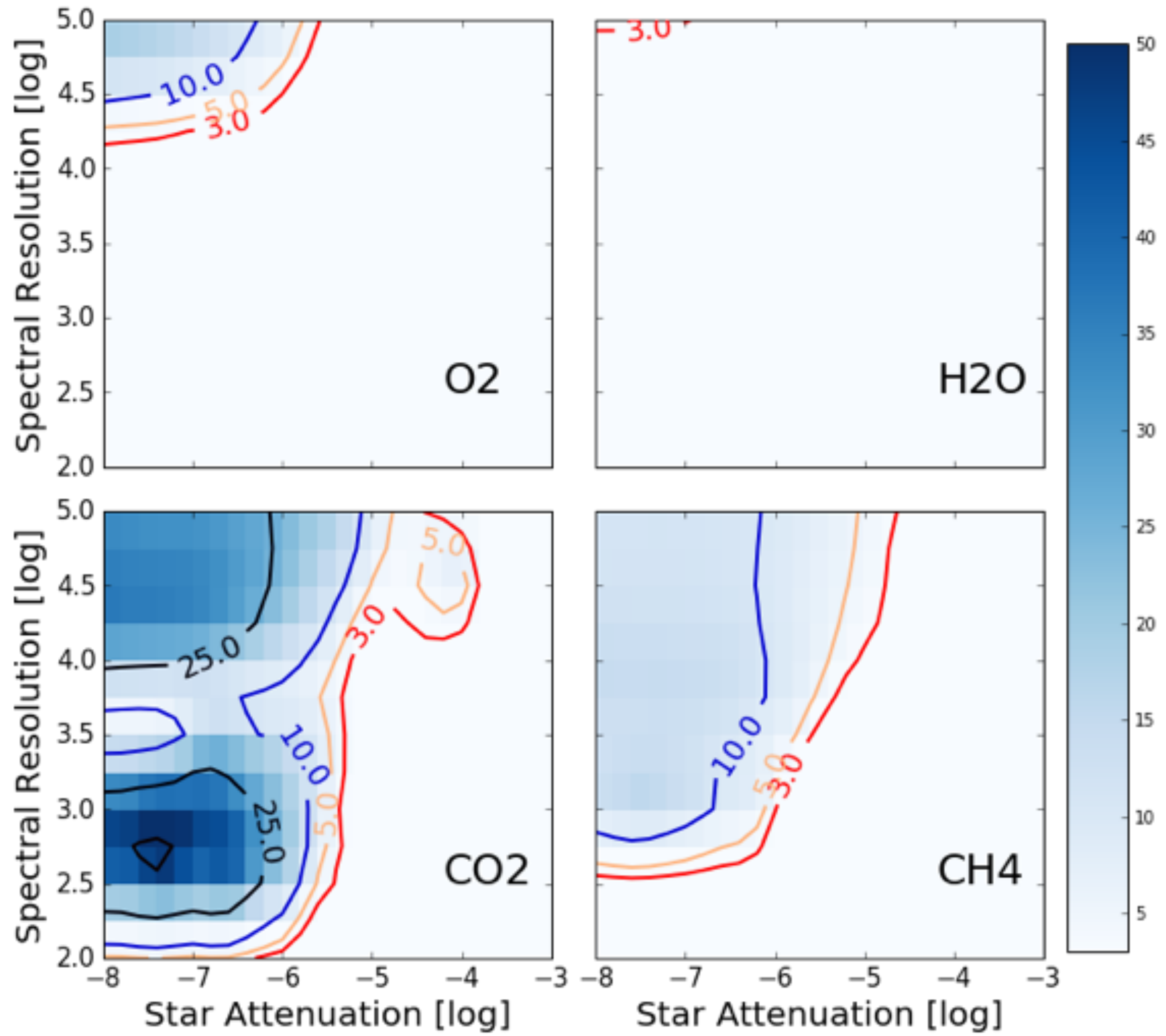
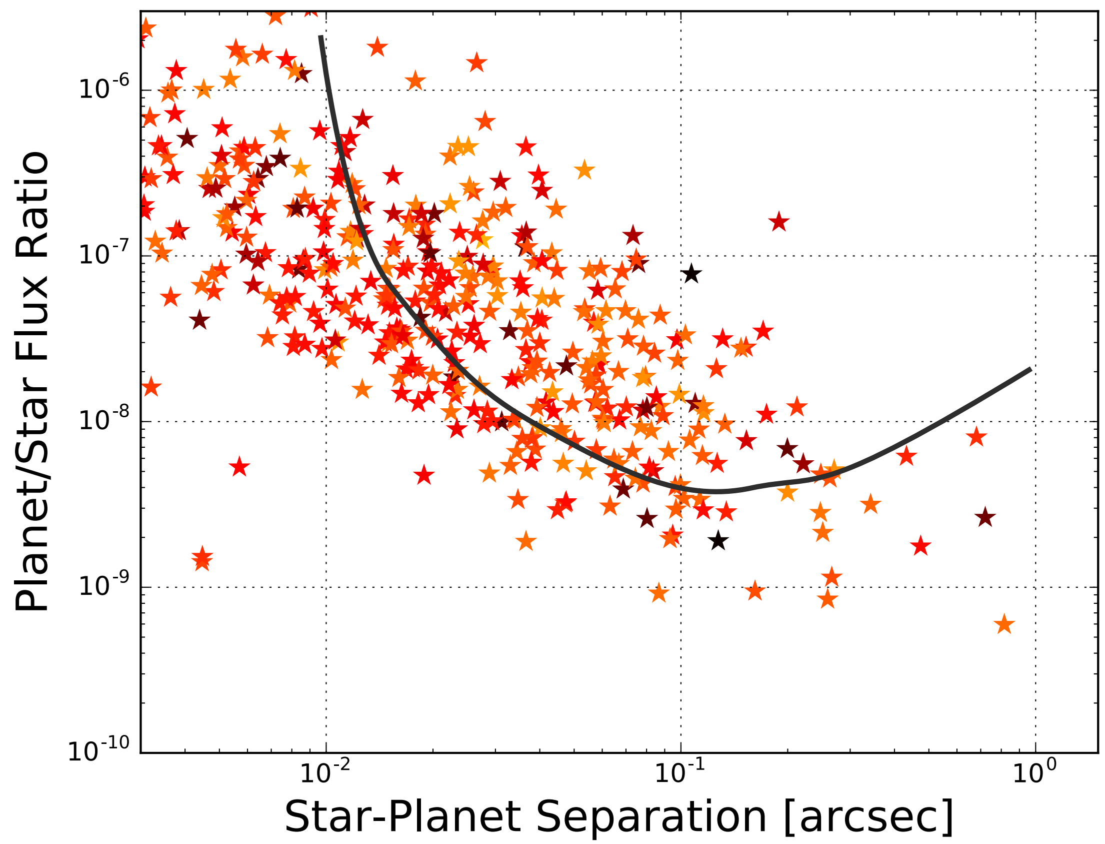


courtesy of Ji Wang, Renyu Hu, Dimitri Mawet

Technical Challenges

- 10-8 detection contrast at ~2 λ/D
  - Extremely low wavefront error
    - High-order wavefront corrector
  - Fast sensing
    - Low-noise high-frame-rate sensors
  - Elimination of non-common-path error
    - Sensing in science focal-plane



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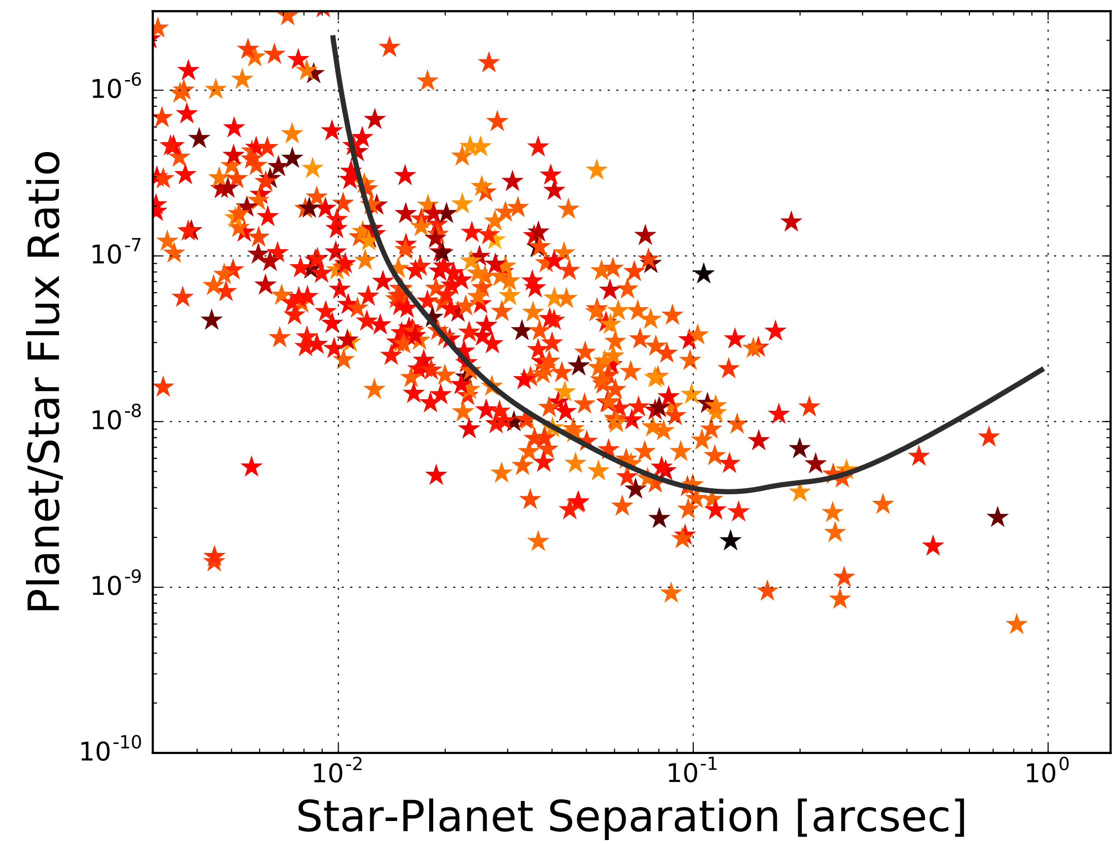

Crossfield (2016)

Significant challenges, but instruments can address these in the near term

ExAO precursor @ TMT

Why consider deploying a precursor ?

High impact science at first light: habitable planets reflected light spectroscopy around the nearest stars

Focusing on a single goal, small number of targets to meet schedule

Risk mitigation for 2nd generation instrument

Learn what works… what needs fixing (instrument/algorithms AND telescope)

Opens up opportunities for a more incremental approach:

Test subsystems / components on precursor

Develop and validate ON SKY : hardware, algorithms

TMT precursor starts NOW on 8m telescope(s)
… see for example SCExAO approach
Extensive testing on 8m telescope(s) + modeling for jump to larger aperture will mitigate risks and avoid lengthy engineering/learning on TMT.
Fully characterized instruments + algorithms (& yrs of experience) would be deployed on TMT

courtesy of Olivier Guyon

Science Along the Way

- Demographics will be largely characterized, e.g. WFIRST
  - Will also have samples of planets around nearby stars (e.g. GAIA, TESS)
- Characterization
  - JWST transit spectroscopy of short-period planets (relatively low spectral resolution)
  - Thermal emission spectroscopy of longer-period planets — still unique from the ground
- Post-JWST direct detection of planets around nearby stars in space is done in visible light

Science Along the Way

- Clear advantage is in spectral resolution
    - Atmospheric characterization, rotation vs. age for census of self-luminous giant planets
- Thermal emission of giant planets will continue to be interesting from now through TMT era
- Technology continues to press on inner working angle
    - Discovery space in context of condensation profiles