Direct planet imaging on TMT: PFI and beyond

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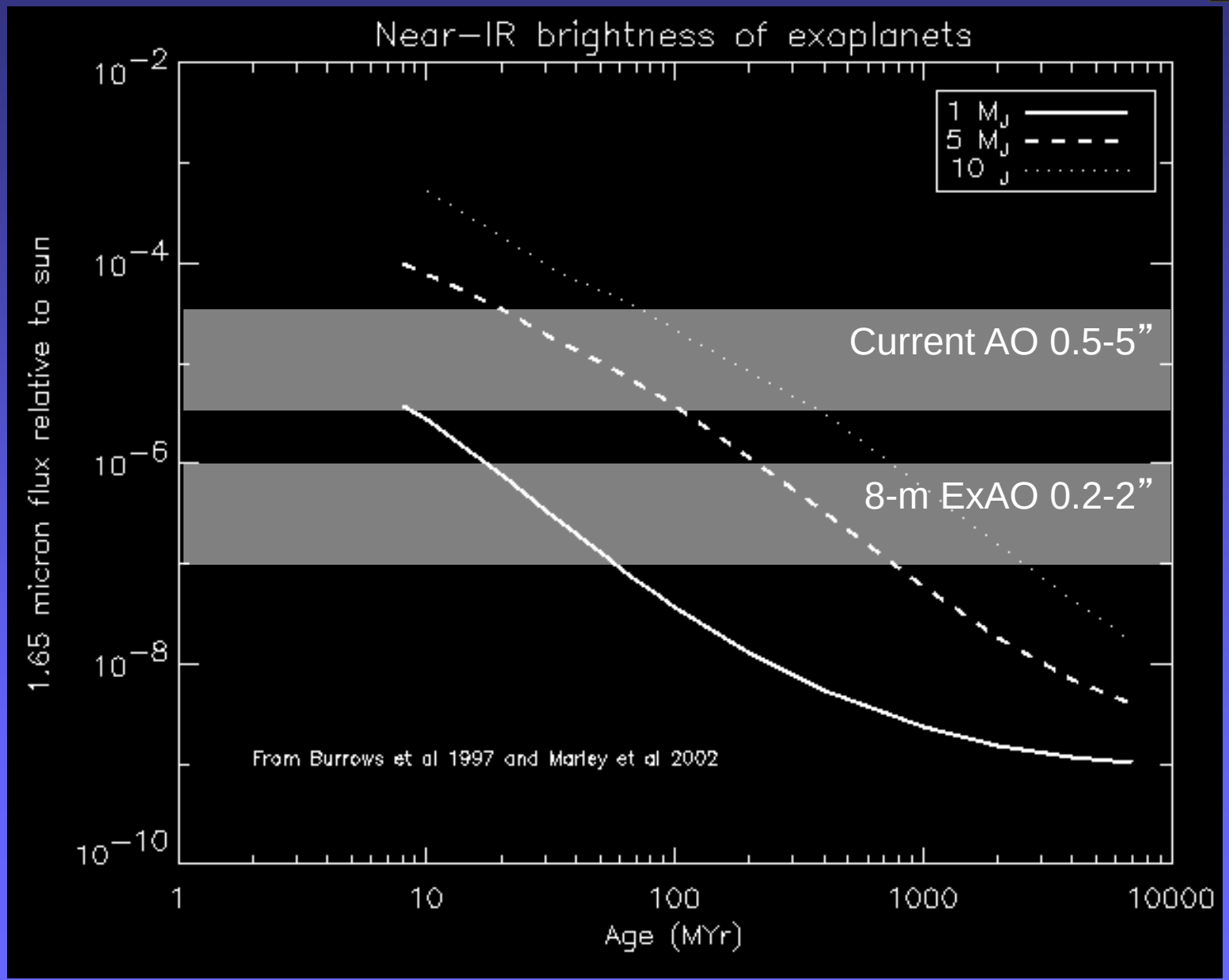
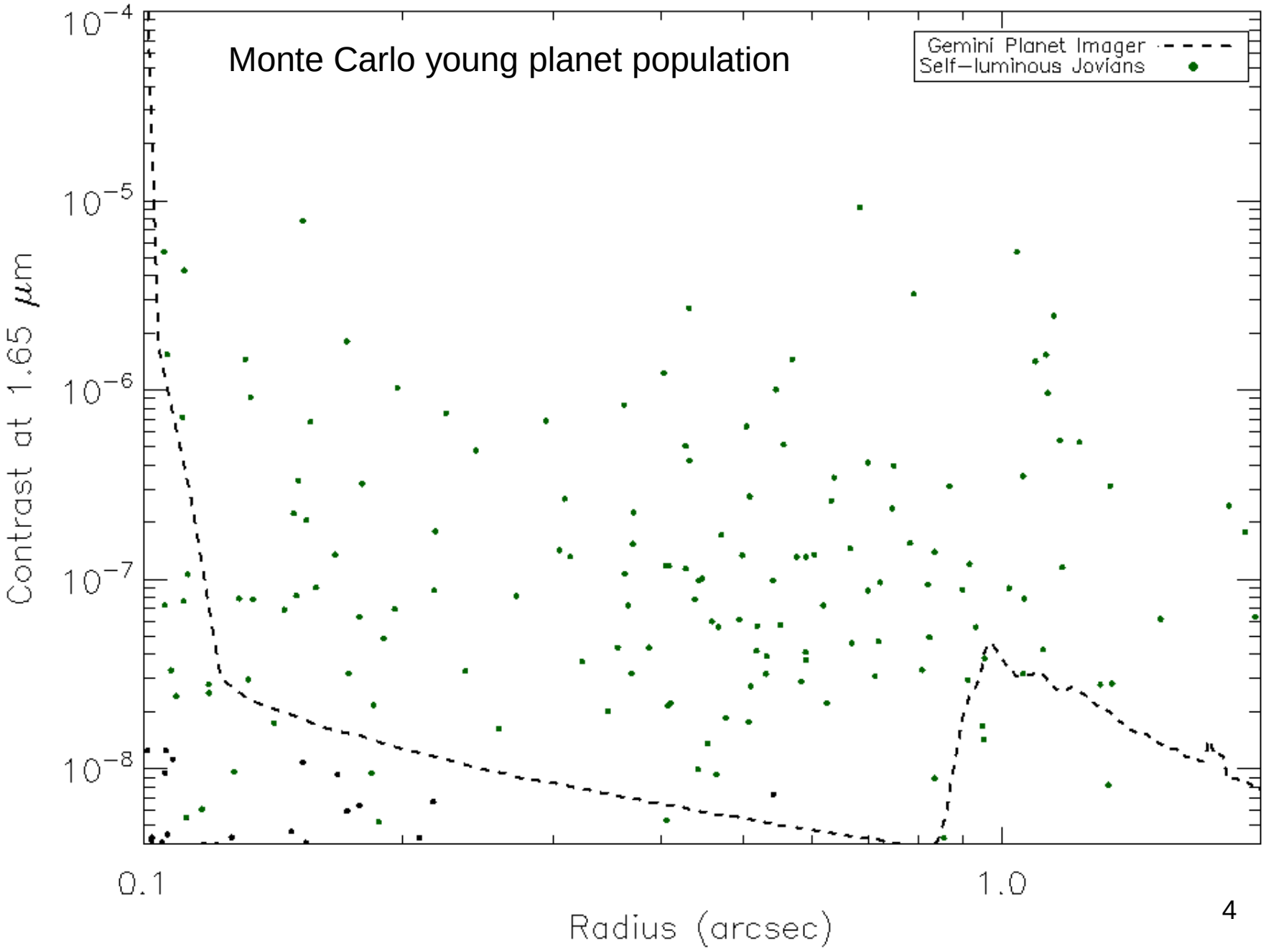
More recently: Dmitry Savransky, Christian Marois, Taro Matsuo

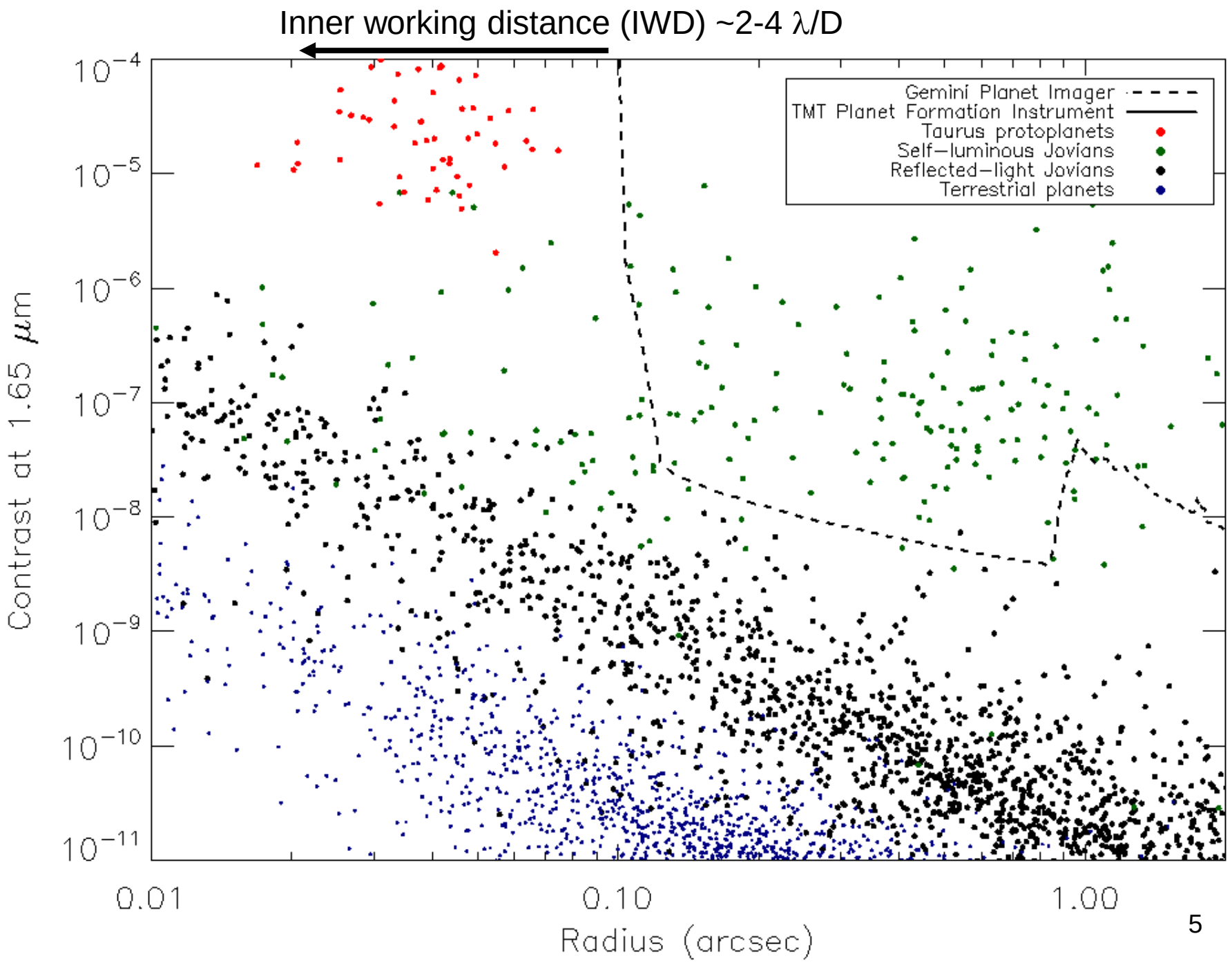
Outline

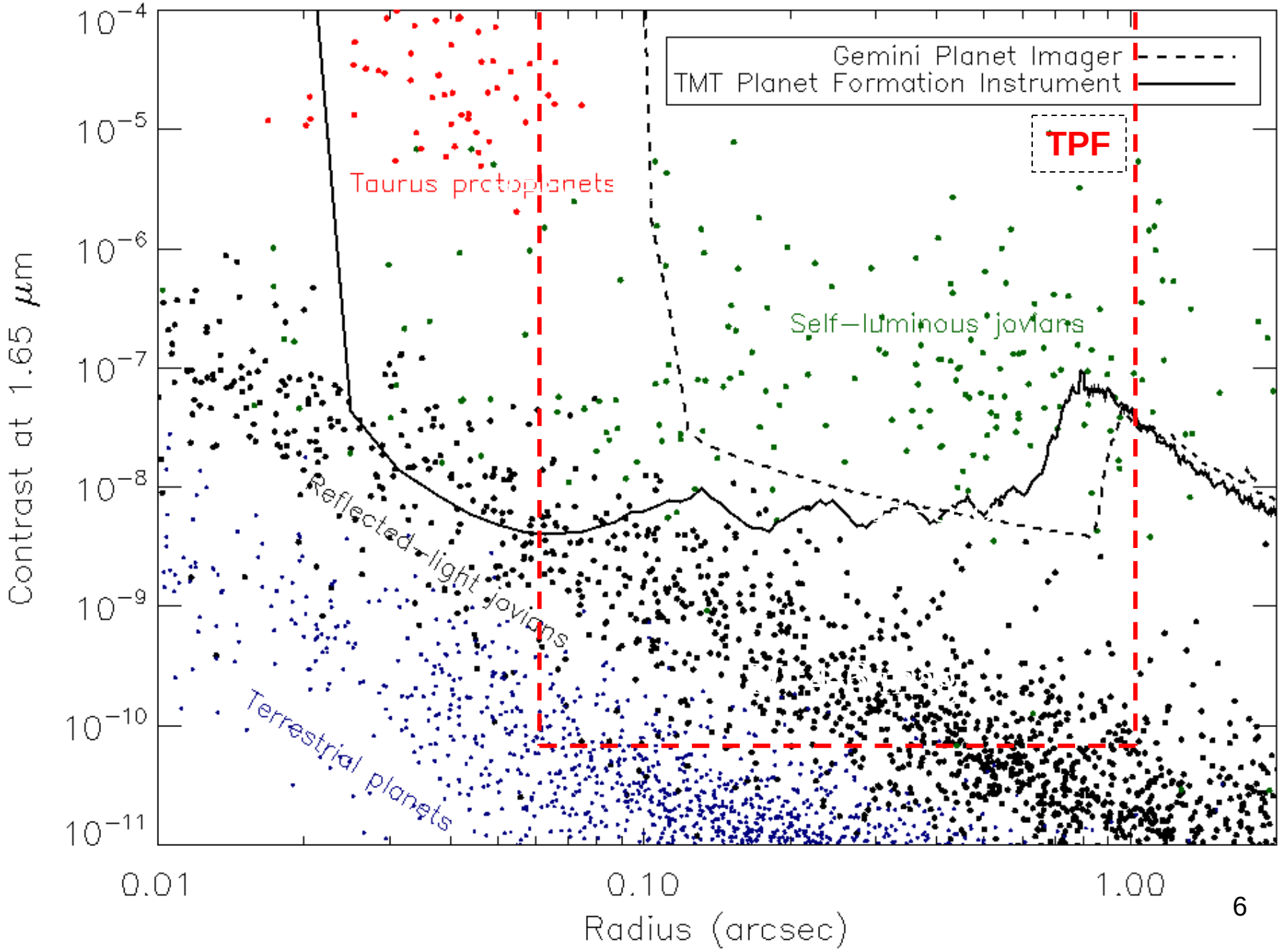
- **TMT Planet Formation Imager (PFI) - 2006**
  - Science case
  - Basic design
- **Direct planet imaging landscape today**
- **Updates to science case for TMT direct imaging**
- **Updates to technology**

Cooling extrasolar planets (late 1990s)




Monte Carlo young planet population
Gemini Planet Imager
Self−luminous Jovians
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Contrast at 1.65 μm
0.1
1.0
Radius (arcsec)


Inner working distance (IWD) ~2-4 λ/D
Gemini Planet Imager
TMT Planet Formation Instrument
Taurus protoplanets
Self−luminous Jovians
Reflected−light Jovians
Terrestrial planets
Contrast at 1.65 μm
10^−4
10^−5
10^−6
10^−7
10^−8
10^−9
10^−10
10^−11
0.01
0.10
1.00
Radius (arcsec)


Gemini Planet Imager
TMT Planet Formation Instrument
TPF
Taurus protoplanets
Self−luminous jovians
Reflected−light jovians
Terrestrial planets
Contrast at 1.65 μm
Radius (arcsec)
10^−4
10^−5
10^−6
10^−7
10^−8
10^−9
10^−10
10^−11
0.01
0.10
1.00

PFI science and requirements

1. Detect and characterize a large sample of extrasolar planets (T_{eff}, R, g)

   è 10^{-8} @ 50 mas, I<8

   Sub-nm static errors, 2000+ Hz

   R~100 spectroscopy

2. High-SNR spectroscopy of planets (abundances)

   è R~1000 spectroscopy

3. Detection of planets in the process of formation

   è 10^{-6} @ 30 mas, H<10

   IR WFS

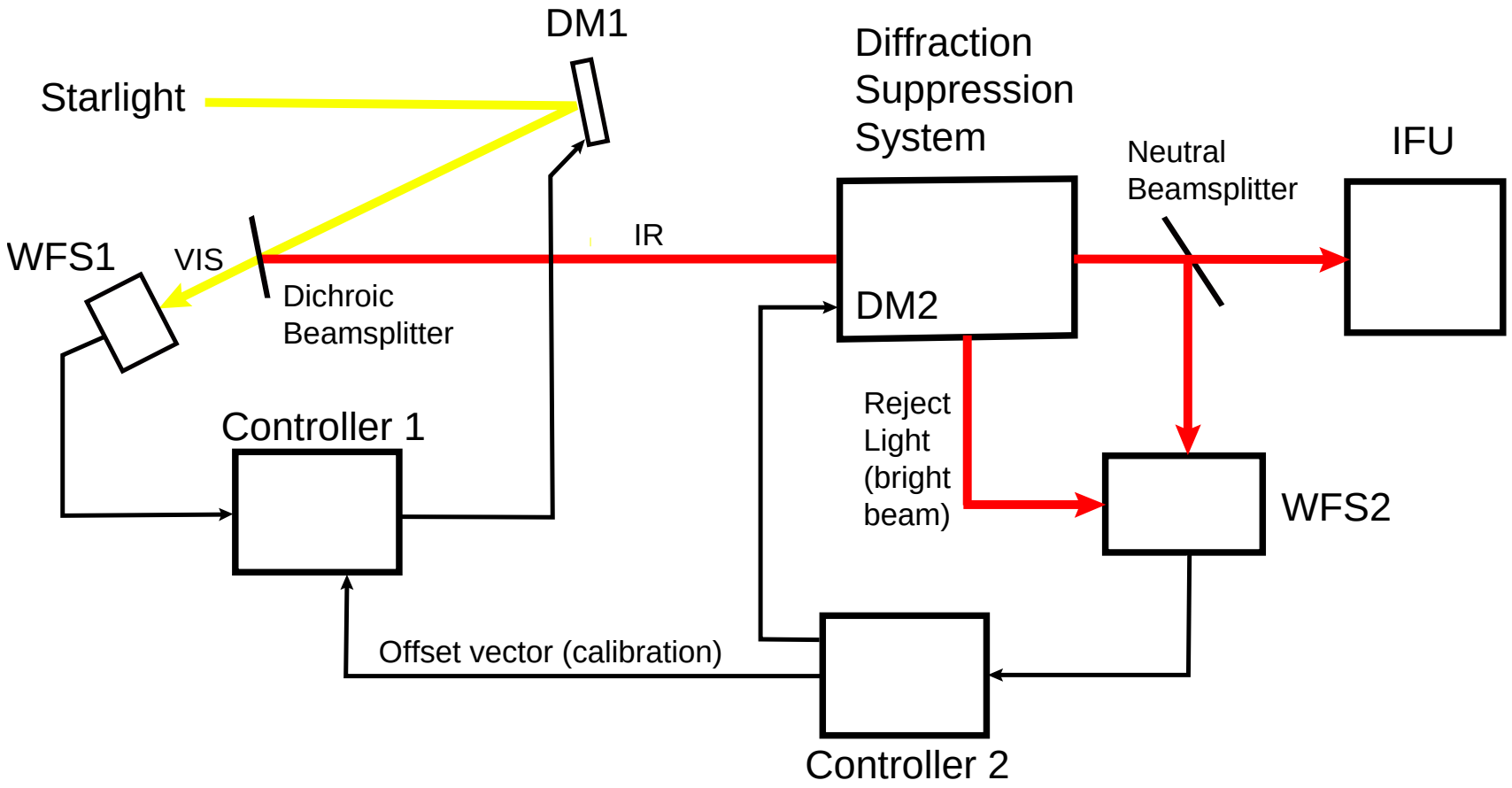
   Polarimetry

4. Studies of circumstellar dust on AU scales

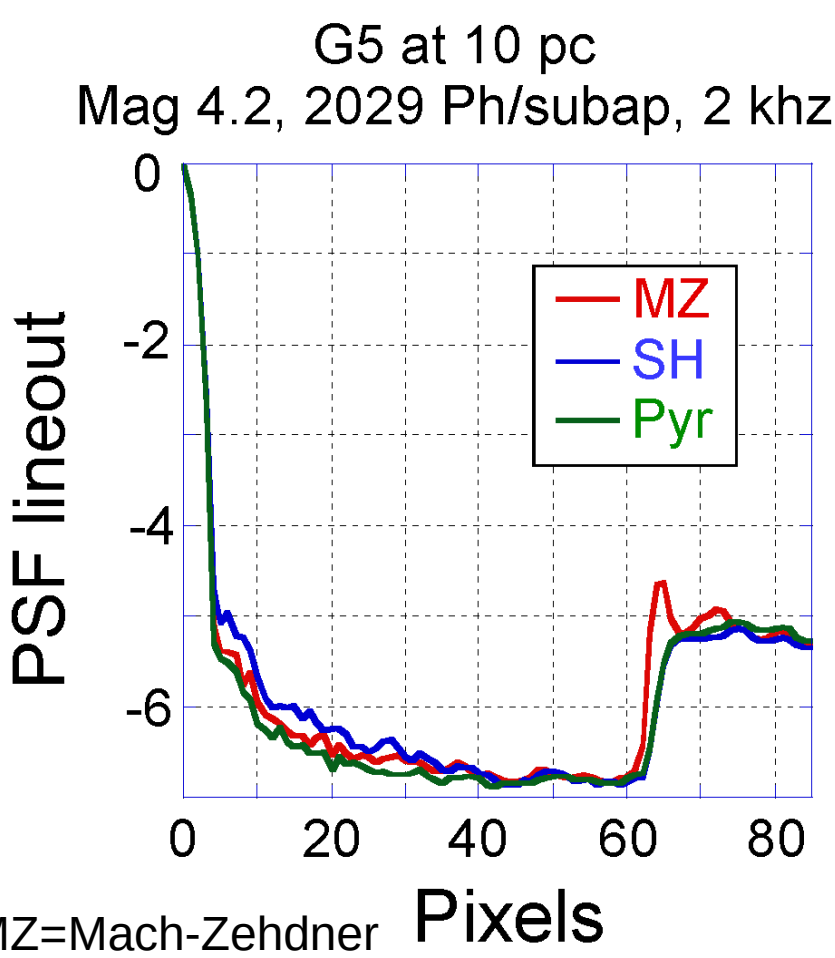
   è Polarimetry

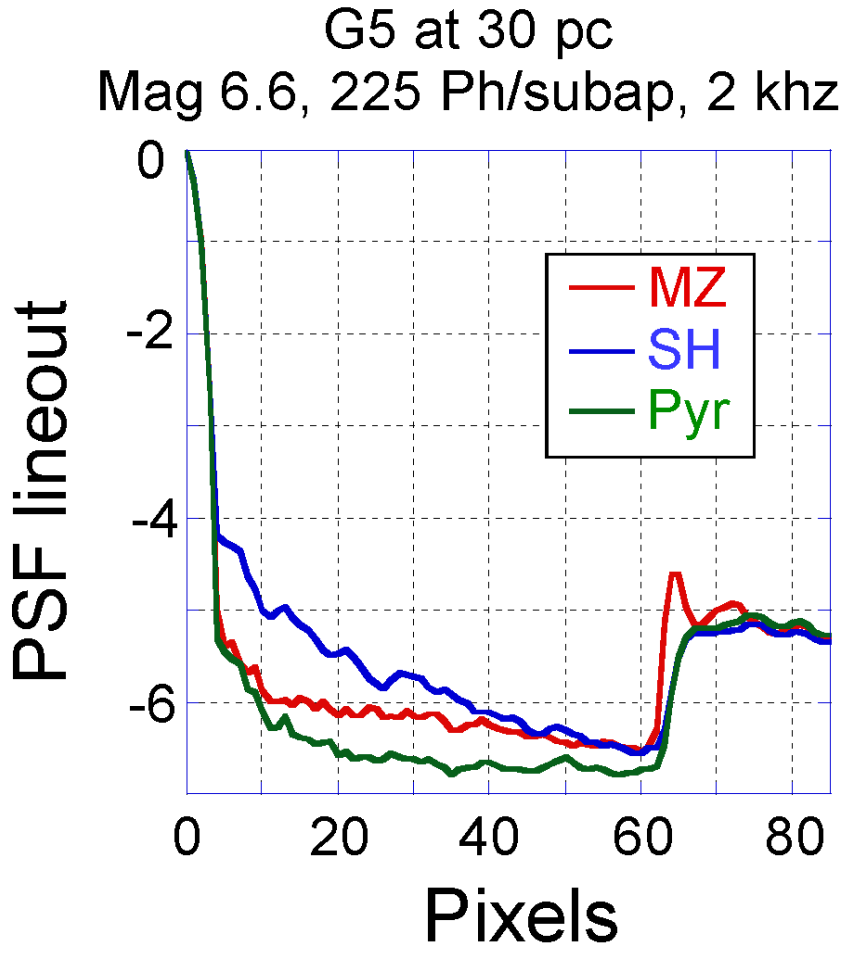
   2”+ FOV

Instrument overview



Pyramid AO system maximizes sensitivity

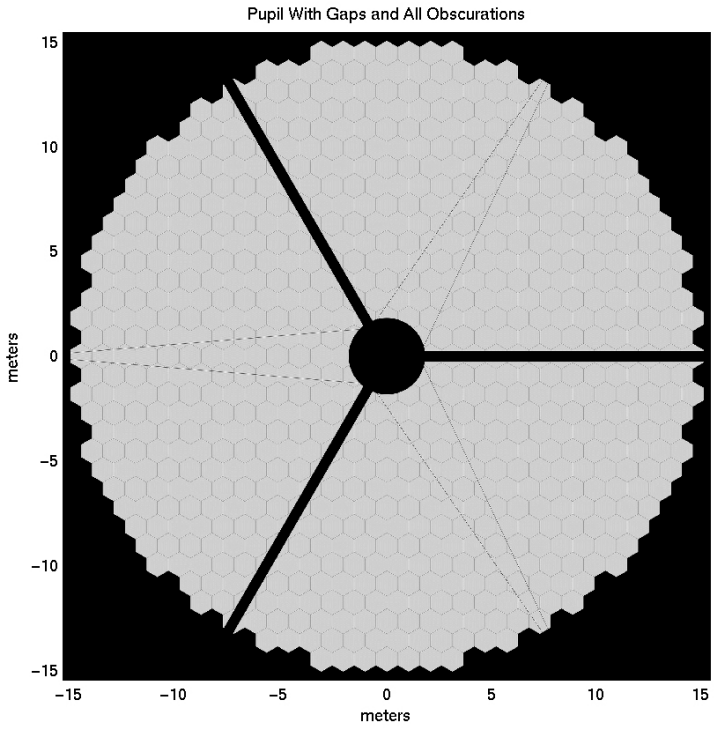


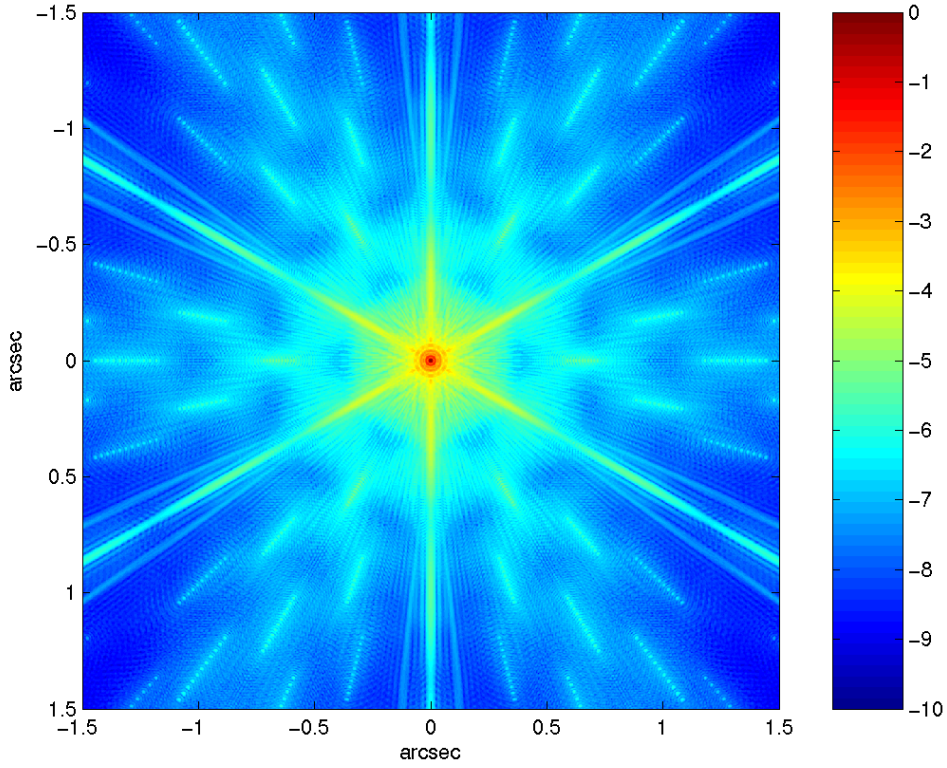


MZ=Mach-Zehdner
SH=Shack-Hartmann
Pyr=Pyramid

THIRTY METER TELESCOPE

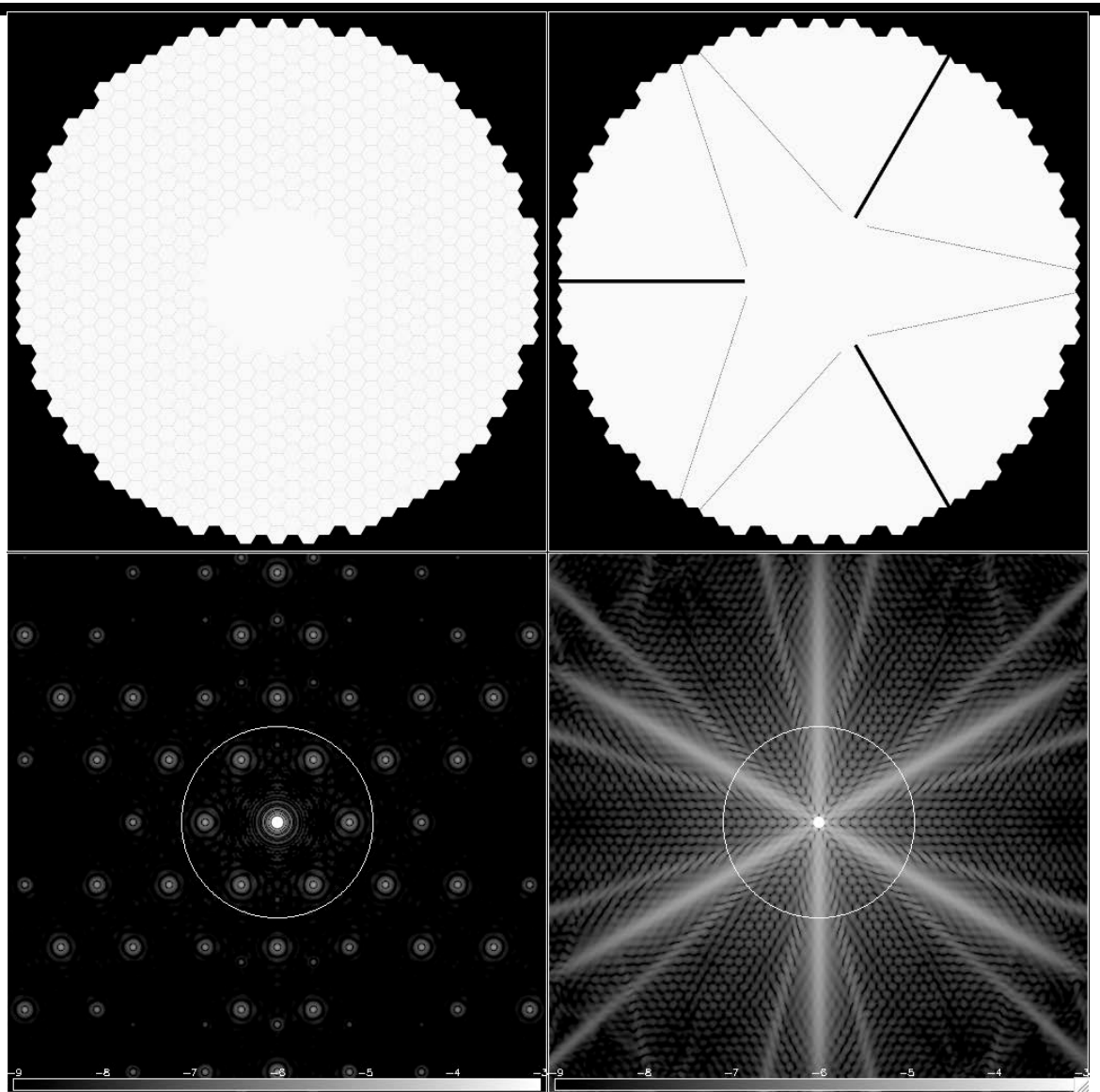
Diffraction





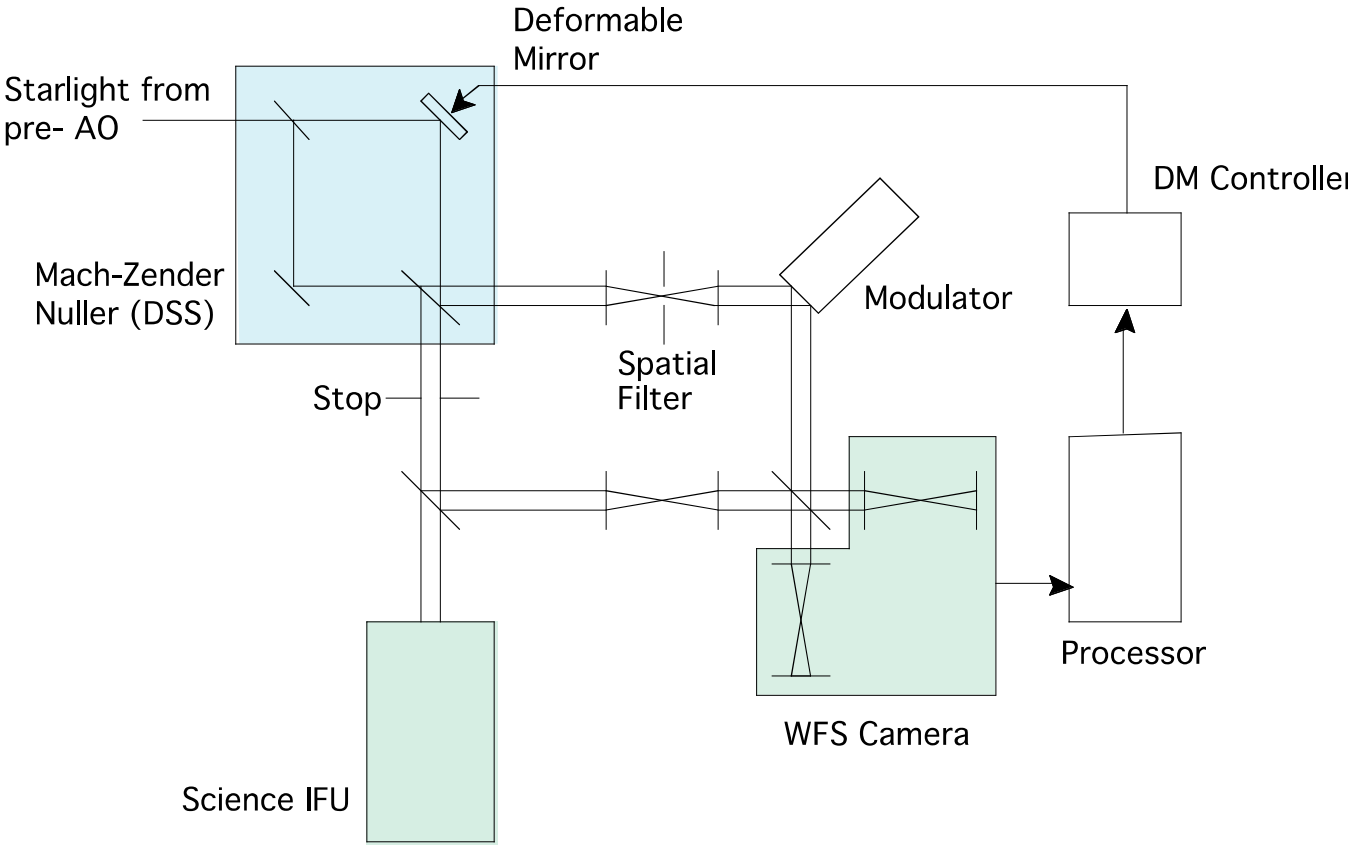
TMT PSFs: Gaps vs M2

Gaps only

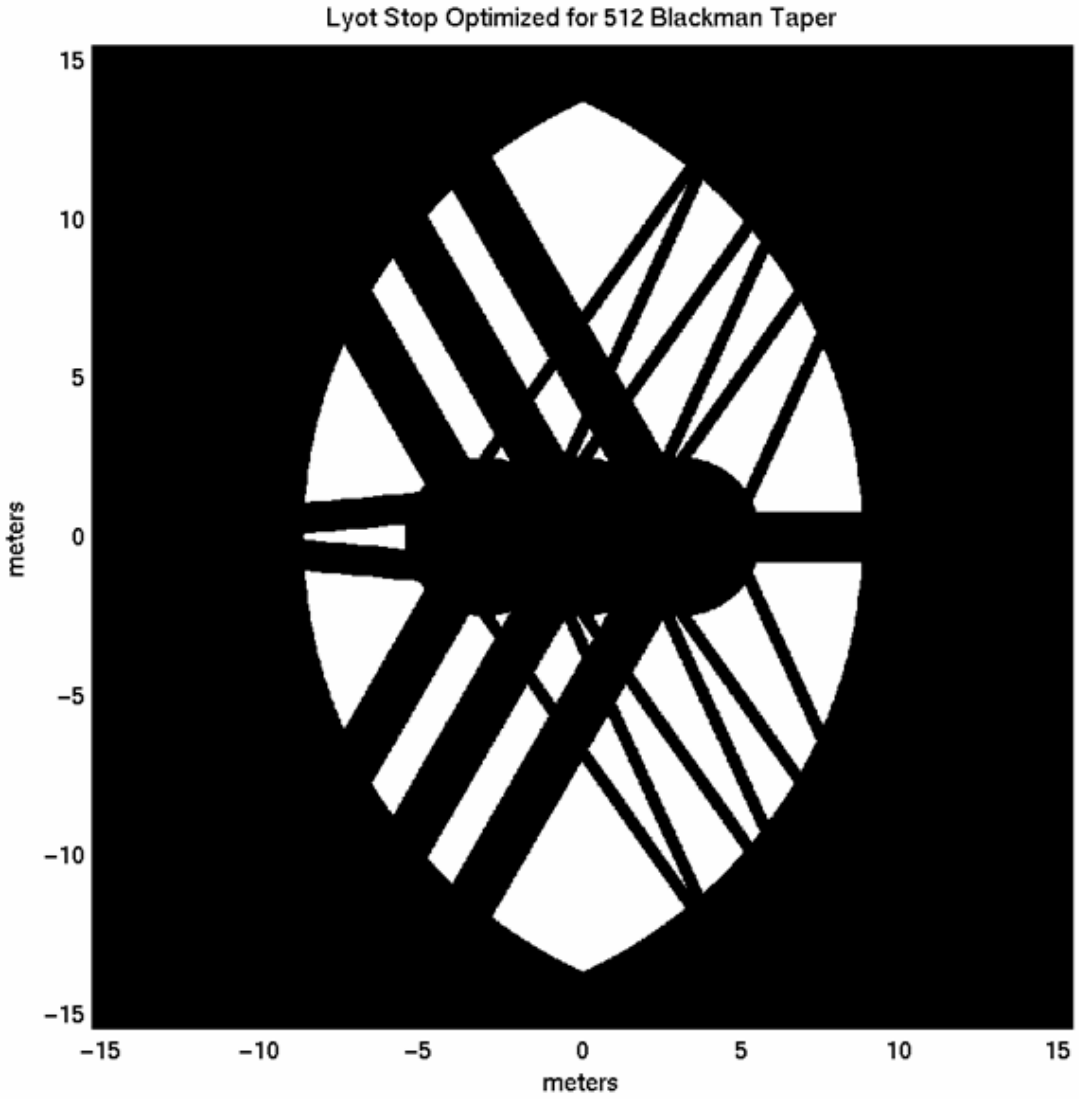


M2 supports only

Nulling interferometer + WFS

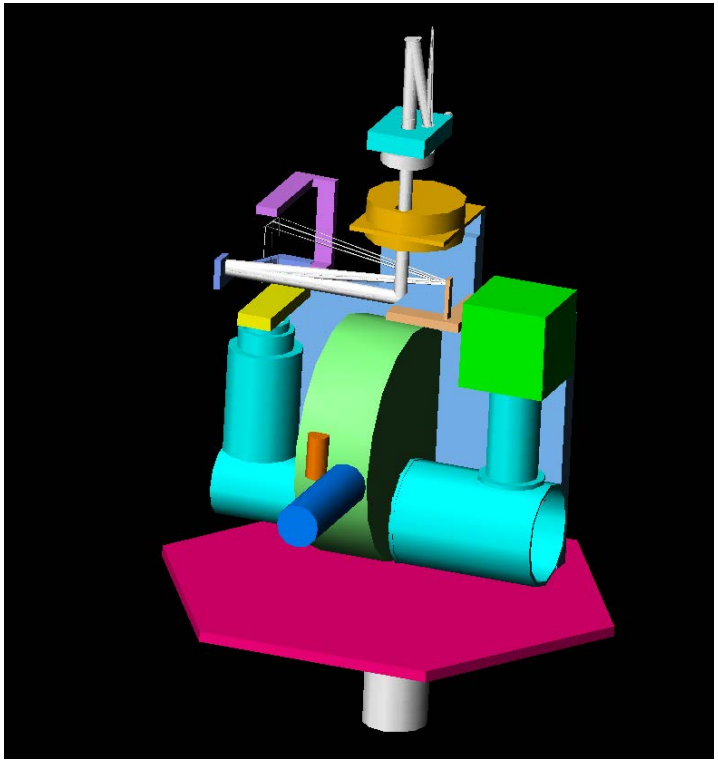


2-stage nuller output pupil

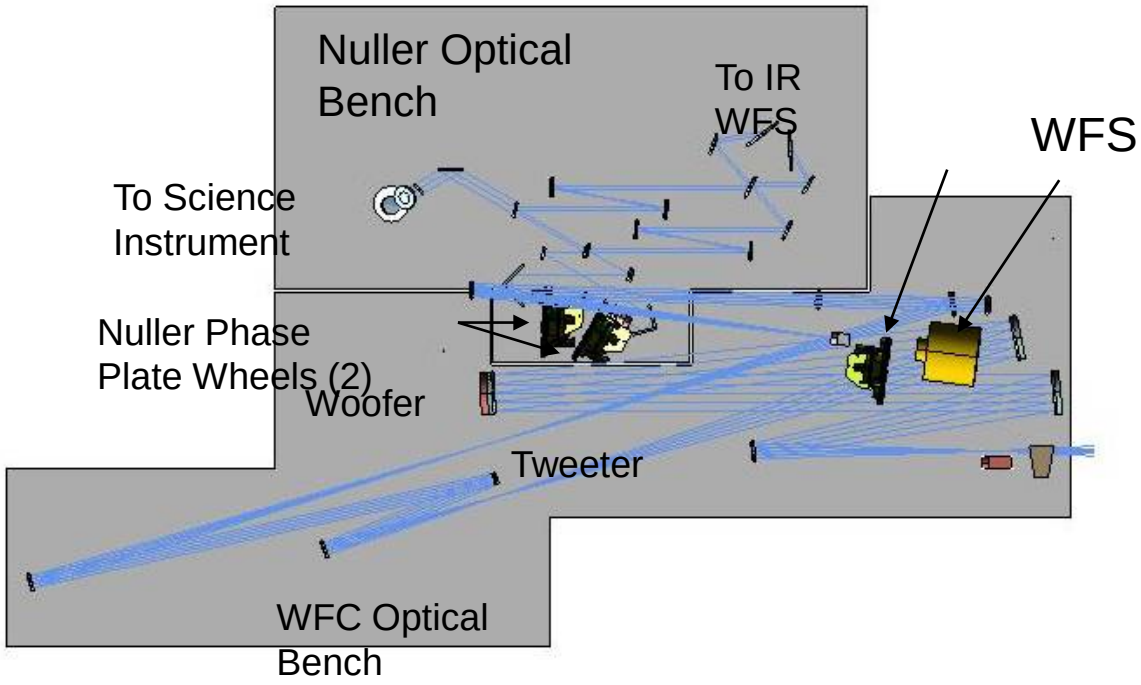


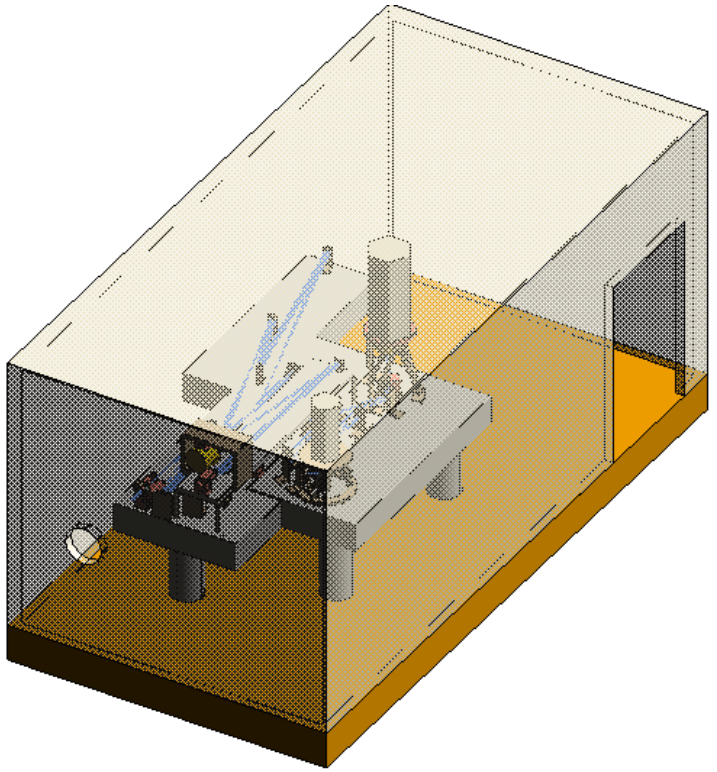
Science instrument: multimode IFS (U. Montreal)

- Lenslet-based IFS
- 2.2 x 2.2” FOV
- 0.054” pixels
- R=70 *YJHK* (goal: *L*’, *M*)
- R=500 narrowband mode
- Differential polarimetry capability

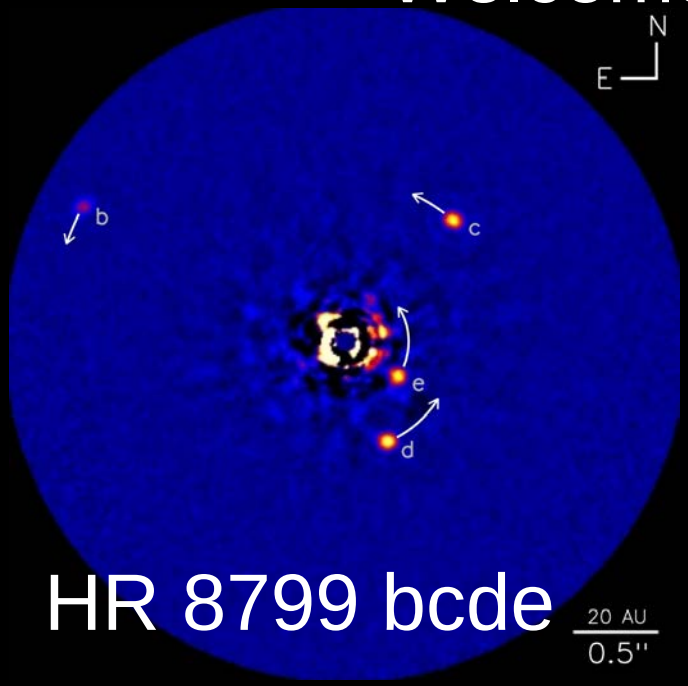


PFI optomechanical layout

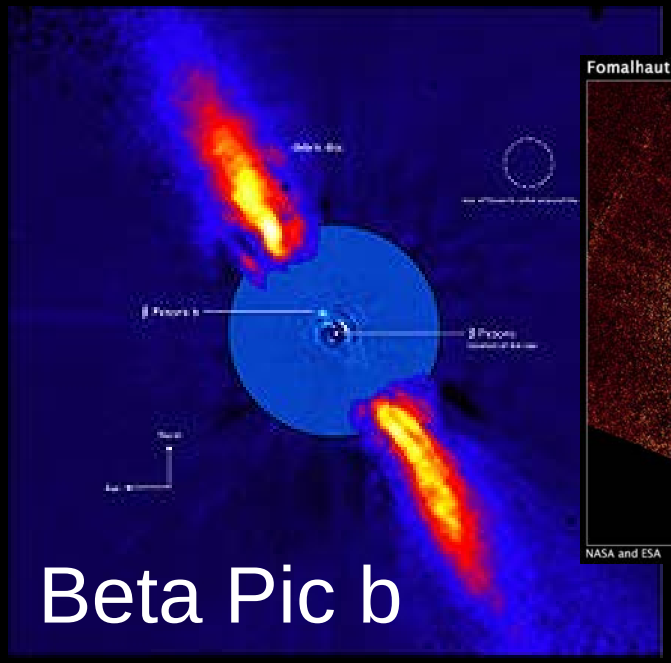




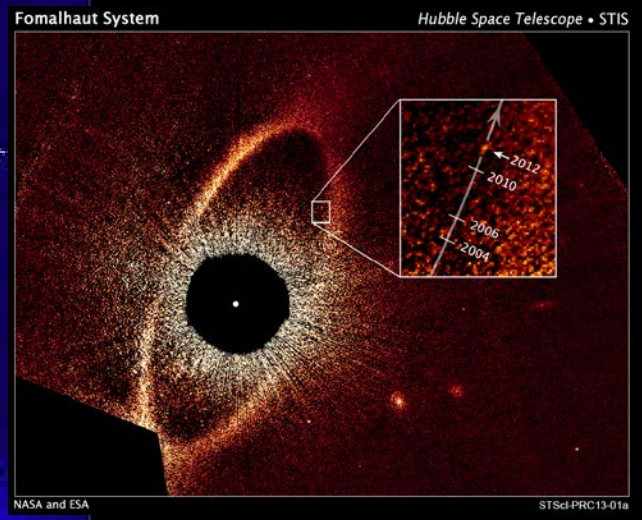
Welcome to 2013



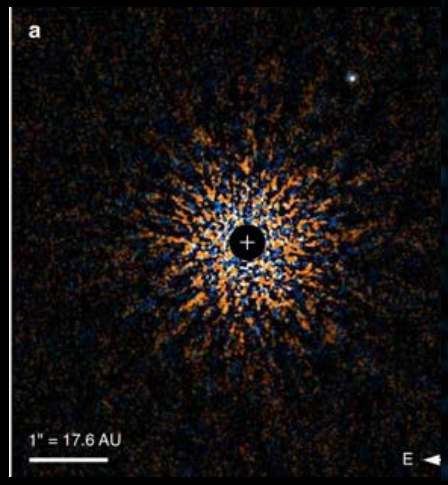
HR 8799 bcde



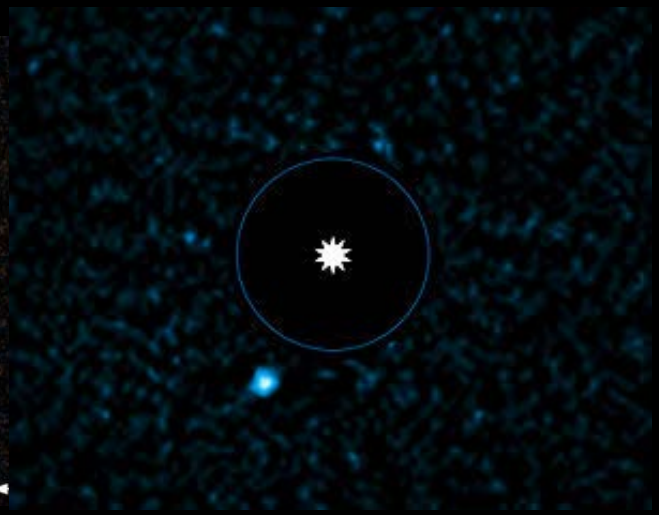
Beta Pic b

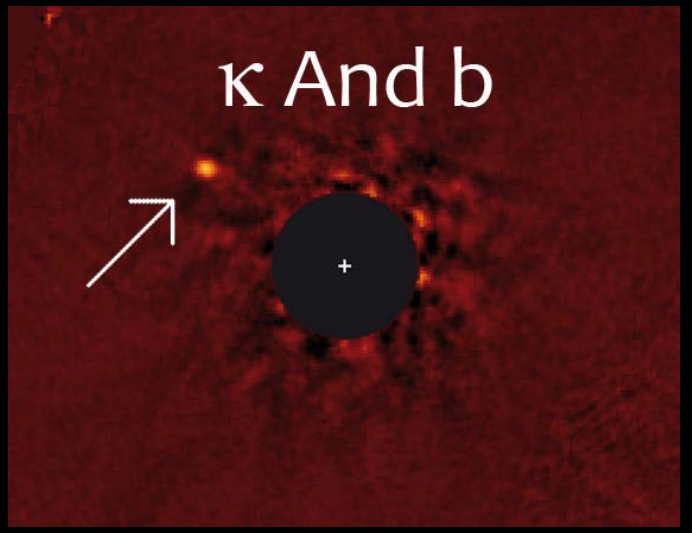


GJ 504 b

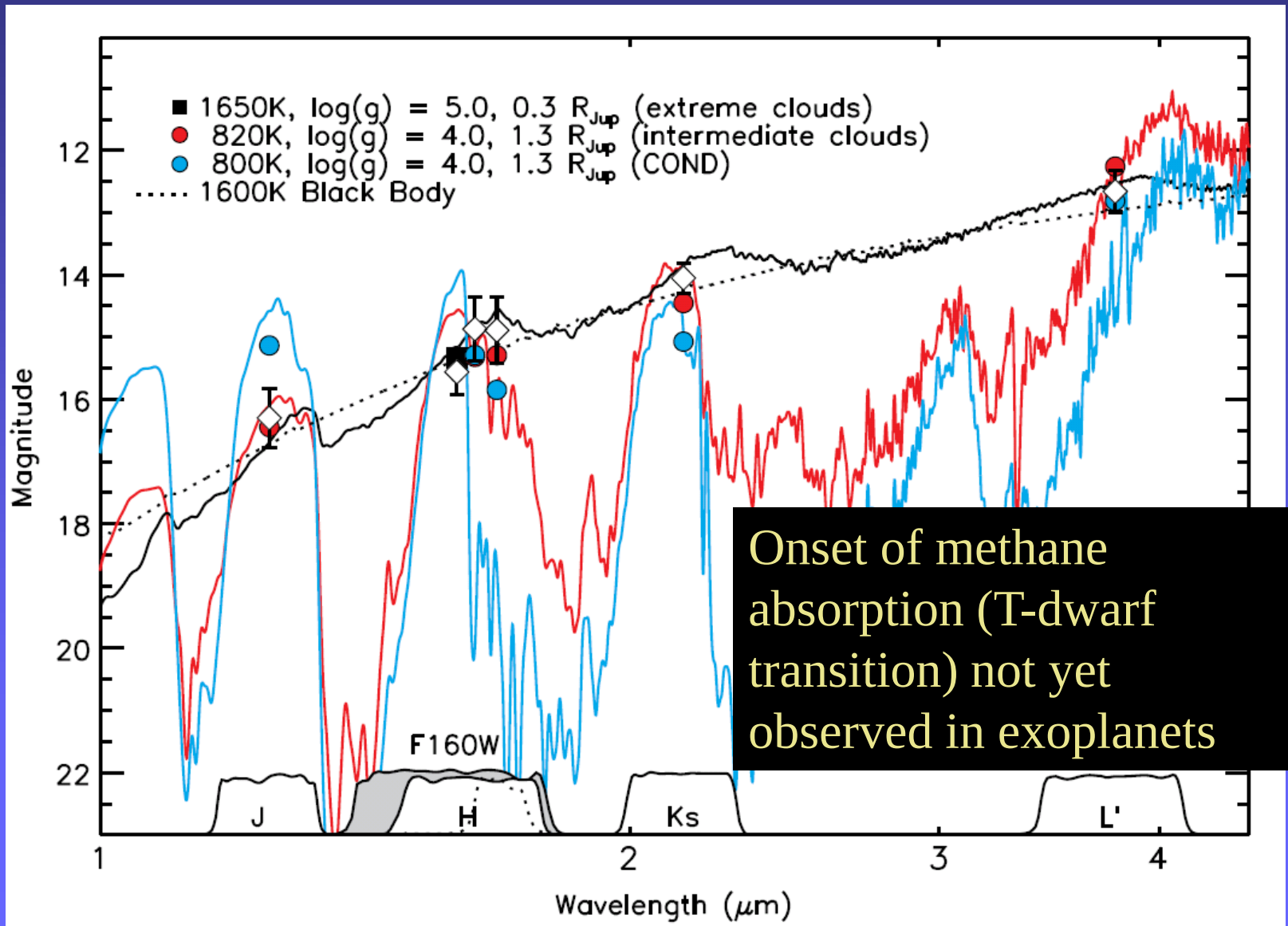


HD 95086 b



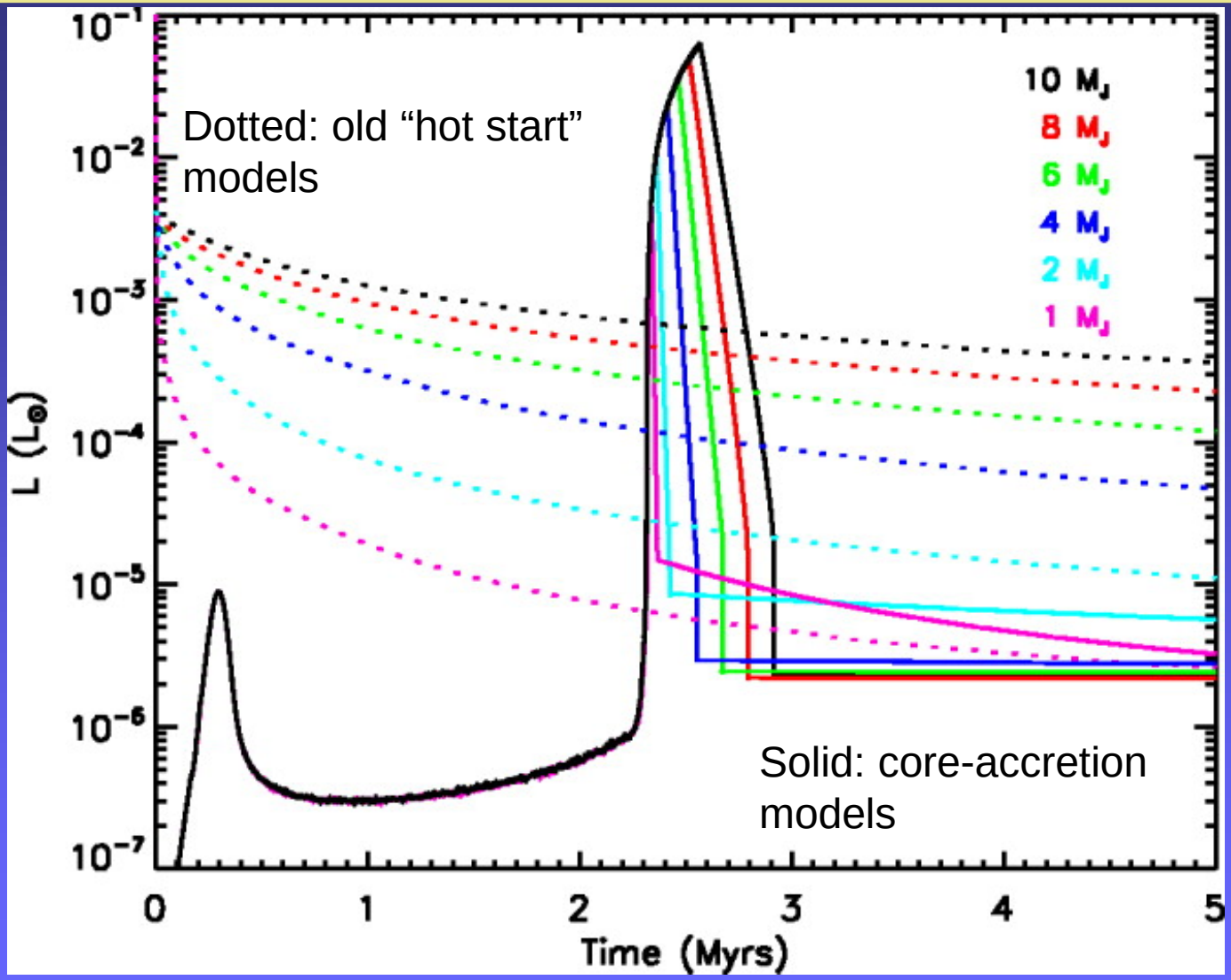


Directly detected planets are very different than early models



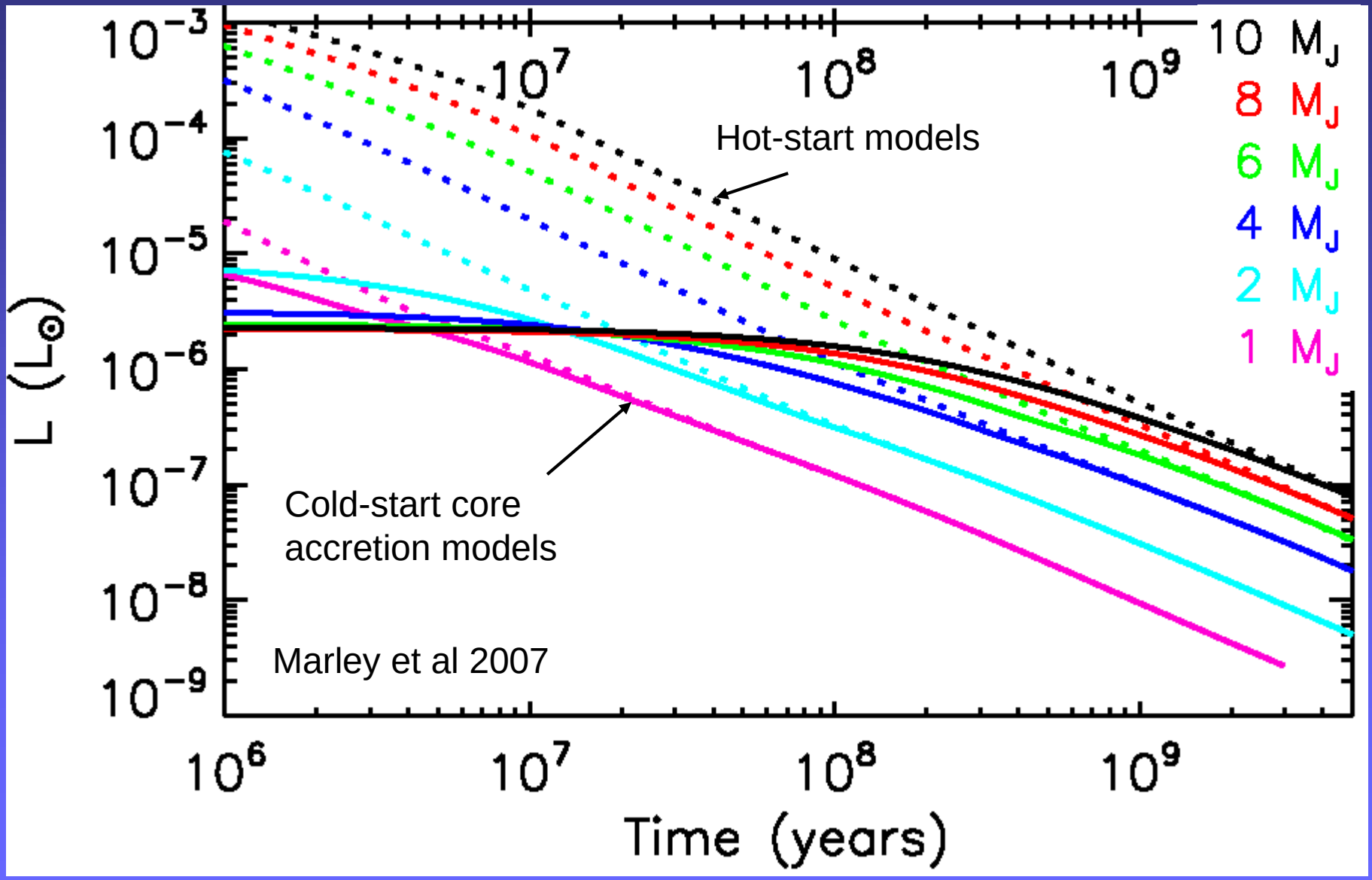
Onset of methane absorption (T-dwarf transition) not yet observed in exoplanets

Planet luminosity histories are formation-dependent

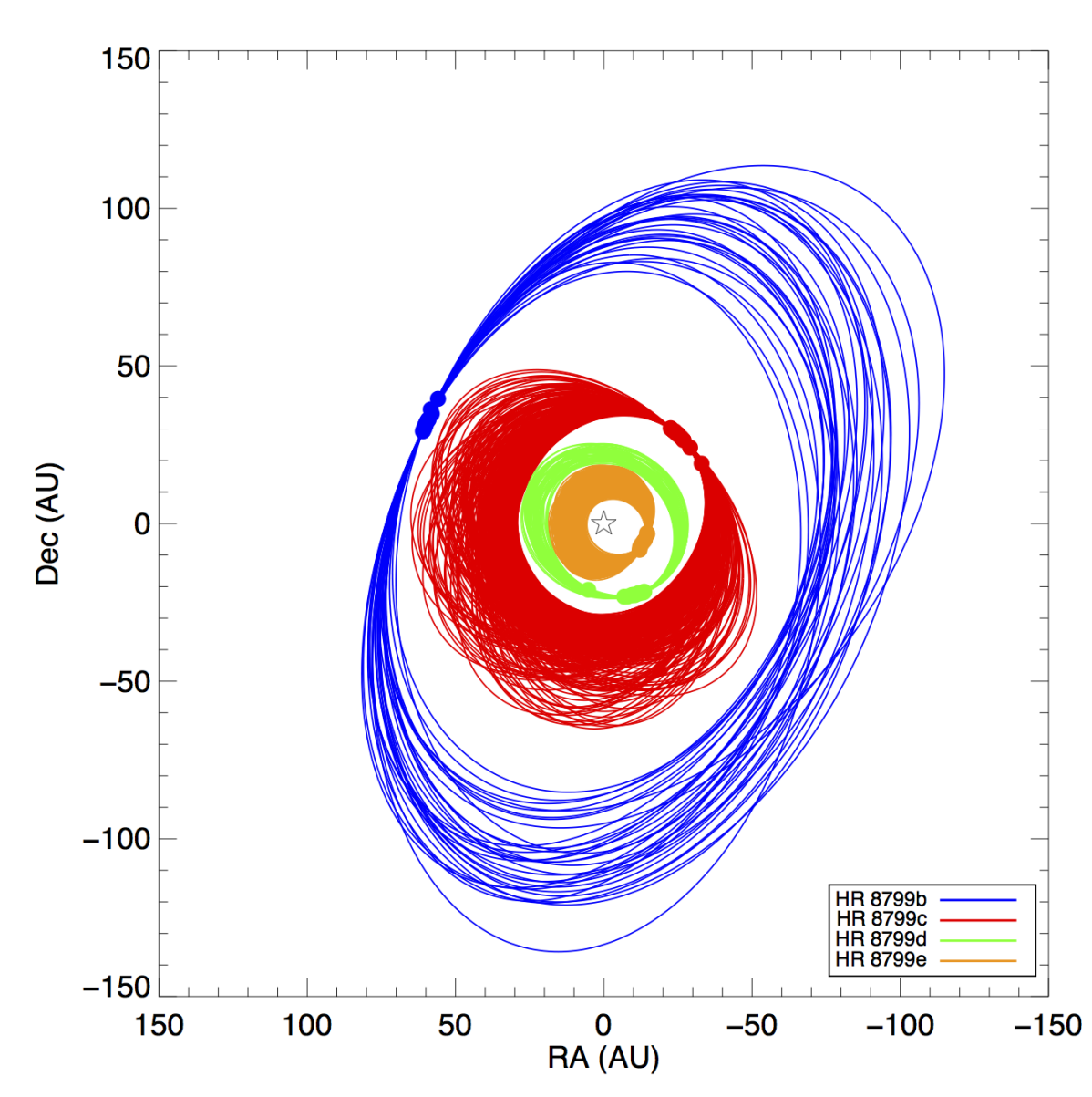


Marley et al 2007

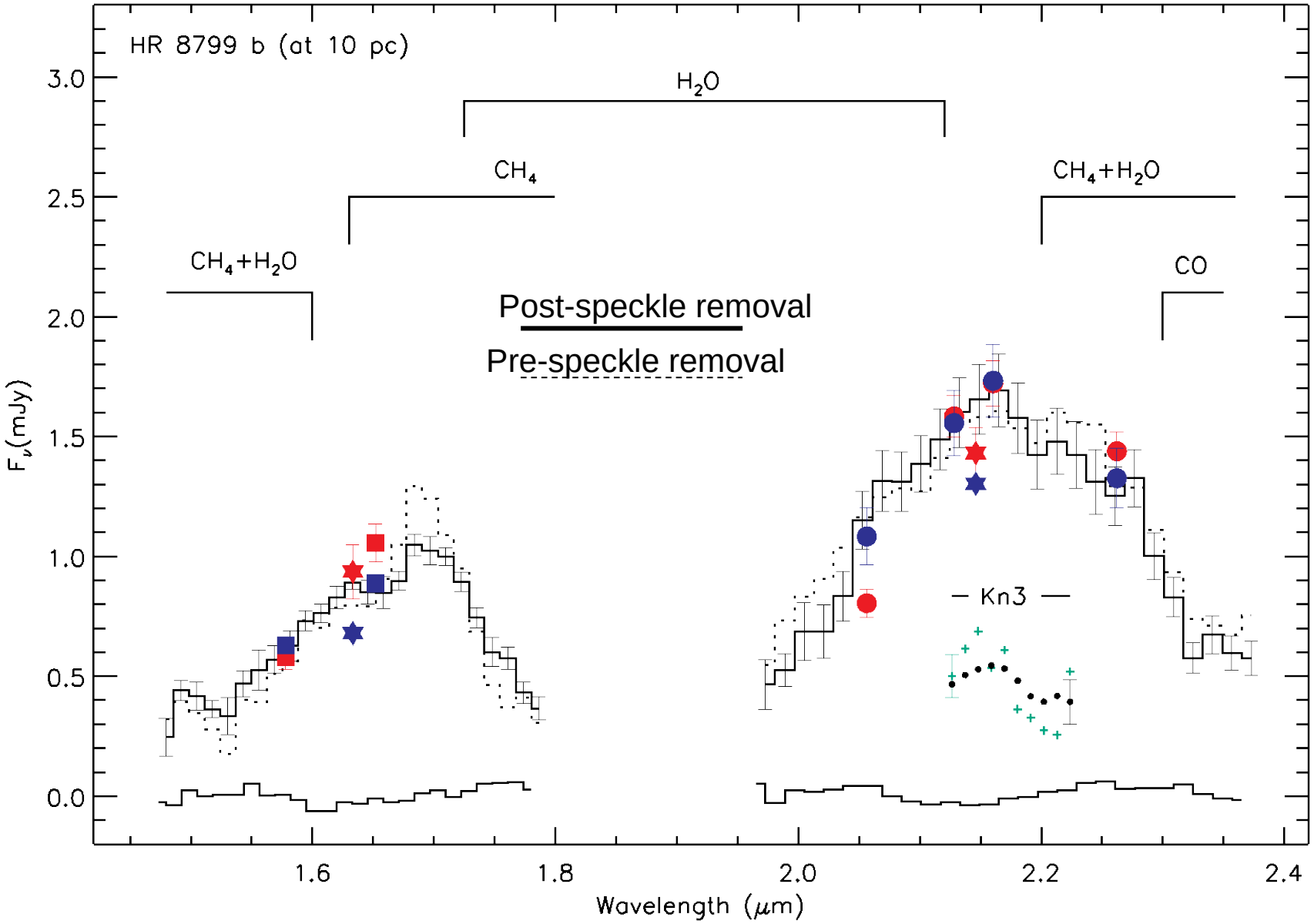
Luminosity & mass encode formation history



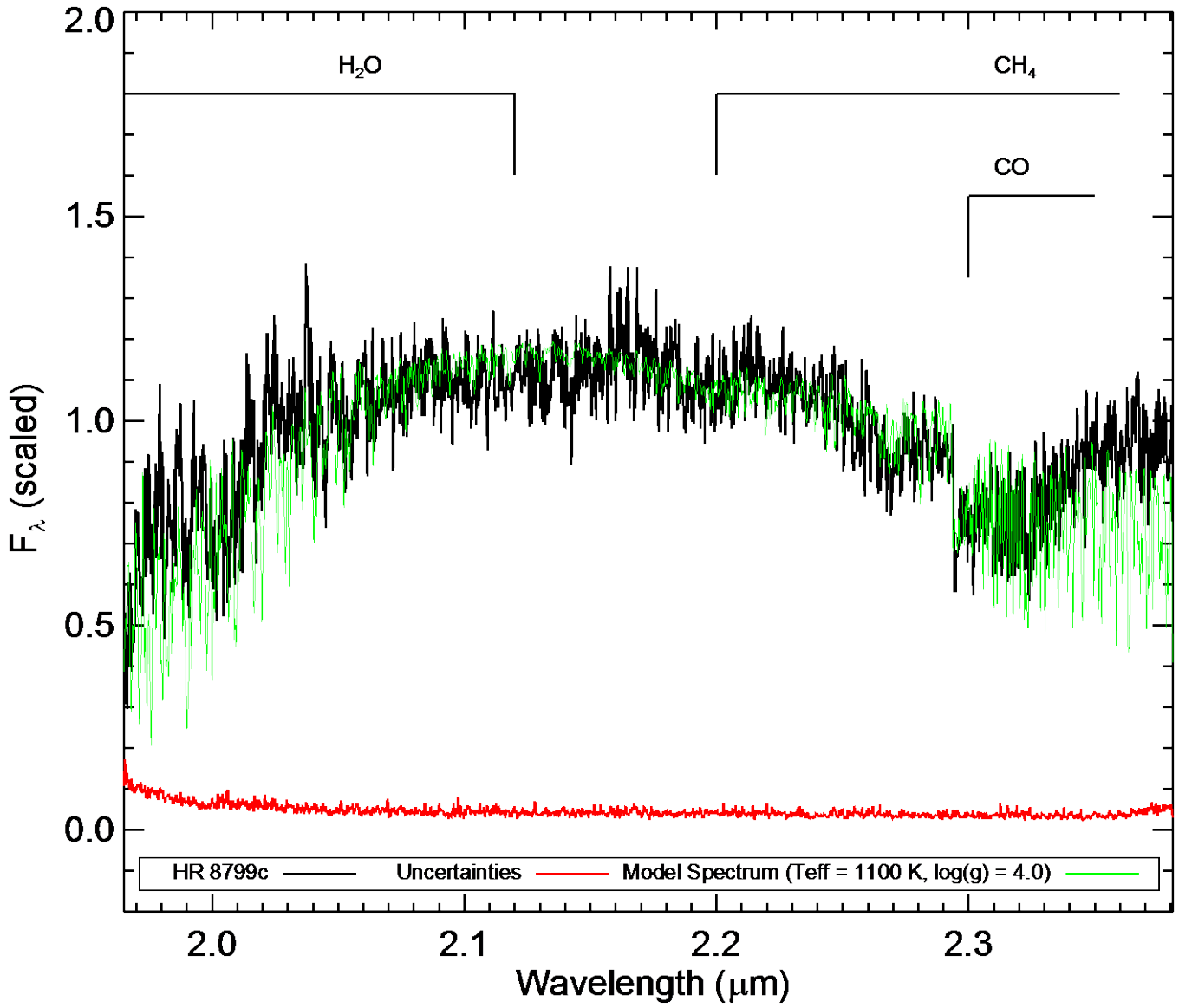
Orbital characterization is a powerful tool

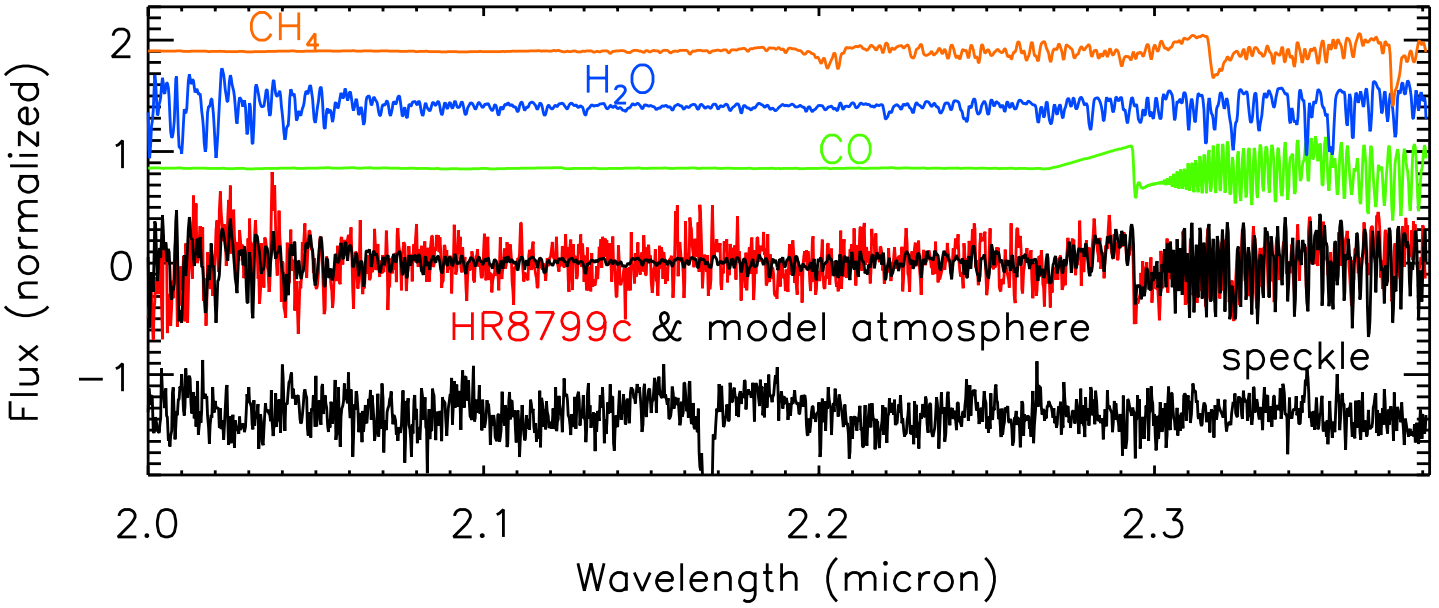


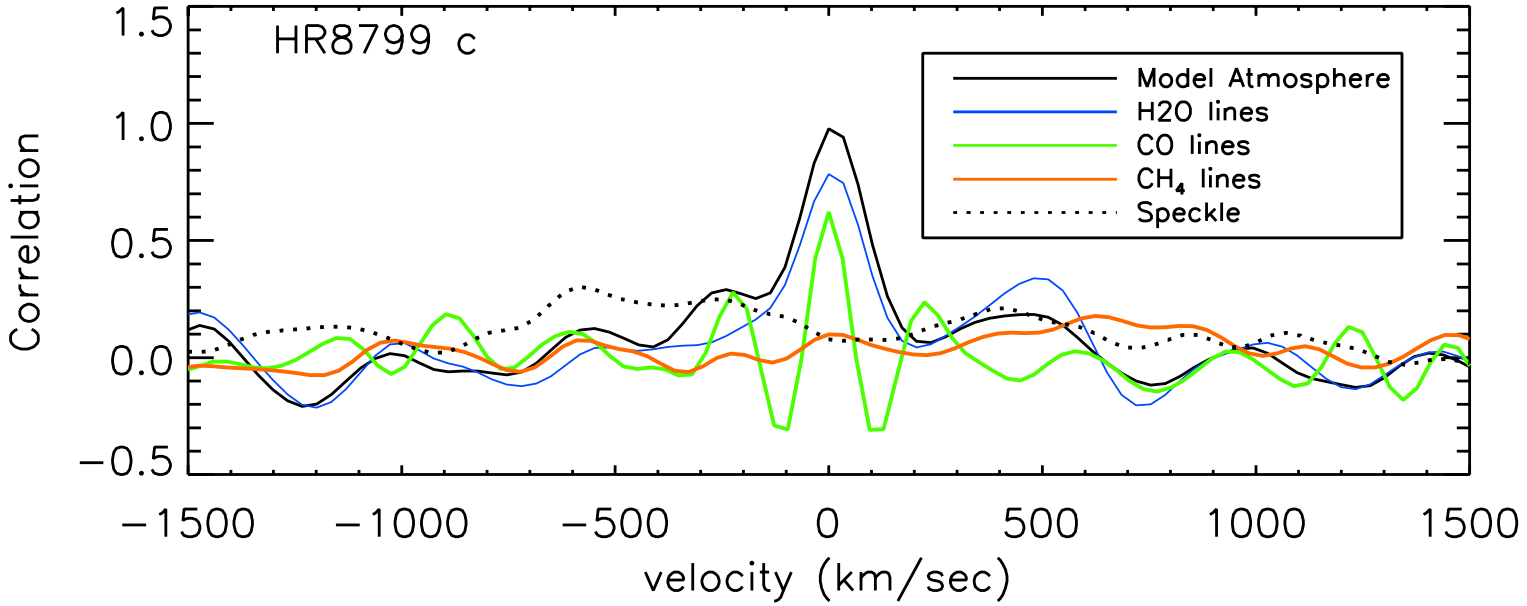
Lowres spectra of planets show broad composition (Barman et al 2011)



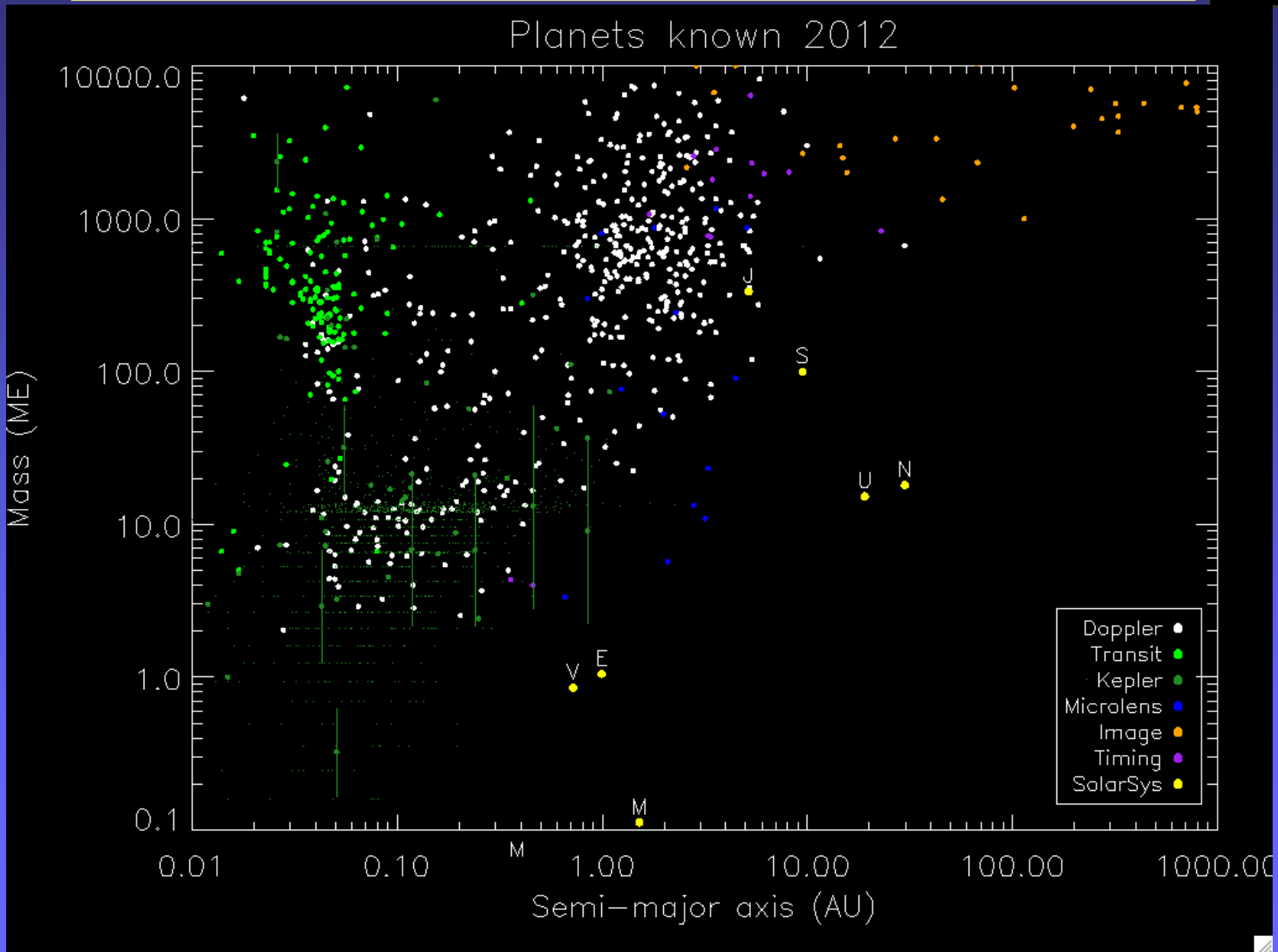
Full OSIRIS resolution spectra have enormous scientific yields (Konpacky et al 2013)



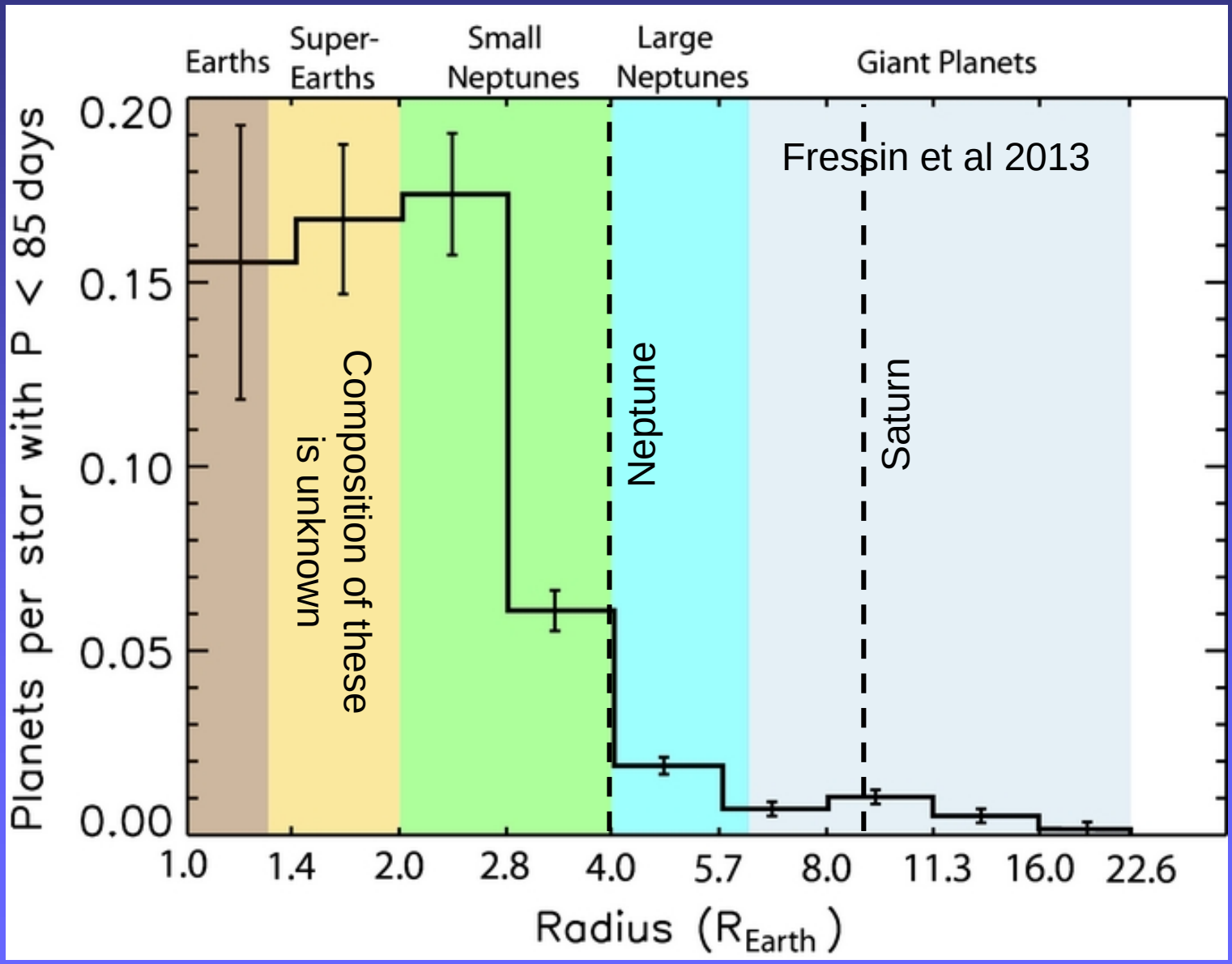

CH4
H2O
CO
HR8799c & model atmosphere
speckle
Flux (normalized)
Wavelength (micron)
2
1
0
−1
2.0
2.1
2.2
2.3

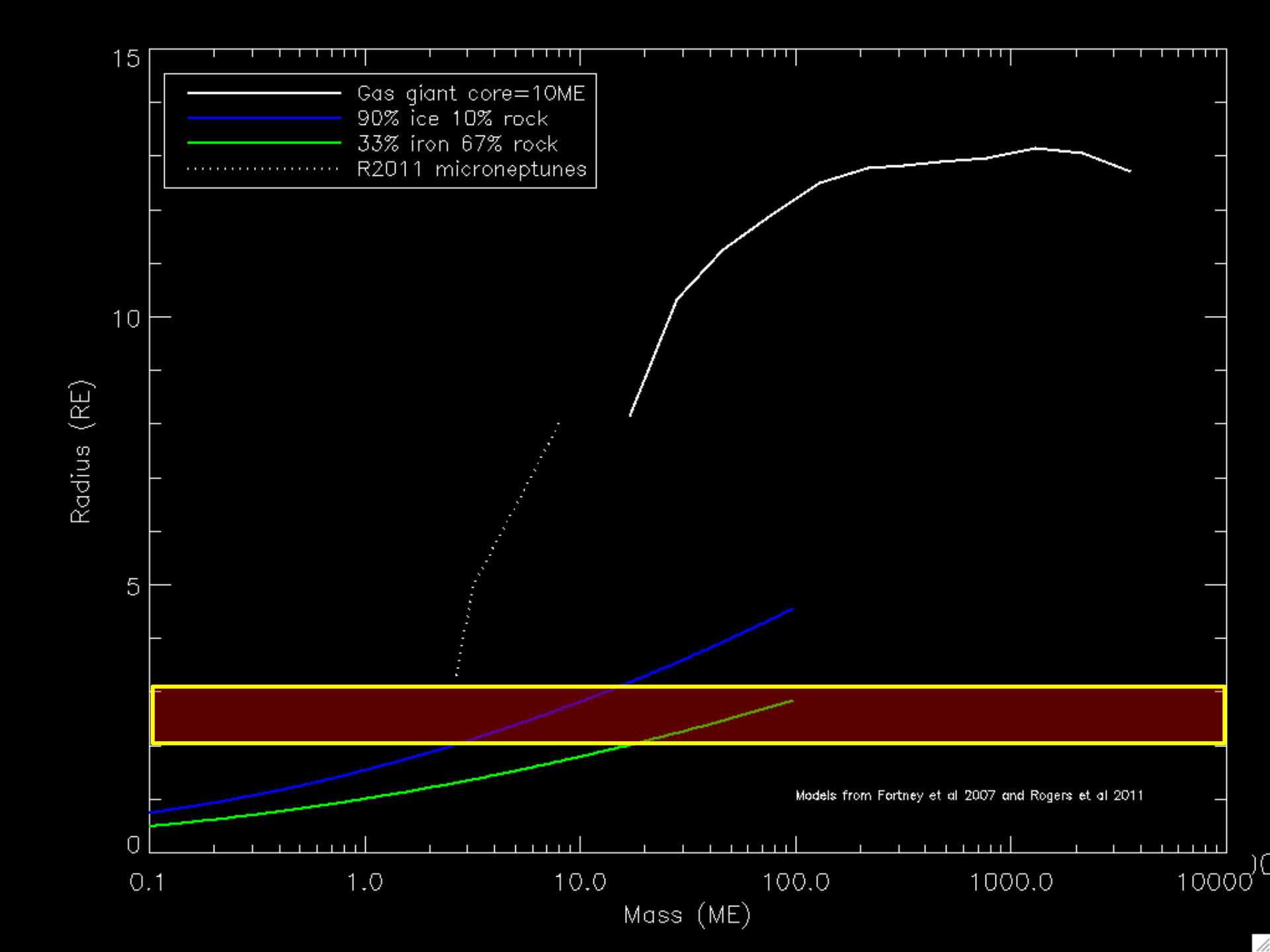

HR8799 c
Model Atmosphere
H2O lines
CO lines
CH4 lines
Speckle
Correlation
velocity (km/sec)
1.5
1.0
0.5
0.0
−0.5
−1500
−1000
−500
0
500
1000
1500

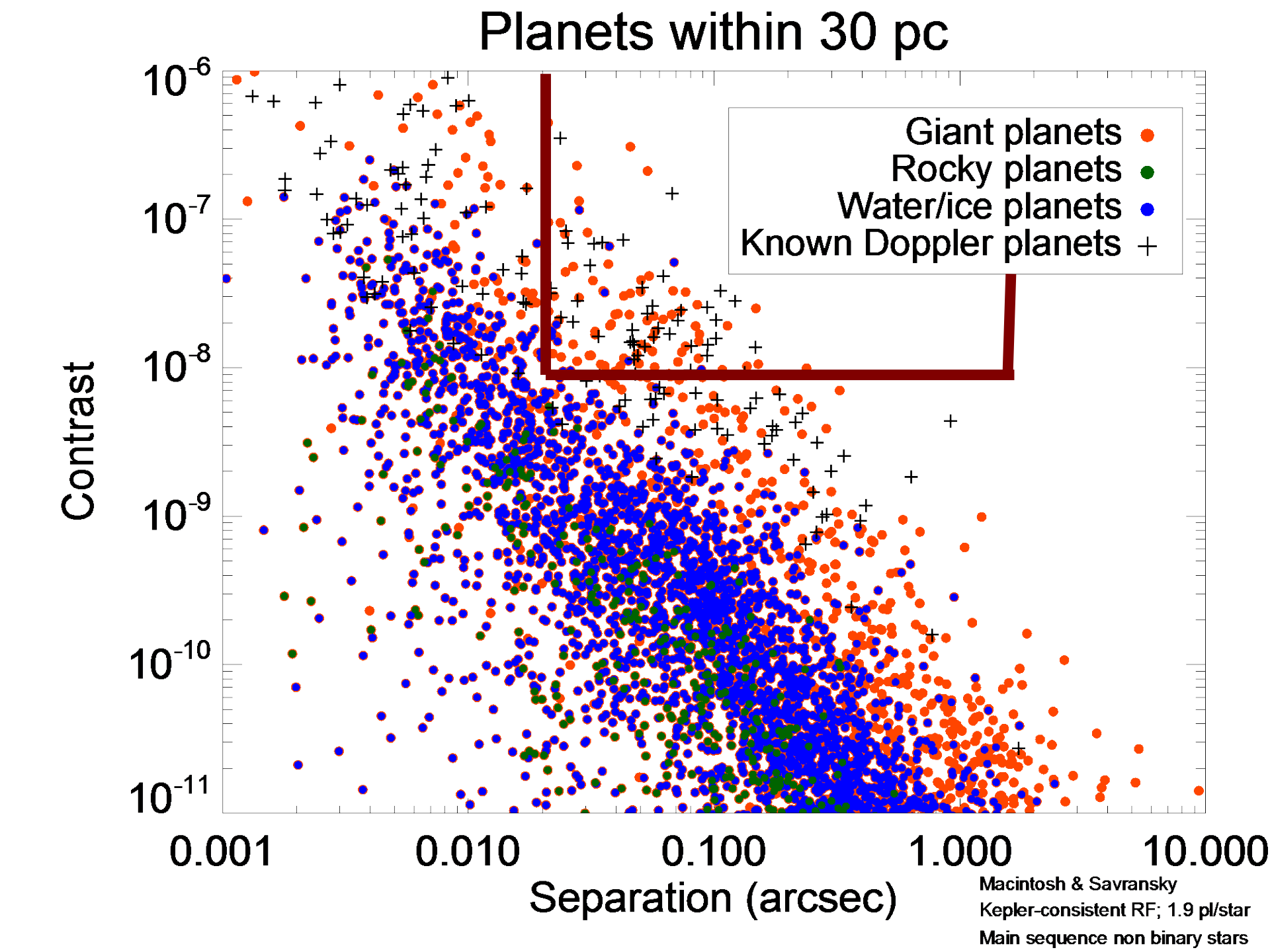
Kepler has changed the exoplanet landscape



…but also introduced new mysteries

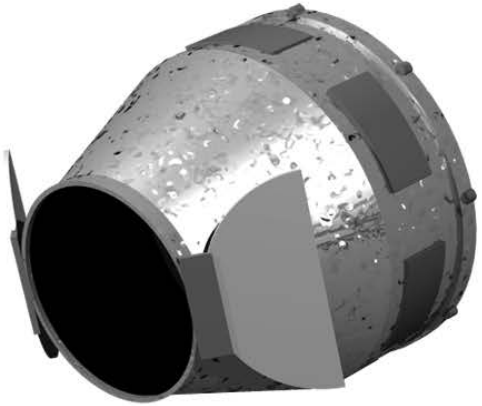


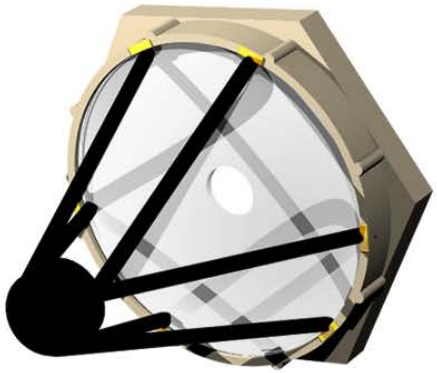

Gas giant core=10ME
90% ice 10% rock
33% iron 67% rock
R2011 microneptunes
Radius (RE)
Mass (ME)
15
10
5
0
0.1
1.0
10.0
100.0
1000.0
10000
Models from Fortney et al 2007 and Rogers et al 2011

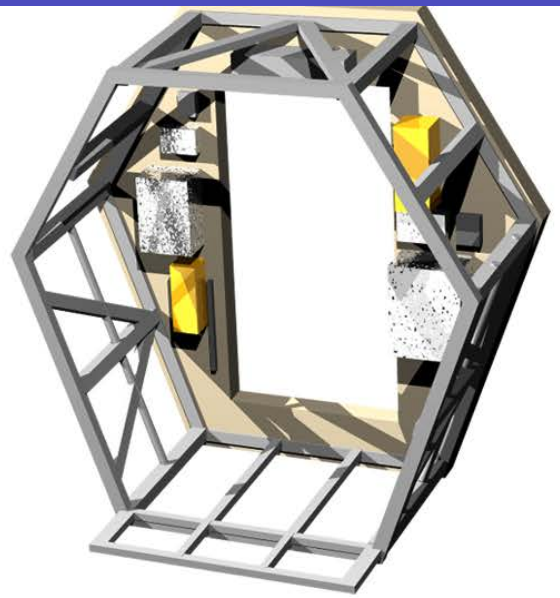

Planets within 30 pc
Giant planets
Rocky planets
Water/ice planets
Known Doppler planets
Contrast
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.001
0.010
0.100
1.000
10.000
Separation (arcsec)
Macintosh & Savransky
Kepler-consistent RF; 1.9 pl/star
Main sequence non binary stars

Landscape for space missions has changed

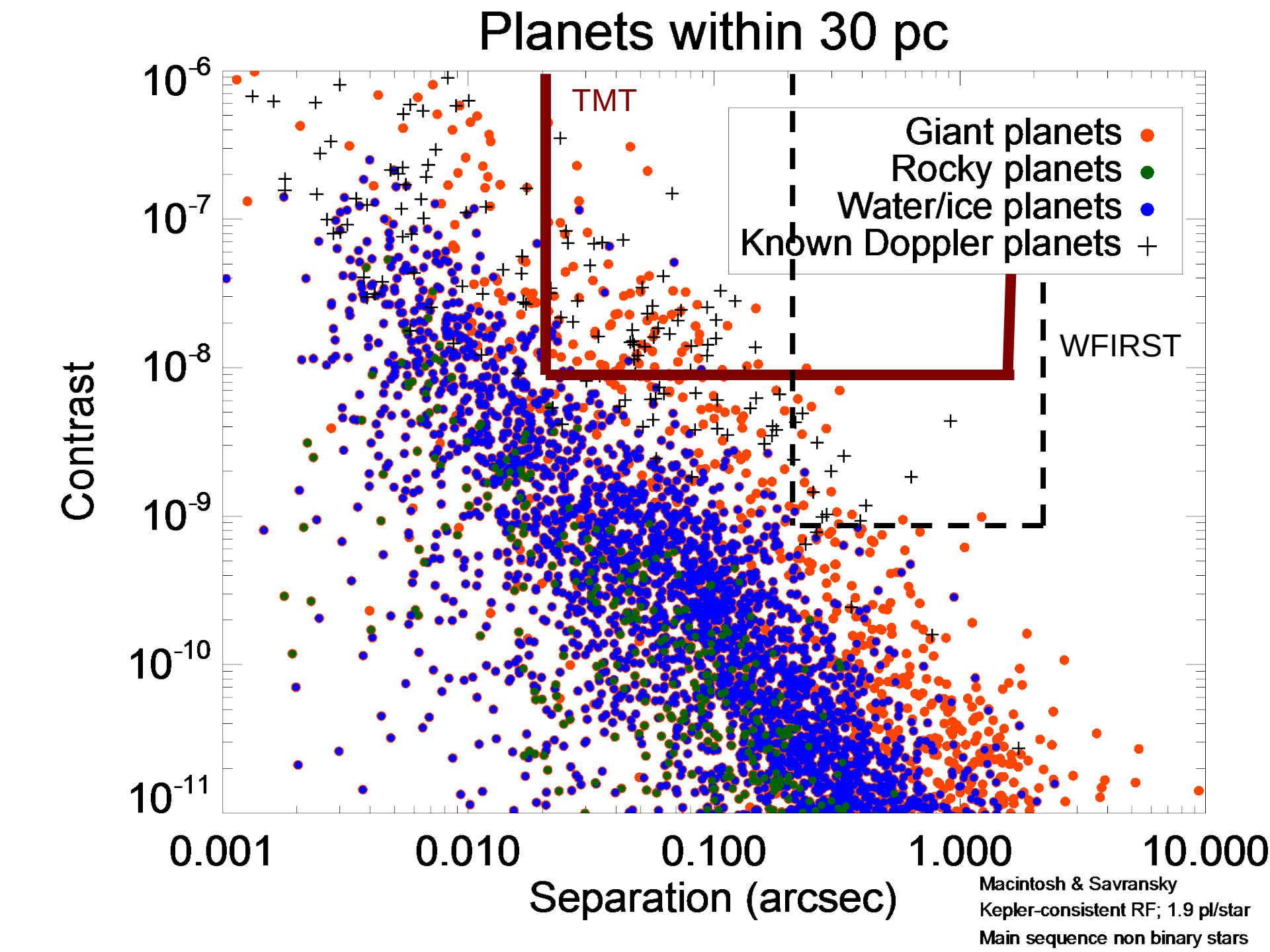
- **Large terrestrial planet-finding missions more than a decade away (though significant progress has been made)**
- **WFIRST 2.4m will likely have a coronagraph**
  - Lowres visible-light spectra of mature planets



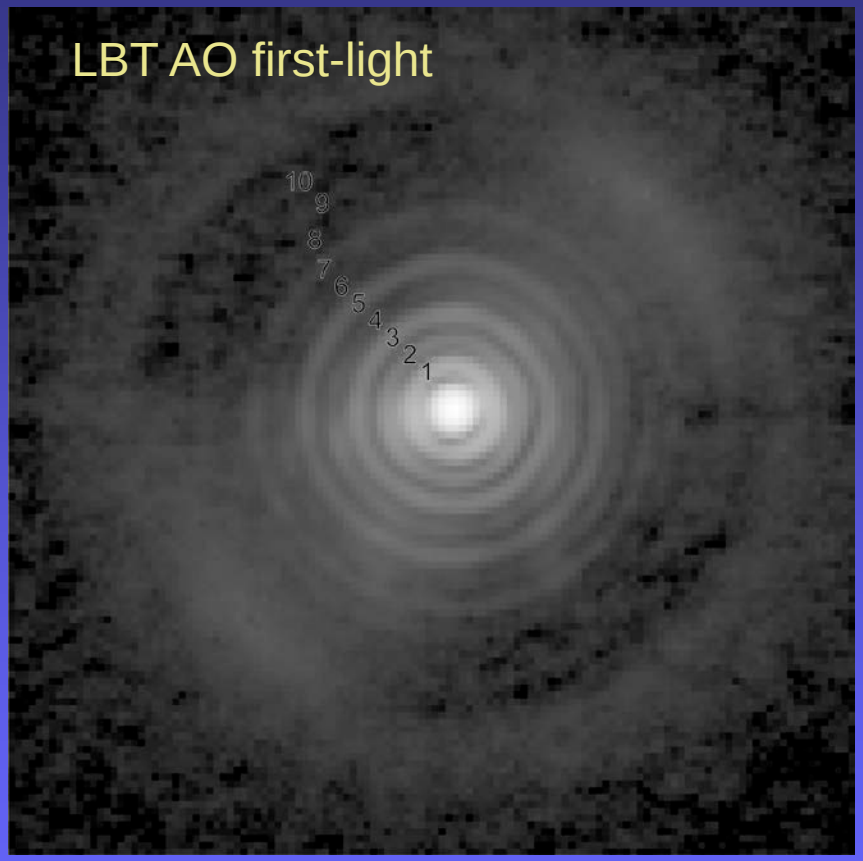


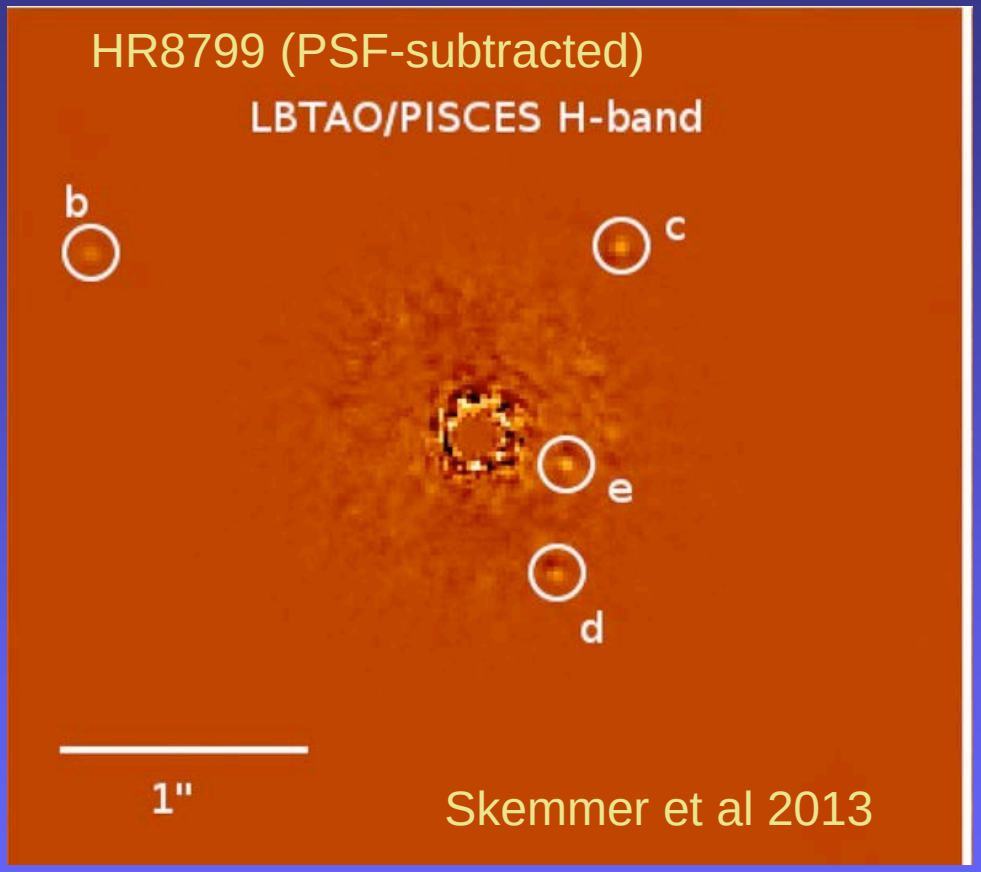


WFIRST 2.4m telescope with NRO assets

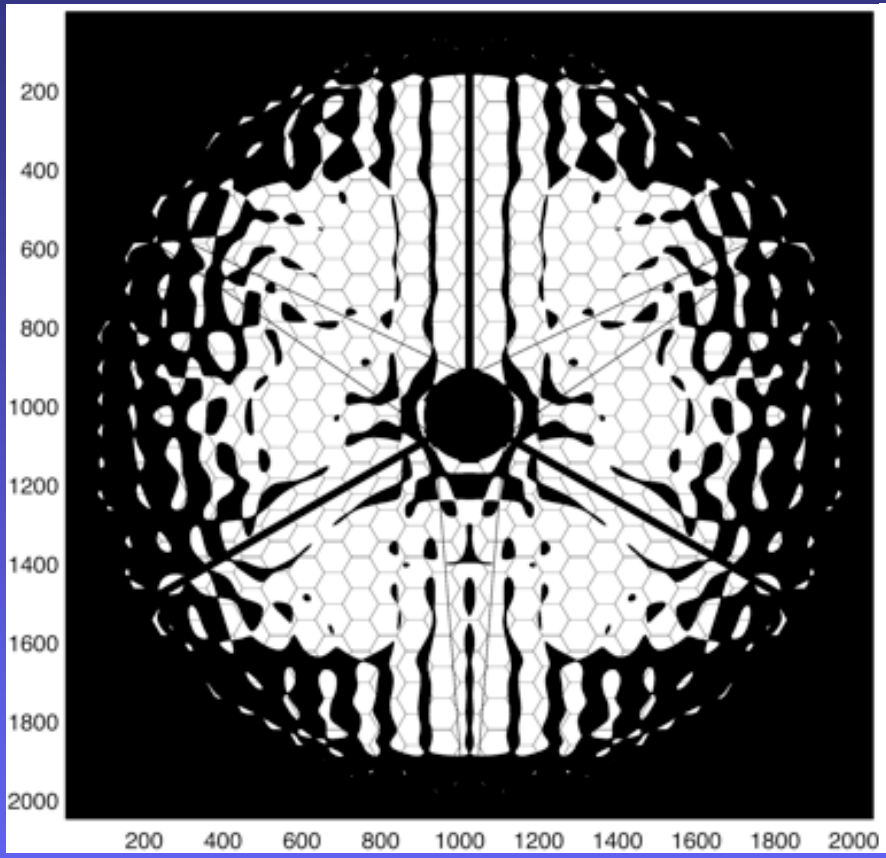

Planets within 30 pc
TMT
WFIRST
Giant planets
Rocky planets
Water/ice planets
Known Doppler planets
Contrast
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.001
0.010
0.100
1.000
10.000
Separation (arcsec)
Macintosh & Savransky
Kepler-consistent RF; 1.9 pl/star
Main sequence non binary stars

LBT & Magellan show power of pyramid sensors

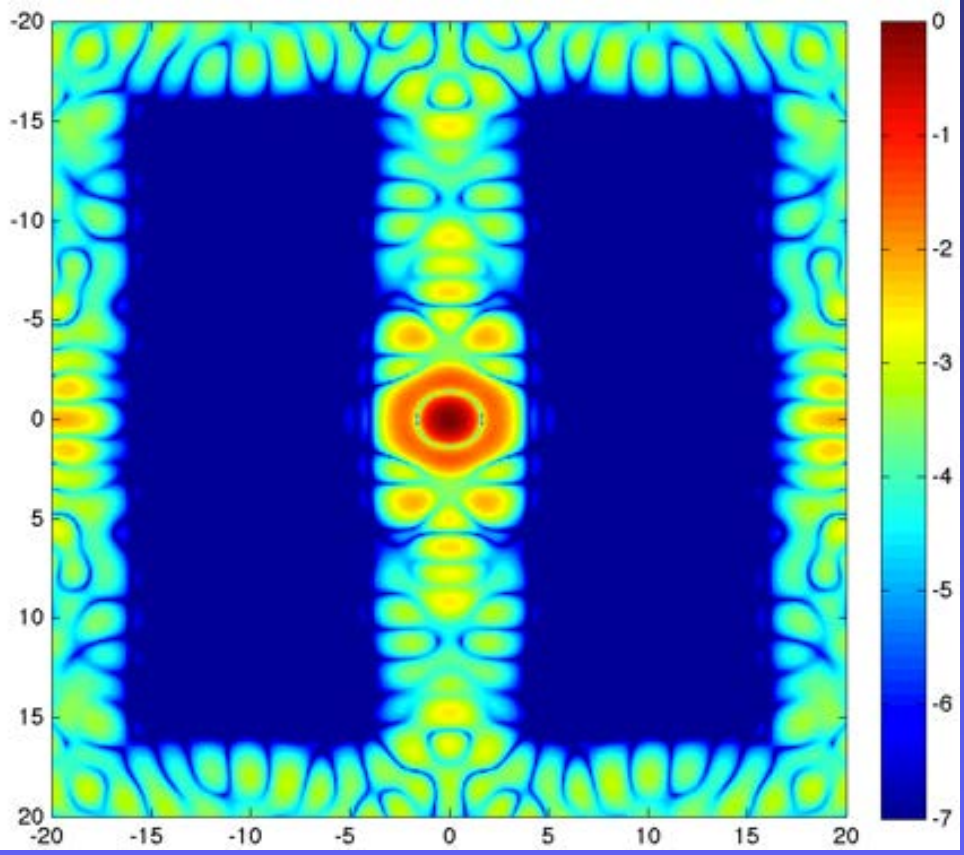




New coronagraph concepts (e.g. Carlotti & Kasdin)

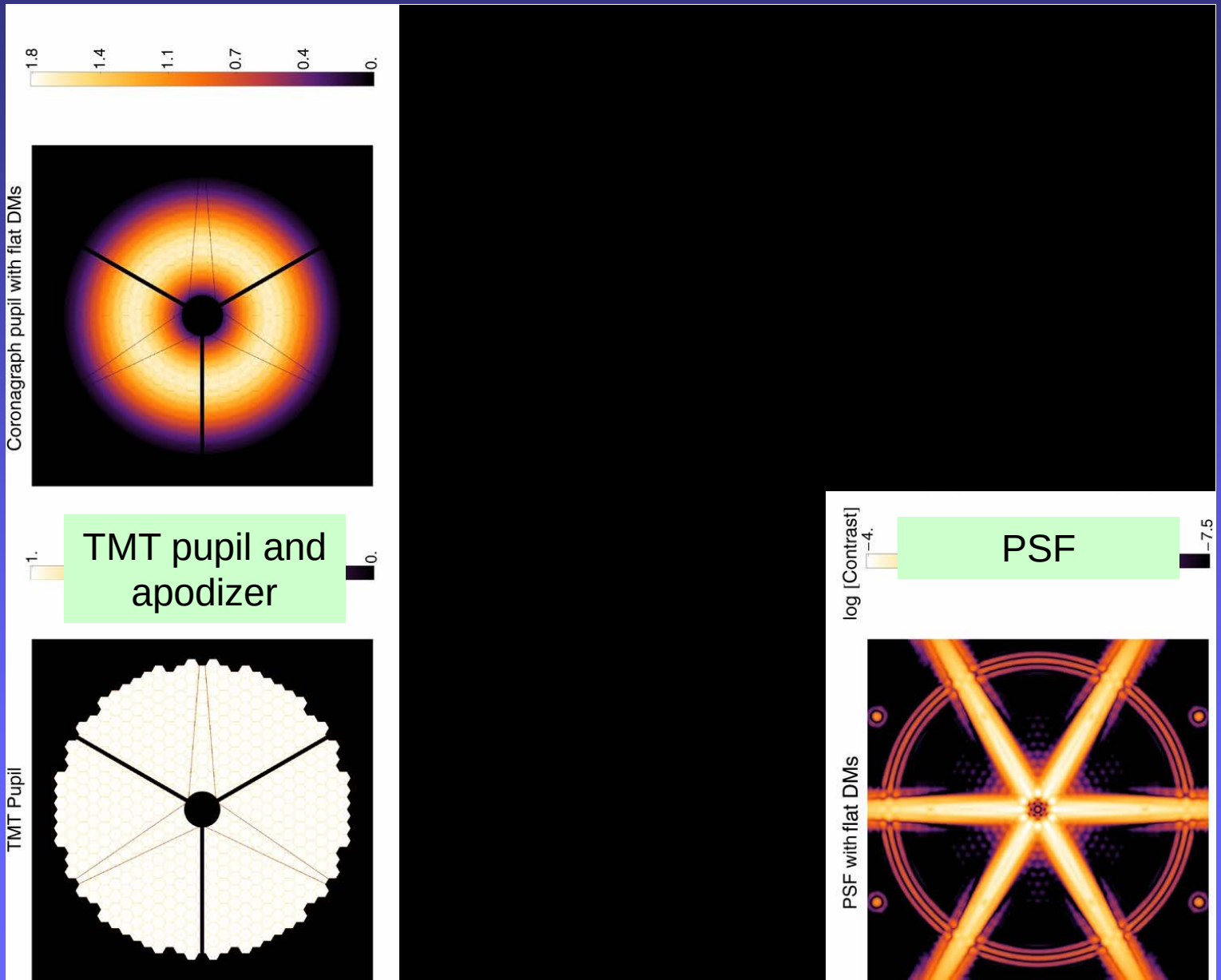


Segmented telescope pupil mask



PSF 10^{-7} contrast at 3-4 λ/D

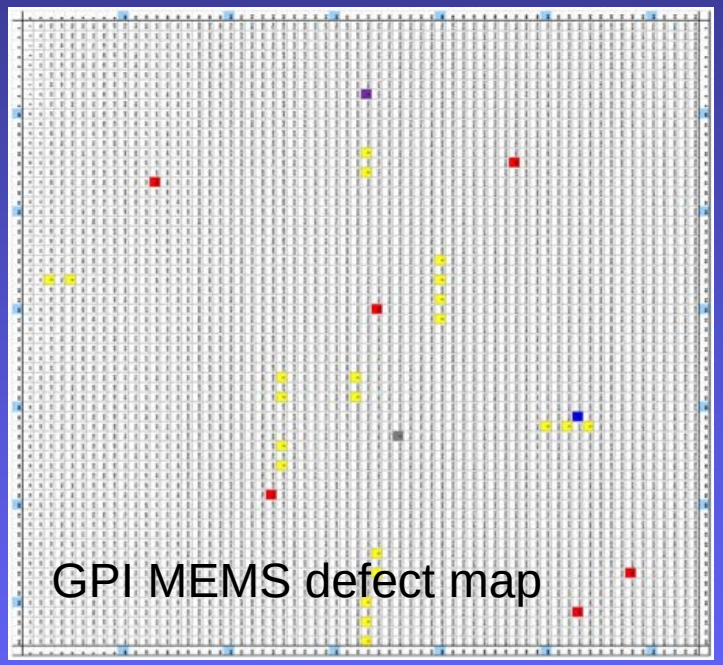
DM correction of TMT diffraction
Puyeo & Norman 2013



Things we don't have yet…

10,000 actuator+ DMs

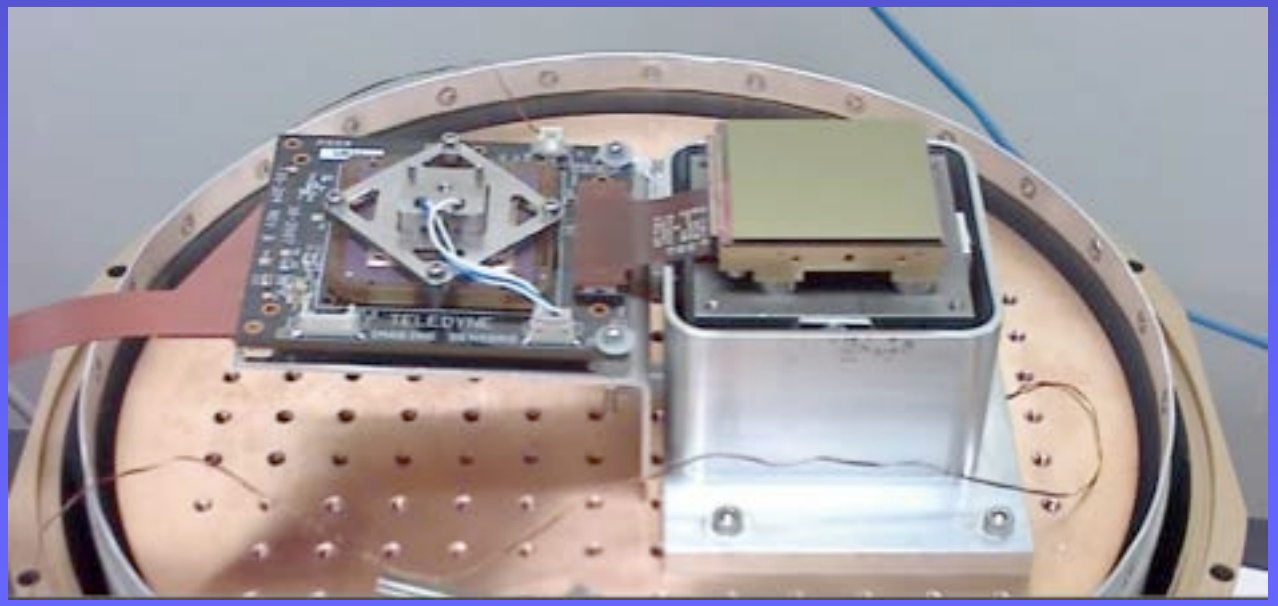
- PFI baseline was 100-actuator diameter mirror
- Largest MEMS available is 64x64 (and that has low yield)
- MEMS multiplexing development has been slow
- Xinetics mirrors are a possibility but low stroke



Things we don't have yet…

10,000 pixel IR WFS detectors

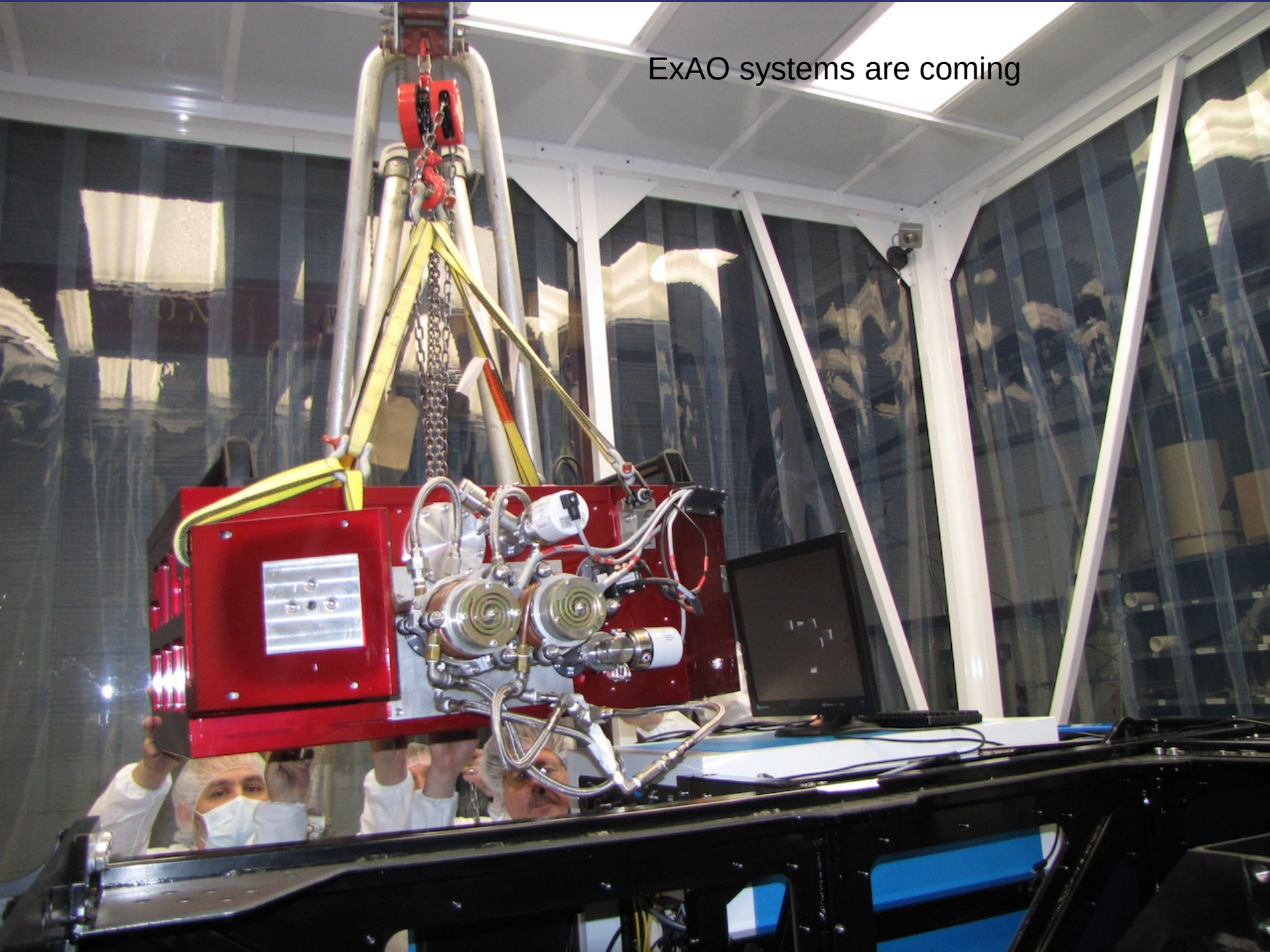
- **3-5 electrons noise**
- **YJHK response**
- **kHz frame rates**



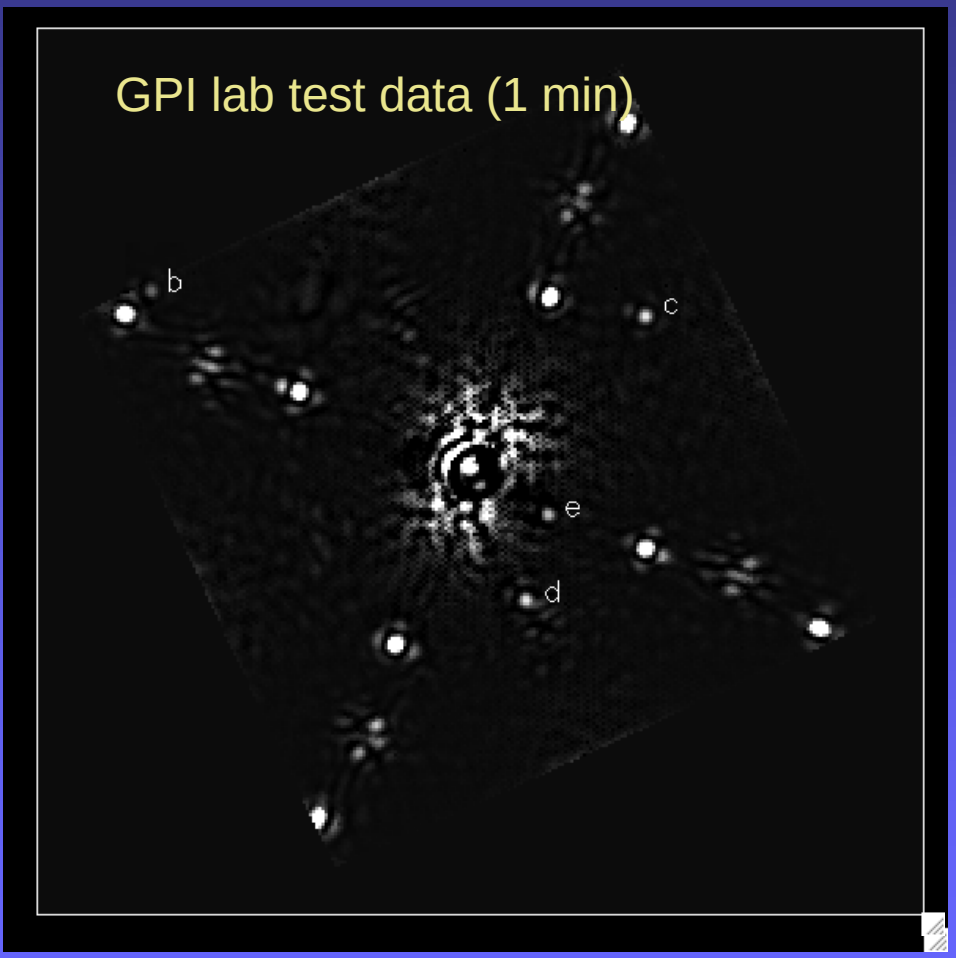
Things we don't have yet…

Flying cars

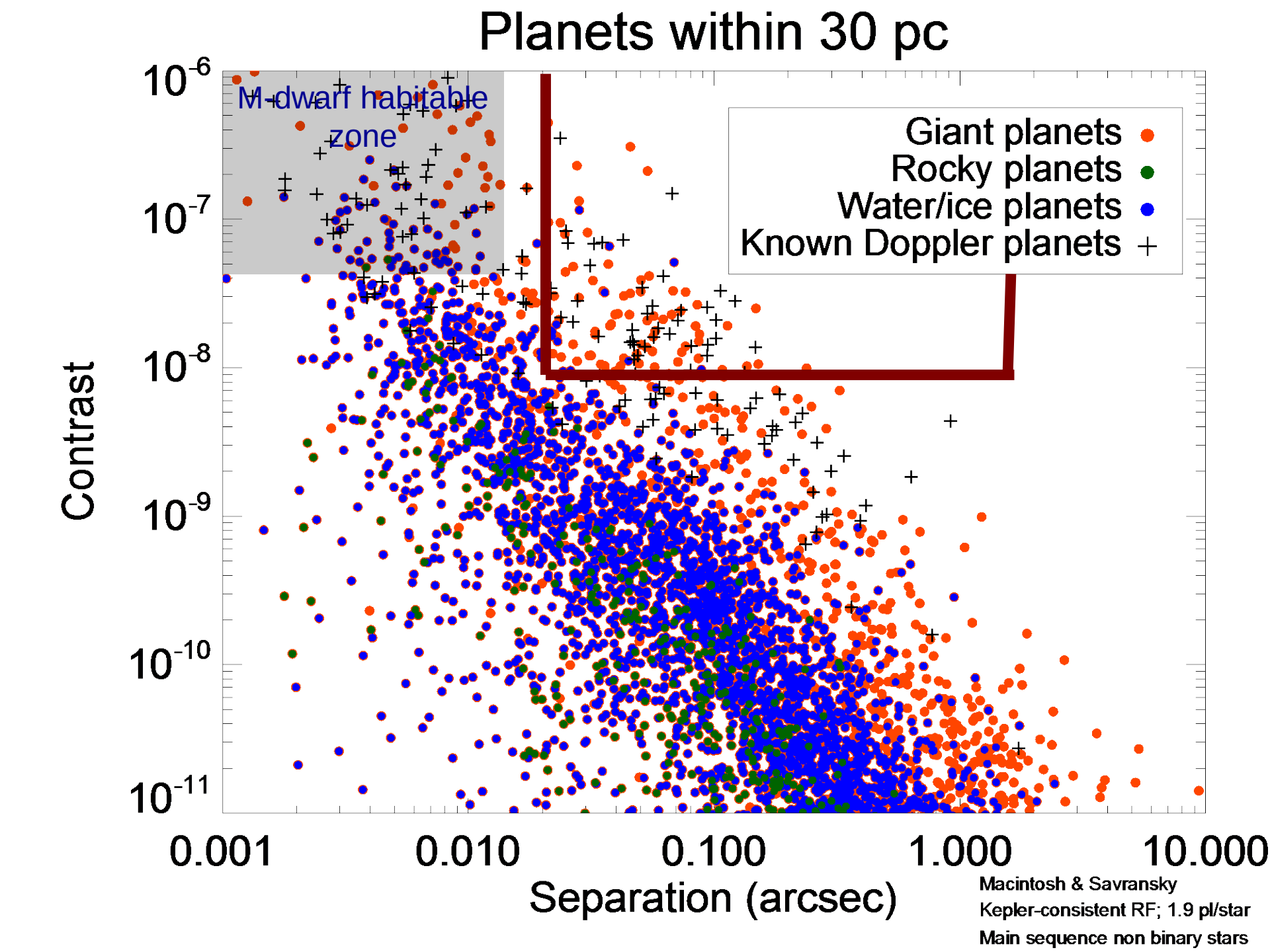
- I blame TMT project office for the lack of a sustained flying-car technology development program


ExAO systems are coming

HR8799 planets: GPI vs Keck



Keck (1 hour)


Planets within 30 pc
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0.001
0.010
0.100
1.000
10.000
Separation (arcsec)
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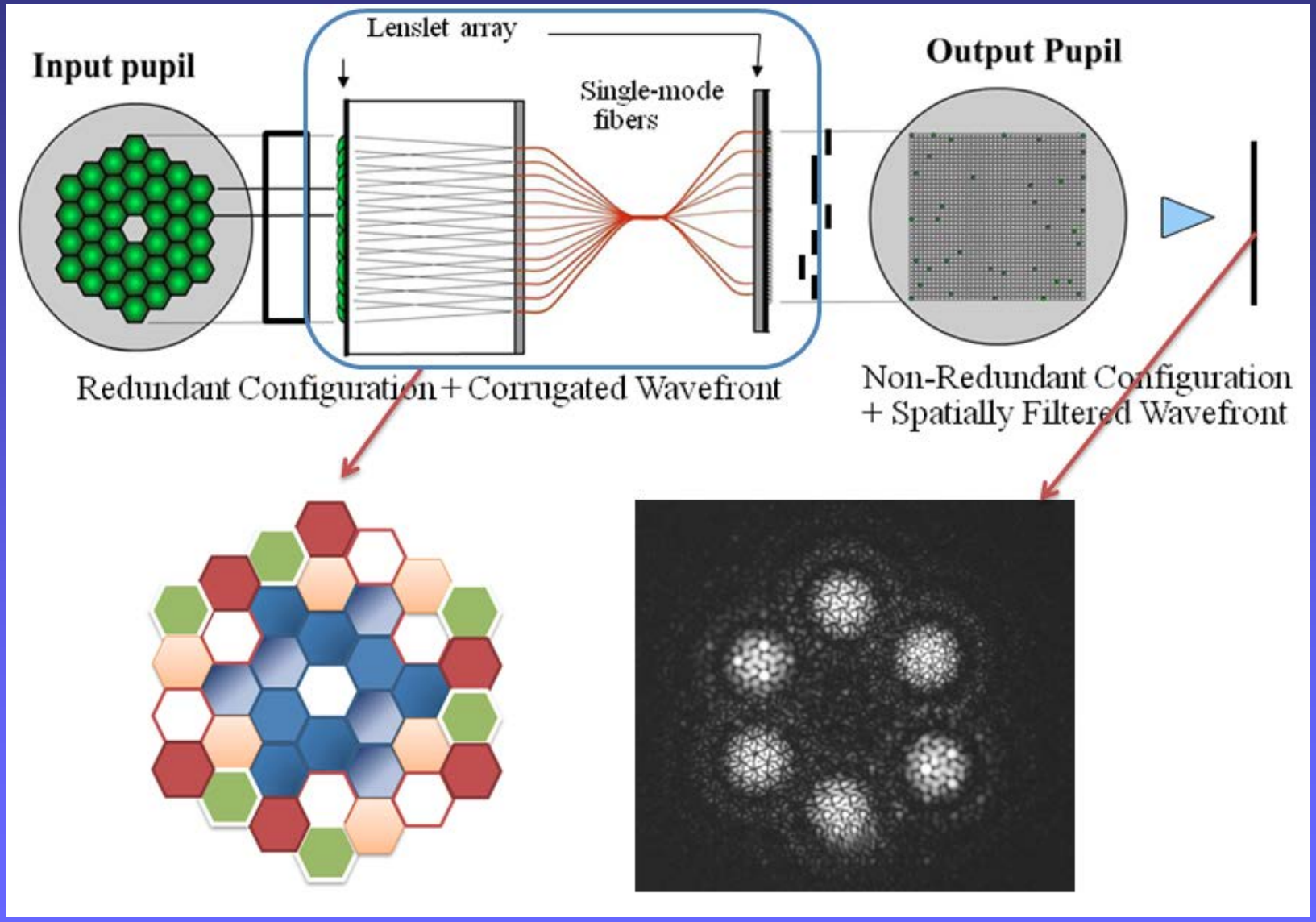
Main sequence non binary stars

Multiple non-redundant aperture masking (SEIT, Matsuo et al)



Conclusions

- **Direct planet imaging on TMT is even more compelling than in 2006**
  - A handful of imaged exoplanets have led to significant progress in studying planet properties
  - High-resolution spectra and broad photometric coverage are important
  - Kepler has identified a large population of unknown objects accessible to TMT (“mini-neptunes” or “super-earths”)
  - Pushing inner working angle is critical
- **Technology marches on**
  - Pyramid sensors are becoming proven and powerful
  - Many coronagraph concepts for segmented apertures
  - MEMS and detector development lags
  - More investment is needed in TMT-specific coronagraphs, WFS
- **We should change the PFI name to something more up to date**
  - Planetary Systems Imager
- **We should build it!**