Coronagraphy review and WFIRST/AFTA

Bruce Macintosh

Based on work by GPI / TMT / WFIRST/AFTA teams

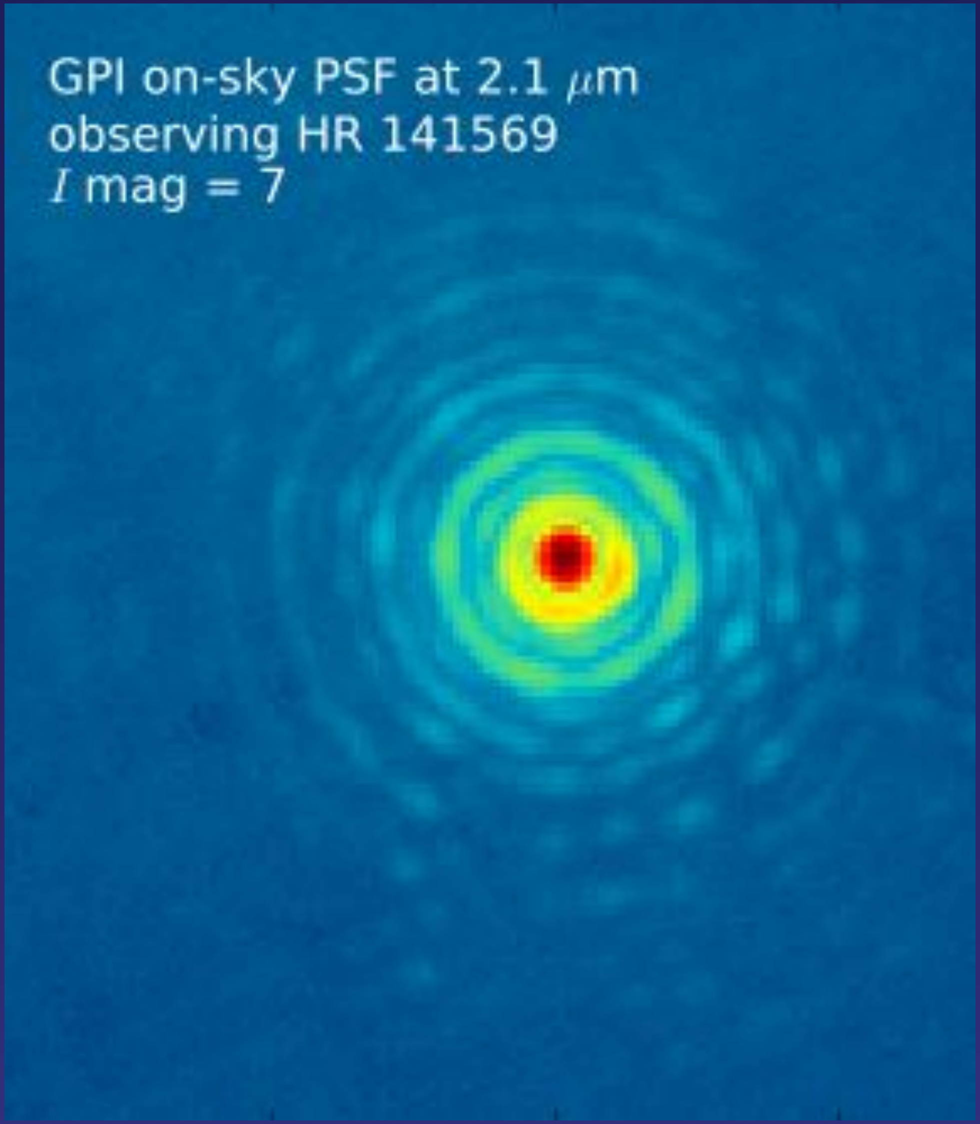
Christian Marois, Dmitry Savransky, Wes Traub, Tom Greene, Mark Marley, Jeremy Kasdin, James Graham, et al.

Outline

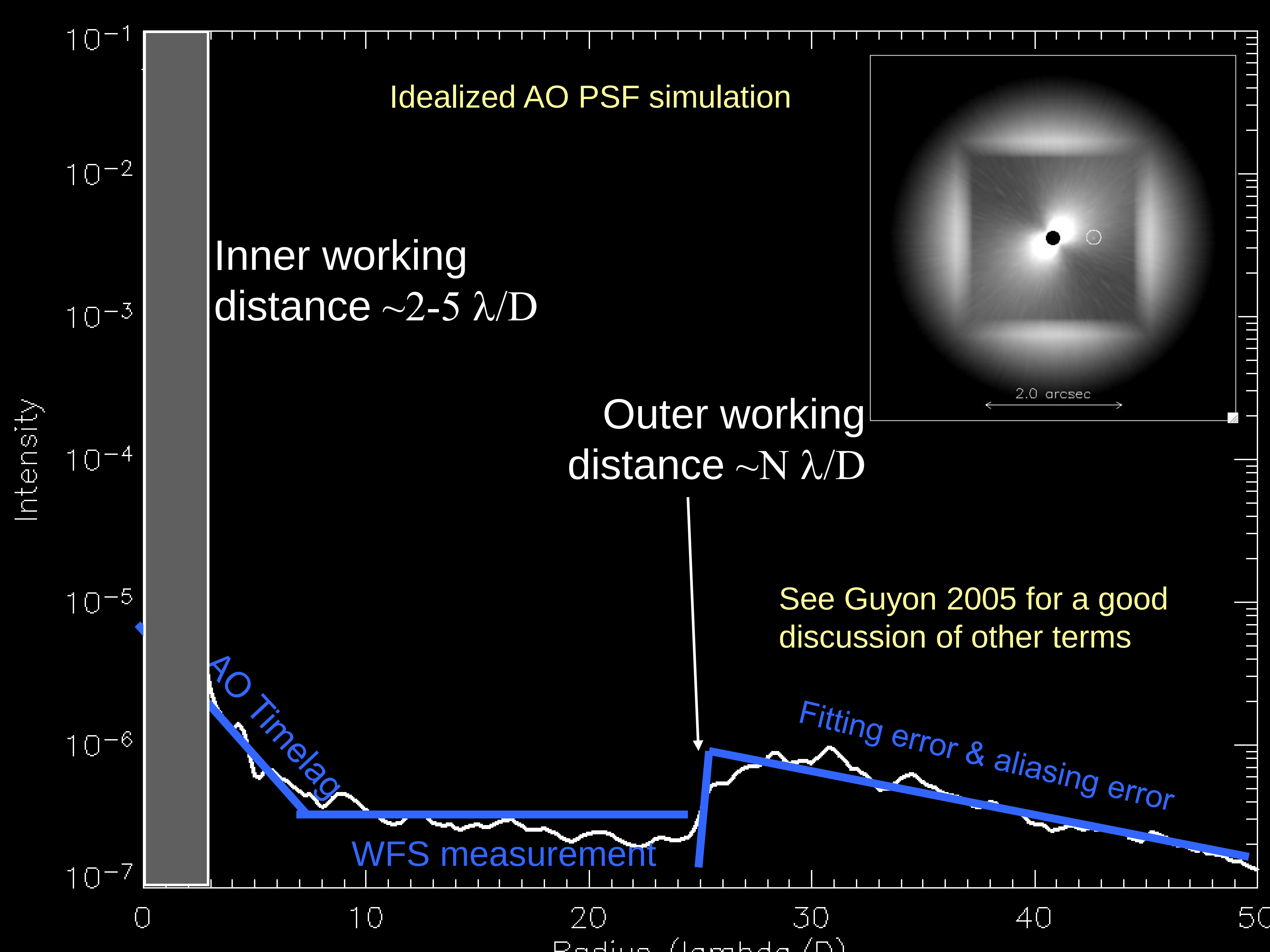
- **Overview of basic high-contrast imaging**
- **Comparison between ground and space**
- **GPI as an example of ground-based imaging**
  - Performance
  - Perfrormance vs simulations
- **WFIRST/AFTA**
  - Science goals
  - Performance update
- **ELTs**
  - General overview
  - TMT examples
  - Science roles

High-contrast imaging basics

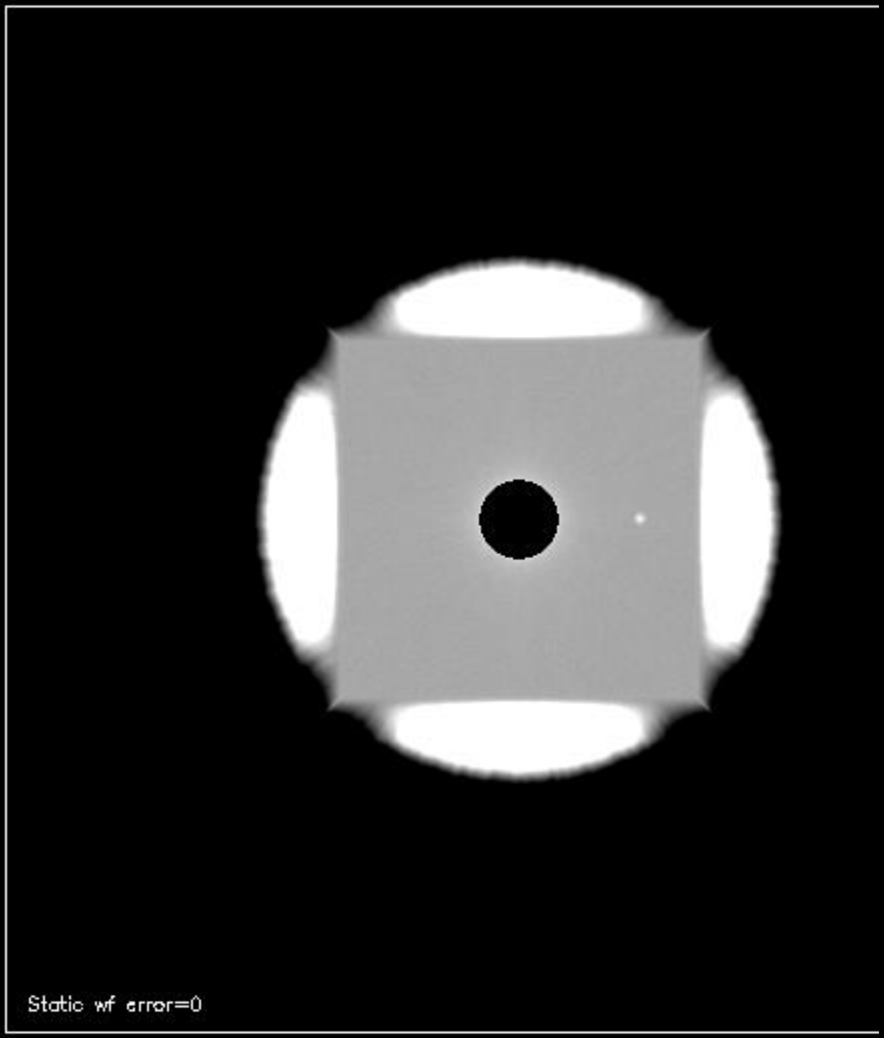
- **First-order high-Strehl PSF is a combination of several things**
- **Fourier relation between pupil and focal planes**
- **Diffraction pattern**
  – Controlled by a coronagraph; dominates at small angles
- **Phase error speckle pattern**
  – Power spectrum of phase; dominates at large angles
- **Cross-terms**
  – Phase errors modulate the Airy pattern
- **Amplitude error speckle pattern**
  – Different chromatic behvior

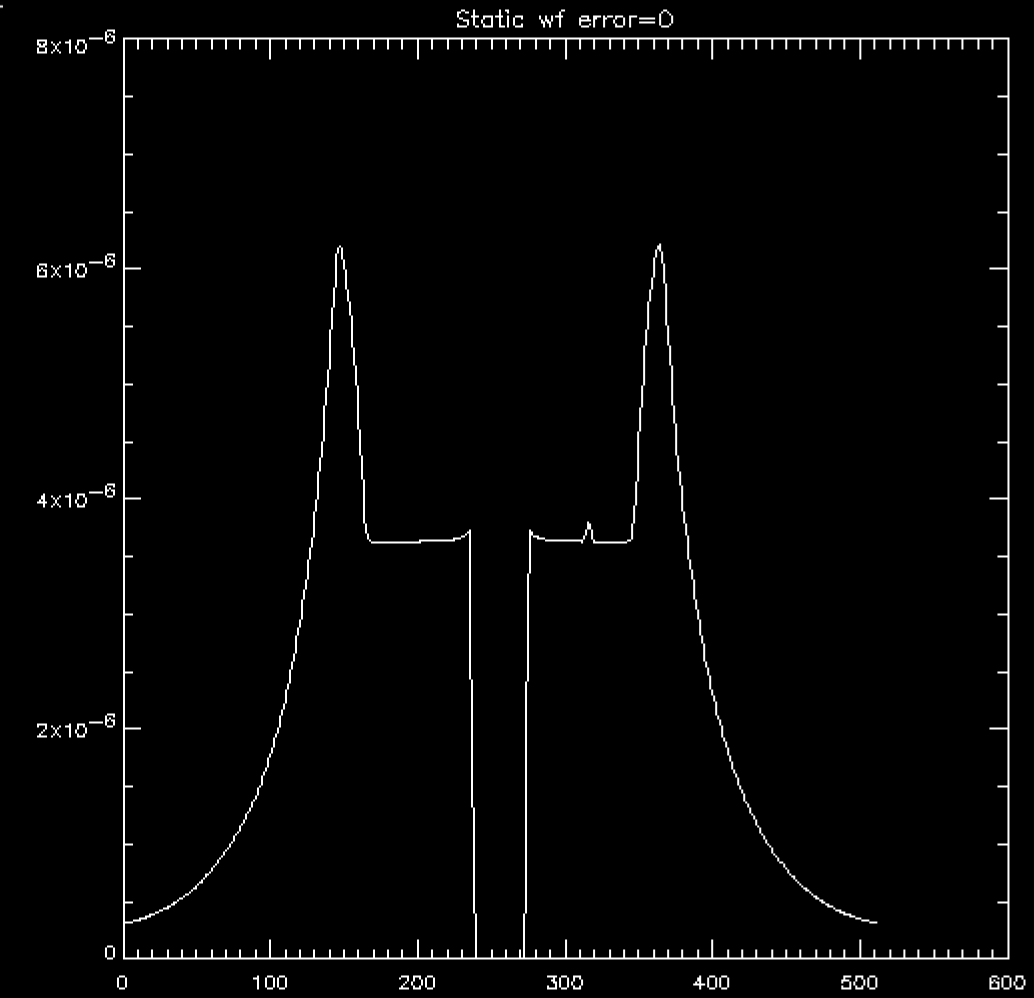


Cf Perrin et al 2003

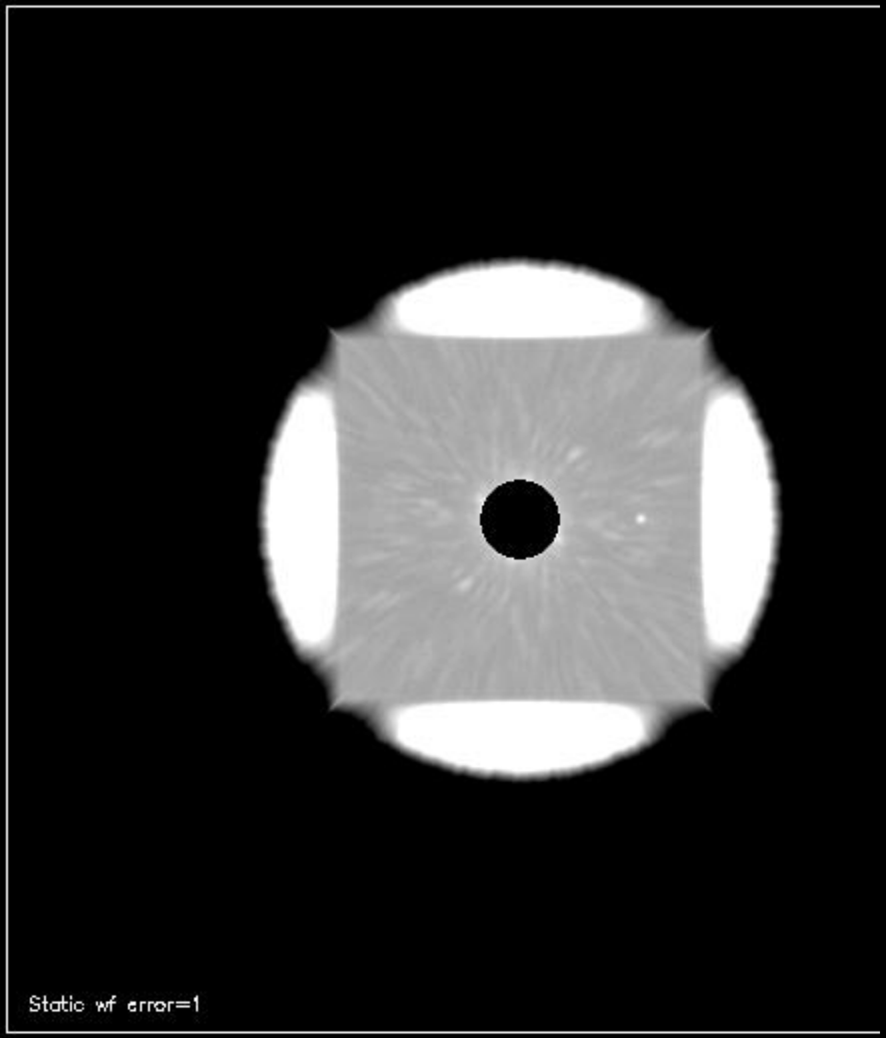

Idealized AO PSF simulation
Inner working distance ~2-5 λ/D
Outer working distance ~N λ/D
See Guyon 2005 for a good discussion of other terms
AO Timelag
WFS measurement
Fitting error & aliasing error
2.0 arcsec
Intensity
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
0
10
20
30
40
50

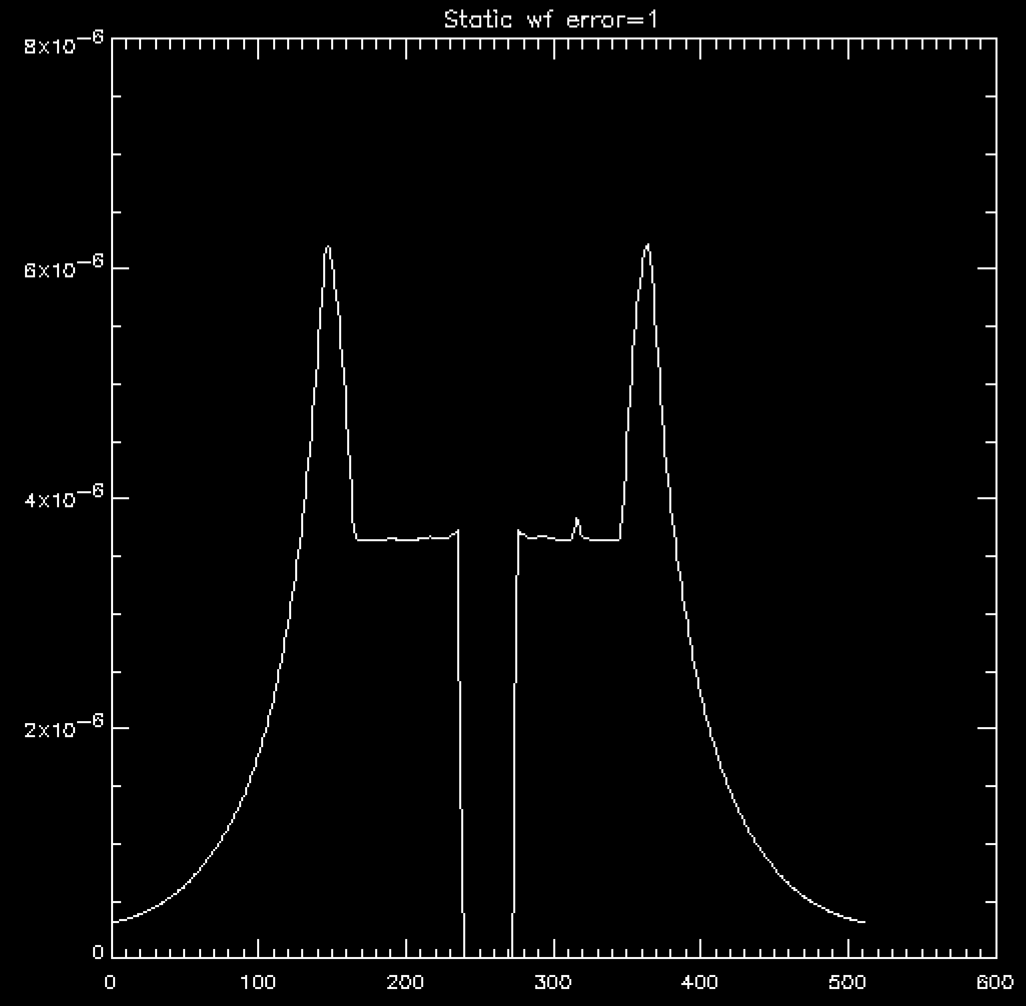
ExAO 0 nm static errors, 5 MJ/500 MYr planet, 15 minute integration



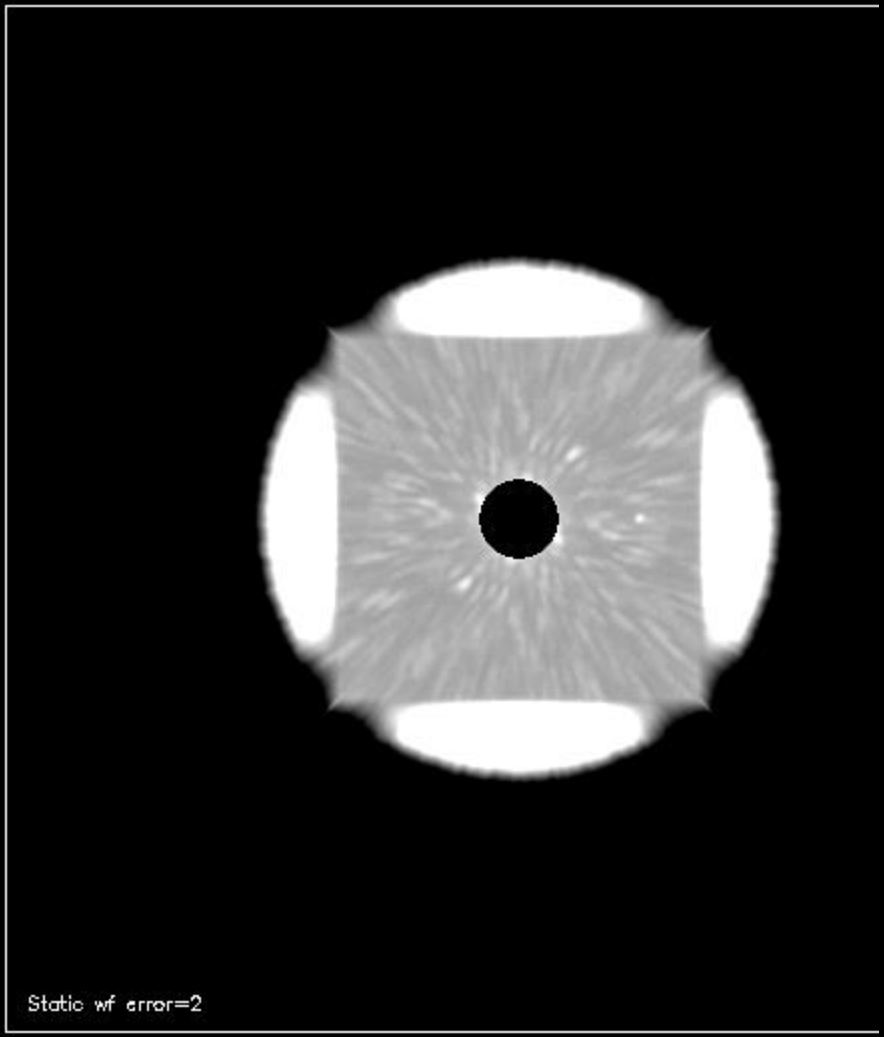


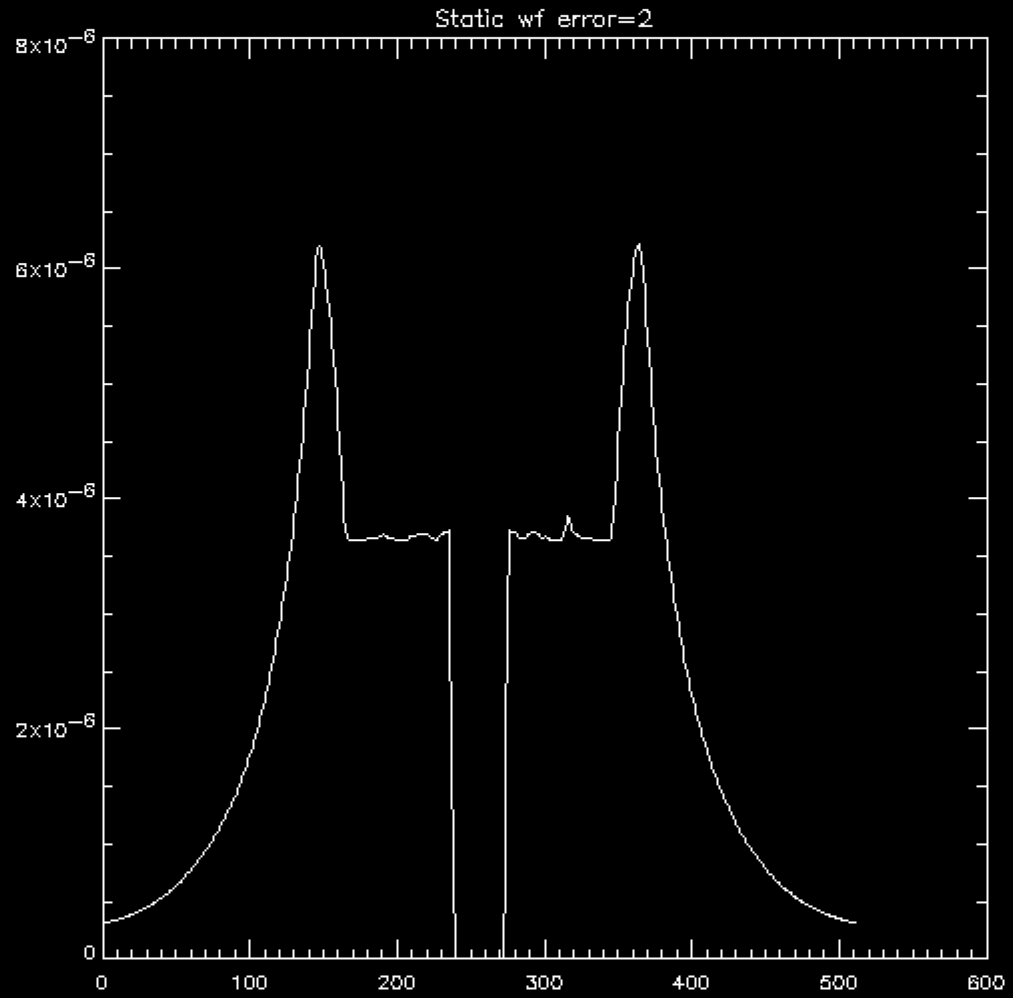
ExAO 1 nm static errors, 5 MJ/500 MYr planet, 15 minute integration



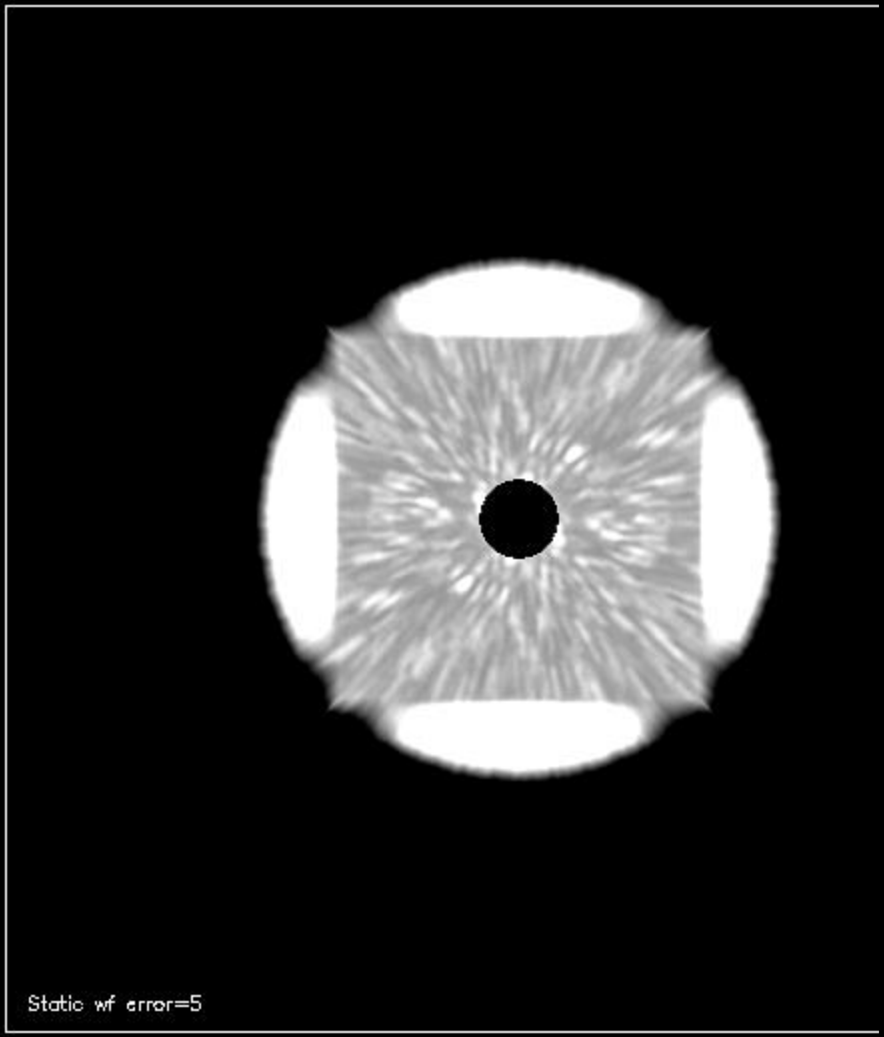


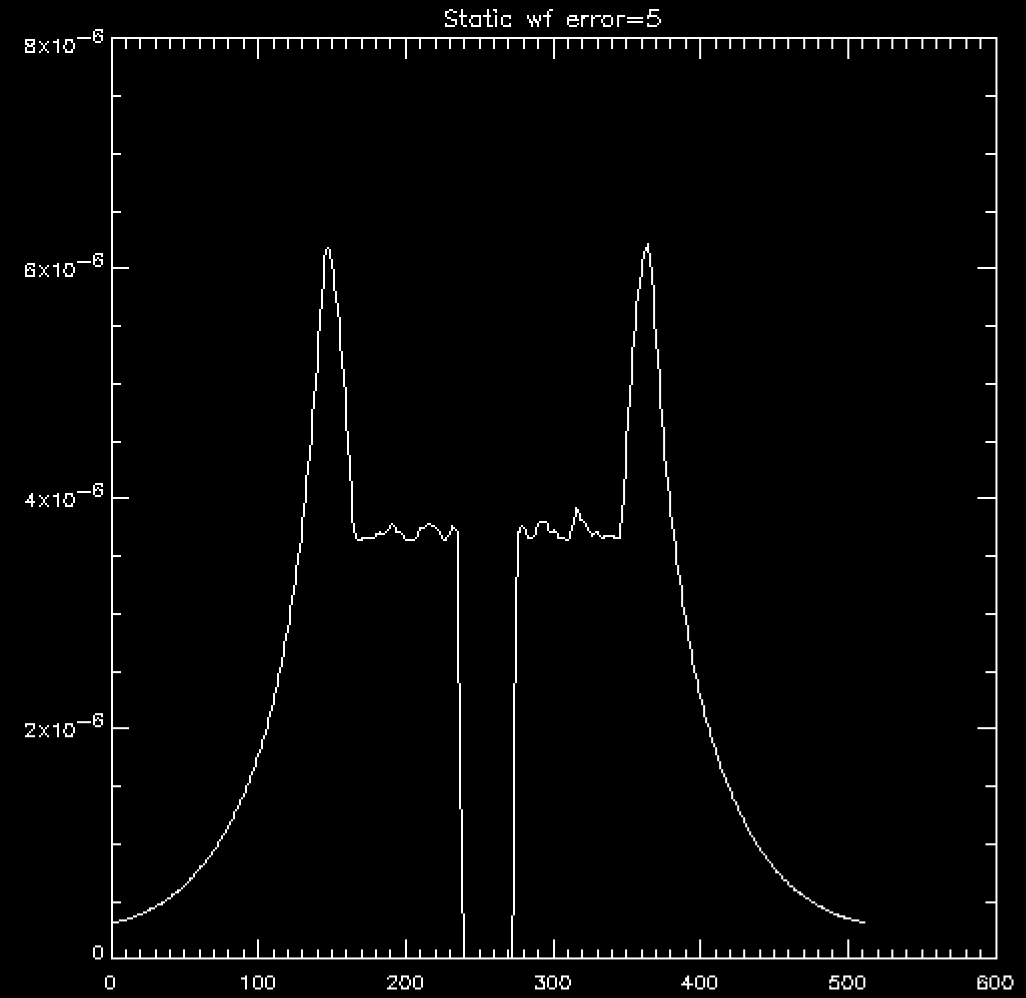
ExAO 2 nm static errors, 5 MJ/500 MYr planet, 15 minute integration





ExAO 5 nm static errors, 5 MJ/500 MYr planet, 15 minute integration



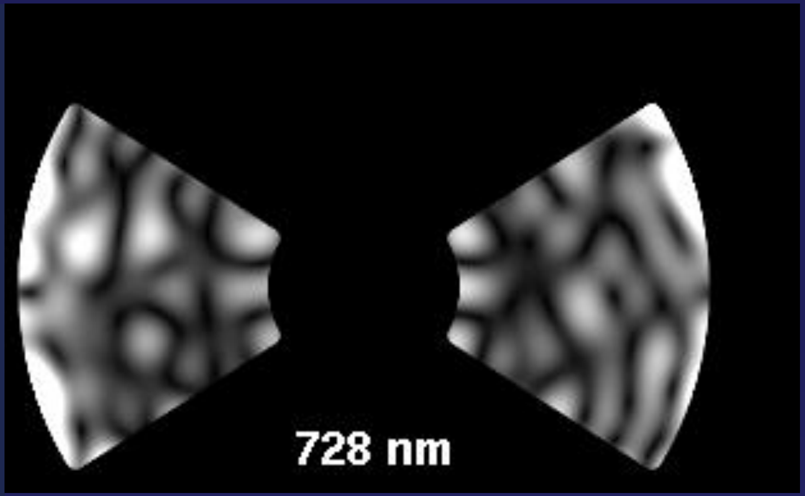


Ground-based high-contrast PSFs

- **PSF intensity dominated by dynamic wavefront error terms (50-300 nm RMS)**
  - AOWFS measurement noise
  - Timelag errors
  - Halo intensity is a strong function of target brightness, atmosphere parameters
- **Photon noise from this halo is one contrast error term**
- **Small quasi-static wavefront errors – non-common-path errors and their evolution - can completely dominate contrast**
  - Aliasing and uncorrectable telescope errors are also significant
  - 10^7 contrast - ~1 nm
  - 10^9 contrast – 0.1 nm
  - Post processing techniques attempt to remove these (λ or t)
  - Depends on temporal and chromatic stability of PSF
  - Speckle noise in a given image is never better than what would have been obtained by the same system in space

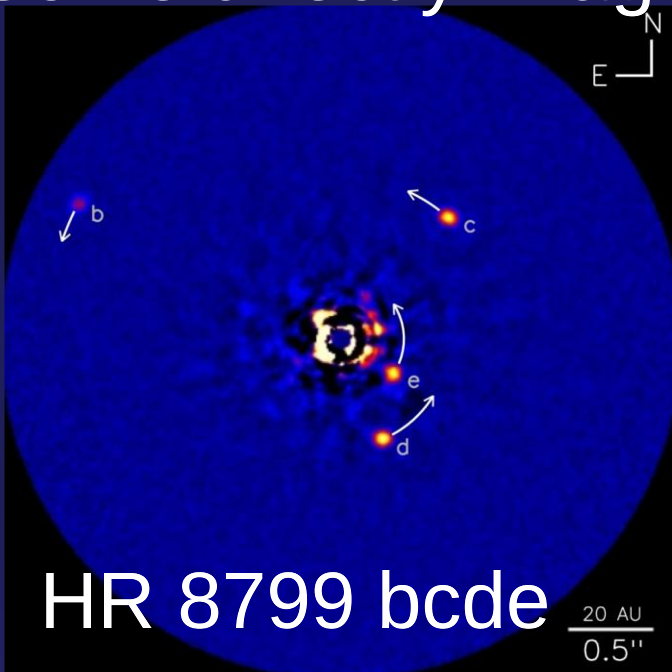
Space coronagraph PSFs

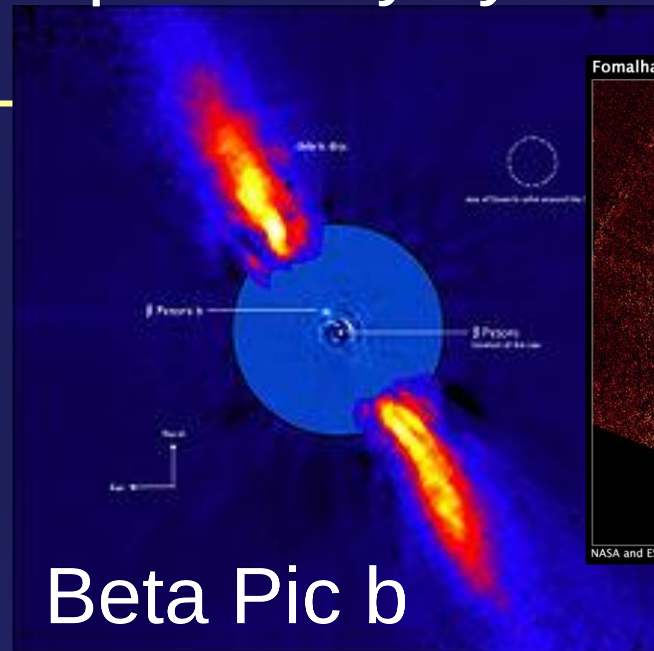
- **Small telescopes require high-performance coronagraphs**
  - Interesting science is always at the smallest possible angle
- **PSF dominated by static or slowly-evolving speckles**
- **Noise from speckle photon noise, speckle pattern / stability, foreground/background zodiacal dust, etc.**
- **Amplitude, polarization, Fresnel-propagation errors are significant**
  - Multiple DMs needed for correction
- **PSF is highly chromatic**
  - Monochromatic PSFs can be near-perfect
  - Chromaticity always sets the contrast floor

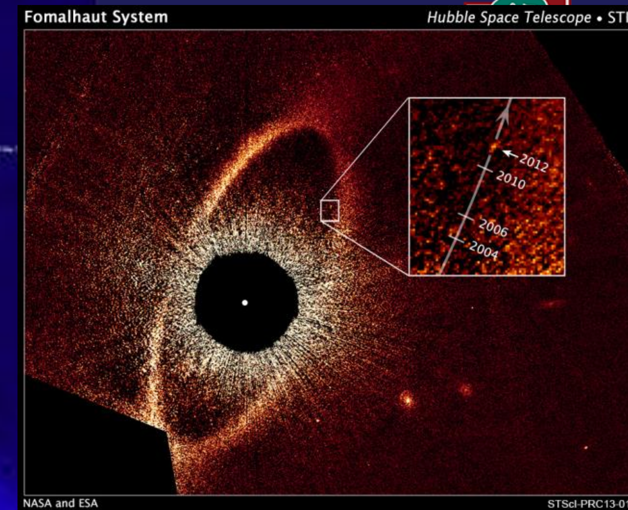


AFTA SP simulation by John Krist

Some directly imaged planetary systems

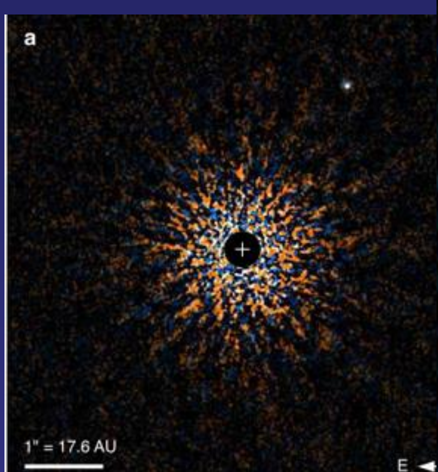




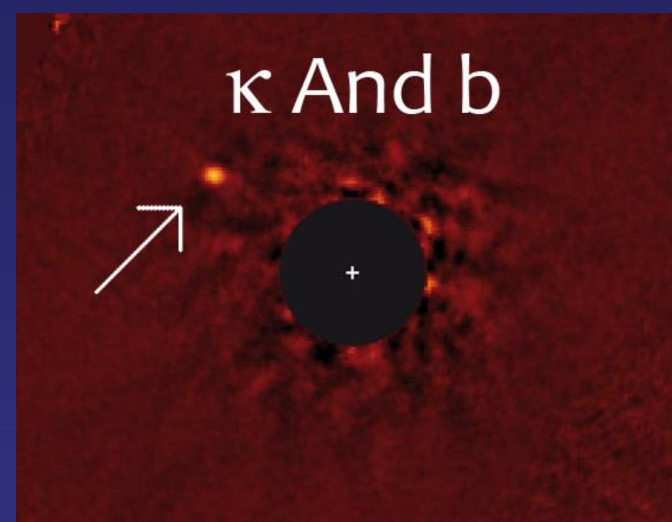


Fomalhaut b

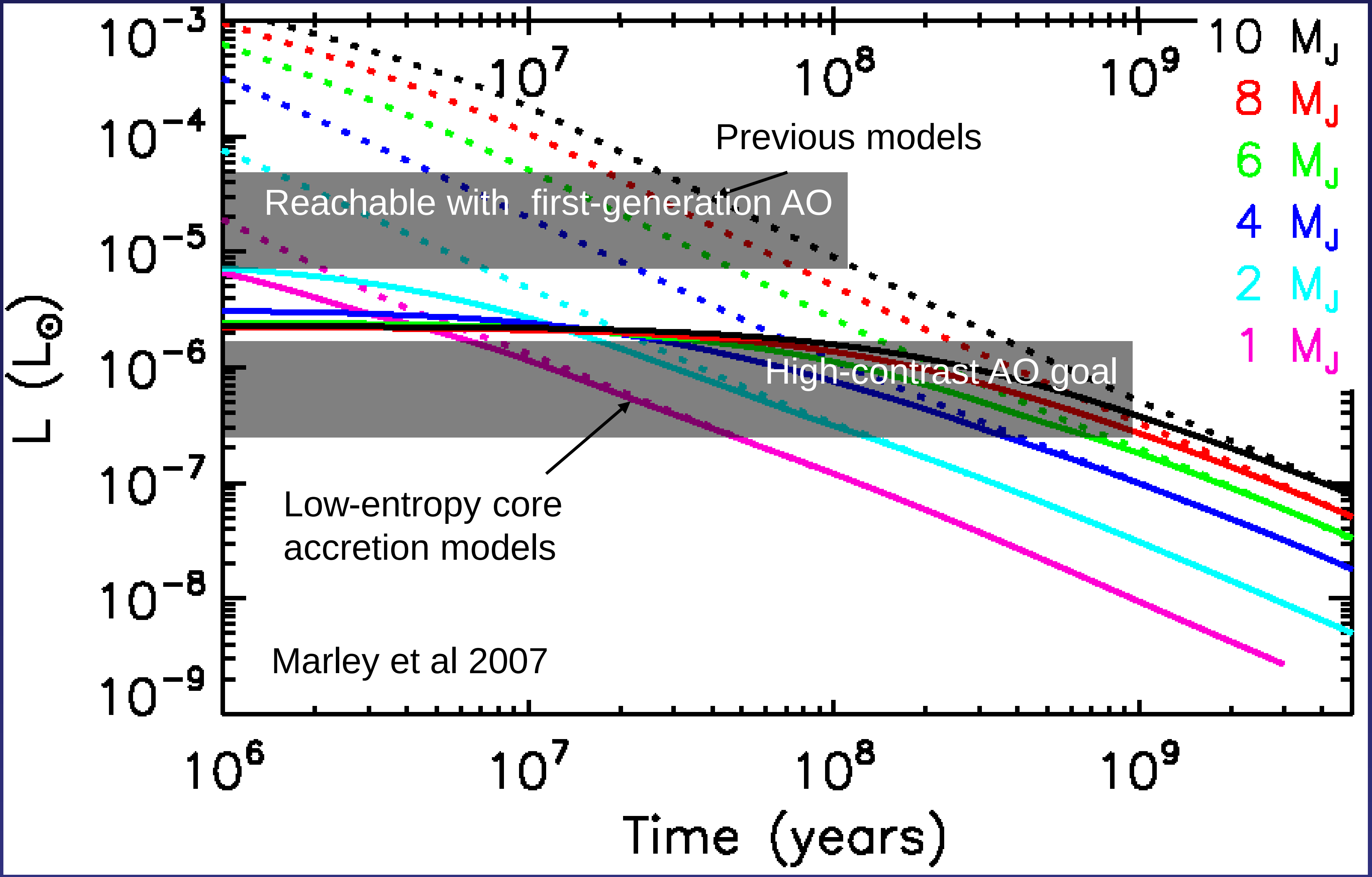
GJ 504 b



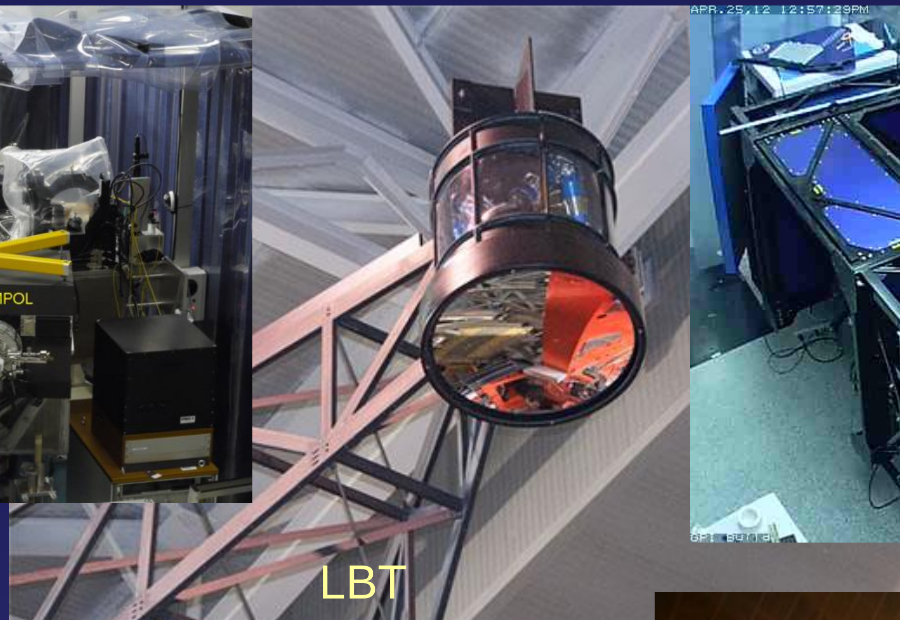
HD 95086 b

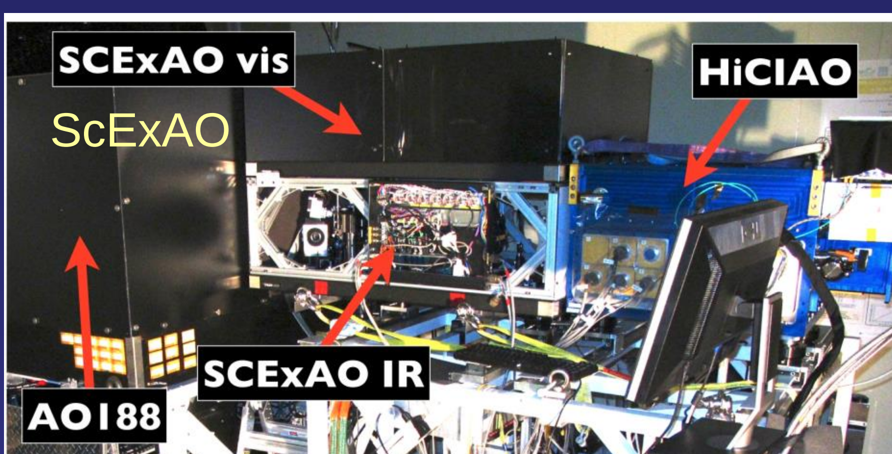


AO imaging emphasizes self-luminous planets

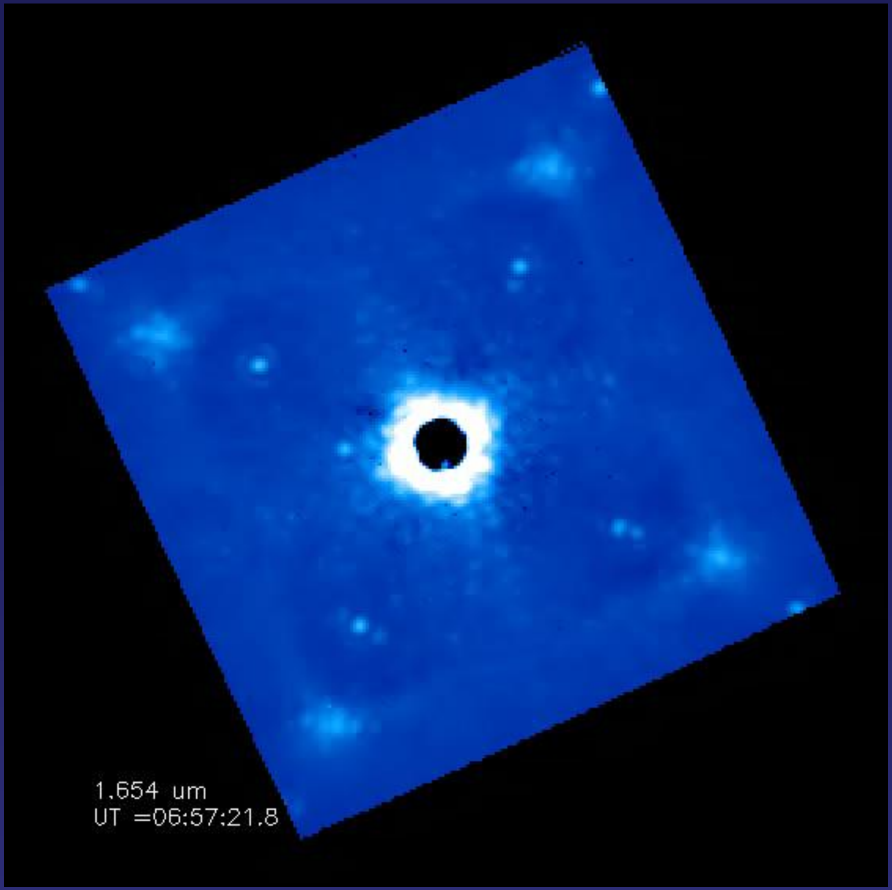


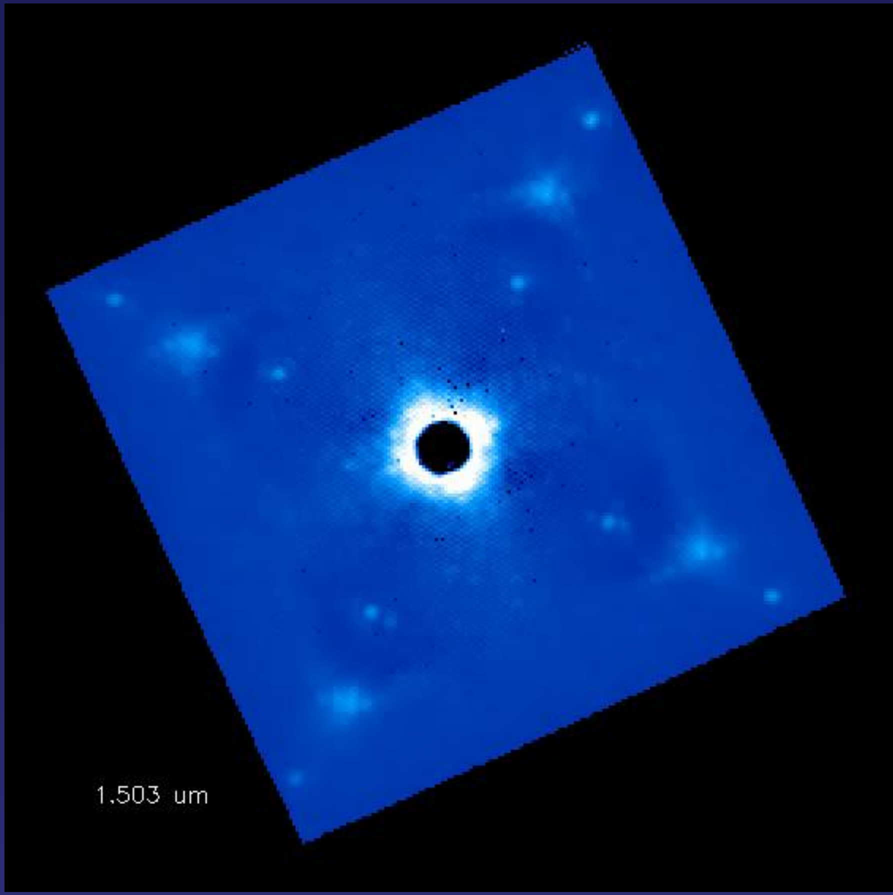
High-contrast AO systems



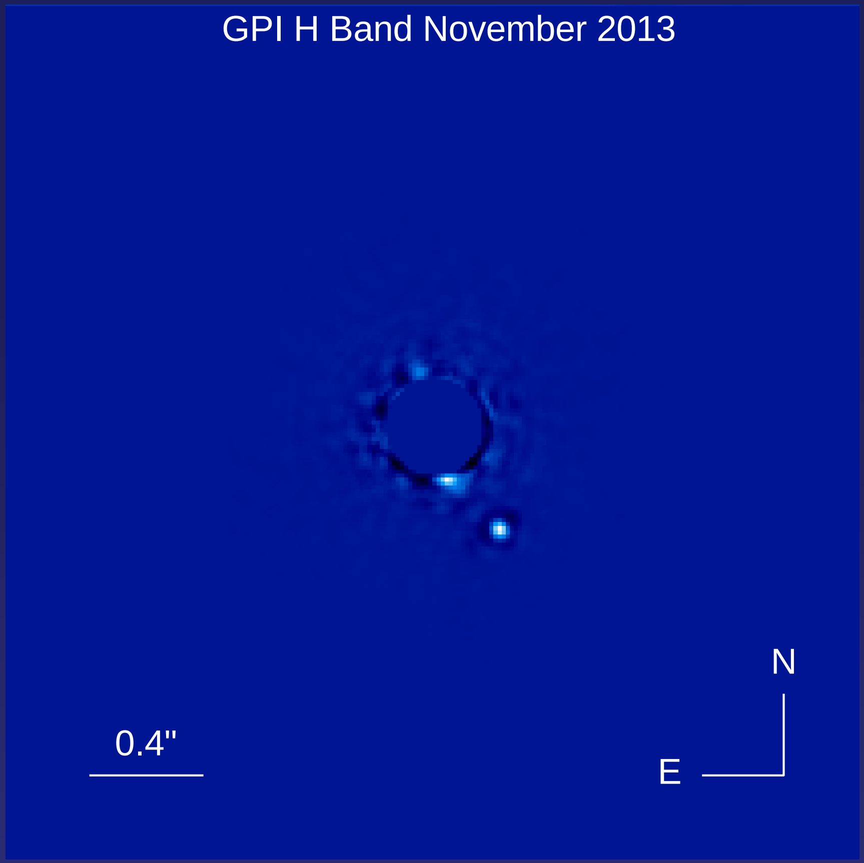


GPI PSF temporal and wavelength stability



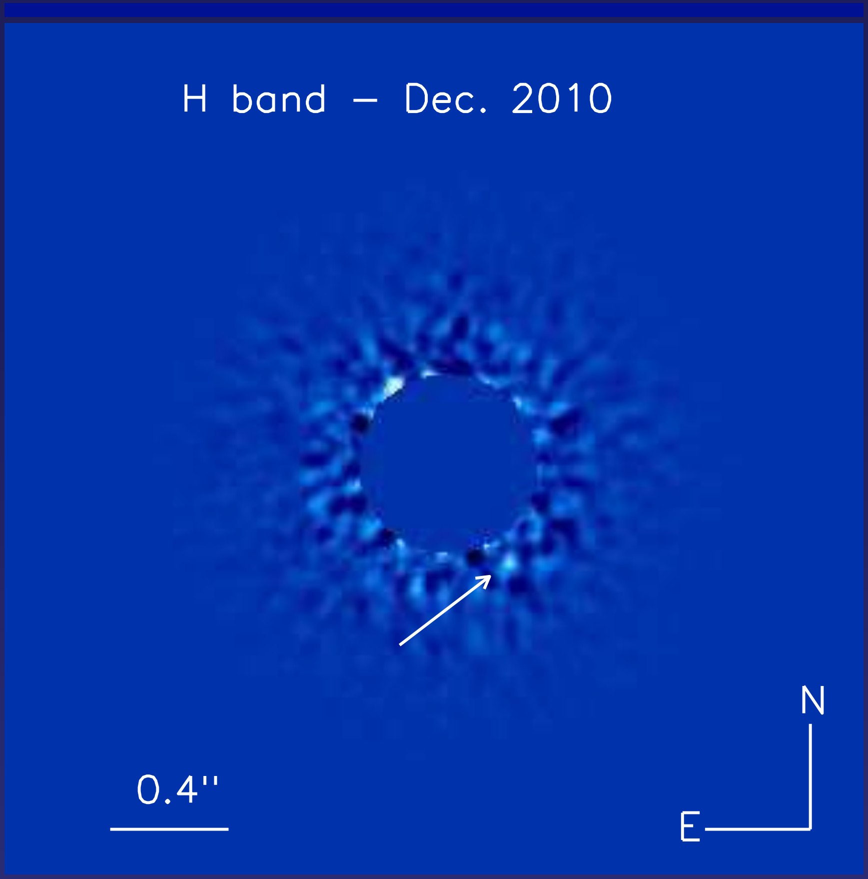


Stacked and combined images



Gemini Planet Imager

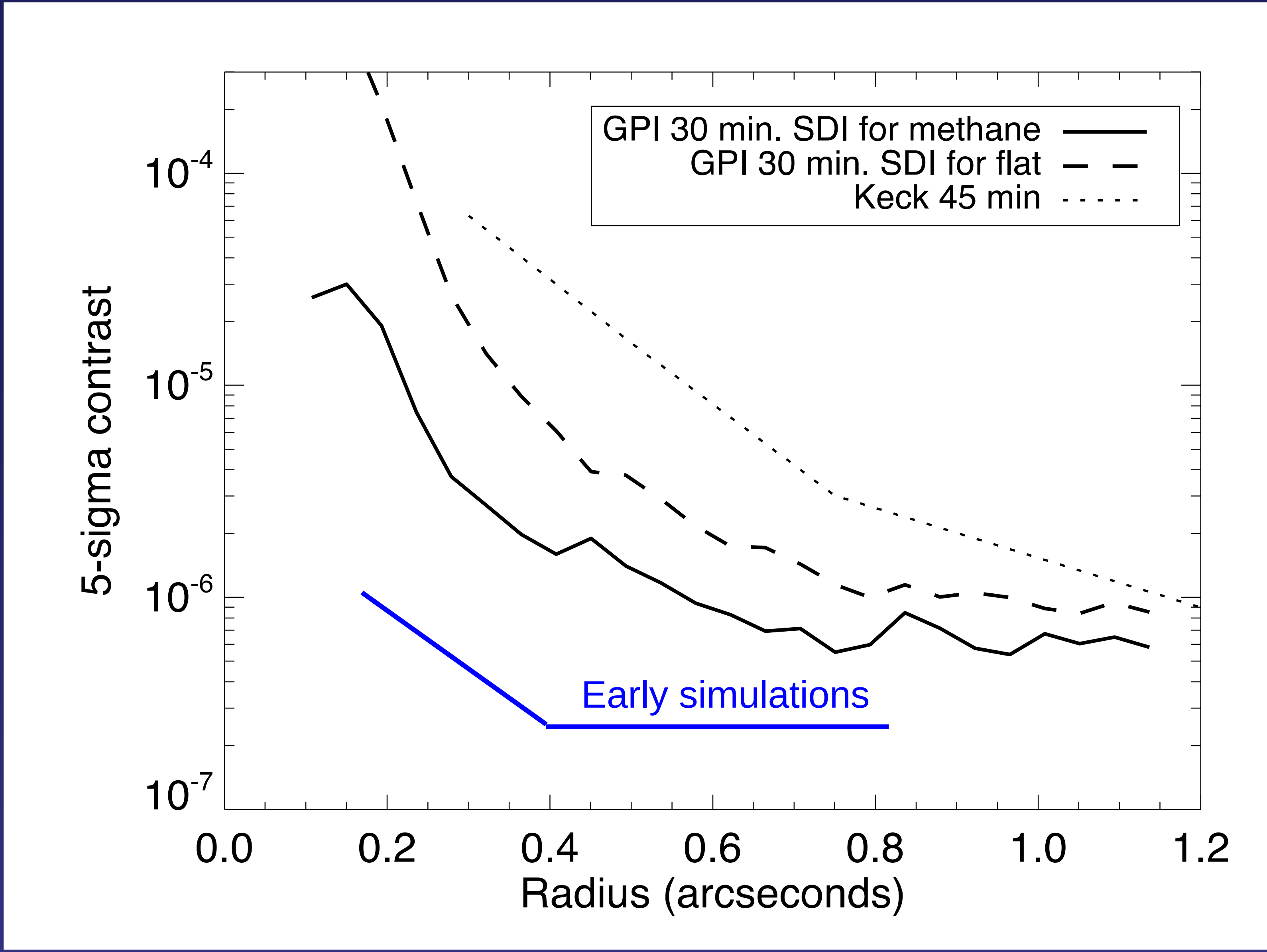
1980 seconds



Gemini NICI (previous generation)

3952 seconds

GPI contrast (beta Pic) after PSF subtraction



Main contrast effects - GPI

- **Timelag – AO CCD and computation are slower than originally specified**
  - CP atmosphere is ‘faster’ than predicted
  - Predictive control could mitigate this
- **Vibration – 60 Hz telescope vibrations**
  - Causes coronagraph leakage at <0.3 arcseconds
- **Static wavefront errors – precision calibration still being improved**
  - AO CCD stability
- **Performance gap is smaller on 6-9th mag stars, which are the main science targets**

Planet detections for 600-star survey - hot-start and cold-start scenarios

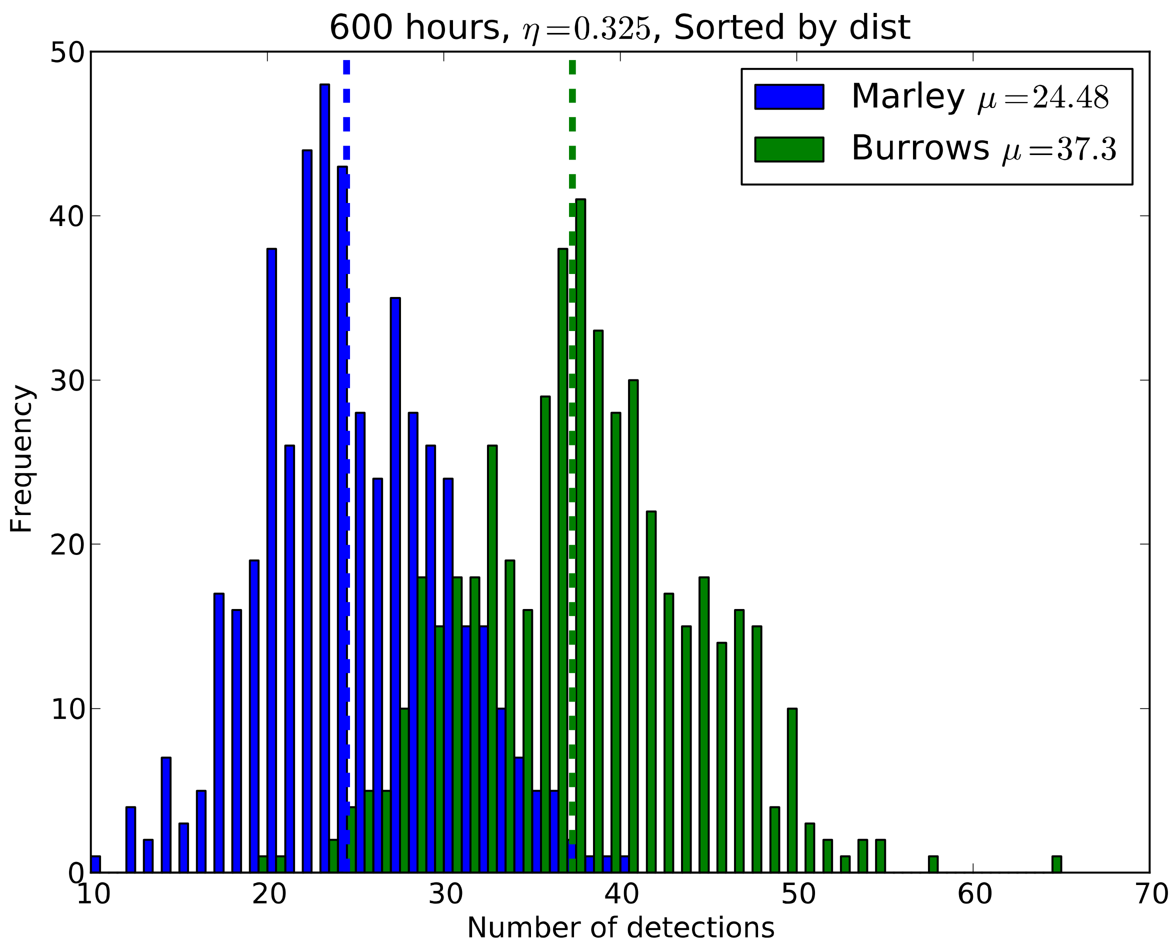
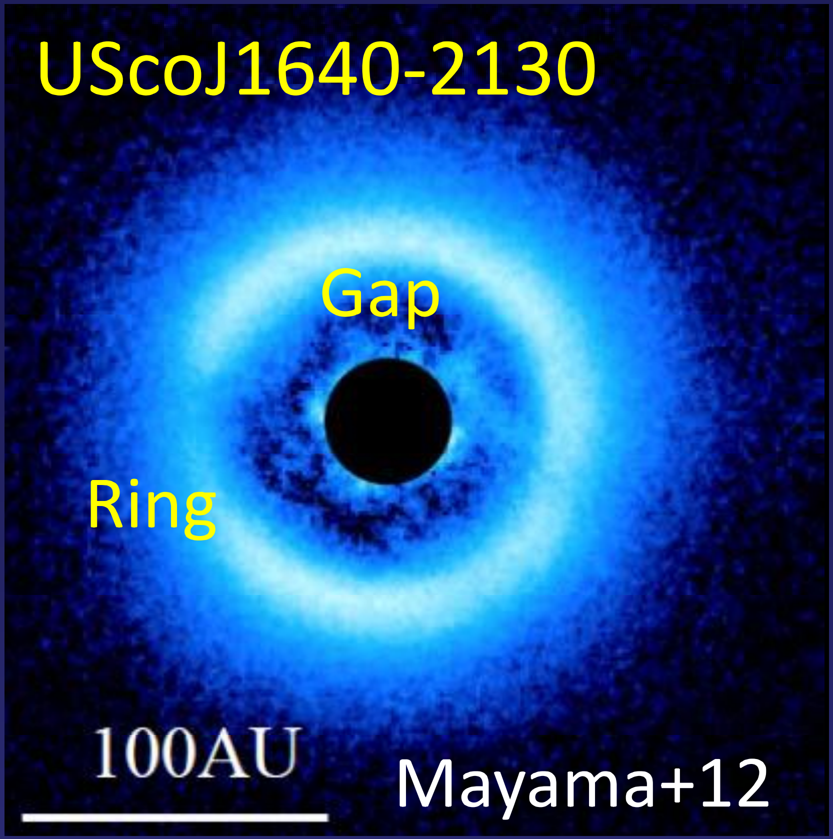
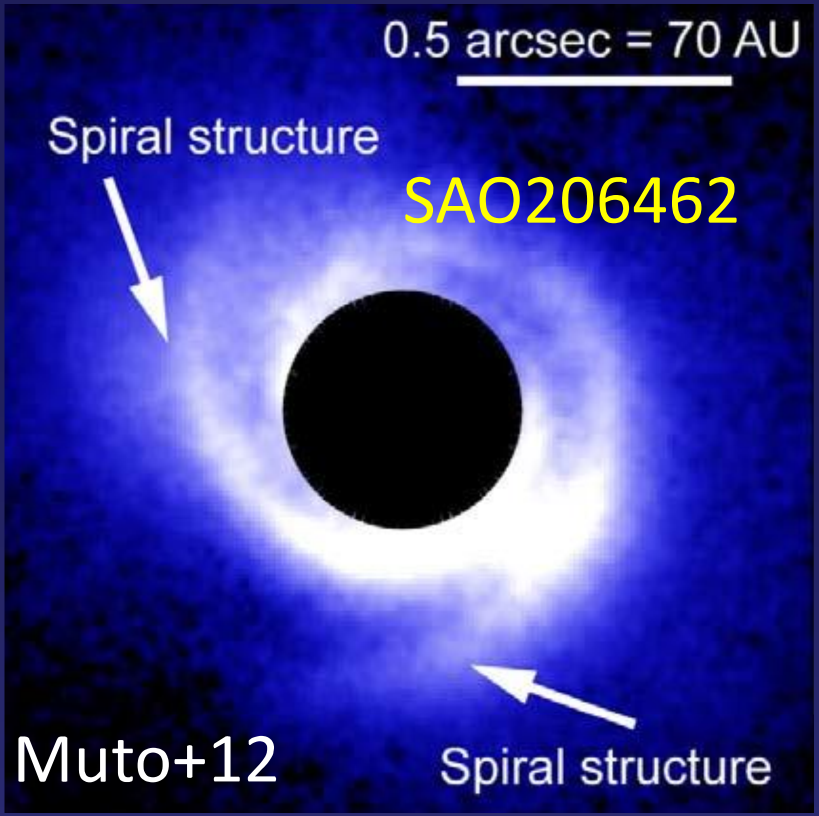


Figure: Distribution of survey results assuming cold and hot start models.

Dmitry Savransky

Disk science enabled by polarimetry - SEEDS





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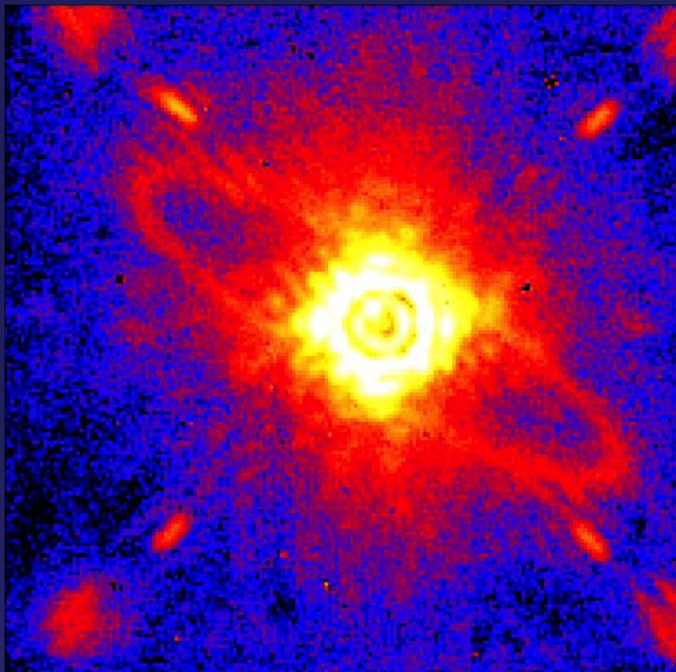
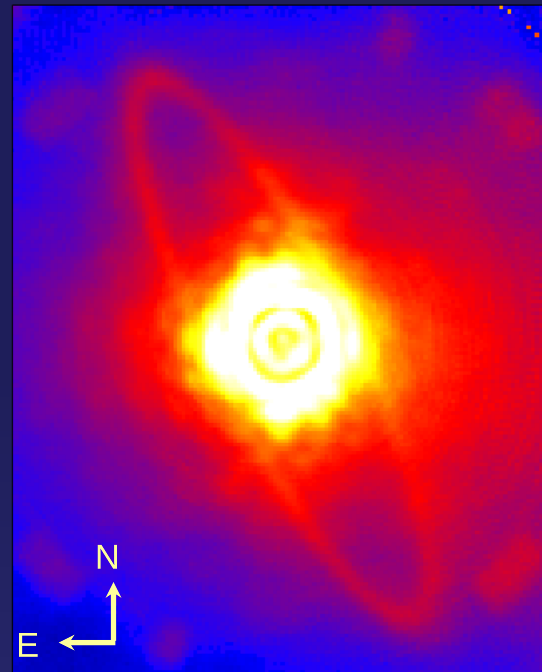
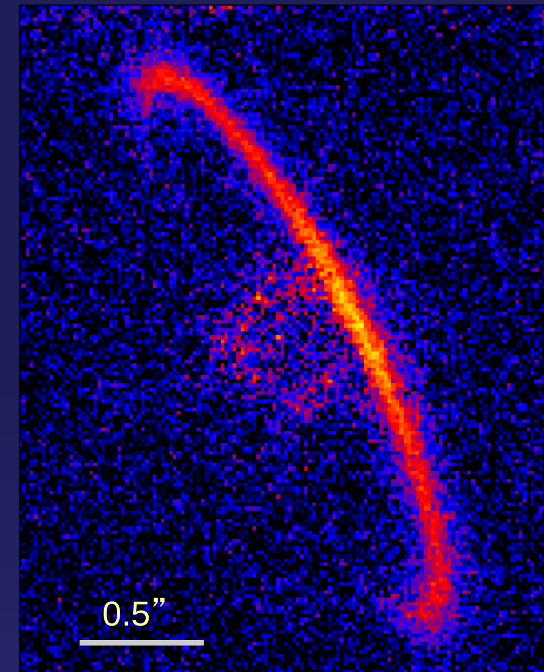
GPI disk science enabled by polarimetry



Individual 60 s images
One linear polarization shown.
Waveplate rotates 0, 22.5, 45...
& the parallactic angle changes



Combined 12 minutes
Total intensity



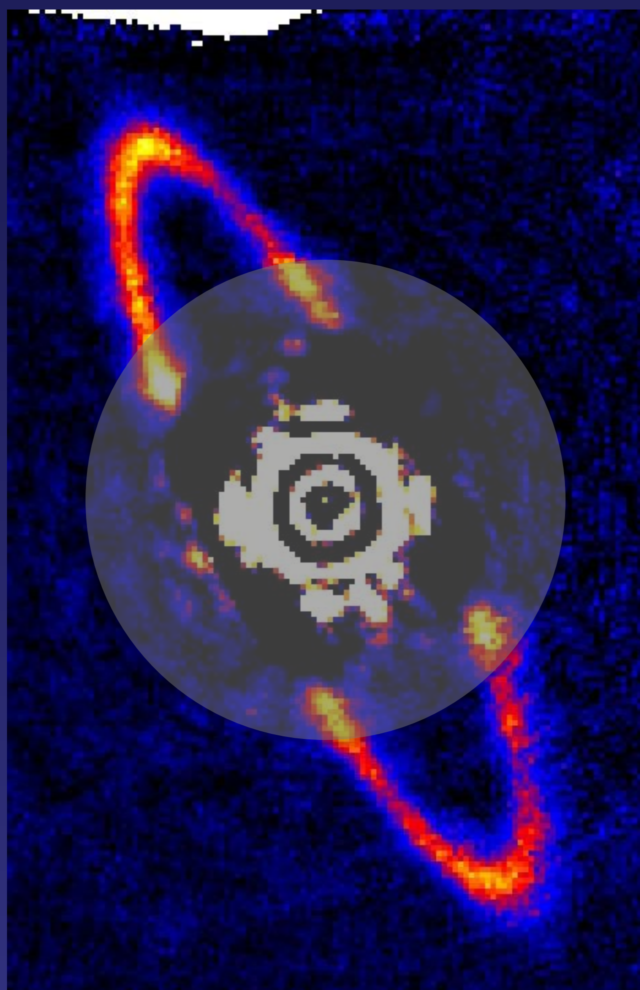
Combined 12 minutes
Linear polarized intensity

Typical systems L_IR/L*=1e-4 at tens of AU
GPI goal 1e-5 at ~5-10 AU
Supermassive Kuiper belt analogs

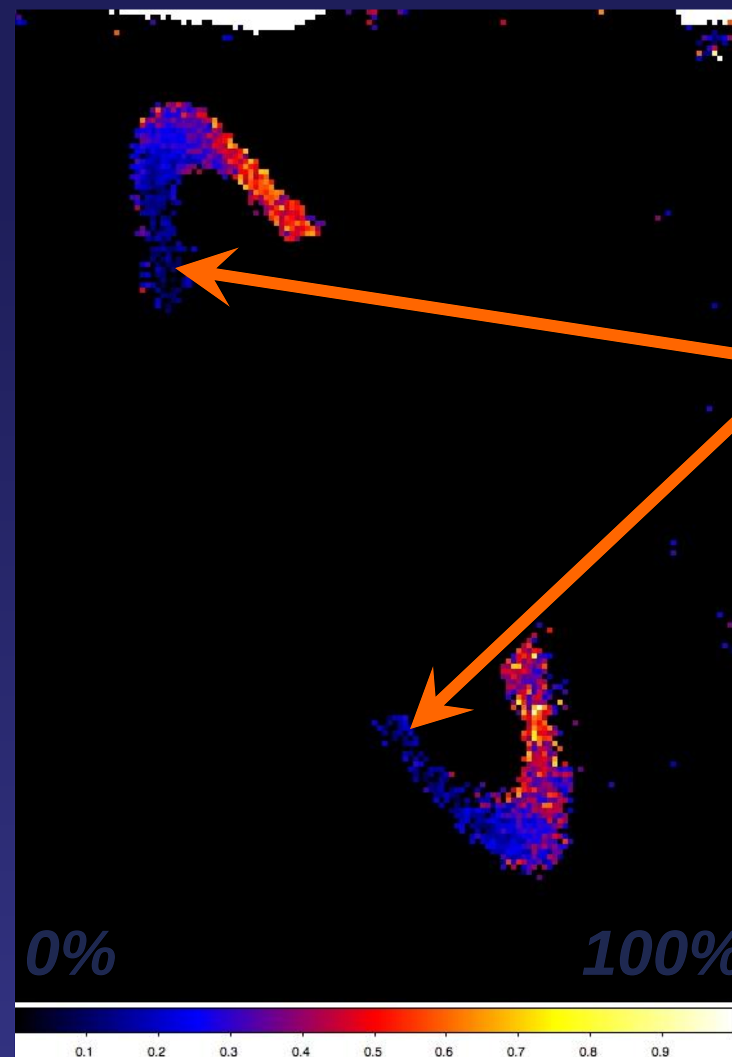
Slide by Marshall Perrin

Sensitivity to unpolarized and face-on disks limited by PSF knowledge

Total intensity (PSF-subtracted)



Polarization fraction



Upper limits

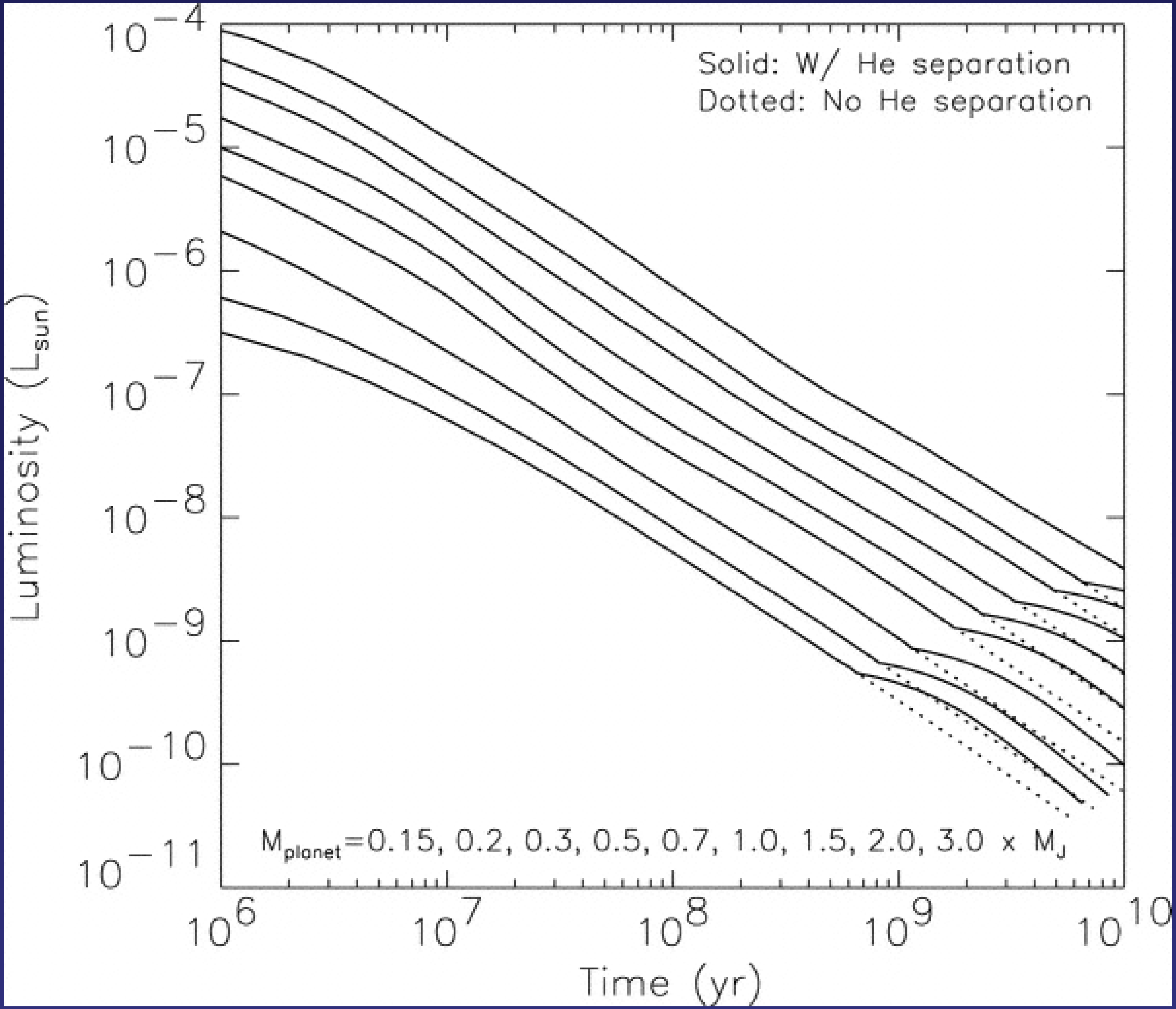
Arbitrary assessment of strengths of new systems

LBT AO	3-5 micron observations of older planets around nearby stars (high sensitivity but larger IWA), northern targets
MagAO	Visible light (accretion), southern hemisphere 3-5 micron
P1640	Broad spectra, new instrument opportunities, northern hemisphere
ScExAO	Very small IWA, novel technology, equatorial
SPHERE	Fainter ref stars, wide field, visible polarimetry, facility ESO system
GPI	Facility Gemini system, good data pipeline, K spectra, good bright star performance

Possibilities for the future

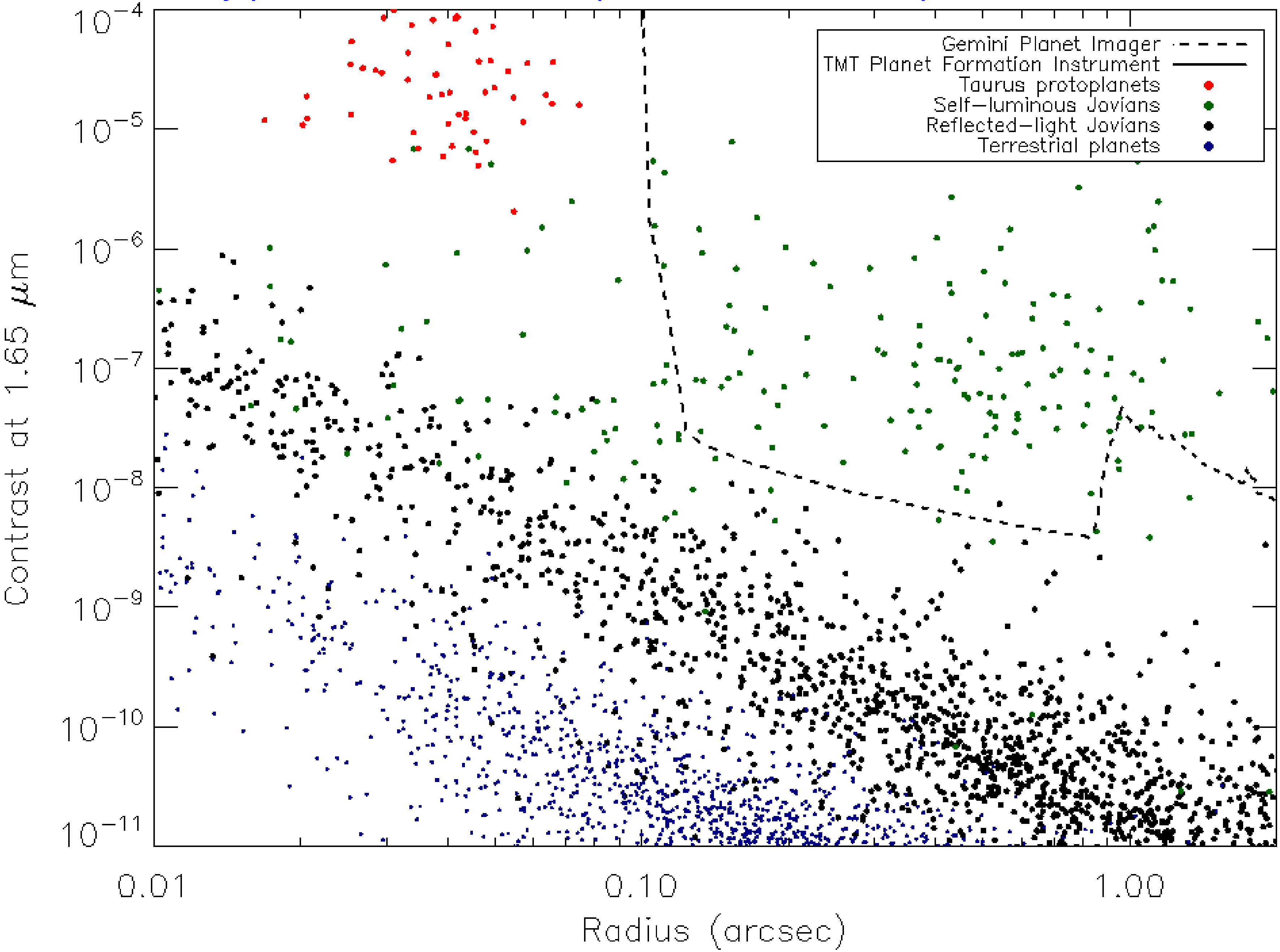
- **Shrinking IWA – younger planets at greater distances**
  - Unlikely to enable reflected-light planets around a significant sample of stars
  - Needs to combine with better control of NCP errors, e.g. focal-plane wavefront sensing
- **Broader instrument suites**
  - 3-5 micron capabilities with advanced coronagraphs
  - High spectral resolution + ExAO
- **Faster AO systems**
  - Better bright star performance, but small overall gain
- **PSF reconstruction**
  - Important for disk science

Even for 'hot start', low-mass planets are almost undetectable in self-luminosity

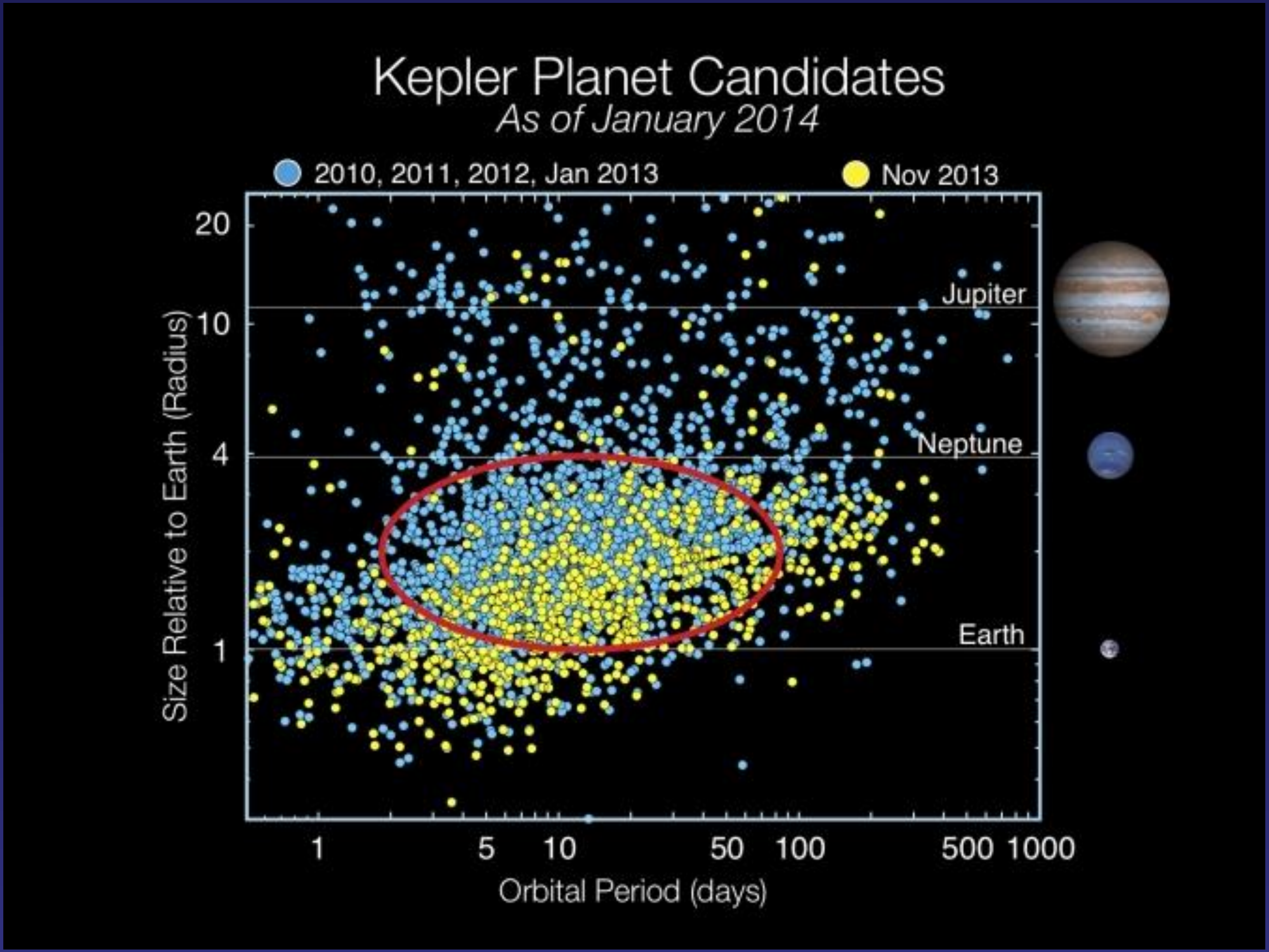


0.5 Saturn to 3 MJ
Fortney&Hubbard 2004

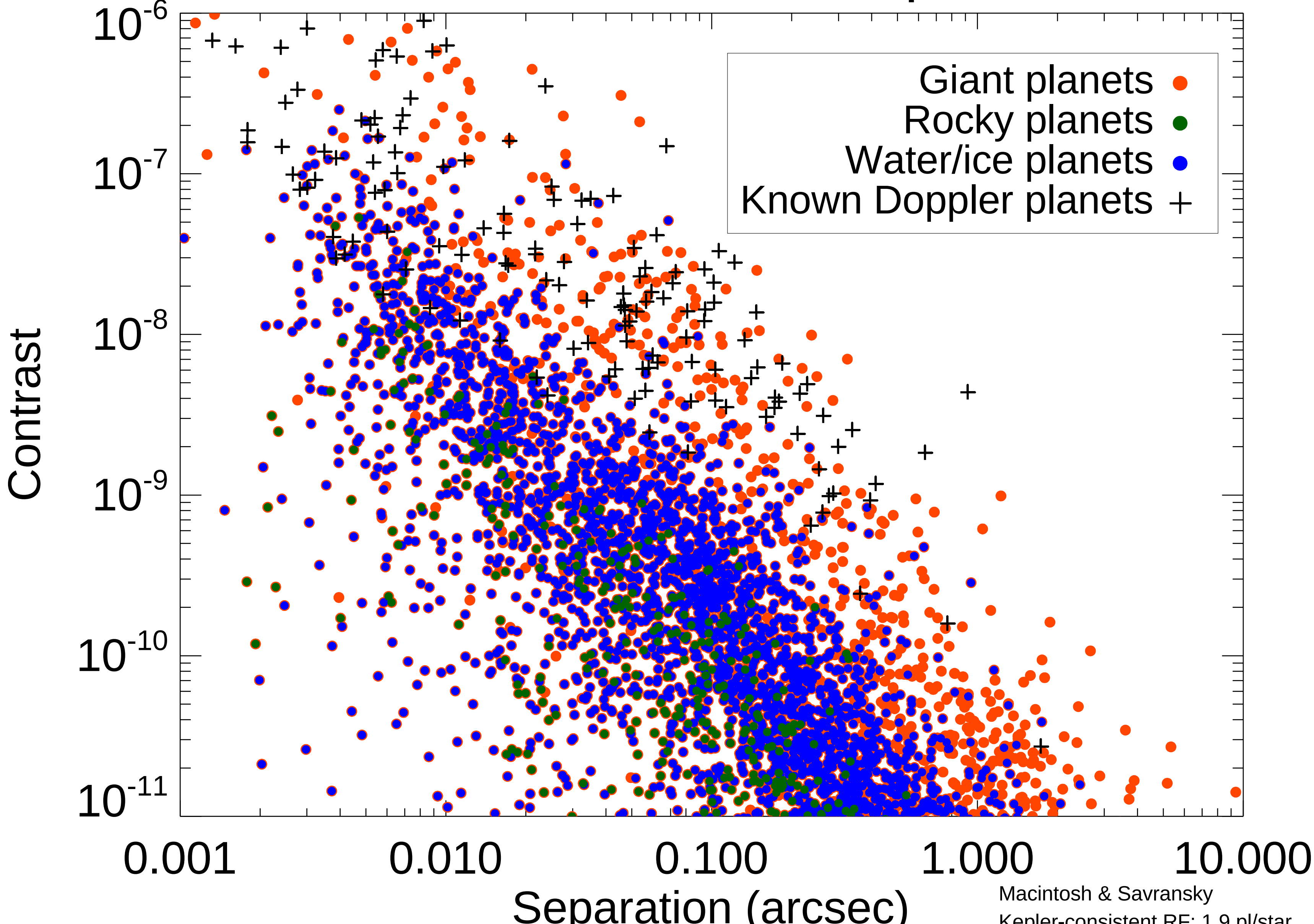
Early planet contrast model (Macintosh et al 2006)



The vast majority of planets are <4 RE

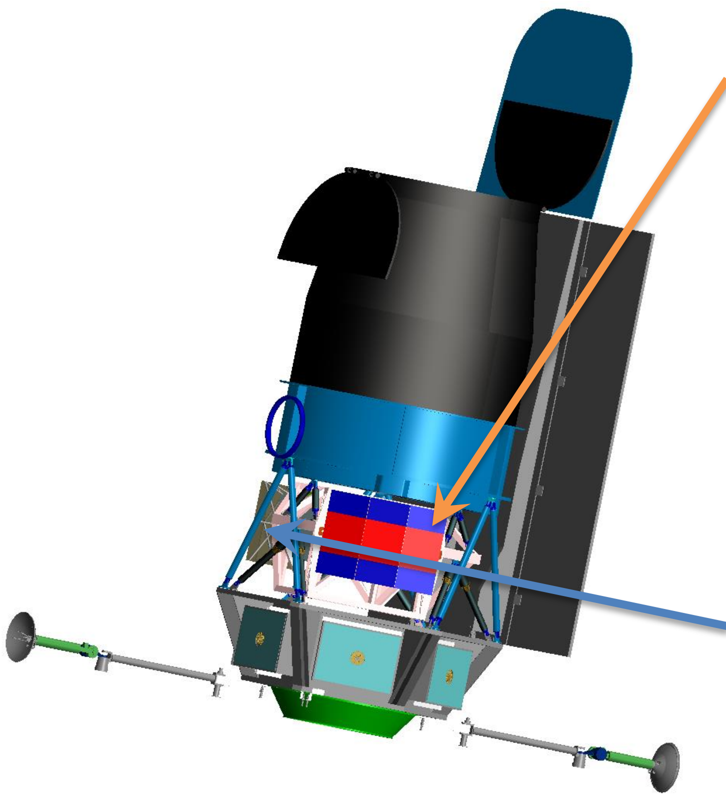


Planets within 30 pc



Macintosh & Savransky
Kepler-consistent RF; 1.9 pl/star
Main sequence non binary stars

WFIRST-AFTA



Wide-Field Instrument

- *Imaging & spectroscopy over 1000s of sq. deg.*
- *Monitoring of SN and microlensing fields*
- 0.7 – 2.0 μm (imaging) & 1.35-1.89 μm (spec.)
- 0.28 deg^2 FoV (100x JWST FoV)
- 18 H4RG detectors (288 Mpixels)
- 6 filter imaging, grism + IFU spectroscopy

Coronagraph

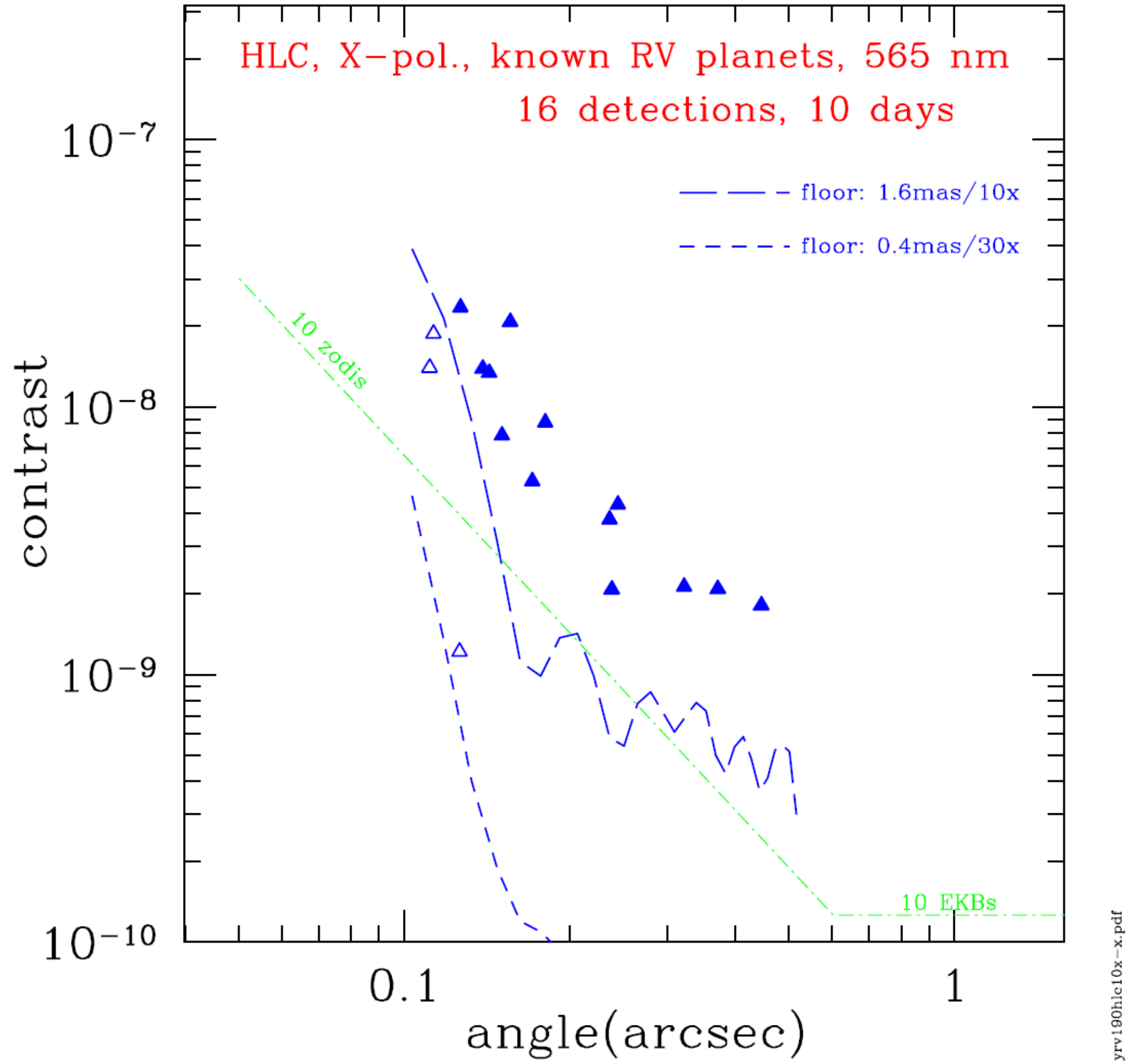
- *Image and spectra of exoplanets from super-Earths to giants*
- *Images of debris disks*
- 430 – 970 nm (imaging) & 600 – 970 nm (spec.)
- Final contrast of 10^{-9} or better
- Exoplanet images from 0.1 to 1.0 arcsec

Characterizing Doppler-detected planets

R~70 spectral characterization of ~6 planets

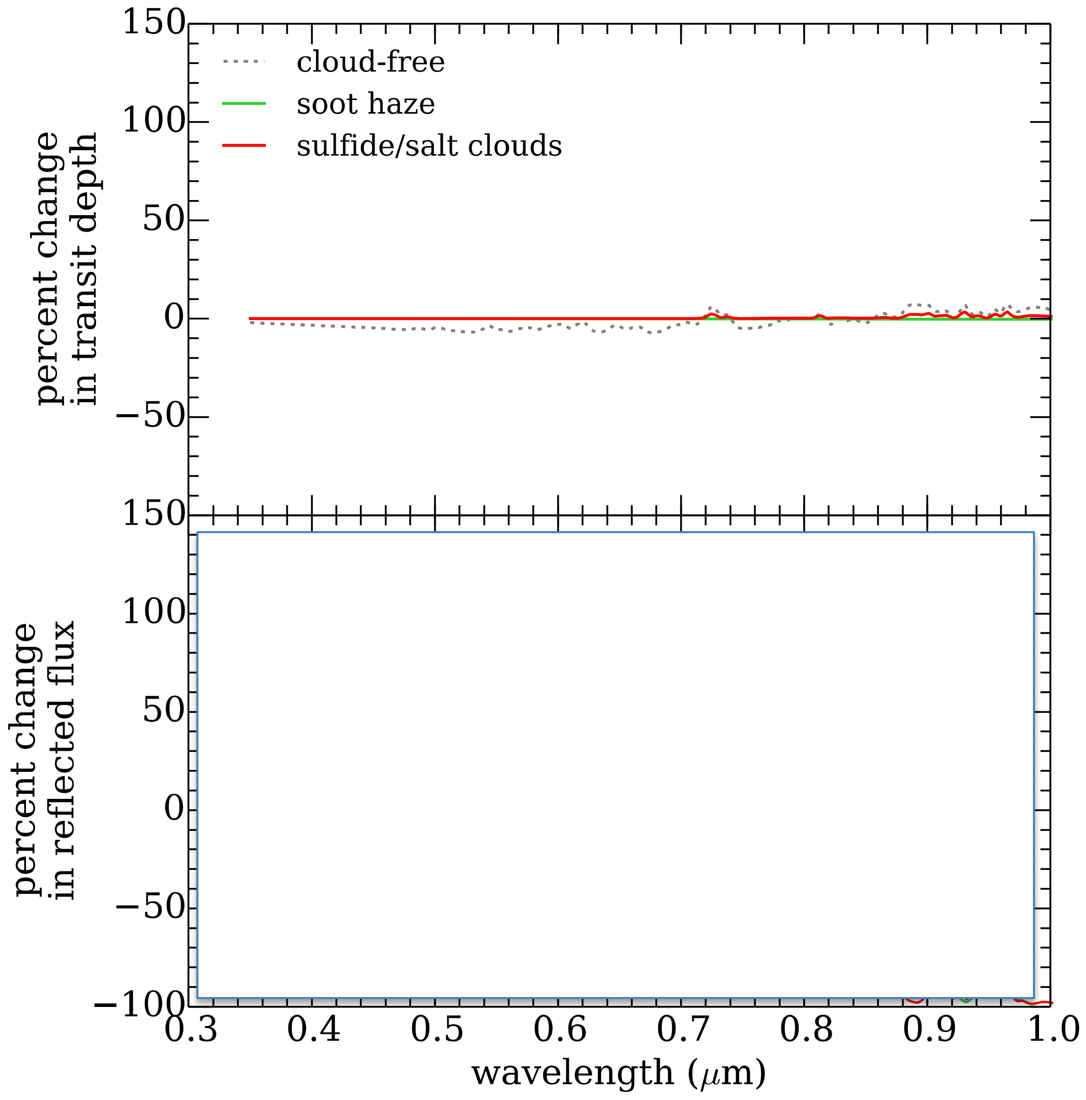
Multiband photometry of ~10 known RV planets

Future Doppler surveys could add 10-15 more

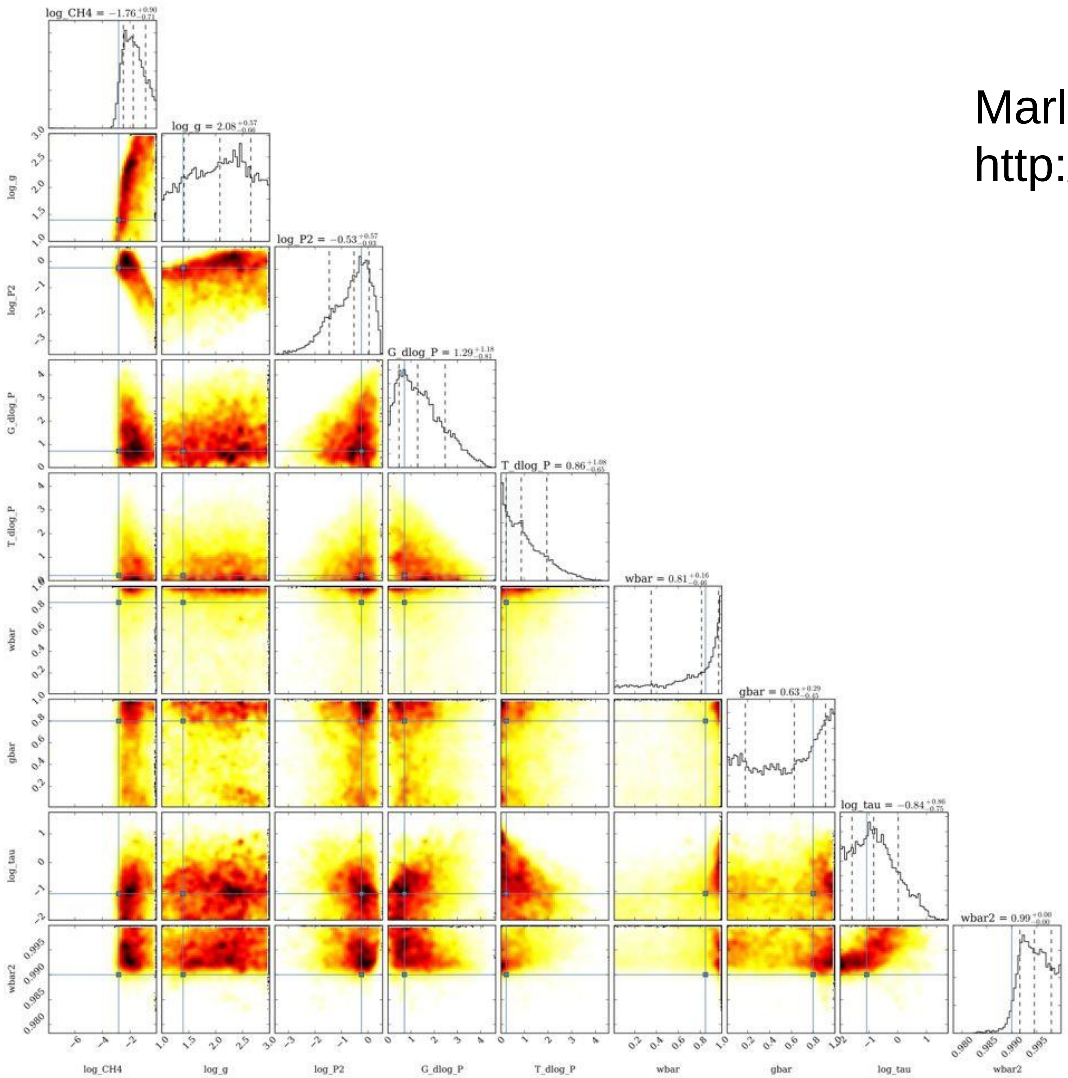


Reflected-light spectra are probes of atmospheres even at low SNR

GJ1214b analog models by Caroline Morley

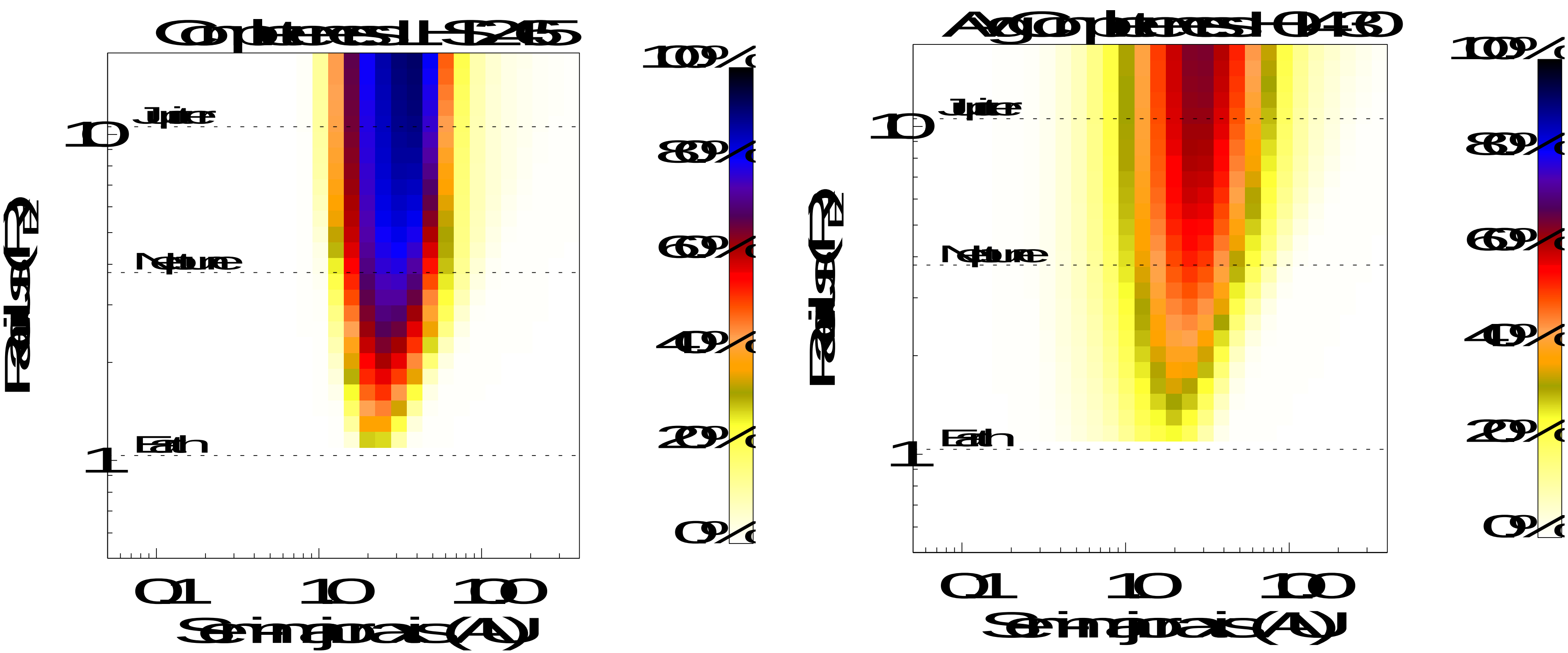


MCMC recovery of Jupiter properties from SNR=10 spectra



Marley et al
http://arxiv.org/abs/1412.8440

Sensitivity to new planets



Models by Dmitry Savransky

WFIRST-AFTA Significantly Expands the Population of Characterized Planets

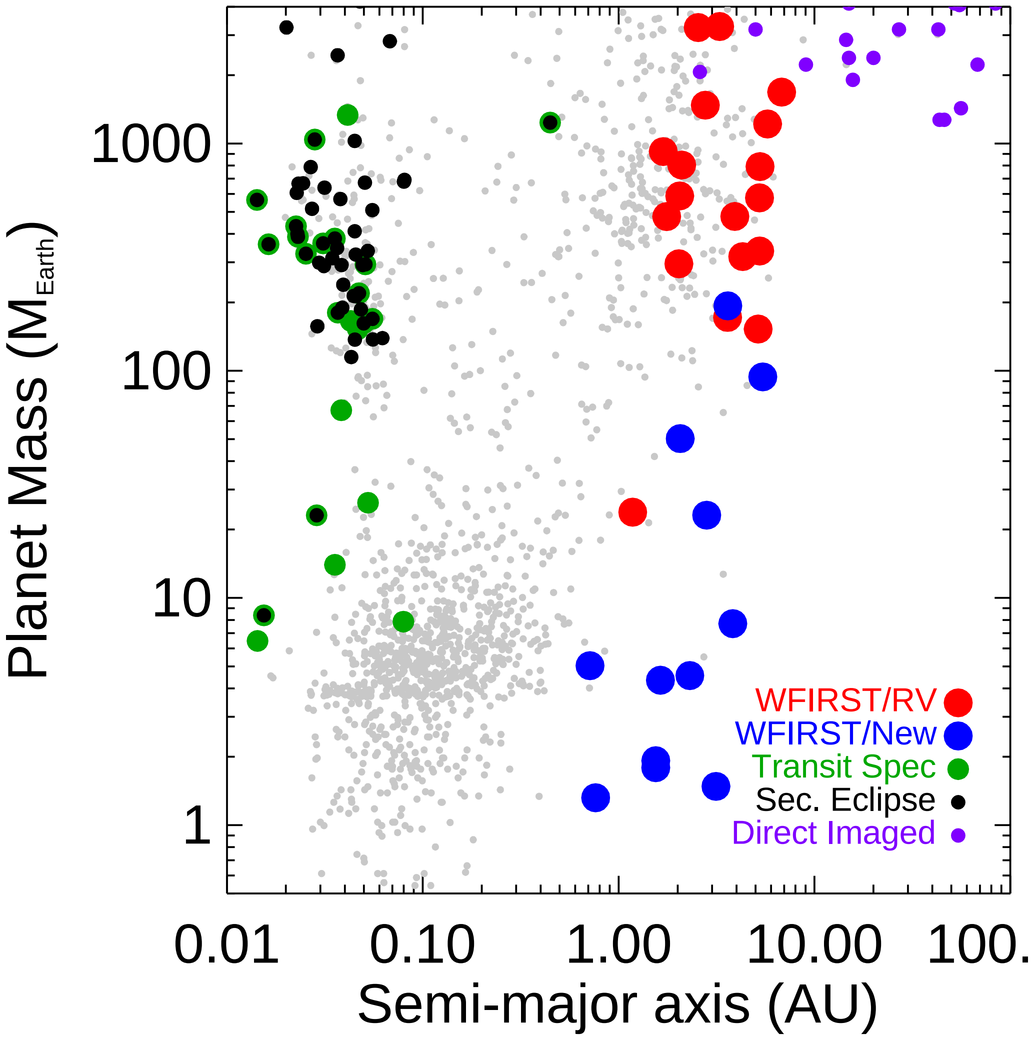


Figure credit Eric Nielsen

Science program	Number of giant planets (4-15 R_E)	Number of sub-Neptune planets (2-4 R_E)	Number of super-Earth planets (1-2 R_E)
Known RV studies	16	0	0
New RV targets	~10?	~few?	0
180-day new planet search	2	6	4
Total	18	6	4

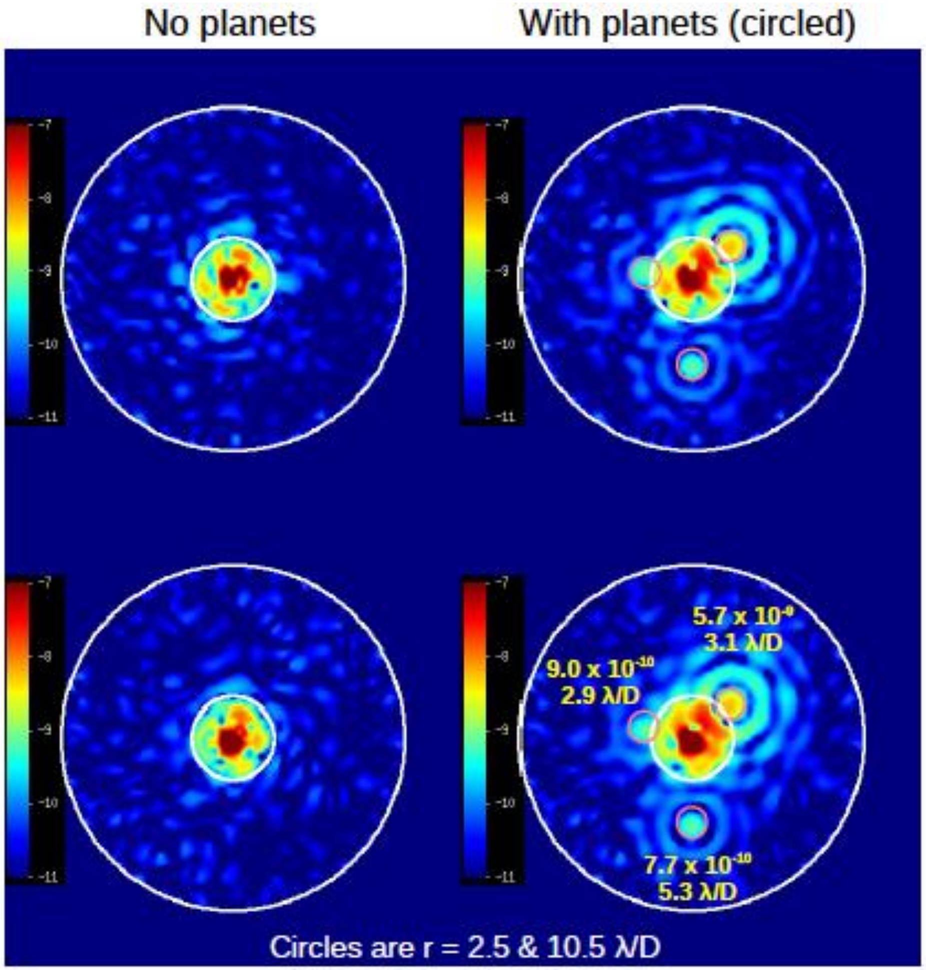
Coronagraph performance validations

GSFC/JPL joint model
Hybrid Lyot Coronagraph

|47 Uma - β Uma|

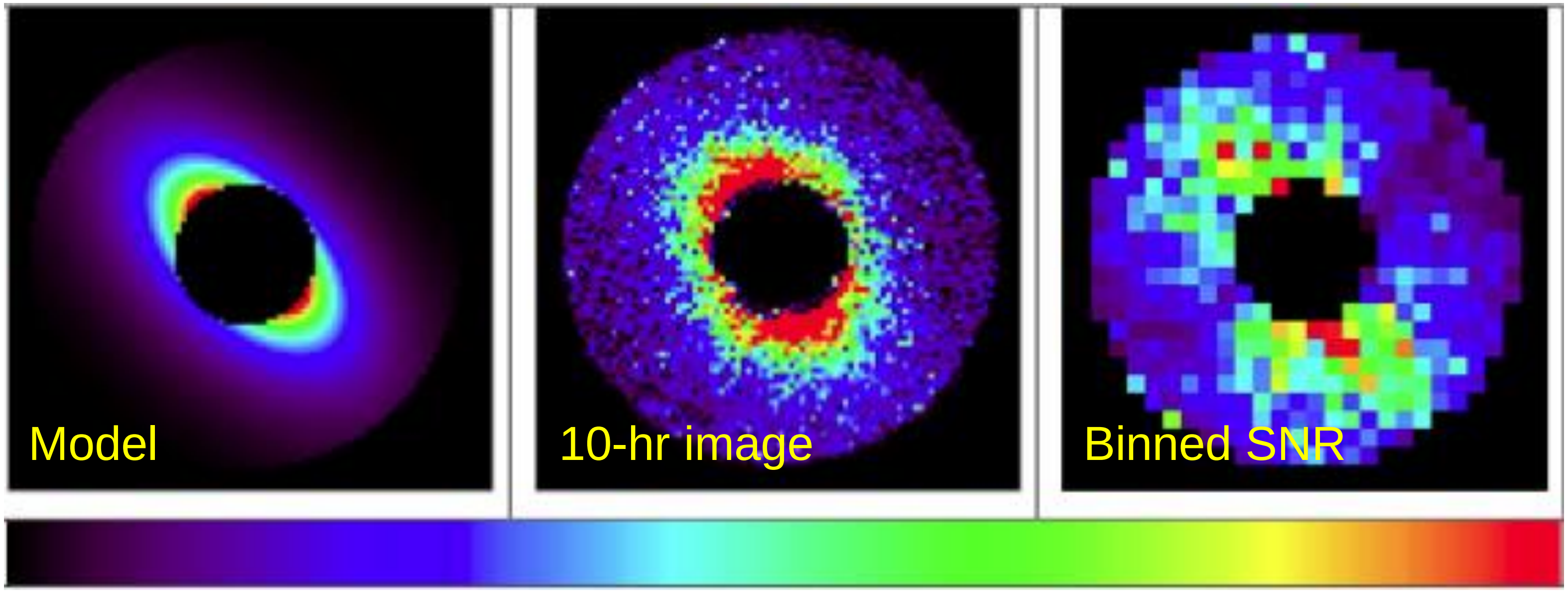
Initial simulations of coronagraph performance in WFIRST-AFTA environment indicate that the coronagraph is likely to achieve all performance goals with the current, unmodified telescope.

|47 Uma - 61 Uma|



Color differences between these stars are not important in 10% bandpass.

WFIRST-AFTA sensitivity down to ~10 x solar zodiacal light



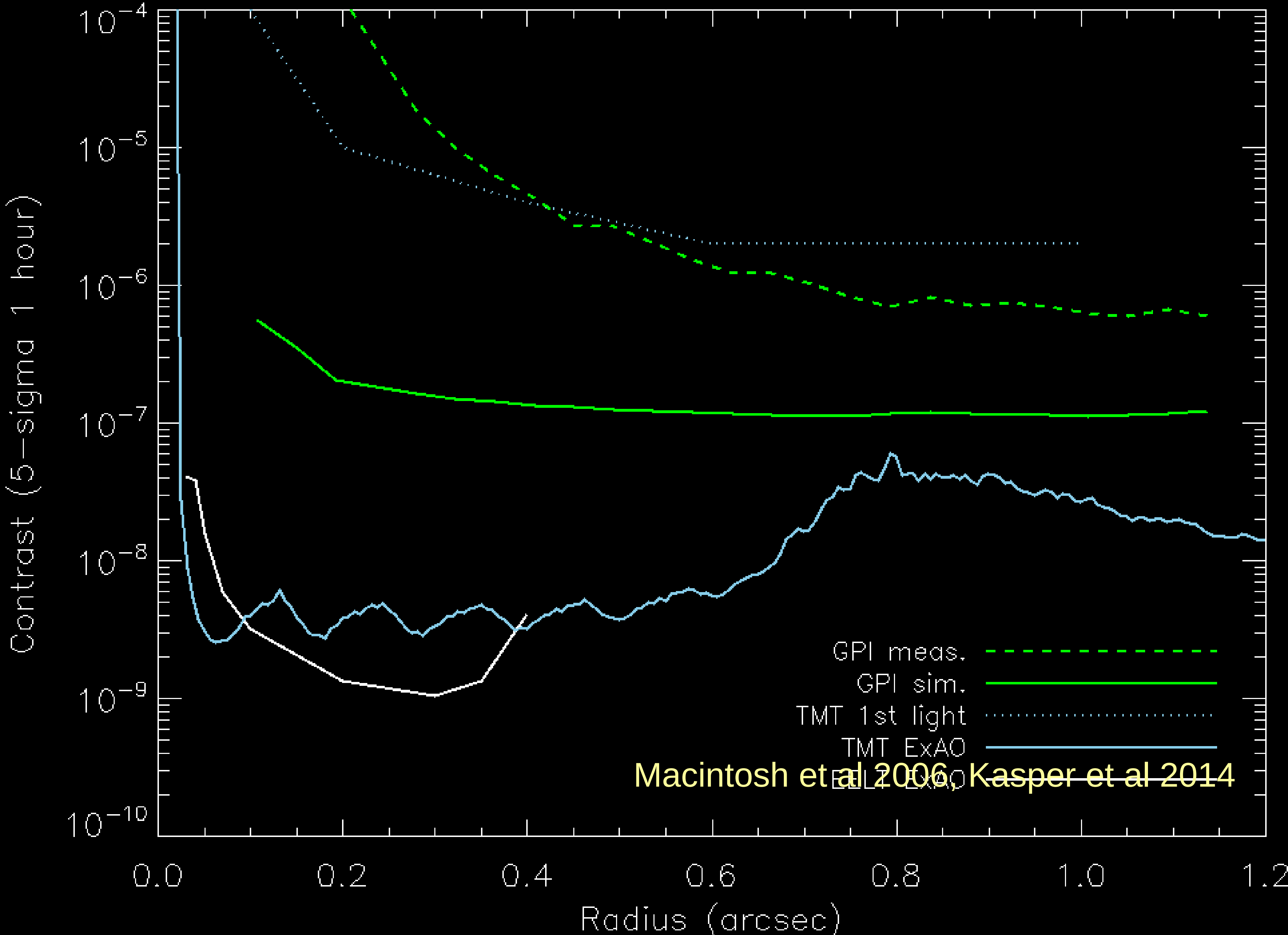
- AFTA observations complement LBTI by probing visible light , structure, and polarization
- Sensitivity down to ~10 x solar at 1-2 AU for 10-20 stars
- Much better sensitivity to unpolarized light than ground

Extremely Large Telescopes

- **All ELTs advertise planet-imaging capability**
- **No planet-finder included in first-light instruments**
- **First-light AO systems sub-optimal for planet imaging**

- **With future ExAO systems:**
  - Greatest area of improvement is inner working angle – potentially to 15-20 mas
  - Contrast improvements ~D^2
  - Technology improvements (fast IR WFS?)
- **Achieving 1e-10 requires spacecraft levels of stability, extremely bright stars, is essentially impossible**

ELT contrast simulations

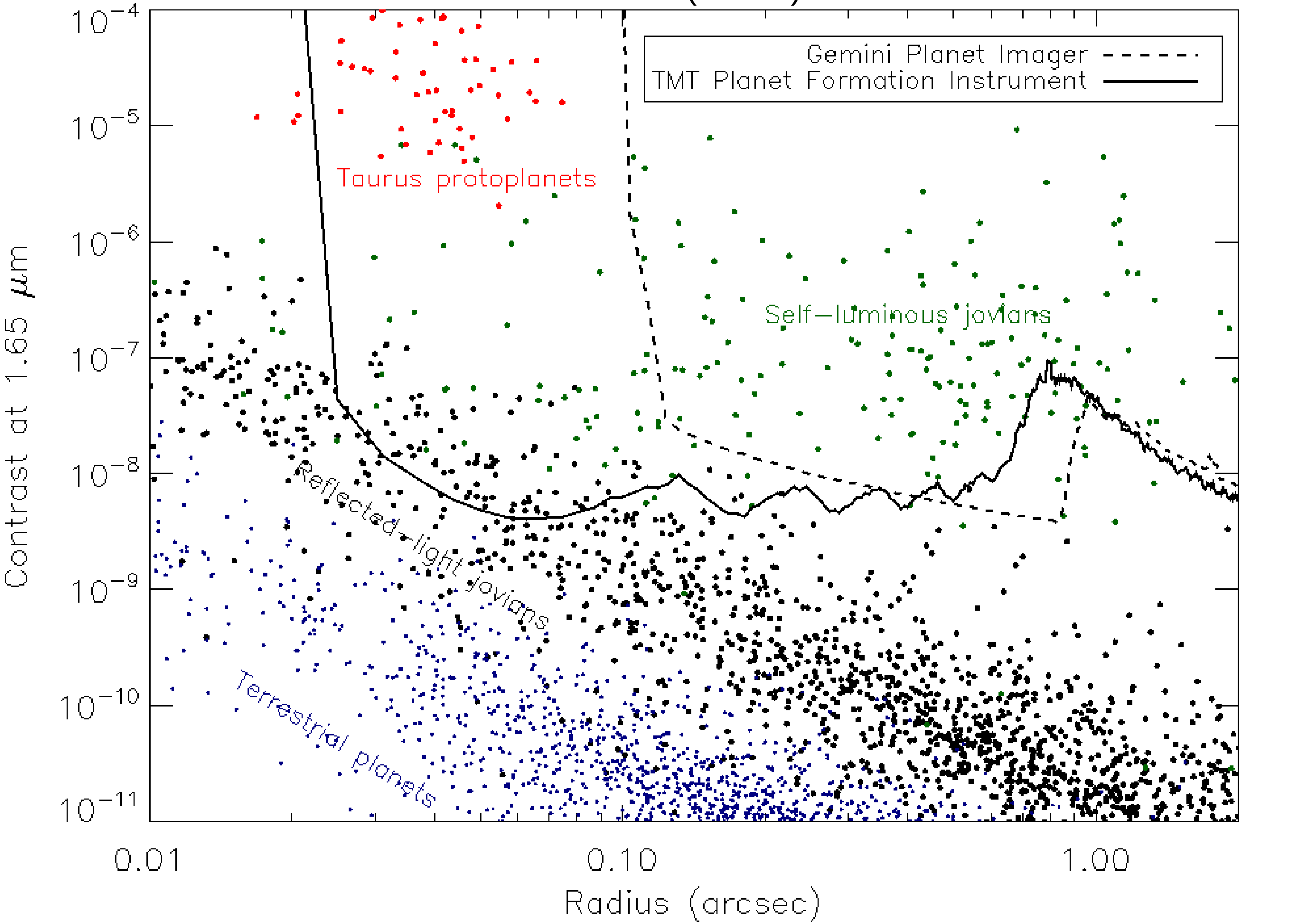


Macintosh et al 2006, Kasper et al 2014

Simulation uncertainties

- **Stability of instrument**
- **Exposure time**
  - Impossible to simulate hour-long sequences with even partial physics
  - Static effects only manifest on multi-minute timescales
- **Non-kolmogorov atmosphere**
- **Predictive control**
- **DM properties and control loop dynamics**
- **Vibration environment…**

Old TMT and GPI simulations (~2006)



Science enabled

- **Small IWA – direct imaging of planet formation**
  - Disentangling from disk?
- **Small IWA – reflected-light planets**
  - Planets get brighter as they get closer to parent star
  - 1 AU giant planets, sub-neptune planets, etc…
- **Very small IWA + very high performance could reach earth-radii**
  - Access habitable zone around nearby M stars if IWA < 10 mas
- **Contrast unlikely to reach GK habitable zones**

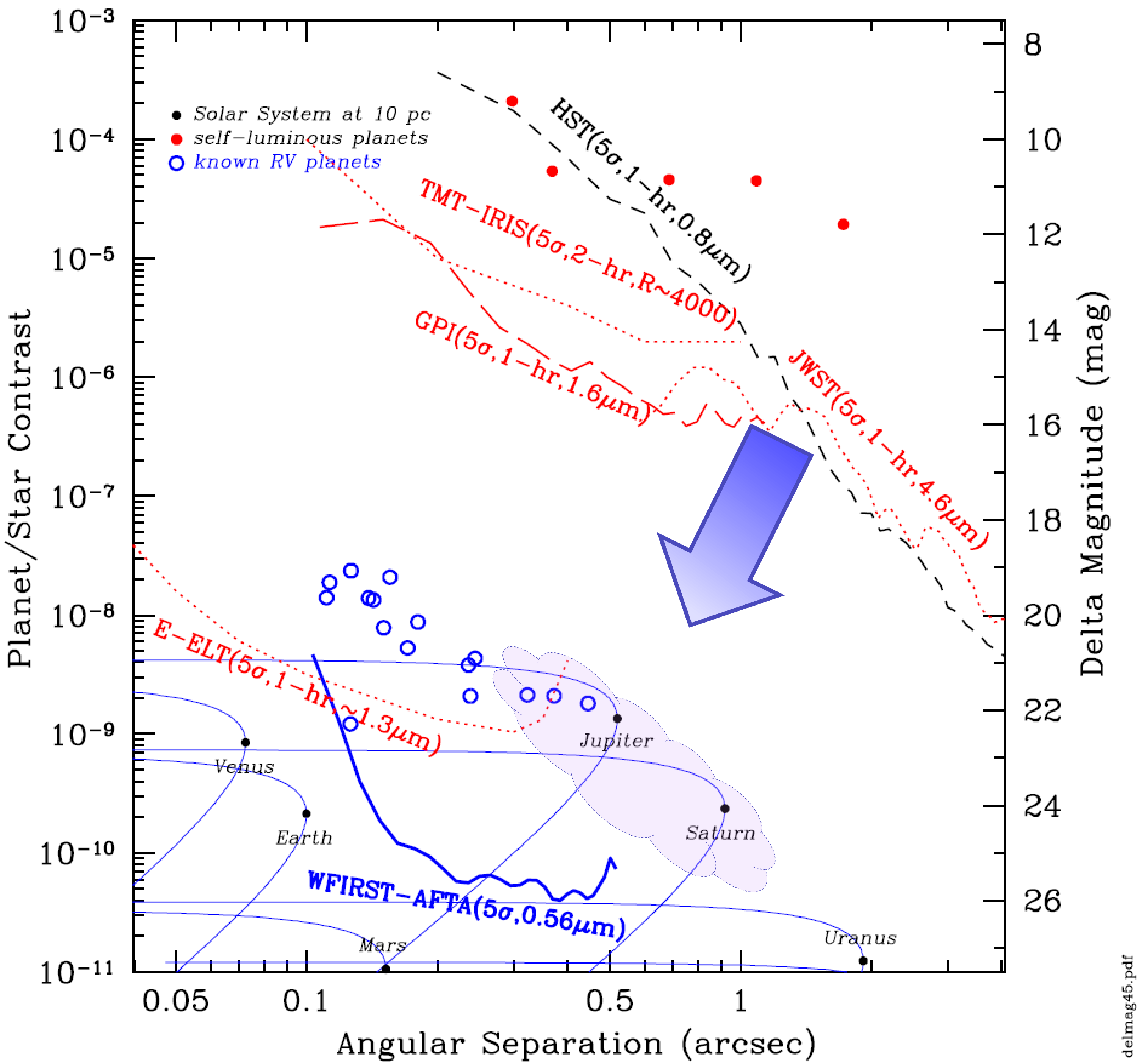
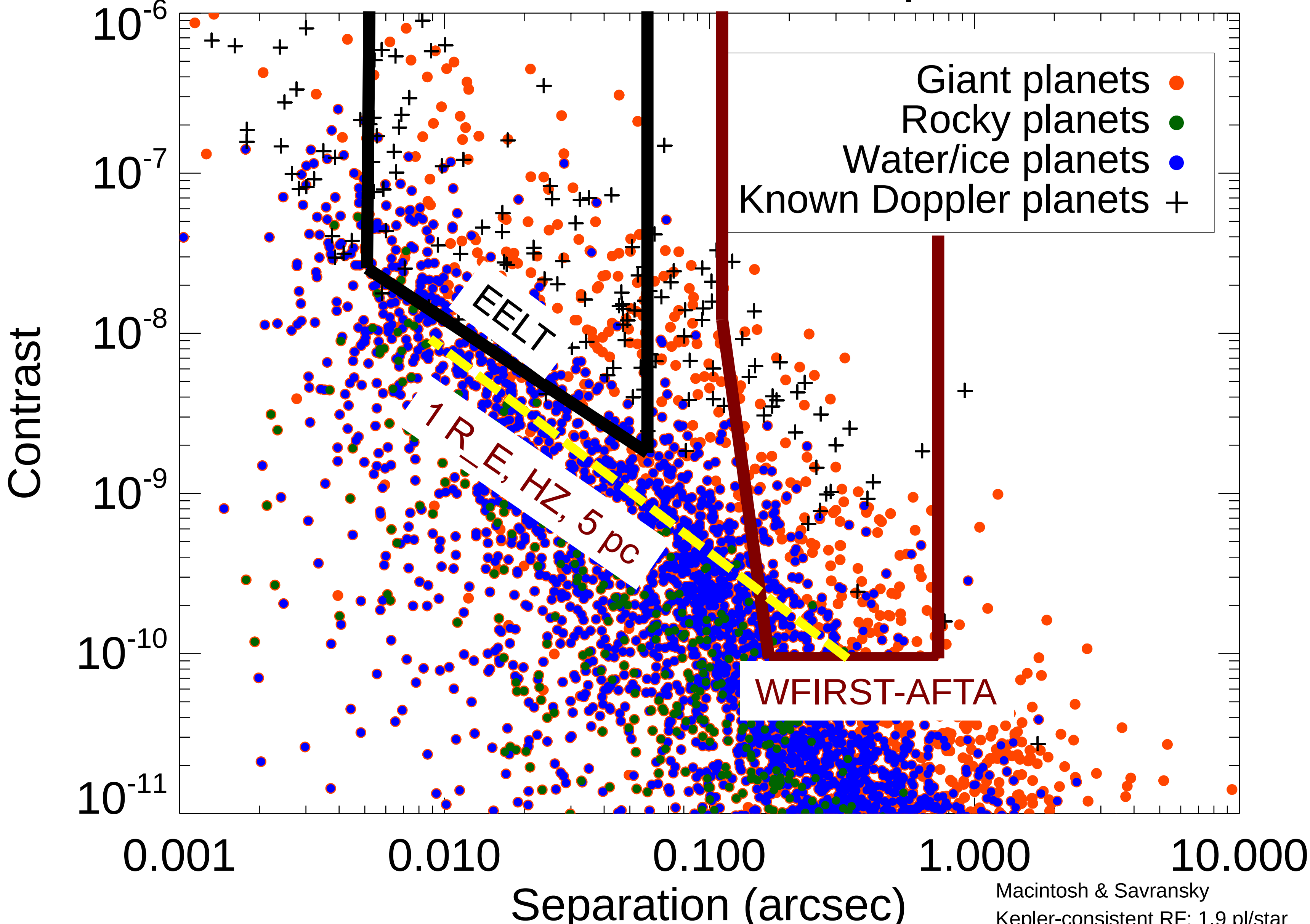


Figure by Wes Traub after Lawson & Mawet

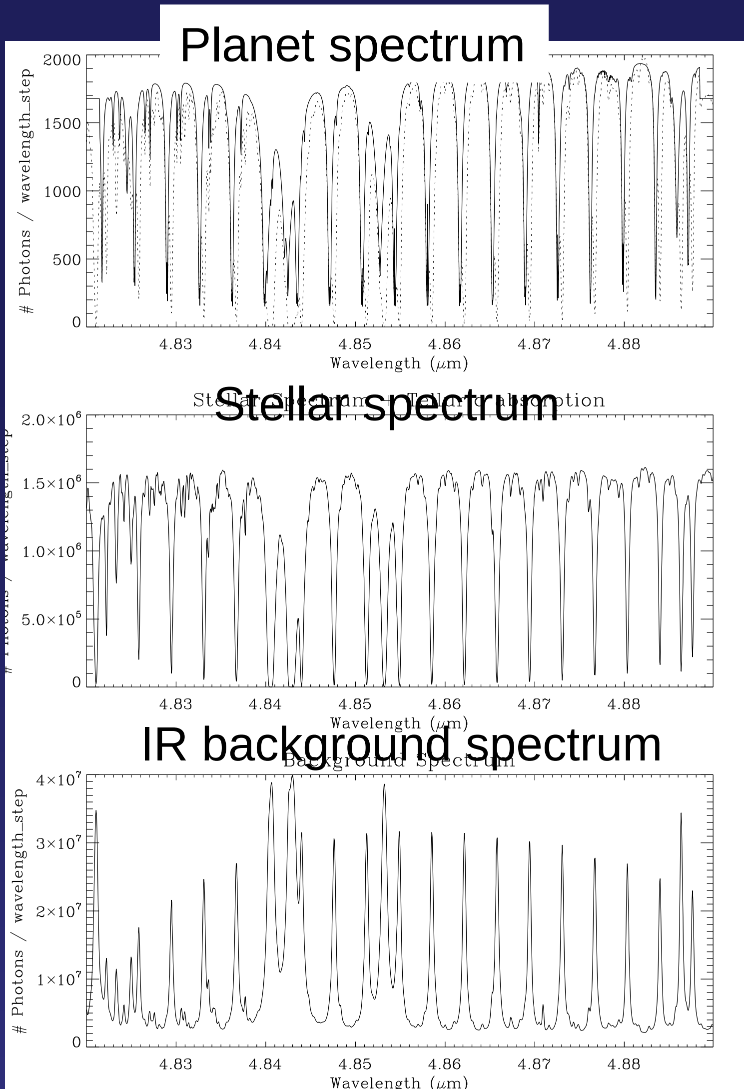
Planets within 30 pc



Macintosh & Savransky
Kepler-consistent RF; 1.9 pl/star
Main sequence non binary stars

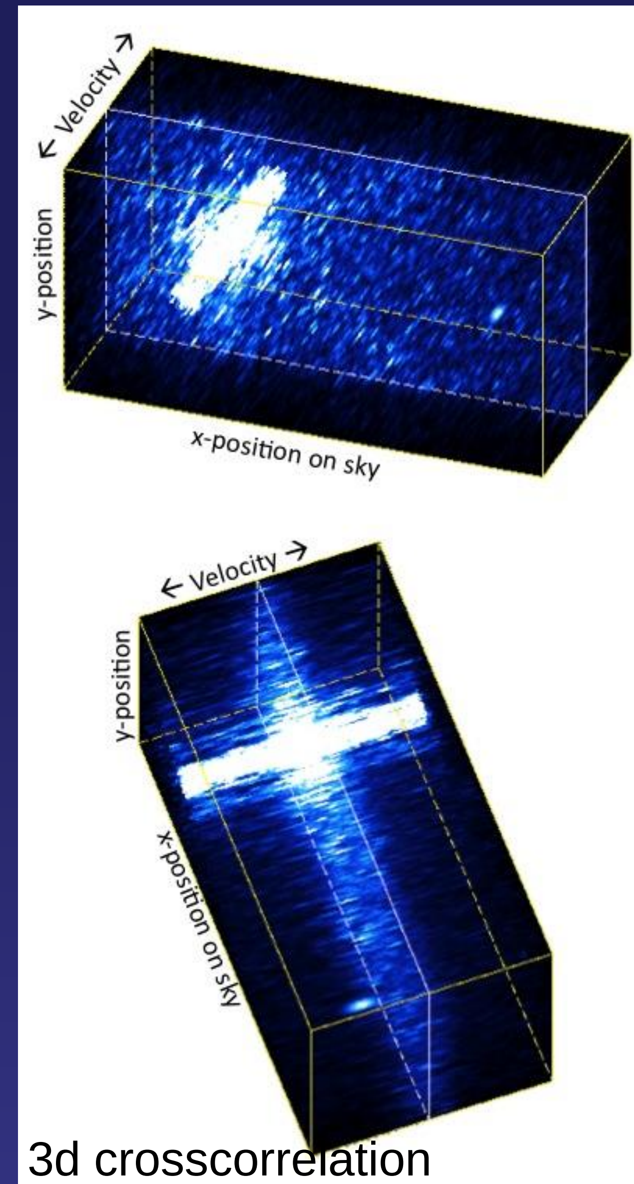
Contrast curves are bright-star/best-case

Cross-correlation of high-resolution spectra in thermal IR (Snellen et al 2015, Quanz et al)



Exploits broad spectrum of speckle artifacts to reach photon noise level (analagous transit techniques exist too)

See Konopacky et al (2013), Snellen et al (2014), Barman et al (2015) for real data examples



Probably only works for very brightest star

Some summaries

- **New ExAO systems are coming online and we're learning a lot**
- **8-10m systems will be limited to self-luminous giant planets**
- **EELT AO could achieve very small inner working angle (0.03 arcseconds), moderate contrast (10^{-8})**
- **Wavelengths are complementary**
  - Albedo vs wavelength needs study
- **Opens up detection of mature planets at small physical separations (<1 AU)**
  - Down to 2RE; smaller if very small IWA can be achieved
  - HZ for M-stars ?
- **WFIRST-AFTA could achieve higher contrast at larger IWA**
  - Detection of mature planets at 1-3 AU separations
  - Down to 1-2 RE, FGK stars
- **Uncertainties in performance are greater for ELTs**
  - Uncertainty in instrument funding?
- **Both could contribute significantly to exoplanet science**