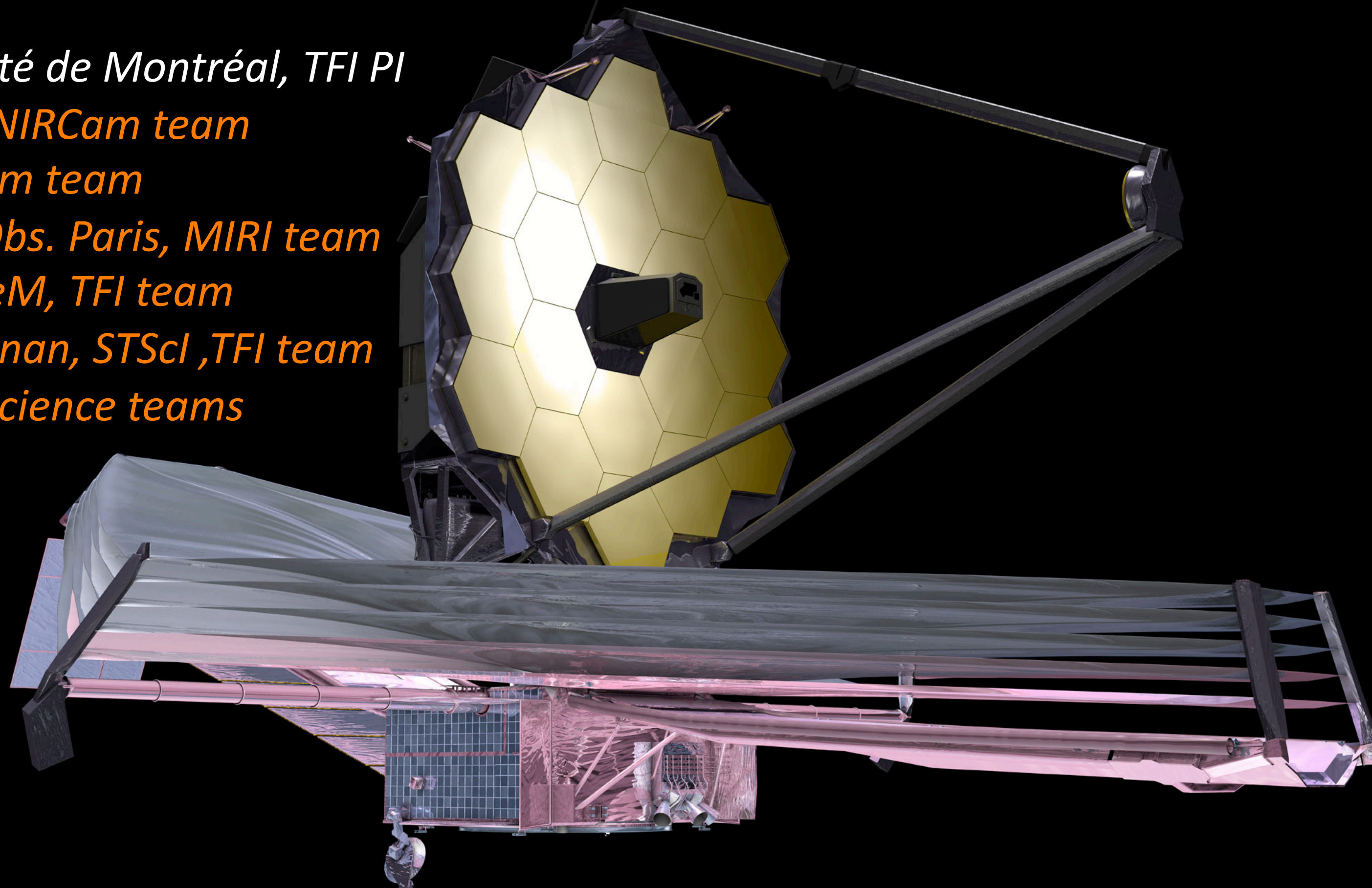
Overview of JWST High-Contrast Imaging

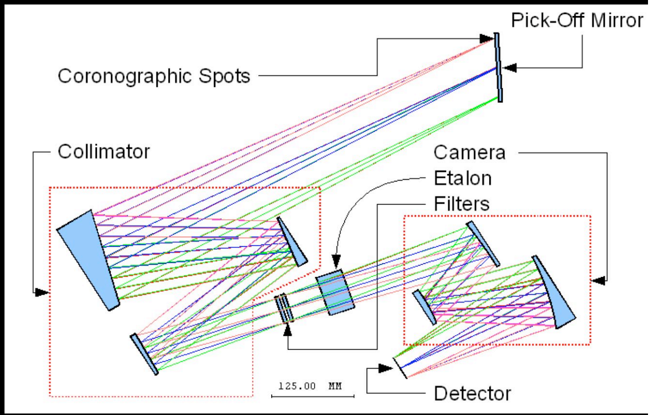
René Doyon, Université de Montréal, TFI PI
Chas Beichman, JPL, NIRCam team
John Krist, JPL, NIRCam team
Anthony Boccaletti, Obs. Paris, MIRI team
David Lafrenière, UdeM, TFI team
Anand Sivaramakrishnan, STScI ,TFI team
TFI, NIRCam & MIRI science teams



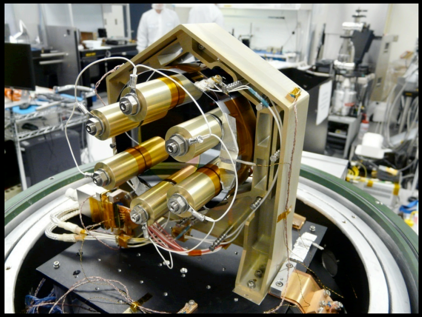
Exploring Strange New Worlds, Flagstaff, 4 May 2011

TFI at a glance

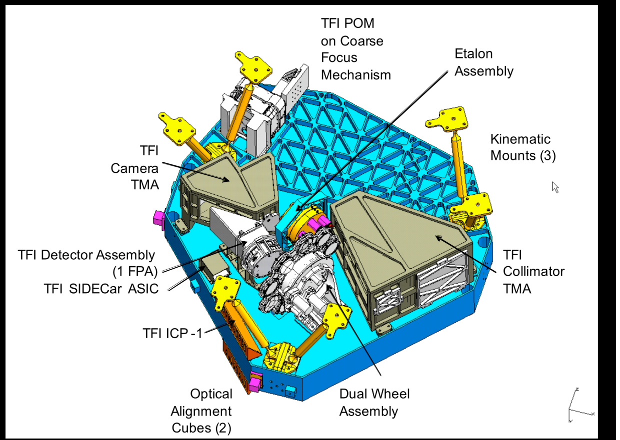
- ✧ FOV: 2.2’x2.2’
  - 65 mas pixel sampling (Nyquist at 4.0 μm)
- ✧ Wavelength range: 1.5-2.6 μm and 3.1-5.0 μm
  - (non-functional: 2.6 - 3.1 μm)



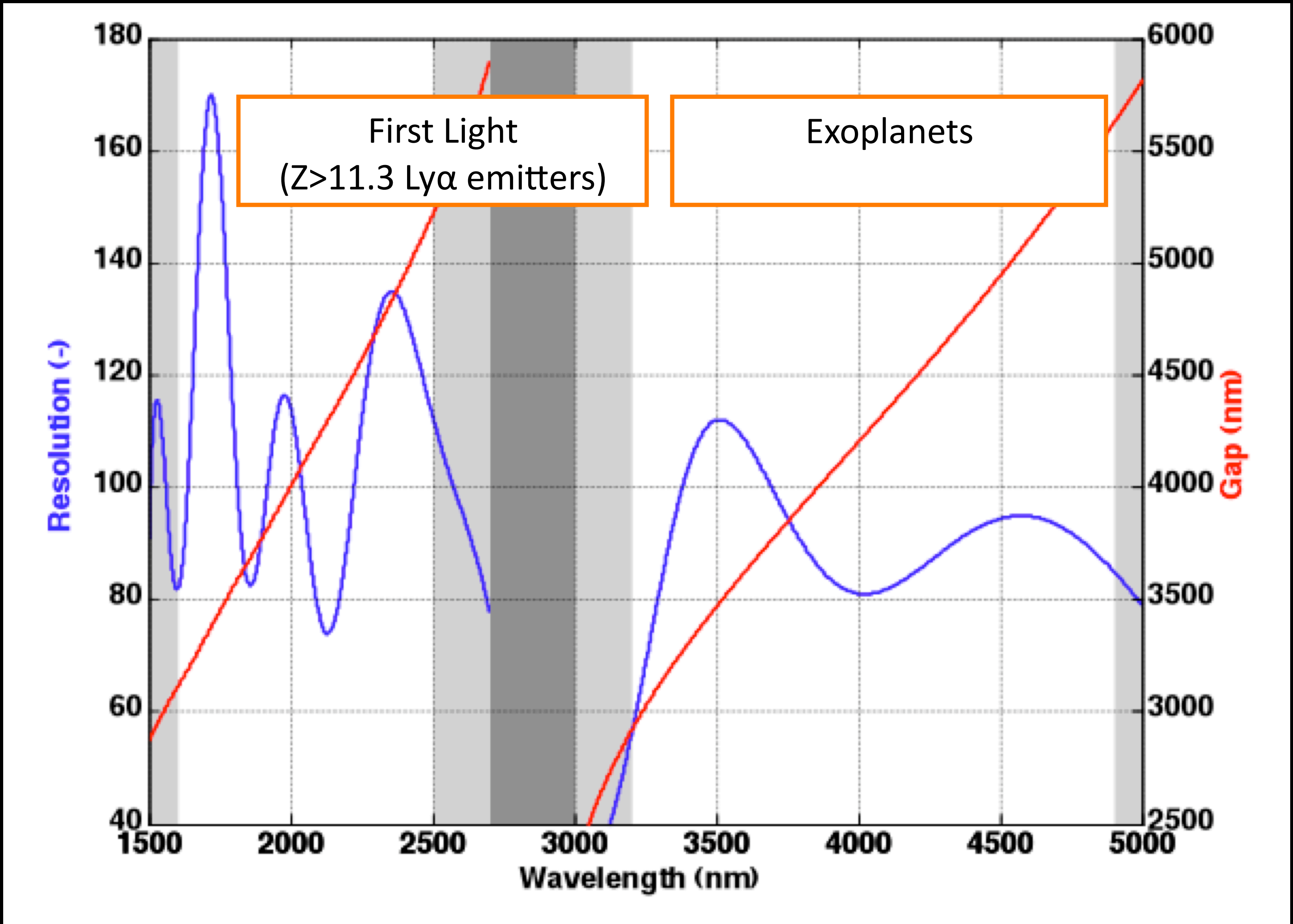
- ✧ Resolving power of ~100 (70-150)



- ✧ Observing modes
  - Normal imaging
  - Lyot coronagraphy
    - 4 occulting spots, 3 lyot masks
  - Non-redundant mask interferometry

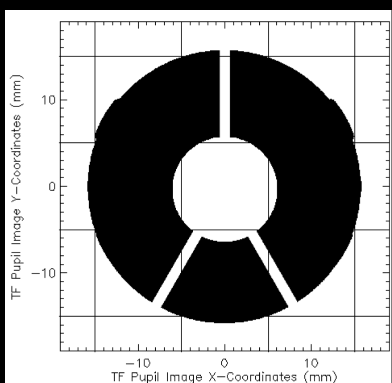


Spectral Resolution



TFI Coronagraphy

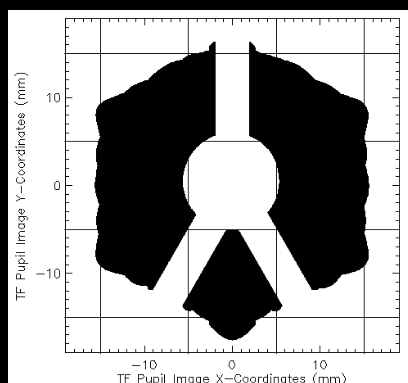
- 4 occulting spots engraved on the pick-off mirror
  - Diameters of 0.58”, 0.75”, 1.5” and 2.0”
- 3 lyot masks
  - Transmissions of 71%, 66% and 21%
  - Robust against pupil shear up to 4%
- Performance validated in the lab



C71

0.58” and 0.75”

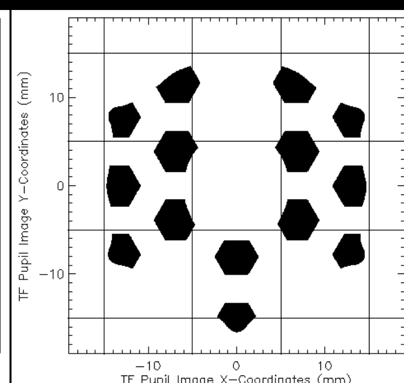
<1”



C66

1.5”

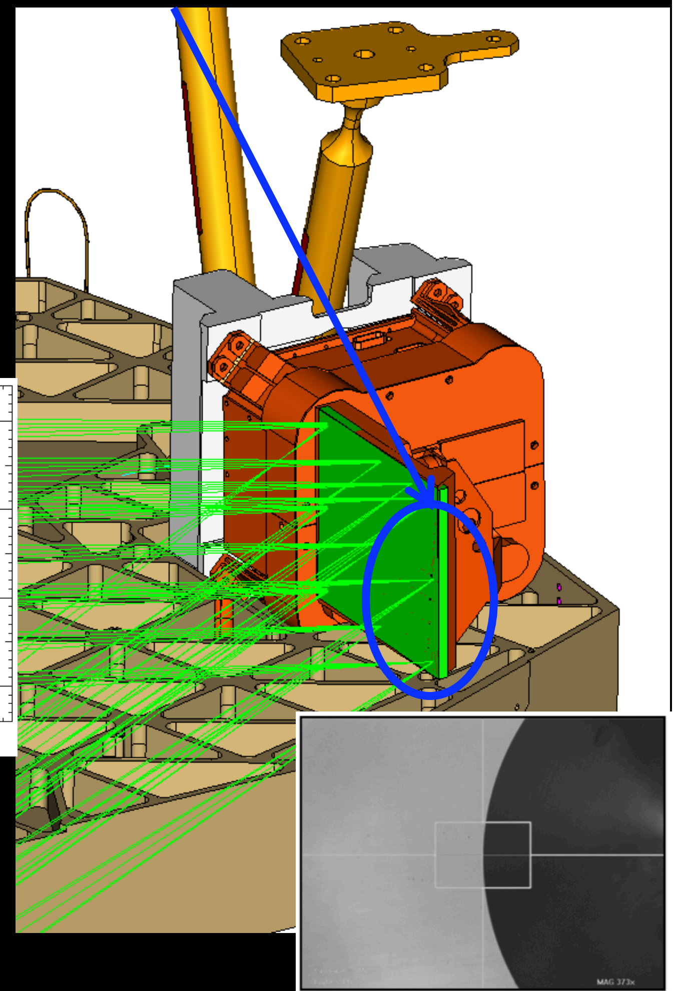
1”-2”



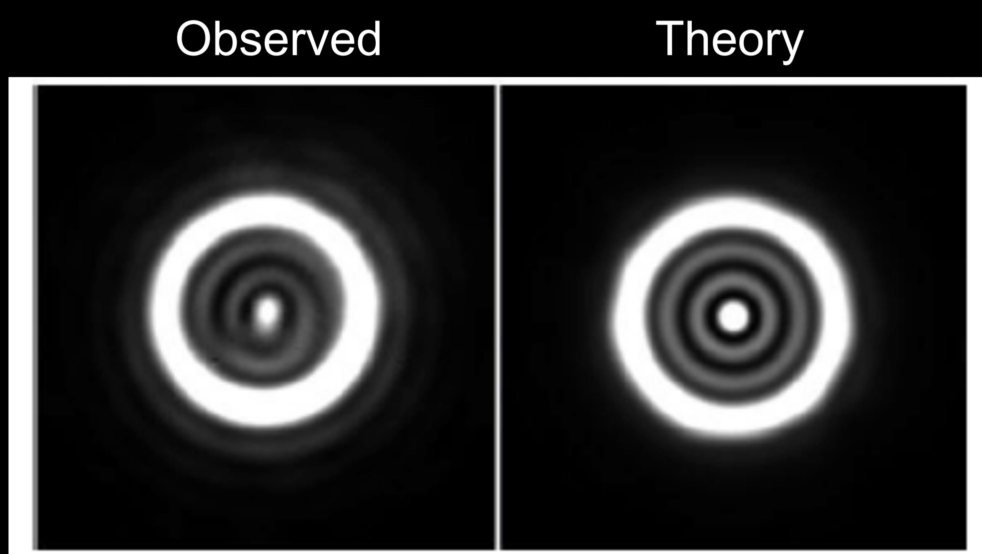
C21

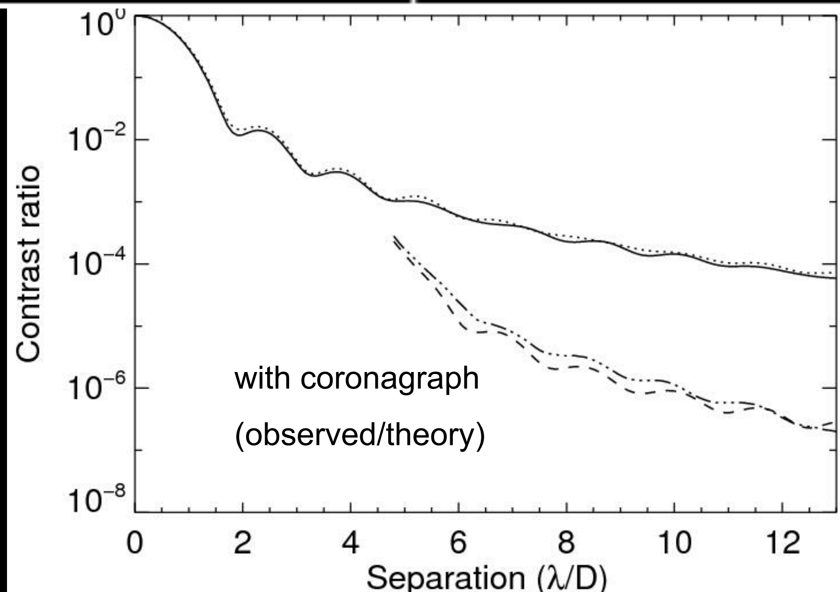
1.5” and 2.0”

>2”



TFI coronagraph testbed

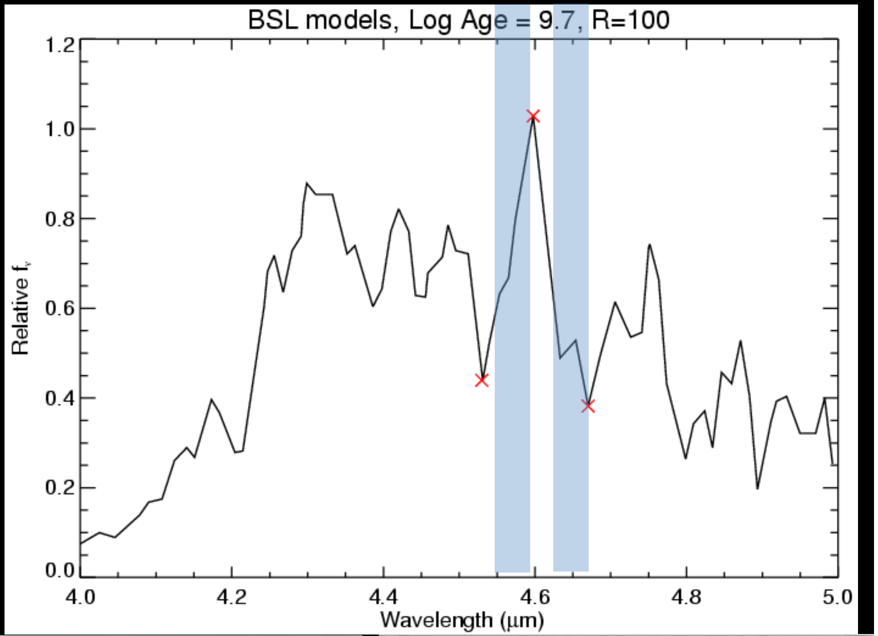




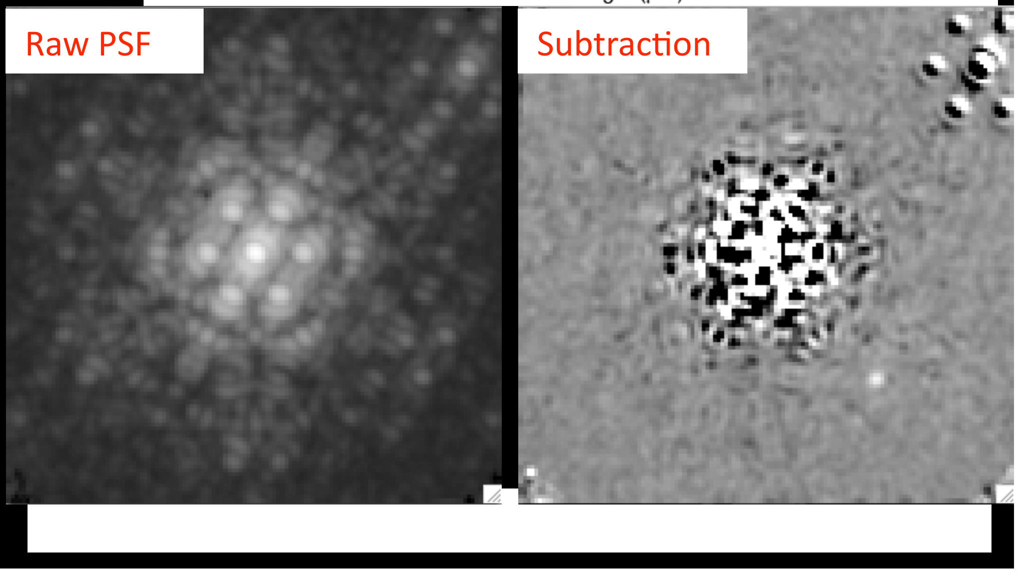
Beaulieu et al (2008)

Multi-Wavelength PSF subtraction (Spectral Differential Imaging)

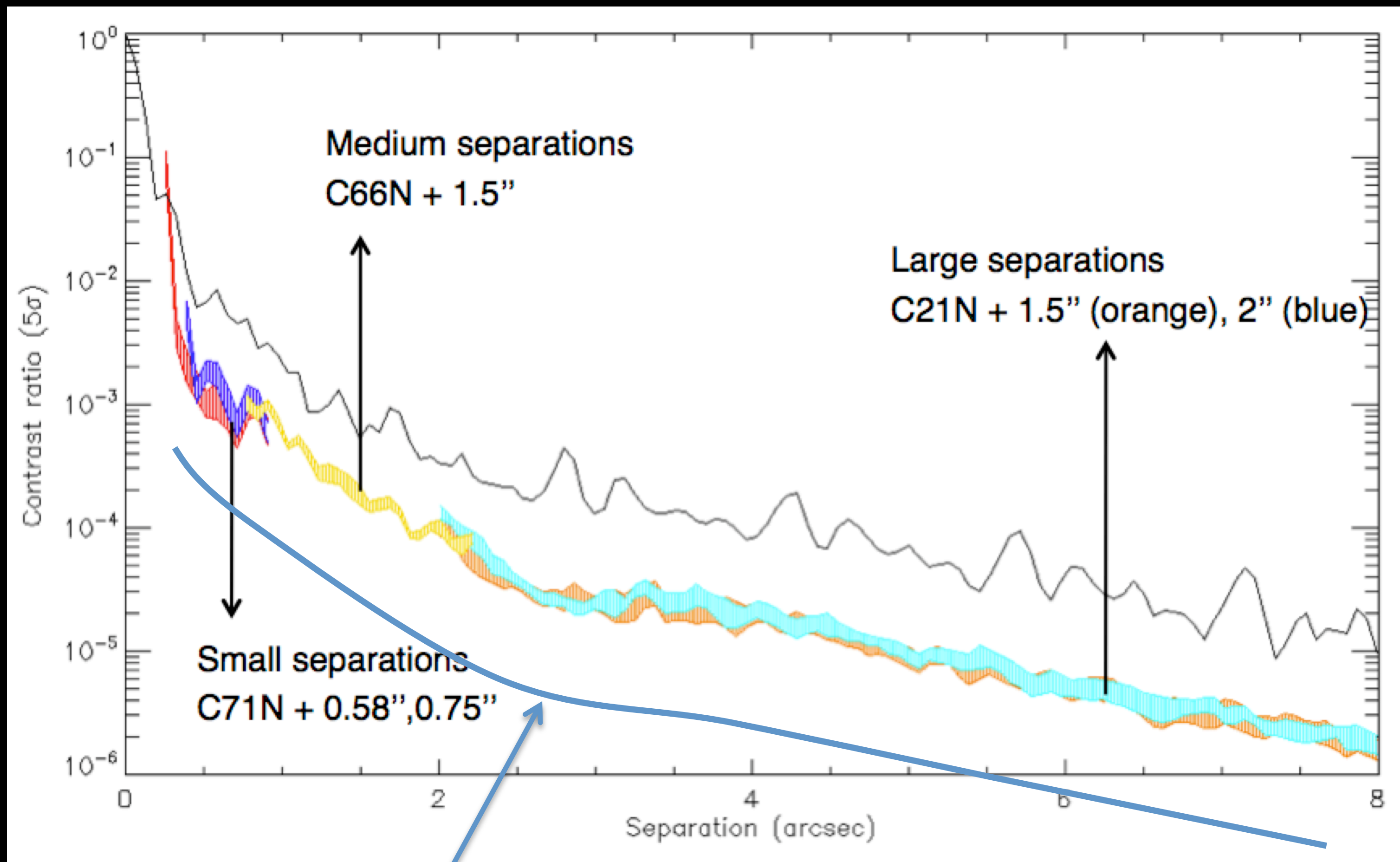
- Image of the target itself at a different wavelength is used as a reference PSF image.
- Works with either a sharp spectral feature or a flat spectrum.



- Demonstrated in the lab with a prototype etalon.



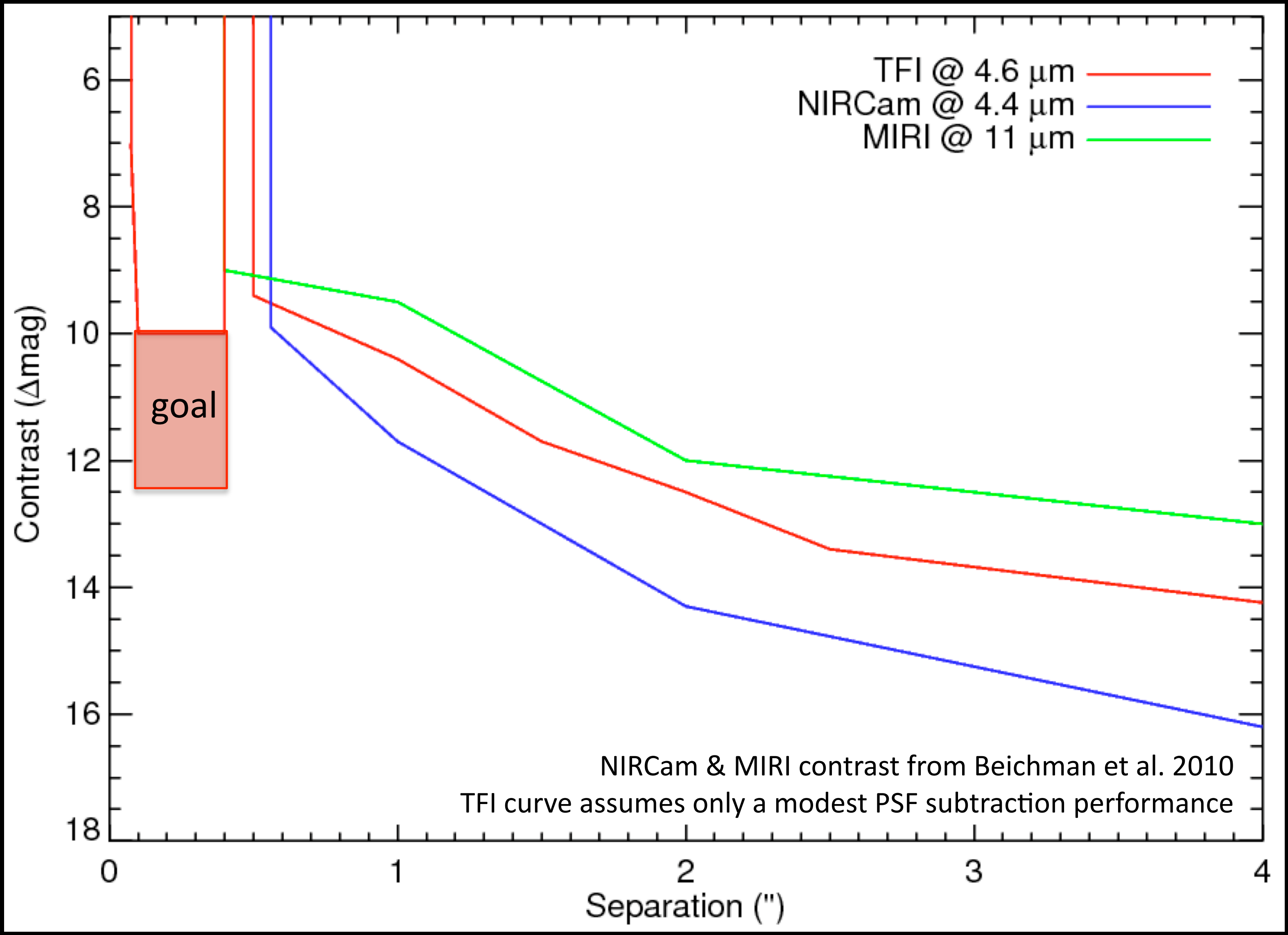
TFI contrast limits



Contrast improvement with SDI

These contrasts can be improved further with PSF subtraction (~10X)

NIRCam/MIRI/TFI contrast performance



A Powerful and Versatile High-Contrast Imaging Capability

Instrument	λ range (μm)	Smallest IWA (arcsec)	*Log* contrast (1 arcsec, 5σ)	*Log* contrast (5 arcsec, 5σ)
NIRCam	2 - 5	0.5 (4.1 μm)[e]	-5.1[a]	-7.5[a]
TFI/Lyot	3.1 - 5	0.4	-4.3(-5.3)[b]	-6.2(-7.2)[b]
TFI/NRM	3.1 - 5	0.07-0.5	See note[c]	-
MIRI/Lyot	5.6 - 23	2.2	-4.4[d]	-6.0[d]
MIRI/4-QPM	10.65,11.4,15.5	0.3	-3	-3

[a] With PSF calibration (roll or other PSF subtraction technique), λ=4.6 μm

[b] With SDI speckle suppression + PSF calibration (in parenthesis), λ=4.6 μm.

[c] -4 (baseline), -5 (goal,with visibility calibration).

[d] At 15.5 μm.

[e] Effective IWA. The true (50% transmission) IWA is 0.78''.

Smallest IWA achievable with a 10 degree roll: 0.1 λ(μm) arcsec

(assumes minimum PSF angular separation of ½ λ/D)

➔ 0.4'' @ 4μm ~< IWA of NIRCam/TFI/MIRI-4QPM

NIRCam or TFI ?

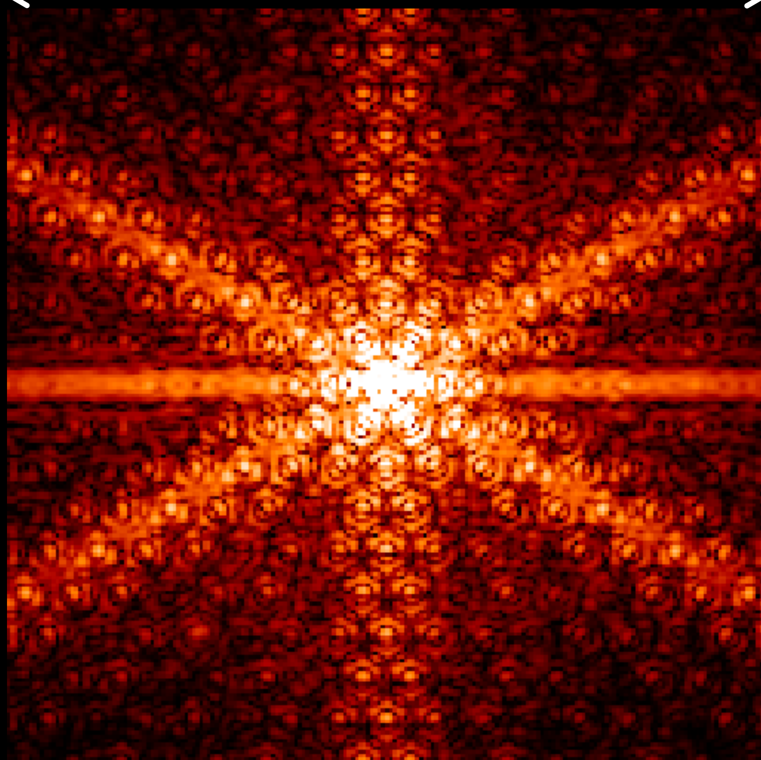
- NIRCam coronagraph is superior to TFI for IWA>0.5’’
  - Soft (apodized) mask for NIRCam vs hard-edge for TFI
  - Ability for NIRCam to adjust their pick-off mirror to null pupil shear
- Overall performance similar (contrast-limited regime)
  - NIRCam+roll ~ TFI+SDI+roll
- NIRCam has broader filters
  - More sensitive at large separation
  - TFI is read noise limited > 2-3’’ for $M_{4.6}$>5
- General rule-of-thumb
  - Use NIRCam with medium filters for detection + 2 more filters for basic characterization
  - Use TFI for in-depth characterization studies
- For IWA<0.5’’, use TFI NRM

Speckle Suppression is crucial …

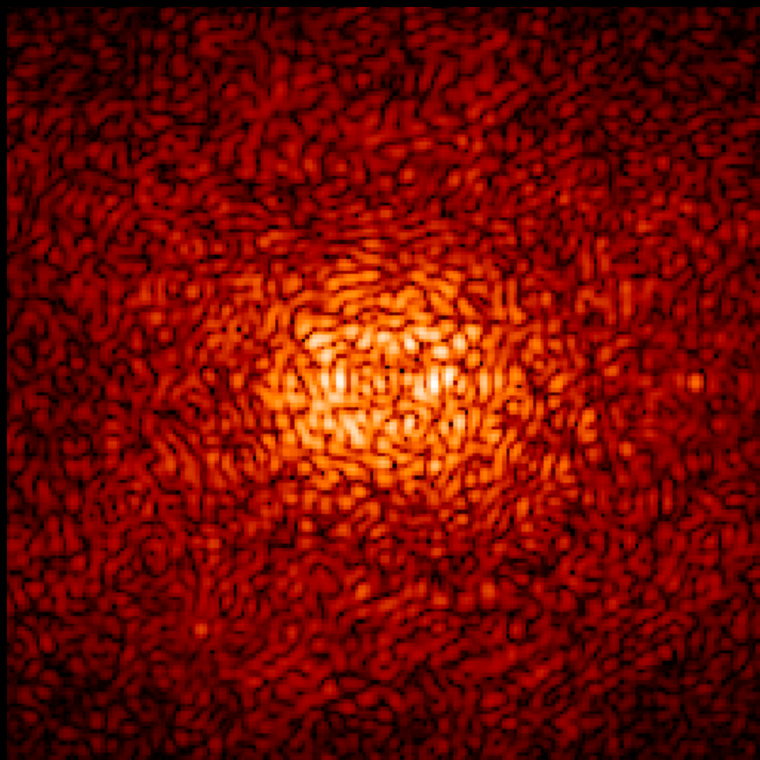
TFI PSF @ 4 μm

No cononagraph

13 ’’

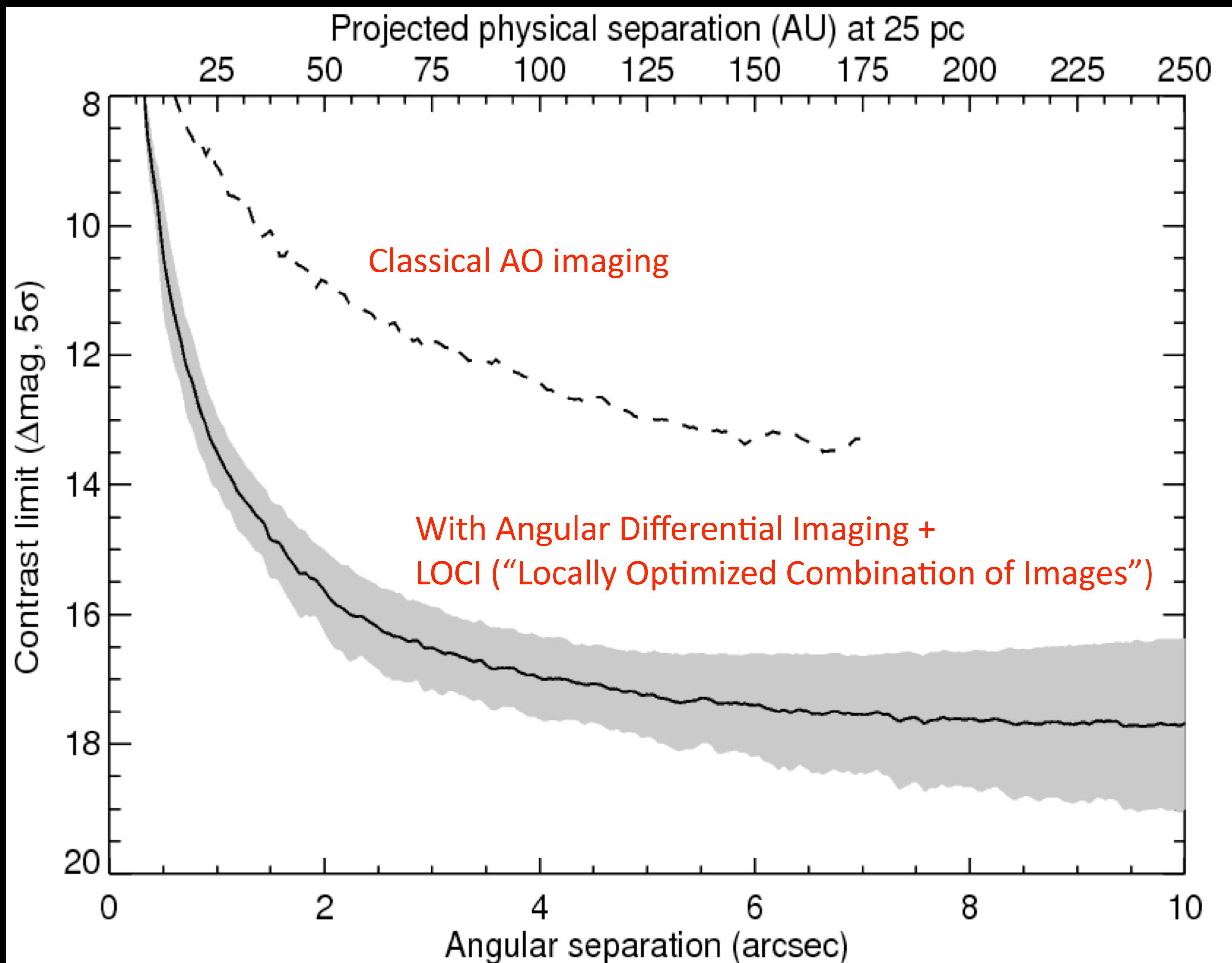


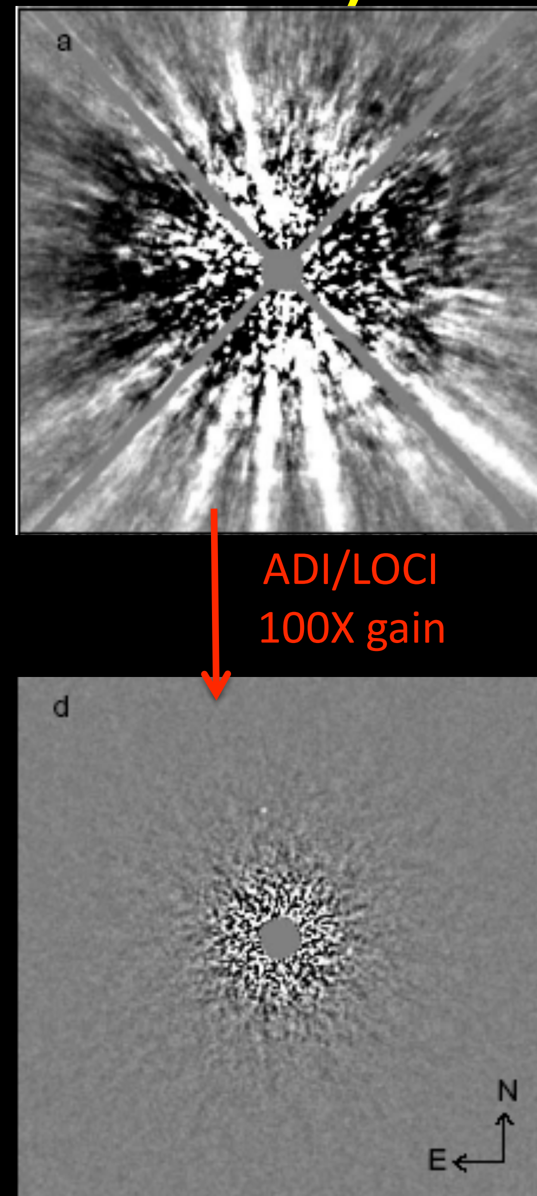
With cononagraph



Speckle noise attenuation of 100x is needed to detect planets even at large angular separation.

…works on the ground (e.g. GEMINI)…



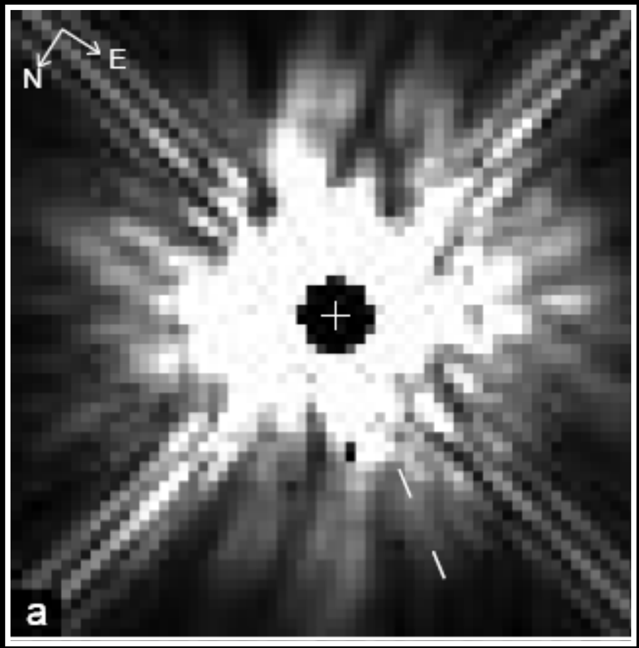


Lafrenière etal 2007

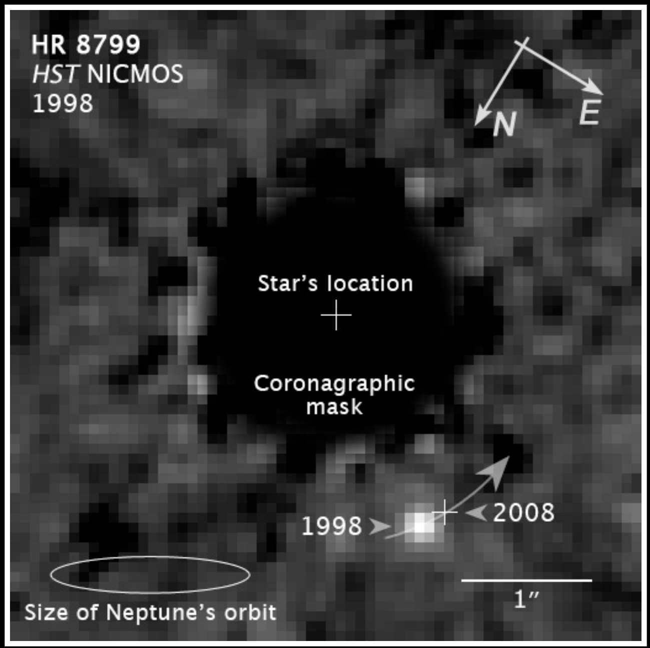
...and in space (HST)

HR8799b recovered from 1998 HST archive data

Simple roll subtraction



LOCI combination of 55 images



Lafrenière et al 2009

- LOCI 10x better than simple roll technique.
- Condition should be much more stable at L2.
- Reasonable to expect speckle noise attenuation better than 10x with JWST

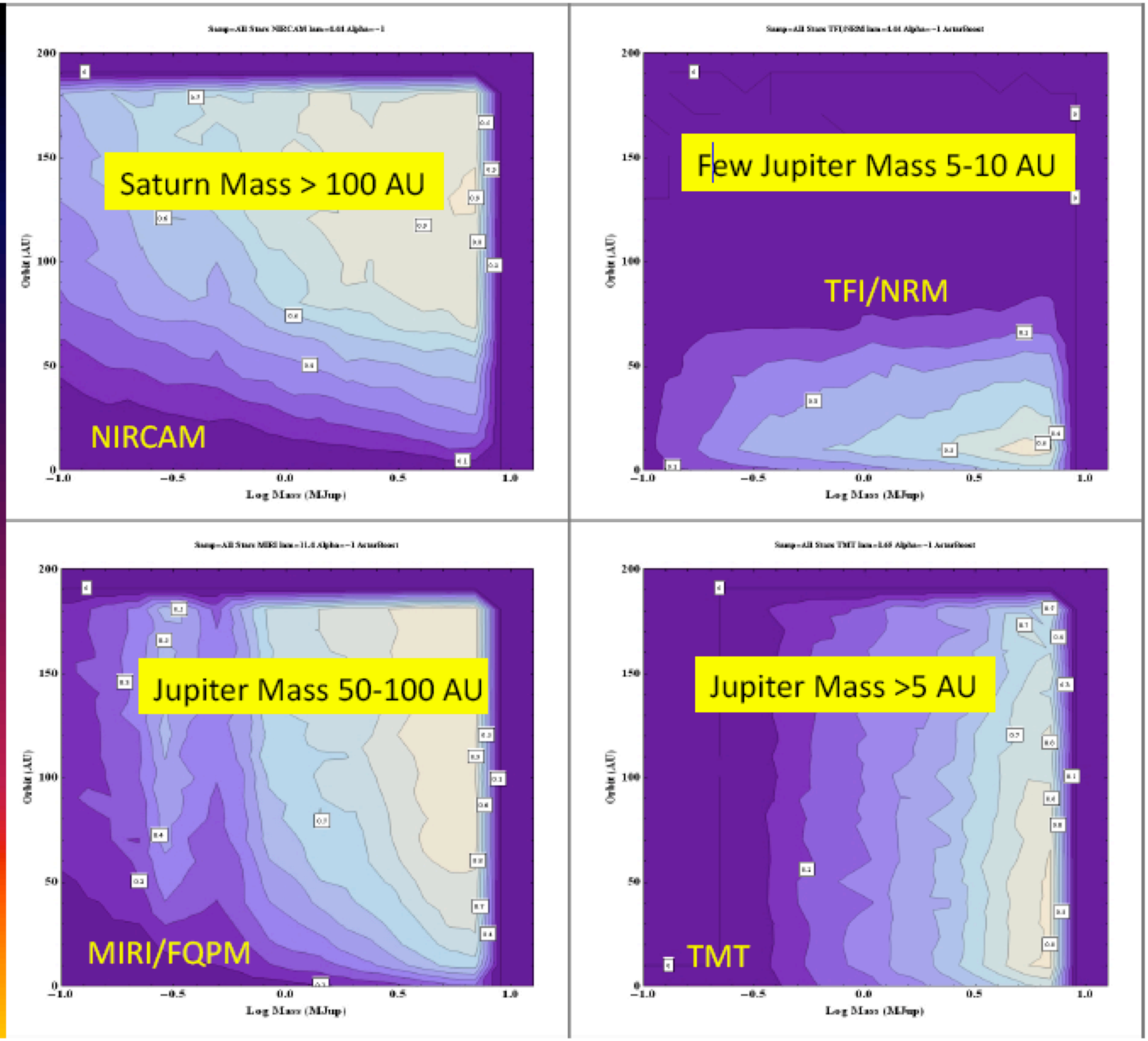
Exoplanet topics for JWST

- What is the frequency of exoplanets as a function of host mass and age?
- Are planets on distant orbits common or rare?
  - Where and how do gas giants form?
    - <10 AU via core accretion
    - >10 AU via fragmentation or accretion + migration
  - How important are migration and dynamical interaction mechanisms?
- What are the physical properties of exoplanets?
  - Is it different for bound and unbound (free-floating) planets?
- Where does star formation end and planet formation begin?

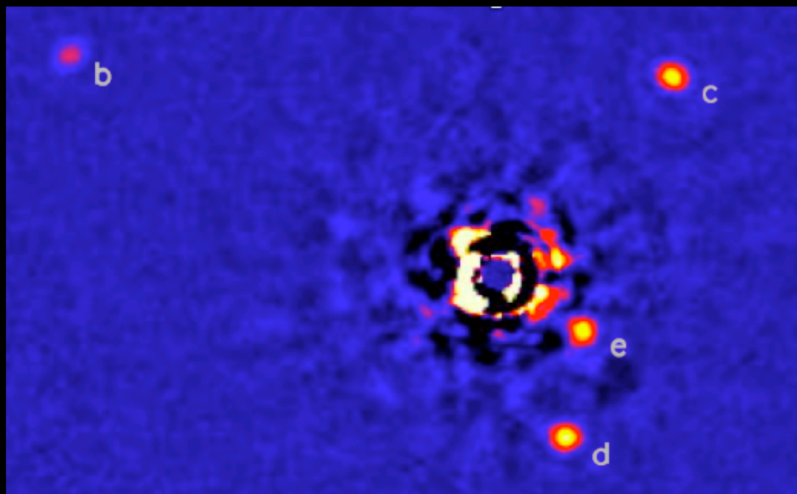
Direct Imaging of Young Gas Giants

- Test Theories of Formation & Migration
- Physical Properties

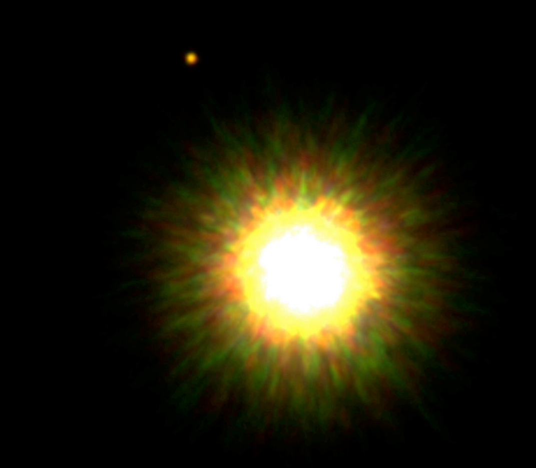
Beichman et al 2010



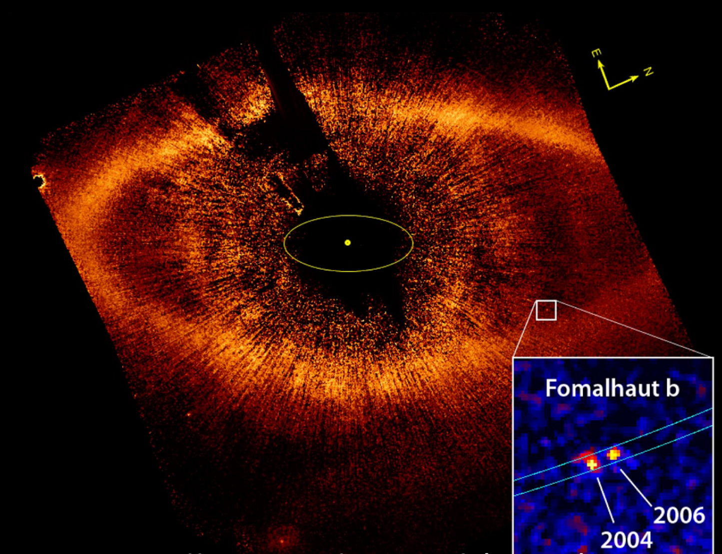
Could JWST detect these planets?



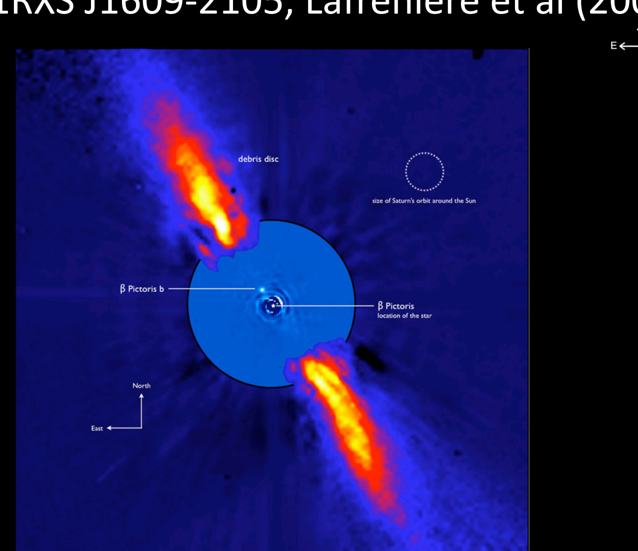
HR 8799, Marois e al (2008)



1RXS J1609-2105, Lafrenière et al (2008)

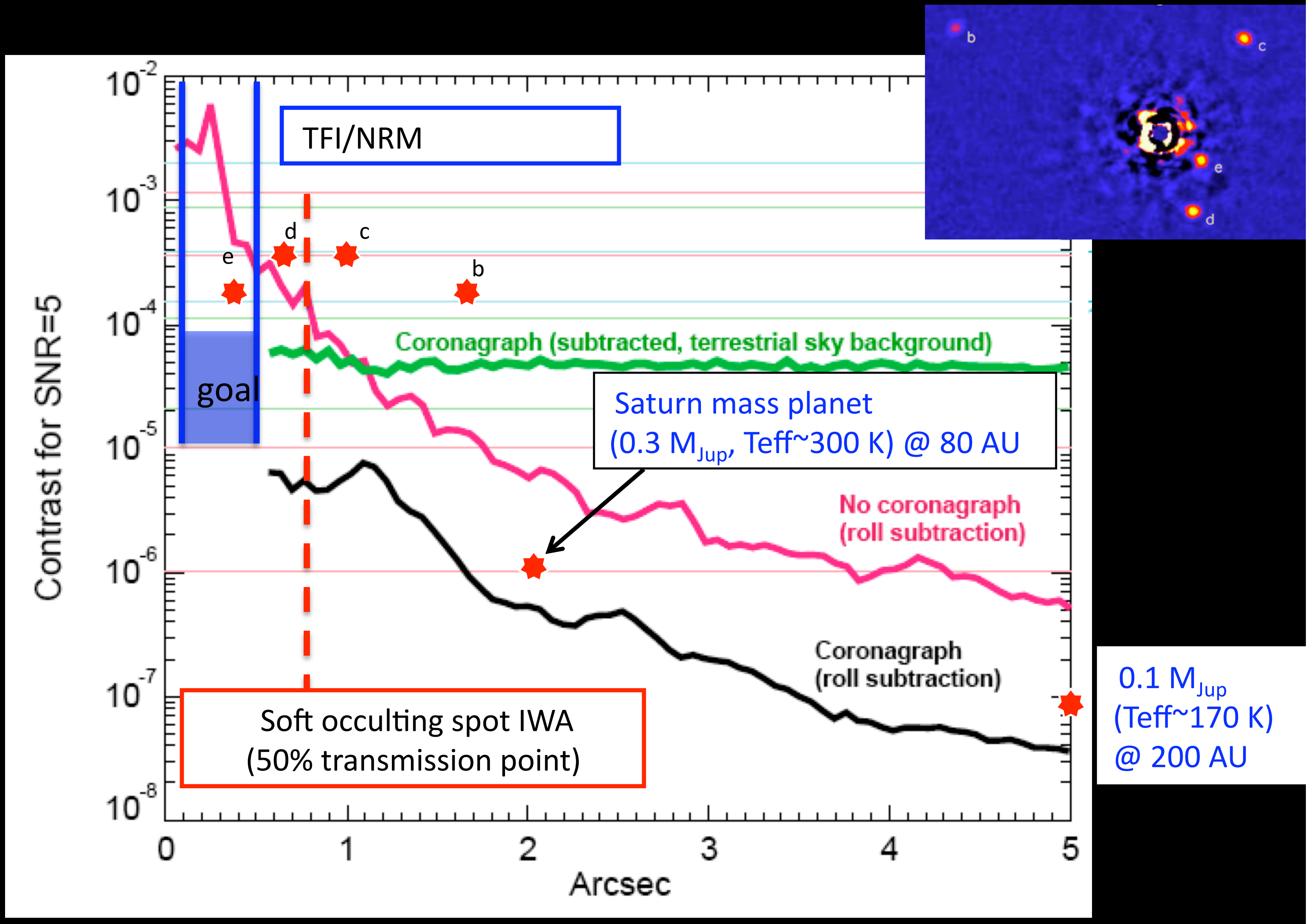


Fomalhaut, Kalas et al (2008)



βPic, Lagrange etal (2008)

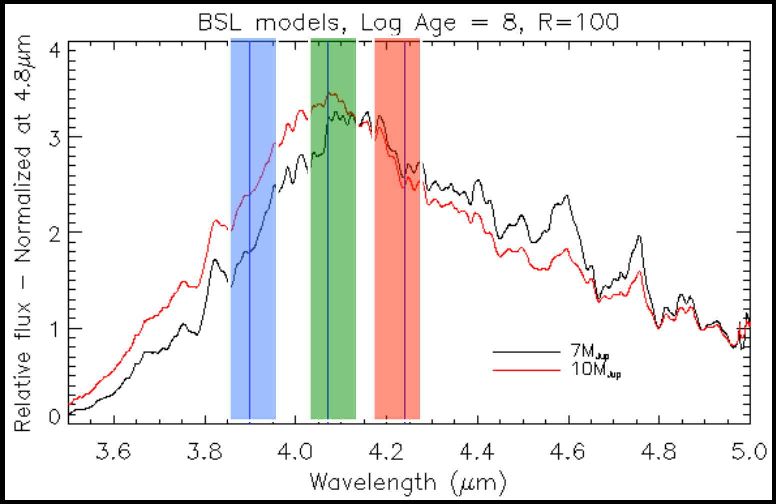
HR8799 - Detection with NIRCam/TFI



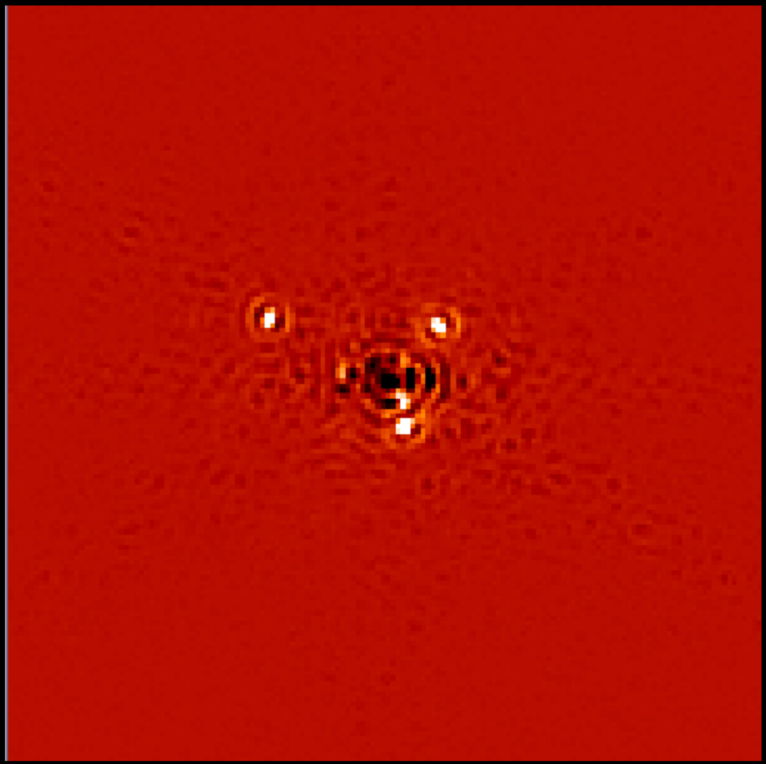
Contrast simulation: John Krist

HR8799 - SDI detection with TFI

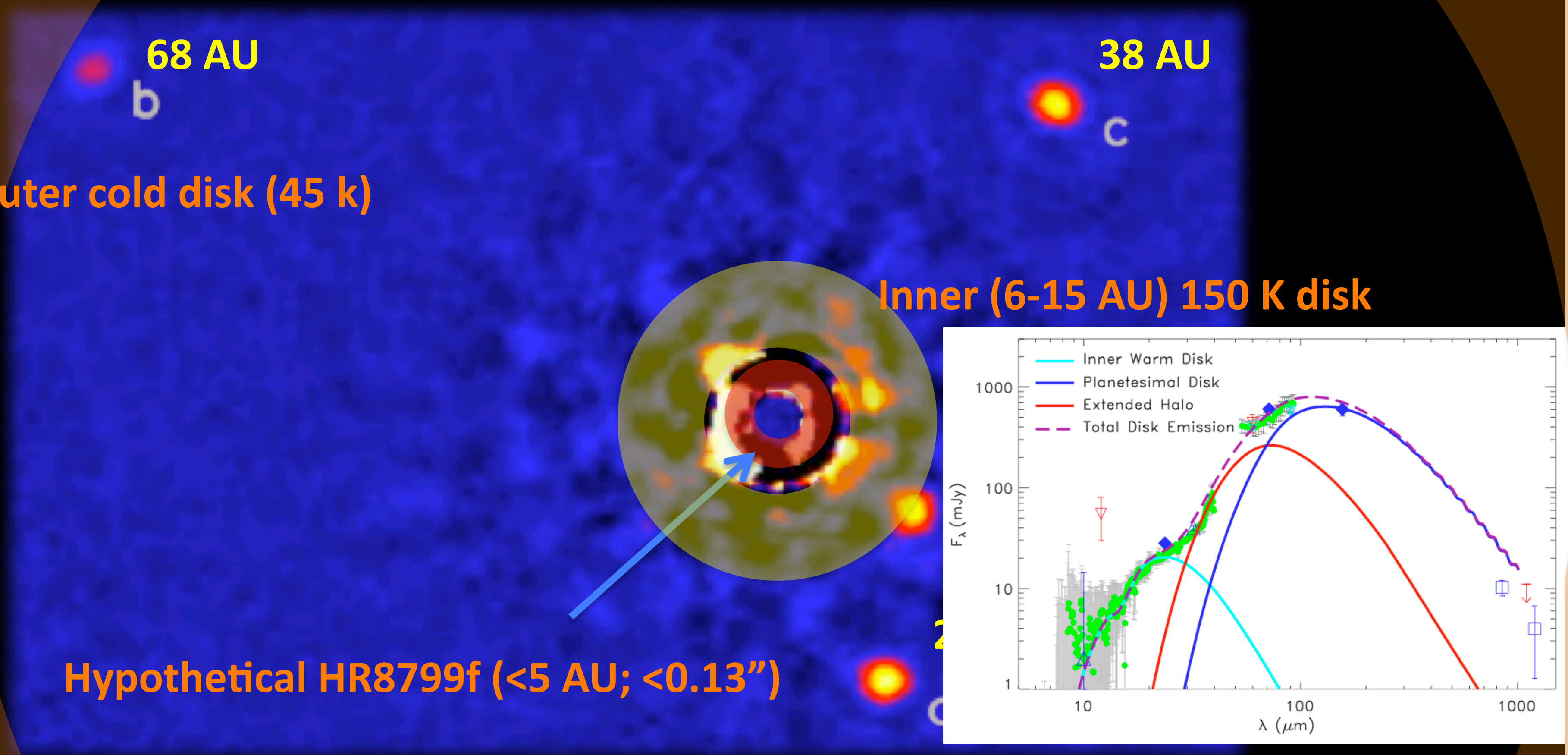
- 0.58” occulter
- 3 λ =[4.07, 3.9, 4.24] (monochromatic PSFs)
- 1000s per filter



Double difference
(4.07, 3.9, 4.24 μm)



Another planet at 3-5 AU around HR8799 ?



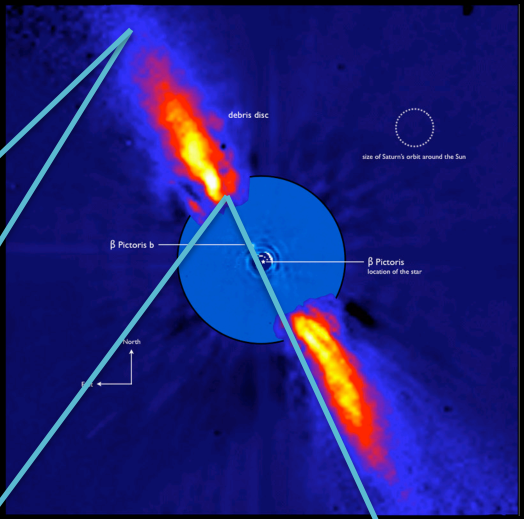
TFI/NRM sensitivity

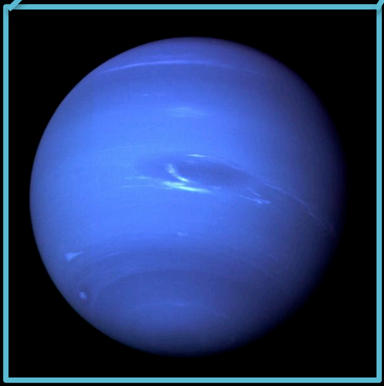
4 M_{jup} if $\Delta m_{4.6}$=10

1 M_{jup} if $\Delta m_{4.6}$=12.5

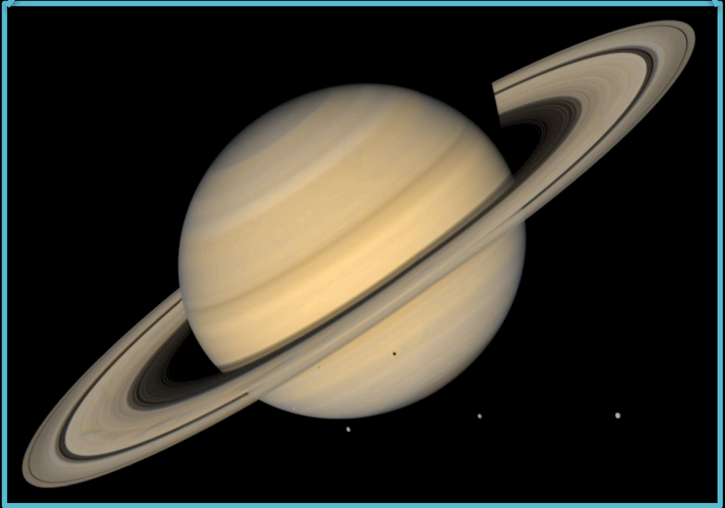
βPictoris

- 7-8 M_{jup} @ 8-15 AU
- β Pic b very close to the IWA (0.4'')
- TFI/NRM detection: yes ($\Delta m_{4.6}$=8)
- Deep NIRCam/TFI imaging to search for Saturn/super-Neptune mass planets beyond 10 AU.



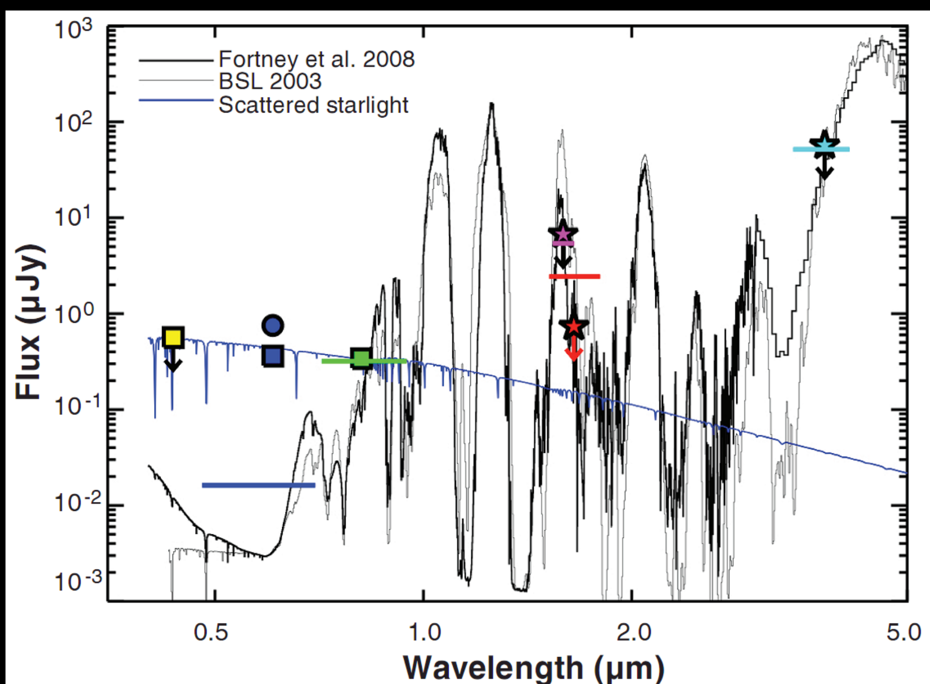


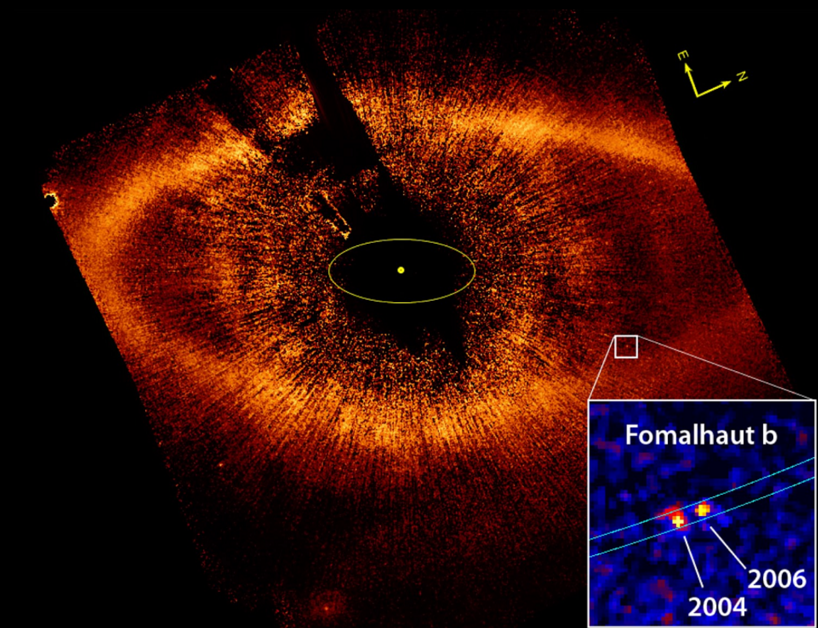
?



Fomalhaut b: a very puzzling world!

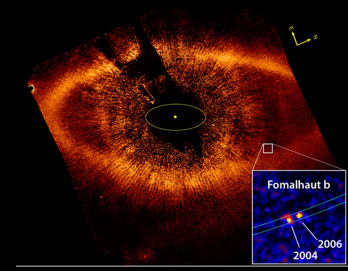
- ✧ Overluminous at 600 nm
  - Circumplanetary disk of radius ~20 R_{jup} ?
- ✧ Variable at 600 nm?
- ✧ Underluminous in near-IR?
- ✧ Need more observations…



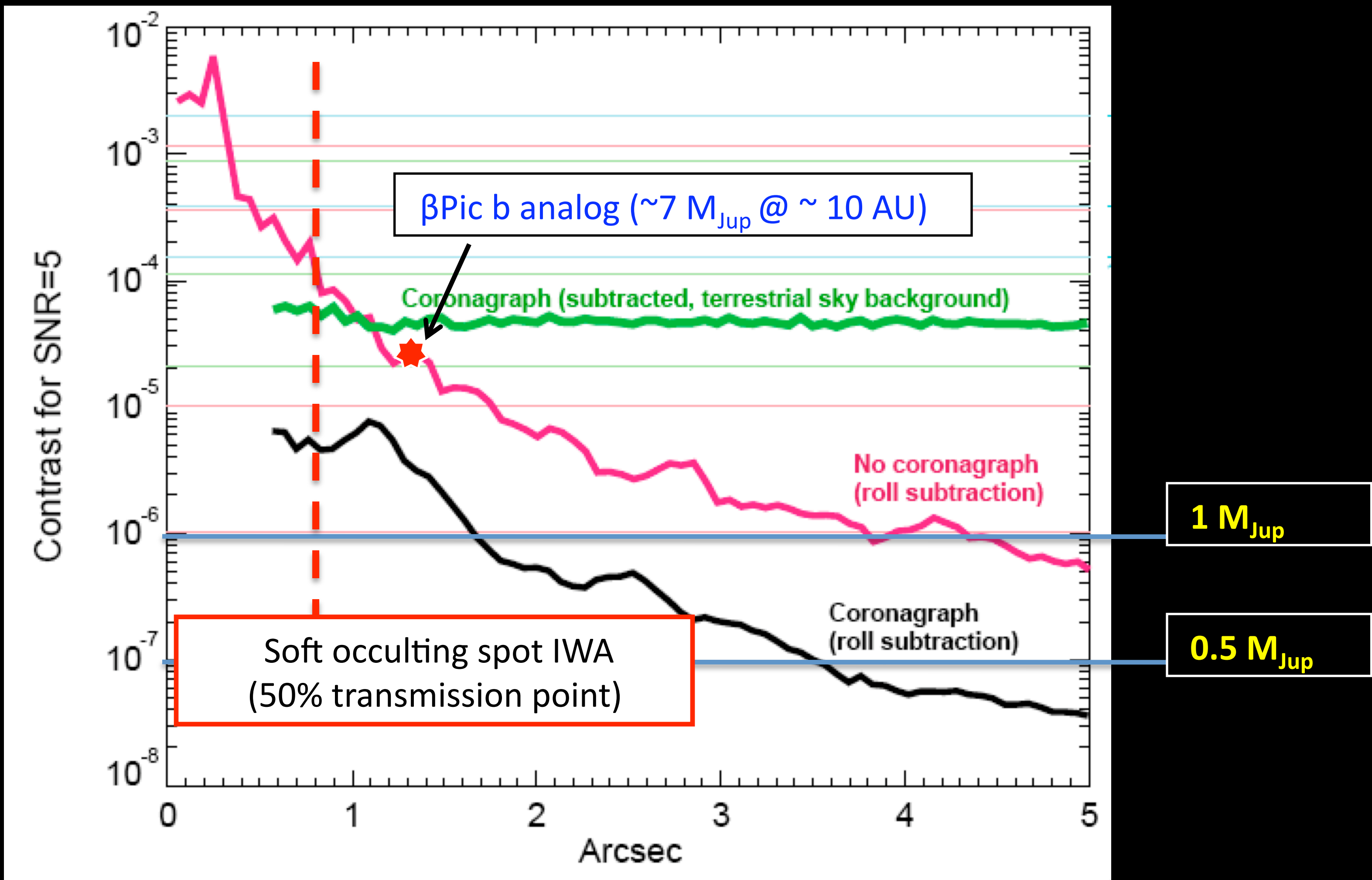


Kalas et al. (2008)

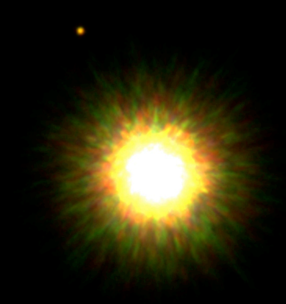
Detection with NIRCam/TFI



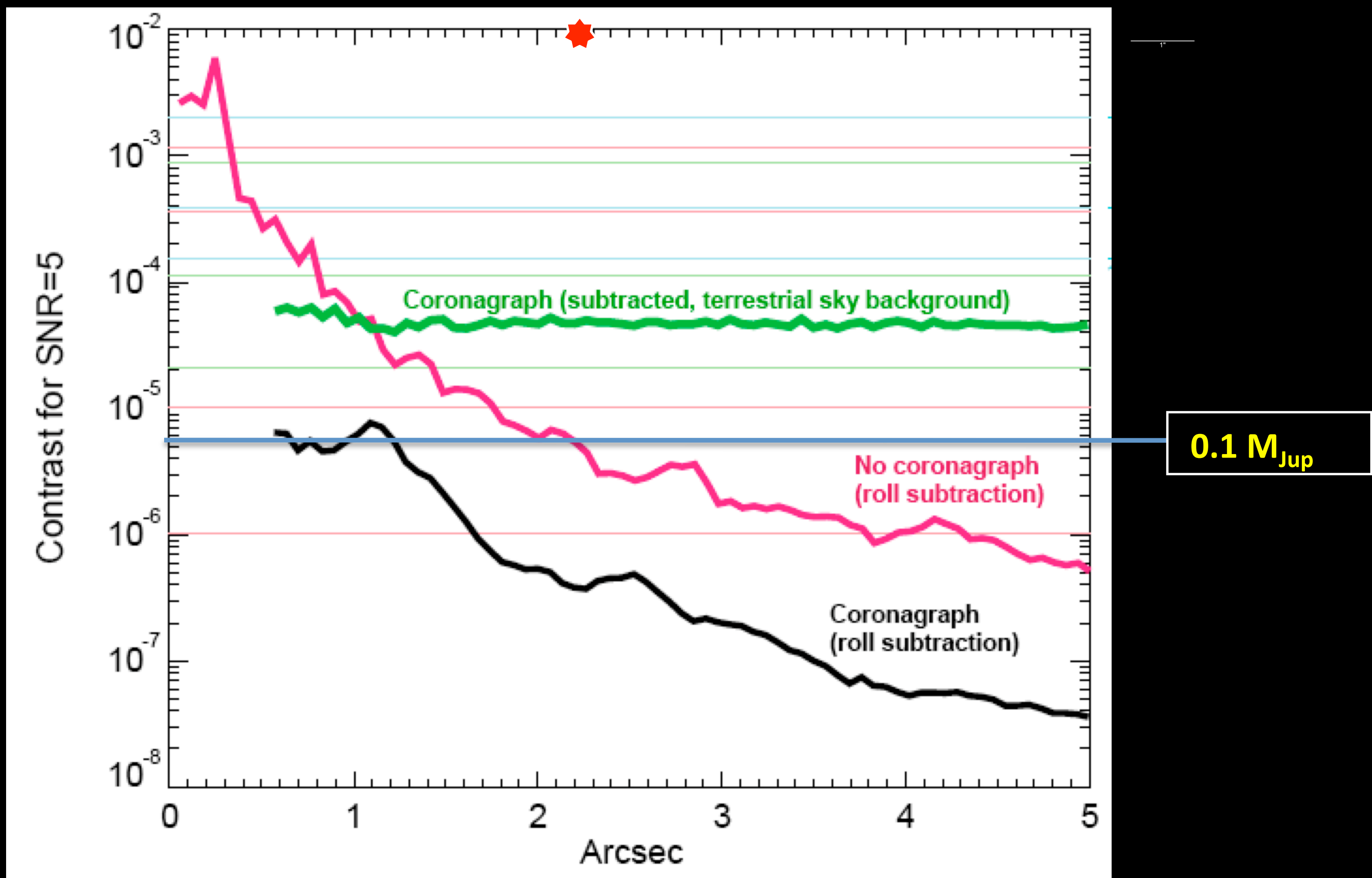
Fomalhaut b @ 12.7’’ . Will be « easily » detected.



Detection with NIRCam/TFI



5 Myr, ~8 M_{JUp} @ 2.2’’ (330 AU). Very bright.
Maybe could be observed with NIRSpec/MIRI IFU. To be explored.



What about MIRI?

Target Name	SNR @ 5.6µm	SNR @ 7.7µm	SNR @ 10.65µm	SNR @ 11.40µm	SNR @ 15.5µm	Total hr
2M1207 b	140	98	49	48	40	3.3
AB Pic b	1280	386	58	56	39	1.75
beta Pic b	-	-	11	13	42	1.0
Fomalhaut b	49	15	34	75	43	3.1
HR 8799 b	10	34	33	51	25	0.4
HR 8799 c	8	8	28	22	32	
HR 8799 d	-	-	-	-	24	
SCR 1845 b	62	125	320	360	295	0.4
RSX1609 b	203	52	27	25	-	4.1
GJ 758 b	54	51	50	51	41	3.9
PZ Tel b	190	206	58	61	51	1.7

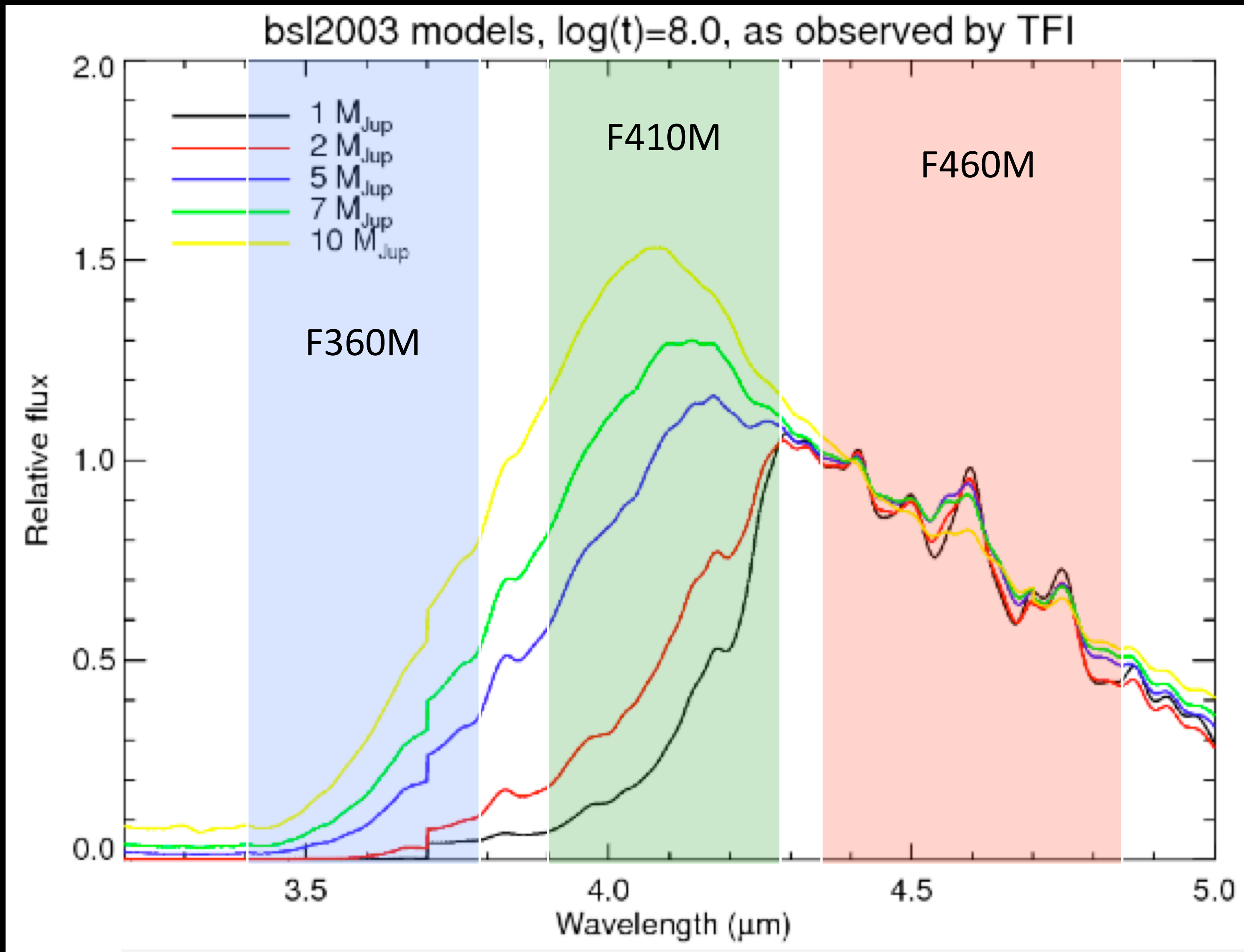
Virtually all planets are detected

Planets around young M stars

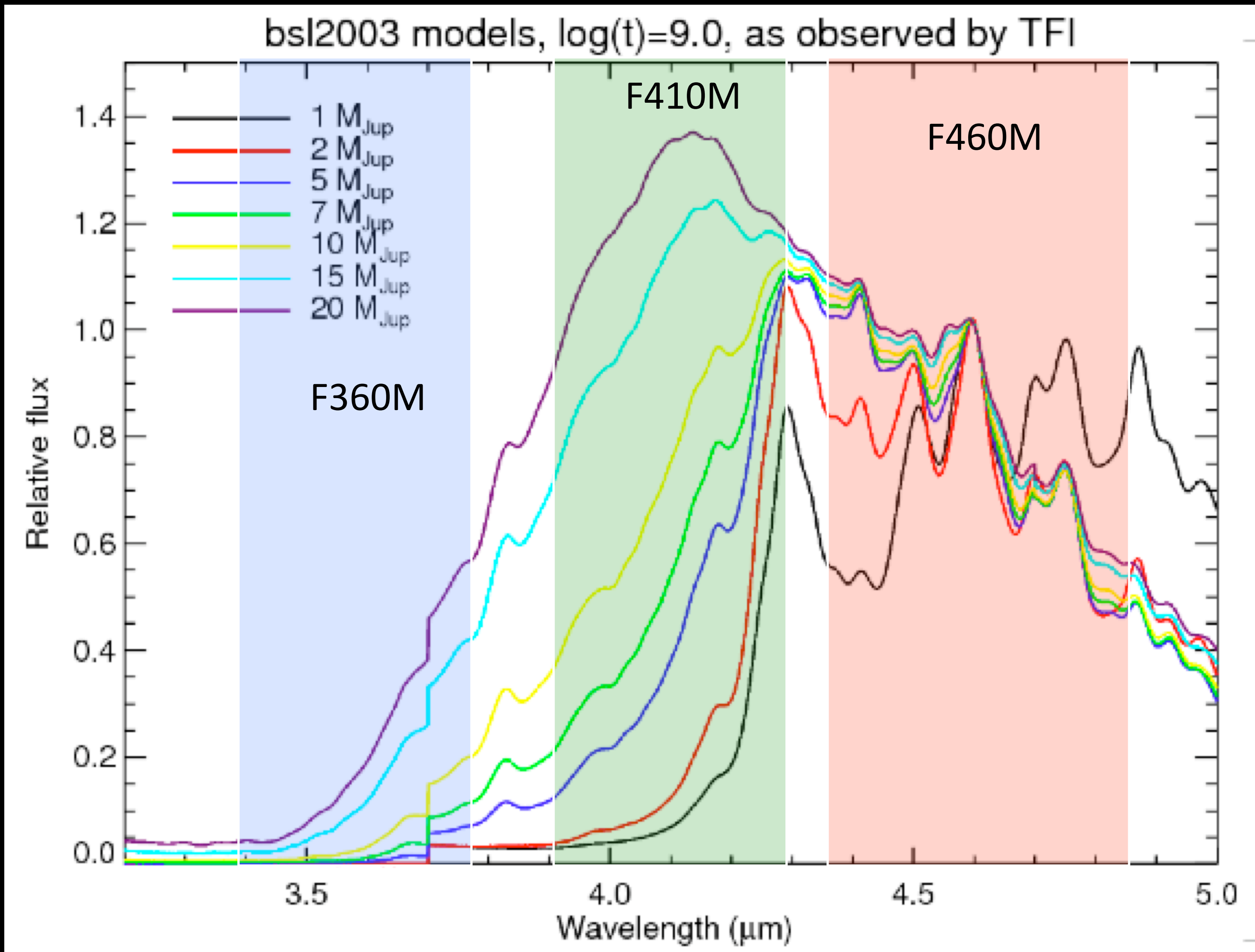
Absil et al. 2010

Name	Dist pc	Age Myr	Sp type	a AU	M Mjup	a AU	M Mjup	a AU	M Mjup	a AU	M Mjup	Group
AU Mic*	9.9	12	M1Ve	2	0.50	5	0.30	10	0.16	25	0.10	Bet Pic
TWA 8A*	21.0	8	M3Ve	4	0.40	11	0.25	21	0.19	53	0.16	TW Hya
TWA 8B*	21.0	8	M5	4	0.33	11	0.23	21	0.18	53	0.17	TW Hya
WW PsA	23.6	12	M4	5	0.50	12	0.30	24	0.21	59	0.20	Bet Pic
CD-57 1054	26.3	12	M0/1	5	0.80	13	0.50	26	0.25	66	0.23	Bet Pic
V1005 Ori*	26.7	12	M0.5V	5	0.80	13	0.50	27	0.25	67	0.23	Bet Pic
TWA 12*	32.0	8	M1Ve	6	0.80	16	0.45	32	0.26	80	0.25	TW Hya
CPD-66 3080B	31.4	12	M3Ve	6	0.80	16	0.42	31	0.28	79	0.27	Bet Pic
TWA 7*	38.0	8	M2Ve	8	0.90	19	0.52	38	0.30	95	0.28	TW Hya
GJ 4020 A	24.0	50	M0	5	2.00	12	1.10	24	0.60	60	0.50	AB Dor
GJ 9809	24.9	50	M0	5	2.00	12	1.10	25	0.60	62	0.50	AB Dor

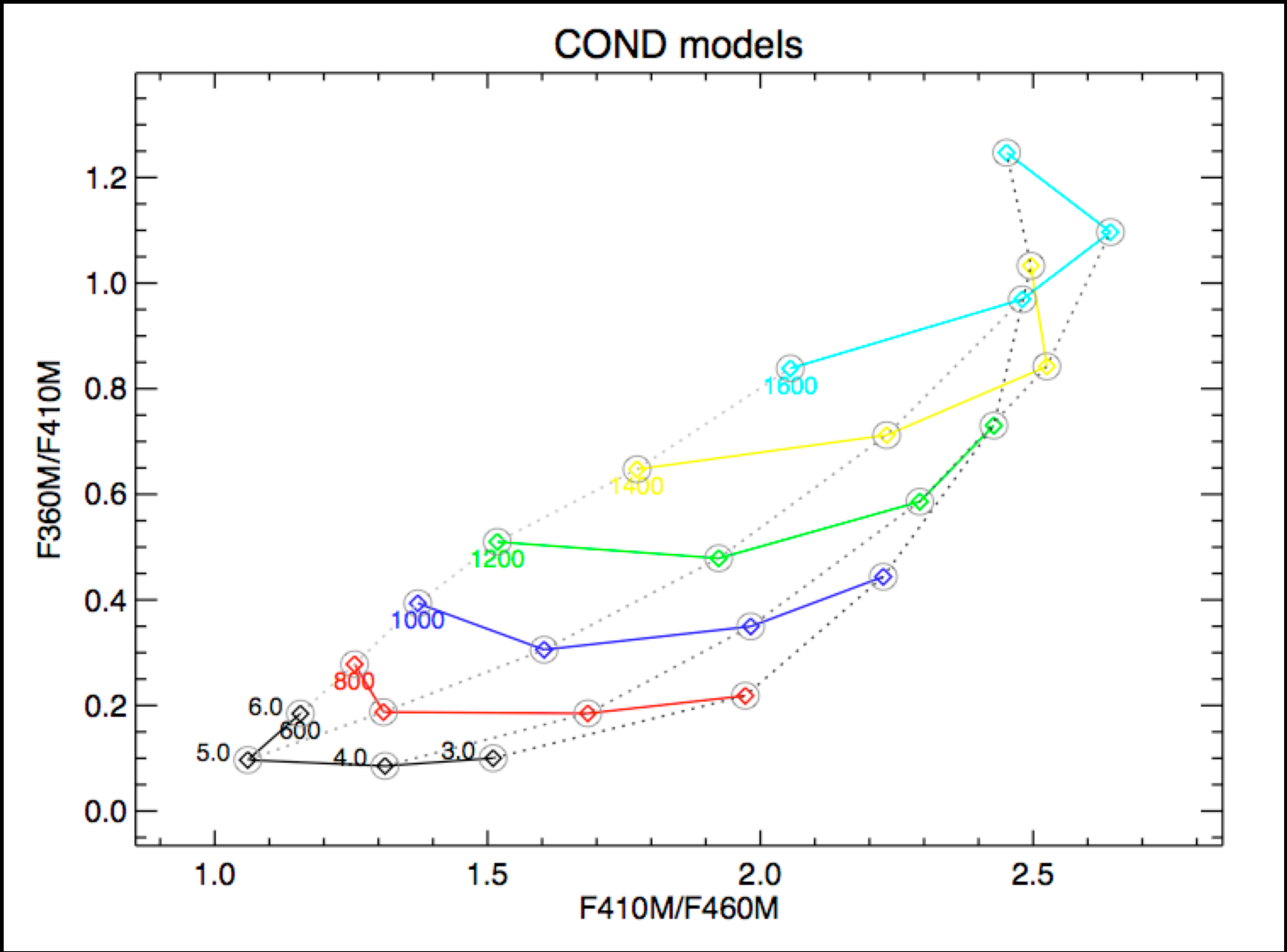
Exoplanet spectra as seen by TFI (100 Myr)
(overlaid with three of NIRCam medium filters)



Exoplanet spectra as seen by TFI (1 Gyr) (overlaid with three of NIRCam medium filters)



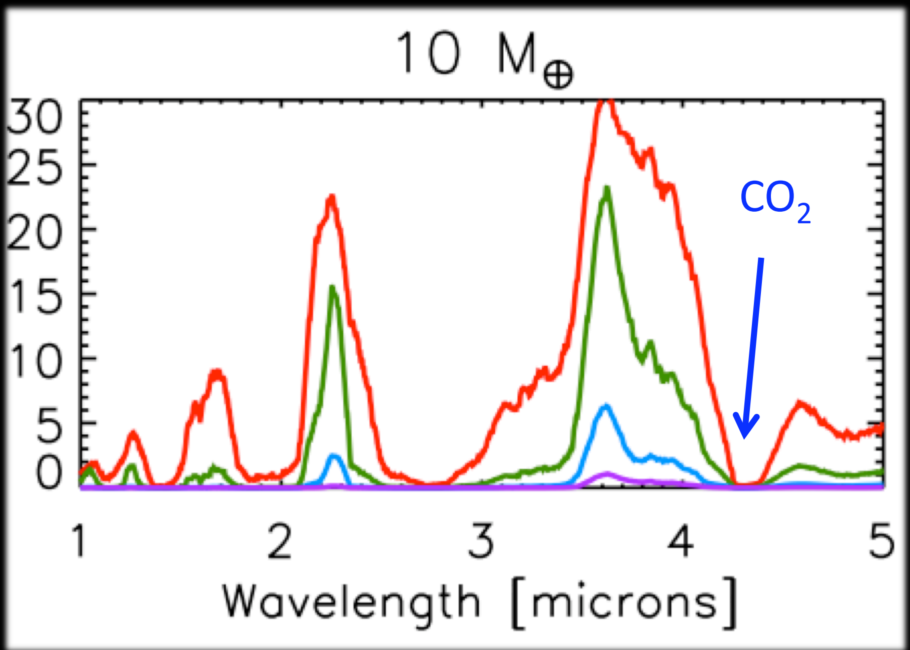
Basic characterization with NIRCam/TFI



Strange New Worlds
Rocky planets in formation

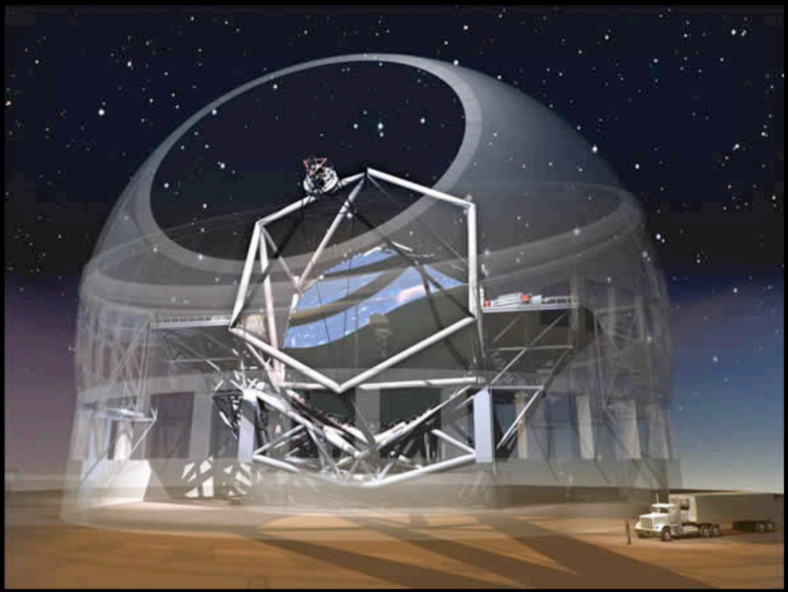
- Some collisions energetic enough to melt planet
- Outgassing creates a thin atmosphere ➔ planet can stay molten (at >1000 K) for several Myr, i.e. observable
  - Region of interest <0.5" (few AUs)
  - Contrast of <10 mag for young late-type stars and brown dwarfs in nearby young associations.

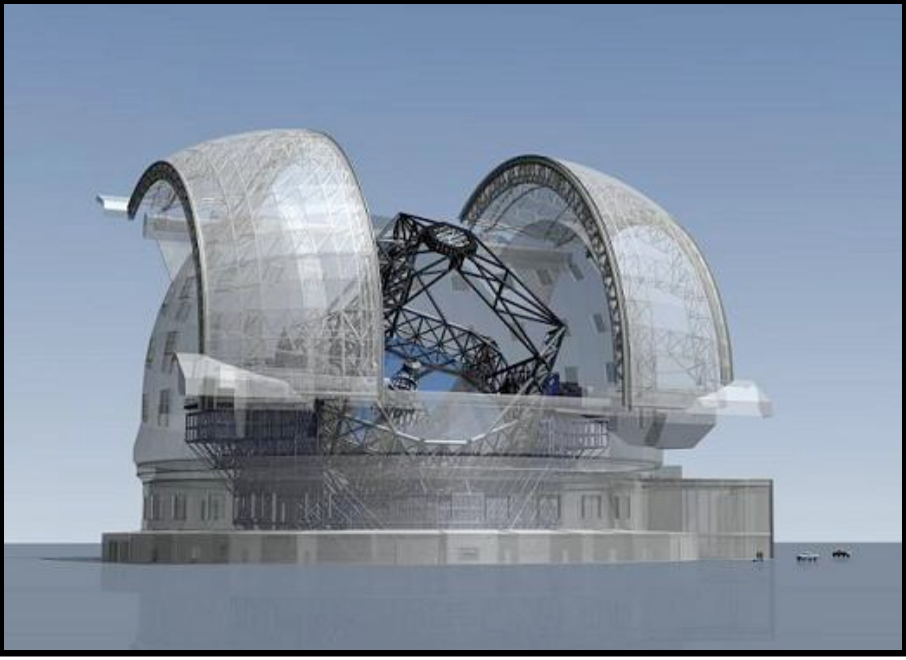
TFI/NRM



Miller-Ricci et al. 2009

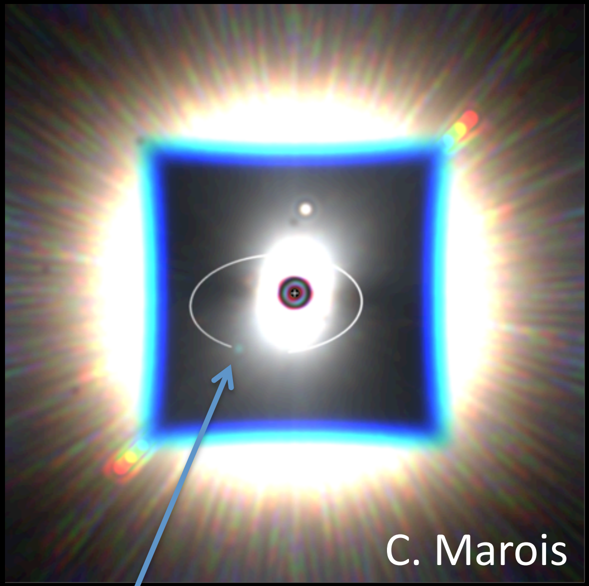
Ground vs space





One example: GPI and SPHERE

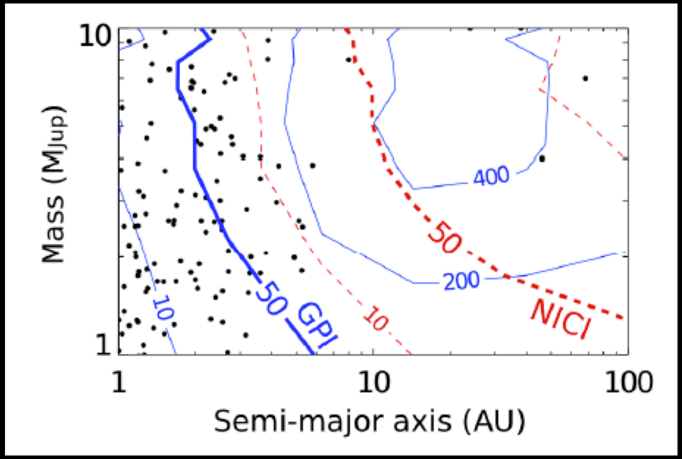
- GPI and SPHERE will have completed their surveys by the time JWST is launched.
- What they will do
  - Probe 0.1”-1” at very high contrast
  - Detect and characterize at <2.5 μm
- What they can’t do
  - Observe faint stars (I>9)
    - SPHERE slightly better for faint targets
  - Observe at > 2.5 μm

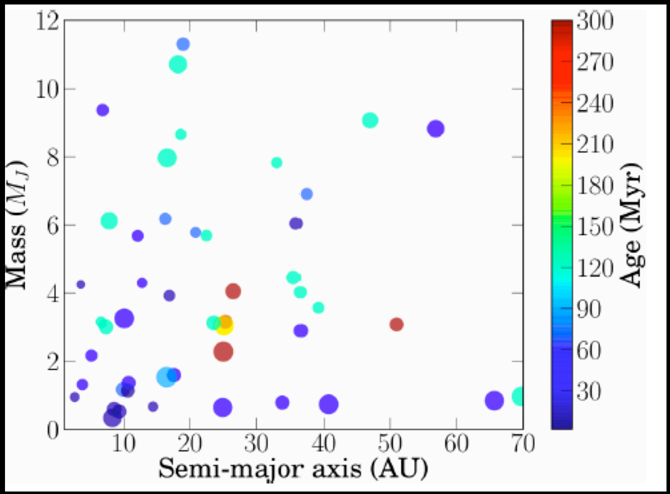


4 M_{Jup} at 11 AU and 75 Myr

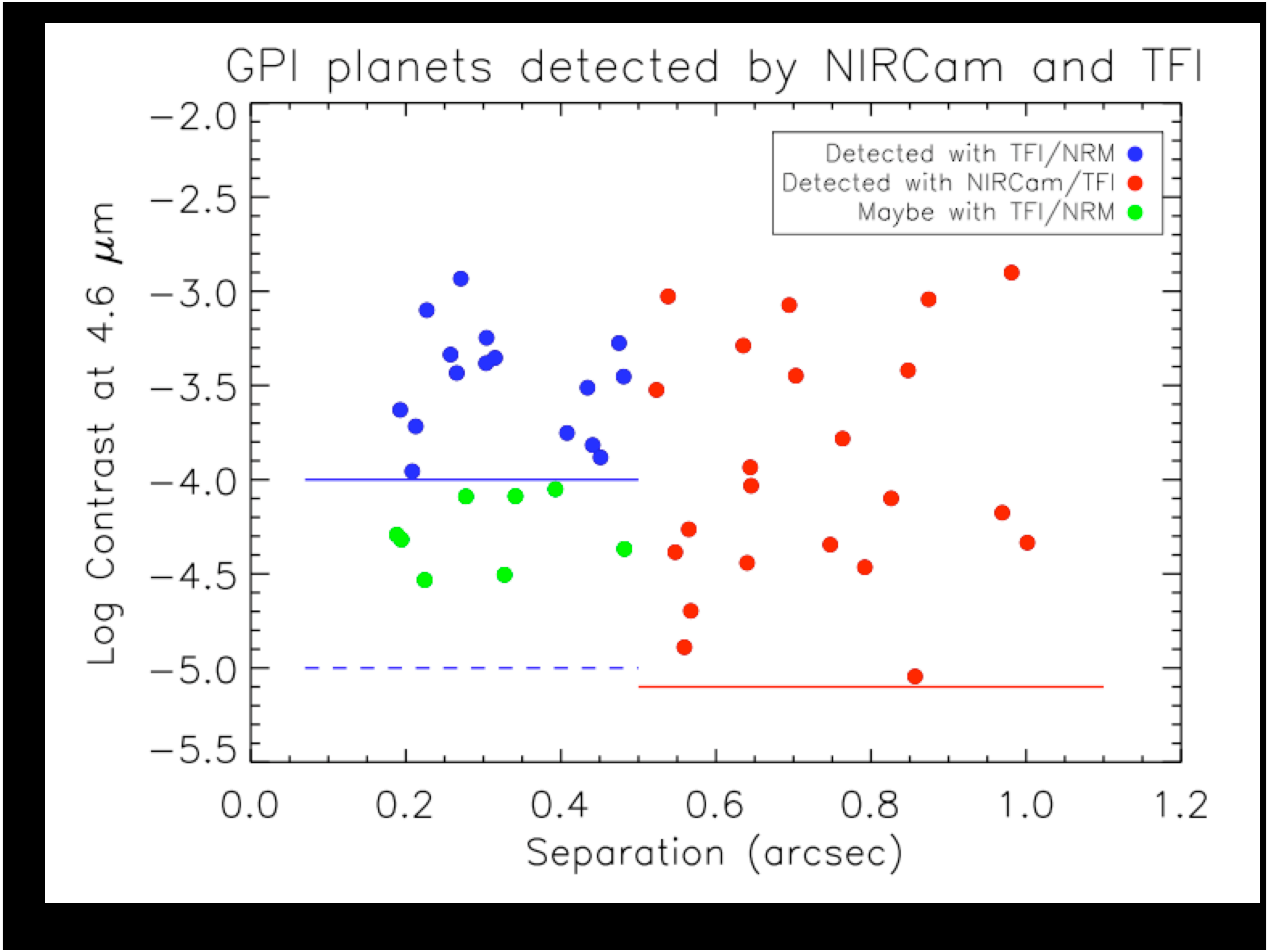
Likely outcome of the GPI campaign

- Number of stars observed: ~600 (1000 hrs)
- Number of detections: ~50
- Overlap with RV planets
- Median properties of the host stars:
  - Mass: 1.12 $M_\odot$ (G0V)
  - Age: 50 Myr
  - Distance: 40 pc
- Median properties of the exoplanets:
  - Mass: 4 M_{jup}
  - T_{eff} = 580 K
  - Projected SMA: 17 AU (0.48”, all within 1”)
- The majority (~3/4)will be detected by NIRCam, TFI/Lyot & TFI/NRM



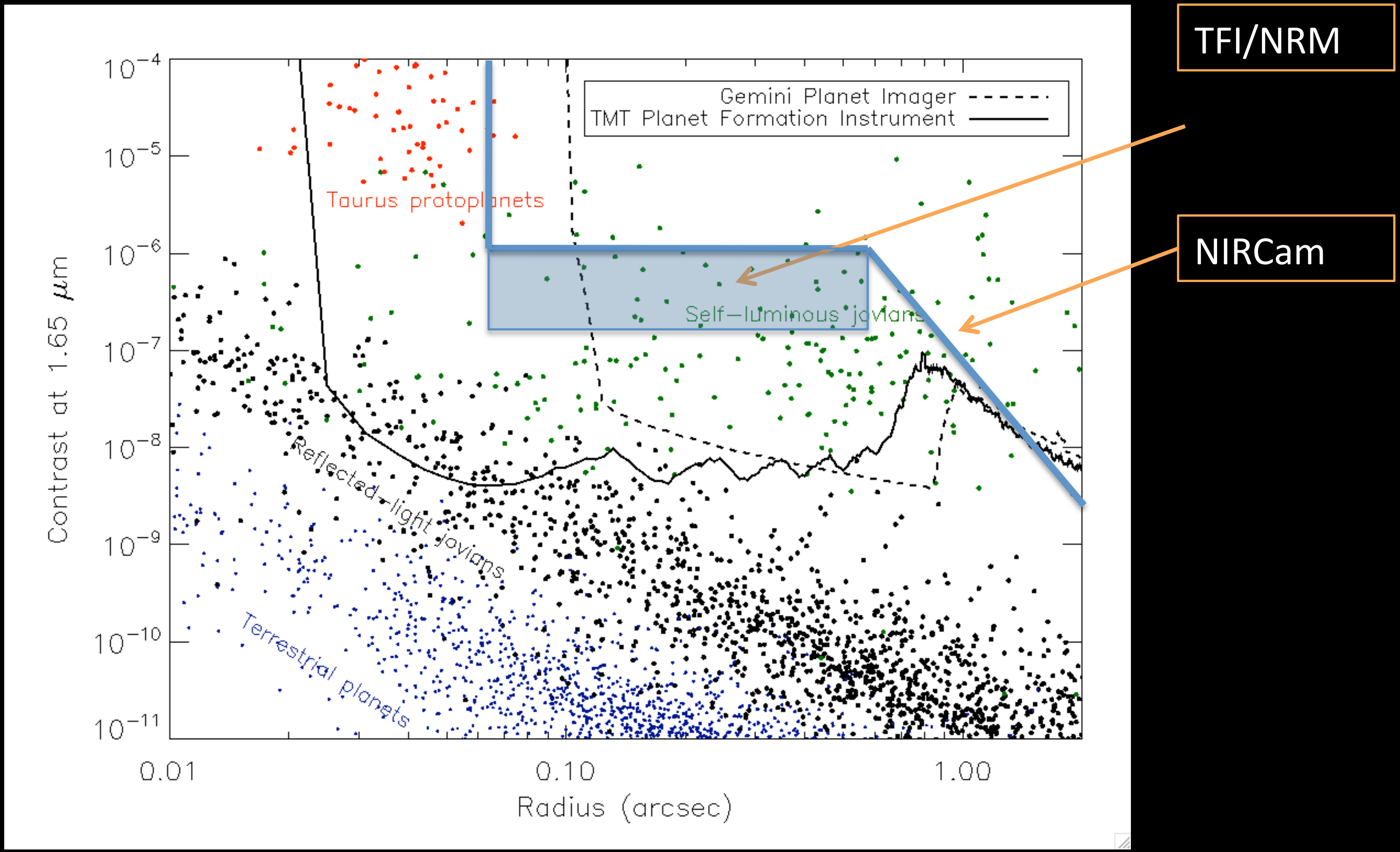


Credit: B. Macintosh & J. Graham



GPI planets detected by NIRCam and TFI
Detected with TFI/NRM
Detected with NIRCam/TFI
Maybe with TFI/NRM
Log Contrast at 4.6 μm
Separation (arcsec)
−2.0
−2.5
−3.0
−3.5
−4.0
−4.5
−5.0
−5.5
0.0
0.2
0.4
0.6
0.8
1.0
1.2

GPI/SPHERE follow-up



From 1.65 to 4.5 μm gain up to 100X in contrast

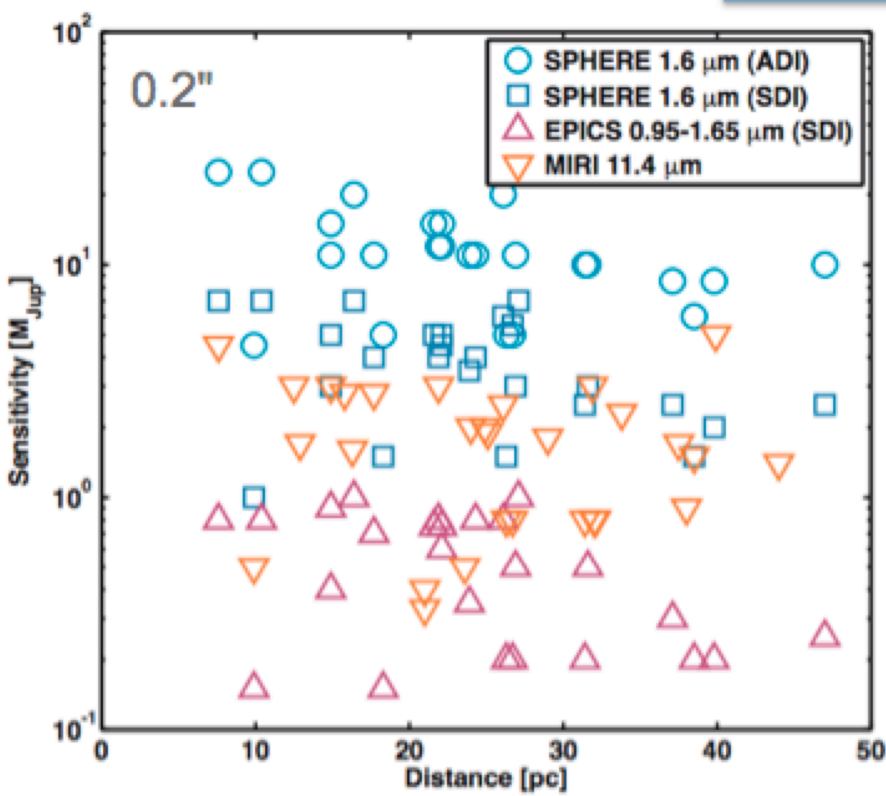
Credit: B. Macintosh

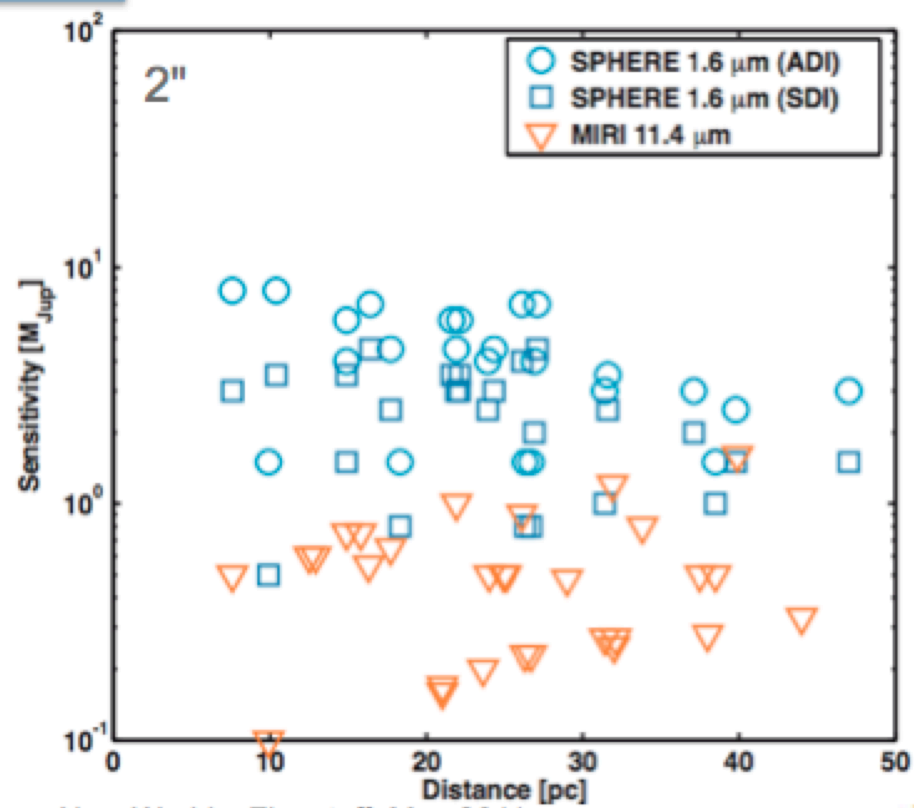
Survey: ground vs. space

- Most M stars too faint for AO systems
- SPHERE competitive with MIRI <0.5"
- EPICS always more sensitive
- EPICS FOV ≈ MIRI IWA

See also Beichman et al. 2010

Hanot et al. 2010





GTO/GO programs

- Characterization (3-15 um SED) of the brightest known exoplanets (several tens)
  - Important legacy work
- Survey of young and mature low-mass stars
  - Complementary to ground-based facilities
  - Could take a significant amount of time
- Survey of young star forming regions (upper Sco, Taurus,..)
- Survey of debris disk systems
- (non-coronagraphic) survey of nearby L dwarfs
- Survey of nearby white dwarfs
- Variability studies

…

Summary

- JWST will be a very powerful high-contrast imaging capability
- JWST will extend searches of exoplanets to young *and* relatively old (~1 Gyr) low-mass stars.
  - Will reach sub-Saturn masses beyond ~50 AU around young (<50 Myr) stars.
- JWST will detect nearly all currently known planets and a sizeable fraction of those to be detected by GPI/SPHERE.
- Legacy
  - Constrain planet frequency to very young and relatively old systems beyond 5-10 AU
  - Characterization: a comprehensive and unique database of exoplanet SEDs (2.5-15 um)
- Get ready! Lots of homework ahead of us!
- *Somewhere, something incredible is waiting to be known*

  - Carl Sagam
- *Good things come to those who wait!*