Exoplanets With JWST: Overview and Coronagraphic Imaging

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and NIRCam exoplanet team

September 14, 2015

Five Major Themes for Exoplanets

1. Coronagraphic Imaging of Young Planets
   - Determine atmospheric composition and physical properties to understand formation mechanism of exterior planets
   - Extend to lower mass limits compared to ground based observations
2. Coronagraphic Imaging of Debris Disks
   - Assess composition and structure of disks, e.g. H2O and other ices
   - Search for planets shepherding or sculpting disks
3. Survey nearby young M stars
   - Provide census of Jovian mass planets at few 10s of AU
4. Spectroscopy of Young Planets
   - Determine atmospheric composition and physical properties to understand formation mechanism of exterior planets
5. Transit Spectroscopy of Mature Planets
   - Determine atmospheric composition and physical properties to understand formation mechanism of interior planets
6. Coolest Brown Dwarfs --- Y dwarfs as exoplanet analogs
7. Solar system science ---KBOs and outer planets

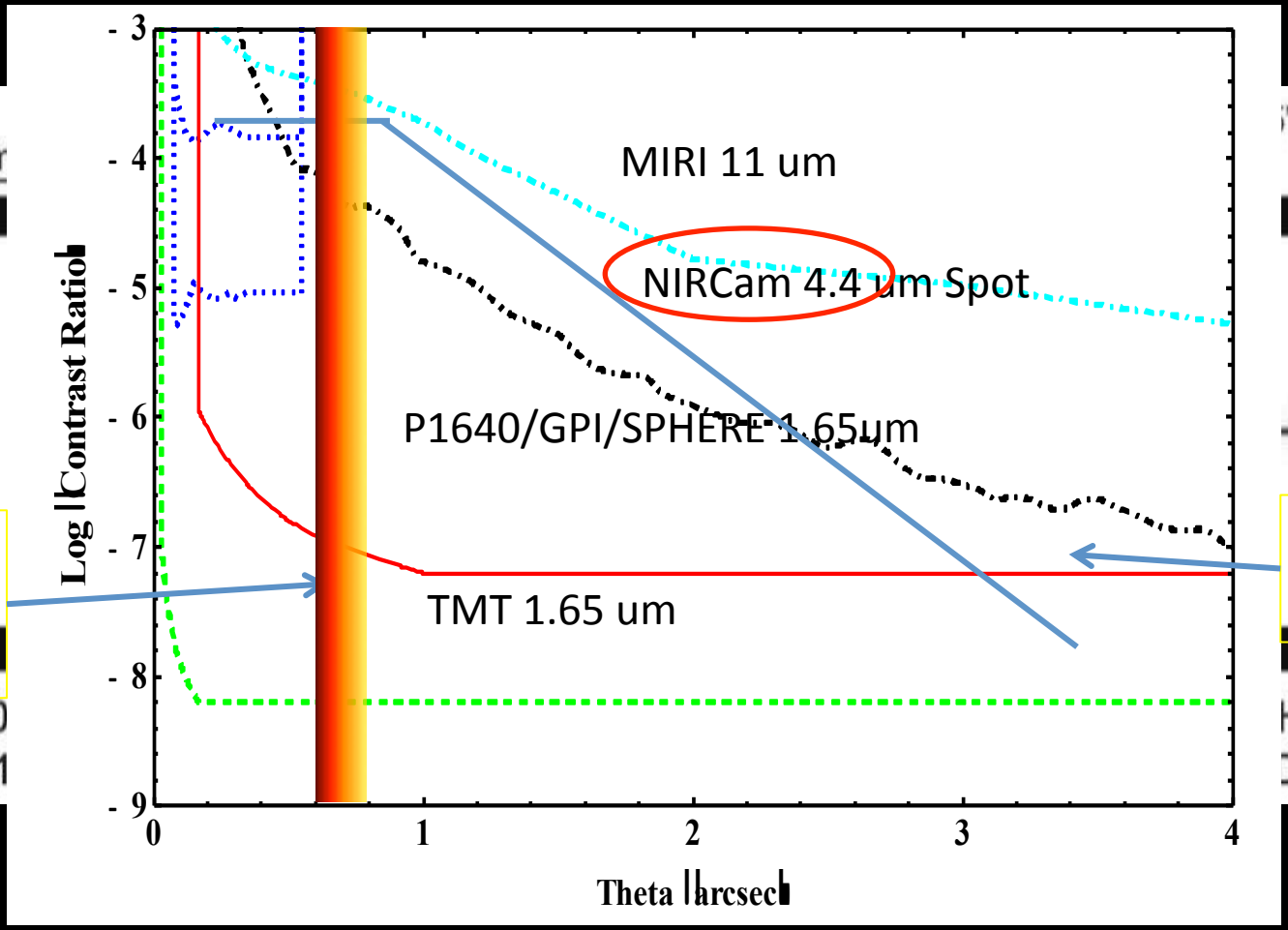
Overview of Program

Program	Lead	# Obj	Potential Collaborations	Comments
Transit Spectroscopy	Greene	5	MIRI, NIRSpec, NIRISS	Critical collaboration
Direct Imaging + Deep Survey	CAB	5	Includes 1 MIRI filter	Possible MIRI
Spectroscopy of Young Planets	Hodapp	~10	NIRSpec and MIRI	Minimum separation?
Imaging of Debris Disks	CAB (Lebreton)	8	MIRI	Possible MIRI
Nearby M stars	Schlieder Meyer	20	MIRI	Ground-based?
Total time 250+ hours				

1. Science Goals for Direct Imaging

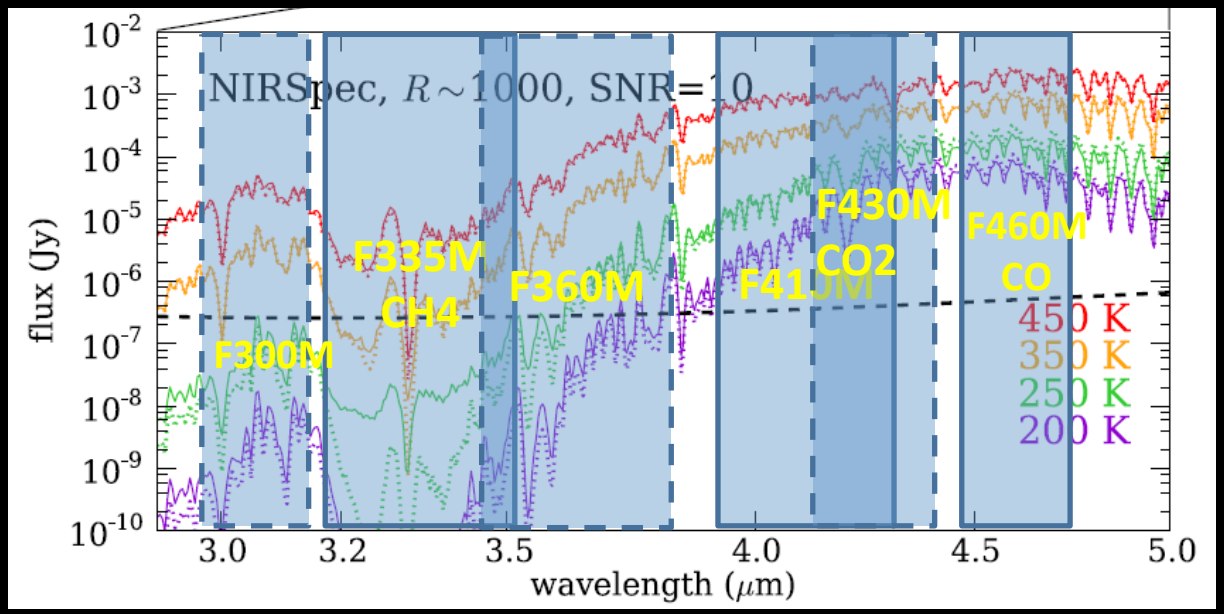
- Characterize physical properties of **known young planets** via coronagraphic imaging
  - Complete Spectral Energy Distribution (3 to >11 μm) to determine effective temperature and total luminosity
  - Atmospheric properties with filter photometry
  - Improve orbital parameters with multi-epoch data
- Search for lower mass planets (~Saturn)

JWST Poor IWA, High Sensitivity @ 3-15 μm



Coronagraphic Imaging

- Multi (4-6)-filter imaging of ~5 known planets (<200 Myr, 500-1500 K)
  - Complete SED: 1.6-11.4 μm (incl ground and MIRI)
  - Diagnostics: Teff, gravity, metallicity(?), C/O (??)



- Deep survey for lower masses
  - Use F444W- F356W color to reject background objects
  - Revisit likely candidates 6 months later? Follow-up policy?

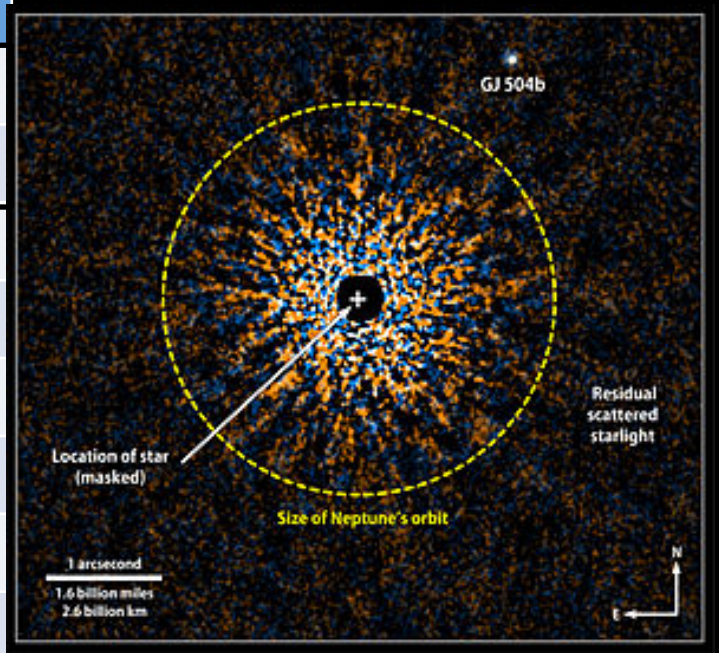
Medium Band Filters
spot_ 335_f300m
spot_ 335_f335m
spot_ 335_f360m
spot_ 430_f410m
spot_ 430_f430m
spot_ 430_f460m

Wide Band Filters
spot_ 335_f356w
spot_ 430_f444w

Illustrative Observation of GJ504

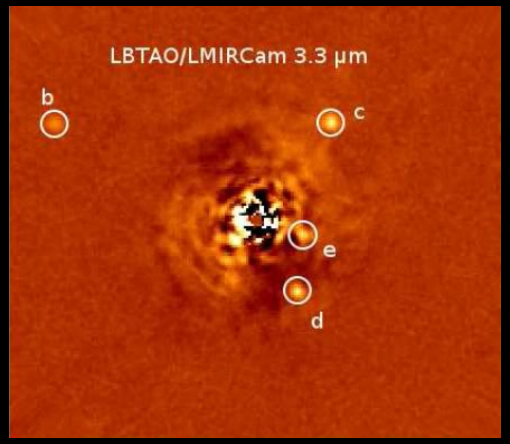
- GJ504 is G0 star 18 pc away. Approx age of 160 Myr
- 4 M_{Jup} @2.4" separation

	Planet	SNR (in 800 sec Medium or 2000 sec Deep)			
Filter	Mass	IWA	1"	2"	5"
F356W	0.25	0.1	0.4	3	8
F444W	0.25	5.4	10	26	47
F300M	4	0.1	0.42	3	6
F335M	4	2.3	5.5	19	36
F360M	4	2.9	7	17	30
F410M	4	8	16	38	62
F430M	4	19	40	71	90
F460M	4	29	47	86	113

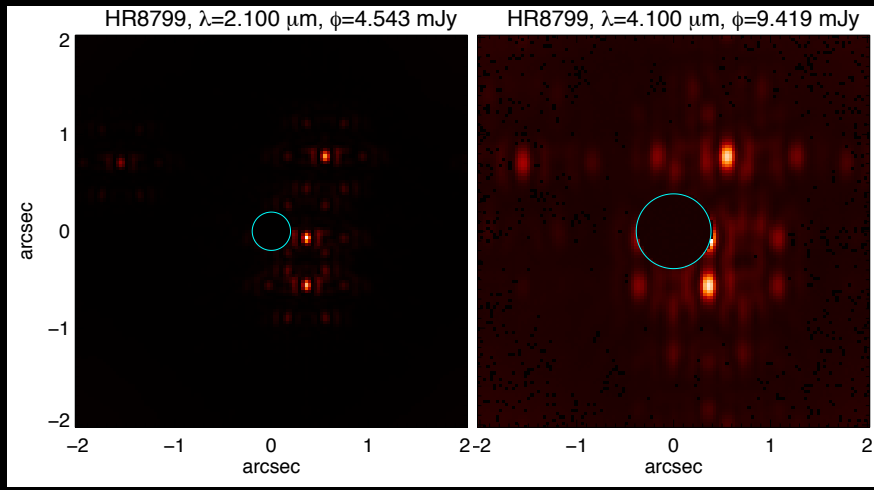


Illustrative Observation of HR8799

- A5 star @ 39 pc. Age ~30 Myr
- 4 planets ~5-7 M_{Jup} @ 0.6”-1.7”
- Good target for Wedge



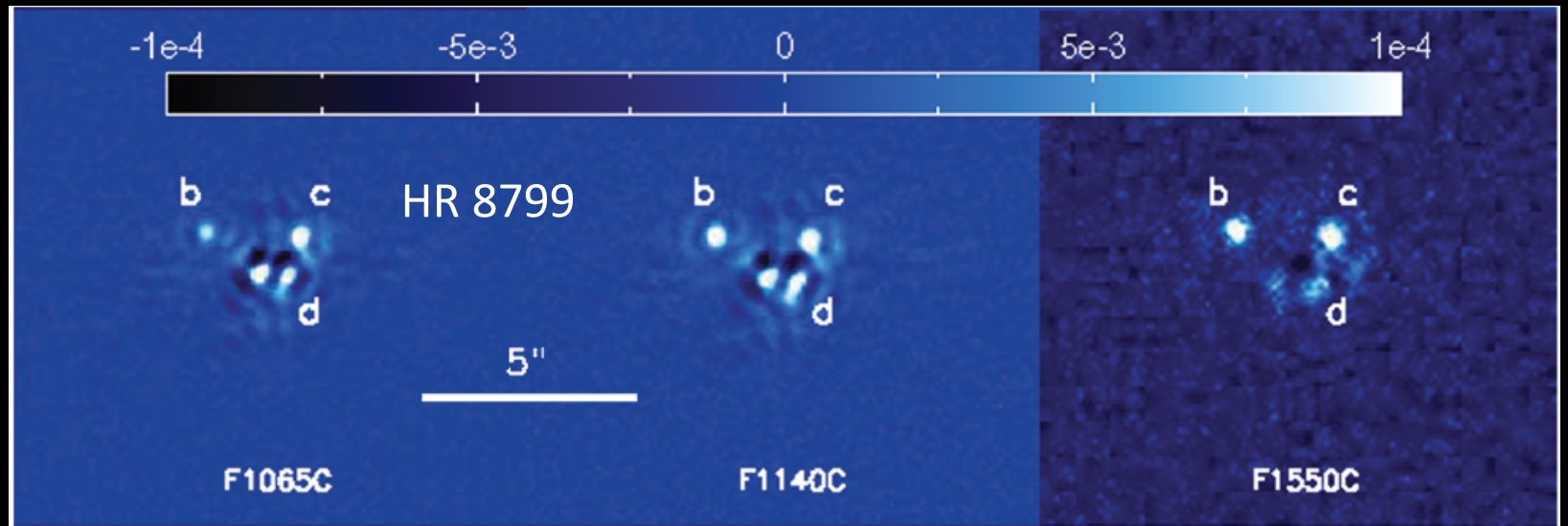
	Planet	SNR in (800 or 2000 sec)			
Filter	Mass	IWA	1”	2”	5”
F356W	0.25	0.1	0.1	1	5
F444W	0.25	1.5	3	9	24
F300M	5	0.3	1.2	8	24
F335M	5	4	10	50	116
F360M	5	6	13	44	99
F410M	5	11	31	76	140
F430M	5	20	44	95	141
F460M	5	30	52	112	176



MIRI Observations Critical

- Teff, Total Luminosity, NH_3 at 10.65 μm
- 4-Quadrant Phase Masks (4QPM) at 10.65, 11.4 and 15.5 μm with IWA ~λ/D , cf NIRCam 4-6 λ/D
- SNR 5-20 in 3 hr/filter on planets b,c,d (Boccaletti et al 2015)

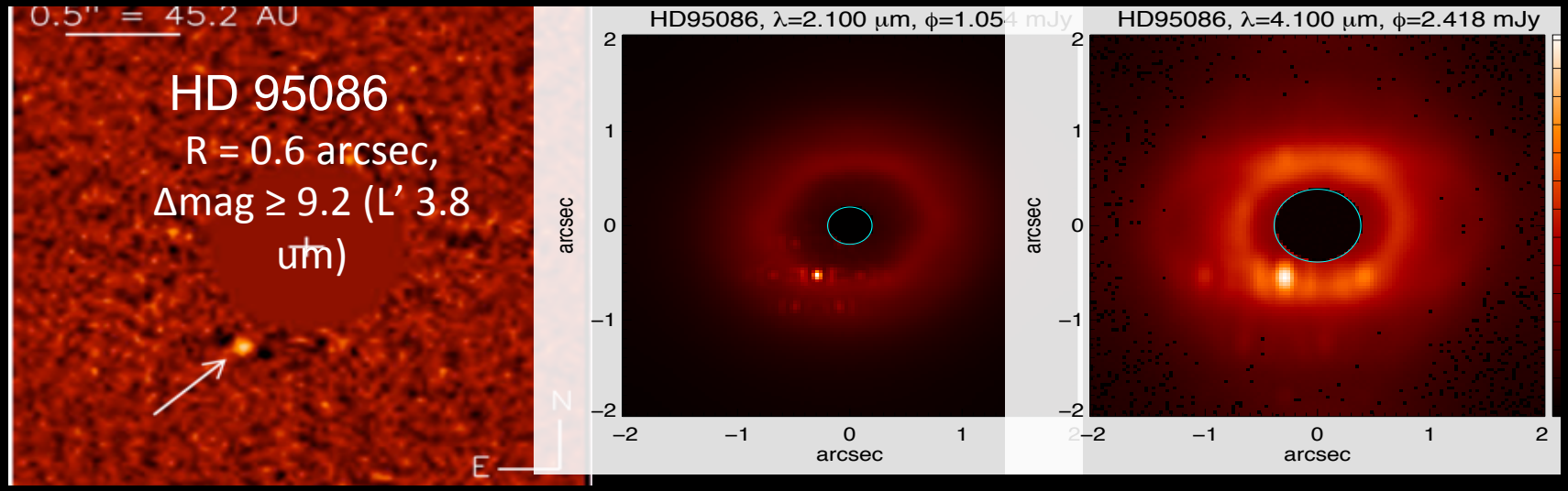
lam	IWA (")
3.3	0.63
3.65	0.70
4.1	0.79
4.6	0.88
10.65	0.34
11.4	0.37
15.5	0.50



Coronagraphic Targets

- Lowest masses <10 M_{Jup}. Separation ~ 0.45” (4 λ/D at 3.5 um) to 3~5” (limit for direct spectroscopy).
- GPI & Sphere will identify more targets

Host Name	Separation (")	Orbit (AU)	Distance (pc)	Spec Type	Age (Myr)	Planet Mass (MJup)
GJ 504	2.42	43.5	17.95	G0 V	160.00	4.00
2MASS J1207	0.88	46	52.4	M8	8.00	4.00
HR 8799	1.70	68	39.94	F0V	50?	7.00
HR 8799	0.95	38	39.94	F0V	50?	10.00
HD 95086	0.61	55.7	91.57	A8 III	10~17	5.00
51 Eri	0.45	13.2	29.4	F0IV	20.00	2.00



2. Science Goals for Debris disk science

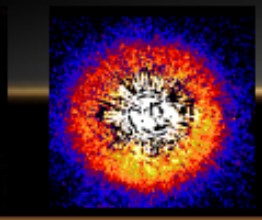
- Scattered light imaging of bright debris disks, $Ld/L_{*}>10^{-4}$ (roughly same level as HST)
- Composition of debris disks, esp. ices
- Search for planets responsible for structures such as narrow rings

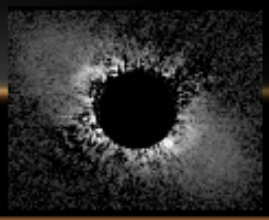
NIRCAM DEBRIS DISK SAMPLE SELECTION

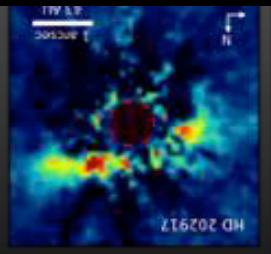
- **A limited number of debris disks** have been **spatially resolved**, most of them in thermal emission, **23 of them in scattered light** (as of Jan. 2015: **HST**, ground)
- Select a limited sample of **extended, high surface brightness debris disks**
- **Follow-up observations of HST disks**: comparable contrast & resolution but in the 2-5 µm range with excellent PSF stability
- Disk stars are **great targets for planet detection** down to (sub-)Neptunian masses

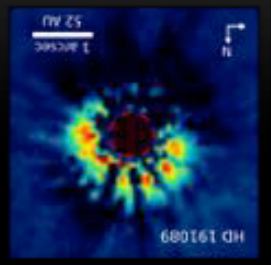


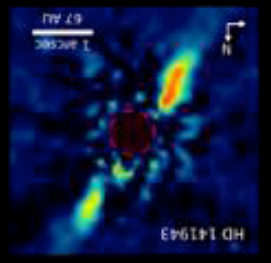
Star	Spectral Type	fdisk/f*	Age [Myr]	Typical radius [arcsec]	Perturbing planet separation [arcsec] 0.1 Mj	1 Mj	10 Mj
HD10647	F8.5V	4.0E-04	1400	4.76	4.32	3.97	3.44
HD181327	F5.5V	6.0E-03	12	1.72	1.57	1.45	1.26
HD32297	A7V	2.0E-03	30	1.05	0.96	0.89	0.79
The Moth	G8Vk	2.5E-03	90	1.77	1.59	1.45	1.25
AU mic	M1Ve	7.6E-03	12	3.53	3.11	2.80	2.35
HD107146	G2V	1.0E-04	140	4.56	4.12	3.78	3.26
HR4796A	A0V	5.0E-03	8	2.10	1.95	1.82	1.62
HD92945	K6	7.7E-04	294	2.09	1.87	1.71	1.46

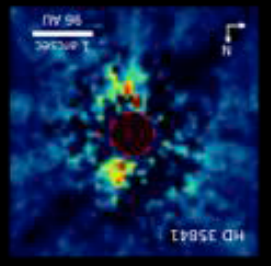



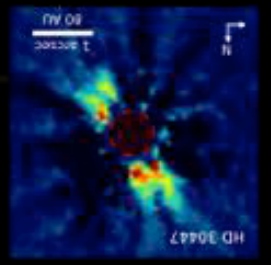










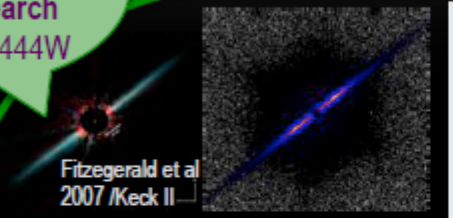


RESULTS FOR THE 8 DISKS OF OUR SAMPLE

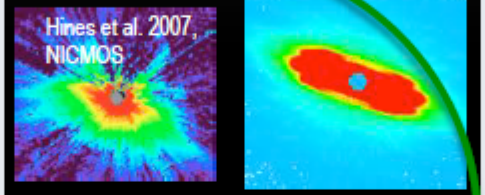
Observations vs models – F300M filter, 2 hours

Detailed radiative transfer models corrected with HST effective albedos
(in prep for PASP)

Broad-band imaging and planet search
F356W , F444W

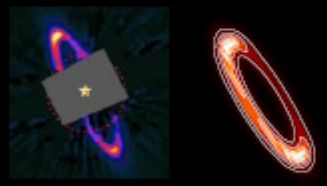


AU Mic, M1Ve, F_{disk}/F_{star}=7.7e-3
91pc, 35AU

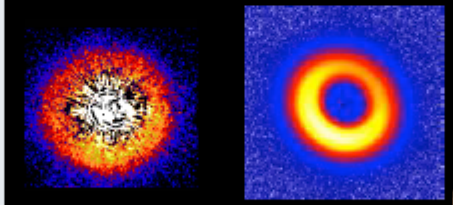


The Moth, G8Vk, F_{disk}/F_{star}=2.5e-3
4.5pc, 61AU

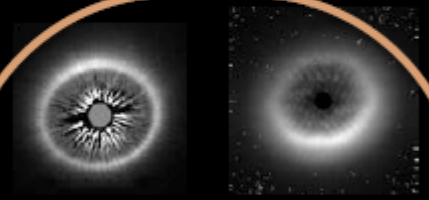
Deep ice search
6 medium filters:
F210M, F300M, F335M: H2O
F410M, F430M, F444W,
F460M: CO2, CO



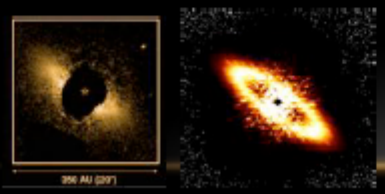
HD 4796A, A0V, F_{disk}/F_{star}=5.0e-3
67pc, 140AU



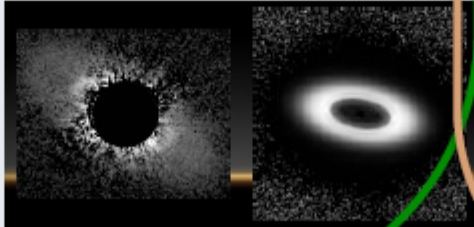
HD 107146, G2V, F_{disk}/F_{star}=1.0e-4
28.5pc, 130AU



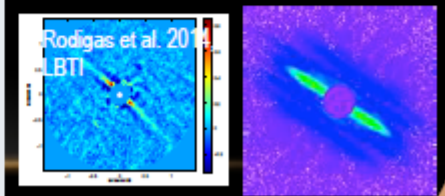
HD181327, F5.5V, F_{disk}/F_{star}=6.0e-3
51.8 pc, 90 AU



HD 10647, G2V, F_{disk}/F_{star}=1.0E-4
17.4pc, 75AU



HD 92945, K6V, F_{disk}/F_{star}=7.7E-4
21.55pc, 45AU



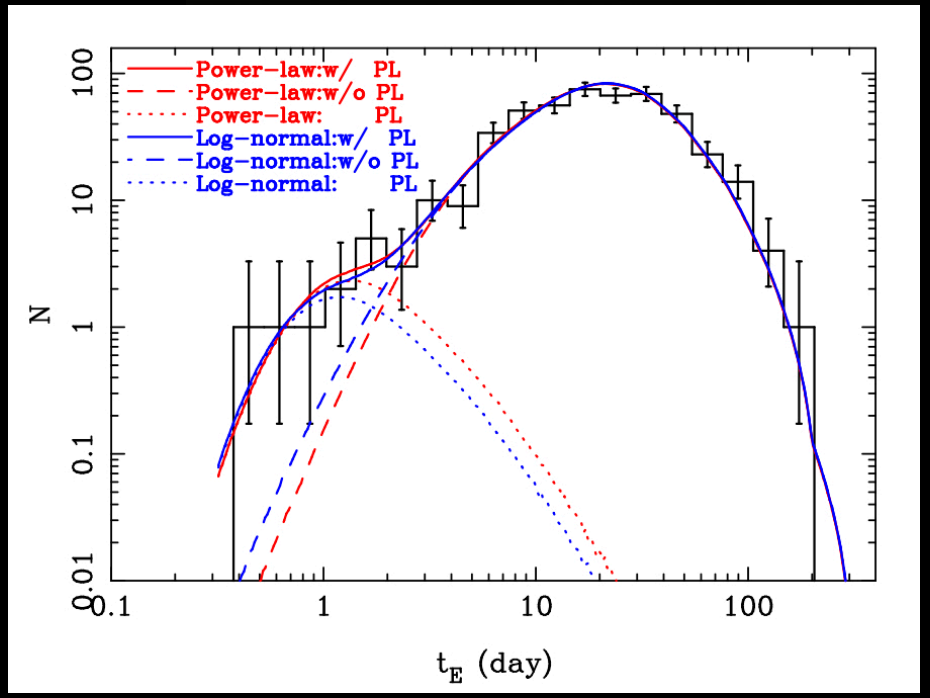
HD 32297, A7V, F_{disk}/F_{star}=7.6e-3
105pc, R ~120AU

3. What Is The Frequency Of Planets Orbiting M Stars?

- Kepler suggests 2 planets (1-4 $R_\oplus$) around each M star w. P<50 d (Dressing and Charbonneau 2015)
- RV/imaging suggest Jupiters rare

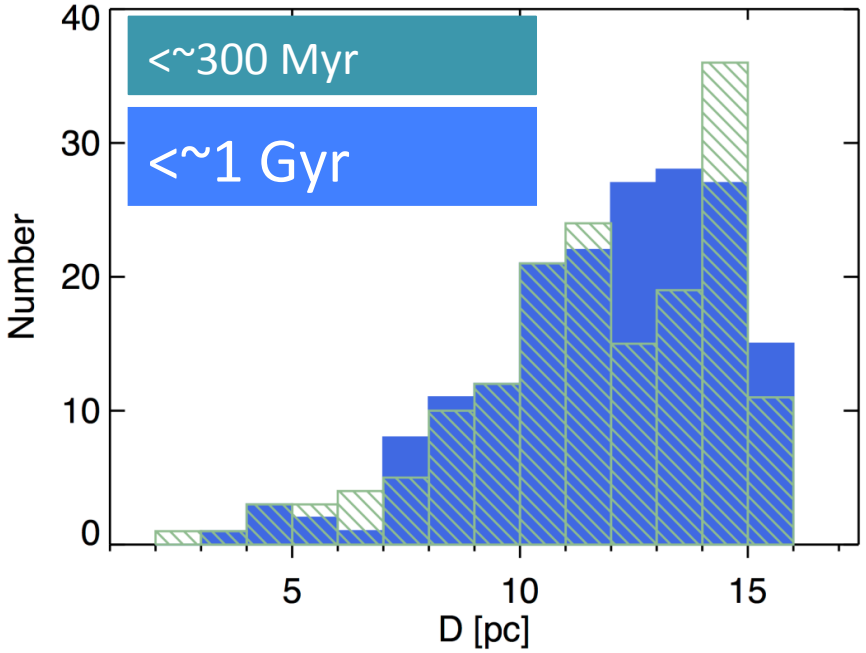
2MASS 1207-- 5 M_{Jup} planet orbiting M8 star at 1”

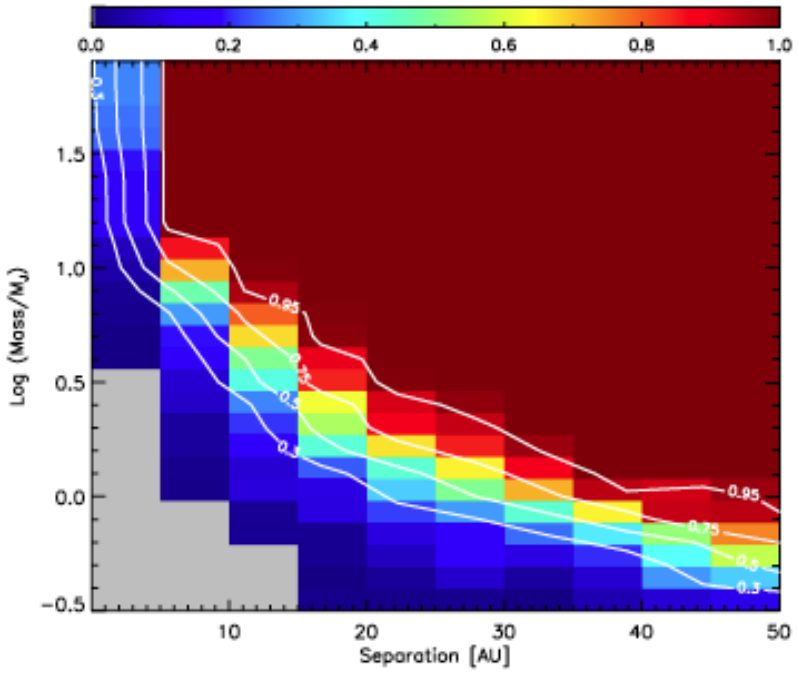
- Microlensing suggests 1 M_{Jup} objects equal in ## to M stars
  - –Planets in wide orbits?
  - –Free floating 1 M_{Jup}?
- JWST can find <Saturn mass orbiting M stars



Nearby Young M Stars (*Schleider & Meyer*)

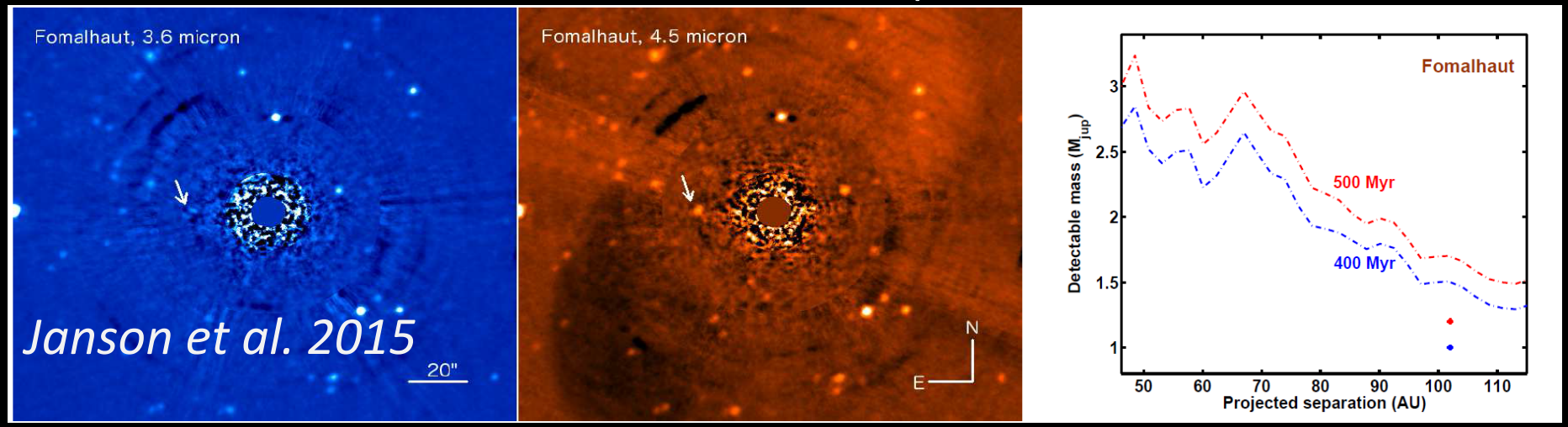
- Difficult targets for ground-based AO
- Search recent catalogs for M dwarfs within 15 pc (Lepine & Gaidos 2011, Winters et al. 2015)
- Ages from ROSAT & GALEX, moving groups, clusters
- 300+ M dwarfs <15 pc @ ~300-1000 Myr old





Observing Strategy

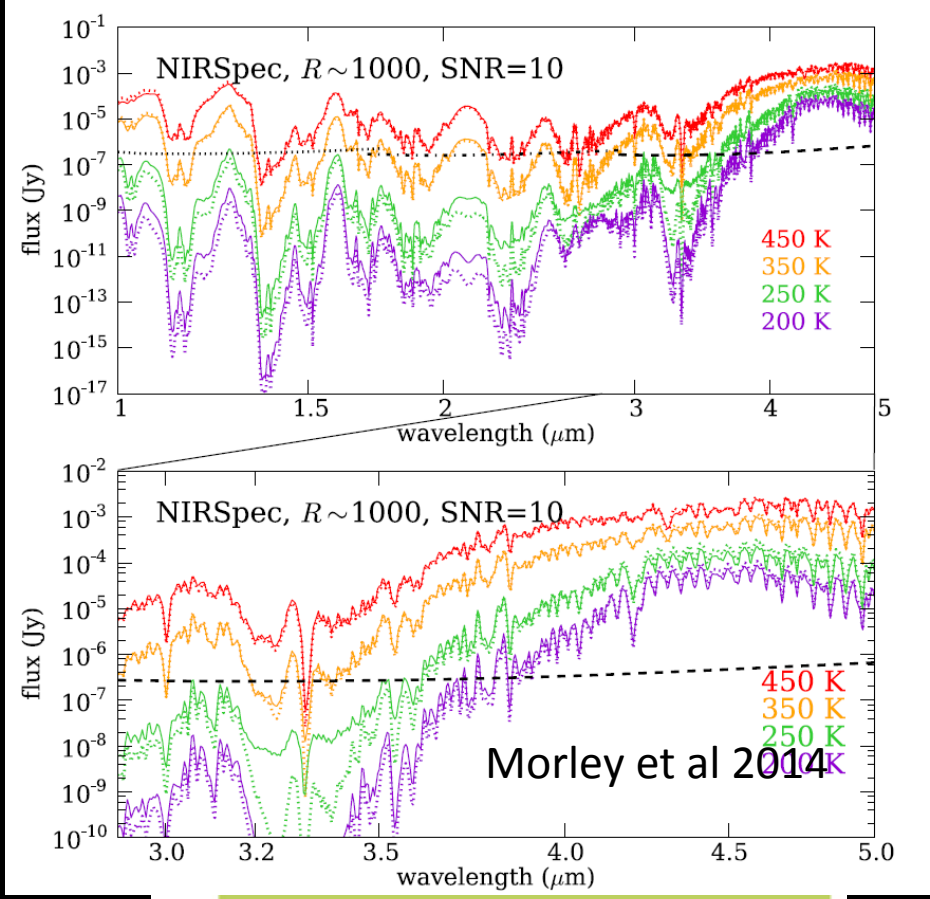
- Two filters to discern planets from background stars: 3.5 and 4.5 μm – 1 M_{Jup} @500 Myr, Δmag ~3

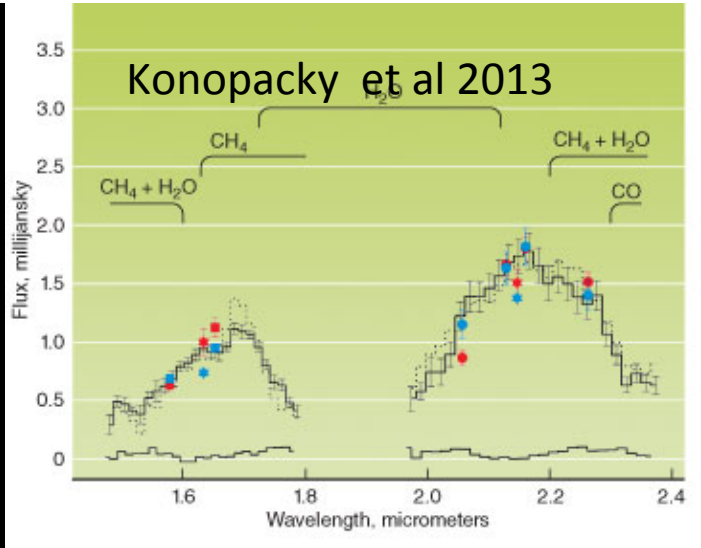


- Coronagraph vs. No Coronagraph
- 25-50 stars for statistically significant sample
- Yield 2-3 planets/100 stars depending on f(M, SMA)→ Is it worthwhile?

4. Spectra of Widely Separated Systems

- For widely separated planets (100 AU, 5”) take high resolution spectra
- NIRSpec (IFU or slit) R=1000) for > 3-5”
- Full spectral coverage: R=1000, S/N=30, 1000 s, 2 hr/object
- Need expert guidance on expected scattered light within IFU



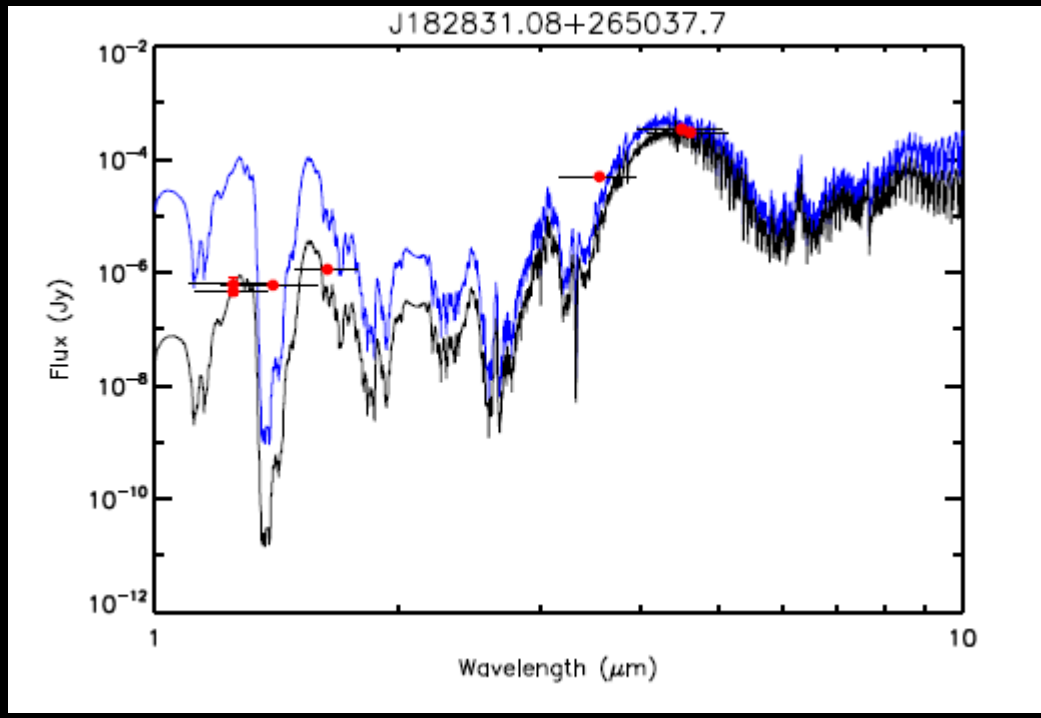


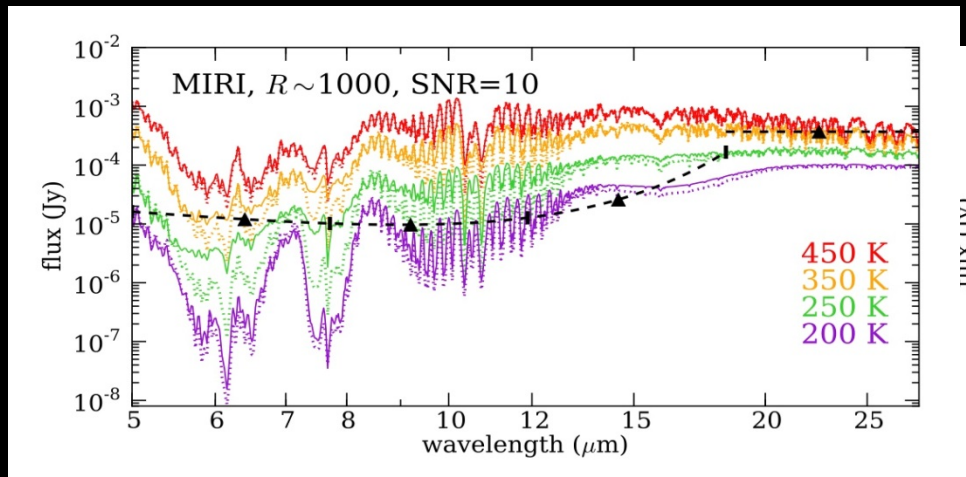
5. Transit Spectroscopy (see Tom Greene)

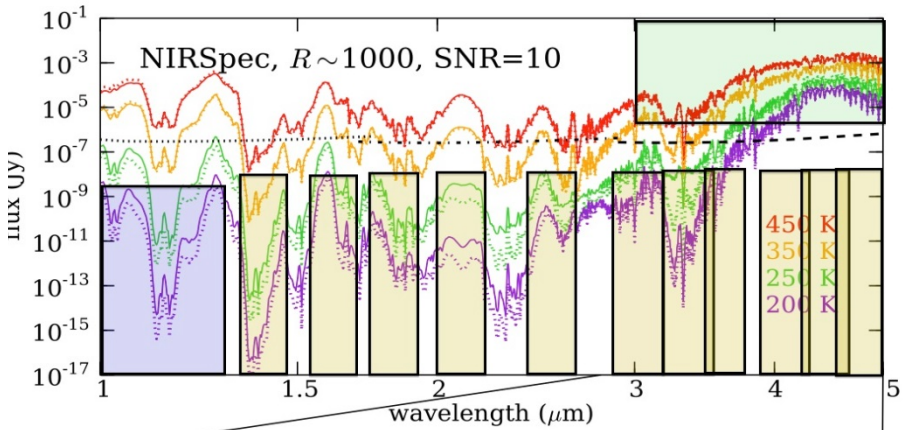
- What are composition, atmospheric properties of hot/temperature Jupiters and mini-Neptunes
- Combine observations from multiple instruments:
  - NIRCAM LW grism and DHS/SW
  - NIRISS grism for short wavelength
  - NIRSPEC for 1-5 um spectrum
  - MIRI LWS

6. Y dwarfs As ExoPlanet Analogs

- 24 WISE Y dwarfs known with Teff <500K based on 1-2 μm spectra, 3-5 um photometry
- Models very poor
- Masses 5 M_{jup}







Conclusions

- NIRCAM team will put forward ambitious program of exoplanet observations
- Direct imaging and spectra of known planets and debris disks
- Survey of known planets for lower mass planets and possibly of nearby, young M stars
- Spectroscopy in transit, eclipse, phase curves

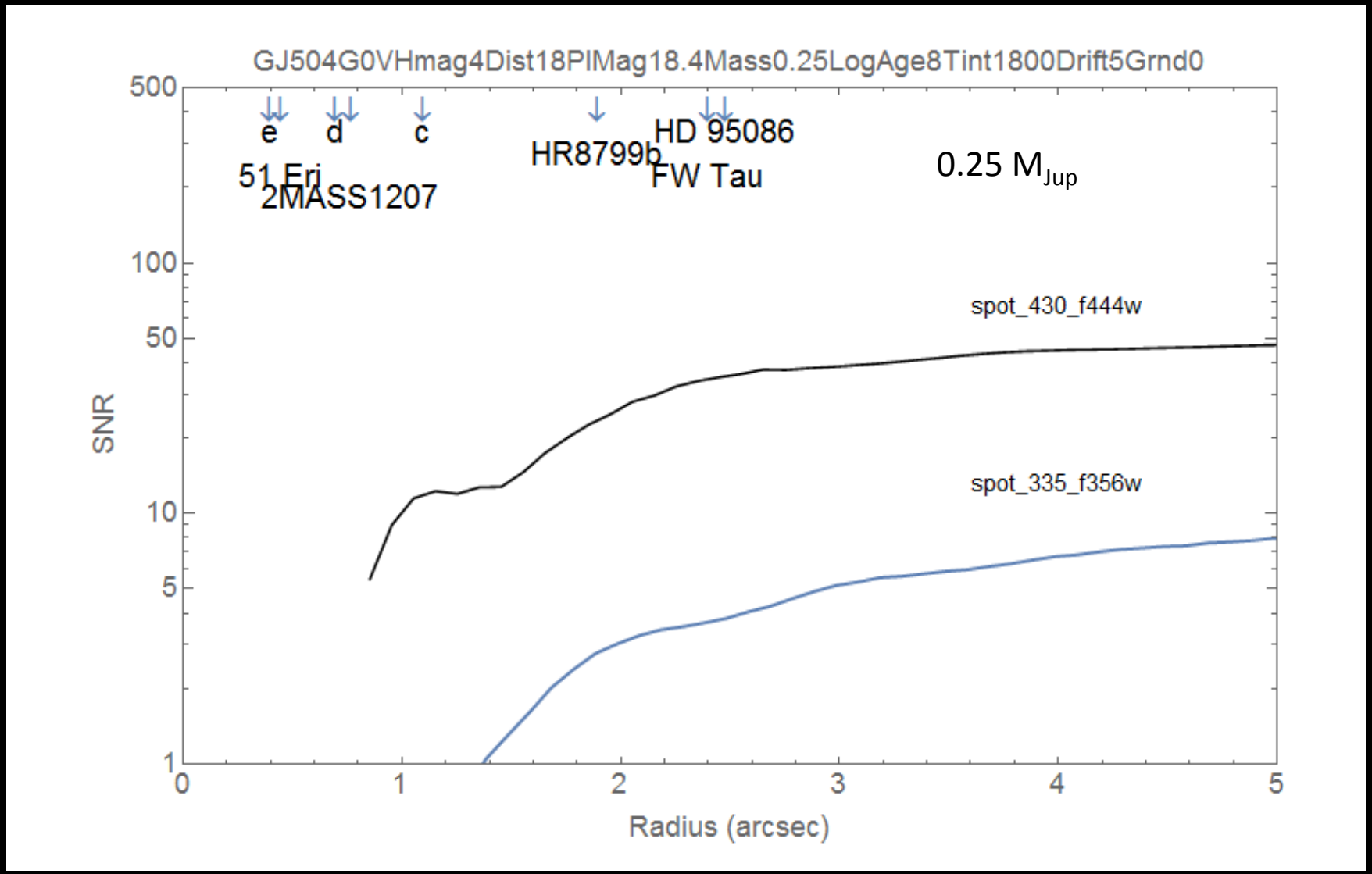
Topics for Discussion and Future Work

- Which measurements to make?
  - Burrows, Greco modeling and retrieval effort
  - Optimize NIRCam filter set (4 or 6 medium band filters) for maximum information content
  - Optimize MIRI filter set (1 4QPM filter and possibly more. Possibly 3-4 shorter wavelength filters using Lyot bar)
  - For deep search what is strategy for confirmation of candidates? 6-18 month revisits to confirm via common proper motion/parallax
- Which objects to target?
  - Most closely separated, lowest mass systems as best analogs to core-accretion planets
  - Dividing line between IFU and coronagraph early in mission?
  - Wait for GPI, etc results as long as possible

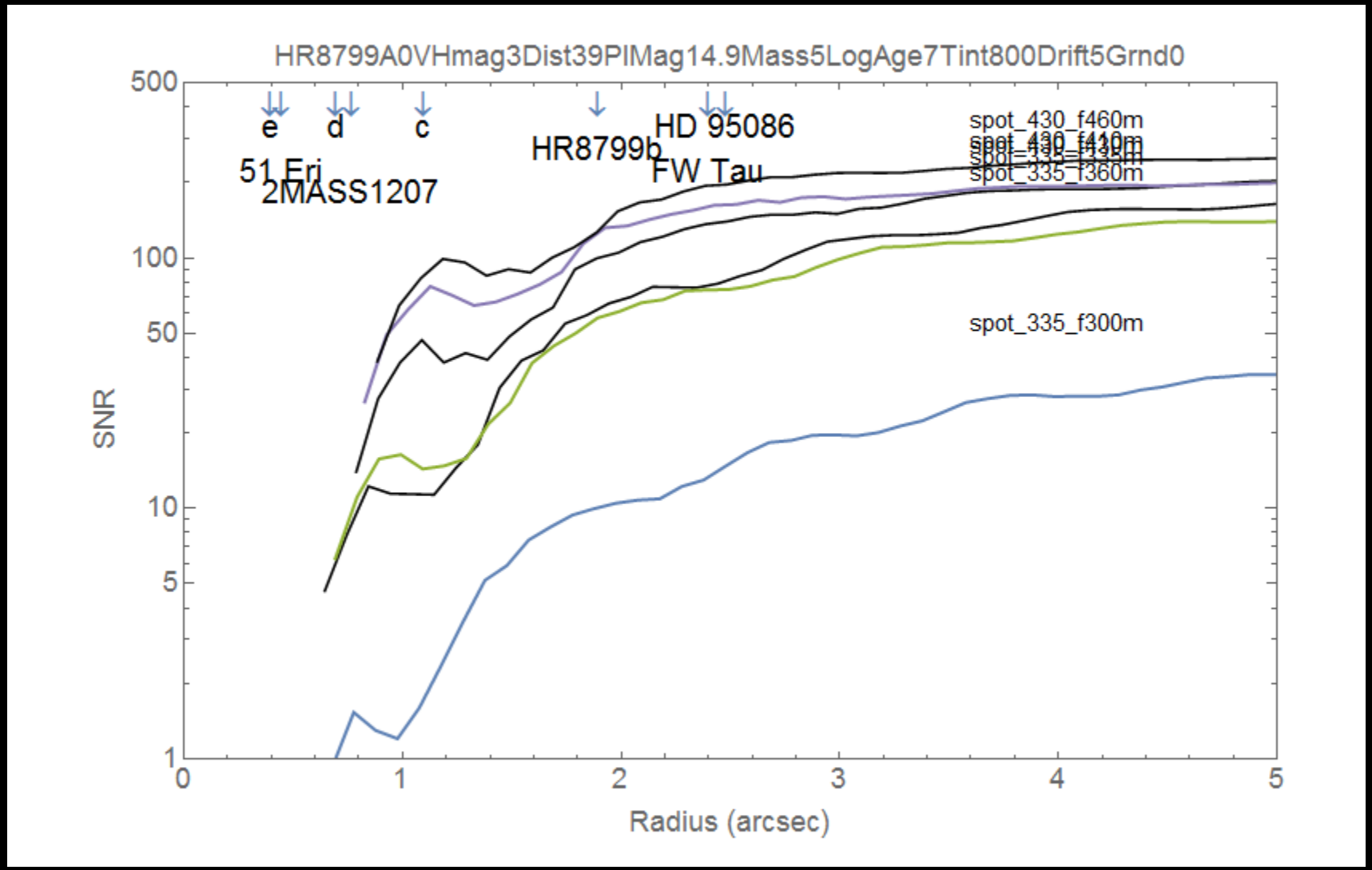
Known Planets Observing Scenario

- Deep Survey & Medium Filter Obs. of known planets
  - Acquire
  - 6 NIRCam medium filters (τ=400 sec each)
  - 2 NIRCam wide filters, F356W and F444W (τ=1000 sec each)
  - 1 MIRI filter (τ=1800 sec) for total luminosity
  - 10^o Roll
  - 1 MIRI filters (τ=1800 sec) for total luminosity
  - 2 NIRCam wide filters, F444W and F356W (τ=1000 sec each)
  - 6 NIRCam medium filters (τ=400 sec each)
  - Reference star (single roll angle)
- 10.2 hours/star: 7 hr NIRCAM and 3 hr MIRI (collaboration?)
- Repeat for 5 planetary systems (NIRCam+MIRI time)
  - 36 hours (NIRCAM only).
- Add multiple MIRI filters with collaboration

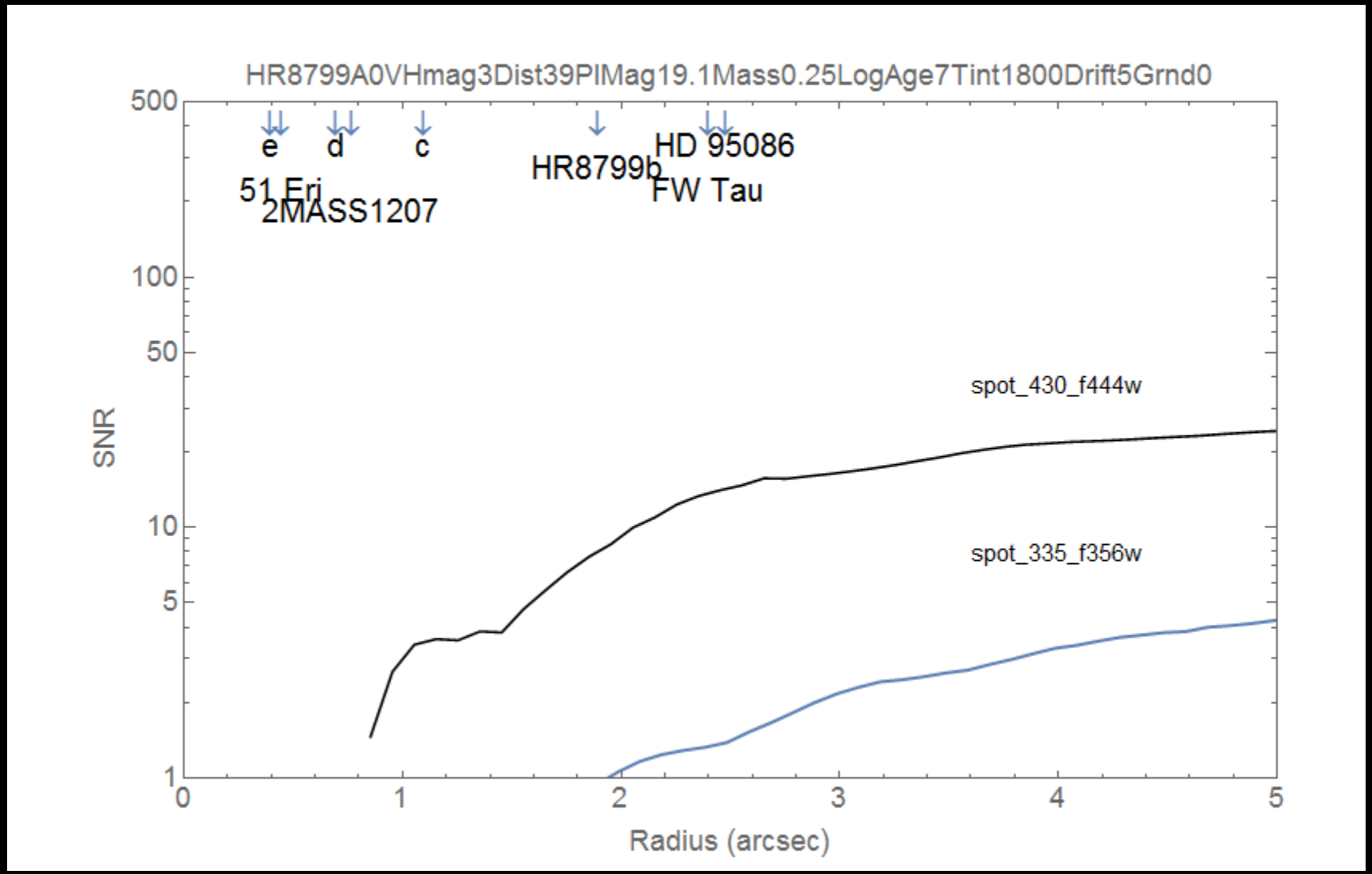
GJ504 Deep Survey



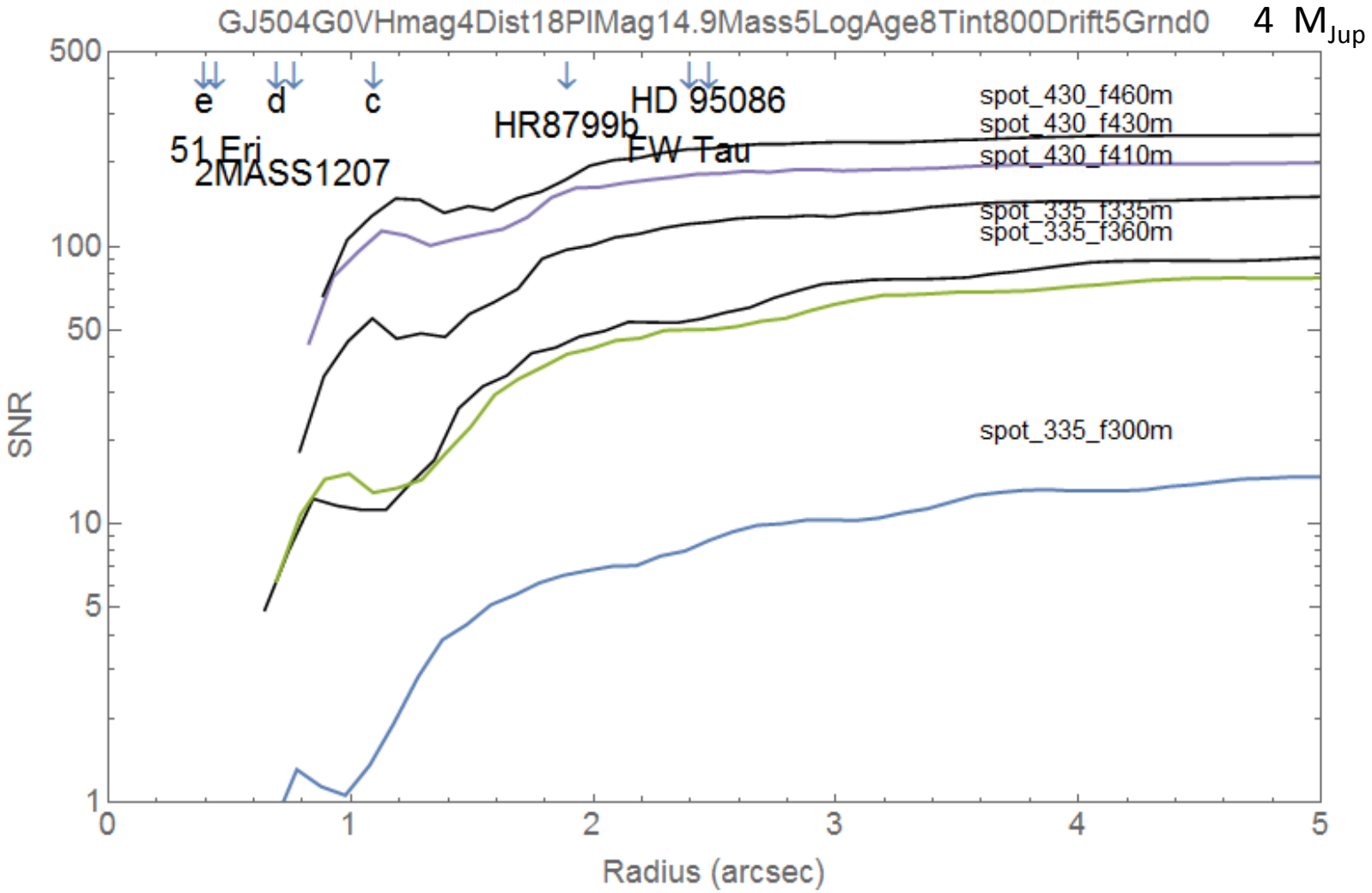
HR8799 Characterization



HR8799 Deep Survey

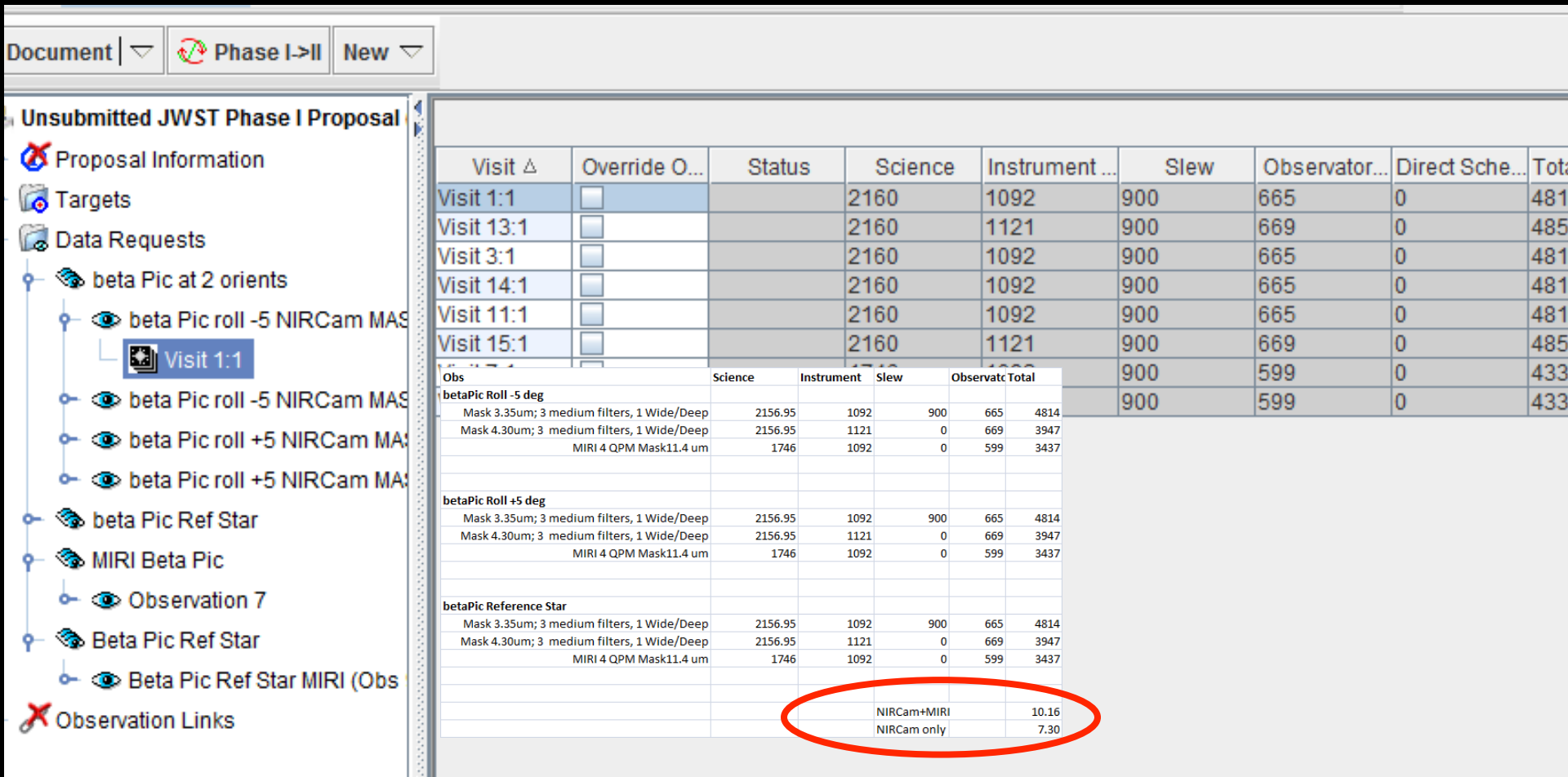


GJ504 Characterization



Illustrative Observation

- NIRCAM: 800 sec in 6 medium filters, 2000 sec in 2 wide filters. Split between 2 rolls plus reference star. 7.3 hours
- MIRI: 1800 sec at 11.4 plus reference star. 3 hours
- Total 10.2 hours. Times 5 stars for 51hours



Potential Targets

- New planetary systems from GPI, SPHERE, etc in next year will yield excellent choice of targets
- RV and GAIA trends may stars also prove fruitful in long run

Host Name	Planet	SMA (AU)	Mass (Mj)	Dist (pc)	Sp Type	WISE 1	AngSep (")
WD 0806-661	b	2500	7.5	19.2	>Y2	13.8	130.2
HIP 63510	c	1168	6.3	11.43	M0.5	5.5	102.2
HN Peg	b	773	22.0	18.39	G0 IV-V	4.5	42.0
GU Psc	b	2000	11.3	48	M3	9.3	41.7
Fomalhaut	b	115	2.6	7.69	A3 V	-1.5	15.0
HD 203030	b	487.1	24.1	40.85	G8 V	6.7	11.9
SR 12 AB	c	1083	13.0	125	K4-M2.5	8.3	8.7
HD 106906	b	650	11.0	91.83	F5 V	6.7	7.1
FU Tau	b	800	15.7	140	M7	8.6	5.7
AB Pic	b	260	13.5	45.52	K2 V	6.9	5.7
HIP 78530	b	710	23.0	131.93	B9 V	6.9	5.4
USco CTIO 108	b	690	14.0	150	M7	12.1	4.6
CT Cha	b	440	17.0	165	K7	7.9	2.7
GJ 504	b	43.5	4.0	17.95	G0 V	3.8	2.4
DH Tau	b	330	11.0	140	M0.5	7.4	2.4
1RXS J160929.1-210524	b	330	8.0	145	K7 V	8.8	2.3
GSC 06214-00210	b	300	13.5	145	M1	9.1	2.1
ROXs 12	b	210	16.0	120	M0	8.4	1.8
HR 8799	b	68	7.0	39.94	F0	5.2	1.7
Oph 11	b	240	21.0	160	M9	12.8	1.5
2MASS J01225093-2439505	b	52	24.5	36	M3.5 V	9.0	1.4
CHXR 73	b	210	12.6		M3.5	10.3	1.3
ROXs 42 B	b	157	9.0	135	M0	8.5	1.2
kap And	b	55	13.6	52.03	B9 IV	4.3	1.1
HR 8799	c	38	10.0	39.94	F0	5.2	1.0
2MASS J12073346-3932539	b	46	4.0	52.4	M8	11.6	0.9
WISEP J121756.91+162640.2	b	8	22.0	10.1	T8.5	16.5	0.8
GQ Lup	b	100	20.0	139	K7e V	6.1	0.7
HD 95086	b	55.7	5.0	91.57	A8 III	6.7	0.6
HR 8799	d	24	10.0	39.94	F0	5.2	0.6
bet Pic	b	9.04		19.28	A5 V	3.5	0.5
HR 8799	e	14.5		39.94	F0	5.2	0.4