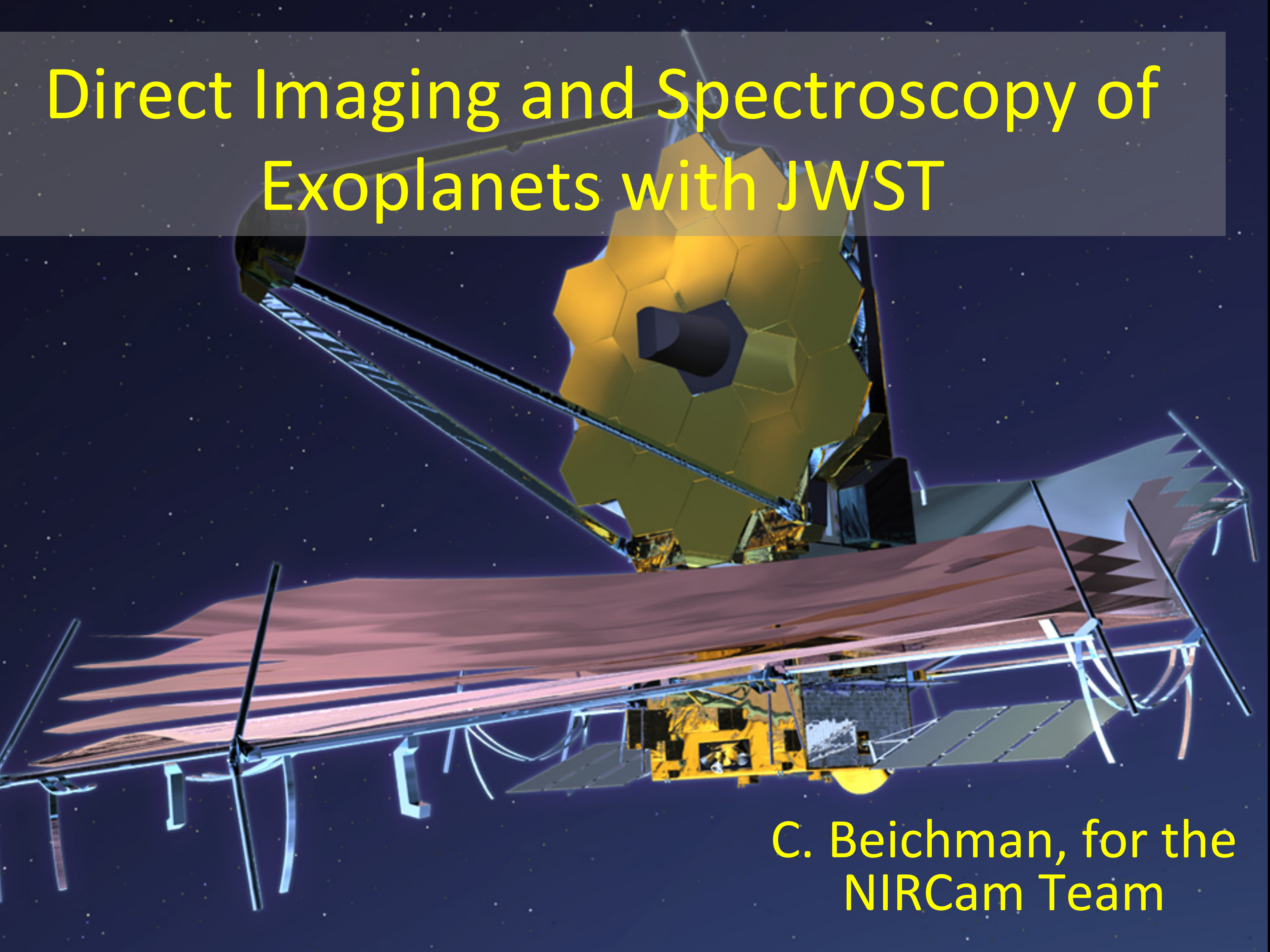
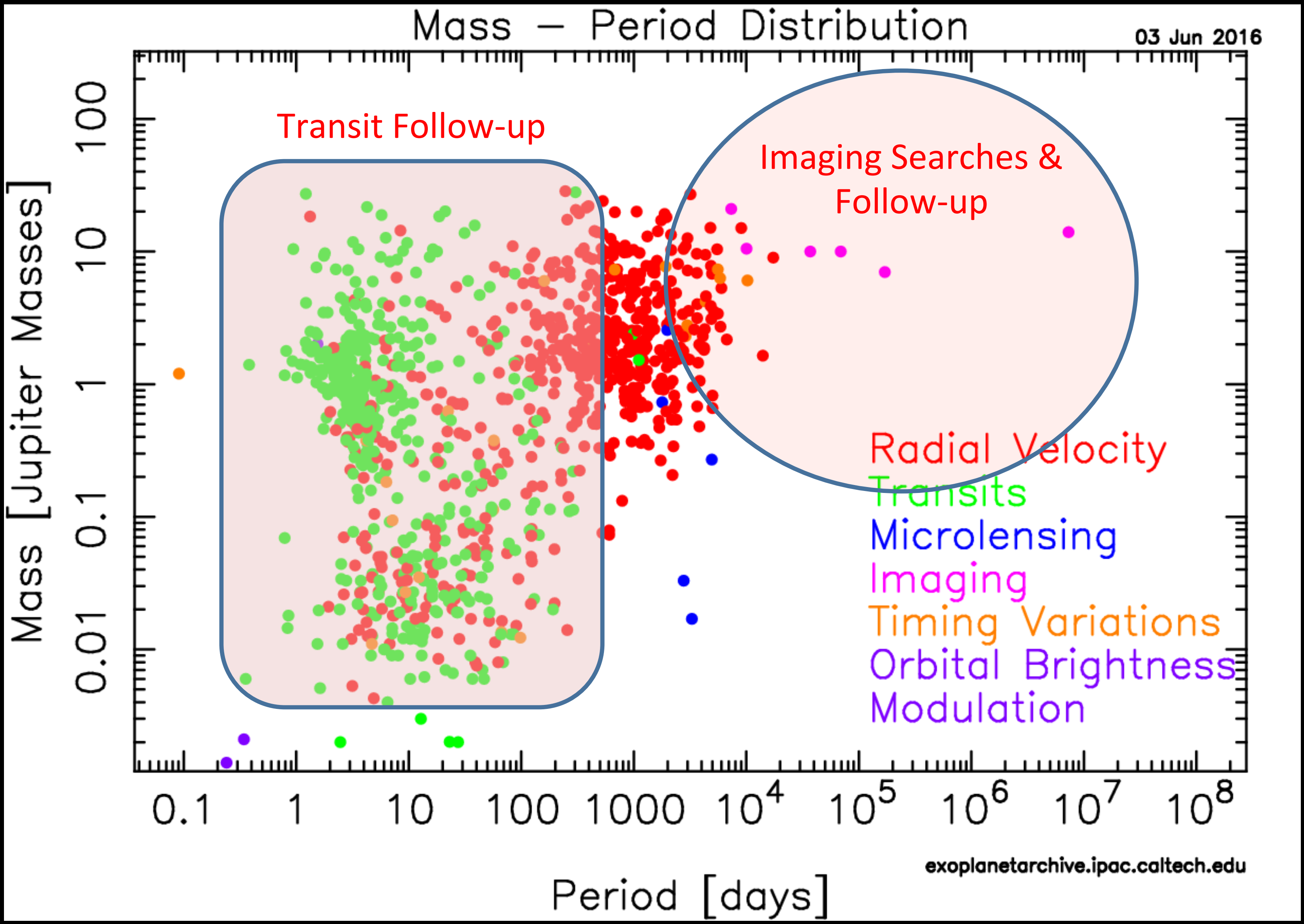
Direct Imaging and Spectroscopy of Exoplanets with JWST



C. Beichman, for the NIRCam Team

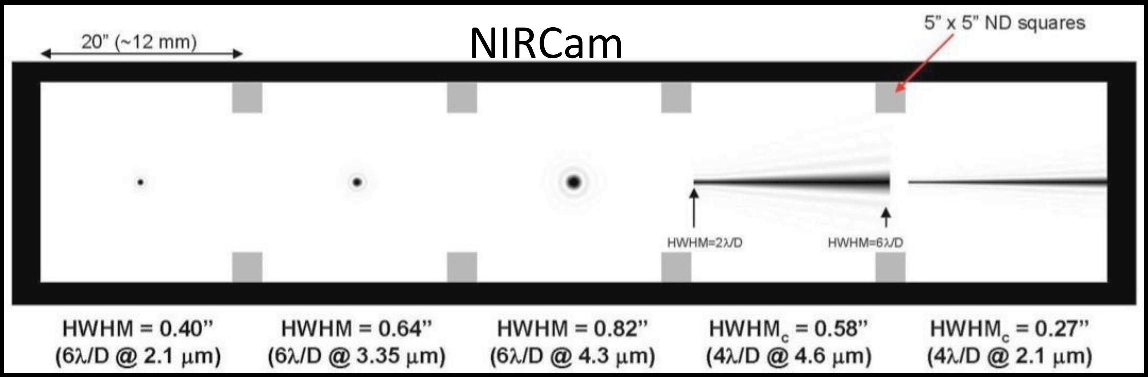
Exo-Planets With JWST

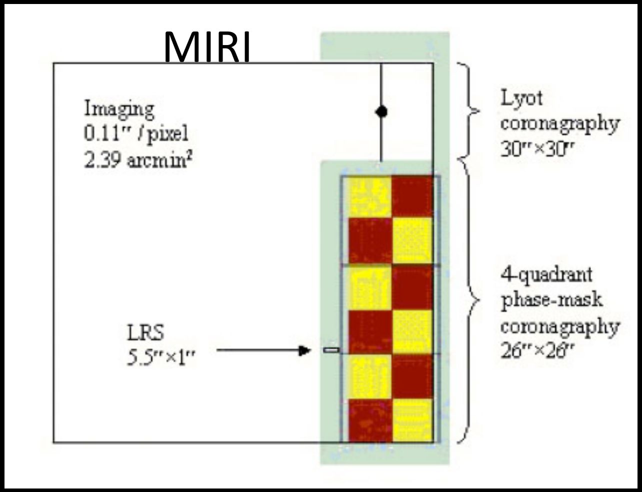


NIRCAM Team Explores Broad Range of Exoplanet Science

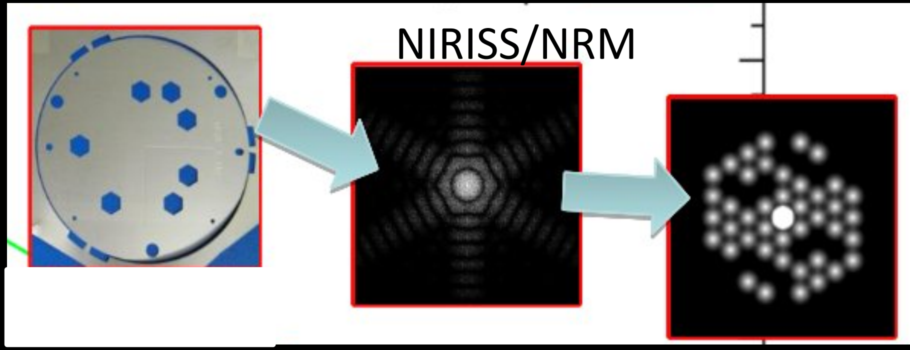
- Imaging of known young planets (NIRCam with MIRI)
- Direct Spectroscopy of known planets (NIRCam team with NIRSpec and MIRI)
- Transit Spectroscopy of known planets (integrated program across all teams, instruments)
- Coronagraphic survey of young M stars (NIRCam and NIRISS/NRM)
- Observations of Coolest Brown Dwarfs (NIRCam team, NIRSPEC, MIRI, NIRISS/NRM)

JWST Coronagraphs Cover 2-15 um

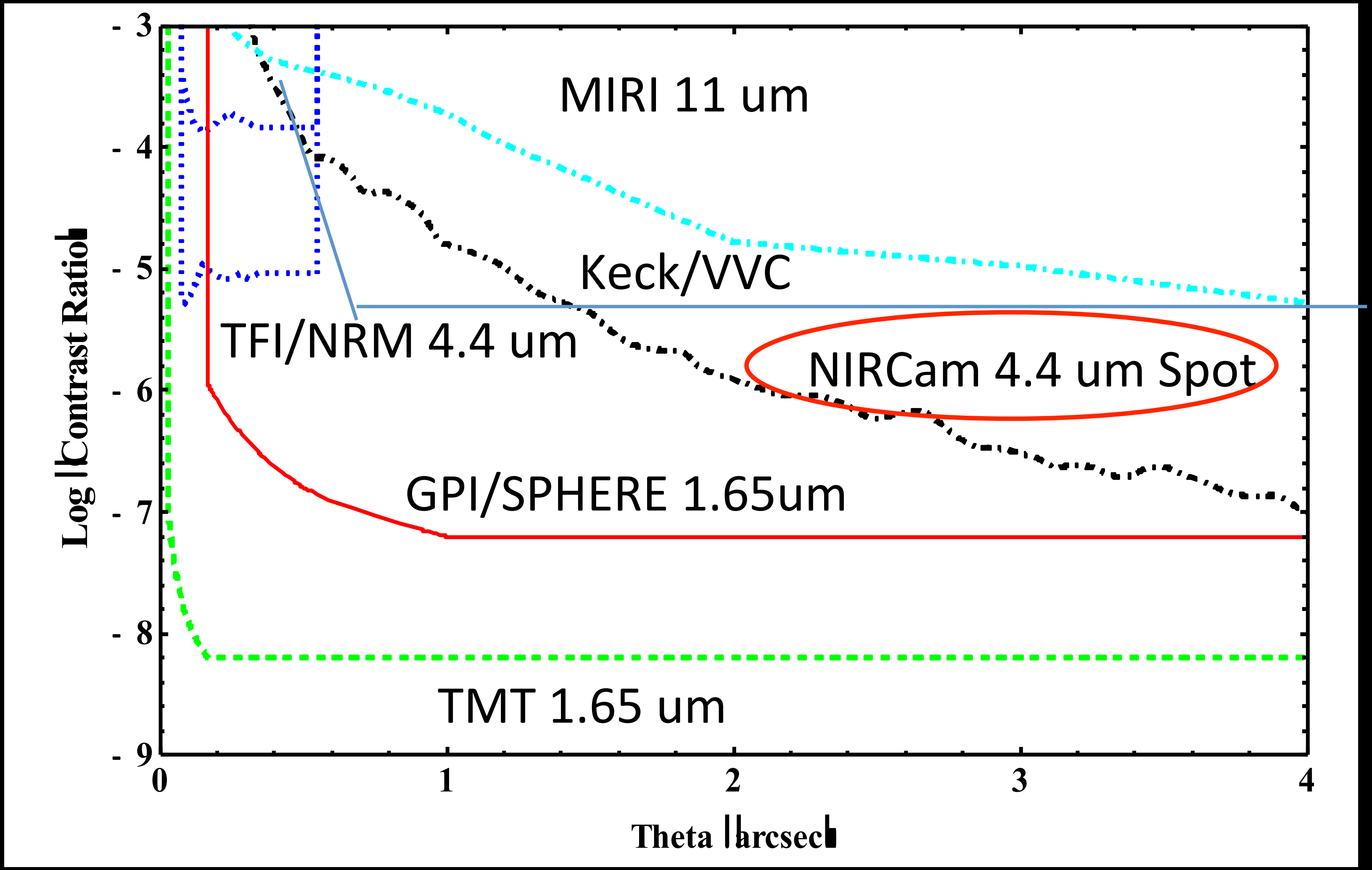




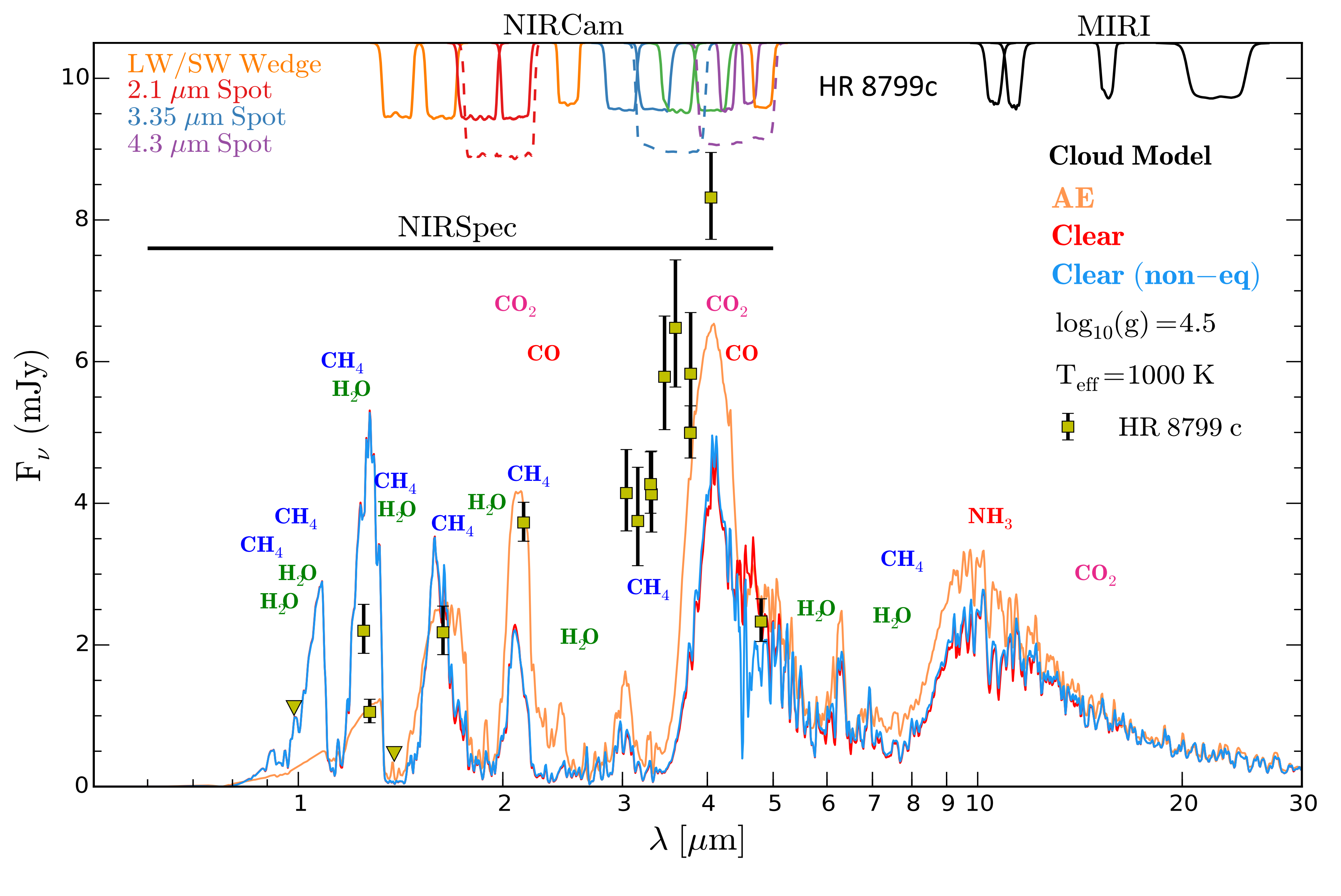
- Ground-based 8-10 m ExAO systems have smaller WFE and better IWA (λ/D)
- JWST trades wavefront error (130nm WFE) and smaller aperture for stability (5-10 nm) and low IR background >1"



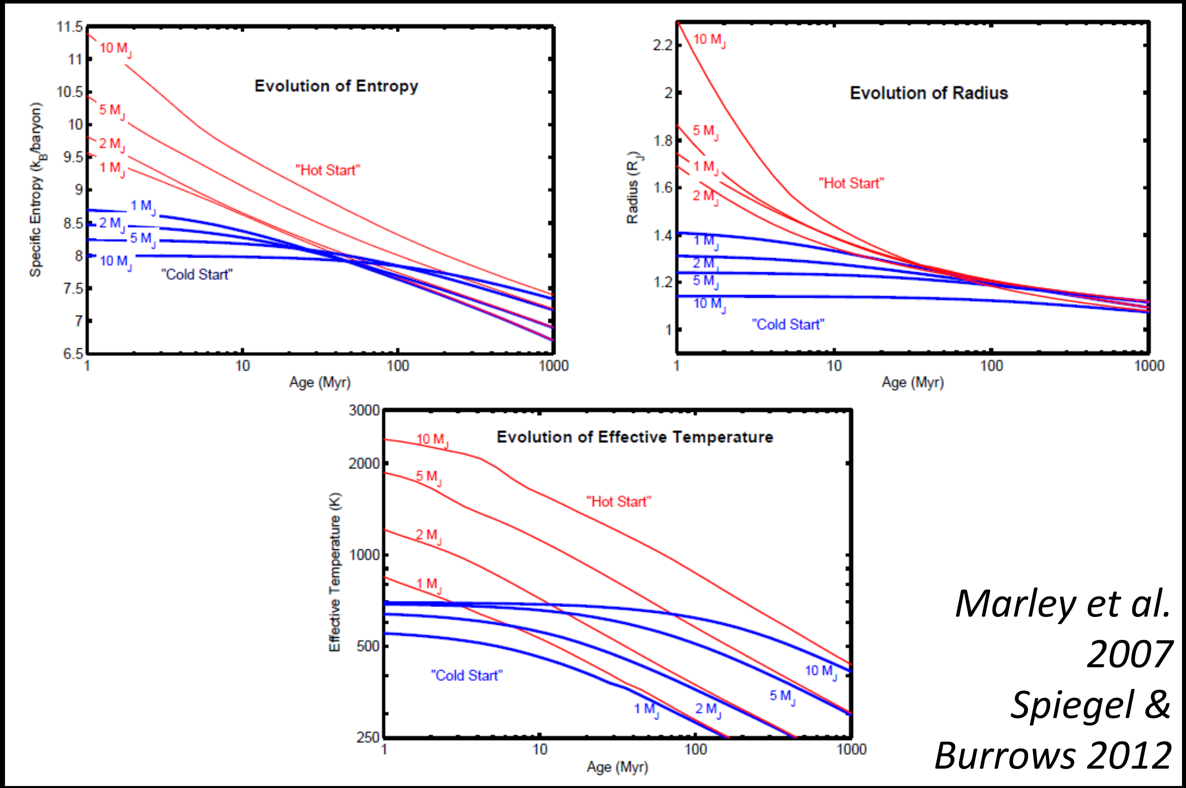
JWST Coronagraphs



Illustrative Spectra for HR8799c



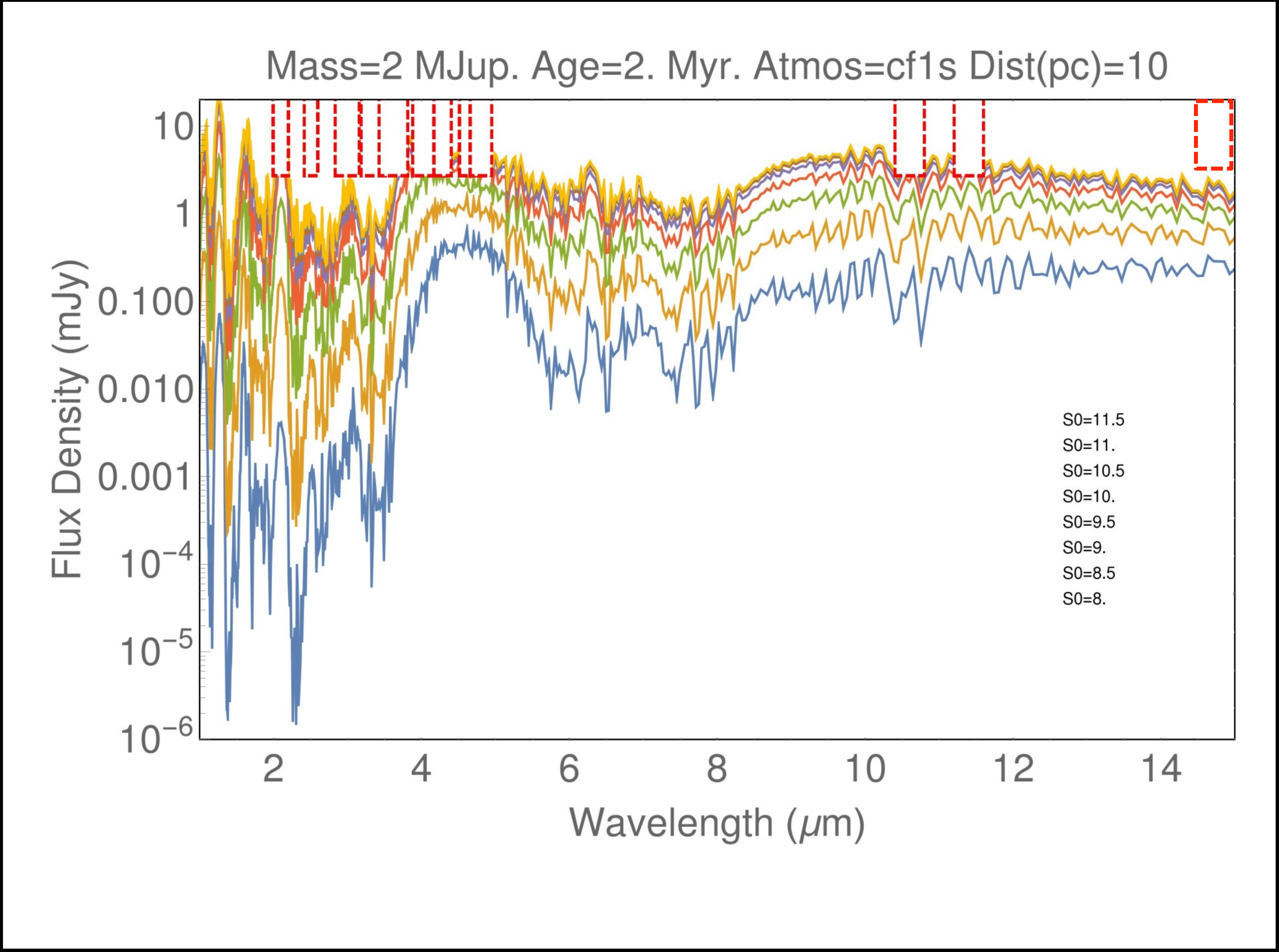
Formation Mechanism Affects Planet Properties



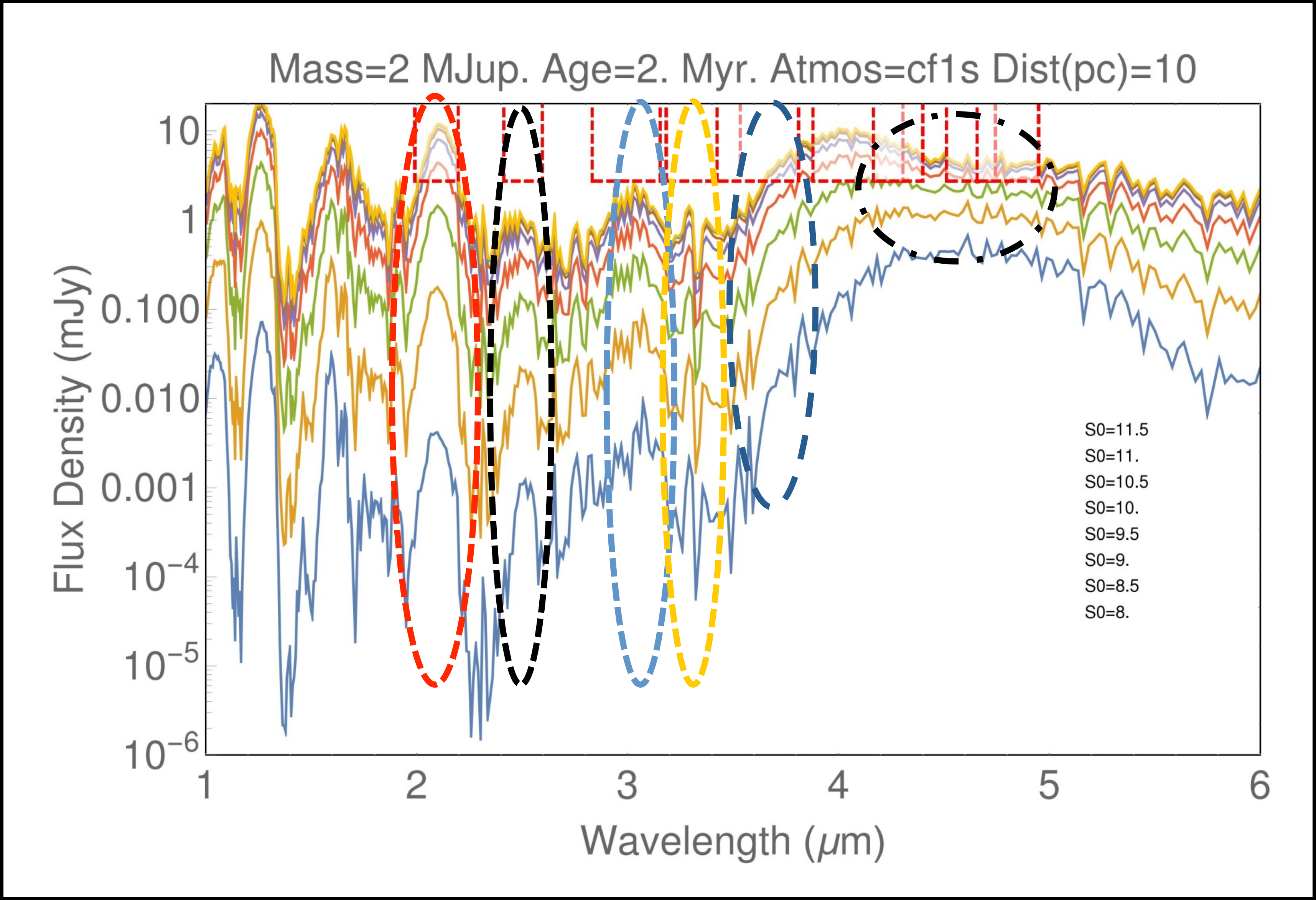
Marley et al. 2007
Spiegel & Burrows 2012

- Initial conditions cause differences in (Radius, T_{eff}, Lumin) for ages <100 Myr and masses 1-10 MJup
  - Disk-instability: High Entropy, Hot Start
  - Core Accretion: Low, Entropy, Cold Start
- Can we recover physical and initial conditions?

NIRCam+ MIRI cover Young Planet Spectra



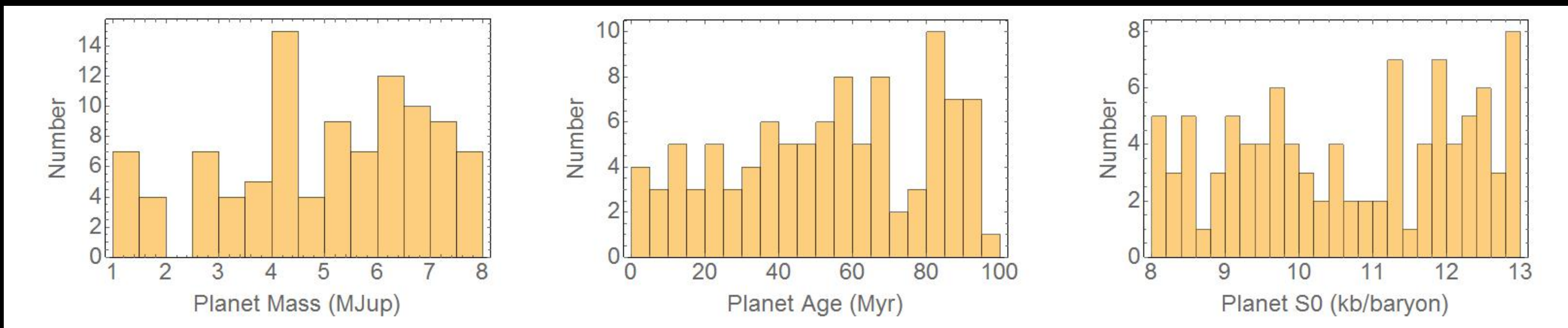
Filter Observations Can Recover Physical Conditions



Planning the NIRCam Imaging Program

- Use representative set of models for young planets (Spiegel and Burrows 2012)
- Run a sequence of Monte Carlo calculations selecting a range of filters and planet properties
  - Fix Target Age to specific value given we know distance and age of star (uncertain of course)
  - Assume detection at SNR from 5-25 based on noise model.
- Examine various sequences of NIRCam and MIRI filters to assess suite of filters needed to match input mass, Entropy, and model atmosphere.
- Assess quality of fit to planet parameters

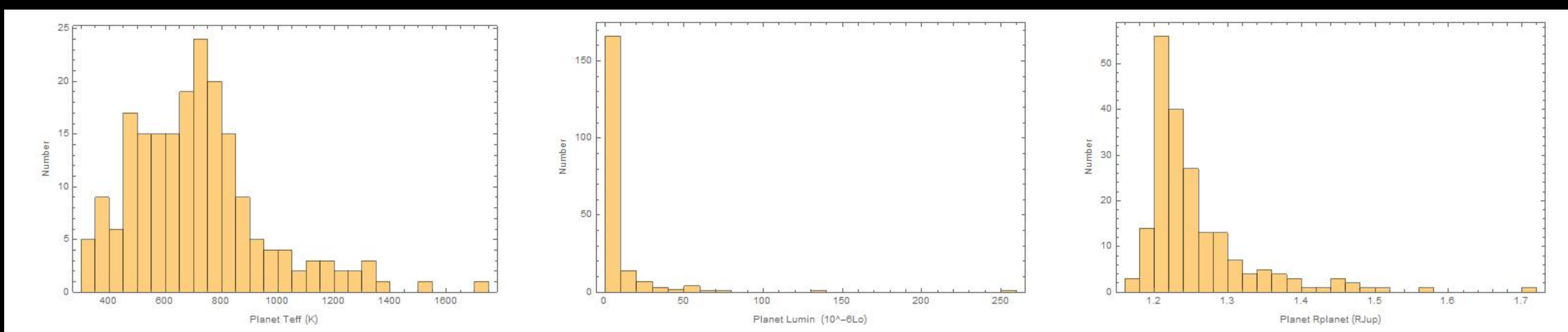
Representative Planet Properties Input For Monte Carlo Analysis



Mass

Age

Initial Entropy



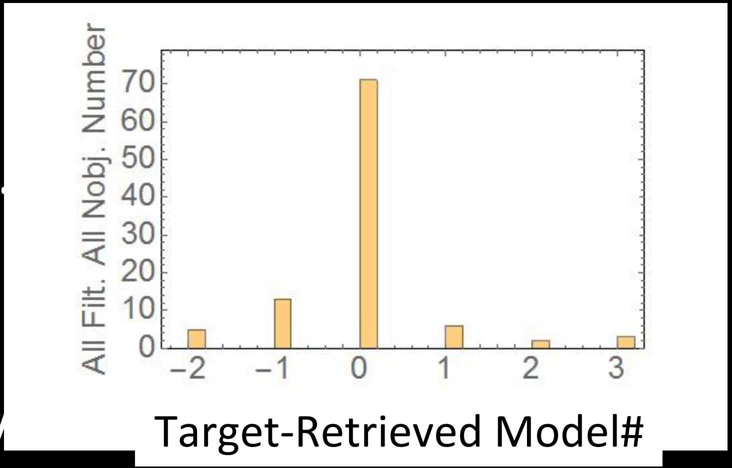
Teff (K)

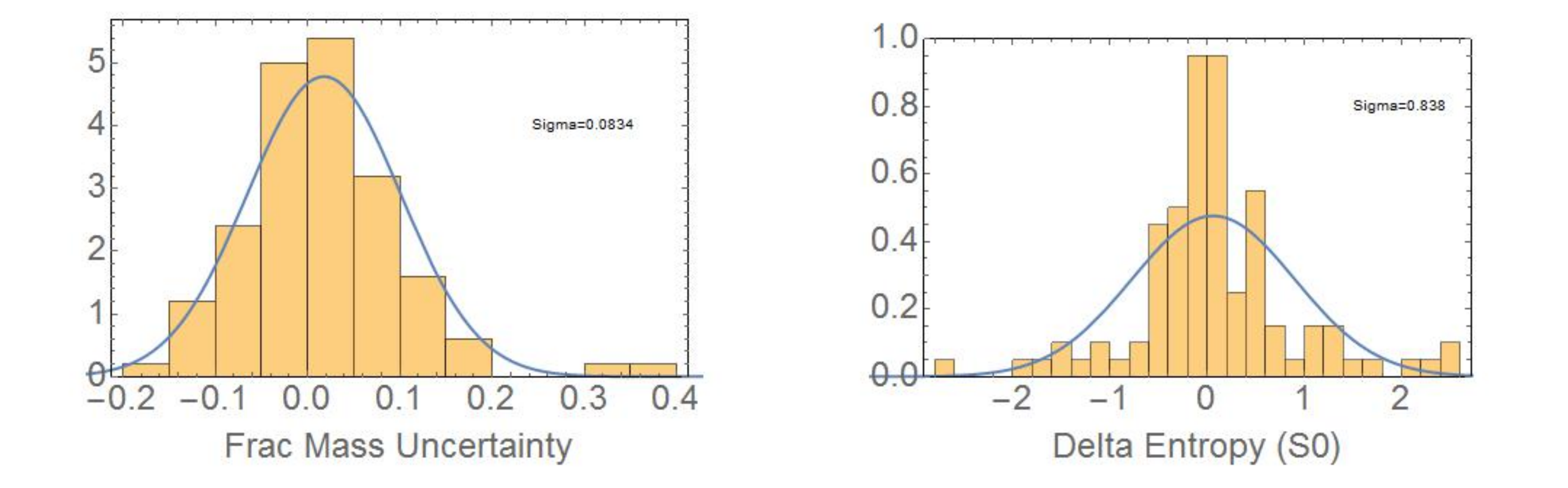
Luminosity (10^-6)

Radius (RJup)

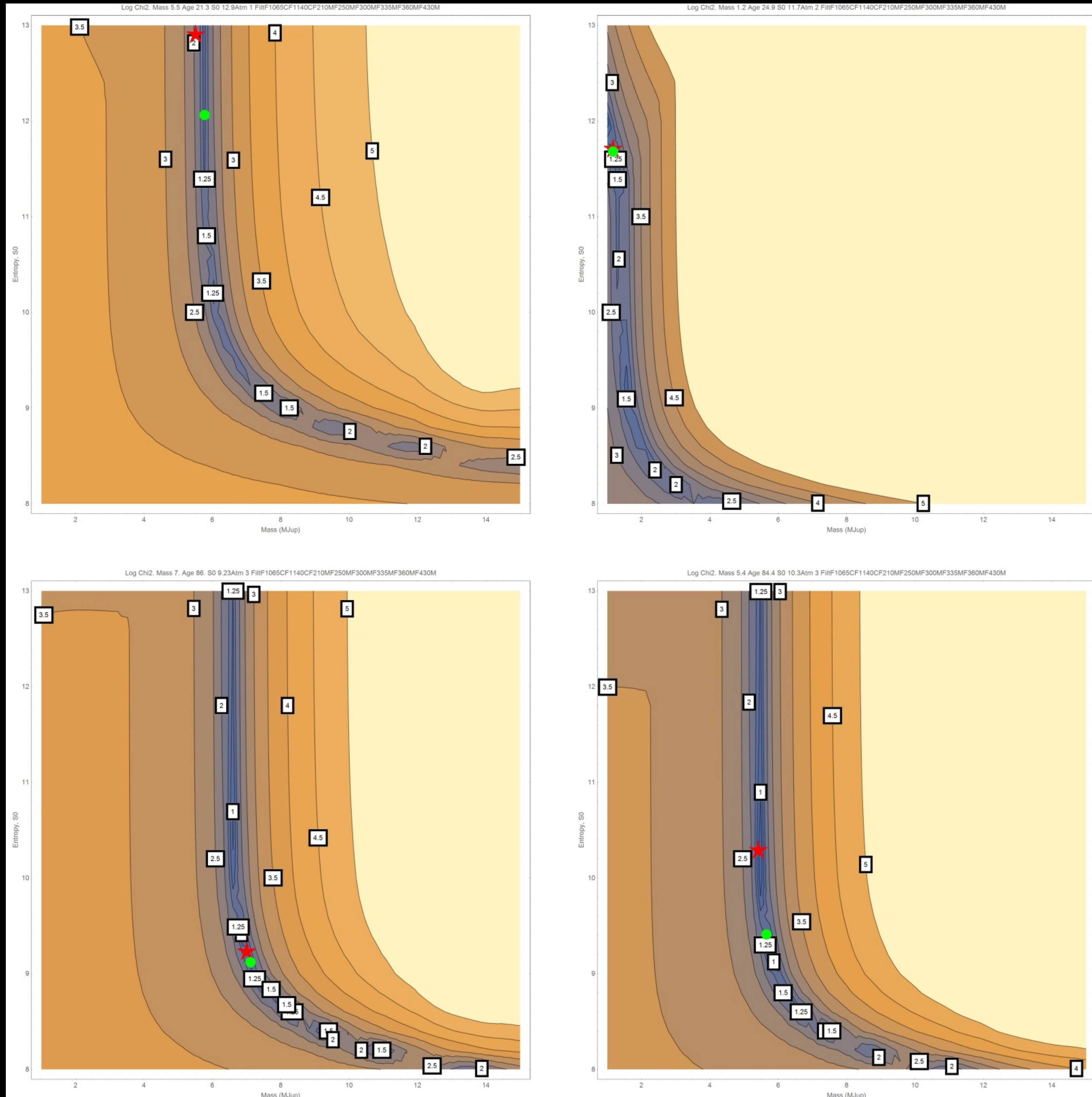
Large Filter Set: 6 NIRCam + 2 MIRI

- 2 MIRI filters plus 6 NIRCam medium band filters: F1065C, F1140C, F210M, F250M, F300M, F335M, F360M, F430M. matched to features in spectra
- Analysis shows favorable retrieval wrt input models: mass within ±8%, entropy within ±0.8 kb/baryon. Atmosphere model > 70% of the time

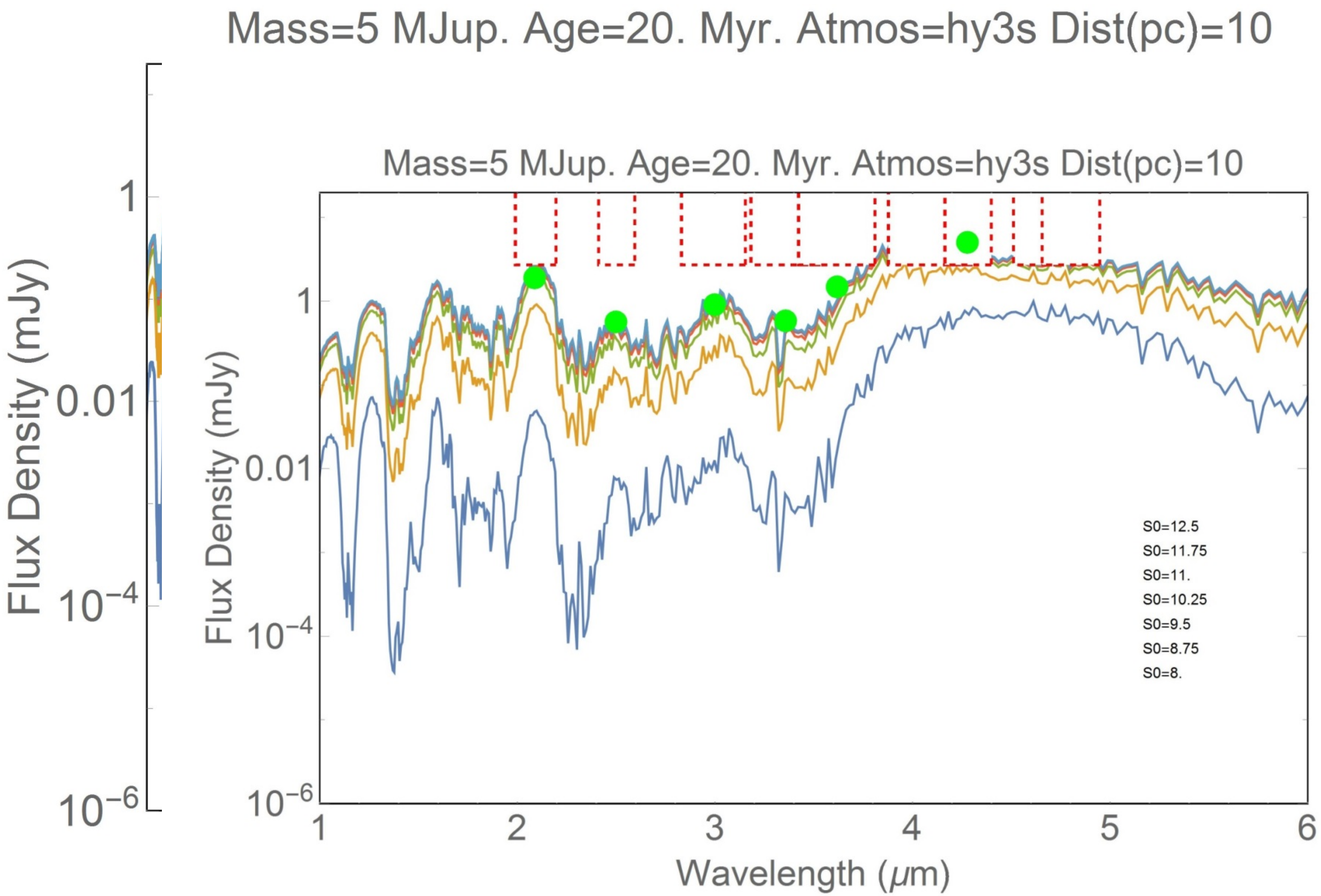


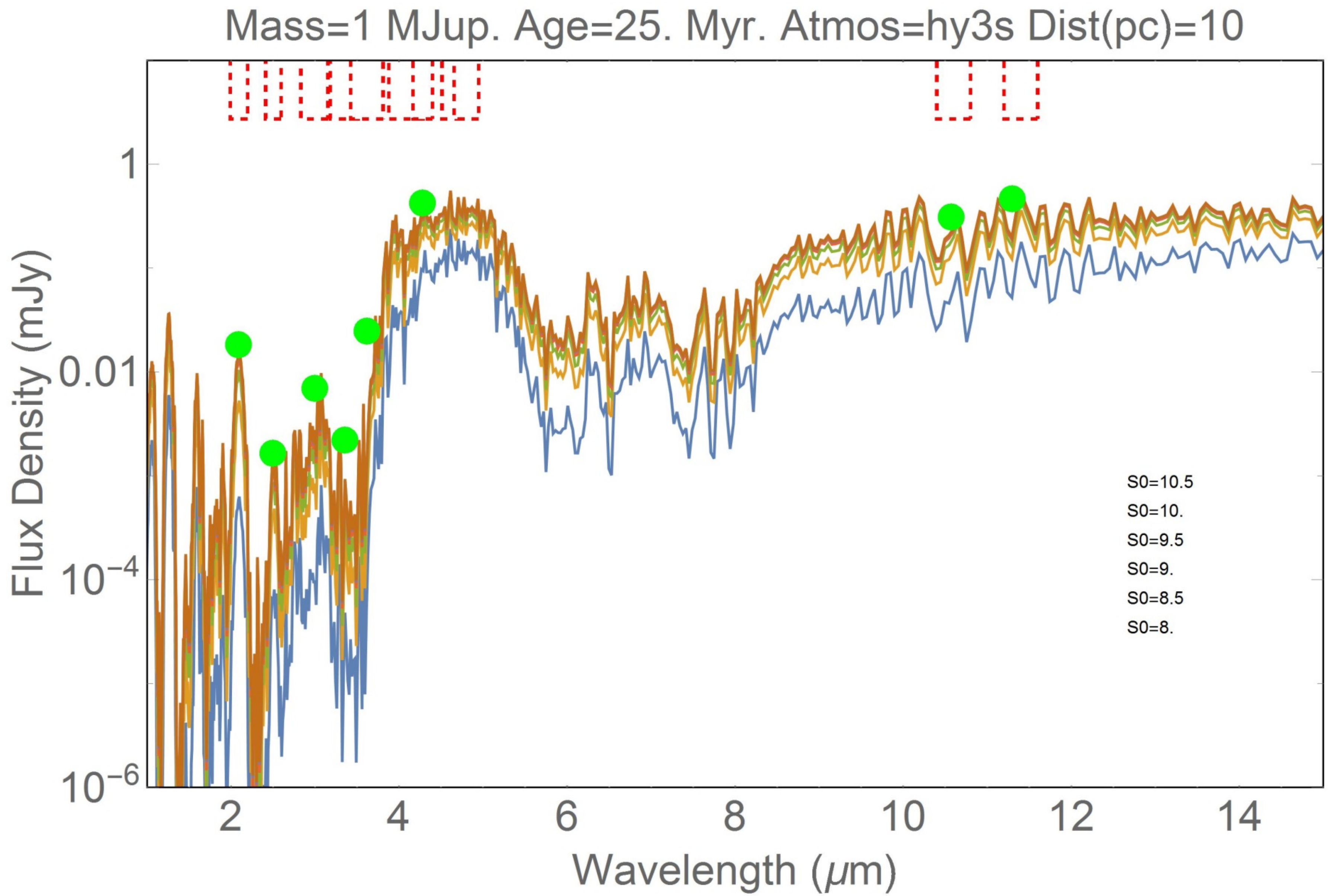


Contour Maps of chi2=f(Mass, Entropy) for fixed ages. Target values and retrieved values are marked



Mass= 5.5 Age=21.3 Entropy=12.9 Atm Model=2

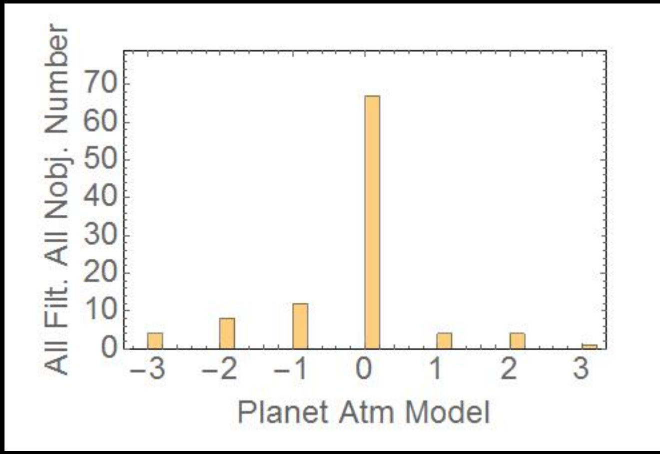


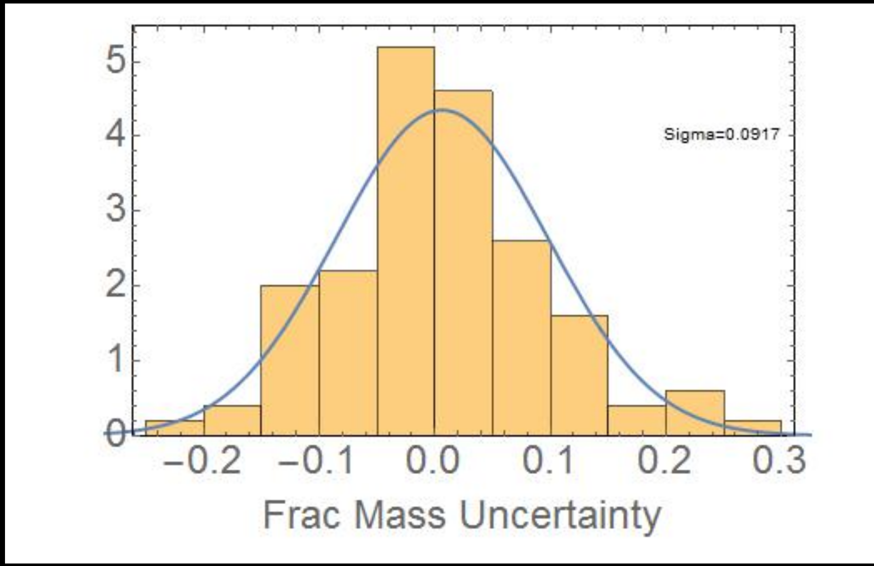


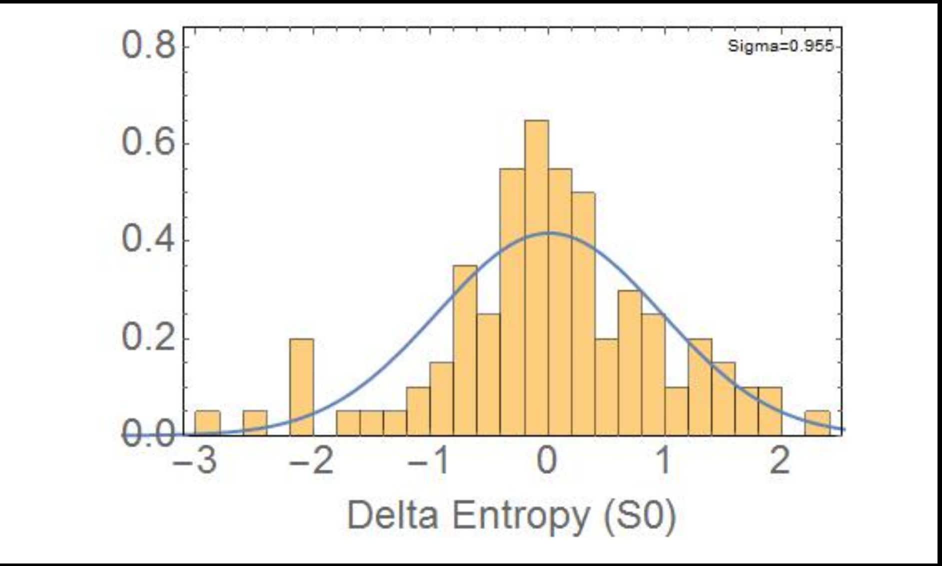
Mass=1 MJup. Age=25. Myr. Atmos=hy3s Dist(pc)=10
Flux Density (mJy)
1
0.01
10^{-4}
10^{-6}
2
4
6
8
10
12
14
Wavelength (μm)
S0=10.5
S0=10.
S0=9.5
S0=9.
S0=8.5
S0=8.

5 NIRCam+2 MIRI Filter Set

- Remove F360M on shoulder of 5 μm peak
  - F1065C,F1140C,F210M,F250M,F300M,F335M,F430M
- Performs slightly more poorly than 6+2 set
  - Still favorable retrieval wrt input models. Fit mass within ±9%, Initial entropy within ±0.95 kb/baryon. Correct atmosphere model retrieved > 65% of time

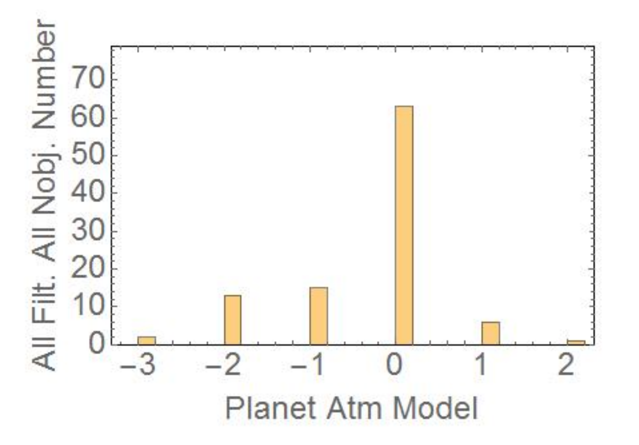


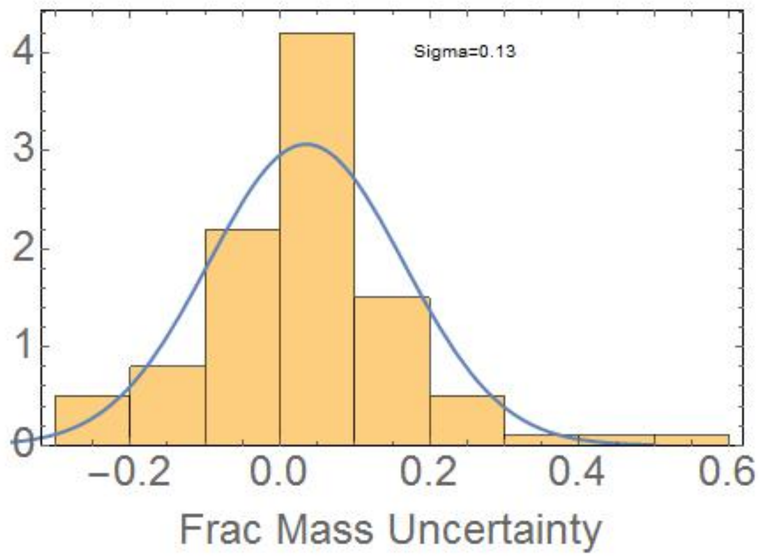


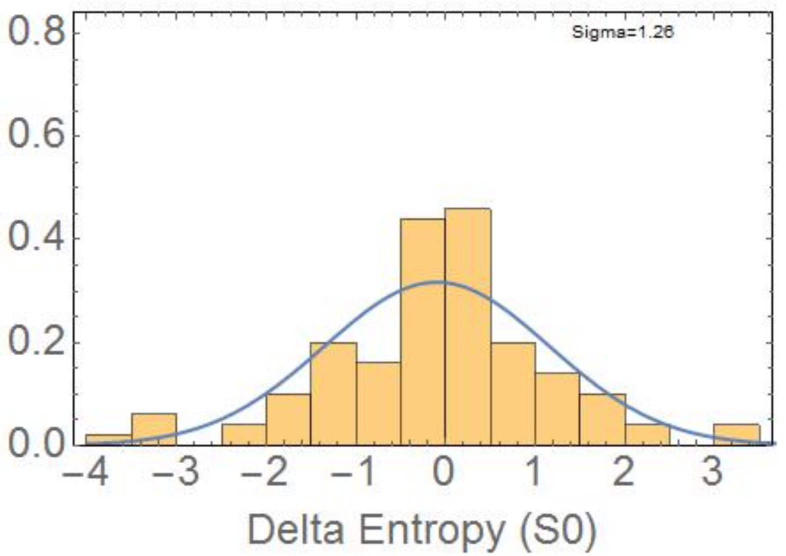


Minimum MIRI+NIRCam

- Two NIRCam +2 MIRI filters:
  - F356W,F444W, F1065C, F1140C
- Broader distribution: ±13% in mass ±1.3 kb/baryon entropy; correct atmosphere, 60%





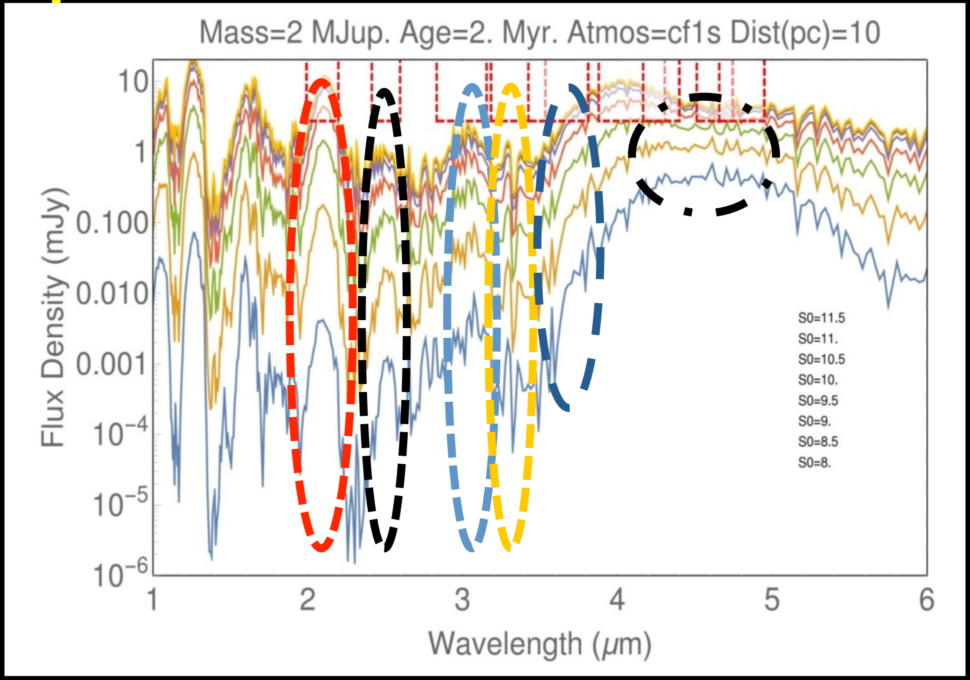


Overall conclusions

- From breadth of wavelengths (2-15 μm) we can calculate Luminosity and Temperature quite accurately → Radius to <5% → hot/cold start discrimination (Initial Entropy)
- Discriminating between various atmospheric models (composition, clouds) more challenging, but higher SNR may be possible for widely separated planets

Planned Coronagraphic Observations

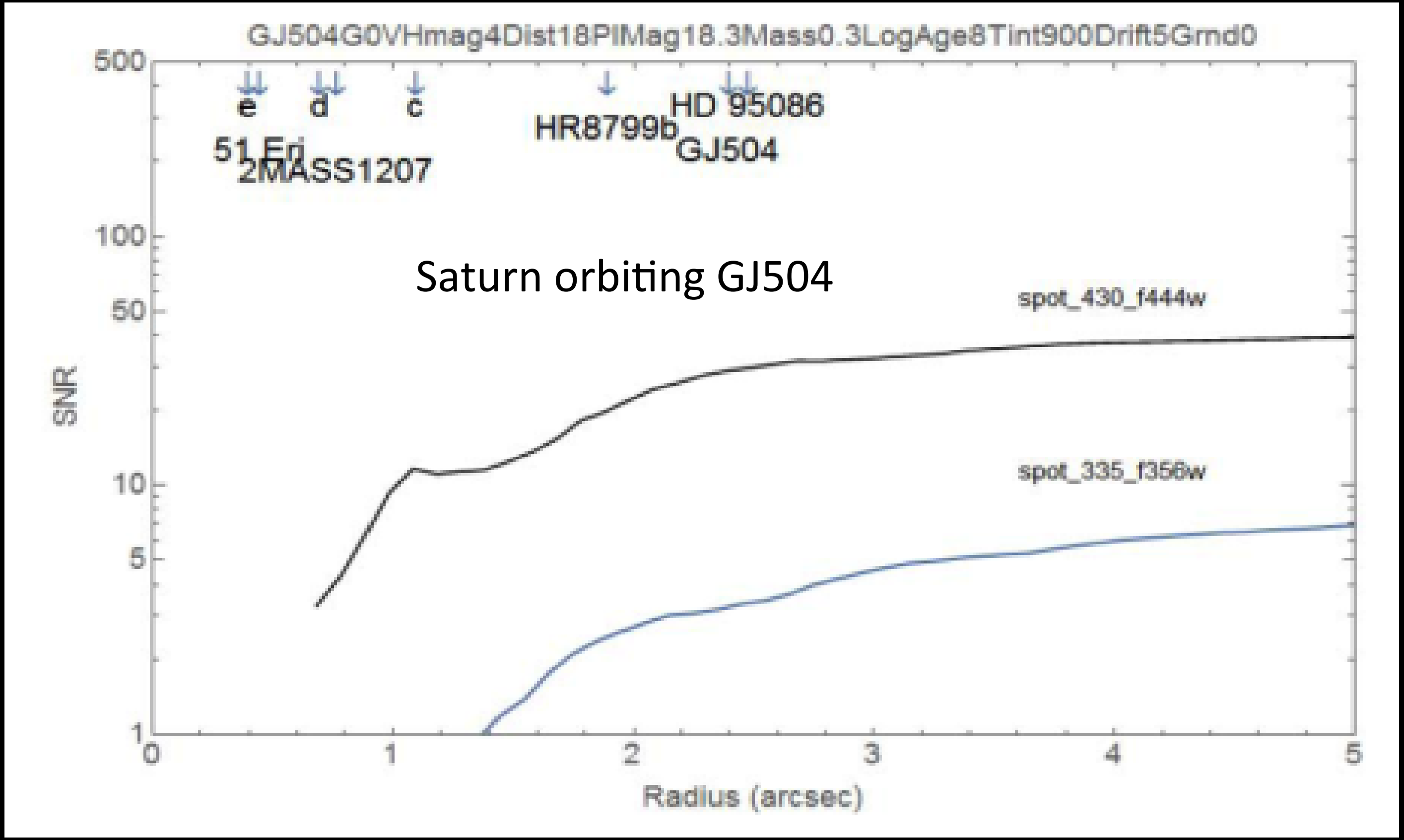
- 5 known planetary systems w. the NIRCam and MIRI
  - Recover physical and atmospheric properties, e.g. Mass, Radius, Teff, Luminosity, Clouds, Composition (NH3 from MIRI), Initial Entropy
- Search for planets <u><</u>0.1 MJup
- Targets in angular separation range 0.4”-3”, masses<13 M_{Jup}



Host Name	Separation (")	Orbit (AU)	Distance (pc)	Spec Type	Age (Myr)	Planet Mass (MJup)
GJ 504b	2.42	43.5	17.95	G0 V	160.00	4
2MASS J1207	0.88	46	52.4	M8	8.00	4
HR 8799b	1.70	68	39.94	F0V	50?	7
HR 8799d	0.95	38	39.94	F0V	50?	10
HD 95086b	0.61	55.7	91.57	A8 III	17	5
51 Eri b	0.45	13.2	29.4	F0IV	20.00	2

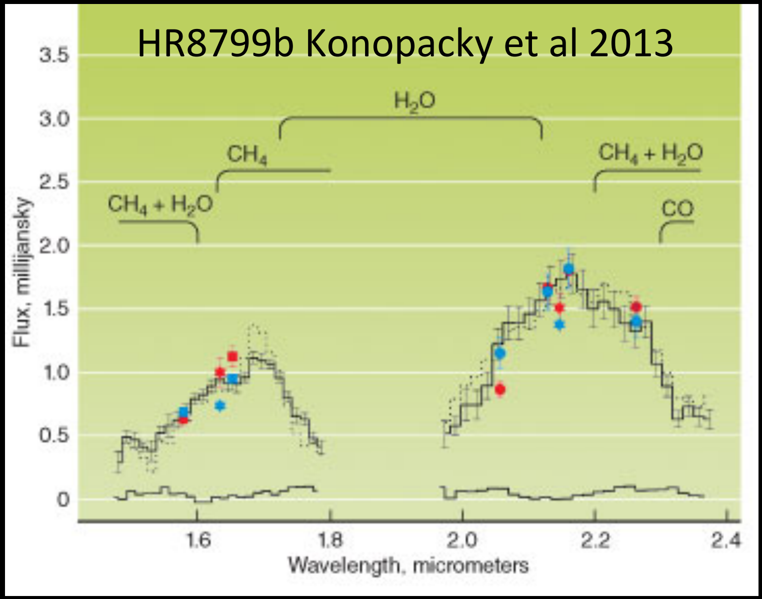
Searching for Lower Mass Companions

- Are multiple systems like HR8799 exception or rule?
- JWST sensitivity will probe for Saturn masses > ~1” at F322W2 and F444W



Direct Spectroscopy

- At modest separations (3”-10”) use NIRSpec IFU to obtain R~1,000 spectra of known planets
  - –Understand scattered light, etc
  - –Tools for speckle suppression tools
- For separations >10” use slit/ IFU for R~3,000 spectra

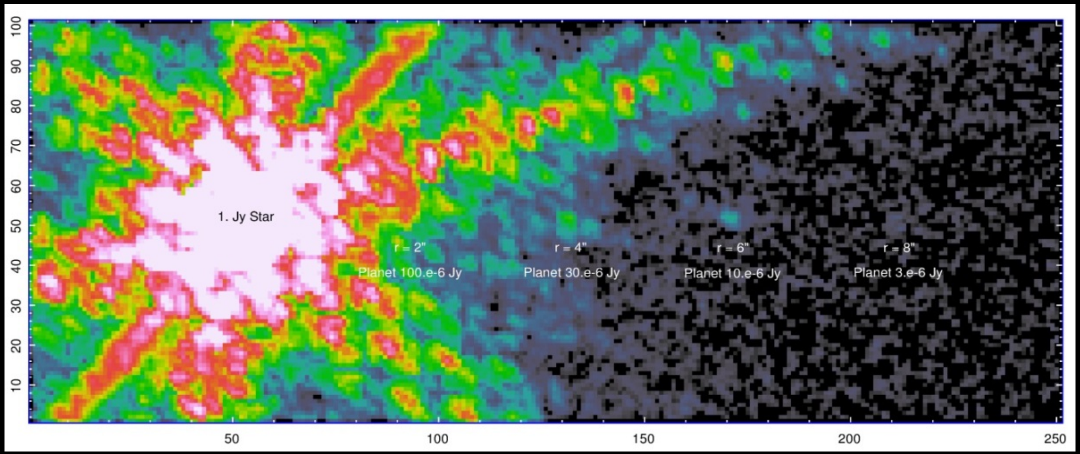


NIRSpec IFU Spectroscopy (3”-10”)

FW Tau, DH Tau, HD 106906

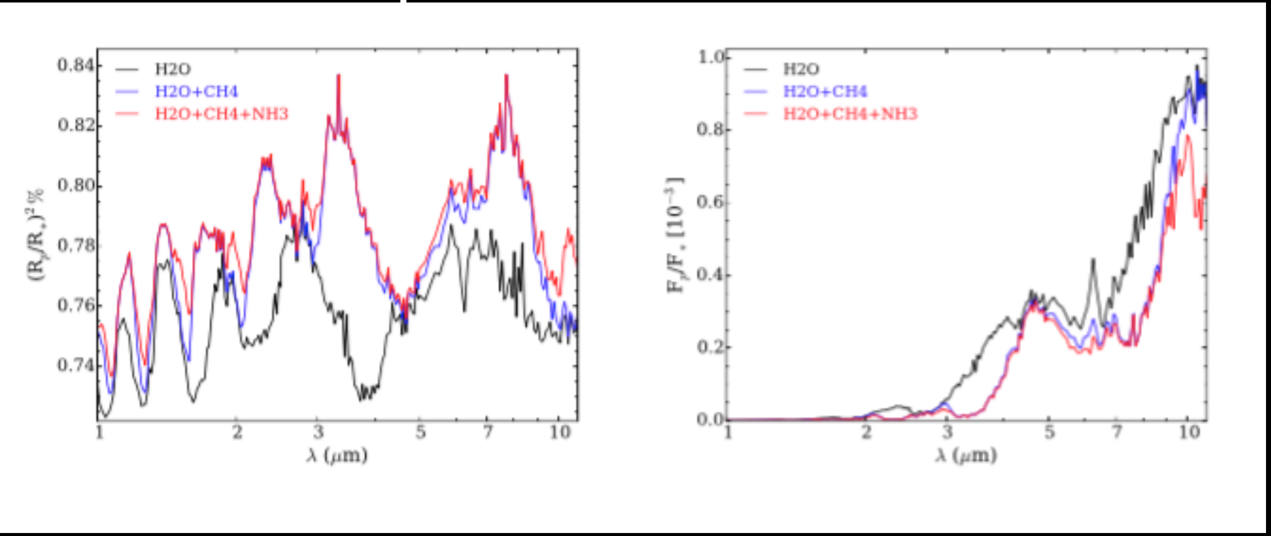
NIRSpec for Planets (>10”)

Fomalhaut-b, WD 0806-66, GU Psc



Integrated MIRI + NIRCam Transit Program Targets Warm (T ~600 – 1000 K) Planets

- 2.5 – 11 μm spectral region covers CH_4 (MIRI & NIRCam), CO & CO_2 (NIRCam), NH_3 (MIRI)
- Sample 20 $M_\oplus$ – 180 $M_\oplus$ (Neptune to 2x Saturn)
- Emission spectra probe atmosphere (P < ~1 bar) and constrain [Fe/H]
- Transmission spectra may see through clouds (λ>2 μm)
- NIRISS and telescope teams have additional targets

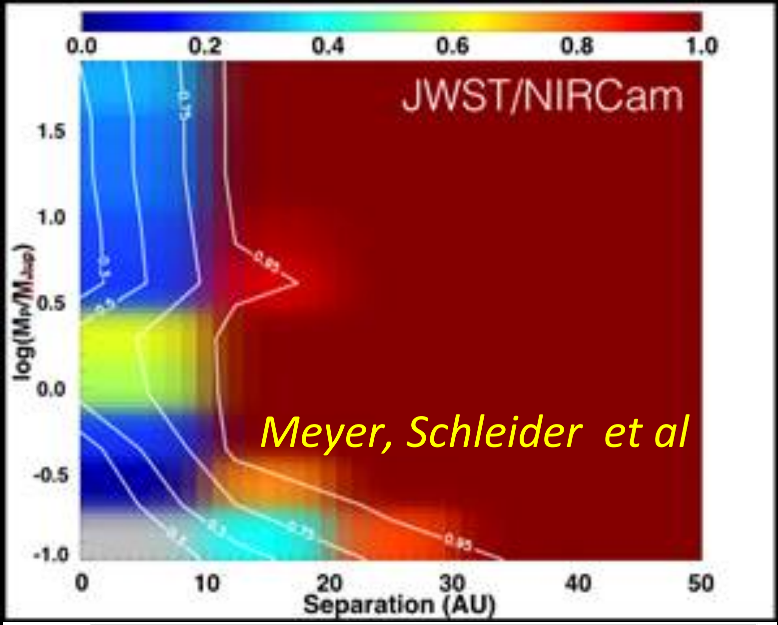


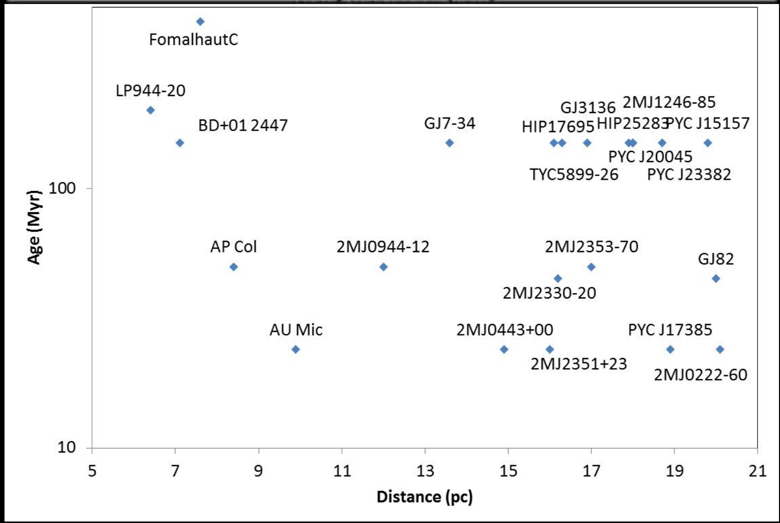
Illustrative NIRCam+MIRI Targets

Name	K(mag)	T_{eq}(K)[a]	$R_p(R_\oplus)$	$M_p(M_\oplus)$	T_{14} (hr)	Geometry[b]	Visits	Mode	NCam T(hr)[c]	MIRI T(hr)[c]	nIR?[d]	Comment
HD 189733 b	5.5	1200	12.5	360	1.82	EMIS	1	NC F322W2	7.3		?	Still Evaluating
HD 189733 b	5.5	1200	12.5	360	1.82	EMIS	1	NC F444W	7.3		?	Still Evaluating
WASP-80 b	8.4	850	10.7	180	2.11	EMIS	1	NC F322W2	8.3		N?	Similar to WASP-67b
WASP-80 b	8.4	850	10.7	180	2.11	EMIS	1	NC F444W	8.3		N?	Similar to WASP-67b
WASP-80 b	8.4	850	10.7	180	2.11	EMIS	1	MIRI LRS		8.3	N?	Similar to WASP-67b
WASP-39 b	10.2	1120	14.2	90	2.80	EMIS	1	NC F322W2	10.7		?	Similar to HAT-P-19b
WASP-39 b	10.2	1120	14.2	90	2.80	EMIS	1	NC F444W	10.7		?	Similar to HAT-P-19b
WASP-39 b	10.2	1120	14.2	90	2.80	EMIS	1	MIRI LRS		10.7	?	Similar to HAT-P-19b
HAT-P-12 b	10.1	960	10.7	67	2.34	EMIS	1	NC F322W2	9.1		?	Low Spitzer S/N
HAT-P-12 b	10.1	960	10.7	67	2.34	EMIS	1	NC F444W	9.1		?	Low Spitzer S/N
HAT-P-12 b	10.1	960	10.7	67	2.34	EMIS	1	MIRI LRS		9.1	?	Low Spitzer S/N
HAT-P-12 b	10.1	960	10.7	67	2.34	TRANS	1	NC F322W2	9.1		Y	Promising retrieval
HAT-P-12 b	10.1	960	10.7	67	2.34	TRANS	1	NC F444W	9.1		Y	Promising retrieval
GJ 436 b	6.1	700	4.2	22	0.76	EMIS	3	NC F322W2	10.8		N	Look for CH_4?
GJ 436 b	6.1	700	4.2	22	0.76	EMIS	3	NC F444W	10.8		N	Look for CO?
GJ 436 b	6.1	700	4.2	22	0.76	EMIS	3	MIRI LRS		10.8	N	CH_4; too bright?
HAT-P-26 b	9.6	1000	6.2	19	2.46	TRANS	1	NC F322W2	9.5		?	Possible H_2O
HAT-P-26 b	9.6	1000	6.2	19	2.46	TRANS	1	NC F444W	9.5		?	Possible H_2O
HAT-P-26 b	9.6	1000	6.2	19	2.46	TRANS	1	MIRI LRS		9.5	?	Possible H_2O
GJ 1214 b	8.8	600	2.6	6.5	0.88	TRANS	2	NC F322W2	7.9		N	Look for abs
GJ 1214 b	8.8	600	2.6	6.5	0.88	TRANS	2	NC F444W	7.9		N	Look for abs
GJ 1214 b	8.8	600	2.6	6.5	0.88	TRANS	2	MIRI LRS		7.9	N	Look for abs
TOTAL									146[f]	56.3		

M Star Imaging Survey

- Kepler & microlensing (?) →abundant small planets orbiting M stars across range in AU
- NIRCam coronagraphy can reach Saturn - Uranus masses for <150 Myr planets within 15 pc.
- NIRCam probes 10-15 AU (CO snow line) favored for ice giants
- Survey 10~15 objects at F322W2 & F444W (best GAIA targets)

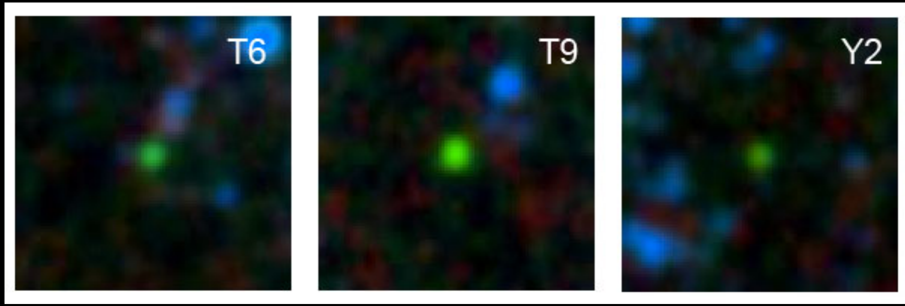


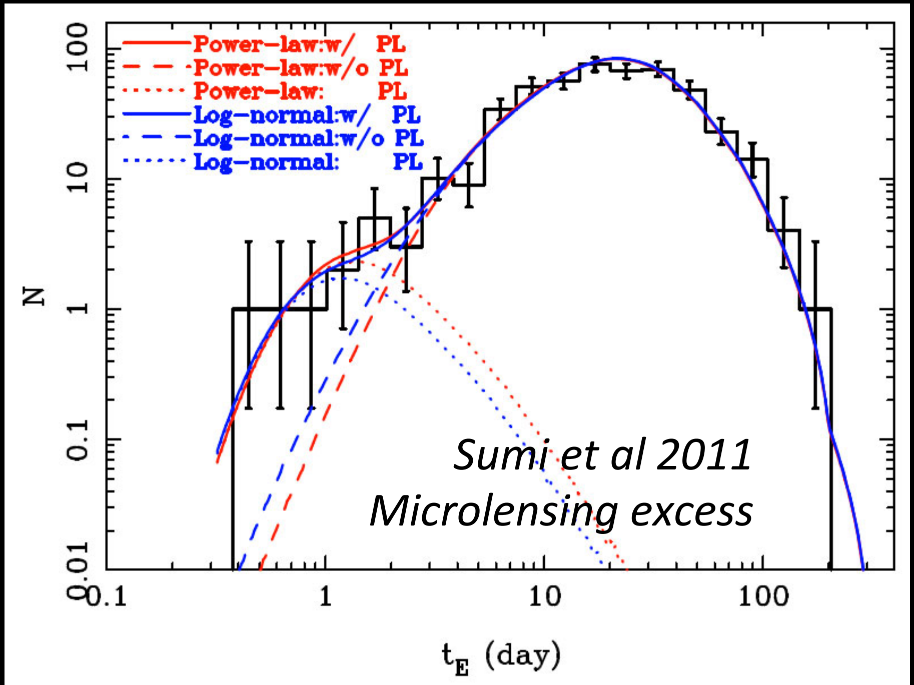


Dist (pc)	Med Spec Type	Min Age (Myr)	Med Age (Myr)	MaxAge (Myr)	WISE W2 (Mag)
16.25	M4	24	150	440	7.26

Nearby T/Y Dwarfs

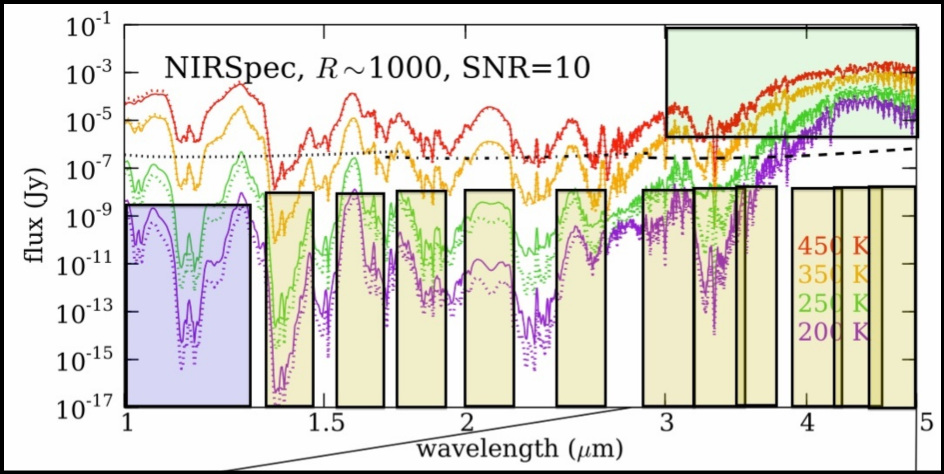
- Analogs to 5-10 M_{Jup} coronagraphic companions
  - –Teff <500 K (WISE, HST, ground based SEDs)
  - –Parallax distances: 2.2(!)-15 pc
  - –Ages ~ 3-5 Gyr from space vel's
  - –Model Masses ~5-10 M_{Jup}
- Runaway planets or runts of stellar litter? Tip of microlensing iceberg?
  - –Possibly lower metallicity than "planets" formed in disks

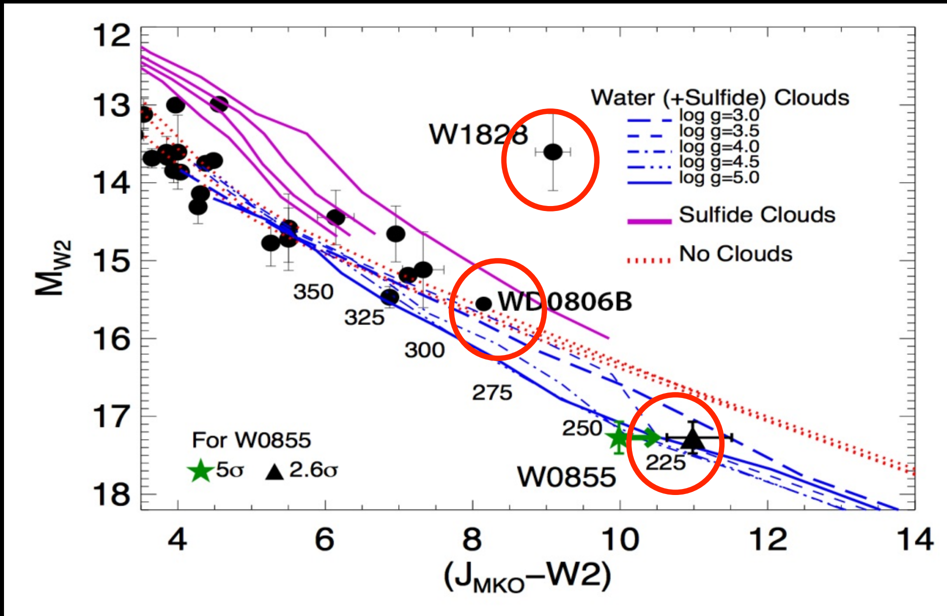




Nearby Y-T Dwarfs

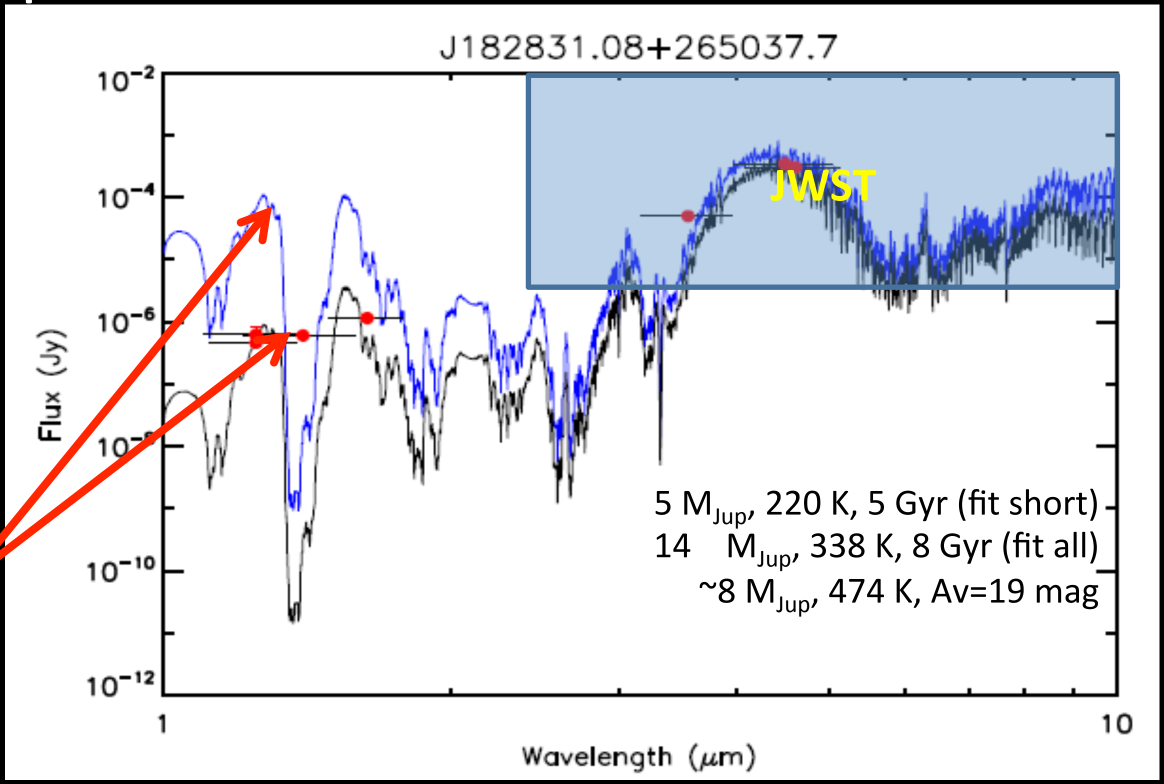
- 10 closest & coldest.
  - BD-BD or BD-WD if possible
  - ~1 rapid rotator for Wx
- High SNR R~1,000-3,000 spectroscopy at 3-15 μm
- Use JWST spatial resolution & sensitivity for companion search
  - NIRCam: 1.3 AU at 10 pc
  - NIRISS/NRM: 0.65 AU at 10 pc (Δmag~5—ΔMass~x3)





JWST Spectra Will Force Better Models

Existing models have great problems fitting mid- and near-IR for coldest sources. Clouds? Non-equilibrium chemistry? Dust absorption?



Dusty Model Av=19 mag fits long and short lams

Illustrative Target List for Y/T BD Program

Name	J (mag)	H (mag)	Spitz Ch1 (mag)	Spitz Ch2 (mag)	Dist (pc)	Teff (K)	Spec Type
WISE J0855-0714	26.5	27	16.2	13.7	2.2	250	>Y2
WD 0806-661B*	25.7*		19.6	13.9	19	275	Y2
WISE J1828+2650		22.5	16.9	14.3	9.4	350	Y2
WISE J0647−6232	22.85	23.31	17.9	15.2	10.8	375	Y1
WISE J0535−7500	22.13	---	17.8	14.9	13.5	475	Y1
WISE J1541−2250	21.63	22.09	16.7	14.2	5.7	350	Y0.5
WISE J2209+2711	22.86	22.39	17.8	14.7	6.8	350	Y0
WISE J0811−8051	19.90	19.86	16.8	14.3	10.2	400	T9.5
WISE J2102−4429	18.34	18.58	16.3	14.1	10.8	450	T9
WISE J0836−1859	18.99	19.5	16.8	15.1	49	662	T8P
0.5” Y/T Binary WISE J0458+6434		A 17.8 B 18.8	16.4	13.0	11	400 350	T9/Y0

*Also observed in exoplanet program (Jmag in (F110W))

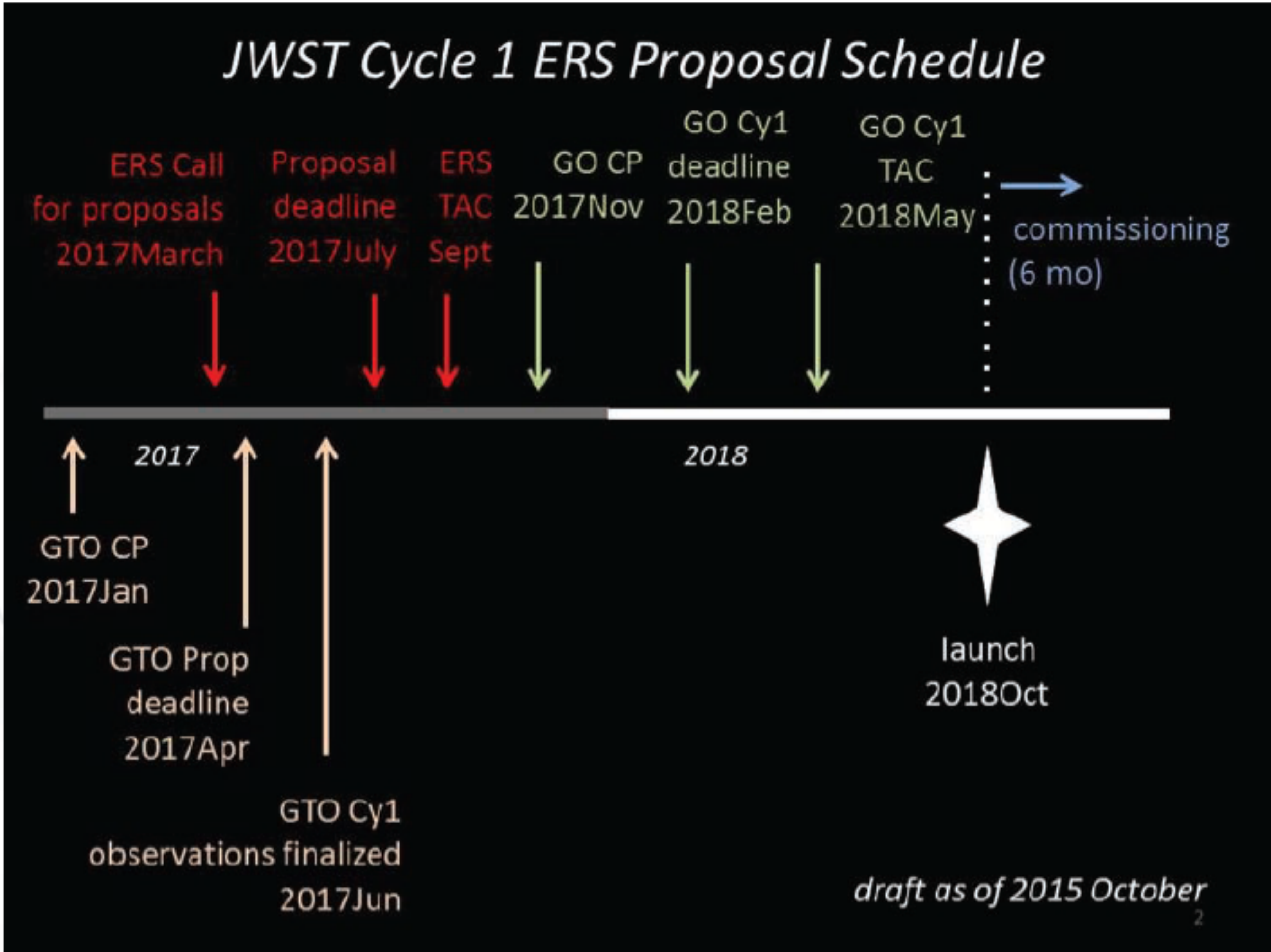
Illustrative JWST Sensitivity

Illustrative Integration Times for NIRSpec Observations					
Grating	Resl'n	tau	λ (μm)	Mag	SNR
[G140M]	1000	900	1.65	20	14
[G235]	1000	900	3	16	20
[G395M]	1000	900	4.6	13	413
[G395H]	2700	100	4.6	13	135
Prism	100	300	1.65	21	34
		300	3	17	76
		300	4.6	14	197

Illustrative Integration Times for MIRI Observations					
Filter	Resl'n	tau(sec)	λ (μm)	Mag	SNR
F1130	16	100	11.3	15	16
F1500	5	200	15.0	15	12
F1800	6	1000	18.0	15	9
MIRI/LRS	200	100	7.5	15	24

Illustrative NIRCam Program

Topic	# Objects	NIRCam Request (hr)	Instruments
Coronagraphic Imaging	5	50	NIRCam & MIRI
Direct Spectroscopy	5-8	20	NIRSpec MIRI
Transit Spectroscopy	10	125	
M star survey	15	50	NIRCam
Y Dwarfs	10	40	NIRSpec &MIRI
Total		250	


JWST Cycle 1 ERS Proposal Schedule
ERS Call for proposals 2017March
Proposal deadline 2017July
ERS TAC Sept
GO CP 2017Nov
GO Cy1 deadline 2018Feb
GO Cy1 TAC 2018May
commissioning (6 mo)
2017
2018
GTO CP 2017Jan
GTO Prop deadline 2017Apr
GTO Cy1 observations finalized 2017Jun
launch 2018Oct
draft as of 2015 October
2

Conclusions

- JWST will find and characterize exoplanets
  - Young Saturns to Young Jupiters via direct imaging and spectra
  - Super Earths to Jupiters via transit spectroscopy
- Use late T and Y dwarfs as analogs of nearby young exoplanets to assess physical conditions, composition & perhaps different formation paths
- The exoplanet community has the opportunity to use a major portion (25%!) of JWST to make dramatic advances

Start now to write great proposals based on the *best* teams, targets, models, and statistical methods.
And don't forget to thank the Sagan Summer Workshop