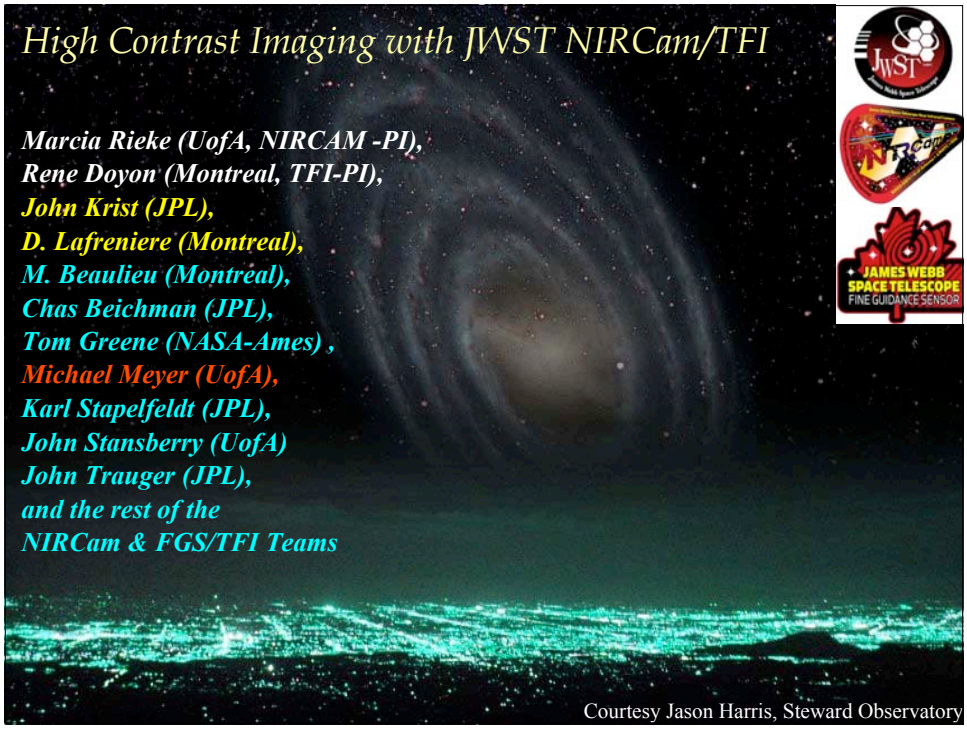


What can pictures tell us?

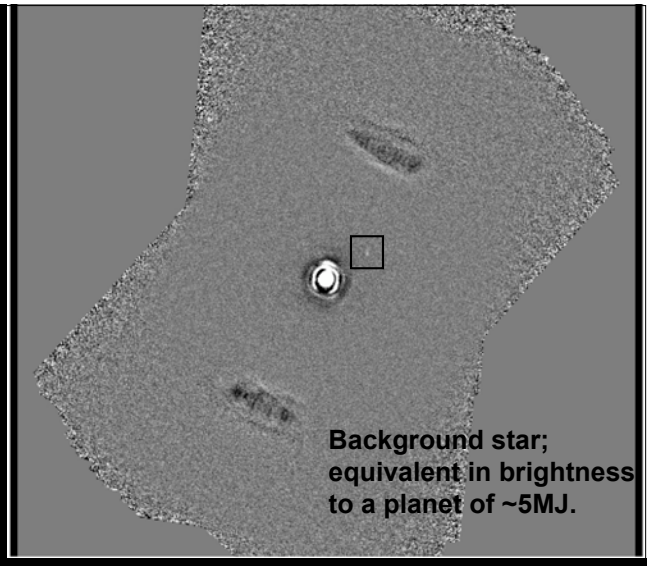
- Do giant planets distributions inferred from RV surveys obtain at larger radii?
- Is there a jump in planet frequency beyond ice line?
- How far out do giant planets form?
- What is the dependence on stellar mass?

>>>Need to complete the work from 3-30 AU.<<<

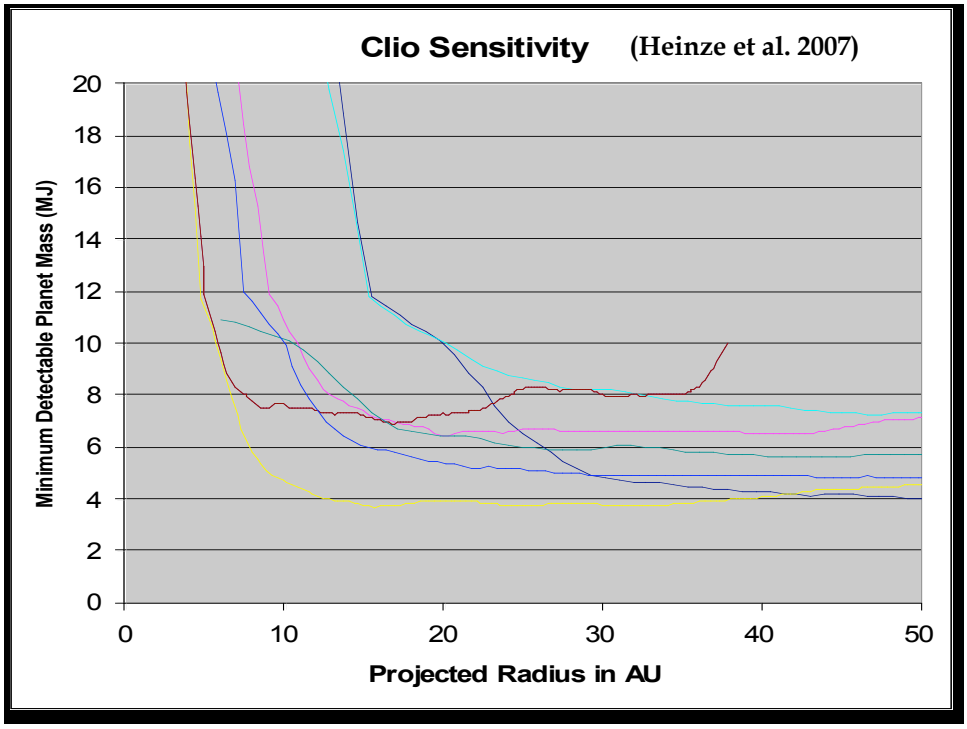
Imaging surveys are complementary to RV, transit, and micro-lensing and we need all to answer the big questions.

Planet Searches with MMT/CLIO

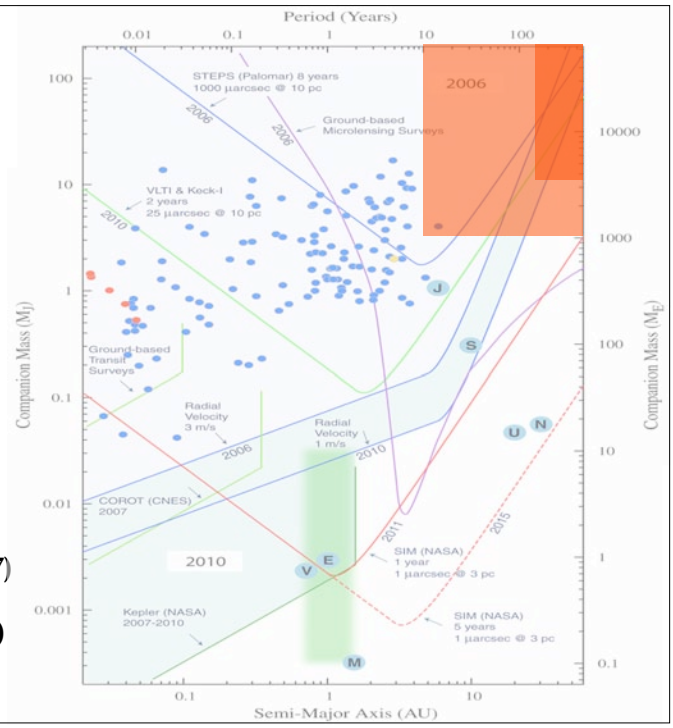
A. Heinze,
P. Hinz (PI),
S. Sivanandam,
M. Kenworthy,
D. Apai,
E. Mamajek,
& M. Meyer



Thermal IR enables the study of mature stars, which are common and thus nearby, providing fine physical resolution, and modest model uncertainties.

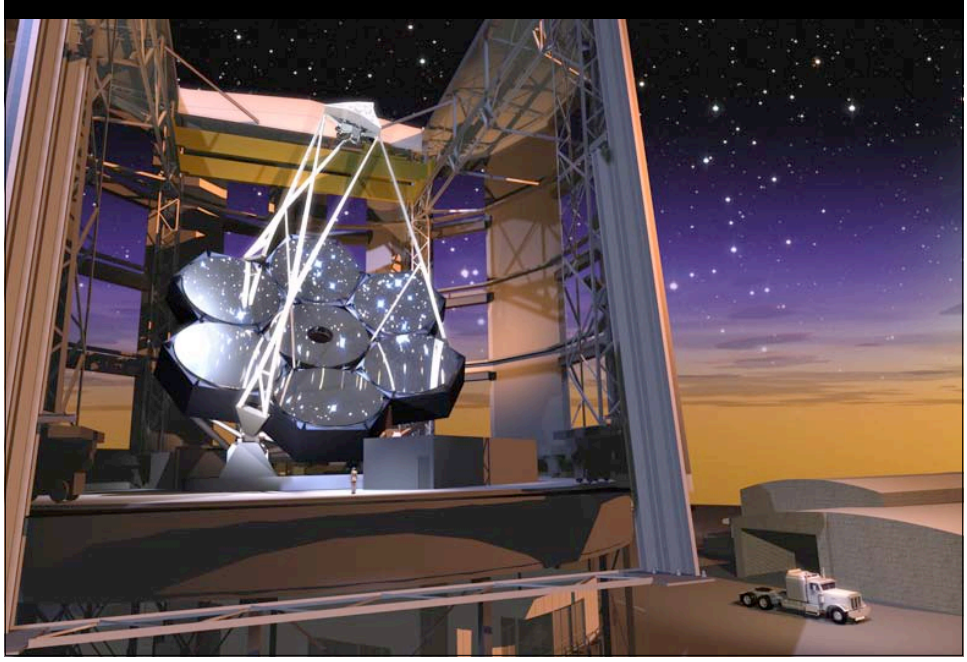


On-going Surveys:

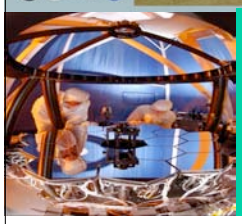


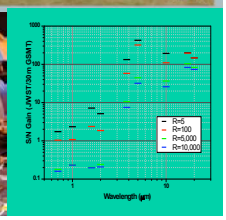
Kasper et al. (2007)
Biller et al. (2007)
Lafreniere et al. (2007)
Heinze et al. (2007)
Lowrance et al. (2005)
And many more…

The Next Big Step: ELTs and JWST



NASA's James Webb Space Telescope (2013)





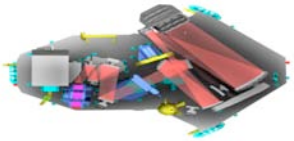
NIRCam

0.6-5 μm imaging.

NIRSpec

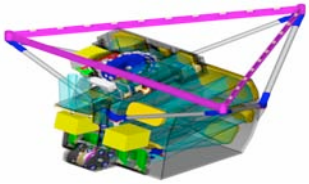
0.5-5 μm

R ~ 100 to 3000 w/ MOS



MIRI

5-29 μm + R~2500 IFU



FGS/TFI

1.5-5.0 μm R~100

- **6.5-m diameter.**
- **Low IR background at L2.**

For more information visit http://www.jwst.nasa.gov (Clampin et al. this meeting)

NIRCam Project at Arizona (PI: M. Rieke) With Lockheed Martin, Rockwell Science.

→ High resolution imaging from 0.6-5.0 μm.

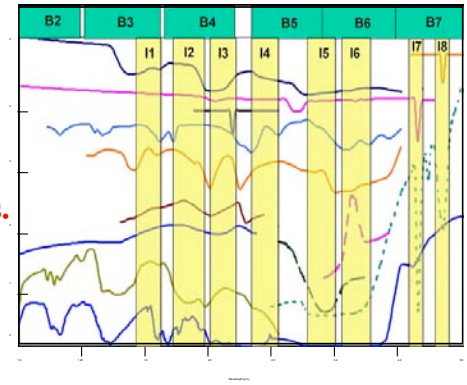
→ Two fields of 2.2'x2.2' in long/short bands simultaneously.

→ 10σ = 14 nJy at 3.6 μm in 3 hrs.

→ Range of filters R = 5/20/100.

→ Coronagraph implemented.

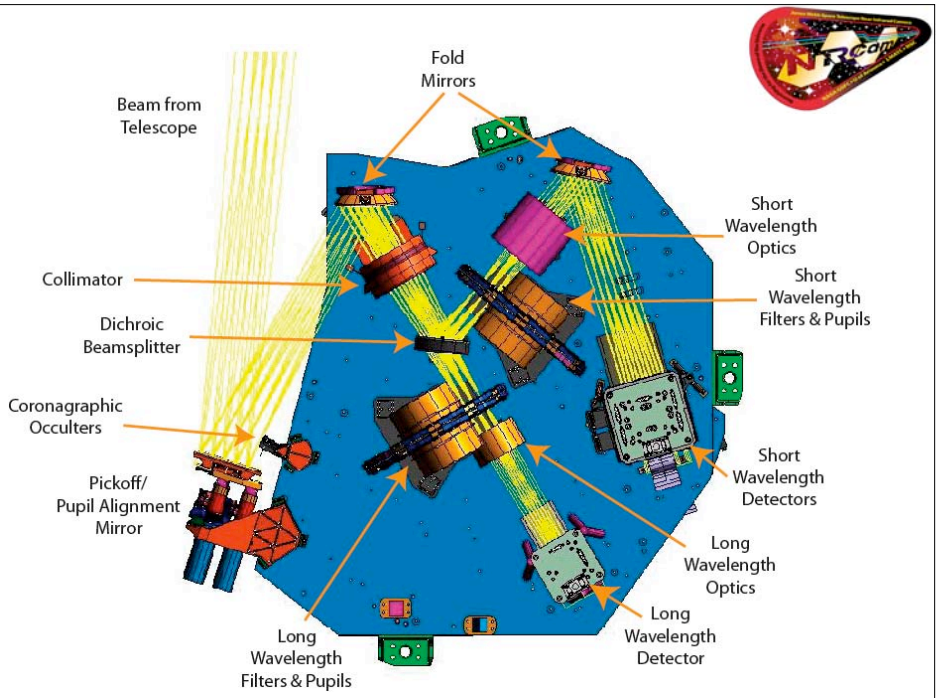
→ Slitless grism possible.



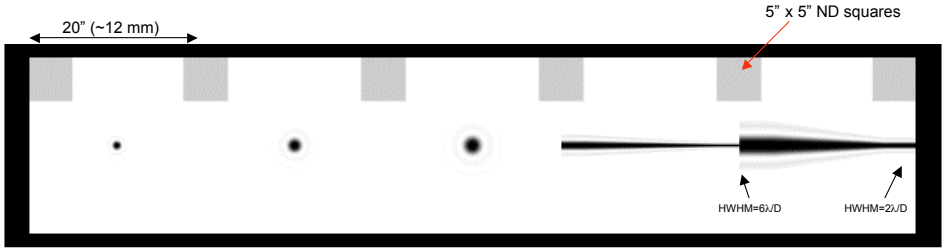
Exoplanet sweet spot?

Lower mass planets at large radii around faint primaries.

For more please visit http://ircamera.as.arizona.edu/nircam



Coronagraphic Slide Layout



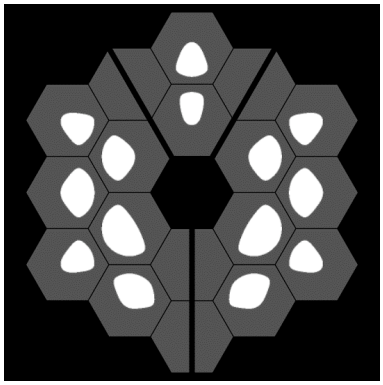
HWHM = 0.40" (6λ/D @ 2.1 μm)	HWHM = 0.64" (6λ/D @ 3.35 μm)	HWHM = 0.82" (6λ/D @ 4.3 μm)	$HWHM_c$ = 0.27" (4λ/D @ 2.1 μm)	$HWHM_c$ = 0.58" (4λ/D @ 4.6 μm)

- Optimized for $\lambda \approx 4.5$ μm imaging
  - » Lyot stops aligned for long wavelength spots and wedges.
  - » Pupil shifts relative to Lyot stops occur at shorter wavelengths. (Fang Shi et al.)

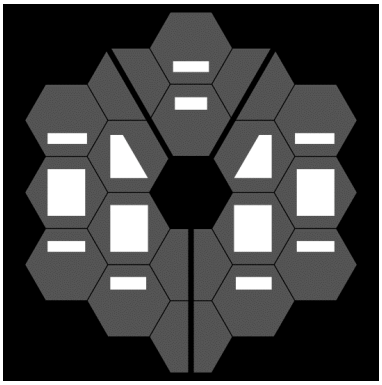
Initial spot/wedge definitions by Joe Green (JPL).

Lyot Stops

Mask clear regions (white) superposed on JWST pupil (grey)



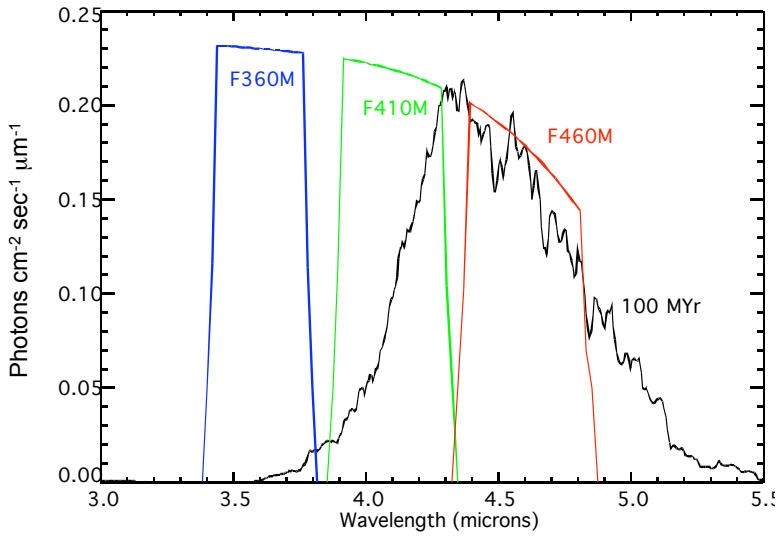
Lyot stop for
6λ/D spot occulters



Lyot stop for
4λ/D wedge occulters

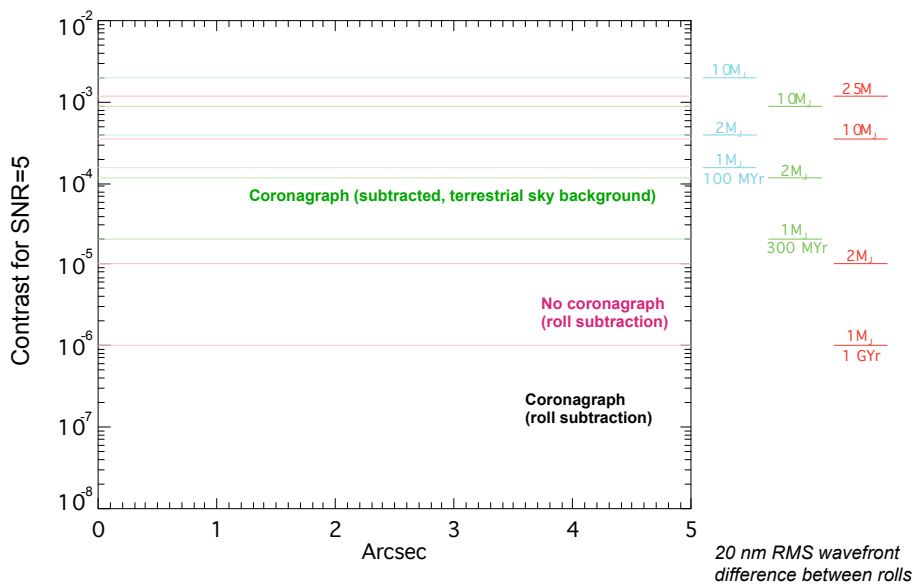
Throughput is ~19%. (cf. Green et al. 2005)

100 Myr-Old, 2 M_{Jup} Planet



Spectrum from Burrows, Sudarsky, & Lunine (2003); cf. Marley et al. (2006)

M0V Star at 4 pc (F460M)



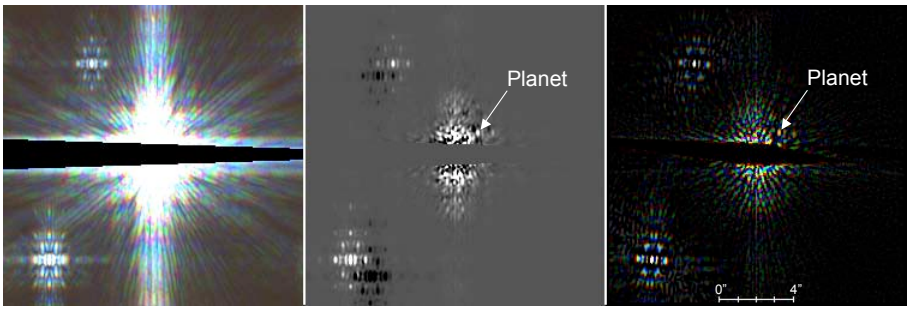
20 nm RMS wavefront difference between rolls

Planet Observations

Multi-filter
Combined, Unsubtracted

F460M
Orient 1 – Orient 2 (10º)

Multi-filter
Combined, Subtracted



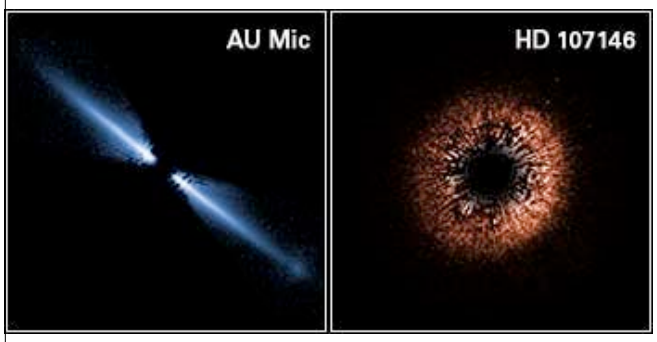
Red = F460M
Green = F410M
Blue = F360M

1 Gyr-old M0V star @ 4 pc
2 M_{Jup} planet @ 7 AU
5000 sec / filter / orientation

The "Perfect" NIRCam Planet Search

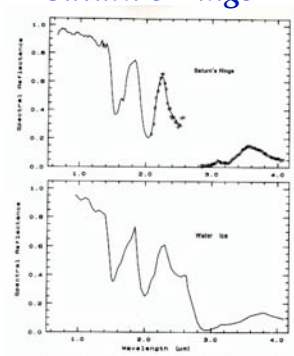
- Design program that cannot be done with ground-based ELT.
  - » **NIRCam "BLIP" is 5-6 mags deeper than ELT from 3-5 μm.**
  - » **Suppose contrast limit of < 10^{-6} at 1 arcsec (Δ [4.6] < 15 mags).**
  - » **Require contrast limit 1.5 mags fainter than ELT "BLIP".**
  - » ***Primary targets must be [4.6] > 6 mags!***
- Program I: Volume-limited survey of late-type stars.
  - » **Targets M3 or later type (< 0.2 Msun) within 6 pc.**
  - » **Defines companion mass ratio distribution to BD limit.**
  - » ***Sensitive to < 0.5 Mjup from 1-6 AU for 1 Gyr old systems.***
- Program II: Young Sun-like Stars.
  - » **Targets G2 dwarfs (or later) at 30 pc (or farther).**
  - » **Sensitive to << 0.5 Mjup at > 30 AU for 100 Myr old systems.**
  - » ***Could see objects x100 smaller if x10 hotter (failed embryos).***
- The Good, the Bad, and the Ugly:
  - » **ELTs will detect (bigger) planets at x4 smaller radii.**
  - » **We don't have decent (any?) evolutionary models << 1 Mjup!**
  - » ***Could apodized phase plates lead to smaller IWA?***

Disks in Scattered Light



(Krist et al. 2005) (Ardila et al. 2005`

Saturn's Rings



Water Ice

Discern disk structure, dust particle size, and composition from multi-color/narrow-band imagery (cf. Debes et al. 2007).

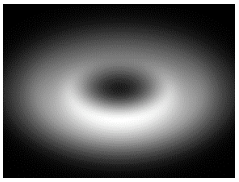
Complementary to TFI capabilities.
Lower surface brightness and finer angular resolution than HST.

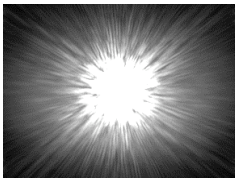
F200W Disk Imaging

A0V star @ 100 pc, r=0.4" spot occulter

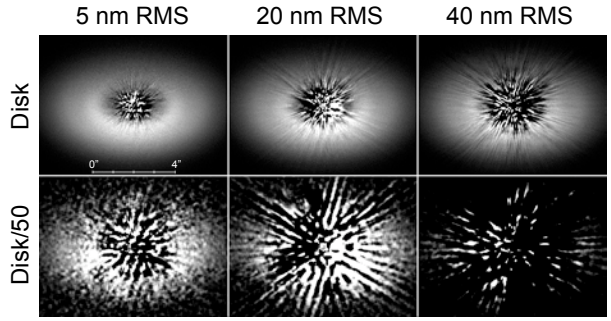
After subtraction of a similarly imaged A1V reference PSF star with the given amount of wavefront error change

Disk Model





Disk Model + Coronagraph

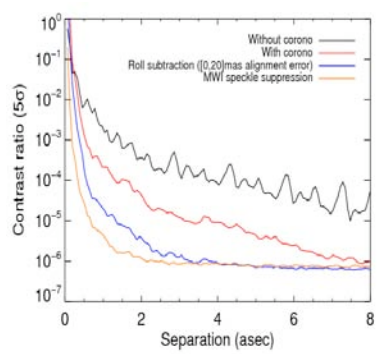


Disk is ~3x Beta Pic optical depth

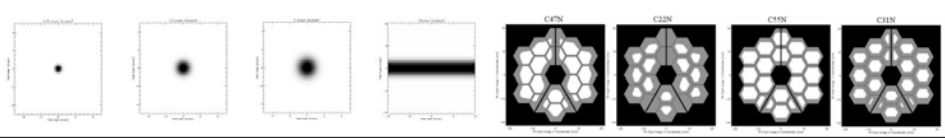
Chromatic effects from pupil wedge not included

FGS/TFI Project (J. Huchings & R. Doyon, PIs) U. Montreal, NRC-CNRC, and Com Dev

- →1.5-2.6, 3.1-5.0 μm
- →8 Blocking filters
- →R ~70-150
- →20"x20" field of view.
- →3 circular Gaussian spots (FWHM=0.75,1.5, 2.0")
- →1 linear Gauss (FWHM=3")
- →4 Lyot masks T = 22-55%

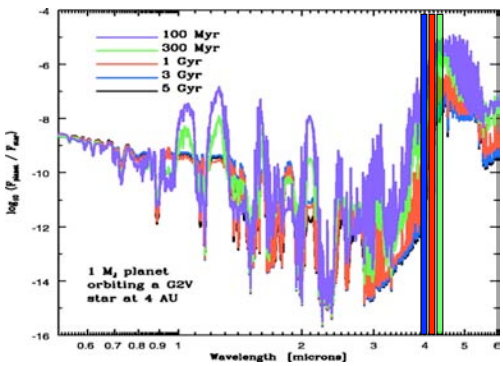


Contrast ratio vs. angular separation. Contrast is defined as the standard deviation of the intensity of the PSF halo integrated over one airy disk divided by the corresponding signal centered on the unocculted PSF, after taking into account the Lyot mask efficiency and transmission profile of the occulting mask.

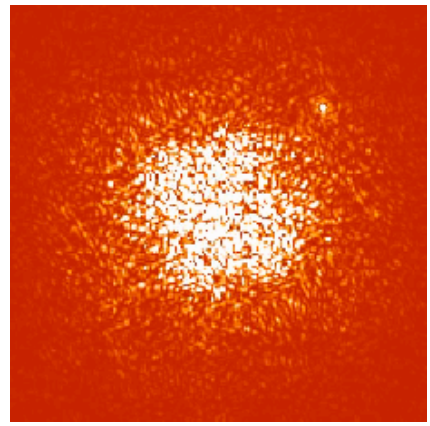


Speckle suppression with multi-λ imaging

Observations at several λ (3-4 TF settings) can be used *judiciously* to suppress the speckle pattern.



Monochromatic PSF movie from 4 to 5 μm



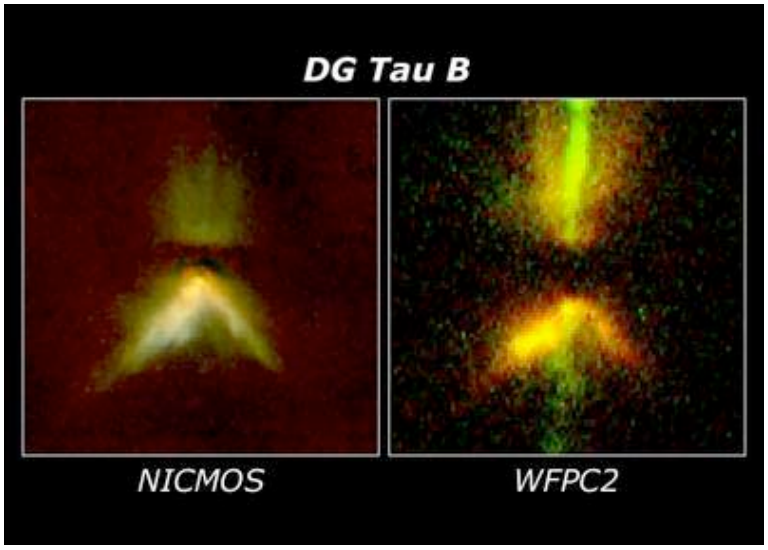
FGS/TFI Exoplanet Discovery Space

Sp	M_m	0.01 Gyrs			0.10 Gyrs			1 Gyrs			5 Gyrs		
		1 M_J	5 M_J	10 M_J	1 M_J	5 M_J	10 M_J	1 M_J	5 M_J	10 M_J	1 M_J	5 M_J	10 M_J
A0	0.78	-5.09	-4.16	-3.78	-5.96	-4.94	-4.47	-7.67	-5.83	-5.33	-8.87	-6.95	-5.97
F0	2.27	-4.49	-3.56	-3.18	-5.37	-4.35	-3.88	-7.07	-5.24	-4.74	-8.27	-6.36	-5.38
G2	3.58	-3.97	-3.04	-2.66	-4.84	-3.82	-3.35	-6.55	-4.71	-4.21	-7.75	-5.83	-4.85
K0	4.29	-3.68	-2.76	-2.38	-4.56	-3.54	-3.07	-6.26	-4.43	-3.93	-7.46	-5.55	-4.59
K5	4.69	-3.52	-2.60	-2.22	-4.40	-3.38	-2.91	-6.10	-4.27	-3.77	-7.30	-5.39	-4.41
M0	5.15	-3.34	-2.41	-2.03	-4.22	-3.20	-2.72	-5.92	-4.08	-3.58	-7.12	-5.20	-4.22
M5	7.98	-2.21	-1.28	-0.9	-3.08	-2.06	-1.59	-4.79	-2.95	-2.45	-5.99	-4.07	-3.09
L0	10.15	-1.34	-0.41	-0.03	-2.22	-1.20	-0.72	-3.92	-2.08	-1.58	-5.12	-3.22	-2.22
L5	10.98	-1.01	-0.08	0.30	-1.88	-0.86	-0.39	-3.59	-1.75	-1.25	-4.79	-2.88	-1.89
T0	11.40	-0.84	0.09	0.48	-1.72	-0.70	-0.22	-3.42	-1.58	-1.08	-4.62	-2.70	-1.72
T5	12.38	-0.45	0.48	0.86	-1.33	-0.31	0.16	-3.03	-1.20	-0.70	-4.23	-2.31	-1.34

Contrast exceeds the 10σ sensitivity beyond 1". [2]
Contrast exceeds the 10σ sensitivity beyond 5". [2]
Contrast exceeds the 10σ sensitivity beyond 1" *without* coronagraph and no PSF calibration.

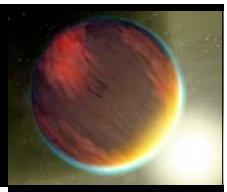
*Log*10 of planet/star contrast at 4.6 μm

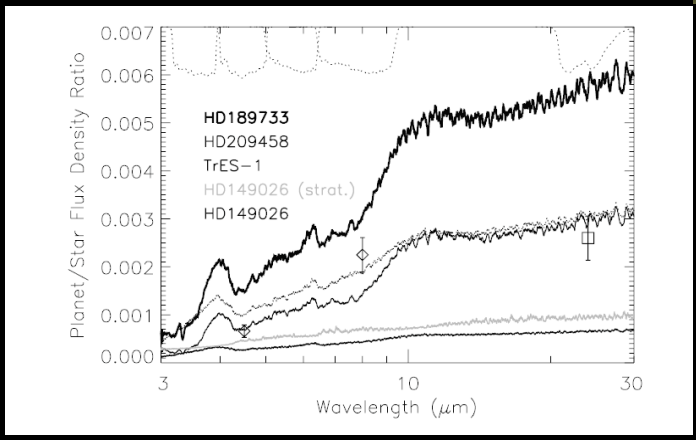
Narrow-band Imaging: Jets from young stars



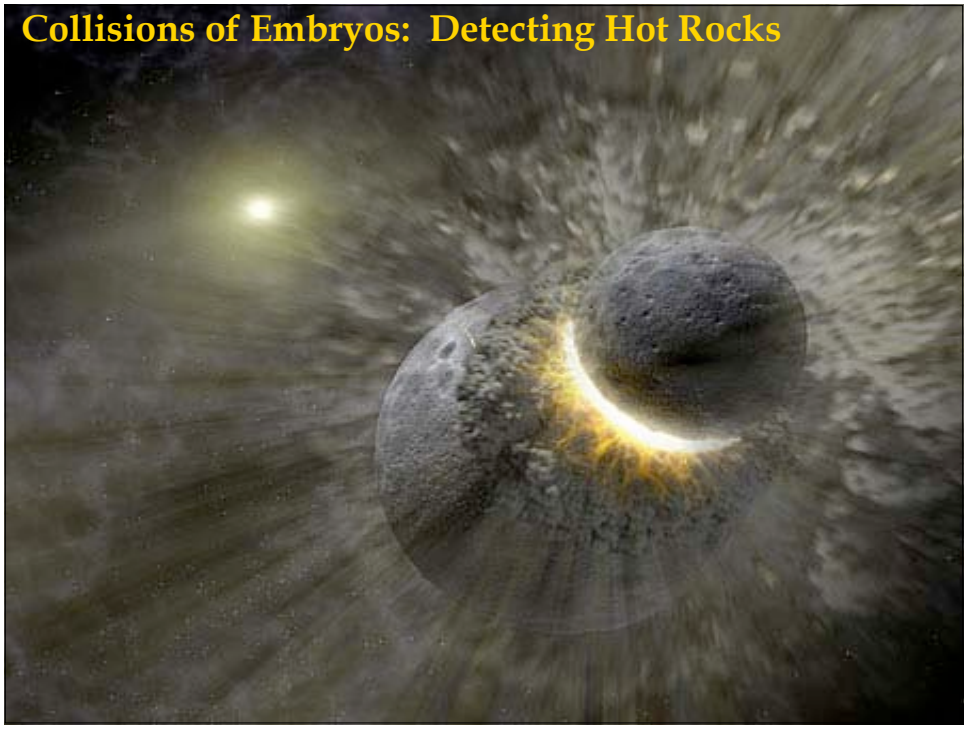
Study jets close to the star in variety of ionized atomic lines And molecular shock tracers at R = 100.

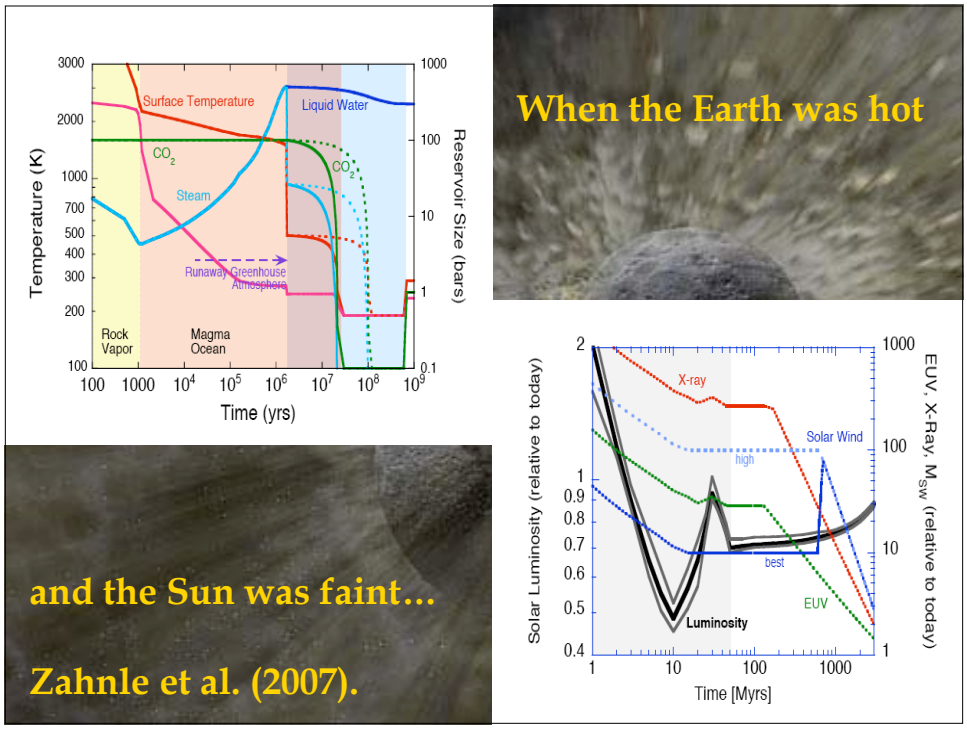
"High Contrast" Transit Spectroscopy With NIRCam Slitless Grism/TFI



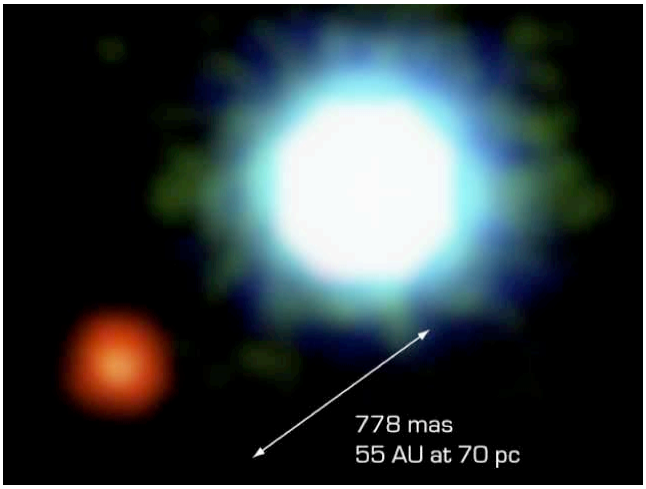


Spitzer photometry of a number of transiting systems (diamonds, TrES-1; square, HD 209458b) compared with theoretical models. Fortney et al 2006 (ApJ, 642, 295)


Collisions of Embryos: Detecting Hot Rocks


Surface Temperature
Liquid Water
CO_2
Steam
Runaway Greenhouse Atmosphere
Rock Vapor
Magma Ocean
Temperature (K)
Reservoir Size (bars)
Time (yrs)
When the Earth was hot
and the Sun was faint…
Zahnle et al. (2007).
X-ray
Solar Wind
high
best
EUV
Luminosity
Solar Luminosity (relative to today)
EUV, X-Ray, M_{SW} (relative to today)
Time [Myrs]

More Discovery Space (for free)…



Grey extinction….
Or a hot Neptune?

Composition and Surface gravity could decide.

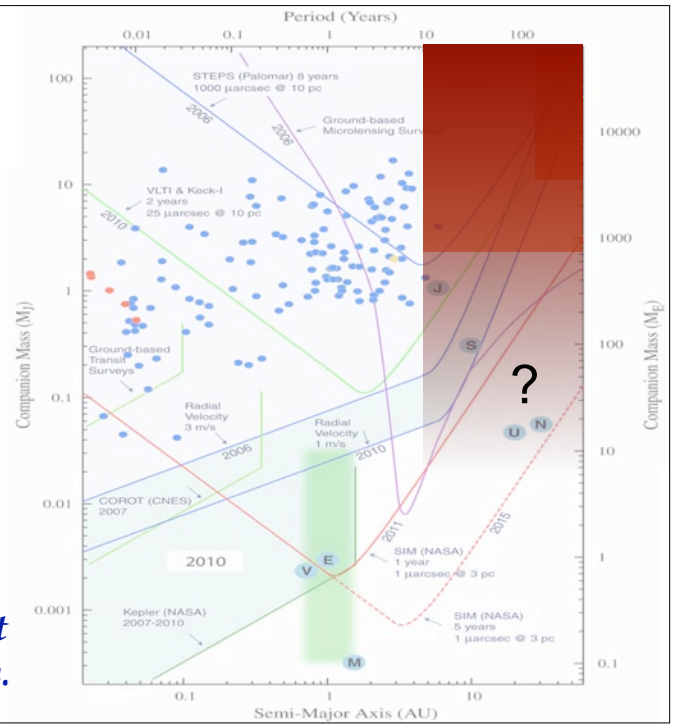
Need better spectra!

(Chauvin et al. 2004; Schneider et al. 2005; Mohanty et al. 2007)

The Design Reference Mission

- NIRCam volume-limited survey for planets around nearby old stars.
  - » **< 0.5 Mjup at 1-6 AU around 0.2 Msun stars.**
  - » **Unique advantage in thermal IR – avoid the contrast limit!**
- NIRCam survey for very low mass planets around nearby young stars.
  - » **<< 0.5 Mjup > 30 AU around 1.0 Msun stars.**
  - » **Will also detect hot embryos in collision.**
- Exploit unique capabilities of TFI.
  - » **Follow-up spectra for log(g), Teff, composition (e.g. Eps Eri).**
  - » **Deep searches for sample of known EGPs (long-term RV trends).**
- NIRCam/TFI Imaging Survey of Disks
  - » **Both primordial and debris disk targets.**
  - » **Multi-color imagery to discern structure and composition.**
  - » **Narrow-band imaging of jets from young stellar objects.**
- Transit Surveys with NIRCam
  - » **Slitless grism differential spectra.**
  - » **Can provide R = 400 spectra from 2.5-5.0 microns.**

NIRCam/TFI "Sweet Spot"



Detect very low mass planets at large radii about the nearest stars.