Future Opportunities In Exo-Planet Research: Transits and Light Curves From Space

“Transit Experiments are the worst form of exoplanet measurements.
Except for all the others which are so much worse.”

---With apologies to Winston Churchill

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With Contributions from John Krist, Tom Greene, Marcia Rieke

Subtracting Two Big Numbers Is Easier in Space

- ☺ Straightforward technology
  - ☺ Compared with angular planet-star separation (TPF-C, TPF-I/Darwin)
- ☺ Sensitivity and stability
  - ☺*Stable* PSF (No seeing)
  - ☺*Stable* environment, esp. non-LEO
  - ☺Low, *stable* sky background
  - ☺Continuous, broad λ coverage
  - ☺Sensitive IR operation
- ☺ Continuous, long- term coverage
  - ☹ Orbital, spacecraft, TAC constraints

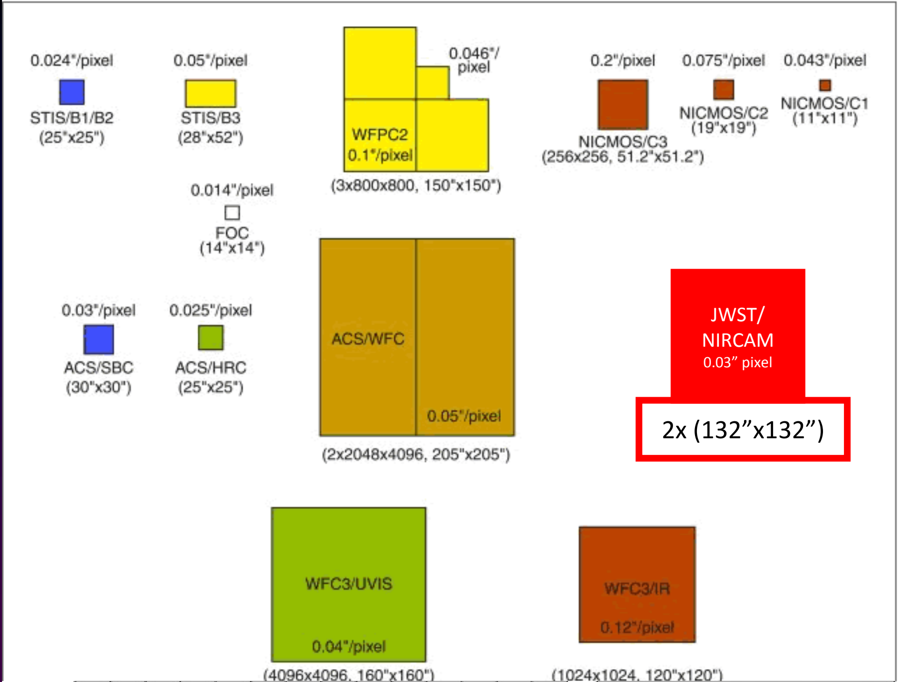
- ☹ Ultra-precision photometry is hard anywhere!
  - ☺ Moon-, earthshine, etc
  - ☺ Cosmic rays, other rad effects
- ☹ Limited Telemetry →Postage stamps, not images
- ☹ Long, expensive development

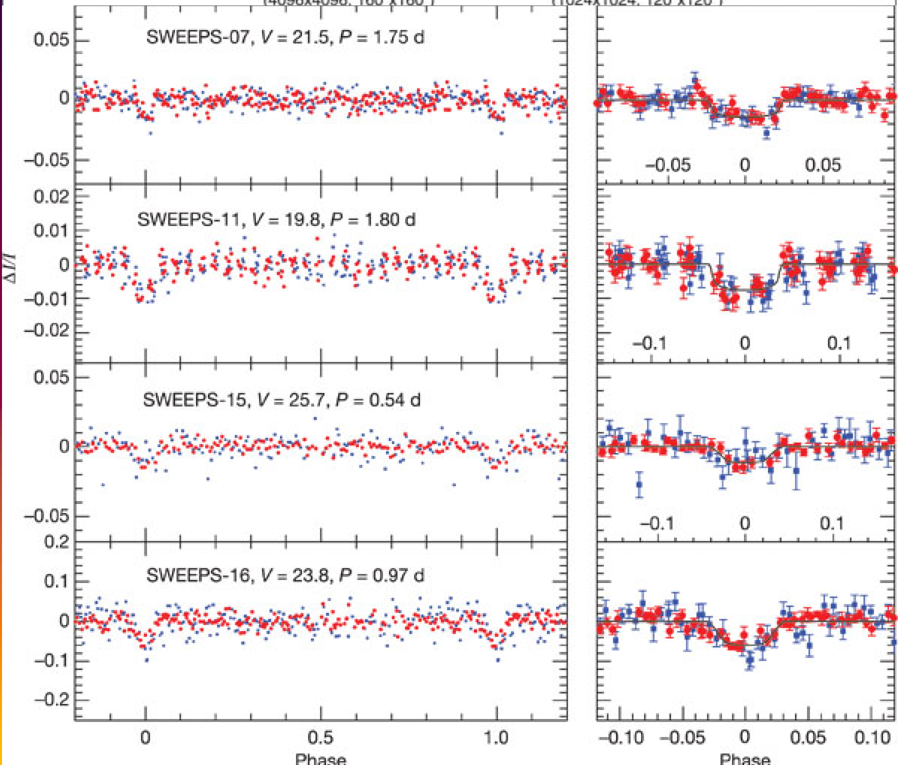
What's Next for Transit and Light Curve Science?

- Surveys for broader range of spectral types & closer stars
- Follow-up observations for detailed characterization

Surveys with Large Space Telescopes

- HST, Spitzer, JWST have *great* sensitivity but *small* fields.
- **Explore distant, peculiar regions**
- HST survey of 1.8×10^5 bulge stars down to 26 mag (Sahu et al 2006)
  - 16 viable candidates (out of 165)
  - Hard to follow-up but 45% estimated to be planets based on light curves.
  - 2 with RV limits consistent with 4-9 M_{Jup}
- NIRCam capable of comparable surveys, e.g. star formation regions
- ***Limited utility compared with small telescopes with large FOV***
  - ***Who wants 20 mag transit candidates?***
  - ***HST, Spitzer, JWST best suited for follow-up than surveys***





Prospects for Future Transit Science

	Sur-vey	Primary Transit Curve	Secondary Transit Curve	Full Orbital Light Curve	Primary Transit Spectroscopy	Secondary Transit Spectroscopy
Spitzer Cold		IRAC	IRAC/MIPS	IRAC/MIPS	IRS	IRS
HST (+SM4)		STIS?			NICMOS, COS	
MOST		Limits to albedos for few stars				
EPOCH						
Upcoming Missions						
Kepler			Albedo for ~1000 giants			
JWST						
Missions Under Consideration						
Spitzer Warm						
PLATO			Albedo for giants			
TESS (All Sky)	Vis					
ASTrO (All Sky)	IR					
Tracer						
Other Characterization Missions: GAIA & SIM, then (sometime) TPI-C,TPF-I/Darwin						

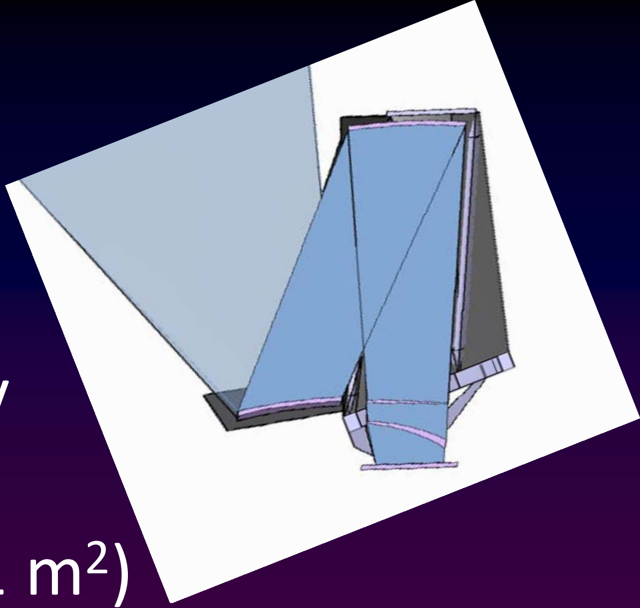
Why Wide Angle Surveys?

- Validation (RV) and characterization need LOTS OF PHOTONS.
- Rare alignments (β~1%) → hosts distant: $D \sim 15\,(40{,}000/\beta\Omega)^{1/3}$ pc
  - 450 pc (Δ=7.5 mag) for 100 sq. deg. (Kepler)
  - 250 pc (Δ=6.1 mag) for 550 sq. deg. (PLATO)
  - 75 pc (Δ=3.4 mag) for 20,000 sq. deg. (Ground, ASTrO, Tess)
- Many small cameras to monitor 10^5-10^6 brightest, closest stars
- Variants: Near-IR for M stars, space for small planets (1/5× radius)

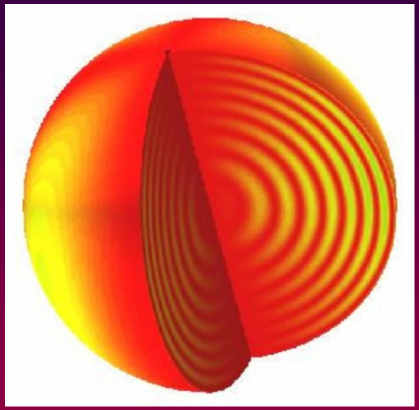
Transit Survey Missions (Ongoing, Planned, Possible)

Survey Property	Ground Based	1st Generation		2nd Generation		
		CoRoT	Kepler	PLATO	TESS	ASTrO
Ω (sq. deg.)	10^2~10^4	54	100	550	40,000	>26,000
λ	Vis	Vis	Vis	Vis	Vis	near-IR
# Stars	10^3-10^5	**10^5**	**10^5**	10^5	2.5×10^6	2×10^6
Brightness (mag)	6-15	11-15	10-14	8-14	4-13.5	4-13.5 (J)
Precision (ppm)	2,000	50	25,1h, V=11	25, 1h, V=11	77,1hr I=9	50-100, 1hr, J=9

PLATO --- Extended Area Survey



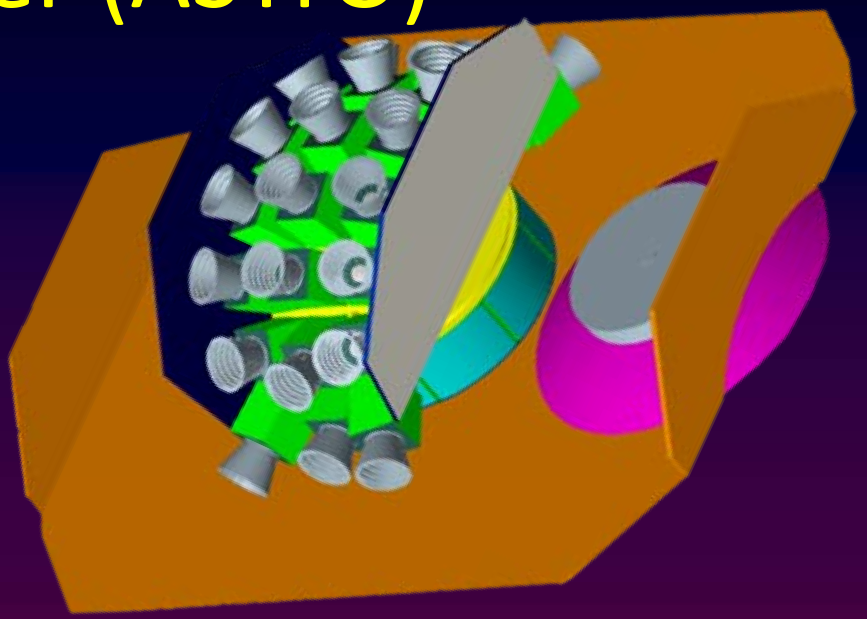
- ESA Cosmic Vision Mission presently approved for Phase A assessment
- 28 (sci.)+2 (tracker) telescopes (0.01 m^2)
  - –550 sq. deg. (x2) with *4k×4k* 12.5” pixels
  - –Continuous monitoring with <5-7% gaps
- 25 ppm/hour for V~11 mag
  - –*SNR>37,000 for 75,000 dwarfs V< 12 mag*
  - –*SNR> 12,500 for 500,000 dwarfs V< 14 mag*
- Roughly 4x as many stars as Kepler to same SNR, but 1~2 mag brighter
- Transit and light curve science as well as asteroseismology of host star



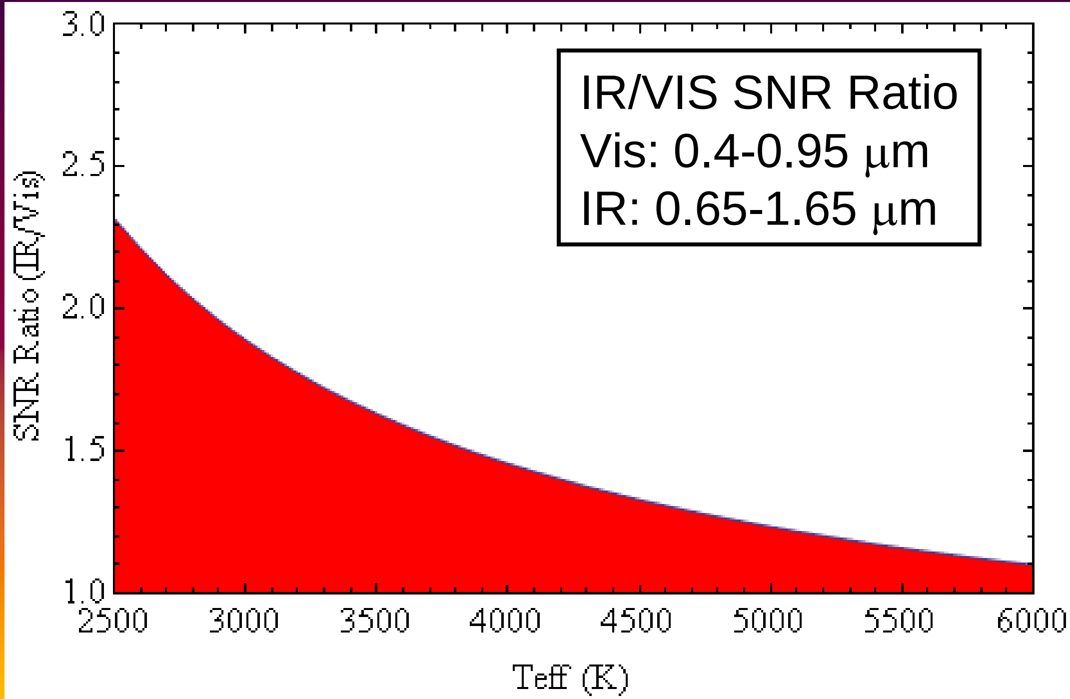
TESS ---Visible All-Sky Survey

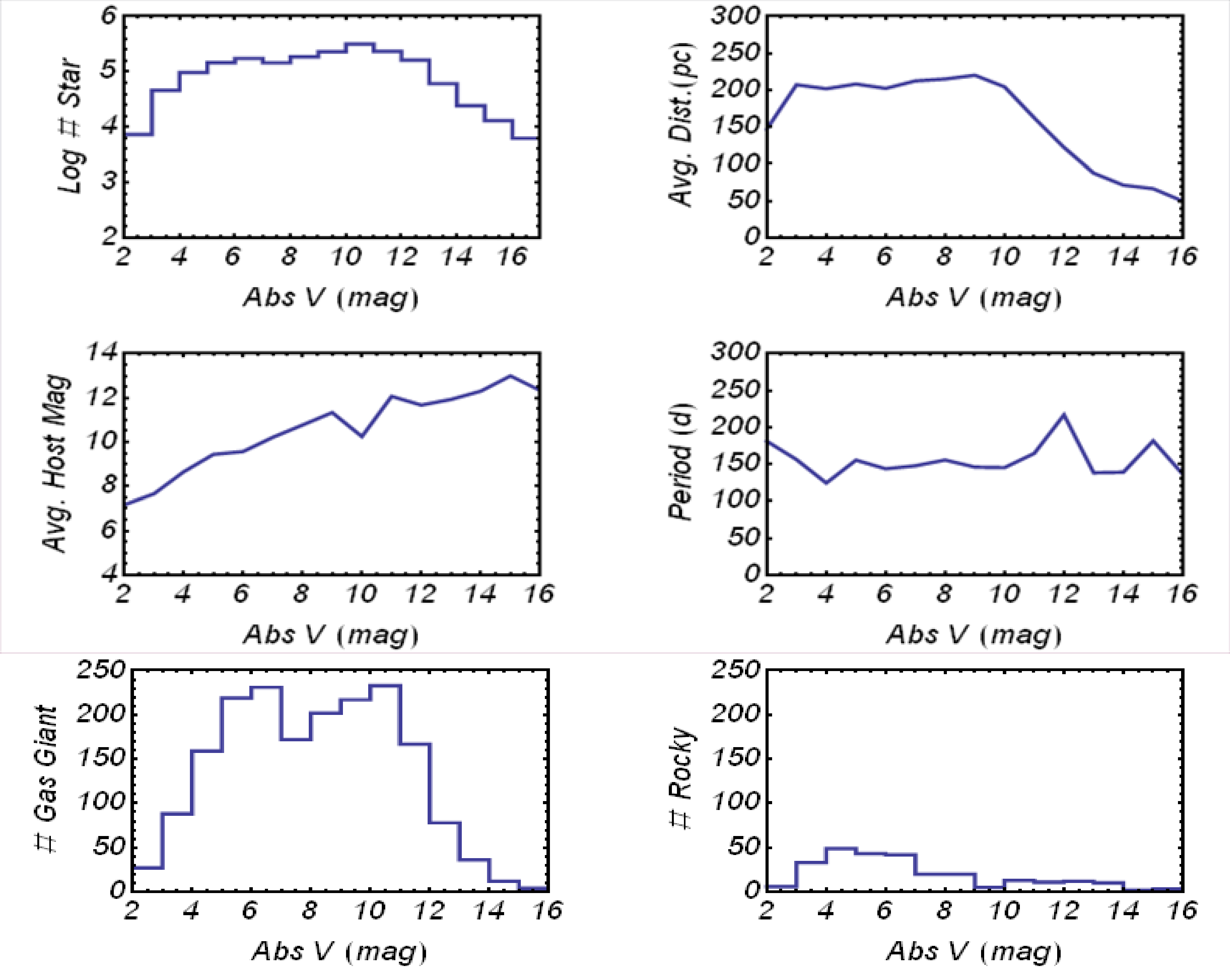
- ***SMEX mission now in Phase A !!!***
- Talk to follow
- Good luck!

All Sky Transit Observer (ASTrO)
Near IR All Sky Survey



- Discovery/Probe Class
- 24x0.1 m cameras
  - 96 2kx2k HgCdTe arrays
  - 0.6-1.6 μm
- L2 orbit for stability
- Improved SNR for K,M stars in NIR vs. Vis
  - Trade SNR (x2), #planets (x3) vs. cost
- Monitor >60% (100%) of sky ~ 2×10^6 stars
- Continuous dadence: for 60d-365d





Planet yield d<100-150 pc: 300 Rocky; 2000, Gas/Icy

Follow-up Opportunities:
Why Bright Stars Are Important!

Follow-up with JWST

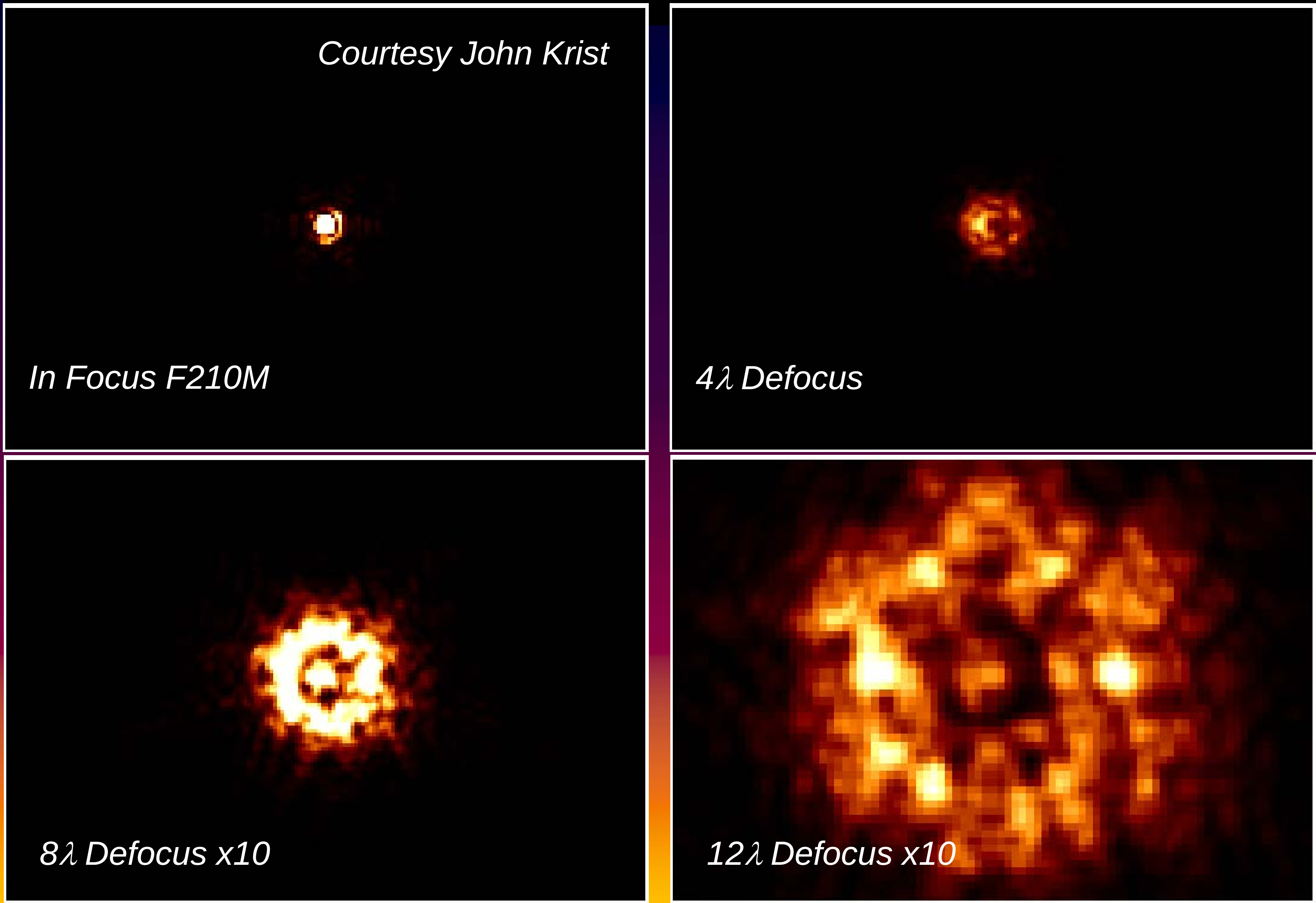
	Validate	Primary Light Curve	Secondary Light Curve	1-2.4 μm Spectra	2.4-5 μm spectra	5-20 μm spectra
NIRCAM						
NIRSPEC						
MIRI						

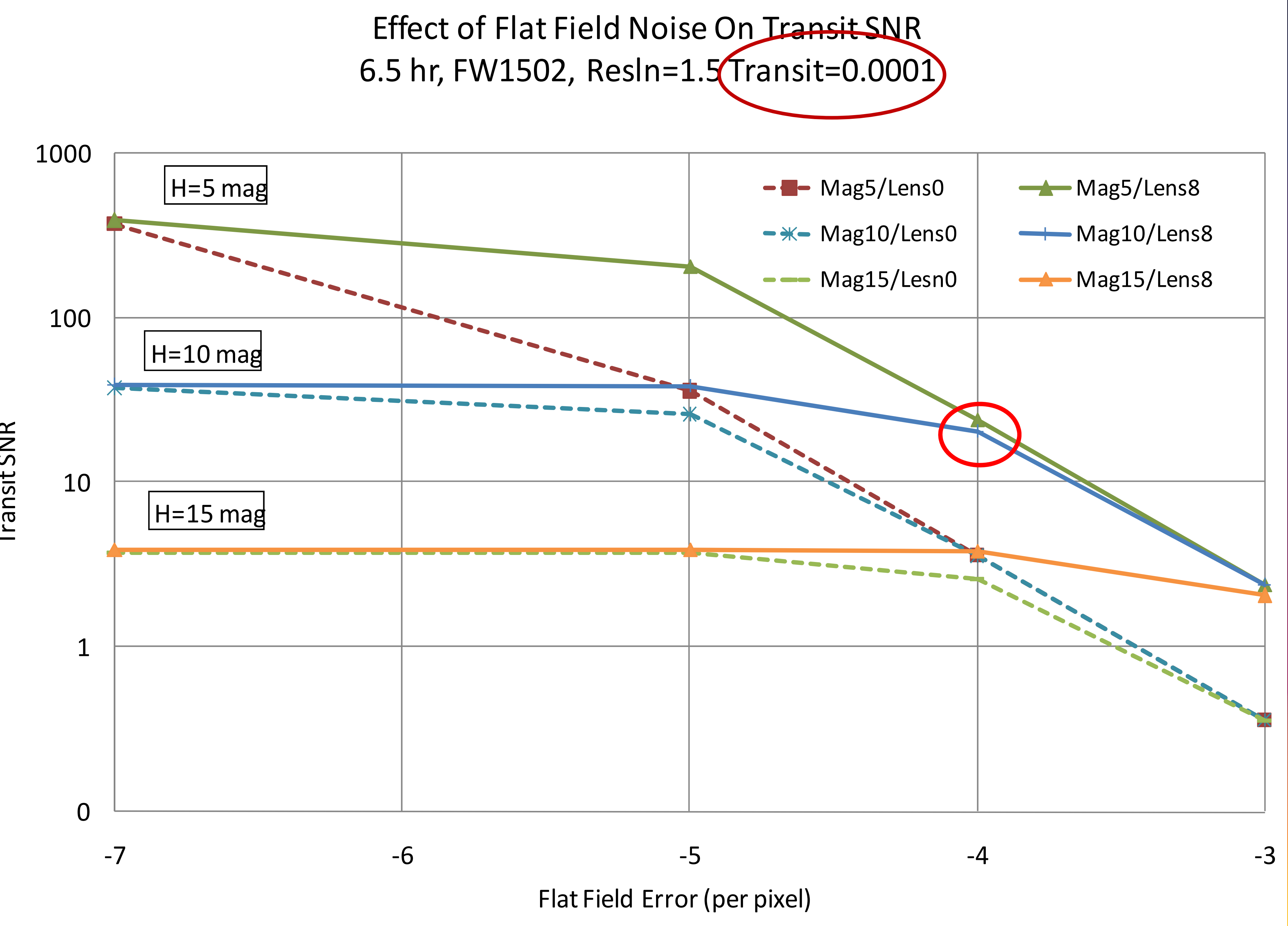
See JWST White paper s by Clampin et al (2007), Seager (2008)

NIRCam Opportunities

- Validate transits with high angular resolution imaging
  - Use stable PSF (coronagraph?) to look 20 mag eclipsing binary next to 10-15 mag Kepler/CoRoT sources
- Primary and secondary transit or Hot Jupiter light curves with high precision using defocused images (1-2.4 μm) and *slitless* grisms (2.4-5.0 μm).
  - Short and long-lam data obtained simultaneously
  - Spectroscopy at R~ 500-2,000 at 2.5-5.0 μm where exoplanets have important spectral features.
- NIRCam may be preferable, or at least highly competitive, with NIRSPEC for many transit observations
  - Immunity to initial pointing and subsequent drifts
  - High photon efficiency and stability due to *no slit losses*
  - Simultaneous long and short lam observations
  - Monitor pointing and some drifts using other arm of NIRCam

NIRCAM F212N w. Weak Lenses




Effect of Flat Field Noise On Transit SNR
6.5 hr, FW1502, Resln=1.5 Transit=0.0001
1000
100
10
1
0
Transit SNR
H=5 mag
H=10 mag
H=15 mag
Mag5/Lens0
Mag10/Lens0
Mag15/Lesn0
Mag5/Lens8
Mag10/Lens8
Mag15/Lens8
-7
-6
-5
-4
-3
Flat Field Error (per pixel)

Long-λ GRISM Spectroscopy

- Grism for JWST segment capture provides R=2,000 spectra
  - Spectra improve saturation limit and reduce flat field error
  - No slit losses → immune to pointing drifts
- Average over few 10^3 pixels for precision mapping
- Average over few 10^2 pixels for R~50-100 spectra

- High S/N R=500 spectra of a Jupiter around M2-3V star
- Secondary transits of Hot Earths around M5V stars

Filter	$\lambda 1$	$\lambda 2$	# pixels	# pixels/2048
F277W	2.42	3.12	696	0.34
F322W2	2.42	4.03	1600	0.78
F356W	3.12	4.01	885	0.43
F410M	3.90	4.31	408	0.20
F444W	3.89	5.00	1104	0.54

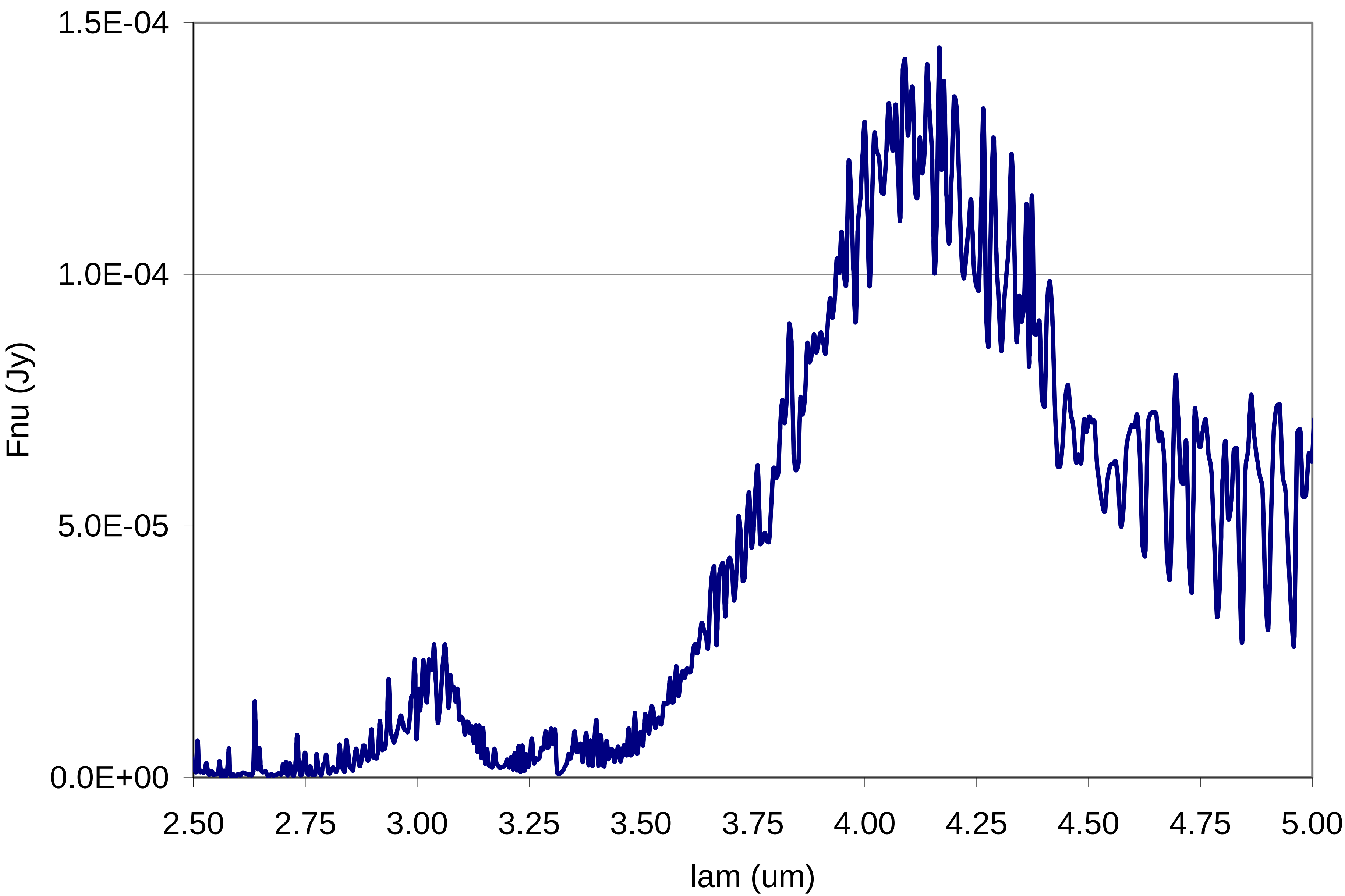
SNR for Primary Transit of M3 V Star. R = 500; τ= 1,000 sec; T_{planet} = 1500K

Jupiter	*M (mag)*			*Earth*	*M (mag)*	
Flat/mag	5	10	15	*Flat/mag*	5	10
1.0E-06	355.97	35.60	3.56	1.0E-06	2.96	0.30
1.0E-05	353.32	35.60	3.56	1.0E-05	2.94	0.30
1.0E-04	224.16	35.33	3.56	1.0E-04	1.85	0.29
1.0E-03	28.76	22.42	3.53	1.0E-03	0.24	0.19

SNR for Secondary Eclipse of M3 V Star. R = 500; τ= 1,000 sec; T_{planet} = 1500K

Jupiter	*M (mag)*			*Earth*	*M (mag)*	
Flat/mag	5	10	15	*Flat/mag*	5	10
1.0E-06	88.45	8.85	0.88	1.0E-06	0.75	0.07
1.0E-05	87.77	8.84	0.88	1.0E-05	0.74	0.07
1.0E-04	55.28	8.78	0.88	1.0E-04	0.47	0.07
1.0E-03	7.06	5.53	0.88	1.0E-03	0.06	0.05

Jupiter at 0.2 AU from G2 Star (Burrows et al)



What is Brightest Star Can NIRCam Observe

- F212N + 12λ lens yields 1 $\times 10^5$ elec (~full well) in 0.25 sec (160x160 pixels) in brightest pixel for **K=1 mag star**. For precision light curve (SNR=34 on Earth transit in 6.5 hr)
- Grism (R=1500) yields 1×10^5 elec (~full well) in 0.16s (1024x16 pixels with 10 pixel spot) for **[4.6] = 3 mag star** (G2V star at ~7 pc)

Subarray Size (Pixels)	Exposure Time(sec)	Rate (sec)	Brightest in focus Source (K mag)	Brightest defocused Source (K mag)	Size Short-λ (arc sec)	Size Long-λ (arc sec)
16x16	.00256	.00768	5.3	N/A	0.5	1.0
48x48	.023	.069	7.6	N/A	1.5	3.1
96x96	.092	.28	9.2	3.8	3.0	6.2
160x160	.256	.77	10.3	3.4	5.1	10.4
320x320	1.02	3.1	11.8	N/A	10.1	20.8
640x640	4.1	12.2	13.3	N/A	20.3	41.6
1024x16	0.16	0.48	3.3	N/A	N/A	Grism spec.
Full Frame*	10.6	31.8	14.3	N/A	135*	135

MIRI Observations of Transits

---Greene, Rieke

- MIRI images with filters for temperature determination
- Disperse w. slitless prism for R~100 spectra (5 – 14 μm)
- Hot Jupiters (spectra) & Hot Super-Earths (photometry)
- Warm (HZ) Super-earths around M stars (no spectra)

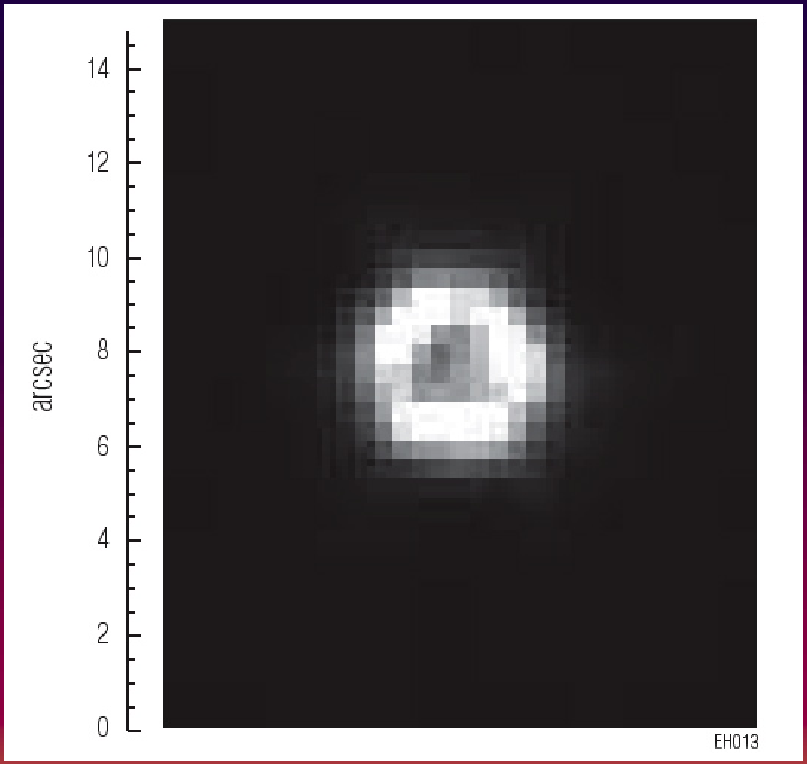
Exoplanets 0.1 AU from a G2 V star at 15 pc distance			
Planet	**10 μm R=5**	**21 μm R=4**	**LRS (10** μm R=30)
1 R_{Jup} Itime (hr) S/N=30	0.1 hr	0.1 hr	1 hr
1 R_{Jup} contrast	8.0E-04	1.5E-03	8.0E-04
2 R_{Earth} Itime (hr) S/N=5	3 hr	4 hr	19 hr
2 R_{Earth} contrast	2.7E-05	5.0E-05	2.7E-05
Exoplanets 0.05 AU from a M5 V star at 10 pc distance			
1 R_{Jup} Itime (hr) S/N=30	4.6 hr	0.4 hr	36 hr
1 R_{Jup} contrast	3.0E-04	2.0E-03	3.0E-04
2 R_{Earth} Itime (hr) S/N=5	118	11	925
2 R_{Earth} contrast	1.0E-05	7.0E-05	1.0E-05

More Mission Concepts:

5 minutes of fame!

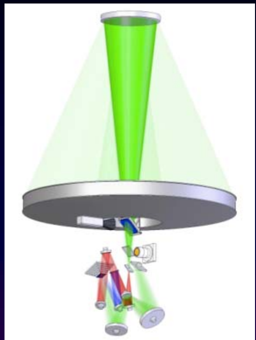
- EPOXI
- TRACER
- BEST
- THESIS
- TESS
- ASTRO
- PLATO
- MOST
- Warm Spitzer
- Hubble
- JWST

EPOCh Transit Observations



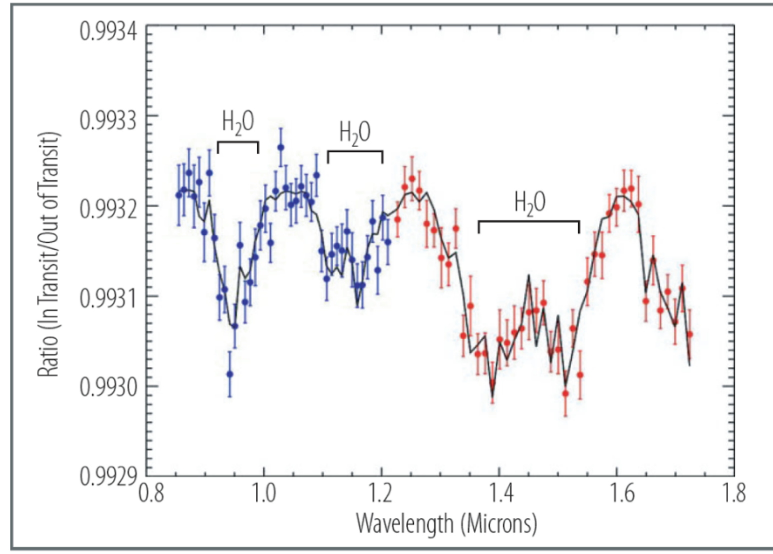
- Deep Impact's 30-cm telescope in 350-950 nm band
  - De-focused image & heliocentric orbit for high precision
- Observations Jan-Aug, 2008
- Giant planet transiting systems
  - Reflected light (secondary transit)
  - Search for rings and moons
  - Search for transits of terrestrial planets - now observing GJ436
  - *Timing search* for planets

Courtesy Deming:
Note EPOCh posters 91, 92
& Christiansen talk!



Tracer ---Transit Characterization Explorer

- SMEX mission not selected this round
- *Characterize Atmospheric Properties*
  - Physical conditions, chemistry, dynamics and cloud properties
- *Determine Physical Structure*
  - Precision light curves for robust radii, detection of rings and/or satellites
- *Detect Unseen Planets*
  - Terrestrial planets in transit or by via perturbations of transit timings



TRACER can measure a spectrum of GJ436b, a hot Neptune, with 10 transits. The water bands are readily detected (1σ error bars)

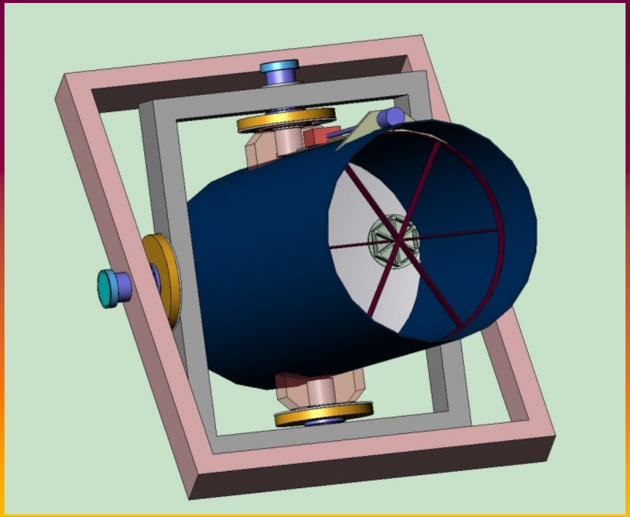
Mark Clampin (PI) NASA/GSFC

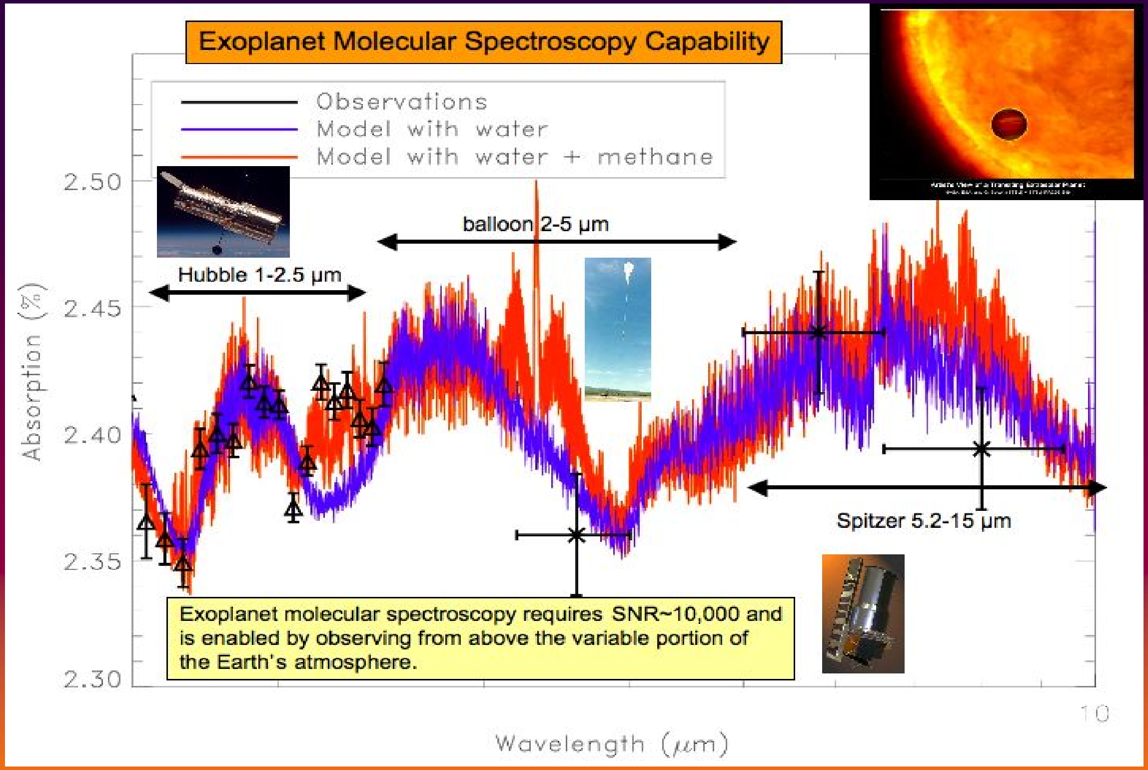
David Charbonneau (Dep.PI) Harvard	Drake Deming NASA's GSFC
Mark Marley NASA's ARC	Sara Seager MIT
Bruce Woodgate NASA's GSFC	Eric Agol Univ . Washington
Randy Kimble NASA's GSFC	Chuck Bowers NASA's GSFC

TRACER uses a 0.6 meter telescope with R~ 50 two channel spectrograph (0.8-1.7 μm)

The Balloon-borne Exoplanet Spectroscopy Telescope (BEST)

- *Using molecules as probes of conditions, composition, and chemistry*
- Great Observatory class exoplanet science
- 70 cm telescope
- 2 - 5 µm
- R~500 spectroscopy
- Fills the spectroscopy gap
- Prebiotic and carbon chemistry
- H_20, CH_4, CO, CO_2, NH_4 …





Mark Swain, Gautam Vasisht, Pin Chen, Drake Deming & Phillip Ward

THESIS: the Terrestrial and Habitable-zone Exoplanet Spectroscopy Infrared Spacecraft

using molecules as probes of conditions, composition, and chemistry

- A purpose built, dedicated exoplanet mission
- No new technology
- Simple & optimized for stability
- ~1.5 m telescope
- 2 - 15 μm
- R~500 spectroscopy
- Detailed FPA characterization
- High-precision pointing
- Optimized for detection of molecules
- 10^5:1 dynamic range possible on bright targets
- Long-term calibrated stability
  - Non-transiting exoplanet spectroscopy
  - Day & night characterization of M dwarf HZ planets
  - Full orbit spectroscopic light curve
  - Long-term weather monitoring
- High-precision transit timing

Swain, Vasisht, Akeson, Deming, Grillmair & Burrows

Transit Science Summary and Recommendations

Transit Science Summary

- Era of (giant, hot) planet characterization is here using transits, light curves + RV
  - Mass, radius, albedo, density, atmospheric composition and temperature structure
- Push to smaller, cooler planets
  - M stars with survey of 10^4-10^5 stars (Earths in HZ!)
  - All sky survey to find targets around bright stars
- Recommendations for future transit observations
  - Warm Spitzer for photometric follow-up
  - Long duration Kepler/CoRoT missions + follow-up
  - Tess (All Sky Survey)
  - High priority for JWST follow-up at all wavelengths
  - Dedicated probe scale missions for spectroscopic characterization