Future Exoplanet Missions For Exoplanet Study

With a strong focus on those that rely on time-series measurements

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WHERE DO WE STAND TODAY?

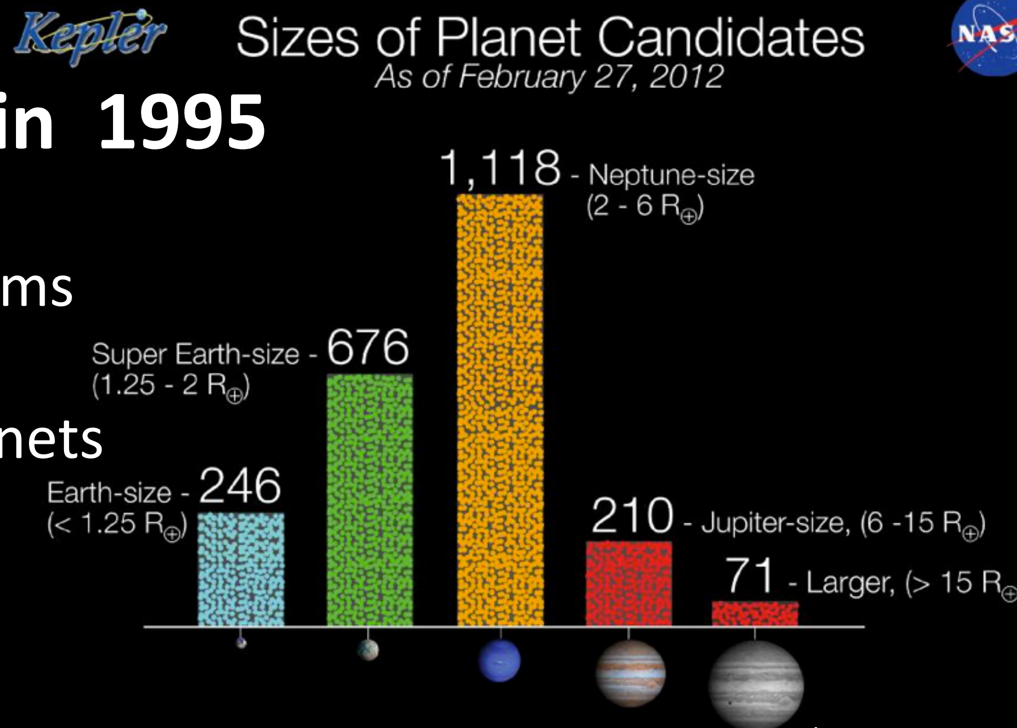
Since first discovery in 1995

763 planets confirmed

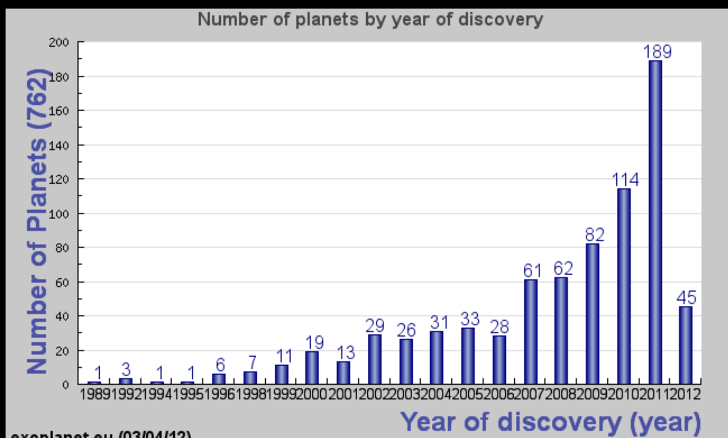
230 confirmed transiting systems

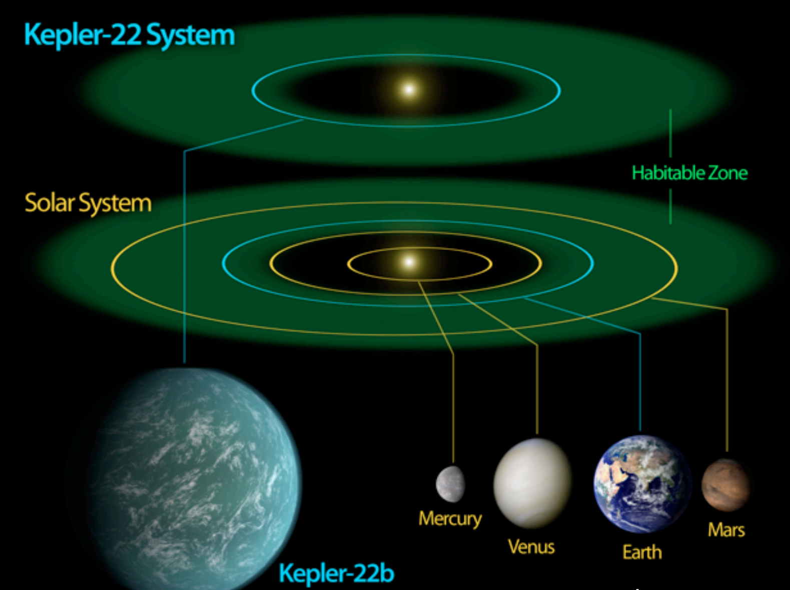
2321 Kepler candidate planets

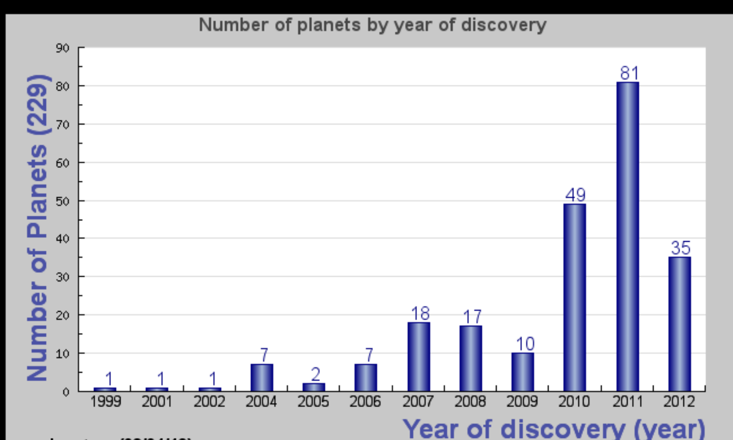
Planet statistics; Habitable planets



Credit: NASA Ames/Wendy Stenzel







Credit: NASA Ames/JPL-Caltech

Pieter Deroo – Government sponsorship acknowledged

Planet Characteristics

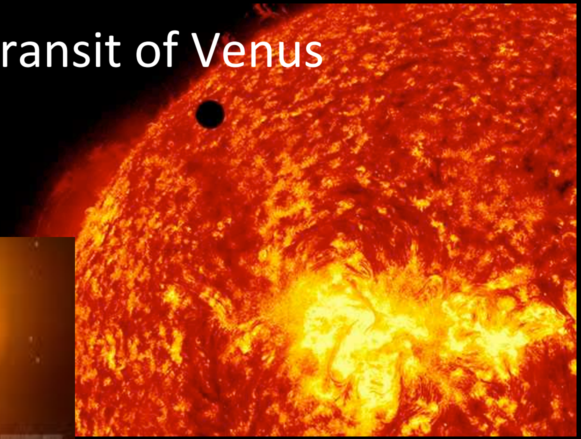
- Broad range of properties
  - Gas Giants (Jupiters/Saturn)
  - Ice Giants (Neptune/Uranus)
  - Rocky Planets (Super Earths
- Incidence of planets rises with smaller size
  - Transits: >15 % of stars, rocky planets (2-4R_{Earth}, P<50 d)
  - Radial Velocity: 25 % of stars, have rocky planets (~2M_{Earth}, P<50 d)
  - Microlensing: all stars have at least 1 planet
- Incidence of Earth analogs (rocky planets in Habitable Zone) ~ 2-10%

Parameter	Smallest	Largest
Mass	2 M_{Earth}	>13 $M_{Jupiter}$
Radius	1.3 R_{Earth}	2.2 $R_{Jupiter}$
Density (water=1)	0.08 (<Styrofoam)	>10 (iron,7; lead,11)
Orbital Dist.	0.014 AU	Few 100s AU
Orbital Period	2 days	Few 100 years
Eccentricity	0	0.97
Temperature	>3000 C	<-150 C

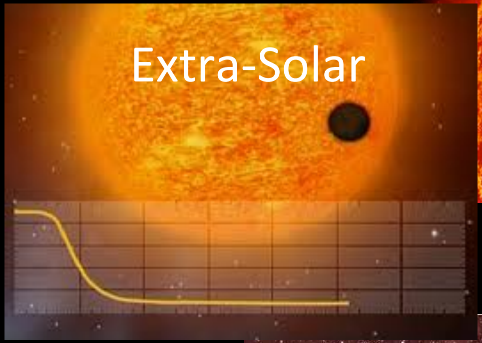
But Are There Any Habitable Planets?

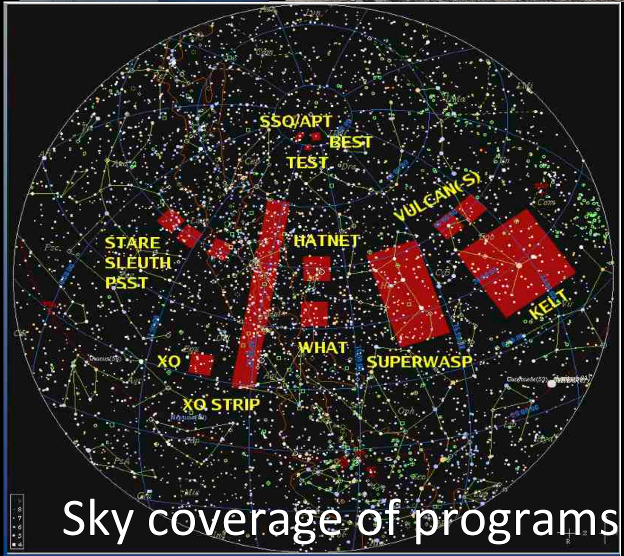
Transiting planets

- 1999: HD 209458b, Charbonneau et al.
- Simple hardware – anyone can join
- Increased speed of discovery!

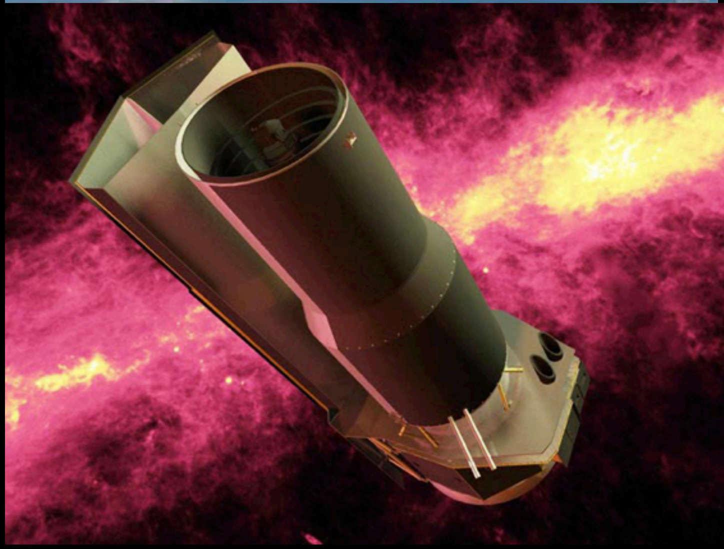


Solar





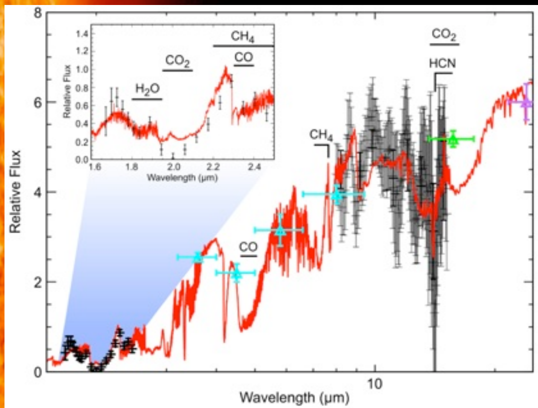
Decade Of Atmosphere Characterization



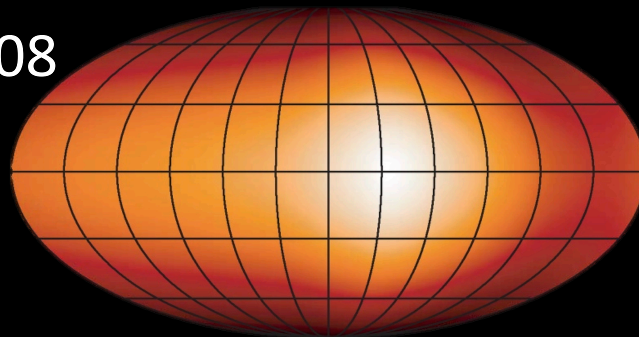
- **2002**: first atmosphere detected (Charbonneau)
- **2003**: hydrogen escape observed (Vidal-Madjar)
- **2005**: first detection of infrared emission (Deming; Charbonneau)
- **2006**: first detection of day & night atmosphere (Harrington)
- **2007**: first emission spectrum of an exoplanet (Richardson; Grillmair)
- **2007**: detection of H_2O in an exoplanet atmosphere (Tinetti)
- **2008**: detection of an atmospheric temperature inversion (Knutson)
- **2008/2009**: detection of H_2O, CH_4 and CO_2 in an exoplanet (Swain)
- **2010**: first ground-based molecular spectroscopy (Swain)
- **2012**: 2D image of an exoplanet dayside (Majeau)

Exoplanet atmosphere characterization is maturing!

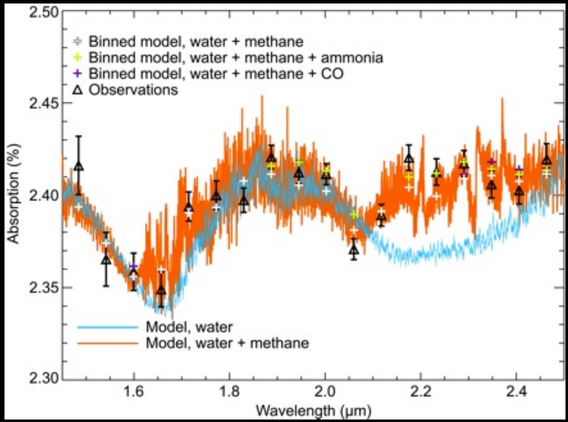
Grillmair et al. 2008
Charbonneau et al. 2008
Swain et al. 2009

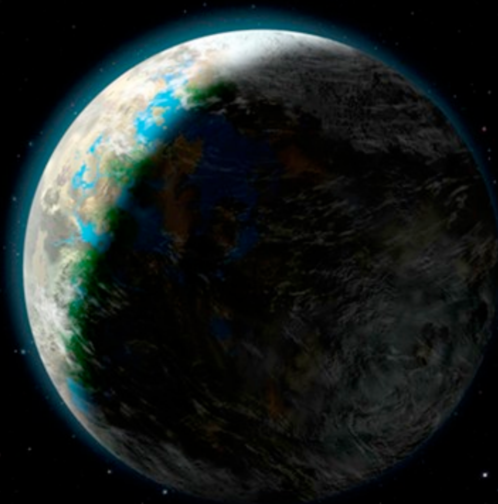


Knutson et al. 2007

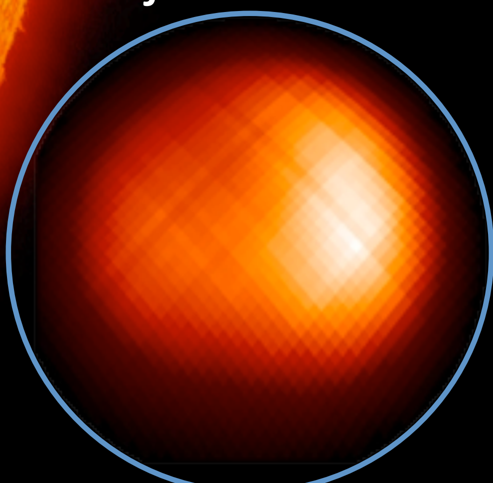


Swain et al. 2008



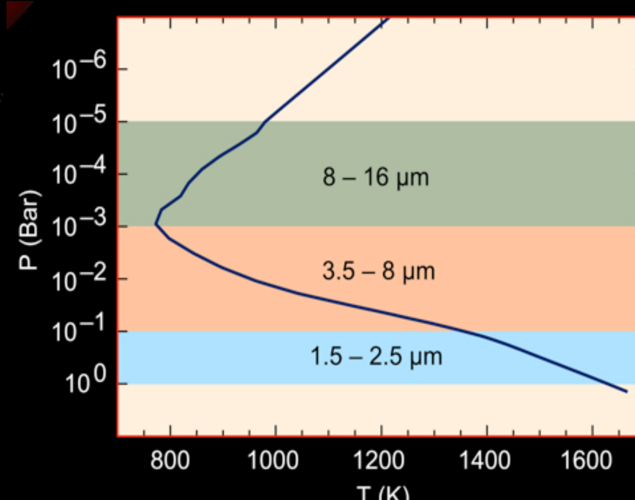


Majeau et al. 2012



done for one target so far

Dayside Temperature Pressure profile



Current State Of Play

Planet finding:

- Planets are everywhere
- Habitable planets are within reach and first examples are being found
- Planet statistics are being completed up to habitable Earths at 1AU
- Multiple methods: ground RV, space & ground transits, ground & space direct imaging, ground based micro-lensing

Planet characterization:

- Decade of discovery and demonstration of techniques
- Detection of H_20, CH_4, CO_2 and CO in few planets.
- Longitudinal atmospheric differences measured
- Progress is driven by time-series analysis
- A few direct imaging spectroscopy demonstrations

Where Do We Want To Go?

Planet finding:

- Complete the census, the family portrait of planetary size, mass & orbits
- Explore beyond the “snow line” to understand planet formation, migration, dynamics
- Start focusing on
  - rocky planets
  - with an atmosphere
  - In the right zone …

Planet characterization:

- Characterize more planets
- Get the statistics, take the family portrait of planet atmospheric conditions and composition
- Start focusing on
  - Rocky planets
  - With an atmosphere
  - In the right zone …

What Missions In Near to Mid-term?

Planet finding:

Funded: Extended Kepler mission

Proposed: WFIRST mission

Proposed: TESS explorer

Ground-based

Multiple RV programs

Multiple transit surveys

Multiple direct imaging programs

Multiple microlensing surveys

Planet Characterization:

Funded: Spitzer Extended Mission and JWST

Proposed: EcHO proposed

Proposed: FINESSE explorer

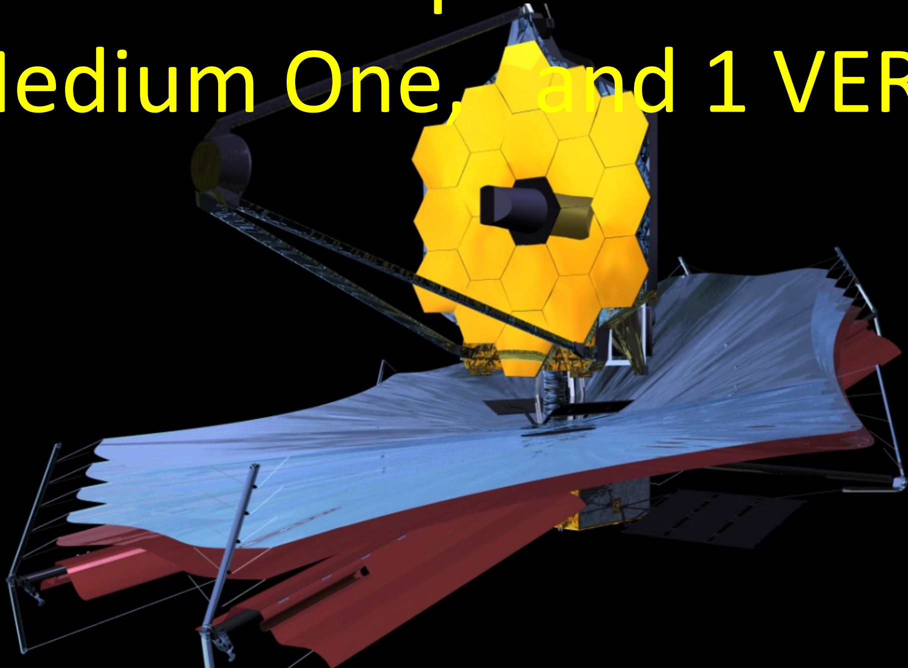
Ground-based

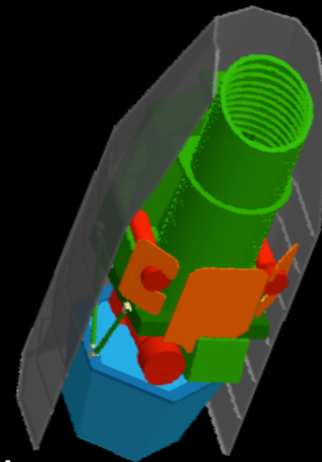
New instruments in developments

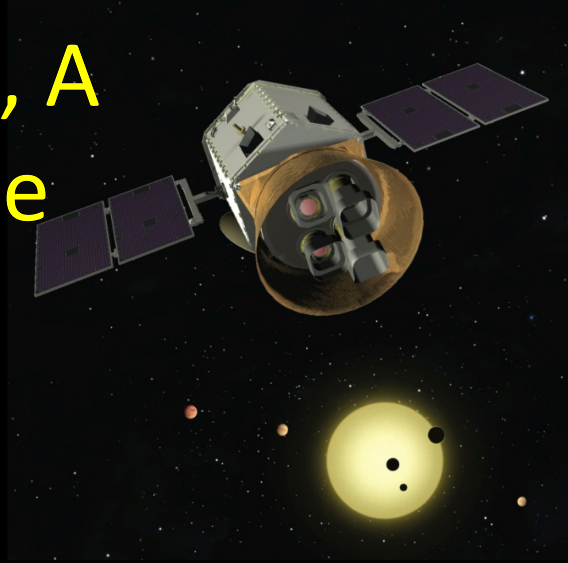
Large and small programs on ground-based telescopes

Very exciting time for exoplanet research

The Next Steps: A Small Telescope, A Medium One, and 1 VERY BIG One







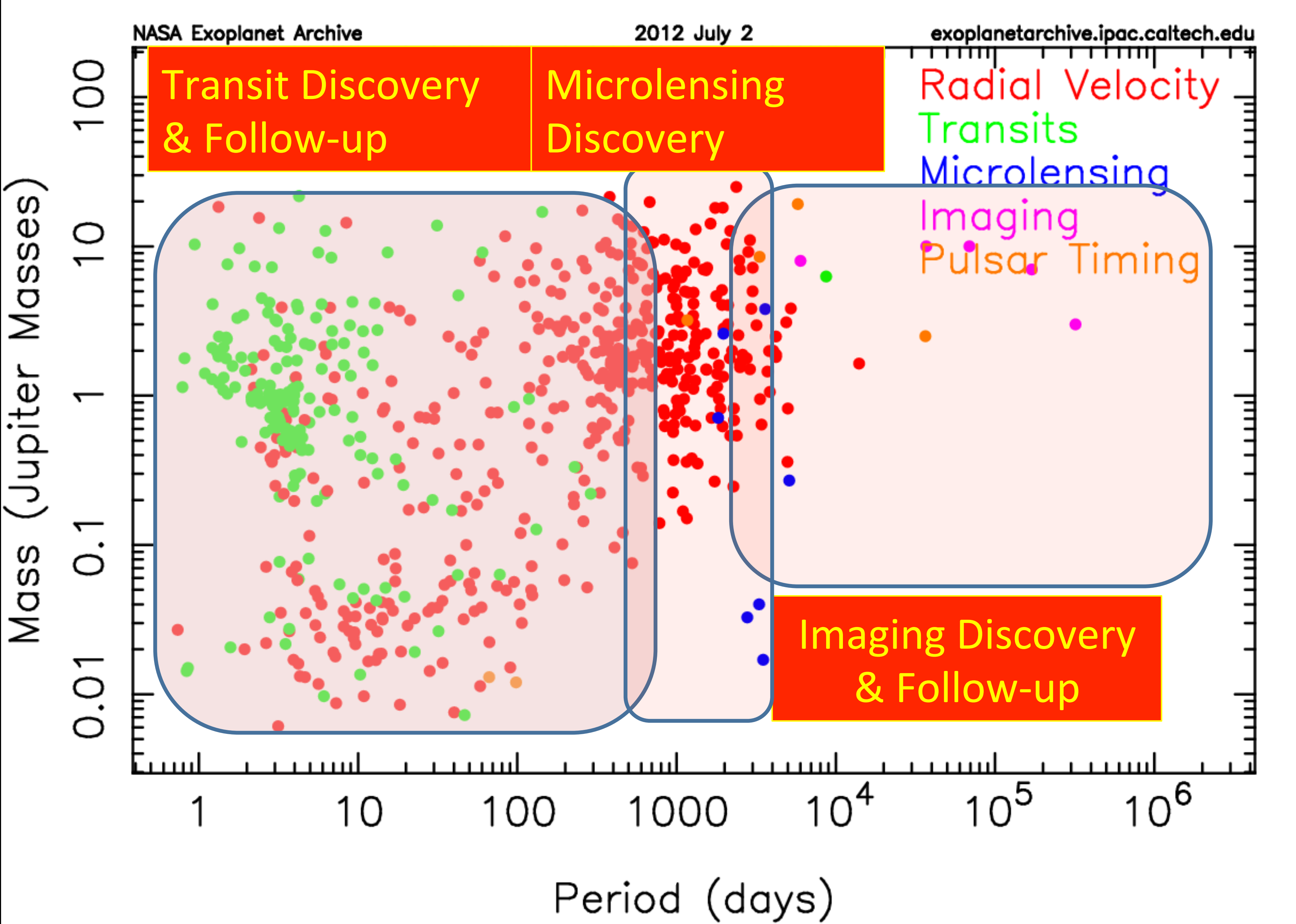
TESS

Not to scale!

FINESSE

- Two small Explorer satellites ($0.2B)
  - All Sky survey for nearby transiting systems
  - 75 cm telescope for atmospheres of known transits
- James Webb Space Telescope ($10B)
  - Direct imaging to find young (hot) planets
  - Transit spectroscopy to characterize Jupiters to Super Earths
- WFIRST for microlensing survey to explore beyond the snow line (~$1-2 B)

Exploring ExoPlanet Phase Space

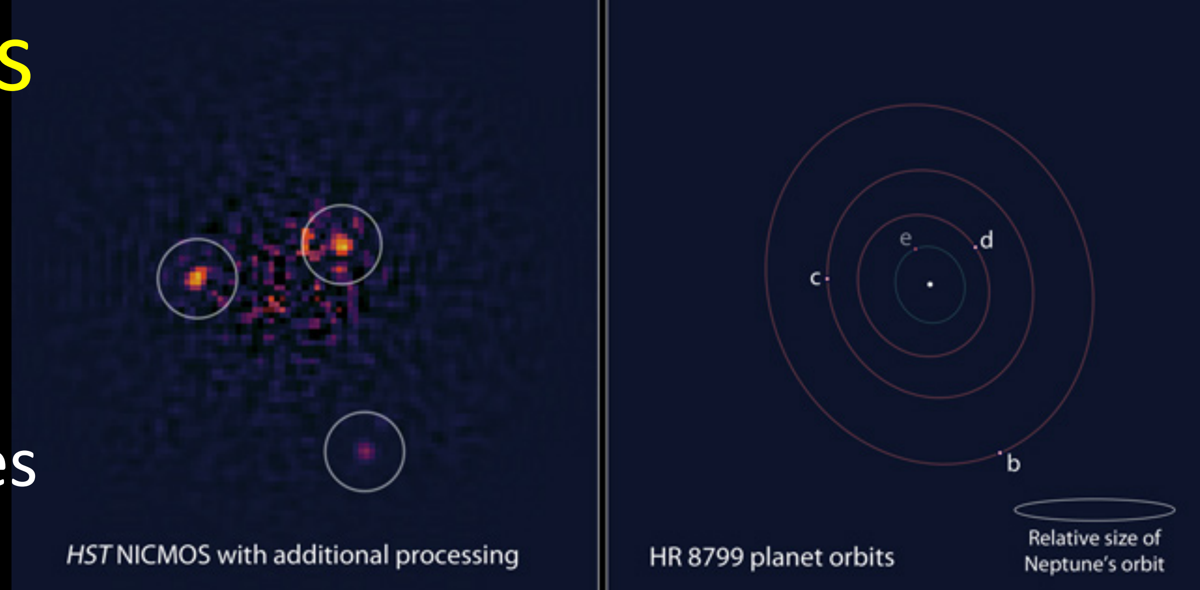


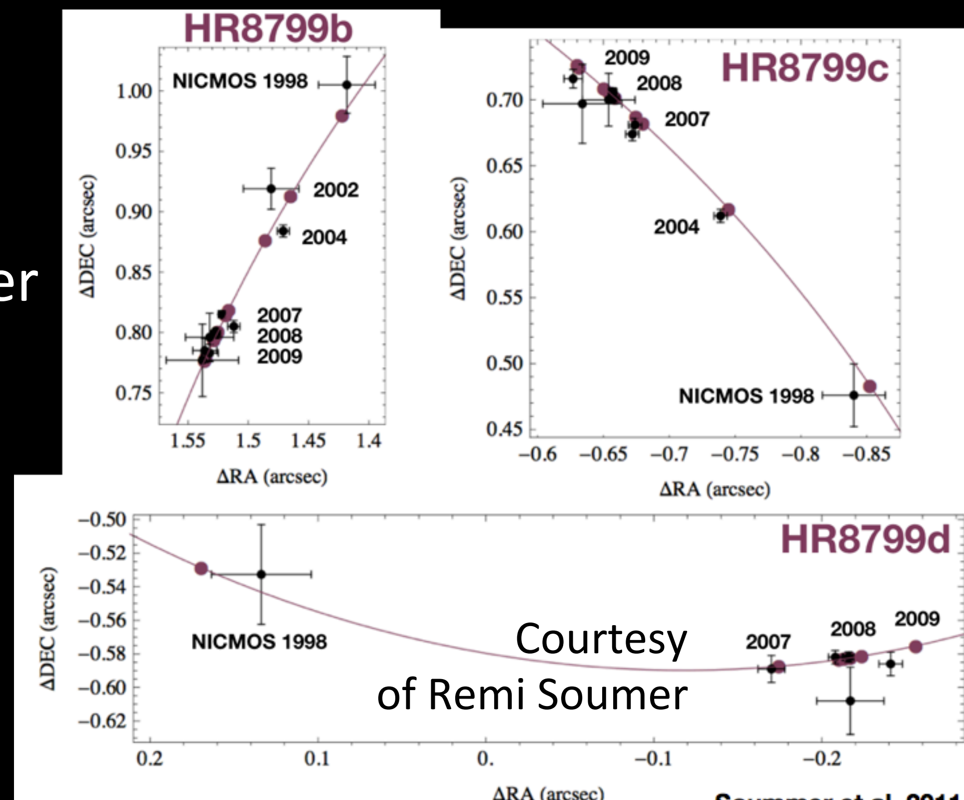
Next Steps in Planet Finding

	Kepler	TESS	WFIRST	Imaging
Area	100 deg^2	~ all sky	<10 deg^2 in Bulge for ulensing	100s of young stars
Planets Sizes	Down to Earth-size	Down to Earth-size	Down to Earth-size	Down to Saturn-size
Planet Orbit &Temp	Hot – to – Habitable (1 year, 1 AU)	Hot, close-in planets (P = 15-30 day)	Habitable – to - Cool, icy planets	300-1500 K 10-100 AU
Focus	Planet Statistics up to 1 AU [η_{Earth}]	All sky survey for close-in planets. Follow-up	Planet Statistics from 1 AU to … [complement of Kepler]	Physical Properties. Formation theories

Imaging Planets Directly

- Extreme Adaptive Optics instruments on 5-10 m telescopes will find Jupiters at 10-100 AU
  - —Unexplored by transits/RV
  - — Detect young planets (<1 Gyr) which remain bright after formation
- JWST will detect lower mass objects (Saturns) on wide orbits. Spectroscopy

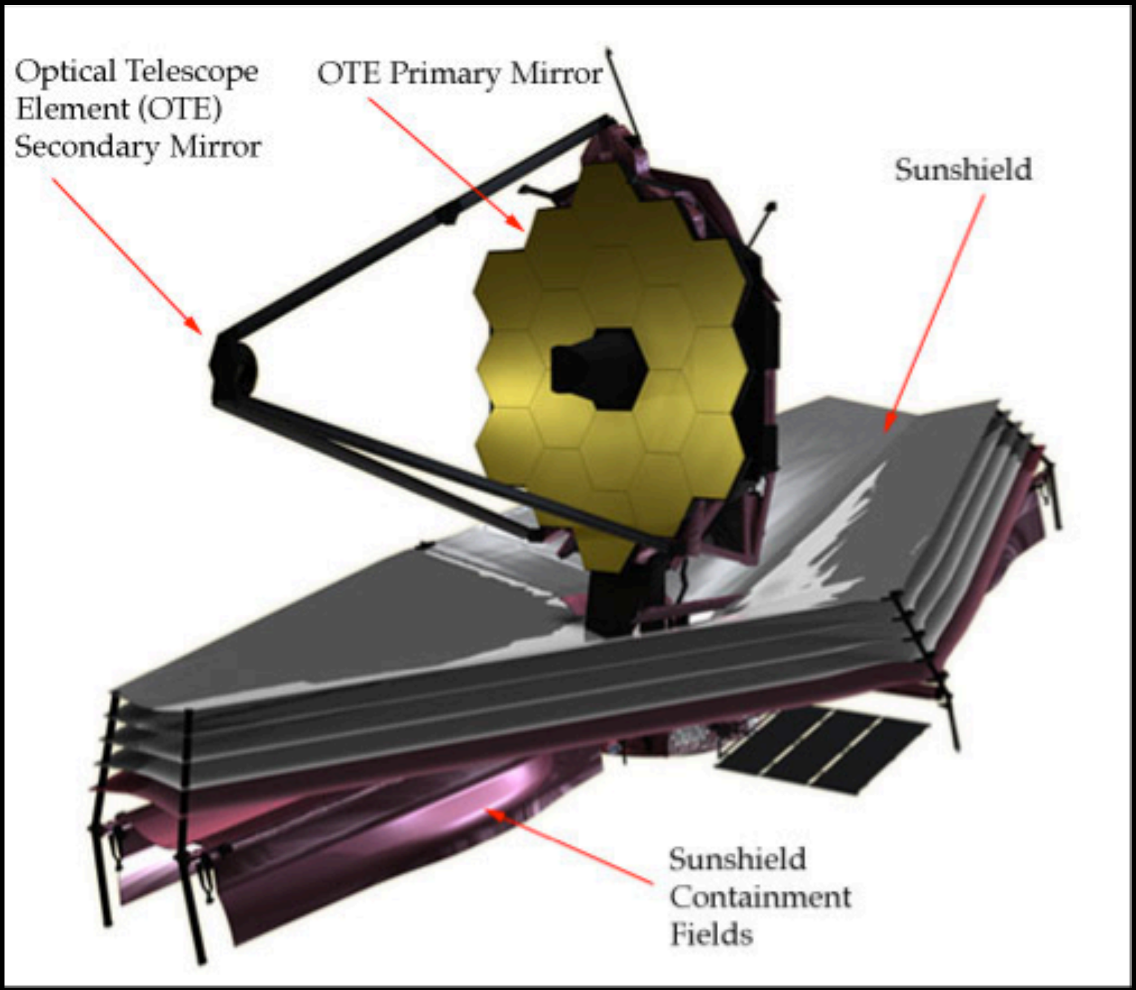




Courtesy of Remi Soumer

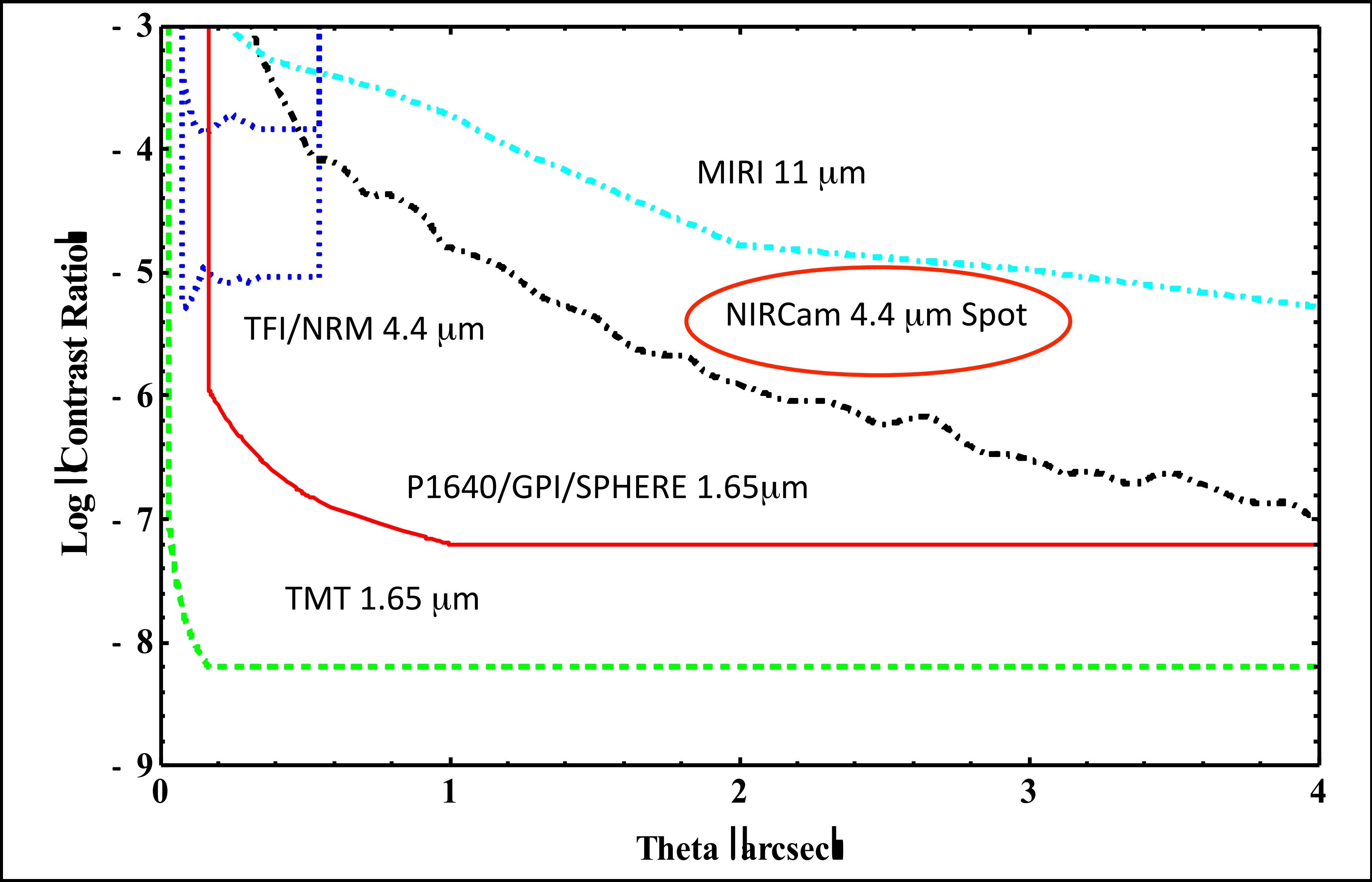
Keck and HST trace HR8799 over decade

JWST in a nutshell



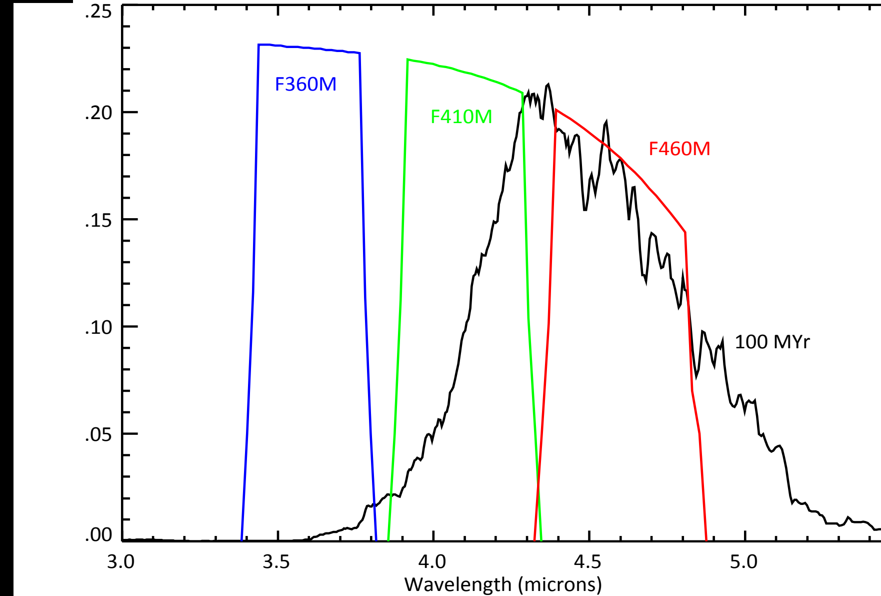
- 6.5-m primary mirror
  - T~40K, bkg. limited
- λ <1 - 28 μm
  - zodi-limited to 10 μm
- Instruments:
  - NIRCam 1 – 5 μm (cam +grism)
  - NIRSpec 1 – 5 μm
  - MIRI 5 – 28 μm (cam + spec)
  - NIRISS: FGS w/slitless spectrograph 1 – 5 μm
- 2018 launch
  - Arianne V to L2
  - 5 yr req life, 10 yr goal

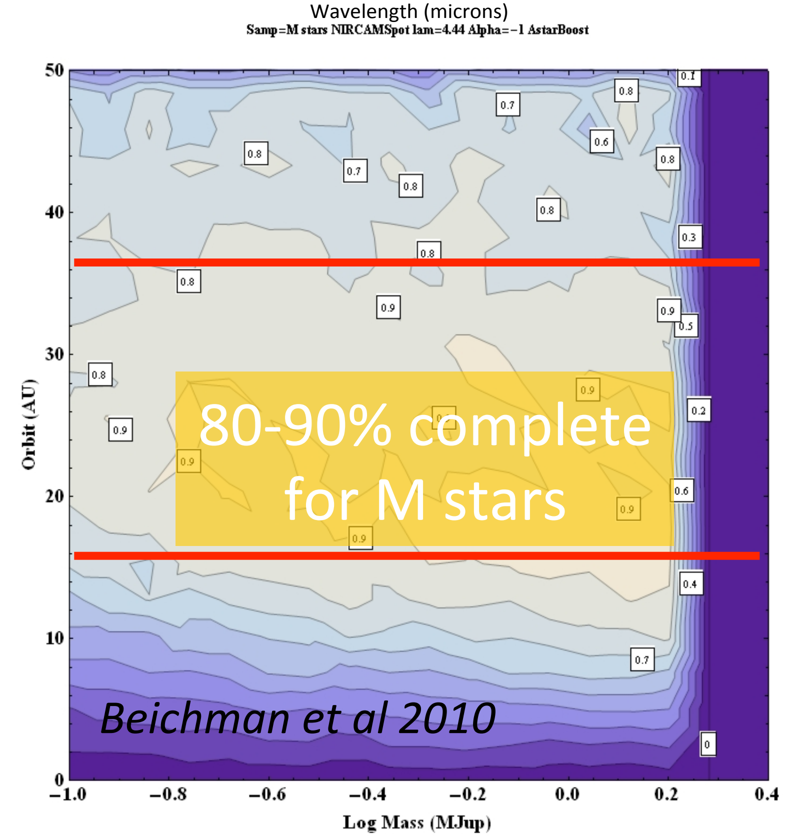
Coronagraphic Capabilities: Ground and Space



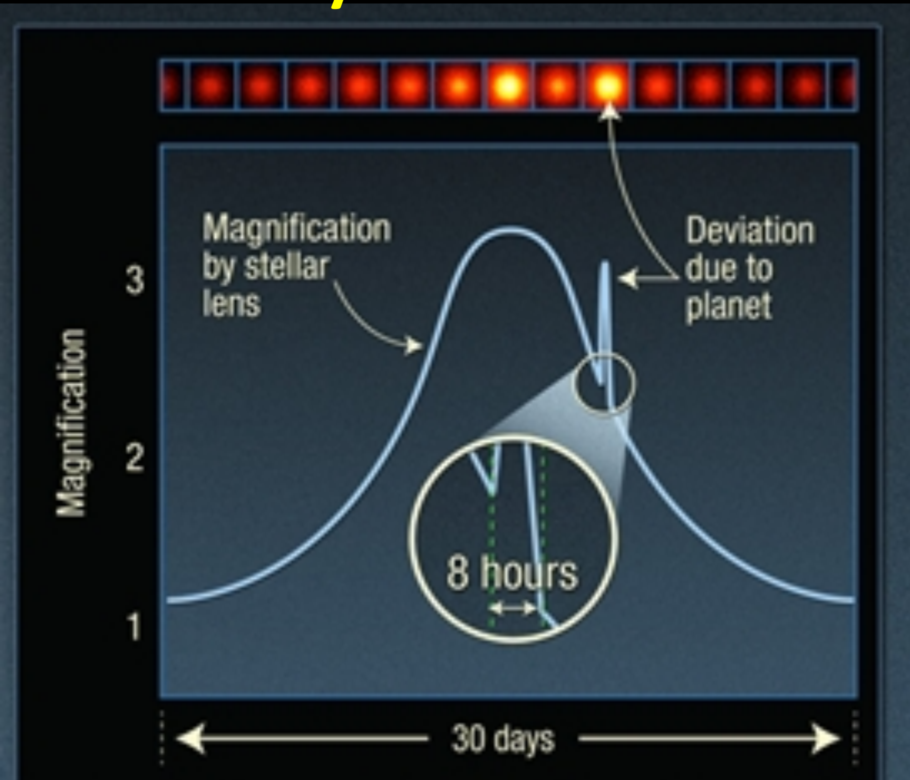
Probing the Outer Solar System

- NIRCam good match to hot young planets, but poor coronagraphic performance wrt. ExAO on ground
- Leave surveys of bright stars to ground-based 8-10 m telescopes (131 nm vs 5 nm of WFE w. ExAO)
- Use JWST for surveys of faint, young M stars with sensitivity to planets M≥ 0.1 MJup at 15-35AU
- GTOs will characterize ~15 systems
  - Complete SEDs (NIRCam + MIRI)
  - Refine orbits w. HST, ground-based
  - Search for additional planets ($\geq M_{Saturn}$)
  - Investigate interactions with rings, incl rings inferred from Spitzer SED



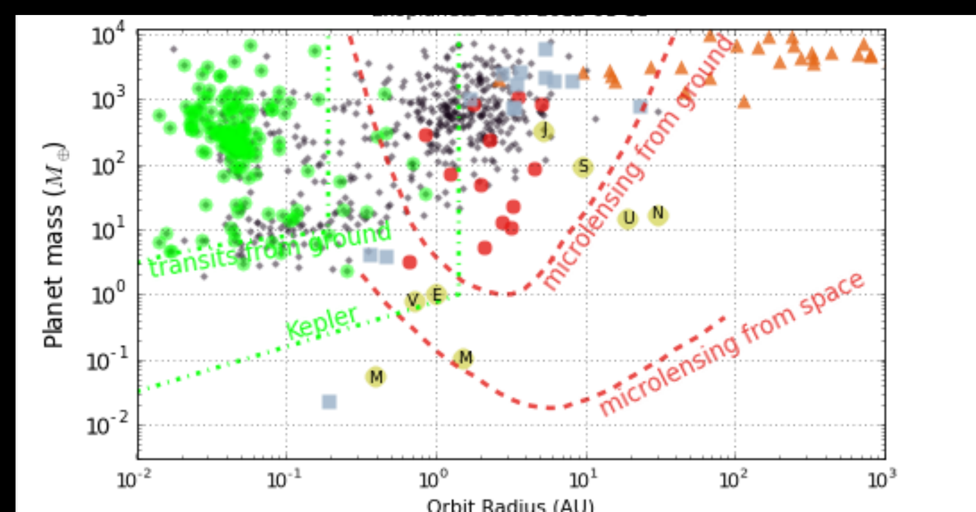


Beyond the "Snow Line' : Gravitational Microlensing

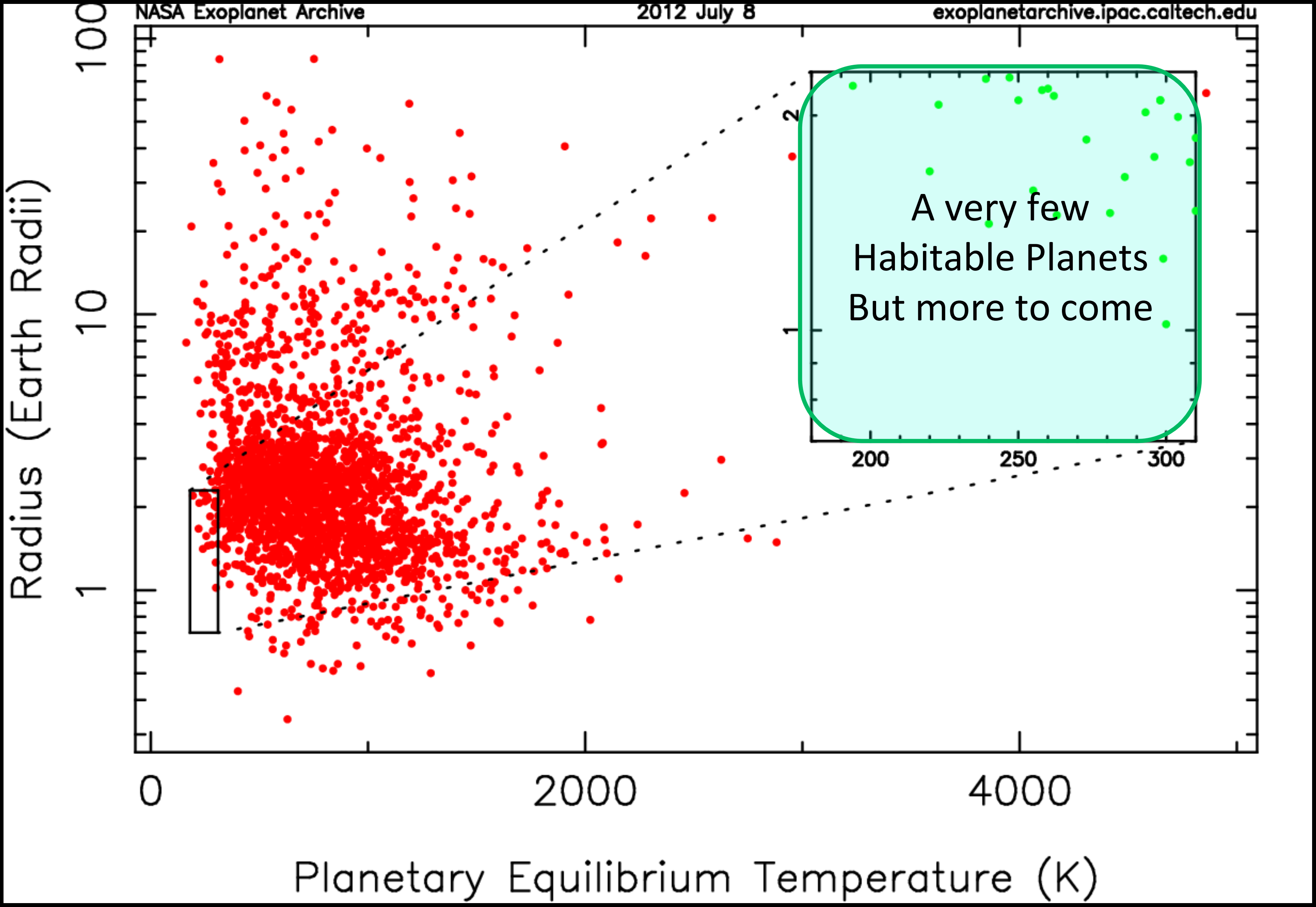


- Another of Einstein's mistakes
- Passing star magnifies light from distant star
- Planet orbiting lens star distorts curve, revealing planet(s)

- Measure ~100 million stars with WFIRST to find dozens of rocky HZ planets
- Good statistics, but no follow-up

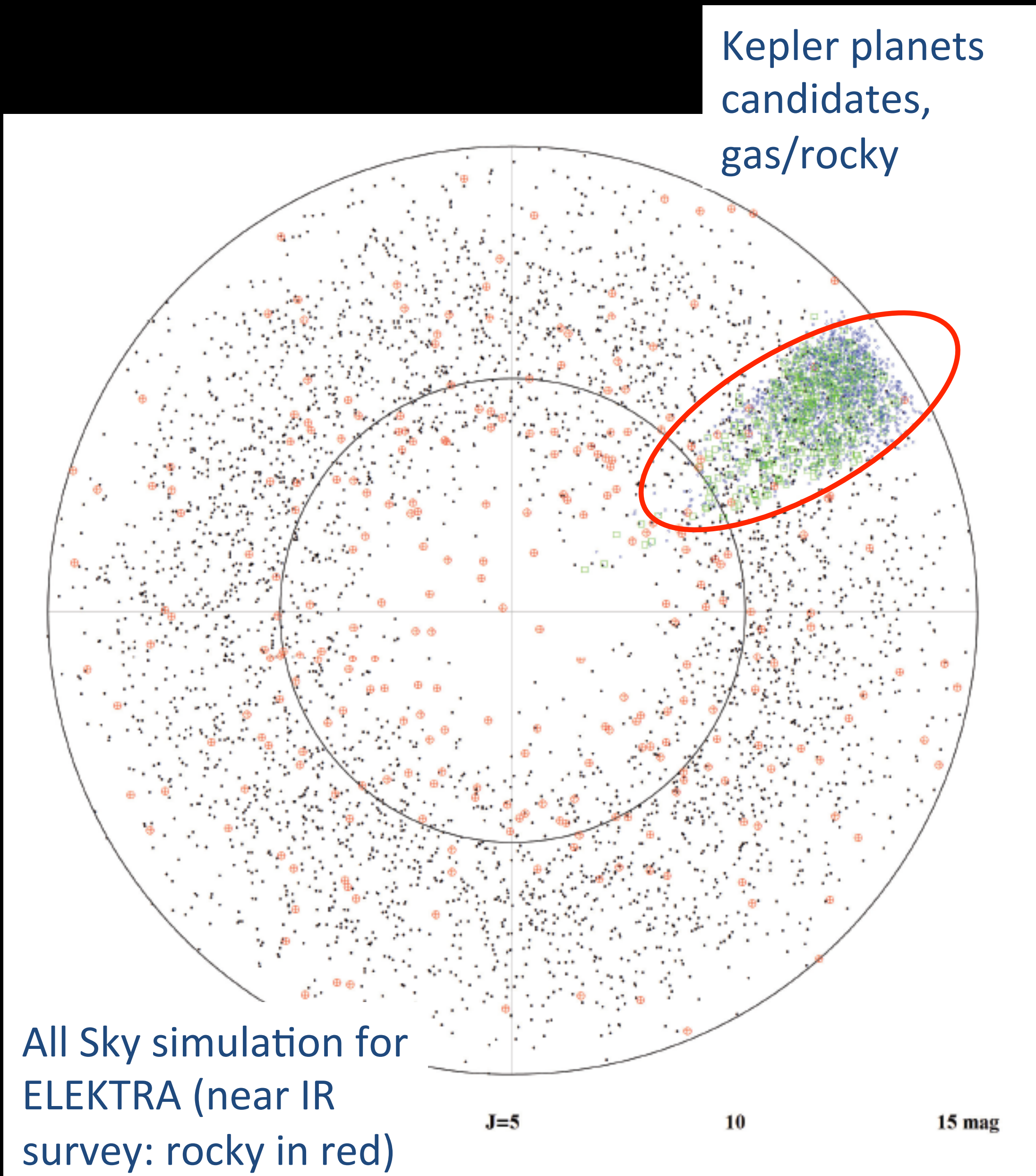


Probing The Habitable Zone: Where Are The Habitable Earthlike Planets?



All Sky Transit Surveys

- Kepler = small/deep (10-15 mag) over 0.25% of sky
- TESS = wide/shallow (5-10 mag) over >50% of sky
- TESS will find targets on 15-30 day periods orbiting bright FGK & some M stars
  - Thousands of gas and ice giants
  - Tens of super Earths (1.5-2 Re) and a few Earths ~1-1.5 Re)
- Ground-based surveys for larger radii planets & low mass stars
- Bright star hosts critical for follow-up spectroscopy

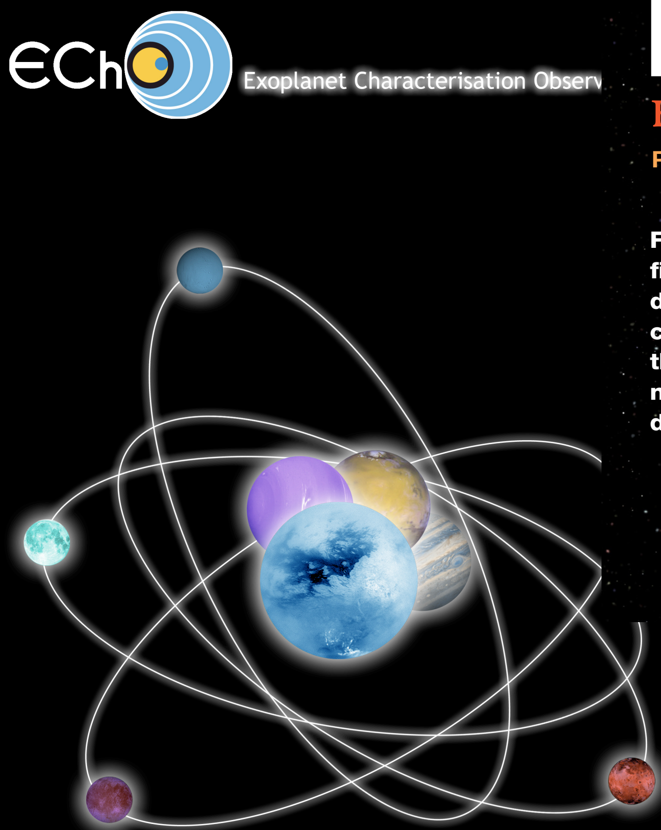


All Sky simulation for ELEKTRA (near IR survey: rocky in red)

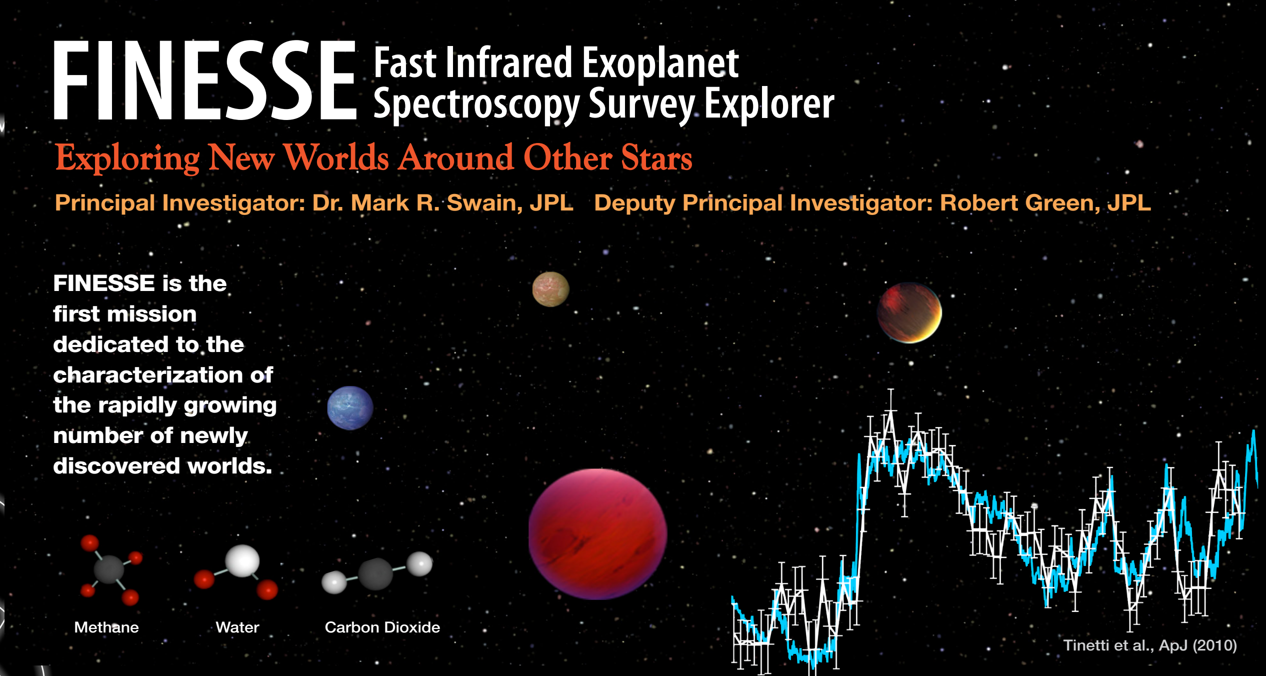
Atmosphere Characterization

	FINESSE	JWST	EcHO
Planets Sizes	Super Earths, Neptunes and Jovians	Super Earths, Neptunes and Jovians	Super Earths, Neptunes and Jovians
Exoplanet spectra	Optical to Near-IR one-shot spectroscopy [0.7 – 5 µm]	Optical to mid-IR with a slew of instruments [1 – 28 µm]	Optical to mid-IR one-shot spectroscopy [0.7 – 16 µm]
Focus	Family portrait of exoplanet atmospheres	In-depth characterization of interesting atmospheres	Survey of the most important/ interesting atmospheres

Next Step: Understand Exoplanets As A Class Of Objects



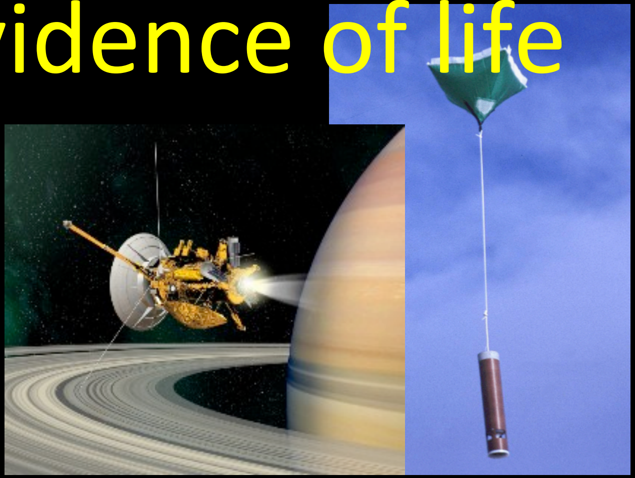
Exploring Atmospheres of Diverse Worlds Beyond our Solar System



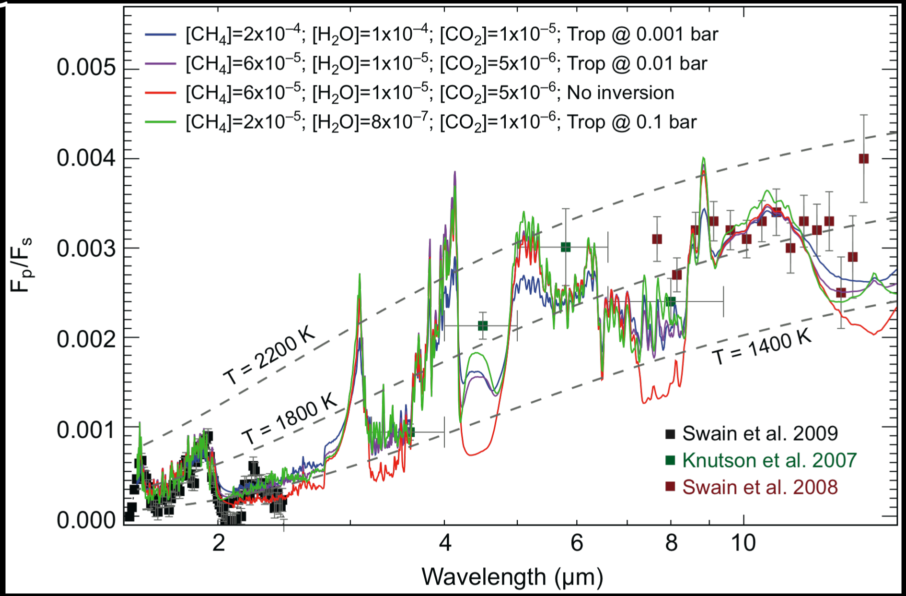
Detailed follow on of the unique discovery space.

Goal: Understand exoplanet atmospheric chemistry & processes Ultimately search for evidence of life

- Molecules serve as probes of atmospheric composition and conditions.
- They are the most powerful tool we have to characterize exoplanet atmospheres
- Potential biological significance
  - possible precursors
  - Biomarkers



Solar system option



Exoplanet option

Which atmospheres? It depends on the star…

Number of Scale Heights we can probe with 25-ppm precision.

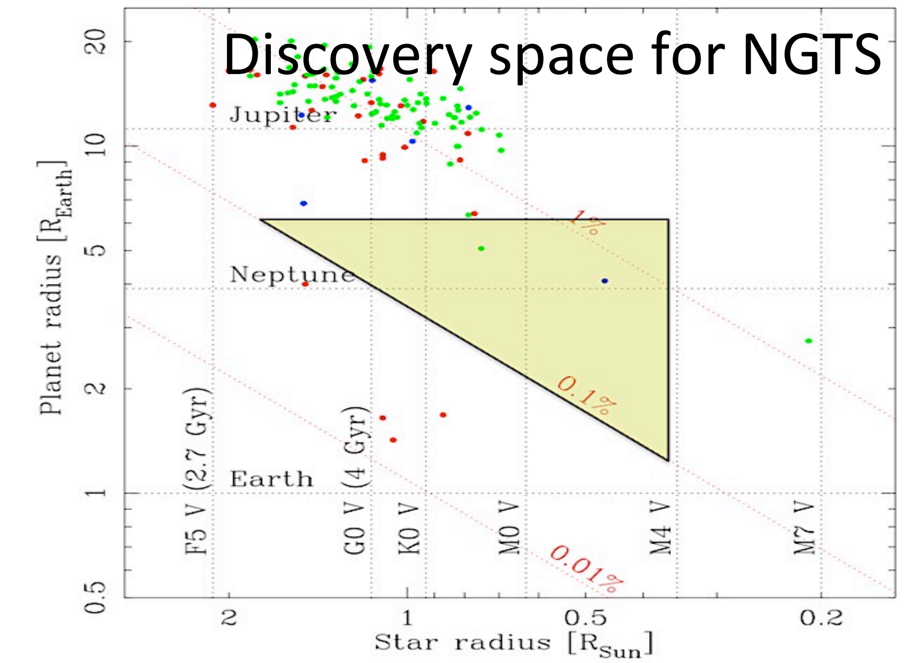
Sp. Type	Neptune	Super-Earth	Earth
K0	30	42	116
K1	30	43	116
K2	27	39	105
K3	28	40	108
K4	23	33	89
K5	23	32	88
K6	21	29	80
K7	20	28	77
K8	19	28	75
K9	19	27	74
M0	19	27	74
M1	17	25	67
M2	15	21	57
M3	14	19	52
M4	8	11	31
M5	5	8	21
M6	3	5	13
M7	3	4	10
M8	1	2	5
M9	1	1	4

No Atmosphere – "Hot Rocks"

- atmosphere detected with 70 ppm
- atmosphere detectable with 25 ppm
- transition region for atmospheric rentention/observability
- atmosphere either not retained or not observable due to contrast

Earth analog can be characterized around an M7 star!

- Jupiter/Neptunes are easy
- Super-Earths are relatively easy
- Earths are possible, but only around very late type stars
- Planet searches are rightfully focusing on the red-stars (Mearth, NGTS, …)

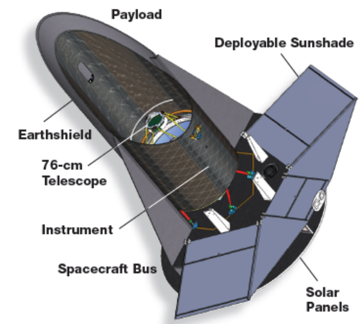


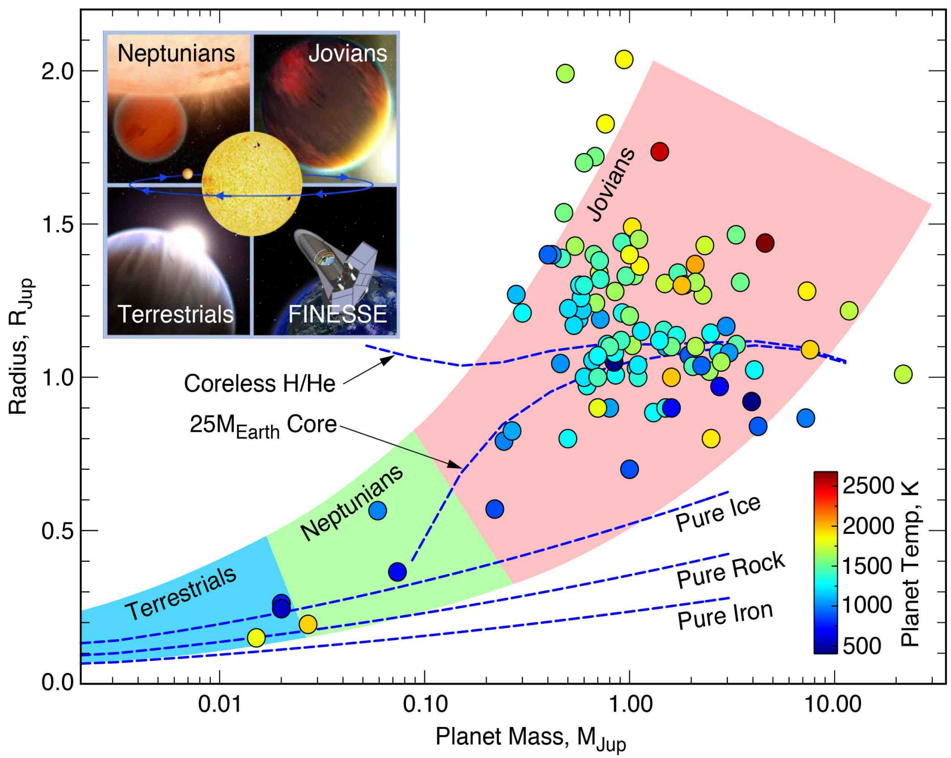
FINESSE Fast Infrared Exoplanet Spectroscopy Survey Explorer

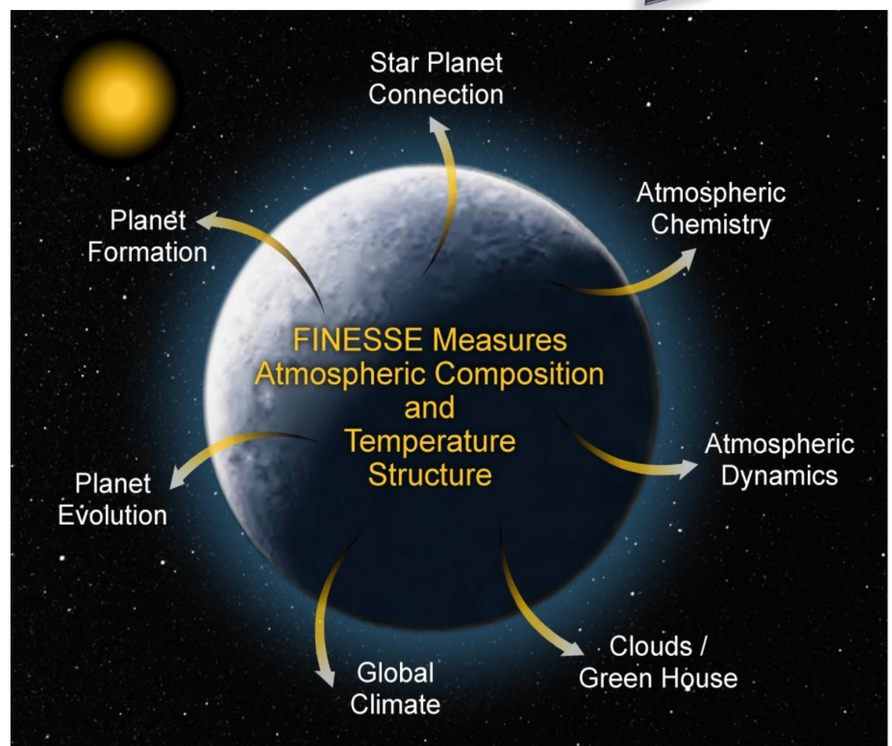
Exploring New Worlds Around Other Stars

Science Overview

FINESSE is a two-year, high-heritage, Earth orbiting mission that **opens the new field of comparative exoplanetology** by probing the atmospheric composition and conditions of transiting exoplanets. FINESSE explores 200 newly discovered worlds ranging from Jovians to Terrestrials by measuring their characteristics with molecular spectroscopy.







An Extraordinary Opportunity

- Astronomers have discovered hundreds of exoplanets, but we know very little about these exciting objects.
- By systematically exploring a large sample of these new worlds, we have the rare and extraordinary opportunity to dramatically advance the emerging field of comparative exoplanetology.

FINESSE provides a transformational data set.

FINESSE will answer two key questions:

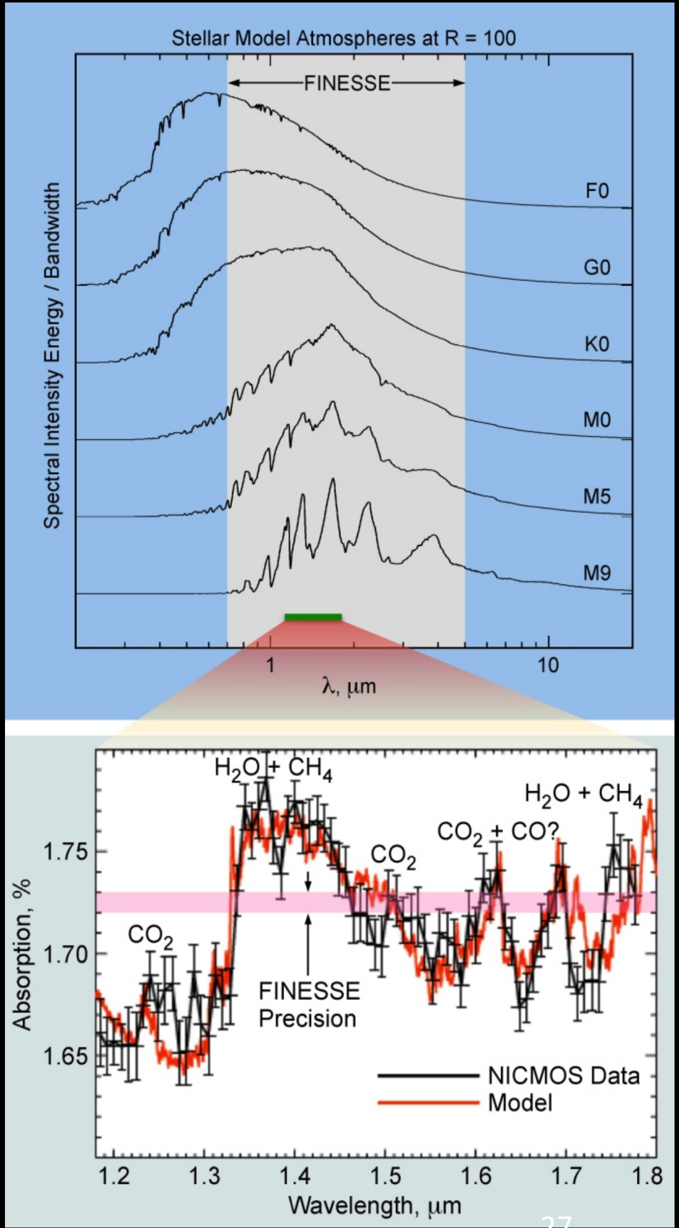
1. What is the composition and temperature of exoplanet atmospheres?
2. How does the composition and temperature change from the dayside to the nightside and with time?

Characterization via Detecting Molecules

- Diagnostic molecules: H2O, CH4, CO2, CO
- Trace C/O and non-equilibrium chemistry
- Detected via spectroscopy in 3 planets

Table D.1-1: Molecules and locations of their prominent bands to be targeted by FINESSE.

	Molecule	0.7–3.0 μm	3.0–5.0 μm
Key Diagnostic	H_2O	0.82, 0.94, 1.13, 1.38, 1.9, 2.69	
	CH_4	0.79, 0.86, 1.65, 2.2, 2.31, 2.37	3.3
	CO_2	1.21, 1.57, 1.6, 2.03	4.25
	CO	1.57, 2.35	4.7
Additional Possible Molecules	C_2H_2	1.52	3.0
	HCN		3.0
	O_3		4.7
	O_2	0.76, 1.27	
	NH_3	0.93, 1.5, 2, 2.25, 2.9	3.0
	C_2H_4		3.22, 3.34
	H_2S	2.5	3.8
	SO_2		4
	N_2O	2.8	3.9, 4.5
	TiO	0.7–3.0	3.0–3.5
	VO	0.7–2.5	



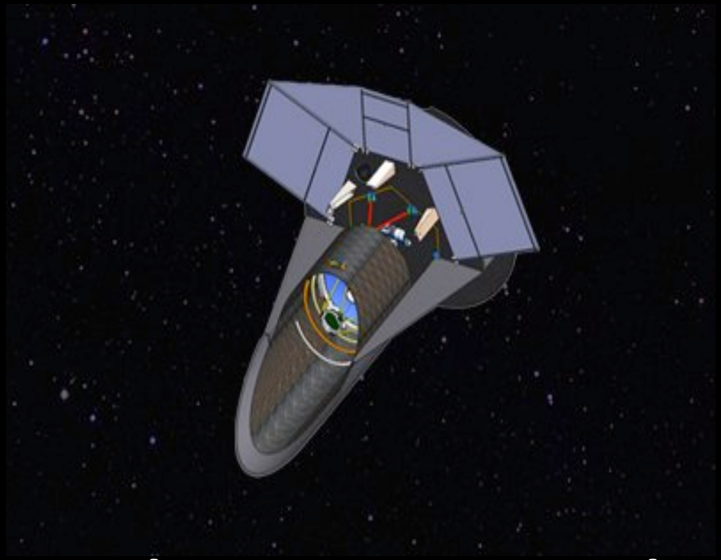
Science Community Engagement

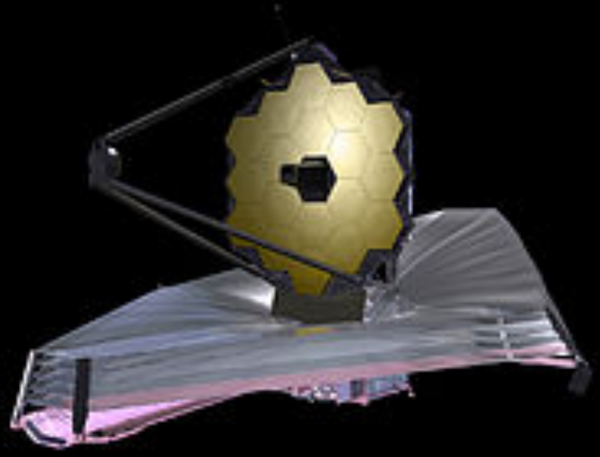
- **The objective is to rapidly extract maximum science from a transformative data set.**

- Completed sets public in 6 months or less.
  - Includes all Level 1-4 data products
  - Includes spectral retrieval results
  - Prelaunch workshop with sample data
- Participating Scientist Program:
  - Joint observing for ground-space bootstrap
  - Non-transiting planets
  - Survey of M dwarfs within ~15 pc
  - ISM organics
  - YSO spectra

www.finesse.jpl.nasa.gov

FINESSE Complements JWST





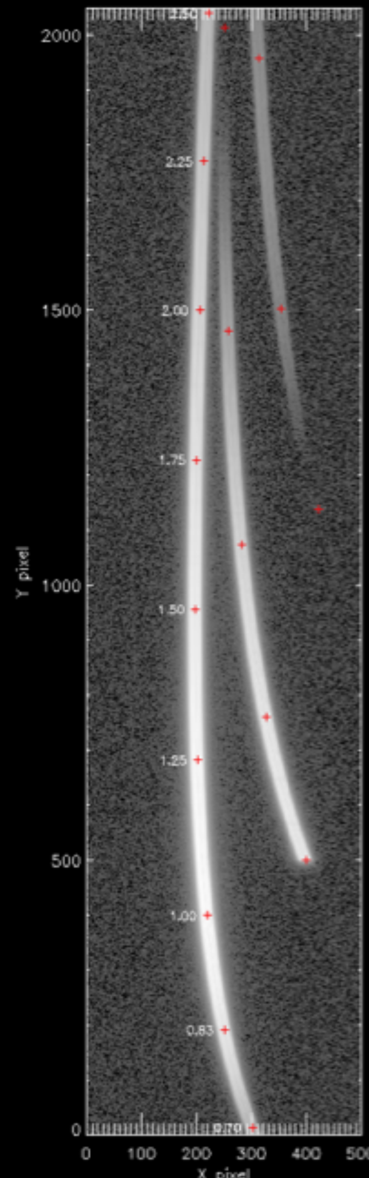
- **FINESSE Enhances JWST Exoplanet Science**
- Identifies the exoplanet targets for in-depth study with JWST.
- Provides the scientific context of a large survey in which to place detailed exoplanet observations made with JWST.
- Provides high-precision near-IR observations that complement JWST's unique mid-IR capability.
- **FINESSE builds upon the success of Hubble and Spitzer and complements the UV/vis capability of Hubble.**

JWST Transit Spectroscopy

- JWST has 6.5 m aperture
  - JWST will be capable of SNR ~ 3 – 8 times present values
  - JWST can provide ~ 20 times higher spectral resolution
- JWST has great spectroscopic capabilities
  - λ = 0.7 – 5 μm, R ~ 100 mode with NIRSpec prism
  - λ = 0.7 – 2.5 μm, R ~ 700 mode with NIRISS grism+prism (slitless)
  - λ = 2.5 – 5 μm, R ~ 1700 mode with NIRCam grisms (slitless)
  - λ = 5 – 12+ μm, R ~ 70 mode with MIRI LRS prisms (slitless)
- JWST is being designed and will be operated to maximize exoplanet spectroscopy SNR
  - Wide NIRSpec slit (1400 mas), slitless mid-IR spectroscopy, NIRISS exoplanet grism (1-2.5 μm), NIRCam grism (2.4-5 μm)
  - Testing spectrophotometric precision and simulating operations
  - Systematic noise due to pixel size and observatory parameters are being modeled (P. Deroo PASP submitted), mitigation possible

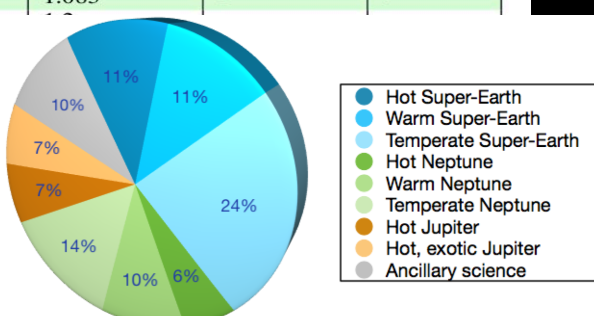
New NIRISS "Exoplanet grism"

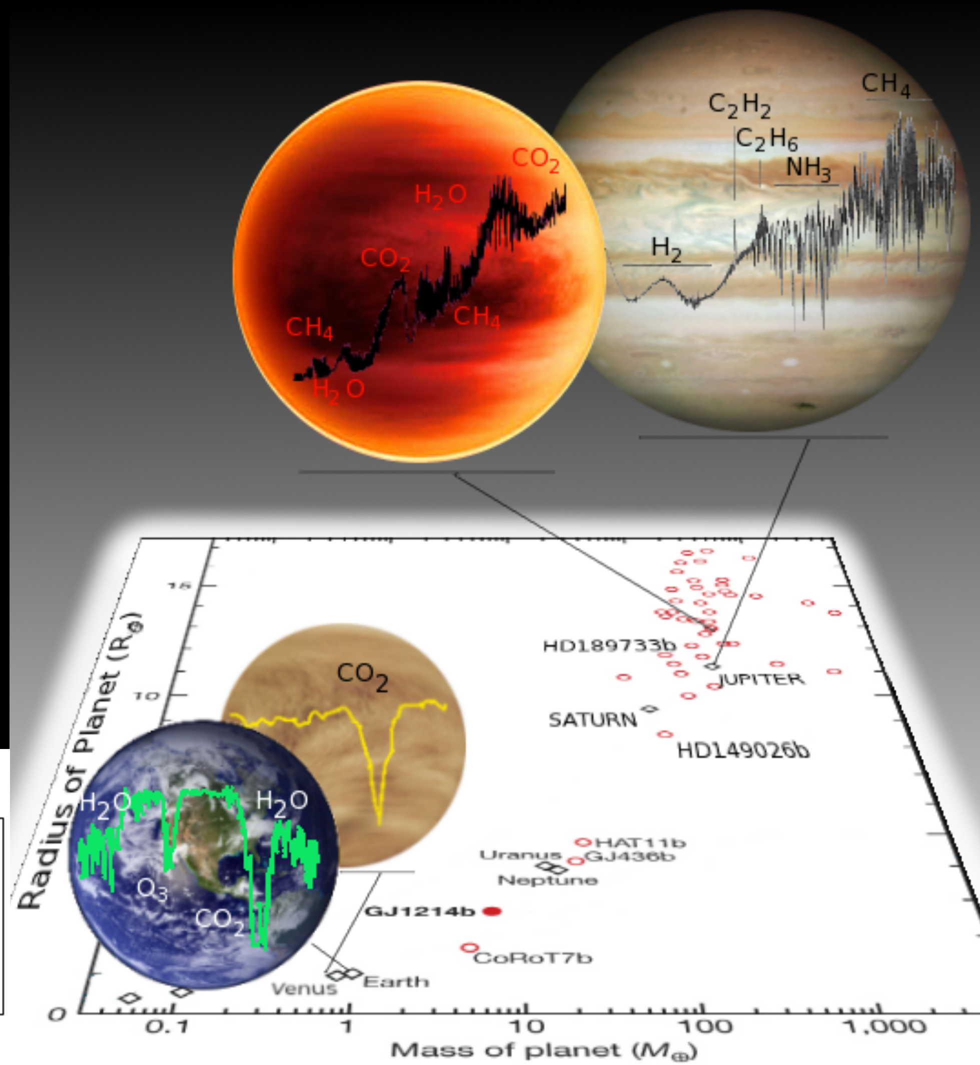
- The Tunable Filter Instrument (TFI) part of the Fine Guidance Sensor (FGS) was discontinued in 2011.
- TFI replaced by the Near-InfraRed Imager and Slitless Spectrograph
  - Recovers TFI exoplanet spectroscopy
  - R = 700 grism covers 0.7 – 2.5 μm
- Cross-disperser prism allows entire wavelength coverage at once
- Cylindrical surface on prism provides WFE in X-dispersed axis. More pixels provide:
  - Less systematic error
  - Brighter saturation limit



In-depth Survey of exoplanets down to the really interesting ones!

	0.4-1 µm	1-5 µm	5-11 µm	11-16 µm
R, baseline	500	300	300	20
R, desired	500	300	300	300
Species				
*H_2O	0.51, 0.57, 0.65, 0.72, 0.82, 0.94	1.13, 1.38, 1.9, **2.69**	6.2	continuum
*CO_2	-	1.21, 1.57, 1.6, 2.03, **4.25**	-	**15.0**
C_2H_2	-	1.52, **3.0**	7.53	**13.7**
HCN	-	**3.0**	-	**14.0**
C_2H_6	-	3.4	-	**12.1**
O_3	0.45-0.75 (the Chappuis band)	4.7	9.1, **9.6**	14.3
HDO	-	2.7,3.67	7.13	-
*CO	-	1.57, 2.35, **4.7**	-	-
O_2	0.58, 0.69, 0.76, 1.27	-	-	-
NH_3	0.55, 0.65, 0.93	1.5, 2, 2.25, 2.9, **3.0**	6.1, **10.5**	-
PH_3	-	4.3	8.9, 10.1	-
*CH_4	0.48, 0.57. 0.6, 0.7, 0.79, 0.86,	1.65, 2.2, 2.31, 2.37, **3.3**	6.5, **7.7**	-
CH_3D	?	3.34, **4.5**	6.8, 7.7, **8.6**	-
C_2H_4	-	**3.22**, 3.34	6.9, **10.5**	-
H_2S	-	2.5, 3.8 ...	7	-
SO_2	-	4	**7.3**, 8.8	-
N_2O	-	2.8, 3.9, **4.5**	7.7, 8.5	-
NO_2	-	3.4	**6.2**, 7.7	13.5
H_2	-	2.12	-	-
H_3^+	-	2.0, 3-4.5	-	-
He	-	1.083	-	-
*Na	0.589			
*K	0.76			
TiO	0.4-1			
VO	0.4-1			
FeH	0.6-1			
TiH	0.4-1			
Rayleigh	0.4-1			
Cloud/haze	yes			
H α	**0.66**			
H β	0.486			
Ca	0.8498, 0.854 0.8662			

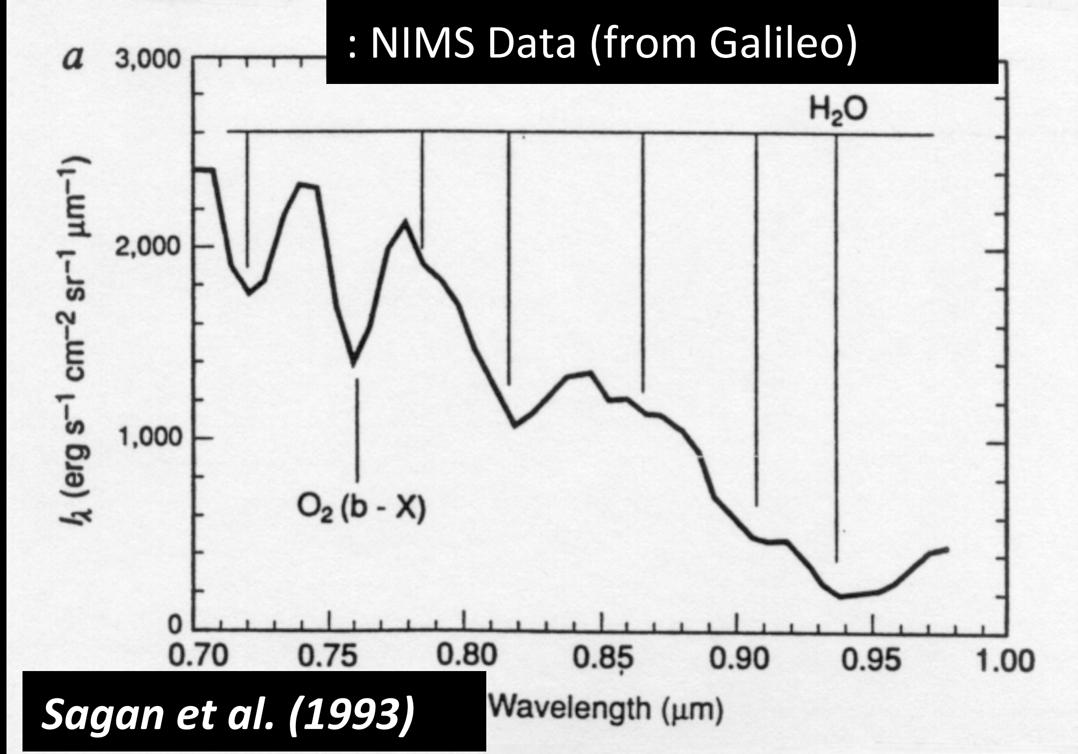




Past–Present-Future

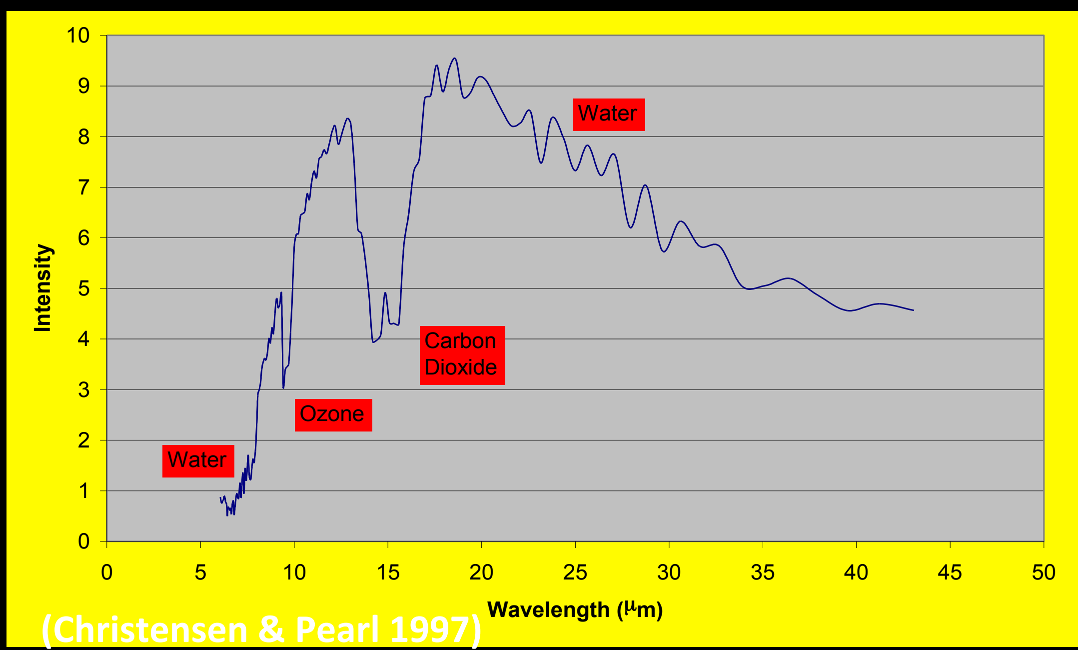
- Exoplanet finding/characterization are booming fields with growing communities
- The last decade has seen tremendous progress with the field/methods maturing rapidly
- Exciting near-term and mid-term and long-term prospects!
- Exoplanets allow us for the first time to understand 'planets as a class of objects'
  - Planet statistics
  - Atmospheric statistics
  - Habitability statistics?

The Final Frontier: Finding Habitable Planets and Life



: NIMS Data (from Galileo)

Sagan et al. (1993)



(Christensen & Pearl 1997)

Long Term Goal: Fly The Greatest Telescopes Ever Built To Find Life