From Protostars to Exoplanets to Life On Other Worlds

Charles Beichman, NASA Exoplanet Science Institute
JPL and Caltech/IPAC

R.M. Petrie Prize Lecture

May 31, 2017

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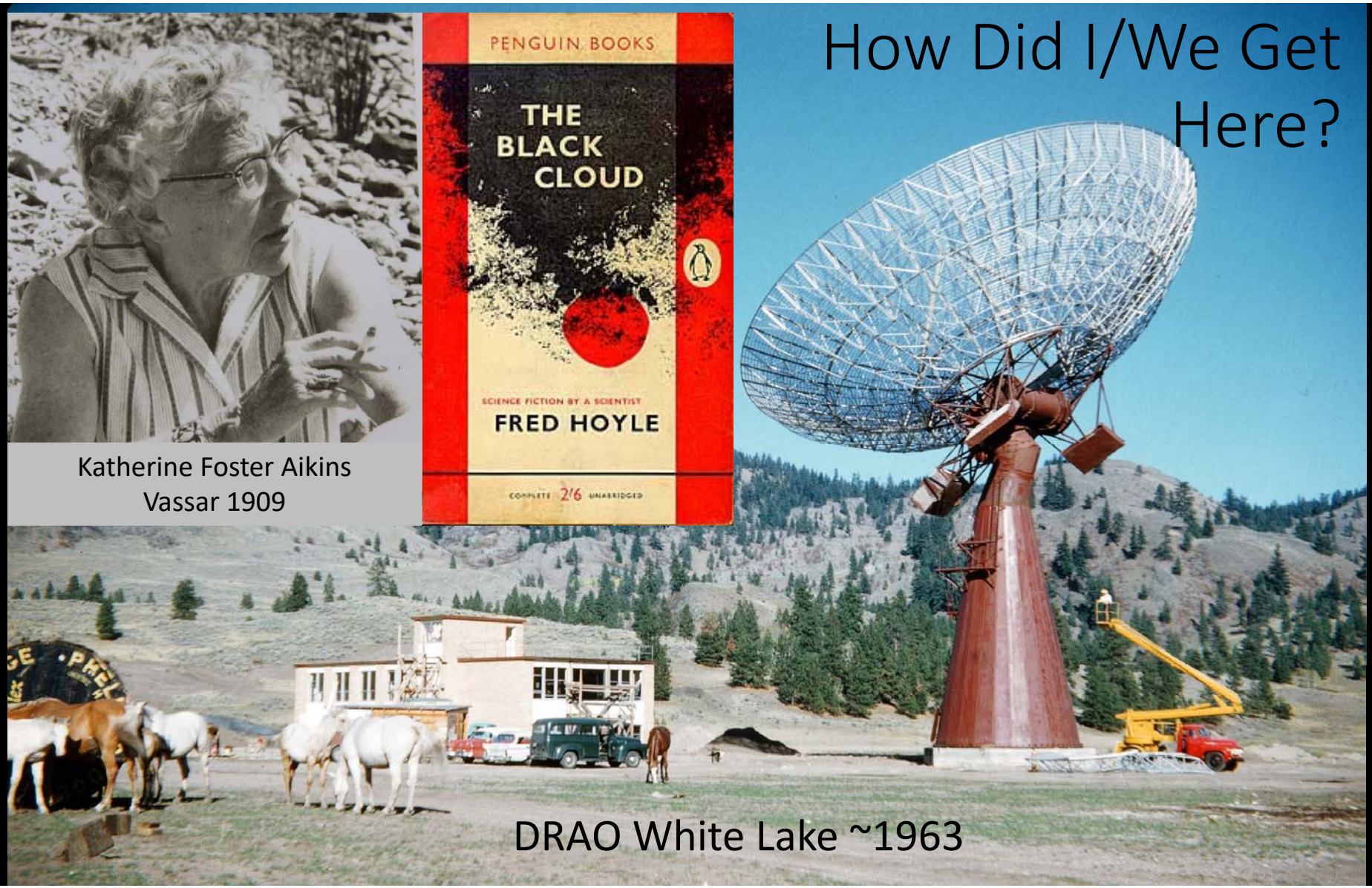
Government sponsorship acknowledged.

How Did I/We Get Here?

Katherine Foster Aikins
Vassar 1909



DRAO White Lake ~1963

Vol. XXXIV, No. 4 APRIL, 1940 WHOLE No. 293

THE ATMOSPHERES OF THE PLANETS

By R. M. PETRIE

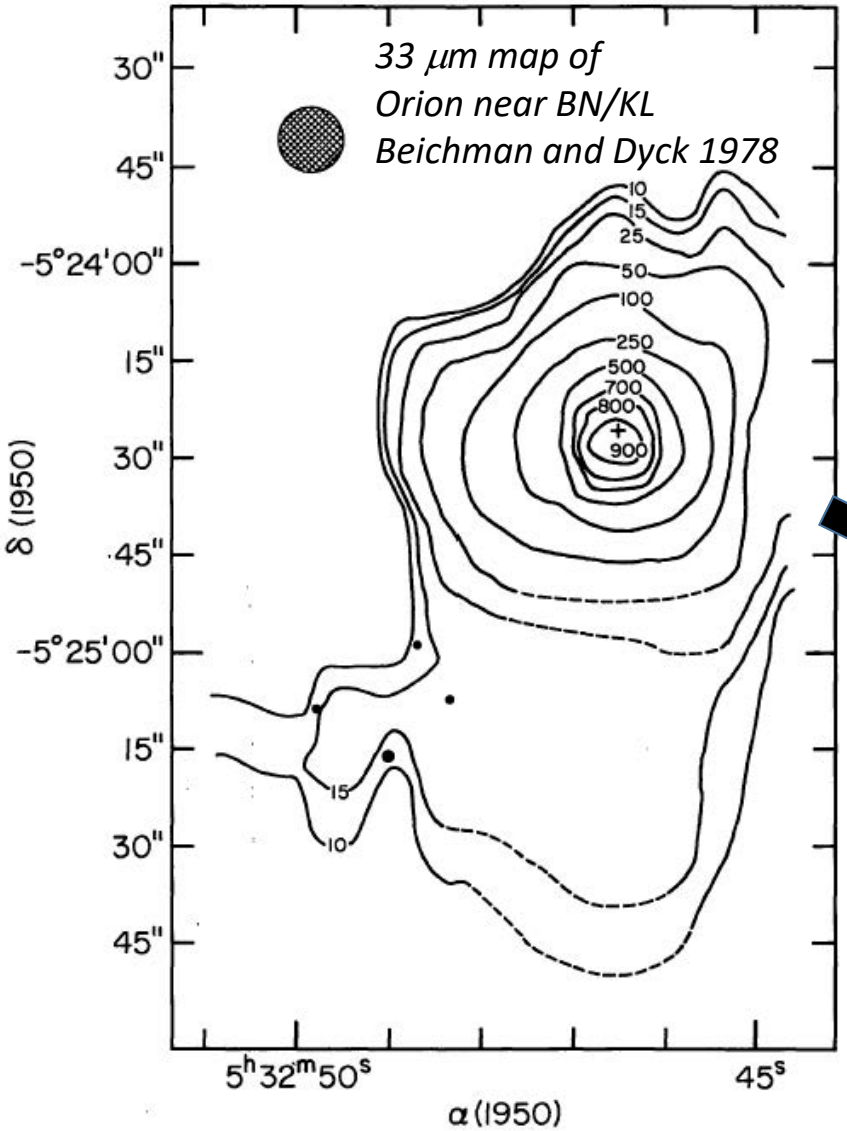
THE subject of tonight's address is one of the astronomical problems which appeals to a large number of persons; not only to those directly interested in scientific studies but also to everyone who takes an interest in extra-mundane affairs. The determination of the presence and composition of a planet's atmosphere is a necessary prerequisite to an intelligent discussion and appreciation of the possibility of life existing thereon.

Petrie 1940

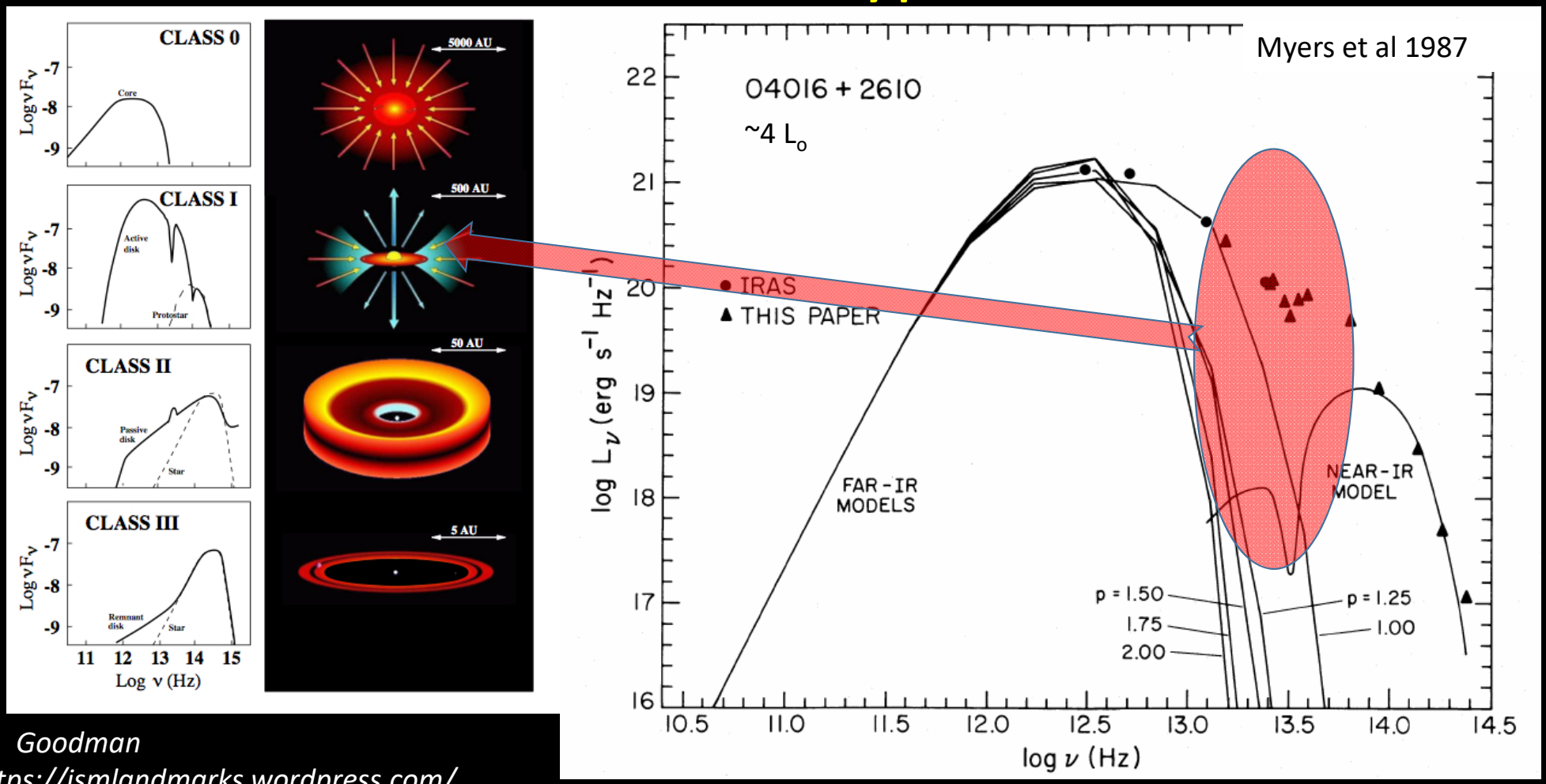
Evidences for the Existence of Planetary Atmospheres

Let us first consider the facts which point to the existence of gaseous envelopes surrounding the planets. The principal lines of evidence are as follows:

(*a*) Surface appearance,
★ (*b*) Albedo or reflecting power,
★ (*c*) Twilight and refraction effects,
★ (*d*) Spectroscopic evidence,
★ (*e*) Gravitational attraction.

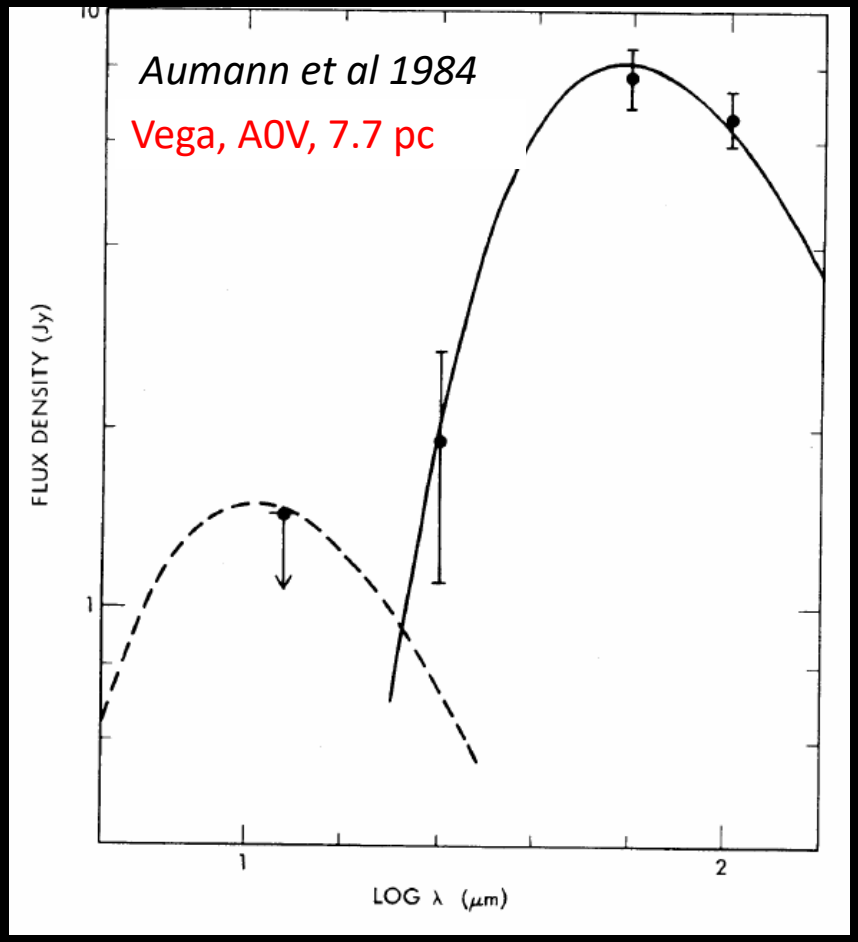

33 μm map of
Orion near BN/KL
Beichman and Dyck 1978
10
15
25
50
100
250
500
700
800
900
15
10
30"
45"
-5°24'00"
15"
30"
45"
-5°25'00"
15"
30"
45"
δ (1950)
5h32m50s
45s
α (1950)

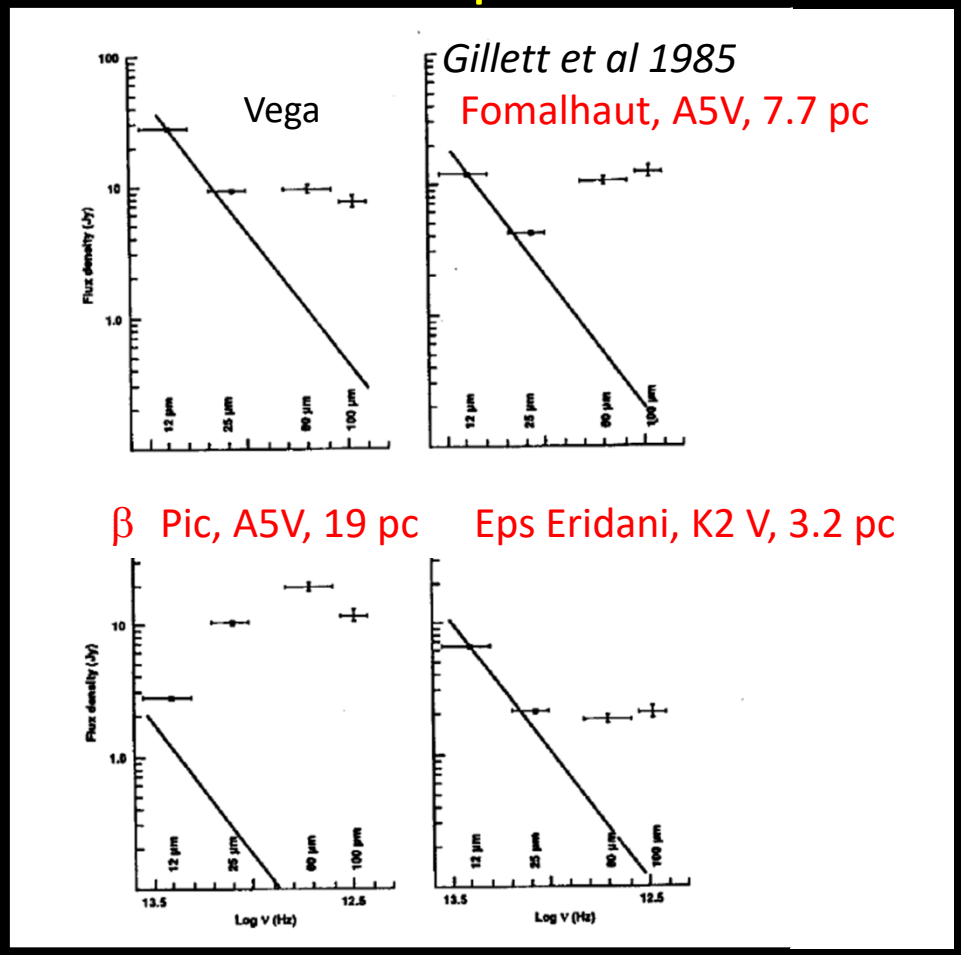
Protostellar-Protoplanetary Disks Around Solar Type Star



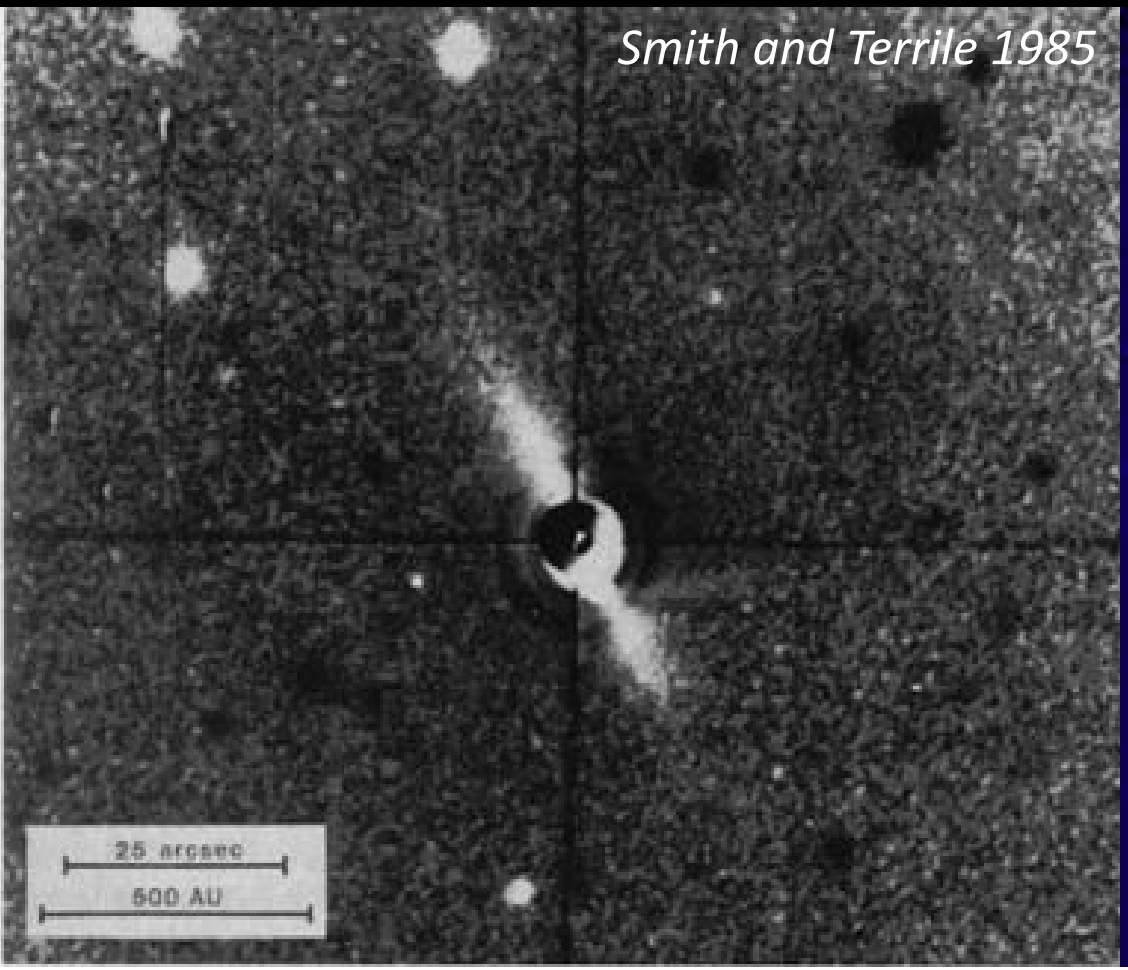
A. Goodman
https://ismlandmarks.wordpress.com/

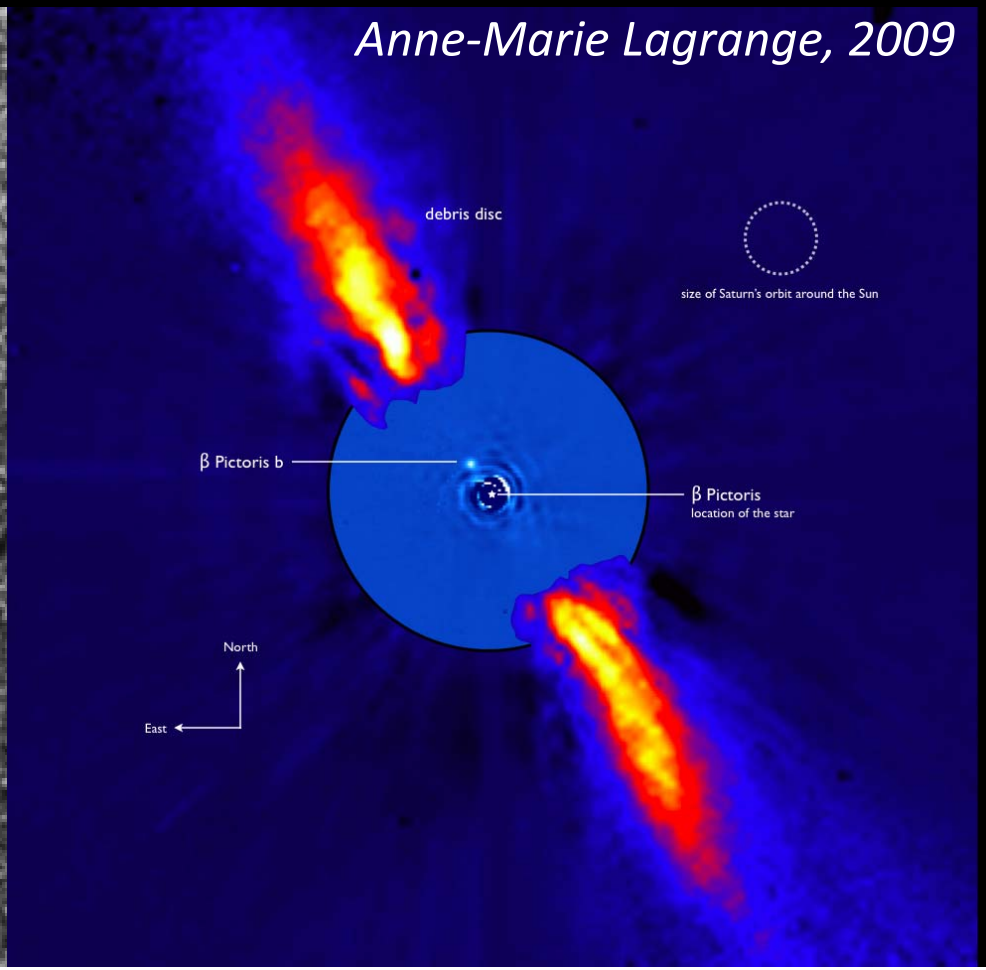
The IRAS Fabulous 4:
Vega, Fomalhaut, beta Pic and Eps Eri



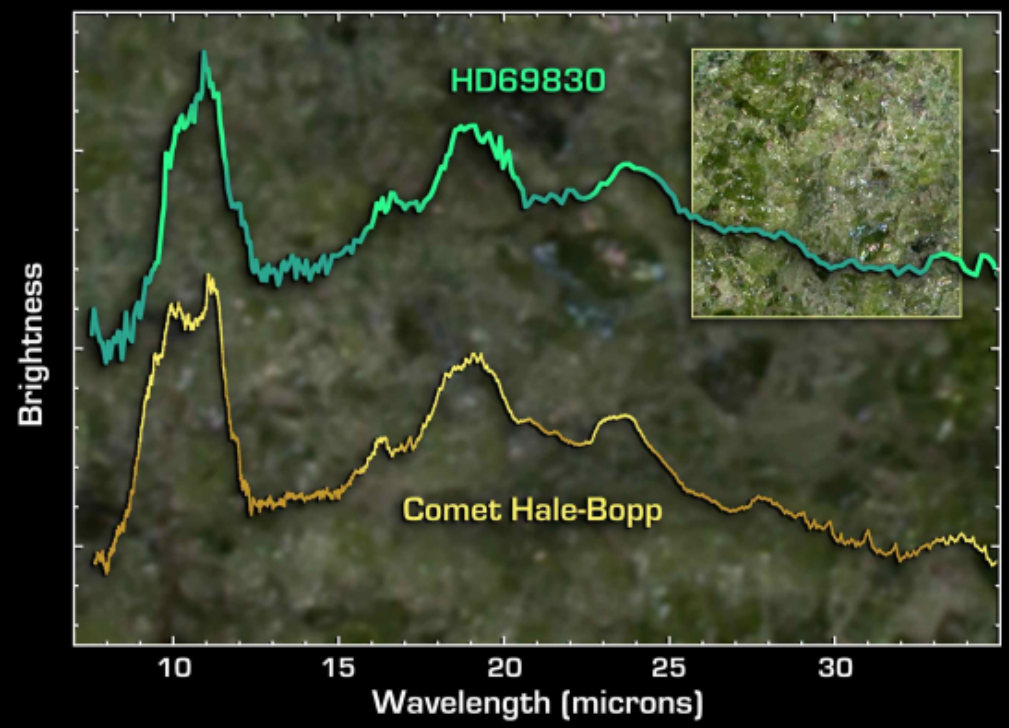


β Pictoris Debris Disk: Then and Now

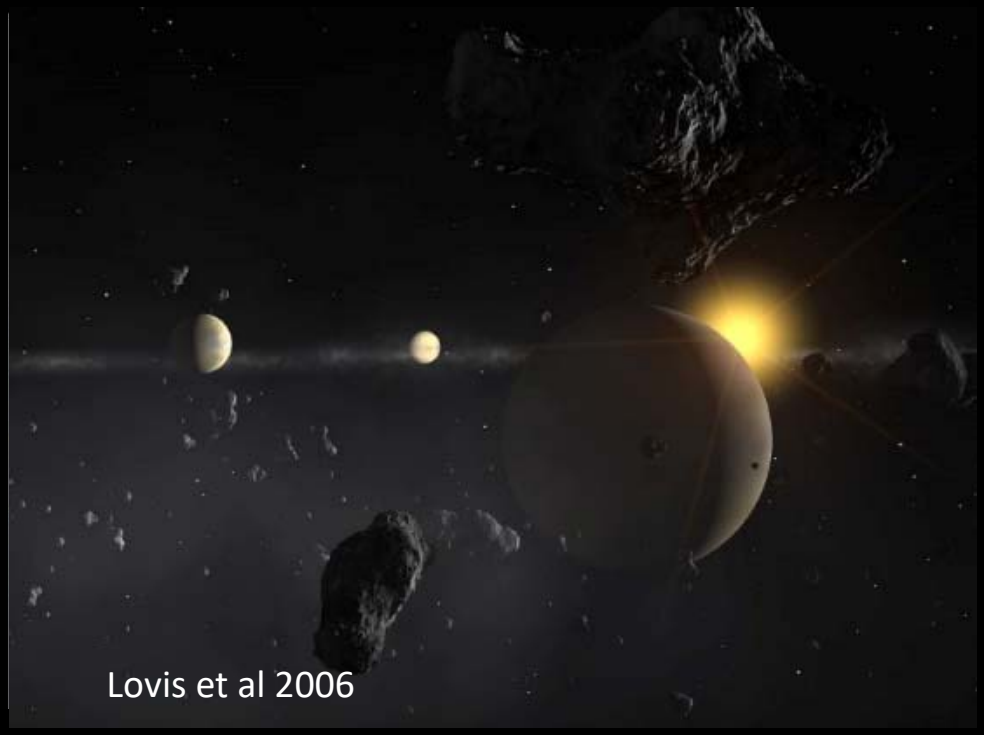




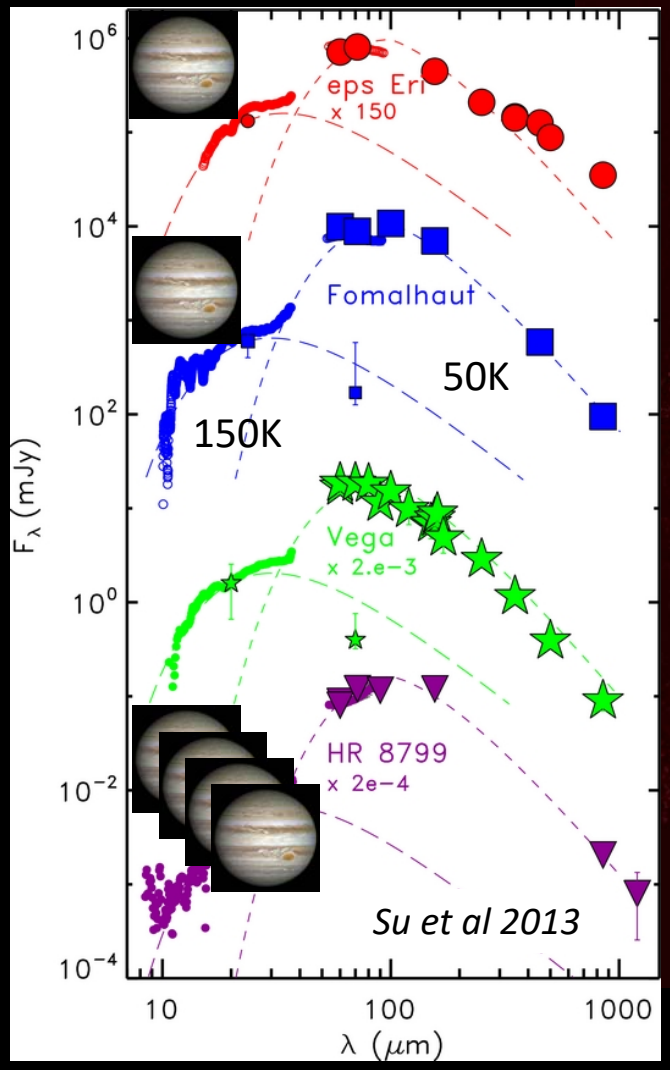
HD 69830 ---A Massive Asteroid Belt & 3 RV planets

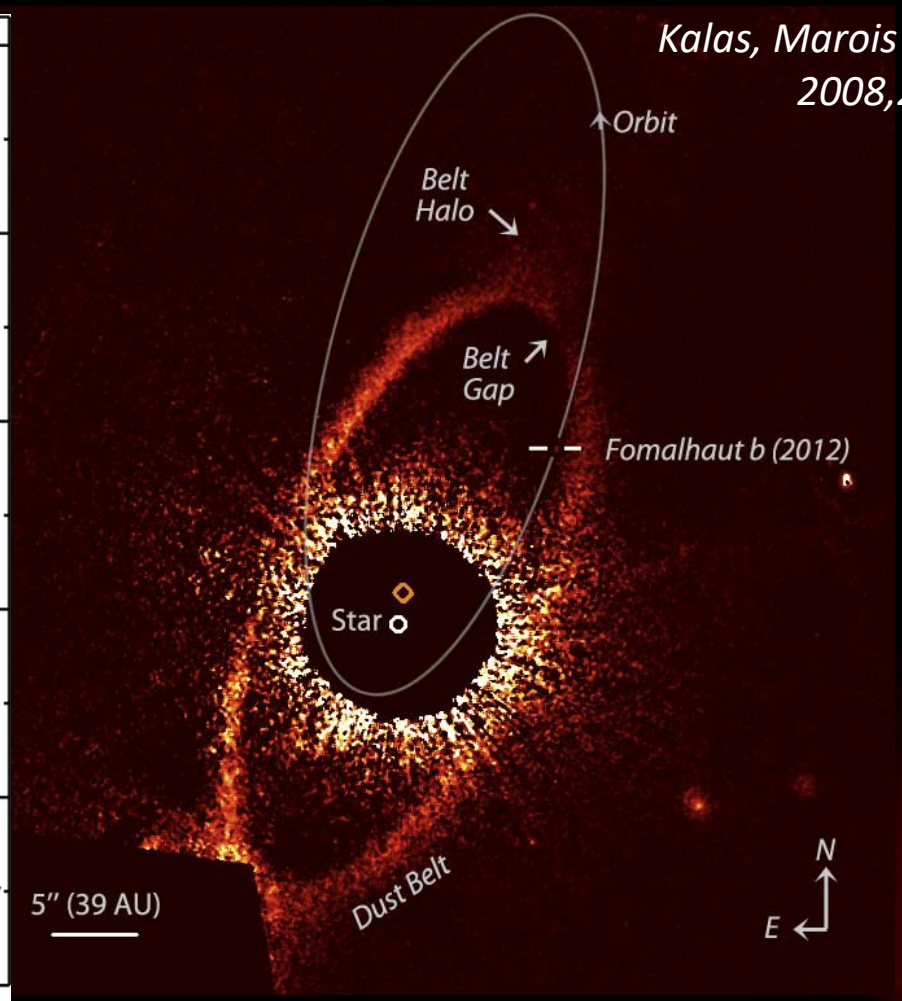


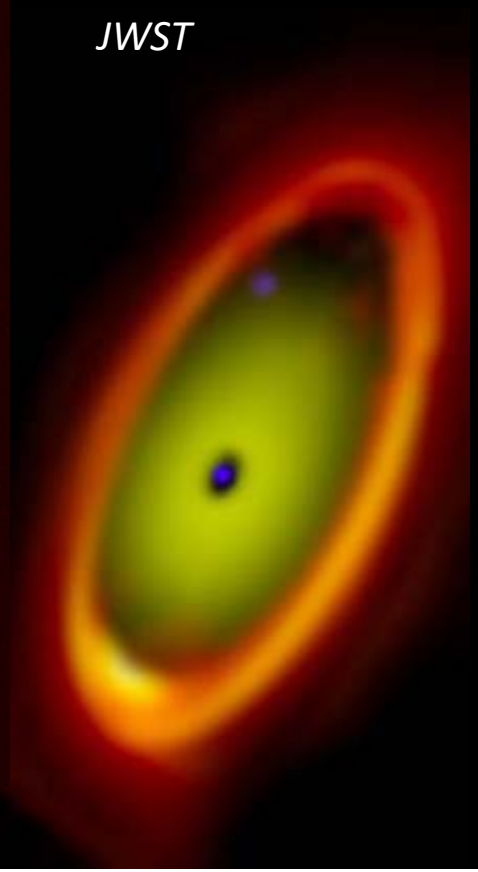
Beichman et al 2005; Lisse et al 2007



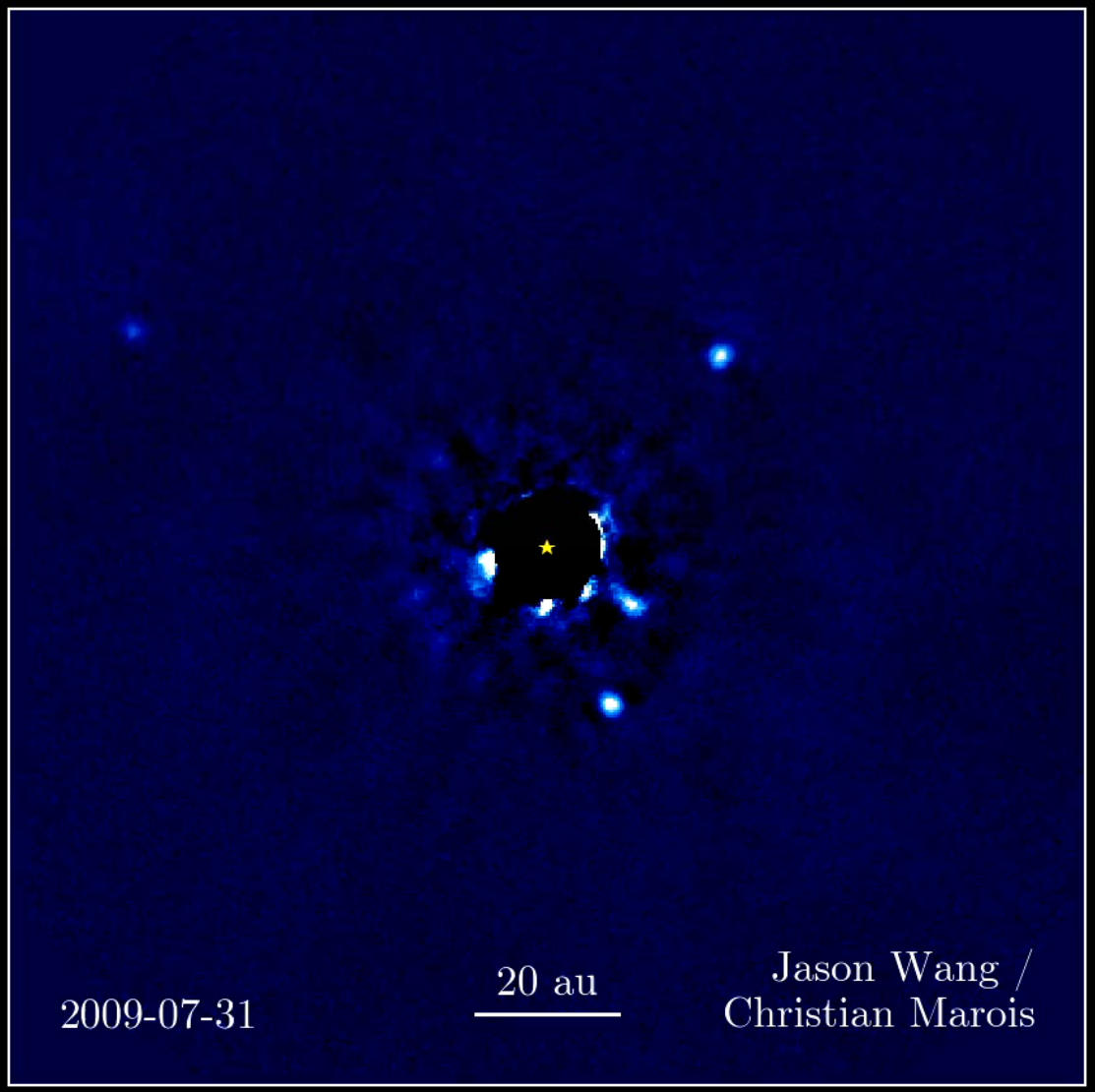
Kuiper Belts, Asteroid Belts & Planets (?)



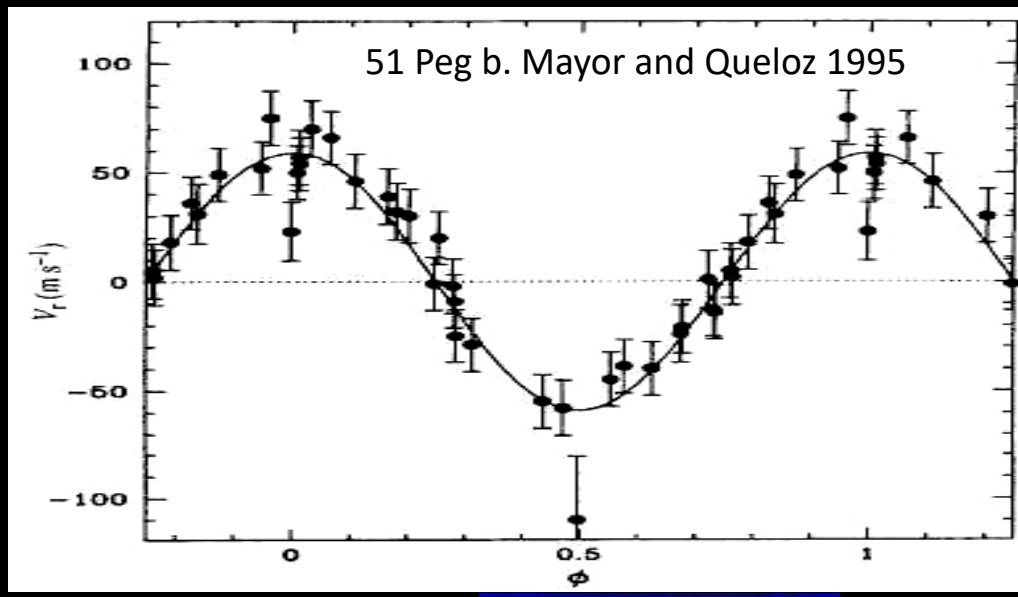




7 Years of Keck Data Reveal Orbits of HR8799 Planets



The "Annus Mirabilis" of Exoplanet Science --- 1995



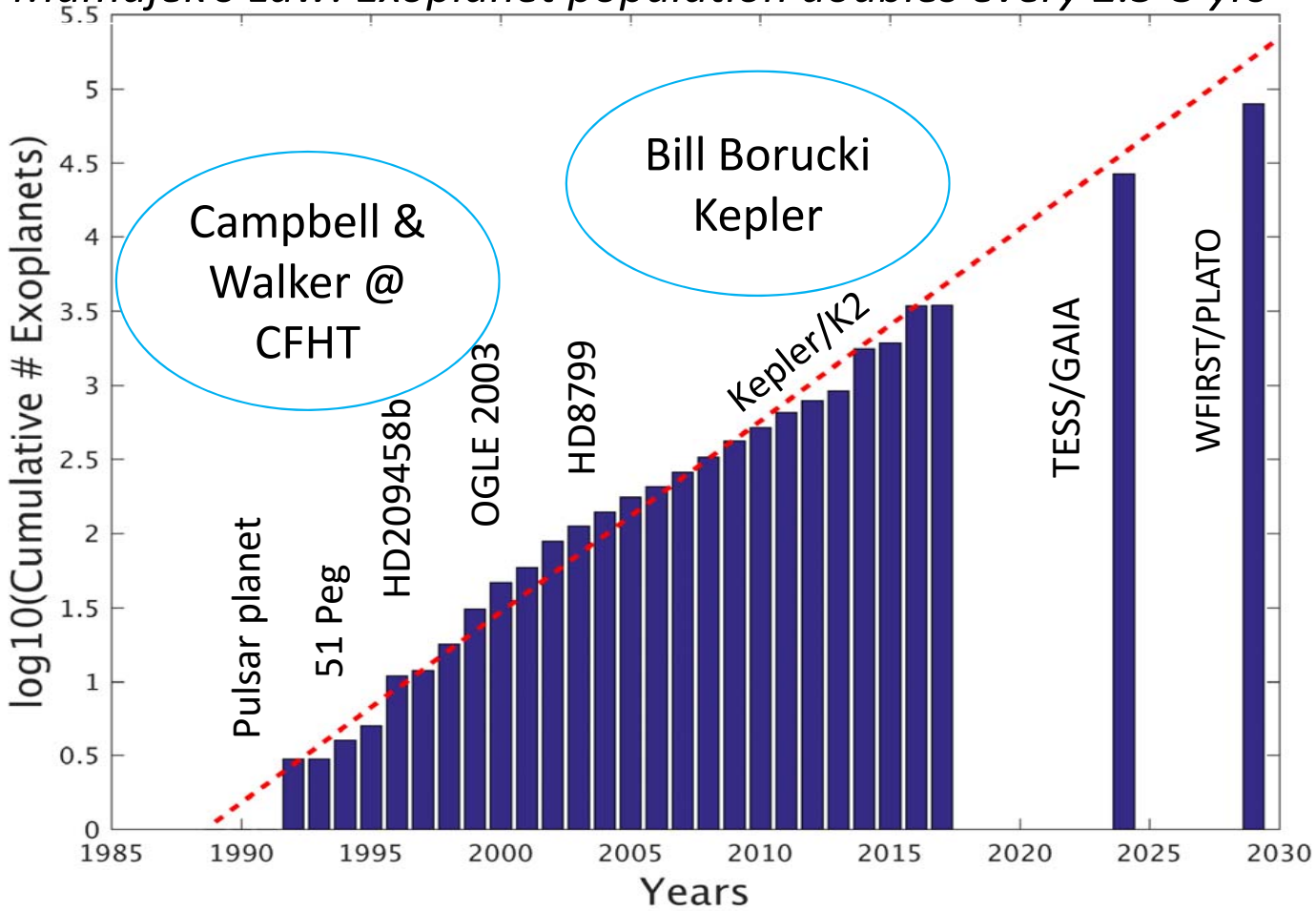
Intense interest by Clinton Administration. Clinton's spin doctor, Dick Morris, leaked Mars Rock story to a $200-an-hour call girl.

"The Rock from Mars: A Detective Story on Two Planets" Kathy Sawyer. (2006)

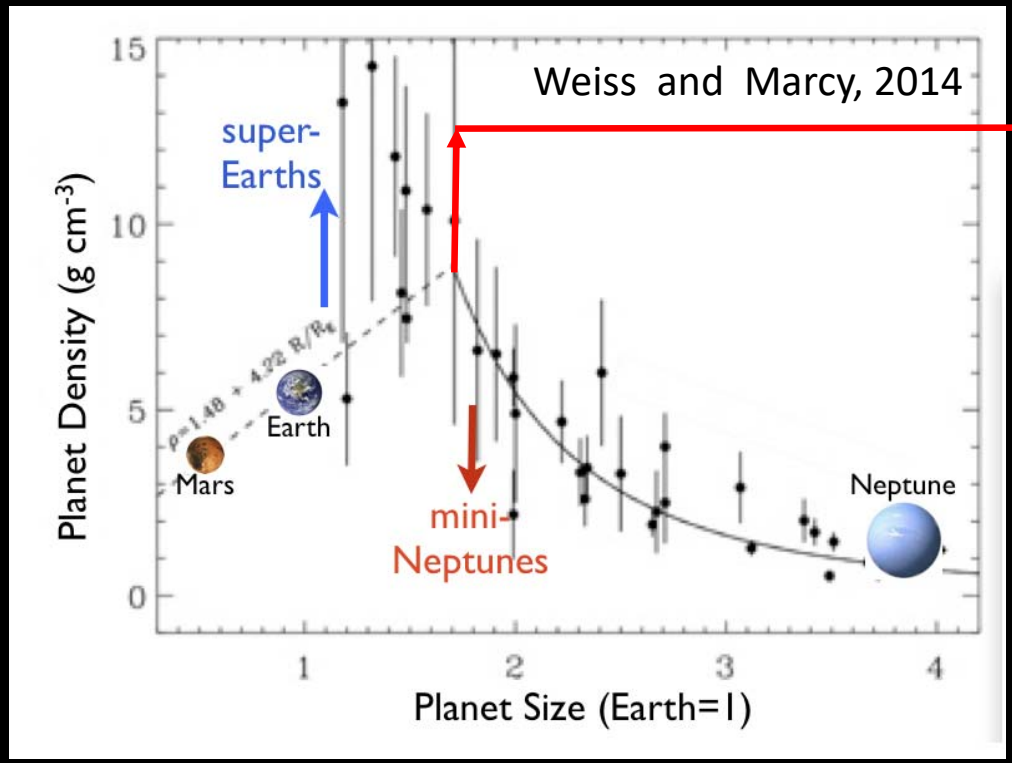
Finding & Characterizing Earths: Circa 2000

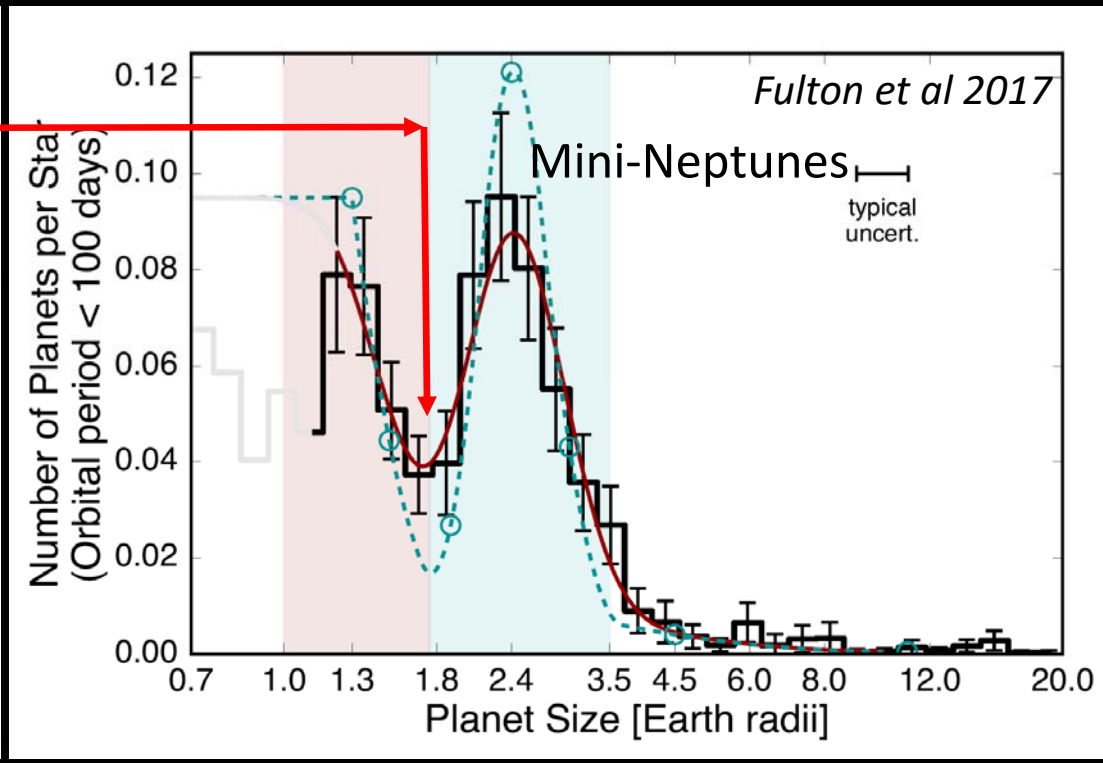
Exoplanet Demographics

Mamajek's Law: Exoplanet population doubles every 2.5-3 yrs



Initial Characterization of Bulk Properties of Kepler Planets





500 Hours of Spitzer Observations of *2MASS* J23062928-0502285, aka TRAPPIST-1

"All the News That's Fit to Print"

The New York Times

Late Edition

Today, patchy morning fog, partly sunny, warm, high 64. Tonight, mostly cloudy, mild, low 52. Tomorrow, clouds and sunshine, showers, high 66. Weather map is on Page B9.

VOL. CLXVI ... No. 57,517 © 2017 The New York Times Company NEW YORK, THURSDAY, FEBRUARY 23, 2017 $2.50

JPL-CALTECH/NASA

A rendering of newly discovered Earth-size planets orbiting a dwarf star named Trappist-1 about 40 light-years from Earth. Some of them could have surface water.

TRUMP RESCINDS OBAMA DIRECTIVE ON BATHROOM USE

ENTERING CULTURE WARS

Question of Transgender Rights Splits DeVos and Sessions

This article is by Jeremy W. Peters, Jo Becker and Julie Hirschfeld Davis.

WASHINGTON — President Trump on Wednesday rescinded protections for transgender students that had allowed them to use bathrooms corresponding with their gender identity, overruling his own education secretary and placing his administration firmly in the middle of the culture wars that many Republicans have tried to leave behind.

In a joint letter, the top civil rights officials from the Justice Department and the Education Department rejected the Obama administration's position that nondiscrimination laws require schools to allow transgender students to use the bathrooms of their choice.

That directive, they said, was improperly and arbitrarily devised, "without due regard for the primary role of the states and lo-

Circling a Star Not Far Away, 7 Shots at Life

By KENNETH CHANG

Uber's Culture Of Gutsiness Under Review

By MIKE ISAAC

Migrants Hide, Fearing Capture on 'Any Corner'

By VIVIAN YEE

No going to church, no going to the store. No doctor's appointments for some, no school for others. No driving, period — not

IMMIGRATION A police department worries a crackdown will harm work to fight gangs. PAGE A14

MEXICO The secretary of state pays a visit at a time of rising

duras.

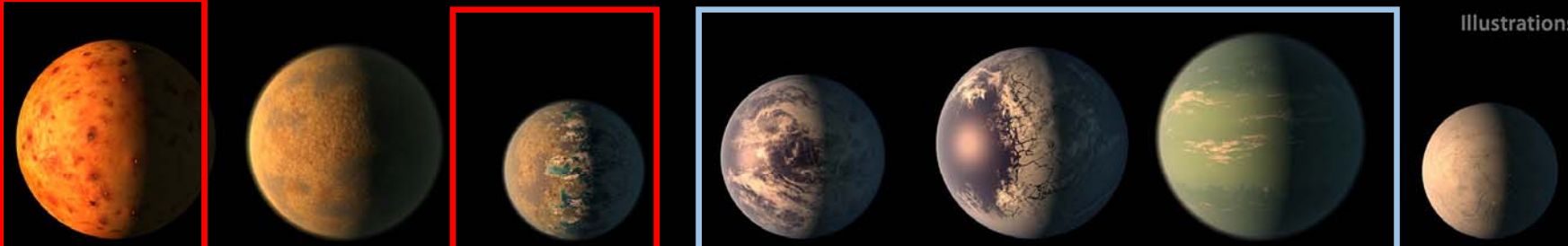
If deportation has always been a threat on paper for the 11 million people living in the country illegally, it rarely imperiled those who did not commit serious crimes. But with the Trump ad-

Gilllon et al 2016, 2017

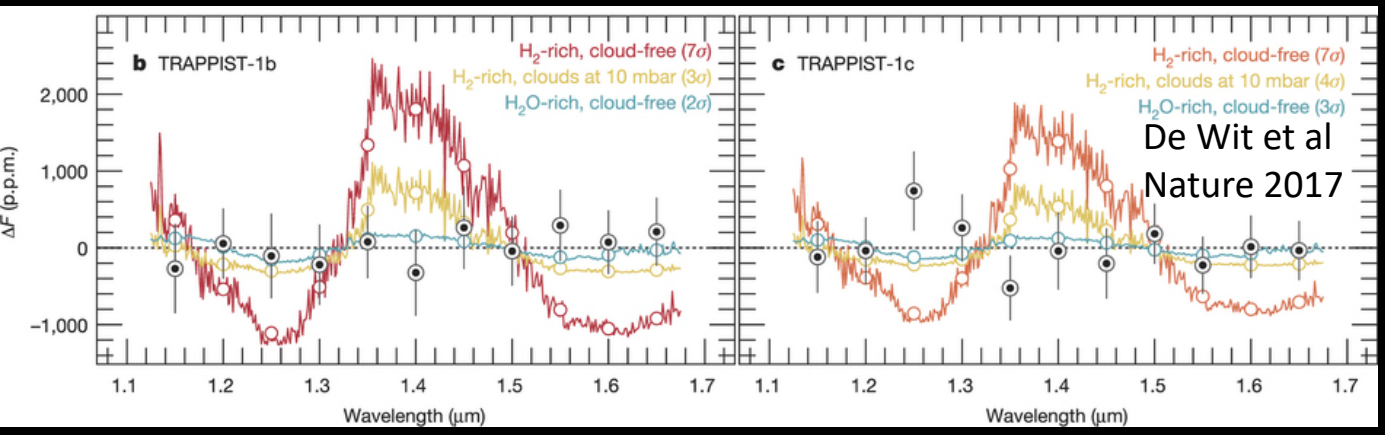
The Trappist-1 System

Habitable Zone Temperatures

Illustrations



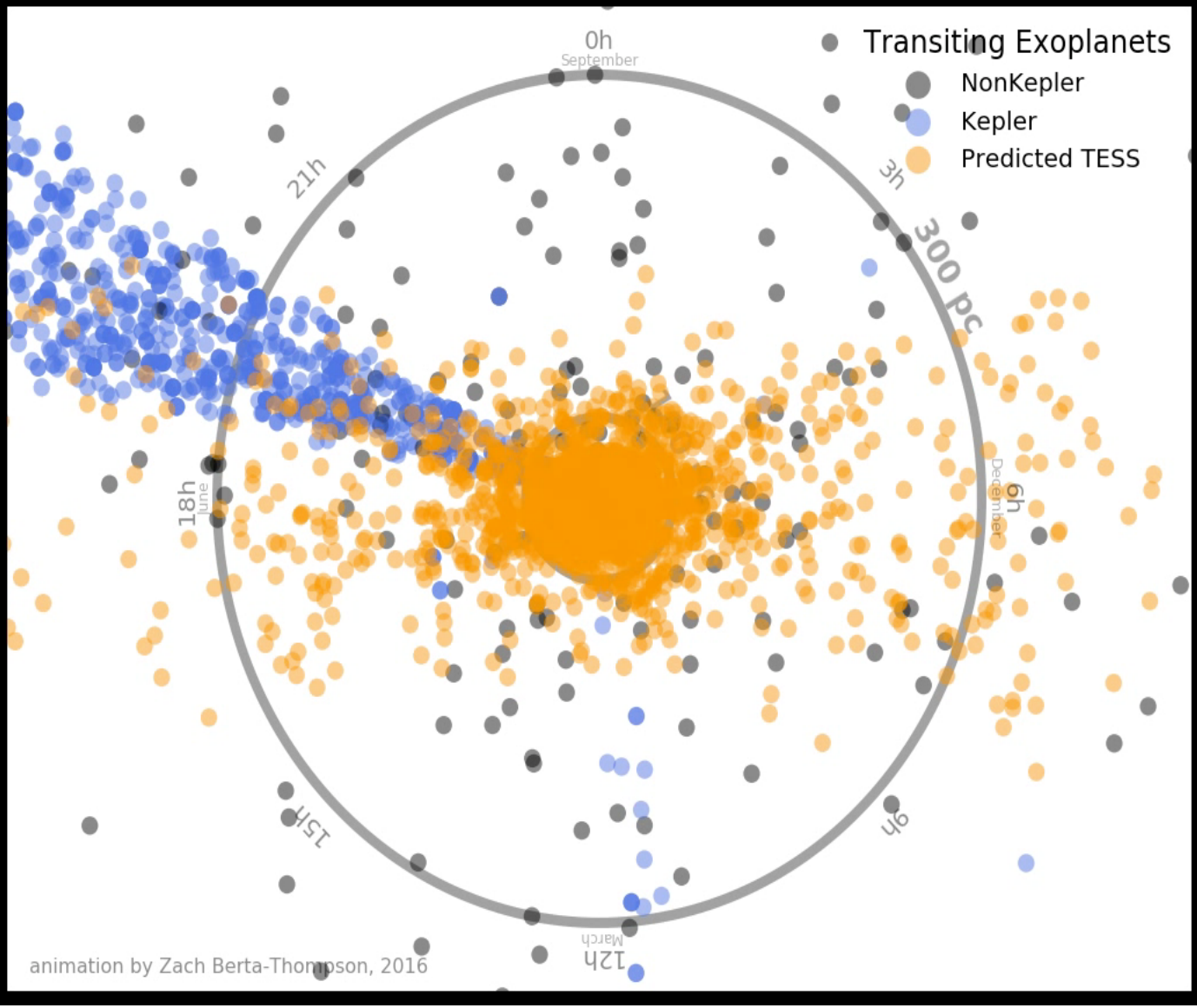
TRAPPIST-1 System	b	c	d	e	f	g	h
Orbital Period *days*	1.51 *days*	2.42 *days*	4.05 *days*	6.10 *days*	9.21 *days*	12.35 *days*	~20 *days*
Distance to Star *Astronomical Units (AU)*	0.011 *AU*	0.015 *AU*	0.021 *AU*	0.028 *AU*	0.037 *AU*	0.045 *AU*	~0.06 *AU*
Planet Radius *relative to Earth*	1.09 R_{earth}	1.06 R_{earth}	0.77 R_{earth}	0.92 R_{earth}	1.04 R_{earth}	1.13 R_{earth}	0.76 R_{earth}
Planet Mass *relative to Earth*	0.85 M_{earth}	1.38 M_{earth}	0.41 M_{earth}	0.62 M_{earth}	0.68 M_{earth}	1.34 $_{earth}$	–



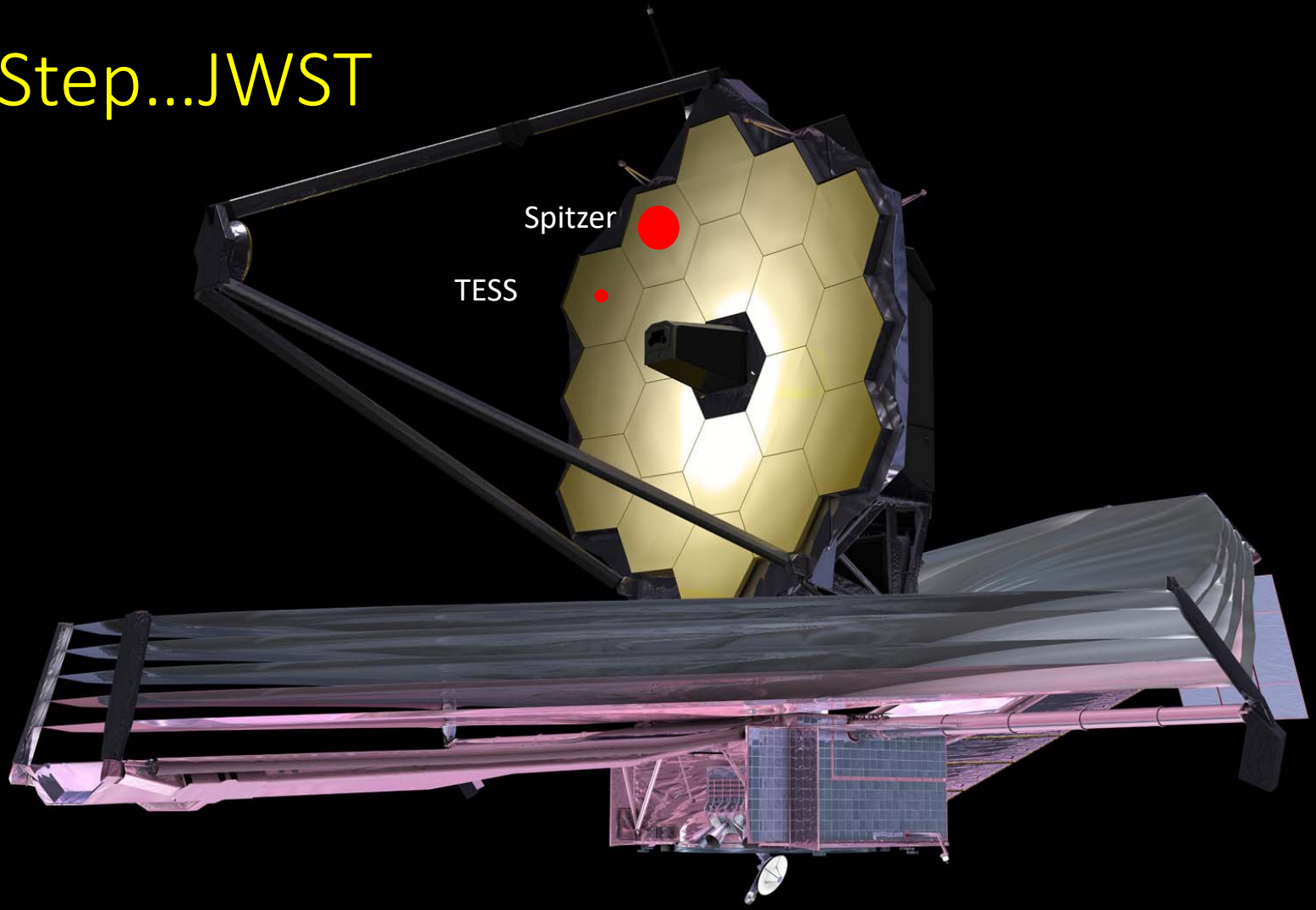
De Wit et al Nature 2017

Featureless spectrum rules out light H2 atmosphere. Possible dense H20-rich atmosphere. Stay tuned for JWST!

TESS. The Next Transit Survey: Finding Targets for JWST

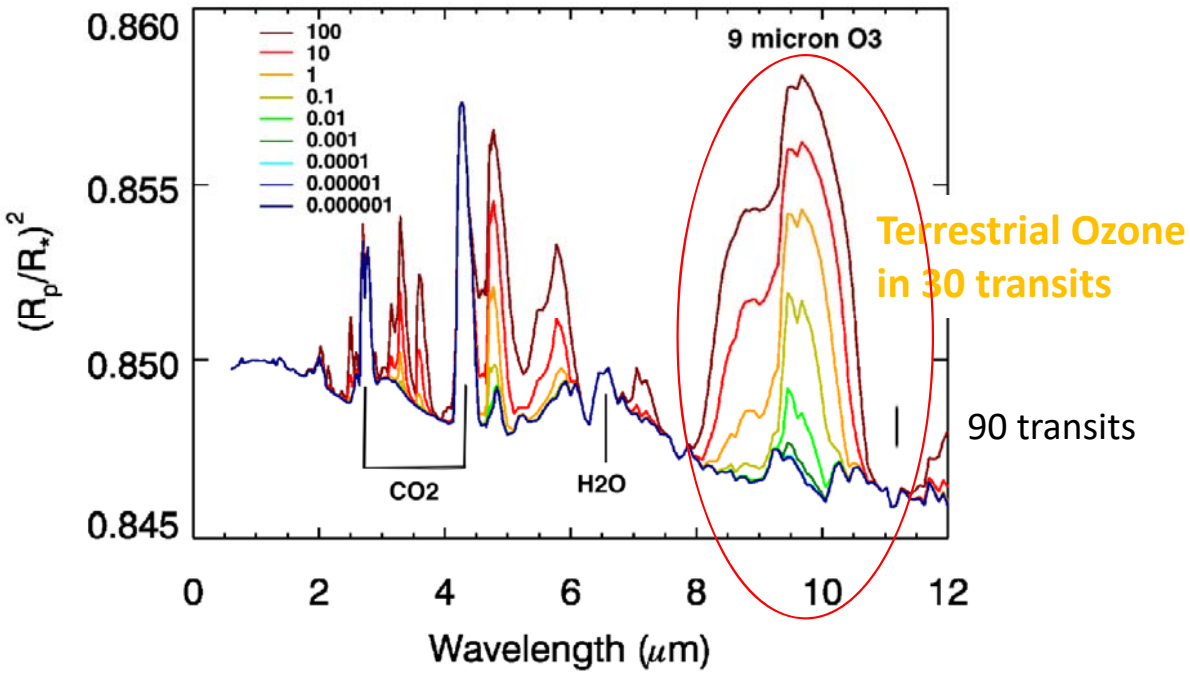


The Next Step…JWST



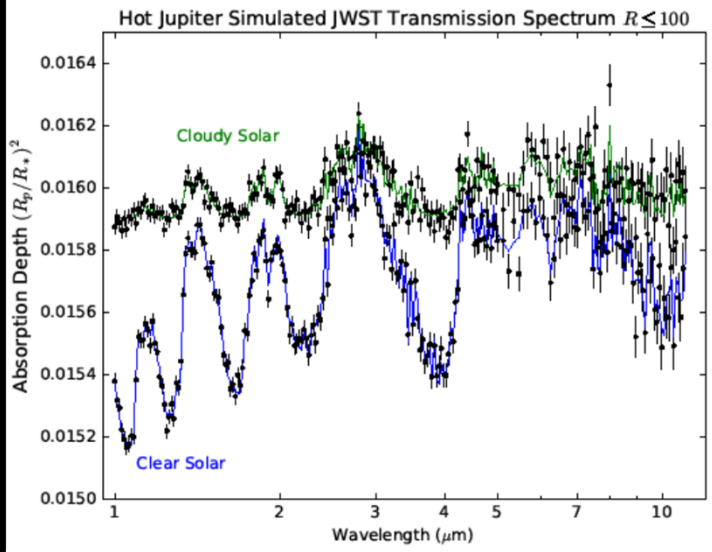
JWST Transit Spectroscopy of Mature Planets

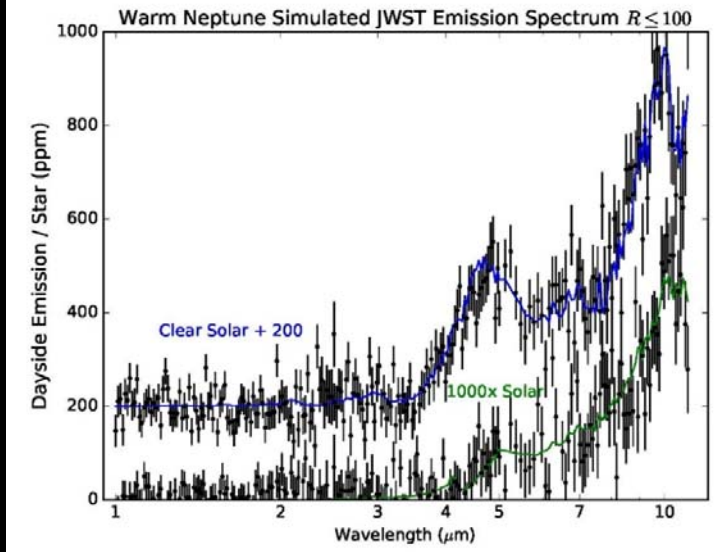
Trappist 1d. Barstow and Irwin 2016



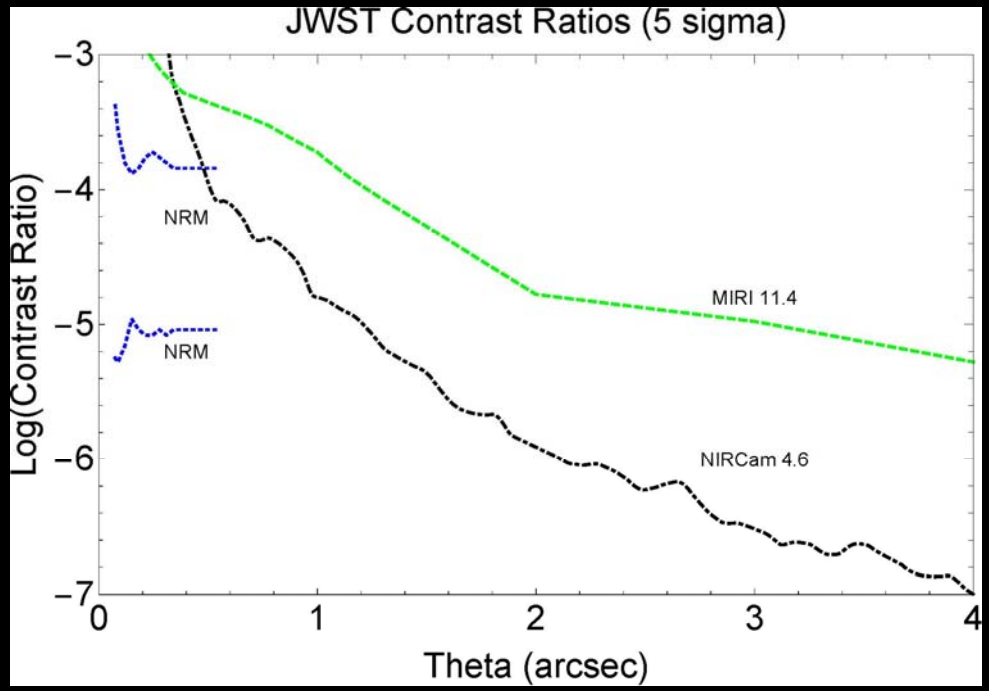
Terrestrial Ozone in 30 transits

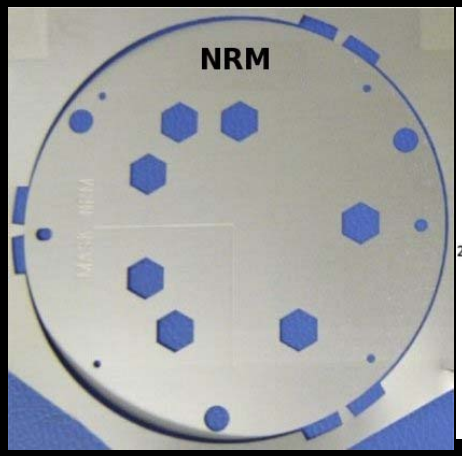
90 transits

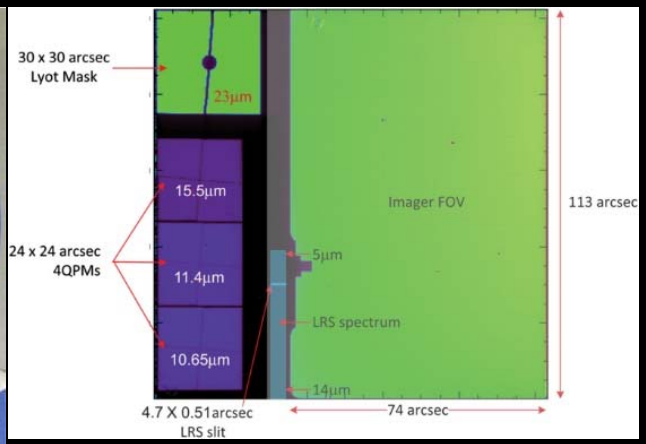




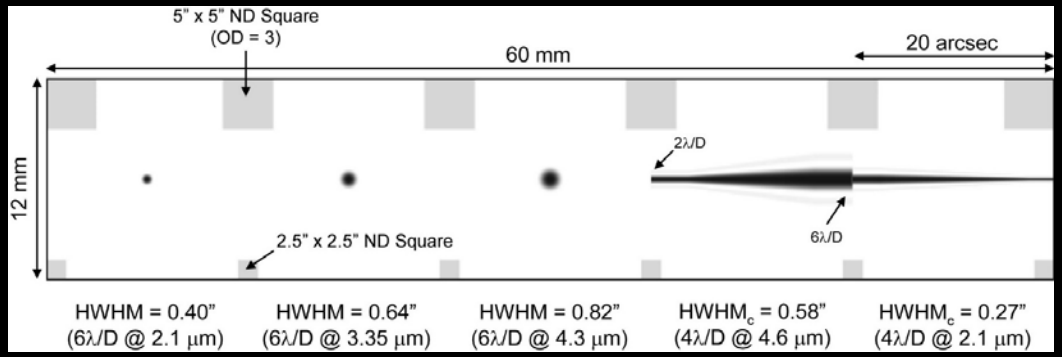
Direct Imaging & Spectroscopy of Young Planets







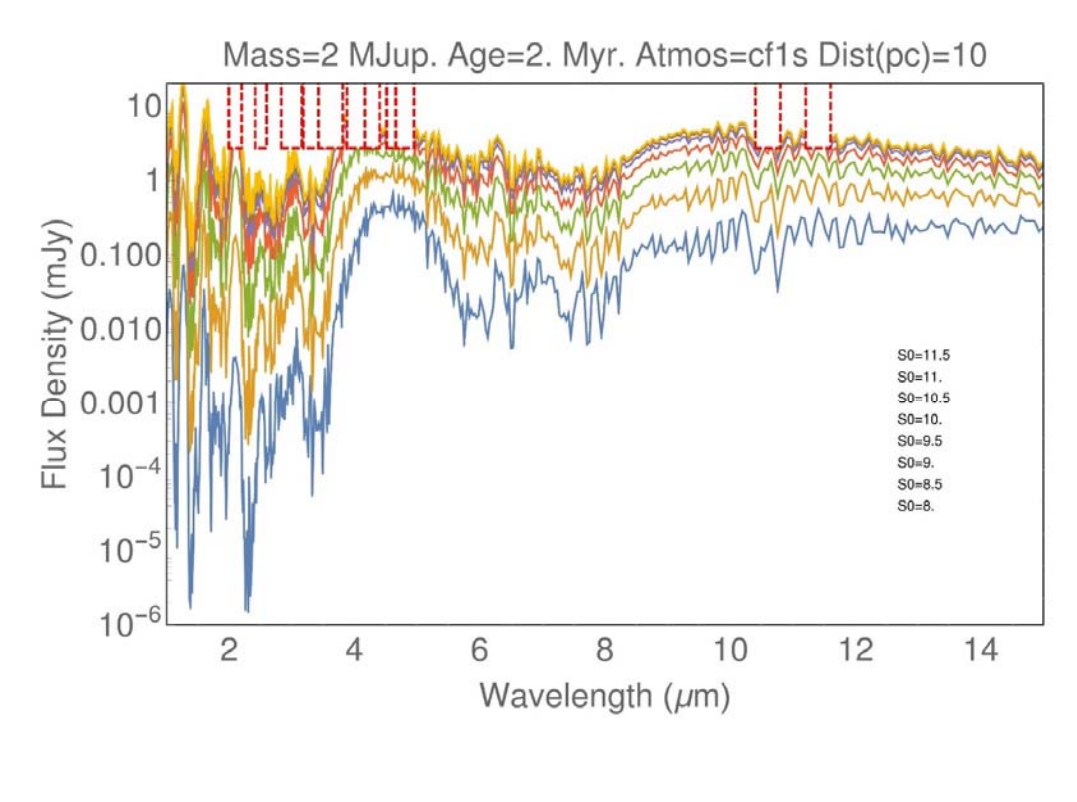
Boccaletti et al 2015



John Krist, Joe Green, Stuart Shaklan, , Bala Balasubramanian

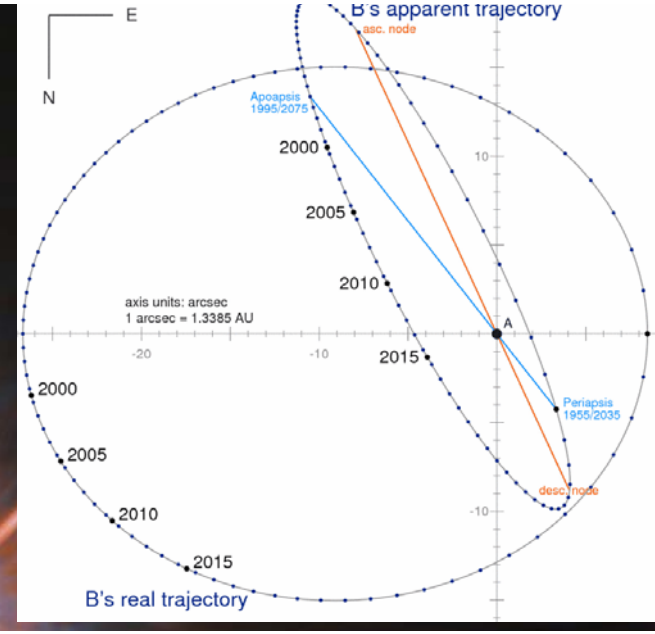
Filter Photometry and Spectroscopy

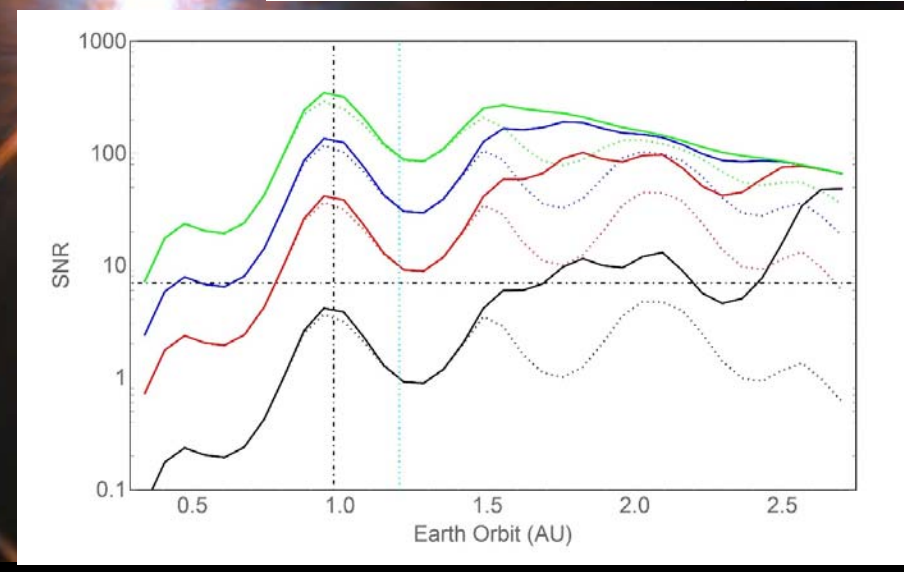
- 2-15 um filter photometry
  - T_{eff}, L_{bol} → Radius & Entropy
  - Composition, CO, CO_2, CH_4, NH_3
- NIRSpec spectra → gravity and composition, atmospheric structure



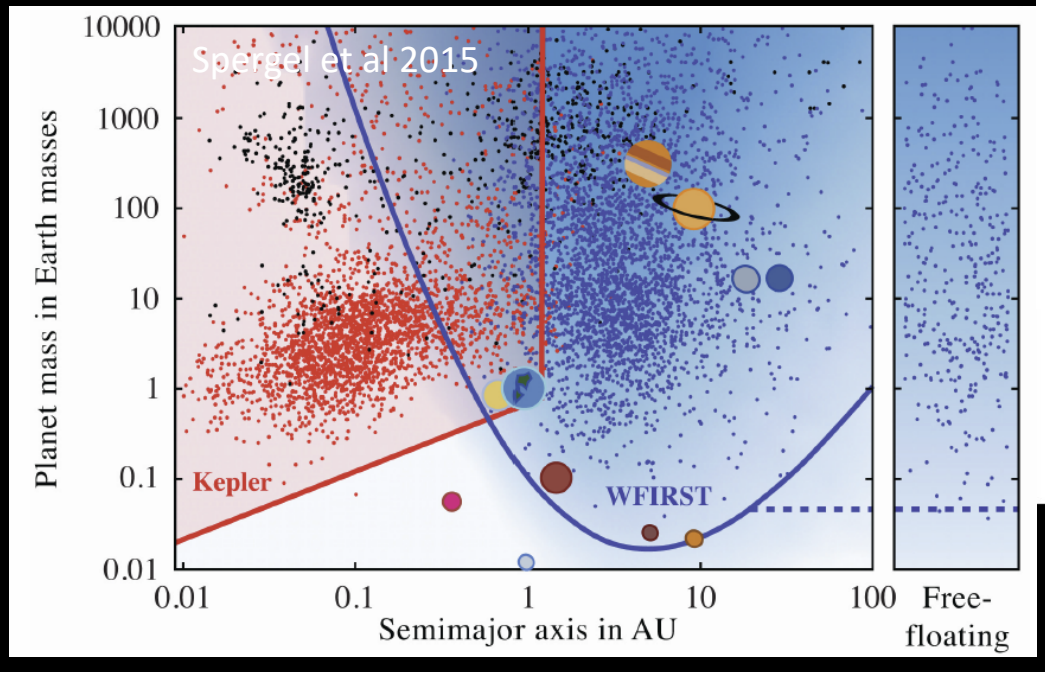
Could JWST Detect An Earth Orbiting Alpha Cen?

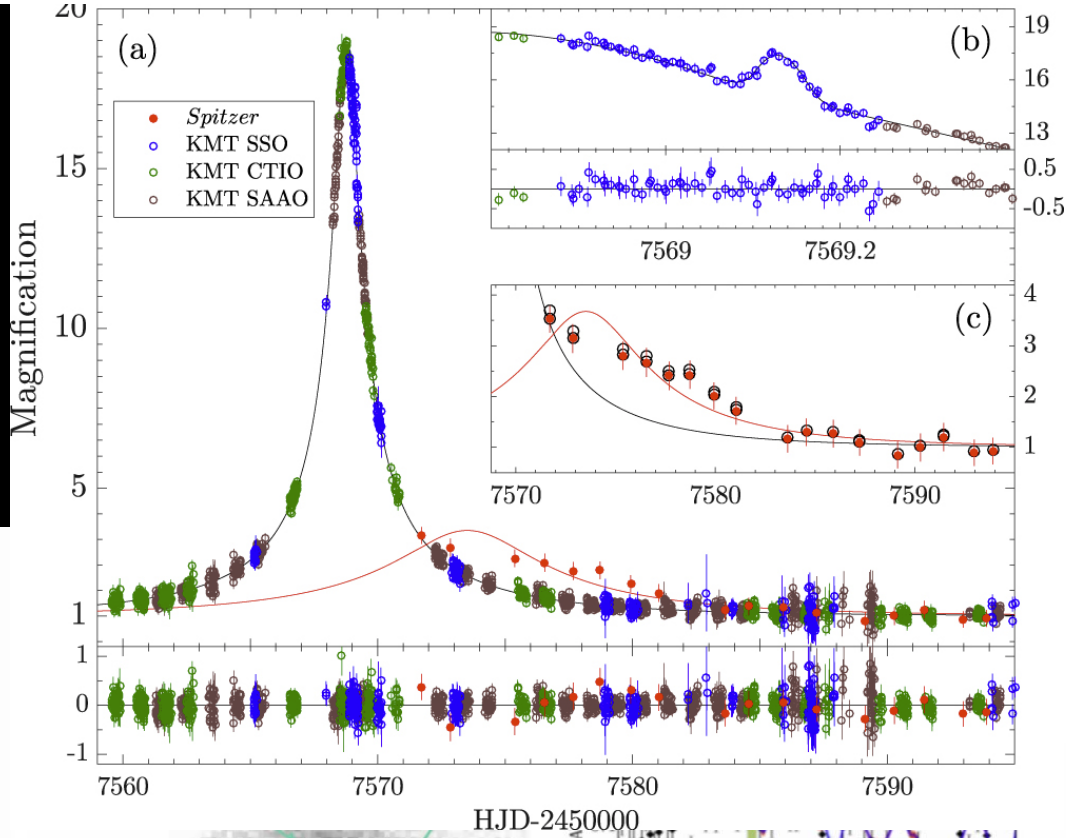
- Earth twin emits ~20 μJy at 11.4 μm detectable with MIRI in 1 hr…Except for α Cen A & B.
- Detectable in 100 hr with super post processing

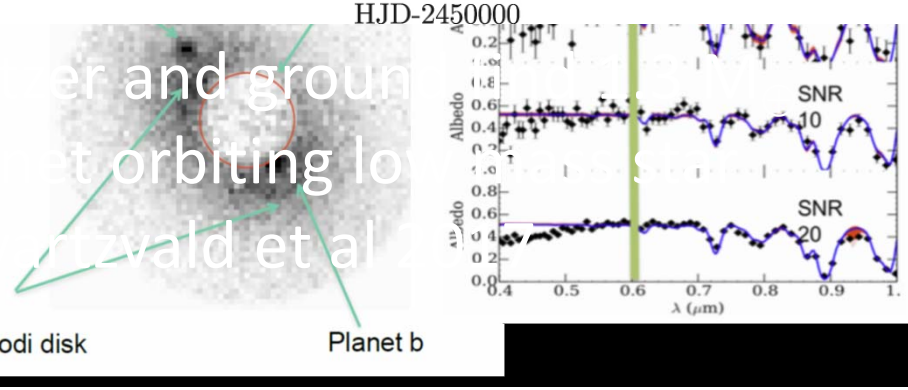




WFIRST --- The Next, Next Step

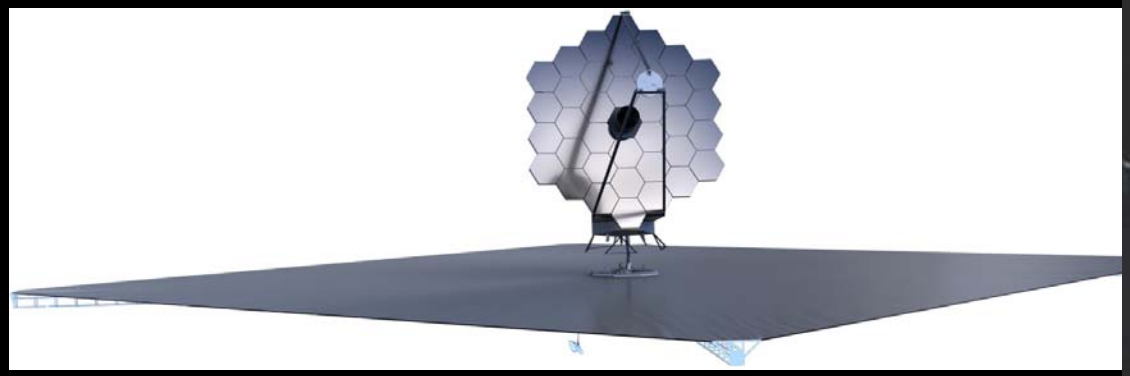






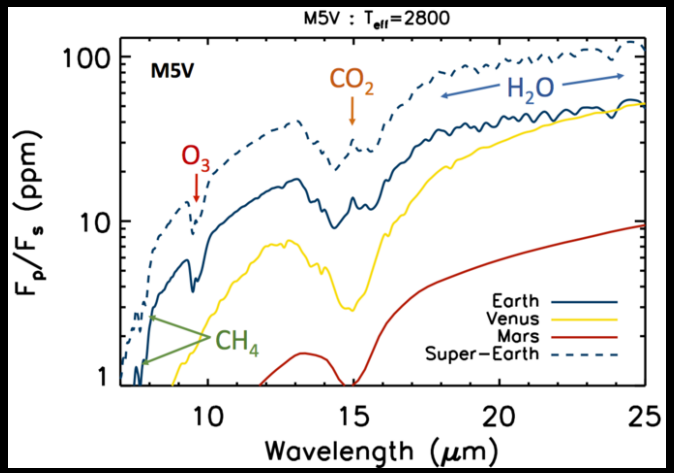
The Next, Next, Next Step

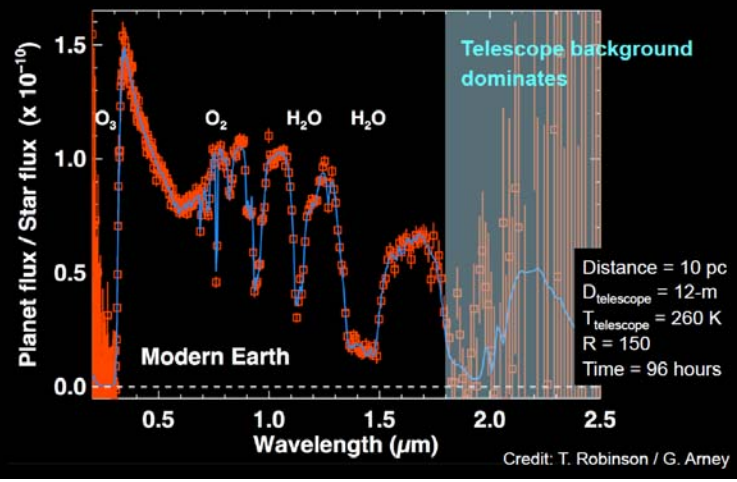
LUVOIR: 9-15 m segmented telescope with an internal coronagraph in UV, visible and NIR



Habitable Exoplanet Imaging Mission (HabEx): 4-6 m monolith with an internal coronagraph or starshade for visible & NIR

Origins Space Telescope (OST): Cooled ~10 m telescope for imaging and transits in mid-IR





In closing this review, we may note with satisfaction how various branches of scientific endeavour, physics, chemistry, geology and technology have united to shed light upon a perplexing and obscure astronomical problem. Although certain aspects of our subject remain unknown as yet, we may anticipate with confidence a completely satisfactory history and description of the atmospheres of **exoplanets**.

R. M Petrie
Dominion Astrophysical Observatory,
Victoria, B.C.
April, 1940.

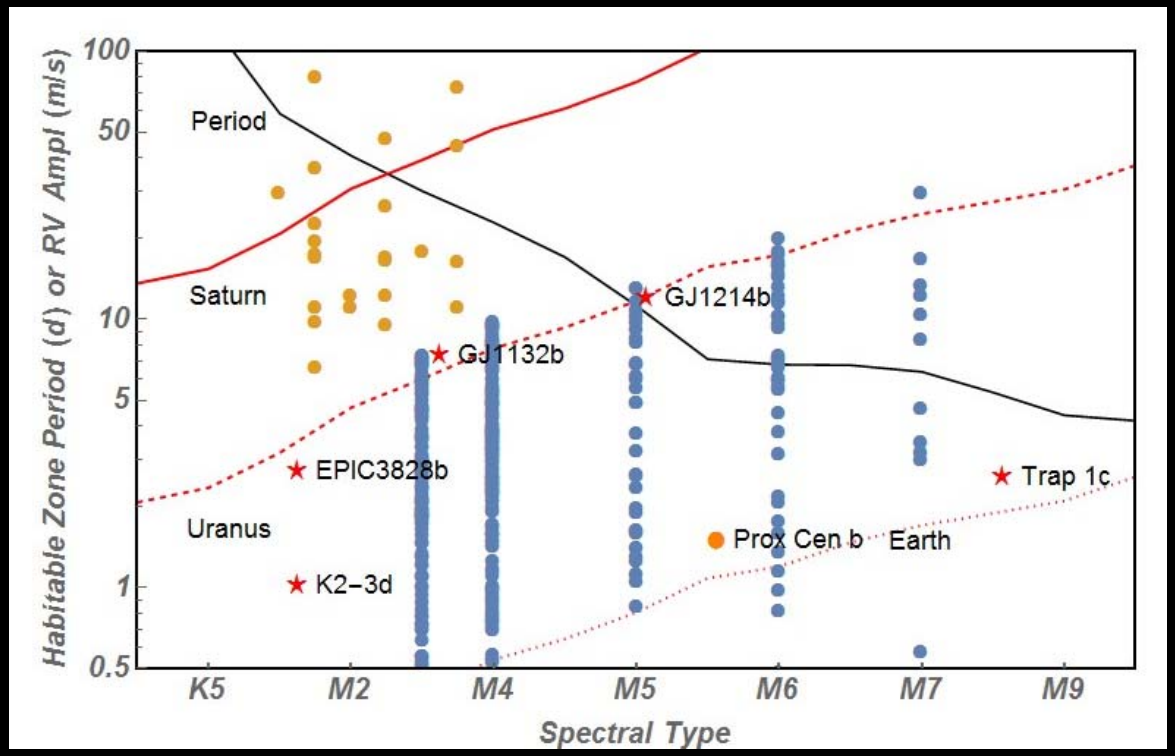
C. Beichman
NASA Exoplanet Science Inst.
Pasadena, CA
May, 2017

Gerry Neugebauer
Frank Low
George Rieke
Peter Martin
Malcolm Fridlund
Marcia Rieke
Annabel Beichman
Charles Elachi
Eric Becklin
Mike Devirian
John Jefferies
Jean Loup Puget
Tom Greene
Susie Burke
Rachel Akeson
Dave Ciardi
Rene Doyon
George Helou
Davy Kirkpatrick
Giovanni Fazio
Roc Cutri
Dawn Gelino
Anne Kinney
Bob Noyes
Arnold and Carroll Beichman

BACKUP

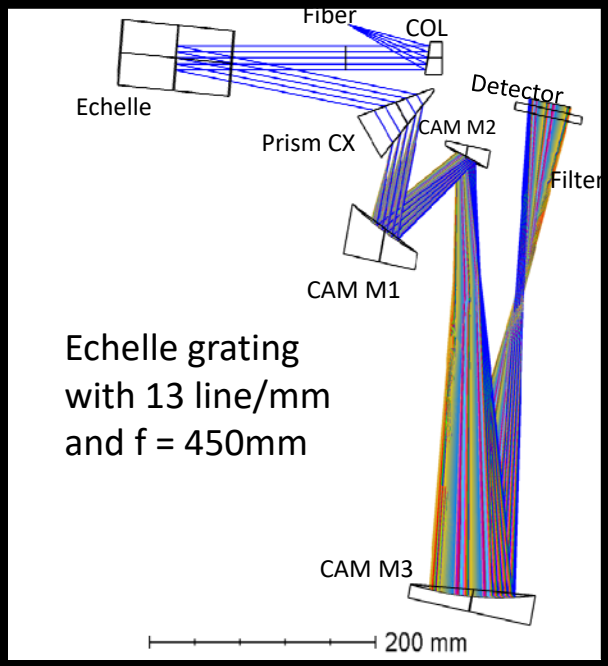
M Stars Favorable for HZ Earths and Super Earths

- Habitable Zone moves in for low Luminosity M stars
- HZ Period decreases leading to larger RV amplitude
- Probability of transit increases as does transit depth for given planet radius
- Lower stellar mass leads to larger RV amplitude for given planet mass

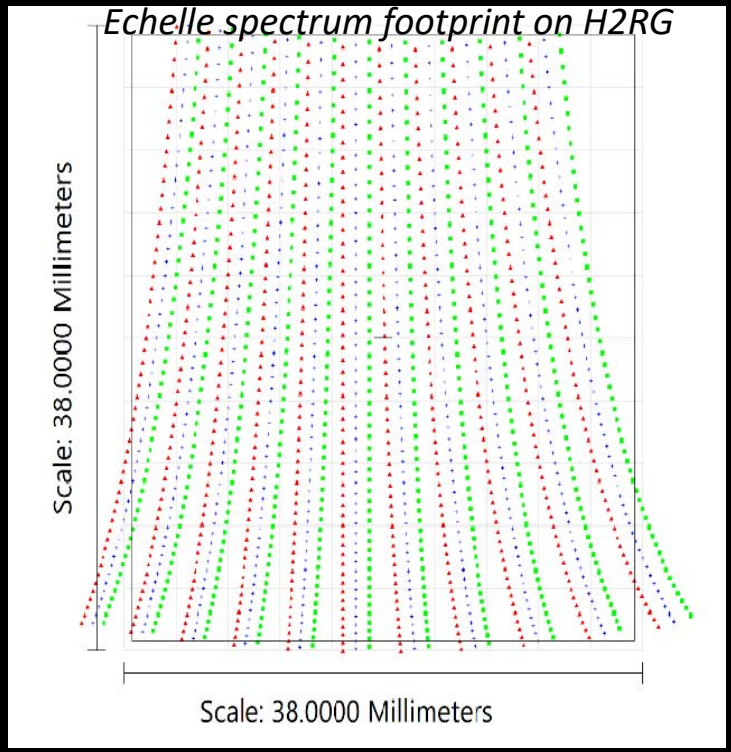


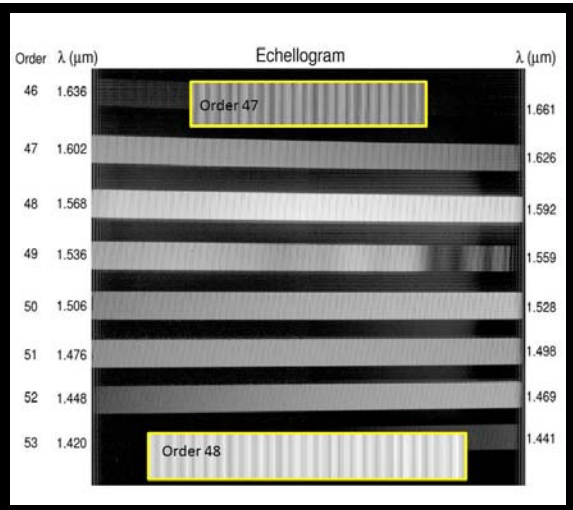
Palomar Radial Velocity Instrument (PARVI)

- Compact design (20x50 cm) uses single mode fiber AO feed
- Highly stable cross-dispersed echelle with R~100,000 at 1-1.6 (2.3) um
- Incorporates LFC for real-time calibration <0.3 m/s (line-referenced) and eventual <0.1 m/s (self-referenced)
- Goal is instrument at <1 m/s



Echelle spectrum footprint on H2RG

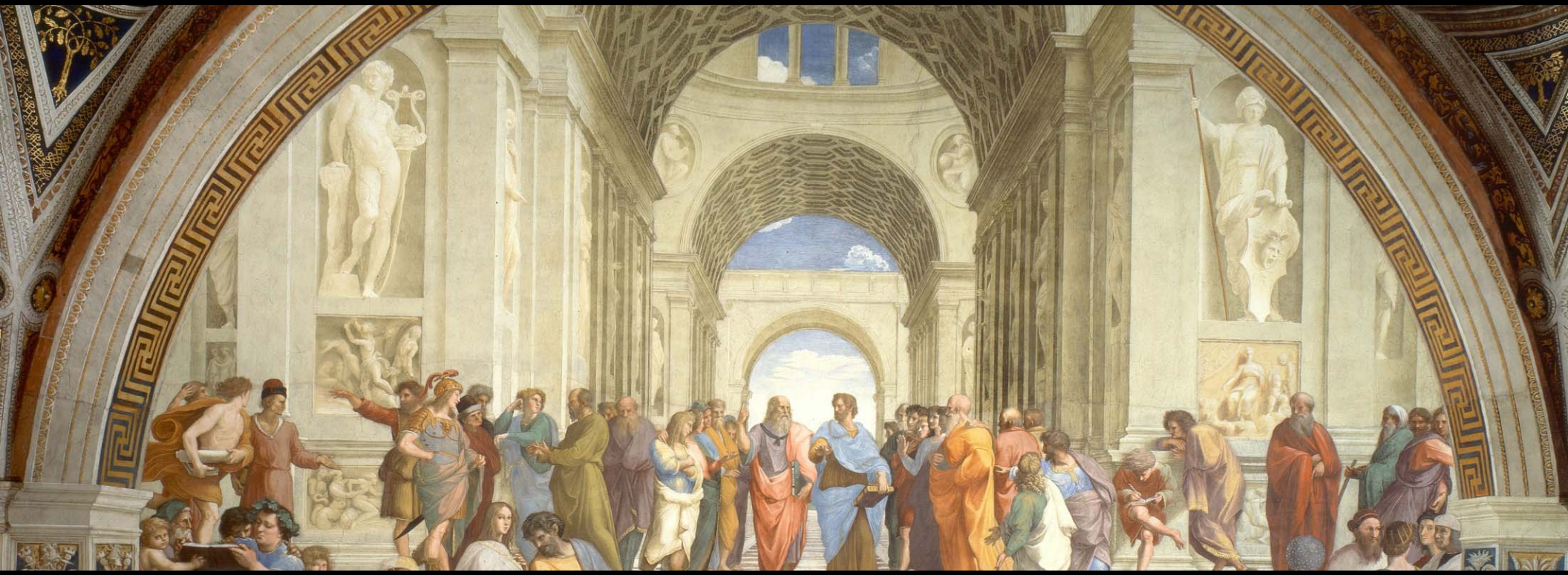




H-band Laser Frequency Comb at NIRSPEC Keck

Wavelength (nm)	Sampling (pixels)	Resolution
1110 (J)	1.62	120,751
1363 (J/H)	1.81	108,335
1790 (H)	2.23	88,266

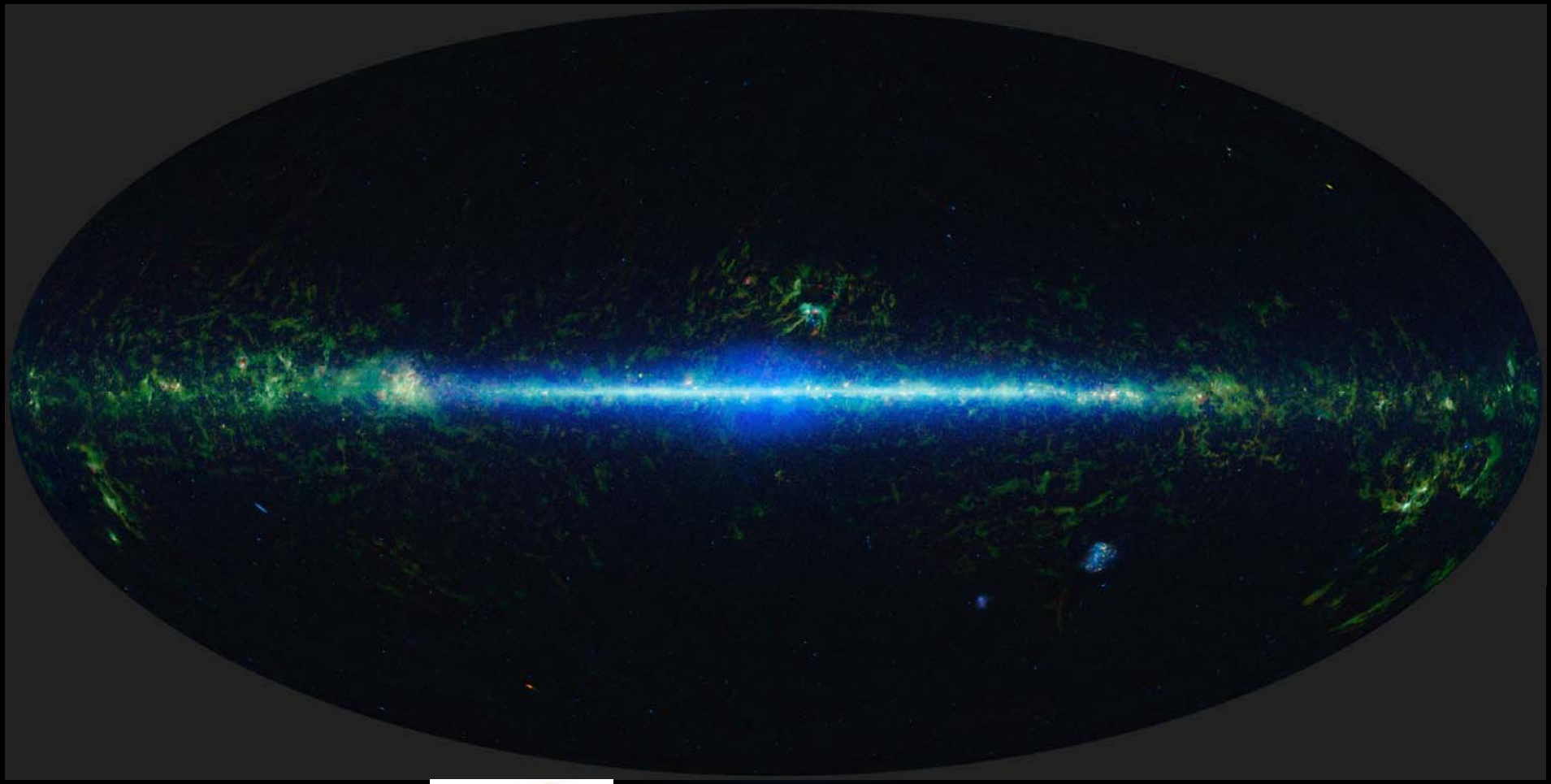
The Search for Other Worlds --- A 2500 Year Quest



"There are infinite worlds both like and unlike this world of ours...We must believe that in all worlds there are living creatures and plants and other things we see in this world."--- Epicurus (c. 300 B.C)

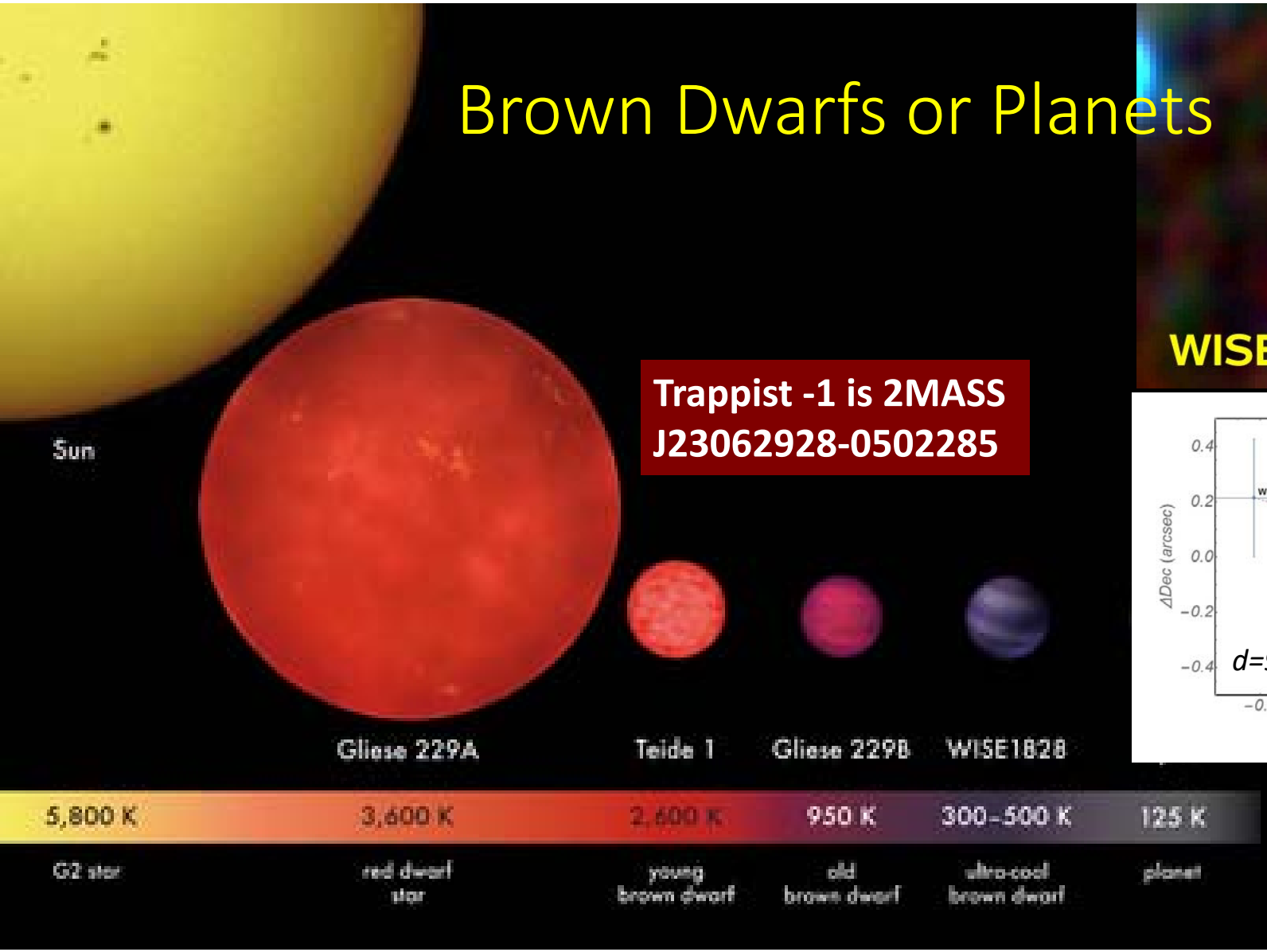
	1970s	1980s	1990s	2000s	2010s	2020s	2030s
Technology or Technique	IR Millimeter Radio	CCD arrays Millimeter Arrays Cryogenic telescopes	IR arrays Iodine cell	AO Coronagraphs Stable spectro-meters IR arrays Drift and L2 orbits	Extreme AO ppm photometry	Starshades Space Coronagraphy ELTs	Extreme Coronagraphy Srarshades
Facility	Ground-based telescopes	IRAS	Hubble Ground-based RV 2MASS ISO	Spitzer	Kepler, WISE GPI/Sphere ALMA TESS & JWST	WFIRST CHEOPS ELTs	LUVOIR or HABEX or OST
Science	High mass protostars Molecular clouds	Low mass protostars Debris disks	RV Planets Disk imaging	Direct Imaged planets Microlensing planets	Census of inner solar system Initial atmospheric char.	Detailed atmospheric char. Census at snowline	Biomarkers and search for life

WISE Covers The Sky

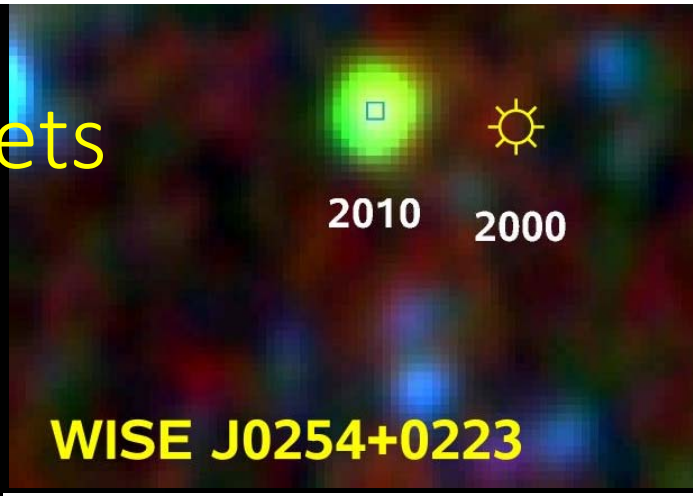


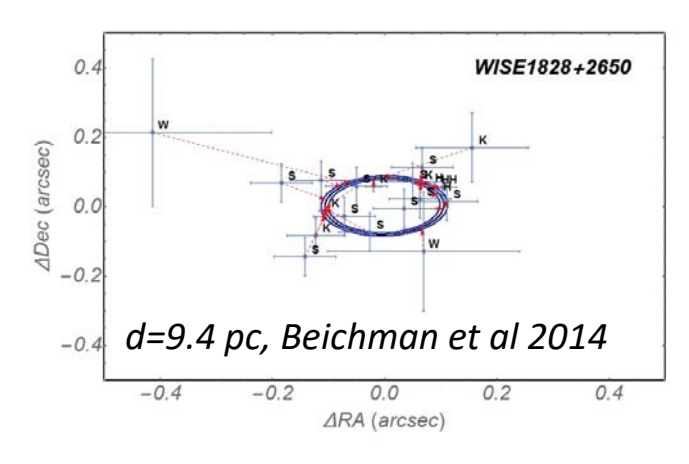
Wide-field Infrared Survey Explorer

Brown Dwarfs or Planets

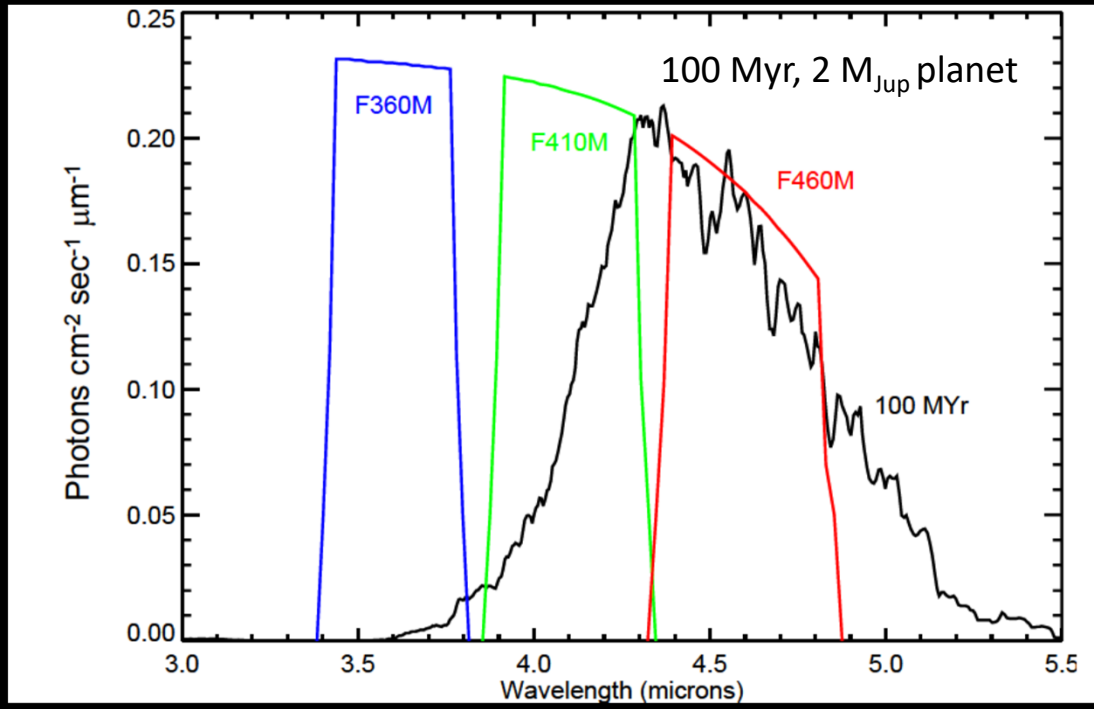


Trappist -1 is 2MASS J23062928-0502285



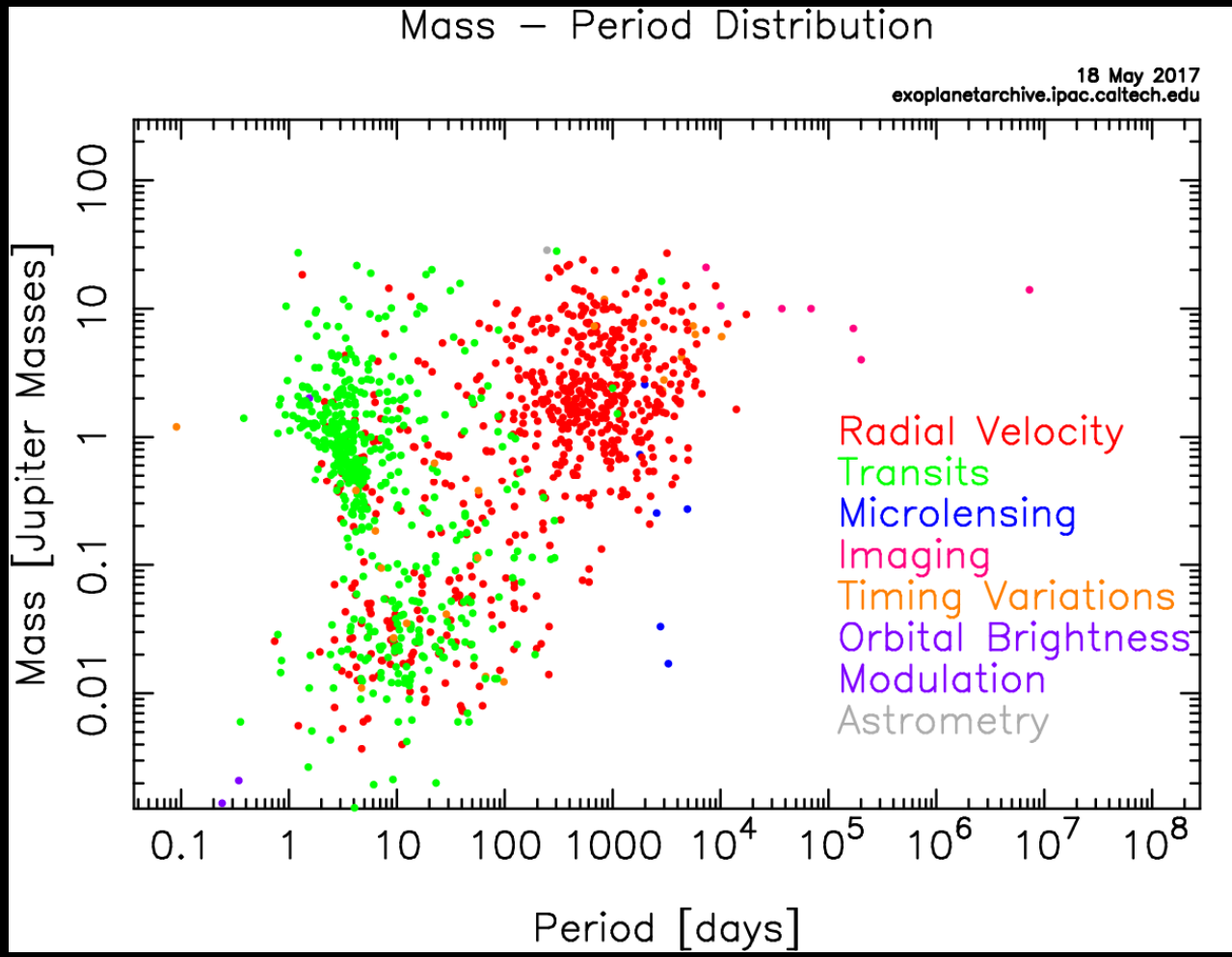


JWST Offers Modest Contrast but High Sensitivity



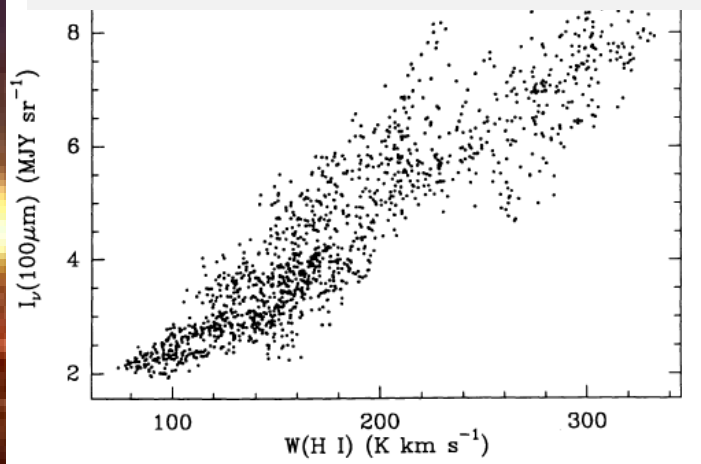
Planet Count

All Exoplanets	**3488**
Radial Velocity	632
Imaging	44
Transiting Exoplanets	2754
Kepler Confirmed	2335
Habitable Zone (HZ)	
(180 K < Teq < 310 K)	290
HZ & R ≤ 1.25 R_{Earth}	22
Kepler Candidates	4496
Transit timing variations	15
Microlensing	46
Astrometry	1
Pulsar timing variations	5
Pulsation timing	2
Eclipse timing variations	8
Orbital brightness vars	6



The Infrared Cirrus---Diffuse ISM Seen by IRAS & DRAO

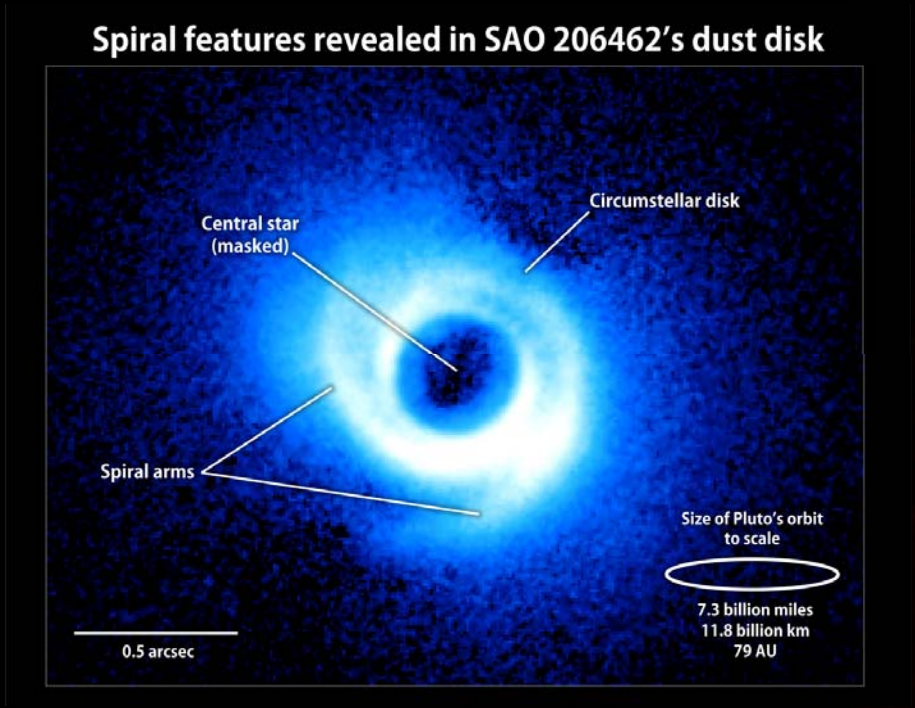
Joncas, Boulanger, Dewdney 1992



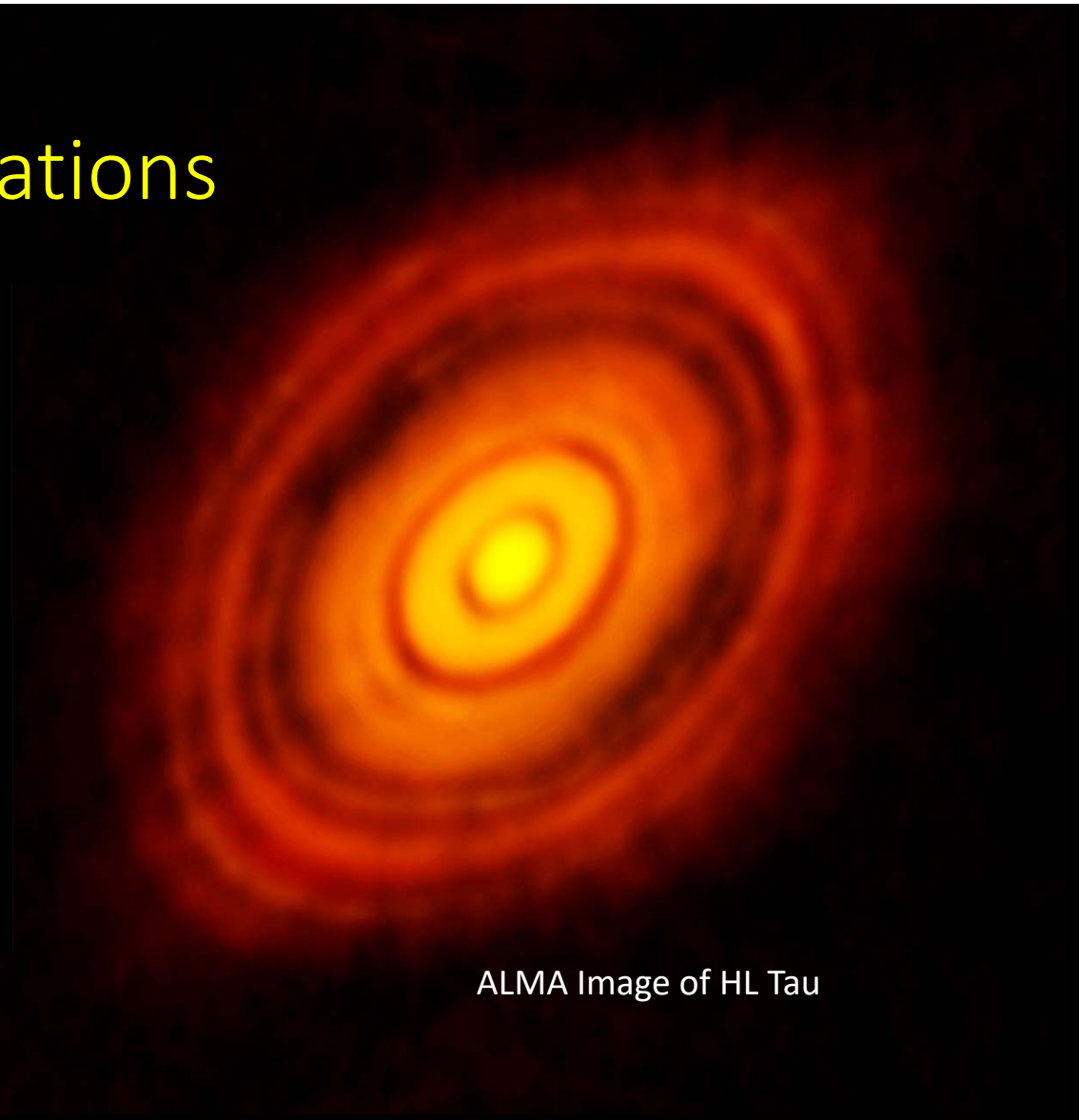
#1 Cited IRAS Paper: *Maps of Dust Infrared Emission for Use in Estimation of Reddening and Cosmic Microwave Background Radiation Foregrounds.* Schlegel *et al* 1998.

Needed for Far-IR Background and Planck B modes limits

These Are Not Simulations



Subaru HiCIAO image of SAO 206462
Muto et al 2012



ALMA Image of HL Tau