Visions of Origins 2020: A 'Post-impressionist' View

Michael R. Meyer
Institute for Astronomy, ETH, Zurich, Switzerland

15 April JWST & ELTs: An Ideal Combination

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Context for ELTs in 2020:

COROT/Kepler results known.

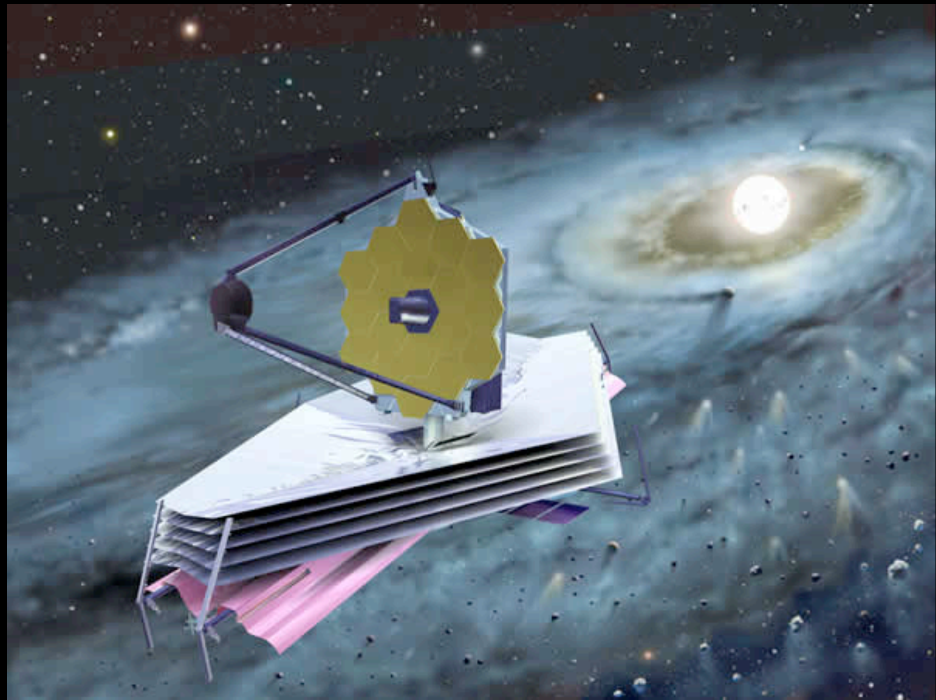
SPHERE/GPI surveys complete.

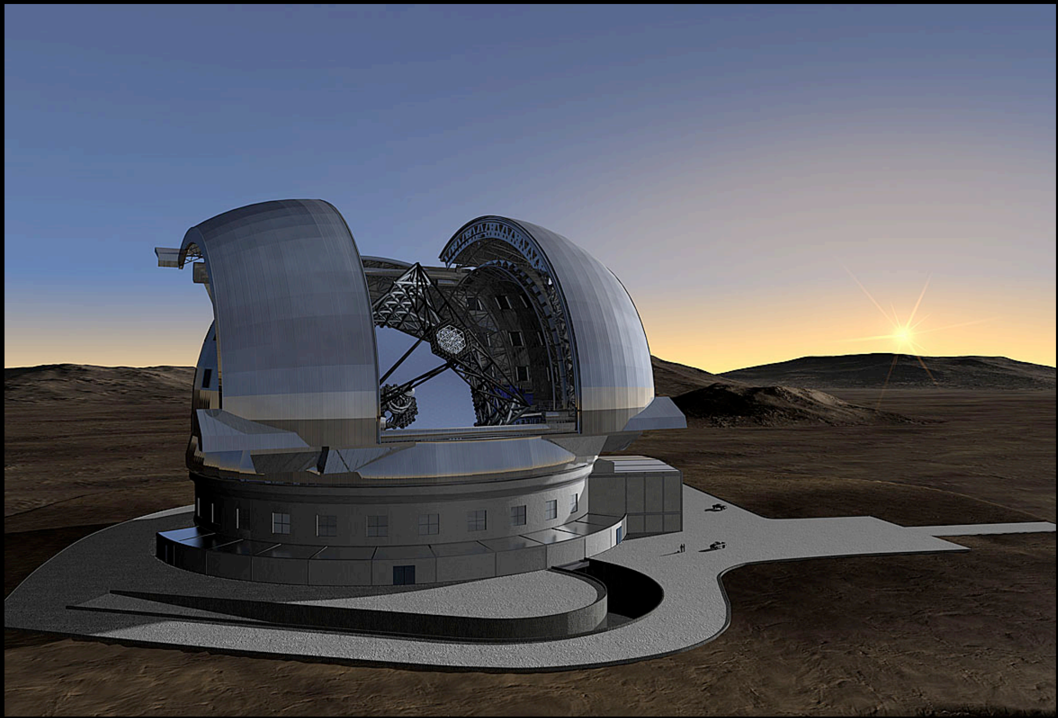
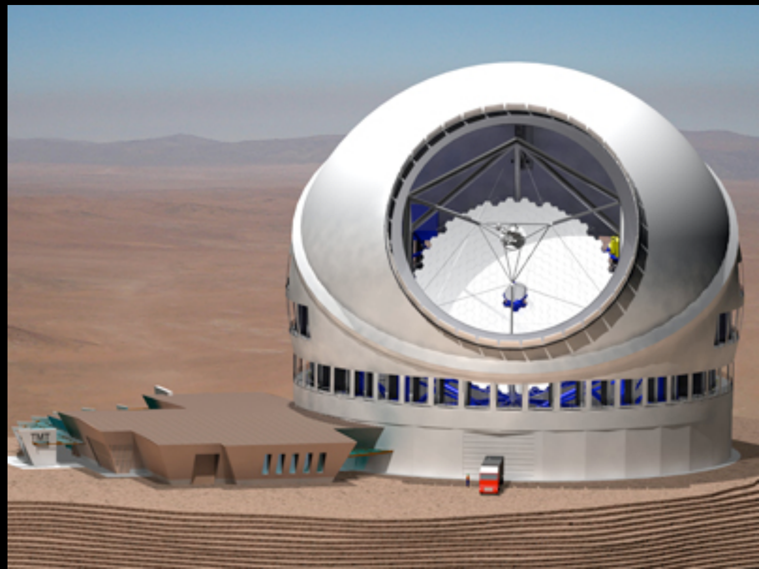
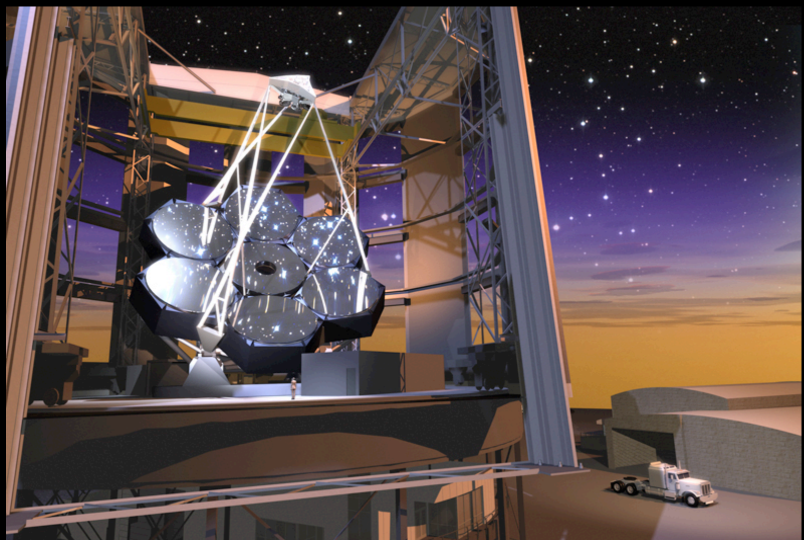
WISE & LSST Surveys Complete.

SOFIA/ALMA normal operations.

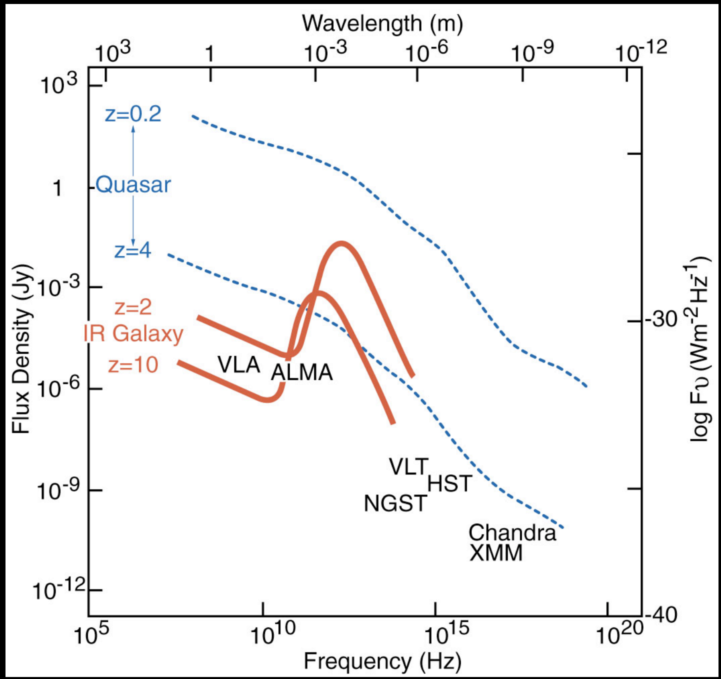
Five years of JWST observations.

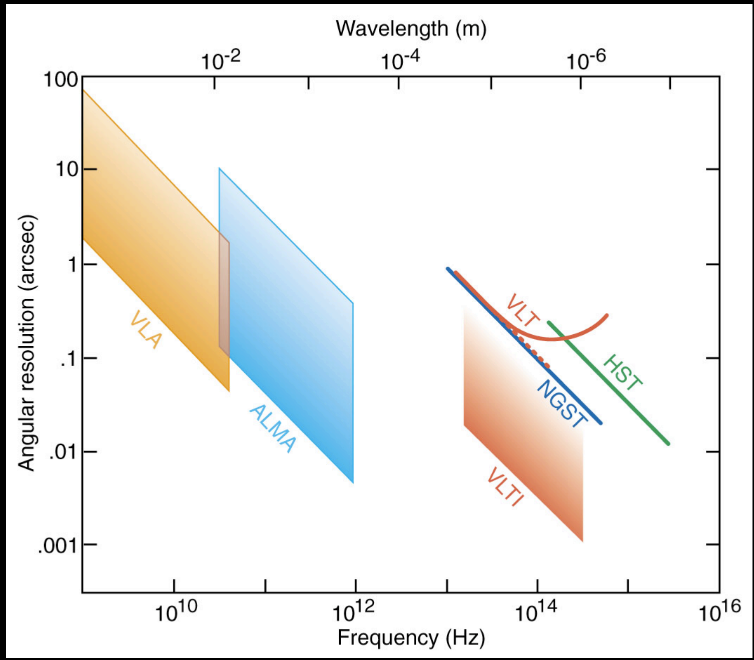
NASA/ESA Probe/“M” Class Missions launched.



2020: Complementary Capabilities:





JWST => sensitivity & field of view.

ELT => resolution (spatial & spectral).

Science Goals Lead to Design Requirements:

Does star formation depend on initial conditions?

Do forming planets contain the ingredients for life?

Are planetary systems like ours common or rare?

Design Requirements: Critical Scales

Physical Resolution: 30 AU (typical binary sep)
5 AU (gas giants like our own)
1 AU (rocky planets)

Spectral Resolution : R = 100 (molecular features)
R = 1000 (atomic features)
R = 10,000 (30 km/sec)
R = 100,000 (3 km/sec)

Field of View: 2' (star clusters within 1 kpc)
1.5" (circumstellar disk at 150 pc)

Design Requirements: Critical Scales

Physical Resolution:		15 pc	50 pc	150 pc	450 pc
JWST	1.65 μm	1 AU	3 AU	10 AU	30 AU
	10 μm	7 AU	20 AU	60 AU	180 AU
ELT	1.65 μm	.2 AU	.5 AU	1.5 AU	5 AU
	10 μm	1 AU	3 AU	10 AU	30 AU

Spectral Resolution :

R = 100 (molecular features)	JWST
R = 1000 (atomic features)	JWST
R = 10,000 (30 km/sec)	ELT
R = 100,000 (3 km/sec)	ELT

Field of View:

2' (star clusters within 1 kpc) JWST

1.5" (circumstellar disk at 150 pc) ELT

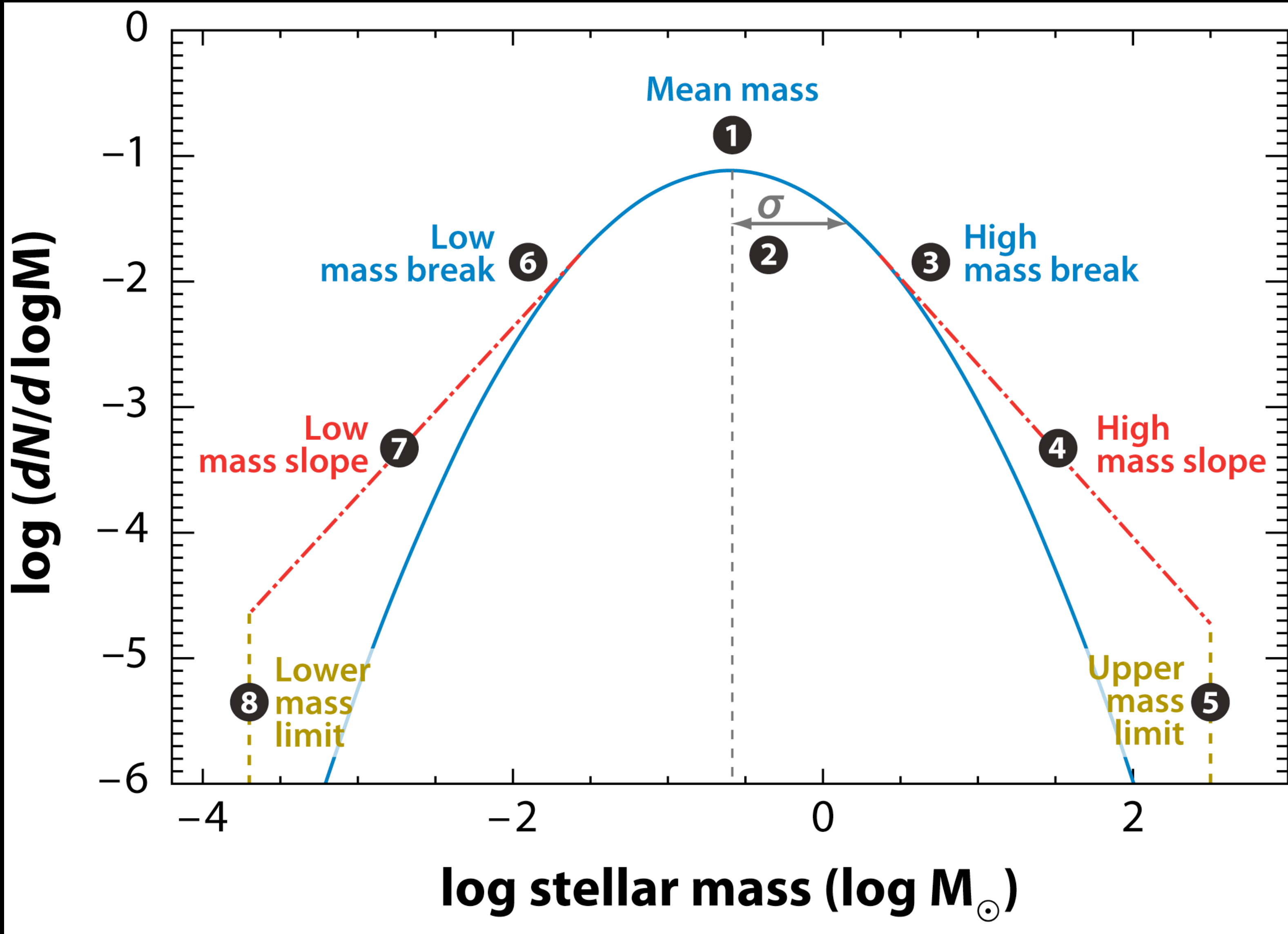
Science Goals Lead to Design Requirements:

Does star formation depend on initial conditions?

Do forming planets contain the ingredients for life?

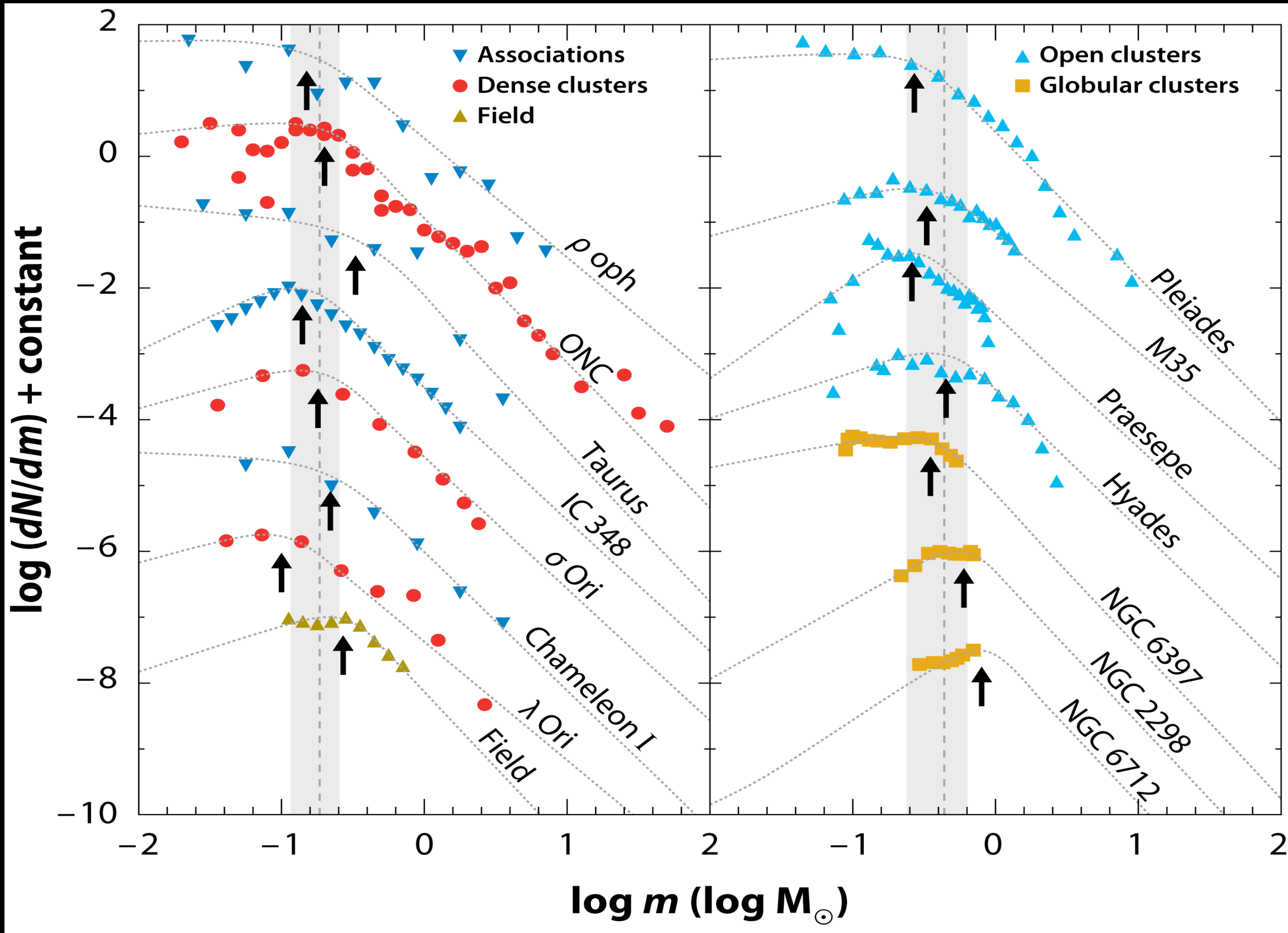
Are planetary systems like ours common or rare?

Initial Mass Function of Stars and Sub-stellar Objects



Bastian, Nate, et al. 2010;
Annu. Rev. Astronomy & Astrophysics vol. 48

Initial Mass Function: Does it Vary with Environment?



Bastian, Nate, et al. 2010;
Annu. Rev. Astronomy & Astrophysics vol. 48

Adapted from de Marchi et al. (2010)

NIRCam Multi-color imaging of Young Clusters

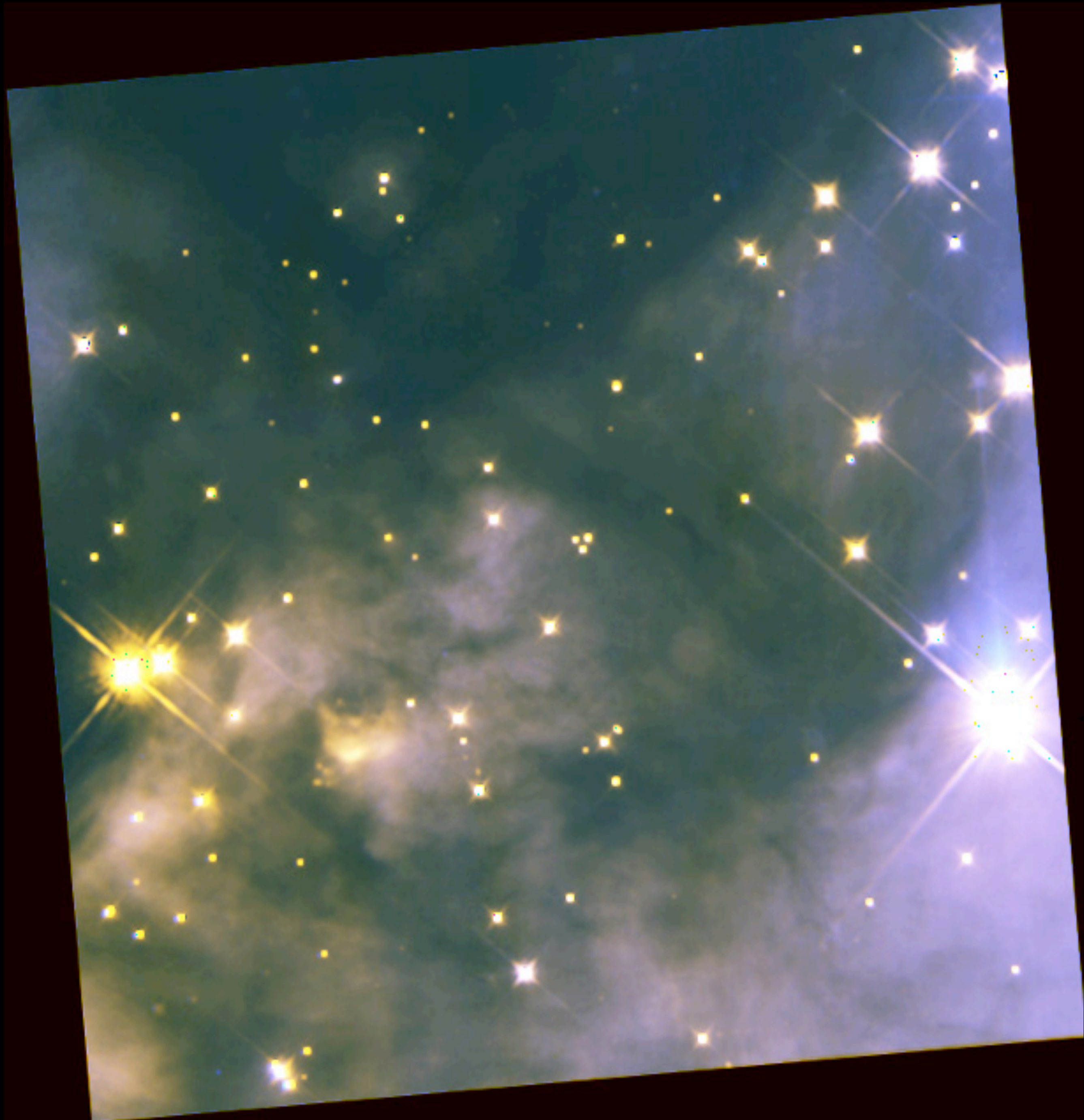
Star Forming Region NGC 1333 Spitzer Space Telescope • IRAC

“Extreme” clusters within Local Group:

Below hydrogen burning limit (Stolte)

Nearest embedded clusters to go deep:

<1 Jupiter mass

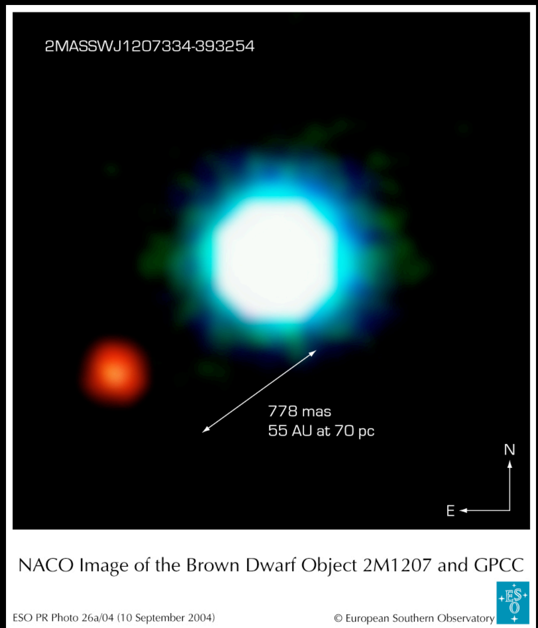


NIRCam can resolve > 30 AU Multiples in Orion.

Multi-epoch Proper motions yield velocities < 1 km/sec.

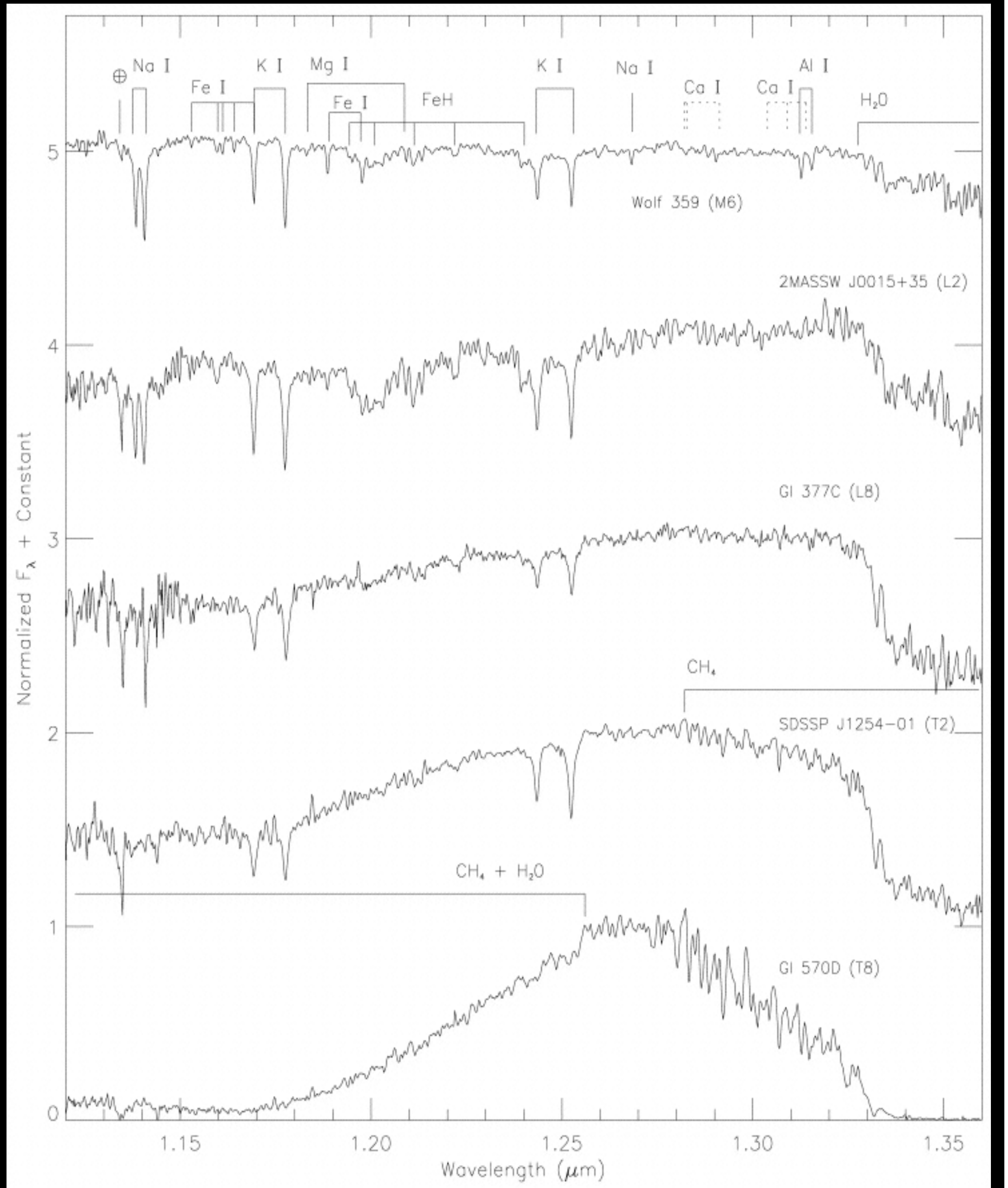
NICMOS/HST Mosaic F810W/F110W/F150W of NGC 2024 (Liu, Meyer, Cotera, and Young 2003, AJ).

NIRSpec/TFI can Distinguish Candidate ***Planetary Companions*** from Background Stars



NACO Image of the Brown Dwarf Object 2M1207 and GPCC

ESO PR Photo 26a/04 (10 September 2004) © European Southern Observatory



Quanz et al. (2009)
Chauvin et al. (2005)
McLean et al. (2003)

Proto-stars & Clusters Emerging from their Cocoons

ISOCAM image of rho Oph

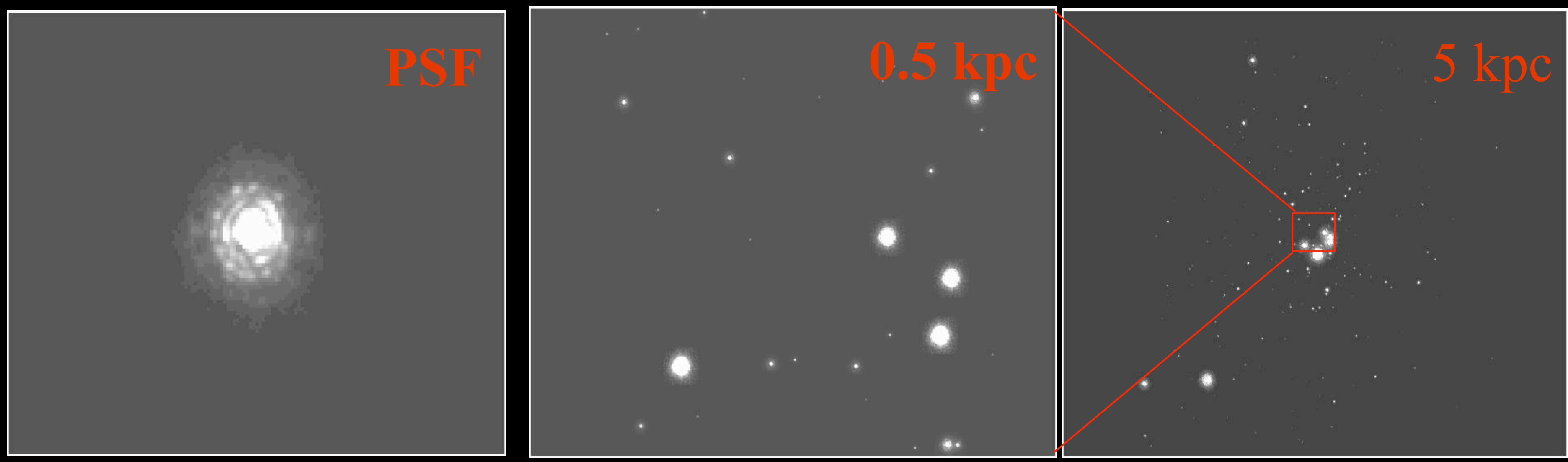
JWST MIRI/NIRCam/TFI multi-color imagery of protostars:

Field of View and Sensitivity in the thermal IR

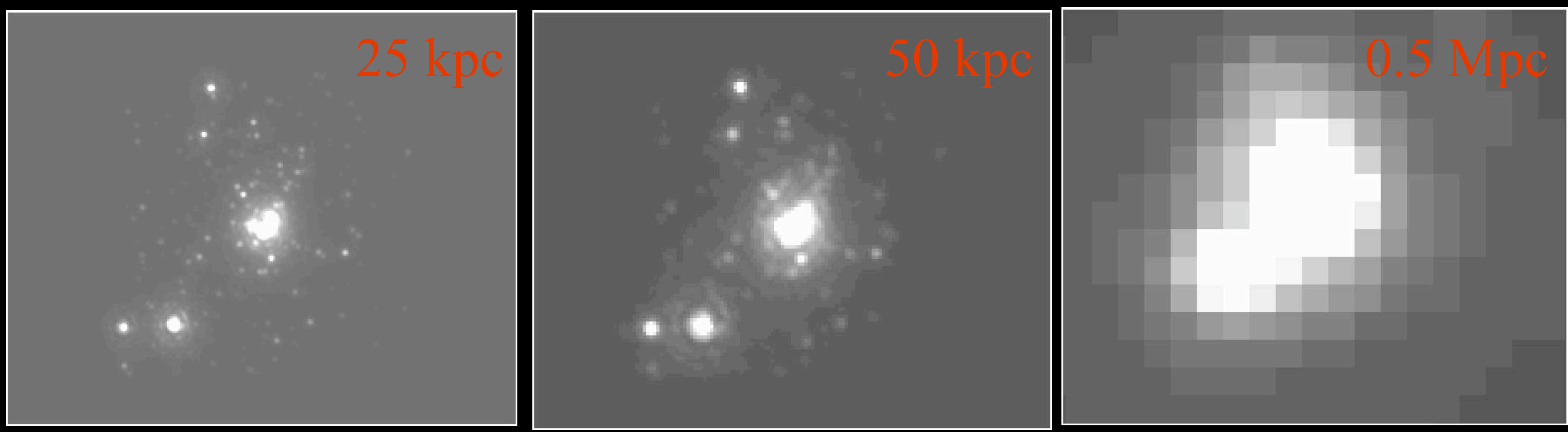
ELTs can study Forming Protostars with ***HST Resolution*** in the Thermal IR

Andersen, Meyer, Oppenheimer, Dougados, and Carpenter (2006)

The Trapezium on the Bleeding Edge: Sensitivity vs. Confusion...



R(Sky Noise) = 1 Rc = 0.2 pc
Hcomp(at Rc) < 24 mag



R(sky noise) = 2.5 Rc = 0.5 pc
Hcomp(at Rc) < 17.8 mag.

R(Sky Noise) = 4 Rc = 0.8 pc
Hcomp(at Rc) < 15.3 mags.

R(Sky Noise) > 20 Rc = 4-5 pc
Core Radius not resolved.

Extreme Star-Formation in NGC 604 in M 33 at 1 Mpc

(see talk by de Marchi)

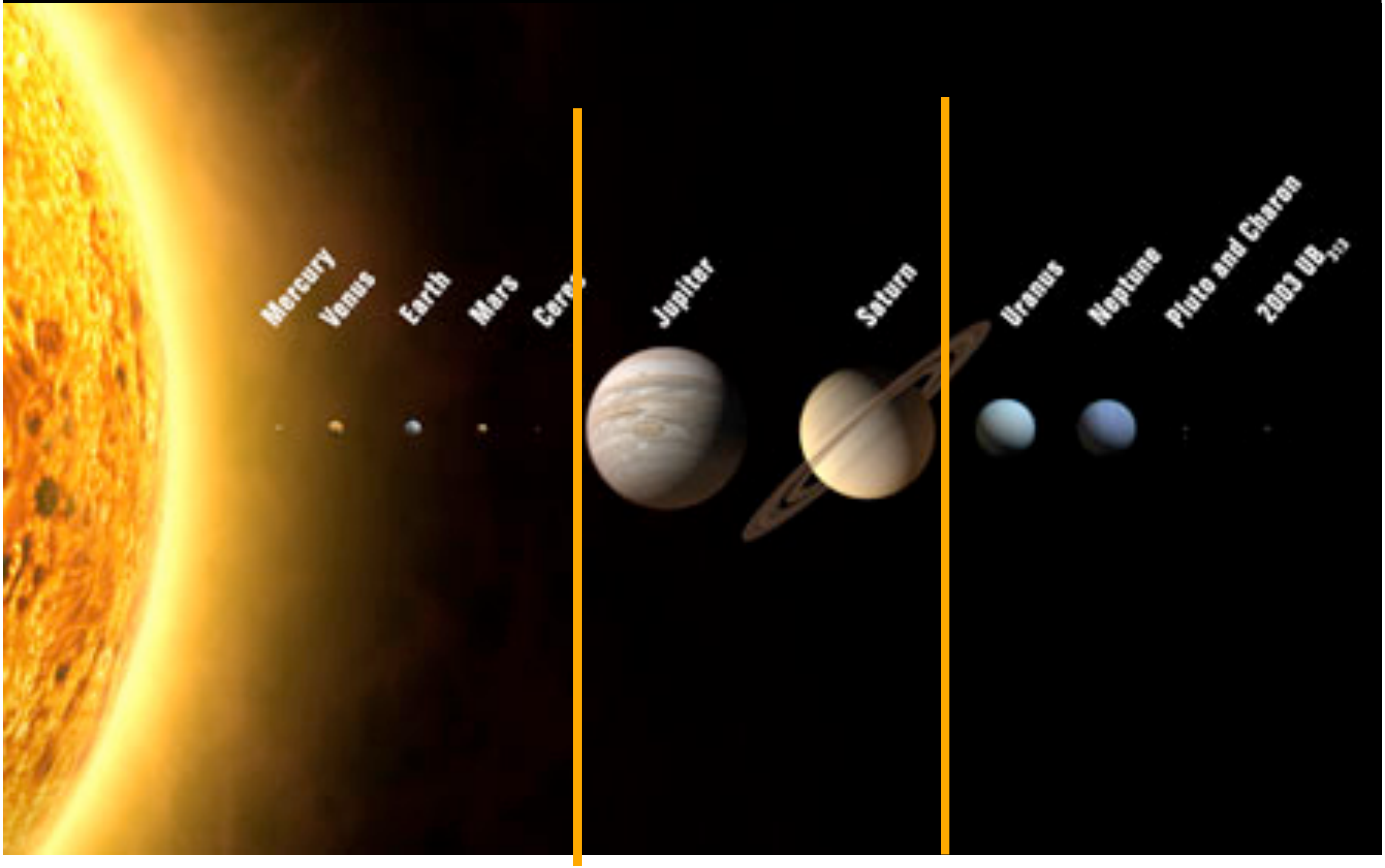
Science Goals Lead to Design Requirements:

Does star formation depend on initial conditions?

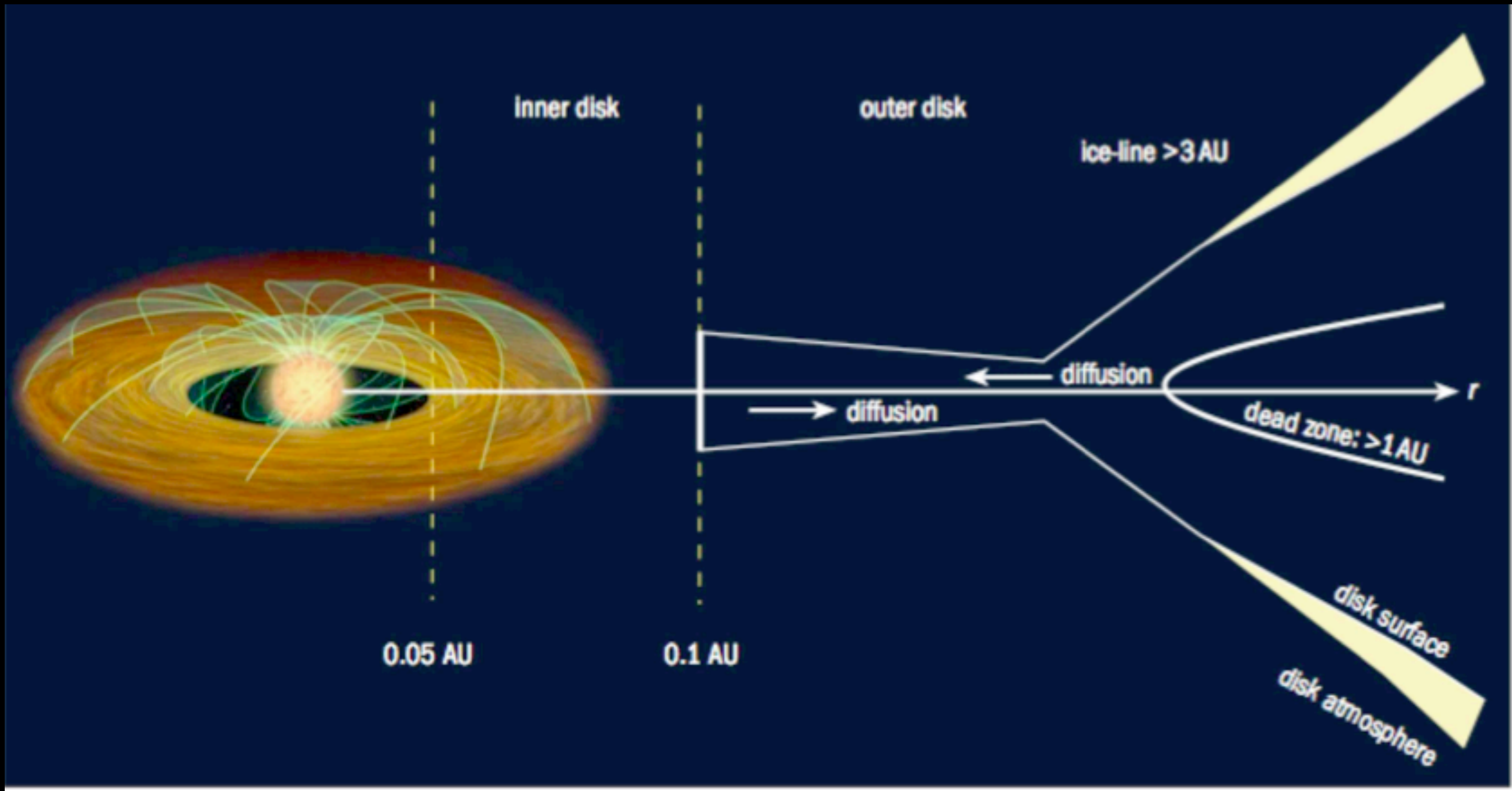
Do forming planets contain the ingredients for life?

Are planetary systems like ours common or rare?

Different Flavors of Planet Formation



Initial Conditions in Protostellar Disks.

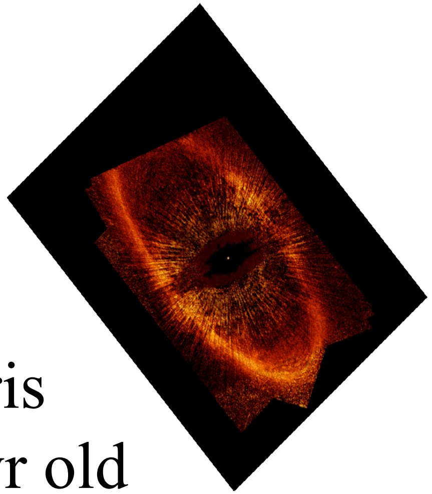


From M. Meyer, Physics World, November, 2009
Based on Dullemond et al. (2001) with artwork from R. Hurt (NASA)

From Active Accretion to Planetary Debris Disks...

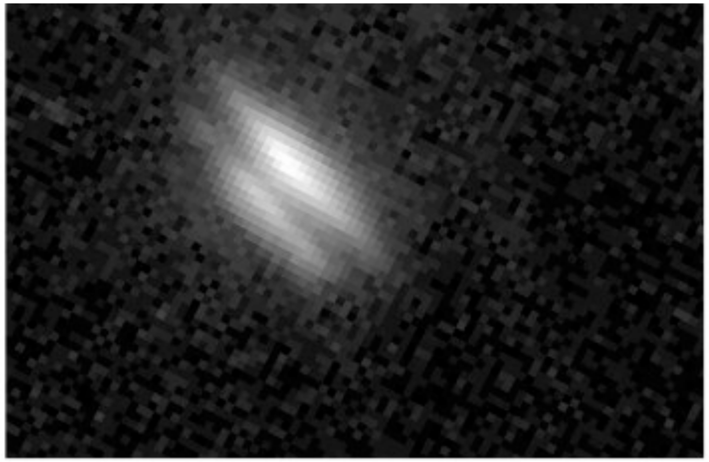
Images courtesy of K. Stapelfeldt, NASA, and P. Kalas.

For recent review see Meyer et al. (2007) Protostars & Planets V

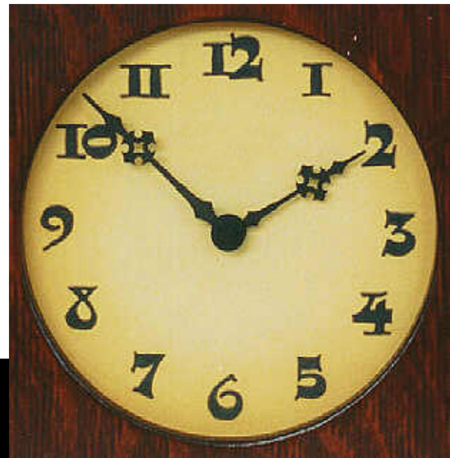


Planetary debris disk ~ 100 Myr old

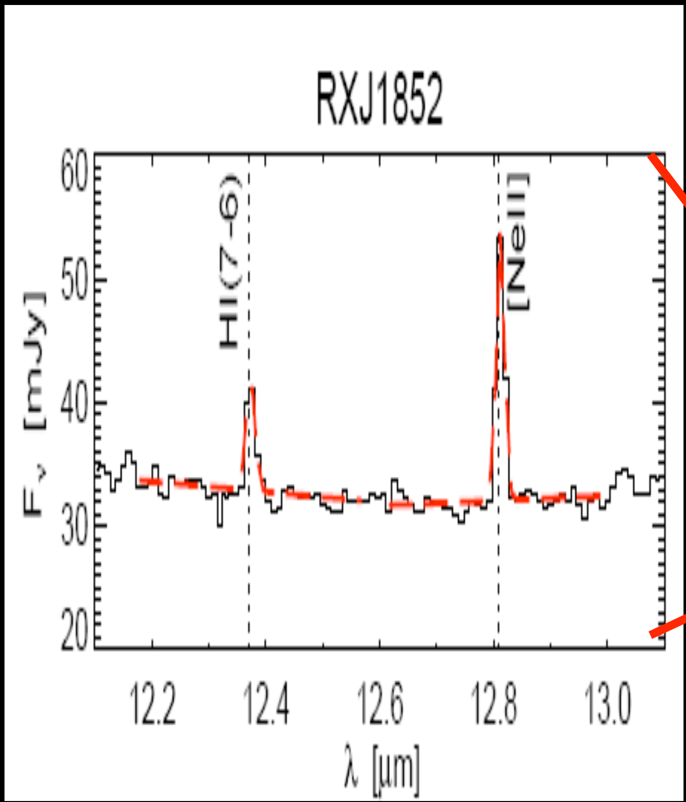
Solar system debris disk 4.56 Gyr old!

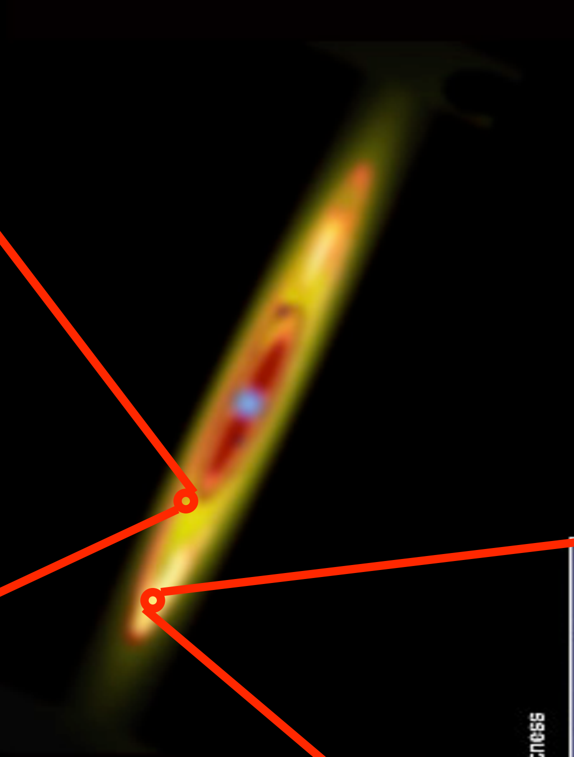


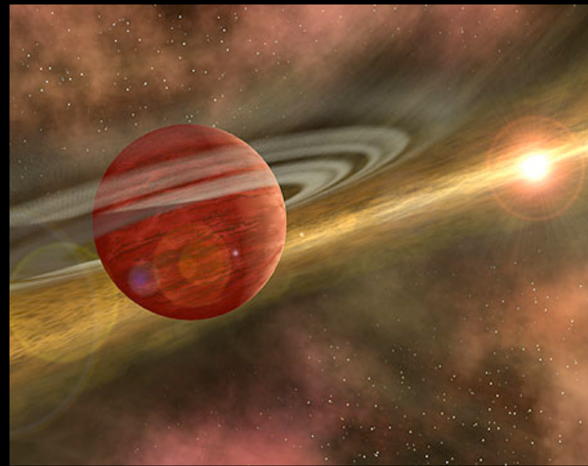
Gas-rich disk ~ 1 Myr old

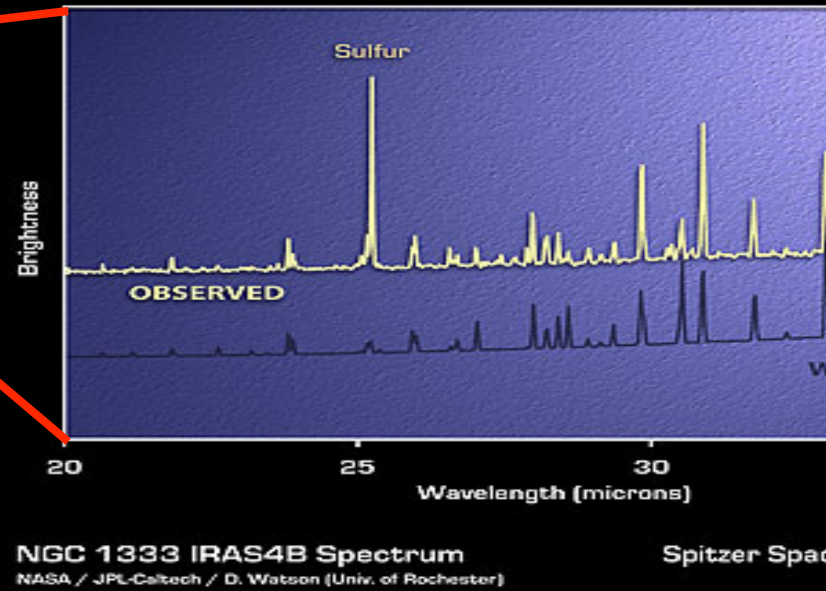


Resolved Spectra of Planet Forming Gas:







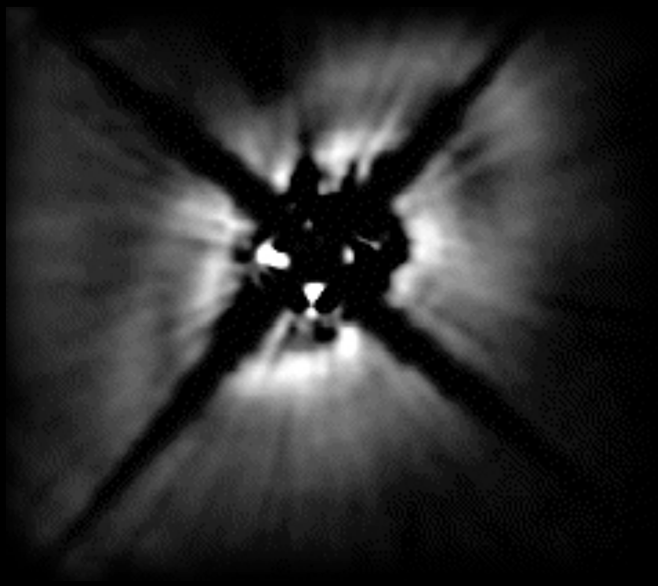


See next three talks!

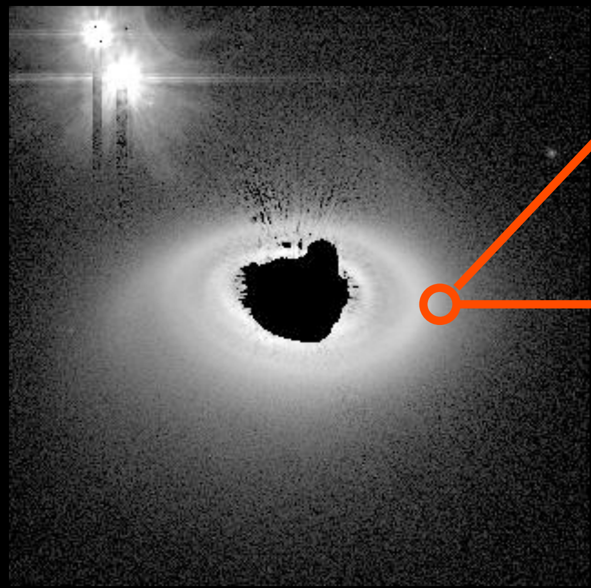
Pascucci et al. (2007)/MIPS Team/MIRI Team.

D. Watson/IRS Disks/c2D/FEPS

Can JWST/ELTs discern the ice-line in scattered light?

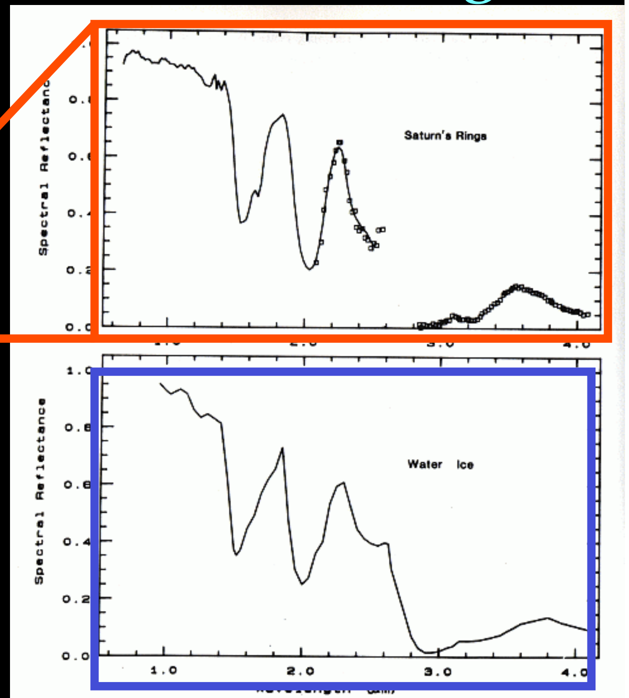


(Weinberger et al. 1999)



(Clampin et al. 2003)

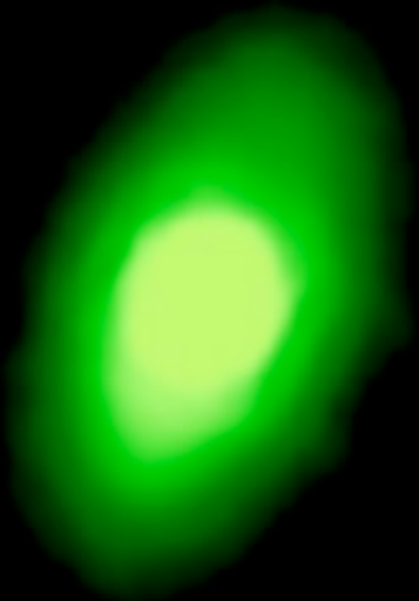
Saturn's Rings

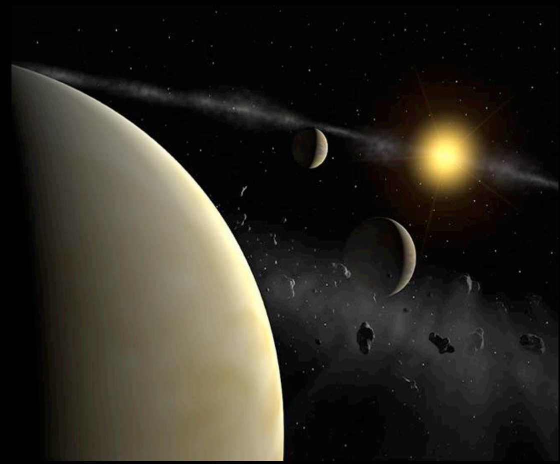


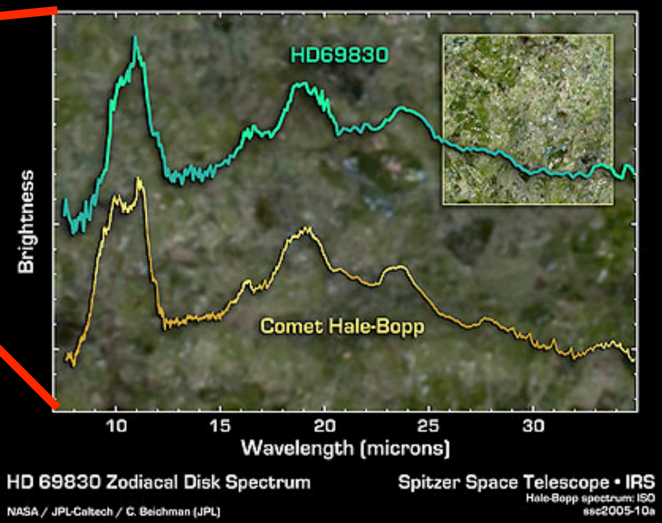
Water Ice

Disk structure, dust particle size, and composition from multi-color imagery (cf. Debes et al. 2007).

Resolved Spectra of Dust Debris

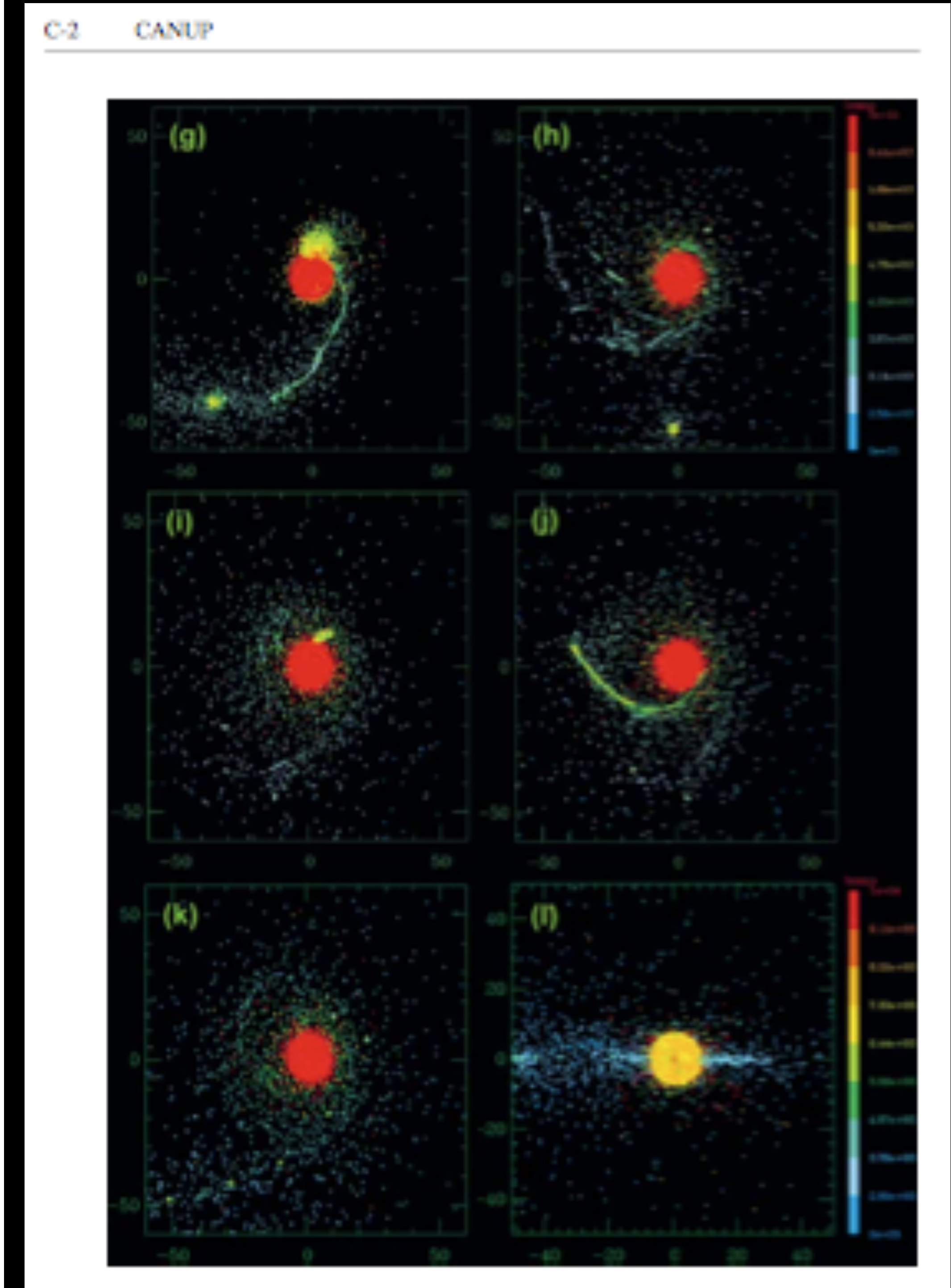


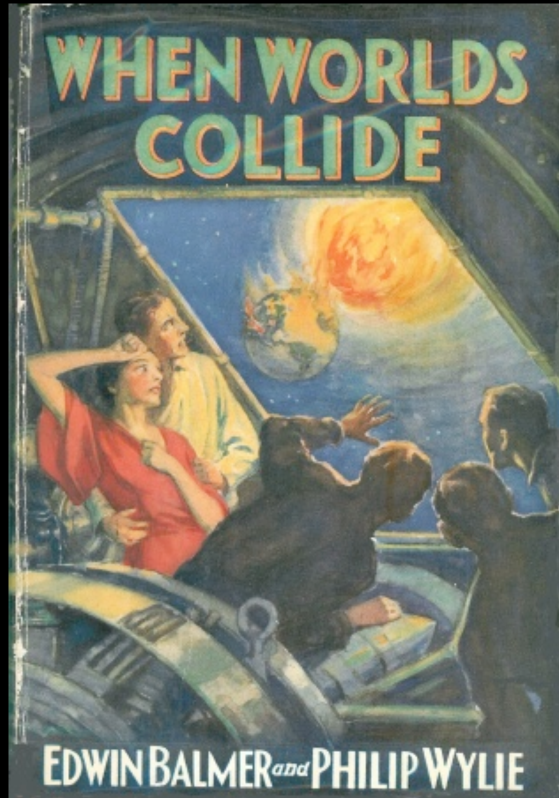


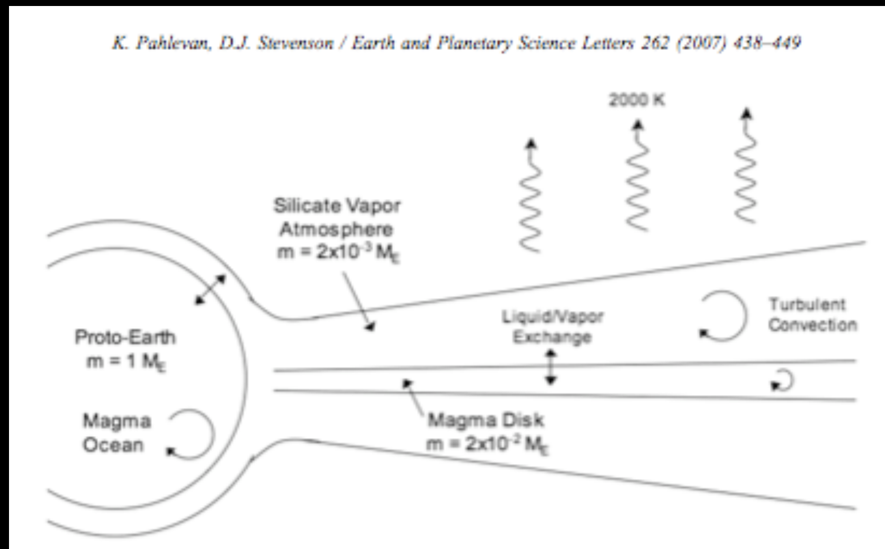


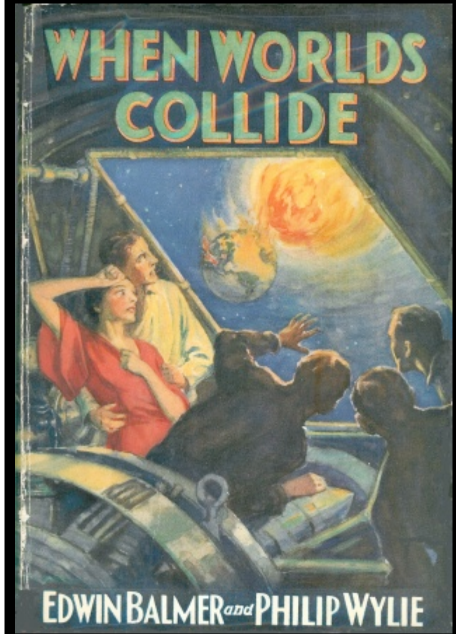
Stapelfeldt et al. (2004)/MIPS Team/MIRI Team.

Beichman et al. (2005); Lisse et al. (2006); Wyatt et al. (2007)


C-2 CANUP
(g)
(h)
(i)
(j)
(k)
(l)

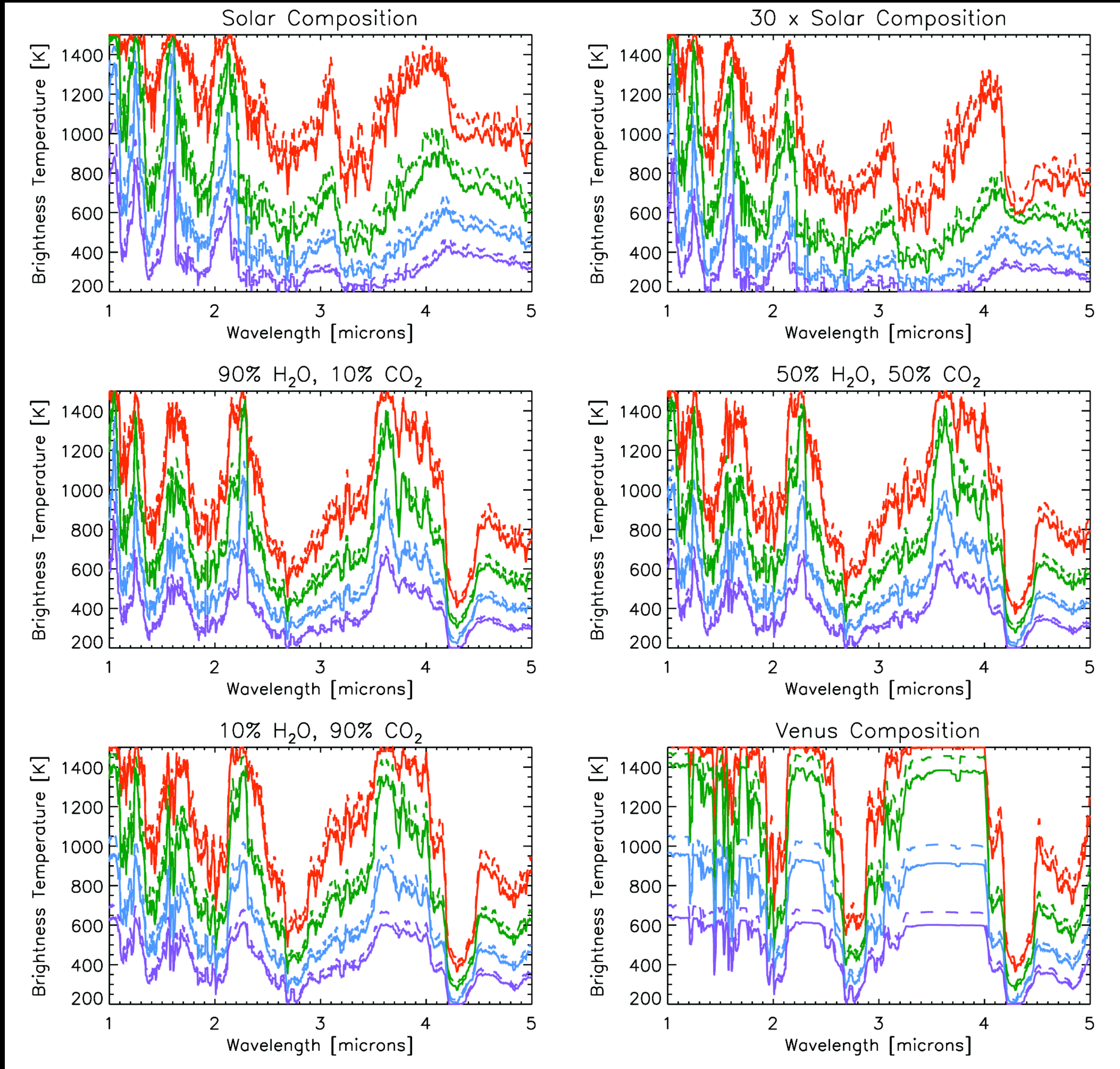

WHEN WORLDS COLLIDE
EDWIN BALMER and PHILIP WYLIE


K. Pahlevan, D.J. Stevenson / Earth and Planetary Science Letters 262 (2007) 438–449
2000 K
Silicate Vapor
Atmosphere
m = 2x10^{-3} M_E
Liquid/Vapor
Exchange
Turbulent
Convection
Proto-Earth
m = 1 M_E
Magma
Ocean
Magma Disk
m = 2x10^{-2} M_E



...you can see them with next generation instruments!

Miller-Ricci, Meyer, Seager, Elkins-Tanton (2009)



Science Goals Lead to Design Requirements:

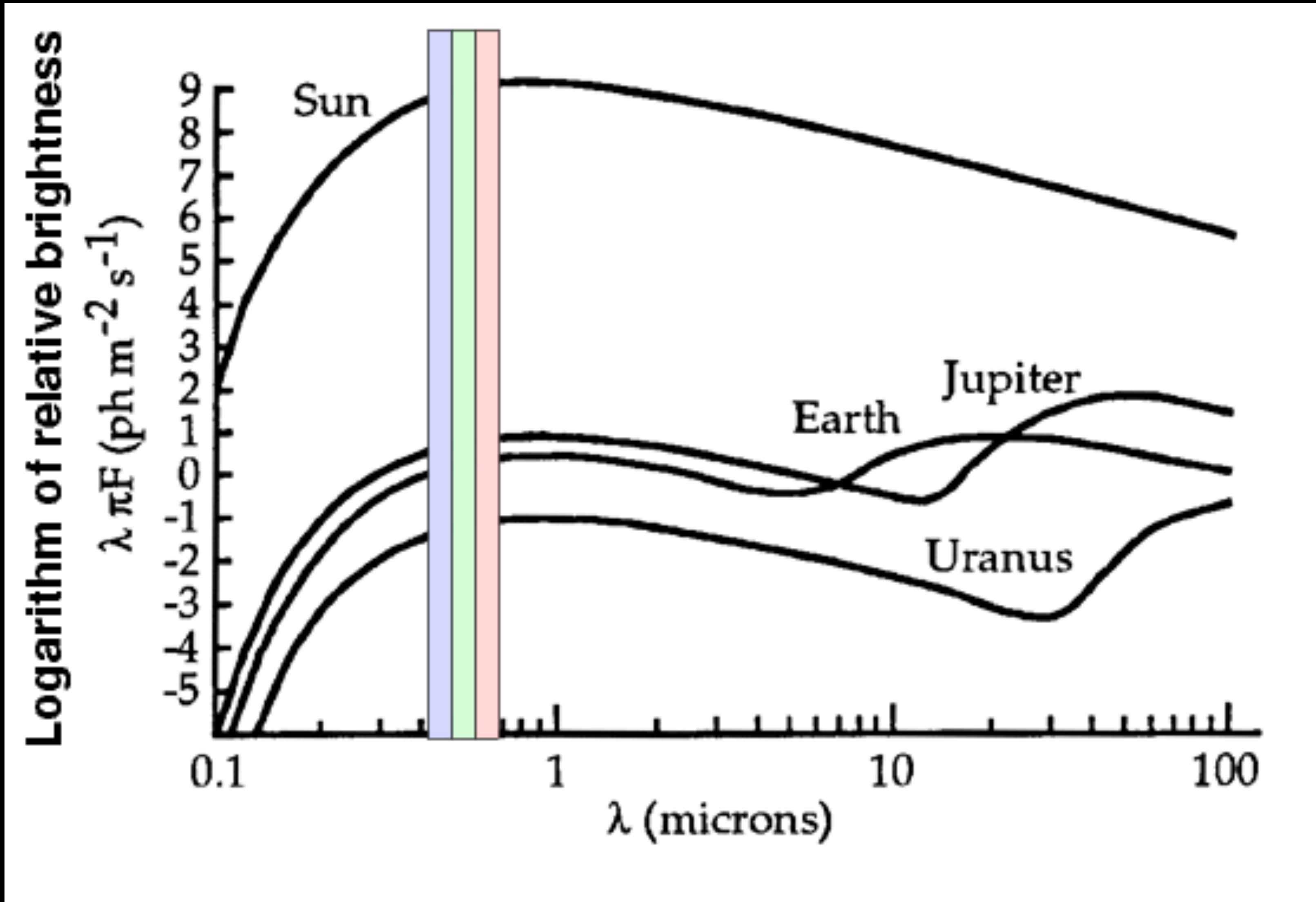
Does star formation depend on initial conditions?

Do forming planets contain the ingredients for life?

Are planetary systems like ours common or rare?

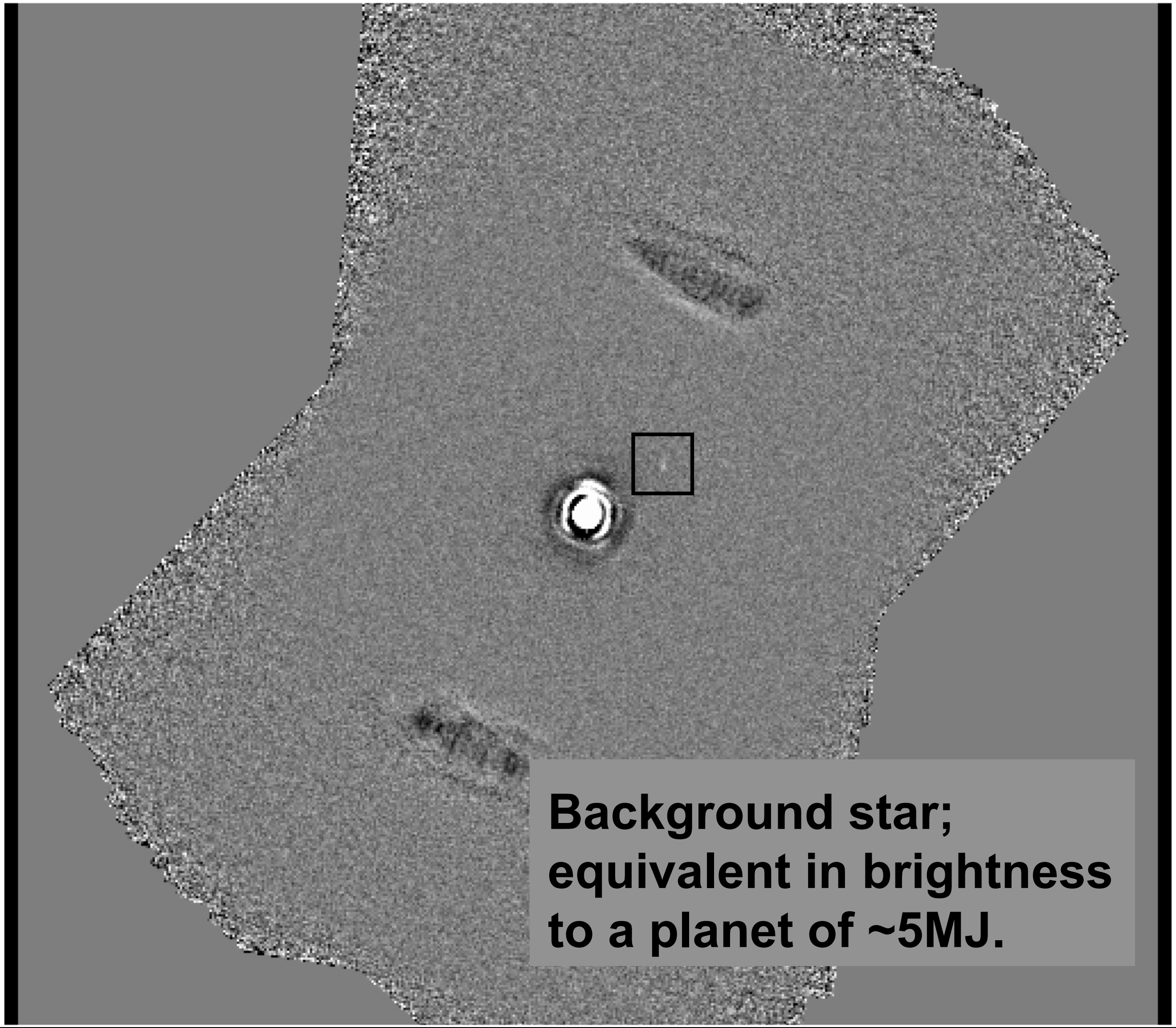
(see presentations in next session for the answer!)

Taking a Picture: The Problem



Planet Searches In Thermal IR

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



Complementary to short-wave high contrast imaging:

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

Direct (Non) Detections of Gas Giant Planets

No massive planets at large orbital radii.

[3 Mjup @ 30 AU]

dN/da ~ a^p

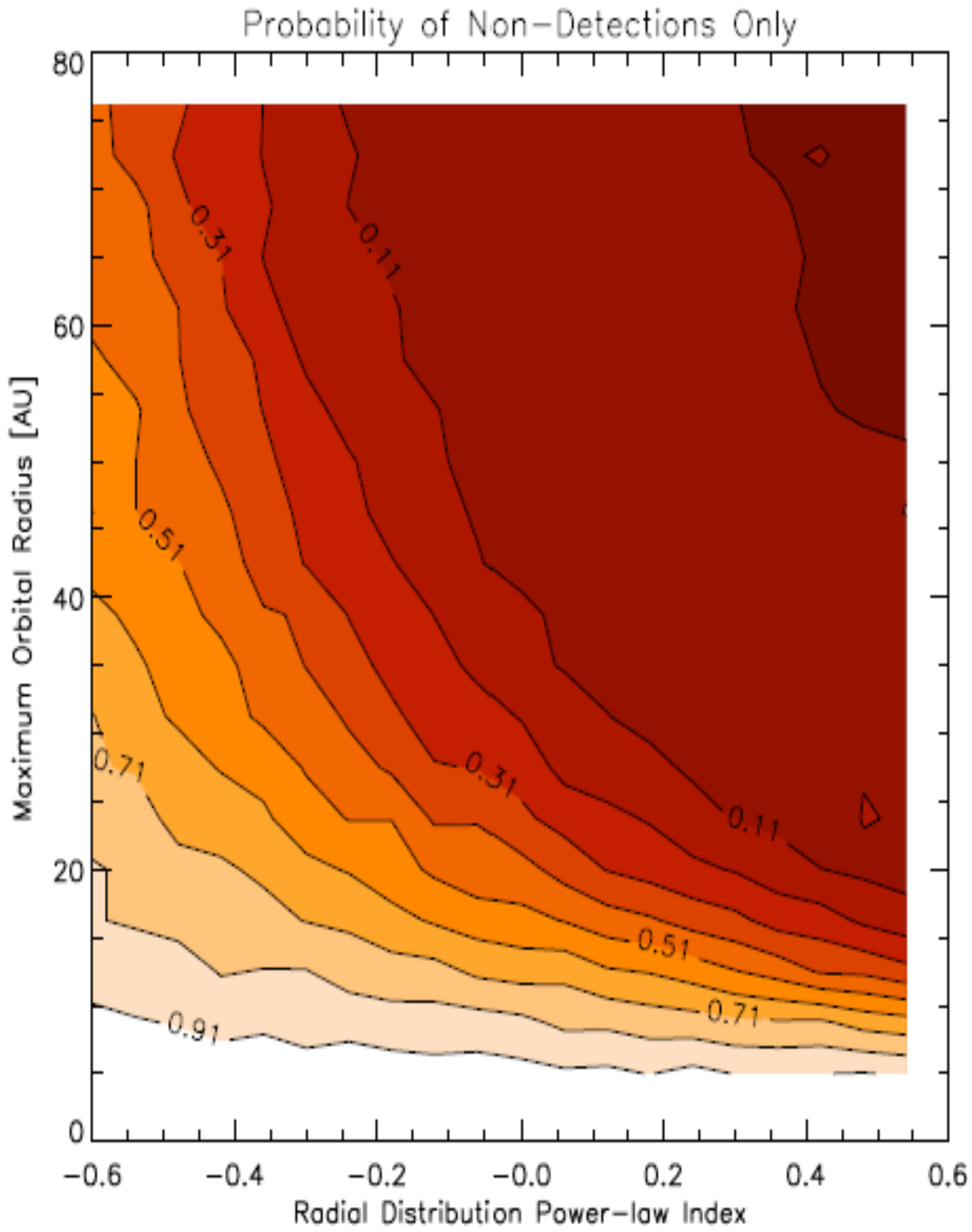
Lafrenerie et al. (2007);

Biller et al. (2007);

Kasper et al. (2007);

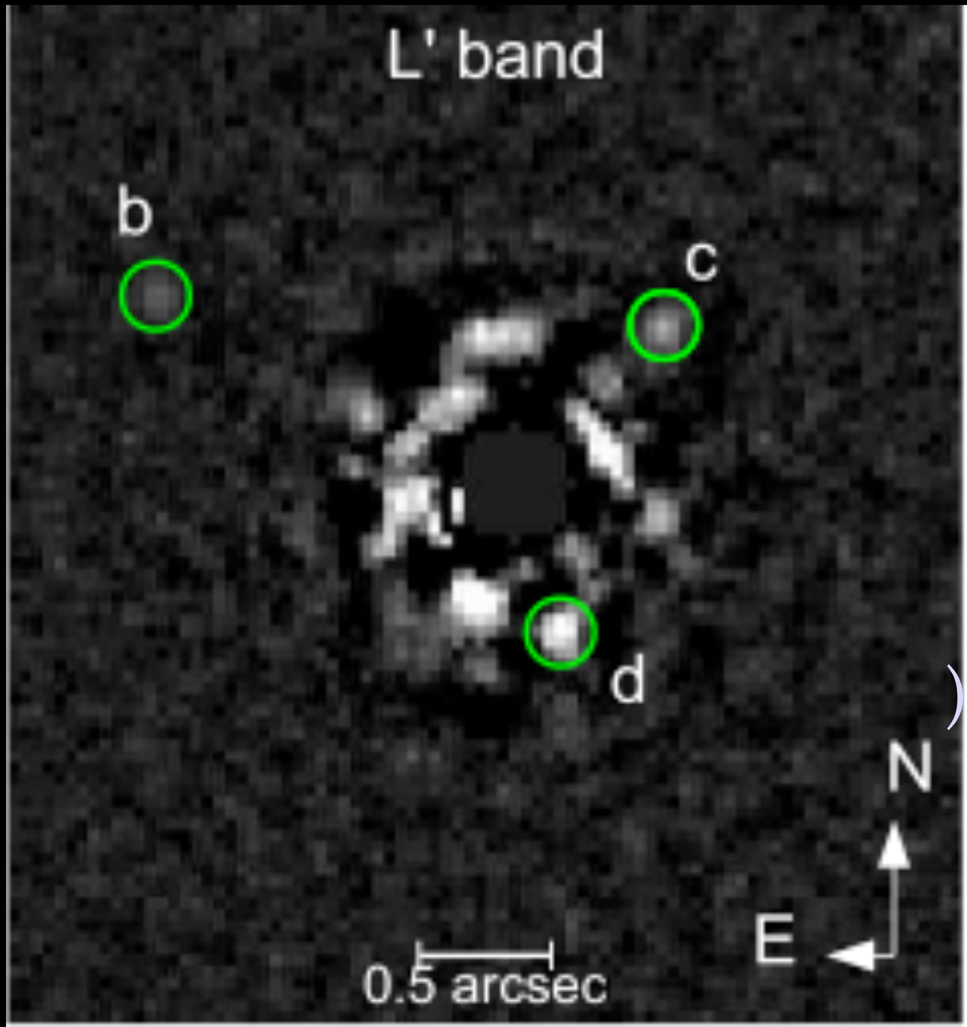
Nielssen & Close (2009);

Heinze et al. (2010)



Direct Imaging is Here!

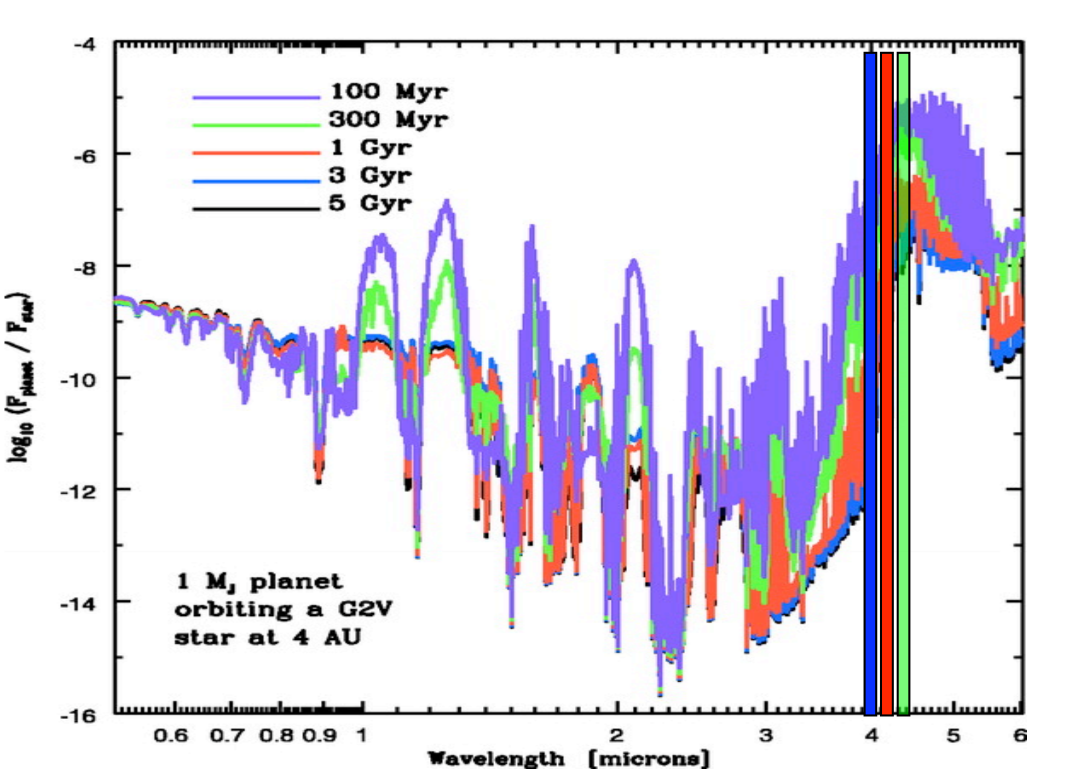
Marois et al. (2008)
Kalas et al. (2008)
Lagrange et al. (2009)

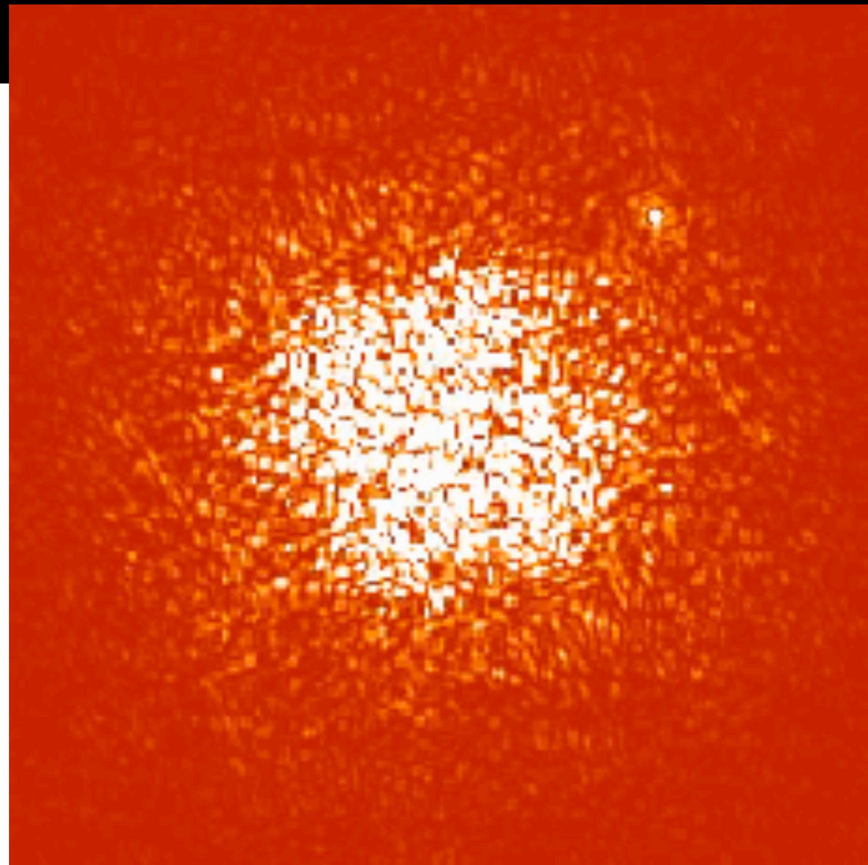


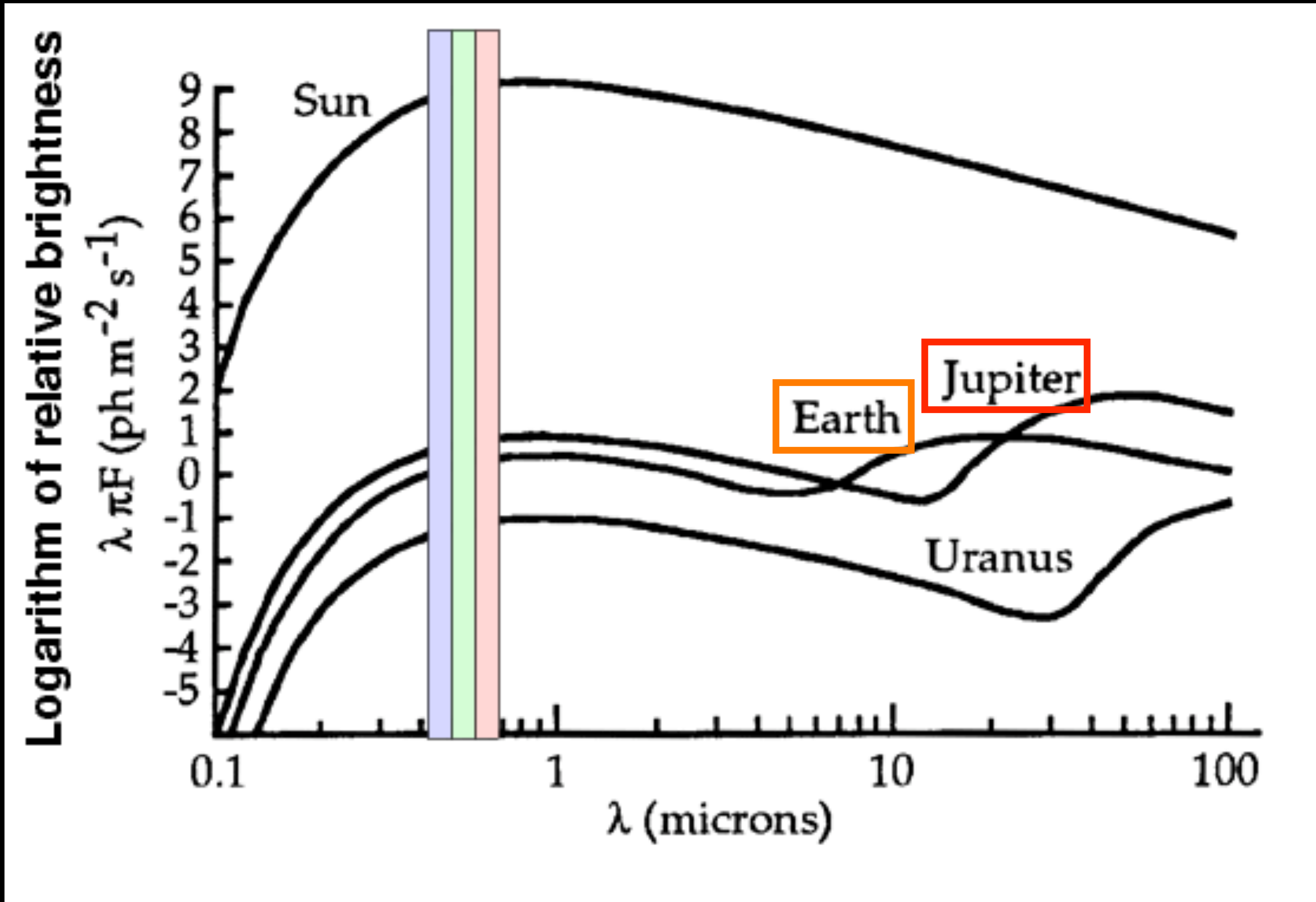
HR 8799 obtained with the MMT-AO system using the CLIO camera on Mt. Hopkins, AZ

Planets are bluer than expected in L'-M indicating non-equalibrium chemistry (Hinz et al. 2010; Janson et al. 2010).

JWST NIRCam/TFI/MIRI multi-λ imaging & ELT High Contrast imaging spectroscopy (several talks next session)







To find other Earths, the problem is *detail*, not light gathering.

ELT Nearby Stars Census in Thermal IR

Number	Star	d (pc)	V	a=280 K (AU)	ang. dist. (“)	Earth flux (uJy)
	alpha Cen C	1.3	11.01	0.08	0.06	28.4
1	Alpha Cen A	1.35	-0.01	1.04	0.77	26.34
2	alpha Cen B	1.35	1.35	0.65	0.48	26.34
3	Sirius	2.64	-1.44	6.3	2.39	6.89
4	eps Eri	3.22	3.72	0.56	0.17	4.63
5	Procyon	3.5	0.4	1.72	0.49	3.92
6	tau Ceti	3.65	3.49	0.78	0.21	3.6
7	Altair	5.14	0.76	3.36	0.65	1.82
8	beta Hyi	7.47	2.82	2.1	0.28	0.86
9	Fomalhaut	7.69	1.16	4.91	0.64	0.81
10	beta Leo	11.1	2.14	4.91	0.44	0.39

Planet detectable beyond 3 λ/D (0.25”) and brighter than 10 μJy

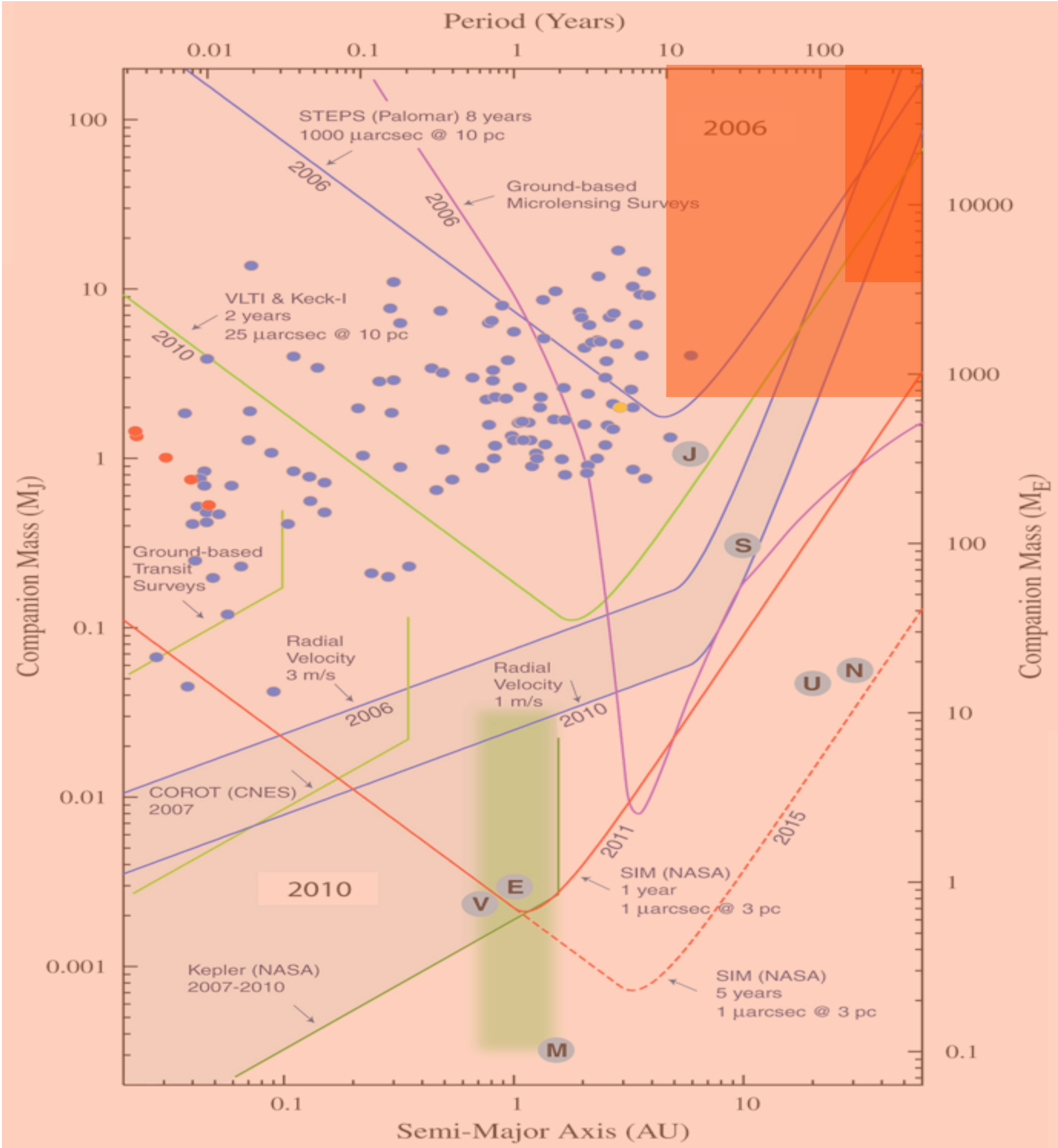
Earth mass planets detectable around alpha Cen A/B with ELT?

x10 M_E (~2 R_E) detectable around 4 stars.

Even more “hot rocks” detectable at L-band (Hinz et al. 2008)

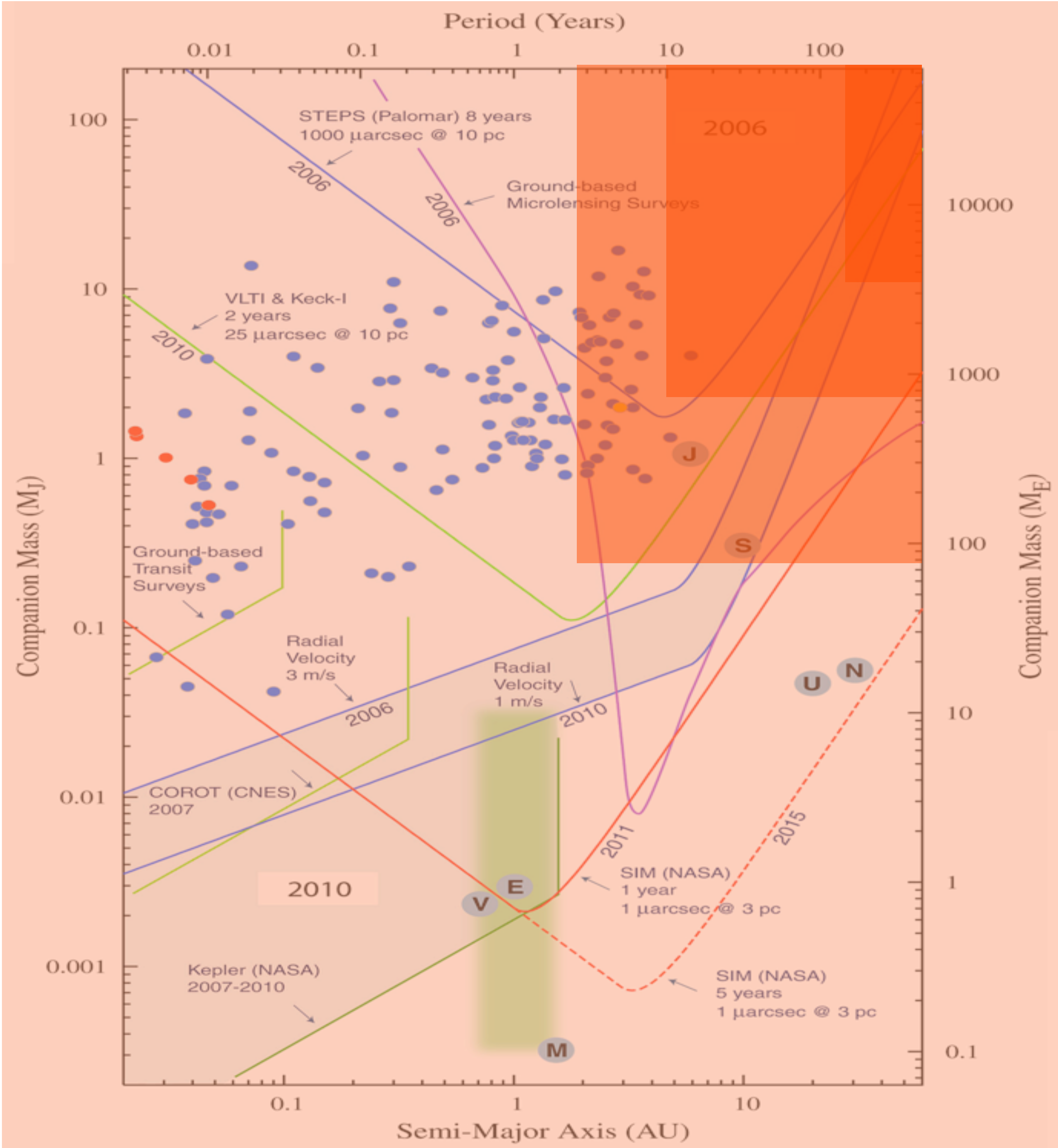
Putting it All Together:

Surveys underway.

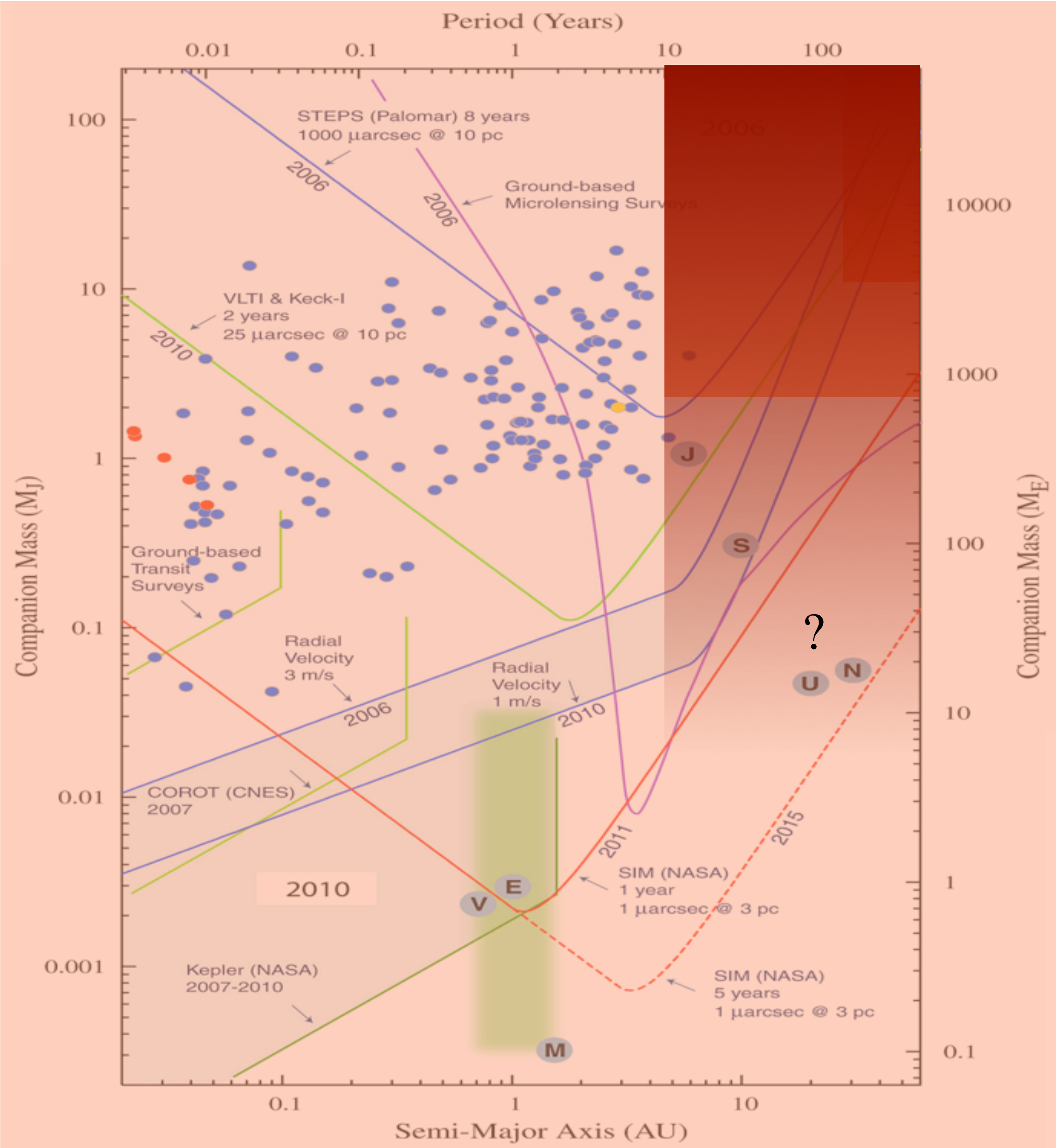


Putting it All Together:

ELT Surveys.



NIRCam/TFI "Sweet Spot"

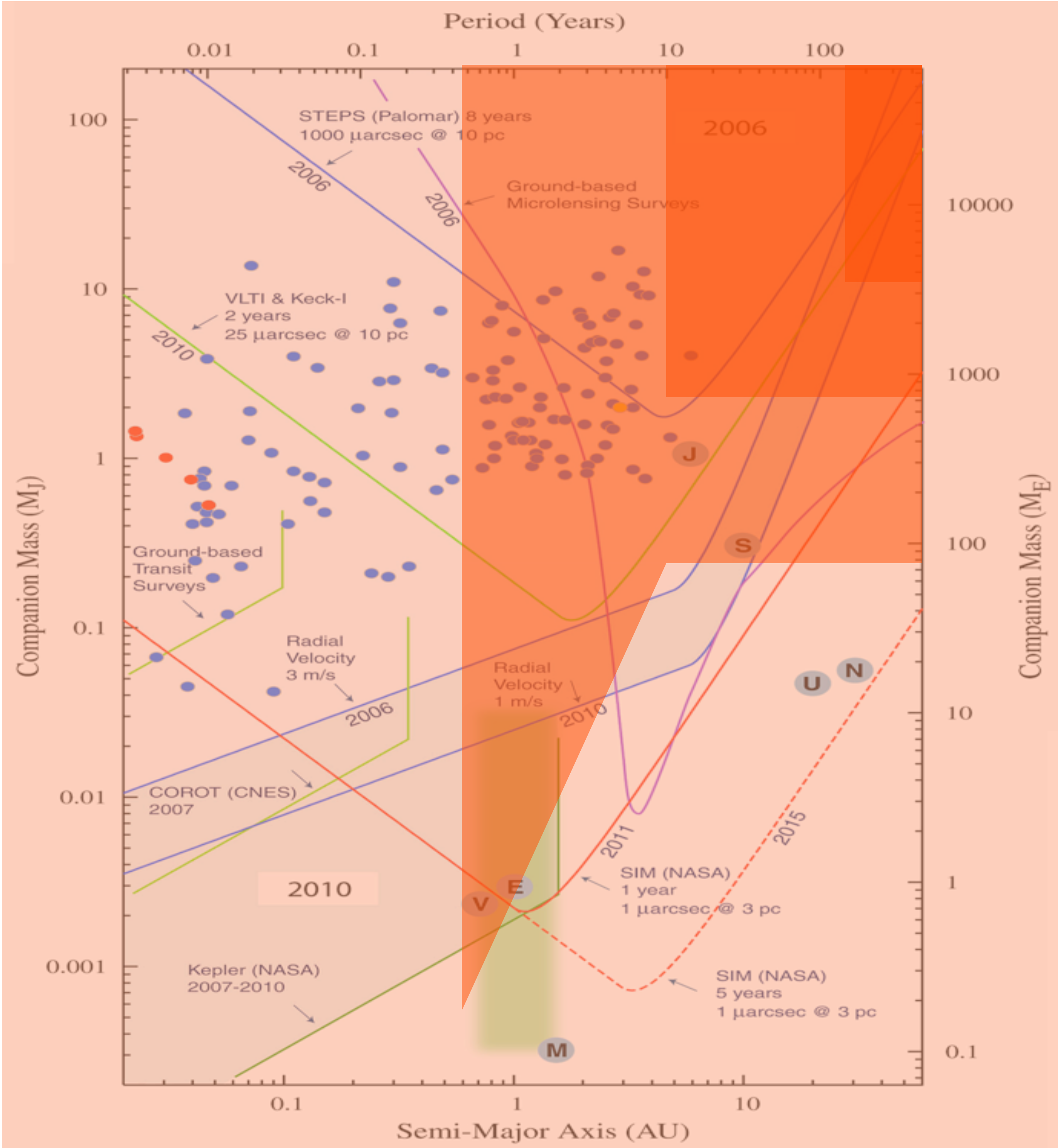


Detect very low mass planets at large radii about the nearest stars. (cf. Beichman et al.)

Putting it All Together:

If terrestrial Planets are Common

ELT Discovery Space?



2020 Vision: Complementary Capabilities

JWST => sensitivity & field of view.
ELT => resolution (spatial & spectral).

Ideal combination? Yes, but more…

Both will play transformational roles in understanding star and planet formation.