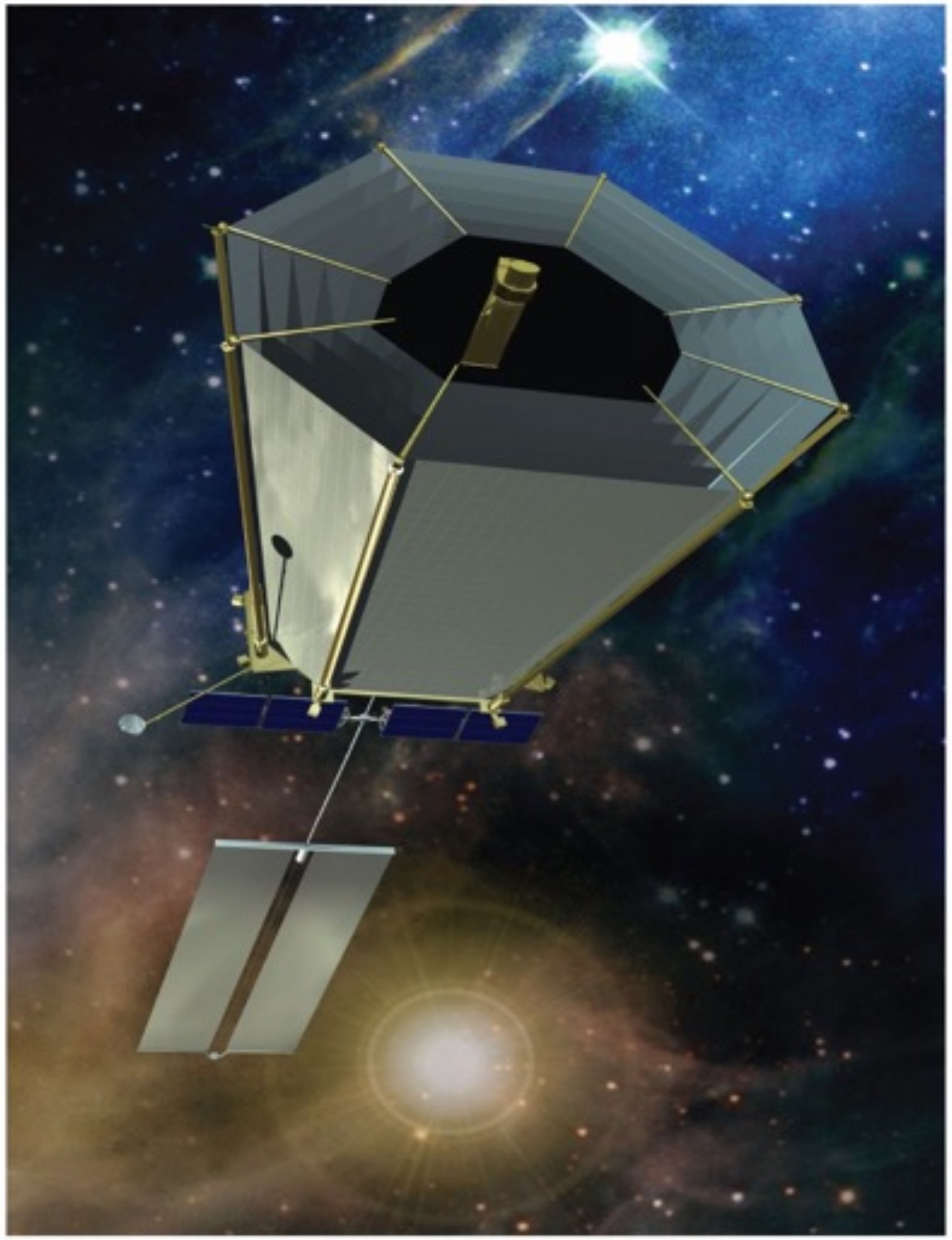
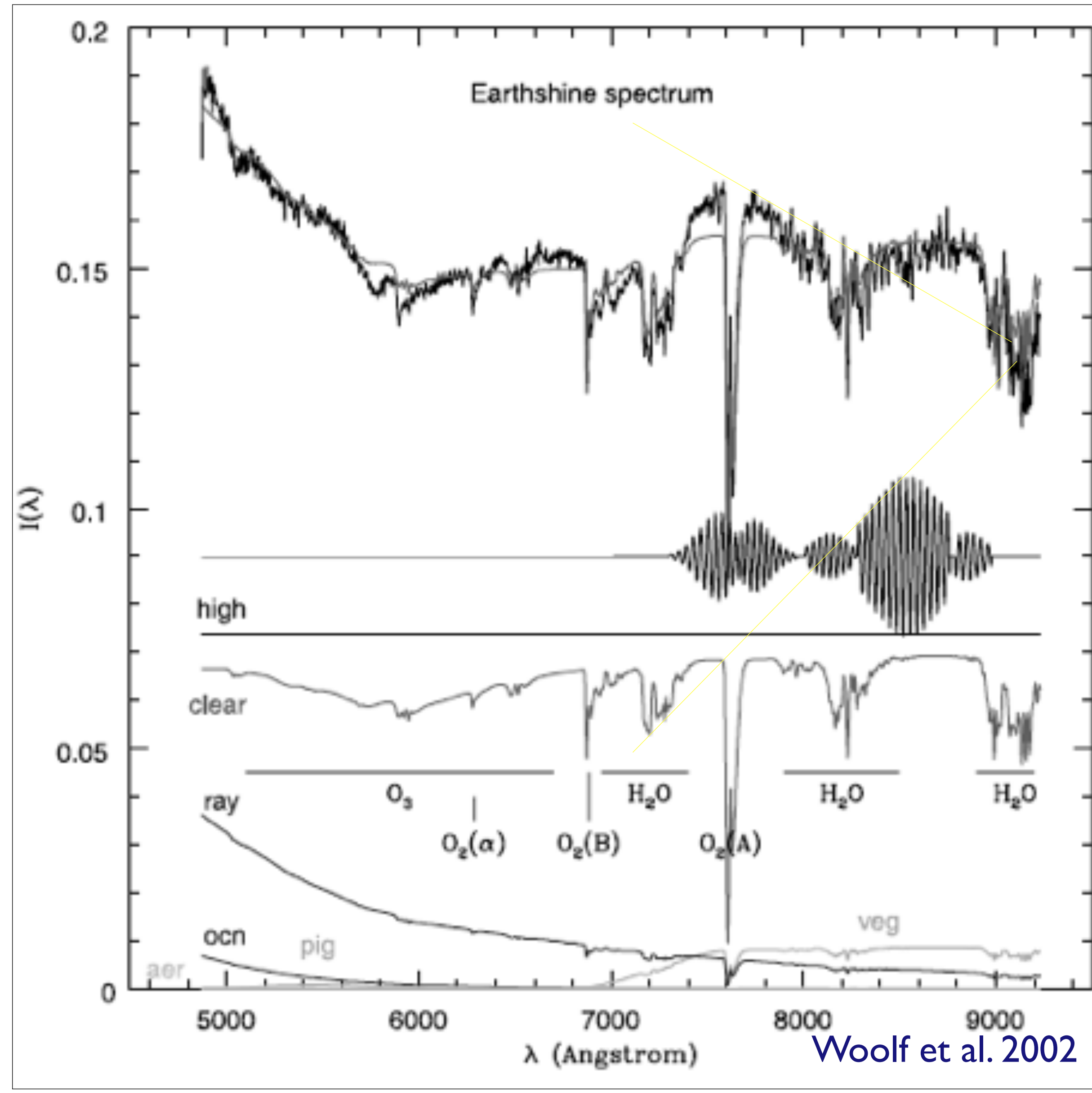
Earths In Other Solar Systems: The Formation of Habitable Zone Earth-Like Planets With Biocritical Ingredients

Dániel Apai

Steward Observatory and Lunar and Planetary Laboratory, University of Arizona
and the
Earths in Other Solar Systems Team




Earthshine spectrum
I(λ)
0.2
0.15
0.1
0.05
0
high
clear
ray
ocn
pig
aer
veg
O3
O2(α)
O2(B)
H2O
O2(A)
H2O
H2O
5000
6000
7000
8000
9000
λ (Angstrom)
Woolf et al. 2002

Diversity of HZ Earth-sized Planets

How many planets do we need to survey?
How far are our targets?
Which specific stars do we target?

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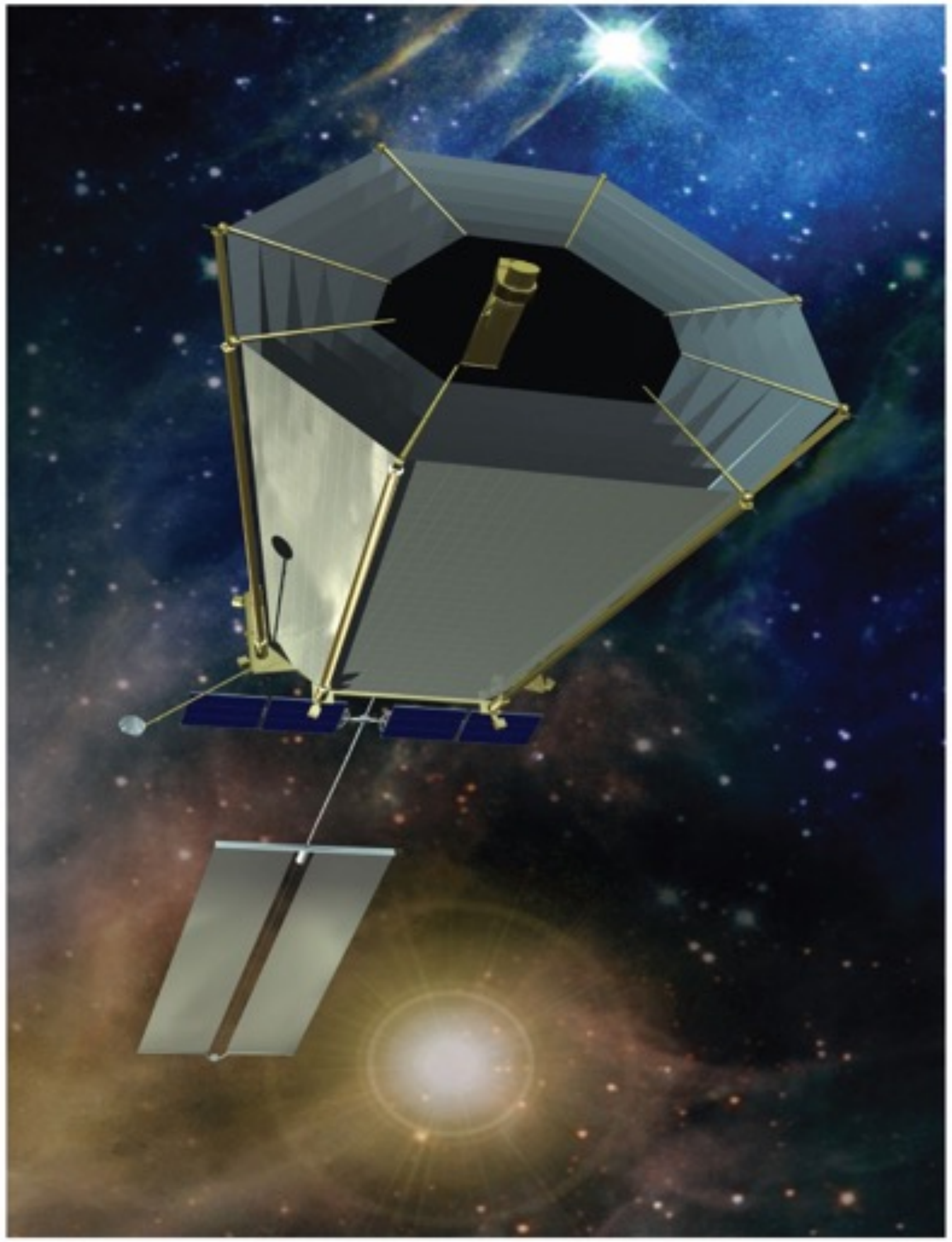

The Chemical Diversity of HZ Earth-sized Planets

What is the Chemical Diversity of
Earth-sized Habitable Zone Planets?

How many planets do we need to survey?
How far are our targets?
Which specific stars do we target?

Which planetary systems are better targets?

Nexus for Exoplanet System Science

Co-Directors:
Natalie Batalha, Dawn Gelino, Tony Del Genio

Earths in Other Solar Systems (EOS)

How do Habitable Zone Earth-sized planets with biocritical ingredients form?
Where can we find these planets?

5-year, $5.7M dollar program; 12 coordinated research projects
25 Co-investigators +13 Postdocs and Grad Students

PI: Daniel Apai (Steward/LPL)
Deputy PI: Tom Zega (LPL)
Team Leads: Lucy Ziurys, Ilaria Pascucci, Fred Ciesla

The EOS Team

Daniel Apai
Lori Allen
Travis Barman
Maitrayee Bose
Fred Ciesla
Laird Close
Josh Eisner
Min Fang
Andras Gaspar
Phil Hinz
Andres Jordan
Serena Kim
Mercedes Lopez-Morales
Renu Malhotra

Gijs Mulders
Krishna Muralidharan
Joan Najita
David O'Brien
Ilaria Pascucci
Sandra Pizzarello
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Colette Salyk
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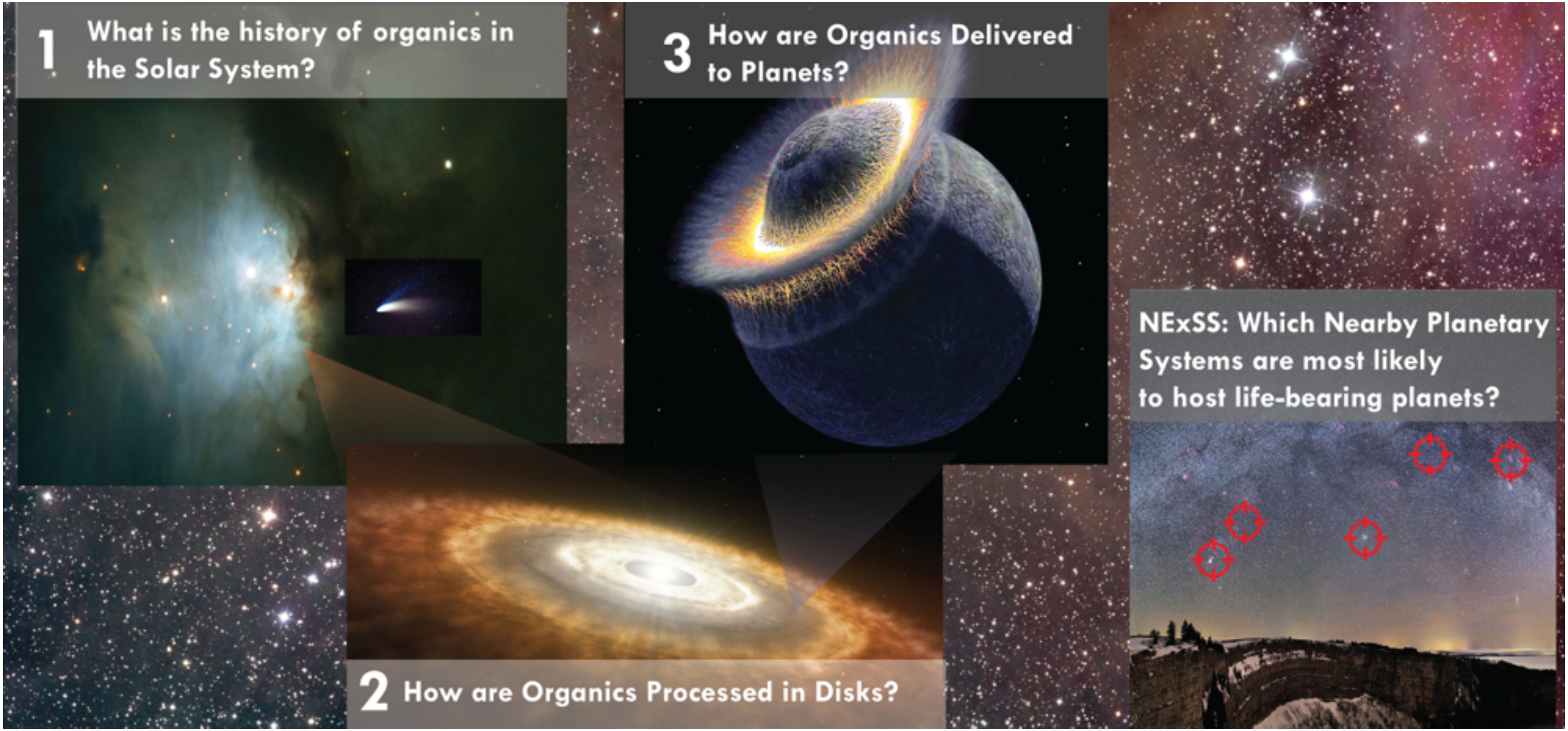
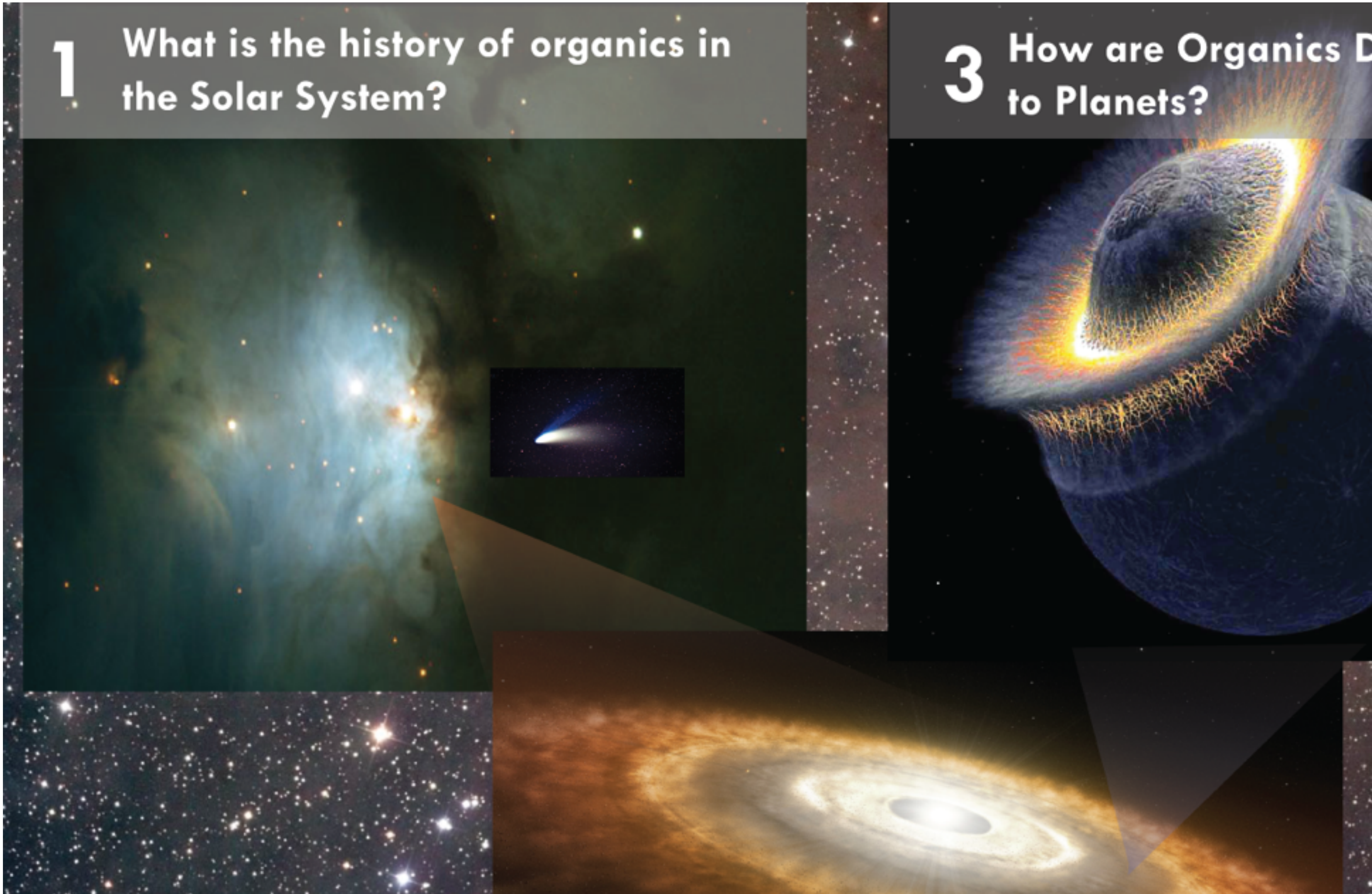

1 What is the history of organics in the Solar System?
2 How are Organics Processed in Disks?
3 How are Organics Delivered to Planets?
NExSS: Which Nearby Planetary Systems are most likely to host life-bearing planets?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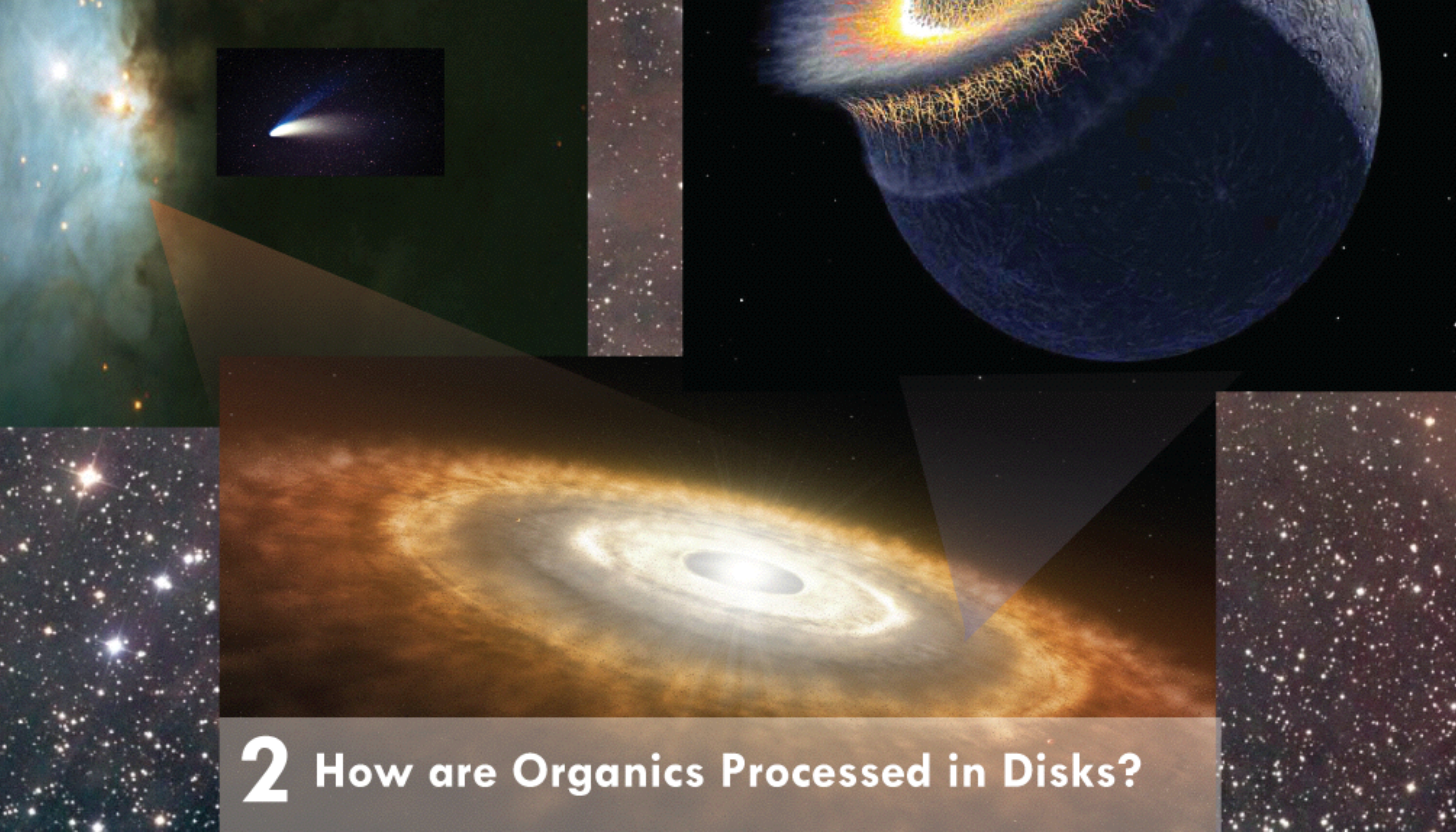
2 How are Organics Processed in Disks?


organics in
3
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NExSS: Which Near
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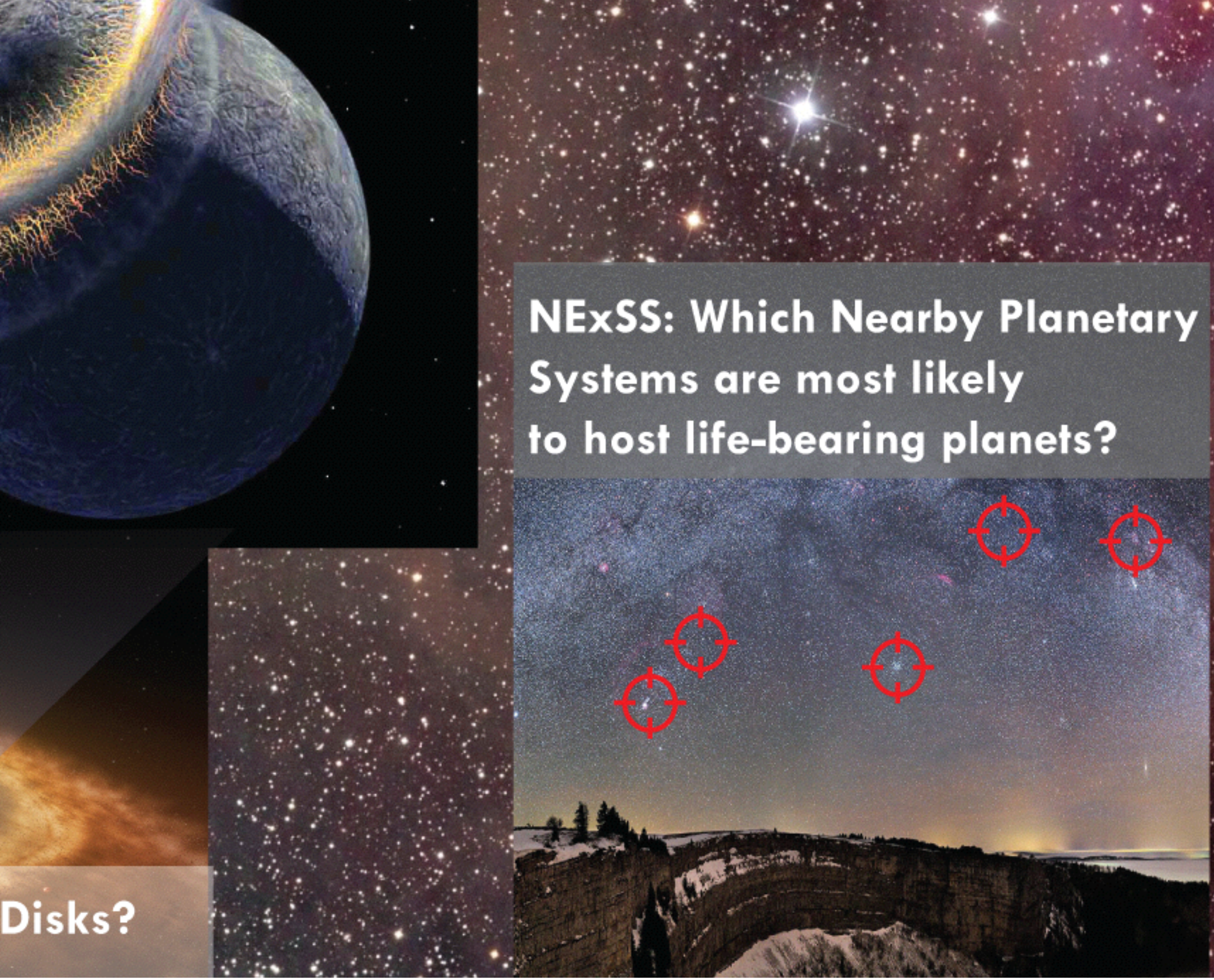
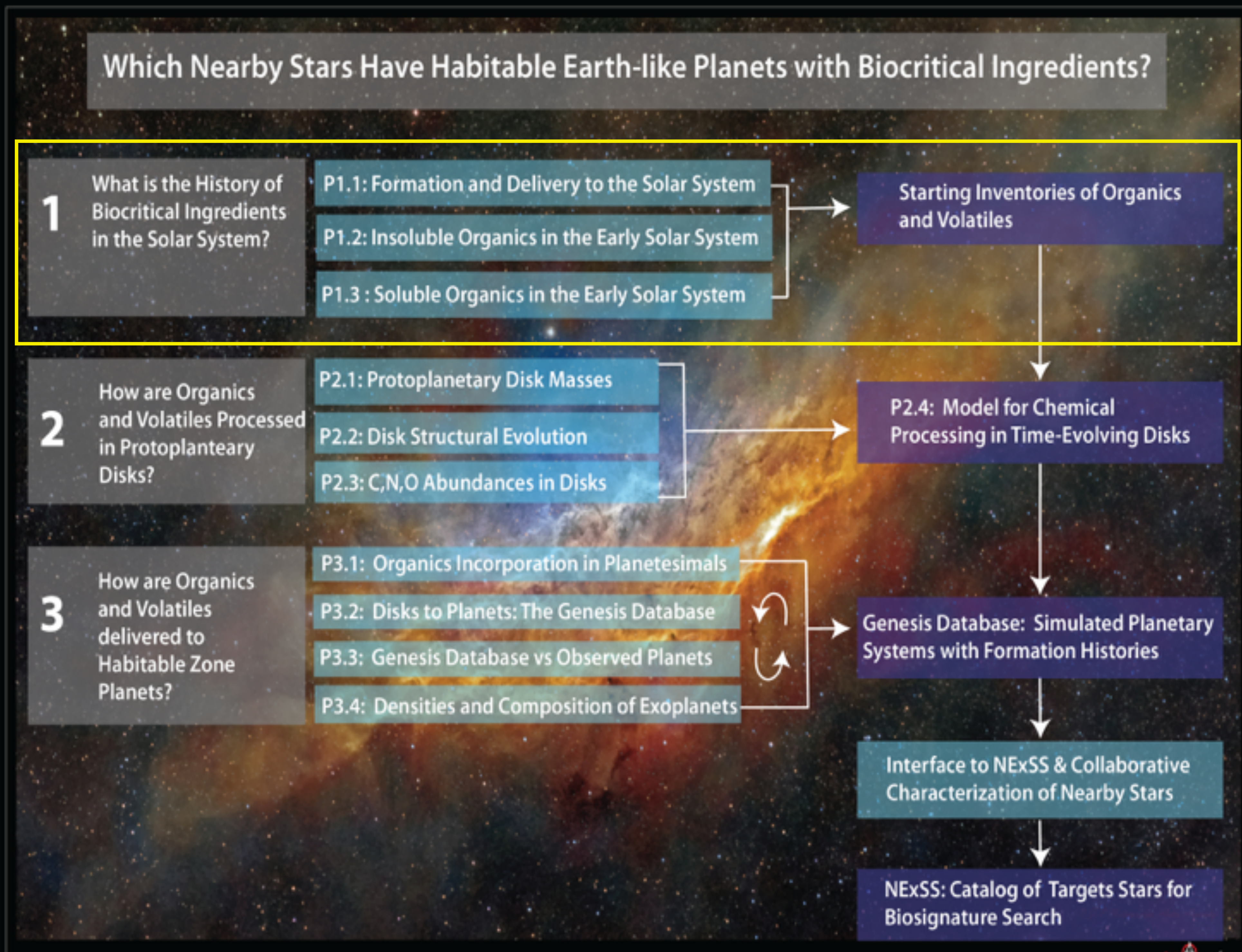

NExSS: Which Nearby Planetary Systems are most likely to host life-bearing planets?
Disks?



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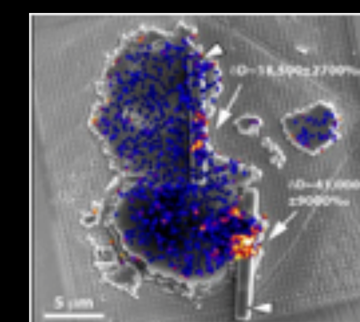

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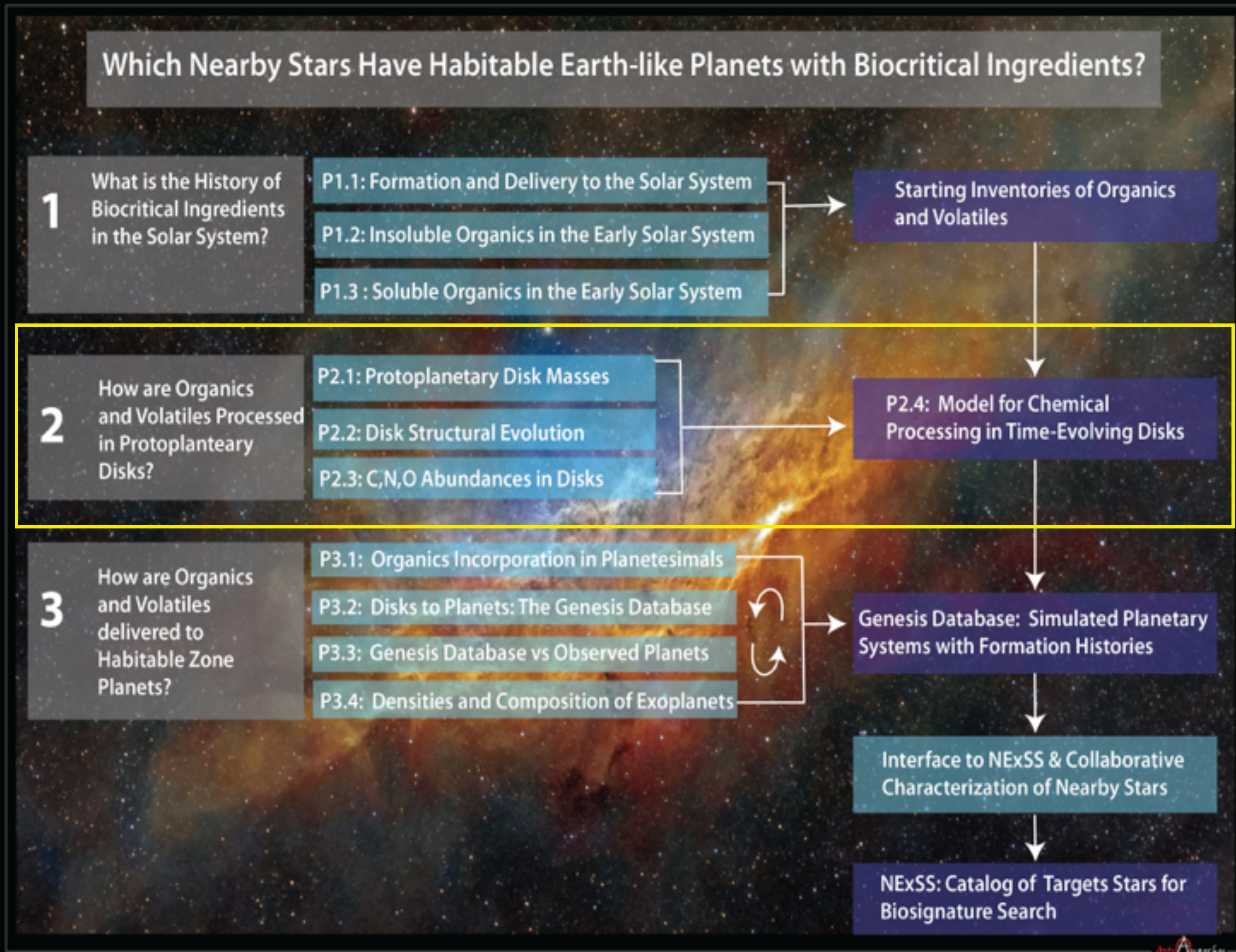

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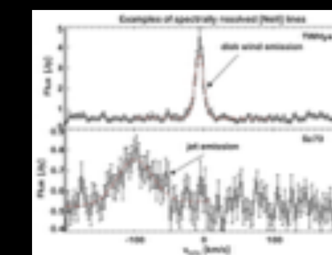

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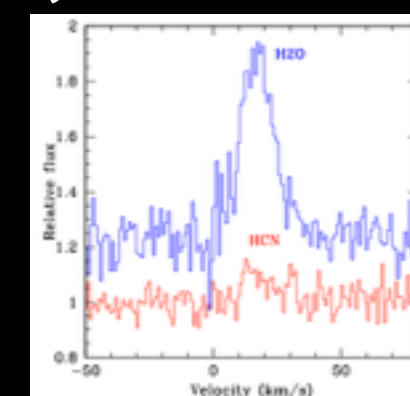
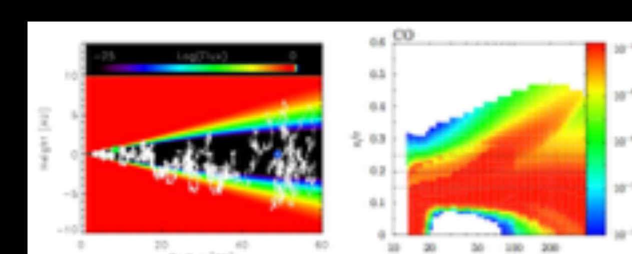
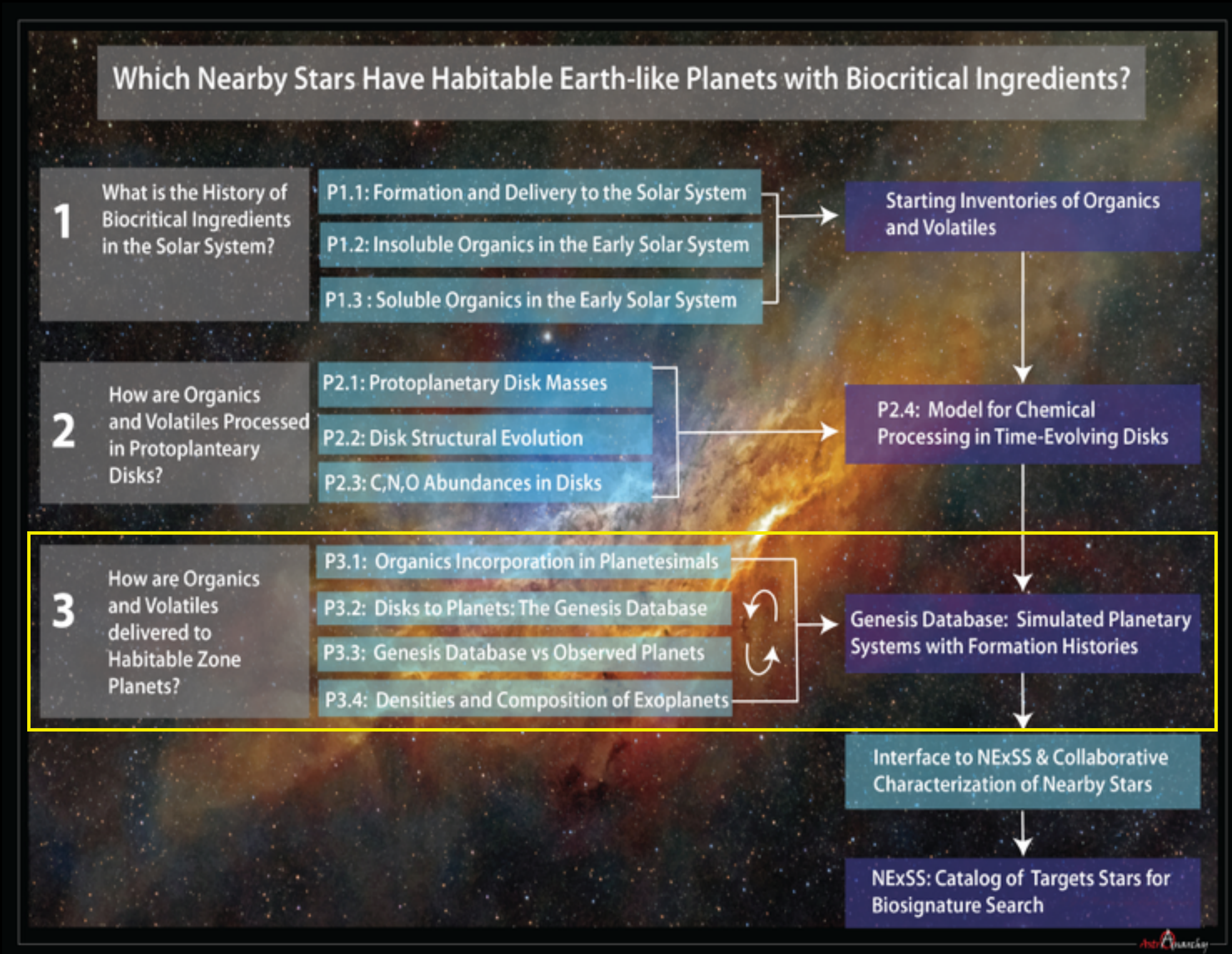
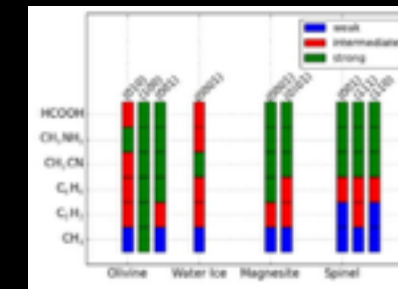
Joan Najita



Fred Ciesla

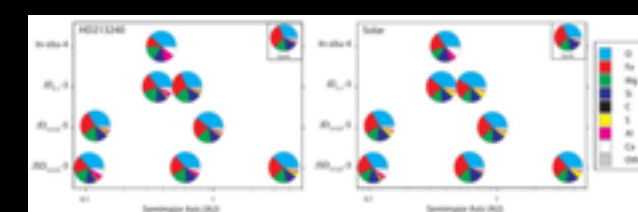






Krishna Muralidharan

Fred Ciesla & Dave O’Brien



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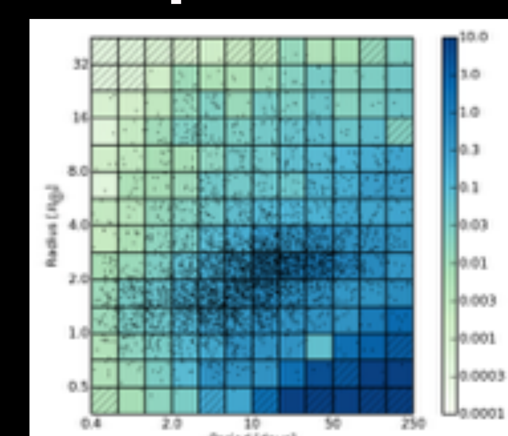
Daniel Apai



EOS Early Science

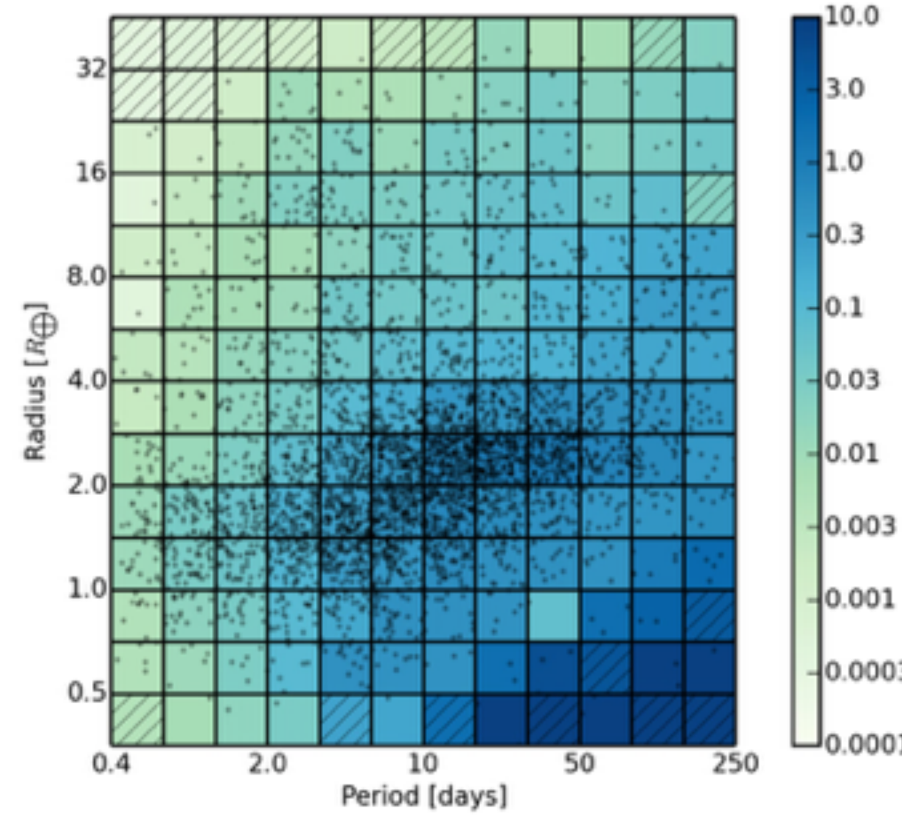
How do the Planet Orbits and Occurrence Rates Depend on Stellar Mass?

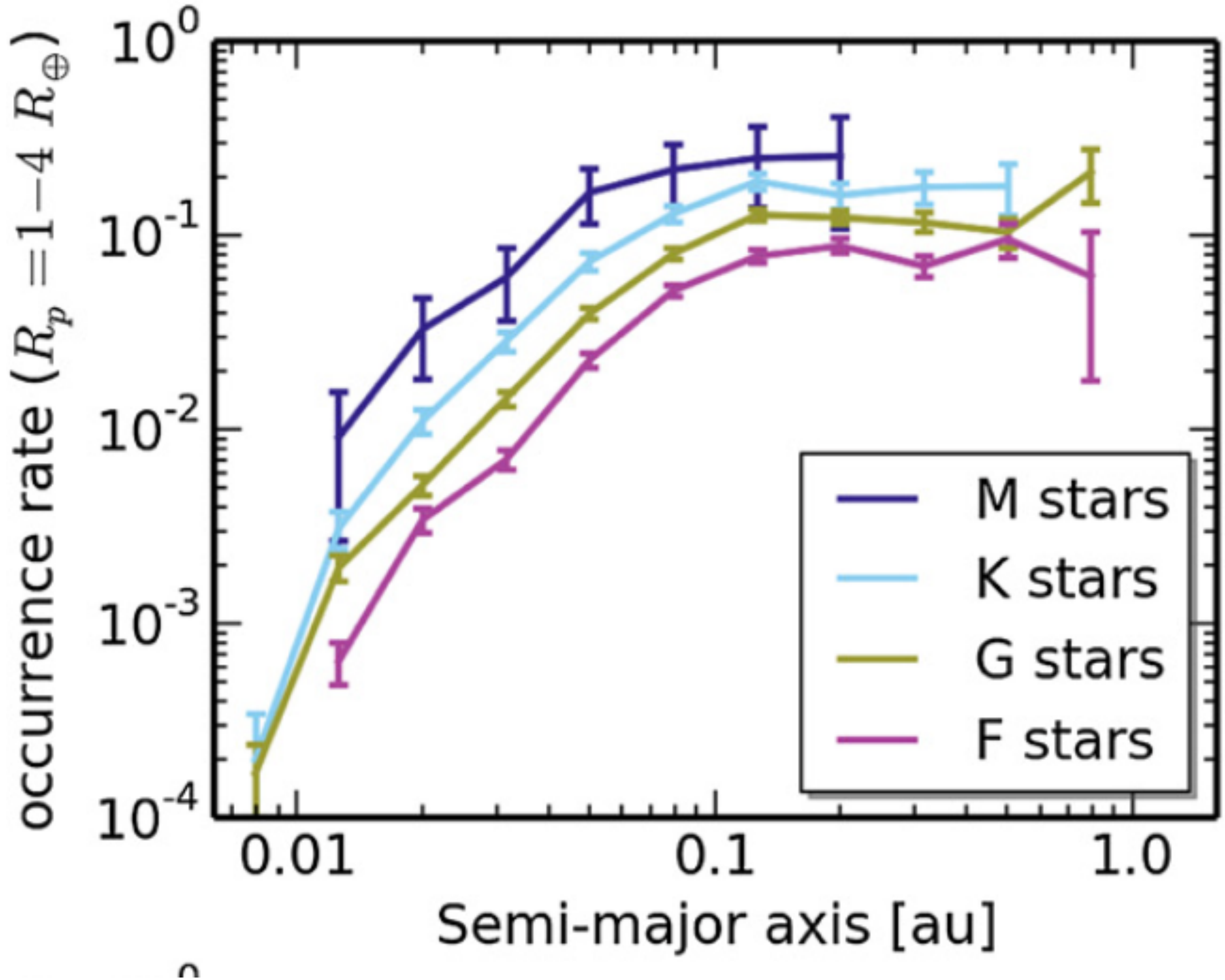
Mulders, Pascucci, Apai 2015 ApJ

e.g. Dressing & Charbonneau 2013, Howard et al. 2012; Plavchan & Bilinski 2013

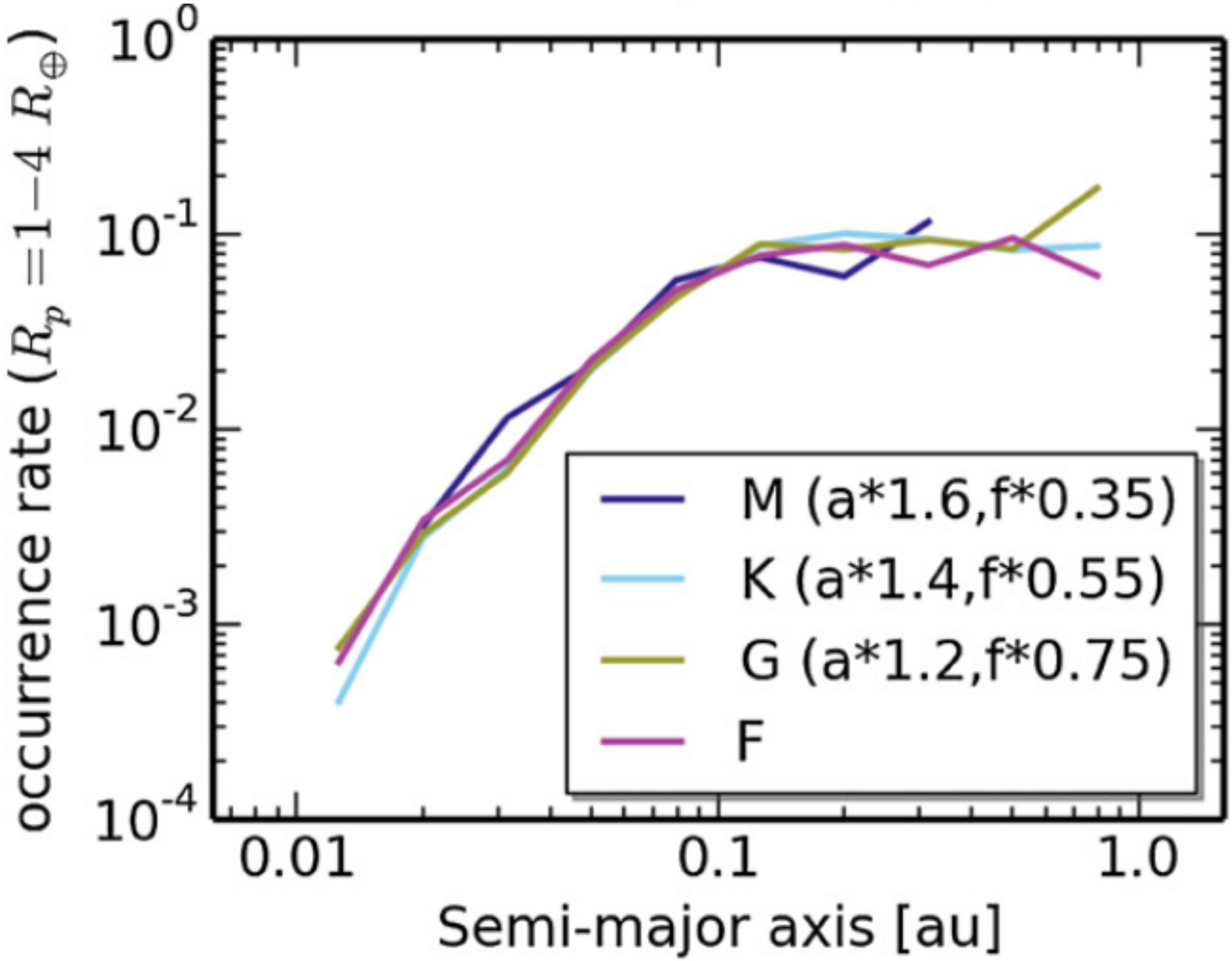
- Updated stellar and planet catalogs (Huber+ 14; Burke+ 14)
- Q1-Q8 data
- For each Kepler star: Probability of planet detection as a function of planet period, radius
- Probabilities vs. Kepler Detection Statistics —> Intrinsic occurrence rates and error bars

- Focusing on 1– 4 R_E planets
- Occurrence rates: semi-major axis, radius, spectral type
- Considering Kepler observing sequence





Mulders, Pascucci, Apai 2015 ApJ



Mulders, Pascucci, Apai 2015 ApJ

Conclusions

1) Planet distribution for 1–4 R_E are similar: increase and plateau
2) Planet occurrence rates are successively higher: $f_M > f_K > f_G > f_F$
3) Distribution scales with $M_*^{1/3}$ down to 2 R_E and up to P=150 d

Planet formation / orbital evolution is stellar mass dependent

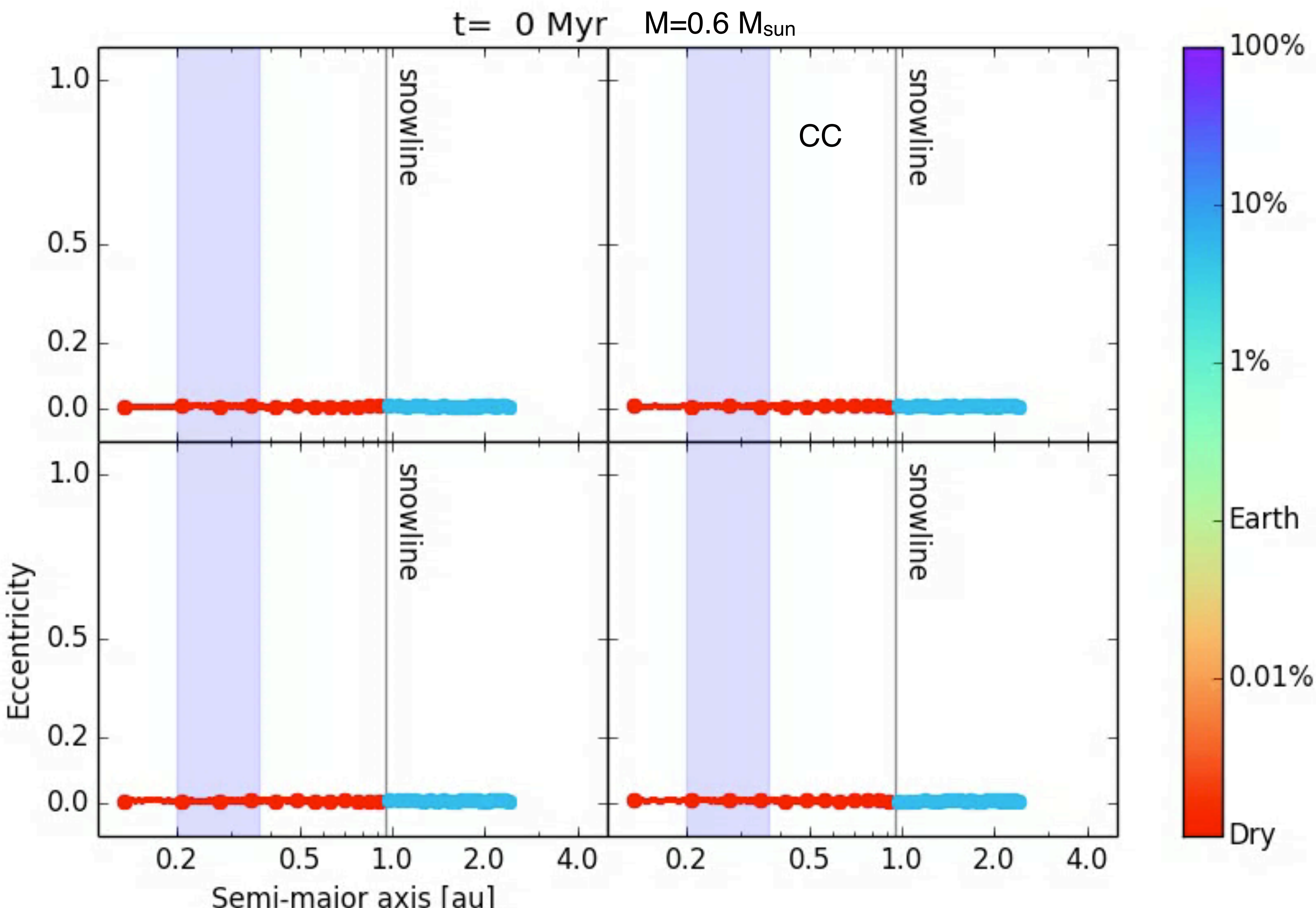
Mulders, Pascucci, Apai 2015 ApJ

Stellar-mass Dependence of Volatile Delivery to HZ Planets

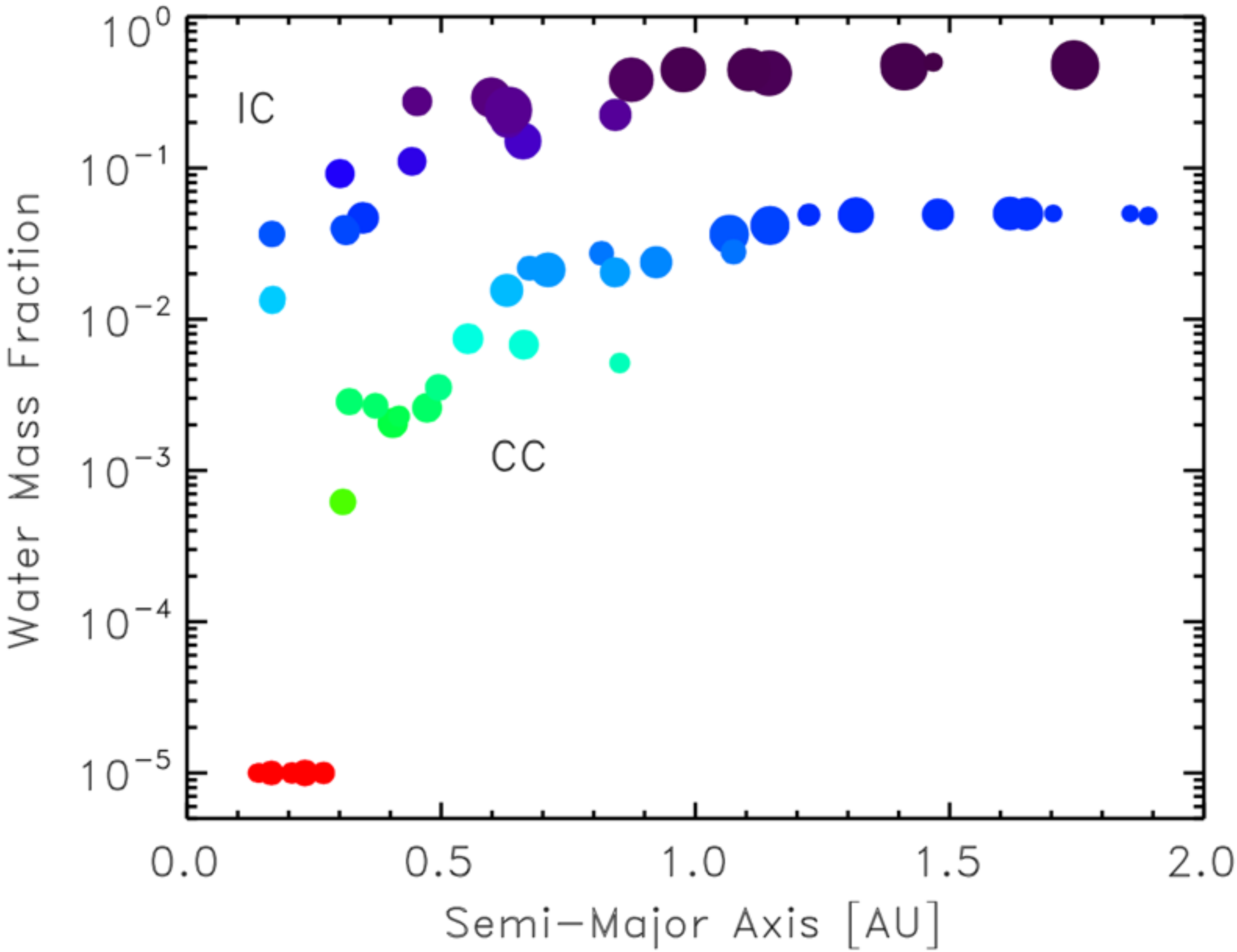
Ciesla, Mulders, Pascucci, Apai 2015 ApJ

- Modified Mercury integrator
- No giant planet
- No volatile loss (see talk by Tian)
- Stellar mass: 0.2 - 1.0 M_{sun}
- Stellar mass-dependent snowline

- Time-dependent snowline
- Large number of planetesimals (~10^3)
- Planetesimals: CC and IC



Ciesla, Mulders, Pascucci, Apai 2015 ApJ



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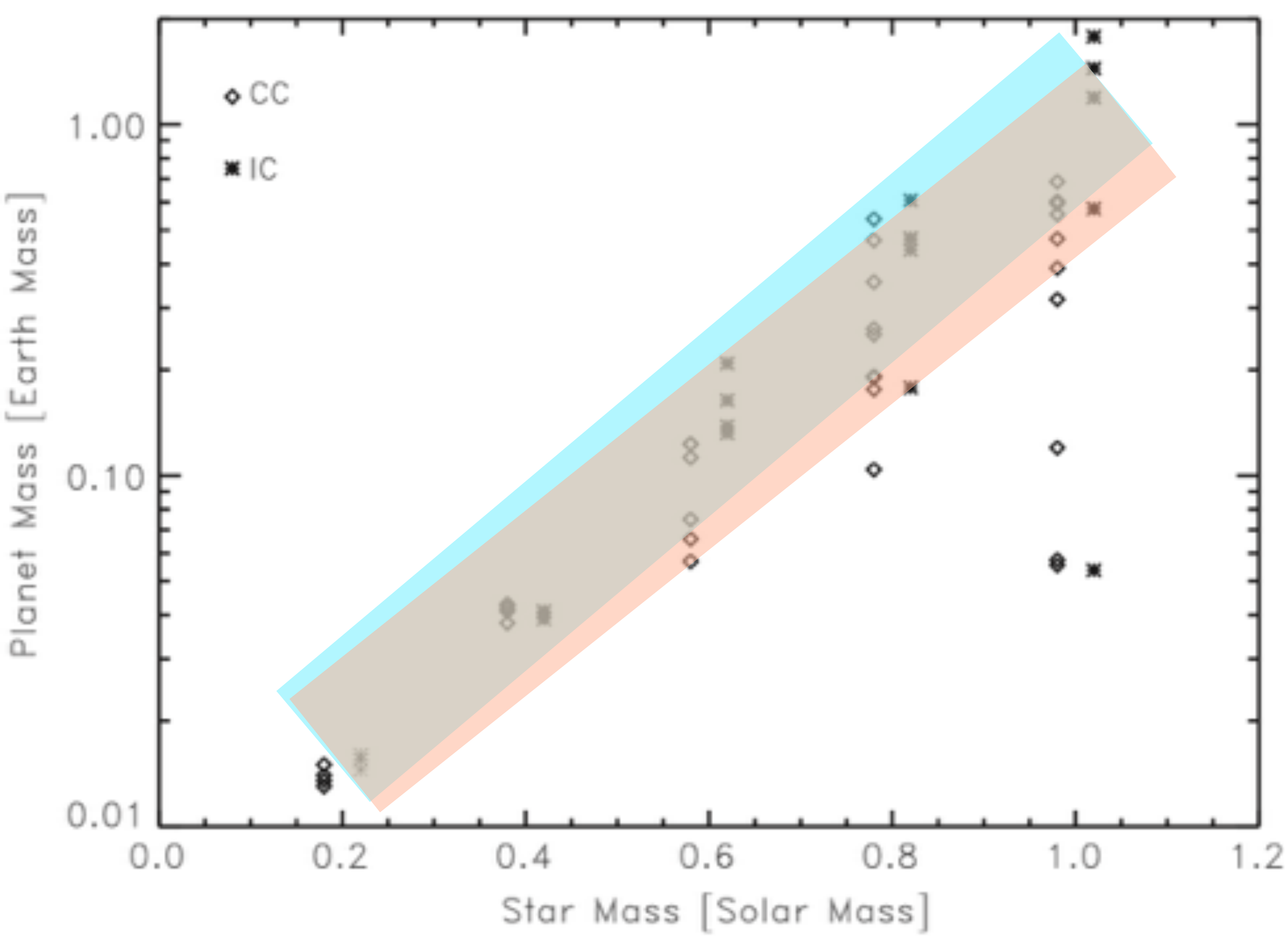
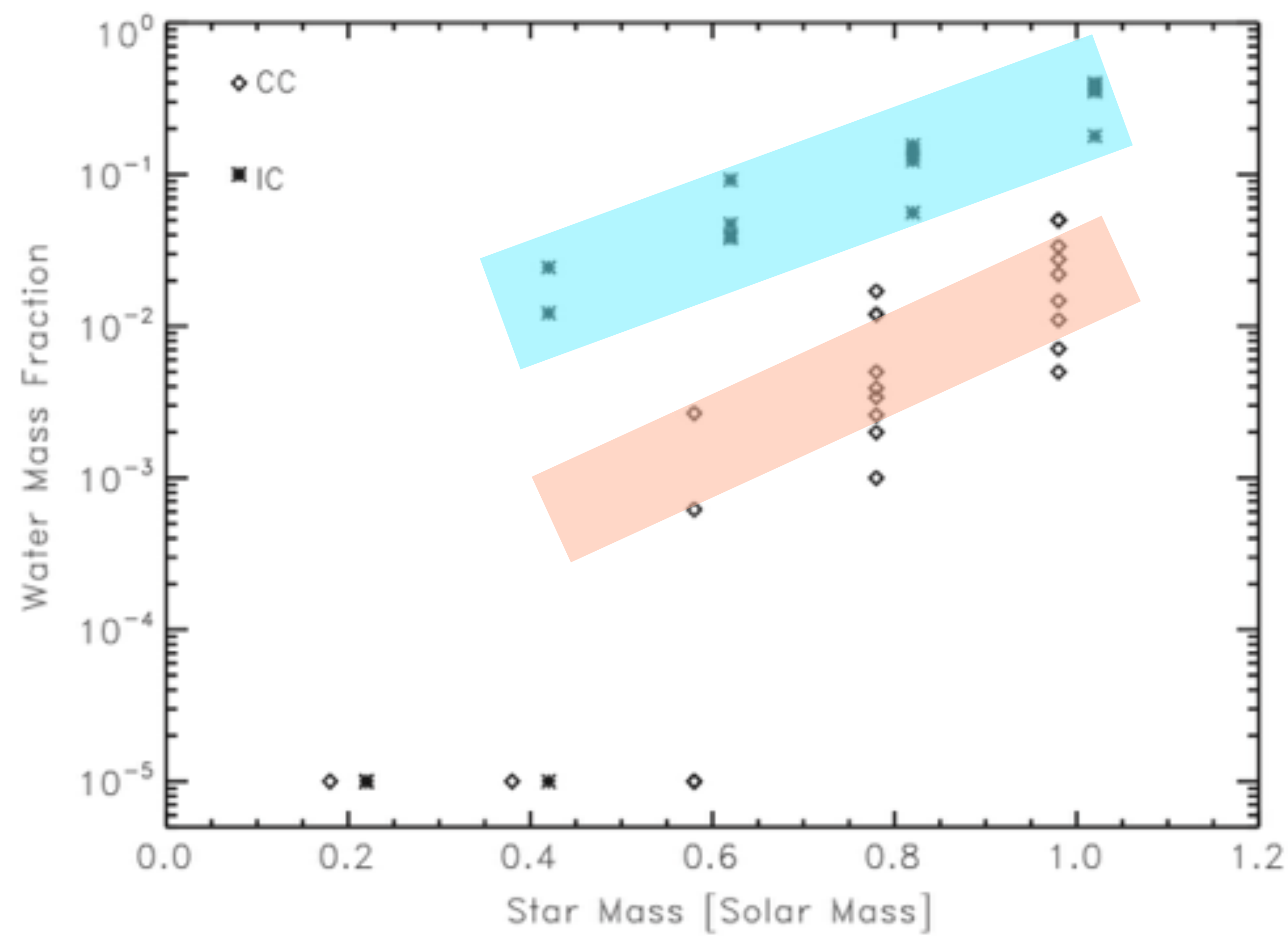
Habitable Zone Planets Only



More massive disks form more massive planets



Ice content of planetesimals is important and can lead to wet planetesimals even around M-dwarfs

Ciesla, Mulders, Pascucci, Apai 2015 ApJ

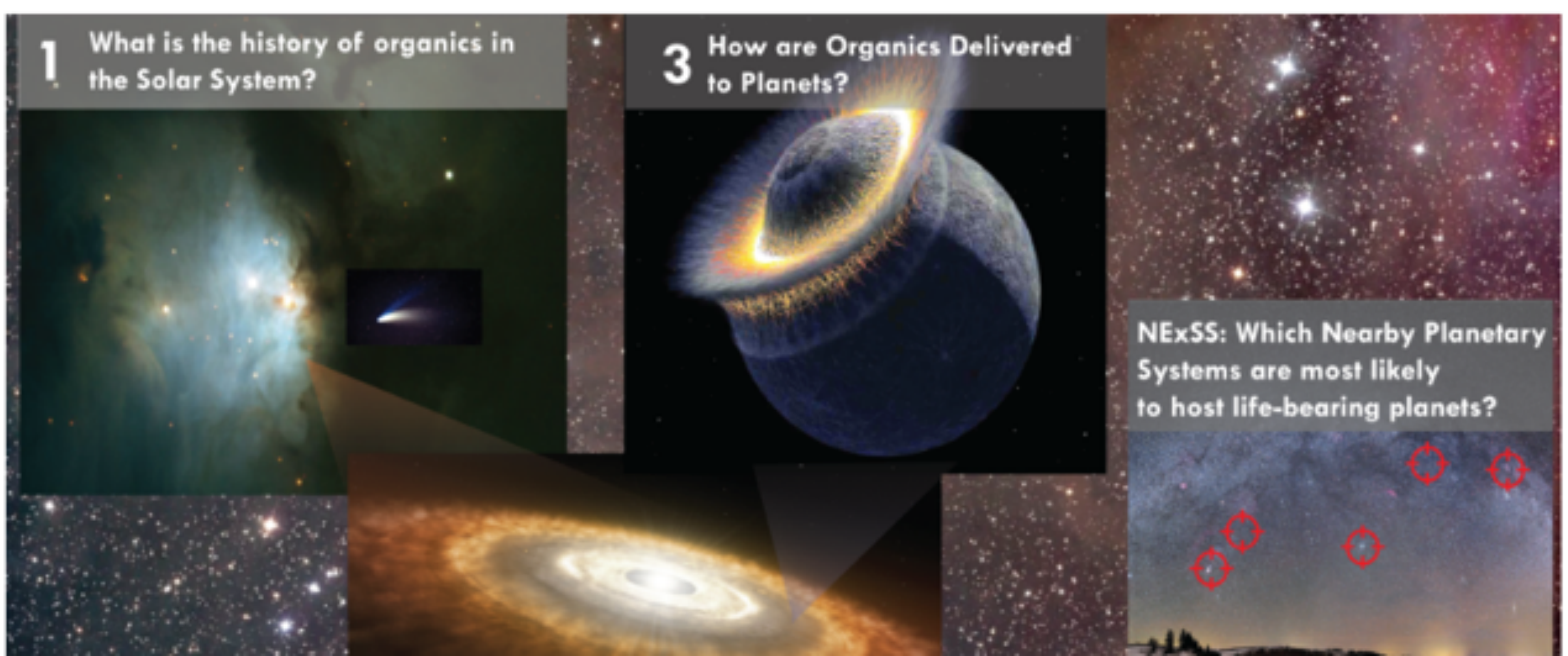
Project EOS Team Objectives » News Search Contact Us

Earths in Other Solar Systems is a NASA-funded five year-duration astrobiology research program aiming to understand how and where habitable, earth-like planets with biocritical ingredients (volatiles and organics) form.

EOS is part of NASA's Nexus for Exoplanetary System Science, which carries out coordinated research toward to the goal of searching for and determining the frequency of extrasolar planets with atmospheric biosignatures in the Solar neighborhood.

The interdisciplinary EOS team includes astrophysicists, planetary scientists, cosmochemists, material scientists, chemists and physicists.

The project is led by The University of Arizona's Steward Observatory and Lunar and Planetary Laboratory.



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Conclusions

Target systems greatly influence the design of biosignature survey

Chemical diversity of Earth-sized planets important

EOS: Major effort to understand volatile and organics delivery

Early Science:

1) Planet distribution depends on stellar mass

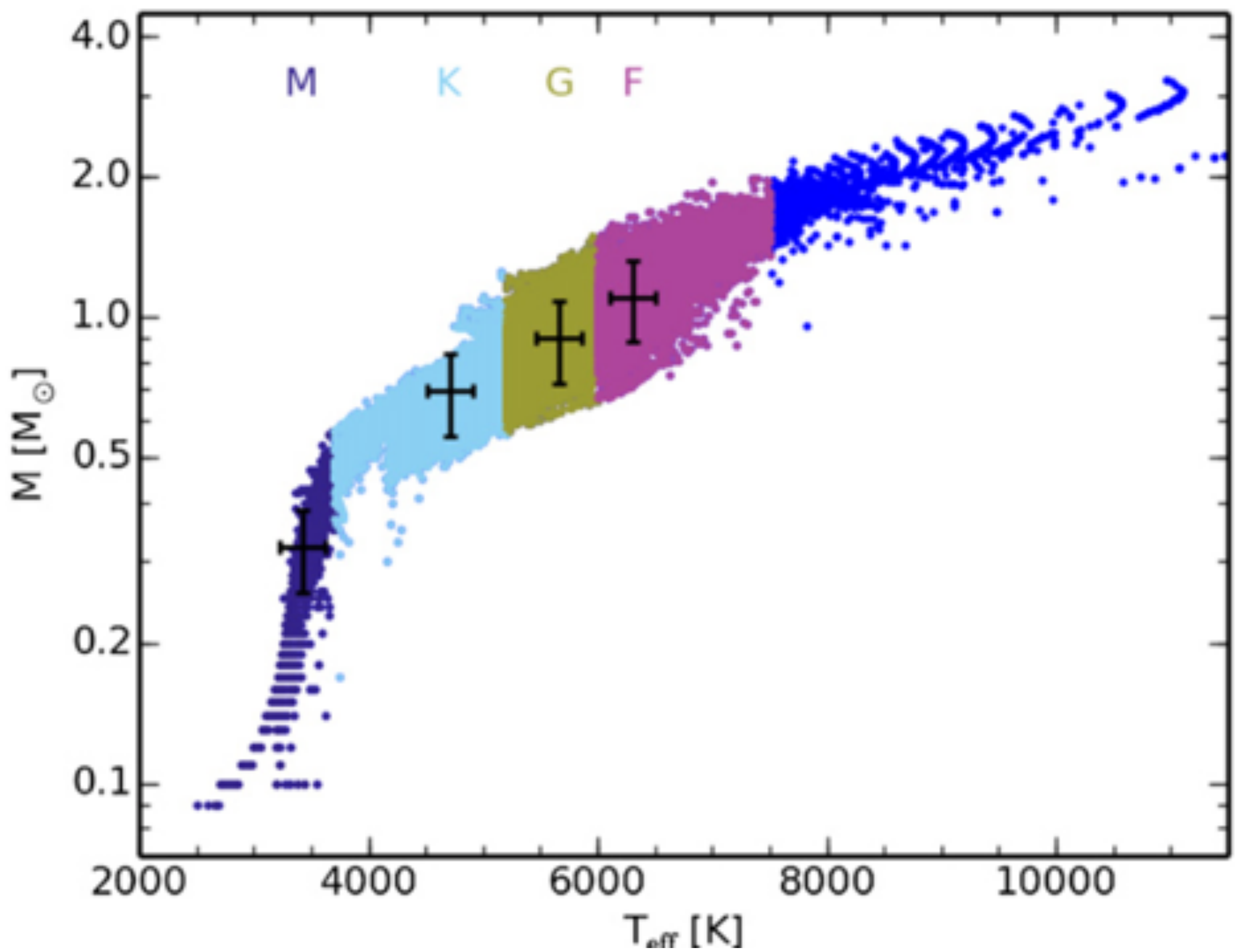
2) Planet accretion: ice-rich planetesimals play important role

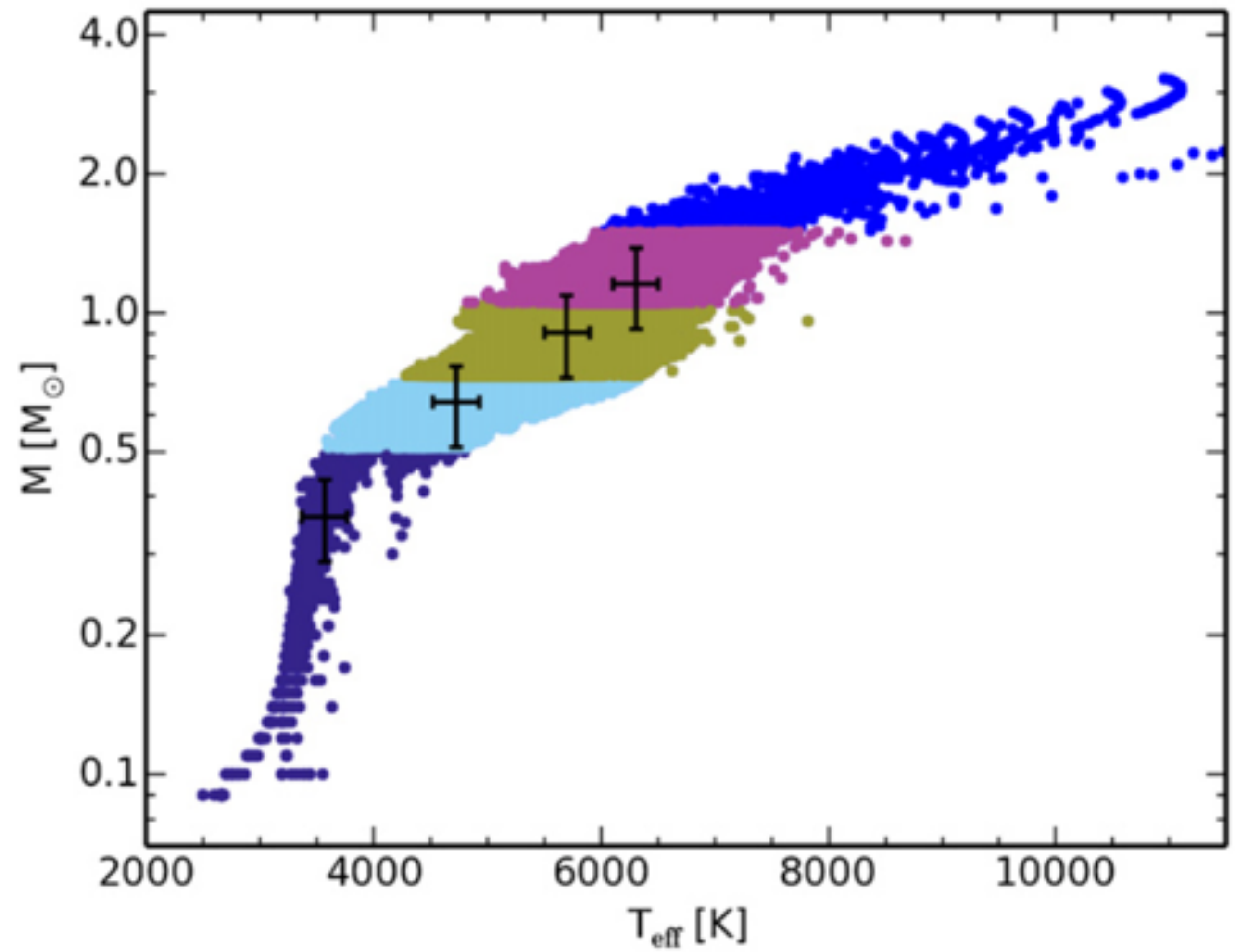
Table 1
Simulation Parameters

M_* ($M_\odot$)	Initial Range (AU)	Water Line (AU)	M_{emb} ($M_\oplus$)	M_{plan} ($M_\oplus$)	N_{emb}^{CC}	N_{plan}^{CC}	N_{emb}^{IC}	N_{plan}^{IC}	Habitable Zone (AU)
1.0	0.5–4.0	1.3	0.05	2.5×10^{-3}	50	974	88	1875	0.8–1.5
0.8	0.2–3.2	1.1	0.04	2×10^{-3}	43	827	72	1528	0.39–0.74
0.6	0.1–2.4	0.9	0.03	1.5×10^{-3}	33	622	54	1122	0.20–0.37
0.4	0.05–1.6	0.8	0.02	10^{-3}	23	420	34	672	0.10–0.19
0.2	0.03–0.8	0.5	0.01	5×10^{-4}	11	196	16	291	0.05–0.10

Note. M_{smb}: embryo mass; M_{plan}: planetesimal mass; N_{emb}: number of embryos, N_{plan}: number of planetesimals. Habitable zone estimates taken from Raymond et al. (2007).

Ciesla, Mulders, Pascucci, Apai 2015 ApJ





Mulders, Pascucci, Apai 2015 ApJ

Table 4
Planet Occurrence Rates for the Entire *Kepler* Sample

	Period (days)											
	0.4–0.68	0.68–1.2	1.2–2.0	2.0–3.4	3.4–5.8	5.8–10.0	10.0–17.0	17.0–29.0	29.0–50.0	50.0–85.0	85.0–150.0	150.0–250.0
32.0–45.0	<0.0012	<0.0017	<0.0025	<0.0036	0.0058 ±0.0066	<0.0073	<0.010	0.048 ±0.029	0.018 ±0.028	0.027 ±0.040	<0.046	0.088 ±0.103
23.0–32.0	<0.0013	<0.0019	0.0048 ±0.0044	0.037 ±0.012	0.023 ±0.012	0.022 ±0.015	0.035 ±0.022	0.082 ±0.038	0.12 ±0.06	0.067 ±0.056	0.10 ±0.08	0.14 ±0.13
16.0–23.0	0.0031 ±0.0023	0.0045 ±0.0033	0.011 ±0.006	0.050 ±0.015	0.090 ±0.023	0.041 ±0.020	0.13 ±0.04	0.097 ±0.044	0.18 ±0.07	0.076 ±0.059	0.11 ±0.09	0.17 ±0.14
11.0–16.0	0.0017 ±0.0019	0.0087 ±0.0045	0.033 ±0.010	0.090 ±0.019	0.099 ±0.026	0.096 ±0.030	0.14 ±0.04	0.21 ±0.06	0.28 ±0.09	0.18 ±0.09	0.27 ±0.13	<0.087
8.0–11.0	0.0048 ±0.0029	0.011 ±0.005	0.028 ±0.009	0.029 ±0.011	0.066 ±0.021	0.13 ±0.03	0.15 ±0.05	0.27 ±0.07	0.33 ±0.10	0.44 ±0.13	0.61 ±0.19	0.83 ±0.29
5.7–8.0	0.0016 ±0.0020	0.022 ±0.007	0.028 ±0.010	0.039 ±0.013	0.16 ±0.03	0.14 ±0.04	0.19 ±0.05	0.17 ±0.06	0.41 ±0.11	0.55 ±0.15	0.97 ±0.24	1.0 ±0.3
4.0–5.7	0.0096 ±0.0041	0.016 ±0.006	0.047 ±0.012	0.081 ±0.019	0.15 ±0.03	0.27 ±0.05	0.38 ±0.07	0.46 ±0.09	0.49 ±0.12	0.78 ±0.18	0.73 ±0.22	0.81 ±0.29
2.8–4.0	0.0083 ±0.0038	0.023 ±0.007	0.059 ±0.014	0.12 ±0.02	0.35 ±0.05	0.59 ±0.08	1.4 ±0.1	1.5 ±0.2	1.8 ±0.2	1.6 ±0.3	1.7 ±0.3	1.5 ±0.4
2.0–2.8	0.028 ±0.007	0.043 ±0.010	0.099 ±0.018	0.28 ±0.04	0.70 ±0.07	1.4 ±0.1	2.8 ±0.2	3.6 ±0.3	3.8 ±0.3	2.7 ±0.4	2.1 ±0.4	1.3 ±0.4
1.4–2.0	0.039 ±0.008	0.12 ±0.02	0.20 ±0.03	0.52 ±0.05	1.0 ±0.1	1.7 ±0.1	2.4 ±0.2	2.1 ±0.2	1.8 ±0.3	1.4 ±0.3	1.4 ±0.4	2.1 ±0.7
1.0–1.4	0.038 ±0.008	0.11 ±0.02	0.18 ±0.03	0.43 ±0.05	1.0 ±0.1	1.3 ±0.1	1.9 ±0.2	1.6 ±0.3	1.6 ±0.4	1.5 ±0.5	3.8 ±1.3	7.5 ±2.6
0.71–1.0	0.019 ±0.006	0.064 ±0.014	0.12 ±0.03	0.34 ±0.06	0.69 ±0.10	1.6 ±0.2	1.6 ±0.3	1.5 ±0.4	0.25 ±0.34	6.4 ±2.9	9.7 ±6.3	<13.2
0.5–0.71	0.019 ±0.008	0.040 ±0.017	0.095 ±0.037	0.33 ±0.10	1.6 ±0.3	1.5 ±0.4	1.5 ±0.8	6.4 ±3.1	19.9 ±6.4	<16.3	230.3 ±69.0	72.3 ±53.6
0.35–0.5	<0.018	0.029 ±0.029	0.061 ±0.074	0.11 ±0.14	<0.82	0.75 ±0.79	<6.5	80.9 ±12.8	<54.7	119.2 ±51.8	<389.7	<867.9

Notes. Occurrence rates per bin. Columns are orbital period P in days, rows are planet radius R_p in Earth radii.

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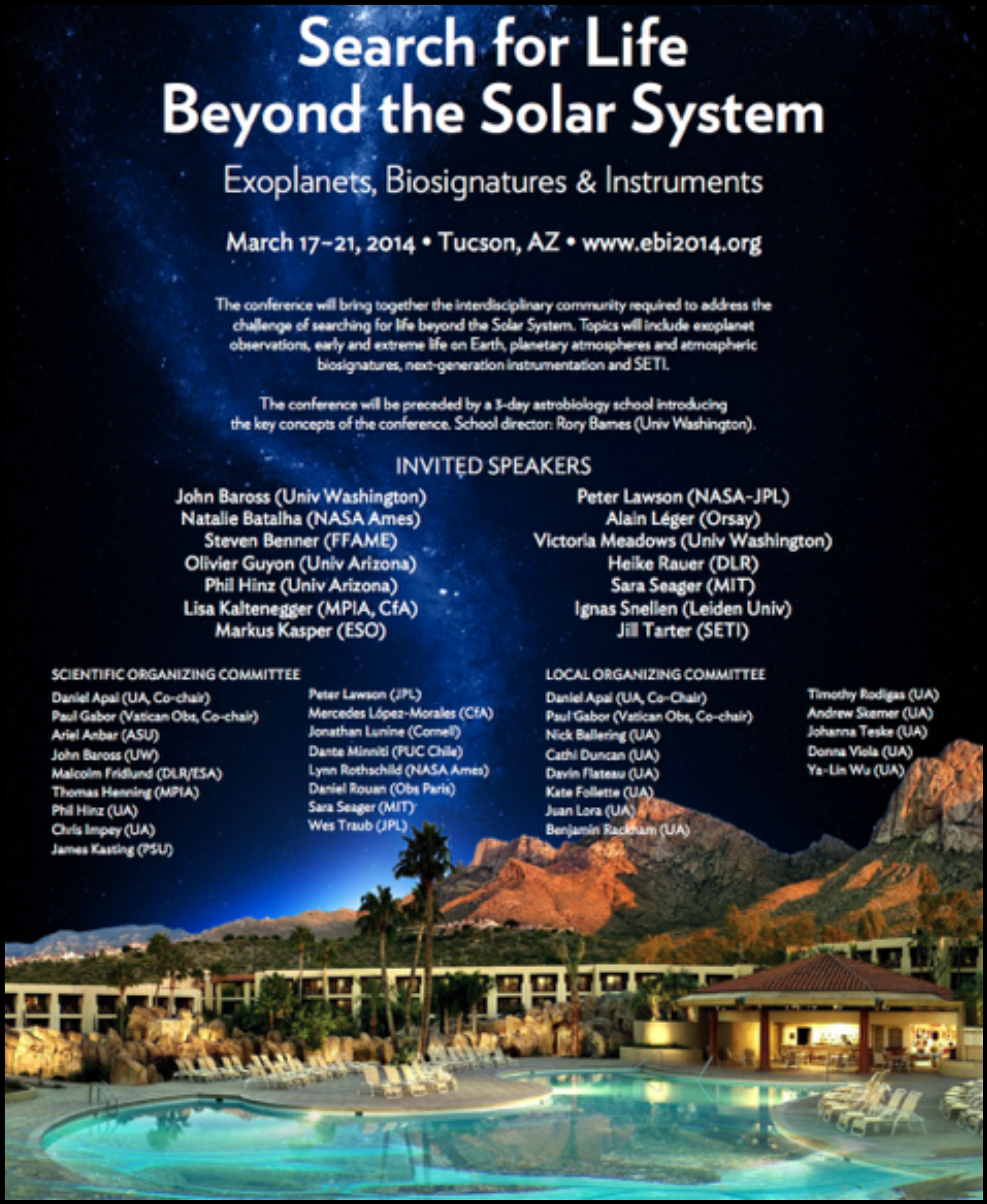
Search for Life
Beyond the Solar System
Exoplanets, Biosignatures & Instruments
March 17–21, 2014 • Tucson, AZ • www.ebi2014.org
The conference will bring together the interdisciplinary community required to address the challenge of searching for life beyond the Solar System. Topics will include exoplanet observations, early and extreme life on Earth, planetary atmospheres and atmospheric biosignatures, next-generation instrumentation and SETI.
The conference will be preceded by a 3-day astrobiology school introducing the key concepts of the conference. School director: Rory Barnes (Univ Washington).
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Steven Benner (FFAME)
Olivier Guyon (Univ Arizona)
Phil Hinz (Univ Arizona)
Lisa Kaltenegger (MPIA, CfA)
Markus Kasper (ESO)
Peter Lawson (NASA-JPL)
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