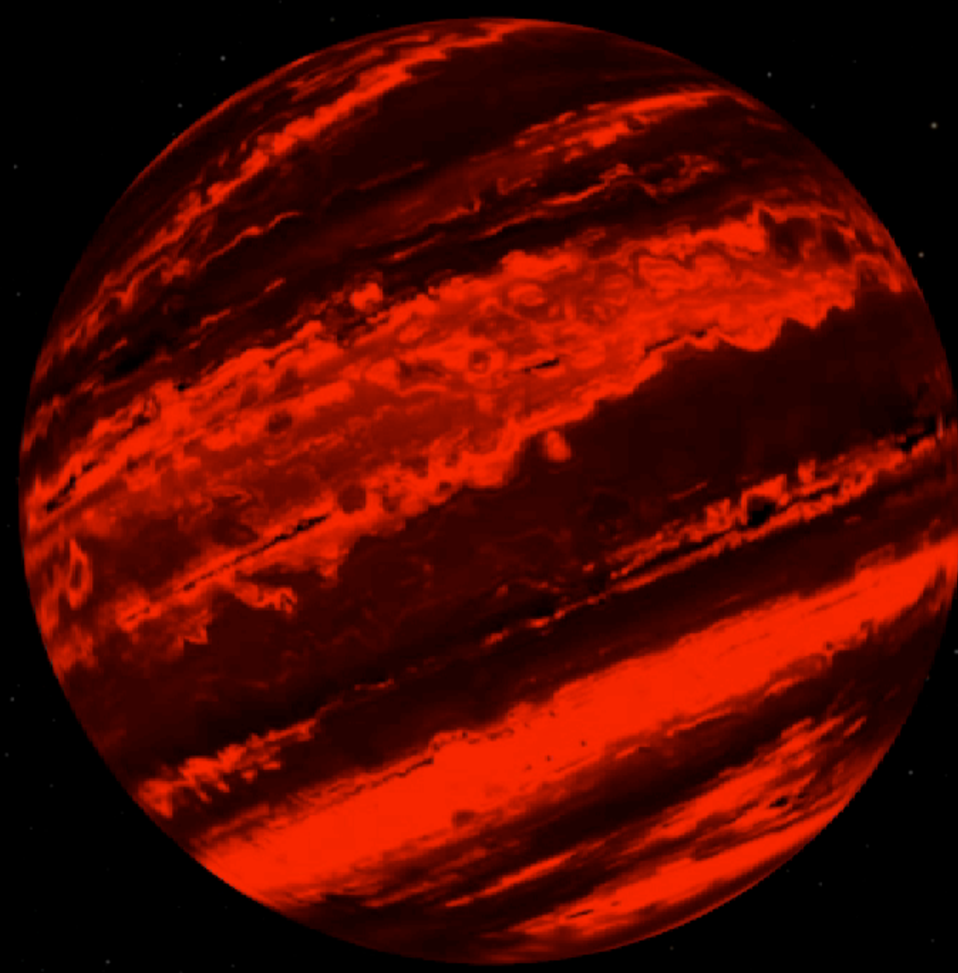
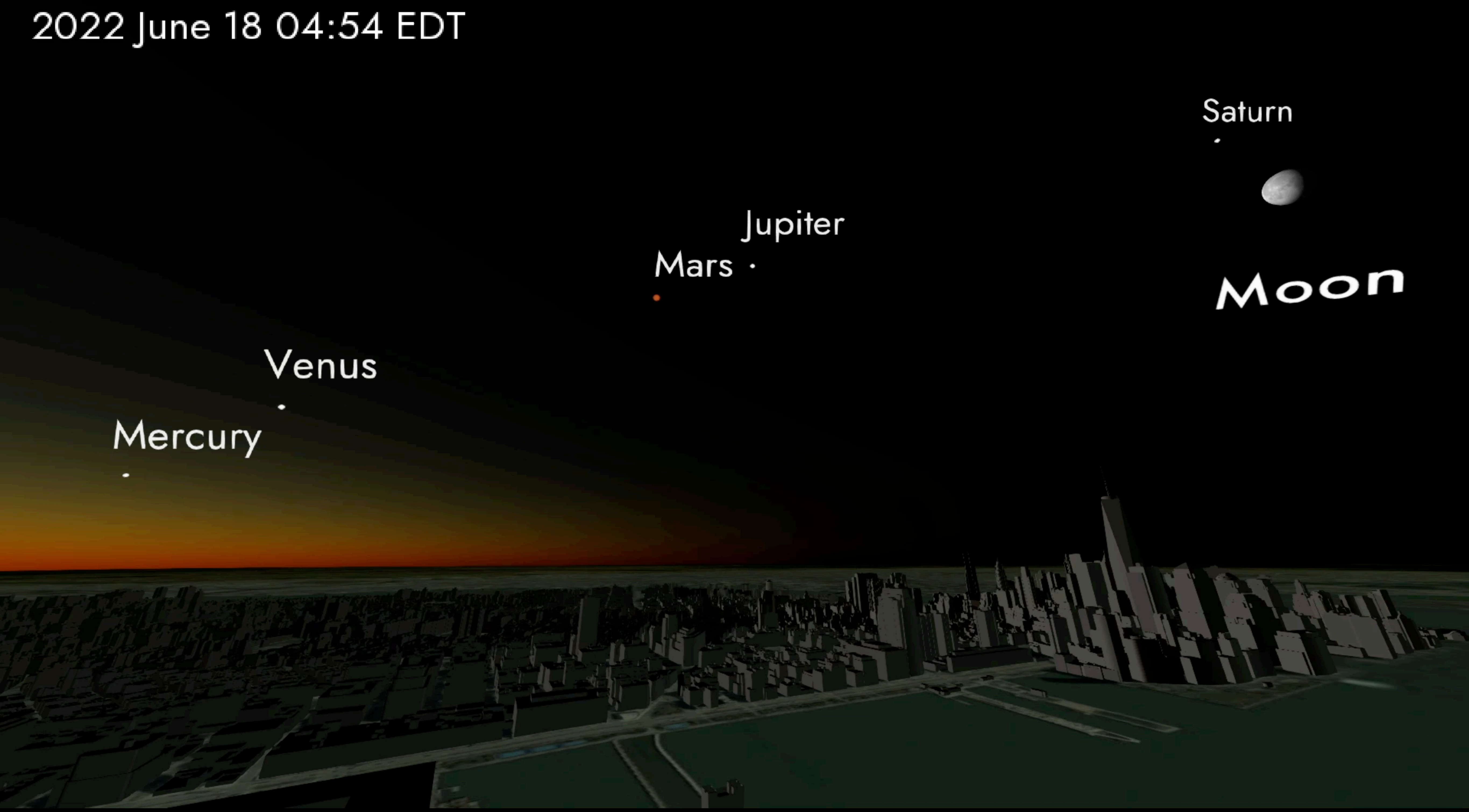
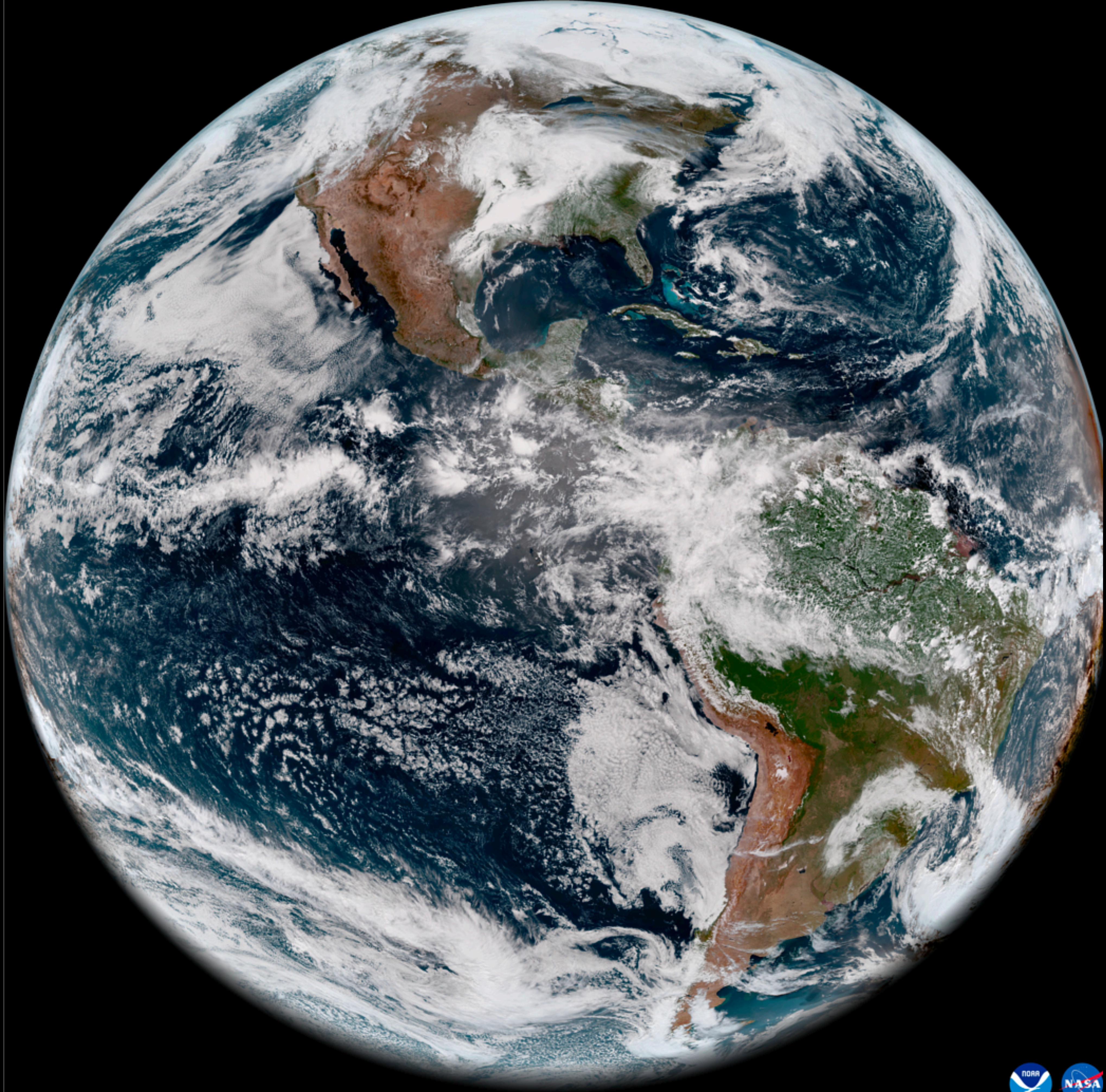
Directly Imaged Exoplanets in the Era of Gaia



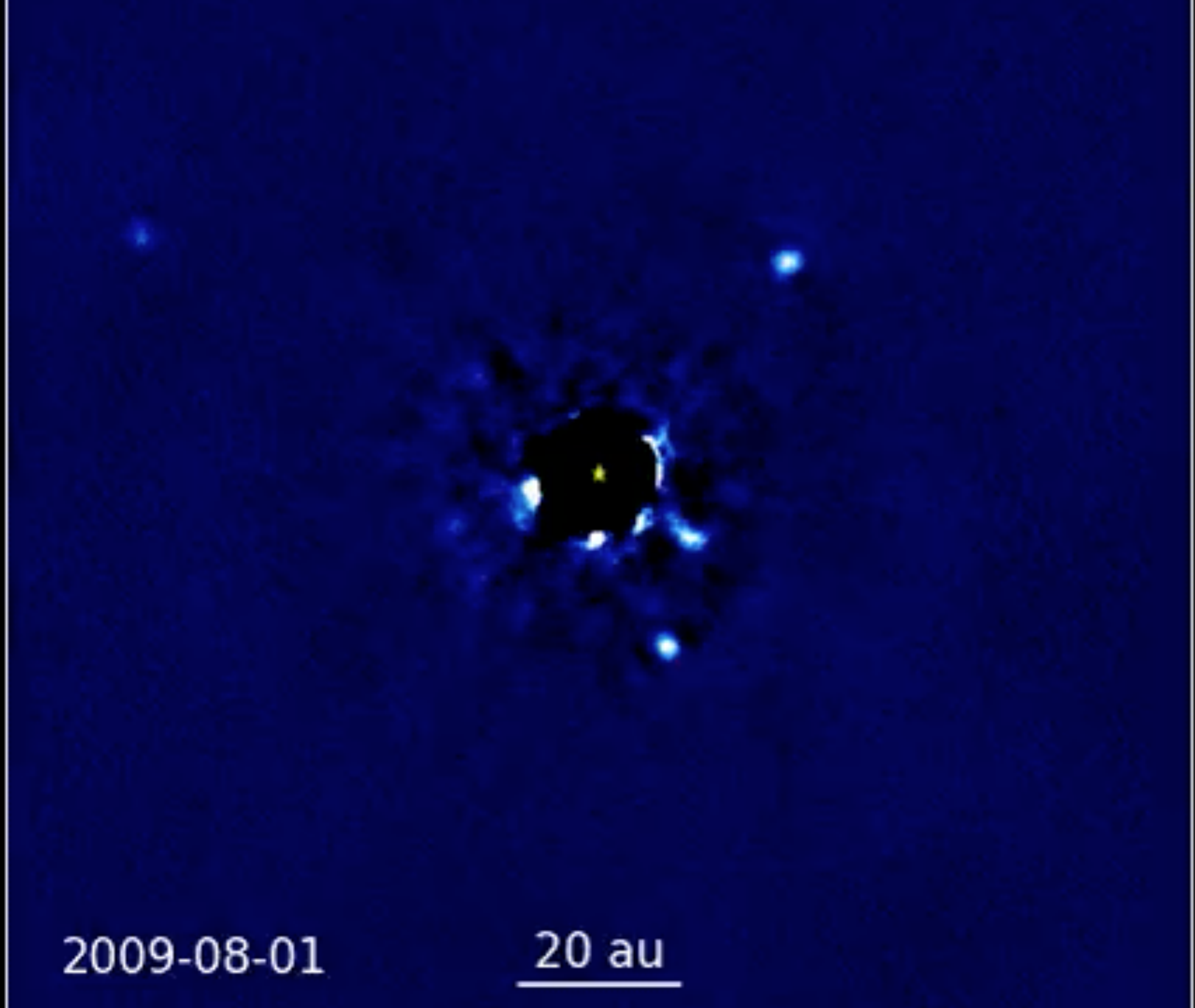
B D N Y C Jackie Faherty
Senior Scientist
American Museum of Natural History
@jfaherty

The OG Directly Imaged Planets

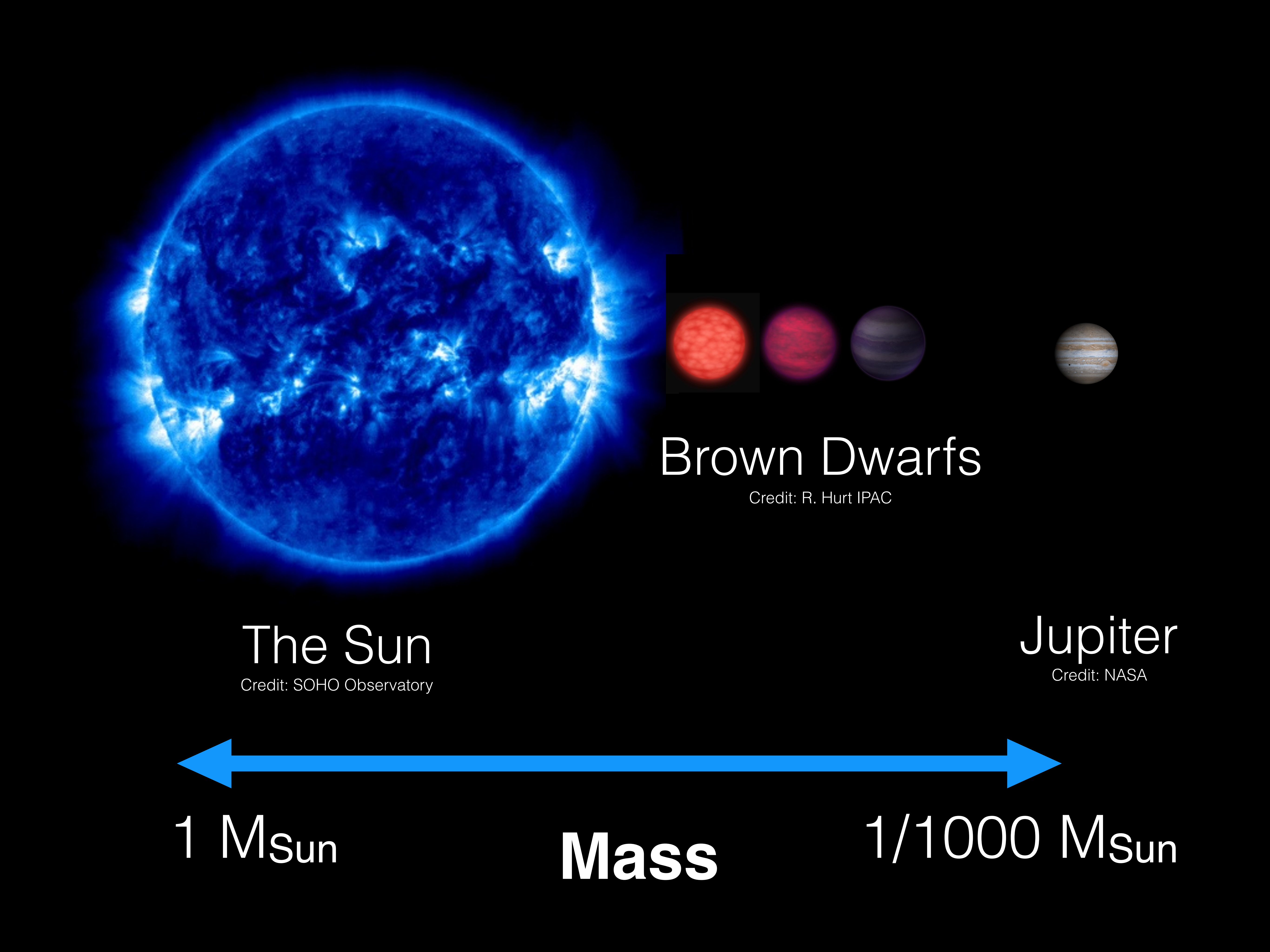


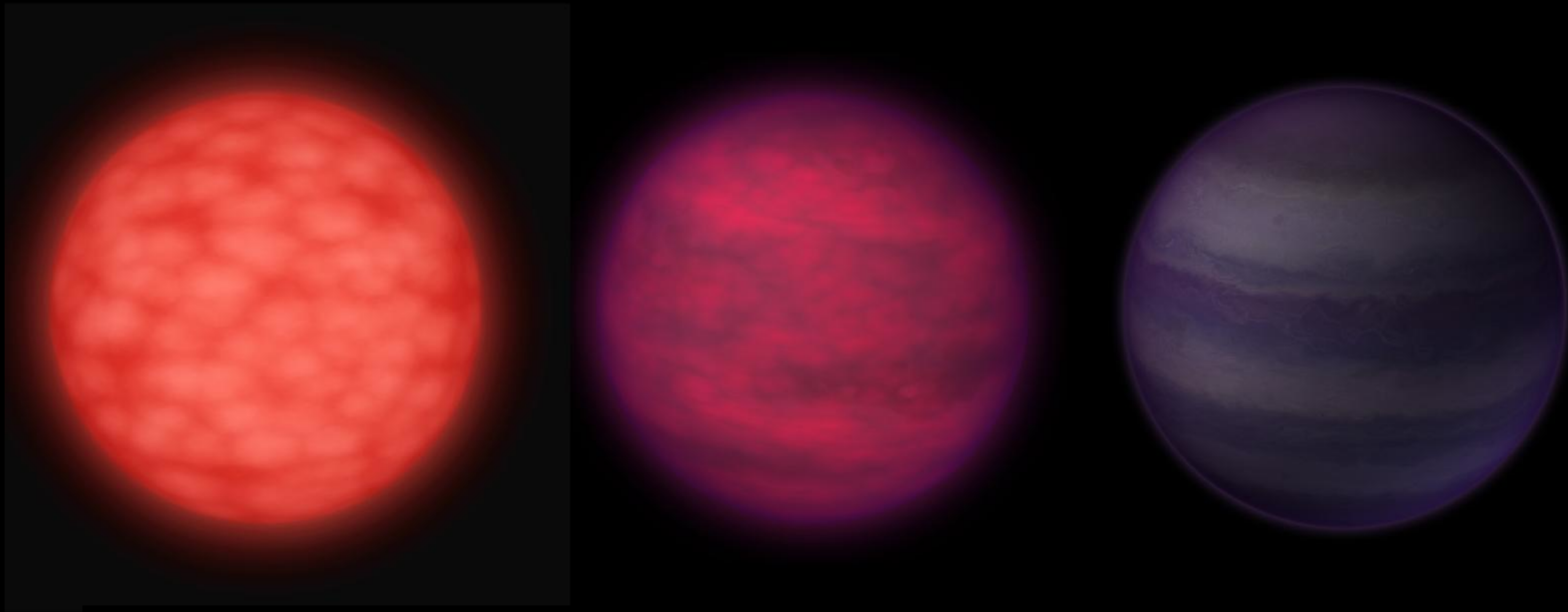


HR8799 planets



Animation made by Jason Wang, Caltech

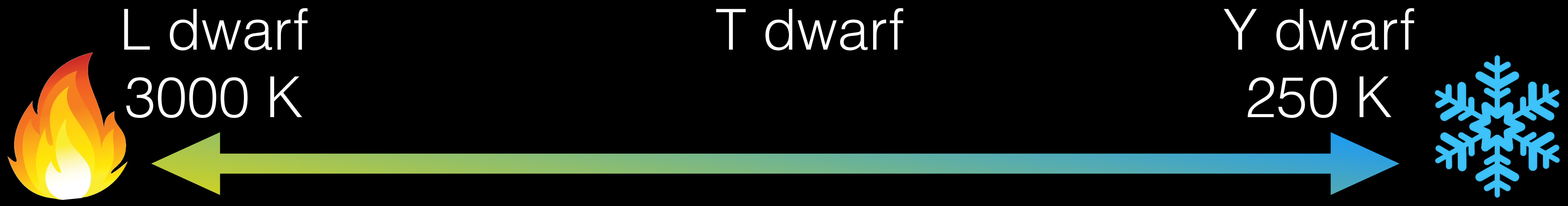

Brown Dwarfs
Credit: R. Hurt IPAC
The Sun
Credit: SOHO Observatory
Jupiter
Credit: NASA
1 MSun
Mass
1/1000 MSun



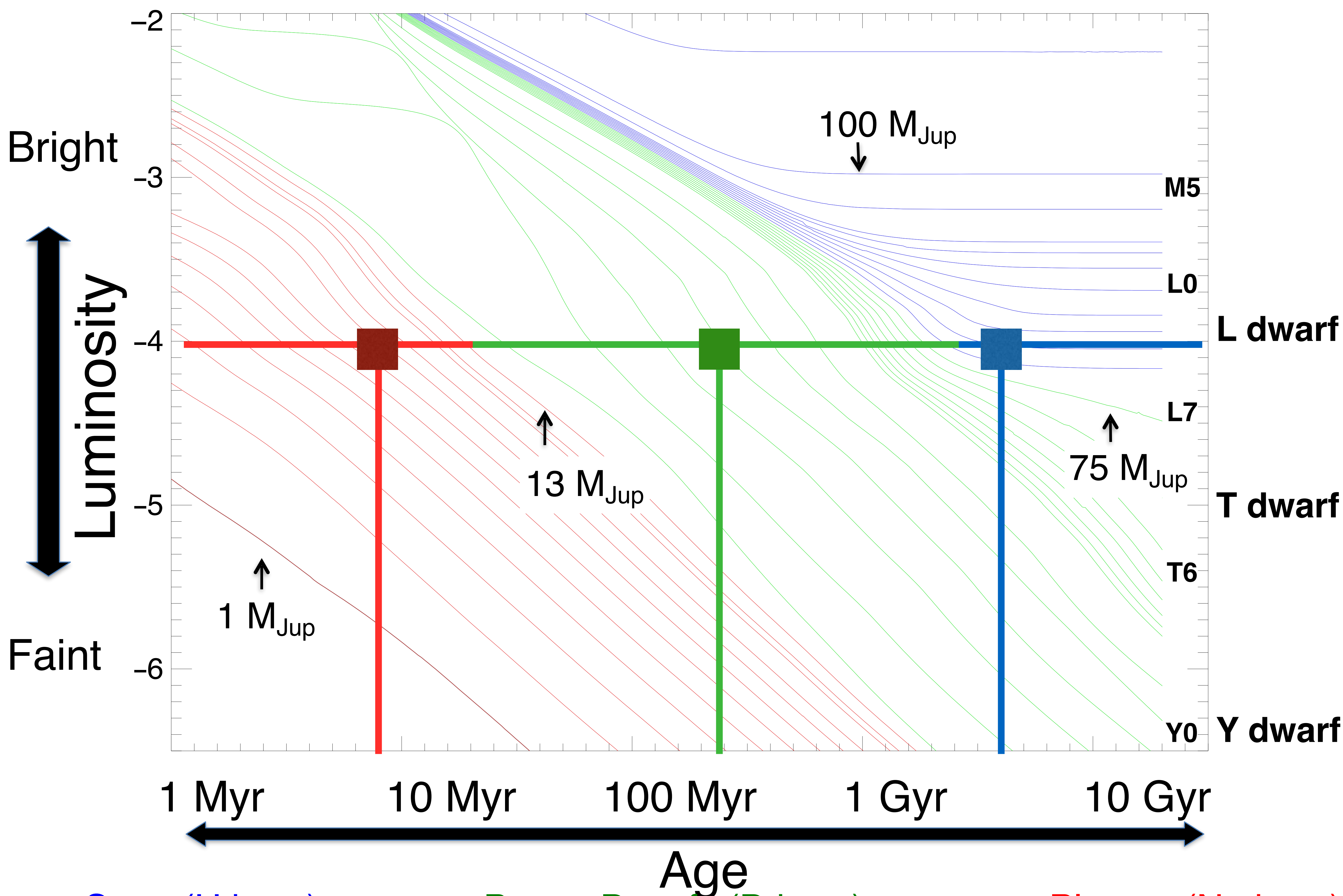
L Dwarfs
Surface Temp:
1500K - 3000 K
Pottery Kilns
Highest Setting

T Dwarfs
Surface Temp:
500 K - 1500 K
Lave Flows to
Conventional Ovens

Y Dwarfs
Surface Temp:
250 K - 500 K
Warm sunny day to a
cold North Pole day



Evolutionary Diagram of **Brown Dwarfs** and Planets



Stars (H burn) Brown Dwarfs (D burn) Planets (No burn)

How does Gaia help us Understand Directly Imaged Exoplanets?

Luminosity

Age

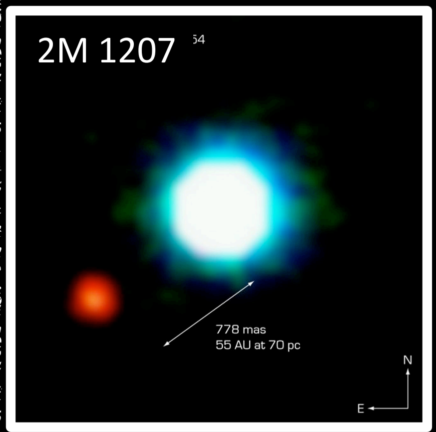
Mass

Chemistry

Dynamic
History

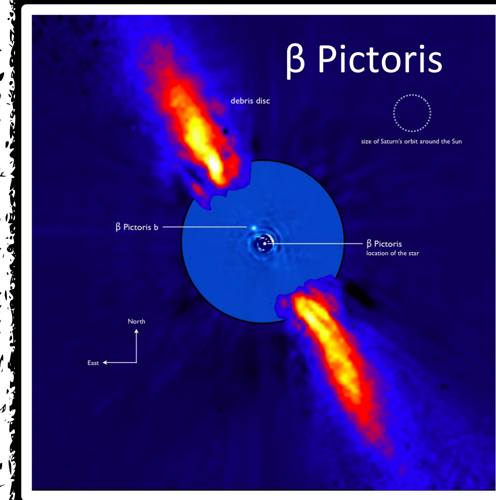
Formation?

Nearby Young Moving Groups



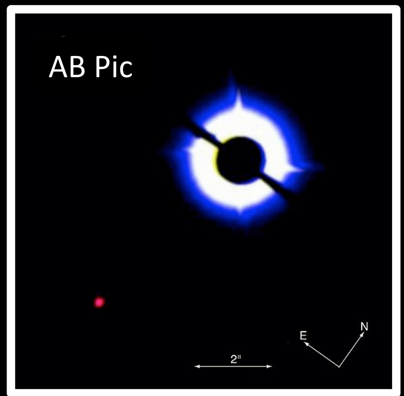
TW Hydrae

10 ± 3 Myr



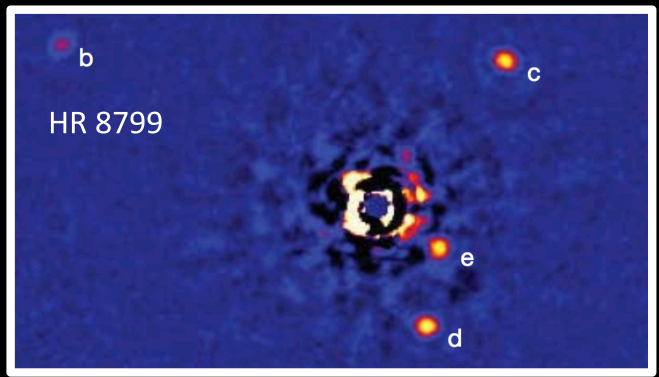
β Pictoris

23 ± 3 Myr



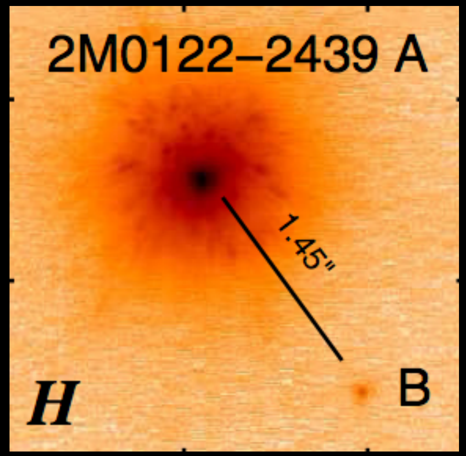
Tuc-Hor

44 ± 5 Myr



Columba

46 ± 8 Myr

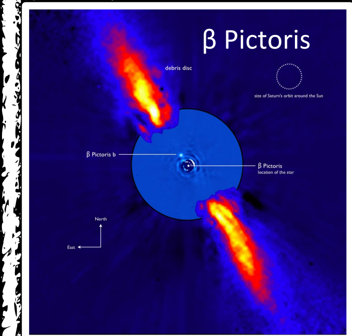


AB Doradus

147 ± 34 Myr

High confidence or Bonafide* M7-T5 dwarfs…

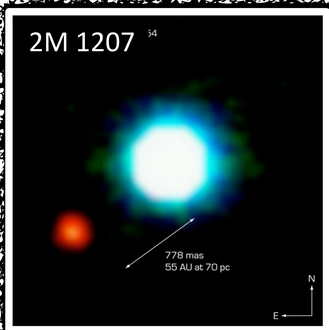
SIBLINGS of the Exoplanets



β Pictoris

23 ± 3 Myr

β Pictoris: 6 →

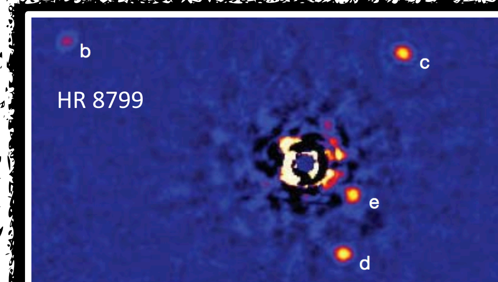


TW Hydrae

10 ± 3

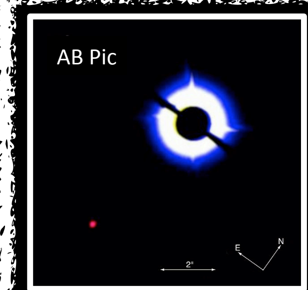
← TW Hydrae: 5

Columba: 5 →



Columba

46 ± 8 Myr



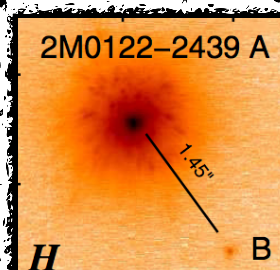
Tuc-Hor

44 ± 5 Myr

← Tuc Hor: 25

Jonathan Gagne

AB Dor: 18

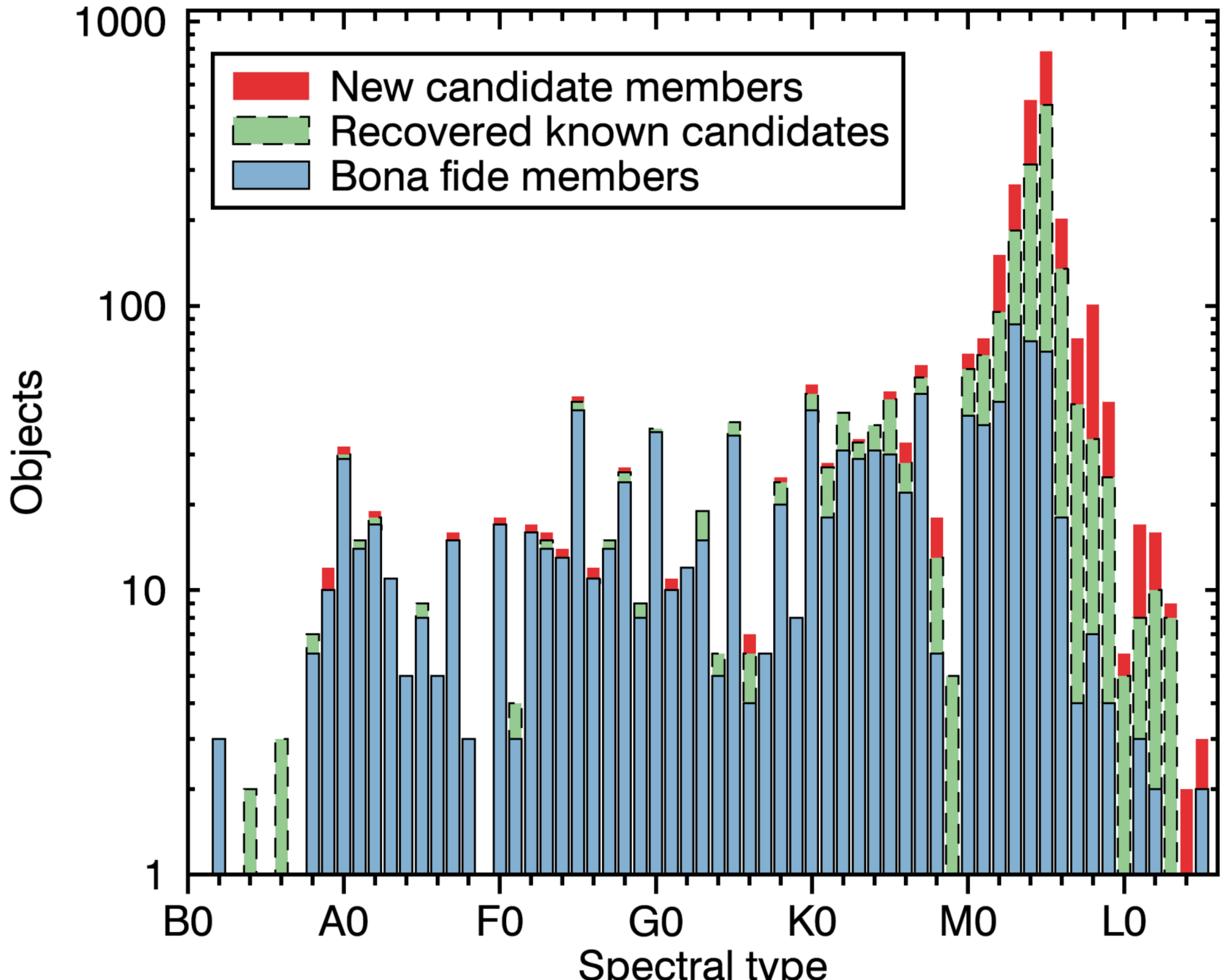


AB Doradus

147 ± 34 Myr

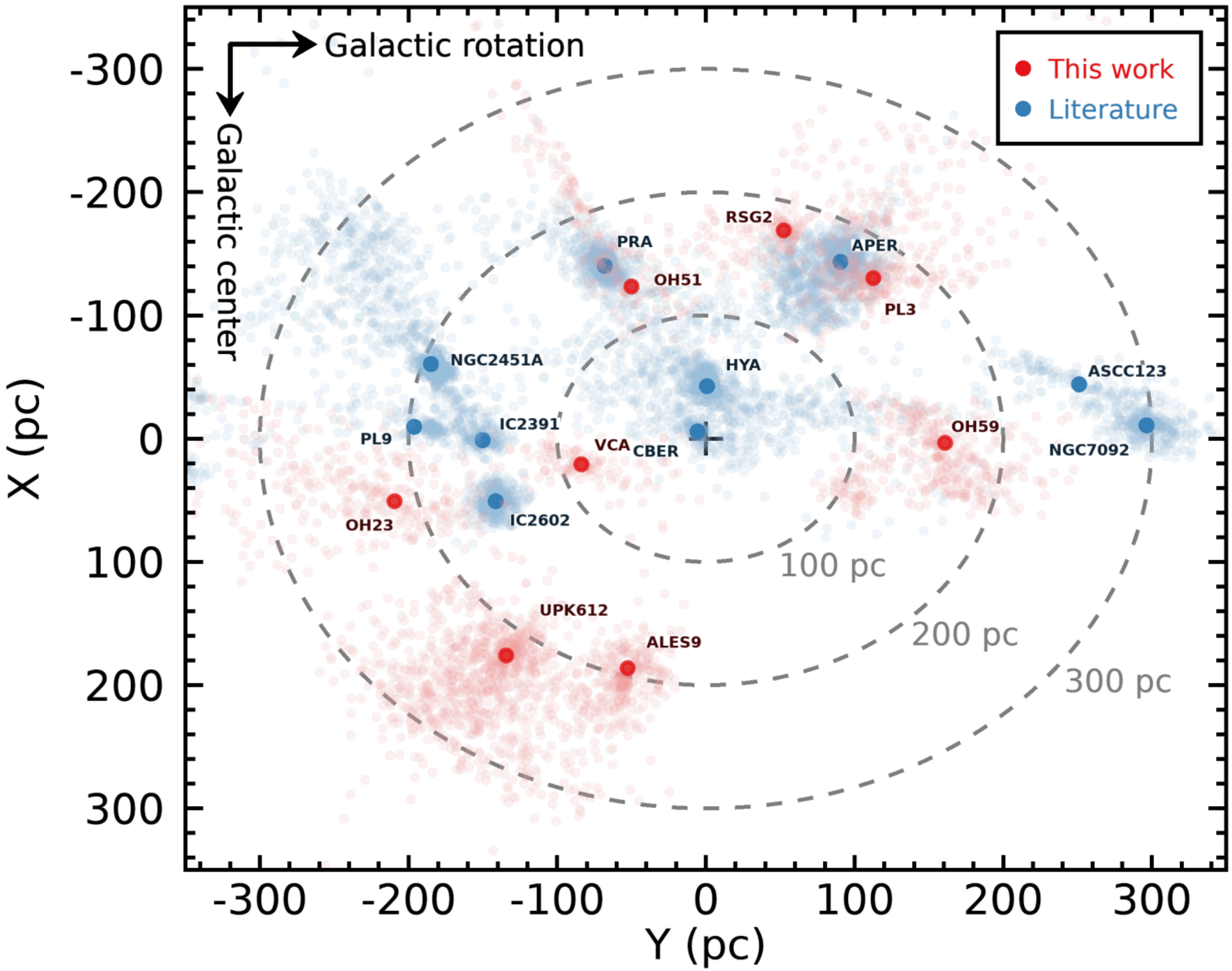
See for e.g.
Faherty et al. 2016, Gagne et al. 2015

Gaia Has Provided New Young Stars to Target for Planets



Gagne & Faherty 2018

Gaia Has Provided New Groups to Target for Planets



Moranta, L. et al. 2022

Gaia Has Provided New Groups to Target for Planets

Table 8. Known exoplanet host stars recovered in Crius groups.

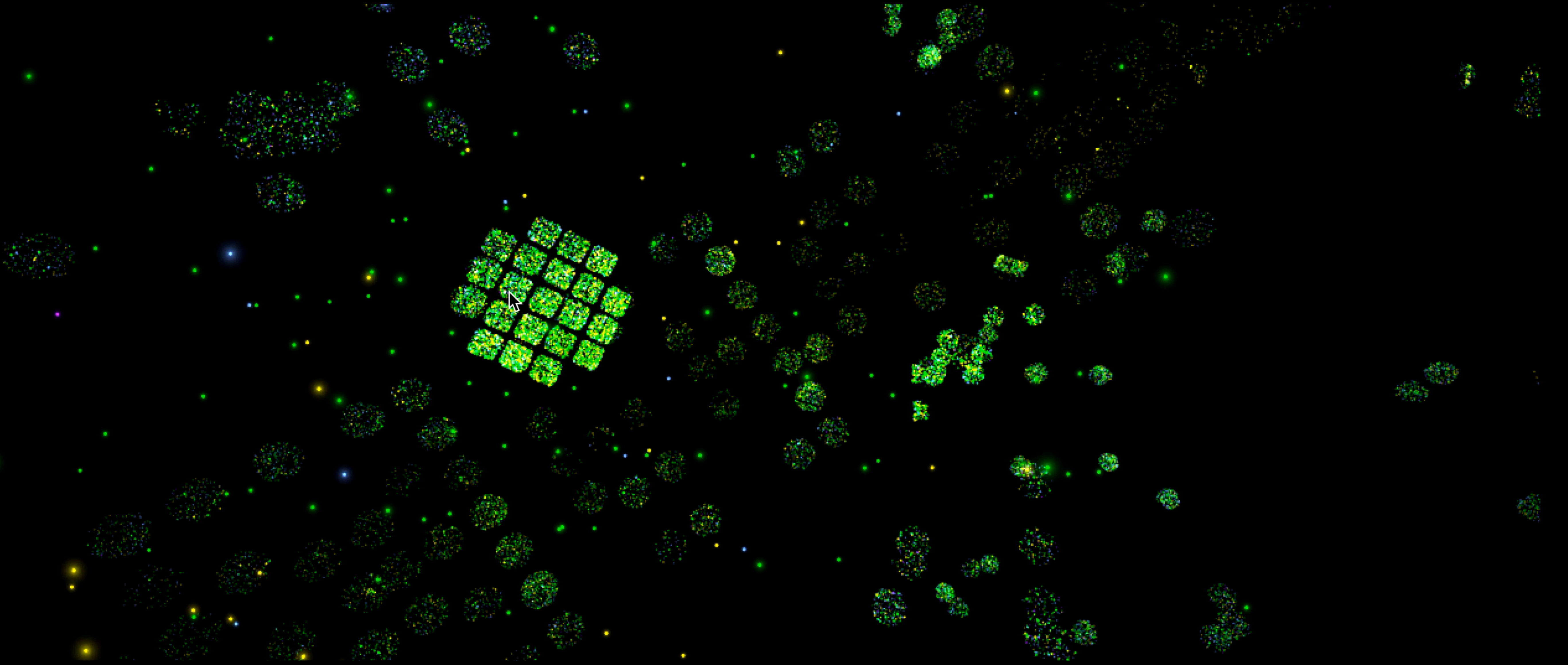
NASA exoplanet IDs	Simbad host ID	Reference	Crius ID	Notes
Confirmed exoplanets in new Crius groups				
HD 103949 b	HD 103949	1	162	New 100–700 Myr Crius group
TOI–1807 b	BD+39 2643	2	224	Previously suspected 180–200 Myr moving group
TOI–2076 b, c, d	BD+40 2790	2	224	Previously suspected 180–200 Myr moving group
Exoplanet candidates in new Crius groups				
TOI–1598 b	BD+36 344	3	109	New $\geq$ 100 Myr Crius group
TOI–2481 b	TYC 103–445–1	3	121	New $\geq$ 100 Myr Crius group
TOI–2133 b	UCAC4 614–055633	3	205	New 100–700 Myr Crius group
Exoplanet candidates with newly recognized host associations				
TOI–2048 b	TYC 3496–1082–1	3	147	Oh et al. (2017) Group 10
TOI–447 b	HD 33512	3	164	Octans association
TOI–4364 b	PM J05202–0414	3	214	Corona of the Hyades
TOI–1224 b	UCAC4 046–001384	3	221	Corona of Volans-Carina
TOI–1990 b	TYC 8613–1781–1	3	235	Corona of IC 2602
Confirmed exoplanets which membership is already known				
HD 63433 b, c	HD 63433	4	141	Ursa Major "moving group"
K2–100 b	K2–100	5	187	Praesepe open cluster
K2–102 b	K2–102	5	187	Praesepe open cluster
Pr0201 b	BD+20 2184	6	187	Praesepe open cluster
Pr0211 b, c	2MASS J08421149+1916373	6,12	187	Praesepe open cluster
K2–101 b	K2–101	5	187	Praesepe open cluster

Moranta et al. 2022

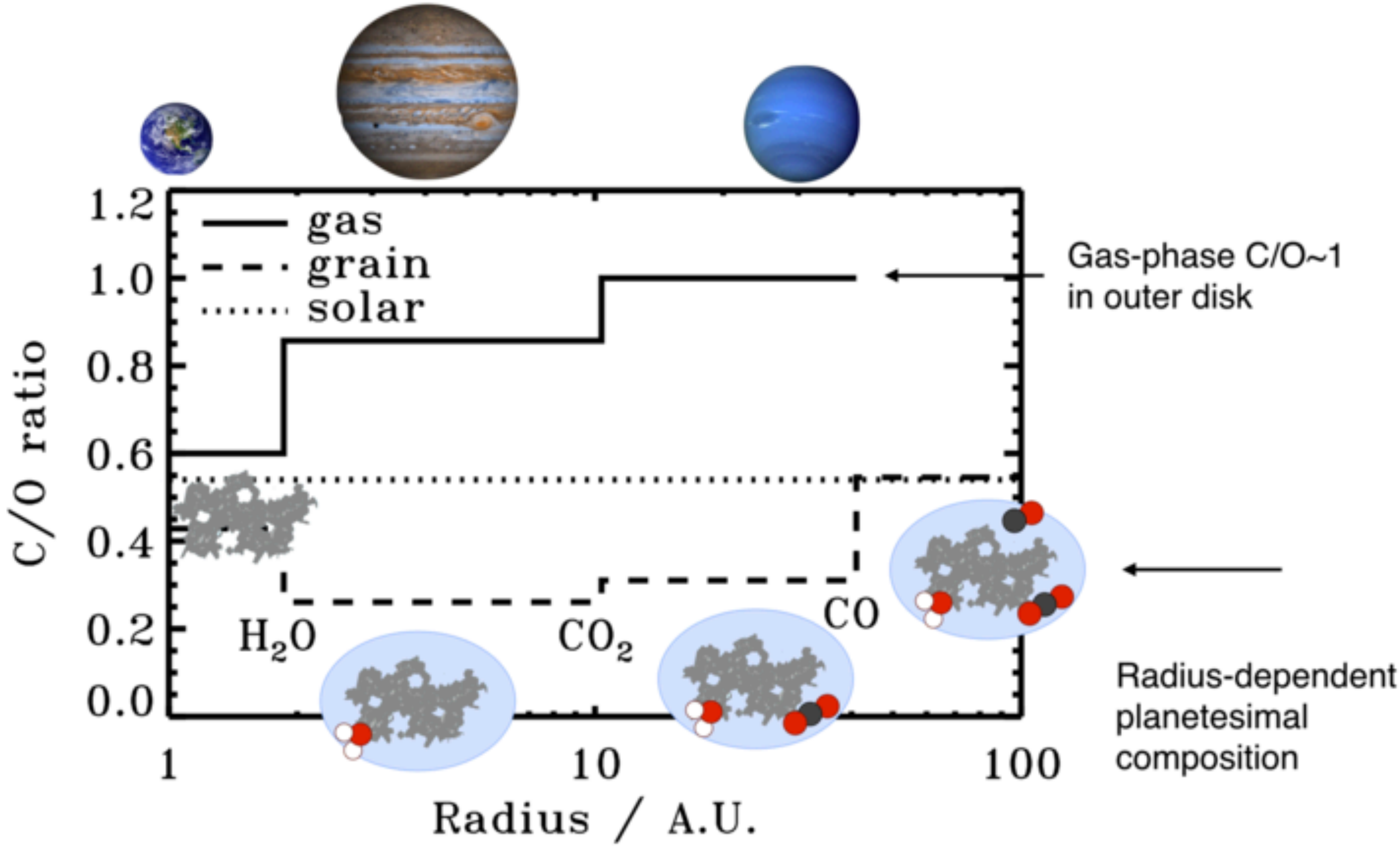
New Coronae and Stellar Associations Revealed by a Clustering Analysis of the Solar Neighborhood

How does Gaia help us Understand Directly Imaged Exoplanets?

Chemistry

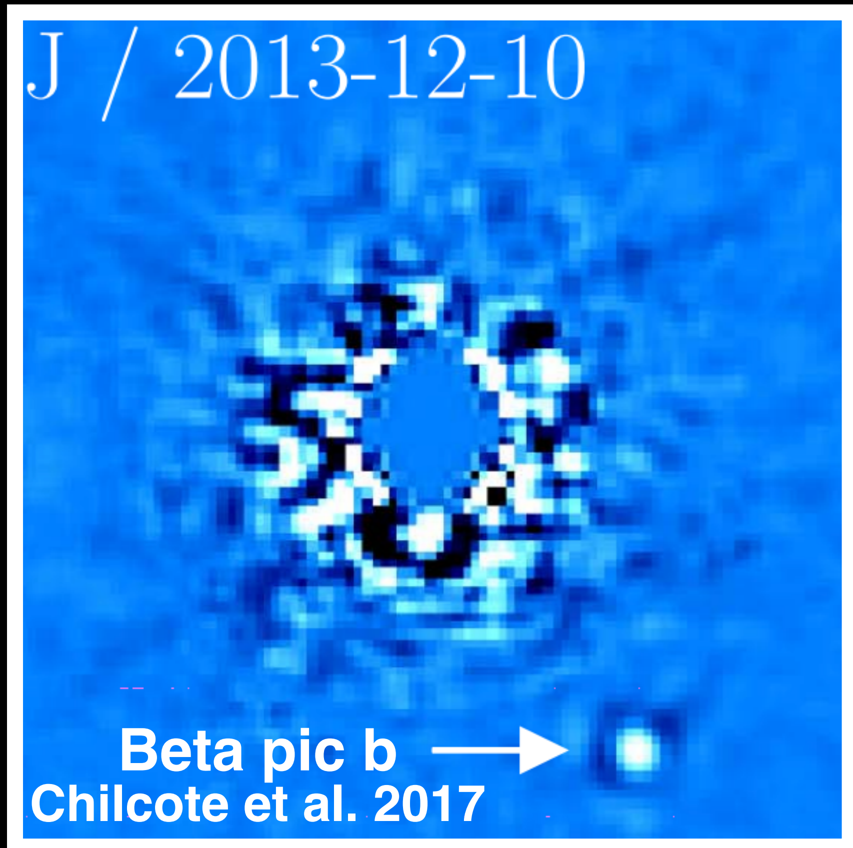


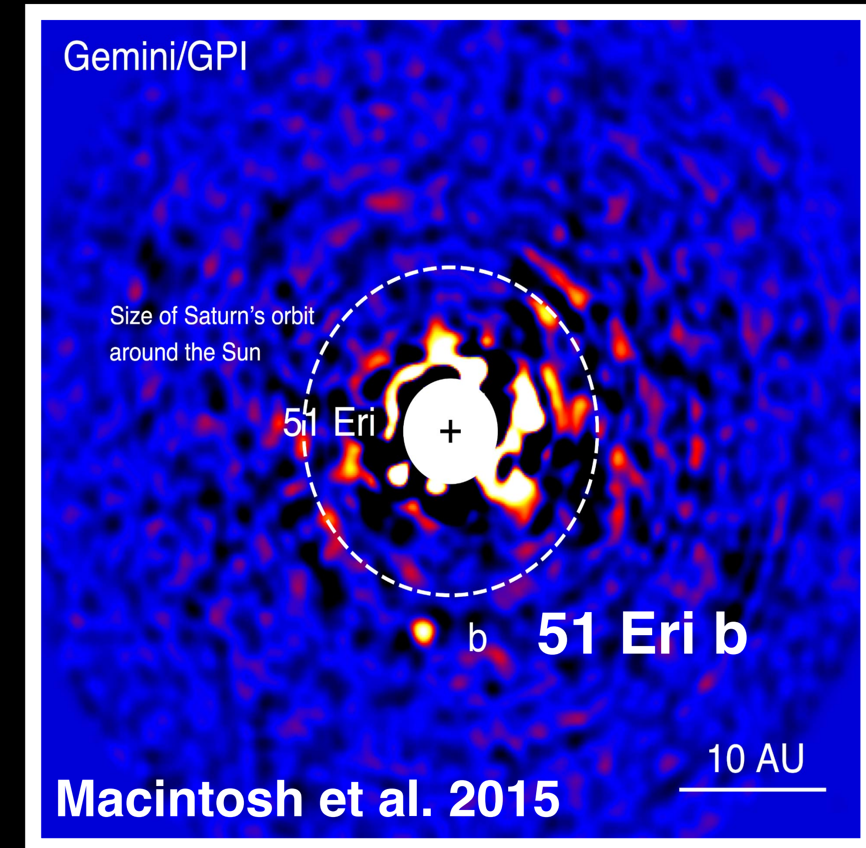
The Chemistry of a Host Star Yields Information about the Planet

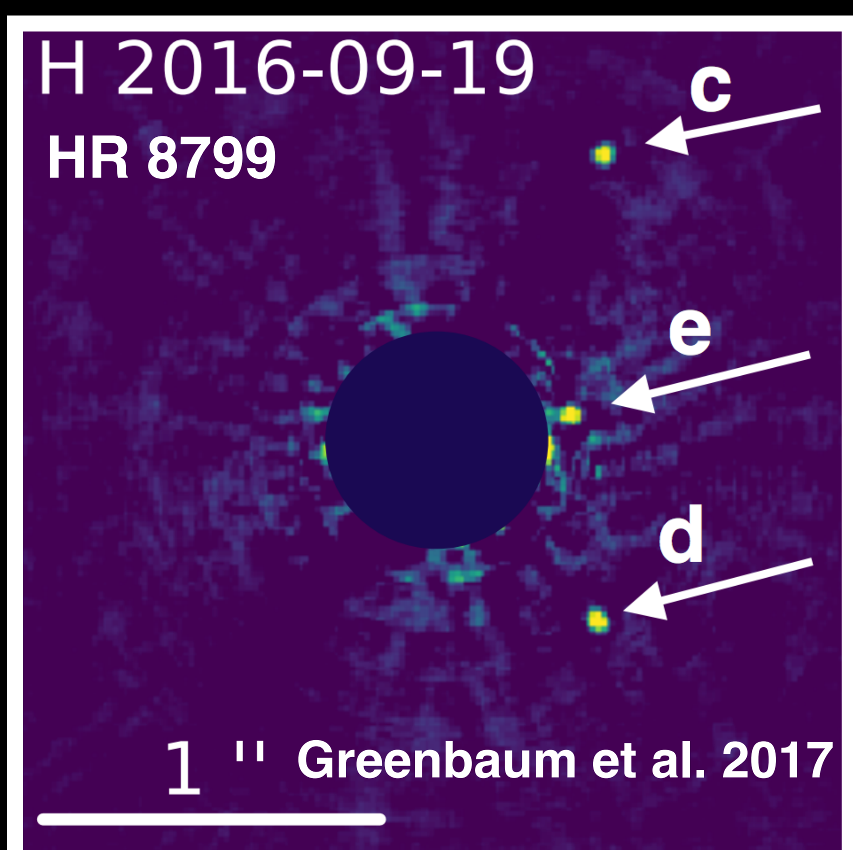


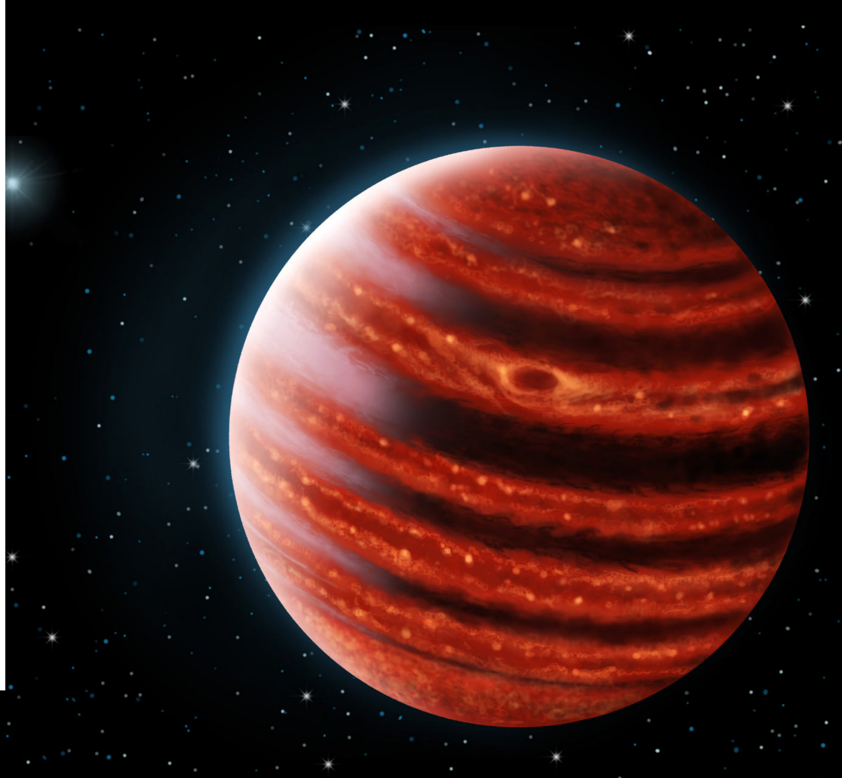
Oberg et al. 2011

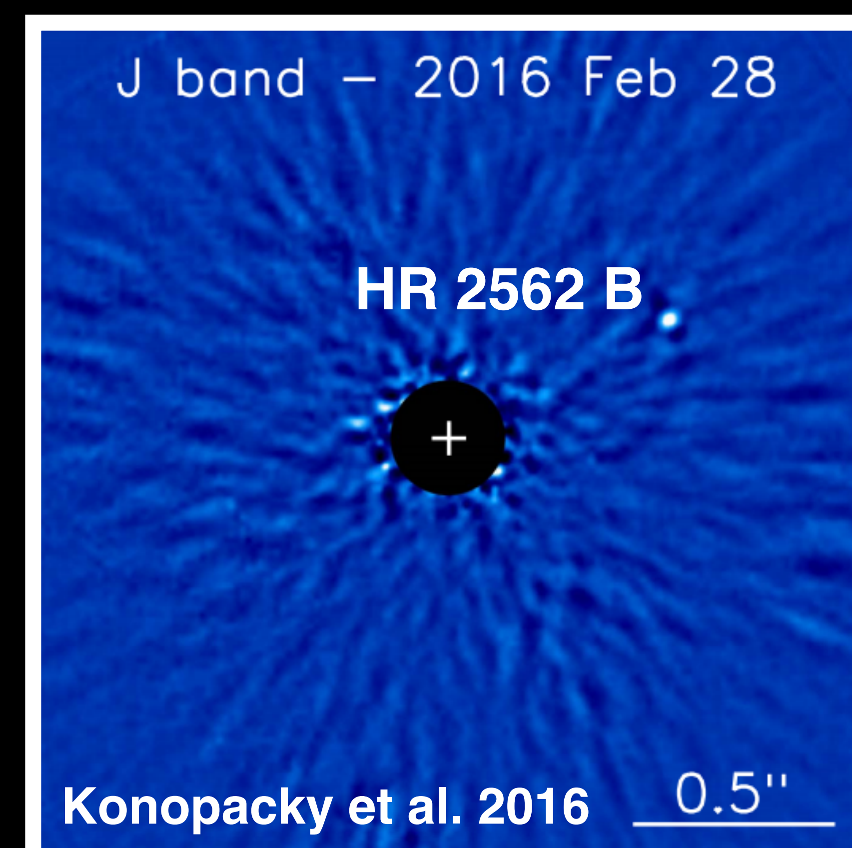
Gemini Planet Imager Data



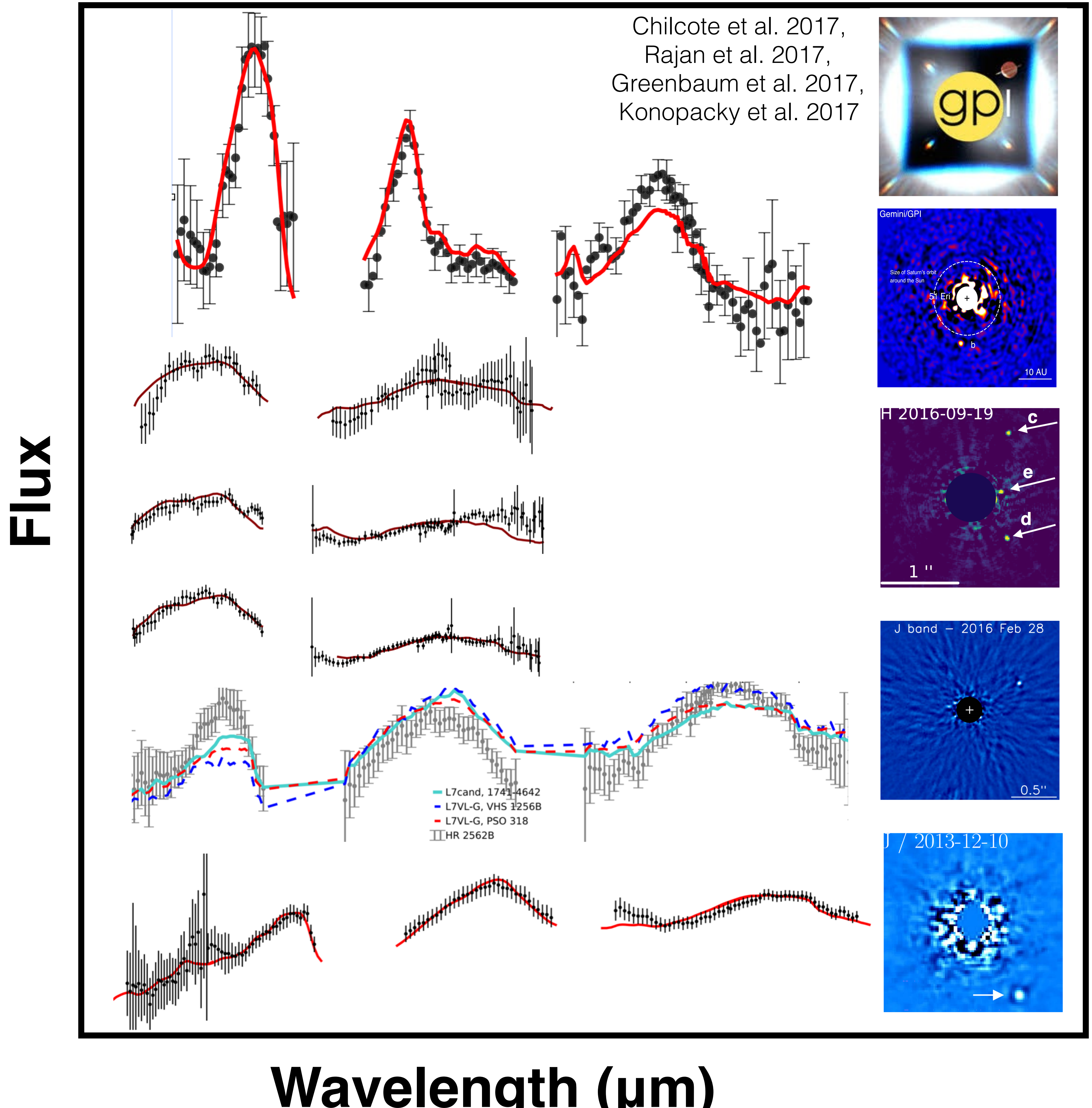




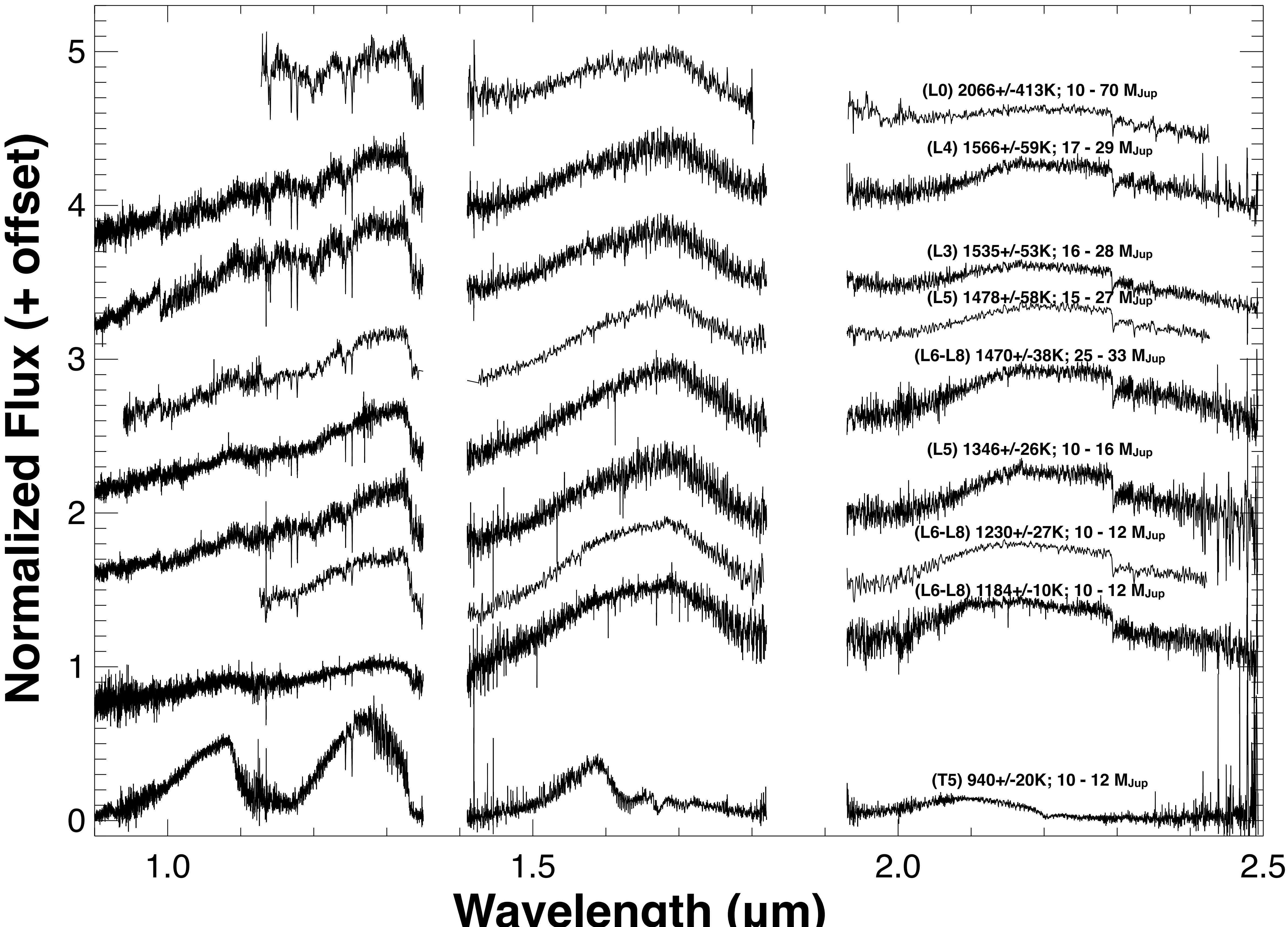




GPI Spectral Library

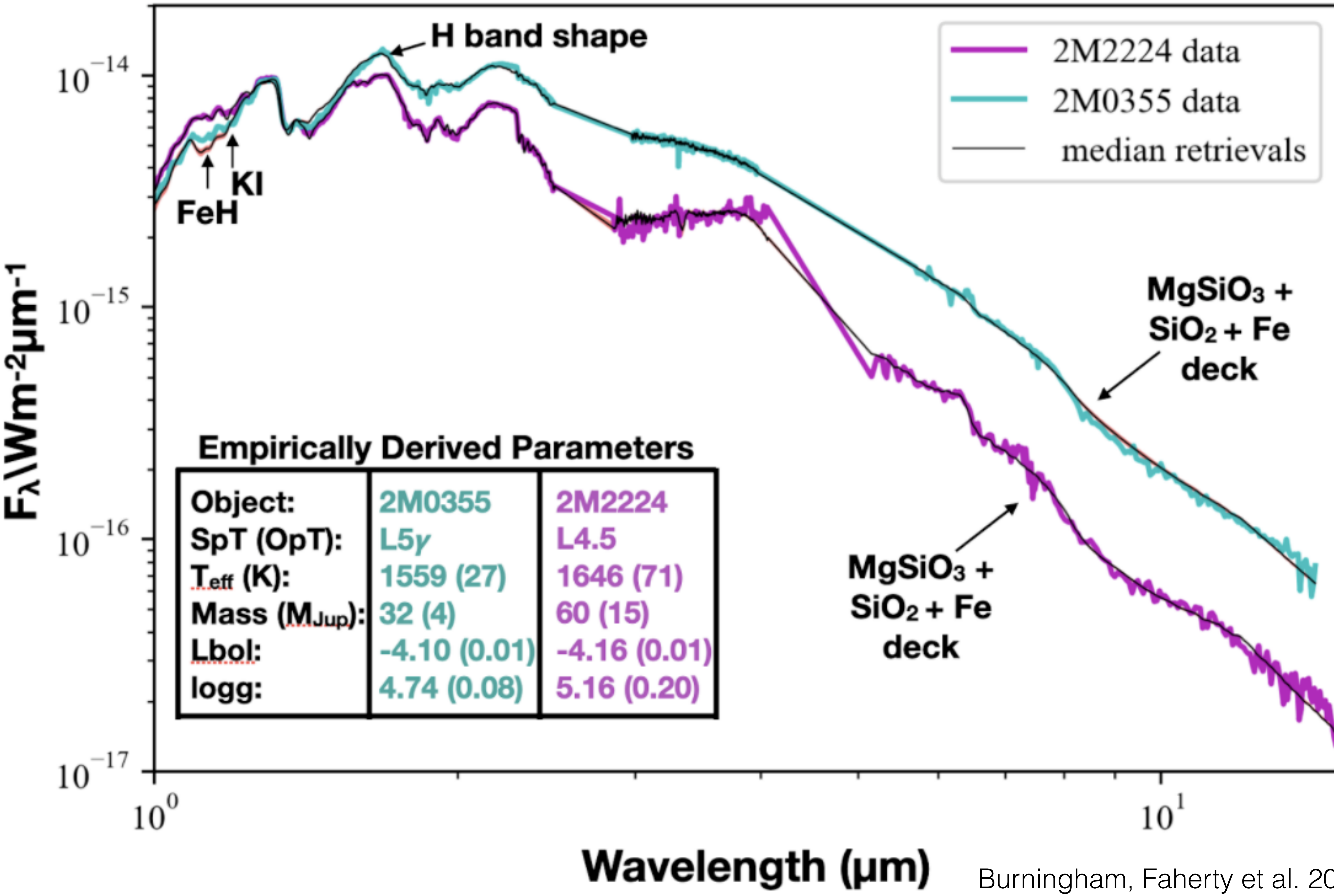


Spectra of the isolated "BD's" in AB Doradus



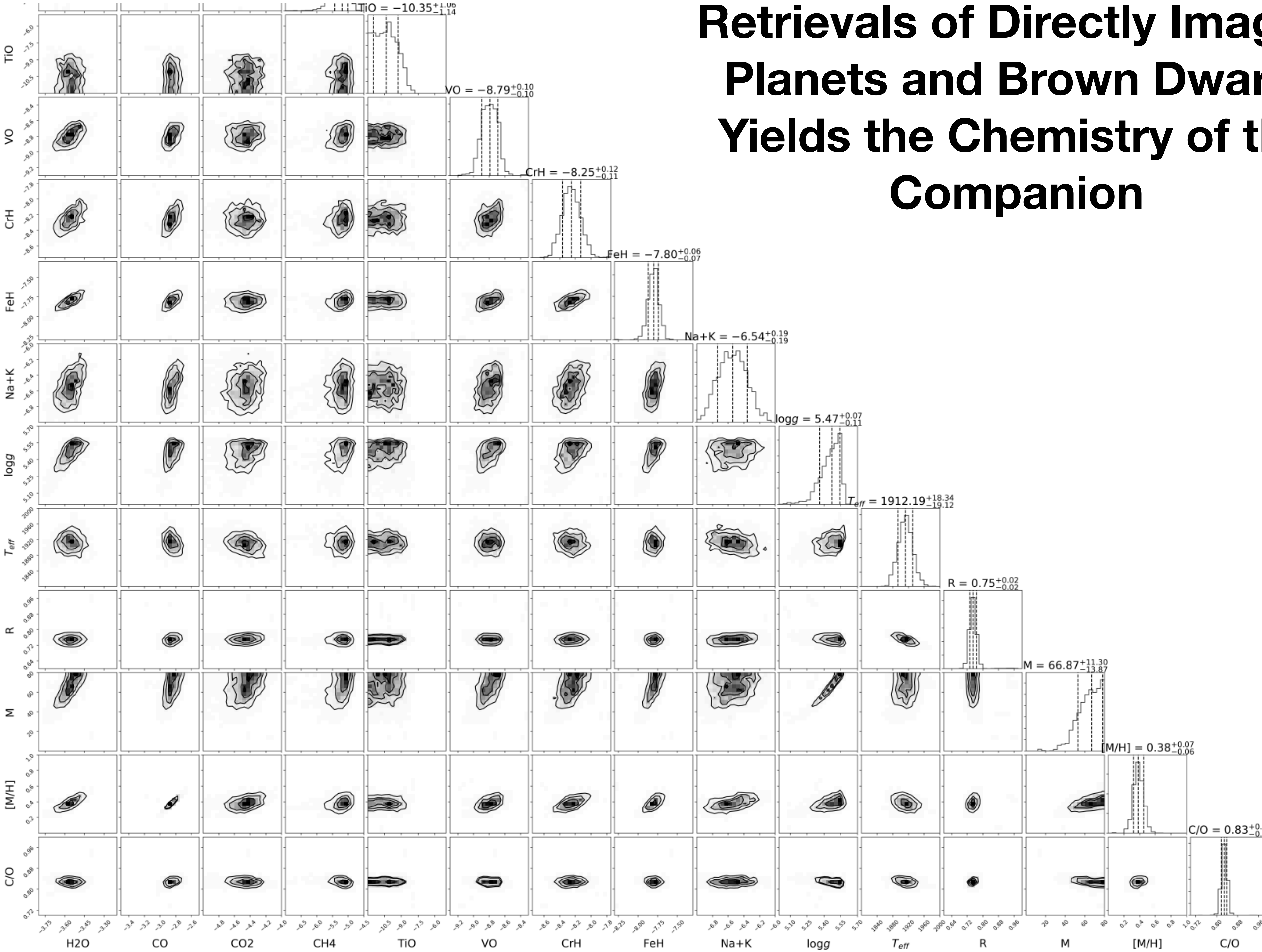
Faherty et al. in prep

Retrievals of Directly Imaged Planets and Brown Dwarfs Yields the Chemistry of the Companion

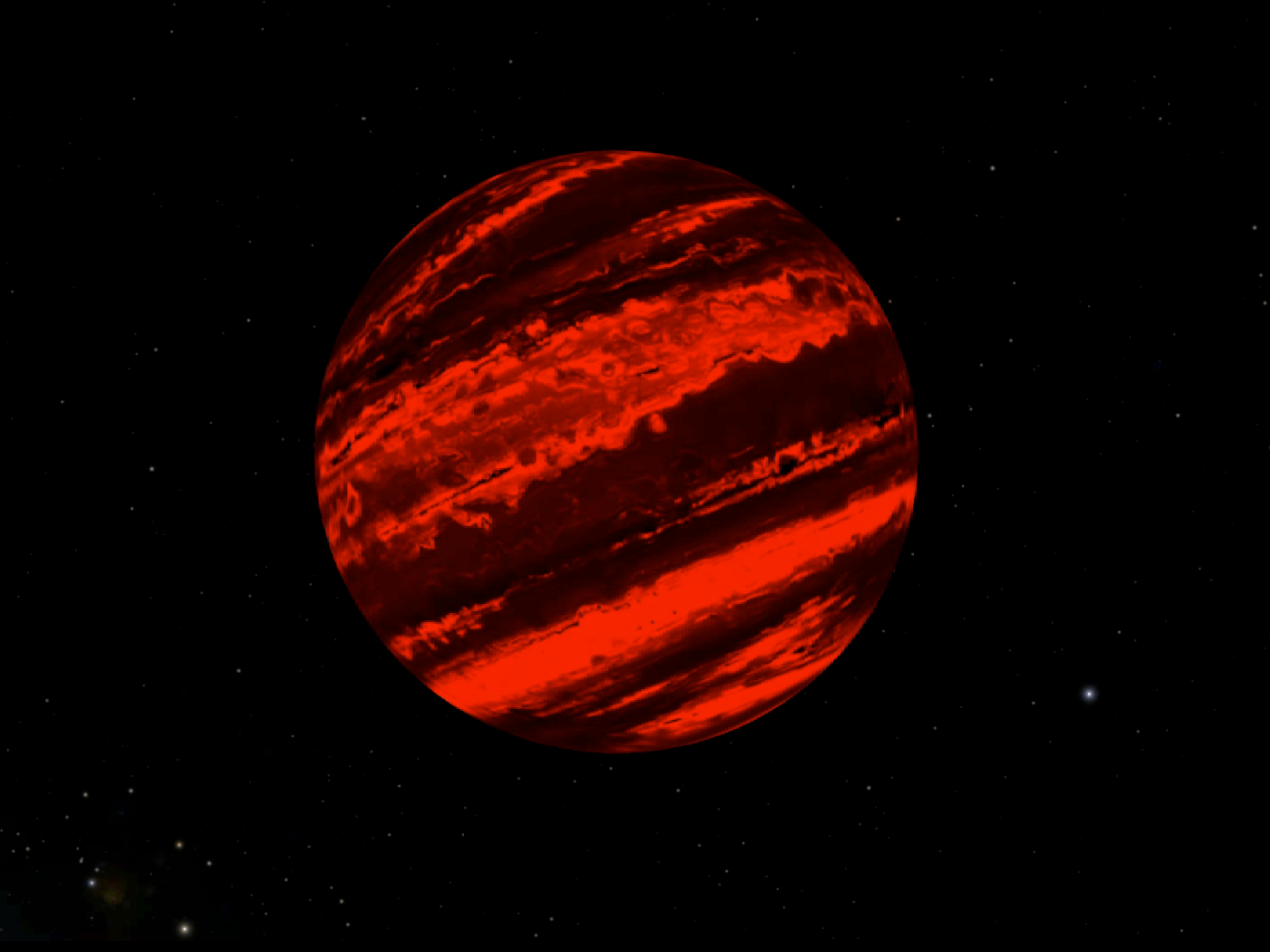


Burningham, Faherty et al. 2021

Retrievals of Directly Imaged Planets and Brown Dwarfs Yields the Chemistry of the Companion



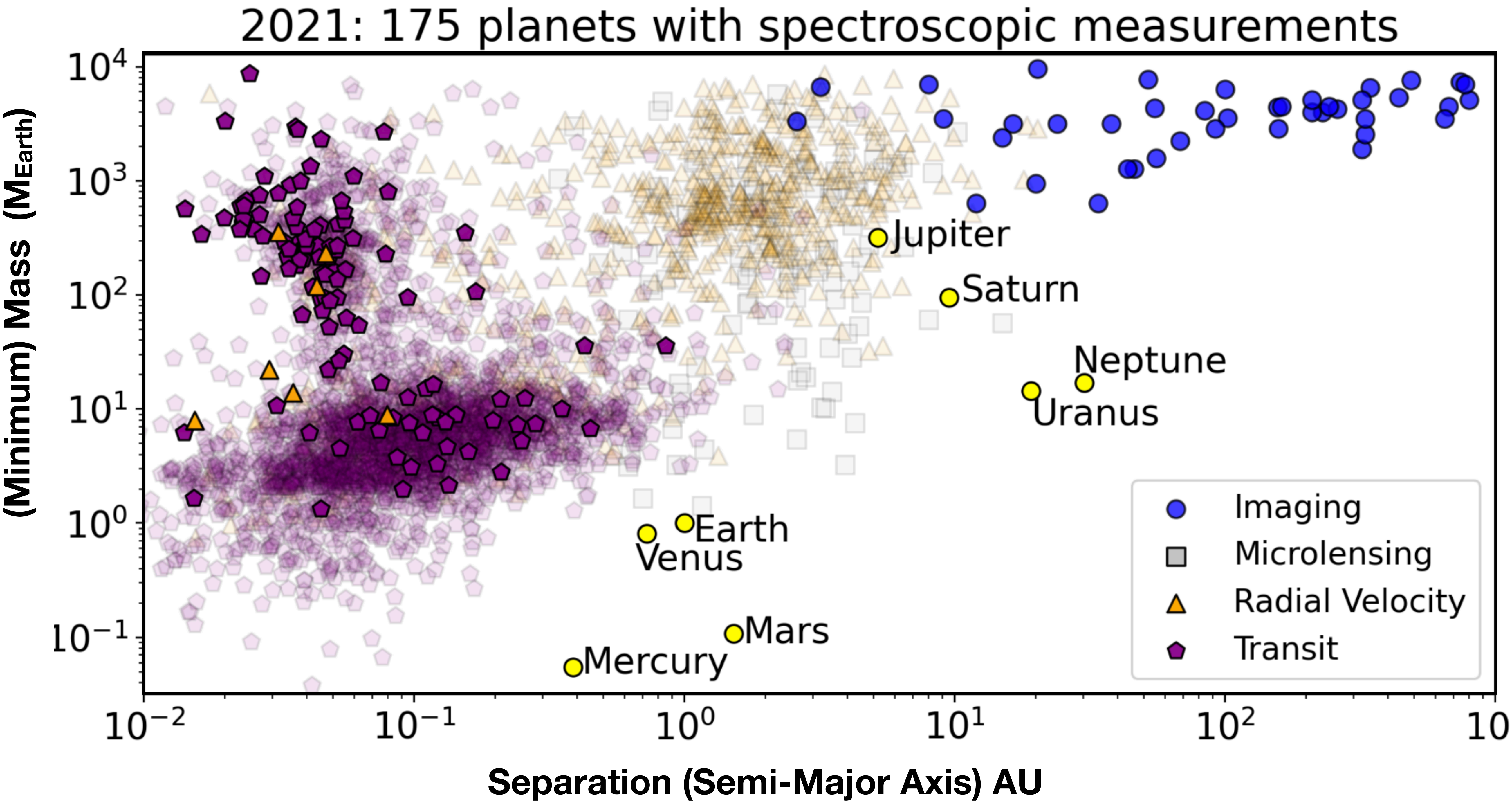
Burningham, Faherty et al. 2021



How does Gaia help us Understand Directly Imaged Exoplanets?

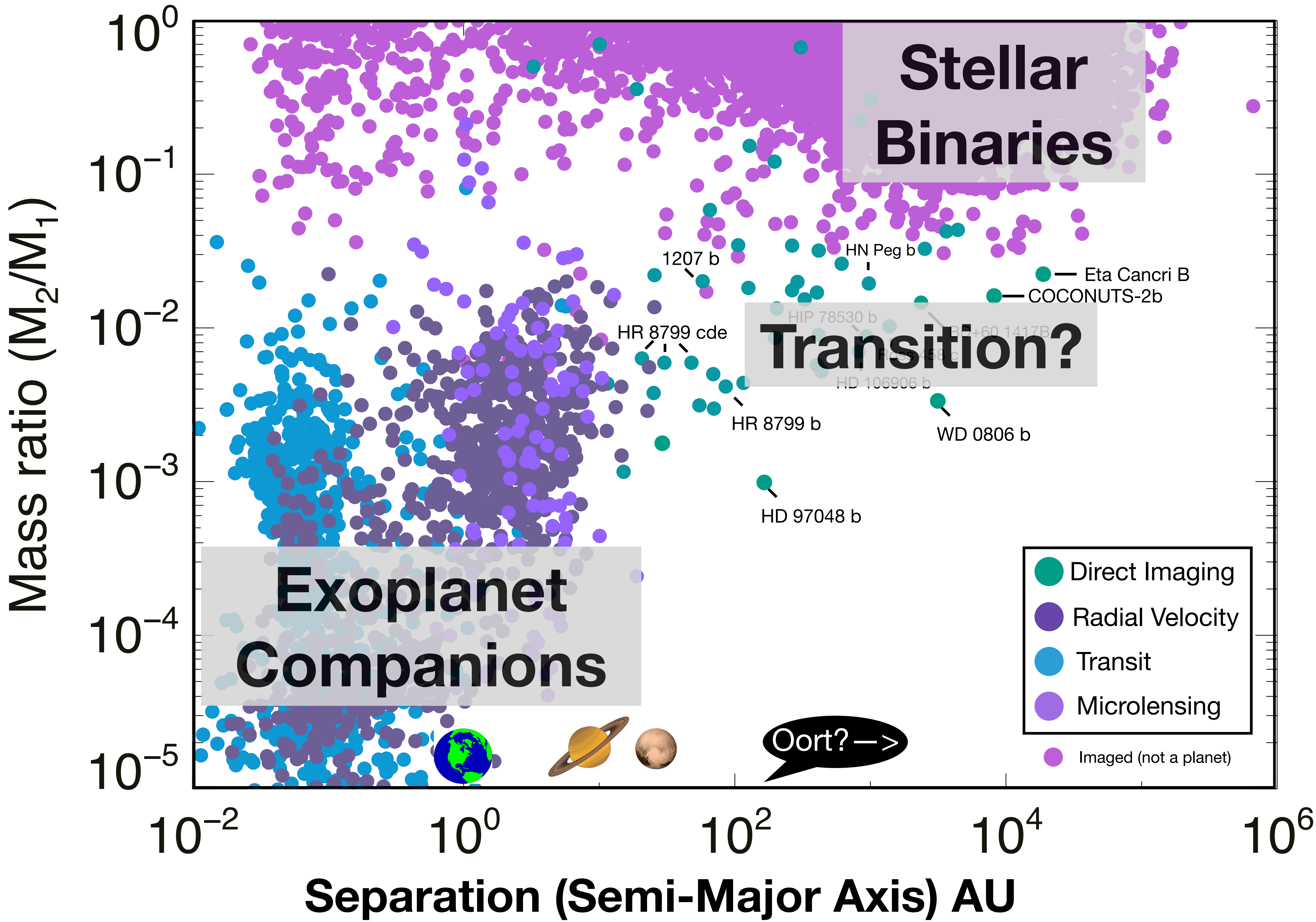
Luminosity
Mass
Formation?

Mass vs Separation for Exoplanets

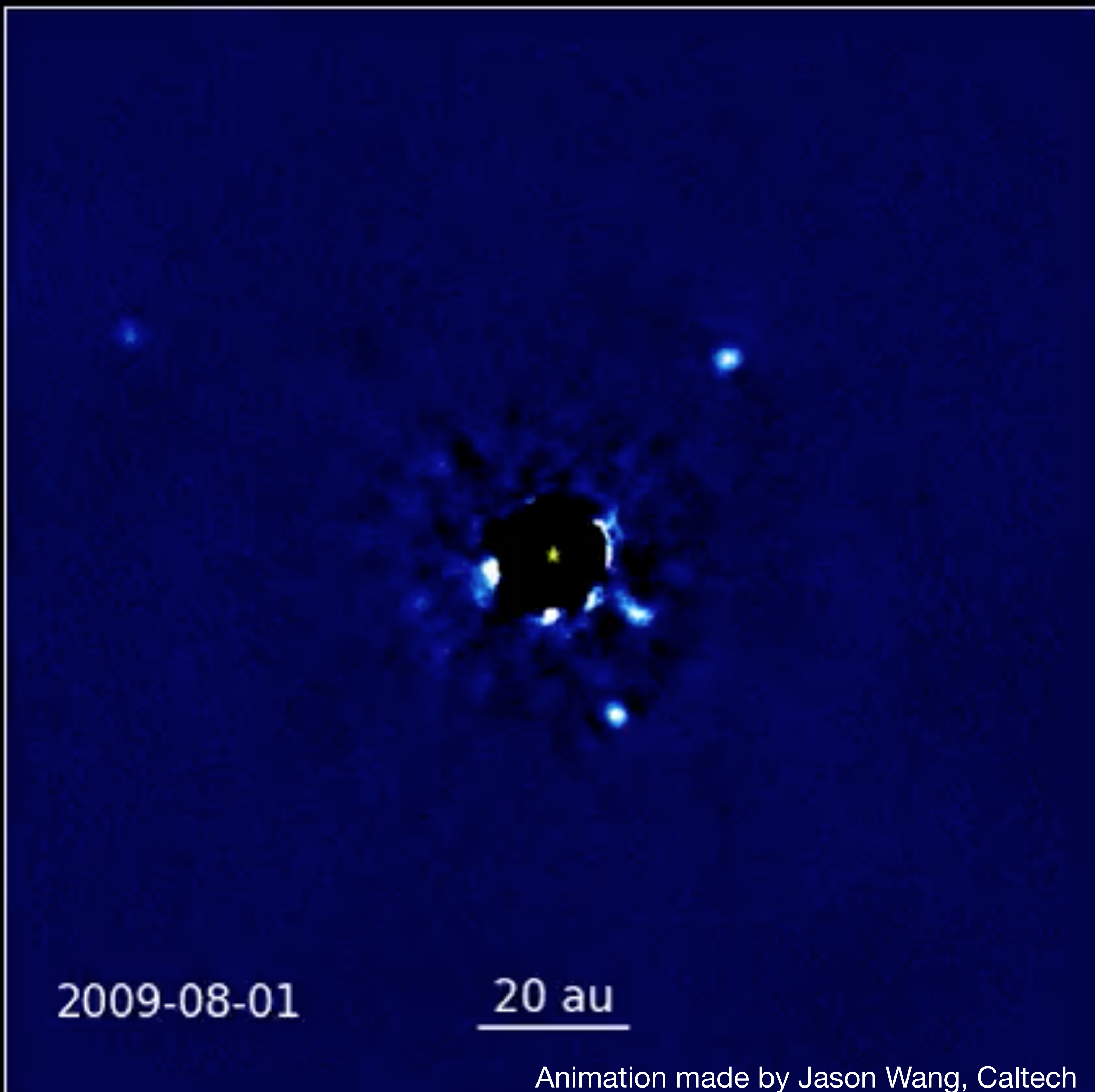


Currie, Biller, Lagrange, et al. 2022

Mass ratio vs Separation for Companions



HR8799e Dynamical Mass



HR8799e

SpT: Late L?

Age: $42^{+24}_{-16}\ Myr$

Mass: $9.6^{+1.9}_{-1.8}\ M_{Jup}$

Gaia gave us:

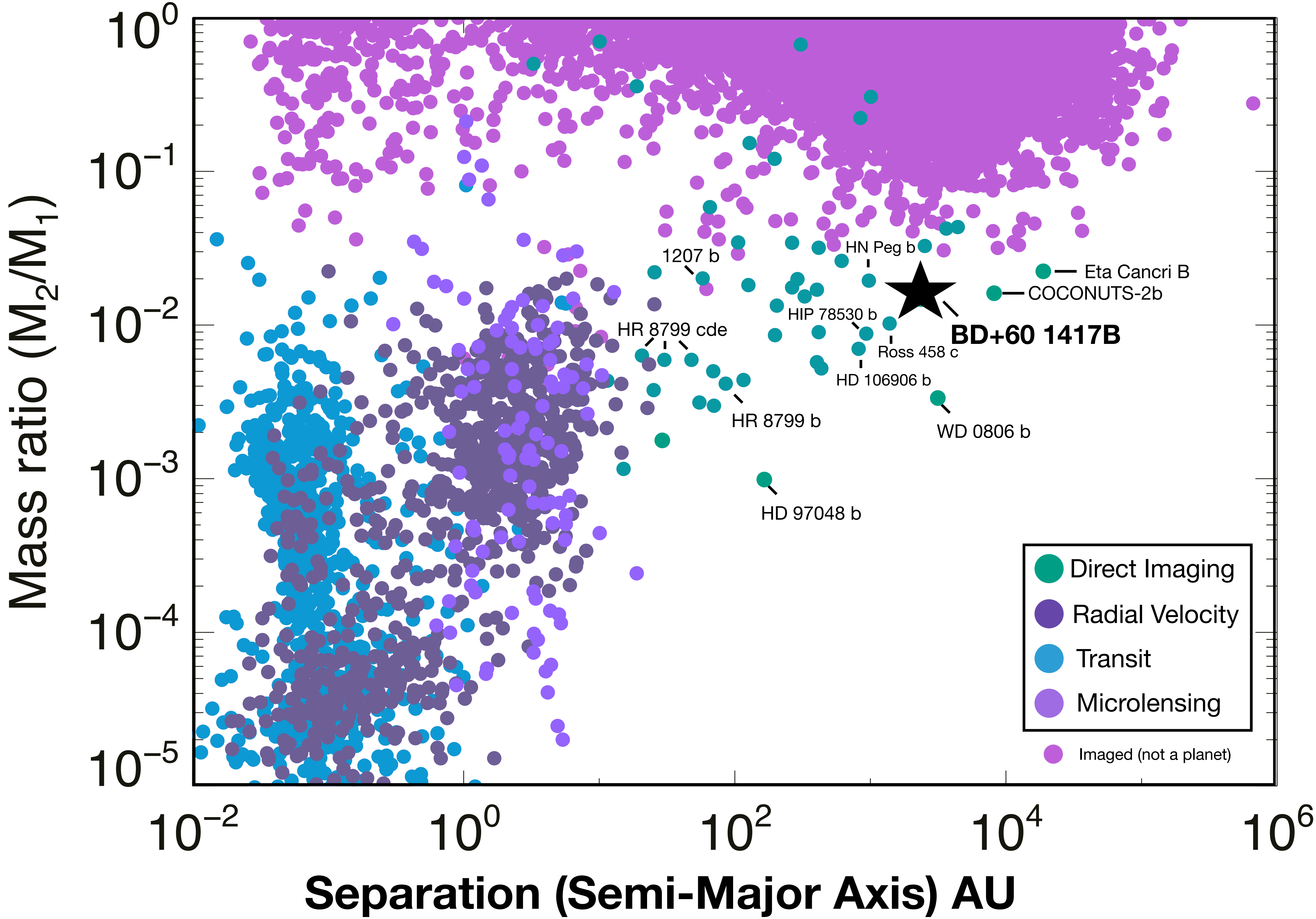
Acceleration: 5σ

Parallax -> Lbol

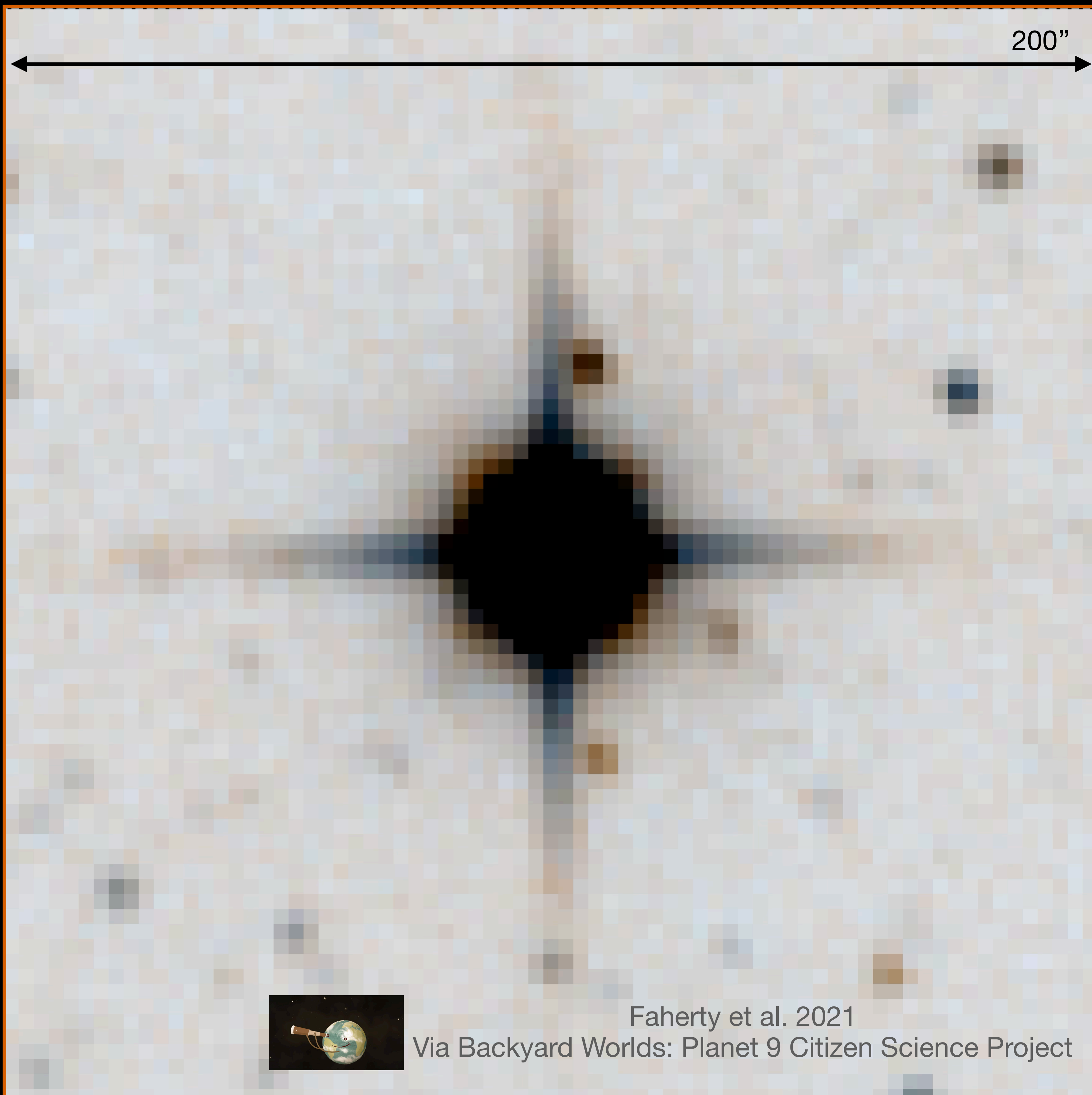
Kinematics -> Age

The First Dynamical Mass Measurement in the HR 8799 System
Brandt, M. et al. 2021 see Mirek's talk

Mass ratio vs Separation for Companions



A Directly Imaged Planet?



BD+60 1417B

SpT: L8

Sep: 37”

Sep: 1662 AU

Age: 50 - 150 Myr

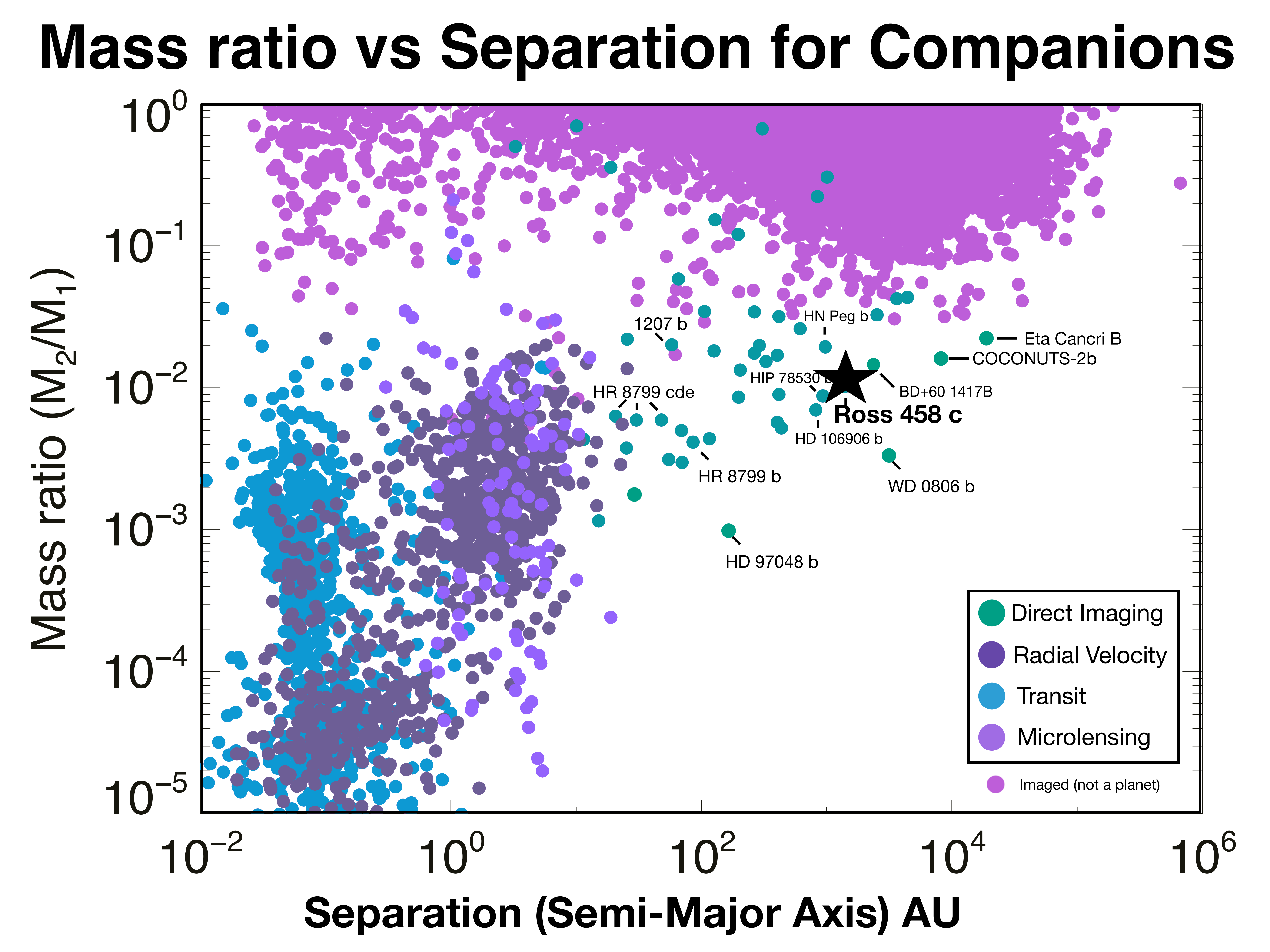
Mass: 15+/-5 M_{Jup}

Gaia gave us:

Parallax -> Lbol

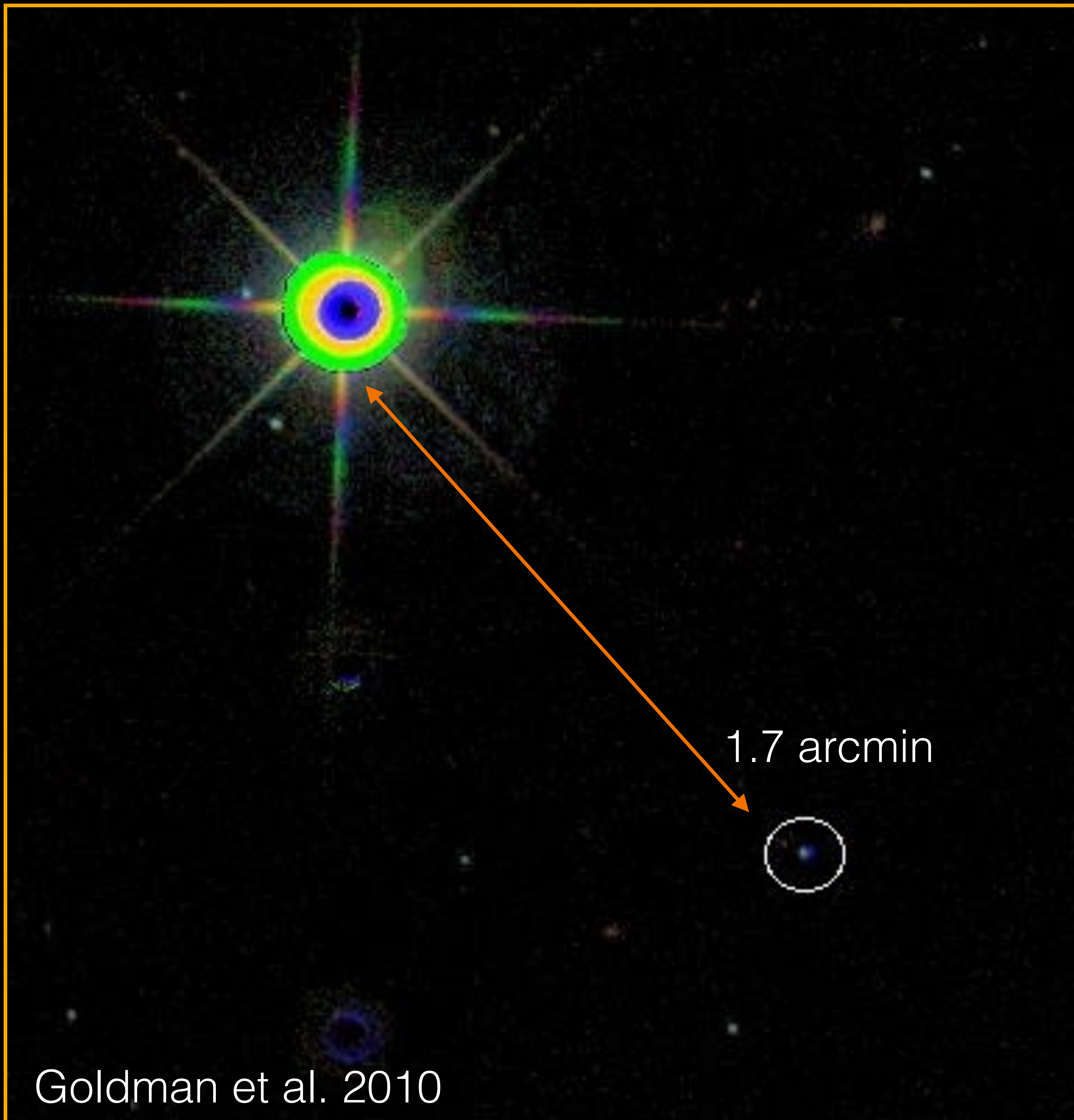
Kinematics -> Age

Vbroad -> Almost



Mass ratio vs Separation for Companions
Mass ratio (M_2/M_1)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Separation (Semi-Major Axis) AU
10^{-2}
10^0
10^2
10^4
10^6
1207 b
HN Peg b
Eta Cancri B
COCONUTS-2b
HIP 78530
BD+60 1417B
HR 8799 cde
Ross 458 c
HD 106906 b
HR 8799 b
WD 0806 b
HD 97048 b
Direct Imaging
Radial Velocity
Transit
Microlensing
Imaged (not a planet)

Ross 458C: Young Direct Imaging Target for JWST



Ross 458C

SpT: T8

Sep: 1.7’

Sep: 1100 AU

Age: ~500 Myr (?)

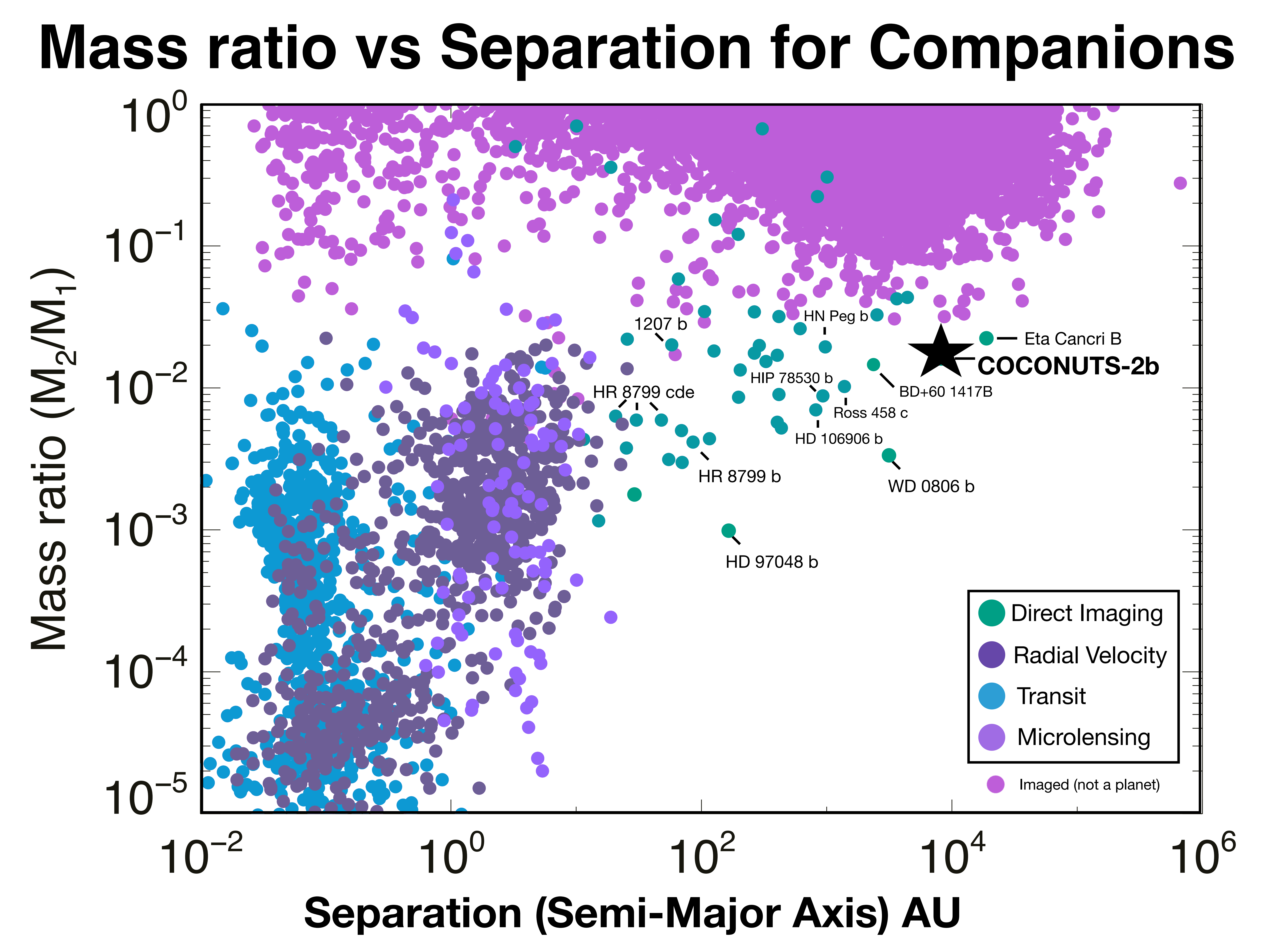
Mass: 9-13 M_{Jup}

Gaia gave us:

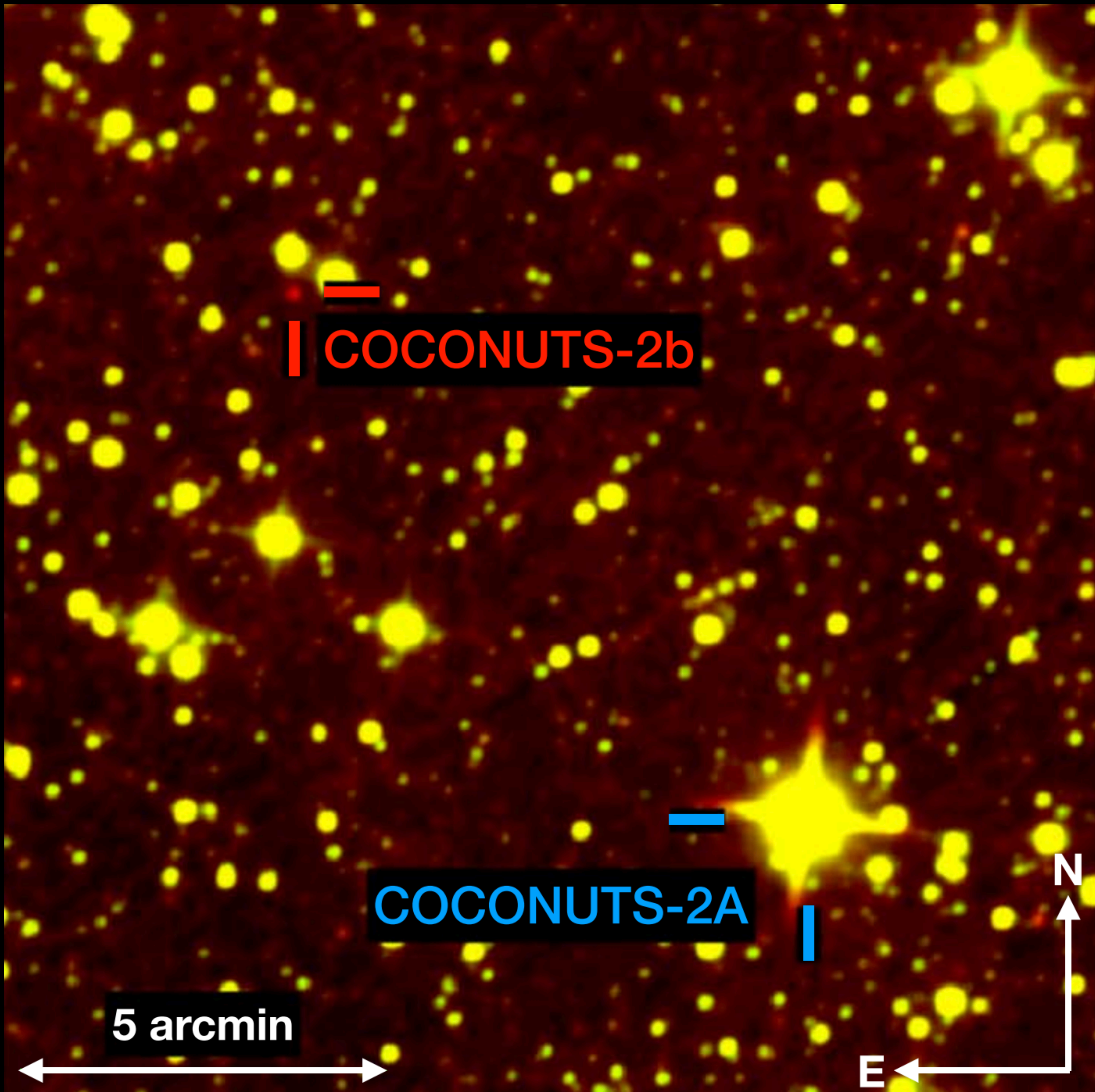
Parallax -> Lbol

Kinematics -> Age

RUWE -> Companion


Mass ratio vs Separation for Companions
Mass ratio (M2/M1)
Separation (Semi-Major Axis) AU
1207 b
HN Peg b
Eta Cancri B
COCONUTS-2b
HIP 78530 b
BD+60 1417B
HR 8799 cde
Ross 458 c
HD 106906 b
HR 8799 b
WD 0806 b
HD 97048 b
Direct Imaging
Radial Velocity
Transit
Microlensing
Imaged (not a planet)

A Directly Imaged Planet?



Coconuts-2b

SpT: T9

Sep: 594”

Sep: 6471 AU

Age: 150-800 Myr

Dist: 10.9pc

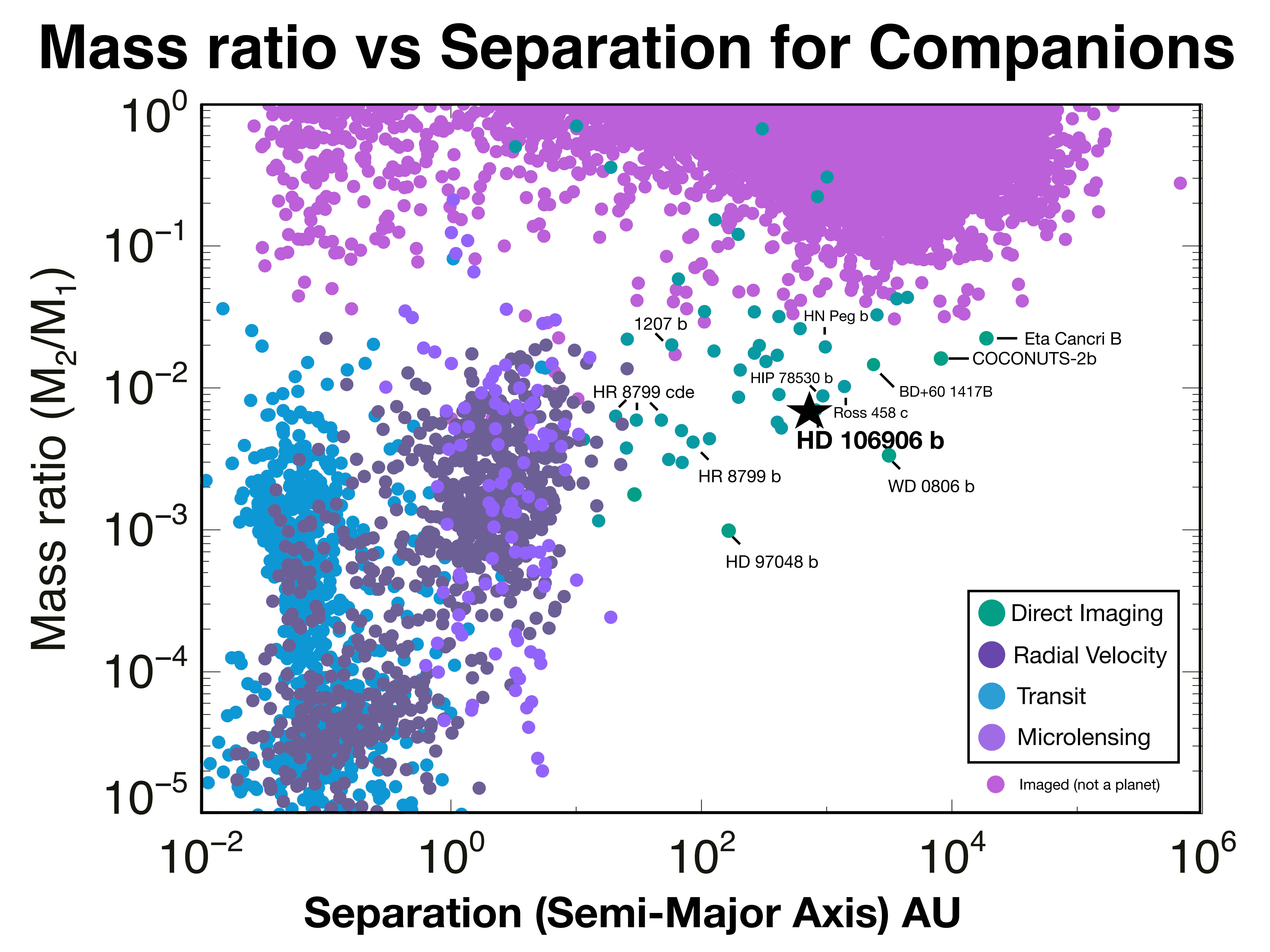
Mass: $6.3^{+1.3}_{-1.9}\ M_{Jup}$

Gaia gave us:

Parallax -> Lbol

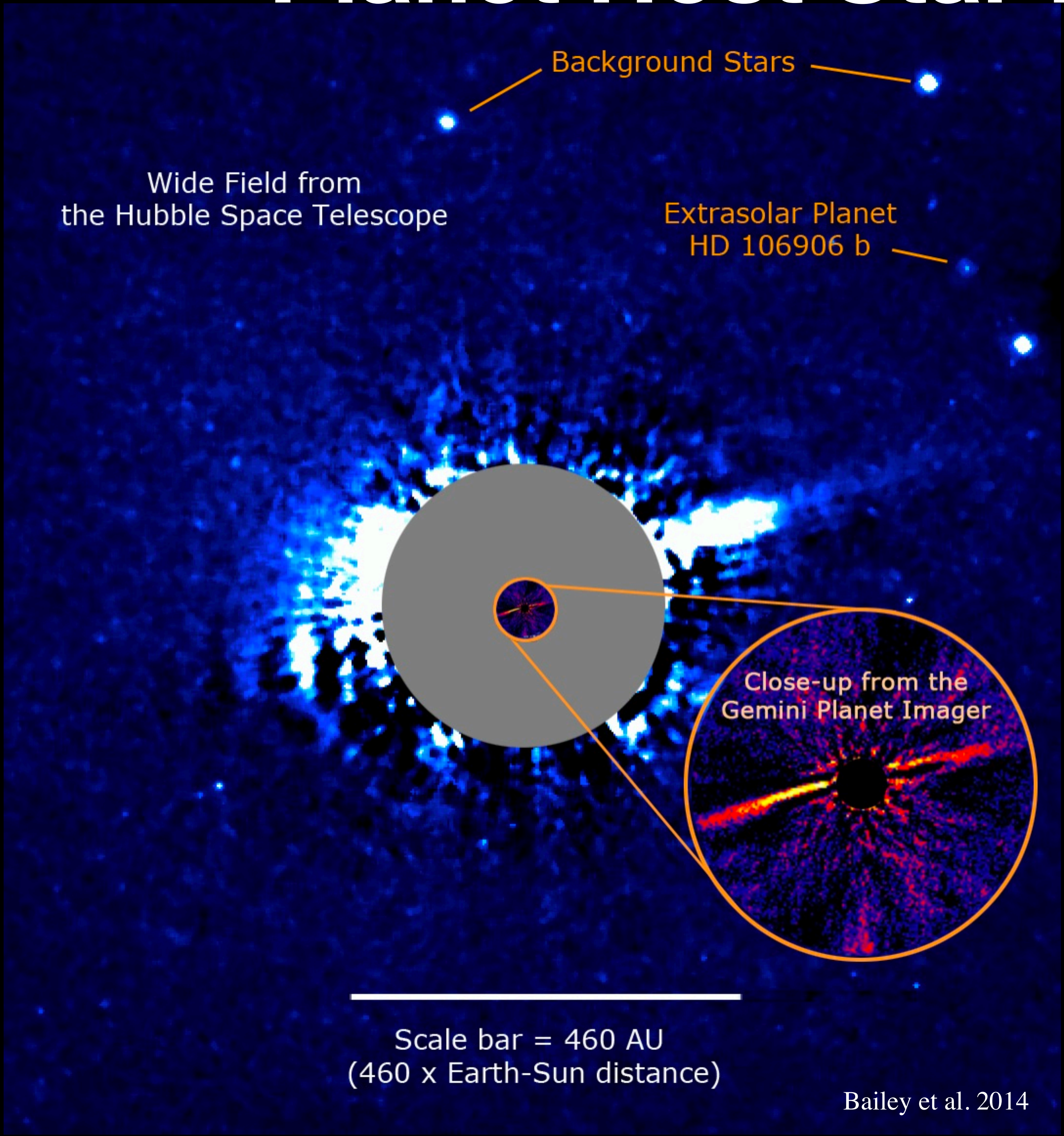
Kinematics -> Age

Zhang et al. 2022



Mass ratio vs Separation for Companions
Mass ratio (M_2/M_1)
Separation (Semi-Major Axis) AU
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-2}
10^0
10^2
10^4
10^6
1207 b
HN Peg b
Eta Cancri B
COCONUTS-2b
HIP 78530 b
BD+60 1417B
HR 8799 cde
Ross 458 c
HD 106906 b
HR 8799 b
WD 0806 b
HD 97048 b
Direct Imaging
Radial Velocity
Transit
Microlensing
Imaged (not a planet)

A Near-coplanar Stellar Flyby of the Planet Host Star HD 106906



HD106906b

SpT: mid L?

Sep: 7.1”

Sep: 738 AU

Age: ~13 Myr

Mass: ~11 M_{Jup}

Gaia gave us:

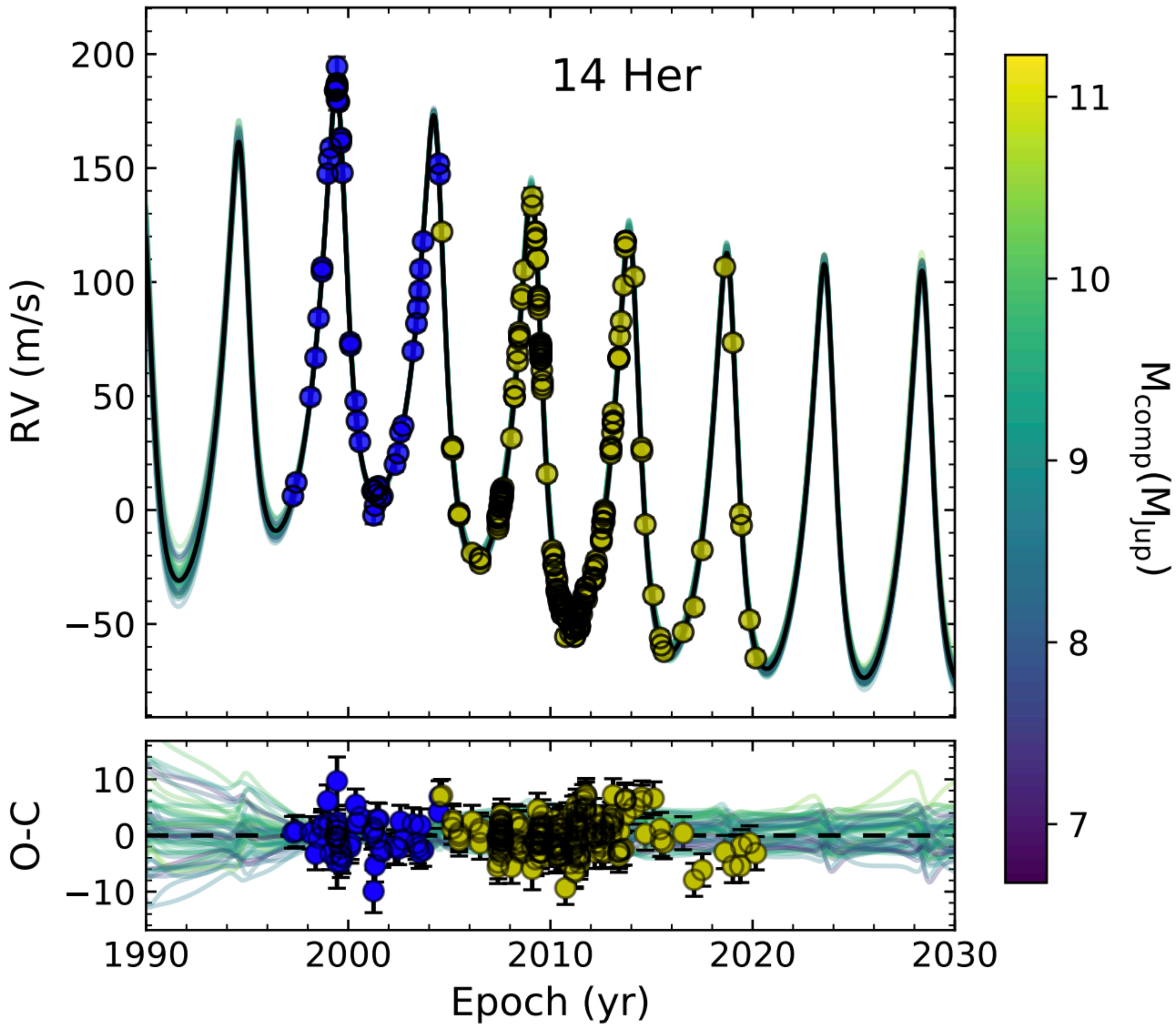
Parallax -> Lbol

Kinematics -> Age

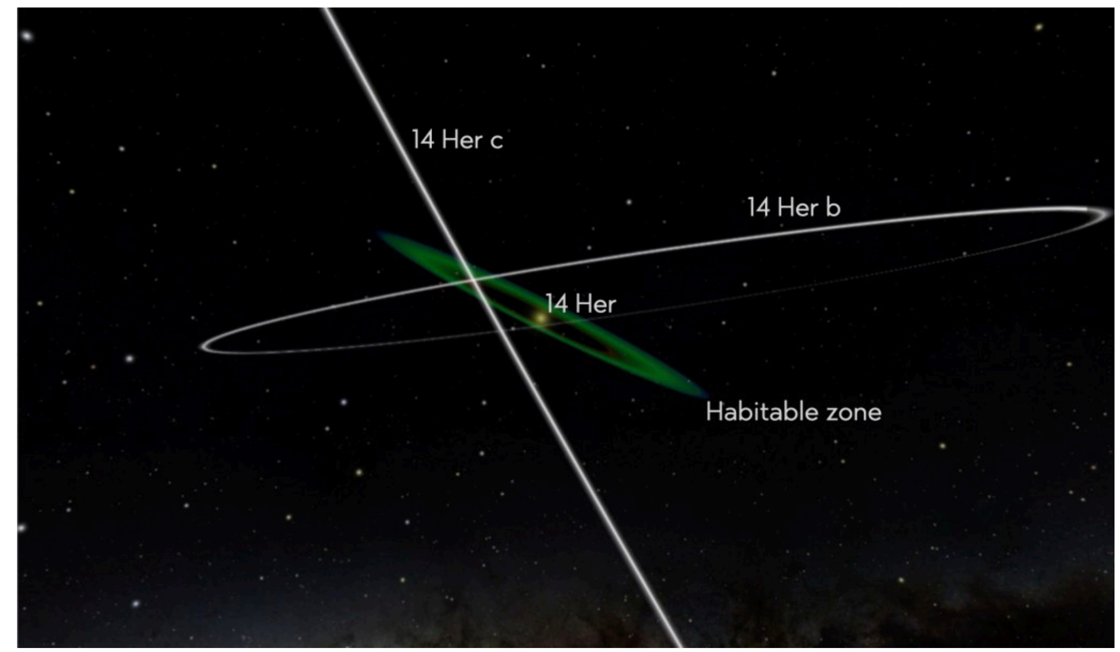
Flyby history

De Rosa et al. 2019

14 Her bc: Candidates for future direct imaging



Planetary parameters	b	c
Planet mass (M)	$9.1^{+1.0}_{-1.1}\ M_{\rm Jup}$	$6.9^{+1.7}_{-1.0}\ M_{\rm Jup}$
Mass ratio (q)	$0.00892^{+0.00090}_{-0.0011}$	$0.00674^{+0.0017}_{-0.00095}$
Semi-major axis (a)	$2.845^{+0.038}_{-0.039}$ AU	$27.4^{+16}_{-7.9}$ AU
Semi-major axis (α)	$158.9^{+2.1}_{-2.2}$ mas	1529^{+869}_{-442} mas
Period (P)	$4.8277^{+0.0022}_{-0.0023}$ yrs	144^{+139}_{-58} yrs
Eccentricity (e)	$0.3686^{+0.0032}_{-0.0031}$	$0.64^{+0.12}_{-0.13}$
Inclination (i)	$32.7^{+5.3}_{-3.2}$ deg	101^{+31}_{-33} deg
Argument of periastron (ω)	$22.78^{+0.53}_{-0.55}$ deg	$15.2^{+6.0}_{-6.0}$ deg
PA of ascending node (Ω)	236^{+15}_{-15} deg	313^{+30}_{-57} deg
Mean longitude at reference epoch	$82.71^{+0.19}_{-0.19}$	36^{+12}_{-10} deg
Epoch at periastron (T_0)	$2456667.4^{+2.3}_{-2.2}$ JD	$2504873^{+50765}_{-21163}$ JD
Minimum mass ($M \sin i$)	$4.93^{+0.51}_{-0.68}\ M_{\rm Jup}$	$6.79^{+1.85}_{-1.03}\ M_{\rm Jup}$



Bardalez-Gagliuffi et al. 2022

Conclusions:

Gaia aids in direct imaging work of exoplanets by providing information on the chemistry, age, distance, and dynamic history of the system. We can then extract mass, luminosity, and potential formation information of planets.

Gaia is providing information on accelerating stars, or nearby young stars that are ideal targets for future direct imaging campaigns.

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