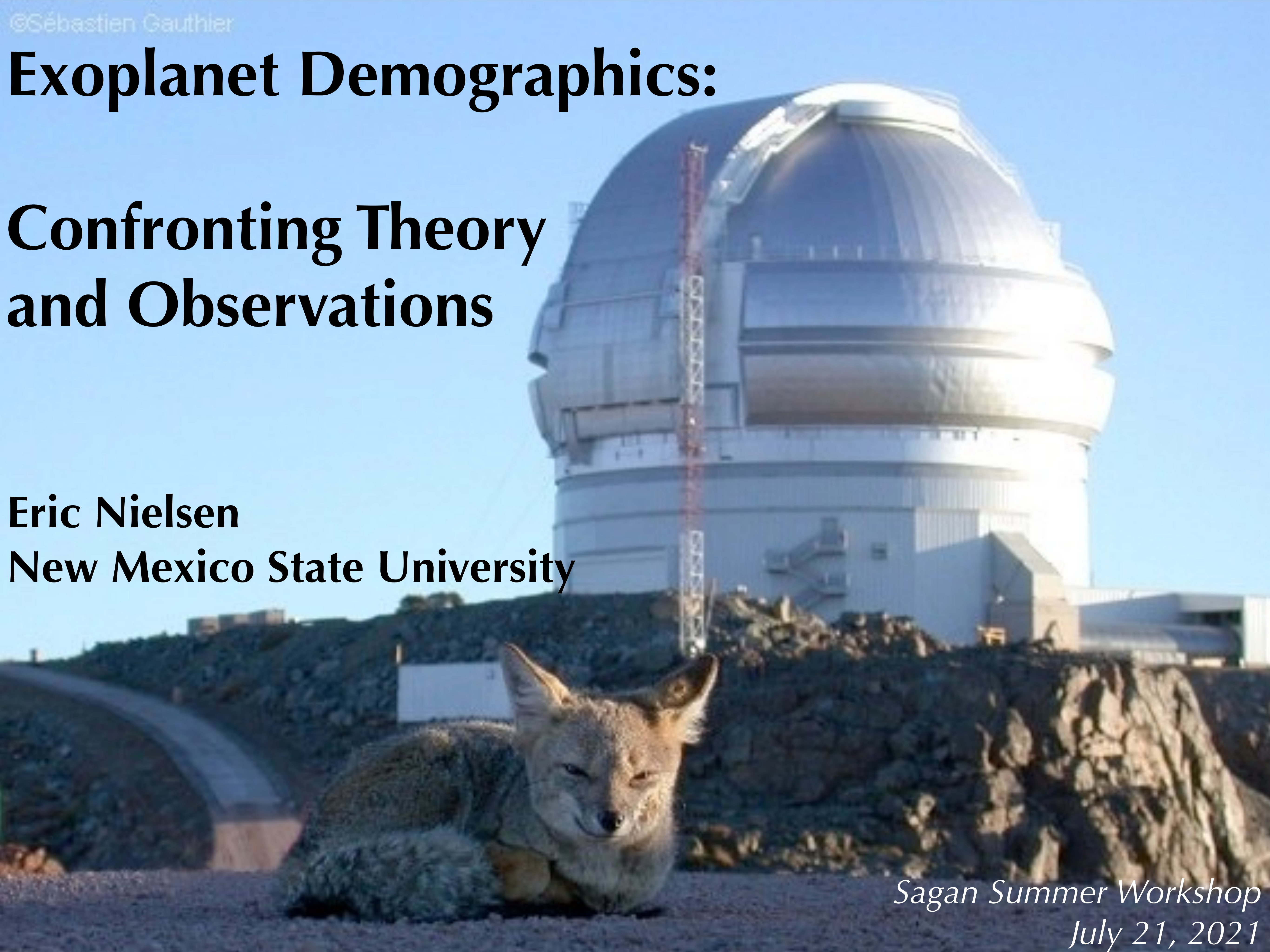


©Sébastien Gauthier

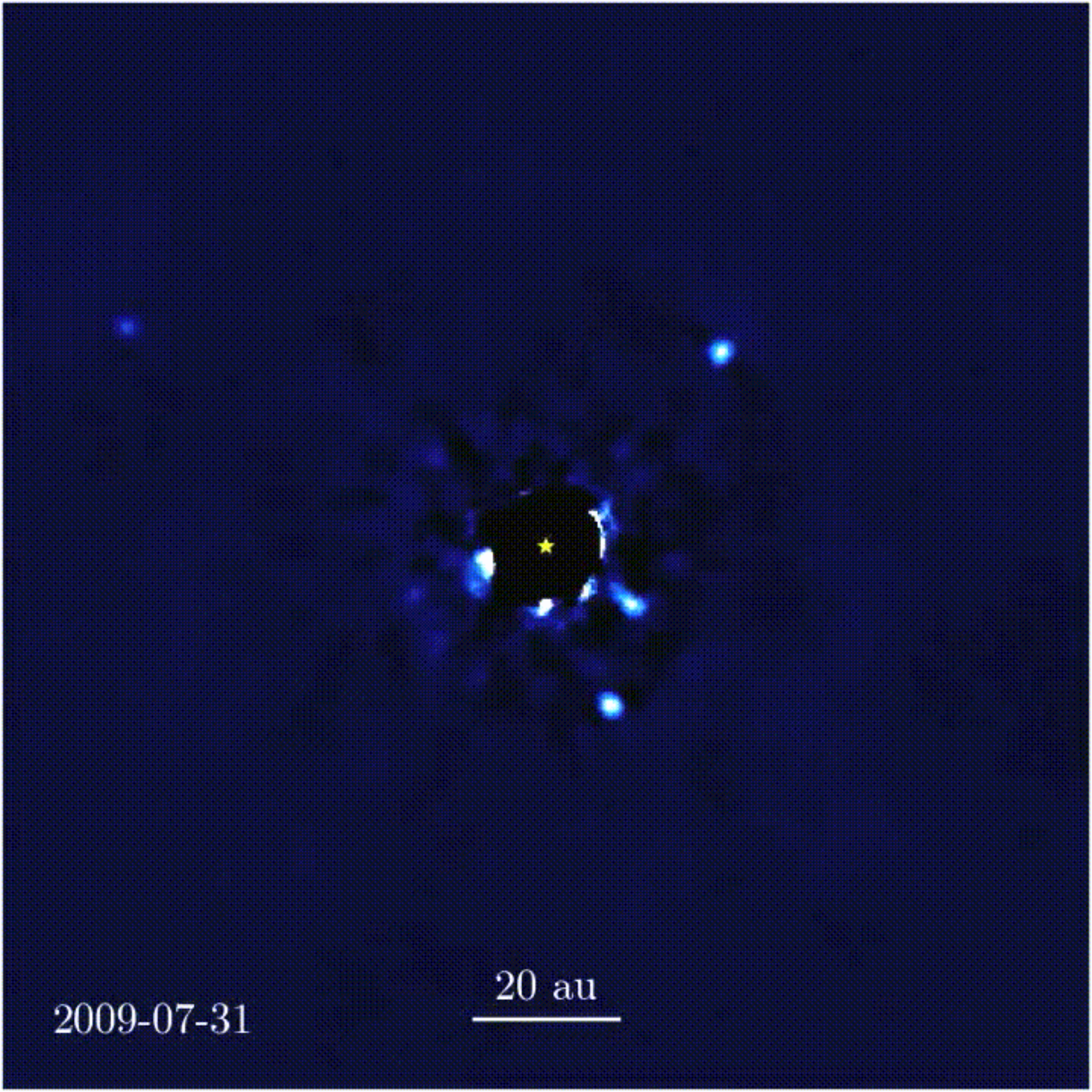
Exoplanet Demographics:

Confronting Theory and Observations

Eric Nielsen
New Mexico State University

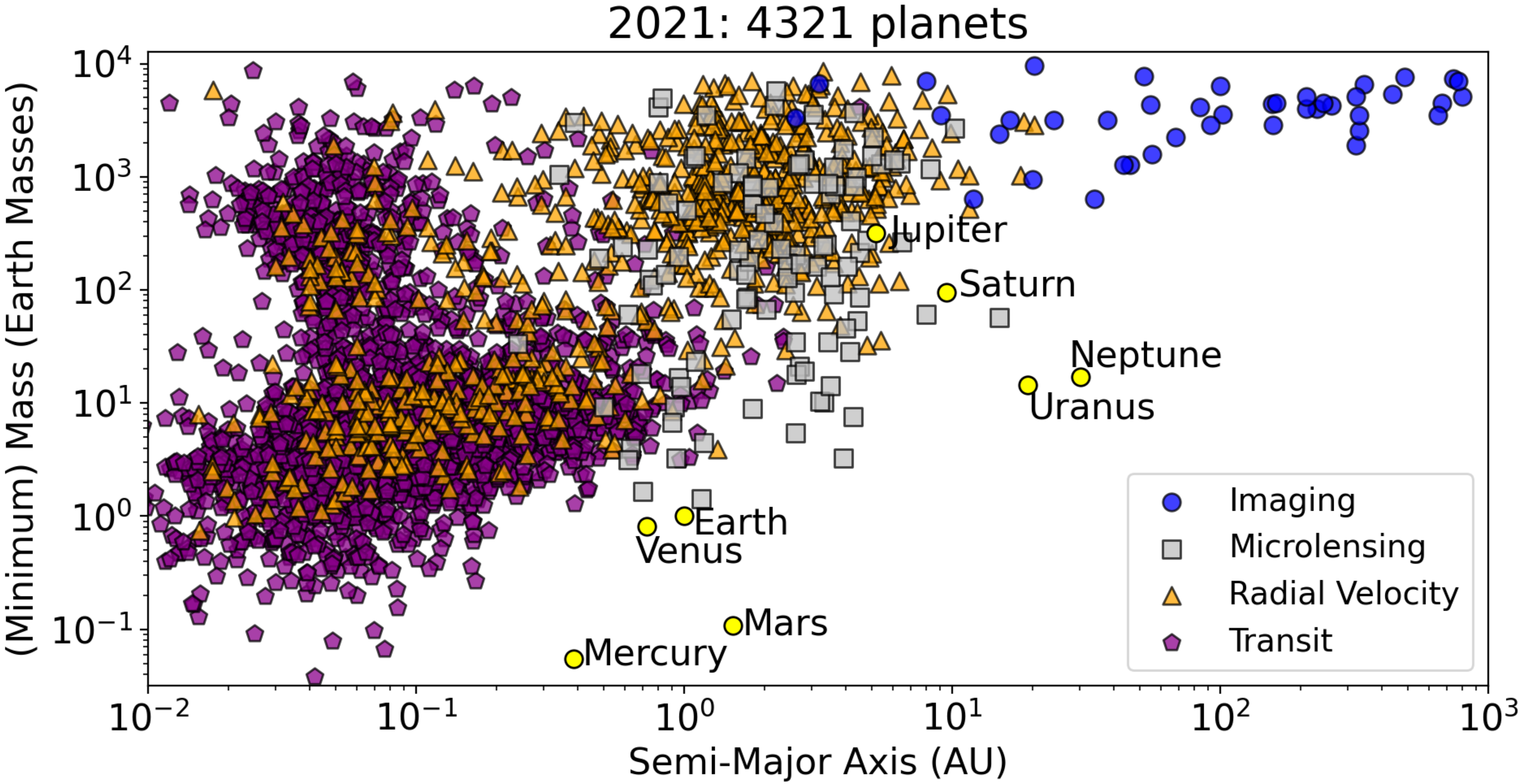
Sagan Summer Workshop
July 21, 2021

HR 8799: exoplanets in motion



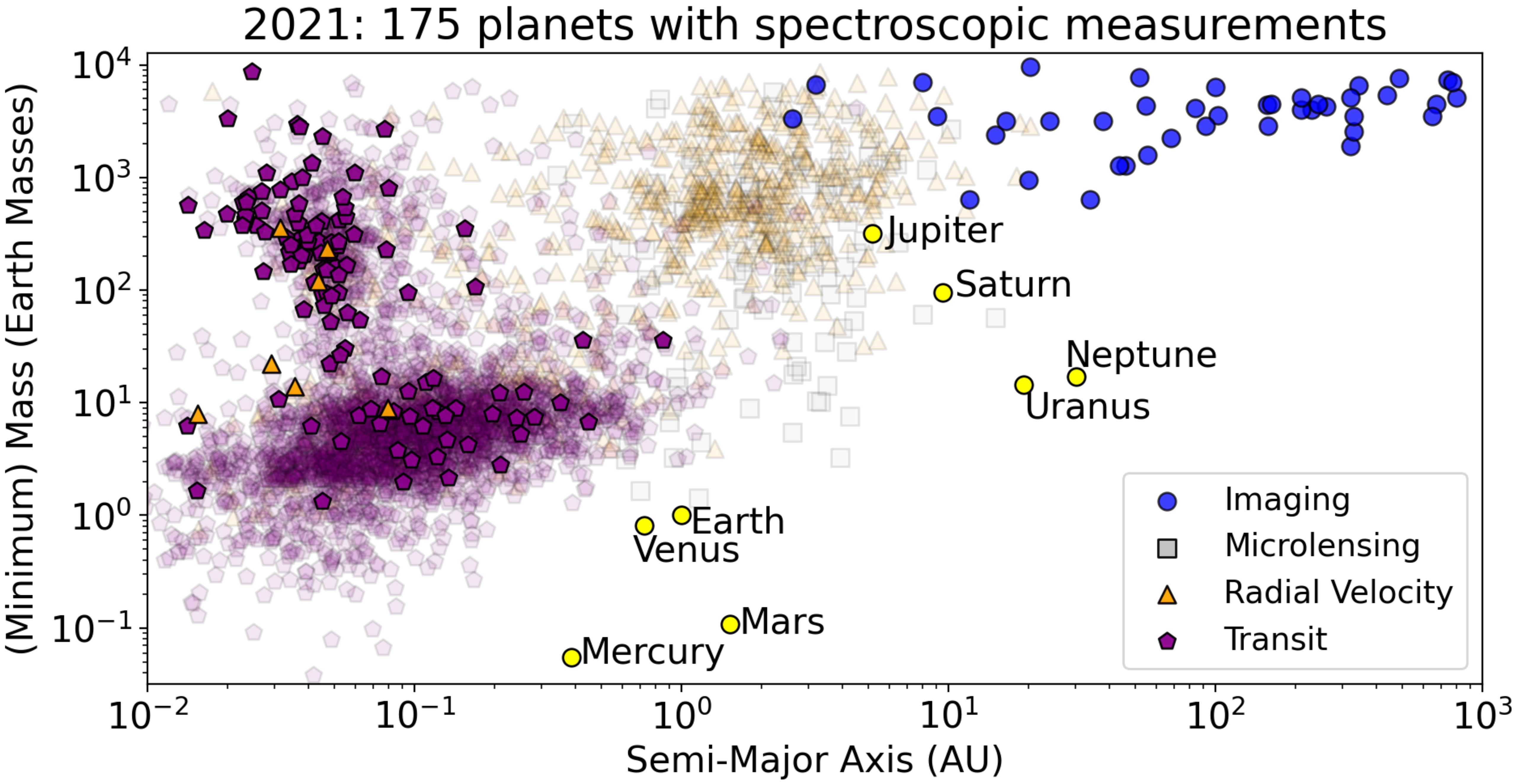
Movie from Jason Wang and Christian Marois

Exoplanet Populations



Dmitry Savransky/NASA Exoplanet Archive

Exoplanet Populations



Dmitry Savransky/NASA Exoplanet Archive

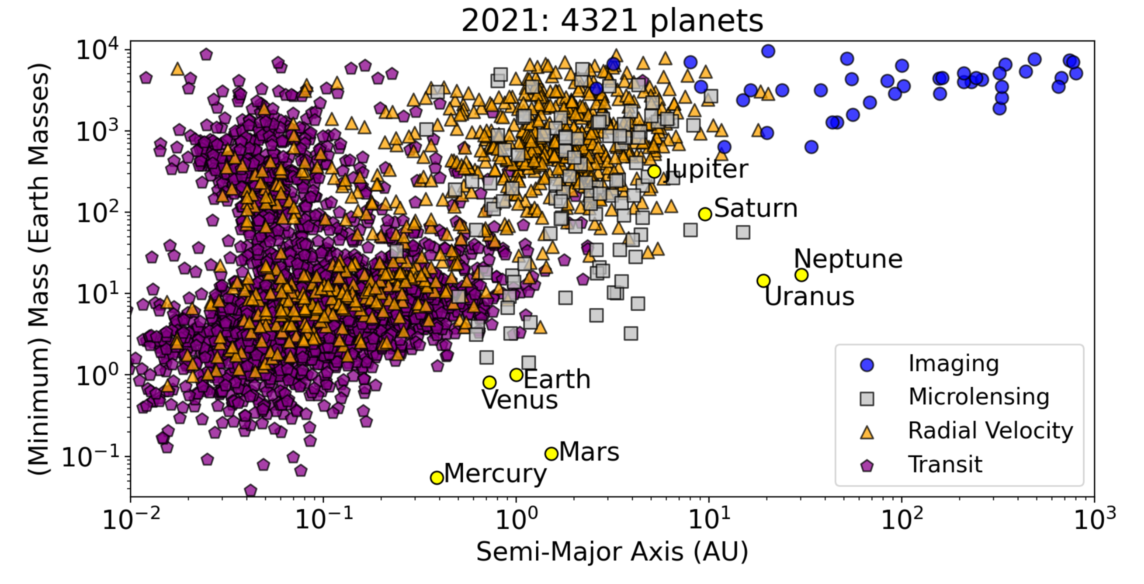
Exoplanet Demographics

What is the occurrence rate of planets?

How does that occurrence rate scale with system properties (planet mass, planet semi-major axis, stellar mass, stellar metallicity, …)?

Demographics let us directly test models of planet formation and evolution

Make predictions for future instrumentation and surveys



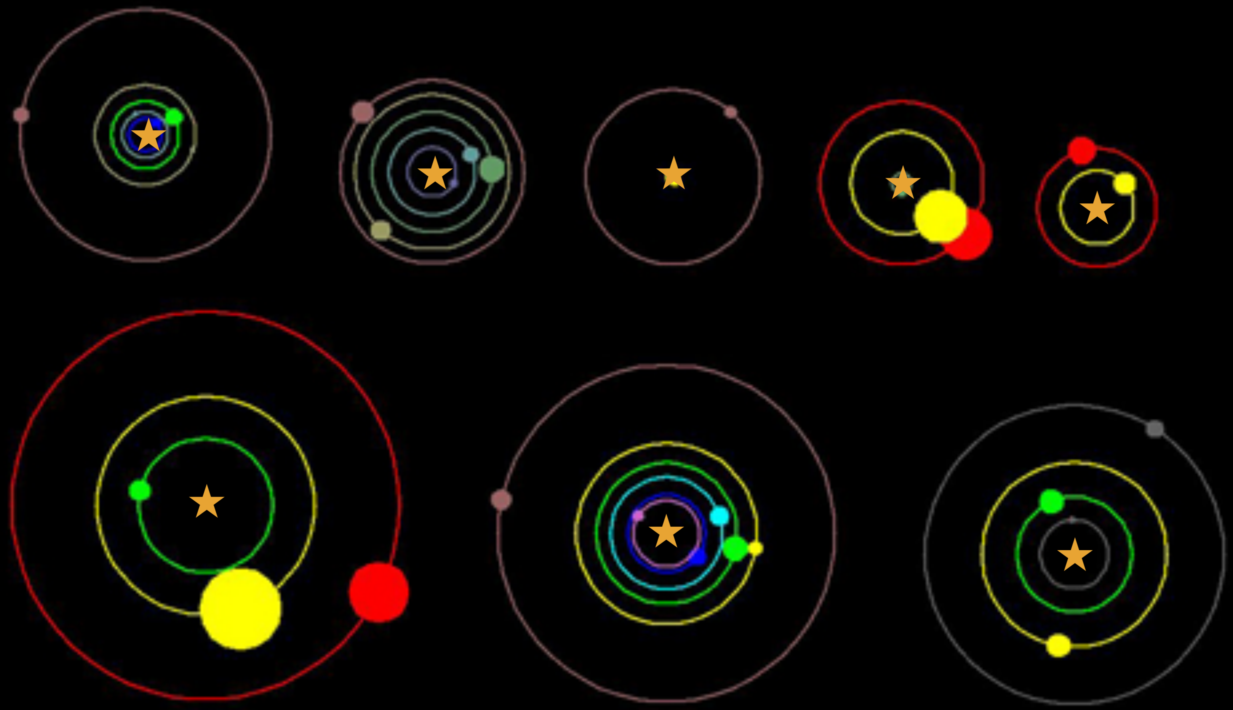
Dmitry Savransky/NASA Exoplanet Archive

Planet Occurrence and Planet Fraction

Planet Fraction: fraction of stars with planets

Planet Occurrence: number of planets per star

Both are often given over a specific range of parameters (e.g. 1-13 M_{Jup}, 10-100 AU, 1.5-2.5 M_{Sun})



Eric Ford/NASA Ames/UC Santa Cruz

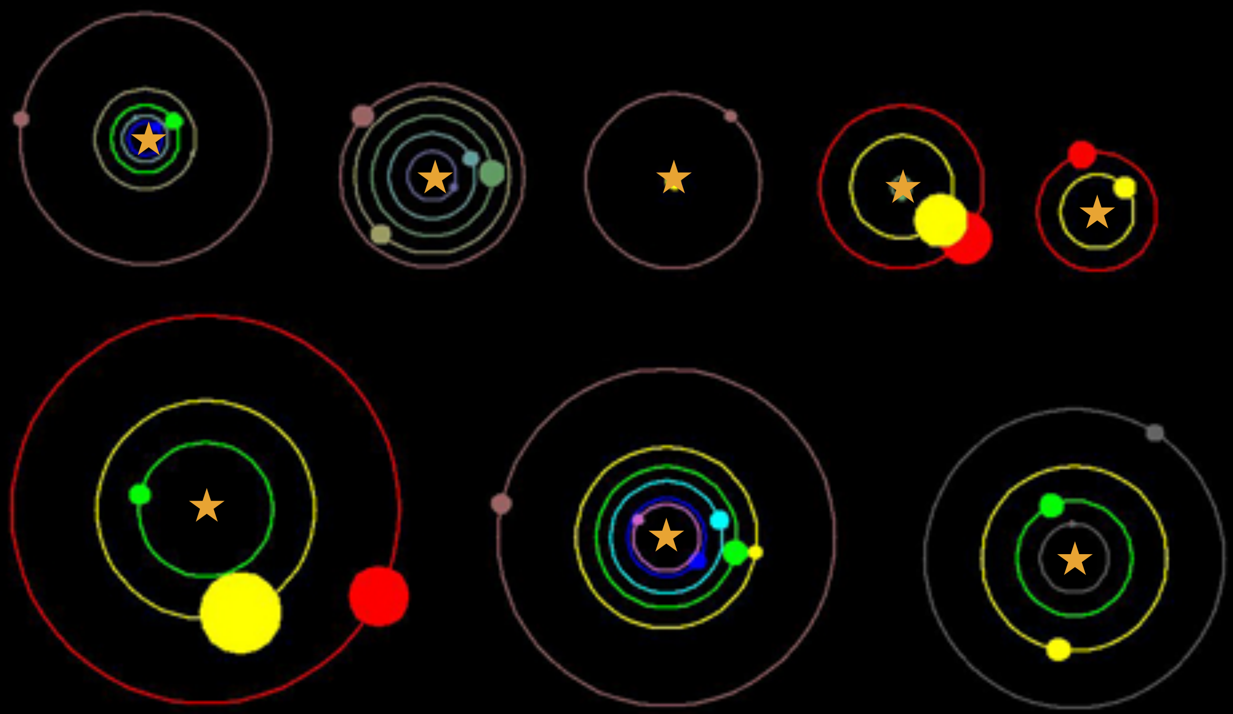
Calculating Occurrence Rate and Planet Fraction

Planet Fraction:

$$\frac{\text{Number of Stars with Planets}}{\text{Total Number of Stars}}$$

Planet Occurrence:

$$\frac{\text{Total Number of Planets}}{\text{Total Number of Stars}}$$



Eric Ford/NASA Ames/UC Santa Cruz

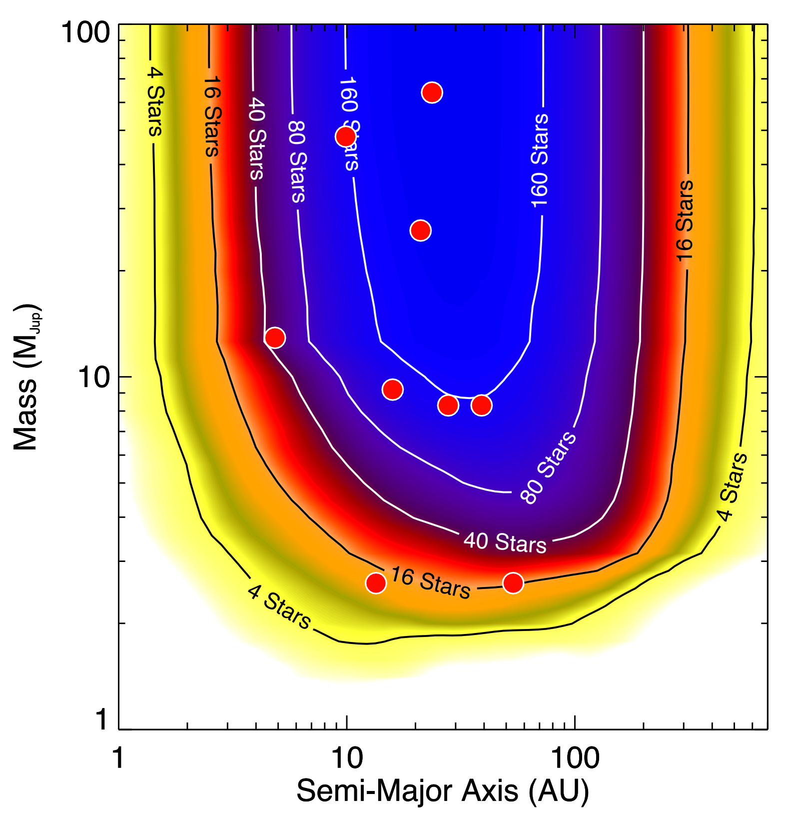
Completeness

Not all planets are equally easy to detect

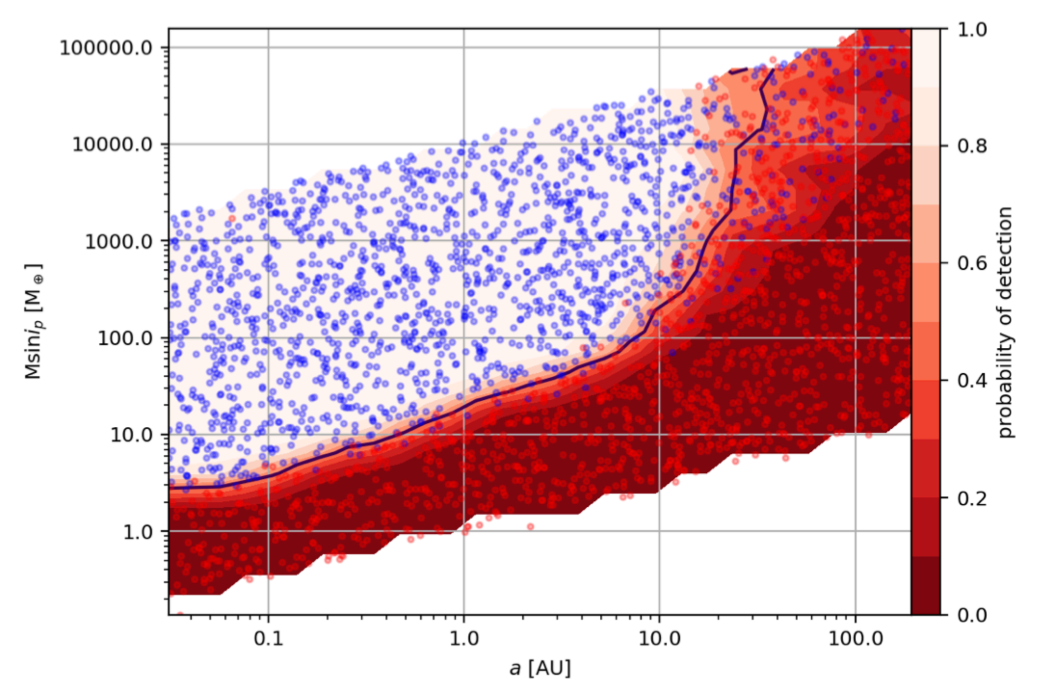
Each detection technique has its own biases

Important to accurately characterize survey completeness

Account for completeness when calculating occurrence or planet fraction



Nielsen et al. 2019

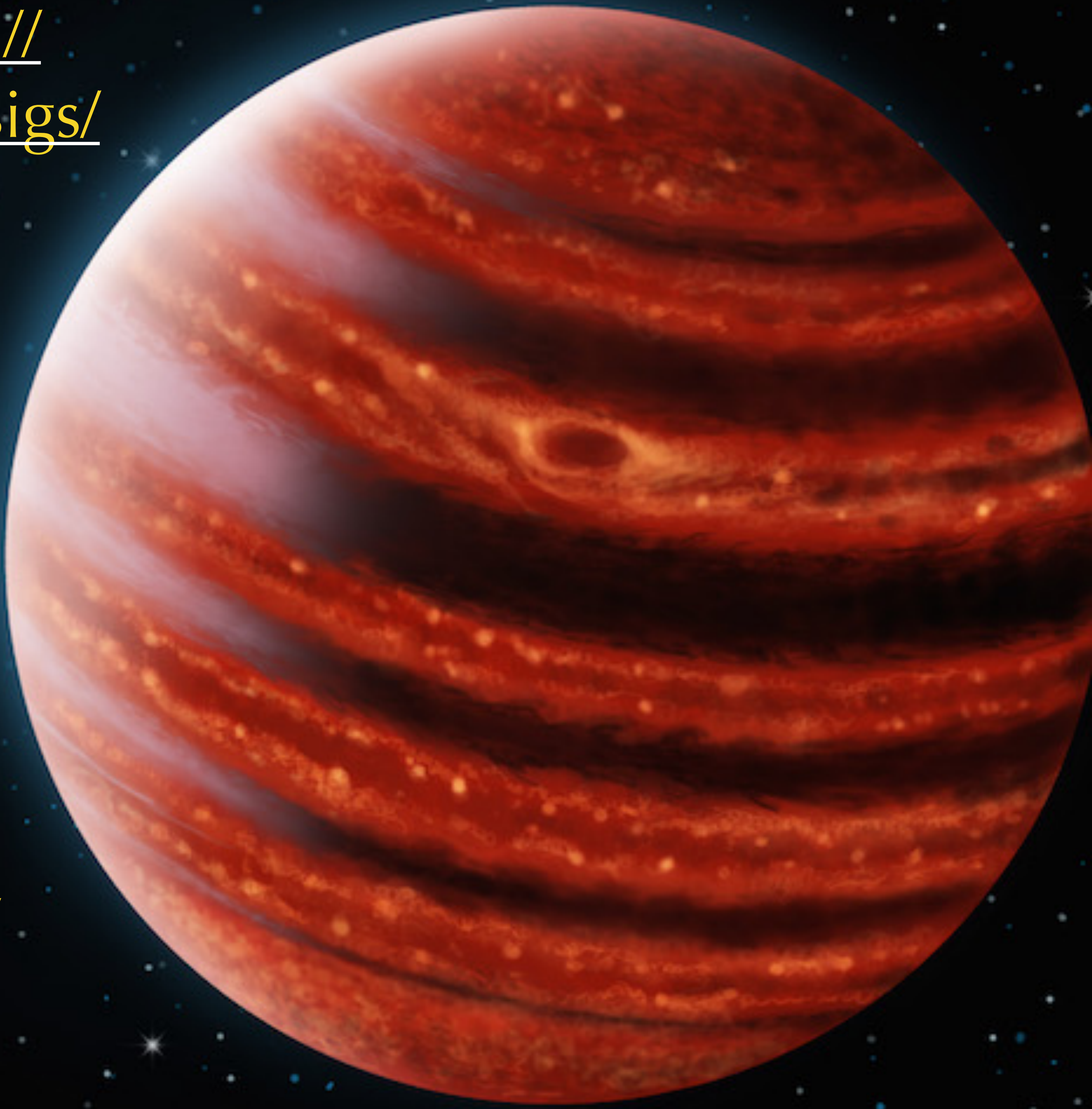


Rosenthal et al. 2021

Exoplanet Demographics

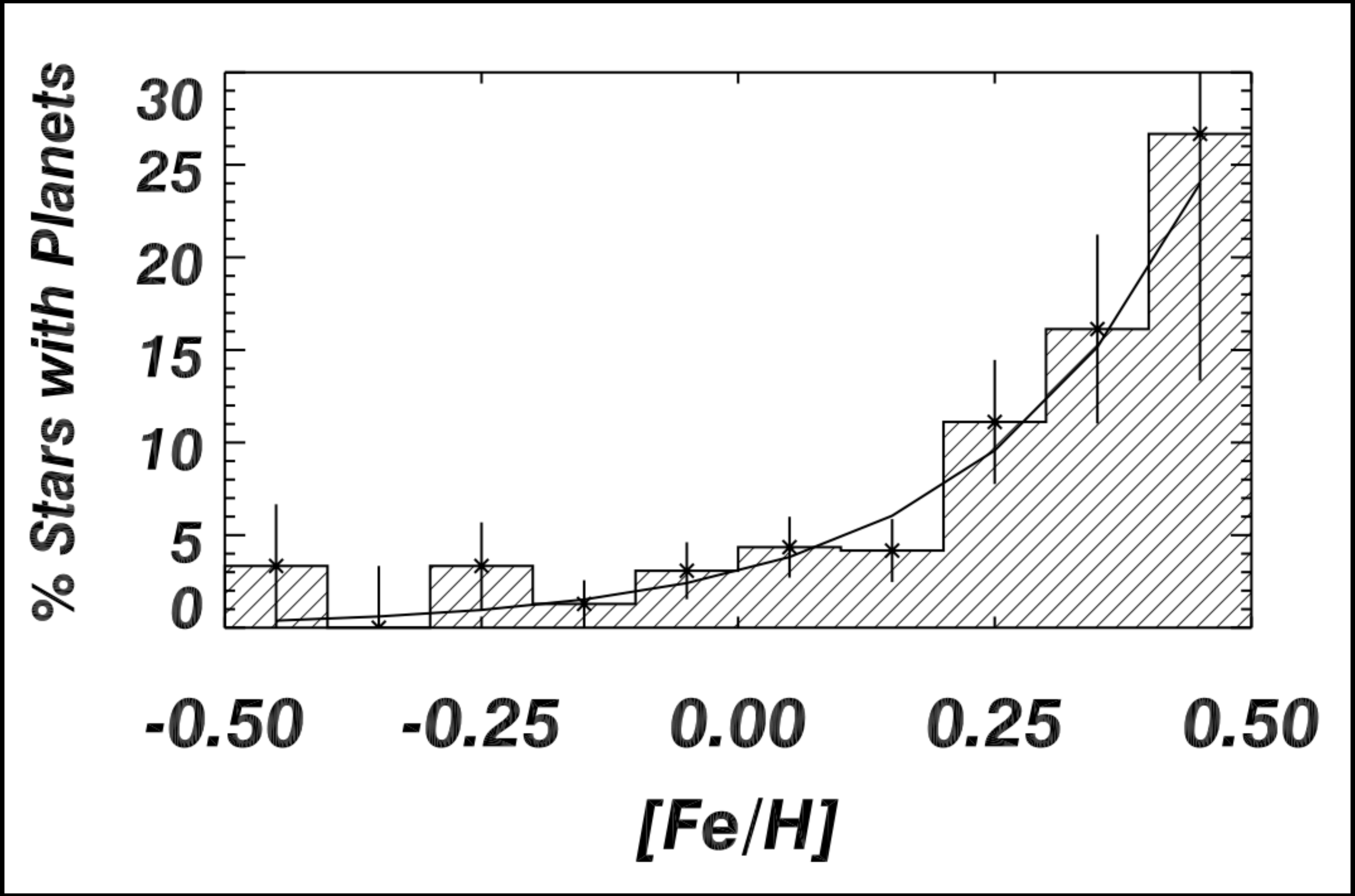
NASA SIG2 (Science Interest Group) on Exoplanet Demographics: https://exoplanets.nasa.gov/exep/exopag/sigs/

Exoplanet Demographics papers on the NASA Exoplanet Archive: https://exoplanetarchive.ipac.caltech.edu/docs/occurrence_rate_papers.html



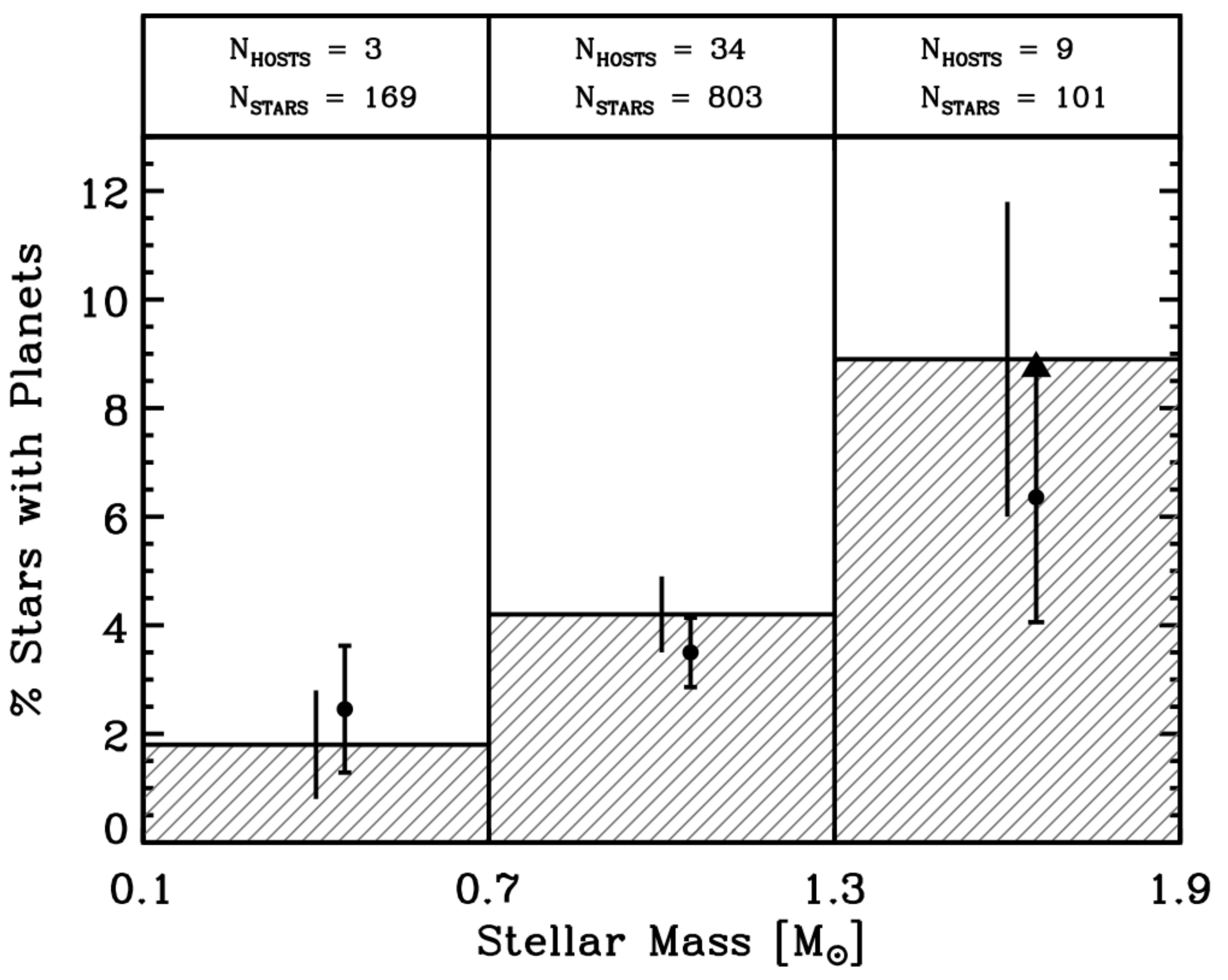
Danielle Futselaar & Franck Marchis, SETI Institute

The giant planet/metallicity correlation



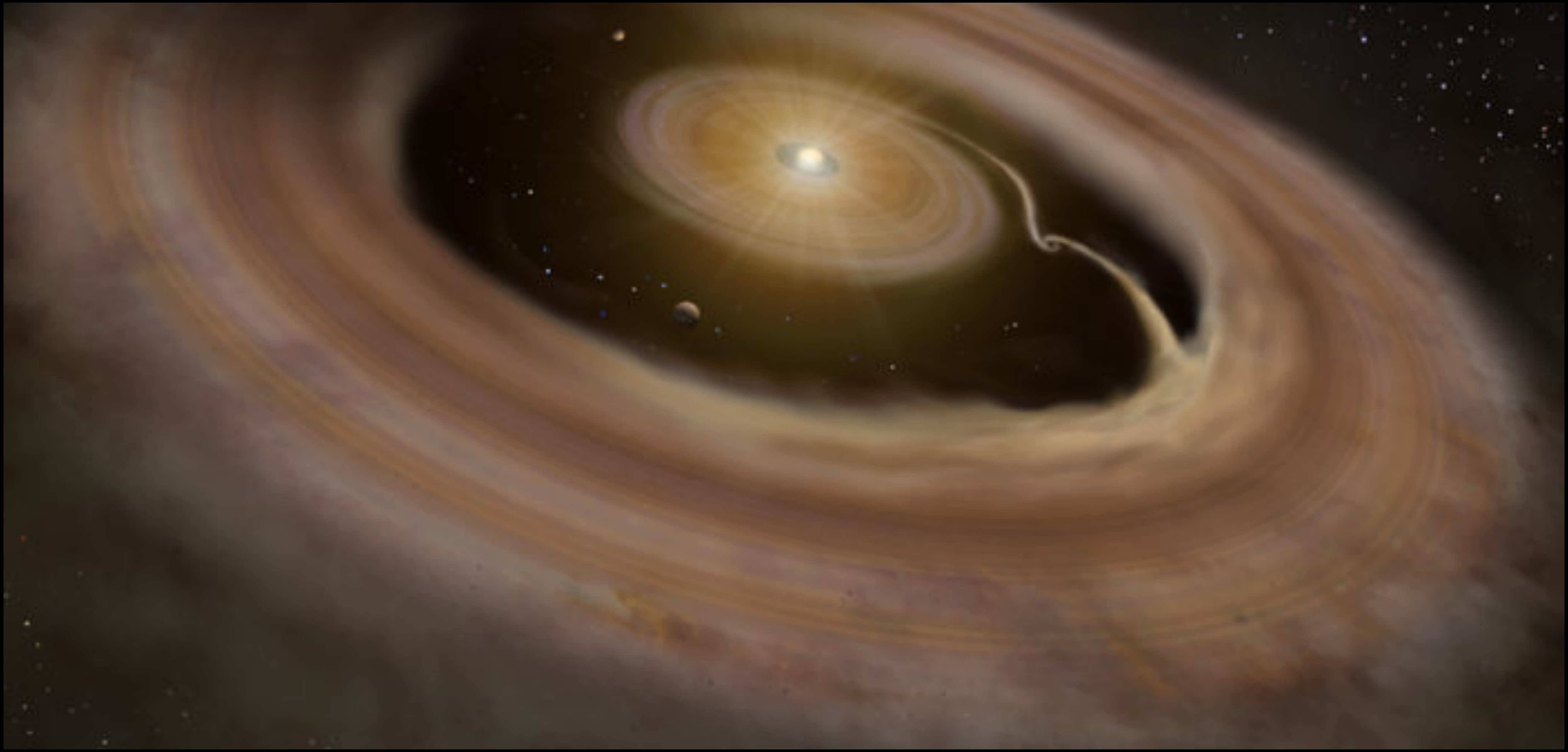
Fischer & Valenti 2005

The giant planet/host mass correlation



Johnson et al. 2007

Giant Planet Formation



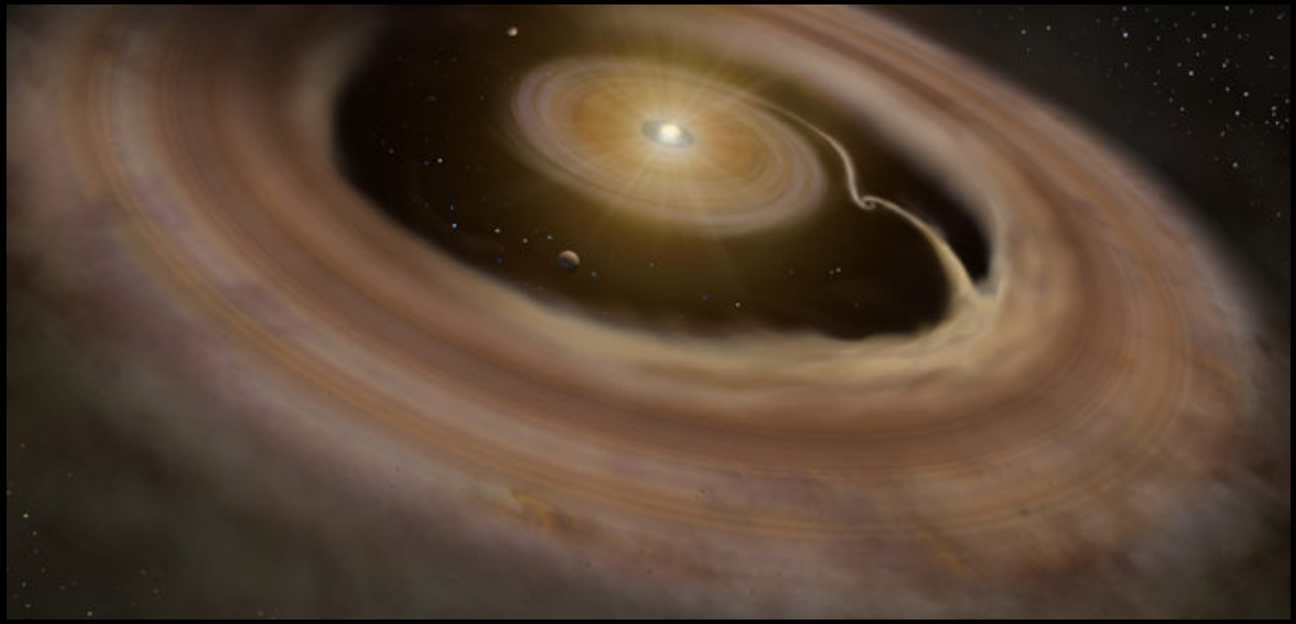
The Graduate Institute for Advanced Studies/NOAJ

Bottom-up: Core Accretion

Step 1: Accrete 10 Earth masses of solids

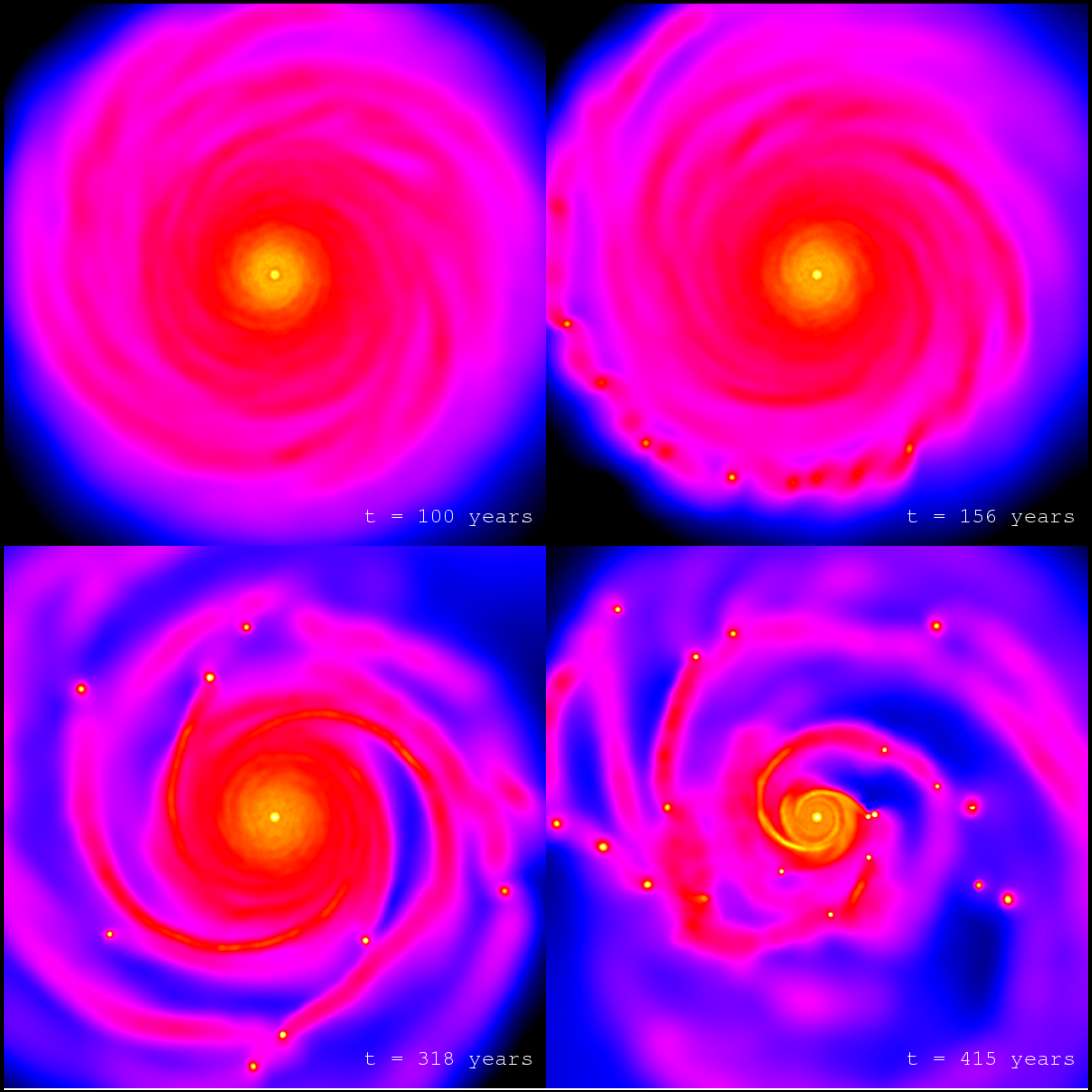
Alan Brandon/Nature

Step 2: Pull 300 Earth masses of gas from disk



The Graduate Institute for Advanced Studies/NOAJ

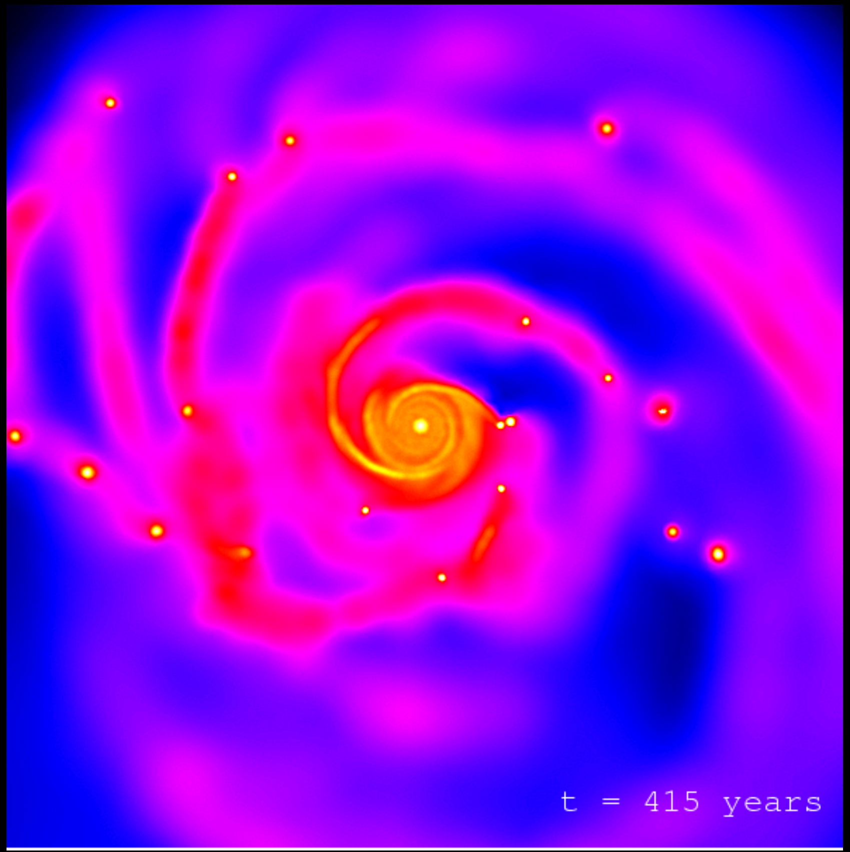
Top-down: Gravitational Instability



G. Lufkin et al.

Comparing to theory

Core accretion

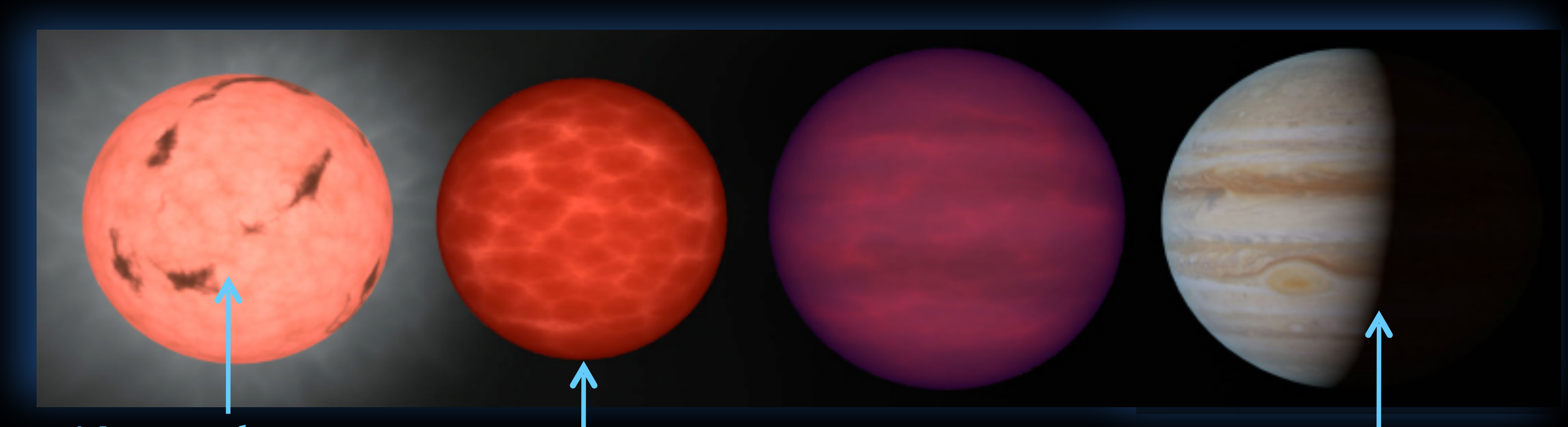


Gravitational Instability

Predicts more giant planet cores forming at higher metallicity

Predicts more giant planets orbiting higher mass stars

Young planets are the easiest to see



New planet:
3000°C

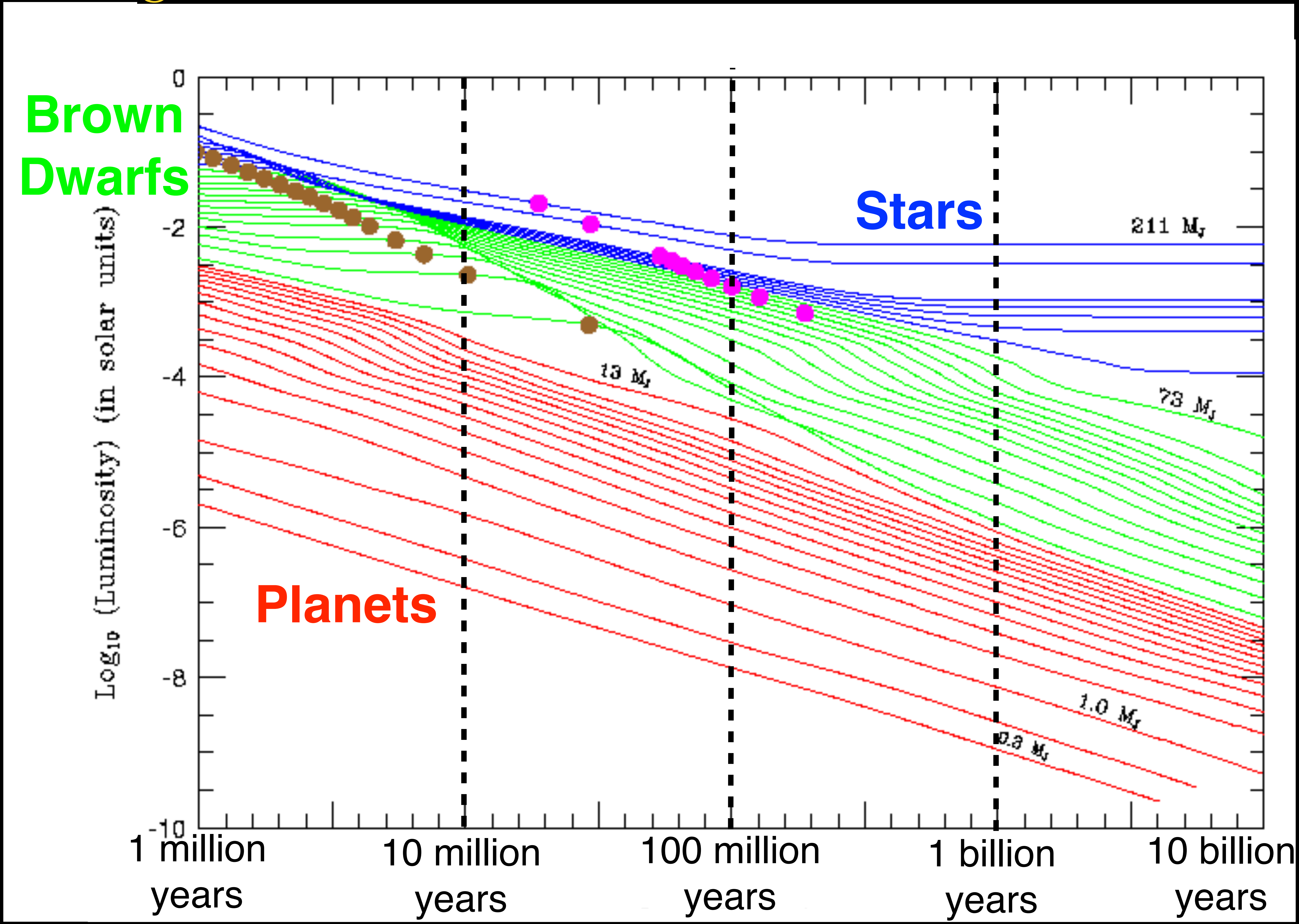
10 million years:
2000°C

100 million years: 1000°C

4600 million years: -145°C

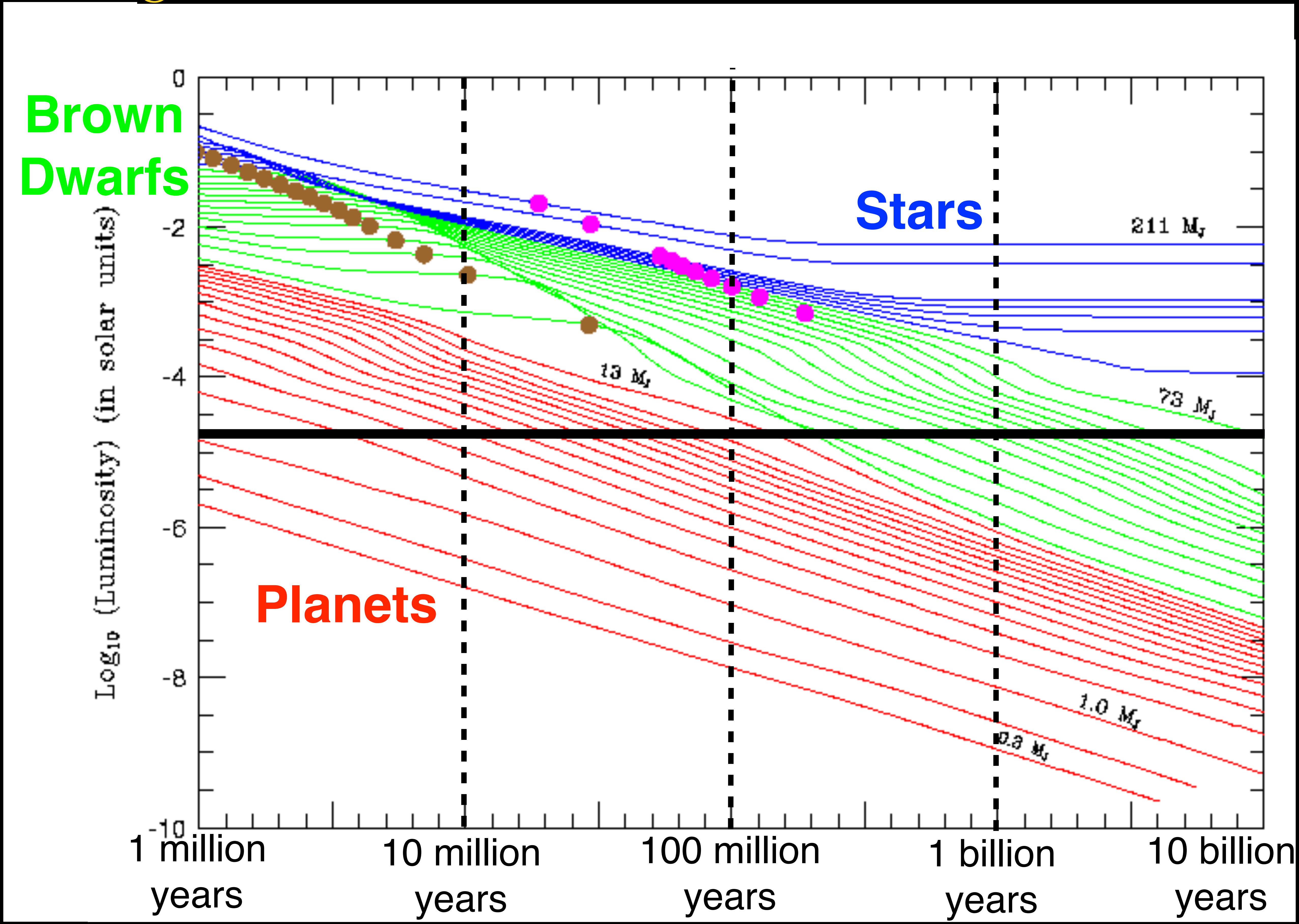
NASA/IPAC/R. Hurt (SSC)

Cooling with time



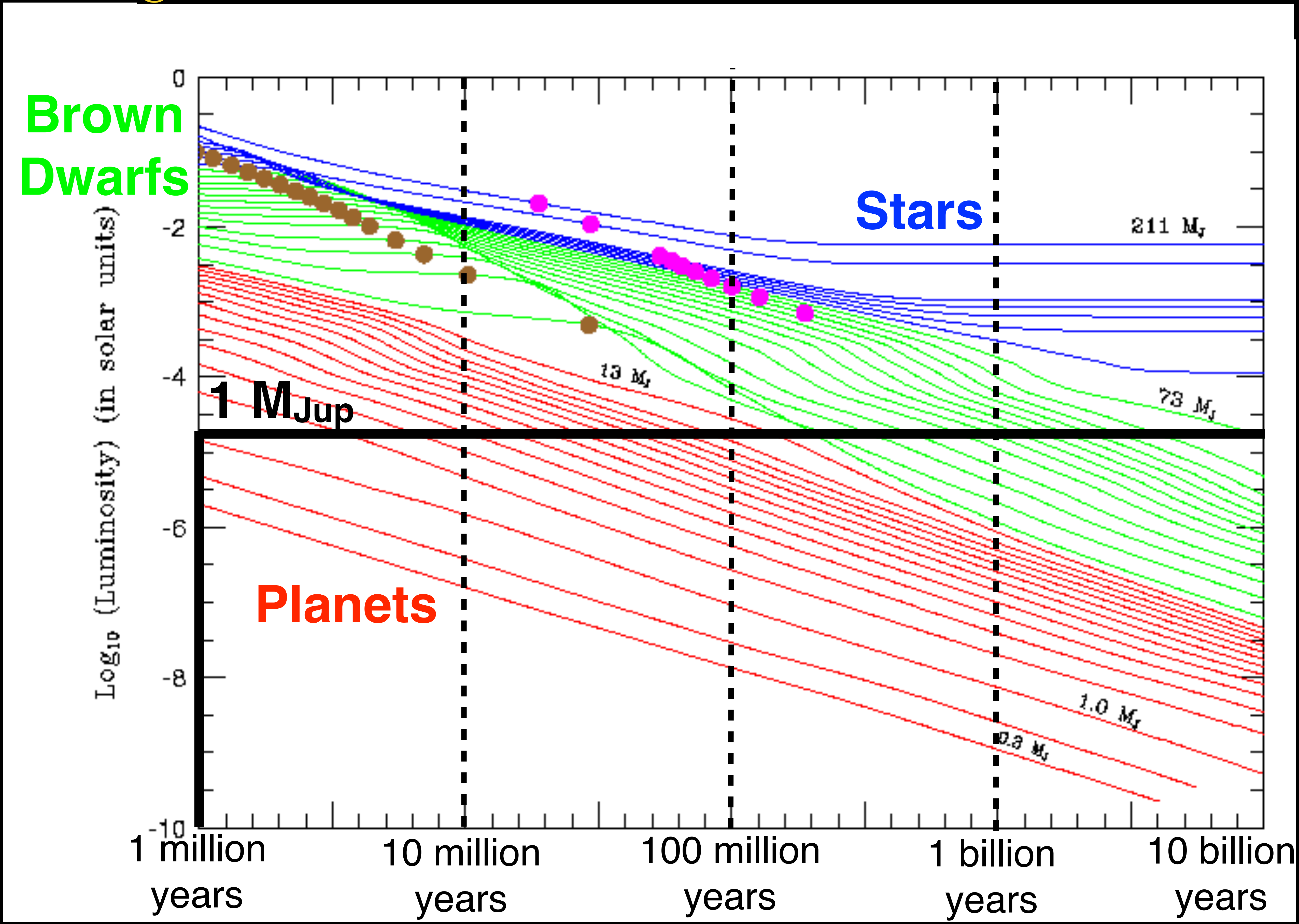
Adam Burrows

Cooling with time



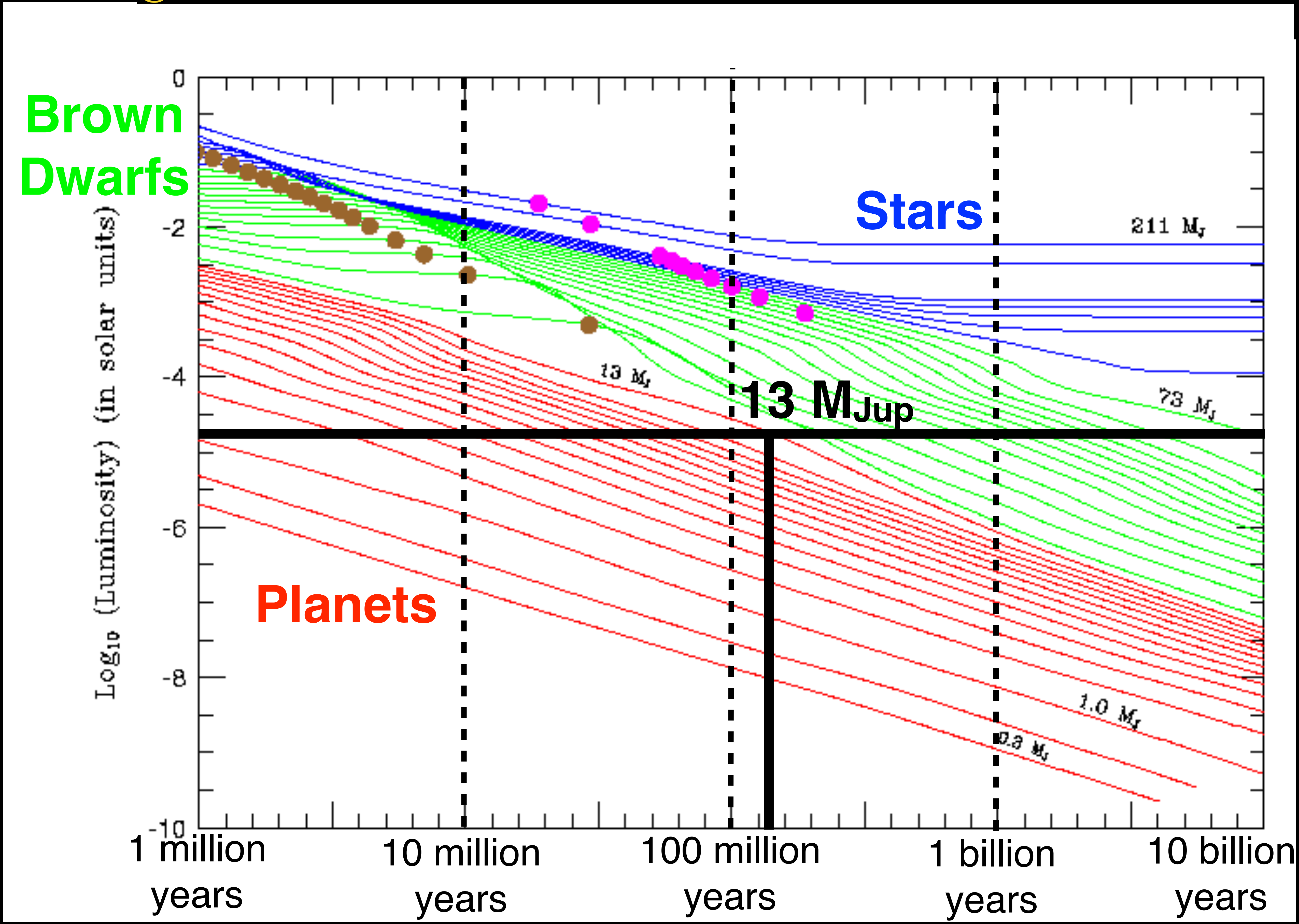
Adam Burrows

Cooling with time



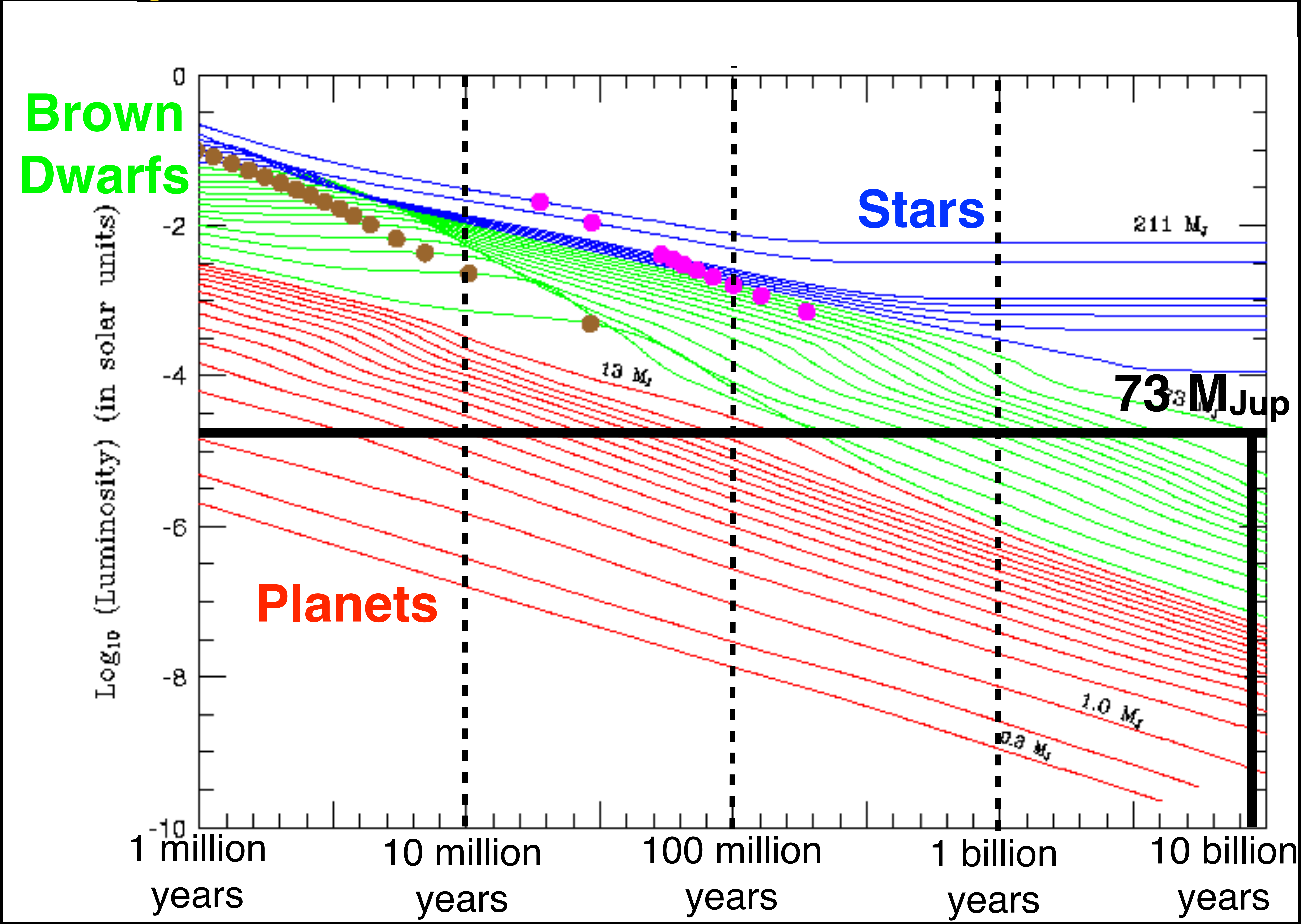
Adam Burrows

Cooling with time



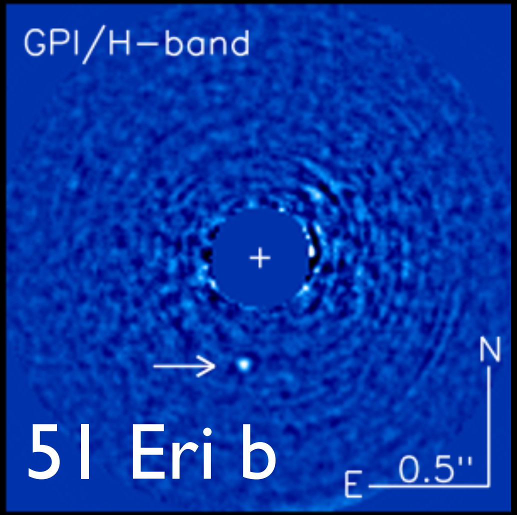
Adam Burrows

Cooling with time

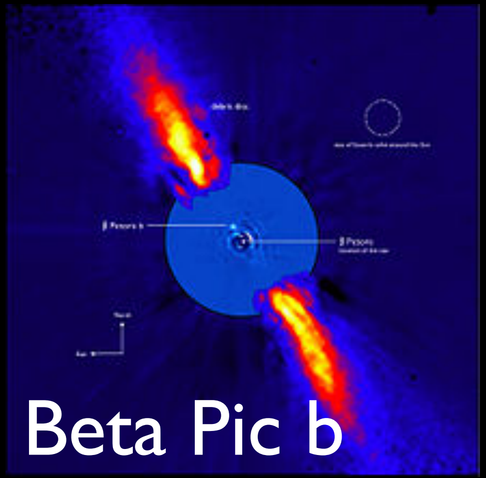


Adam Burrows

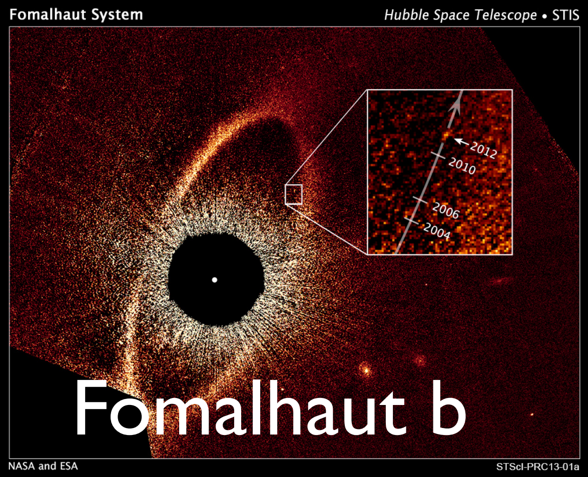
Directly Imaged Planets



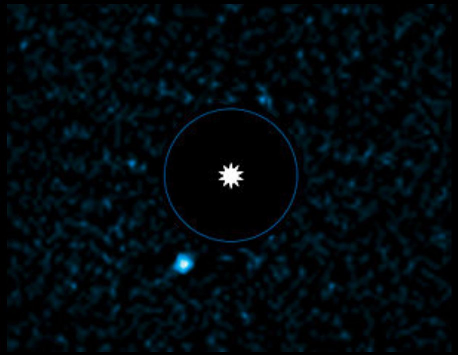
51 Eri b



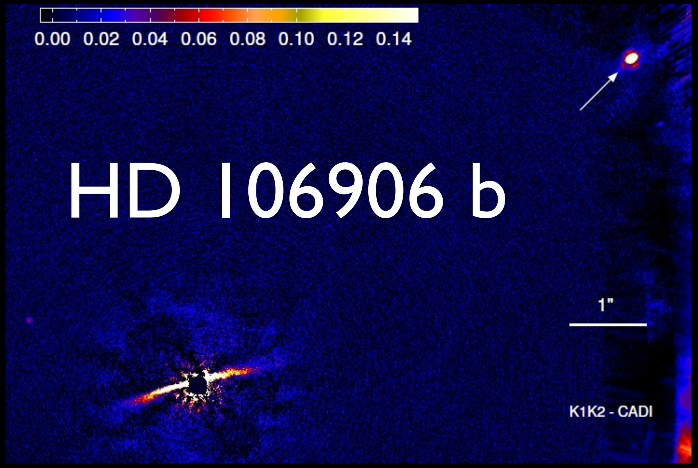
Beta Pic b



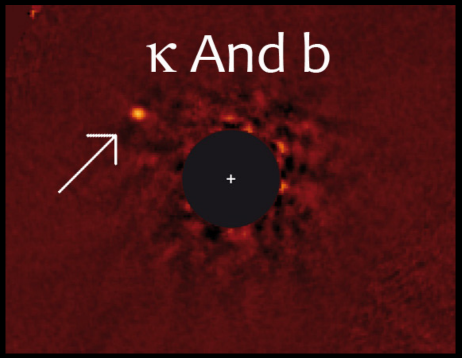
Fomalhaut b



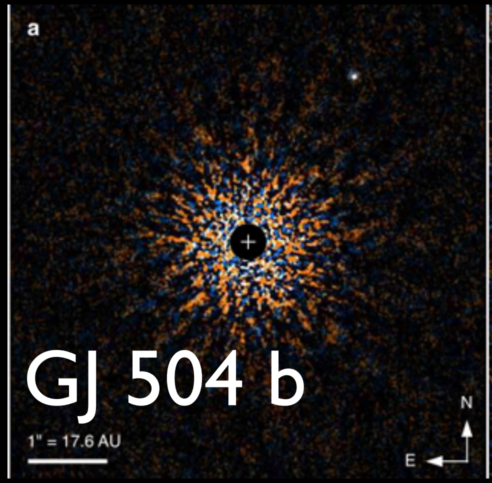
HD 95086 b



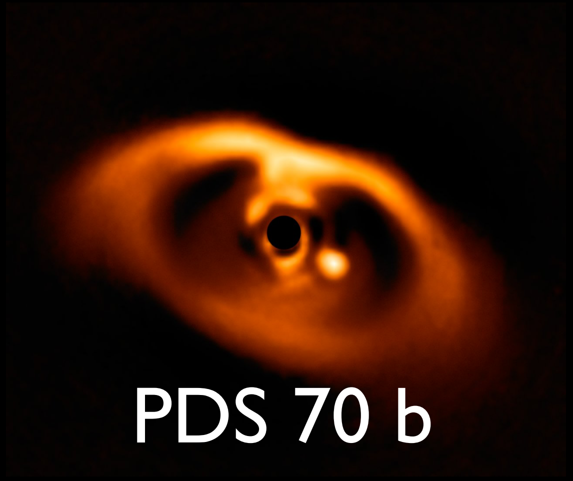
HD 106906 b



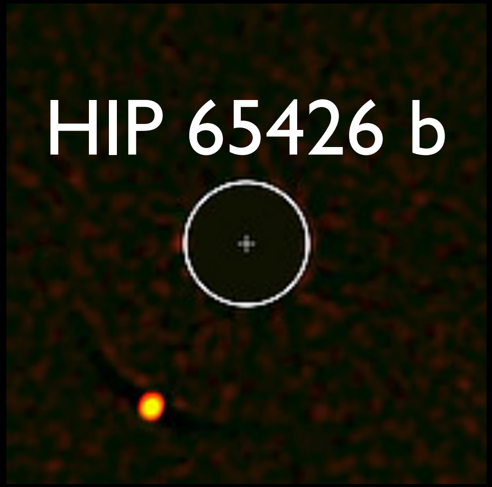
κ And b



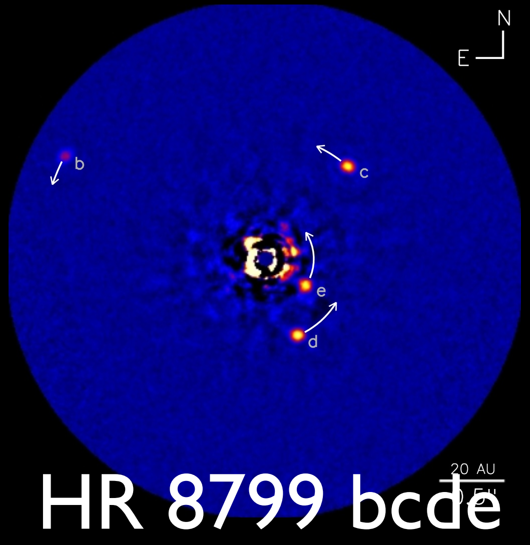
GJ 504 b



PDS 70 b

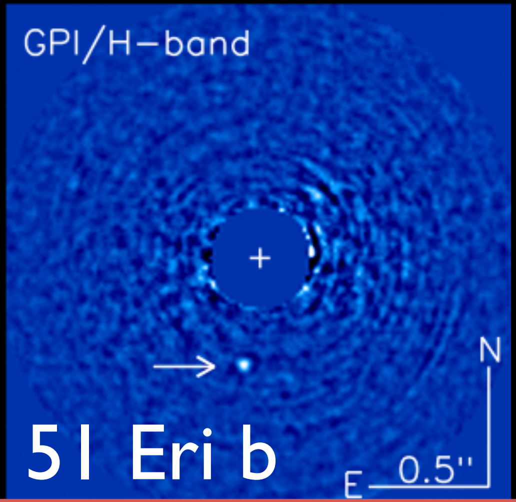


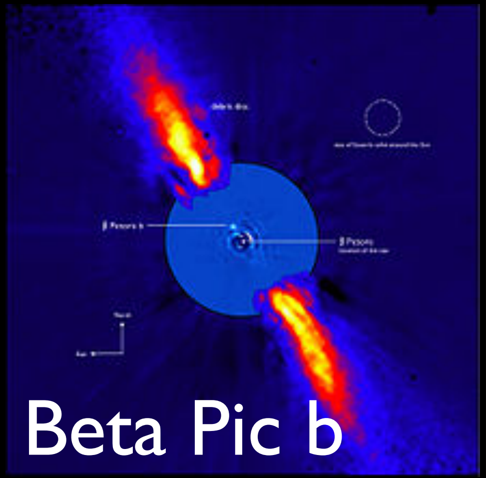
HIP 65426 b



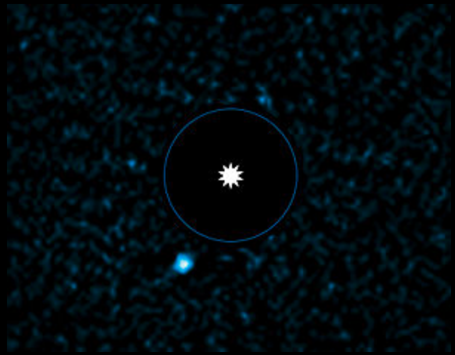
HR 8799 bcde

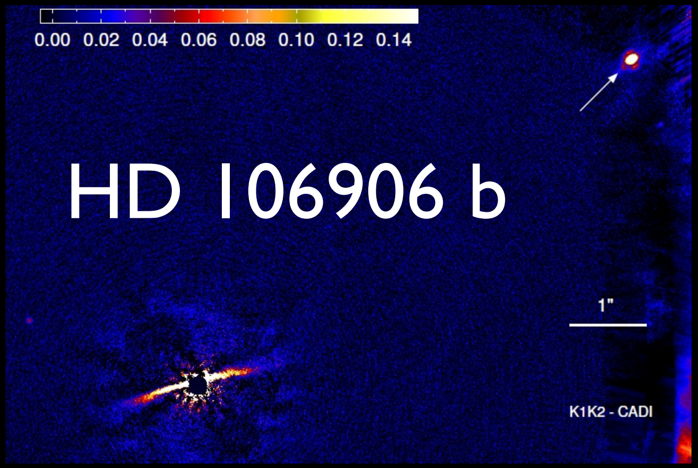
Directly Imaged Planets

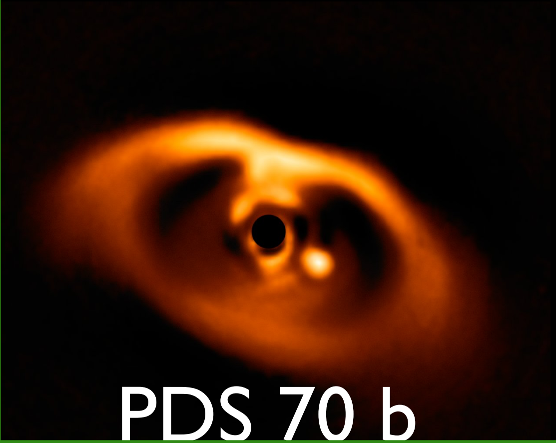

51 Eri b

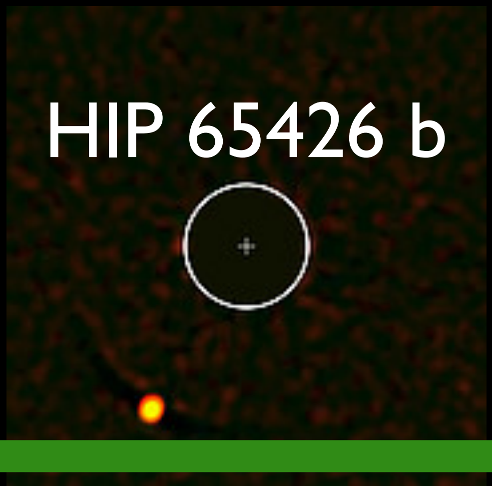

Beta Pic b

Beta Pic Moving Group

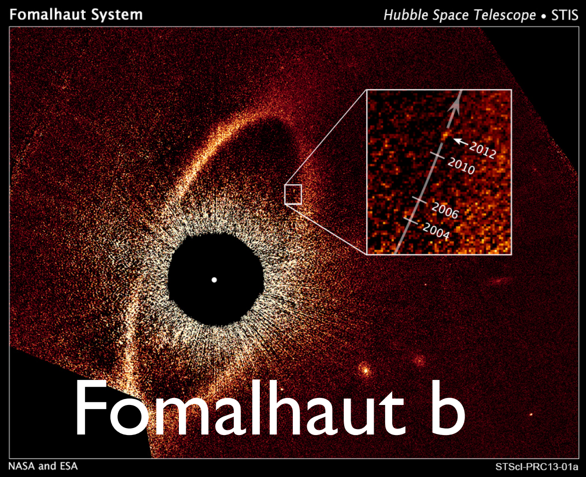

HD 95086 b

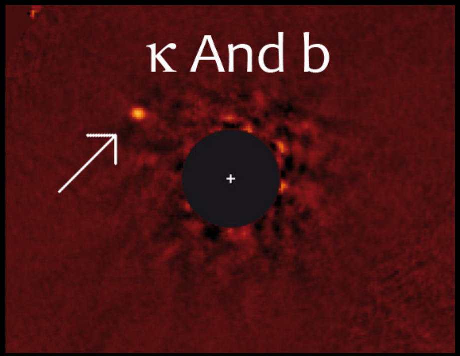

HD 106906 b

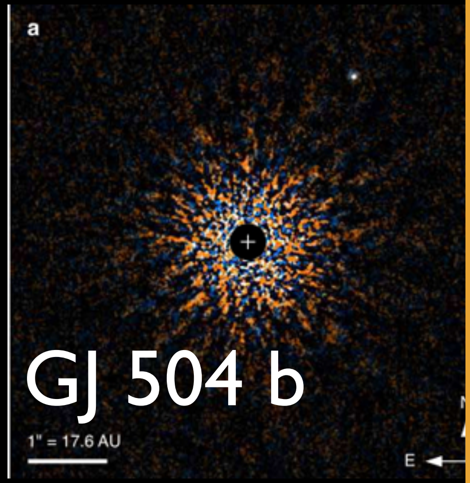

PDS 70 b


HIP 65426 b

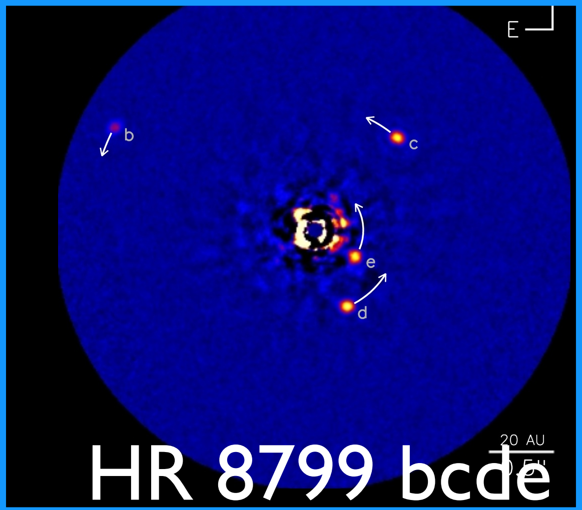
Sco/Cen Association


Fomalhaut b


κ And b


GJ 504 b

Field Stars


HR 8799 bcde

Columba Association

Ages of Stars

Moving group stars:

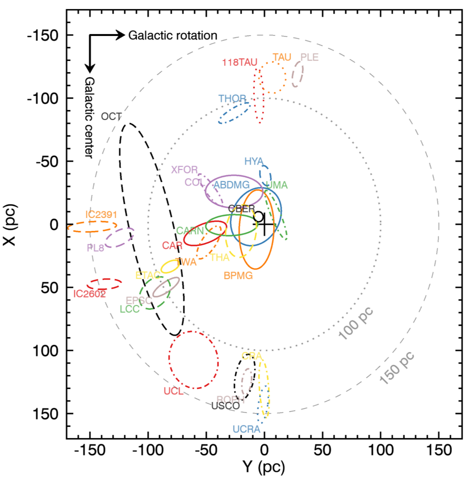
BANYAN (http://www.exoplanetes.umontreal.ca/banyan/ , Gagne et al. 2018)

LACEwING (https://github.com/ariedel/lacewing , Riedel et al. 2017)

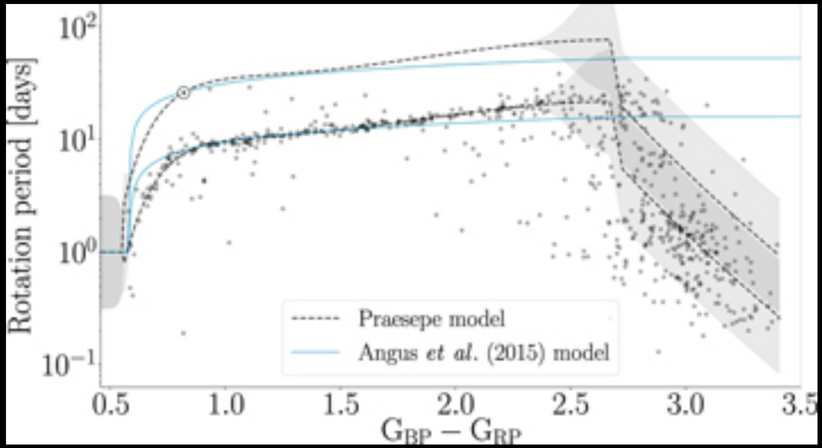
Field stars:

Rotation and Isochrones: stardate (https://github.com/RuthAngus/stardate , Angus et al. 2019)

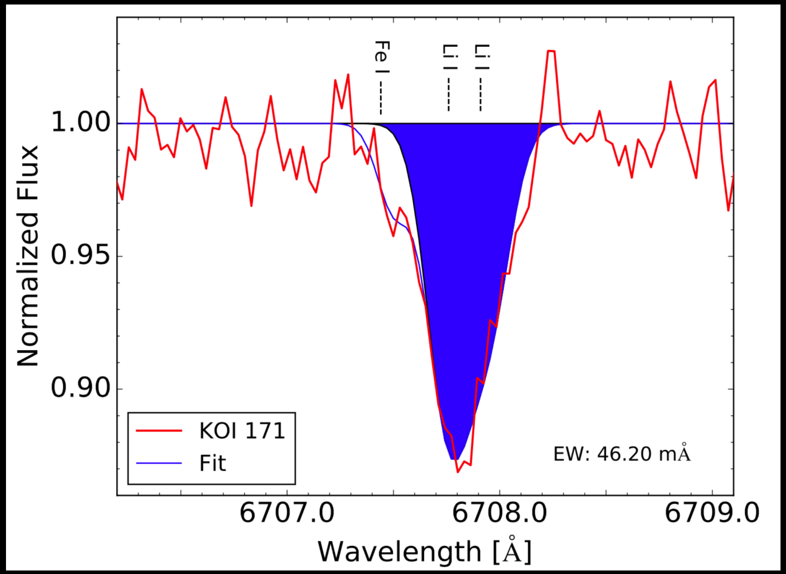
Calcium and Lithium: BAFFLES (https://github.com/adamstanfordmoore/BAFFLES , Stanford-Moore et al. 2020)



Gagne et al. 2018



Angus et al. 2019



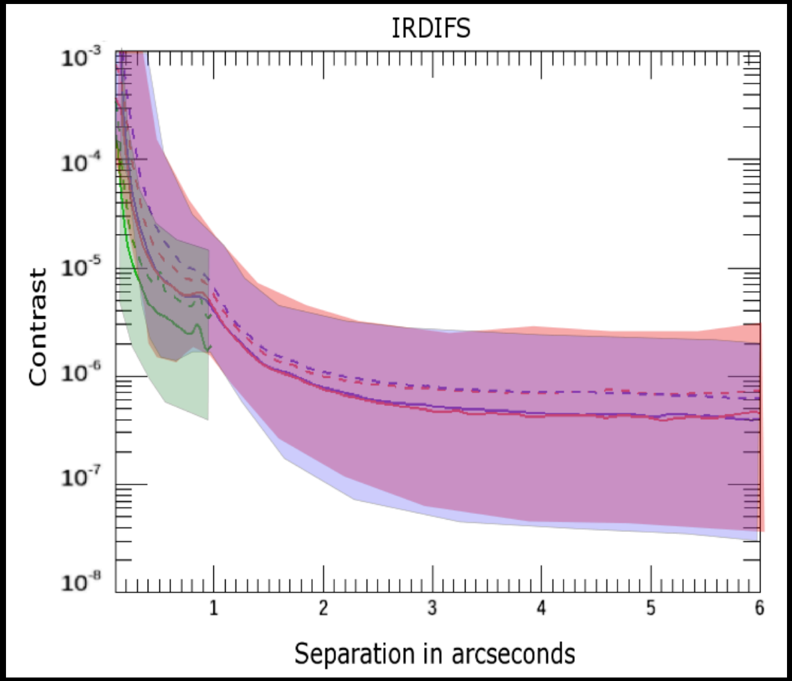
Berger, Howard, & Boesgaard 2018

Contrast Curves

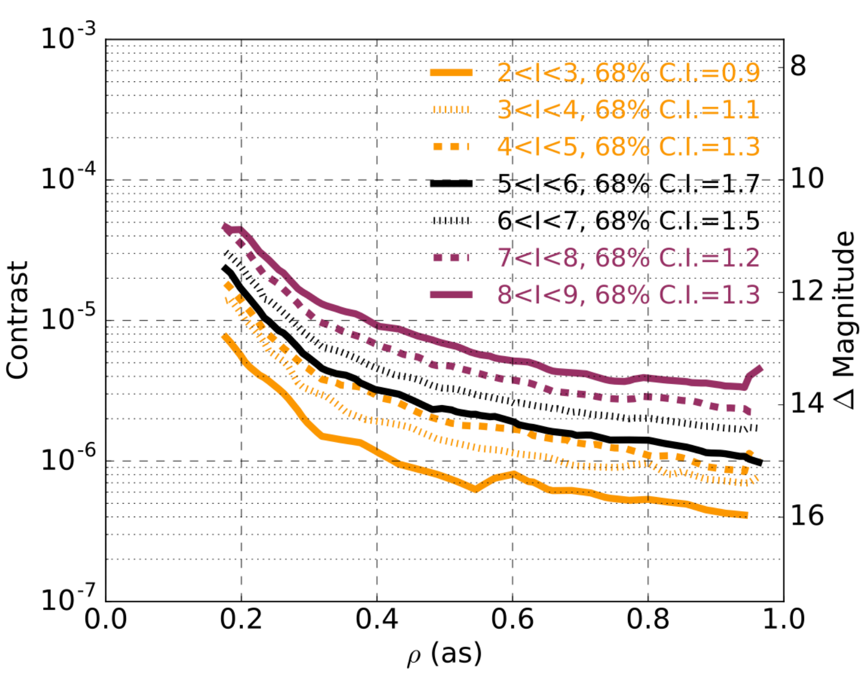
Limiting flux ratio (or magitude difference) where a companion can be detected

Typically less sensitive closer to the star, more sensitive further out

Depends on: instrument, data reduction, brightness of star, airmass, amount of rotation, weather…



Langlois et al. 2019



(a) T-type

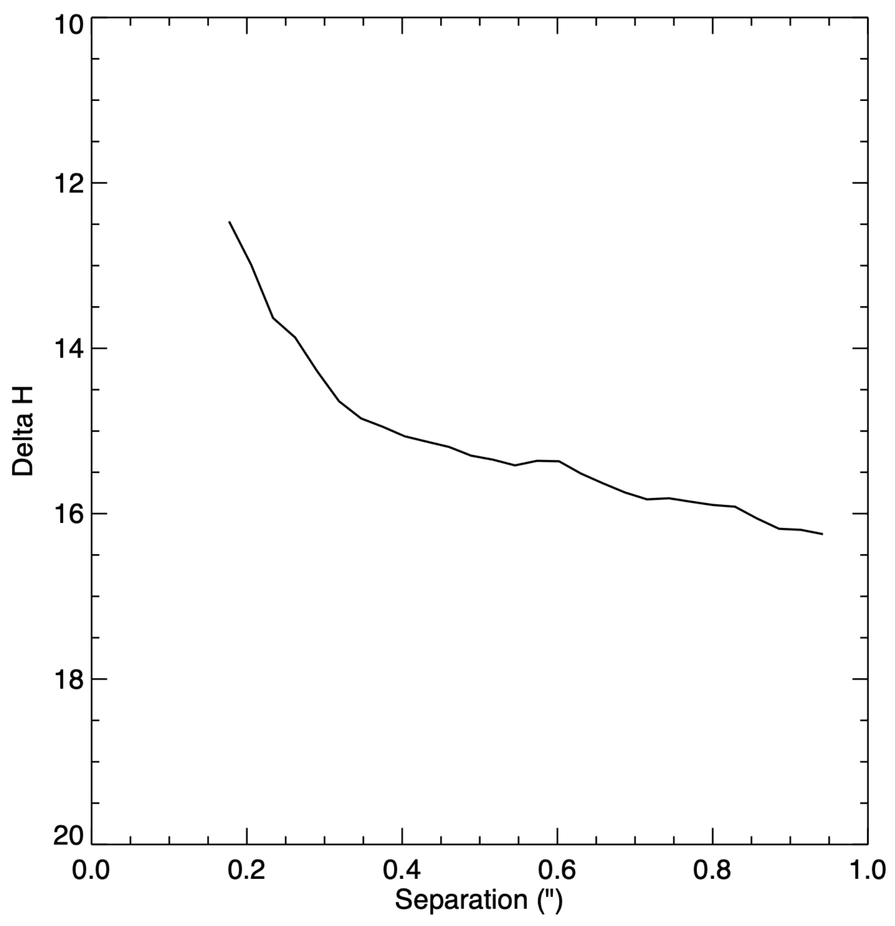
Ruffio et al. 2017

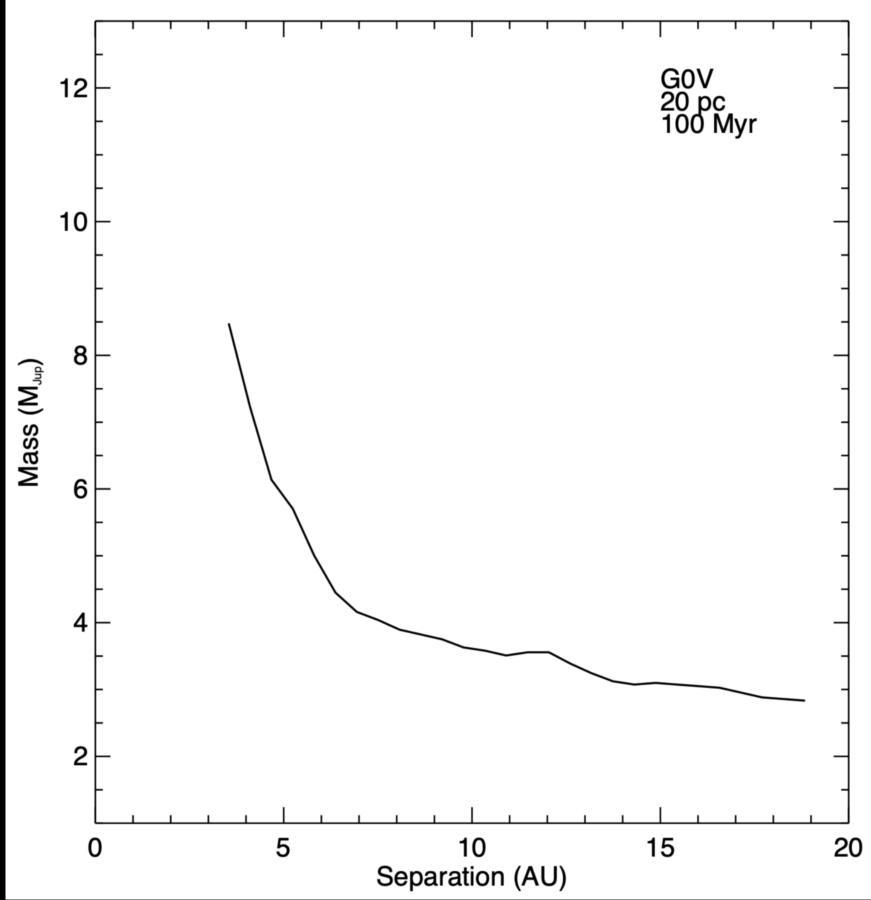
Contrast Curves and Stellar Properties

Contrast curves are delta-magnitude (or flux ratio) vs. projected separation in arcseconds

We use the star's absolute magnitude, the star's age, and evolutionary models (e.g. COND, Sonora, BT-Settl, etc) to convert to planet mass

We use the star's distance to convert to separation in AU

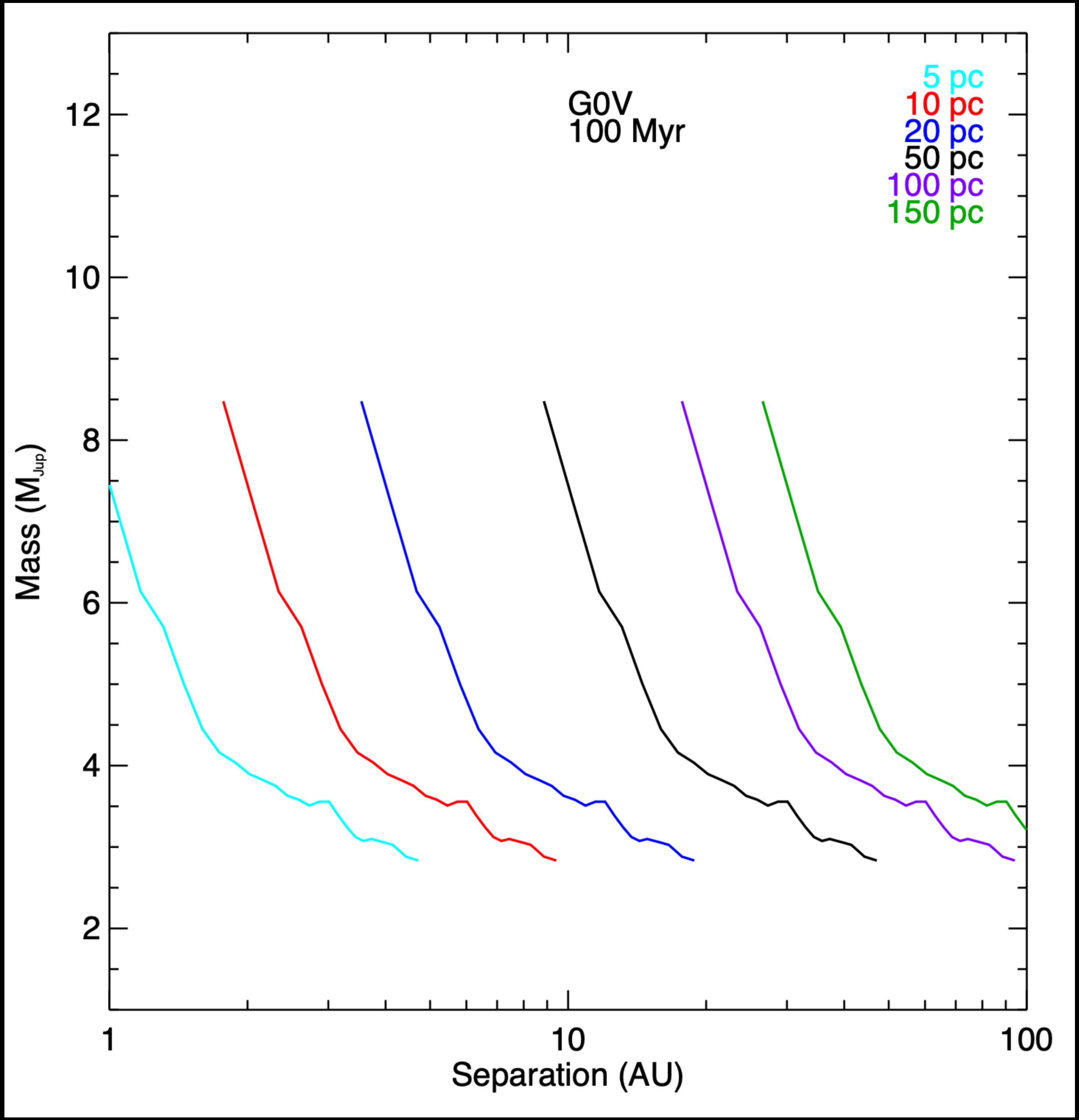




Contrast Curves and Distance

The same contrast curve reaches closer physical separations for closer stars

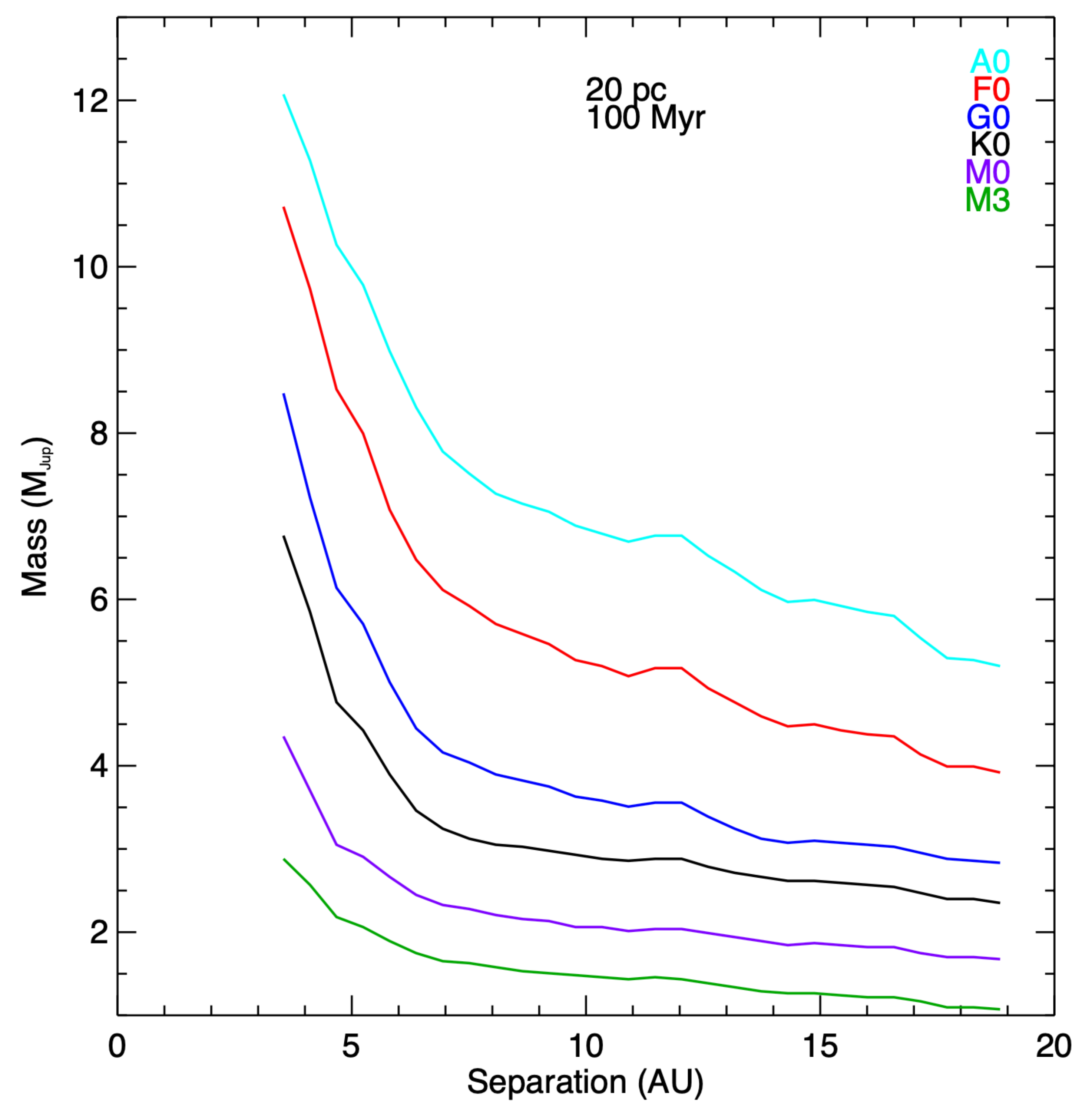
(Another effect: more distant stars have a fainter apparent magnitude, leading to worse AO performance and more significant read noise)



Contrast Curves and Spectral Type

Earlier-type stars are intrinsically brighter

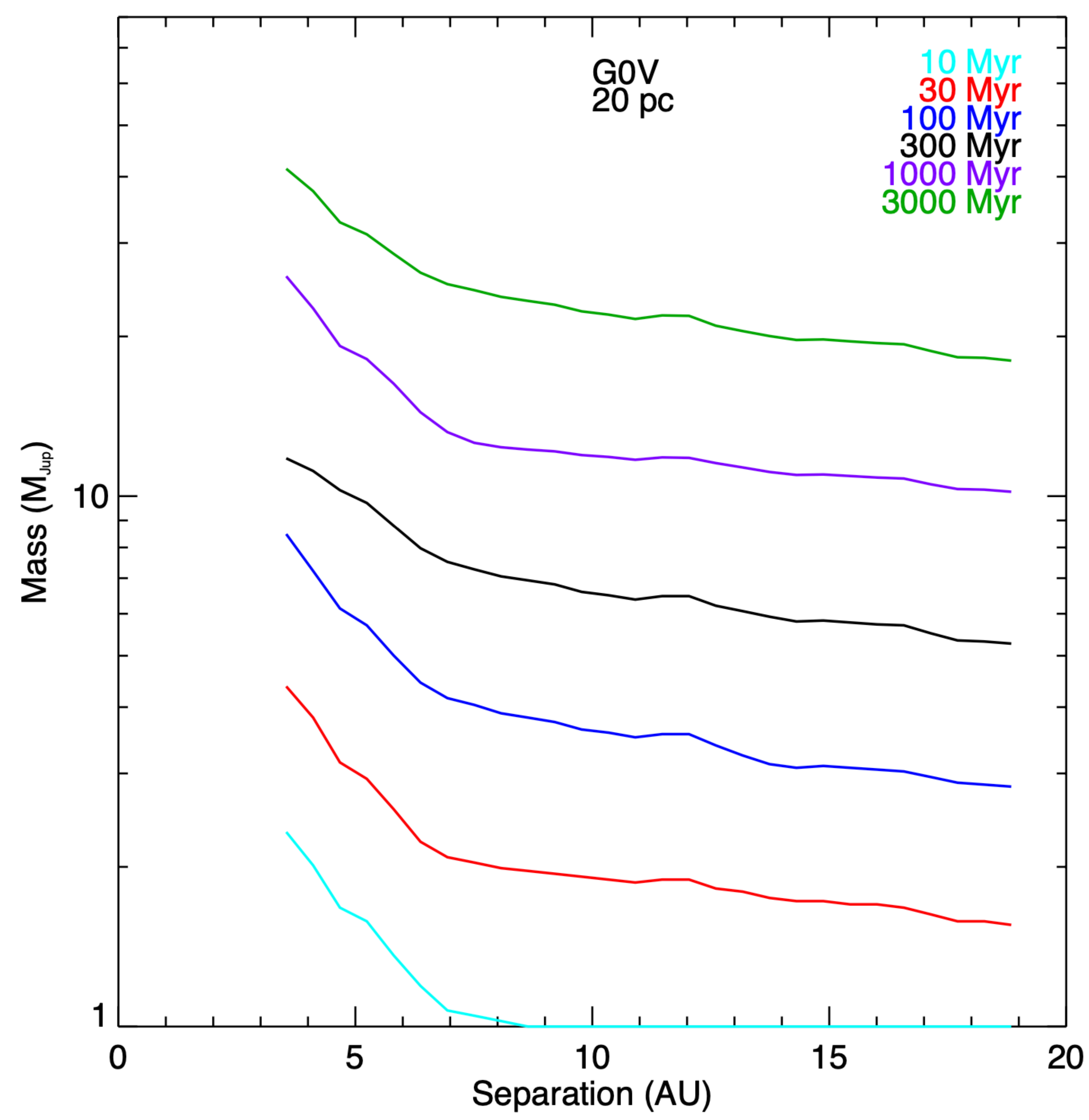
The same contrast curve will reach lower-mass planets for later-type stars



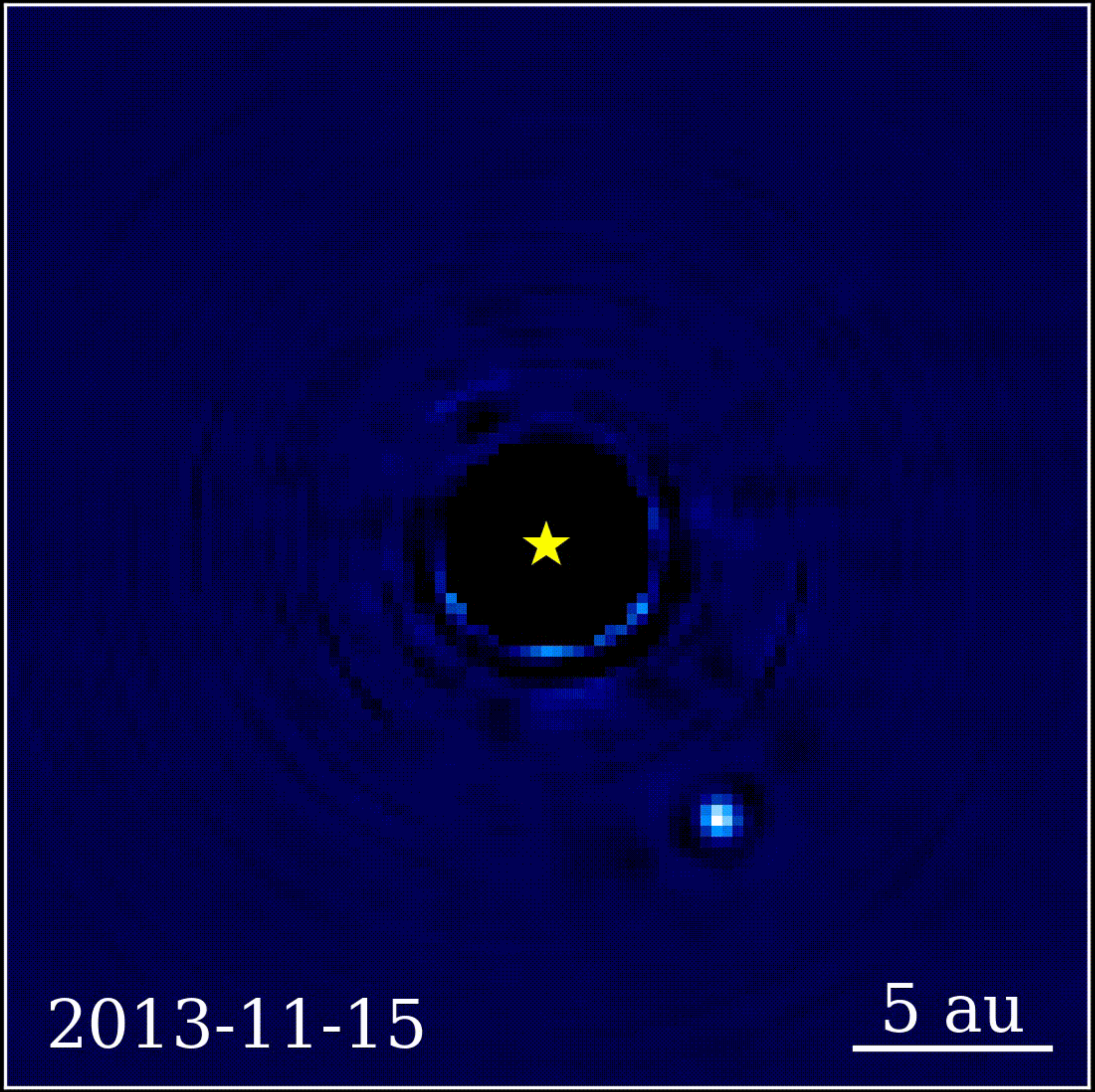
Contrast Curves and Age

Younger planets are brighter and easier to detect

The same contrast curve can detect Jupiter-mass planets around a younger star, and only brown dwarfs around an older star

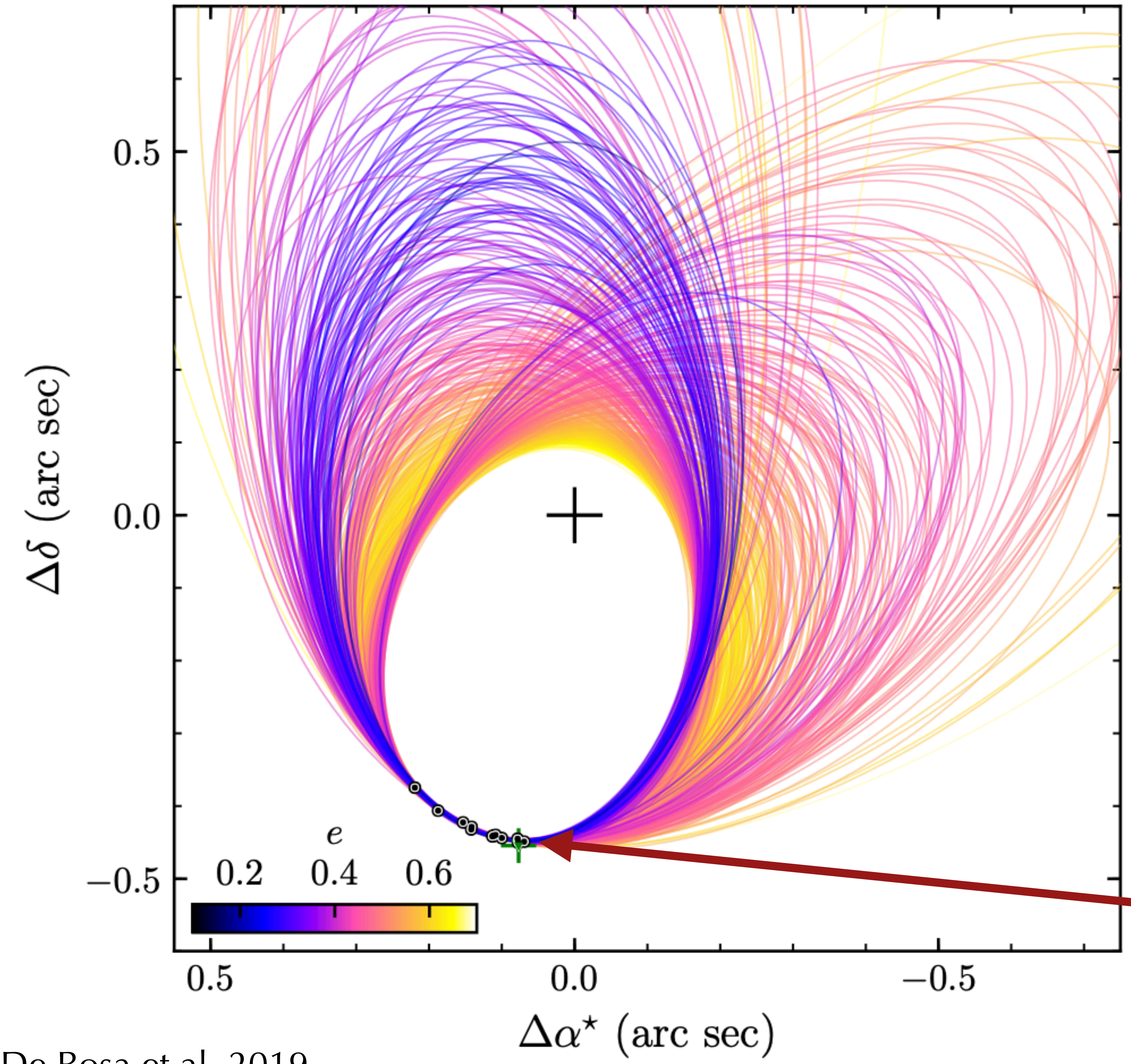


Separation and semi-major axis



Movie from Jason Wang

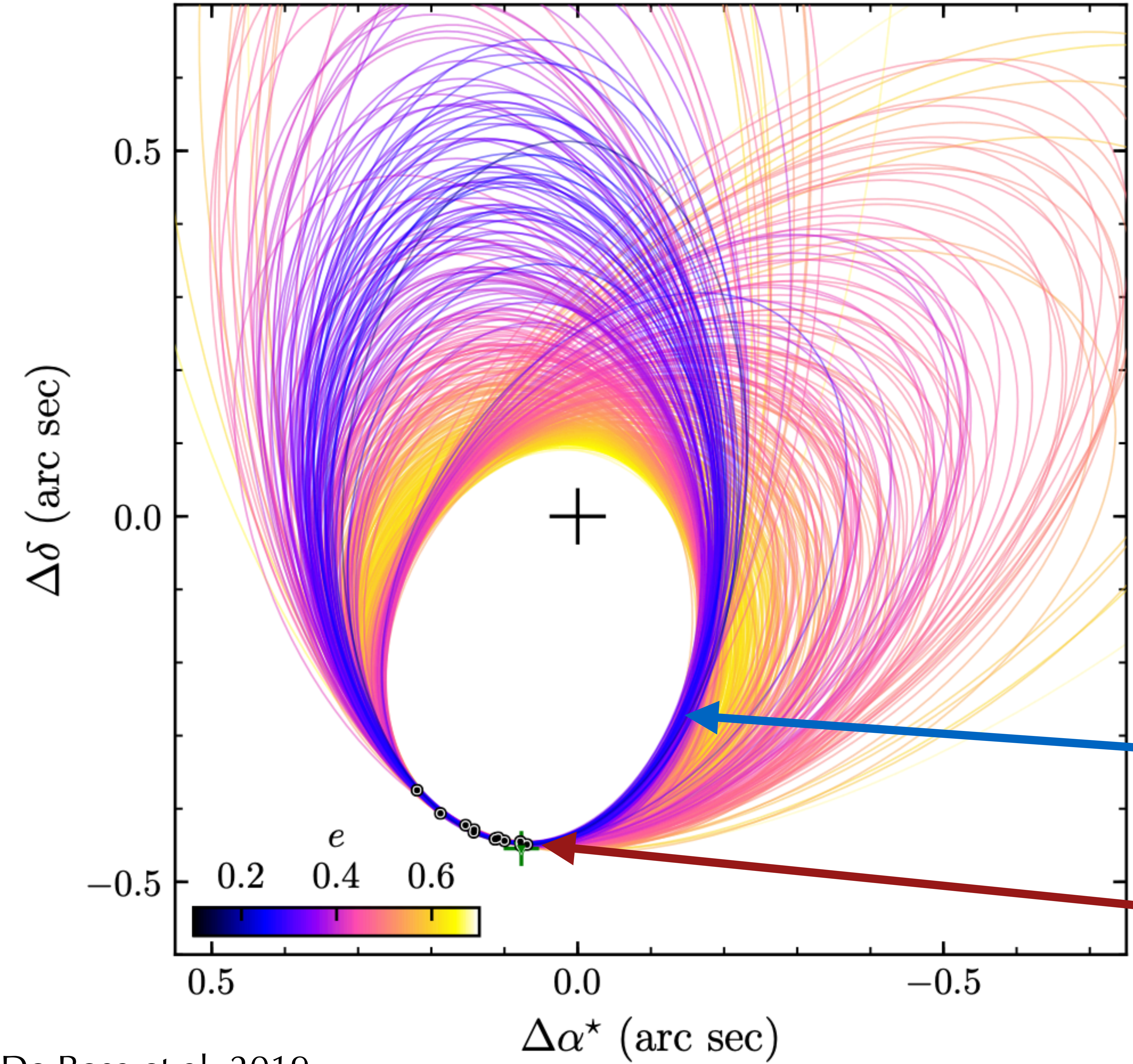
51 Eridani b and orbital completeness



2014: Detected by GPIES

De Rosa et al. 2019

51 Eridani b and orbital completeness

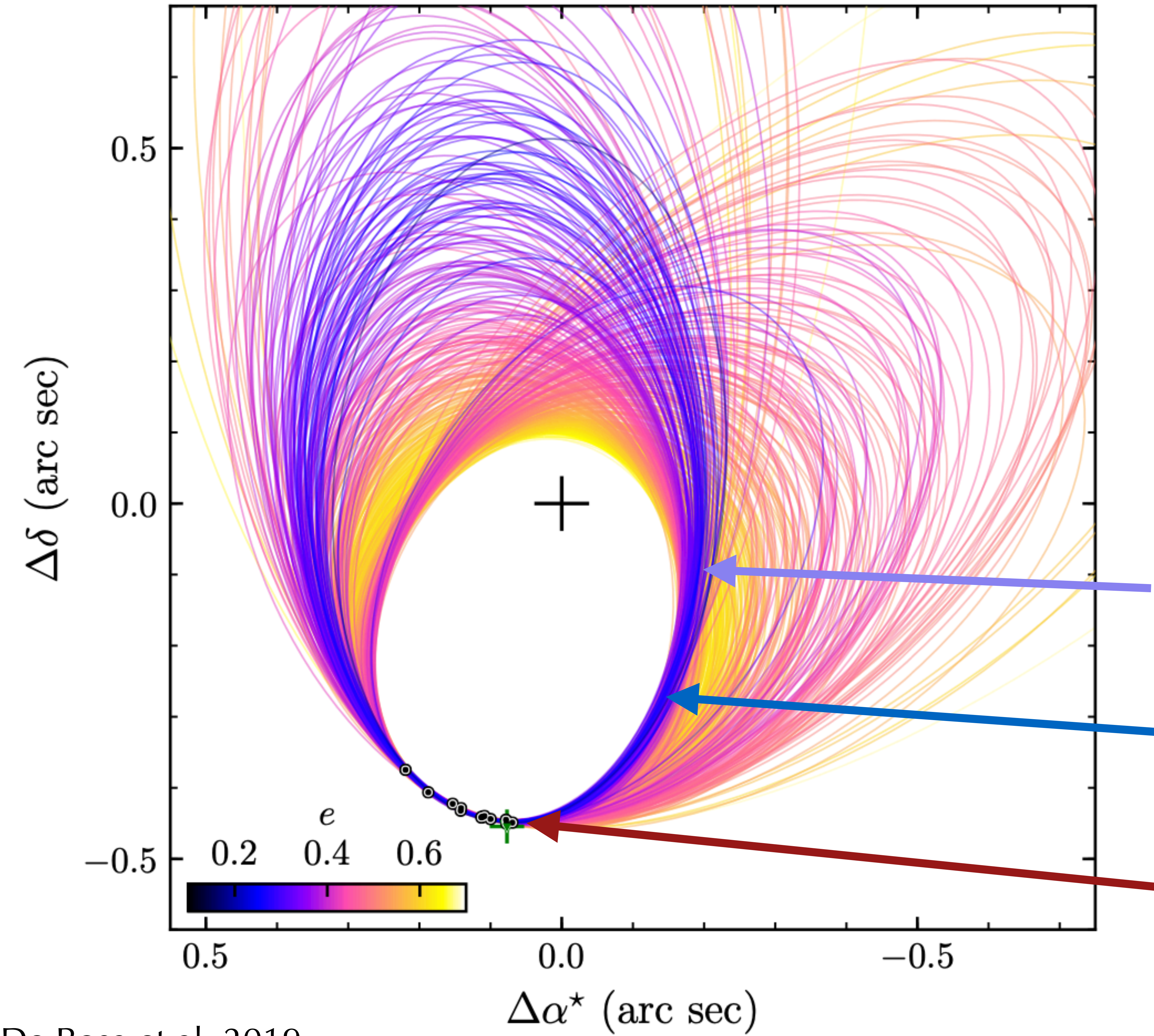


2011: Not detected by IDPS

2014: Detected by GPIES

De Rosa et al. 2019

51 Eridani b and orbital completeness



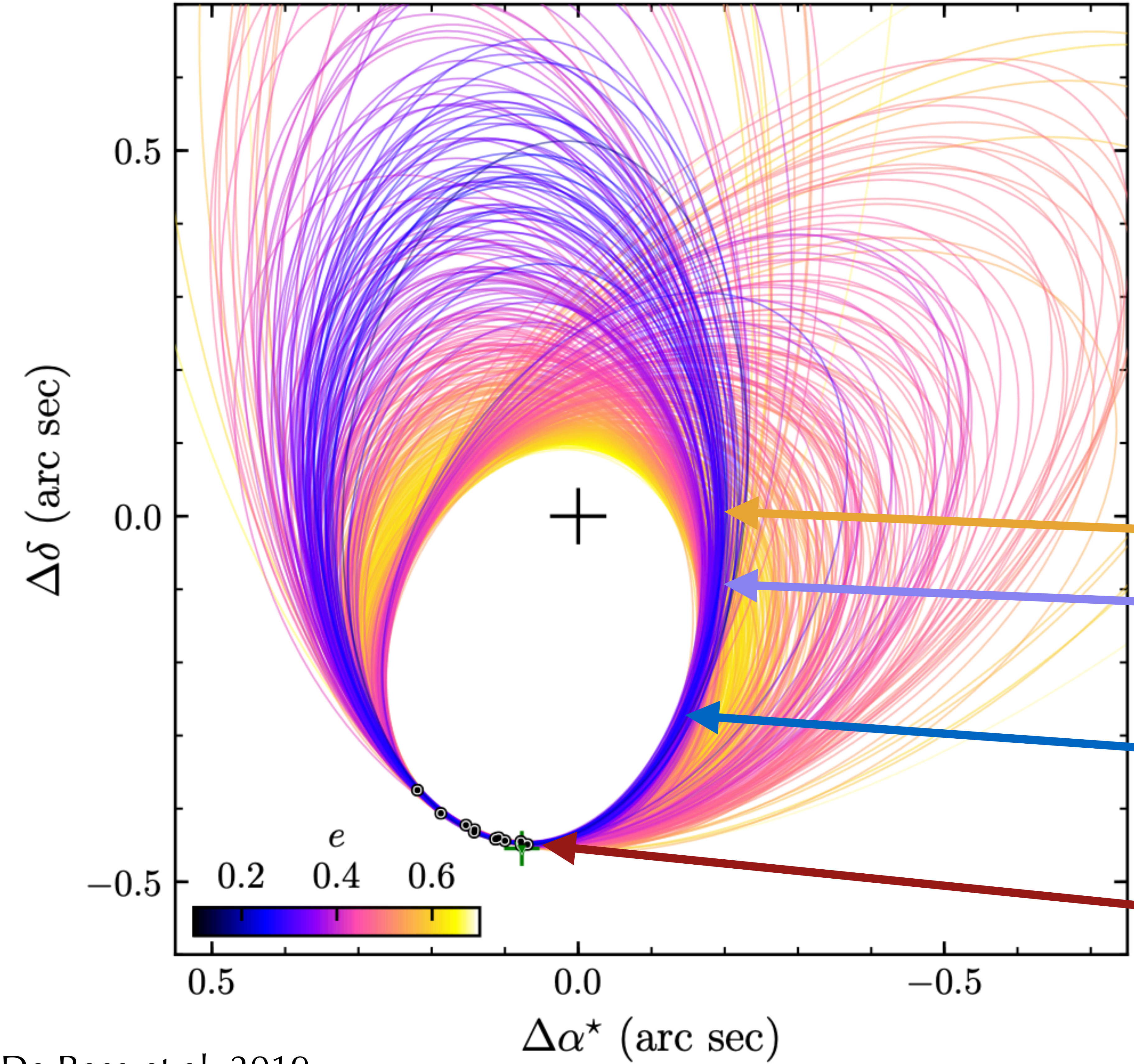
2008: Not detected by NICI

2011: Not detected by IDPS

2014: Detected by GPIES

De Rosa et al. 2019

51 Eridani b and orbital completeness



2006: Not detected by MMT

2008: Not detected by NICI

2011: Not detected by IDPS

2014: Detected by GPIES

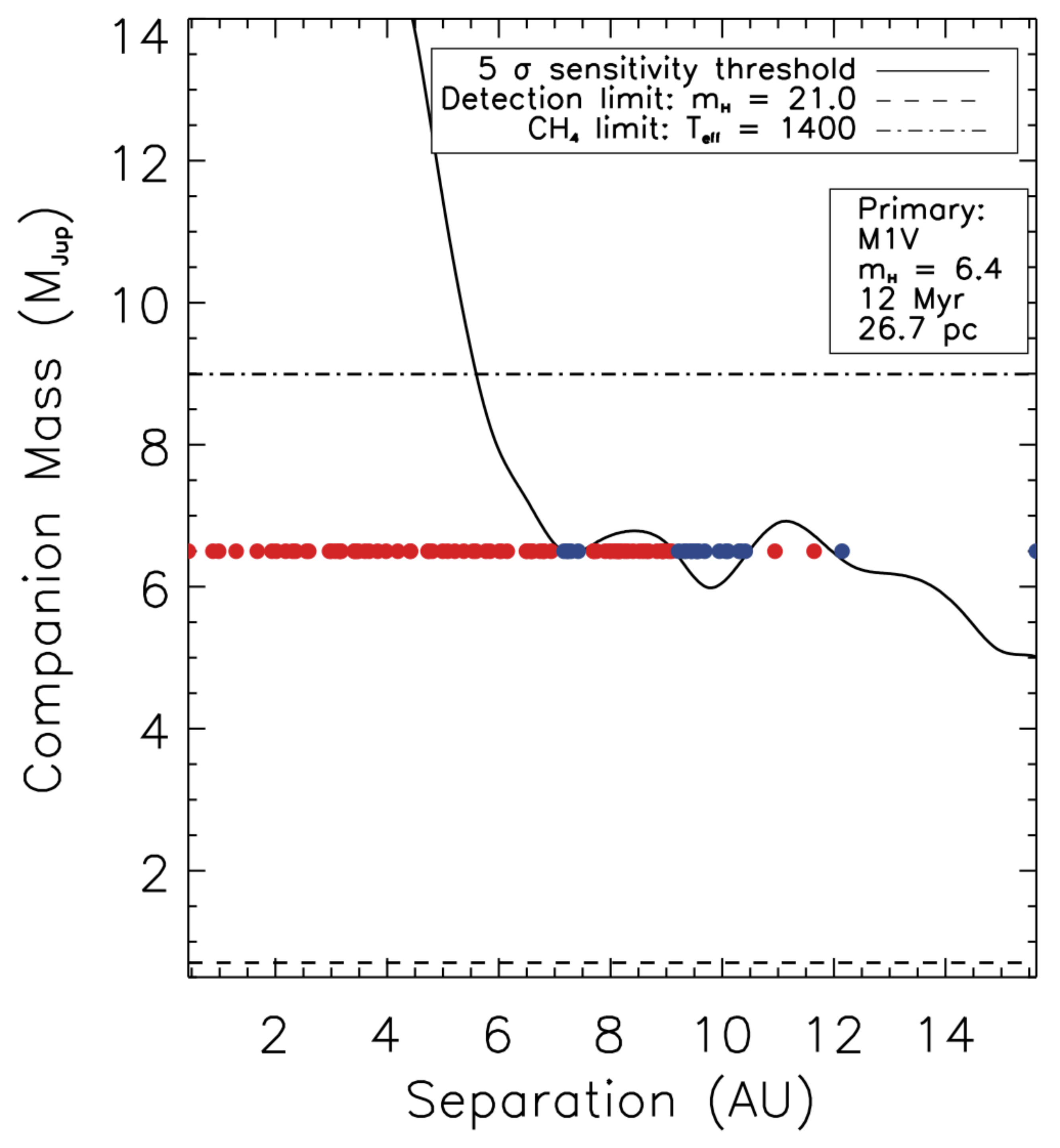
De Rosa et al. 2019

Orbital properties and completeness

Some planets may be missed while at an unfortunate orbital phase

Monte Carlo simulations (e.g. Nielsen et al. 2008, MESS: Bonavita et al. 2013) marginalize over orbital elements and phase

Completeness is the fraction of injected planets that lie above the contrast curve

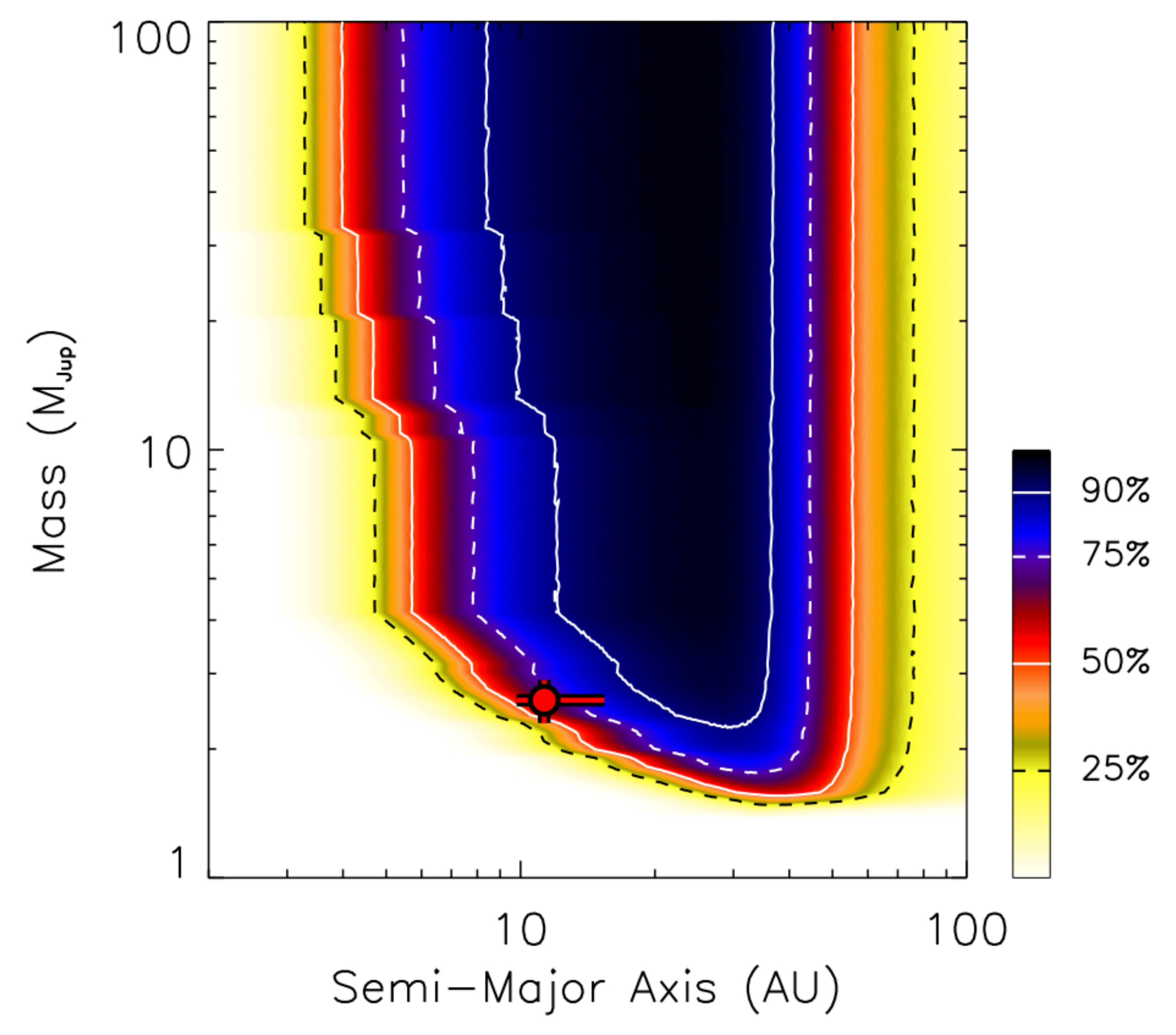


Nielsen et al. 2008

Completeness for a single star

Completeness maps: fraction of planets at a given mass and semi-major axis that could be detected

Can be generated for a single observation, or multiple observations at different epochs with different instruments (accounting for orbital motion)

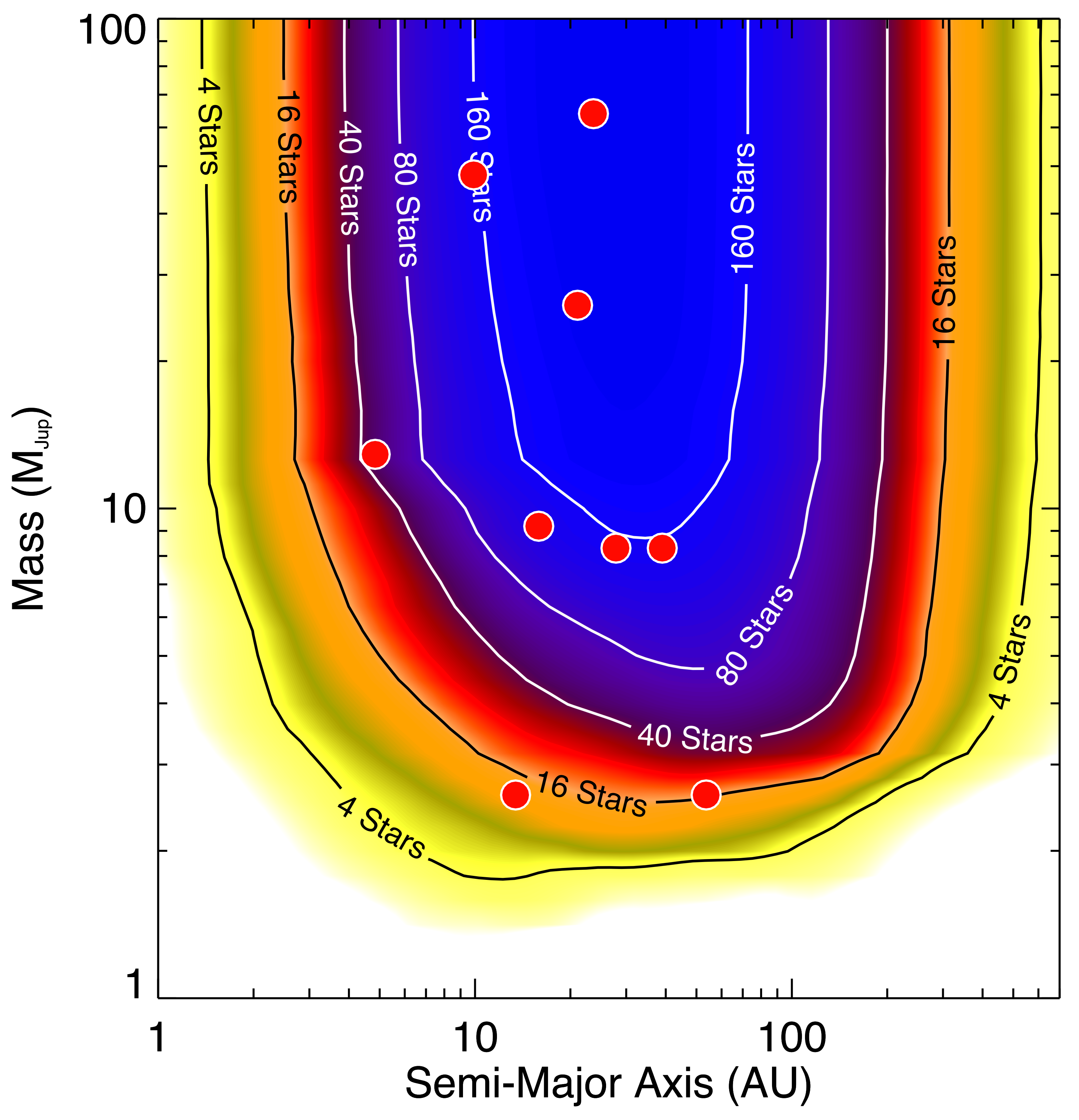


De Rosa et al. 2019

Depth of Search (Tongue Plots)

Completeness maps for all stars in a survey summed together

At a given location: the number of stars in the survey where a planet of that mass and semi-major axis could be detected



Demographics model fitting (one method)

Parameterized model for planet occurrence:

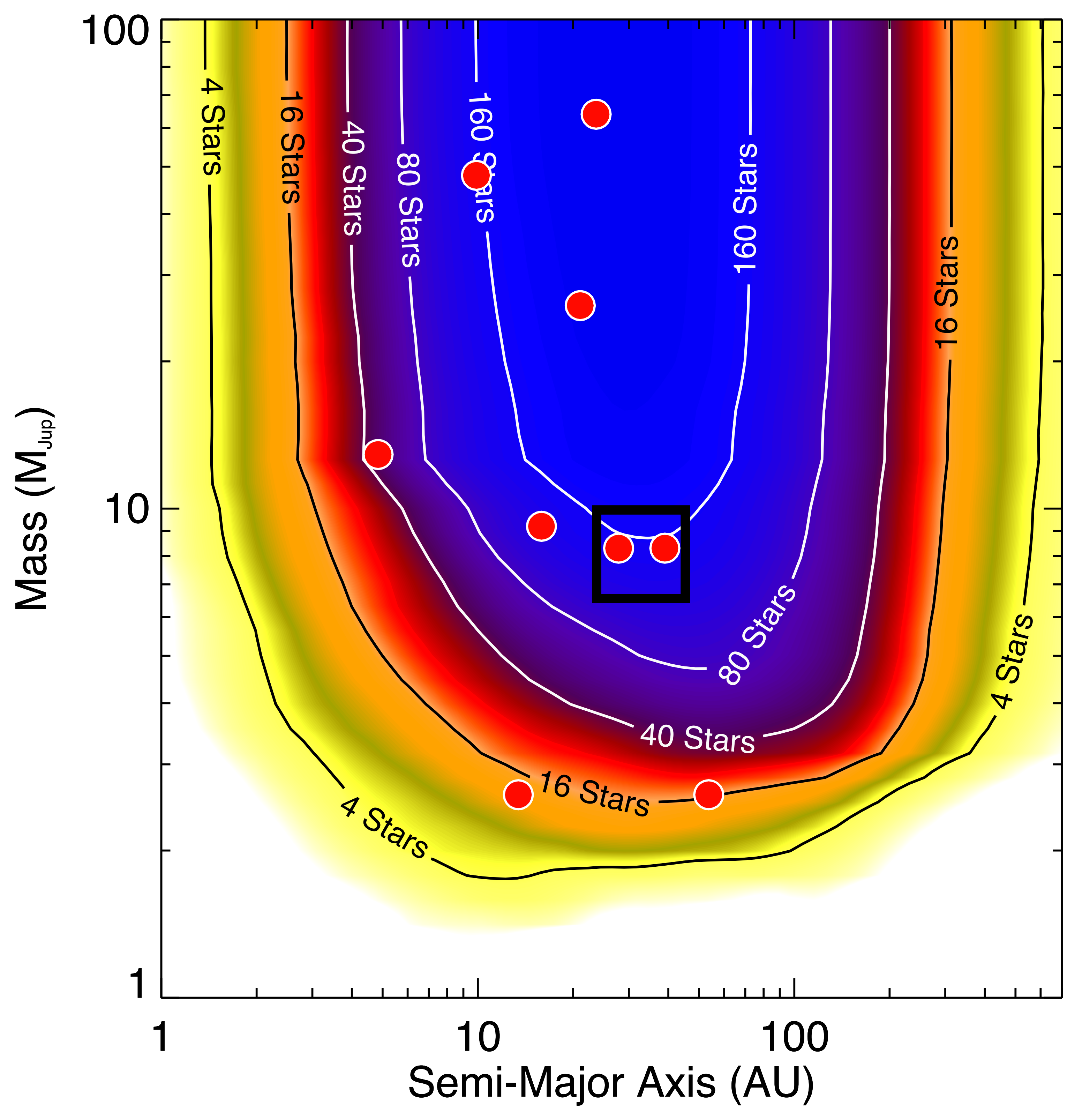
$$\frac{d^2N}{dm\,da} \propto f\, m^{\alpha}\, a^{\beta}$$

Poisson likelihood:

$$p(f,\alpha,\beta) = \frac{E^M e^{-E}}{M!}$$

Measured (M): Number of planets in a bin

Expected(E): Expected number of planets in that bin



Likelihood (one method)

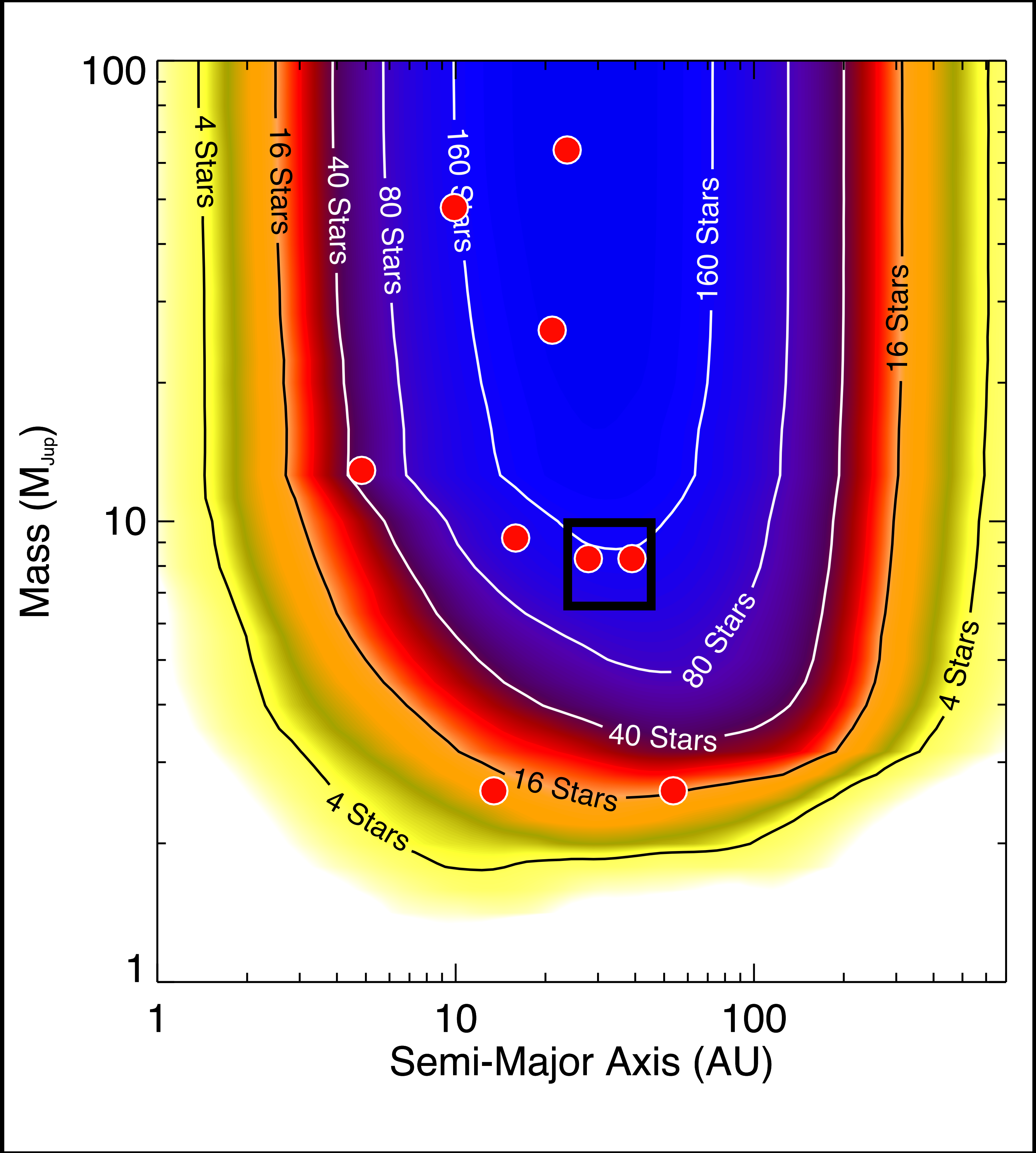
Poisson likelihood:

$$p(f, \alpha, \beta) = \frac{E^M e^{-E}}{M!}$$

$$E = N_* \int\int C(m, a) \frac{d^2N}{dm\, da} dm\, da$$

C(m,a): fractional completeness

N*: Number of stars in the survey

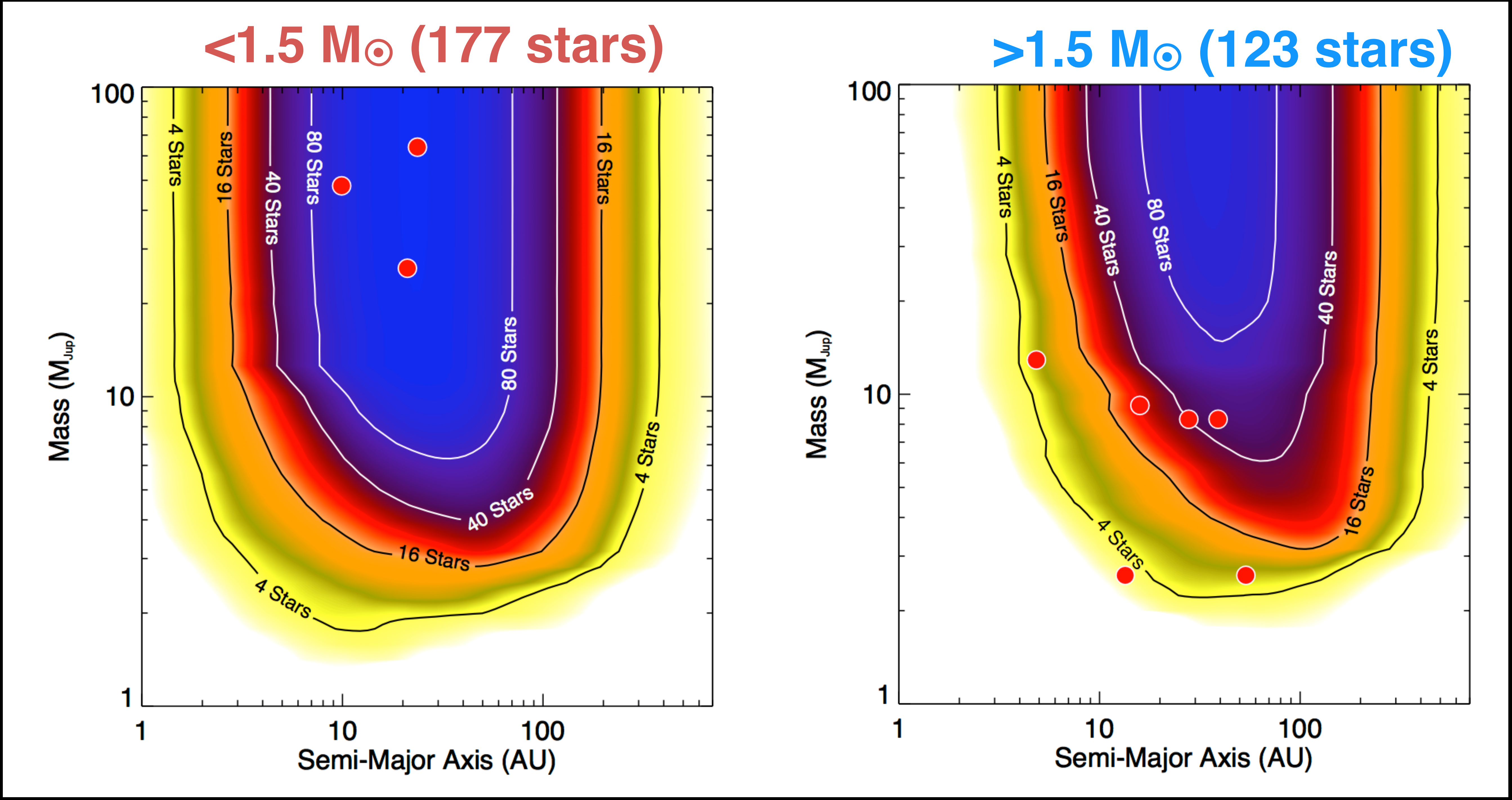


The Gemini Planet Imager Exoplanet Survey (GPIES)

The GPI team (a subset)

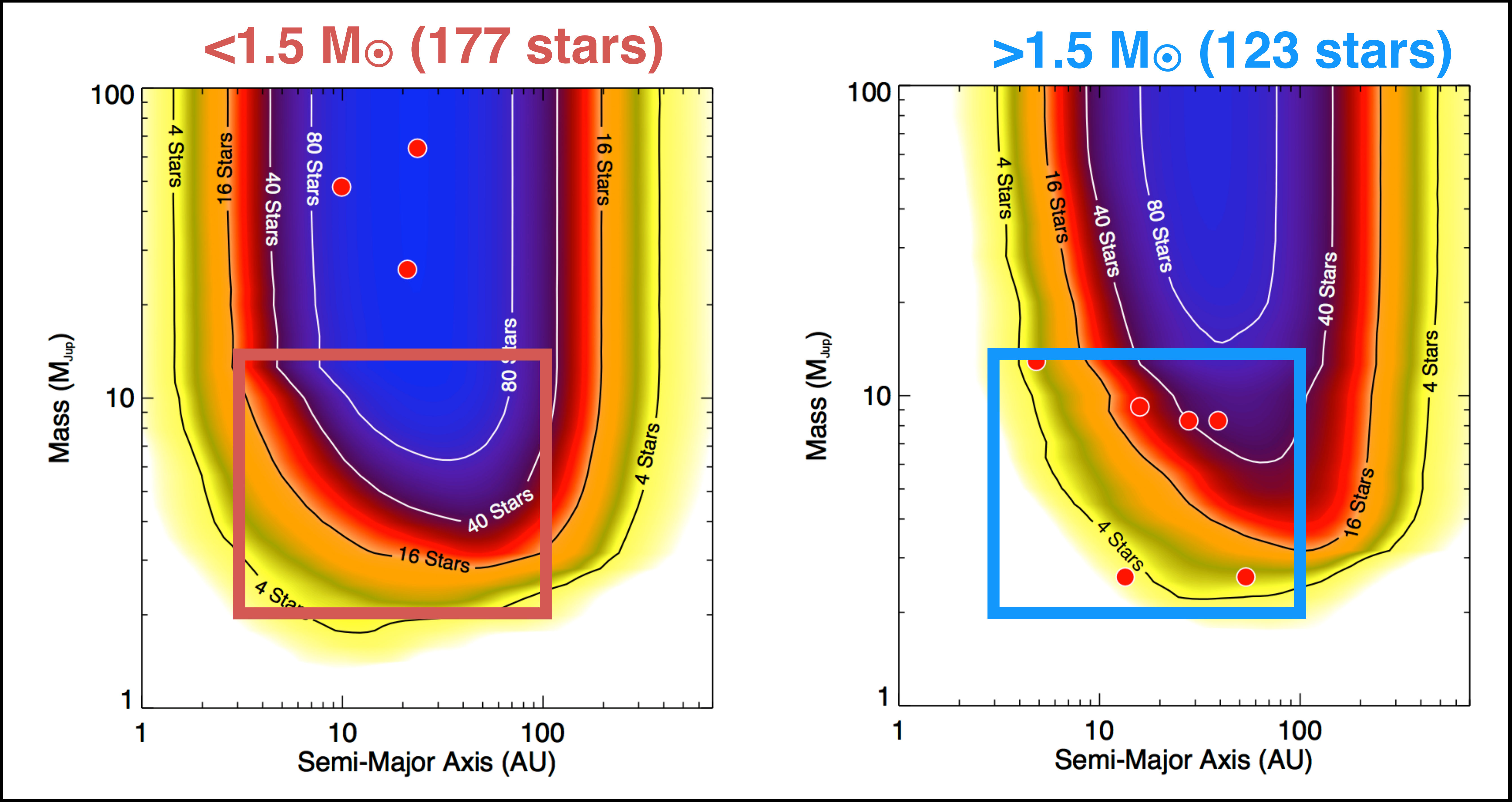
Jonathan Aguilar, S. Mark Ammons, Pauline Arriaga, Etienne Artigau, Vanessa Bailey, Travis Barman, Steve Beckwith, Sebastian Bruzzone, Joanna Bulger, Ben Burningham, Adam S. Burrows, Eric Cady, Christine Chen, Eugene Chiang, Jeffrey K. Chilcote, Rebekah I. Dawson, Robert J. De Rosa, Ruobing Dong, René Doyon, Zachary H. Draper, Gaspard Duchêne, Thomas M. Esposito, Daniel Fabrycky, Michael P. Fitzgerald, Katherine B. Follette, Jonathan J. Fortney, BJ Fulton, Benjamin Gerard, James R. Graham, Alexandra Z. Greenbaum, Pascale Hibon, Sasha Hinkley, Lea Hirsch, Justin Hom, Andrew Howard, Tara Hufford, Li-Wei Hung, Patrick Ingraham, Rebecca Jensen-Clem, Mara Johnson-Groh, Paul Kalas, Quinn Konopacky, David Lafreniere, James E. Larkin, Samantha Lawler, Eve Lee, Jinhee Lee, Michael Line, Bruce Macintosh, Jerome Maire, Franck Marchis, Mark S. Marley, Christian Marois, Brenda C. Matthews, Stanimir Metchev, Max Millar-Blanchaer, Caroline V. Morley, Katie M. Morzinski, Ruth Murray-Clay, Eric L. Nielsen, Andrew Norton, Rebecca Oppenheimer, David W. Palmer, Rahul Patel, Jenny Patience, Marshall D. Perrin, Charles Poteet, Lisa A. Poyneer, Laurent Pueyo, Roman R. Rafikov, Abhijith Rajan, Julien Rameau, Fredrik T. Rantakyrö, Emily Rice, Malena Rice, Patricio Rojo, Jean-Baptiste Ruffio, M. T. Ruiz, Dominic Ryan, Maissa Salama, Didier Saumon, Dmitry Savransky, Adam C. Schneider, Jacob Shapiro, Anand Sivaramakrishnan, Inseok Song, Rémi Soummer, Sandrine Thomas, Gautam Vasisht, David Vega, J. Kent Wallace, Jason J. Wang, Kimberly Ward-Duong, Sloane J. Wiktorowicz, Schuyler G. Wolff, Joe Zalesky, Ben Zuckerman

A stellar mass/giant planet occurrence correlation



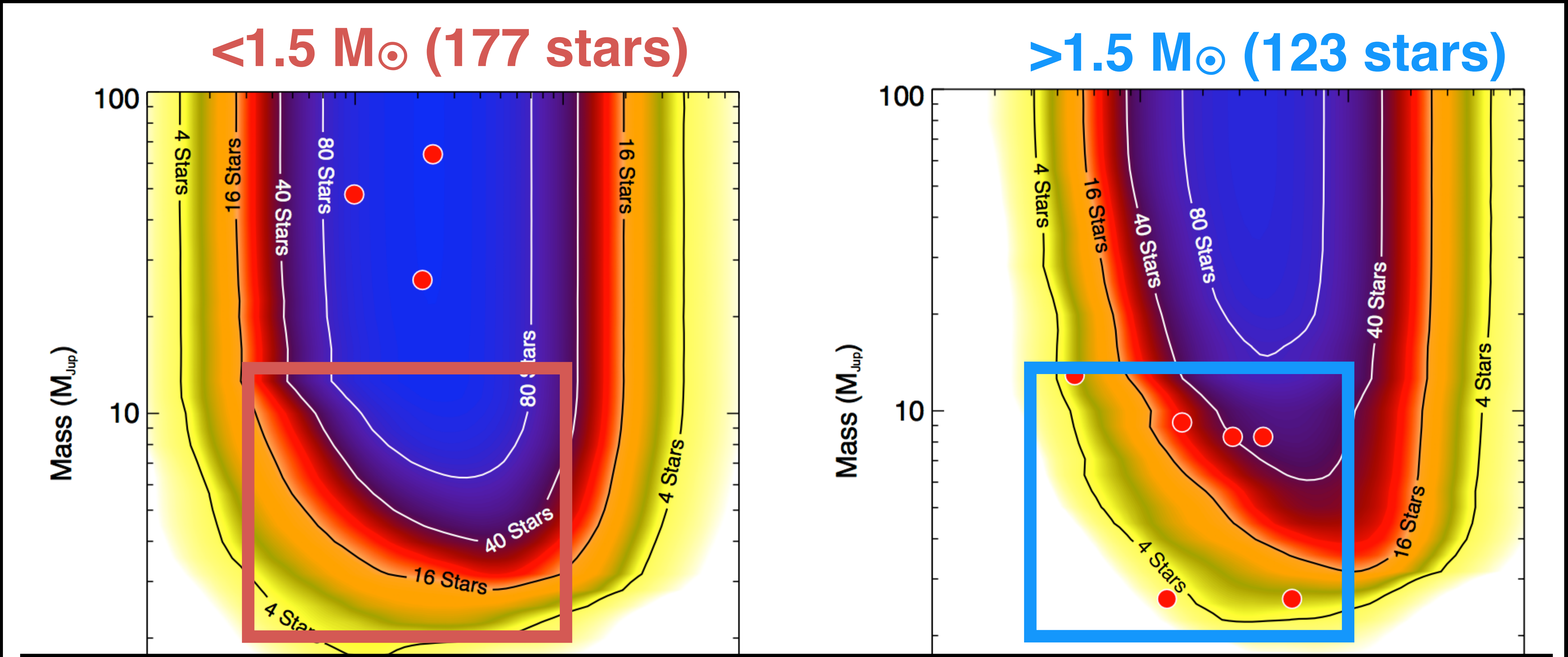
Nielsen et al. 2019

A stellar mass/giant planet occurrence correlation



Nielsen et al. 2019

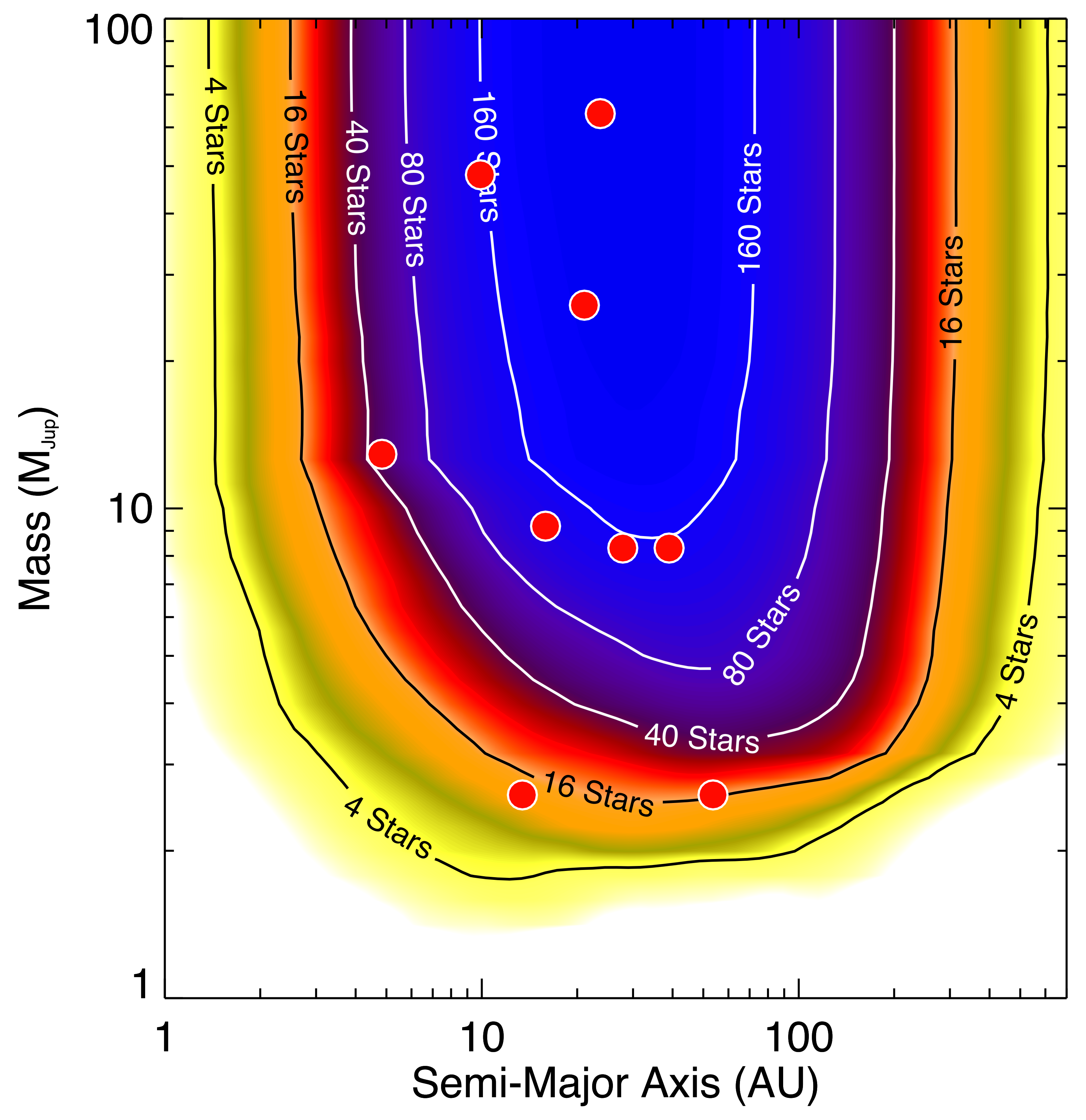
A stellar mass/giant planet occurrence correlation



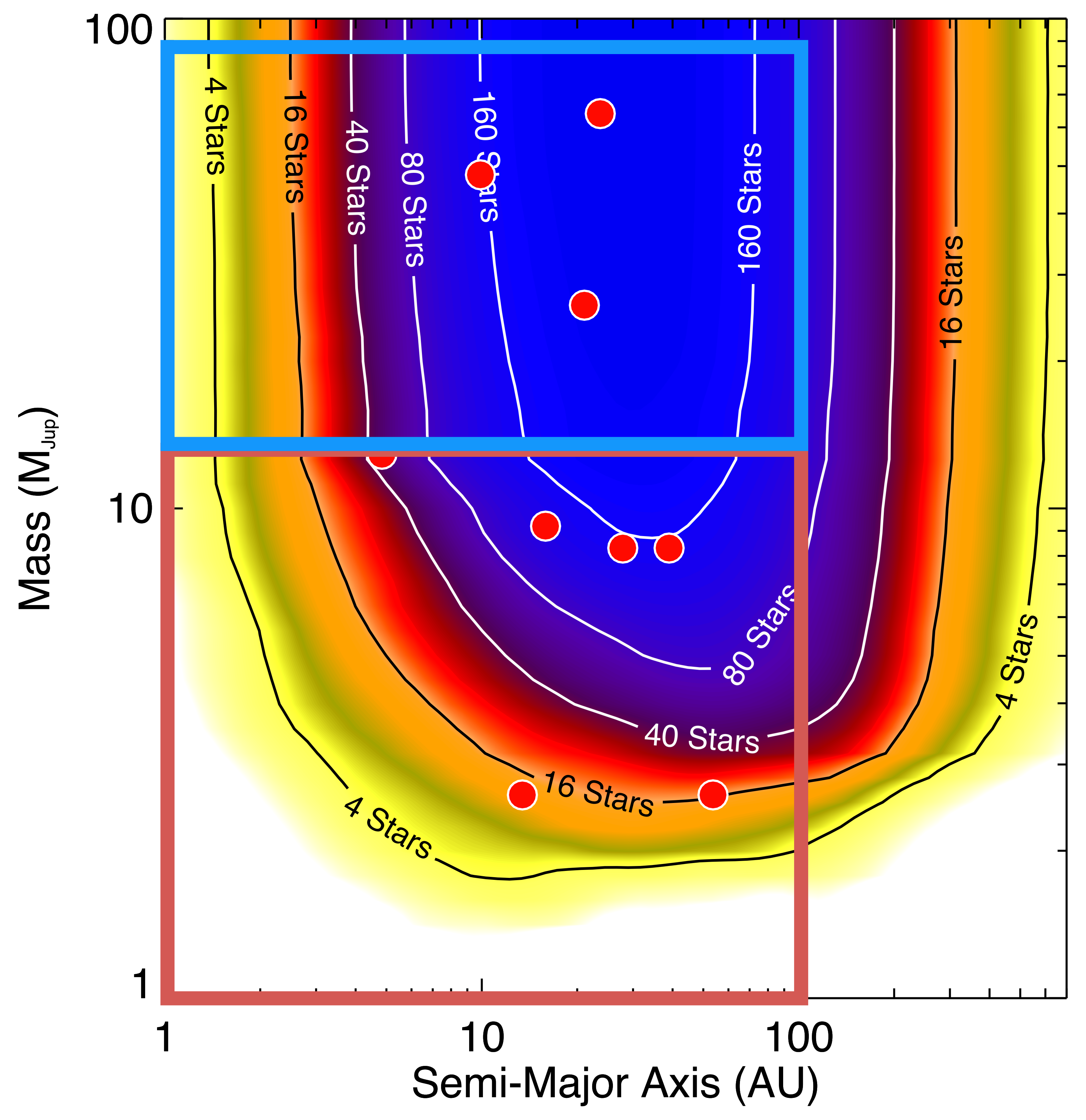
Conclusion 1: wide-separation giant planets are more common around higher-mass stars

Nielsen et al. 2019

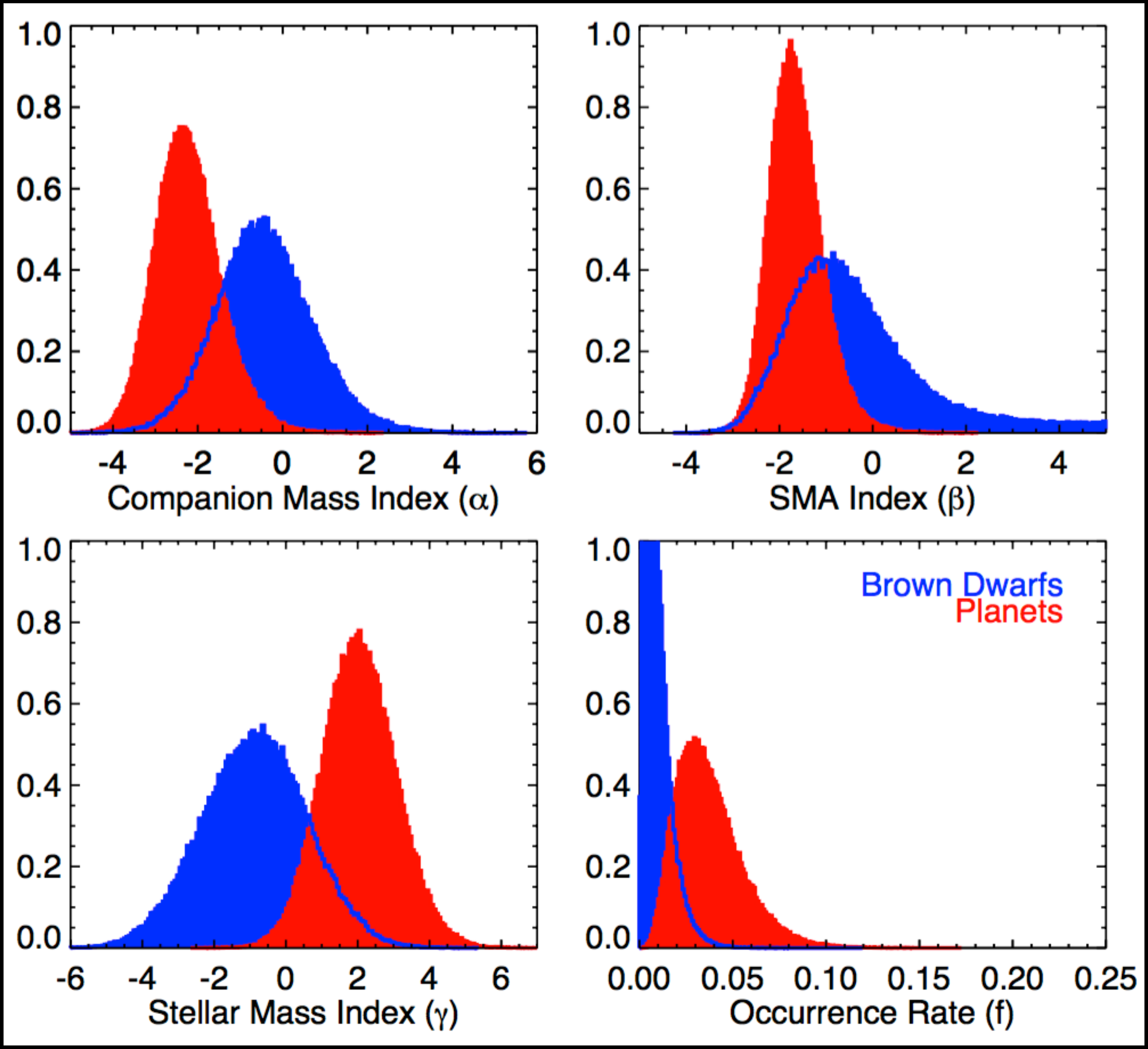
Planets and brown dwarfs



Planets and brown dwarfs

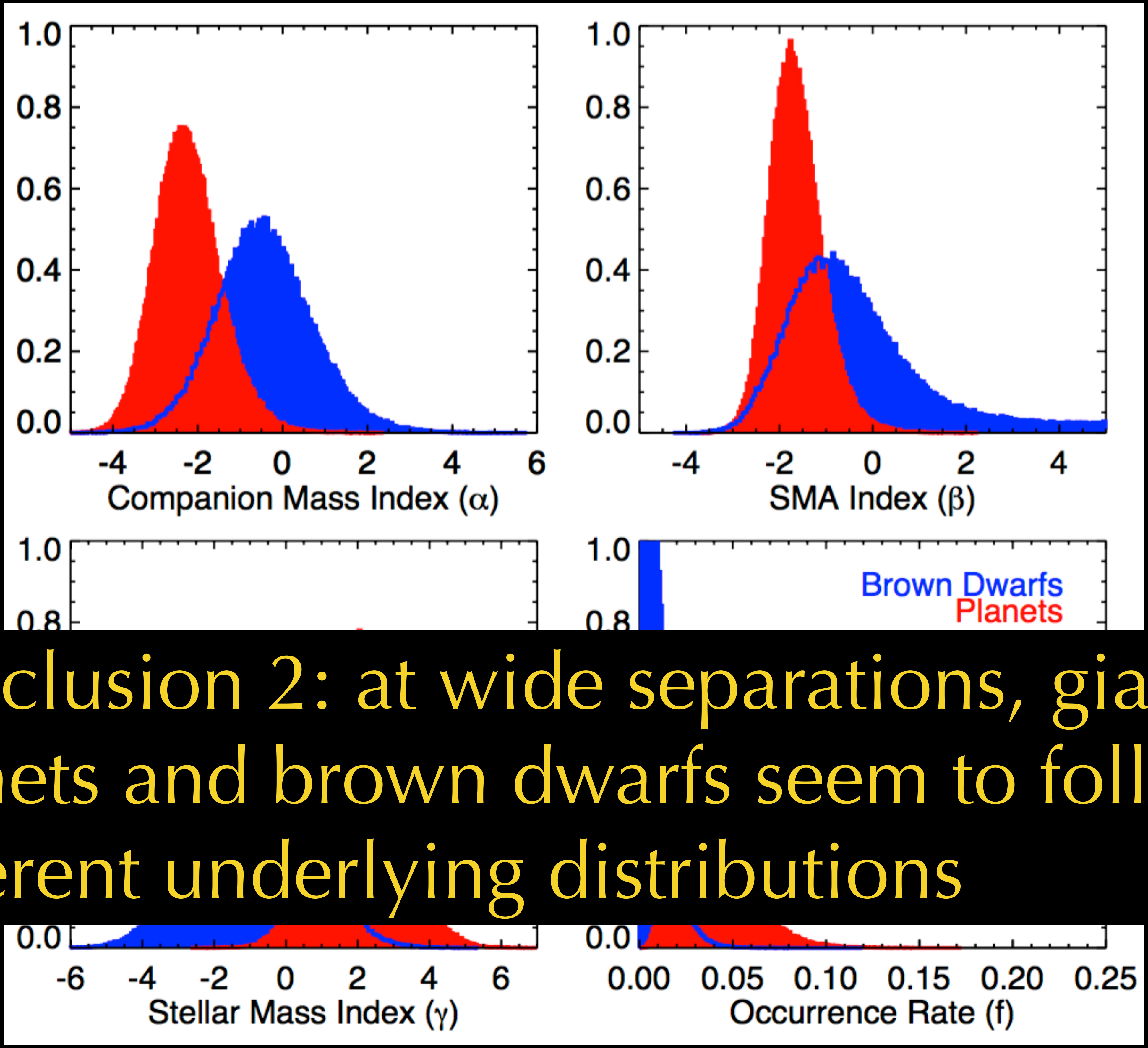


Planets and brown dwarfs



Nielsen et al. 2019

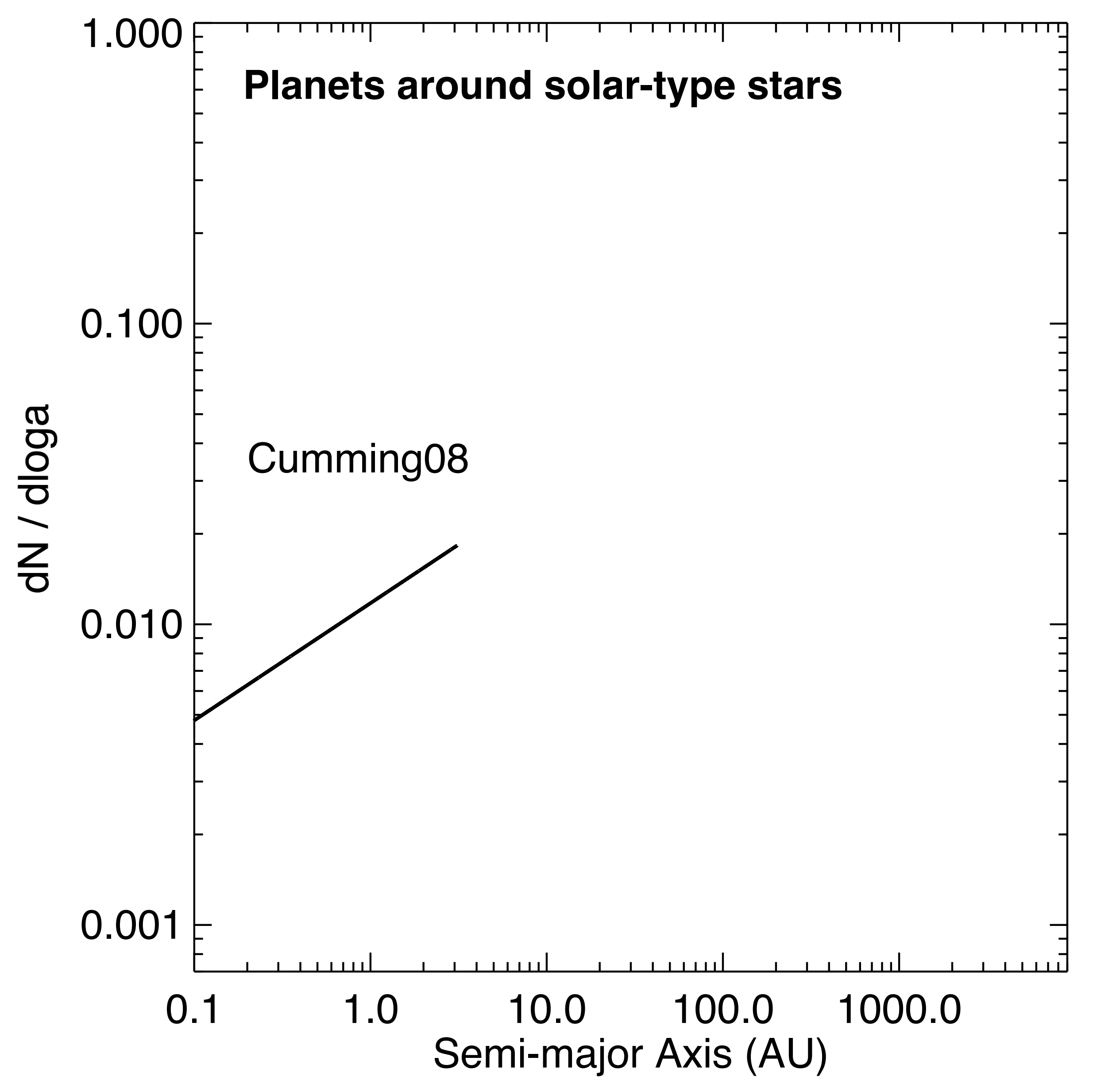
Planets and brown dwarfs



Conclusion 2: at wide separations, giant planets and brown dwarfs seem to follow different underlying distributions

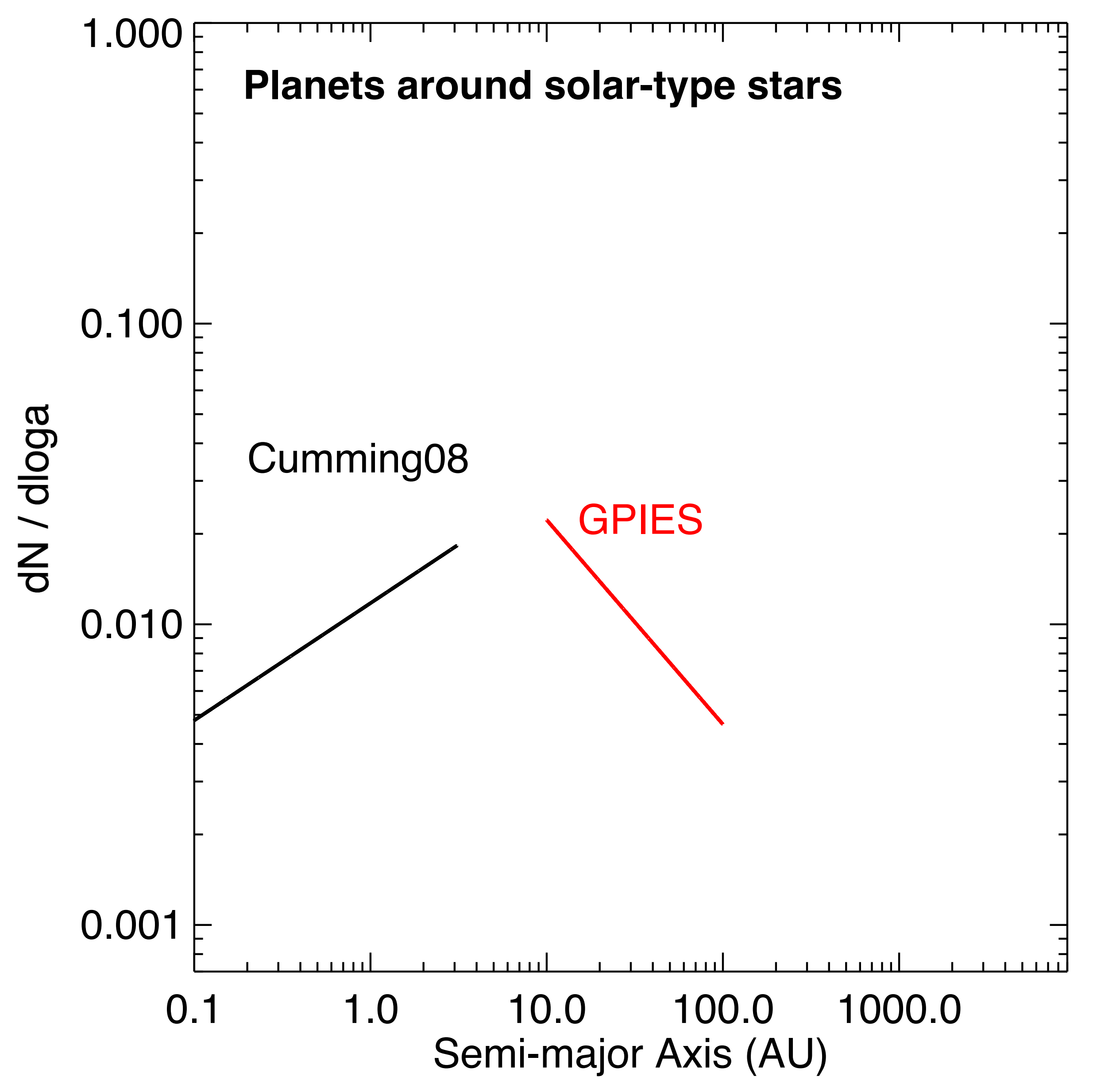
Nielsen et al. 2019

Giant planets demographics vs. semi-major axis



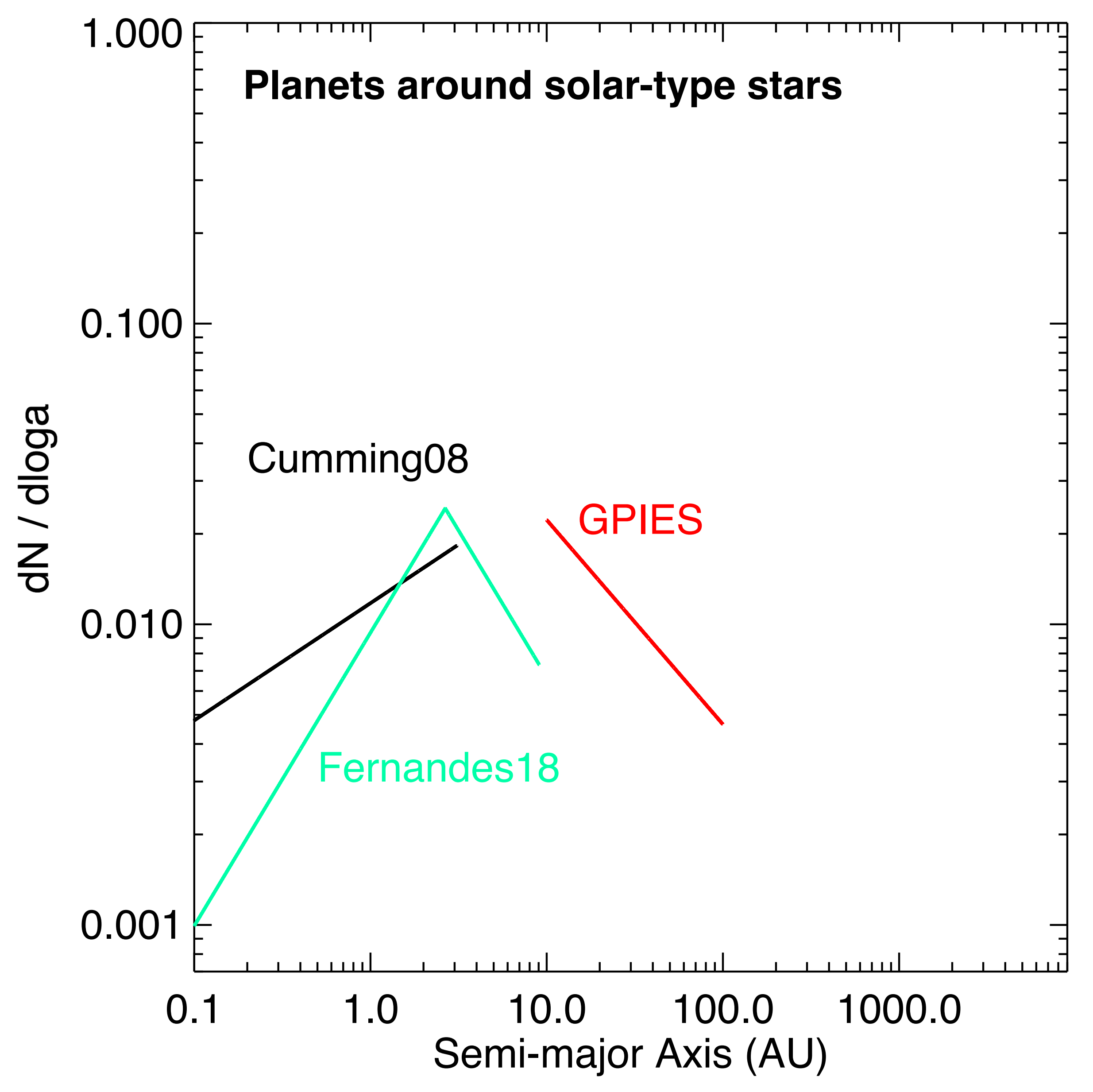
Nielsen et al. 2019

Giant planets demographics vs. semi-major axis



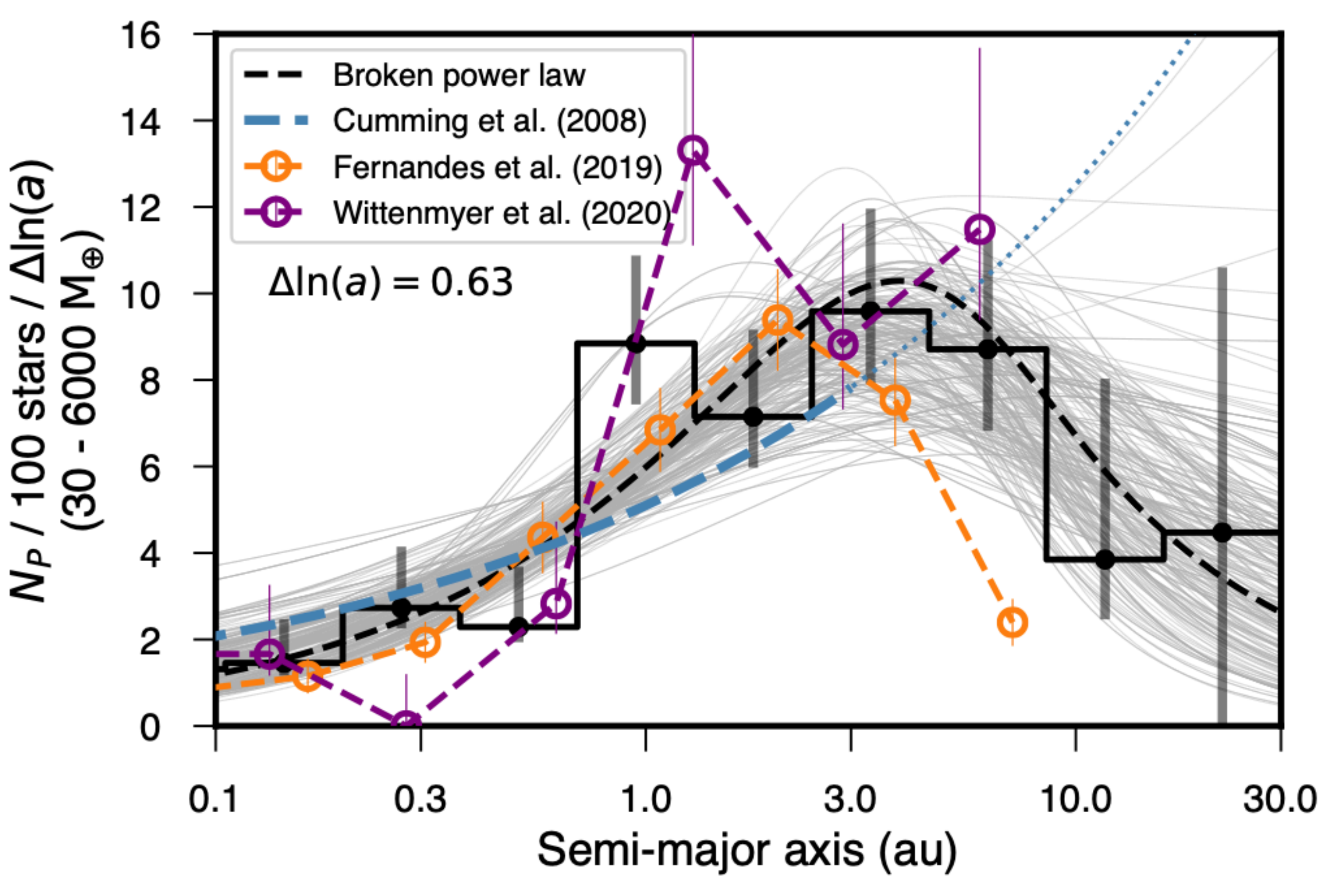
Nielsen et al. 2019

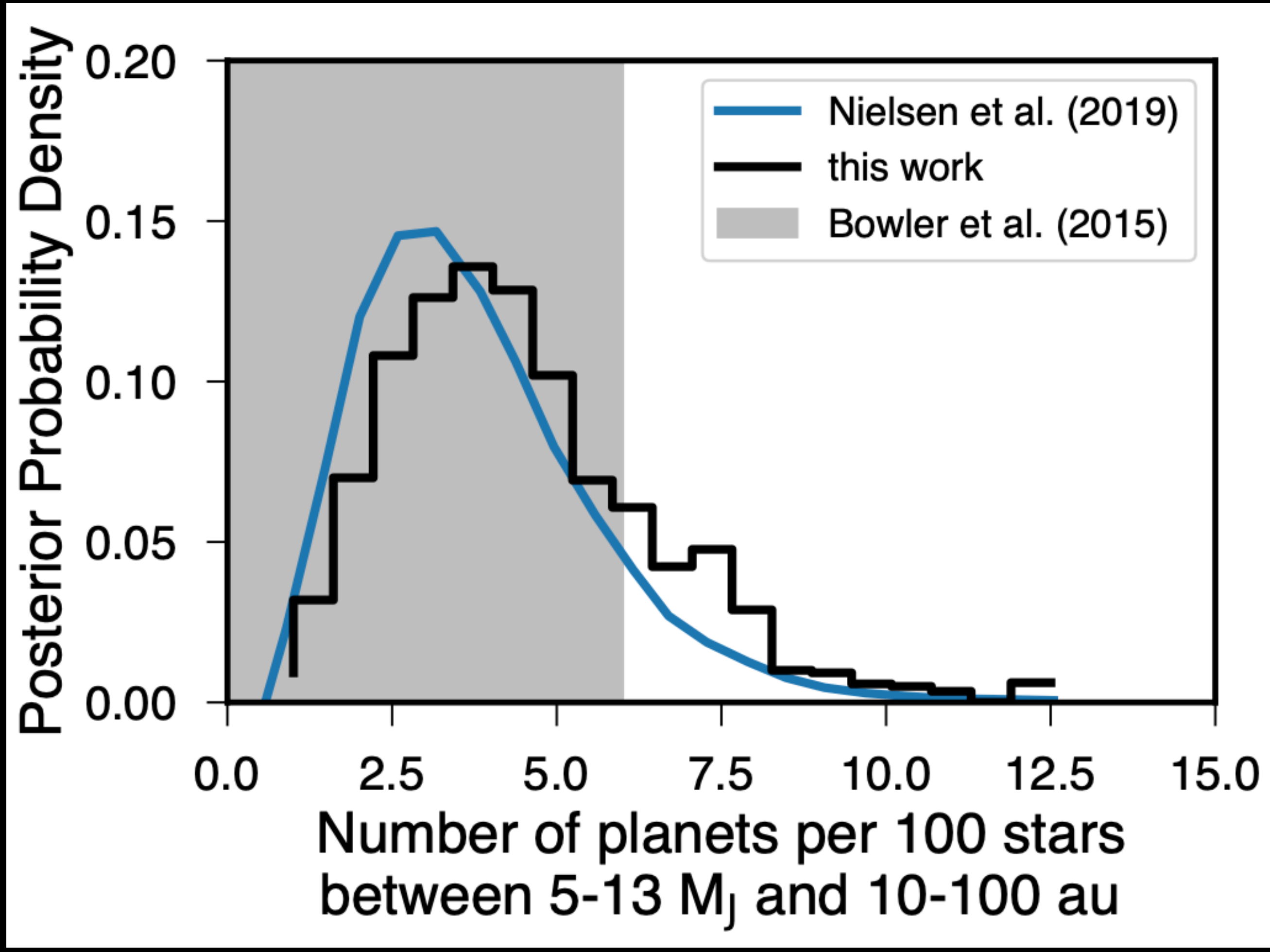
Giant planets demographics vs. semi-major axis



Nielsen et al. 2019

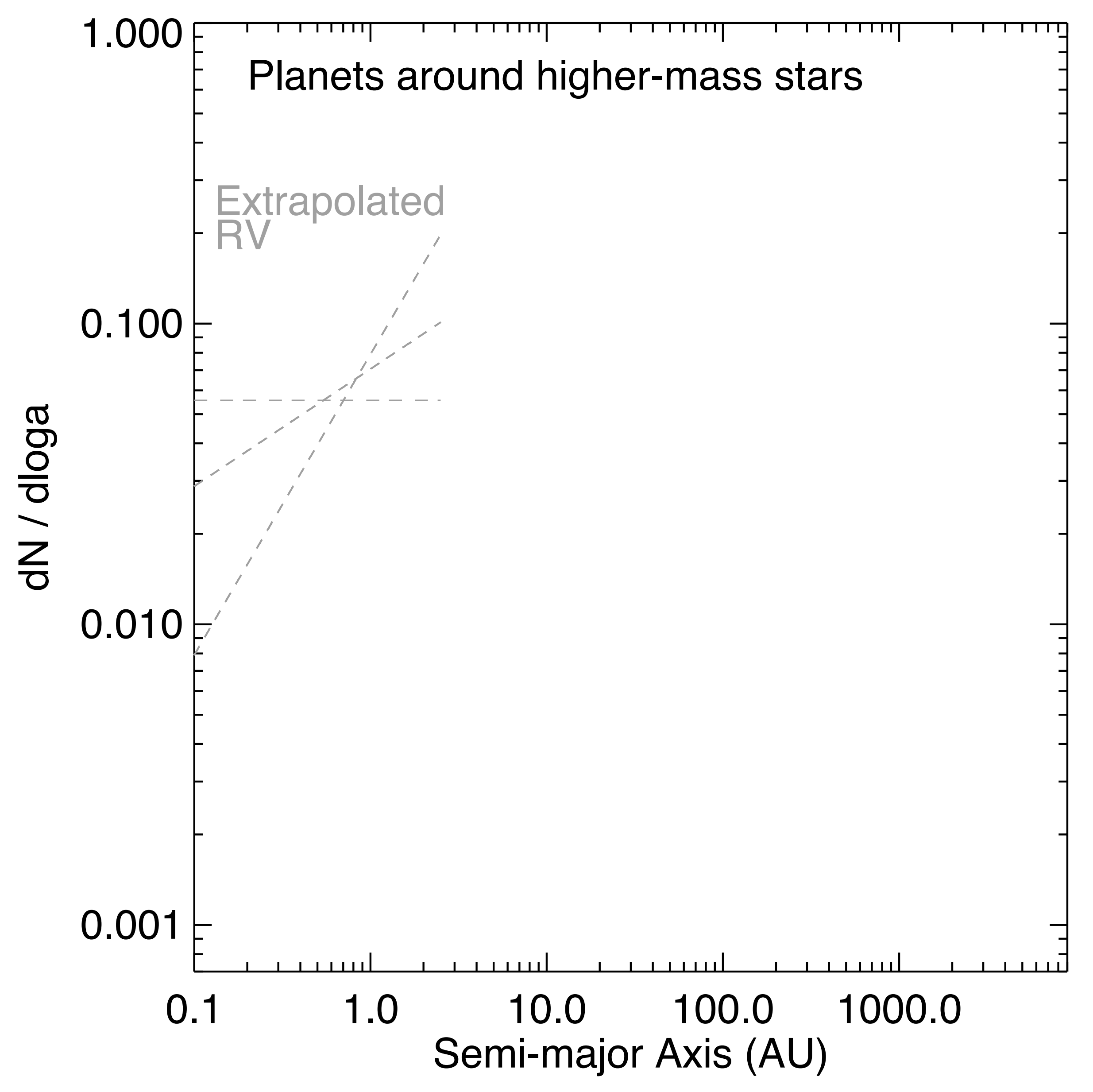
Giant planets demographics vs. semi-major axis





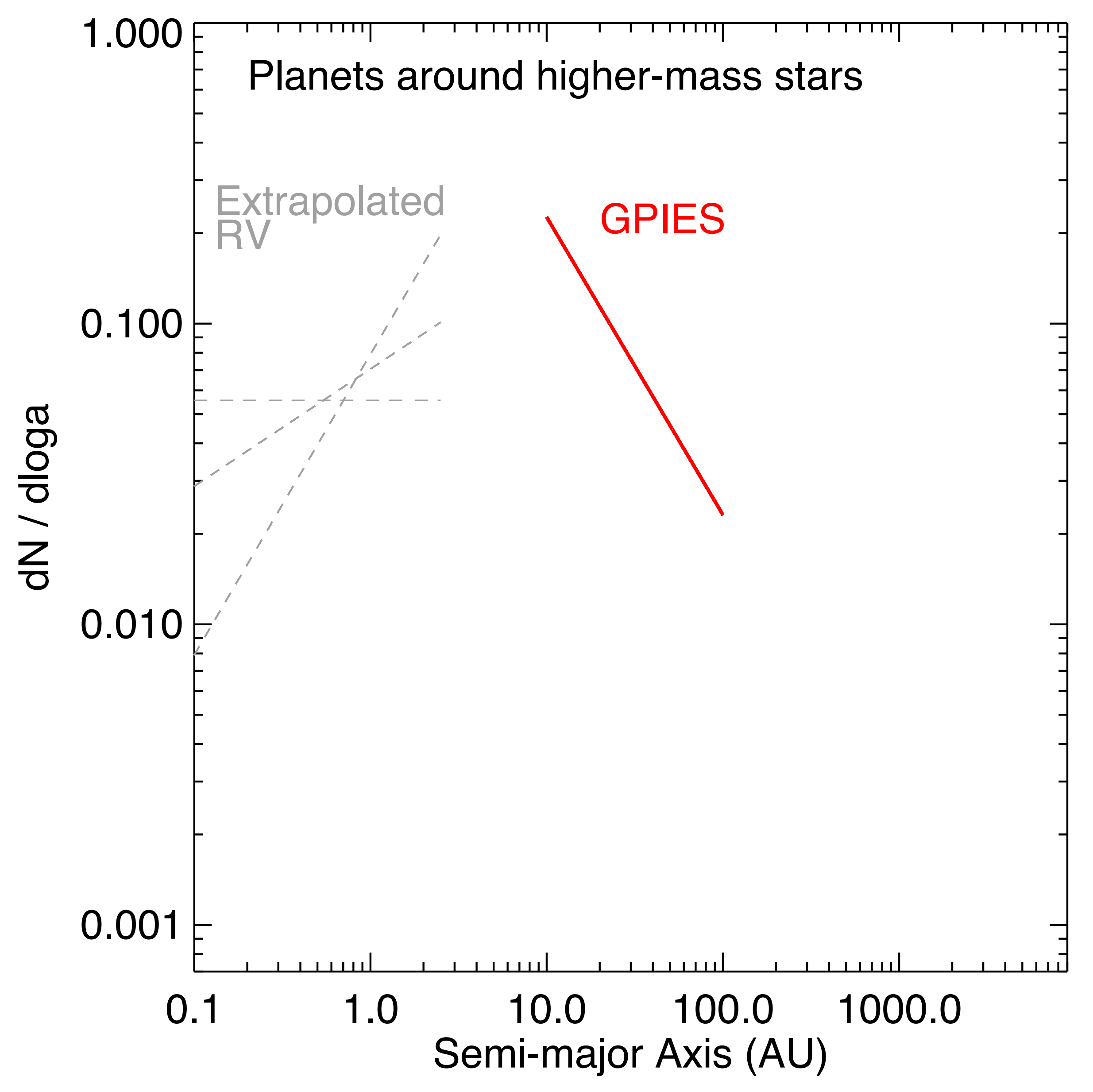
Fulton, Rosenthal et al. 2021

Giant planets demographics vs. semi-major axis



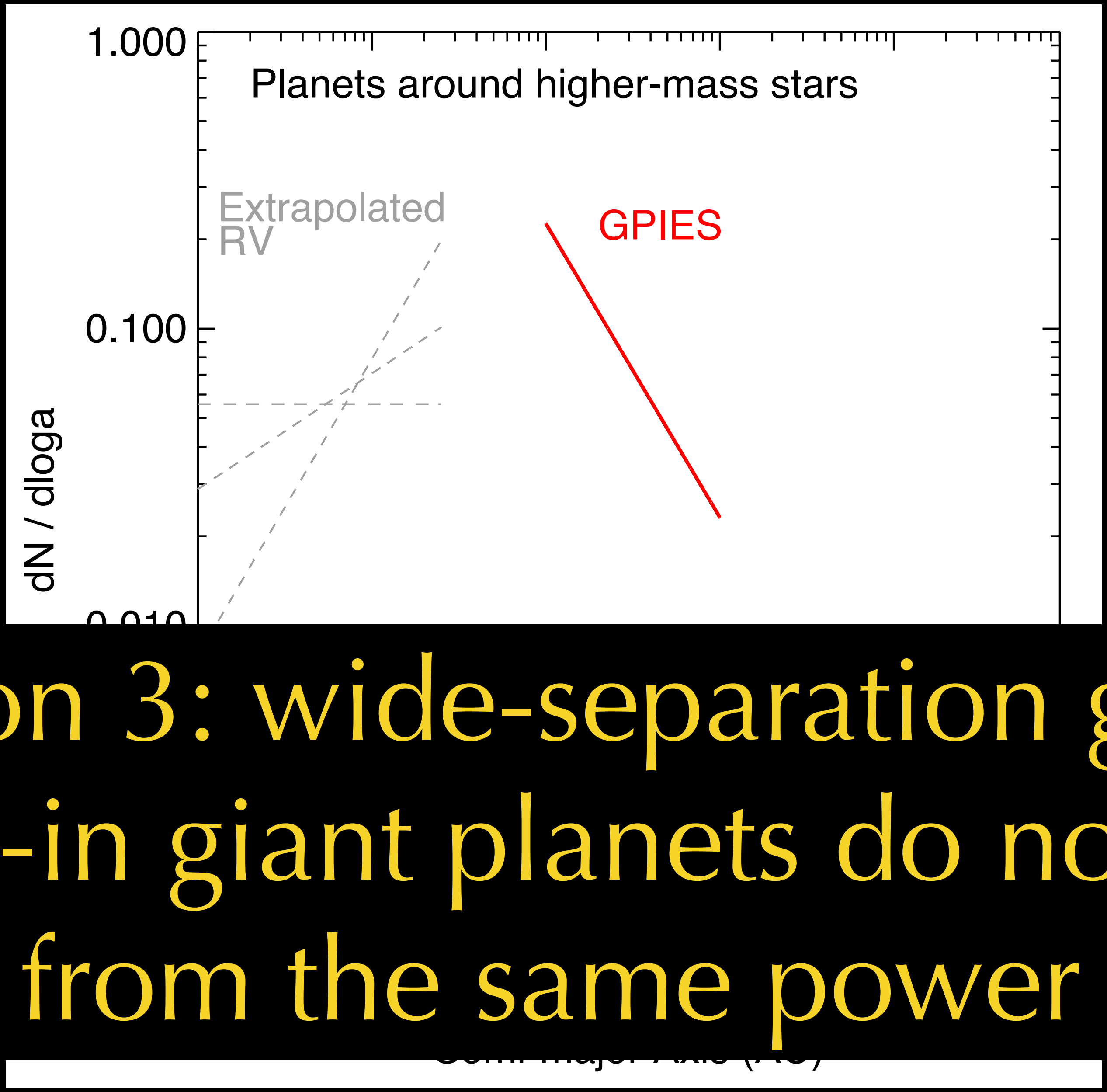
Nielsen et al. 2019

Giant planets demographics vs. semi-major axis



Nielsen et al. 2019

Giant planets demographics vs. semi-major axis

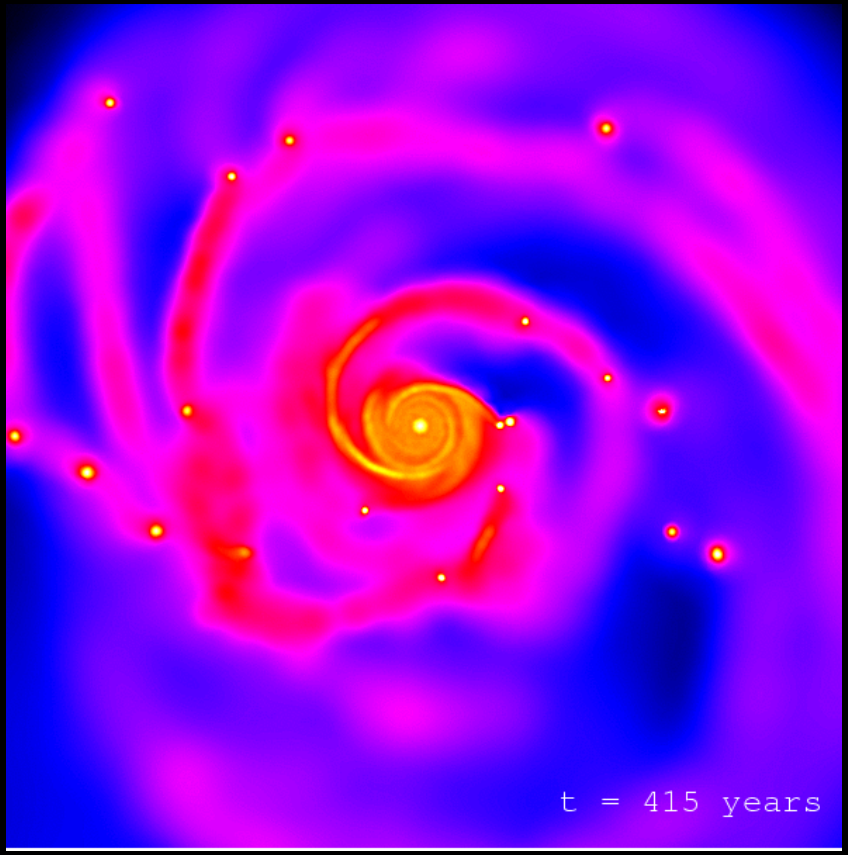


Conclusion 3: wide-separation giant planets and close-in giant planets do not appear to be drawn from the same power law

Nielsen et al. 2019

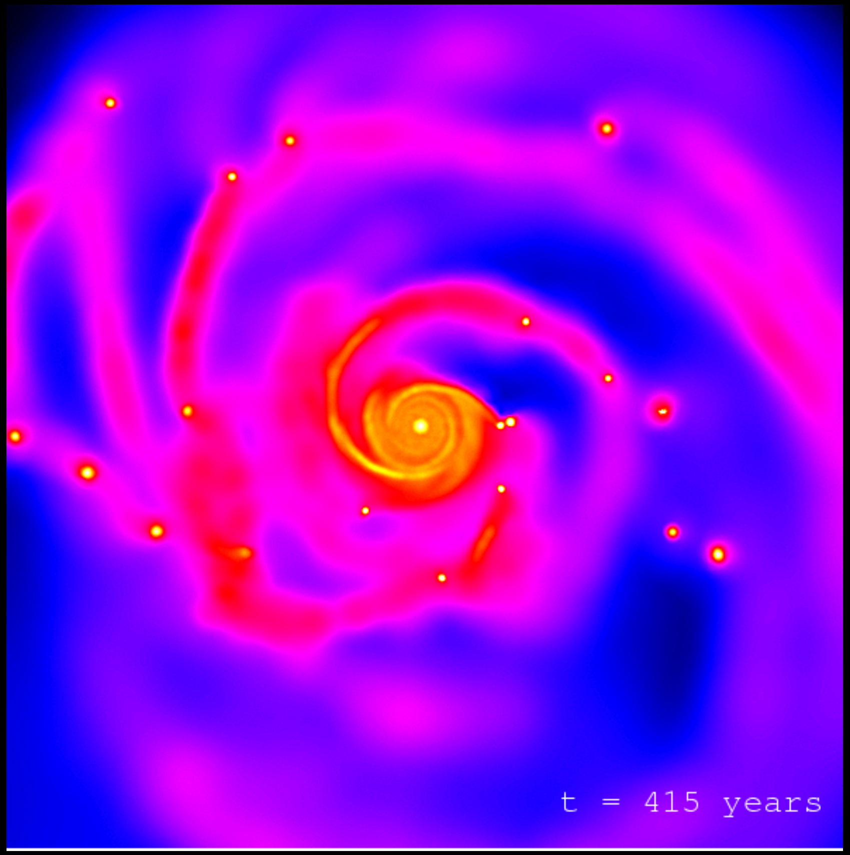
Comparing to predictions

Core accretion



Gravitational Instability

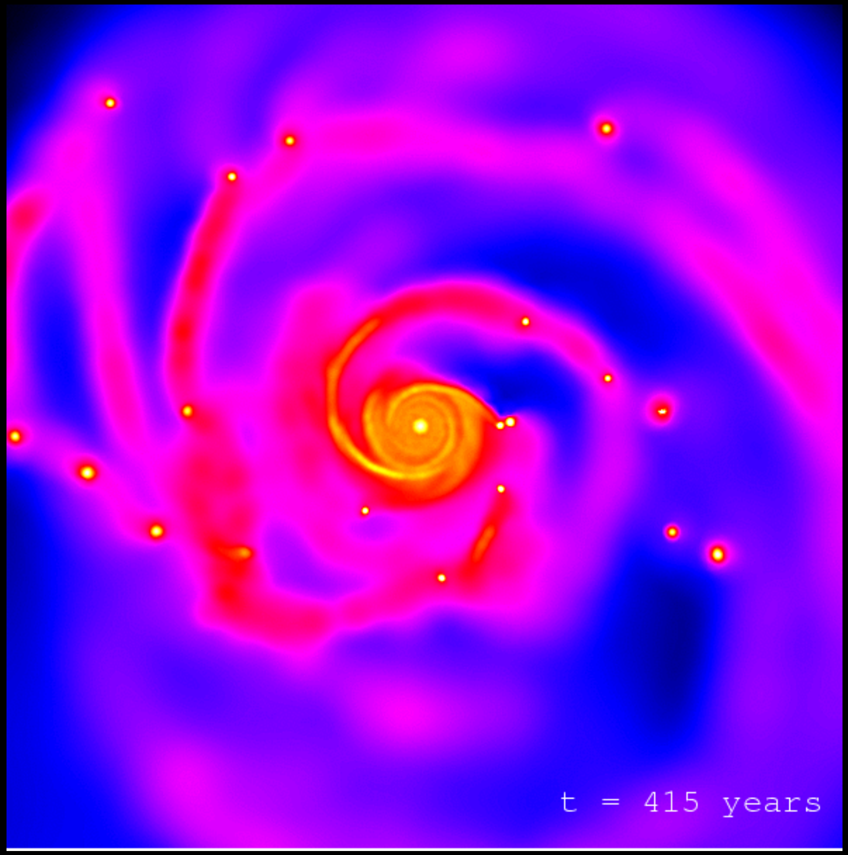
Comparing to predictions



Core accretion
—More companions around higher-mass stars

Gravitational Instability
—Weak dependence on mass of host star

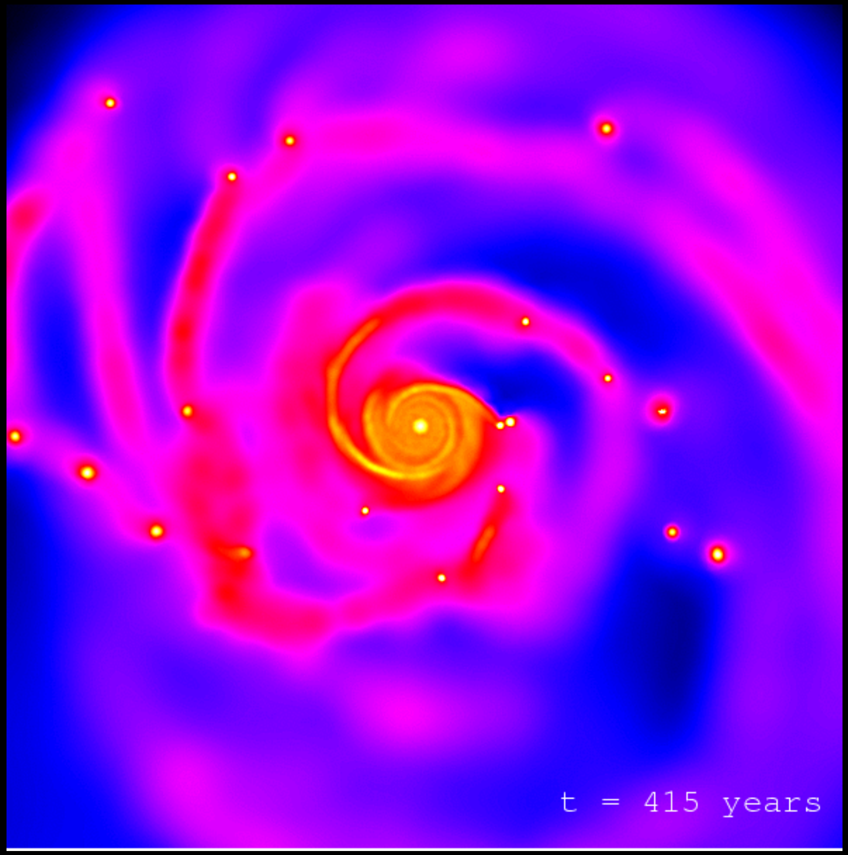
Comparing to predictions



Core accretion
—More companions around higher-mass stars
—More low-mass companions than high-mass

Gravitational Instability
—Weak dependence on mass of host star
—More high-mass companions than low-mass

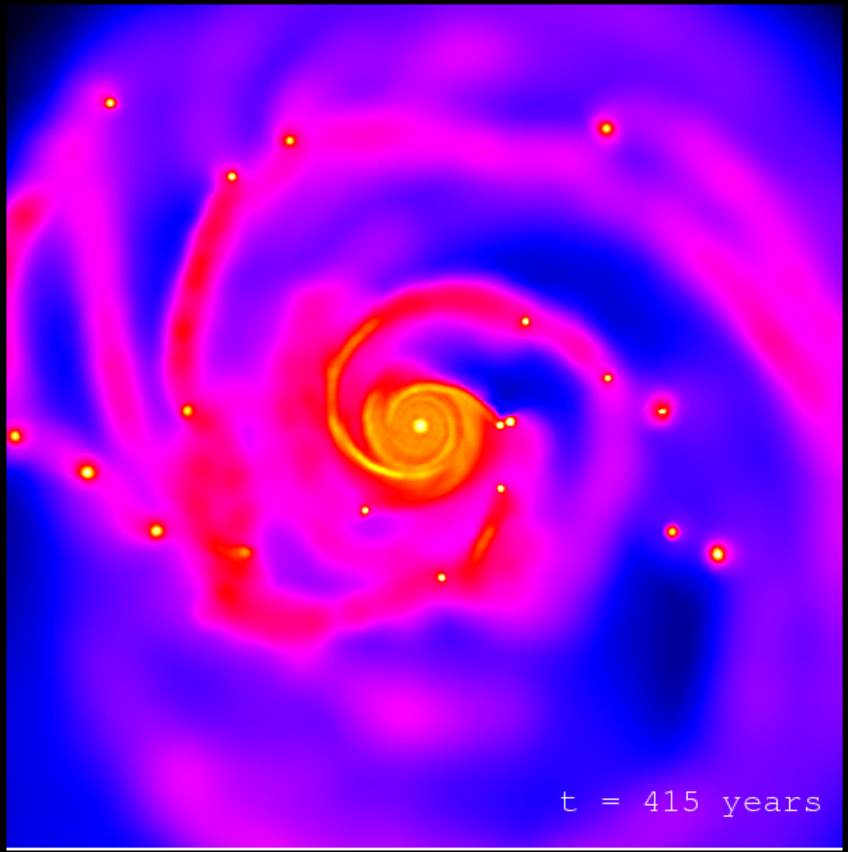
Comparing to predictions



Core accretion
—More companions around higher-mass stars
—More low-mass companions than high-mass
—More close-in companions than farther-out

Gravitational Instability
—Weak dependence on mass of host star
—More high-mass companions than low-mass
—Should be at much larger orbital separations

Comparing to predictions



Core accretion
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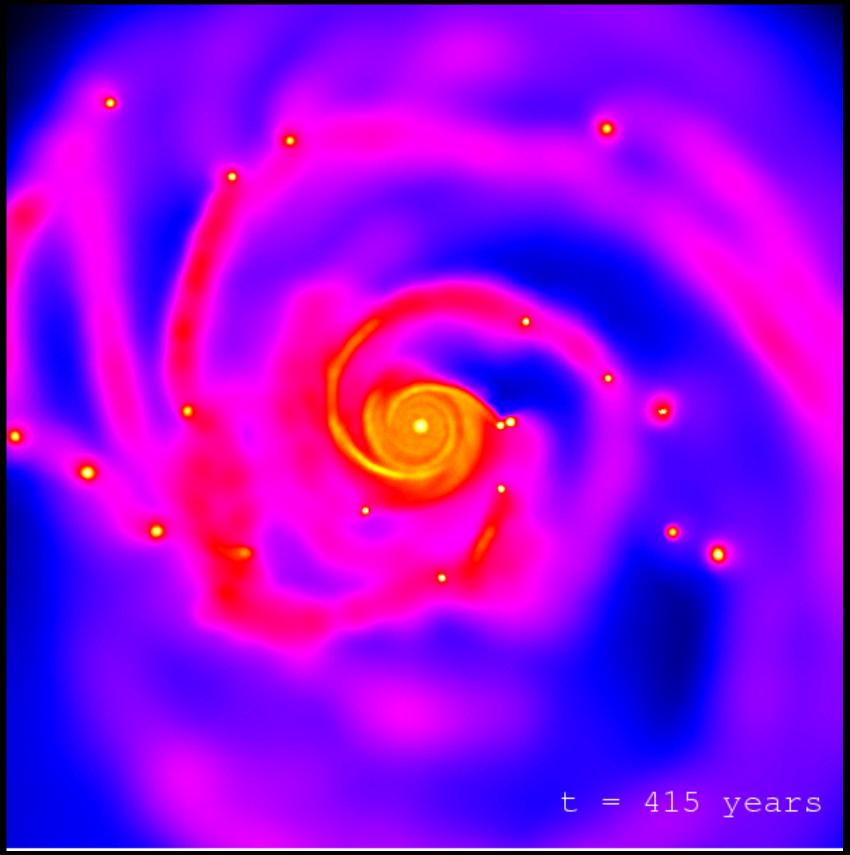
GPIES Planets

Comparing to predictions



Core accretion
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Gravitational Instability
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—More high-mass companions than low-mass
—Should be at much larger orbital separations

GPIES Planets

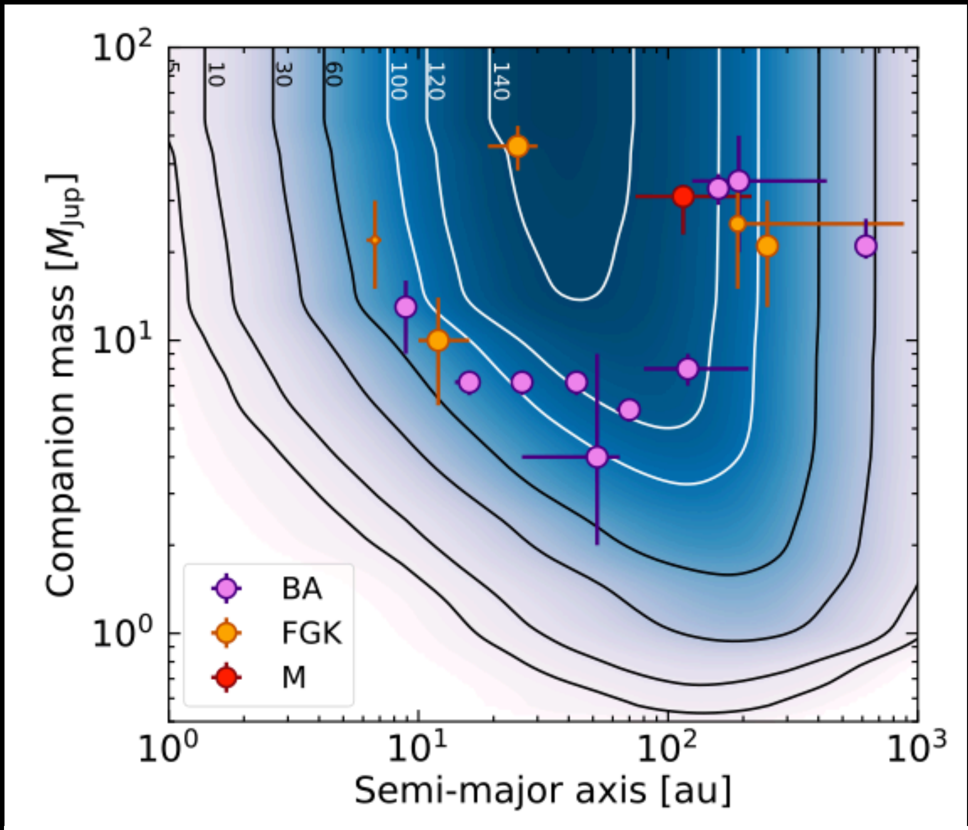
GPIES Brown dwarfs

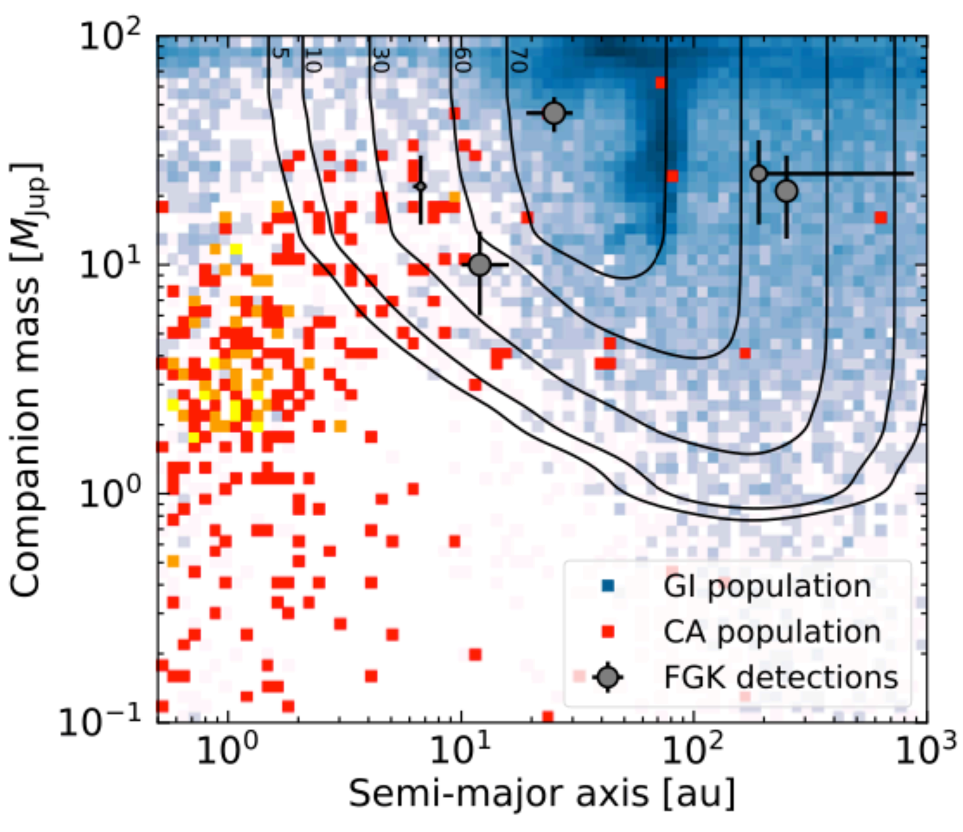
VLT SPHERE SHINE

Demographics from the first 150 stars observed by SHINE

Population synthesis: gravitational instability or core accretion alone can’t reproduce substellar companions to FGK stars

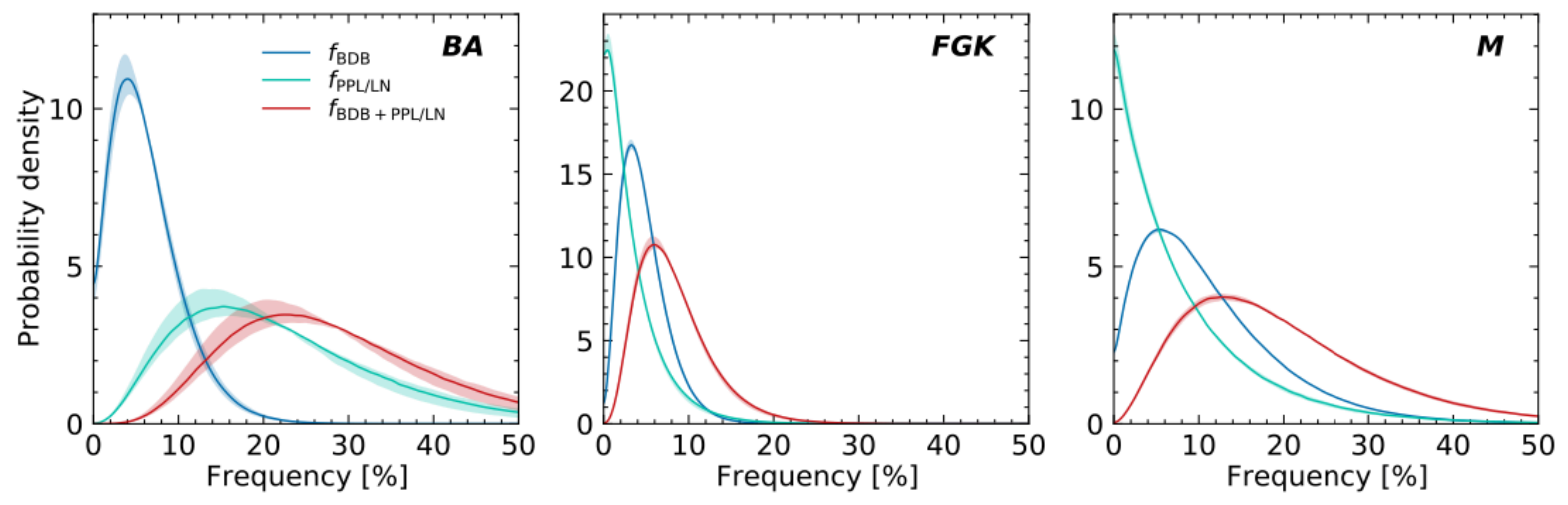
Mixture of two mechanisms is plausible





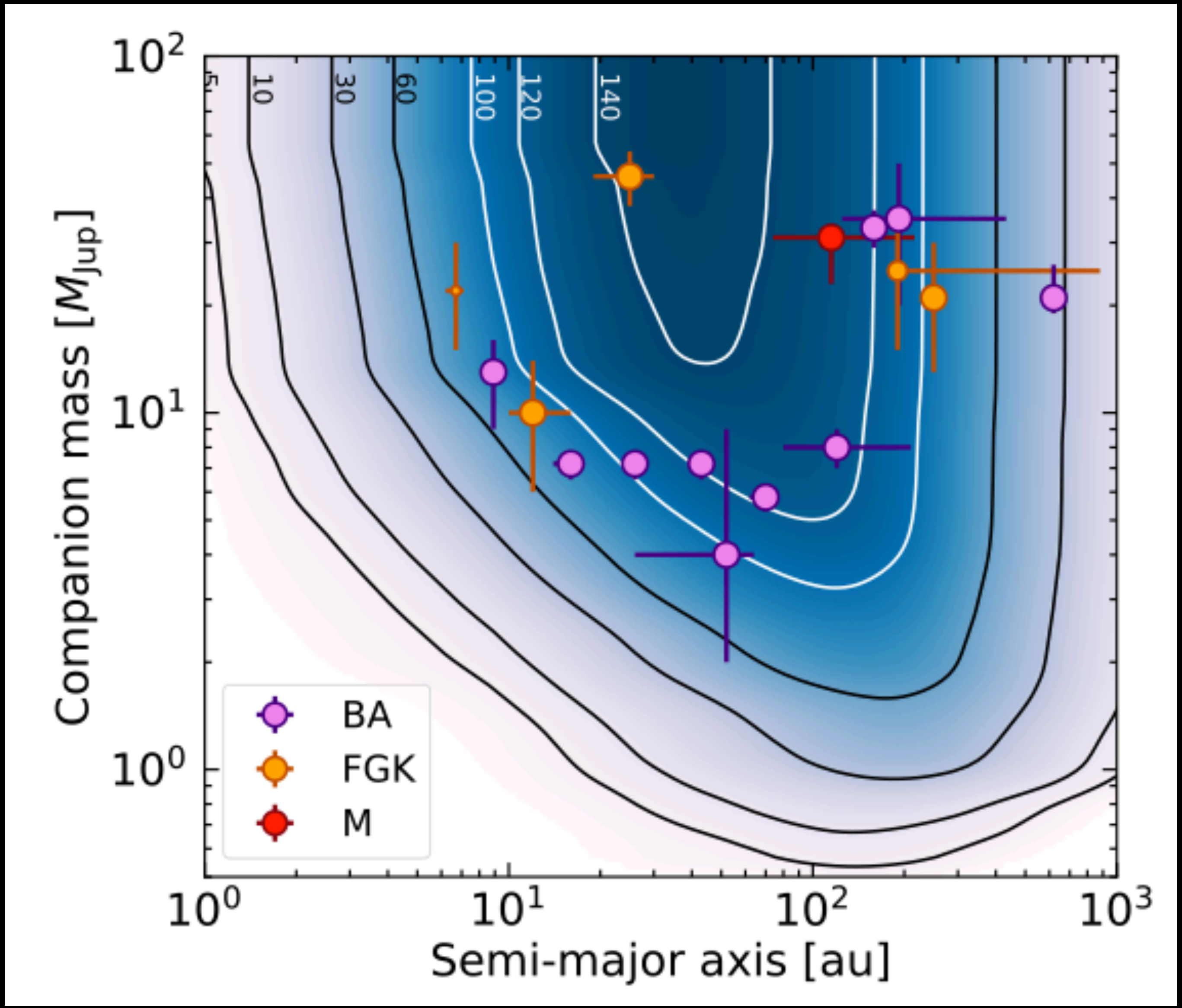
Vigan et al. 2020

VLT SPHERE SHINE

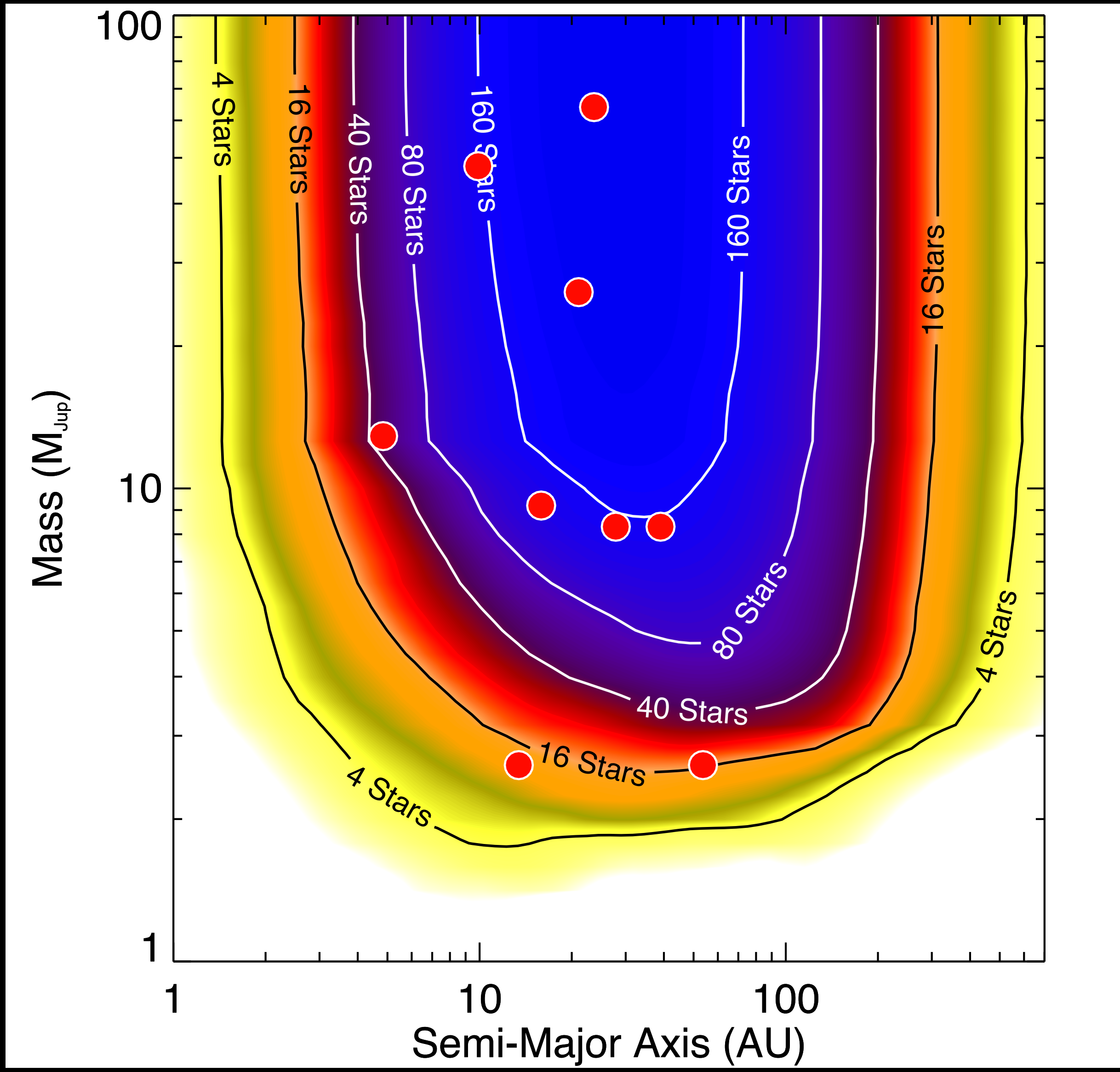


Vigan et al. 2020

SHINE and GPIES



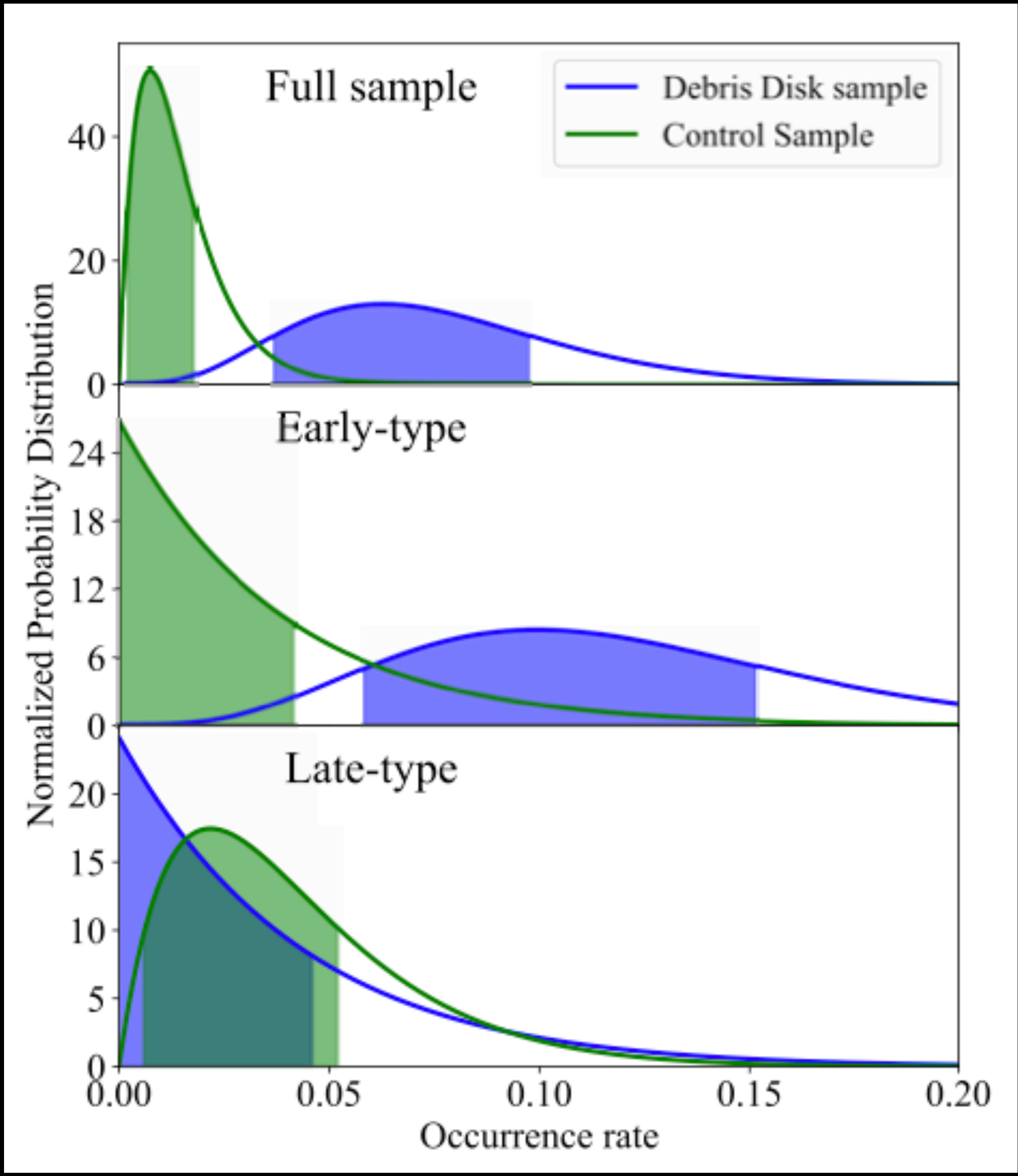
Vigan et al. 2020



Nielsen et al. 2019

Demographics of debris disk stars and exoplanets

Early-type stars with debris disks are more likely to have a wide-separation giant planet

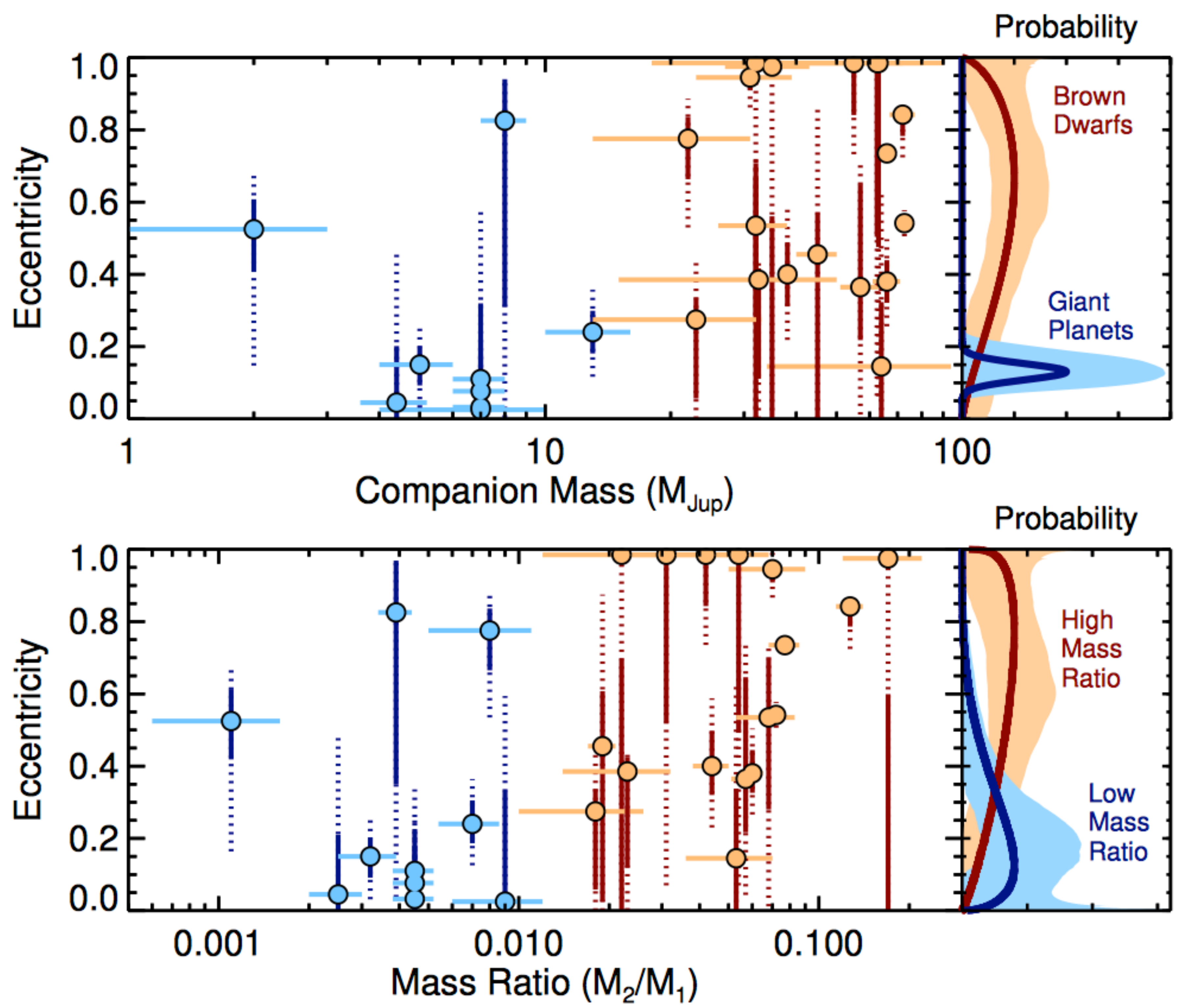


Meshkat et al. 2017

Demographics of substellar companions: eccentricity

Directly imaged brown dwarf and giant planet companions to have different eccentricity distributions

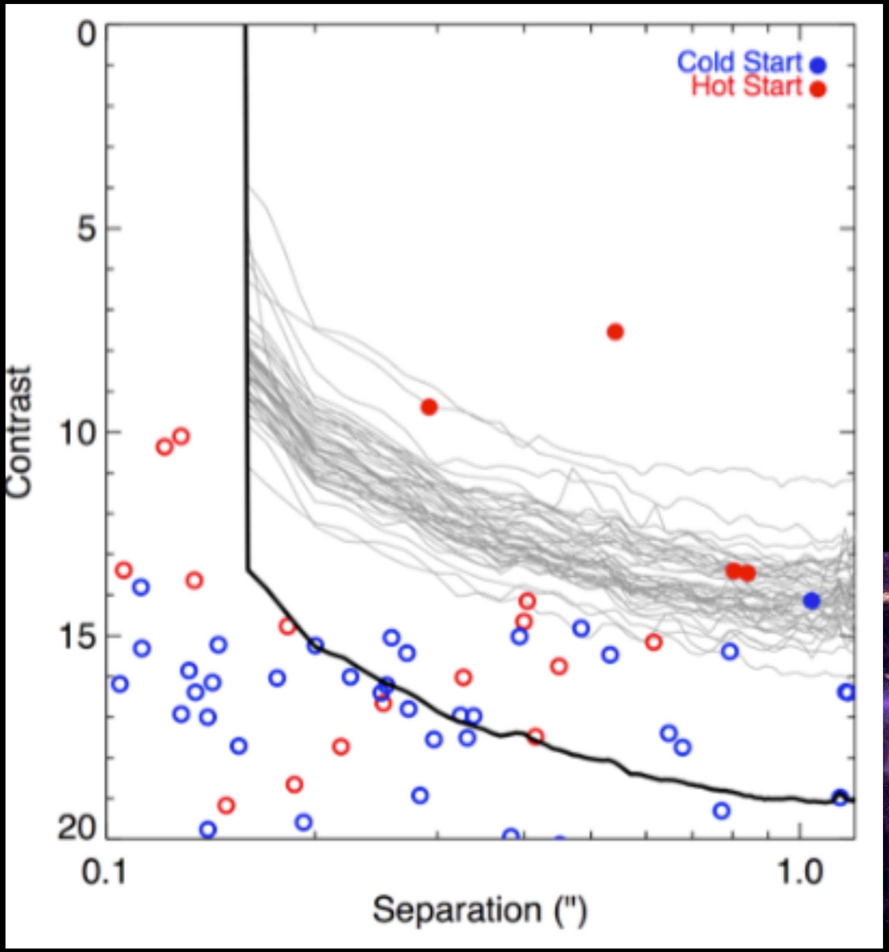
Consistent with different formation mechanisms

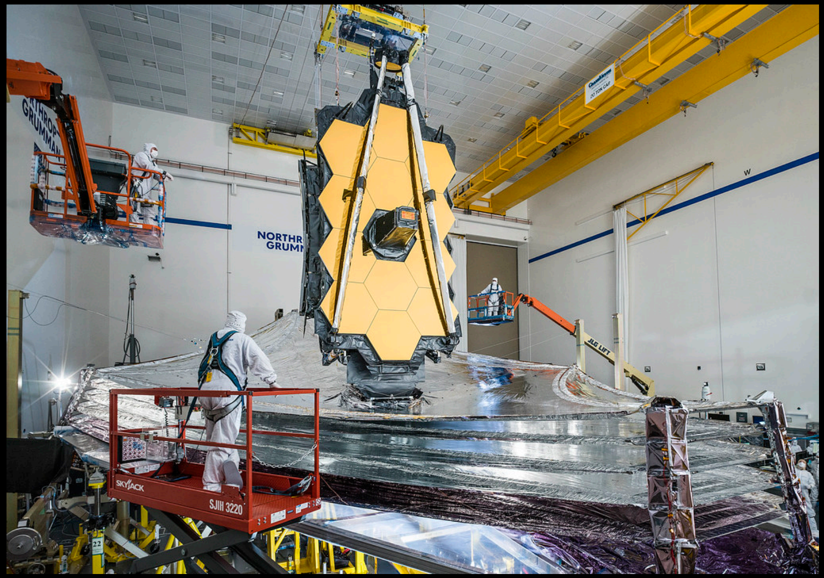


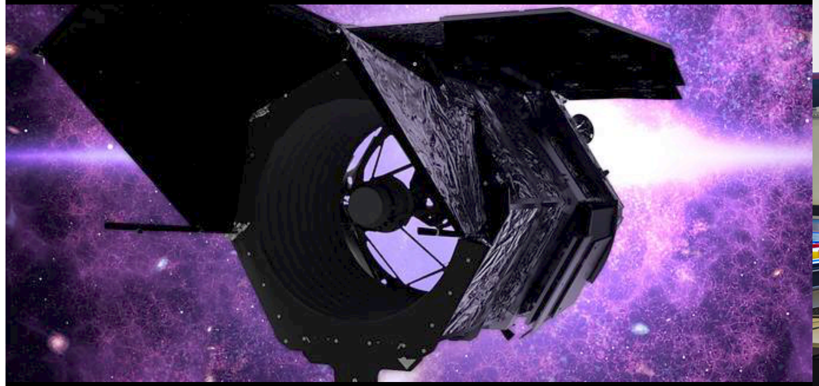
Bowler, Blunt & Nielsen 2020

The future of young planet demographics: direct imaging

gpi 2





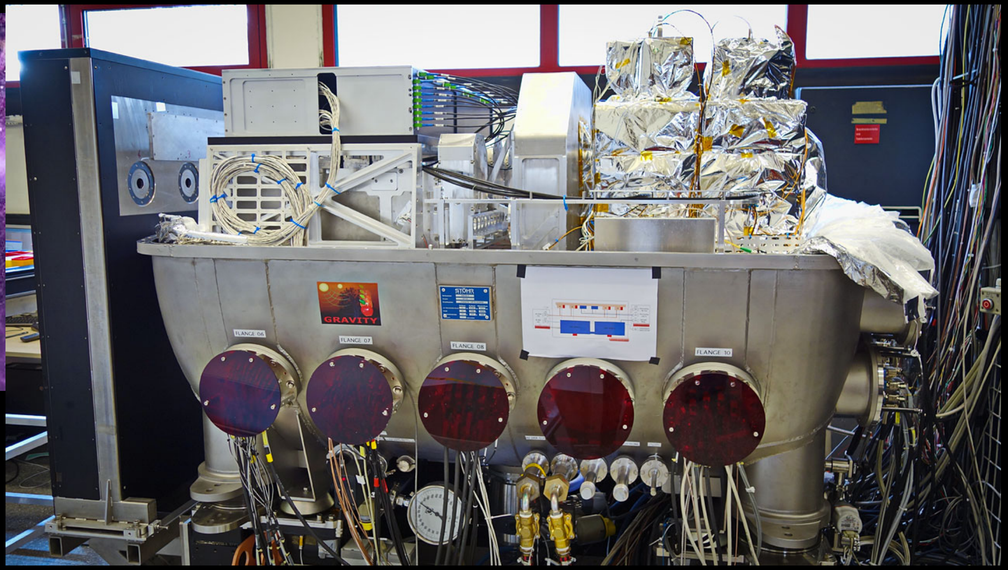


SUBARU TELESCOPE
National Astronomical Observatory of Japan

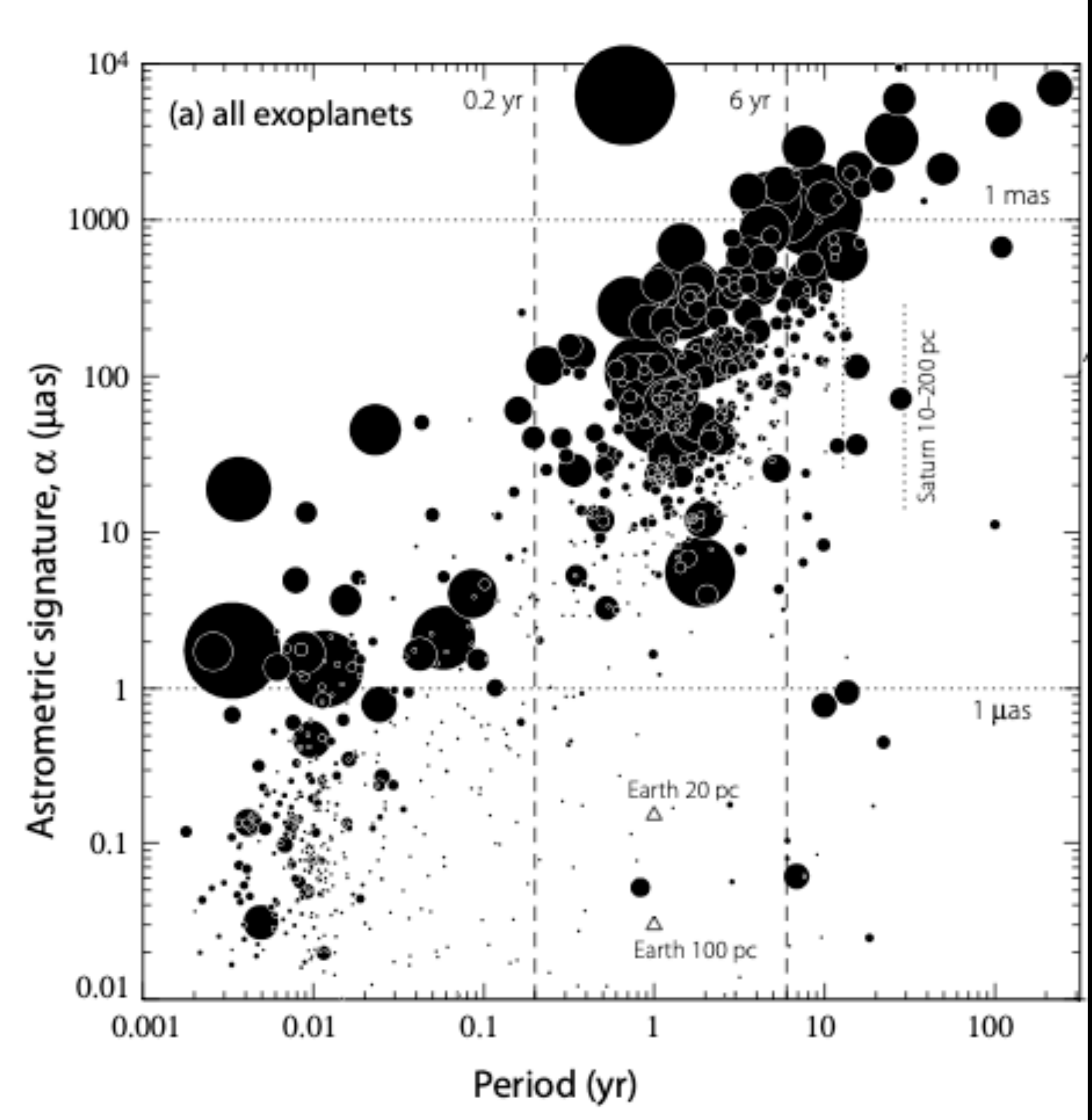
SCExAO

KPIC

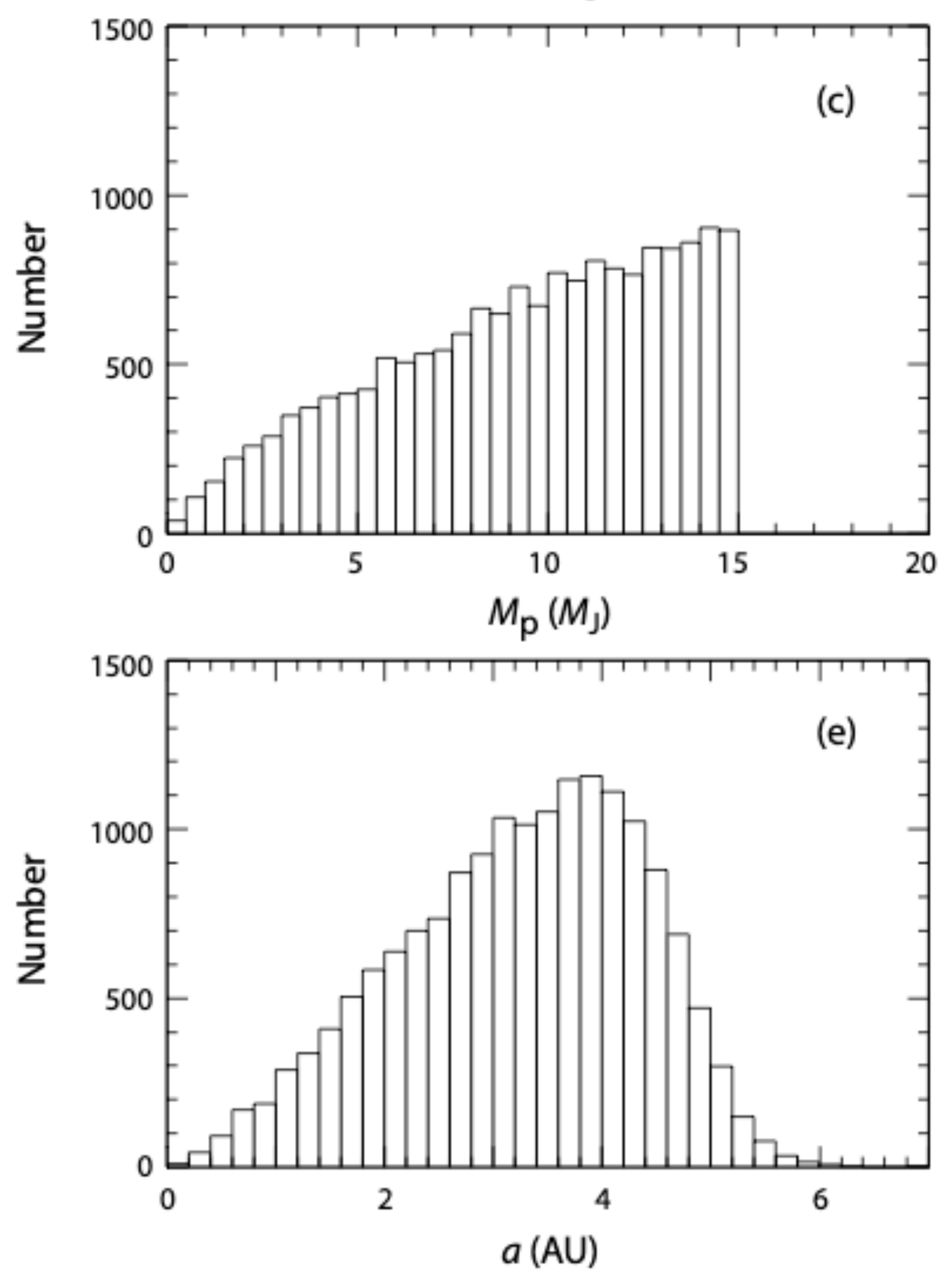
VLTI GRAVITY



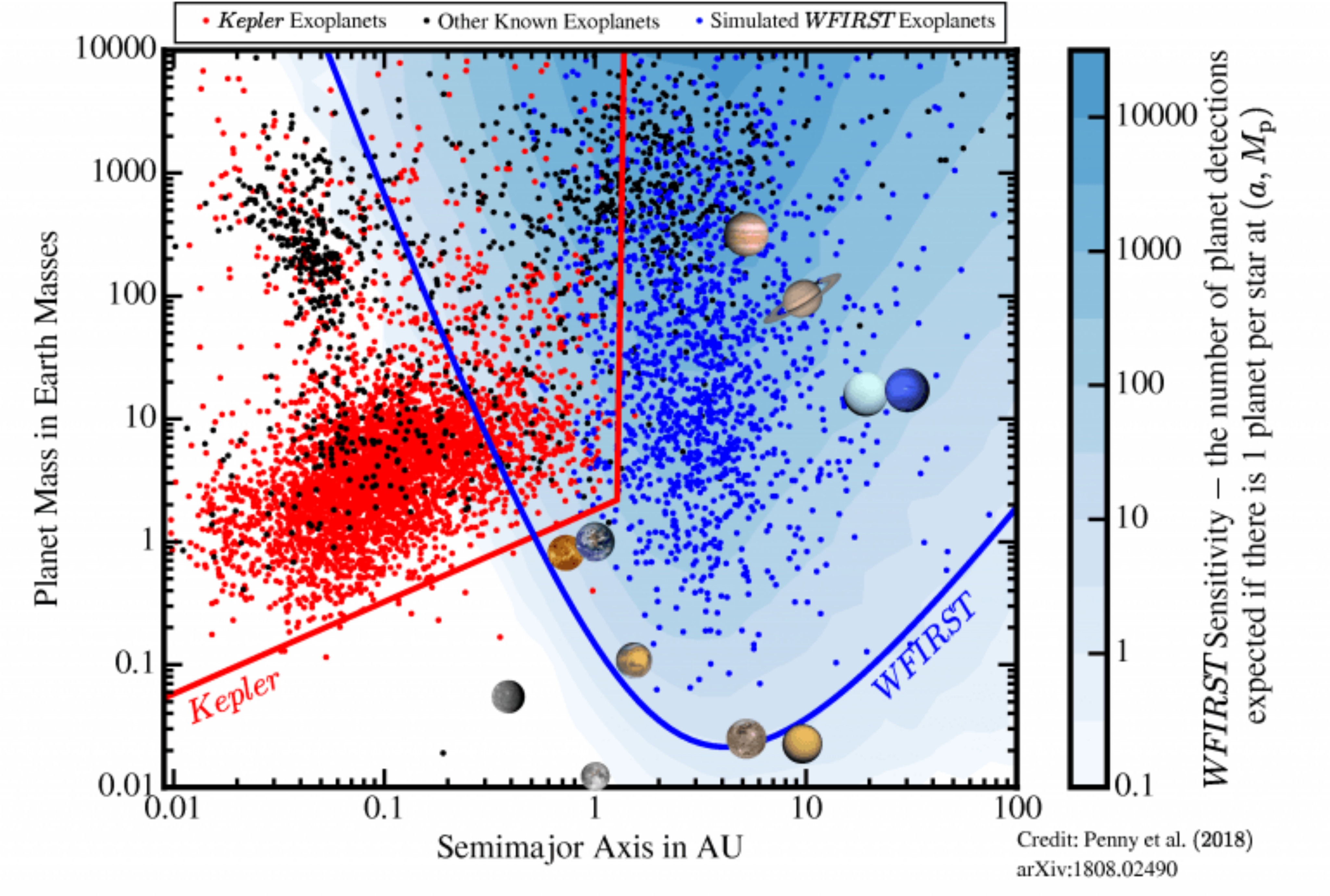
The future of young planet demographics: astrometry



Perryman et al. 2015



The future of planet demographics: microlensing



Credit: Penny et al. (2018)
arXiv:1808.02490

Conclusions

Exoplanet demographics let us test predictions from theories of planet formation and evolution

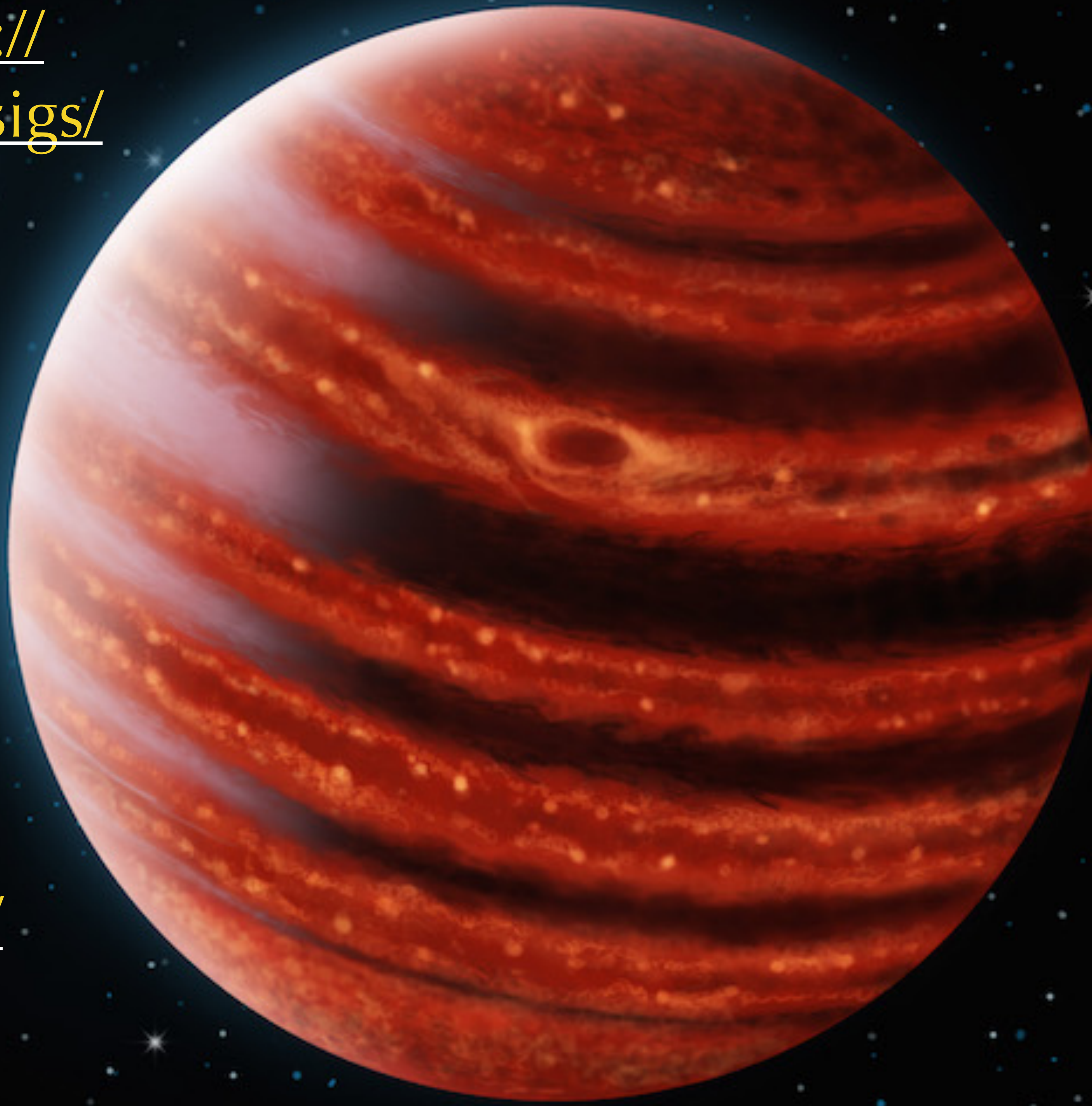
Demographics results from direct imaging surveys currently favor core accretion for wide-separation giant planets, but with limited statistical significance

Future instrumentation and telescope will enable more precise measurements of giant planet demographics, with more overlap between direct imaging and other techniques

Exoplanet Demographics

NASA SIG2 (Science Interest Group) on Exoplanet Demographics: https://exoplanets.nasa.gov/exep/exopag/sigs/

Exoplanet Demographics papers on the NASA Exoplanet Archive: https://exoplanetarchive.ipac.caltech.edu/docs/occurrence_rate_papers.html



Danielle Futselaar & Franck Marchis, SETI Institute