Exoplanet Occurrence Rates and Types of Planets Possible in Alpha Centauri AB

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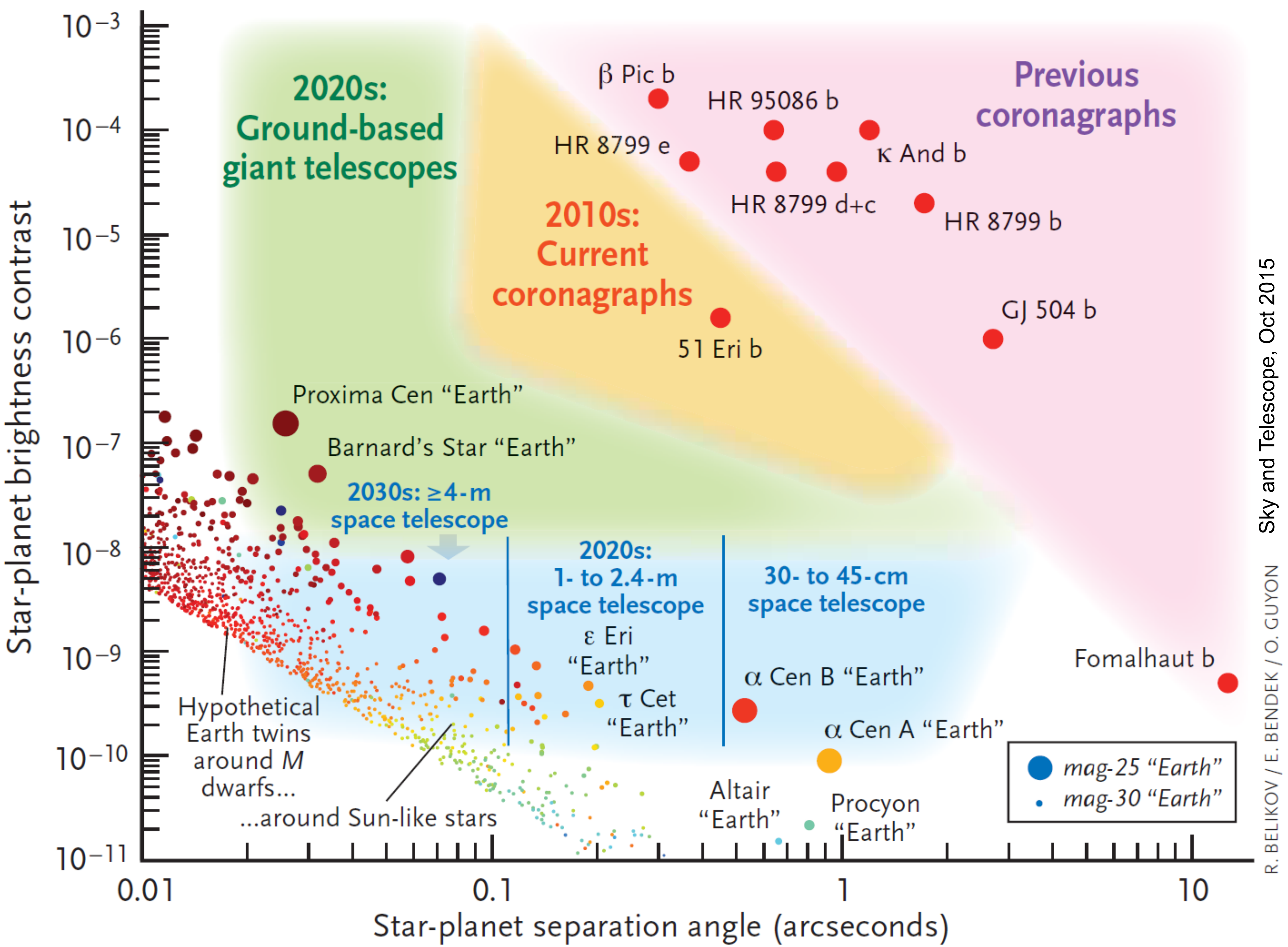
The Alpha Centauri system workshop, Nice, France (remote)
6/27/2023

Why Alpha Centauri?



R. BELIKOV / E. BENDEK / O. GUYON

Sky and Telescope, Oct 2015

Alpha Centauri: not your typical target

Simulations of an Earth twin detection for a ~1.5 class telescope
(similar to Exo-C, Exo-S)

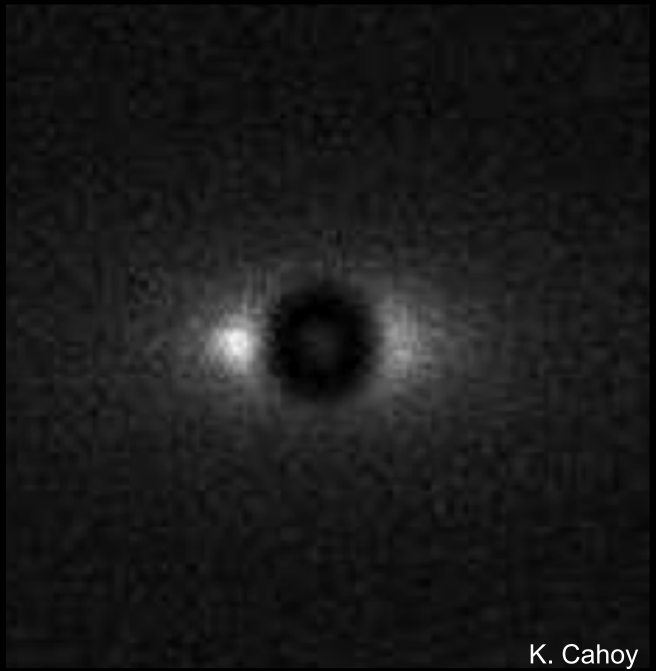
α Cen (A)


K. Cahoy

1.5m aperture, 1 hour exposure

nothing
in-between
←→

τ Cet (~ best of everything else)


K. Cahoy

1.5m aperture, 1 hour exposure

> *"Alpha Centauri system, if not for the fact that it is a binary, would easily be the best target for direct imaging searches for planets"*
>
> -- HabEx final report, 2019

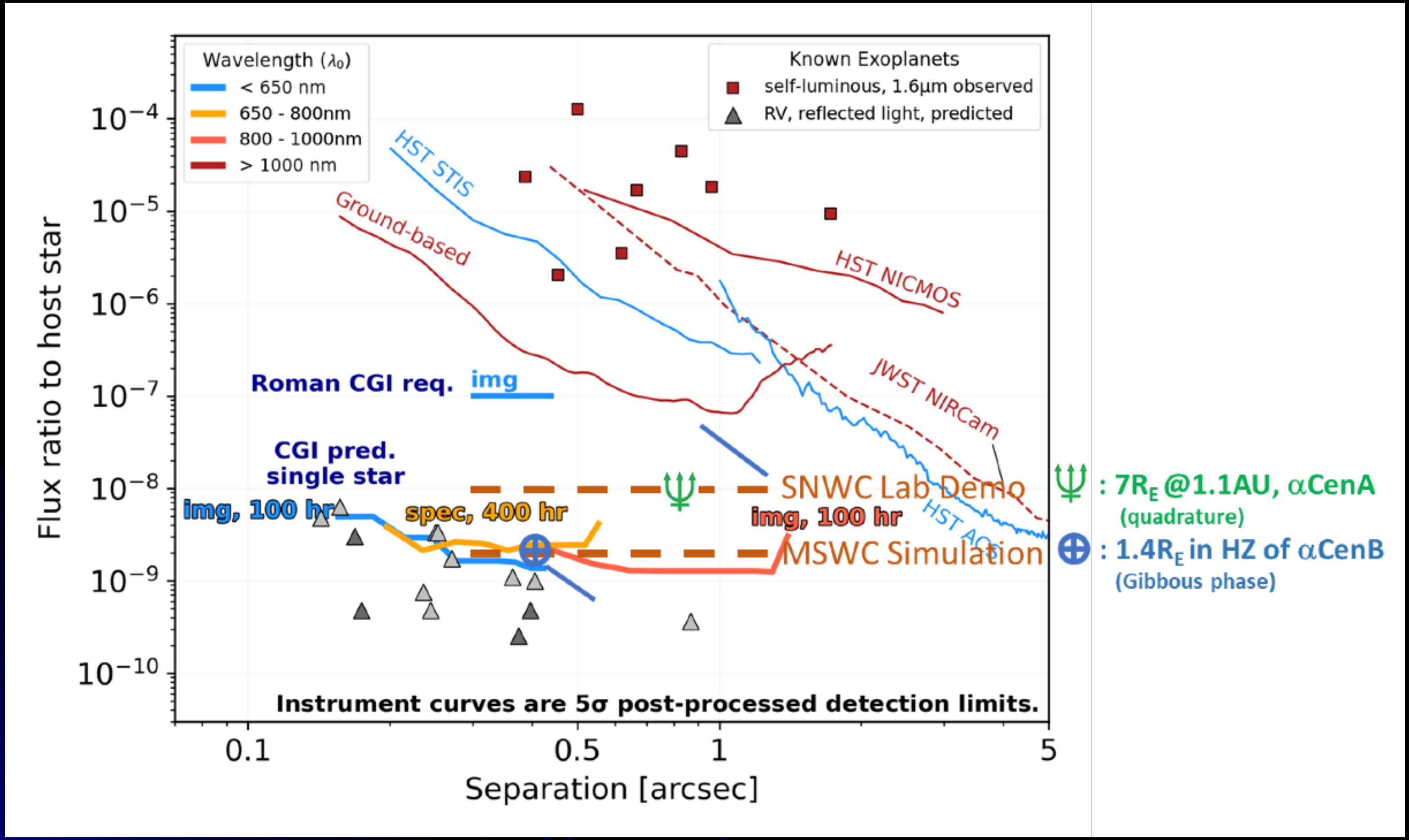
Interest in searching for planets in the Alpha Centauri AB system is increasing

- VLT / NEAR (thermal IR direct imaging)
- JWST / MIRI (F1550C, 15.5μm)
- ALMA (astrometry)
- Toliman (astrometry w/ small space telescope)
- Etc.

- Also, work is on-going to enable aCenAB imaging on Roman, HWO, ELTs, potentially small direct imaging missions

(2021 Breakthrough Discuss conference was dedicated to Alpha Centauri: https://breakthroughinitiatives.org/initiative/5/discuss2021)

Alpha Centauri Opportunities on Roman

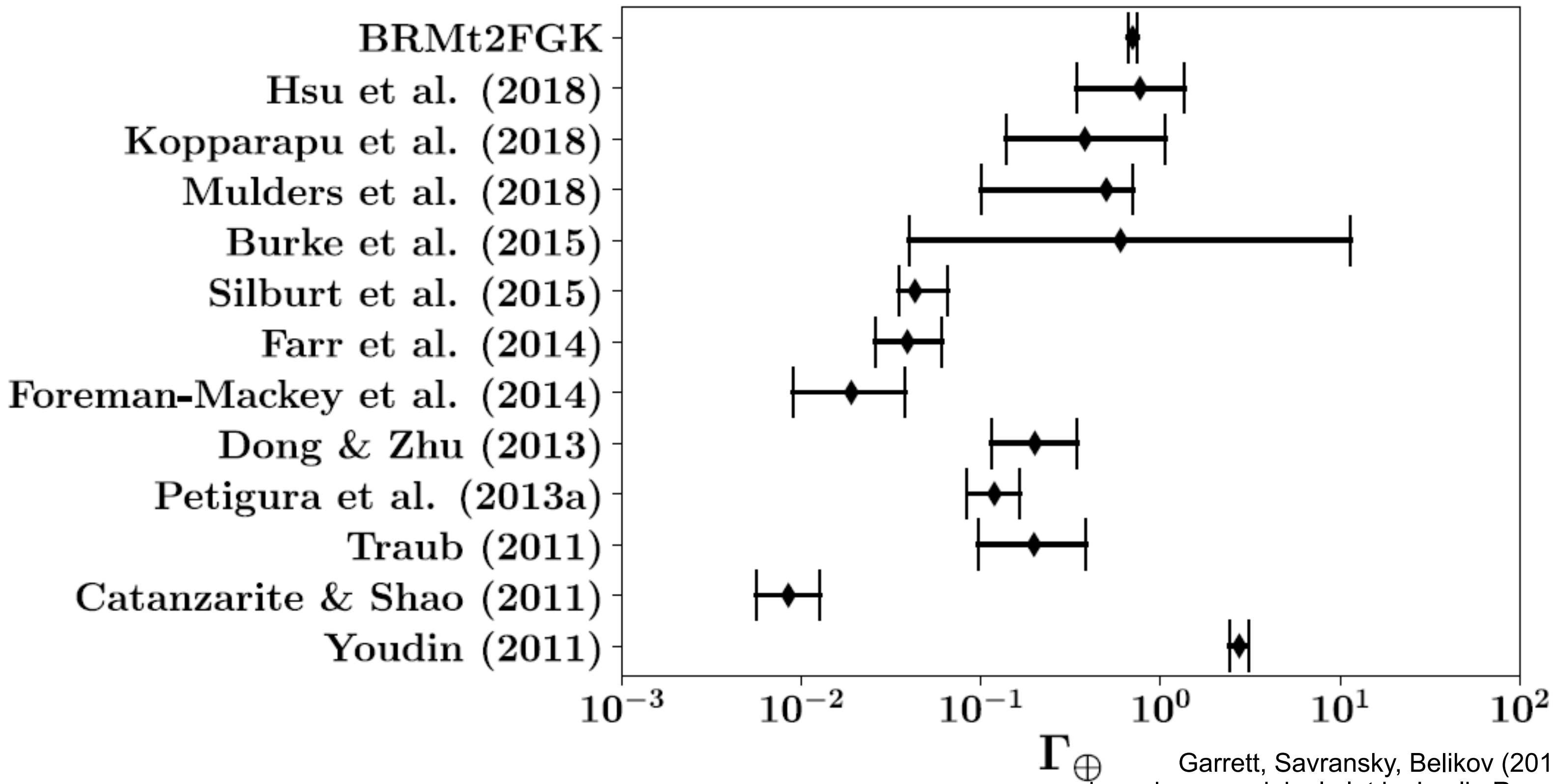


- If we can overcome the challenge of imaging Alpha Centauri with Roman CGI:
  - The NEAR planet candidate is within current SNWC lab demo performance
  - A large potentially habitable planet around aCen B is within current (single-star) Roman CGI best estimated performance (as of ~mid 2021)

Approach to calculating planet occurrence rates around Alpha Centauri

- Start with single-star occurrence rates
- Fold in:
  - Suppression due to binarity
  - Constraints from dynamical stability
  - Constraints from non-detections (mainly RV)
  - Implications if NEAR candidate is real

Γ_{earth} literature agreement improving



Garrett, Savransky, Belikov (2018)
based on an original plot by Leslie Rogers

What is Γ_{earth} ?

For most definitions of η_{Earth} , Γ_{earth} ~ η_{Earth}

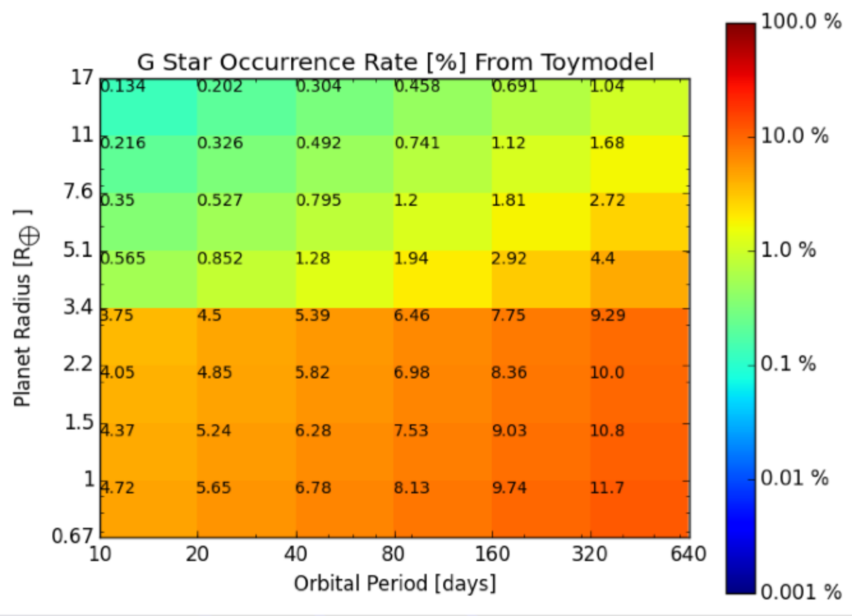
$$\Gamma_{earth} = \left. \frac{\partial^2 N(R, P)}{\partial \ln R \, \partial \ln P} \right|_{R=1,\ P=1\mathrm{y}}$$

Key advantage: Γ_{earth} is independent of definitions of HZ or habitable size range, which allows apples-to-apples comparisons between different studies

Burke et al. 2015: “We generally find higher planet occurrence rates and a steeper increase in planet occurrence rates towards small planets than previous studies of the Kepler GK dwarf sample”

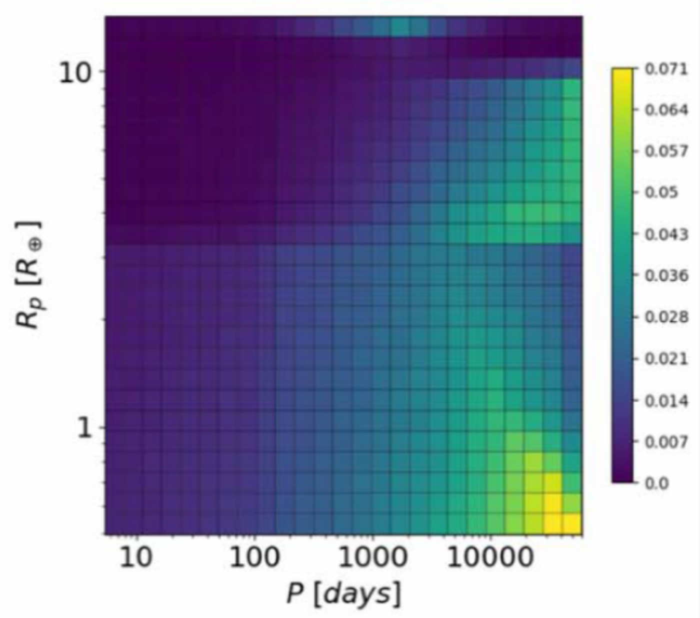
Selected Exoplanet Occurrence Rates for single Sun-like Stars

SAG13 (2016)

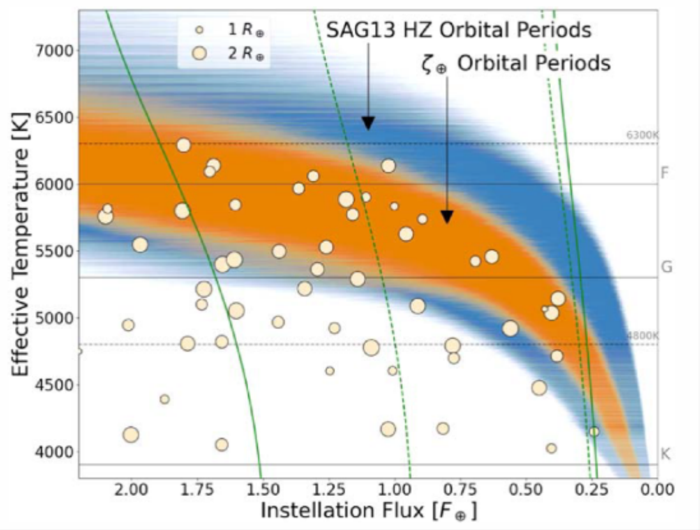


0.134	0.202	0.304	0.458	0.691	1.04
0.216	0.326	0.492	0.741	1.12	1.68
0.35	0.527	0.795	1.2	1.81	2.72
0.565	0.852	1.28	1.94	2.92	4.4
3.75	4.5	5.39	6.46	7.75	9.29
4.05	4.85	5.82	6.98	8.36	10.0
4.37	5.24	6.28	7.53	9.03	10.8
4.72	5.65	6.78	8.13	9.74	11.7

Dulz et al. 2020



Bryson et al. 2021



- Meta-analysis of Kepler occurrence rates as of 2016

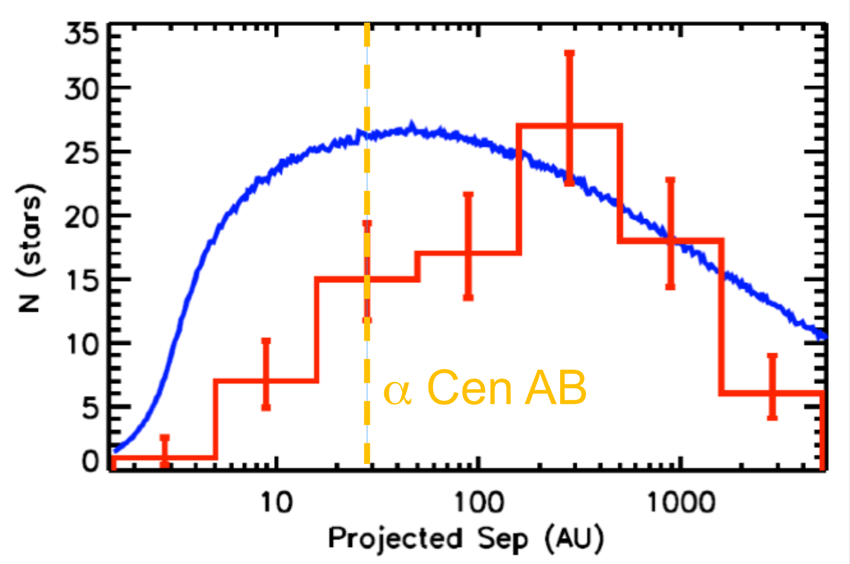
- Extended SAG13 to larger periods
- Used for LUVOIR / HabEx yields

- Most recent analysis by Kepler team
- Accounts for updated stellar radii, reliability, etc.
- Treats occurrence rates in terms of instellation flux instead of period

	SAG13 / Dulz et al	Bryson, low extrapolation	Bryson, high extrapolation
Conservative Kopparapu HZ, 0.5-1.5 Re			
Optimistic Kopparapu HZ, 0.5-1.5 Re			

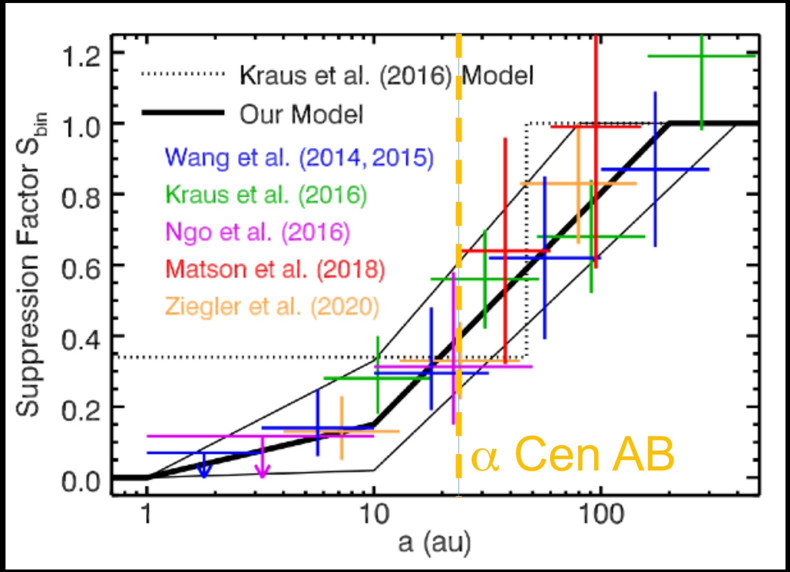
Can binaries form planets? (as efficiently as single stars?)

Kraus et al. 2016



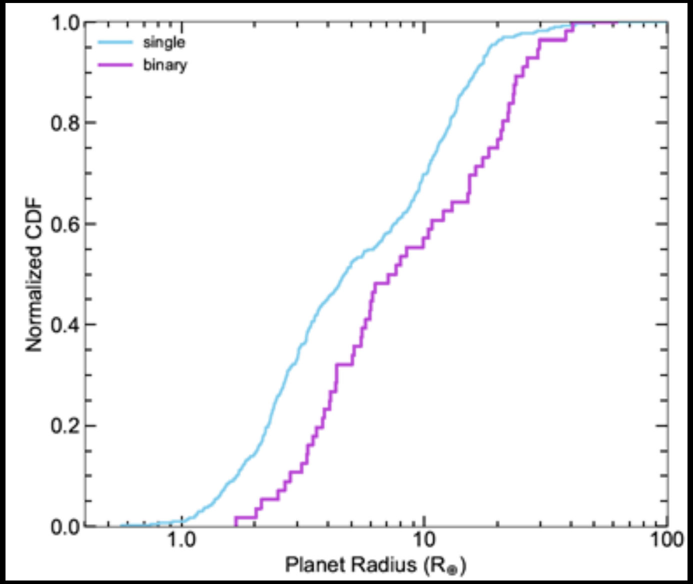
Suppression factor ~0.3

Moe and Kratter, 2020



Suppression factor $\sim 0.25^{+0.15}_{-0.10}$

Howell et al. 2021 (in prep)



Due to observation bias against binaries, suppression factor estimates may be too aggressive

$$\eta_{earth}(\text{aCenA}) = \eta_{earth}(\text{aCenB}) = \underset{\text{Conservative HZ single+binary } \eta_{earth}}{0.40^{+0.5}_{-0.2}} \times \underset{\text{Conversion to single-star } \eta_{earth}}{1.44^{+0.12}_{-0.12}} \times \underset{\text{Binary suppression}}{0.25^{+0.15}_{-0.1}} = 0.15^{+0.19}_{-0.09}$$

$$\eta_{earth}(\text{aCenAB}) = \eta_{earth}(\text{aCenA}) + \eta_{earth}(\text{aCenA}) = 0.30^{+0.27}_{-0.13}$$

Habitable Zones and Stable Orbits around αCen AB

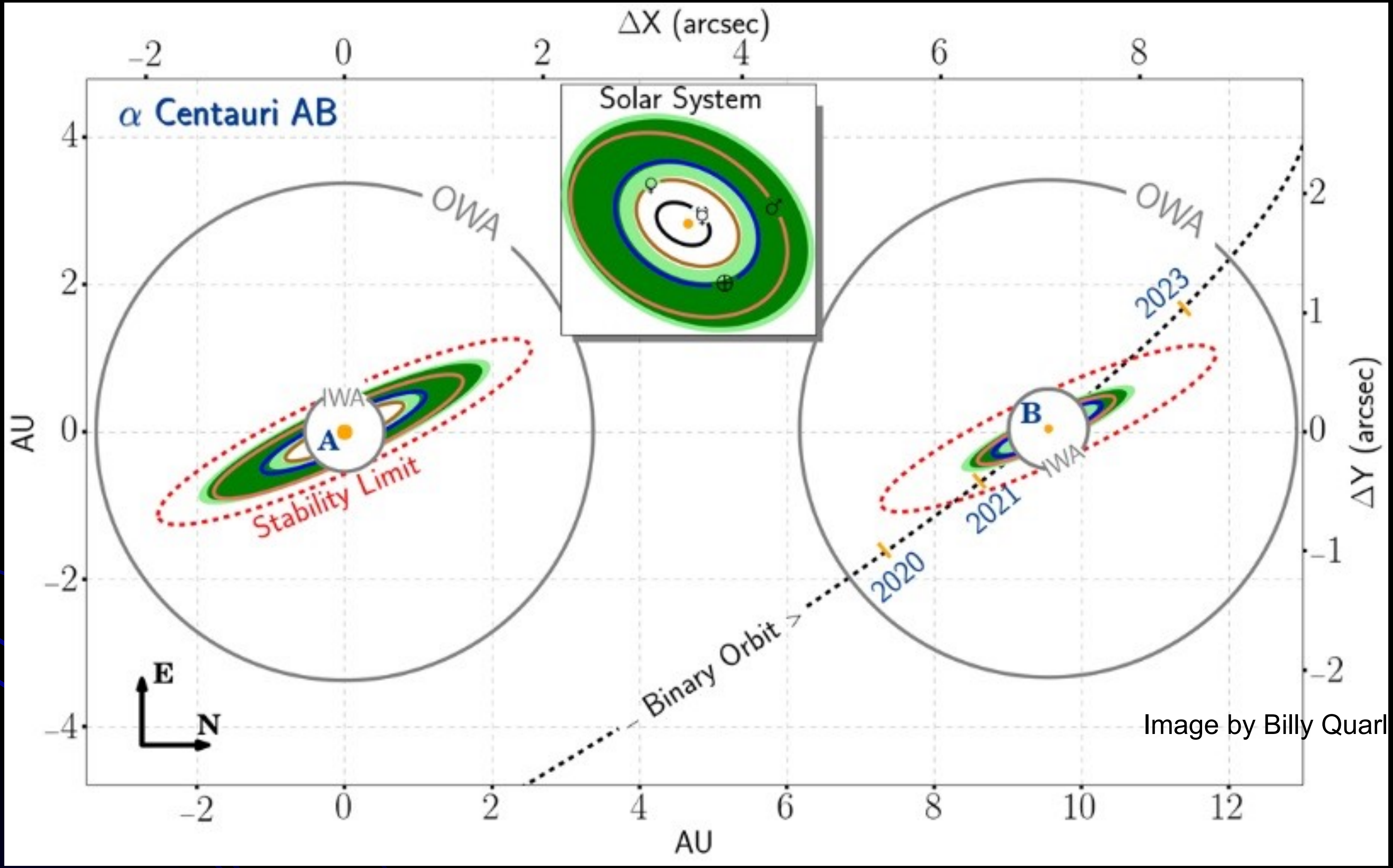


Image by Billy Quarl

see Quarles and Lissauer 2016 for aCen stability
https://arxiv.org/abs/1604.04917

- Both HZs are fully accessible with a 0.4” (0.5AU) inner working angle (IWA)
- Orbits are stable out to ~ 2.5 AU (Holman & Wiegert 1999, Quarles and Lissauer 2016)

Posterior distributions

(accounting for dynamical stability)

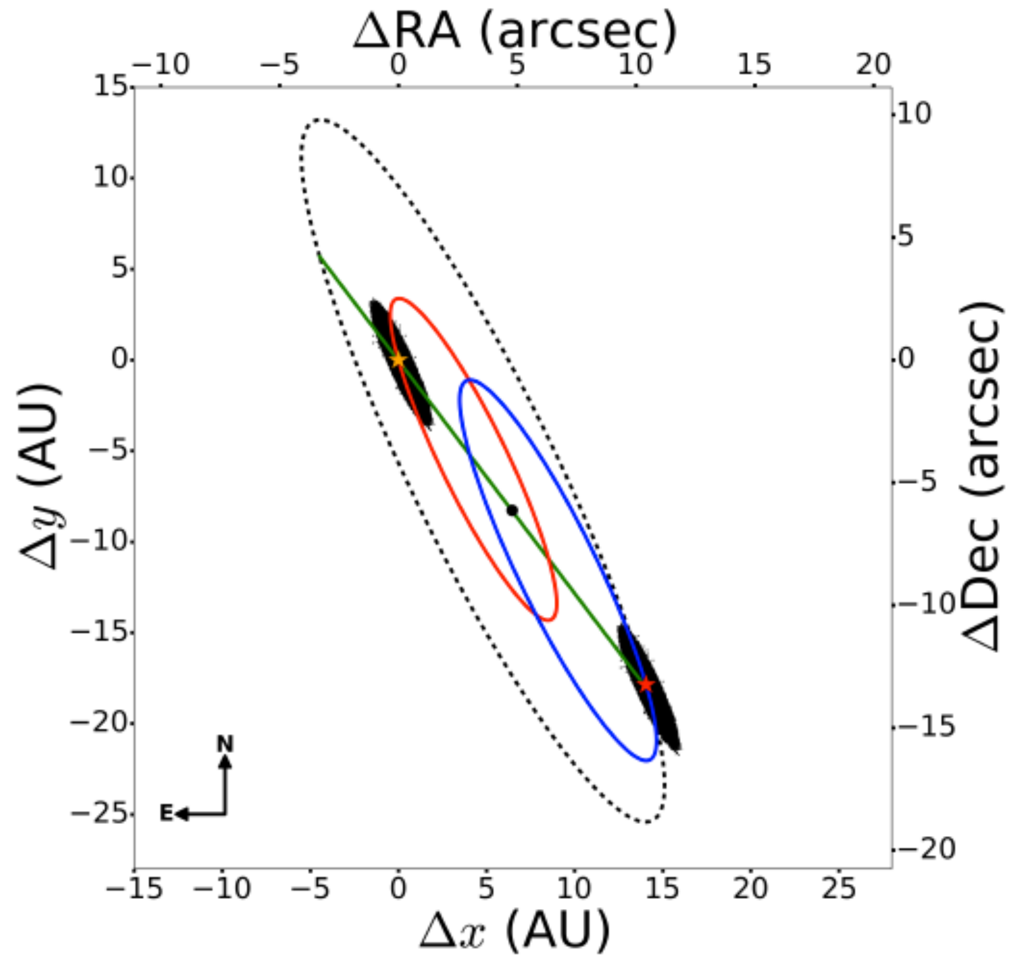
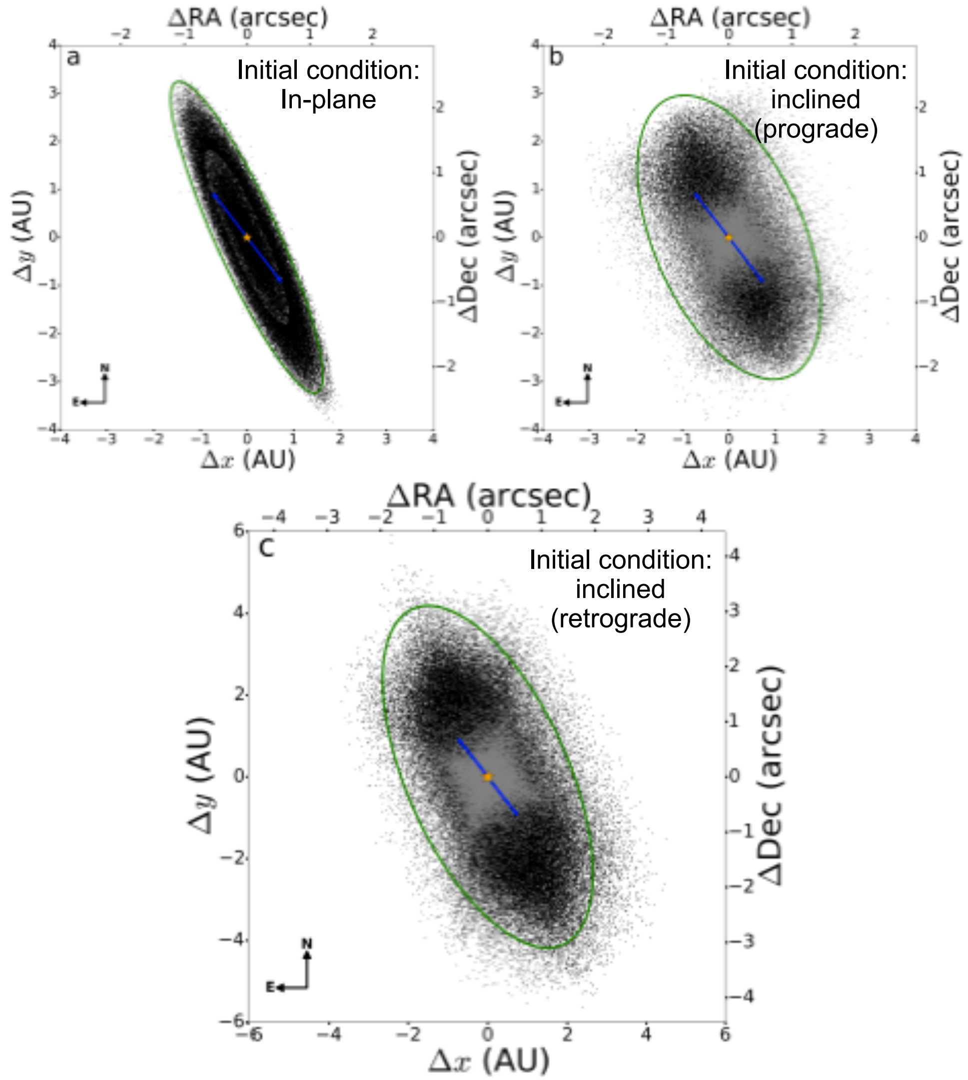
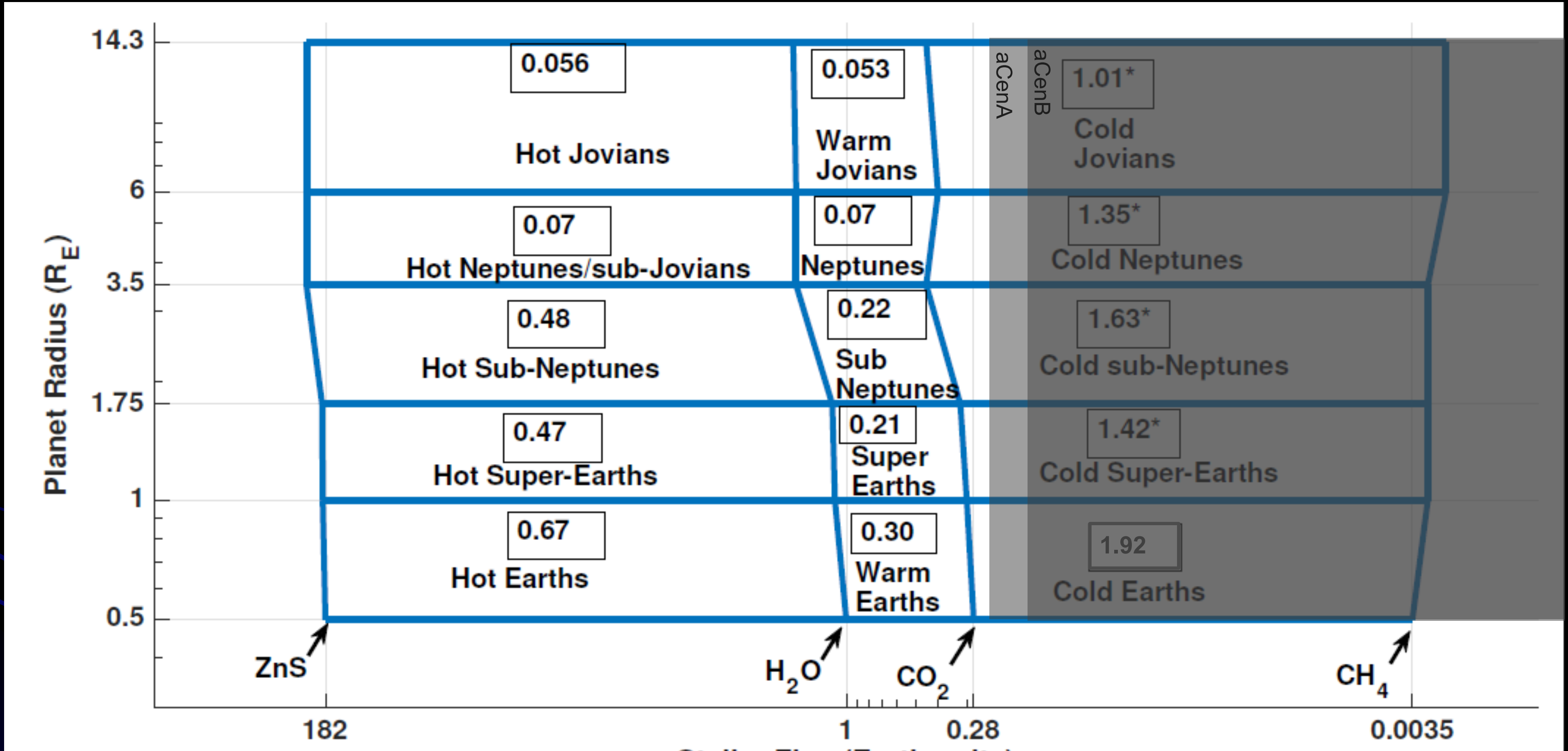


Figure 9. Projection of the stellar orbit of α Cen AB at apastron onto the sky. The astrocentric orbit α Cen B about α Cen A is shown by the dashed curve, with the stars shown at apastron. The center of mass (dot near the center of the image) is shown along with the barycentric ellipses for both α Cen A (red) and α Cen B (blue). Disks have been placed around each star to illustrate the areal coverage of stable test particles orbiting with the plane of the binary. The scale for potential observers in Right Ascension and Declination is given on the top and right axis, respectively.



Quarles and Lissauer, 2016

Occurrence rates for different planet types



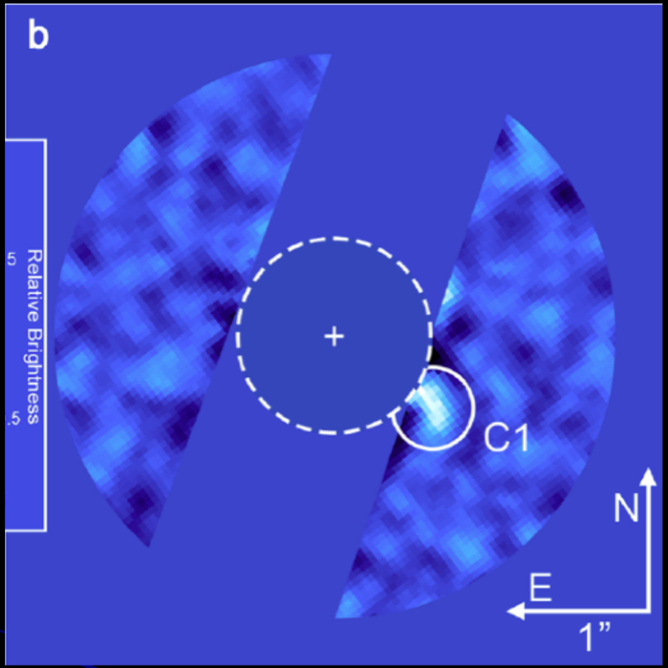
Kopparapu et al 2018

Total hot and warm planets ~3 per star
(similar to the Solar system!)

*Cold planet numbers are based on extrapolations and are likely overestimated
Most cold planets would be on unstable orbits around Alpha Centauri AB

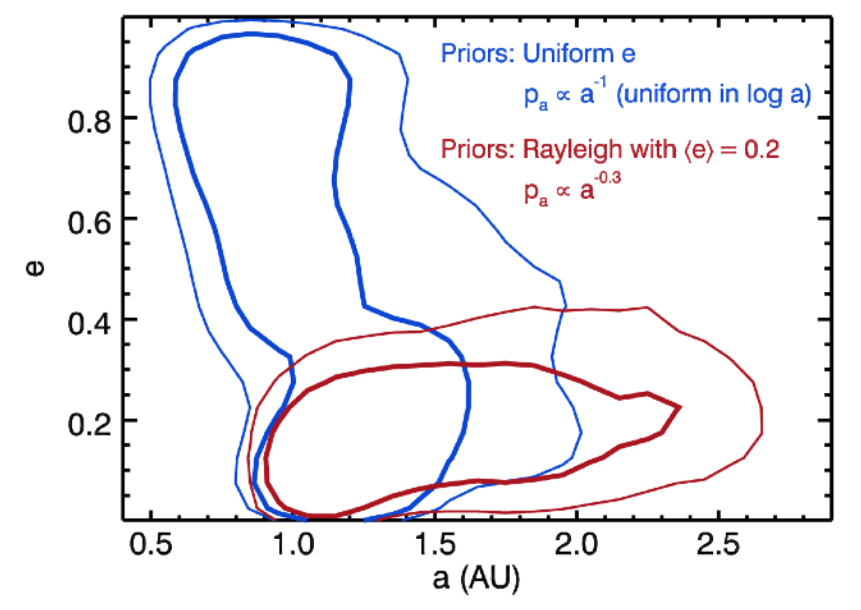
Candidate detection by NEAR around aCen A

aCen A C1 detection image



Wagner et al. 2020
R ~ 3.3 – 7 Re

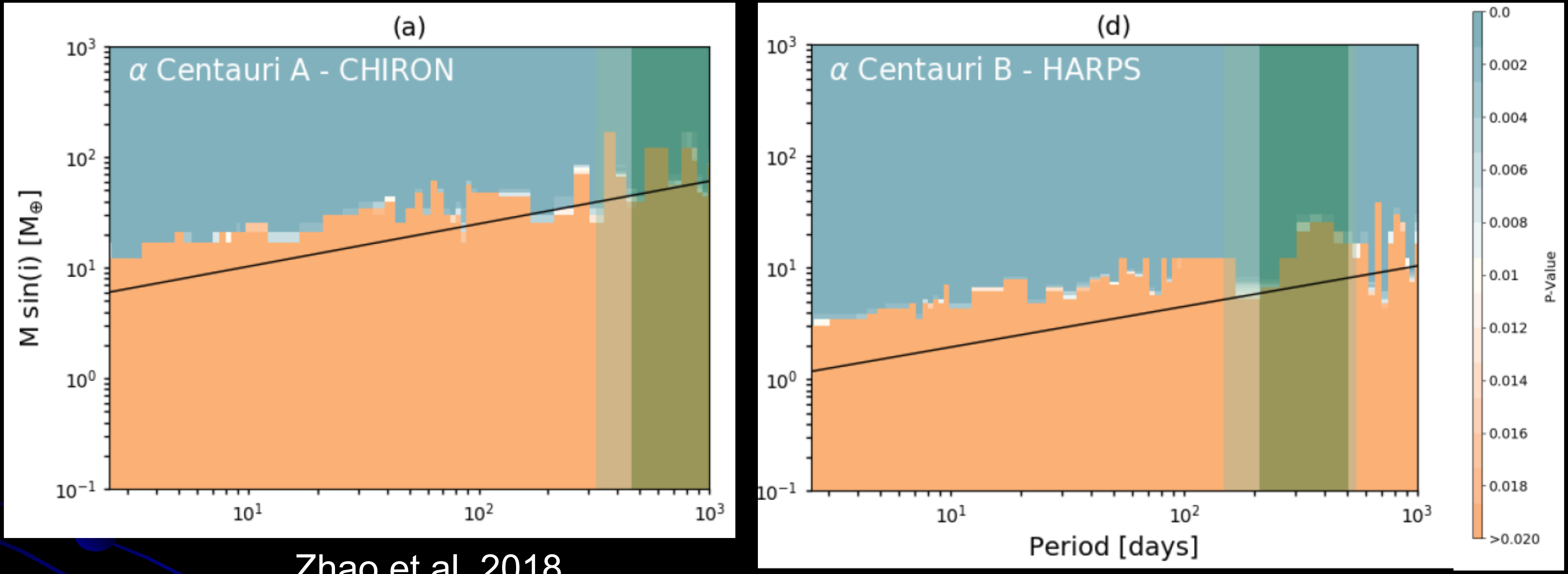
Eccentricity and SMA posteriors



Maxwell Moe

- If C1 is a real planet, then the suppression factor (probably) goes away – aCenAB occurrence rates become similar to single stars.
- However, because C1 is in the HZ, it will “carve out” some of the HZ, leaving less space for rocky HZ planets
  - Habitable zone planets are still possible, if eccentricity is low (private communication, Lissauer and Quarles)
- With uniform priors on e and log a (Wagner et al. 2020), optimal solution for C1 is 1.1 AU, and high eccentricity
- With possibly more realistic priors, optimal solution is 1.6 AU and low eccentricity, which is not as strong of a HZ disruption

m sin(i) limits from RV non-detections



Zhao et al. 2018

- Limits for habitable zone (p-value = 0.01)
    - 53 M_Earth (0.17M_Jup) for aCen A
    - 8.4 M_Earth (0.026M_Jup) for aCen B
    - (For reference, Neptune mass: ~17 Earths)

Mass-Radius Relationship

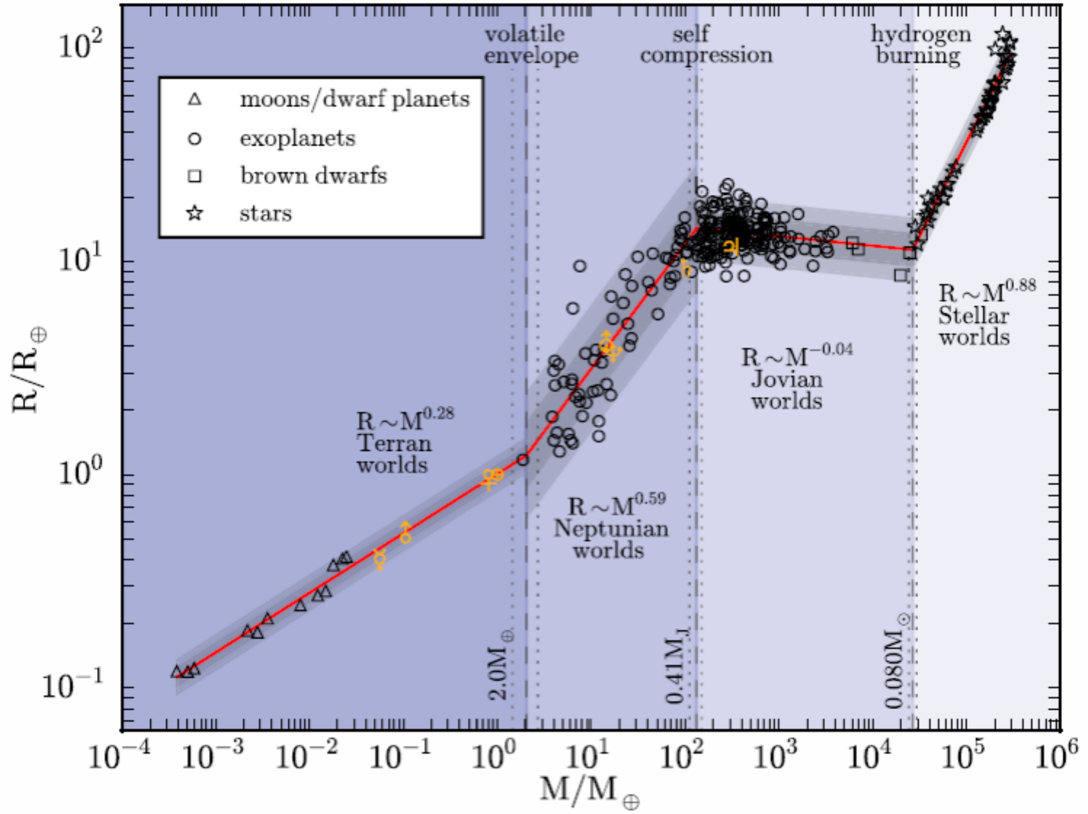


Figure 3. Mass–radius relation from dwarf planets to late-type stars. Points represent the 316 data points against which our model is conditioned, with the data key in the top left. Although we do not plot the error bars, both radius and mass uncertainties are accounted for. The red line shows the mean of our probabilistic model and the surrounding light and dark gray regions represent the associated 68% and 95% confidence intervals, respectively. The plotted model corresponds to the spatial median of our hyper-parameter posterior samples.

Chen and Kipping 2017

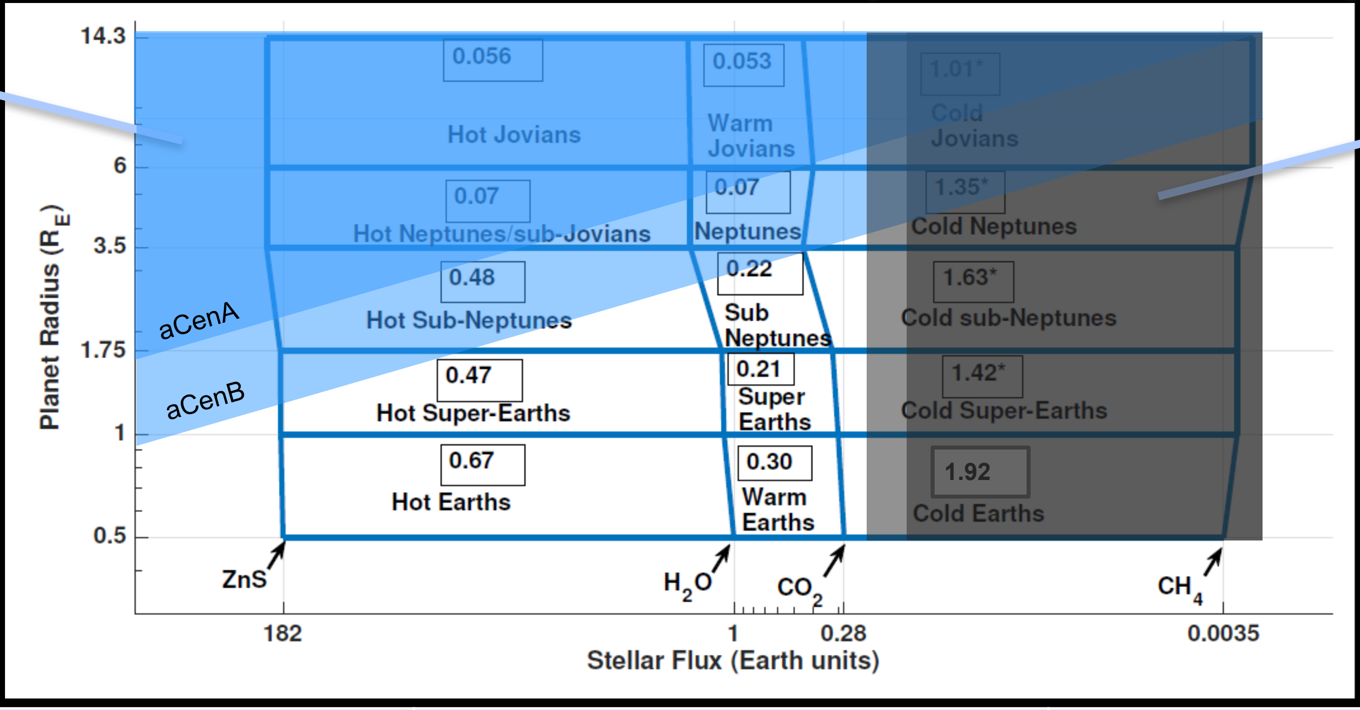
Putting everything together:

what occurrence rates can we expect around Alpha Centauri AB?

Ruled out by RV non-detections

(note: this region boundary is very uncertain due to mass-radius relationship uncertainty)

Ruled out by dynamical stability



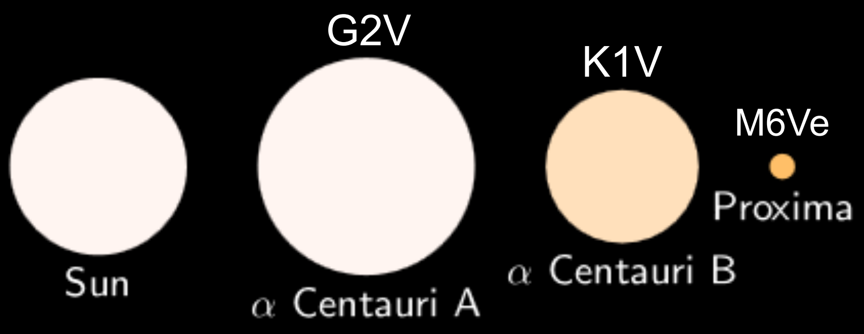
	Total expected number of planets [0.5-13 Re, 0-2.5AU]	**Expected number of Potentially habitable planets [0.5-1.5 Re, Kopparapu et al. 2013 conservative HZ]**
Combined single+binary occurrence from Kepler (per star)	~ 3	
after correction for binarity (counting both stars)	~ 2	
after accounting for RV non-detections (both stars)	~ 2	
if NEAR candidate is real, and assuming it does not disrupt HZ (both stars)	~ 8	~

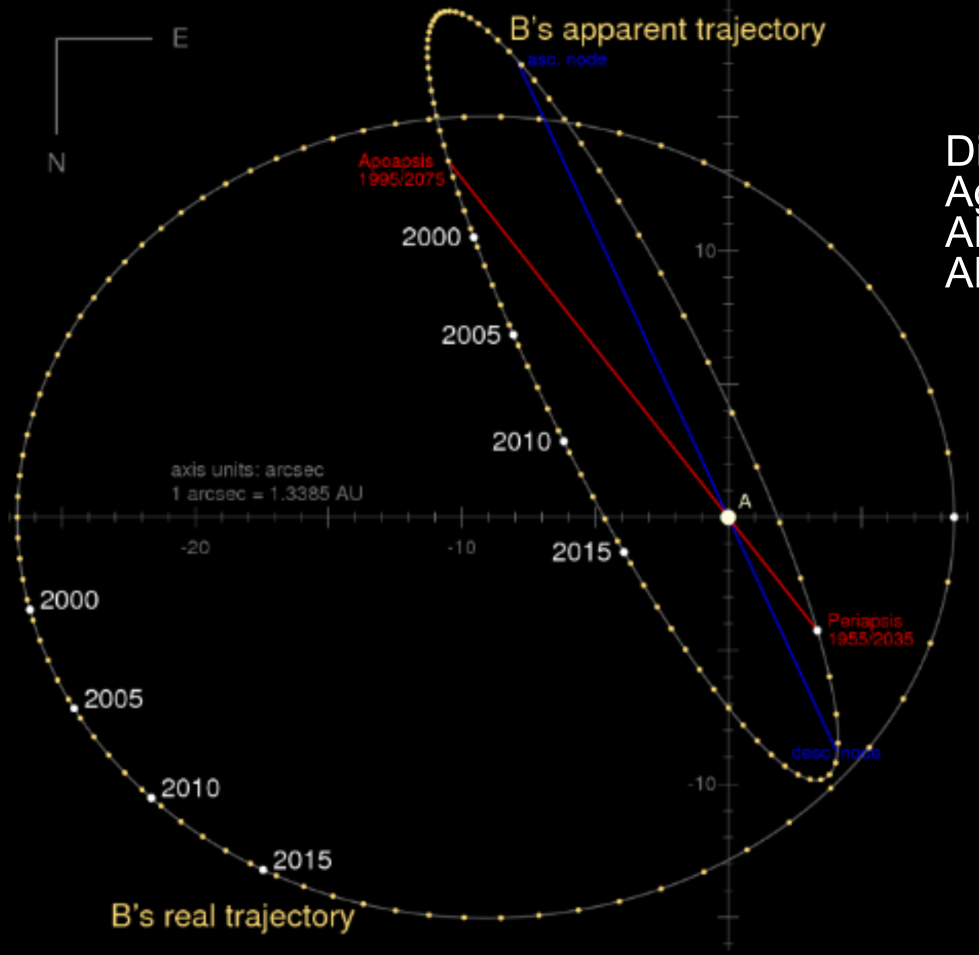
Caveat: due to numerous uncertainties, and evolving understanding of various effects, the above numbers can still change

Conclusions

- Alpha Centauri AB is a promising system in the search for potentially habitable planets, representing the closest (by a large margin) Sun-like stars to the Solar System.
- Planets can and do form around binary stars like Alpha Centauri, and the habitable zones of both stars are stable. However, planet formation around binaries may not be as efficient as around single stars
- This work estimates the number of potentially habitable planets around Alpha Centauri AB system as $0.28^{+0.25}_{-0.12}$, but if at least one planet is confirmed, this number can rise to $1.2^{+0.7}_{-0.3}$. A lot of uncertainty still remains

α Cen System Overview





Distance: 1.3pc
Age: ~4.5 – 7 Gy
AB Period: 79.91y
AB SMA: 17.57 AU