University of Southern Queensland

Like a wrecking ball: understanding giant planets as the key to finding Earths

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2023 August 31

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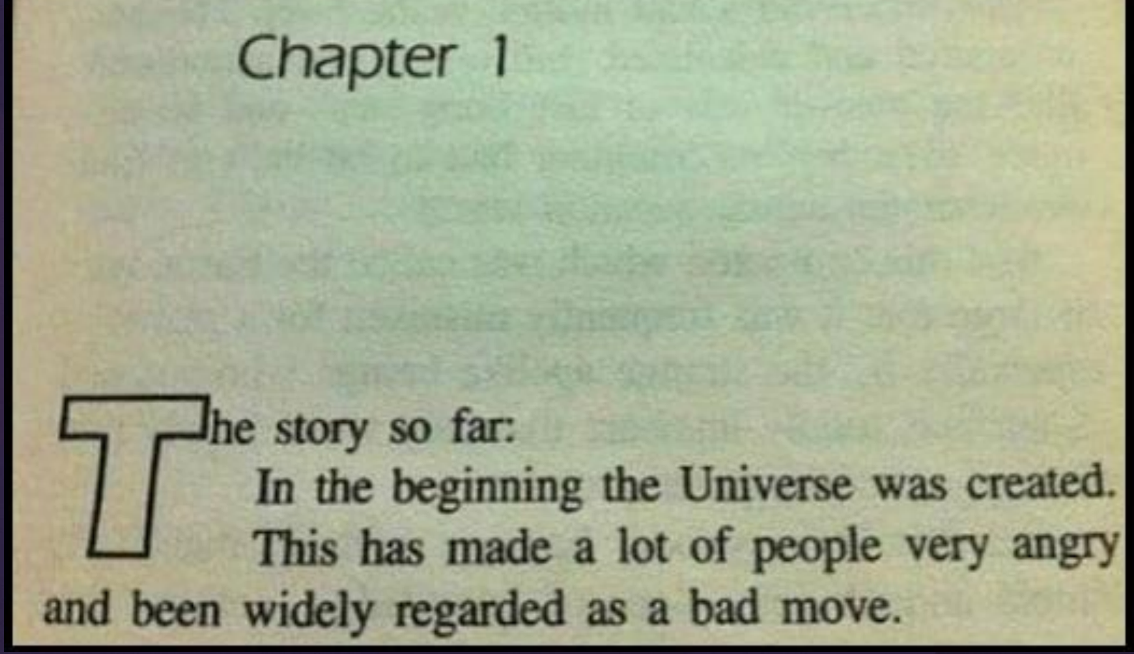
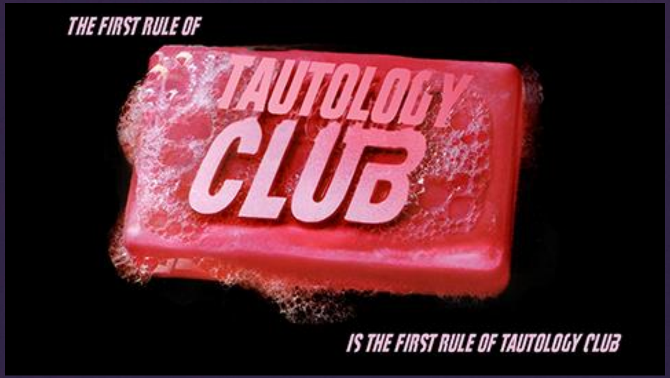

Chapter 1

The story so far:
In the beginning the Universe was created.
This has made a lot of people very angry and been widely regarded as a bad move.

- To first order, the Solar system consists of the Sun, Jupiter, and some debris.
- Seems that Earth-size planets are everywhere, but are they Earth-LIKE?
- Jupiter analogs are the key!

Why a Jupiter matters

1. Giant planets are giant!



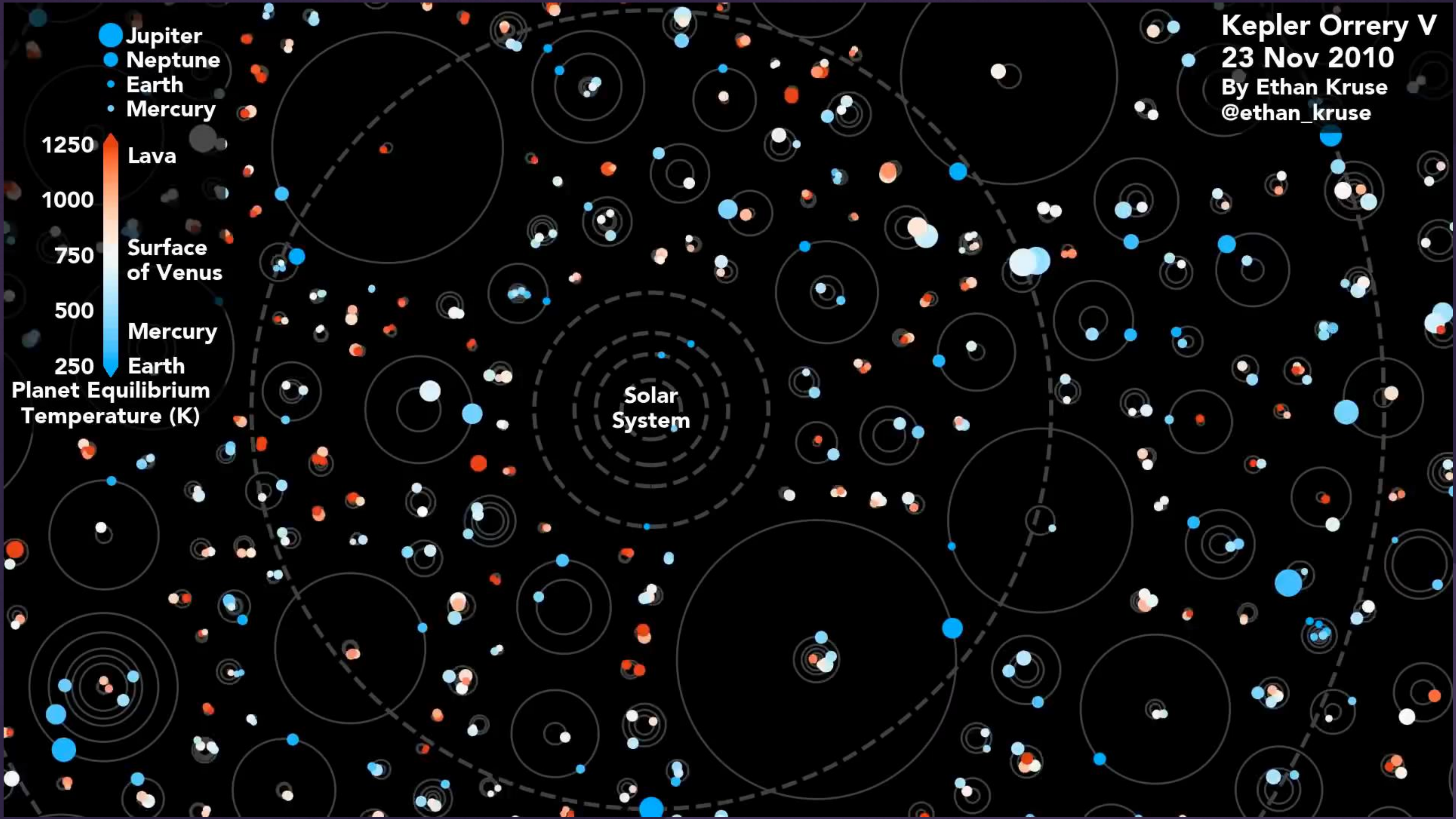
So they are the dynamically dominant force, driving the architecture of the system.

2. They can deliver water to inner planets.

3. If they are in the habitable zone, they preclude any "Earths."

Planetary systems are everywhere

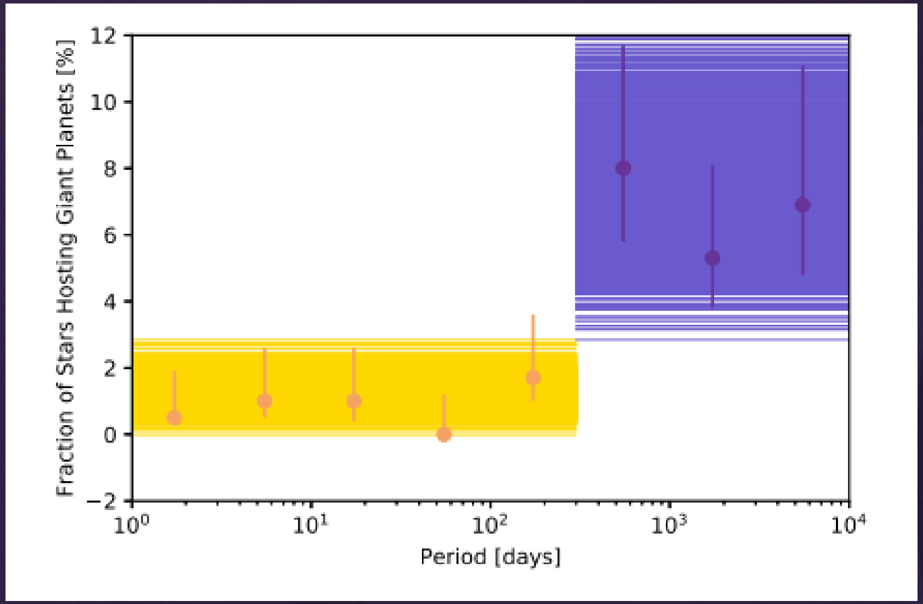
But don't look much like our Solar system



Jupiter analogs are rare

Only ~6% of systems have one with "room" for Earths

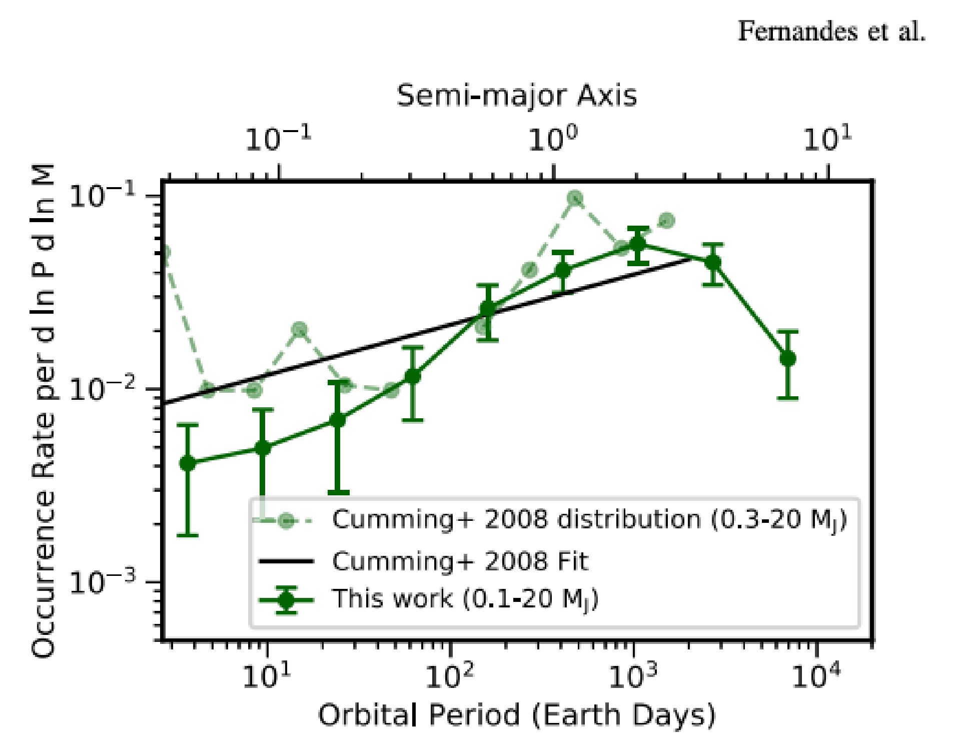
- 5-10% of stars host cool Jupiters beyond the snow line (~3 au) in general.
- 6.2 (+2.8)(-1.6) % host cool Jupiters with no [detected] interior giants. Wittenmyer+ 2016

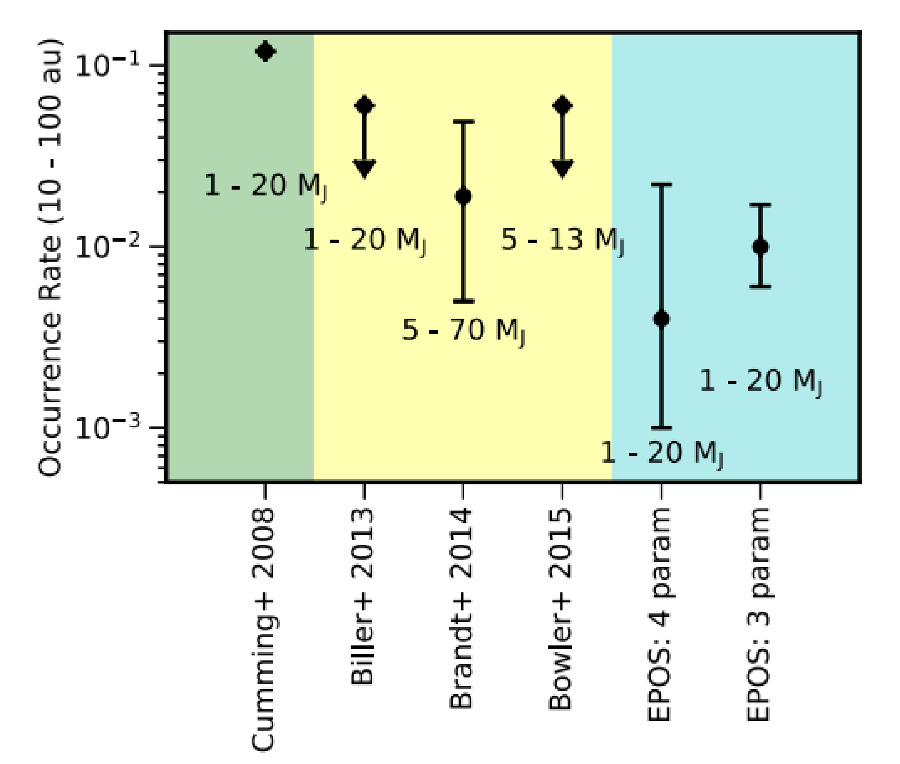


Wittenmyer+ 2020

It’s not just me

Cold giants are uncommon





Fernandes+ 2019

Friends of Cold Jupiters?

Jupiter analog systems may be more likely to host inner small planets

THE ASTRONOMICAL JOURNAL, 157:52 (18pp), 2019 February

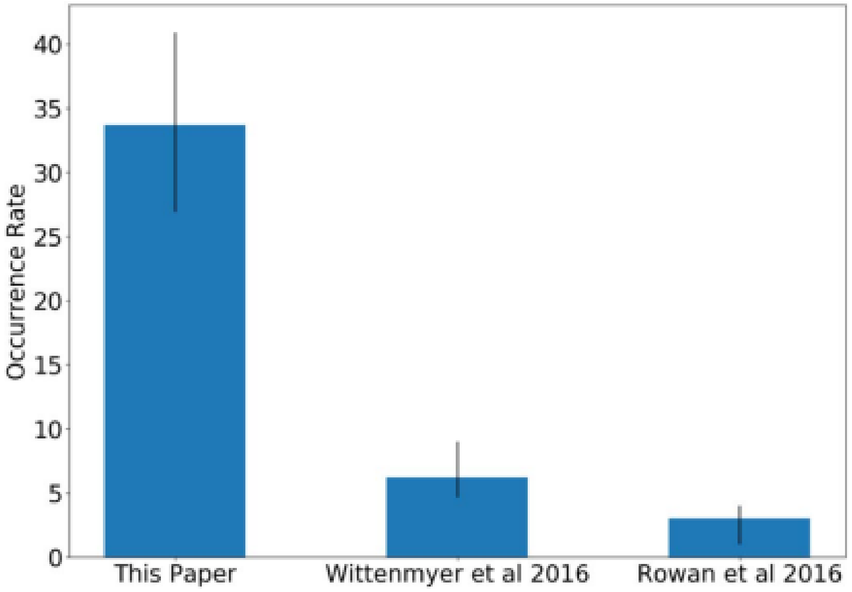


Figure 6. Compared to the Jupiter analog occurrence rate estimates published in Rowan et al. (2016) and Wittenmyer et al. (2016), this study finds a higher occurrence rate of distant gas giant planets in super-Earth systems than would be expected just based on chance. Occurrence rate integration ranges are 0.3–13 M_{Jup} and 3–7 au for this paper and Wittenmyer et al. (2016) and 0.3–3 M_{Jup} and 3–6 au for Rowan et al. (2016).

Bryan+ 2019

- Systems with inner super-Earths seem to be more likely to host cold Jupiters.

  Bryan+ 2019, Rosenthal+ 2022

- See also Weiss+ "Kepler Giant Planet Search":

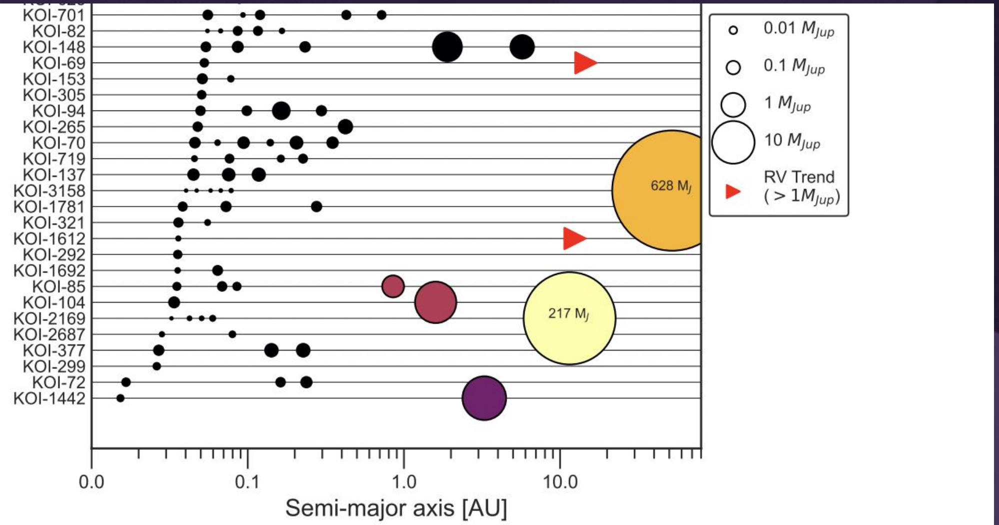
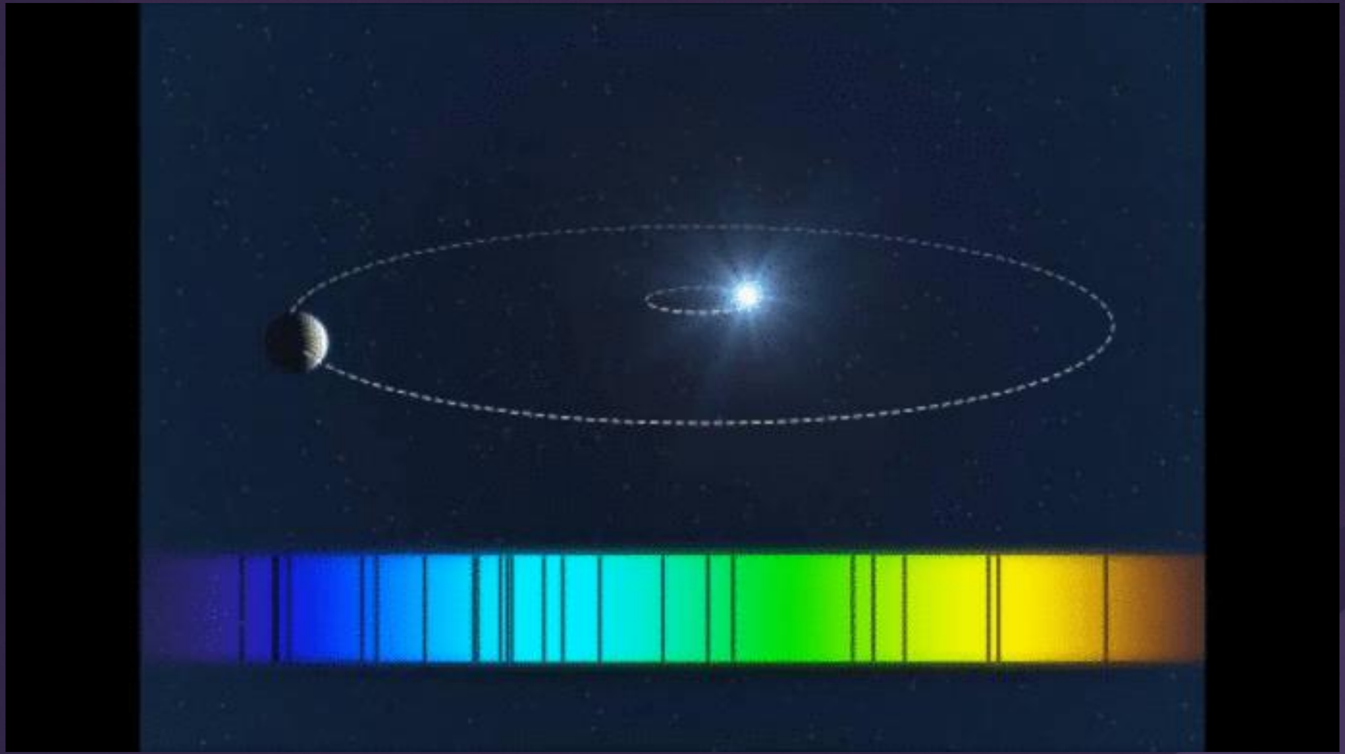


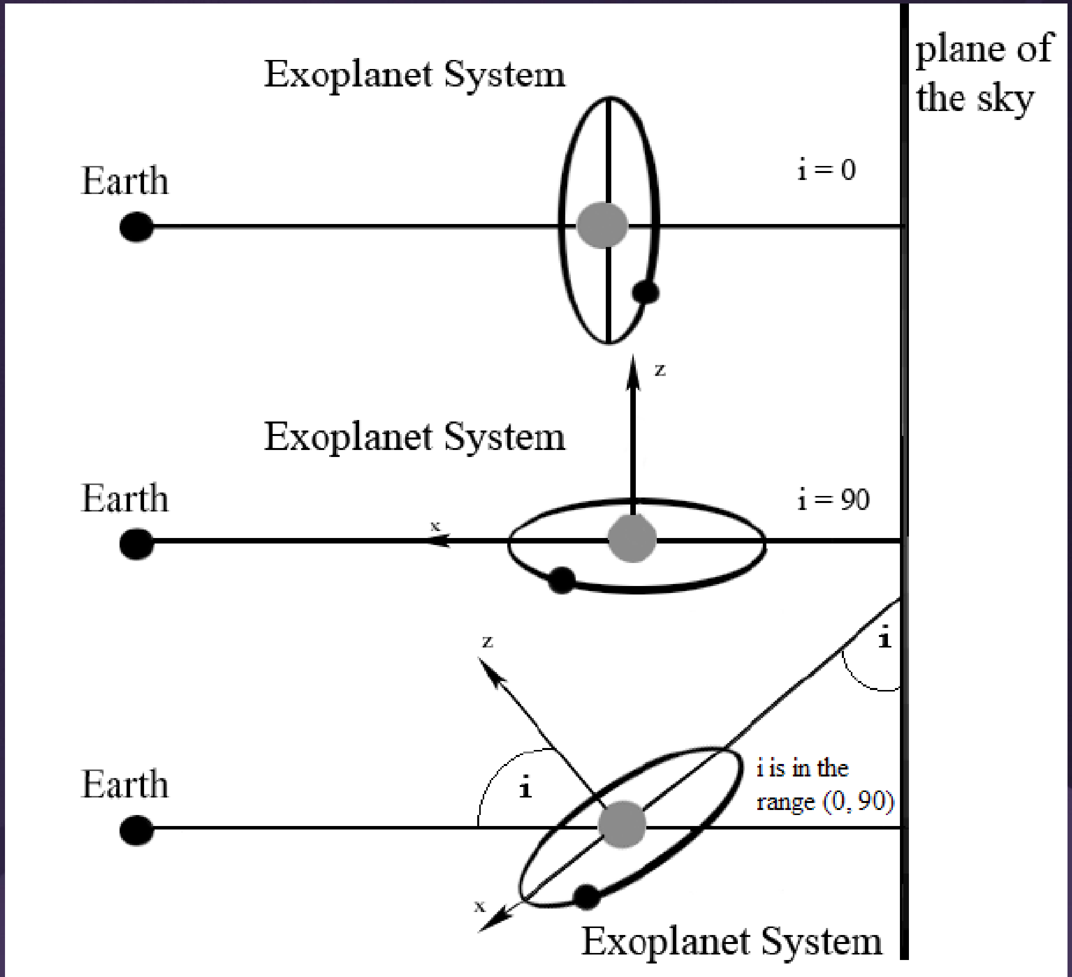
Figure 4: Architectures of the KGPS I planetary systems. Systems are ranked by the semi-major axis of the innermost known (transiting) planet. Point sizes scale with the square root of planet masses, $M \sin i$'s, or mass estimates from the Weiss & Marcy (2014) mass-radius relationship. Colors correspond to eccentricities (if measured); low-mass planets are assumed to have circular orbits.

The dirty secret

Long-period RV "planets" may be stars

- Sadly, the universe is 3-dimensional.
- This makes radial velocity mass measurements potentially confusing.





The dirty secret

Long-period RV “planets” may be stars

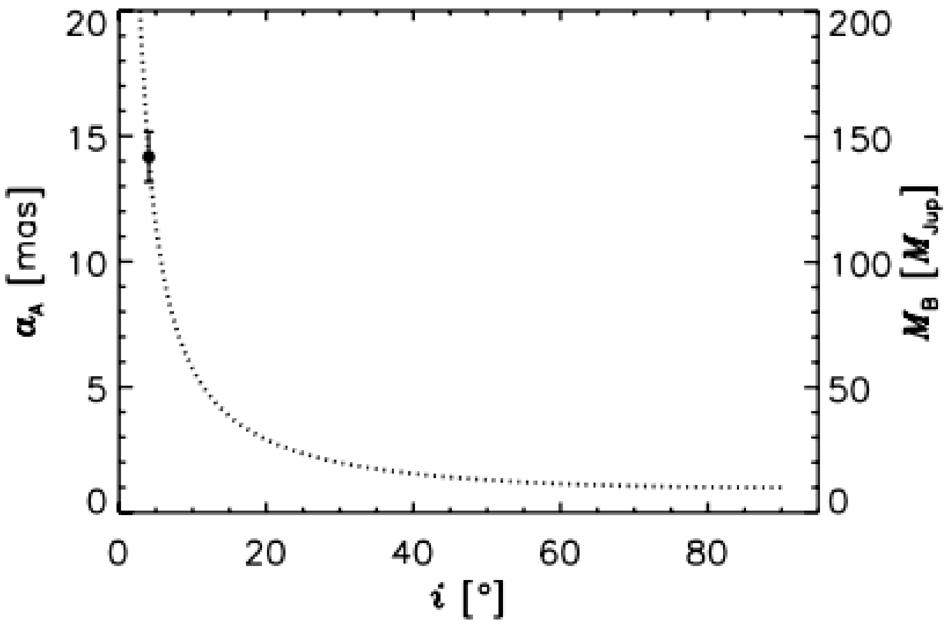


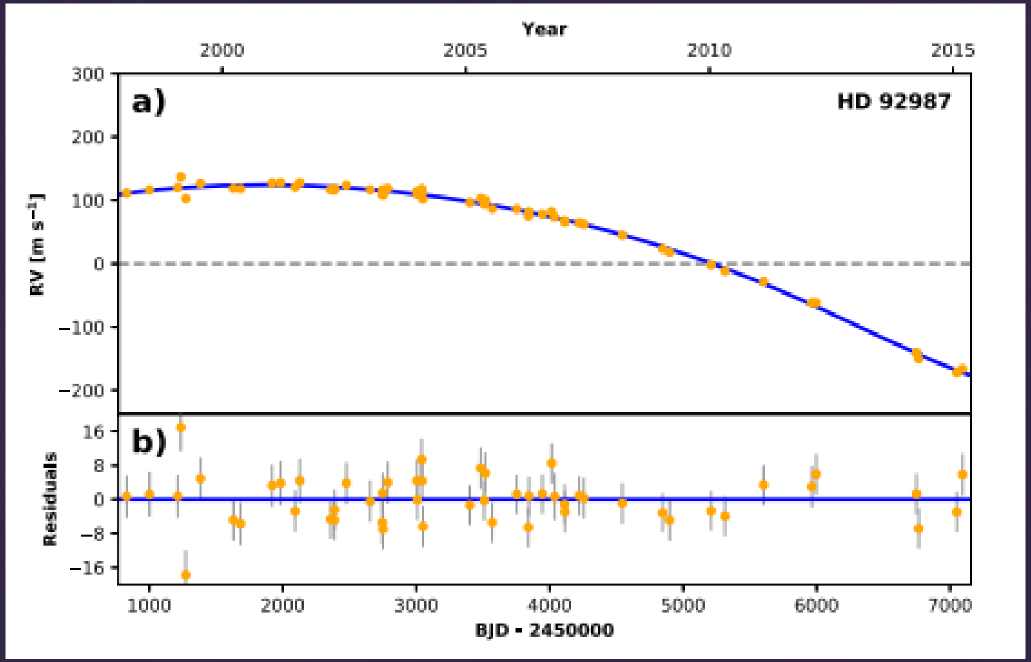
FIG. 4.—Relationship (*dotted line*) between the perturbation size (a_A) and inclination angle (i) for fixed P, K_A, e, and π_{abs} through the Pourbaix & Jorissen (2000) relationship (eq. [6]). Our determined value for the perturbation size and inclination is given by the circle. The right axis maps the inclination to the corresponding companion mass (M_B). Our adopted value for the uncertainty in the companion mass is plotted as the error bar for this axis. The formal uncertainties in our determined a_A and i are smaller than the circle.

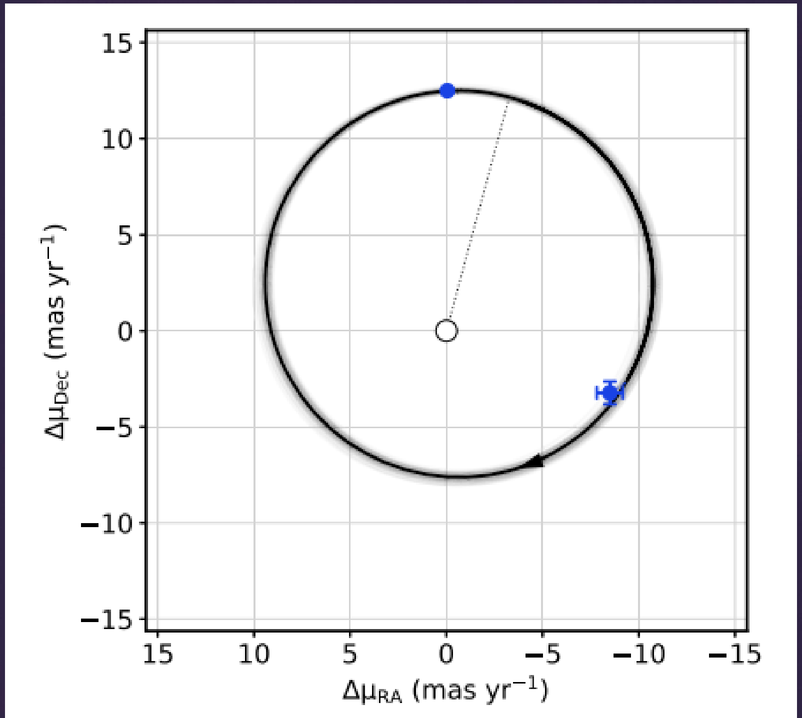
- ~170 known Jupiter analogs, nearly all disovered by RV
- So they only have minimum masses due to unknown inclination angles.
- Example: HD 33636b – P=5.8 yr, M sin i = 9.3 M_{jup}
- HST FGS astrometry → Oops i=4.1 degrees and true mass 0.14 solar masses!

Bean+ 2007

Another one bites the dust

Super-Jupiter becomes a star



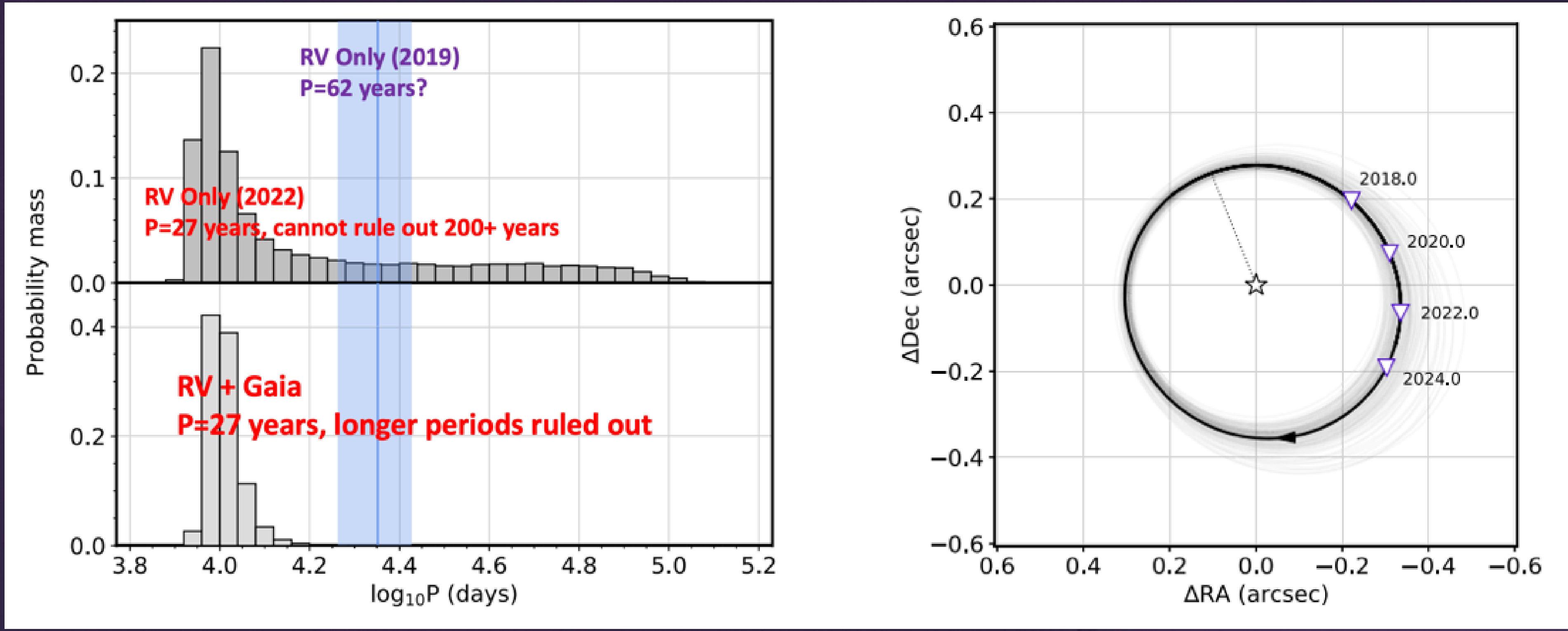


Venner+ 2021

- HD 92987b: We declared a planet in Kane+ (2019)
- P~30 yr, M sin i ~ 18 M_{Jup}
- Oops! Hipparcos-Gaia astrometric detection reveals a nearly face-on orbit
- True mass 0.256 +/- 0.005 solar

It’s not all bad news

Astrometry can constrain orbits

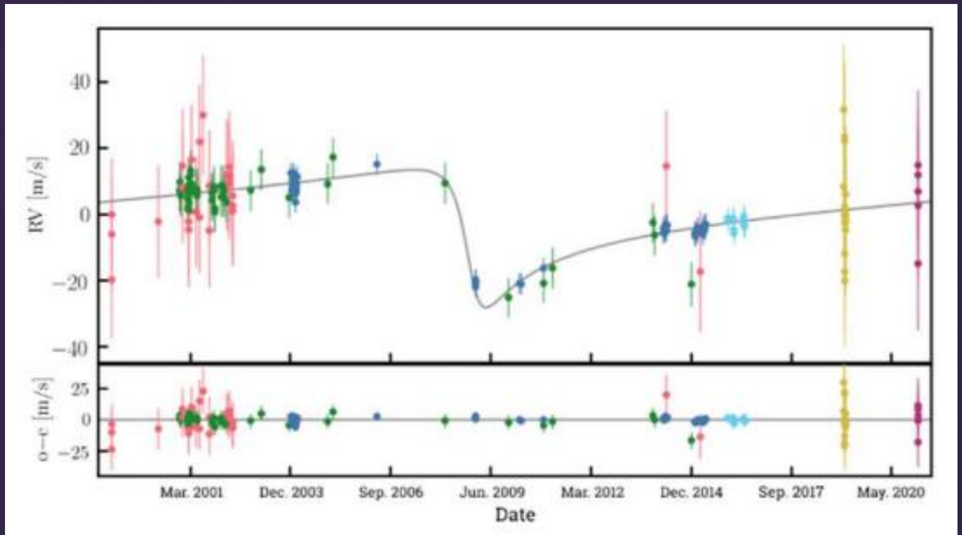


Venner+ 2021

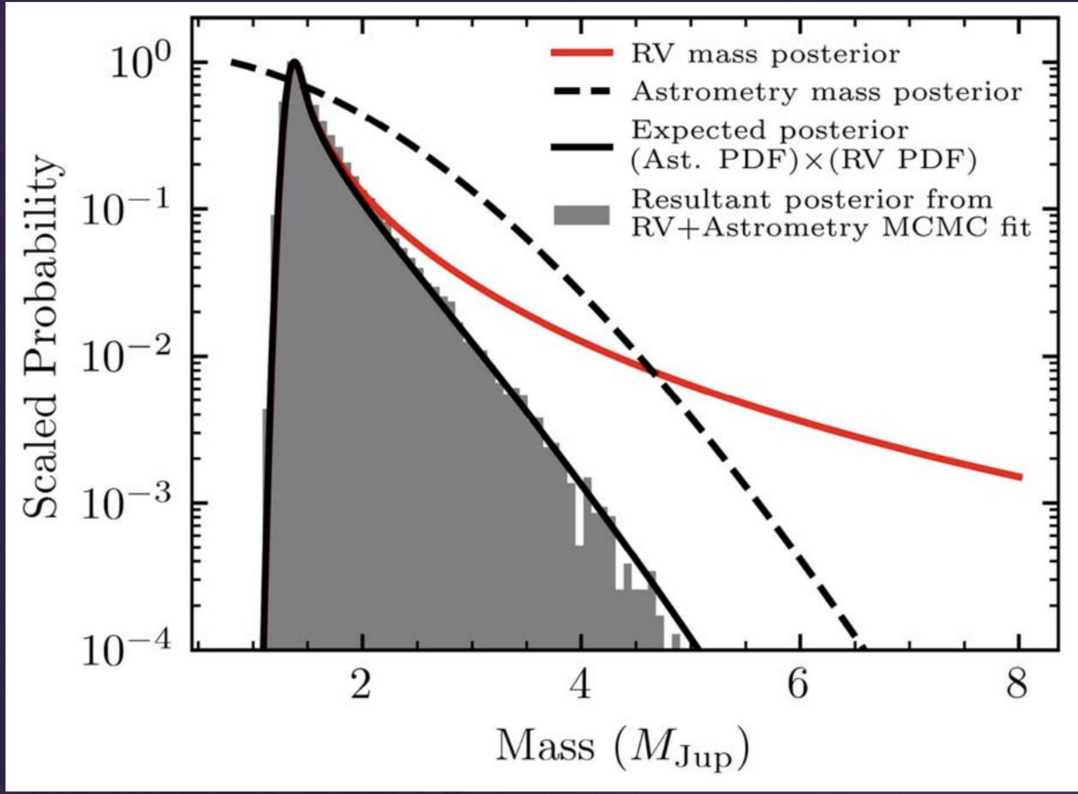
- HD 221420b: Highly uncertain orbital period refined with astrometry
- Another nearly face-on one…. True mass ~23 M_{Jup}.

Even if you do not detect the astrometry

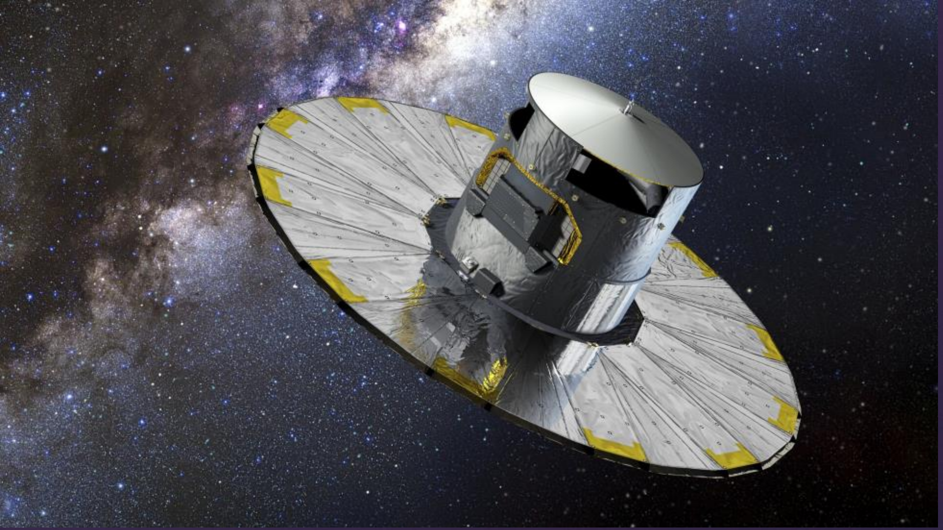
It's really a planet!



Errico+ 2022



- HD 83443c: Eccentric 22-year giant
- Hipparcos-Gaia NON-detection constrained mass!
- 1.5 (+0.5)(-0.2) M_{Jup}



Gaia will save the day

It wouldn't be an Astro talk without that statement

- DR4 will drop epoch astrometry, then we can do this for MORE PLANETS!
- Ideally do this astrometry+RV game for all ~170+ cold Jupiters.
- Detection not required – upper limits + RV limits can still usefully constrain the mass.
- Result: True masses and orbits for cold Jupiters!!

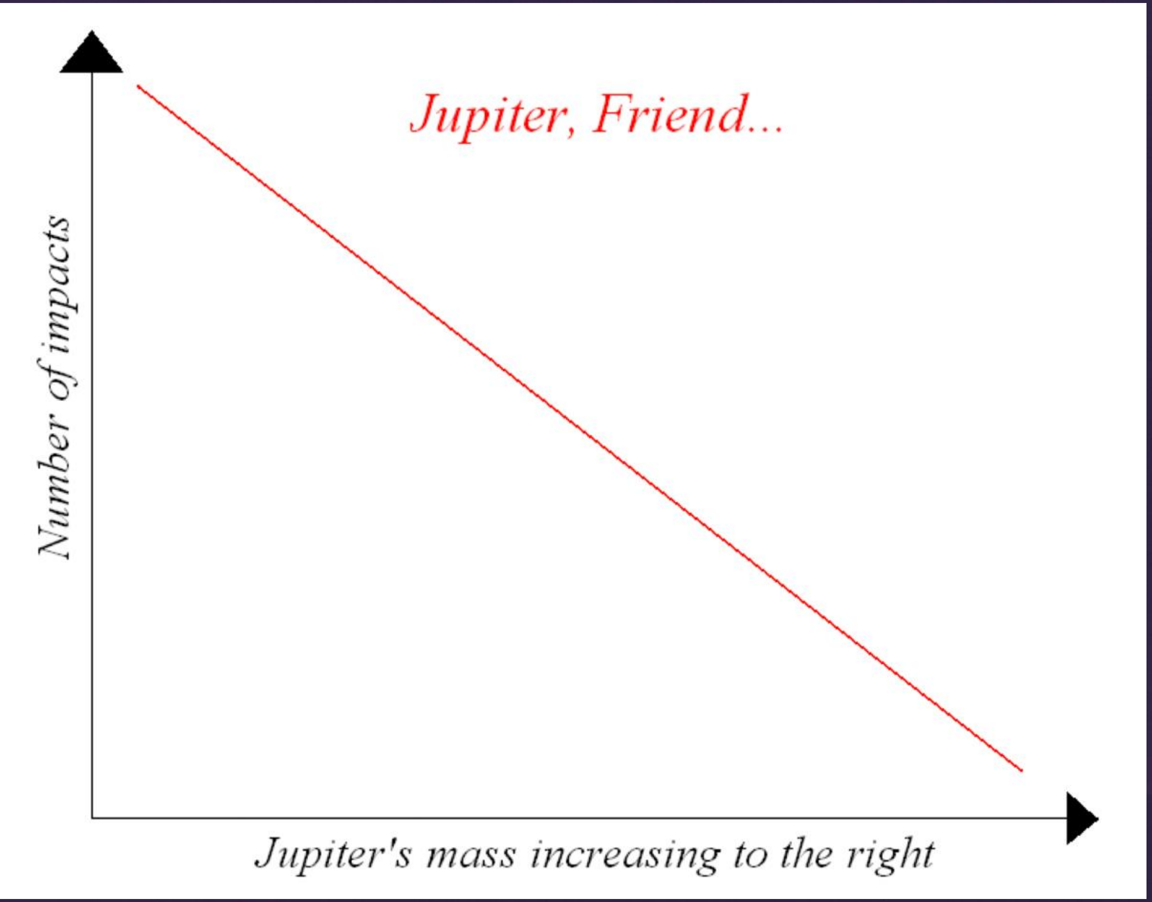
Jupiter: Friend or foe?

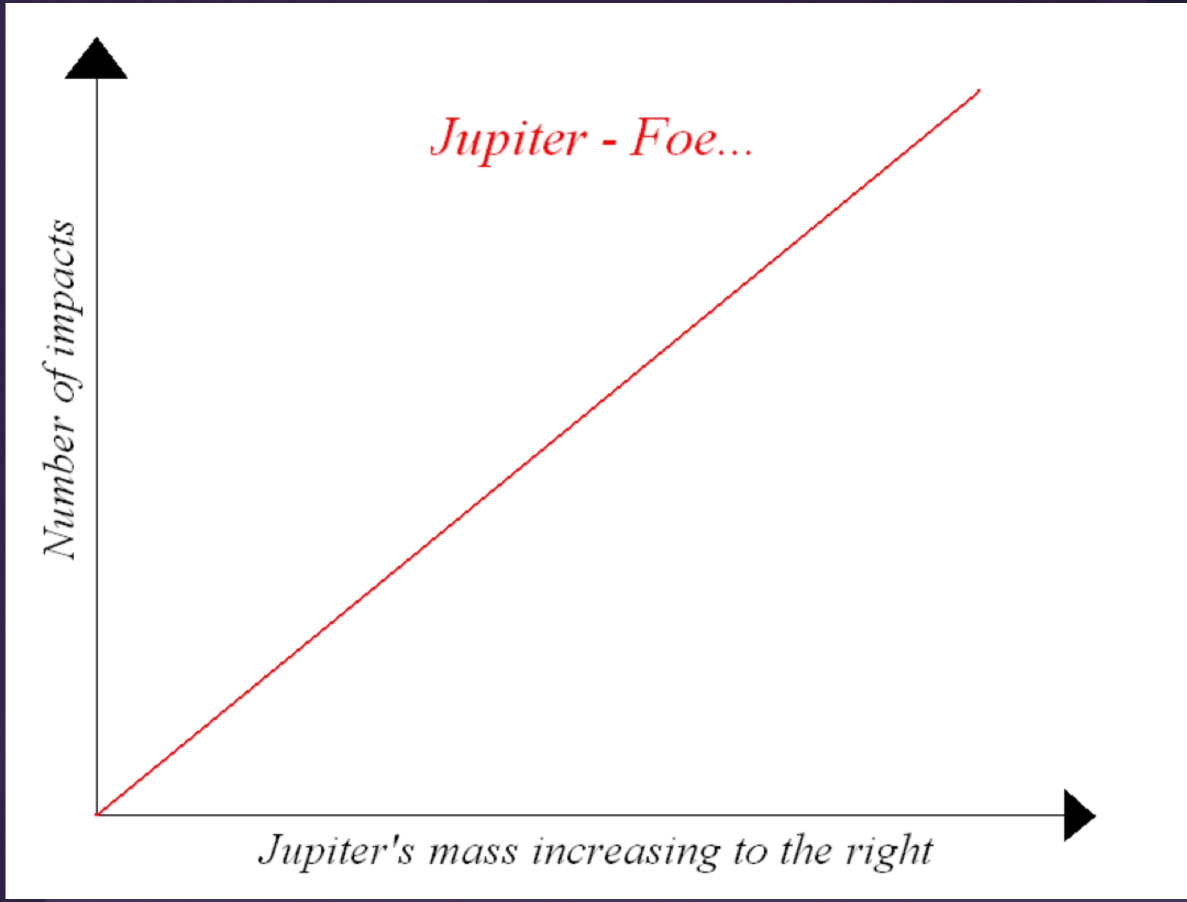
Is Jupiter a magic shield?

- Shoemaker-Levy 9 impact with Jupiter in 1994 gave people the idea that Jupiter hoovers up potentially hazardous objects
- “Jupiter as a shield” is born

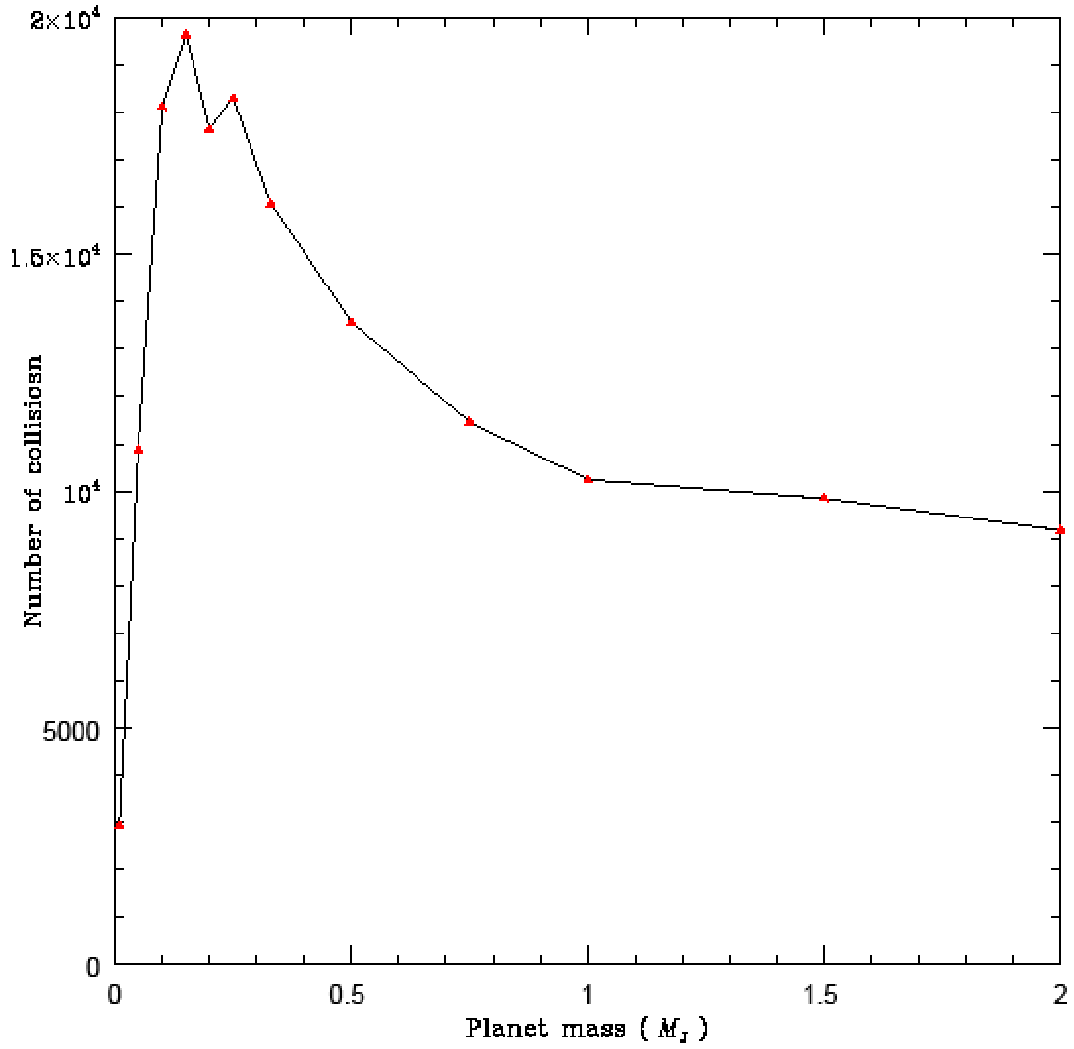
Jupiter: Friend or foe?

What if we change the mass of Jupiter?





Horner & Jones 2008, 2009, 2012



Jupiter: Friend or foe?

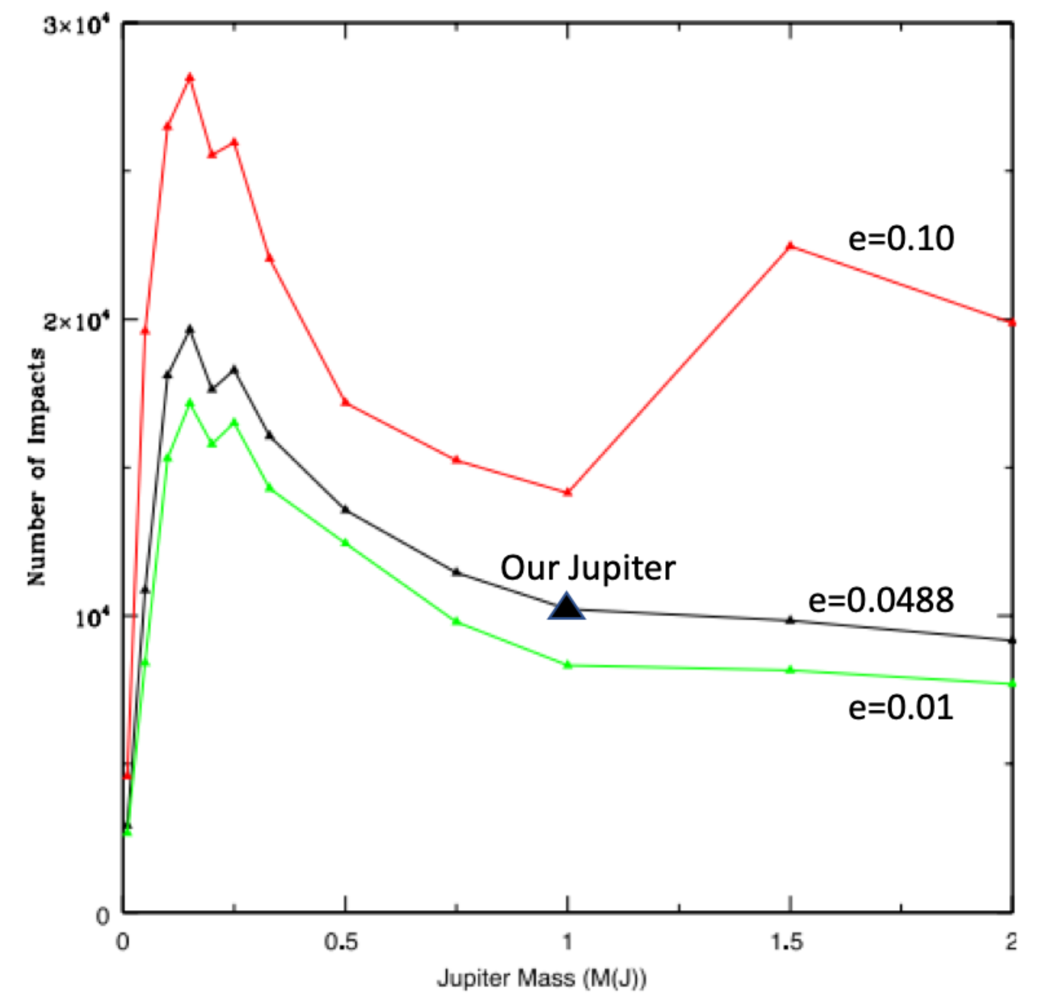
What if we change the mass of Jupiter?

- Simulate various masses of Jupiters, count how often Earth gets whacked.
- No Jupiter means far fewer impacts.
- Good news if you are a modern human, or a dinosaur.
- Small Jupiters (”Saturns”) boost impacts by ~2x

Horner & Jones 2008

Jupiter: Friend or foe?

Yes



- Changing the eccentricity also matters (so we would like to know the eccentricities of extrasolar Jupiters!)
- Guess what? RV+astrometry will help us know BOTH masses and eccentricities!

Horner & Jones 2012

Giant Meteor 2024
JUST END IT ALREADY

We like water

But not too much of it

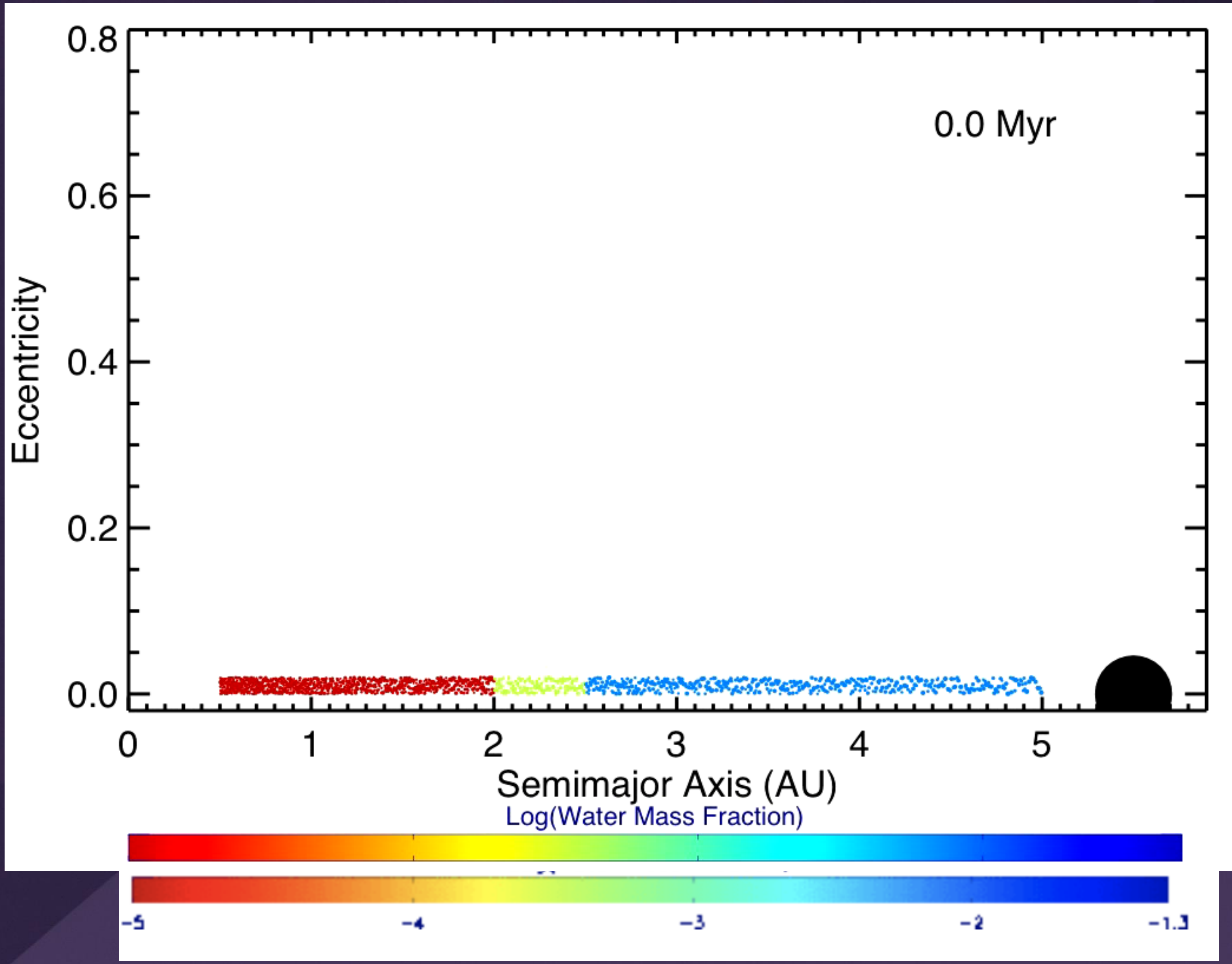
HYDRO HOMIES

- Earth formed well inside the water ice-line.
- So it formed as a desiccated hellscape.
- Our water must have been delivered by impacts!

deliveroo

- Most likely from outer asteroids 2.5-4 au

e.g. Morbidelli+ 2000



Raymond+ 2006, *Science*

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We like water

But not too much of it

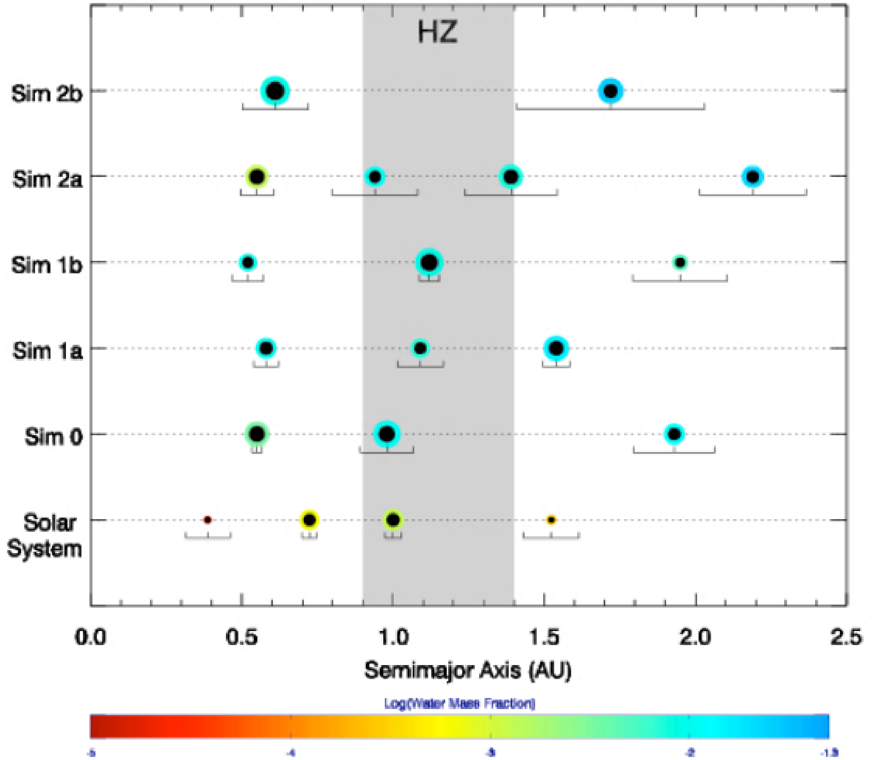

Figure 6 -- Final configurations of all five high-resolution simulations, with the Solar system terrestrial planets shown for scale. The relative size of each body corresponds to its relative physical size, and the color of each body represents its water mass fraction. The size of the dark inner region corresponds to the relative size of each planet's iron core. The shaded region (labeled "HZ") represents the habitable zone.

- Forming Earths with a Jupiter present
- But we often end up with too much water
- See also the "water worlds" transit surveys keep finding with like an Earth mass of water.
- So the size and orbit of a Jupiter analog matter!

Raymond+ 2006, *Icarus*

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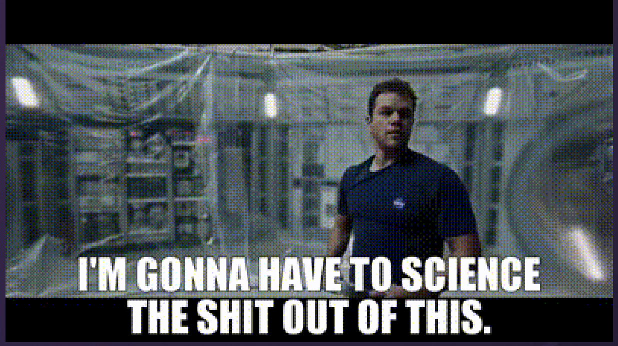
Putting it together

Did someone say ”simulations”?



- Design your universe: Using the true masses and better-constrained periods + eccentricities of Jupiters thanks to *Gaia*....
- Set up N-body simulations of those extrasolar systems
- Include debris belts (Bonus if we can get info about that from our debris disc friends)
- Run for 100 Myr, get a coffee, see how often an “Earth” gets hit.

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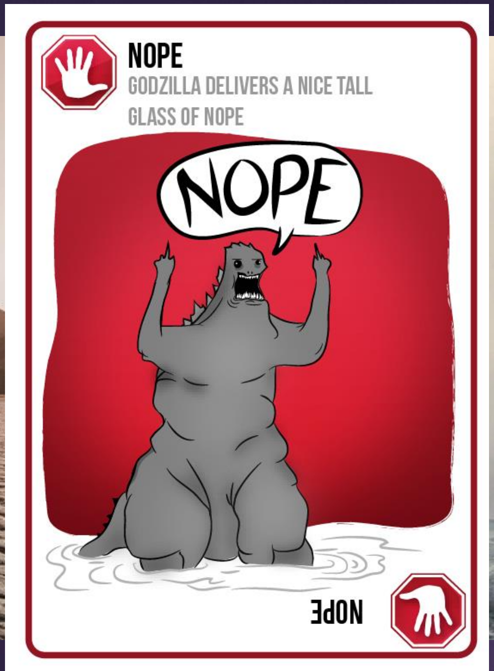
Putting it together

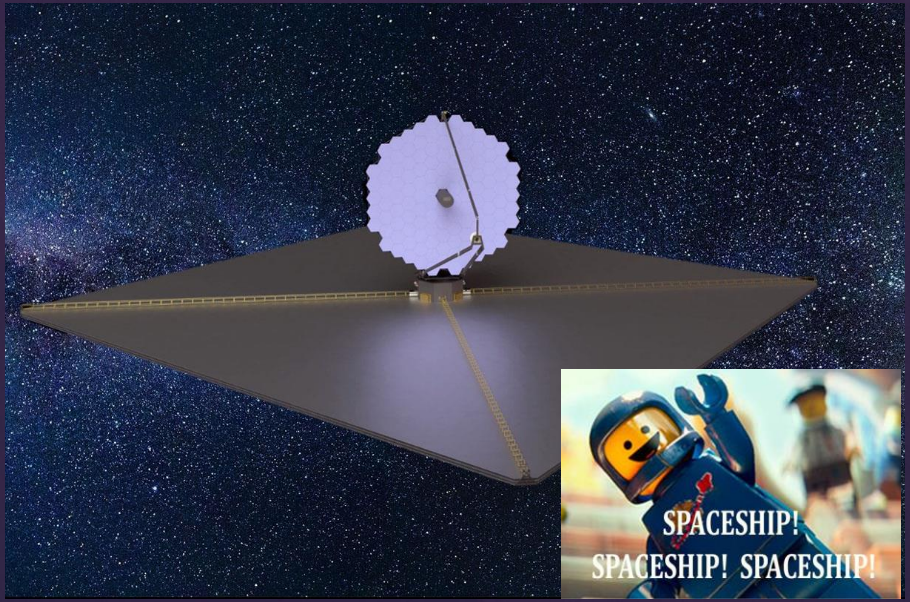
Did someone say ”simulations”?

- Result: If those systems had an Earth, would it have a chance at being hydrated enough? (and not too much?)

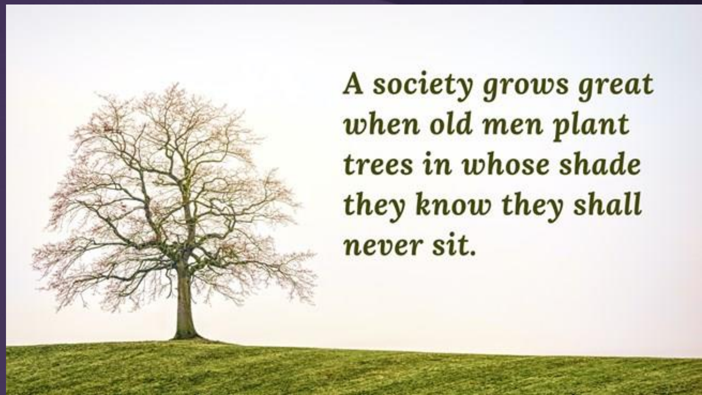


I like big telescopes

And I cannot lie



- Habitable Worlds Observatory… Imma just say "Luvex" here.
- Launch 2040s at great expense
- Goal: Image rocky planets in the habitable zone.
- Target ~100 nearby Sun-like stars
- Which targets will be the best?



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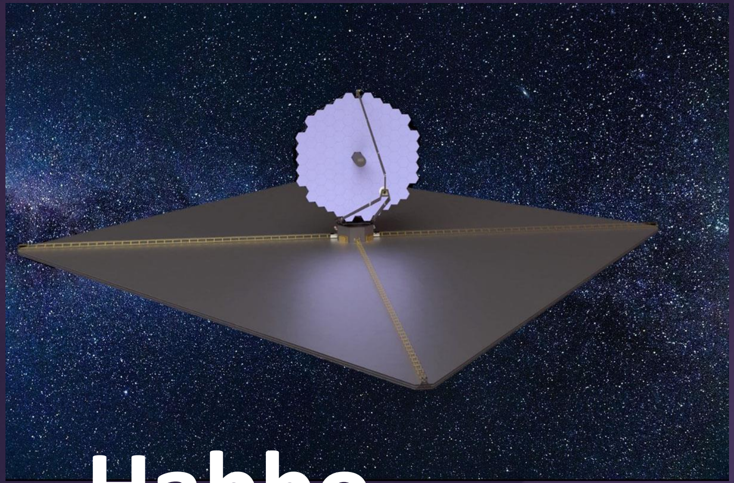
Aussies like shortening words

I have 20 years to make "Habbo" happen



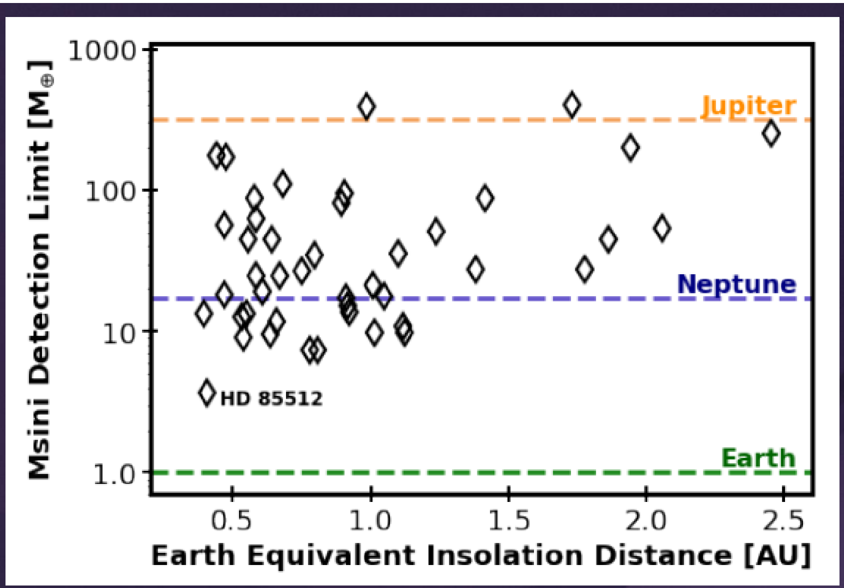
Habbo

Gaseous troublemakers

Not the ones in Canberra or Washington

Doppler Constraints on Planetary Companions to Nearby Sun-like Stars:
An Archival Radial Velocity Survey of Southern Targets for Proposed NASA Direct Imaging Missions*

Katherine Laliotis,[1] Jennifer A. Burt,[2] Eric E. Mamajek,[2,3] Zhexing Li,[4] Volker Perdelwitz,[5,6] Jinglin Zhao,[7] R. Paul Butler,[8] Bradford Holden,[9] Lee Rosenthal,[10] B. J. Fulton,[10,11] Fabo Feng,[12,13] Stephen R. Kane,[4] Jeremy Bailey,[14] Brad Carter,[15] Jeffrey D. Crane,[16] Elise Furlan,[17] Crystal L. Gnilka,[18] Steve B. Howell,[18] Gregory Laughlin,[19] Stephen A. Shectman,[16] Johanna K. Teske,[8] C. G. Tinney,[20] Steven S. Vogt,[9] Sharon Xuesong Wang,[21] and Robert A. Wittenmyer[15]



Laliotis+ 2023

observations to confirm. Our results show that for many of these stars we are not yet sensitive to even Saturn-mass planets in the habitable zone, let alone smaller planets, highlighting the need for future EPRV vetting efforts before the launch of a direct imaging mission. We present evidence that the

There might be giants

Which do not play well with Earths

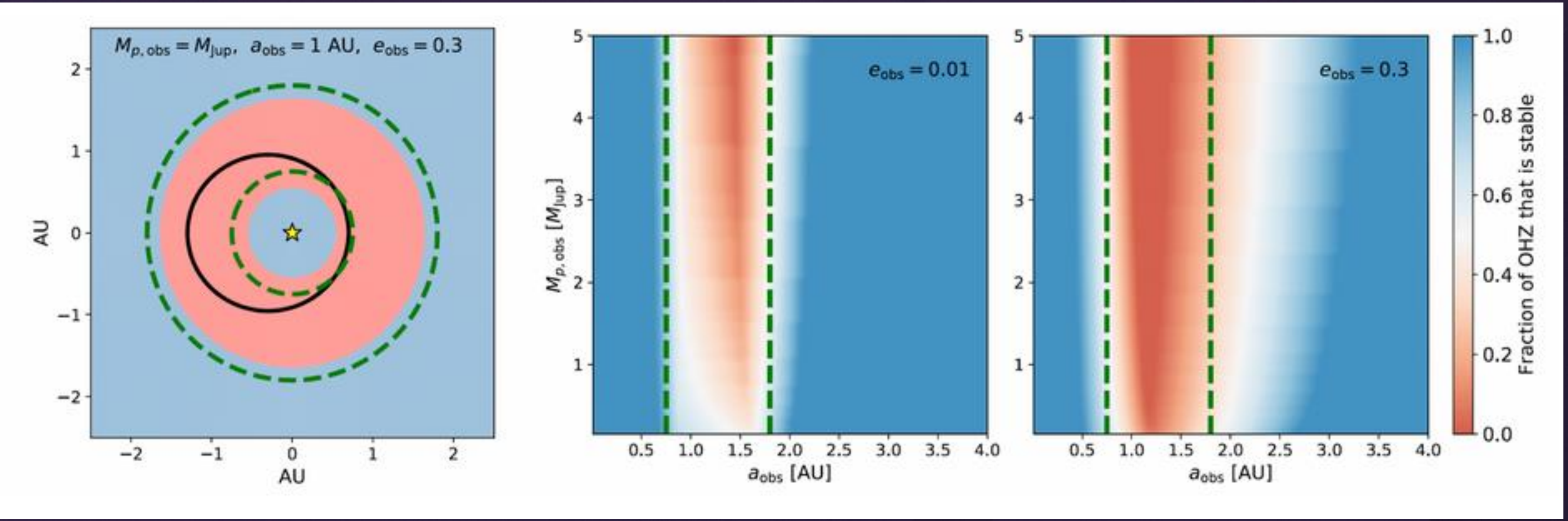
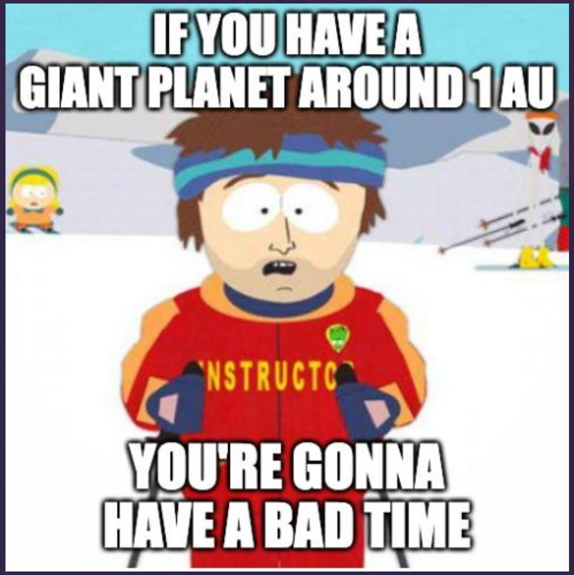


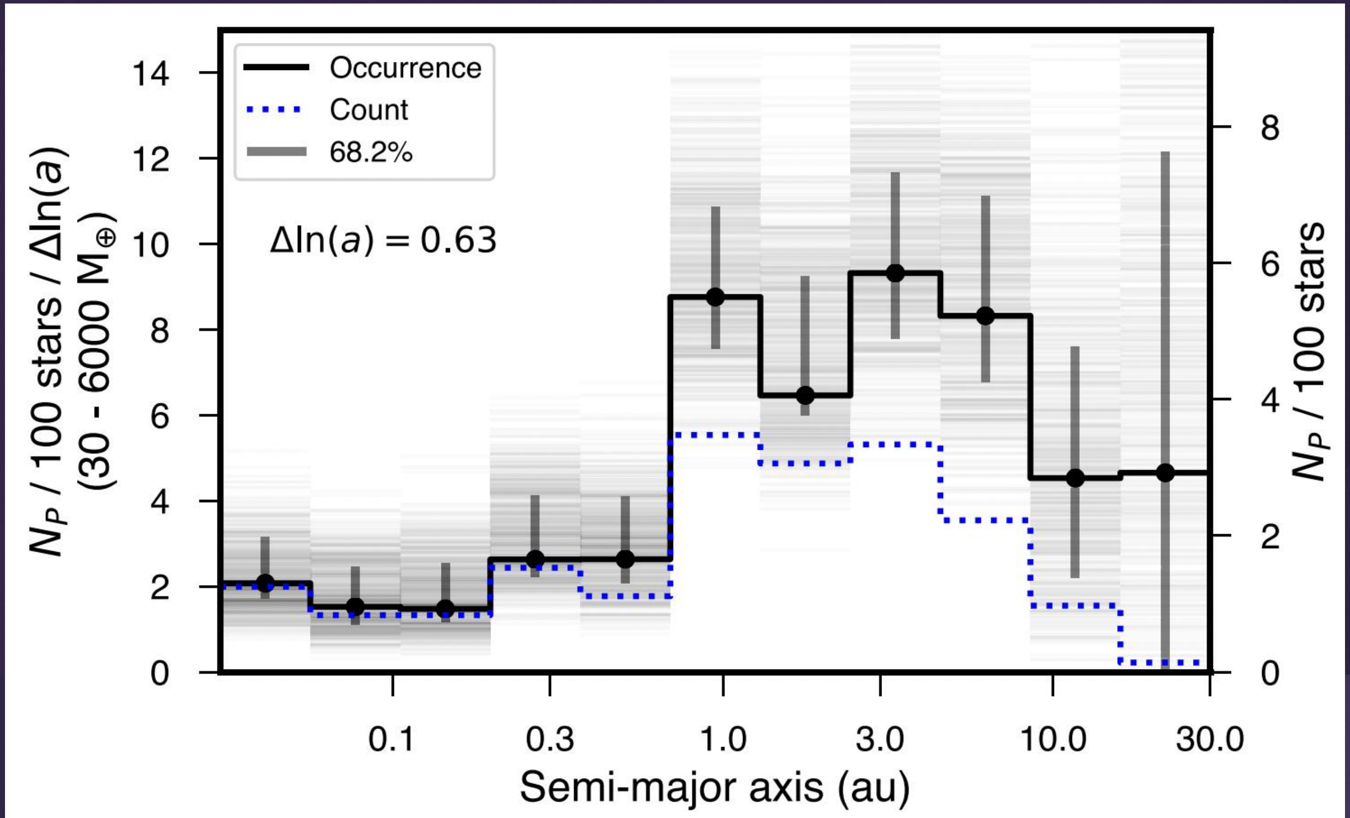
Image credit: Sarah Milholland



- RV legacy data remain shockingly insensitive to ~100ish Earth-mass planets in the habitable zone!
- Such interlopers are…dynamically incompatible with an Earth analog

And they are relatively common

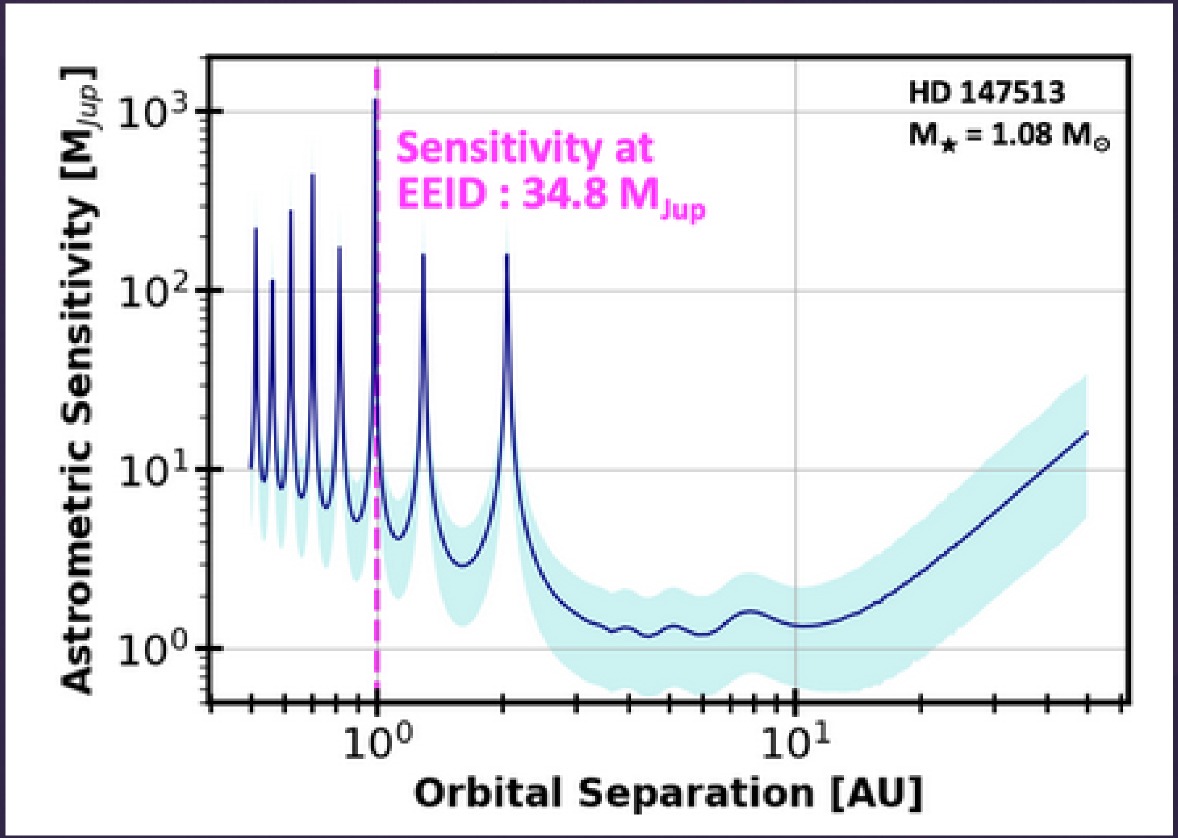
Ish



Fulton+ 2021

Gaia will NOT save the day

Betcha didn't see that one coming



- These disruptive giants are too close to star to be detected with *Gaia*.
- The only way to rule them out is with RVs, and TIME.
- Orbital periods ~100-500 days or so at habitable zones
- You'll really want several orbital cycles
- So 3-5 years intensive RV monitoring

Kervella+ 2022

The best time to start was 20 years ago

The second best time is now

- The likely Luvex/Habbo targets are pretty much all well-studied RV targets.
- So there are 10-20+ years of quality RV data
- But the data are cursed (well, just irregular cadence)
- But we can solve that by observing them MORE

Planets are like cockroaches

If you see one, there are many more you missed

- If you look hard enough, planets are everywhere!
- But vast amounts of data are needed to get these signals.
- The required observing intensity is impractical for large telescopes... No TAC will give me 300 nights of HARPS time for this.

So I built my own bloody telescopes

The O.G. MINERVA, Mt Hopkins

MINiature Exoplanet Radial Velocity Array

Founding PIs: John Johnson, Jason Wright, Nate McCrady, and me

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How it works

A series of tubes

Spectrometer

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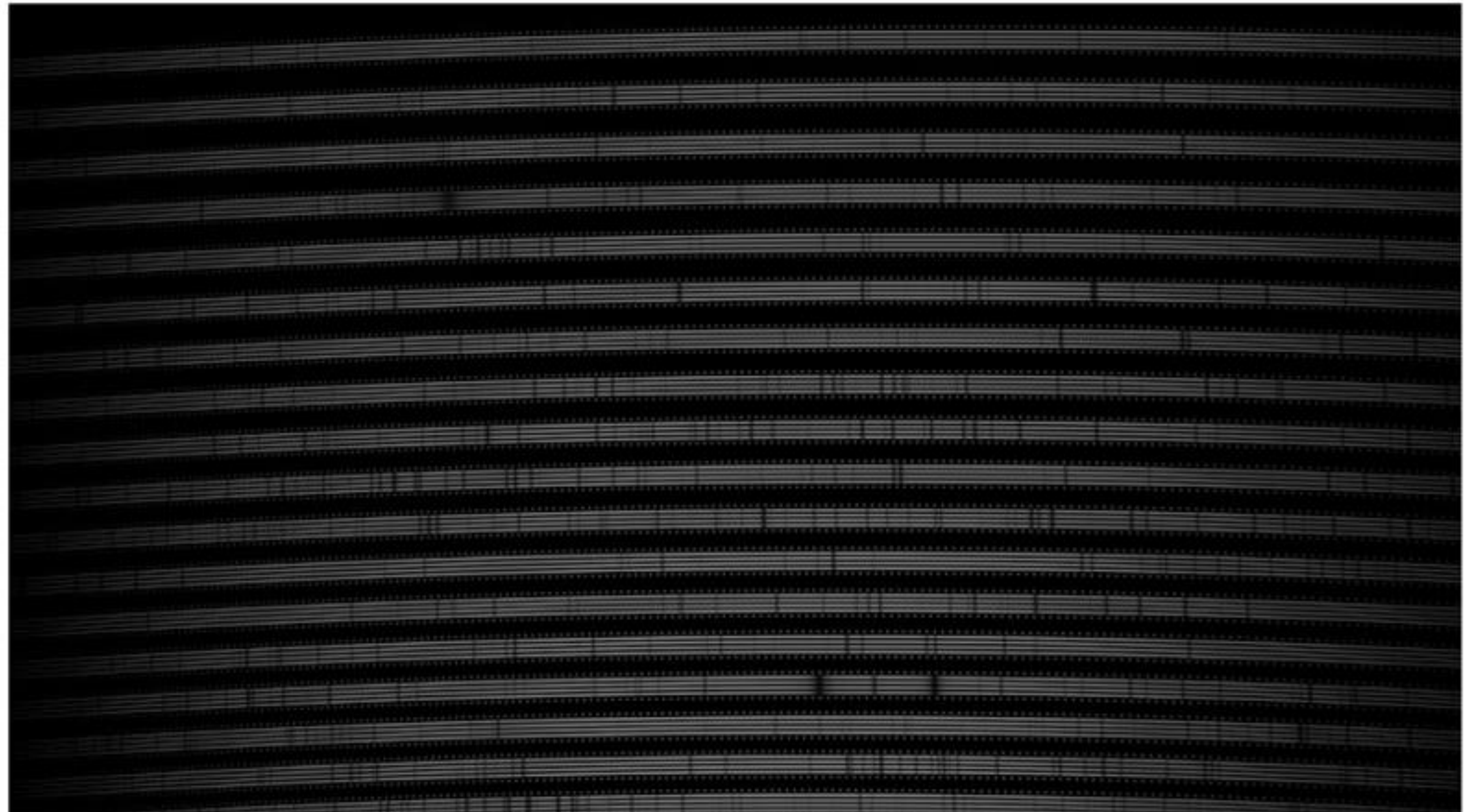
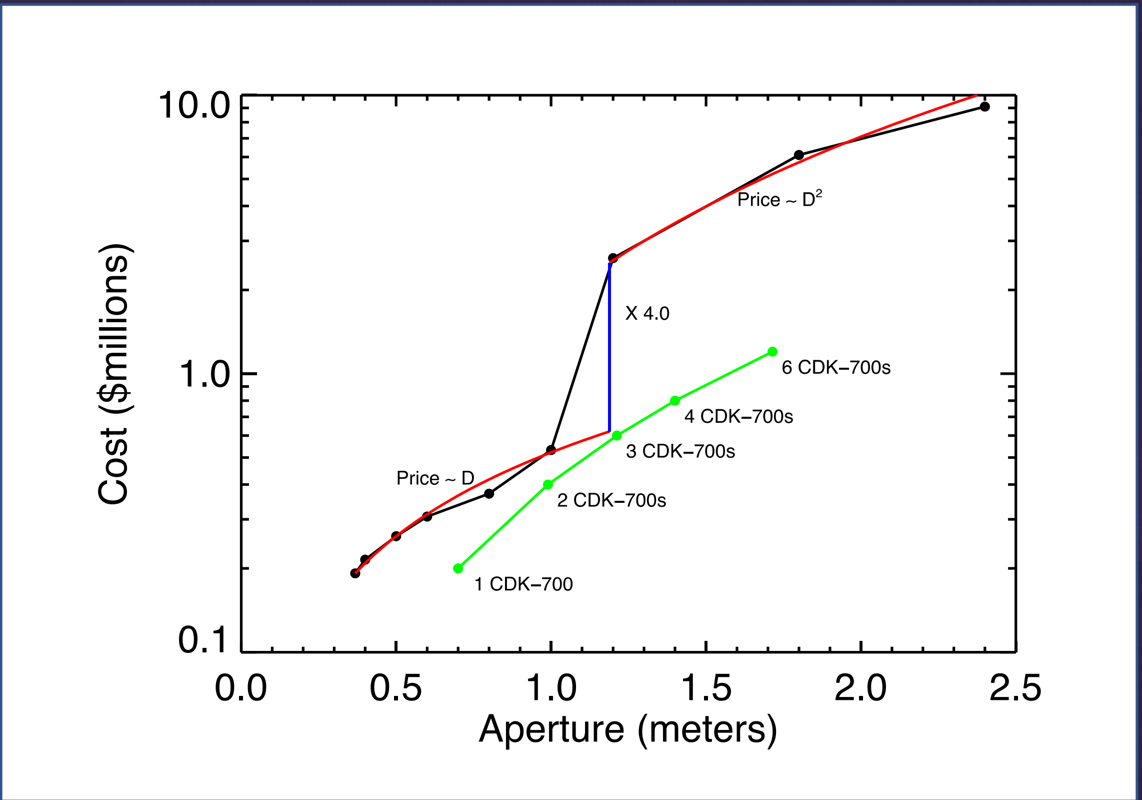
How it works

It is not interferometry



How it works

Saving serious dollary-doos



The power of MINERVA: Many small telescopes are more cost-effective than a single larger one.

Retire risk by using off-the-shelf products.

MINERVA-Australis: Partners

"From many, we are one"

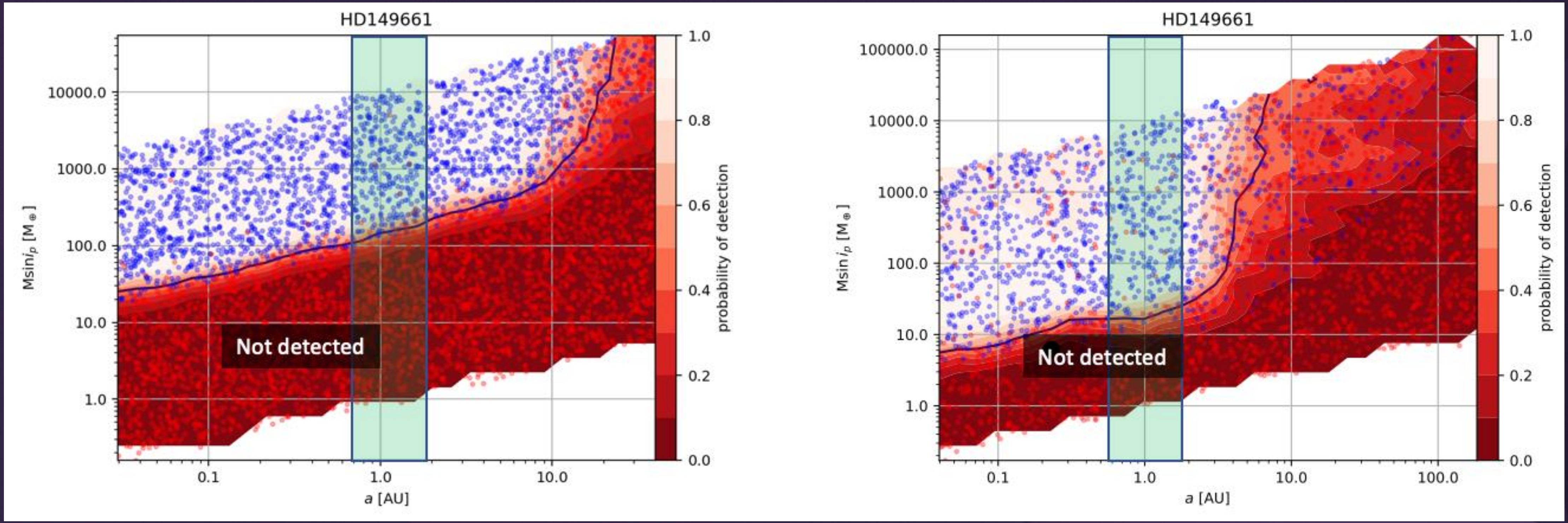
It pays to own the telescope

I haven't written a proposal since 2018

- Precise radial velocities for "well-behaved" stars V<11.
- Flexible scheduling: We do what we want, when we want.
- We can hammer away on Habbo targets until the ~~cows~~ wallabies come home.

Cadence is king

And it is good to be the king



- Left: The current state of play for one example. HZ sensitivity ~150 Earth masses
- Simulated data for 3 years, 1 obs per ~10 nights, include usual seasonality.
- Right: Run RVSearch injection/recovery on new high-cadence data ONLY → 20ish Earth masses

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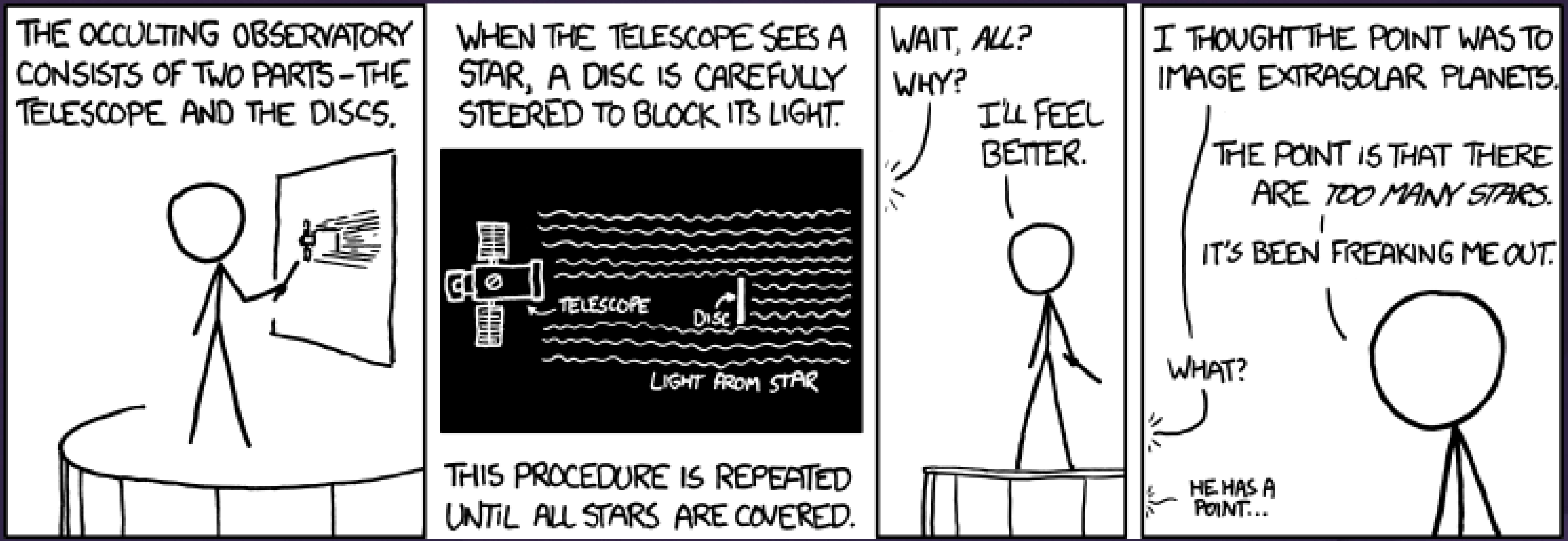
Can we do it?

Yes

- 62 stars from Laliotis+ visible from Minerva-Australis
- Once per ~10 days, 20 min exposures
- 3-5 m/s precision (V mag <7)
- 744 telescope-hours, or 186 hr wall-clock time in formation breaking mode
- Adds up to 24 clear nights per year, easily fits in with other programs
- You don’t need 30 cm/s EPRV to do this!

Can we do it?

Yes



- Result: We can rule out unsuitable Habbo targets that have inconveniently-placed planets!
- “A penny saved is a penny earned” → “A star eliminated is millions of dollars saved”

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Conclusions

Elbow your neighbour to wake them up

- Giant planets matter
- Even when everyone is chasing the smallest planets!
- It's important to consider the whole system
- "Regular" RV plays a critical role in our EPRV world