Exoplanets

Lecture 7
14.11.2025
MFF UK

Outline

- Evolution of exoplanetary systems
- Frequency of exoplanets
- Interesting exoplanetary systems

Formation of exoplanetary systems

- Evolution in protostars with discs
- Two main theories:

  - Core accretion (Safronov 1969, Pollack 1996, ...)

  - Gravitational instability (Kuiper 1951, Cameron 1978)
- How do theories apply to real exoplanetary systems?

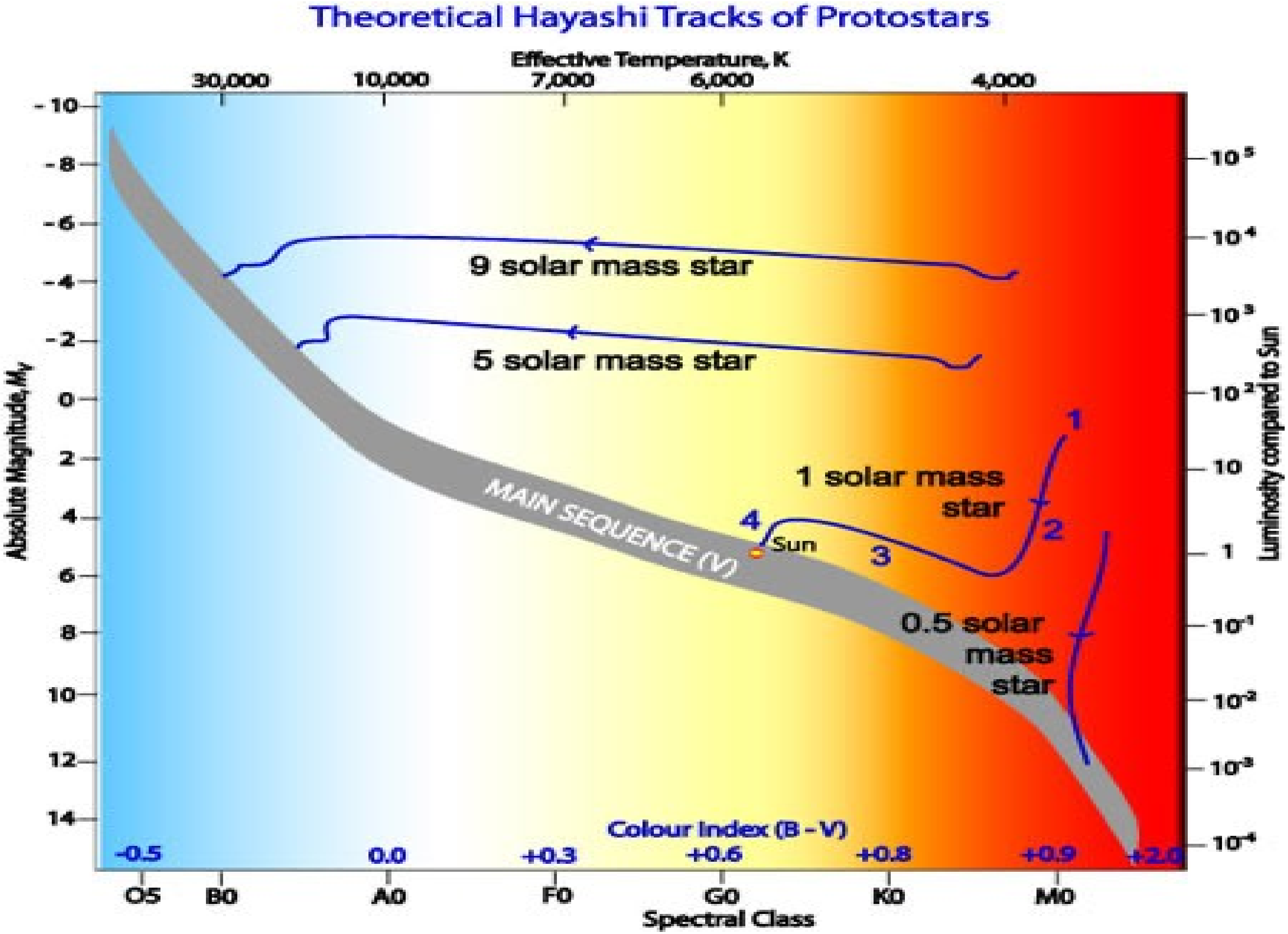
Let`s start from the beginning (first steps in the planetary systems evolution)

Hayashi track (new system is born)

- Track in the HR diagram

  along which T Tauri stars

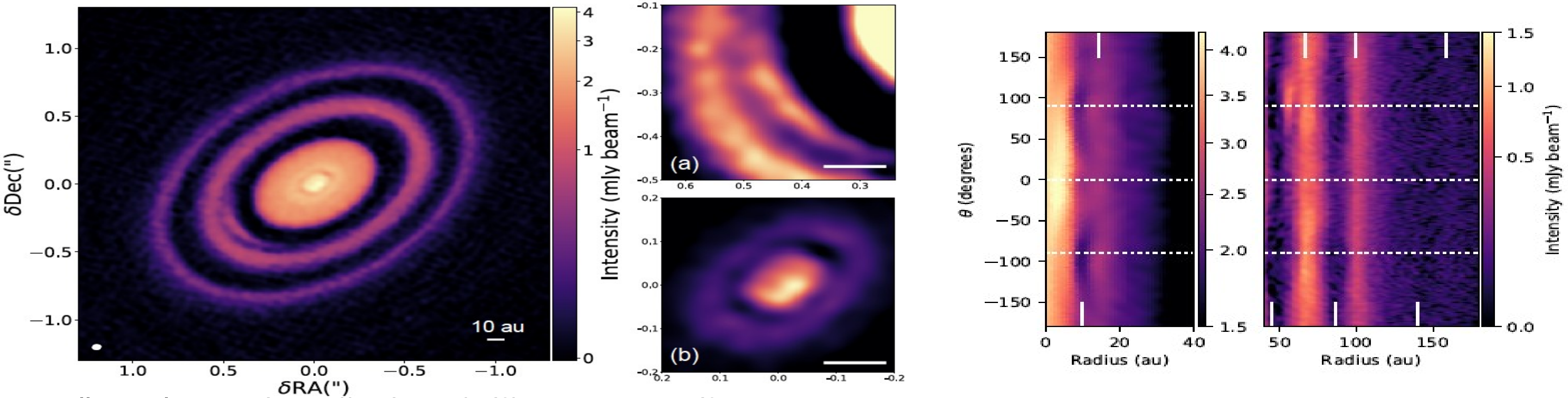
  move towards the MS
- The time and track depend on the mass of the young star
- Hayashi, http://articles.adsabs.harvard.edu/pdf/1961PASJ...13..450H



Credit: https://www.atnf.csiro.au/outreach/education/senior/astrophysics/stellarevolution_formation.html

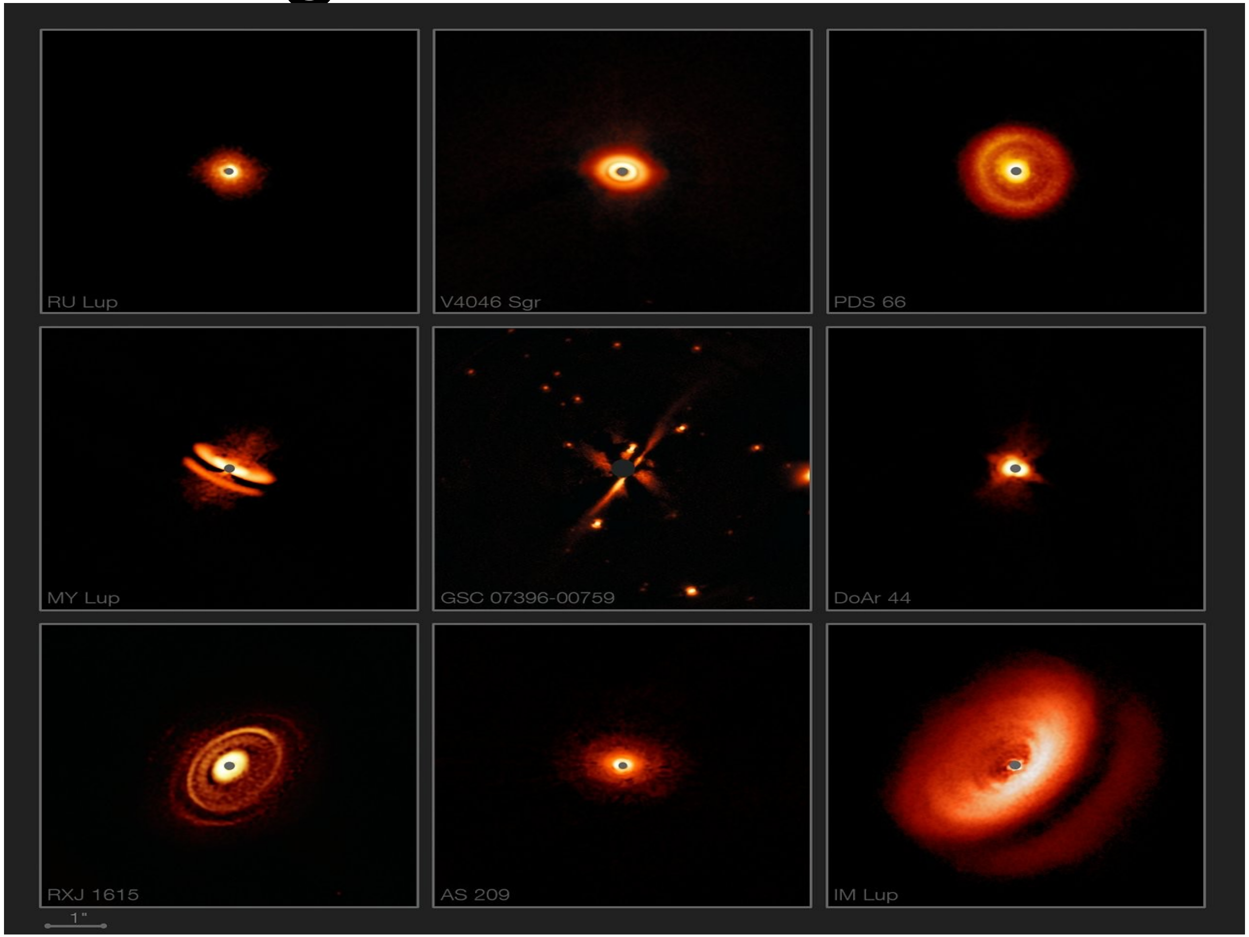
HD163296 disc with planets

- Structures in the disc observed by ALMA
- Rings formed by planetary system
- https://arxiv.org/pdf/1812.04047.pdf



From Isella et al. 2018, https://arxiv.org/pdf/1812.04047.pdf

Young stars with discs



https://www.eso.org/public/images/eso1811a/ SPHERE ESO VLT instrument obseravtions

New star is born

- T Tauri type stars
  - young, active stars
  - collapsing gravitationally
  - masses < 3 $M_{\odot}$
  - with discs!
  - Li abundant
- T Tauri stars become later main sequence (MS) stars
- Evolution to MS 10^{5}-10^{8} years

Image: V1331 Cyg a young T Tauri star – pole onwards
https://www.nasa.gov/content/goddard/hubble-sees-a-young-star-take-center-stage

Disc imaging

- PDA 70
  - imaged by VLT (NACO, SPHERE)
  - young object (5.4 Myr)
  - disc present
  - particle grains estimated
- Hosts a planet
  - anything between
- 5-14 Jupiters masses

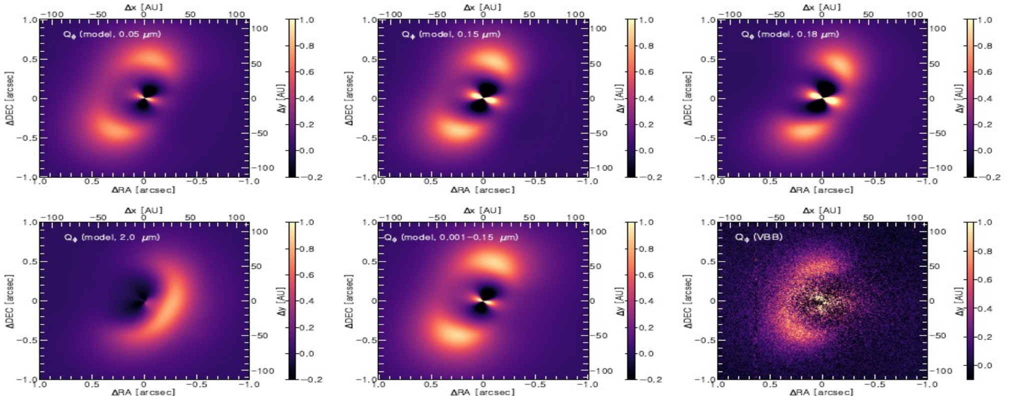


Fig. 8. Convolved ray-traced Q_ϕ-images evaluated at 0.7 μm using different grain size distributions. Successively, the central source polarisation emerging from the unresolved inner disk (radius 2 au) was subtracted using a U_ϕ-minimisation. The lower right panel shows the VBB observation, for comparison. North is up and East is to the left.

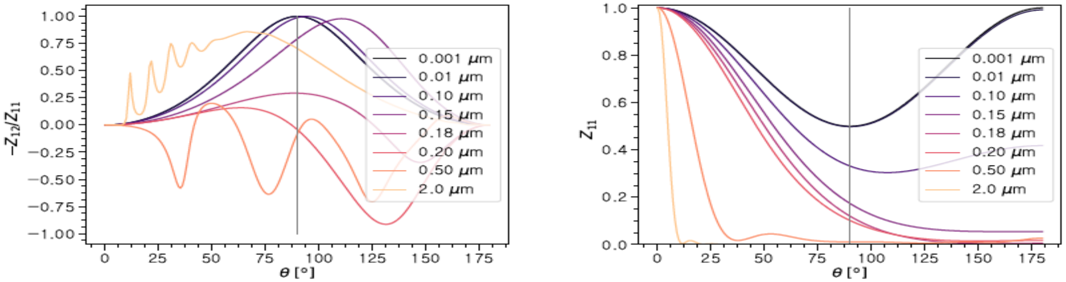
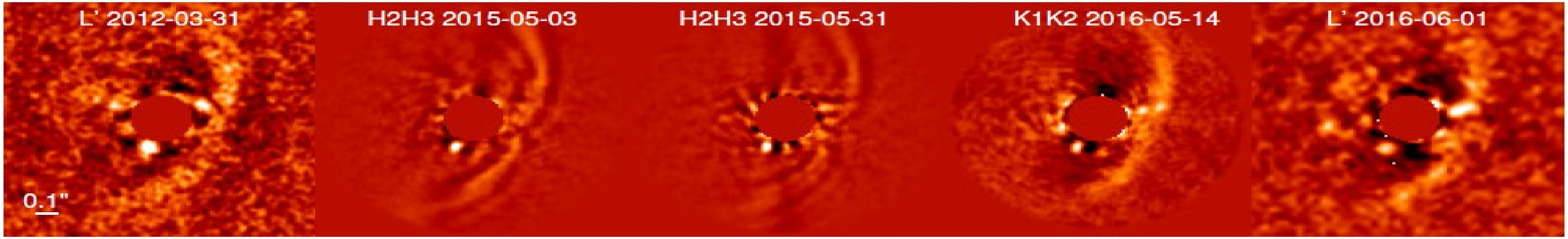


Fig. 7. Linear polarisation degrees for silicates of different (semi-mono dispersive) grain sizes (left), and their phase function (right, normalised to $Z_{11}(0)$). The curves were computed for an observing wavelength of 0.7 μm.

PD 70b

- And here is the planet….



M. Keppler et al. 2018 - https://www.eso.org/public/archives/releases/sciencepapers/eso1821/eso1821a.pdf

And there is another one

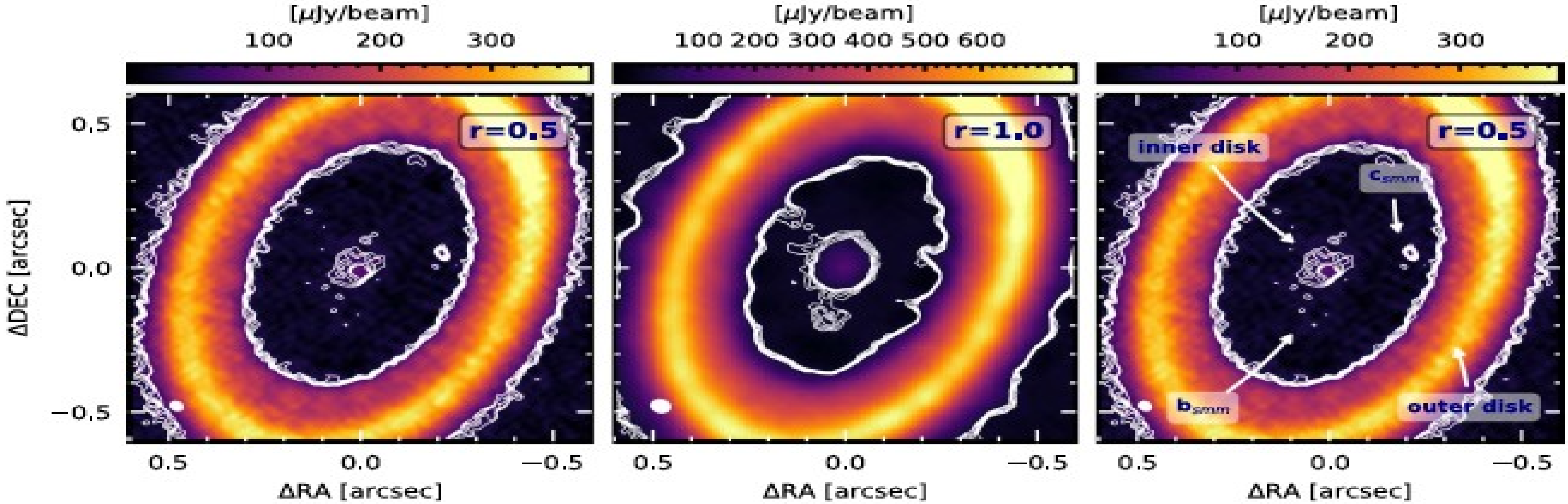


Figure 1. Images of the new continuum observations of PDS 70 (LB19+SB16). The data were imaged with a robust parameter of 0.5 (left panel) and 1 (middle panel), with resolutions of 0."036 × 0."030 and 0."051 × 0."044, respectively. The right panel shows the same image as in the left panel, with annotations. Beams are in the bottom-left corner of each panel. Contours are 3 to 7σ, spaced by 1σ (with σ = 8.8 and 4.8 μJy beam^{-1}, respectively). An image gallery for all data sets is given in Appendix A.2.

Benisty et al. 2021, https://doi.org/10.3847/2041-8213/ac0f83

And well, maybe discs forming moons?

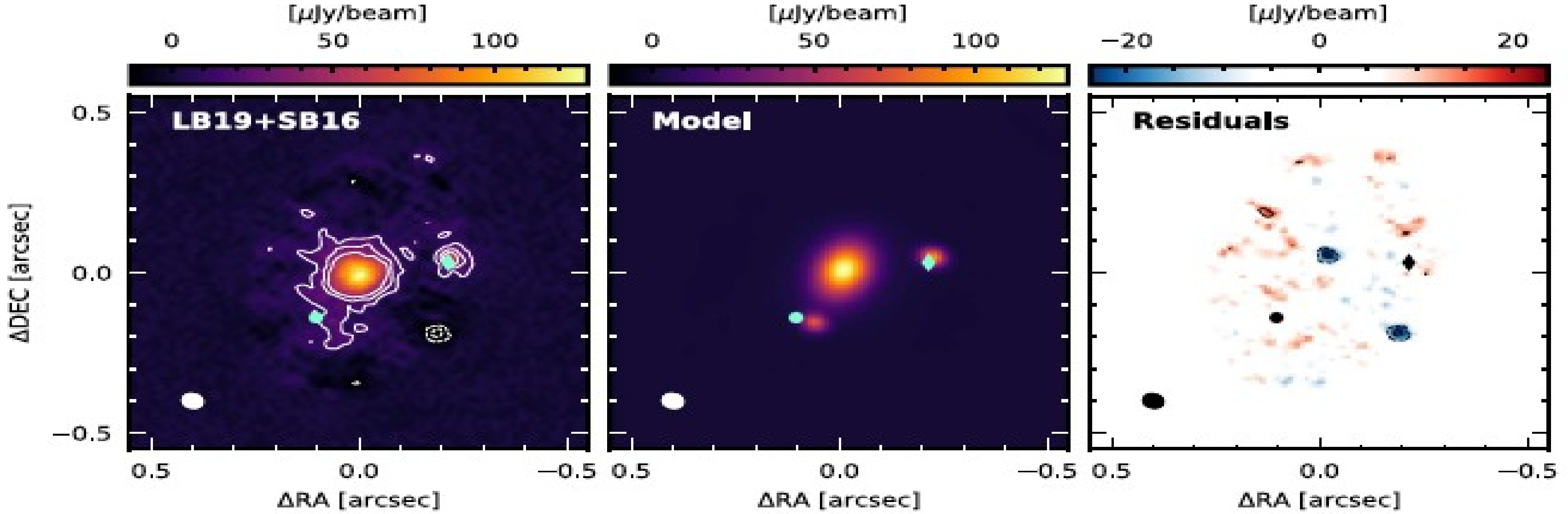


Figure 3. Panels from left to right: cavity image for LB19+SB16; Galario best-fit model for the inner disk, b[illegible], and c[illegible]; Residuals from the Galario best-fit model. All images are obtained with $r = 1$. Contours are 3, 6, and 9 σ. Dashed contours correspond to -6 and -3σ. The predicted positions of the two planets in 2019 July are indicated with a circle and diamond (PDS 70 b and c, respectively).

Benisty et al. 2021, https://doi.org/10.3847/2041-8213/ac0f83

Planets are forming

Disc instability

- Gravitational collapse of the gas from the disc material
- Usually drives planet formation in outer parts of the disc
- Fairly fast process around a few thousands years
- Jeans mass – if the mass of the object is larger than the Jeans mass then gravitational force starts to dominate

$$M > \left(\frac{5kT}{Gm}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2}$$

Core accretion

- Safronov 1972, Pollack 1996
- Small solid dust grains (less than micro meters) collide and grow into larger particles (dozens of kilometers) – planetesimals
- Gravity starts to shape a planetesimal
- Planetesimal grows into planetary core
- Usually drives formation in warm inner disc

Real exoplanets and formation hypothesis

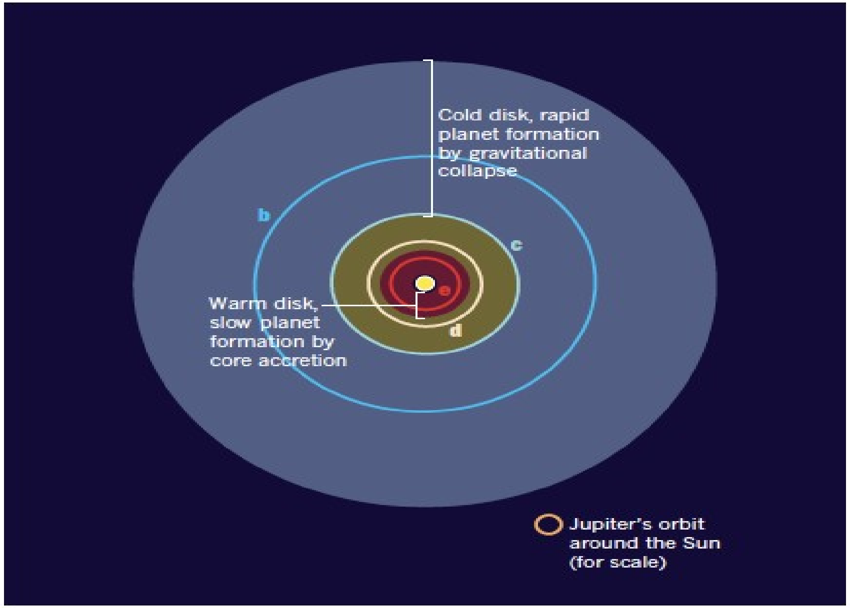
The case of HR8799

- Intriguing system HR 8799 – A type 1.5 Solar masses star
- The system includes 4 gas giants within
- Masses between 5-10 Jupiter masses
- How did they form?

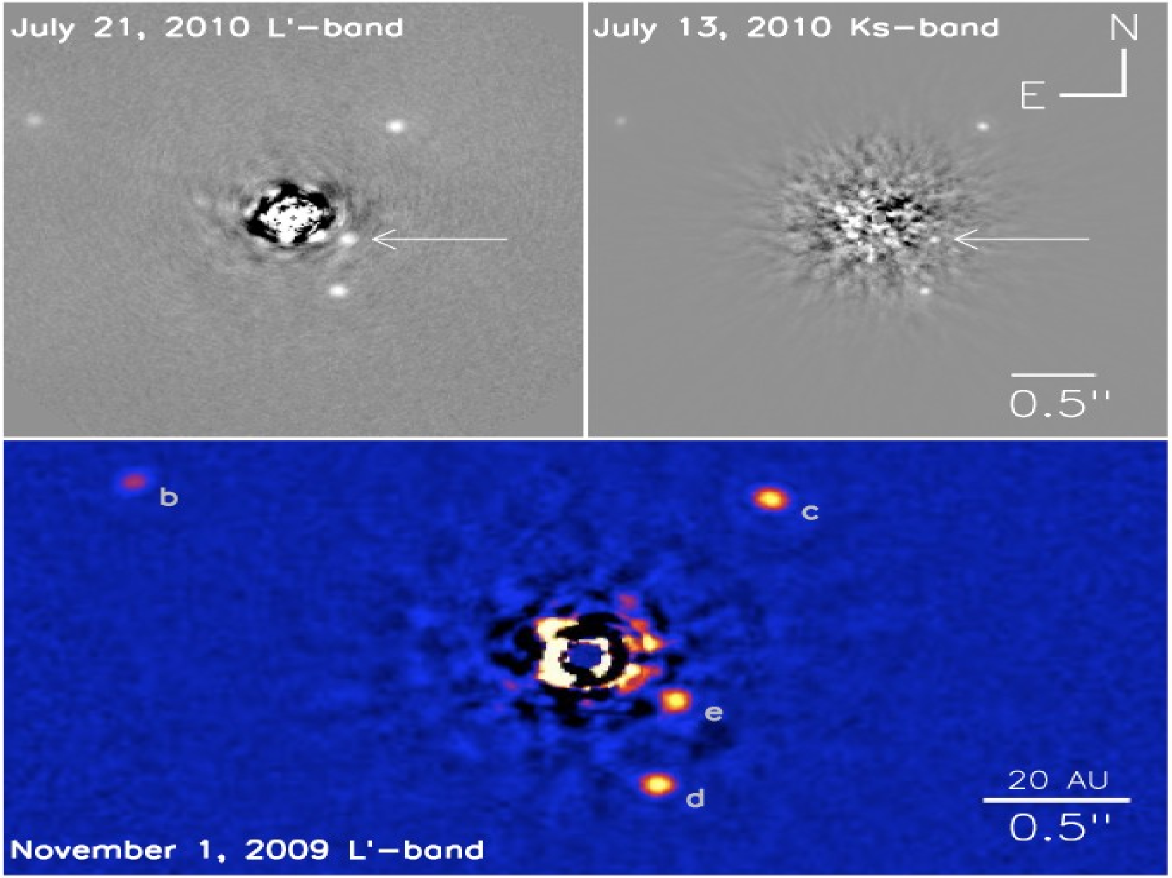
  - Core accretion, gravitational collapse or both?

  - were they migrating inwards or onwards?

The HR8799 system

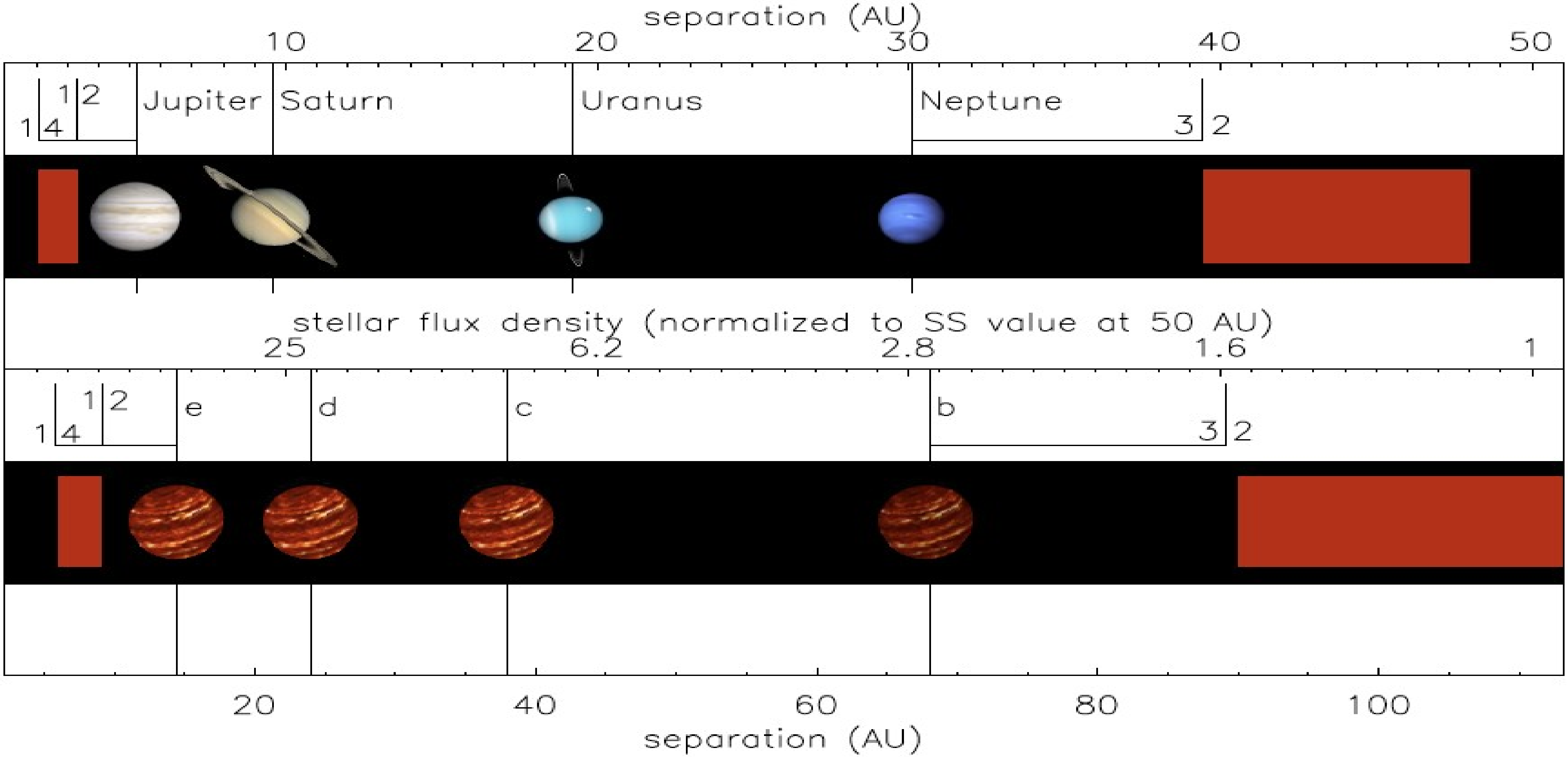


Credit:
https://www.nature.com/articles/nature09716.pdf



Marois et al. 2010, Nature: https://arxiv.org/pdf/1011.4918.pdf

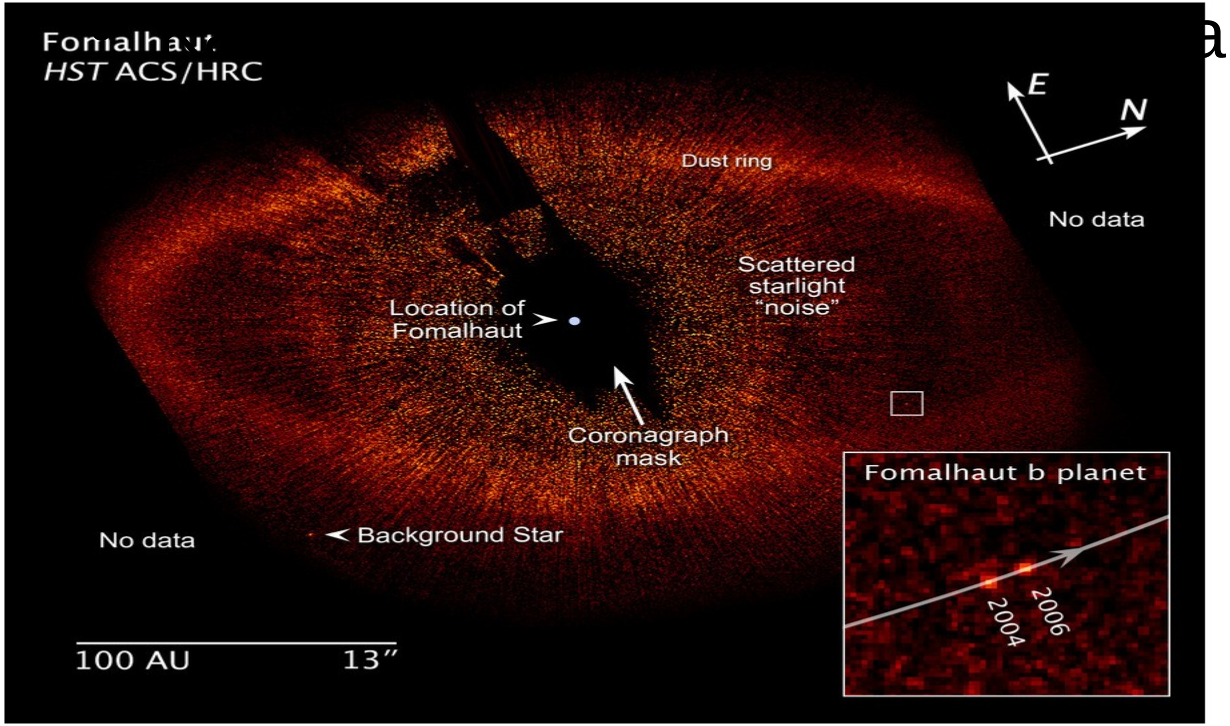
The HR8799 system



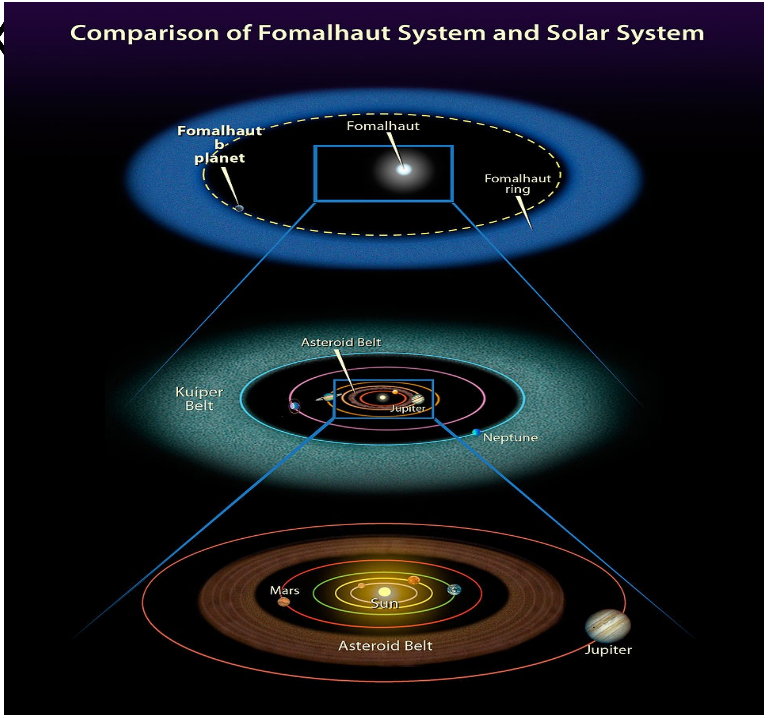
Marois et al. 2010, Nature: https://arxiv.org/pdf/1011.4918.pdf

The Fomalhaut system

- A forming planet b? A product of collision? Is there any other planet c – if yes then must be less massive.

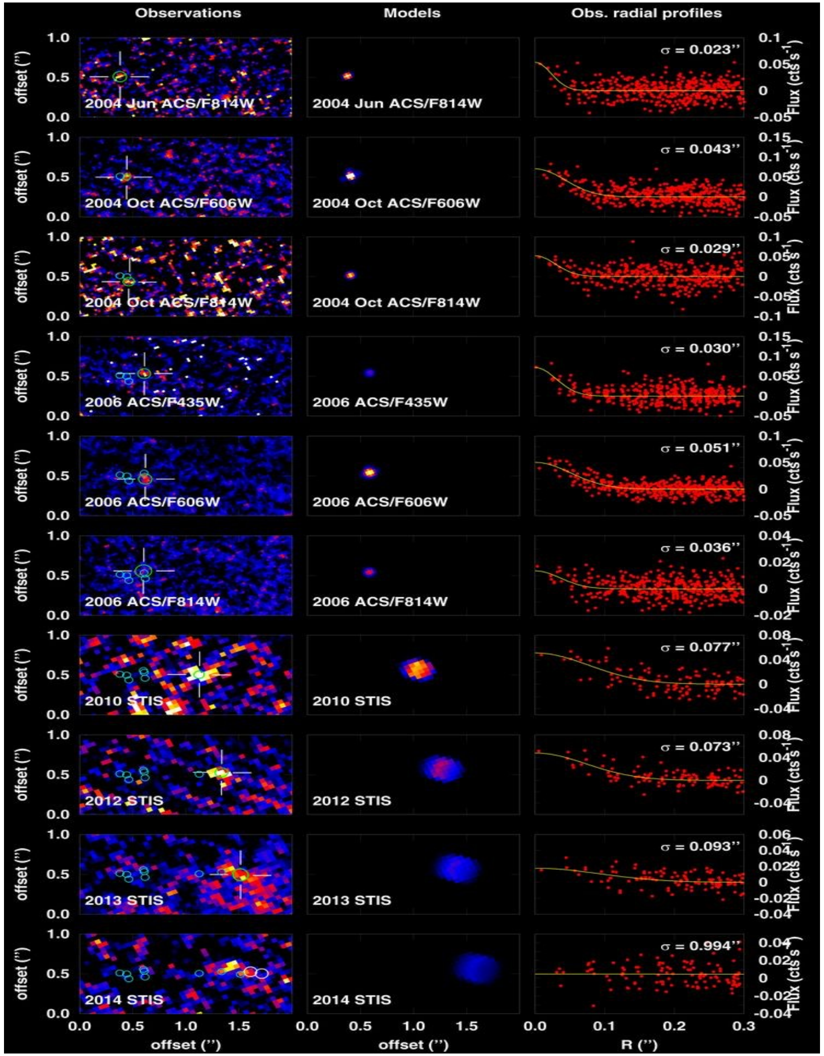


arx



https://hubblesite.org/contents/news-releases/2008/news-2008-39.html - Credit NASA/ESA

And all turned to dust?



Bakos et al. 2020, PNAS:
https://www.pnas.org/content/117/18/9712

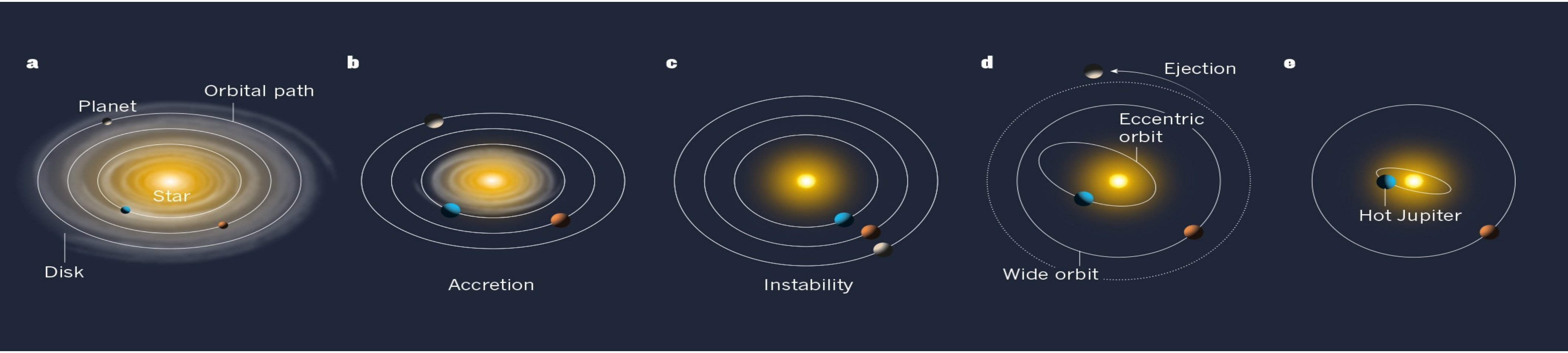
The Fomalhaut system

- The mass of the object is about 2 masses of Jupiter
- Did the planet b form in situ by core collapse?
- Or was the planet b ejected from the system?
- Is there any other unseen planet closer to the star?
- If there is a c planet what would be its mass?
- Is it a planet or not?

Wandering planets
(Hot Jupiters case)

Migration

- Why are hot Jupiters so close to their stars?
- One of the theories is migration



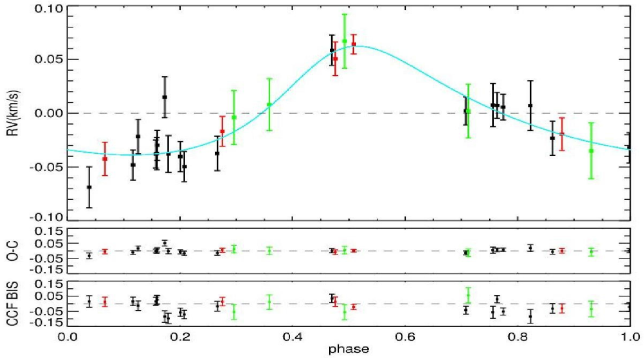
Credit: Triaud, A. Migration of giants. *Nature* **537,** 496–497 (2016)

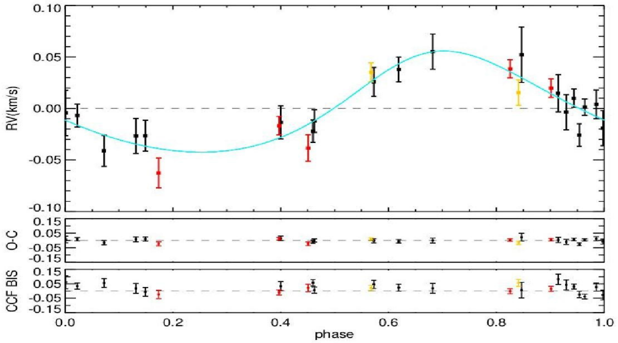
Migration types

- Type I migration – smaller planets migration (without opening a gap)
- Type II migration – large planets with opening a gap
- Type III migration – migration through the gas disk

Migration of HJs

- HJs in an open cluster M67 – approx. 4% occurance rate
- Host stars are as massive as the Sun
- Why is the occurance of HJs in cluster M67 higher than for normal FGK stars (about a 0.5-1%)?
- The interaction of stars in the cluster plays a role?





Brucalassi et al. 2016https://doi.org/10.1051/0004-6361/201527561

Important questions

- How do gas planets form?

  - in situ?

  - in outer regions and they migrated?
- How do gas planets and small planets live together?
- What can tell us the orbital elements about the formation of the planetary system?

Could the HJ form in situ?

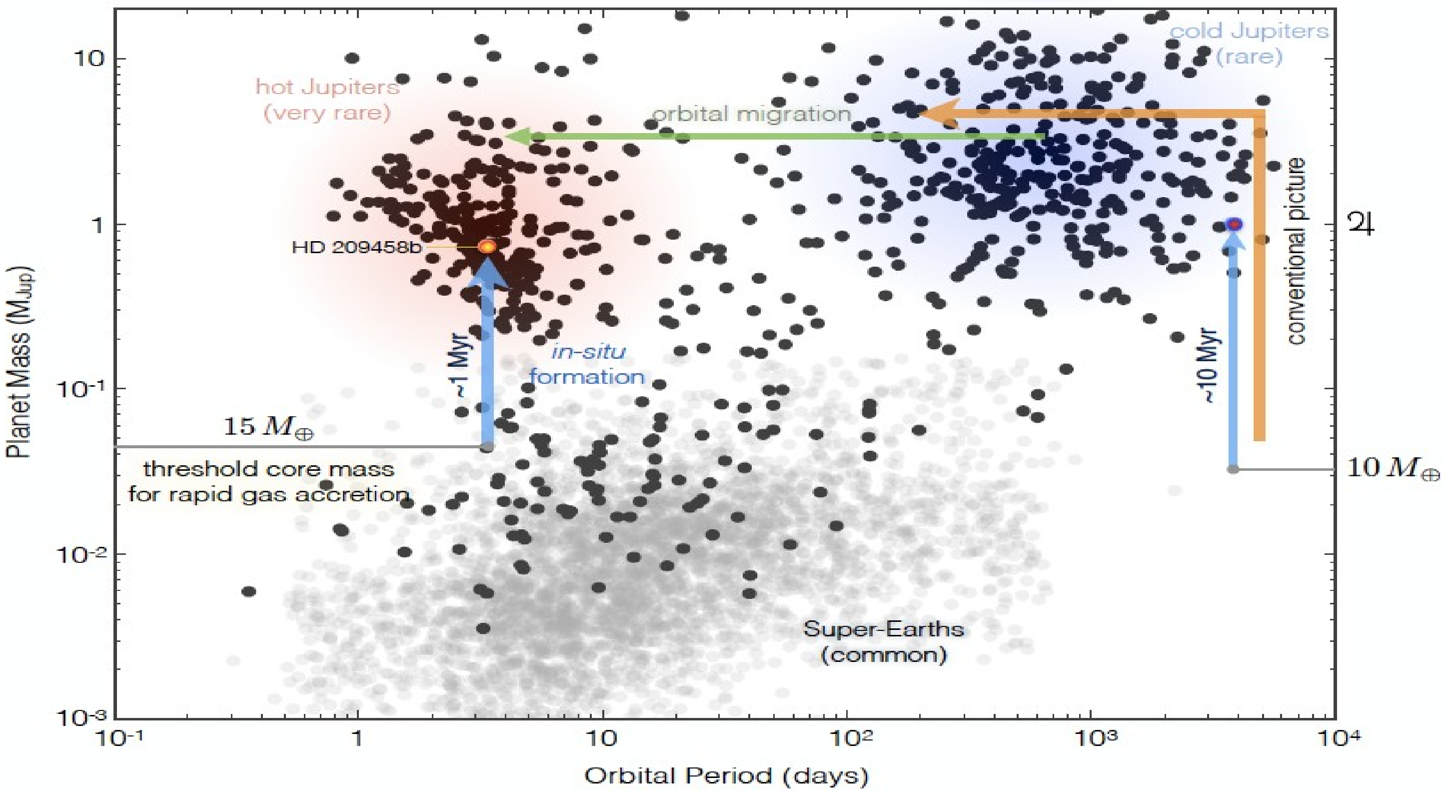
- It was widely accepted as unlikely

  - high temperatures close to star prevent the gravitational instability scenario

  - however, core accretion might be possible under some assumptions, perhaps...

- But one would need a Super-Earth as a core for future hot Jupiter (Batygin et al. 2016: https://arxiv.org/pdf/1511.09157.pdf)

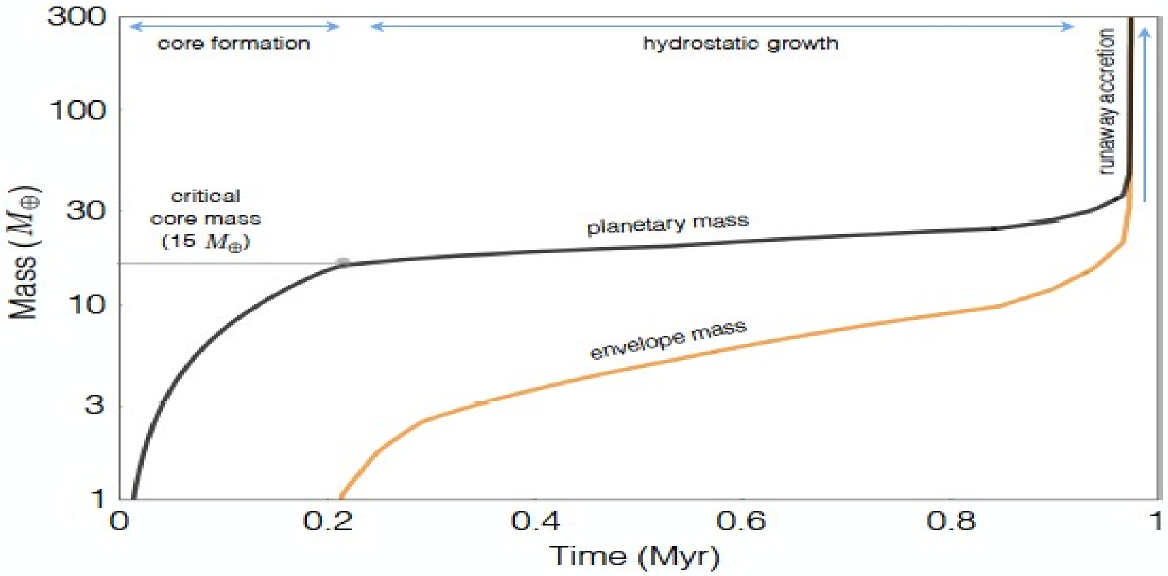
Formation in-situ?



Batygin et al. 2016: https://arxiv.org/pdf/1511.09157.pdf

In situ formation

- First the cores of 15 M Earth form
- Then the accretion creates the envelope



Batygin et al. 2016: https://arxiv.org/pdf/1511.09157.pdf

Possible scenarios for an in-situ option

15

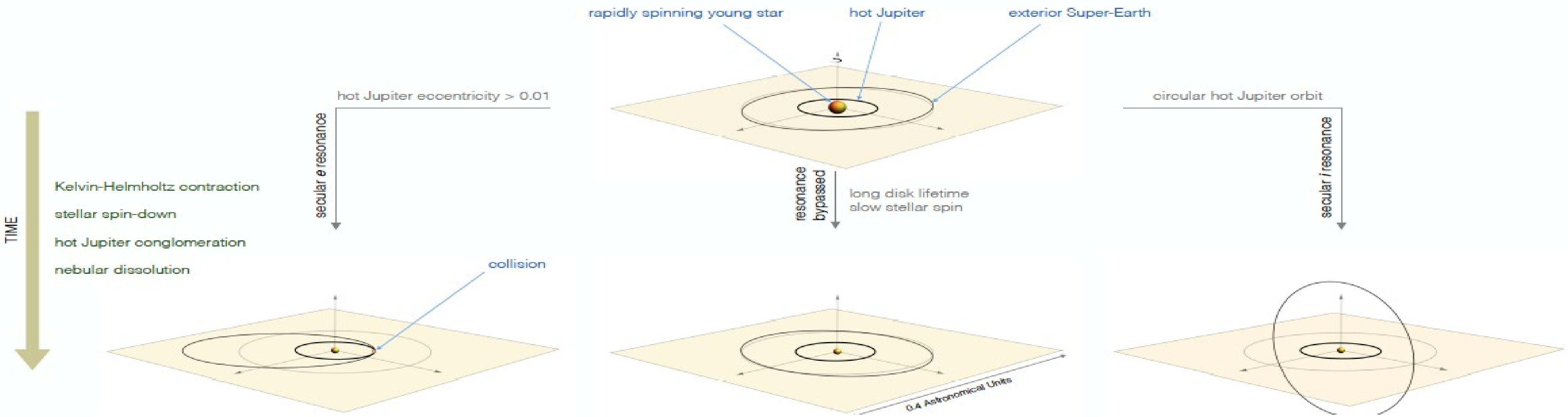


FIG. 10.— Potential outcomes of dynamical evolution of hot Jupiter-hosting planetary systems. An initially nearly-planar, quasi-circular, low-mass multi-planetary system is taken to evolve under the influence of mutual gravitational coupling, interactions with the protoplanetary nebula, as well as the quadrupole field of the young, rapidly rotating star. As the nebula dissipates, the inner orbit experiences *in situ* conglomeration. Meanwhile, the star undergoes gravitational contraction and loses angular momentum, thereby shedding its quadrupole moment. Cumulatively, these physical processes can give rise to scanning secular resonances that sweep through the inner region of the planetary system. As a result, exterior companions to hot Jupiters can be driven onto intersecting trajectories, or acquire nearly orthogonal orbits, depending on whether hot Jupiters maintain eccentricities above or below $e_{\rm HJ} \sim 0.01$ during the early stages of their lifetimes. On the other hand, coplanarity and dynamical stability can be maintained if disk lifetime is sufficiently long, or stellar rotation is sufficiently slow, to preclude the establishment of secular resonances.

Batygin et al. 2016: https://arxiv.org/pdf/1511.09157.pdf

Solar system example

- Recall Batygyn et al. 2016 describing a perturber in our Solar System on wide orbit

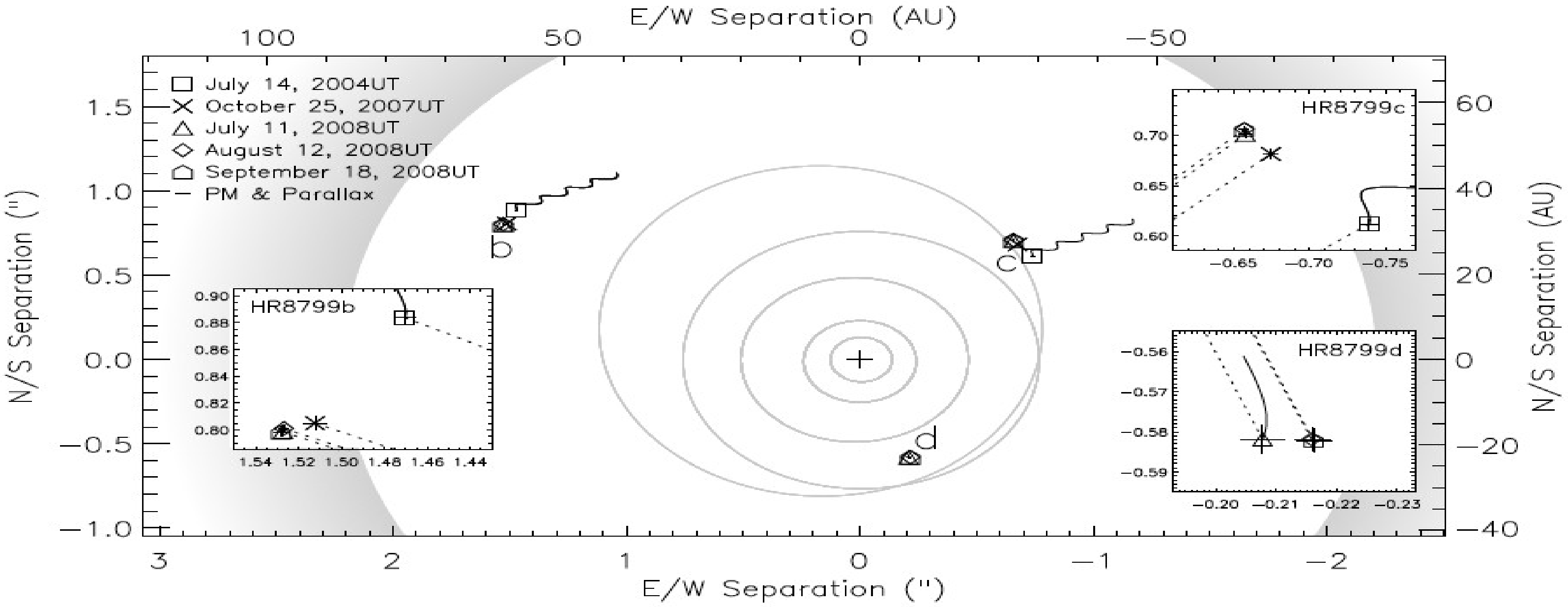
  (Planet Nine) – 150-250 AU
- The planet Nine combines all above effects

  - it would have to be ejected (not in-situ)

  - it explains highly eccentric orbits of dwarf planets (Sedna etc….)
- But is it there? Or could it be out there?

Recalling HR 8799

- We know already HR 8799 system as an example of large orbit. So why not Planet Nine?

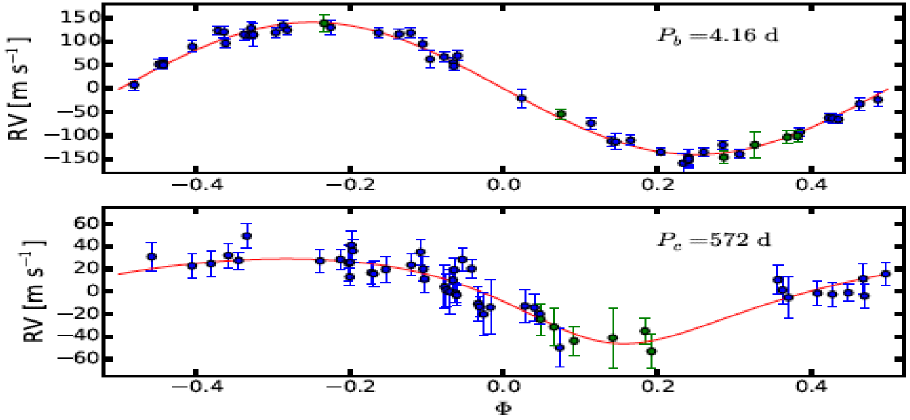


Maroise 2008, https://arxiv.org/pdf/0811.2606.pdf - grey lines Solar system gas planets and Pluto

Back to Hot Jupiters
(large and small living together)

Wasp-47 system

- First system
  with HJ, Super-Earths
  and a long periodic planet
  of Jupiter size.
- The Period of c
  planet is 572 days

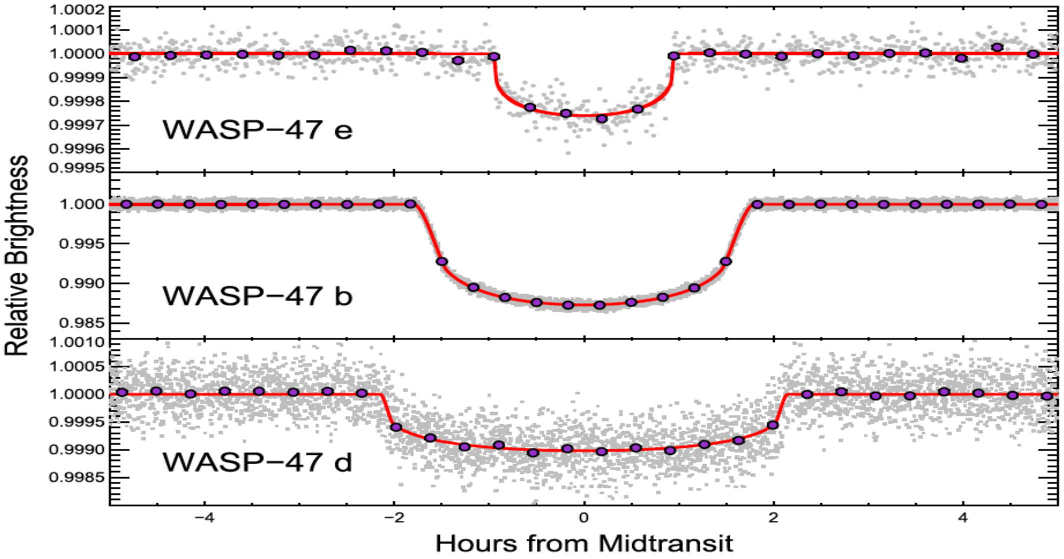


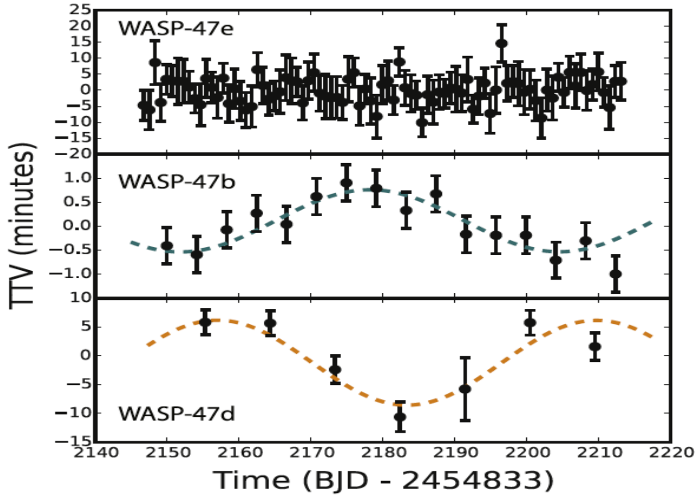
Neveu-VanMalle 2018 https://arxiv.org/pdf/1509.07750.pdf

- But is this system unique or is it rather a common representative of the formation process in-situ? We do not know, yet for sure.

Wasp-47 system

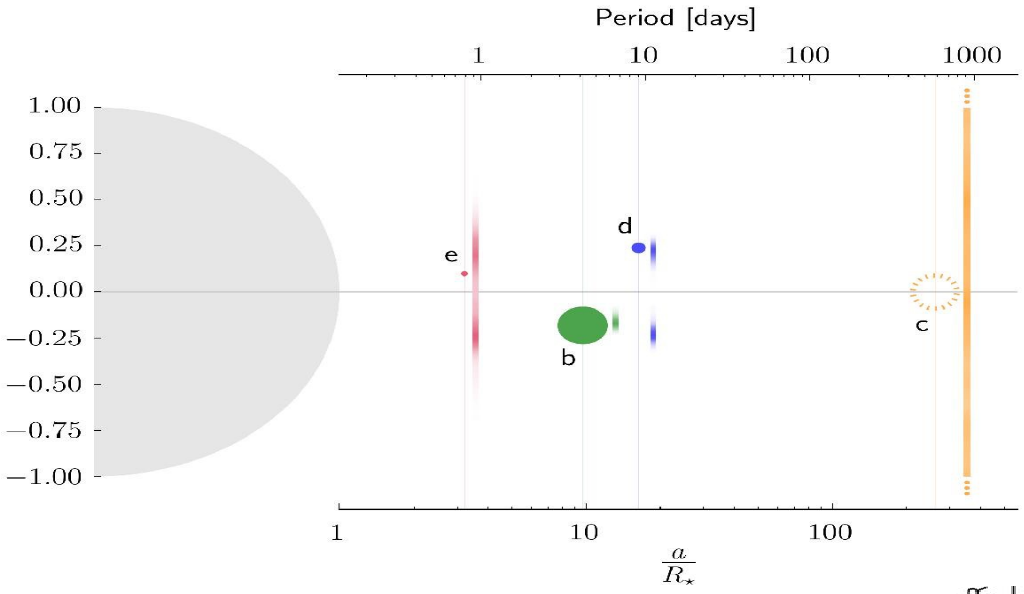
- Is it rather an exception or a rule?
- Example of an in-situ formation?





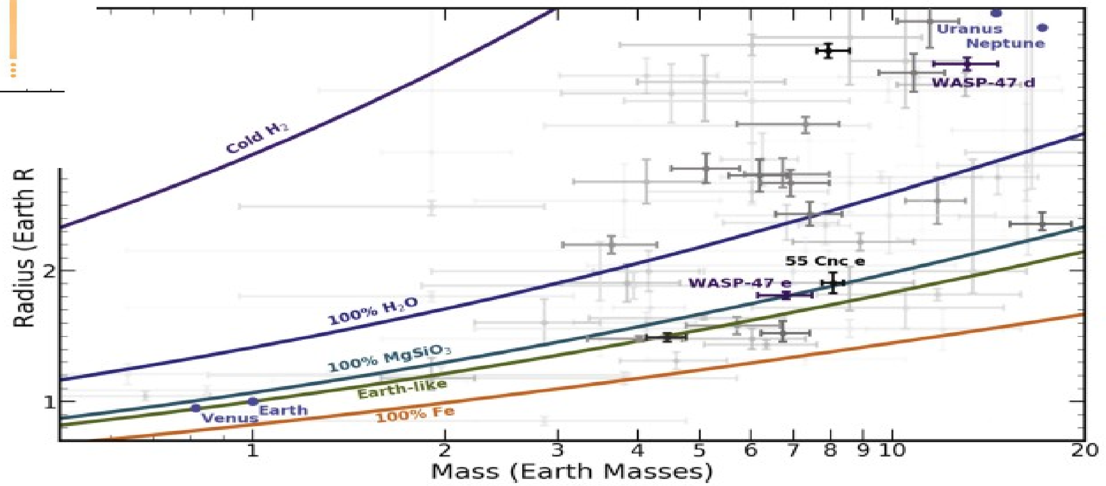
Becker et al. 2015: https://iopscience.iop.org/article/10.1088/2041-8205/812/2/L18/pdf

Wasp-47 system



Alemenara et al. 2016: https://www.aanda.org/articles/aa/abs/2016/11/aa29770-16/aa29770-16.html

Vanderburg 2017, https://iopscience.iop.org/article/10.3847/1538-3881/aa918b/pdf



Warm Jupiters

Warm Jupiters

- Gas giants with orbital periods 10-200 days
- HD 80606 b – 111 days period

  - binary component HD 80607

  - 4 Jupiter masses

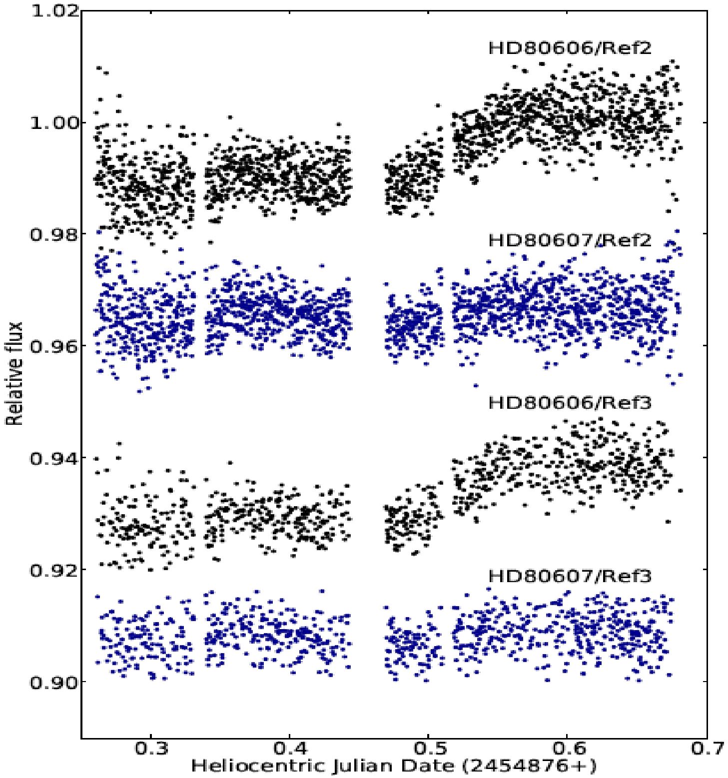
  - 12 hrs. Transit

  - 0.93 eccentricity (very high)
- Orbital parameters

  might be the key to formation?
- Discovery:

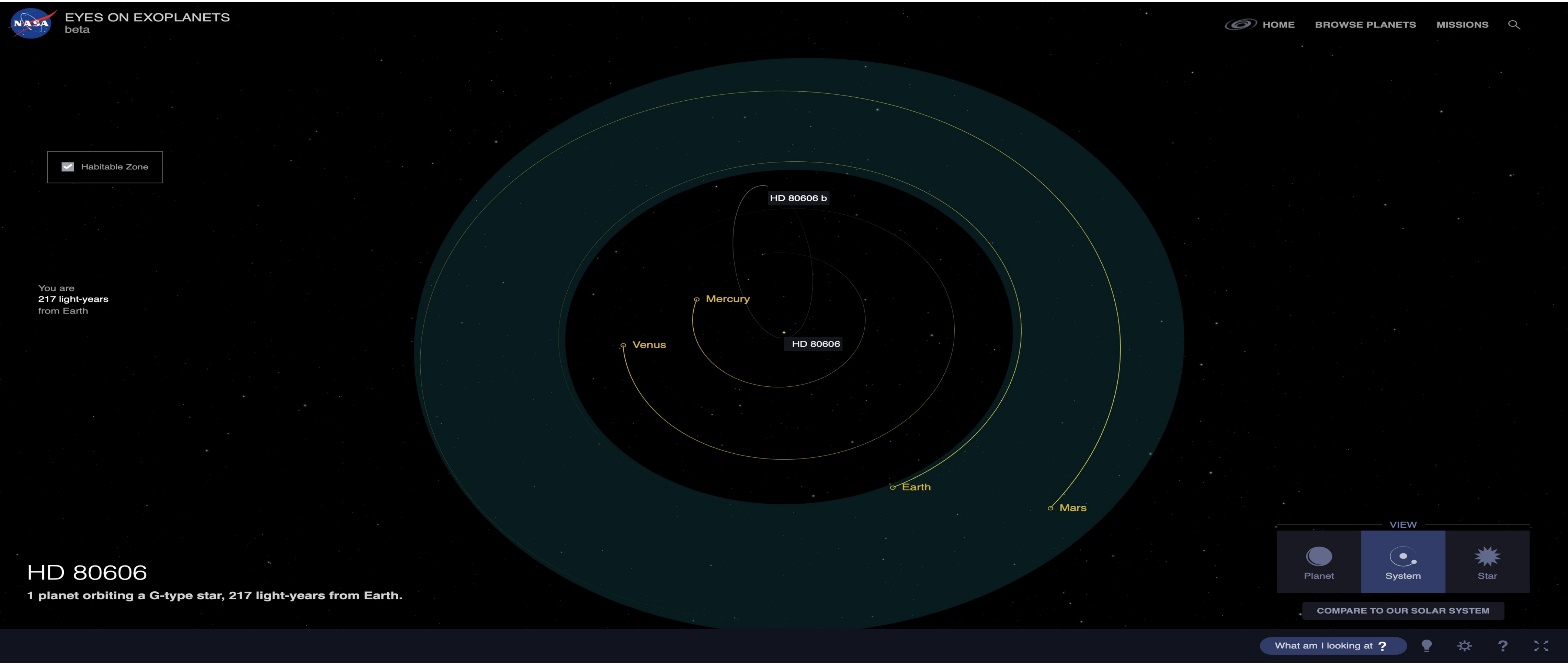
  Naef et al. 2001

  https://www.aanda.org/articles/aa/pdf/2001/32/aade293.pdf

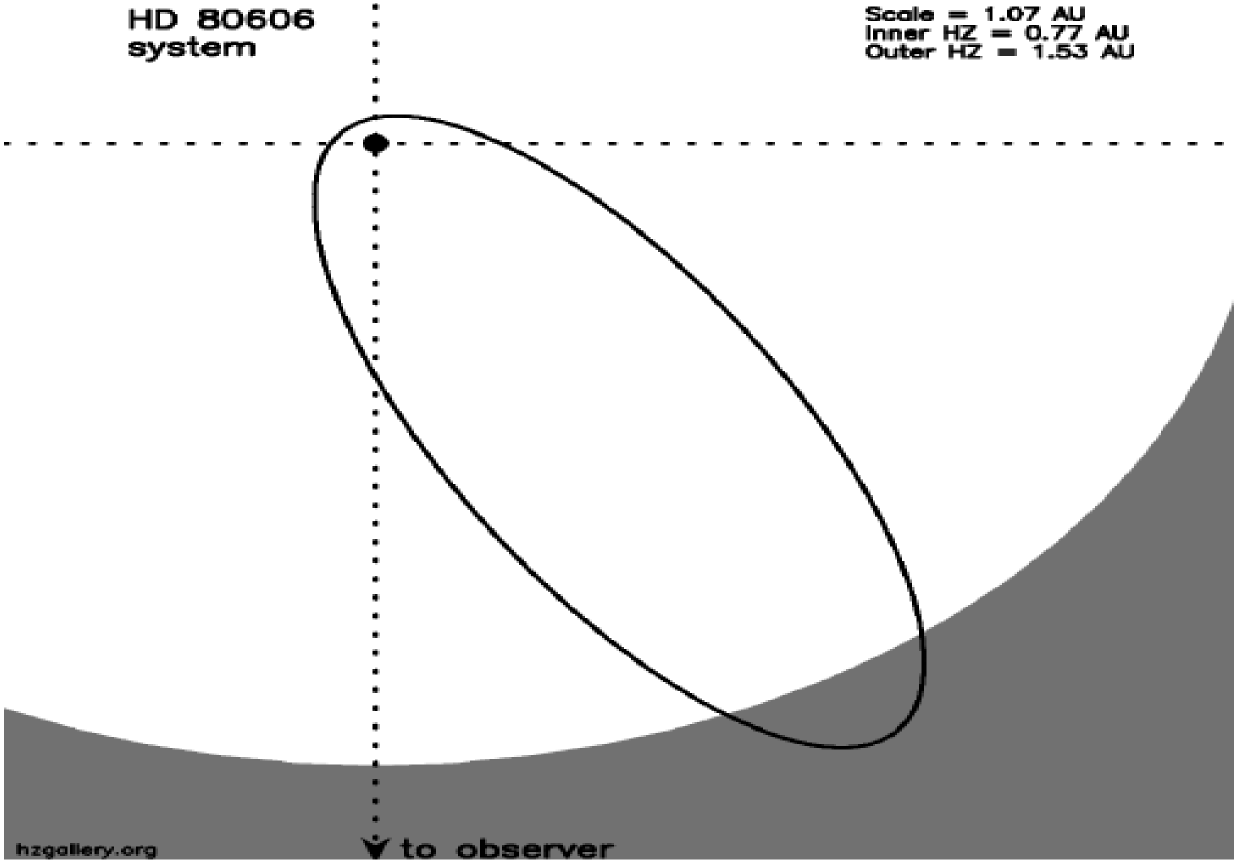


Fossey et al. - https://arxiv.org/pdf/0902.4616.pdf

Orbit of HD80606b

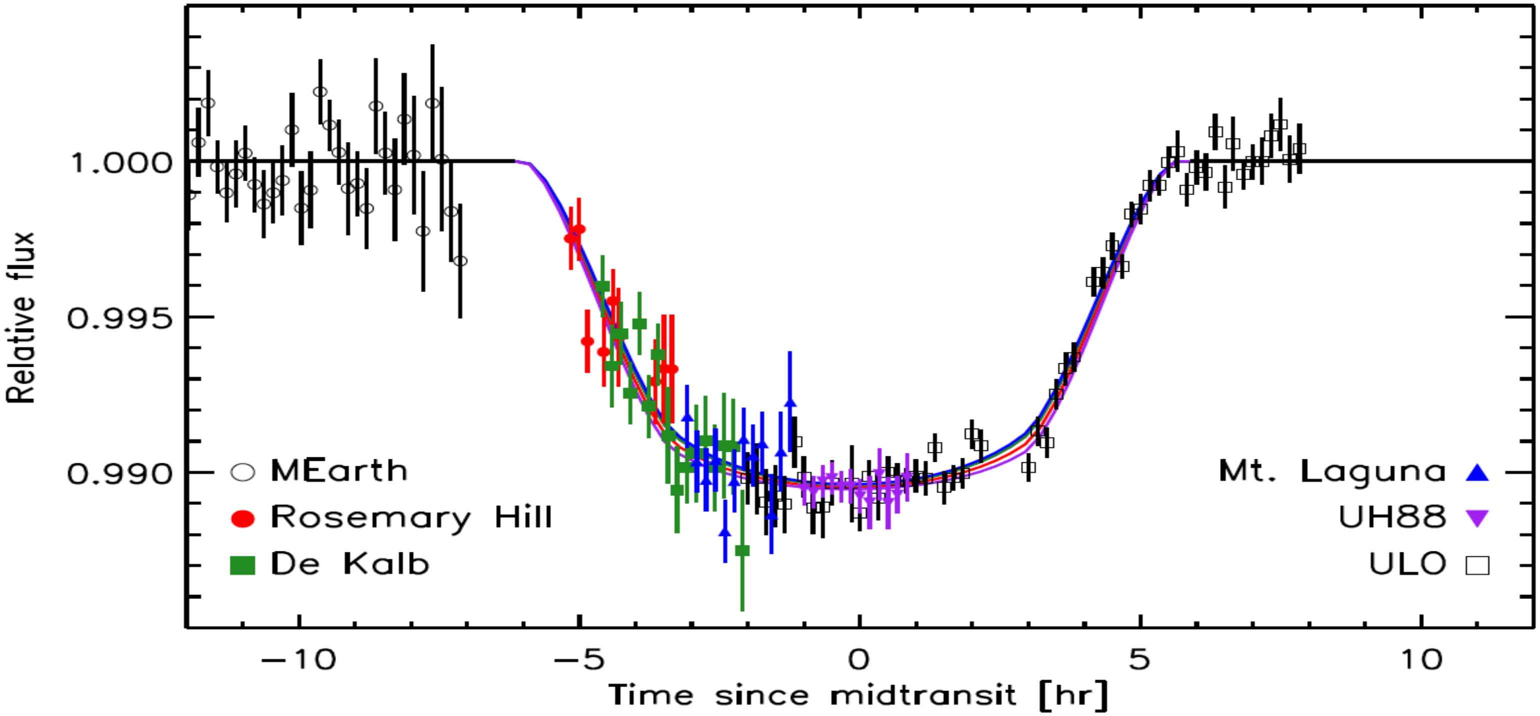


Habitable zone HD80606 b



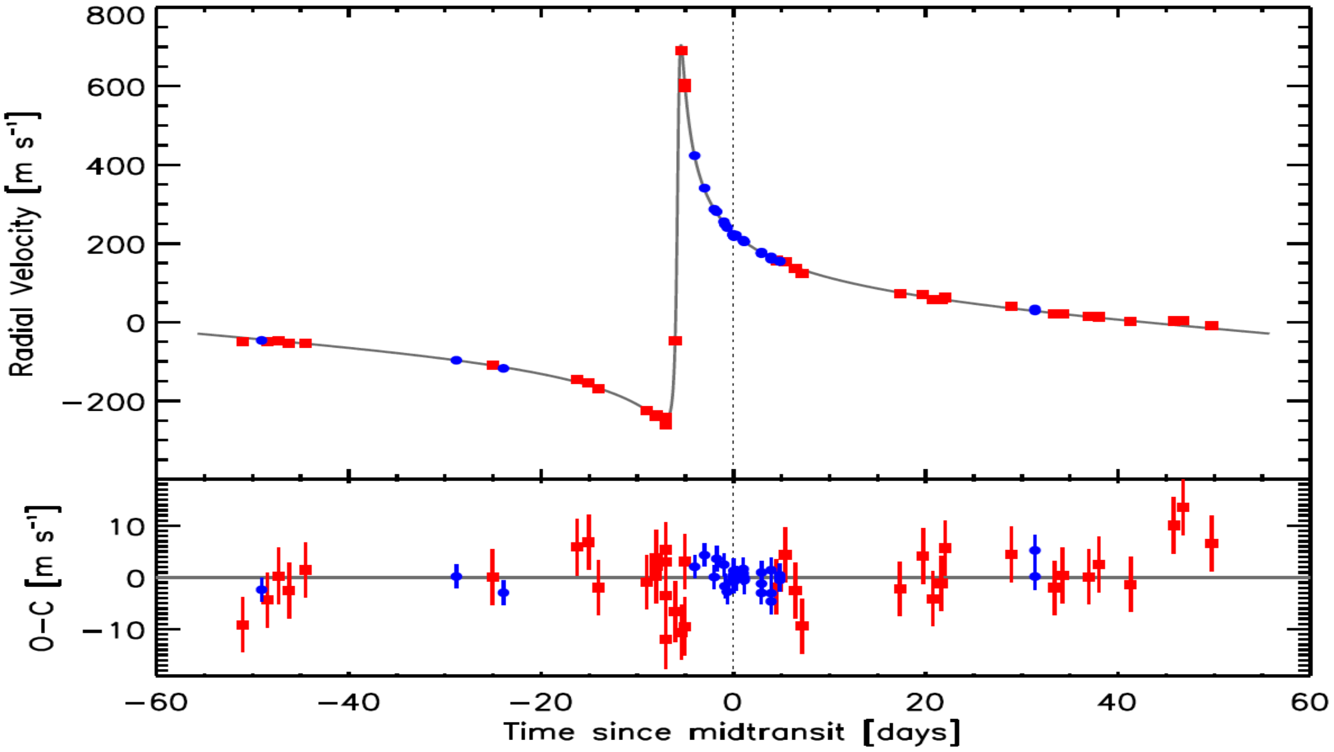
Kane, Stephen & Gelino, Dawn. (2012). The Habitable Zone and Extreme Planetary Orbits. Astrobiology. 12. 940-5. 10.1089/ast.2011.0798.

A challenging transit



From Winn et al. 2009, https://arxiv.org/abs/0907.5205

HD 80606 b



From Winn et al. 2009, https://arxiv.org/abs/0907.5205

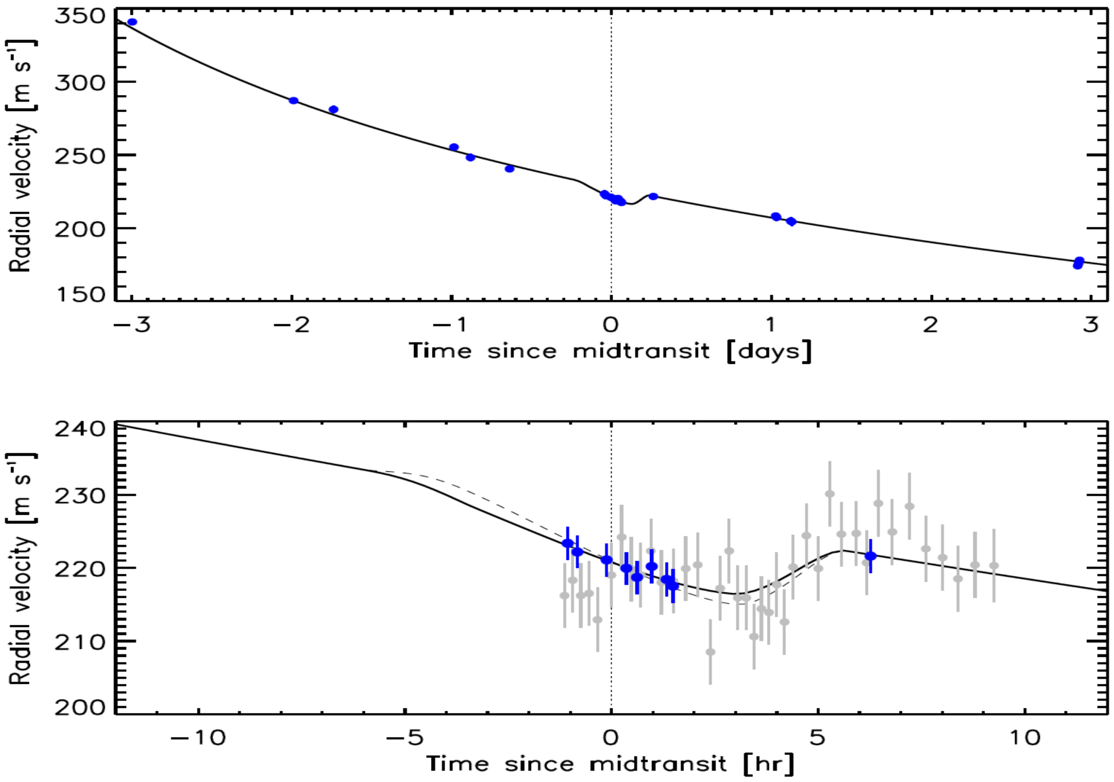
Spin orbit alignment

HD 80606b

RM effect shows
misalignment of the
rotational axes
Misalignment might
point towards migration
scenario

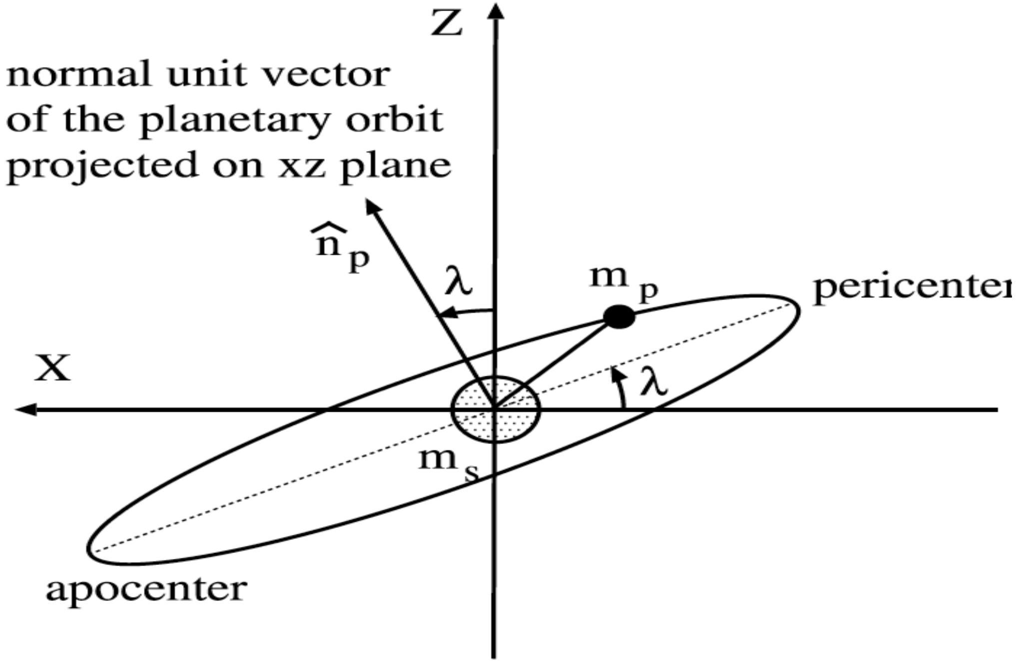
Therefore, the better
the characteristics of
the orbital parameters
the better is the understanding
of the evolution

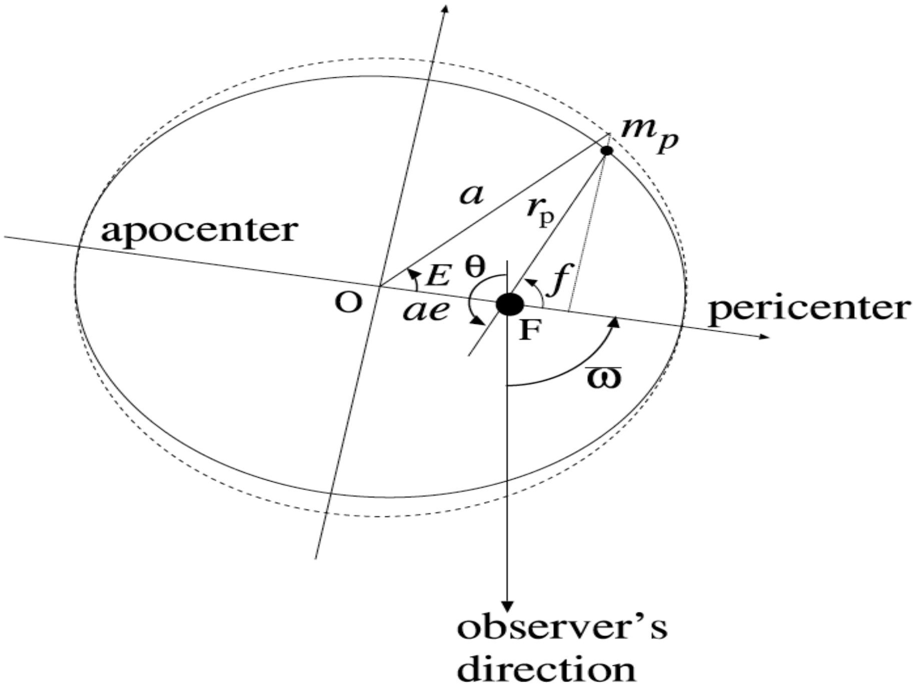
Kozai-Lidov process migration
Fabrycky 2007:
https://arxiv.org/pdf/0705.4285.pdf
Naoz et al 2016 (review)
https://arxiv.org/pdf/1601.07175.pdf



From Winn et al. 2009, https://arxiv.org/abs/0907.5205

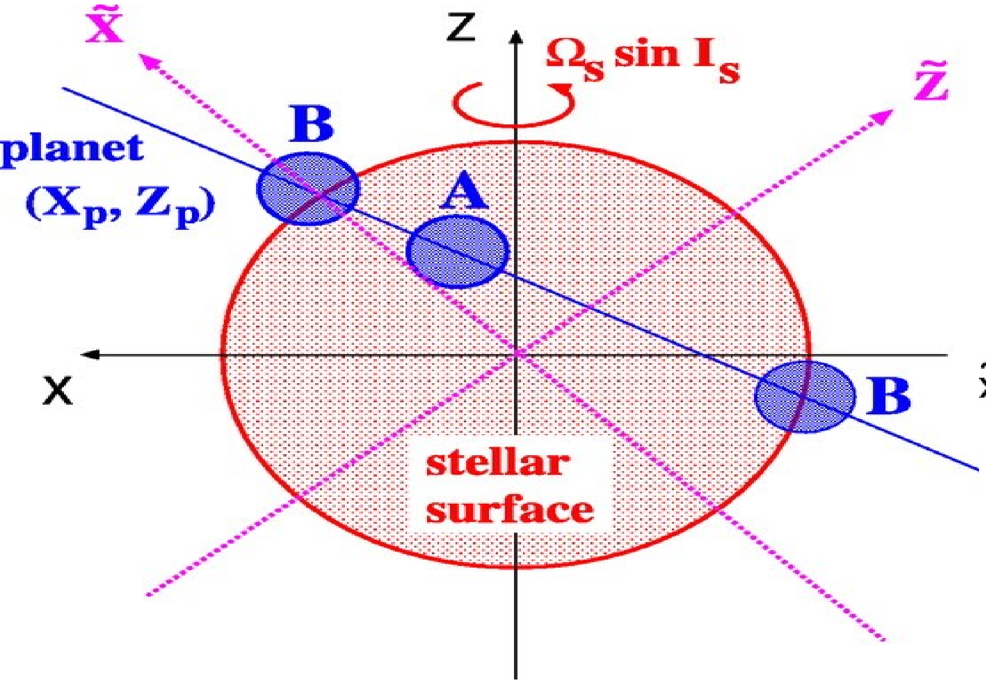
R-M effect - info

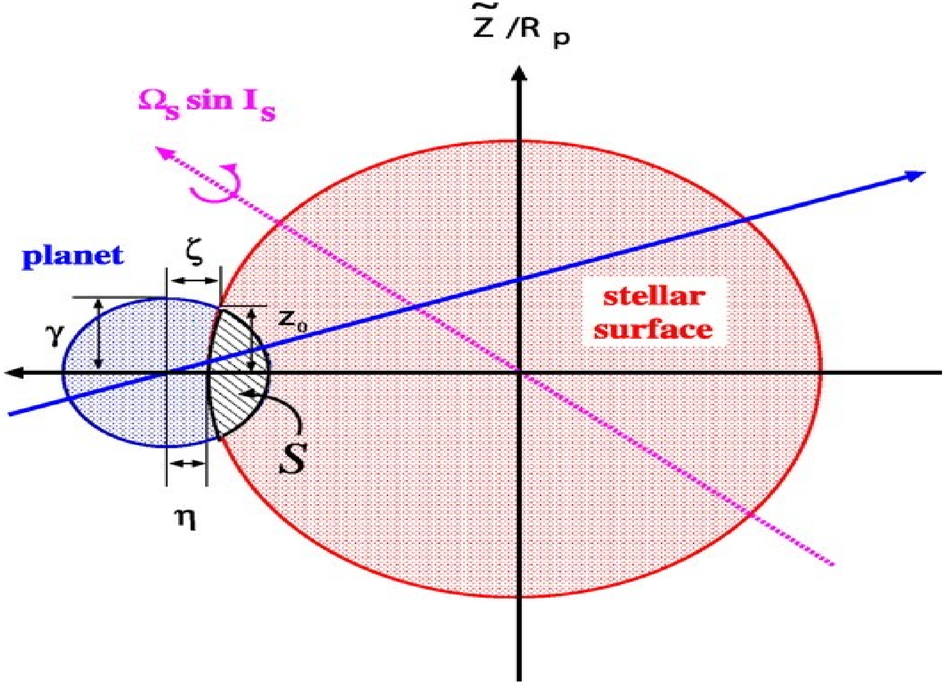




Ohta et al. 2005: https://arxiv.org/abs/astro-ph/0410499

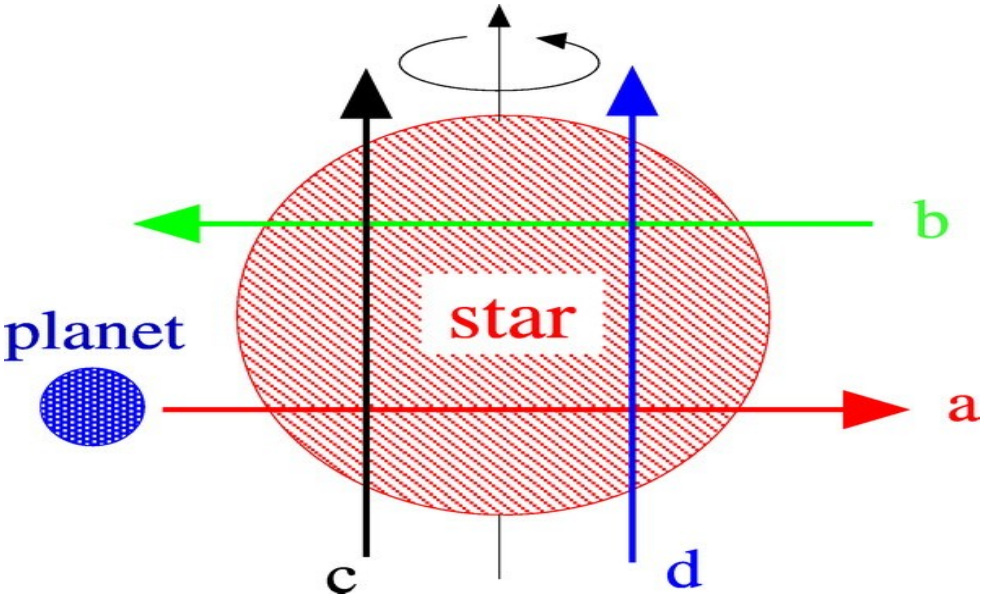
R-M effect

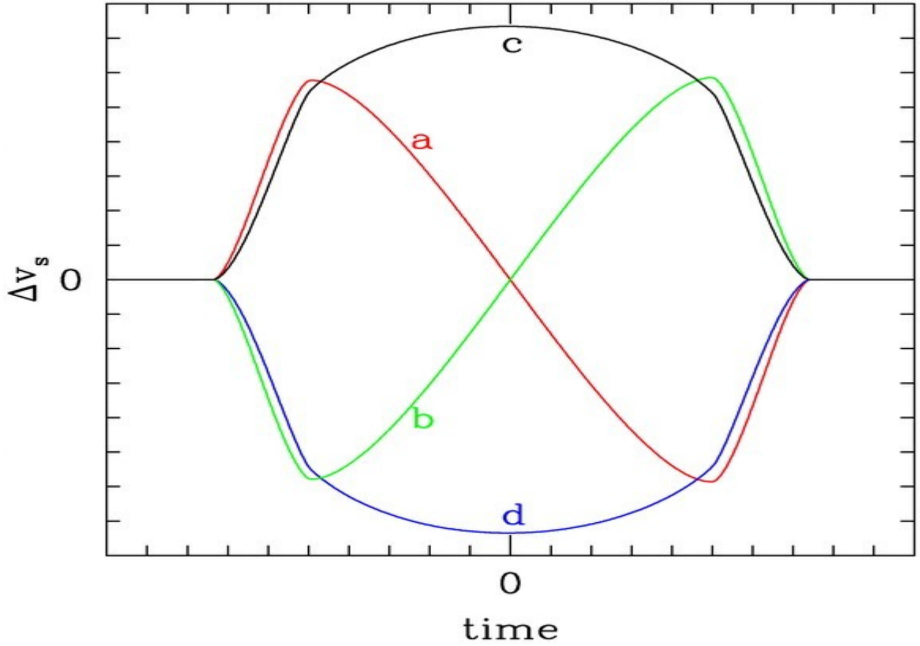




Ohta et al. 2005: https://arxiv.org/abs/astro-ph/0410499

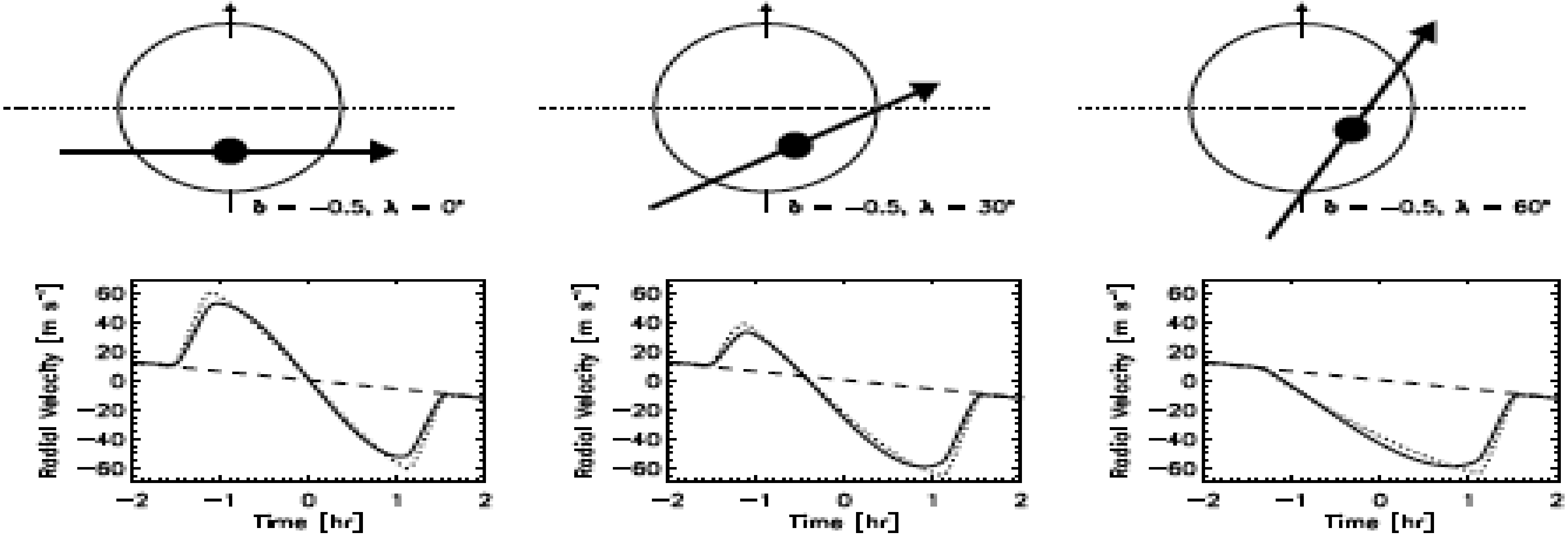
R-M effect





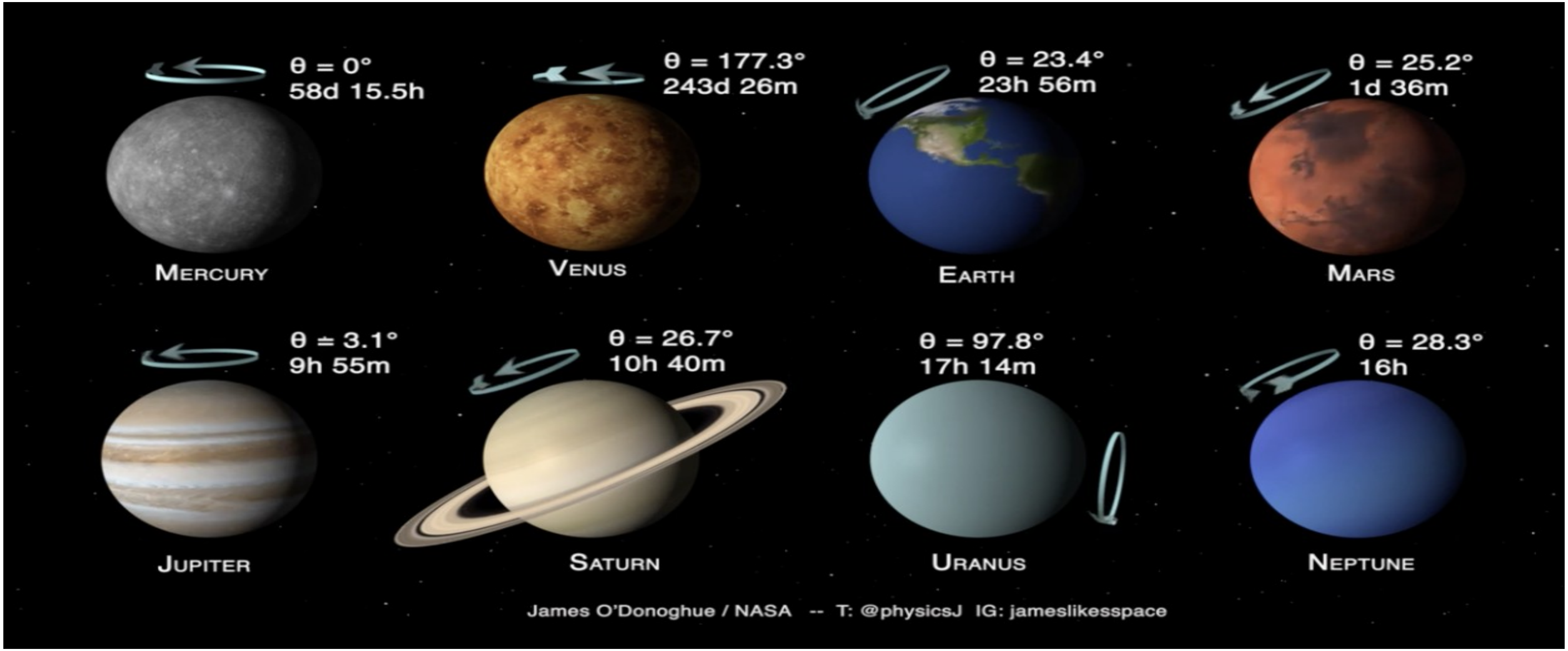
Ohta et al. 2005: https://arxiv.org/abs/astro-ph/0410499

Examples of R-M



Winn et al. 2006: https://arxiv.org/pdf/astro-ph/0612744.pdf

Solar system compared (tilts)



https://wasp-planets.net/2018/12/30/solar-system-planet-tilts/

HD 80606b

- Which process is responsible for the high eccentricity?
- Did the planet form close to the star in a circular orbit?
- Is the Kozai-Lidov mechanism responsible for the HD 80606b orbital parameters – high eccentricity (perturber star HD 80607)?

Recap

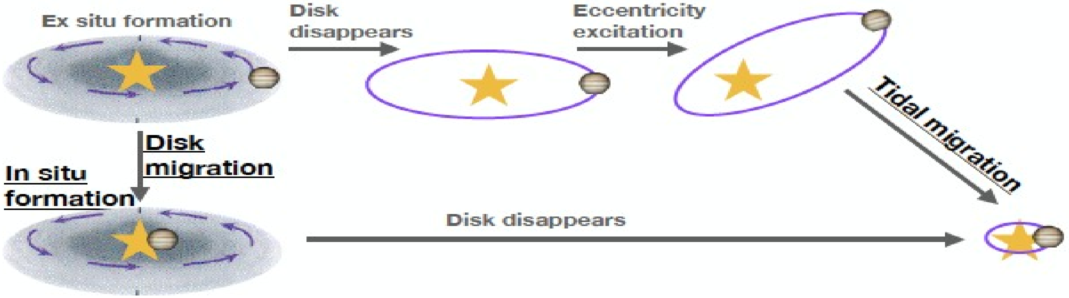
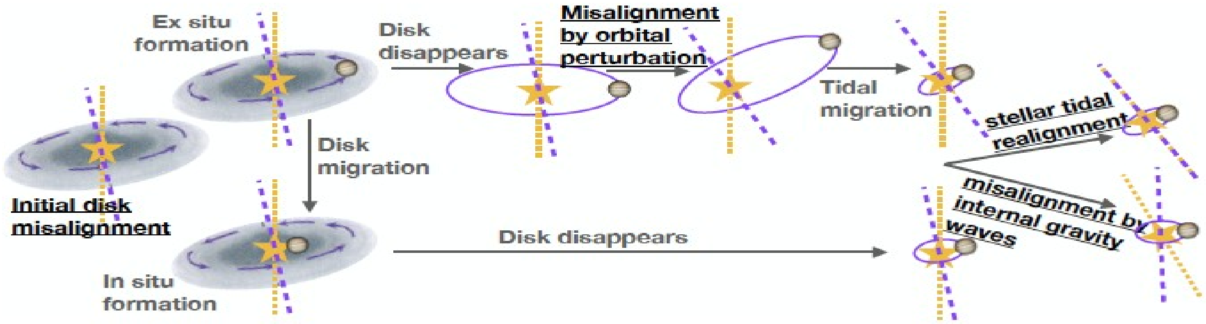


Figure 1 Three origins hypotheses for hot Jupiters: in situ formation (§2.1), disk migration (§2.2), and tidal migration (§2.3).



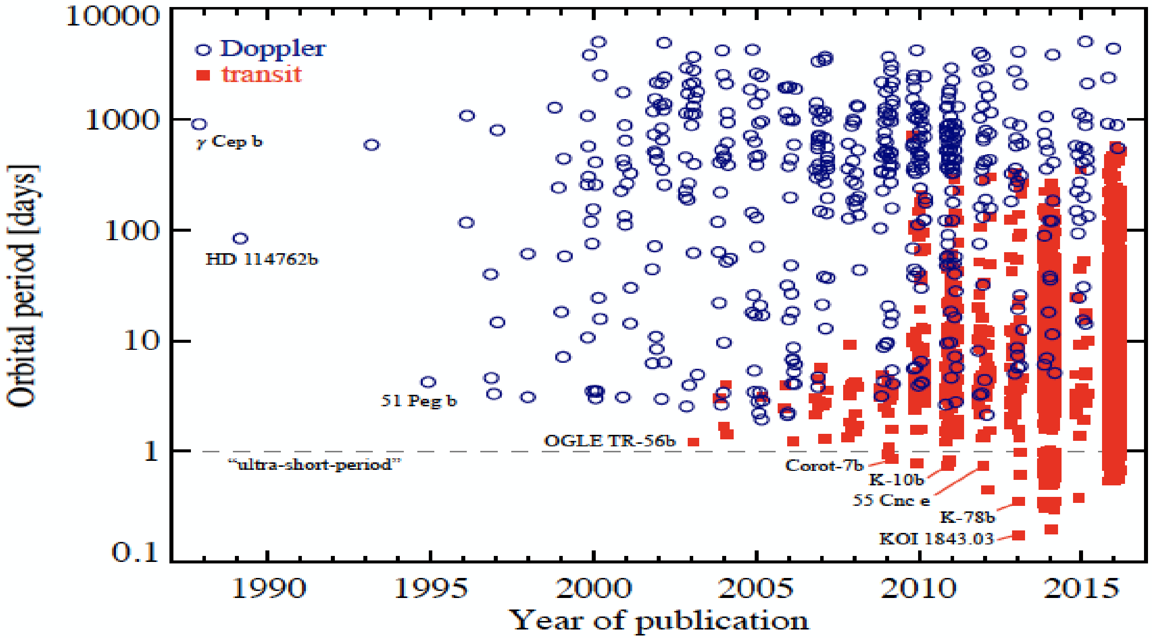
Dawson 2018, https://arxiv.org/pdf/1801.06117.pdf

Another interesting group of planets (moving towards smaller planets)

Ultra Short Period Planets

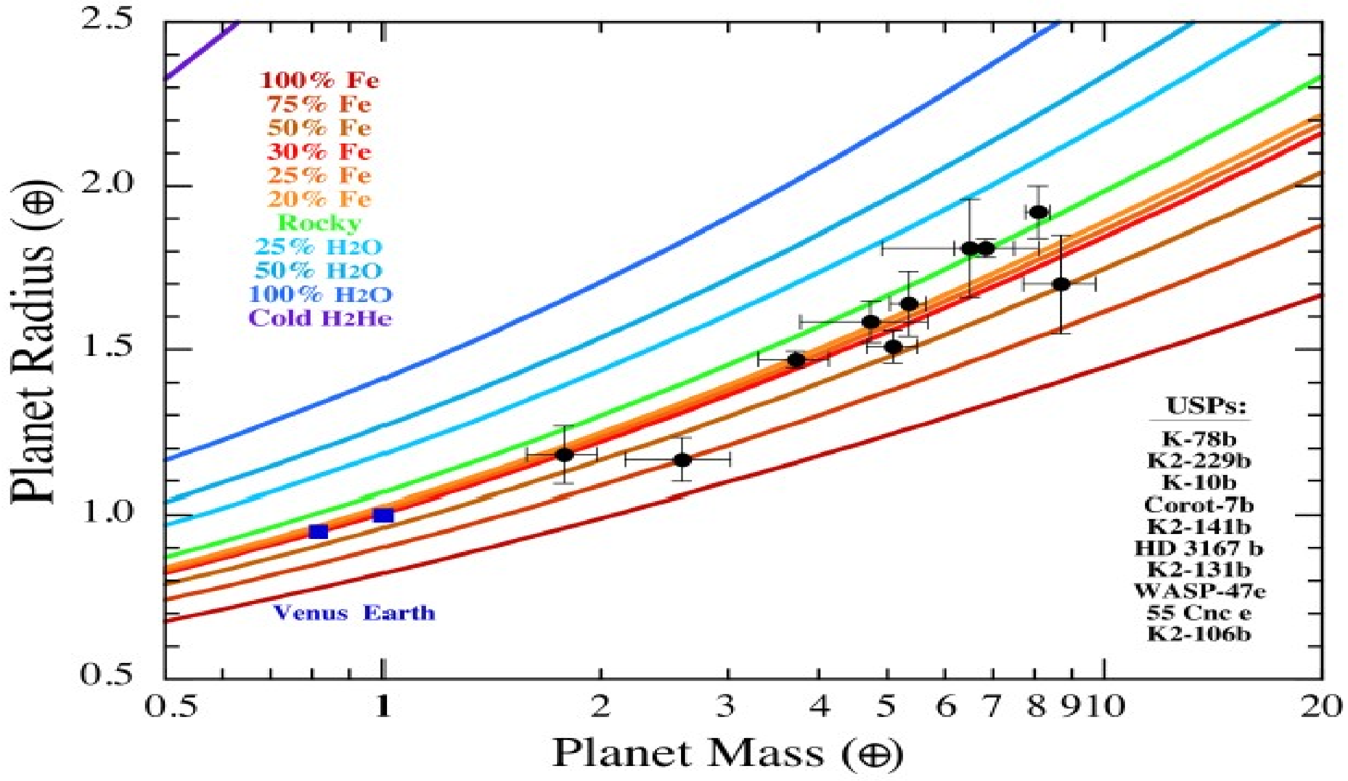
Ultrashort period planets (USPs)

- Small planets often called Lava worlds
- Orbital periods < 1 day
- Very close to host stars
- Very high surface temperature



Winn et al 2020 https://arxiv.org/pdf/1803.03303.pdf

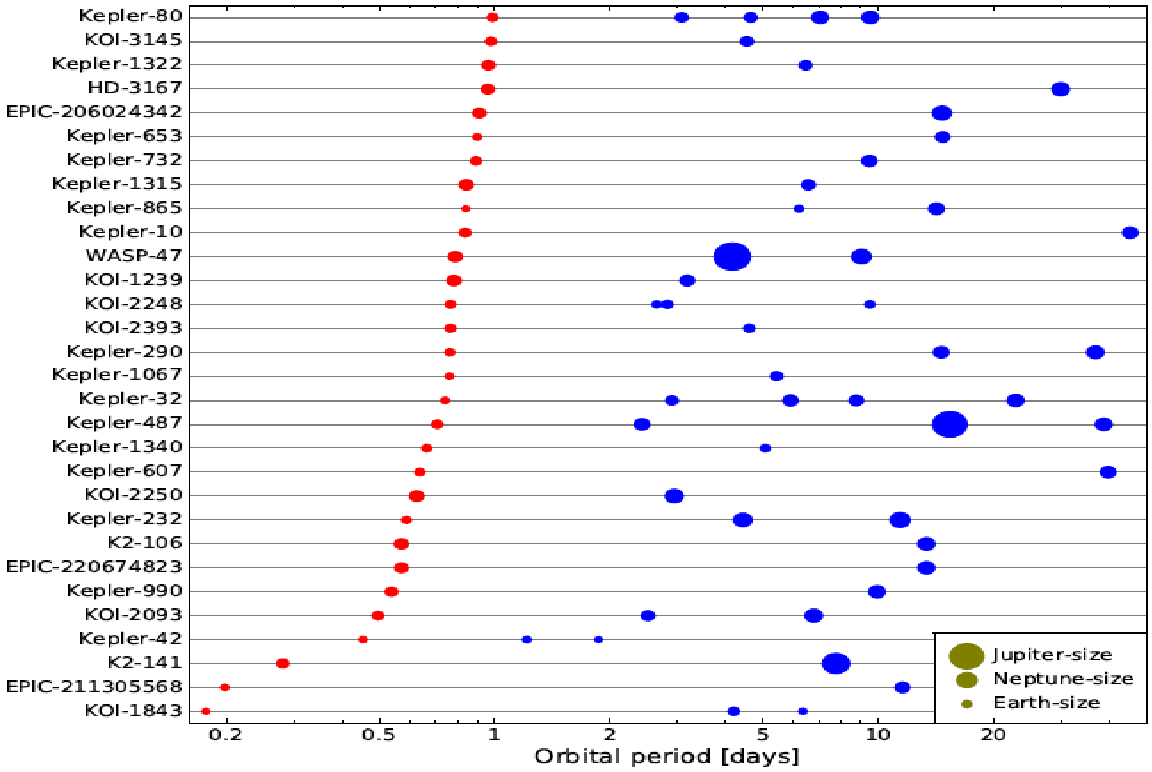
Composition of USPs



Winn et al 2020 https://arxiv.org/pdf/1803.03303.pdf

Architecture of USP systems

- USP resides usually in a system with more planets
- USP is less frequent with HJ planets (only Wasp-47
- system)



Winn et al 2020 https://arxiv.org/pdf/1803.03303.pdf

Formation scenarios

- In-situ – leads usually to several Super-Erath planets in the warm part of the disc
- Migrating through the disc towards inner part

  (infrequent)
- Migrating giants provide material for the USP

  (Wasp-47?)
- Tidal circularization – however most USPs are with companions
- Stripping the giant planet of their envelope once they migrate too close to the star

Ultra-short planets

- See TESS USP

  Vanderspeck et al. 2018,

  https://arxiv.org/abs/1809.07242

How about small planets?

Terrestrial planets

- They could form in-situ by accretion
- They could form with “help” of migrating giants
- They could form by circularization of orbits
- They could form by evaporation of gas from large inward migrating planet

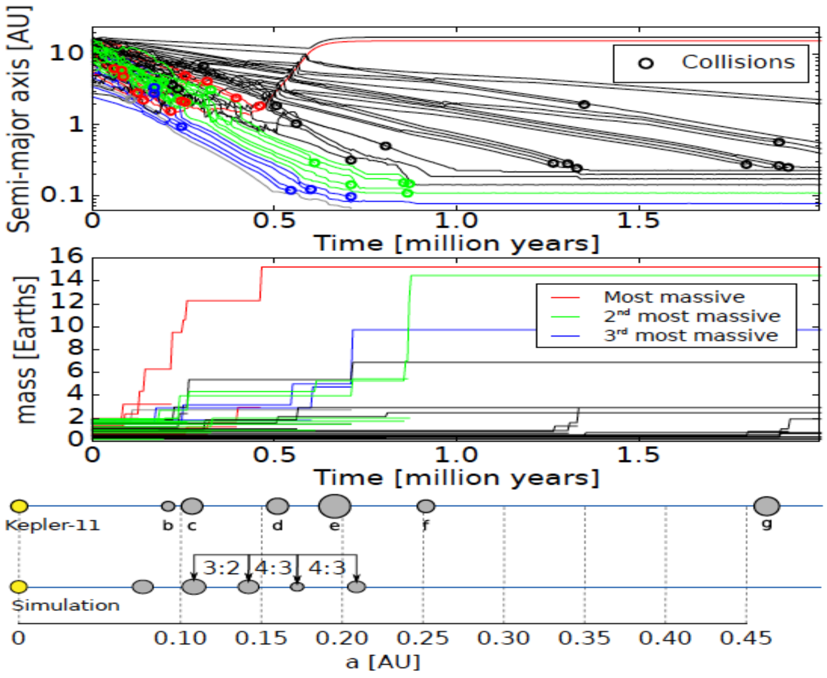


Fig. 6.— Formation of a system of hot Super Earths by type 1 migration. The top panel shows the evolution of the embryos' orbital radii and the bottom panel shows the mass growth. The red, green and blue curves represent embryos that coagulated into the three most massive planets. All other bodies are in black. Only the most massive (red) planet grew large enough to trigger outward migration before crossing into a zone of pure inward migration. From *Cossou et al.* (2013).

Raymond et al. https://www2.mpia-hd.mpg.de/homes/beuther/raymond.pdf

And what do observations tell us?

How frequent are gas giants?

- The rate of Jupiter-sized planets around GFK stars is estimated to be around 1%

  Wright et al. 2012, https://arxiv.org/pdf/1205.2273.pdf

- Are smaller planets more frequent?
- Jupiter-sized planets on long periodic orbits have a frequency of about 14% - see next slides.

Planet frequency

- We have now larger data set
- HARPS and CORALIE data
- Planets are quite frequent, at least every

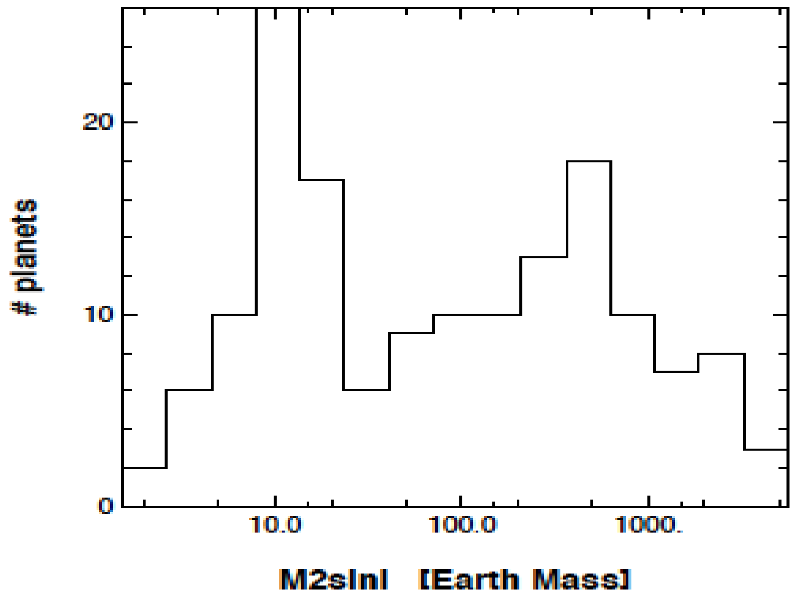
Table 1. Occurrence frequency of stars with at least one planet in the defined region. The results for various regions of the $m_2 \sin i$ – log P plane are given.

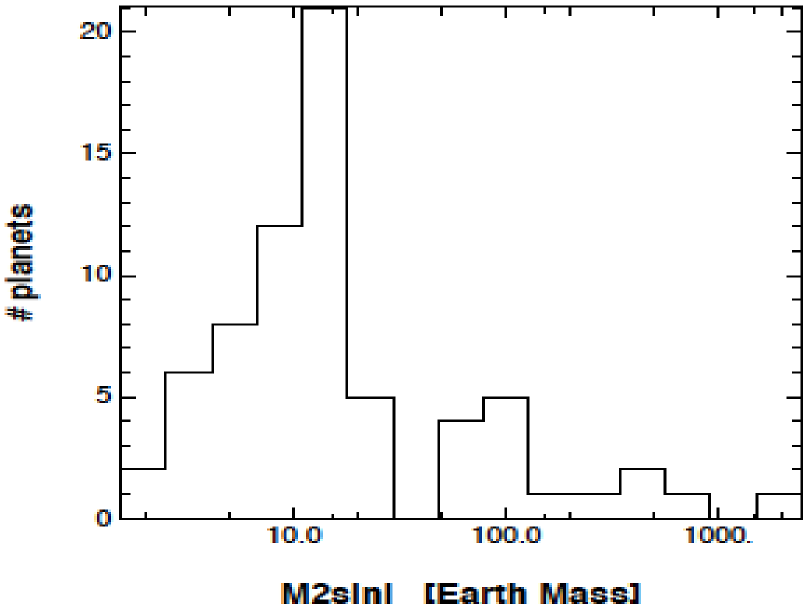
Mass limits	Period limit	Planetary rate based on published planets	Planetary rate including candidates	Comments
$> 50\ M_\oplus$	$<$ 10 years	13.9 ± 1.7 %	13.9 ± 1.7 %	Gaseous giant planets
$> 100\ M_\oplus$	$<$ 10 years	9.7 ± 1.3 %	9.7 ± 1.3 %	Gaseous giant planets
$> 50\ M_\oplus$	$<$ 11 days	0.89 ± 0.36 %	0.89 ± 0.36 %	Hot gaseous giant planets
Any masses	$<$ 10 years	65.2 ± 6.6 %	75.1 ± 7.4 %	All "detectable" planets with $P <$ 10 years
Any masses	$<$ 100 days	50.6 ± 7.4 %	57.1 ± 8.0 %	At least 1 planet with $P <$ 100 days
Any masses	$<$ 100 days	68.0 ± 11.7 %	68.9 ± 11.6 %	F and G stars only
Any masses	$<$ 100 days	41.1 ± 11.4 %	52.7 ± 13.2 %	K stars only
$< 30\ M_\oplus$	$<$ 100 days	47.9 ± 8.5 %	54.1 ± 9.1 %	Super-Earths and Neptune-mass planets on tight orbits
$< 30\ M_\oplus$	$<$ 50 days	38.8 ± 7.1 %	45.0 ± 7.8 %	As defined in Lovis et al. (2009)

Mayor et al 2012, A&A, https://arxiv.org/pdf/1109.2497.pdf

Small planets vs. large planets

- Left: low mass vs. High mass, right: same but only for short periodic planets less than 100 days

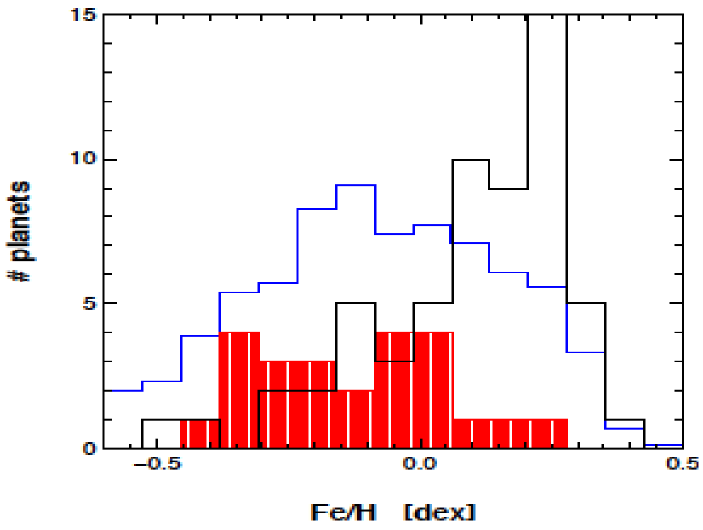


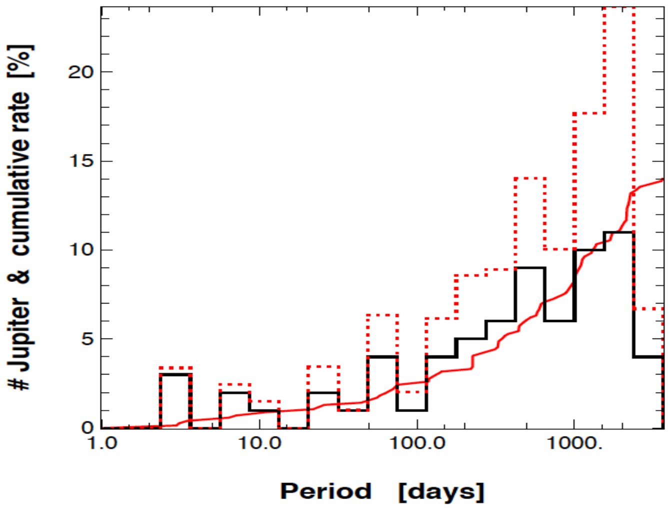


Mayor et al 2012, A&A, https://arxiv.org/pdf/1109.2497.pdf

Small vs. Large

- Metallicity of the system is a factor
- Large planets favor large metallicities
- Smaller planets are abundant also with lower metallicities

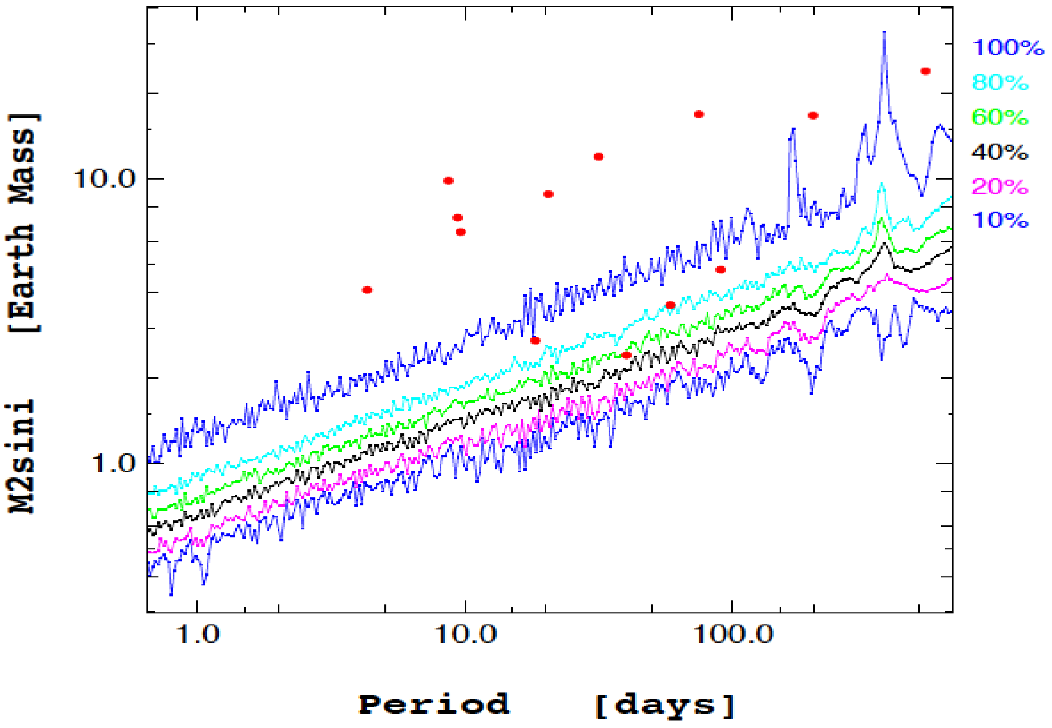




Mayor et al 2012, A&A, https://arxiv.org/pdf/1109.2497.pdf

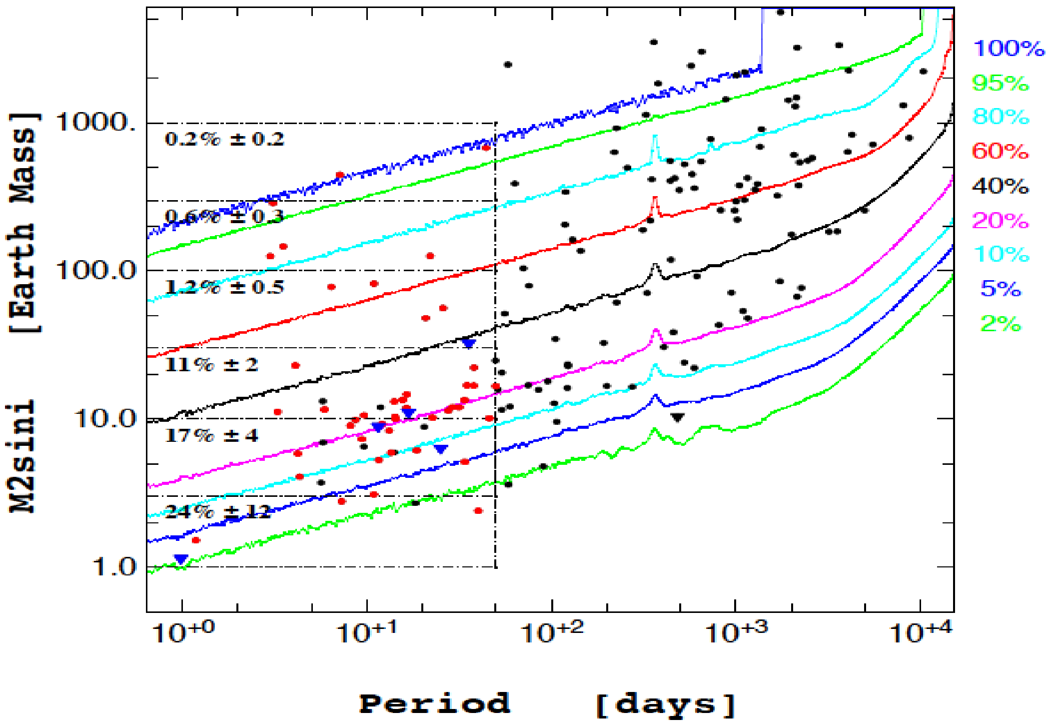
Small planets frequency

- Sample of 10 stars hosting 29 planets
- Sensitivity to detect 10 M Earth planet is close to 100%
- A 3 M Earth planet sensitivity is about 20%
- ESPRESSO is here now!



Mayor et al 2012, A&A, https://arxiv.org/pdf/1109.2497.pdf

We have pretty good chances!



Mayor et al 2012, A&A, https://arxiv.org/pdf/1109.2497.pdf

Next week(s)

- Composition of exoplanets
- Interesting exoplanetary systems
- Looking for the Solar System analogue