

# Exoplanets

Lecture 7  
23.11.2024  
MFF UK

# 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?

# Solar System formation

- Widely accepted formation theory is the nebular theory
- There are other alternative theories of formation such as capture theory
- Nebular theory has still its flaws but the nebular theory refined with new knowledge also from exoplanet research can explain most accurately observed Solar system features

# Capture theory

- Woolfson 2017 <https://arxiv.org/pdf/1709.07294.pdf>
- It was proposed in early early sixties in the past century by M. Woolfson
- It states that the Sun and a passing protostar interacted
- The matter from the Sun and from the protostar was the building stone for planets
- Earth and Venus were created by collision of two large protoplanets
- Mars and Mercury were escaped moons by one of the collided planets as well as dwarf planets

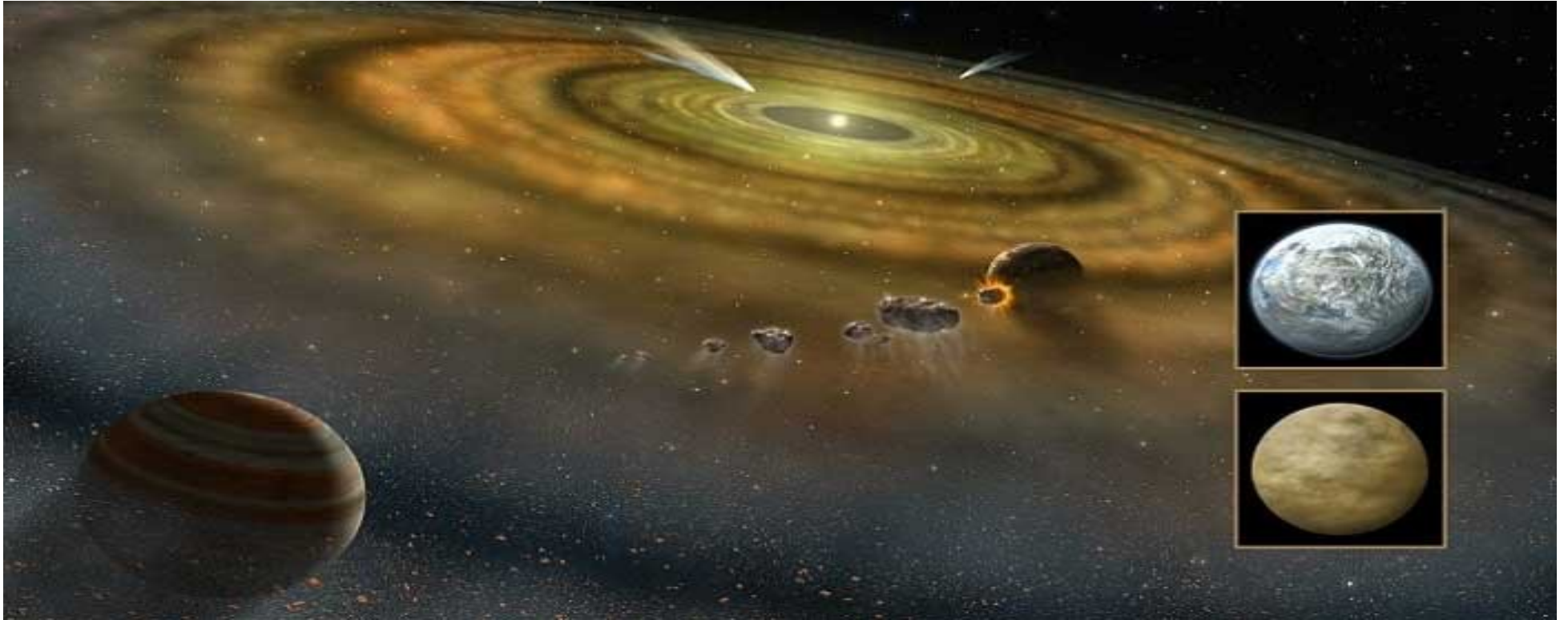
# Capture theory

- The encounter of stars is only less probable
- Hot gas would not contract to form planets but it would expand

# Nebular theory

- Solar nebula collapse
  - what was the event causing the formation?
  - perhaps supernova?
  - how do we know? We do not but we have hints from material in Solar System, namely short lived isotopes which needed to be produced in Supernovae
- Banerjee et al. <https://www.nature.com/articles/ncomms13639>
- Cameron & Truran [1977Icar...30..447C](#)

# Solar System formation



Credit NASA

# Solar System formation

- Protoplanetary disc rotates
- Angular momentum conservation
- The sun and clumps of planets are formed
- Inner (rocky) planets and outer (gas) planets
- Beyond ice line ice giants formed
- Large planets migrated inwards and back outwards
  - see e.g. Nesvorny et al. 2018 Nat Astronomy  
<https://arxiv.org/pdf/1809.04007.pdf>
  - Pierens & Raimond  
<https://www.aanda.org/articles/aa/pdf/2011/09/aa17451-11.pdf>
  - D Angelo  
<https://iopscience.iop.org/article/10.1088/0004-637X/757/1/50/meta>



# Jumping Jupiter?

- Migration of Jupiter and Saturn inwards and outwards (700M years)
- Preventing growth of Mars
- Ejection of 5<sup>th</sup> large planet?
  - Batygin <https://arxiv.org/pdf/1111.3682.pdf>
  - Nesvorny <https://arxiv.org/pdf/1109.2949.pdf>
- Changing climate on Venus?
  - <https://iopscience.iop.org/article/10.3847/PSJ/abae63/pdf>

# Planet IX?

- Planet IX?

-

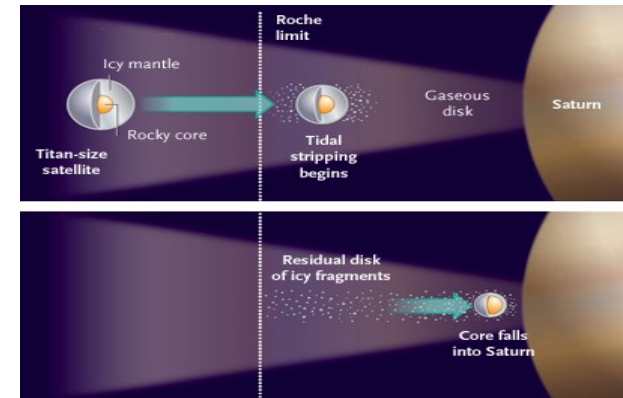
[https://www.nature.com/news/polopoly\\_fs/1.19182!/menu/main/topColumns/topLeftColumn/pdf/529266a.pdf?origin=ppub](https://www.nature.com/news/polopoly_fs/1.19182!/menu/main/topColumns/topLeftColumn/pdf/529266a.pdf?origin=ppub)

- <https://www.nature.com/news/evidence-grows-for-giant-planet-on-fringes-of-solar-system-1.19182>

# The mystery of Saturn's rings

- Young or old? Were the rings formed in the early history of the Solar System or more recently?
- The rings are composed from ice but if they were from the early Solar System, there would be also some silicates and they would appear darker.....
- Canup 2010, Nature, <https://www.nature.com/articles/nature09661>(  
<https://www.boulder.swri.edu/~robin/canup2010.pdf>)
- Charnoz et al.  
- <https://arxiv.org/abs/0809.5073>

LHB role for formation of Saturn's rings



Credit: Nature

# The Saturn rings mystery

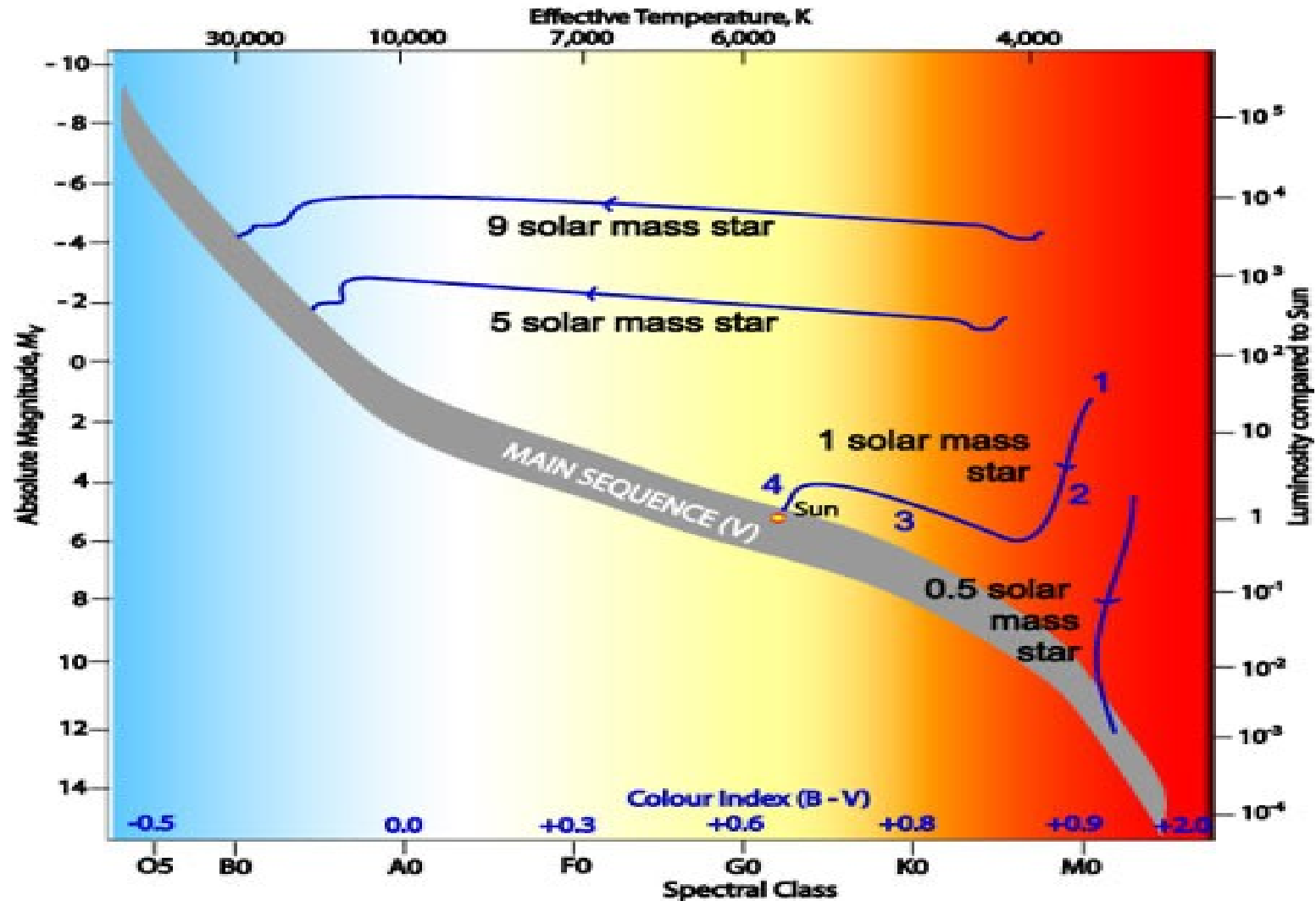
- Or young....
- Crida et al. 2019, Nature,  
<https://www.nature.com/articles/s41550-019-0876-y>
- The measured mass of the rings  $10^{19}$  kg is consistent with young but also with old rings scenario
- For old rings scenario a cleaning mechanism is needed, to clean-up silicates

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

# Hayashi track (new system is born)

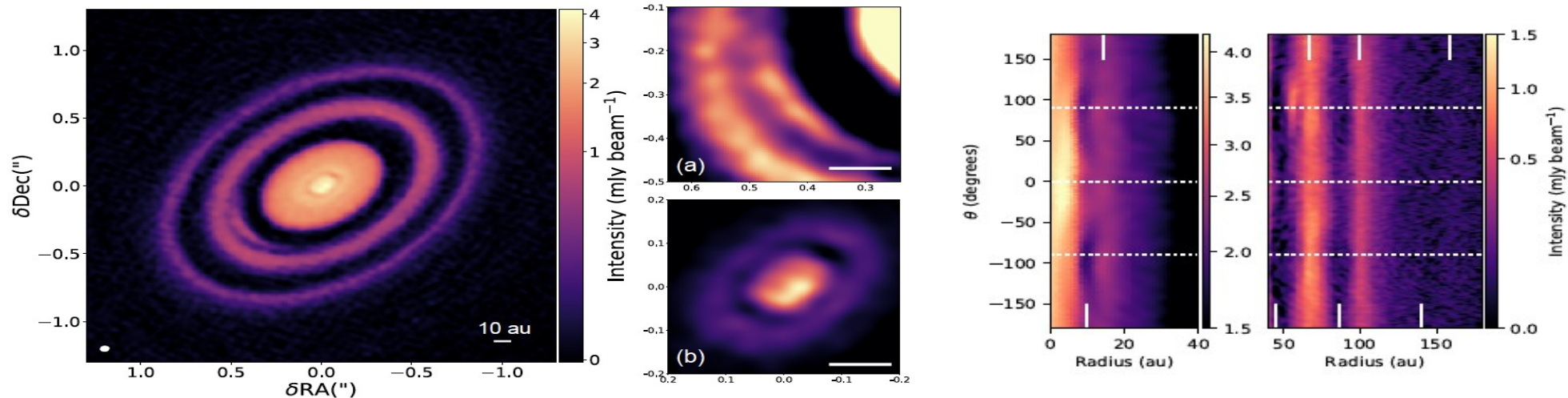
- Track in the HR diagram  
along which T Tauri stars  
move towards the MS
- The time and track depend on the mass of the young star
- Hayashi,  
<http://articles.adsabs.harvard.edu/pdf/1961PASJ...13..450H>

## Theoretical Hayashi Tracks of Protostars



# HD163296 disc with planets

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





# Young stars with discs



# 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

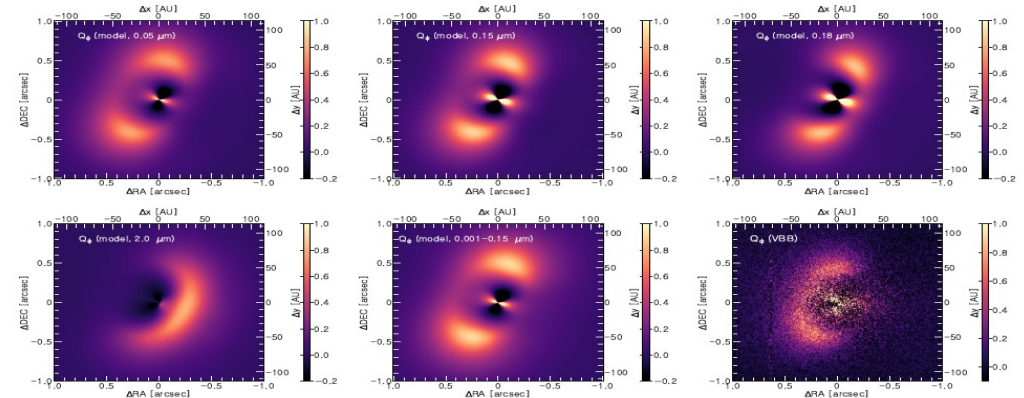
<https://www.nasa.gov/content/goddard/hubble-sees-a-young-star-take-center-stage>

# Disc imaging

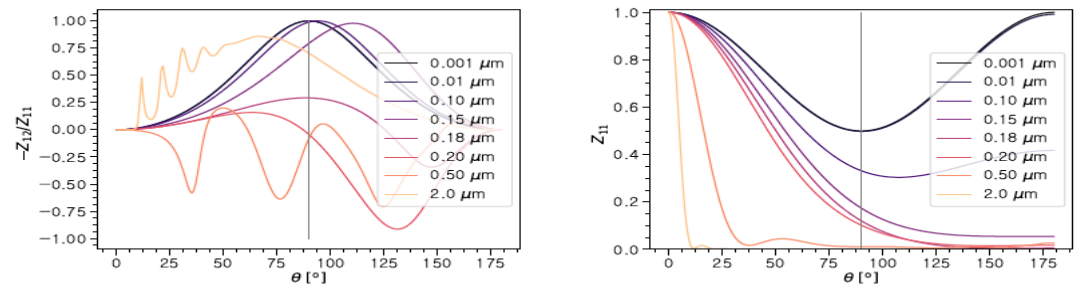
- PDA 70
  - imaged by VLT (NACO, SPHERE)
  - young object (5.4 Myr)
  - disc present
  - particle grains

estimated

- Hosts a planet
  - anything between
- 5-14 Jupiters masses



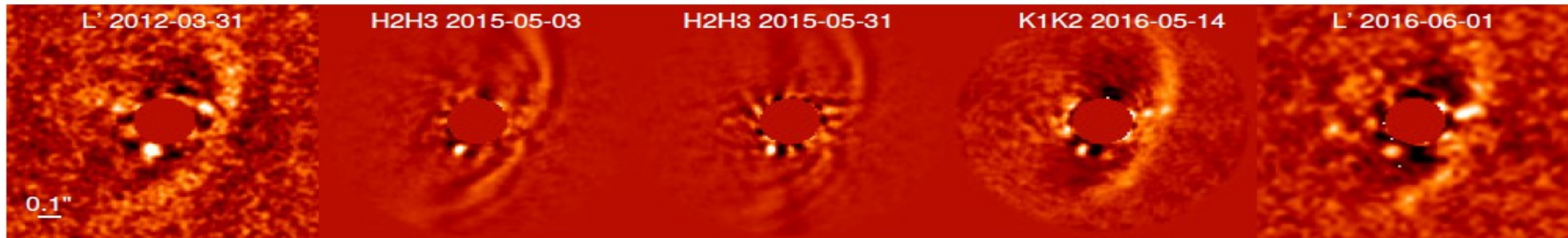
**Fig. 8.** Convolved ray-traced  $Q_\theta$ -images evaluated at  $0.7 \mu\text{m}$  using different grain size distributions. Successively, the central source polarisation emerging from the unresolved inner disk (radius 2 au) was subtracted using a  $U_\theta$ -minimisation. The lower right panel shows 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  $0.7 \mu\text{m}$ .

# PD 70b

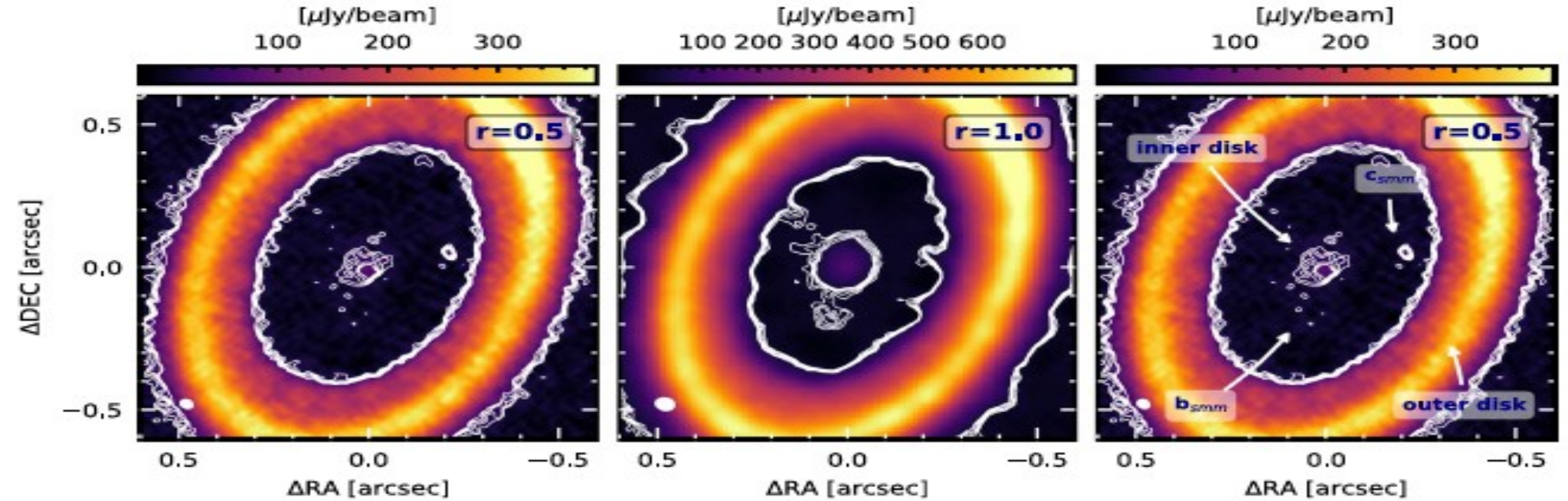
- And here is the planet....



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

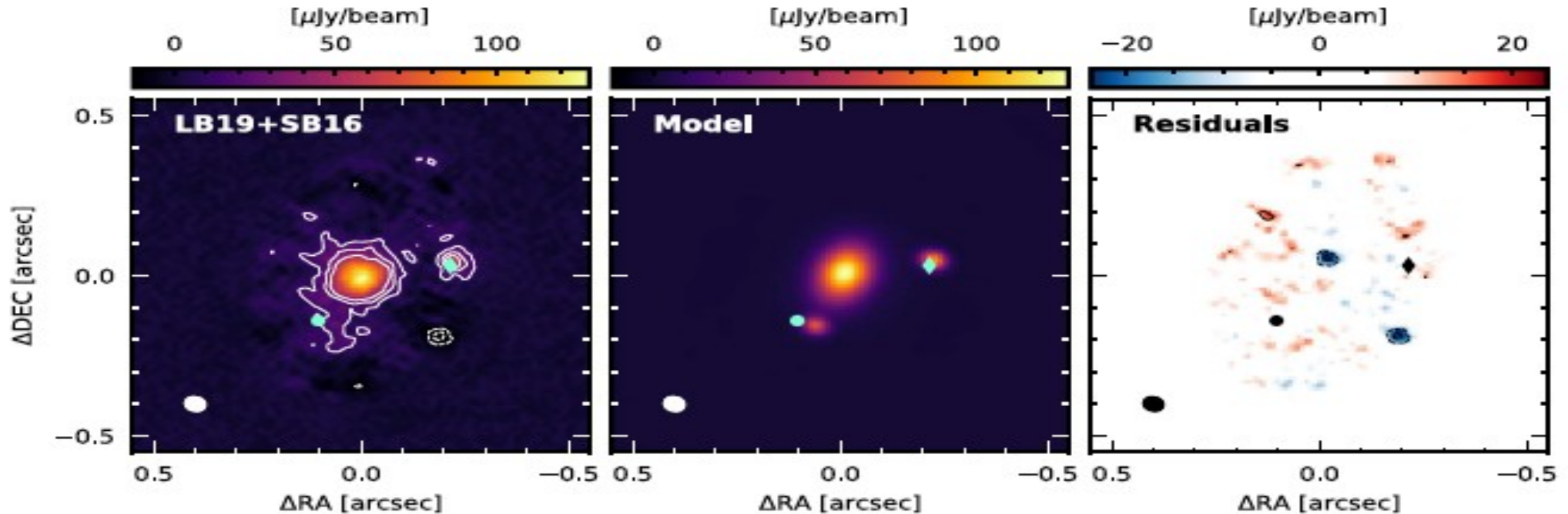


# And there is another one



**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  $0''.036 \times 0''.030$  and  $0''.051 \times 0''.044$ , 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 7  $\sigma$ , spaced by 1  $\sigma$  (with  $\sigma = 8.8$  and  $4.8 \mu Jy beam^{-1}$ , respectively). An image gallery for all data sets is given in Appendix A.2.

# And well, maybe discs forming moons?



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

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

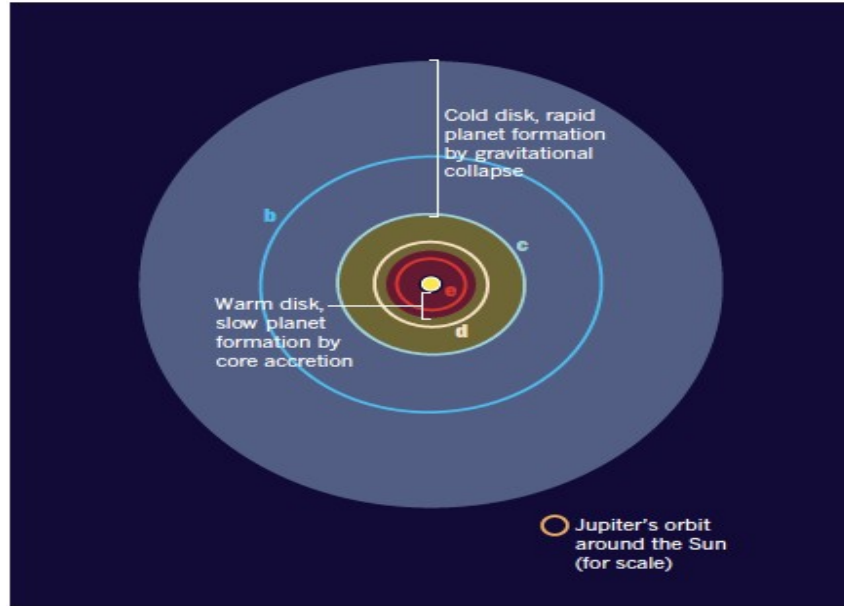
- Safronov 1972, Pollack 1996
- Small solid dust grains (less than micro meters) collide and grow into larger particles (dozens of kilometers) – planetesimals
- Gravity starts to shape a planetesimal
- Planetesimal grows into planetary core
- Usually drives formation in warm inner disc

# Real exoplanets and formation hypothesis

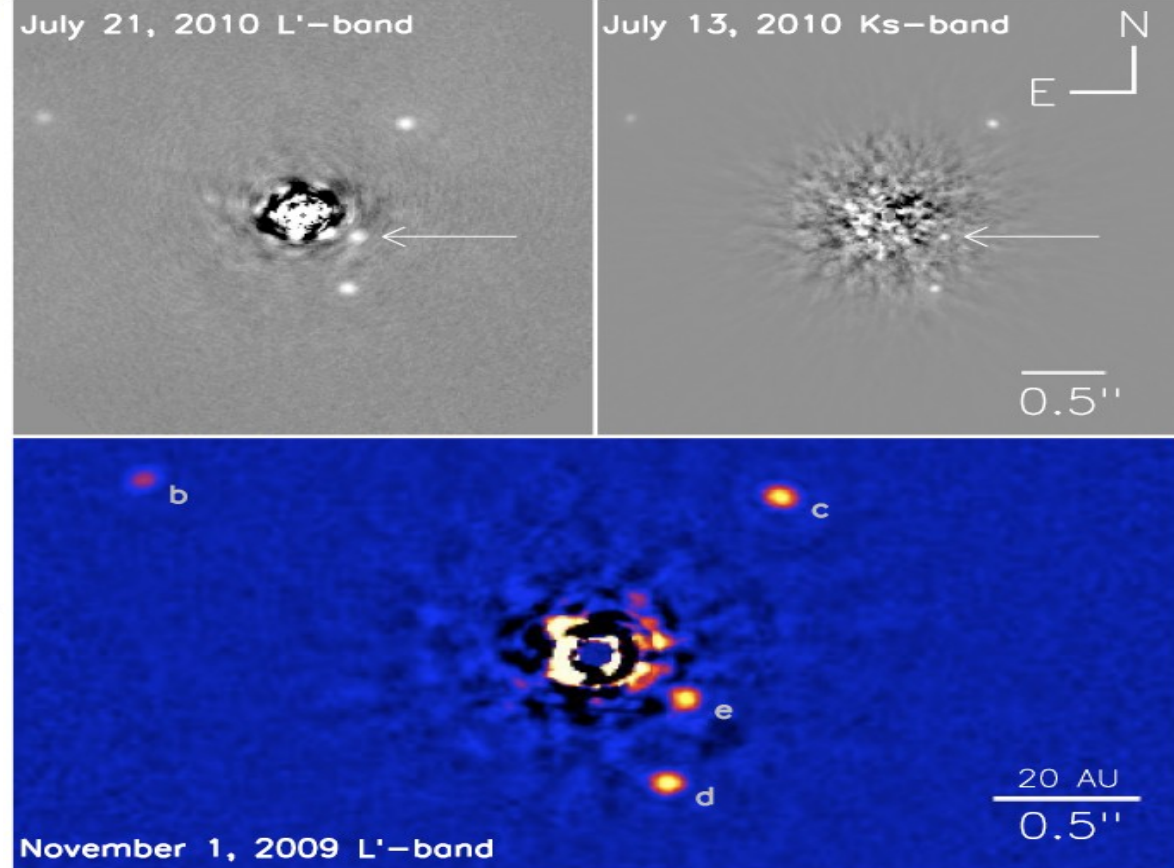
# The case of HR8799

- 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

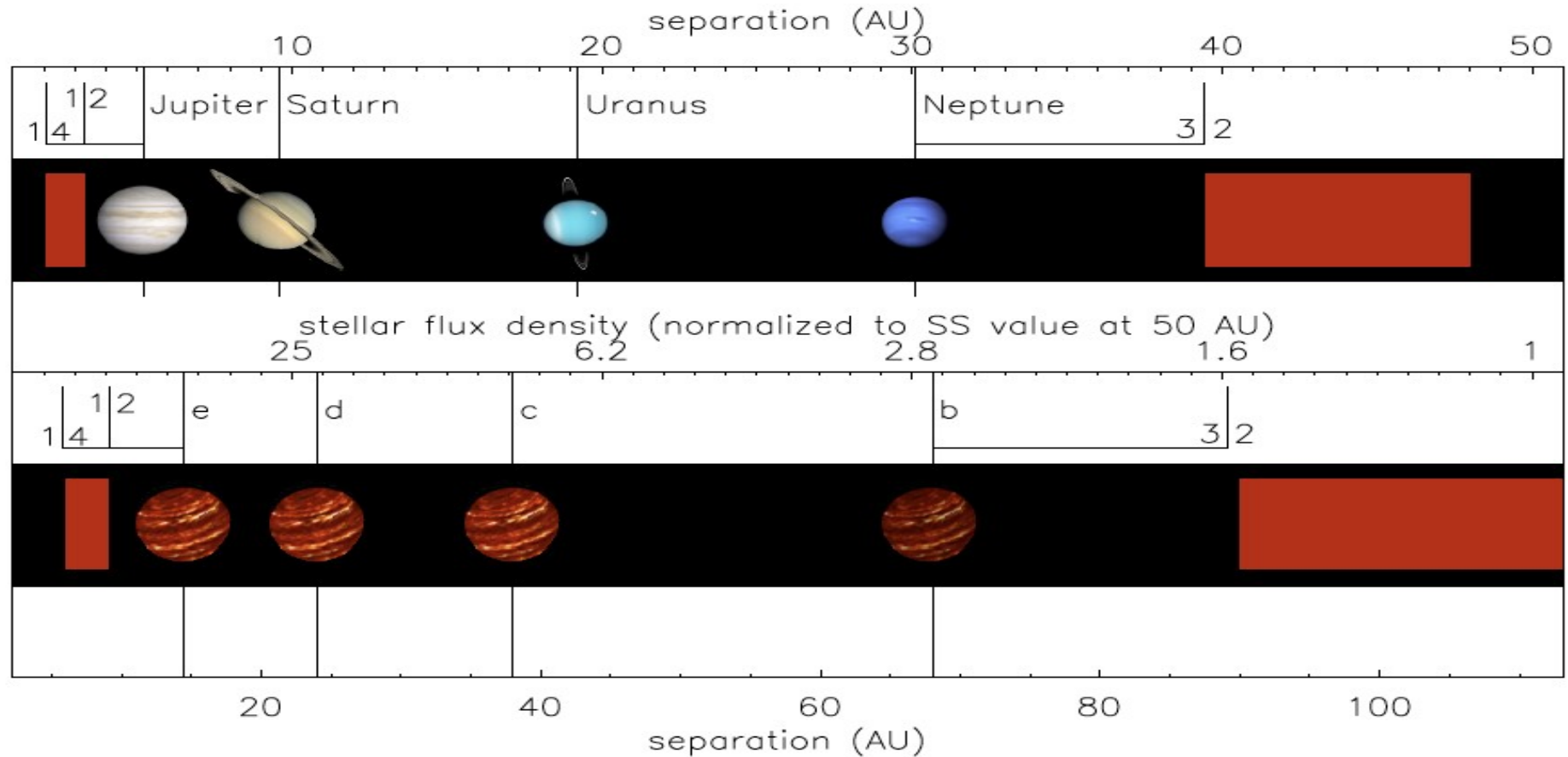


Credit:  
<https://www.nature.com/articles/nature09716.pdf>



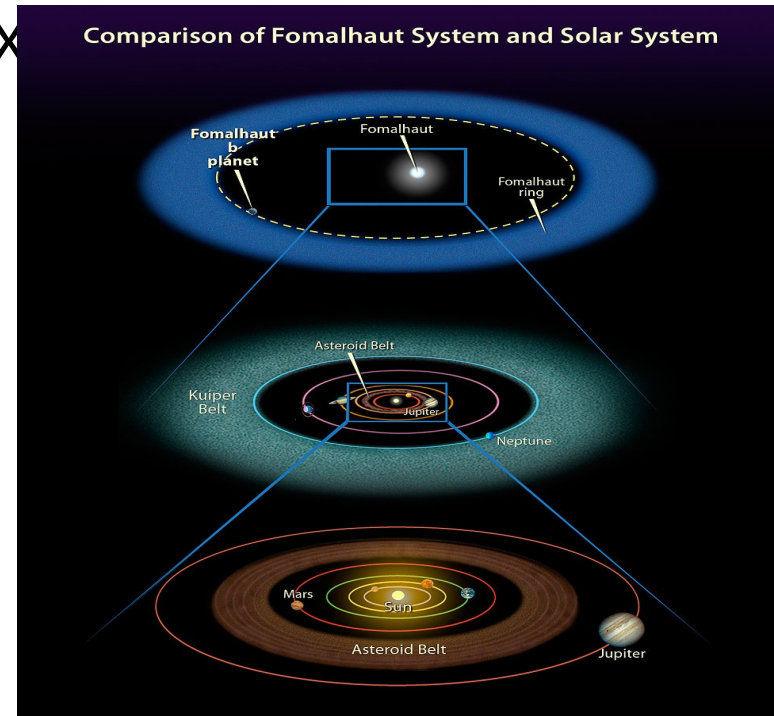
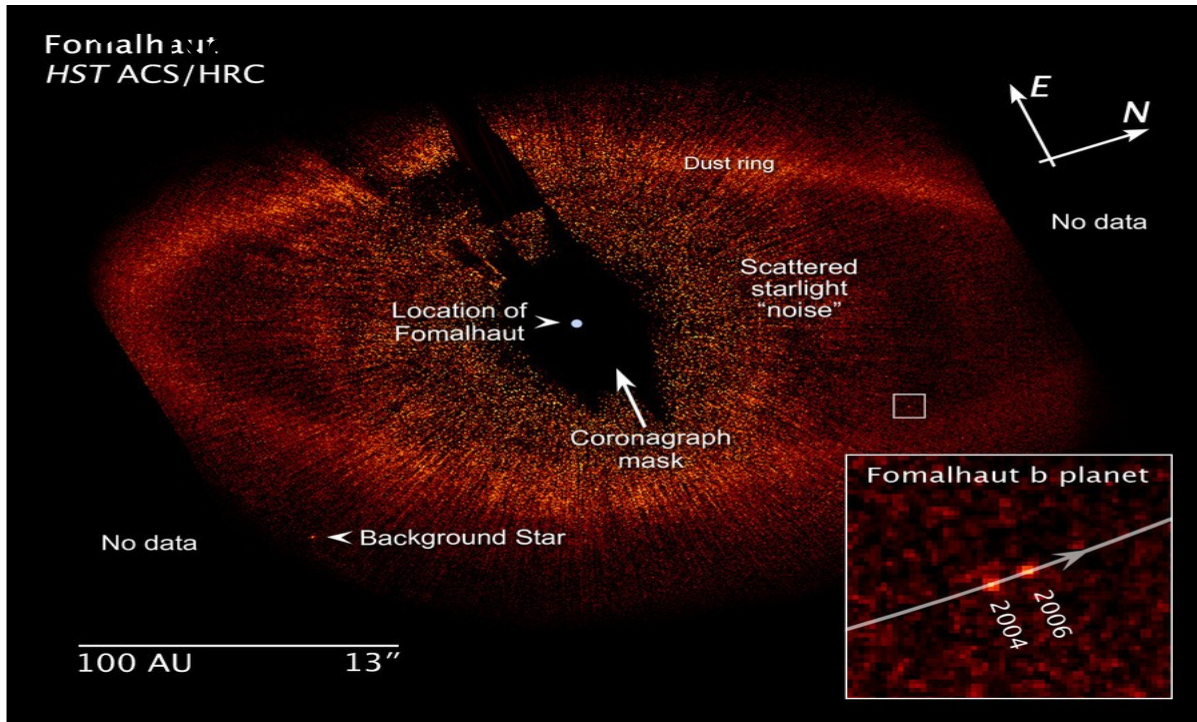
Marois et al. 2010, Nature: <https://arxiv.org/pdf/1011.4918.pdf>

# The HR8799 system

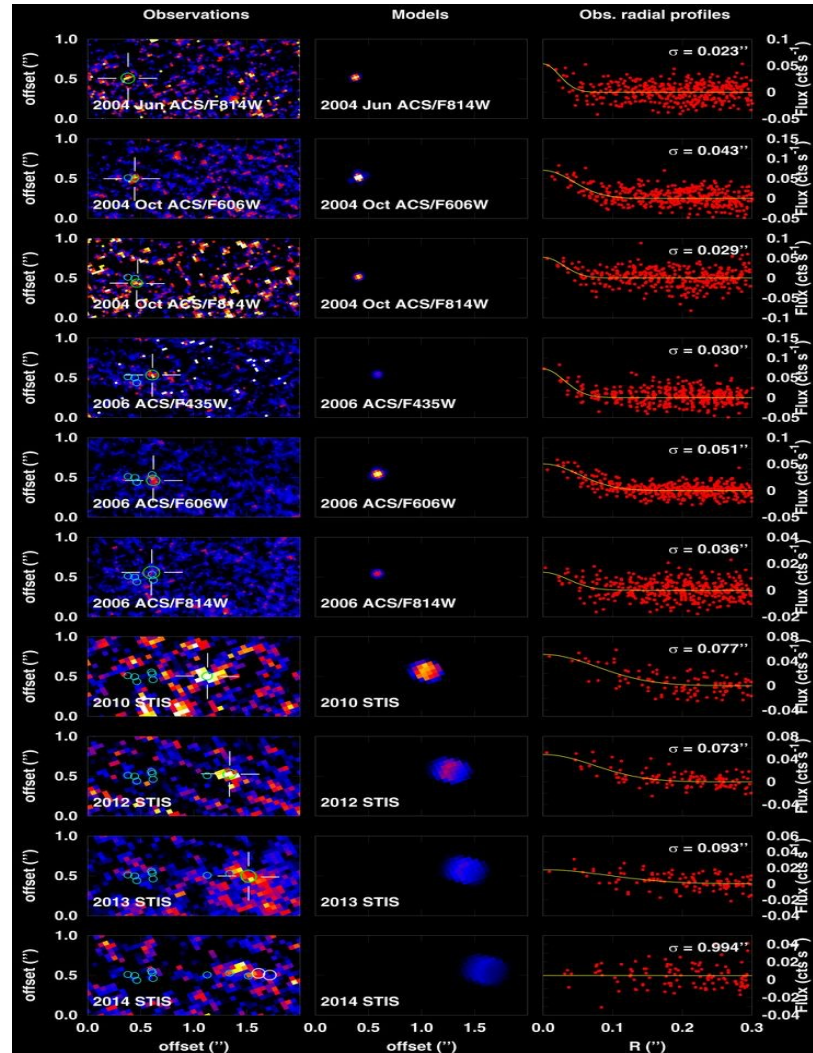


# The Fomalhaut system

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



# And all turned to dust?



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

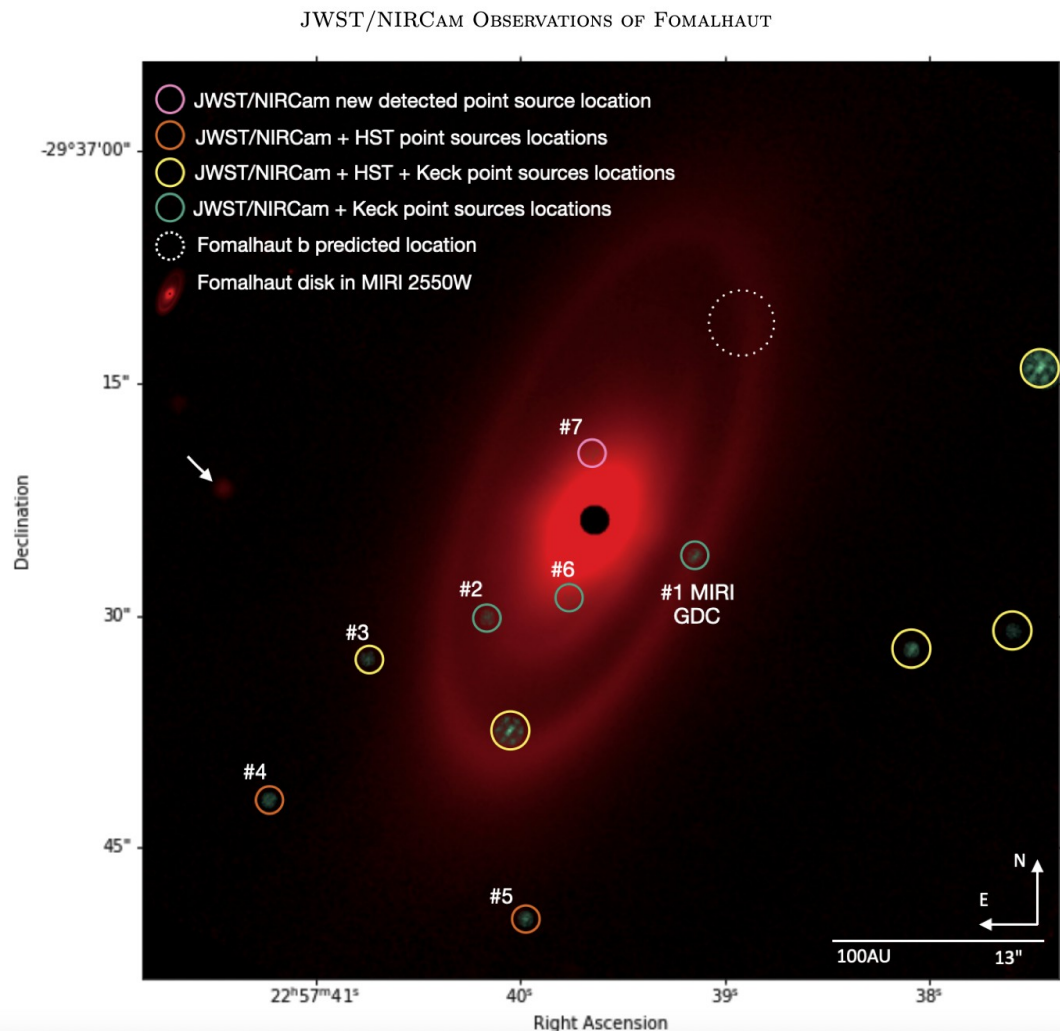
# The Fomalhaut system

- 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?



# But,

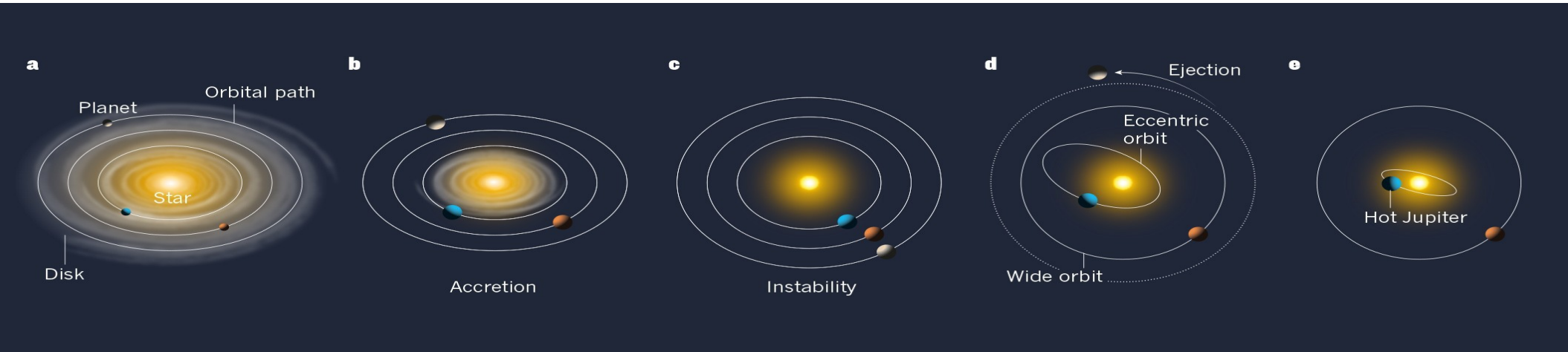
- JWST search
- Ygouf et al. 2023
- No Fomalhaut b
- Consistent with dust interaction event
- However, signal S7 might be a planet?
- More planets possible due to complex disc



# Wandering planets (Hot Jupiters case)

# Migration

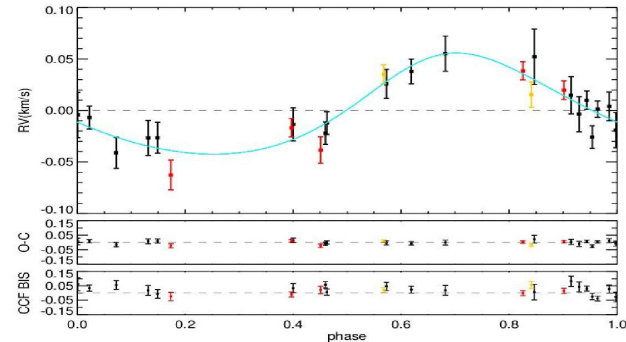
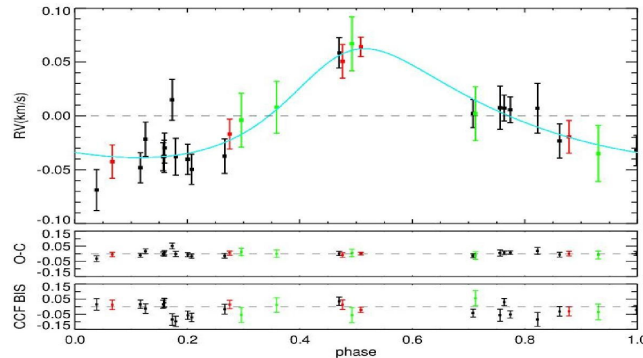
- Why are hot Jupiters so close to their stars?
- One of the theories is migration



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

# Migration of HJs

- HJs in an open cluster M67 – approx. 4% occurrence rate
- Host stars are as massive as the Sun
- Why is the occurrence 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?



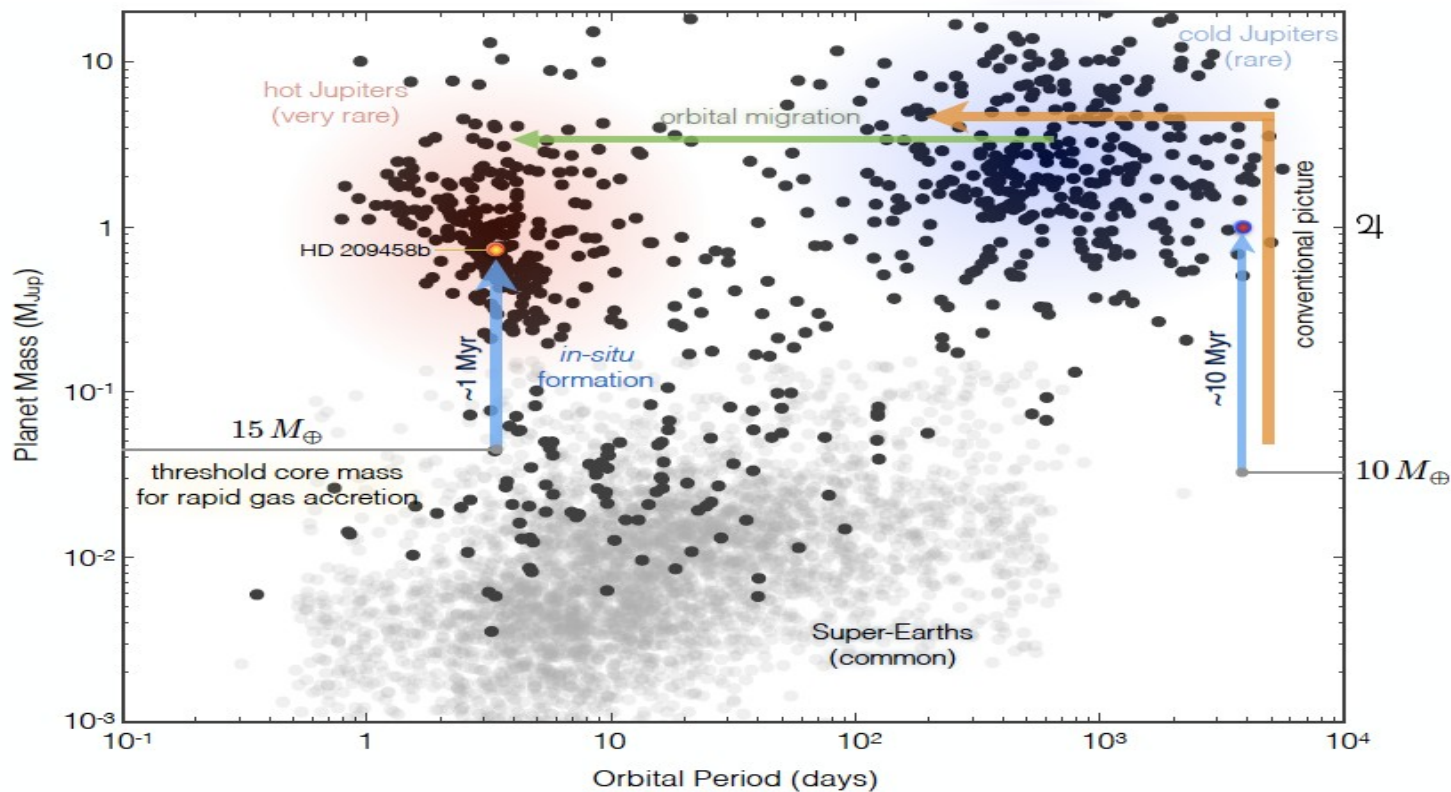
# Important questions

- 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?

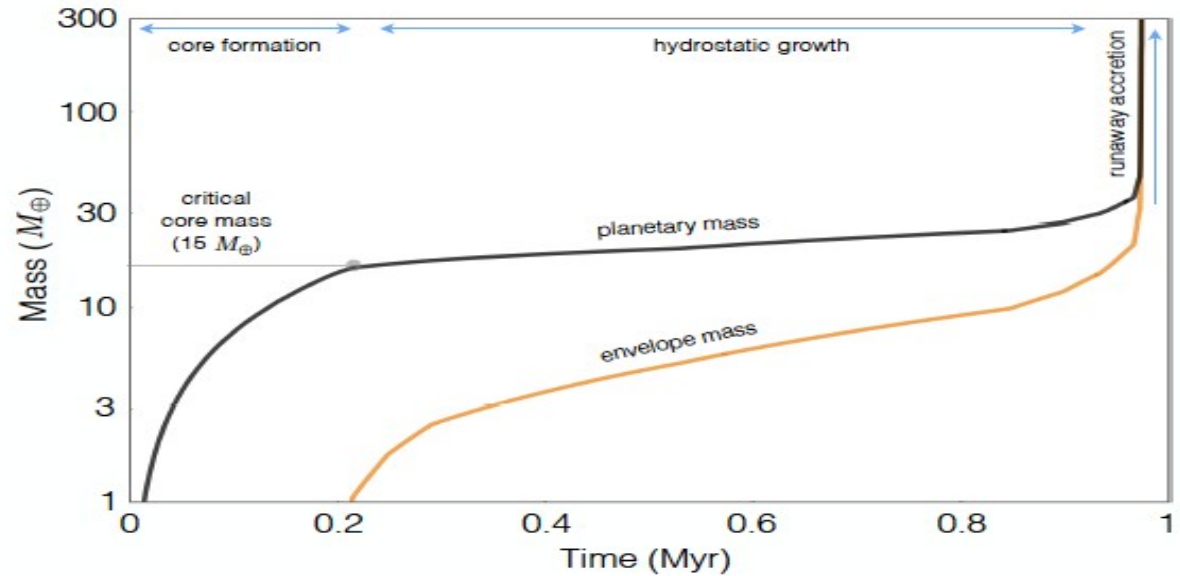
- It was widely accepted as unlikely
  - high temperatures close to star prevent the gravitational instability scenario
  - however, core accretion might be possible under some assumptions, perhaps...
- But one would need a Super-Earth as a core for future hot Jupiter (Batygin et al. 2016:  
<https://arxiv.org/pdf/1511.09157.pdf>)

# Formation in-situ?



# 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 migration

15

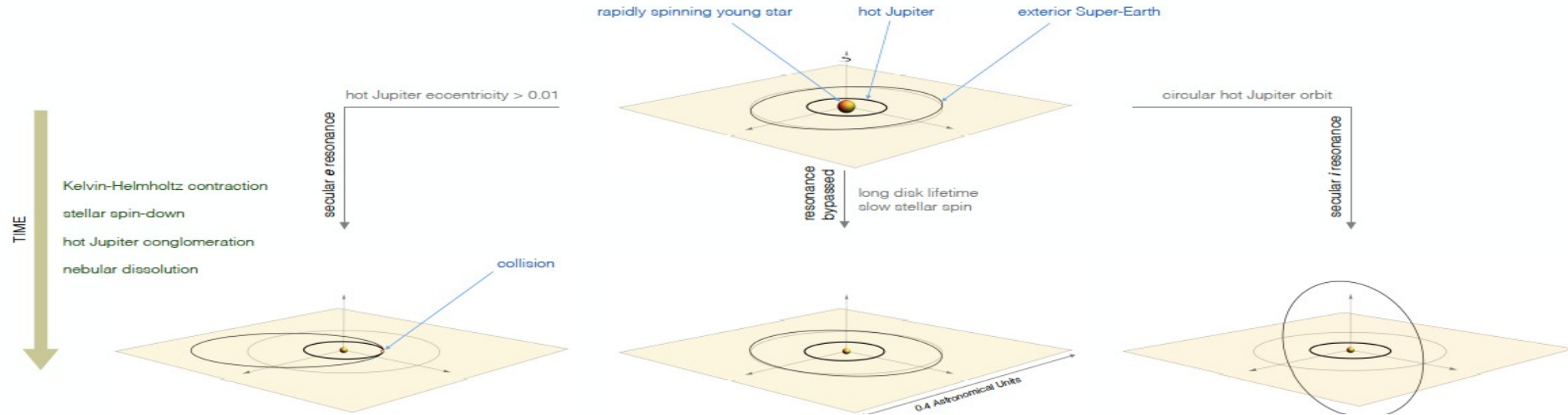


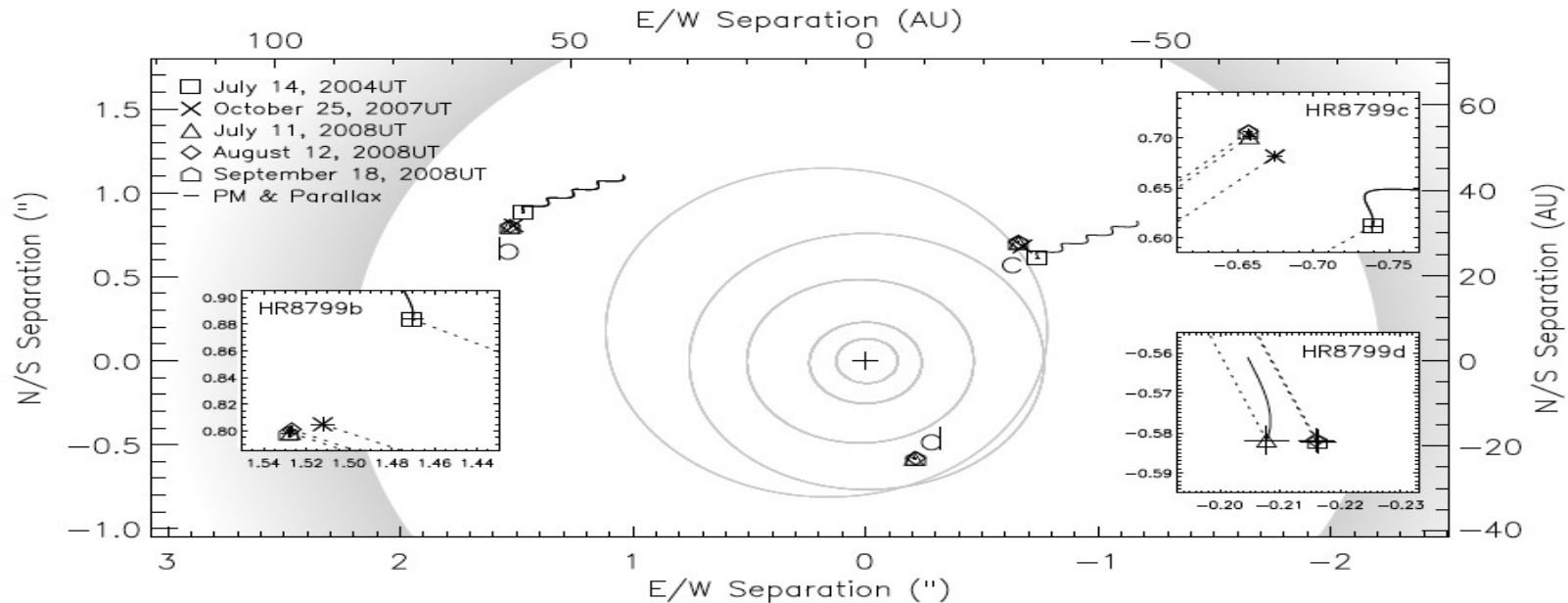
FIG. 10.— Potential outcomes of dynamical evolution of hot Jupiter-hosting planetary systems. An initially nearly-planar, quasi-circular, low-mass multi-planetary system is taken to evolve under the influence of mutual gravitational coupling, interactions with the protoplanetary nebula, as well as the 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  $e_{\text{HJ}} \sim 0.01$  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.

# Solar system example

- Recall Batygin 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

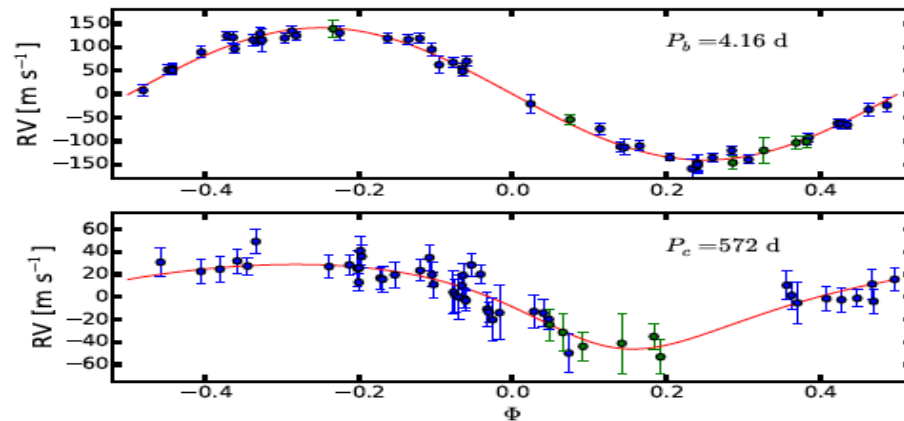
- We know already HR 8799 system as an example of large orbit. So why not Planet Nine?



Back to Hot Jupiters  
(large and small living together)

# Wasp-47 system

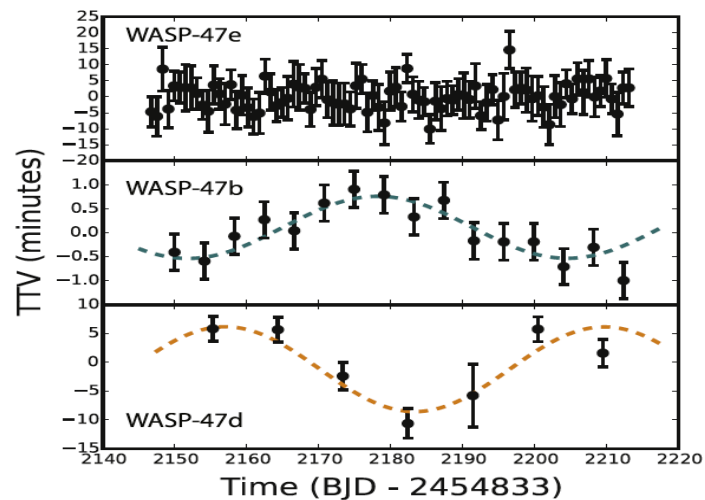
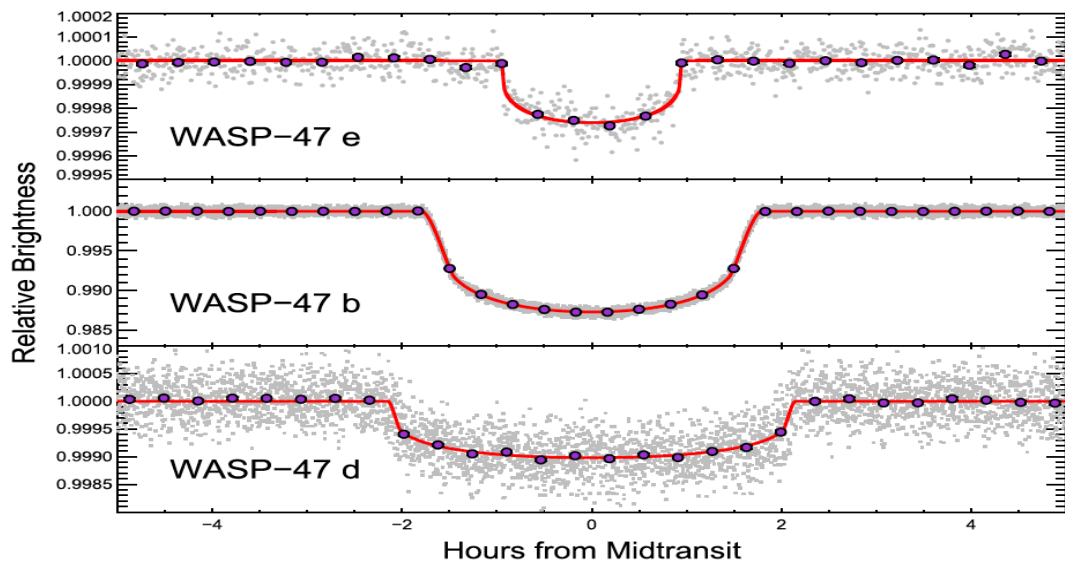
- First system with HJ, Super-Earths and a long periodic planet of Jupiter size.
- The Period of c planet is 572 days
- But is this system unique or is it rather a common representative of the formation process in-situ? We do not know, yet for sure.



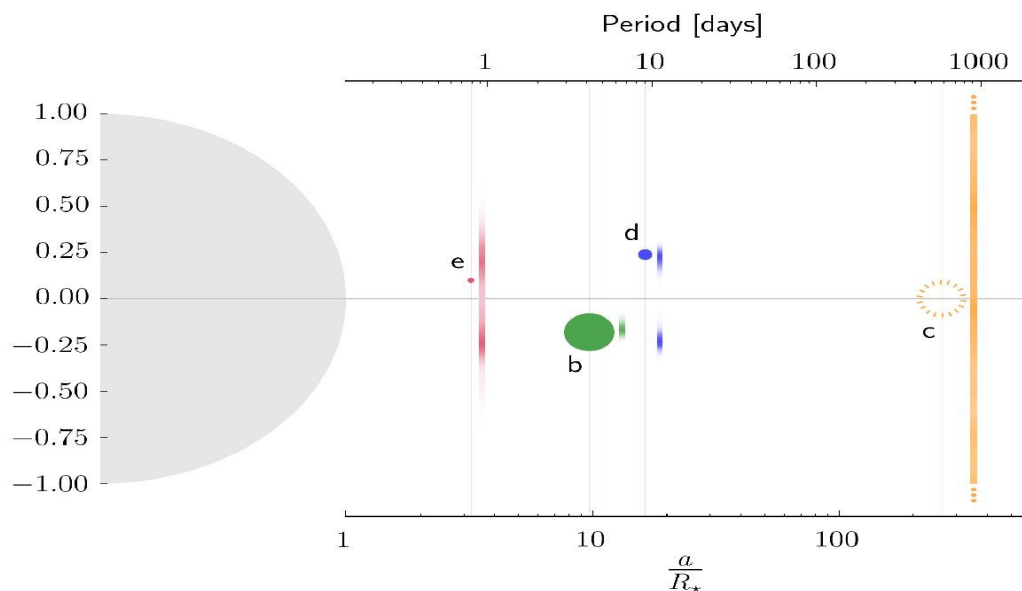
Neveu-VanMalle 2018 <https://arxiv.org/pdf/1509.07750.pdf>

# Wasp-47 system

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

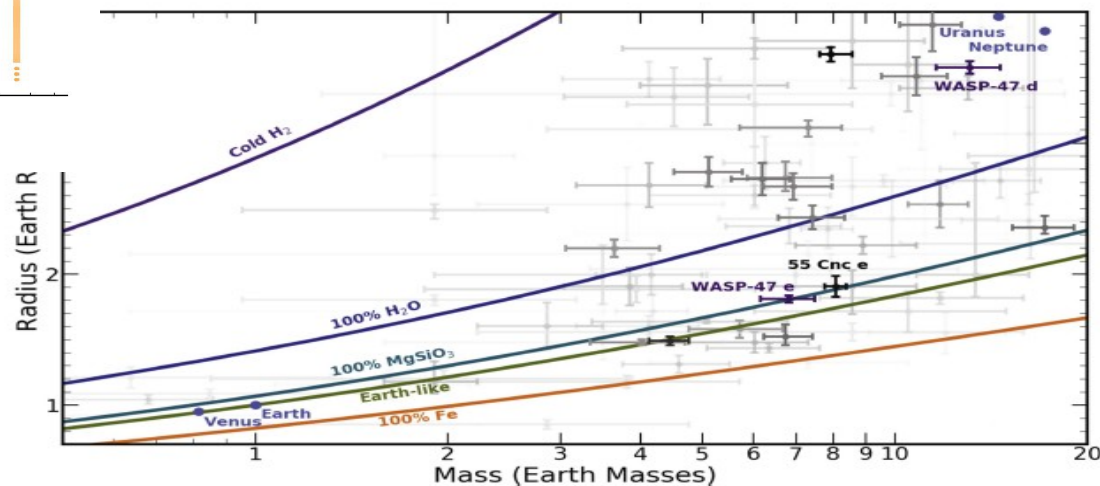


# Wasp-47 system



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

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

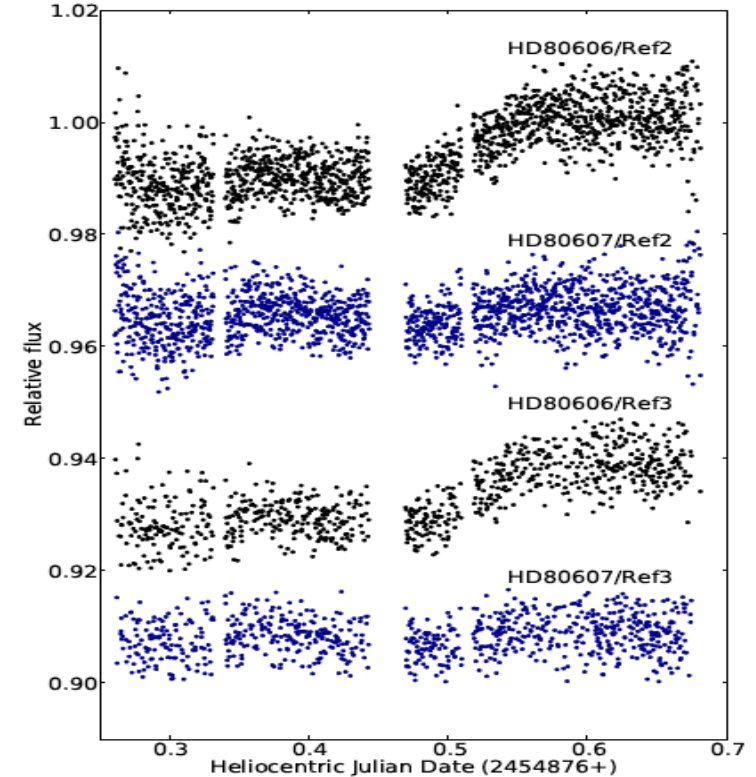


# Warm Jupiters

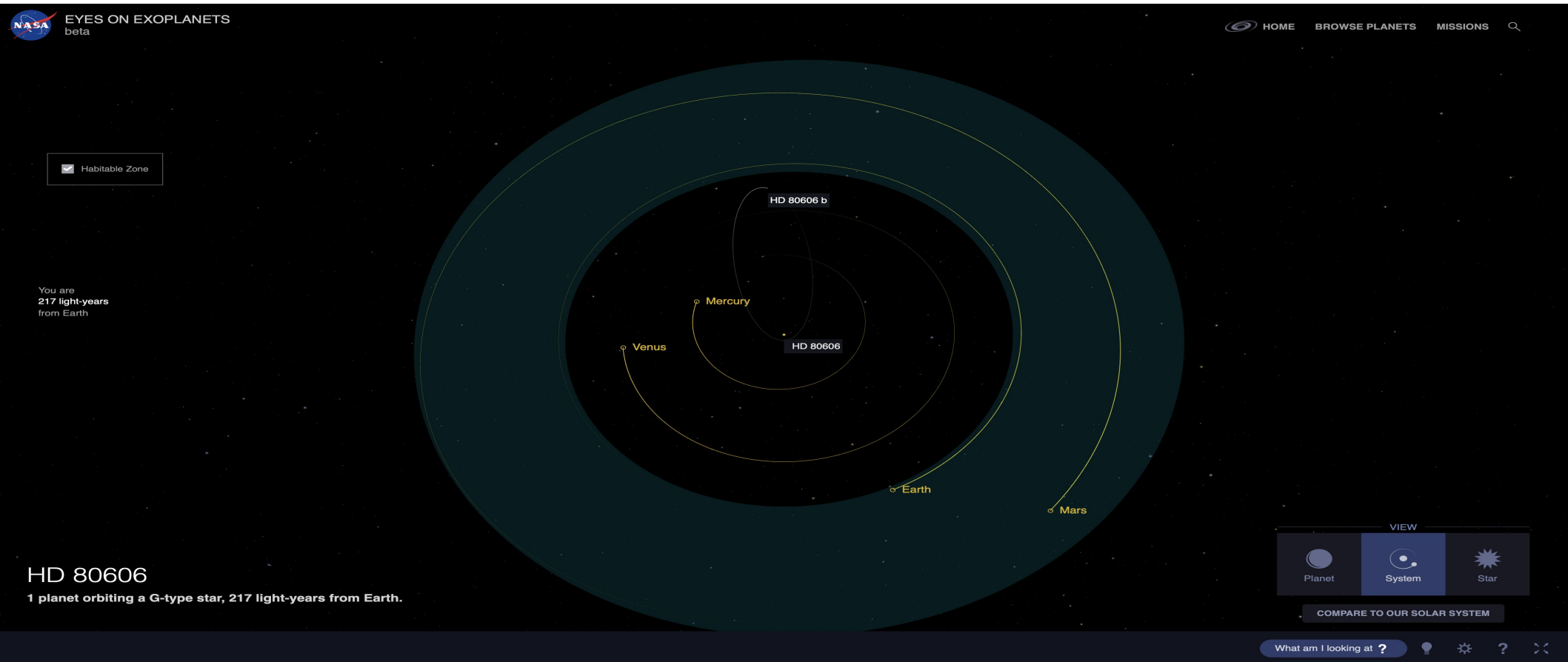


# Warm Jupiters

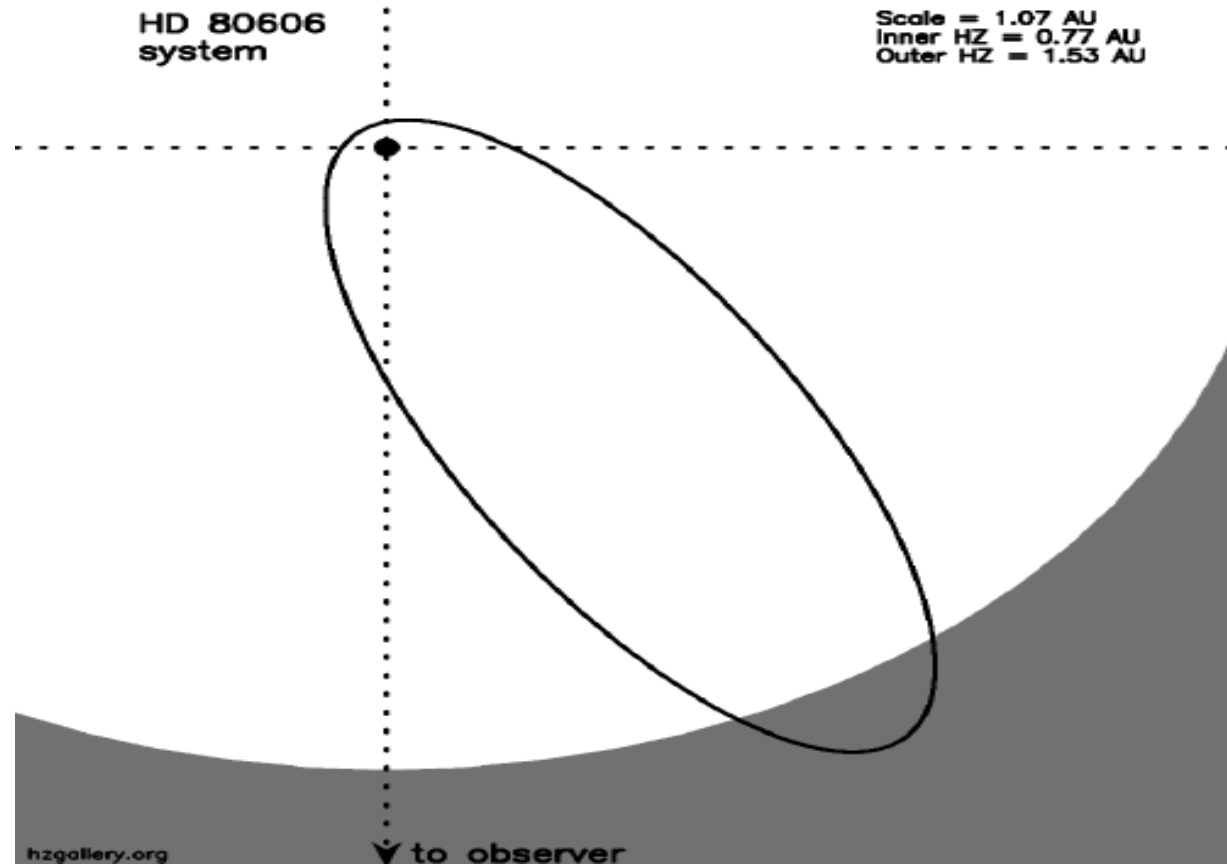
- Gas giants with orbital periods 10-200 days
- HD 80606 b – 111 days period
  - binary component HD 80607
  - 4 Jupiter masses
  - 12 hrs. Transit
  - 0.93 eccentricity (very high)
- Orbital parameters  
might be the key to formation?
- Discovery:  
Naef et al. 2001  
<https://www.aanda.org/articles/aa/pdf/2001/32/aade293.pdf>



# Orbit of HD80606b

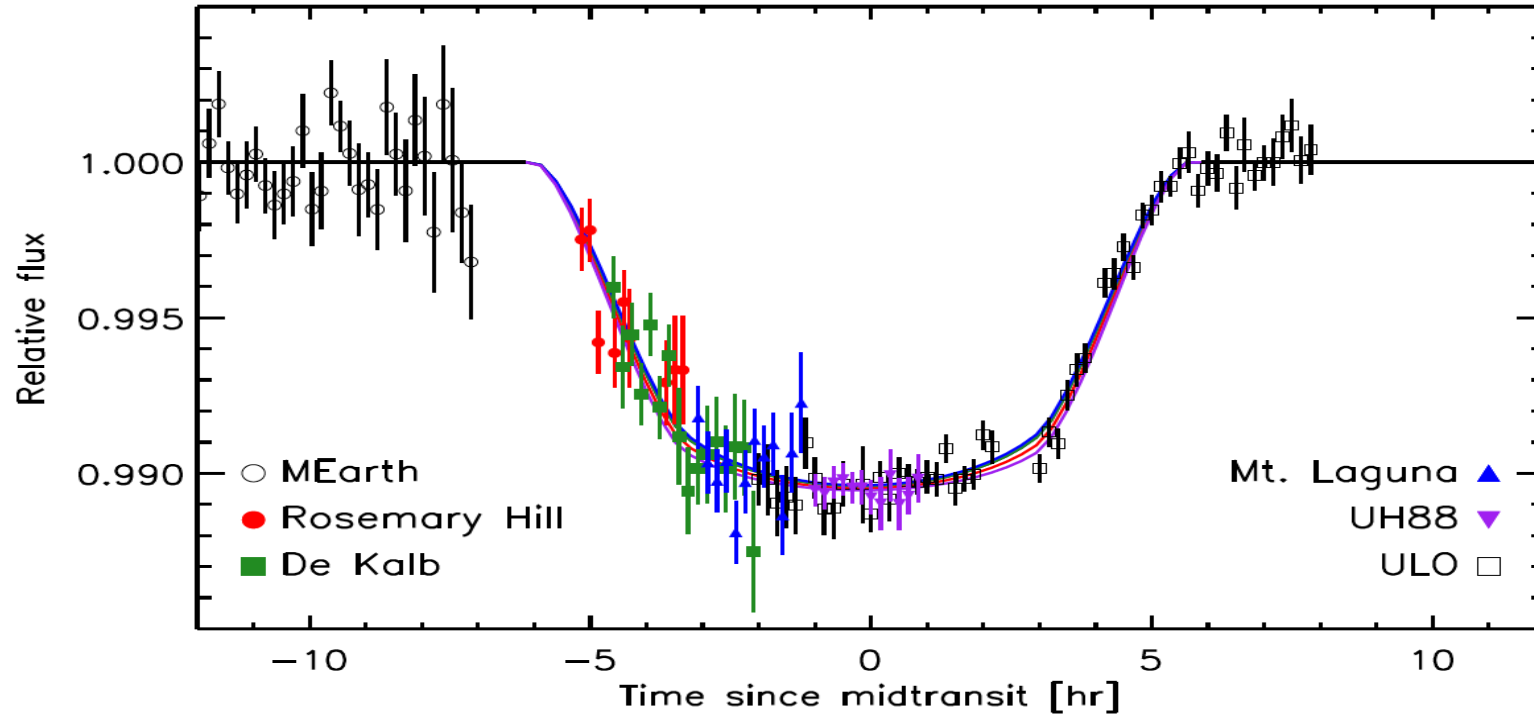


# Habitable zone HD80606 b

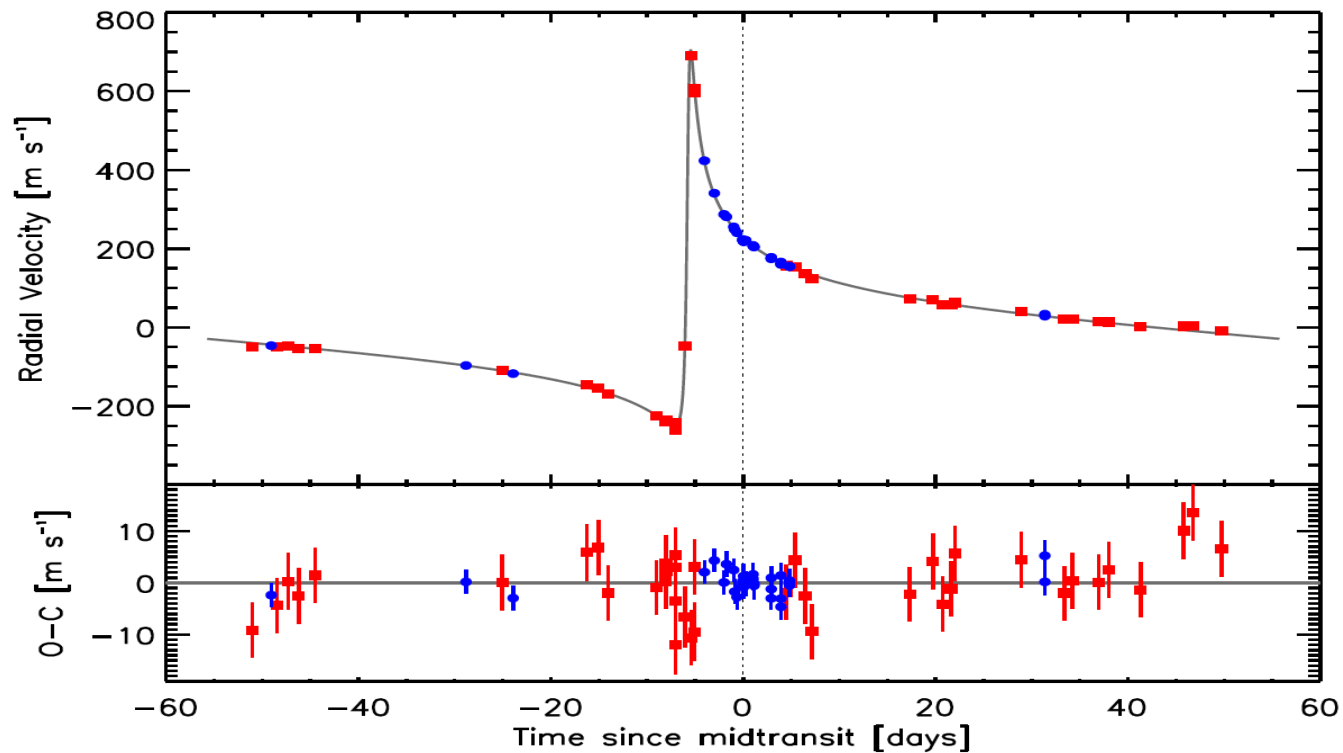


Kane, Stephen & Gelino, Dawn. (2012). The Habitable Zone and Extreme Planetary Orbits. *Astrobiology*. 12. 940-5. 10.1089/ast.2011.0798.

# A challenging transit



# HD 80606 b



# 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

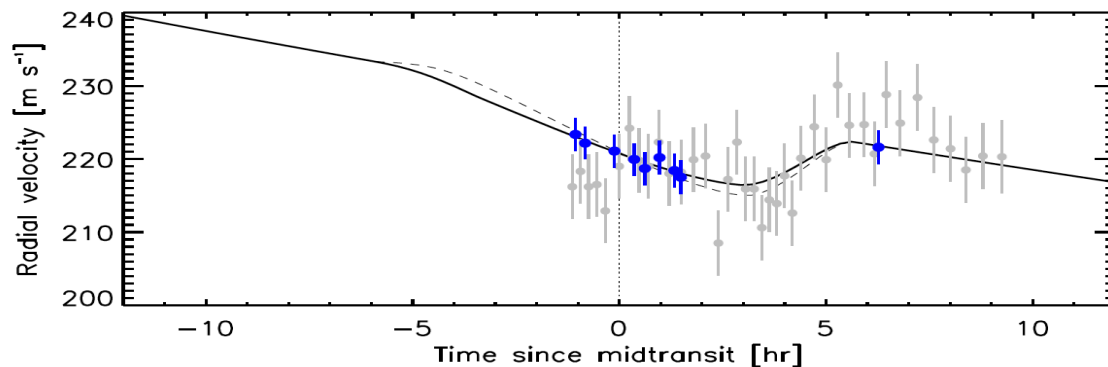
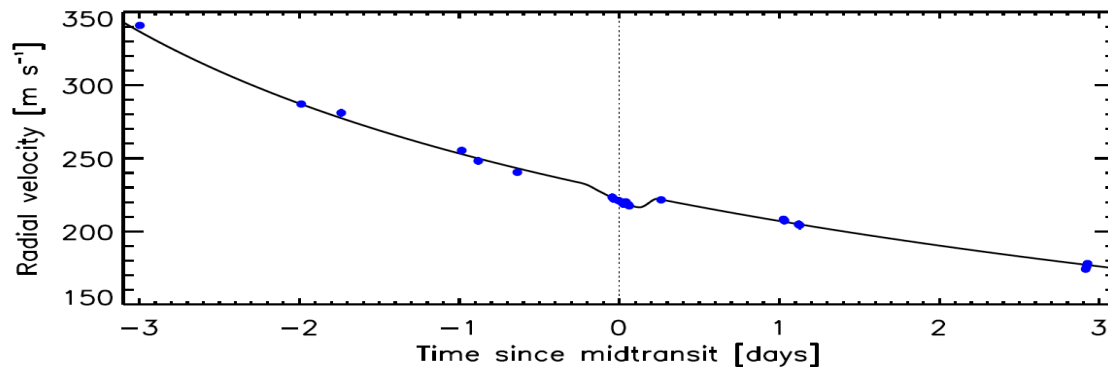
Kozai-Lidov process migration

Fabrycky 2007:

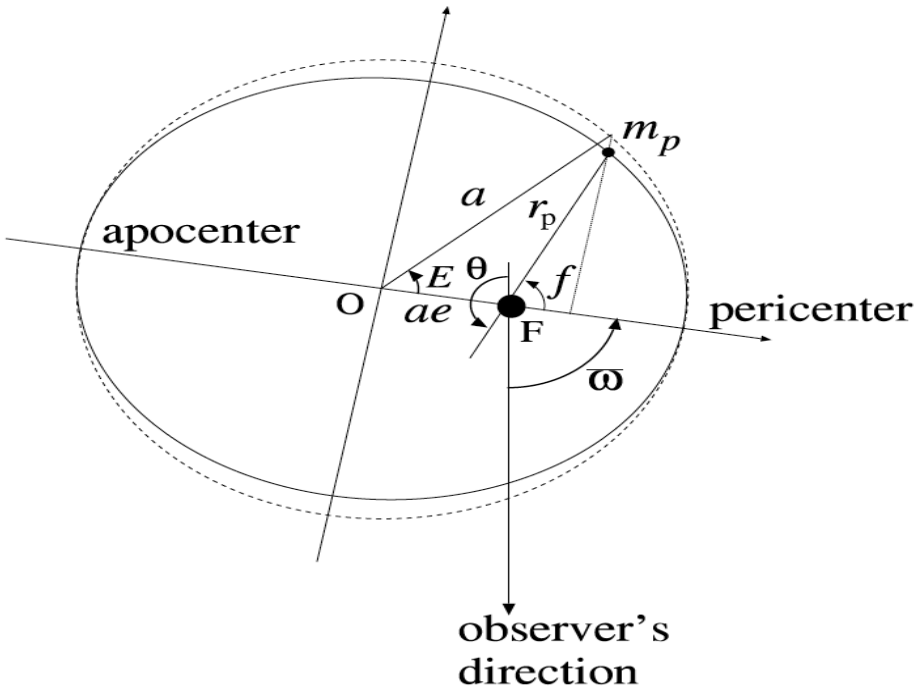
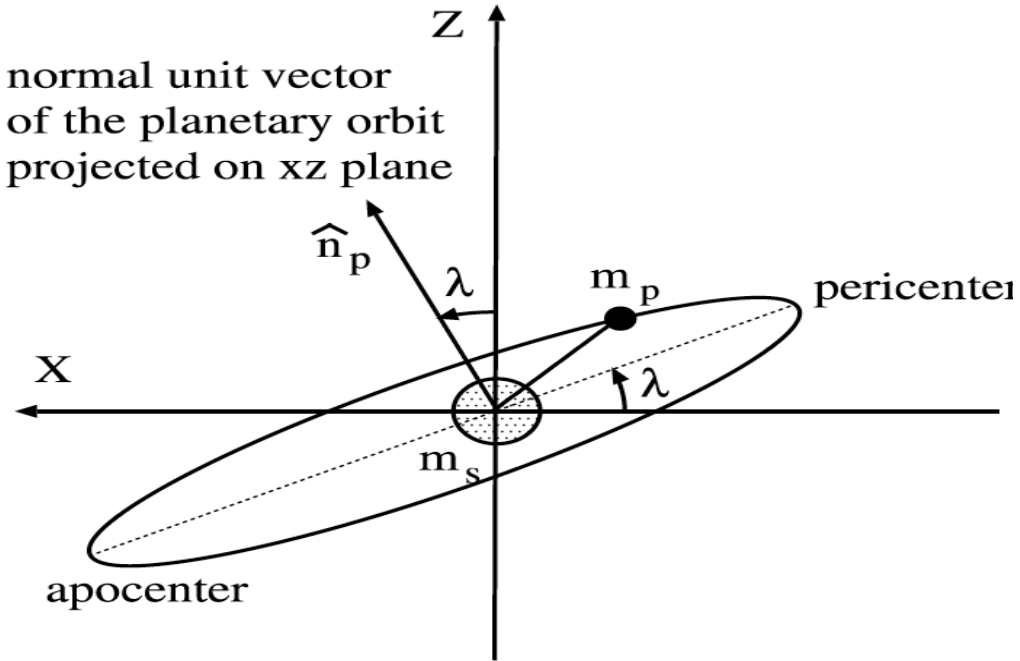
<https://arxiv.org/pdf/0705.4285.pdf>

Naoz et al 2016 (review)

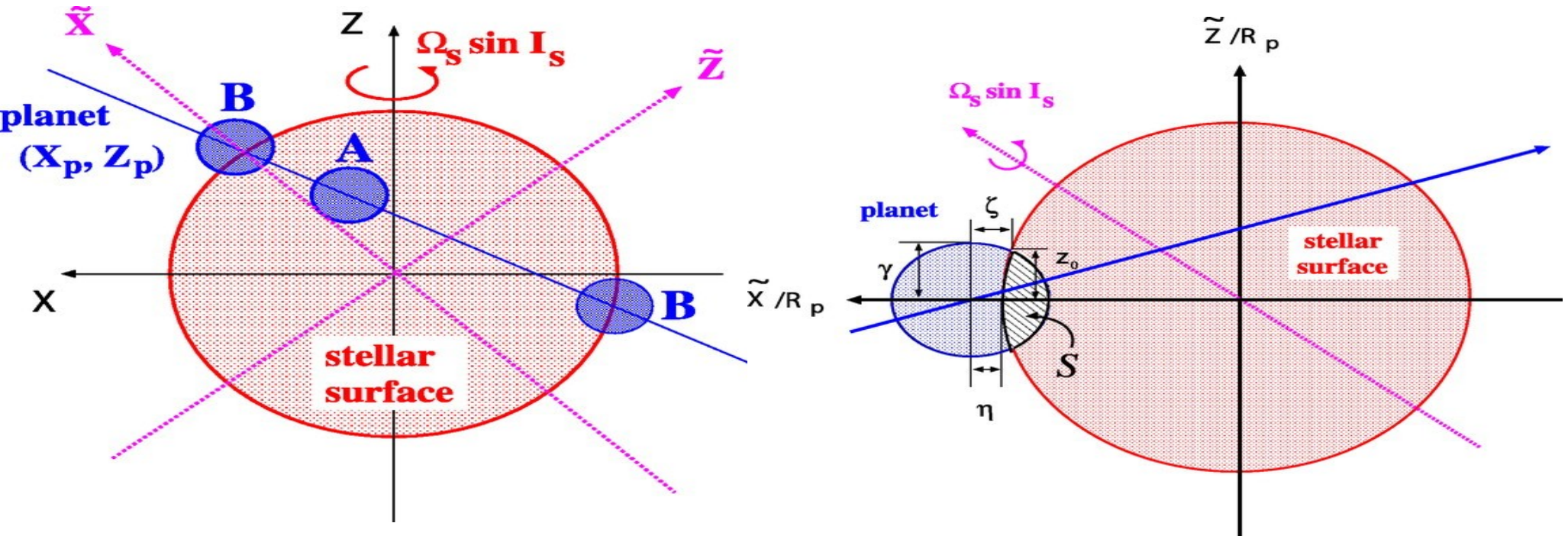
<https://arxiv.org/pdf/1601.07175.pdf>



# R-M effect - info

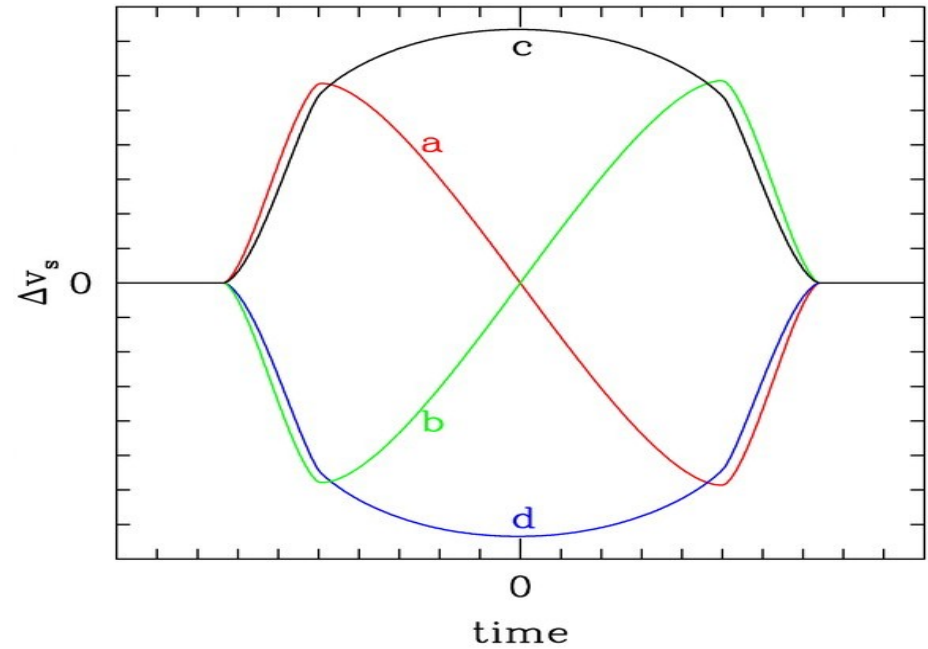
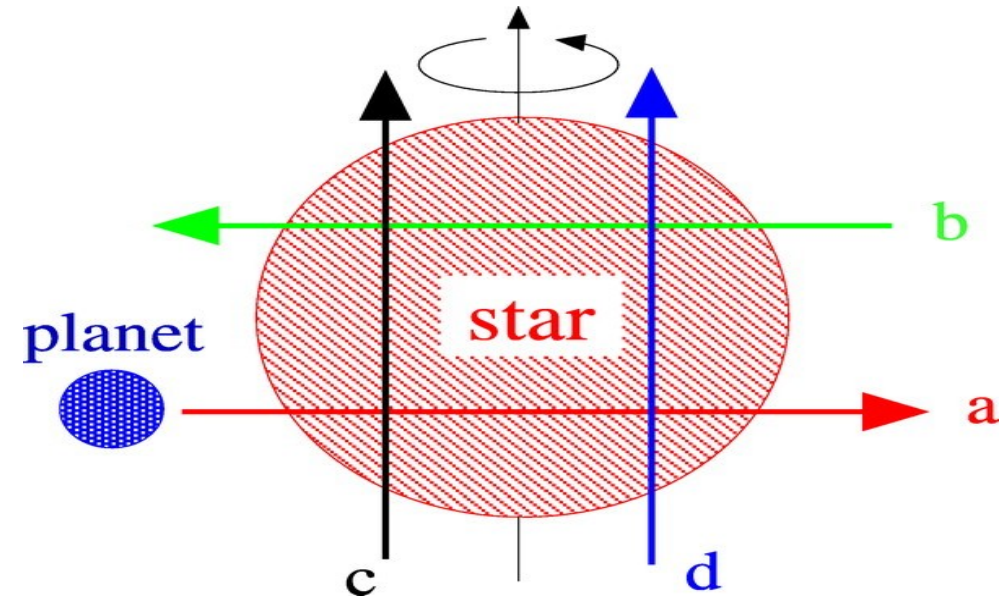


# R-M effect

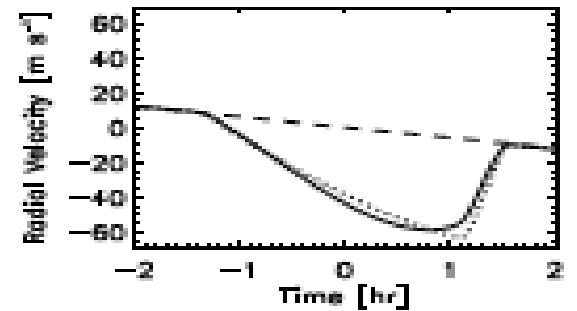
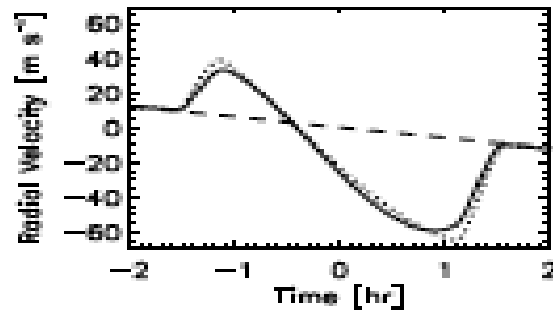
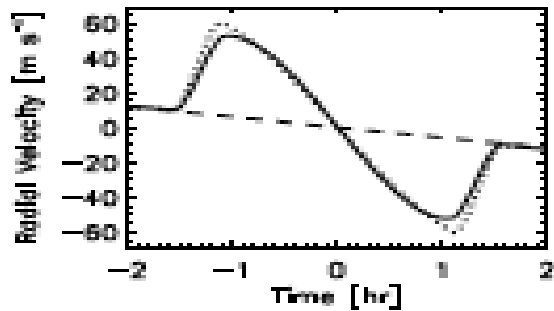
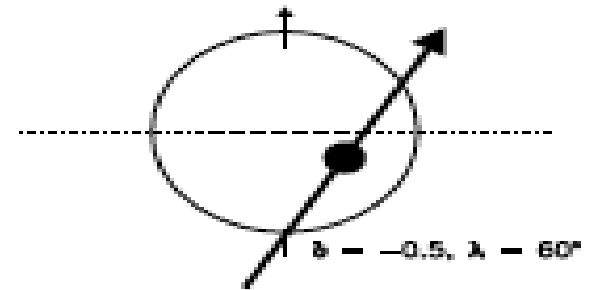
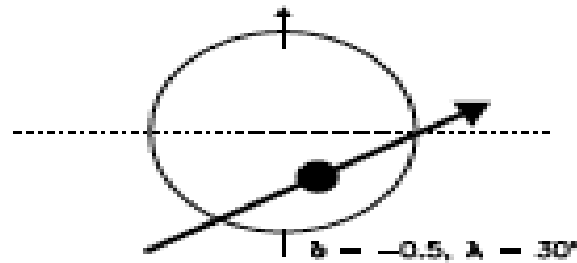
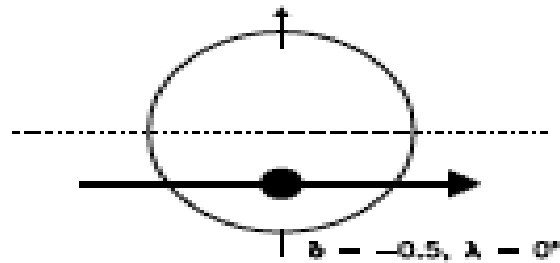




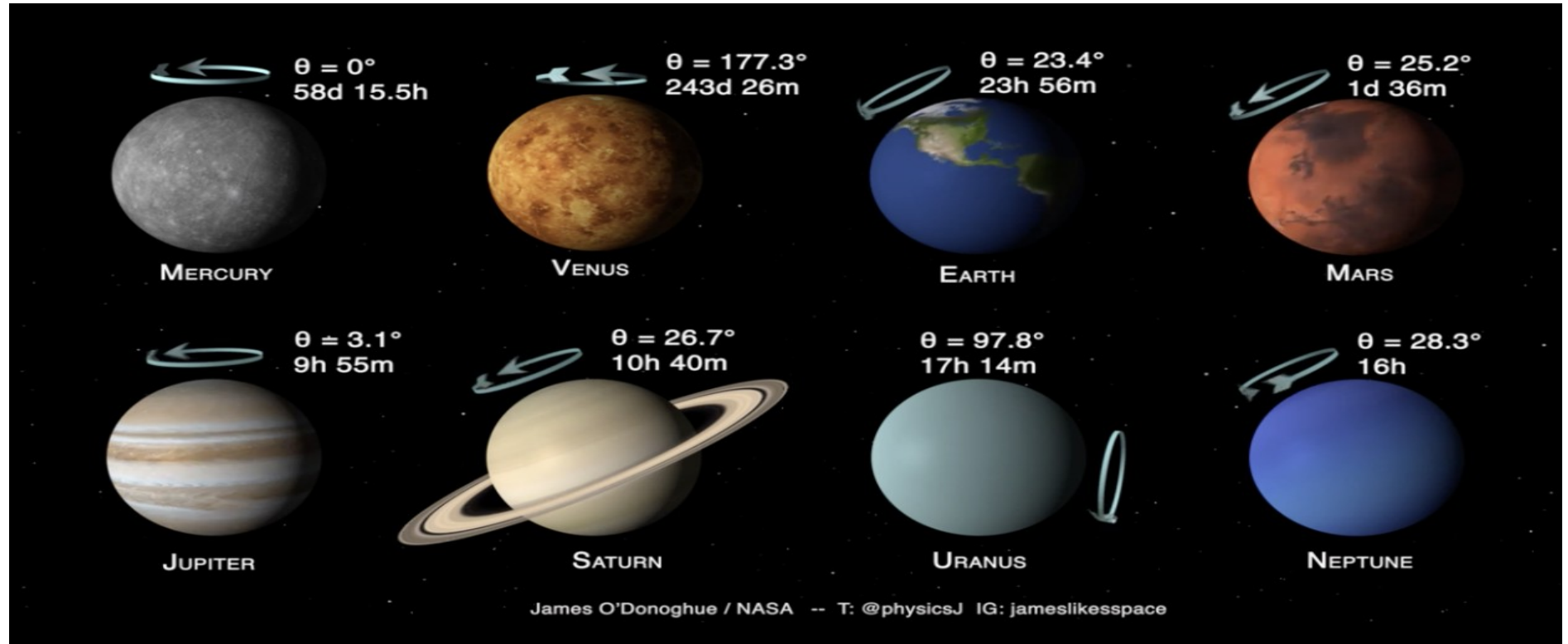
# R-M effect



# Examples of R-M



# Solar system compared (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

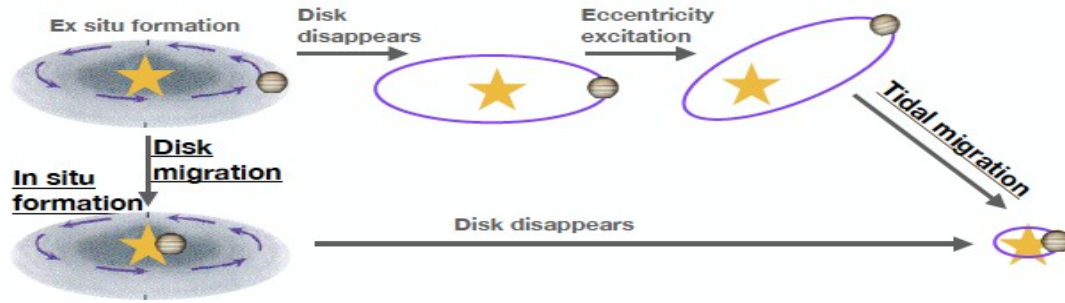
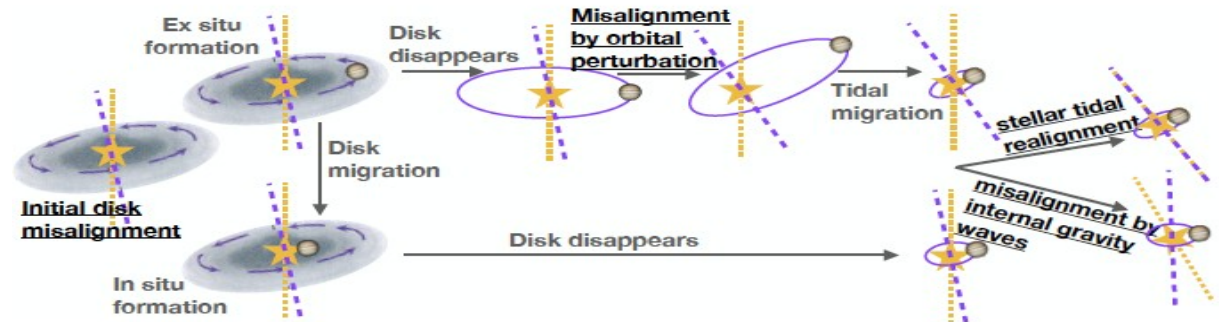


Figure 1 Three origins hypotheses for hot Jupiters: in situ formation (§2.1), disk migration (§2.2), and tidal migration (§2.3).

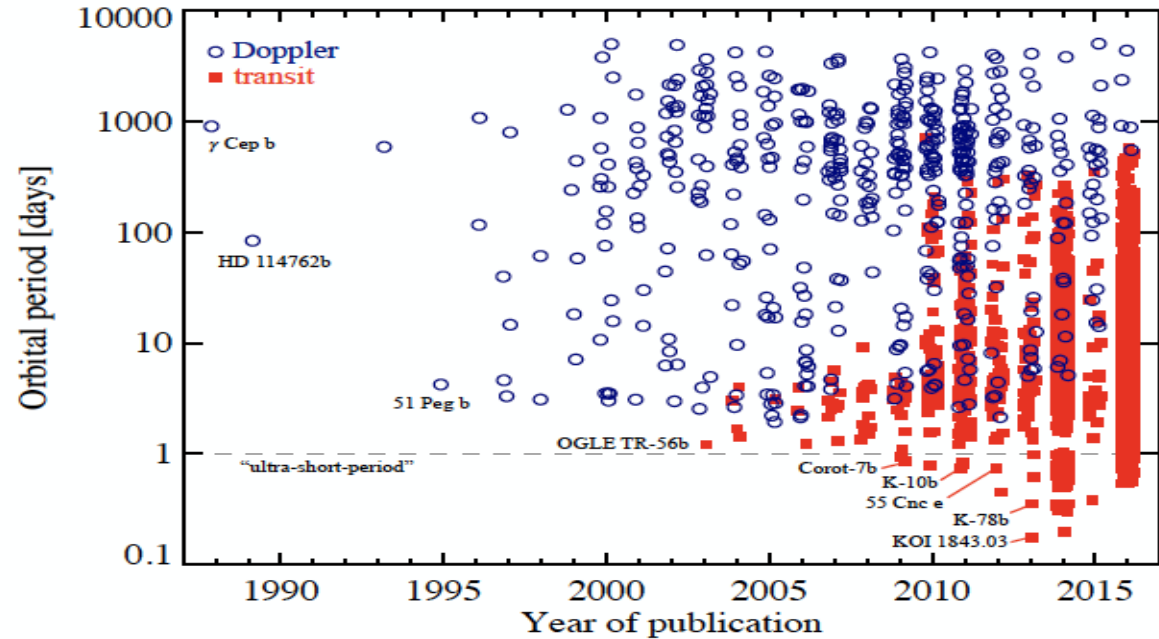


Another interesting group of planets  
(moving towards smaller planets)

# Ultra Short Period Planets

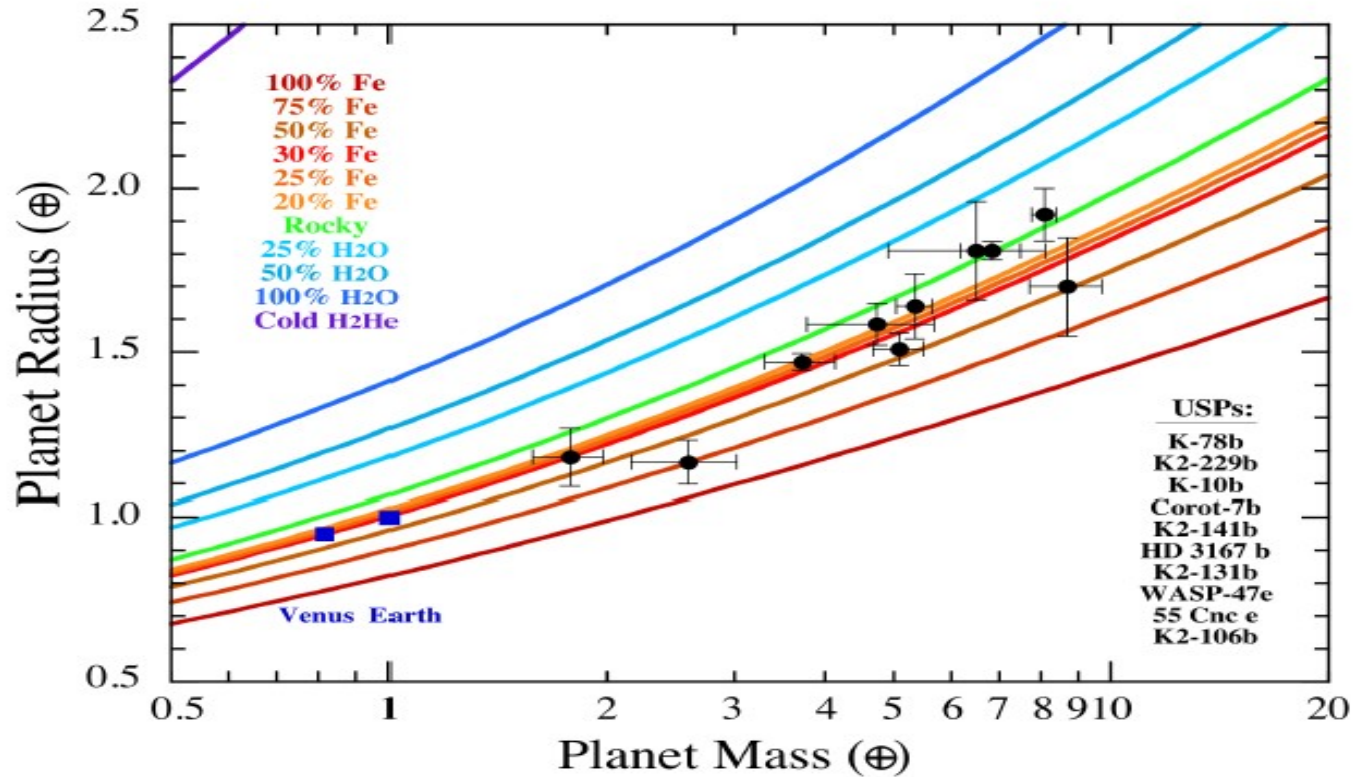
# Ultrashort period planets (USPs)

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



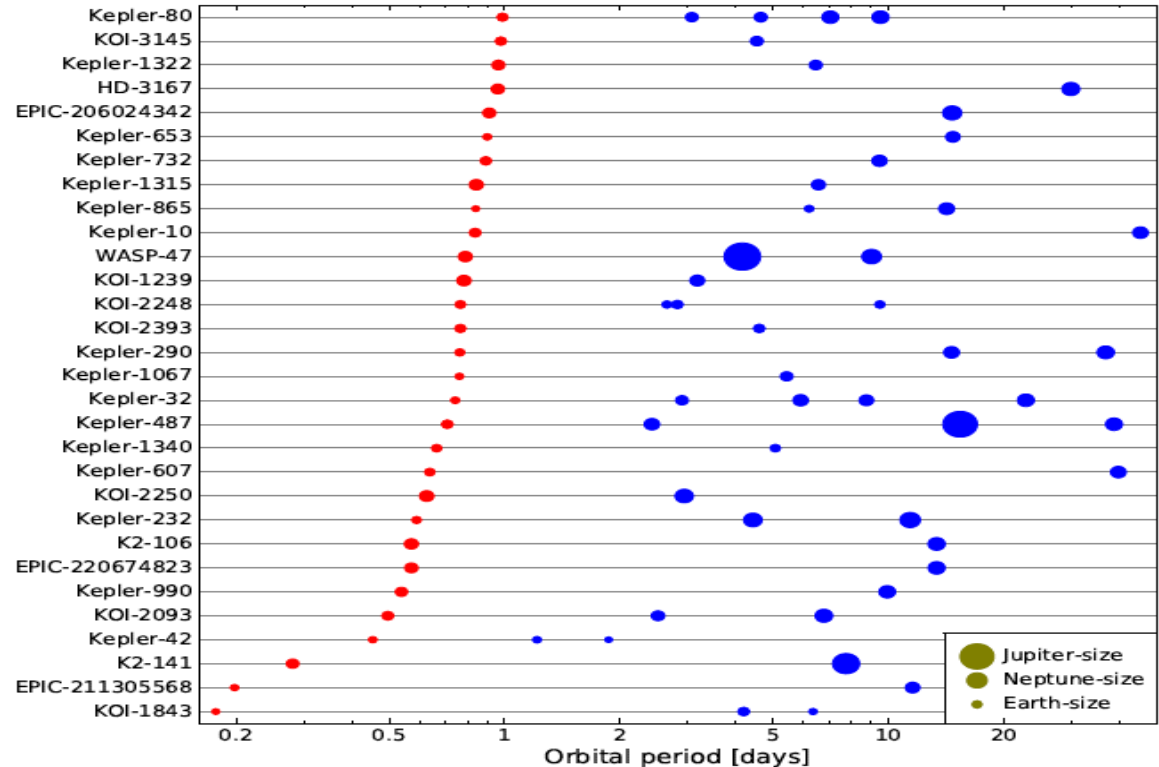


# Composition of USPs



# Architecture of USP systems

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



# Formation scenarios

- In-situ – leads usually to several Super-Earth 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

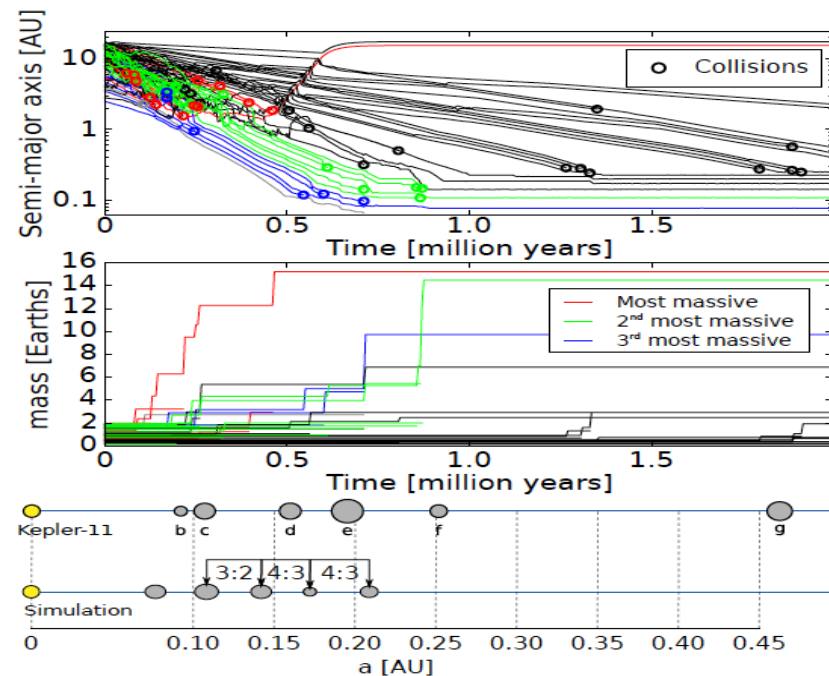


Fig. 6.— Formation of a system of hot Super Earths by type 1 migration. The top panel shows the evolution of the embryos’ orbital radii and the bottom panel shows the mass growth. The red, green and blue curves represent embryos that coagulated into the three most massive planets. All other bodies are 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)*.

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

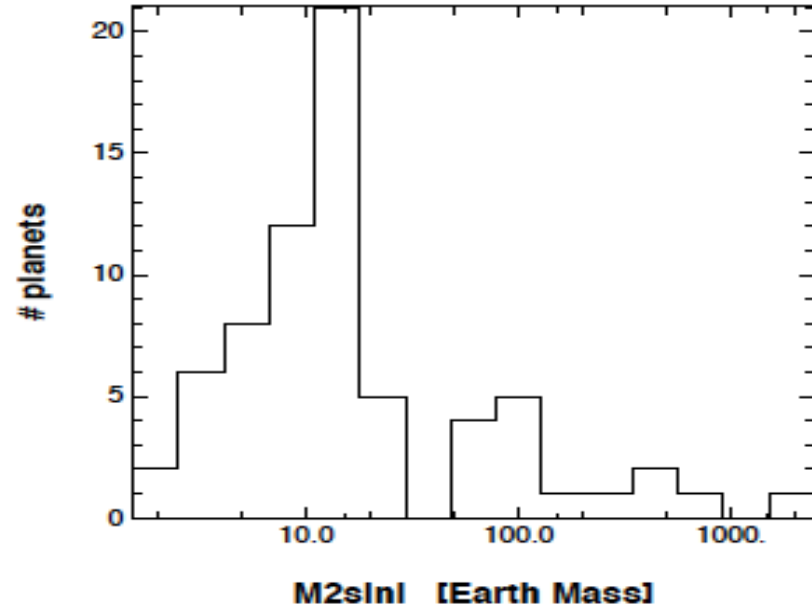
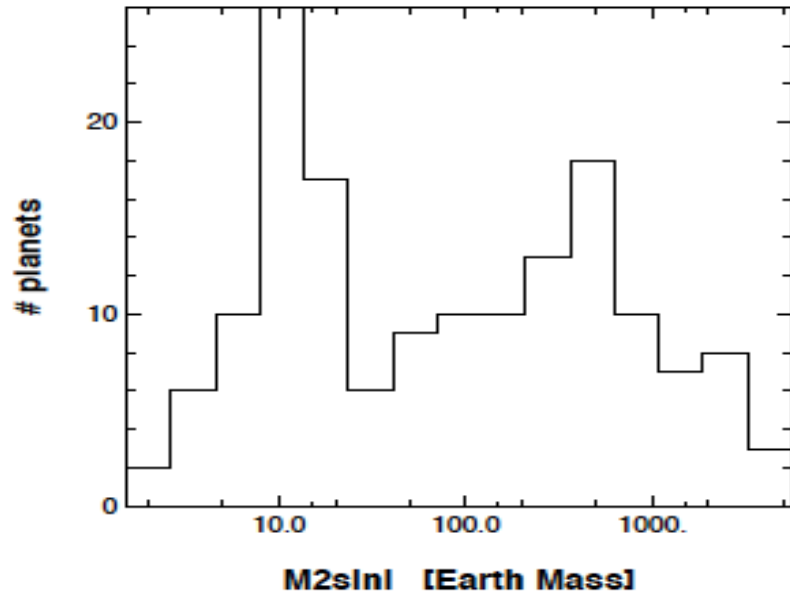
- We have now larger data set
- HARPS and CORALIE data
- Planets are quite frequent, at least every

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

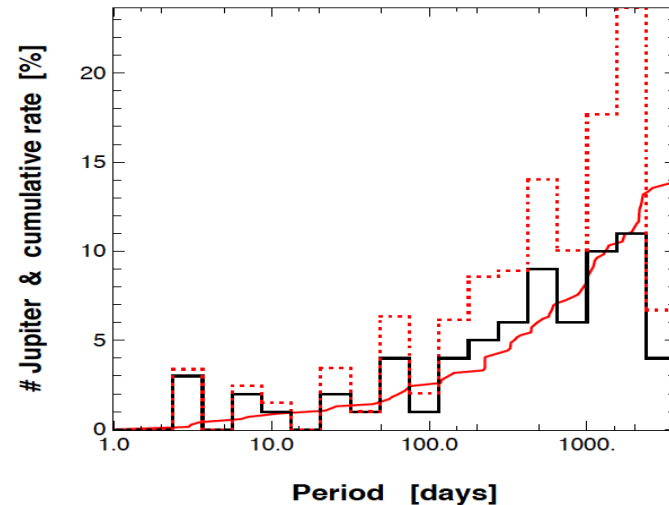
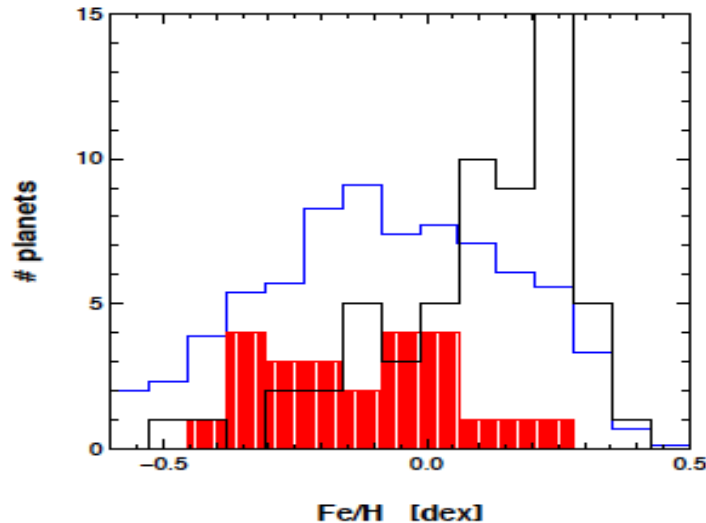
# Small planets vs. large planets

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



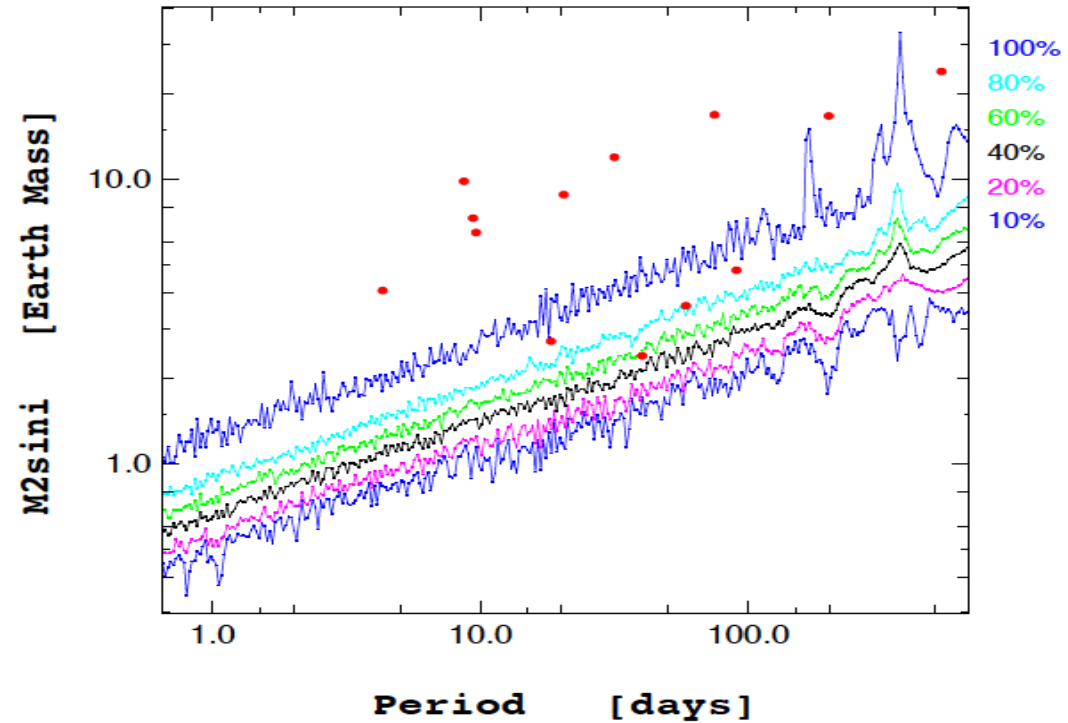
# Small vs. Large

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

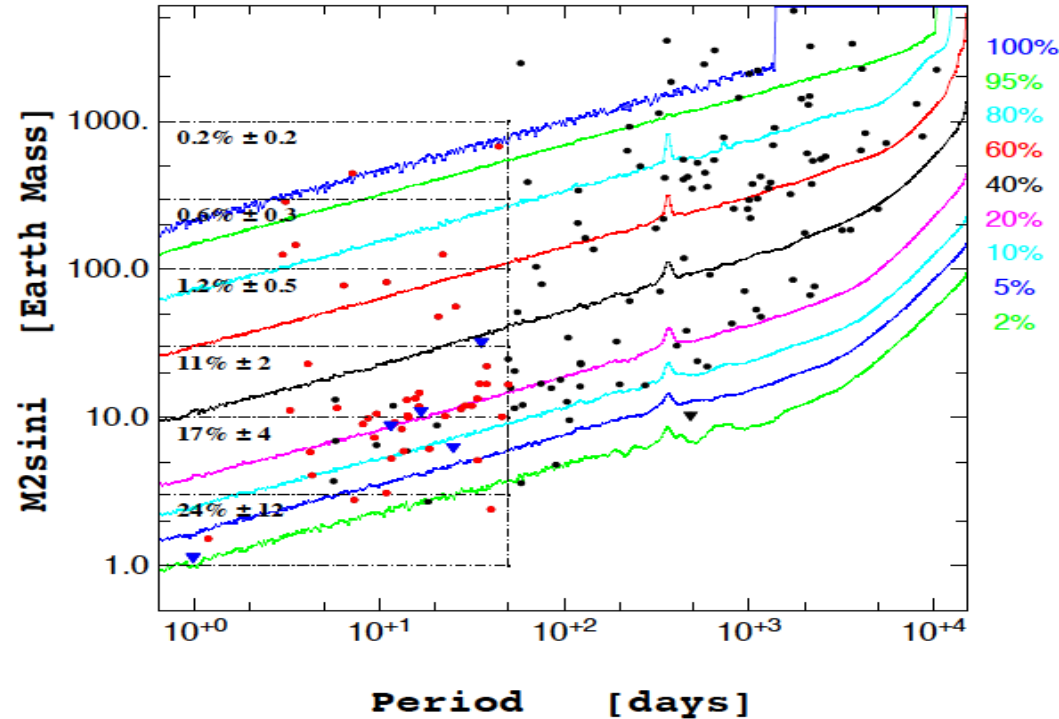


# Small planets frequency

- 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!



# 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