Where is everybody?

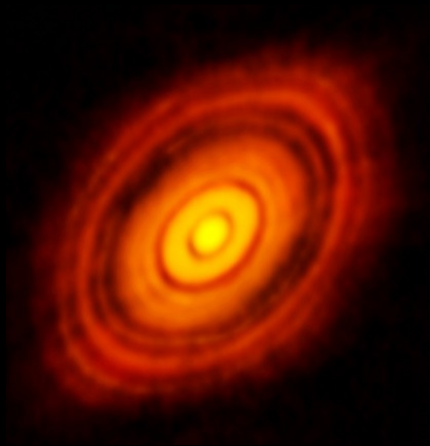
Adventures and misadventures of planet searching around young stars

Aurora Sicilia-Aguilar

SUPA

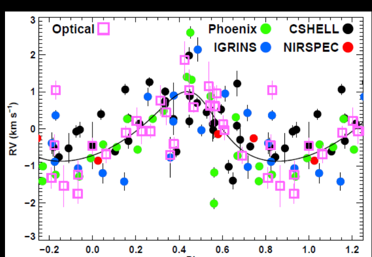
University of Dundee

Young Planets vs Mushrooms

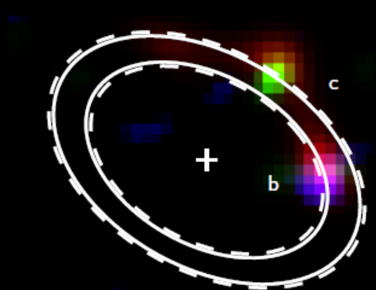


They are not always what they seem to be

- They are **small** and **faint**.



- They grow in **complex environments** that make them hard to detect.
- Their **key signatures** may also match some ***dangerous species***.



- If you are not sure about them, you may need to contact **other experts**.
- Messing them up may give you some *headaches*.

"Know the star, know the planet"

Do we know the star?

Young stars are a lot more problematic than old ones: see the definition of T Tauri star:

Eleven irregular variable stars have been observed whose physical characteristics seem much alike and yet are sufficiently different from other known classes of variables to warrant the recognition of a new type of variable stars whose prototype is T Tauri. The distinctive characteristics are: (1) irregular light-variations of about 3 mag, (2) spectral type F5–G5 with emission lines resembling the solar chromosphere, (3) low luminosity, and (4) association with dark or bright nebulosity. The stars included are RW Aur, UY Aur, R CrA, S CrA, RU Lup, R Mon, T Tau, RY Tau, UX Tau, UZ Tau, and XZ Tau. They are situated in or near the Milky Way dark clouds in the direction either of the center or of the anticenter of the galaxy.

Discussion of the spectra.—The spectral types of the T Tauri stars are estimated to be between F5 and G5, although for many of them the absorption lines generally used in classification are lacking. A small variation of type with phase was found for T Tau and RY Tau. Bright hydrogen has been found in all stars of the group, and bright *Ca* II (H and K) in all except R CrA. Most of the stars show an emission spectrum composed of many bright lines of low excitation. The strongest lines are those of *Ca* II, *H*, *Fe* II, *Ca* I, *Sr* II, *Fe* I, and *Ti* II. The identification and relative maximum intensities of 160 lines of the different stars are shown in Table 16. The intensity of the emission spectrum varies greatly from time to time in each star, the bright lines becoming more prominent at maximum light of the variable.

Absolute magnitudes and color indices.—Spectroscopic absolute magnitudes of three stars of the group, together with meager indirect evidence, indicate that the T Tauri stars are dwarfs of the main sequence. Color indices for five stars show some color excess, which is probably the result of selective absorption by surrounding nebulosity.

[Joy 1945]

Do we know the star?

Young stars are a lot more problematic than old, *quiescent* ones:

- Strong levels of activity.
- Variability and variable color excesses.
- Accretion.
- Extinction.

⇒ If you don't know the star, it will be tough to know the planet.

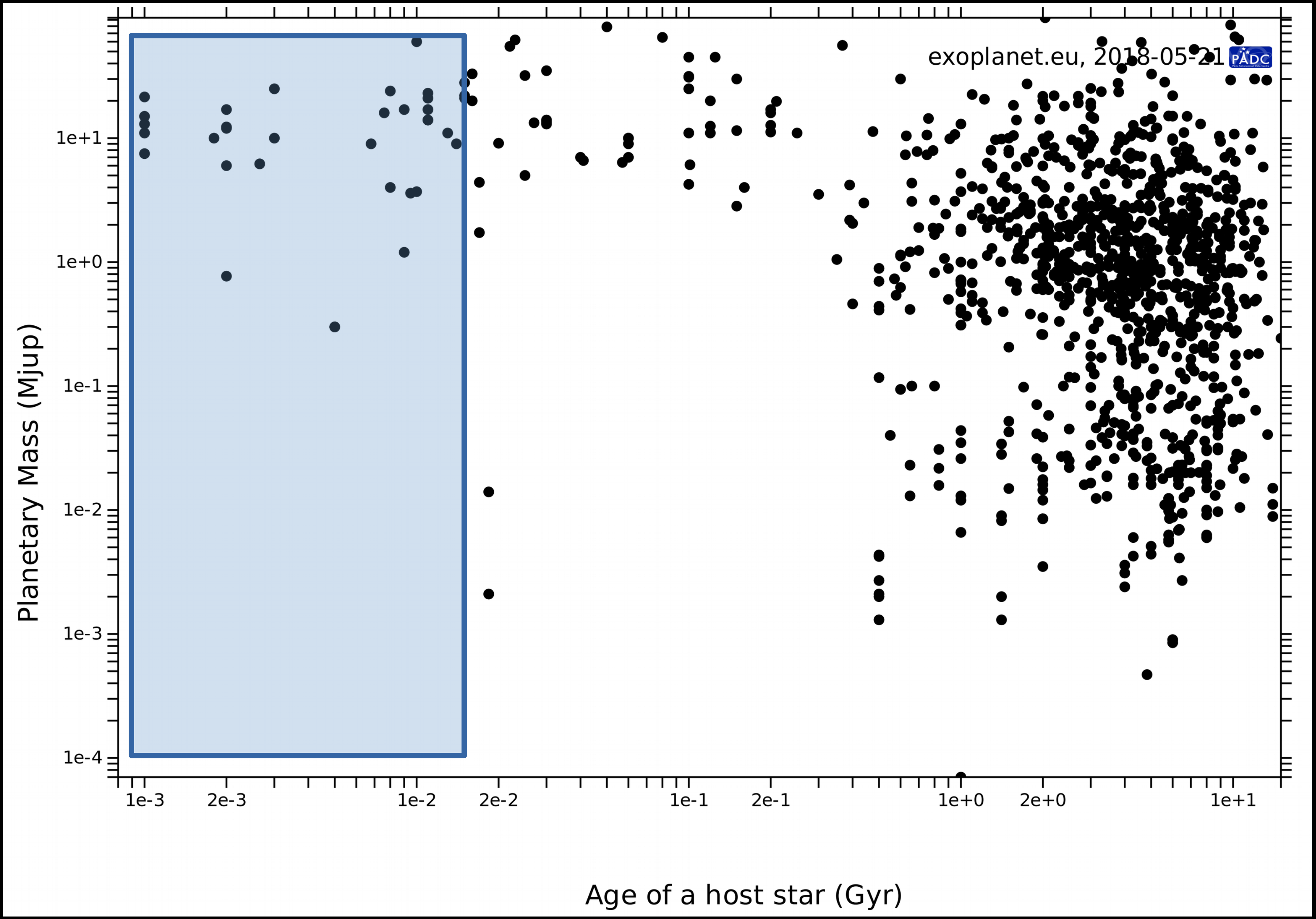
What do we know about the planet?

Young planets are also quite unknown:

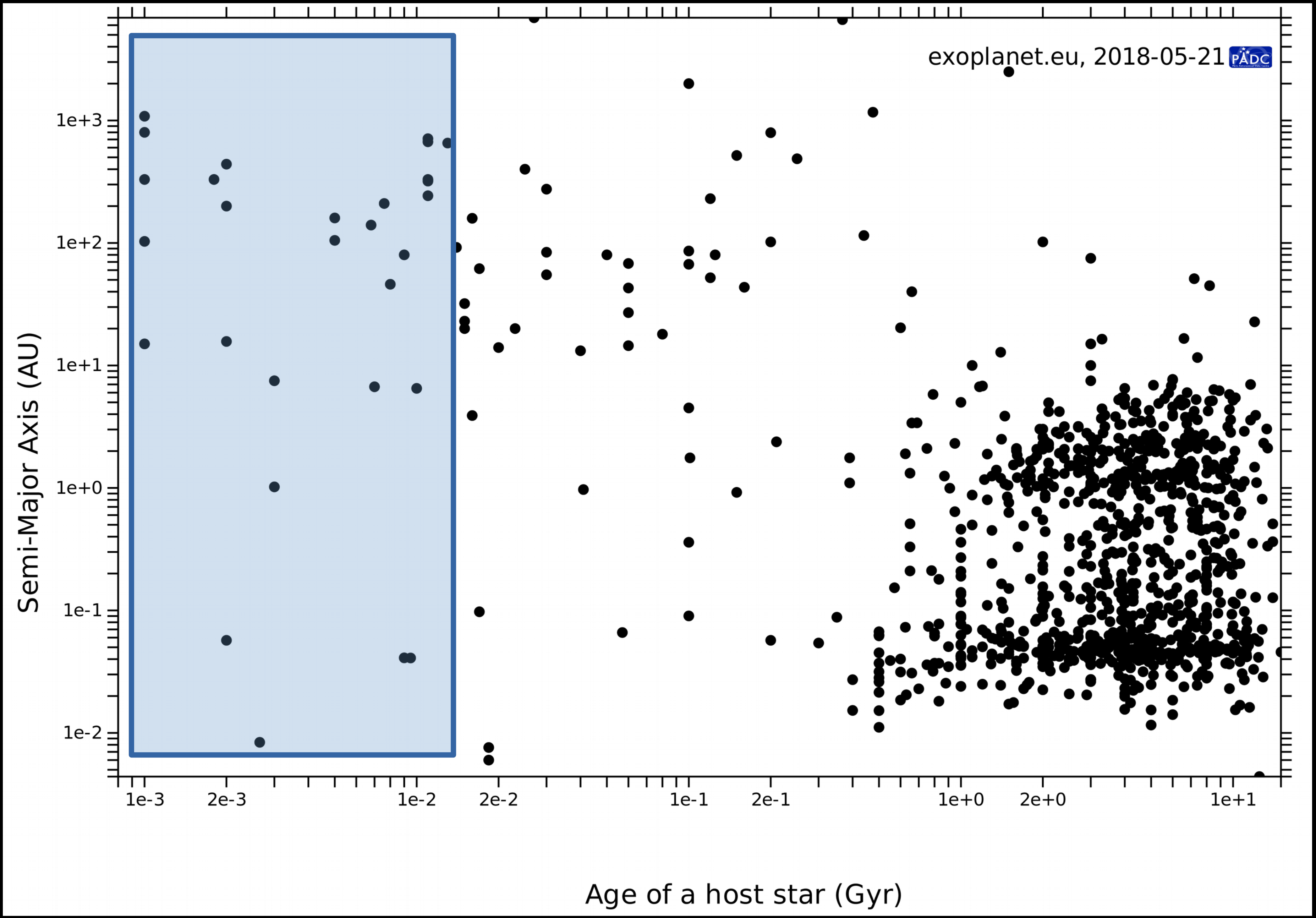
- When do they form?
- Where are they (initially) located?
- Do we see them accreting?
- What temperatures do they have?
- How does the planet-disk interaction look like?

→ If you don't know what the planet looks like, it will be hard to find it.

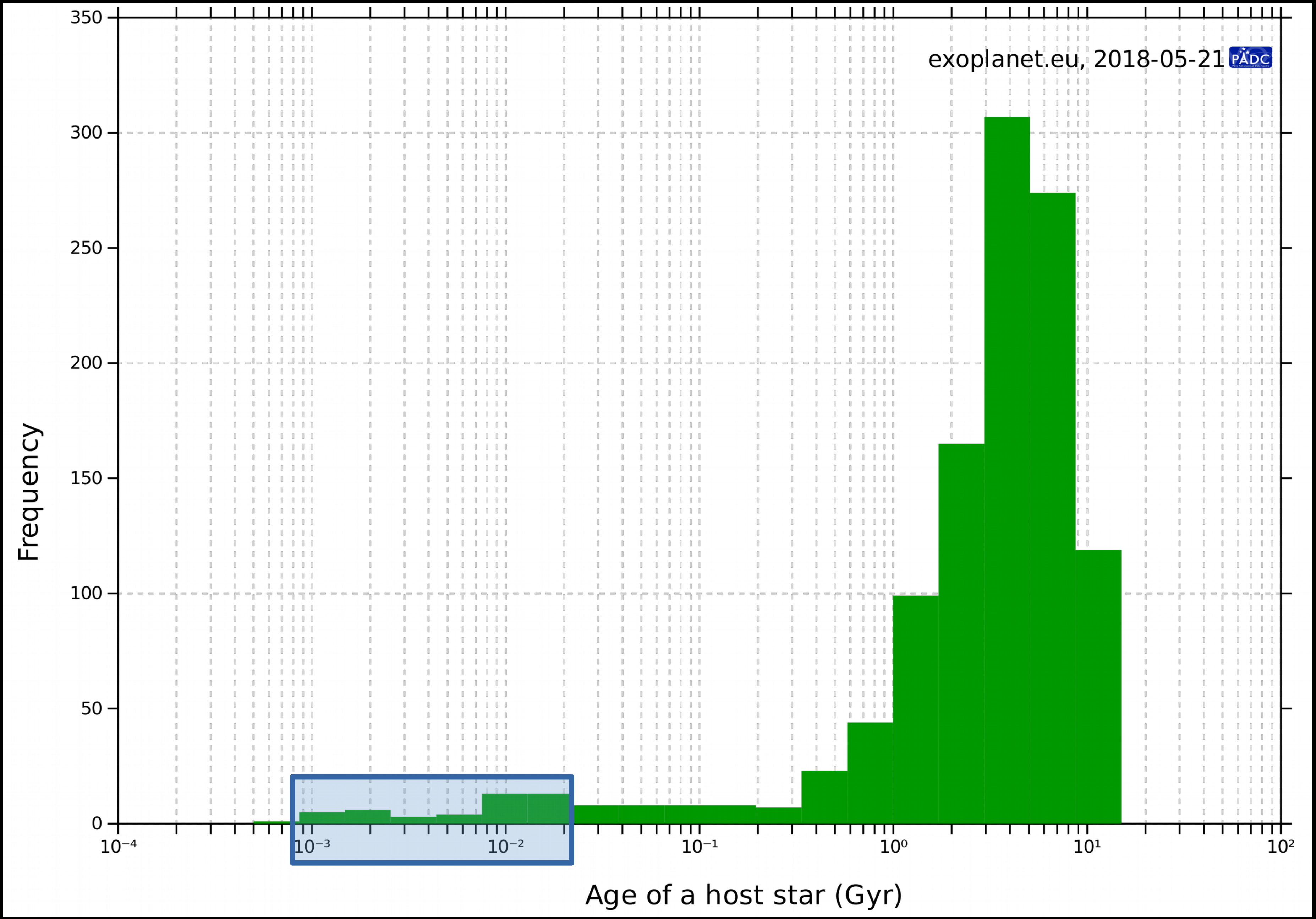
The known ones...



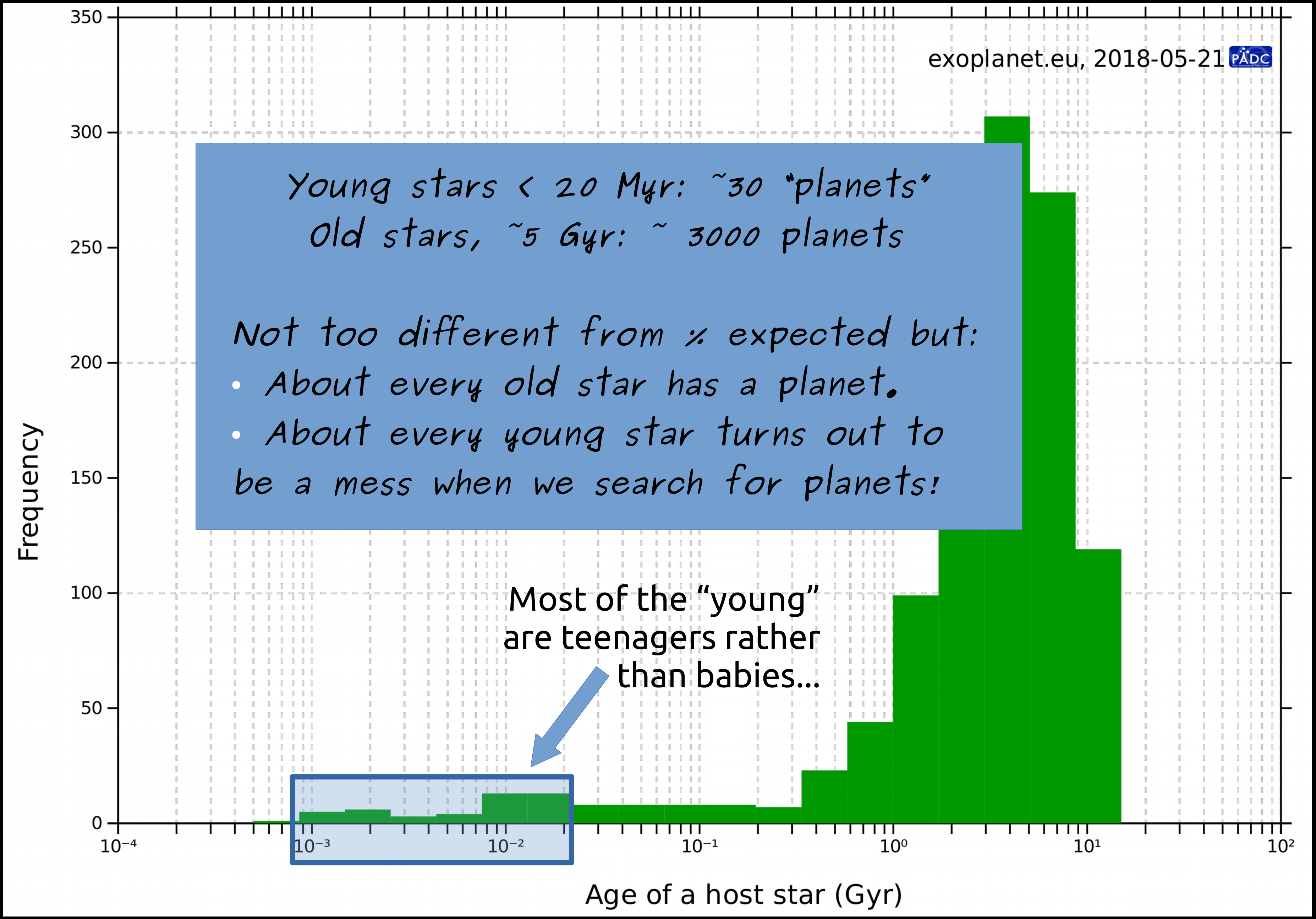
The known ones...



The known ones...

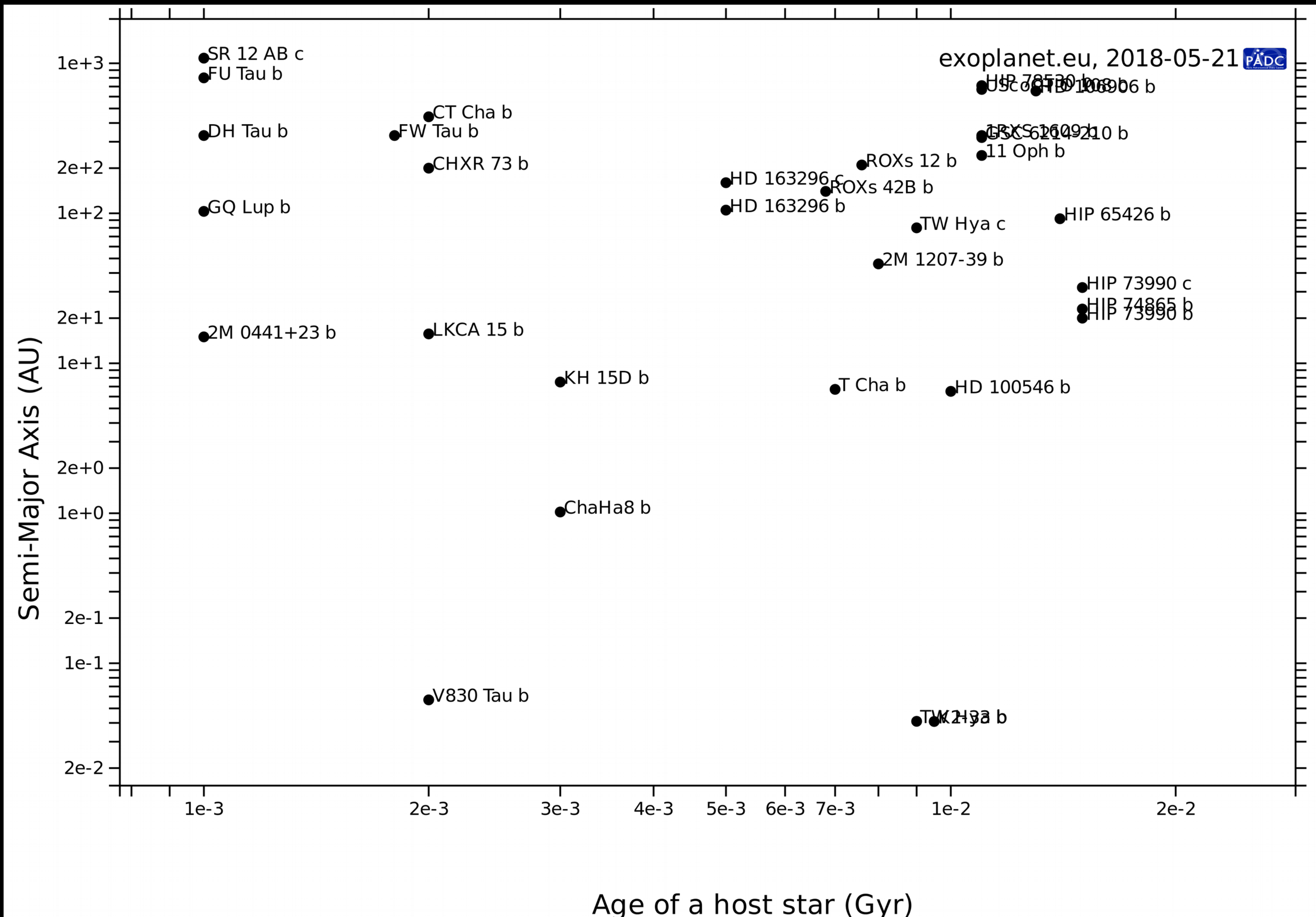


The known ones...



The known ones...

Total: 38, although exoplanet.eu keeps some that are uncertain



The known ones...

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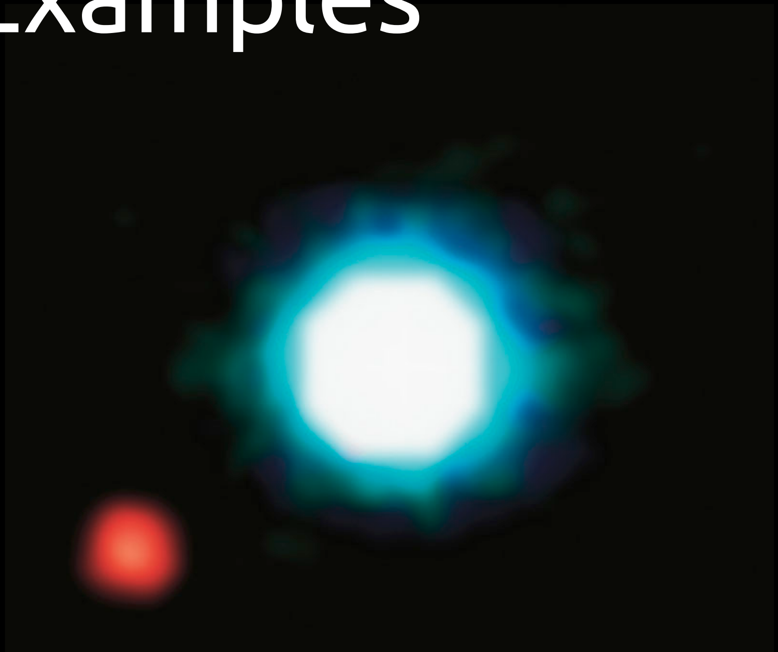
name	planet_sta...	mass	mass_sini	radius	orbital_period	semi_major_axis	eccentricity	star_age
Proplyd 133-353	Confirmed	13.						0.0005
2M 0441+23 b	Confirmed	7.5				15.		0.001
DH Tau b	Confirmed	11.				330.		0.001
FU Tau b	Confirmed	15.				800.		0.001
GQ Lup b	Confirmed	21.5		1.8		103.		0.001
SR 12 AB c	Confirmed	13.				1083.		0.001
FW Tau b	Confirmed	10.				330.		0.0018
CHXR 73 b	Confirmed	12.				200.		0.002
CI Tau b	Confirmed	12.31			8.9965			0.002
CT Cha b	Confirmed	17.		2.2		440.		0.002
LKCA 15 b	Confirmed	6.			40000.	15.7		0.002
V830 Tau b	Confirmed	0.77	0.63		4.93	0.057	0.	0.002
CVSO 30 b	Confirmed	6.2	5.5	1.91	0.44841	0.00838		0.00265
HD 163296 b	Confirmed	0.3				105.		0.005
HD 163296 c	Confirmed	0.3				160.		0.005
ROXs 42B b	Confirmed	9.		2.5		140.		0.0068
ROXs 12 b	Confirmed	16.				210.		0.0076
2M 1207-39	Confirmed	24.						0.008
2M 1207-39 b	Confirmed	4.				46.		0.008
K2-33 b	Confirmed	3.6		0.451	5.42513	0.0409	0.	0.0095
2MASS J11193254 AB	Confirmed	3.7			32850.			0.01
11 Oph b	Confirmed	21.			7.300000E5	243.		0.011
1RXS 1609 b	Confirmed	14.		1.7		330.		0.011
GSC 6214-210 b	Confirmed	17.				320.		0.011
HIP 78530 b	Confirmed	23.04				710.		0.011
UScoCTIO 108 b	Confirmed	14.				670.		0.011
HD 106906 b	Confirmed	11.				654.		0.013
HIP 65426 b	Confirmed	9.		1.5		92.		0.014
HIP 73990 b	Confirmed	21.				20.		0.015
HIP 73990 c	Confirmed	22.				32.		0.015
HIP 74865 b	Confirmed	28.				23.		0.015
1SWASP J1407 b	Confirmed	20.	20.		3725.	3.9		0.016
HIP 64892	Confirmed	33.				159.		0.016
HD 95086 b	Confirmed	4.4				61.7	0.2	0.017
TAP 26 b	Confirmed	1.73	1.73		10.91	0.0975		0.017
Kepler-70 b	Confirmed	0.014		0.068	0.2401	0.006		0.0184
Kepler-70 c	Confirmed	0.0021		0.078	0.34289	0.0076		0.0184
51 Eri b	Confirmed	9.1		1.11	14965.	14.	0.21	0.02

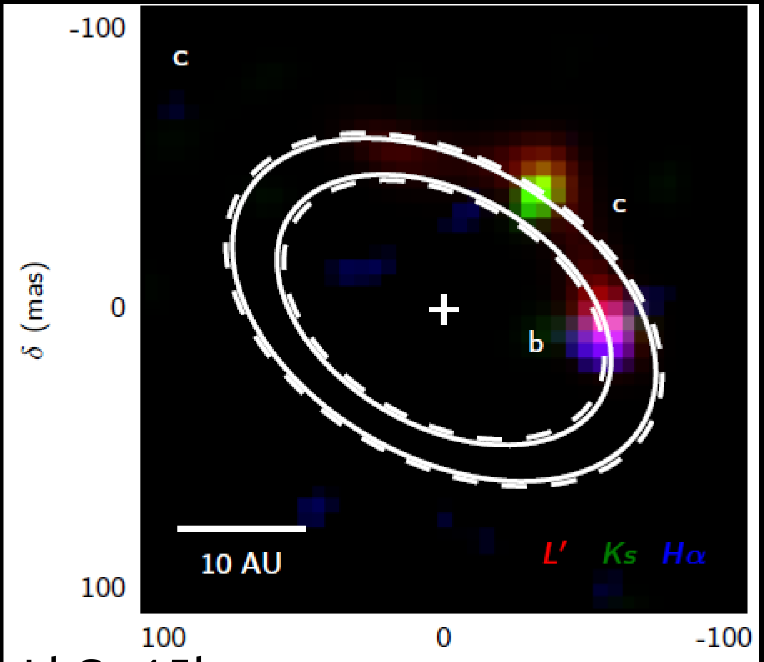
… and what we expect from them
(Homework: complete this)

- If giants, be formed before the disk is gone.
- If rocky, may not be ready for another few tens/hundreds of Myr, but we should at least have some large boulders.
- In any case, contain less mass than the mass of the disk.
- Be allowed to migrate, but only as long as there/where the disk is massive enough.
- Hopefully, leave signatures in the disk as they form.

Examples

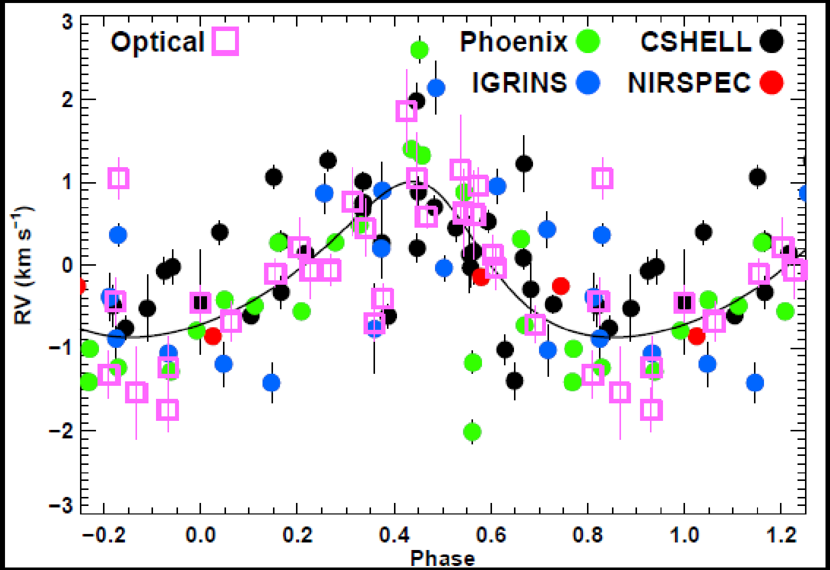


2M1207b [Gauvin et al. 2004]

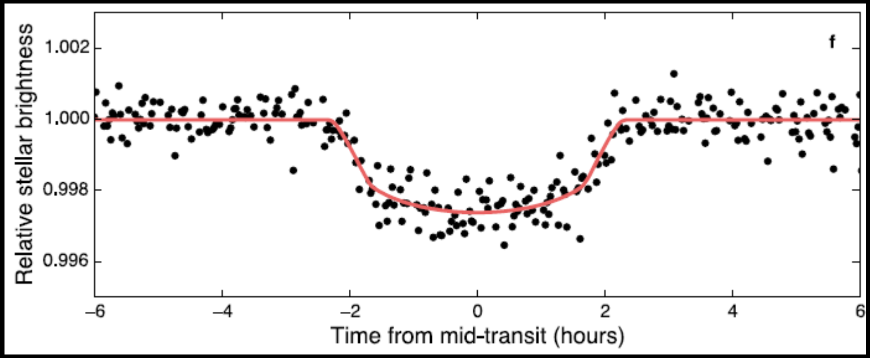


LkCa 15b, c

[Kraus & Ireland 2012; Whelan+ 2015; Sallum+ 2015]



CI Tau b [Johns-Krull et al. 2016]

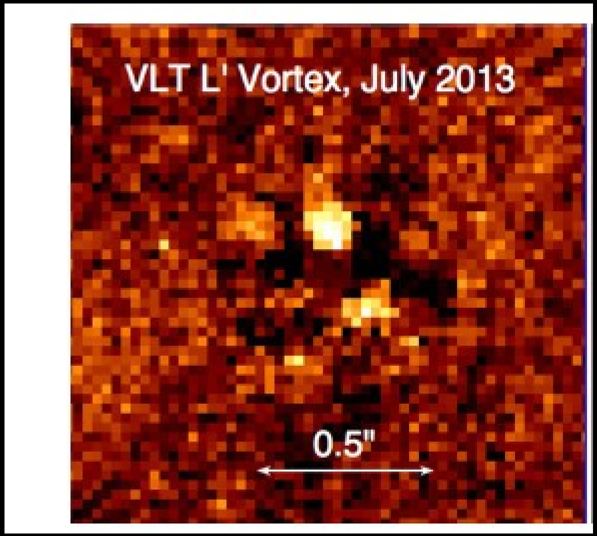


K2-33b [David et al. 2016]

The issues with planet detection techniques

- Direct imaging
- Transits
- Radial velocities
- Indirect detection (from signatures in disks)

Problem 1: Imaging: Planet? Disk feature?



[Biller et al. 2014;
Reggiani et al. 2014]

HD 169142

- **Too hot** for an irradiated or accretion disk feature.
- **Too odd** for a planet (not detected in all bands as a proper black body would be).
- **Detected by 2 teams**, so definitely "a something"

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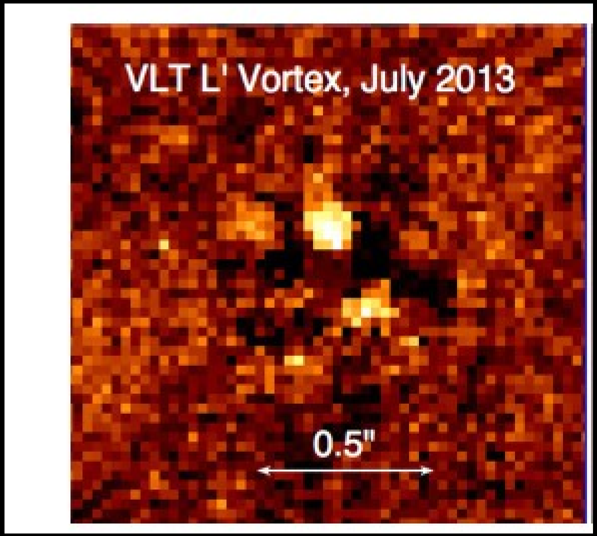


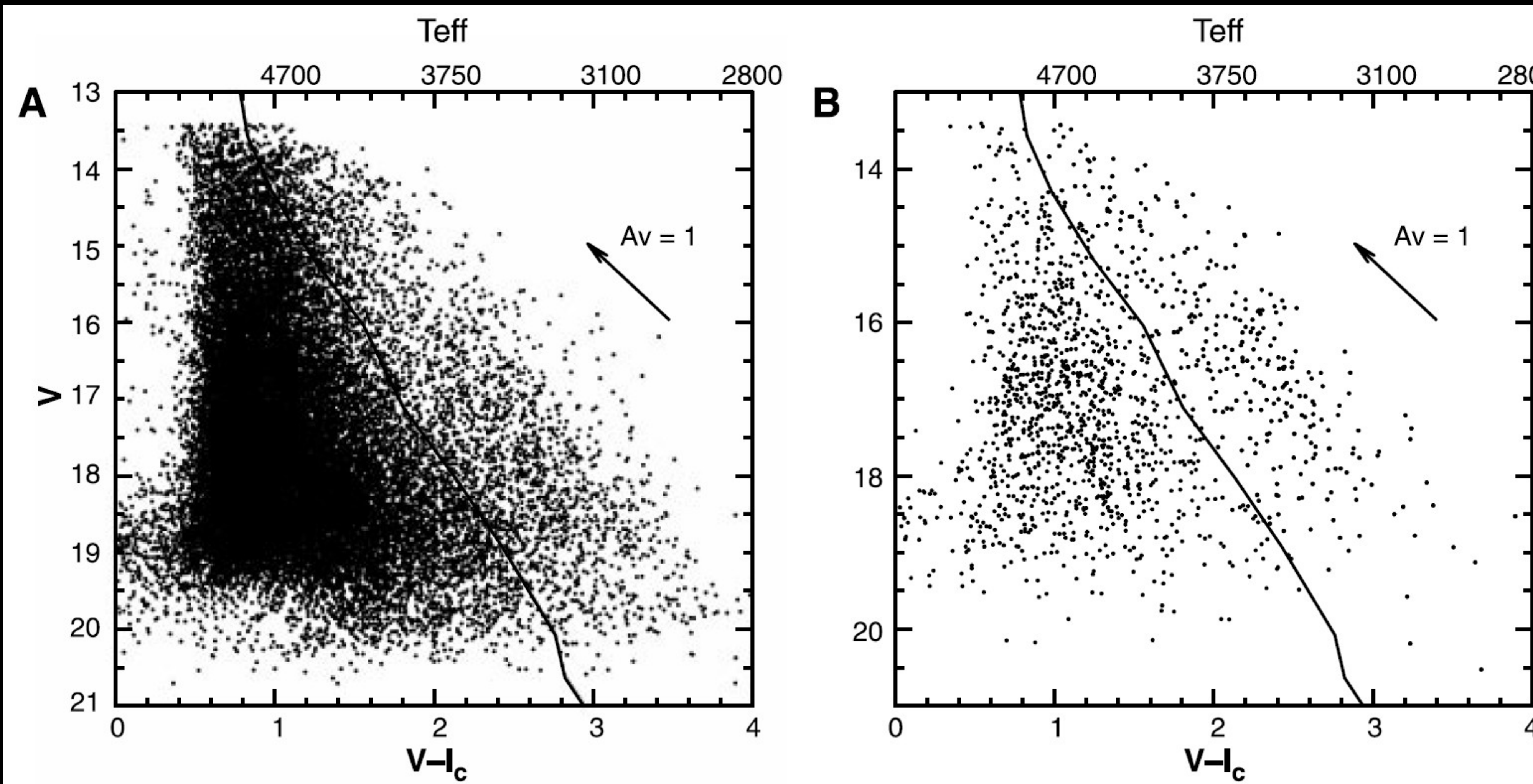
[Biller et al. 2014; Reggiani et al. 2014]

HD 169142

- **Too hot** for an irradiated or accretion disk feature.
- **Too odd** for a planet (not detected in all bands as a proper black body would be).
- **Detected by 2 teams**, so definitely "a something"

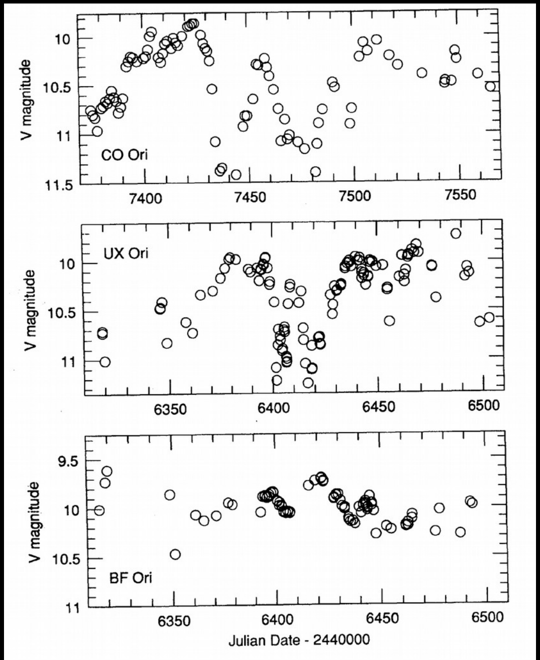
→ Many uncertainties about disk features and planet properties!

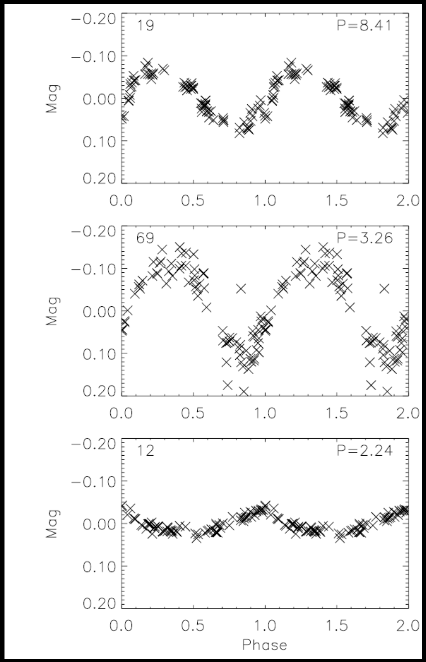
Problem 2: Transiting the variable



It's not only that young stars are variable… the variable tend to be the young stars! [Briceño et al. 2001]

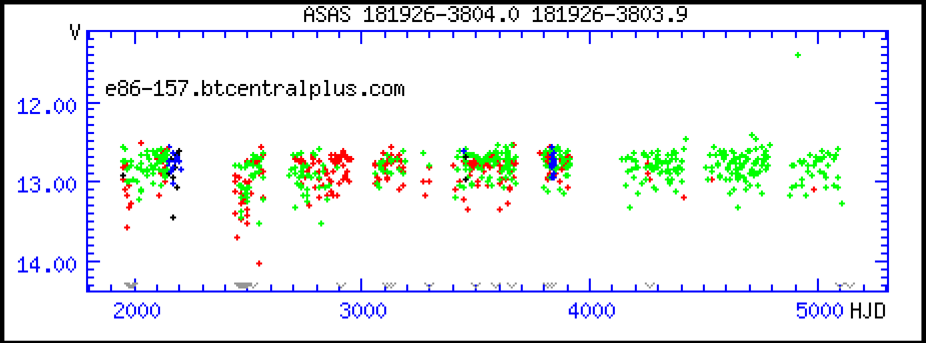
Problem 2: Transiting the variable





See any transit here?

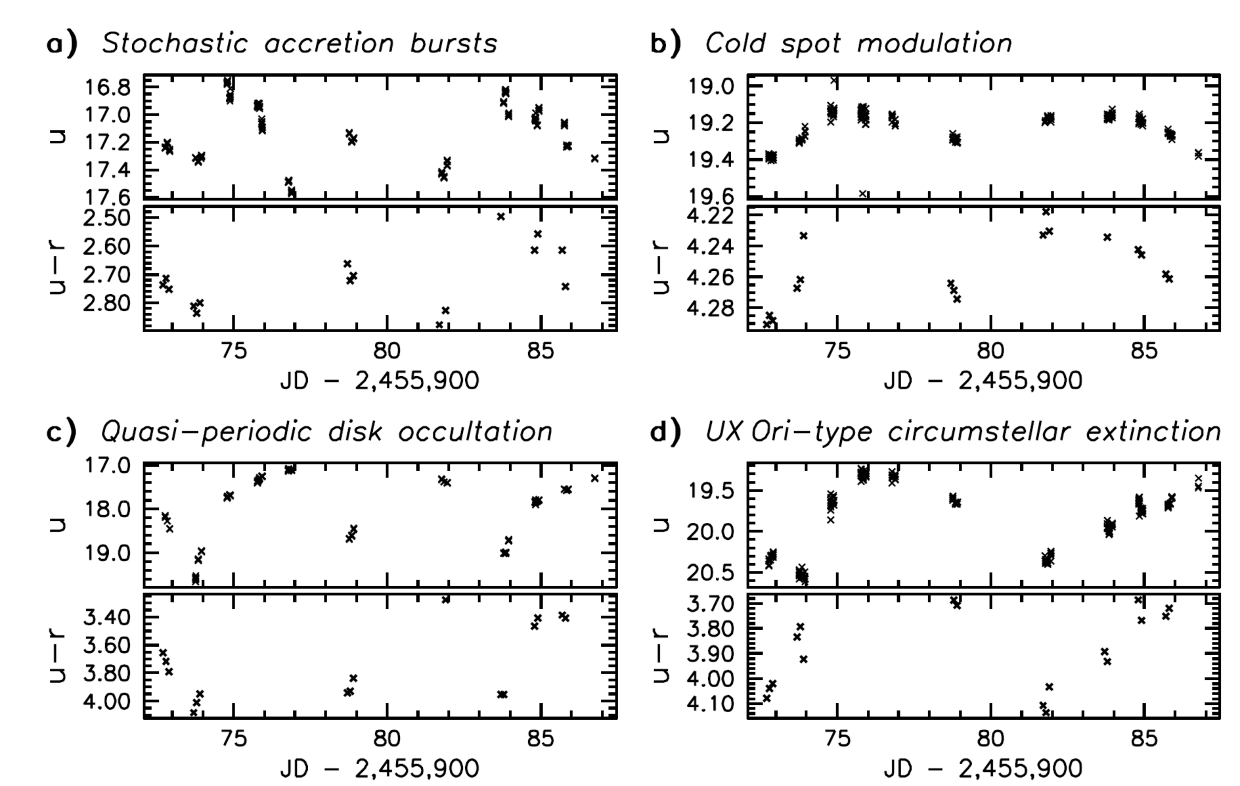
[Herbst et al. 1994, 2000]

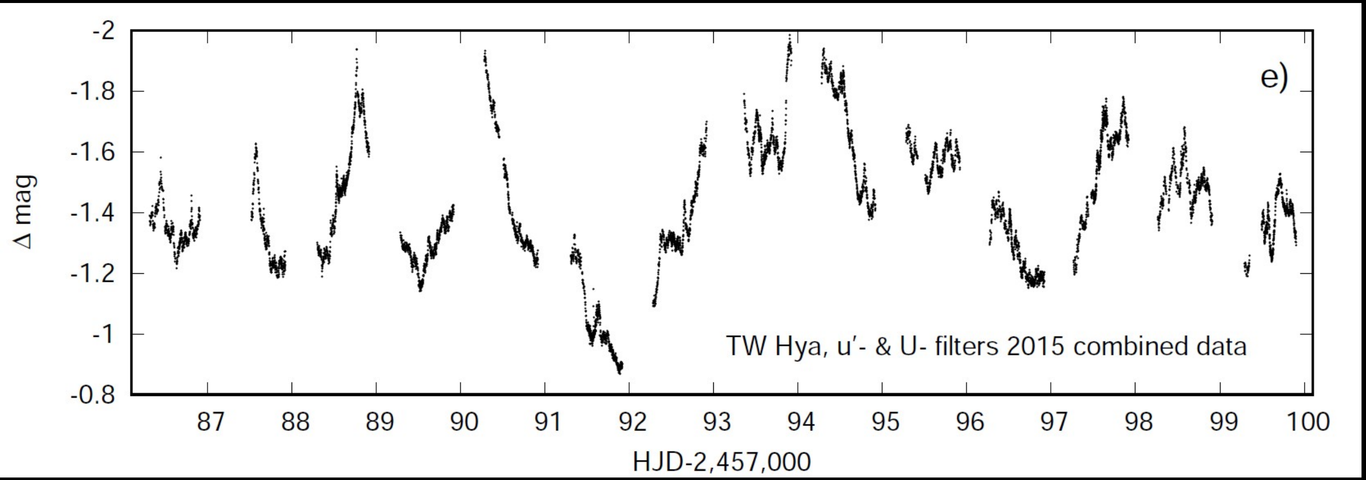


http://www.astrouw.edu.pl/asas/?page=catalogues00

Problem 2: Transiting the variable

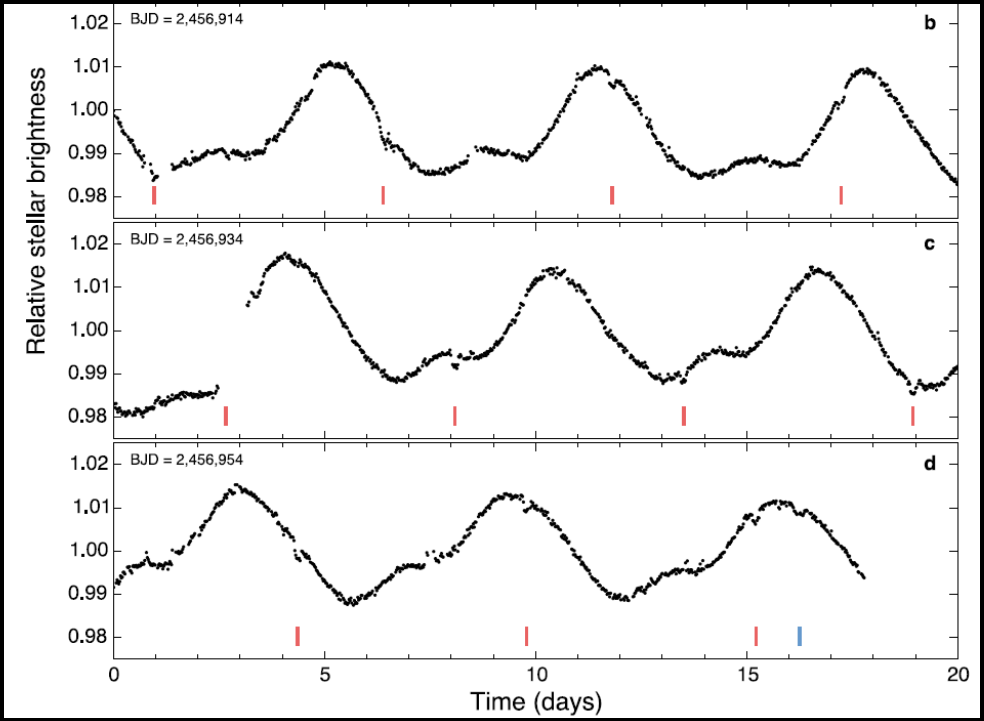
Luckily, data are getting better and better
[Venuti et al. 2015]

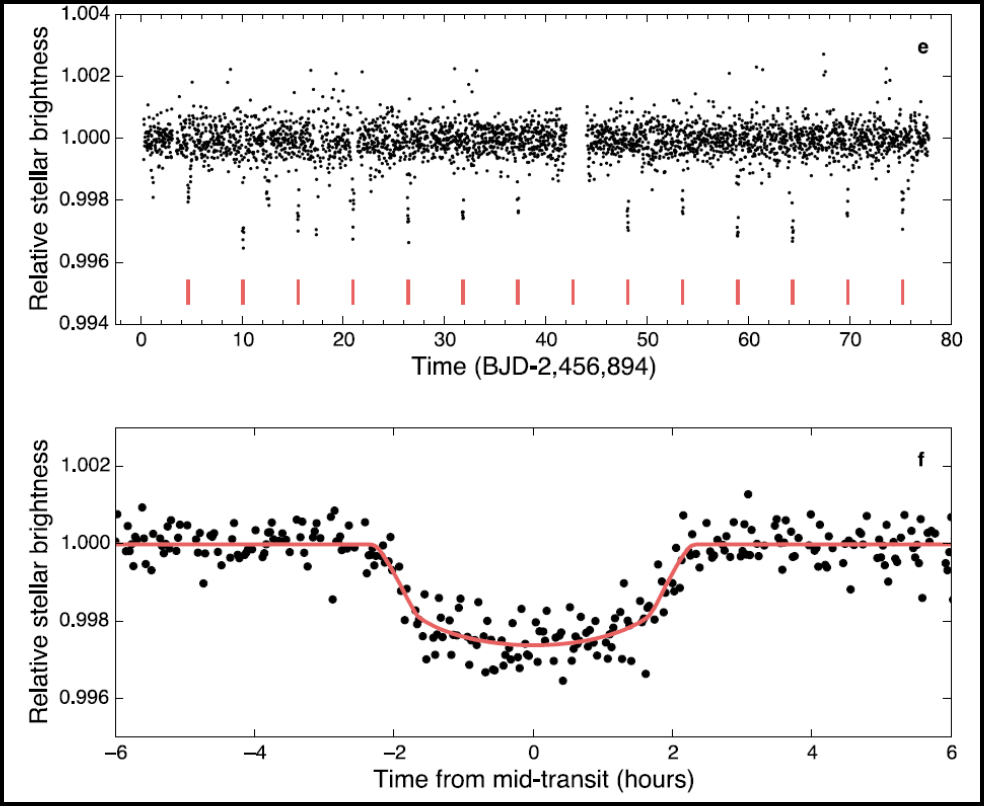




Tracing high- and low cadence with MOST
[Siwak et al. 2018]

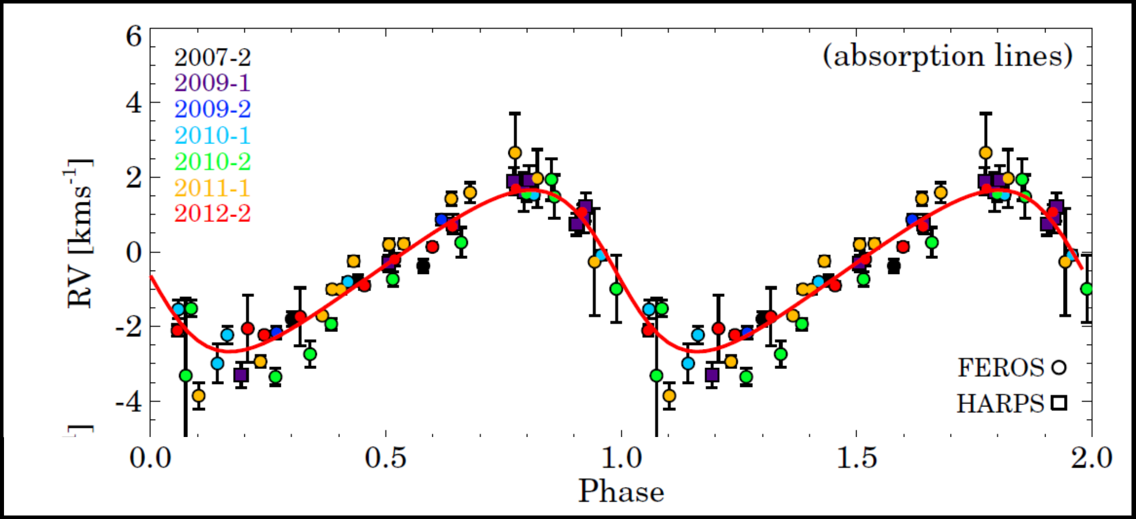
Problem 2: Transiting the variable





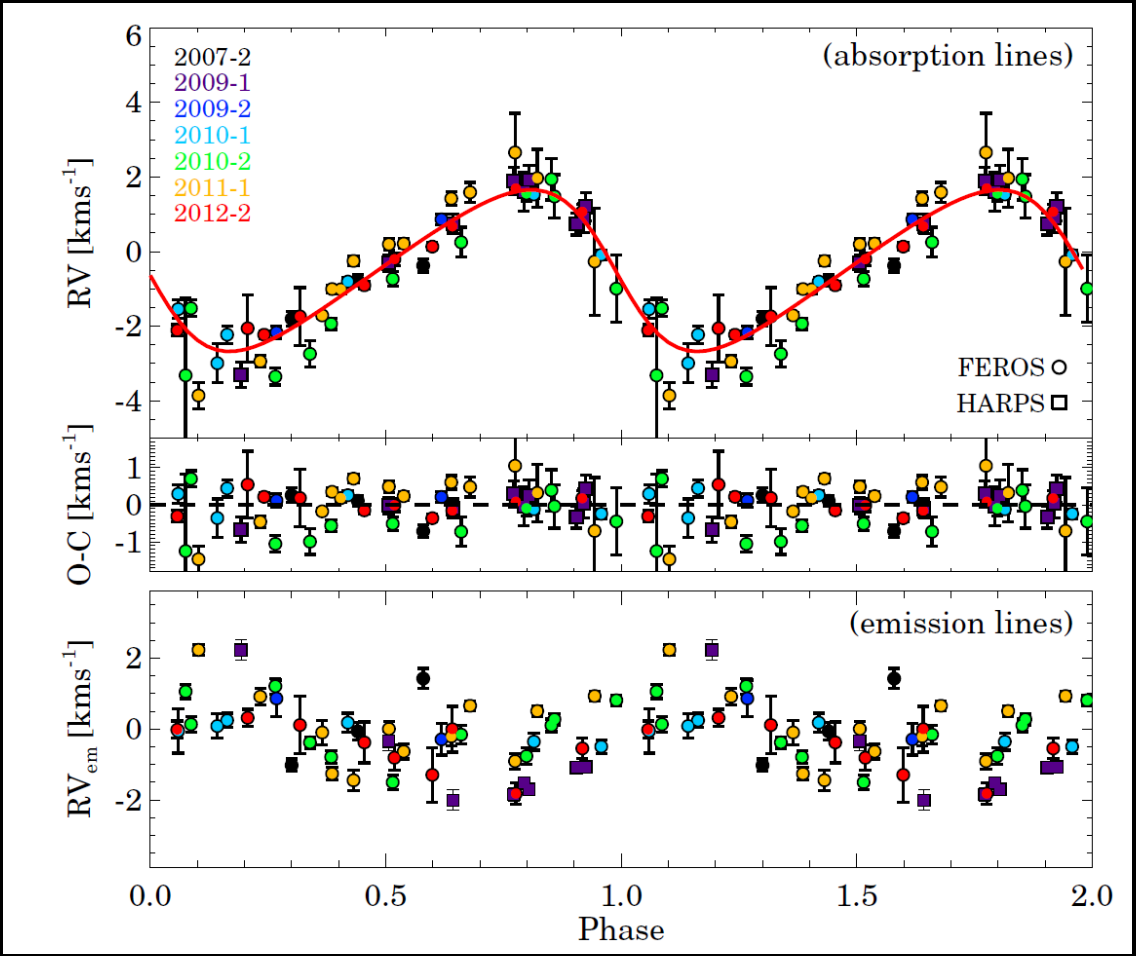
And a good understanding of the photometric variability makes it possible: e.g. K2-33b [David et al. 2016]

Problem 3: RV: Planet? Accretion? Spots?



Is this **a planet?**

Problem 3: RV: Planet? Accretion? Spots?



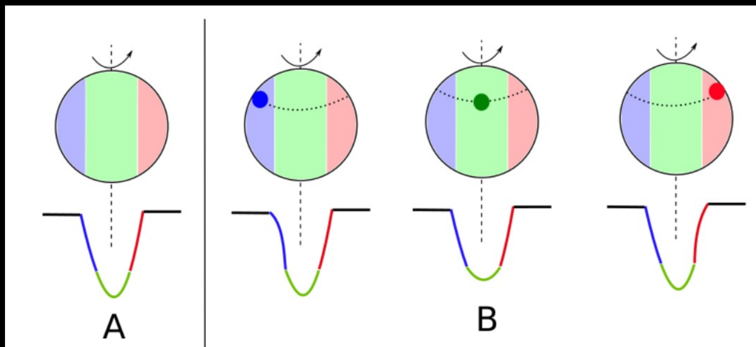
[Kospal et al. 2014]

Is this **a planet?**

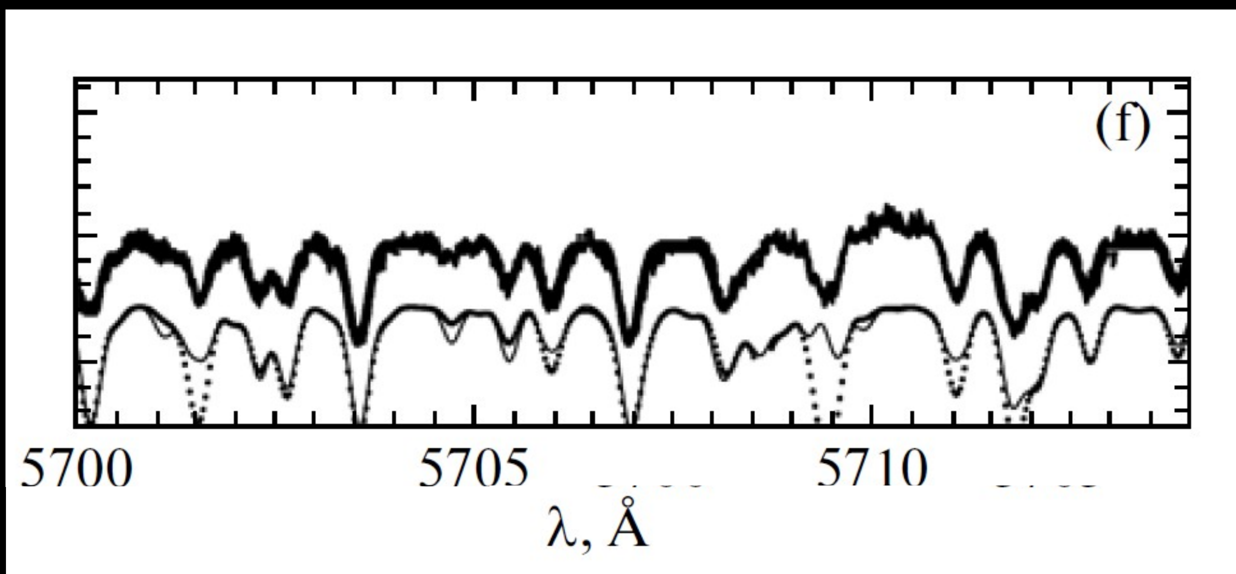
Rather not.

→ Even massive companions can be hard to distinguish from accretion/activity

Problem 3: RV: Planet? Accretion? Spots?



Features induced by spots/accretion tend to affect the absorption line profile… but this may not be the case if there is line-dependent veiling or tilting continuum.

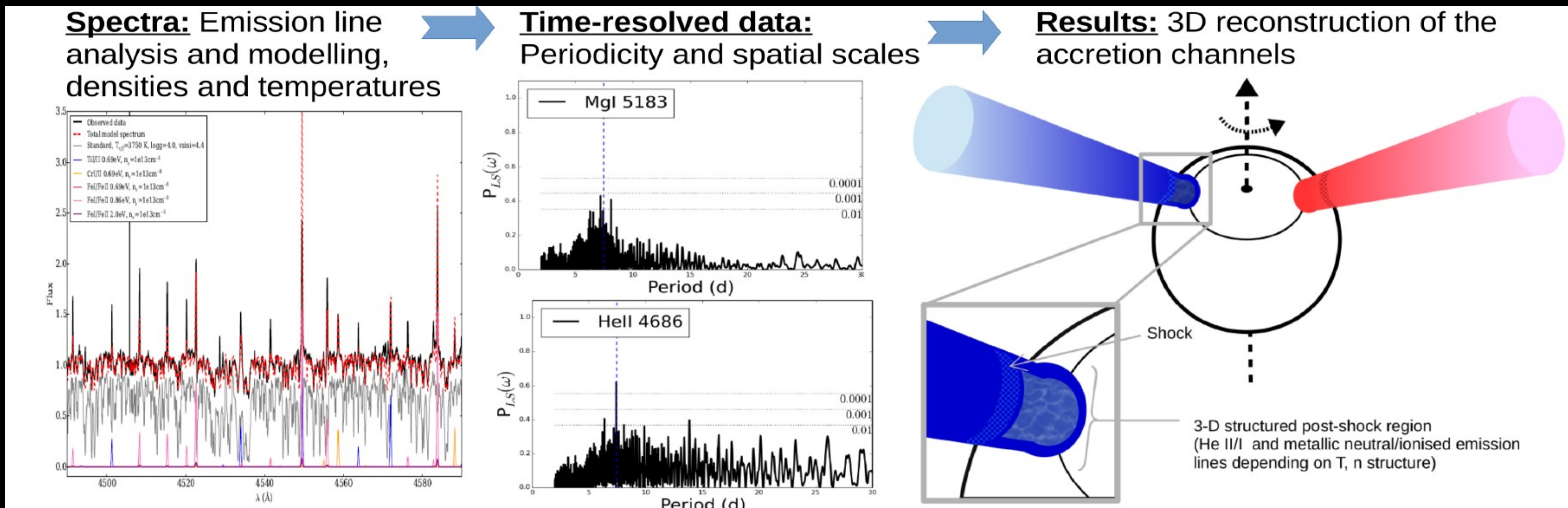


[Dodin & Lamzin 2012]

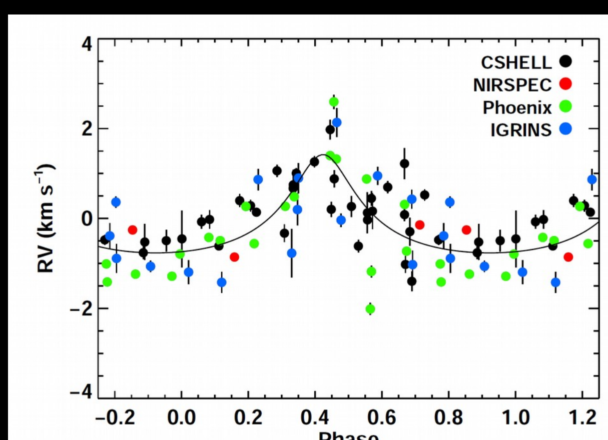
Even massive companions can be hard to distinguish from accretion/activity

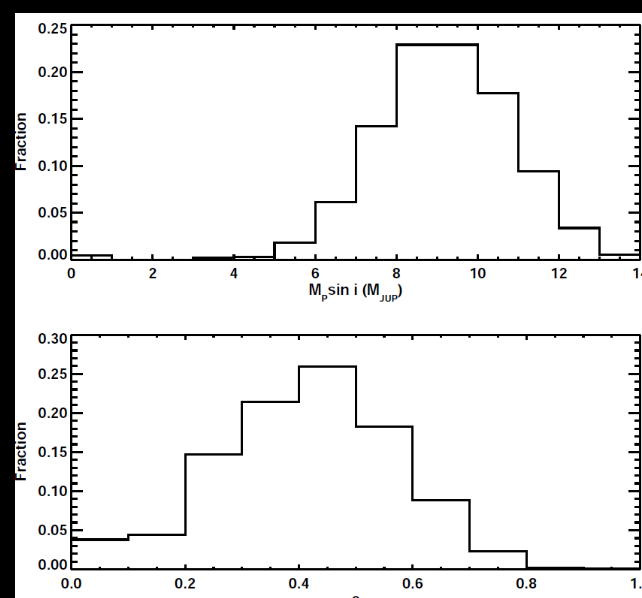
Problem 3: RV: Planet? Accretion? Spots?

Line-dependent variability can reveal the star/accretion: [SA et al. 2015]



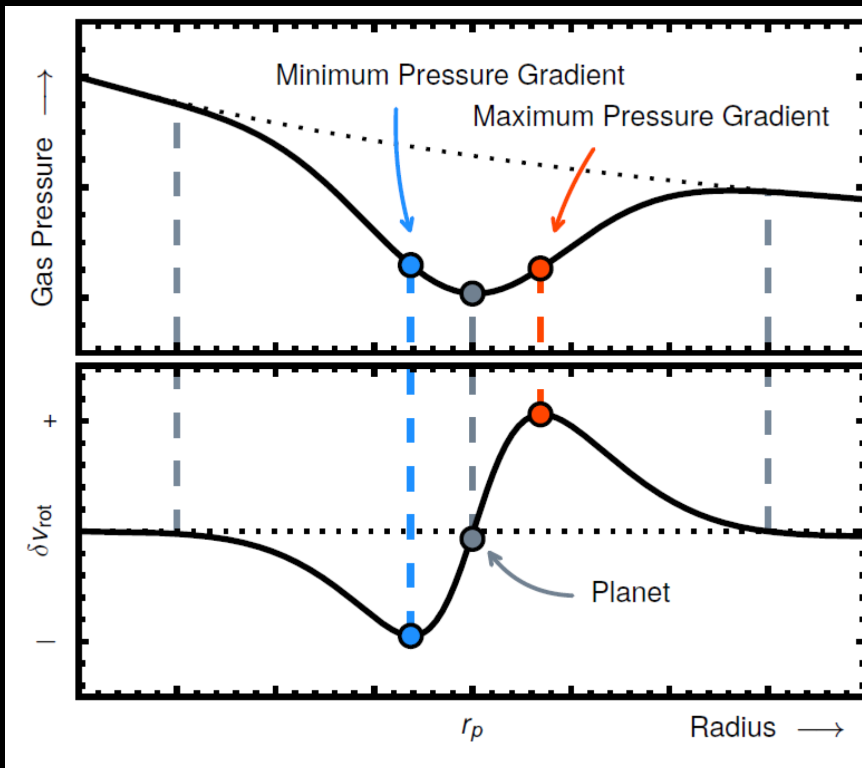
Or the planet, e.g. CI Tau:





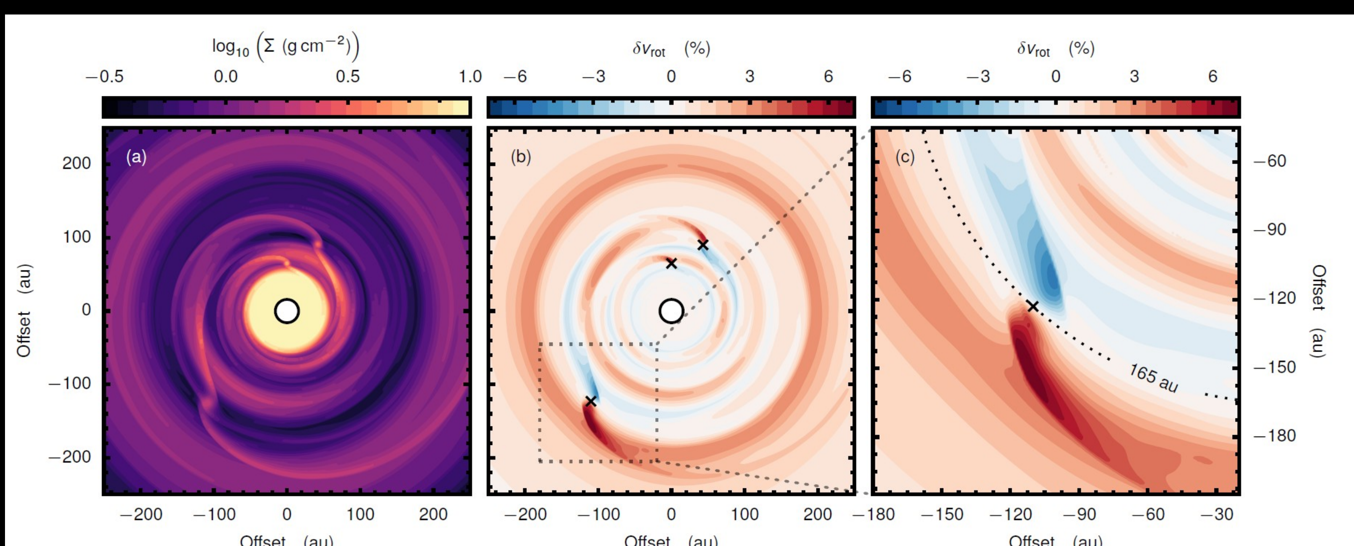
[Johns-Krull et al. 2016]

Problem 3b: Dynamics in other lines



New techniques being developed to use the CO lines velocities. Semi-theoretical method, could evolve in the same way we use radial velocities nowadays.

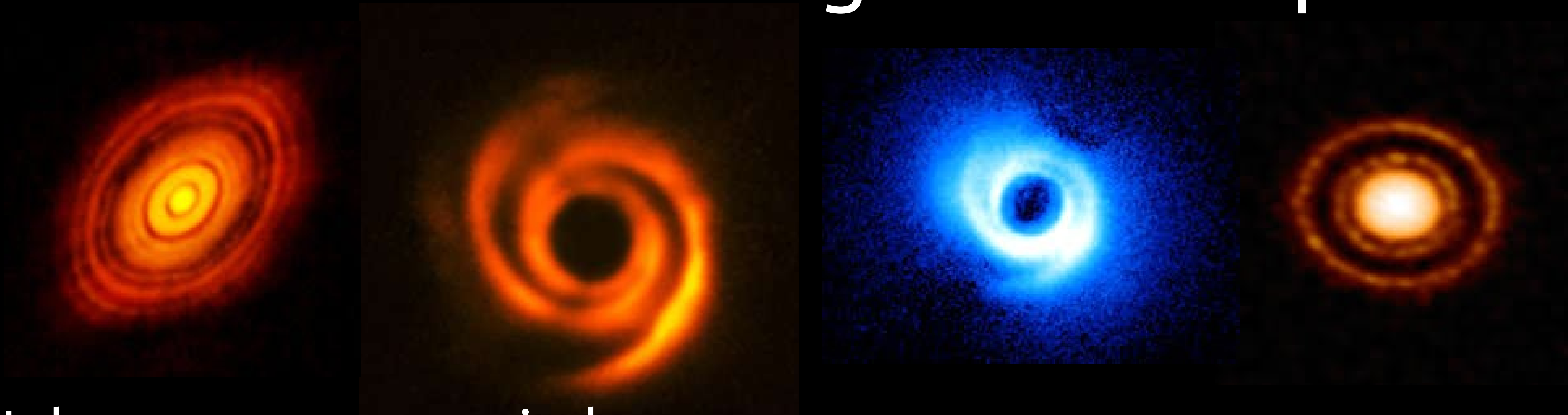
Main issue: **disk properties are a lot more unknown** than stellar photospheres...



HD163296b,c

[Teague et al. 2018]

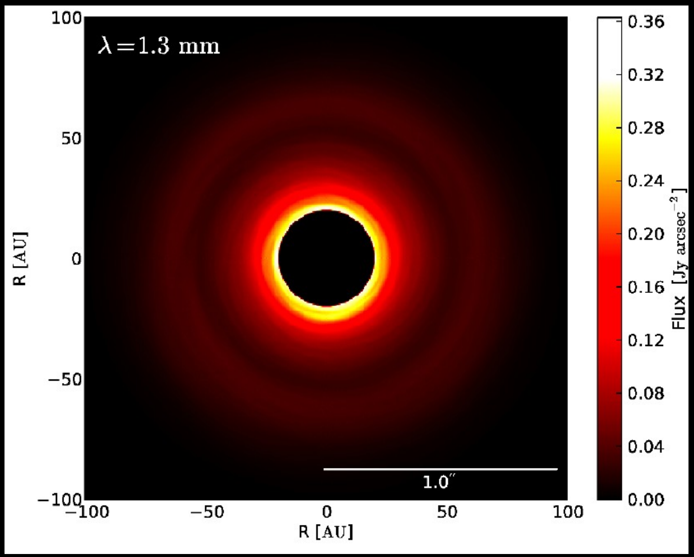
Problem 4: Indirect signatures of planets



Holes, gaps, warps,spirals, are very common...
but are they caused by:

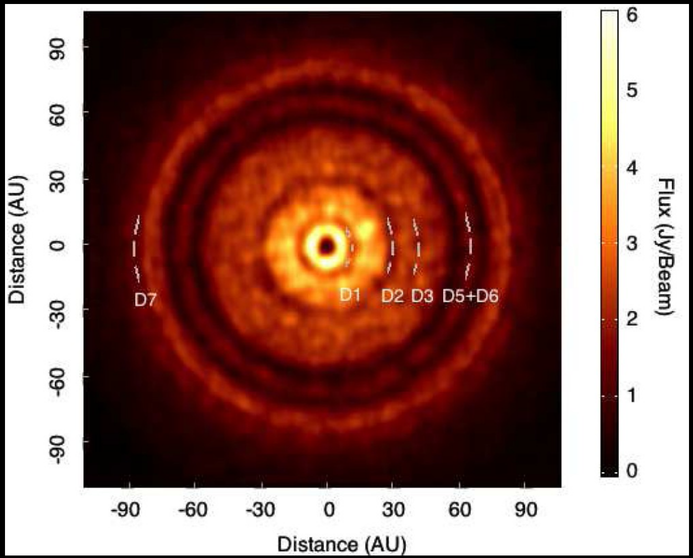
- **Planets**? [e.g. Tamayo et al. 2015, Dipierro et al. 2015, Tabeshian & Wiegert 2018]
- **Something else**? Non-ideal MHD + winds [Hasegawa et al. 2017]
  large pebbles in condensation fronts [Zhang et al. 2015] ,
  dead zones edges [Miranda et al. 2016]
  shadows [e.g. Benisty+ 2016, Stolker+ 2016, Garufi+ 2016, Kama+ 2016]
  snowlines [e.g. Banzatti et al. 2016]
- **Half-half**? E.g. some planets + secular GI [Takashi et al. 2016]
- **Planets-to-be**? [Carrasco et al. 2016]

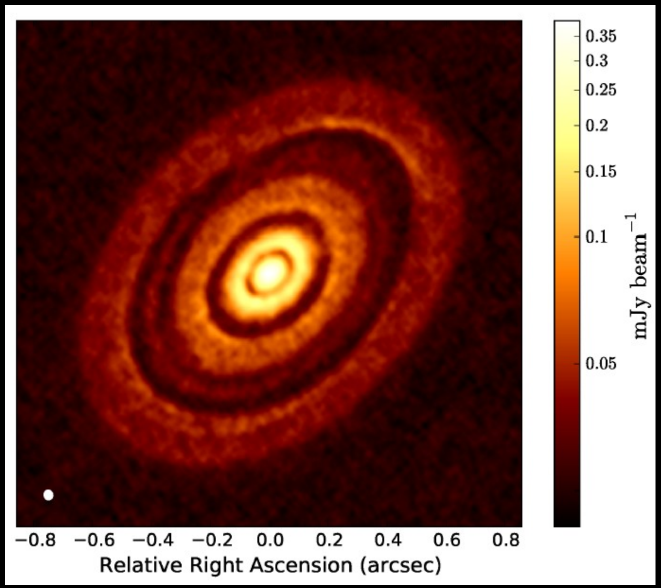
Problem 4: Inverting the problem?



No planets
[Flock et al. 2014]

Planets + secular interac.
[Tabeshian & Wiegert 2018]



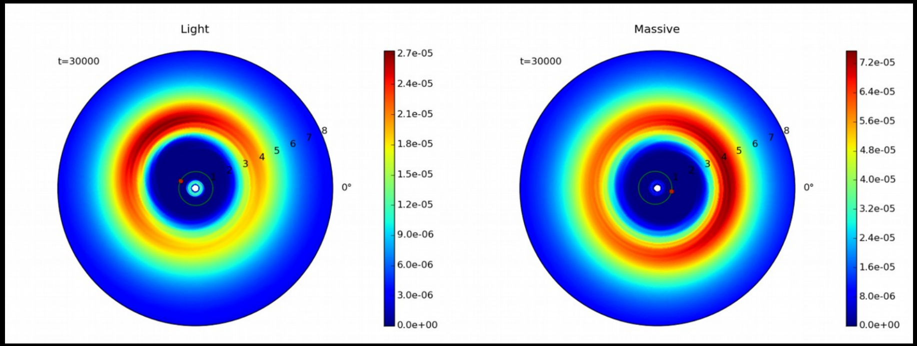


3 Planets only
[Dipierro et al. 2015]

- What **mechanisms** produce holes, gaps, asymmetries?
  Are they **unique**?
- Are “transition disks” in **transition** or “normal” features of disks?
- How do disks evolve? Do they all follow the same path?
- How do planets and their disks **interact**?

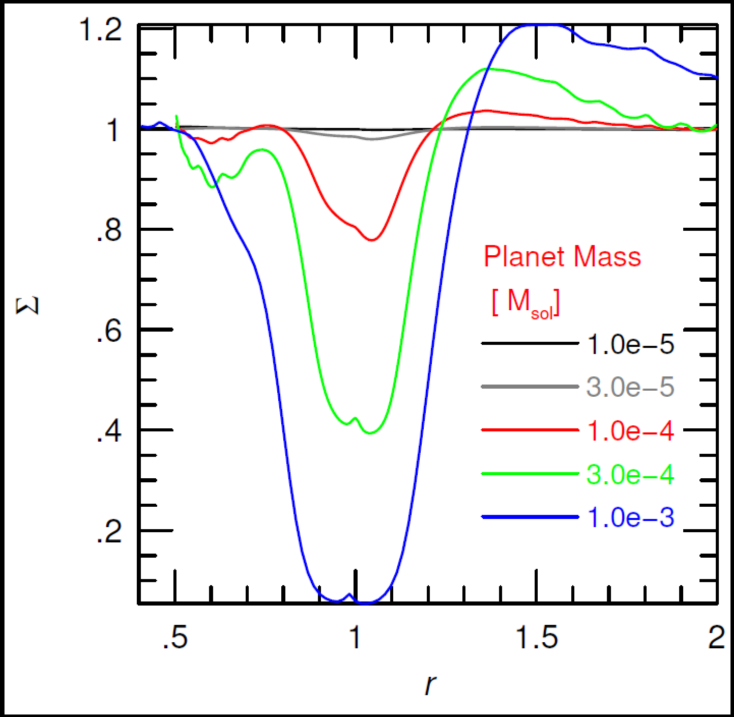
Problem 4b: How would a disk behave if it had planets in it?

Planet-disk interaction depends on planet and disk properties…



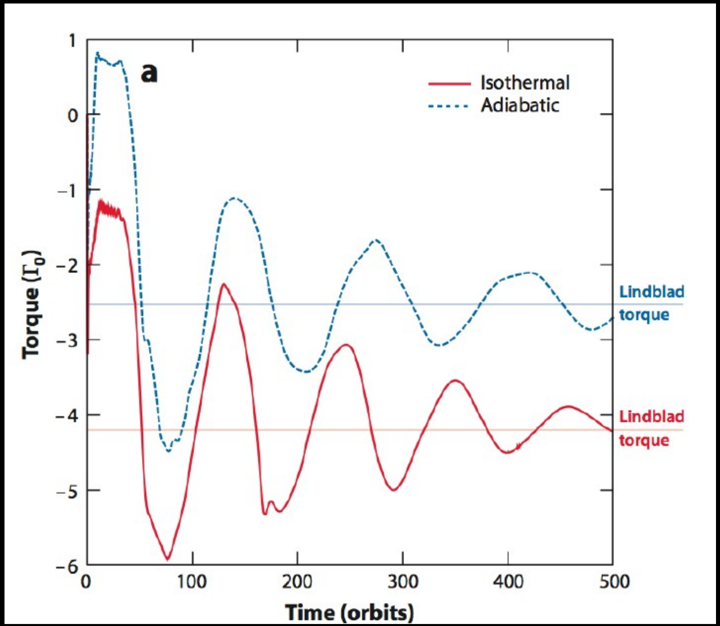
Disk mass

[Ragusa et al. 2017]



Planet mass

[Kley 2017]



Disk physics

[Paardekooper, et al. 2010]

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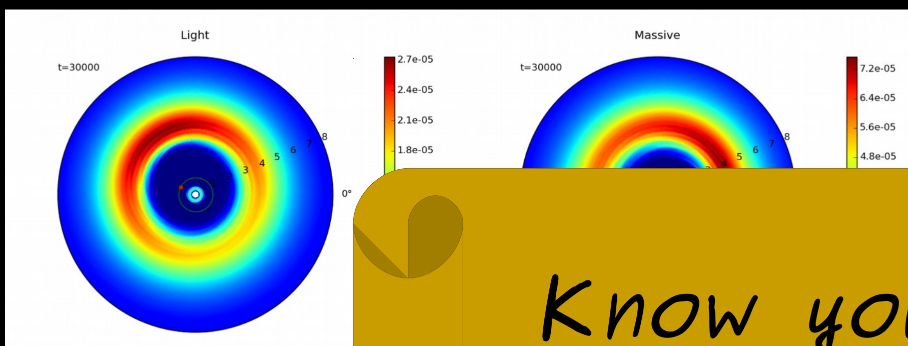
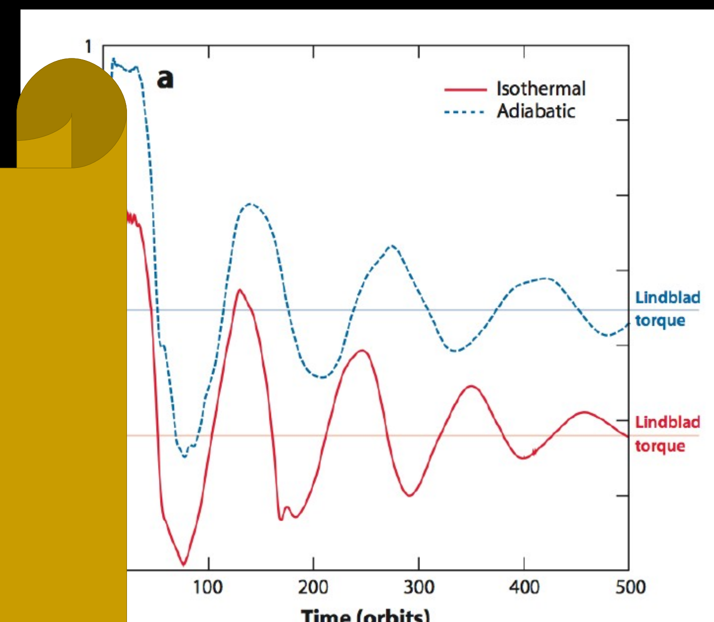


Disk mass

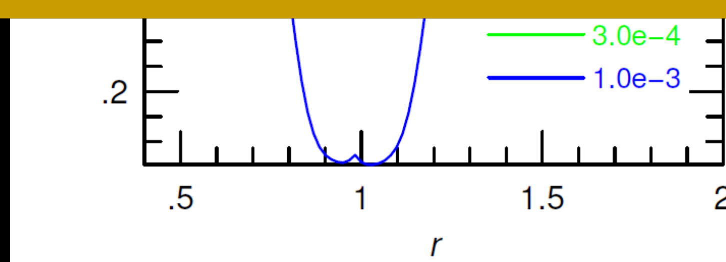
[Ragusa et al. 201

Know your star,
Know your disk,
Know your planet
?



isk physics

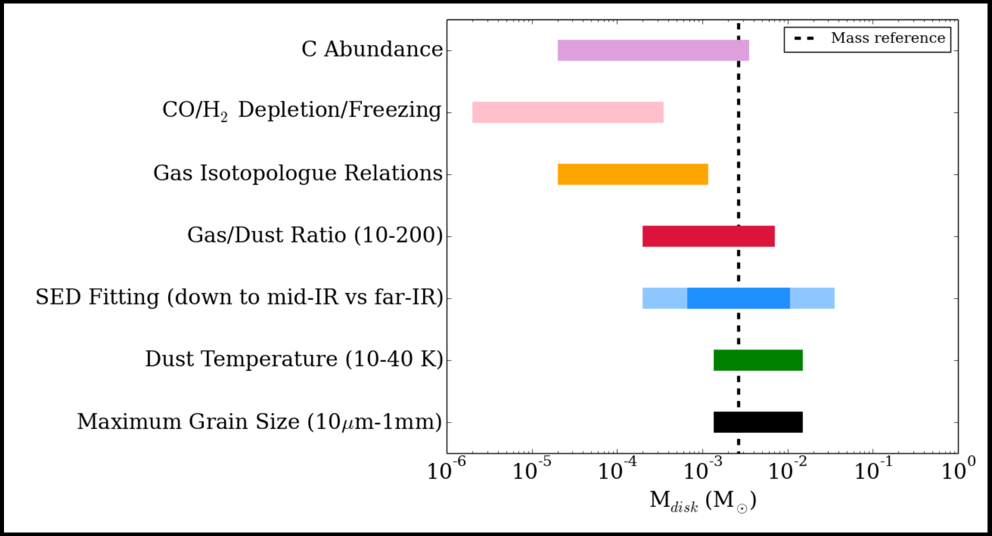
aardekooper, et al. 2010]



Planet mass

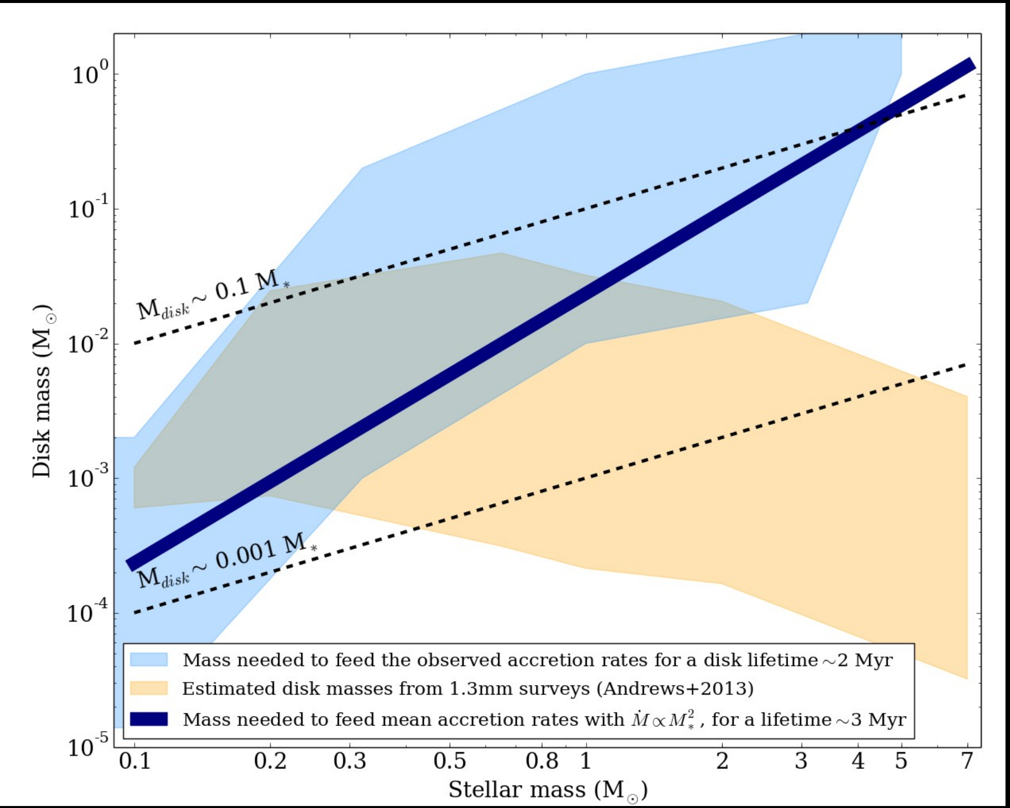
[Kley 2017]

Problem 4b: Know your disk?



Useful disk properties:
Mass, radius, accretion, viscosity, composition,...

Homework: **What level of accuracy do we need?**
There are still many things not well understood...

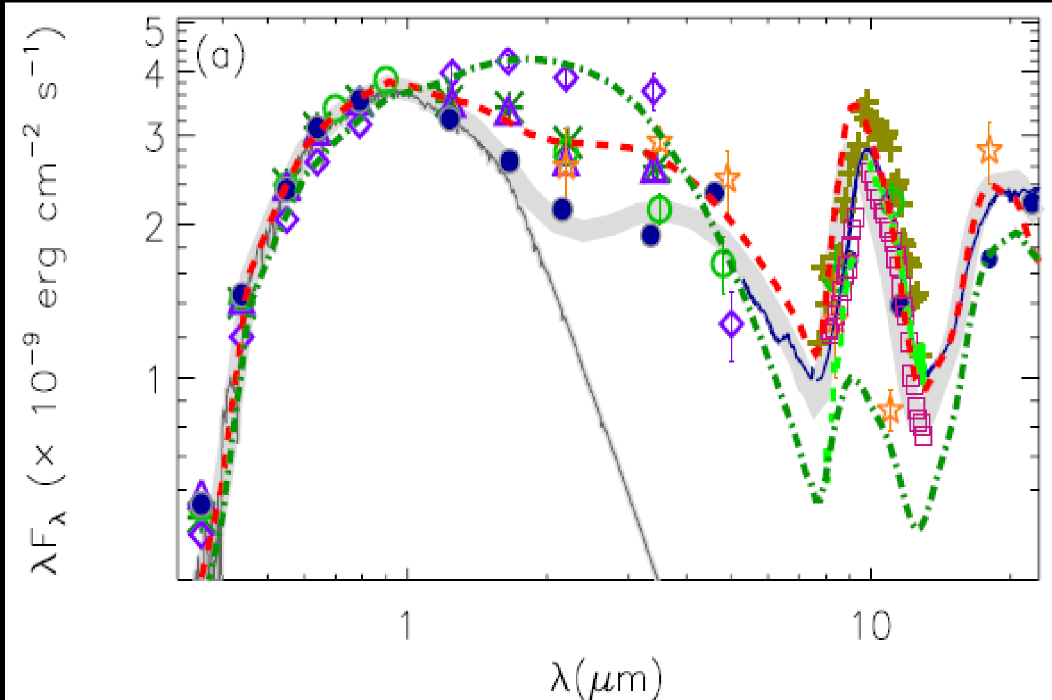


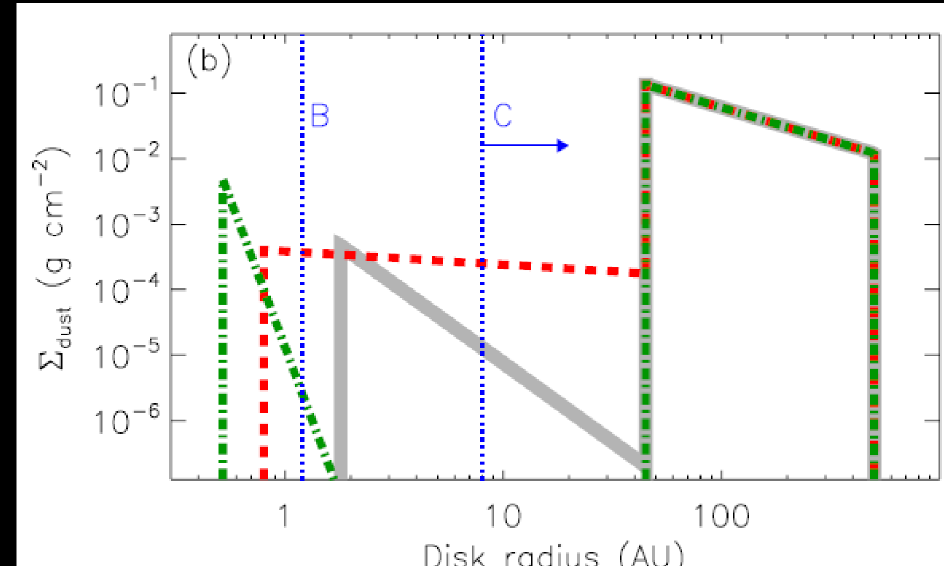
[Sicilia-Aguilar, Banzatti, et al. 2016]

Problem 4b: How would a disk behave if it had planets in it?

Problem (and blessing): Planets are intrinsically dynamic.

Look at upscaled "planetary systems"?
GW Ori, triple system with disk, the inner disk structure and SED are highly variable, dust filtering is time-dependent.





[Fang et al. 2014]

Baby planet candidates

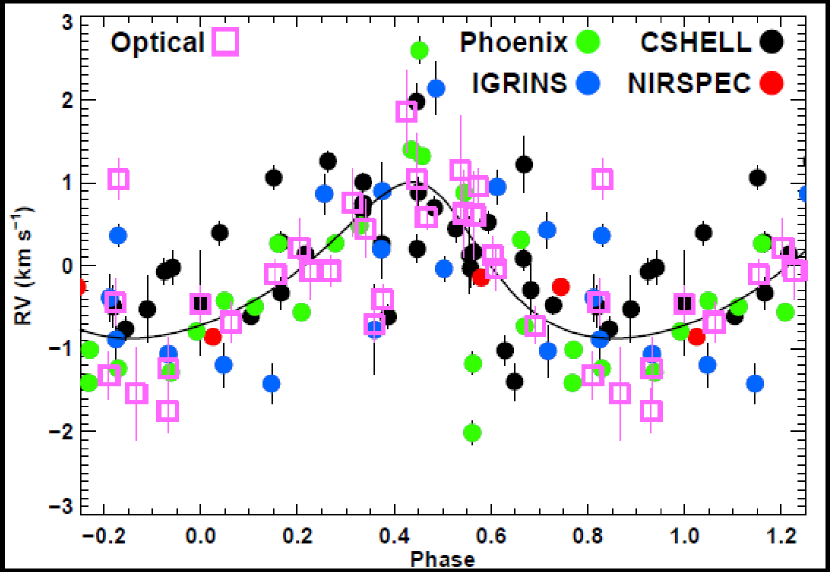
Some open questions before we move on:

- **How young** do we want them? Still in disk? Still evolving dynamically? Just around a PMS?
- Do we consider **BDs in disks** as “planets”?
- Do we consider **free-floating** planets as “planets”?
- Do we consider planetary-mass **companions of BDs** as binaries or “planets”?
- **How far out** can you form a planet in a “planet-way”?

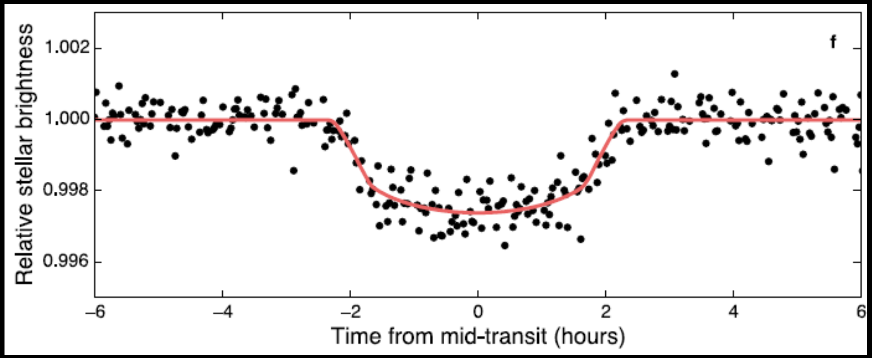
→ Starting point: *“things”* around stars <10 Myr old

Our best candidates

- **CI Taub** : Radial velocity, 2 Myr
- **FW Taub**: Direct imaging, 1.8 Myr, 330 AU, 10 M_j
- **K2-33b**: Transit and radial velocity, 10 Myr, 4 M_j
- **LkCa 15b**: Direct imaging, 2Myr, 6 M_j
- **ROXs 42Bb**: Direct imaging and spectroscopy, 7 Myr, 9M_j



CI Tau b [Johns-Krull et al. 2016]



K2-33b [David et al. 2016]

Potential candidates

Because of uncertainties finding them:

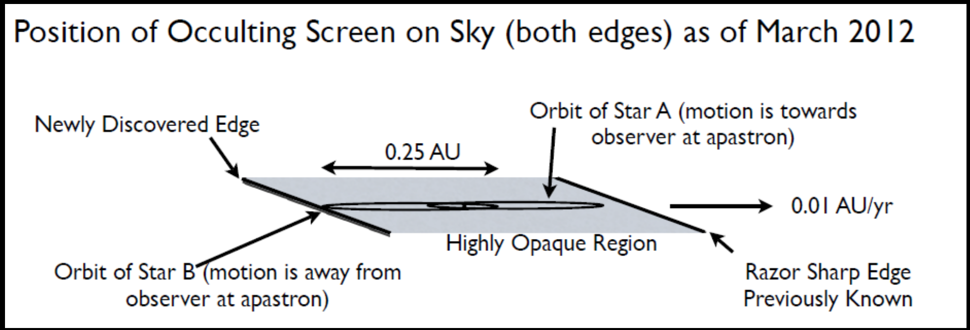
- **CSVO30b:** Planet or clump? lots of discussion ongoing…
- **HD163296c**: Discovered with new technique, to be followed in the future.
- **TW Hya c:** Unconfirmed, mostly indirect detection.
- **AS205Ab:** Radial velocity, pending further confirmation.

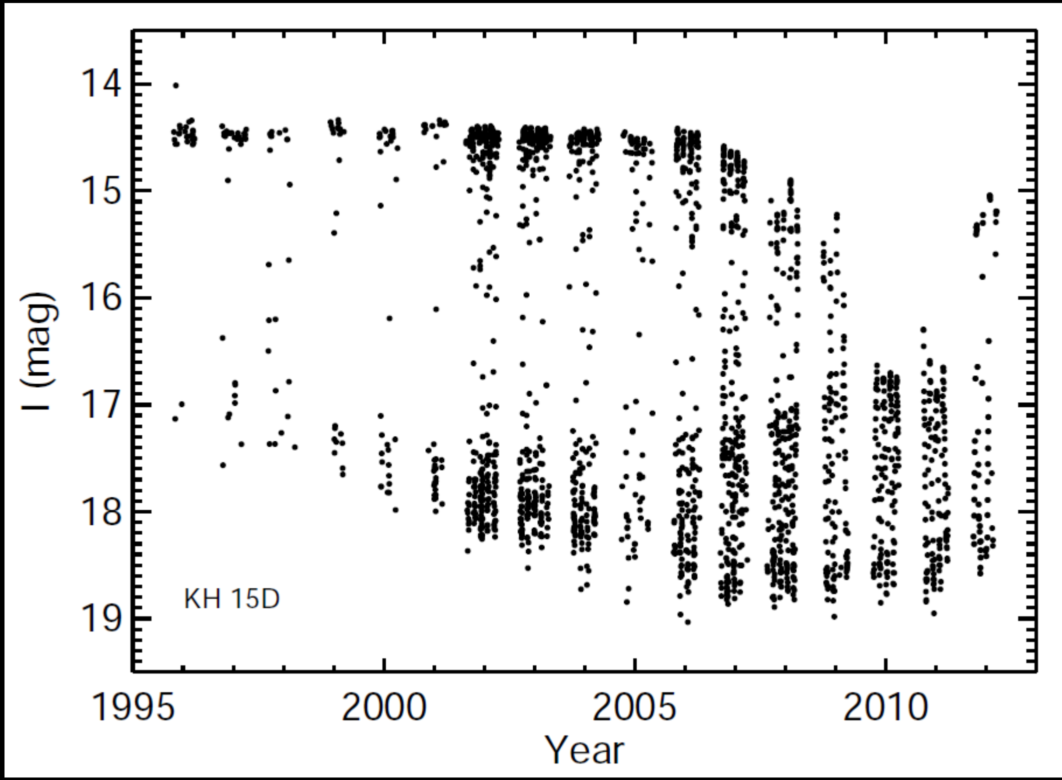
Because of their properties not being fully standard for planets:

- **Proplid 133-353:** Free floating.
- **2M0441+23b:** Planet or binary BD?
- **CT Chab:** Binary BD at 440 AU? Cluster member?
- **DH Taub:** Probably BD companion.
- **FU Taub:** Probably BD companion, very (800 AU)
- **GQ Lupb:** Well confirmed but seems BD companion.
- **HD100546:** BD/dwarf companion to intermediate-mass star.
- **ROXs12b:** Probably BD companion.
- **SR12ABc 1:** Probably BD companion
- **2M1207-39a,b:** 24Mj + 4Mj: binary BD or planet?
- **2MASS J11193254AB:** binary BD or planet + BD?
- **ChaHa8b:** BD companion.

Poisonous mushrooms?

- **KH15Db:** a mess of a binary star with disk.
- **TW Hya b:** 10 years of discussions.



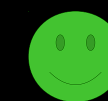
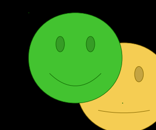
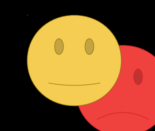
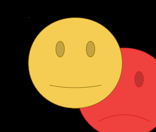


KH15D [Capelo et al. 2012]

Homework (to be discussed)

Are we ready for it?

 Yes!  Kinda  Good question.

- Determine how many are we missing, among what we expect. 
- Do we find what we thought we were going to find? 
- Determine what we are looking for and what it looks like. (a.k.a. “know your planet”). 
- How can we improve further the detection techniques? (a.k.a. “know your star, know your disk”). 
- How can we combine various observational techniques (tracing the disk, the star, accretion, etc) to find an answer?