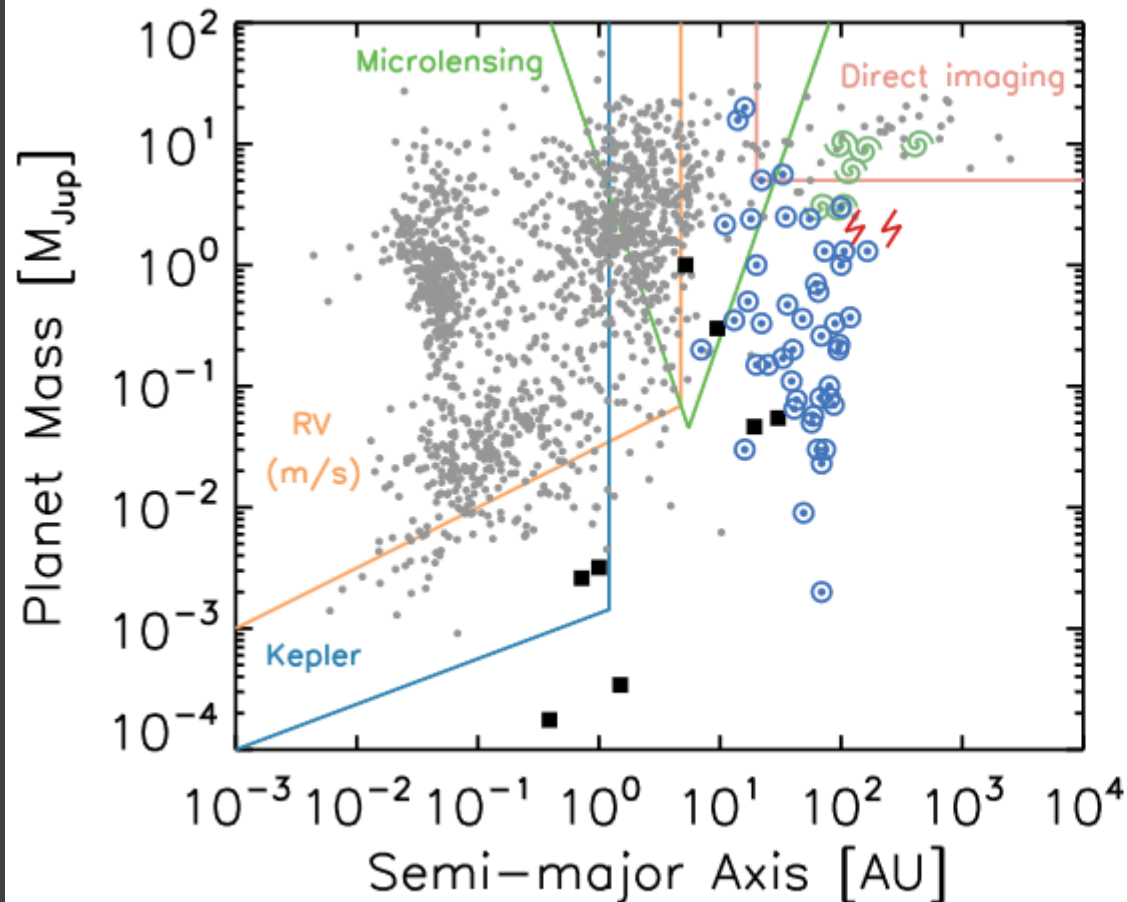


Young planetary systems

SERGEI POPOV

Planets and discs



- confirmed exoplanets
- solar system planets

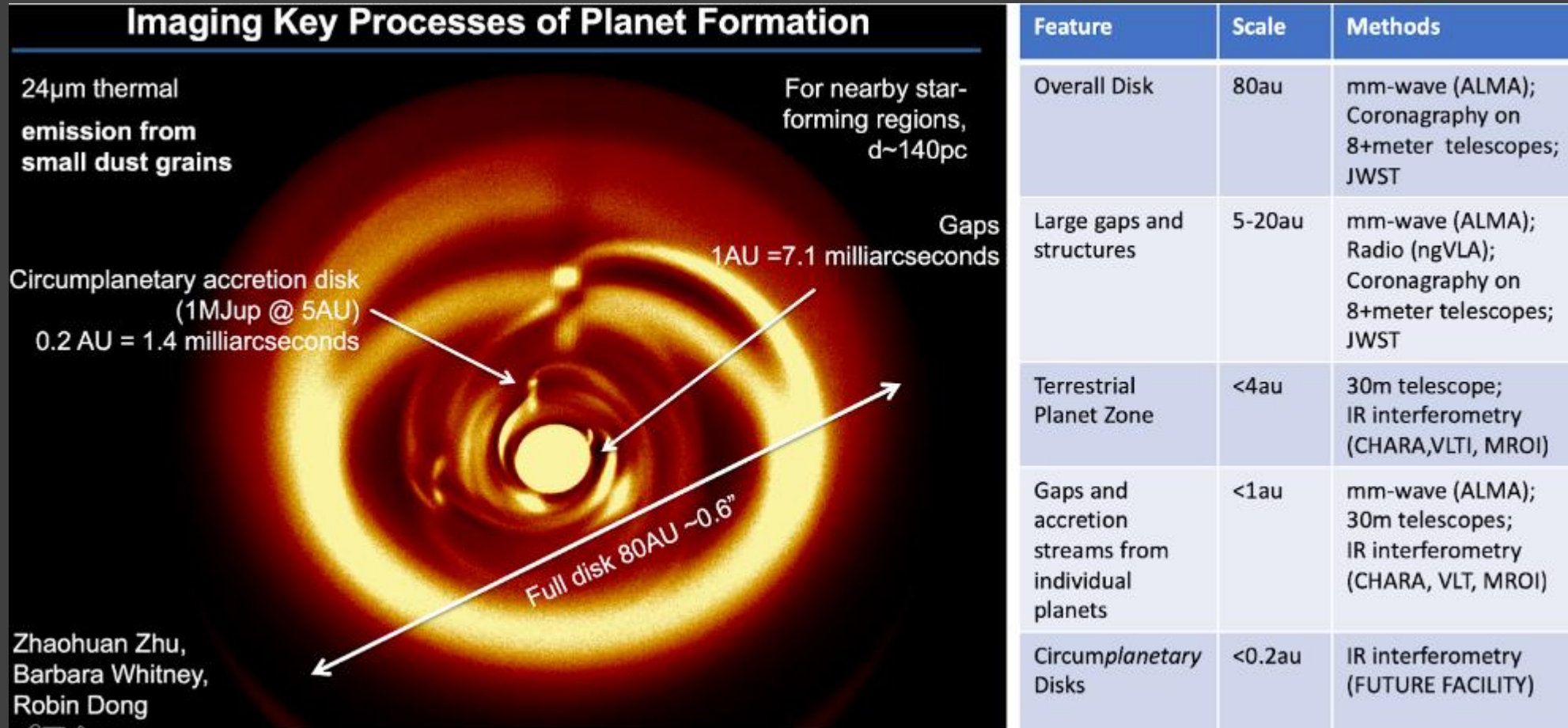
putative protoplanets to reproduce disk substructures:

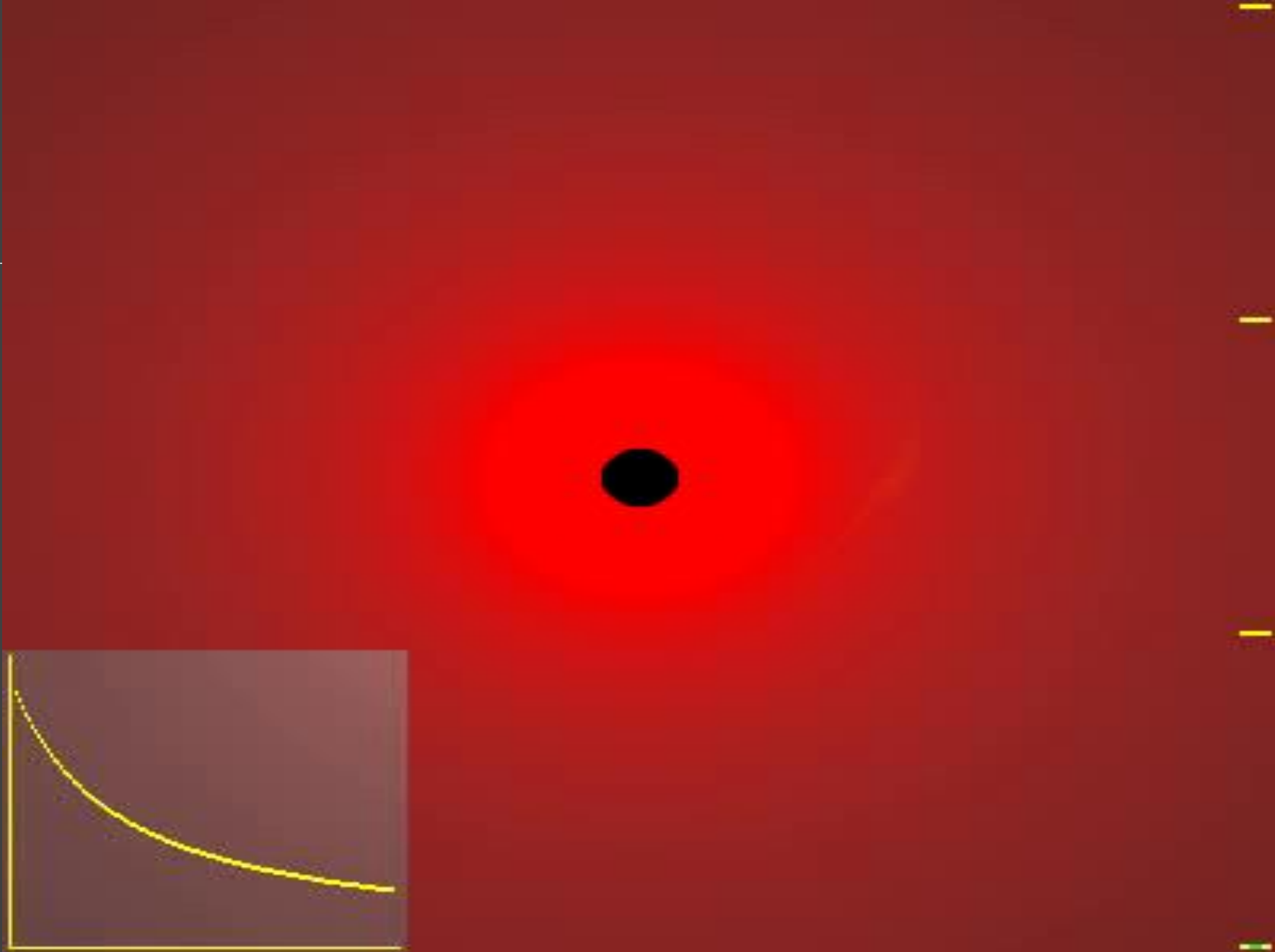
⊙ spirals

⊙ rings/gaps

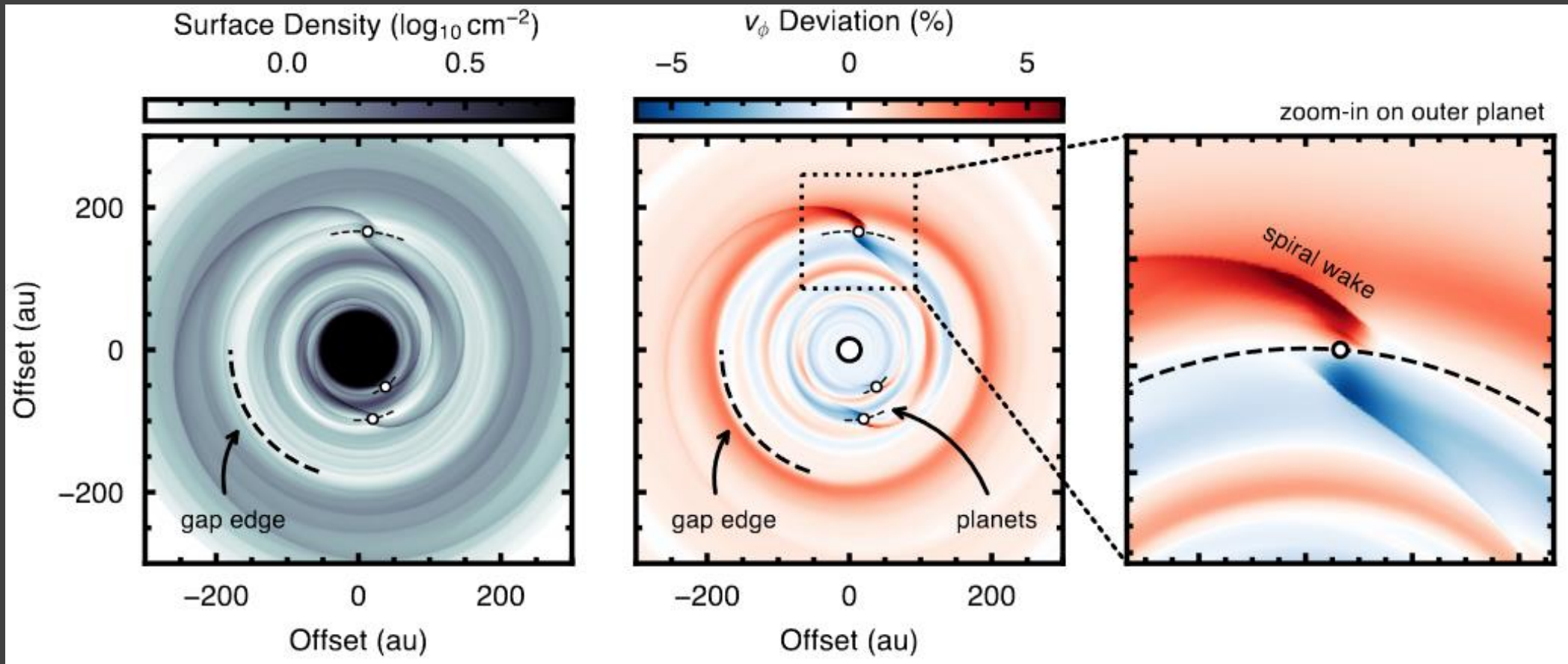
⚡ kinematic planetary signatures

Modeling and imaging planet formation



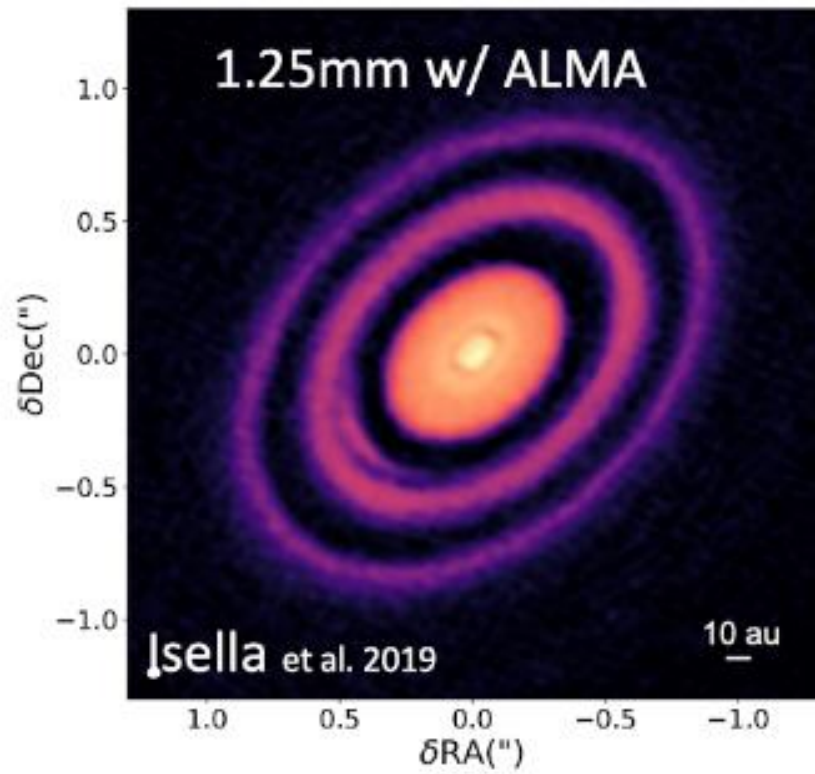


Planet-disc interaction

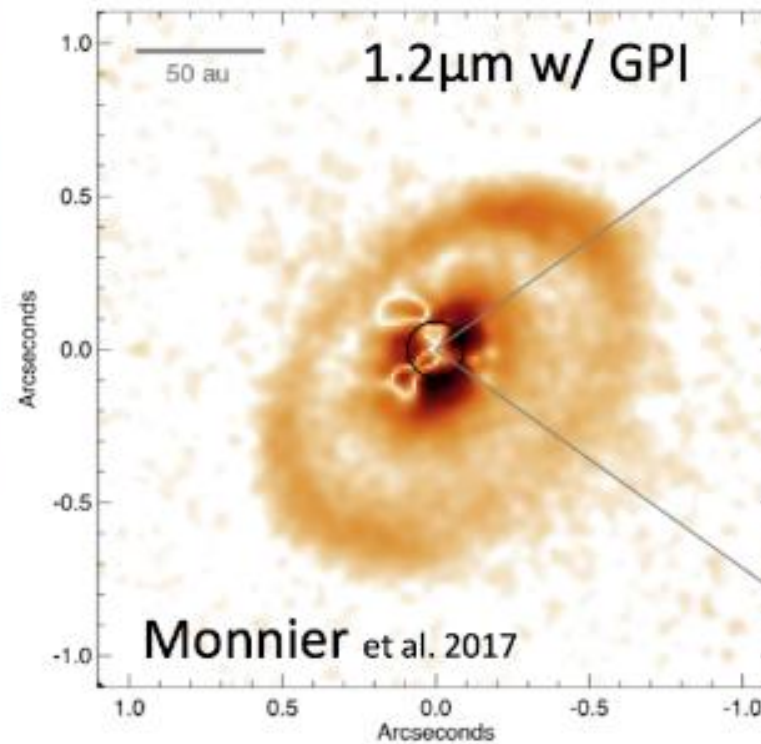


More details with different techniques

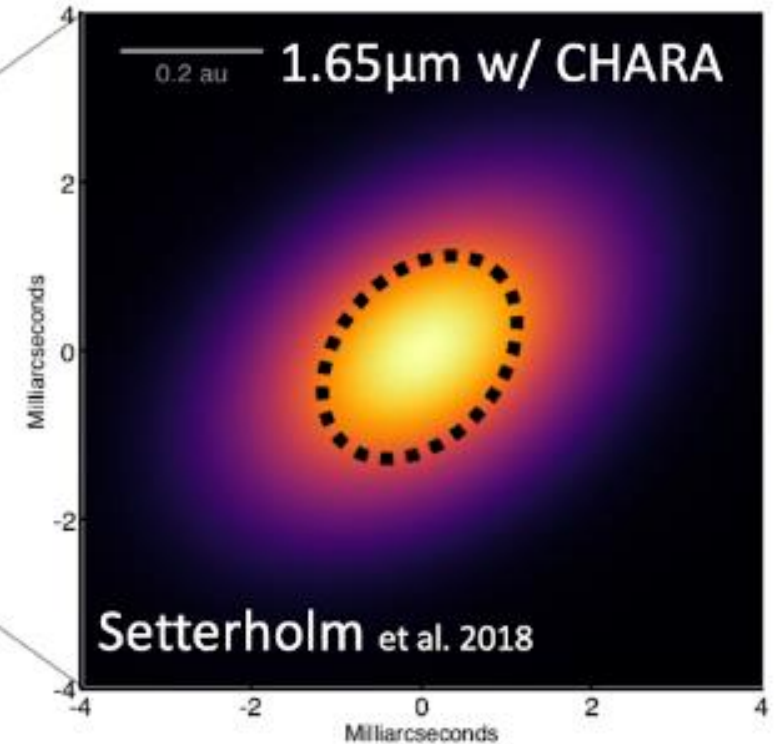
mm-wave imaging



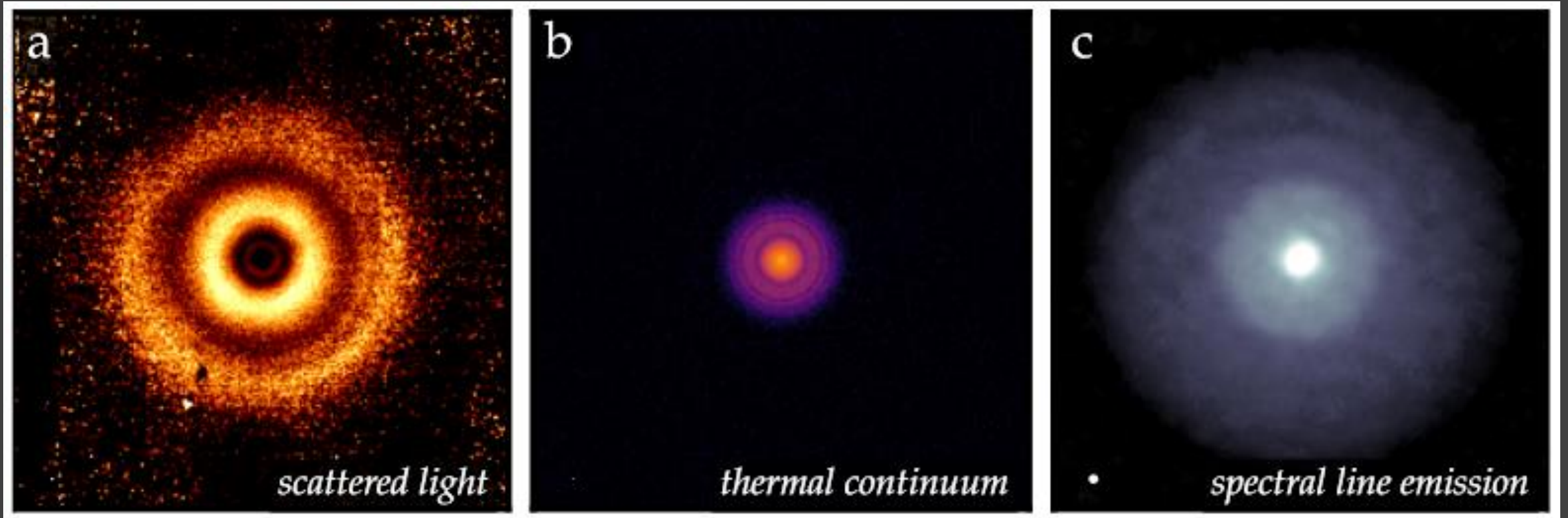
8+m telescope coronagraphy



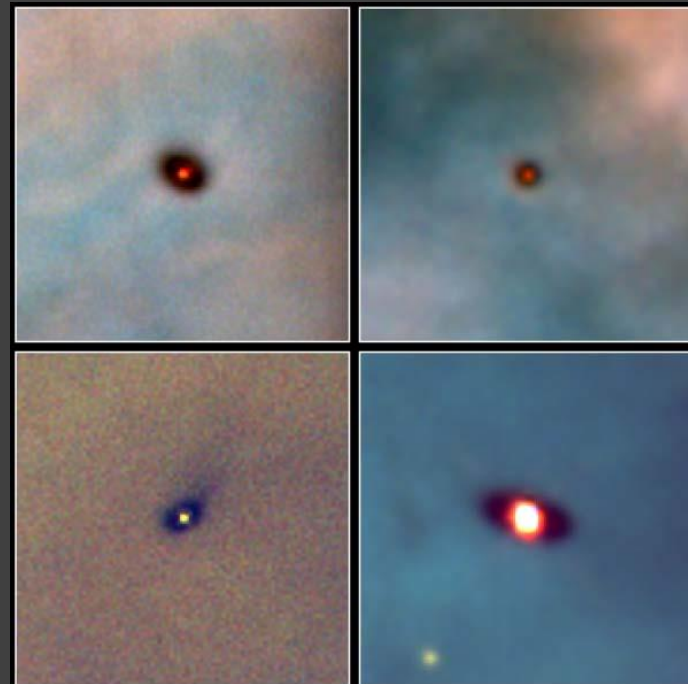
IR interferometry



Different structures in different light



Protoplanetary discs

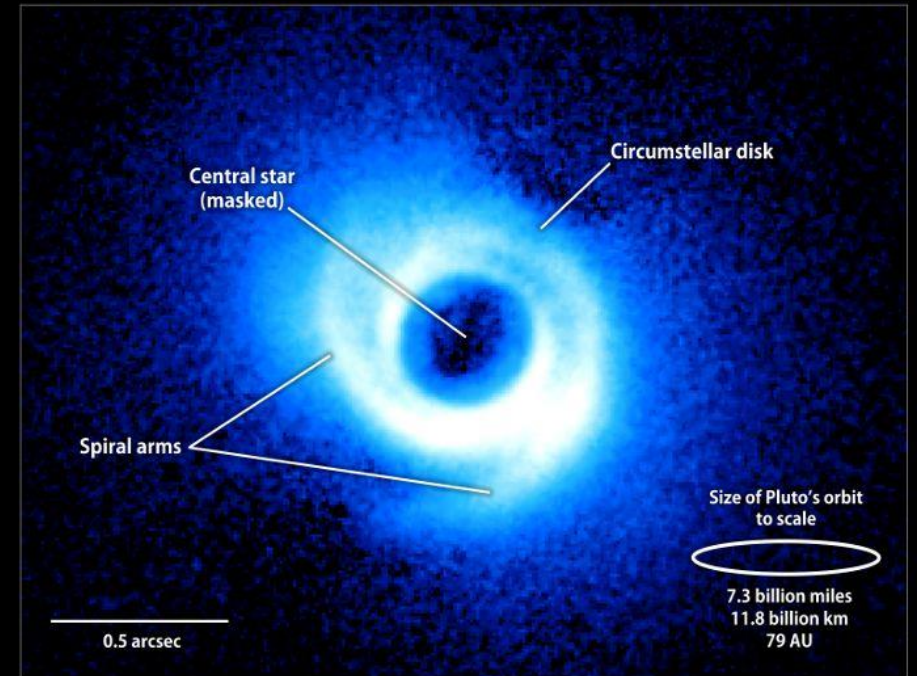


**Protoplanetary Disks
Orion Nebula**

PRC95-45b · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

HST · WFPC2

Spiral features revealed in SAO 206462's dust disk



https://online.science.psu.edu/astro140_sp201314wd001/node/7717

<http://news.softpedia.com/news/Exoplanets-Can-Form-Spiral-in-Stellar-Protoplanetary-Disks-228792.shtml>

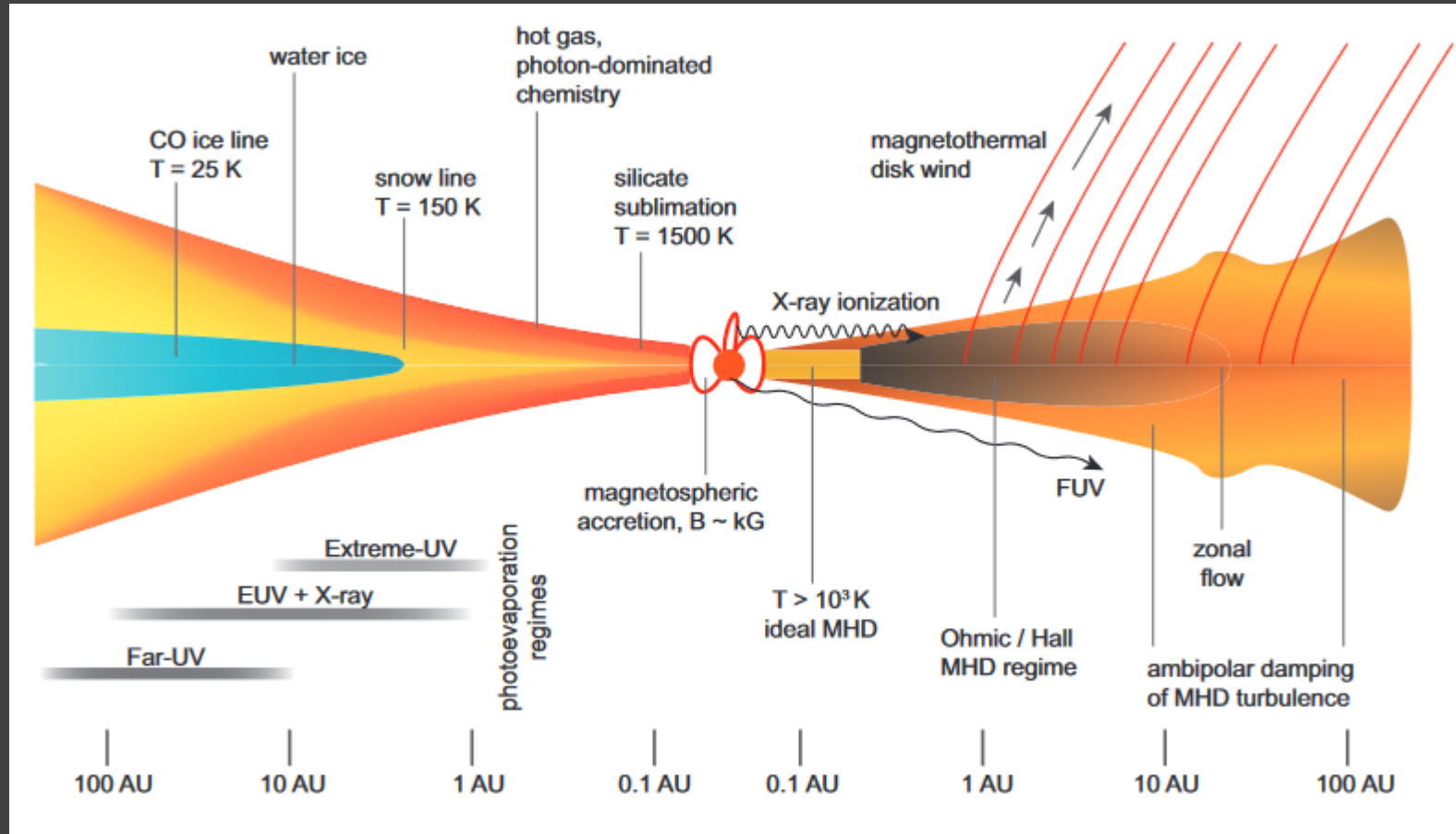
Dusty discs



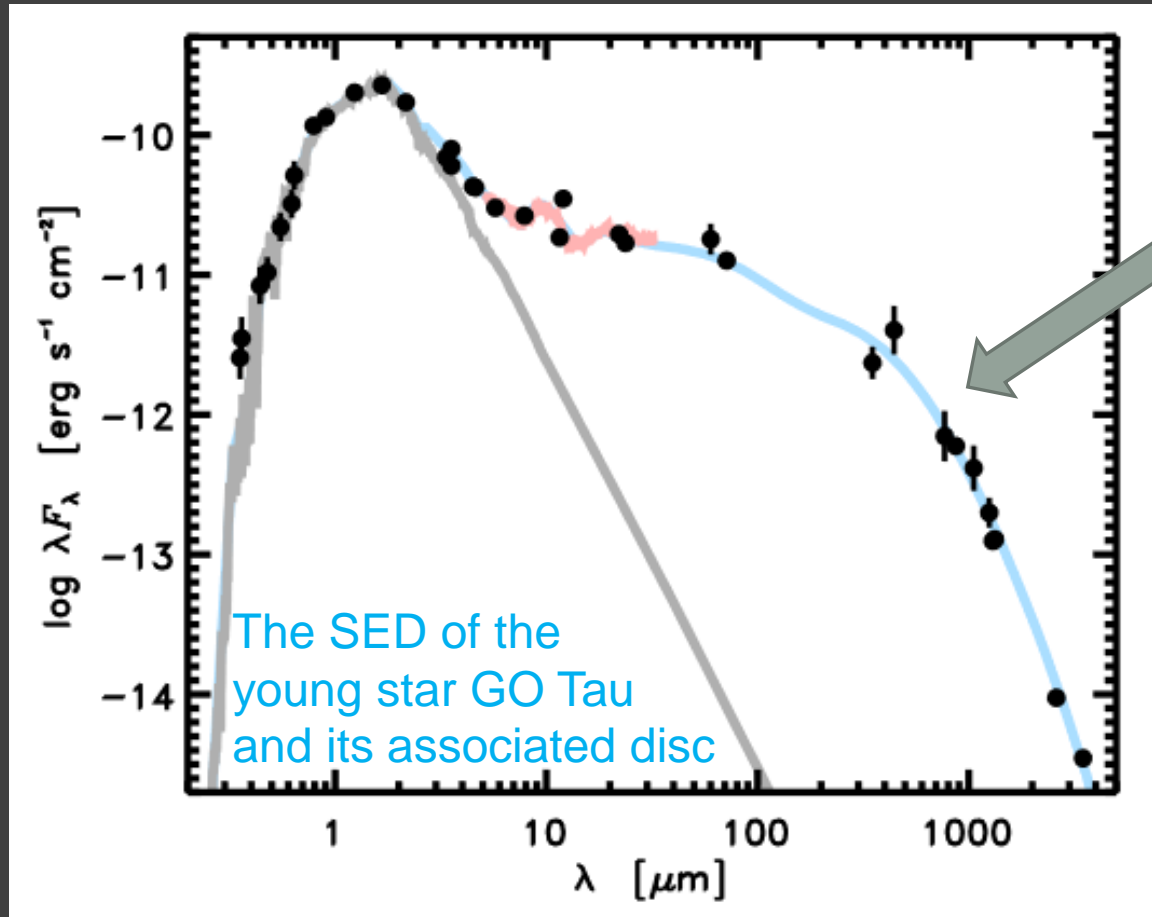
Disc is visible edge-on.

HST observations

Disc structure



Discs and stars



Optically thin disc.
Allows to determine dust mass.

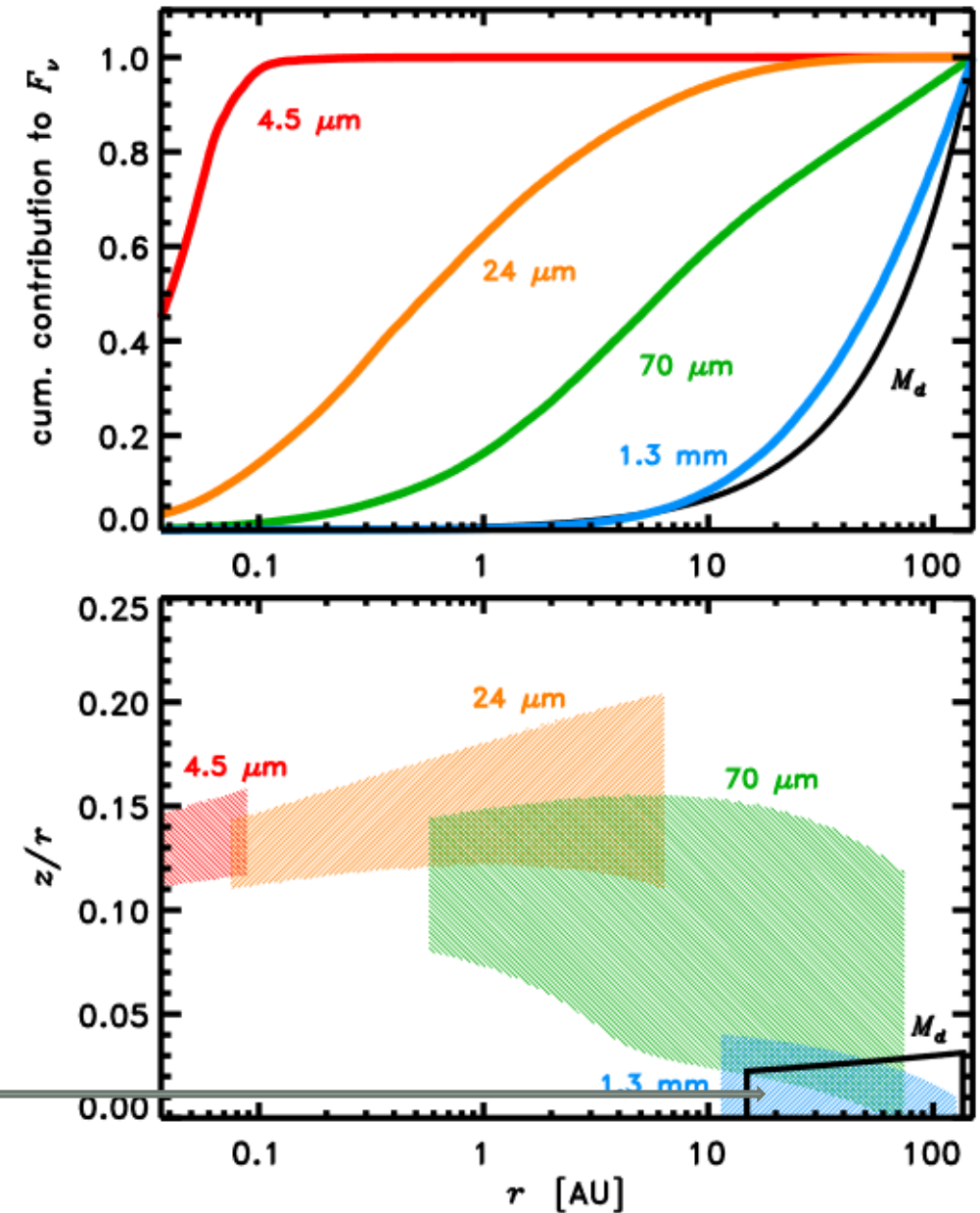
$$M_{\text{dust}} = \frac{F_{\text{v}} d^2}{\kappa_{\text{v}} B_{\text{v}}(T_{\text{dust}})},$$

See 1807.09631
about different methods
of dust mass determination

$$M_{\text{dust}} \propto M_{\text{star}}^{1.8}.$$

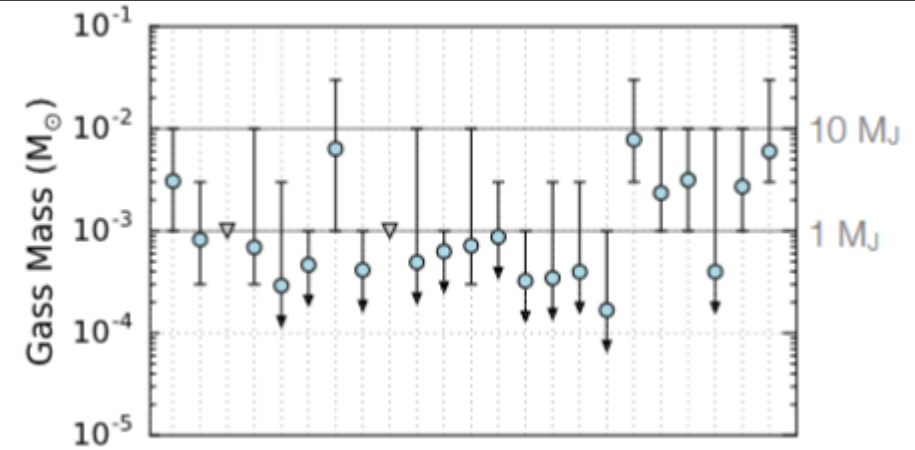
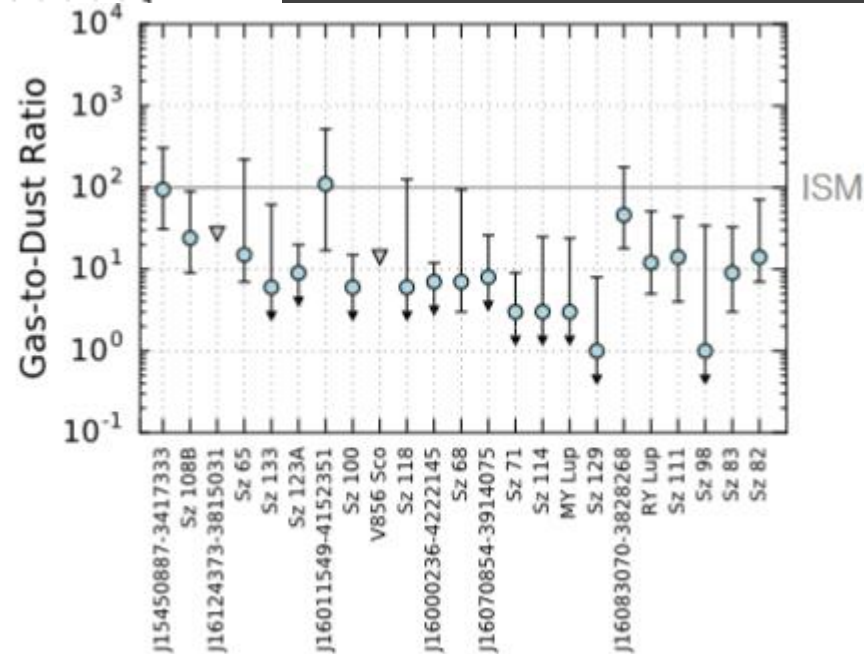
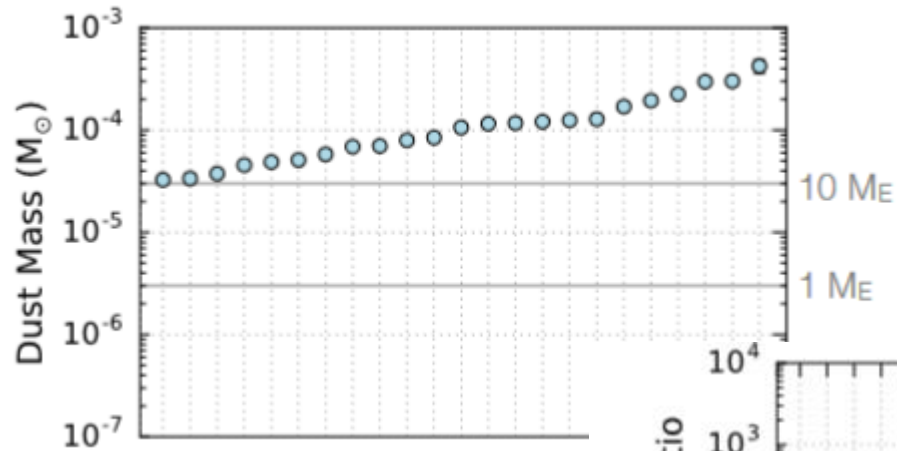
Dust in the disc

Observations in different wavelengths allow to probe different parts of the disc and determine dust mass and distribution.

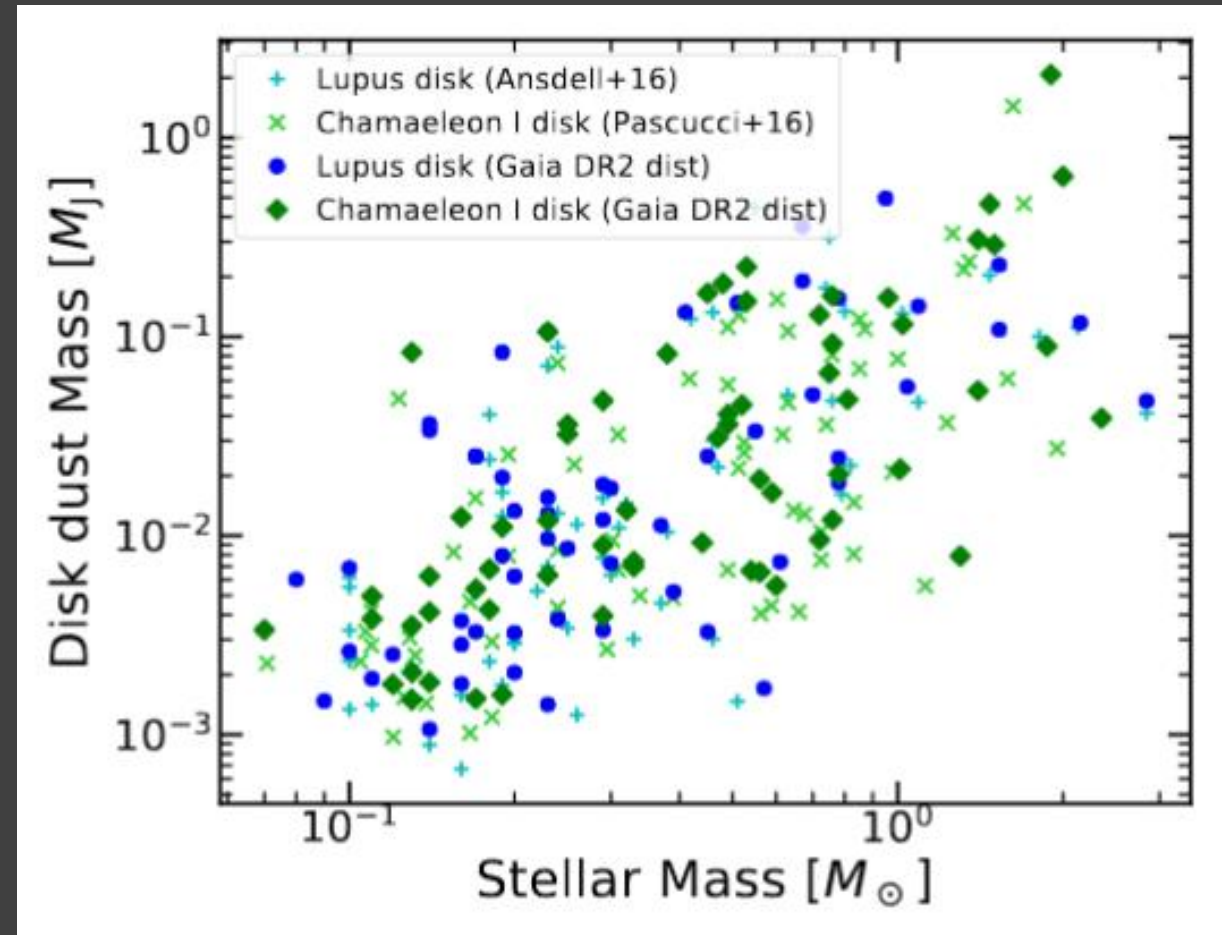
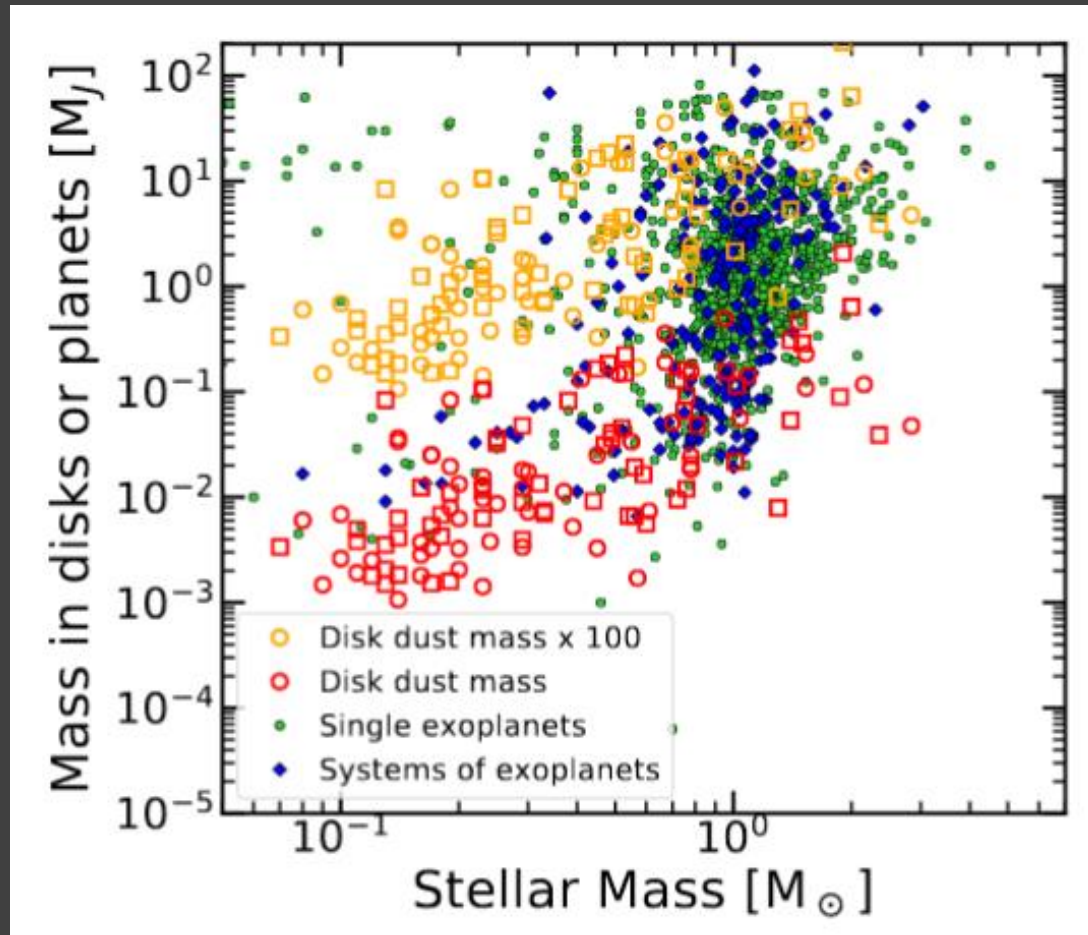


80% of dust

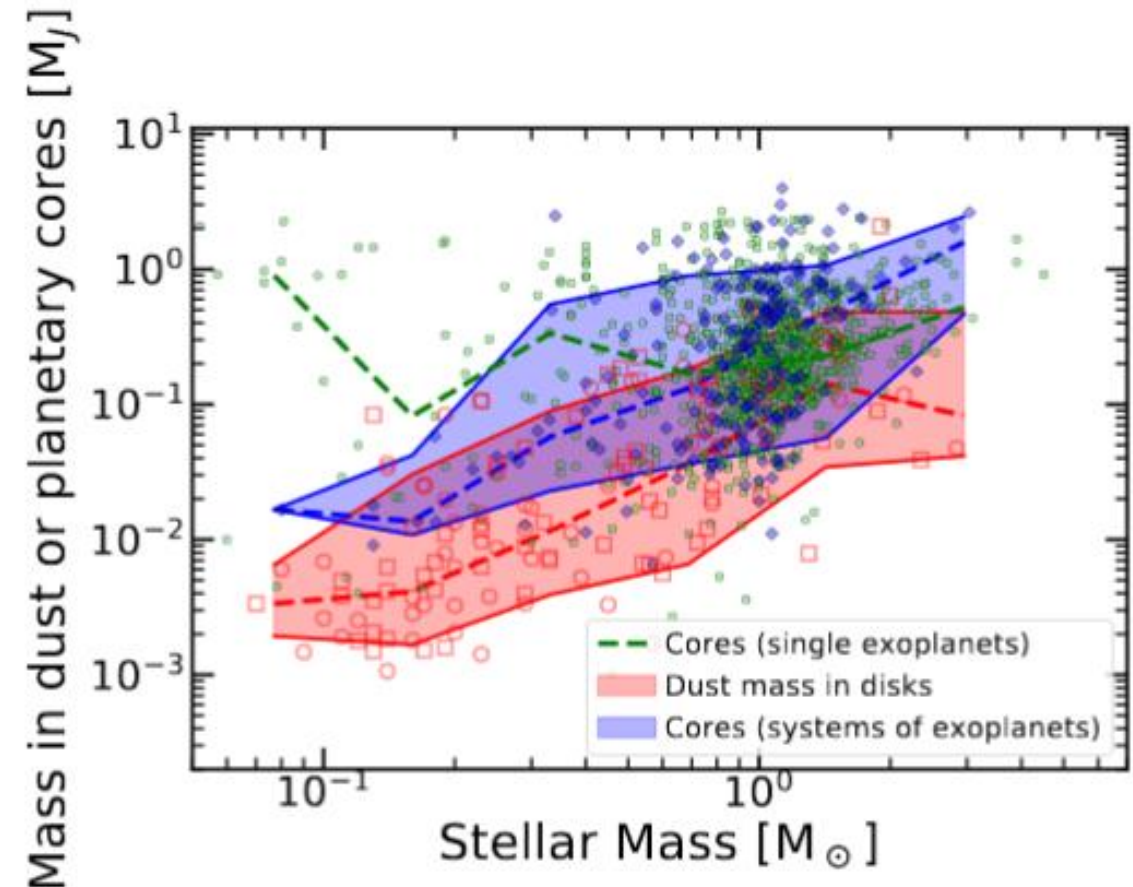
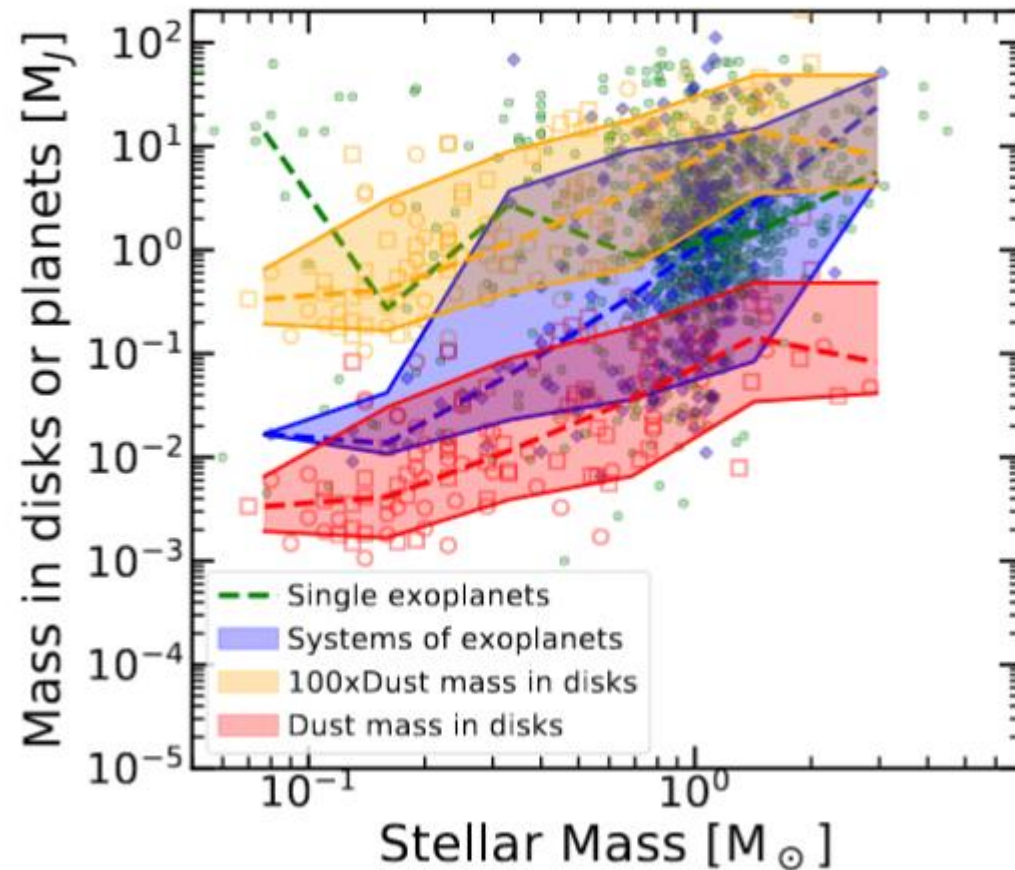
Disc mass: gas + dust



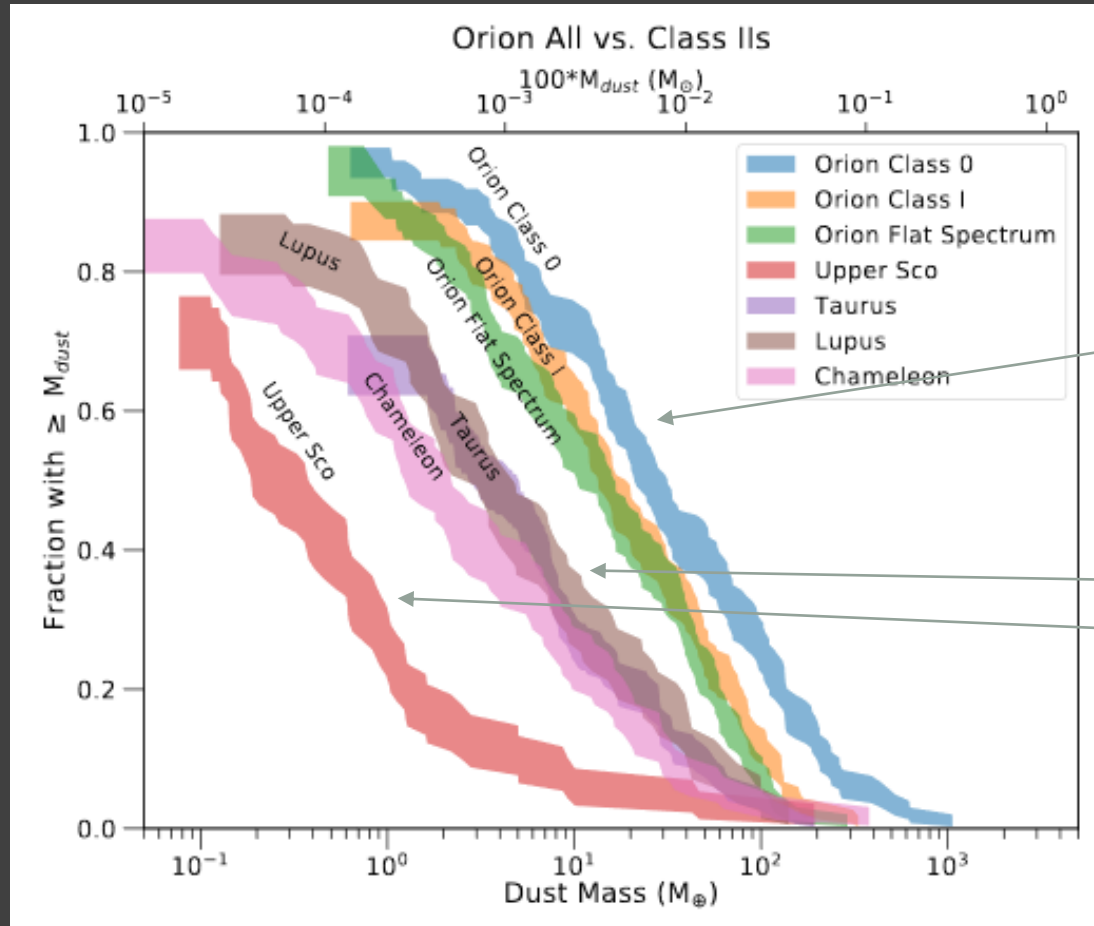
Disc mass vs. star mass



Disc and planet mass correlations with the stellar mass



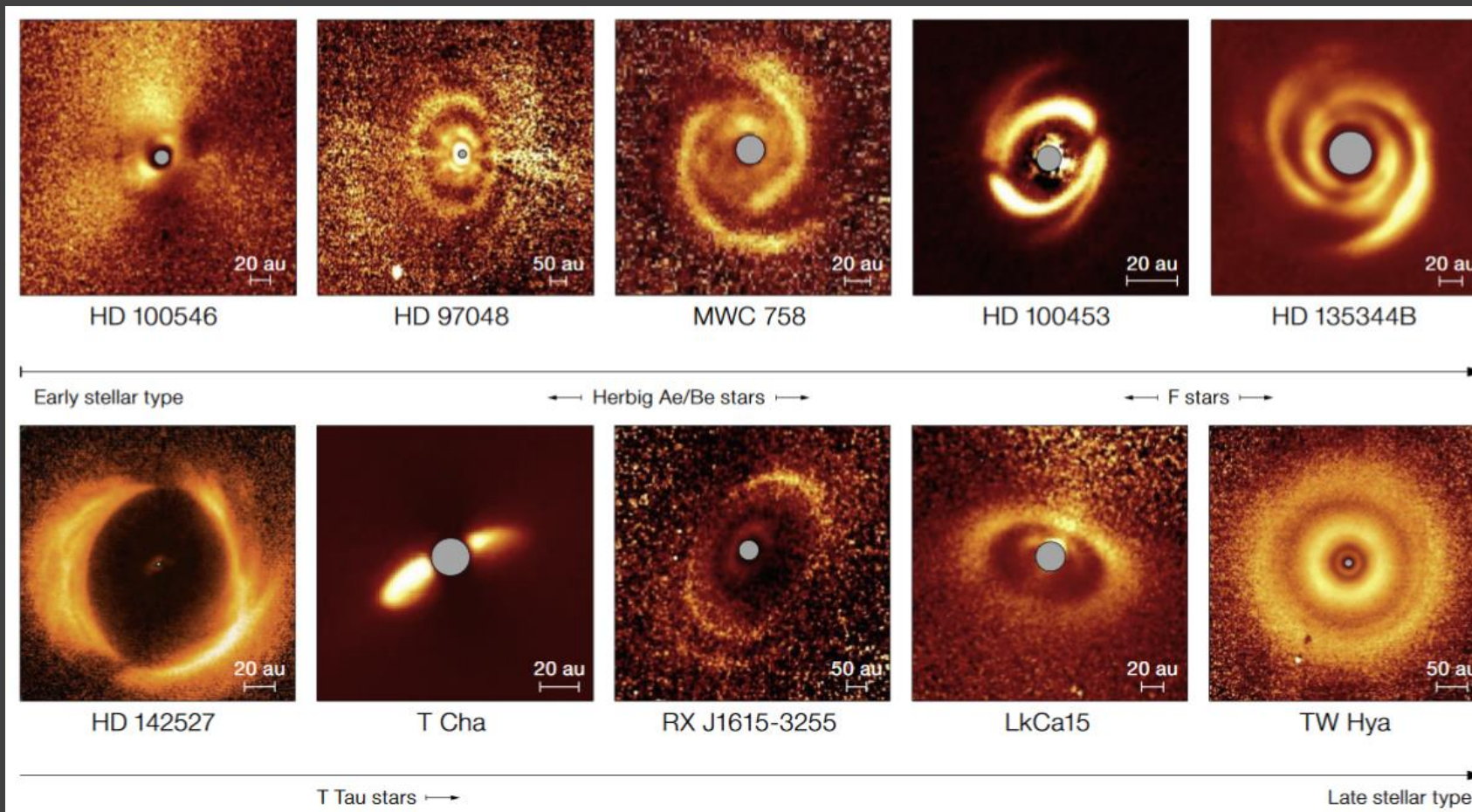
Indeed, evolution, baby



Young discs

Older discs

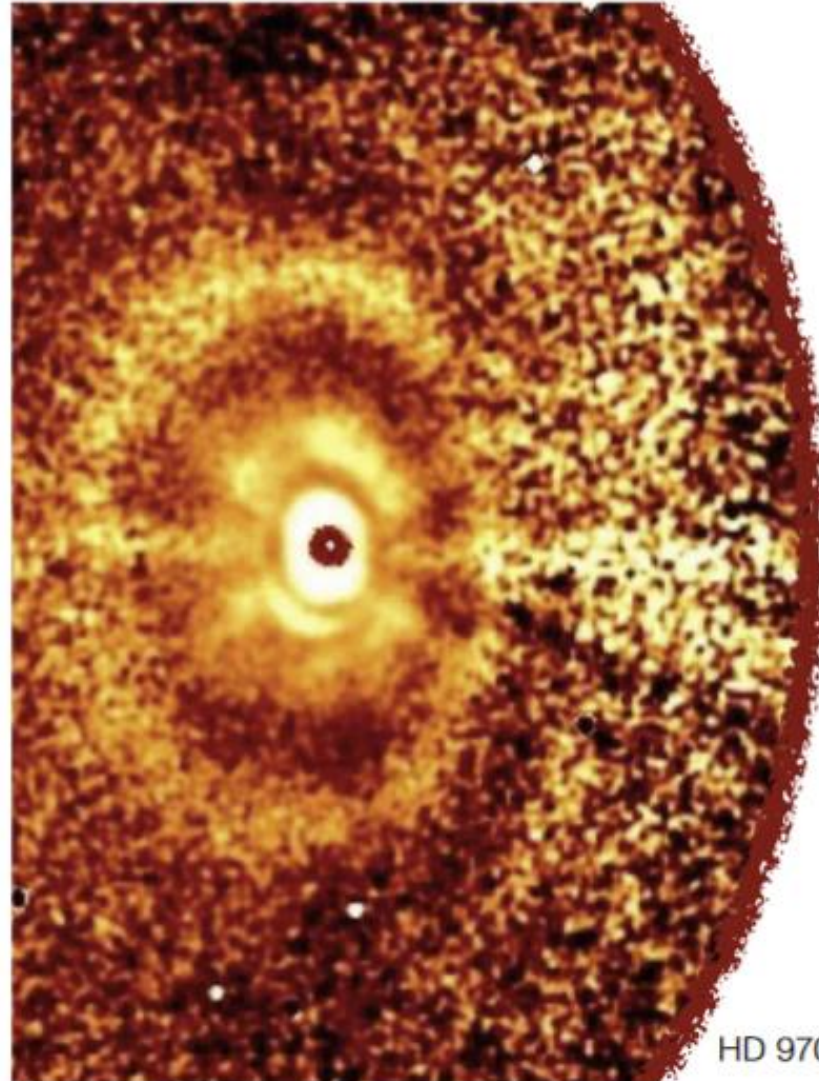
VLT/SPHERE



0.5-2.3 micrometers

1710.02795

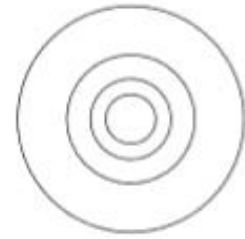
PDI images are sensitive to micron-sized dust grains at the disc surface



HD 97048



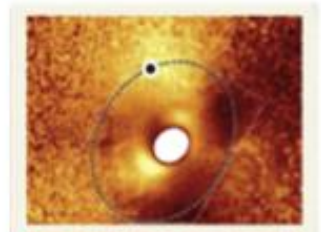
Outer
Solar System



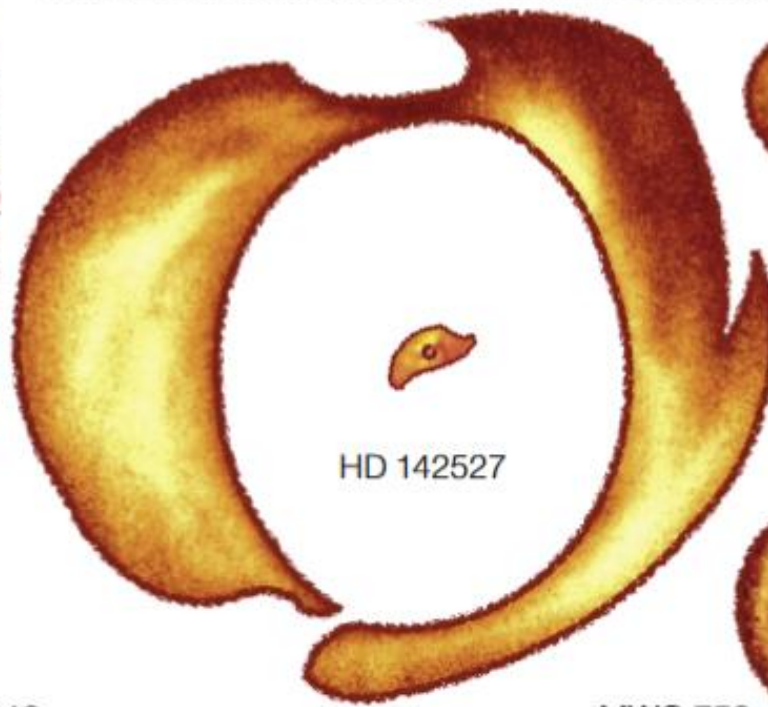
HR 8799



Kepler transits



HD 100546b



HD 142527



LkCa15



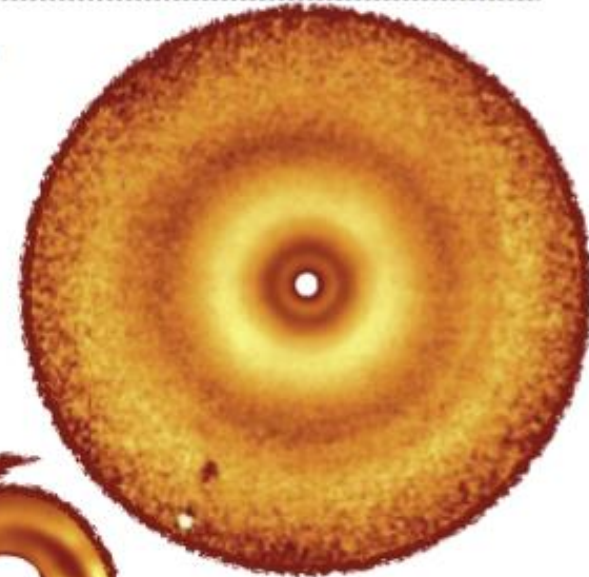
HD 100453



MWC 758


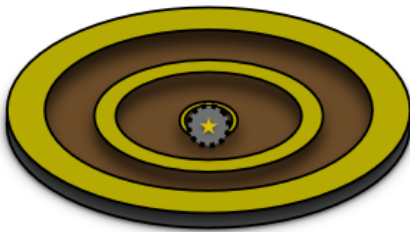

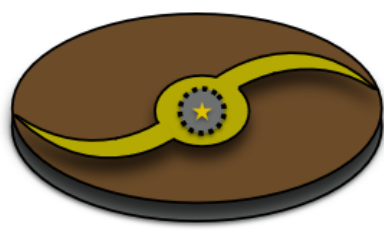




HD 135344B

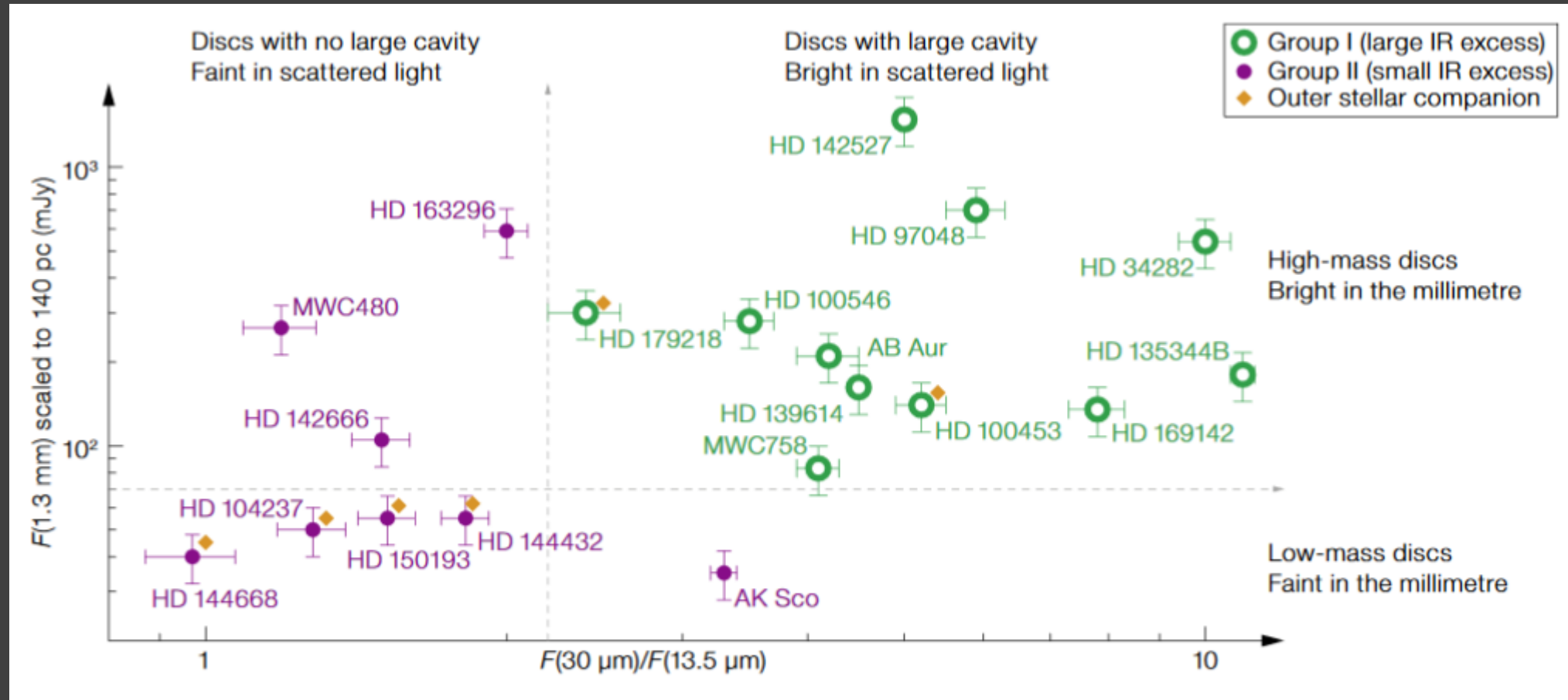


TW Hya

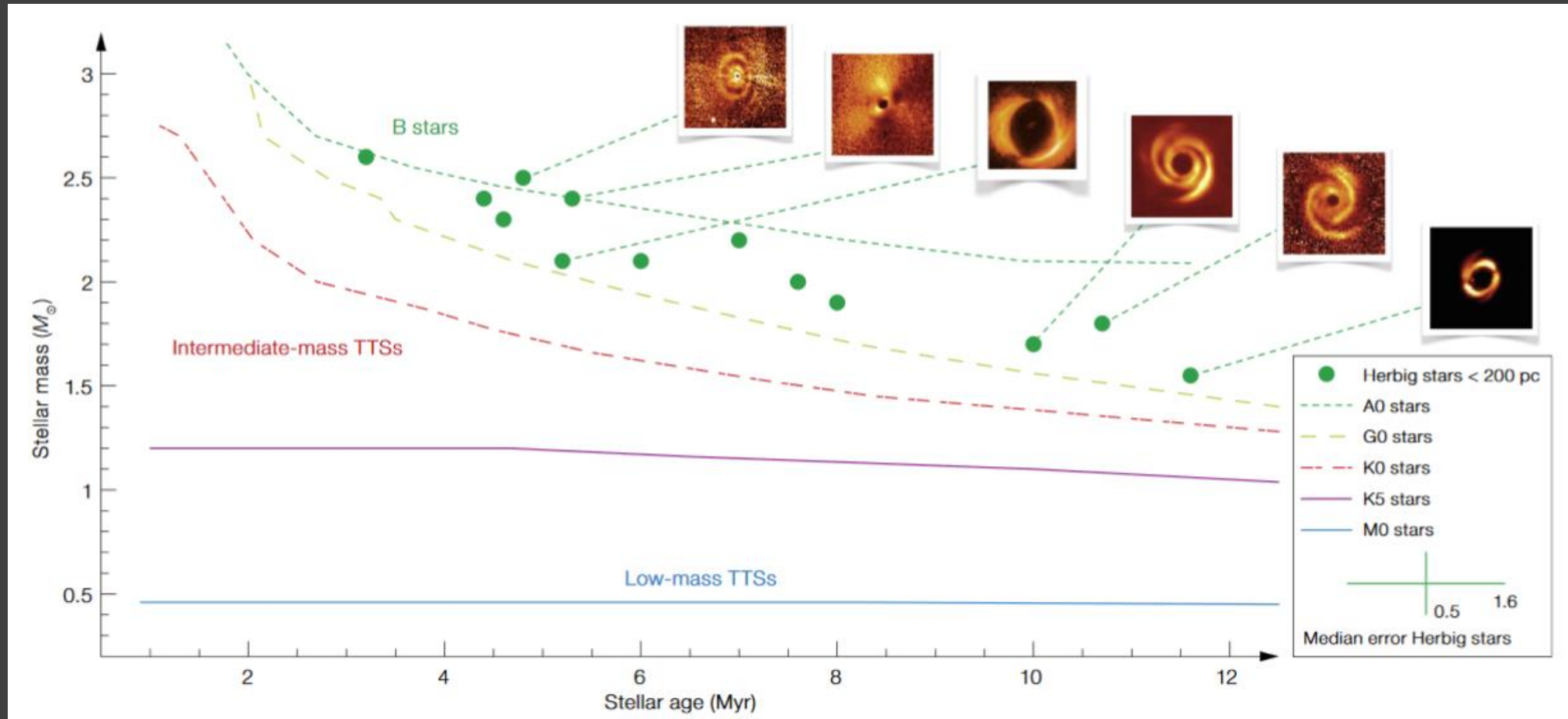
Structures in discs

<p>🎯 Rings</p>  <p>Multiple symmetric, bright annuli. <i>Prototypes: TW Hya, HD97048.</i></p>	<p>✗ Spirals</p>  <p>Symmetric, bright spirals on small scale. <i>Prototypes: HD135344B, MWC758.</i></p>	<p>◆ Giant</p>  <p>Wrapped, asymmetric arms on large scale. <i>Prototypes: HD100546, HD34282.</i></p>
<p>○ Rim</p>  <p>Mainly one ring around a cavity. <i>Prototypes: J1604, PDS70.</i></p>	<p>▲ Faint</p>  <p>Low signal. No feature visible. <i>Prototypes: RU Lup, MWC480.</i></p>	<p>● Small</p>  <p>Signal on very small scale. <i>Prototypes: HD150193, CS Cha.</i></p>

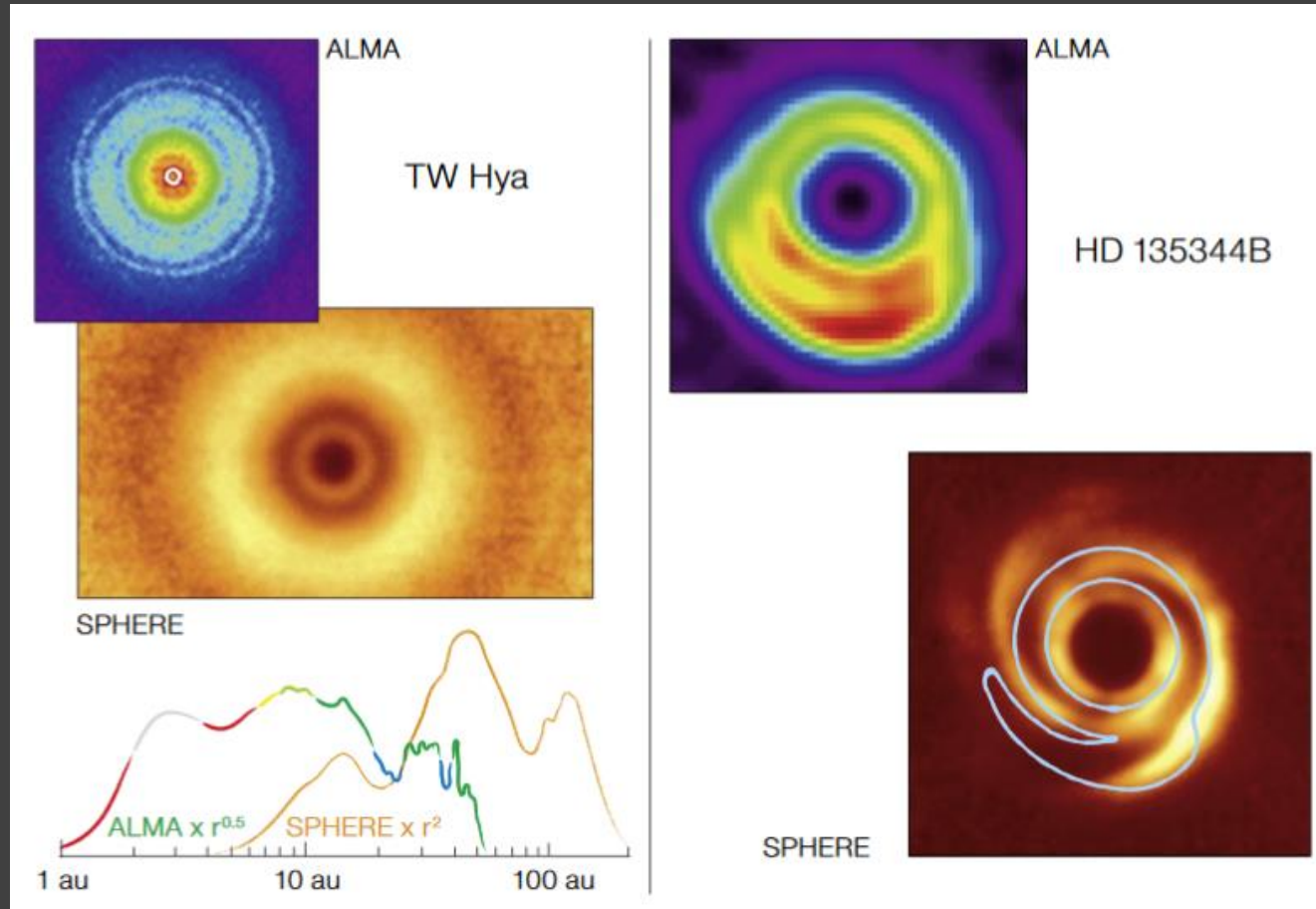
Different discs



Disc evolution

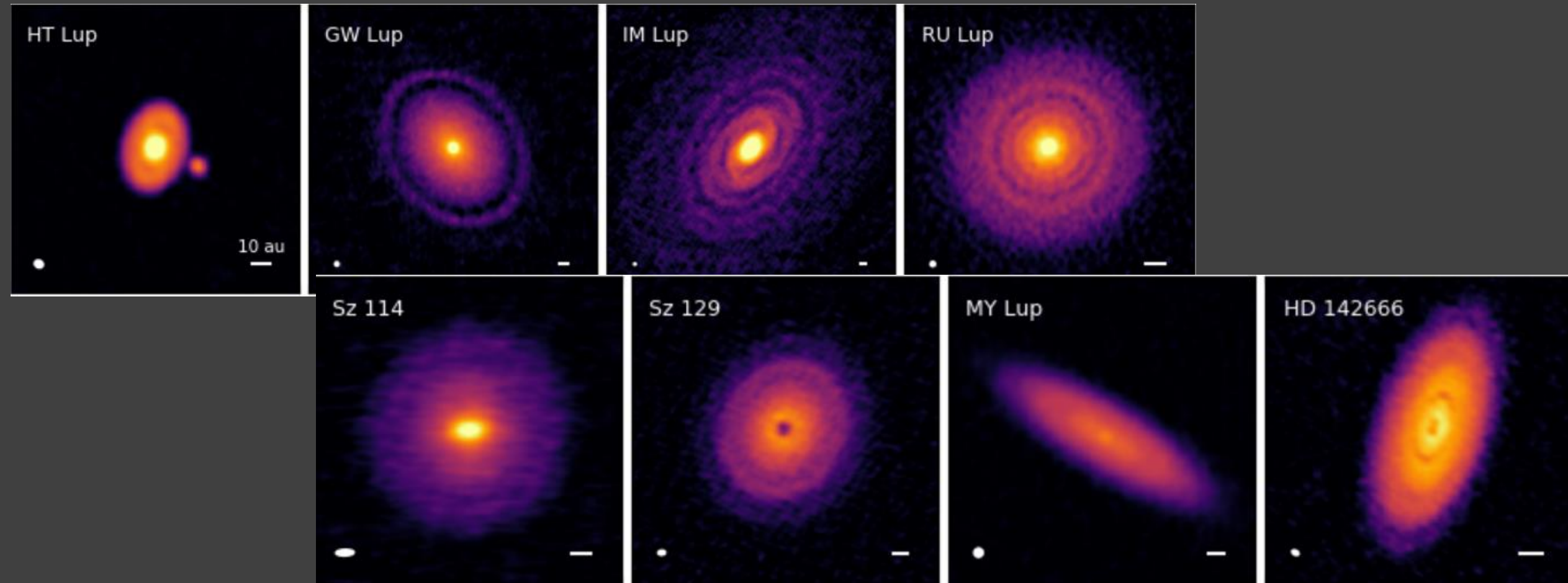


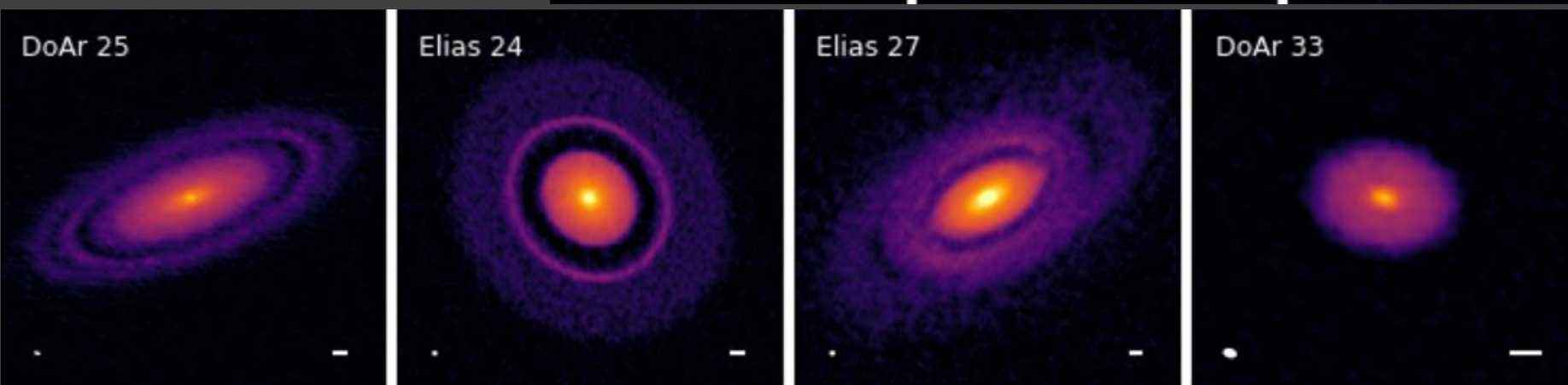
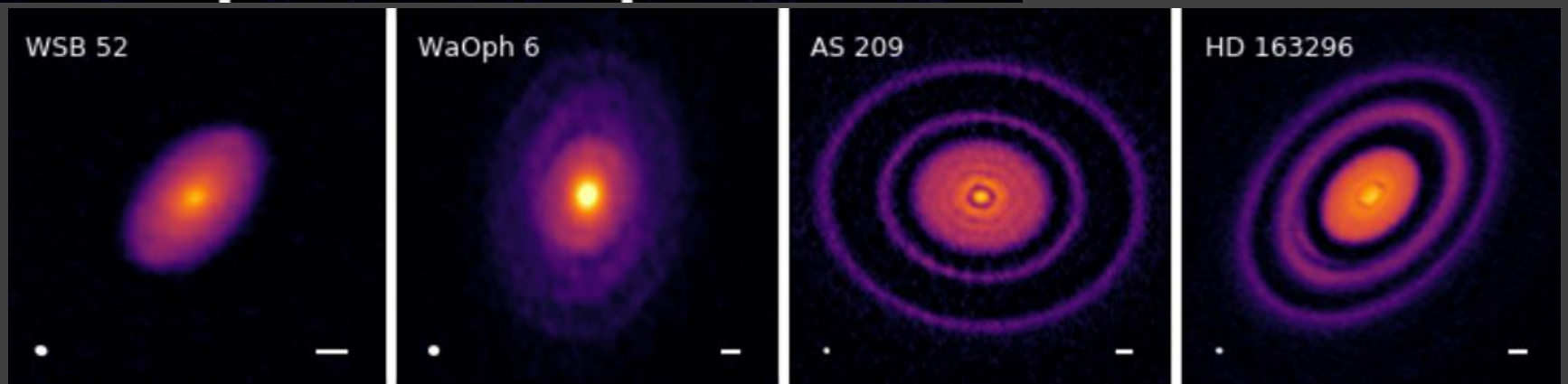
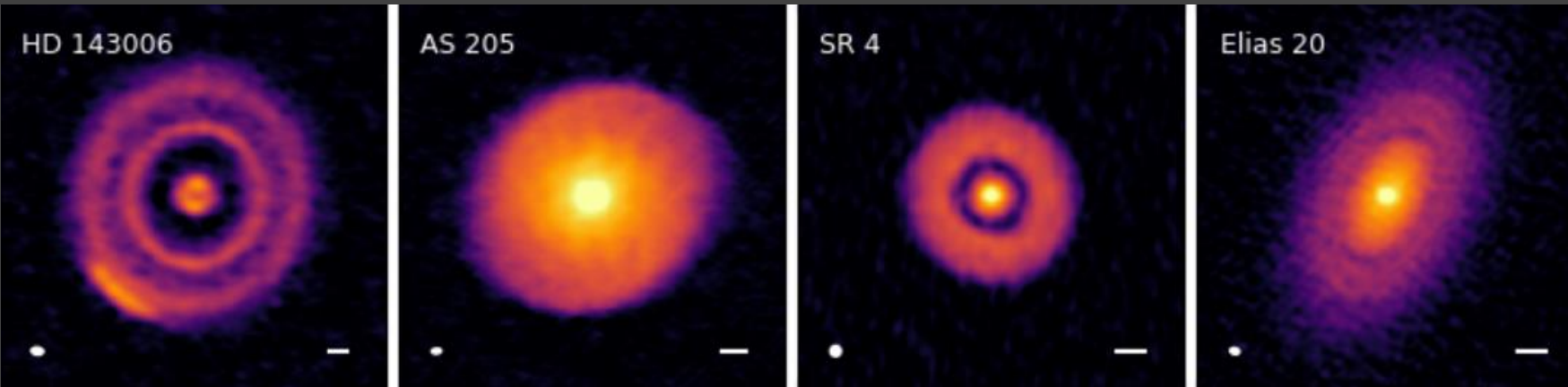
Different wavelengths – different dust



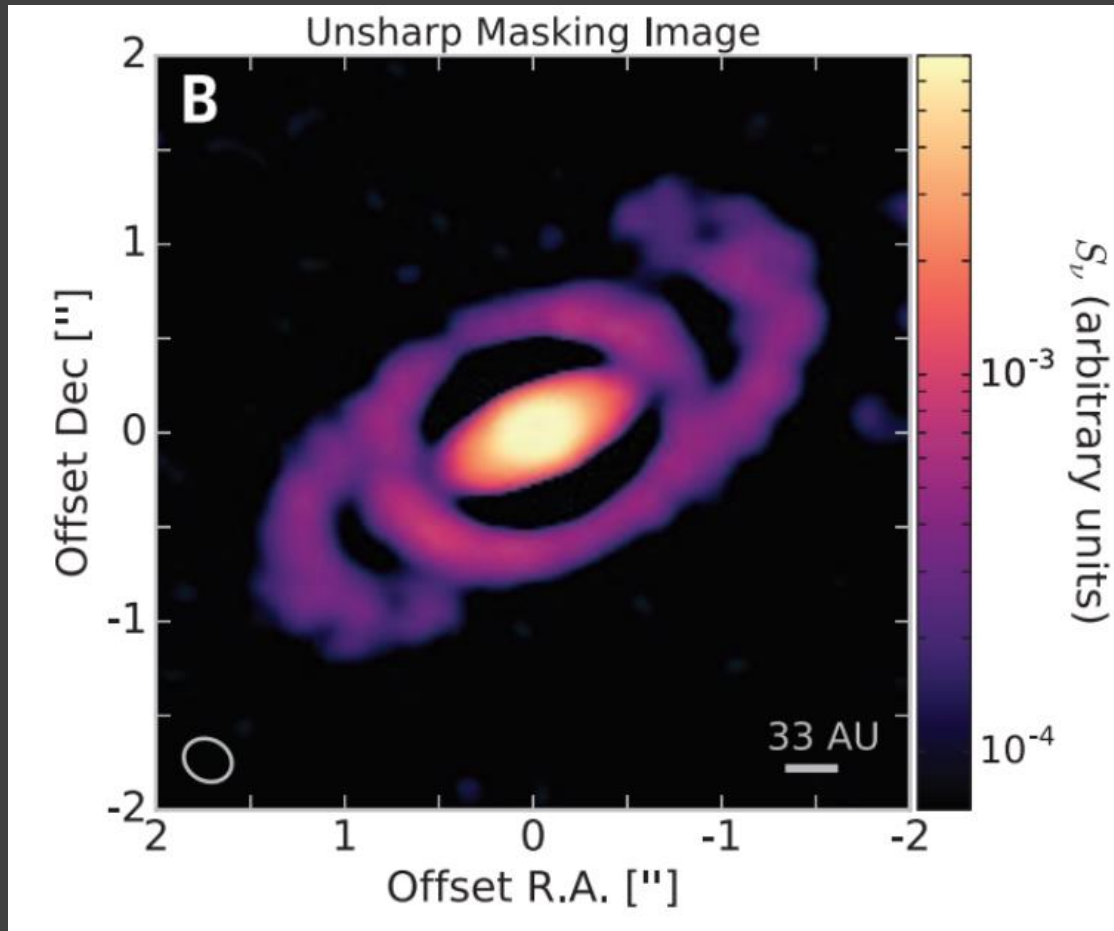
SPHERE – micron grains
ALMA – larger grains

ALMA gallery of discs





Disc around Elias 2-27



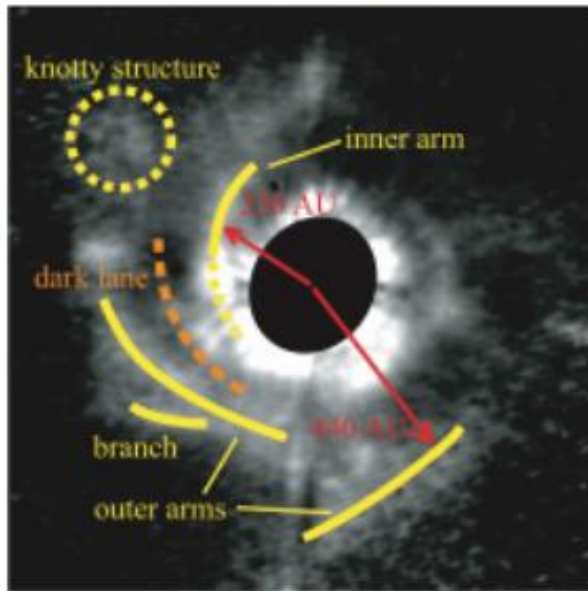
Spiral structure around Elias 2-27
Obtained by ALMA

The star has mass $\sim 0.5 M_{\text{solar}}$,
but a very massive disc ($> 0.1 M_{\text{solar}}$) around.

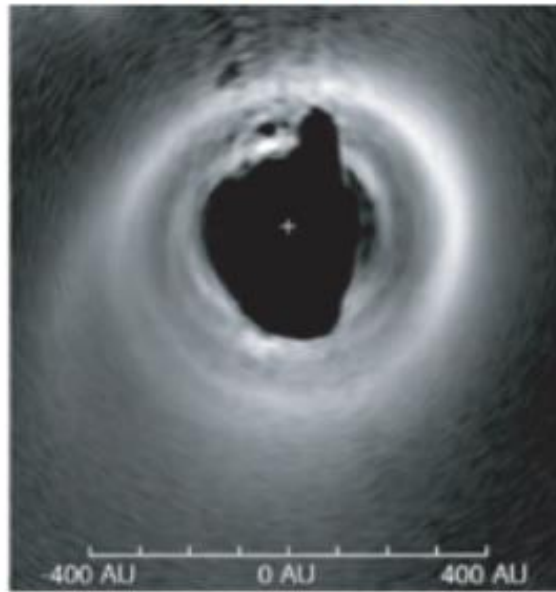
It is important that at distance > 10 AU
the disc is transparent for 1.3 mm emission.
So, the spiral pattern is related to the matter
also in the disc midplane.

Gallery of spirals

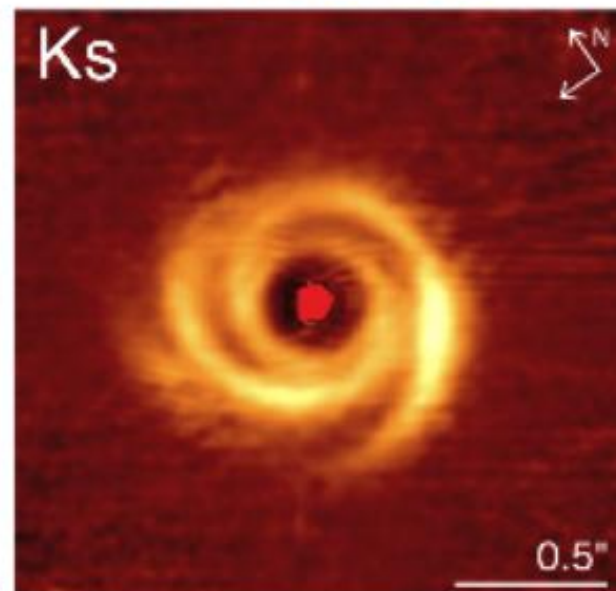
AB Aur



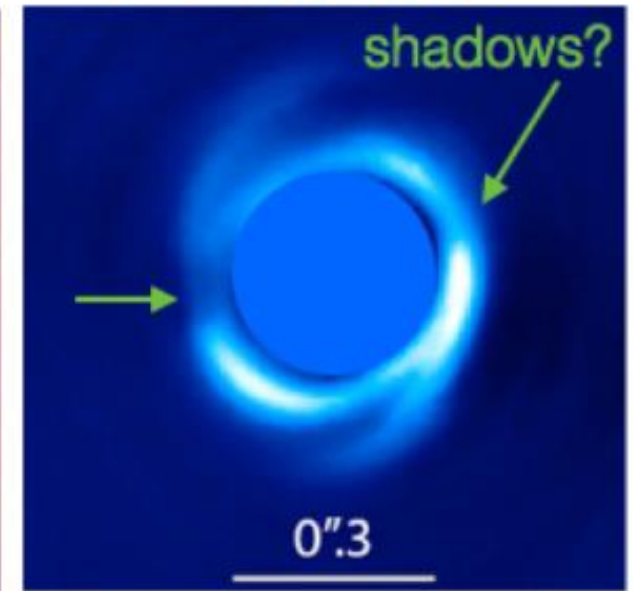
HD 141569A



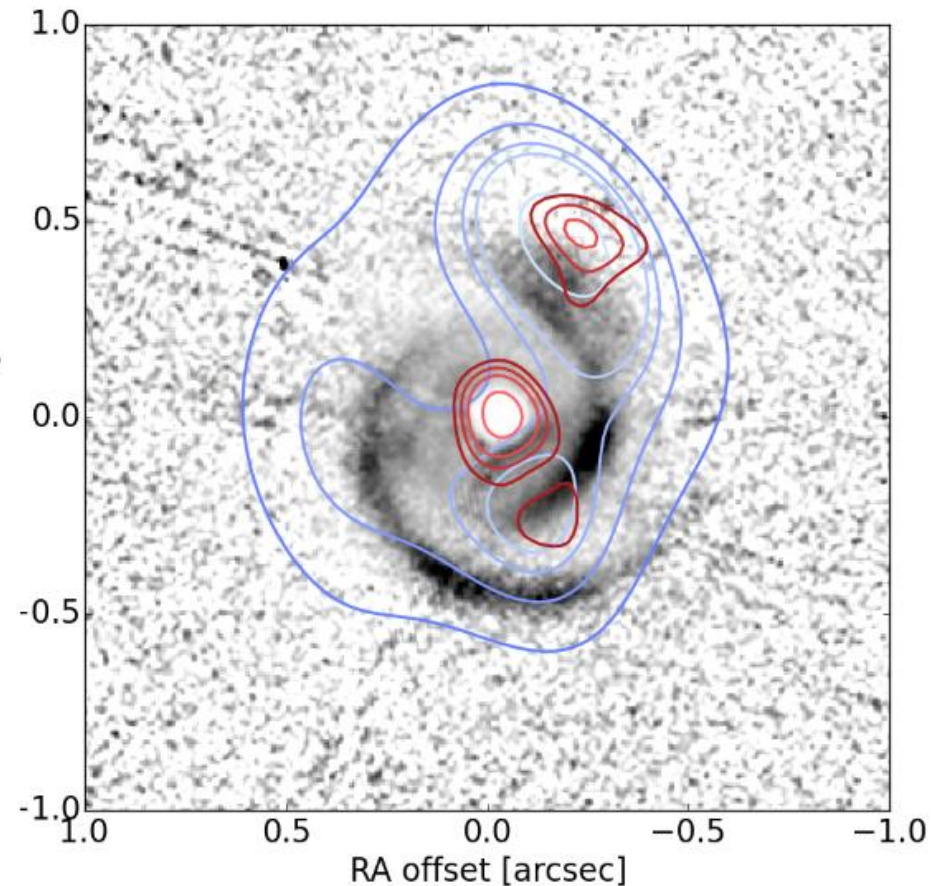
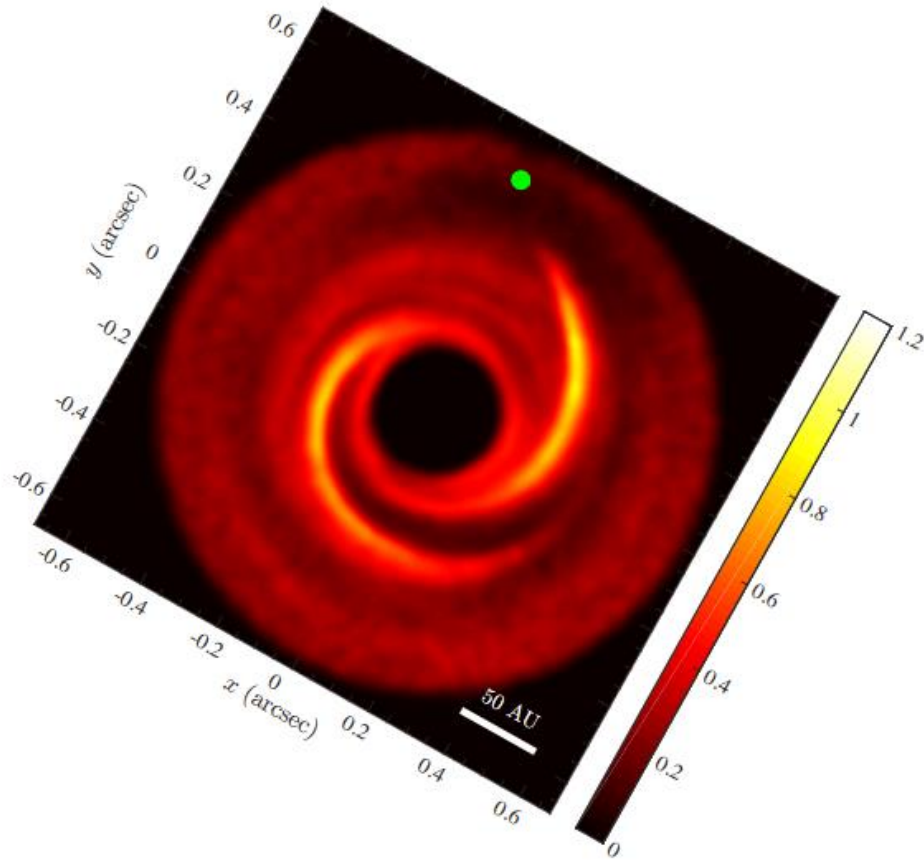
HD 135344B



HD 100453



Spirals: model and observations



MWC 758

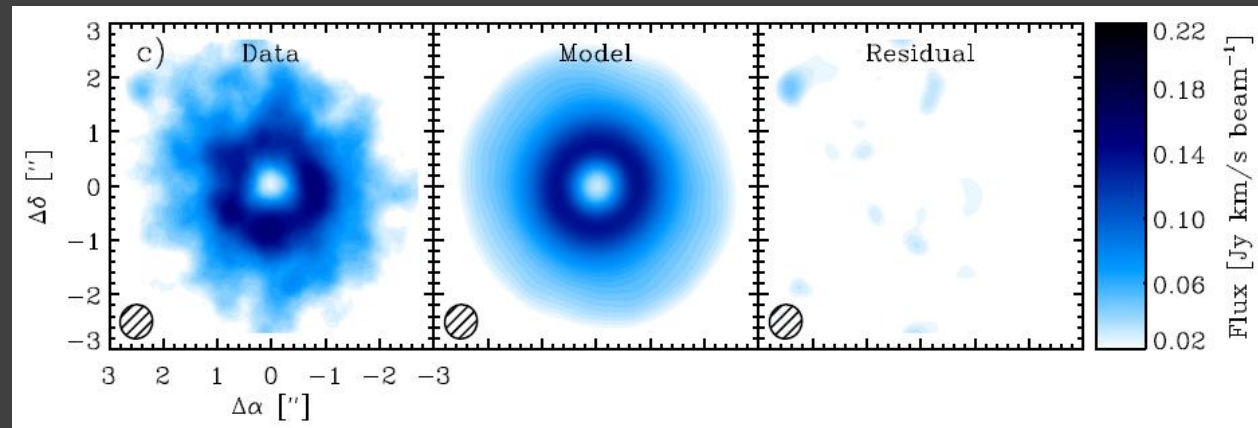
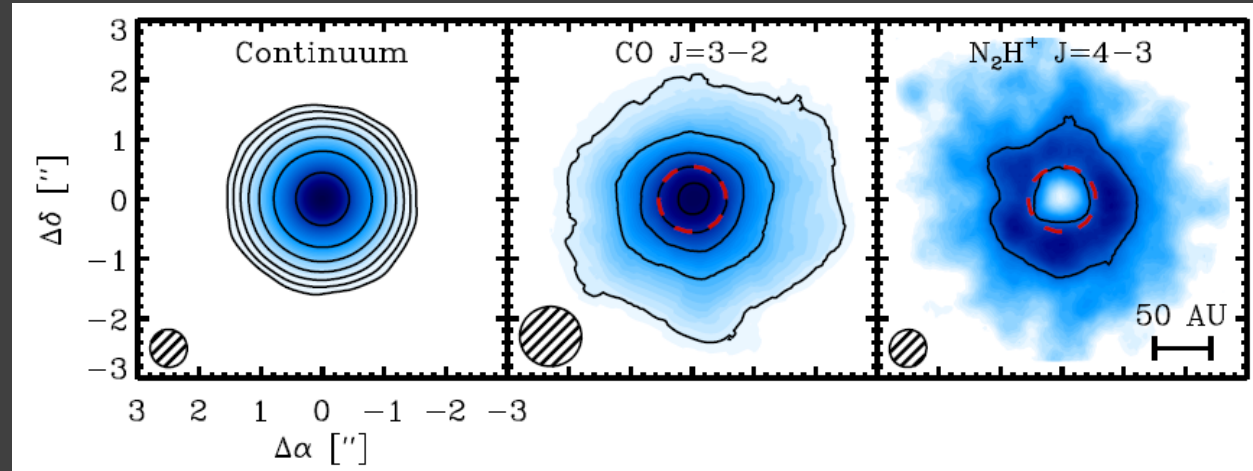
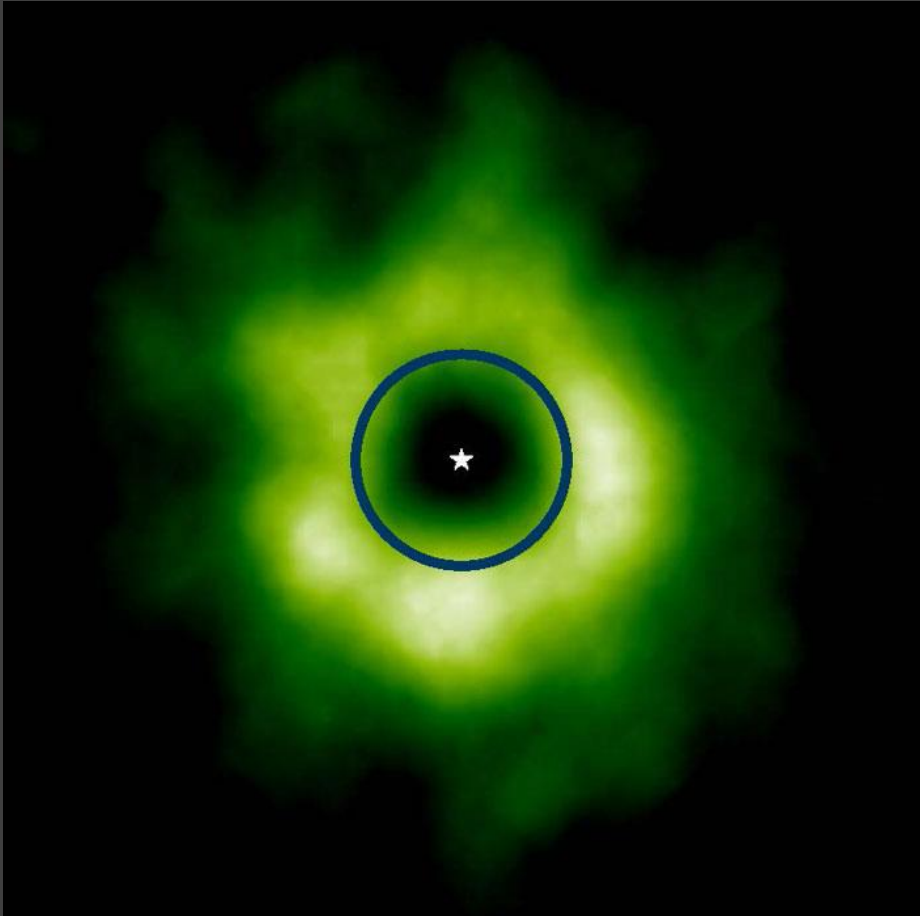
Left: model

Right: VLA+ALMA+SPHERE

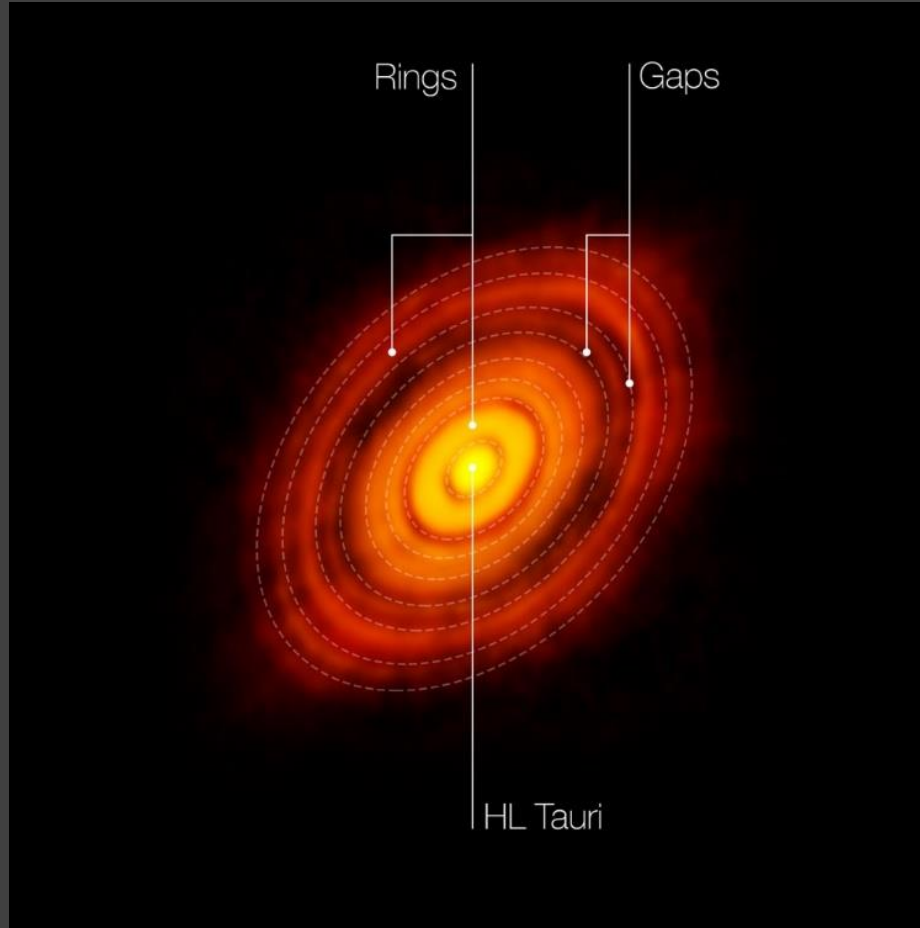
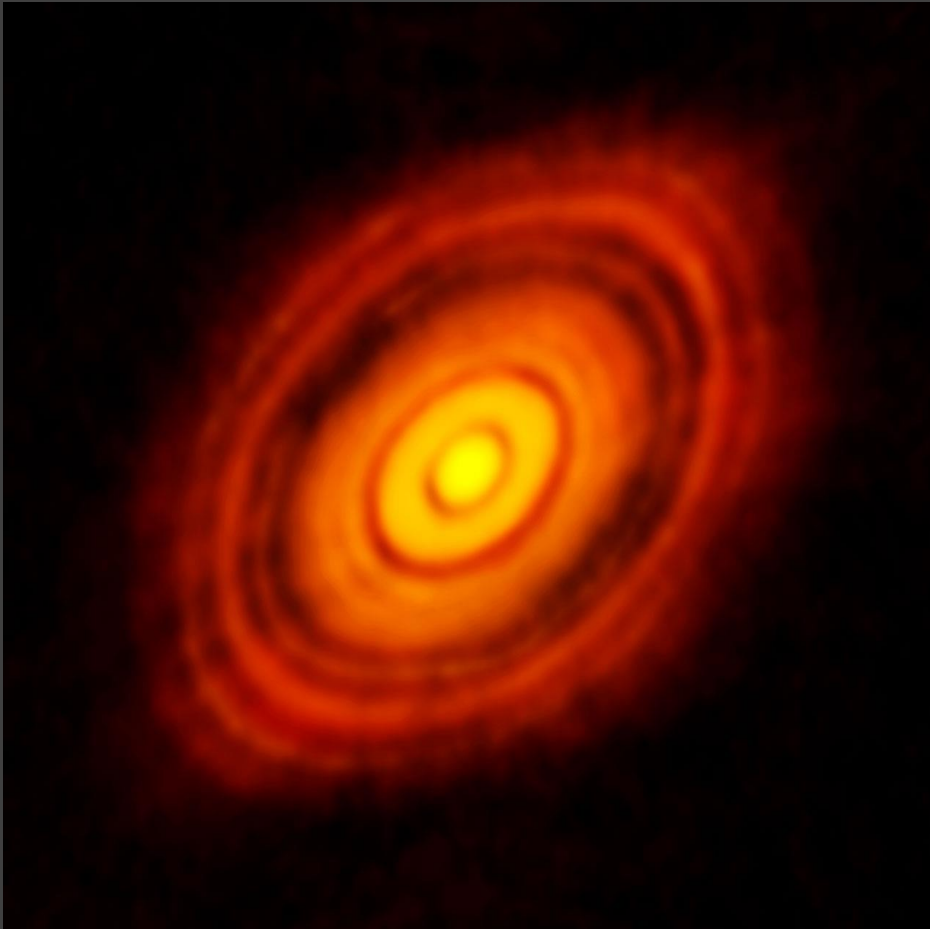
1602.06523, see new data in 1907.06655

TW Hydra

N_2H^+ visible only if CO is frozen out

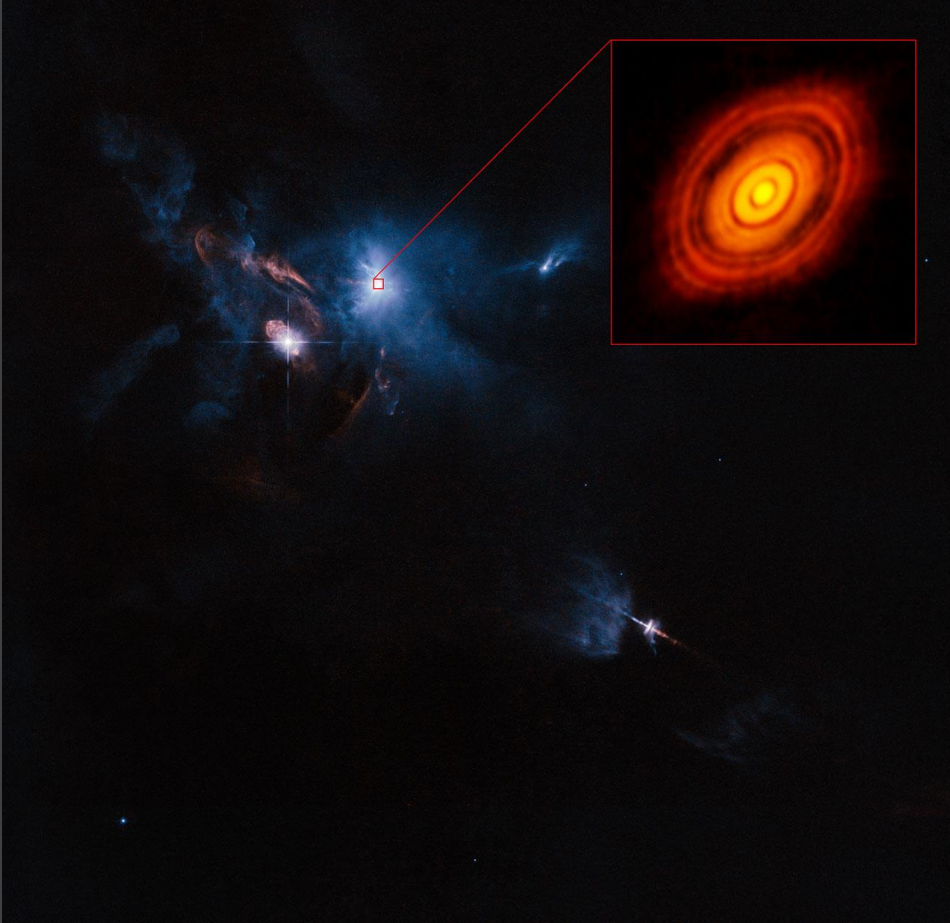


Protoplanetary disc of HL Tau

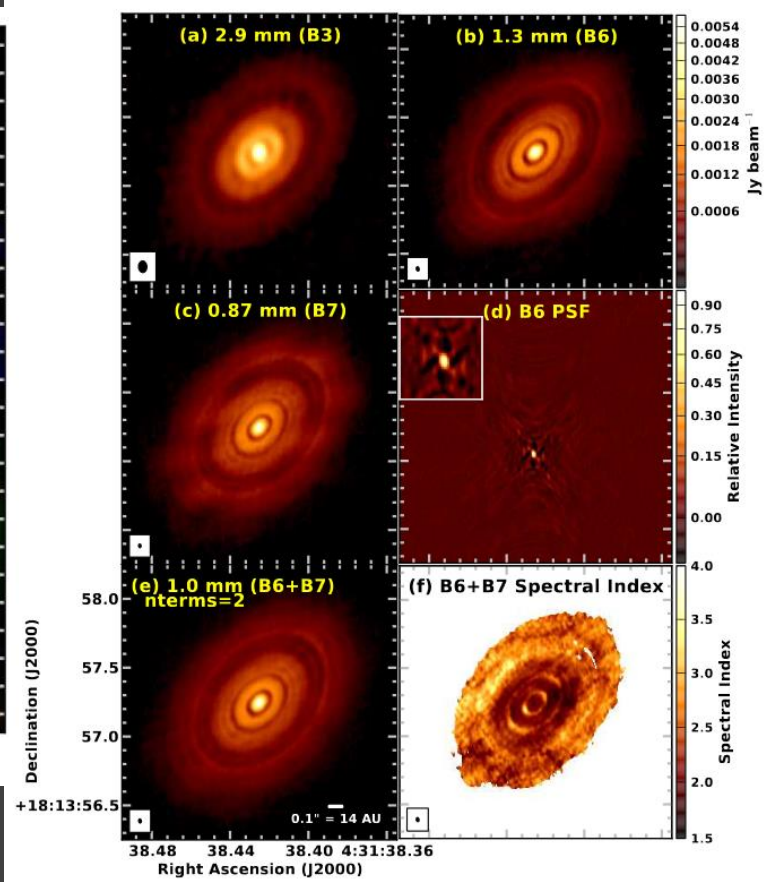
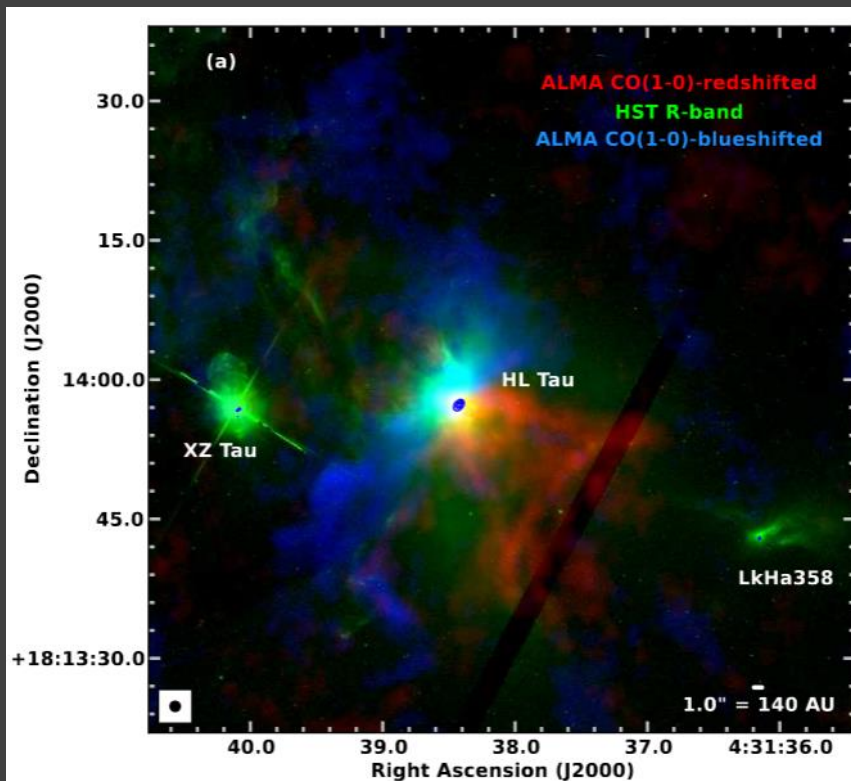


140 pc
Massive disc
Jet
Age <1-2 Myrs

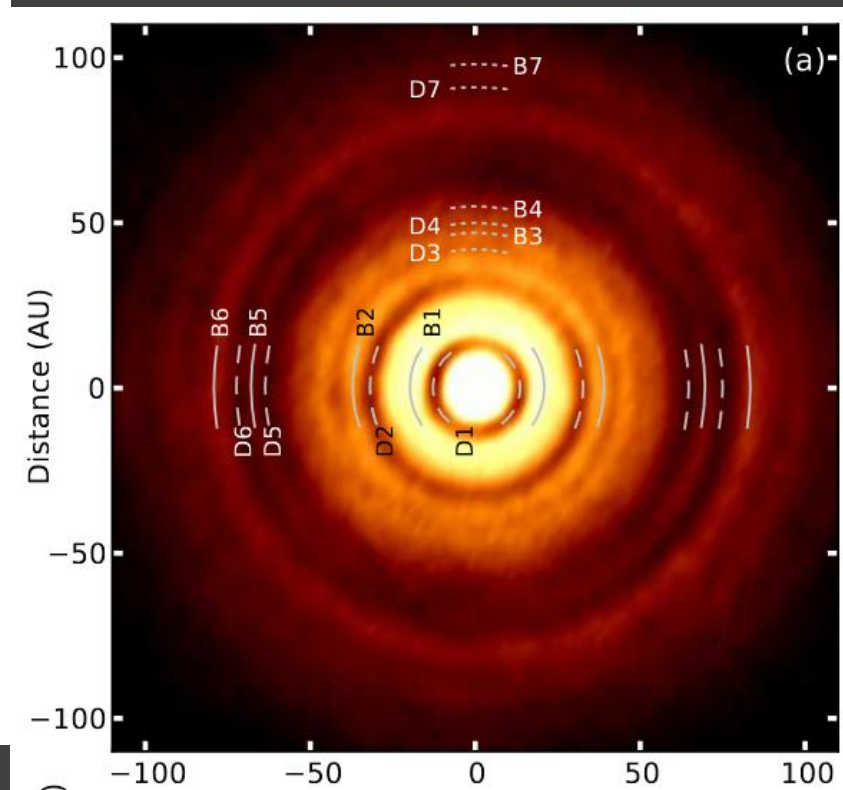
Where stars are born



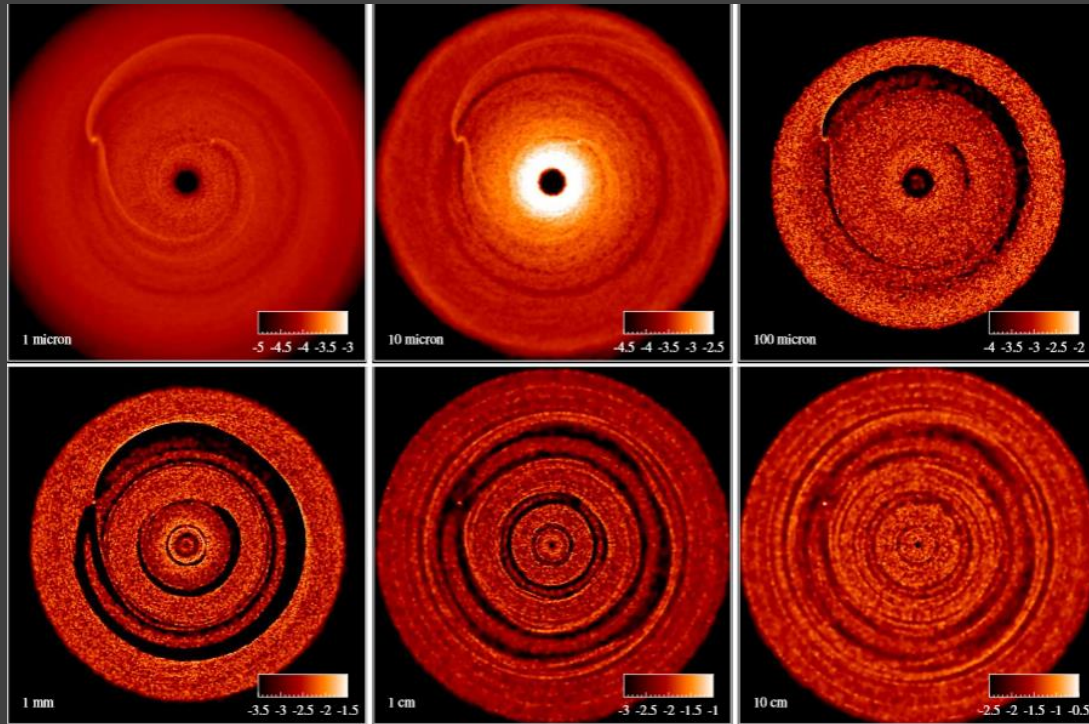
More details on the disc of HL Tau



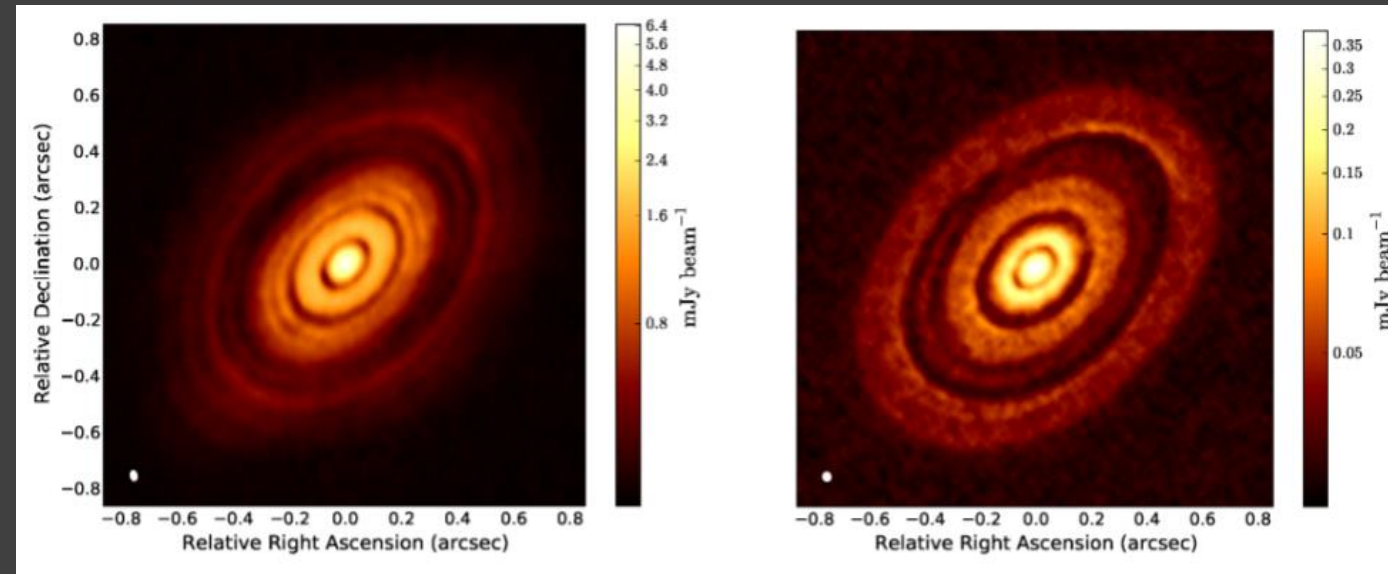
Some rings are in resonance with each other.



Modeling of the HL Tau disc



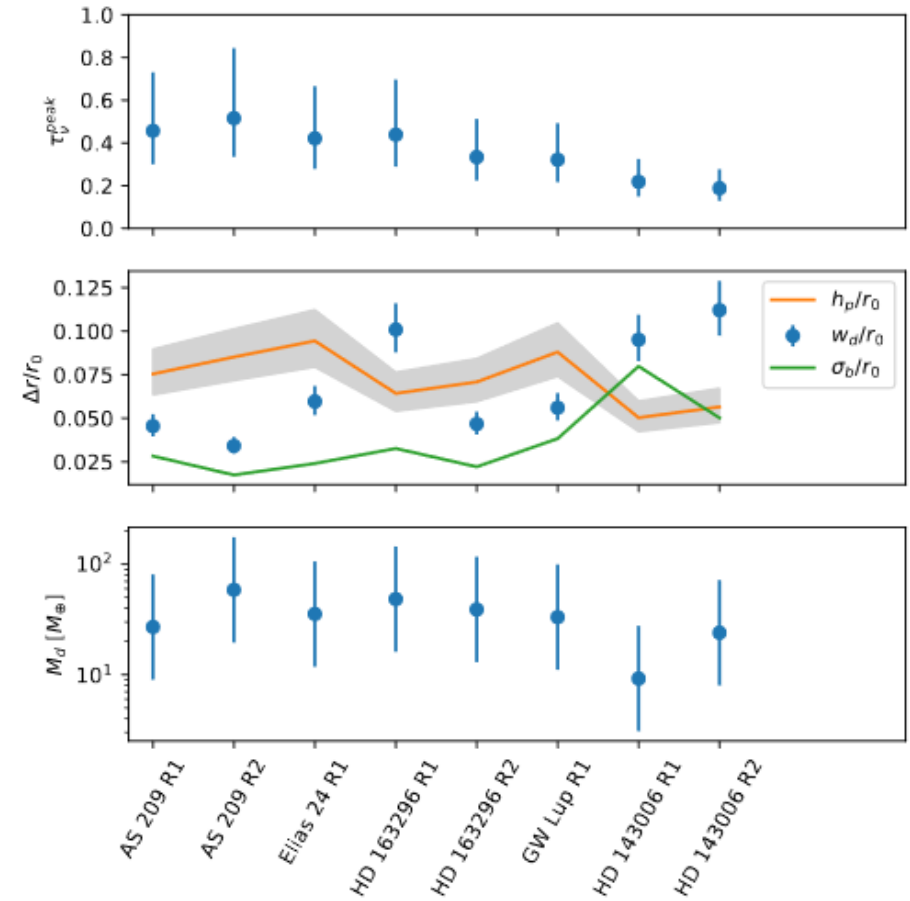
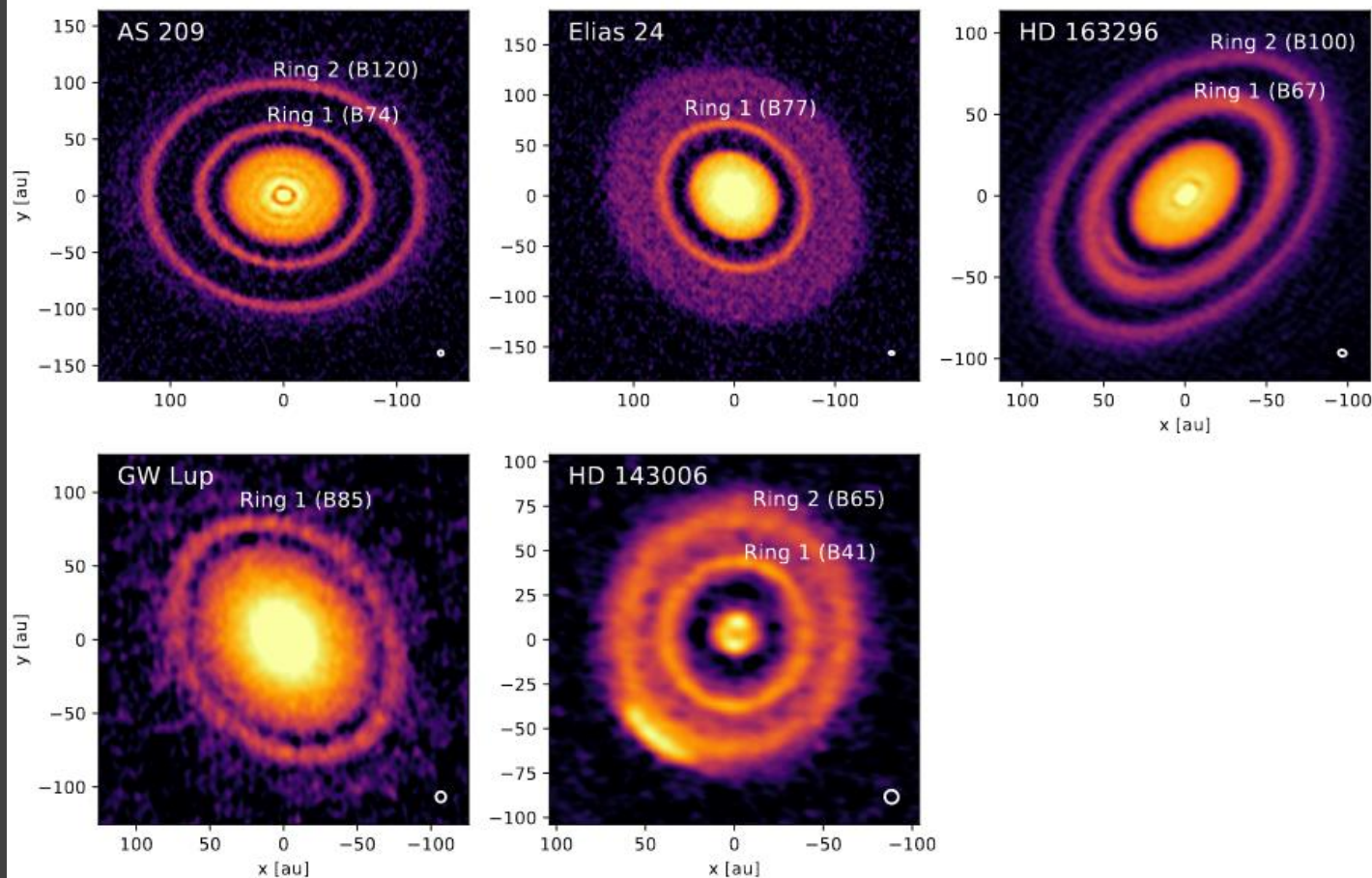
Three planets with masses from 0.2 up to 0.55 Jupiter mass



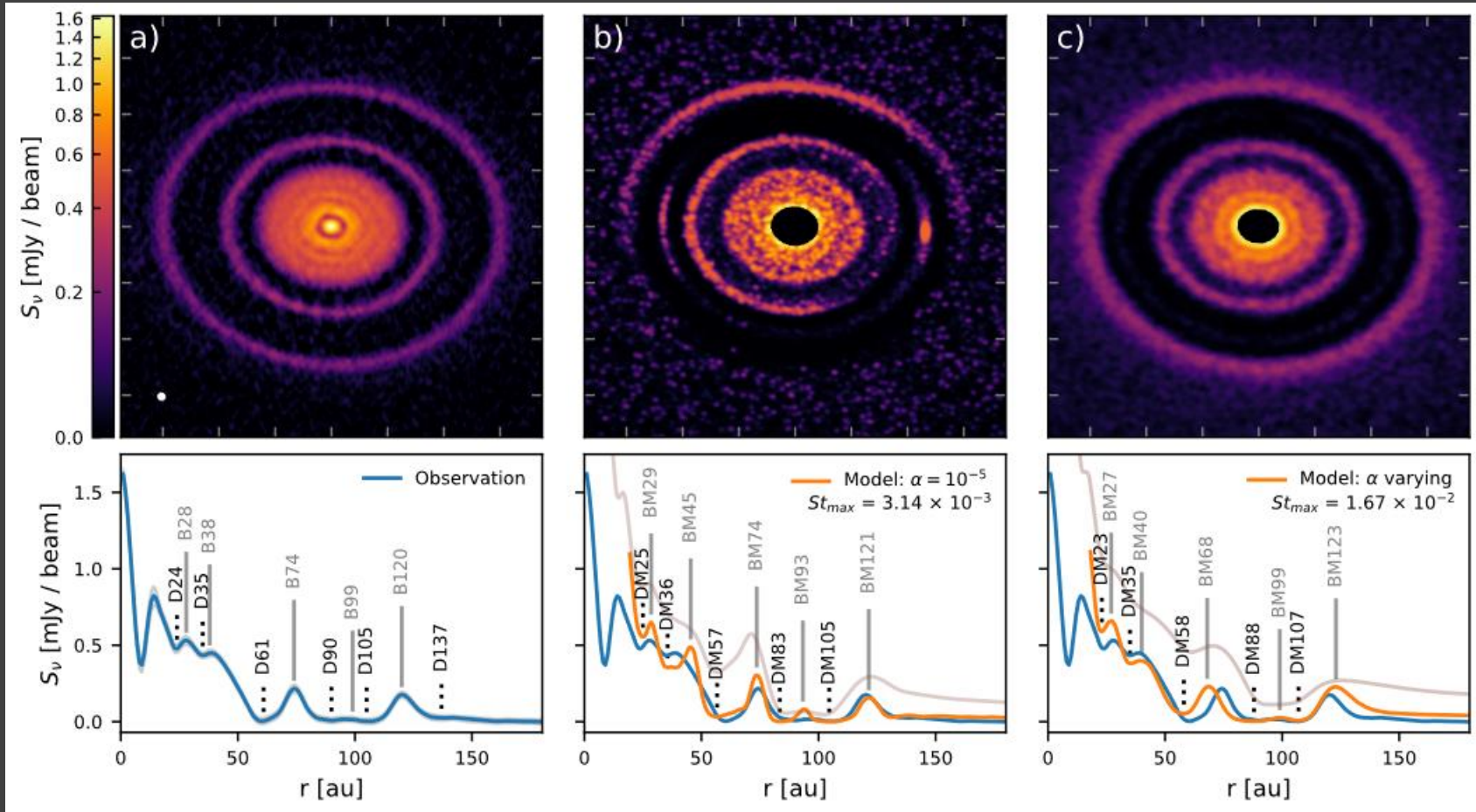
Observations

Modeling

More rings from ALMA



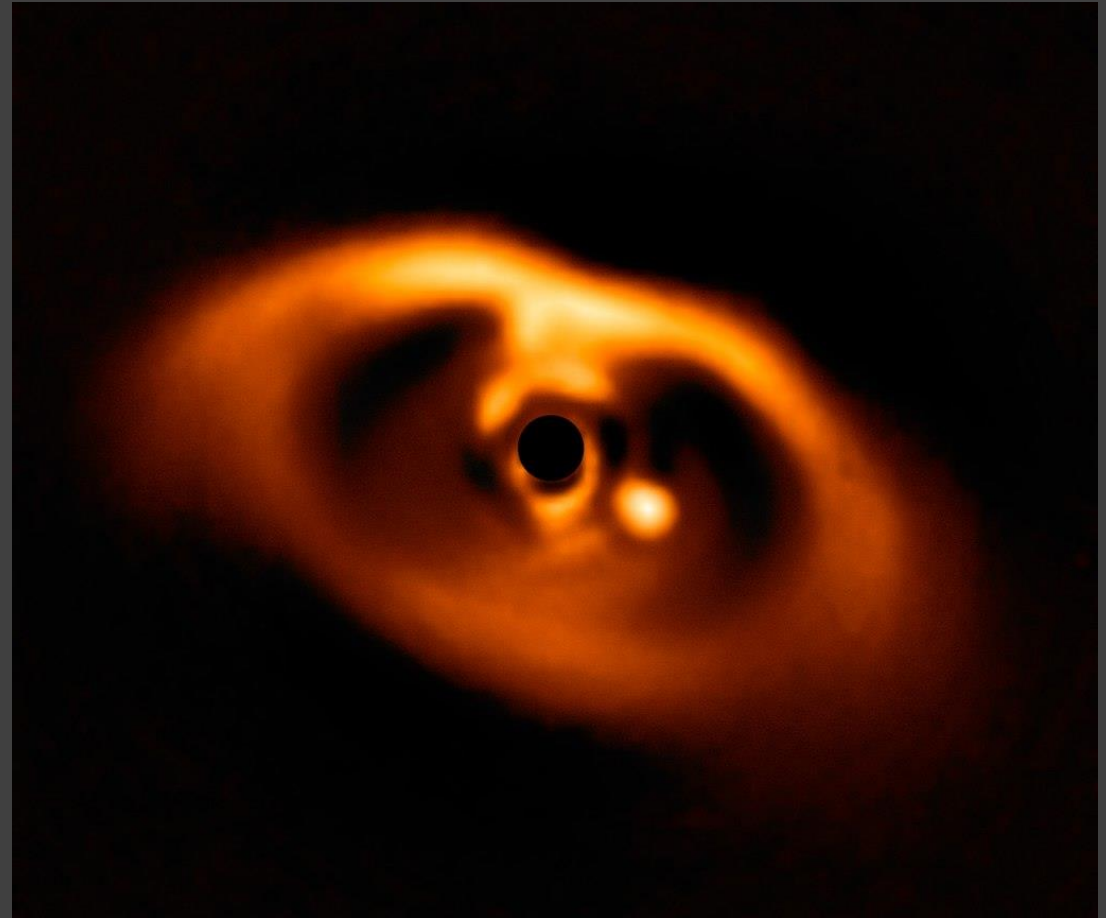
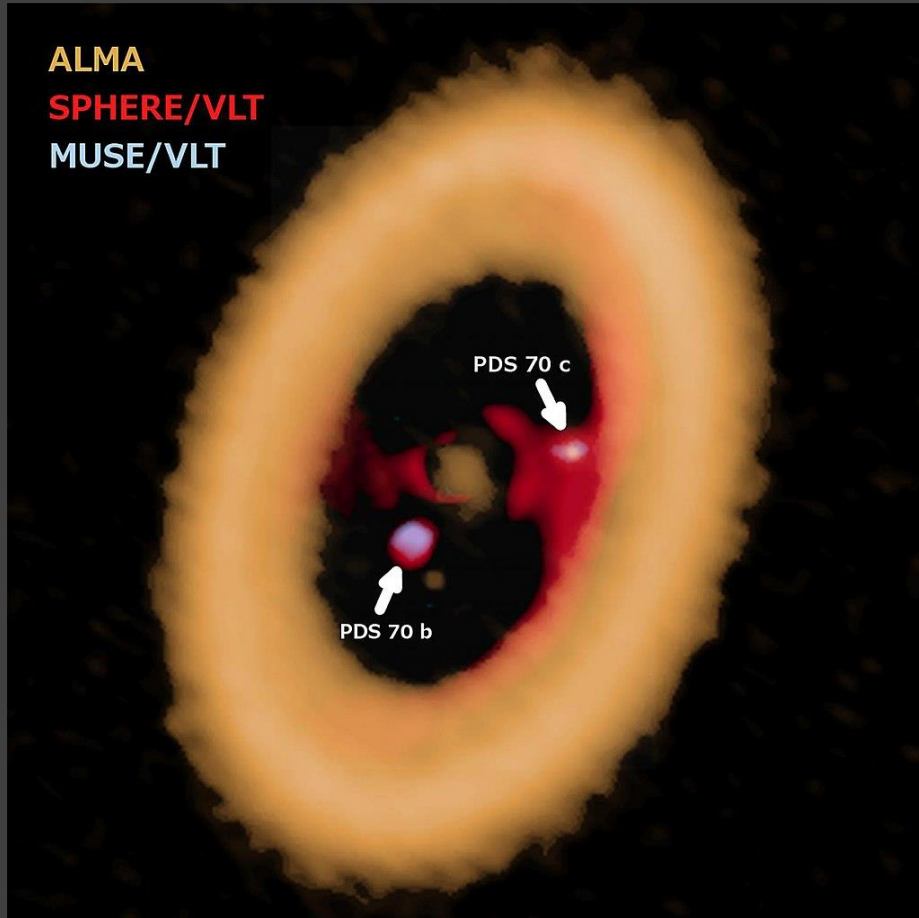
Modeling ring structure. Planets



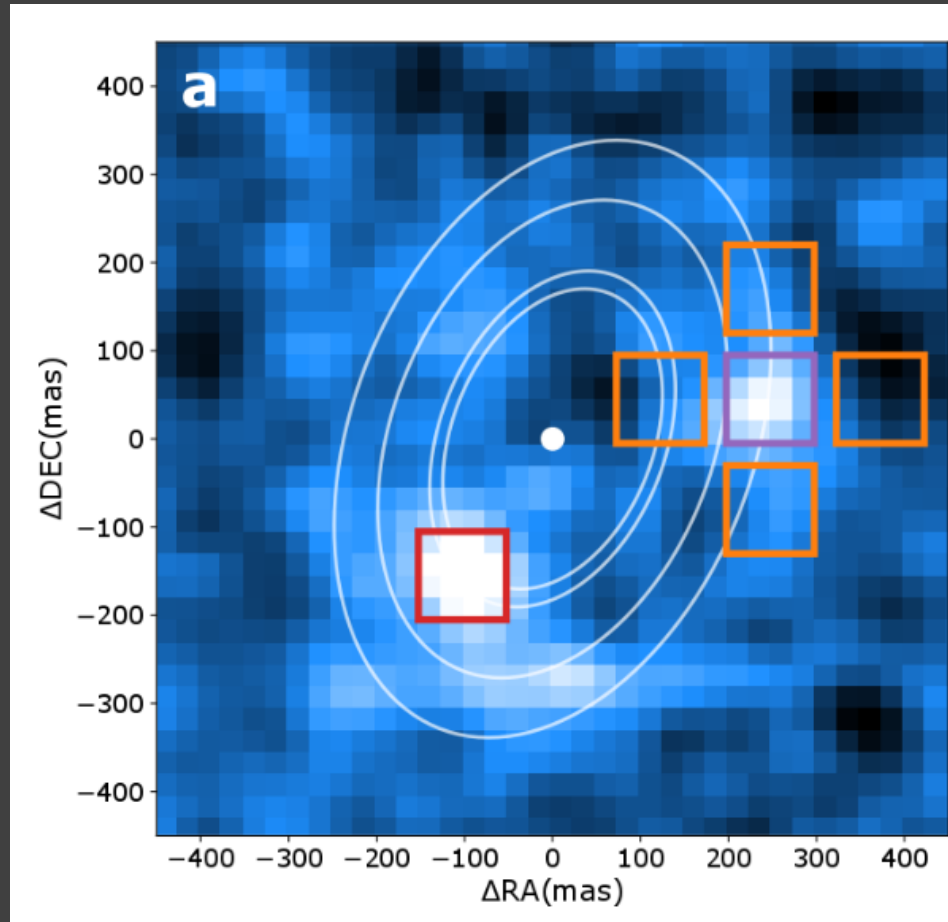
One planet at 99 au.

- A) Observations
- B) Model. Constant α
- C) Model. Varying α .

PDS 70: two planets in a disc

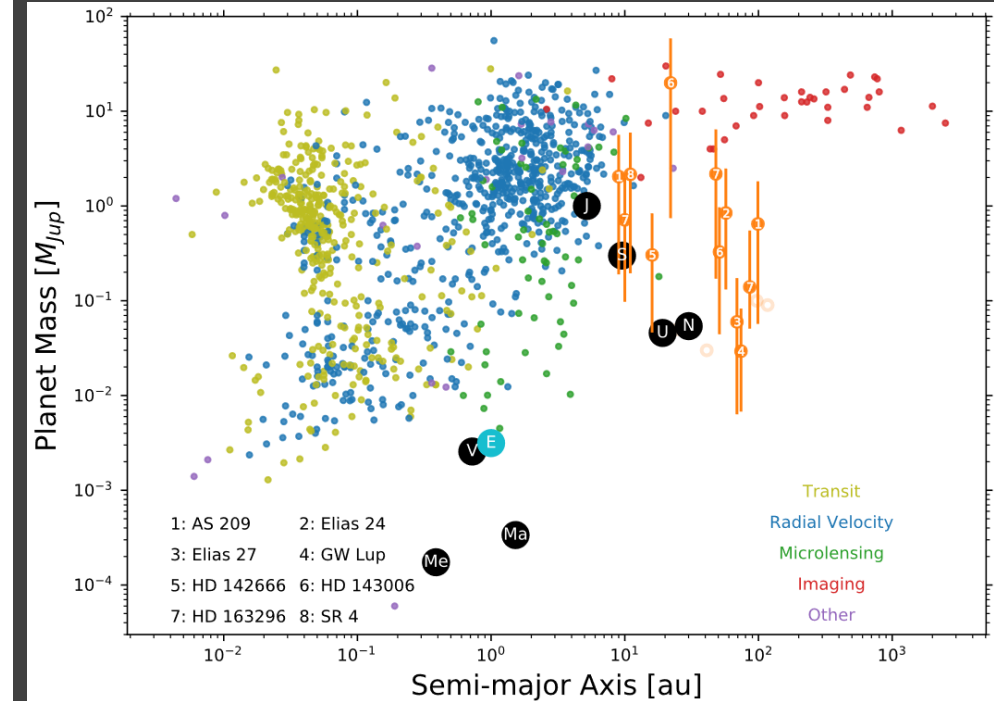


PDS 70. The second planet



Properties of (invisible) planets

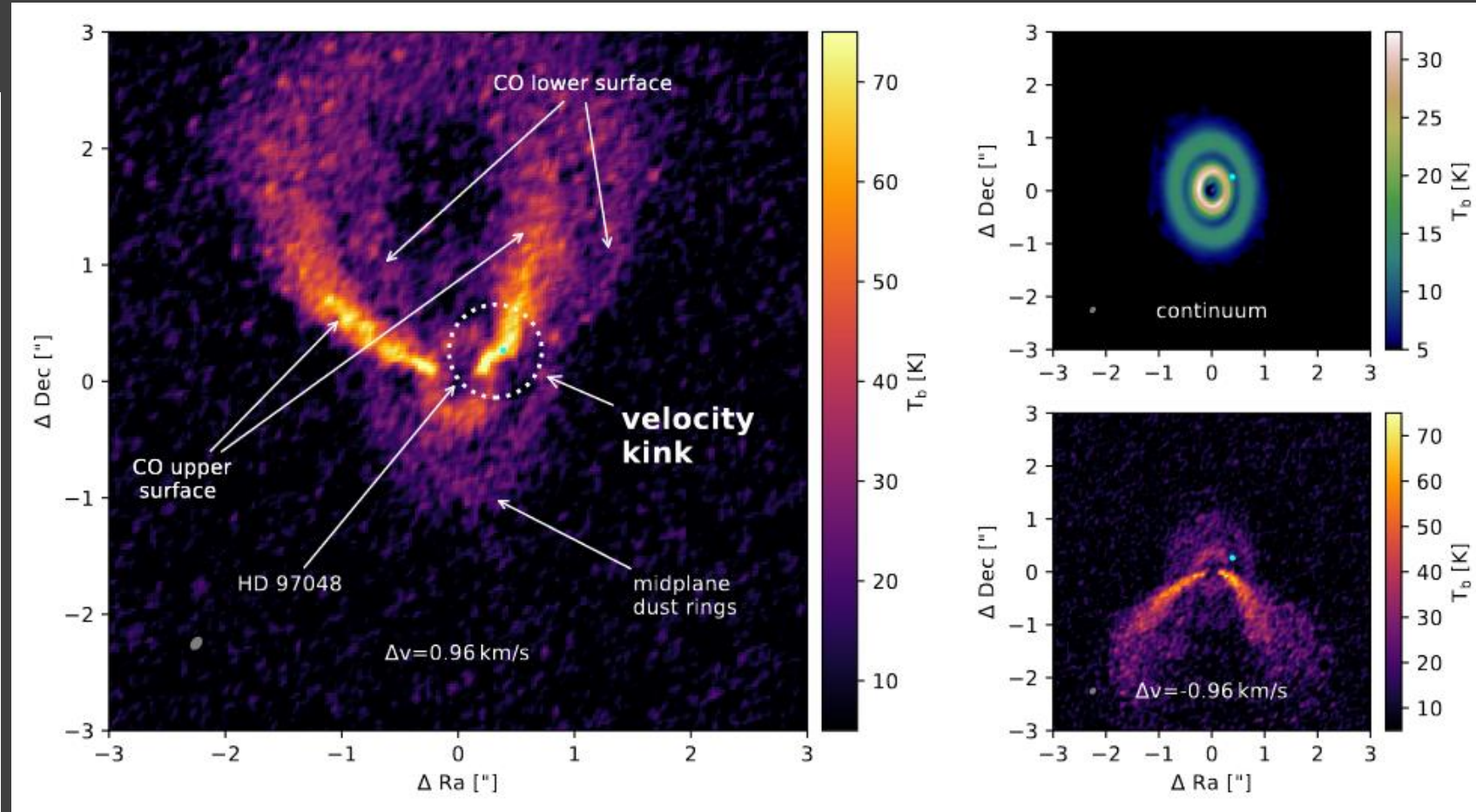
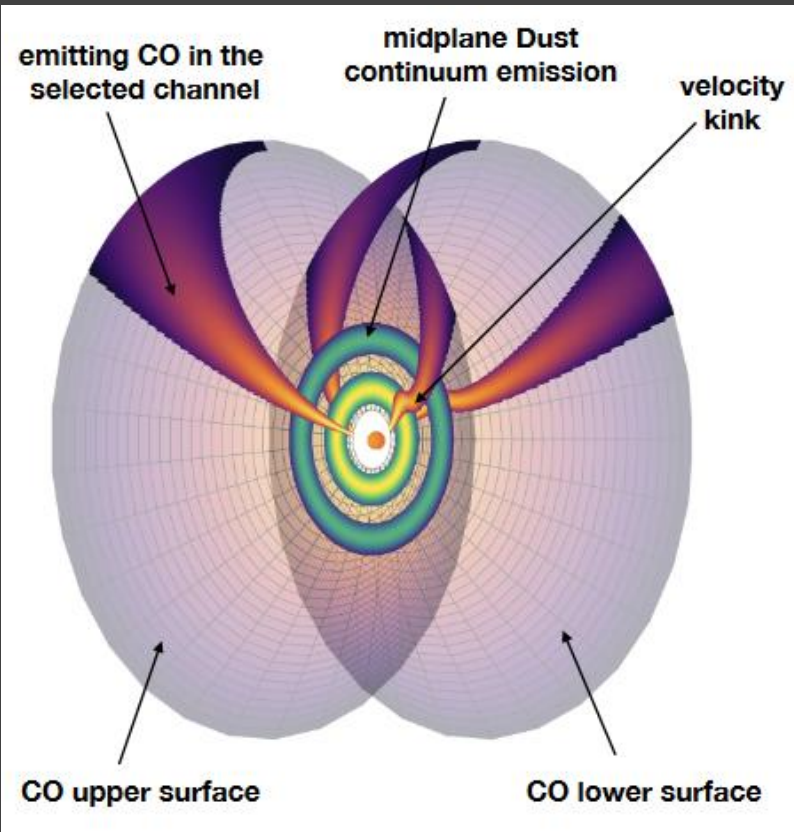
Name	M_*	r_{gap}	width	$M_{p,am4}$	$M_{p,am3}$	$M_{p,am2}$	Uncertainty
	(M_\odot)	(au)	(Δ)	(M_{Jup})	(M_{Jup})	(M_{Jup})	($\log_{10}(M_p)$)
(1)	(2)	(3)	(4)	(11)	(12)	(13)	(14)
AS 209	0.83	9	0.42	1.00, 0.81, 0.37	2.05, 1.66, 0.76	4.18, 3.38, 1.56	+0.13 +0.14 +0.28 -0.16' -0.17' -0.29
AS 209	0.83	99	0.31	0.32, 0.18, -	0.65, 0.37, -	1.32, 0.75, -	+0.14 +0.21 - -0.17' -0.50' -
Elias 24	0.78	57	0.32	0.41, 0.19 -	0.84, 0.40, -	1.72, 0.81, -	+0.16 +0.22 - -0.14' -0.16' -
Elias 27	0.49	69	0.18	0.03, 0.02, -	0.06, 0.05, -	0.12, 0.10, -	+0.16 +0.21 - -0.14' -0.50' -
GW Lup*	0.46	74	0.15	0.01, -, -	0.03, -, -	0.06, -, -	+0.14 -, - -0.17' -, -
HD 142666	1.58	16	0.20	0.15, 0.12, 0.09	0.30, 0.25, 0.19	0.62, 0.50, 0.38	+0.13 +0.14 +0.28 -0.16' -0.17' -0.29
HD 143006	1.78	22	0.62	9.75, 2.35, -	19.91, 4.80, -	40.64, 9.81, -	+0.16 +0.21 - -0.14' -0.50' -
HD 143006	1.78	51	0.22	0.16, 0.14 -	0.33, 0.28, -	0.67, 0.57, -	+0.16 +0.21 - -0.14' -0.50' -
HD 163296	2.04	10	0.24	0.35, 0.28, 0.19	0.71, 0.58, 0.39	1.46, 1.18, 0.79	+0.13 +0.14 +0.28 -0.16' -0.17' -0.29
HD 163296	2.04	48	0.34	1.07, 0.54, -	2.18, 1.10, -	4.45, 2.24, -	+0.16 +0.21 - -0.14' -0.50' -
HD 163296	2.04	86	0.17	0.07, 0.08, -	0.14, 0.16, -	0.29, 0.34, -	+0.16 +0.21 - -0.14' -0.50' -
SR 4	0.68	11	0.45	1.06, 0.86, 0.38	2.16, 1.75, 0.77	4.41, 3.57, 1.57	+0.13 +0.14 +0.28 -0.16' -0.17' -0.29
DoAr 25*	0.95	98	0.15	(-, 0.10, -)	(0.10, -, -)	(-, 0.95, -)	-, -, -
DoAr 25	0.95	125	0.08	(0.03, -, -)	-, -, -	-, -, -	-, -, -
Elias 20	0.48	25	0.13	-, -, -	(0.05, 0.05, 0.05)	-, -, -	-, -, -
IM Lup	0.89	117	0.13	(0.09, -, -)	(0.09, -, -)	-, -, -	-, -, -
RU Lup	0.63	29	0.14	(0.07, -, -)	(-, 0.07, 0.07)	-, -, -	-, -, -
Sz 114	0.17	39	0.12	(0.02, 0.02, -)	-, -, -	-, -, -	-, -, -
Sz 129	0.83	41	0.08	(-, 0.03, -)	(0.03, -, -)	-, -, -	-, -, -



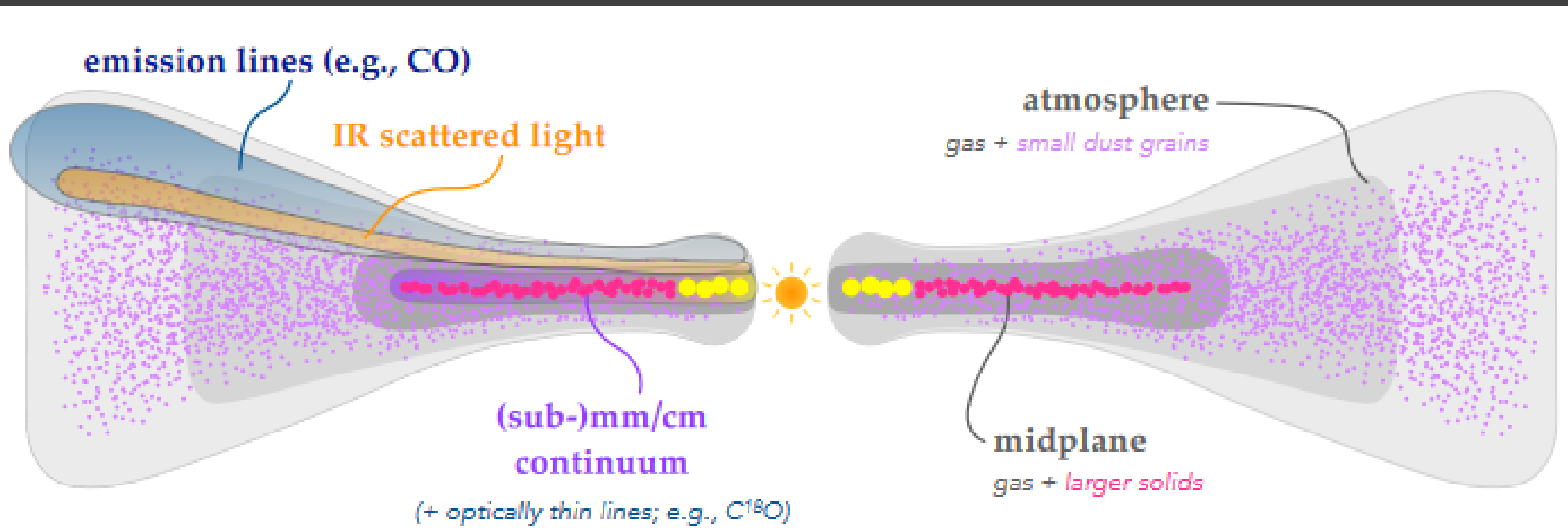
Three values of planet mass for each alpha correspond to different models of dust size.

Kinematic detection of a planet HD 97048

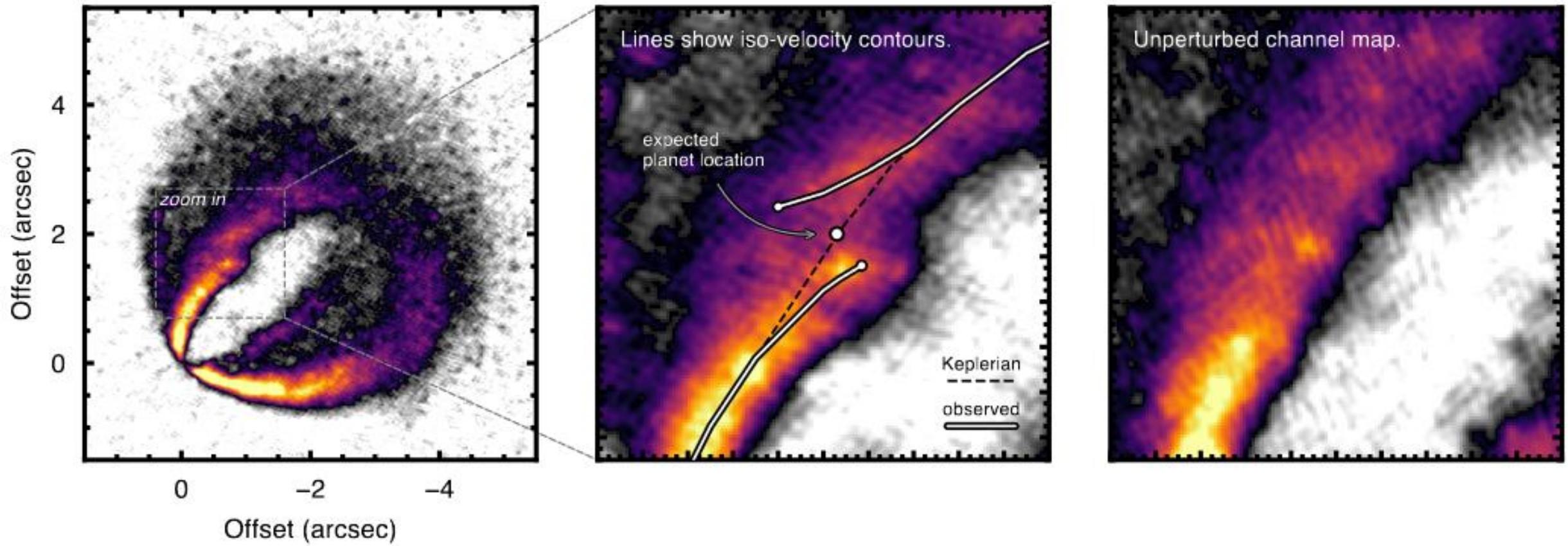
Gap + disturbance in the gas flow



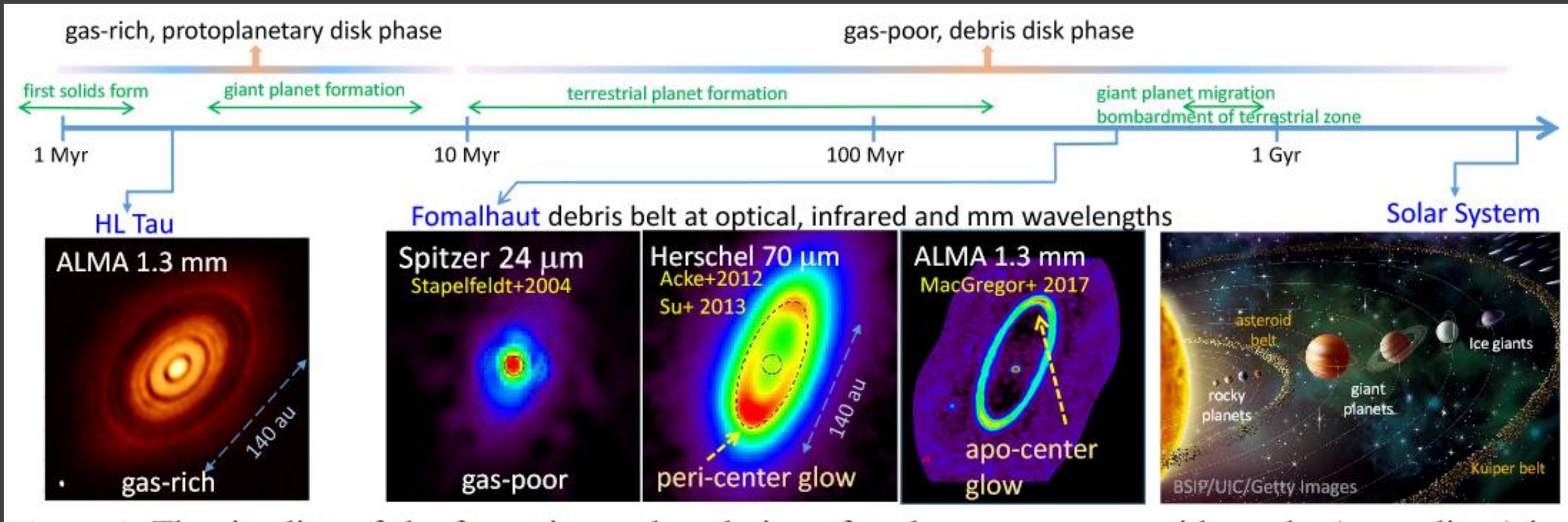
Disc structure and emission zones



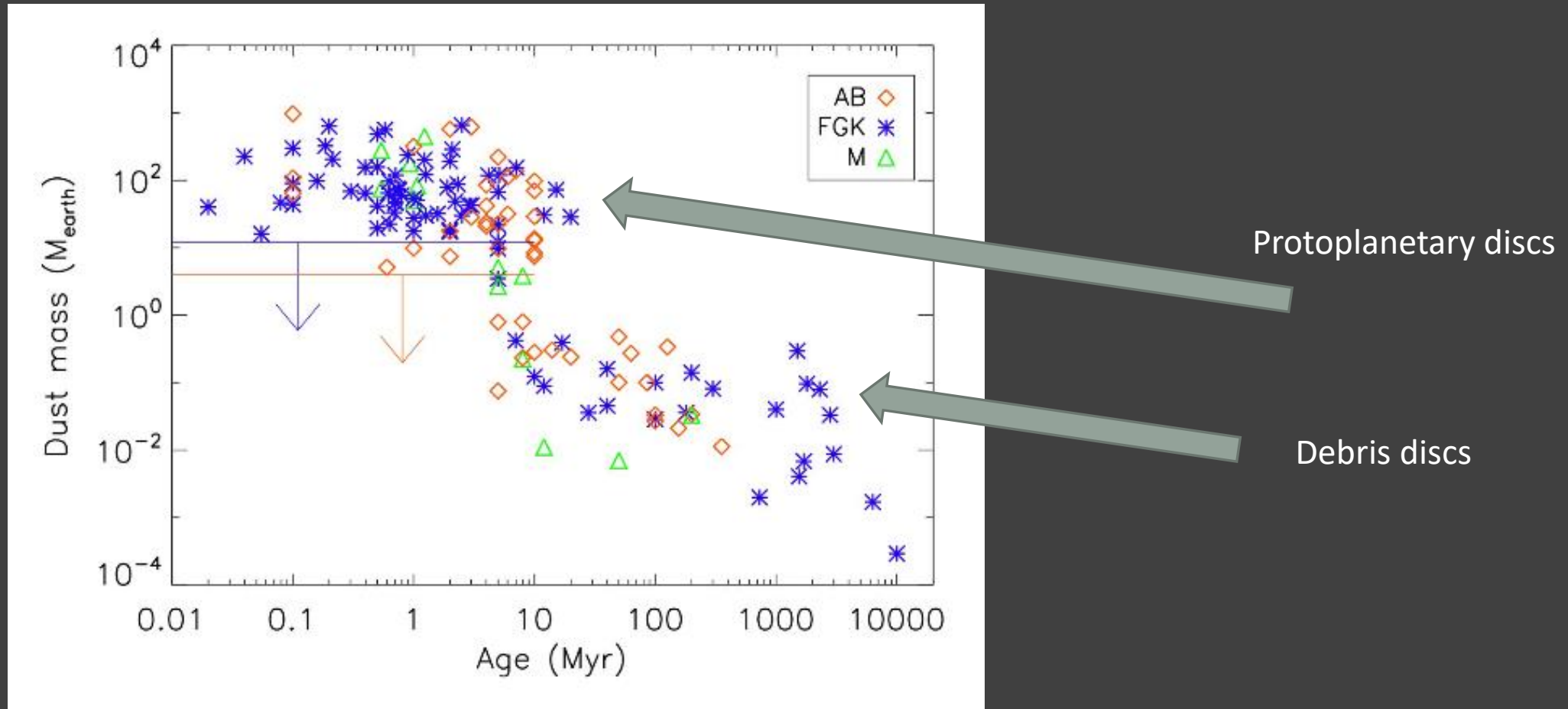
Planet and gas velocity in the disc HD 163296



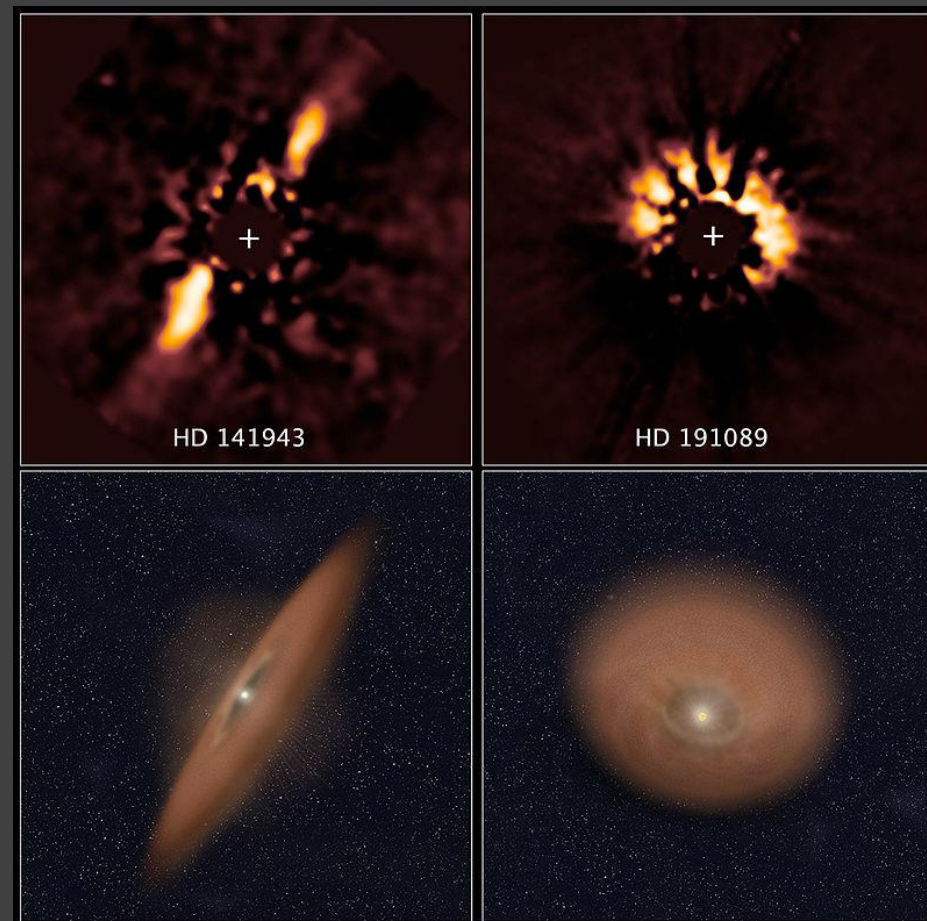
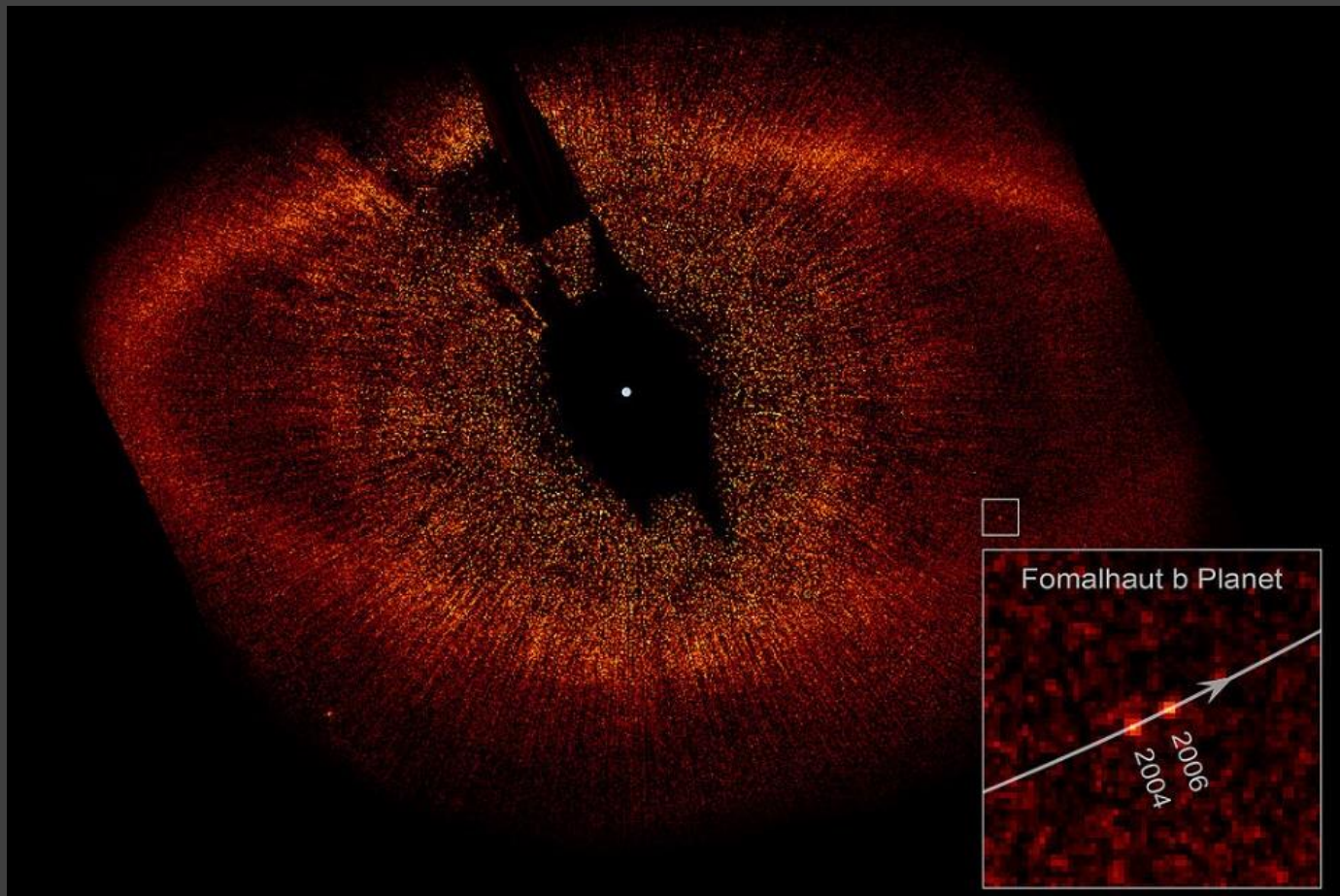
Protoplanetary and debris discs. Evolution



Evolution of the dust mass in discs



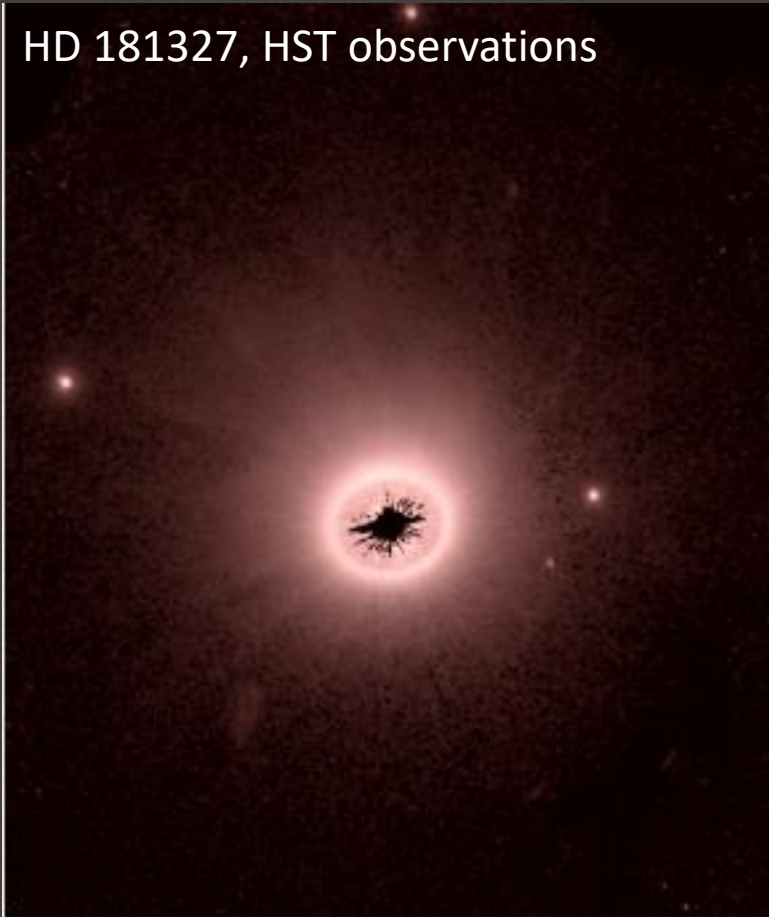
Debris discs



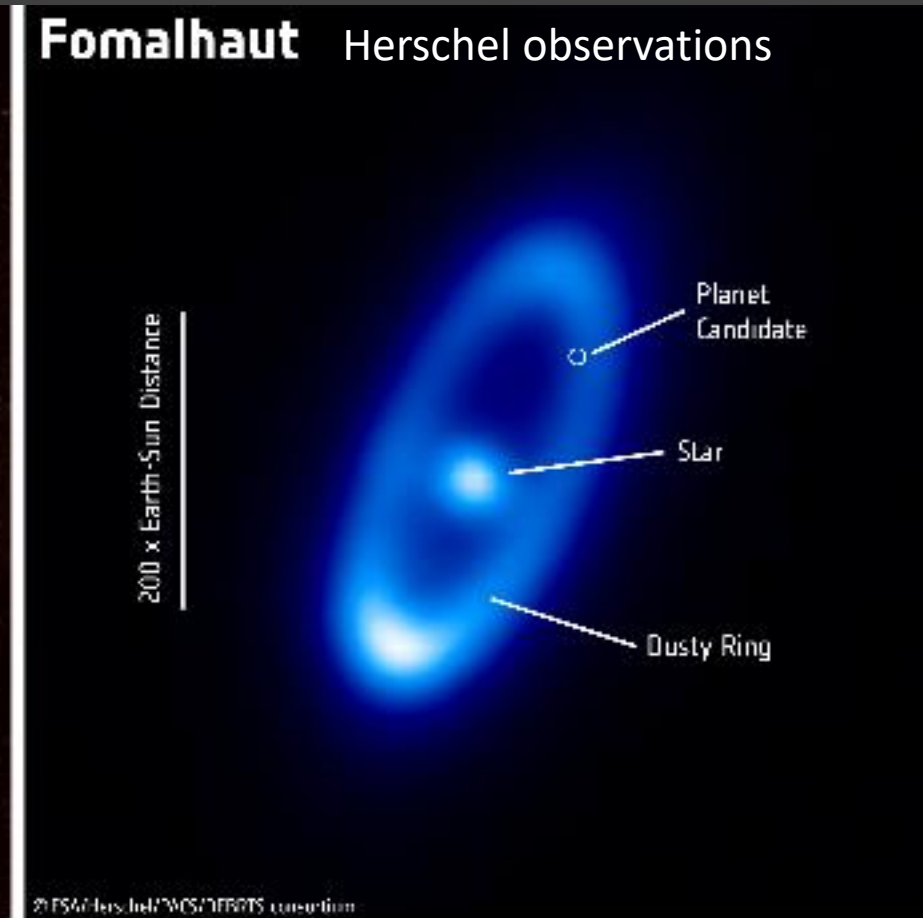
See a review in 1802.04313, 1804.08636

Two debris disc examples

HD 181327, HST observations

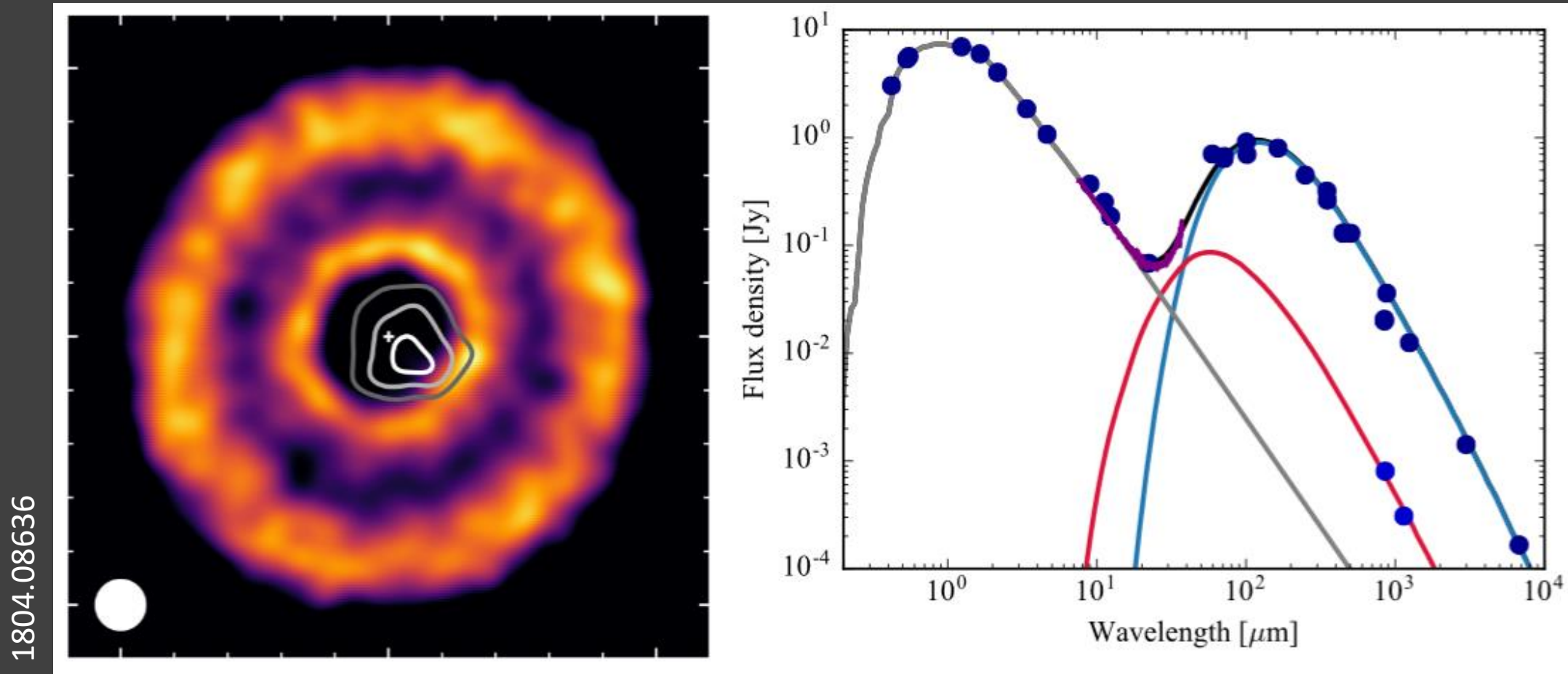


Fomalhaut Herschel observations

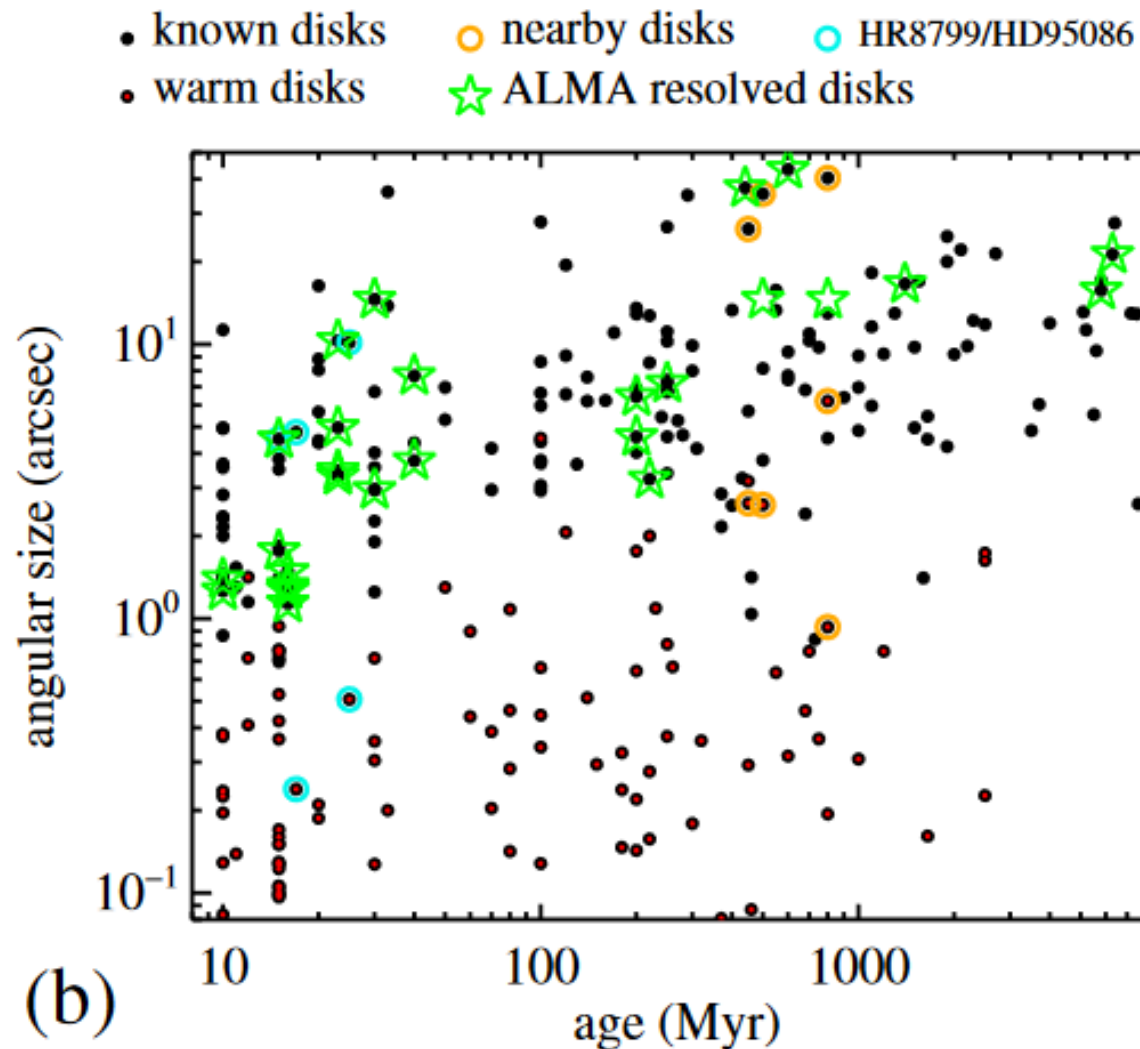
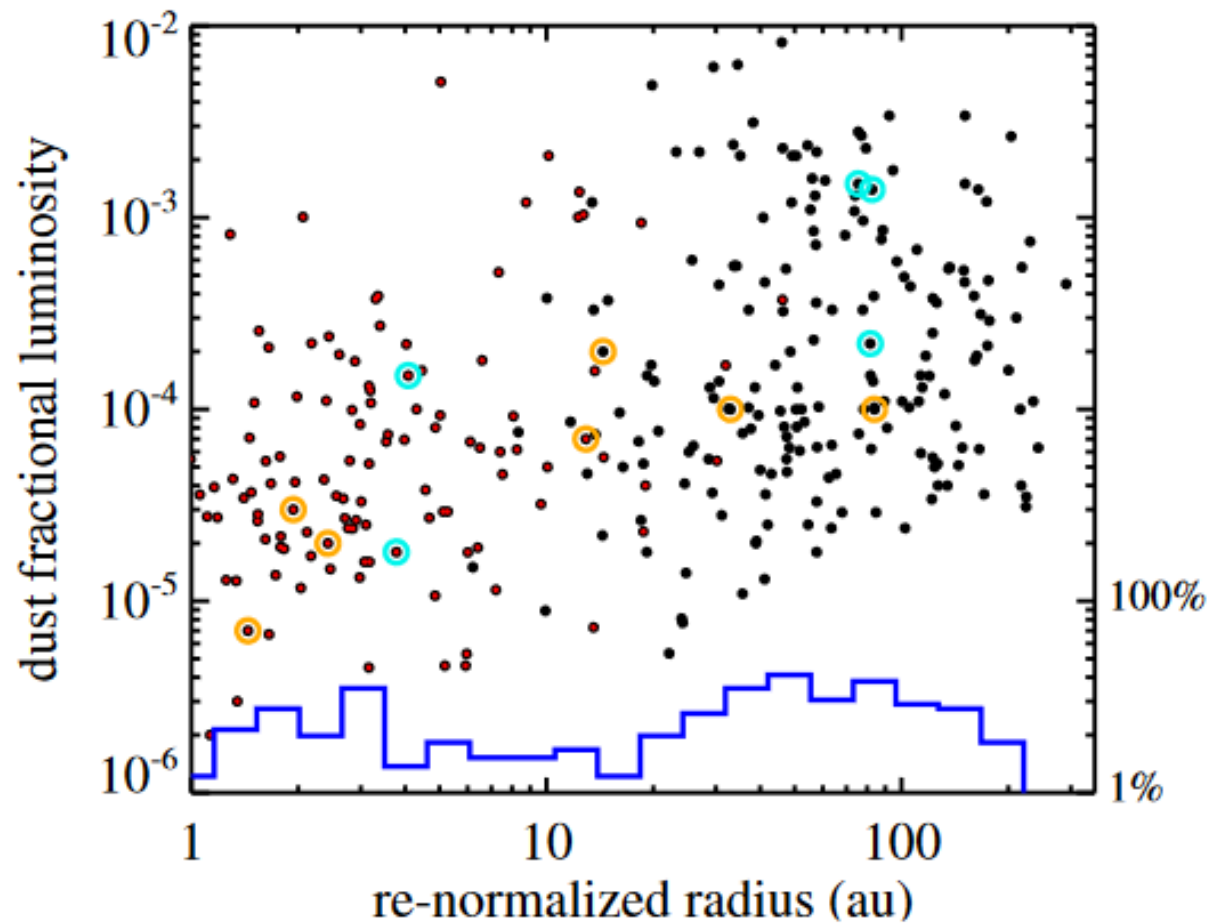
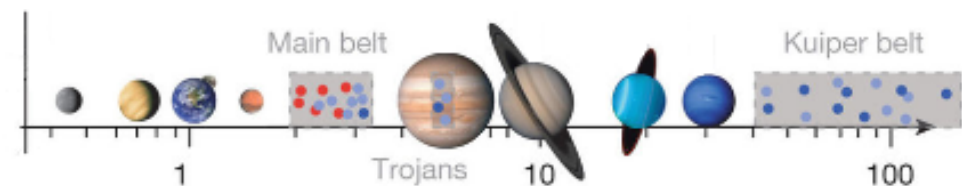


Hundreds of debris discs are known.

HD107146. ALMA observations

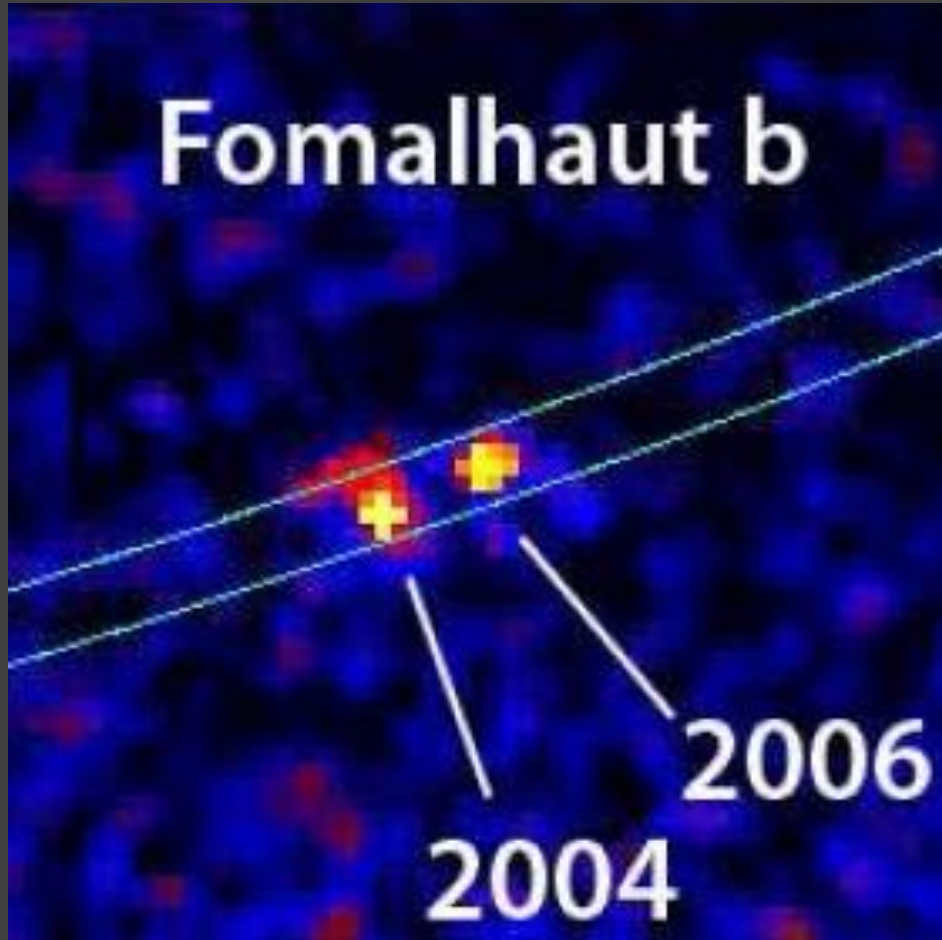


Debris disks are the dust disks found around $\sim 20\%$ of nearby main sequence stars in far-IR surveys.



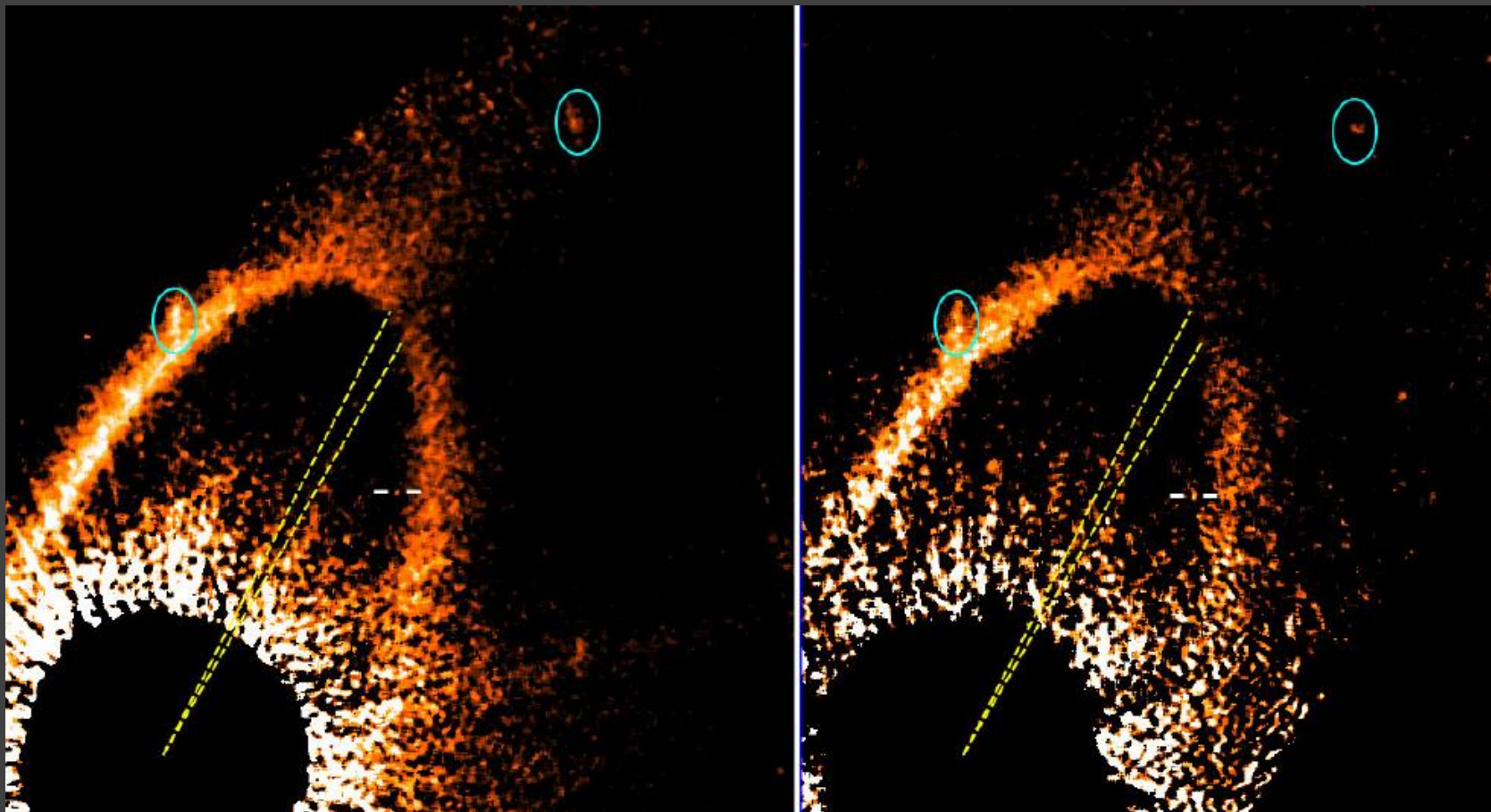
Debris disc sizes are renormalized with luminosity $\sqrt{L_*}$ to co-align snow lines.

Fomalhaut b



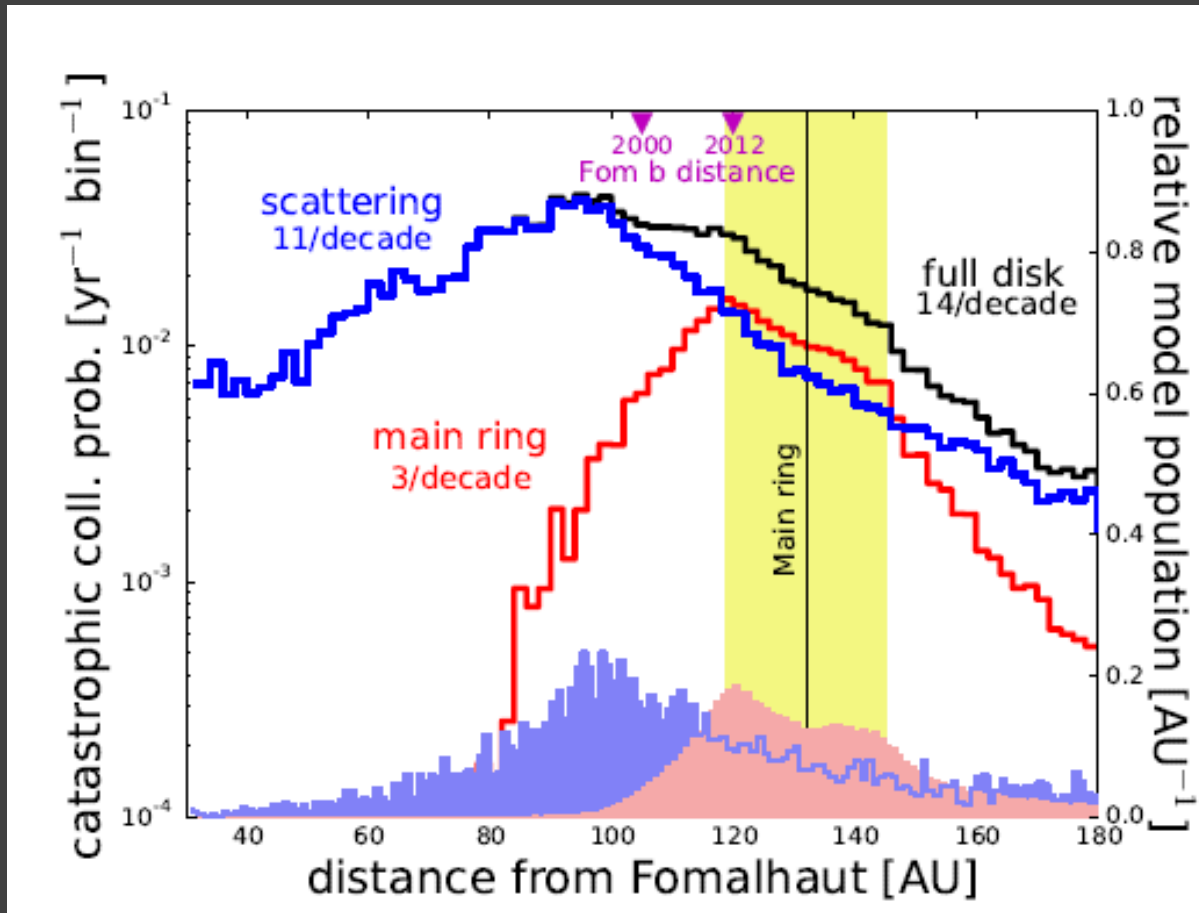
115 AU from the star

Is Fomalhaut b a real planet?



A planet or not a planet?
This is the question!

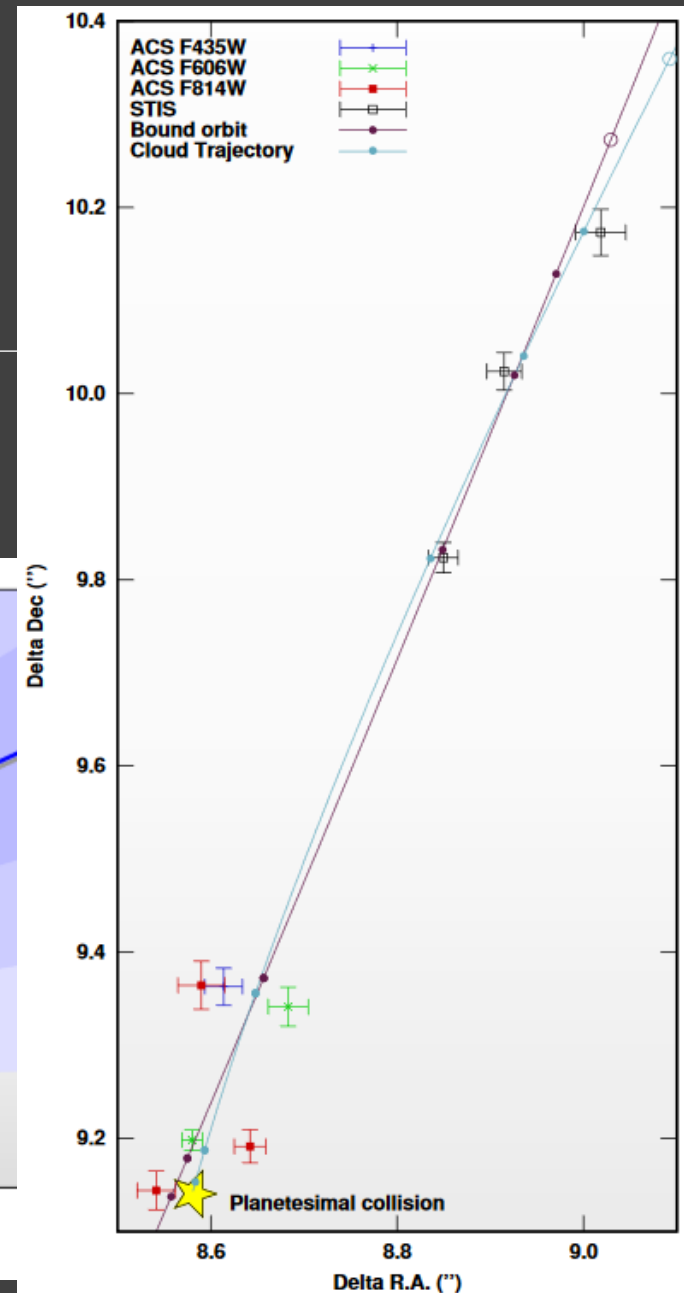
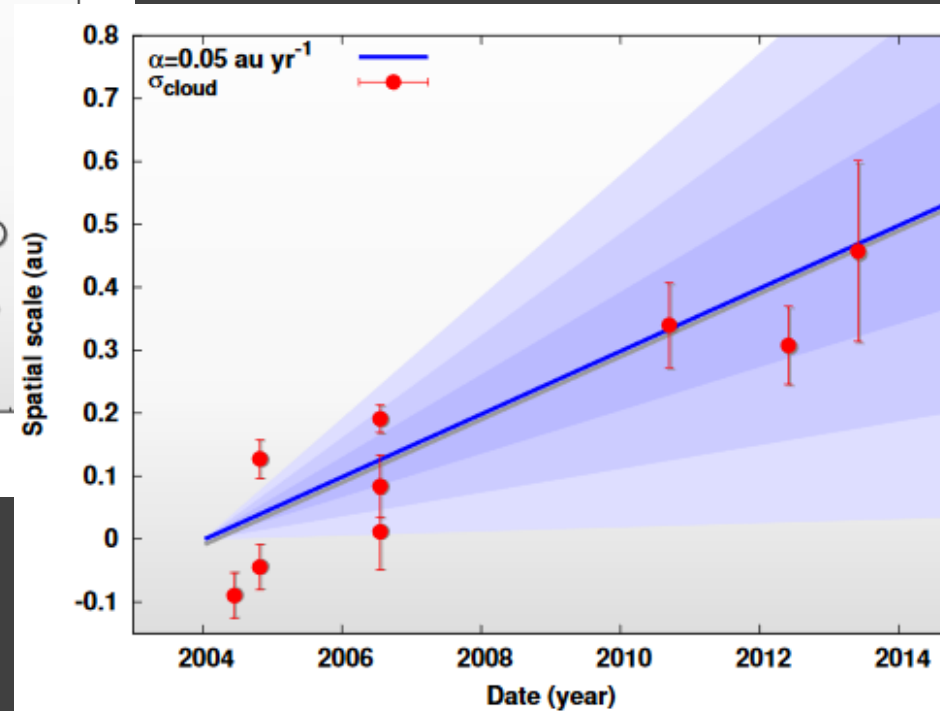
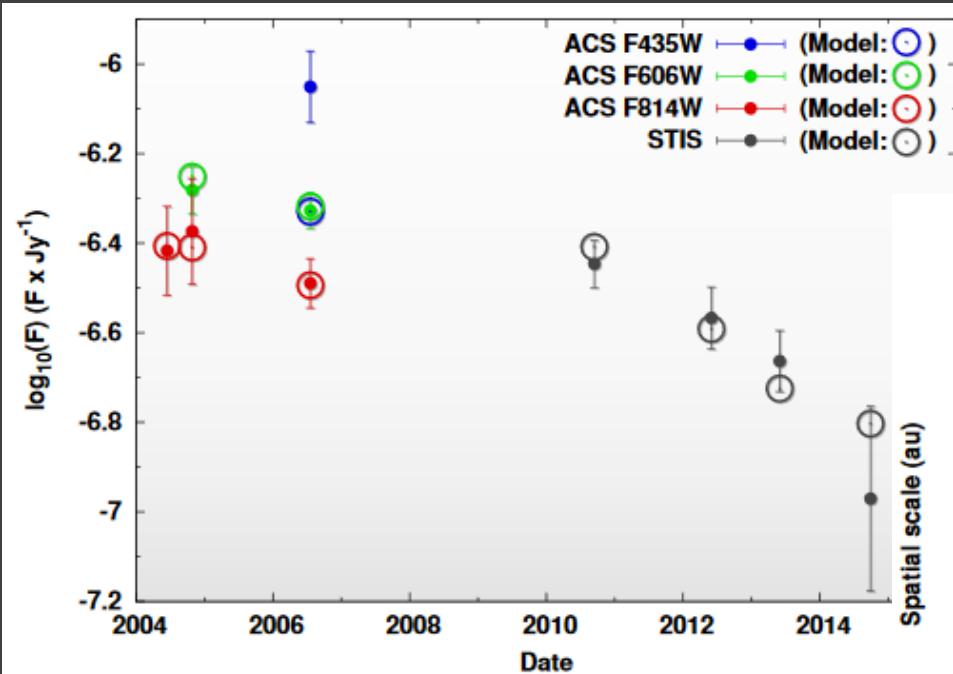
Result of a recent collision?



The object is situated in the region where collisions are very probable.

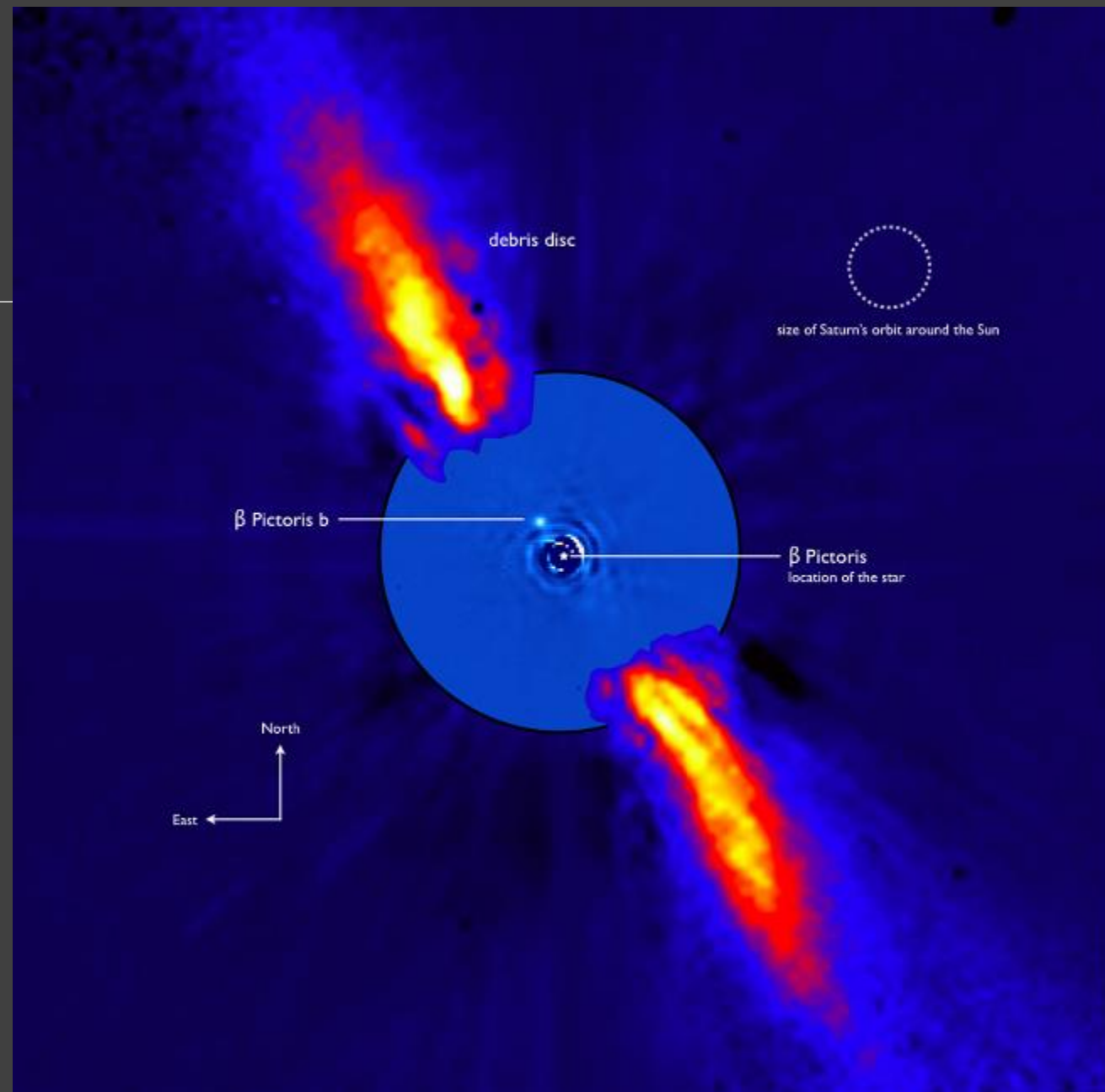
Two bodies with ~ 100 km size might be enough.

Collision is almost proved

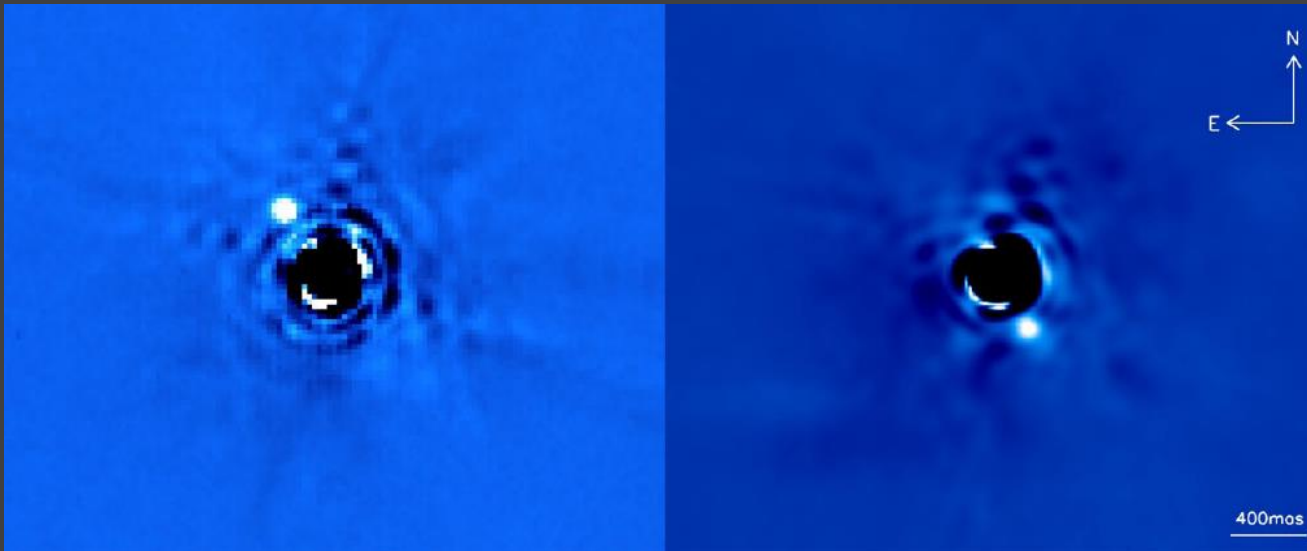


Beta Pictoris

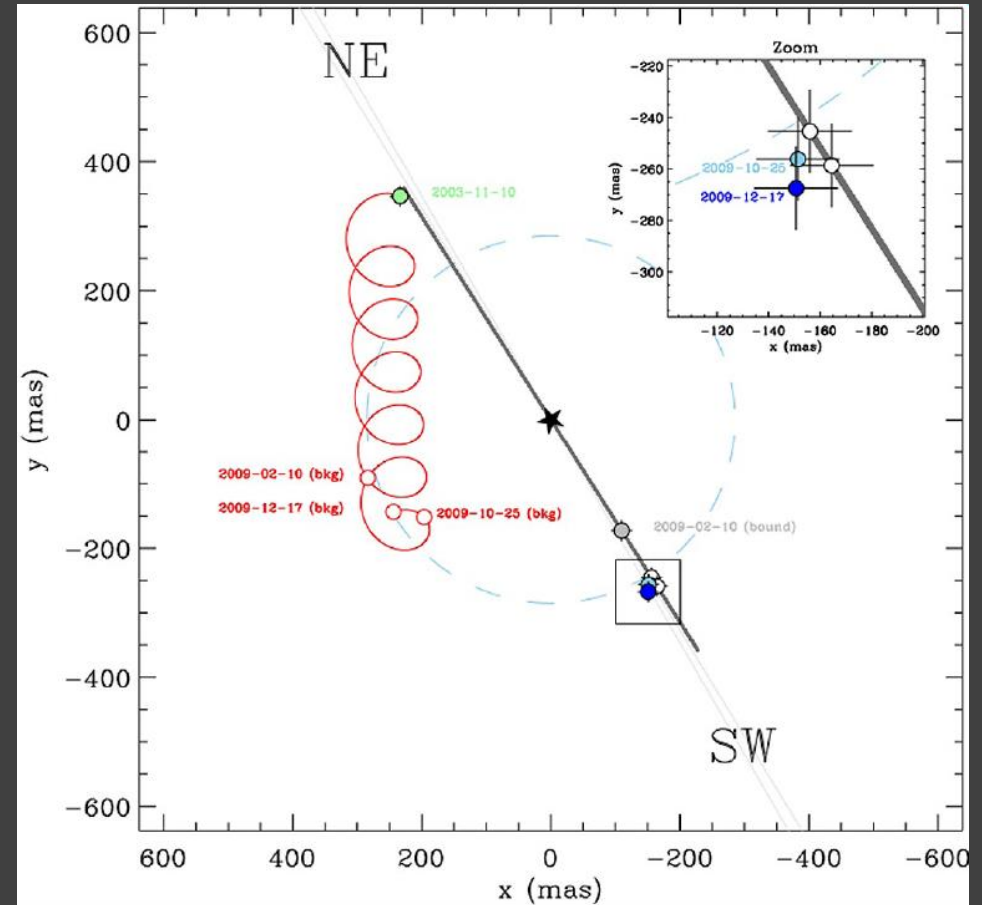
Composite image obtained
by two instruments



Beta Pictoris



Age ~ 10 Myr
Distance ~ 9 AU

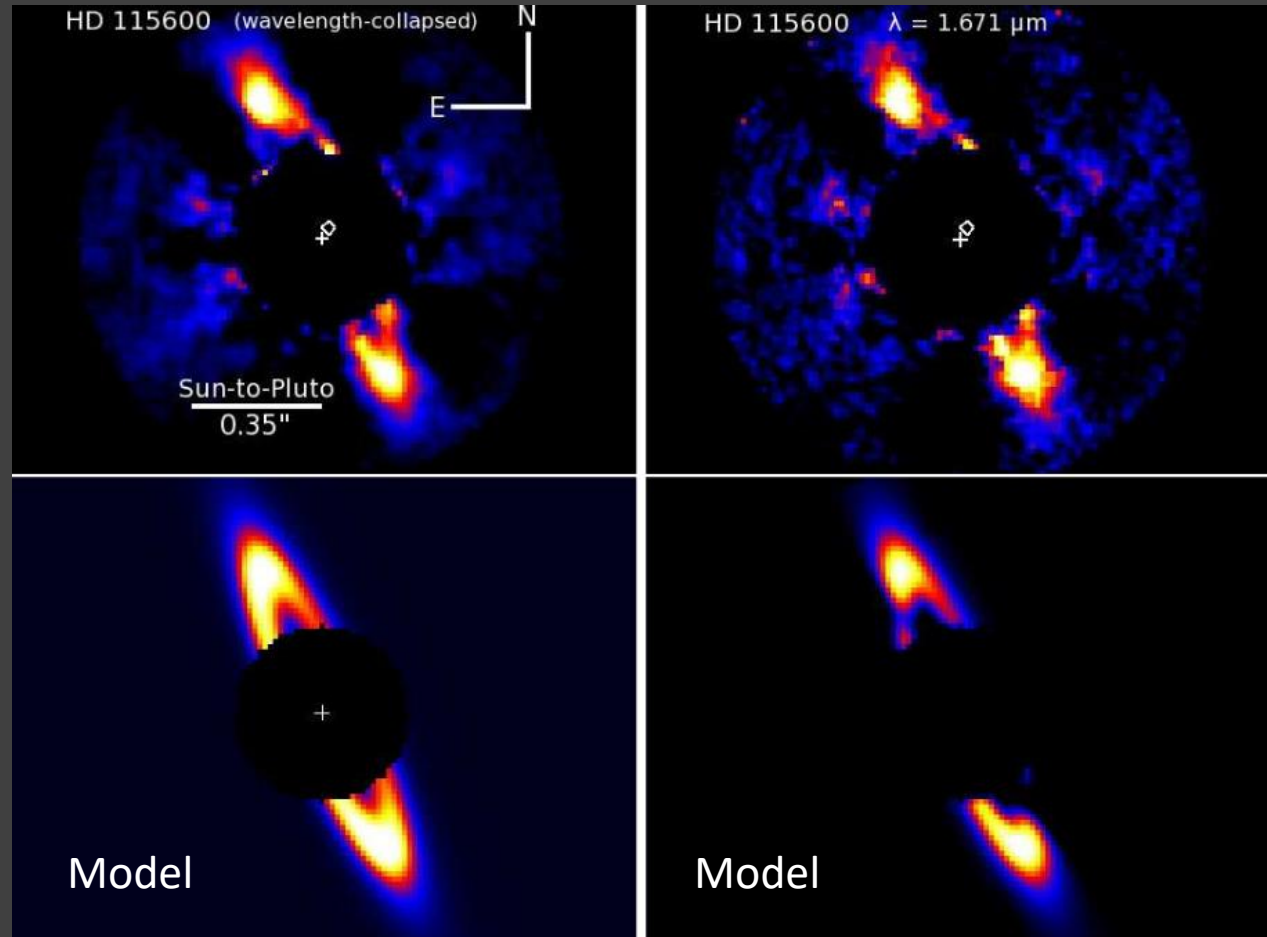


Young Kuiper belt-like debris disc

HD 115600
110 pc
15 Myrs
1.4 solar mass star

Gemini planet imager

Size of the disc 48 AU



Disc around planetary mass object

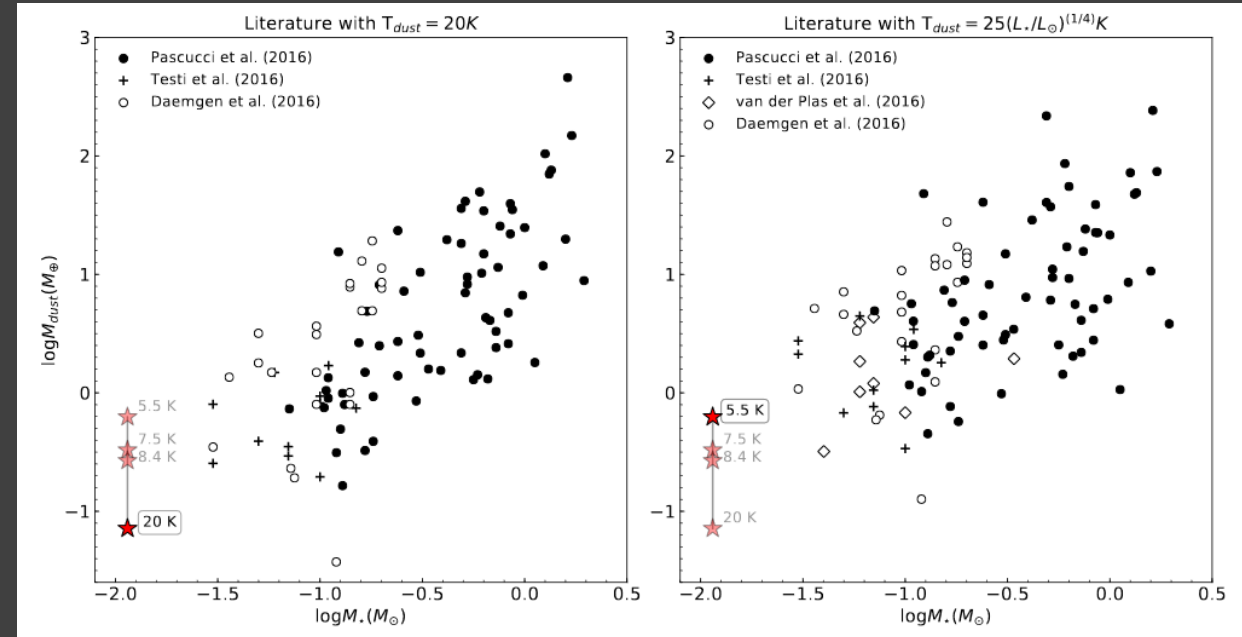
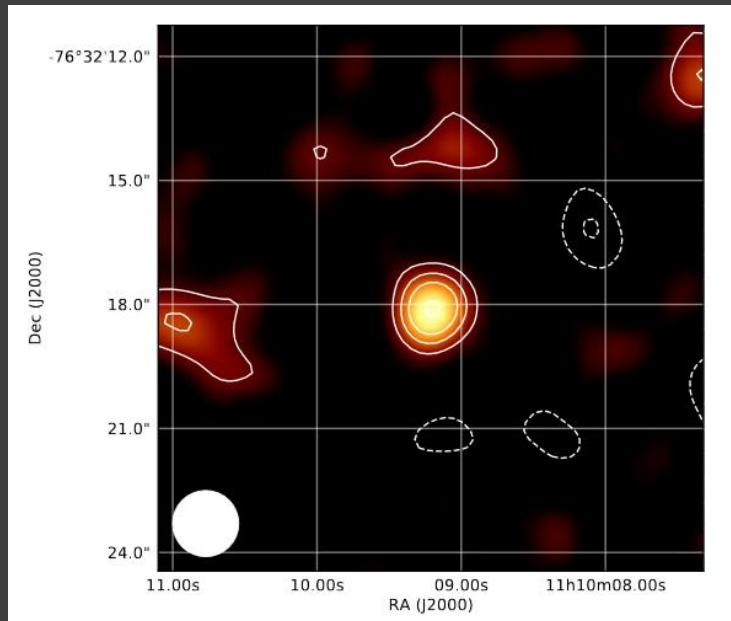
OTS44 is one of only four free-floating planets known to have a disc.

Mass $\sim 12 M_{\text{jupiter}}$

IR excess seen by Spitzer and Herschel

ALMA observations

$M_{\text{dust}} \sim 0.07\text{--}0.7 M_{\text{Earth}}$

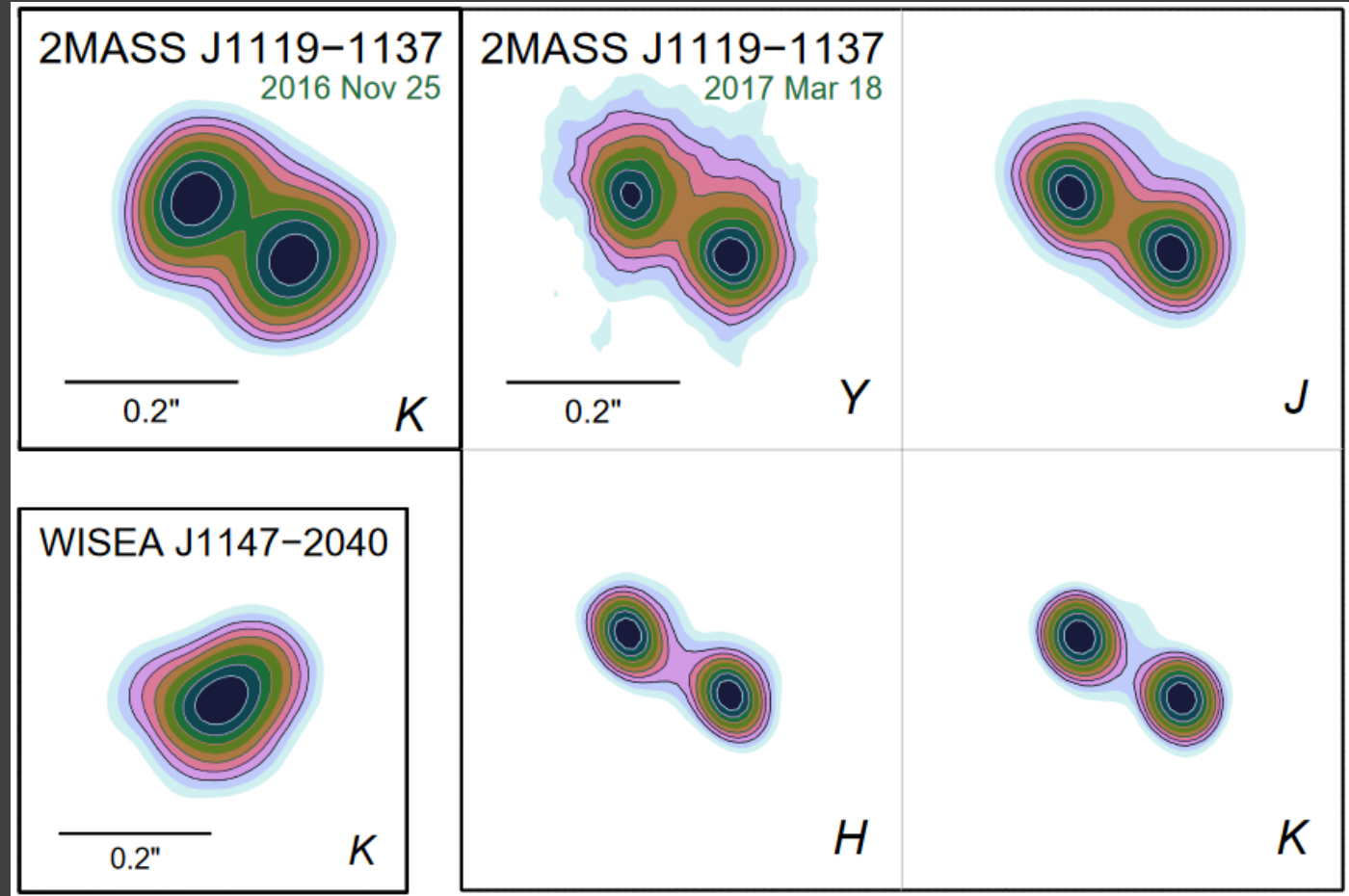


A brown dwarf is a pair of planets

2MASS J11193254-1137466

Age ~10 Myr
20-30 pc

$M \sim 3-5 M_{\text{jupiter}}$
Orbital period ~50-150 yrs
3-5 AU



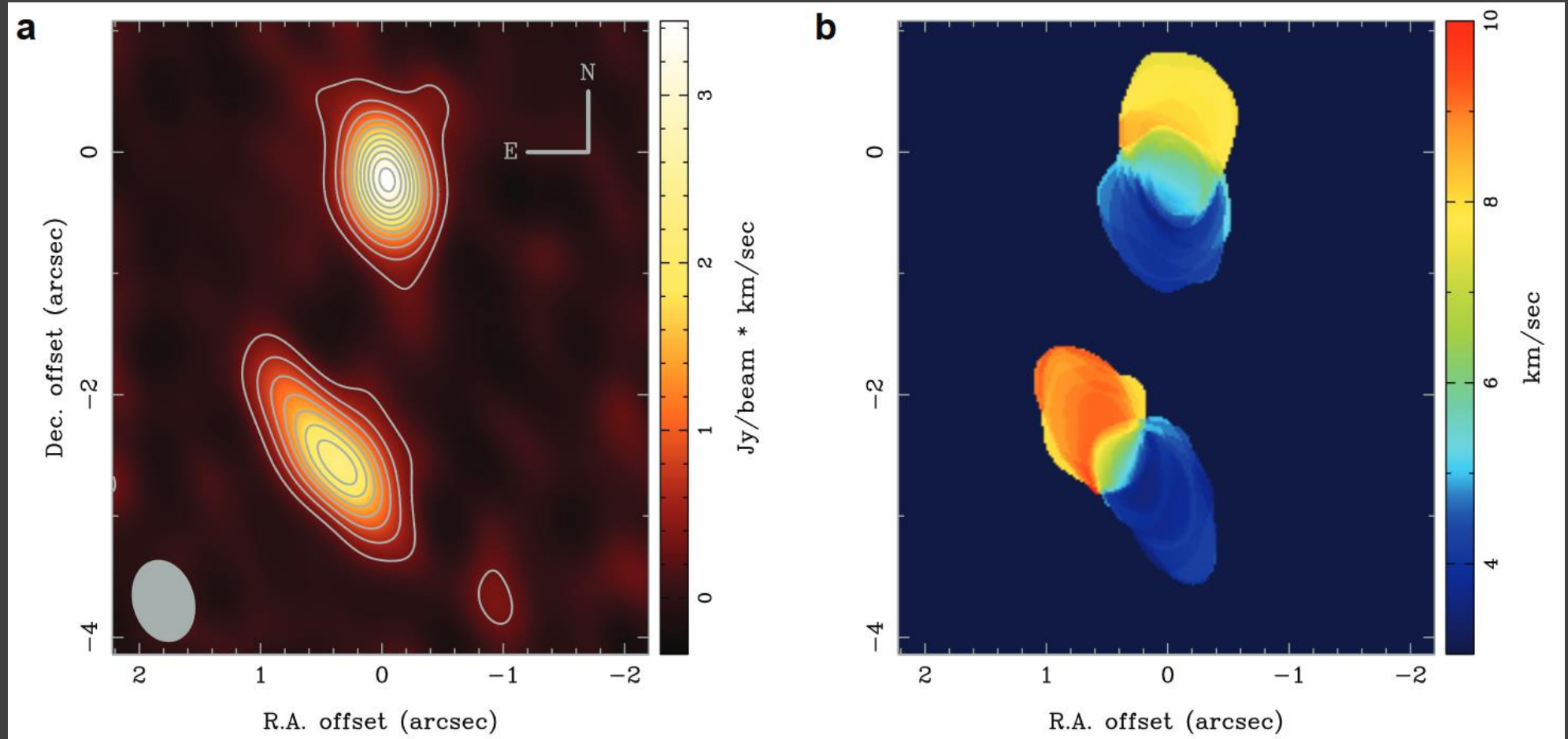
Protoplanetary discs in a binary system

HK Tau
161 pc

1-4 Myr

386 AU binary

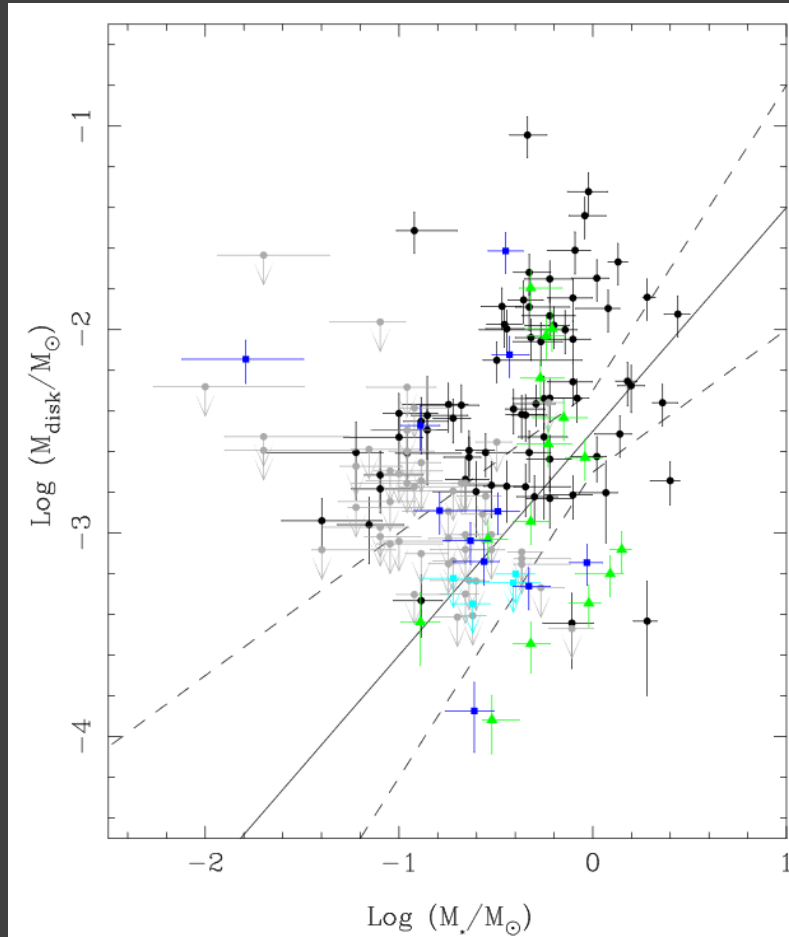
ALMA observations



Statistics of circumstellar discs in binaries

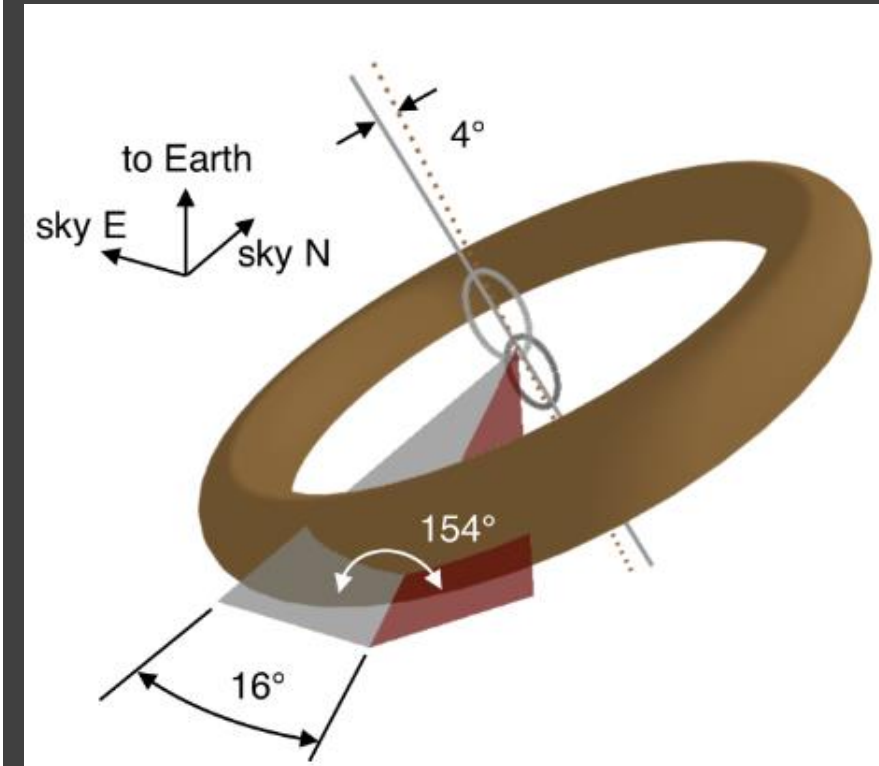
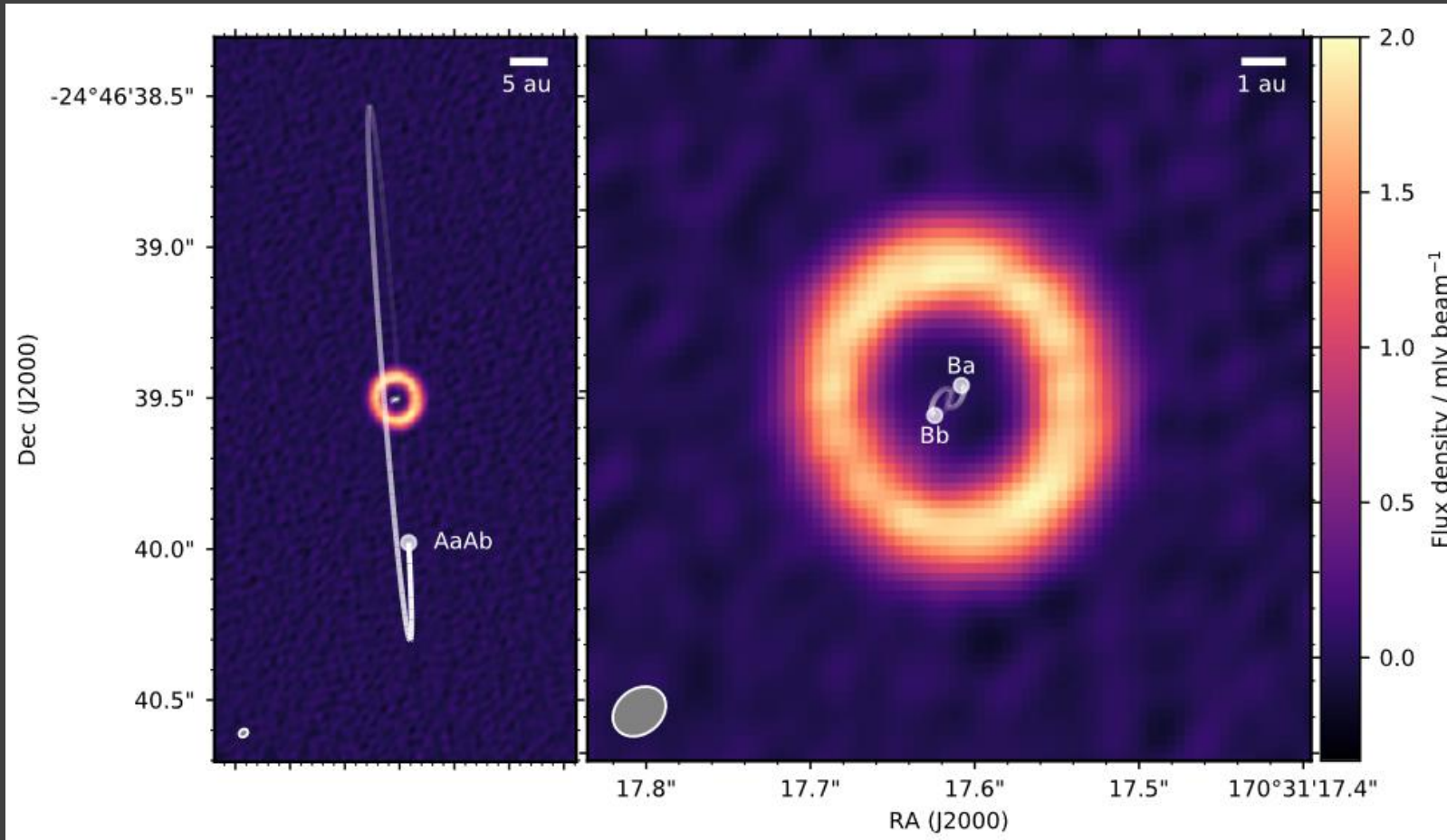
17 binary systems
100-1400 AU
ALMA observations

Secondary discs in two cases are brighter than discs around primaries.

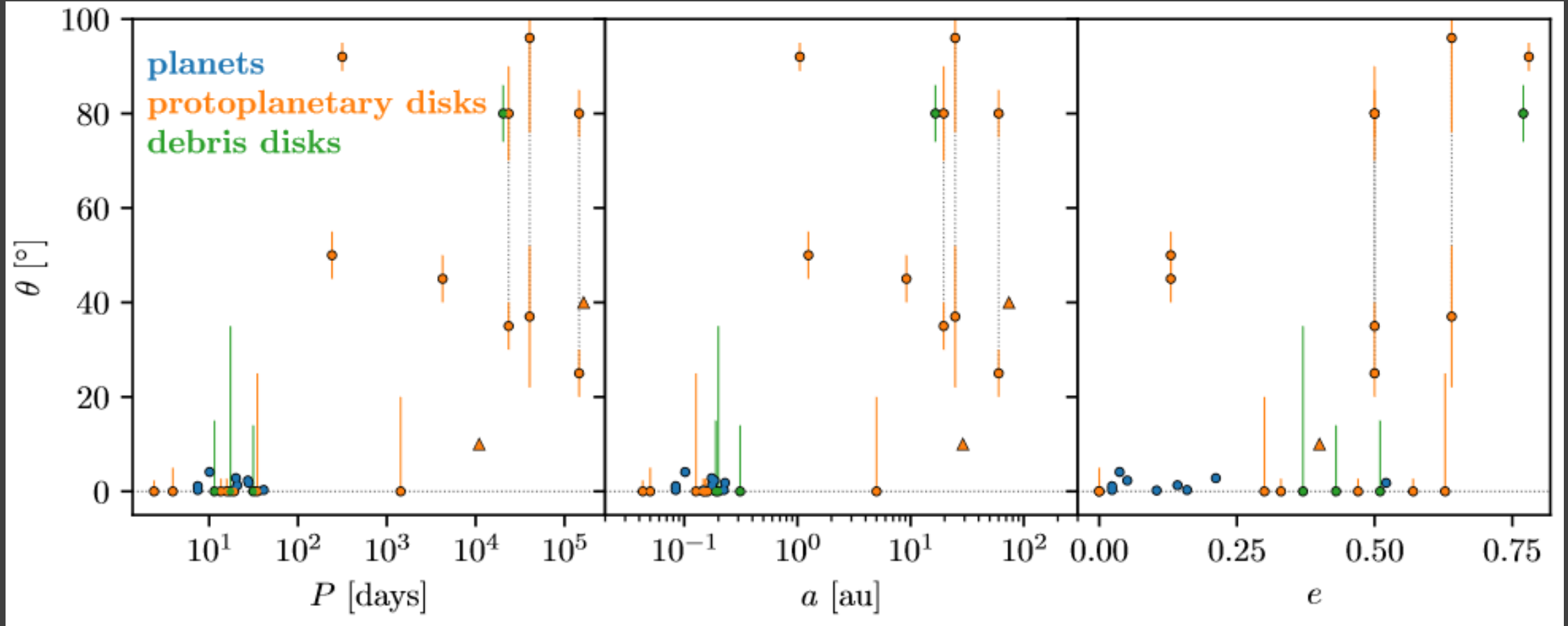


Green triangles – primaries;
Squares – secondaries
(dark blue – detected,
light blue – non-detected);
black dots – single stars
from other studies of the Taurus;
grey dots – single non-detections.

A circumbinary protoplanetary disc in a polar configuration



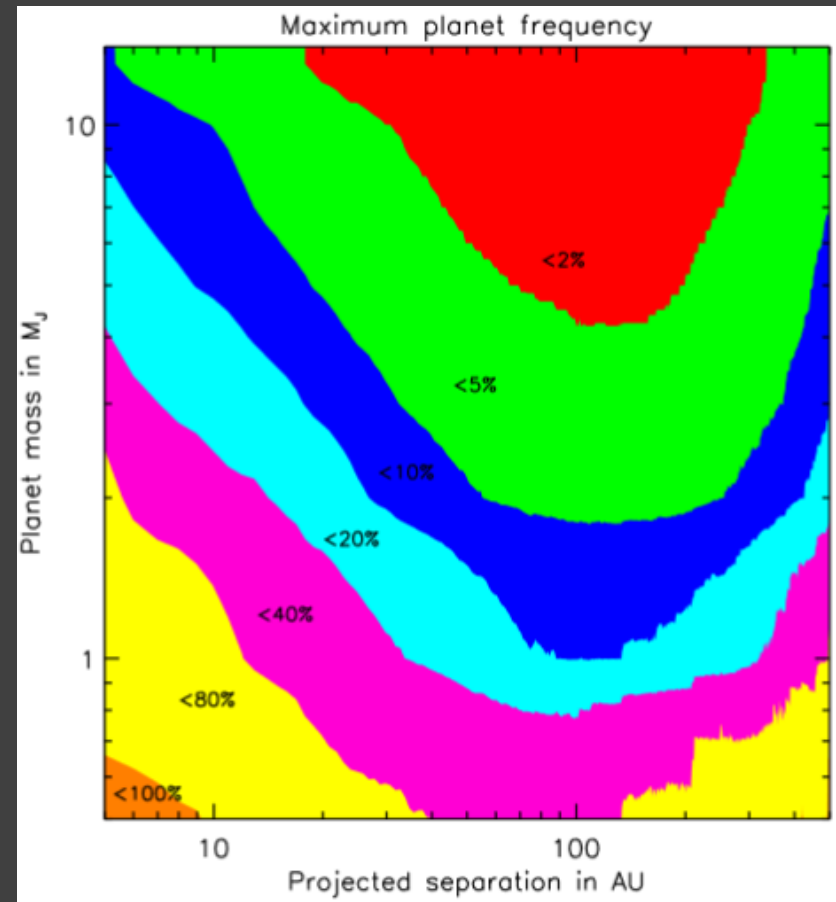
Circumbinary discs are often inclined



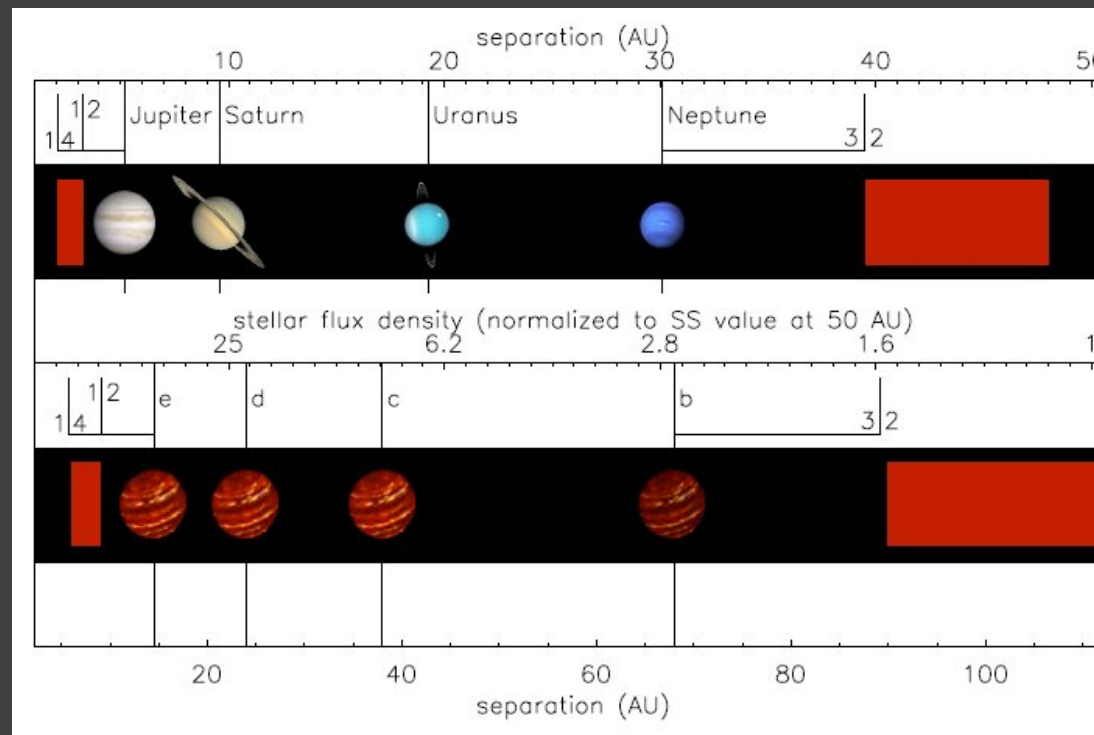
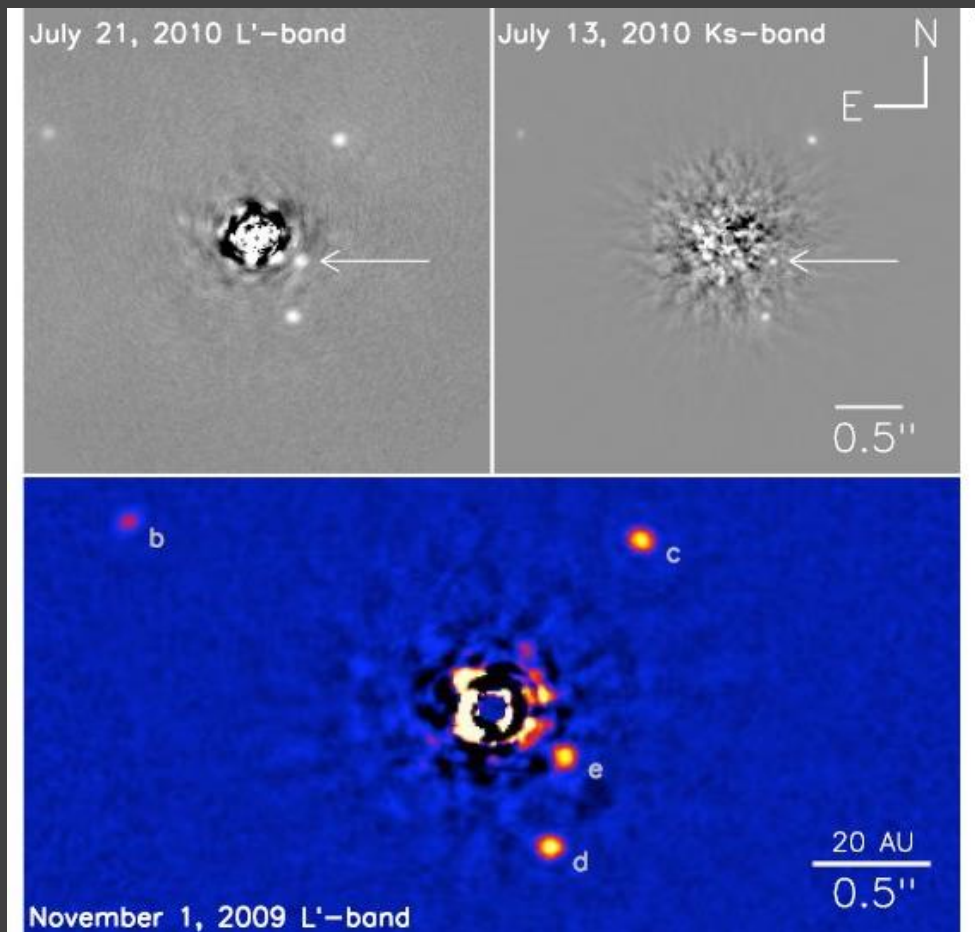
Direct imaging of planets

Recent survey with direct imaging resulted in an estimate that ~few percent of star have a planet 0.5-14 M_{Jup} at 20-300 AU.

HR8799 system and several brown dwarfs were found



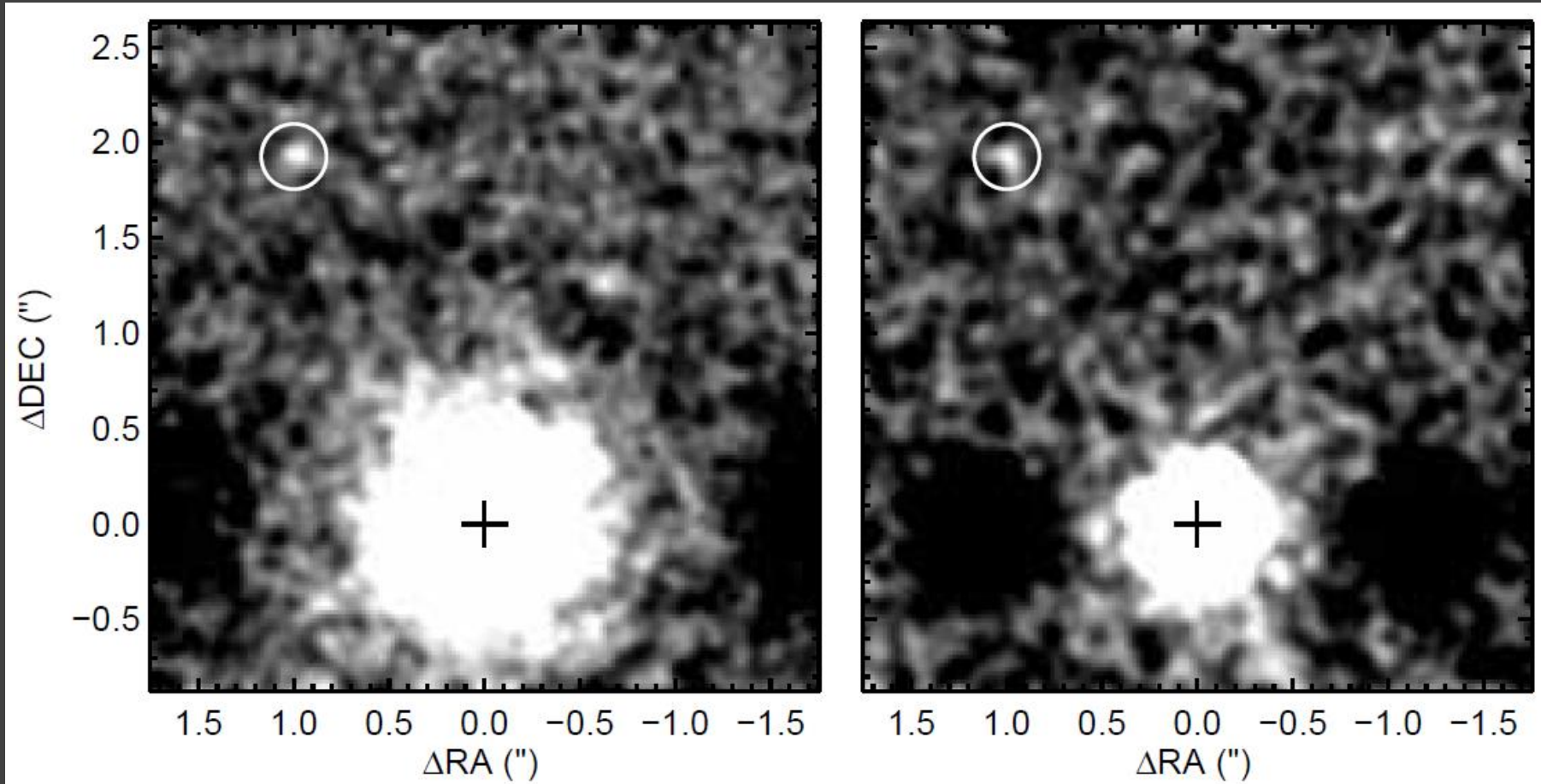
HR 8799



Keck II

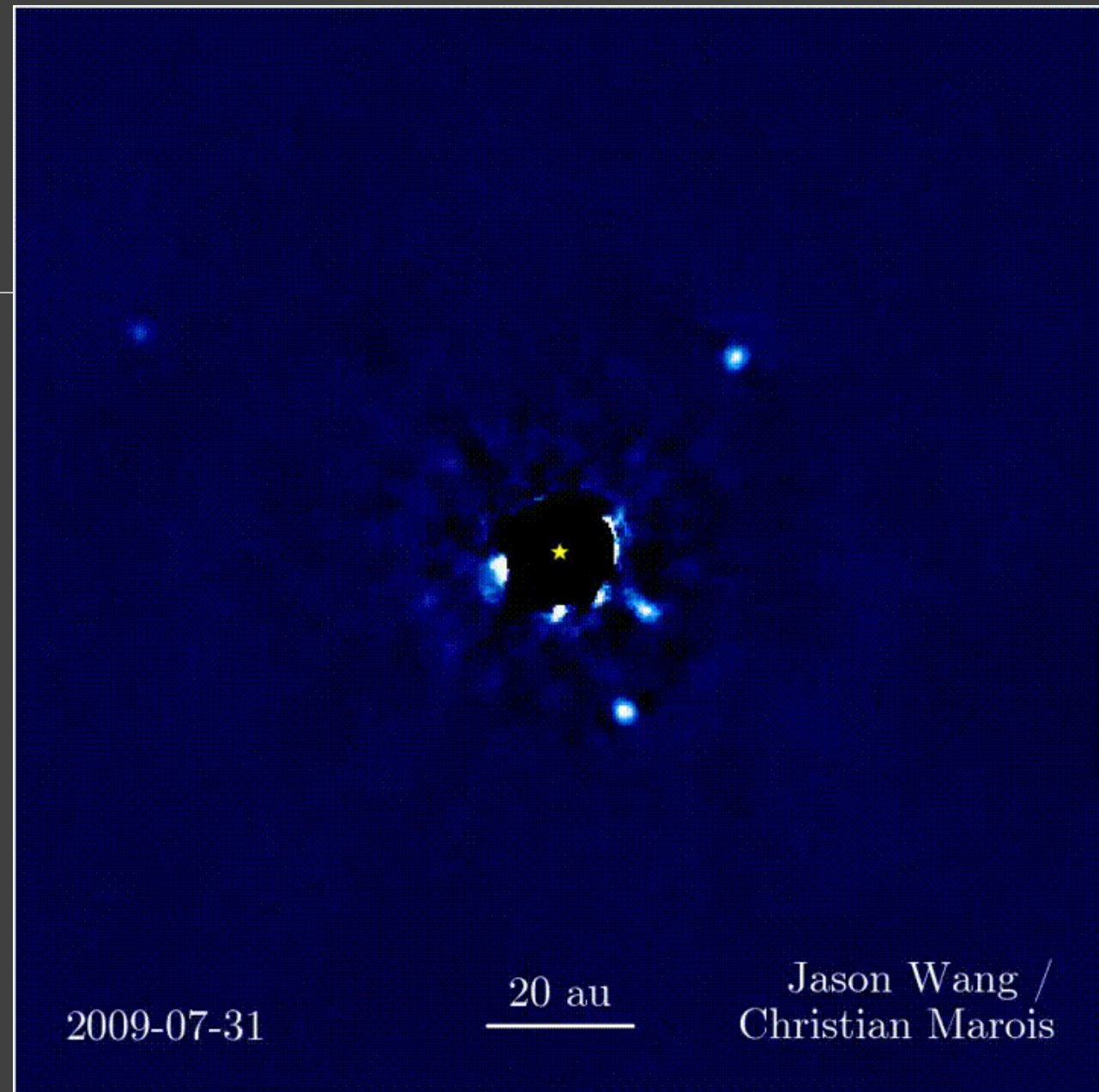
Structure similar to the Solar system,
but if expanded by factor 2

Young star 1RXS J160929.1-210524



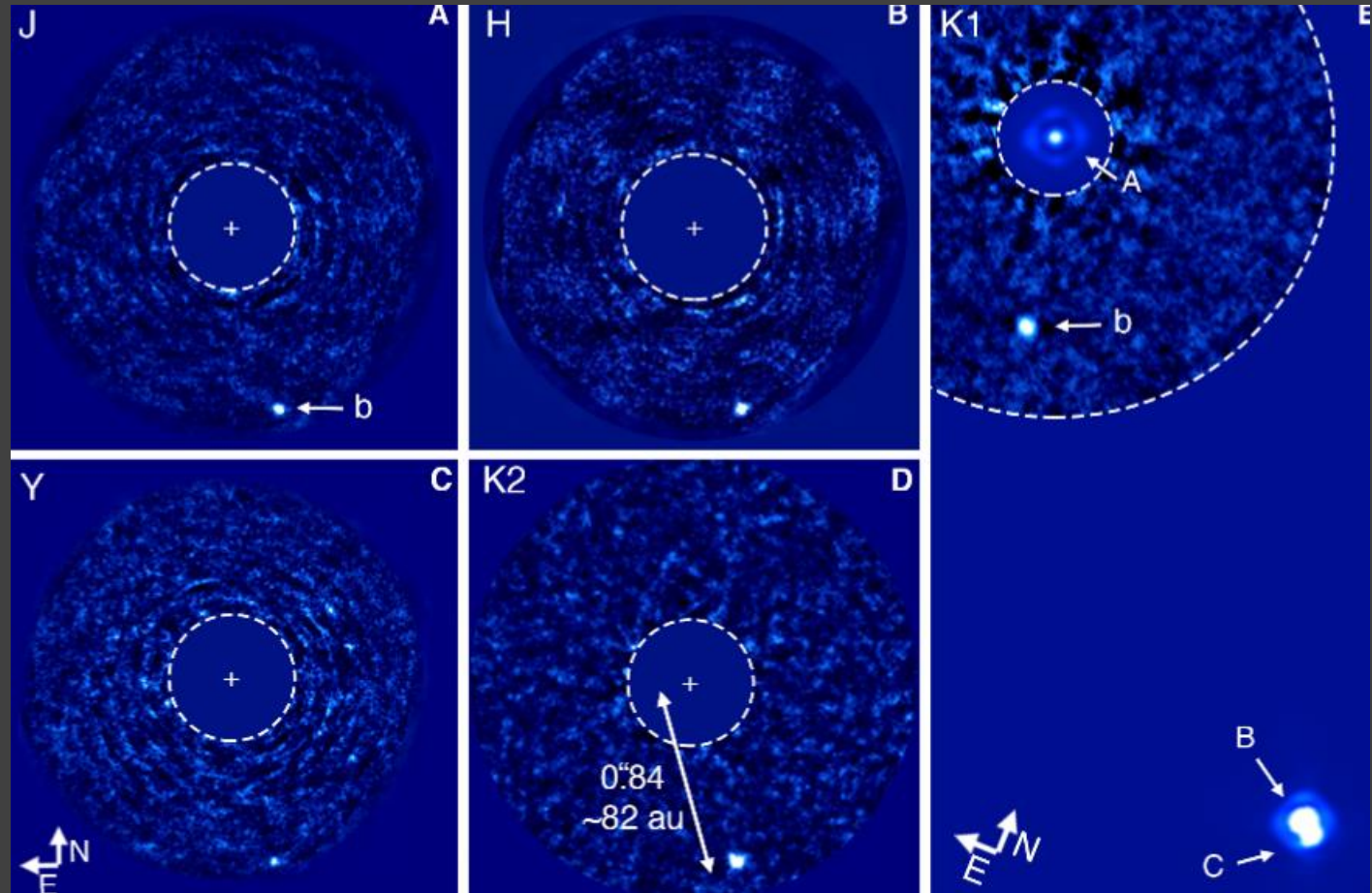
Gemini North

HR 8799

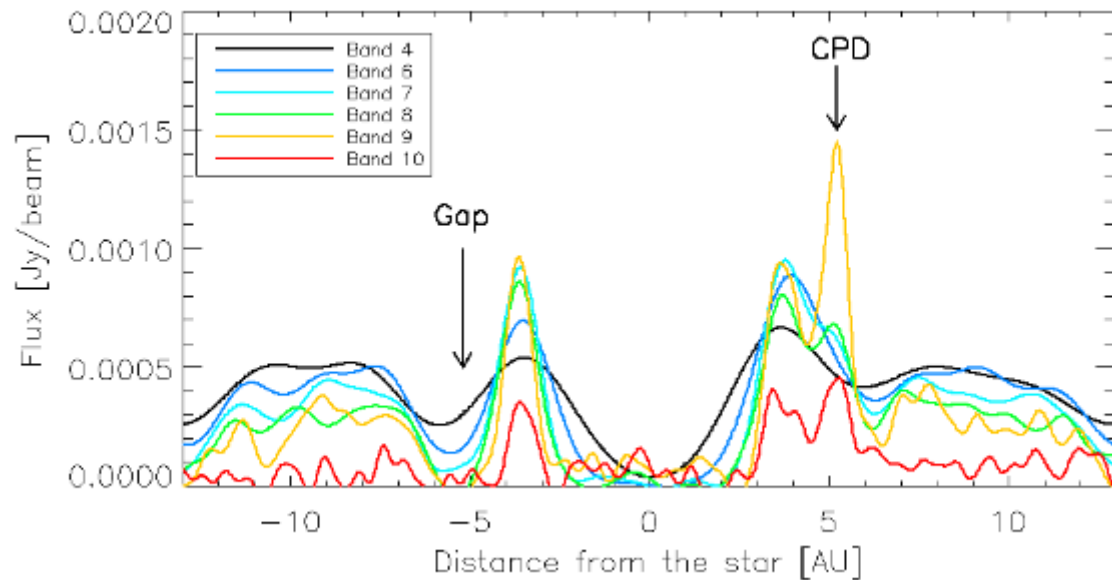


Planet in a triple system

Young planet ~16 Myr.
Observed by VLT
Orbit might be unstable.

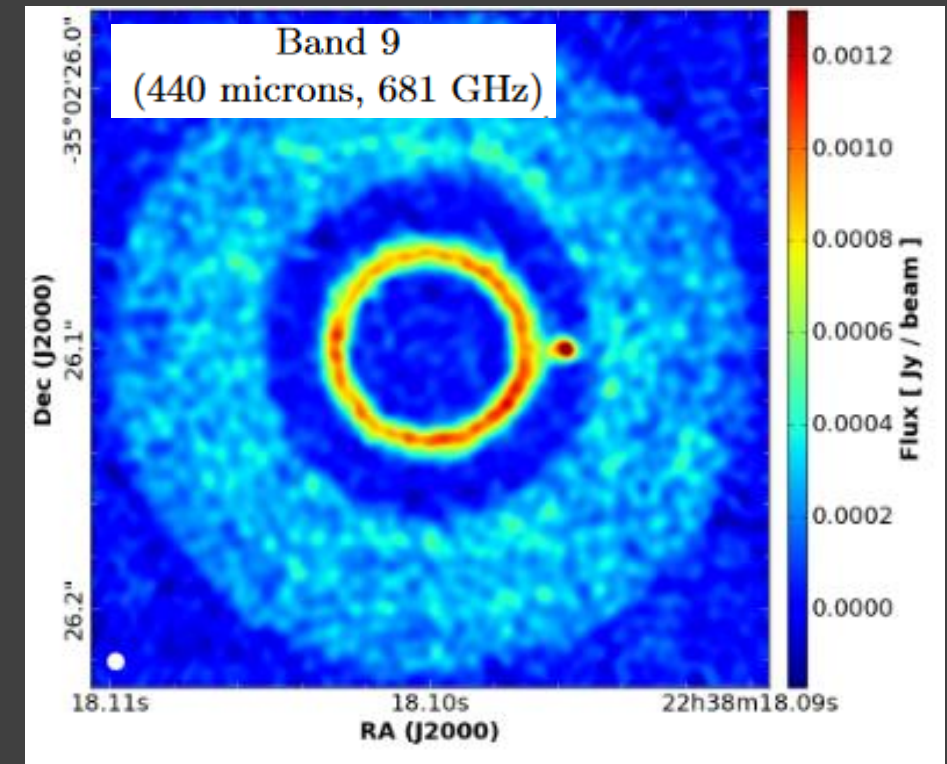


Circumplanetary discs (mock simulations)

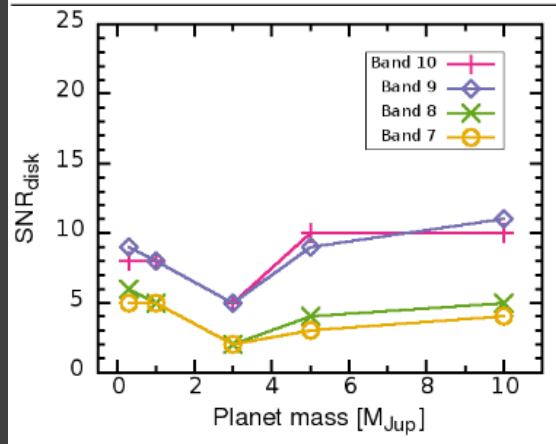
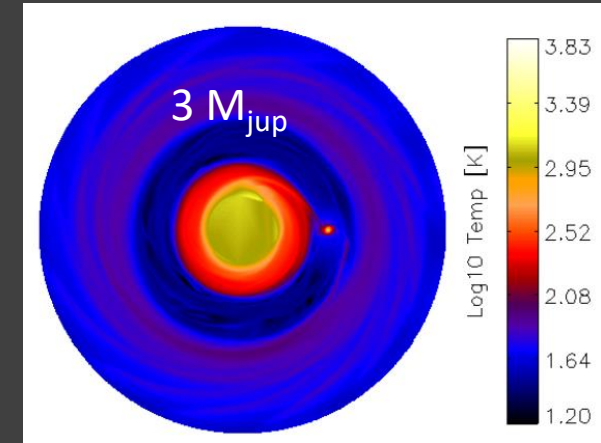
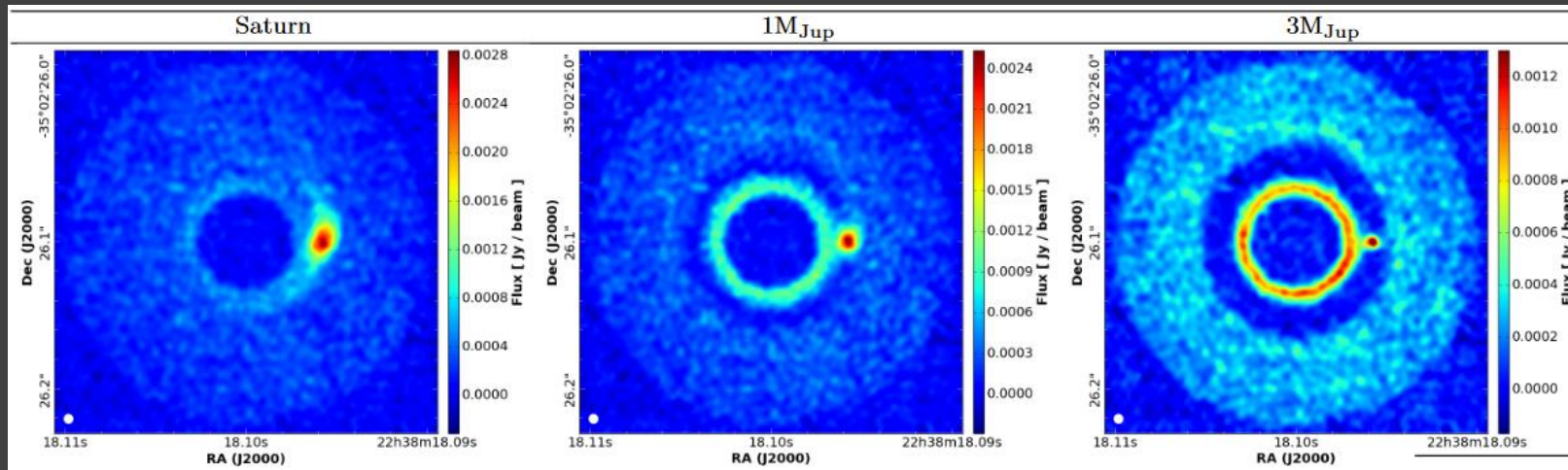


3 Jupiter masses
5 hours of observations
Better visible at shorter wavelengths
Gap opening is important
Planet temperature 4000K (age ~ 1 Myr)

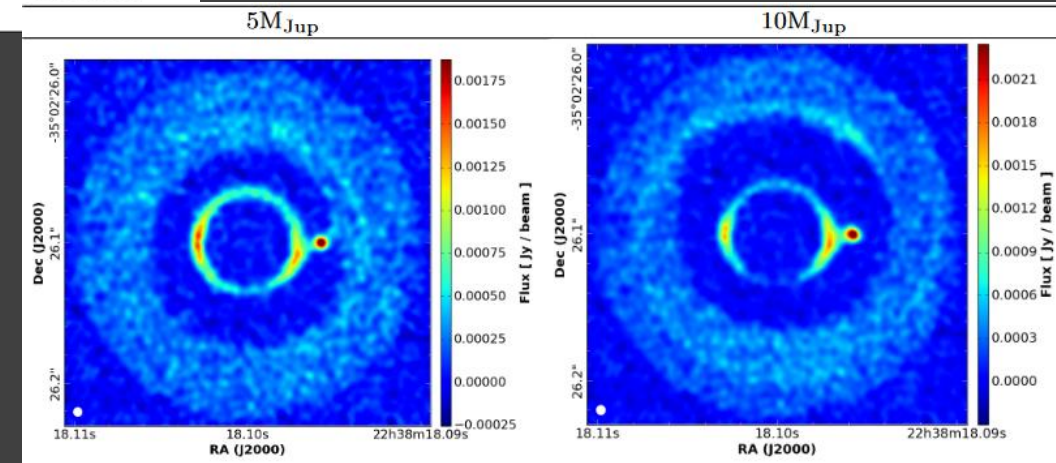
Size of a circumplanetary disc is about $\frac{1}{2}$ of the Hill sphere.
Thus, it can be hardly resolved by ALMA, but can be detected.
Presently, only upper limits are available (2003.08658).



Dependence on the planet mass



Light planets, like Saturn, can also be detected.



Literature

arxiv:1507.04758 Observations of Solids in Protoplanetary Disks

arxiv:1703.08560 Circumstellar discs: What will be next?

arXiv: 1804.08636, 1802.04313 Debris discs

arxiv:1602.06523 Resolved observations of transition disks

arxiv:1607.08239 The International Deep Planet Survey II:
The frequency of directly imaged giant exoplanets with stellar mass

arXiv:1801.07721 Population synthesis of protostellar discs

arXiv:2001.05007 Observations of Protoplanetary Disk Structures

arXiv: 2009.04345 Visualising the Kinematics of Planet Formation