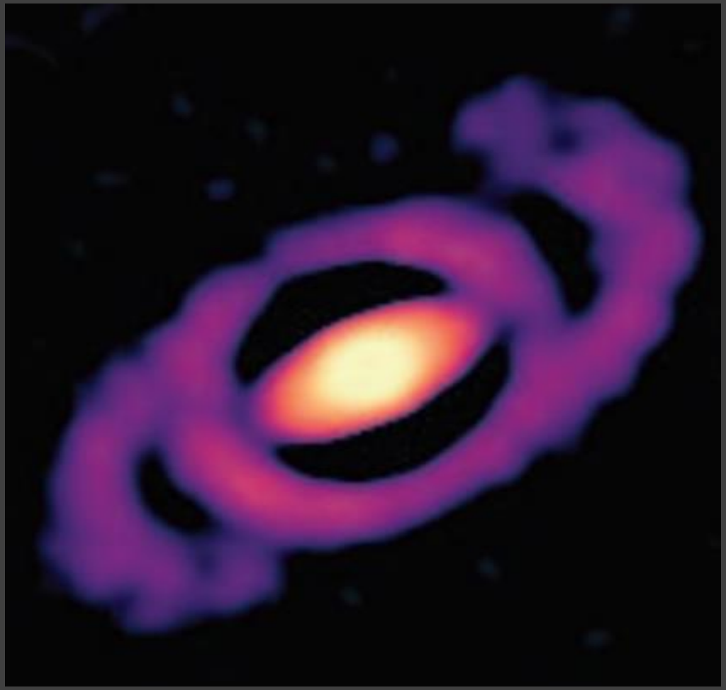
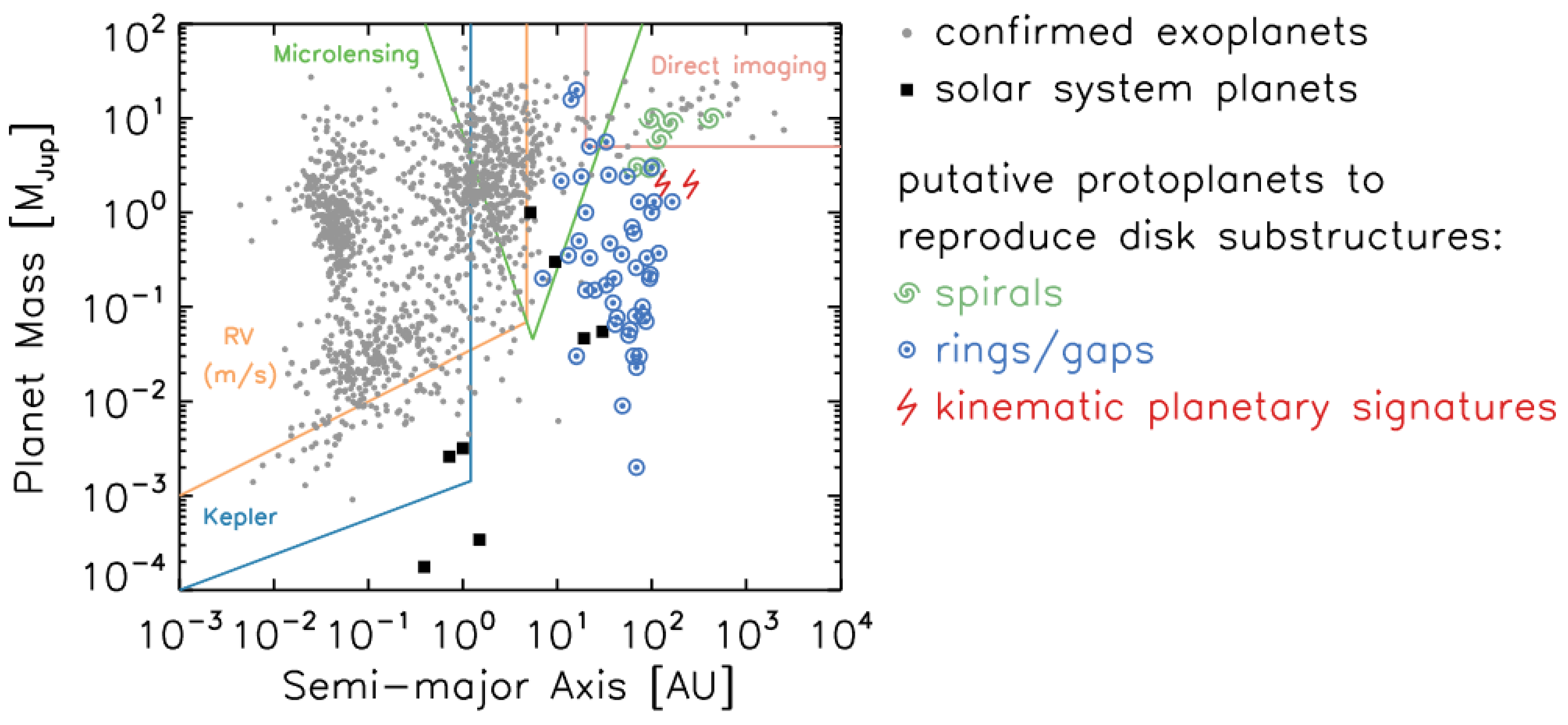


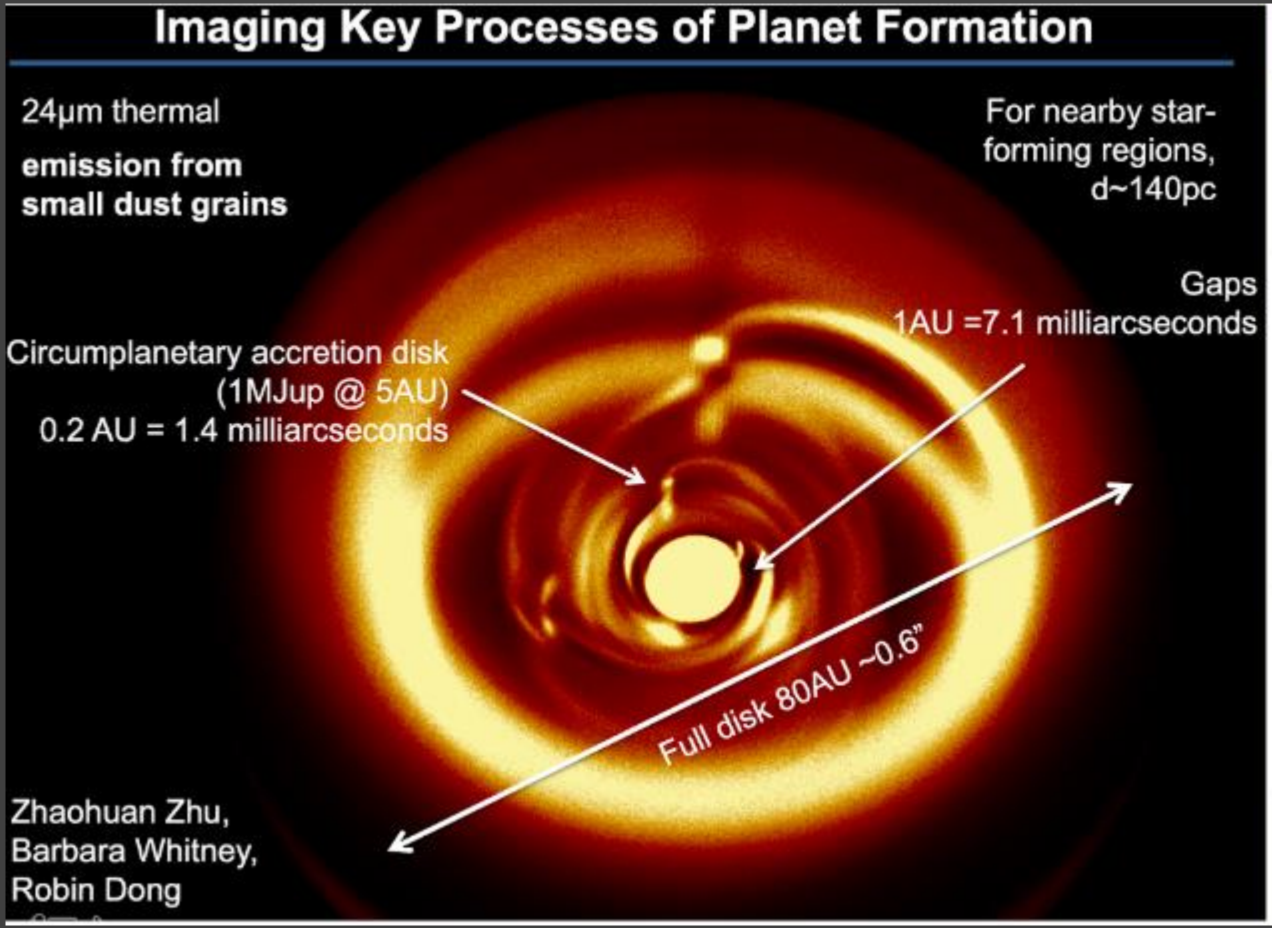
Young planetary systems

SERGEI POPOV

Planets and discs



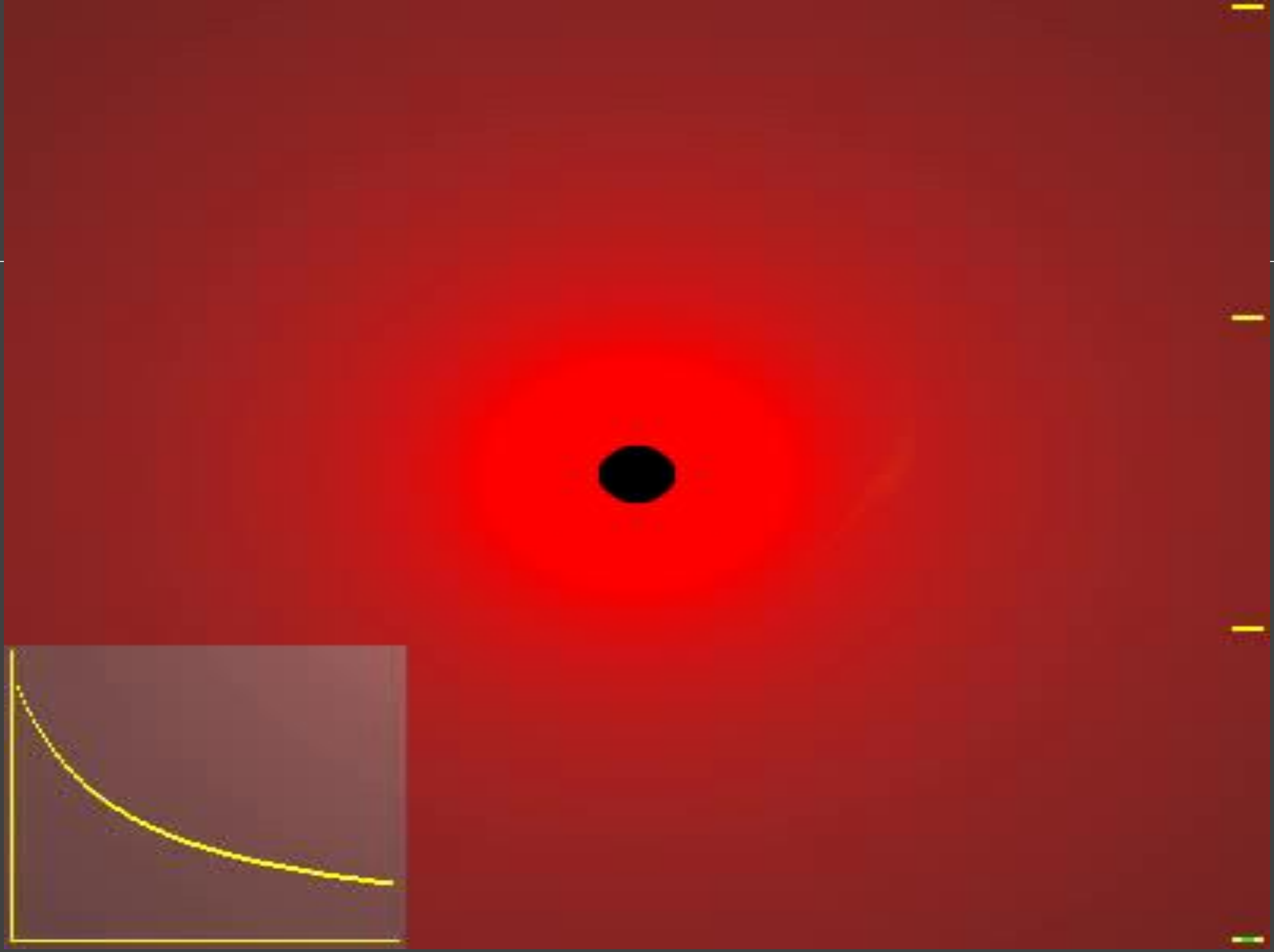
Modeling and imaging planet formation



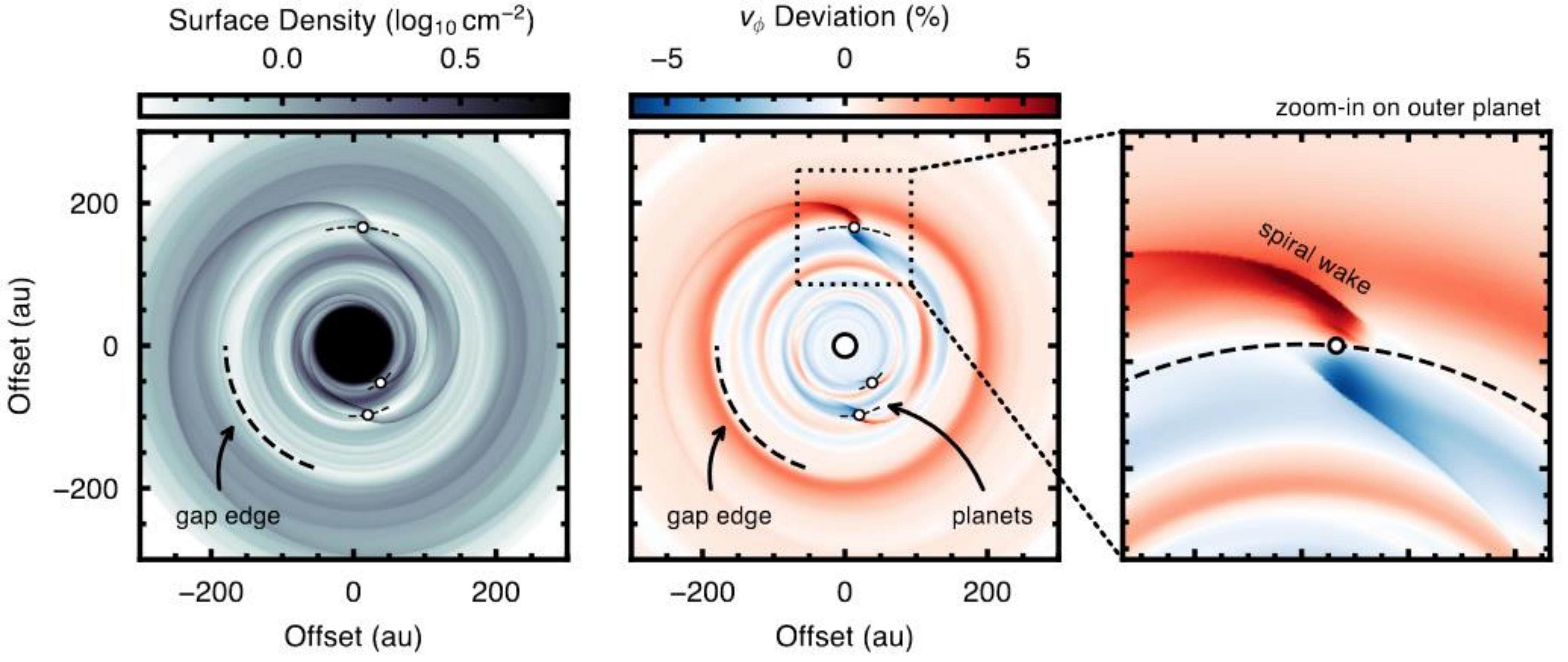
Feature	Scale	Methods
Overall Disk	80au	mm-wave (ALMA); Coronagraphy on 8+meter telescopes; JWST
Large gaps and structures	5-20au	mm-wave (ALMA); Radio (ngVLA); Coronagraphy on 8+meter telescopes; JWST
Terrestrial Planet Zone	<4au	30m telescope; IR interferometry (CHARA,VLTI, MROI)
Gaps and accretion streams from individual planets	<1au	mm-wave (ALMA); 30m telescopes; IR interferometry (CHARA, VLT, MROI)
Circum*planetary* Disks	<0.2au	IR interferometry (FUTURE FACILITY)

1907.09564

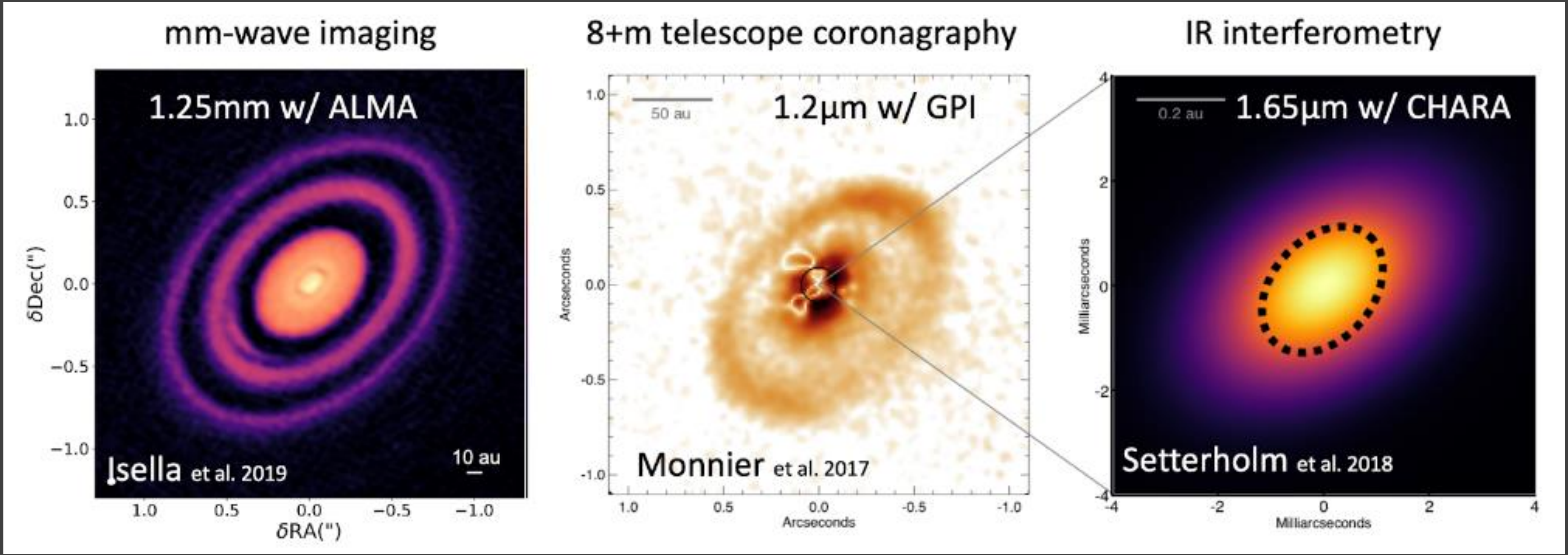
Picture shows results of computer simulation.



Planet-disc interaction

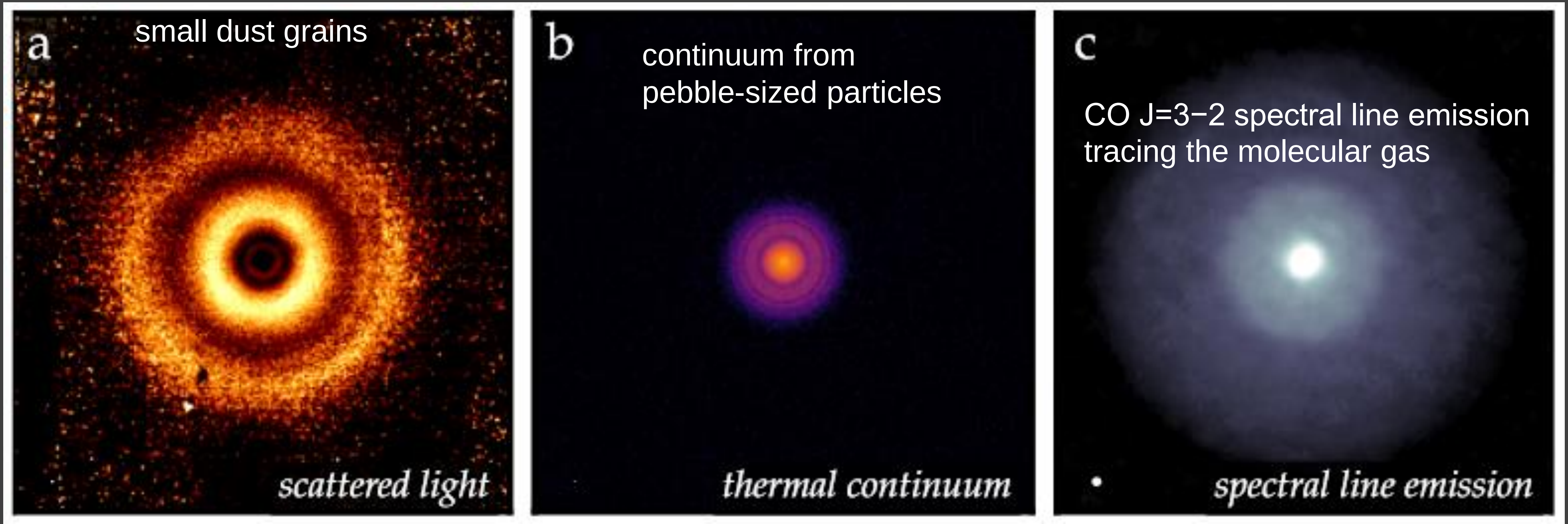


More details with different techniques

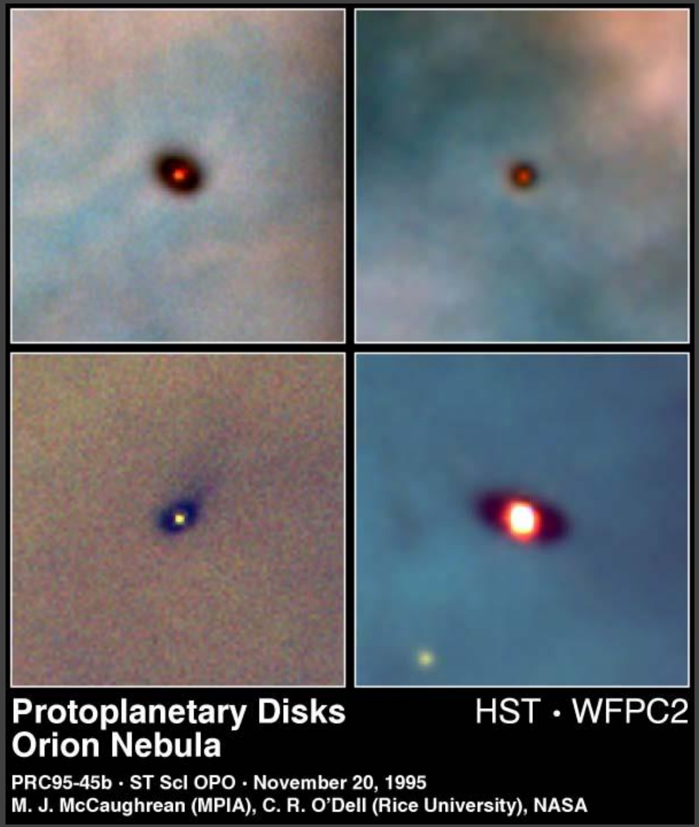


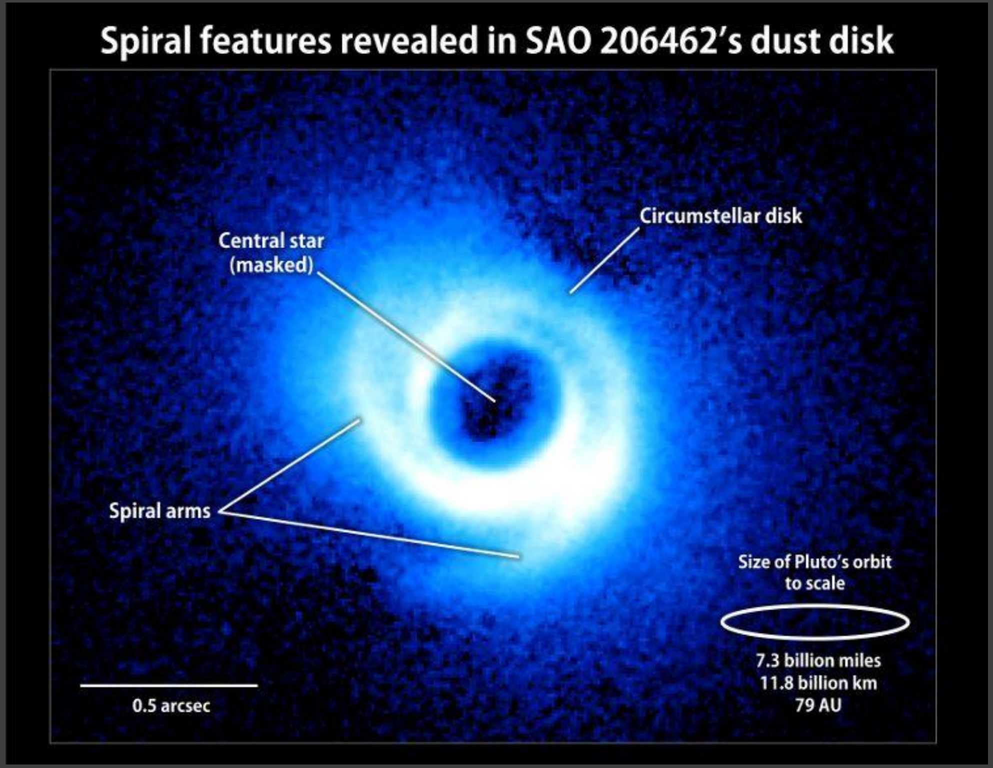
Different structures in different light

TW Hya disk



Protoplanetary discs





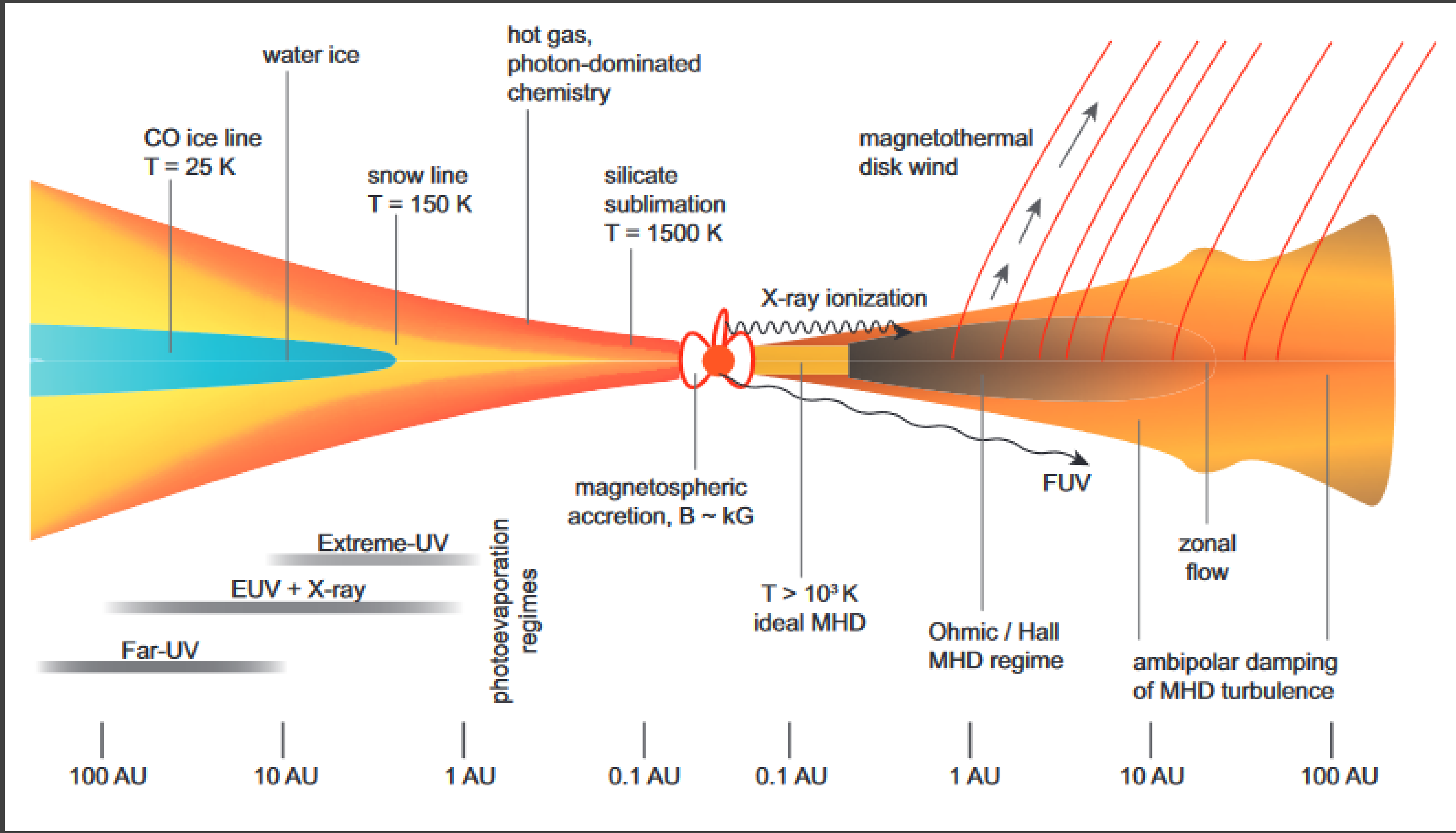
https://online.science.psu.edu/astro140_sp201314wd001/node/7717
http://news.softpedia.com/news/Exoplanets-Can-Form-Spiral-in-Stellar-Protoplanetary-Disks-228792.shtml

Dusty discs

HST observations

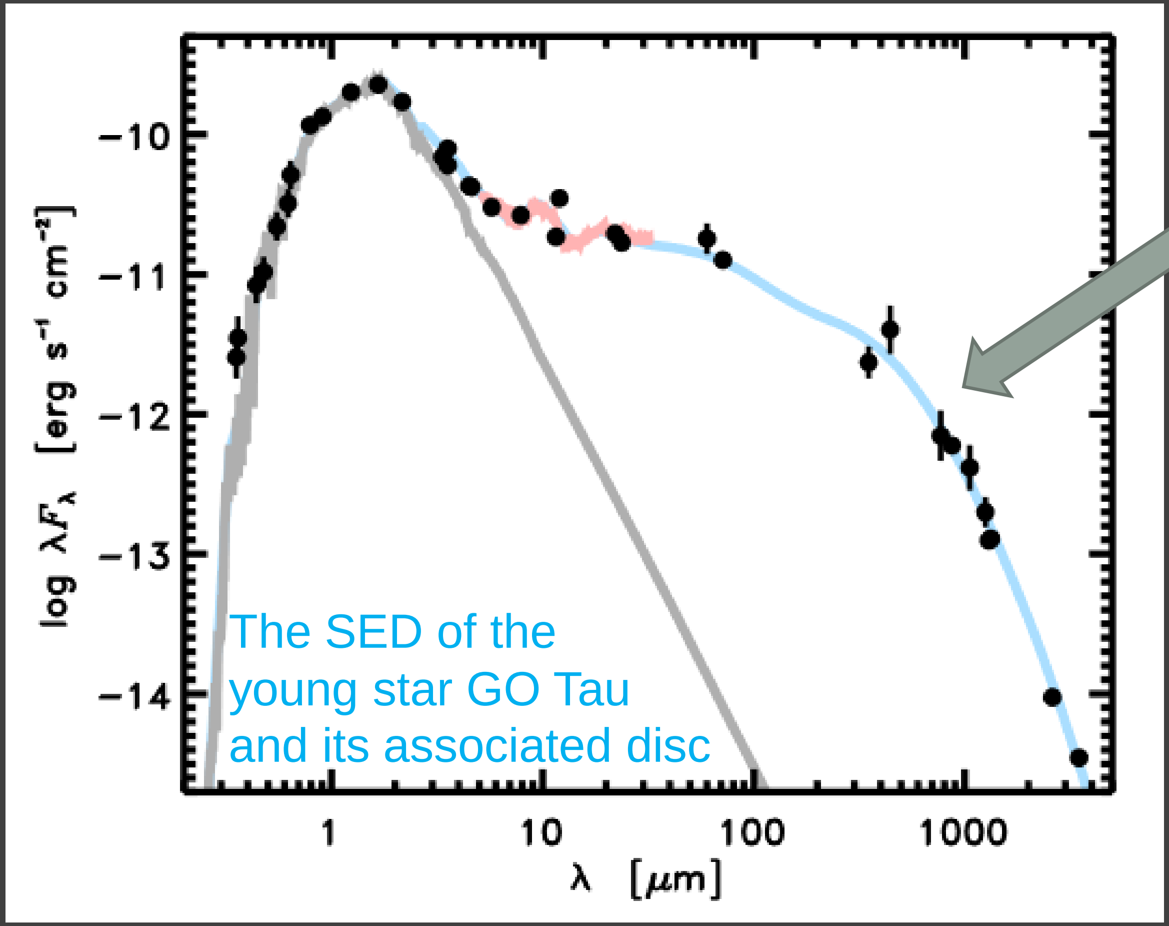
Disc is visible edge-on.

Disc structure



1803.10526

Discs and stars



Optically thin disc.
Allows to determine dust mass.

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

See 1807.09631
about different methods
of dust mass determination

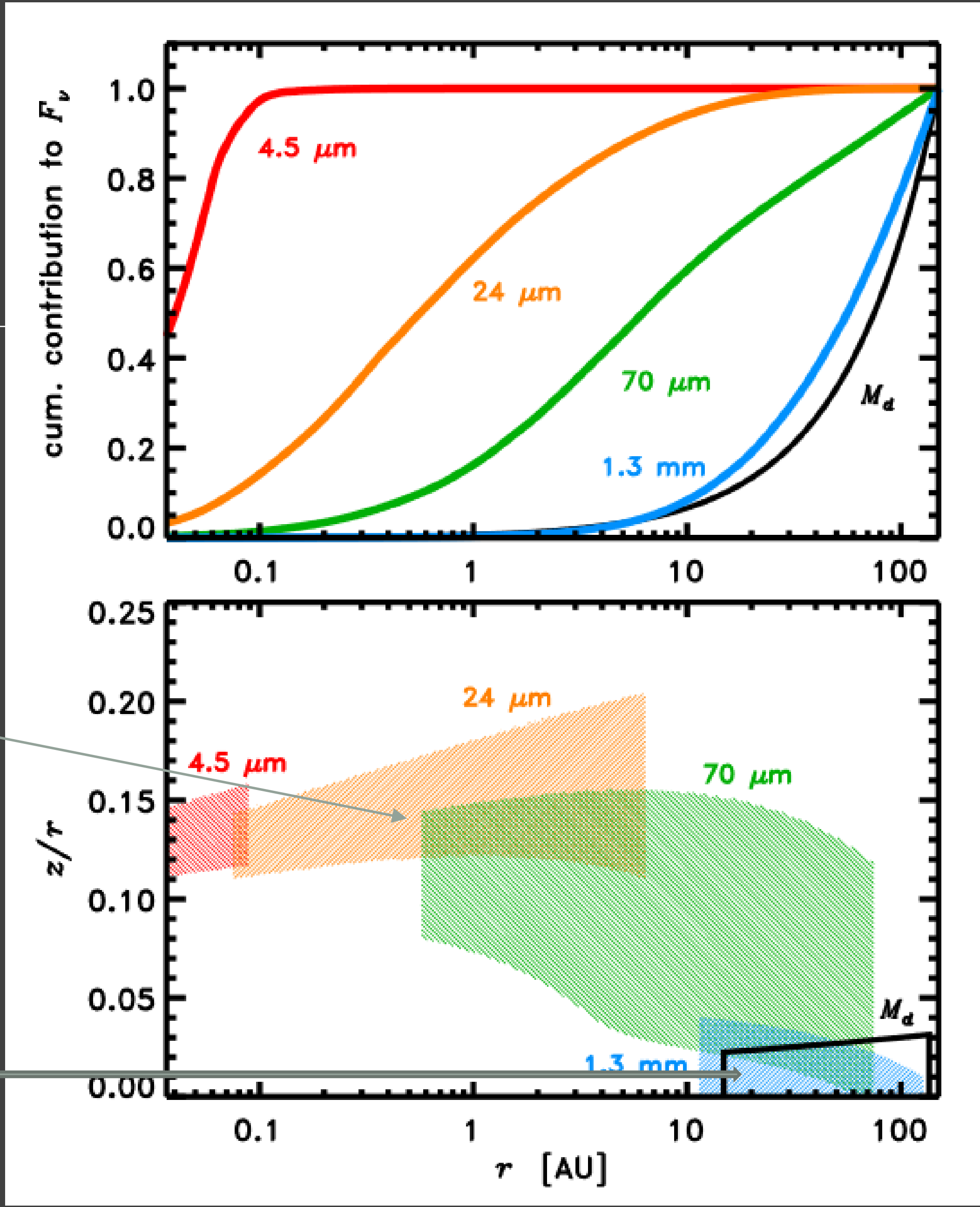
$$M_{\rm dust} \propto M_{\rm star}^{1.8}.$$

Dust in the disc

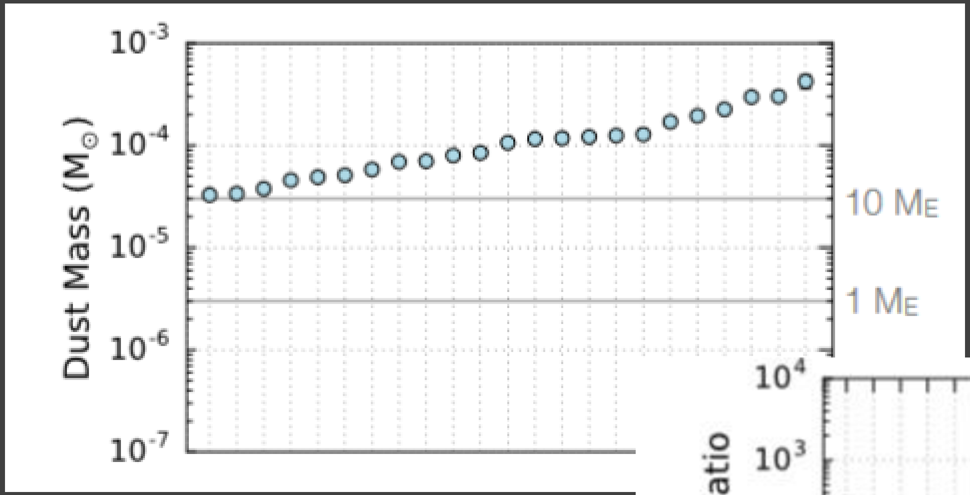
Observations in different wavelengths allow to probe different parts of the disc and determine dust mass and distribution.

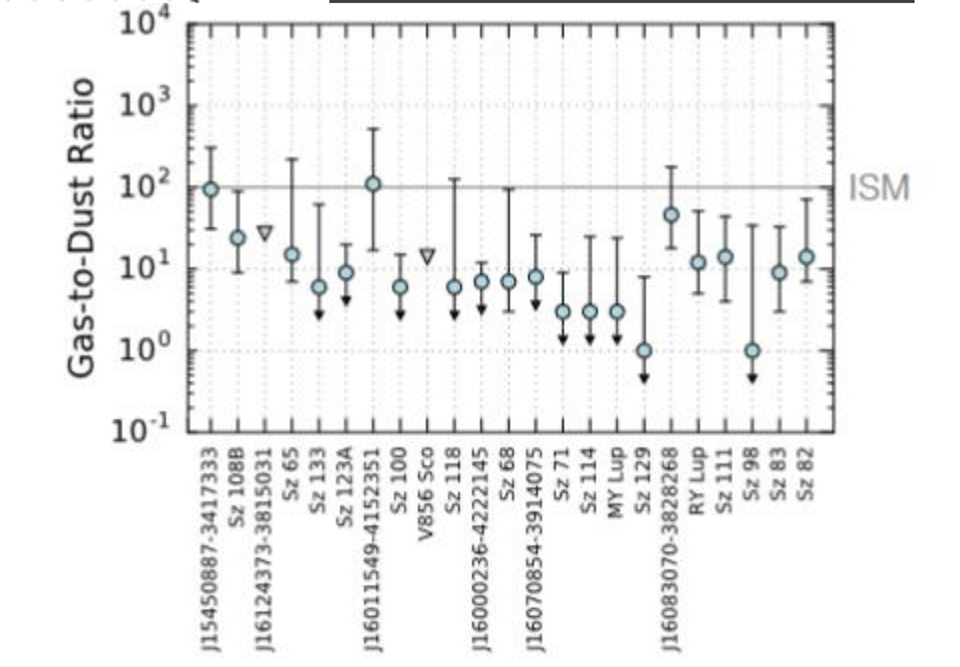
Regions of 80% of emission in each band

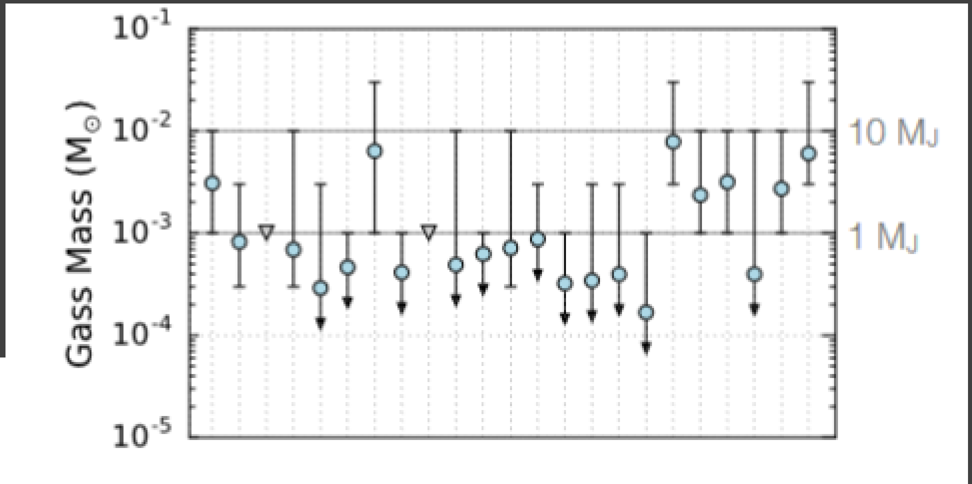
80% of dust



Disc mass: gas + dust

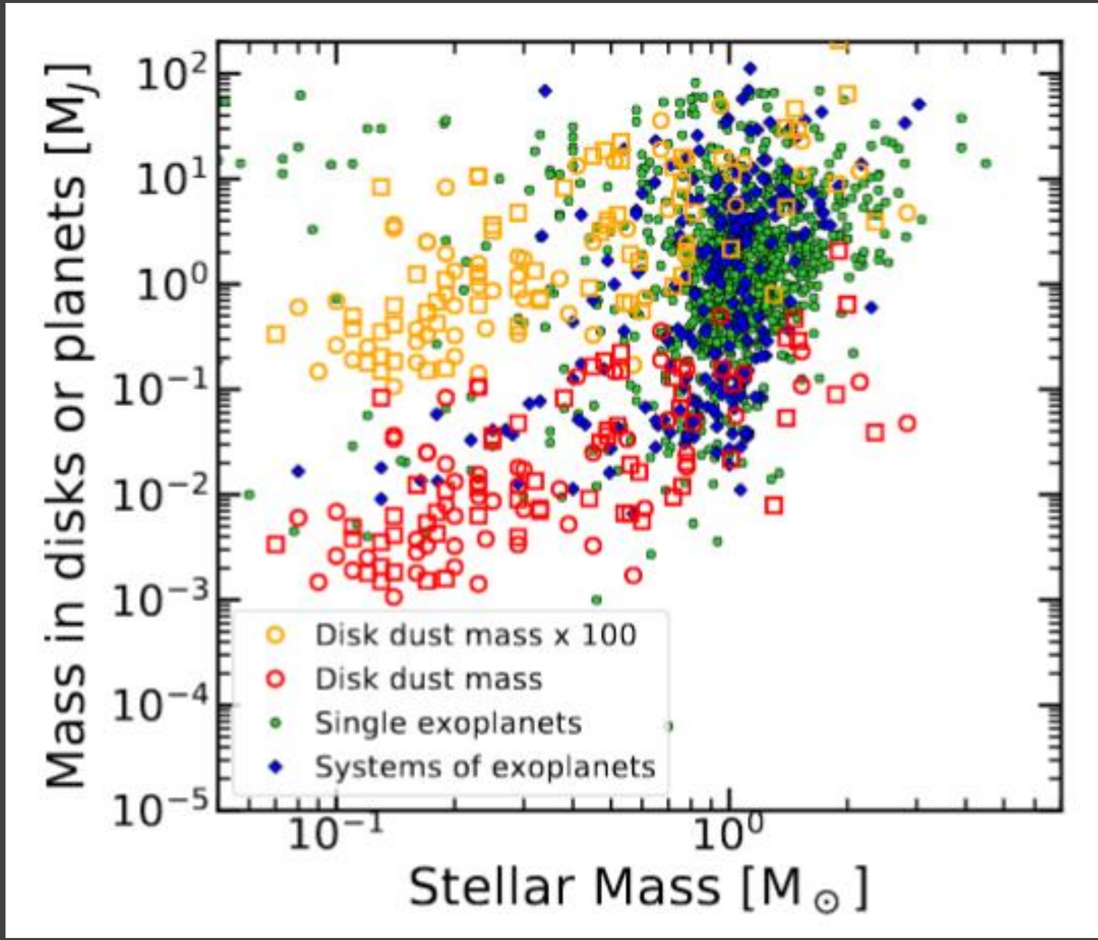


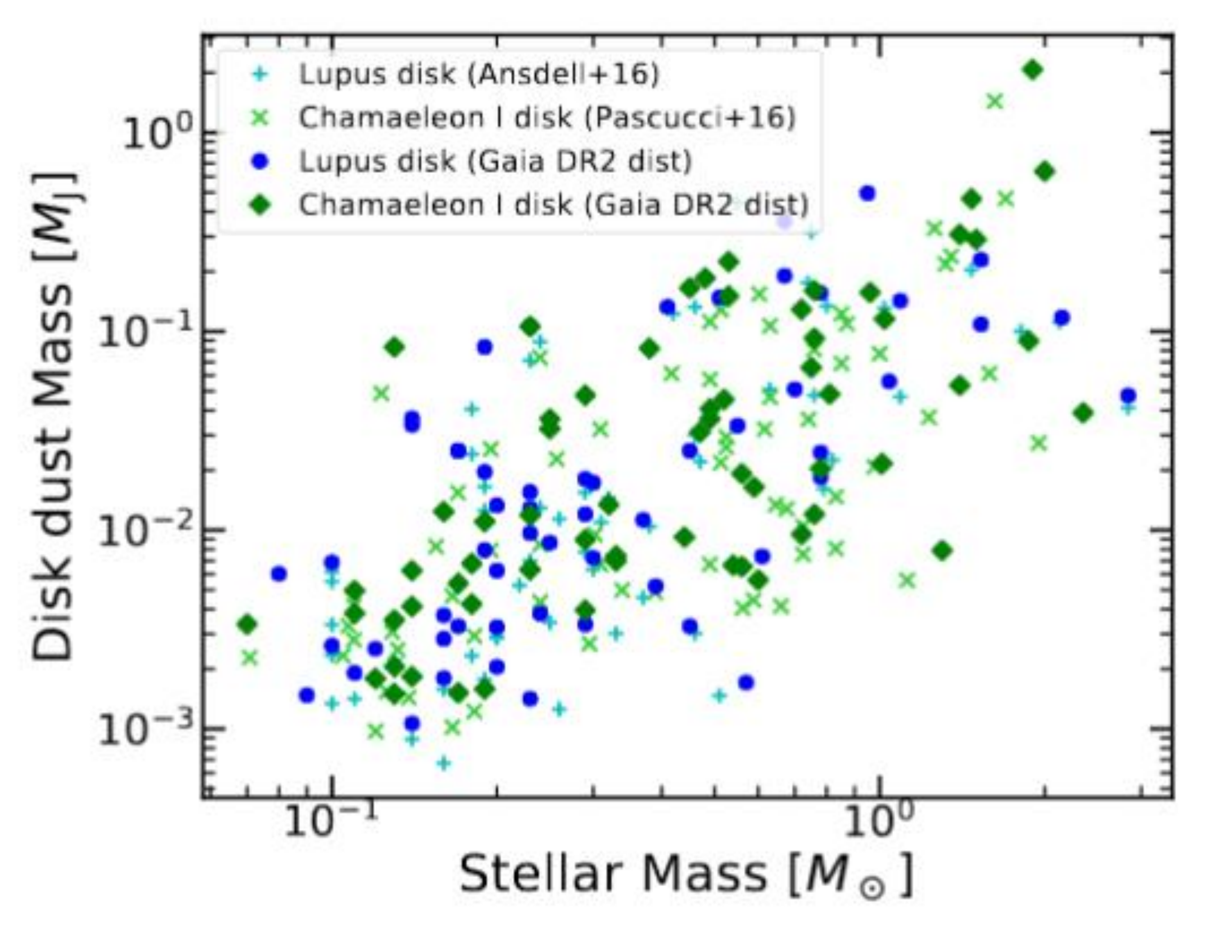




Gas mass determined
by Co observation (ALMA).

Disc mass vs. star mass

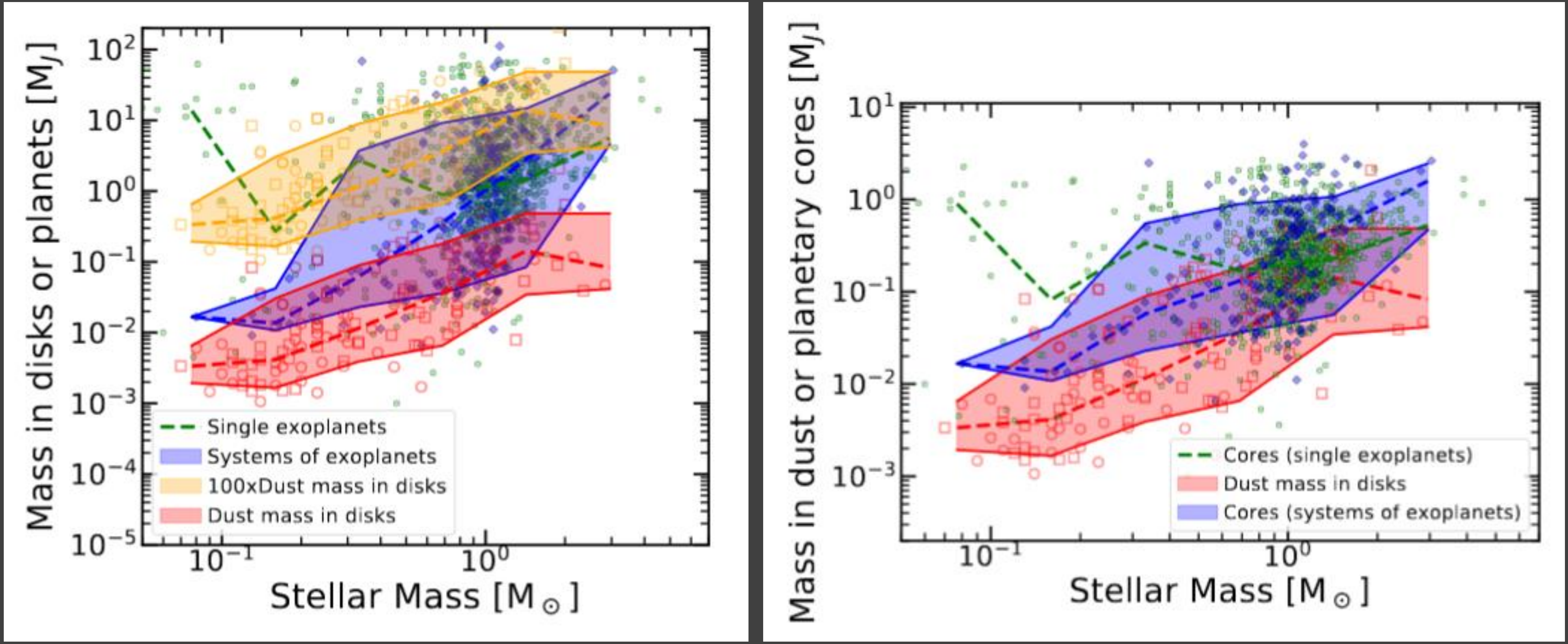




1809.07374

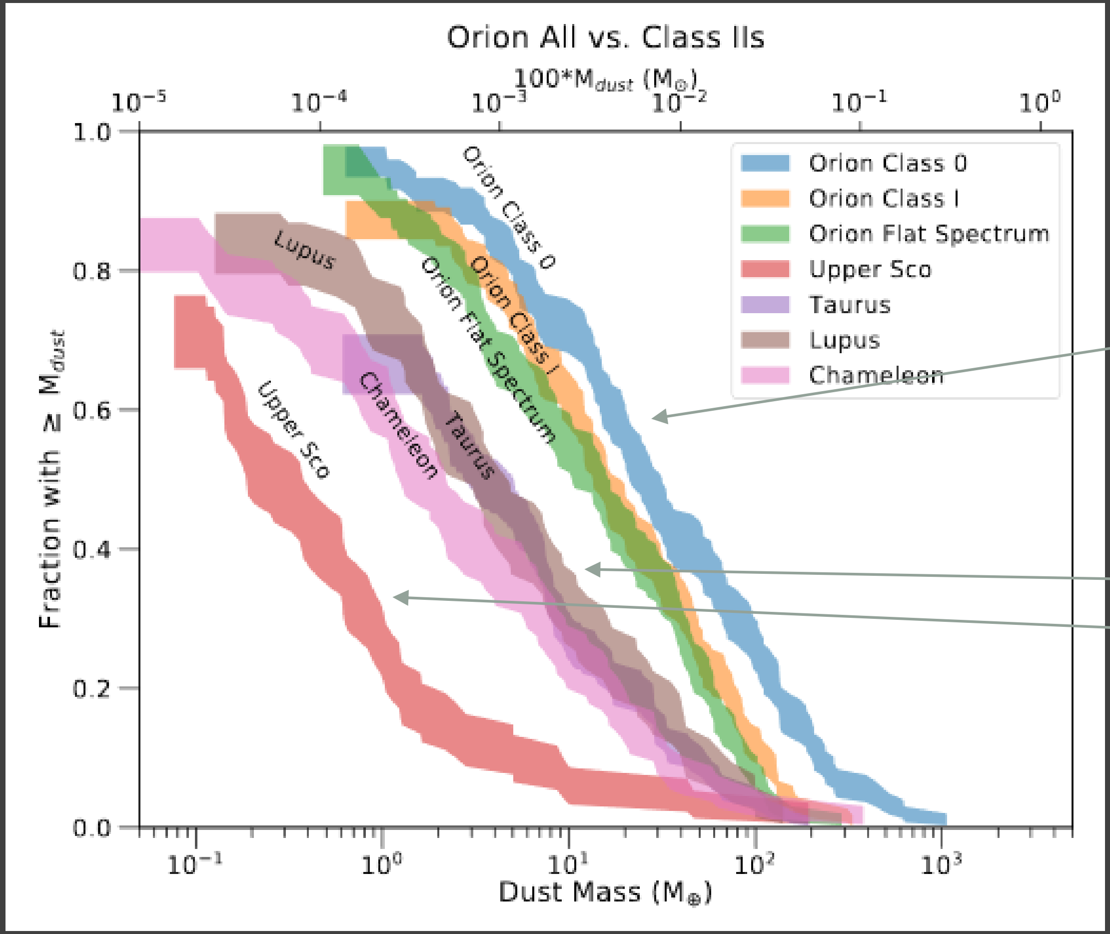
Not enough mass is discs??? Rapid early evolution???

Disc and planet mass correlations with the stellar mass



1809.07374

Indeed, evolution, baby

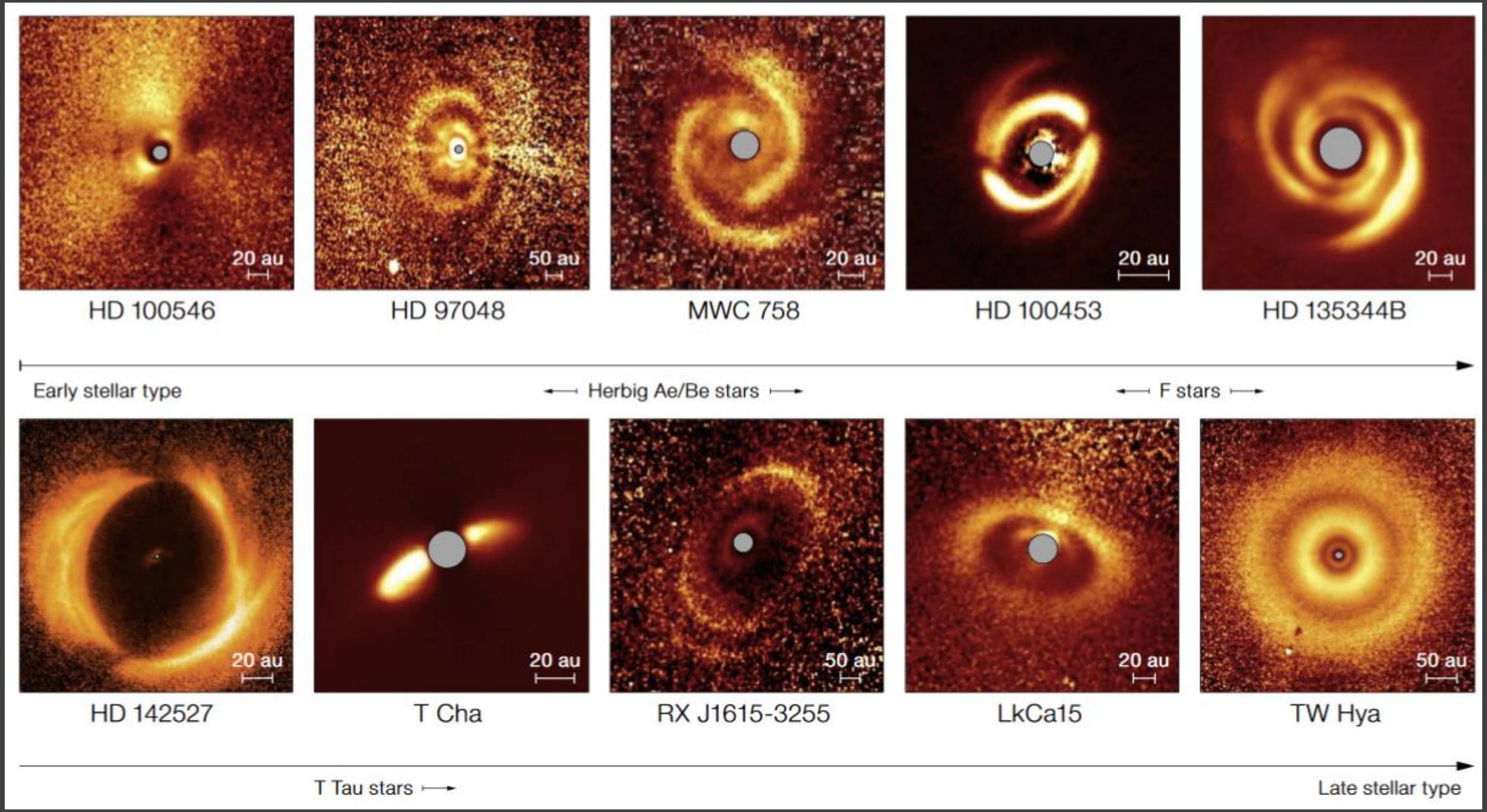


Young discs

Older discs

2001.04468

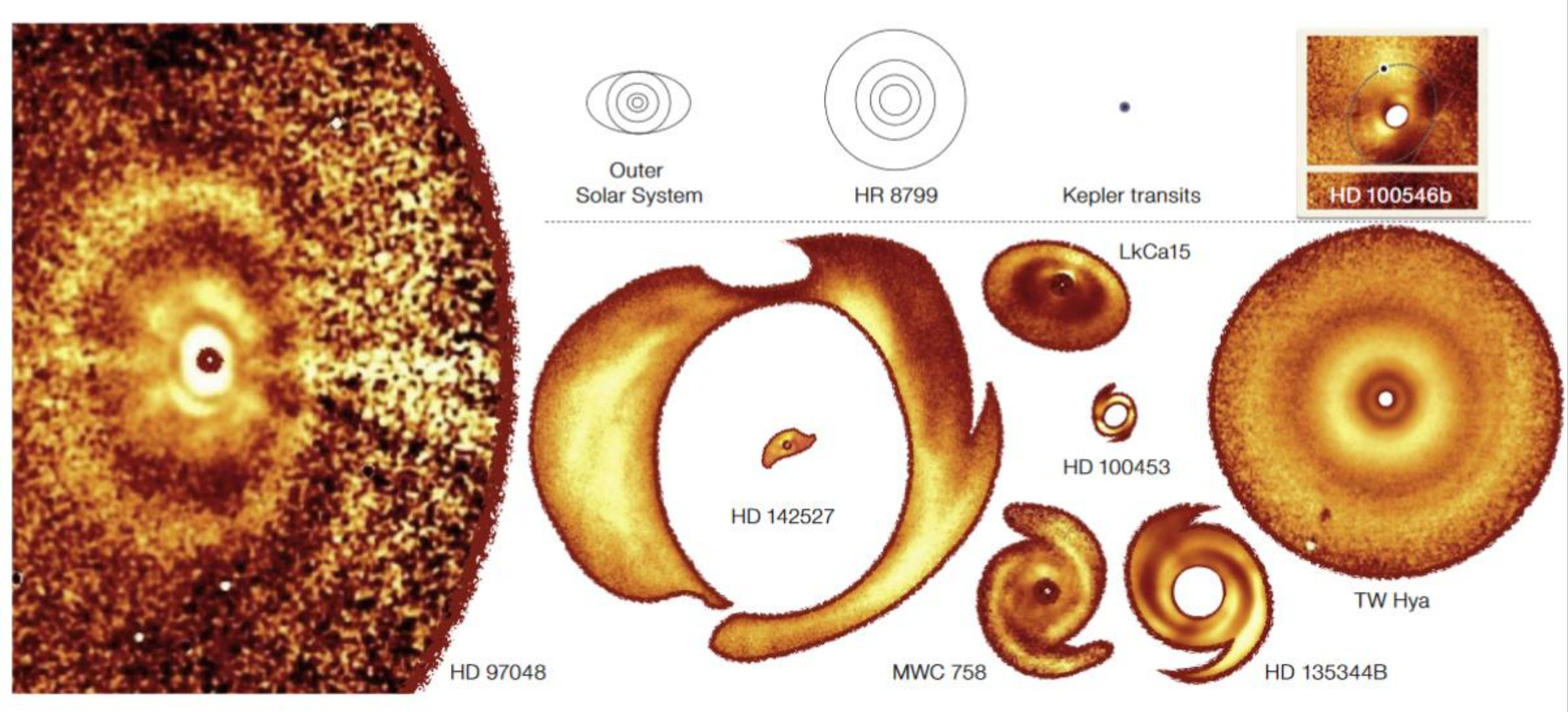
VLT/SPHERE



1710.02795

0.5-2.3 micrometers

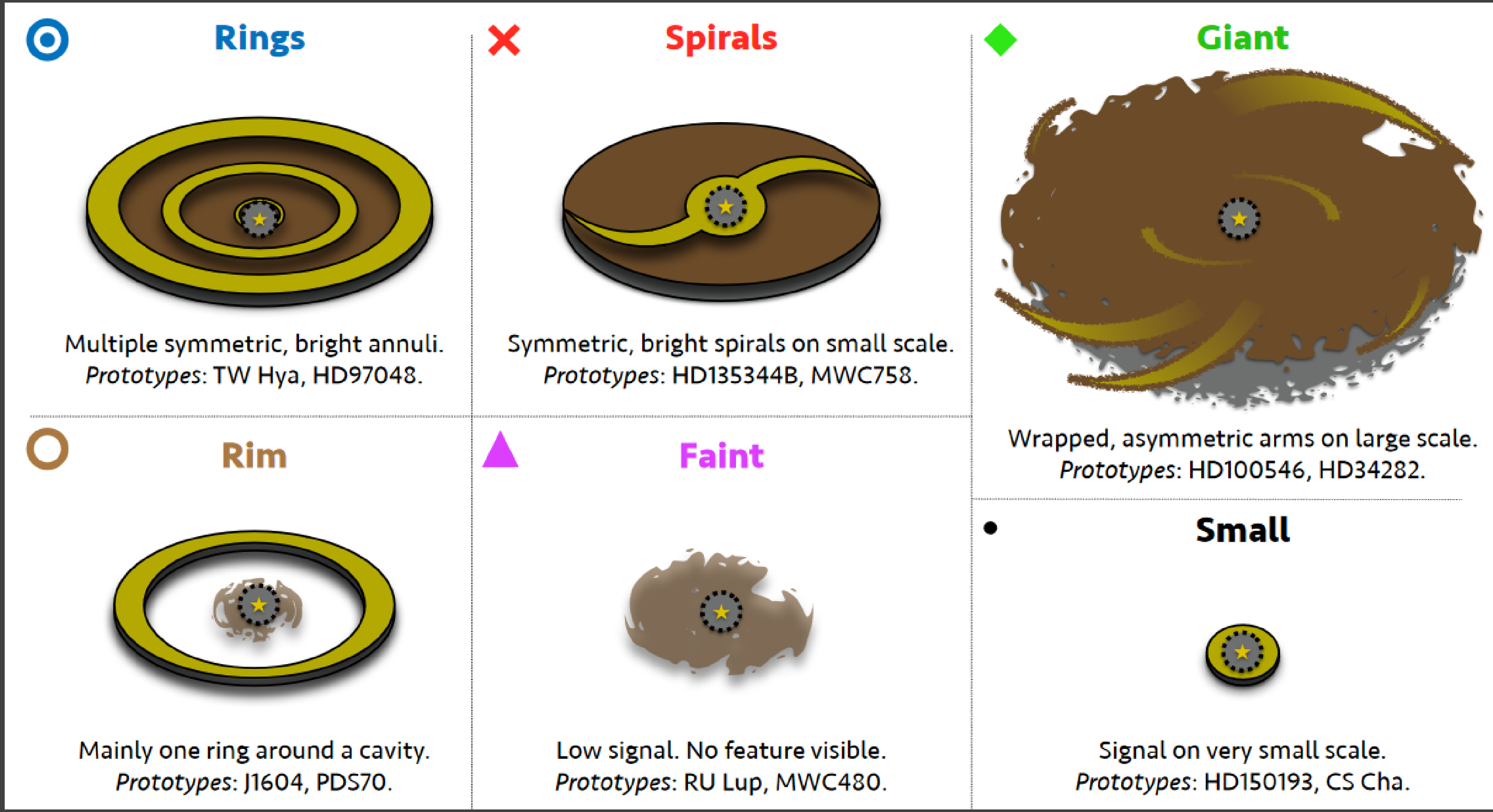
PDI images are sensitive to micron-sized dust grains at the disc surface



Outer
Solar System
HR 8799
Kepler transits
HD 100546b
LkCa15
HD 100453
HD 142527
TW Hya
HD 97048
MWC 758
HD 135344B

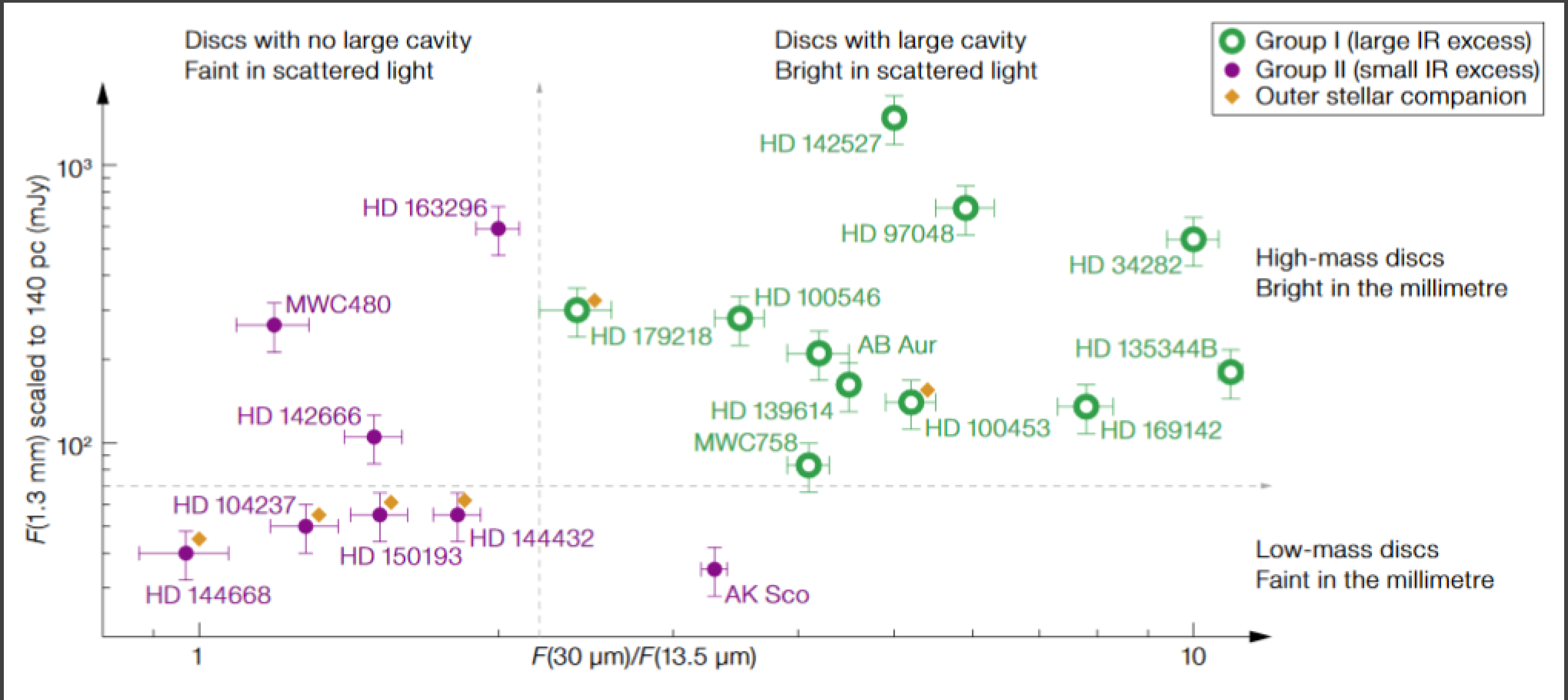
1710.02795

Structures in discs



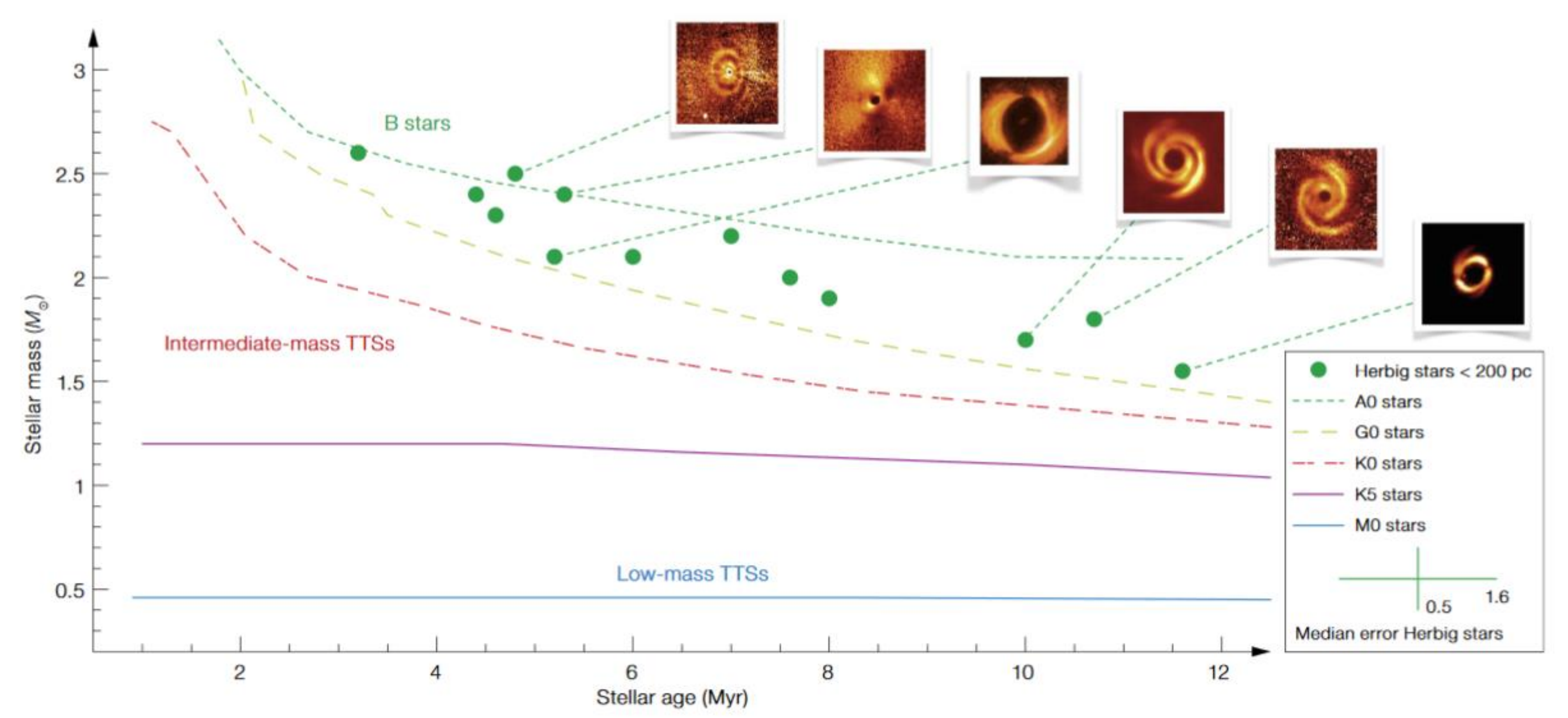
1810.04564, see a review also in 2001.05007

Different discs



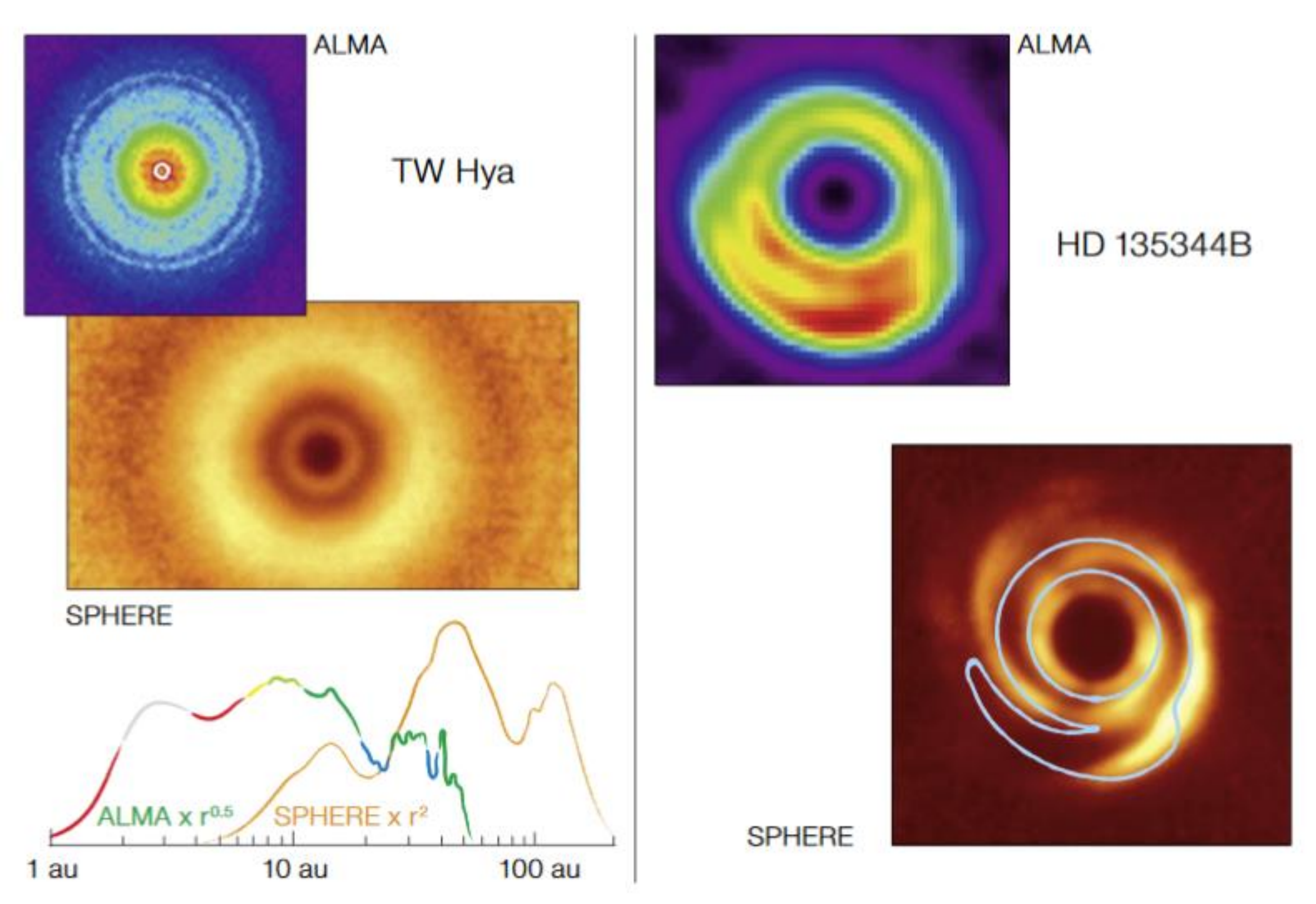
1710.02795

Disc evolution



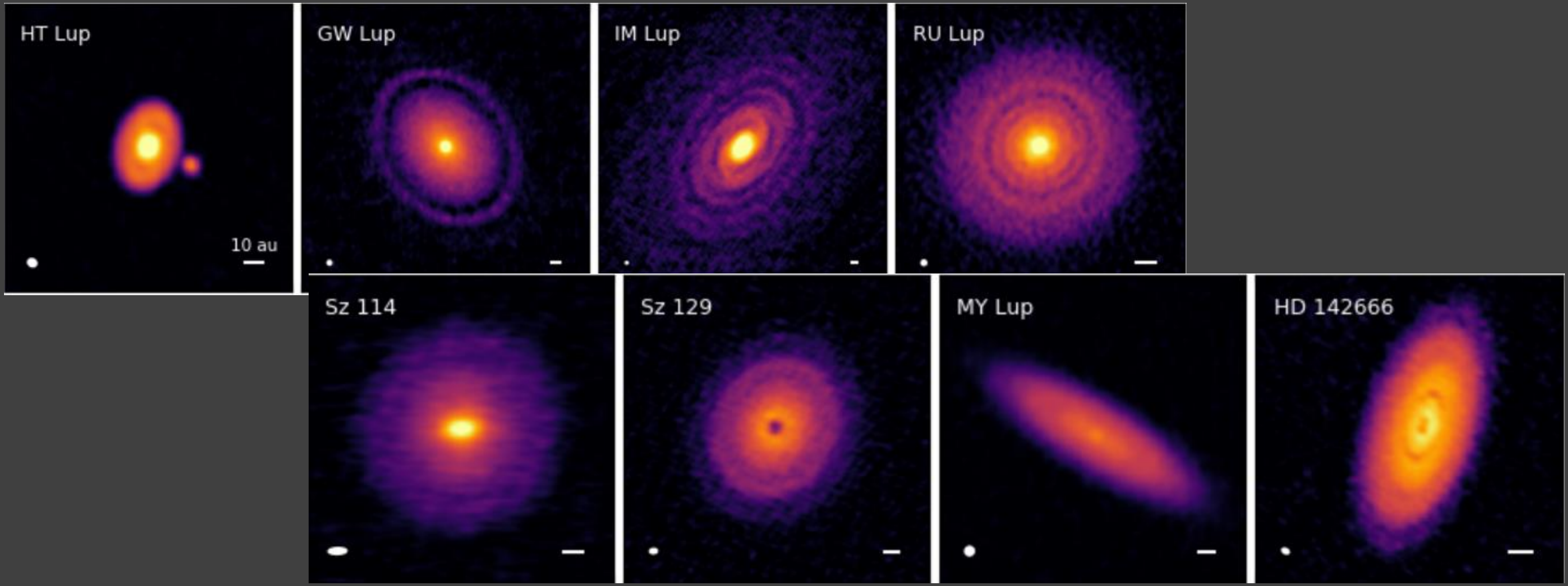
1710.02795

Different wavelengths – different dust

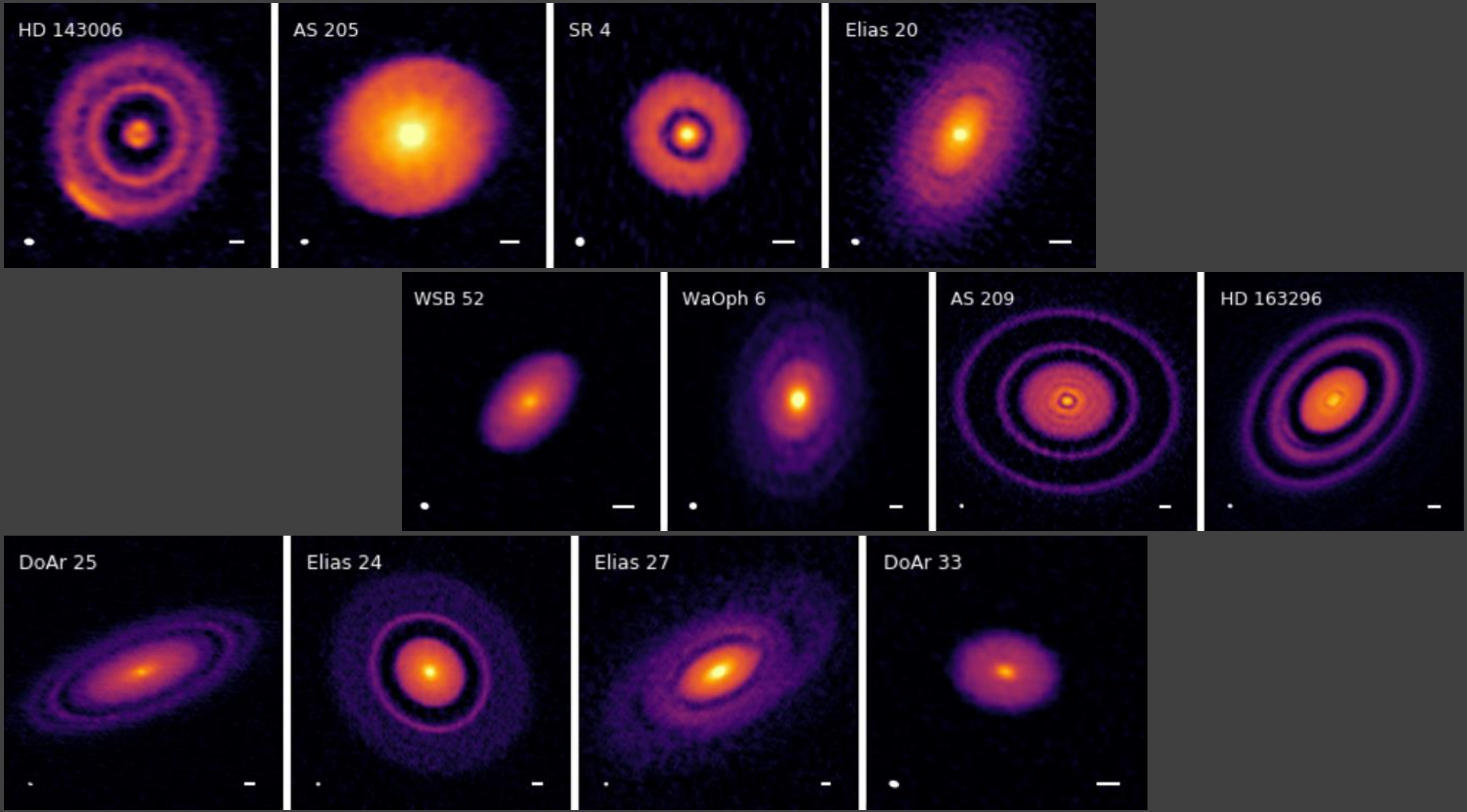


SPHERE – micron grains
ALMA – larger grains

ALMA gallery of discs

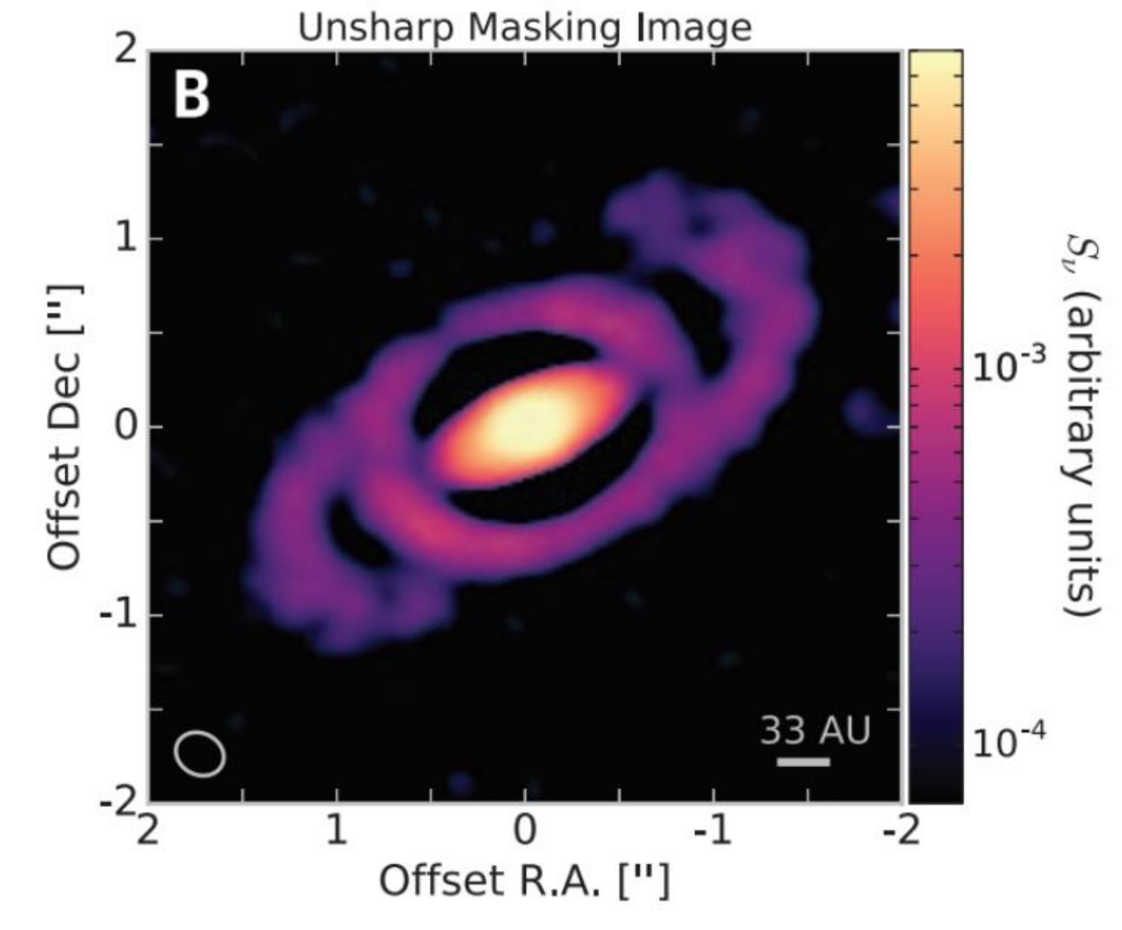


1812.04040



1812.04040, see also the rest of papers in the serie up to 1812.04049

Disc around Elias 2-27



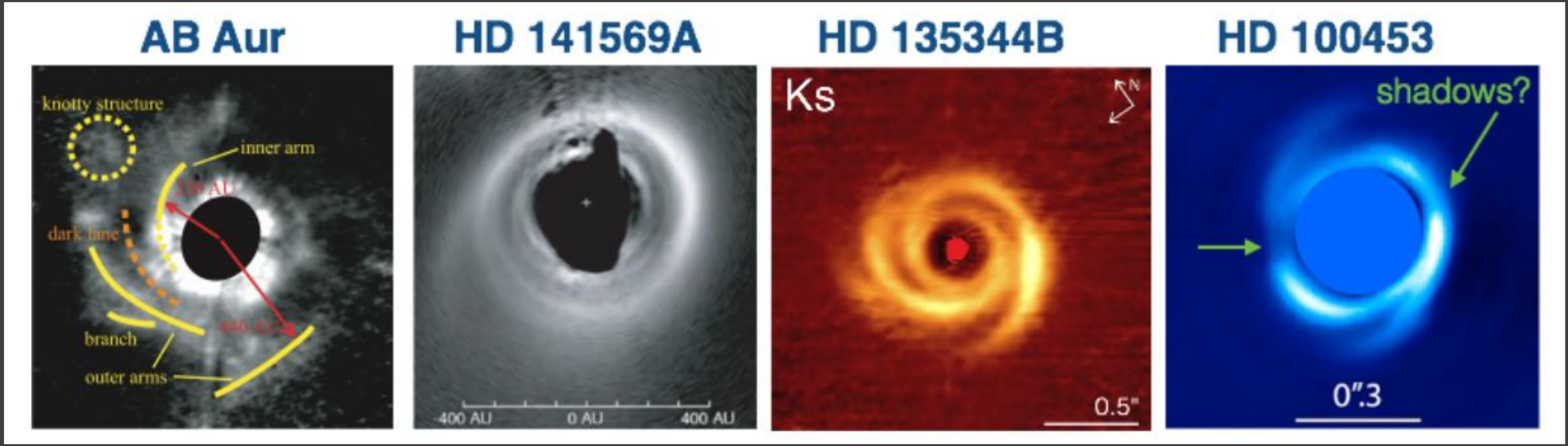
Spiral structure around Elias 2-27
Obtained by ALMA

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

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

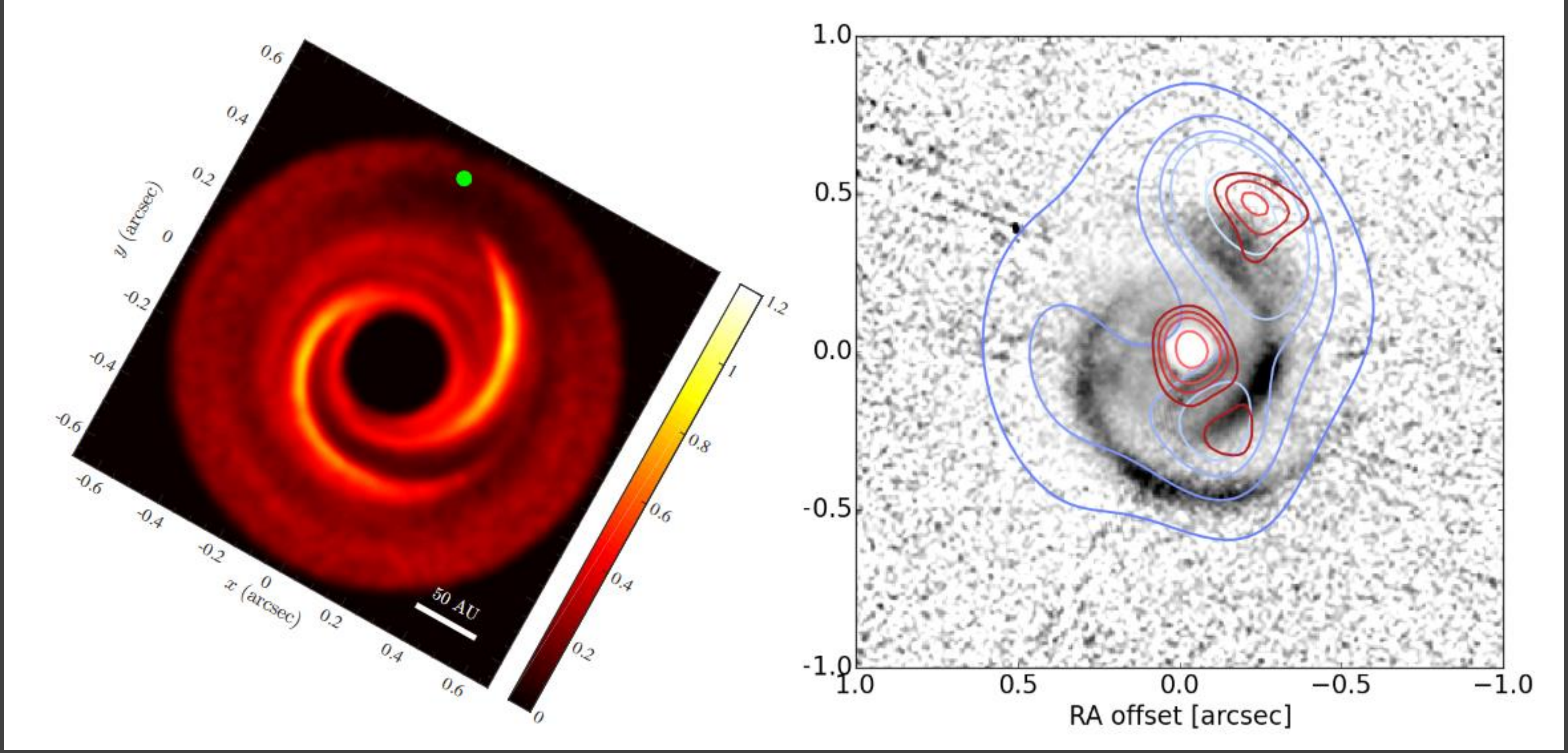
Perez et al. 2016 (1610.05139), taken from the review 1703.08560

Gallery of spirals



1602.06523

Spirals: model and observations

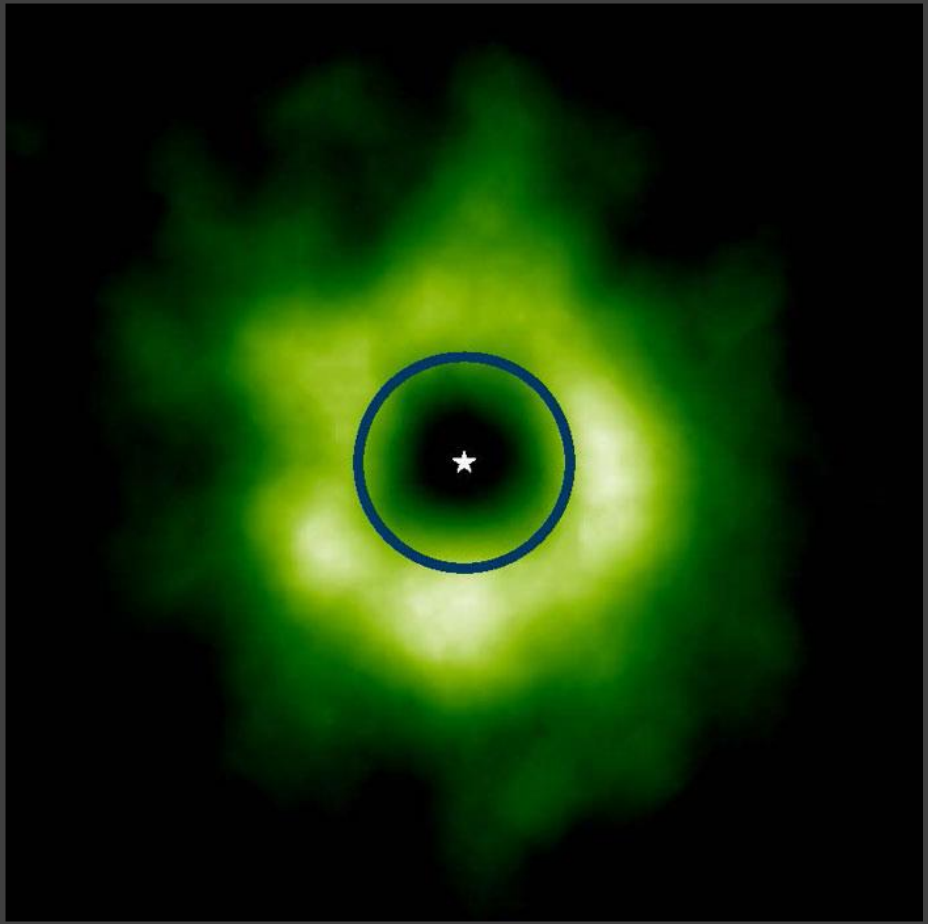


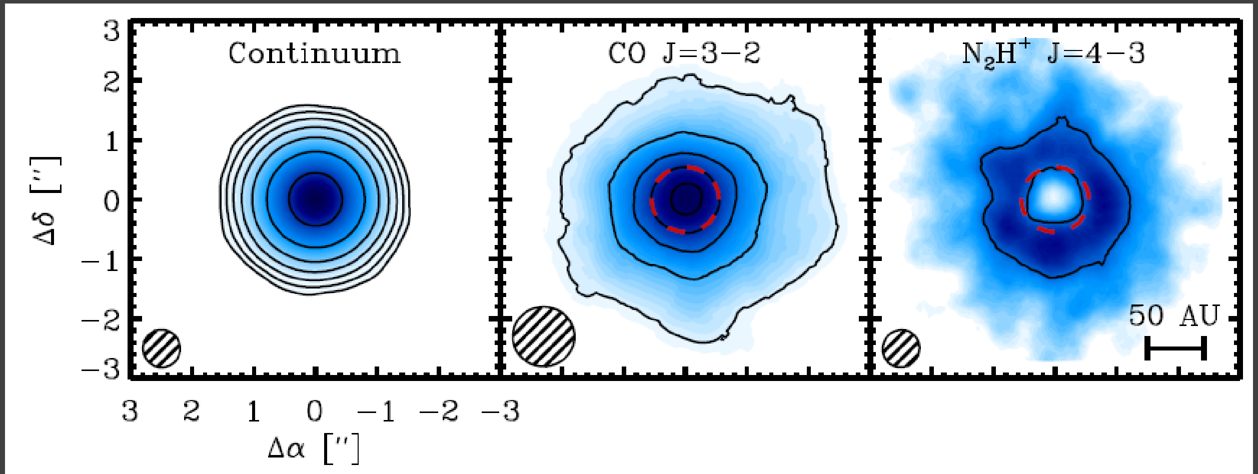
MWC 758
Left: model
Right: VLA+ALMA+SPHERE

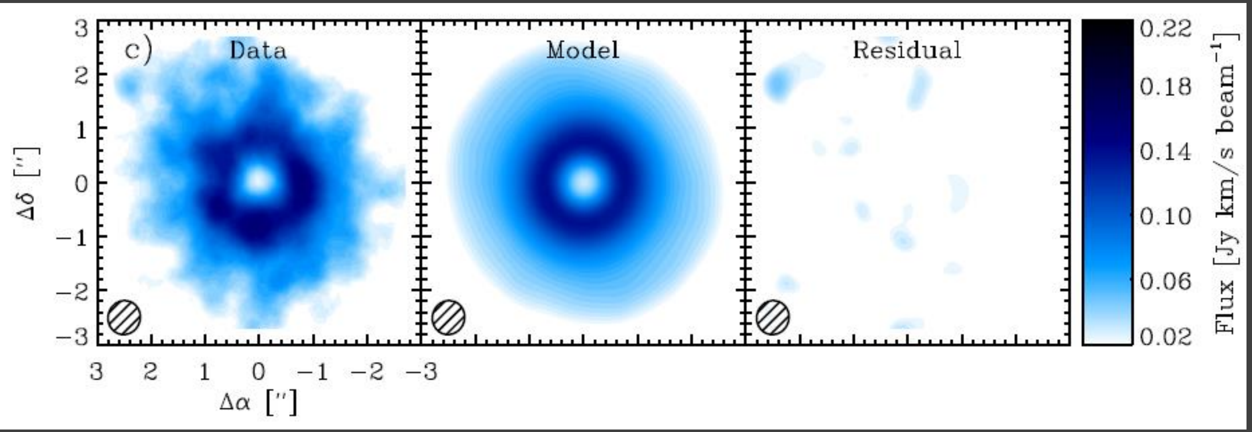
1602.06523, see new data in 1907.06655

TW Hydra

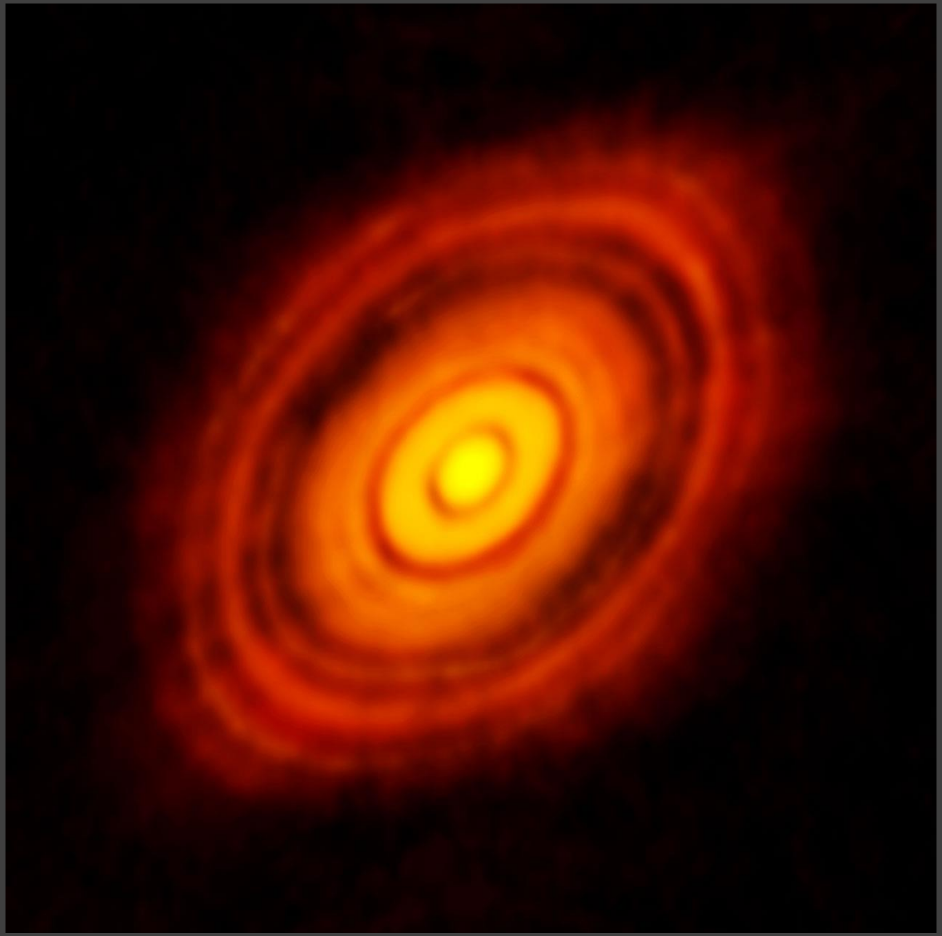
N_2H^+ visible only if CO is frozen out

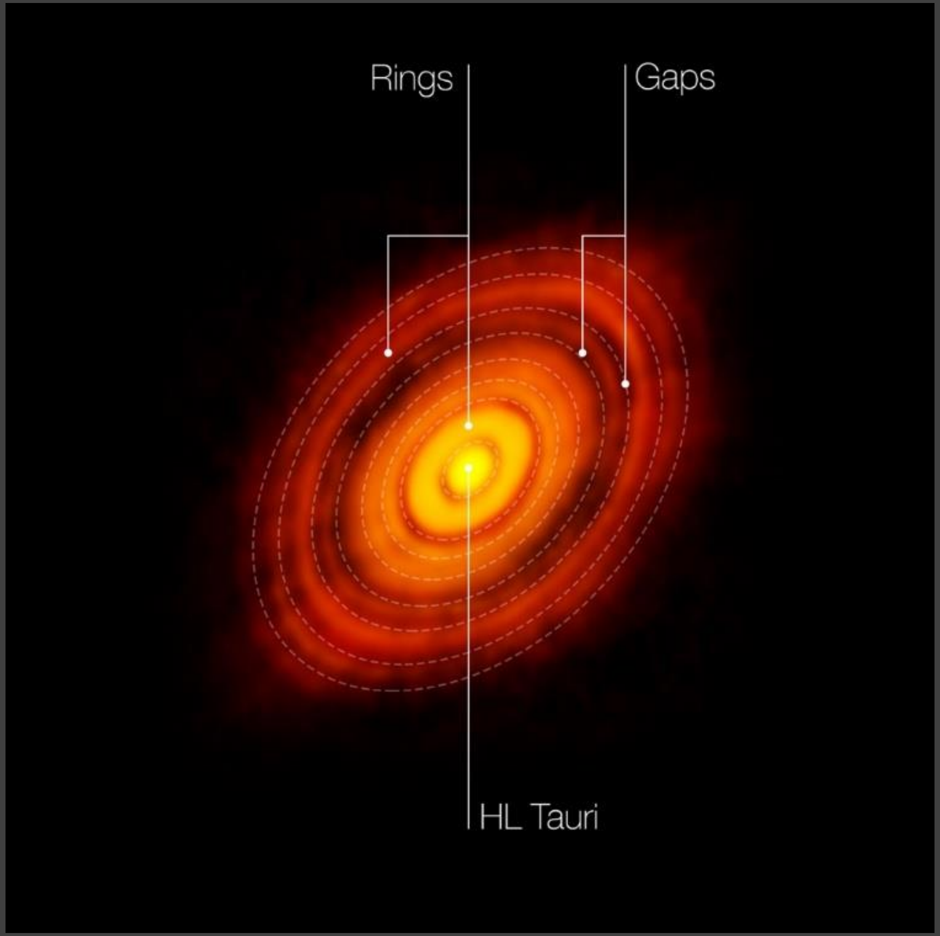






Protoplanetary disc of HL Tau



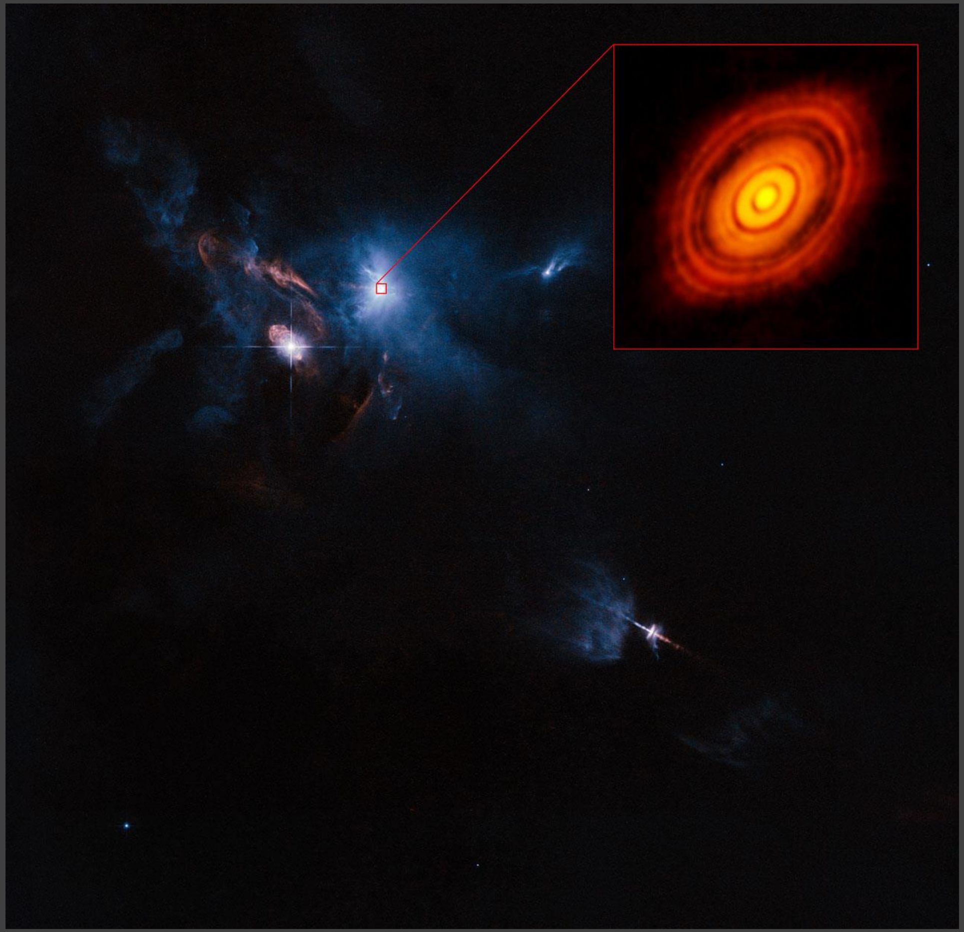


140 pc
Massive disc
Jet
Age <1-2 Myrs

http://www.eso.org/public/images/eso1436a/

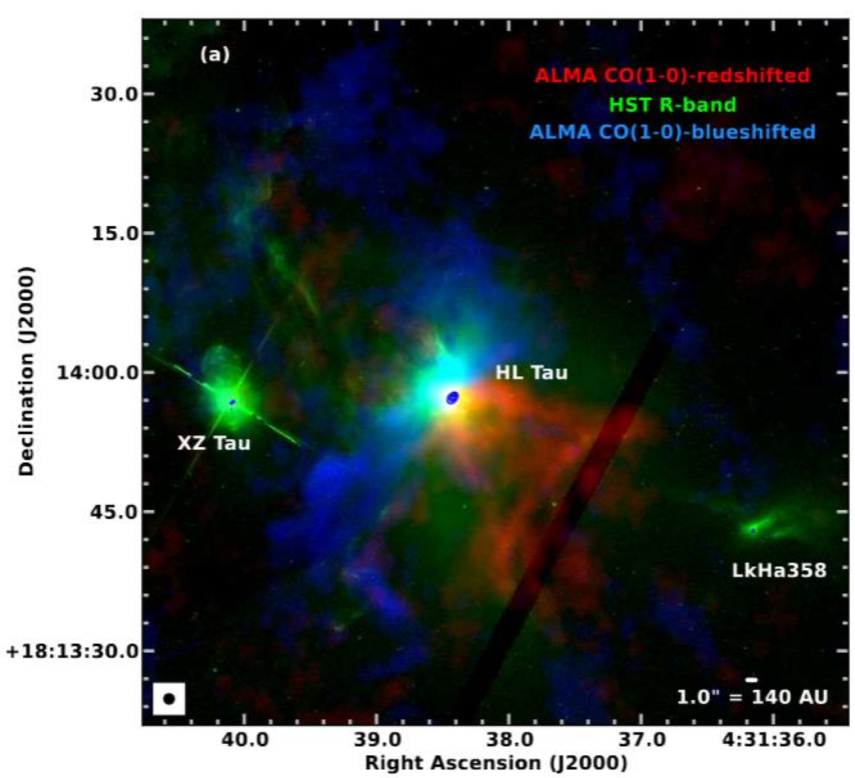
Where stars are born

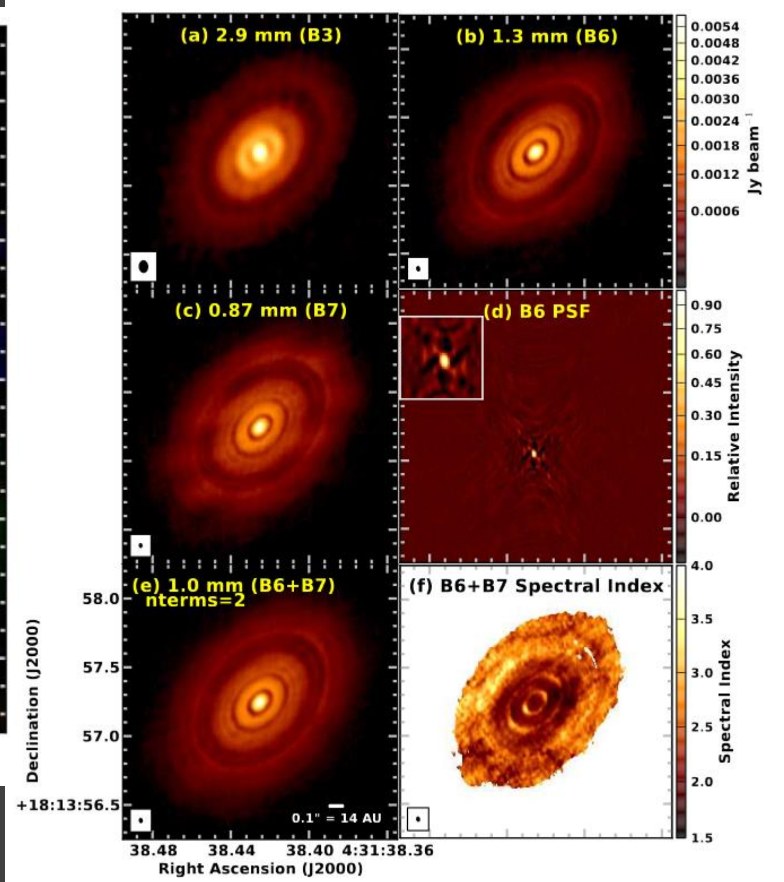
http://www.eso.org/public/images/eso1436b/



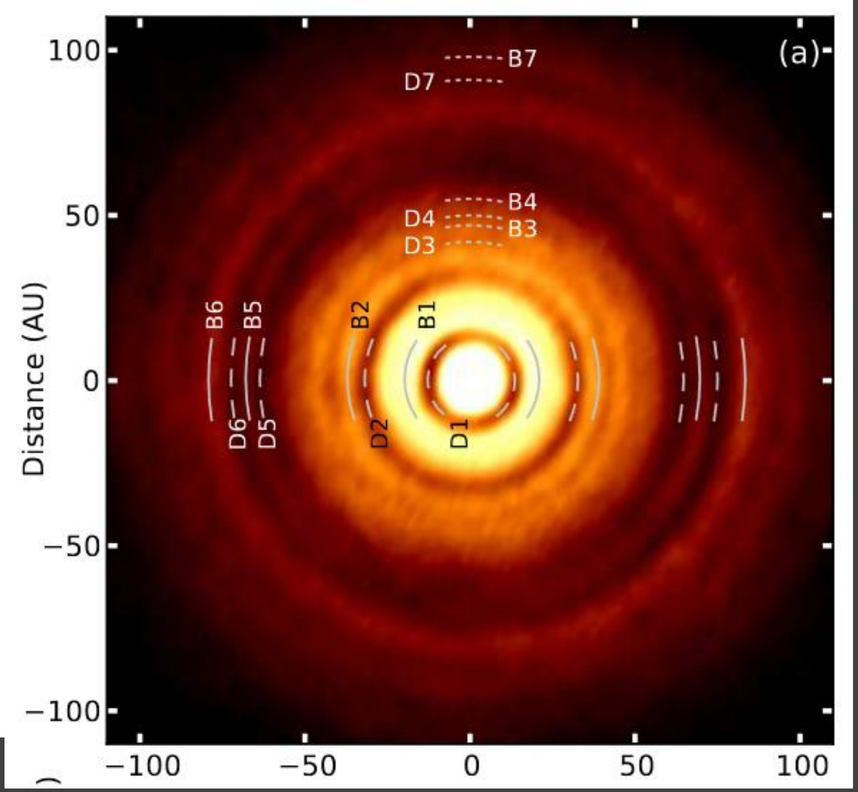
https://public.nrao.edu/AlmaExtras/

More details on the disc of HL Tau

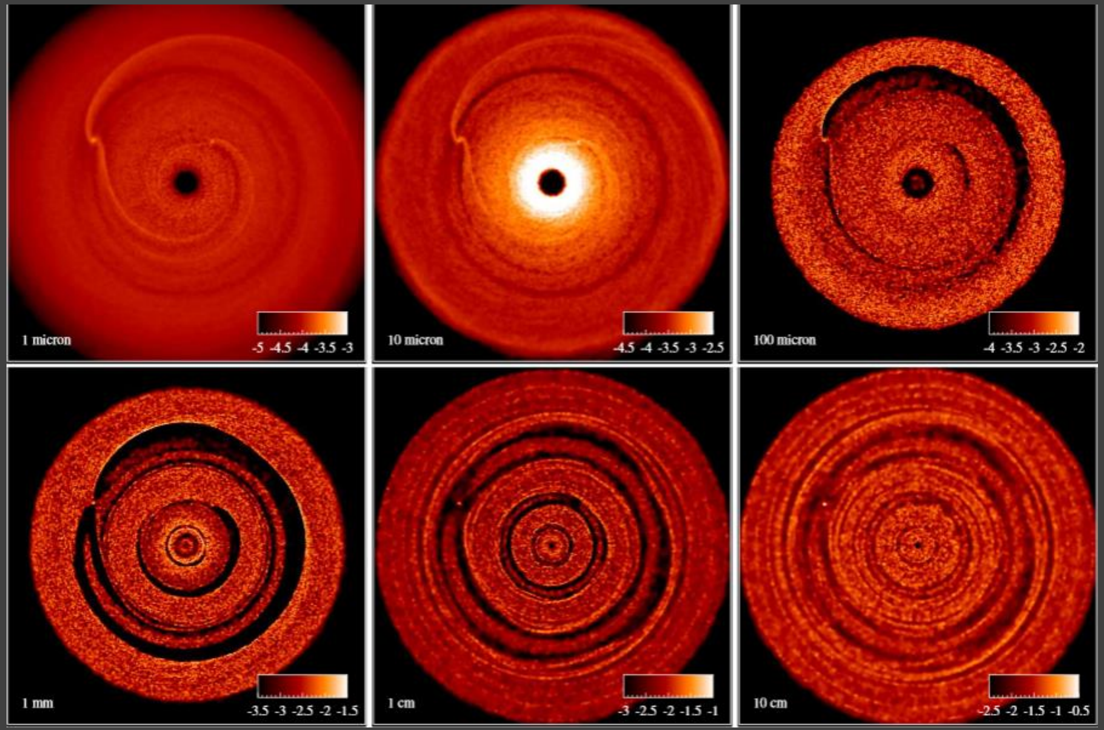




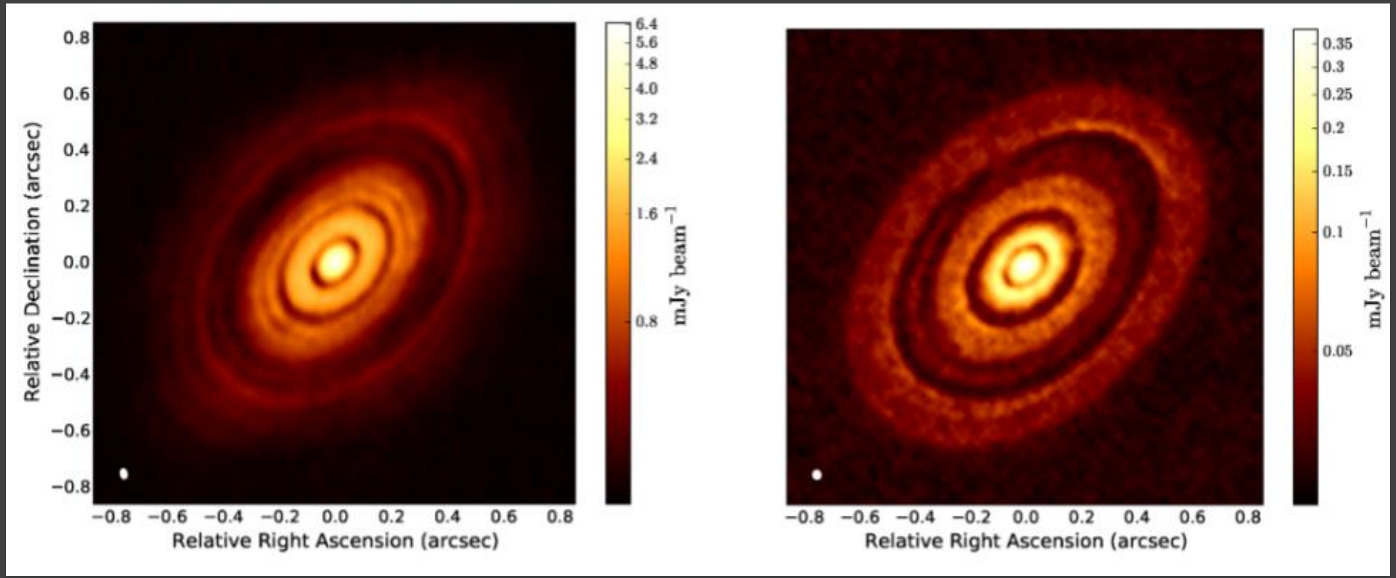
Some rings are in resonance with each other.



Modeling of the HL Tau disc



Three planets with masses from 0.2 up to 0.55 Jupiter mass

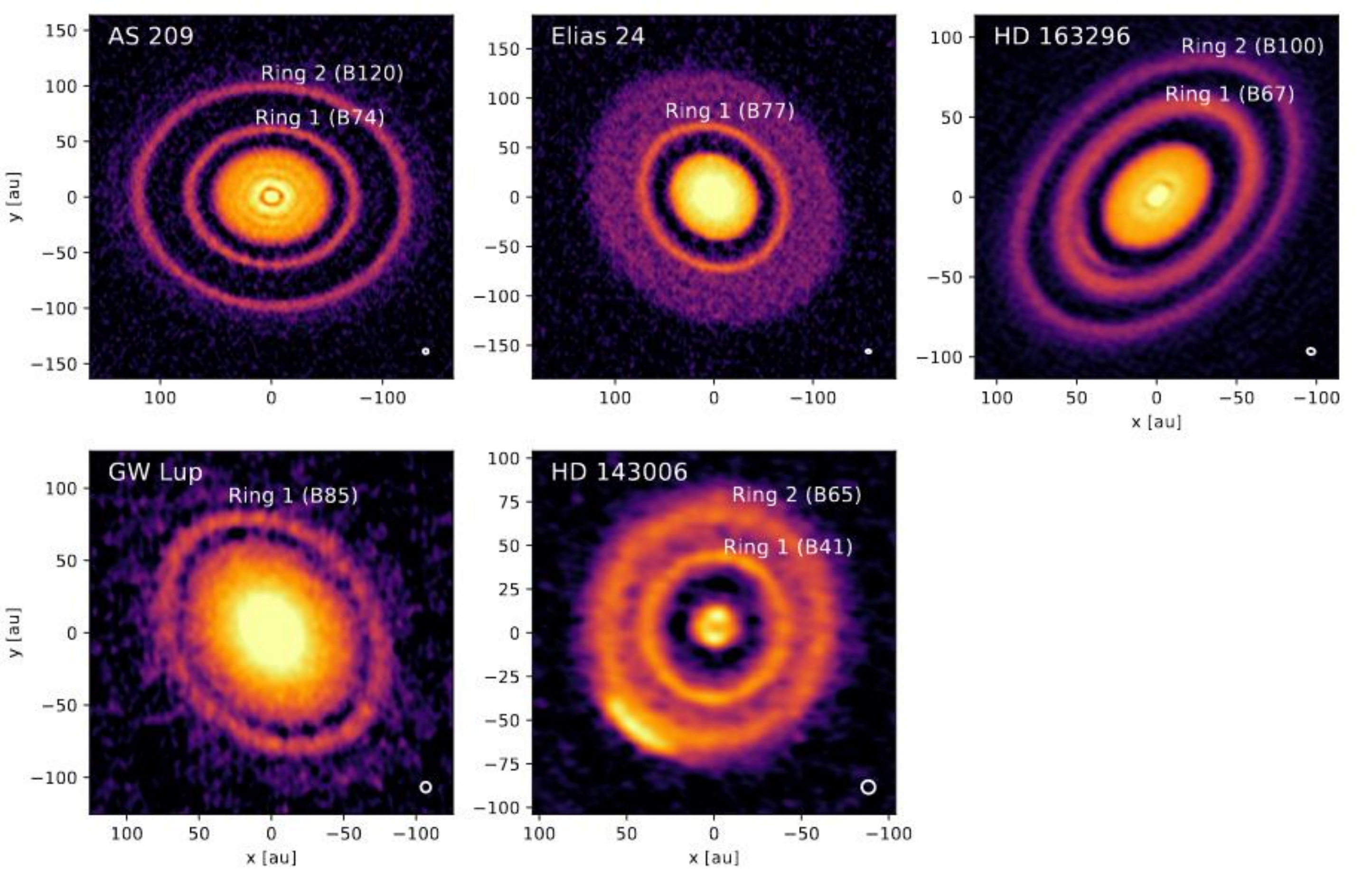


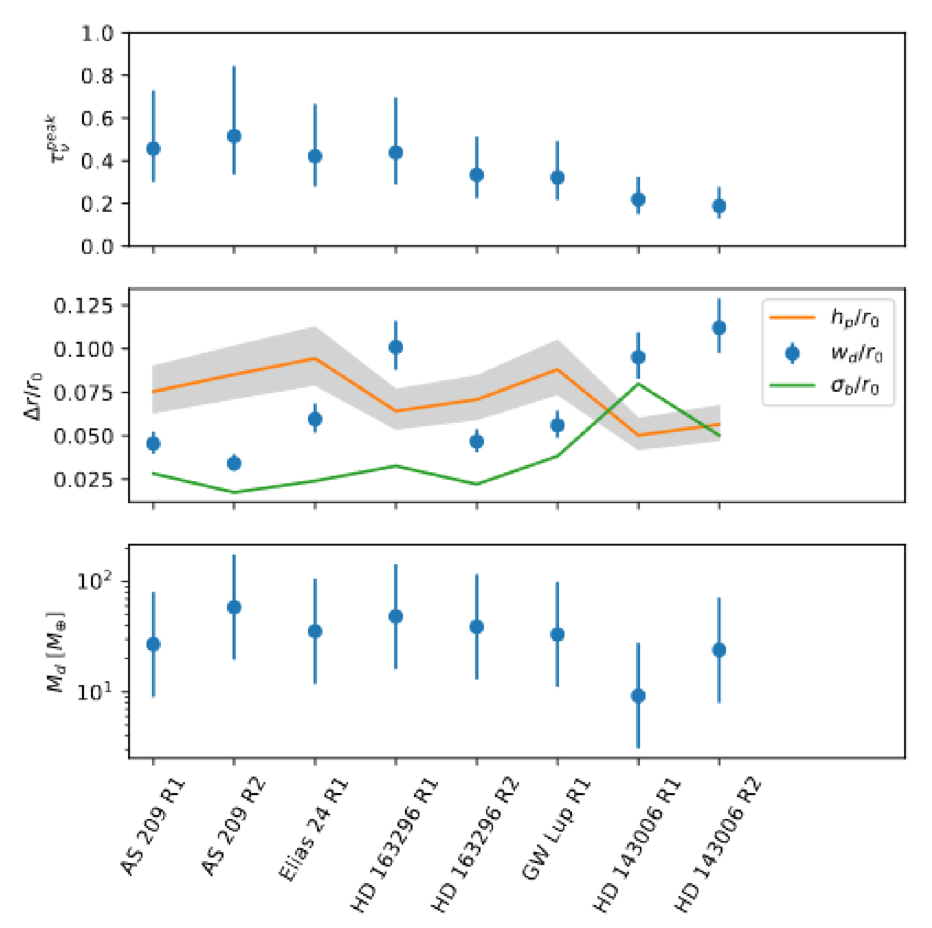
Observations

Modeling

1507.06719

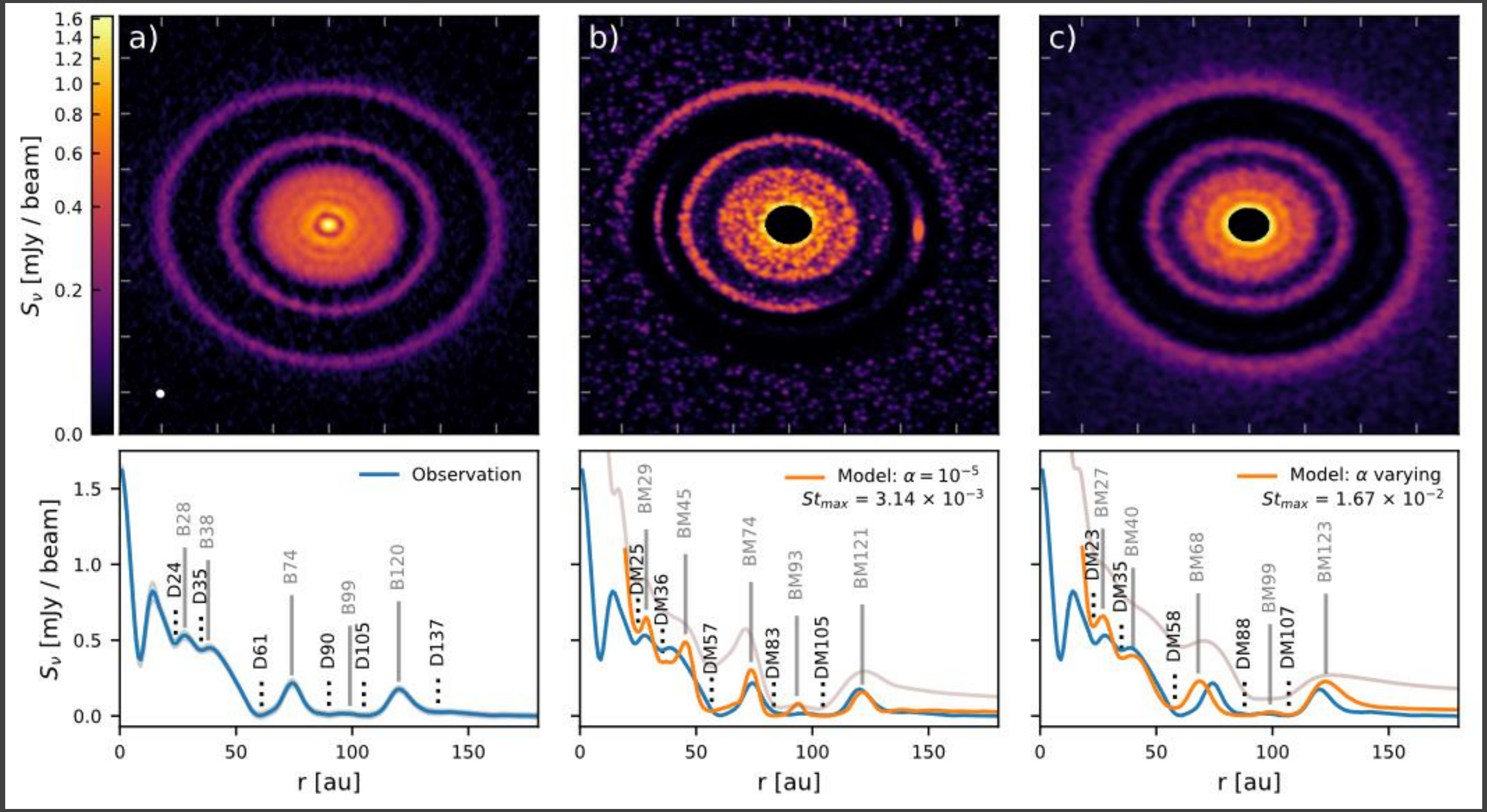
More rings from ALMA





1812.04044

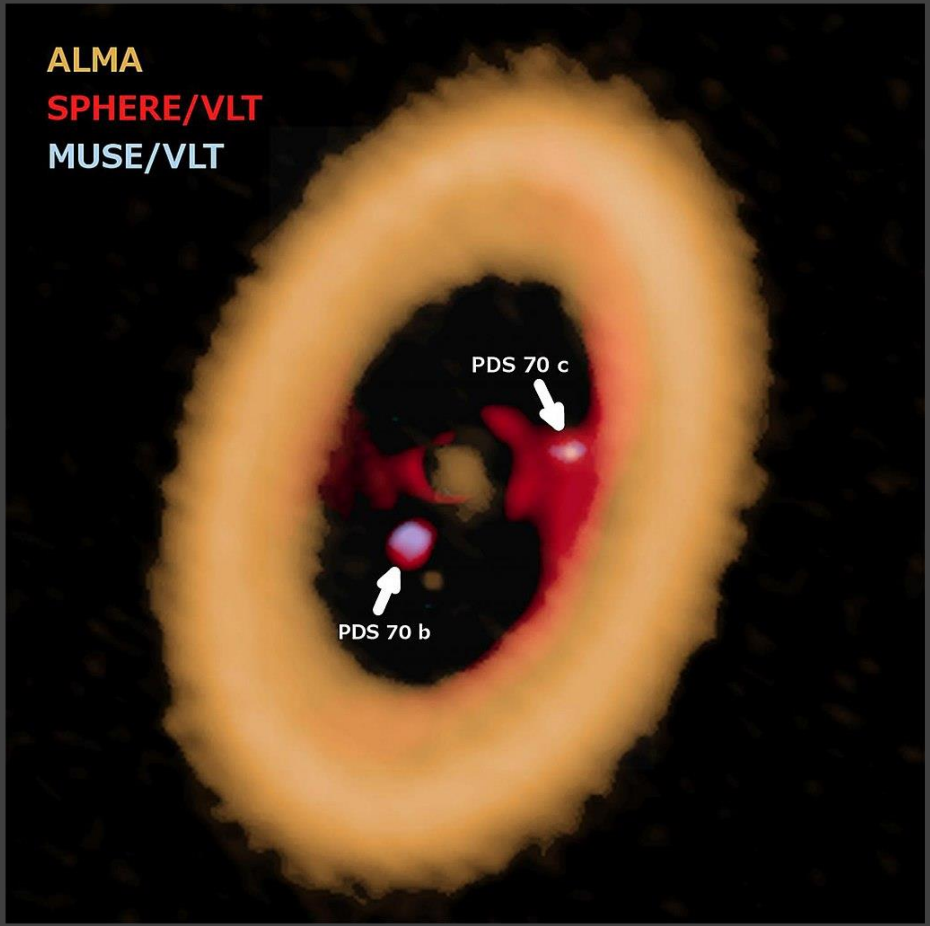
Modeling ring structure. Planets

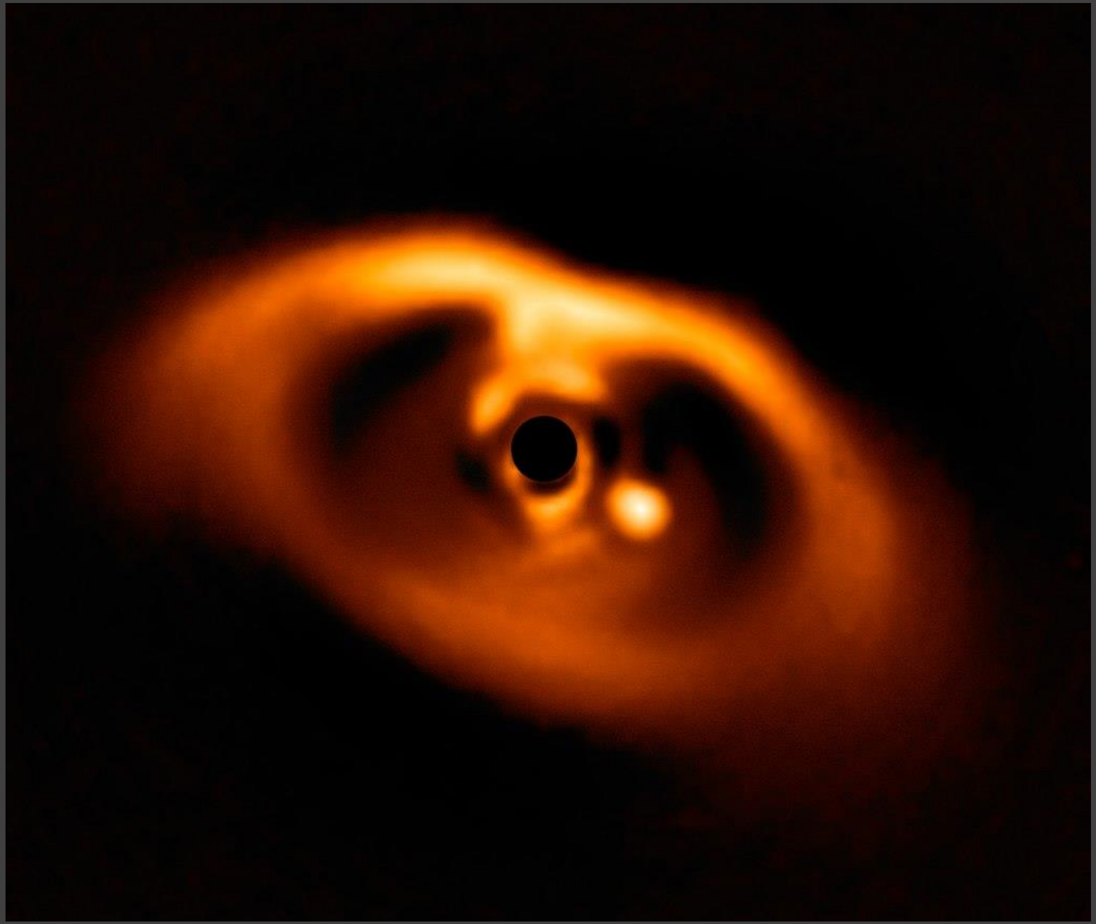


One planet at 99 au.

A) Observations
B) Model. Constant alpha
C) Model. Varying alpha.

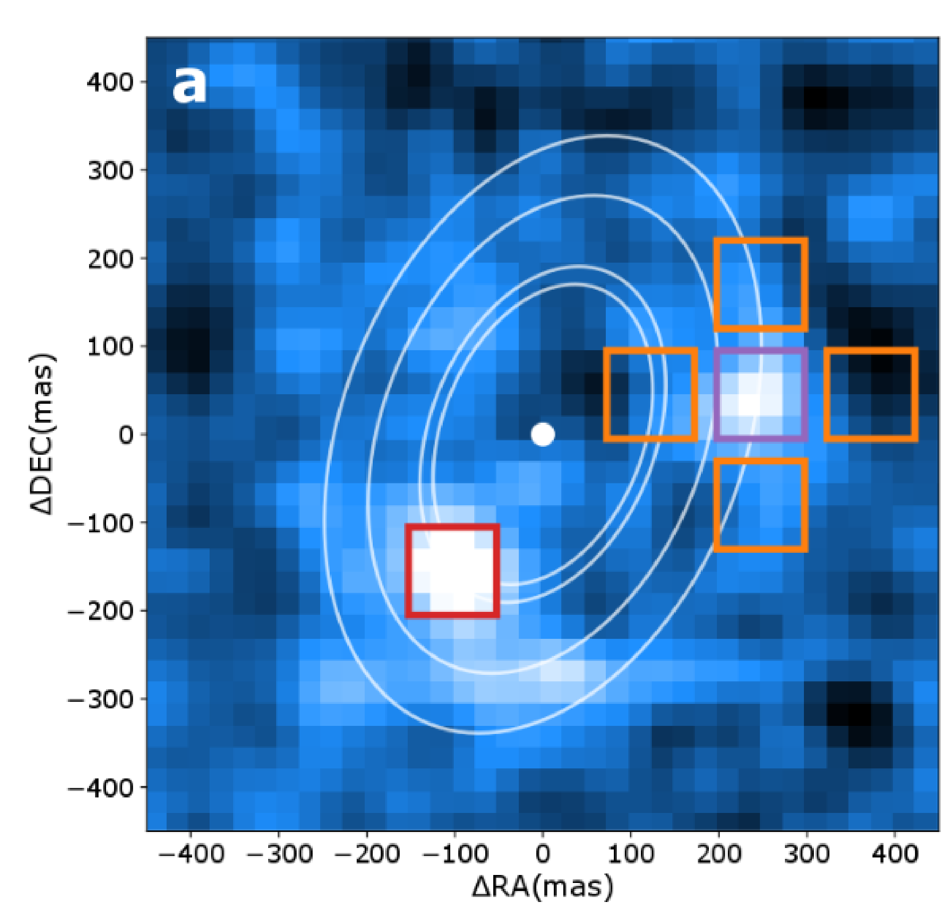
PDS 70: two planets in a disc





Wikipedia

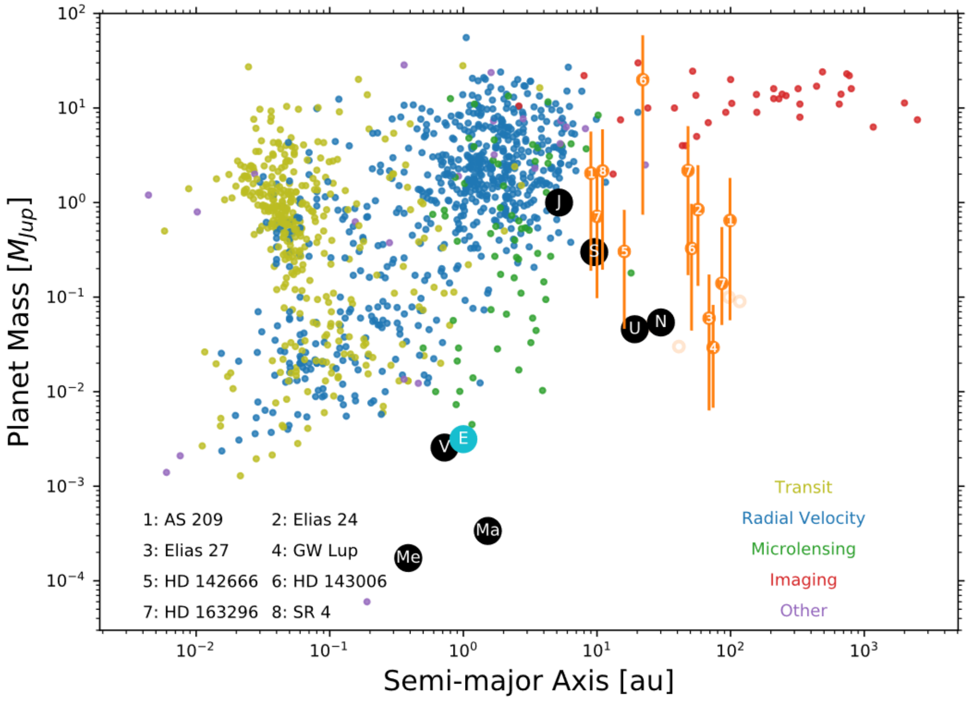
PDS 70. The second planet



1906.01486

Properties of (invisible) planets

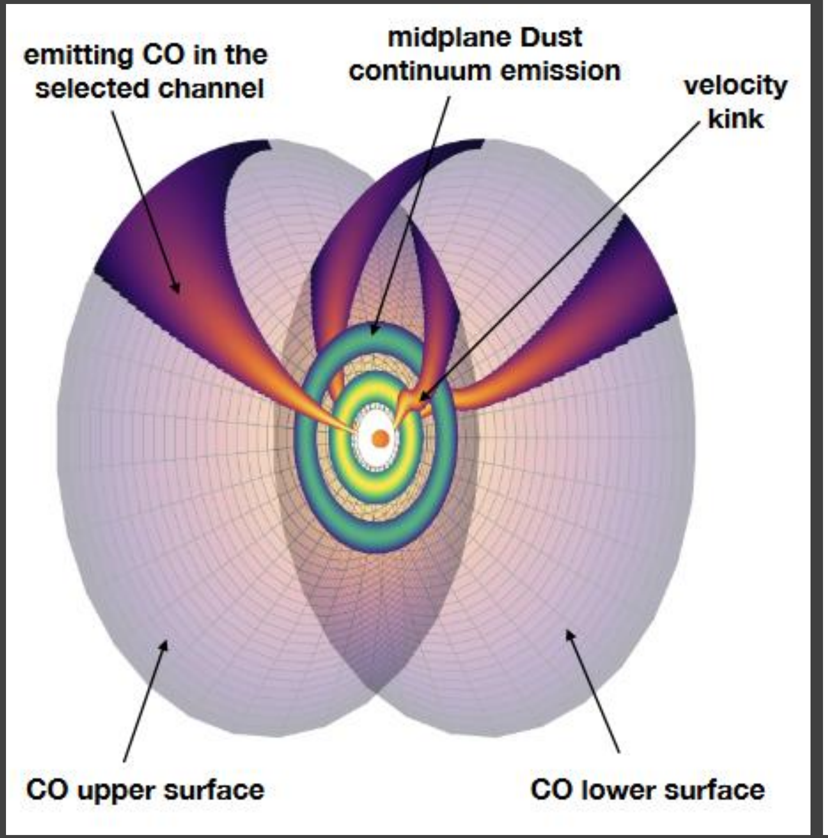
Name	M_*	r_{gap}	width	$M_{p,am4}$	$M_{p,am3}$	$M_{p,am2}$	Uncertainty
	$(M_\odot)$	(au)	(Δ)	(M_{Jup})	(M_{Jup})	(M_{Jup})	$(log_{10}(M_p))$
(1)	(2)	(3)	(4)	(11)	(12)	(13)	(14)
AS 209	0.83	9	0.42	1.00, 0.81, 0.37	2.05, 1.66, 0.76	4.18, 3.38, 1.56	$^{+0.13}_{-0.16}$, $^{+0.14}_{-0.17}$, $^{+0.28}_{-0.29}$
AS 209	0.83	99	0.31	0.32, 0.18, –	0.65, 0.37, –	1.32, 0.75, –	$^{+0.14}_{-0.17}$, $^{+0.21}_{-0.50}$, –
Elias 24	0.78	57	0.32	0.41, 0.19 –	0.84, 0.40, –	1.72, 0.81, –	$^{+0.16}_{-0.14}$, $^{+0.22}_{-0.16}$, –
Elias 27	0.49	69	0.18	0.03, 0.02, –	0.06, 0.05, –	0.12, 0.10, –	$^{+0.16}_{-0.14}$, $^{+0.21}_{-0.50}$, –
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	$^{+0.13}_{-0.16}$, $^{+0.14}_{-0.17}$, $^{+0.28}_{-0.29}$
HD 143006	1.78	22	0.62	9.75, 2.35, –	19.91, 4.80, –	40.64, 9.81, –	$^{+0.16}_{-0.14}$, $^{+0.21}_{-0.50}$, –
HD 143006	1.78	51	0.22	0.16, 0.14 –	0.33, 0.28, –	0.67, 0.57, –	$^{+0.16}_{-0.14}$, $^{+0.21}_{-0.50}$, –
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	$^{+0.13}_{-0.16}$, $^{+0.14}_{-0.17}$, $^{+0.28}_{-0.29}$
HD 163296	2.04	48	0.34	1.07, 0.54, –	2.18, 1.10, –	4.45, 2.24, –	$^{+0.16}_{-0.14}$, $^{+0.21}_{-0.50}$, –
HD 163296	2.04	86	0.17	0.07, 0.08, –	0.14, 0.16, –	0.29, 0.34, –	$^{+0.16}_{-0.14}$, $^{+0.21}_{-0.50}$, –
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	$^{+0.13}_{-0.16}$, $^{+0.14}_{-0.17}$, $^{+0.28}_{-0.29}$
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, –, –)	–, – , –	–, –, –

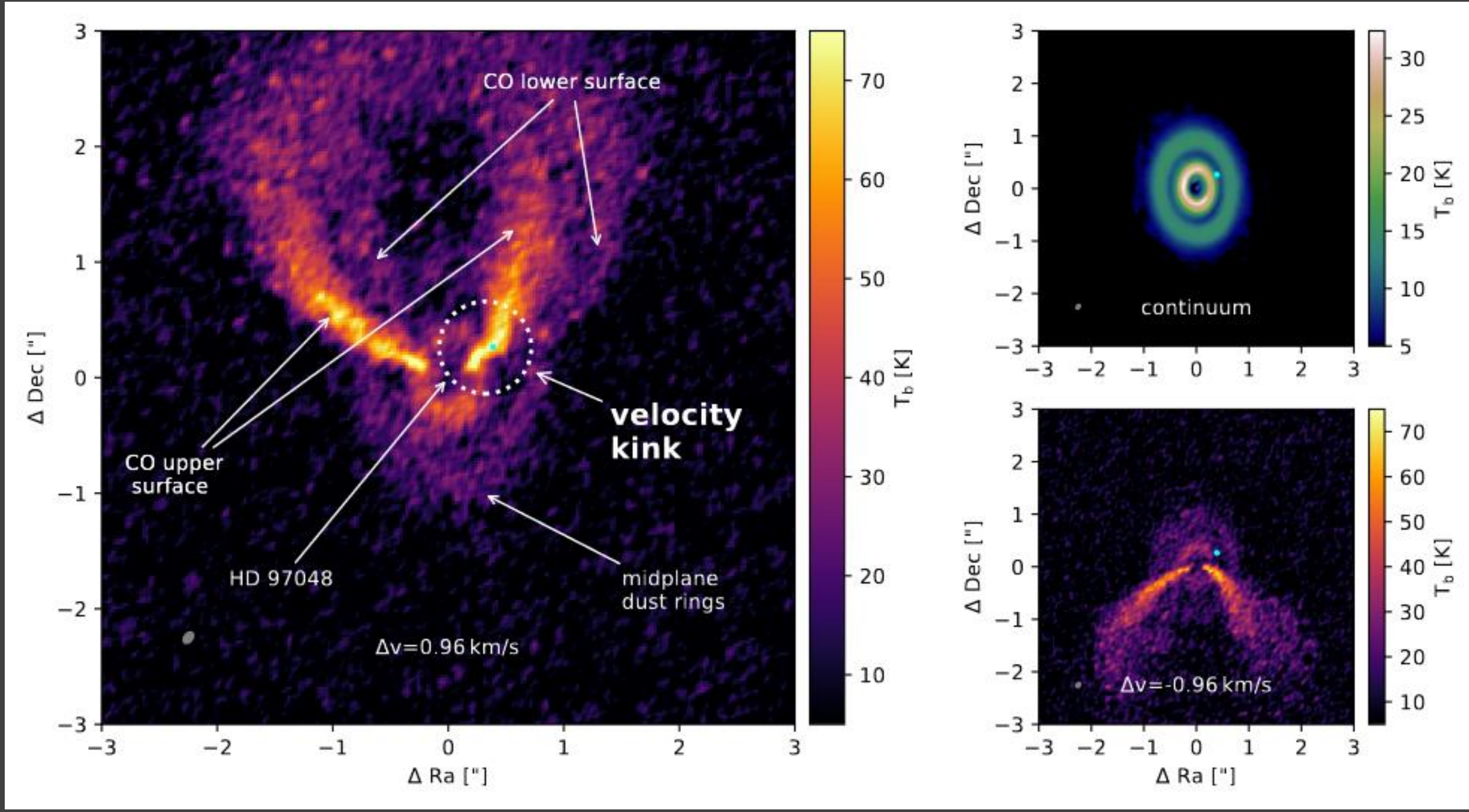


Three values of planet mass for each alpha correspond to different models of dust size.

Kinematic detection of a planet HD 97048

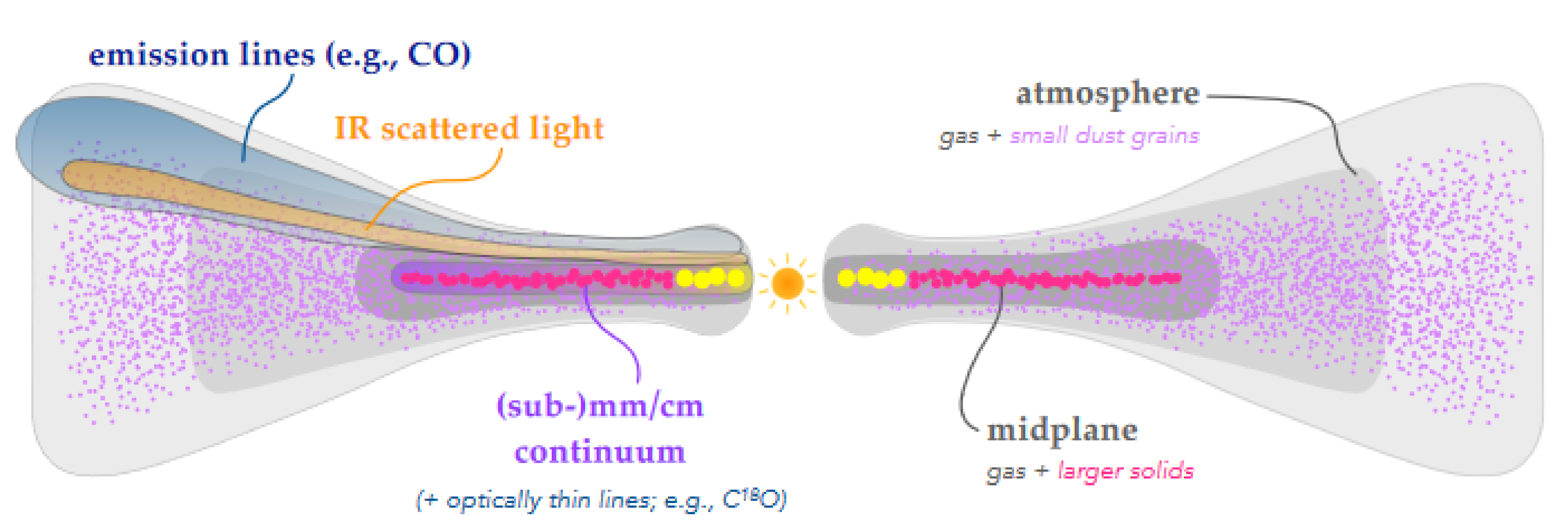
Gap + disturbance in the gas flow





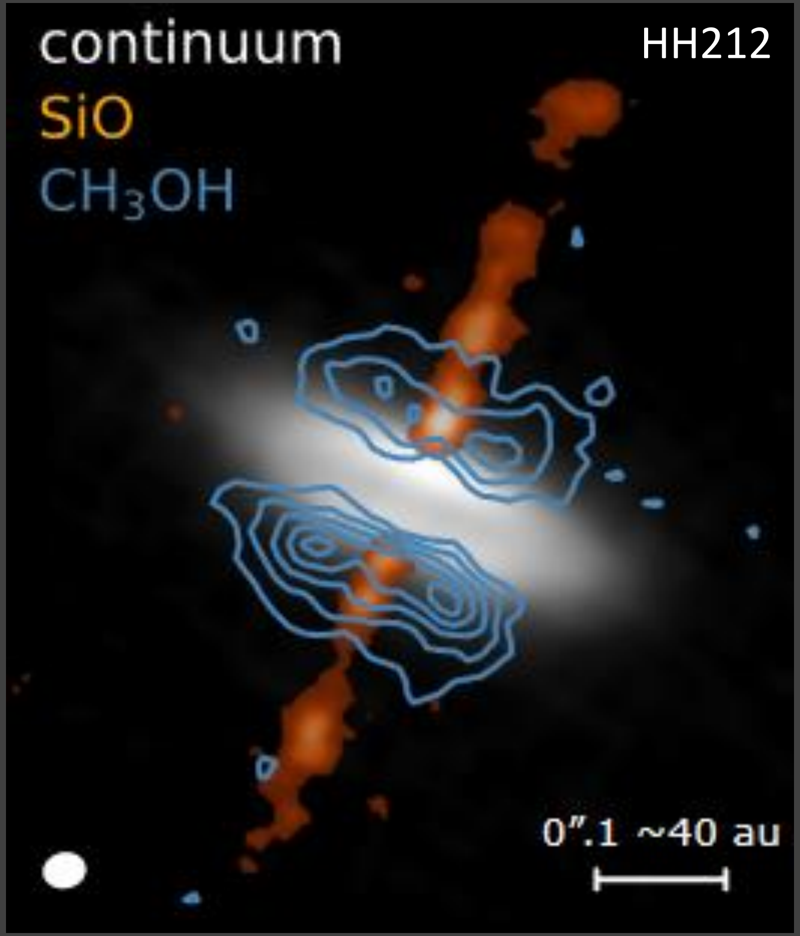
1907.02538

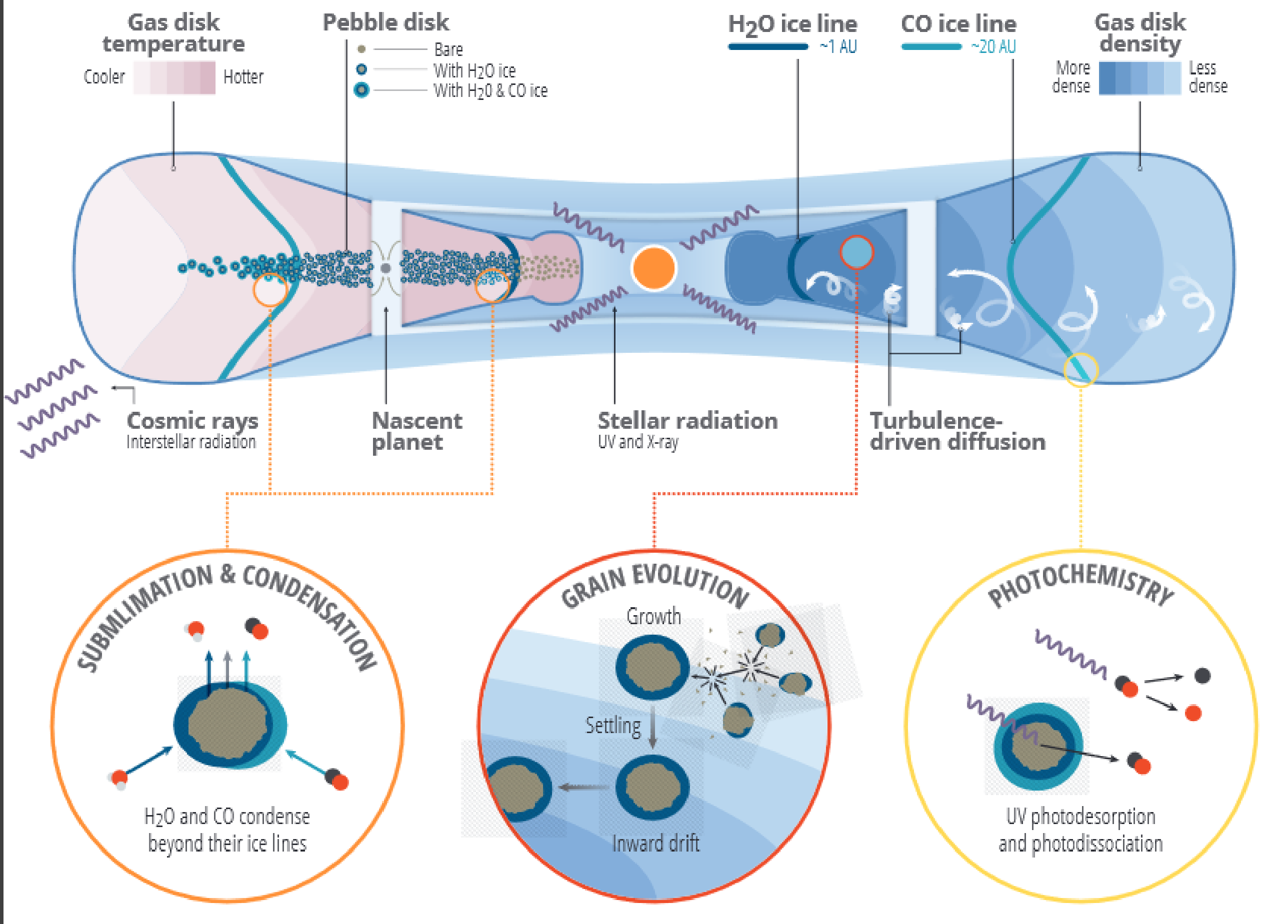
Disc structure and emission zones



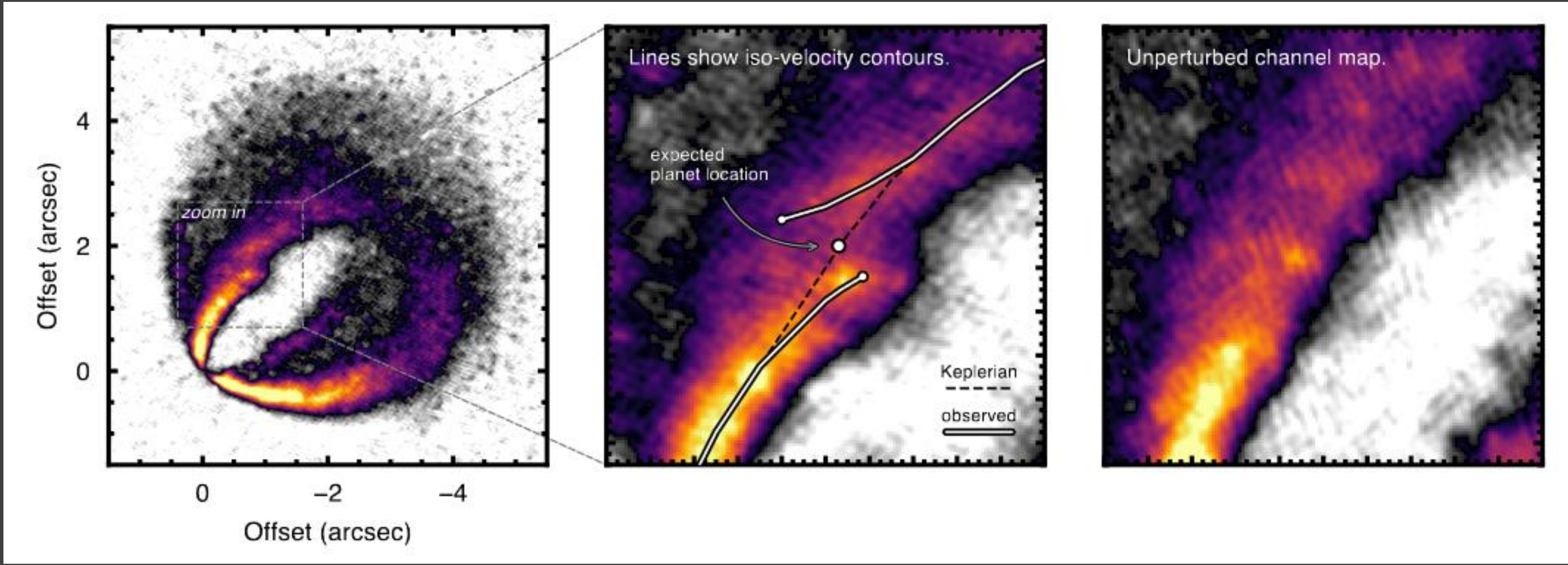
2001.05007

Structure and processes

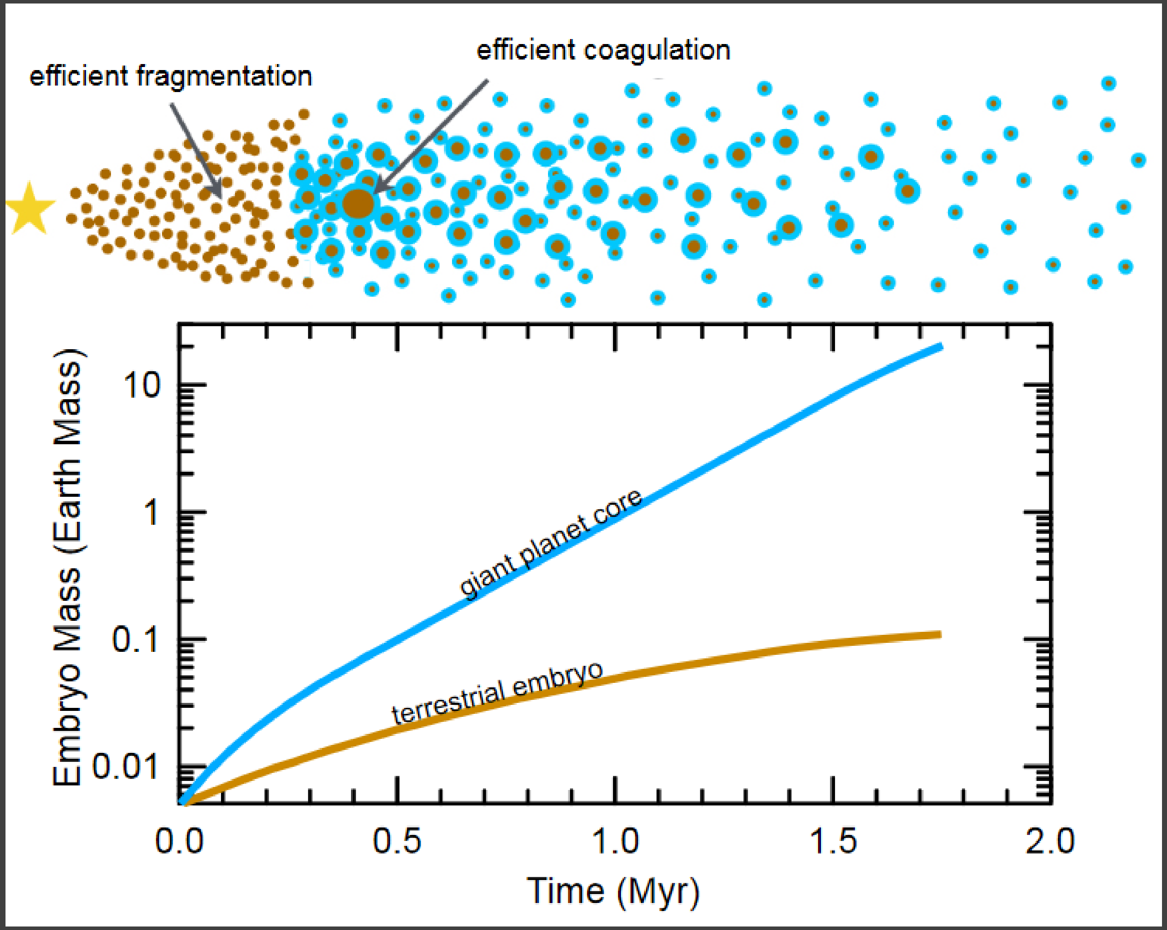




Planet and gas velocity in the disc HD 163296



Where planets grow?

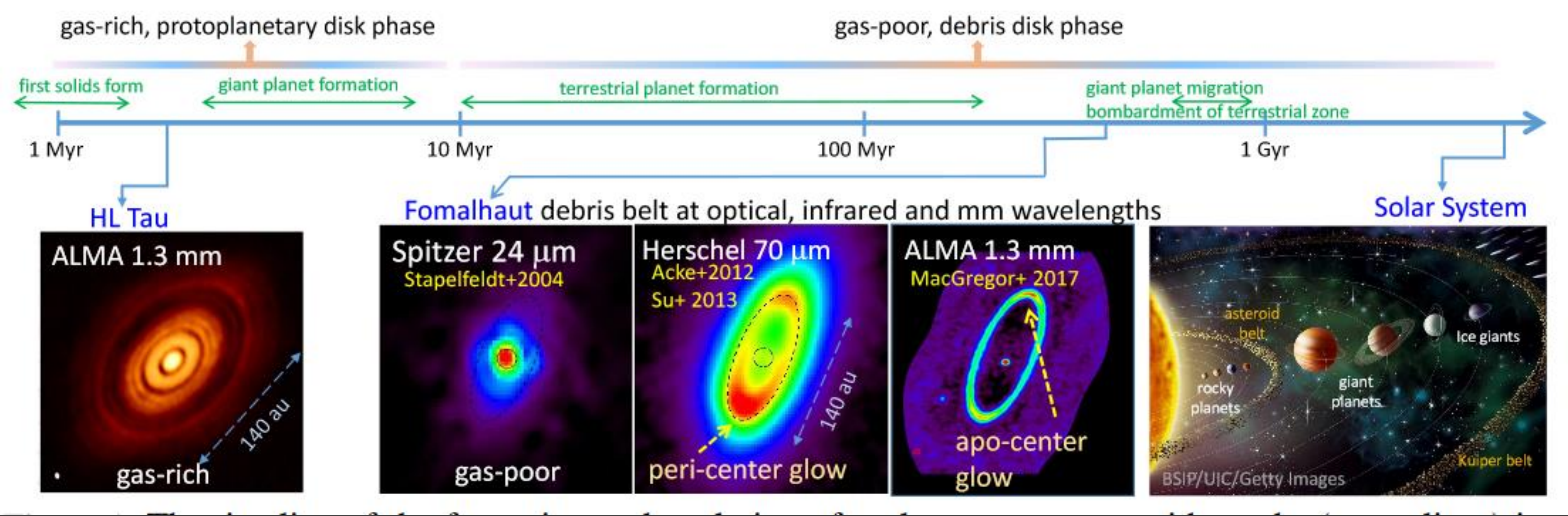


To become giant planets have to grow fast
as they need also to accrete gas
within the lifetime of the gaseous disc.

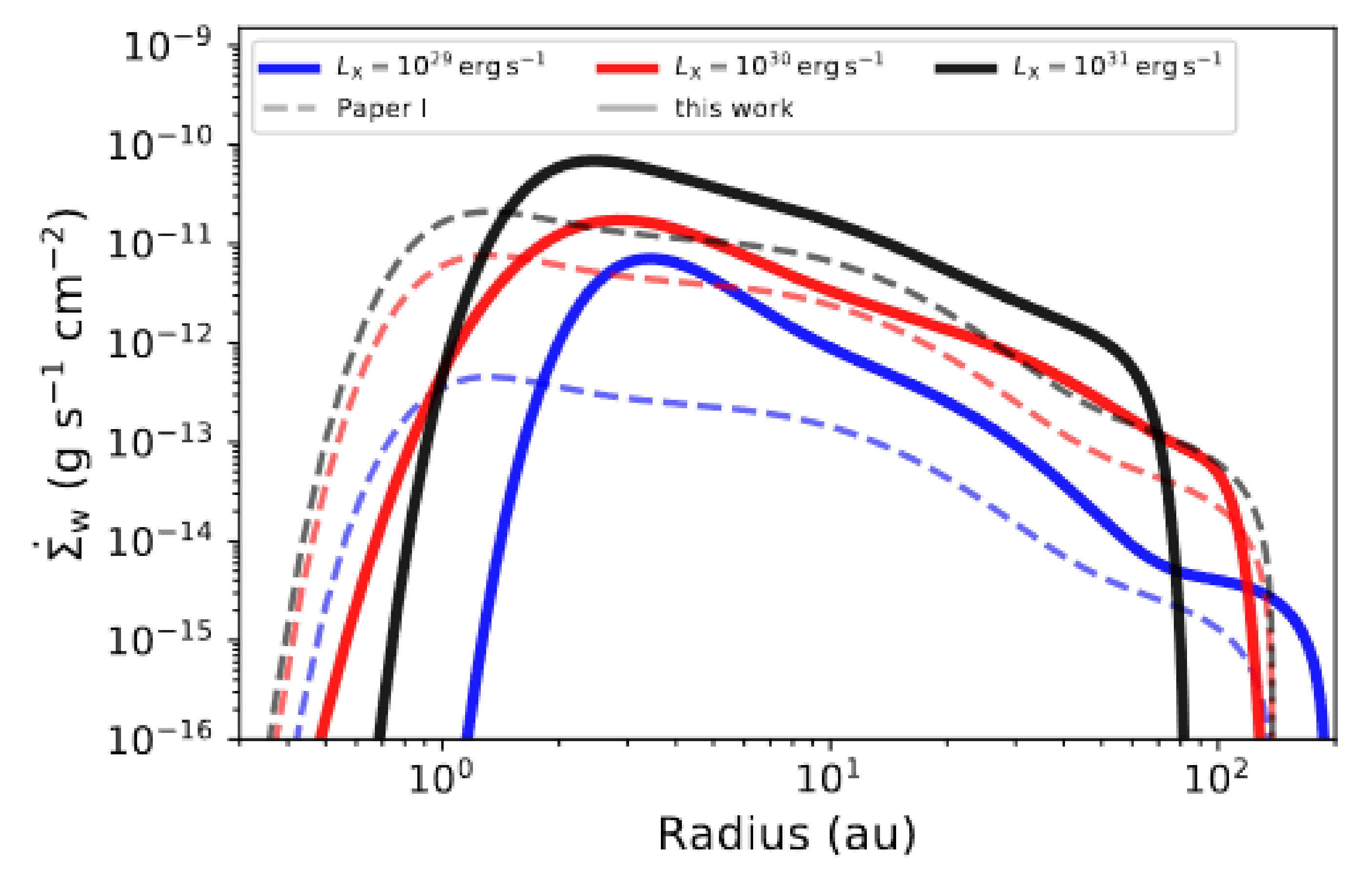
Fast growth is possible in the region of ice dust.

However, often we see giant planets
out of region of ices.
This means – migration.

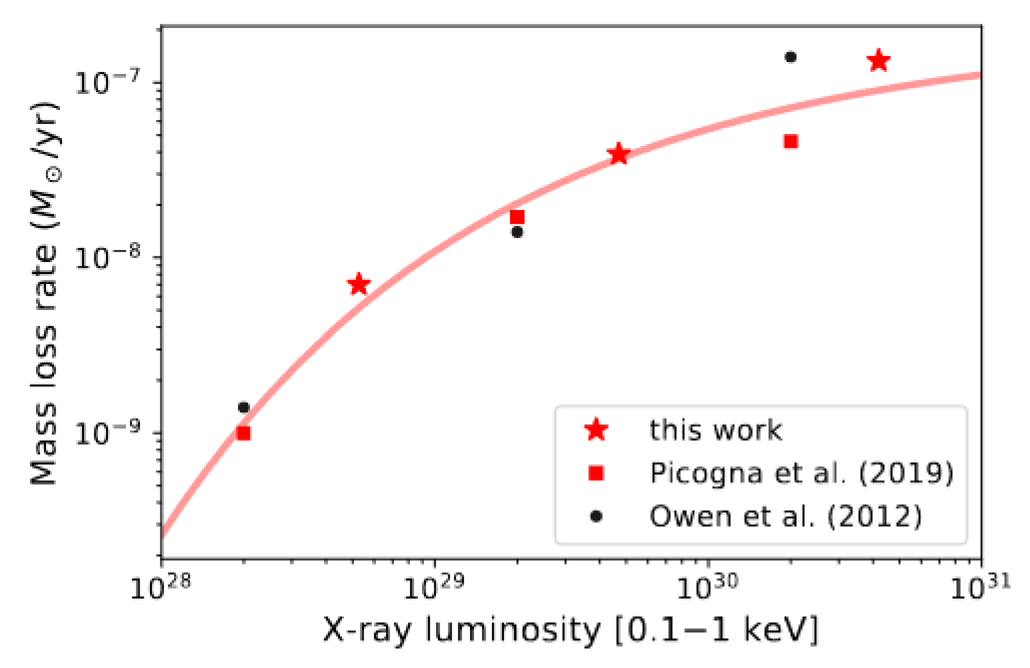
Protoplanetary and debris discs. Evolution



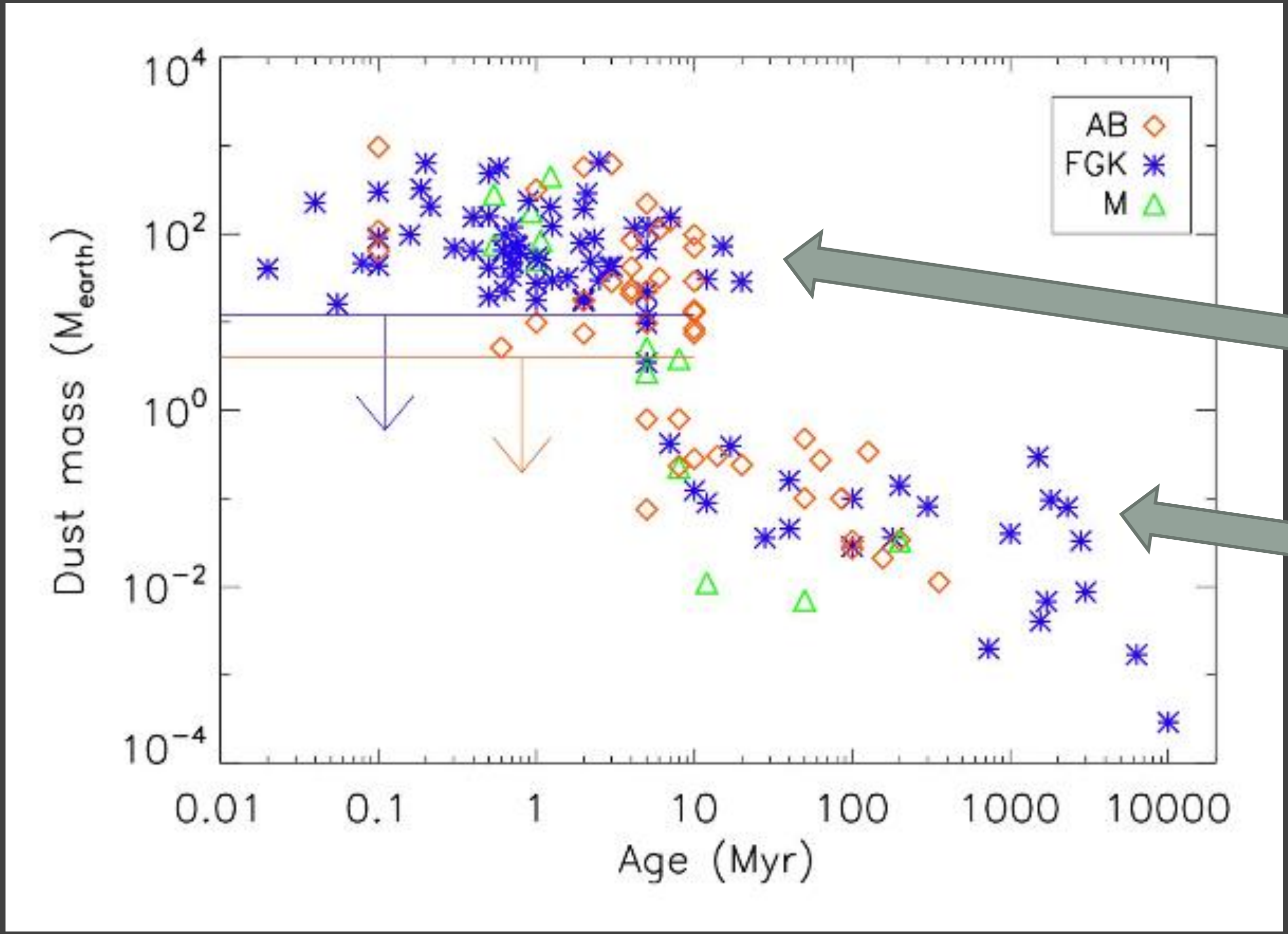
Photoevaporation



Gas is lost from the disc mainly due to X-ray and UV emission of the central star on the time scale ~few Myrs.



Evolution of the dust mass in discs

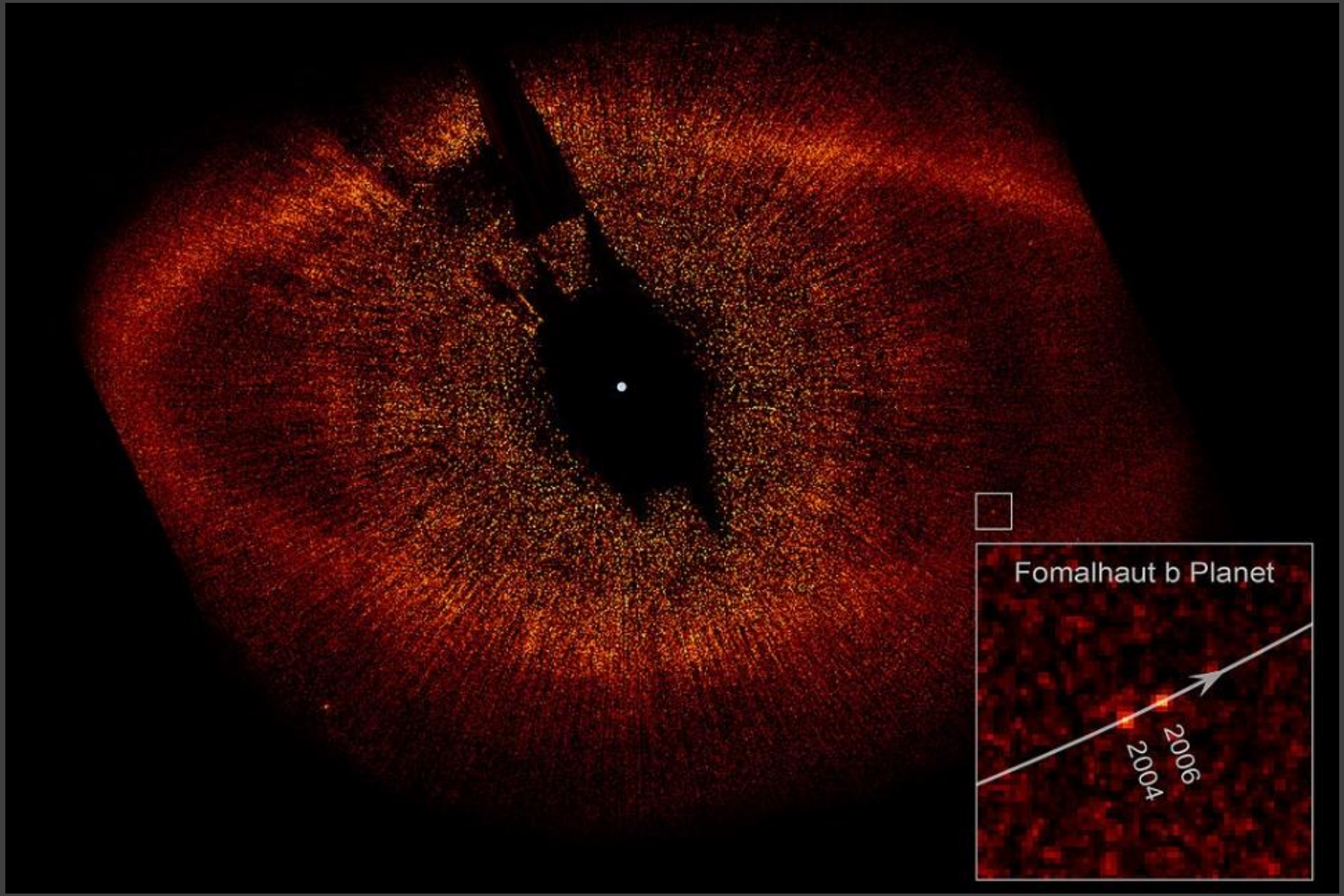


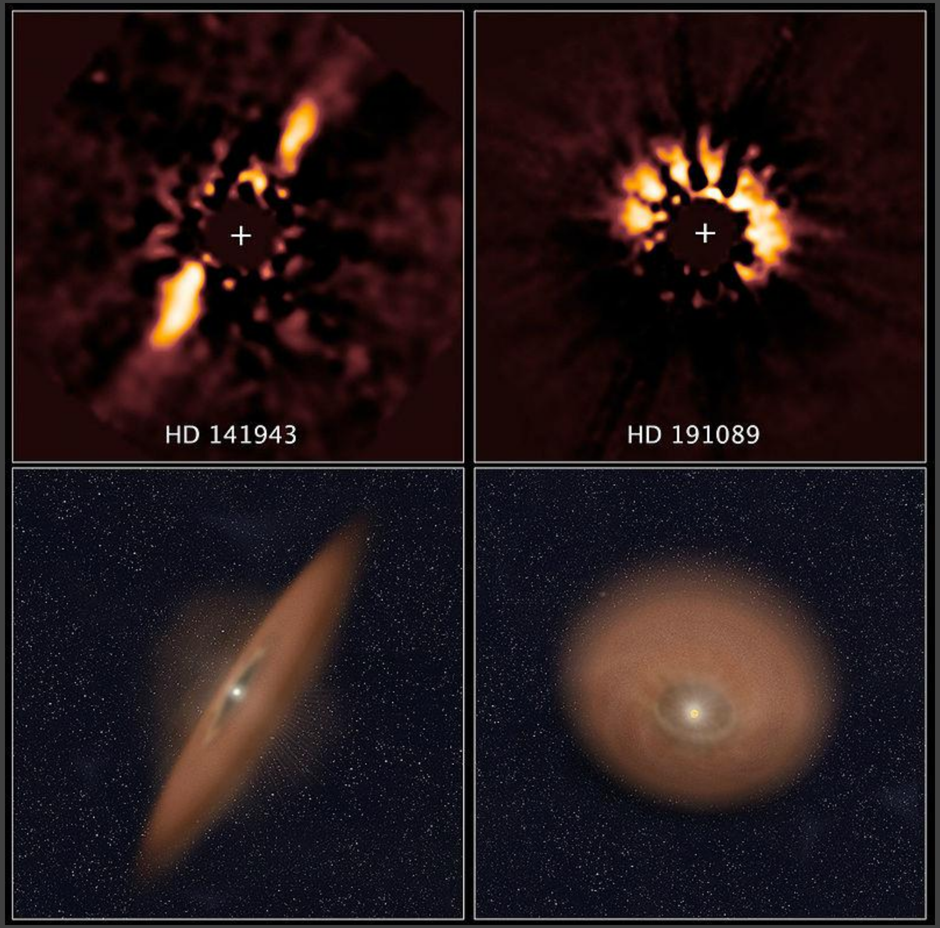
Protoplanetary discs

Debris discs

Panic et al. 2013, taken from the review 1703.08560

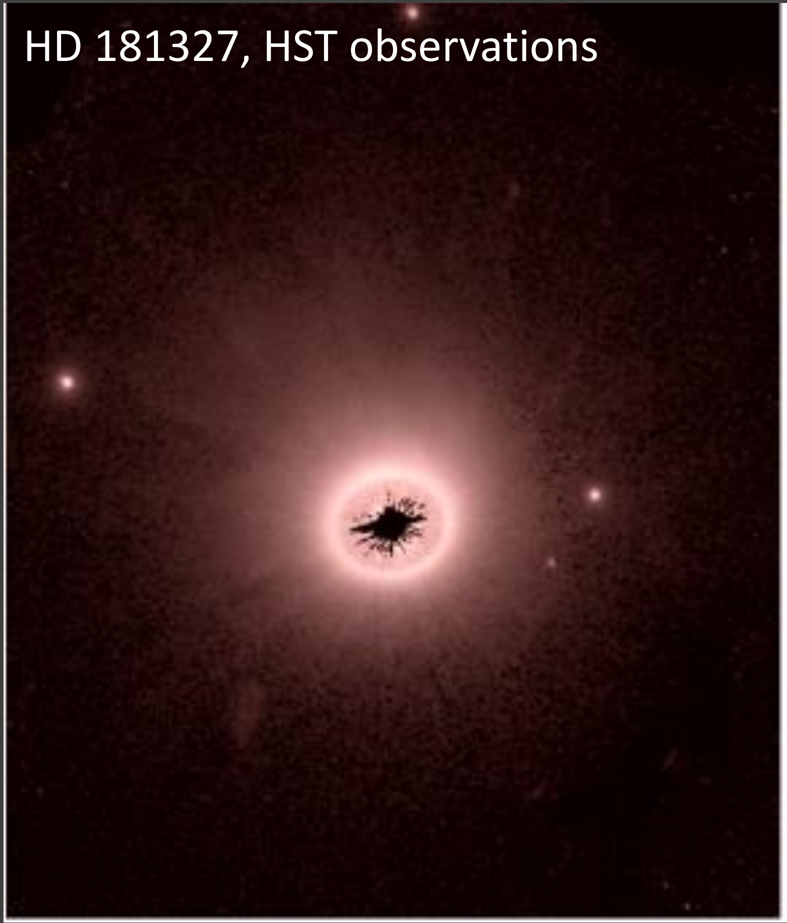
Debris discs

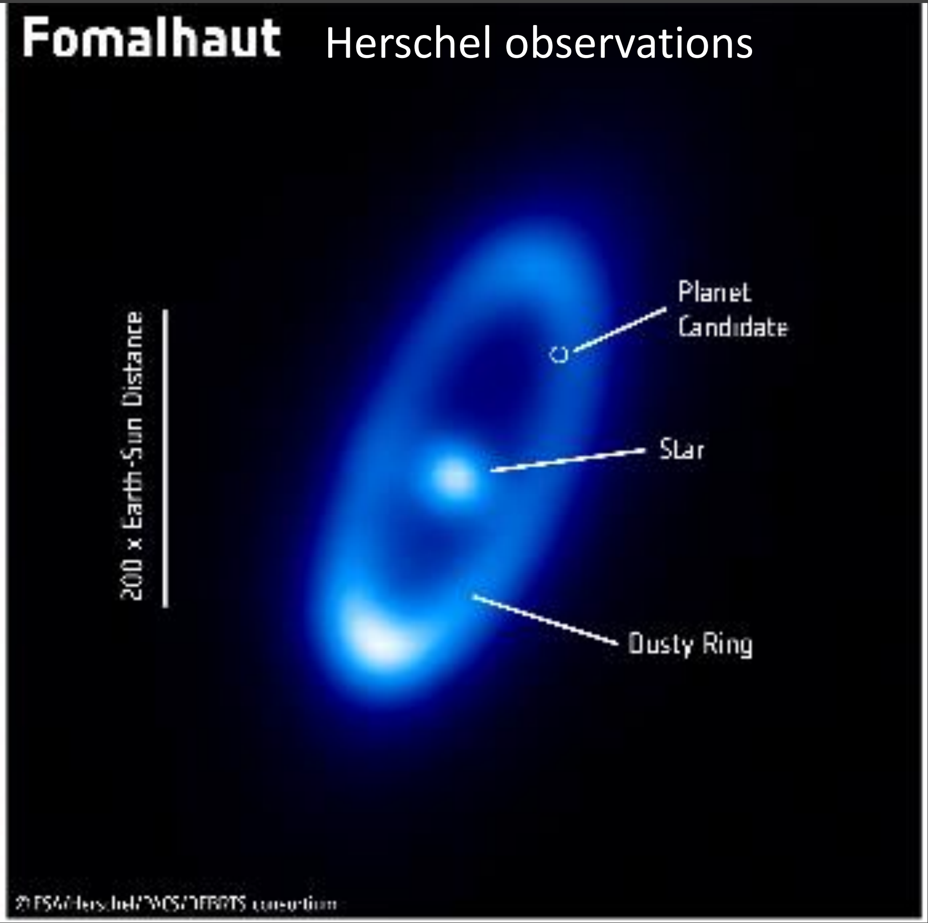




See a review in 1802.04313, 1804.08636

Two debris disc examples

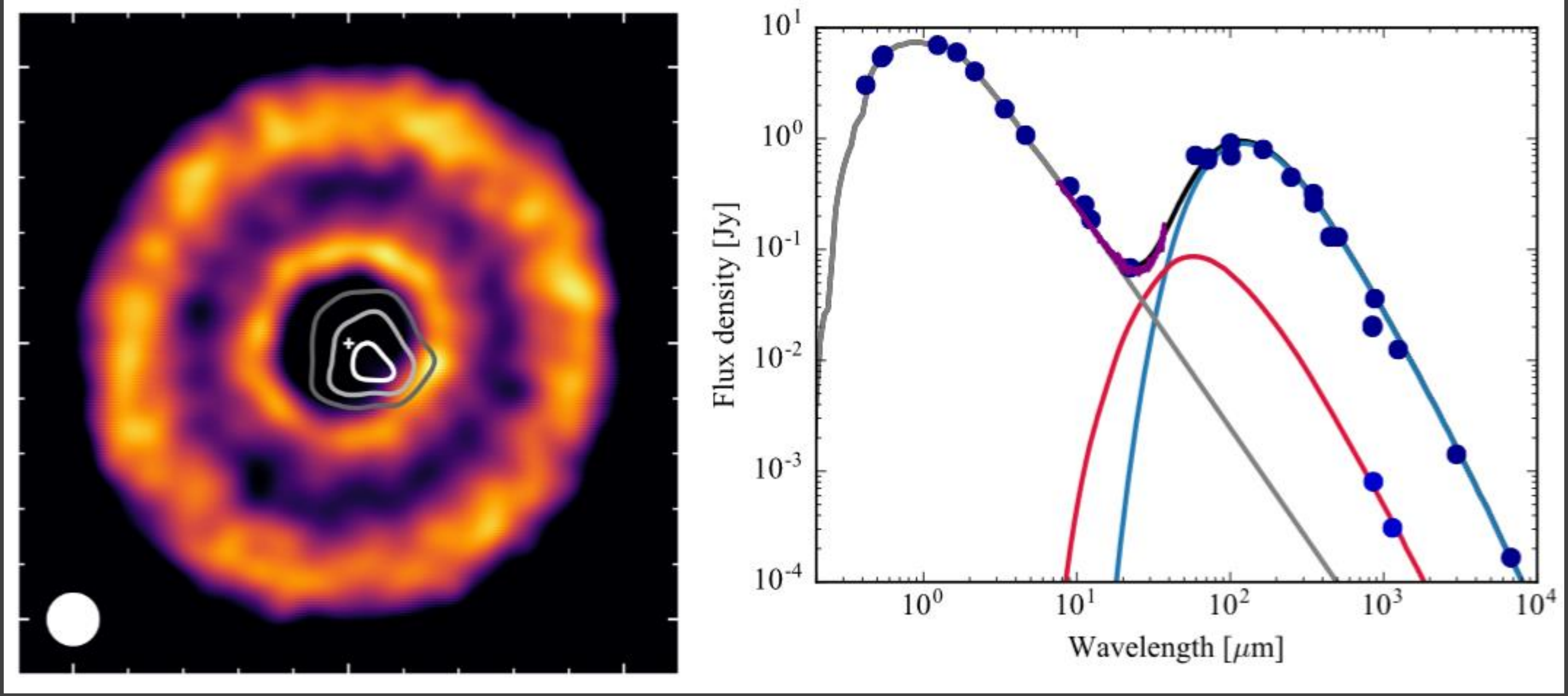




Hundreds of debris discs are known.

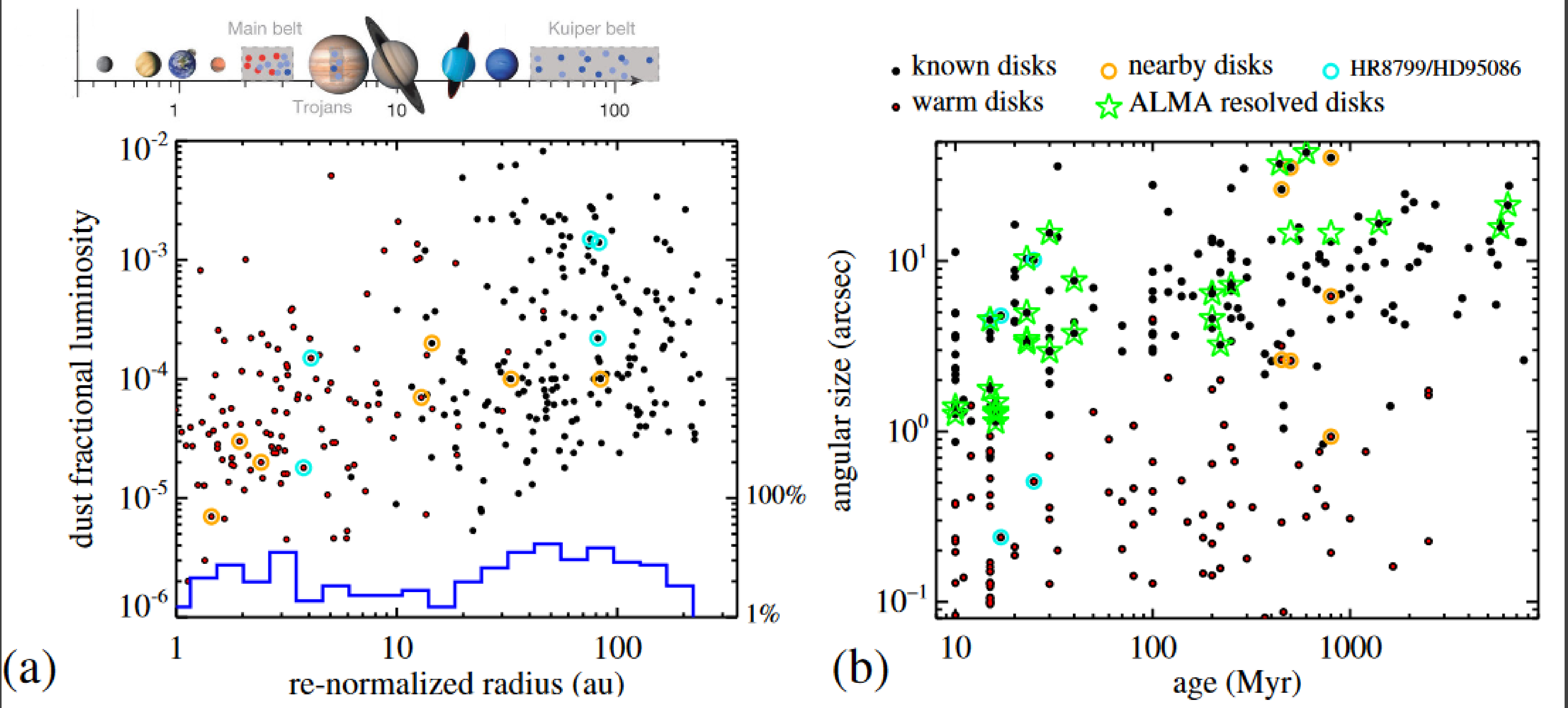
taken from the review 1703.08560

HD107146. ALMA observations



1804.08636

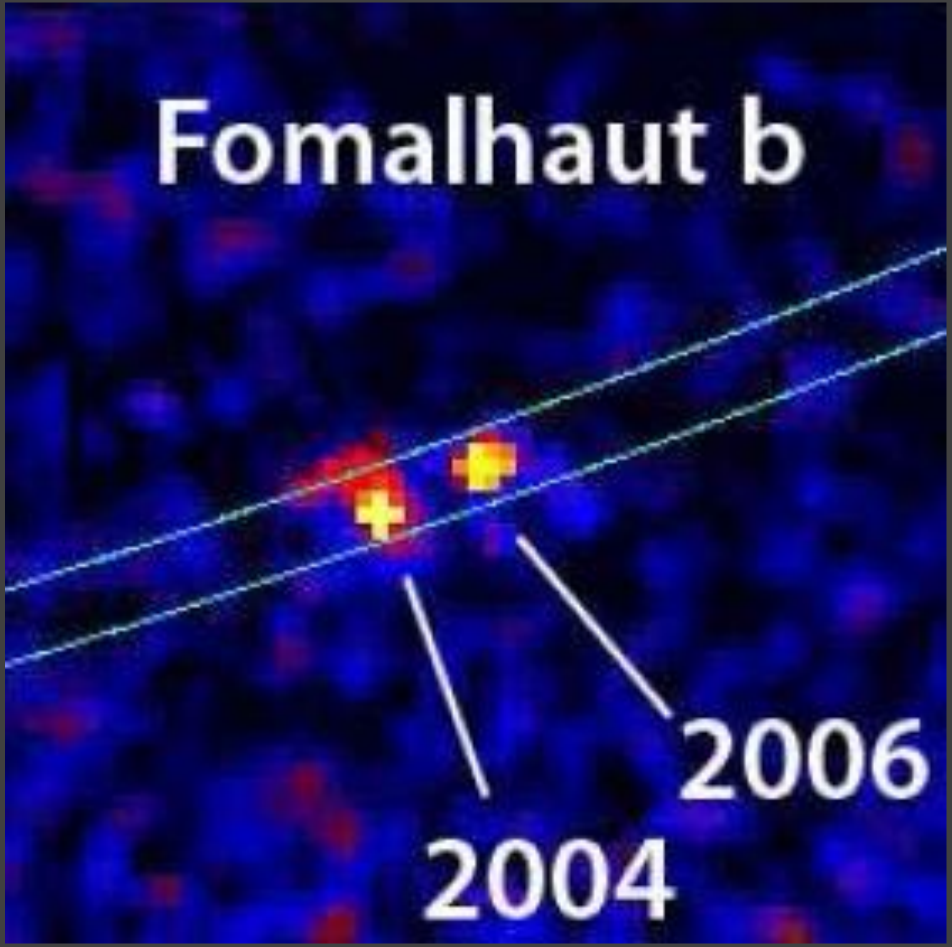
Debris disks are the dust disks found around ~20% of nearby main sequence stars in far-IR surveys.



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

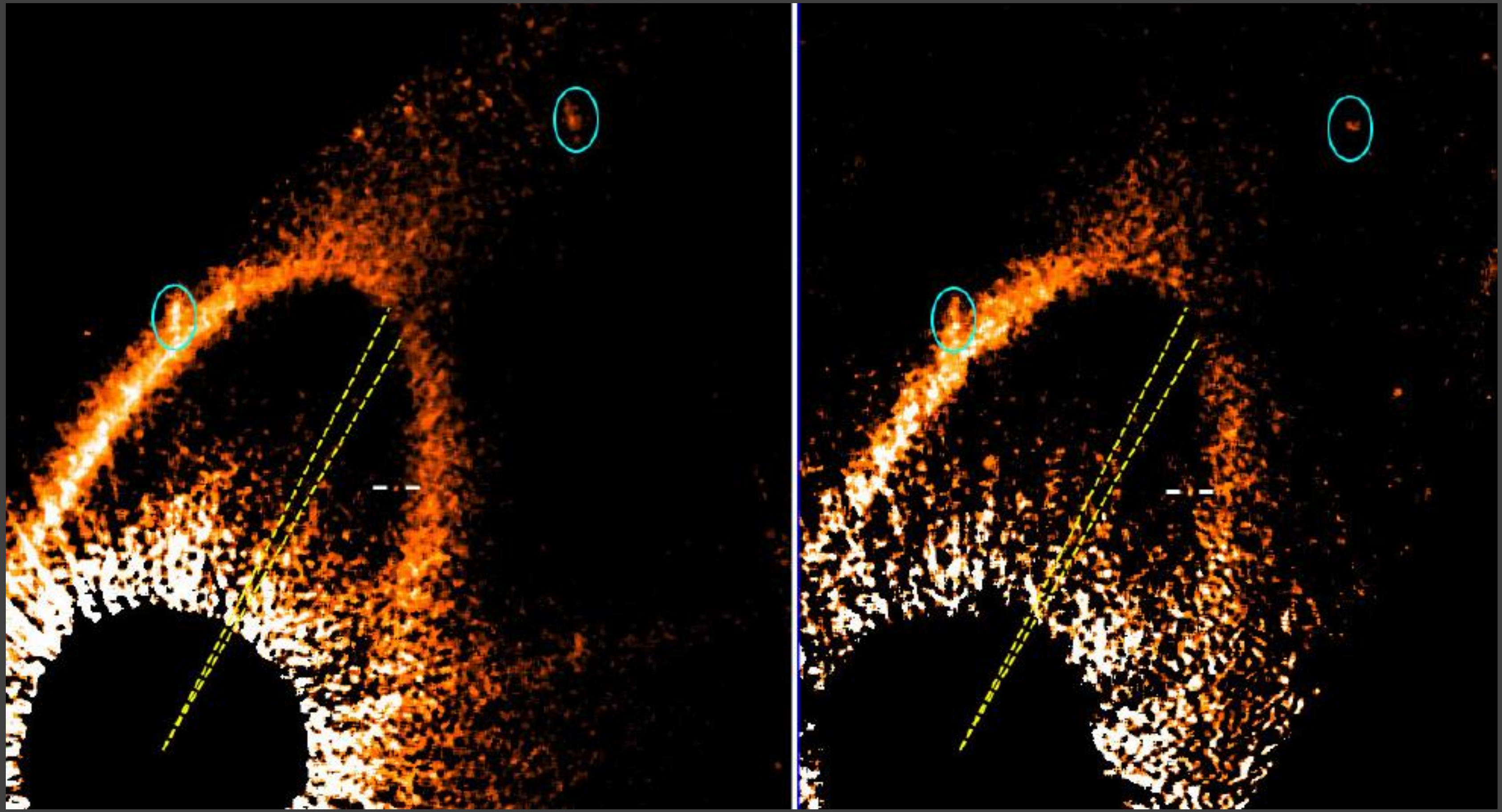
1903.10616

Fomalhaut b



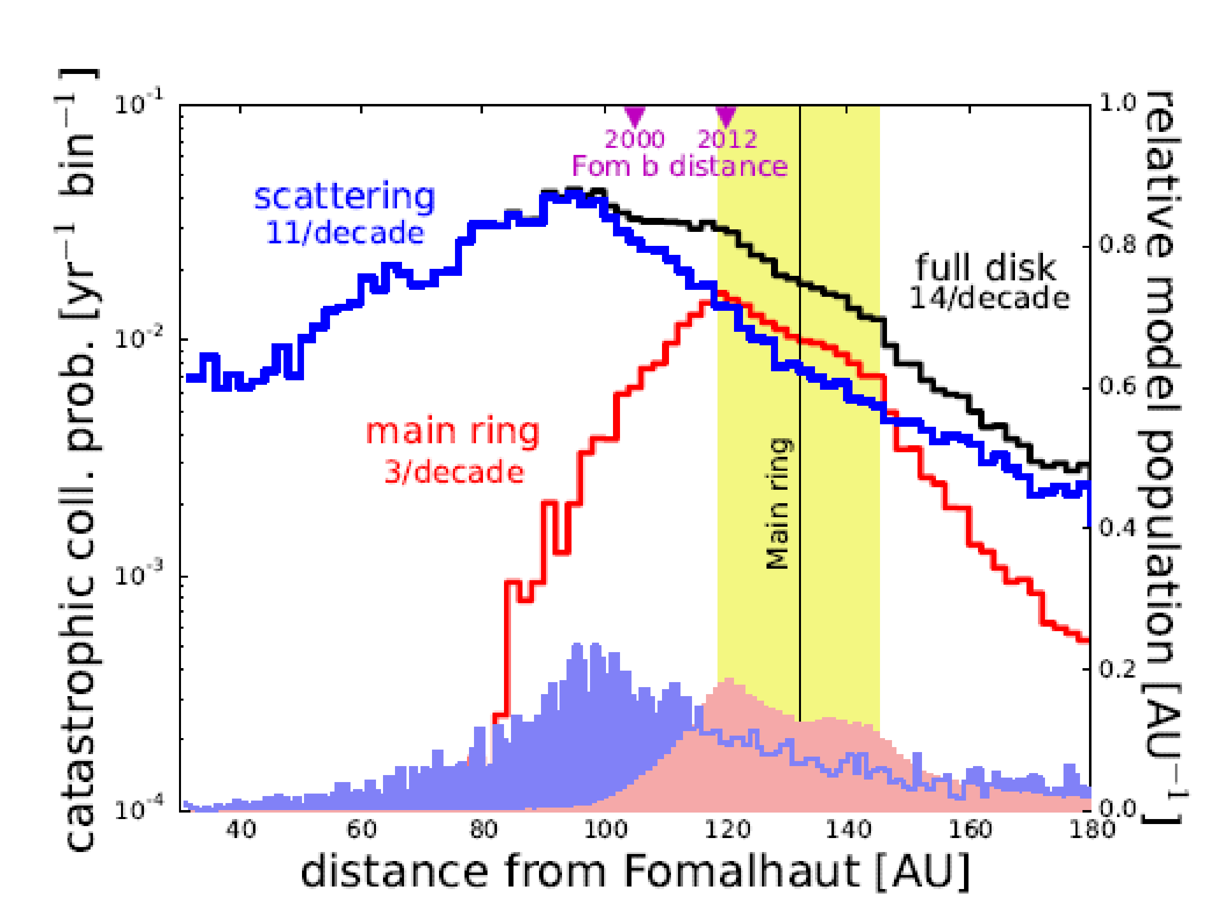
115 AU from the star

Is Fomalhaut b a real planet?



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

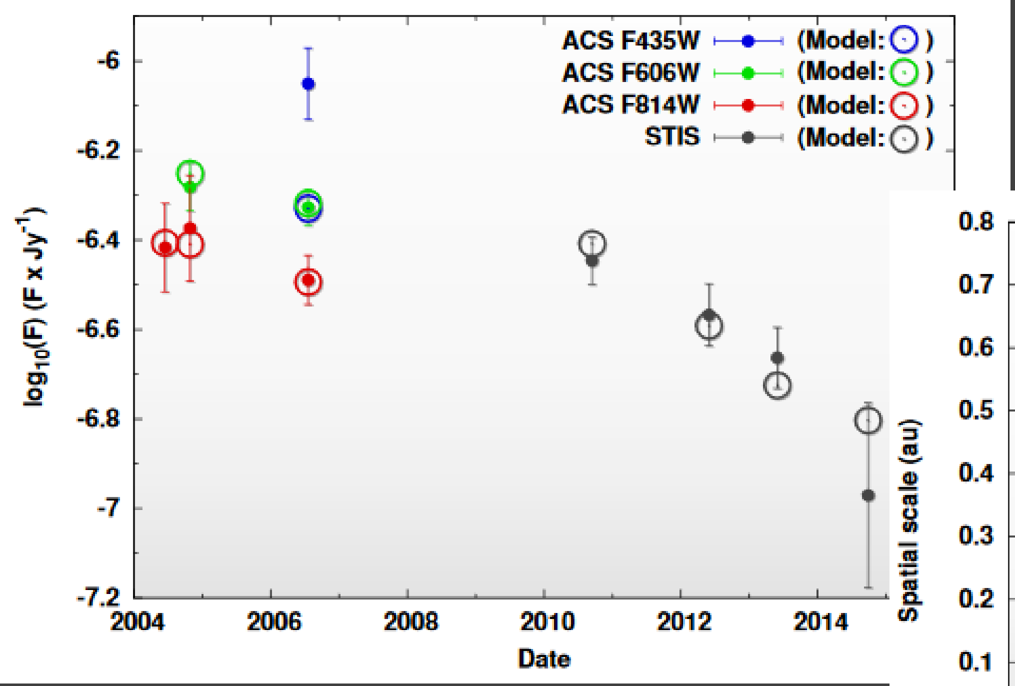
Result of a recent collision?

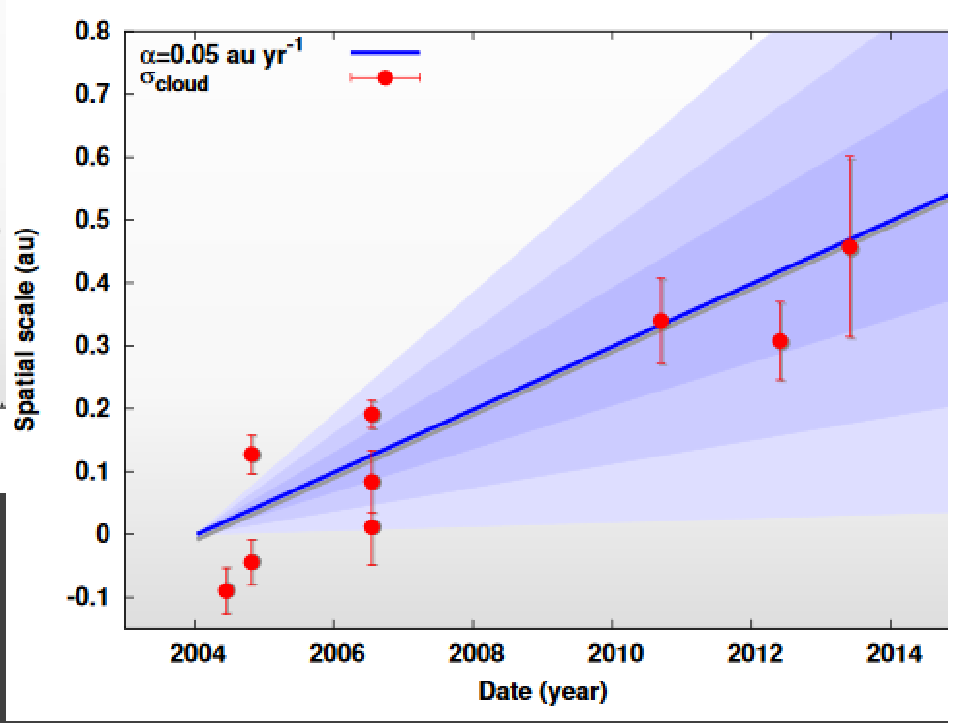


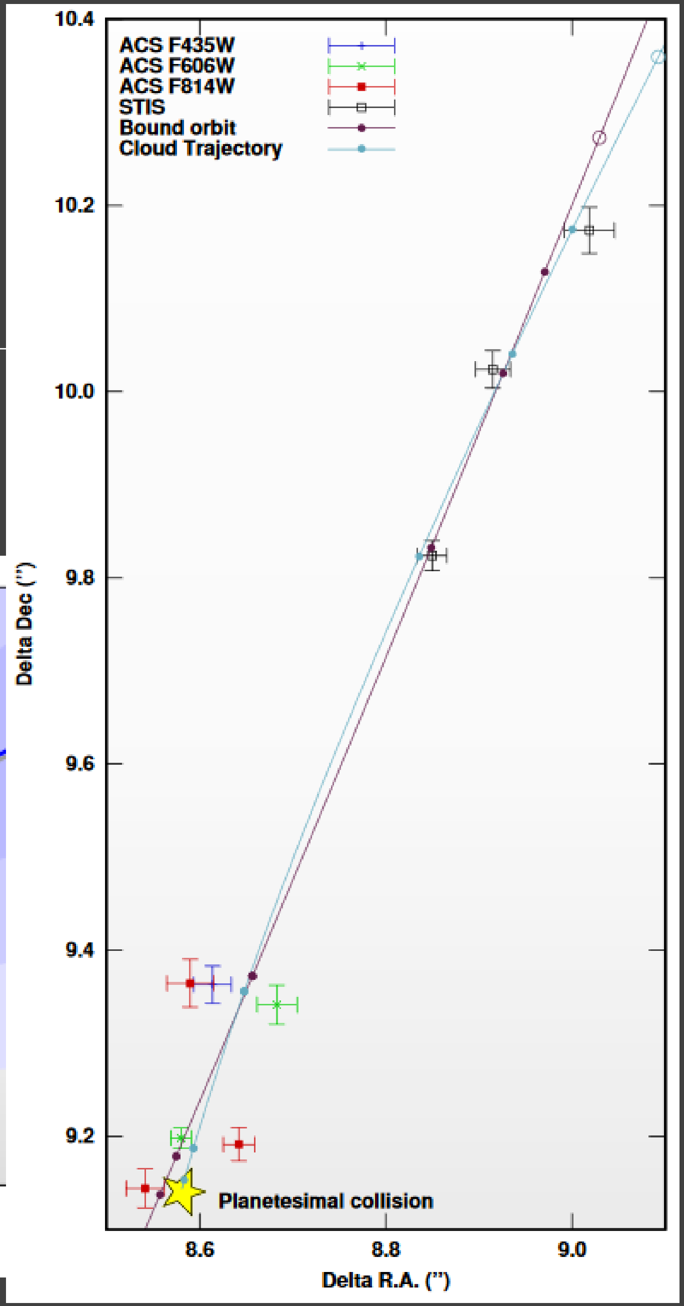
The object is situated in the region where collisions are very probable.

Two bodies with ~100 km size might be enough.

Collision is almost proved

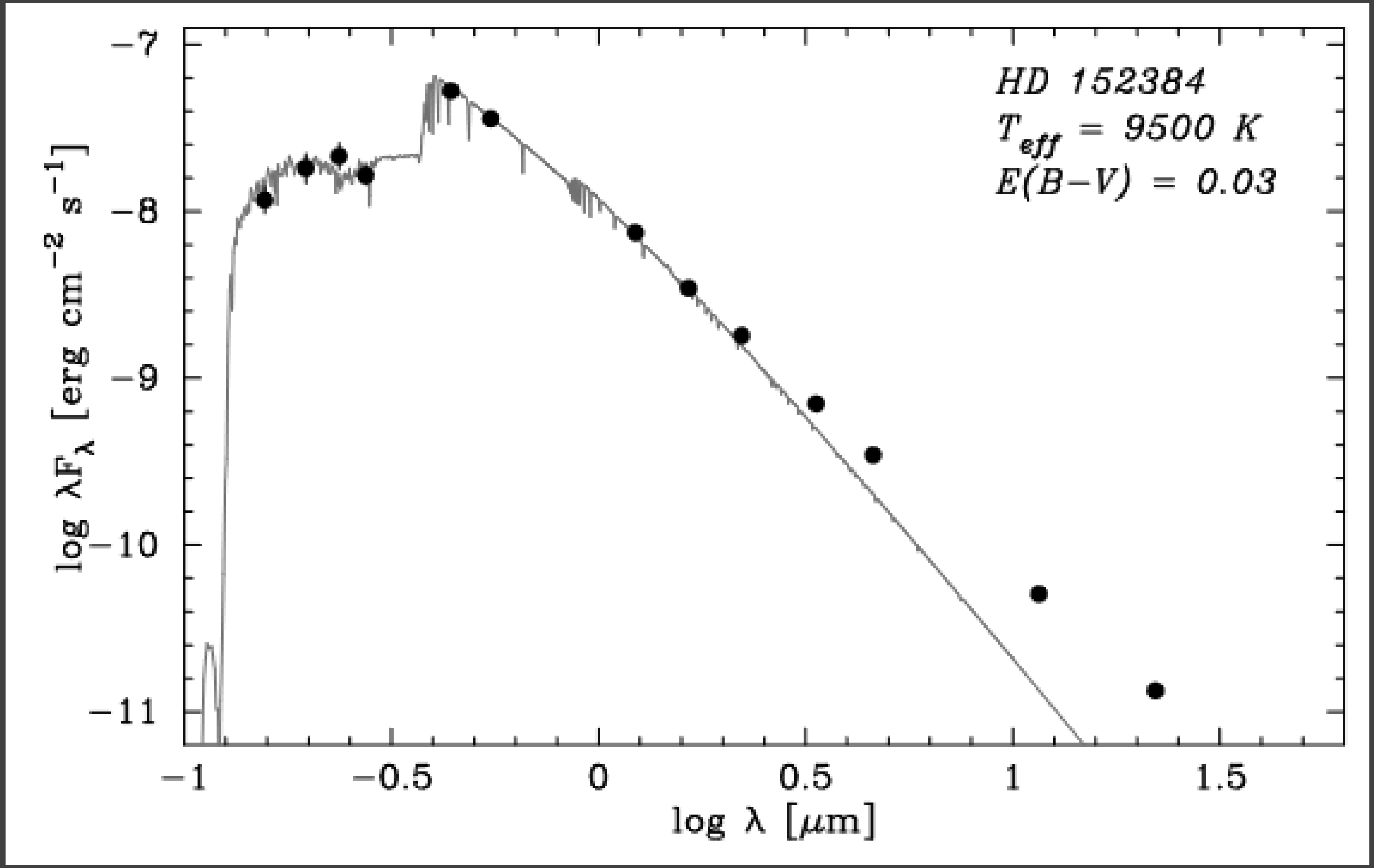






2004.08736

Collision around an A-star



Age 5-10 Myrs.
Wide binary (~10 000 AU).

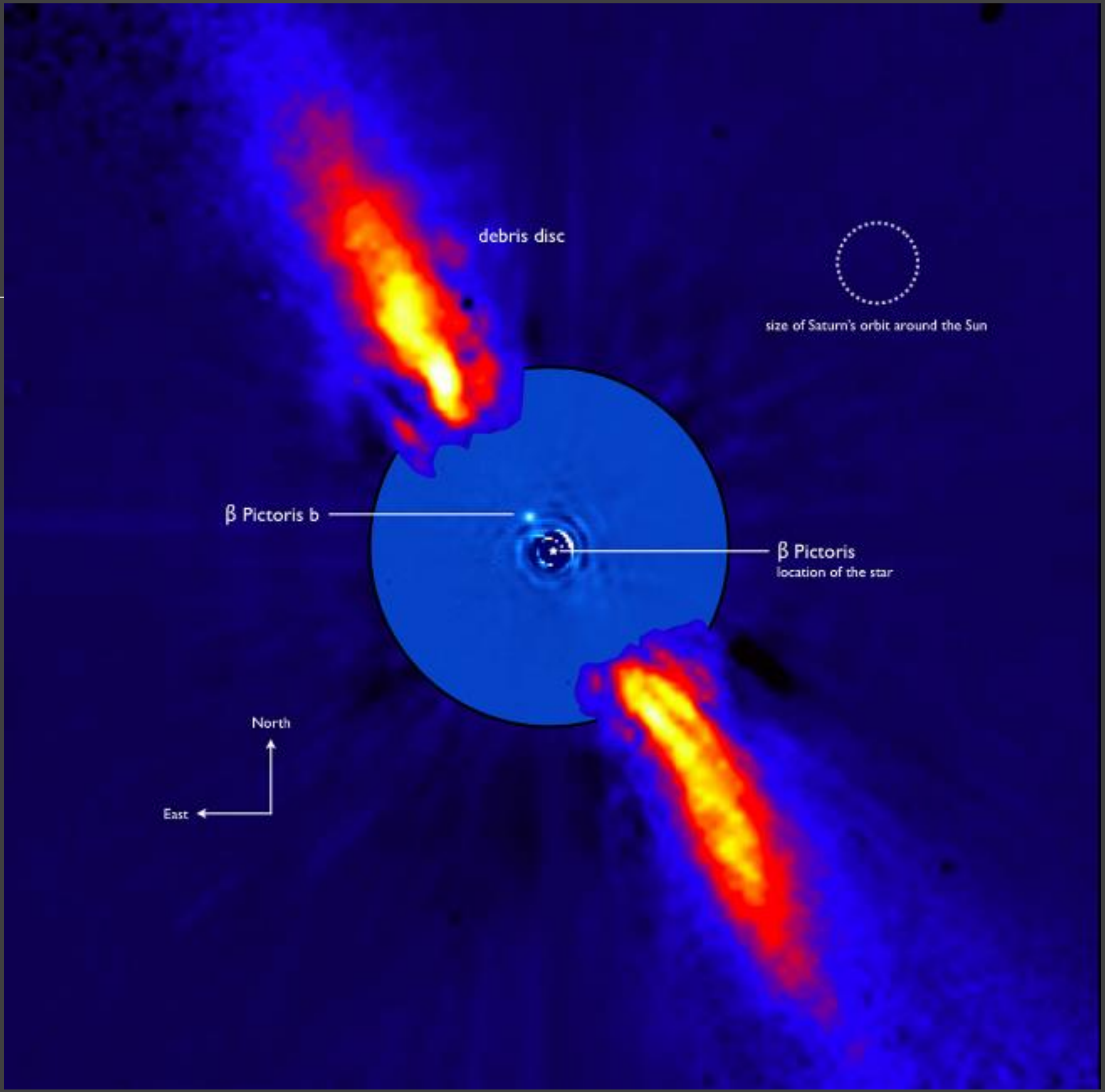
VLT observations. XSHOOTER spectrograph.

Compact (<0.3 AU) debris-like disc without volatile materials (hydrogen, helium – only in absorption) while Ca, Mg, Si, Fe are seen in emission.

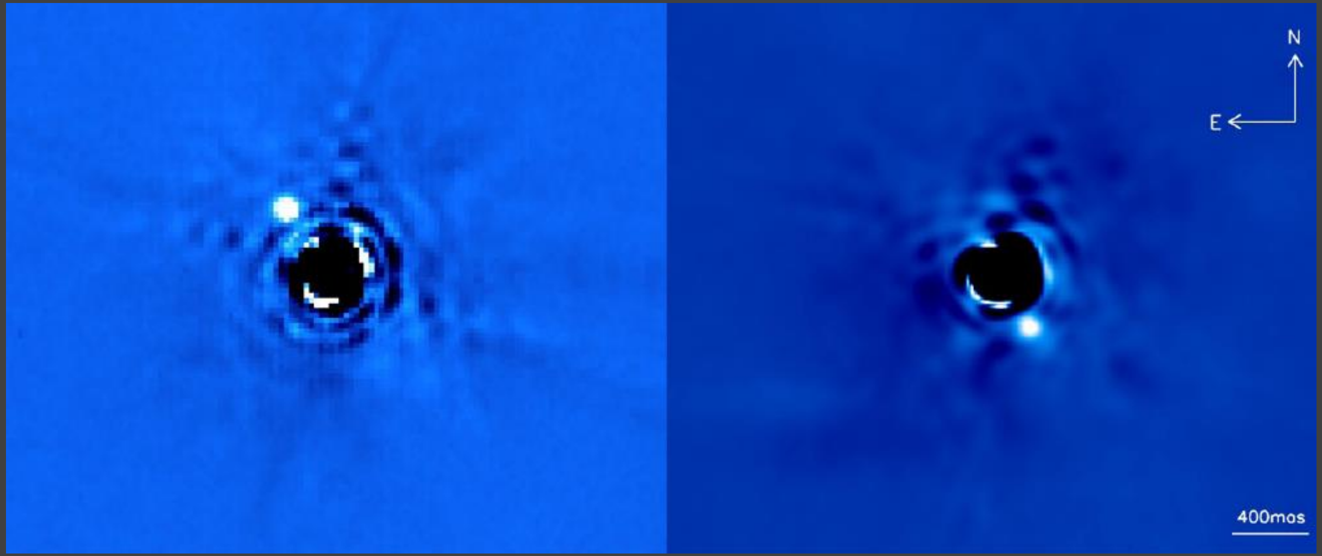
May be a result of collision of rocky planets.

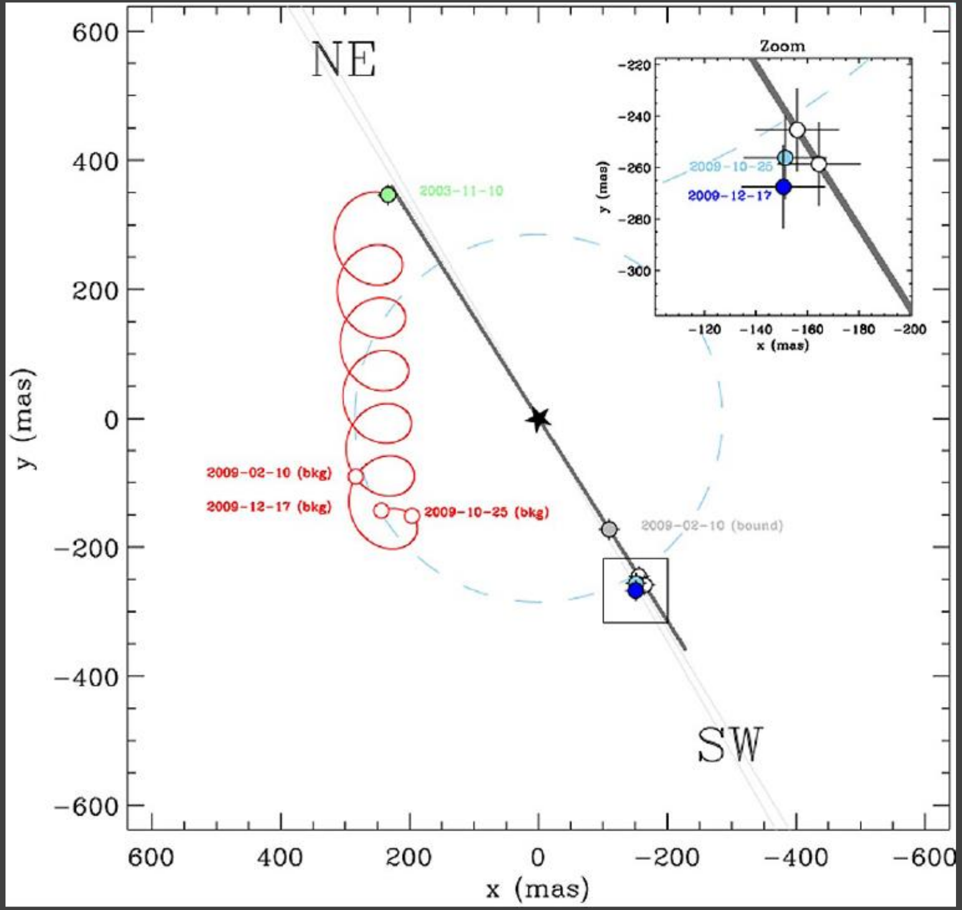
Beta Pictoris

Composite image obtained
by two instruments



Beta Pictoris





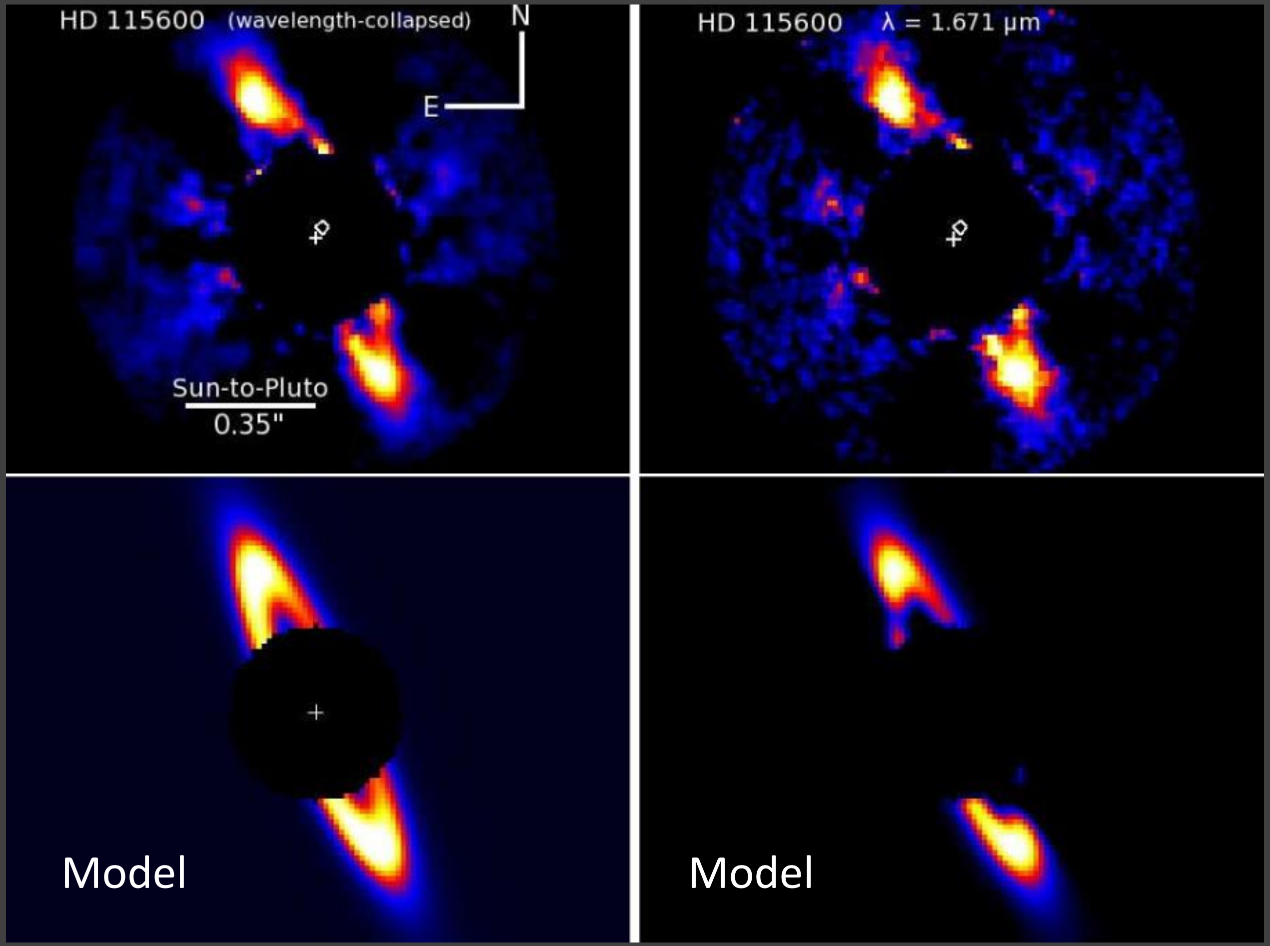
Age ~10 Myr
Distance ~ 9 AU

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



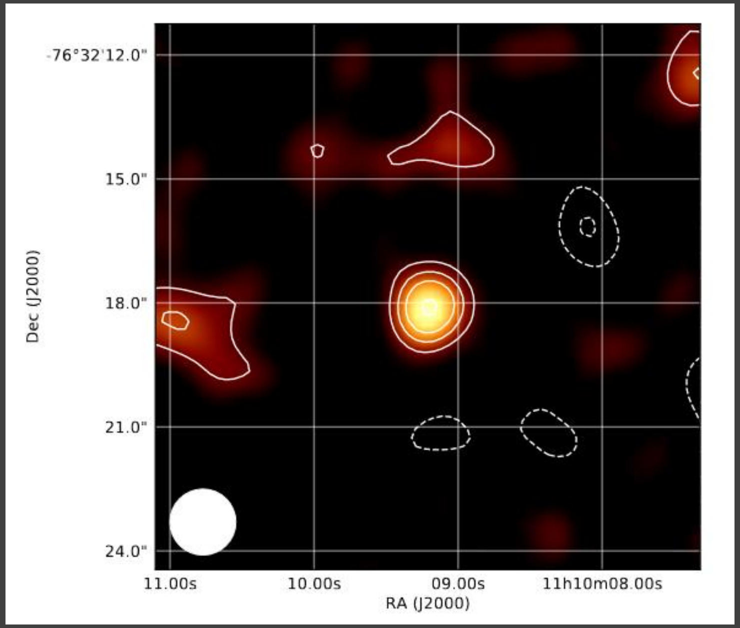
Disc around planetary mass object

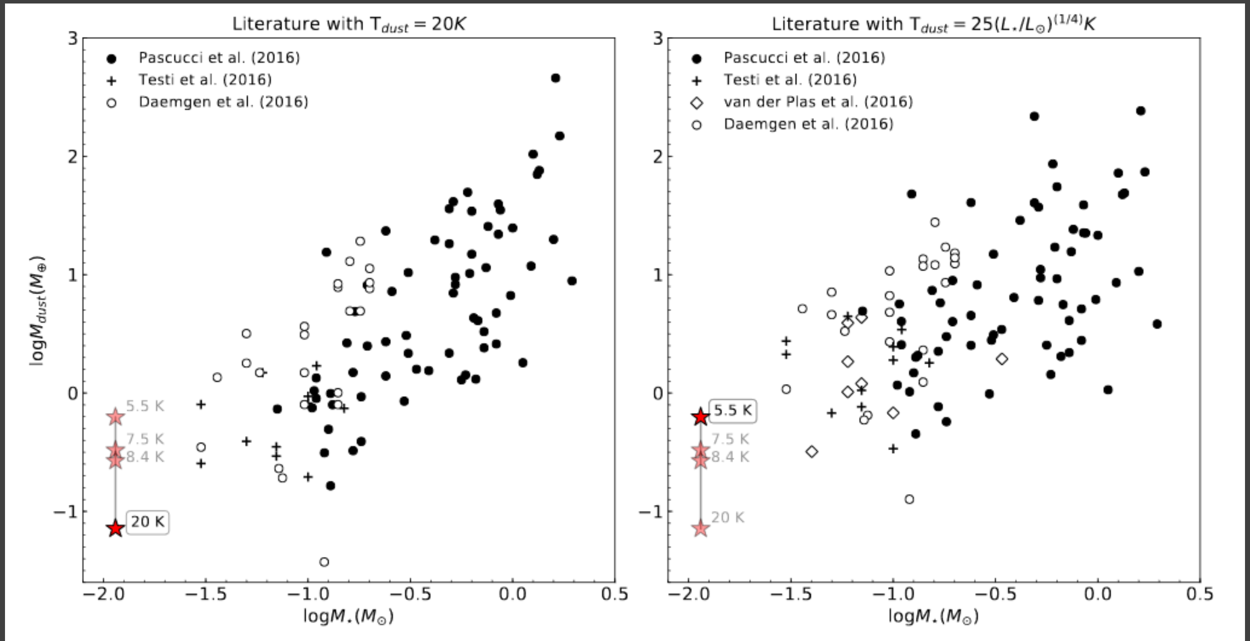
OTS44 is one of only four free-floating planets known to have a disc.
Mass ~12 $M_{jupiter}$

IR excess seen by Spitzer and Herschel

ALMA observations

M_{dust} ~0.07-0.7 M_{Earth}



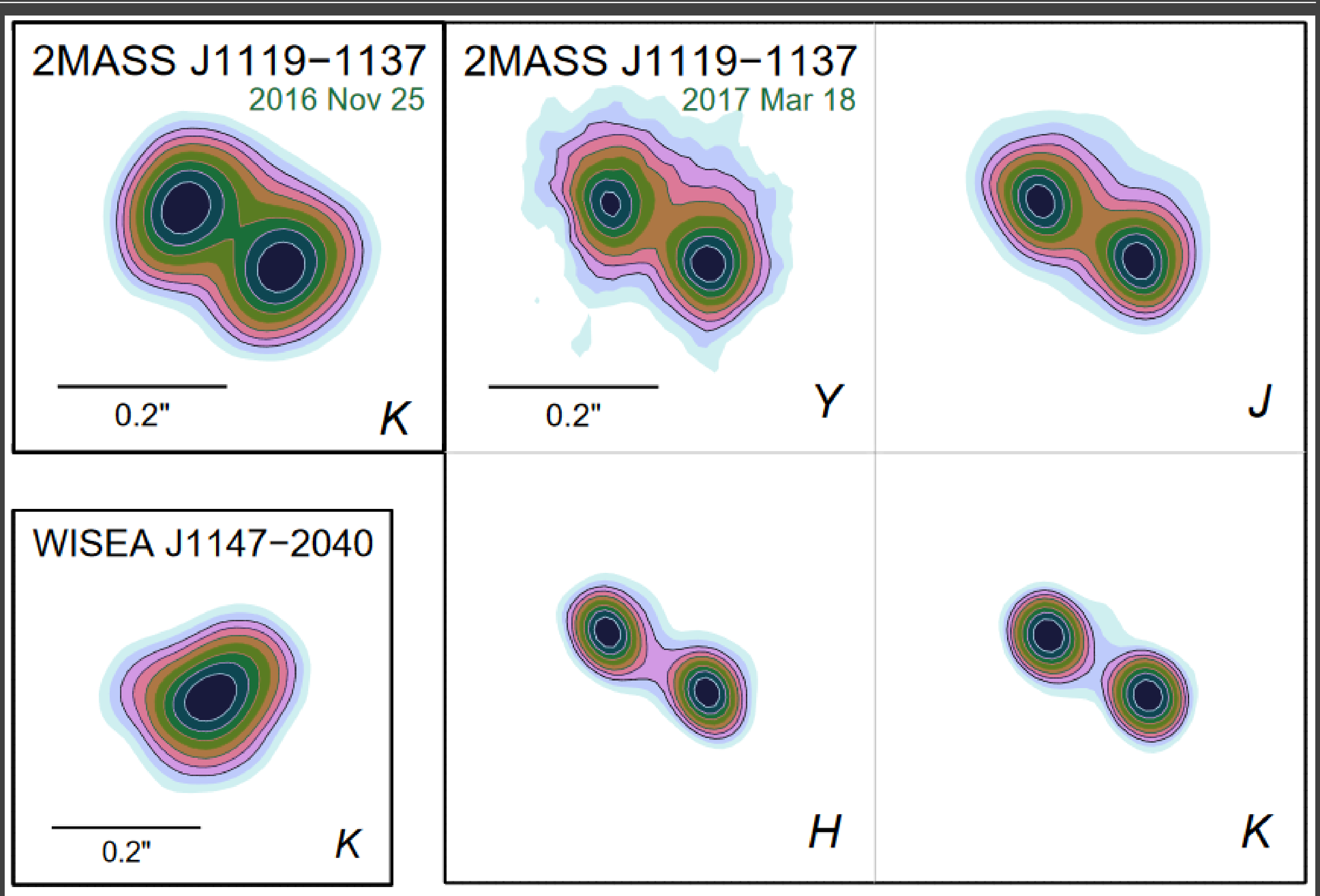


A brown dwarf is a pair of planets

2MASS J11193254−1137466

Age ~10 Myr
20-30 pc

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



1706.01883

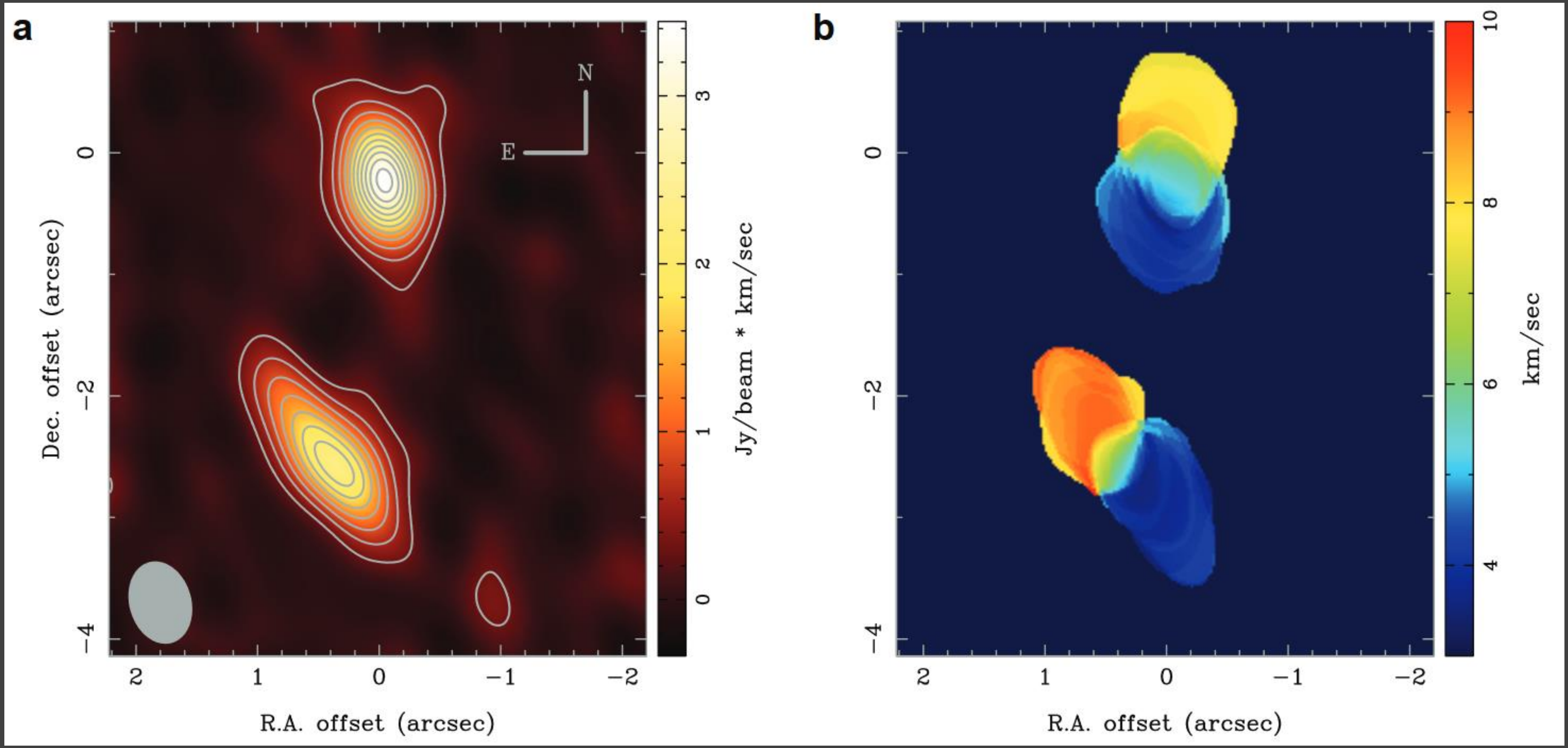
Protoplanetary discs in a binary system

HK Tau
161 pc

1-4 Myr

386 AU binary

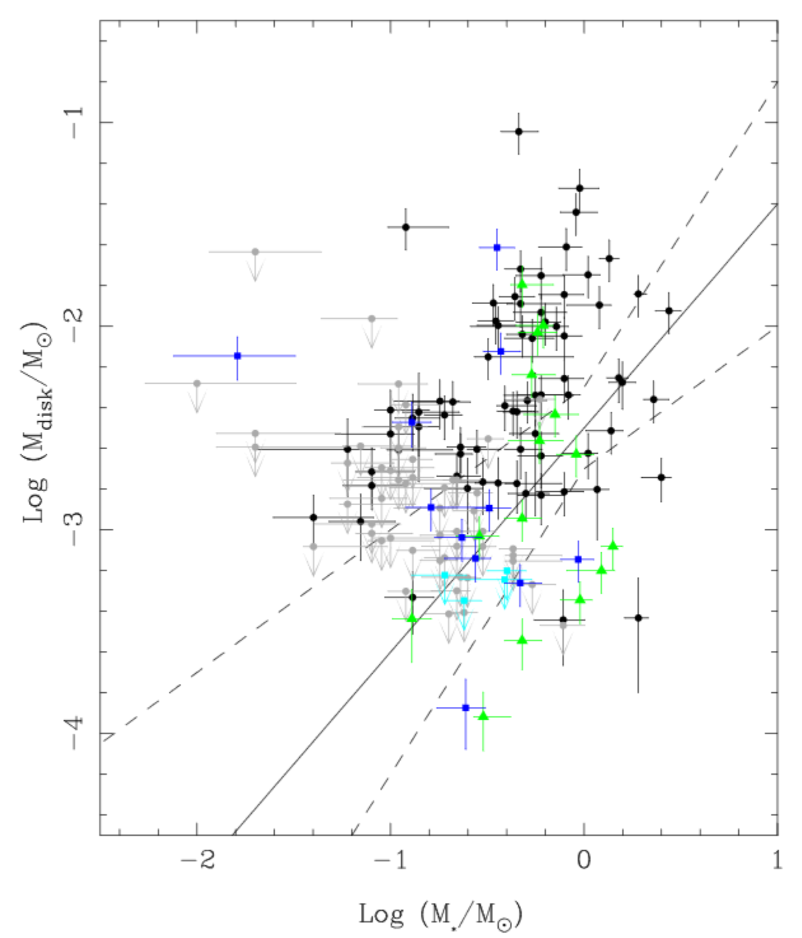
ALMA observations



1407.8211

Statistics of circumstellar discs in binaries

17 binary systems
100-1400 AU
ALMA observations

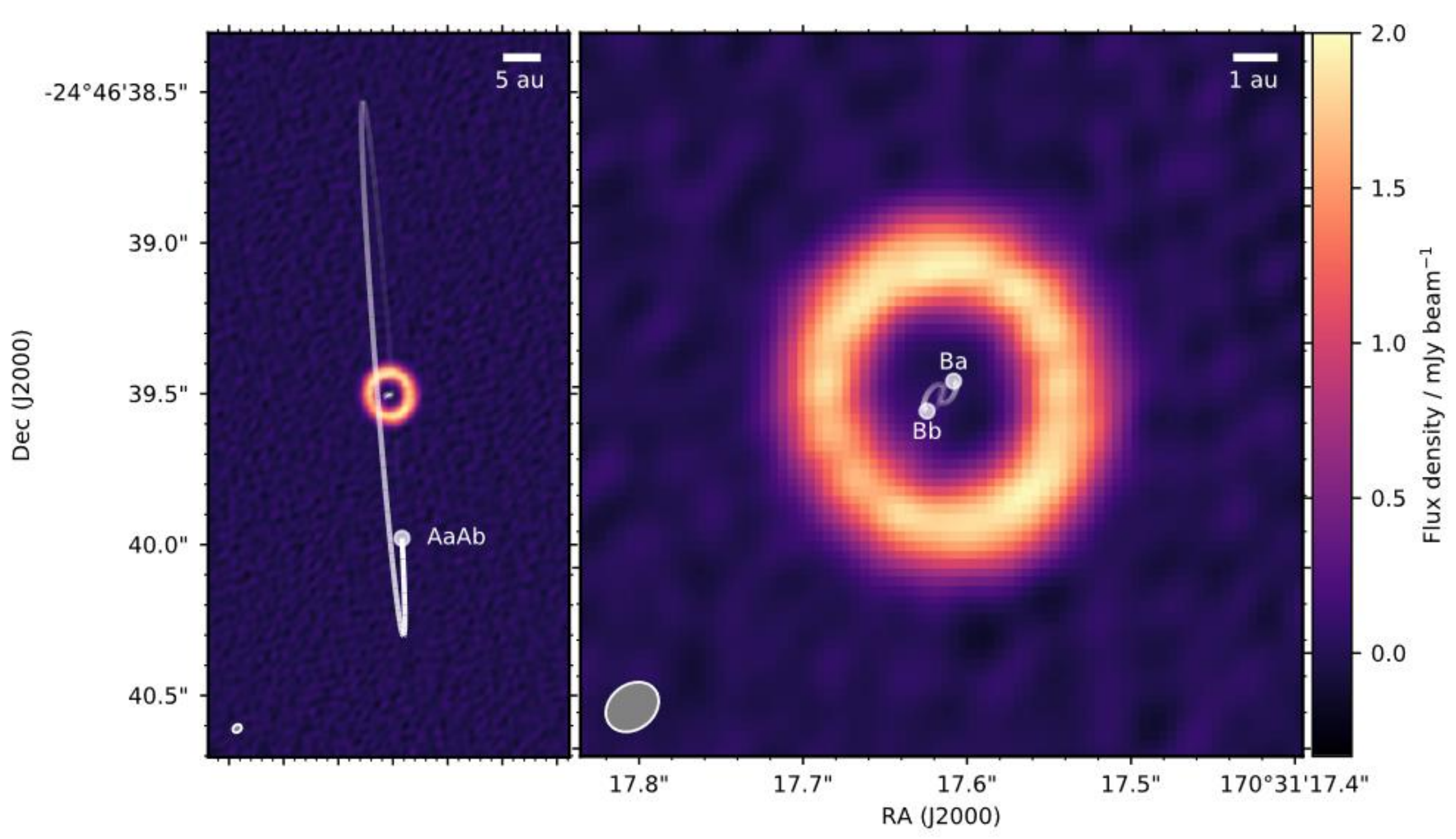


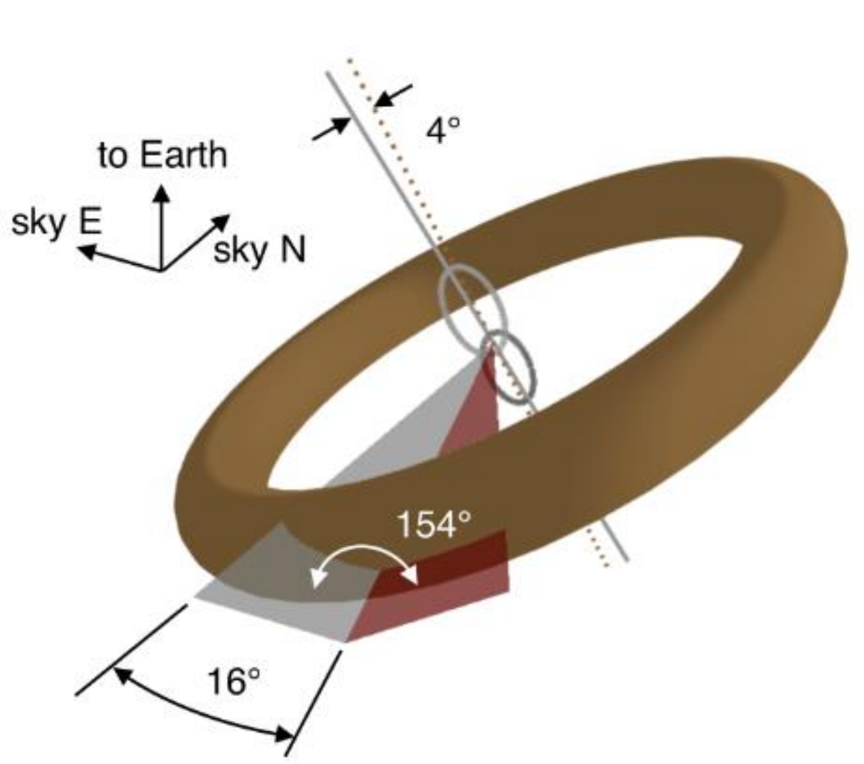
Green triangles – primaries;
Squares – secondaries
(dark blue – detected,
light blue – non-detected);
black dots – single stars
from other studies of the Tauris;
grey dods – single non-detections.

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

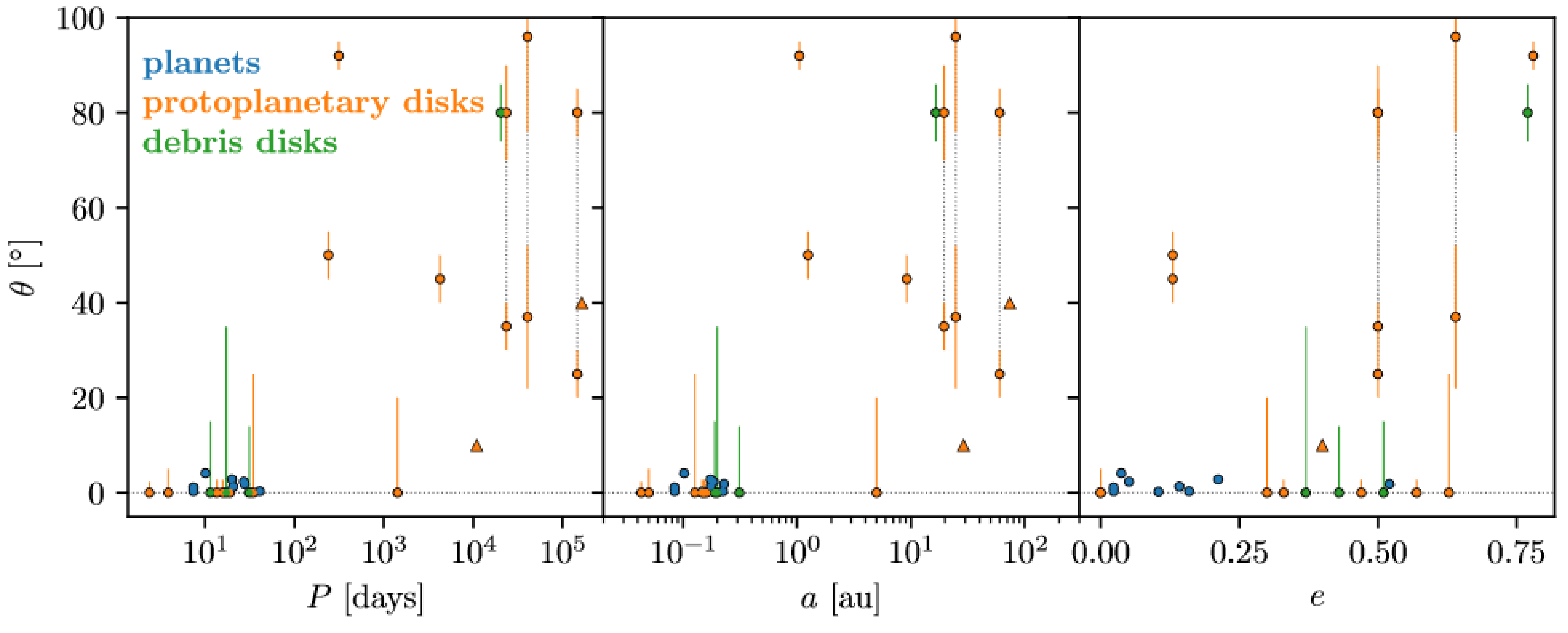
1402.5363, see more recent results in 1901.05029

A circumbinary protoplanetary disc in a polar configuration





Circumbinary discs are often inclined

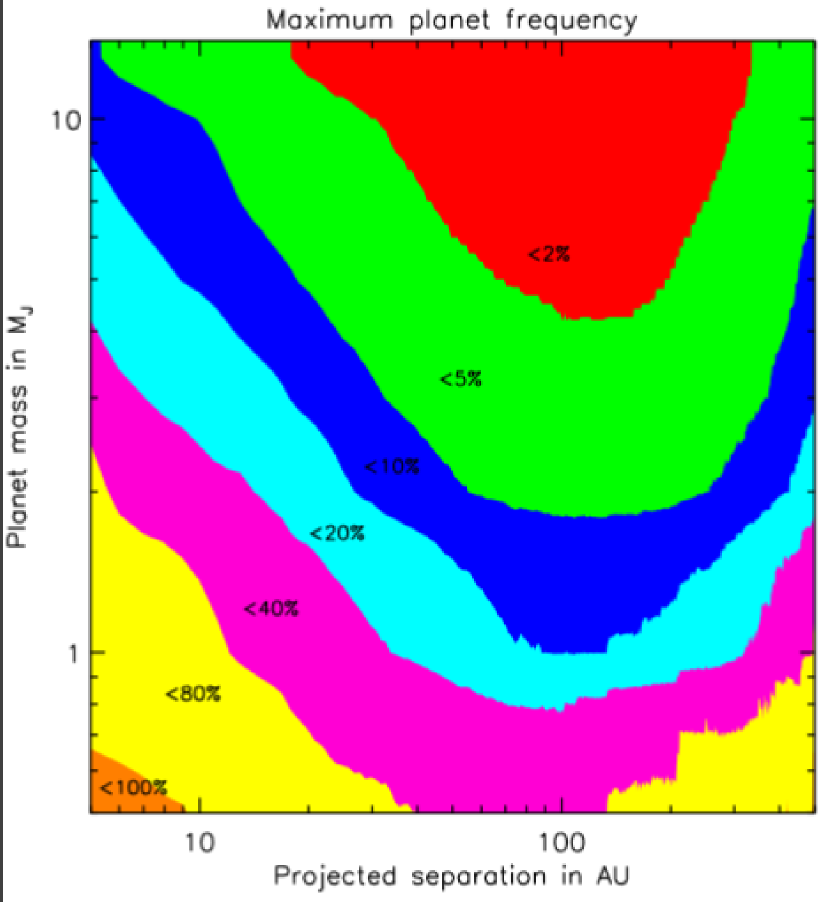


1906.03269

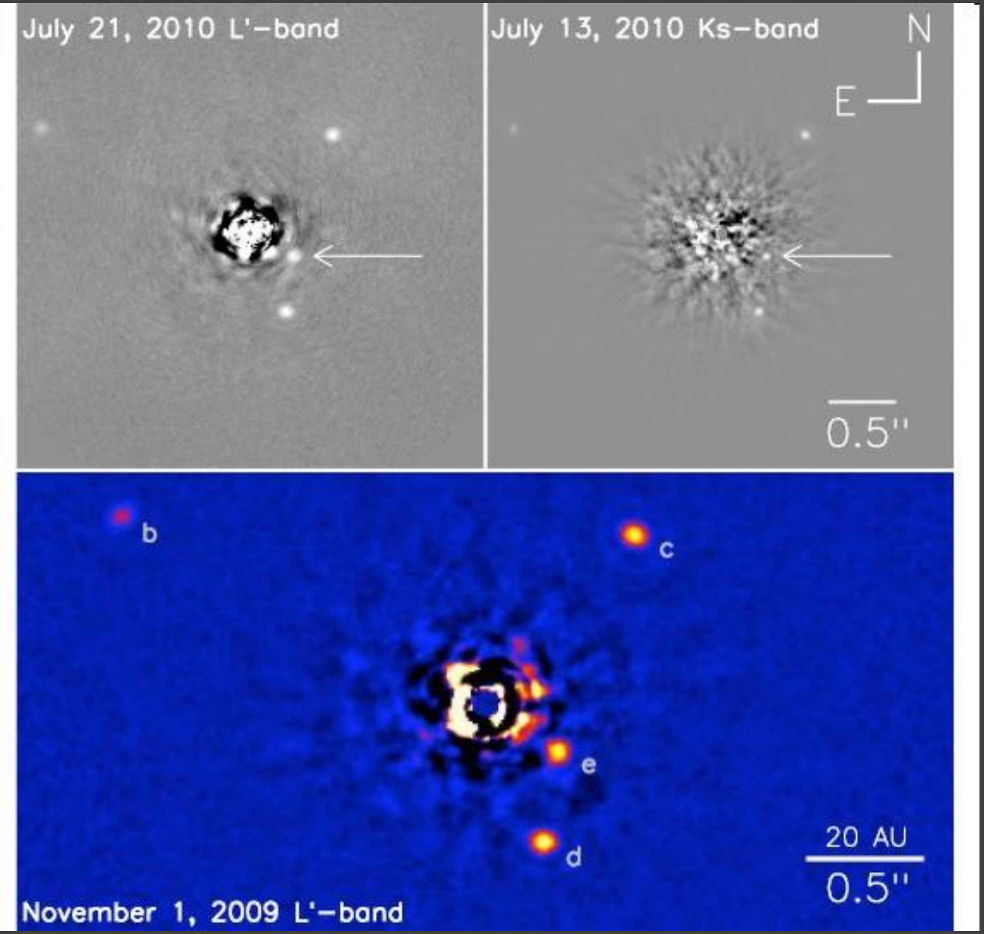
Direct imaging of planets

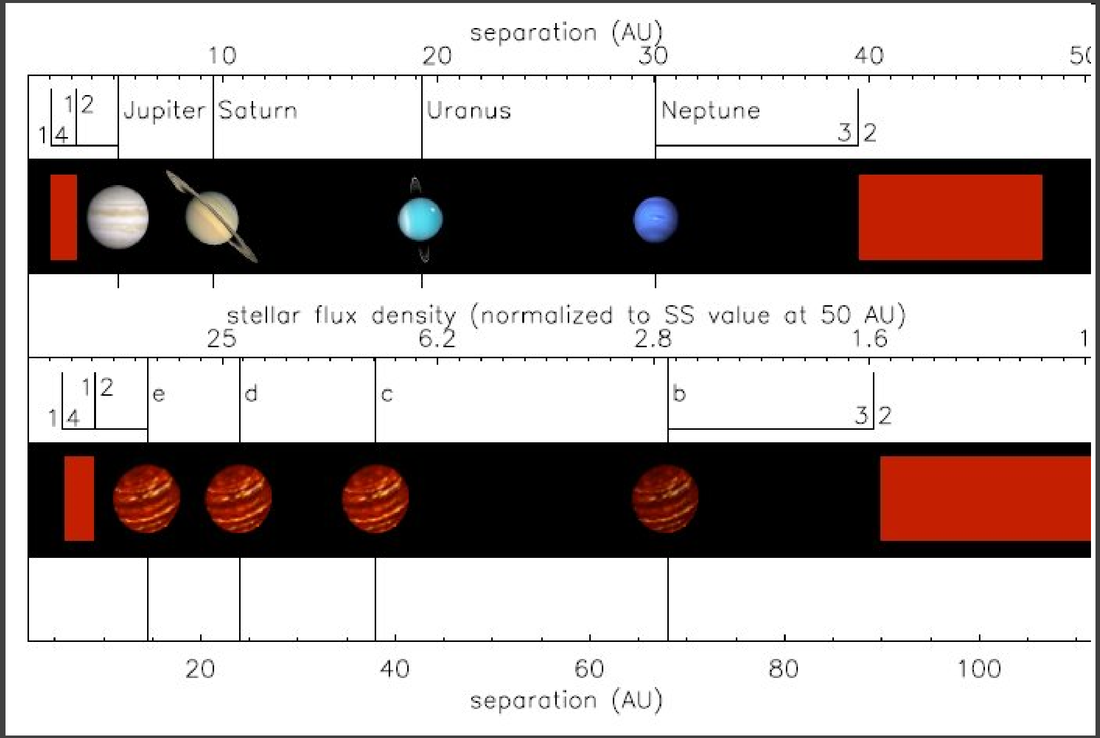
Recent survey with direct imaging resulted in an estimate that ~few percent of star have a planet 0.5-14 Mjup at 20-300 AU.

HR8799 system and several brown dwarfs were found



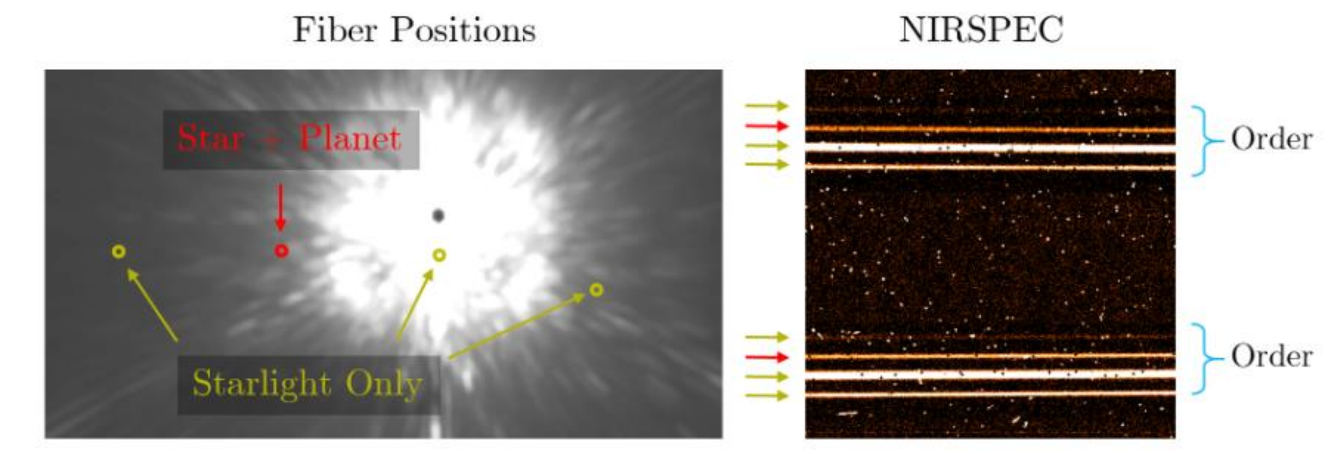
HR 8799

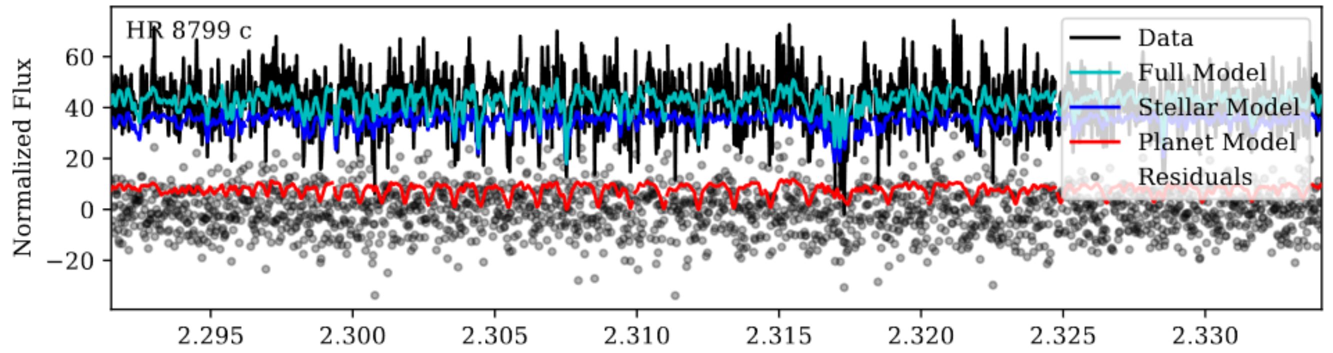


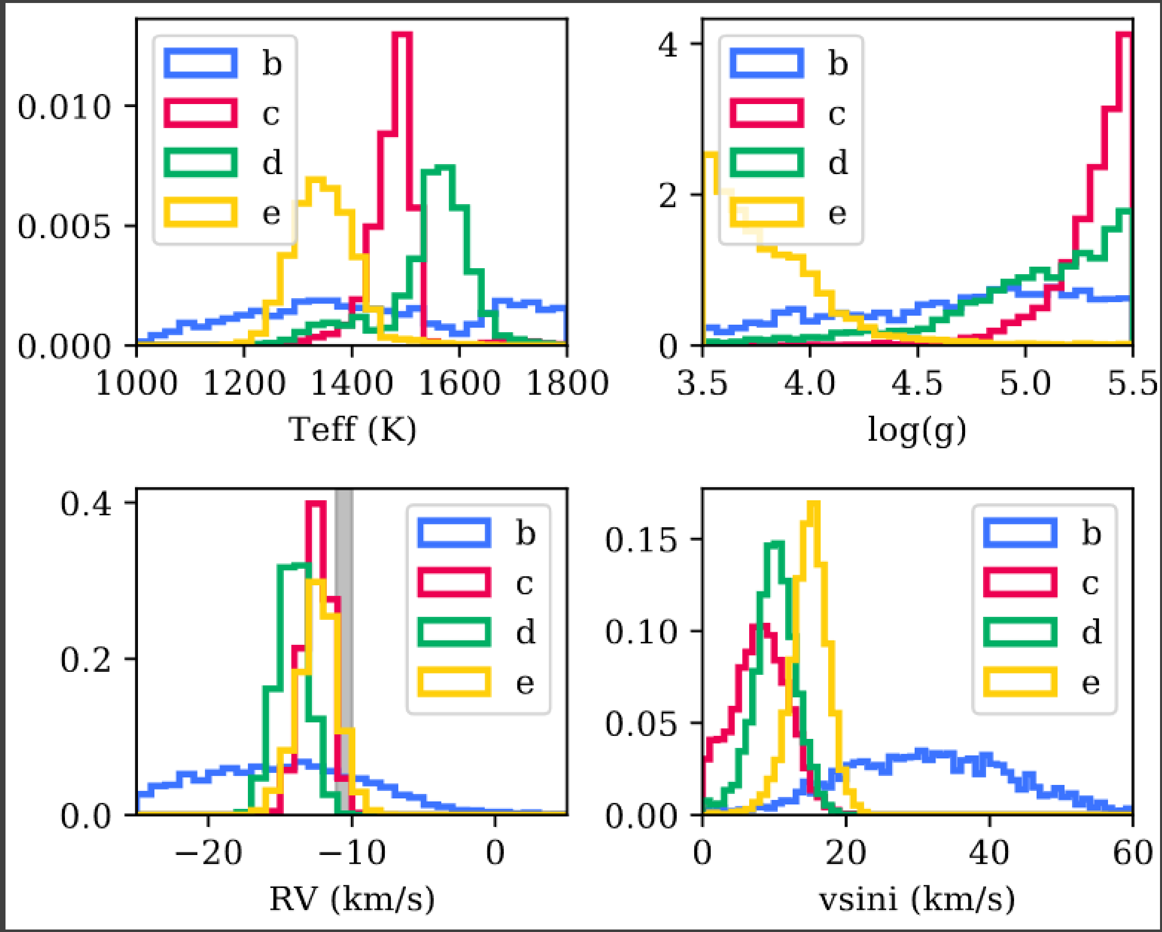


Keck II
Structure similar to the Solar system,
but if expanded by factor 2

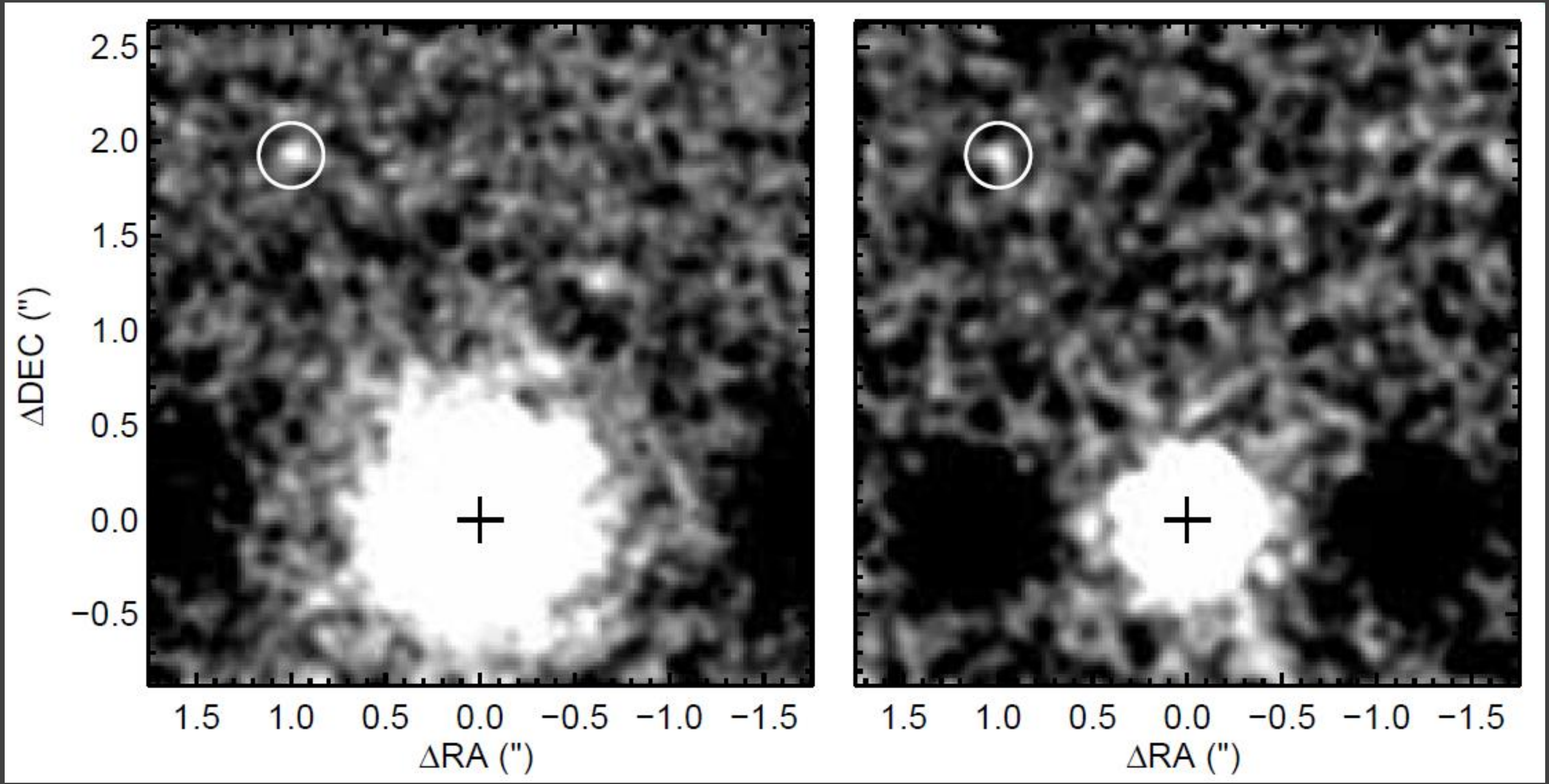
Obtaining spectra and atmospheric data







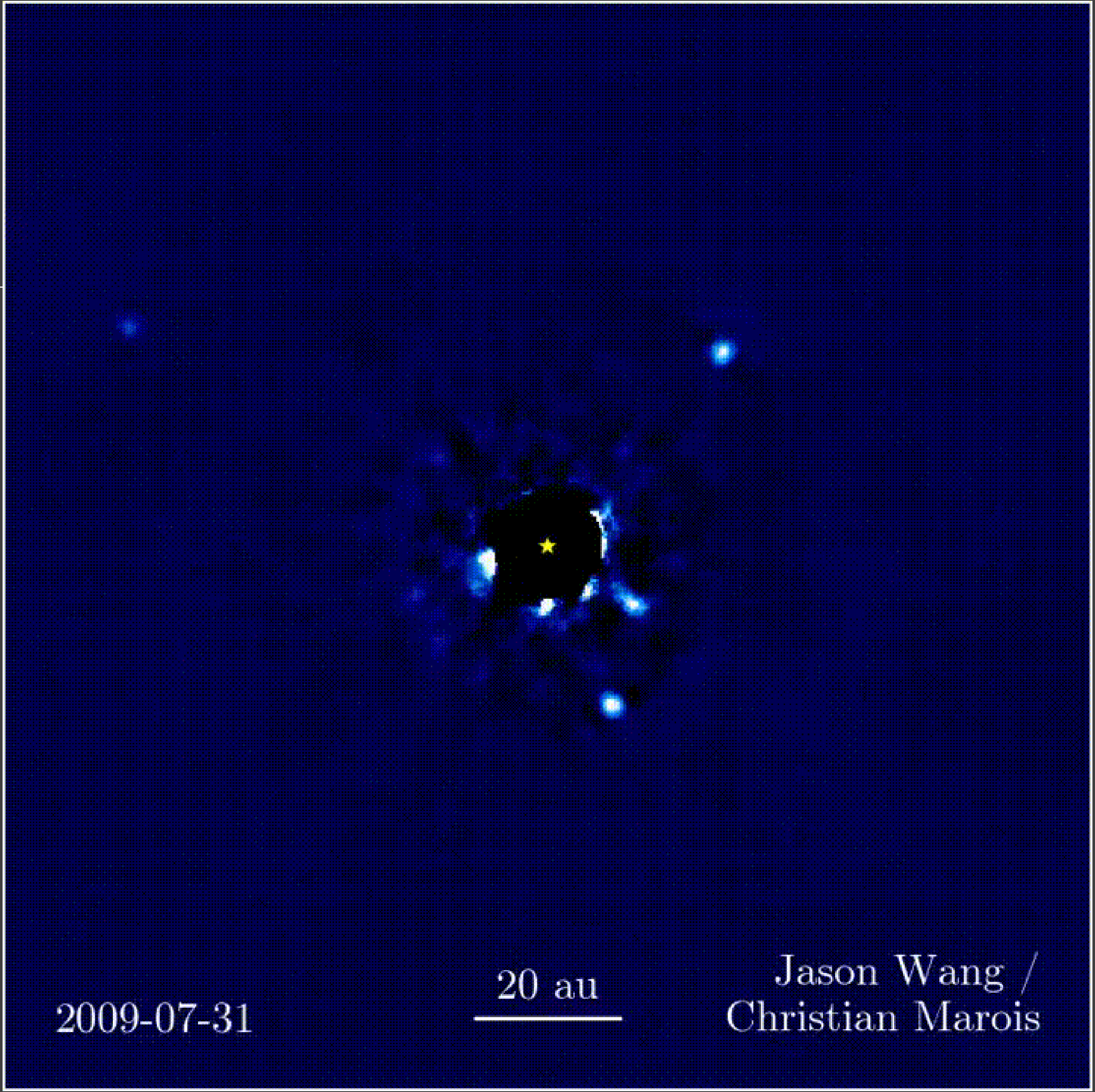
Young star 1RXS J160929.1-210524



Gemini North

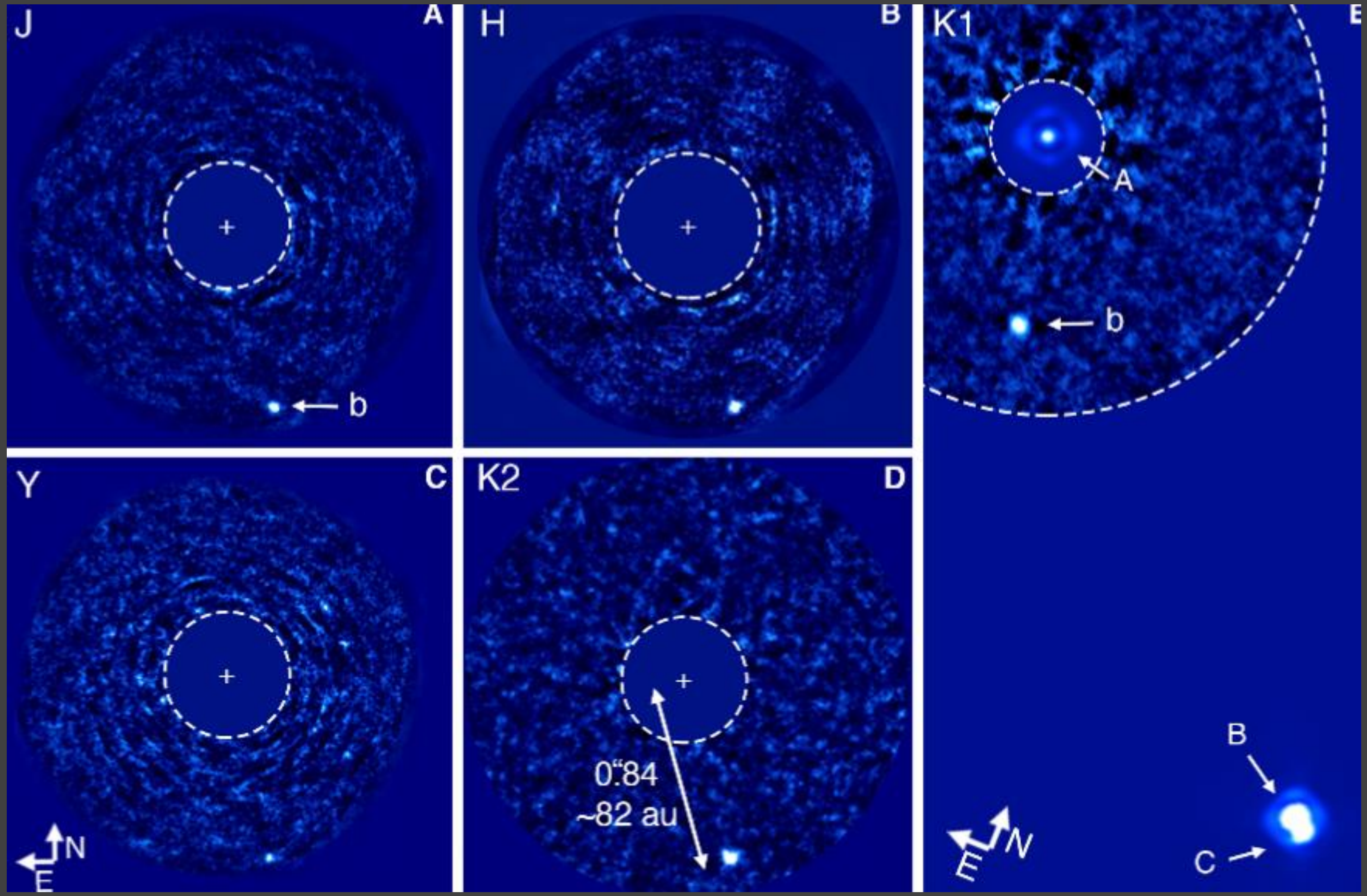
1006.3070

HR 8799

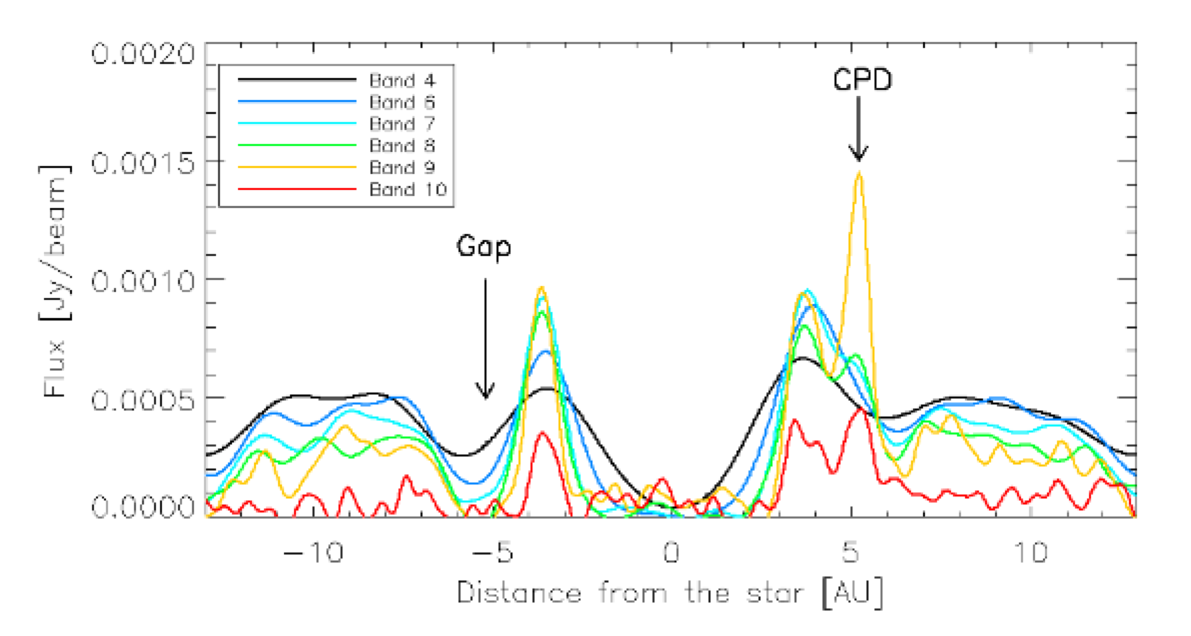


Planet in a triple system

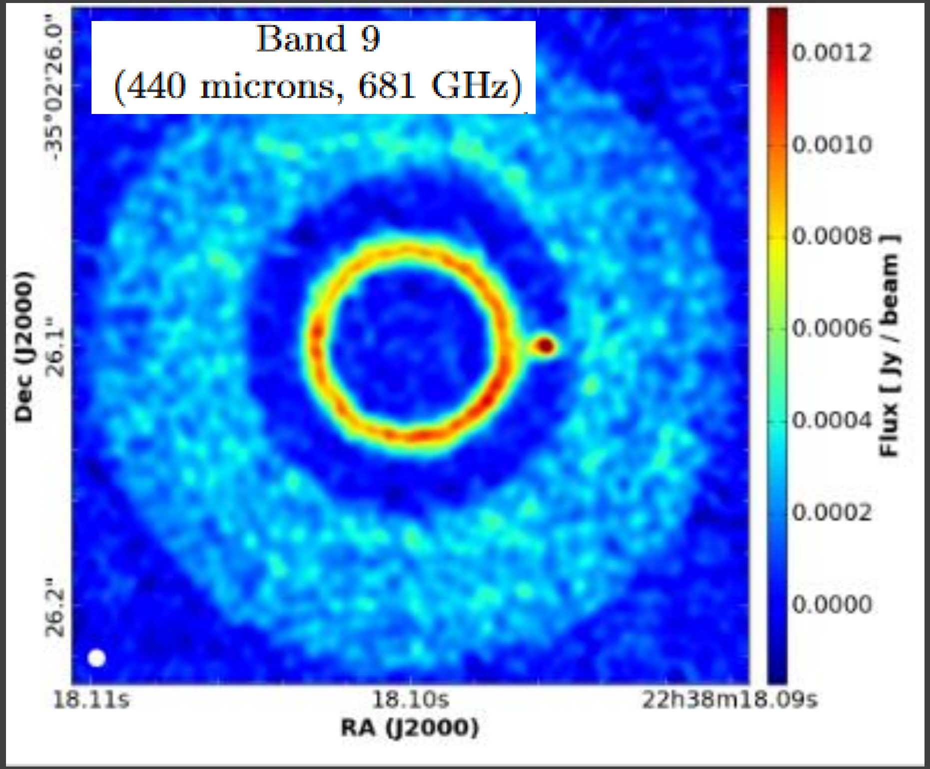
Young planet ~16 Myr.
Observed by VLT
Orbit might be unstable.



Circumplanetary discs (mock simulations)



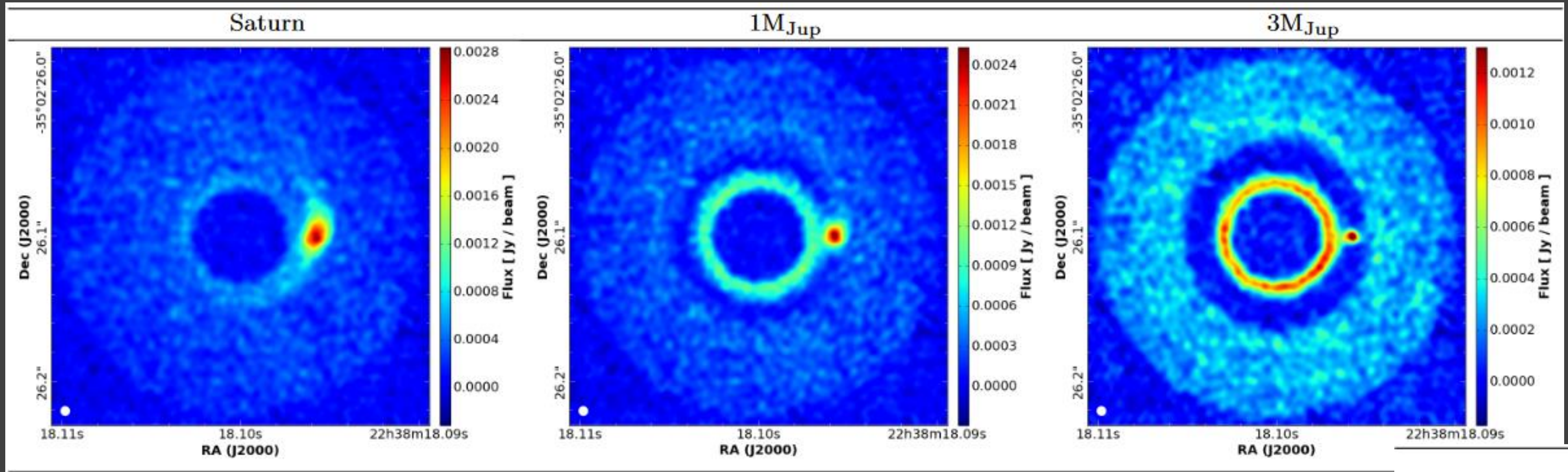
Size of a circumplanetary disc is about ½ of the Hill sphere.
Thus, it can be hardly resolved by ALMA, but can be detected.
Presently, only upper limits are available (2003.08658).

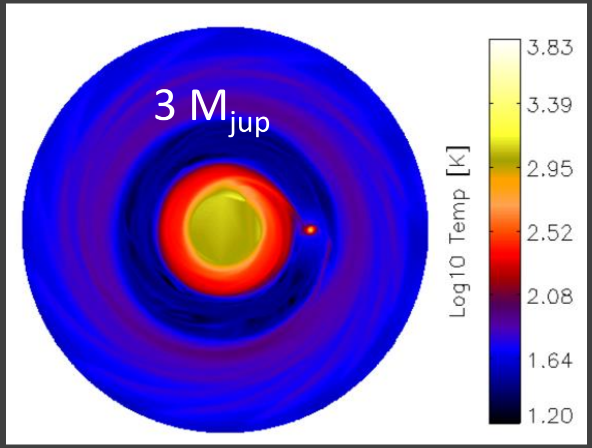


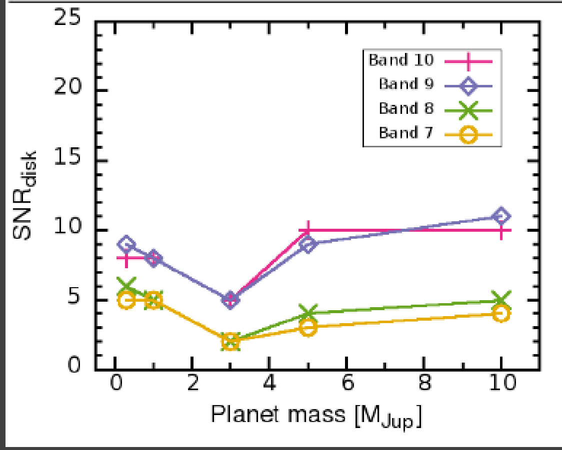
3 Jupiter masses
5 hours of observations
Better visible at shorter wavelengths
Gap opening is important
Planet temperature 4000K (age ~1 Myr)

1709.04438

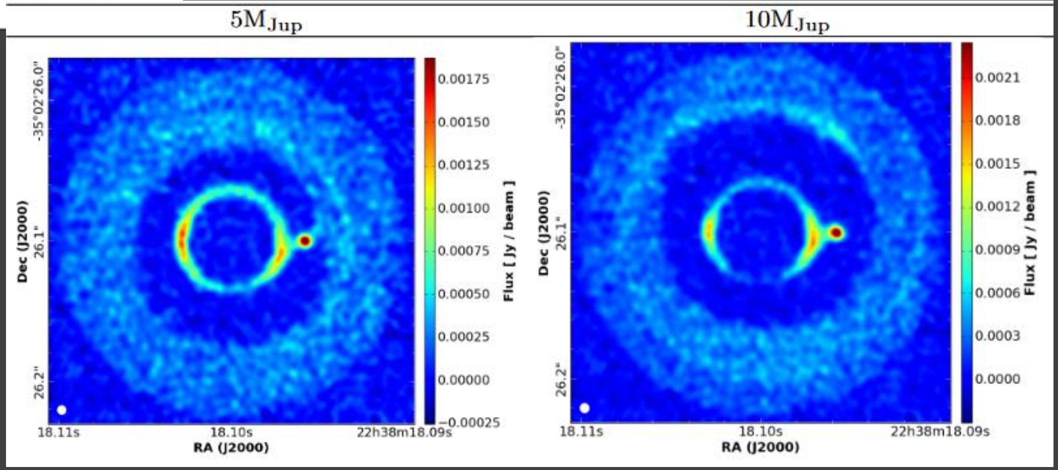
Dependence on the planet mass







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