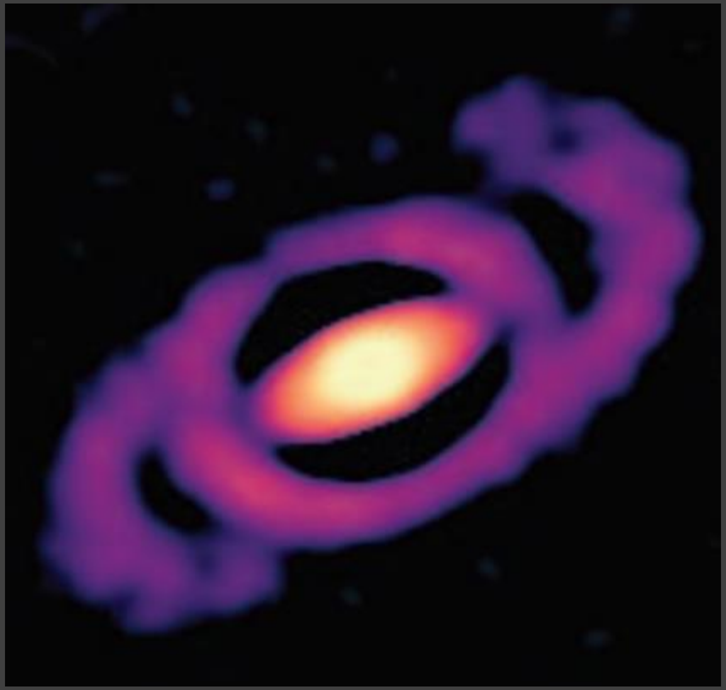
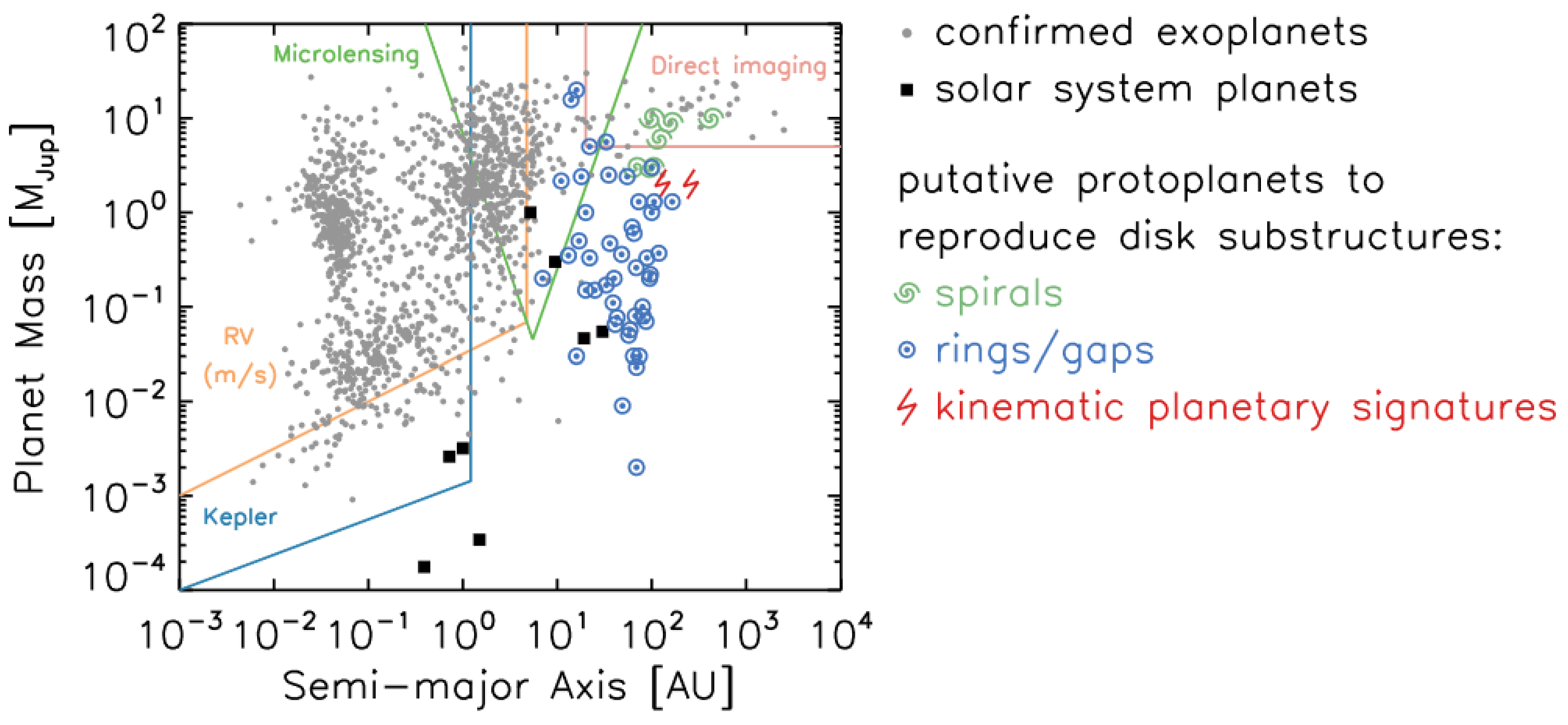


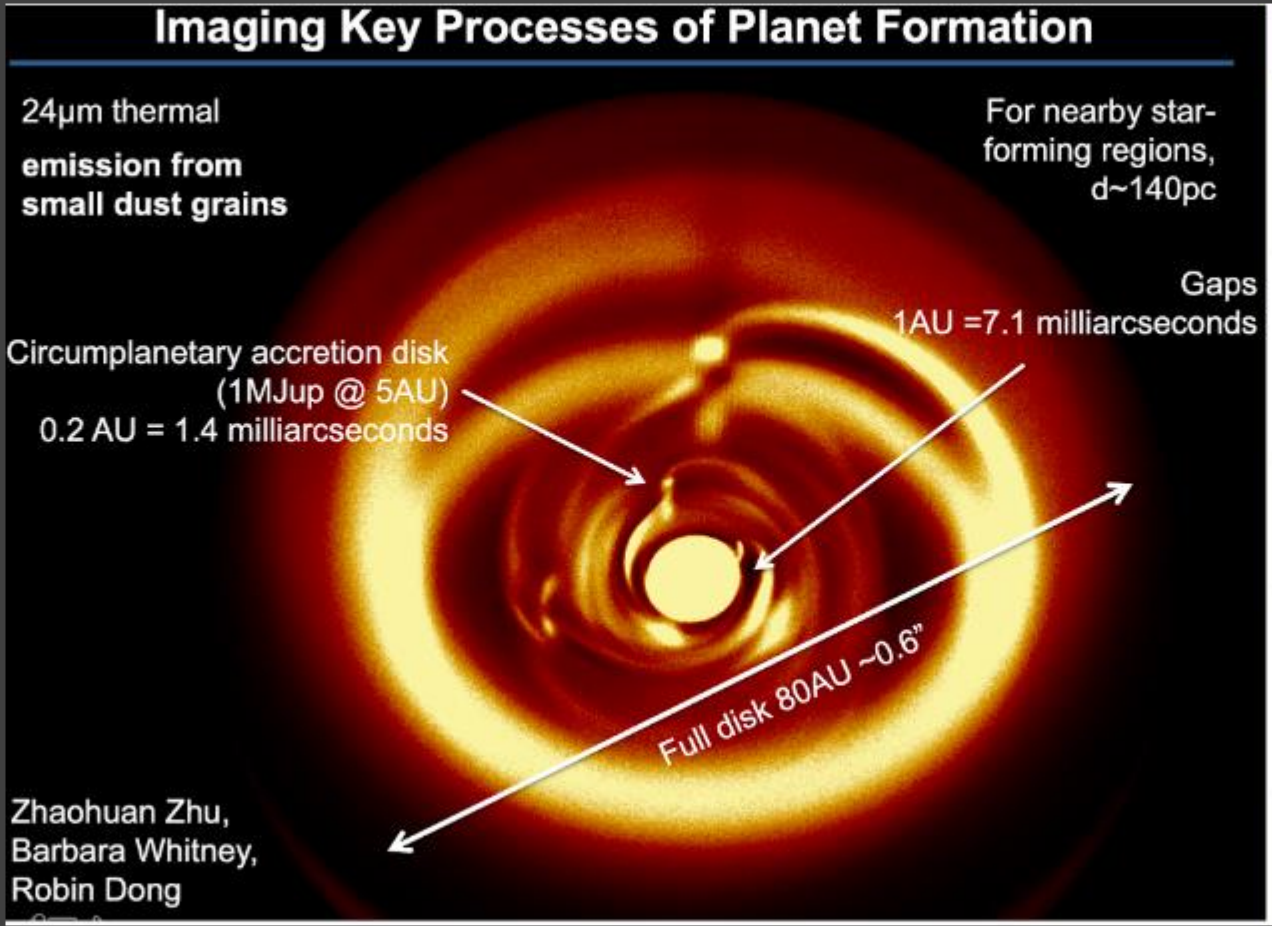
Young planetary systems

SERGEI POPOV

Planets and discs



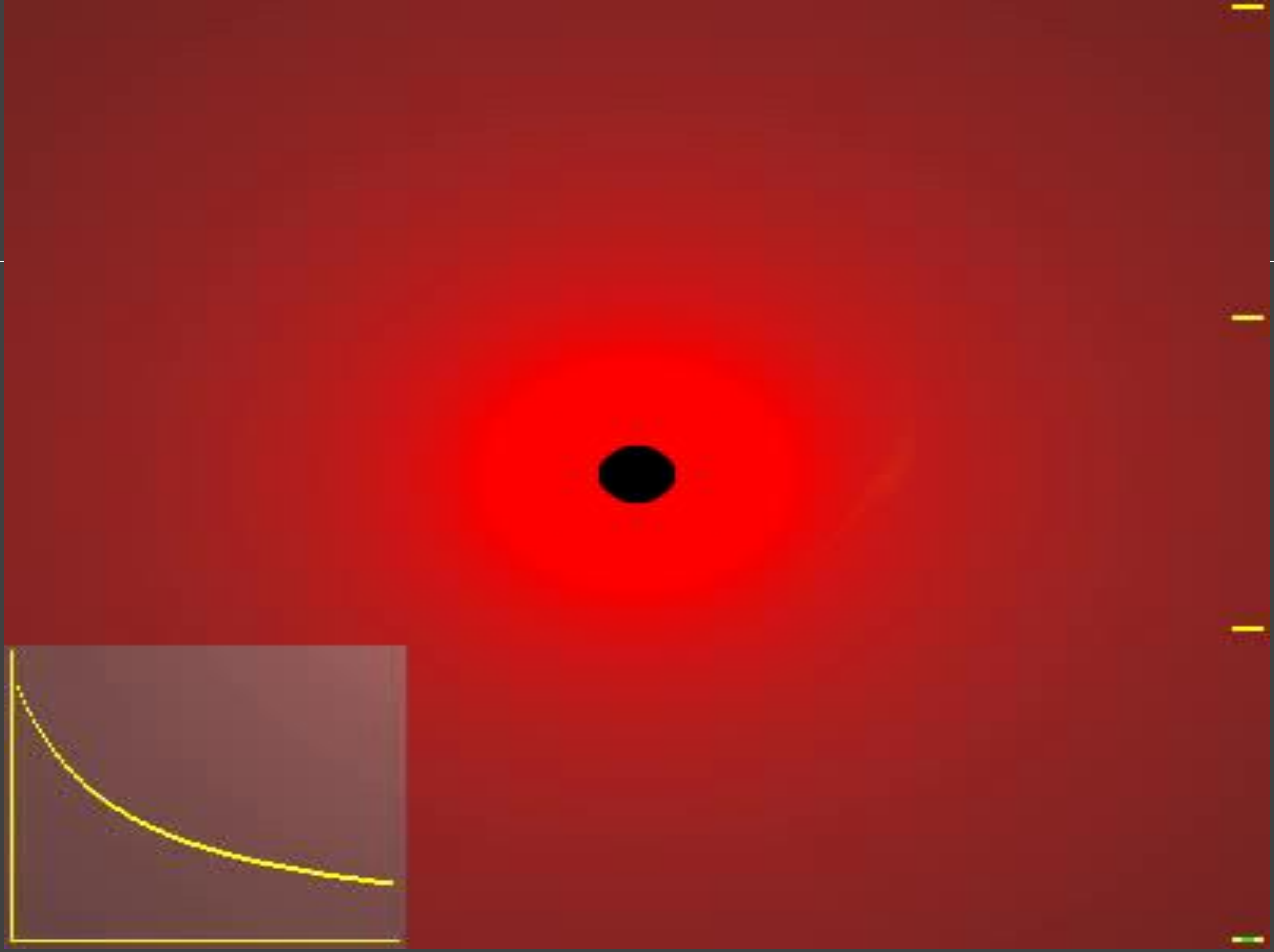
Modeling and imaging planet formation



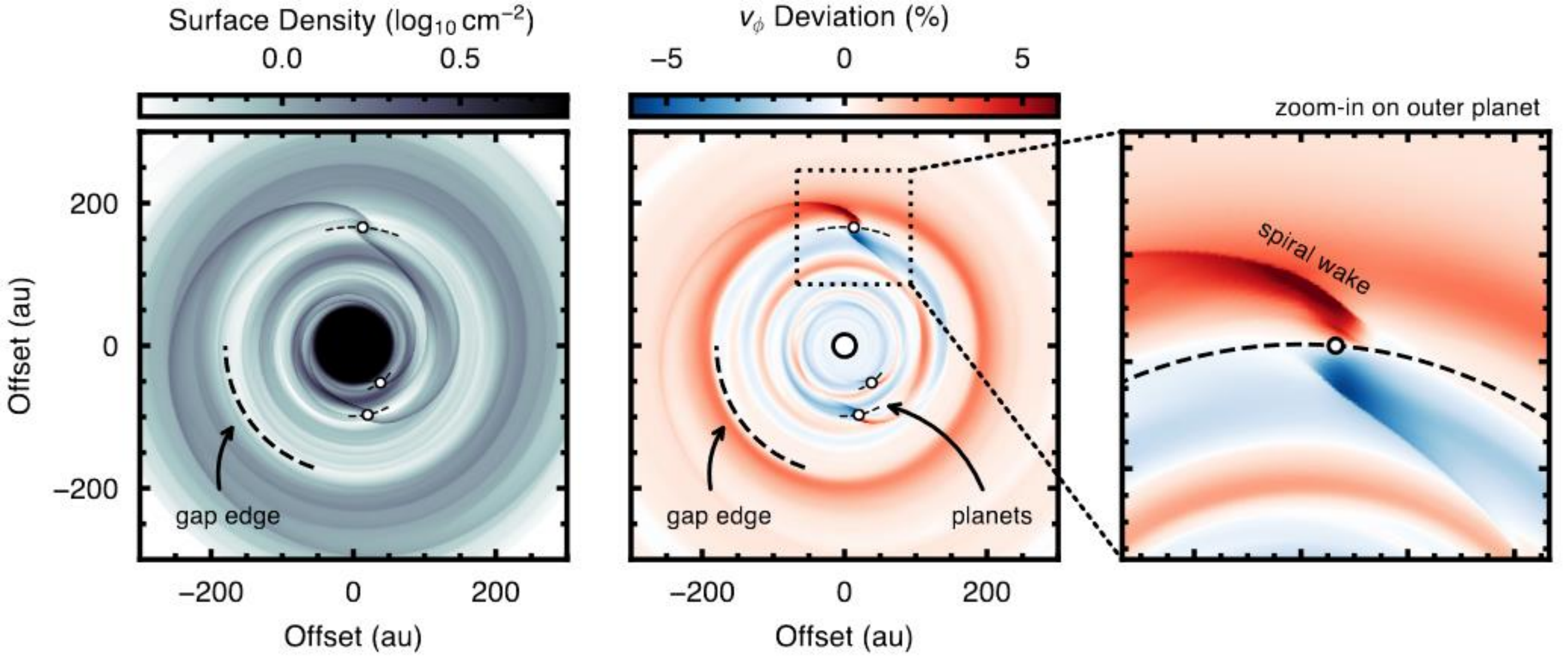
Feature	Scale	Methods
Overall Disk	80au	mm-wave (ALMA); Coronagraphy on 8+meter telescopes; JWST
Large gaps and structures	5-20au	mm-wave (ALMA); Radio (ngVLA); Coronagraphy on 8+meter telescopes; JWST
Terrestrial Planet Zone	<4au	30m telescope; IR interferometry (CHARA,VLTI, MROI)
Gaps and accretion 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.

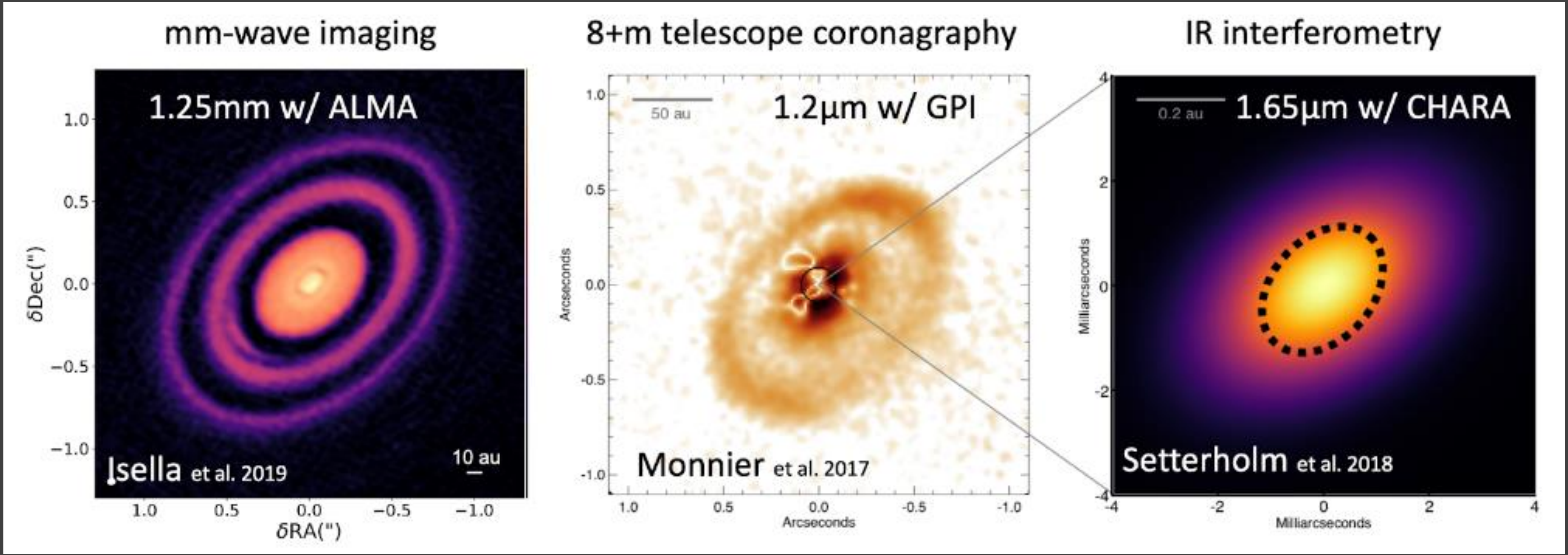


Planet-disc interaction



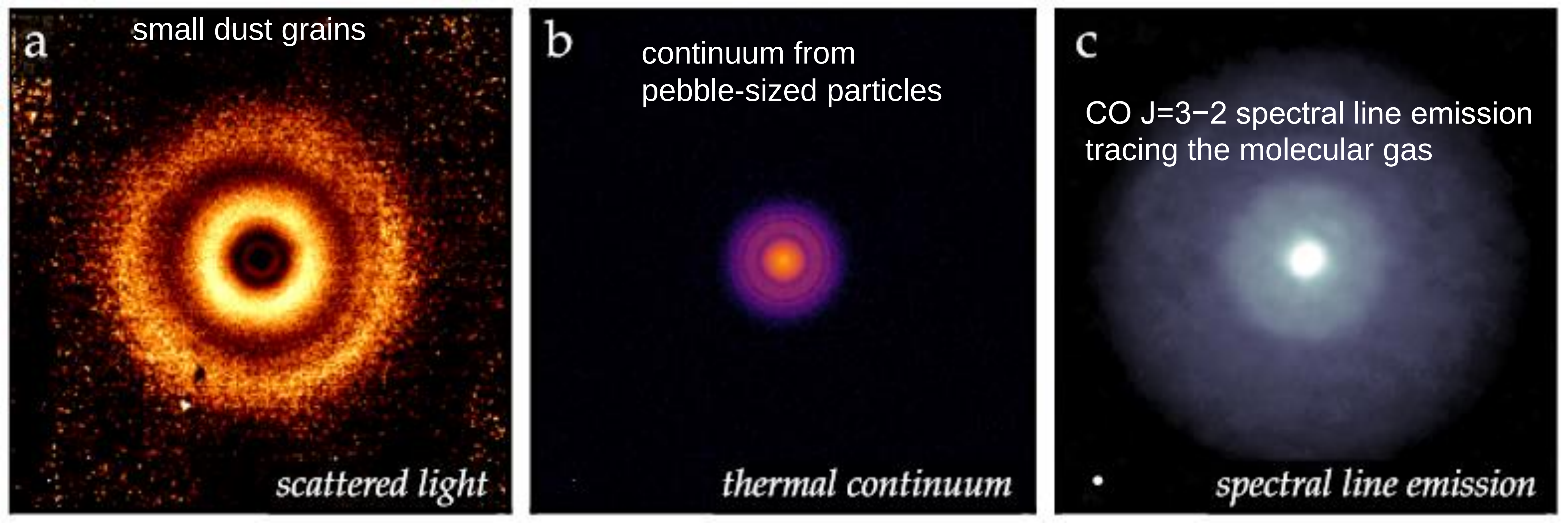
2009.04345

More details with different techniques

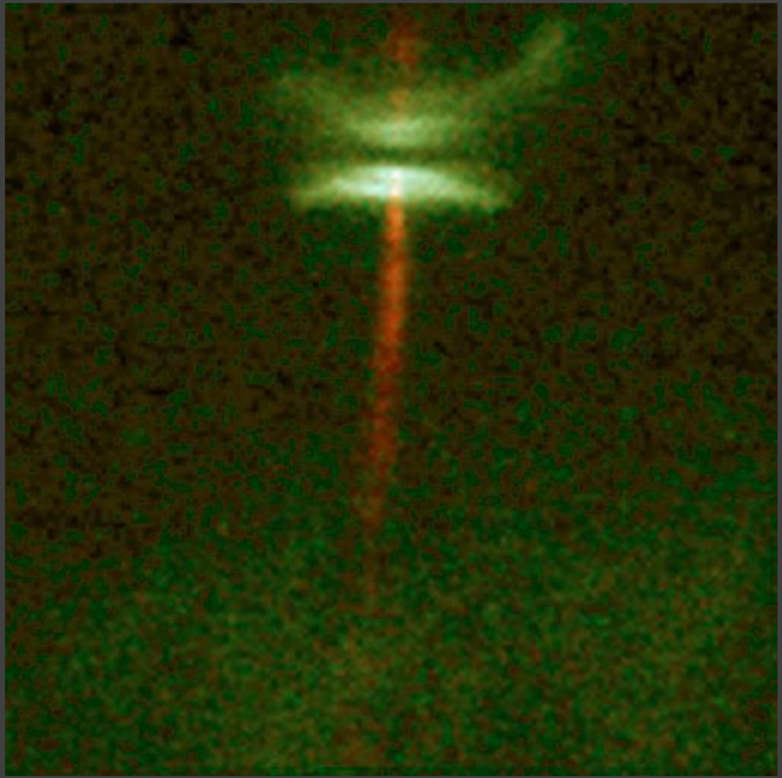


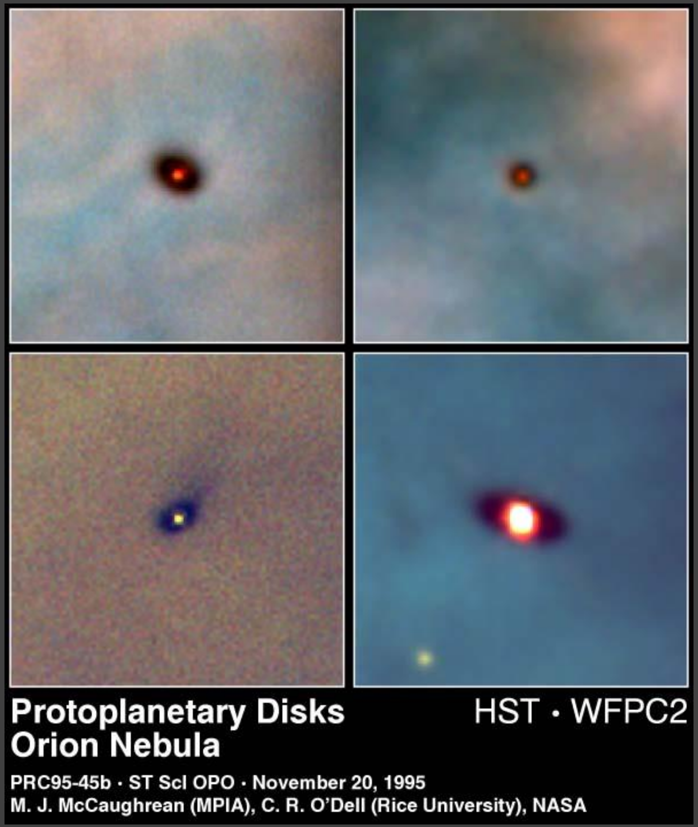
Different structures in different light

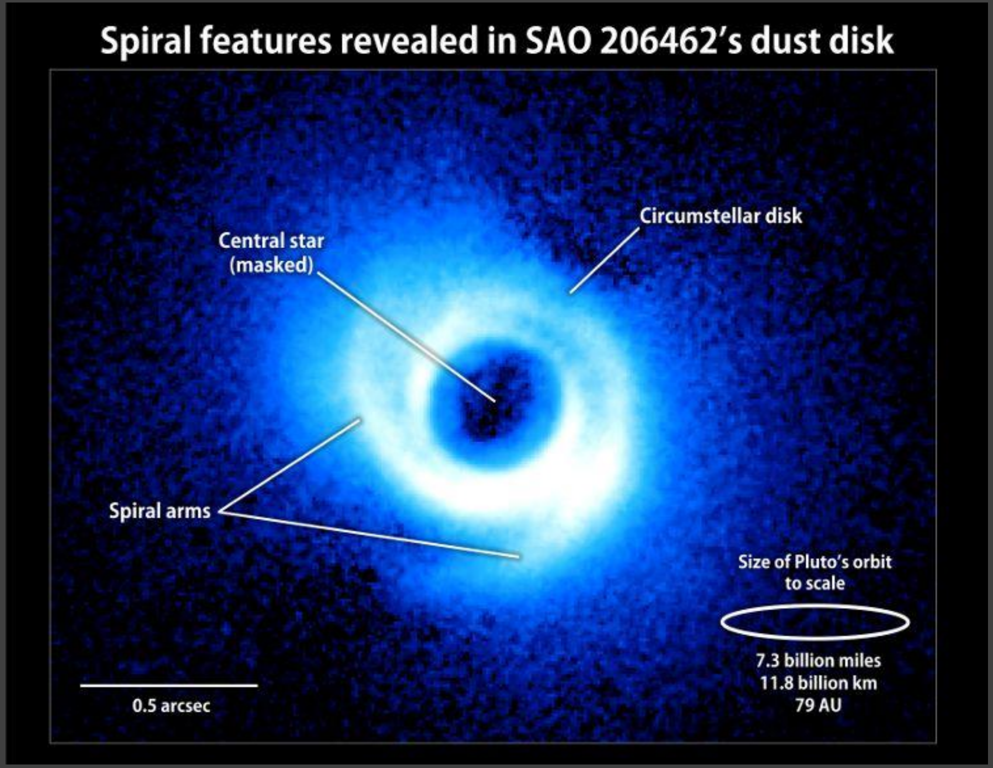
TW Hya disk



Protoplanetary discs







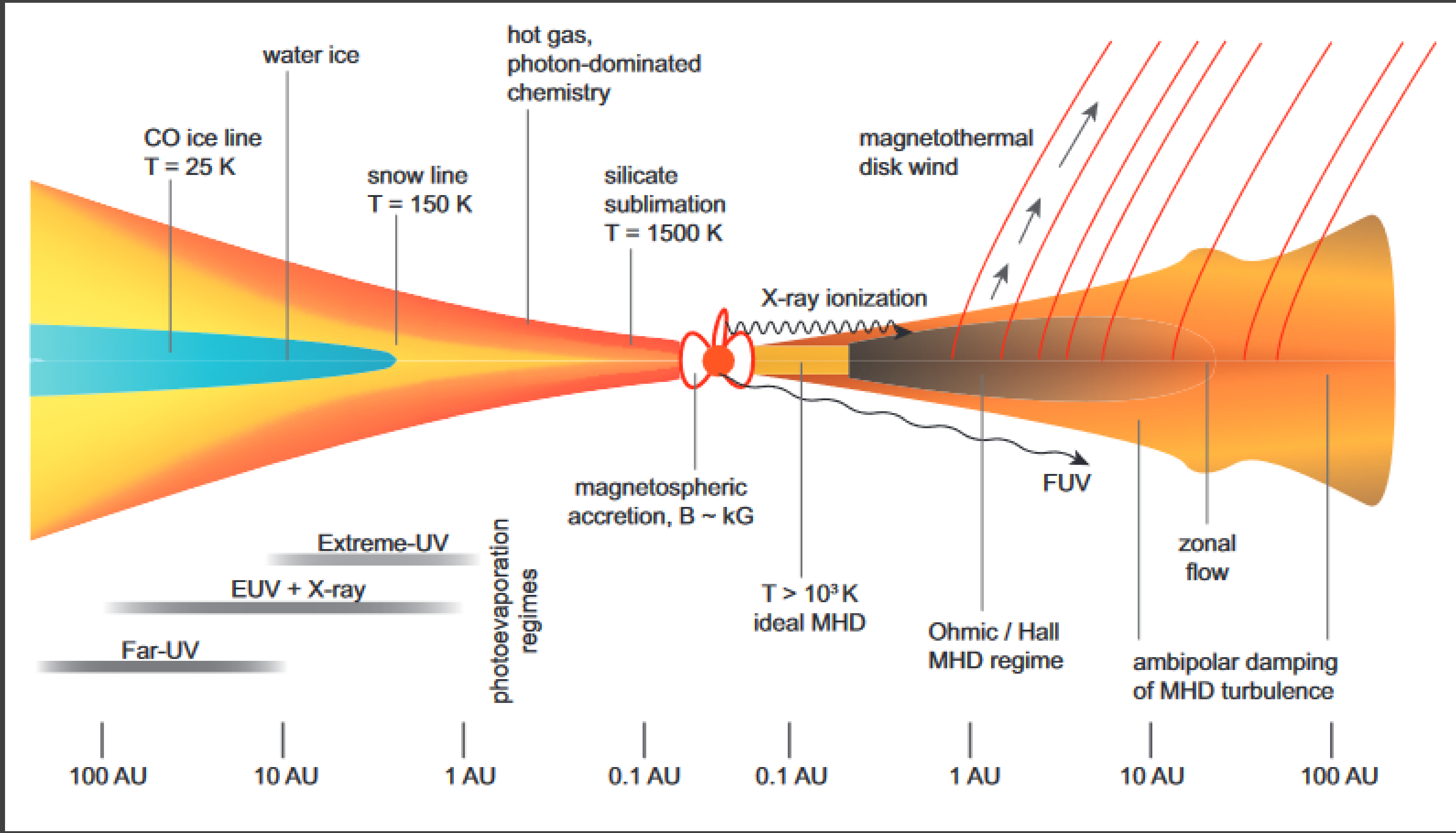
https://online.science.psu.edu/astro140_sp201314wd001/node/7717
http://news.softpedia.com/news/Exoplanets-Can-Form-Spiral-in-Stellar-Protoplanetary-Disks-228792.shtml

Dusty discs

HST observations

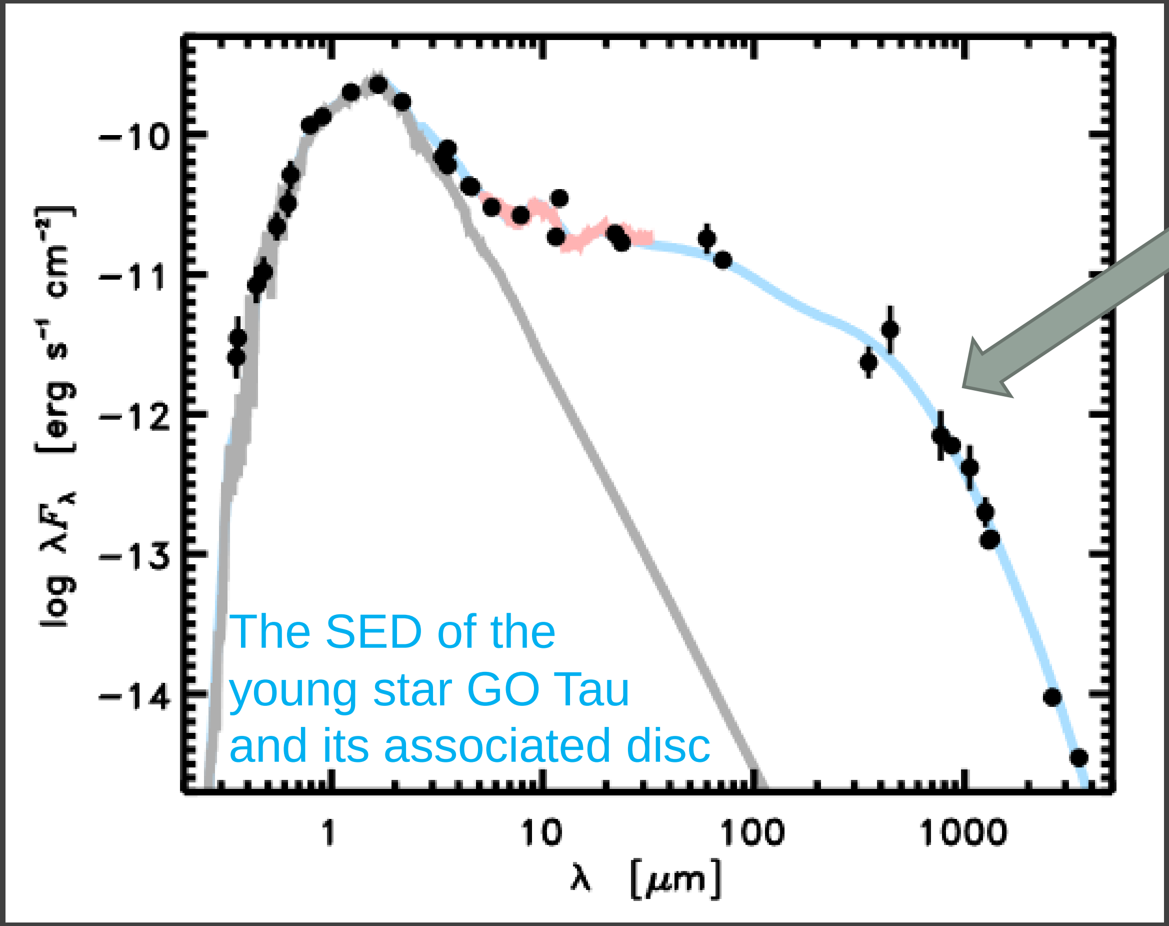
Disc is visible edge-on.

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

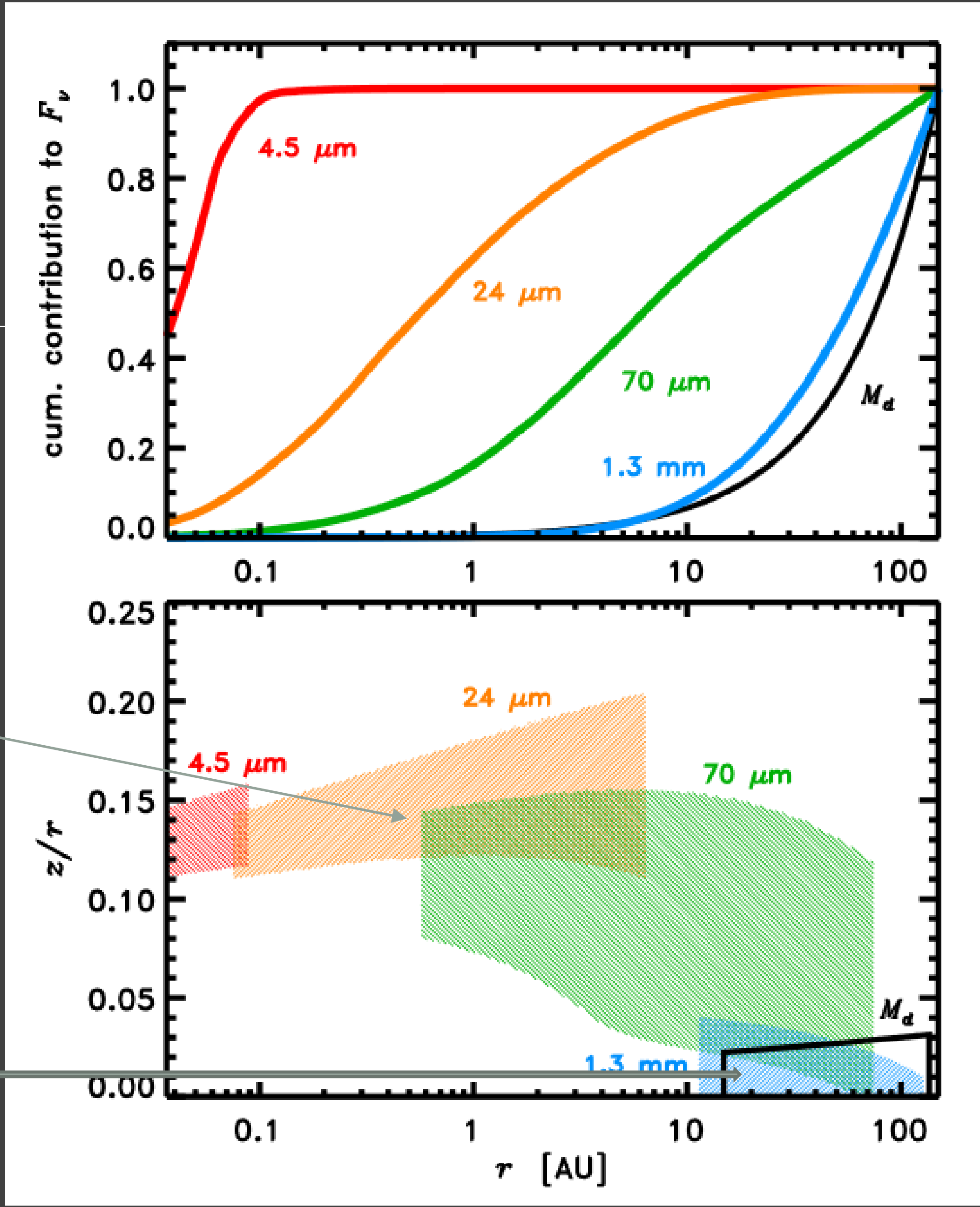
$$M_{\rm dust} \propto M_{\rm star}^{1.8}.$$

Dust in the disc

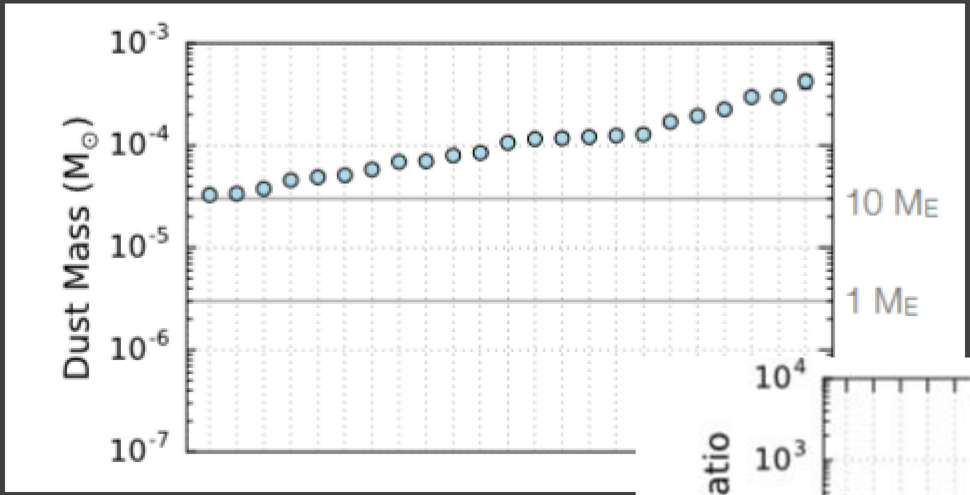
Observations in different wavelengths allow to probe different parts of the disc and determine dust mass and distribution.

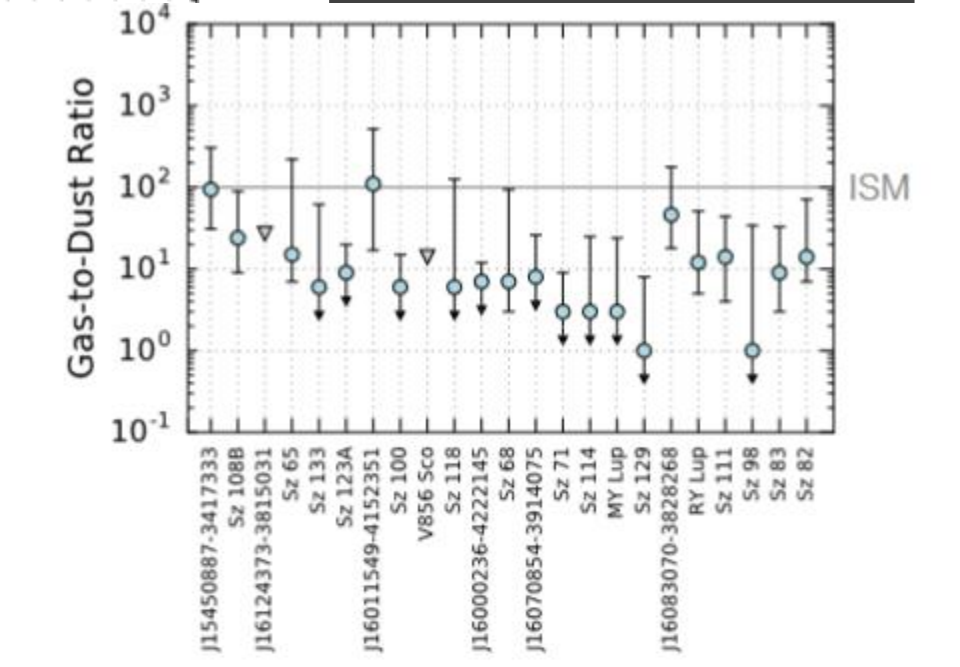
Regions of 80% of emission in each band

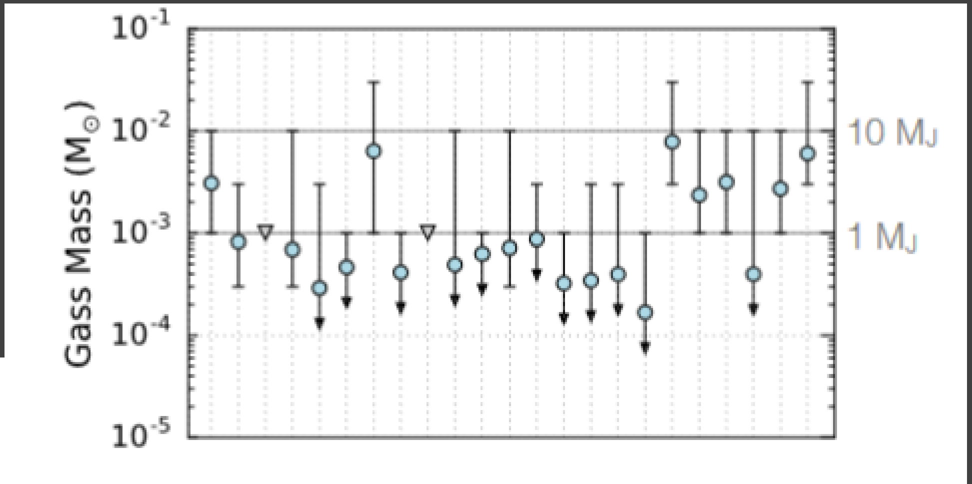
80% of dust



Disc mass: gas + dust

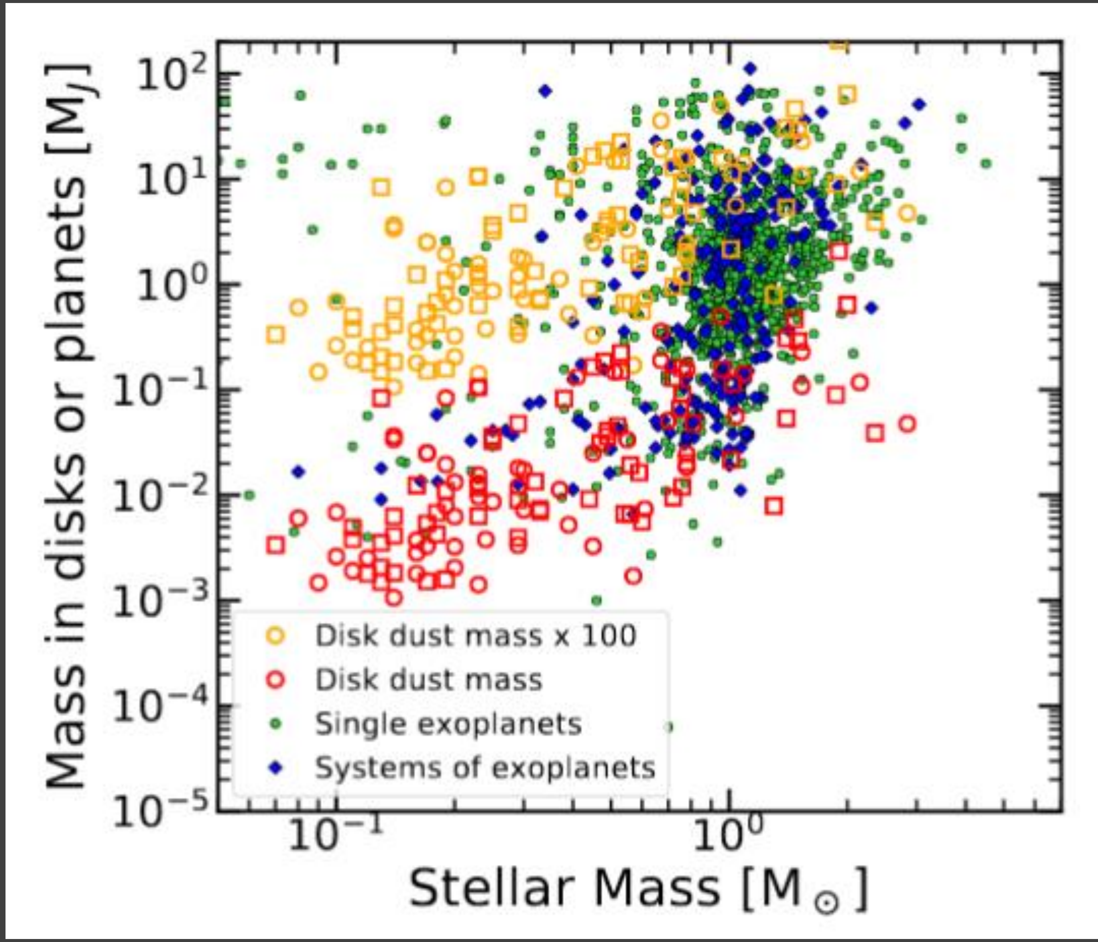


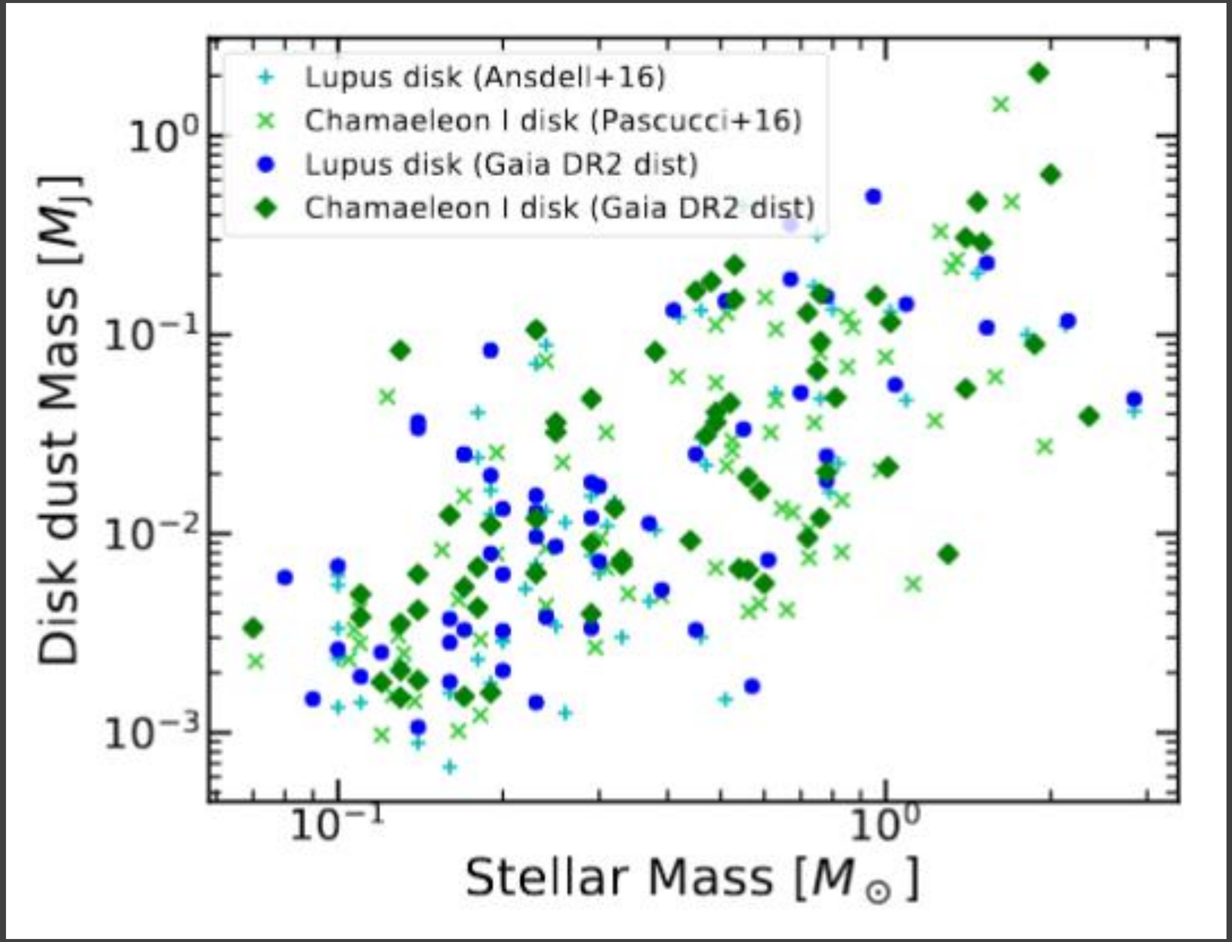




Gas mass determined
by CO observations (ALMA).

Disc mass vs. star mass

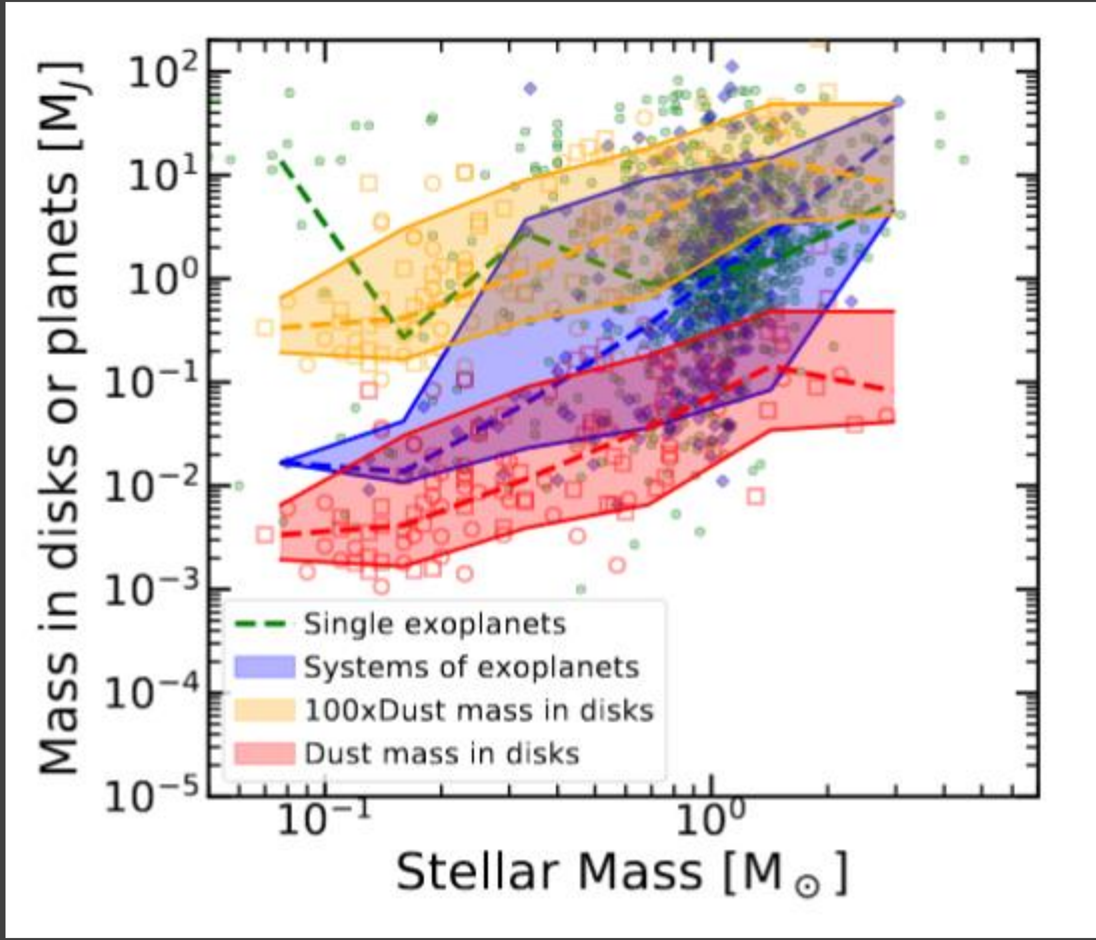


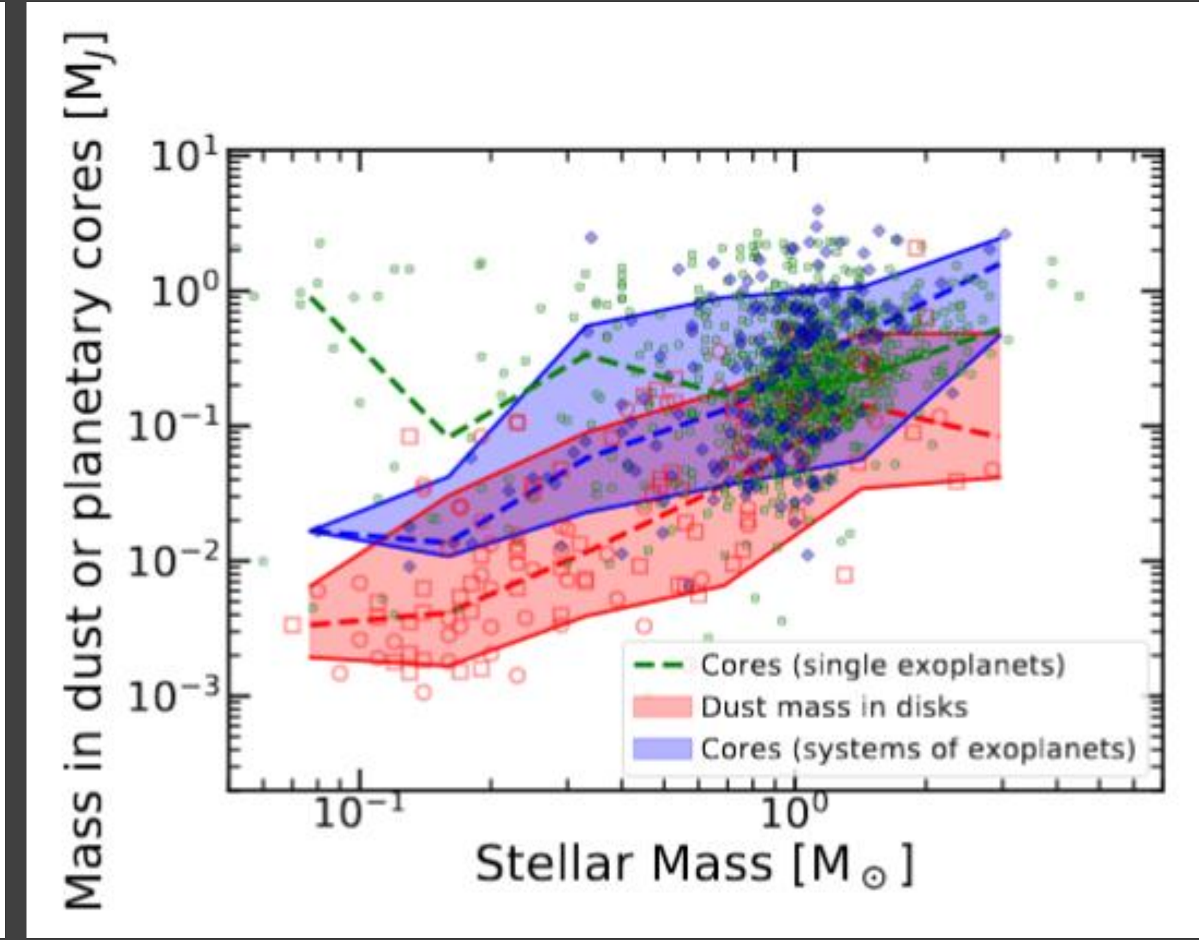


1809.07374

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

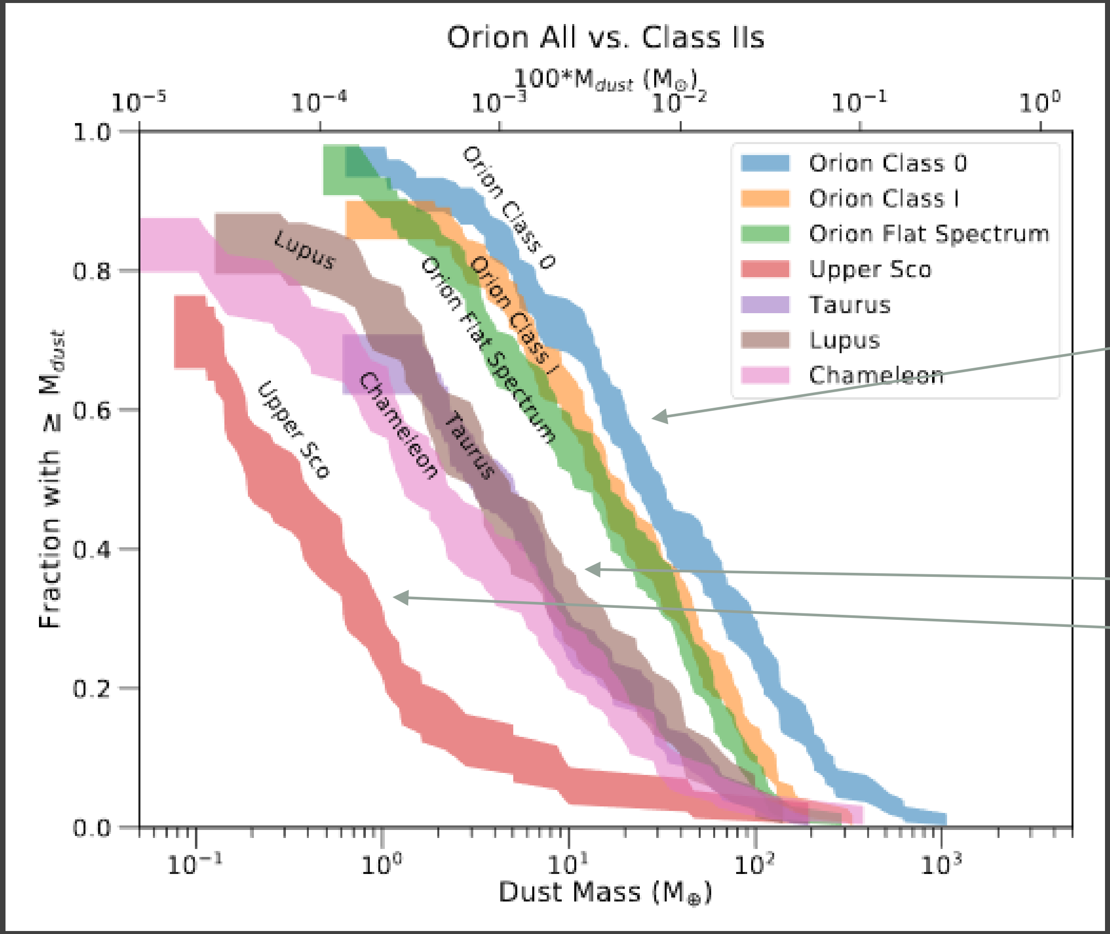
Disc and planet mass correlations with the stellar mass





1809.07374

Indeed, evolution, baby



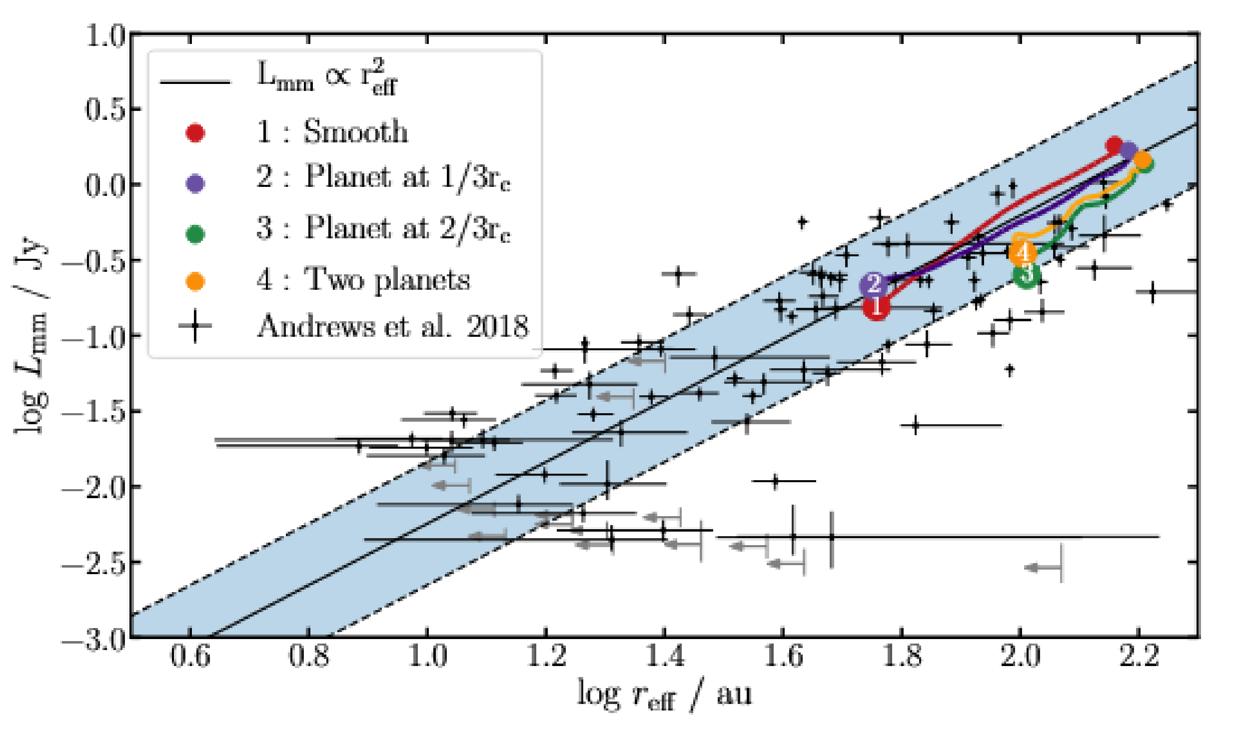
Young discs

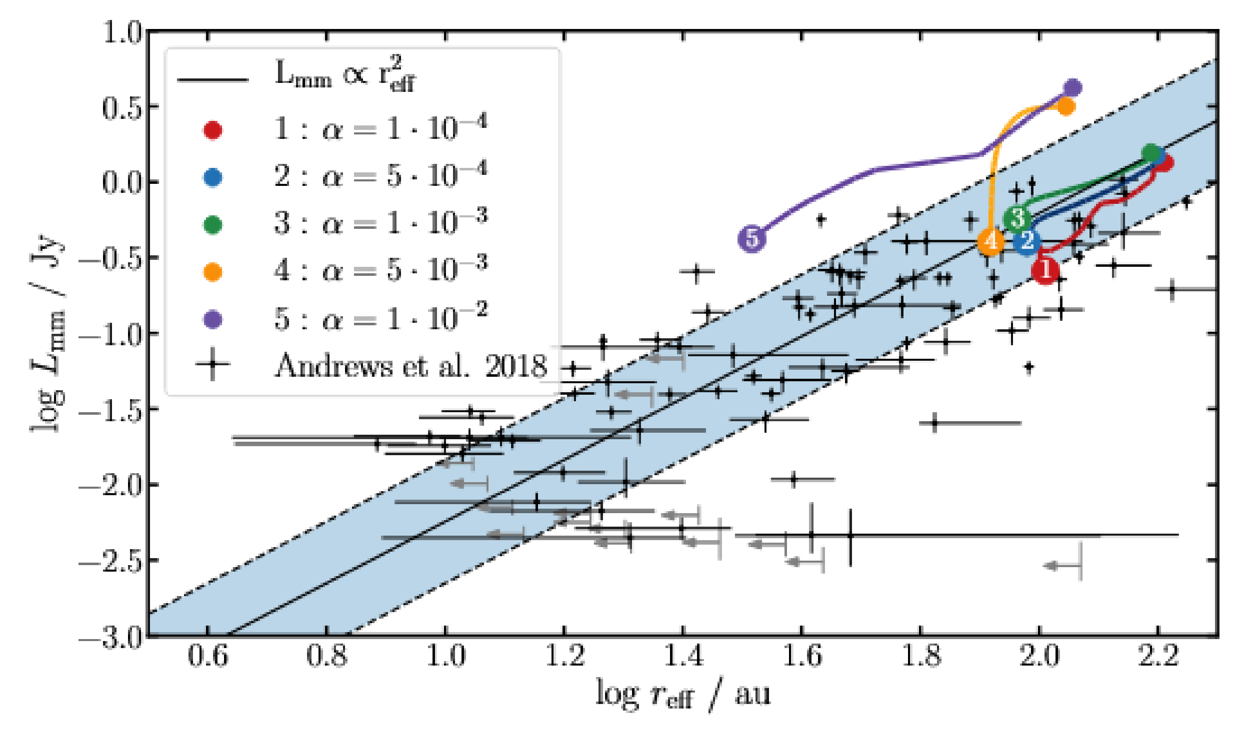
Older discs

2001.04468

Modeling of evolution discussed in 2208.04330

Population modeling of protoplanetary discs

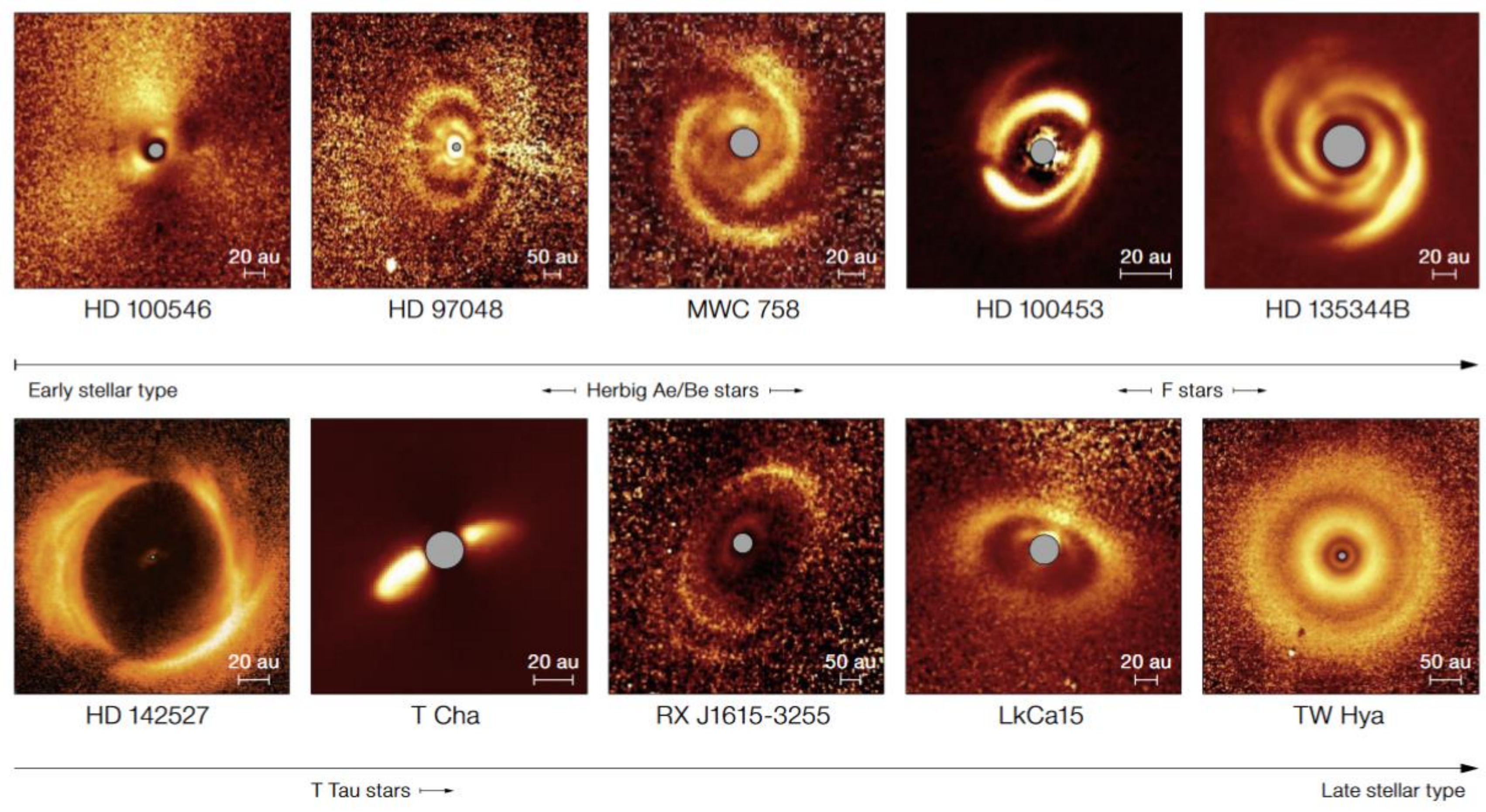




Discs with and without massive planets have different relations Luminosity vs. size.

2202.01241

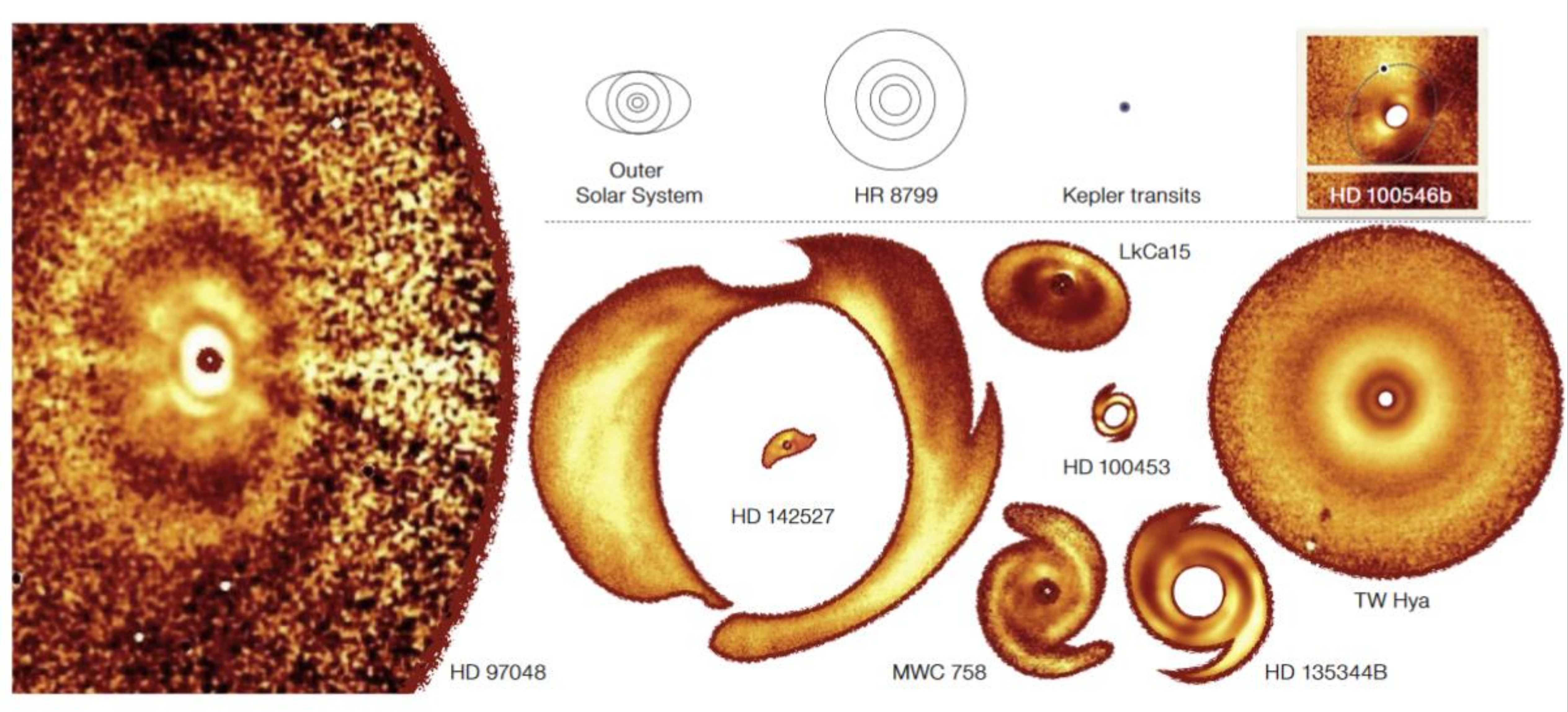
VLT/SPHERE



0.5-2.3 micrometers

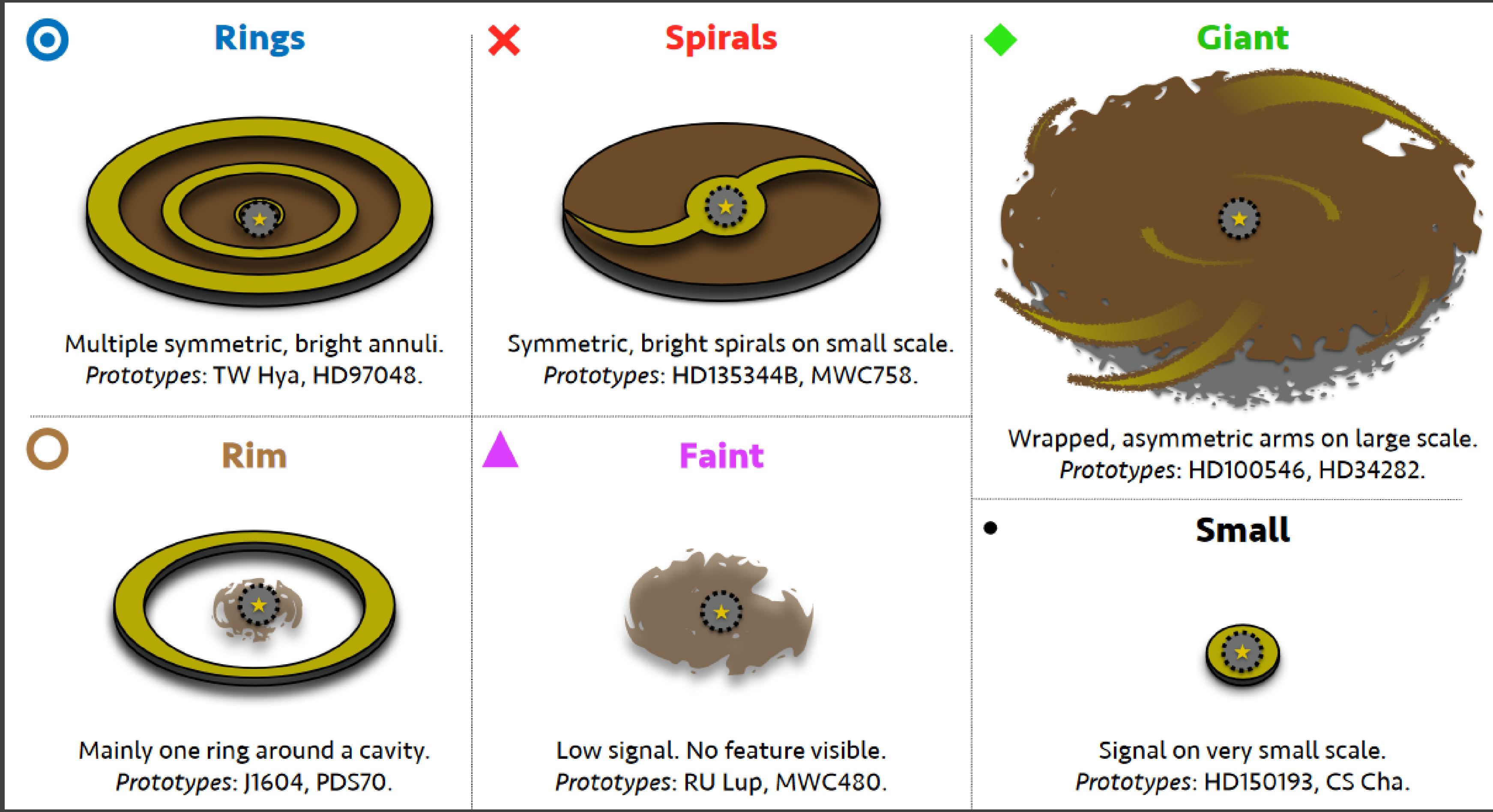
1710.02795

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
TW Hya
HD 142527
HD 97048
MWC 758
HD 135344B

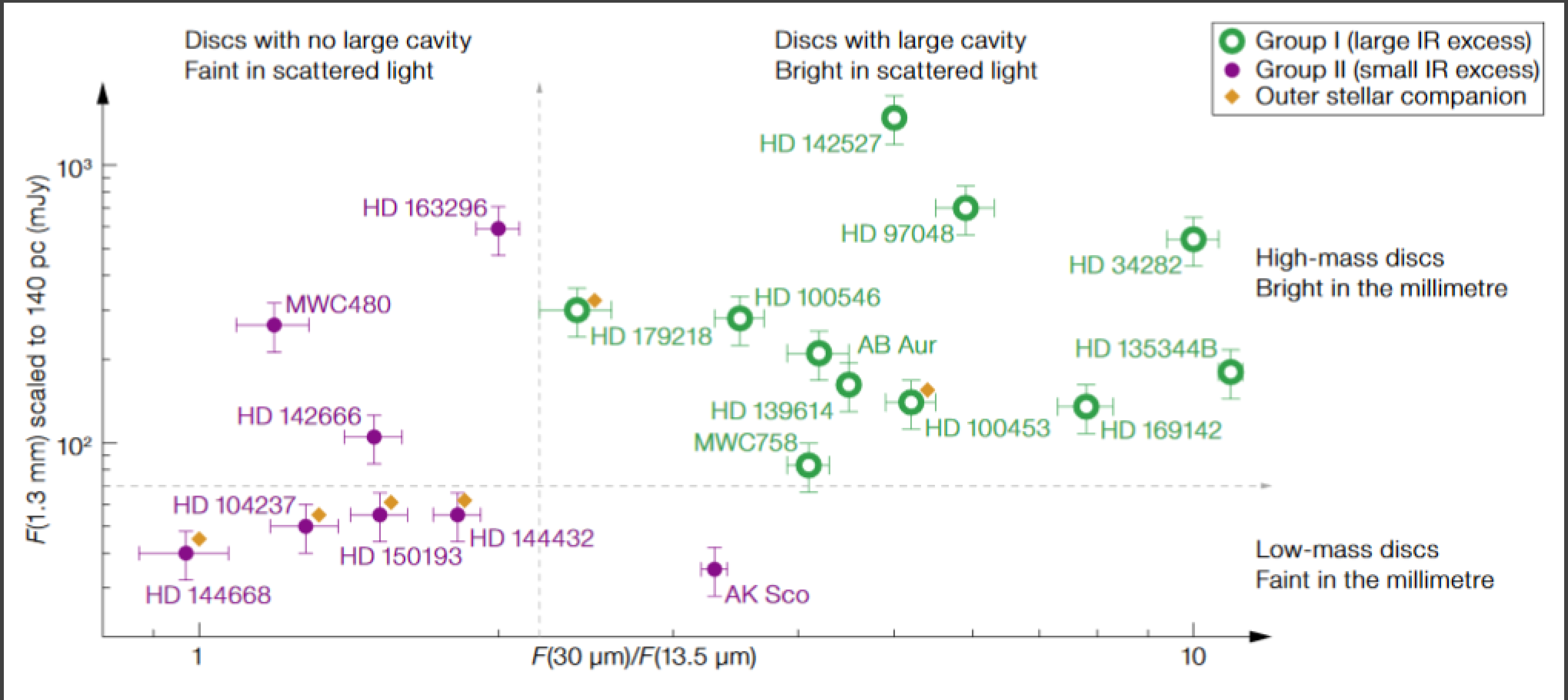
1710.02795

Structures in discs

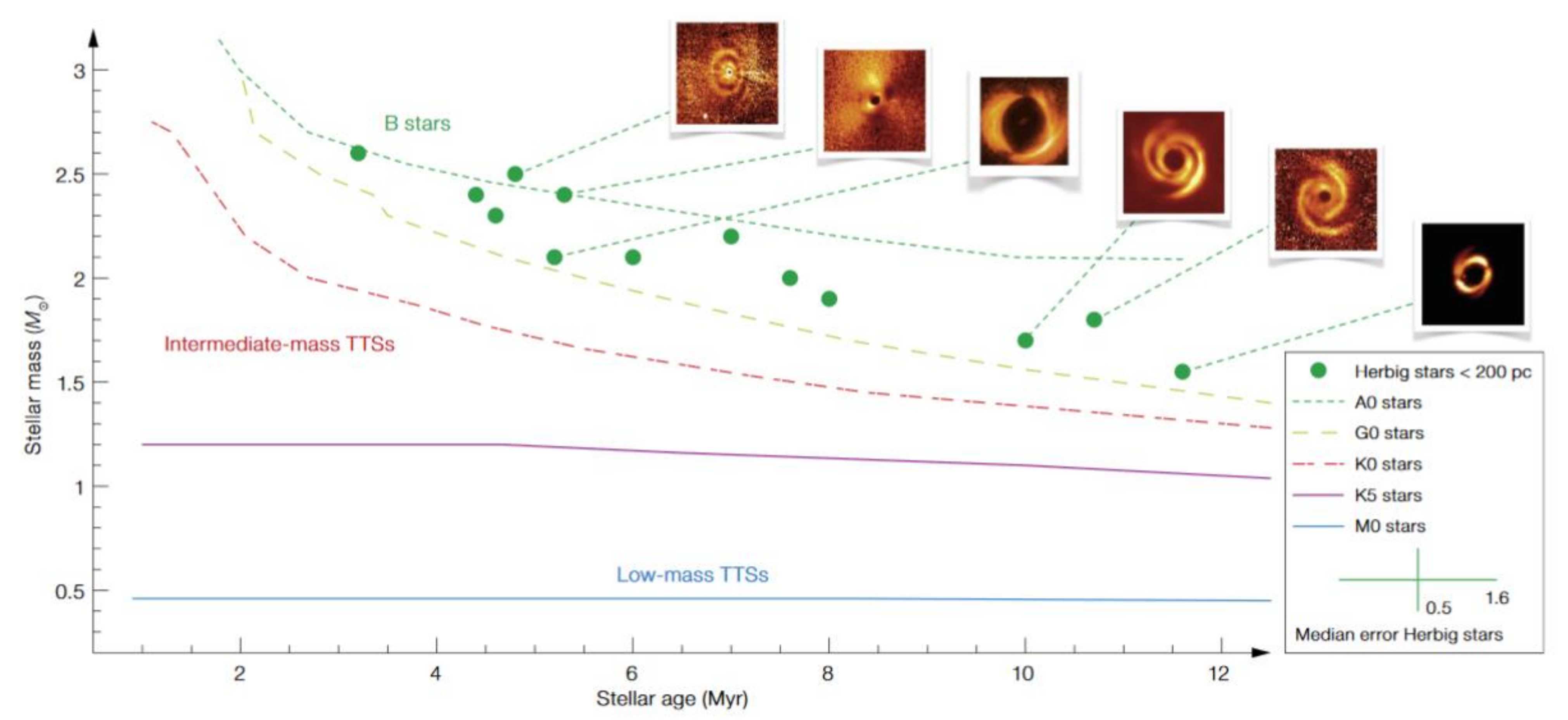


1810.04564, see a review also in 2001.05007

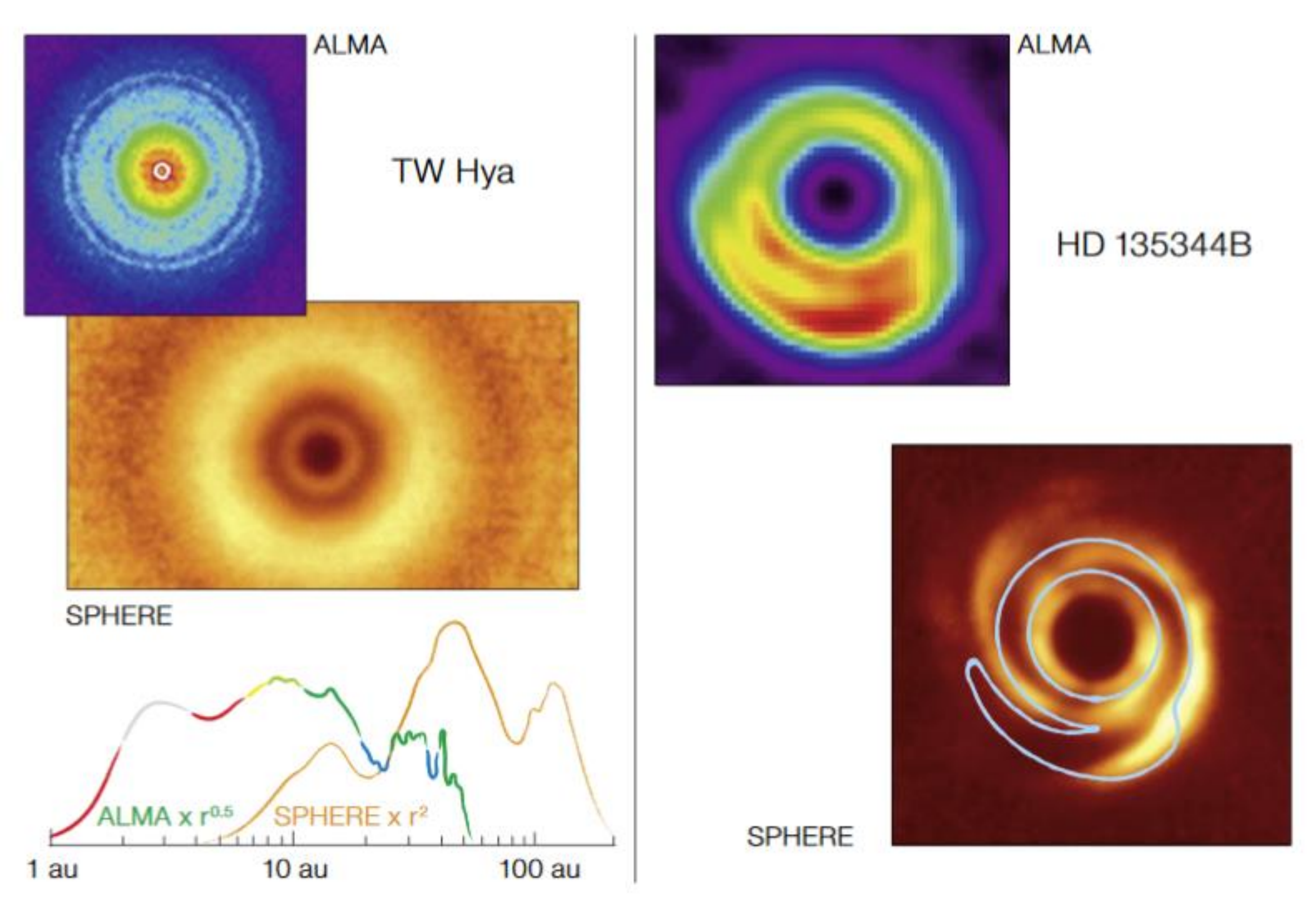
Different discs



Disc evolution

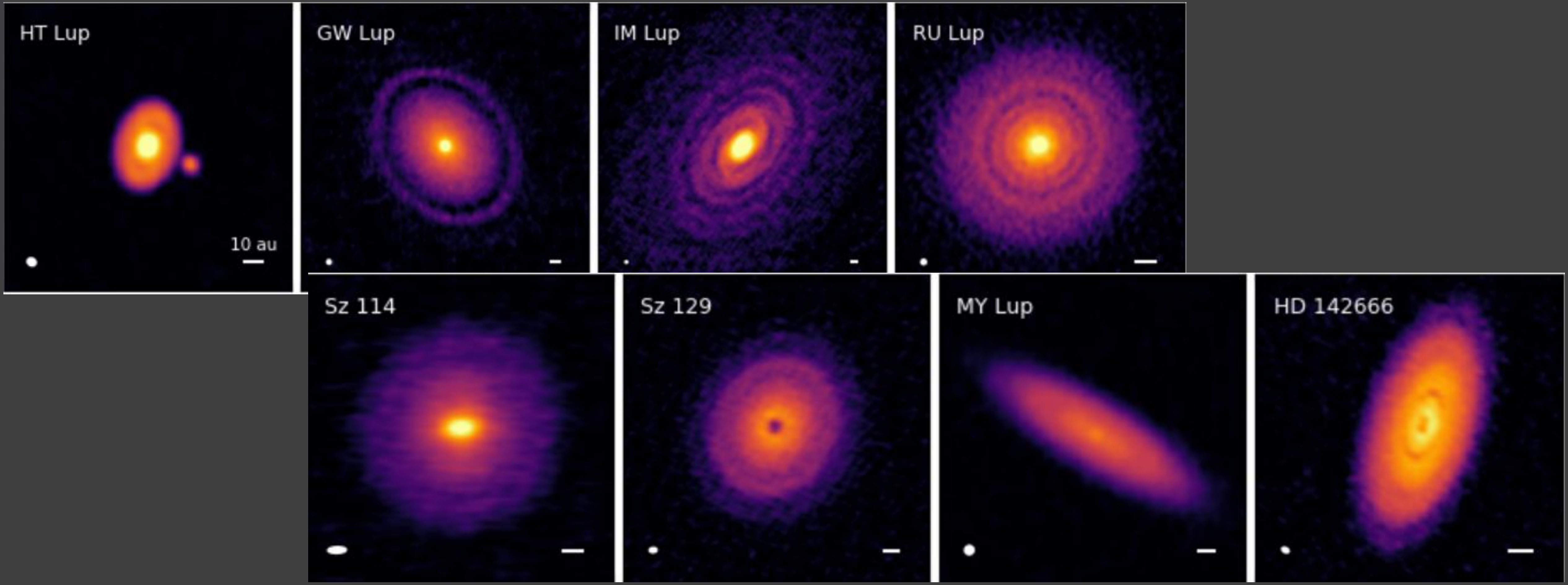


Different wavelengths – different dust

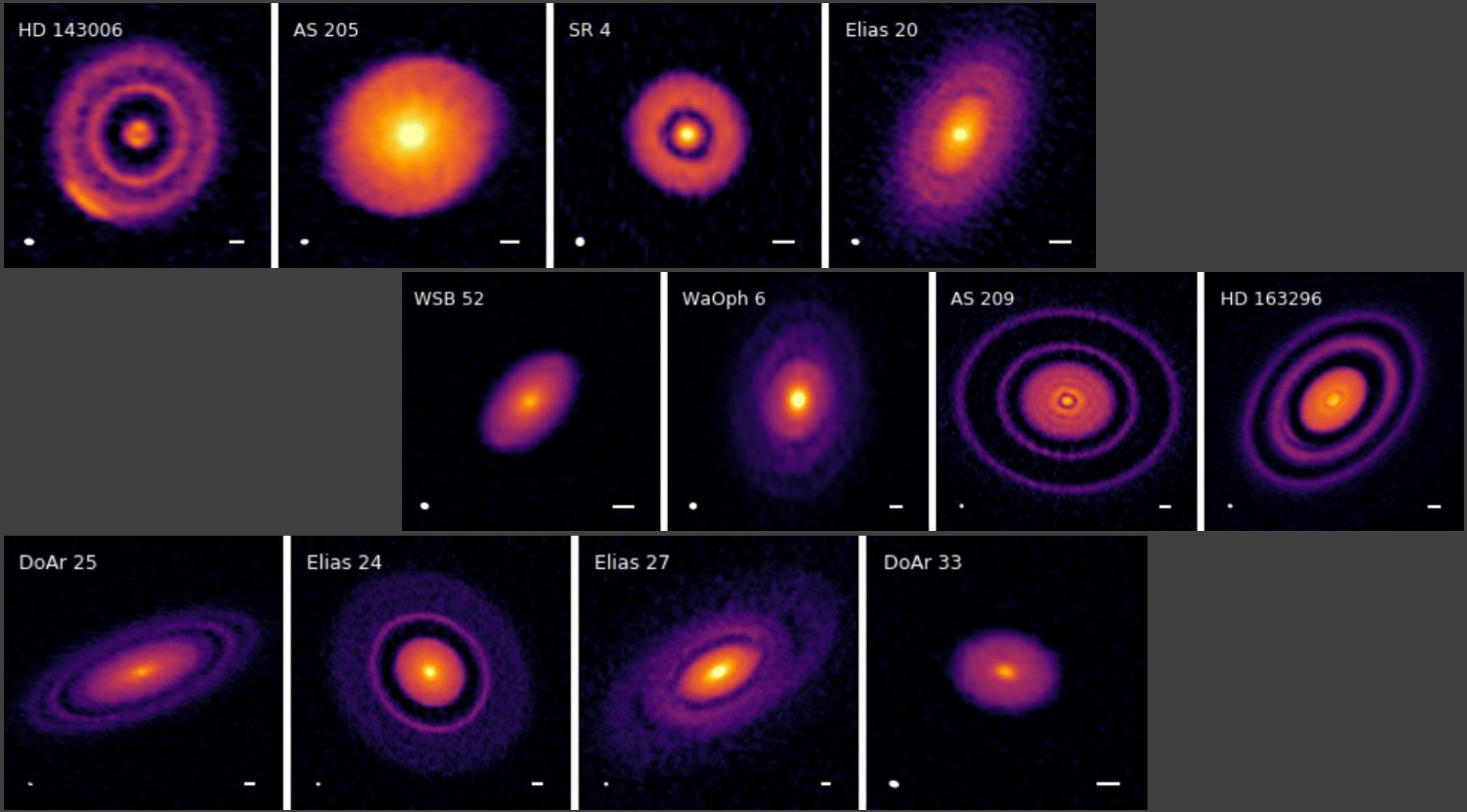


SPHERE – micron grains
ALMA – larger grains

ALMA gallery of discs

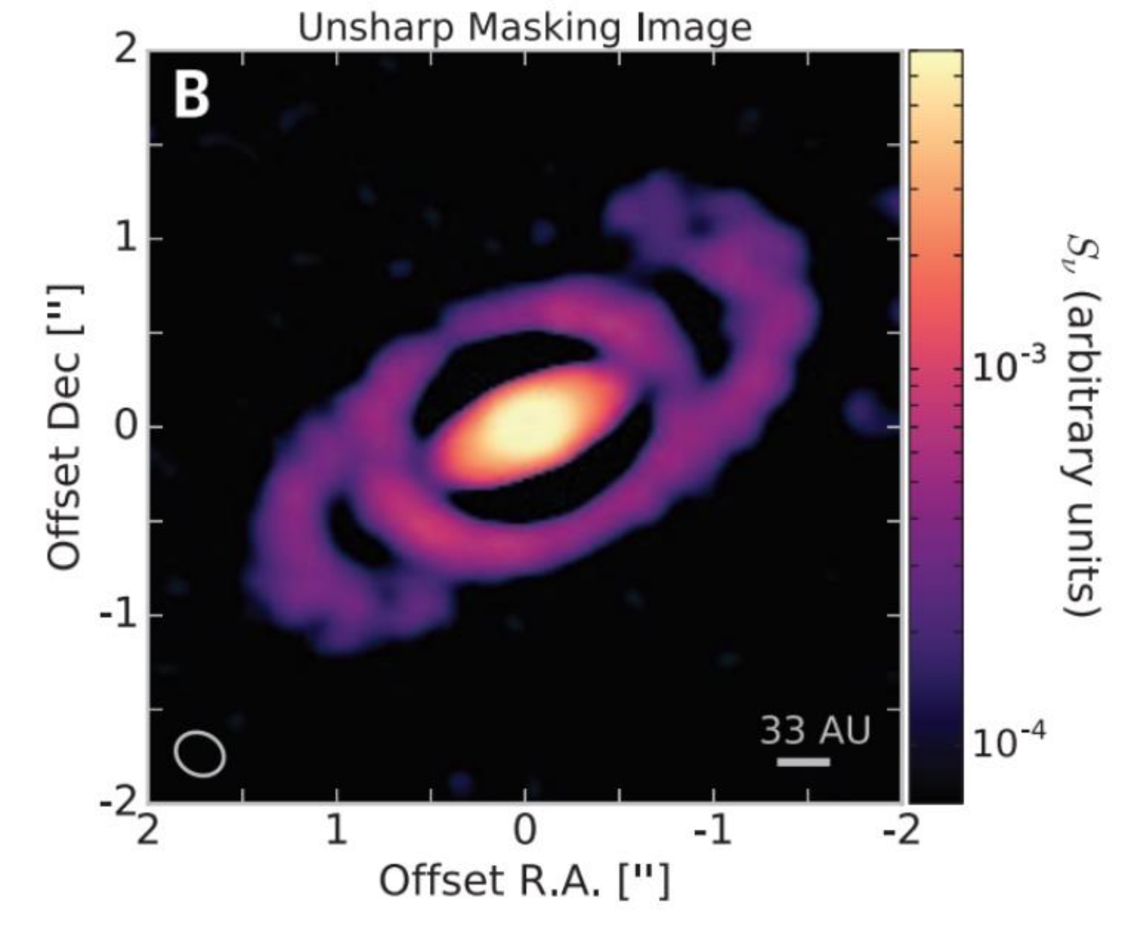


1812.04040



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

Disc around Elias 2-27



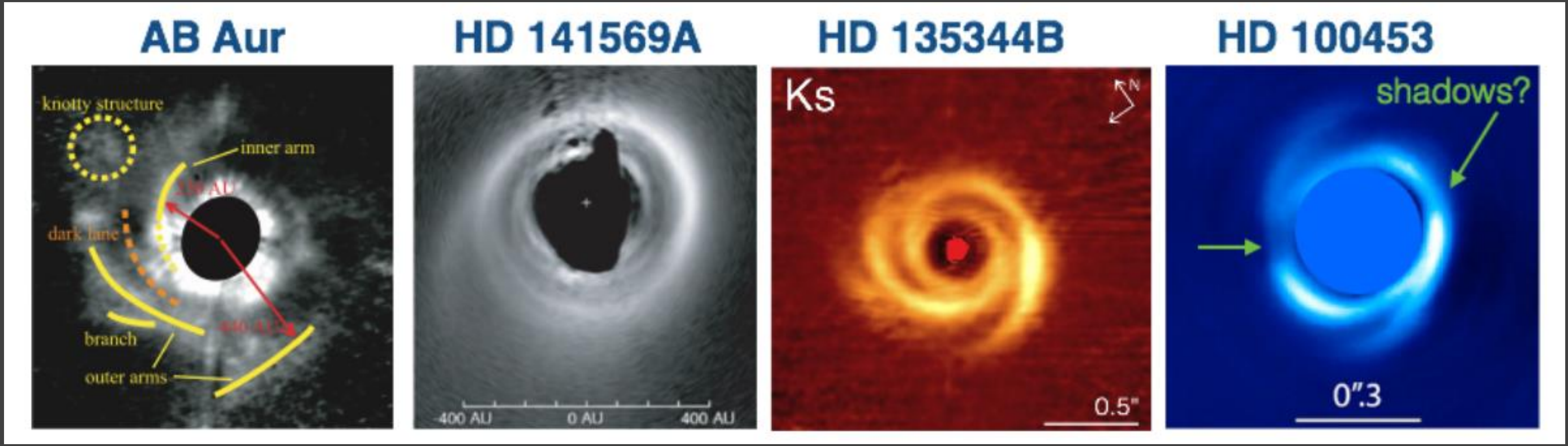
Spiral structure around Elias 2-27
Obtained by ALMA

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

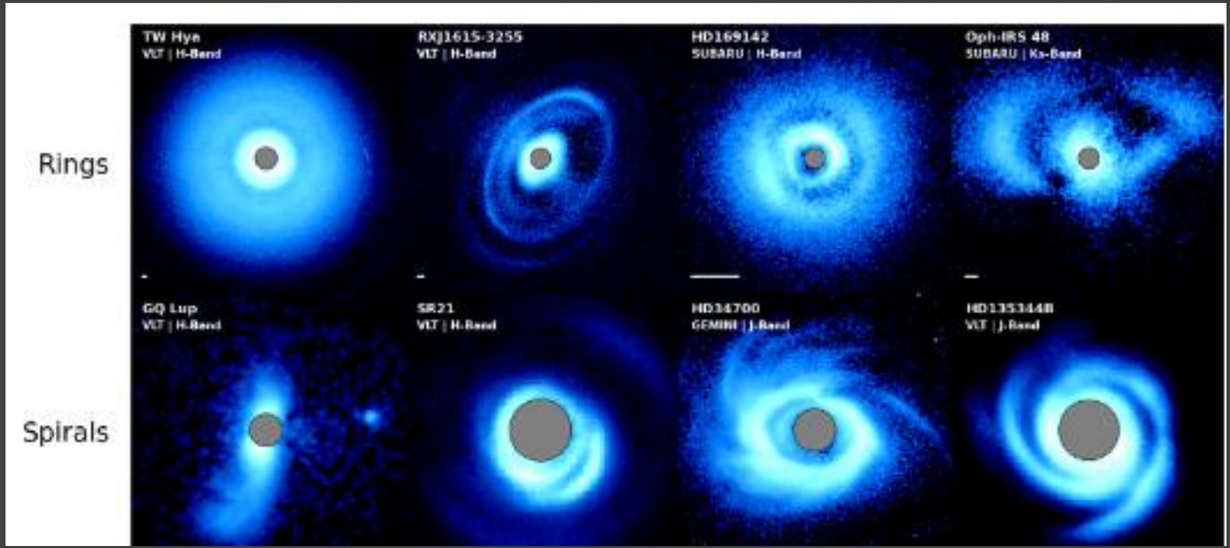
It is important that at distance >10 AU
the disc is transparent for 1.3 mm emission.
So, the spiral patter is related to the matter
also in the disc midplane.

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

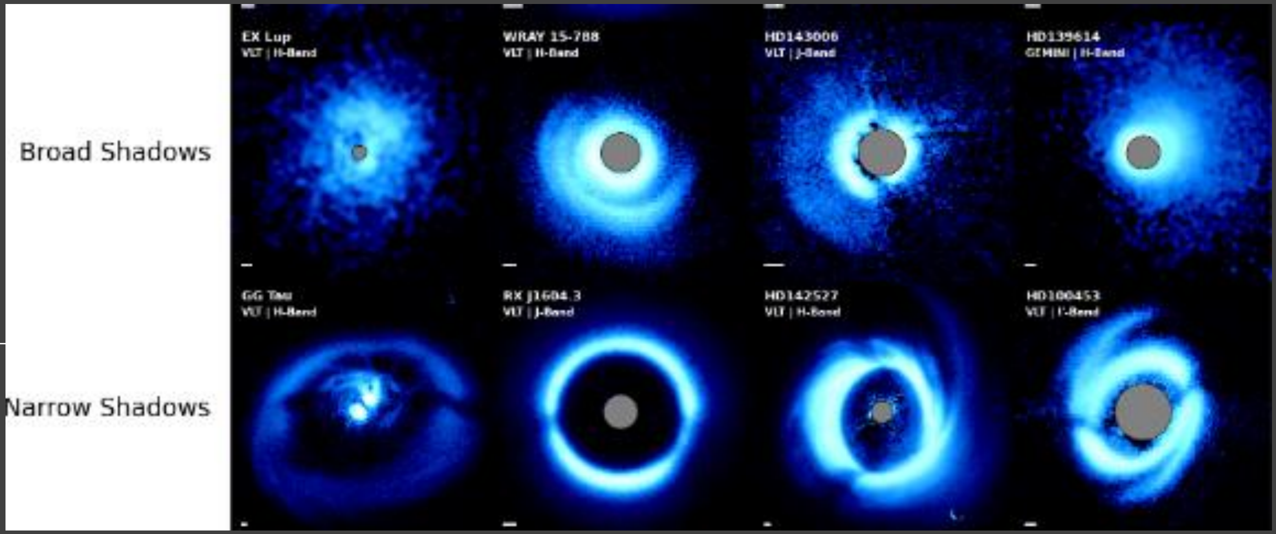
Gallery of spirals

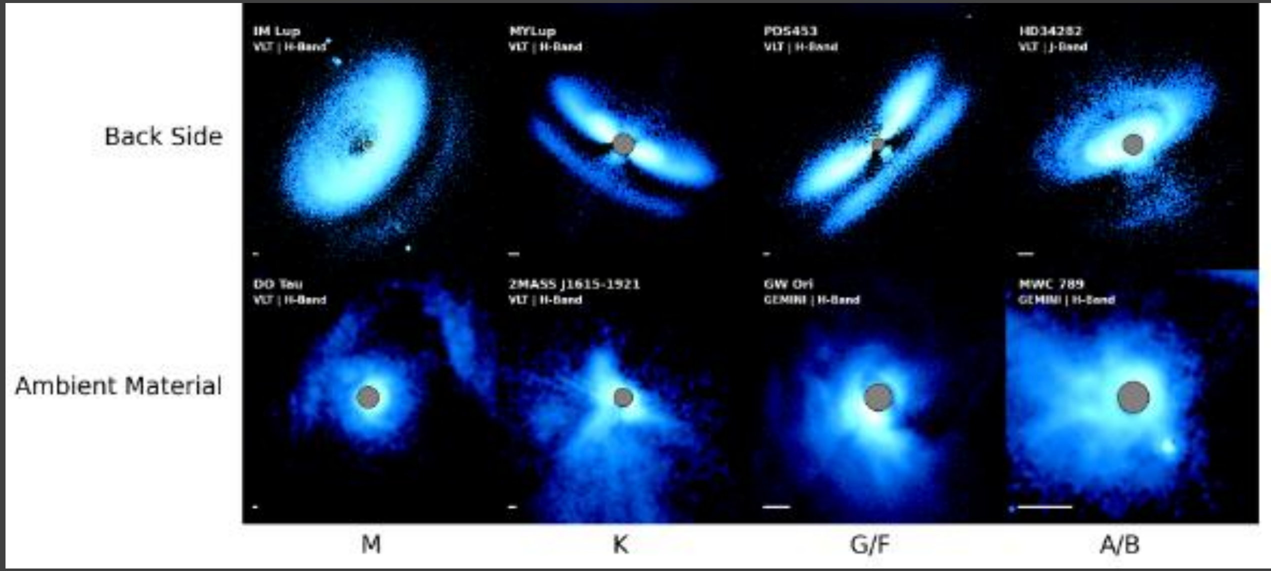


Another gallery



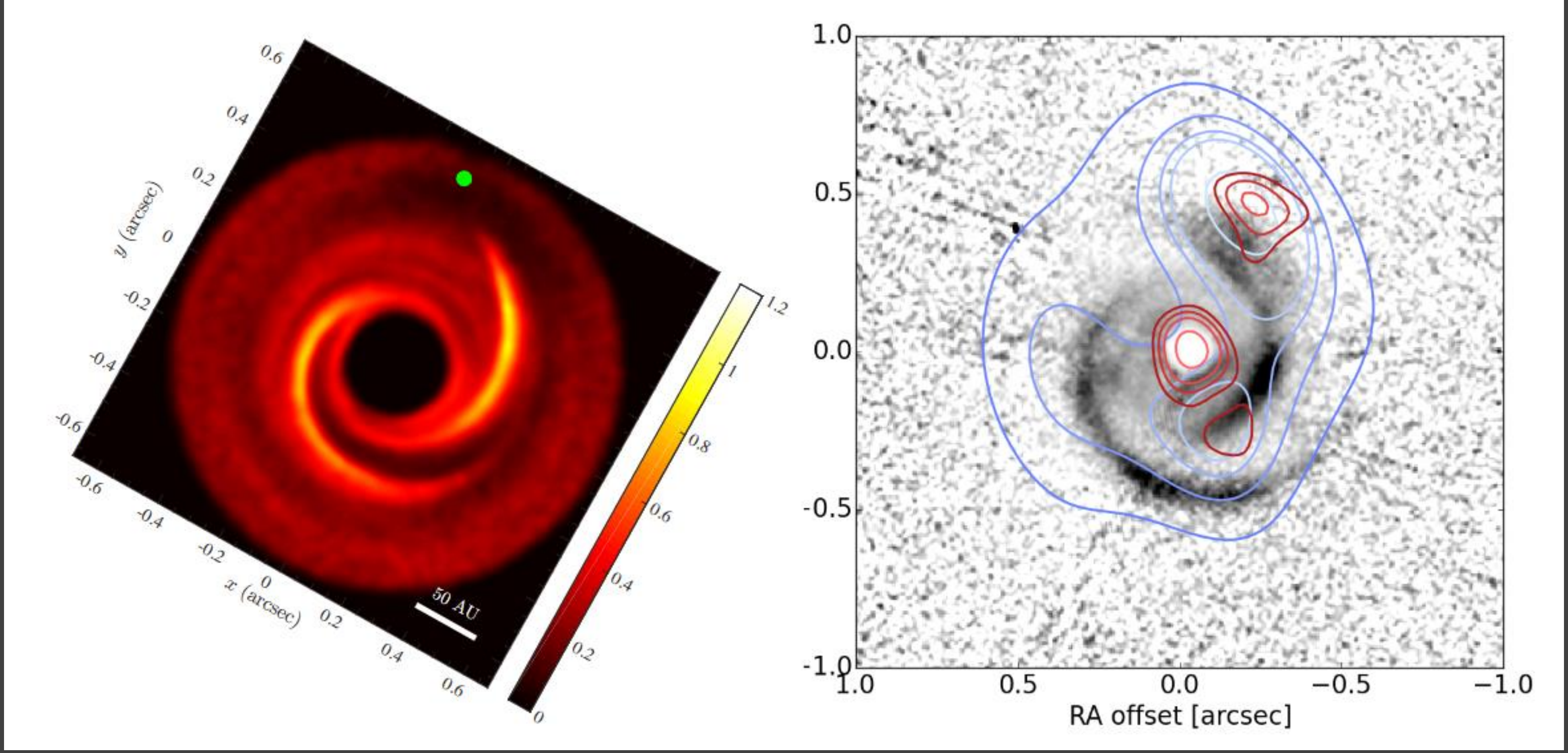
All disks observed with the SPHERE, GPI, and HiCIAO





2203.09991, see more images in this review

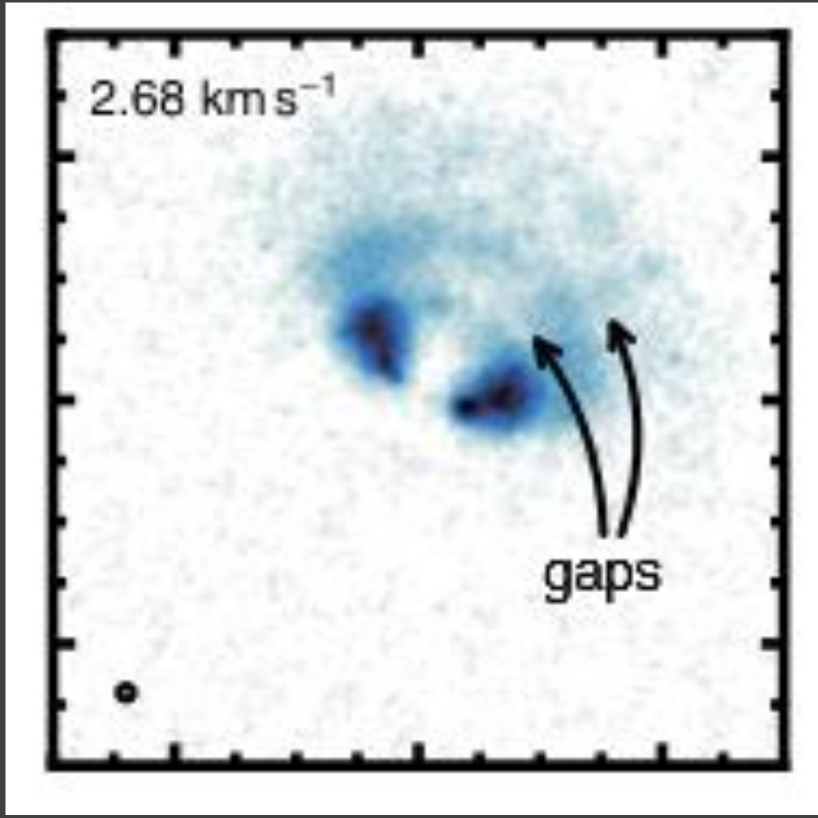
Spirals: model and observations



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

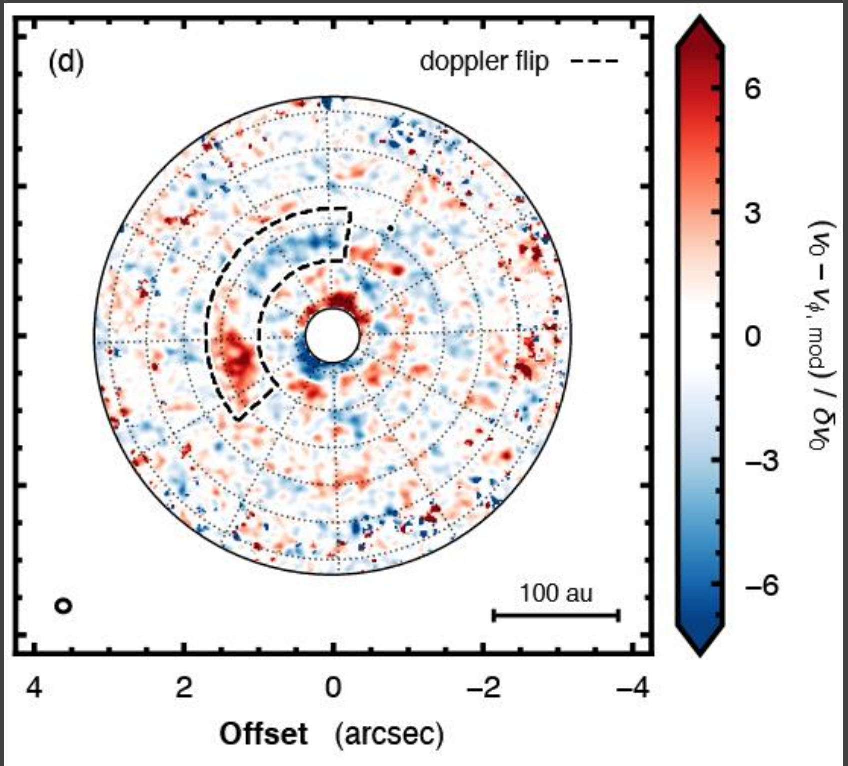
1602.06523, see new data in 1907.06655

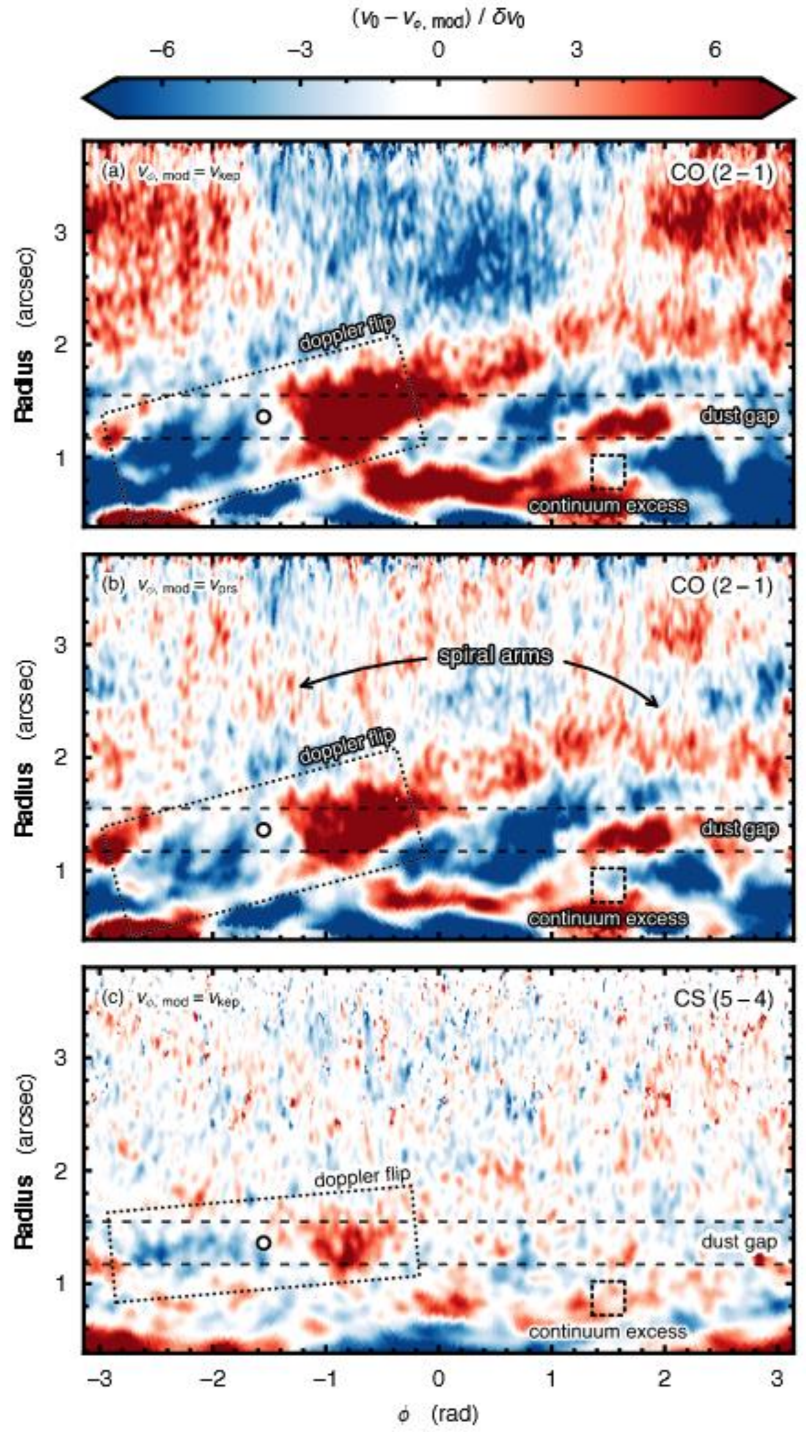
Disc mapping for TW Hydra



CS map

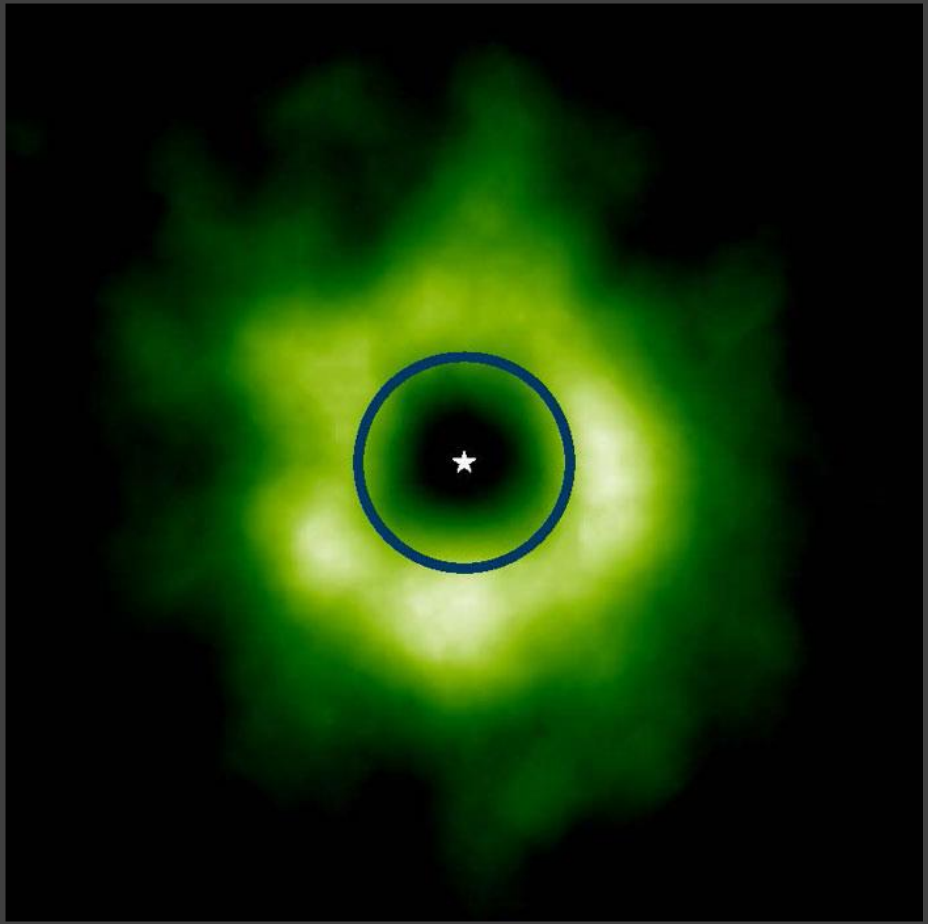
Residual map in CS line

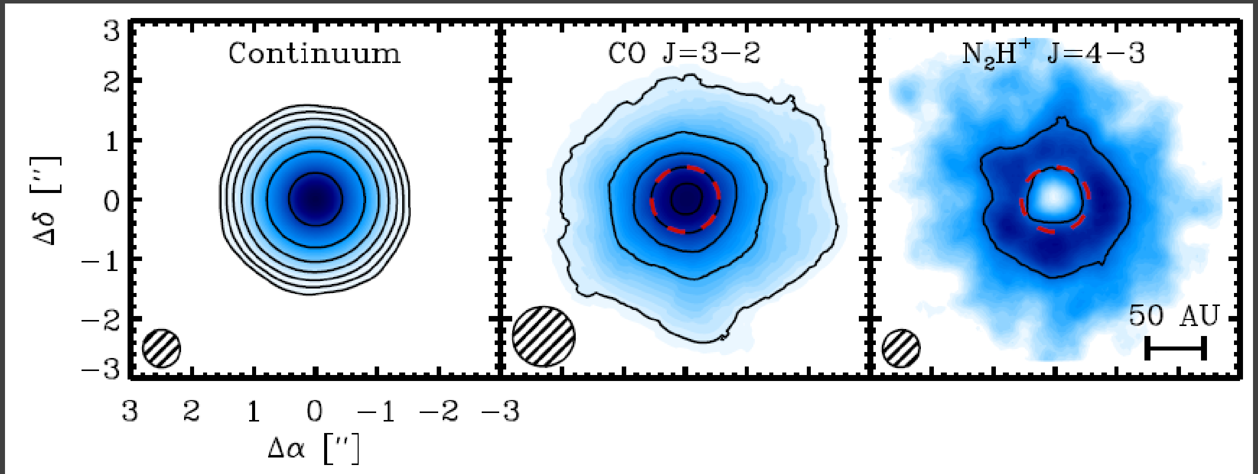


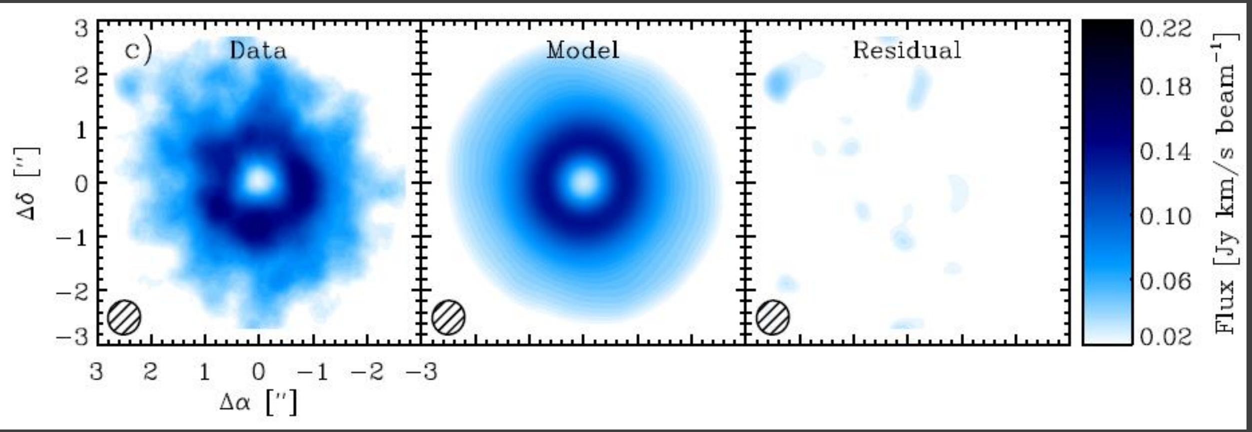


TW Hydra

N_2H^+ visible only if CO is frozen out







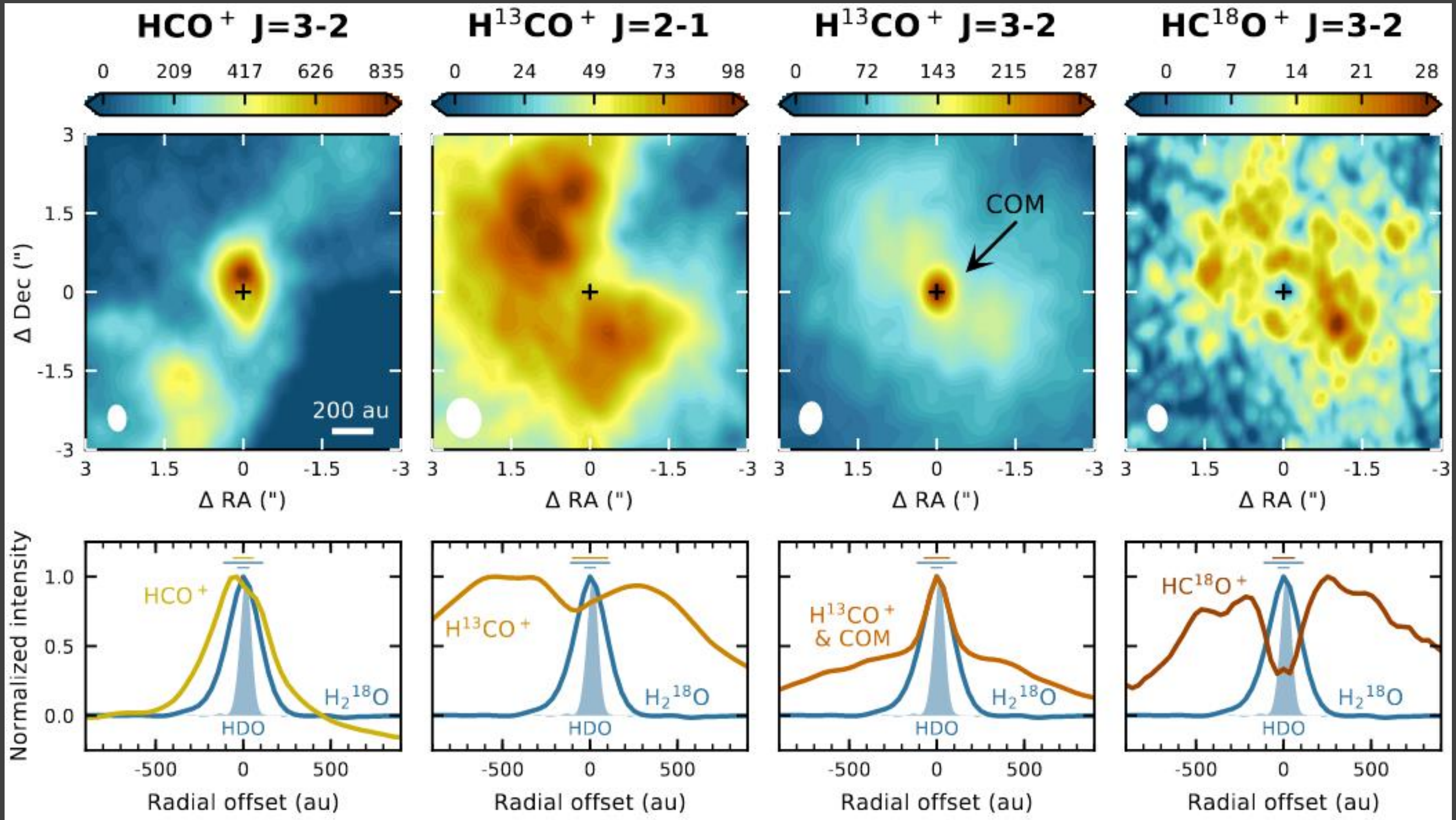
HCO+ as a tracer of the water snowline

Water destroys HCO+ in warm gas.
ALMA observations allow to probe existence of HCO+.

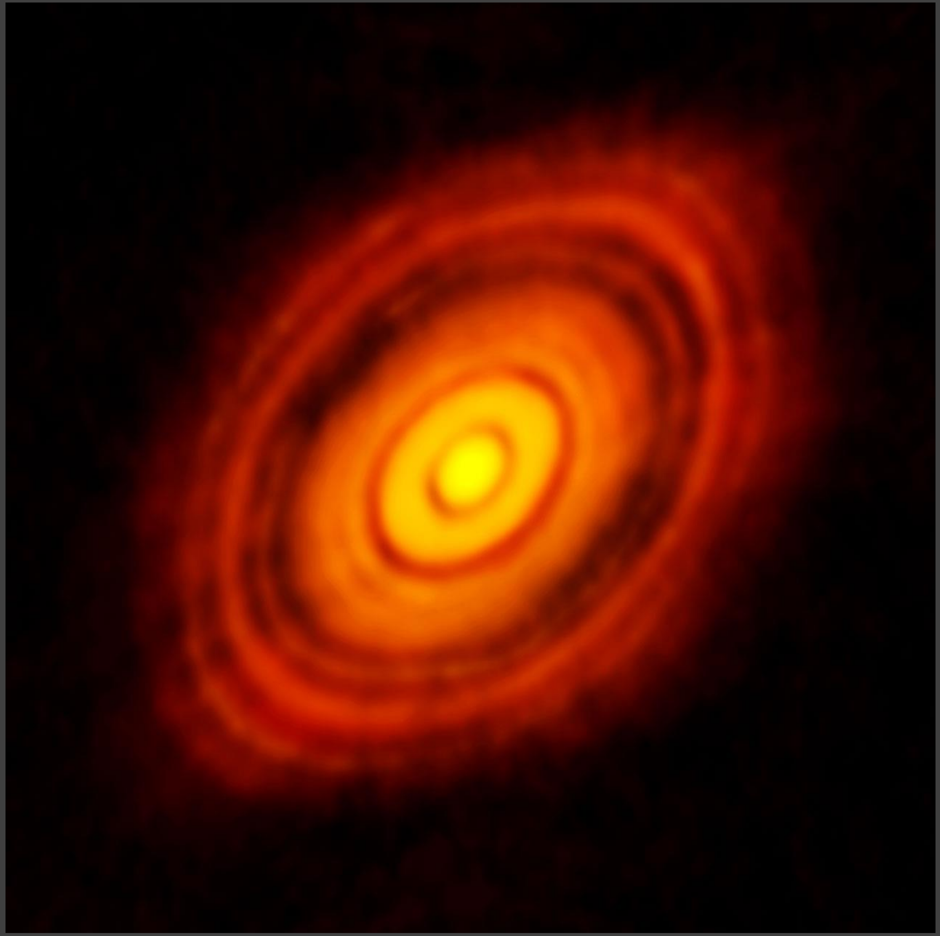
Different isotopes can be used (HCO^+, $H^{13}CO^+$, $HC^{18}O^+$).
Protostars observations are presented.

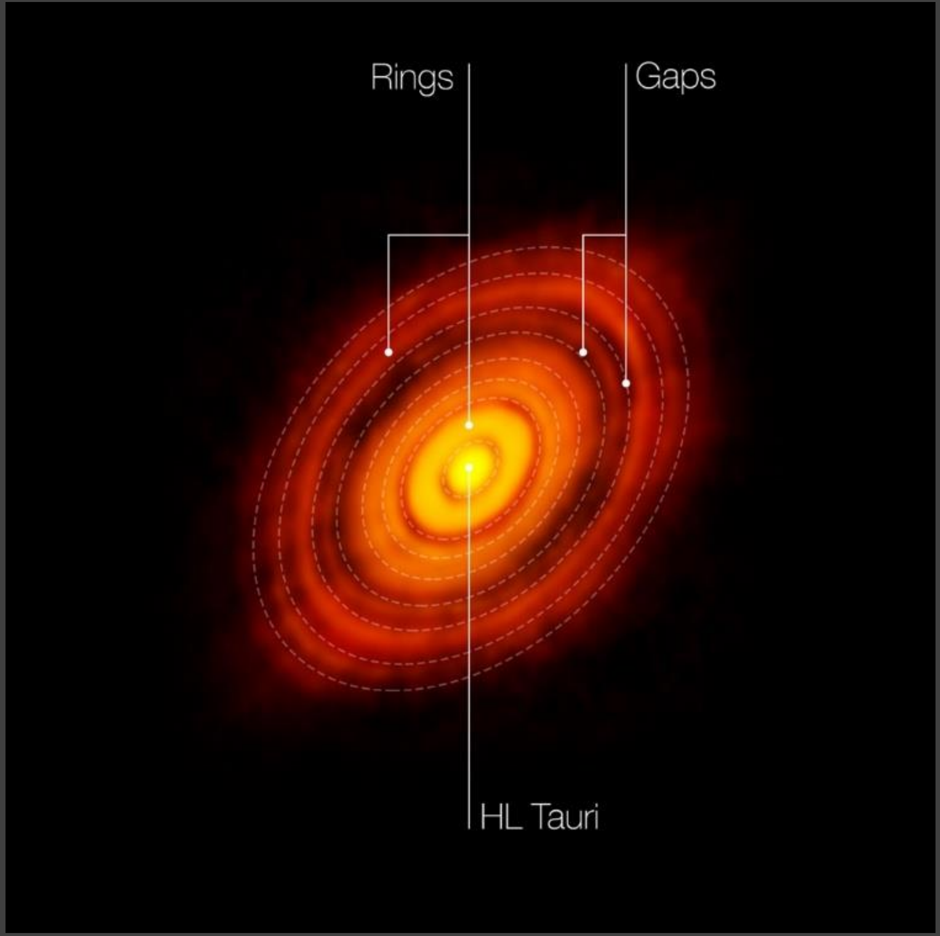
HCO+ is expected to be abundant only in the region where water is frozen out and gaseous CO is available for its formation.

Large size of the snowline is due to accretion bursts in protostellar envelopes.



Protoplanetary disc of HL Tau



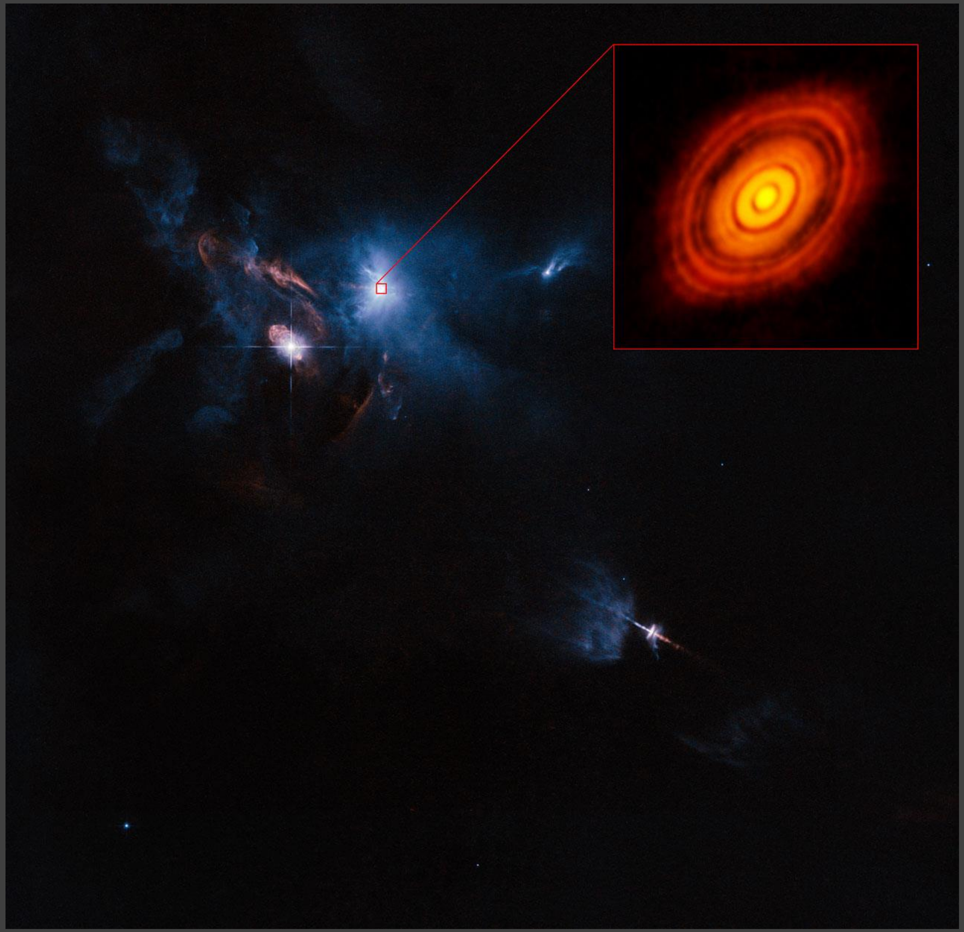


140 pc
Massive disc
Jet
Age <1-2 Myrs

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

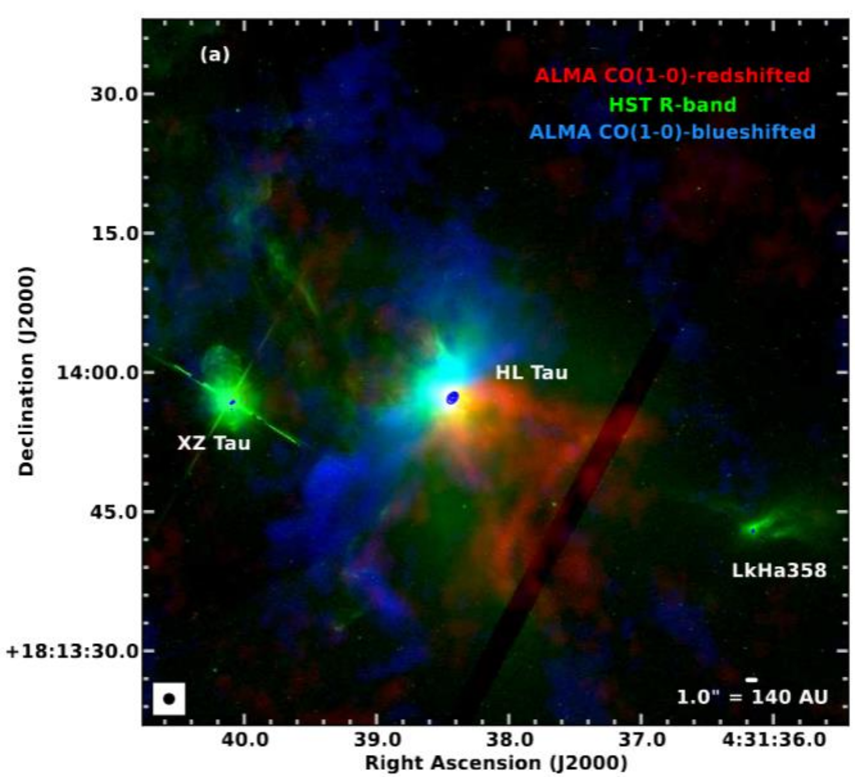
Where stars are born

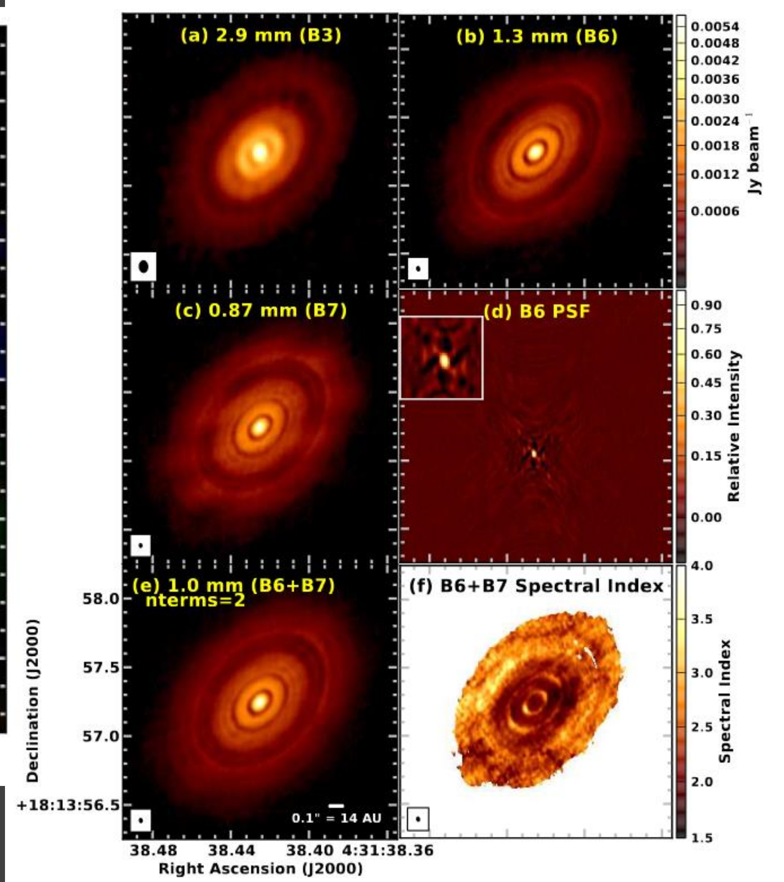
http://www.eso.org/public/images/eso1436b/



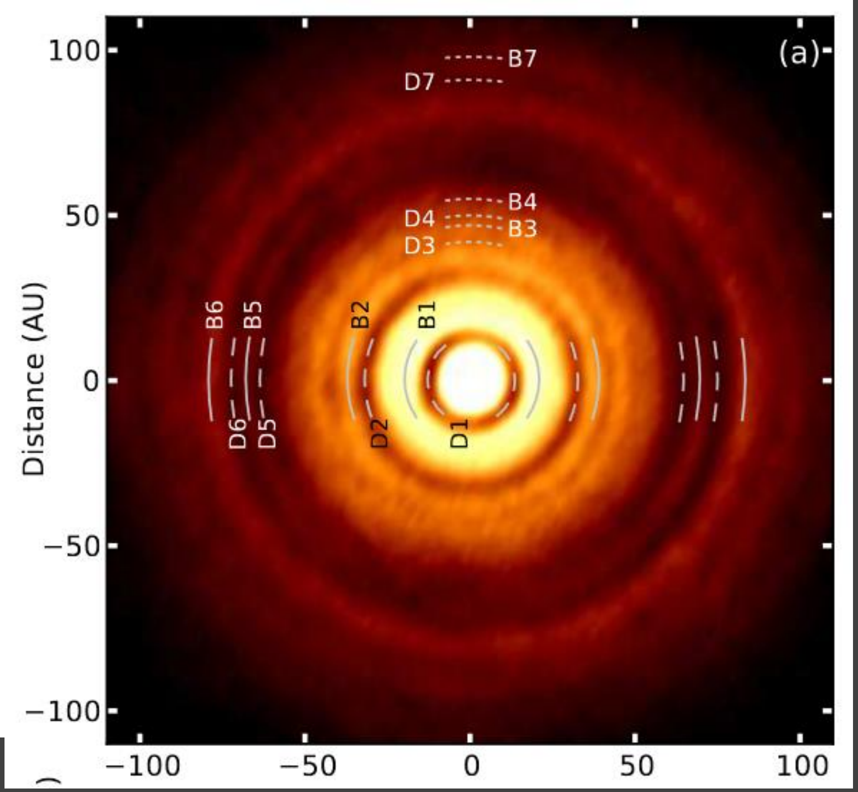
https://public.nrao.edu/AlmaExtras/

More details on the disc of HL Tau

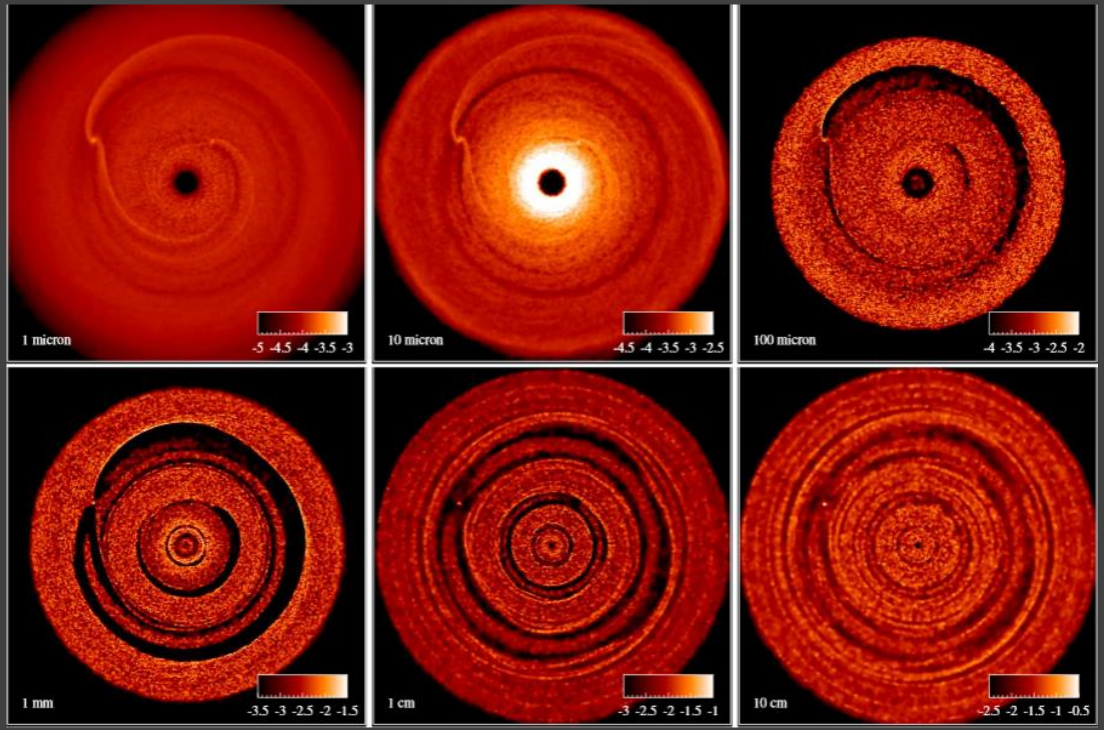




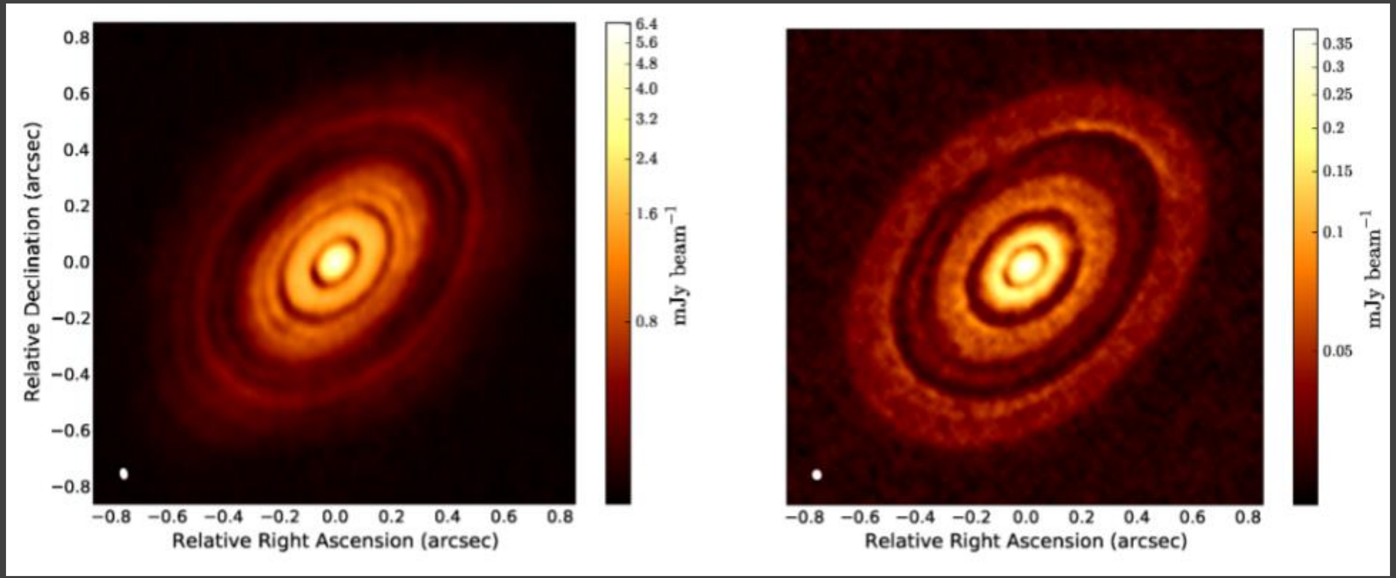
Some rings are in resonance with each other.



Modeling of the HL Tau disc



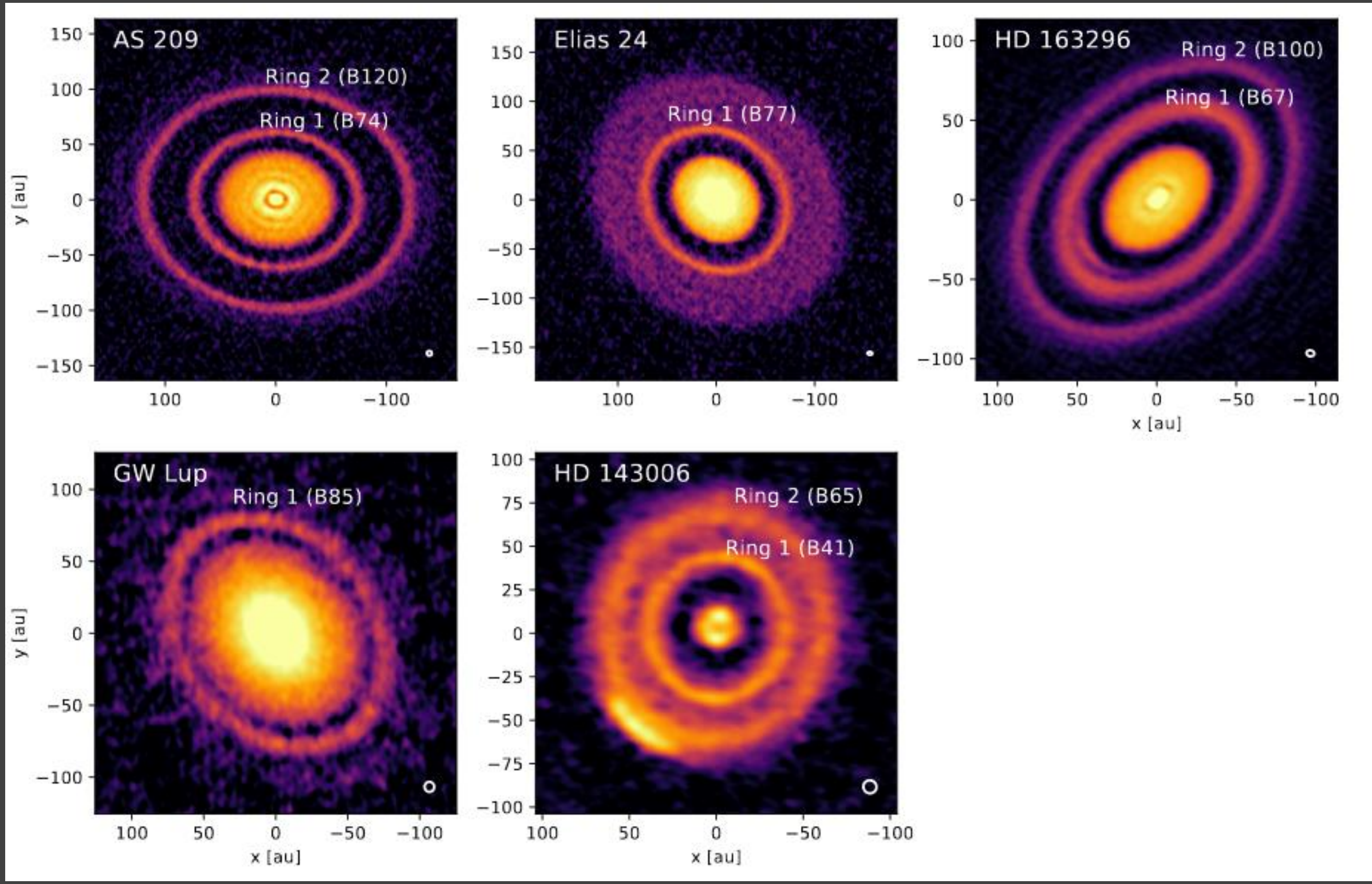
Three planets with masses from 0.2 up to 0.55 Jupiter mass

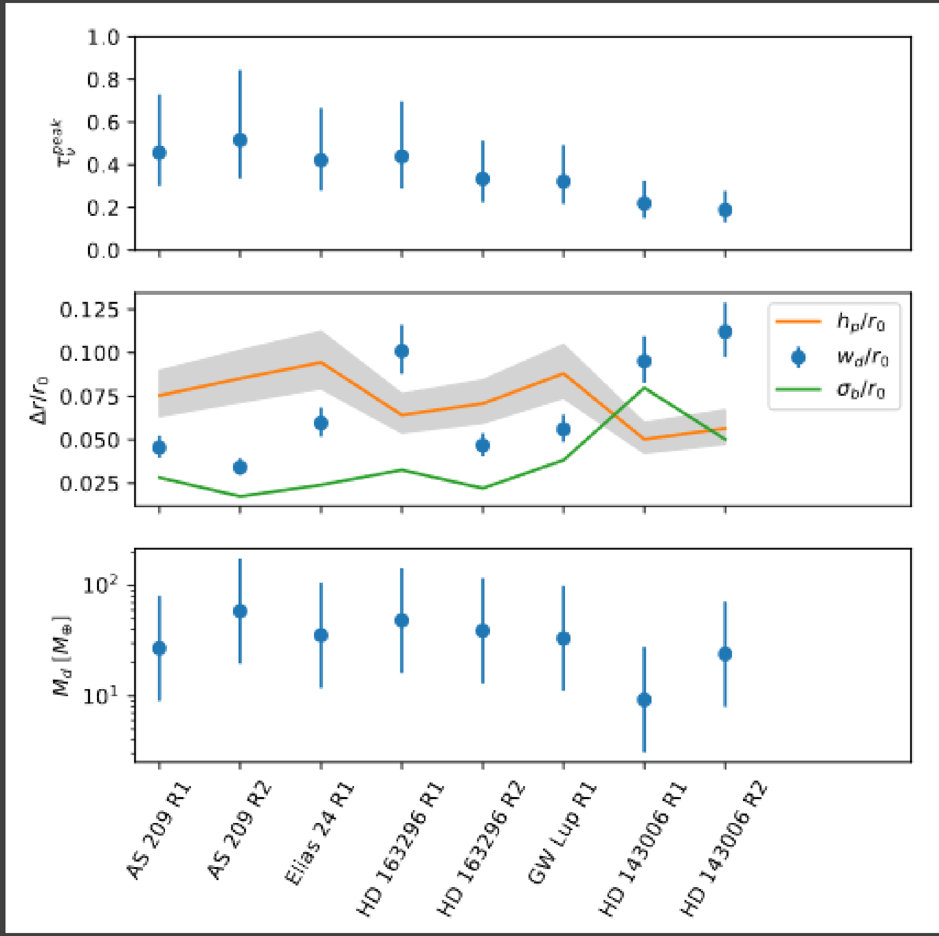


Observations

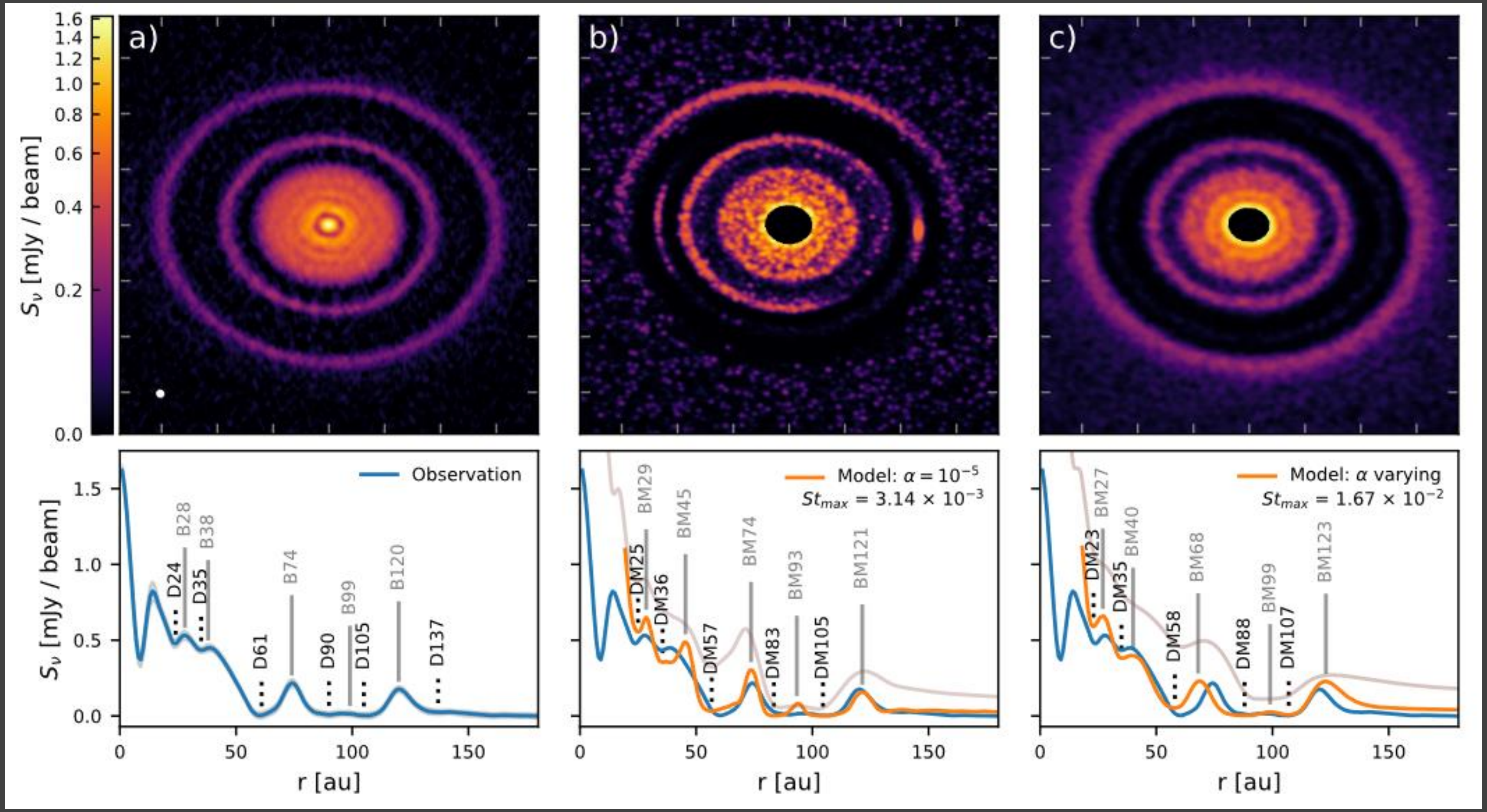
Modeling

More rings from ALMA





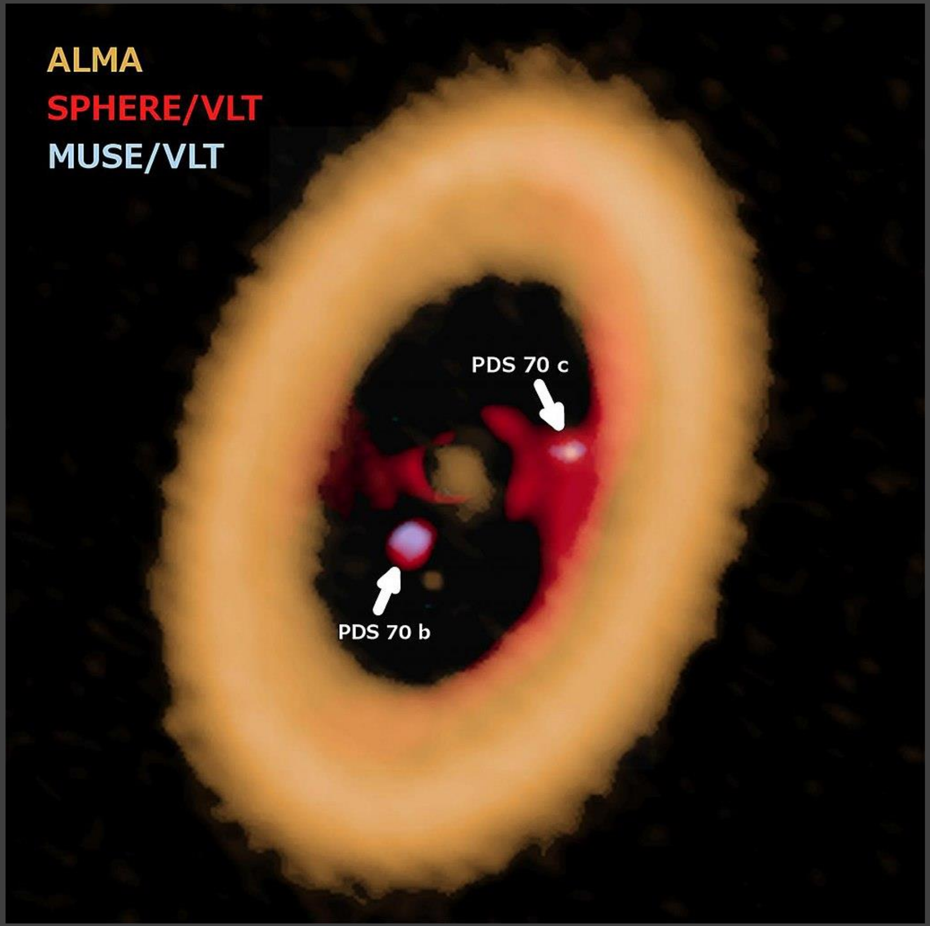
Modeling ring structure. Planets

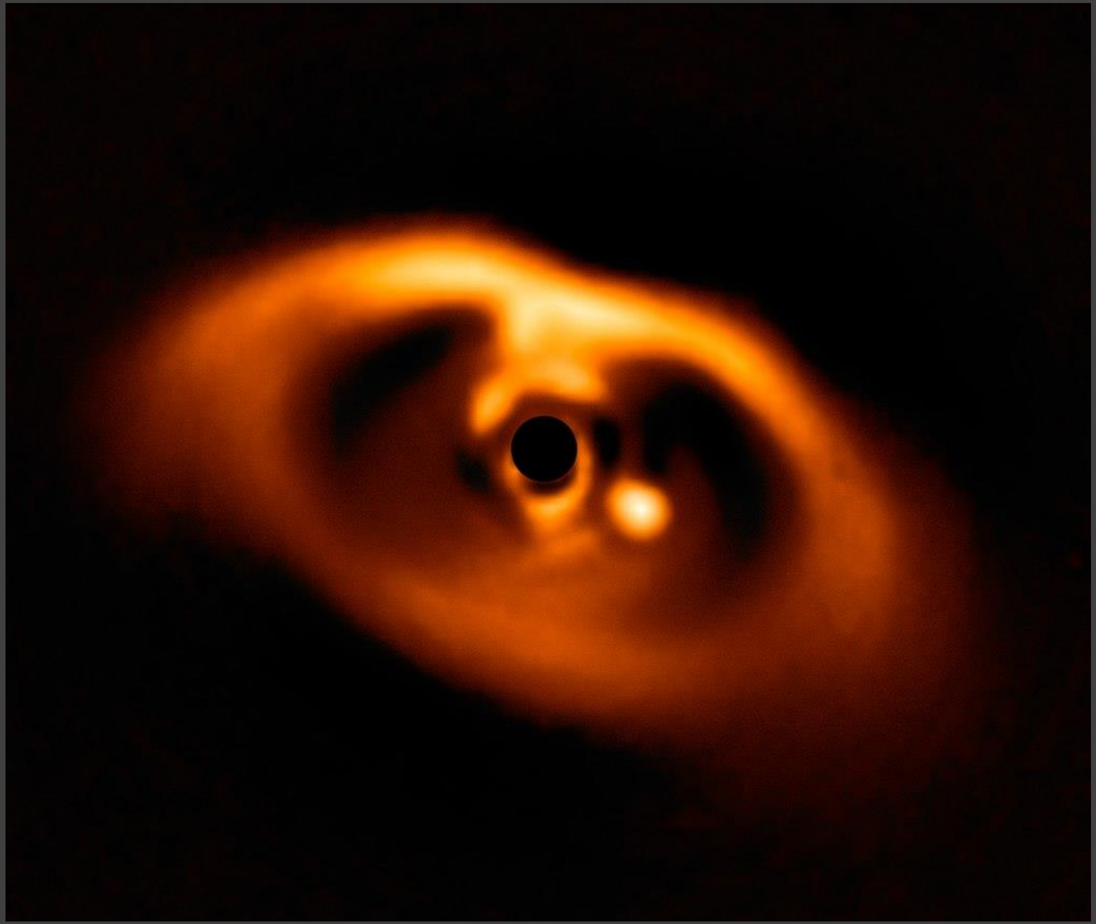


One planet at 99 au.

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

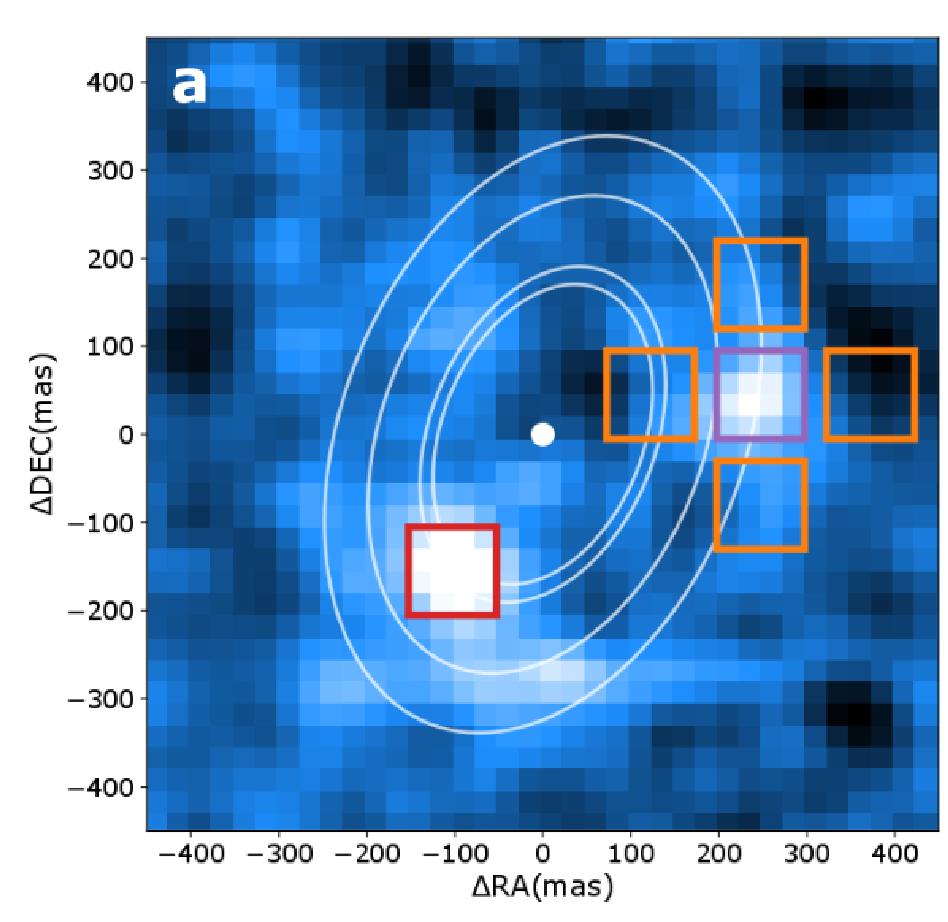
PDS 70: two planets in a disc





Wikipedia

PDS 70. The second planet



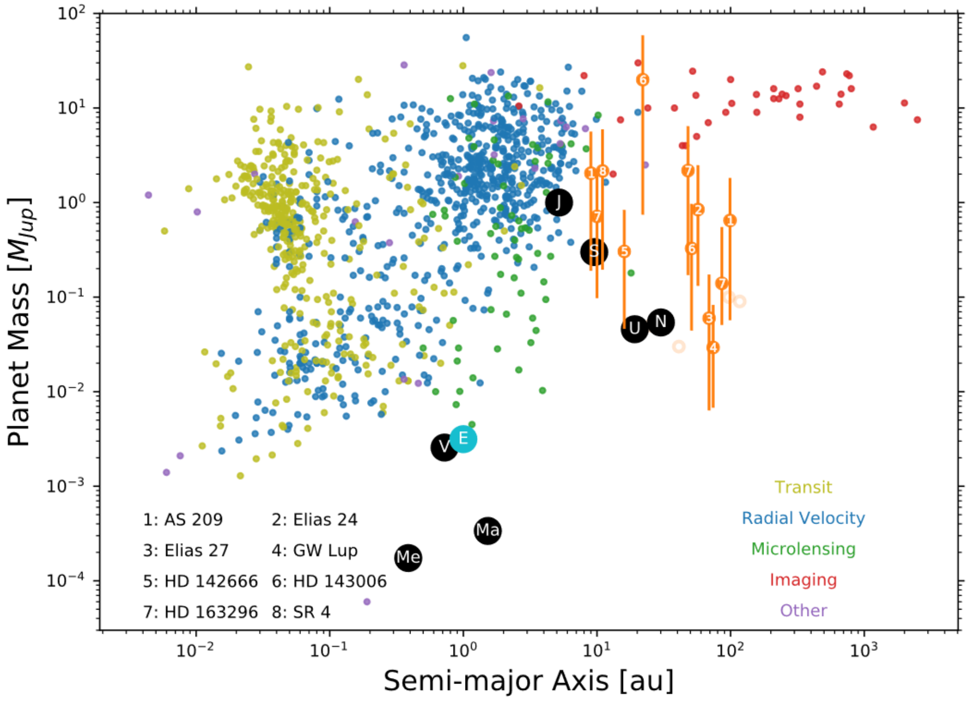
VLT observations

MUSE (Multi Unit Spectroscopic Explorer)

Halpha image

Properties of (invisible) planets

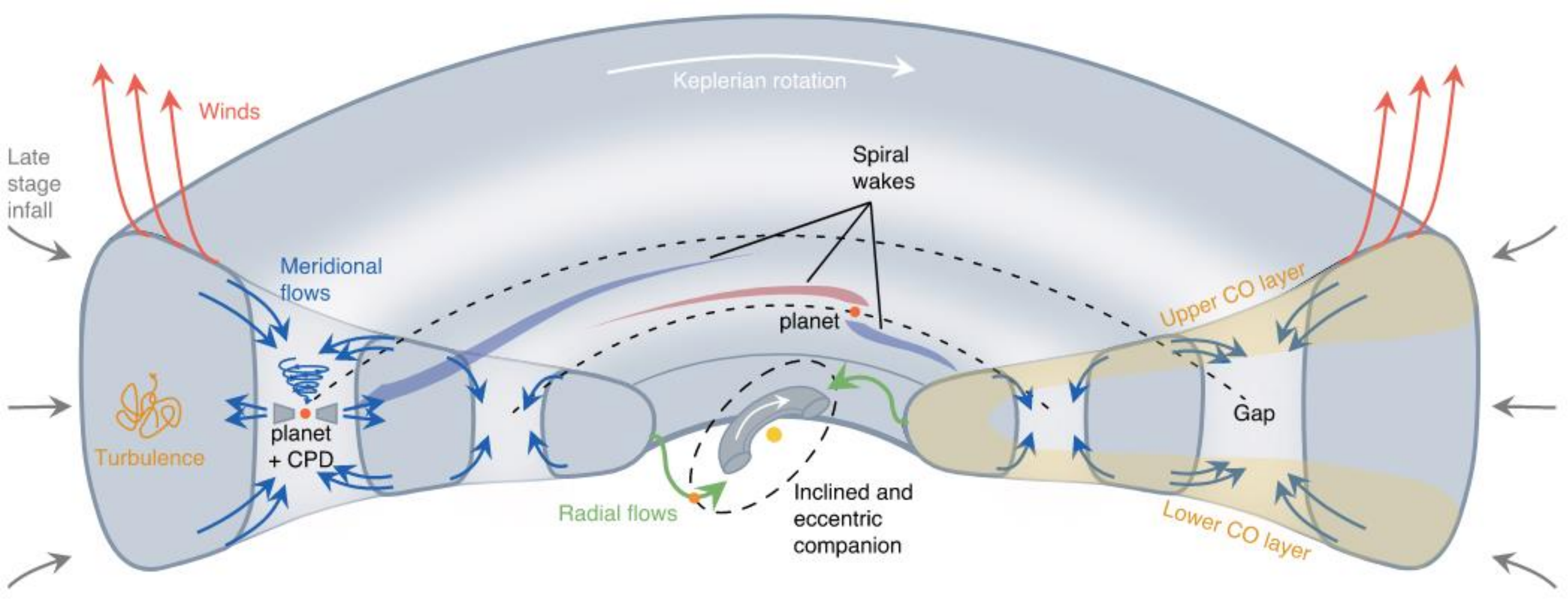
Name	M_*	r_{gap}	width	$M_{p,am4}$	$M_{p,am3}$	$M_{p,am2}$	Uncertainty
	$(M_\odot)$	(au)	(Δ)	(M_{Jup})	(M_{Jup})	(M_{Jup})	$(log_{10}(M_p))$
(1)	(2)	(3)	(4)	(11)	(12)	(13)	(14)
AS 209	0.83	9	0.42	1.00, 0.81, 0.37	2.05, 1.66, 0.76	4.18, 3.38, 1.56	$^{+0.13}_{-0.16}$, $^{+0.14}_{-0.17}$, $^{+0.28}_{-0.29}$
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.

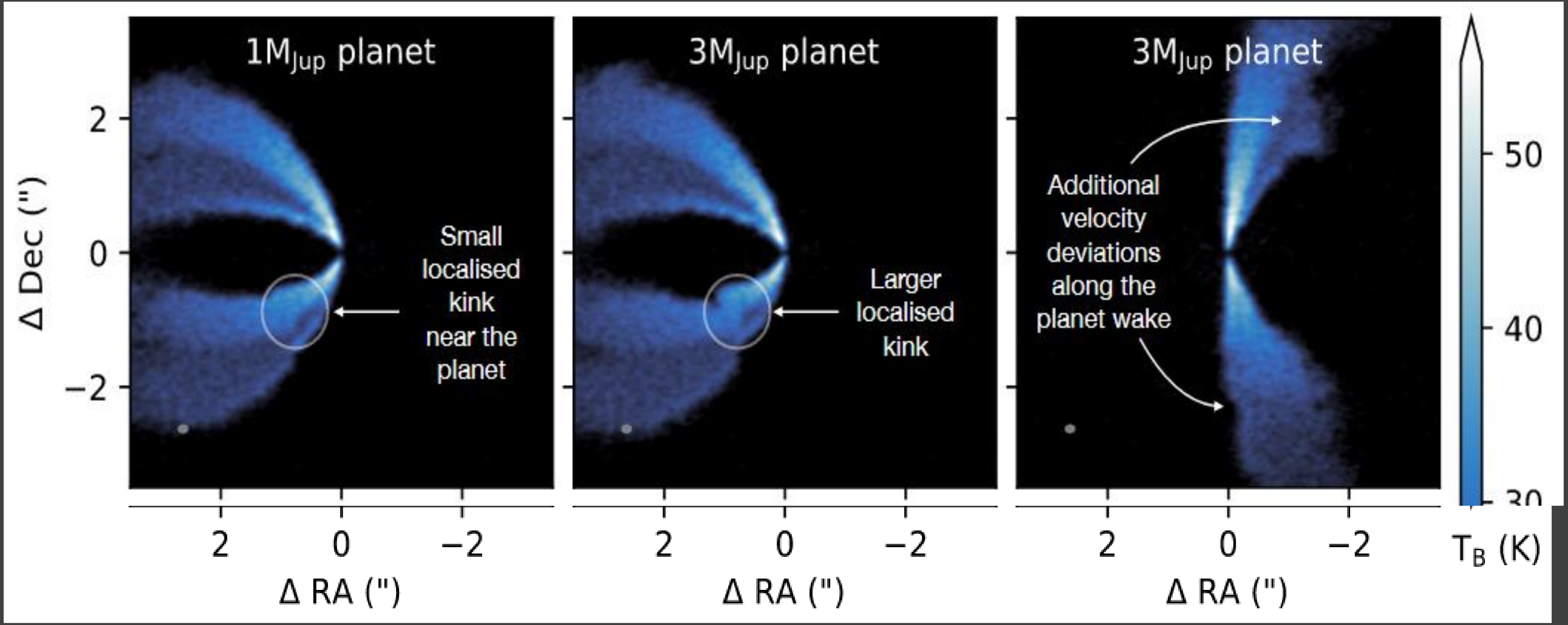
1812.04045

Disc structure with spirals, etc.



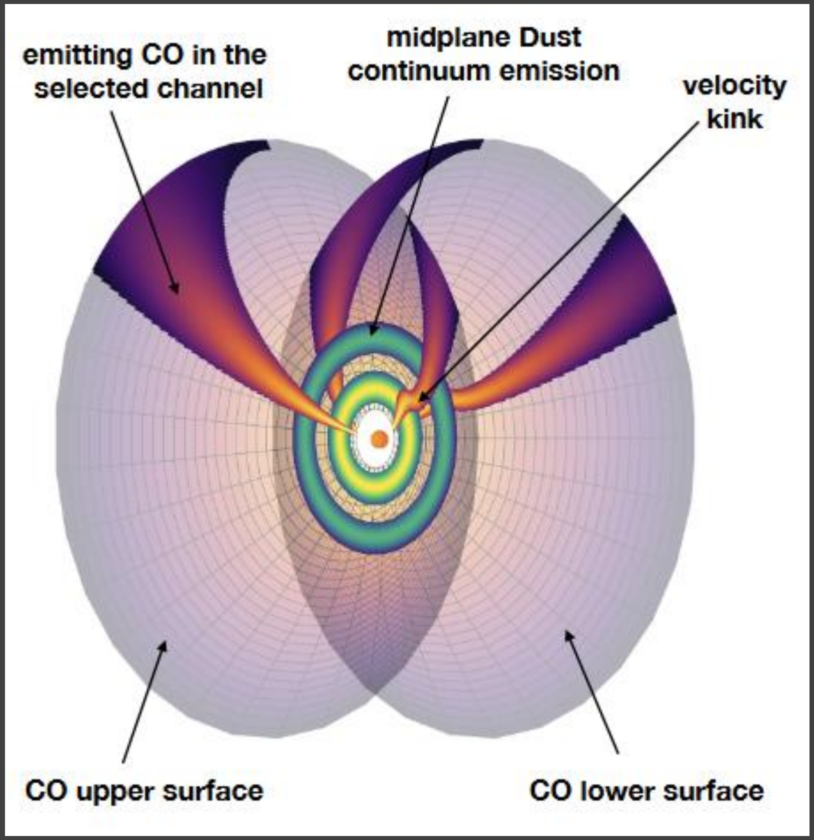
See a review in 2203.09528

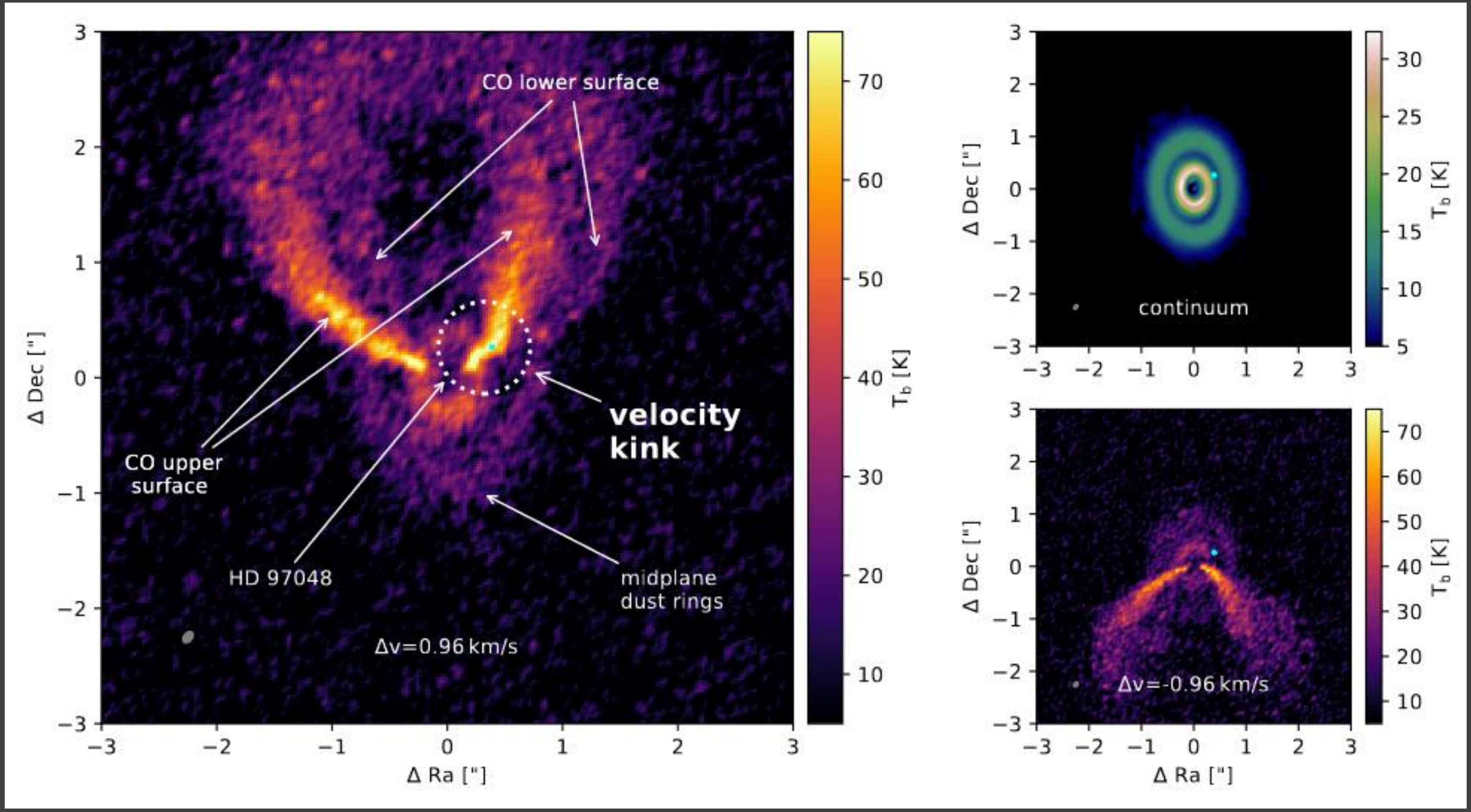
Modeling of kinematic structures (CO maps)



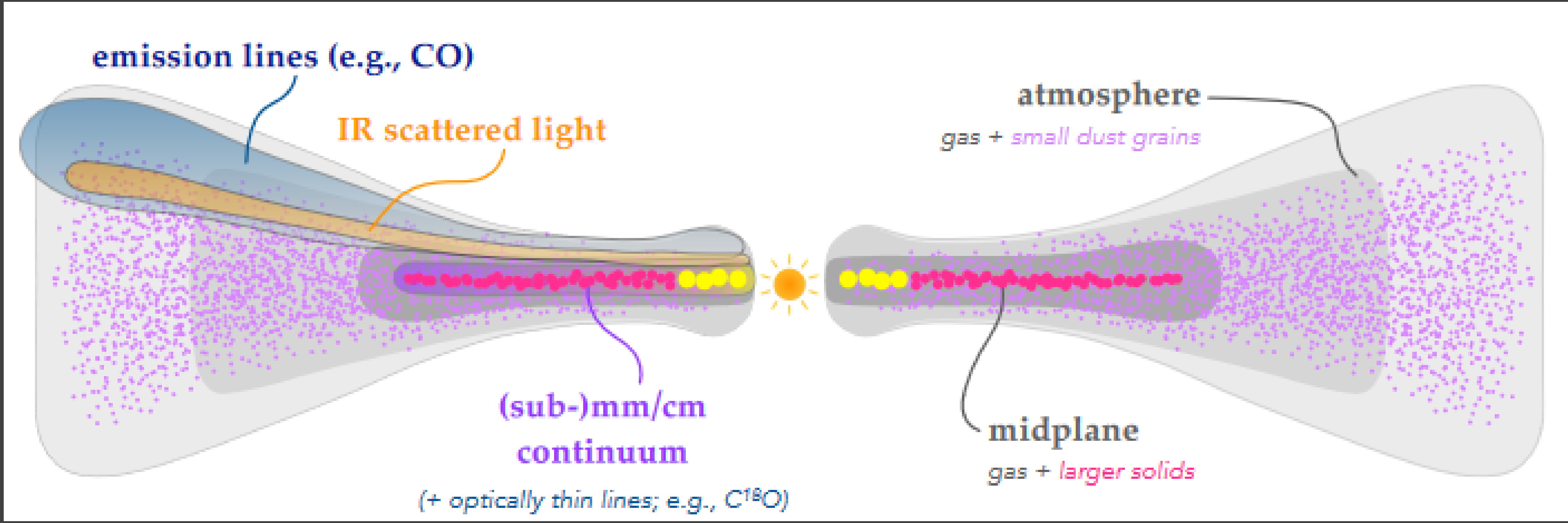
Kinematic detection of a planet HD 97048

Gap + disturbance in the gas flow



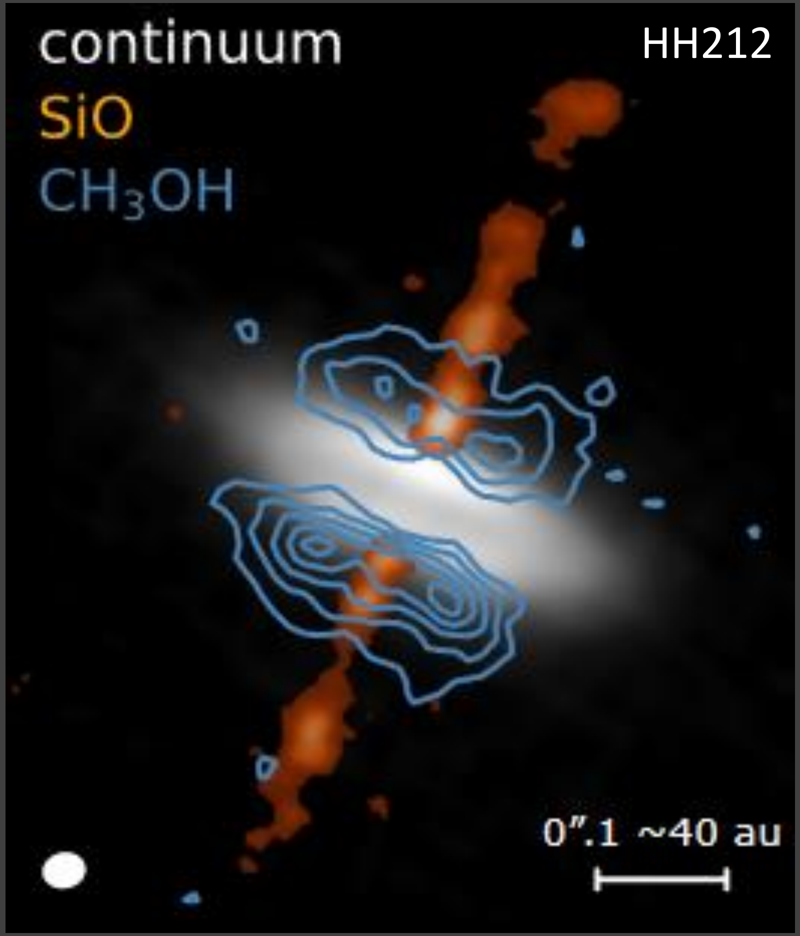


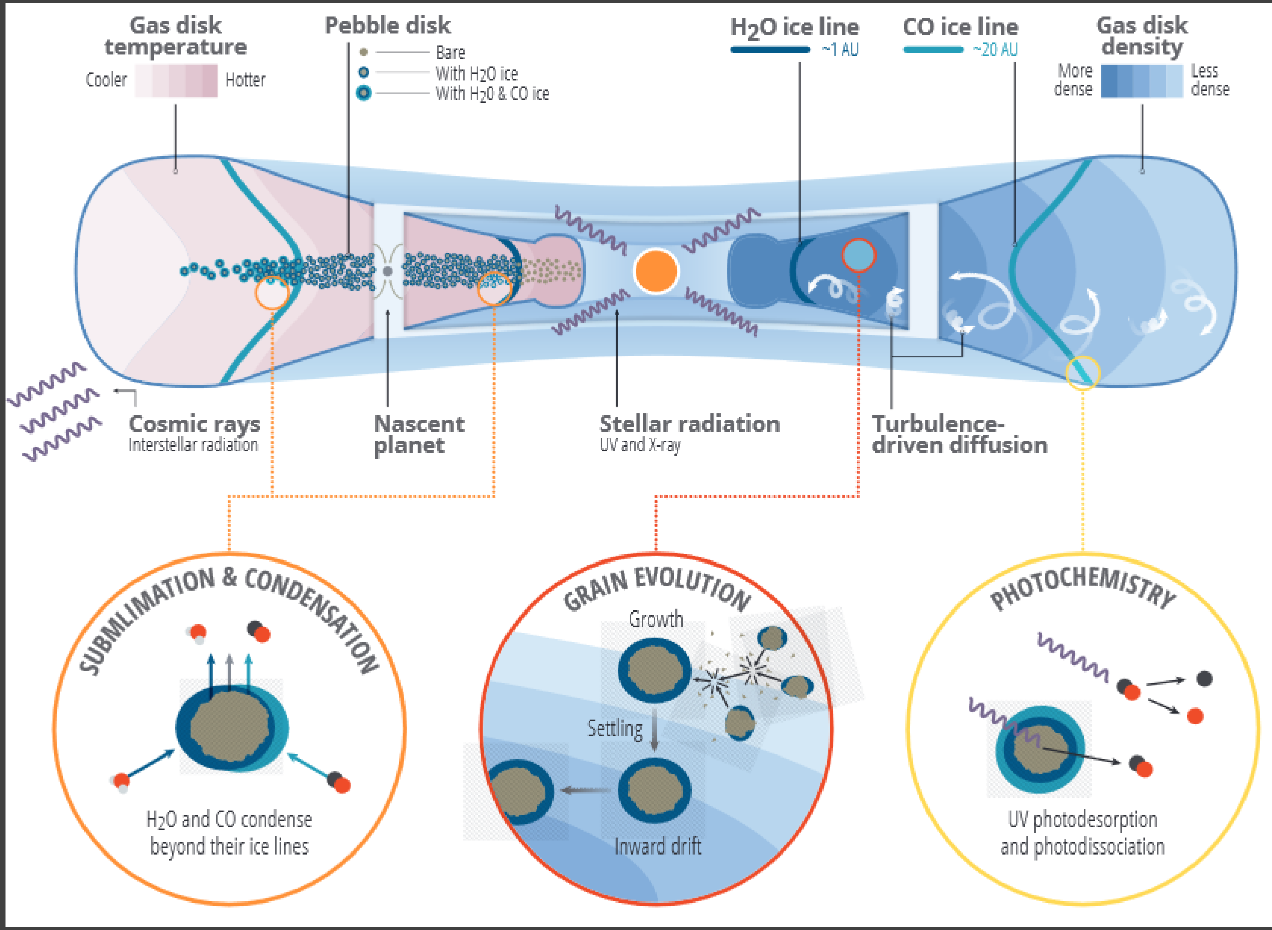
Disc structure and emission zones



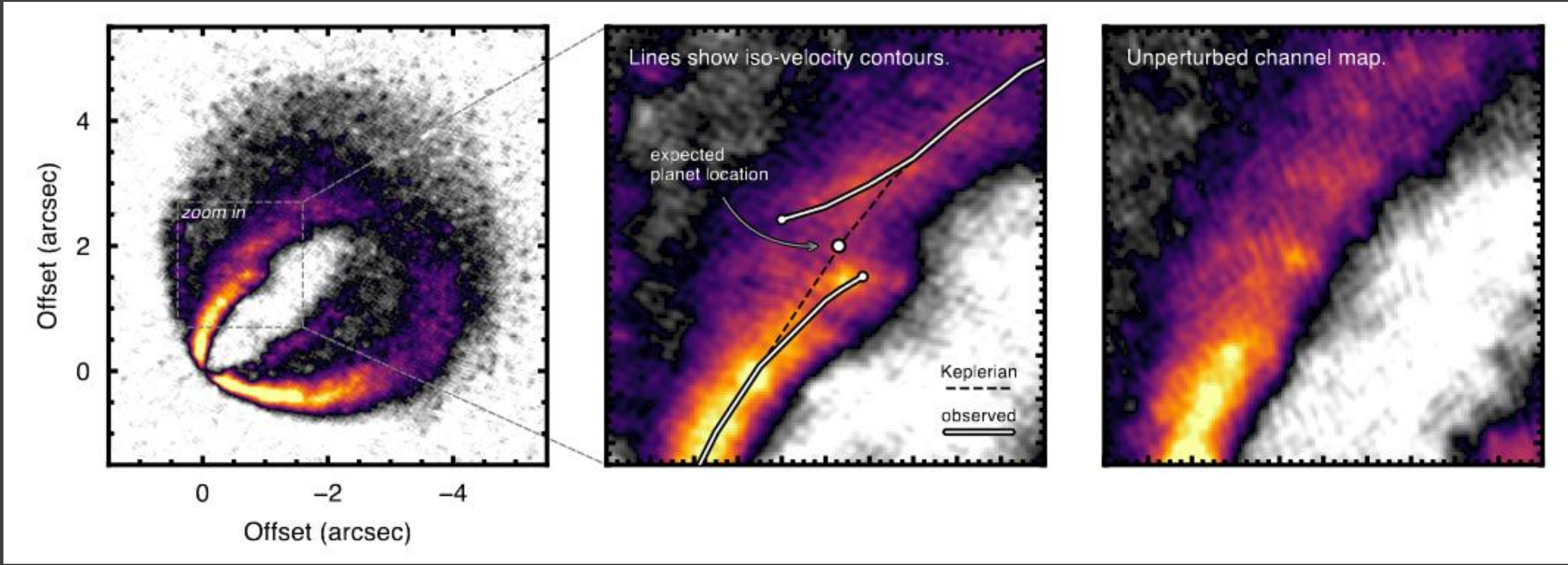
2001.05007

Structure and processes

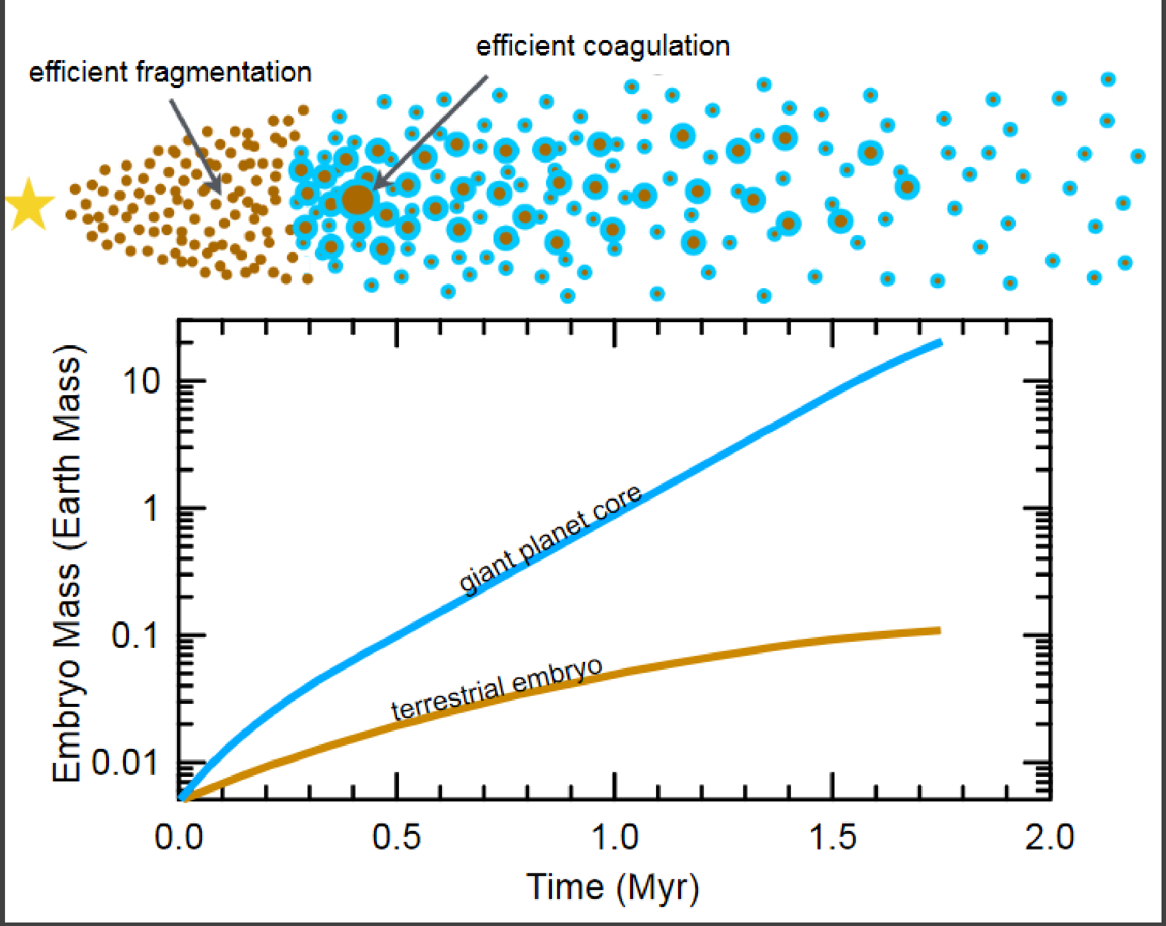




Planet and gas velocity in the disc HD 163296



Where planets grow?

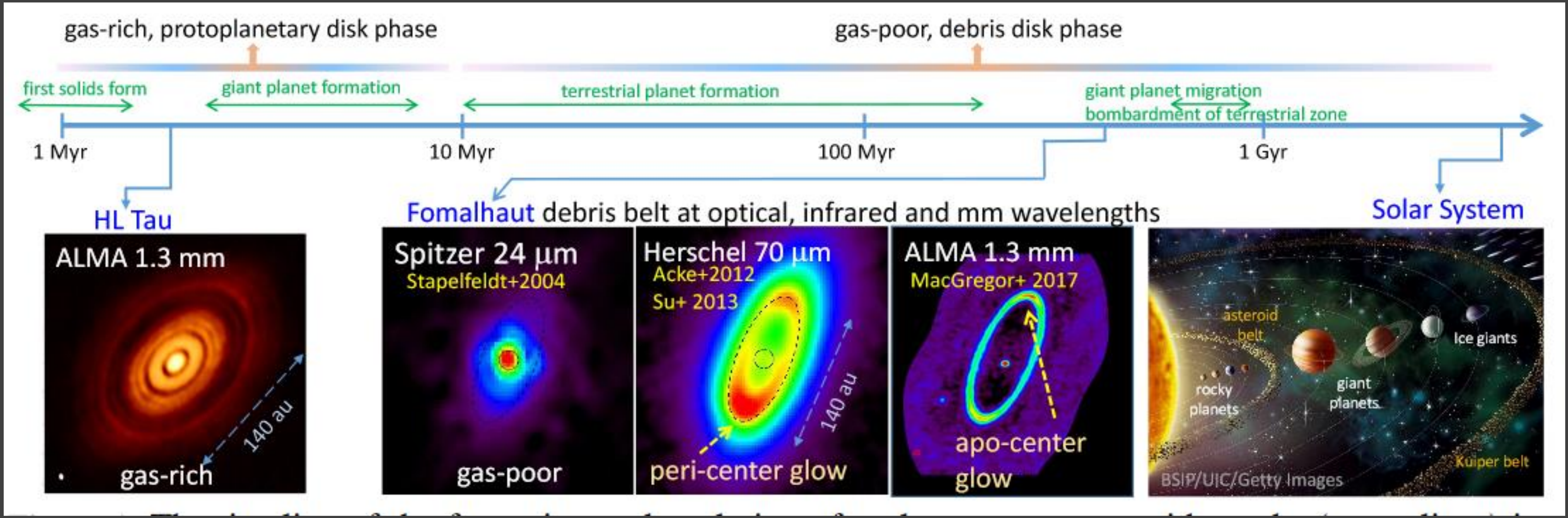


To become giant planets have to grow fast
as they need also to accrete gas
within the lifetime of the gaseous disc.

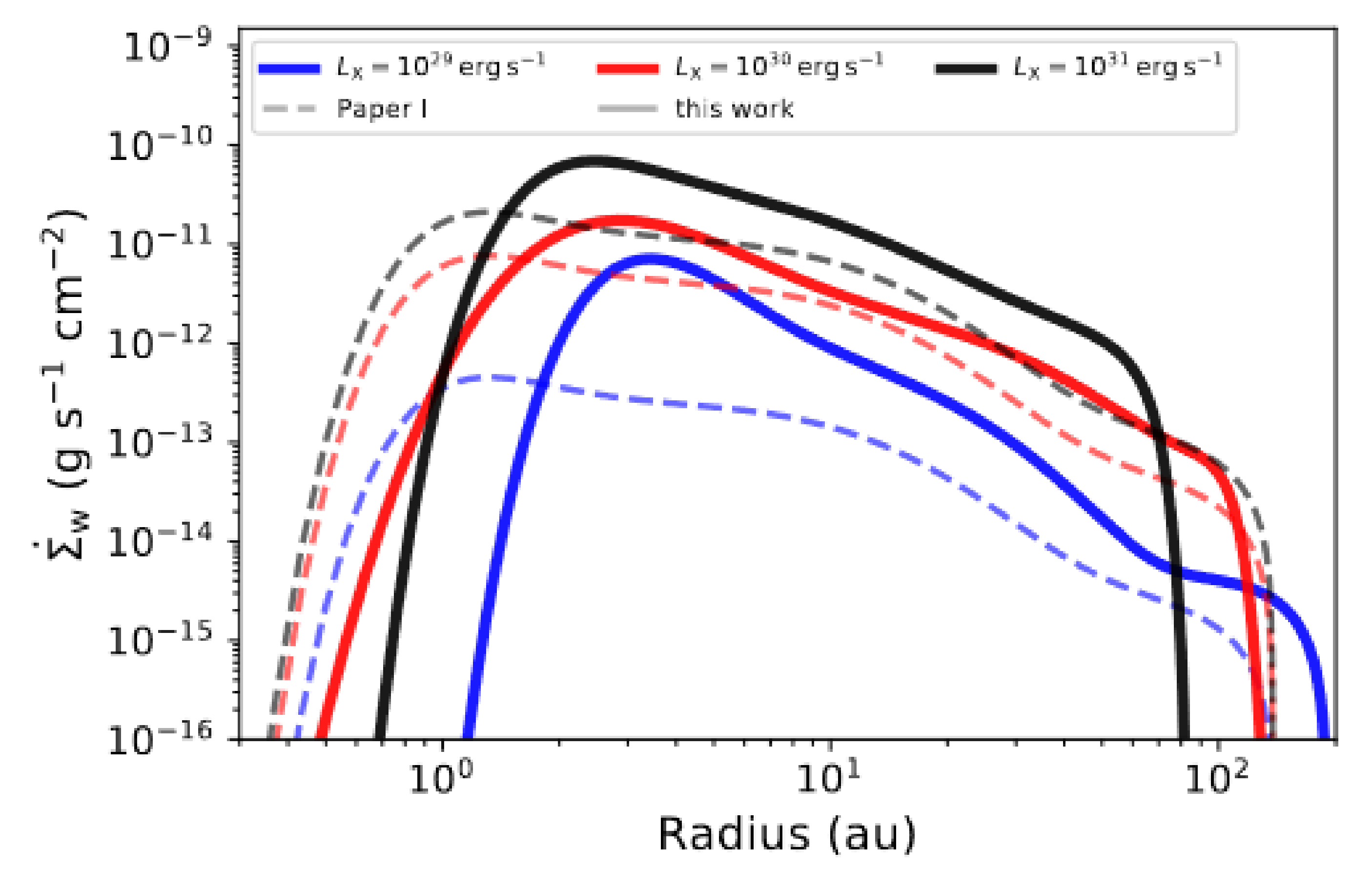
Fast growth is possible in the region of ice dust.

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

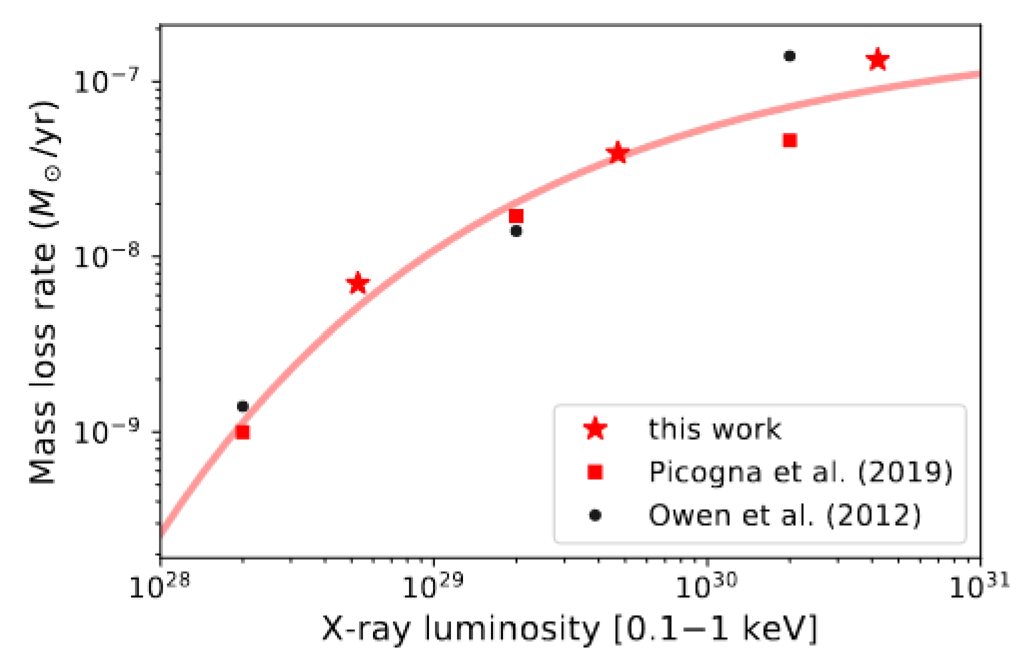
Protoplanetary and debris discs. Evolution



Photoevaporation



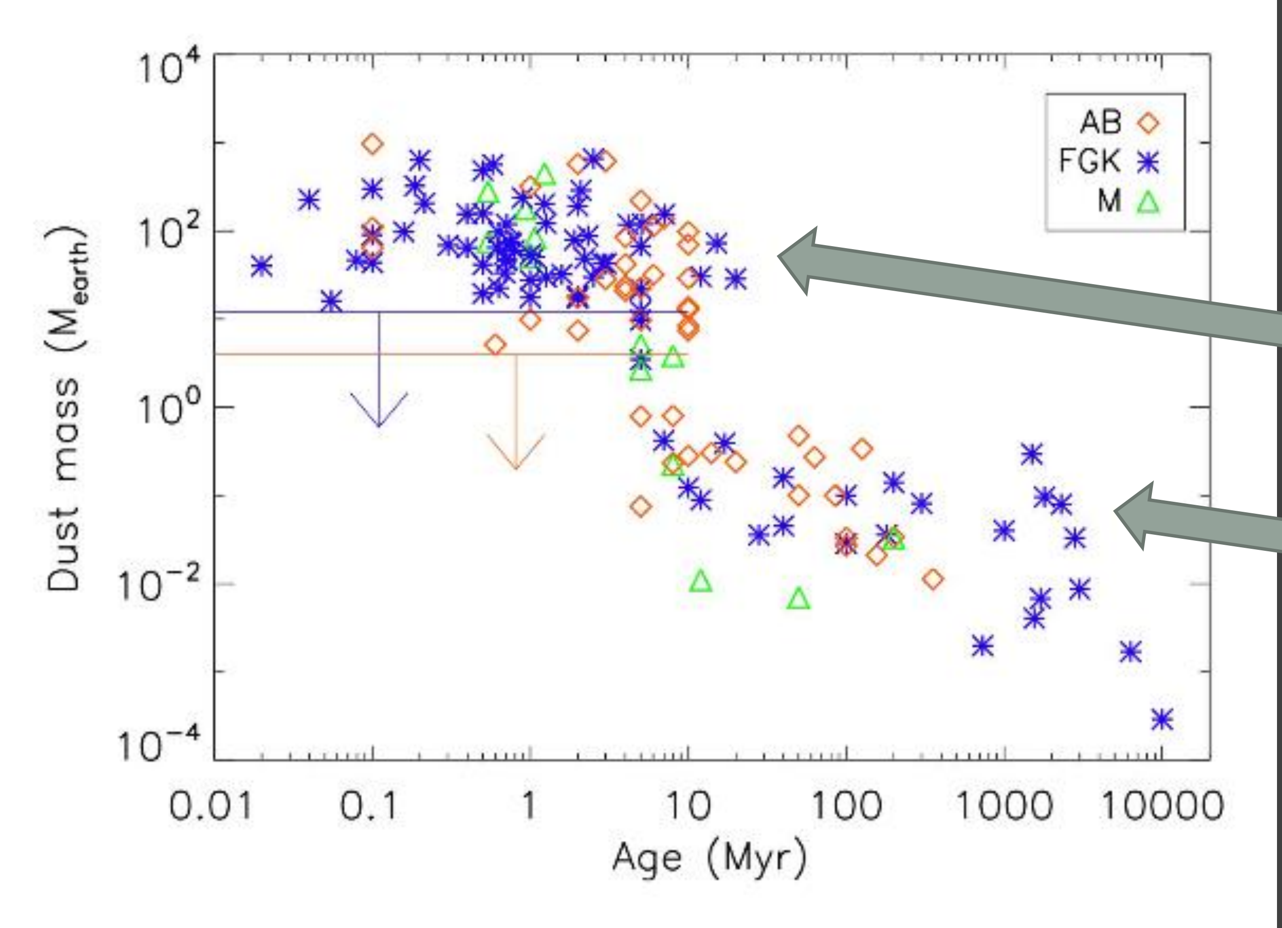
Gas is lost from the disc mainly due to X-ray and UV emission of the central star on the time scale ~few Myrs.



2109.04113

See 2204.09704 for some recent discussion

Evolution of the dust mass in discs

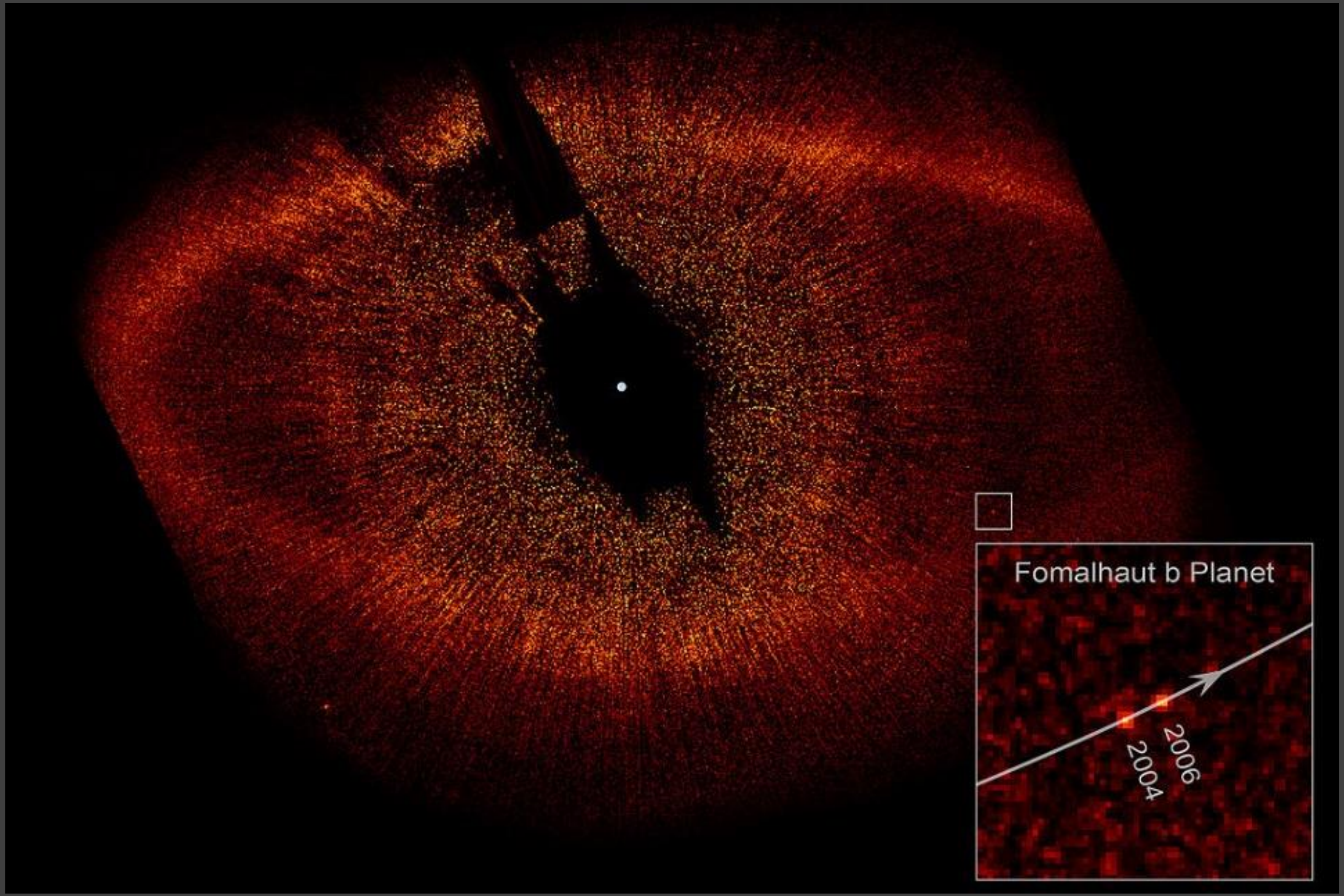


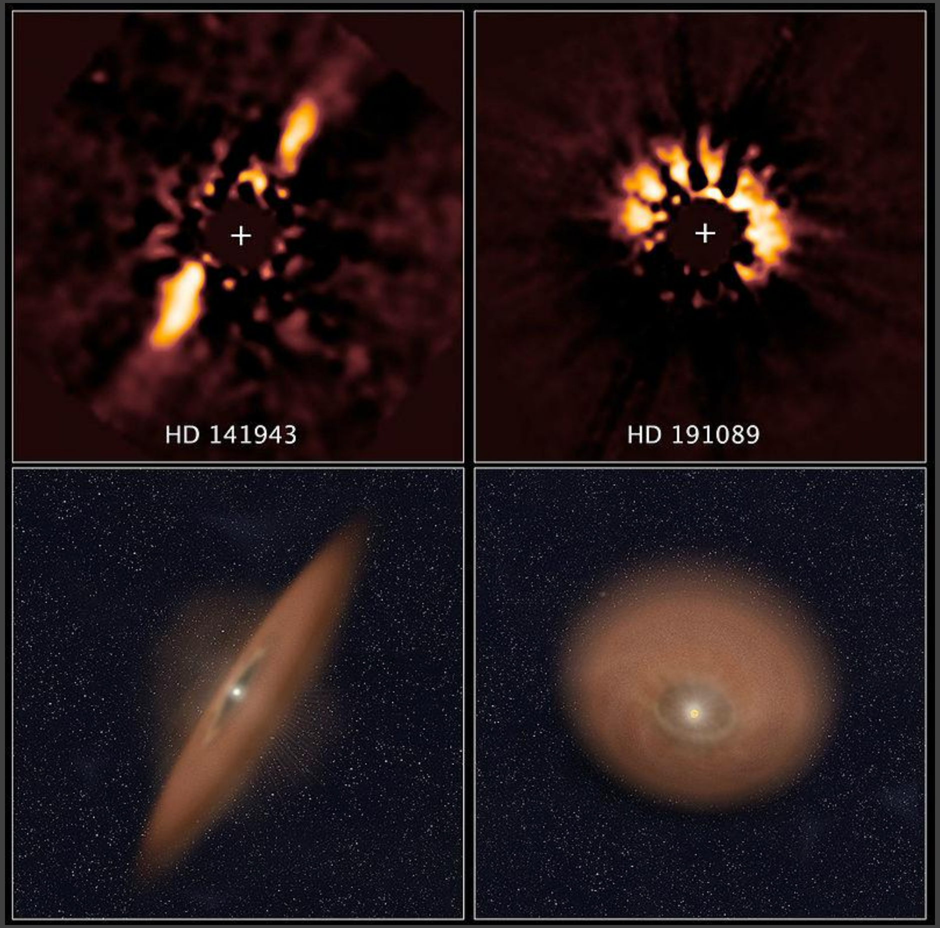
Protoplanetary discs

Debris discs

Panic et al. 2013, taken from the review 1703.08560

Debris discs





See a review in 1802.04313, 1804.08636, 2110.04319

About 100 are imaged now, 2110.04319

Failed future plans

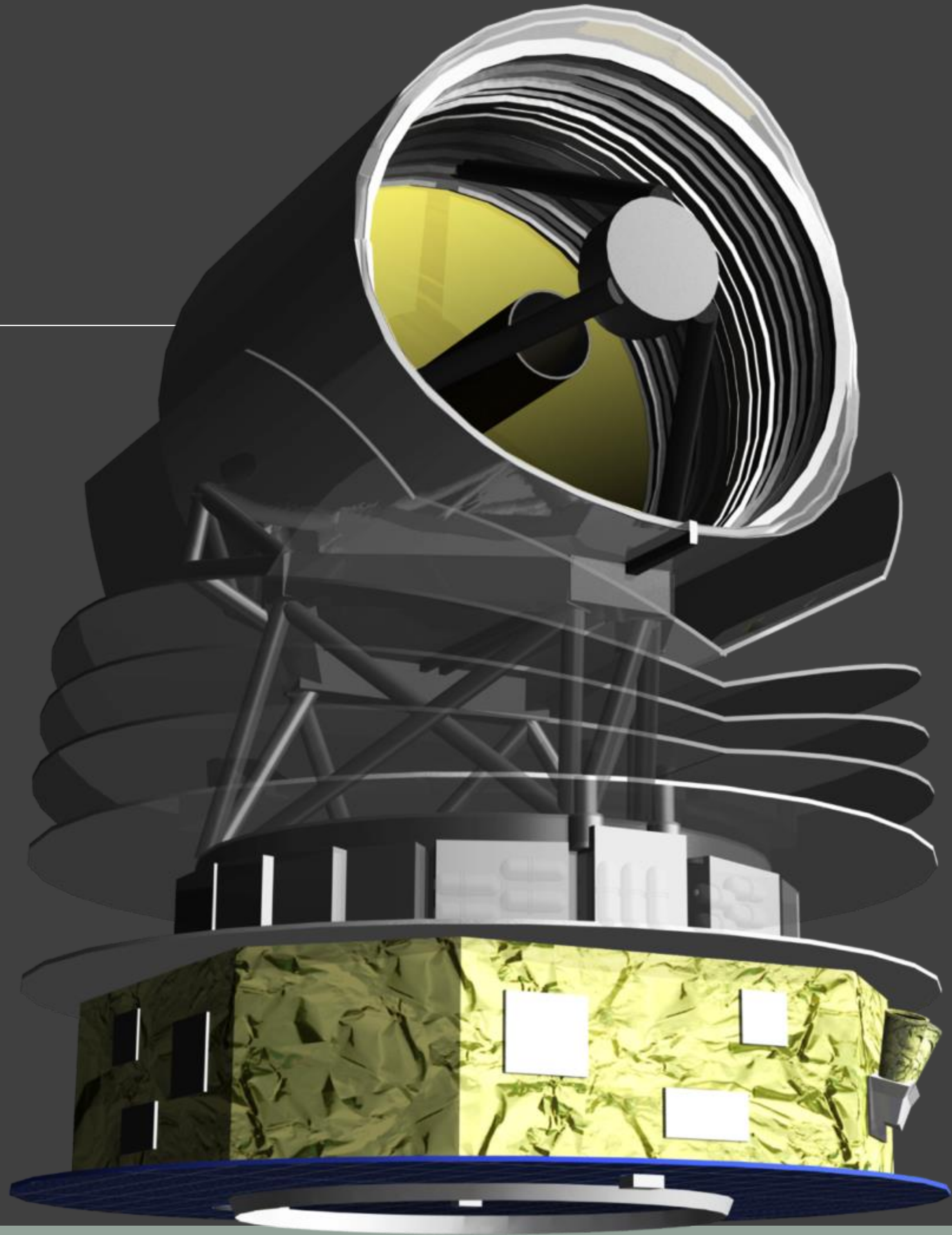
A major breakthrough could be achieved with the launch of *Spica* in 2032. This was a joint project by ESA and JAXA.

Now ALMA give an important contribution.

In near future – WFIRST (Roman Telescope).

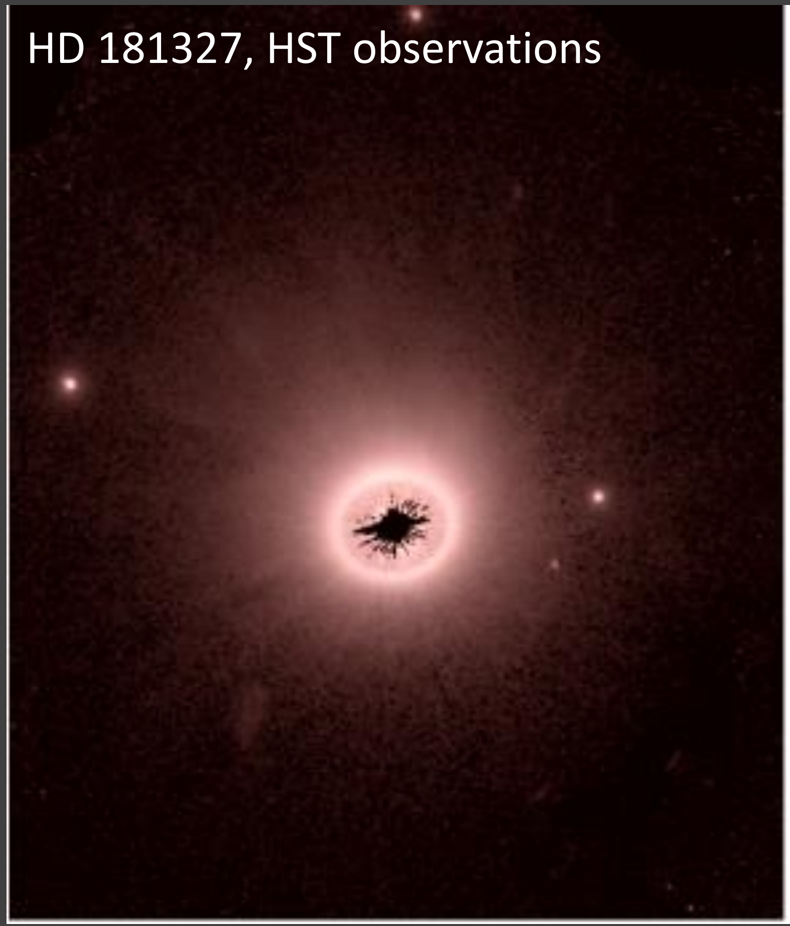
Space Infrared Telescope for Cosmology and Astrophysics (SPICA)
2.5-meter telescope in L2.
Range from 12 up to 230 micrometers.

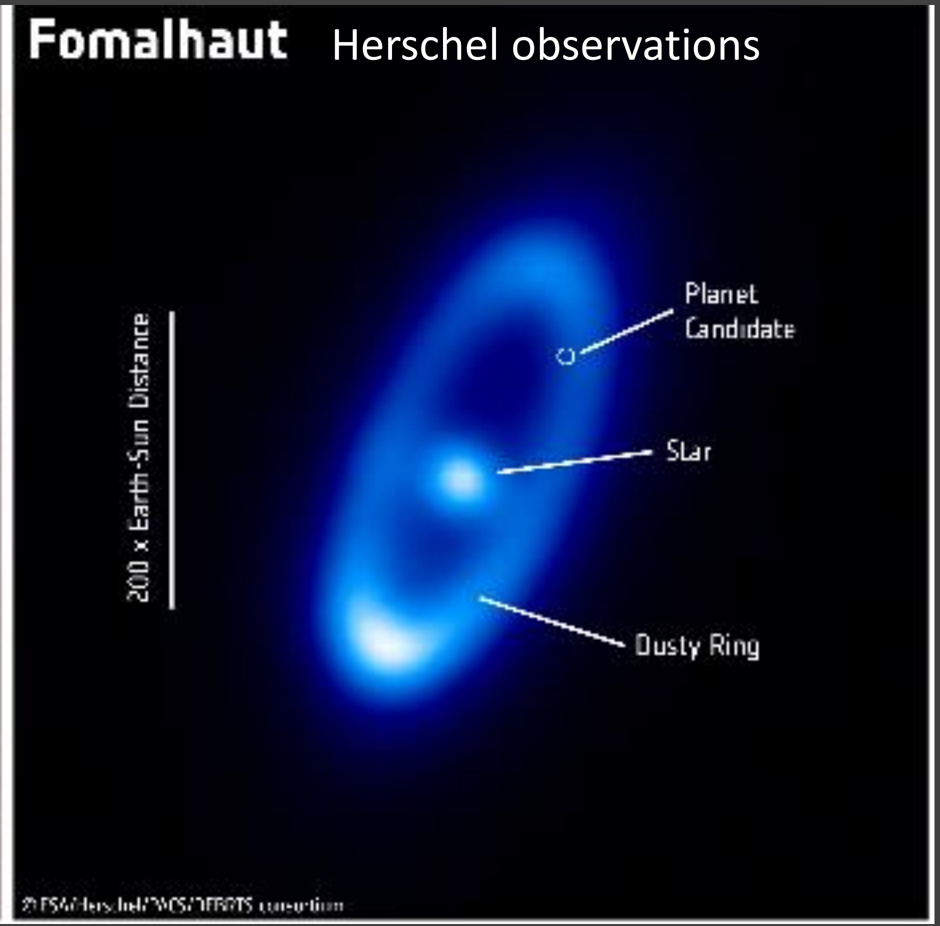
In 2020 the mission was stopped due to financial constraints.



JAXA / SPICA Team

Two debris disc examples

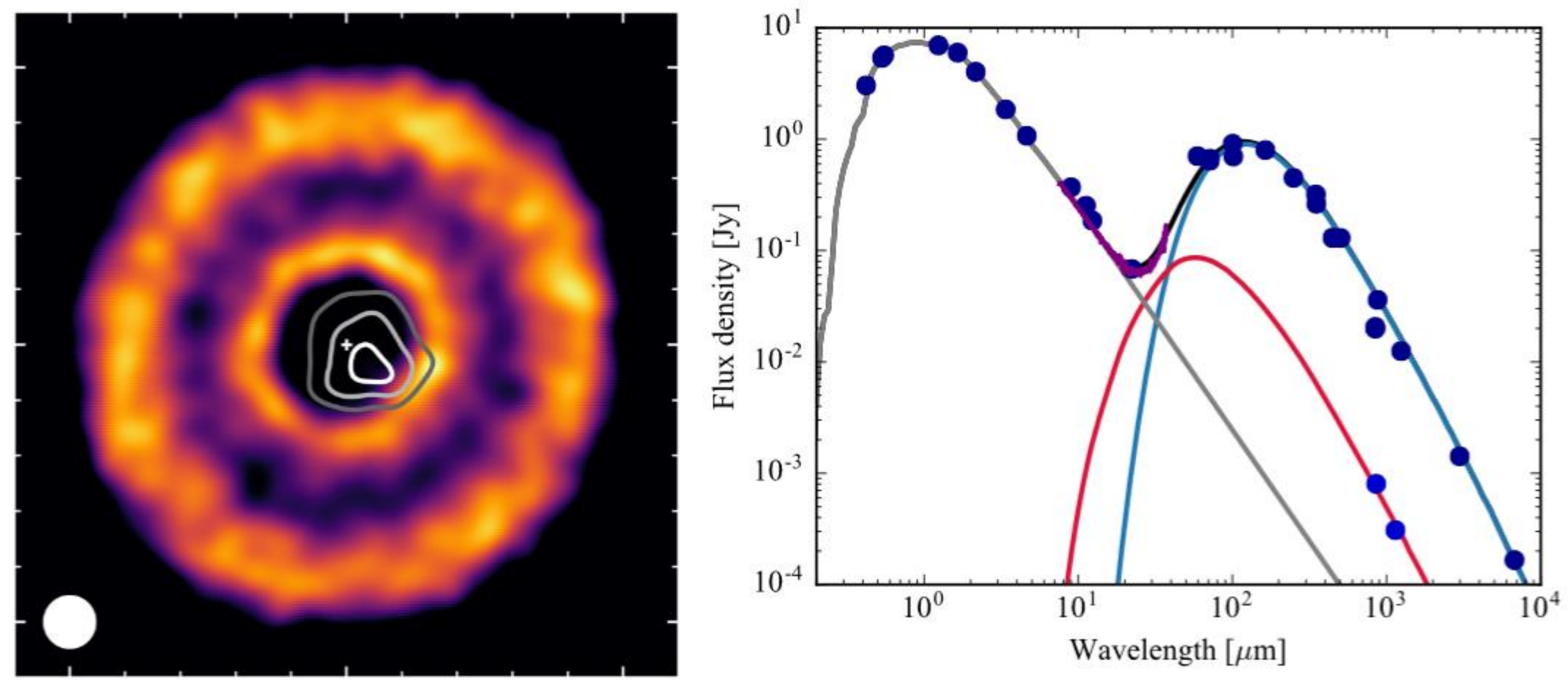




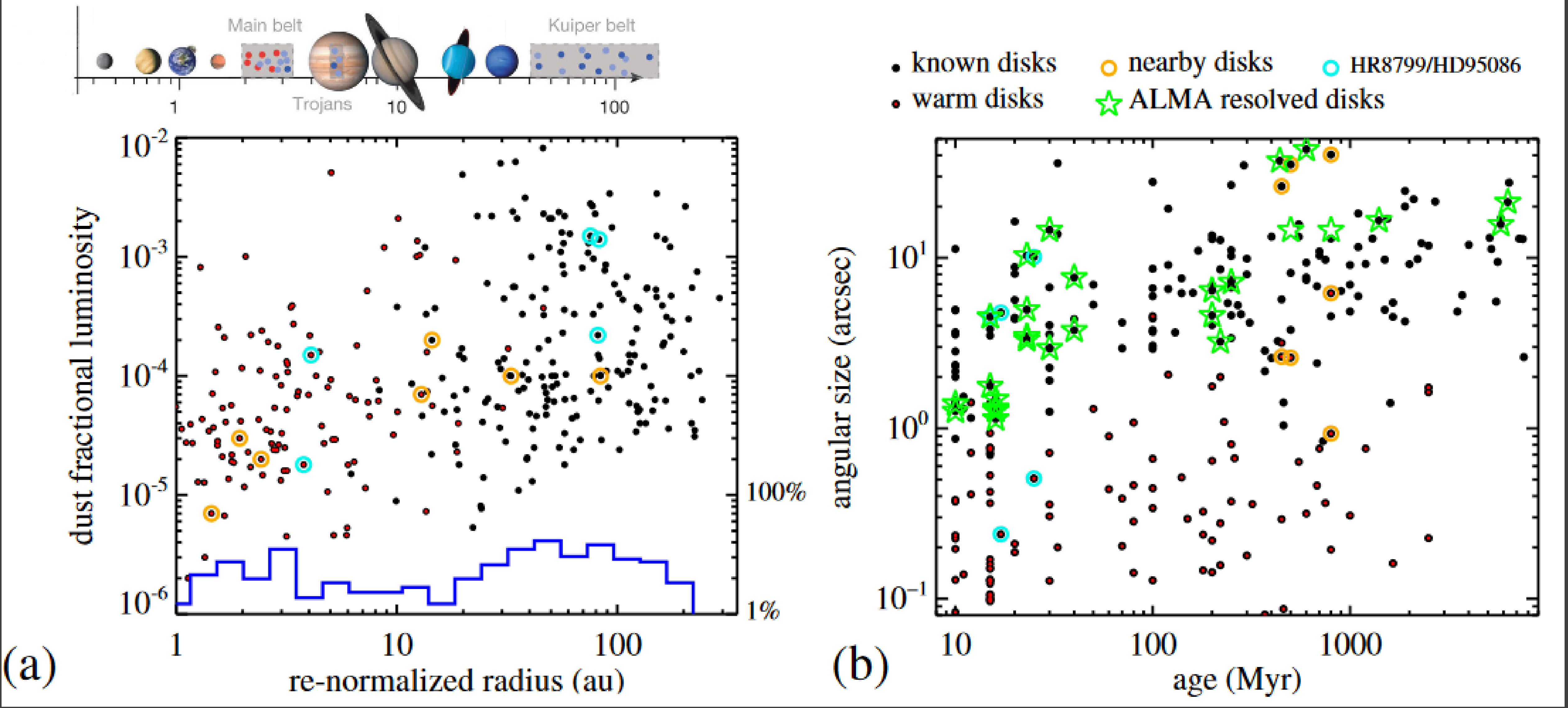
Hundreds of debris discs are known.

HD107146. ALMA observations

1804.08636

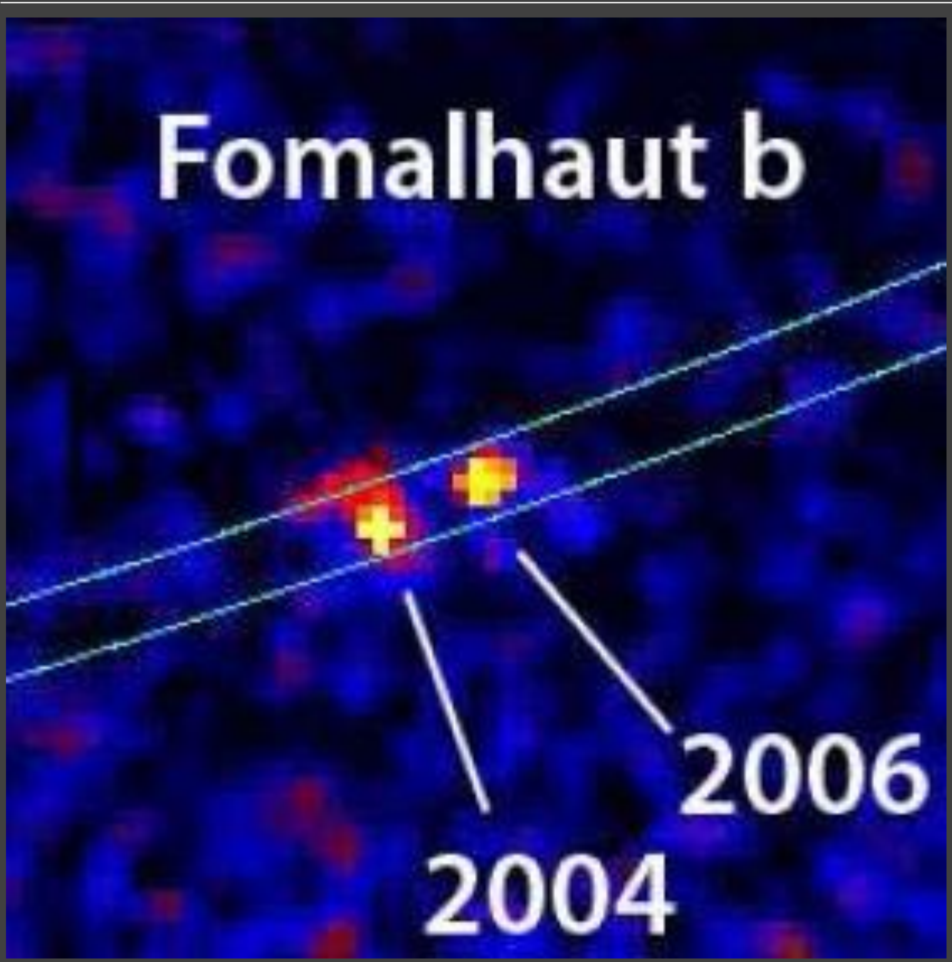


Debris disks are the dust disks found around ~20% of nearby main sequence stars in far-IR surveys.



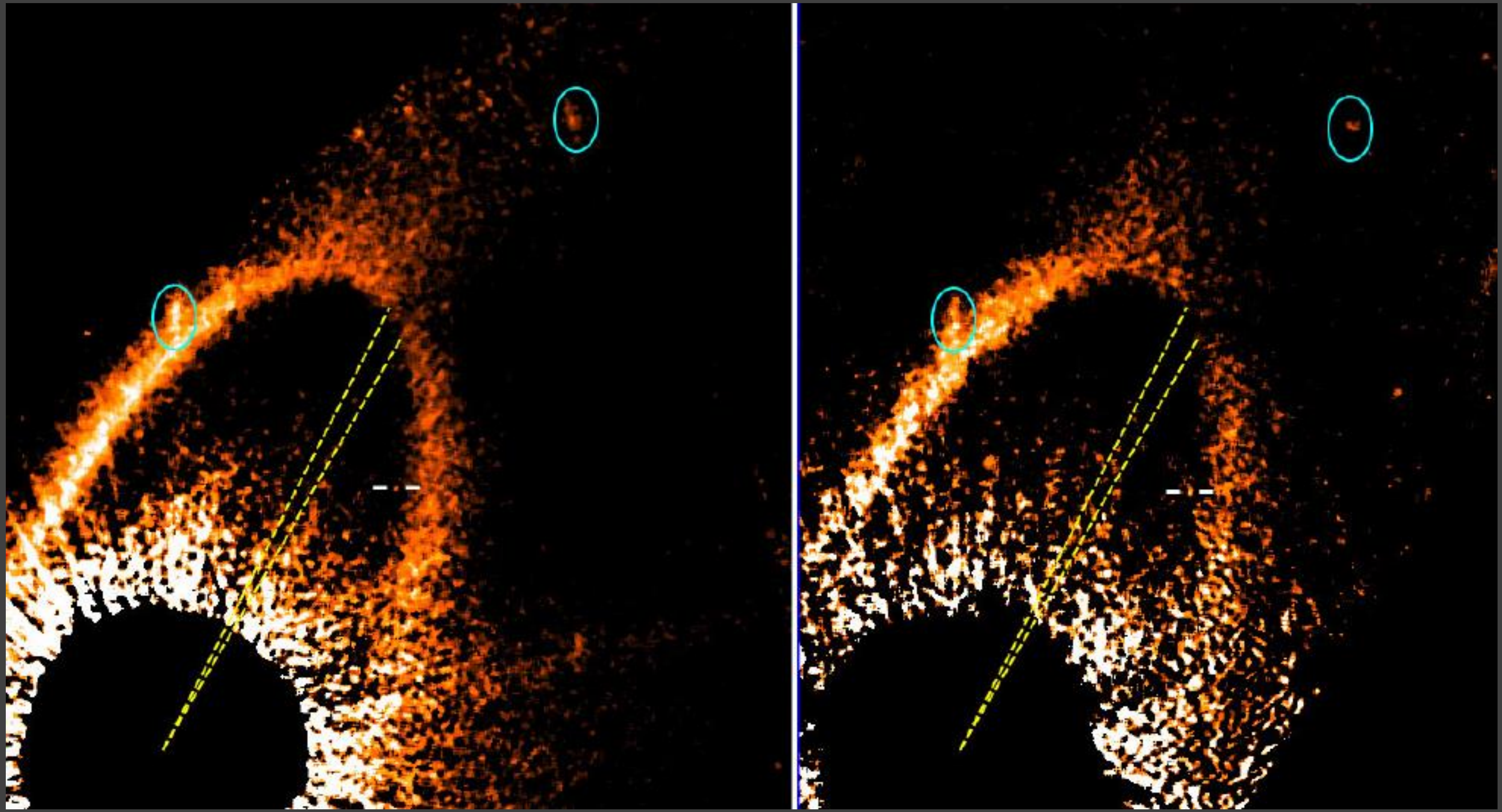
Debris disc sizes are renormalized with luminosity $\sqrt{L_*}$ to co-align snow lines.

Fomalhaut b



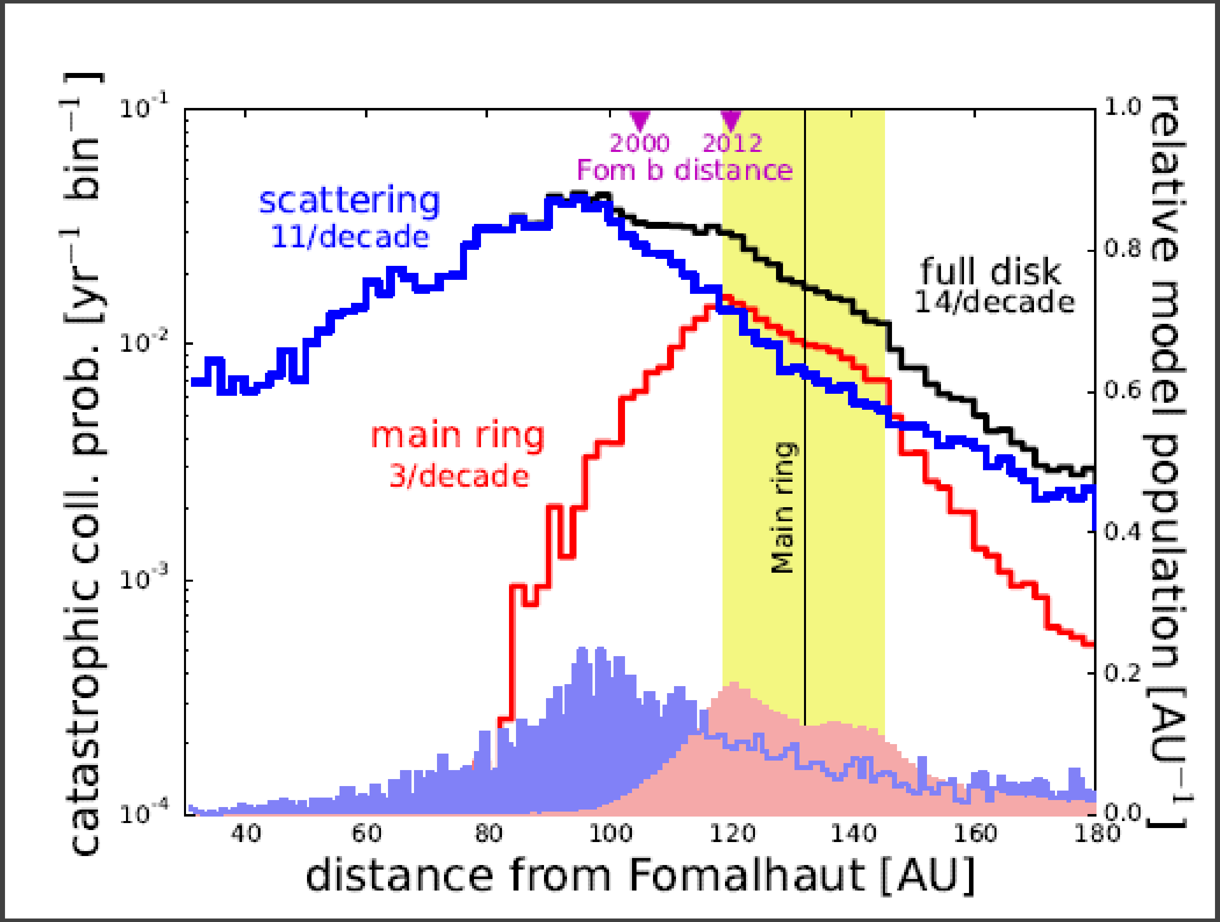
115 AU from the star

Is Fomalhaut b a real planet?



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

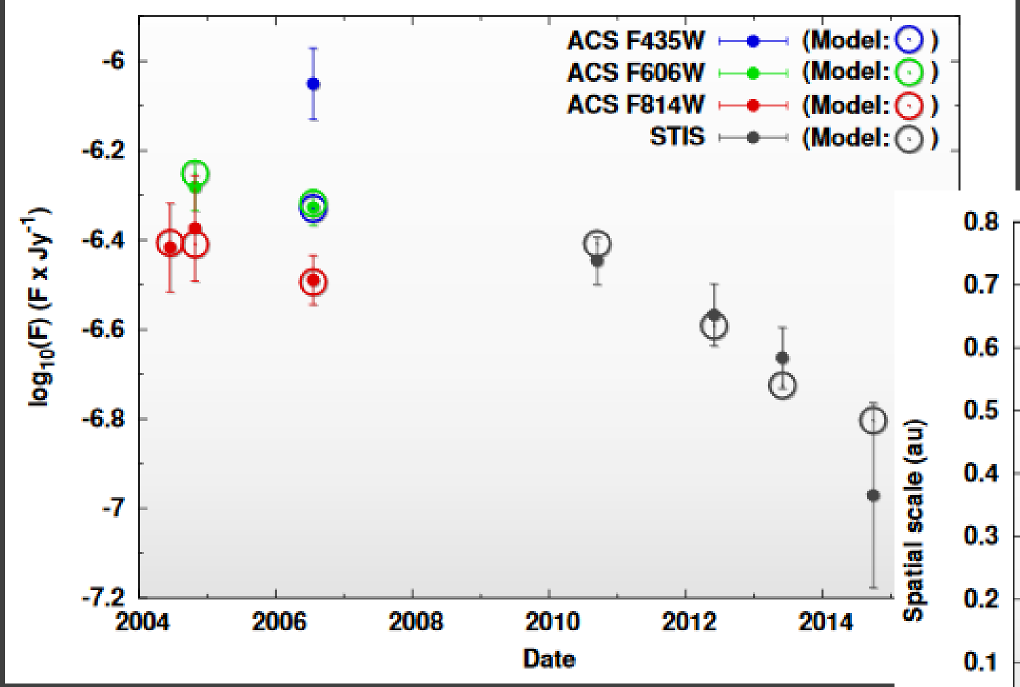
Result of a recent collision?

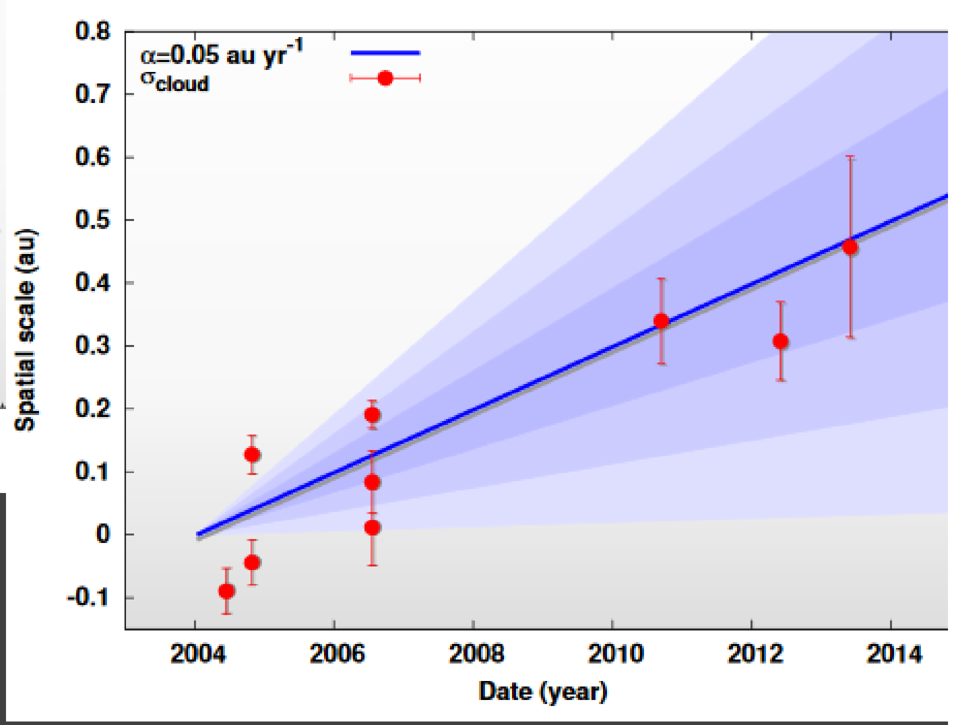


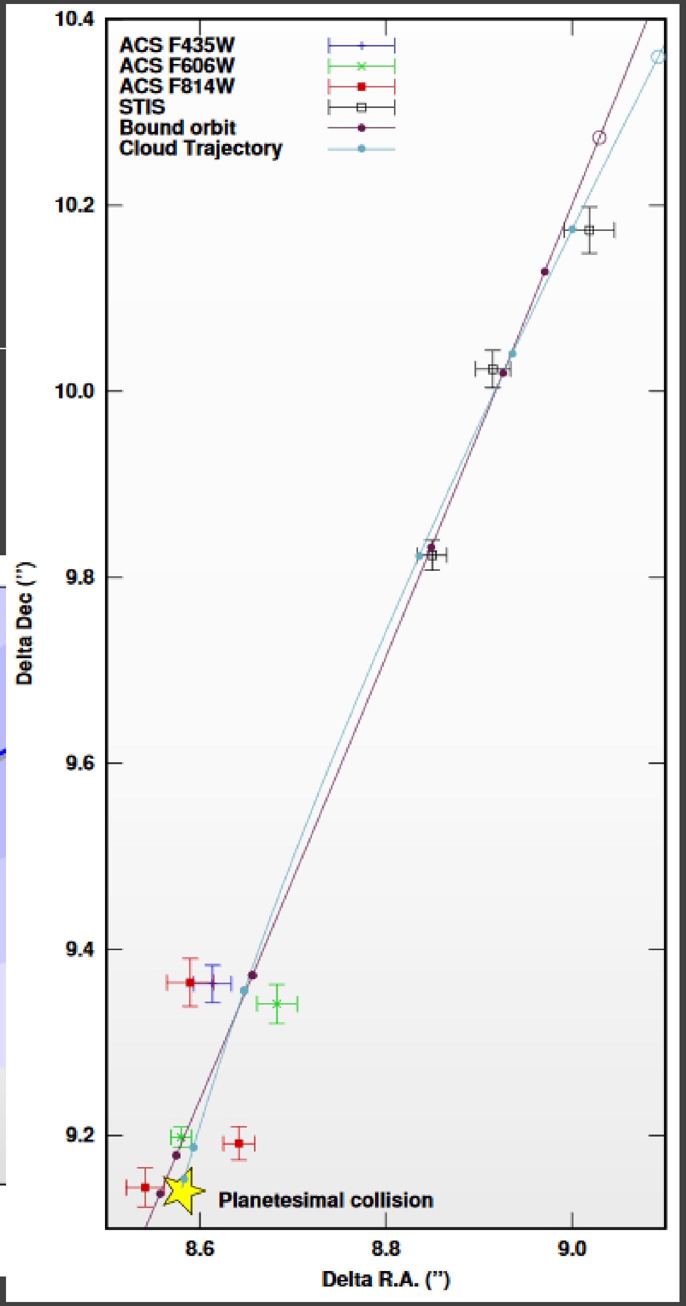
The object is situated in the region where collisions are very probable.

Two bodies with ~100 km size might be enough.

Collision is almost proved

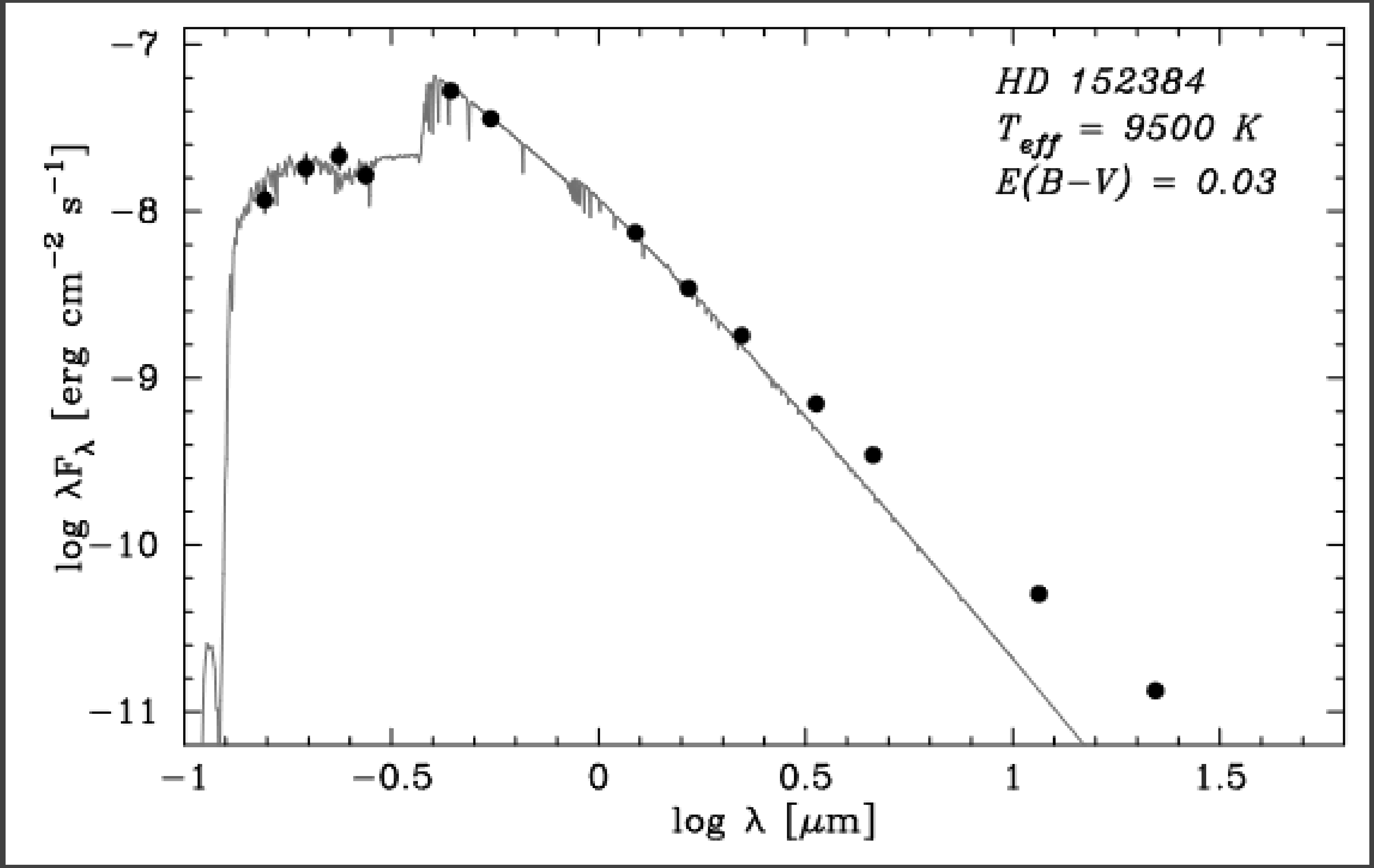






2004.08736

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.

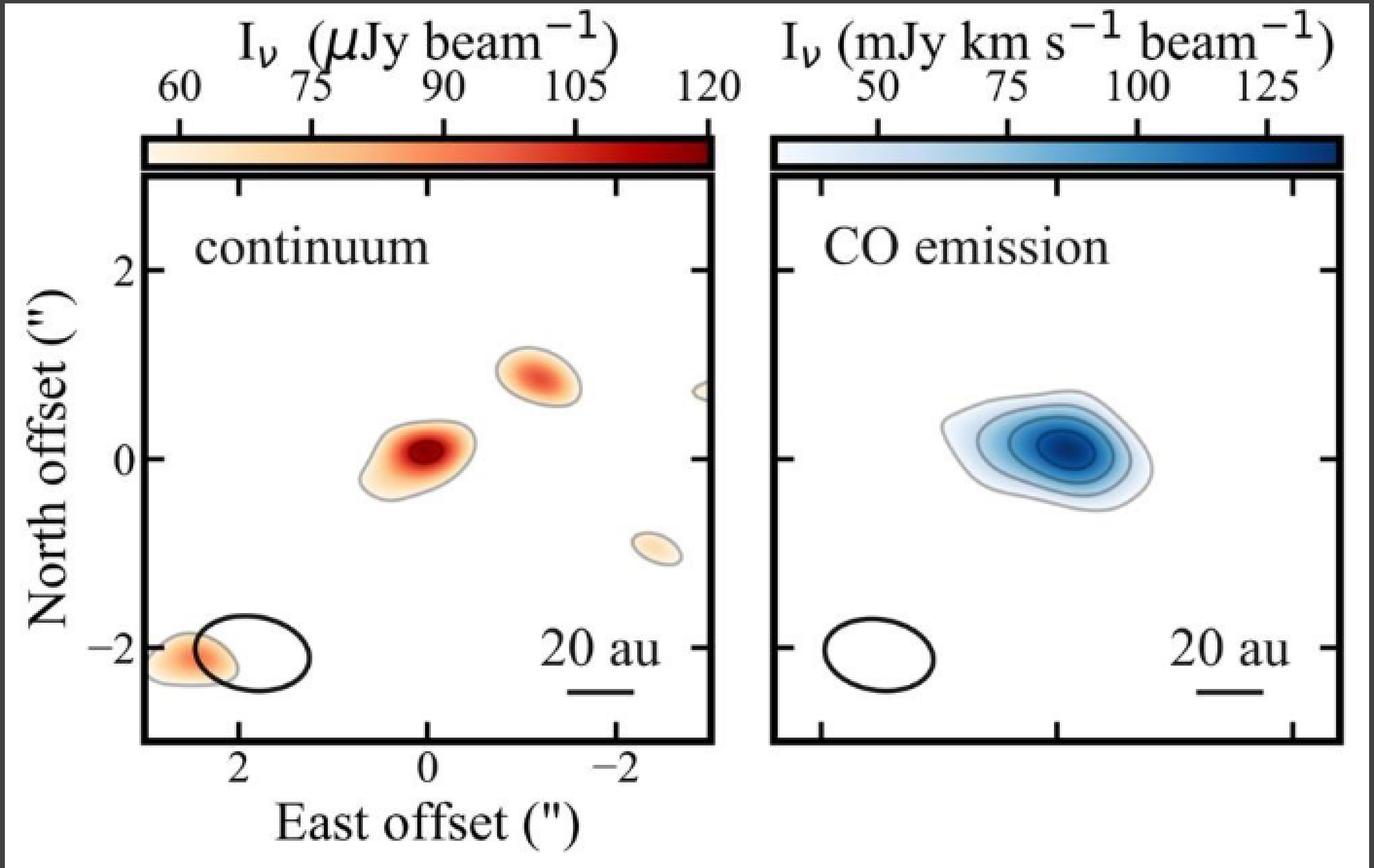
May be a result of collision of rocky planets.

CO observations confirm a giant impact

HD 172555, age 23 Myr

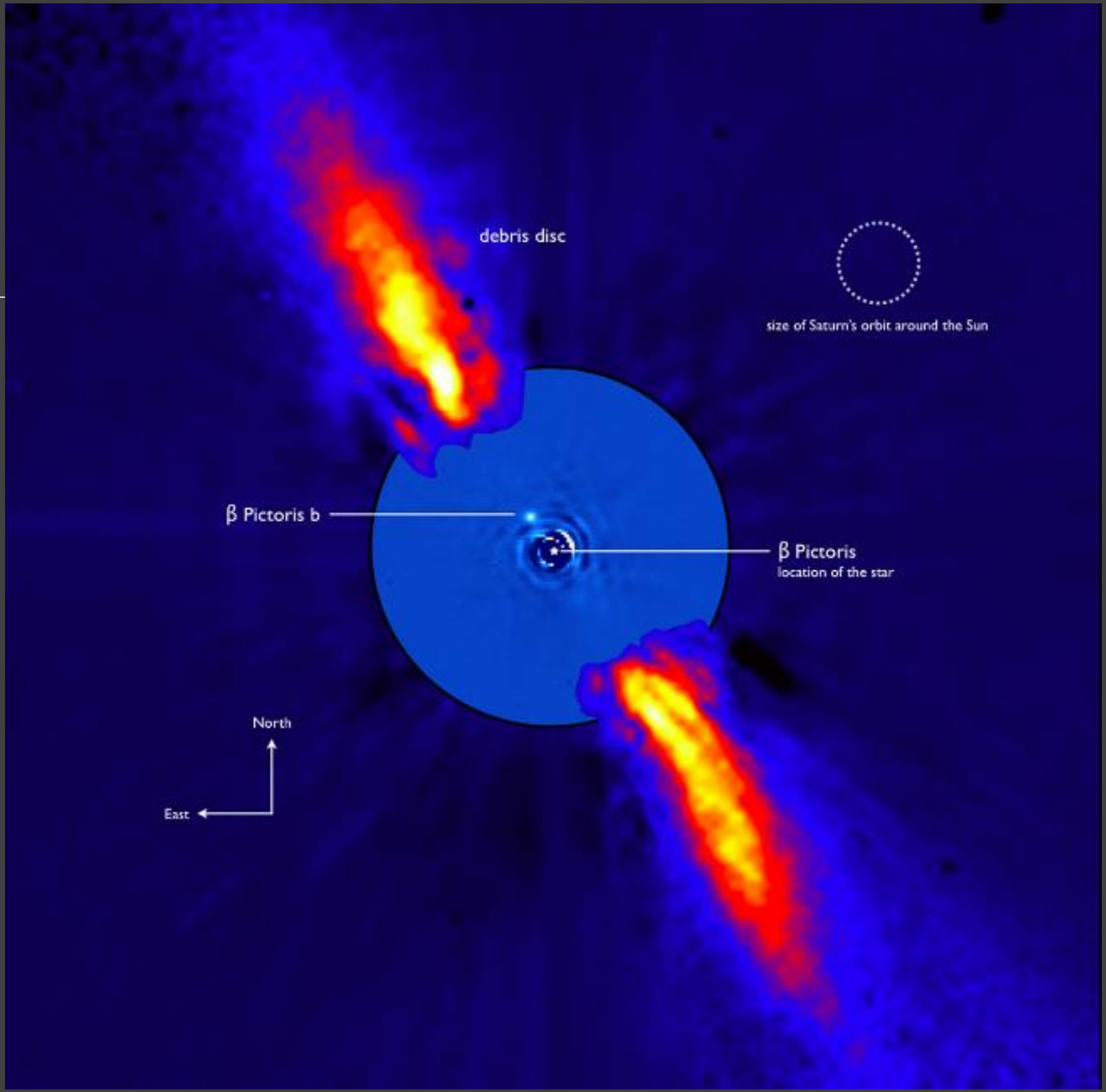
ALMA observations

CO is confined to a ring
of radius ~7.5 au and width ~3.3 au.

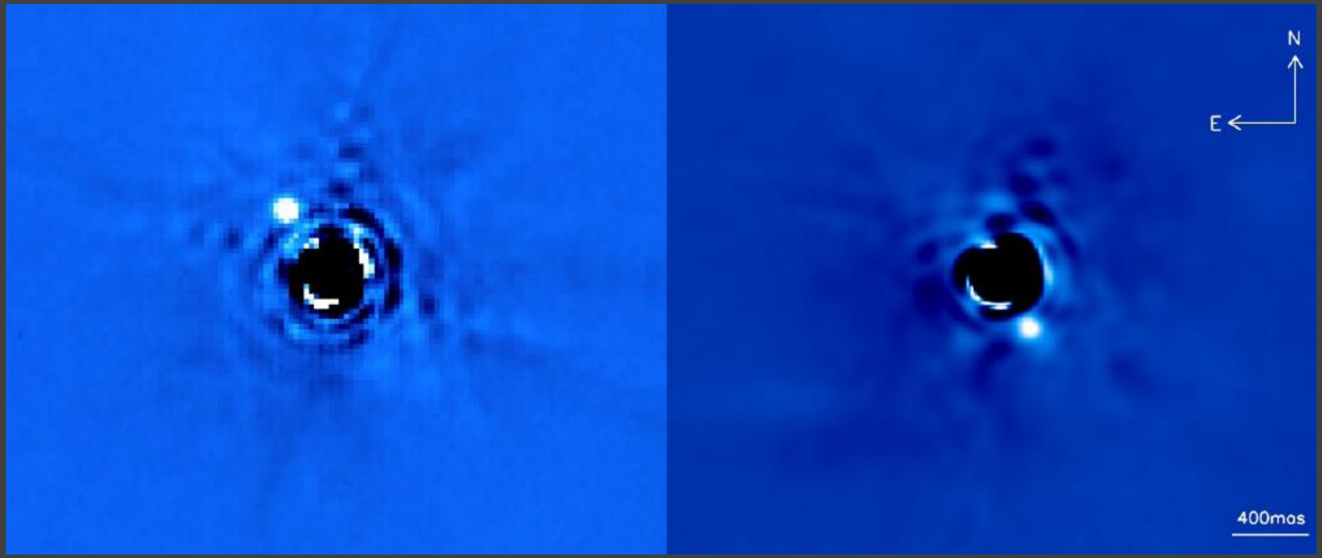


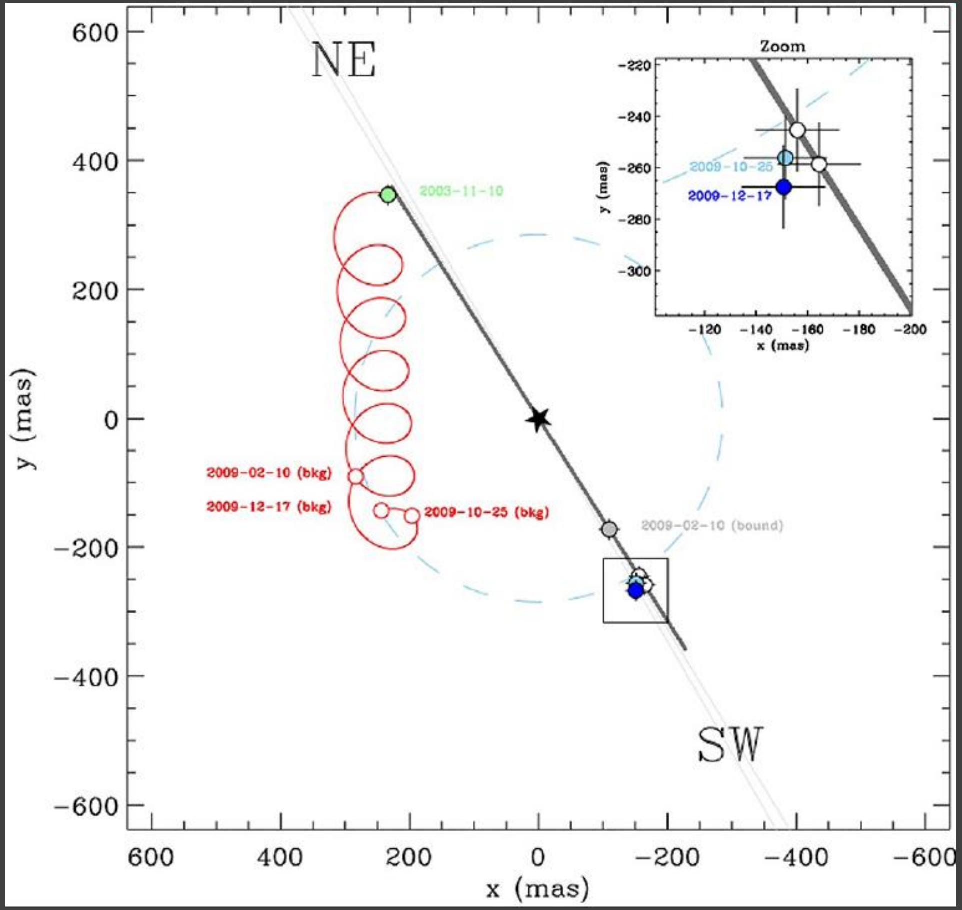
Beta Pictoris

Composite image obtained
by two instruments



Beta Pictoris





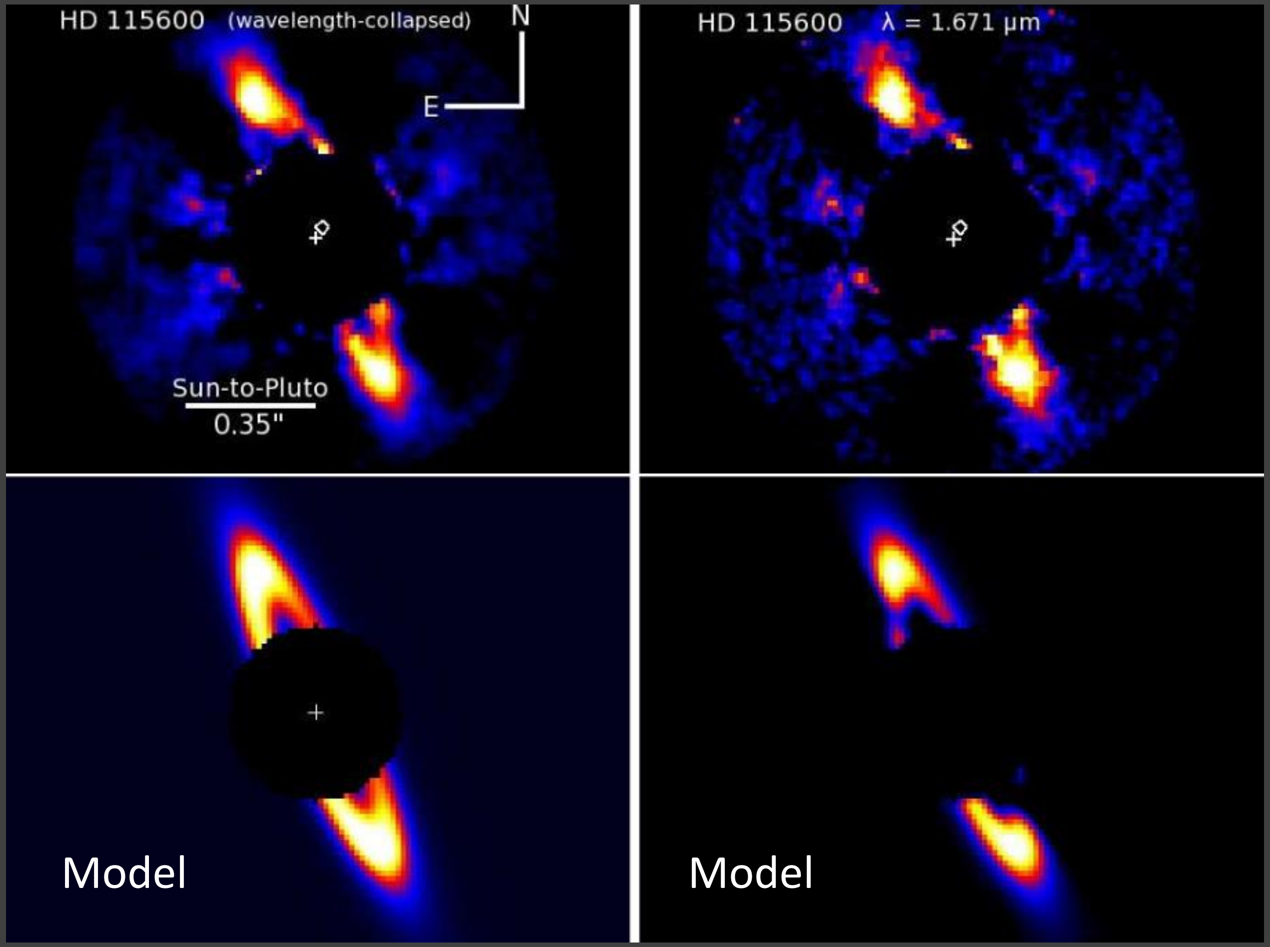
Age ~10 Myr
Distance ~ 9 AU

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



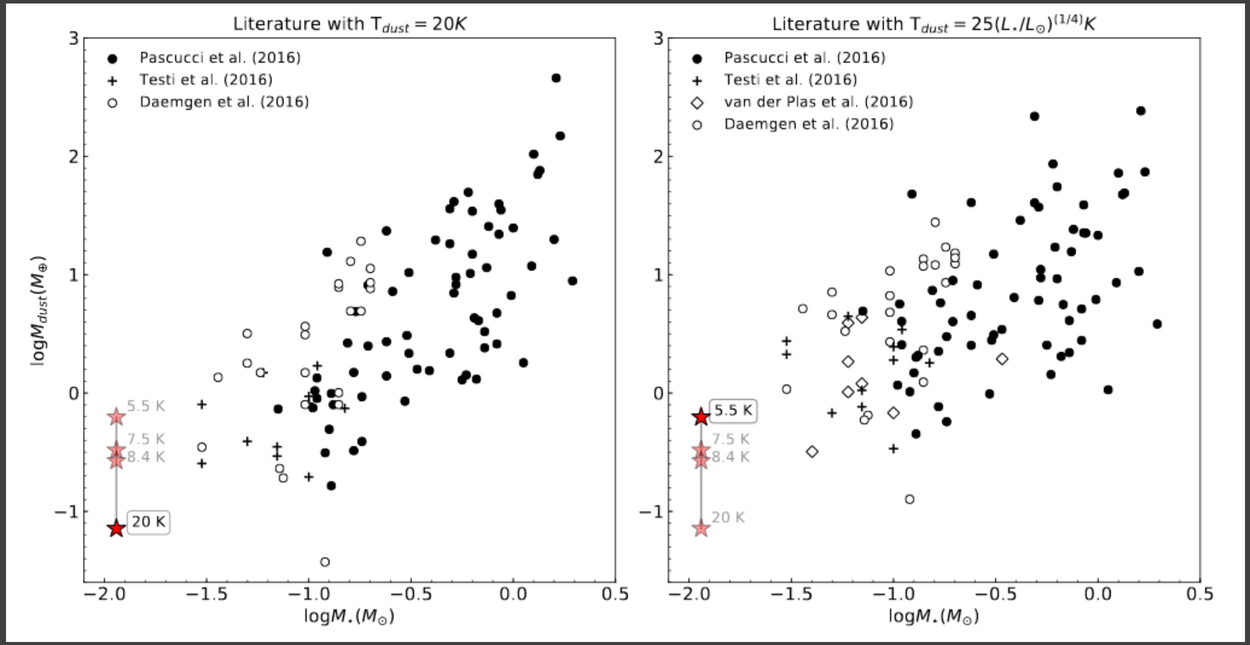
Disc around planetary mass object

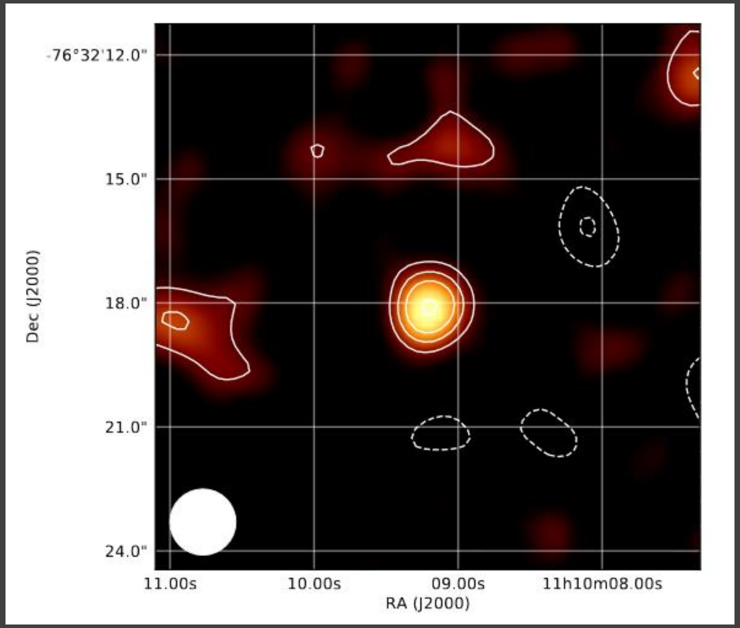
OTS44 is one of only four free-floating planets known to have a disc.
Mass ~12 $M_{jupiter}$

IR excess seen by Spitzer and Herschel

ALMA observations

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



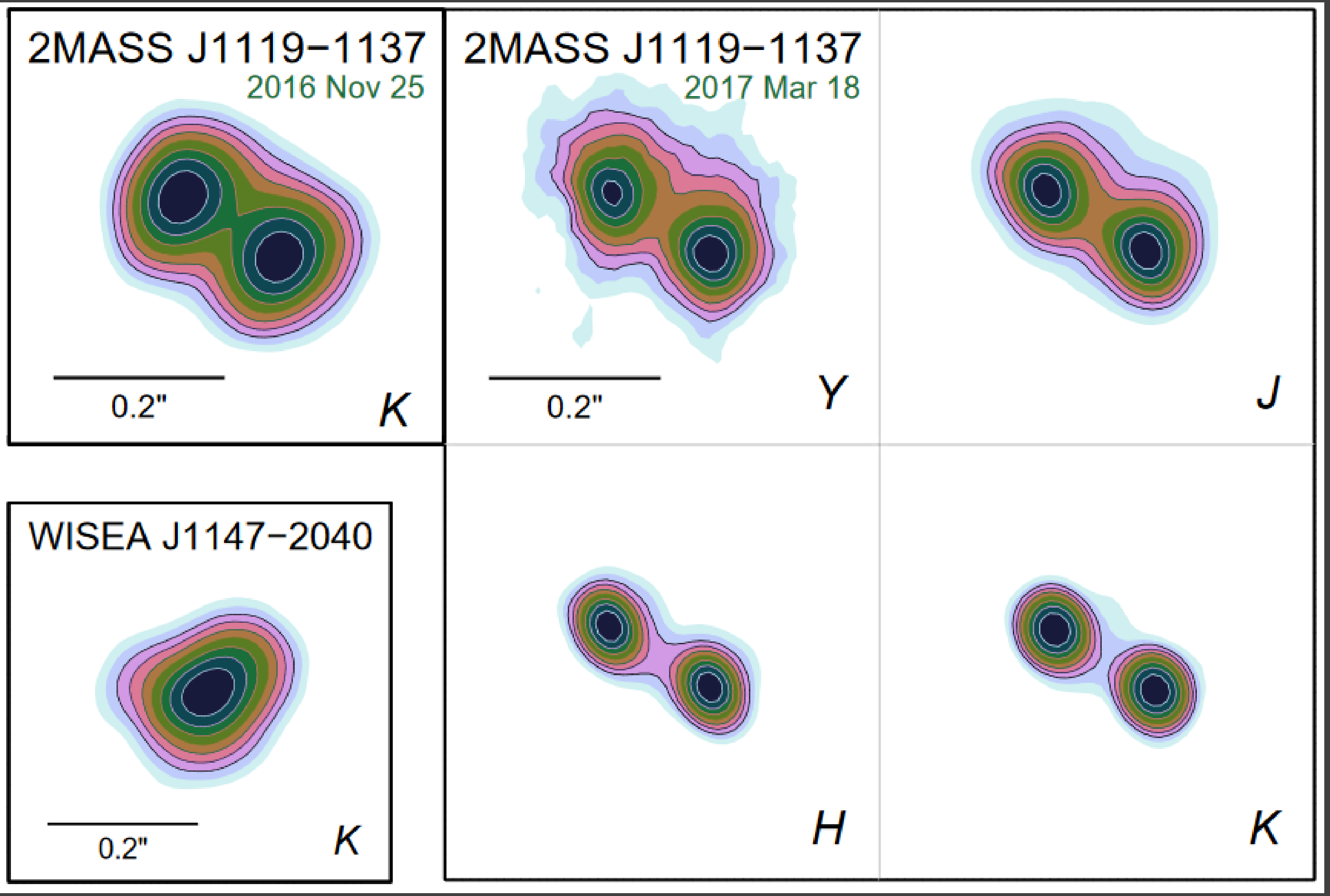


A brown dwarf is a pair of planets

2MASS J11193254−1137466

Age ~10 Myr
20-30 pc

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



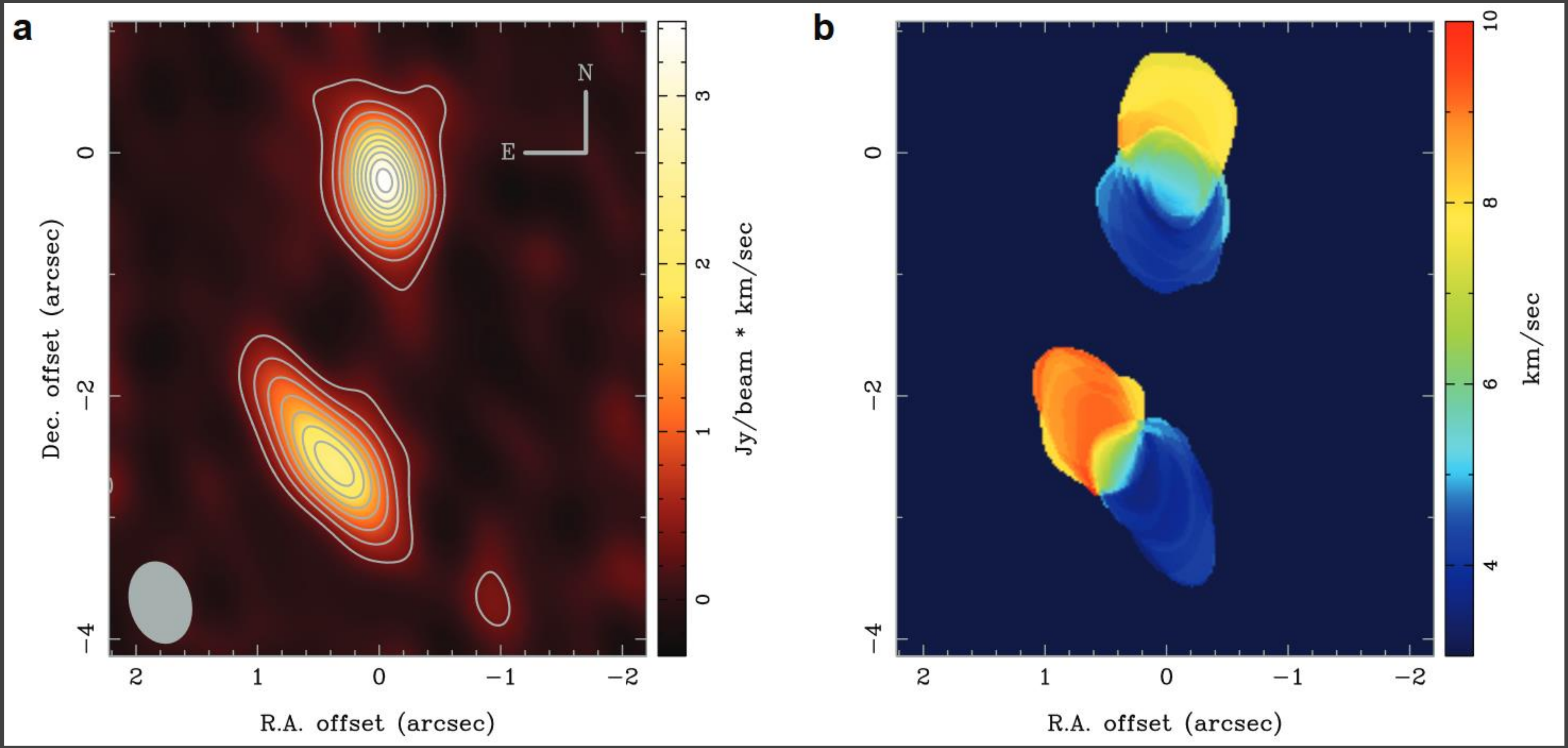
Protoplanetary discs in a binary system

HK Tau
161 pc

1-4 Myr

386 AU binary

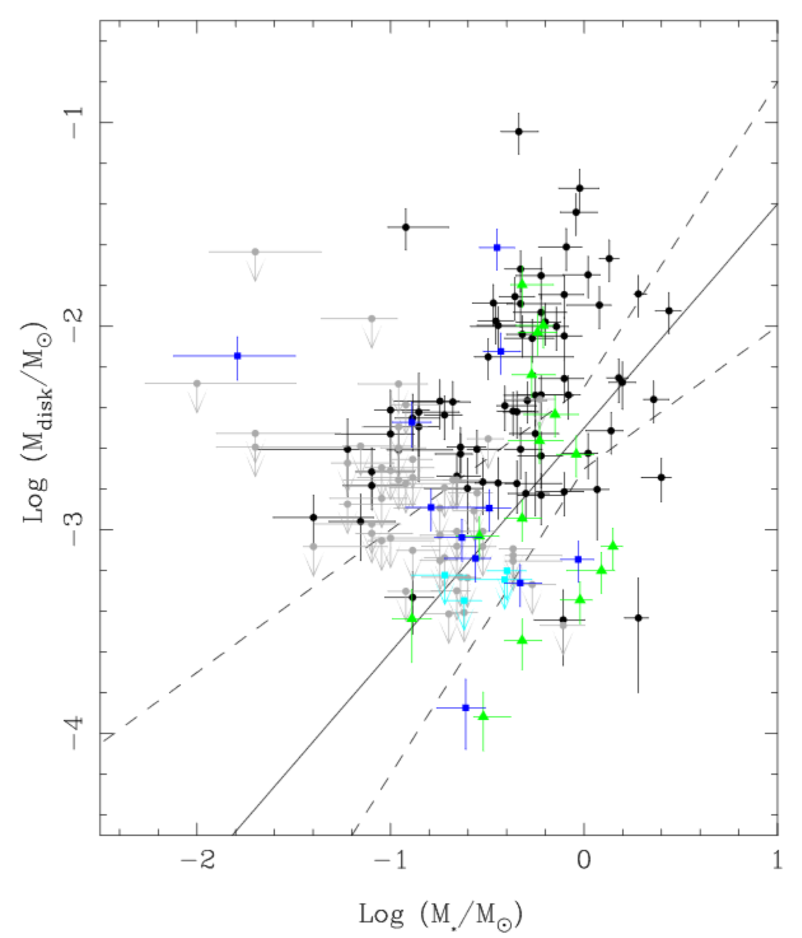
ALMA observations



1407.8211

Statistics of circumstellar discs in binaries

17 binary systems
100-1400 AU
ALMA observations

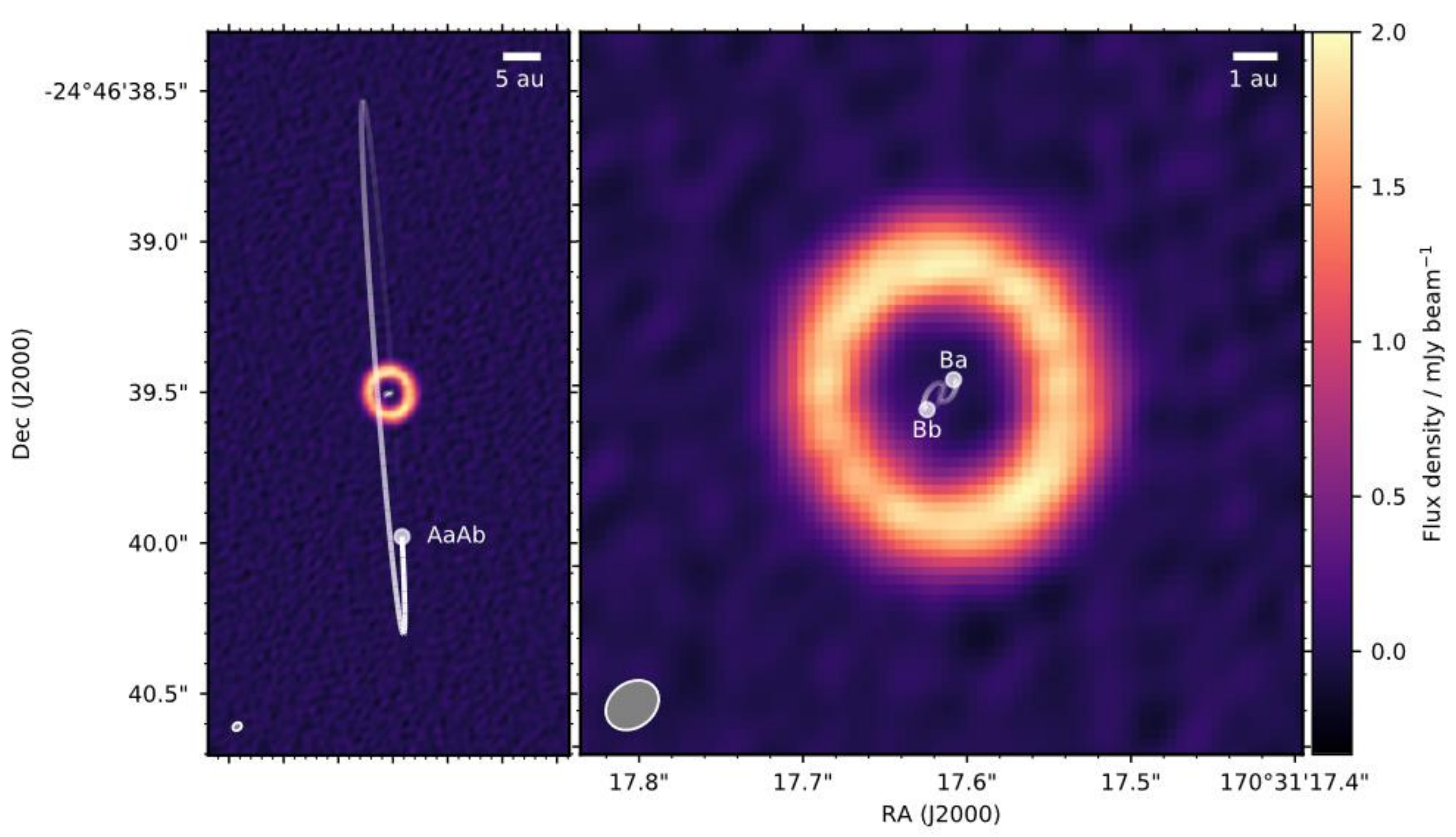


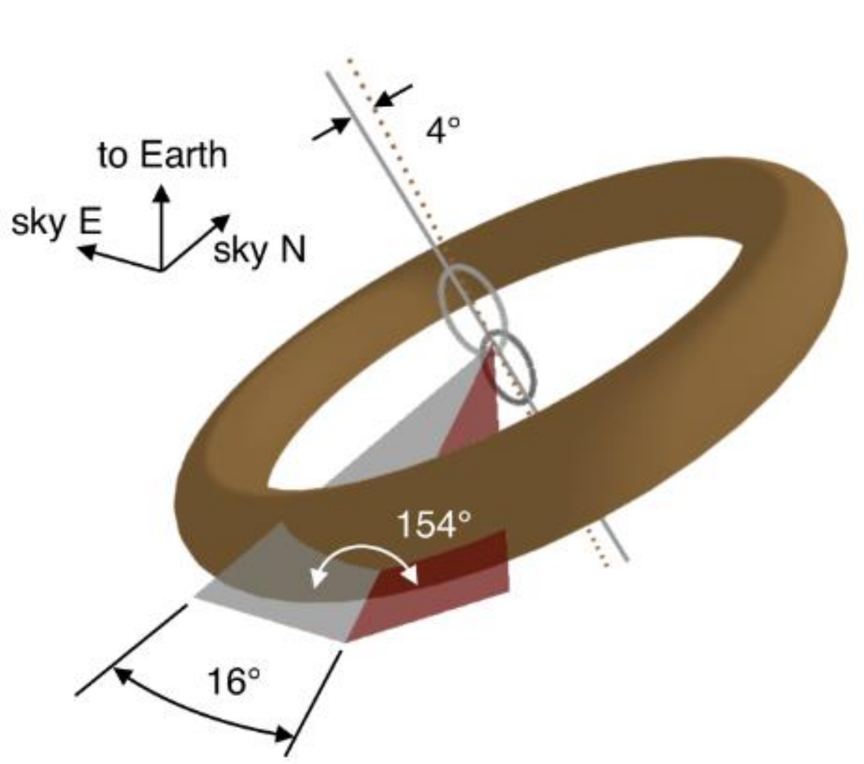
Green triangles – primaries;
Squares – secondaries
(dark blue – detected,
light blue – non-detected);
black dots – single stars
from other studies of the Tauris;
grey dods – single non-detections.

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

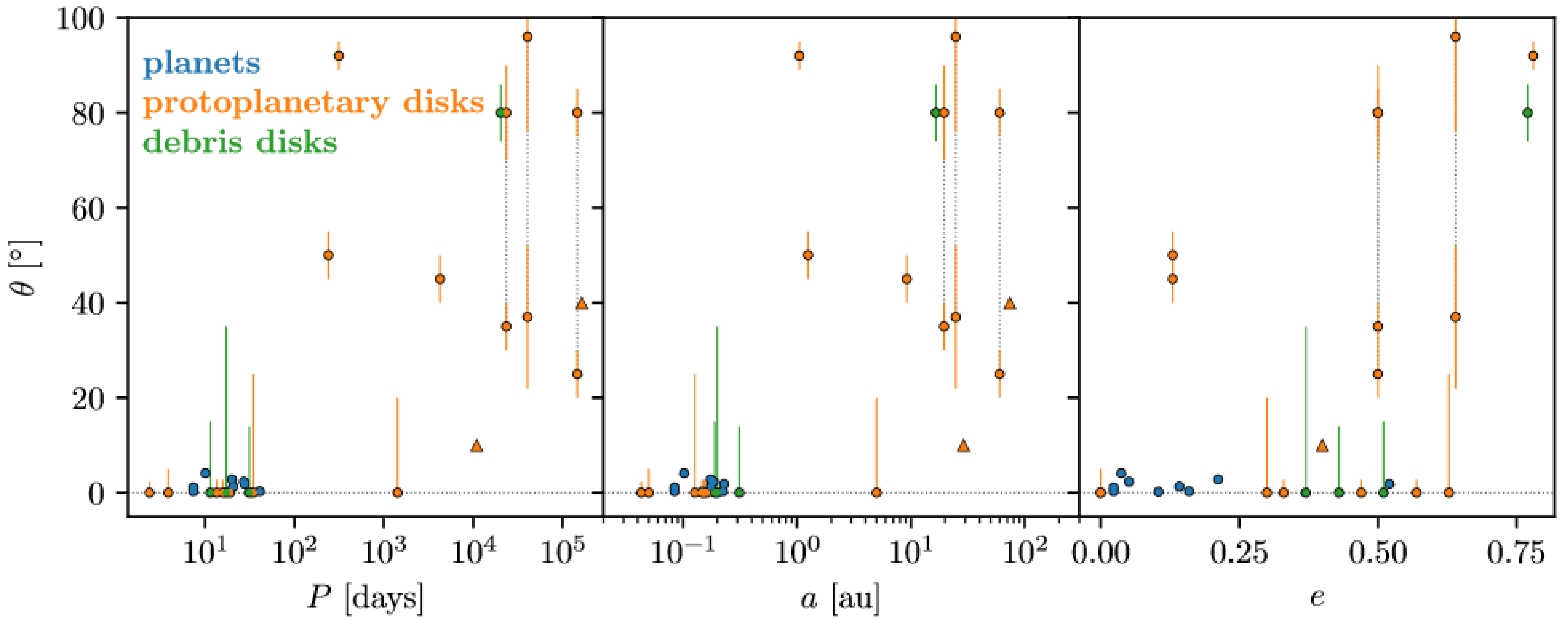
1402.5363, see more recent results in 1901.05029

A circumbinary protoplanetary disc in a polar configuration





Circumbinary discs are often inclined

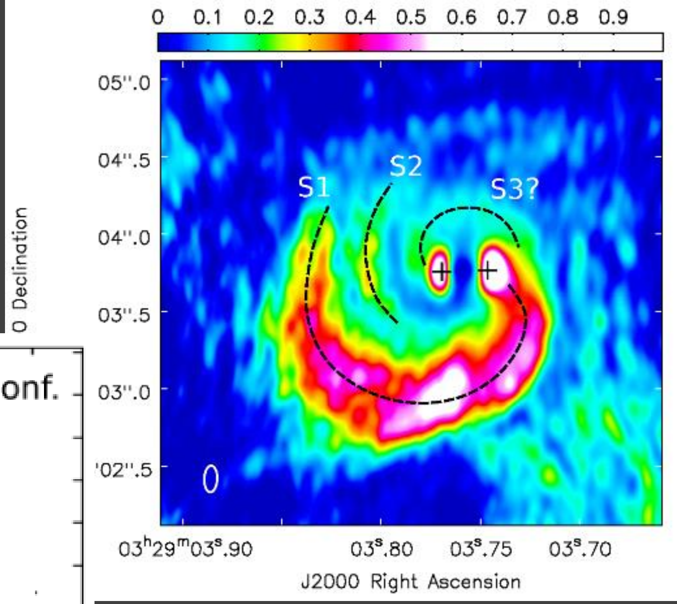


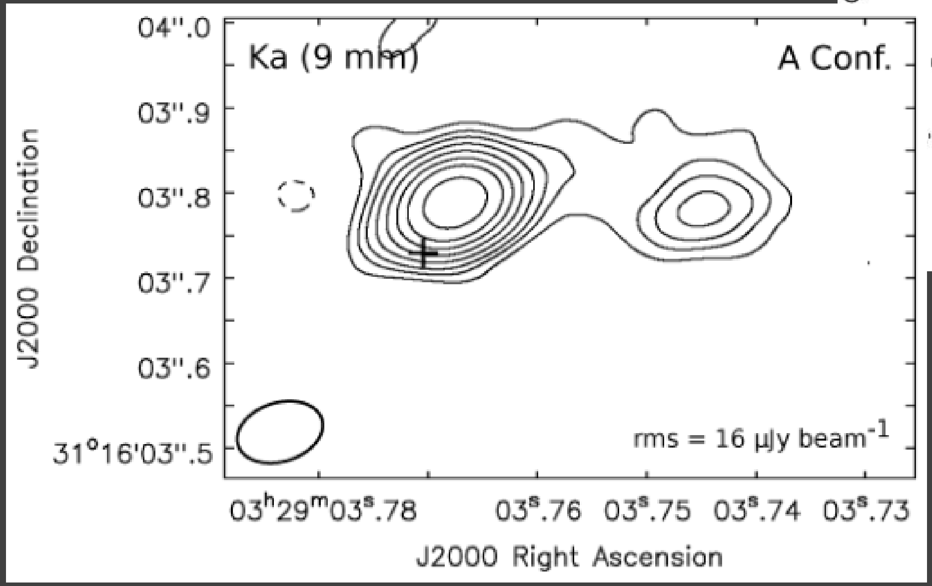
1906.03269

Circumstellar and circumbinary discs

SVS 13 system

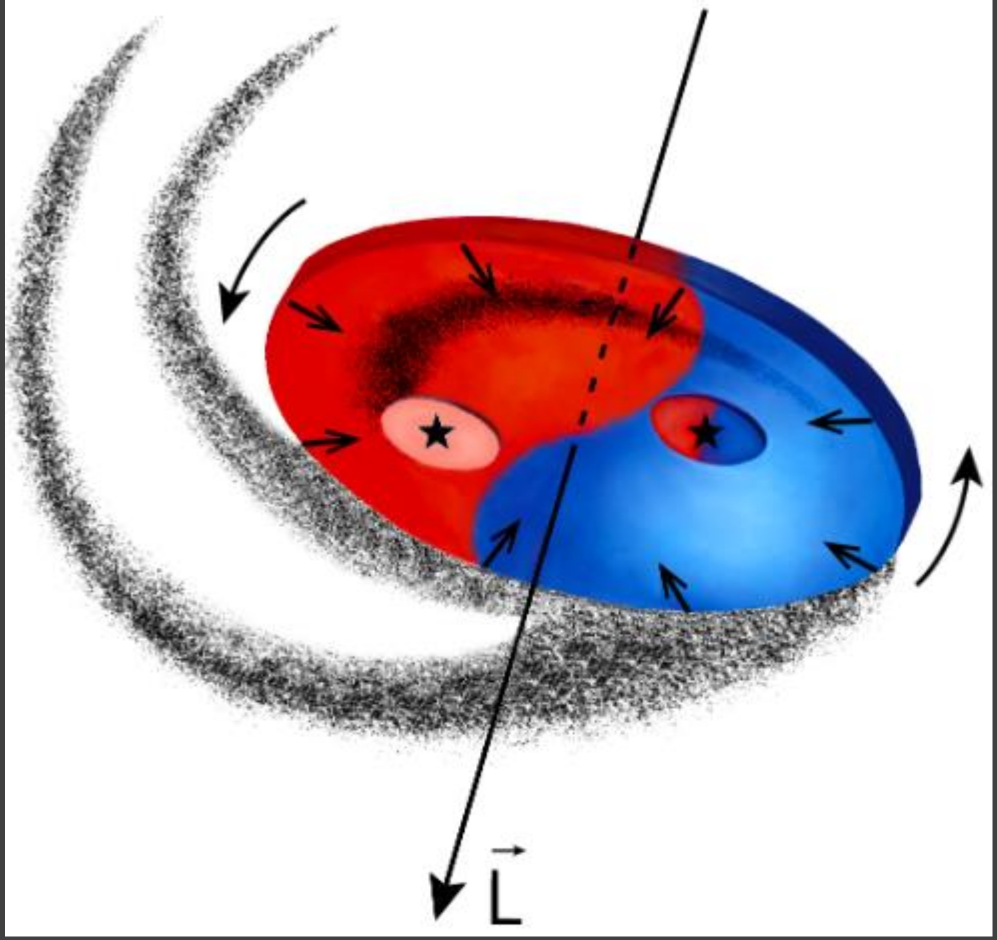
VLA and ALMA observations





ALMA

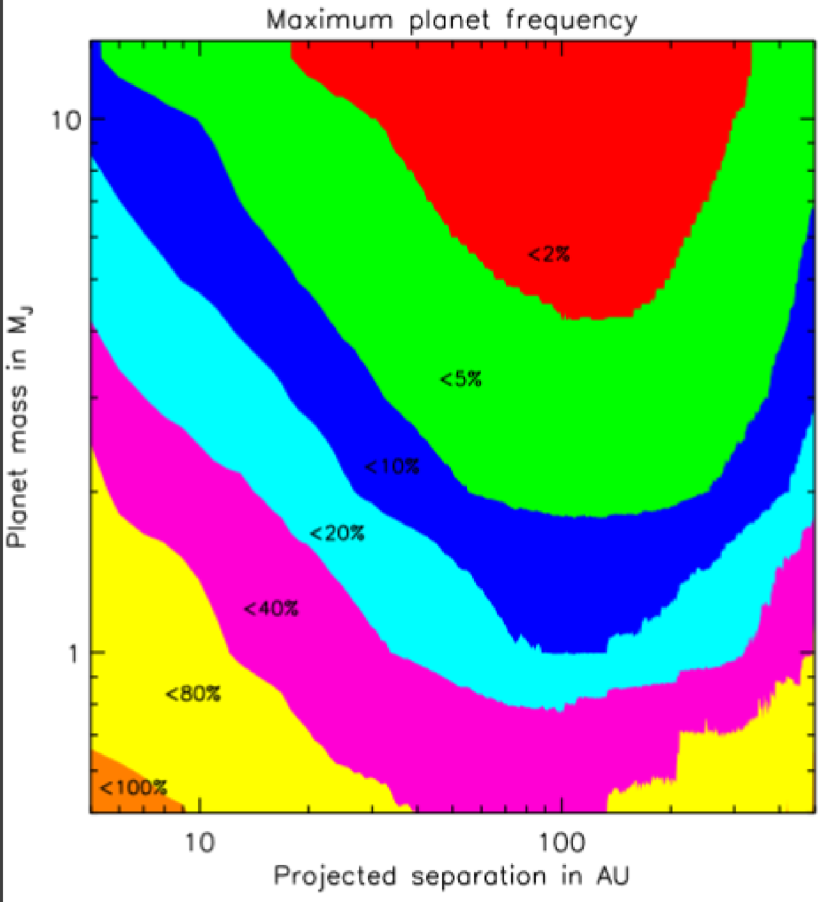
VLA



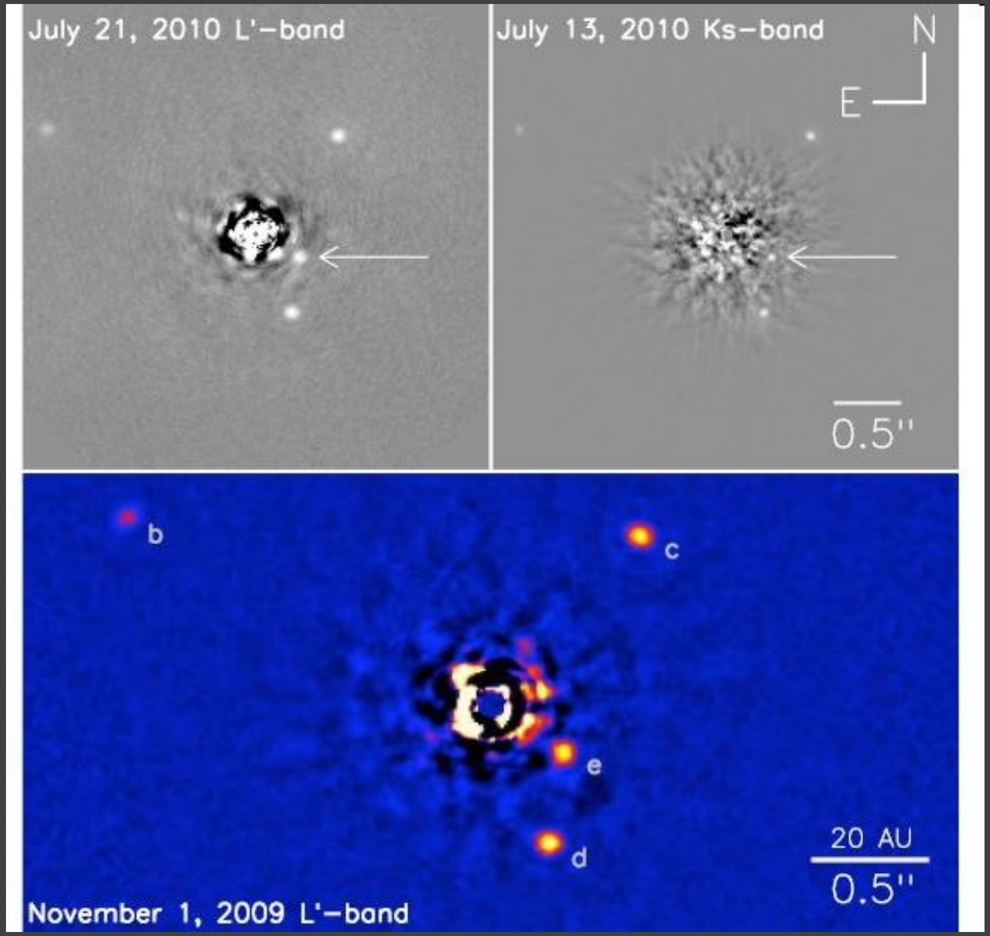
Direct imaging of planets

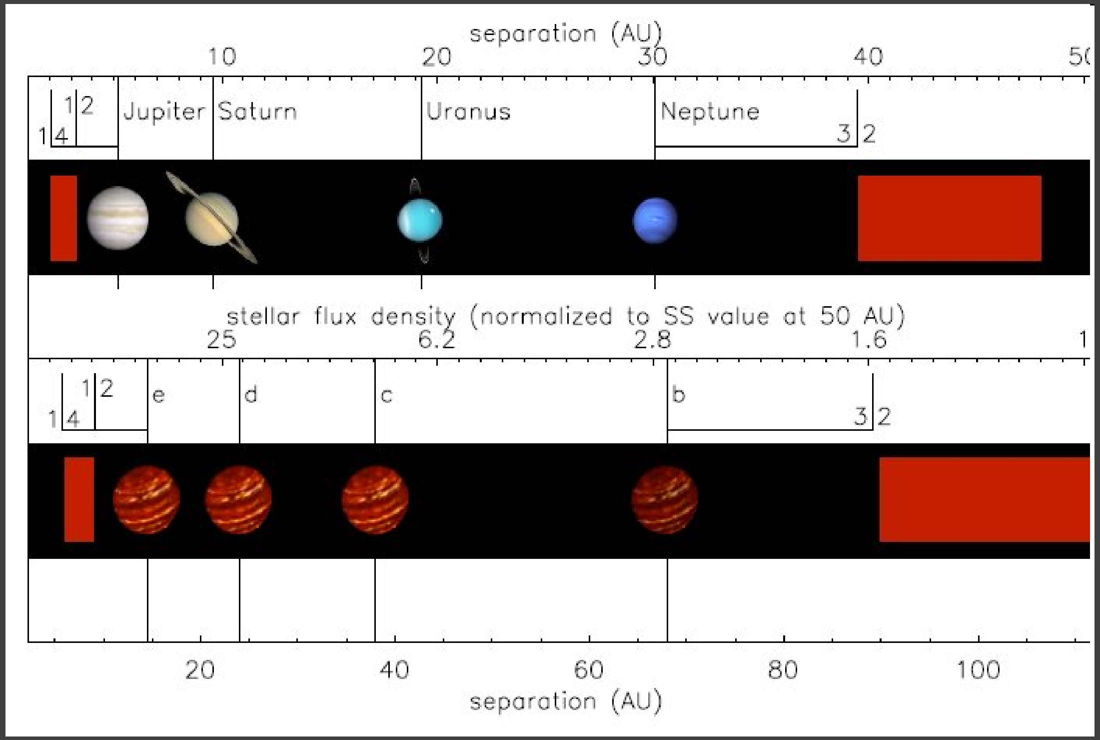
Recent survey with direct imaging resulted in an estimate that ~few percent of star have a planet 0.5-14 Mjup at 20-300 AU.

HR8799 system and several brown dwarfs were found



HR 8799

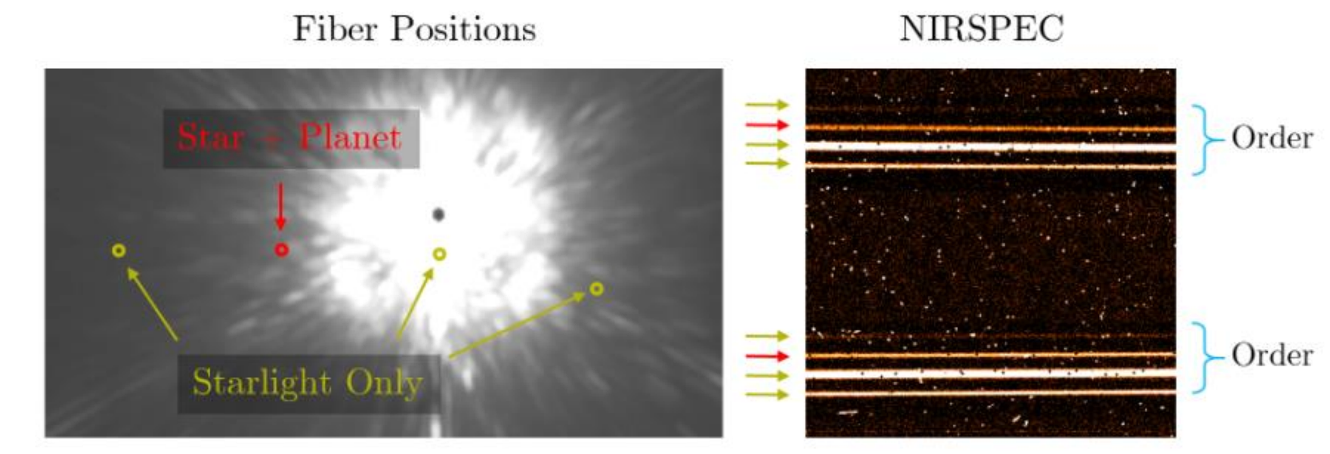


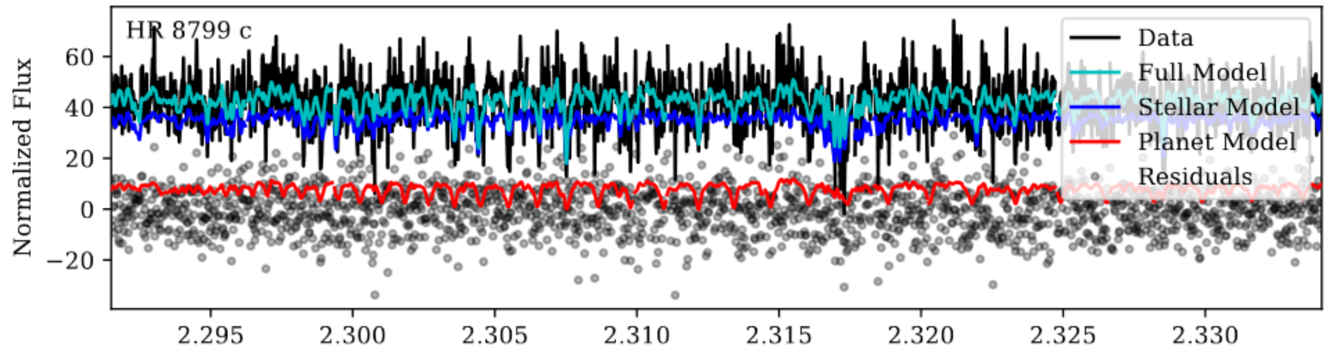


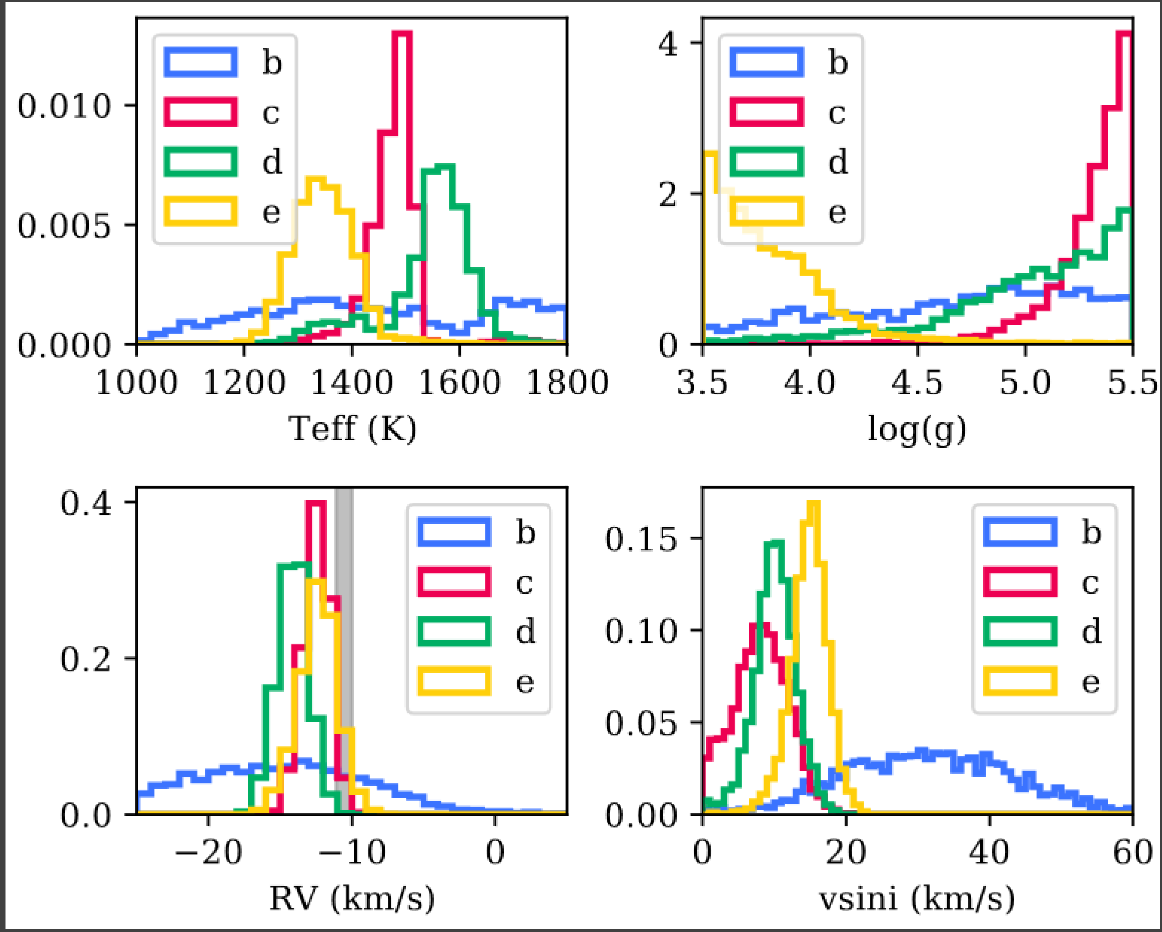
Keck II

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

Obtaining spectra and atmospheric data

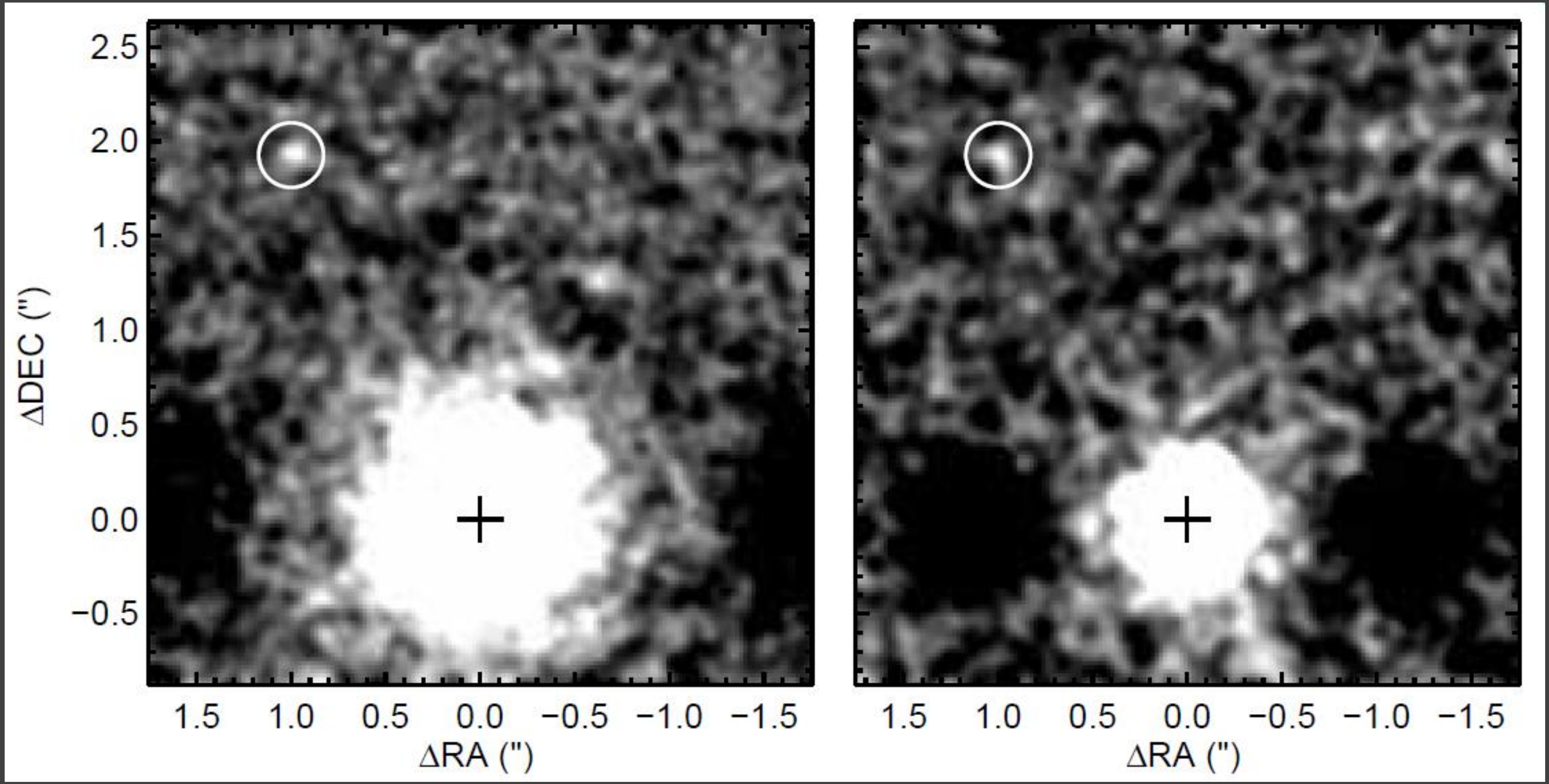






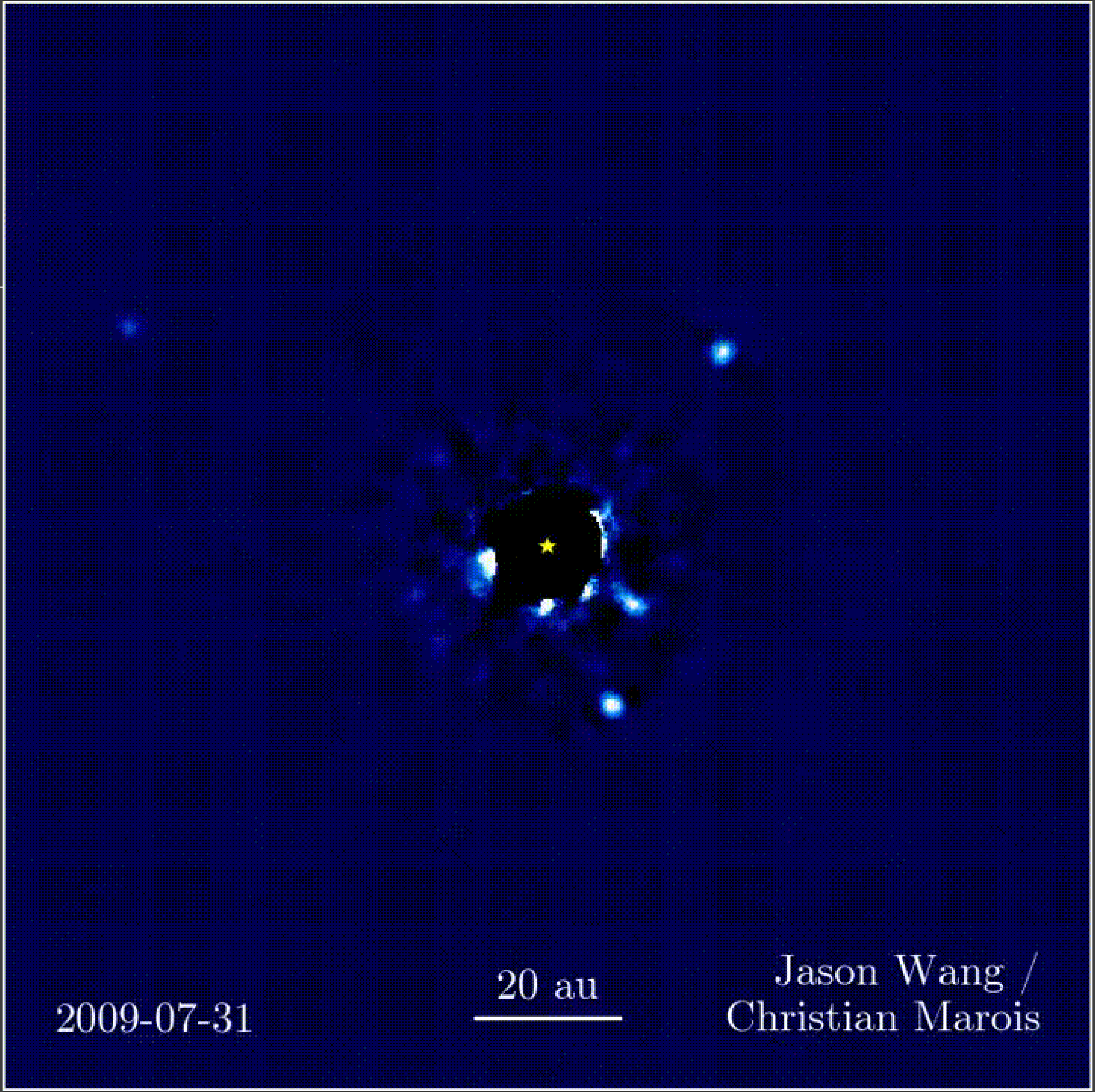
2107.06949

Young star 1RXS J160929.1-210524



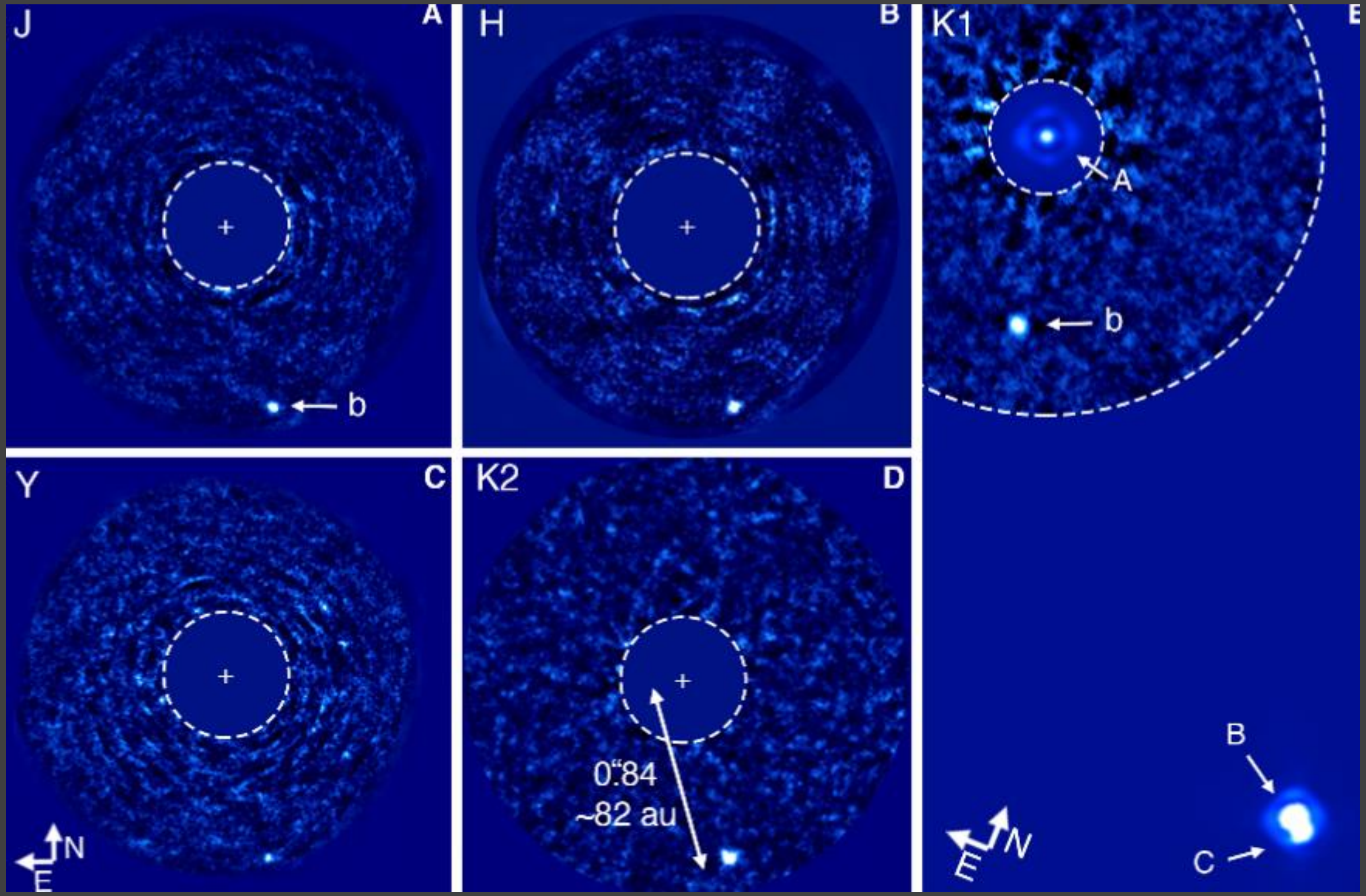
Gemini North

HR 8799

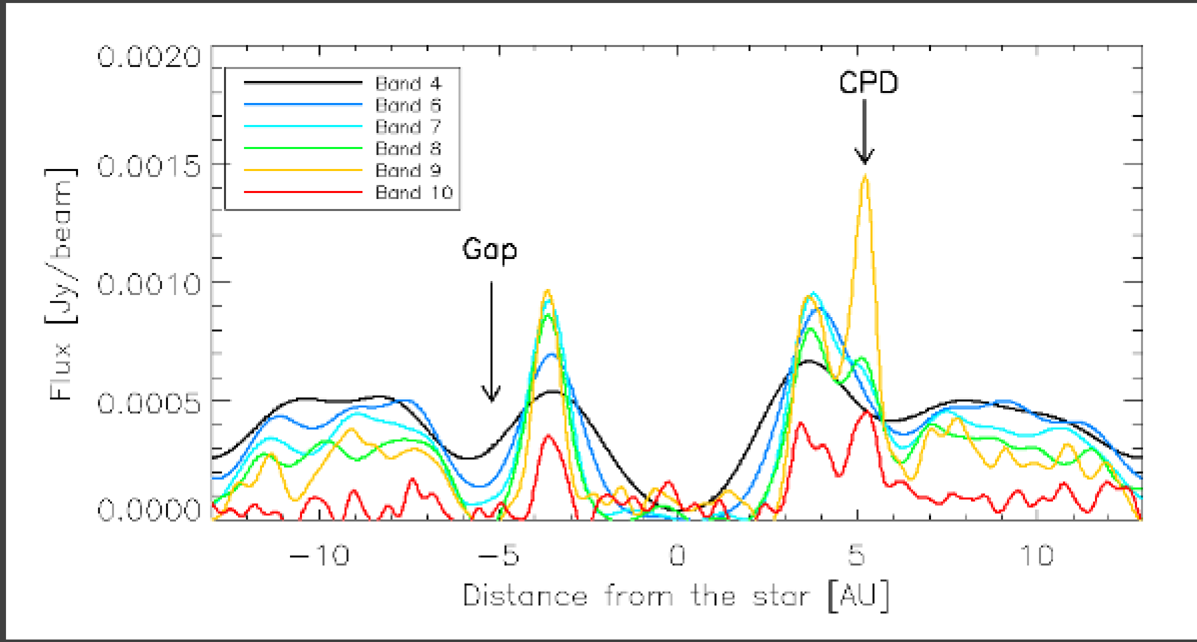


Planet in a triple system

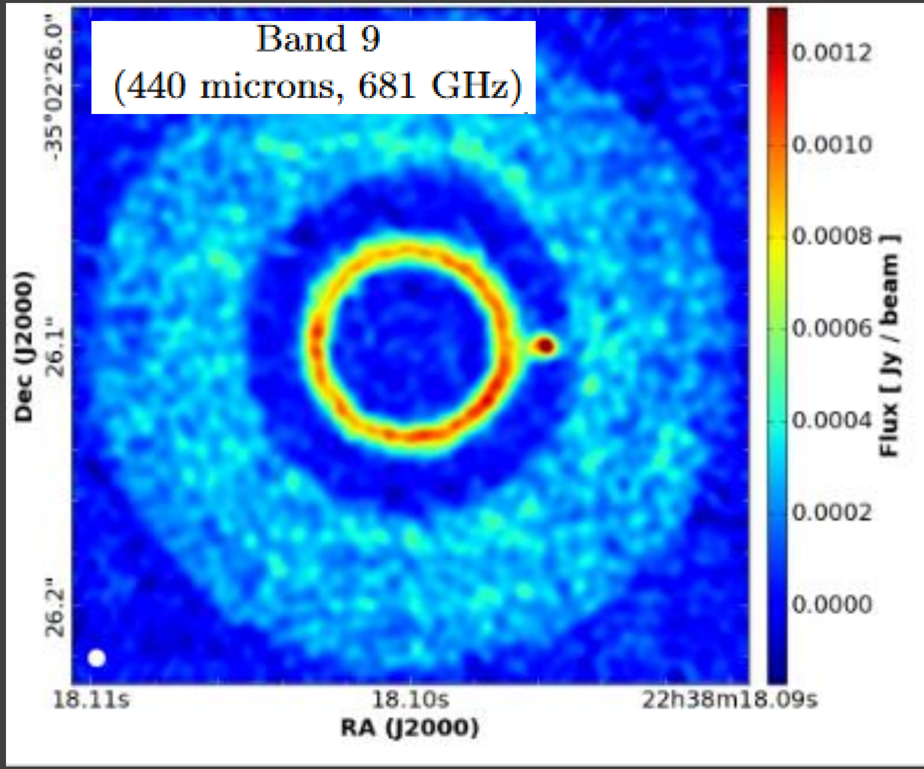
Young planet ~16 Myr.
Observed by VLT
Orbit might be unstable.



Circumplanetary discs (mock simulations)

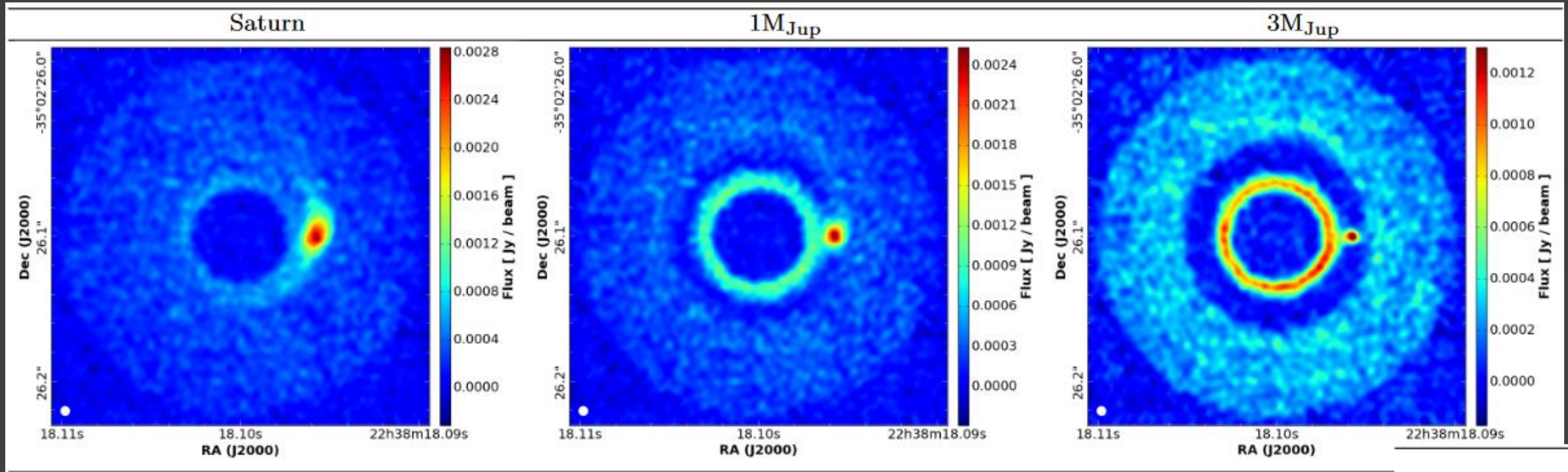


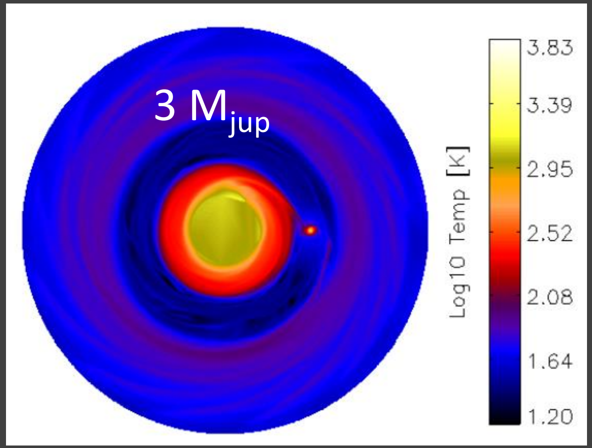
Size of a circumplanetary disc is about ½ of the Hill sphere. Thus, it can be hardly resolved by ALMA, but can be detected. Presently, only upper limits are available (2003.08658).

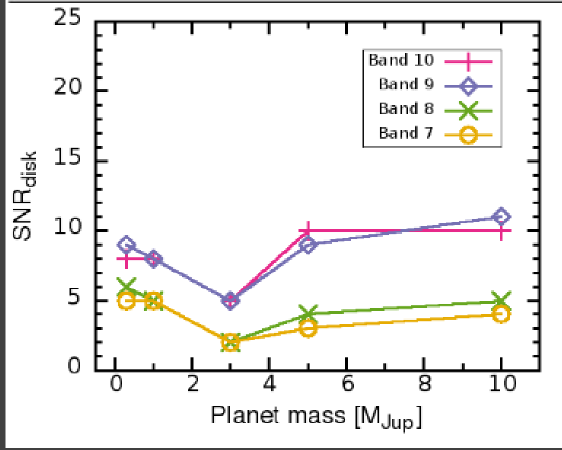


3 Jupiter masses
5 hours of observations
Better visible at shorter wavelengths
Gap opening is important
Planet temperature 4000K (age ~1 Myr)

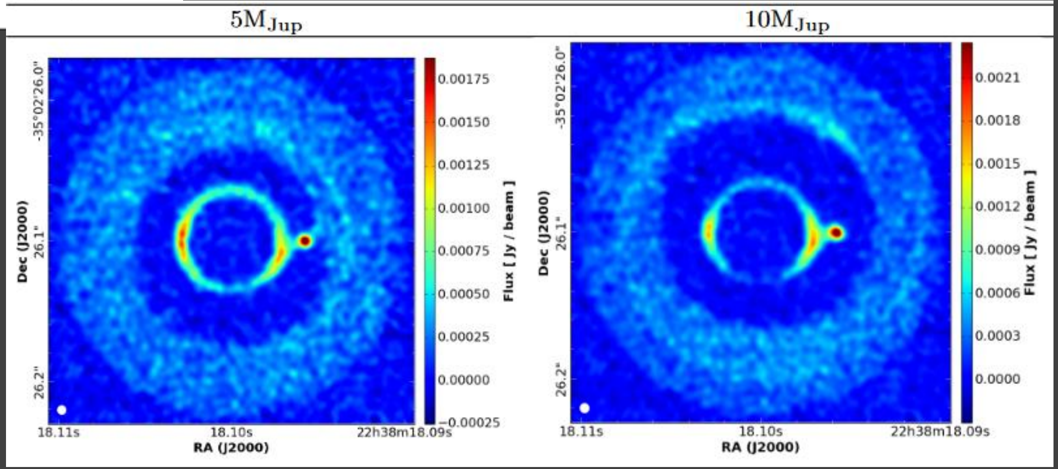
Dependence on the planet mass





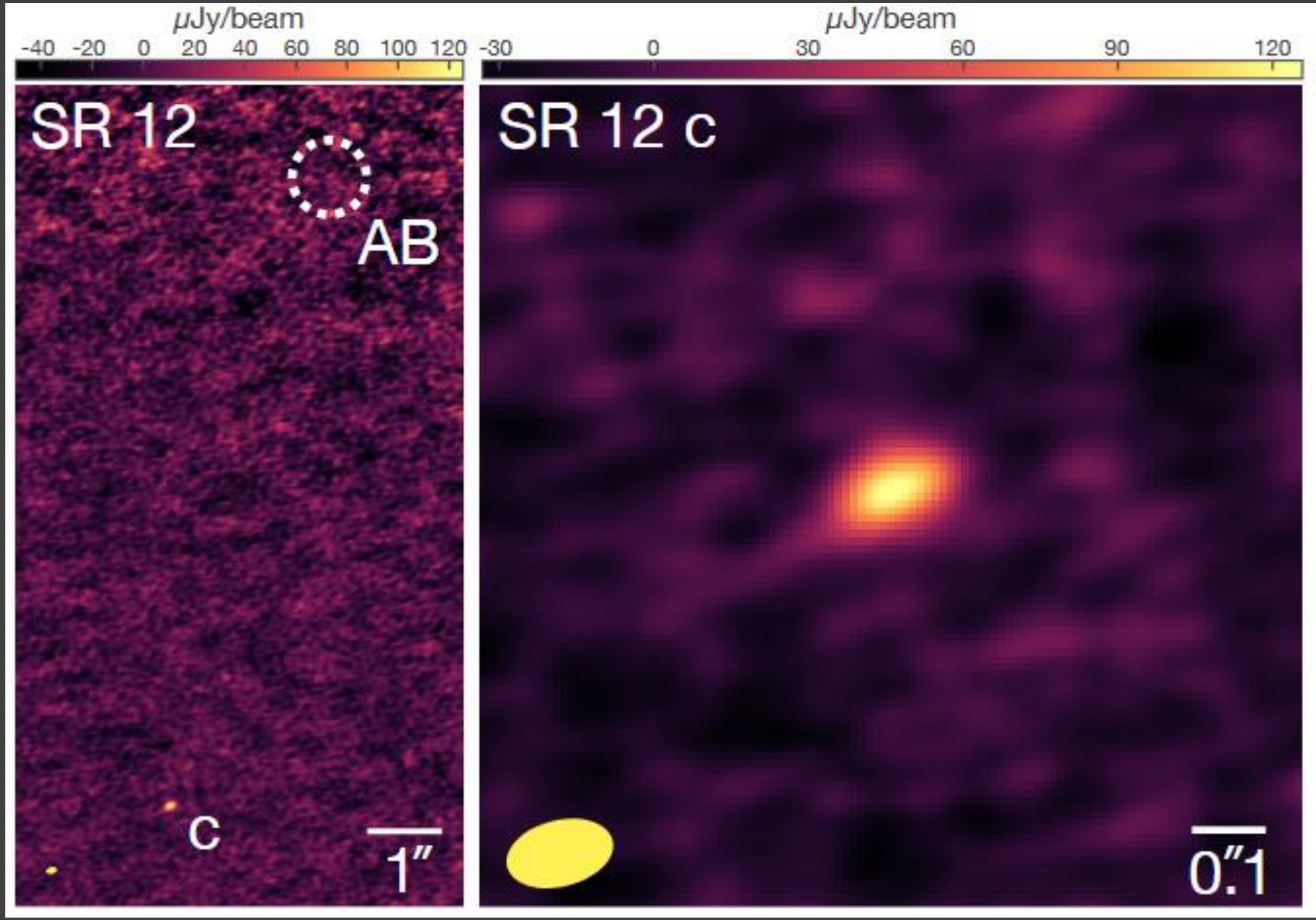


Light planets, like Saturn,
can also be detected.



Disc around a planet

ALMA observations.
Planet SR 12 c – 11 Mjup
a~980 AU
SR 12 AB – T Tau binary



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Literature

- arxiv:1507.04758 Observations of Solids in Protoplanetary Disks
- arxiv:1703.08560 Circumstellar discs: What will be next?
- arXiv: 1804.08636, 1802.04313, 2110.04319 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
- arXiv: 2203.09528 Kinematic structures in disks