Accretion disk models in diverse environments

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Star and planet formation

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6th Summer School, Life Cycle of Dust

INSTITUTO DE ASTROFÍSICA DE ANDALUCÍA

EXCELENCIA SEVERO OCHOA

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spfe star planet formation and evolution

By studying the first and last phases of a star, one of our objectives is to understand which the limits are as regards planetary formation conditions and their survival, and how this can be explained within the diversity of the exoplanets observed in the surroundings of the sun.

Research

People

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Star and Planet Formation teams

IAA+UB+ICE(Institute of Space Sciences)

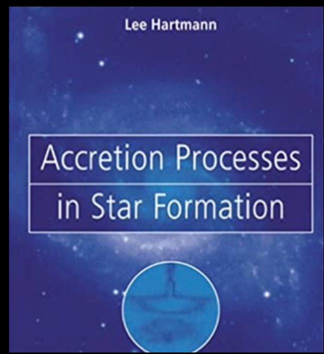
Barcelona

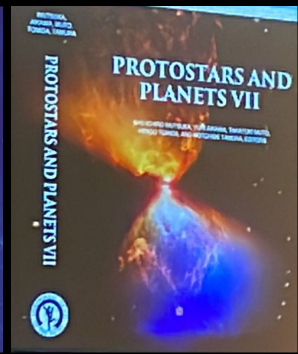
Granada

Outline

- First part: Fundamental properties of accretion disks, applications of α disk models to the observations.

- Second part: Examples of models in peculiar accretion disks: Planet formation in extreme conditions.





Bibliography

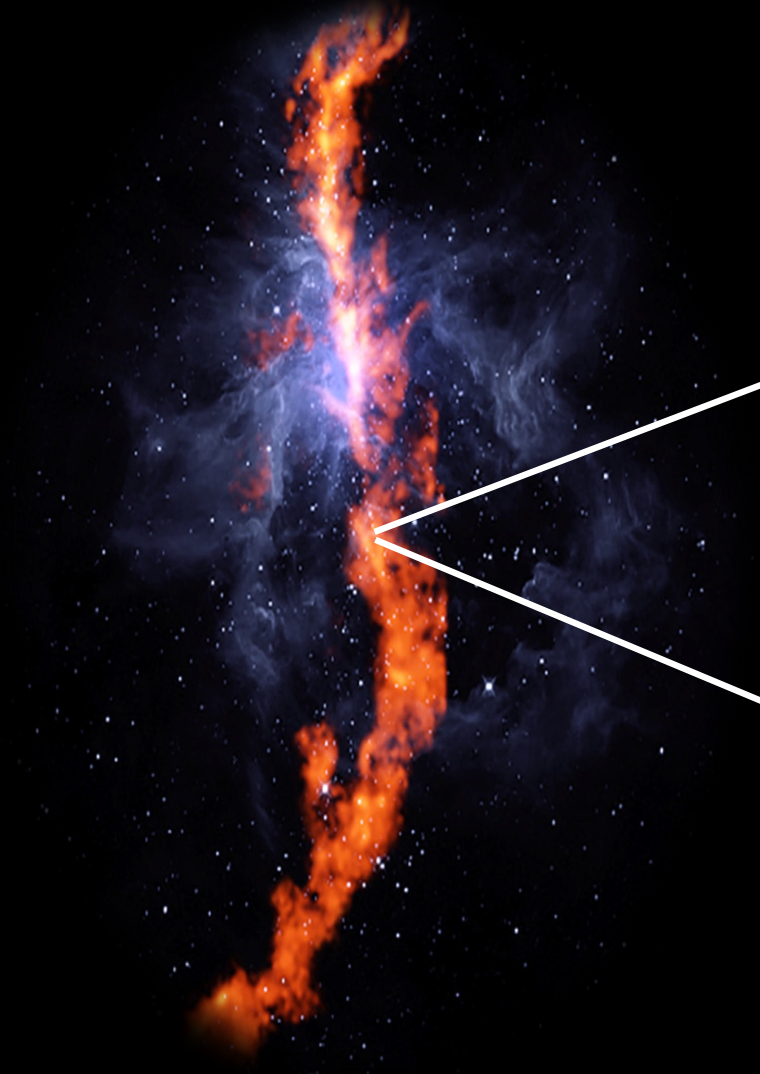
Accretion processes in Star Formation (Hartmann's book)

Protostars and Planets VII, 2023.

Planet formation in extreme conditions (M. Osorio), Proceedings of the XV Scientific Meeting of the Spanish Astronomical Society

Star Formation

Interestelar Molecular Cloud



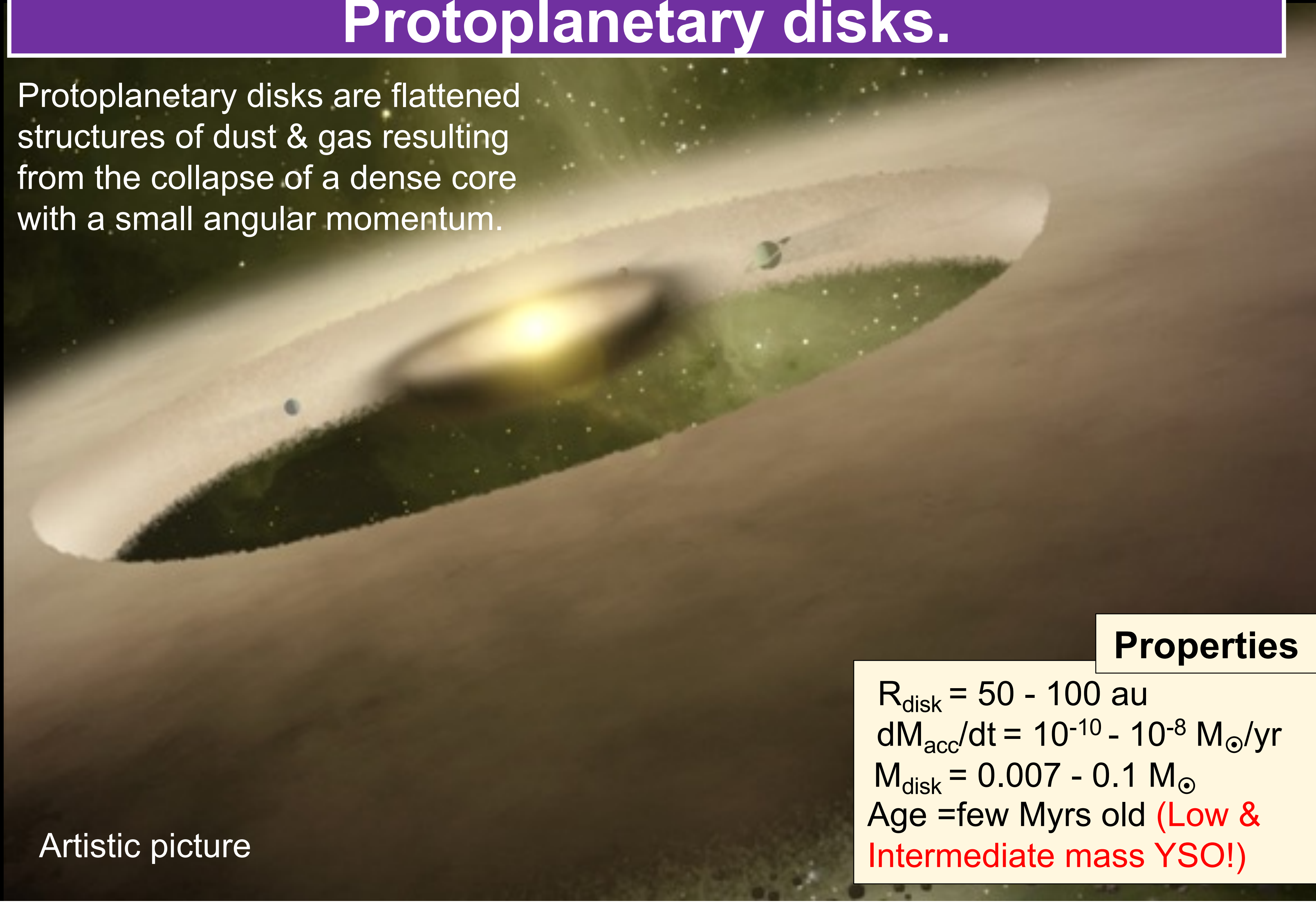
Stars

Size: x10^{-7}
Density: x10^{20}
Temperature: x10^{6}

Planets

Progenitors of the exoplanetary systems: Protoplanetary disks.

Protoplanetary disks are flattened structures of dust & gas resulting from the collapse of a dense core with a small angular momentum.



Artistic picture

Properties

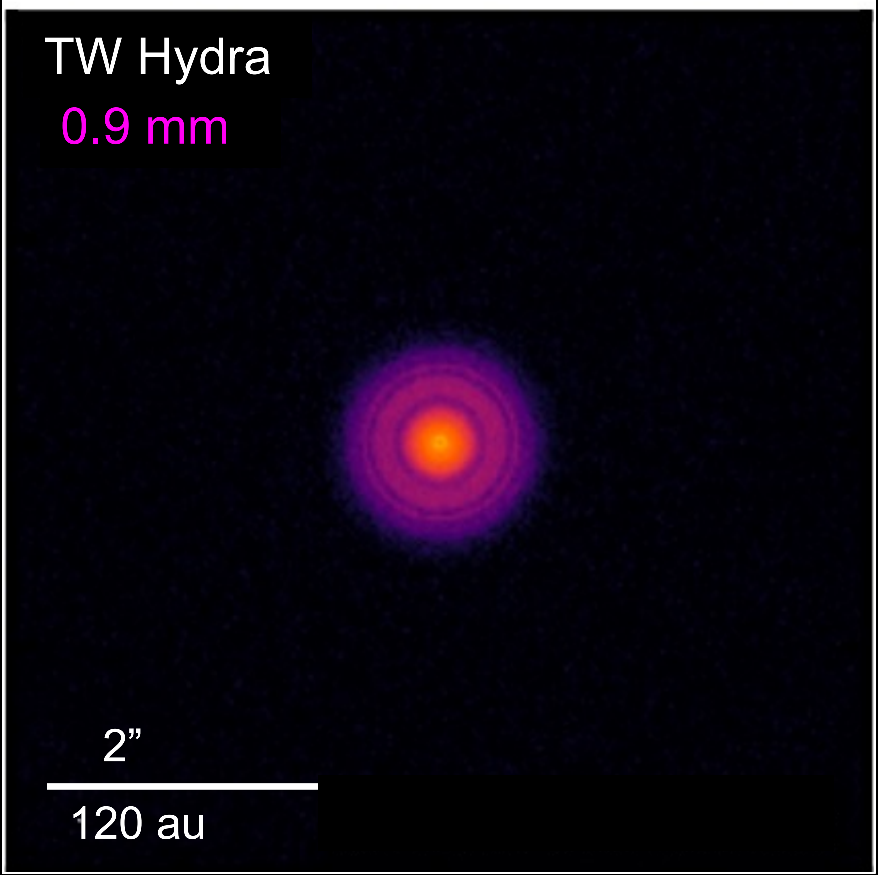
R_{disk} = 50 - 100 au

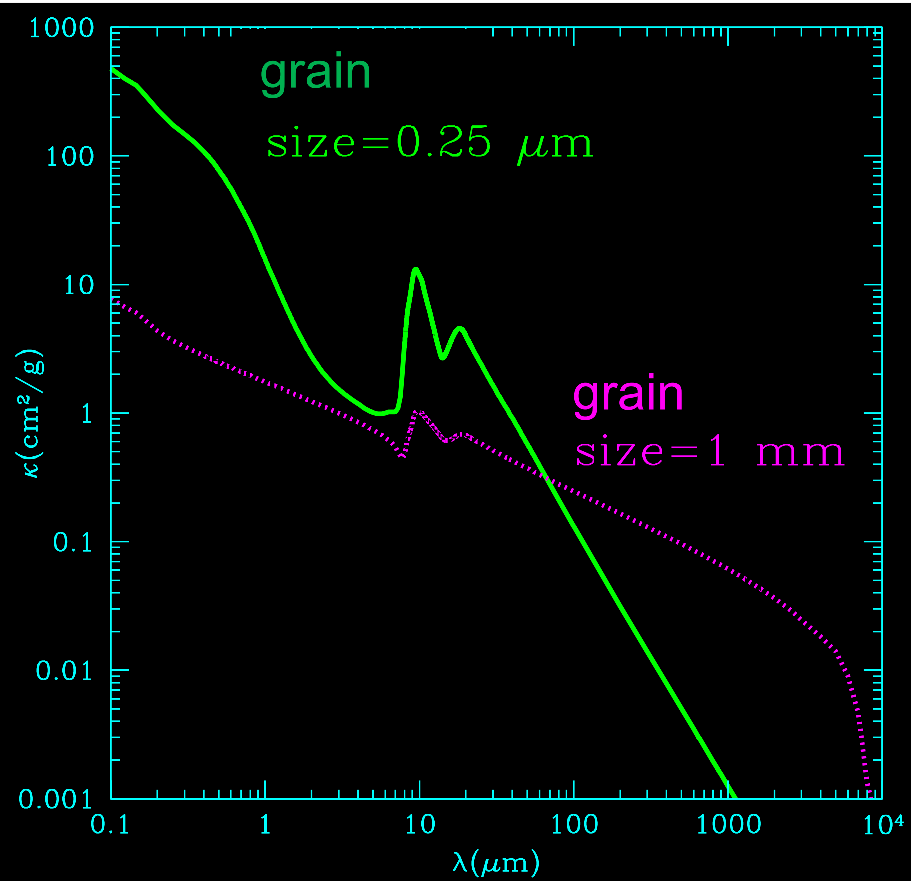
$dM_{acc}/dt = 10^{-10} - 10^{-8}\ M_{\odot}/yr$

$M_{disk} = 0.007 - 0.1\ M_{\odot}$

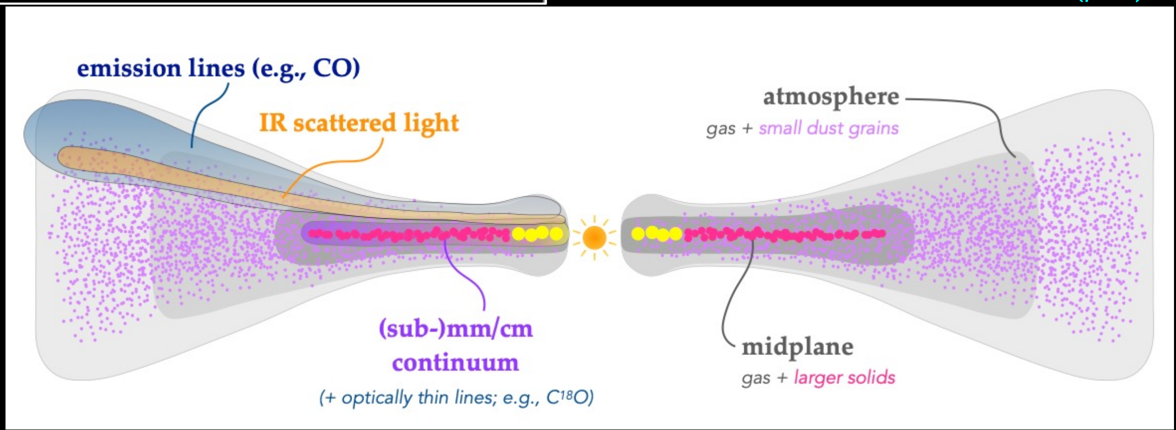
Age =few Myrs old (Low & Intermediate mass YSO!)

Disks are observed in dust thermal emission (radio observations)



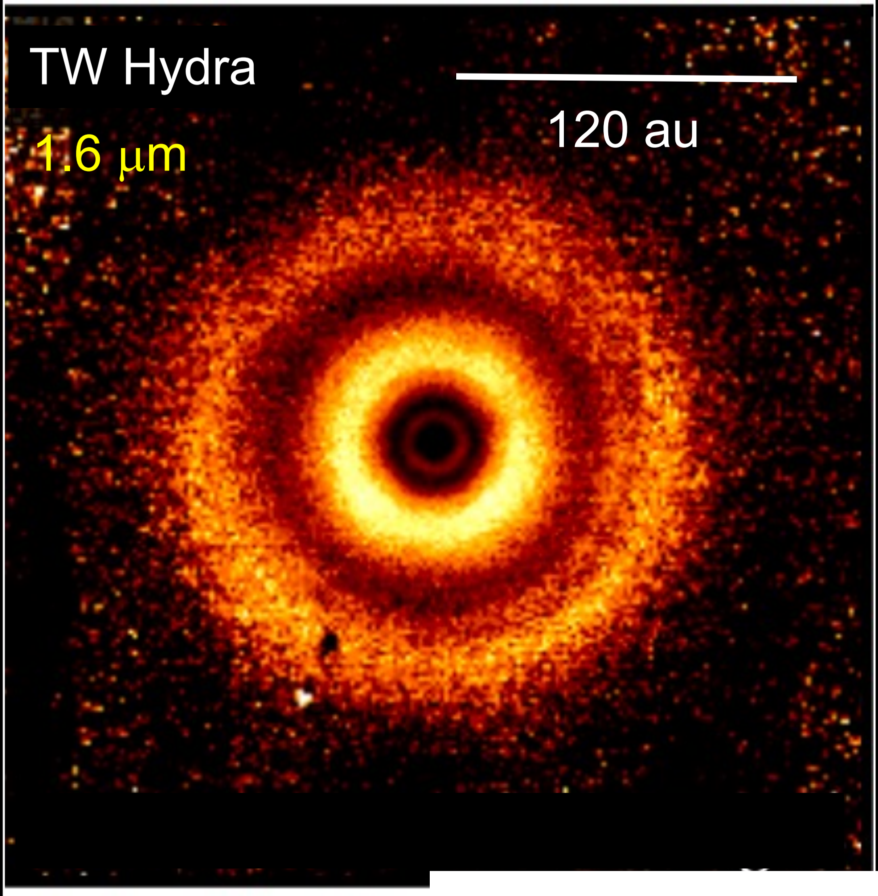


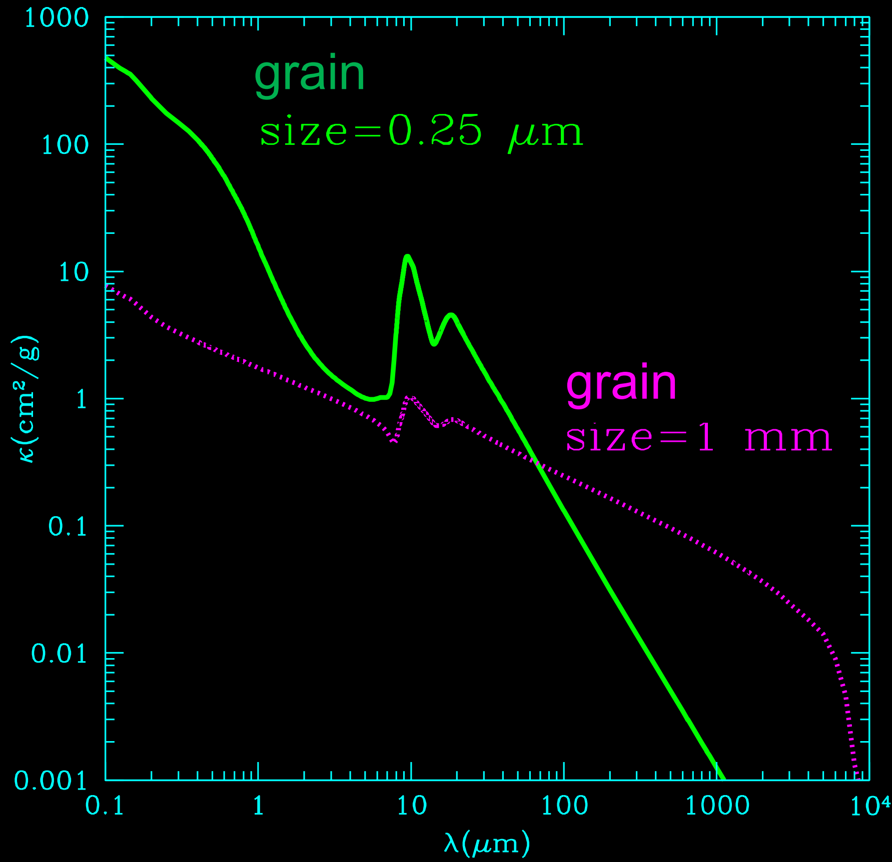
Andrews+2016



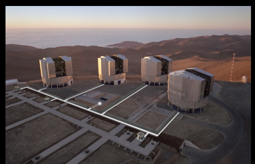
schematic cross section of the disk

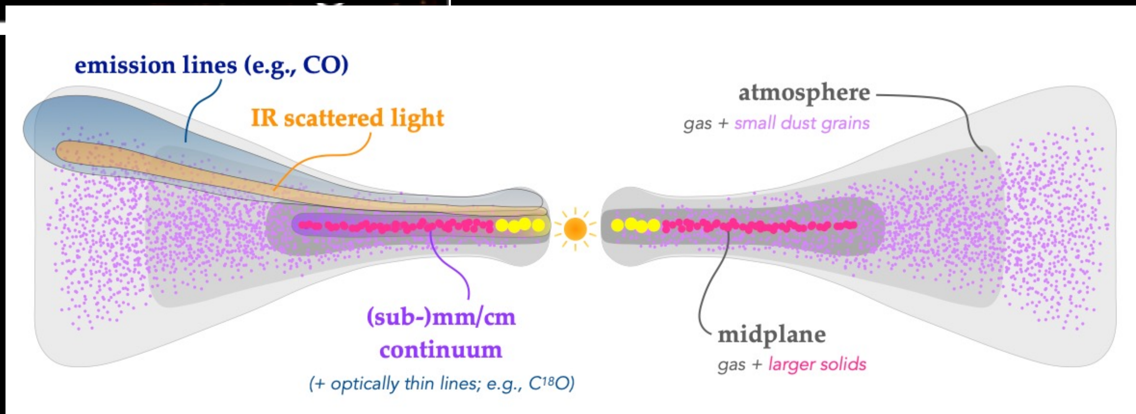
Disks are observed in IR scattered light (Near Infrared observations)



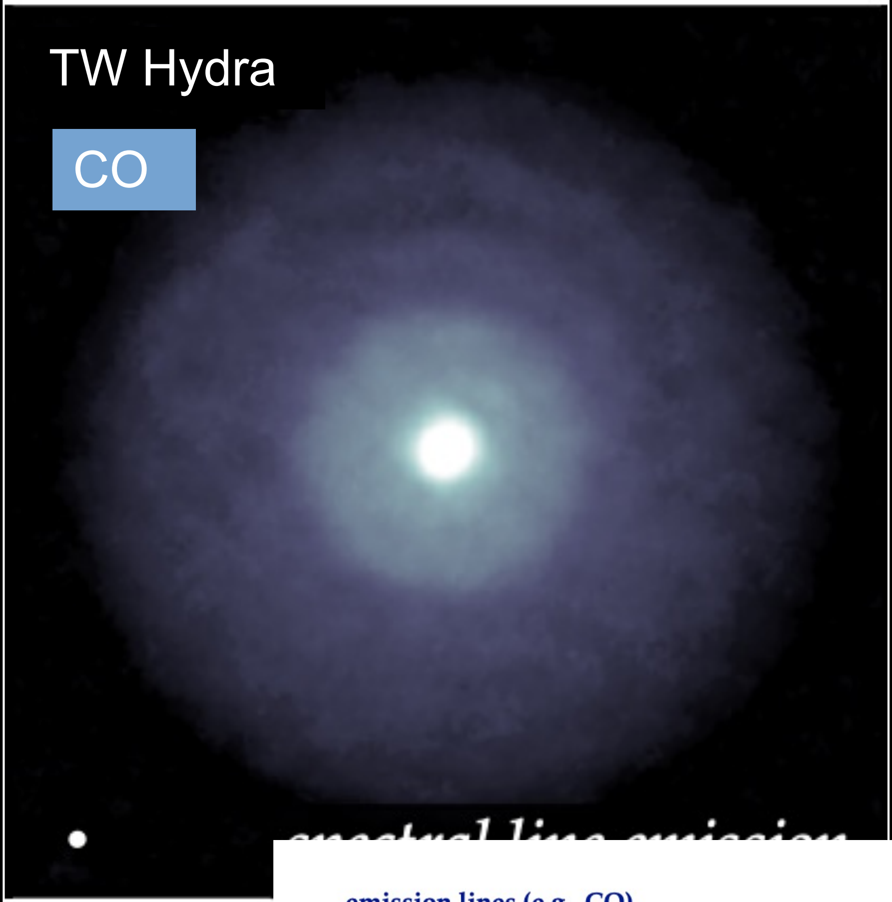


Van Boekel+2018

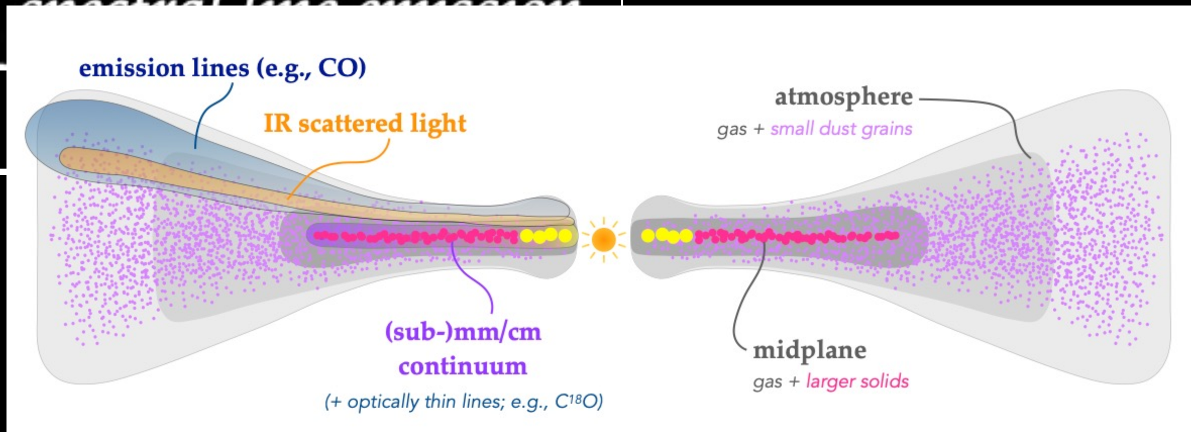




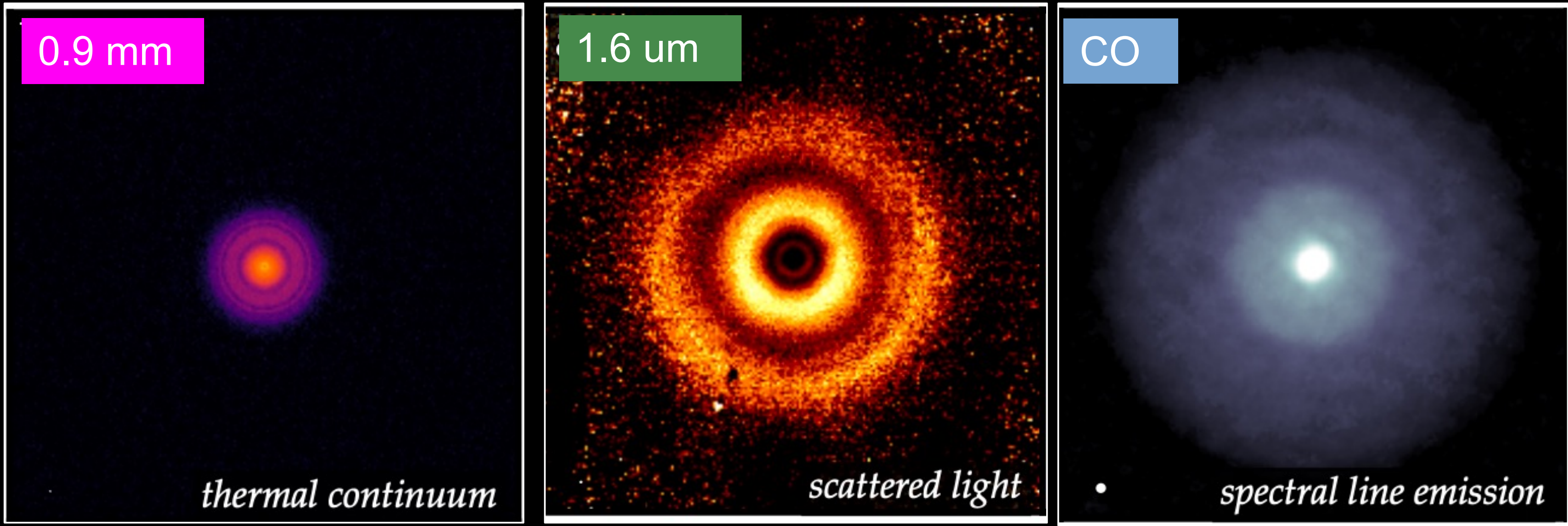
Disks are observed in molecular emission (radio observations)



Huang+2018

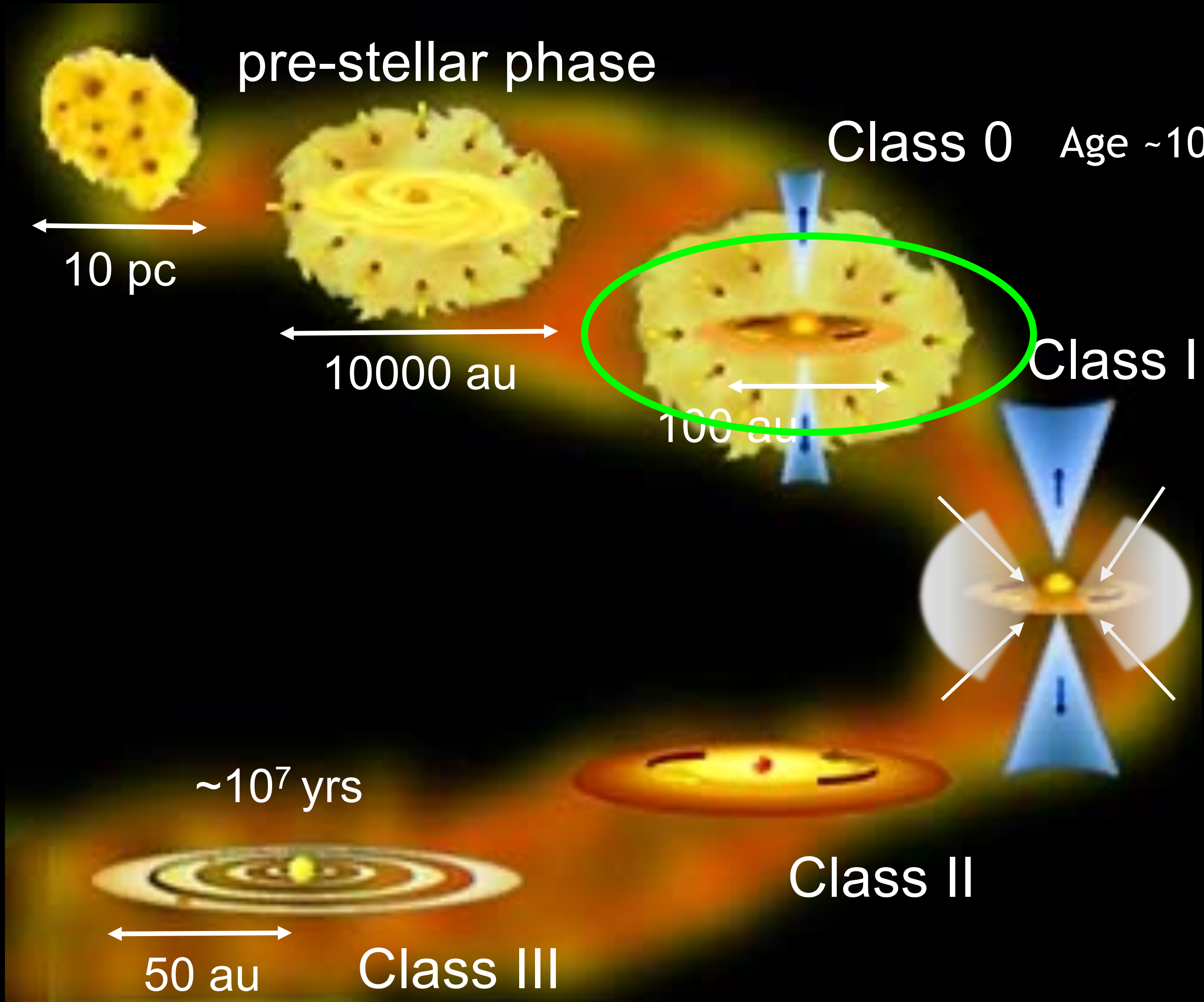


Protoplanetary disks (IR and radio observations)

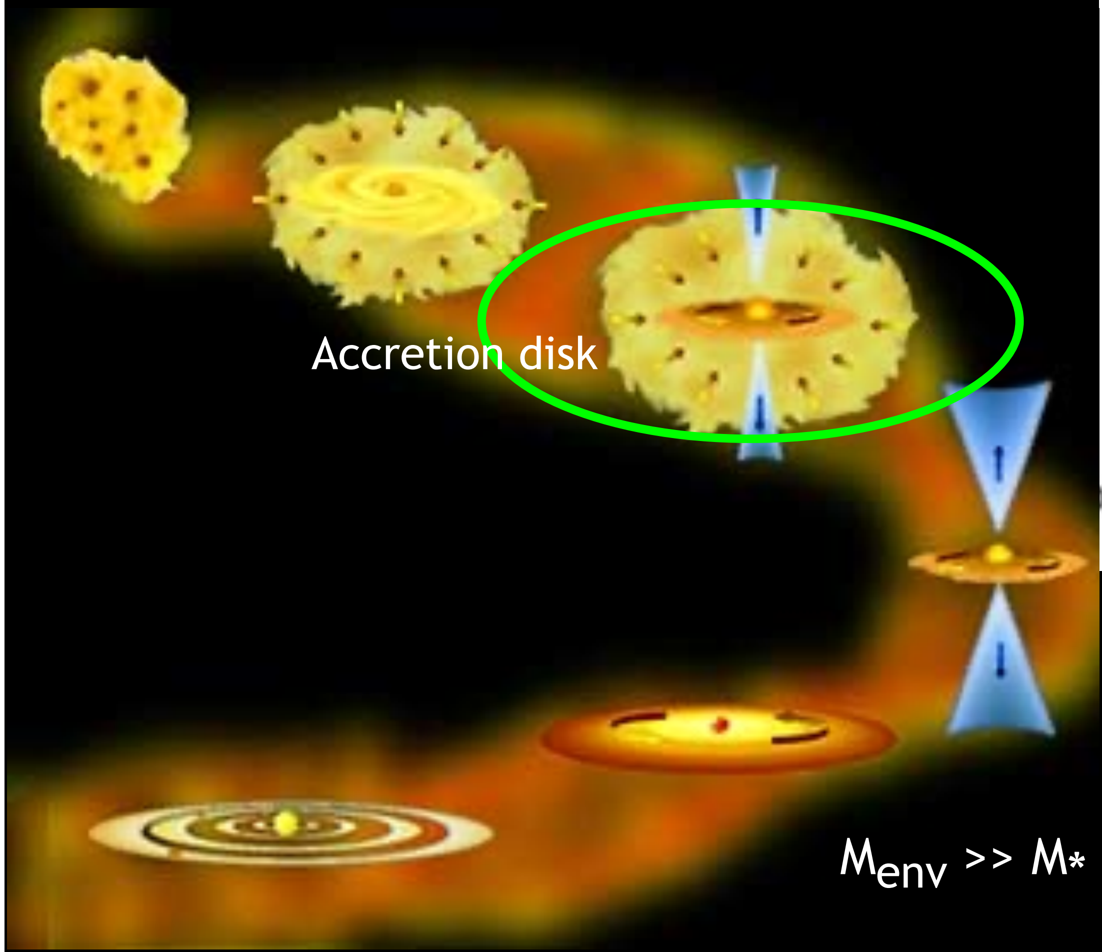


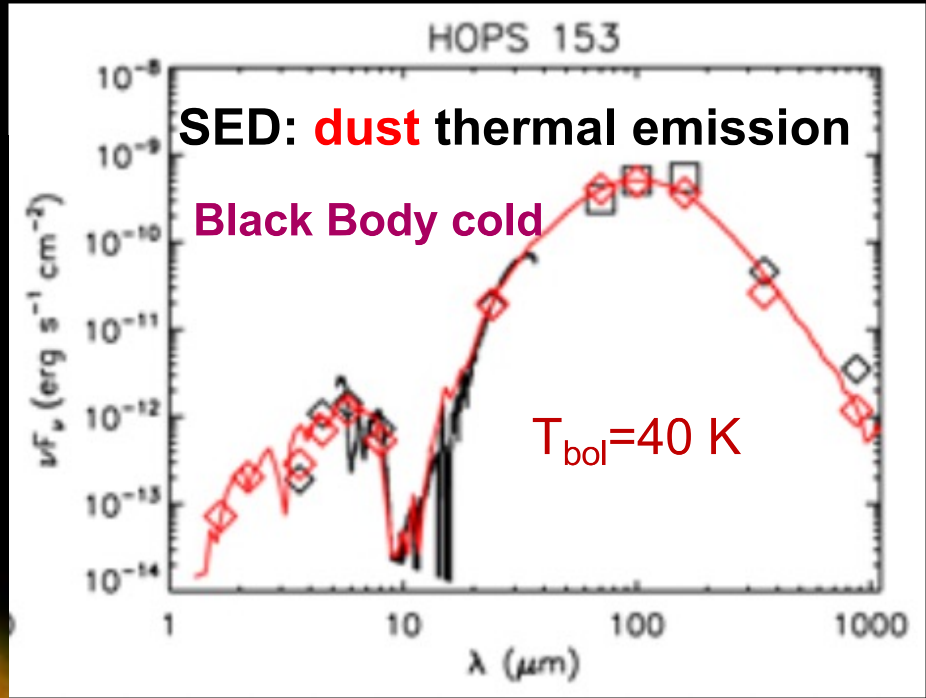
The disk is much smaller, traced by millimeter emission than when it is detected by scattered light and molecular emission.
Radiation pressure pushes small grains which are coupled to the gas outwards, in this process small grains drag large grains toward the center. (radial drift, Widenschilling 1977).

Star formation paradigm (Shu, Adams, Lizano 1987)



Class 0 (dominated by the envelope)



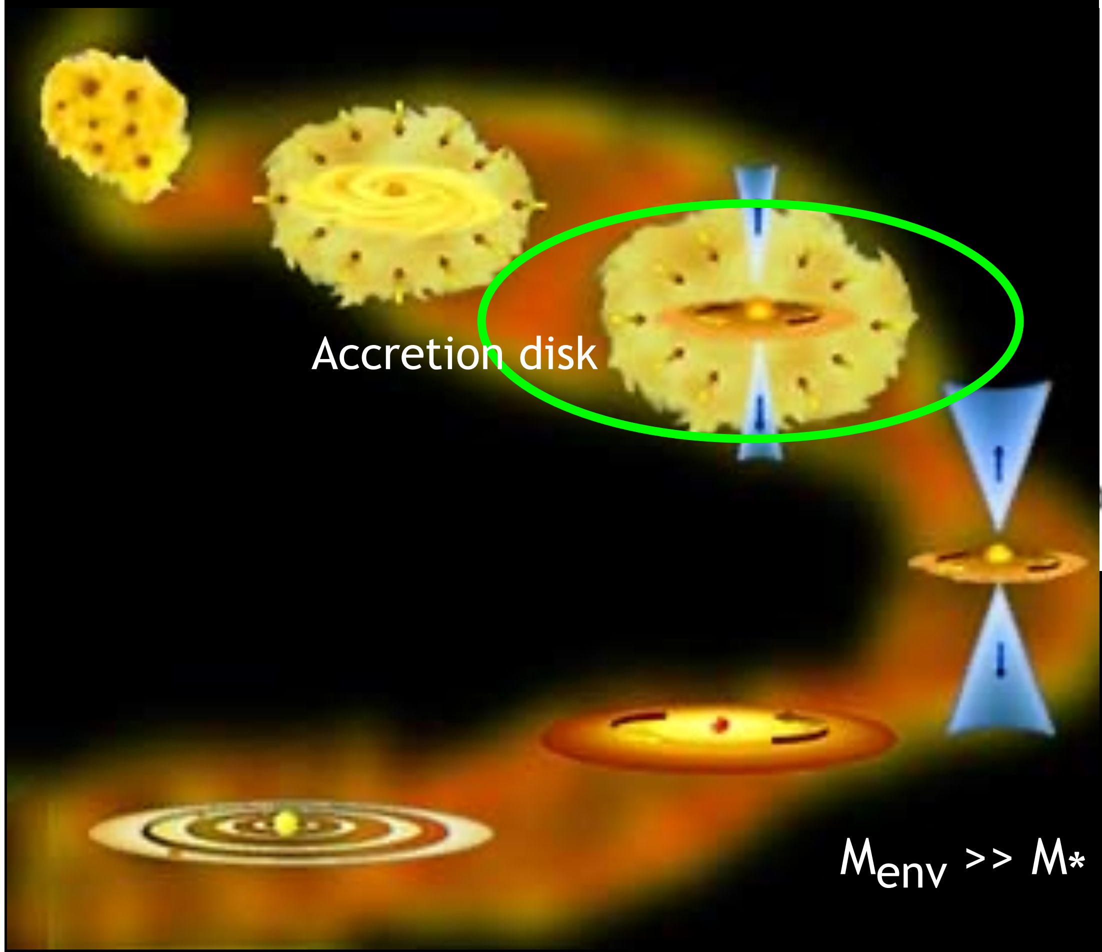


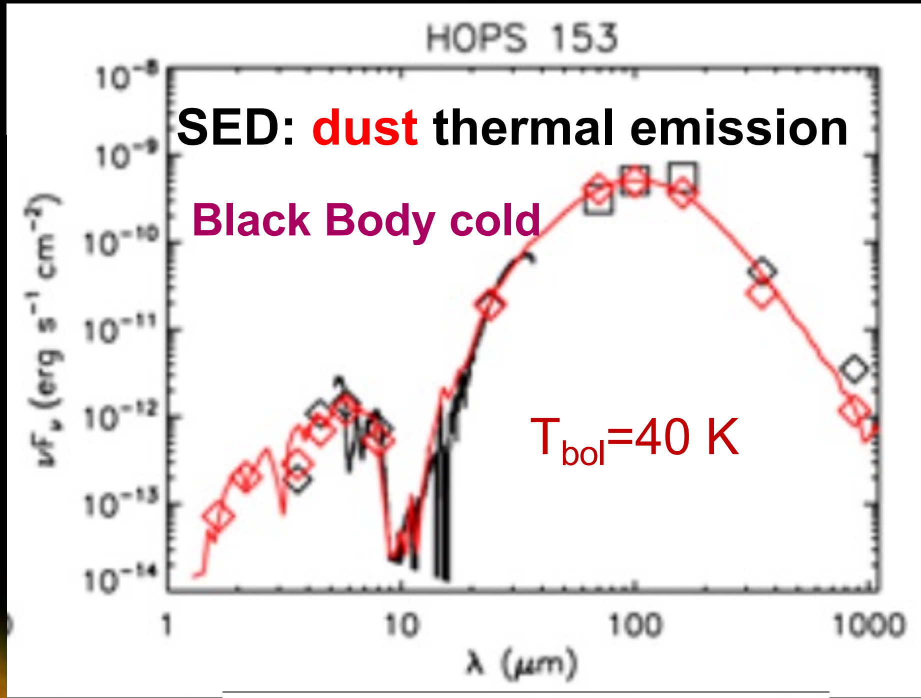
$M_{env} >> M_*$

$T_{bol} < 70$ K

Age ~10^4 yrs

Class 0 (dominated by the envelope)





$M_{env} >> M_*$

$T_{bol} < 70$ K

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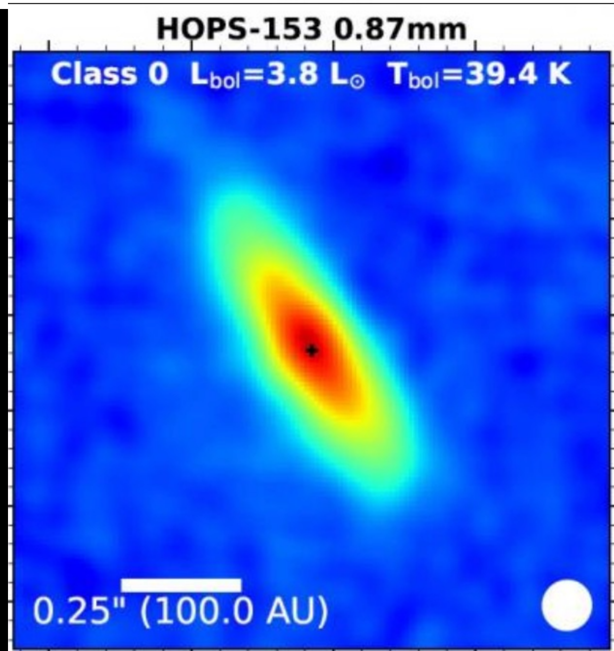
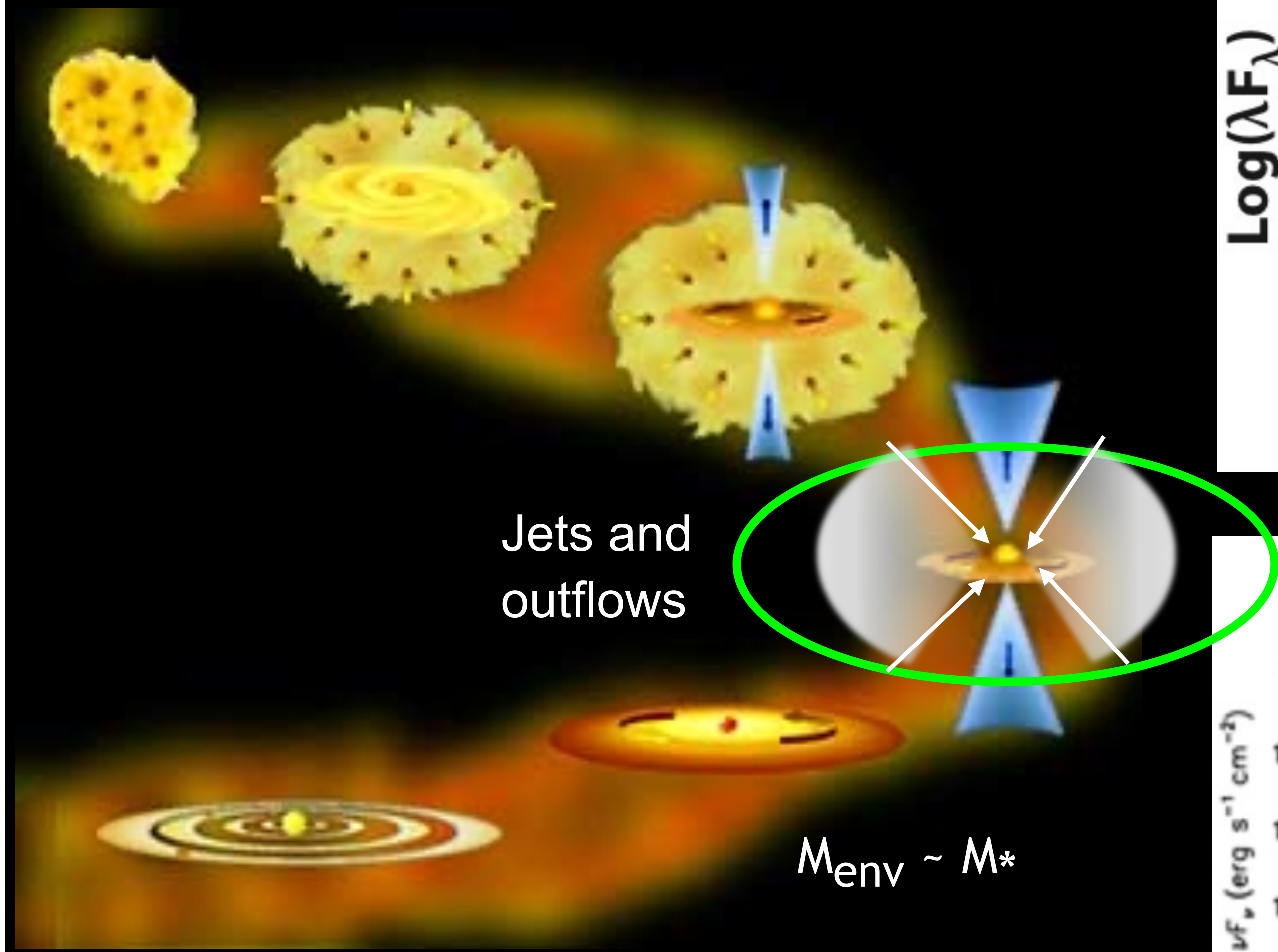
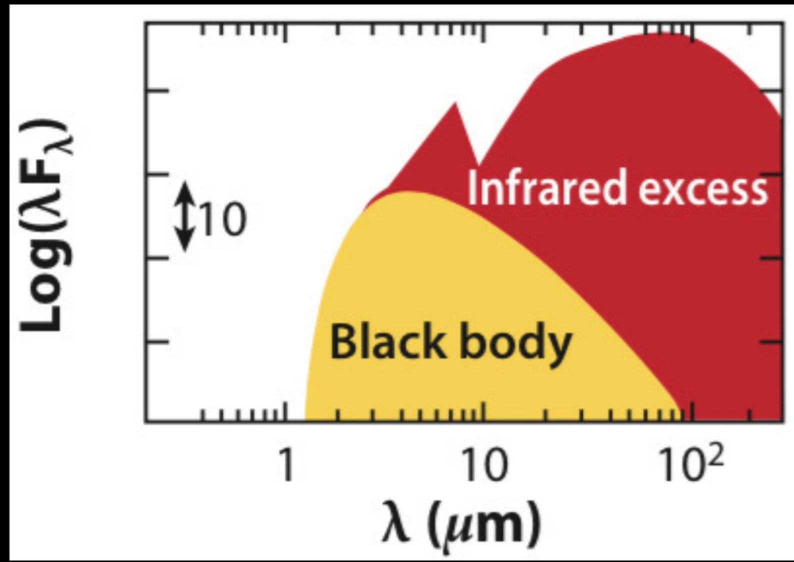
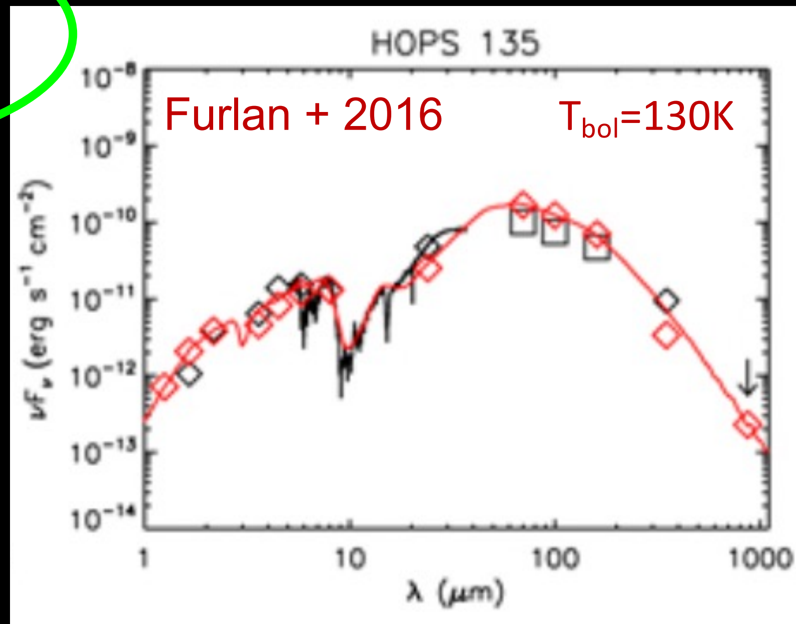


Class I (disk + envelope)



Jets and outflows





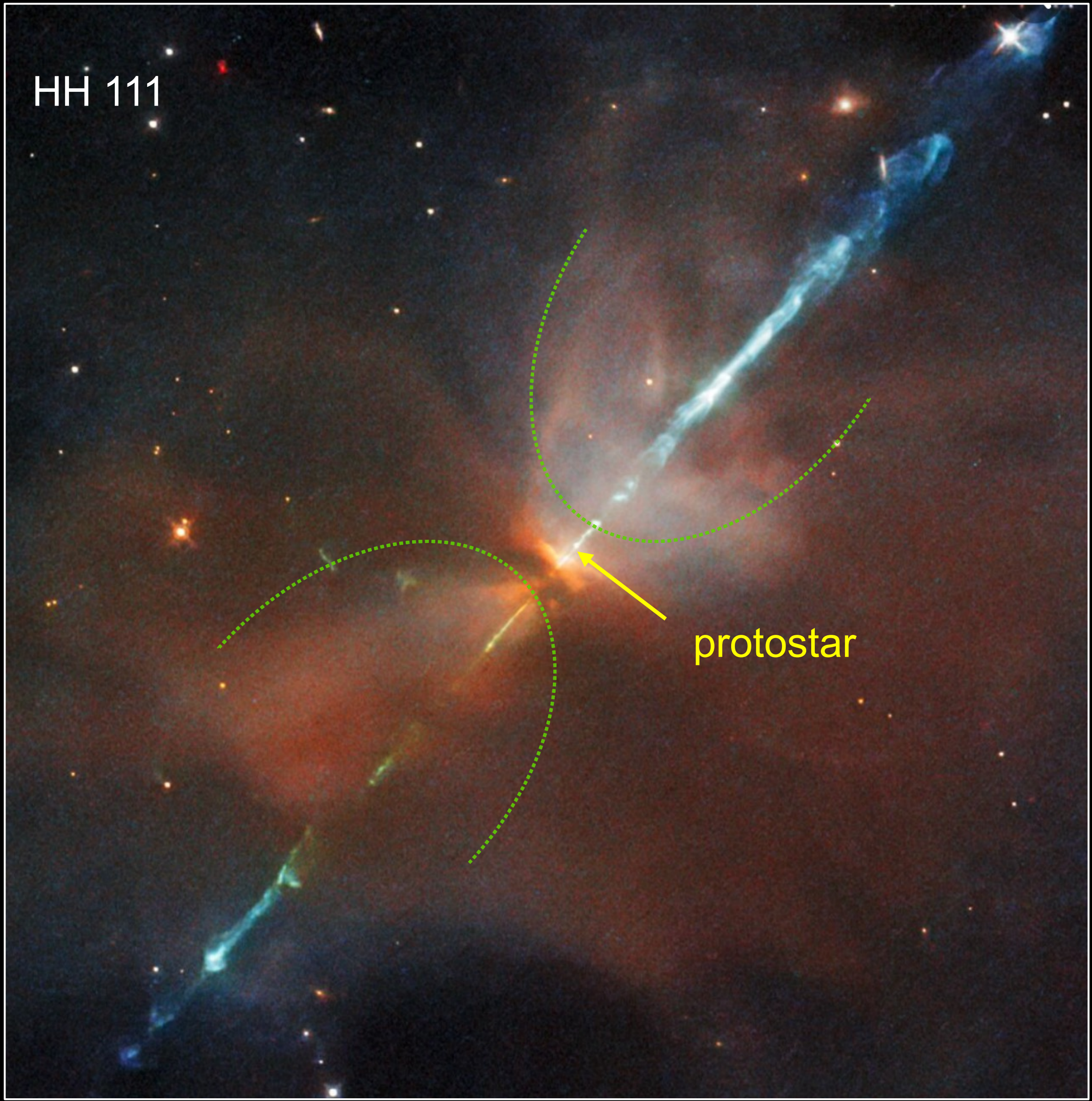
M_{env} ~ M_*

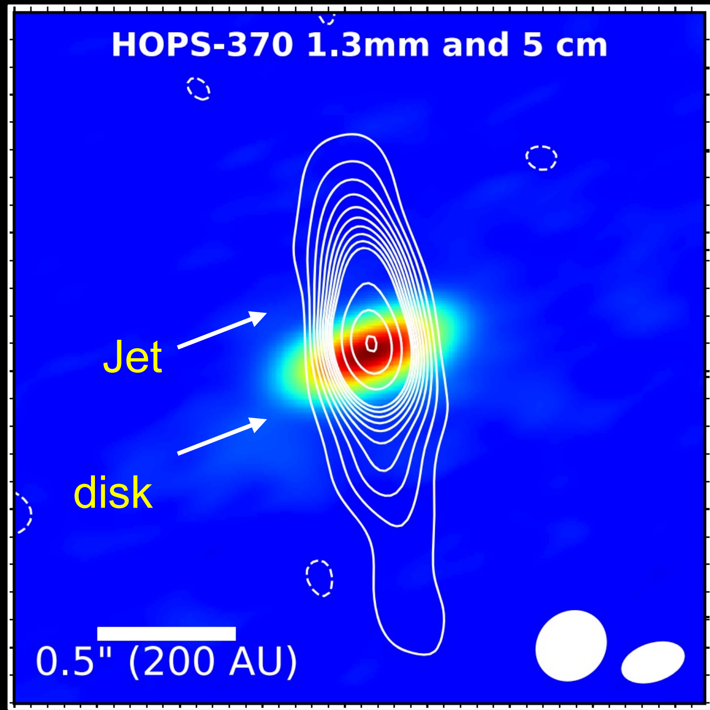
T_{bol} ~100-700 K

Age ~10^5 yrs

Class I (disk + envelope)

The disk plays a crucial role not only in feeding material the protostar, but also in collimating these spectacular optical jets.

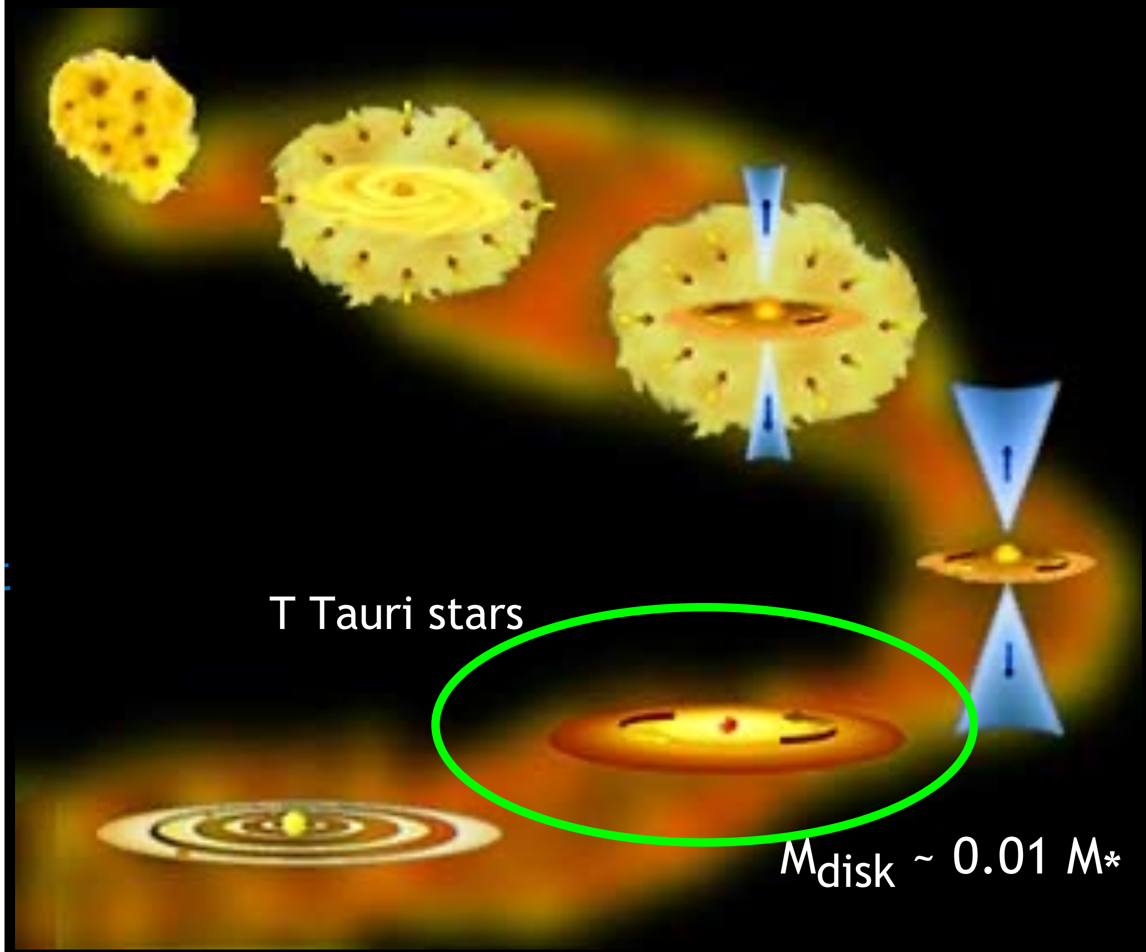


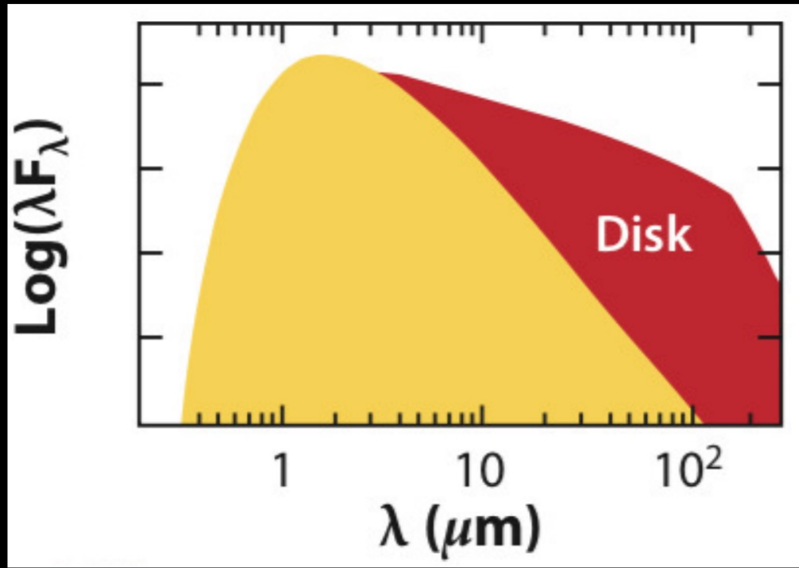


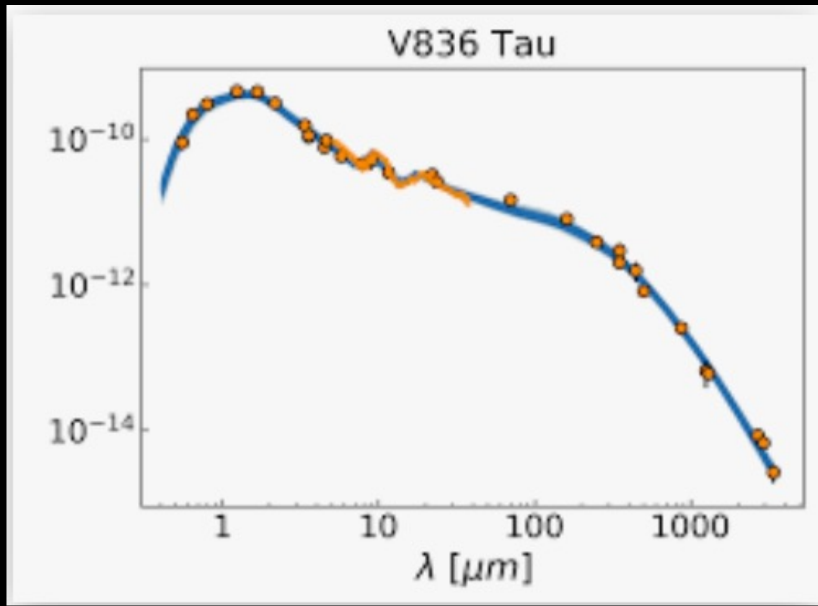
Tobin+2020

https://spfe.es/en/catalogs/

Class II (dominated by the disk)







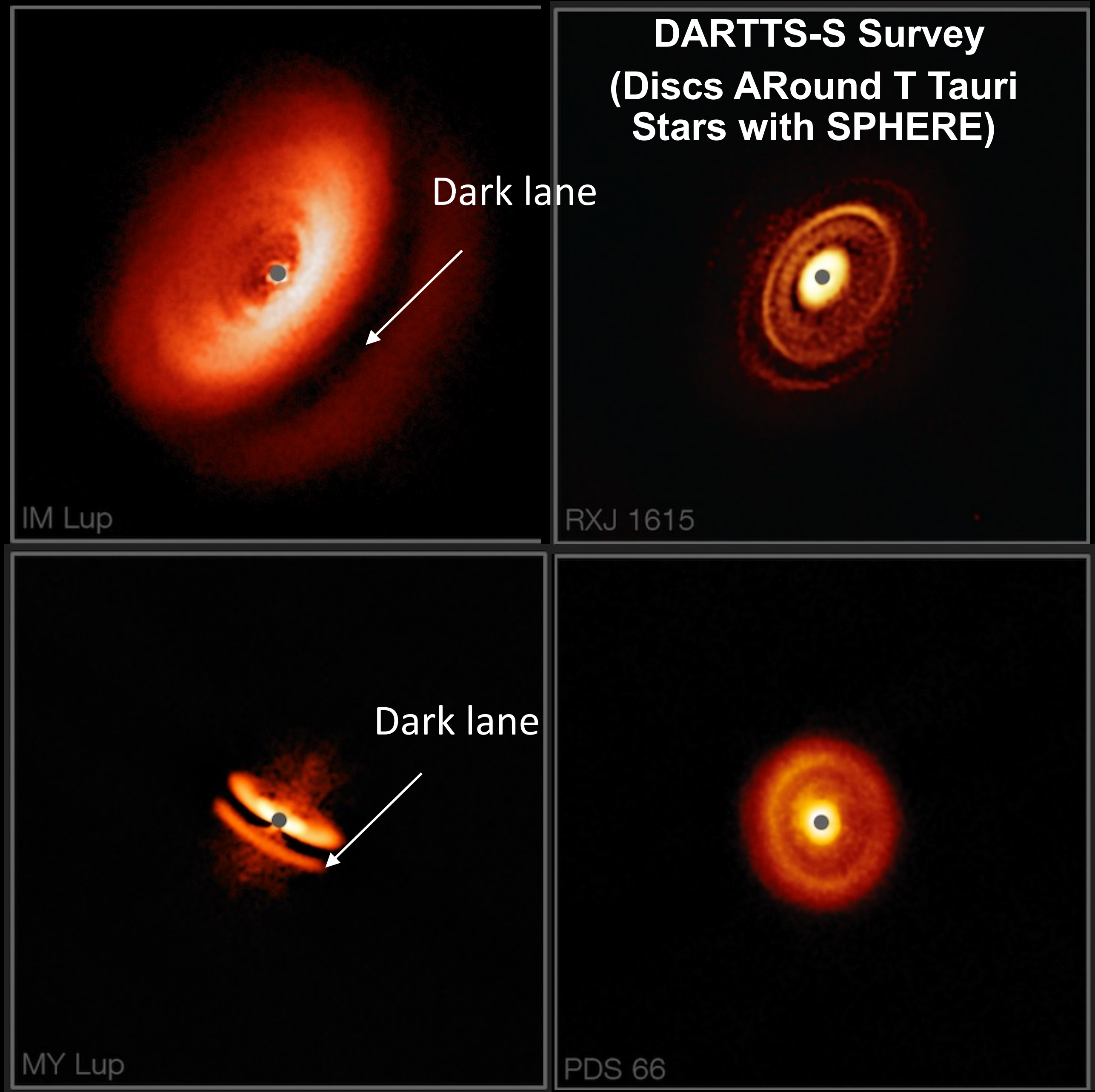
M_{disk} ~ 0.01 M_*

T_{bol} ~700-3000 K

Age ~10^6 yrs

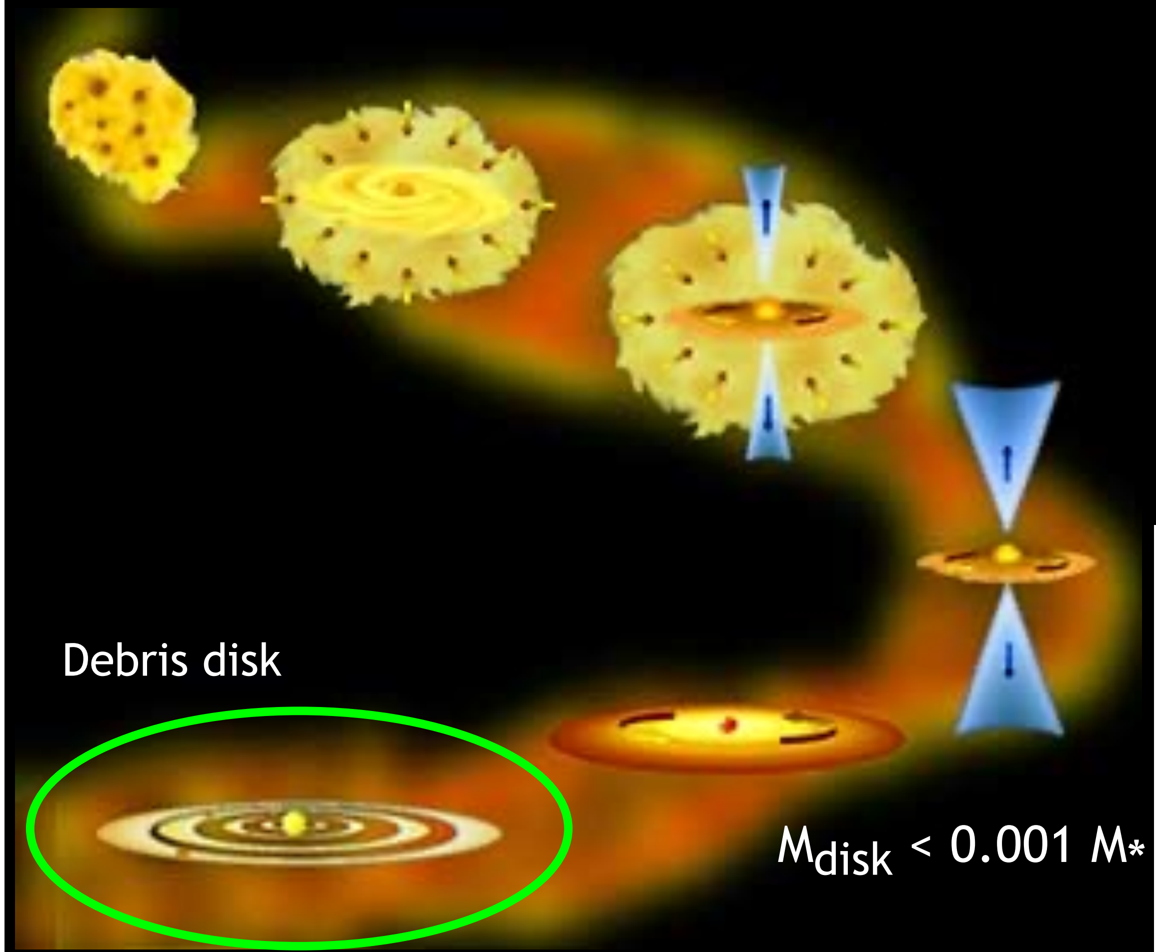
Since the circumstellar disk becomes a planetary system, it is called protoplanetary disk in this stage..

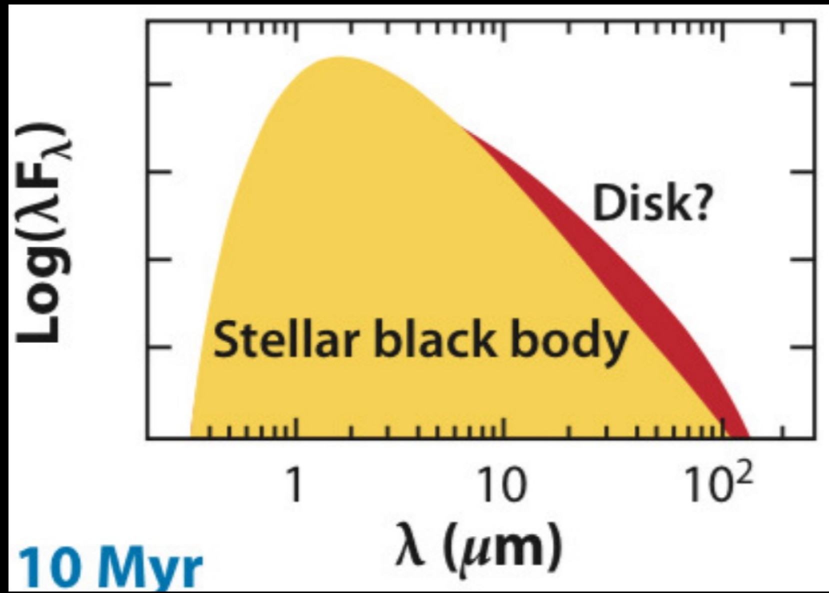
Class II (observations)

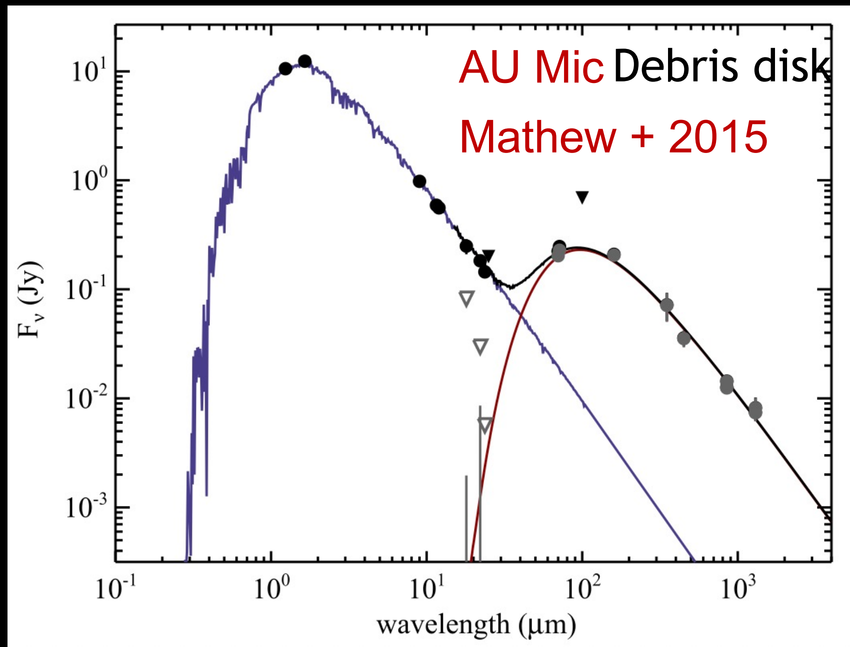


Avenhaus+2018

Class III (star + debris disk)





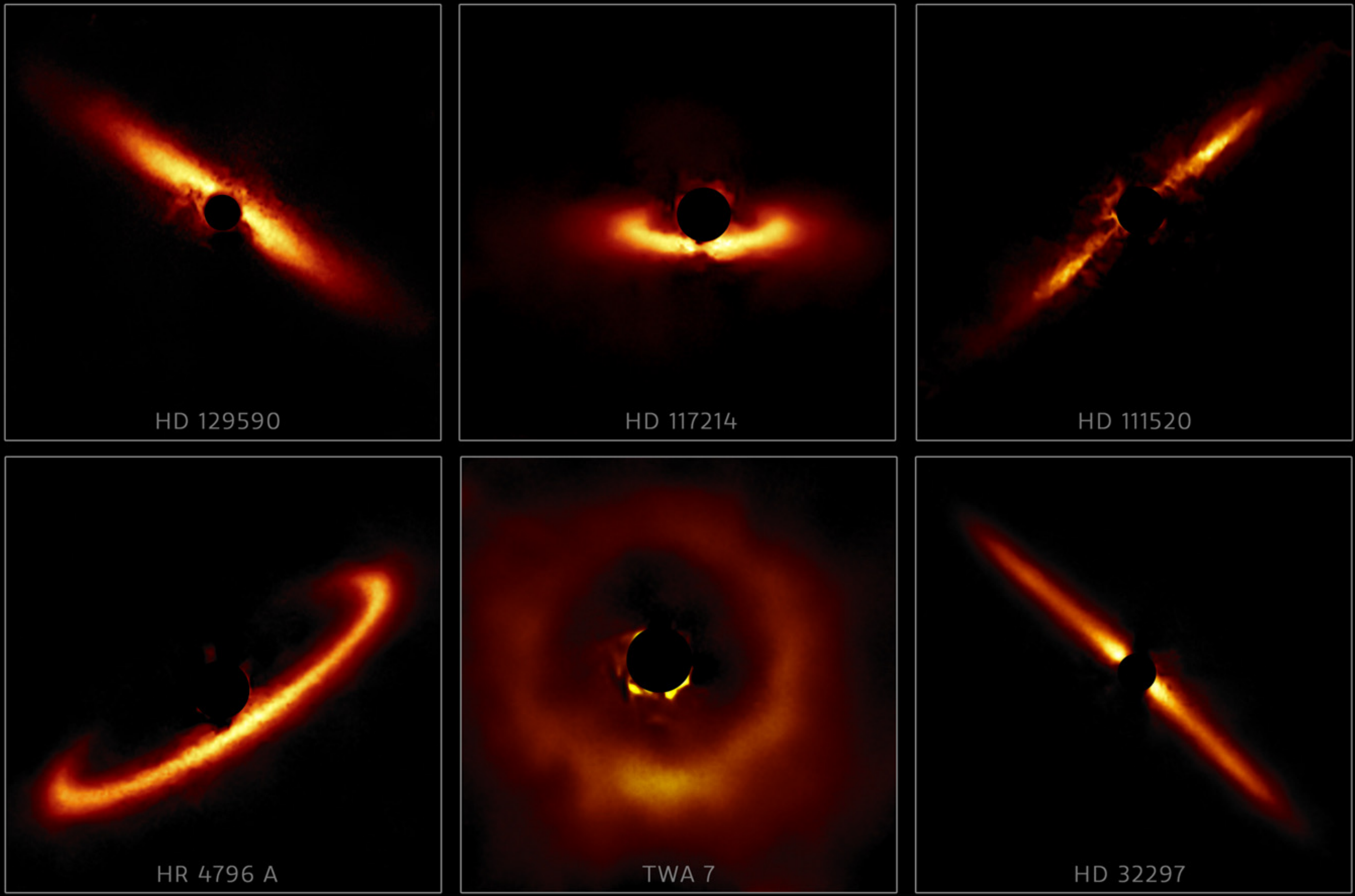


M_{disk} < 0.001 M_*

T_{bol} >3000 K

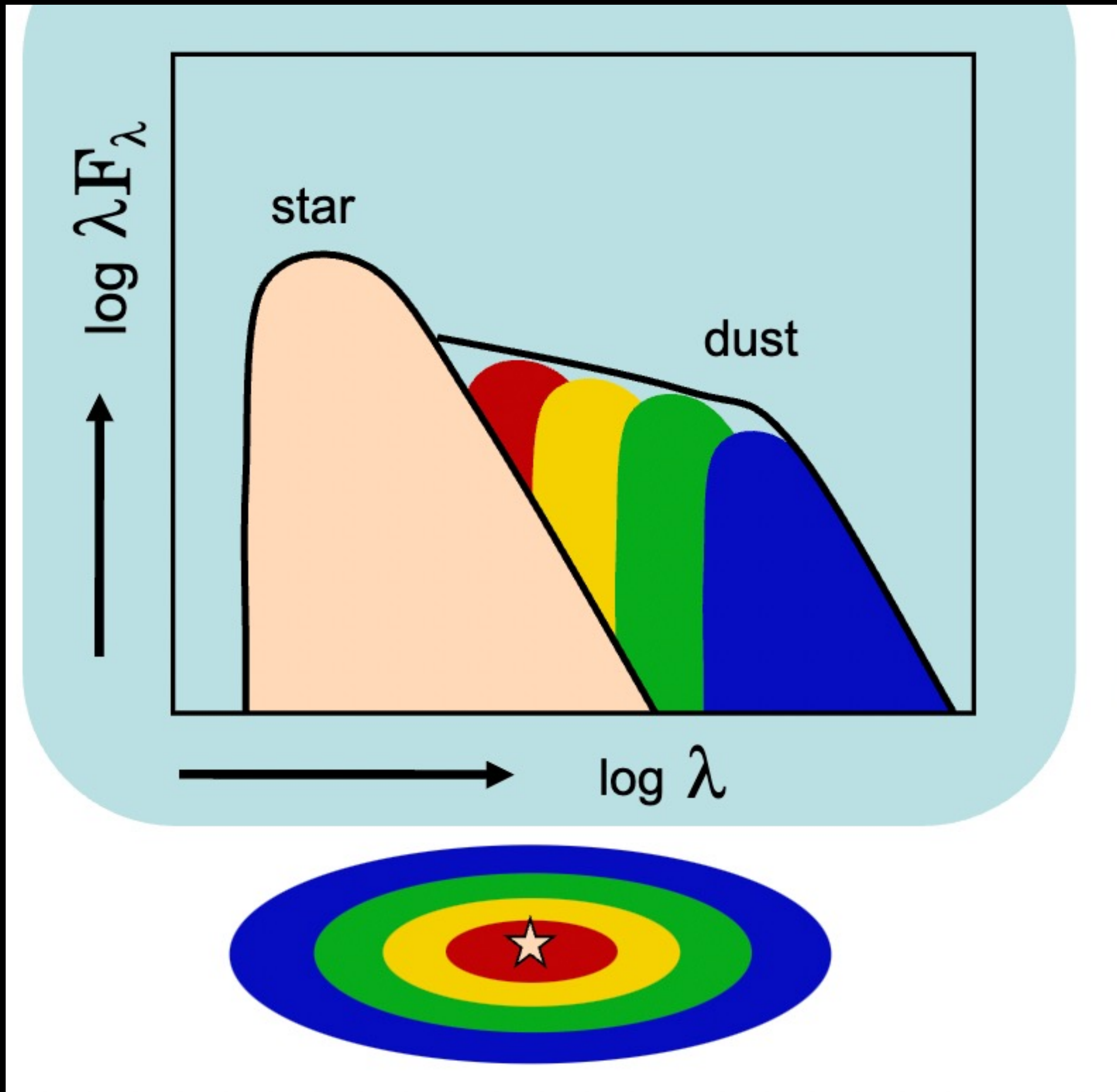
Age ~10^7 yrs

Class III (observations)



GPI (Gemini planet image)

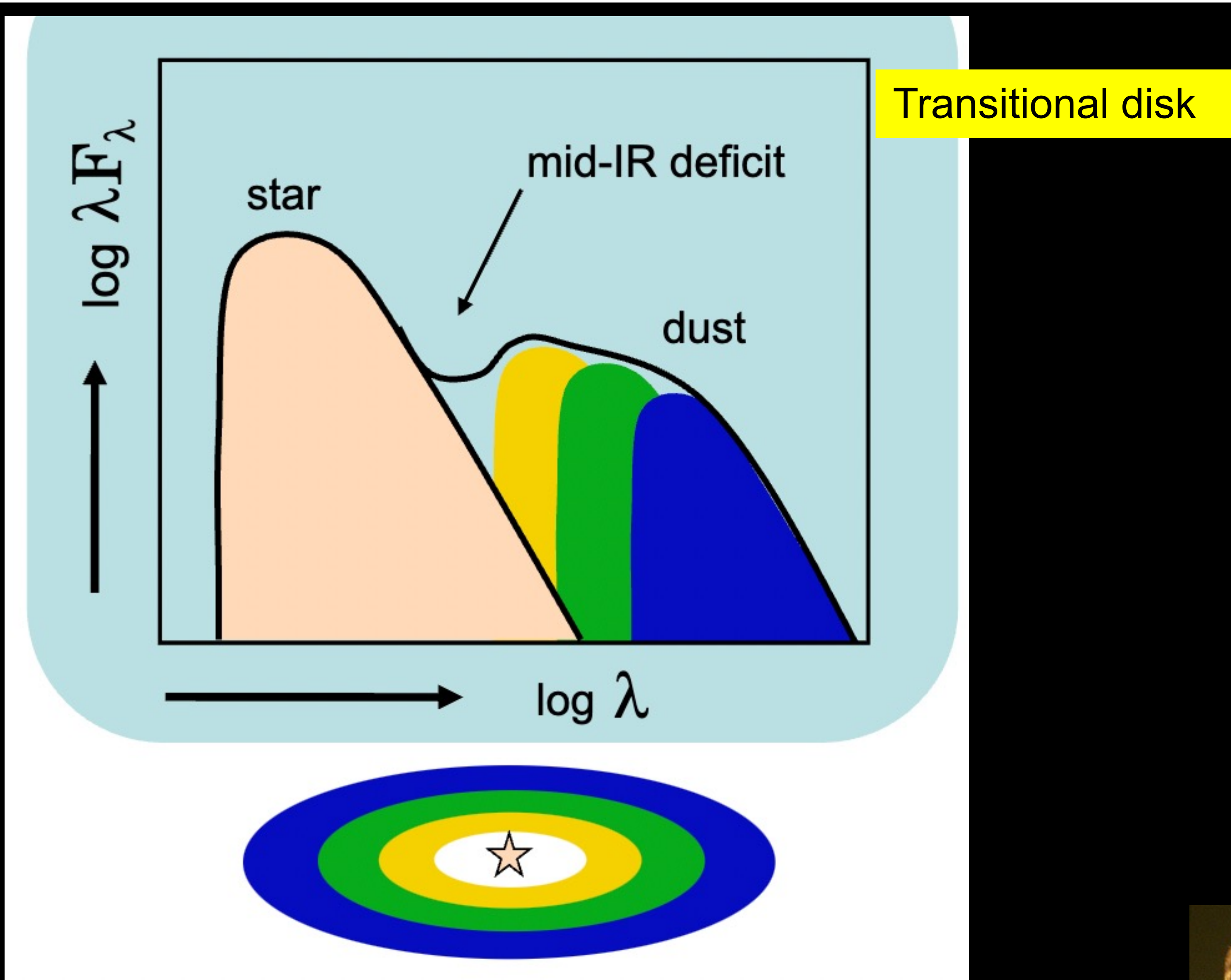
Flat spectrum (class II)



Full disk

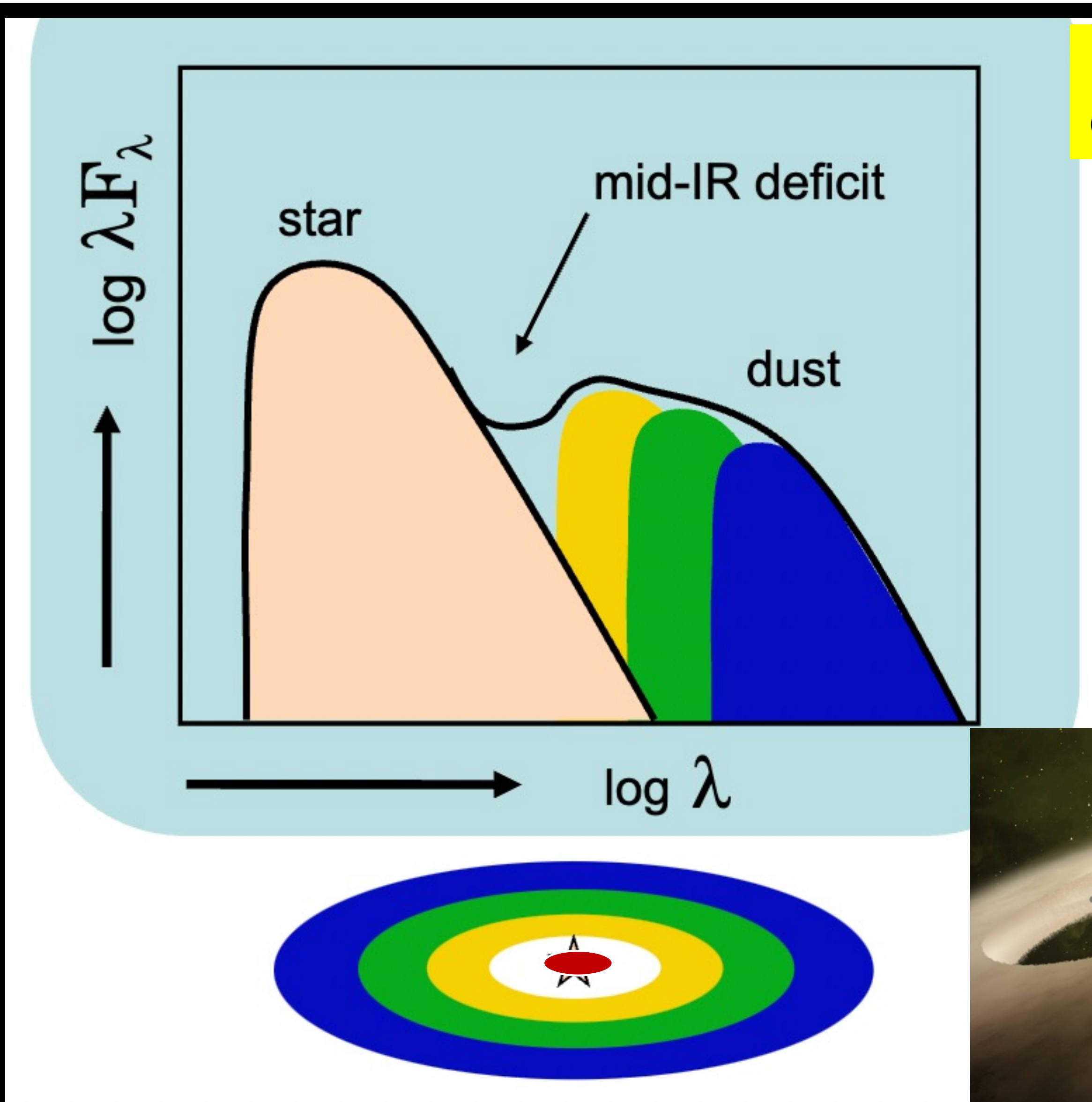
The disk SED shows a flattened shape that can be explained for a superposition of several disk layers emitting as a BB at different temperatures.

Flat spectrum



Based on the modelling of the spectra observed by Spitzer telescope, Calvet + identified many of these protostellar disks. ALMA has confirmed their central cavities

Flat spectrum

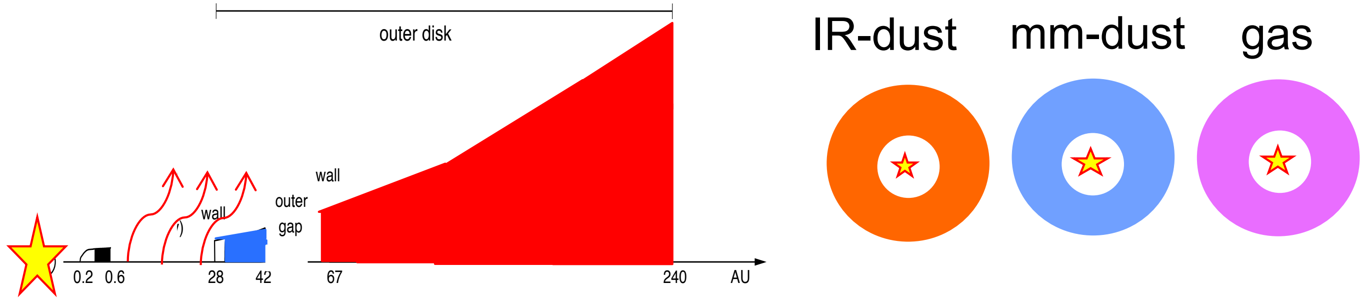


Pre-Transitional disk

Terrestrial protoplanets?

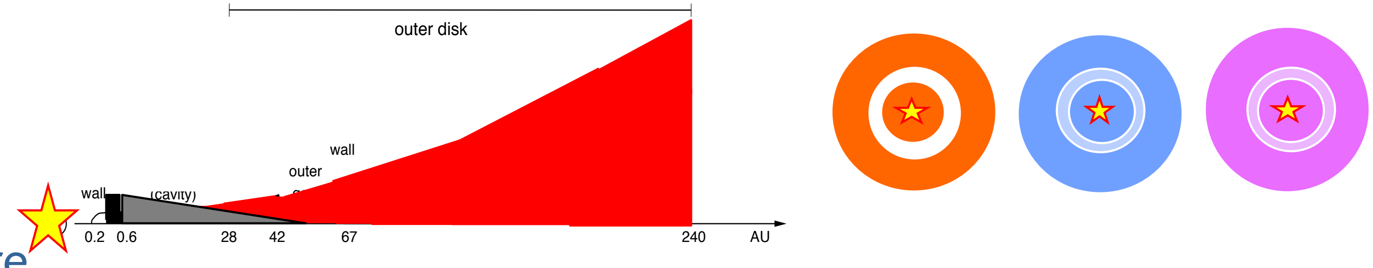
A subset of these disks shows still a significant amount of dust inside the cavity

Origin of cavities in Transitional disks

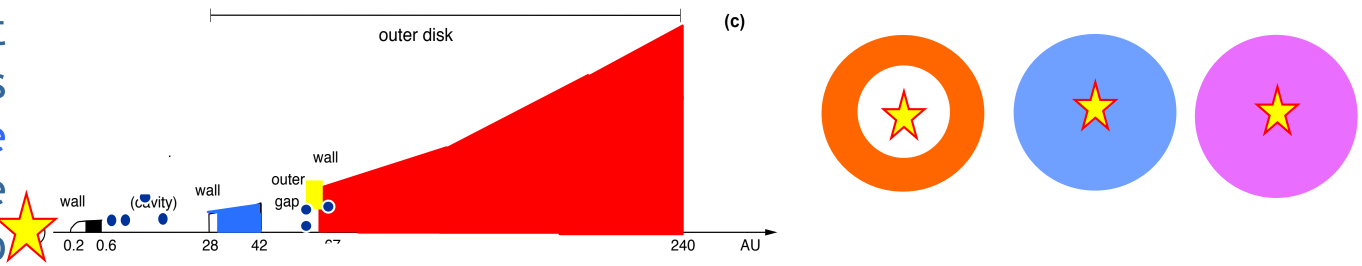


Photoevaporation

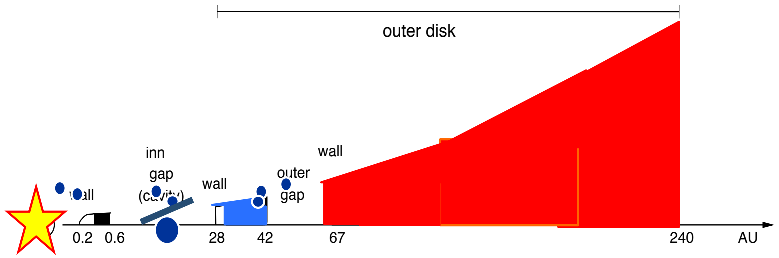
EUV or X rays from the Star

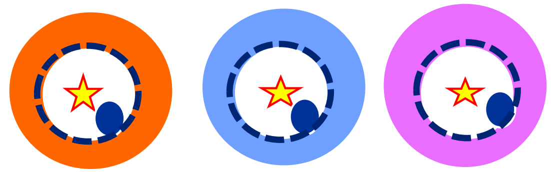


Geometric shadowing.
Shadow casts by a wall or residual disk



Grain growth Some cavities are seen in IR scattered light but not in mm wavelengths. This suggests that they are not true cavities, but regions where dust grains may have grown to a size whose IR emission is undetected.





Companions

The presence of another body that dynamically creates a gap

Adapted from Van der Marel

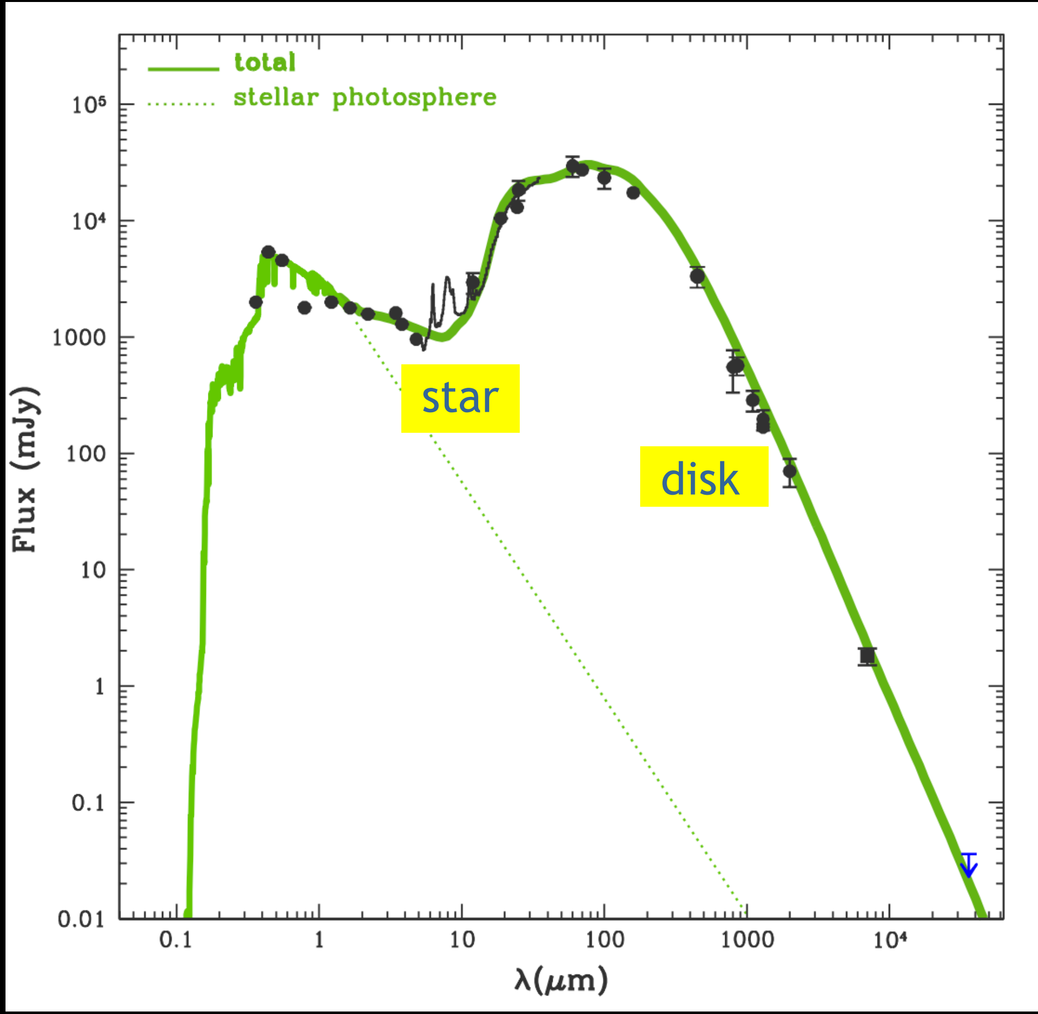
The protoplanetary disk of HD169142

Relatively isolated intermediate mass protostar with an age ~6Myr (D=140pc Gaia)

This source has been observed from ultraviolet to cm wavelengths.

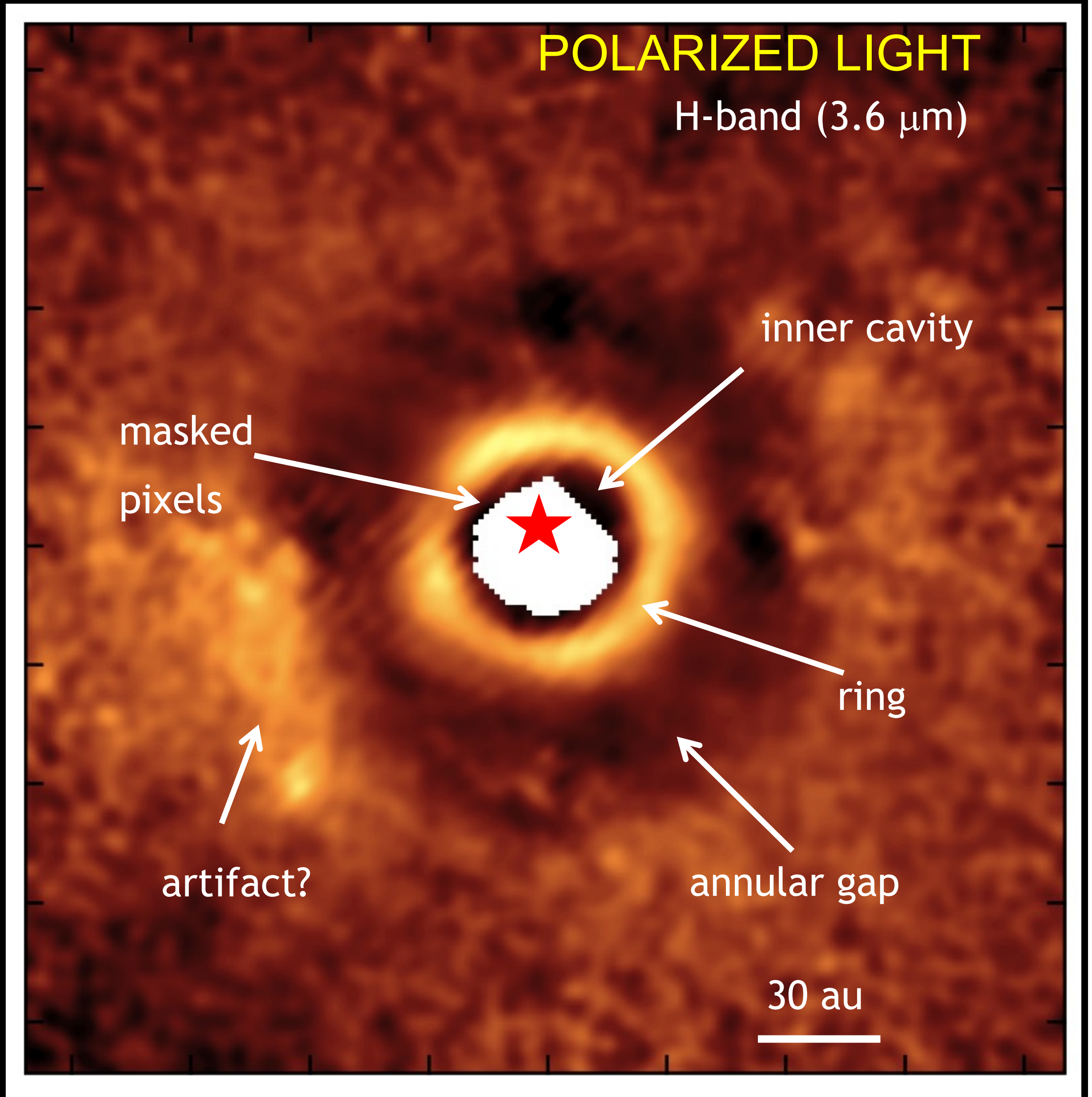
Based on the SED modelling (deficit in the near IR) Grady+(2007), Meeus+(2010), Honda+(2012) predicted the existence of a central cavity in this protoplanetary disk=> Transitional disk!

Dent + 2006, Osorio + 2014



Near-IR polarized light imaging of HD169142

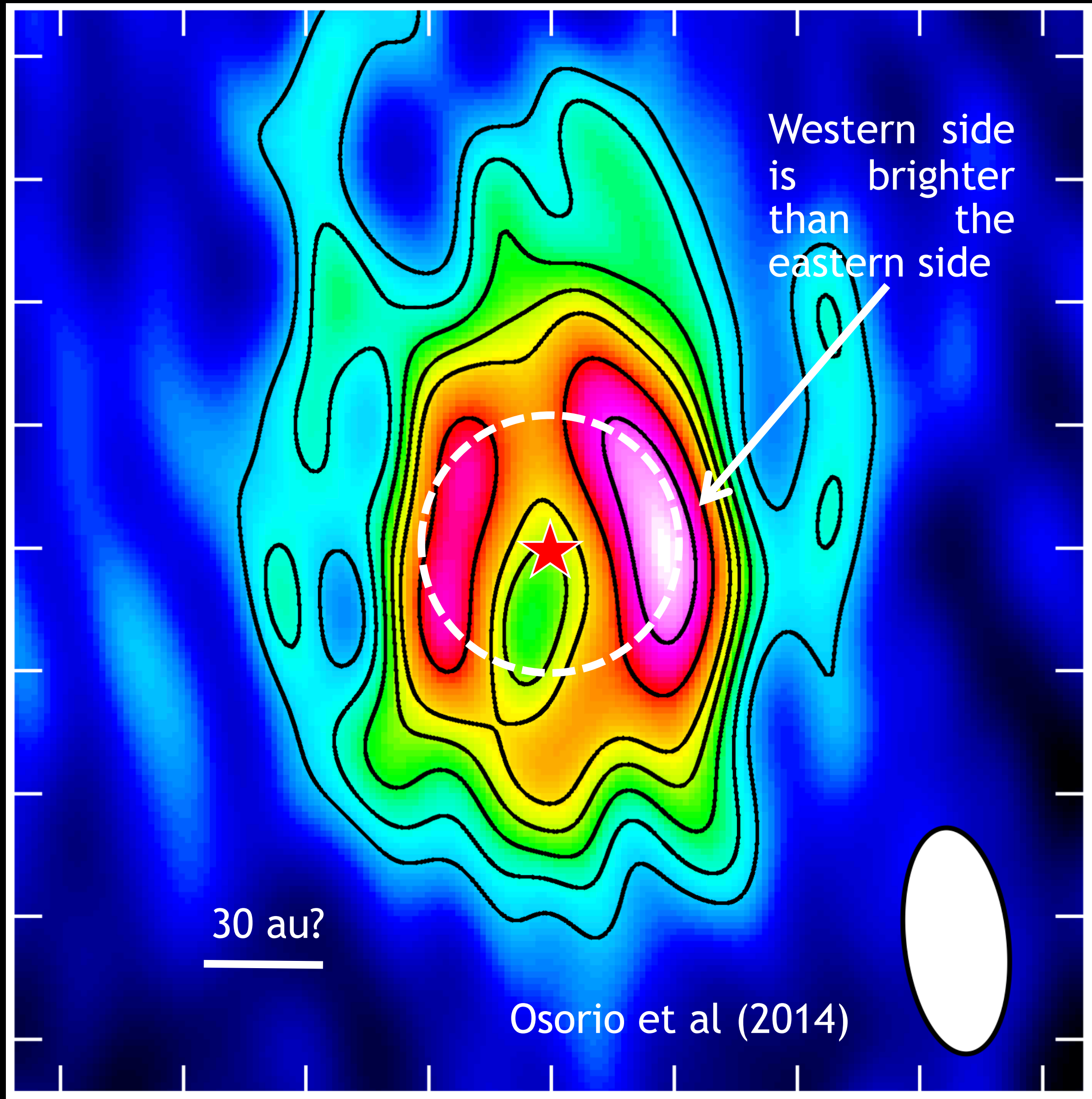
- Face-on disk, R=200 au
- Central cavity
- Ring at 30 au (cavity's wall)
- Gap spanning from 40 to 70 au, where the surface brightness decreases by a factor of 3.



(Quanz et al 2013)

VLA 7 mm imaging of HD169142

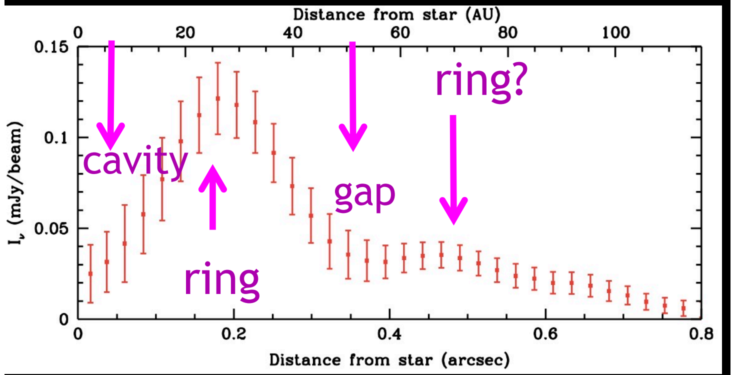
The cavity and ring were confirmed (may be a second ring) by dust thermal emission.

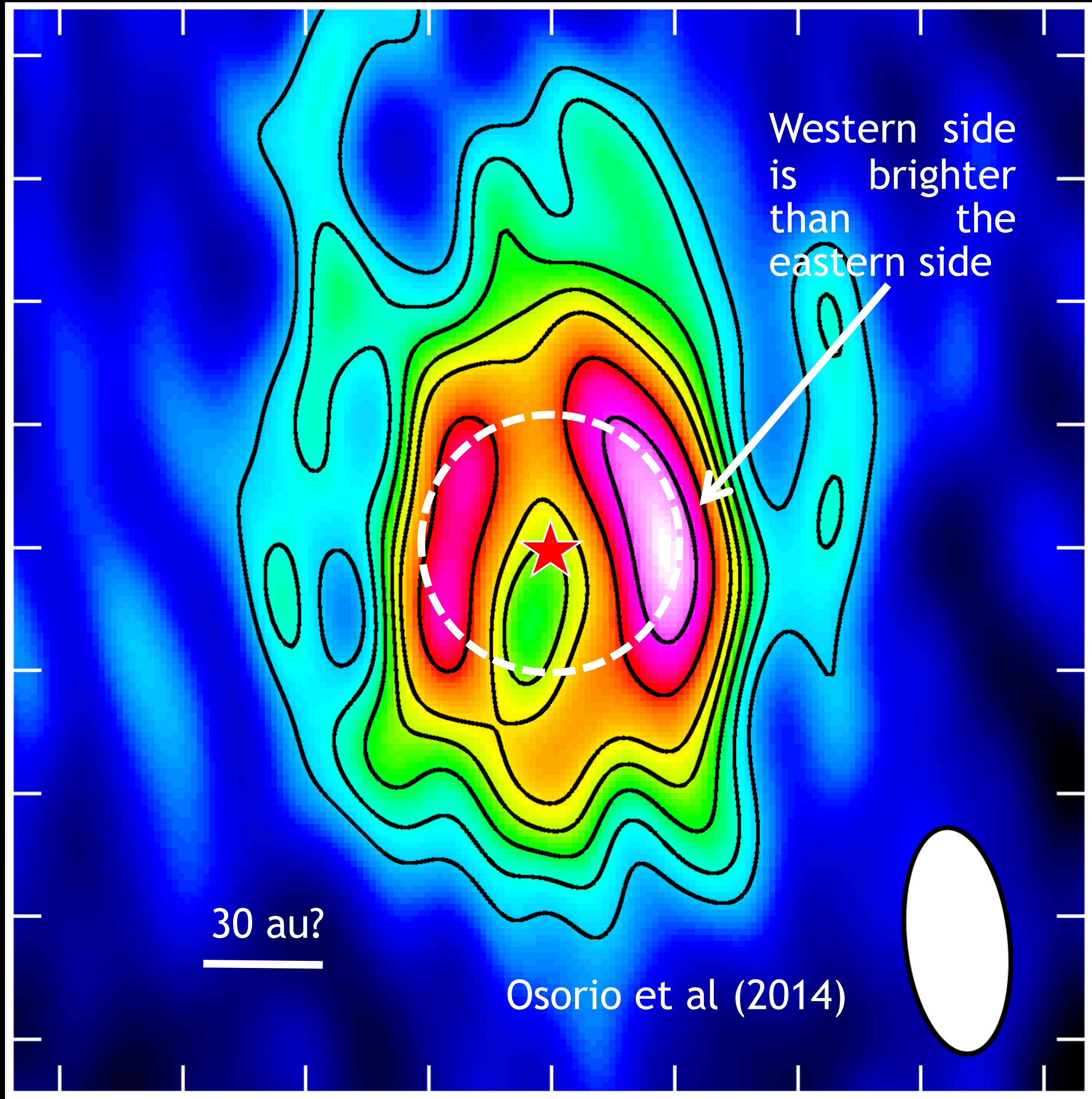


VLA 7 mm imaging of HD169142

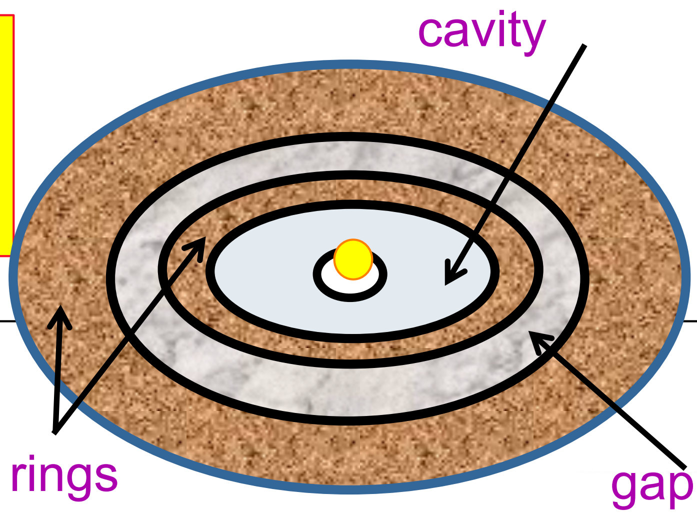
The cavity and ring were confirmed by dust thermal emission.

7mm azimuthally-averaged radial profile

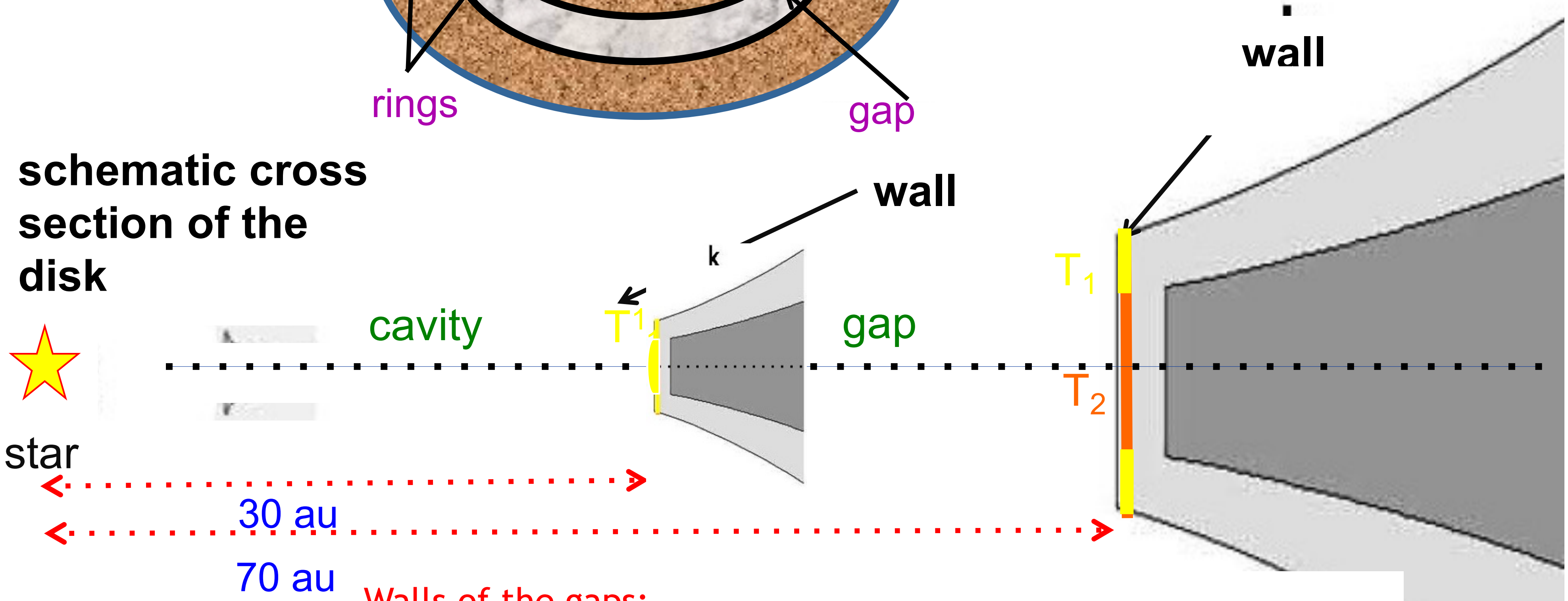




Double-ringed disk

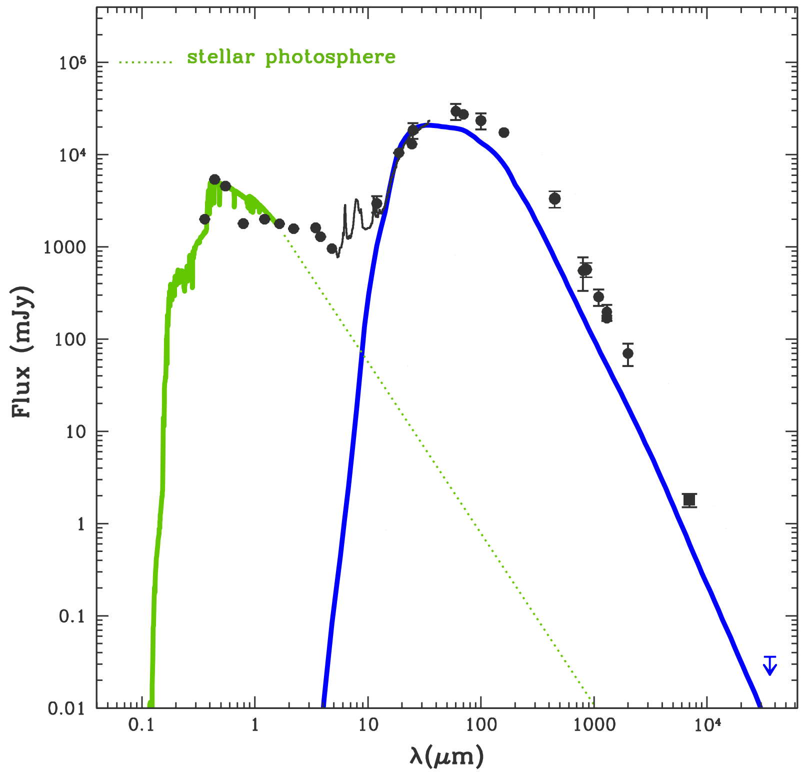


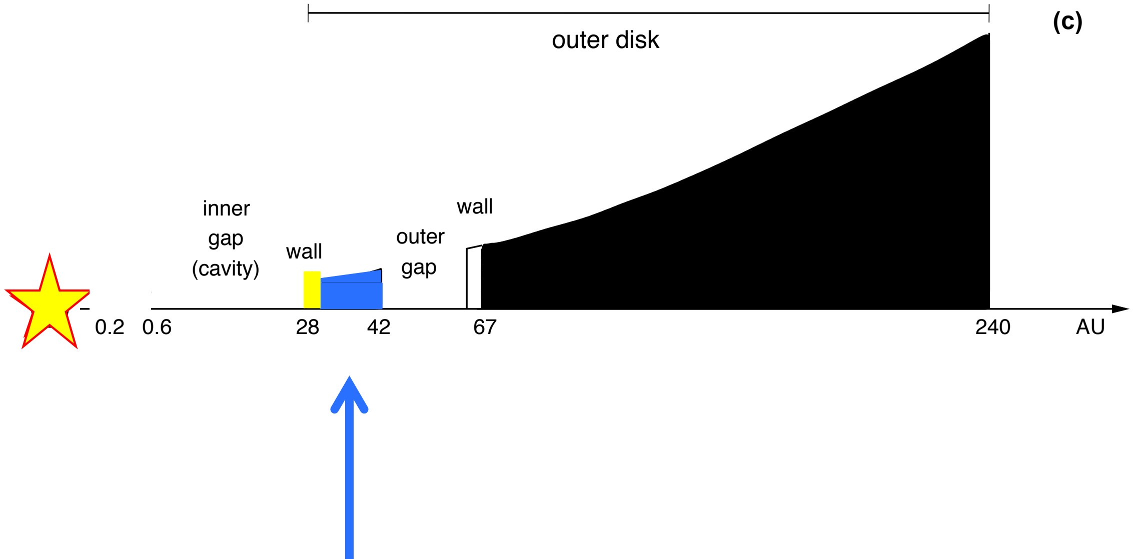
schematic cross section of the disk



Walls of the gaps:
T_1: illuminated zone
T_2<T_1: shadowed zone
large accumulation of big grains in the outer edges of the walls of each gap (relevant to explain 7mm image)

Contribution to the SED of the disk components

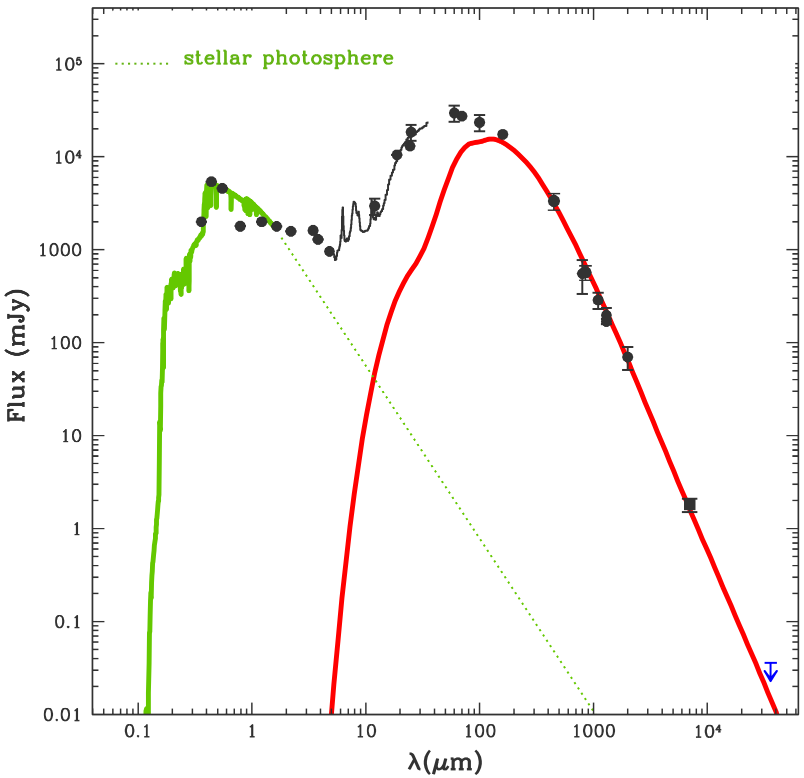


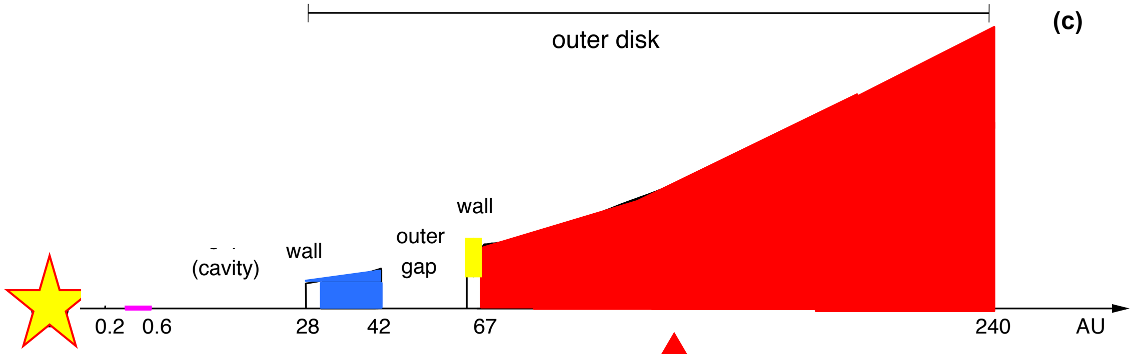


Disk + Wall of the inner Gap

H=9au, T_1=110K,

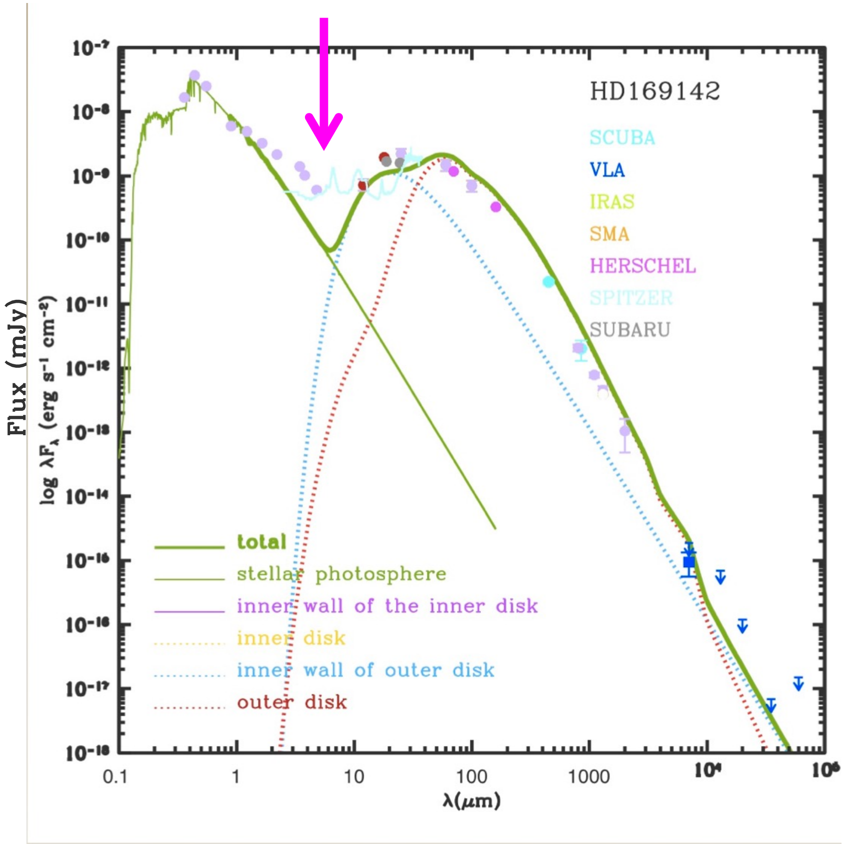
Contribution to the SED of the disk components

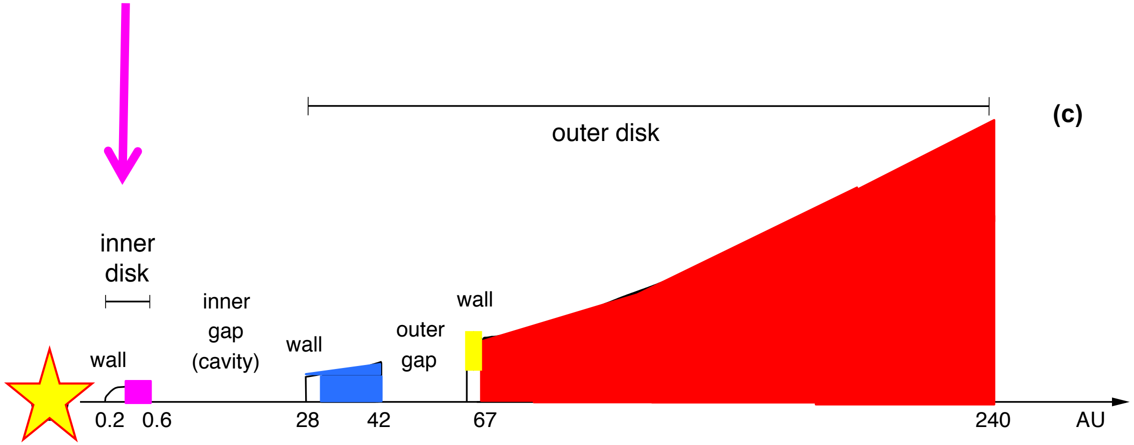




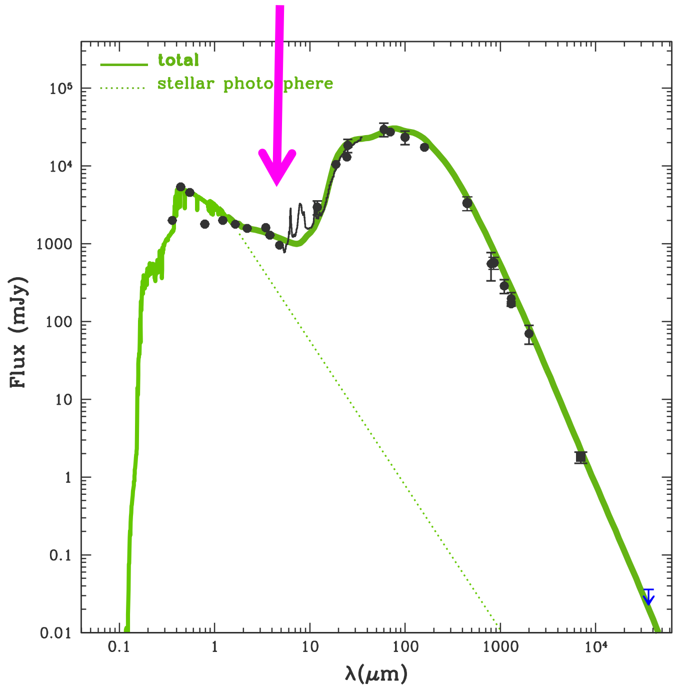
-Outer disk + Wall of the Outer gap
(H=30 au,
upper layers: T_1=70K,
lower layers: T_2=40K)
-Illuminated fraction:10%

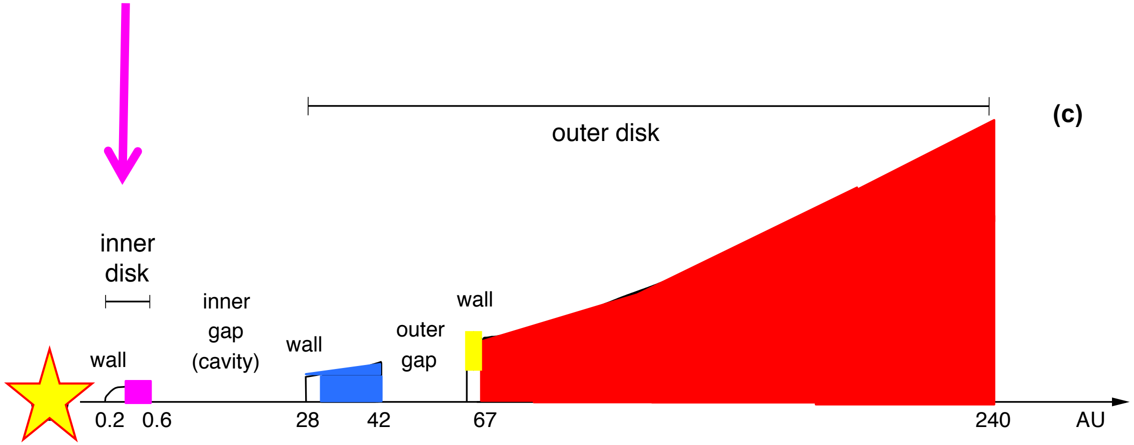
Contribution to the SED of the disk components

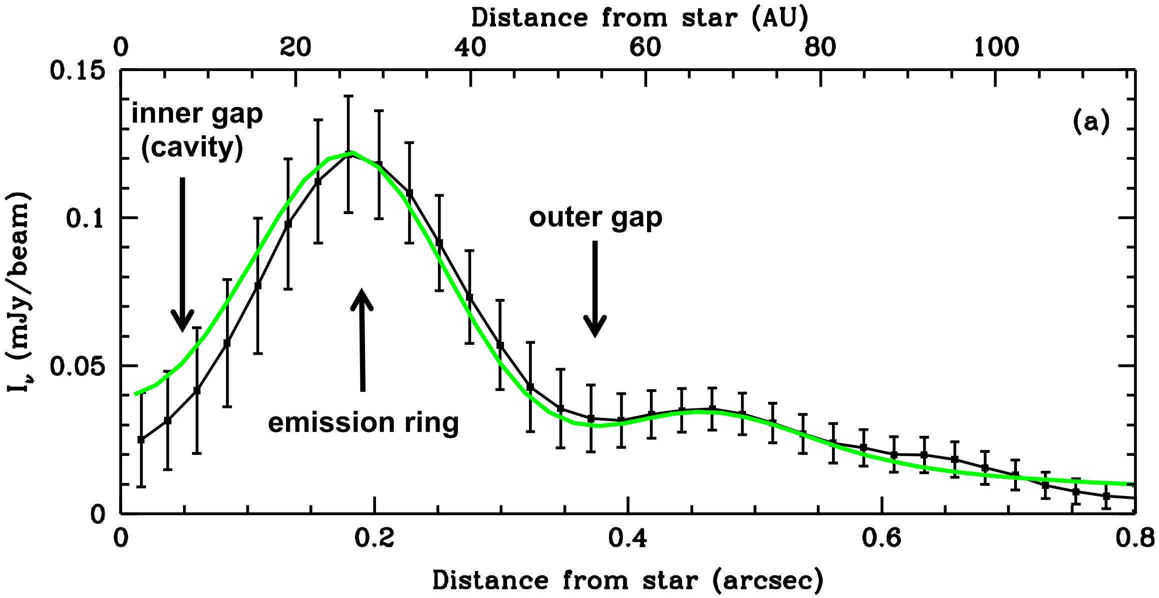


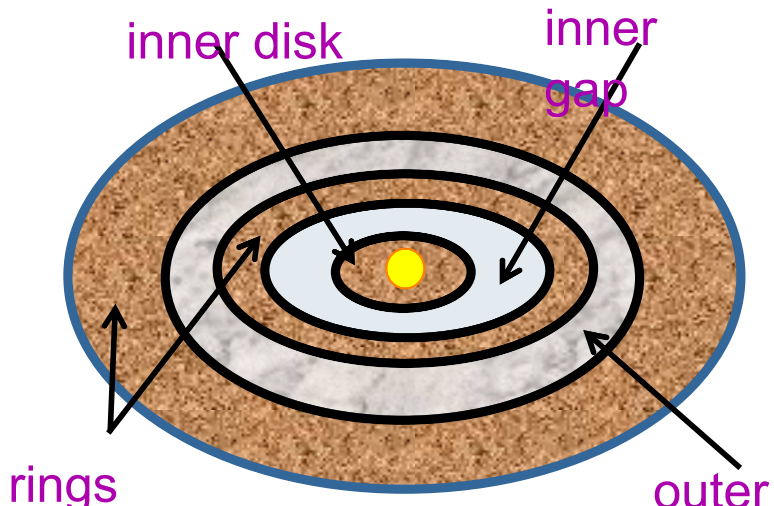


Contribution to the SED of the disk components



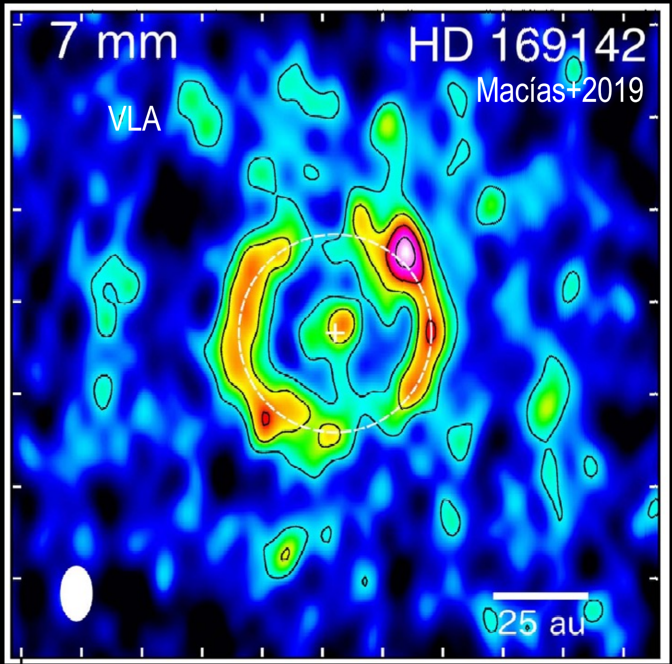


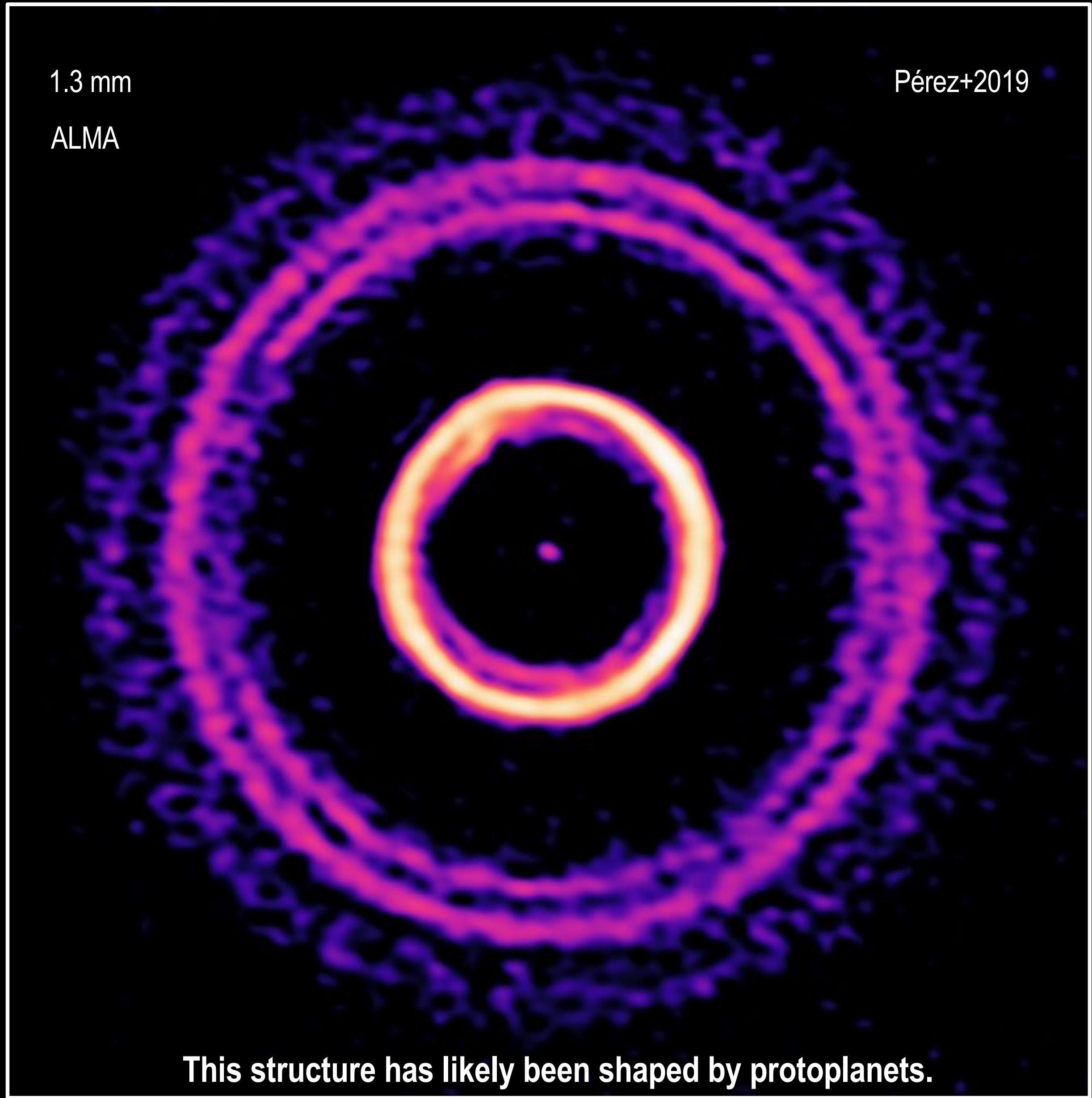


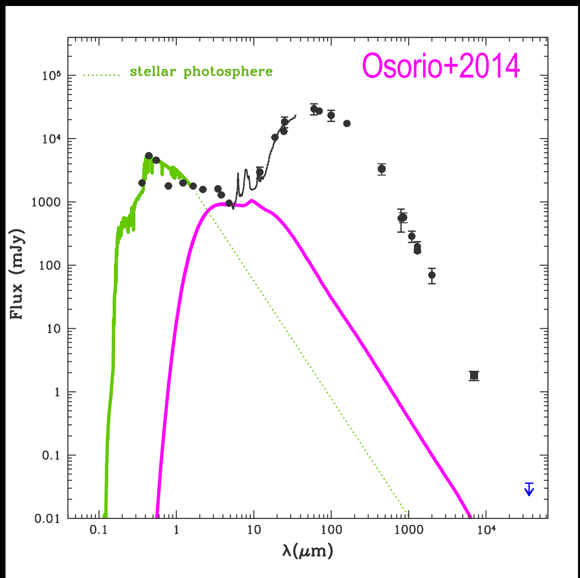


In conclusion this is a pre-transitional disk

ALMA and VLA observations of HD169142 disk







Signs of planet formation in the HD169142 disk

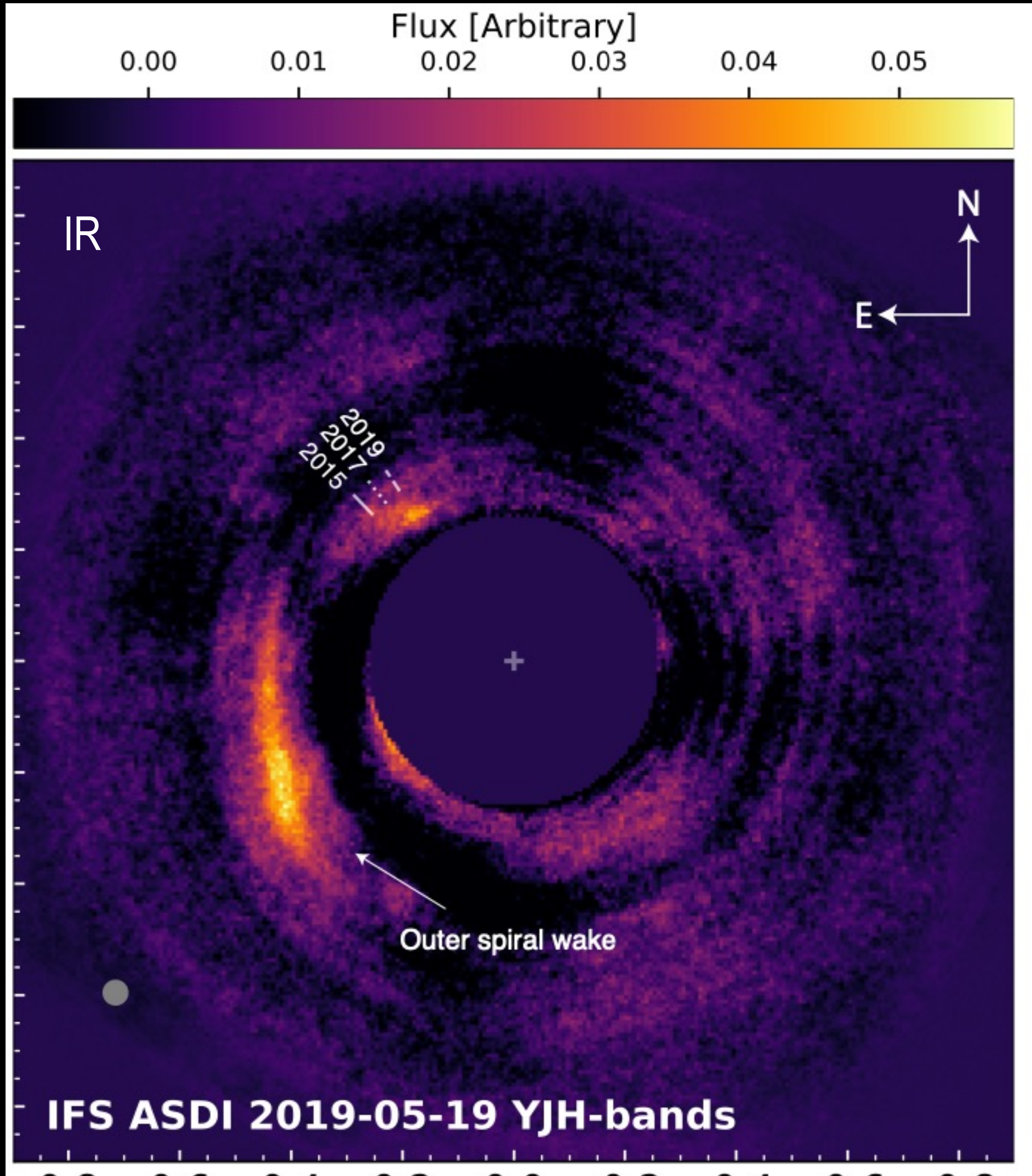
Sequential planet formation?

Protoplanet candidates inside of the cavity and gap (one of the most compelling cases).

Orbital proper (Keplerian) motions, measured during 4 years, showing the candidate is orbiting the star.

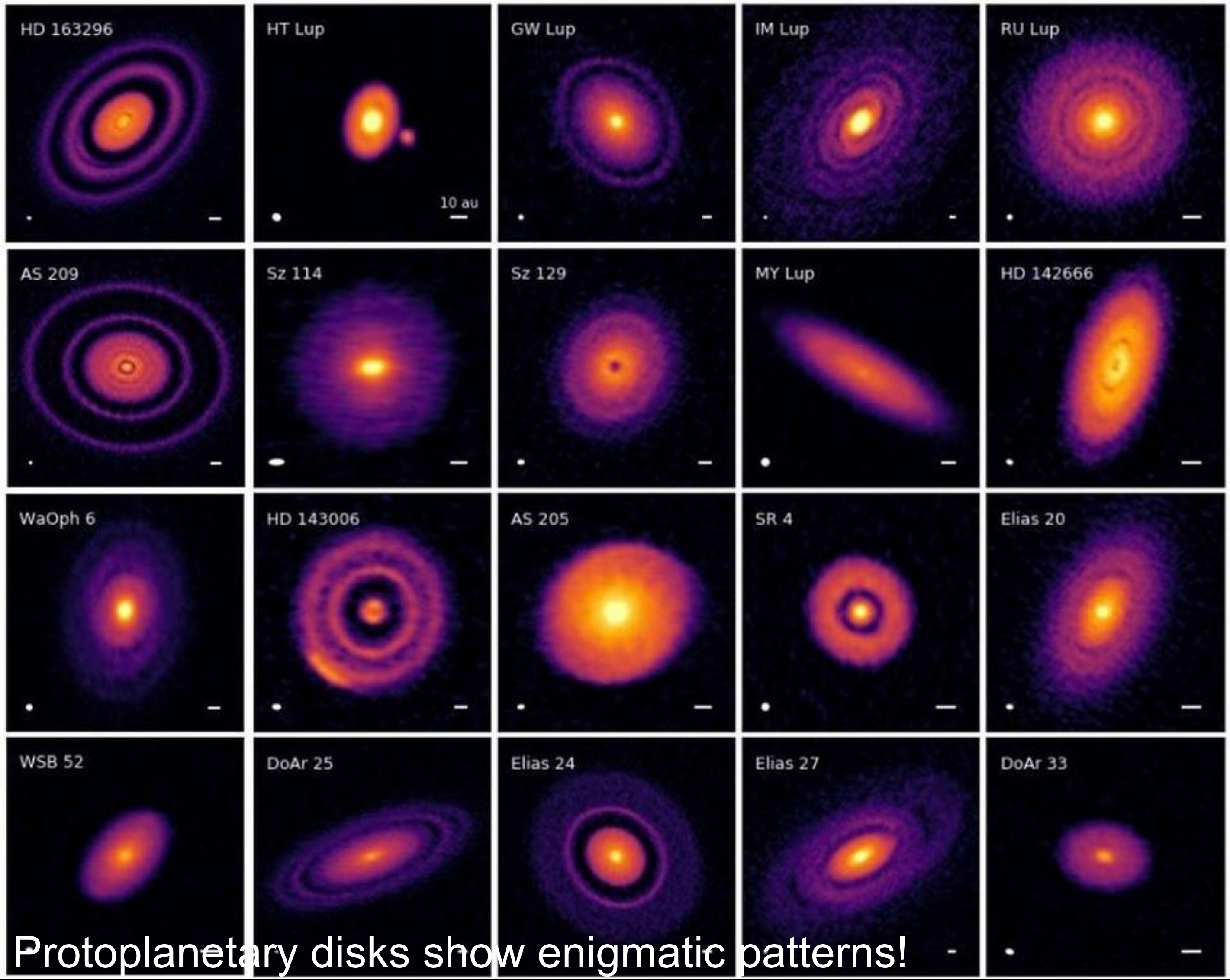
This would be the first baby planet where researchers have been able to follow its movement.

Grattom+2019, Hammond+2023



Transitional disks: evidence of planet formation?

In the last years the focus on the study of star Formation have shifted to planet Formation



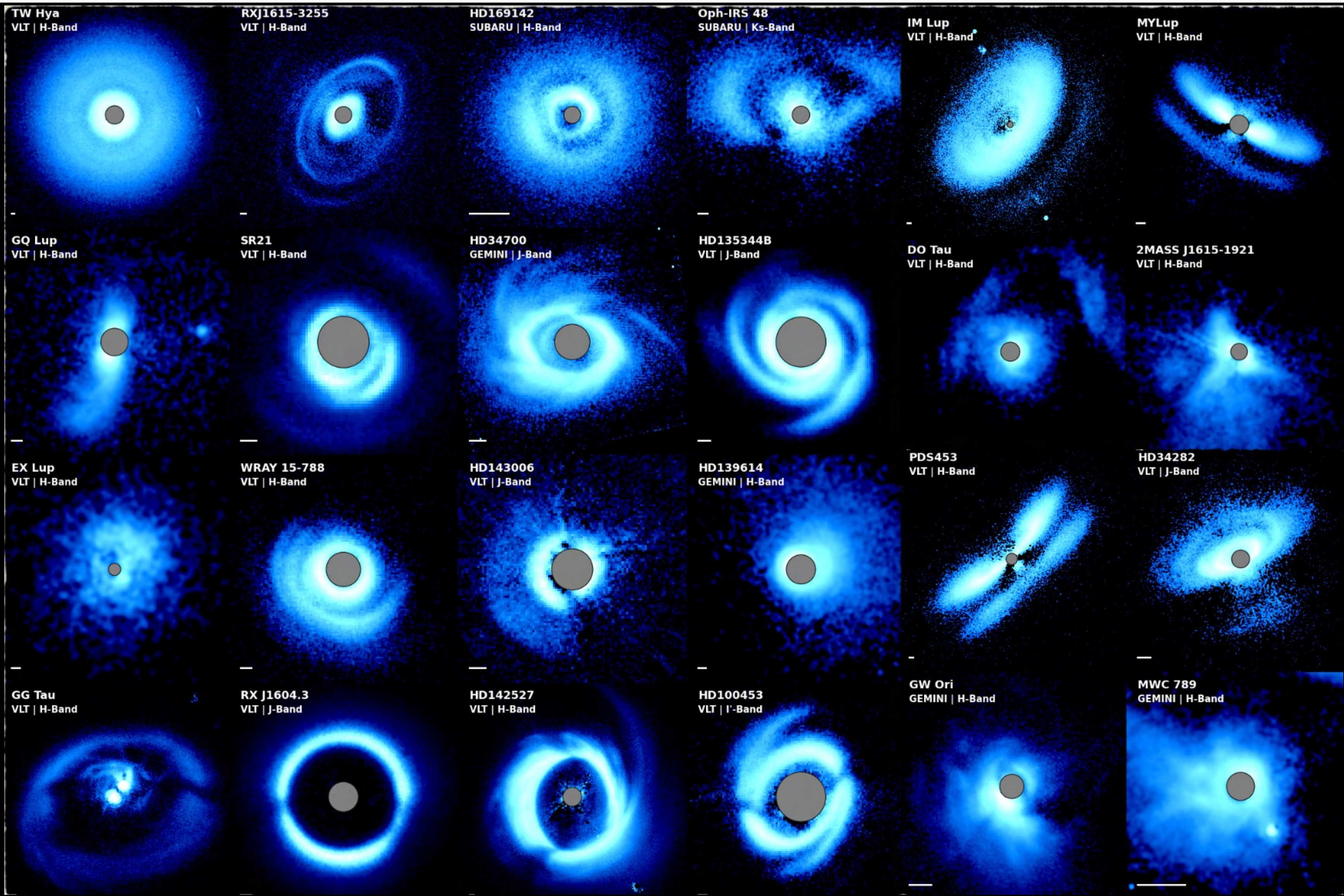
Signspots of planet formation:

- Cavities
- Walls
- gaps
- rings
- Spiral
- Azimuthal asymmetries

reminiscent of the lopsided structures produced by dust trapping of large grains

DSHARP+2018

Transitional disks: evidence of planet formation?

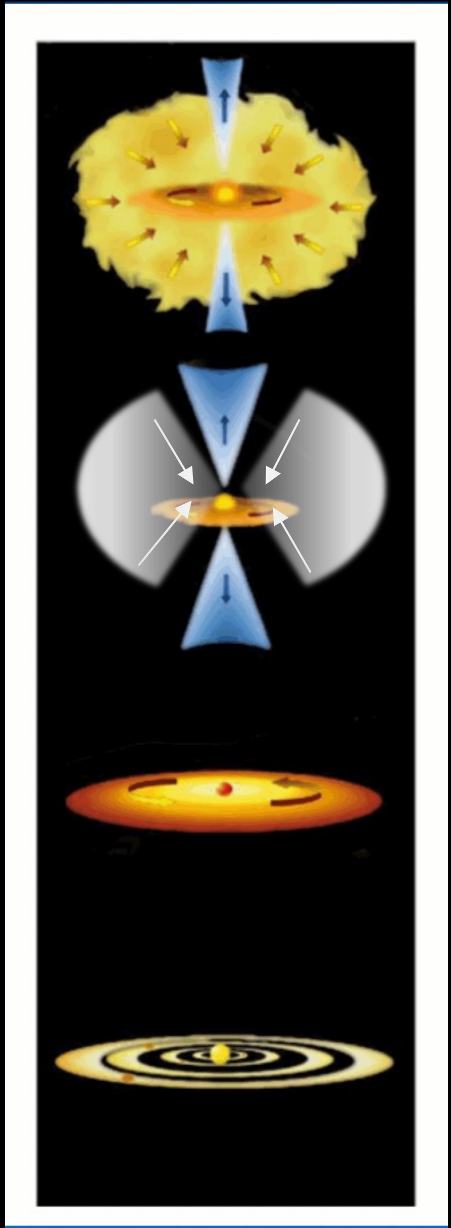


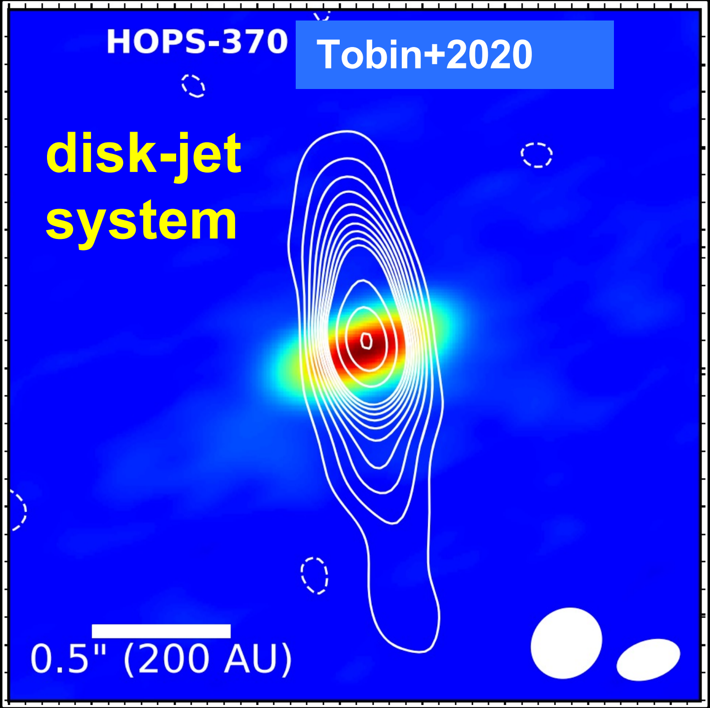
Protoplanetary disks show enigmatic patterns!
such as bright rings, empty gaps, spirals, etc

Garufi+ 2023 PPVII

Planet formation in extreme conditions

How do other scenarios fit into the standard star-formation paradigm?





Are disk/jet systems present in other star-formation scenarios?

Examples:

-Multiple star formation

-High-mass star formation

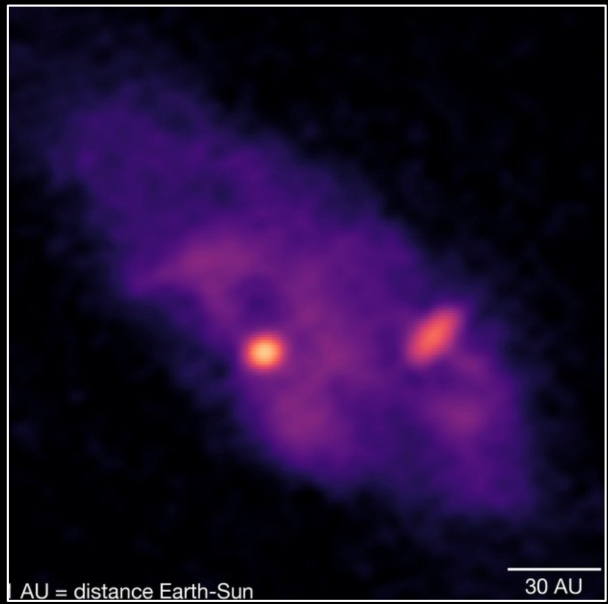
Can planetary systems be formed in these scenarios? How these planetary systems are expected to be?

The study of these additional star/planet forming scenarios can provide the clues for a better understanding of the conspicuous diversity of all the known exoplanetary systems.

Formation of disks in multiple stellar systems

The standard star formation scheme is not directly applicable to binaries:

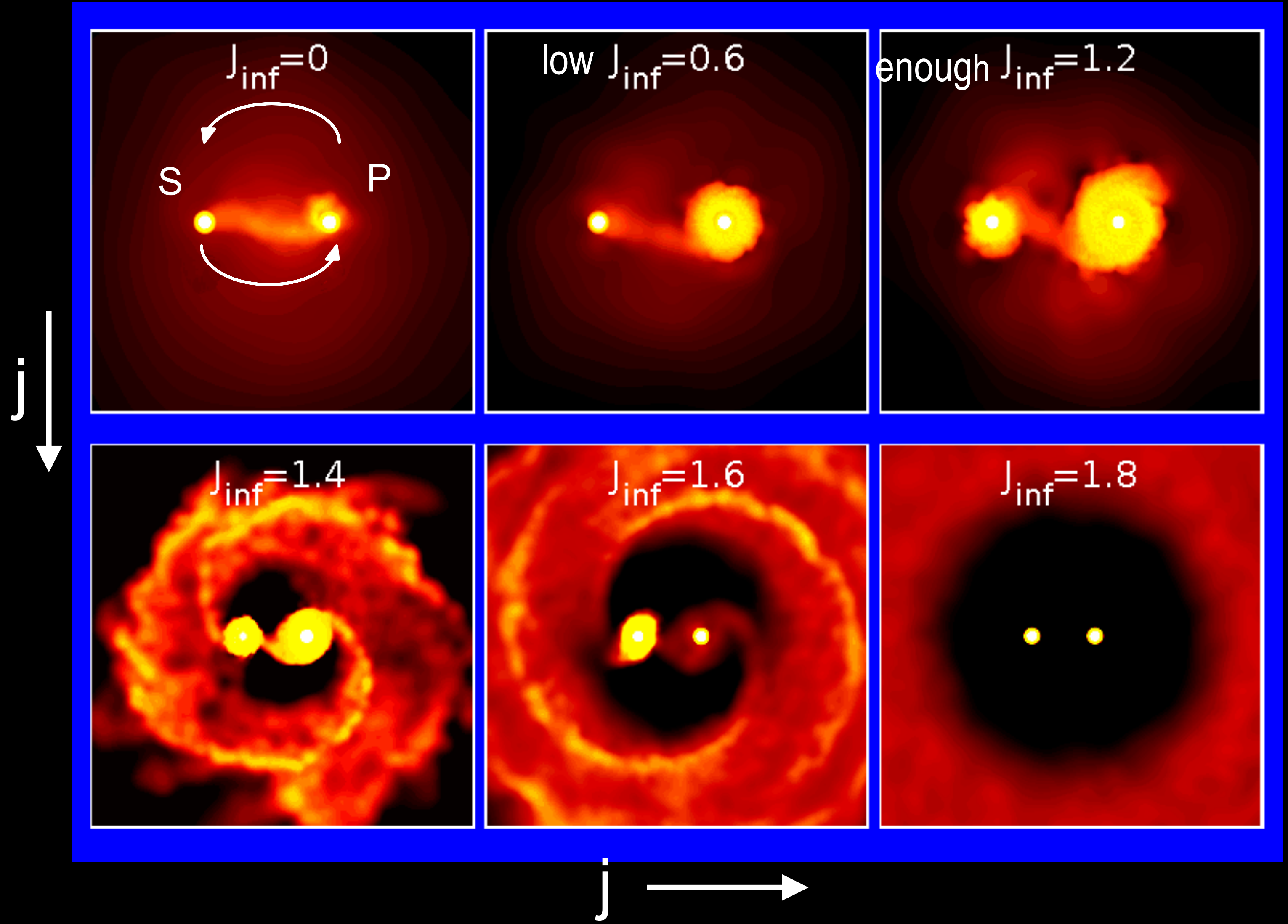
- Each star may develop its own disk and jet, but the whole system is more complex.
- There may be up to three disks: circumstellar disks and also a circumbinary disk.
- In close binaries there may be interaction between stars, even matter exchange.



- The evolution of one star may affect the other; one of the stars may even be formed from the fragmentation of its companion's disk.
- High angular resolution data (<1'') are needed to disentangle the emission of the two stars, especially for those separated by <100 au.
- The standard paradigm of star formation may be used for the study of binary star formation, but it is more complex.

Formation of disks in binary systems (hydrodynamic simulations)

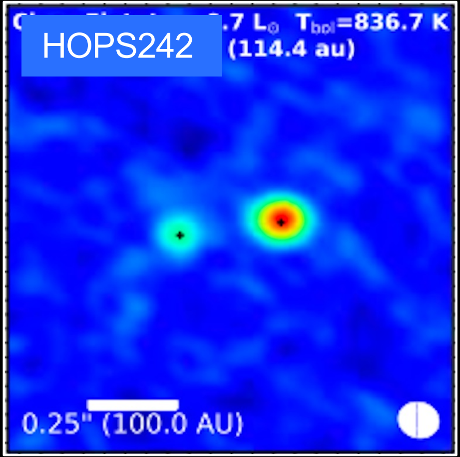
The revelant parameter for disk formation is the specific angular momentum of the infalling gas (**j** = **r** x **v**)



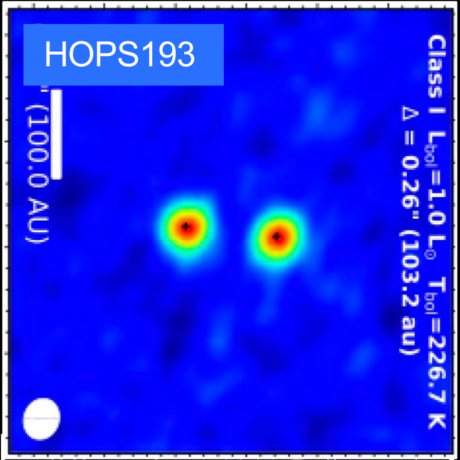
Bate 1997

In summary, a protobinary system might develop one, two or three protoplanetary disks.

Disks in binary systems (observations)

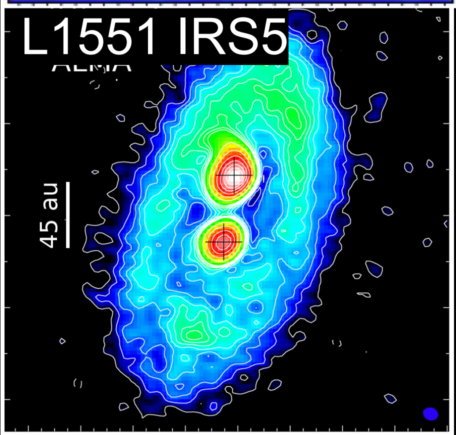


Tobin+2020

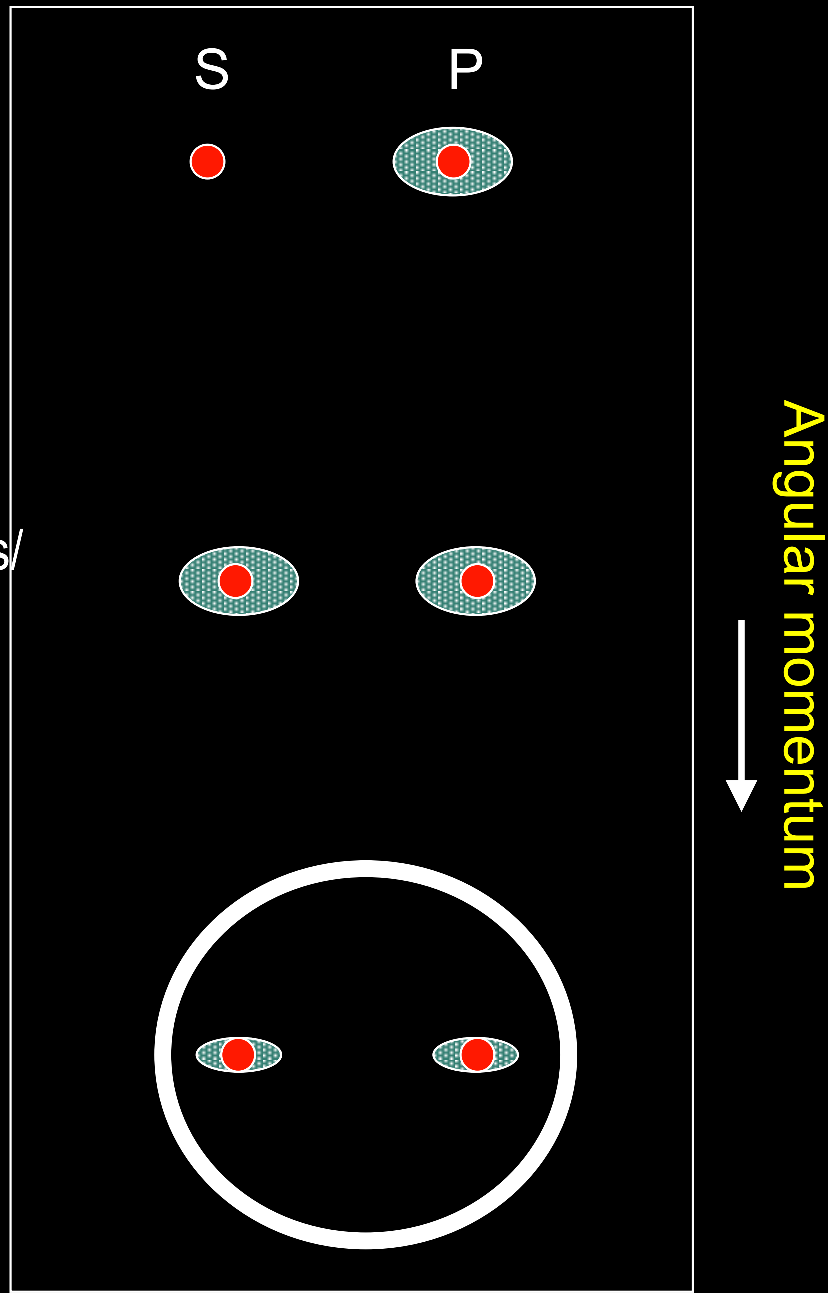


Tobin+2020

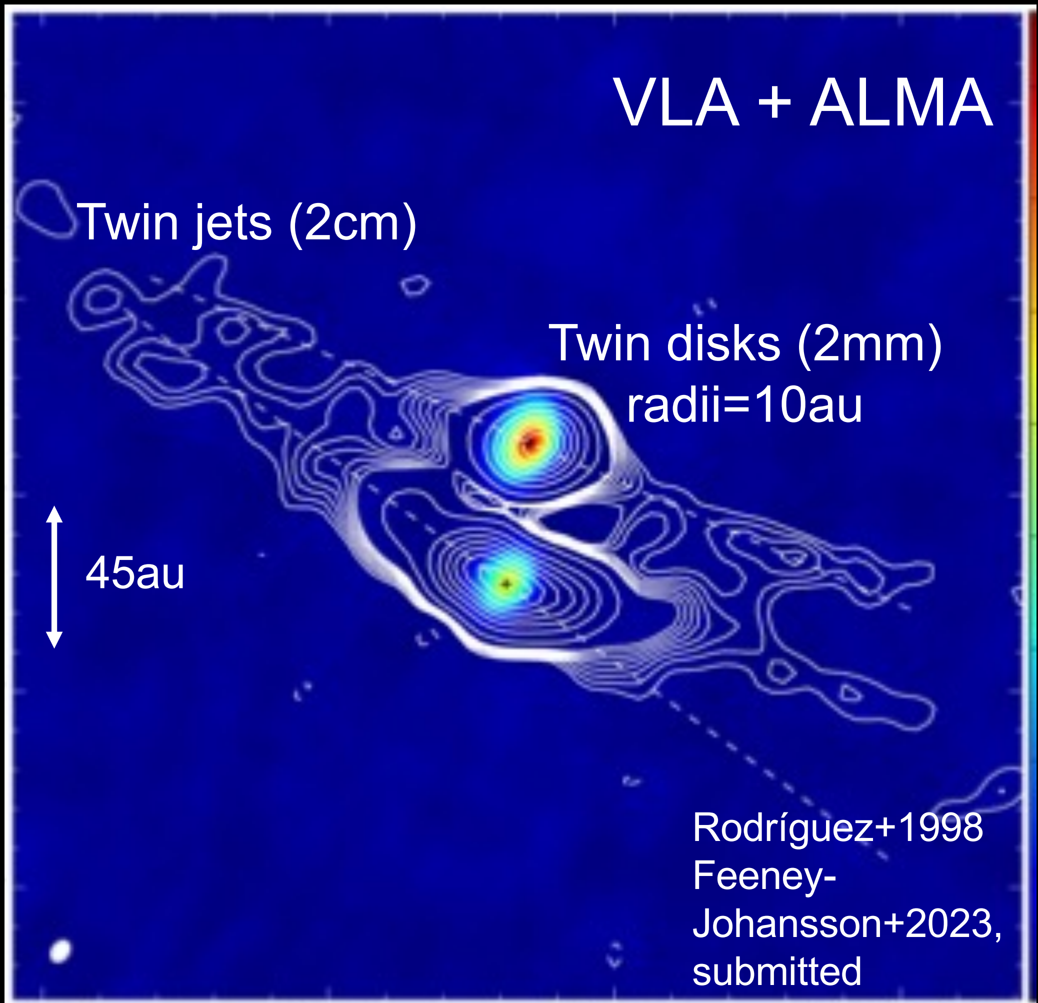
https://spfe.es/en/catalogs/



Takakuwa+2020



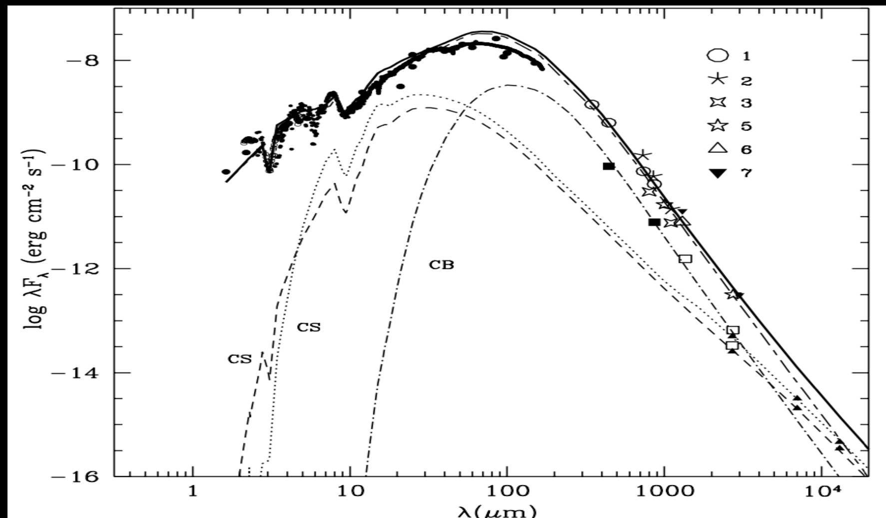
A comprehensive modeling of the protobinary system L1551 IRS 5 (Osorio et al. 2003)



First binary where a disk/jet system in each protostar was identified. => formation similar to single stars.

Disks probably truncated by tidal interaction, they have small radii of 10 au.

Osorio+2003 modeling predicted a circumbinary disk (R ~100-300 au).



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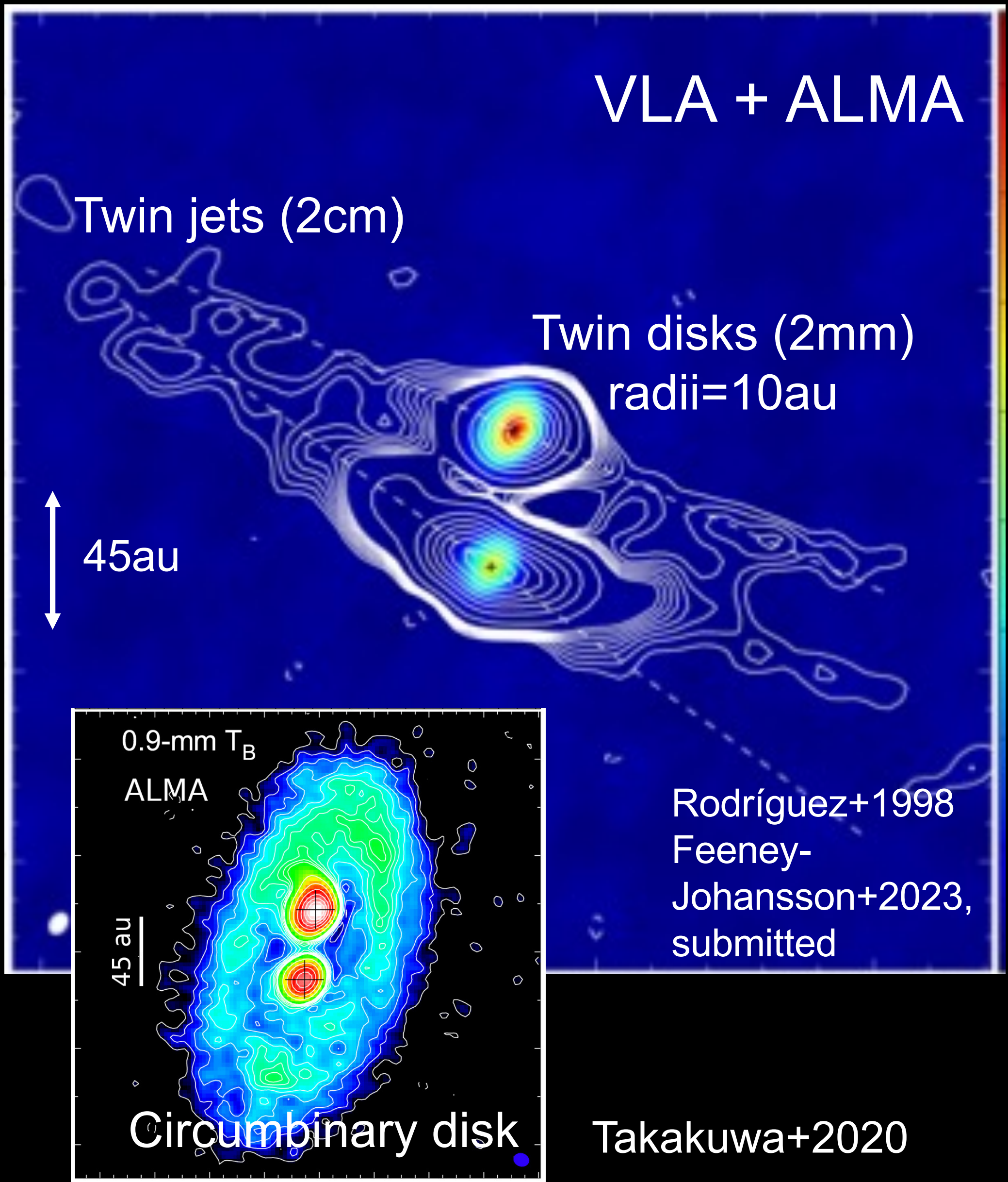

Takakuwa+2020

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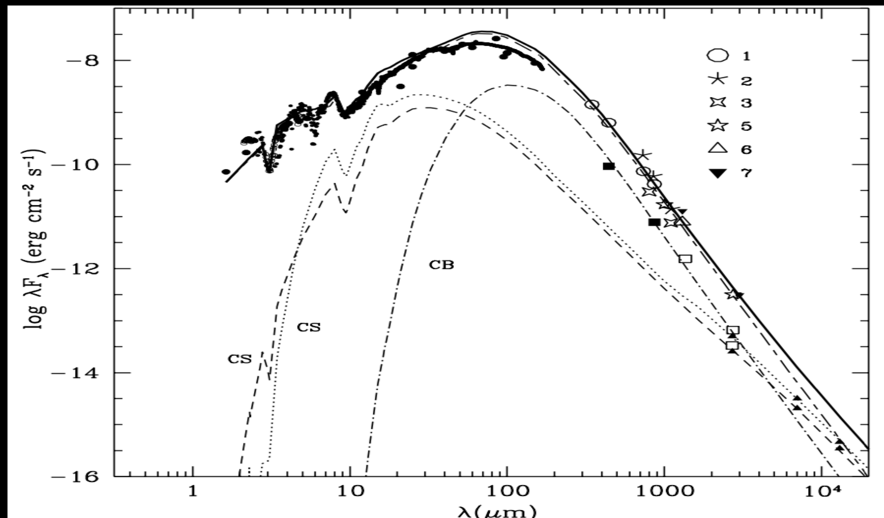
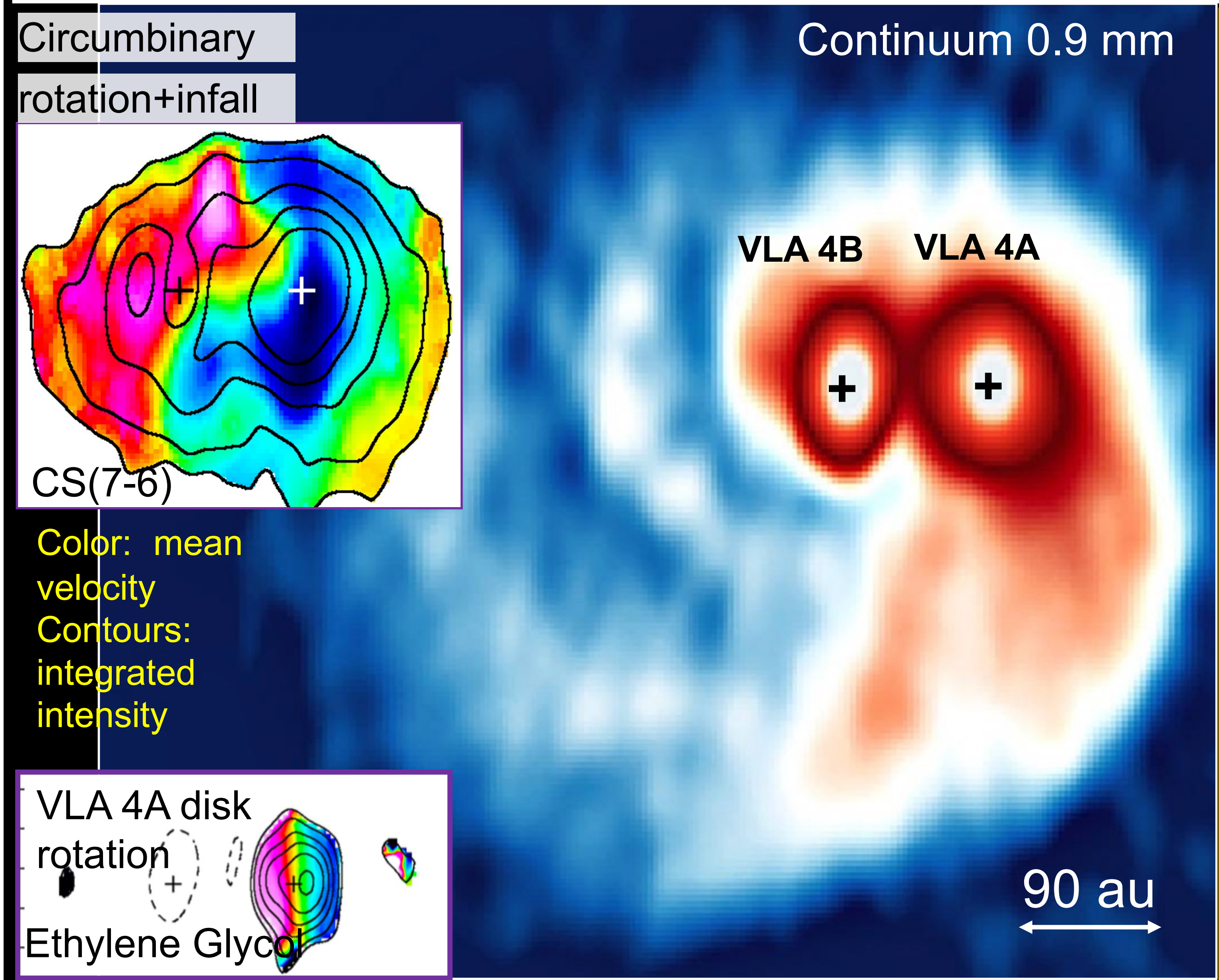


A comprehensive observational study of the protobinary system SVS 13: a circumbinary disk in the making

(Díaz-Rodríguez+2022)



Circumstellar disks

R ~10 au (dust)
~30 au (gas)

VLA 4A

M_*=0.3 $M_\odot$

M_{disk} = 4-9 M_J

T_{dust}=140-300 K

VLA 4B

M_*=0.6 $M_\odot$

M_{disk} = 9-30 M_J

T_{dust} =140-400 K

Circumbinary disk

R ~500 au,

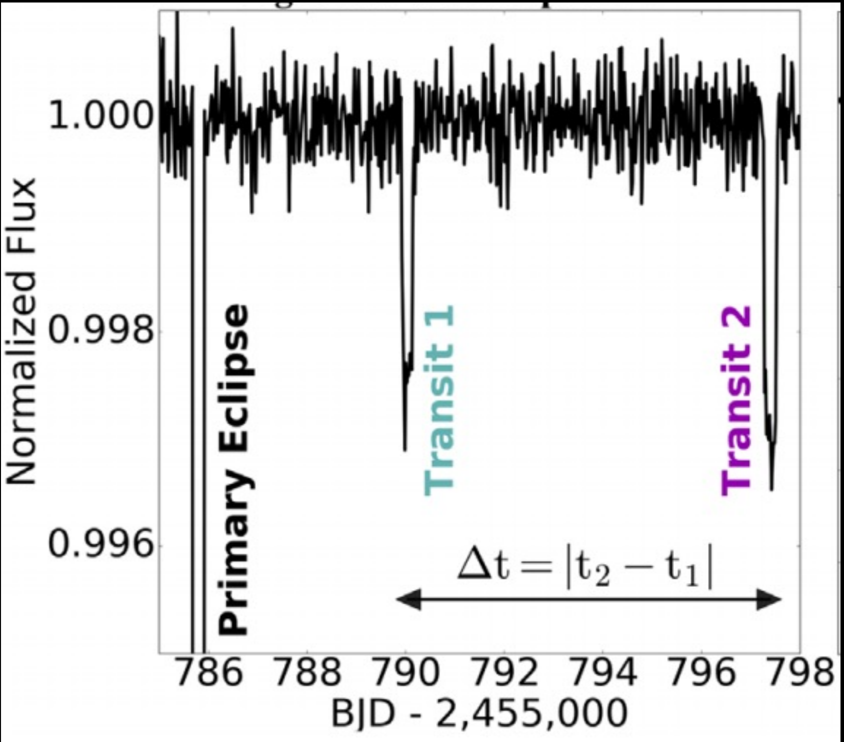
M_{disk} = 50 M_J

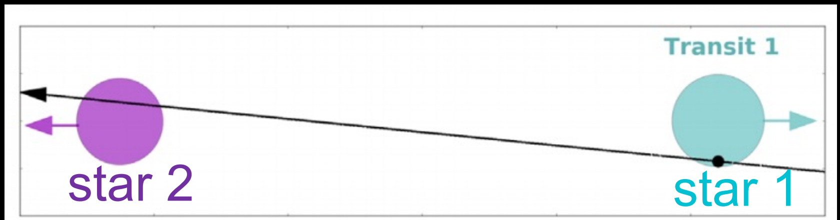
T ~140 K

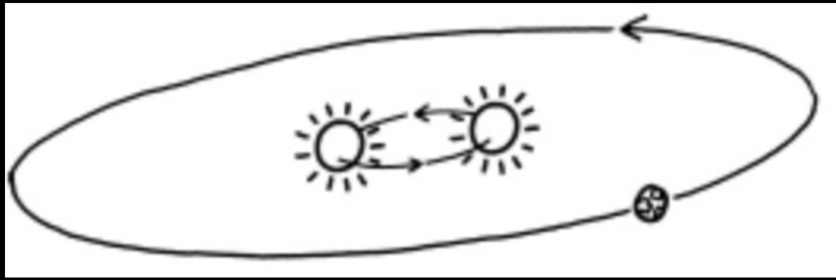
counter-clockwise rotation

Detection of circumbinary exoplanets

Kepler 34 (TESS data; Kostov+2021)



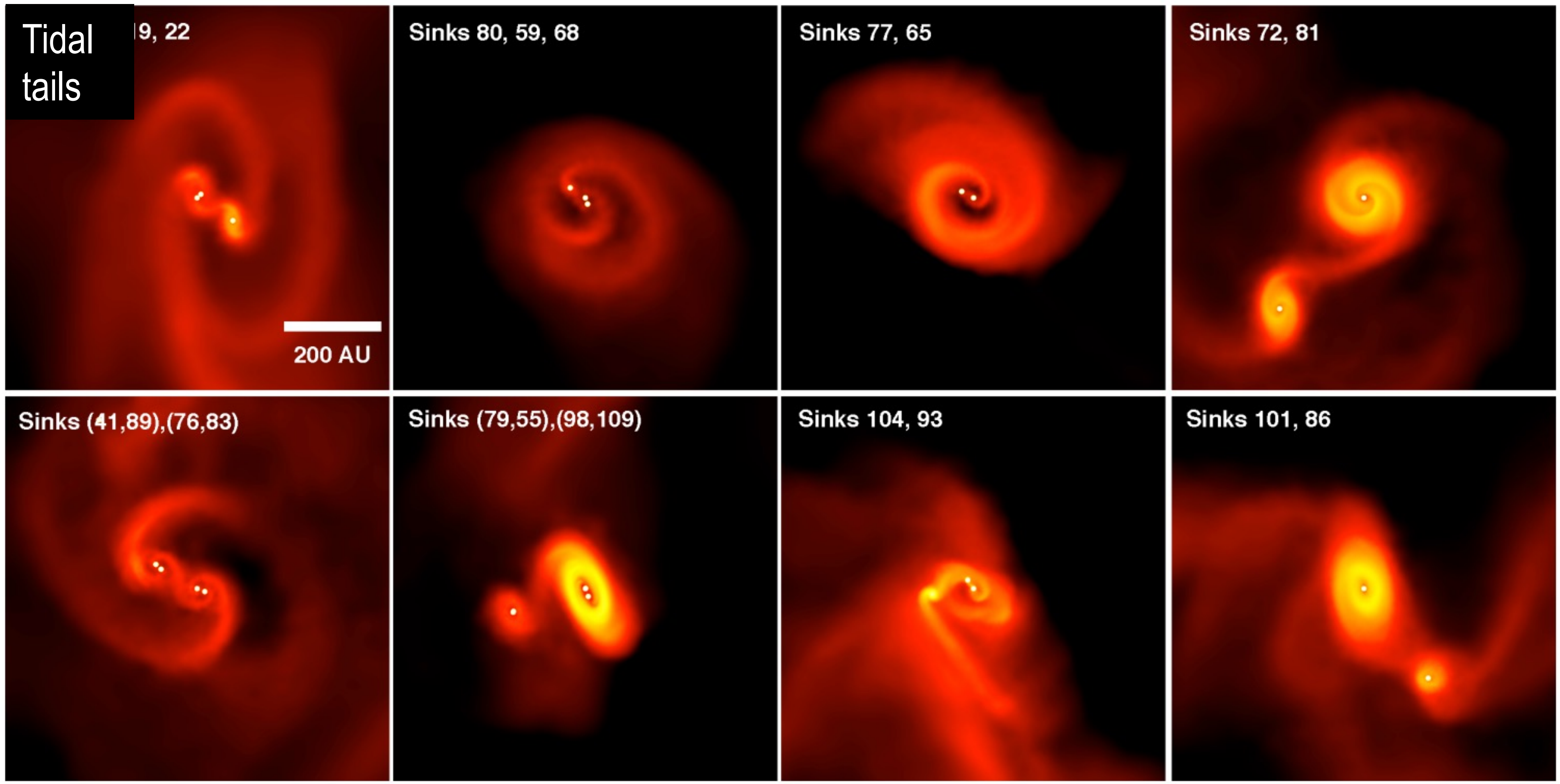




Eclipse of the primary star by the secondary star (big dip), transit of the planet across the primary (transit 1), and across the secondary star (transit 2)

Simulations of disk interaction in multiple systems: matter exchange, tidal interaction, spirals, fragmentation.

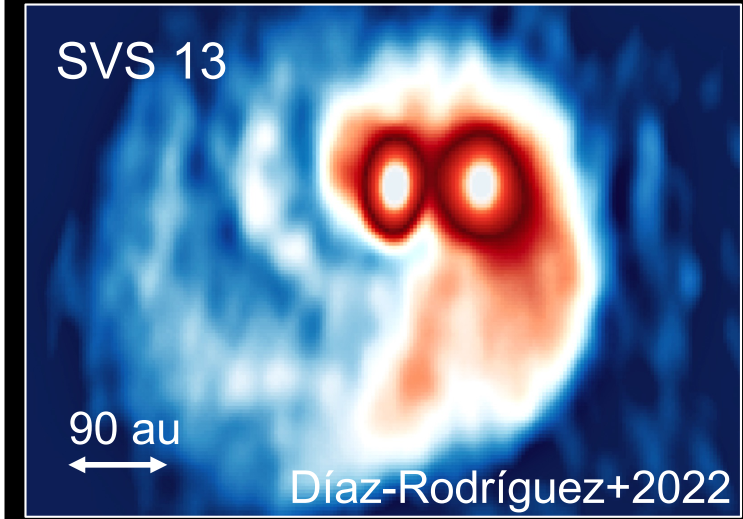
These panels are close-ups of several groups of stars, corresponding to a snapshot of the whole system at a given time

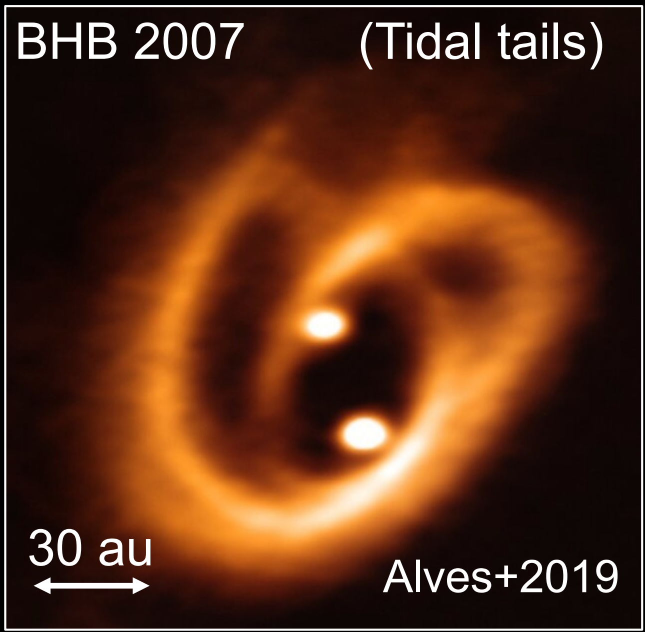


(Bate 2018)

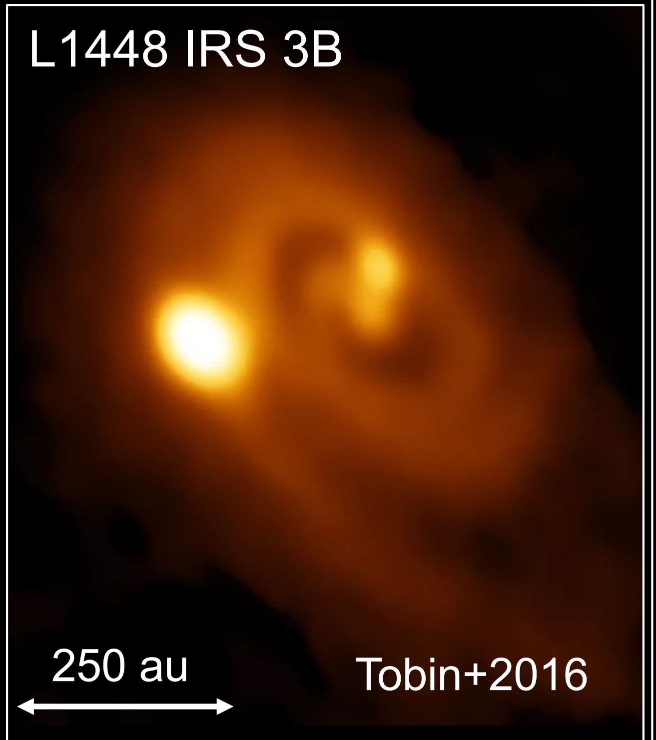
Observations of disk interaction in multiple systems

Two stars (spirals)

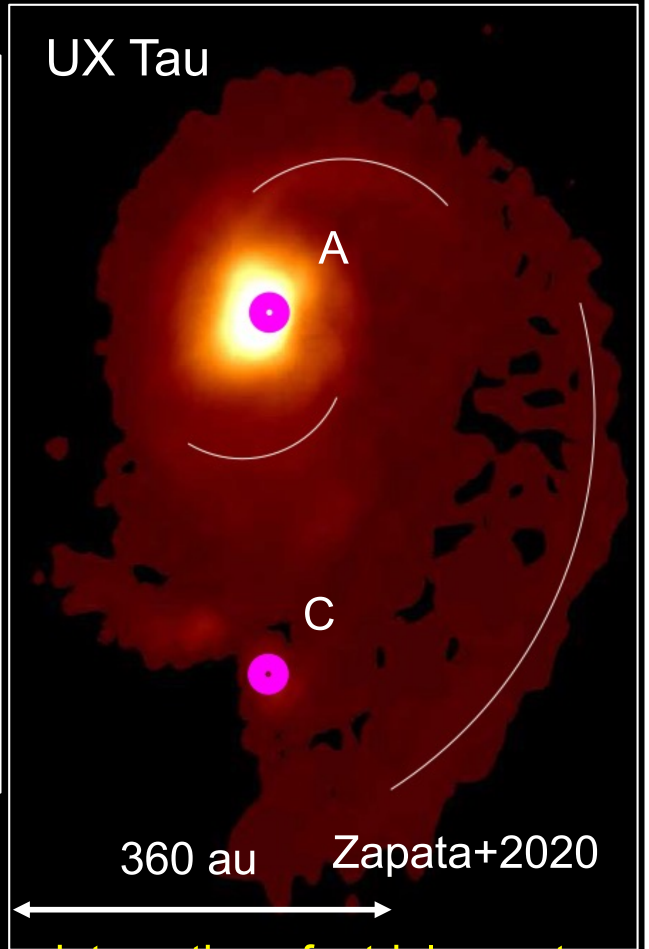




Three stars (fragmentation)

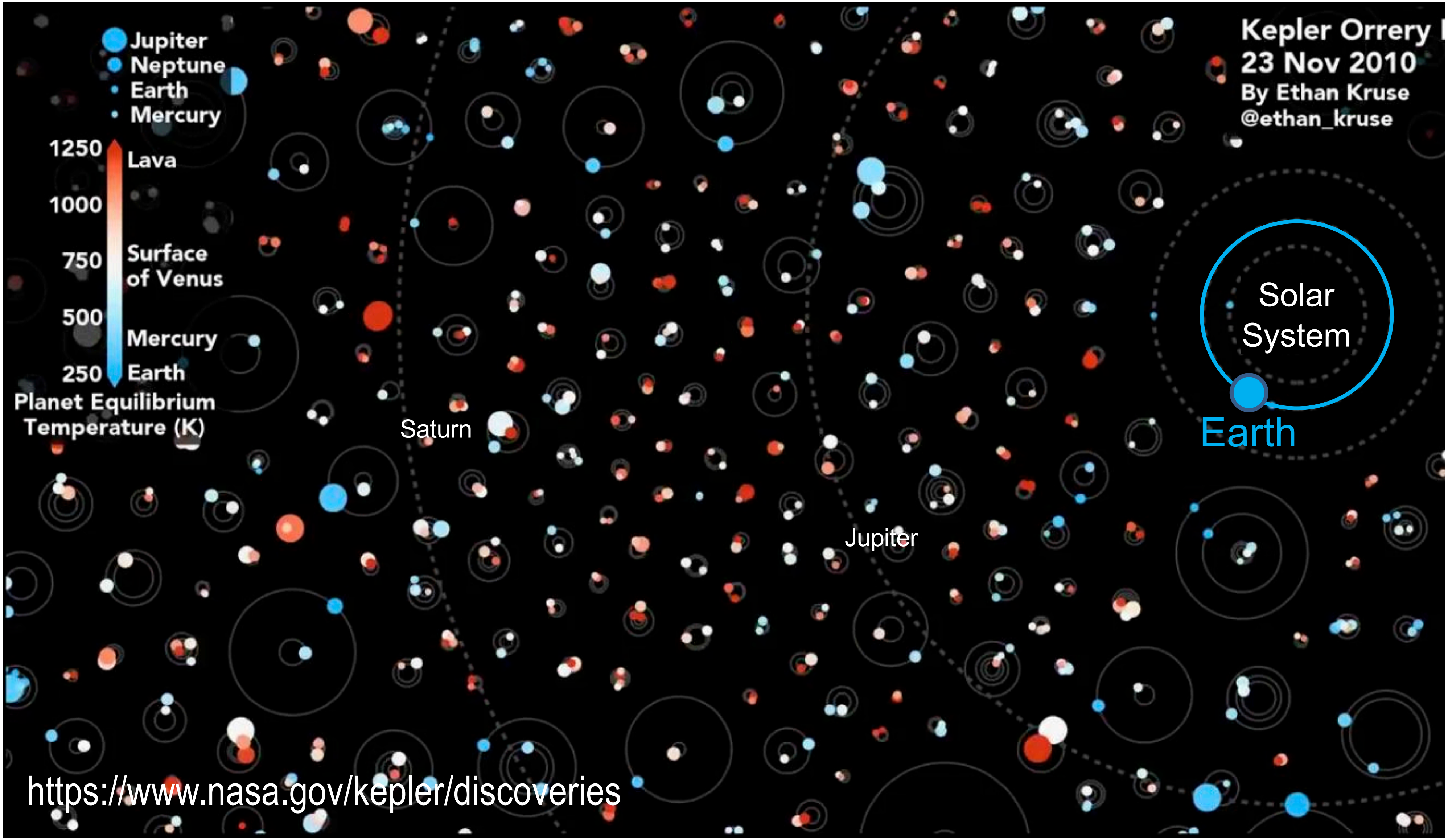


High-order multiple stellar systems (flybys)



The interaction of a triple system usually results in the ejection of the less massive star.

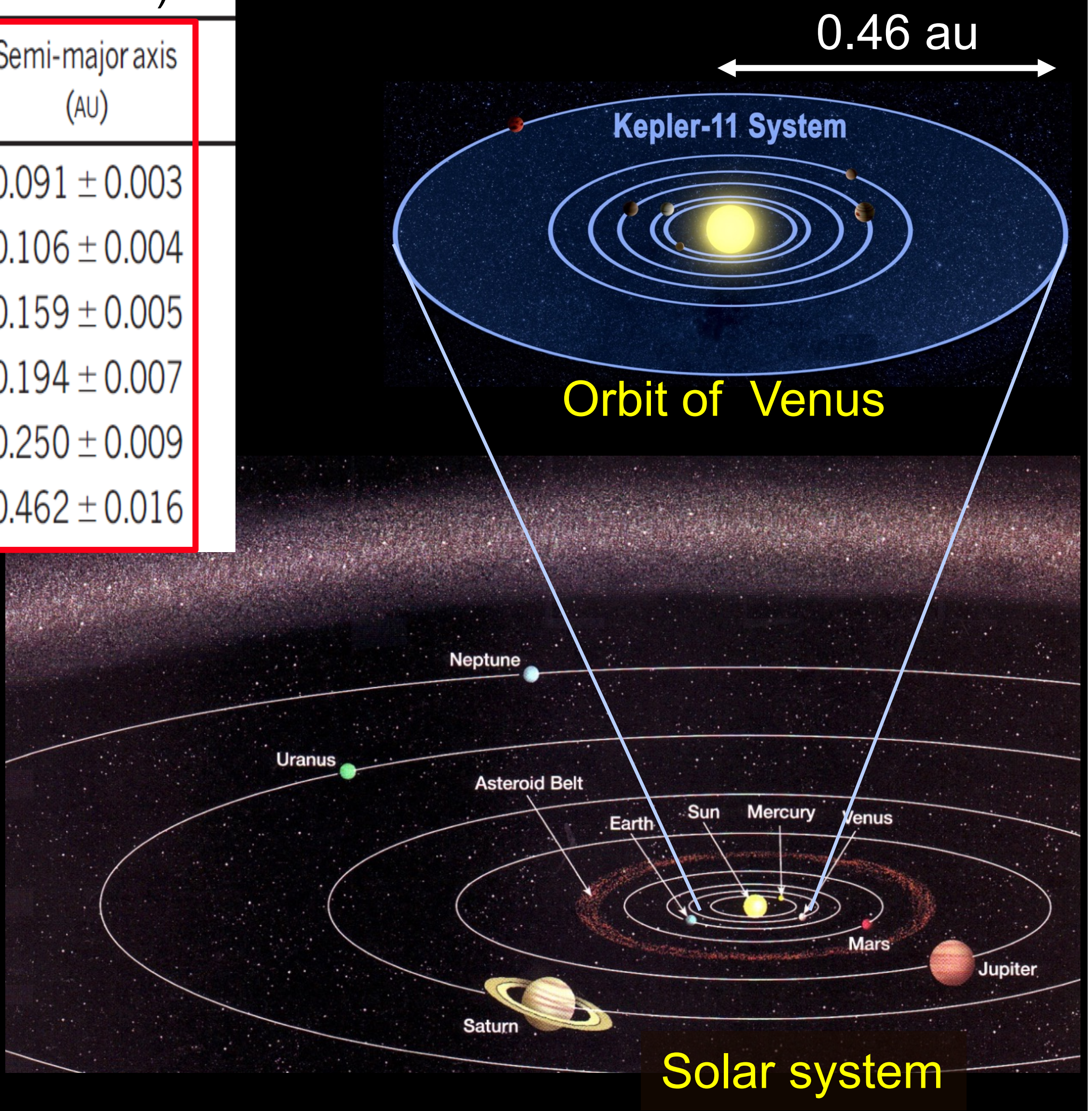
Diversity of exoplanetary system architectures



Closely-packed compact exoplanetary systems

Kepler-11 Planet Properties (Lissauer et al 2011)

Planet	Period (days)	Epoch (BJD)	Semi-major axis (AU)
b	10.30375 ± 0.00016	2,454,971.5052 ± 0.0077	0.091 ± 0.003
c	13.02502 ± 0.00008	2,454,971.1748 ± 0.0031	0.106 ± 0.004
d	22.68719 ± 0.00021	2,454,981.4550 ± 0.0044	0.159 ± 0.005
e	31.99590 ± 0.00028	2,454,987.1590 ± 0.0037	0.194 ± 0.007
f	46.68876 ± 0.00074	2,454,964.6487 ± 0.0059	0.250 ± 0.009
g	118.37774 ± 0.00112	2,455,120.2901 ± 0.0022	0.462 ± 0.016



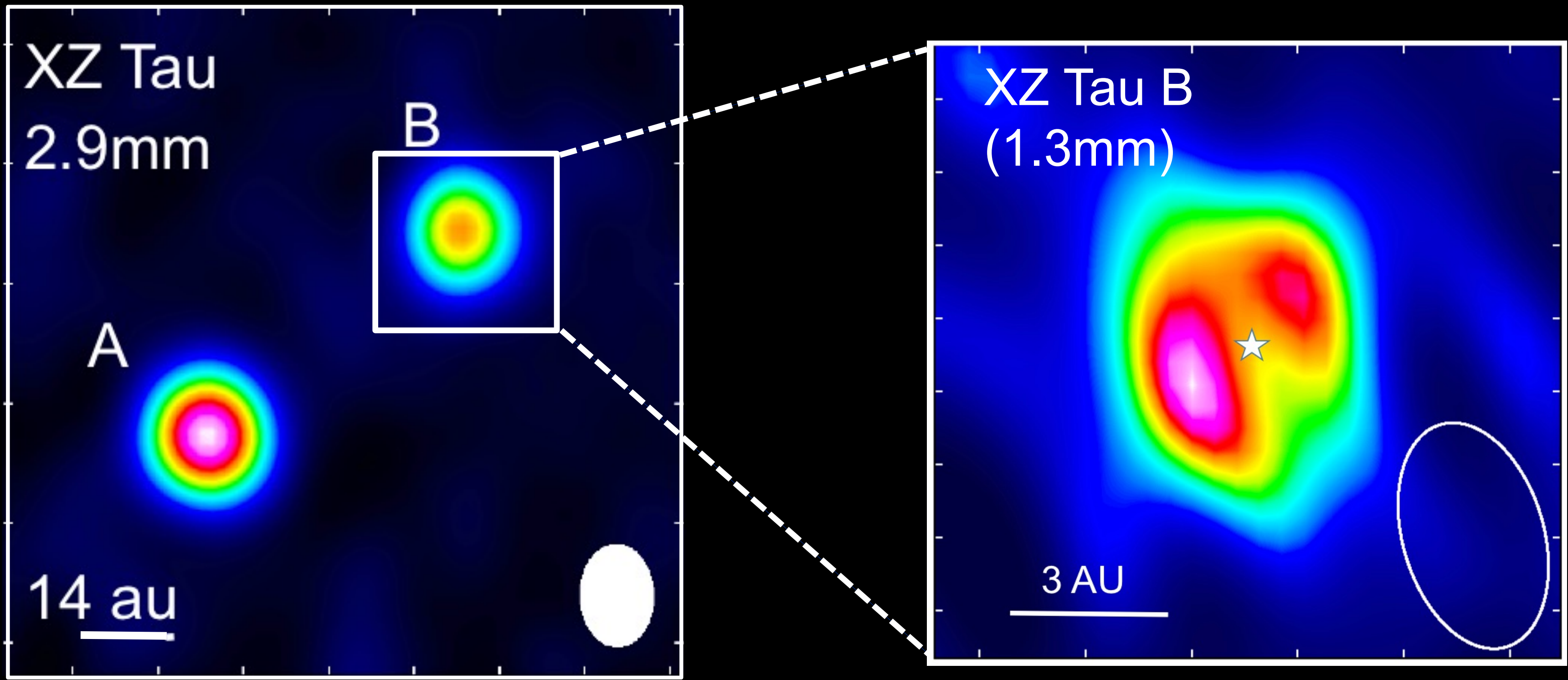
Kepler 11: 6 planets at r <0.46 au

Trappist 1: 6 planets at r <0.7 au

Do compact exoplanetary systems originate from dwarf protoplanetary disks?

A dwarf protoplanetary disk in XZ Tau B
(Osorio et al. 2016)

ALMA Long Base Science Verification observations

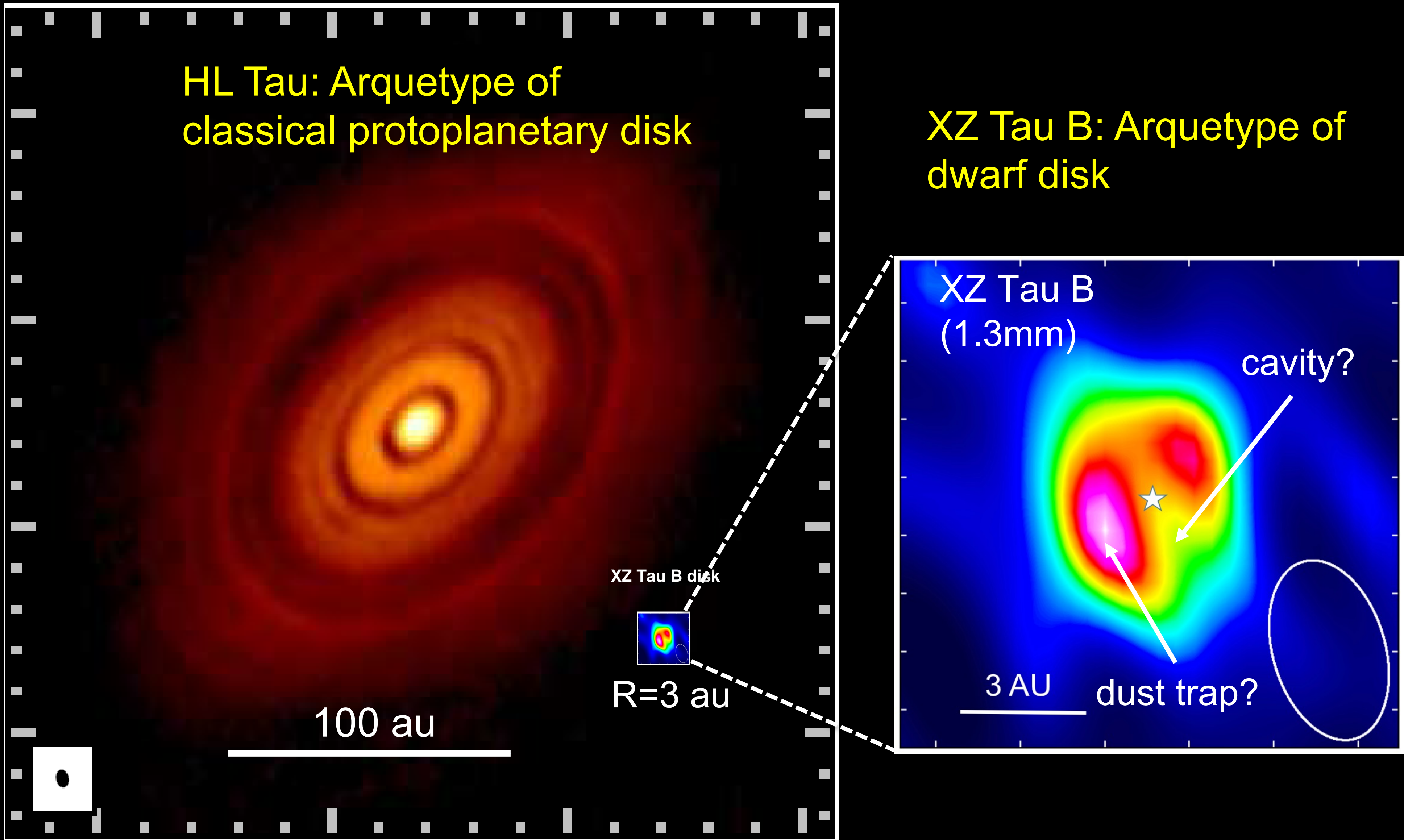


beam = 0.09"x 0.06"=13au x 8au

beam = 0.03" x 0.02" = 4.2au x 2.8au

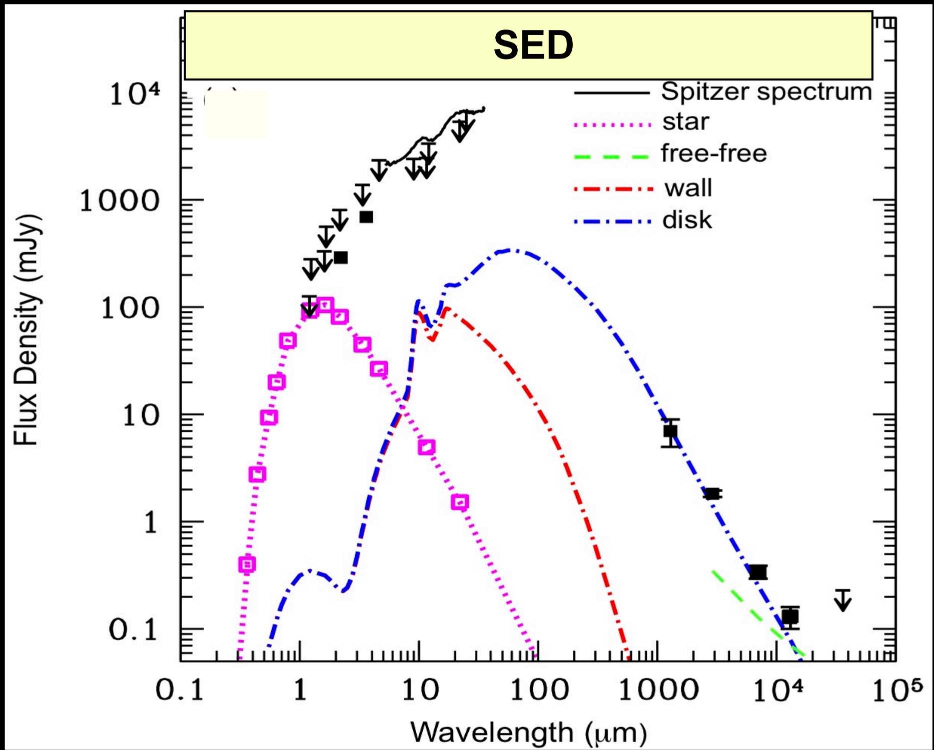
The large improvement in the angular resolution of ALMA allow us to probe scales of only 2au

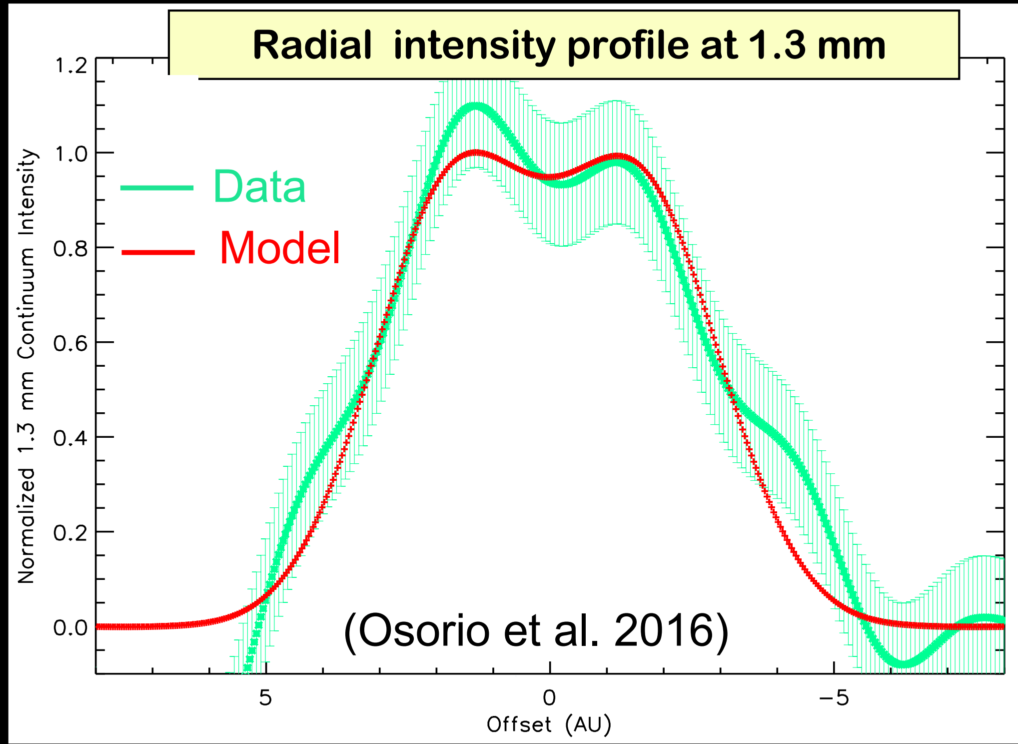
Comparison between HL Tau and XZ Tau B disks



we think, that just as HL Tau is considered an archetype for classic disks, XZ Tau B may be a prototype of small disks.

Modeling of the dwarf disk in XZ Tau B





XZ Tau B Disk	Classical Disk
R_{disk} = **3.4 au**	**50-100 au**
M_{disk} = 9 M_{Jup}	50-500 M_{Jup}
Σ(r=1 ua) = 2700 g/cm^2	100-1000 g/cm^2

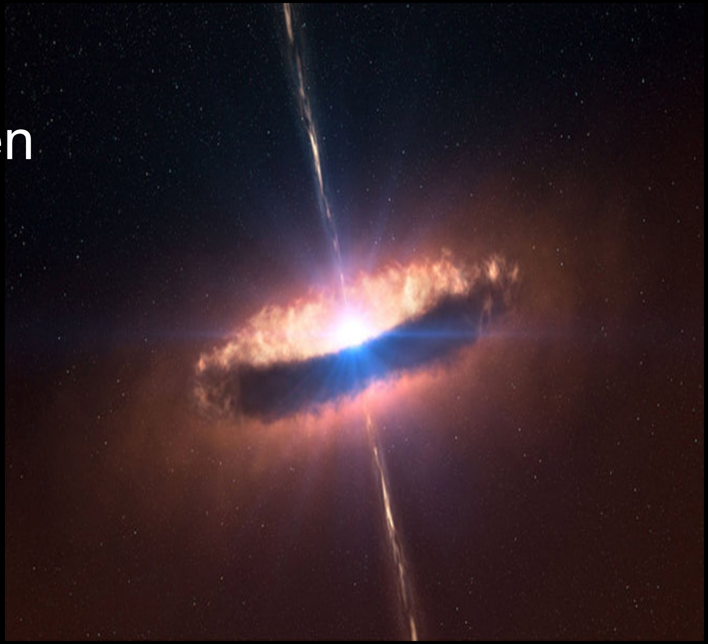
The model predicts a disk with enough mass to form planets (9 M_{Jup}) even though it is very small.

A large population of these small disks could exist but they have remained hidden, because, so far only few extremely high angular resolution observation have been performed.

Formation of massive stars

If massive stars (>8$M_\odot$) could be formed via accretion, with a disk/jet system, then they could form a planetary system, however:

-The contraction time that a massive star requires to reach the main sequence is very short (10^4 yr).



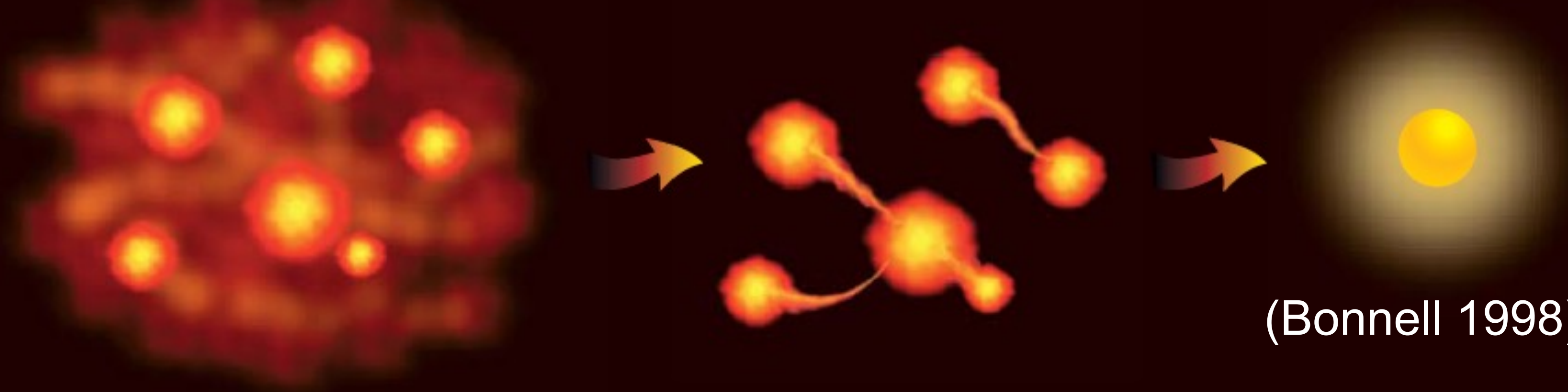
-Massive stars reach the main sequence when they are still accreting material.

-Massive stars develop HII regions with a high UV photon rate. Radiation pressure may halt the collapse, therefore the star cannot grow larger to reach a high mass.

So, in recent years it has been debated if it is possible to form high-mass stars via accretion.

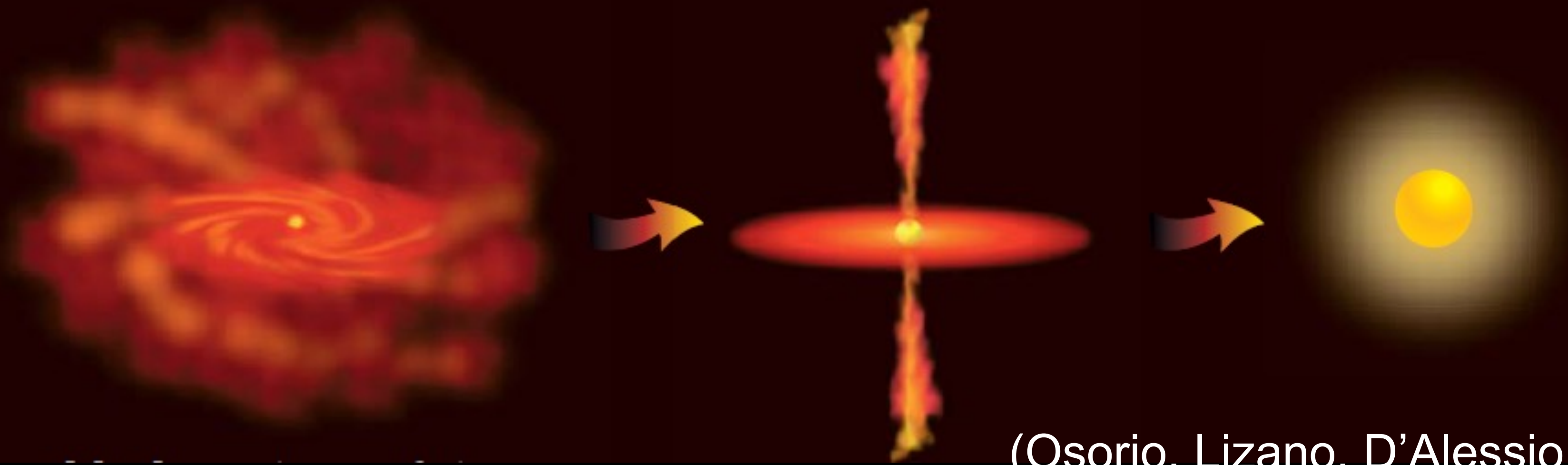
Star formation of high mass protostars: Acreccion or coalescence?

Coalescence



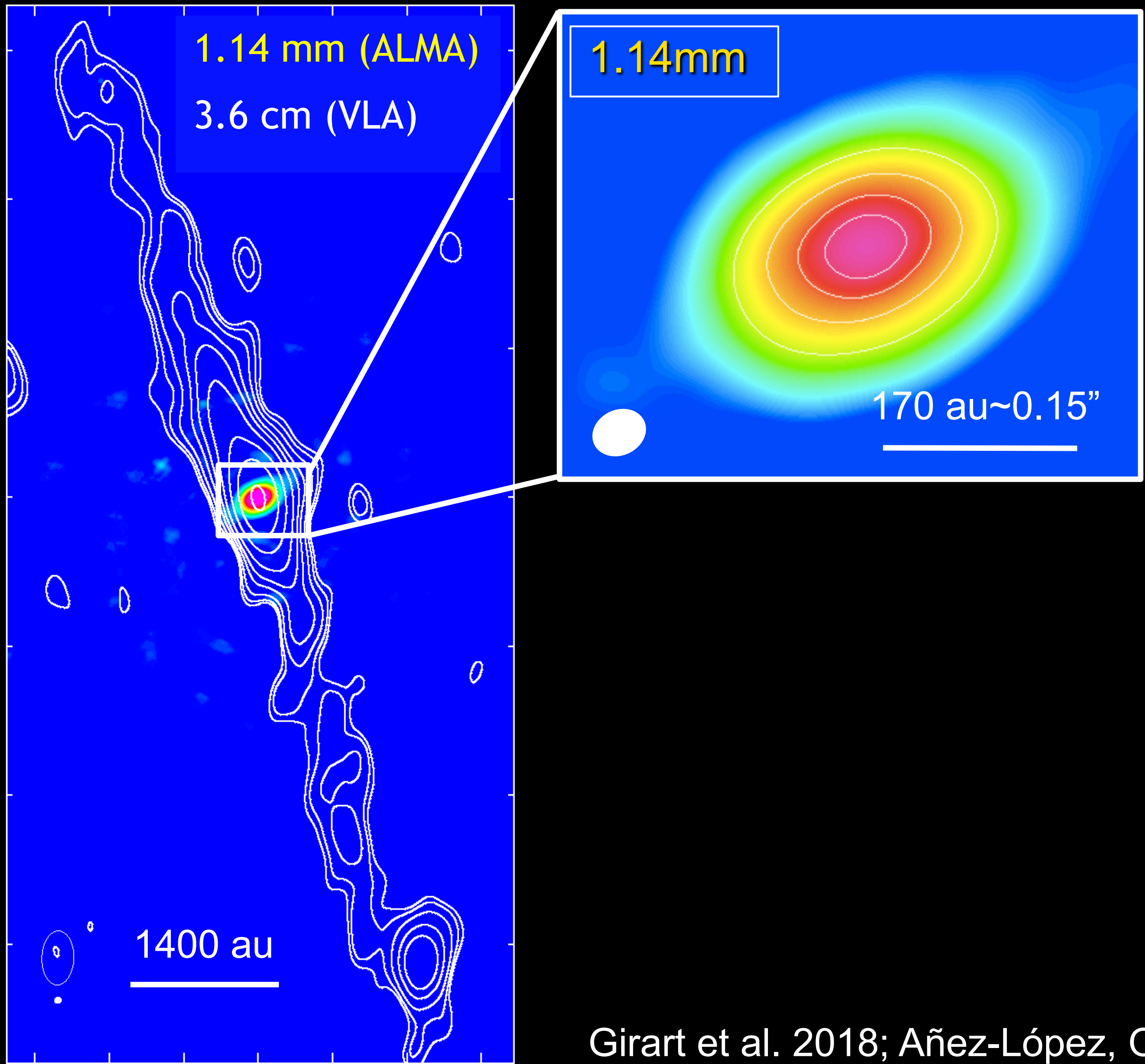
(Bonnell 1998)

Accretion



(Osorio, Lizano, D'Alessio 1999)

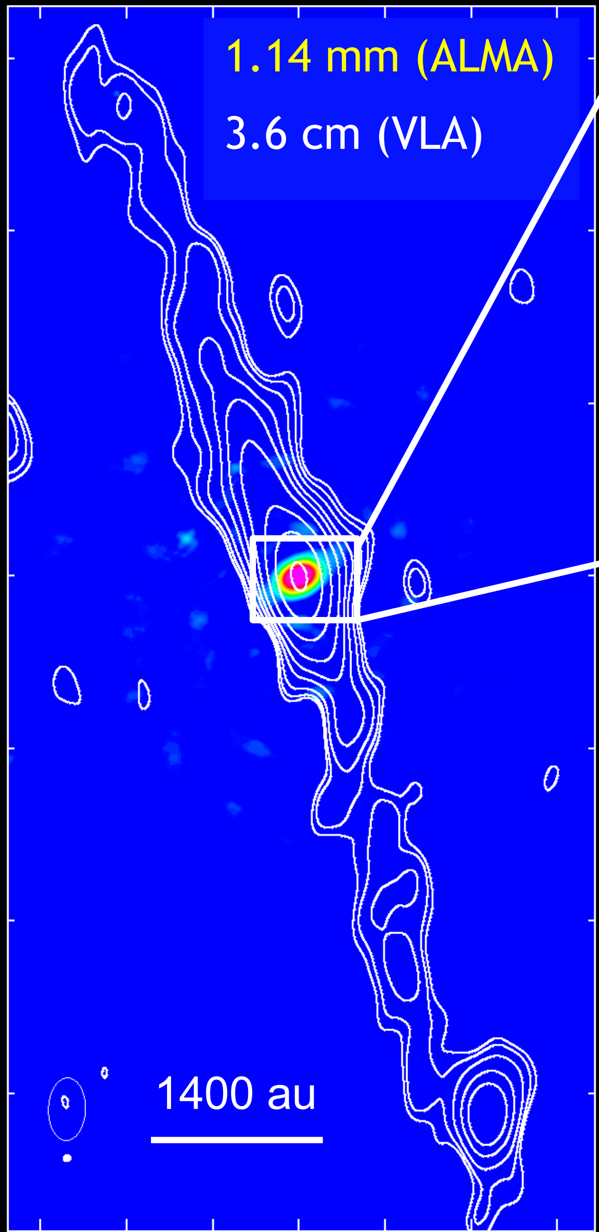
The disk/jet system of the HH80 massive protostar

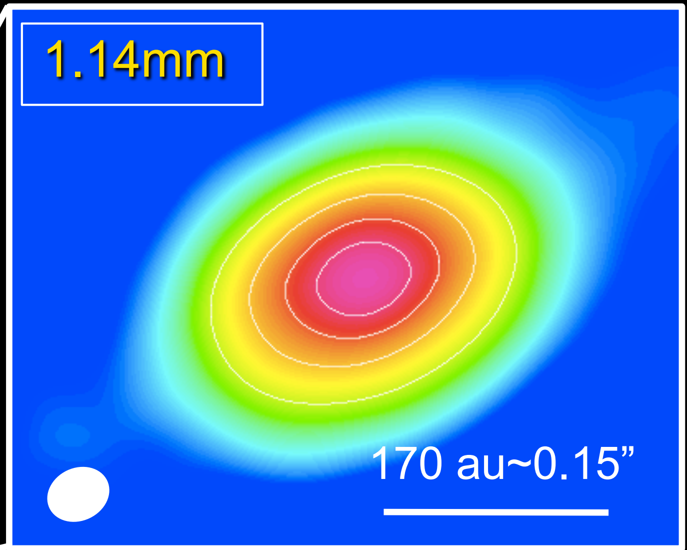


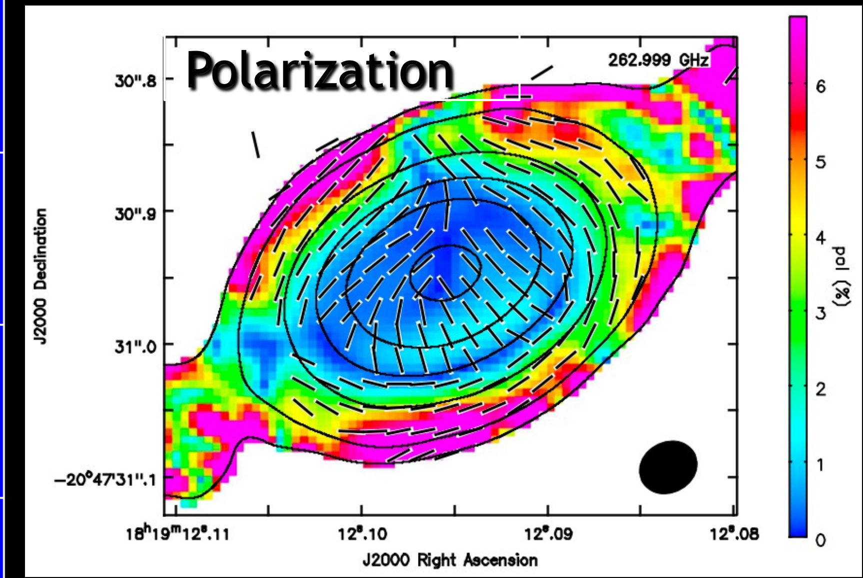
Resolved disk, perpendicular to the jet, R~200 au
→ bona-fine disk

Girart et al. 2018; Añez-López, Osorio et al. 2020

The disk/jet system of the HH80 massive protostar







Resolved disk, perpendicular to the jet, R~200 au
→ bona-fine disk

The polarization pattern indicates that there is no settling onto the disk midplane, and that the size of the dust grains is ~50-500 μm.
→ Inputs for the models.

Girart et al. 2018; Añez-López, Osorio et al. 2020

Modeling of the HH80 disk (massive protostar)

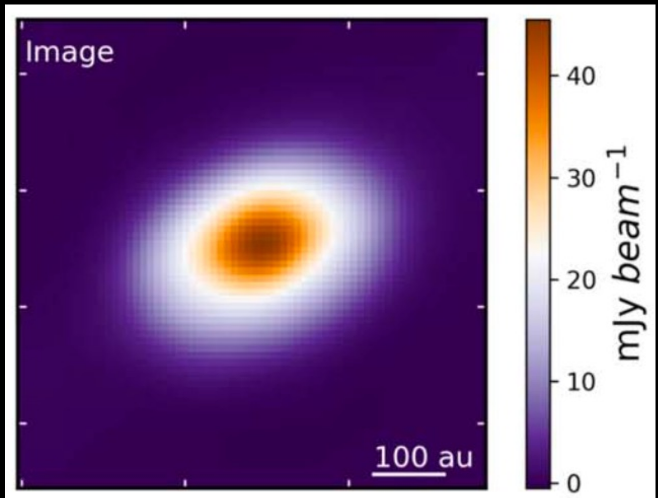
(Añez-López+2020)

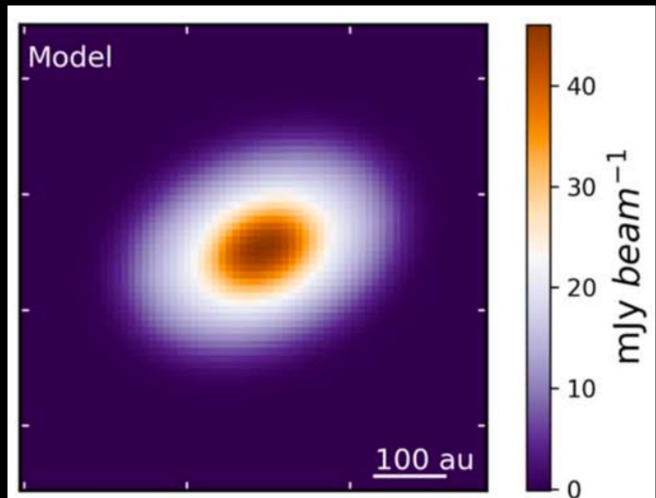
Sources of heating:

-Irradiation by the stellar luminosity

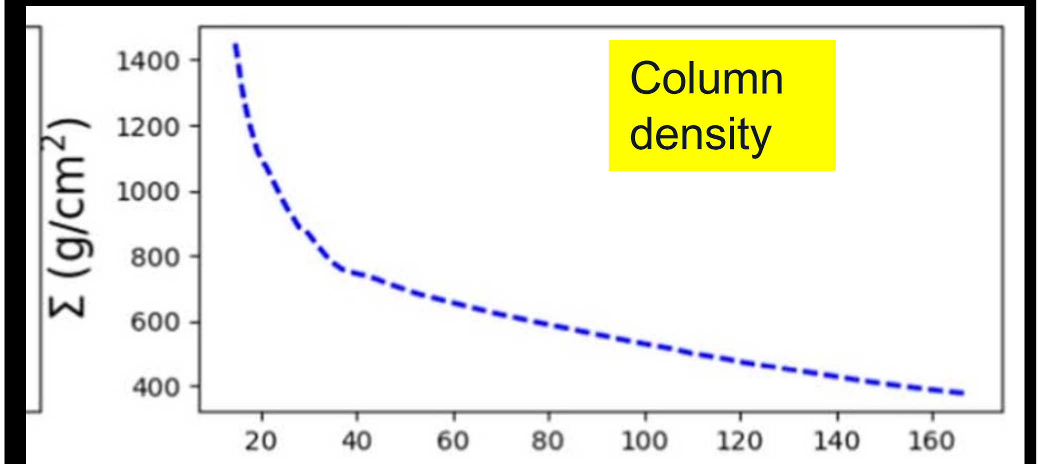
-Irradiation by the accretion shock (disk surface)

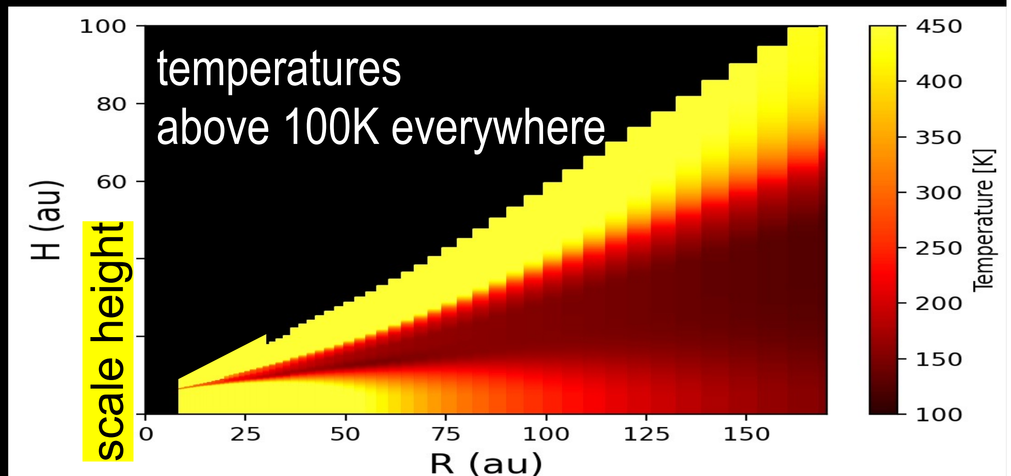
-Viscous dissipation (disk mid-plane)





$\dot{M}$ ($M_\odot$ yr^{-1})	7×10^{-5}
M_{disk} ($M_\odot$)	5
R_{disk} (au)	168
H_{100} (au)	7
R_{in} (au)	14
i (°)	49
a_{max} (μm)	500
α	0.1



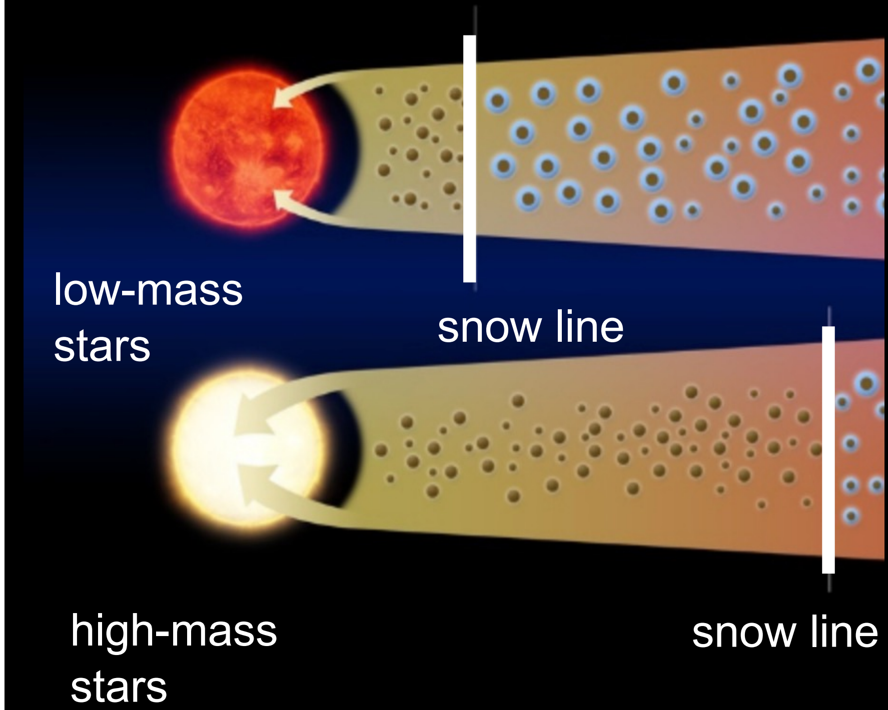


Implications of the HH80 disk modeling for planet formation

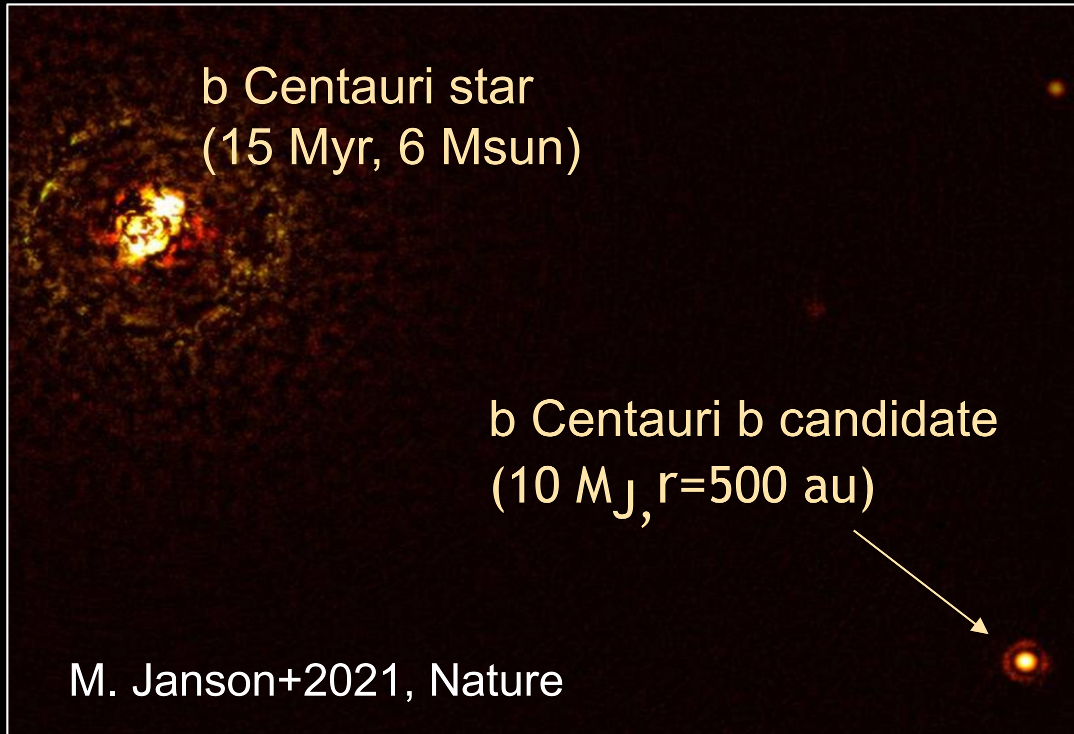
Very hot and dense disk: T > 120 K (T <30-40 K for low-mass stars).

→ The volatile molecules (CO, CH_3OH, H_2O) will be sublimated in the disk, due to the high temperatures (snow line outside/at the border of the disk). So, volatile molecules could only be found in the envelope surrounding the disk.

→ The formation of giant gas planets would be difficult. Only the formation of rocky planets would be possible in the HH80 disk.

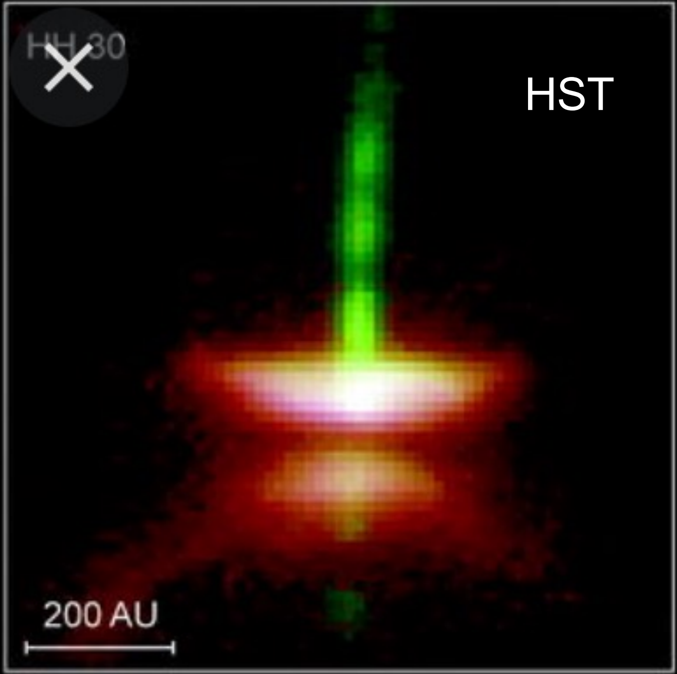


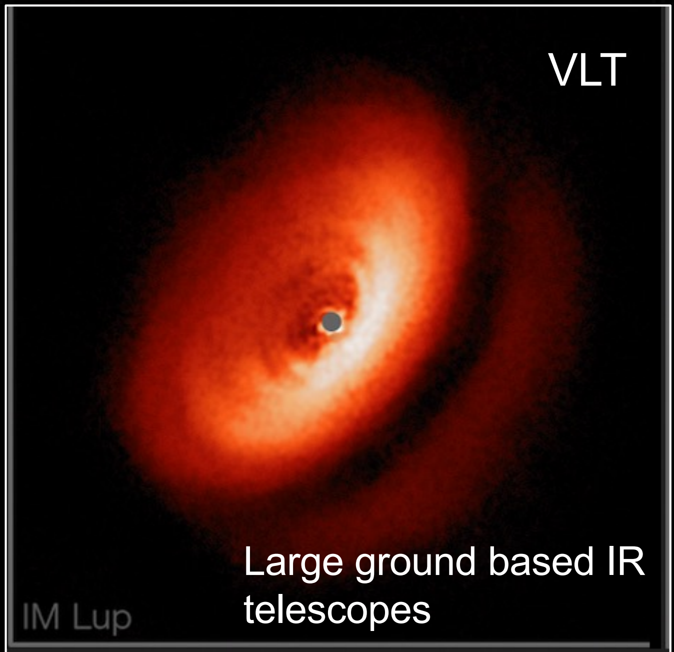
Discovery of a planetary system in a high-mass star



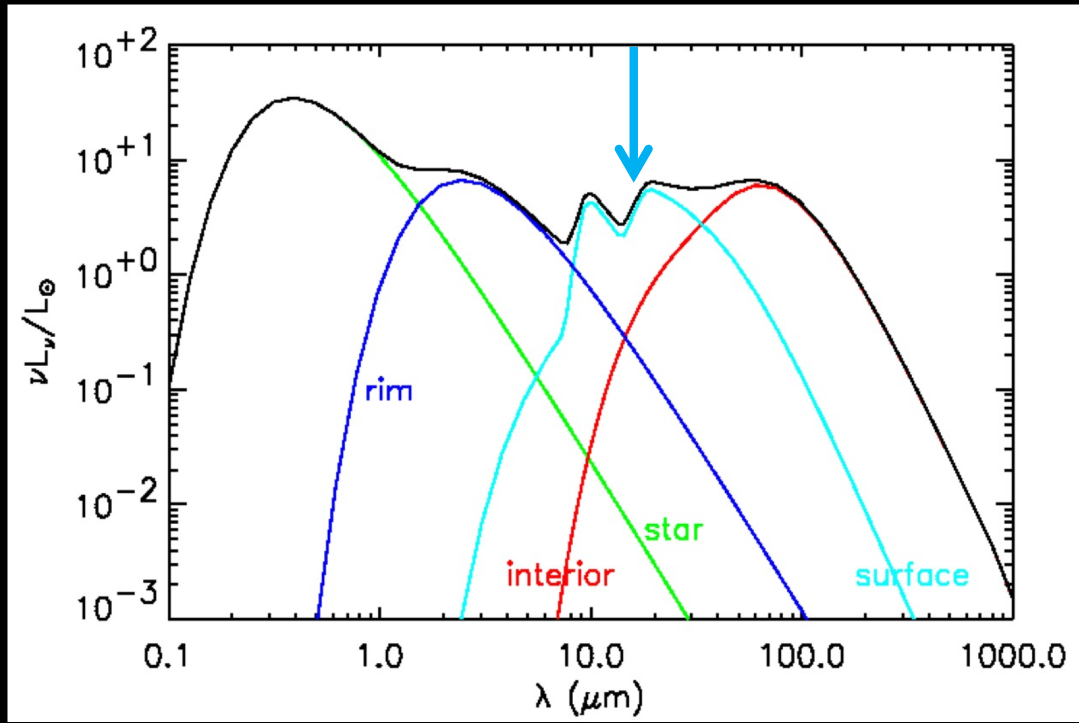
Fundamental properties of accretion disks

Flared disks





Large ground based IR telescopes



H: pressure scale height (ratio of the sound speed C_s=sqrt($kT/\mu m_H$) and the Keplerian angular speed Ω).

$$H = \frac{c_s}{\Omega} = \left(\frac{kT}{\mu m_{\rm H}} \frac{r^3}{GM_*}\right)^{1/2}$$

For a typical temperature profile of $T \propto r^{-1/2}$

The ratio $H/r \propto r^{1/4}$ increases with r.

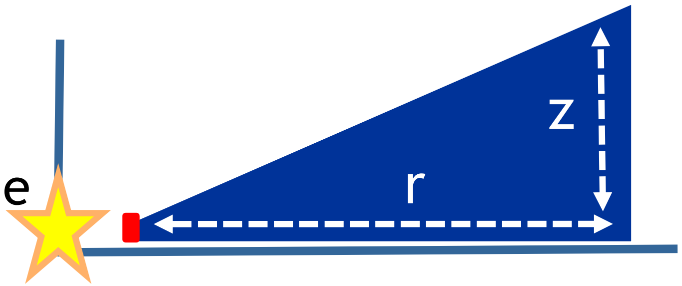
Disks thus have a *flaring geometric shape*

Hartmman 1987

Physical Structure (disk density)

Volumetric density: assuming that disk is in vertical hydrostatic equilibrium:

$$\frac{\partial P}{\partial z} = -\rho\, g_z,$$



Assuming: P= ρ k T and that the star dominates the gravitational potential. The latter equation becomes:

$$\frac{\partial \ln \rho}{\partial z} = -\left[\frac{\mu m_{\rm H}}{kT}\frac{G M_* z}{(r^2+z^2)^{3/2}} + \frac{\partial \ln T}{\partial z}\right],$$

For a geometrical thin disk (z<<r) and with a small Temp gradient (ϑT/ϑZ=0), the solution of the this equation is a simple Gaussian distribution:

$$\rho = \rho_o \exp\left[-\frac{1}{2}\left(\frac{z}{H}\right)^2\right],$$

with

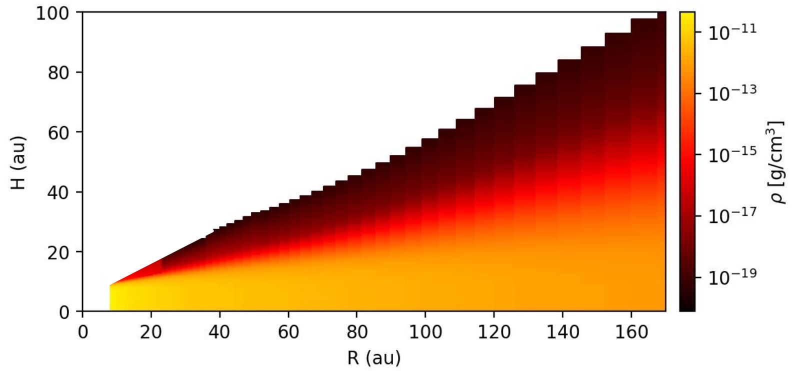
$$H = \frac{c_s}{\Omega} = \left(\frac{kT}{\mu m_{\rm H}}\frac{r^3}{G M_*}\right)^{1/2}$$ H: pressure scale height

ρ decreases exponentially with height *H*.

Physical Structure (disk surface density)

The disk surface density Σ is defined as the vertical integral of the ρ(r,z)

$$\Sigma_\infty = \int_{-z_\infty}^{z_\infty} \rho \, dz$$



If ρ(r,z) is unknown, Σ can be estimated from the equation for conservation of angular momentum in a steady α-disk:

$$\Sigma_\infty = \frac{\dot{M}}{3\pi\langle v_t \rangle}\left[1 - \left(\frac{R_*}{R}\right)^{1/2}\right]$$

ν is the viscosity, given in terms of the characteristic length (< H) and α turbulent velocity (< c_s). So it can be parametrized as $\nu = \alpha \; c_s H$, where α < 1 (Shakura & Sunyaev 1973) thus:

$$\Sigma = (M_{dot}/dt \,/ 3\,\pi\,\alpha\; c_s H) \,[\, 1 - (R_*/R)^{1/2} \,]$$

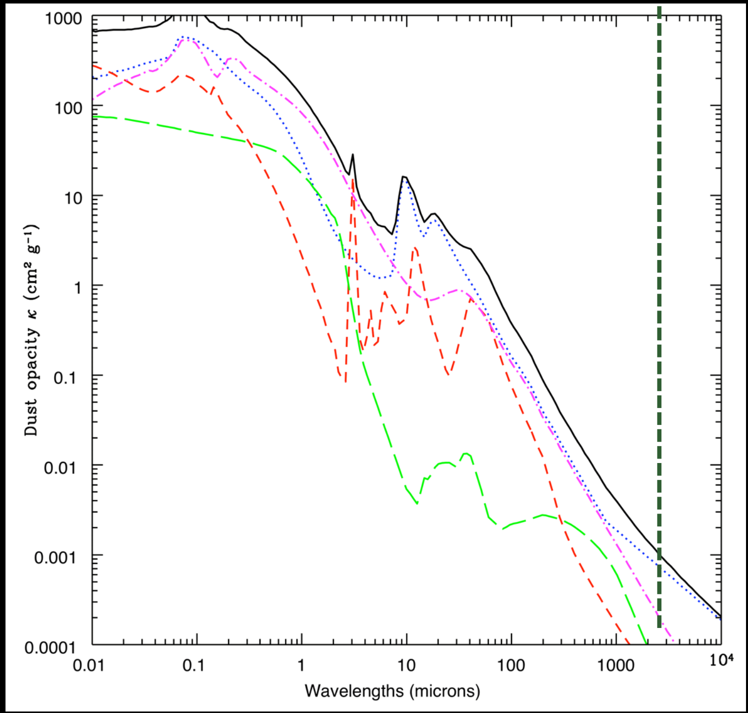
Equation of Σ in term of dM_{dot}/dt, α and c_s that involved T.

Σ increases if dM_{dot}/dt increases and α and T decrease.

Disk mass, simple assumptions

$$S_\nu = B_\nu\,(T_d)\,\kappa_\nu\,M_{disk}/D^2$$

ALMA flux Band 6 — 20 K — 0.001 g/cm² — Distance (Gaia)



Assumptions:

- an averaged disk temperature
- an averaged dust opacity

τ <<1, optically thin regime

- κT <<$h\nu$; Rayleigh-Jeans regime

HD169142 disk $M_{disk\ (dust)}=20M_{earth}$!

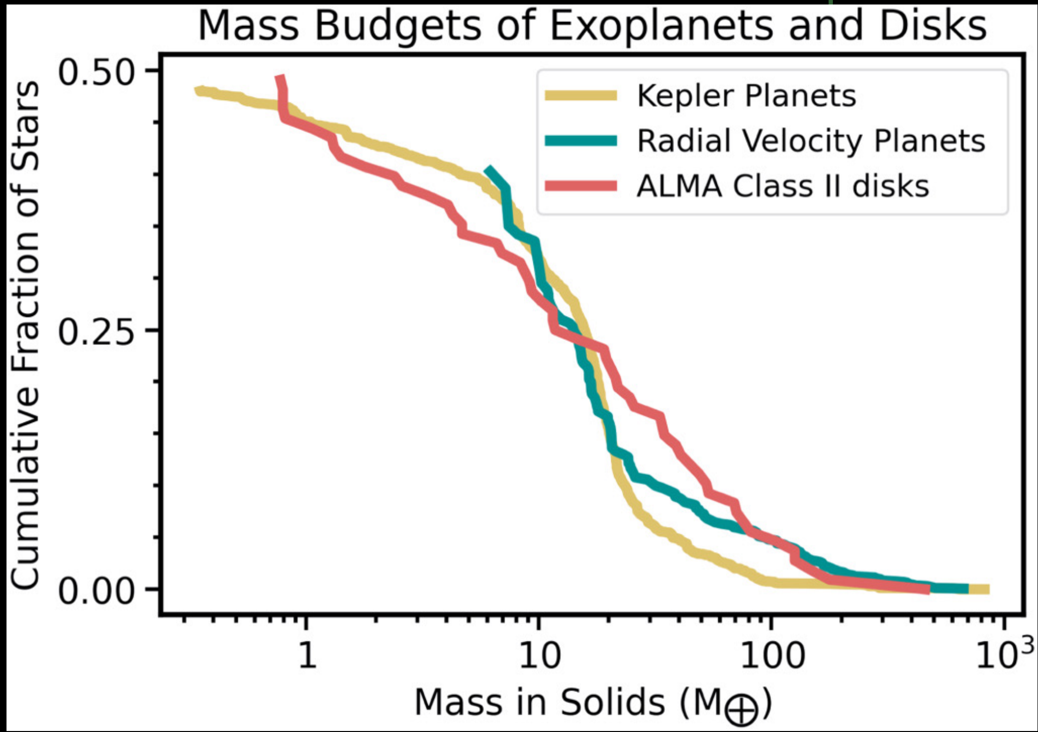
$M_{disk(dust)}=400\ M_{earth}$
$M_{disk}=0.12M_\odot$

Minimum-Mass Solar Nebula MMNS~40 M_{earth}. (Andrews 2020)

Disk mass, simple assumptions

$$S_\nu = B_\nu\,(T_d)\,\kappa_\nu\,M_{disk}/D^2$$

- S_ν: ALMA flux Band 6
- T_d: 20 K
- κ_ν: 0.001 g/cm²
- D: Distance (Gaia)



Assumptions:

- an averaged disk temperature
- an averaged dust opacity
- τ <<1, optically thin regime
- κT <<$h\nu$; Rayleigh-Jeans regime

careful with the masses derived from this approximation!

Minimum-Mass Solar Nebula MMNS~40 M_{earth}

Disk dust opacities

-At short wavelengths κ_ν is almost flat.

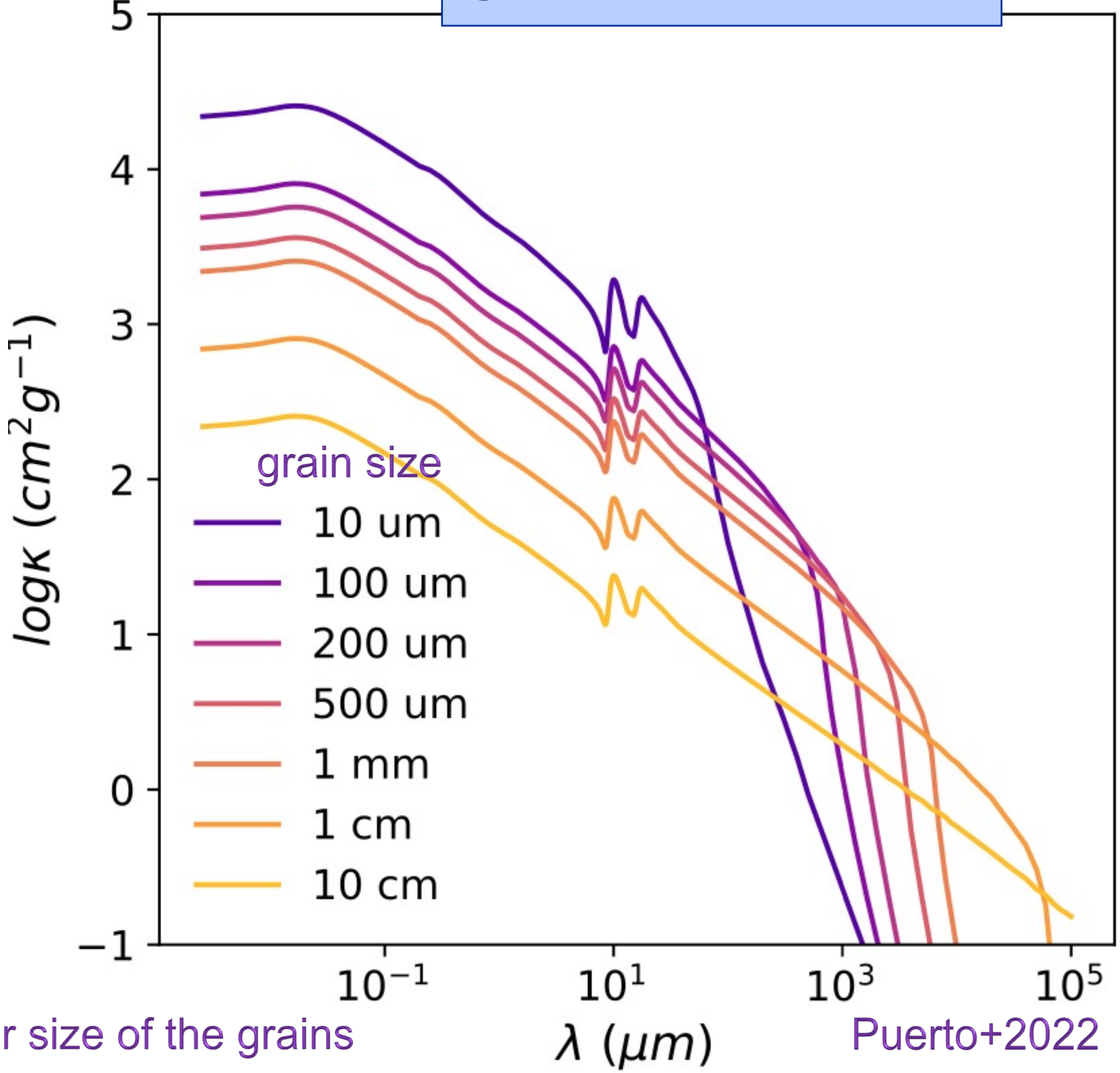
-At long wavelengths a power-law is assumed:

$\kappa = \kappa_0(\nu/\nu_0)^\beta = \kappa'_0(\lambda/\lambda_0)^{-\beta}$

small grains (steep slope $\beta \sim 2$)

big grains (shallow slope $\beta \sim 0$)

grain size variation



β decreases with larger size of the grains

Puerto+2022

Disk dust opacities

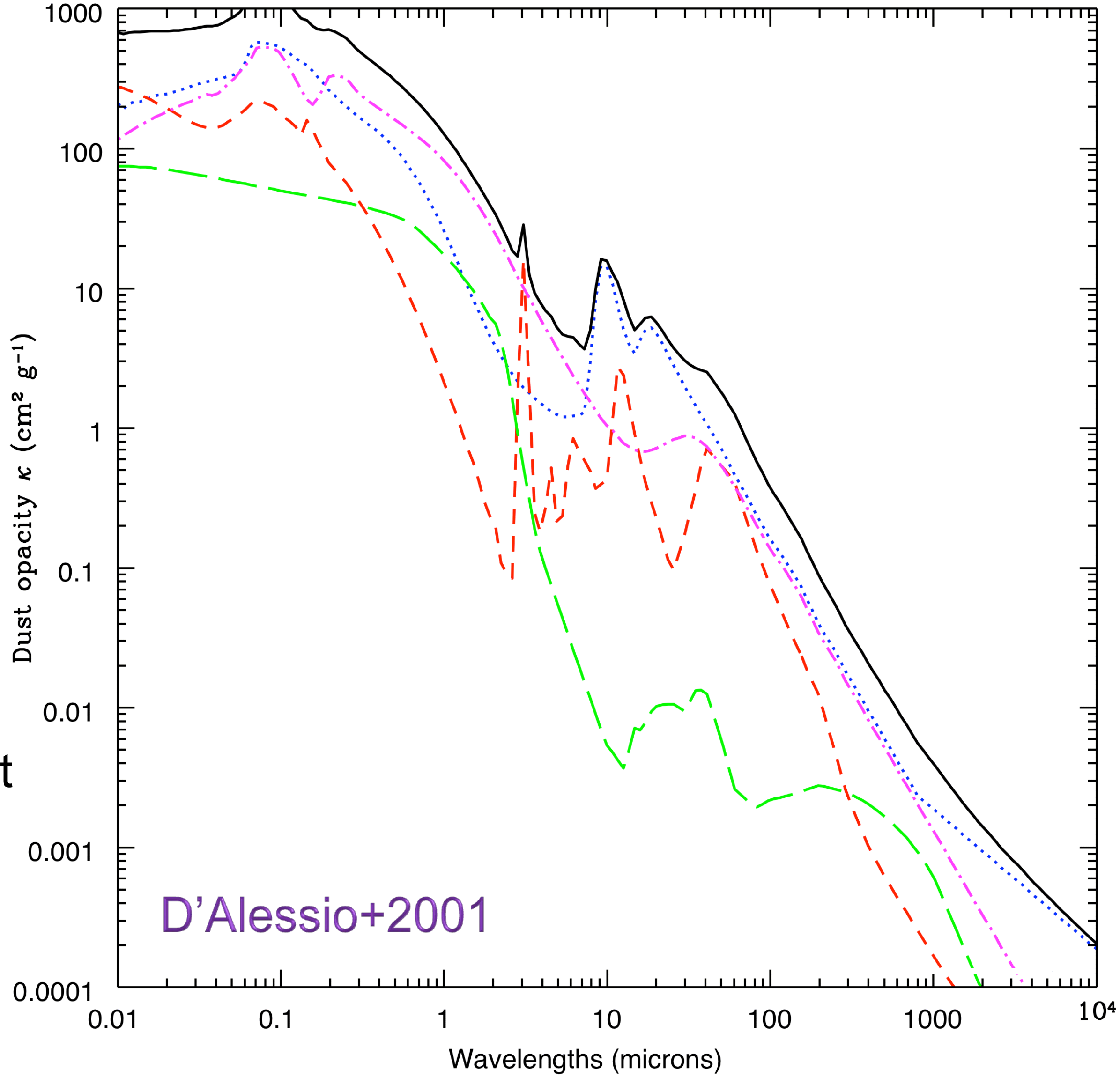
The dust opacity depends on:
*grain-size distribution:

Standard grain-size distribution
n(a) α $a^{-3.5}$, with
a=0.05μm - 1mm

*Shapes of the grains (Mie Spheres)
*Composition
*Abundance

Since the gas is the dominant component we need to convert the dust into gas. To do that, a standard dust-to-gas mass ratio= 1/100 is assumed.

Absorption coefficient for a mixture of grains of different compouds



How could the dust opacity exponent (β) be infer from the observations?

(Sub) millimeters Spectral index

$F_{\nu 1} = F_{\nu 2} (\nu_1/\nu_2)^{\alpha}$

$\alpha = \log(S_{\nu 1} - S_{\nu 2})/\log(\nu_1 - \nu_2)$

If optically thin emission

$\alpha = \beta + 2$ so that

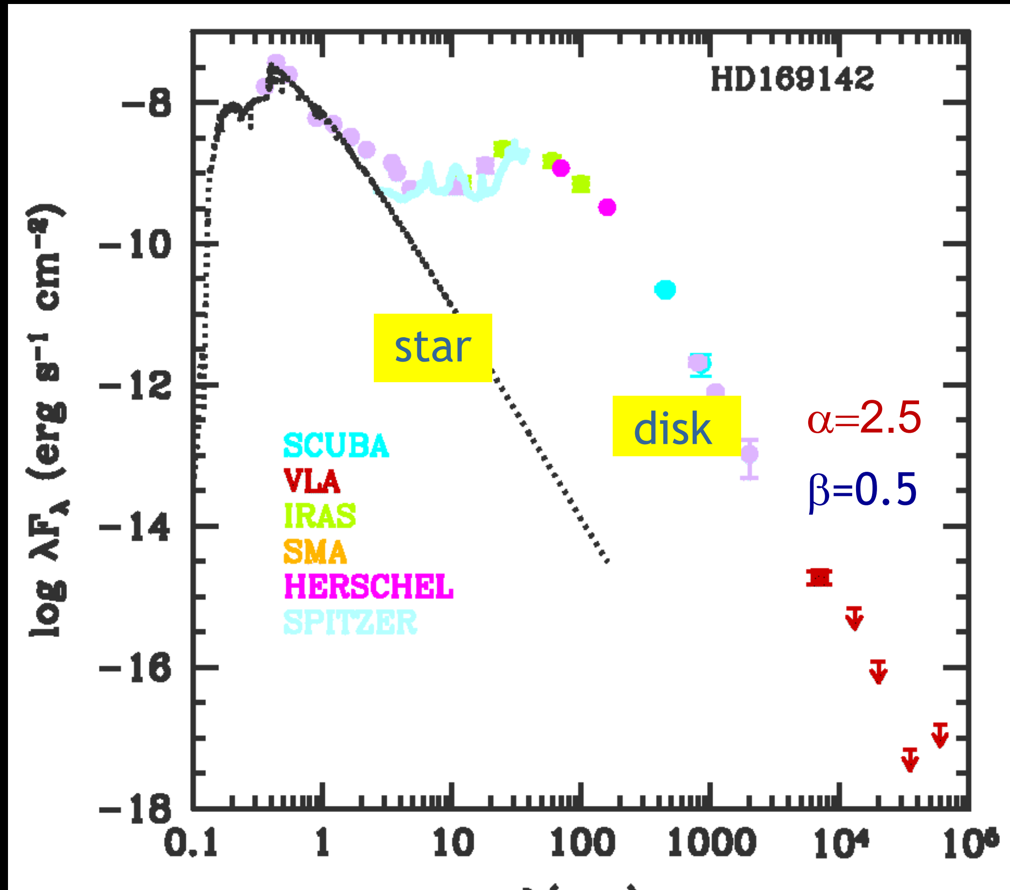
$\alpha \sim 2$, $\beta \sim 0$ big grains

$\alpha \sim 4$, $\beta \sim 2$ small grains

HD169142 disk:

The spectrum has a spectral index, $\alpha = 2.5 \Rightarrow \beta = 0.5$ indicative of a shallow dependence of the opacity with the frequency which in turn implies dust grain growth.

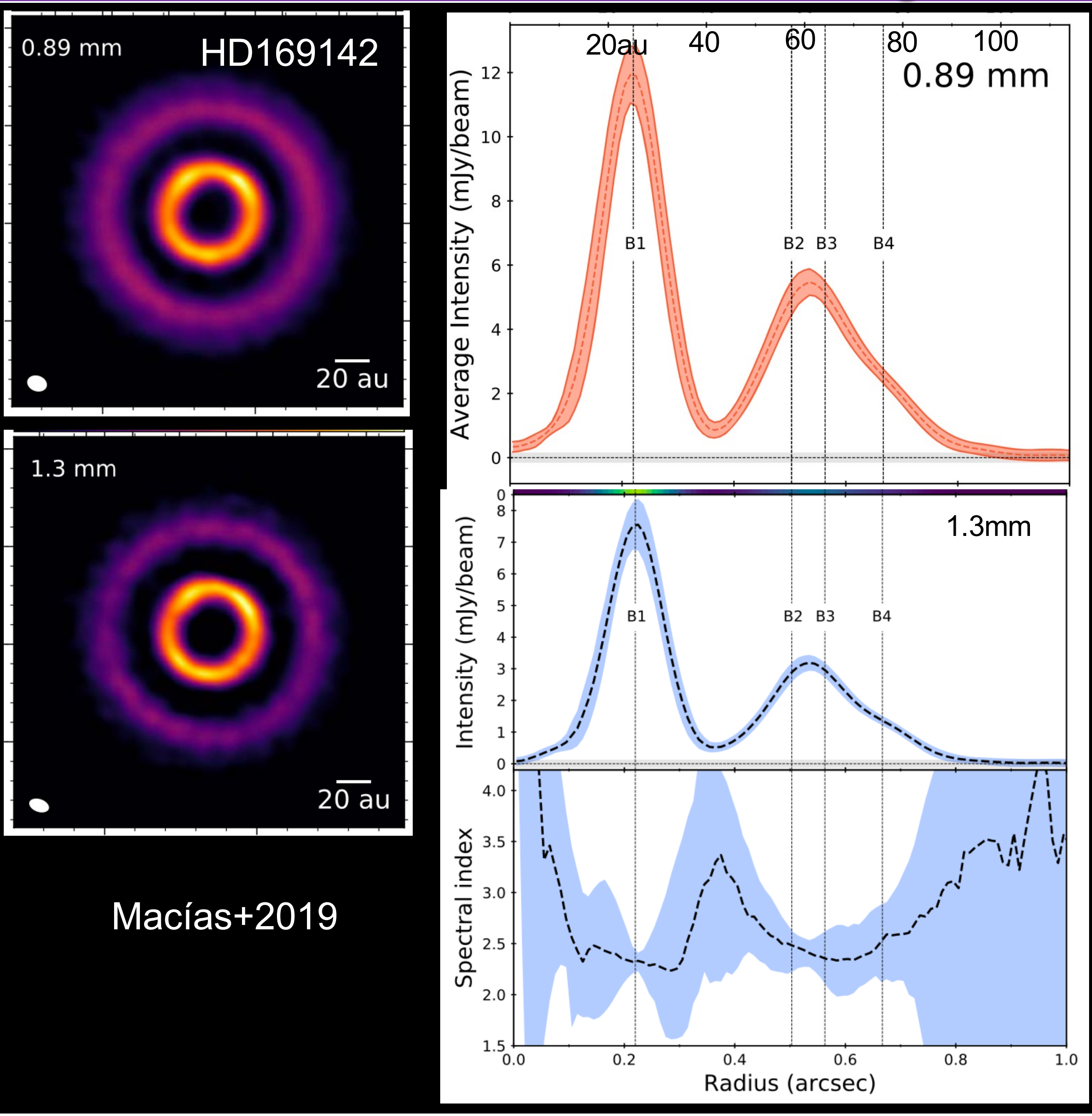
The presence of big grains is a prerequisite for planet formation.



λ (microns)

Dent + 2006, Osorio + 2014

The resolved images of the disks allow us to infer radial variations of the grain size



Macías+2019

*From ~ 20 to 100 au α increases from ~ 2.4 to 3.5, as derived from two ALMA bands. This indicates a decrease of the grain size with radius, consistently with radial migration

*There might be an accumulation of big grains in the rings.

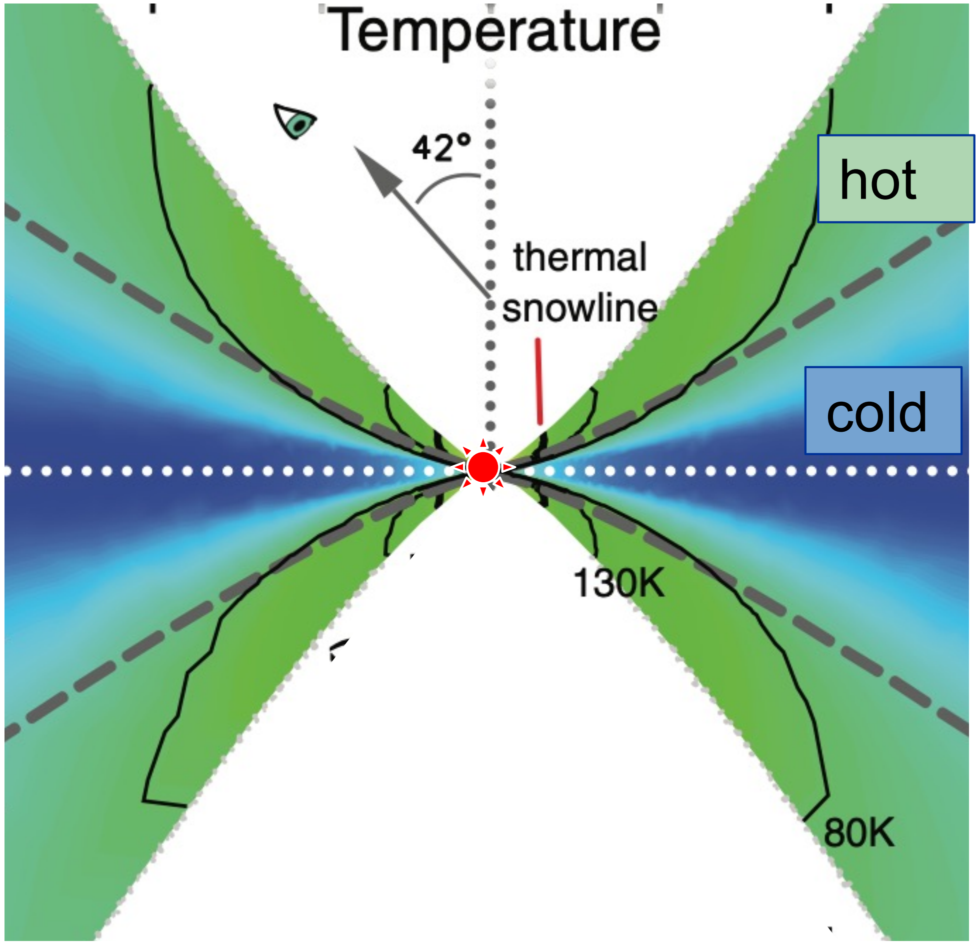
Physical Structure (disk temperature distribution (r,z))

Main heating mechanisms:

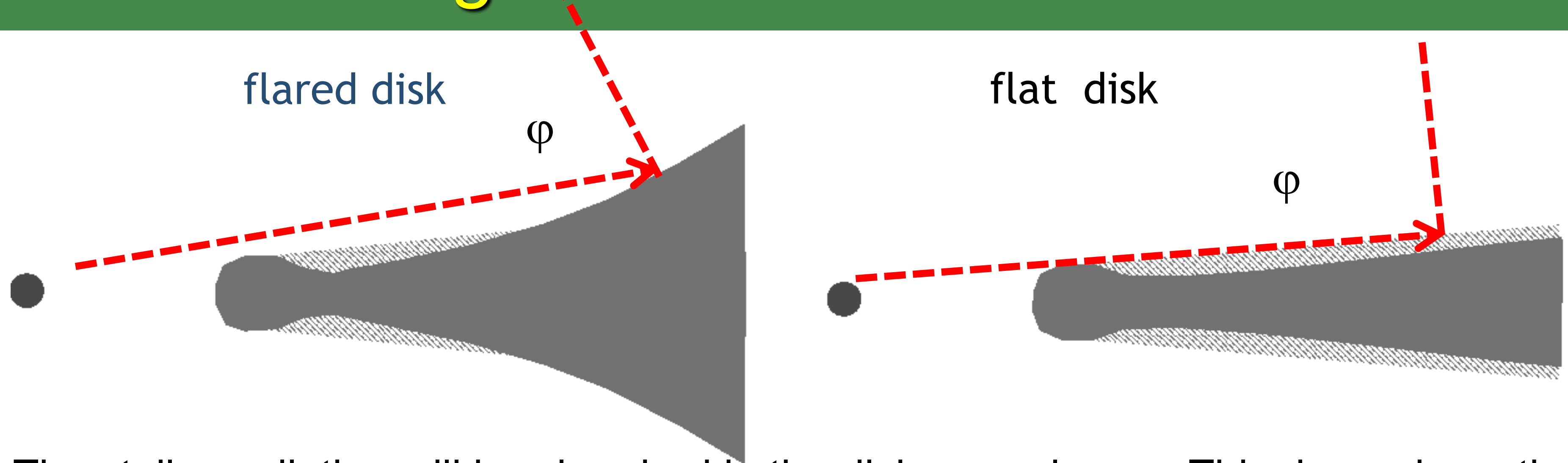
- Stellar irradiation
- Viscous dissipation

the idea behind this is that the friction (viscosity) between two neighboring disk layers (at different velocities) produces heat.

The density and temperature are crucial to determine the snowline position(s).



Heating due to the stellar irradiation



The stellar radiation will be absorbed in the disk upper layers. This depends on the geometric shape of the disk. A flared disk will absorb more stellar radiation than a flat disk. The flux of stellar radiation at distance r from the star is $L_*/2 \pi r^2$. however, the projection of this flux onto the disk surface is $\cos(\varphi) L_*/2 \pi r^2$, where φ is the grazing angle.

heating rate: $Q_+ = \varphi L_*/2 \pi r^2$

Assuming the disk's surfaces can radiate as a Planck functions with temperature T_{eff} :

cooling rate: $Q_- = 2\sigma_{SB} T_{eff}^4$

equating these two equations, T_{eff} can be obtained by:

$$T_{eff} \propto L_*^{1/4} r^{-1/2}$$

Viscous heating due to the accretion process

The heating per gram of gas is proportional to the viscosity coefficient ν and the square of shear, $\nu\,(r\, d\Omega\,/dr)^2$.

The total heating per cm^2 is then:

heating rate: $$Q_+^{\rm accr} = \Sigma\nu \left(r \frac{d\Omega_K}{dr} \right)^2 = \frac{9}{4}\Sigma\nu\Omega_K^2$$

If we insert $dM_{acc}/dt=3\pi\Sigma\nu$, then we get

$$Q_+^{\rm accr} = \frac{3}{4\pi}\dot{M}\Omega_K^2$$

The release of energy is proportional to the amount of matters that accrete.

Assuming the disk's two surfaces can radiate as a Planck functions with temperature T_{eff} :

cooling rate: $$Q_- = 2\sigma_{\rm SB} T_{\rm eff}^4$$

equating these two equations, T_{eff} can be obtained by:

$$T_{\rm eff} \propto \dot{M}^{1/4}\, r^{-3/4}$$

Physical Structure (Temperature distribution (r,z))

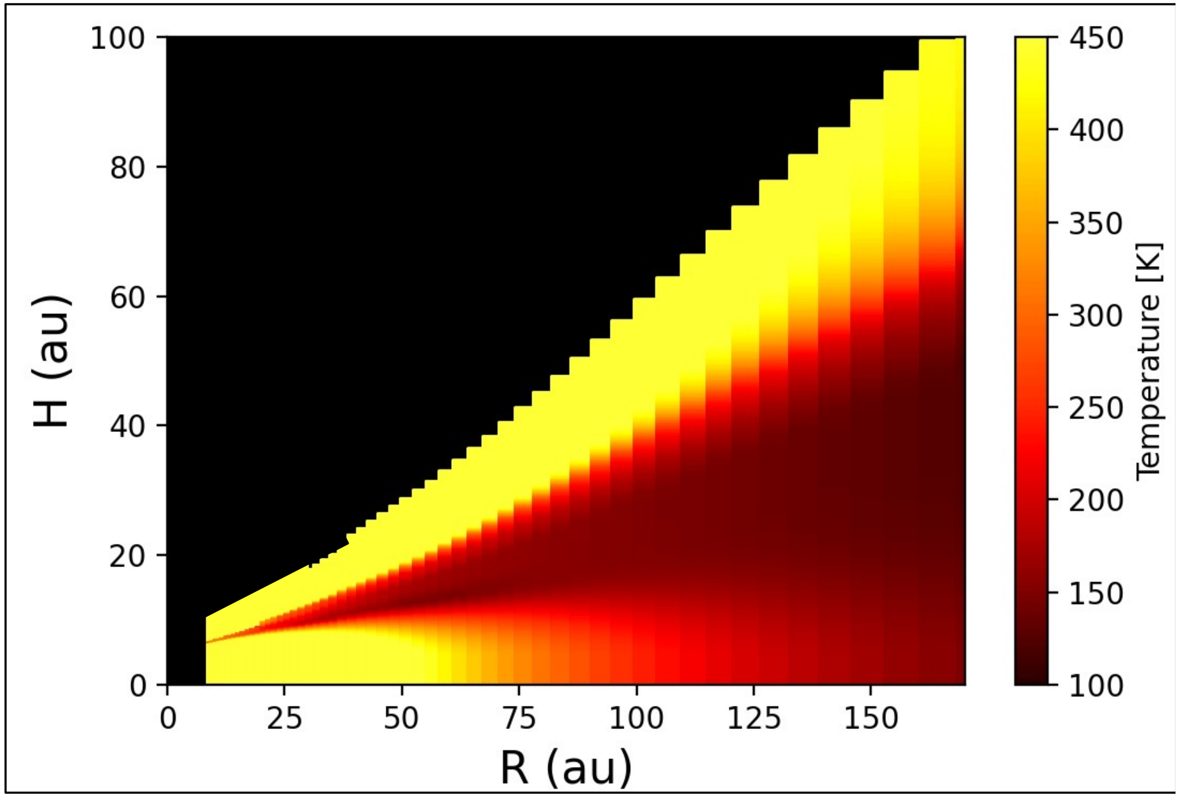
Main heating mechanisms:

- Viscous dissipation (accretion)
- Stellar irradiation

$$T_{\rm eff} = \left\{ \frac{3}{8\pi\sigma_{\rm SB}} \dot{M}\Omega_K^2 + \varphi \frac{L_*}{4\pi\sigma_{\rm SB} r^2} \right\}^{1/4}$$

$$T_{\rm eff} \, \alpha \, (r^{-3} + r^{-2})^{1/4}$$

Since for viscous dissipation the Teff drops steeper than for irradiation, Teff is dominated by irradiation for large r, while by accretion for small r.

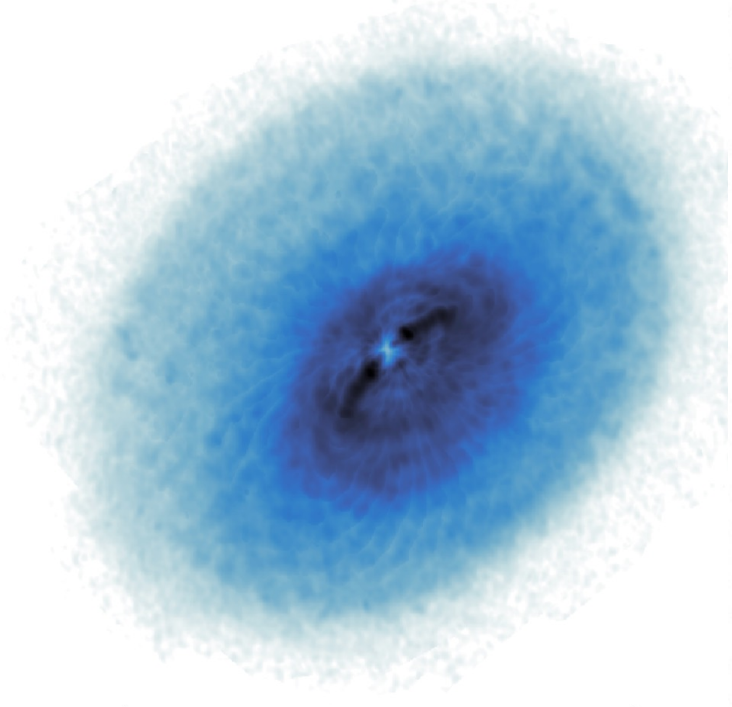


Others:

- Envelope irradiation,(class 0, MYSO)
- Accretion shock (eruptive variables, MYSO)
- Cosmic rays
- Resistive dissipation by magnetic fields (Lizano+2016)

Physical Structure (disk velocity distribution)

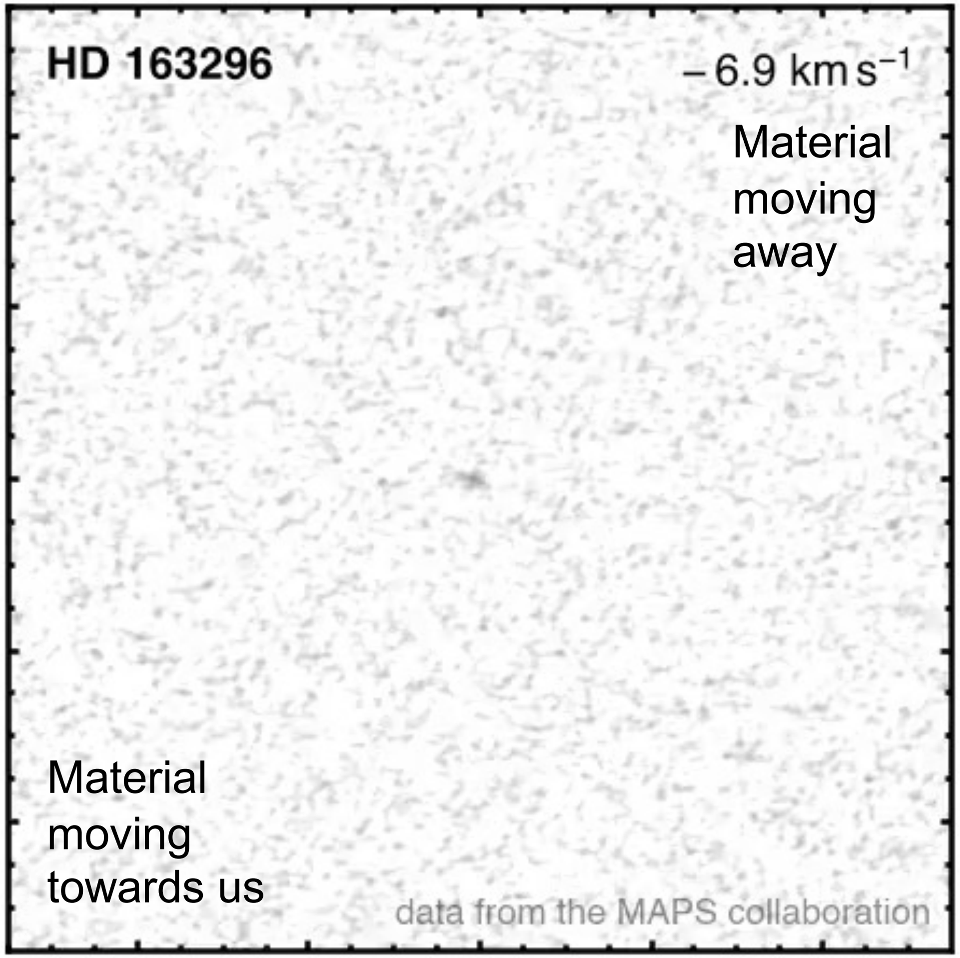
HD 163296



CO (2-1) emission
Teague+2021

Additional information can be obtained from the molecular line emission.

Channel map as a function of the V_{los}

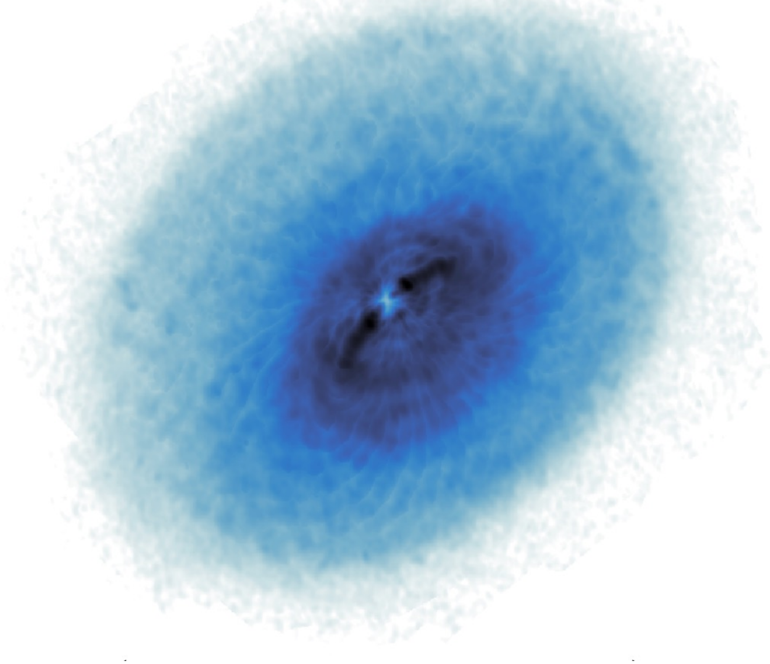


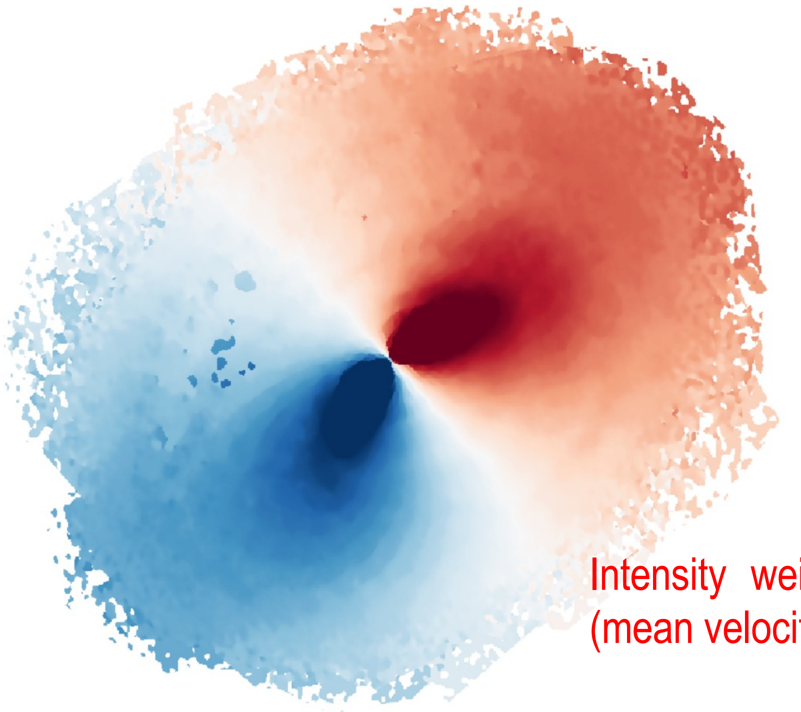
Observed butterfly pattern

This is better defined when disks have an intermediate inclination

Physical Structure (velocity distribution)

HD 163296

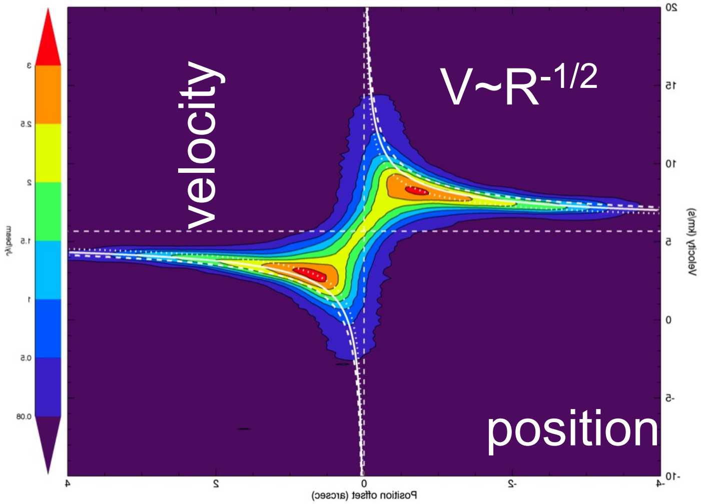




Intensity weighted velocity (mean velocity)

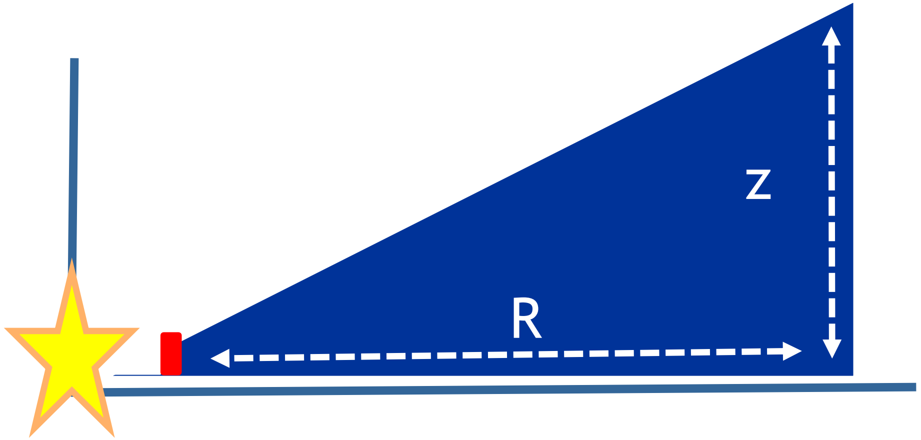
CO (2-1) emission
Teague+2021

PV diagram shows a perfect Keplerian pattern. This is the most reliable method used to derive M_*



D'Alessio Irradiated Accretion Disk models, DIAD

- Geometrically thin and axisymmetric
- Steady mass accretion rate dMacc/dt and viscosity through the disk (α–prescription)
- Hydrostatic equilibrium
- Keplerian rotation Ω=sqrt(GM$*$/R^3)
- Viscous and irradiated disks

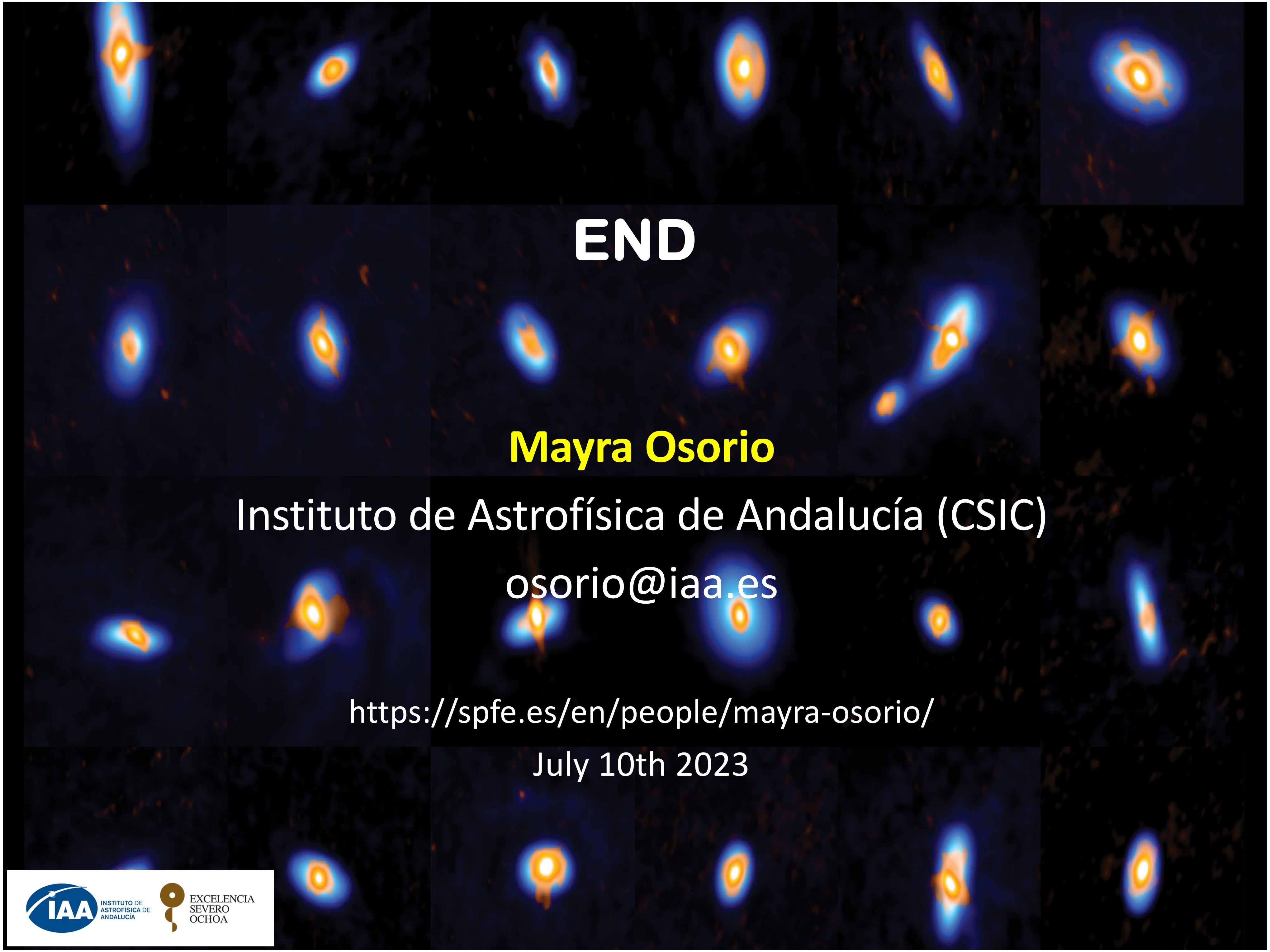


The dust mixture includes two grain populations:

•a_{min} = 0.005 μm, a_{max} ~1 μm (disk upper layers)

•a_{min} = 0.005 μm, a_{max} ~ 1 mm - 1 cm (disk midplane).

Disk model catalog (D'Alessio+1998, 1999, 2001, 2006)
https://dept.astro.lsa.umich.edu/datasets/accretion/catalog.html
Paola's calculations have defined the state of the art in models of protoplanetary disks


END
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