Signs of Planet Formation in Protoplanetary Disks

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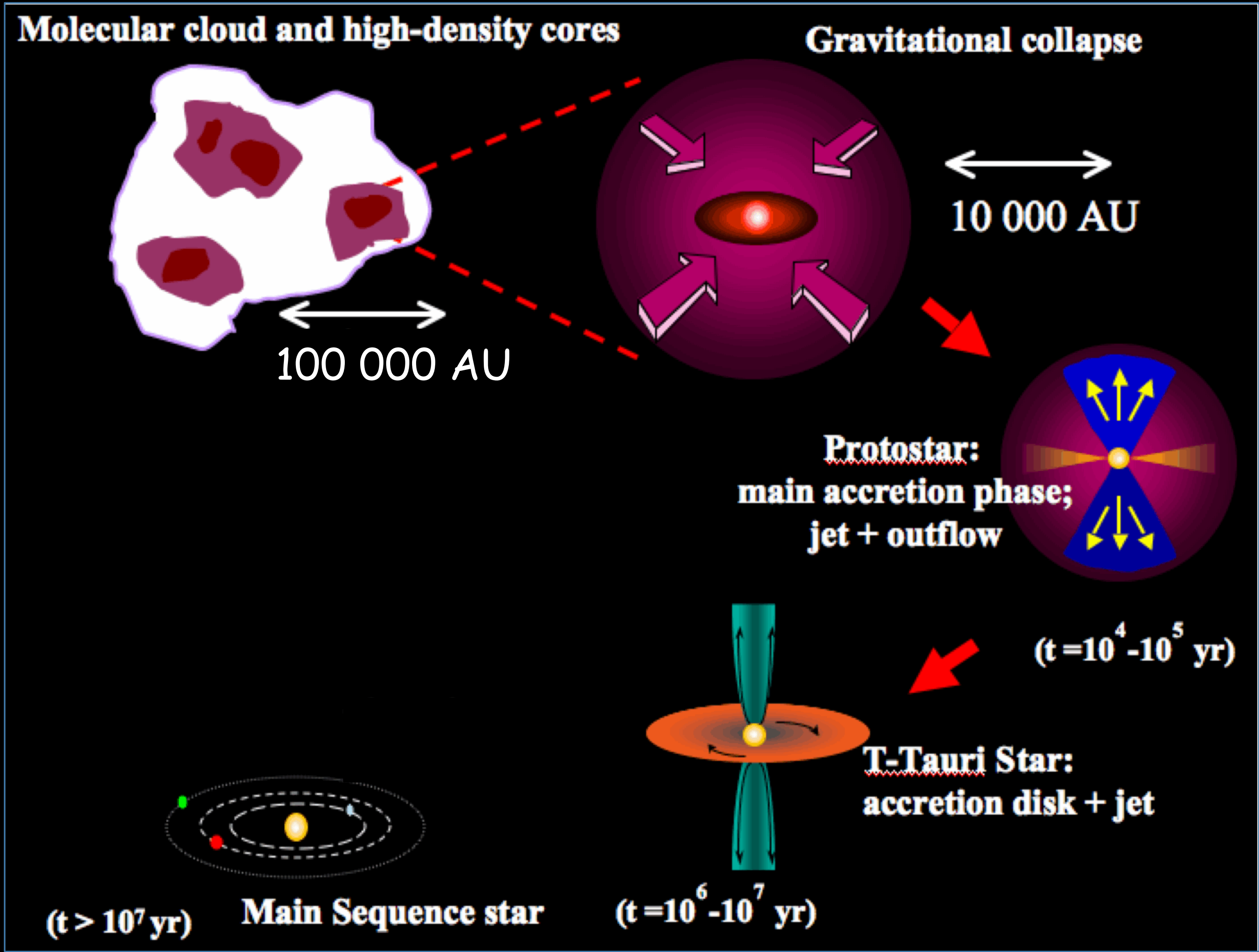
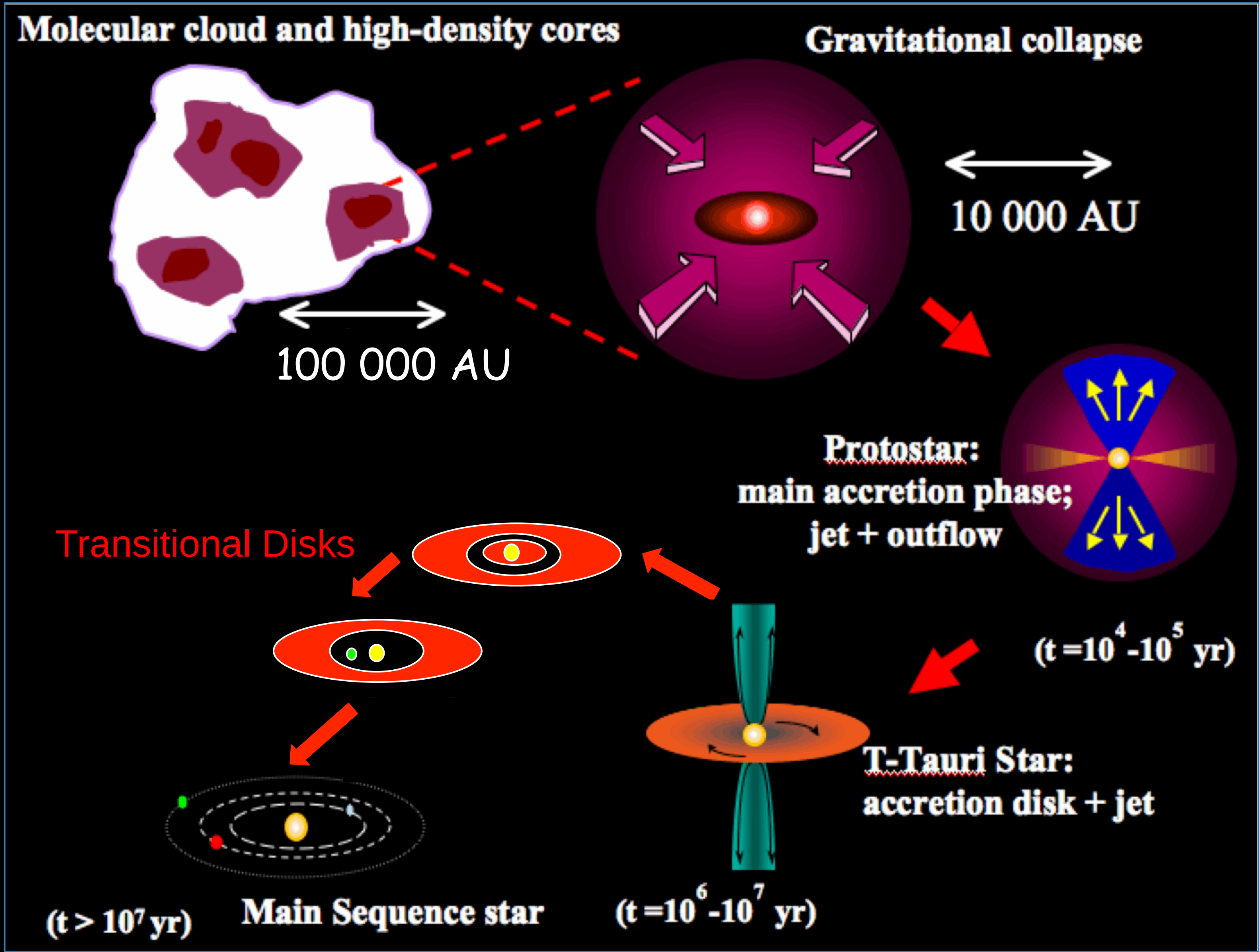
Standard Scenario for Star Formation

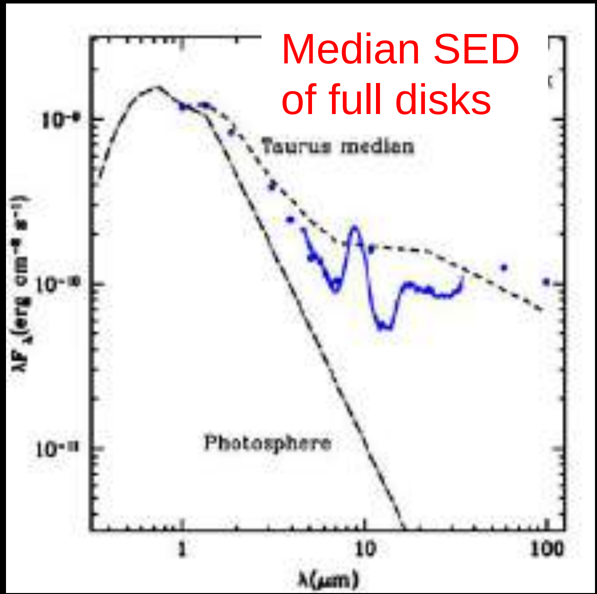


Standard Scenario for Star Formation



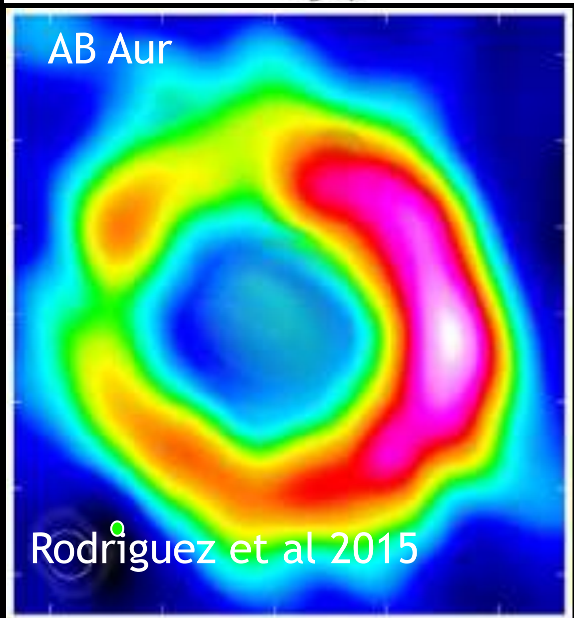
Cavities in Disks: Signatures of Planet Formation

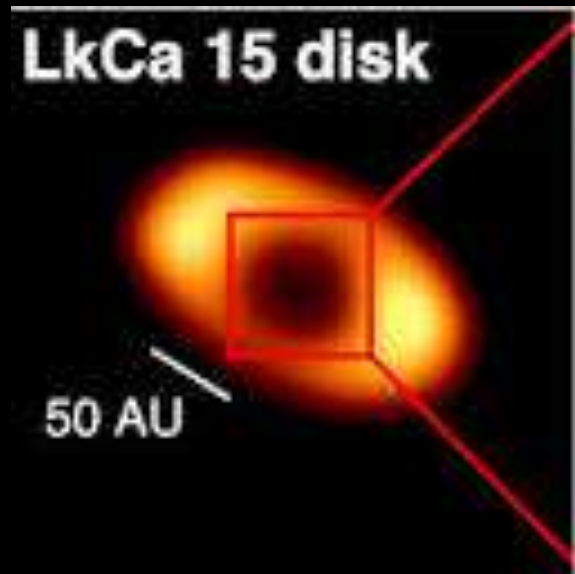
Transitional Disks



XXX

van der Marel et al 2016





The transitional disk of HD169142

Relatively isolated Herbig Ae/Be star

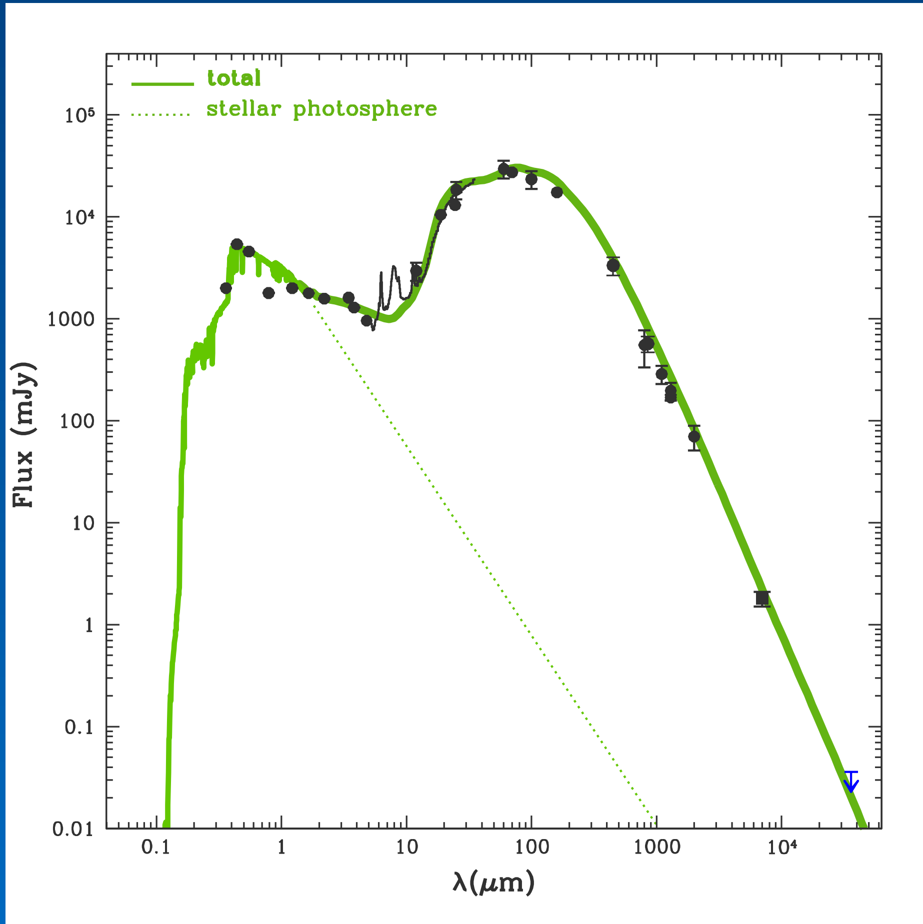
Stellar mass = 2 $M_\odot$

Age = 2-10 Myr

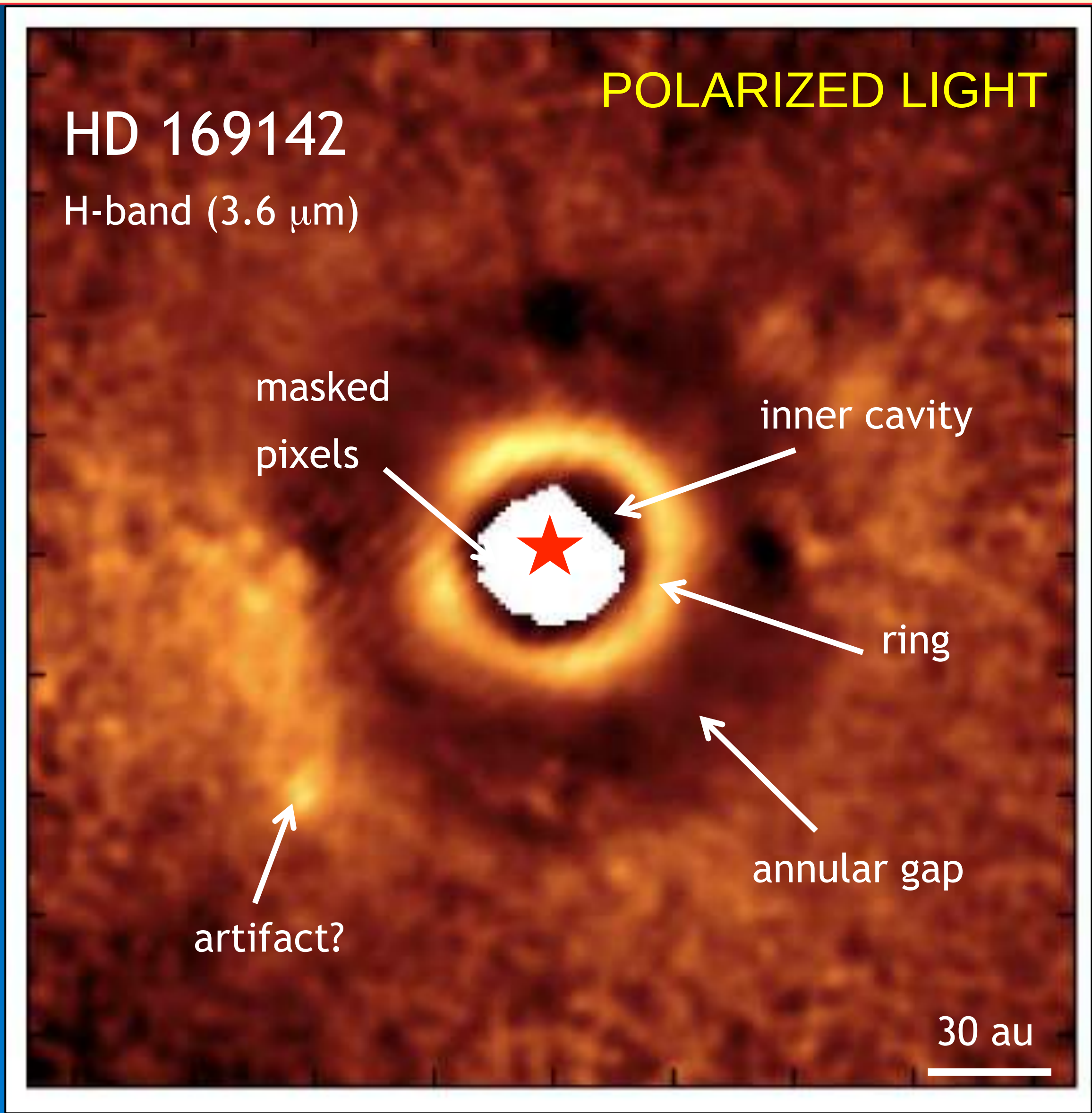
Distance = 145 pc (Sylvester et al 1996)

SED:

Based on the SED modeling Grady et al. (2007), Meeus et al. (2010) and Honda et al. (2006) predicted the existence of a central cavity in this protoplanetary disk.



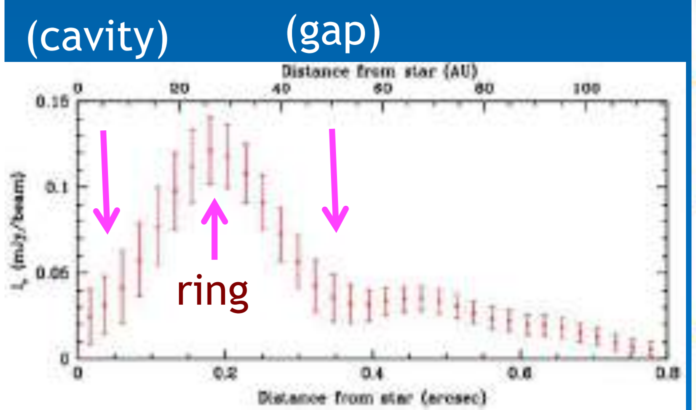
Near-IR polarized light imaging of HD169142



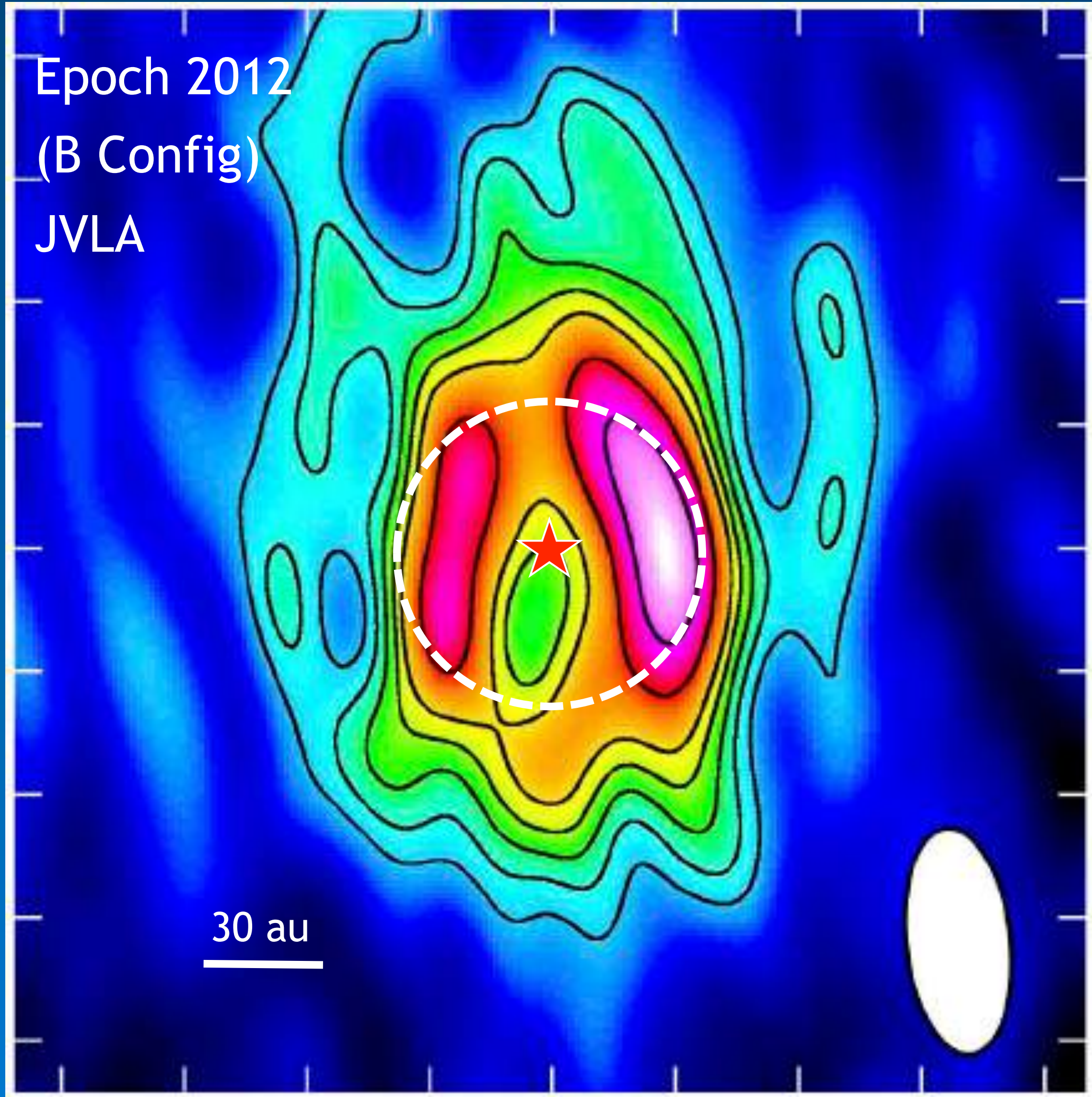
(Quanz et al 2013)

New VLA 7 mm imaging of HD169142

7mm azimuthally averaged intensity profile

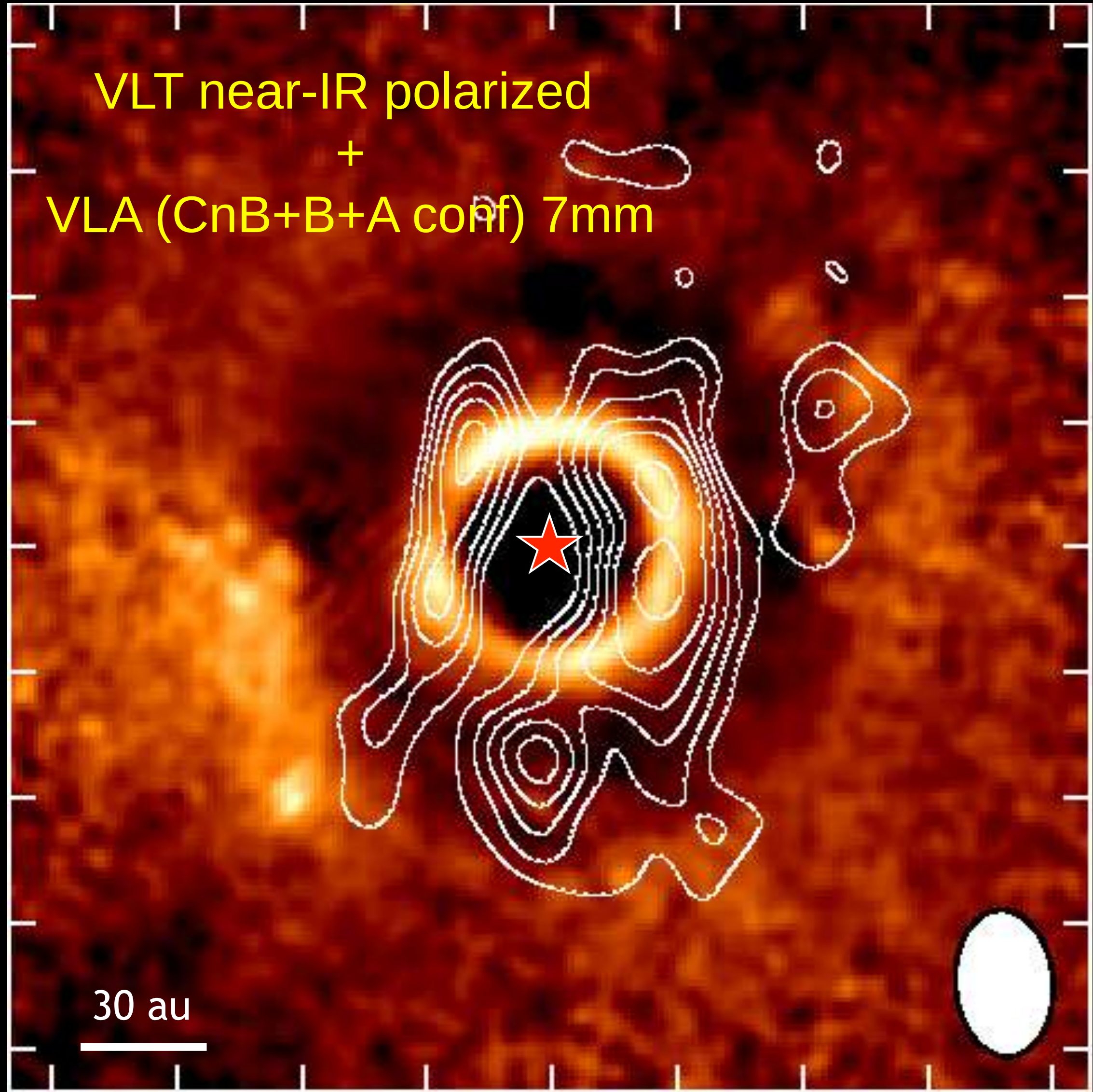


Osorio et al 2014



Comparison of the 7mm dust emission and the IR polarized light images

The ring seen in the IR is traced by small dust grains, and coincides with the ring seen at 7 mm, which traces big grains (pebbles)



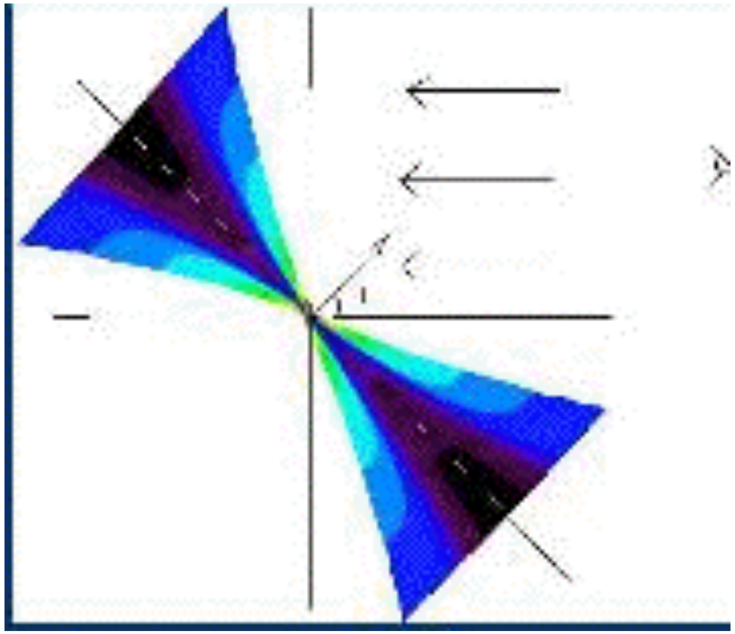
Modeling the HD169142 disk

The D'Alessio et al. (2006) disk models consider irradiated flared accretion disks heated by a central star and viscous dissipation.

Vertical settling of the particles in the disk mid-plane is included assuming a standard grain-size distribution $n(a) \propto a^{-3.5}$, with

$a = 0.005$ - 1 μm (upper layers)

$a = 5\mu$m - 1mm (mid-plane)



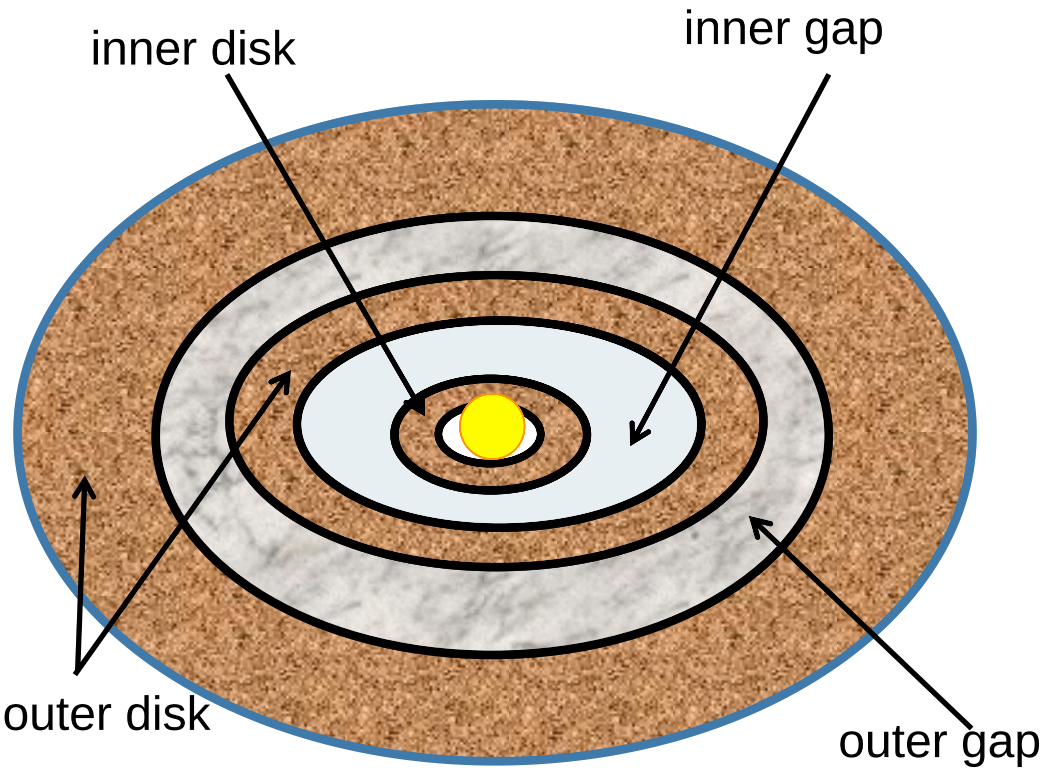
The viscosity, $\nu_{turb} = M_{acc} / 3\pi\,\Sigma$, is set through the α-prescription (Shakura & Sunyaev 1973).

$M_{acc} < 10^{-9}\,M_{sun}$/yr (UV excess, Grady et al 2007).

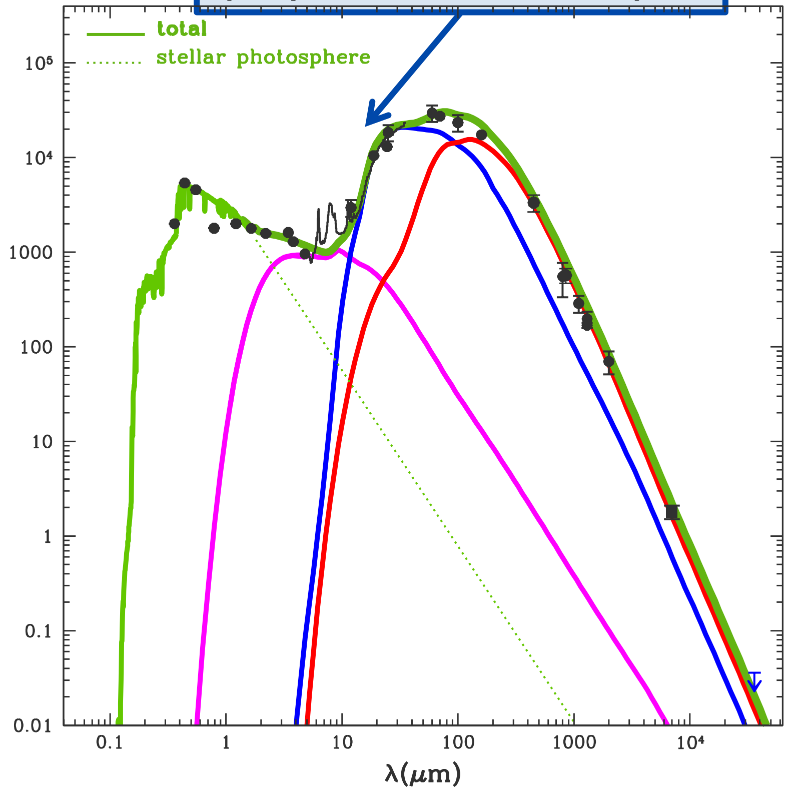
Strong mm flux densities => high Σ => small ν_{turb}

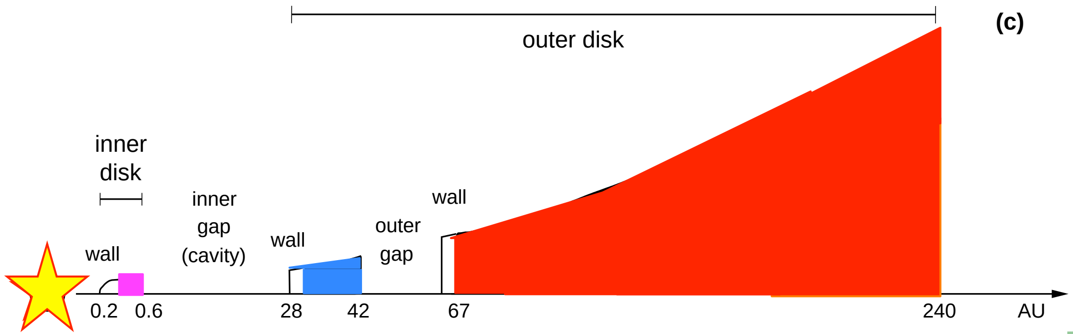
We have modified the D'Alessio's models to include the cavity and annular gap observed in the HD169142 disk.

Components of the HD169142 disk model



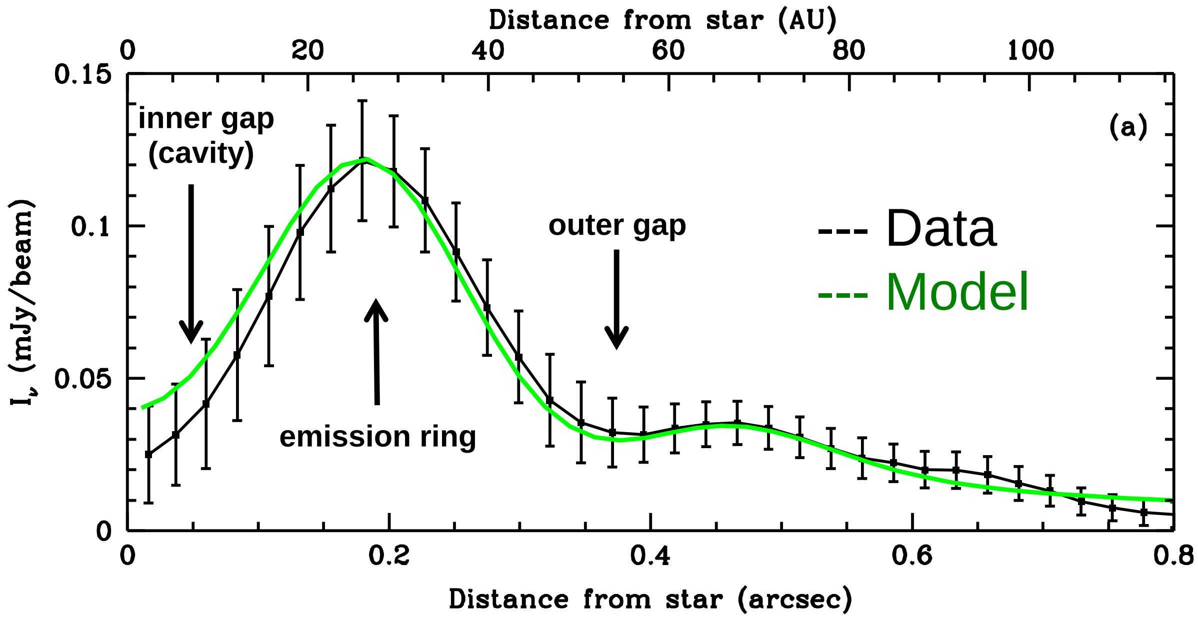
inner disk
=> pre-transitional disk
(Espaillat et al 2011)





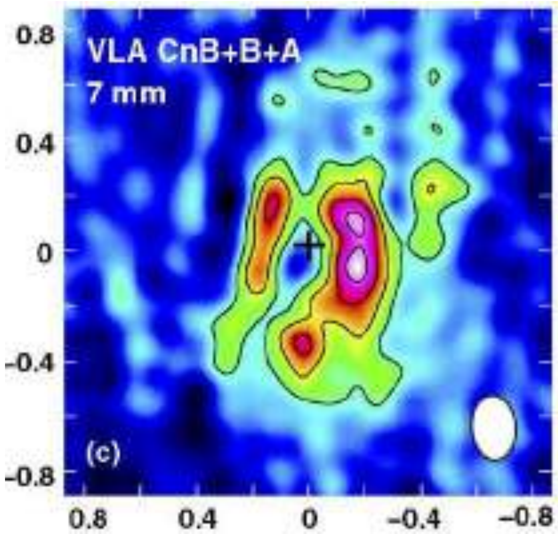
- **Star**
- **Disk with two gaps**
- **A sublimation wall and 2 walls of the gaps.**

Fitting the 7mm intensity profile

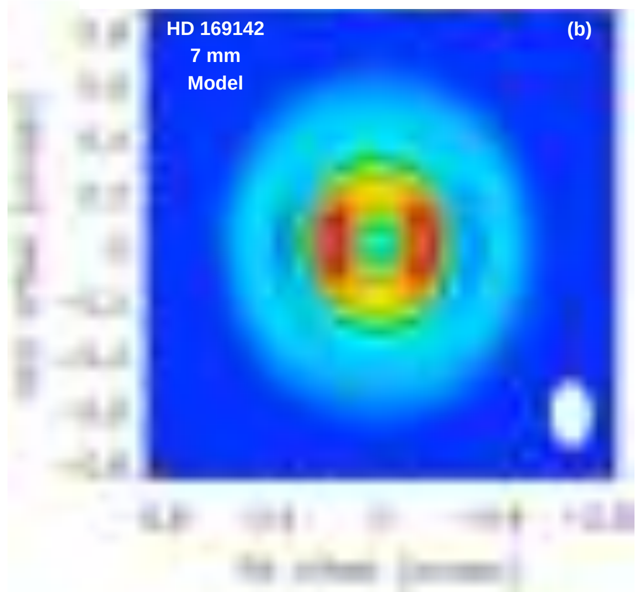


Large accumulation of big grains in the walls

OBSERVED IMAGE



CASA SIMULATED IMAGE



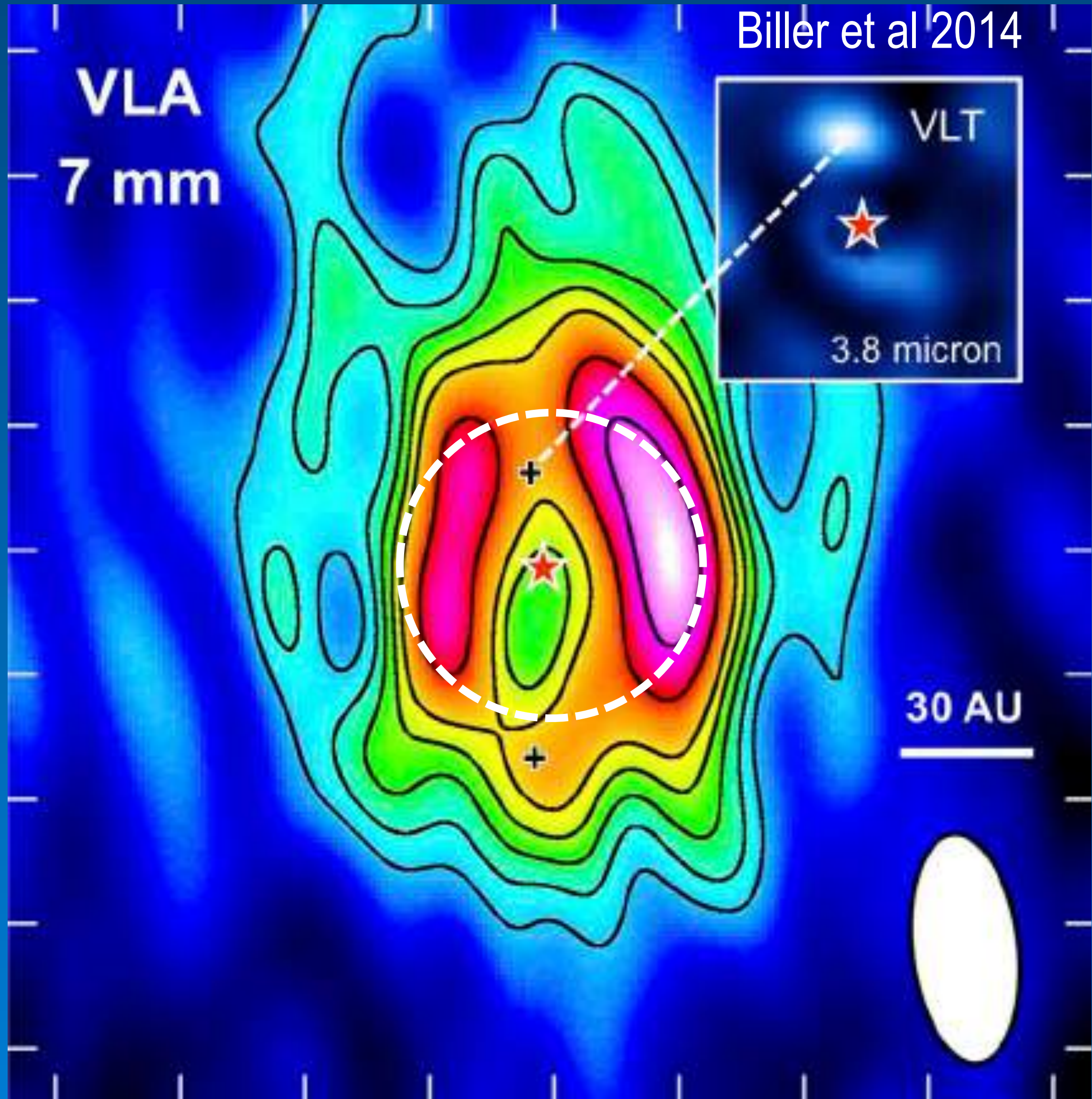
Signs of planet formation in the HD169142 disk gaps

Reggiani et al 2014
Biller et al 2014

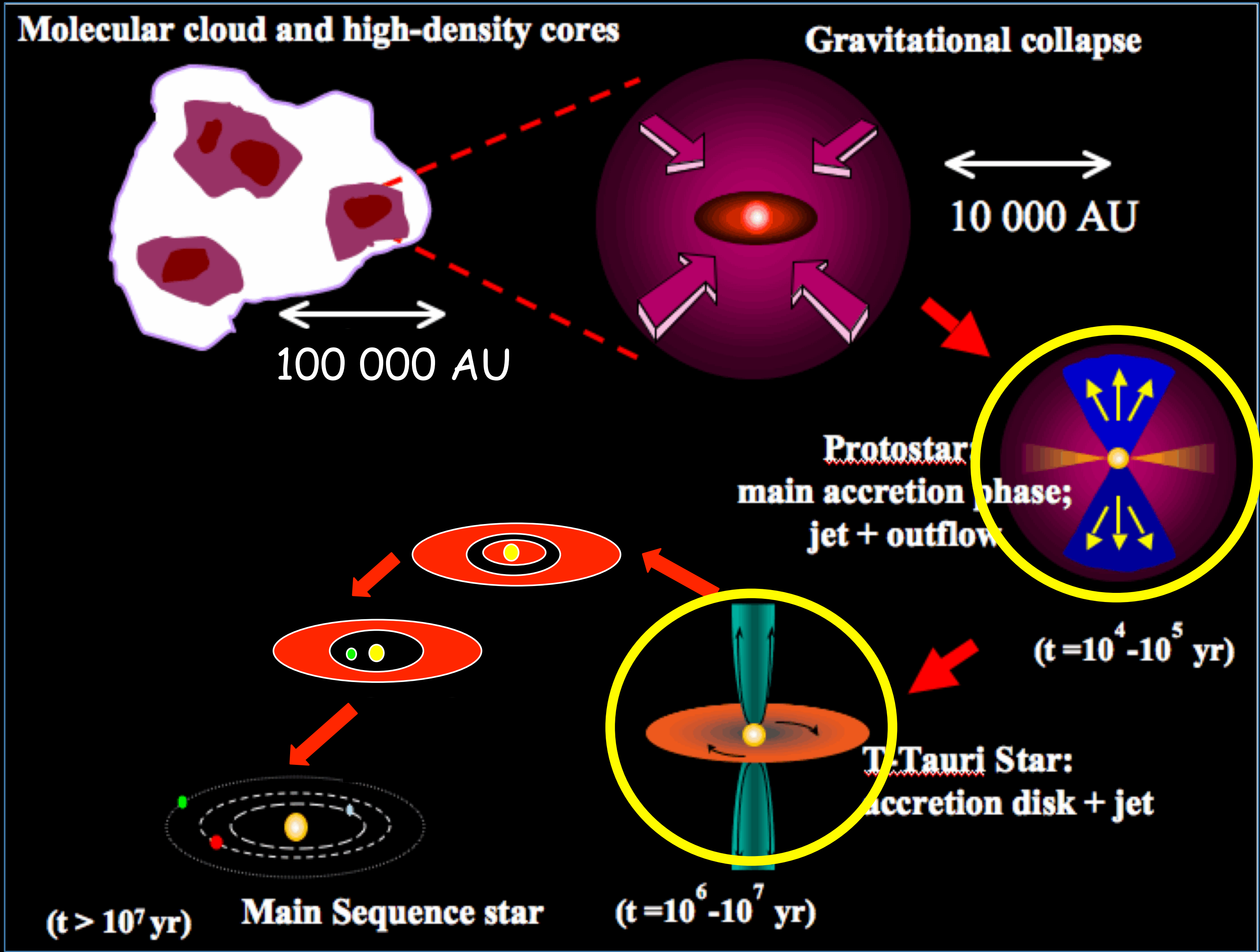
New IR source (protoplanet candidate/ substellar companion) detected at r=23 au

Mass=28-32 M_{Jup}

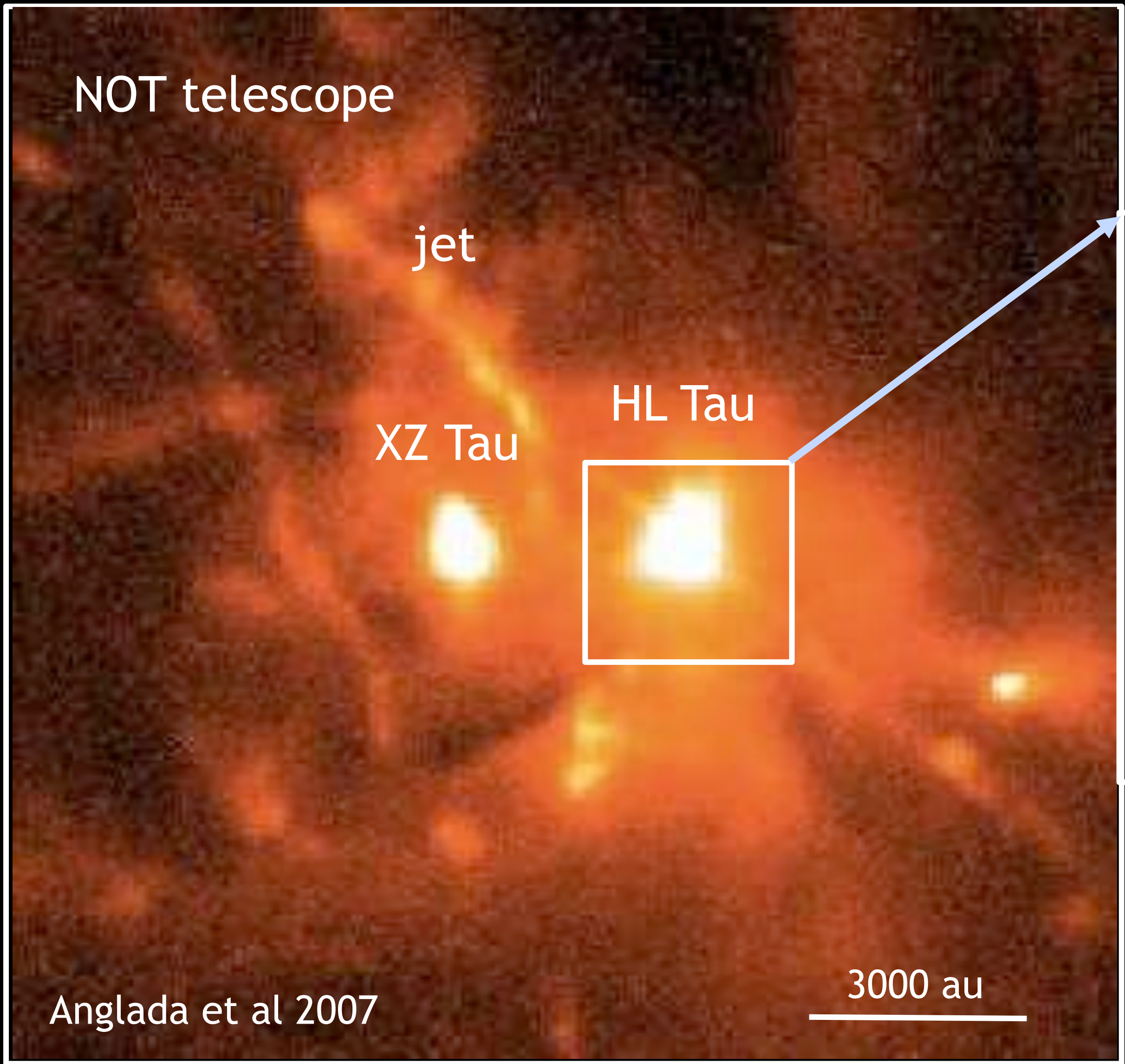
Orbital Period=80yrs

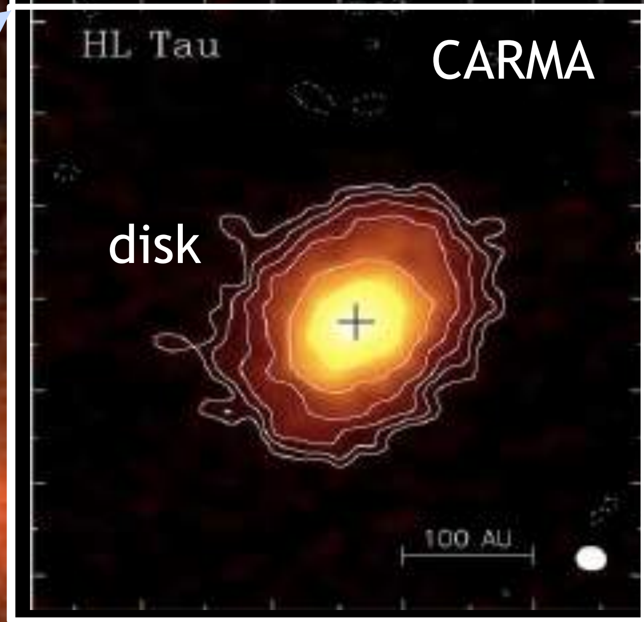


Standard Star Formation Scenario



HL/XZ Tau system





We do not expect to find cavities/gaps in this young source

ALMA observations of the HL Tau Disk

*Seven pairs of dark and bright rings might be created by protoplanets

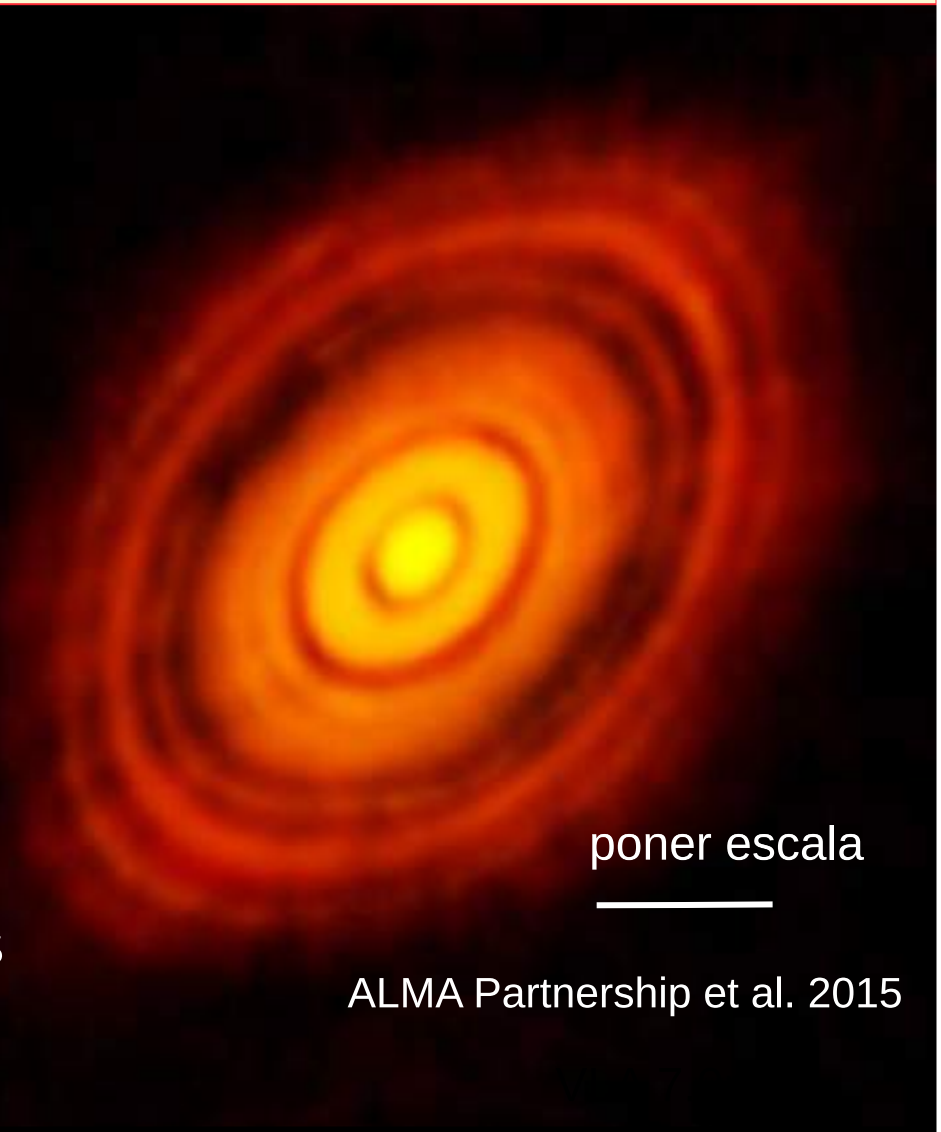
*However, HL Tau too young to host planets at 10 and 100 au!

*IR searches have not detected point sources inside the gaps.

*ALMA emission is optically thick in

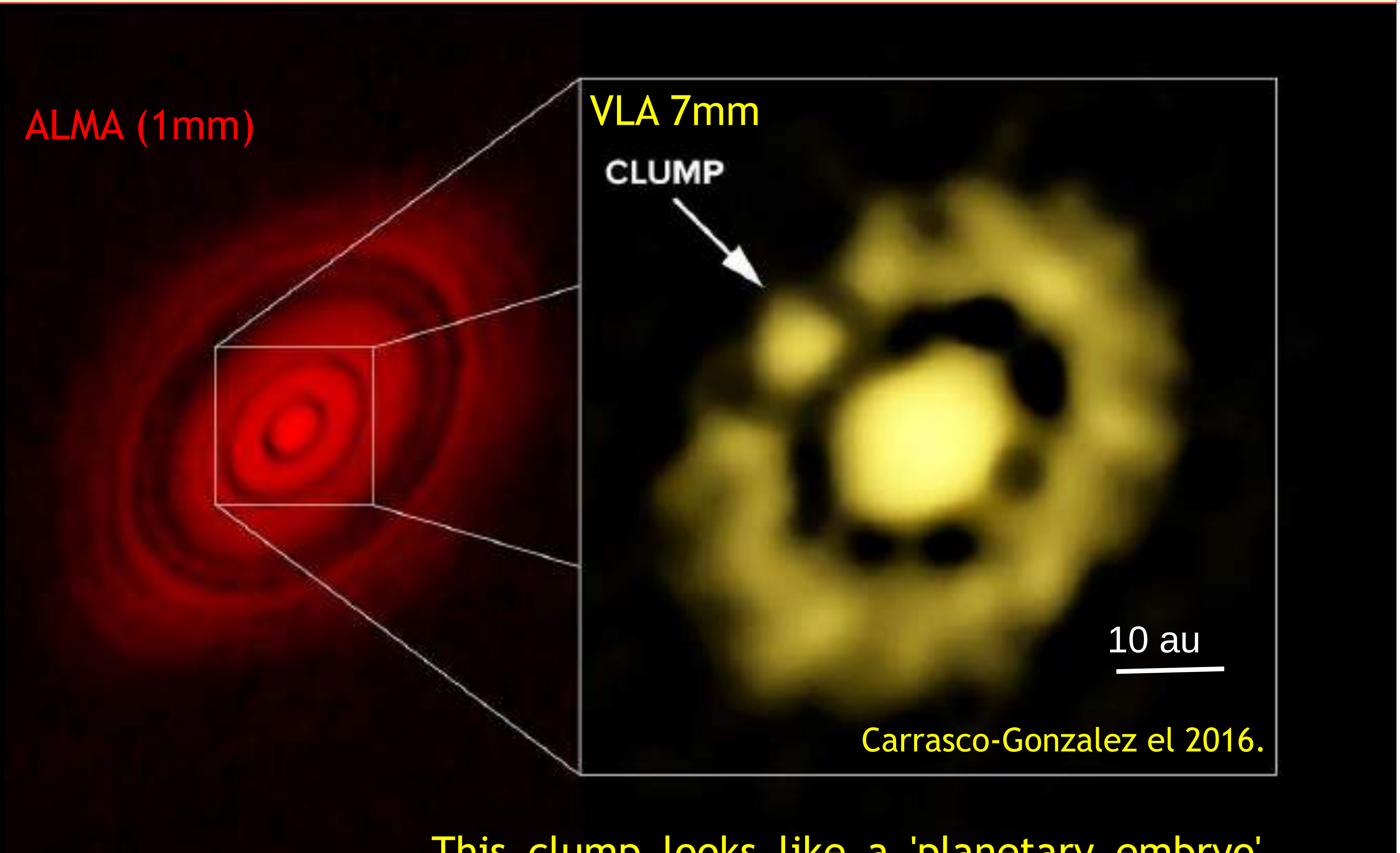
the bright rings.

VLA observations at 7mm trace optically thin emission that could reveal substructure in the bright rings



ALMA Partnership et al. 2015

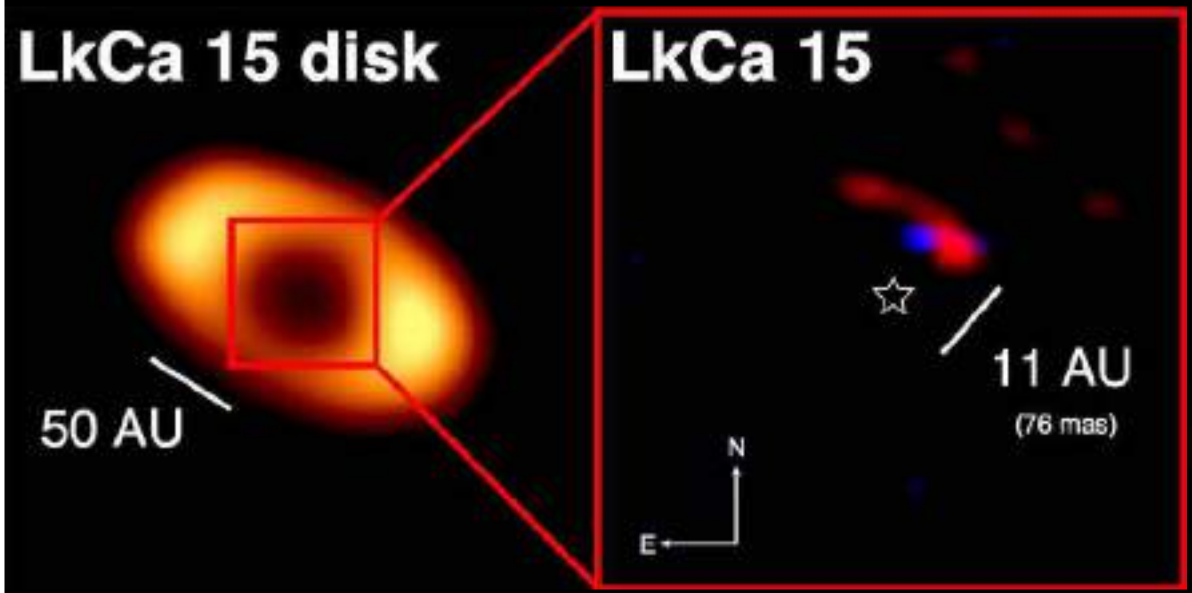
Observing HL Tau with the Very Large Array

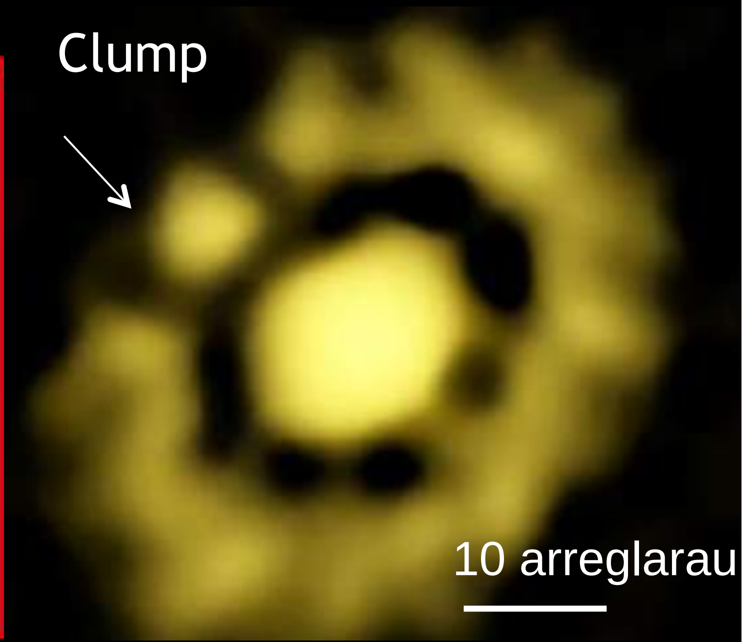


This clump looks like a 'planetary embryo', which may become a planet over the next millions of years

LkCa 15 and HL Tau, two stages of planet formation?

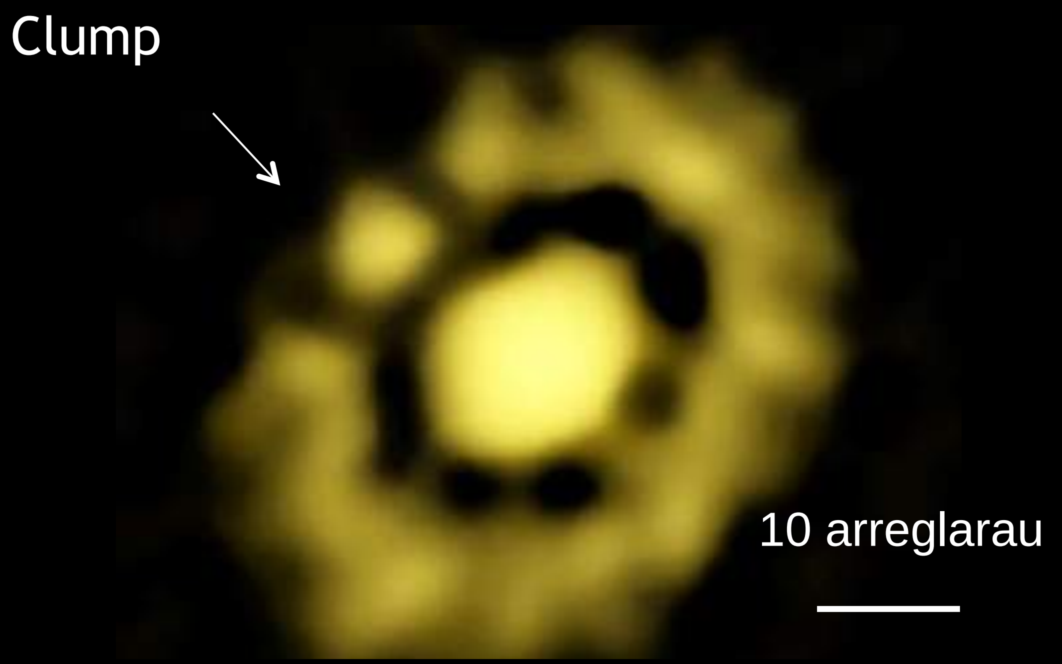
Clump in HL Tau may be in earlier evolutionary stage of planet formation than the IR source detected within the cavity of LkCa 15





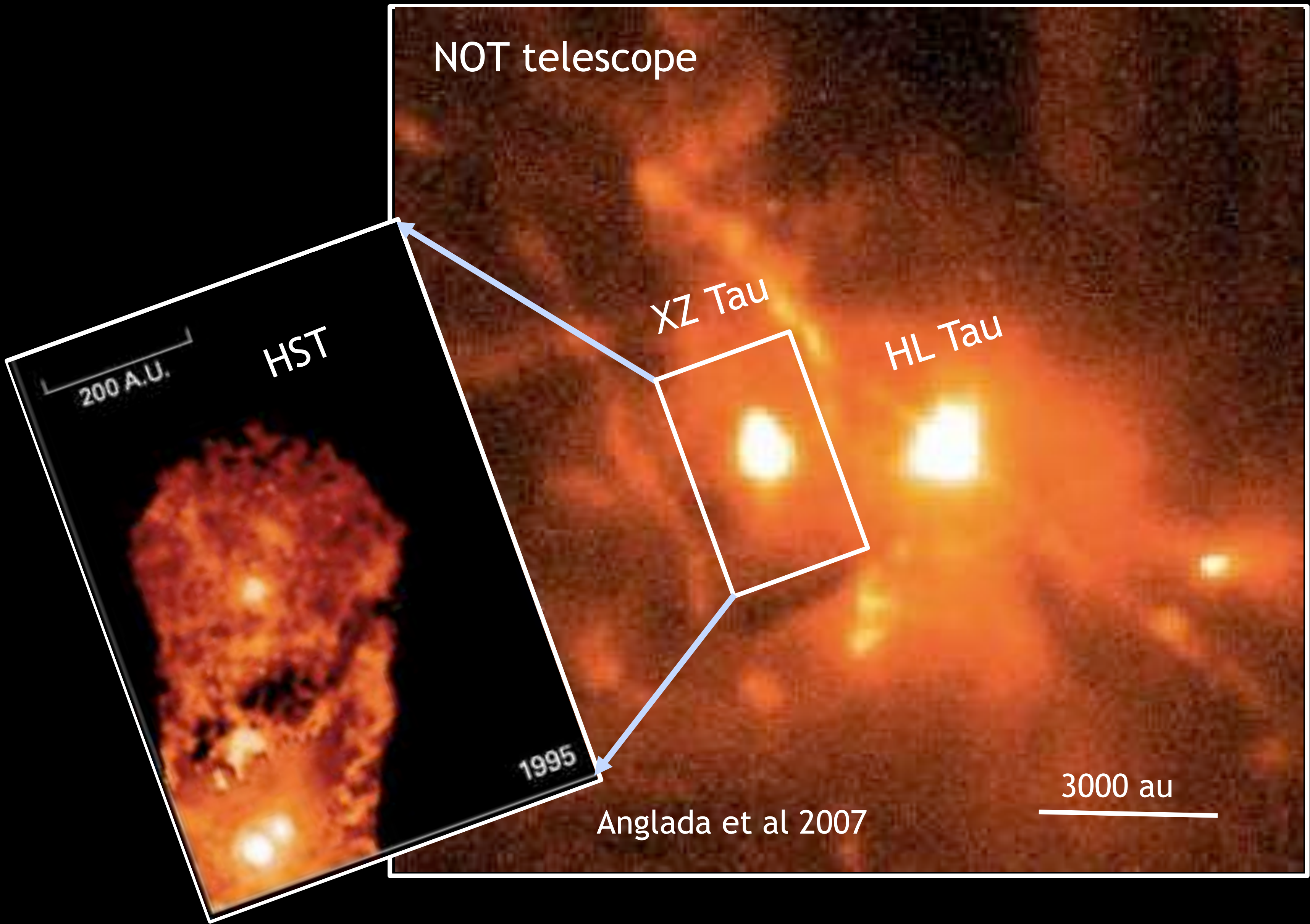
Laplace (1796) gave scientific form to the latter interpretation (Fig. 1). In his model the nebula began as an approximately spherical slowly-rotating dusty cloud. As it cooled and collapsed so it spun faster to conserve angular momentum and flattened along the spin axis. Eventually material at the equator would have been moving in free orbit around the central mass. Further collapse led to material, in the form of annular rings, being left behind in circular Keplerian motion about the interior mass. Condensations within each ring, all orbiting at slightly different rates, gradually accumulated to form a single planet. A smaller scale version of the process for each collapsing protoplanet then yielded satellite systems.

HL Tau, in an early stage of planet formation

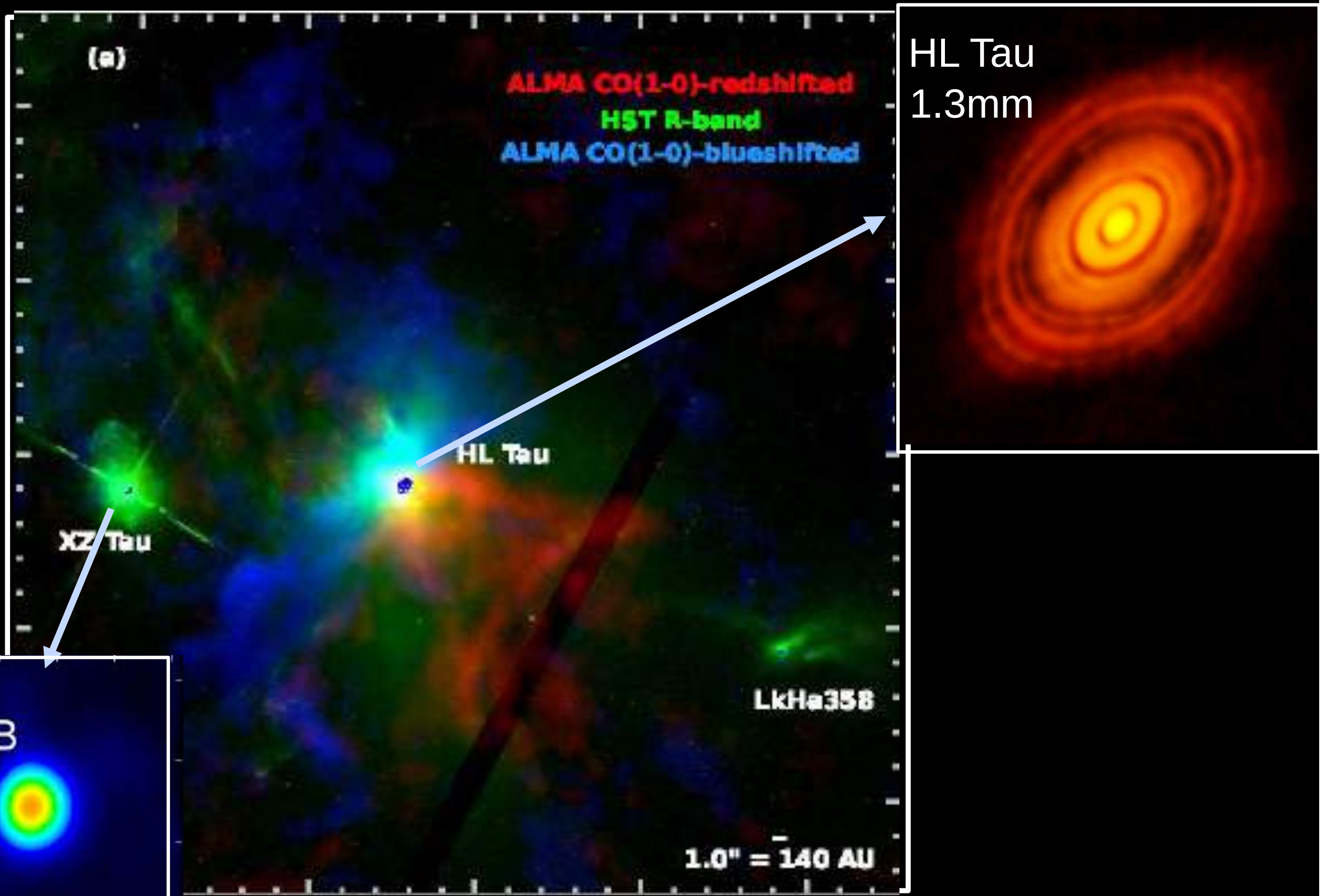


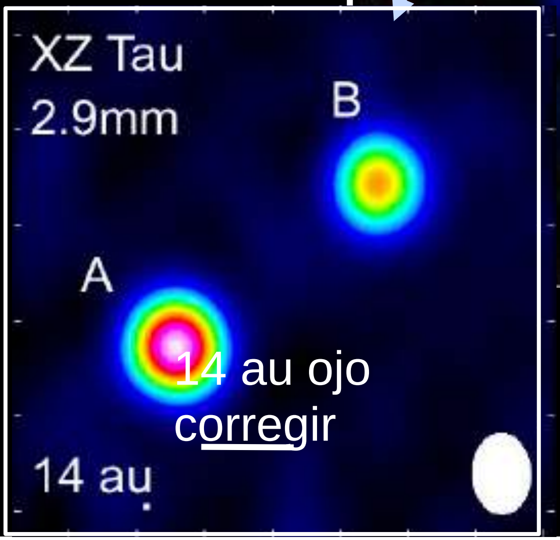
HL Tau does not host planets already formed, but its disk may undergone a fragmentation process, after which the first planet embryos are being formed.

HL/XZ Tau system



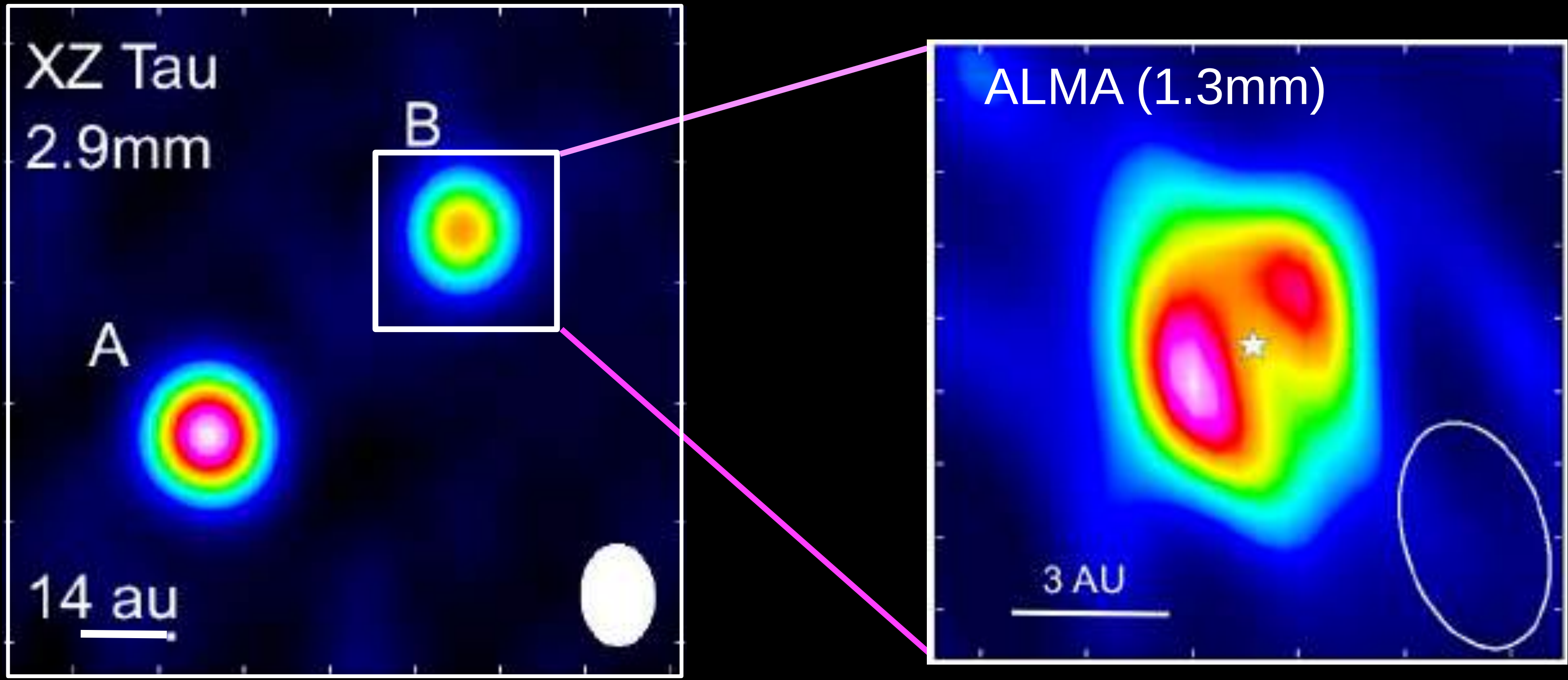
ALMA observations of the HL tau/XZ Tau system





ALMA Science Verification data program
for the long baseline campaign

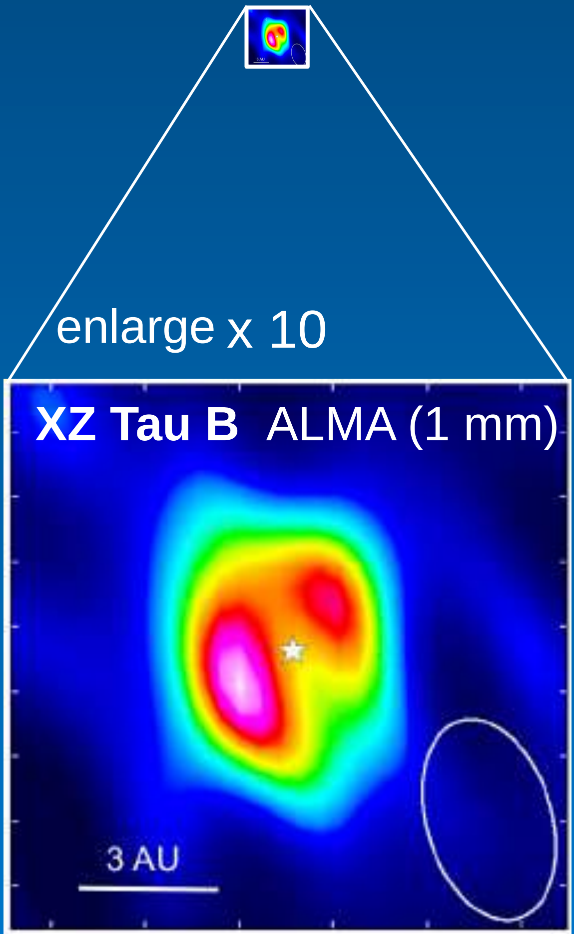
A dwarf transitional disk in XZ Tau B



Osorio et al. 2016

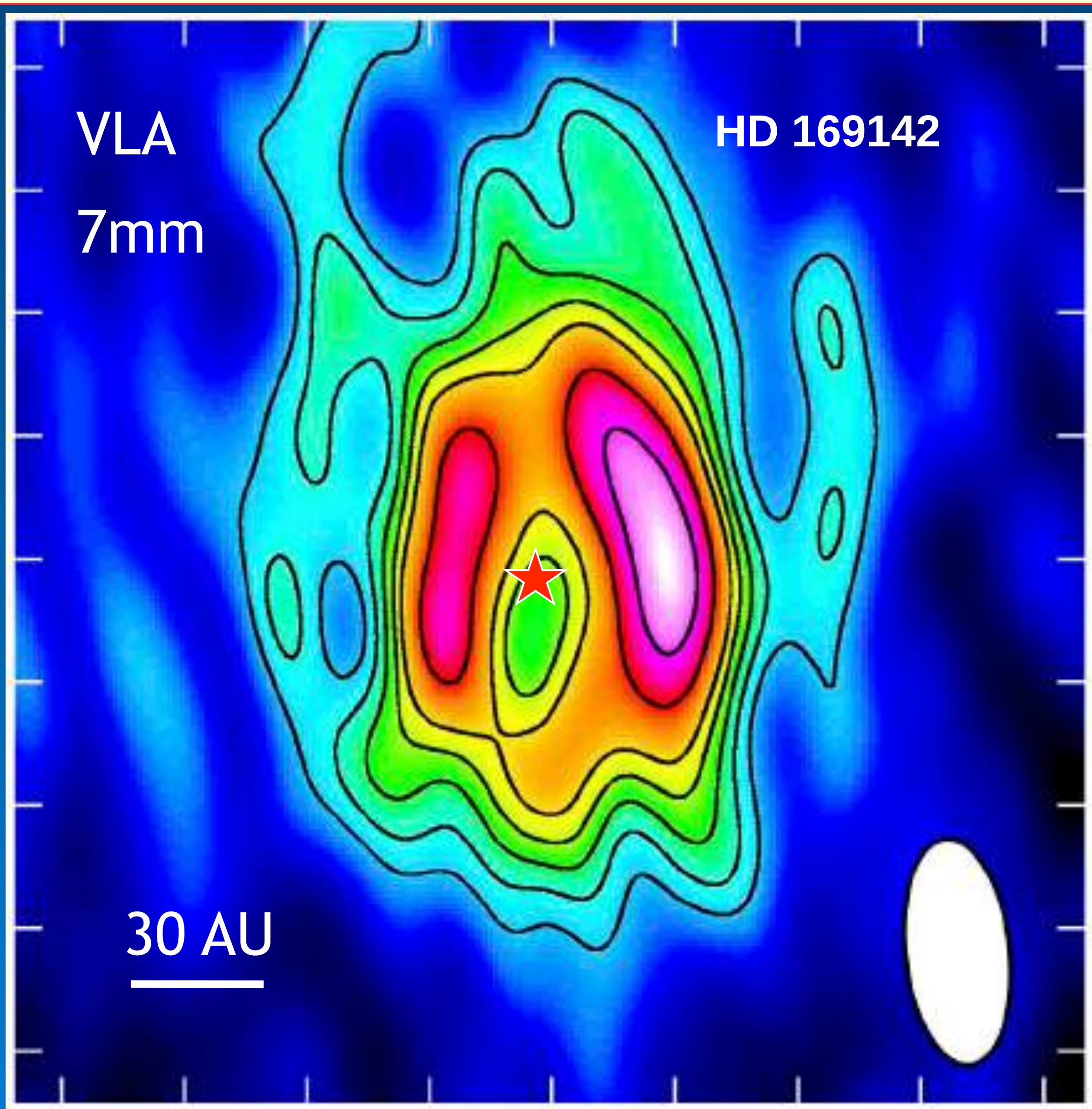
-This is the first time that a small disk so small is angularly resolved.
-Typical properties of large disks: R_{disk}=50-100au, $R_{cavities}$=10-70au

Comparison at the same scale of the XZ Tau B and the HD 169142 transitional disk



(Osorio et al 2016)

au scale features evolve on timescales of months!

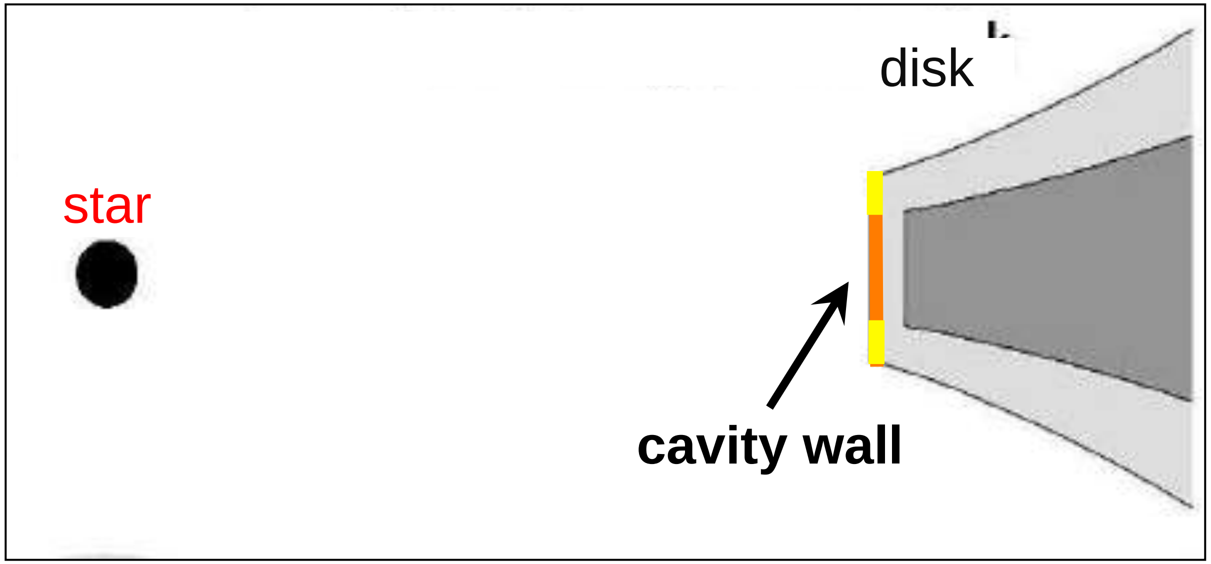


100-200 yrs

(Osorio et al 2014)

Radiative Tranfer Modeling of the XZ Tau B disk

*We used an updated version of accretion disk models developed by D'Alessio et al. (2006).



*M_{acc} (10^{-8}--$10^{-7} M_{sun}$/yr) in the disk can go as:

M_{acc}(star)<<M_{acc} disk << 10_{Macc}(star)

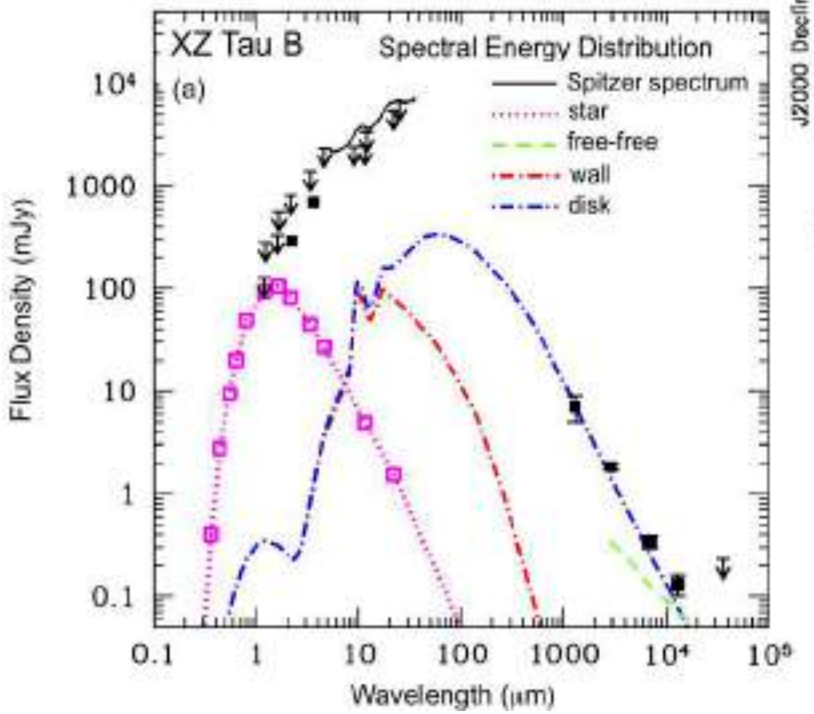
*Viscosity parameter α (0.01, 0.001, 0.0001)

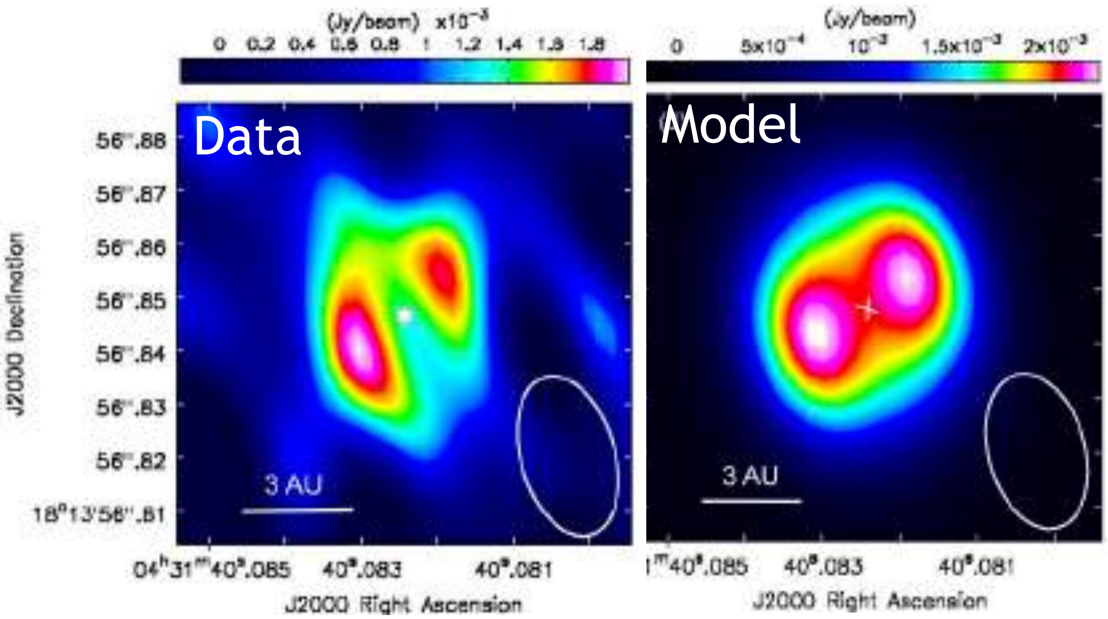
*Vertical settling of the particles onto the disk mid-plane (gas-to-dust mass ratio ~100).

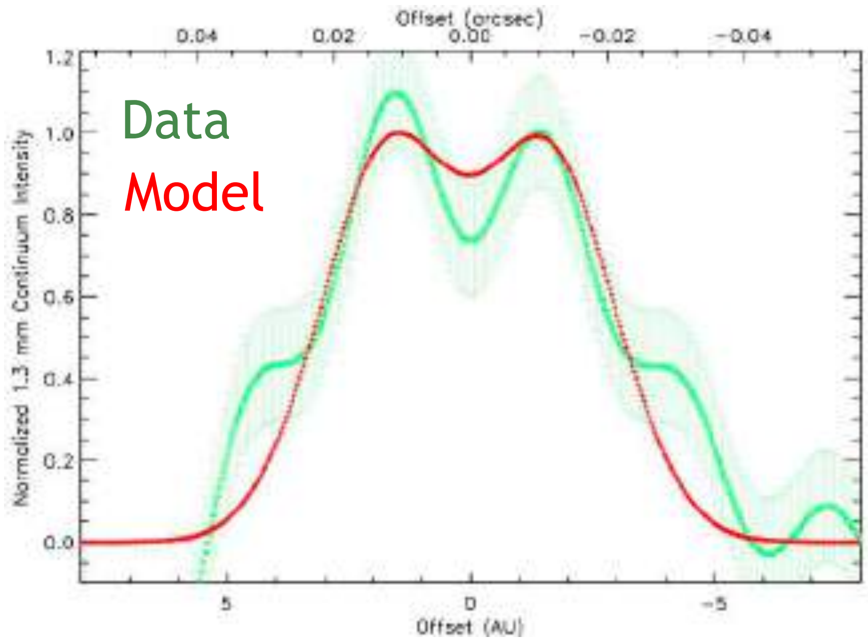
A high degree of settling is explored to ensure the presence of big grains (millimeter-sized dust grains) near the disk mid-plane that eventually will become planets.

Modeling results: SED, Image, Intensity profile

*SED (several solutions), we select the model of minimum mass (10M_{jup}) and with the capability of forming planets **(α=0.001).**





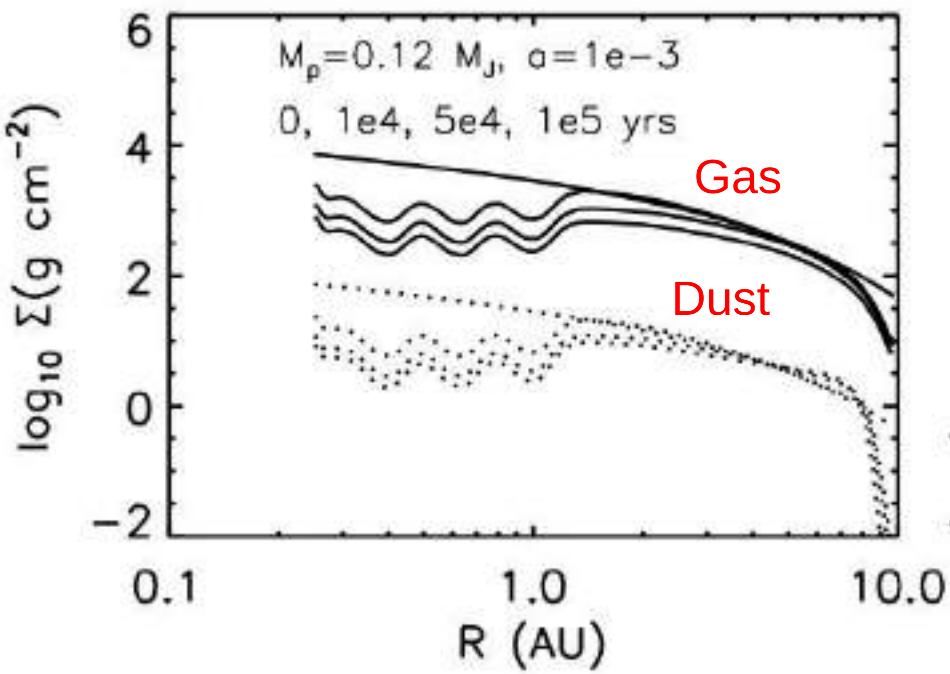


*Slope of the intensity profile constrains disk size (3.5 au, consistent with upper limit set by 2.9mm data), and cavity size. (1.3au similar size of the inner cavity in TW Hydra)

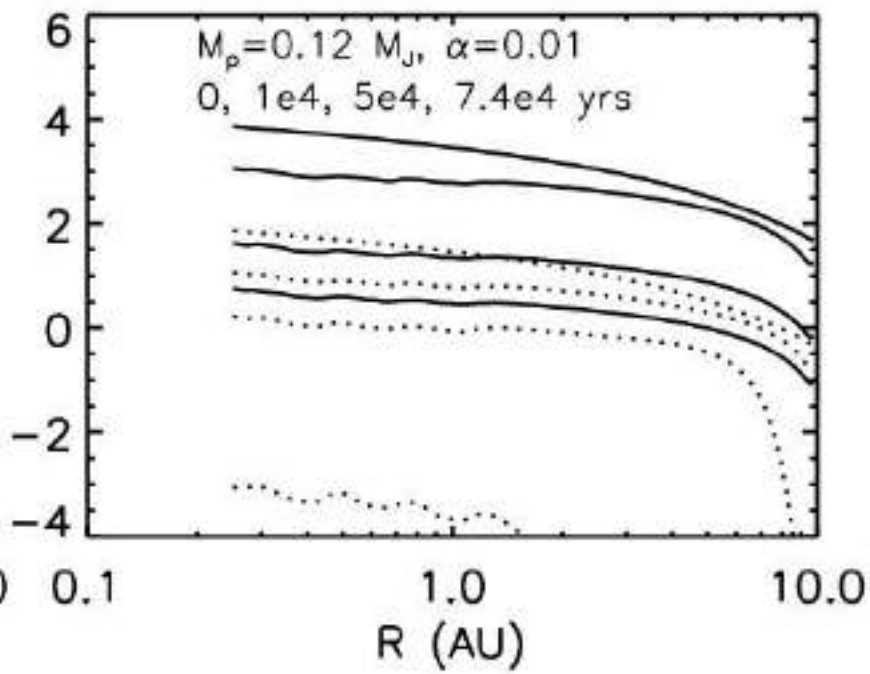
Hydrodynamical Simulations

To check whether in the 10Mjup model (viscosity, α=0.001) protoplanets will open a cavity, we performed gas-dust two fluid simulations.

low viscosity dis (α=0.001)



high viscosity disk (α=0.01)

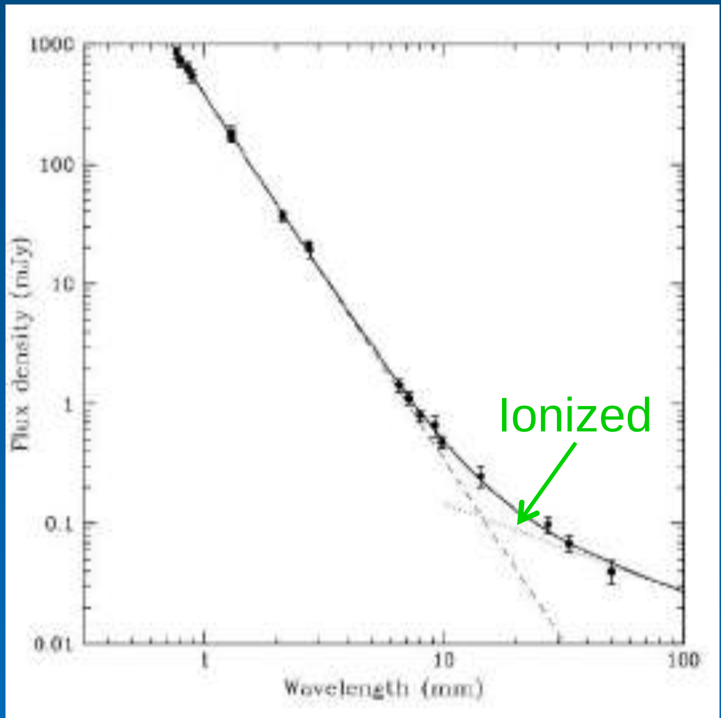


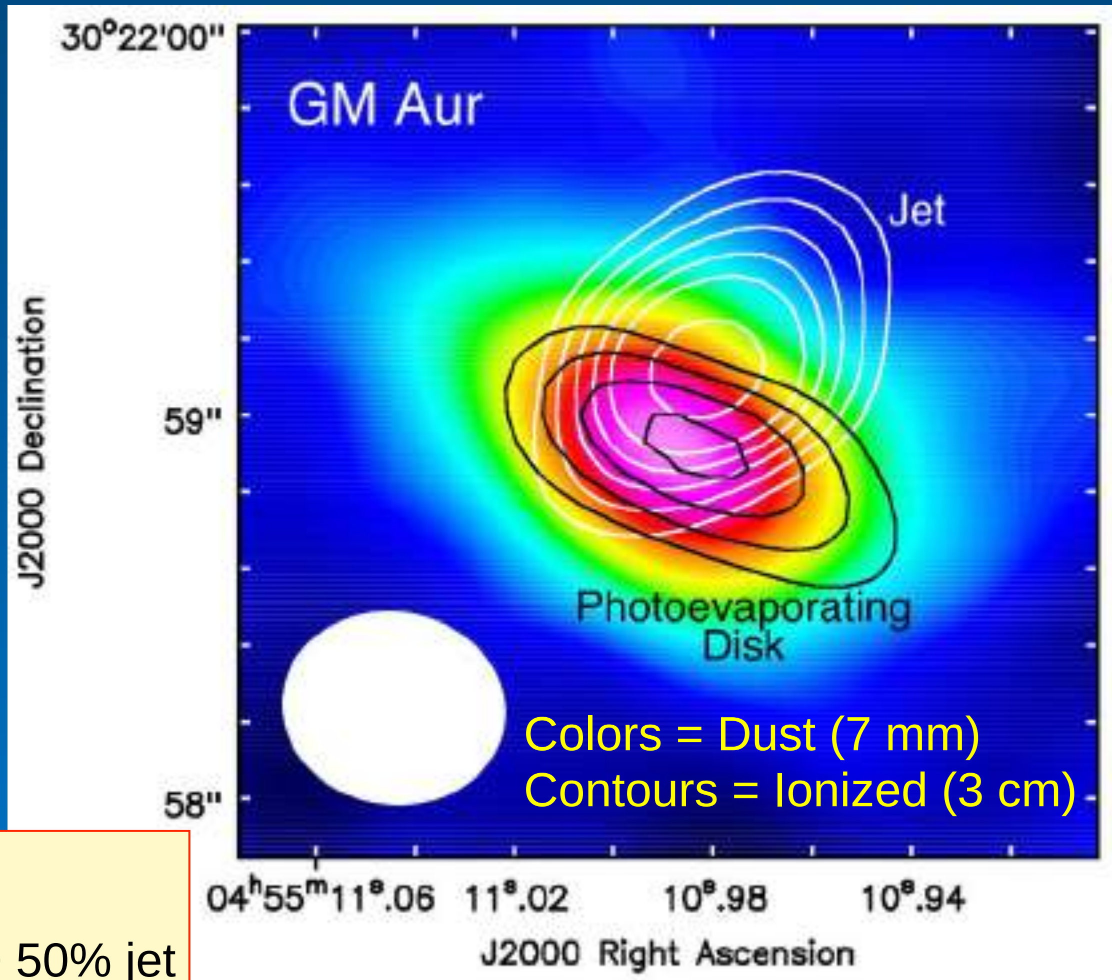
Planet orbits are at 0.4 au, 0.63 au, 1 au

XZ Tau B possible precusor of compact exoplanetary systems

- Protoplanetry disks like XZ tau B can explain the diversity of architure found in exoplanets.
In particular, the compact planetary systems found by the Kepler Mission

An ionized jet, and a photoevaporating disk in GM Aur





7 mm → 85% dust + 15% free-free

3 cm → 15% dust + 35% photoev + 50% jet

(Macías et al. 2016)