Protoplanetary disk evolution

Nuria Calvet

Collaborators
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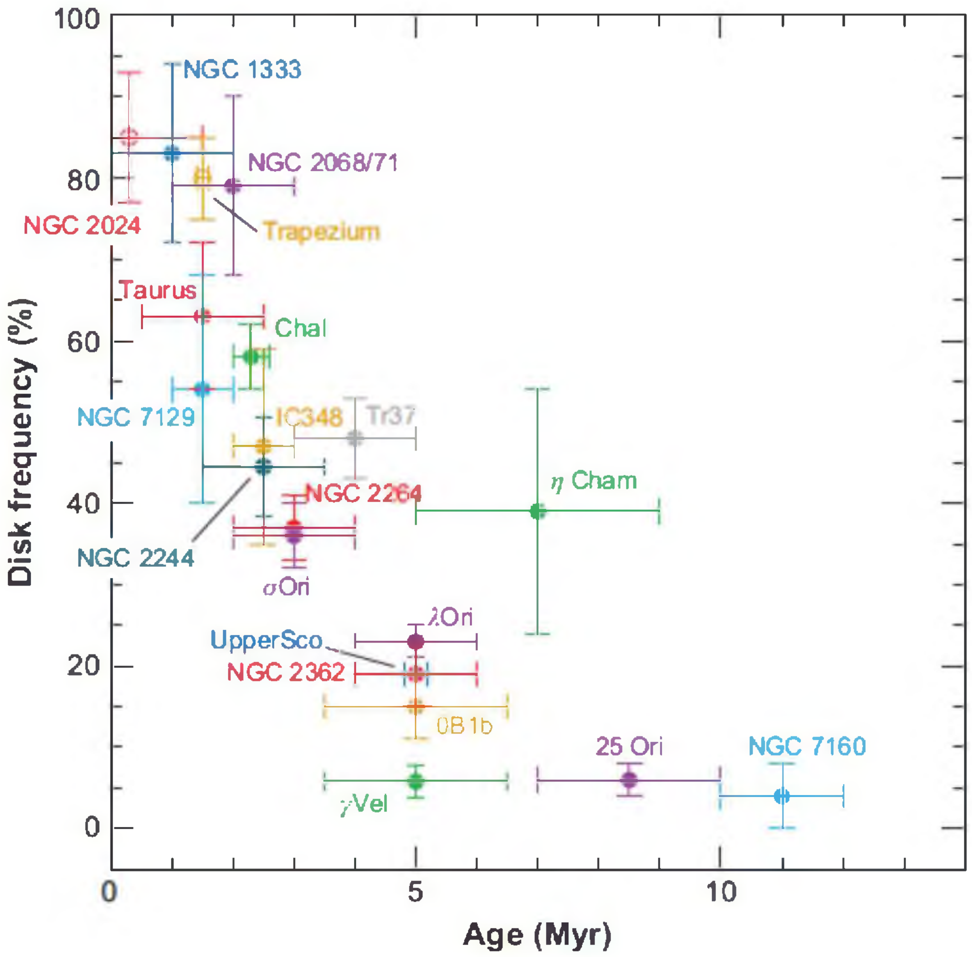
Disk evolution

Stars are born surrounded by disks
Disks are 99% gas, 1% solids = dust

Disks are accreting
Disks evolve from gas-rich primordial to dust-rich debris disks – planetary systems in few Myrs

Evidence of evolution
- Decrease with age of
  - Disk frequency
  - Mass accretion rate
  - IR excess
- Structure/Planets

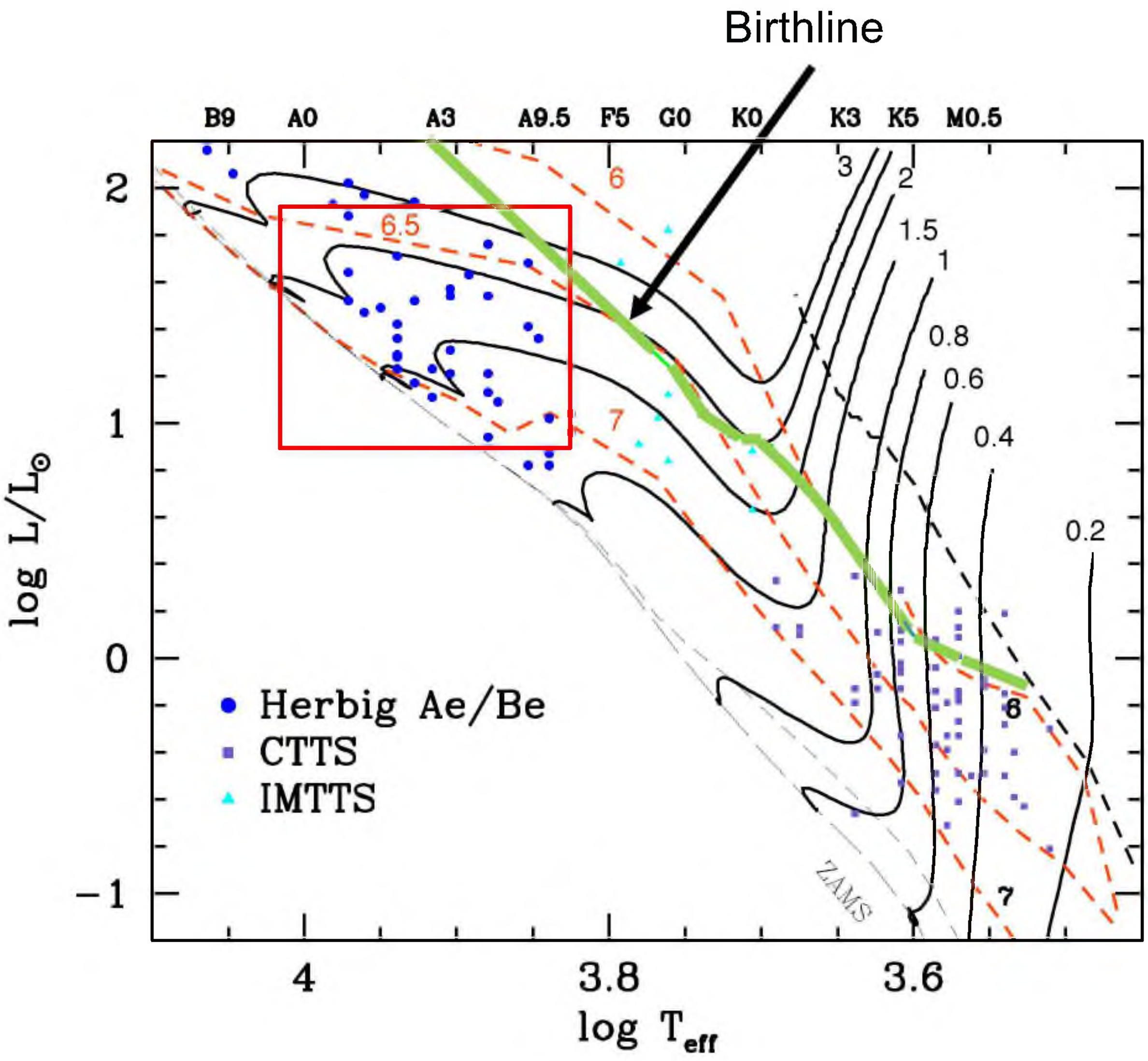
Disk frequency decreases with age of population



From Spitzer photometry => inner disk

Wyatt 2008, adapted from Hernandez+ 2006,2008

Age determination: effects of birthline



Bressan's talk
Birthline : locus of stars still accreting mass (Stahler+ 1983, 1990; Hartmann+1997)

t ~ 0 in pre-main sequence evolution

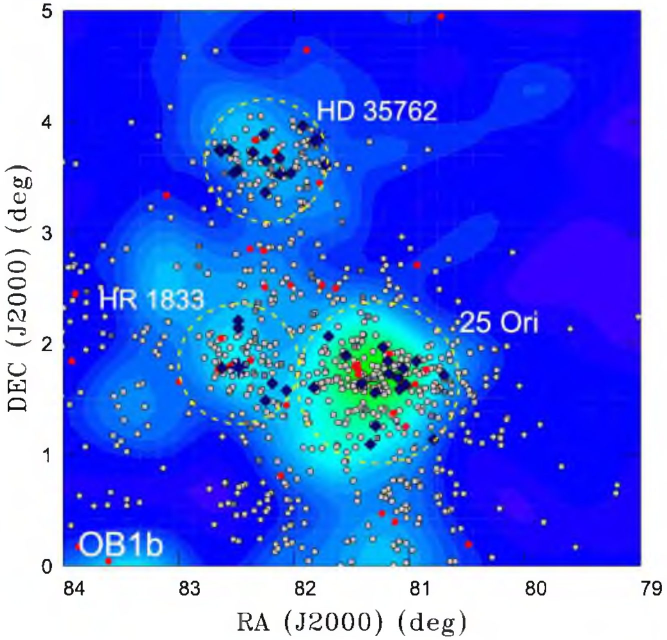
Birthline depends on rate and mode of accretion (steady vs episodic, cf, Lucas and Hartmann's talks)

Many birthlines (cf. Hartmann+ 2016)

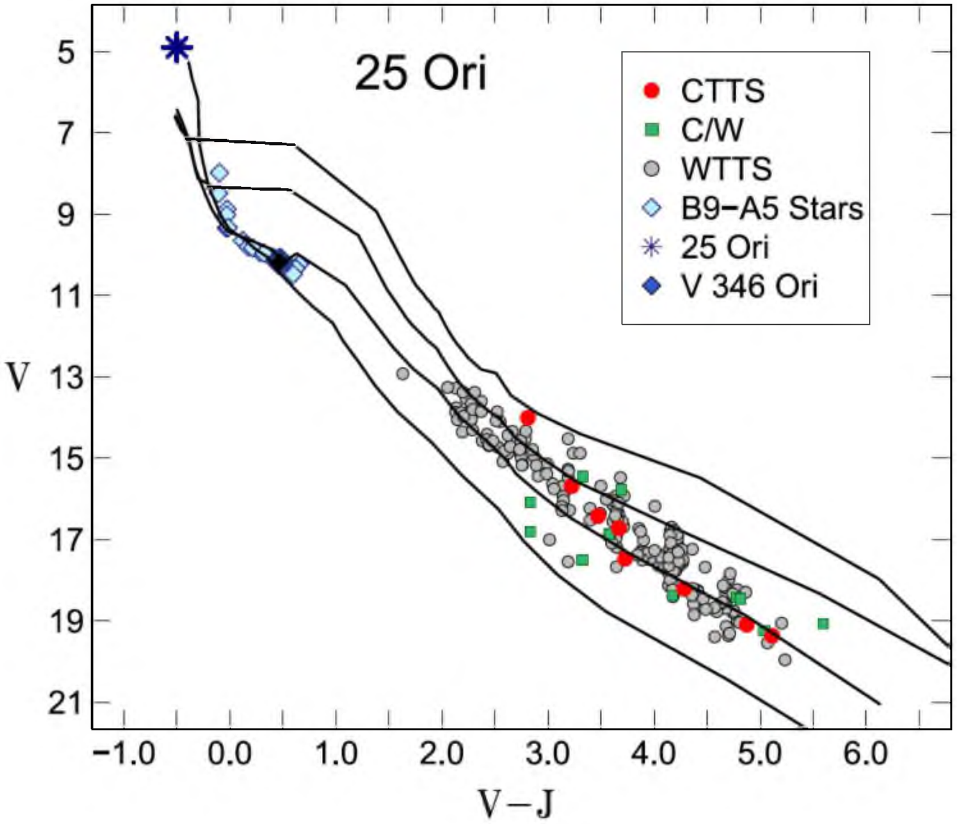
Shown Bernasconi+ 96 (Geneva group)

With this birthline:
Actual ages including t ~ 0 at birthline: ``Isochronal ages" – 3 Myr :

Age determination

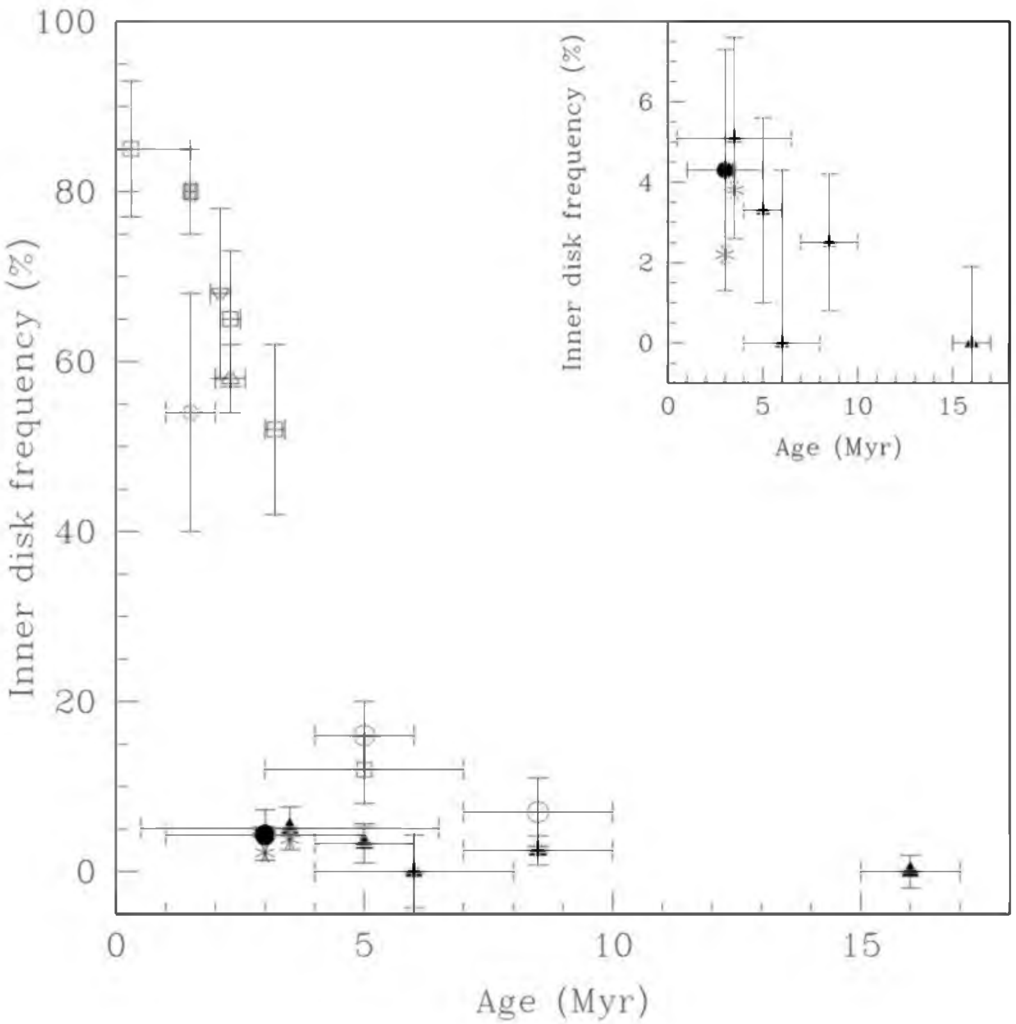


Use isochronal ages of low mass stars in population (less affected, birthline ~ D main sequence)



Results from the CIDA variability survey of Orion, Briceno+ 2019

Disk evolution



Solid: Intermediate mass stars
Open: Low mass stars

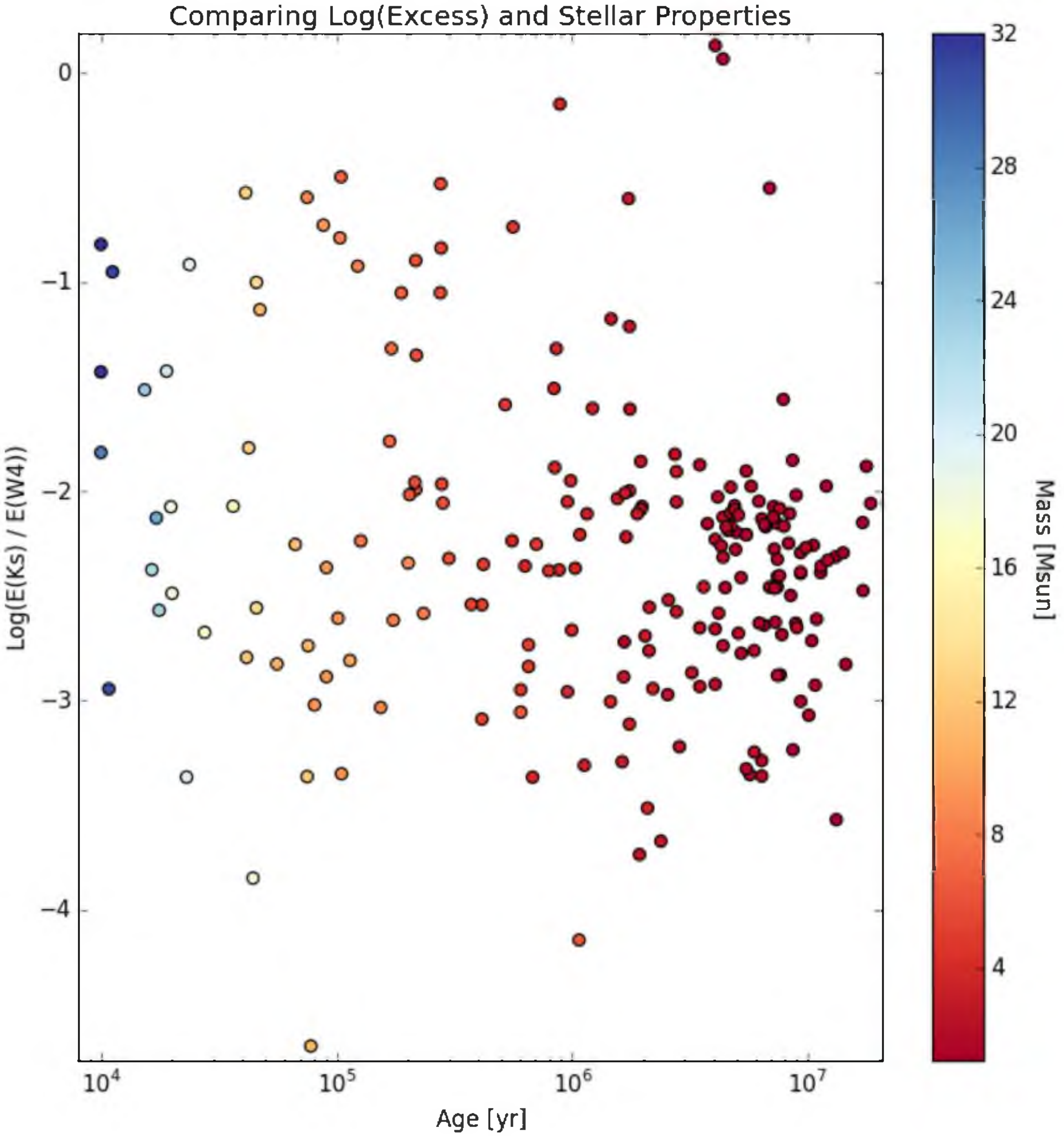
Hernandez+ 2005: Frequency of Herbig Ae/Bes in populations covering range of ages

Ori OB1bc
Upper Sco
Per Ob2
Ori OB1a
Lac OB1

Disks around intermediate mass stars evolve much faster

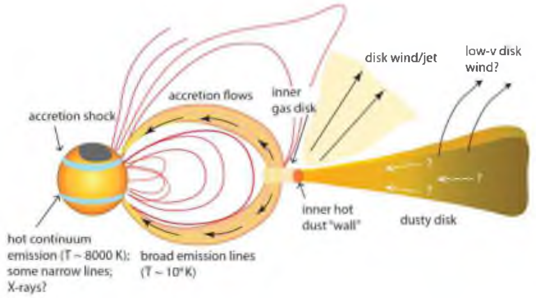
(see also Yao+2018)

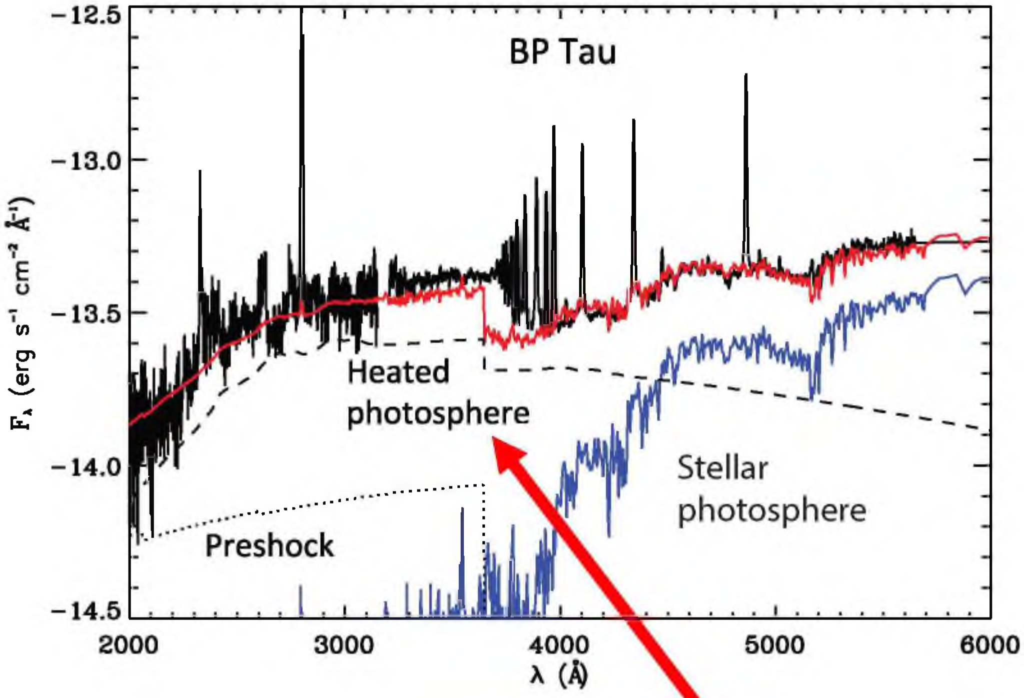
Birthline effects?

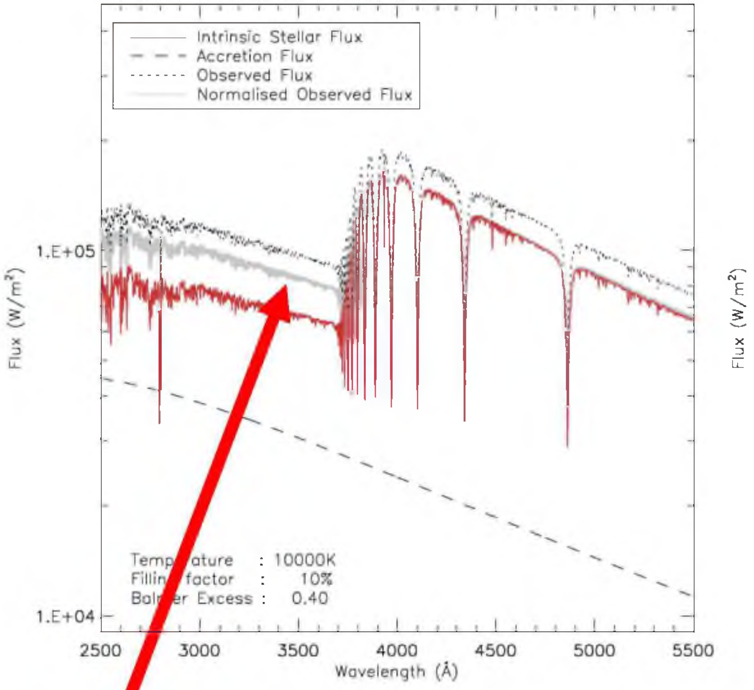


Vioque+2019

Accretion luminosity from shock emission







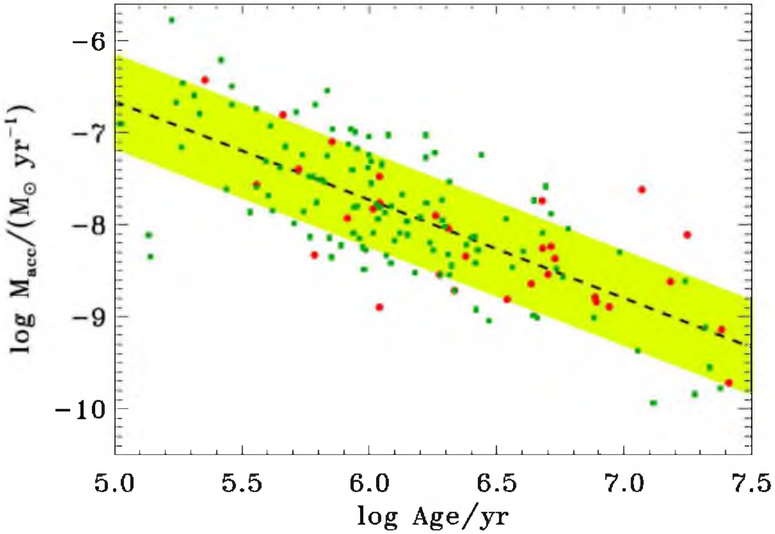
Excess luminosity = Shock emission

~ $L_{acc} = G M_*$ **Mdot**/R_*

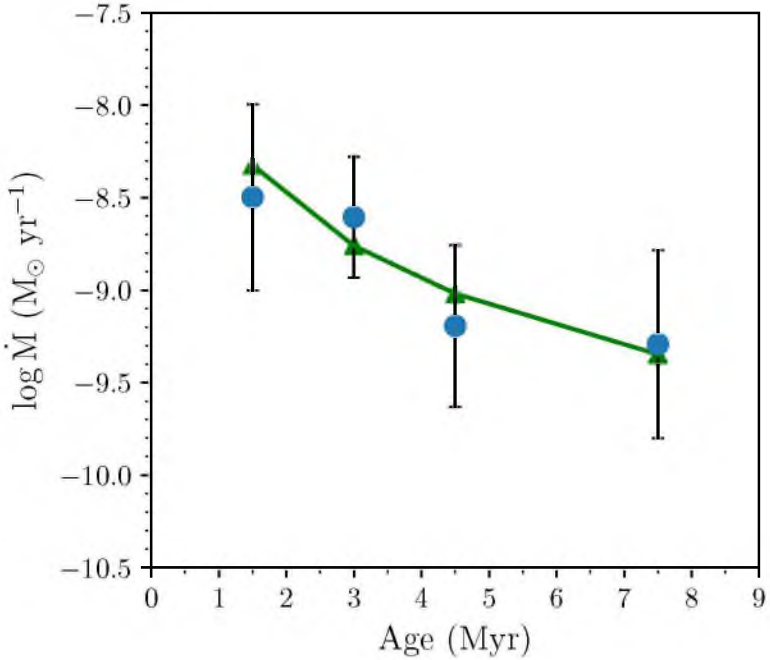
Calvet & Gullbring 1998; Hartmann+ 2016; Fairlamb+ 2015

Evolution of the mass accretion rate

Group populations of similar age (from isochrone fitting of low mass stars) in bins
Medians and Quartiles



Consistent with viscous evolution
R_1 = 10 pc, $M_d(0)$ = 0.06 M_{sun}, α = 0.01



Individual determinations of Mdot and age (compilation and references in Hartmann+ 2016)

Manzo-Martinez+

Viscous Evolution

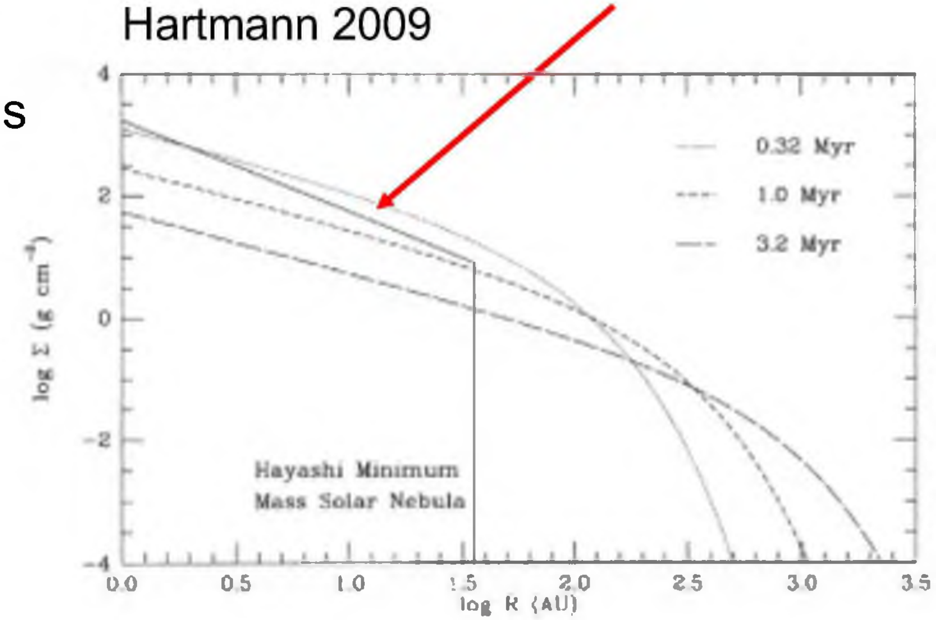
Disk expands as it accretes mass onto star to conserve J

Surface density Σ decreases,
  Mass accretion rate and mass fall (lost to the star)

Evolution in viscous time scale

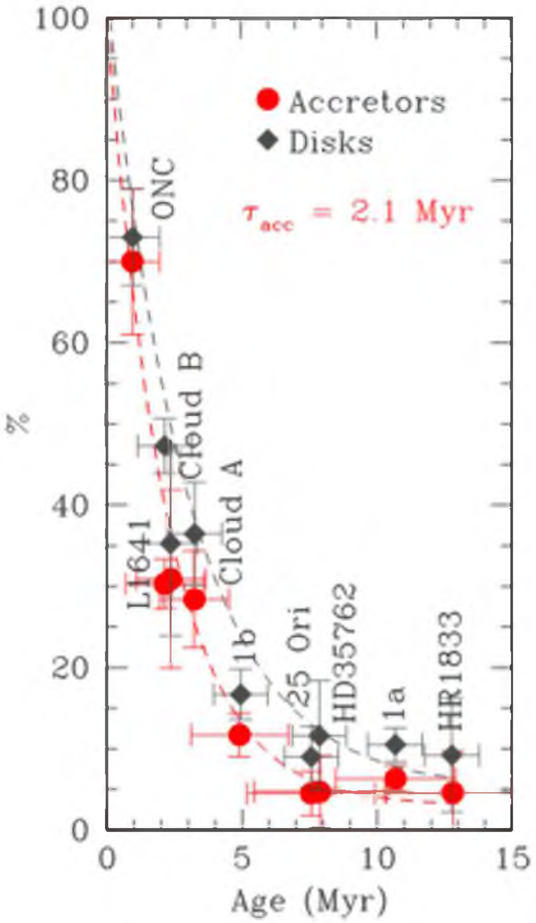
$$t_\nu \sim 8 \times 10^4 \left(\frac{R}{10au}\right)\left(\frac{\alpha}{0.01}\right)^{-1}\left(\frac{M_*}{0.5M_\odot}\right)^{1/2} \text{ yrs}$$

Disk may not be steady:
- Dead zone
- Mass into forming planets
- Still constrains *mass onto star*


t=0

Hartmann 2009

Accretors frequency also decreases with age of population



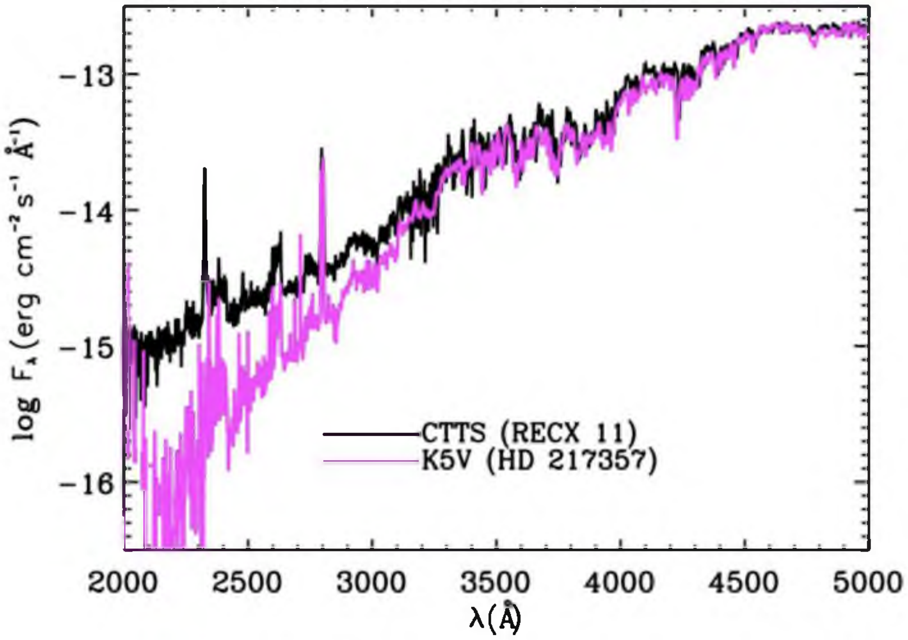
Fewer accretors as age increases
Cannot be explained by viscous evolution

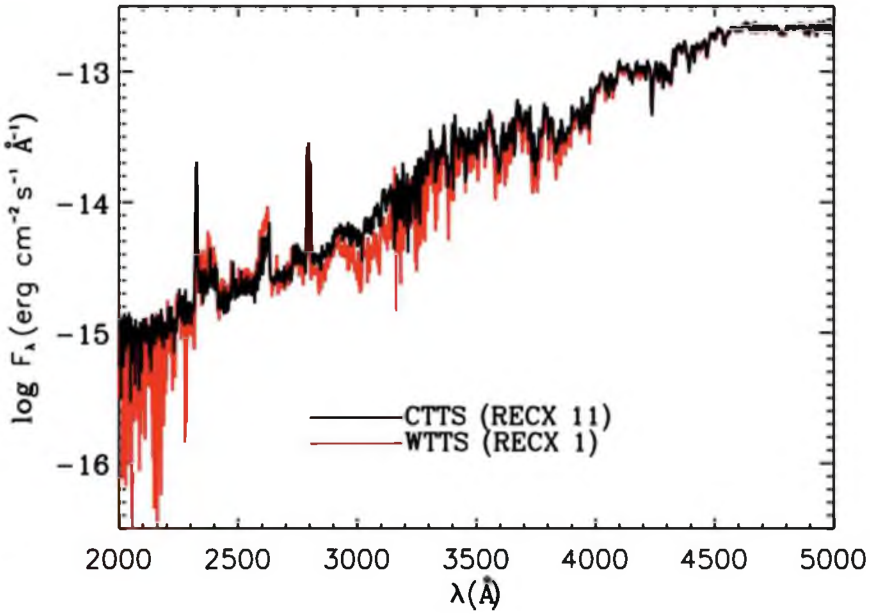
Decrease comparable to inner disk frequency
But fewer accretors than inner disks at old ages

Search for low accretors:
About ~ 25+ % of “WTTS” with detectable IR excess are accreting!
Low rates (TBD)
(Thanathibodee+ 2019)

Briceno+ 2019, Fedele+ 2006

The danger of determining **low** Mdots from UV excess

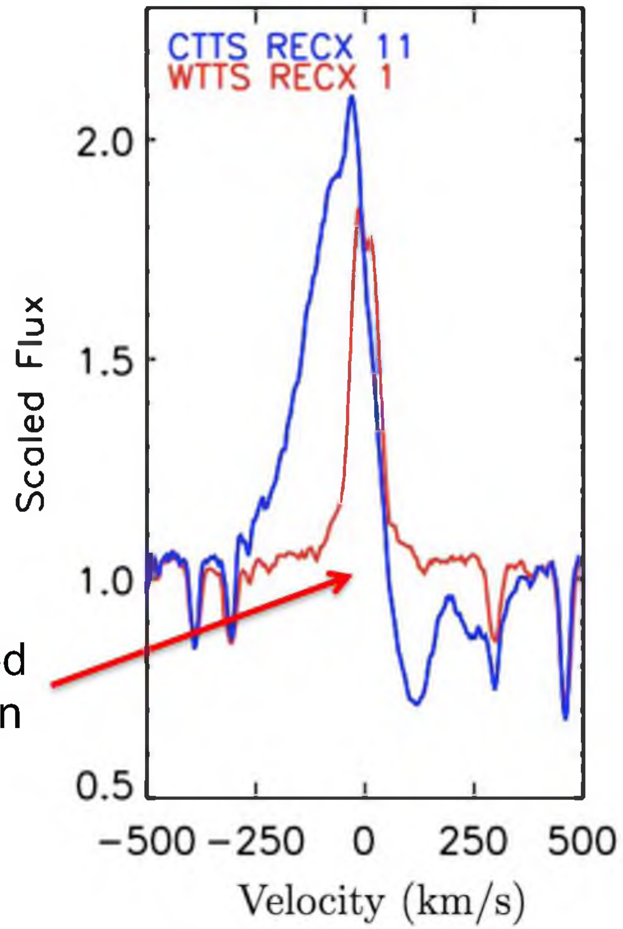




WTTS = **Non accreting stars have strong chromospheres**
Cannot measure rates < few x 10^{-10} M_{sun}/yr from U excesses

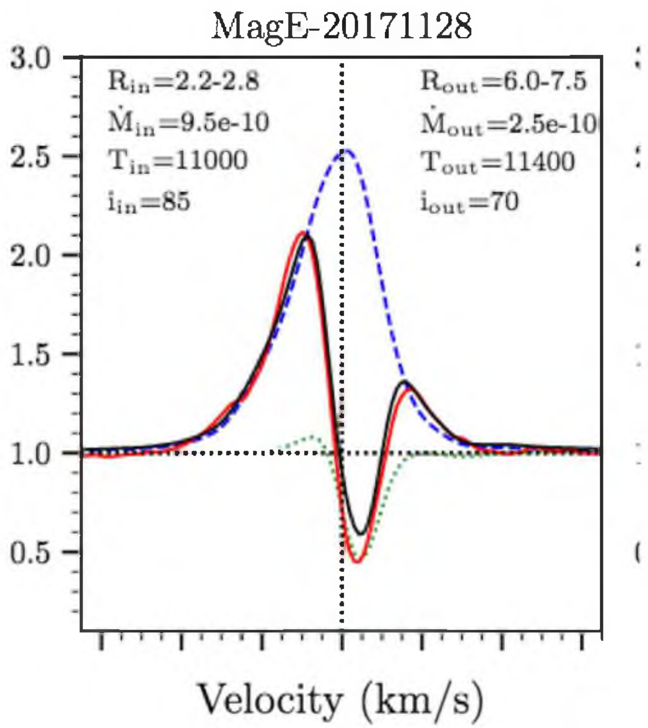
Ingleby and the DAO collaboration, 2011

Use emission lines to check and meassure accretion – Hα most common



Redshifted absorption

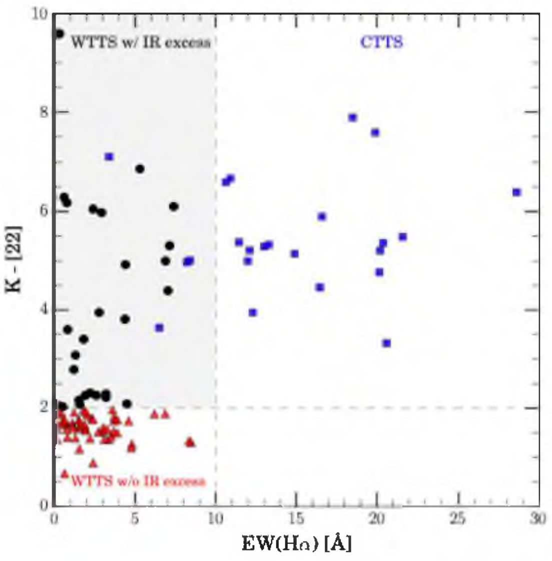
Ingleby+ 2011b

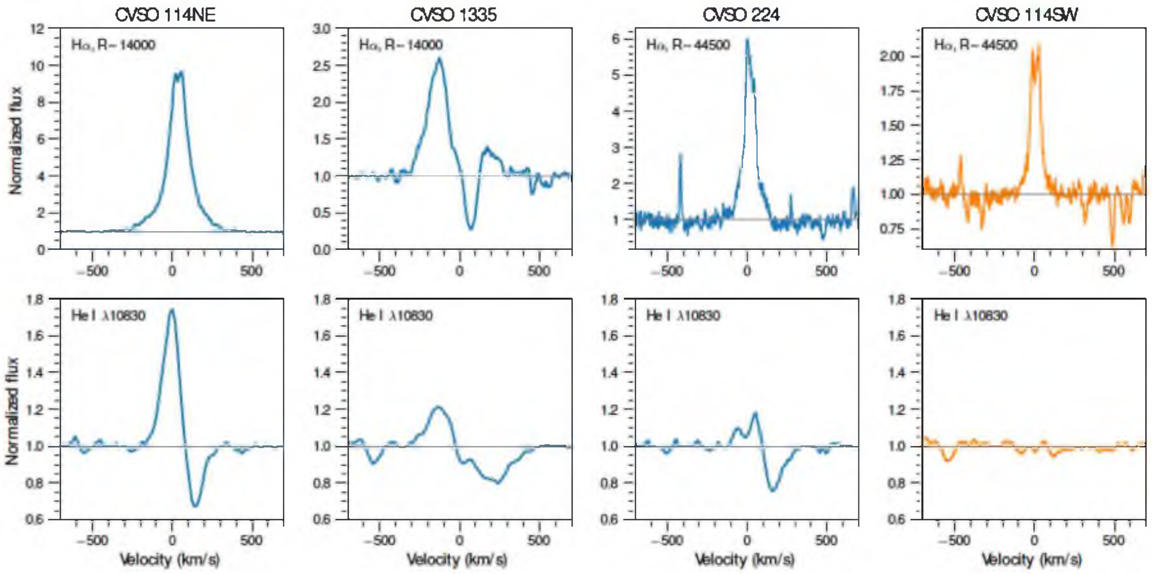


Thanathibodee+ 2019

Lowest accretors are hiding!

Look among WTTS with IR excess
Look for redshifted absorption at He I 10830, best indicator!





Hα

He I
10830

Thanathibodee+ 2019

Evolution of disk NIR flux excess

Comparing to optically thick disks: Taurus

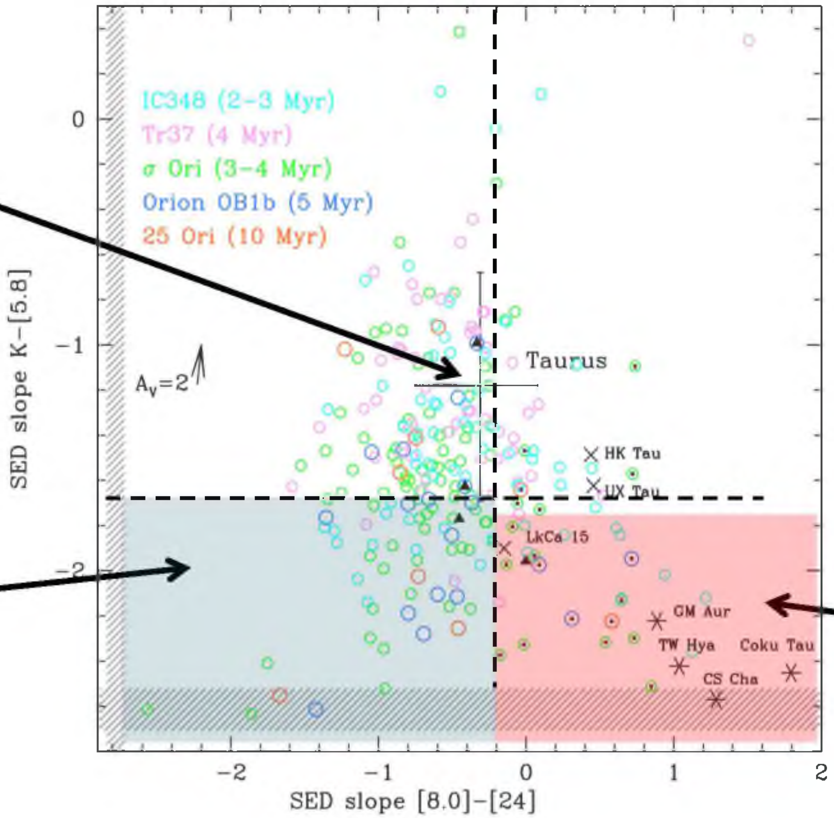
Evolved (anemic, homologously depleted) disks:

flux decreases at all bands

Transitional disks:

near IR close to photosphere

mid-far IR comparable or higher than Taurus



Taurus
optically thick,
full disks

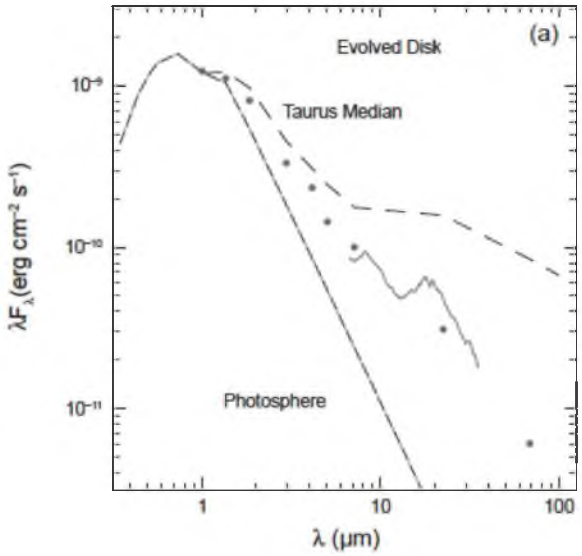
Evolved

Transitional

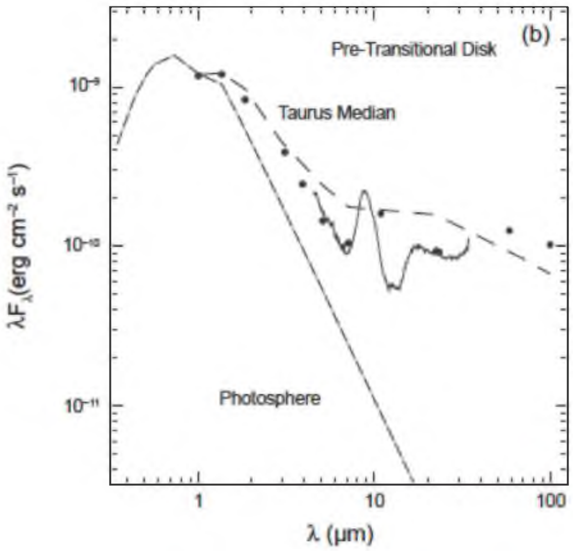
Hernandez et al
2007, 2008, 2010

Representative SEDs

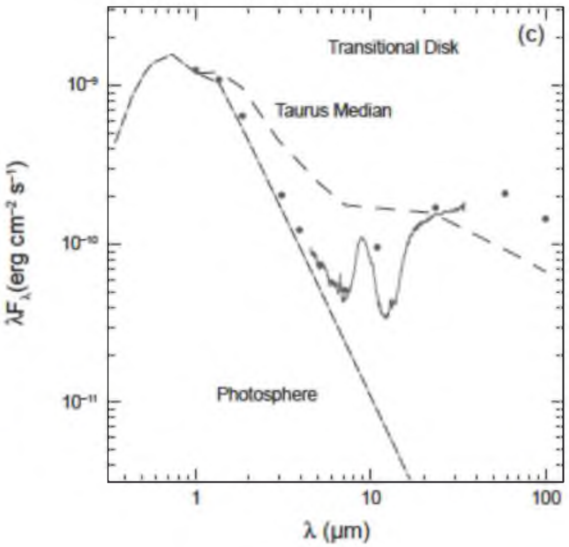
Evolved



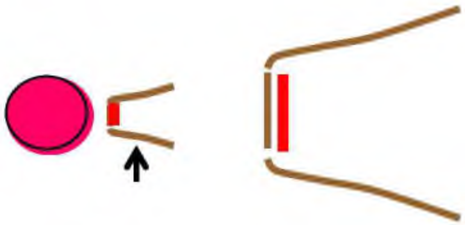
Pre-transitional



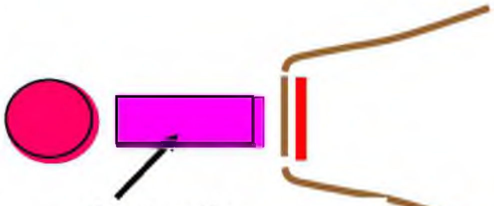
Transitional



Full Disk



Optically thick region



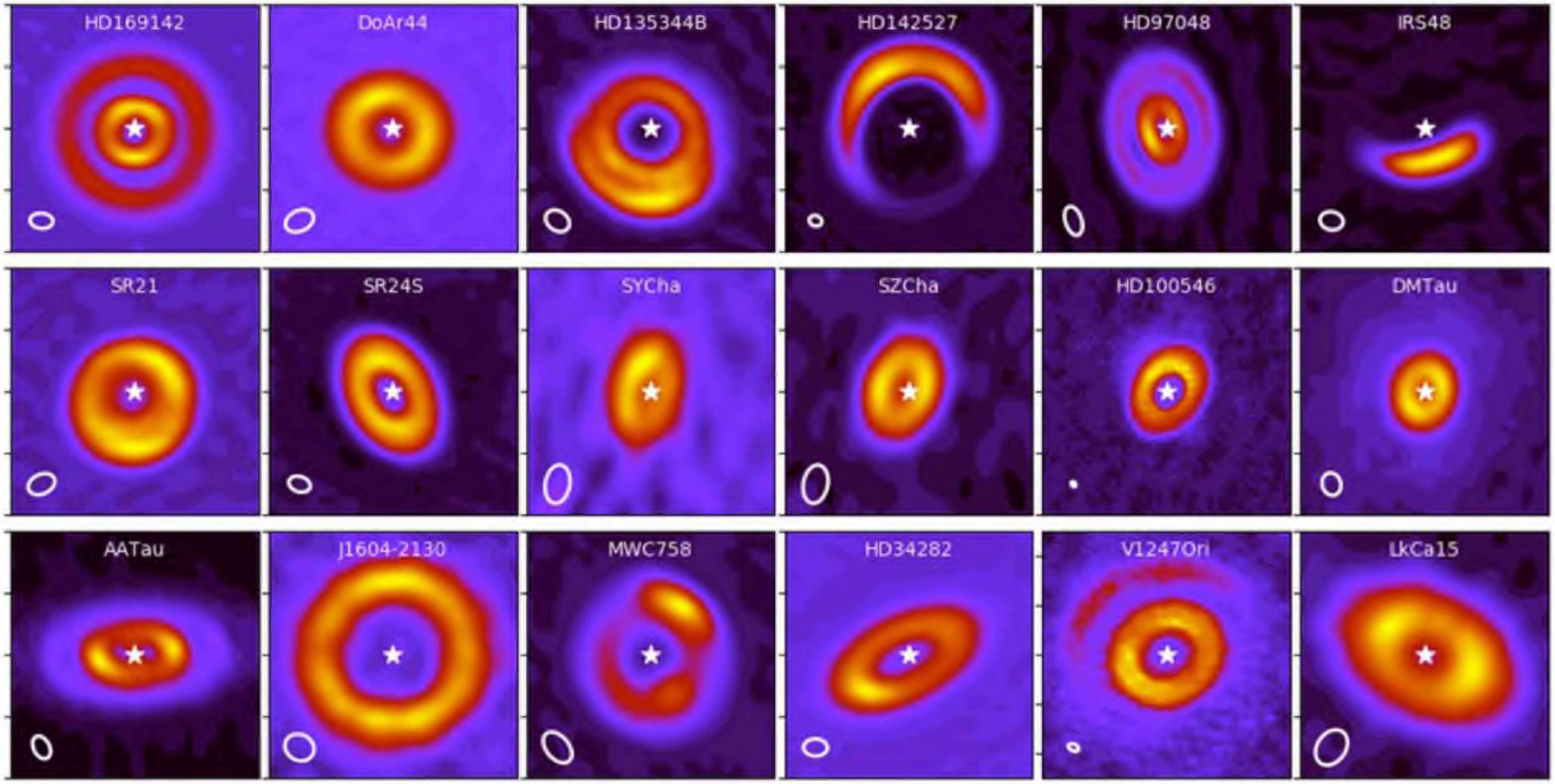
Optically thin region

Espaillat+ 2014, PPVI

ALMA images of transitional and pre-transitional disks

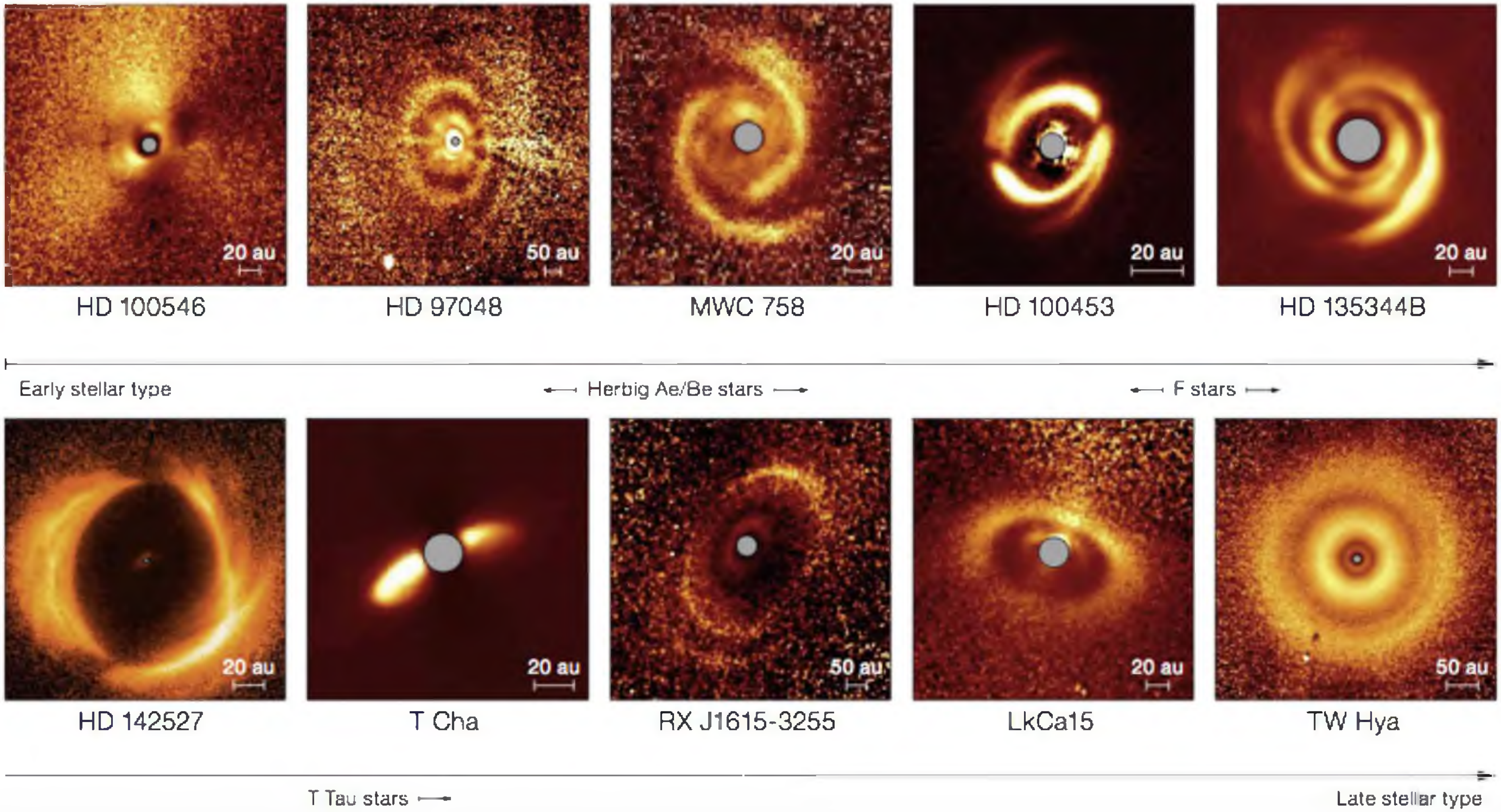
Cavities of ~ few x 10 au's

Gallery of ALMA continuum images of transition disks (credits Nienke van der Marel).



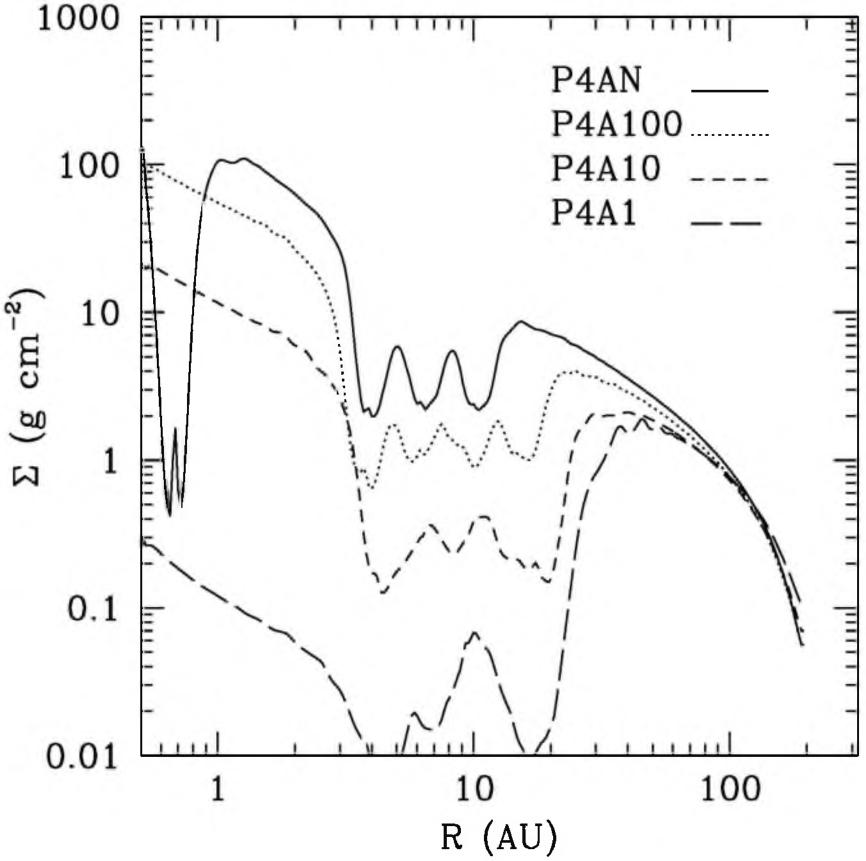
http://www.nienkevandermarel.com/research.html

Images in near-IR

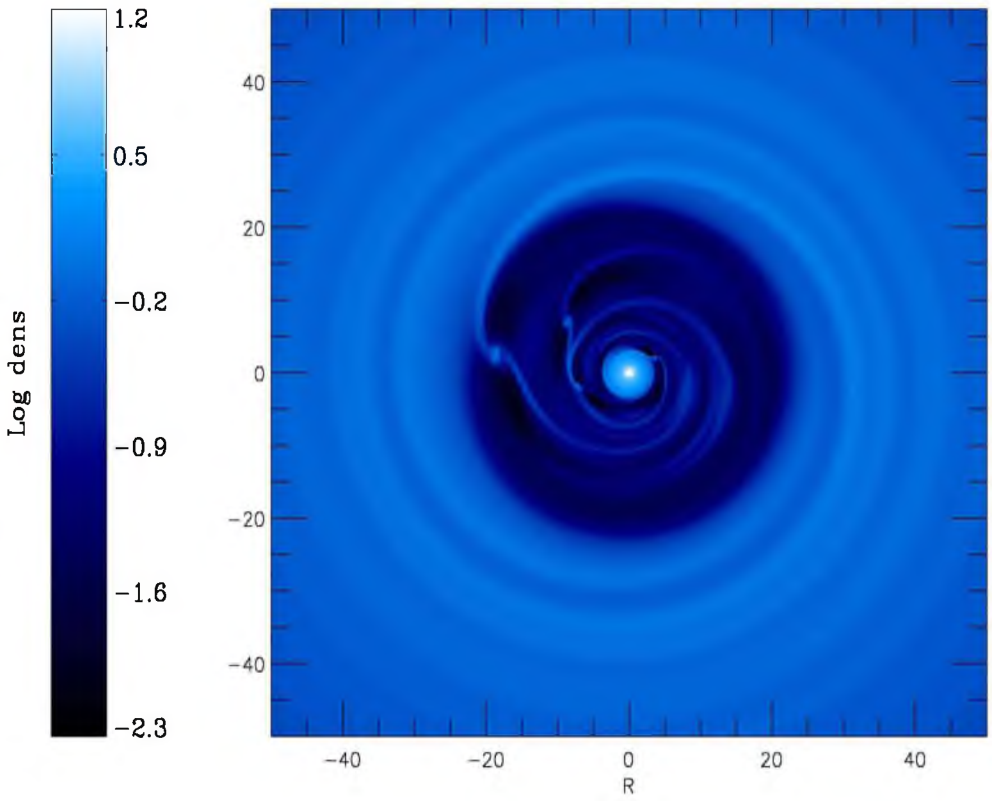


Garufi+ 2017

Need multiple planets to open large gaps

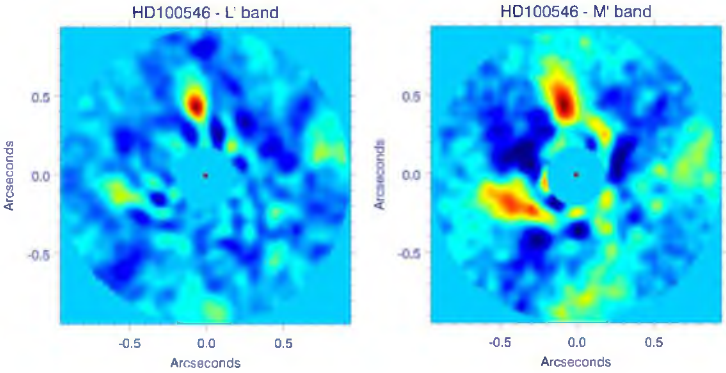


Fargo 2-D simulations of gap opening by planets



Zhu et al. 2011

Planets inside cavities of P/TD



HD 100546b, Quanz 2015

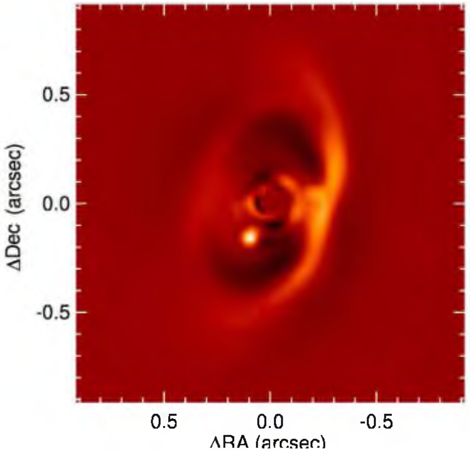


Fig. 1. IRDIS combined $K_1 K_2$ image of PDS 70 using classical ADI reduction technique showing the planet inside the gap of the disk around

Muller+2008
PDF 70

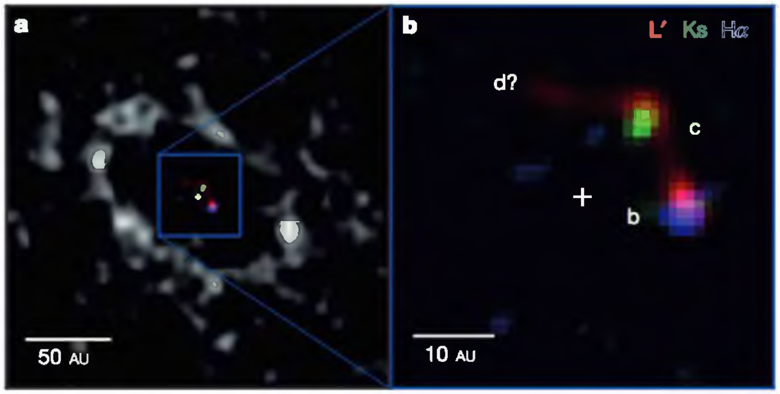
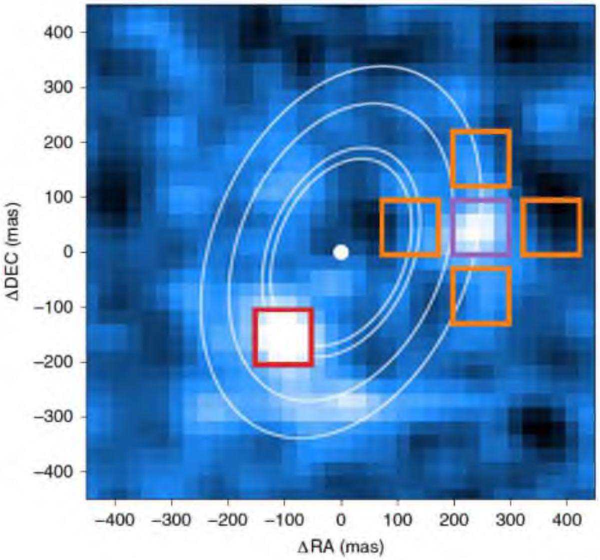


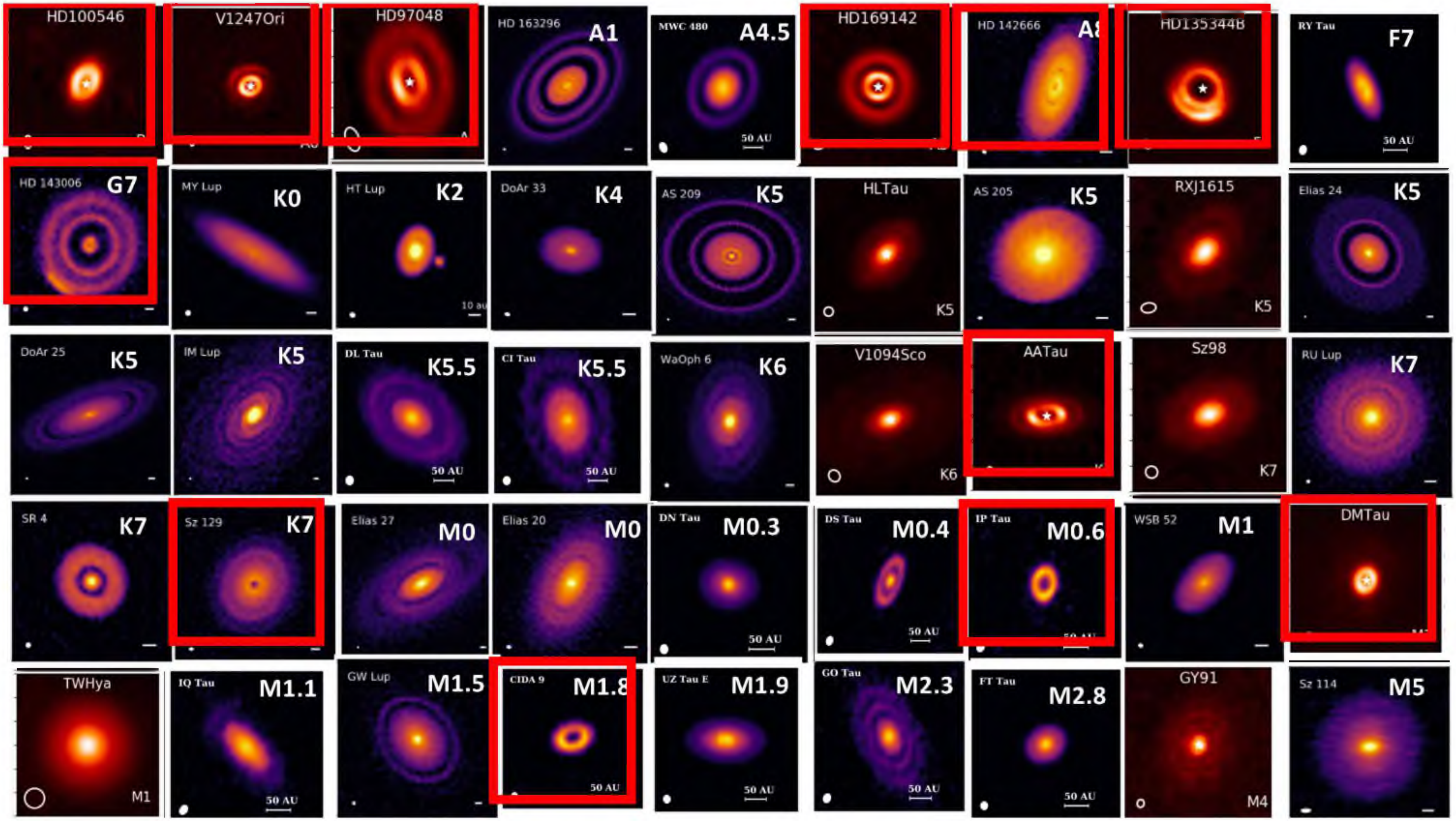
Figure 1 | Composite Hα, Ks, and L′ image. a, The coloured image shows Hα (blue), Ks (green), and L′ (red) detections at the same scale as VLA millimetre observations[29] (greyscale). **b**, Zoomed in composite image of LBT and Magellan observations, with b, c, and d marked.

Sallum+2015



Haffert+ 2019
PDS 70

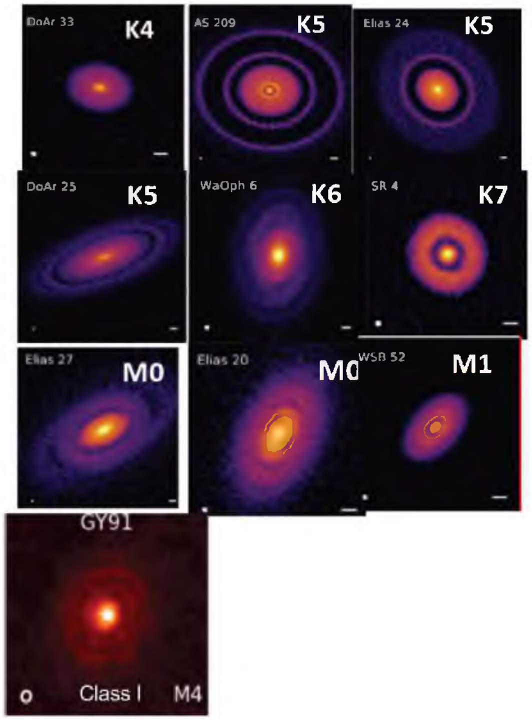
Disk evolution: Structure in ALMA images



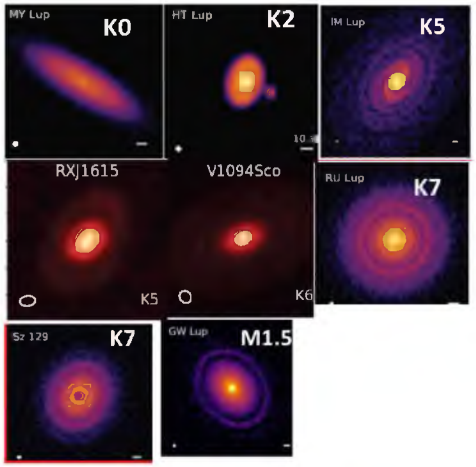
Compilation by Jaehan Bae
Andrews+2018, Long+2018, and van der Marel+2019

Structure: mass/age dependence?

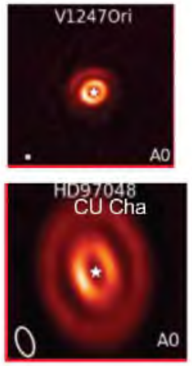
Rho Oph 1 Myr



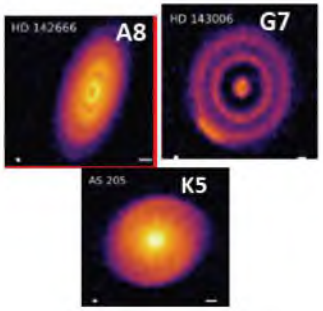
Lupus 2 Myr

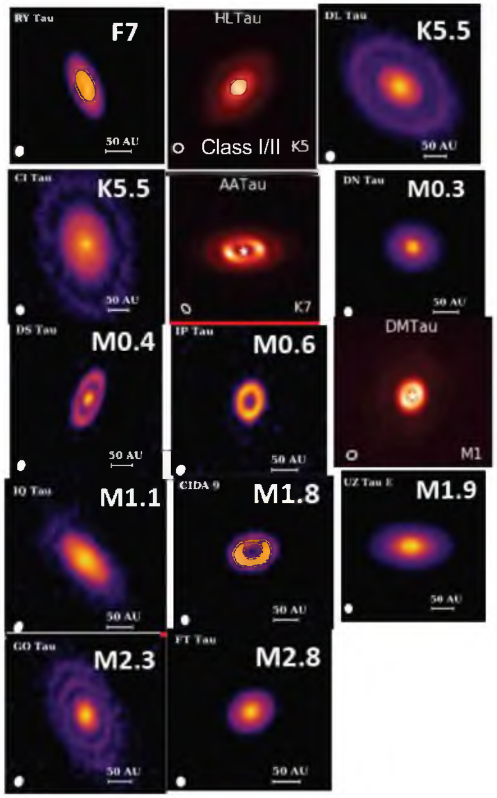


L1641 2 Myr



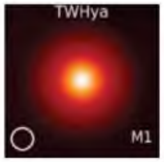
Upp Sco 5-10 Myr





Taurus 2 Myr

TW Hya 10 Myr

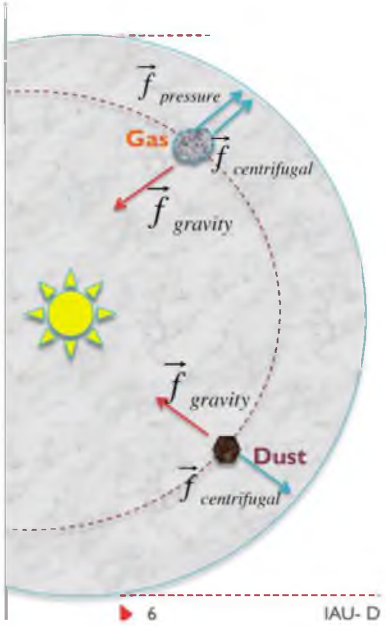


Not obvious

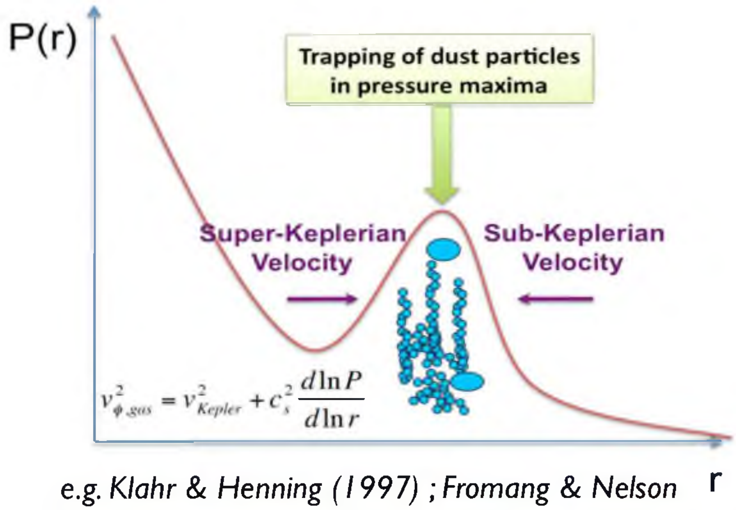
Compilation by Jaehan Bae

Structures: Dust evolution

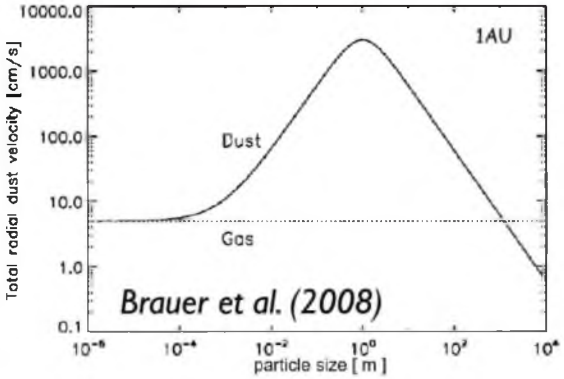
Radial drift



Pressure traps



e.g. Klahr & Henning (1997) ; Fromang & Nelson (2005); Johansen et al. (2009); Pinilla et al. (2012a)

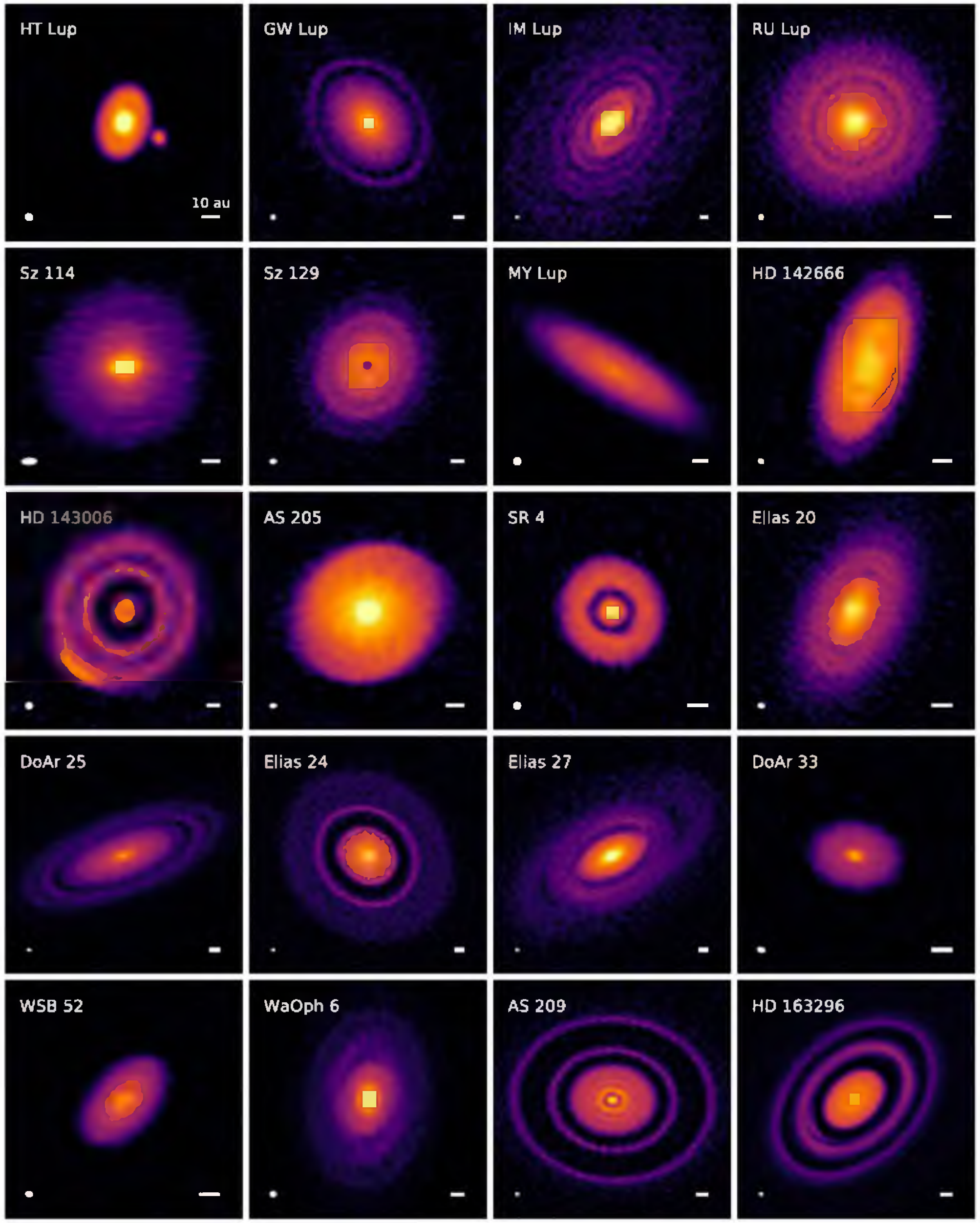


Brauer et al. (2008)

Pressure bumps:
Edge of cavity formed by planet
Edge of dead zones
MRI instabilities
Spiral arms

Images from P. Pinilla 2015
https://www.iau.org/static/science/scientific_bodies/divisions/h/2015/2015_iauga_dh_pinilla.pdf

Structure in "Full" disks

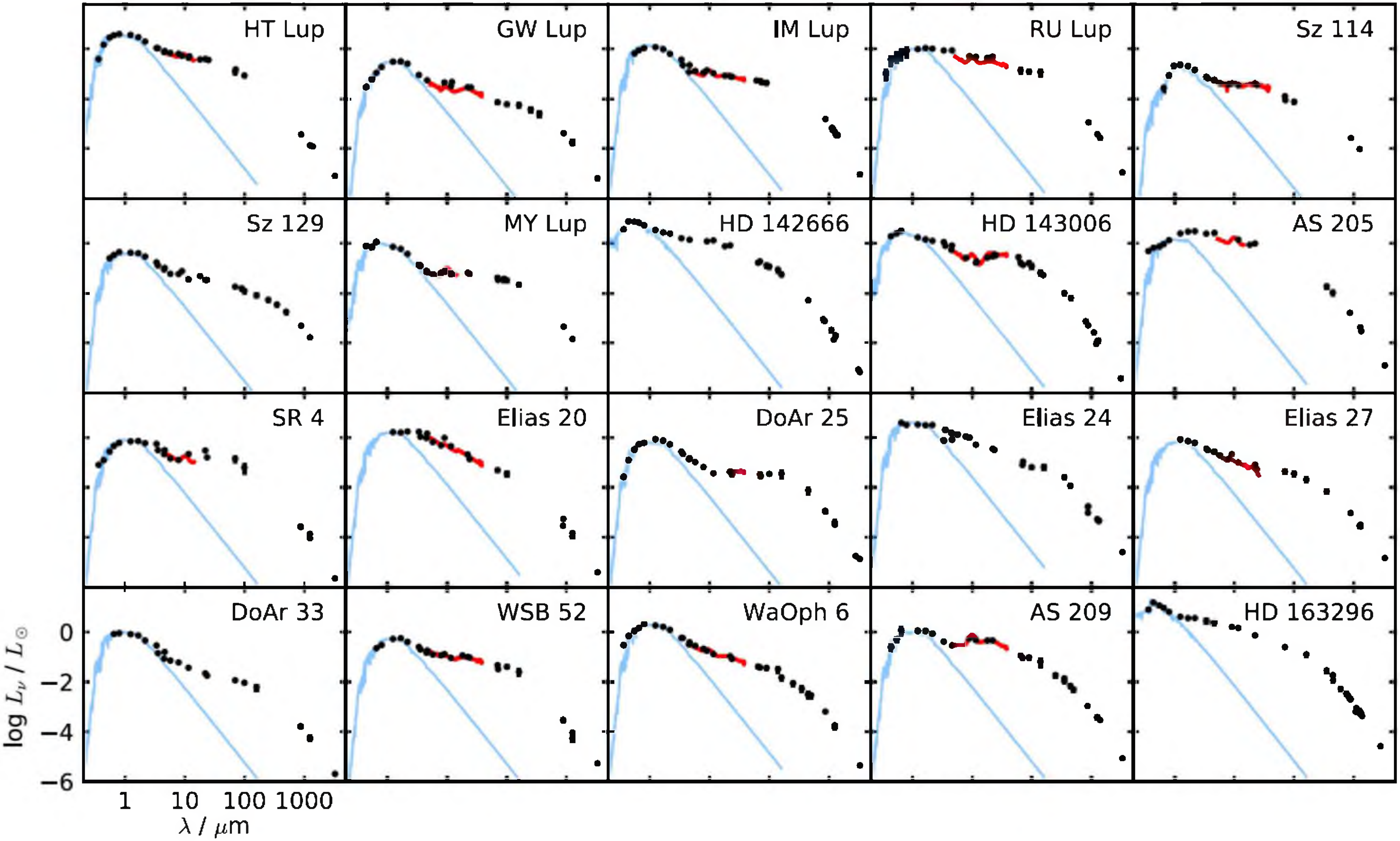


The ALMA revolution!

How does structure fit into global evidence of disk evolution?

DSHARP collaboration, S. Andrews et al

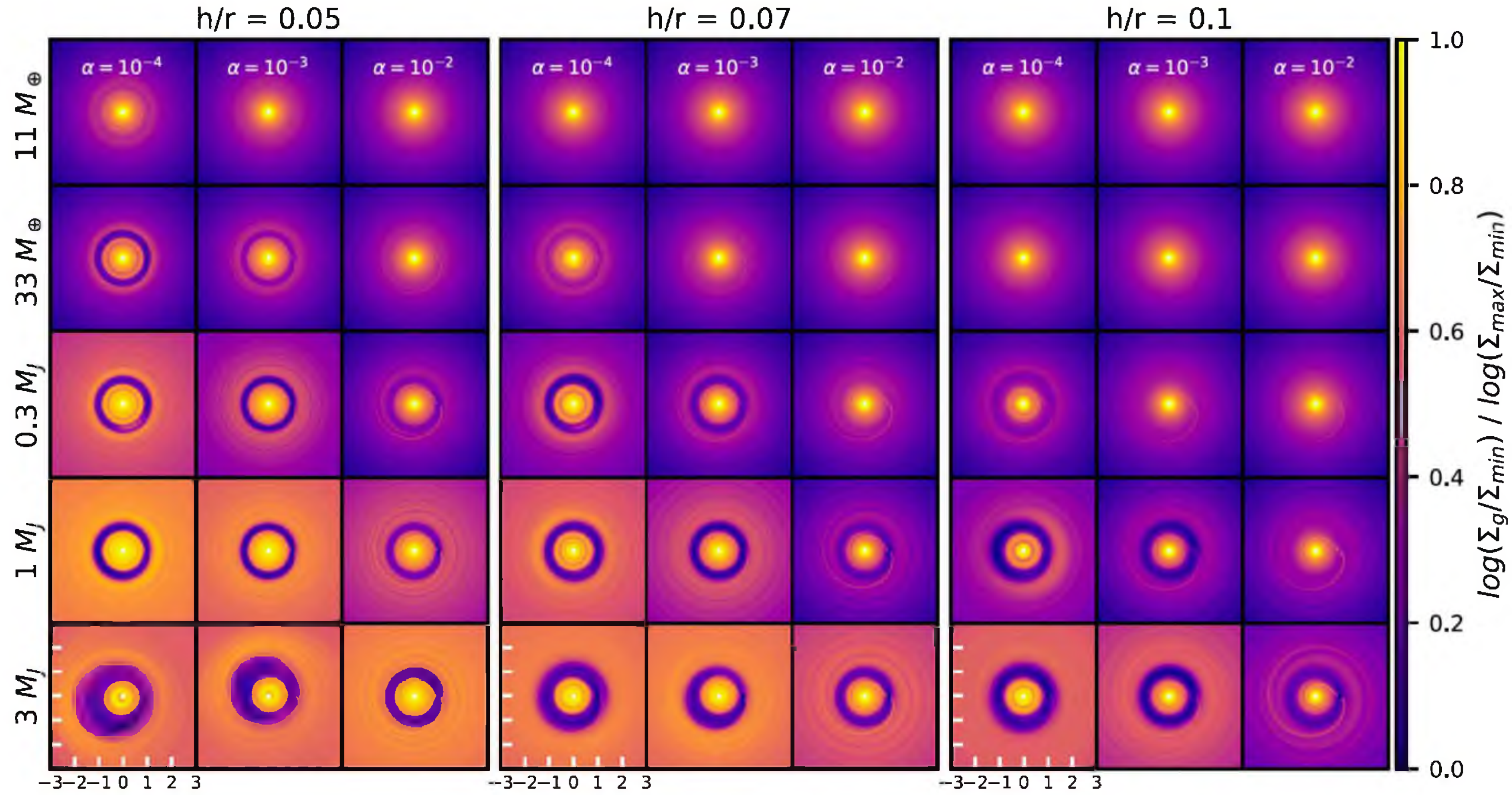
Disk evolution: "Full" disks! Not TD



$$L_\nu = 4\pi d^2 \nu F_\nu$$

DSHARP collaboration, S. Andrews et al

Structure: planet formation



Parameters: Σ_0, α, h/r, M_p/M_*, dust size distribution

Deeper gaps with more massive planets, lower α

Zhang,S, Zhu+ 2019

Application: AS 209

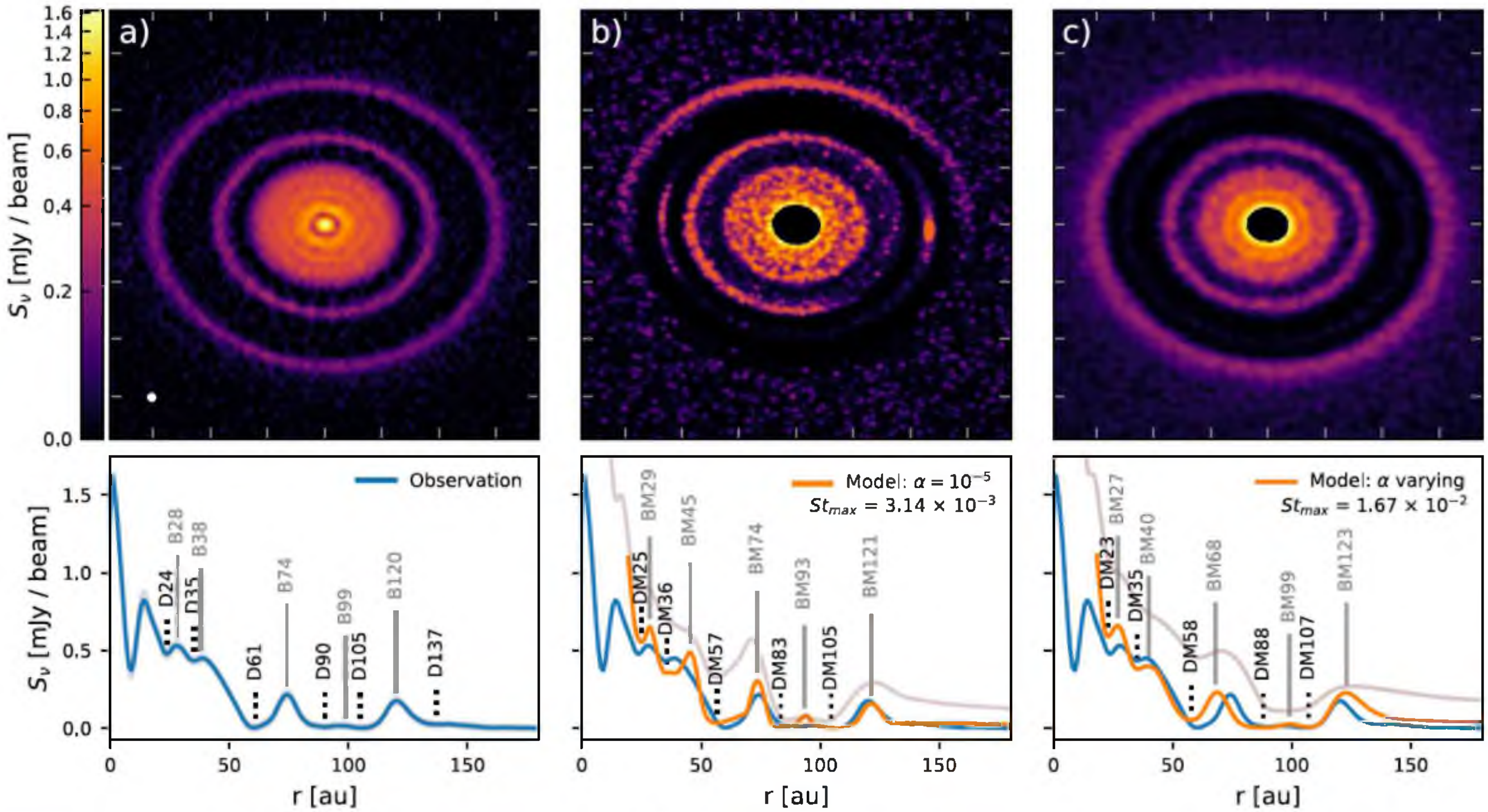
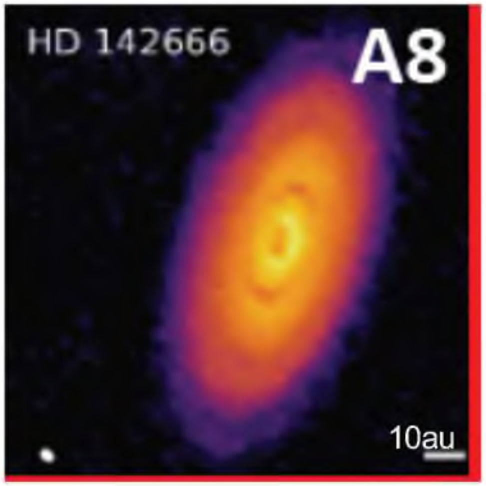
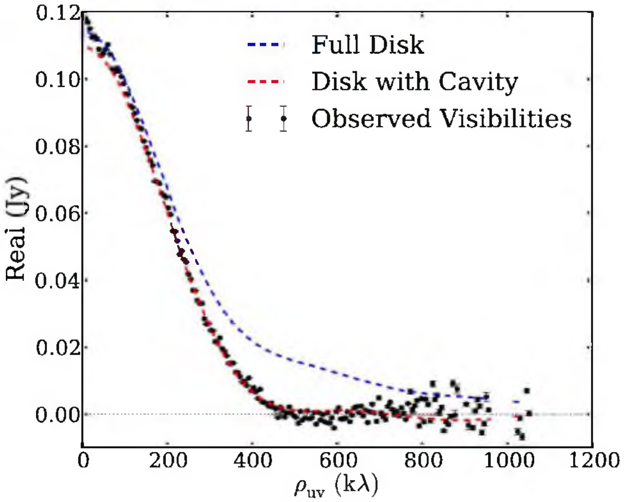


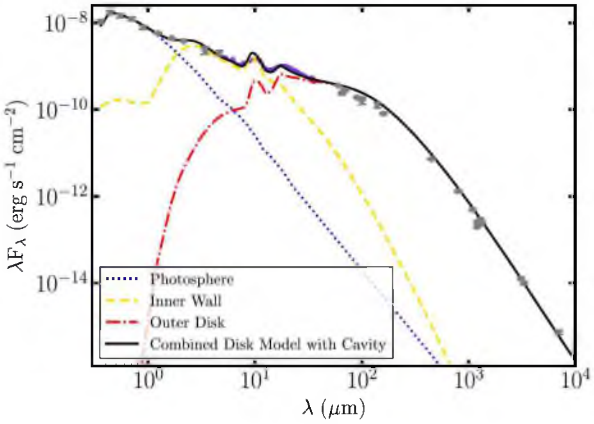
Figure 19. Top panels: (a) the observation image of AS 209 (see Guzmán et al. 2018, Huang et al. 2018a). The distance between two ticks on the axes is 40 au. (b) The synthetic image from the simulation with a single planet ($M_p/M_* = 0.1\, M_J/M_\odot$) at 99 au in a $\alpha = 10^{-5}$, $\Sigma_{g,0} = 15$ g cm^{-2}, $s_{\max} = 0.3$ mm, and $p = -3.5$ disk at 2000 orbits (~2 Myr). (c) The synthetic image from the simulation with a single planet ($M_p/M_* = 0.1\, M_J/M_\odot$) at 99 au in a varying α, $\Sigma_{g,0} = 6.4$ g cm^{-2}, $n(s) \propto s^{-3.5}$, and $s_{\max} = 0.68$ mm disk at 1350 orbits (~1.35 Myr). Bottom panels: the azimuthally averaged intensity profiles. Panel (a) is the profile from the observation, and (b) and (c) are the profiles from the simulations above. The "DM" and "BM" stand for dark annulus and bright ring in the model, respectively; the digits coming after mark the position in astronomical units. The gas density profiles of two models are overplotted on the bottom panels in gray in arbitrary units.

Zhang,S, Zhu +2019

Dust evolution







Rubinstein+2019

R_{cav} ~ 16 au

Substantial amount of small grains in inner disk

~ 10% of large grains

** M_d ~ 0.05 M_{sun} ~ 52 M_J

Mdot ~ 10^{-8} – 10^{-7} M_{sun}/yr

M_p ~ 0.1 – 0.3 M_J (Zhang+ 2019)

Long term dust evolution

Once a planet form in disk, what is the subsequent evolution of the disk?

Of these disks with remaining small dust in inner disk, what follows?

Why is dust remaining in some and not others?

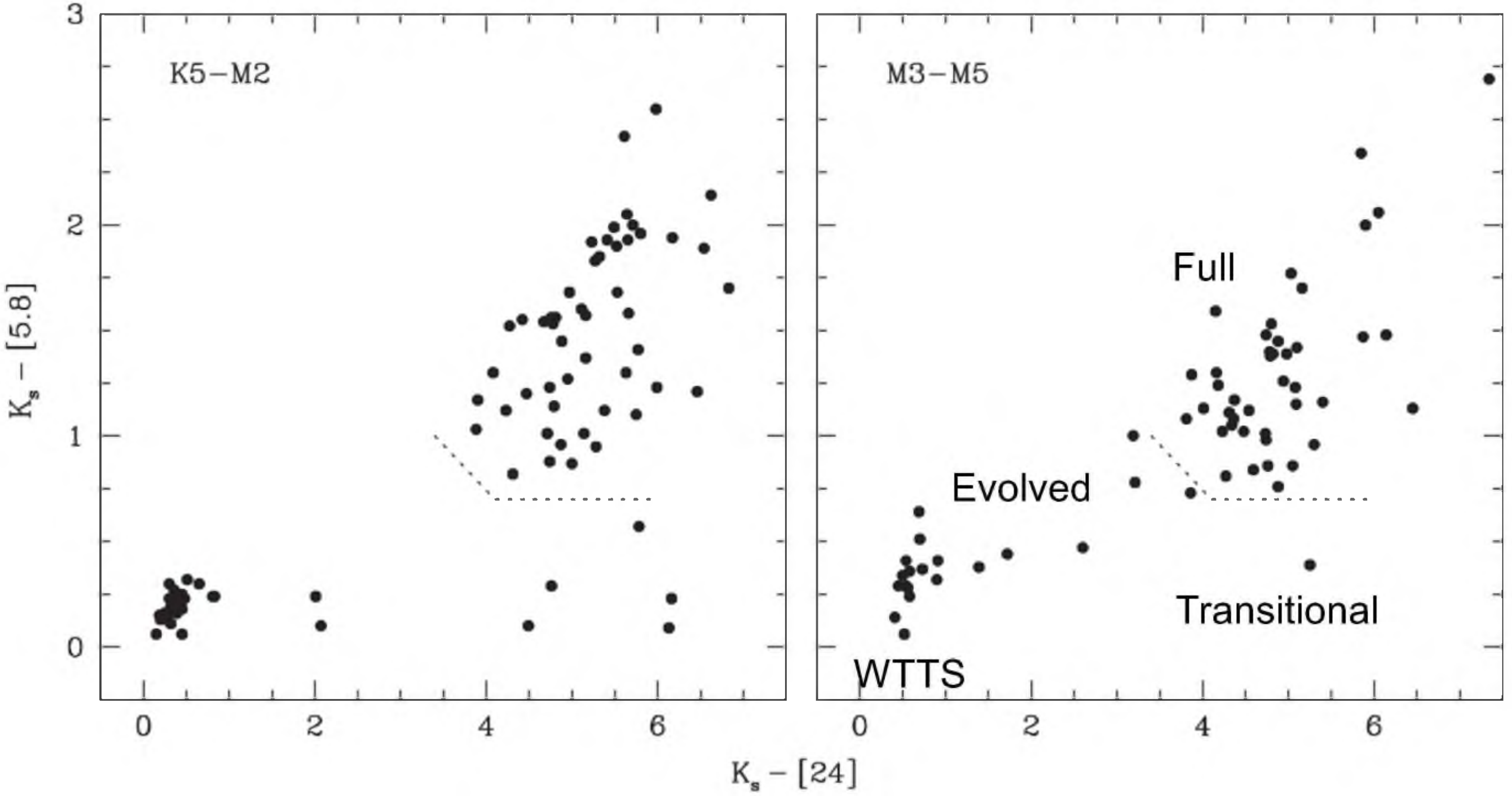
How is the overall disk evolution affected by formation of planets?

Bias towards bright and larger disks
Disks fainter as they age – more difficult to get high resolution observations

Have to look at colors

Low mass stars

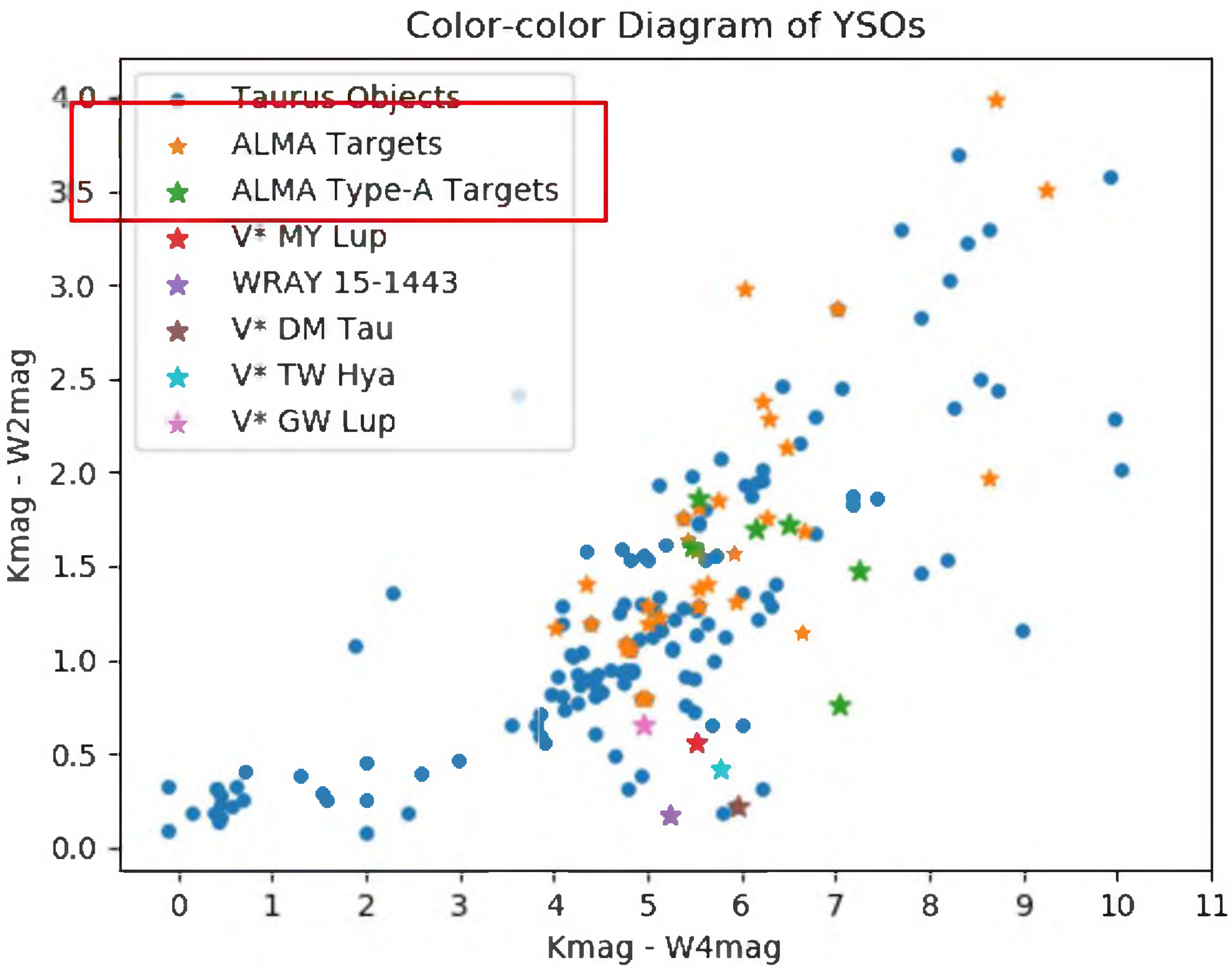
Taurus



Luhman+2008

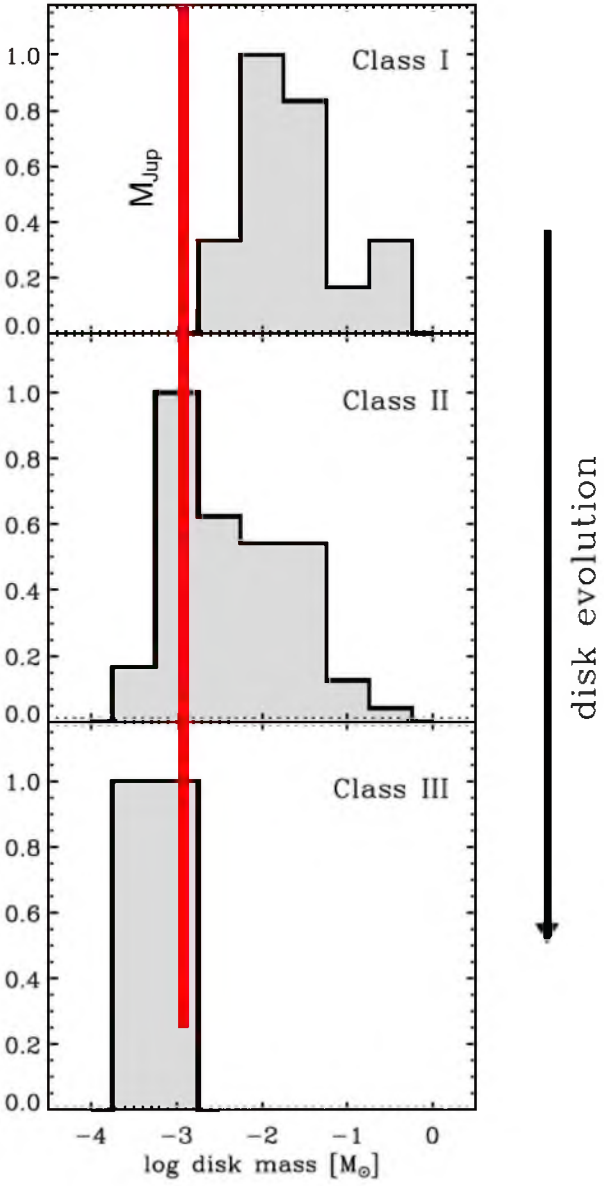
Colors of ALMA disks

Disks with structure are not distinguishable from the general population of disks in color-color diagrams



Taurus: Esplin+2019

Disk Masses



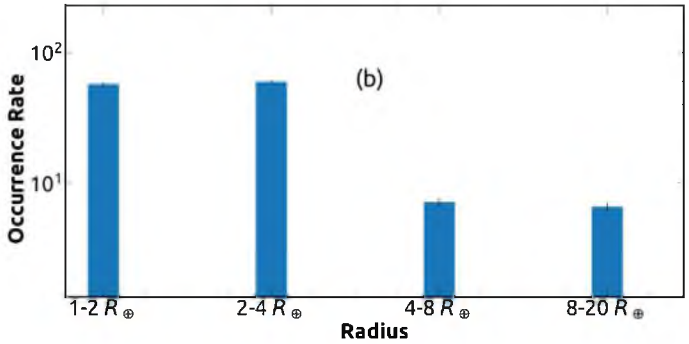
Andrews 2008

Do planets affect disk evolution?
Mass of disk/Mass of planets

Gas mass – uncertain, depends on indicator
    CO low, Williams+ 2014
    HD Bergin+2013, McClure+2016

Most exoplanetary system do not have Jupiter mass planets

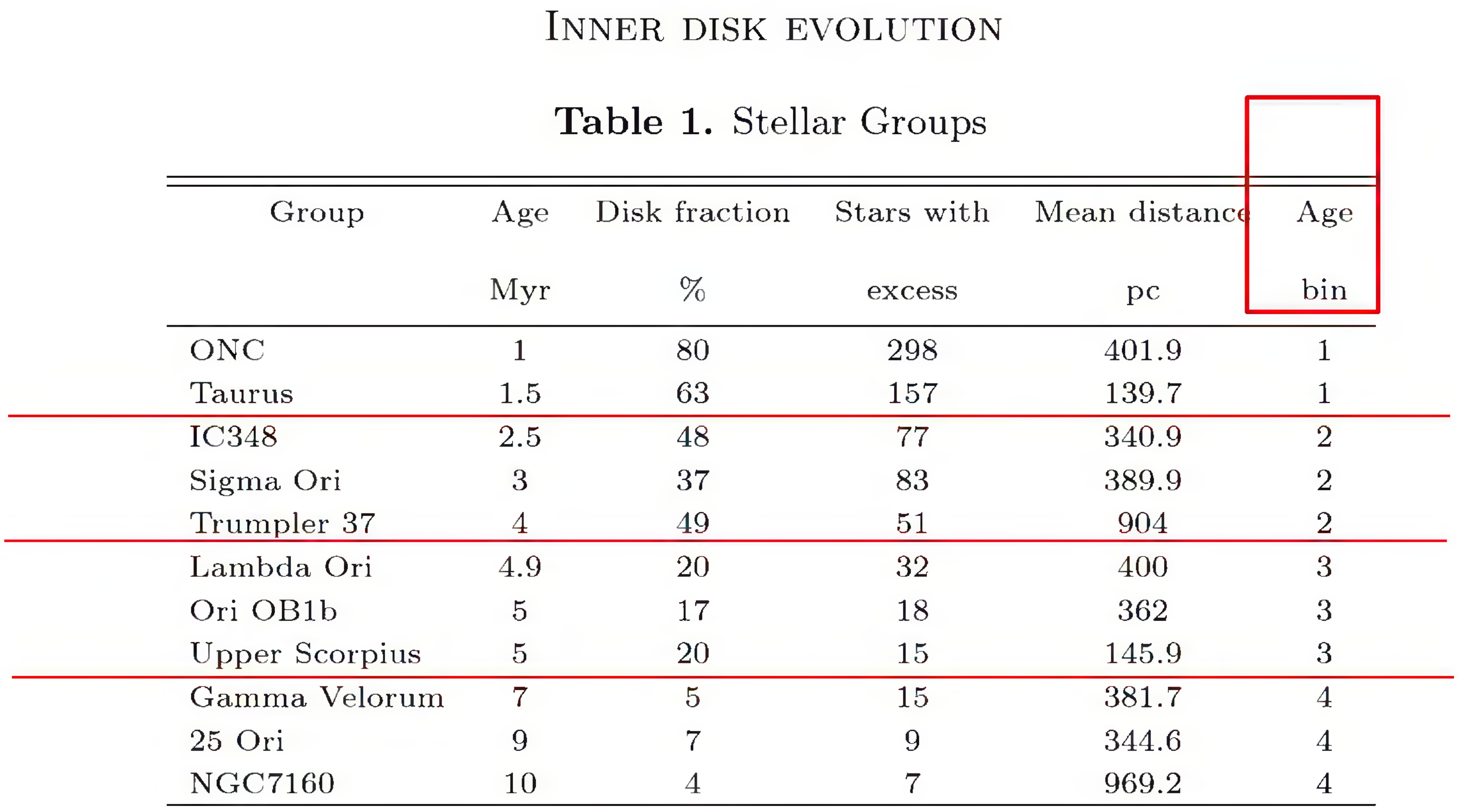
Some systems w multiple giants
    multiplicity not precisely known



Narang+2018

Evolution of IR excess

Assuming the planets do not affect disk evolution
Study how IR excess and accretion changes with time
Large set of populations of different ages



INNER DISK EVOLUTION

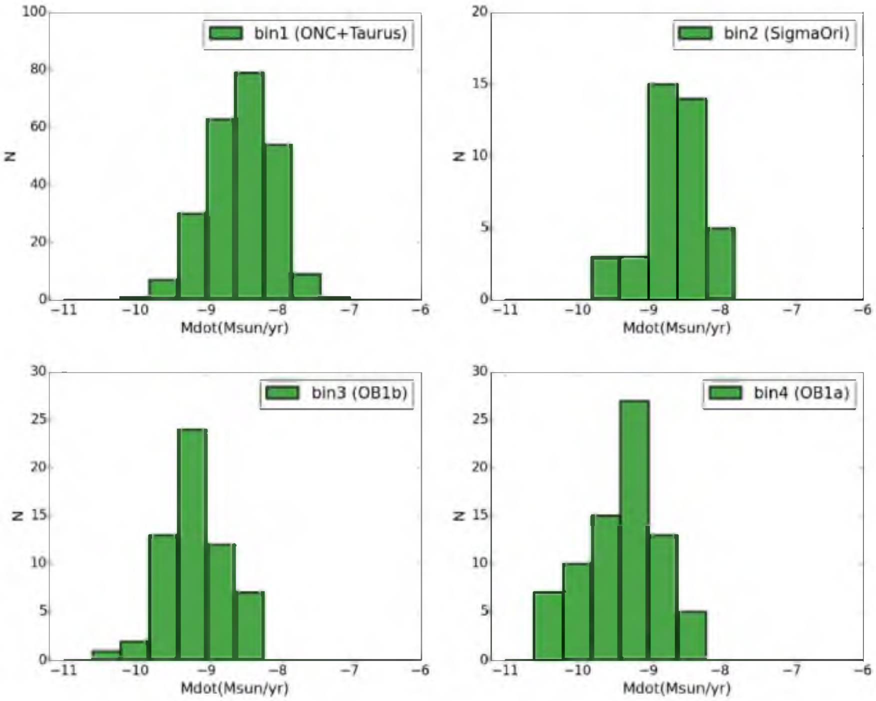
Table 1. Stellar Groups

Group	Age Myr	Disk fraction %	Stars with excess	Mean distance pc	Age bin
ONC	1	80	298	401.9	1
Taurus	1.5	63	157	139.7	1
IC348	2.5	48	77	340.9	2
Sigma Ori	3	37	83	389.9	2
Trumpler 37	4	49	51	904	2
Lambda Ori	4.9	20	32	400	3
Ori OB1b	5	17	18	362	3
Upper Scorpius	5	20	15	145.9	3
Gamma Velorum	7	5	15	381.7	4
25 Ori	9	7	9	344.6	4
NGC7160	10	4	7	969.2	4

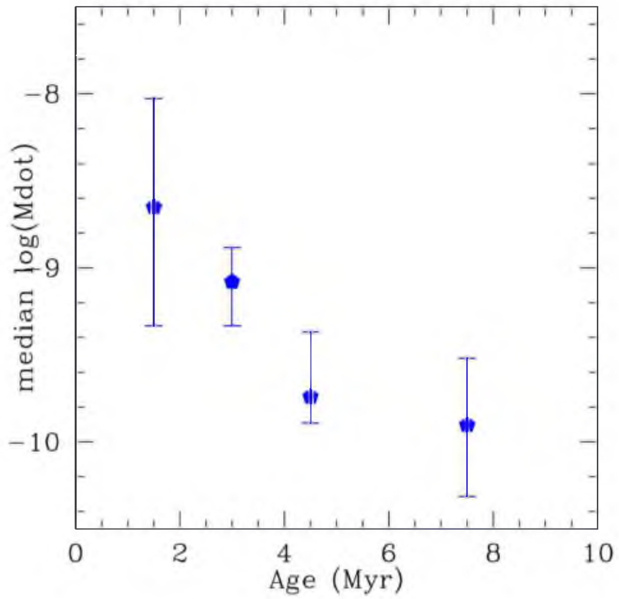
Manzo-Martinez+ (in prep)

Evolution of the mass accretion rate

Distributions for each age bin



Medians and Quartiles



Manzo-Martinez+

Evolution of disk color excess

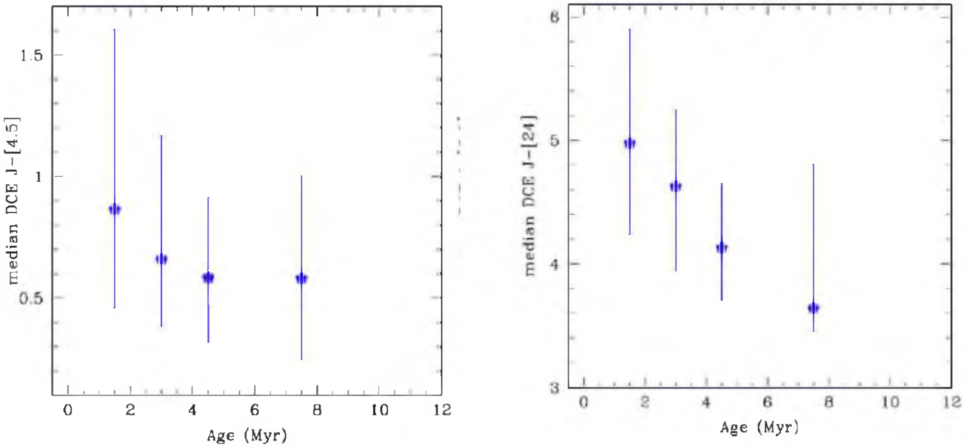
$\mathrm{DCE} = (J - [*])_{\mathrm{obs}} - (J - [*])_{\mathrm{phot}}$

* Spitzer

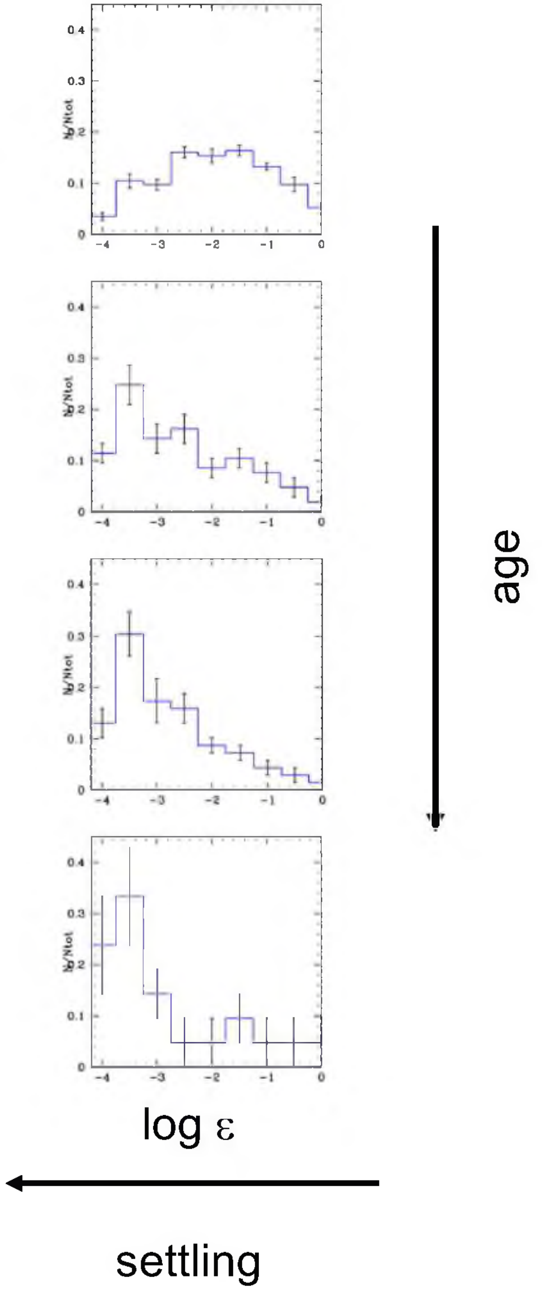
IRAC: 3.6, 4.5, 5.8, 8

MIPS: 24

Median and Quartiles



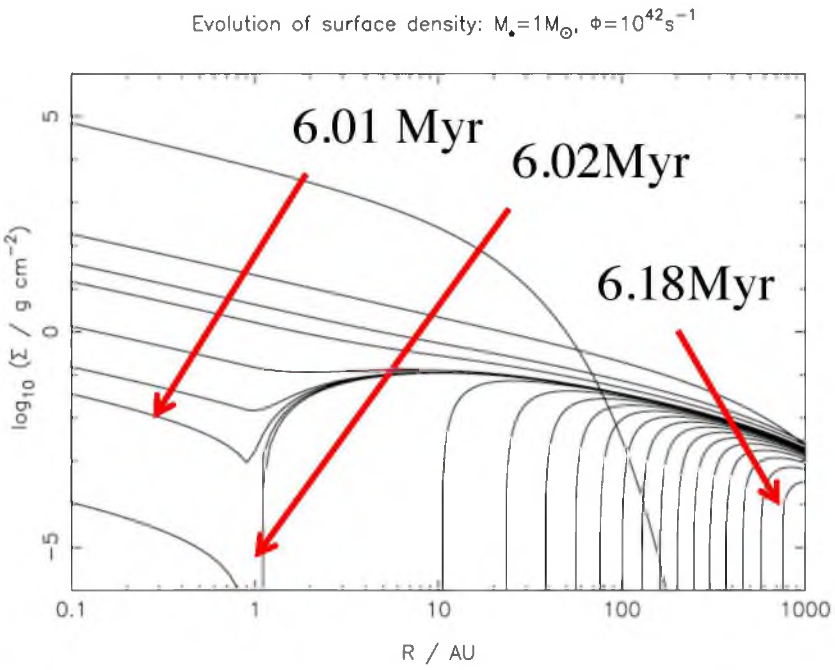
[4.5] [24]



Manzo-Martinez+

Effects of Photoevaporation

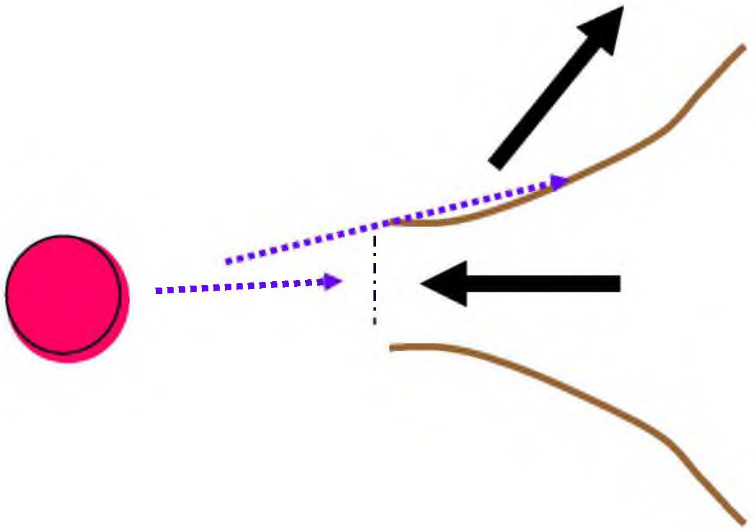
Alexander et al. 2006



High energy radiation photoevaporates disk
$c_s \sim V_{esc}$

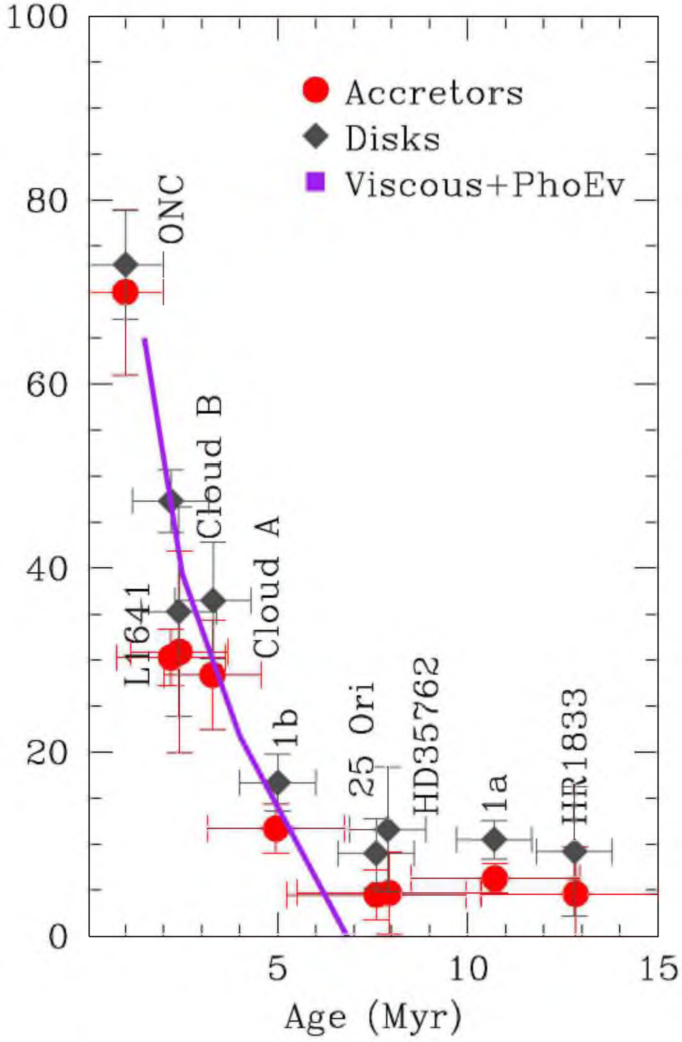
When mass accretion rate (decreasing by viscous evolution) ~ mass loss rate, no mass reaches inner disk, depleted in viscous time scale of inner disk (~ 10^5 yrs or less)

After hole forms, direct photoevaporation of edge, inner cleared region grows fast, no inner disk left

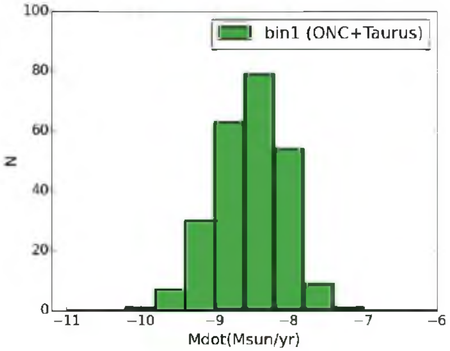


Gorti, Pascucci, Clark, Owens, Ercolano, Alexander

Photoevaporation determines frequency



Data from Briceno+2019



Distribution of Mdot at 2 Myr

Manzo-Martinez+2019

Let Mdot(t_0) distribution evolve viscously

If/when Mdot(t) falls below Mdot_{lim} disk photoevaporates quickly

$\text{Mdot}_{\text{lim}} = 3 \times 10^{-10}\ M_{\text{sun}}/\text{yr}$

$\alpha = 0.01$

Conclusions

Viscous evolution and photoevaporation are the main drivers of evolution for the gas in protoplanetary disk

- large spread at given age, initial conditions?
- can photoevaporation explains dependence of disk lifetime with stellar mass?

The decrease of disk and accretors frequencies are consistent with a low mass rate in the photoevaporative wind

Solids seems to evolve separately from gas, evolution gives rise to structure, planets

Planets do not seem to influence much the overall disk evolution

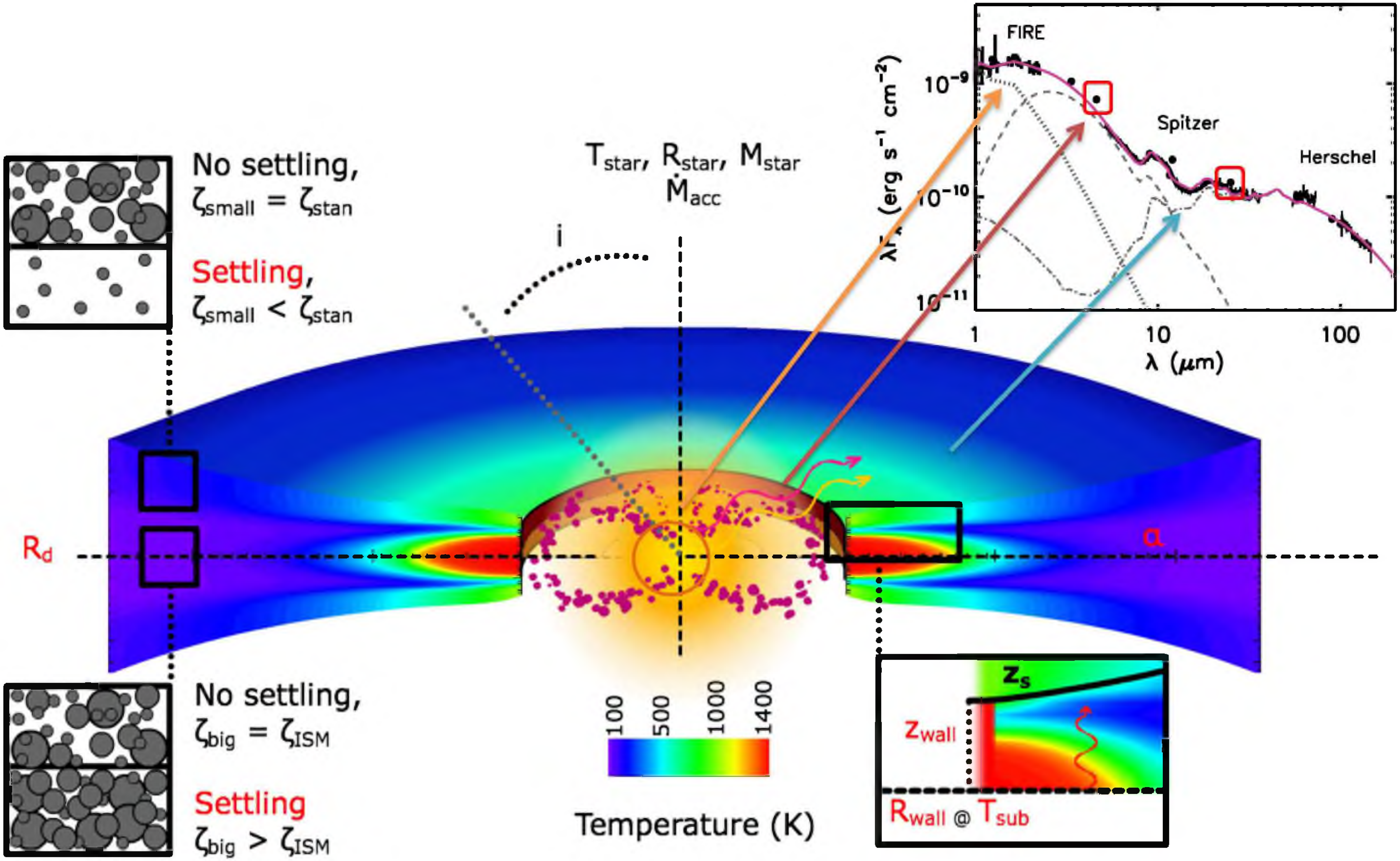
- needs to be explored in more detail

Caution with ages – birthline effects

Dust evolution indicated by two parameters:

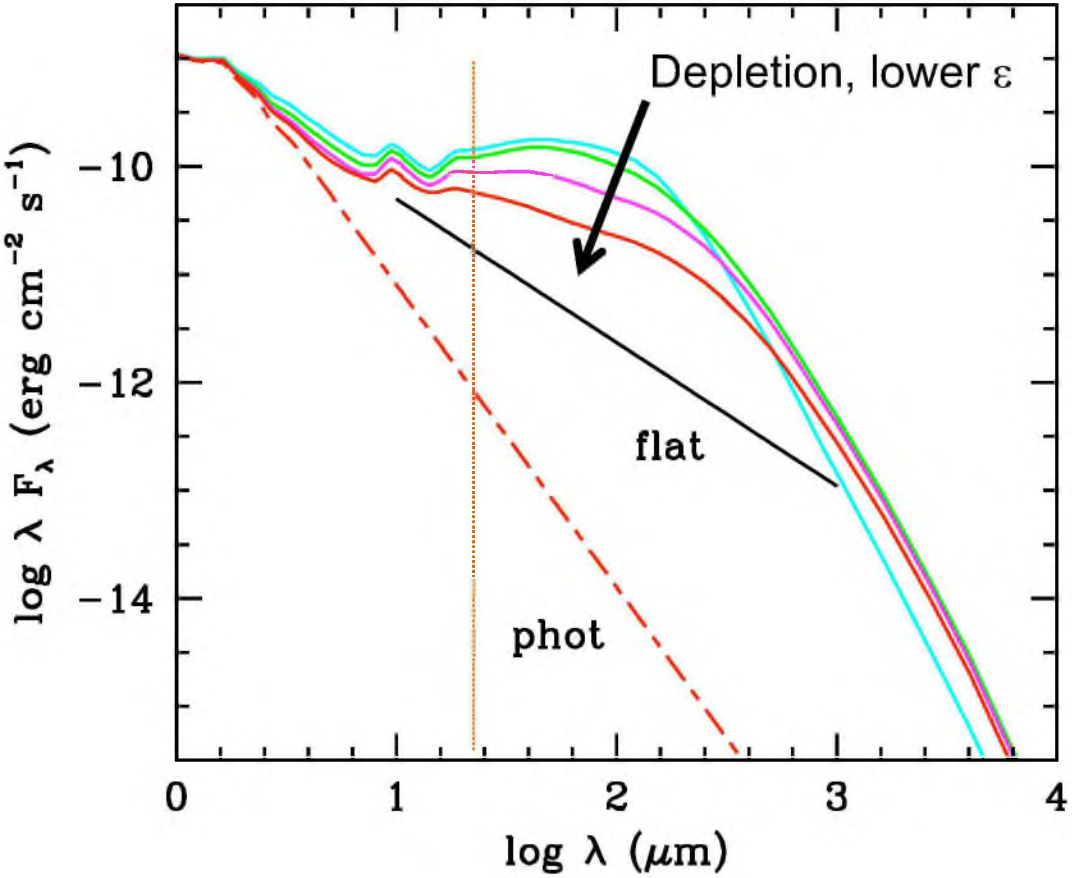
z_{wall} ~ height of disk at dust destruction radius, DCE J – [4.5]

ε = dust2gas mass ratio of grains in upper levels $=\zeta_{small}/\zeta_{ISM}$, DCE J – [24]



D’Alessio+(2006). Art: Melissa McClure

Effects of dust settling in SED



Less opacity in upper layers, less heating, lower flux

Dullemond & Dominik 2004; D' Alessio+ 2006