Protostellar and protoplanetary disk accretion

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ISIMA 2011

Michigan Star and Planet Formation

A request

If you have asked me for a reference to other work or a pre-publication paper, etc.:

would you please send an email to me at

lhartm@umich.edu

that way, I

- have your email address in order to
- respond to (remember!) your request

"Luminosity problem" (Kenyon et al. 1990, 94) (low mass stars)

Must lose energy to make star.

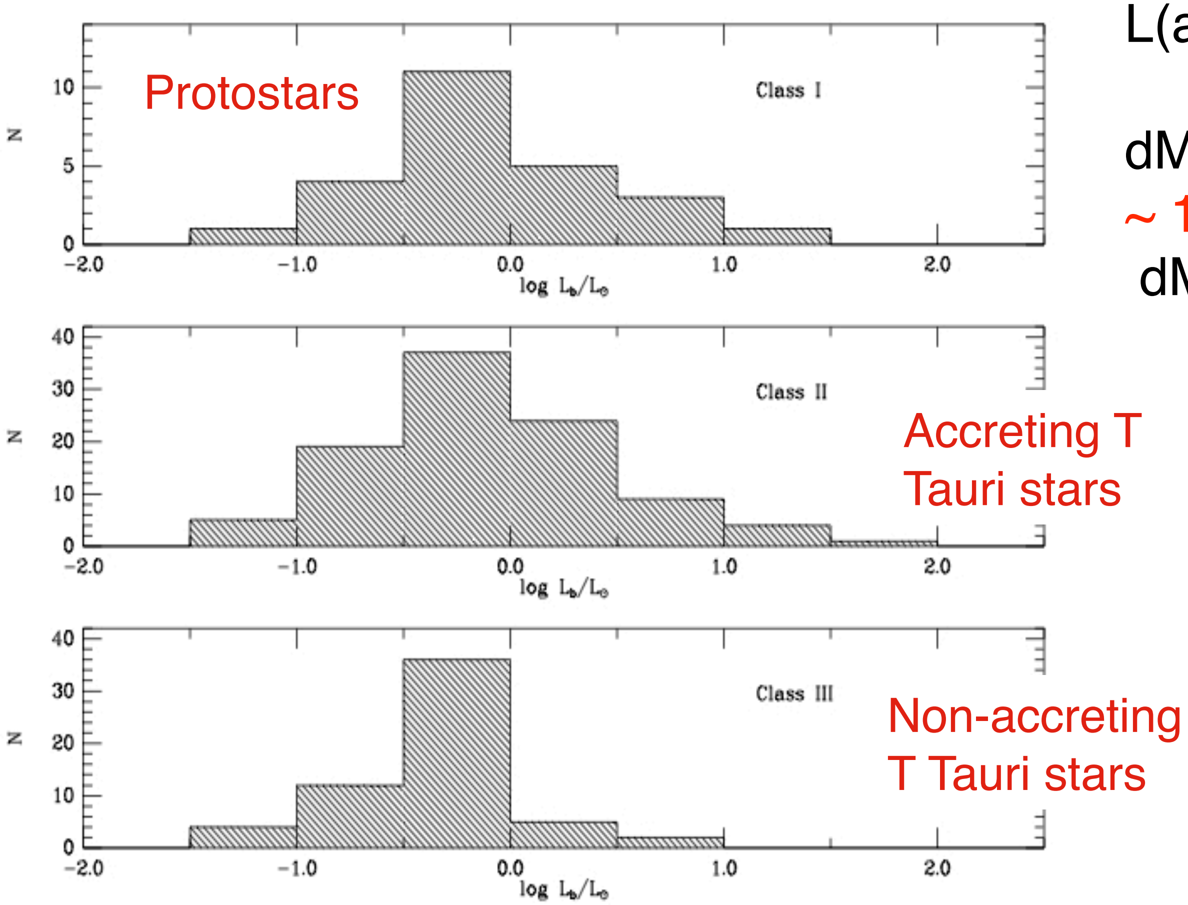


Fig. 5.1. Luminosity distributions of Class I, II, and III sources in Taurus.

L(acc) = G dM/dt M/R

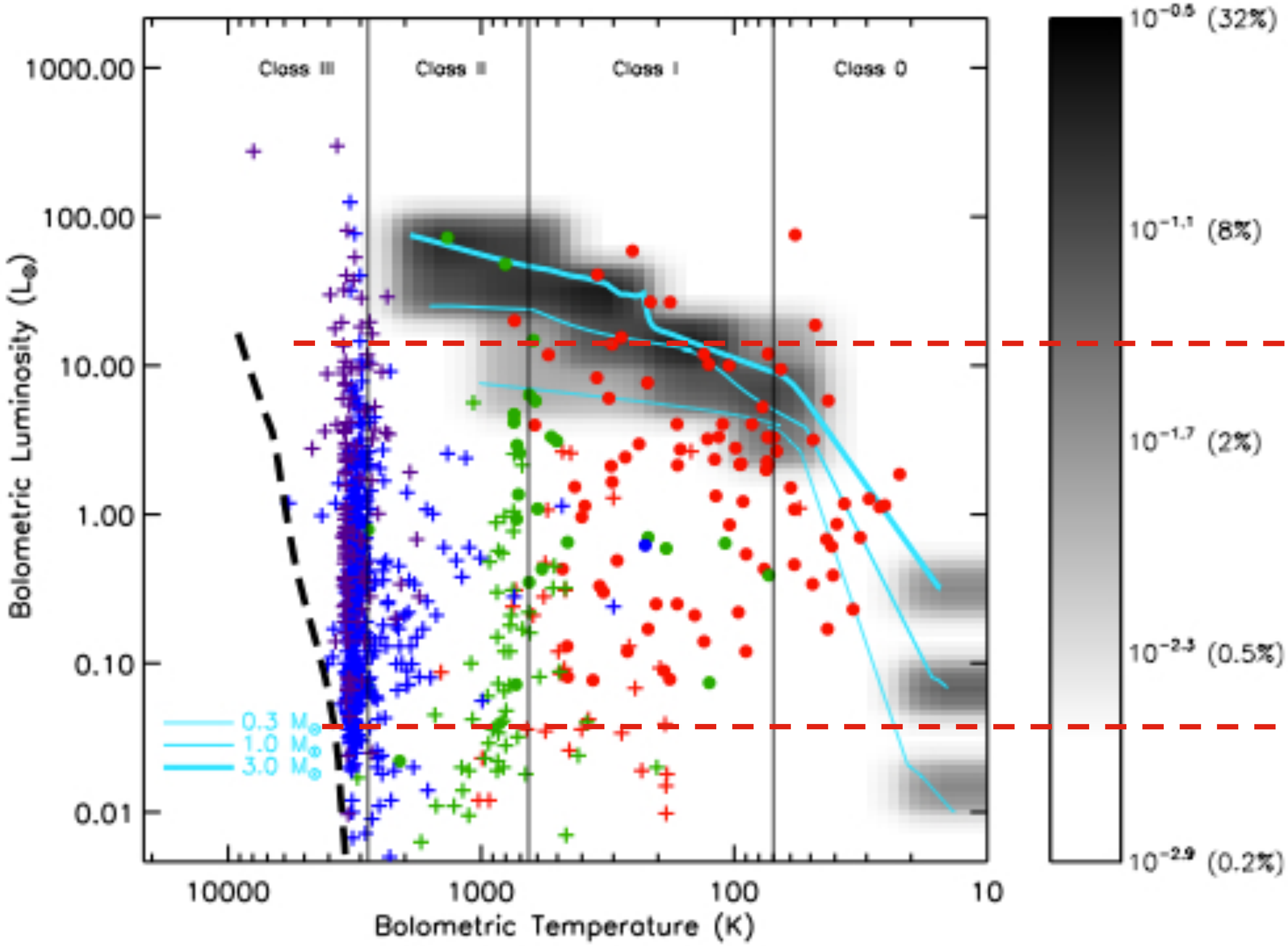
dM/dt >~ 0.6 Msun/0.2 Myr

~ 10 - 20 L(sun) for

dM/dt >~ 2 x 10^{-6} M(sun)/yr

? what's wrong ?

recent Spitzer results seem to confirm missing accretion luminosity



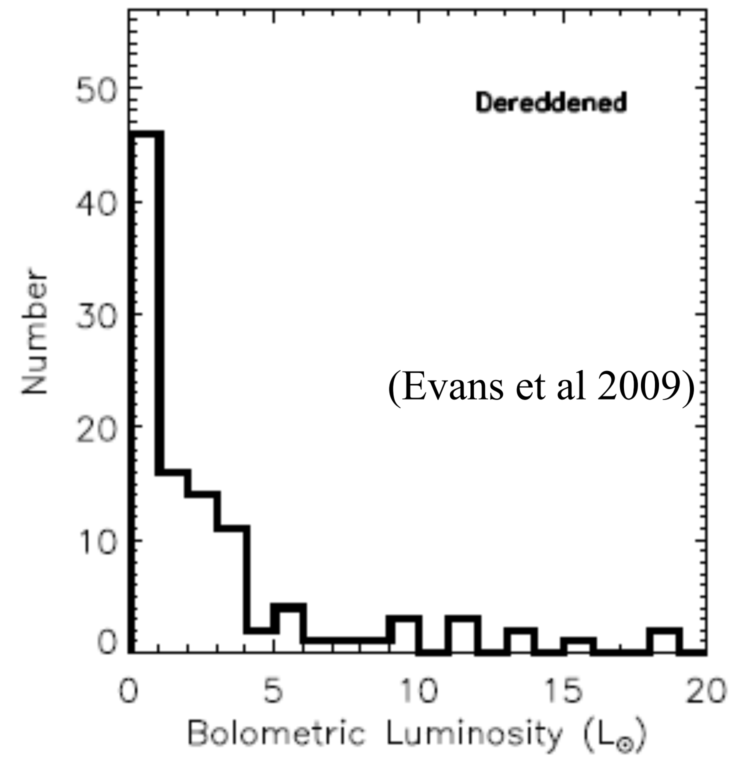
similar L range for protostars and T Tauri *s

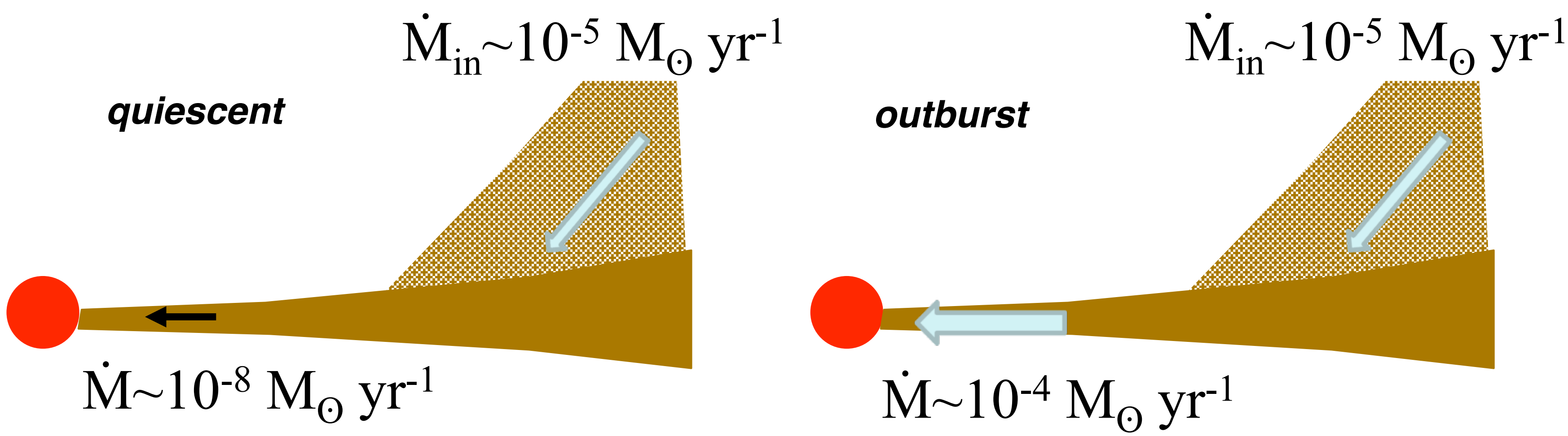
Dunham, Evans et al. 2009

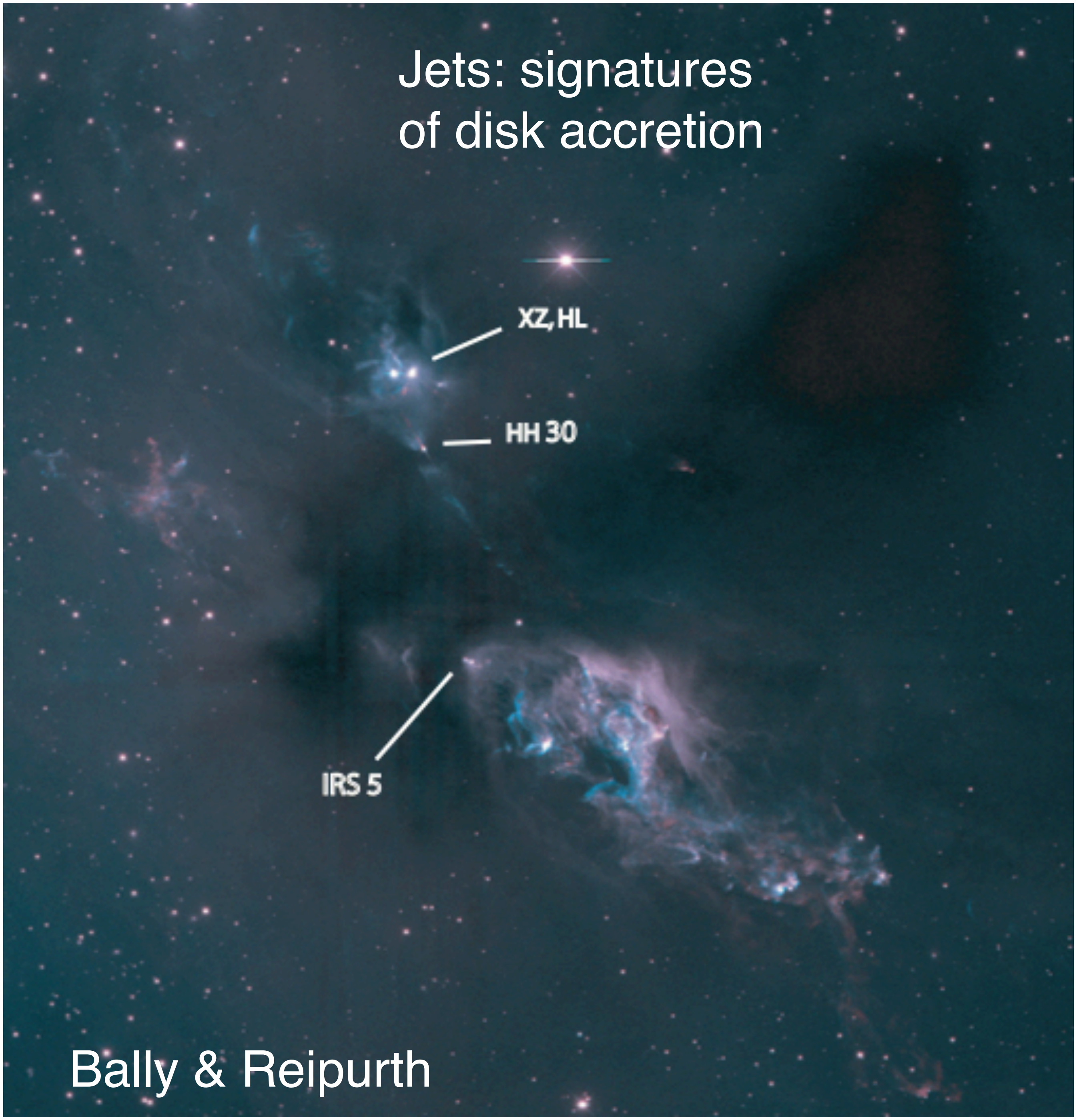
Solutions: dM/dt not steady;

• Class I too late- "Class 0" short-lived, rapid accretion… but not obvious Class 0 are that much more luminous.

• Episodic accretion; first to disk, then in short-lived disk accretion outbursts?






Jets: signatures
of disk accretion
XZ, HL
HH 30
IRS 5
Bally & Reipurth

dM/dt (wind)
~ 0.1 dM/dt (acc)

→L(wind) ~ L(acc)!

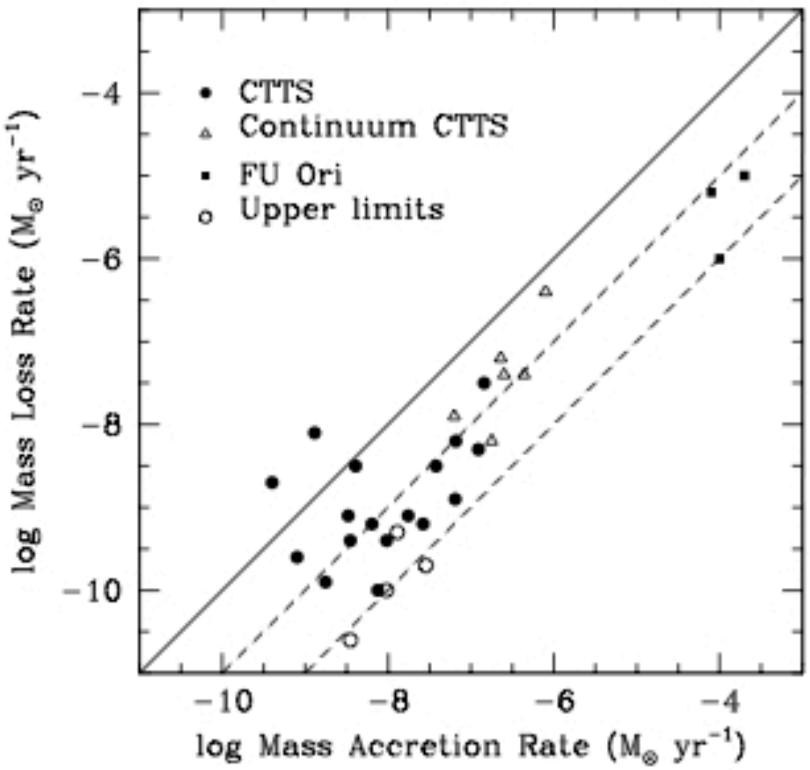


Fig. 10.9. Mass accretion rates vs. mass loss rates. Errors are probably factors of three or more in each coordinate. The solid line is $\dot{M}(wind) = \dot{M}(accretion)$; the dashed lines are wind mass loss rates of 10% and 1% of the mass accretion rate. Overall, the observations indicate that mass ejection is about 10% of the mass accretion rates, consistent with energetic requirements of driving the mass loss by accretion energy (see text). Taken from Calvet (1998).

time-dependent mass ejection → time-dependent accretion

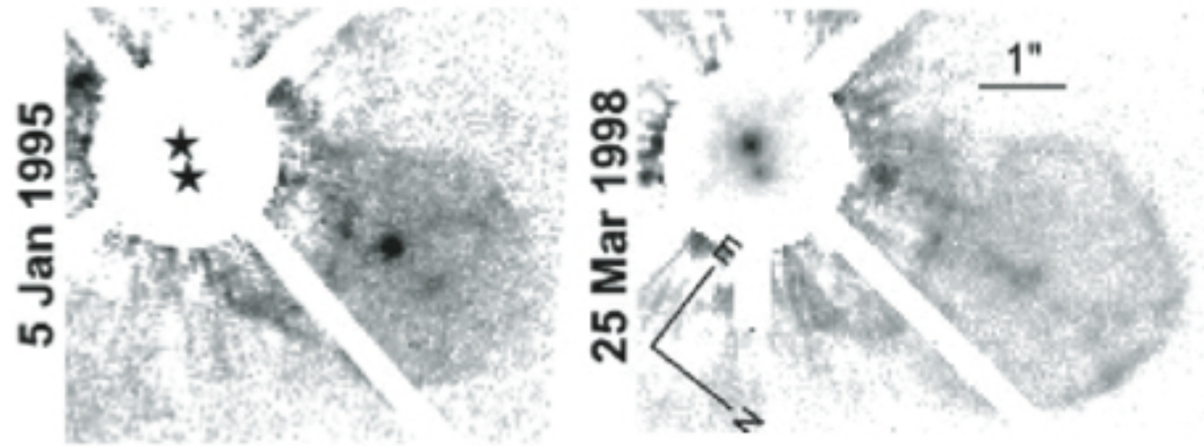
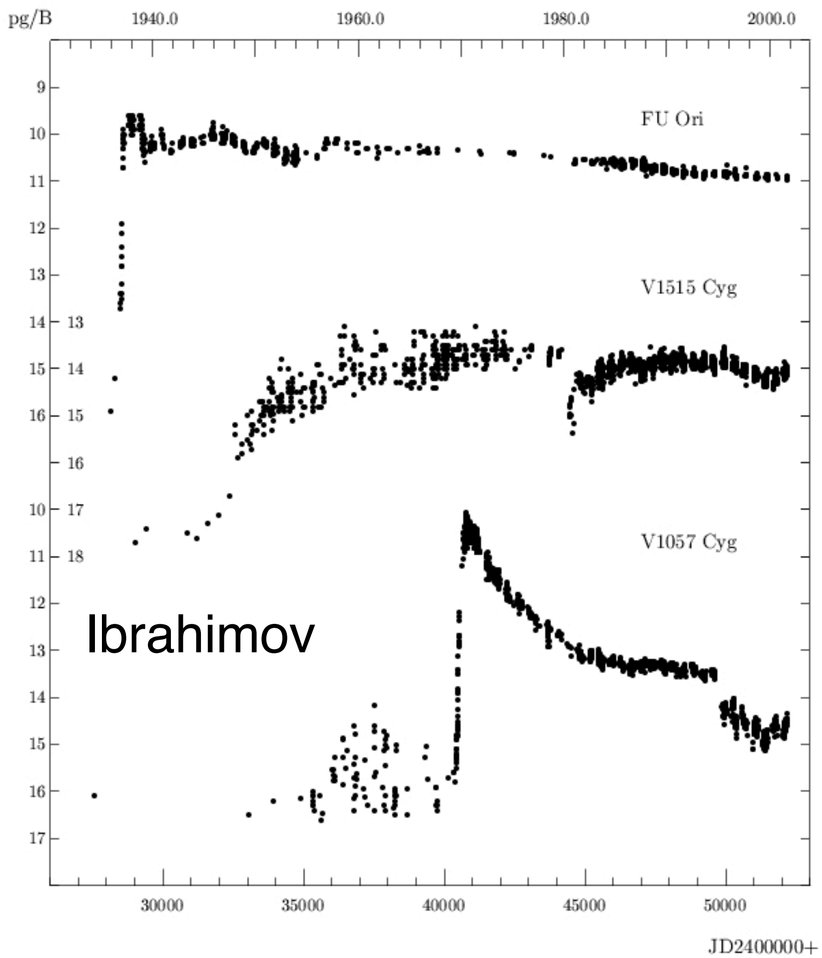


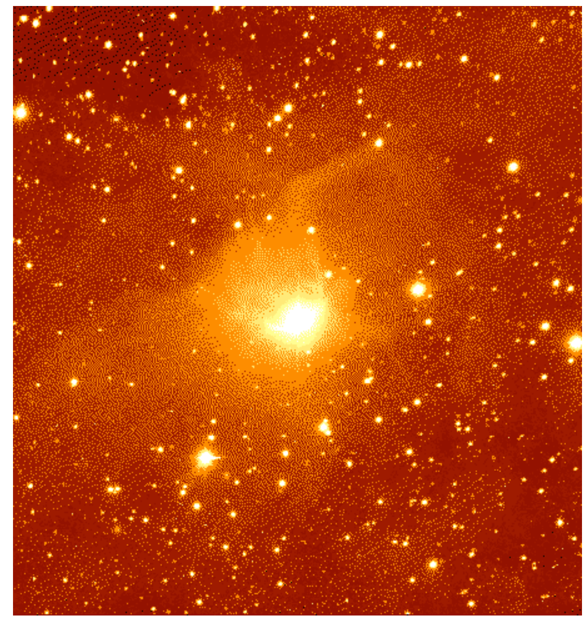
Fig. 10.2. Images of XZ Tau in R-band (0.675μm) with point-spread function subtraction of the central binary; the 1998 data shows a short exposure inserted into the center. The indication is that of a broad bubble of shocked gas expanding at about 150 $\mathrm{km\,s^{-1}}$ (projected velocity) in the same direction as a previously-known jet. The knots bisecting the bubble may be in the collimated jet. From Krist *et al.* (1999).

FU Ori objects: big outbursts of mass accretion, probably up to dM/dt ~ 10^{-4} M(sun)/yr

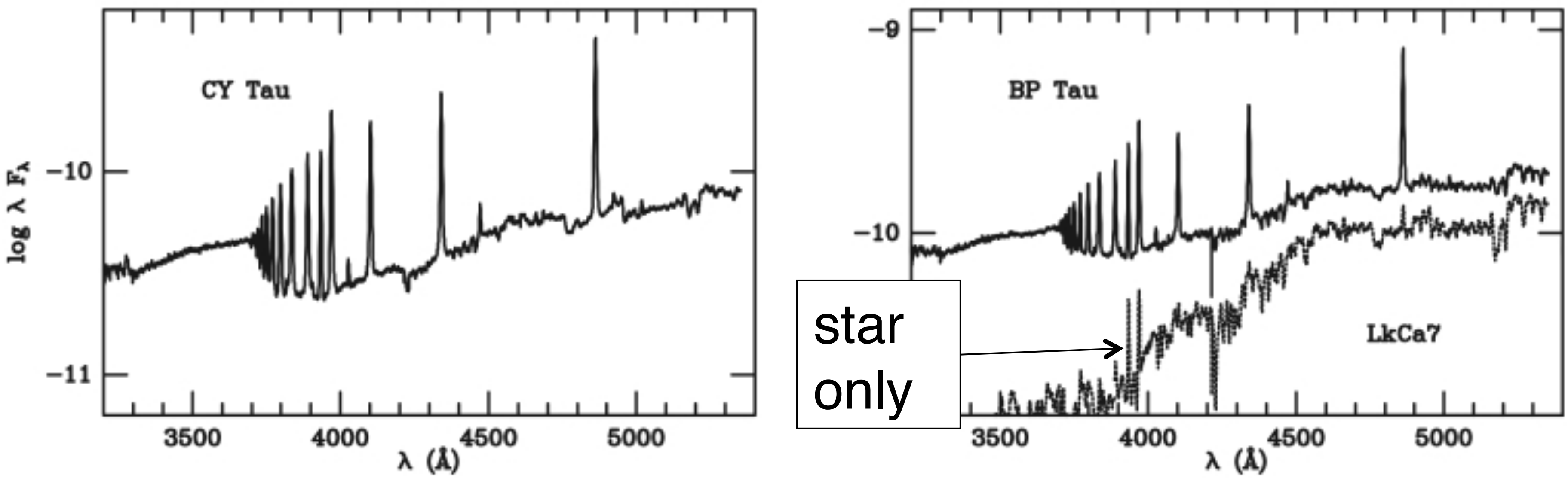
“EXORs”; ~ year timescale outbursts of 10^{-7} – 10^{-6} ms/yr

duty cycle/repetition time unknown.





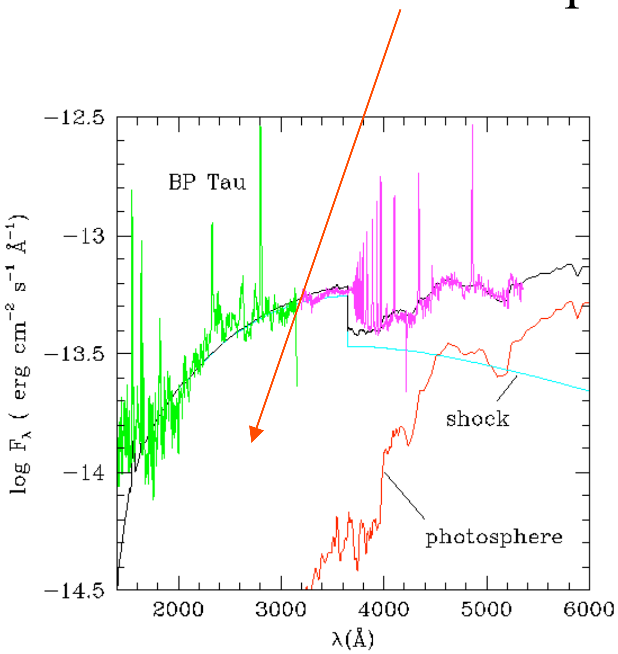
“baseline case” for disk accretion during the post-infall phase: T Tauri stars



Class II (T Tauri) stars have excess continuum emission arising from the accretion shock on the star, and emission lines from both the magnetosphere and the shock region

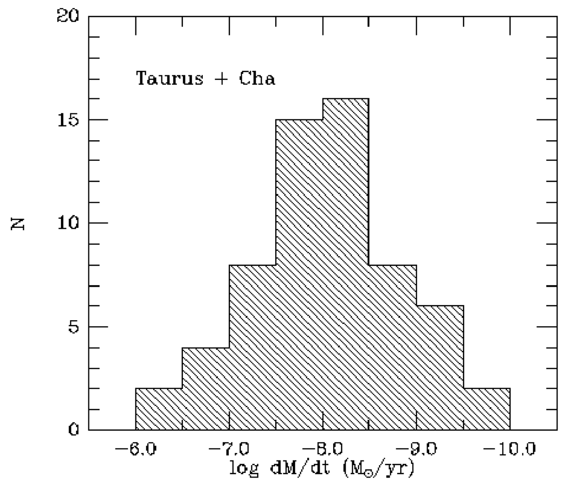
Measurement of mass accretion rates

Excess emission over photosphere $\sim L_{acc} = G\,M\,(dM/dt)\,/\,R$



Ingleby & Calvet 2009

Gullbring et al. (1998)

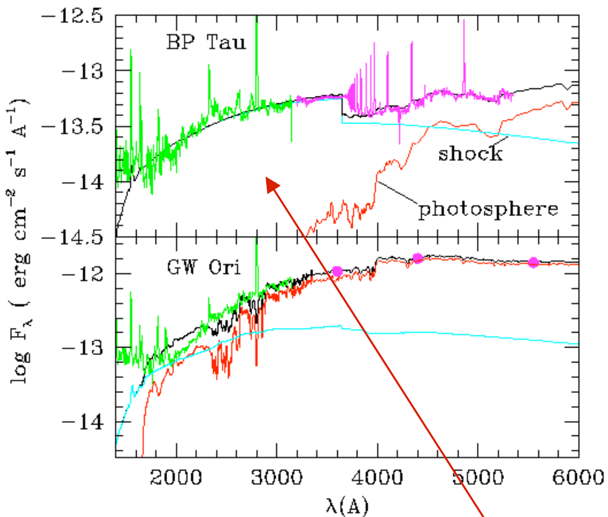


$L_{acc} \sim 0.1\ L_*$

Evidence for magnetospheric accretion

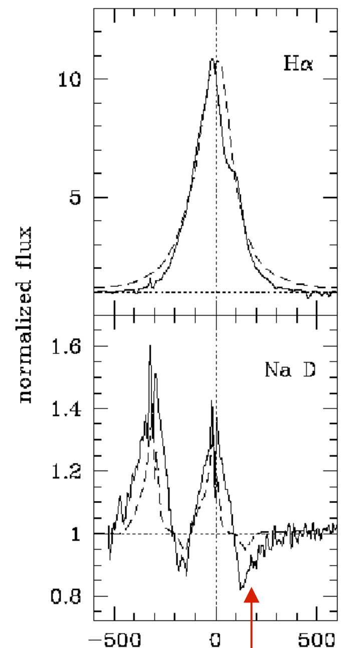
Excess emission/veiling

Calvet & Gullbring 1998



Broad emission lines

Muzerolle et al. 1998, 2001

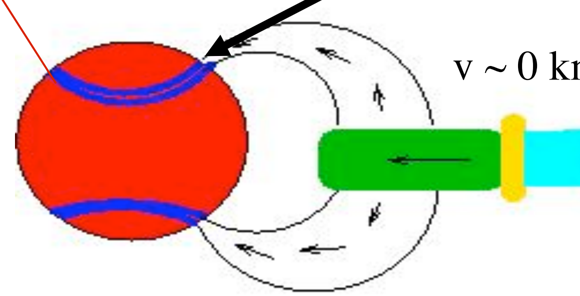


Redshifted absorption
if right inclination

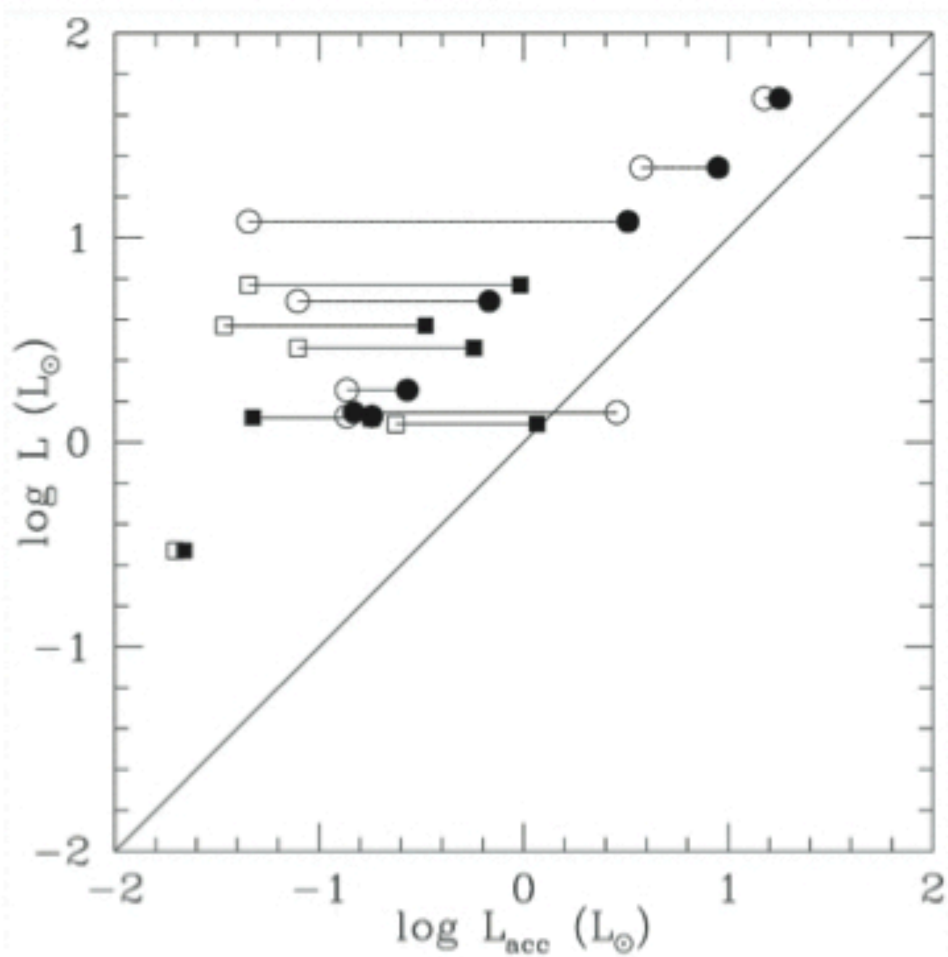
v ~ 250 km/s

v ~ 0 km/s

Measure dM/dt



total (star + disk) L →



Use Br γ emission @ 2 μm correlation with L(acc) in low-extinction T Tauri *s to estimate L(acc) in Class I protostars (not too extincted)

→ L(acc) <~ L* :
→ dM/dt <~ 10^{-7} msun/yr

Fig. 5.2. Total luminosity (vertical axis) as a function of accretion luminosity estimated from the 2.1μm Brγ emission line. Circles are Ophiuchus Class I sources, squares are Taurus Class I objects, and open and filled symbols are rates inferred before and after reddening correction, respectively. From Muzerolle *et al.* (1998b).

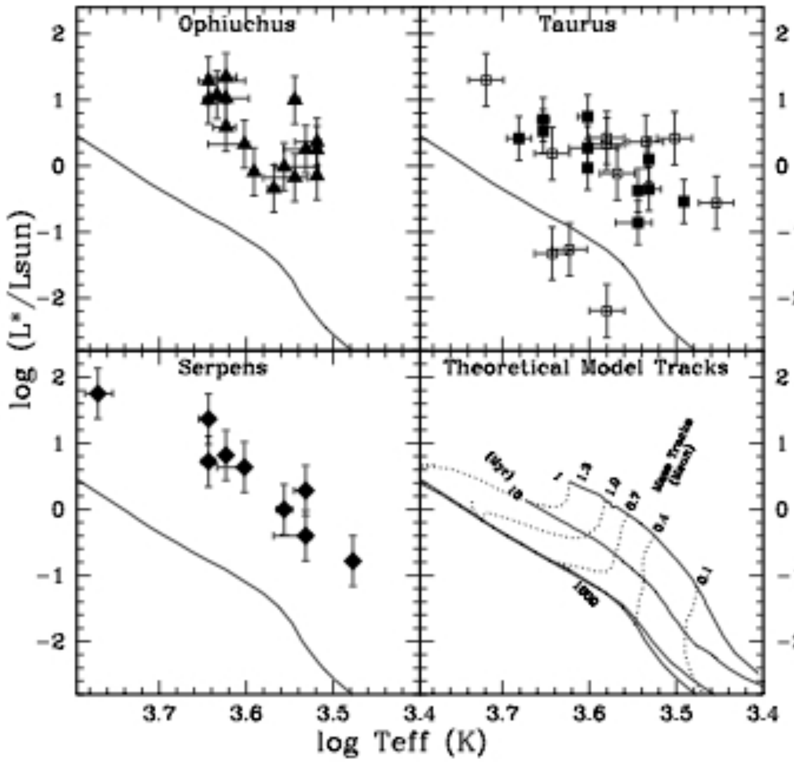


Fig. 4. Stellar luminosities and effective temperatures of Class I and flat-SED stars ($\alpha > -0.3$) in ρ Oph, Tau-Aur, and Serpens are shown on an H-R diagram. Filled symbols are from D05 and unfilled symbols are from WH04. The evolutionary models of *Baraffe et al*. (1998) are also shown for comparison.

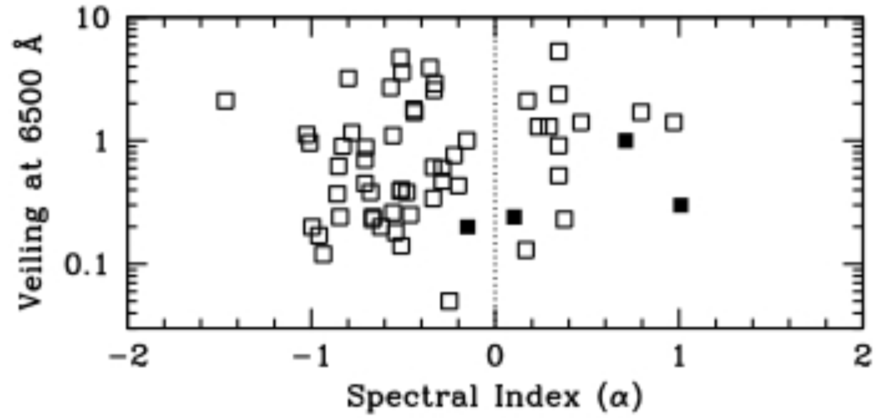


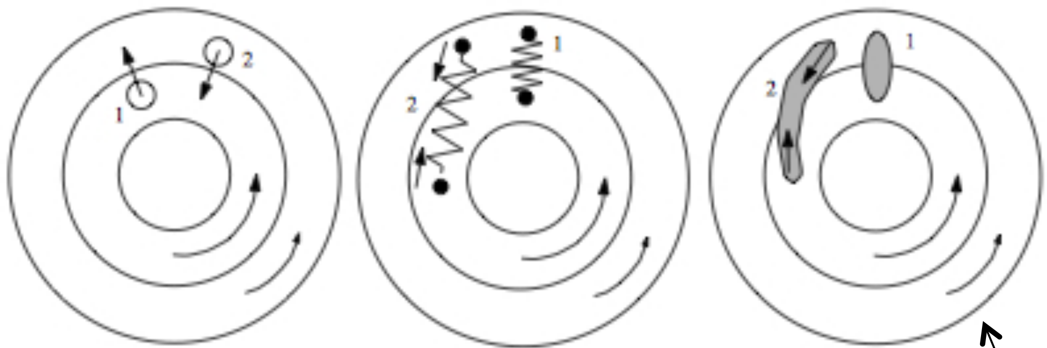
Fig. 6. Optical veiling versus spectral index for stars in Tau-Aur. Measurements are from *WH04* and *Hartigan et al*. (1995). Veiling measurements are shown as open symbols while upper limits are shown as filled symbols. The dashed vertical line separates Class I stars from Class II stars.

HR diagram positions of not-too-extincted Class I similar to T Tauris (M/R similar); optical excess also similar

White et al. 2007

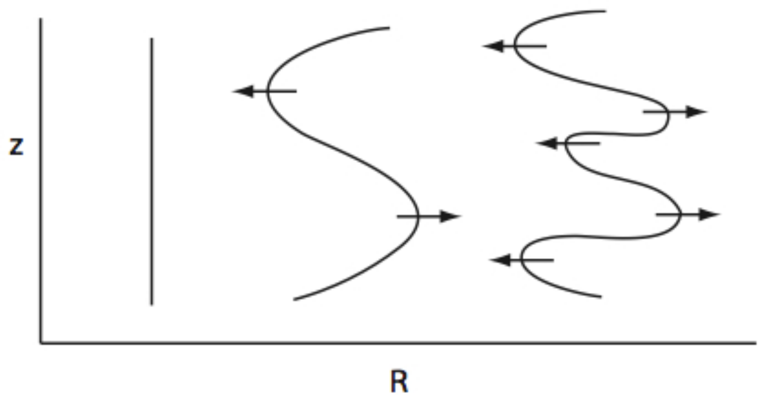
some argue infall is stopping in these objects; but they still have substantial FIR excess…

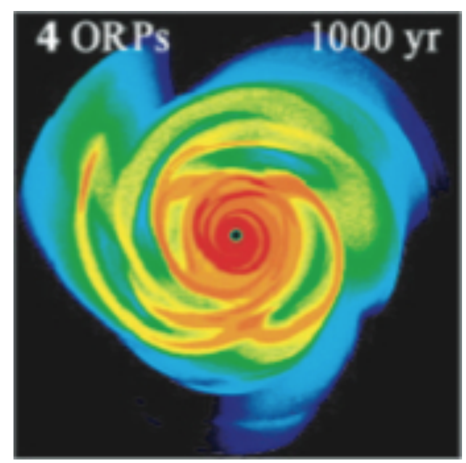
Why do T Tauri disks accrete? what is the mechanism of angular momentum transport?



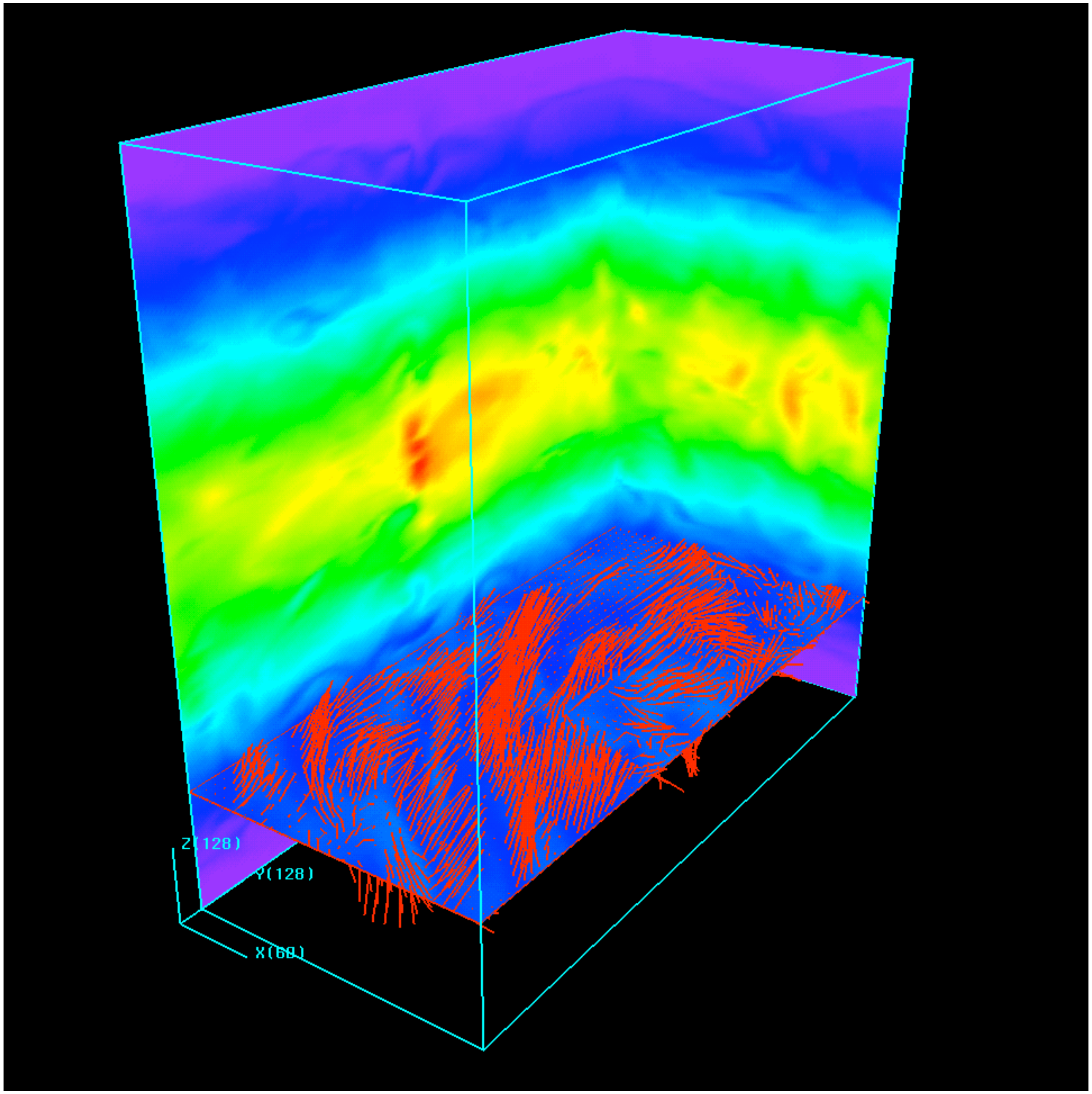
MRI?

GI?





The ionization/MRI/"dead zone" issue…



from Jim Stone's webpage

The accretion rate for a steady α viscosity disk (vertically averaged) is

$$\dot{M}/(3\pi) = \nu\Sigma = \alpha c_s^2 \Sigma/\Omega\,. \tag{1}$$

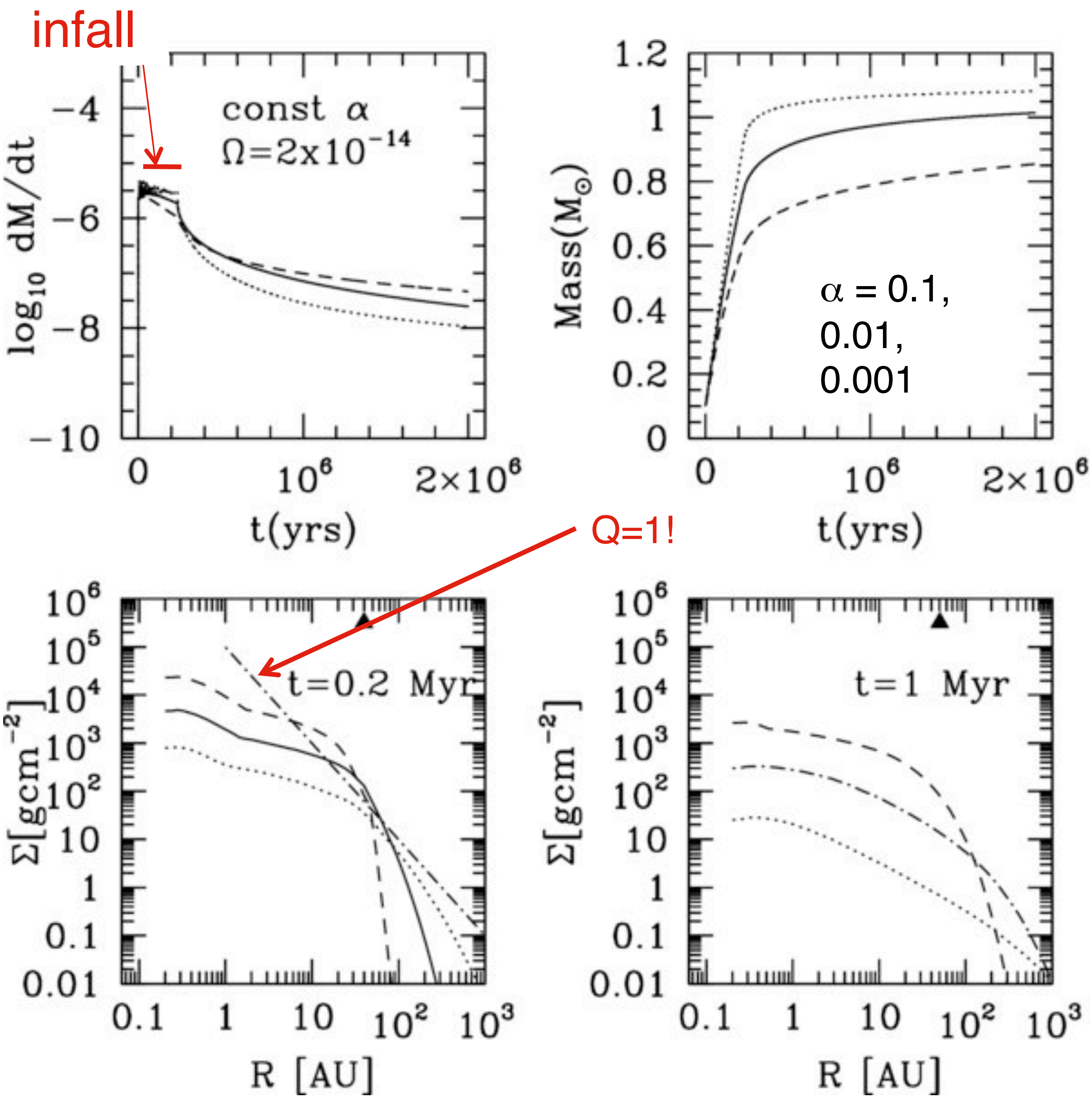
Putting in fiducial numbers of $T = 200(R_{AU})^{-1/2}$ K for a $1\,\mathrm{M}_\odot$ central star,

$$\dot{M} \sim 5\times 10^{-10}\Sigma(R) R_{AU}^{-1}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}\,. \tag{2}$$

For a fixed surface density that is viscous (as in many models of cosmic ray/X-ray ionization), the accretion rate *decreases* with decreasing R; $\rightarrow$ pile-up of material!

T Tauri accretion rates are of order $10^{-8}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$; only the inner $\lesssim 0.1$ AU should be hot enough for thermal ionization to fully activate the MRI; this means that the accretion rate is set by the active layer accretion at this radius, which would require $\Sigma(active) \gtrsim 100\mathrm{g\,cm}^{-2}$, which is problematic.

:: if one forms the star/disk system from infall with reasonable angular momentum, hard to avoid $\Sigma > 10^2$ g cm^{-2} ("accretion velocity" < free fall), so density must be much higher). Need high transport rates to avoid disk pileup!

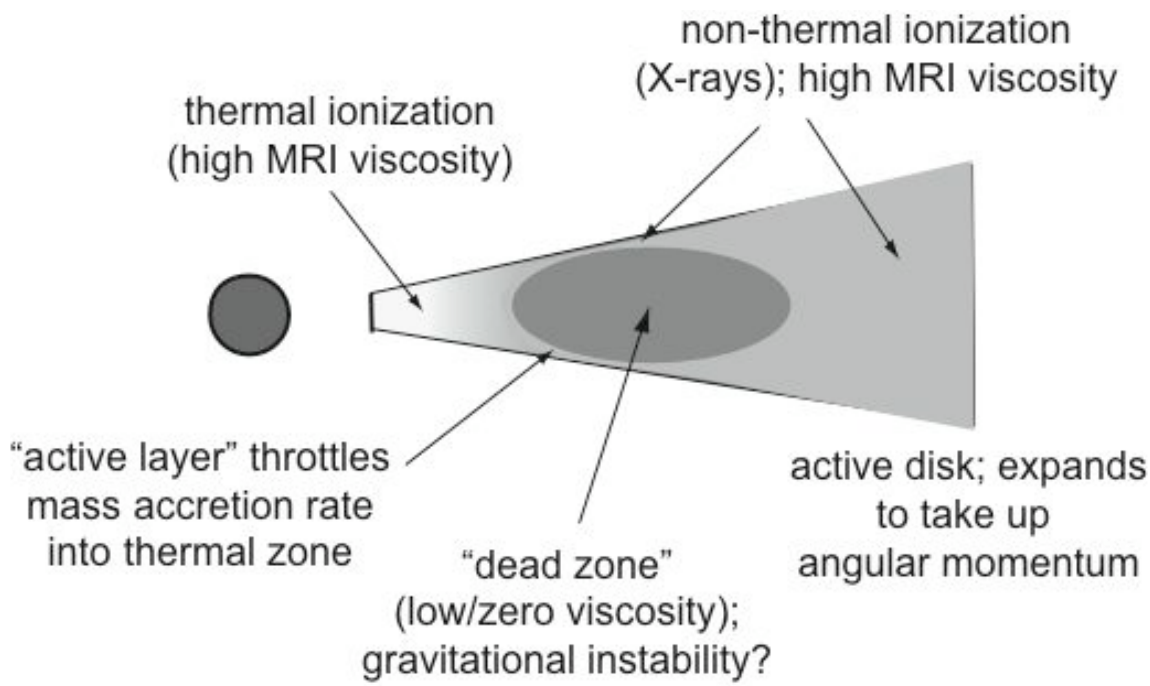


Zhu et al. 2009

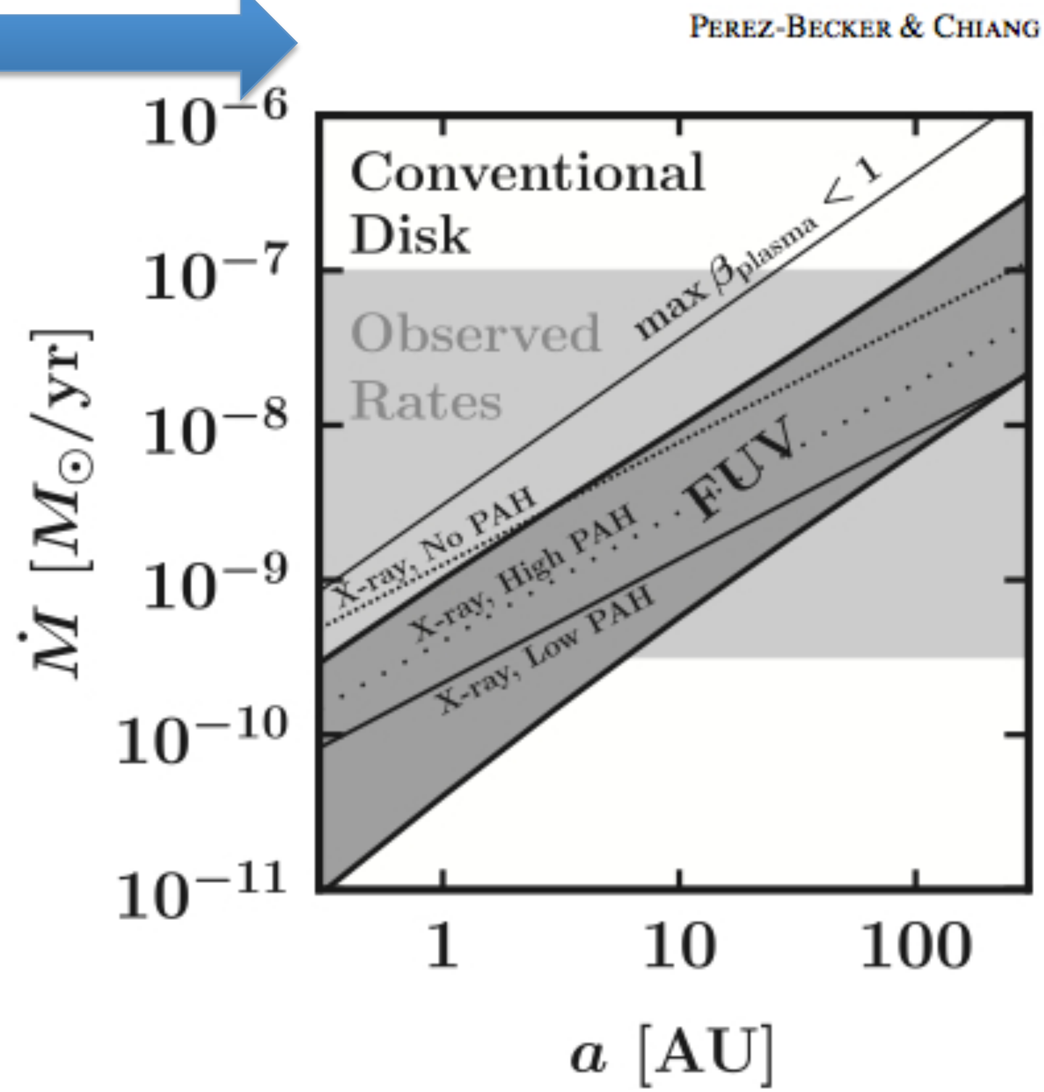
Infall models; needed to form star

even fully viscous disks can pile up to become gravitationally unstable unless large α AND Σ(active) > 10^2 g cm^{-2} (unlikely!)

“Dead zone” (Gammie 1996)

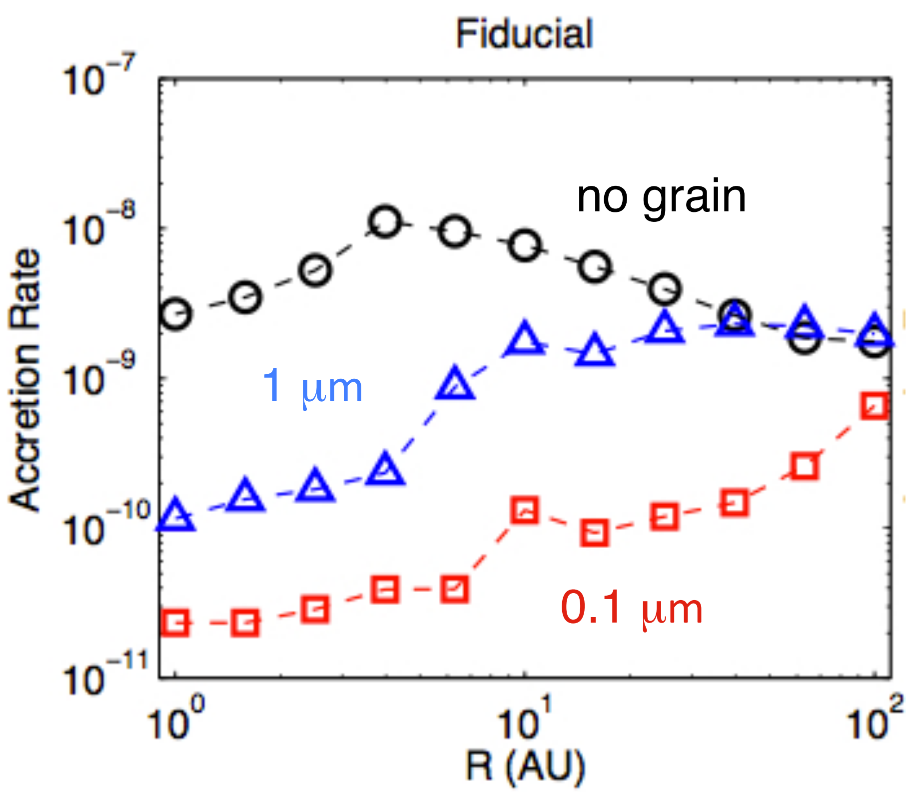


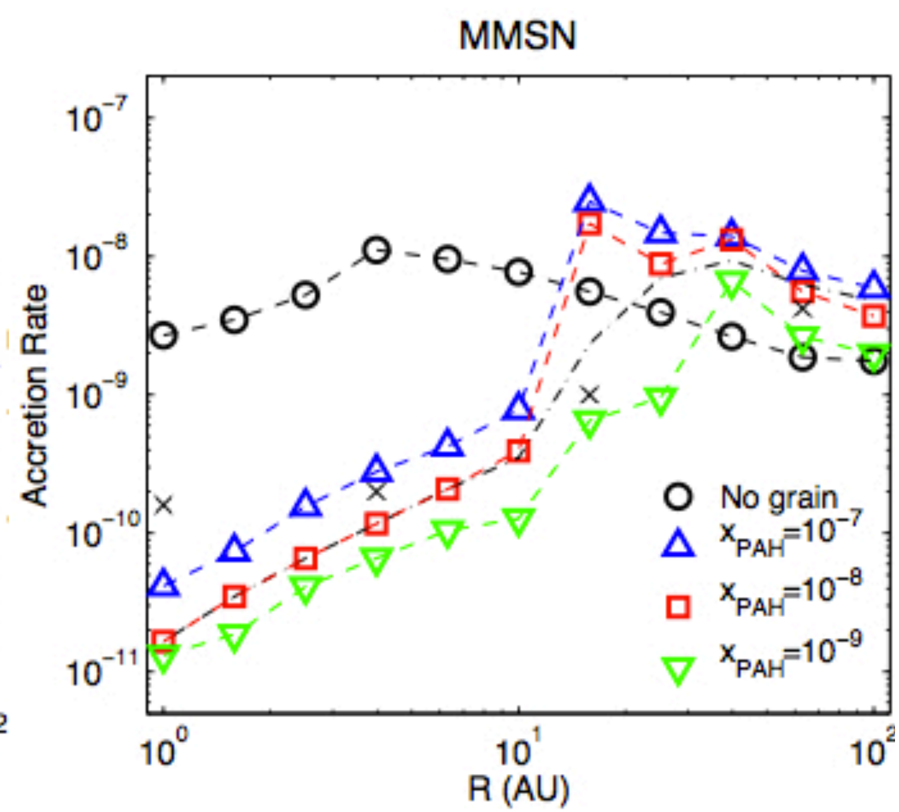
Need dM/dt here to prevent pileup in disk during infall!



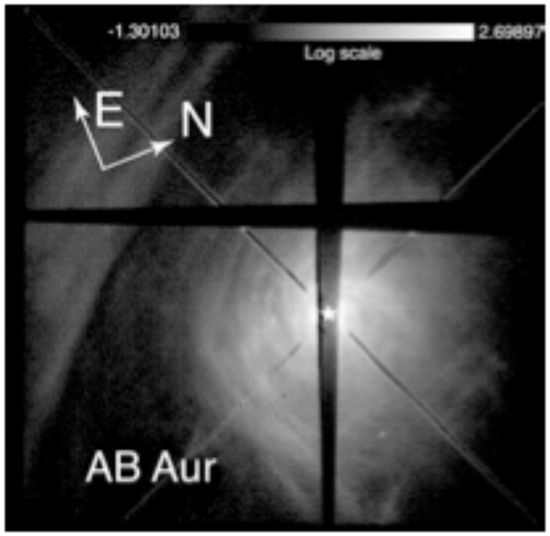
Need dM/dt
here to prevent
pileup in disk
during infall!

Xue-Ning Bai





Spiral arms? GI?



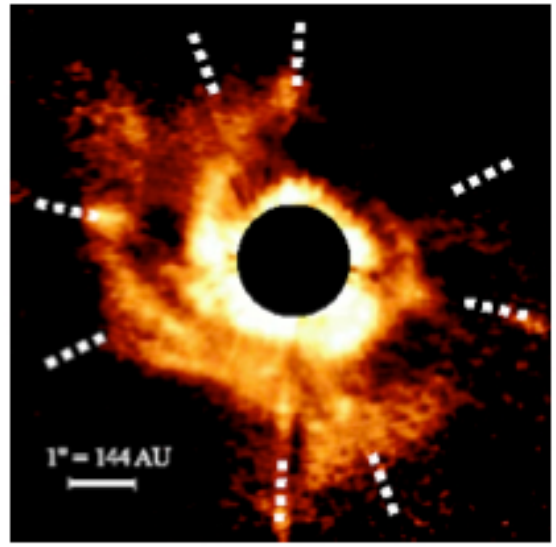


Fig. 8.2. Scattered light images of the Herbig Ae star AB Aur: left, optical image taken in coronagraphic mode with the STIS instrument on board HST (Grady et al. 1999, 2005), in a field of 25 arcsec square; right, near-infrared (H band) adaptive optics/coronagraphic image of AB Aur taken with the Subaru telescope (Fukagawa et al. 2004), spanning 8 arcsec square (about 110 AU). The disk is very extended and has suggestions of spiral structure (compare with Figure 7.9)

The criterion for gravitational instability in a disk can be explained by requiring the length scales over which gas pressure can resist collapse ($\sim$ Jeans length) to be smaller than the length scale beyond which angular momentum resists collapse. Alternatively, a perturbation of radius ΔR can grow if its self-gravity is greater than the tidal forces on the perturbation, i.e. the differential acceleration due to the central gravitating regions. Assuming most of the mass is in the central star,

$$\frac{GM}{R^2}\frac{\Delta R}{R} \sim \pi G\Sigma\frac{\Delta R}{R} < \frac{G\Delta M}{\Delta R^2} = \pi G\Sigma\,, \tag{1}$$

so that

$$\Delta R < \pi G\Sigma\frac{GM}{R^3} = \pi G\Sigma\Omega^{-2}\,. \tag{2}$$

Now, ΔR must be larger than the disk thickness (i.e., the scale height H) to satisfy the Jeans criterion, because by construction the gas pressure can support the disk against its own self-gravity in the z direction. Assuming that the disk self-gravity does not markedly change the rotation from Keplerian values,

$$\frac{c_s}{\Omega} = H < \Delta R\,. \tag{3}$$

Putting these two constraints together,

$$\frac{\Omega c_s}{\pi G\Sigma} < 1 \tag{4}$$

once again emerges as the criterion for gravitational instability.

It is straightforward to show using dimensional analysis arguments that instability requires a disk of mass M_d such that

$$M_d \ > \ \eta \frac{H}{R} M_* \, , \tag{5}$$

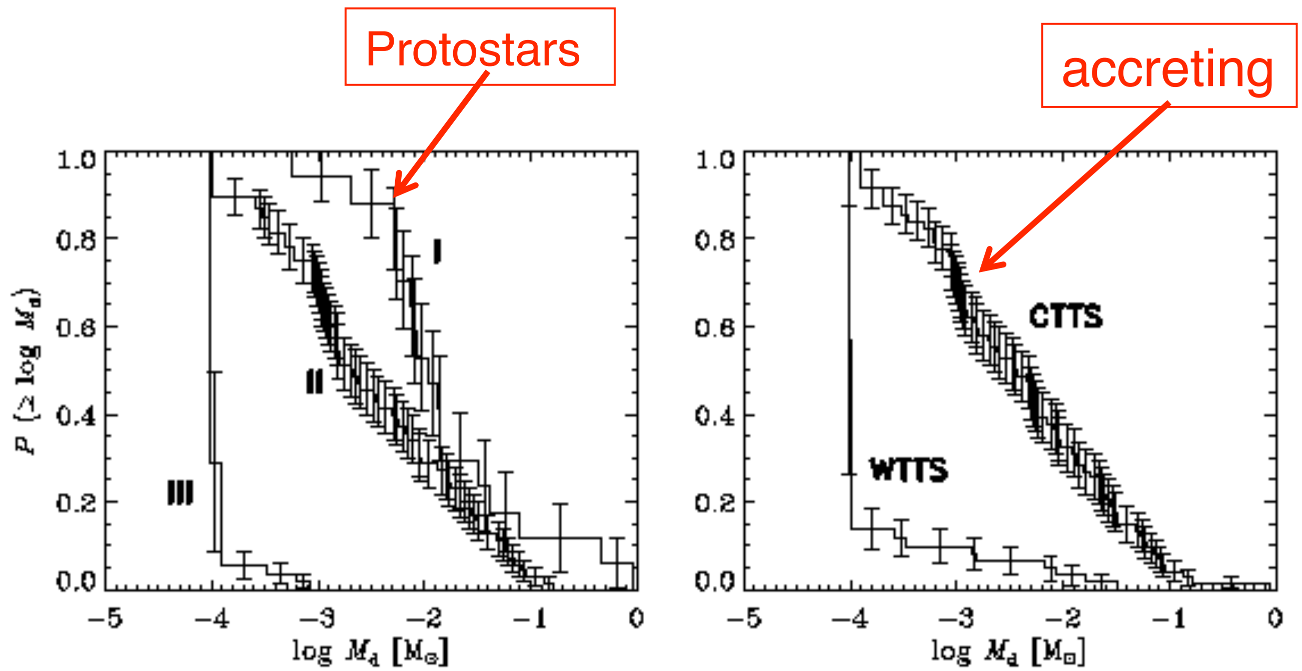
where H is the disk scale height, and η is 1-3, depending upon conditions.

need massive disk, M(d) >~ 0.1 M(star)

Disk masses from dust emission

850μm fluxes (Taurus)

Andrews & Williams 2005



median “mass” (100x dust) ≈ 0.01 Msun ~ 10 M(J)

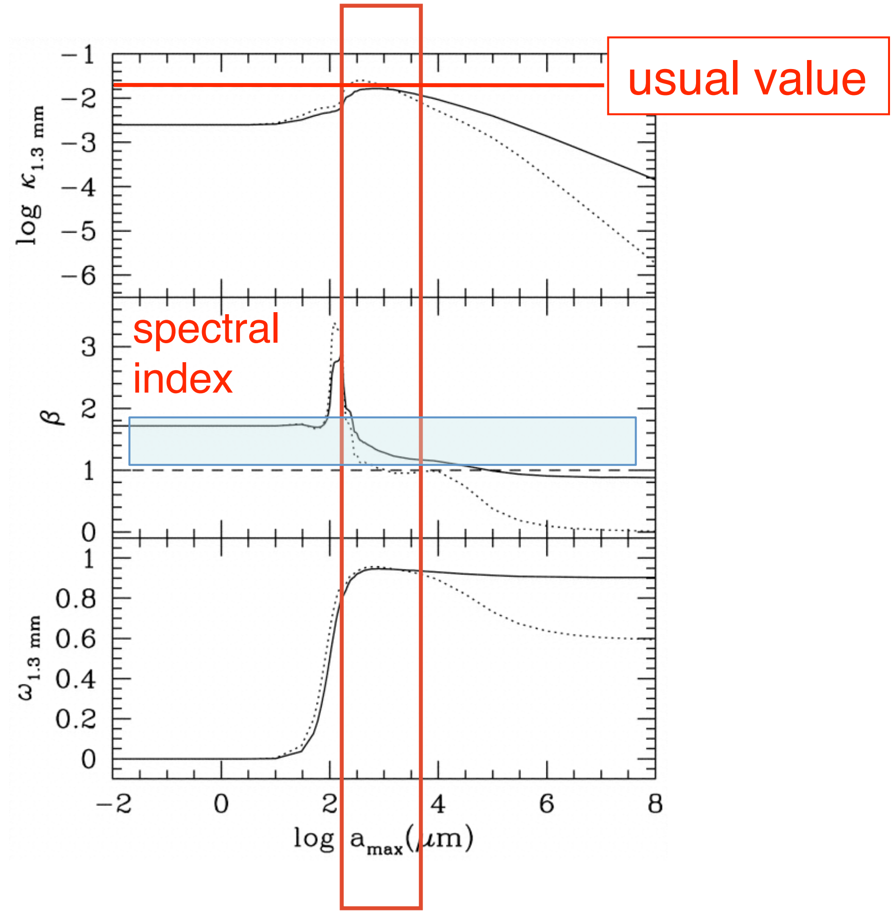
→ not gravitationally unstable!

The dust opacity problem

Observed spectral slopes imply that dust must grow from ISM sizes;

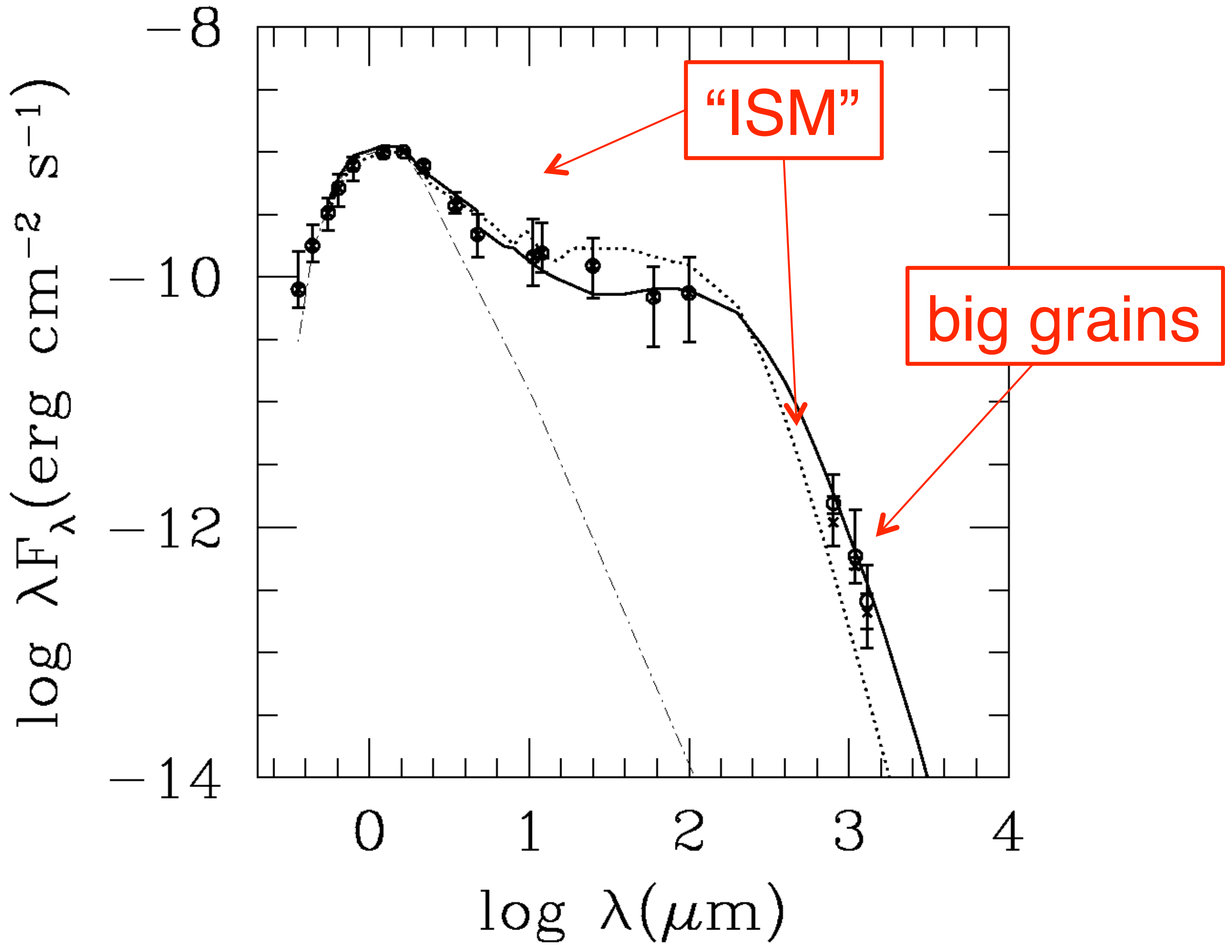
if growth is does not stop at ~ few cm, opacities per unit mass are LOWER than typically adopted – disk masses are then larger than usually estimated

basically, we observe the mass in mm-sized grains



Mie calculation for power-law size distribution to a(max); D'Alessio et al. 2001

Grain growth for mm-wave emission but not at 10 μm ⇒ upper layers have small dust (<~ 1μm)

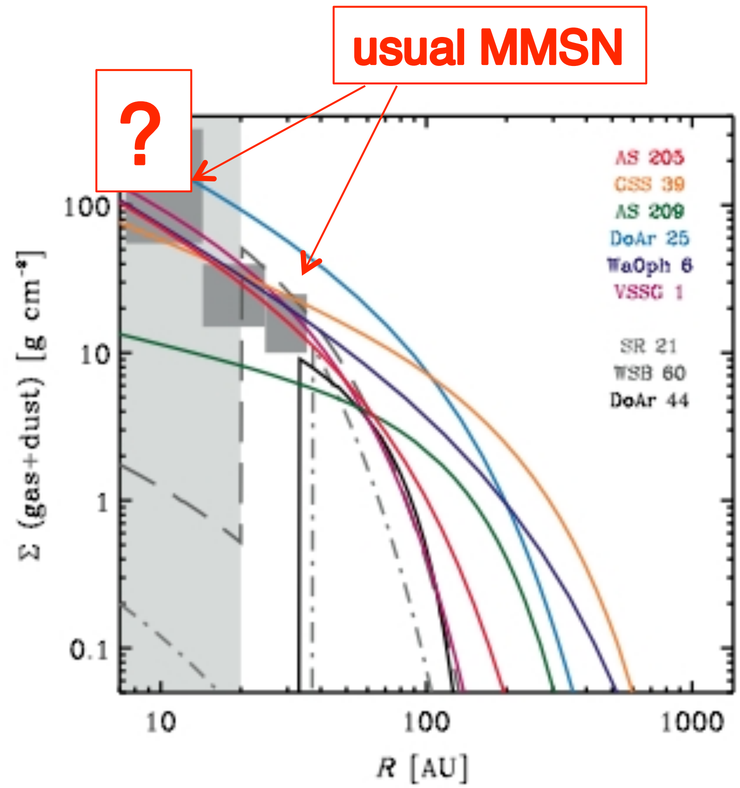


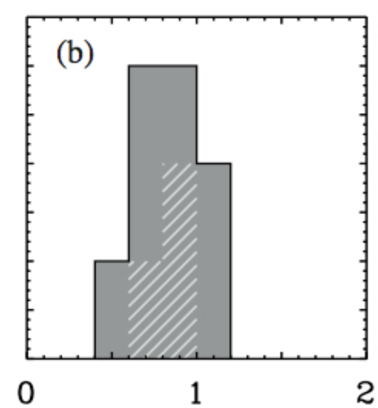
D'Alessio et al. 2001

Where is the mass?

Conventional models (MMSN) yield $\Sigma \propto R^{-p}$, $p \sim 1.5 - 0.4$, $\langle p \rangle \sim 0.8$:
$\Rightarrow$ most mass at large R

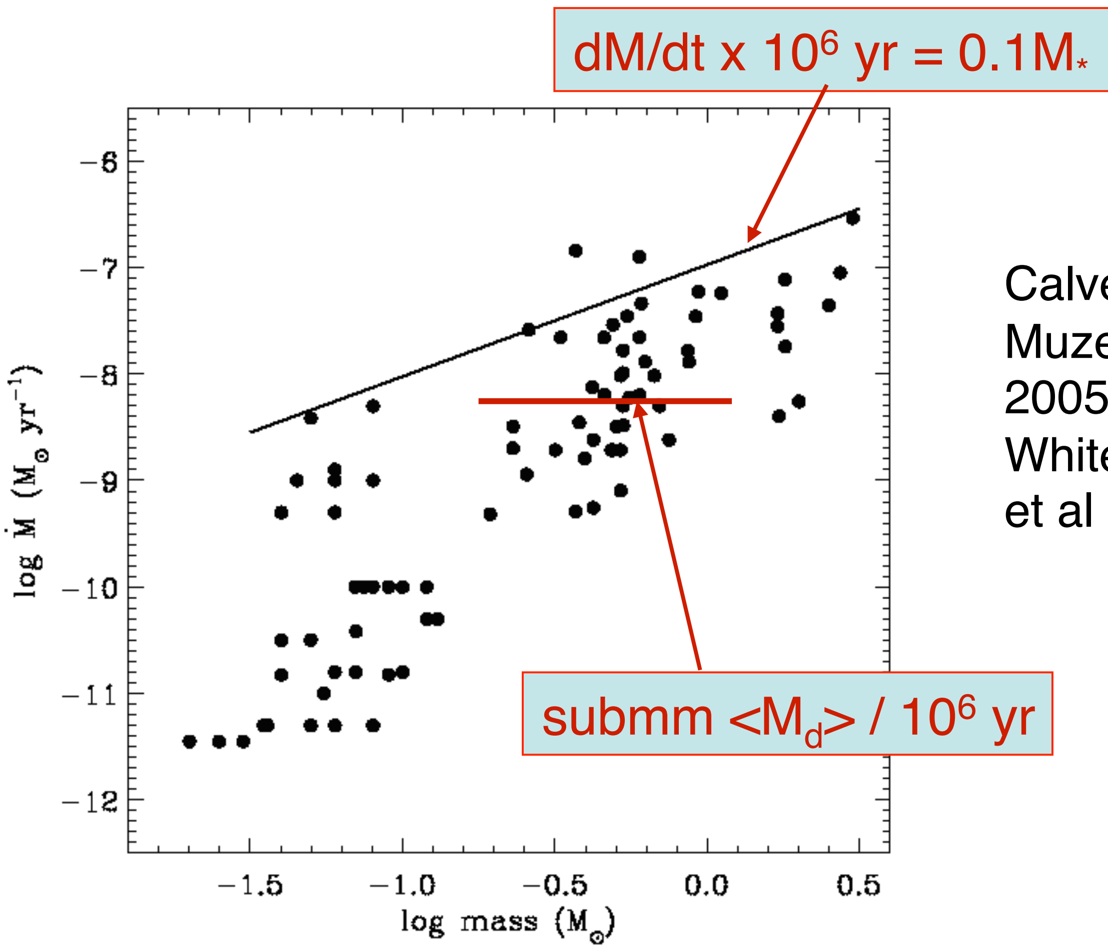
Best we can do: however
- can't resolve R< 10 AU
- either optically thick (unless strong dust growth) RIGHT WHERE THE DEAD ZONE WOULD BE!





Andrews et al. 2009

Disk accretion: statistical measure of gas



⇐ ~ grav inst limit?

Calvet et al. 2004, Muzerolle et al. 2003, 2005, White & Ghez 2001, White & Basri 2003, Natta et al 2004

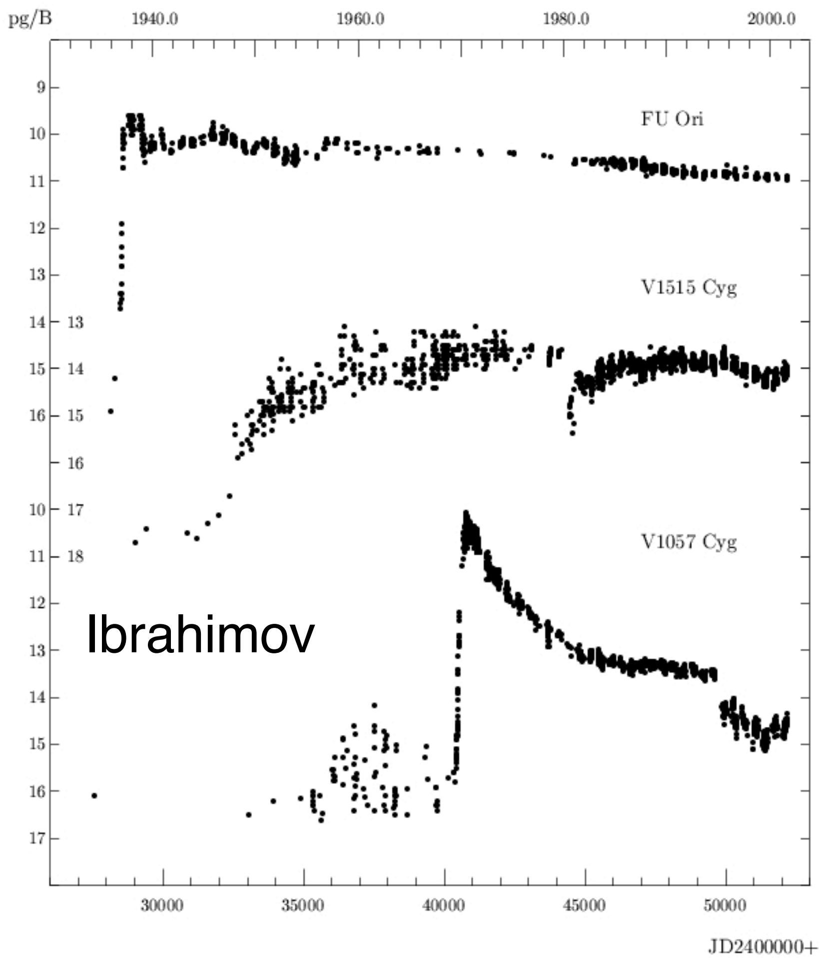
⇒ masses from dust emission may be underestimates if stars accrete most of their mass though disks... why aren't the disks very massive?

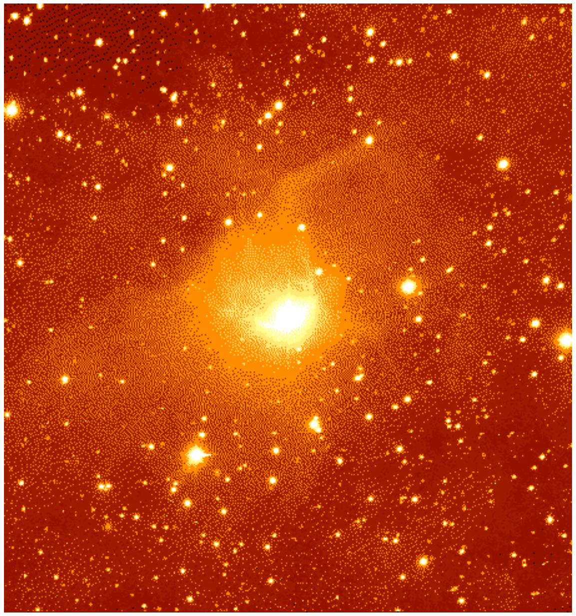
IF magnetic turbulence is well-established; then accretion onto the central star proceeds rapidly, draining the disk

but protoplanetary disks are cold, low ionization; accretion in disk may be driven by gravity, resulting in a massive disk

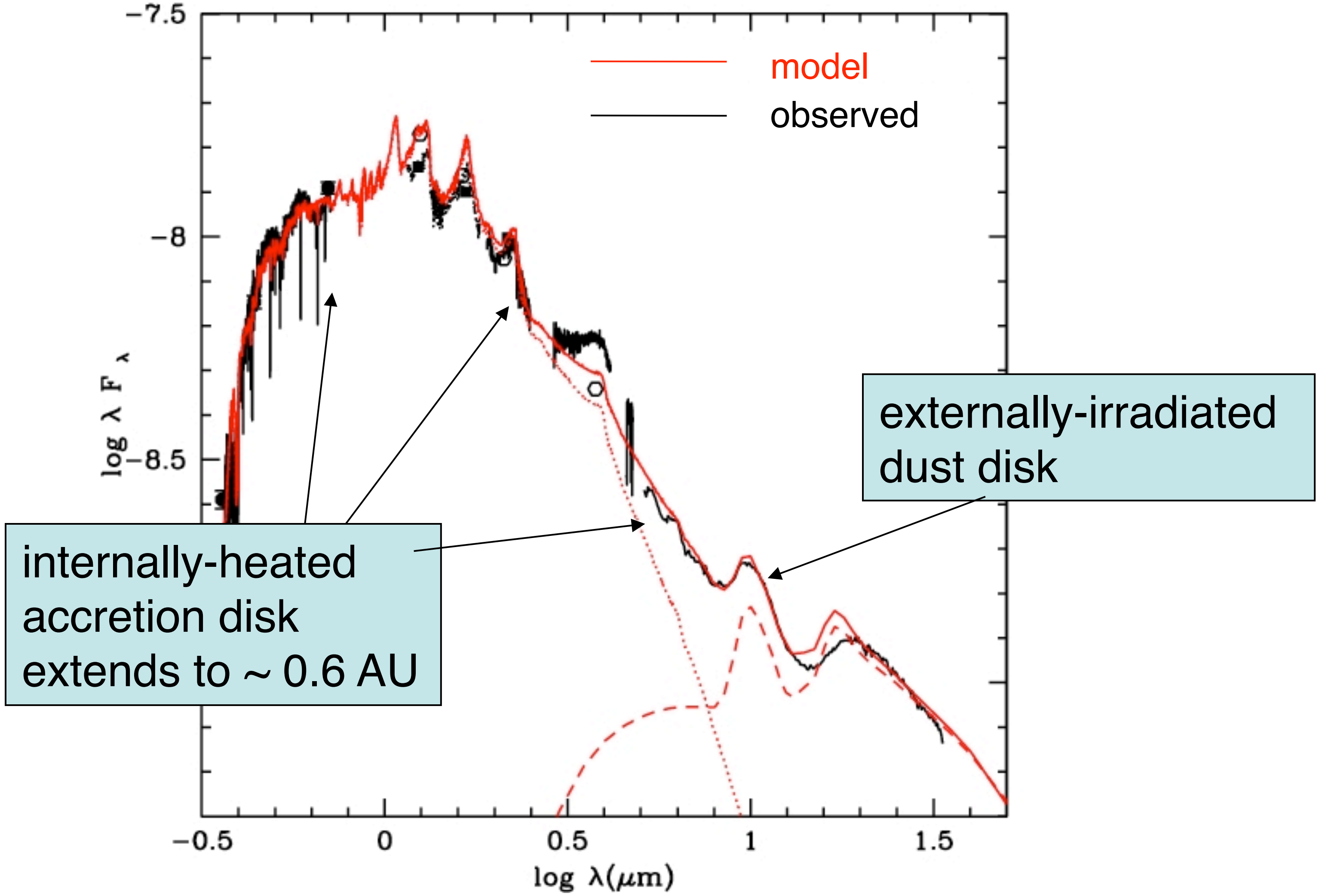
FU Ori objects: ~ 0.01 M(sun) accreted in ~ 100 years; very unlikely to be accreted from 100 AU in this time

⇒ large lump of material (> MMSN) at ≈ few AU, at least in protostellar phase





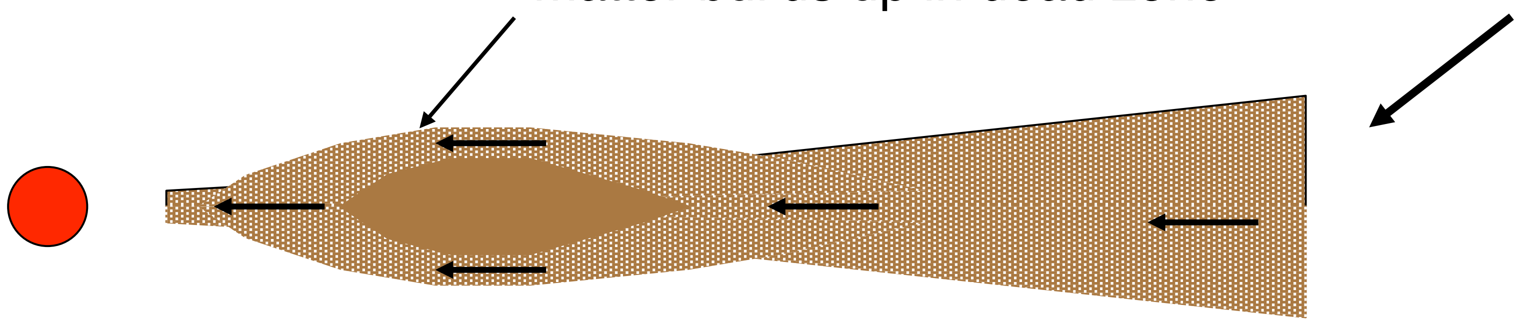
FU Ori: 10^{-4} M(sun)/yr accretion outburst; pure steady disk model (no boundary layer!)



Zhaohuan Zhu et al. 2007, 2008

Why outbursts? best guess so far; MRI - GI Instability
(Armitage et al. 2002; Zhu et al. 2009)

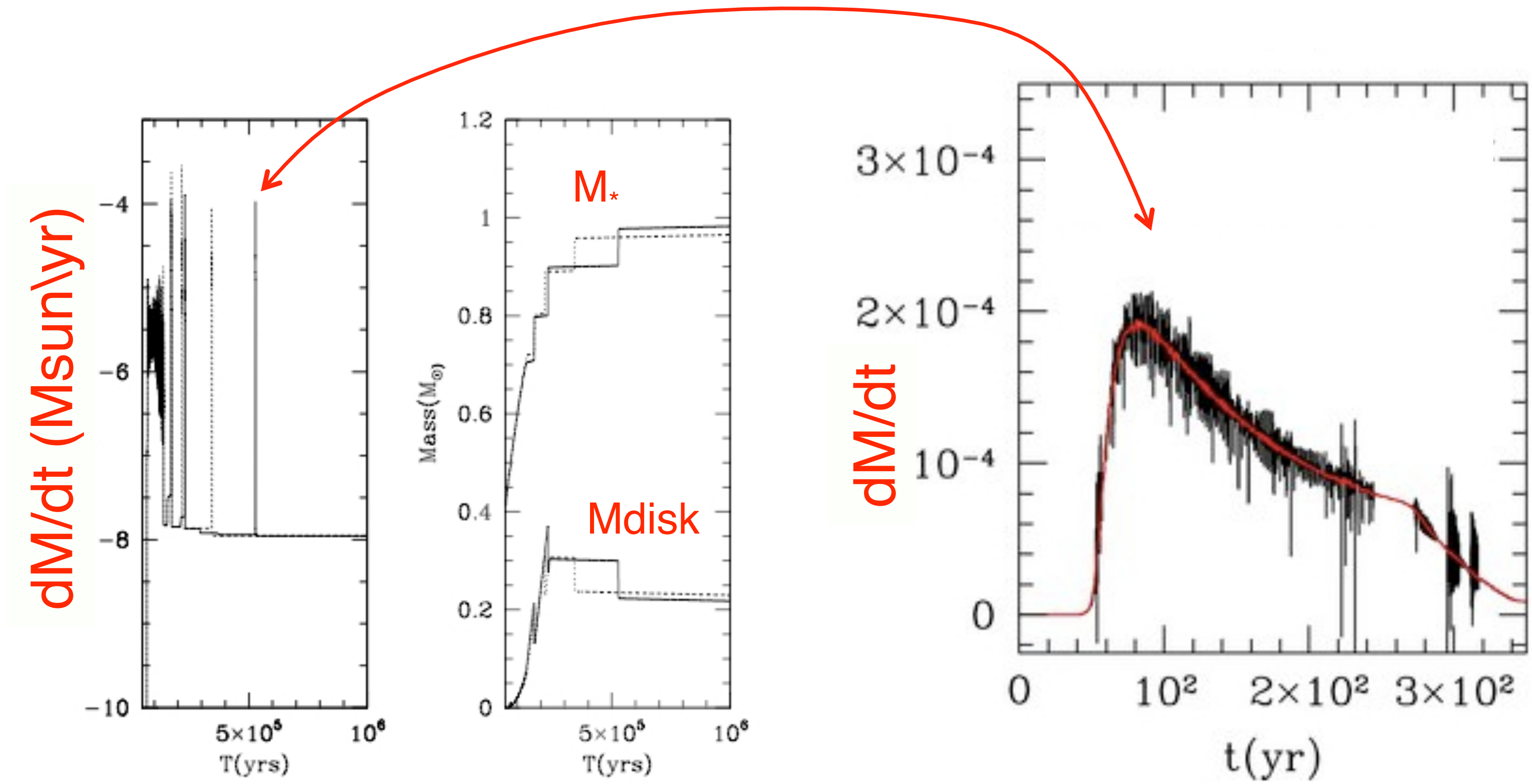
(alternative Vorobyov & Basu 2005+; accrete self-gravitating clumps made by GI + cooling)



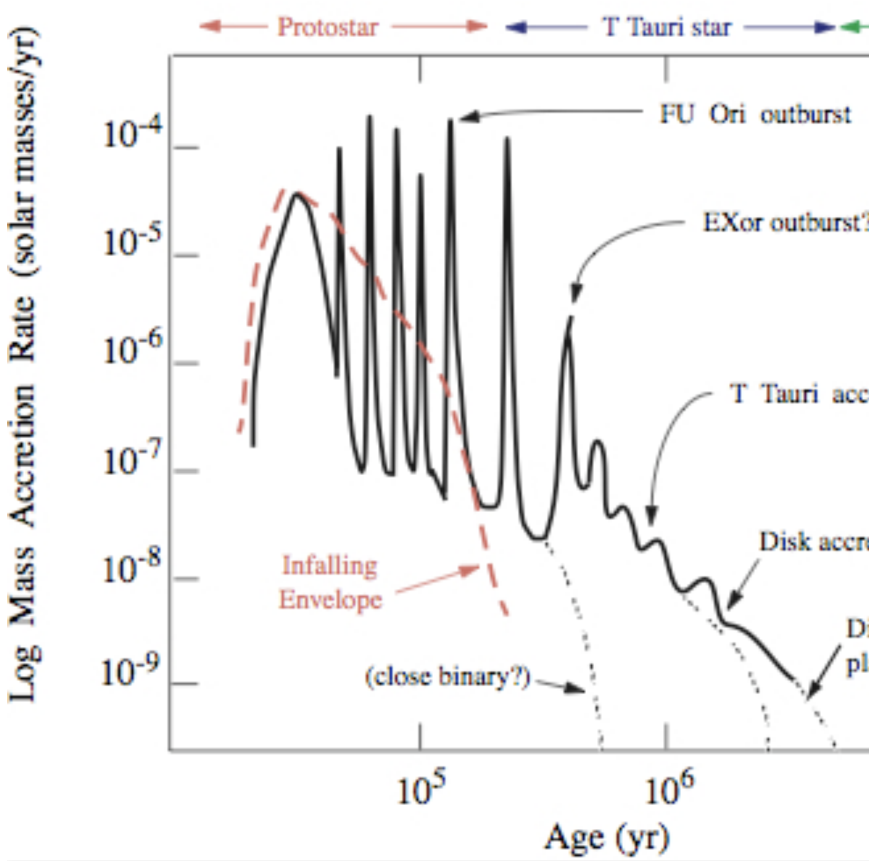
1. matter comes in from outer disk (via MRI/gravitational instability)
2. piles up in inner disk because MRI is not sufficiently active - too cold!
3. with some dissipation at high Σ, T increases - *thermal* activation of MRI
4. inward cascade of material driven by sudden increase in viscosity

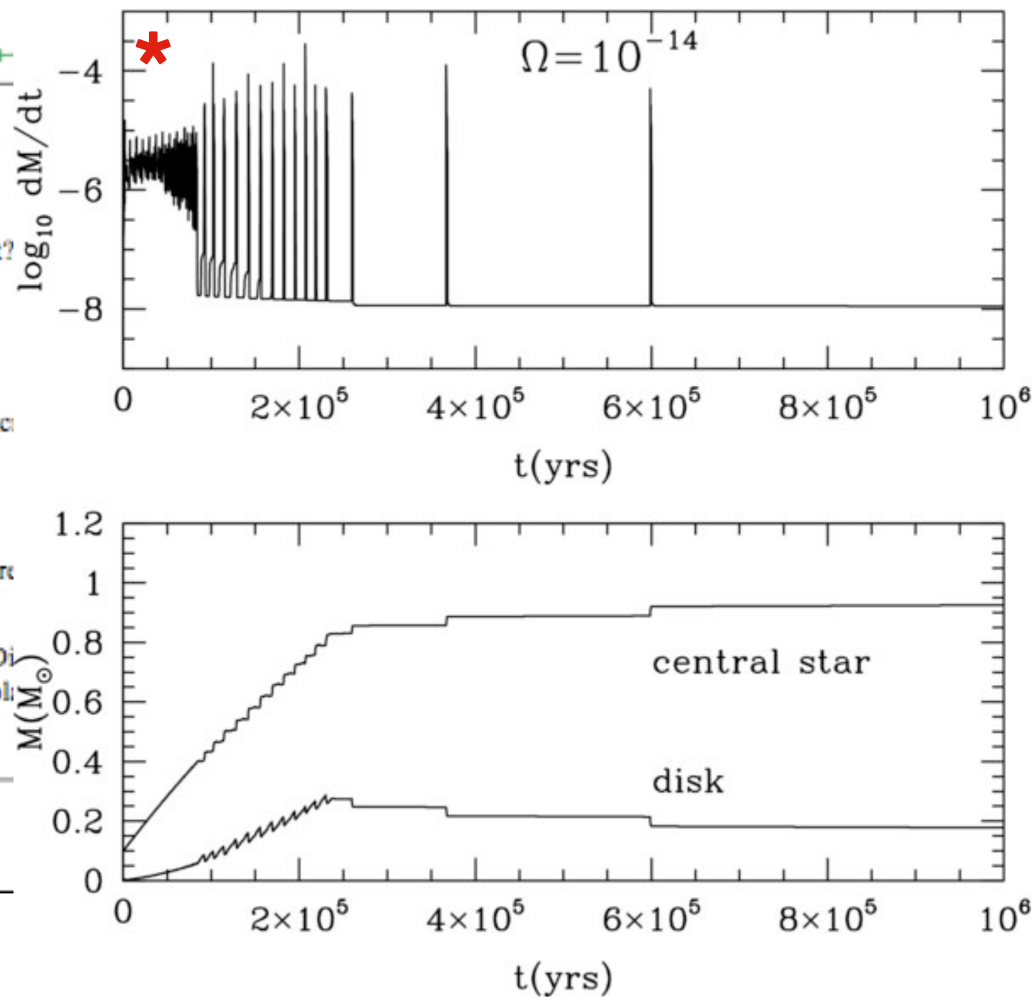
Zhu et al. 2008, 2009, 2010: outbursts during infall to disk

(also Armitage et al. 01, Vorobyov & Basu 05,6,7,8)



Timescale of outburst set by viscous time R^2/ν of accreting region; ~ AU

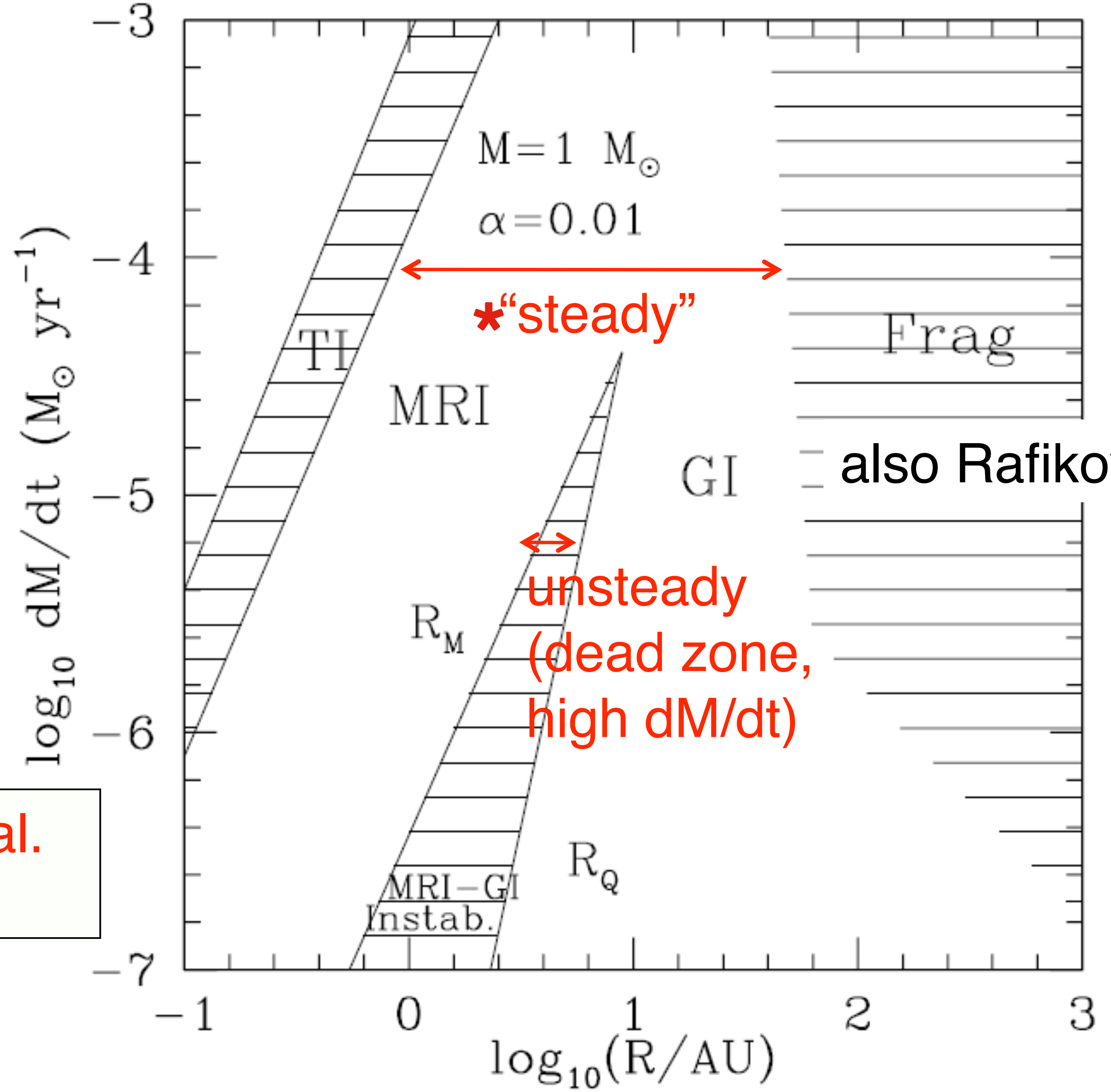




Evidence from luminosity function, outflows that accretion non-steady

Zhu et al. 2010: theory of accretion outbursts; driven by gravitational instability + magnetic turbulence

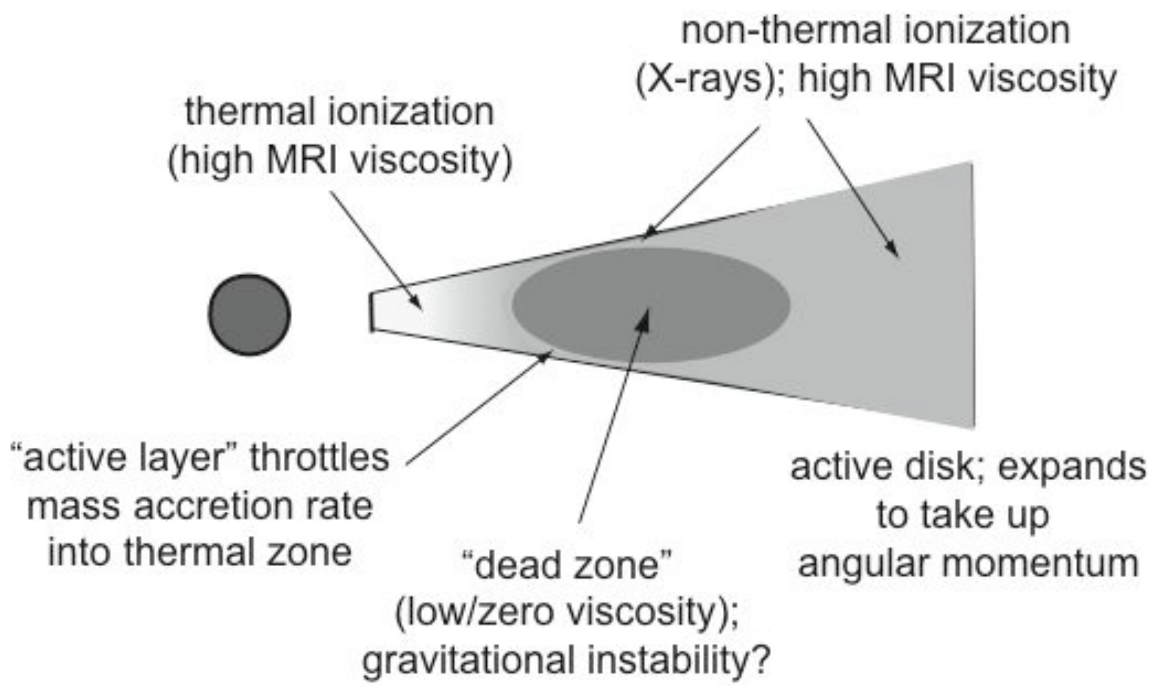
(c.f. Armitage et al. 2001)



also Rafikov 2005

Zhu et al. 2009b)

“Dead zone” (Gammie 1996)



Difficult to explain FU Ori outburst without something like a massive dead zone at ~ 1 AU

Angular momentum transport or gravitational fragmentation?

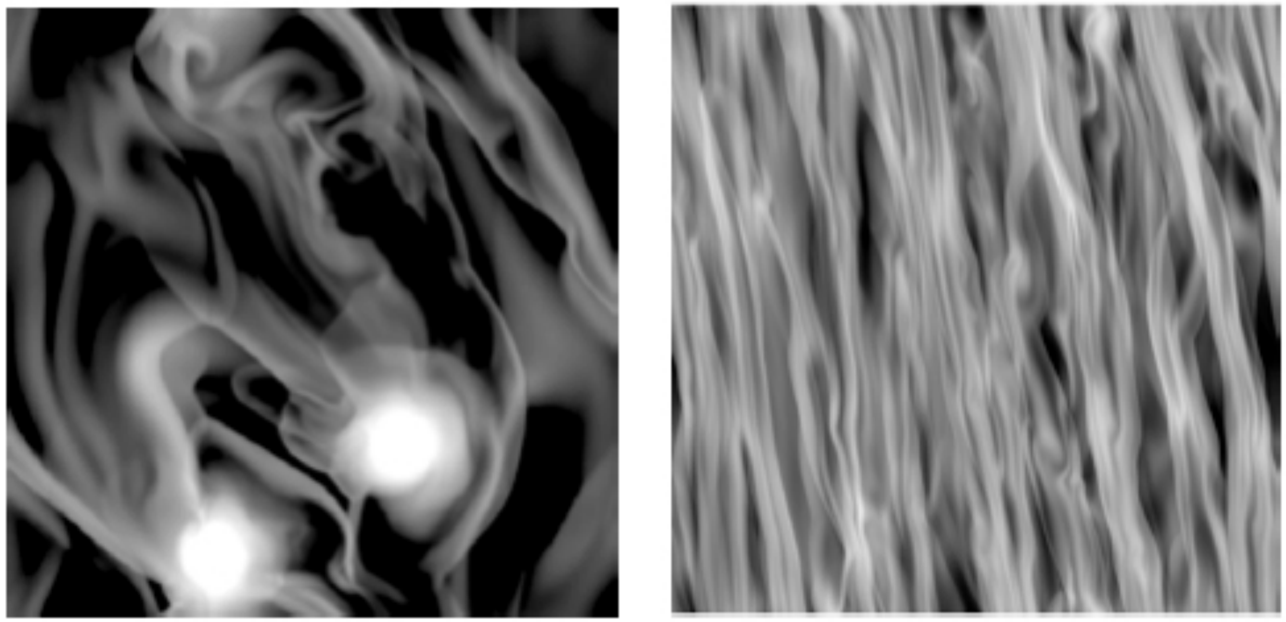
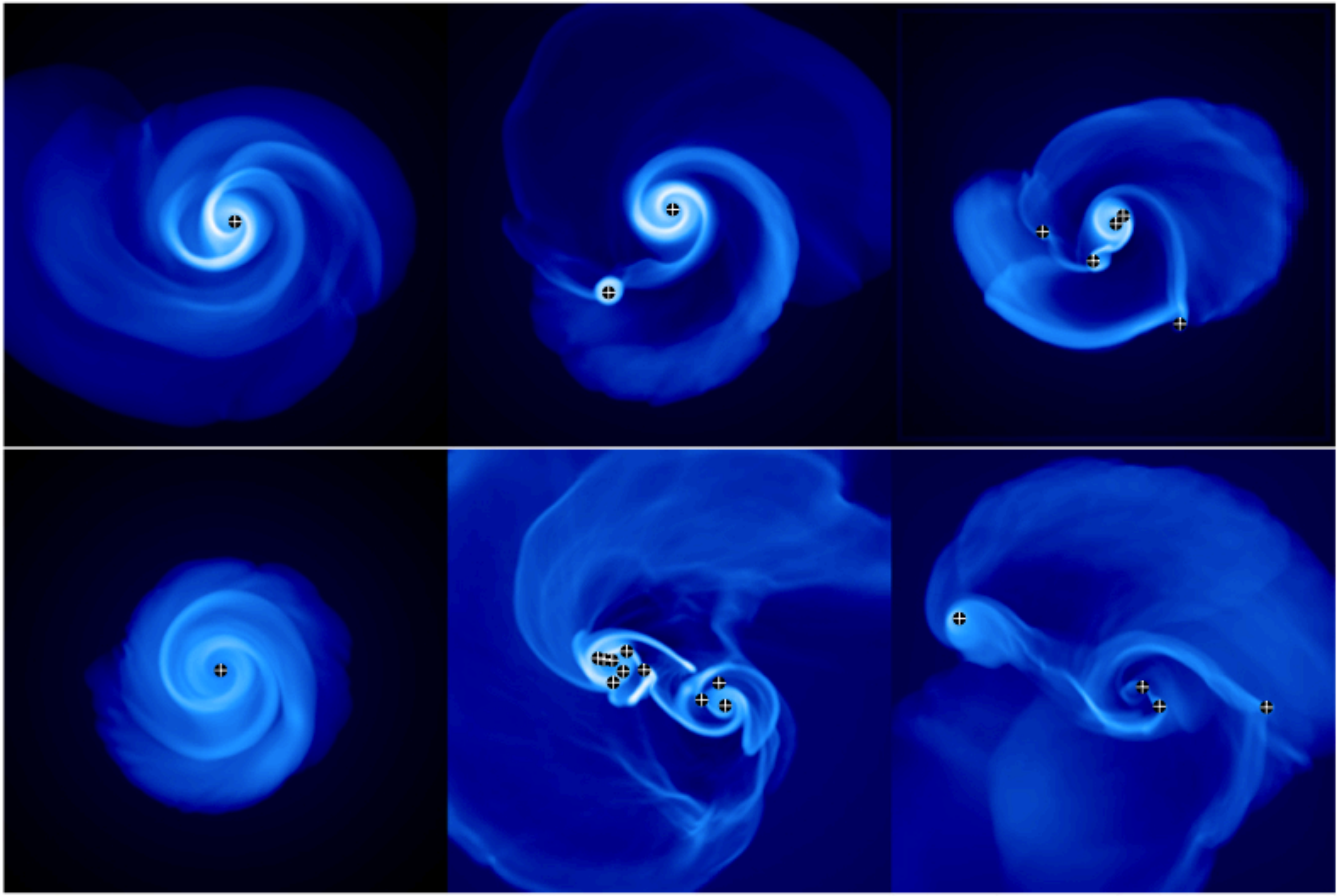


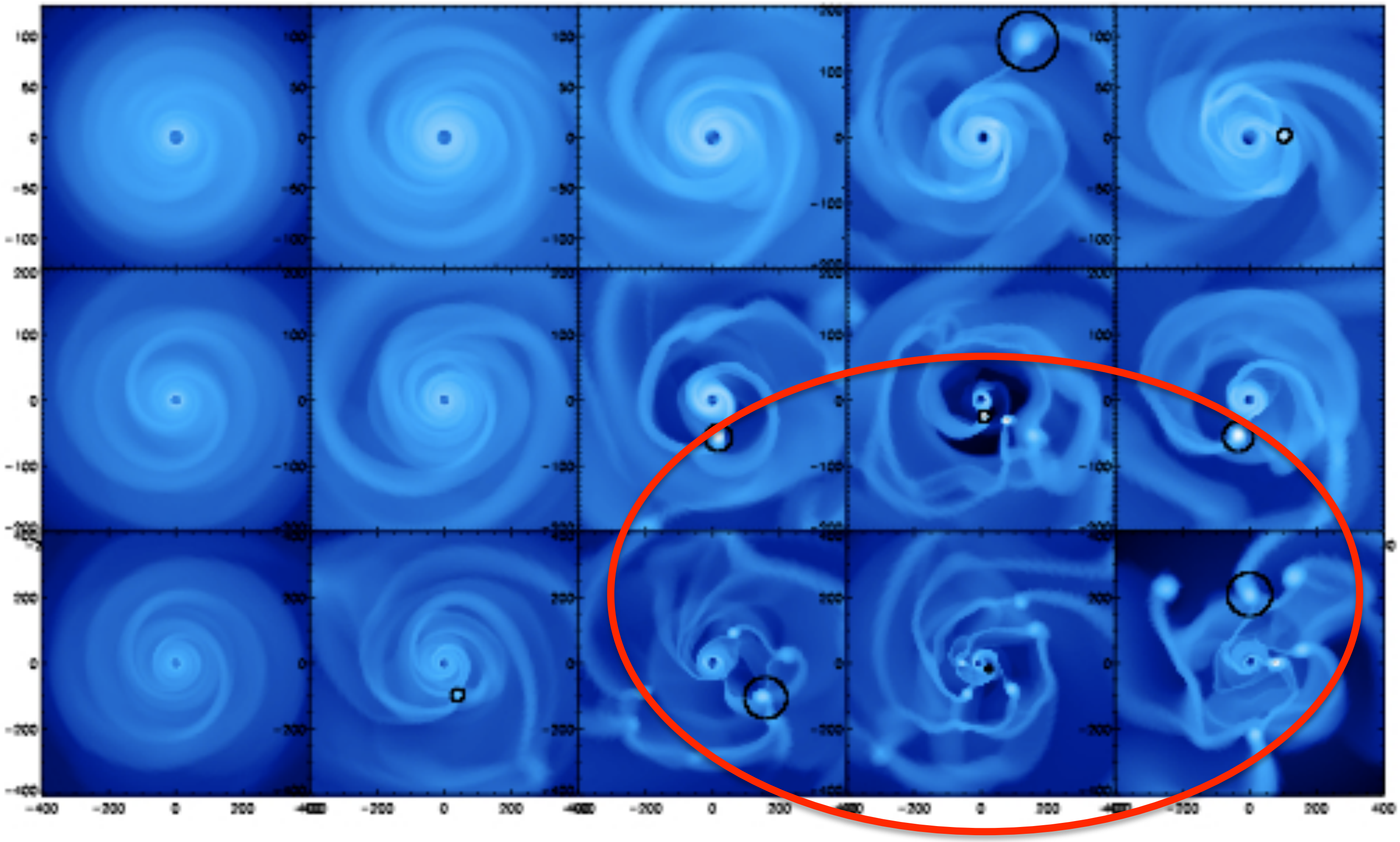
Fig. 7.8. Surface density maps for a shearing box simulation of a thin disk. Left panel: gravitational fragmentation results for a short cooling time ($t_c = 2\Omega^{-1}$). Right panel: a quasi-steady pattern of turbulence present for a long cooling time ($t_c = 10\Omega^{-1}$). The direction of rotation is from bottom to top. From Gammie (2001).

criterion for fragmentation; clump can cool in something less than an orbital time (also Rice et al. 2003)

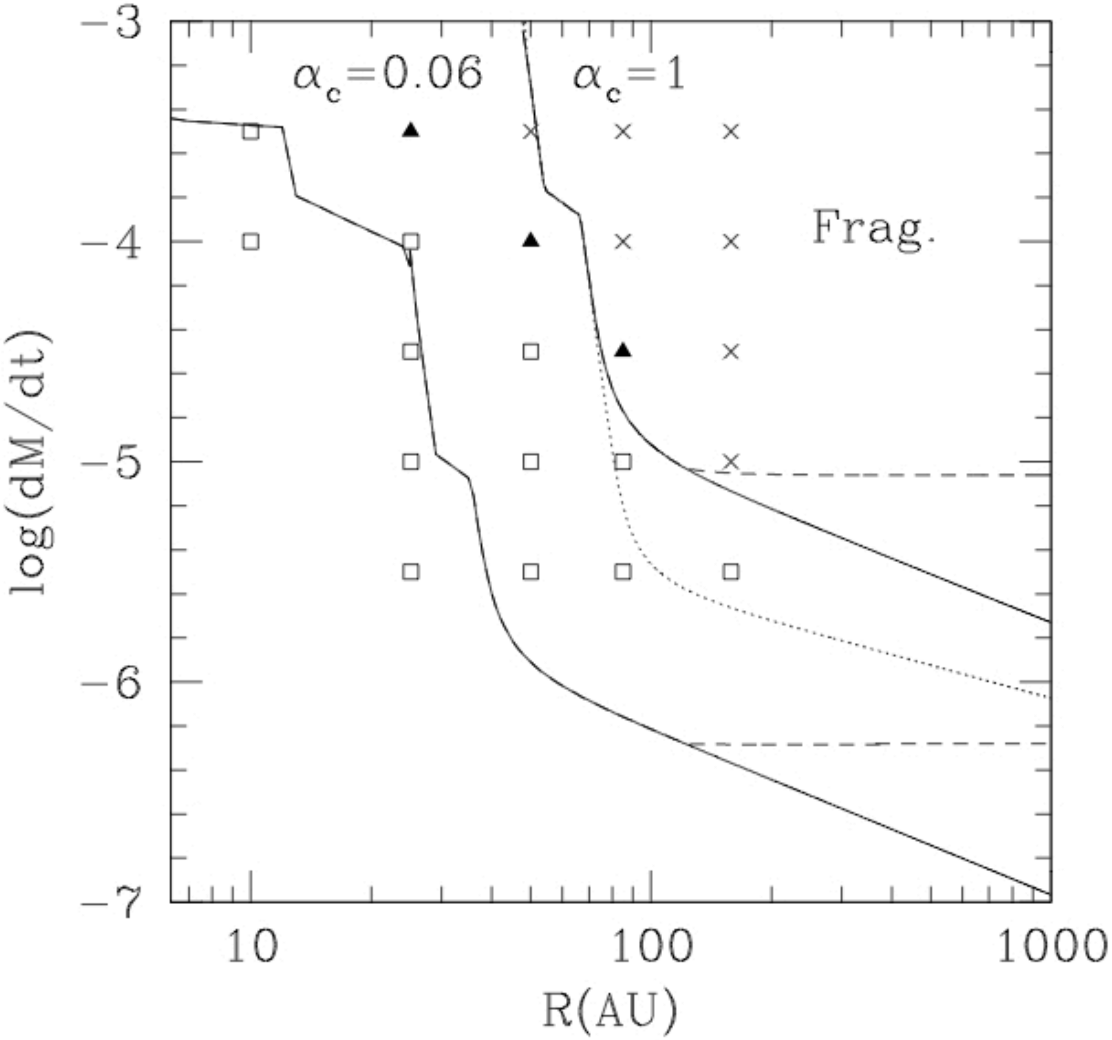


increasing dM/dt (infall) →

← increasing infall radius

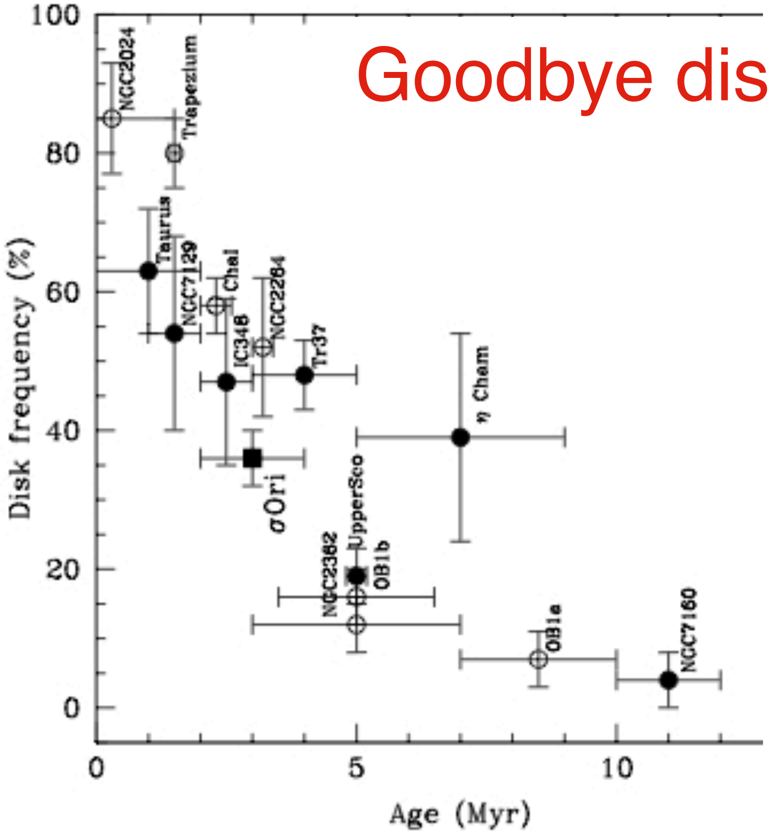


Zhu et al. 2010, in preparation



Zhu et al. 2011, in prep

Goodbye disks!



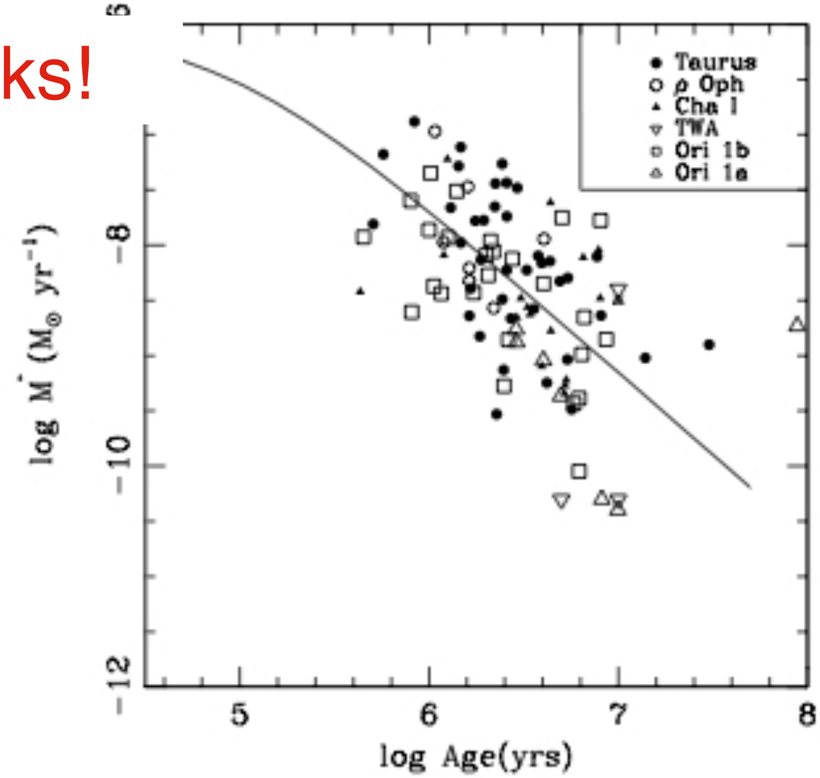
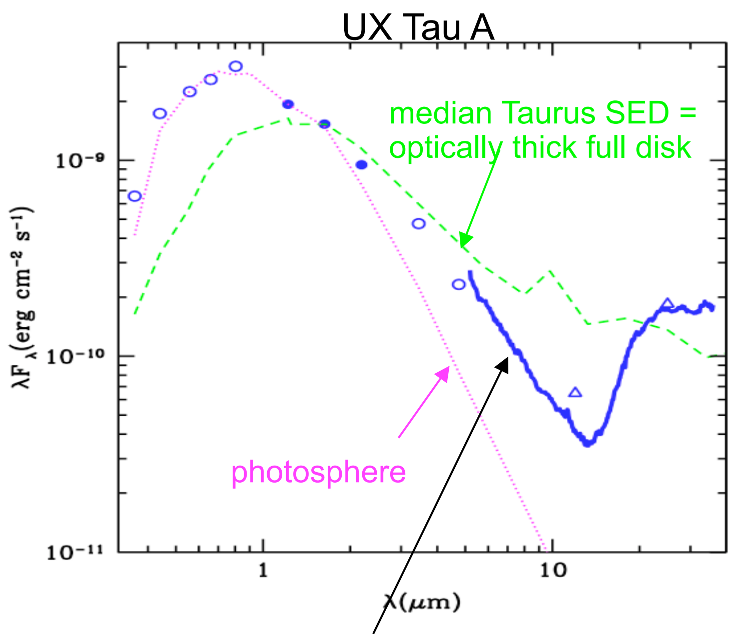


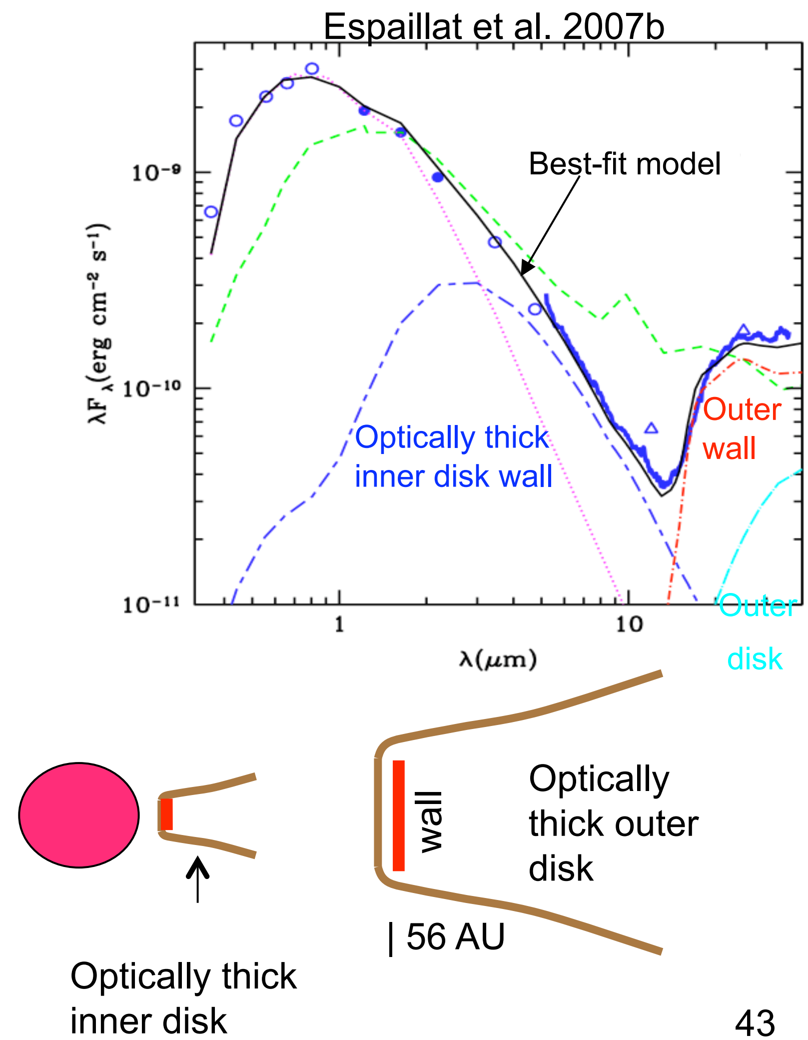
Fig. 12.1. Fraction of stars with near-infrared disk emission as a function of the age of the stellar group. Open circles represent the disk frequency for stars in the T Tauri mass range, derived using JHKL observations: NGC2024, Trapezium, NGC2264 and NGC2362 from Haisch et al. (2001), Chamaleon I from Gomez & Kenyon (2001), and Orion OB1a and OB1b sub-associations from Hernandez *et al.* (2005). Solid symbols represent the disk frequency calculated for stars in the TTS mass range using IRAC data: Taurus from Hartmann *et al.* (2005), NGC7129 from Gutermuth *et al.* (2004), IC348 from Lada *et al.* (2006), Tr 37 and NGC7160 from Sicilia-Aguilar *et al.* (2006), Upper Scorpius from Carpenter *et al.* (2006), η Chameleontis from Megeath *et al.* (2005a), and the σ Orionis cluster. Modified from Hernandez et al. (2007).

IR excess+
dM/dt vs. age

Pre-Transitional Disks: optically thick disks with gaps



large excess,
~optically thick
disk



Disk dust can “disappear” by forming large bodies… but what about the gas? Need to remove it!

• accretion – too slow
• too much (giant) planet migration, accretion

solution – photoevaporation (Armitage, Clarke, Owen, Ercolano, Gorti, Hollenbach…

problem – sensitive to fairly uncertain parameters (in LH opinion) – factors of a few in dM/dt make a difference (along with how much M(disk) one needs to get rid of)

c_s (10^4 K) ~ v(escape)

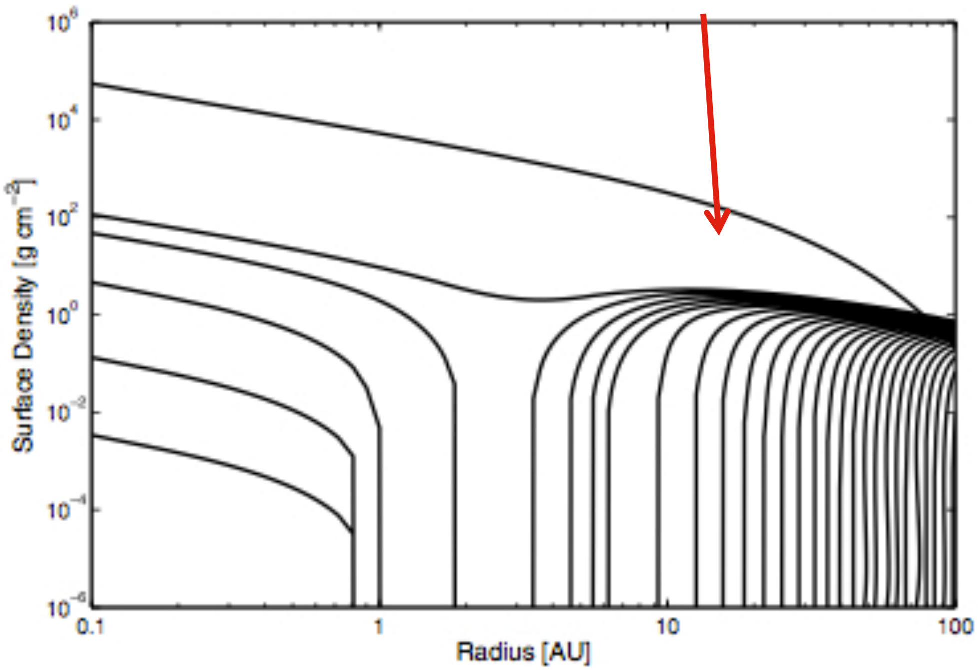


Figure 9. The evolution of the disc's surface density during the disc clearing phase. The first line shows the zero time surface density profile, the next shows the profile at 75 per cent of the discs lifetime (~3.5 Myr) and the remaining lines show the surface density at 1 per cent steps in disc lifetime.

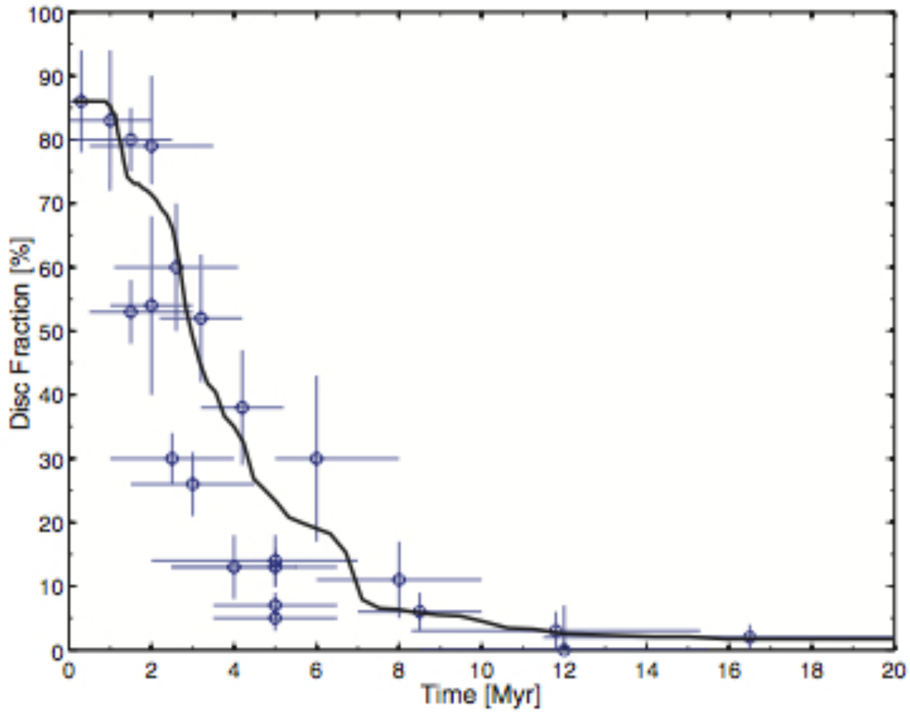
Owen et al. 2011; X-ray photoevaporation

get maximum effect from just inside escape radius due to radial falloff of X-rays (because " ionization parameter" = $L_{X(}/n\ r^{2)}$

Make gap! when dM/dt(evap) > dM/dt(accretion)

evolution accelerates once there is a directly illuminated gap wall

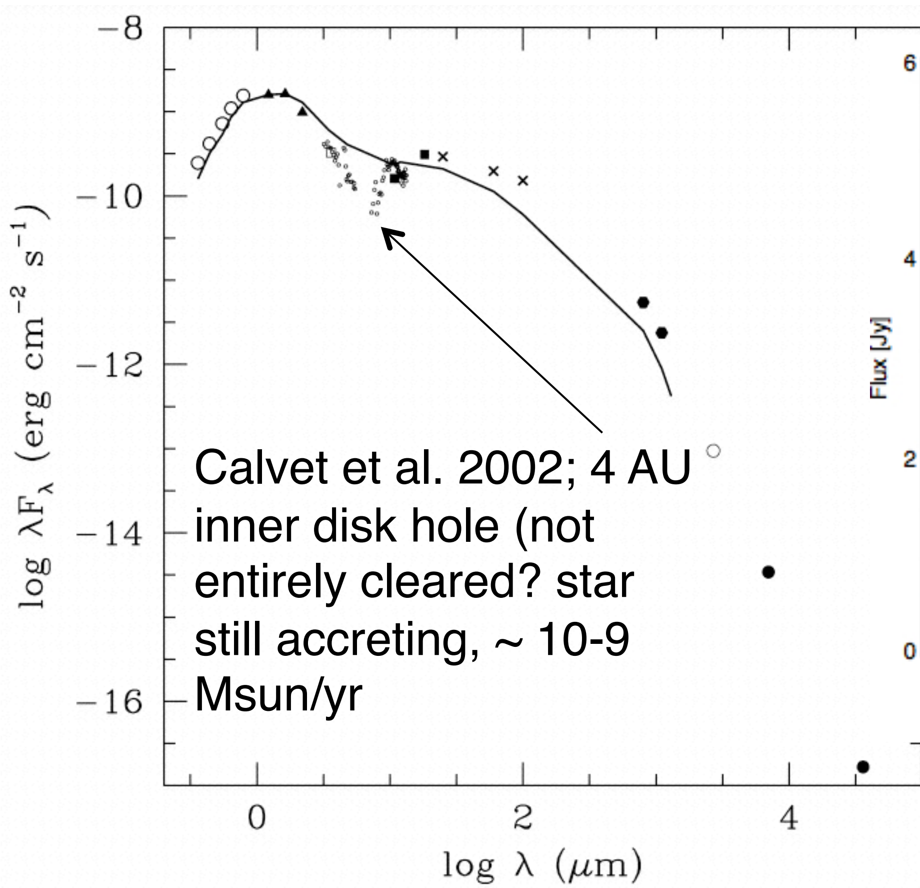
claim this can explain some but not all transitional disks



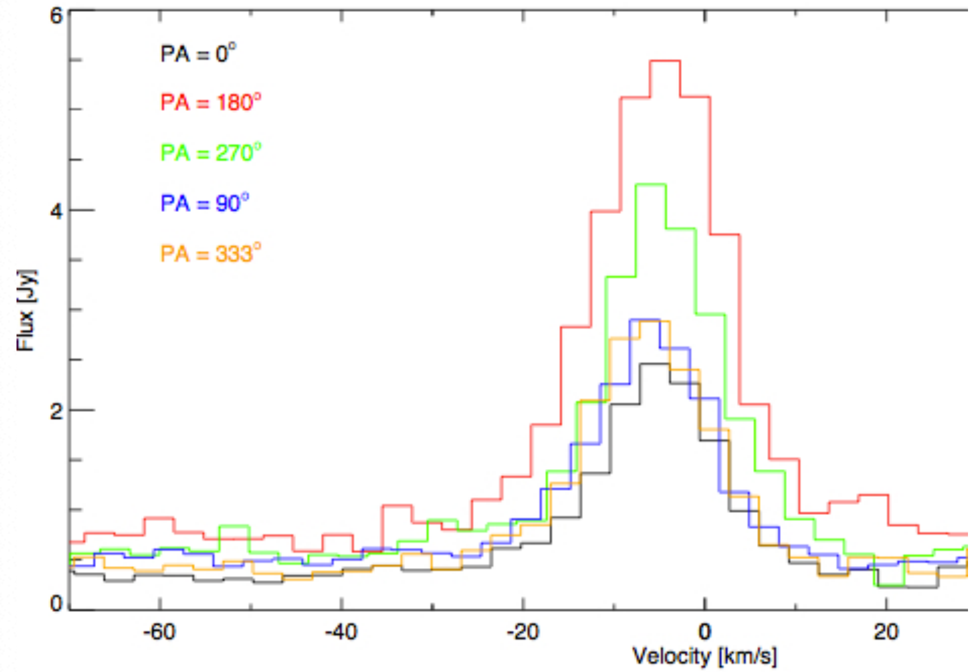
Owen et al. 2011; claim that X-ray photoevaporation can explain disk clearing timescales

But; this assumes fully viscous disks at $\alpha \sim 0.01$ and something like MMSN at the start. If low alpha – dead zone, not what is clearing the (inner) disk.

TW Hya; can we observe the photoevaporative flow directly to calibrate loss rates?



Calvet et al. 2002; 4 AU inner disk hole (not entirely cleared? star still accreting, ~ 10-9 Msun/yr



Pascucci et al. 2011; [Ne II] blueshifted, wind; but [O I] not, indicates low dM/dt (~ 10^{-10} msun/yr)… ?

bottom line; probably photoevaporation, but uncertain timescales by factors of several

My guesses:

photoevaporation (combination of X-rays and FUV heating) empties out gas (and some dust) from outer disk (>~ 10 AU), where disk MIGHT be more viscous, and thus lower surface density

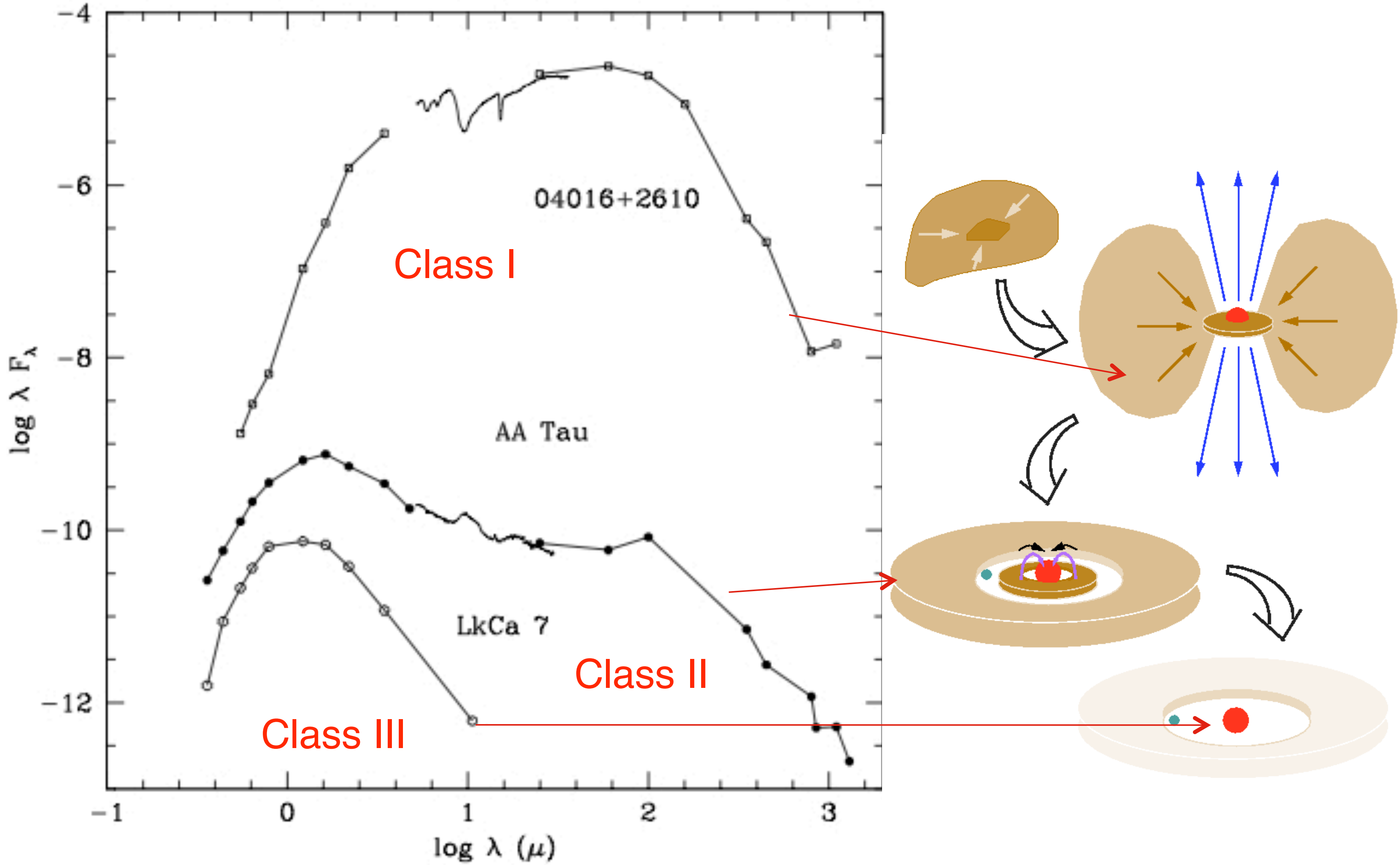
viscous (accretion) too slow to get rid of the gas

but there are dead zones, and photoevaporation will prevent adding mass, but not ridding it.

must accrete onto something.

N.B.; some of the transitional disk holes are LARGE (~ 50 AU); rapid evolution at by <~ 3 Myr.

Supplemental material



04016+2610
Class I
AA Tau
LkCa 7
Class II
Class III
log λ F_λ
log λ (μ)

Consider a thin disk composed of particles moving essentially on circular orbits in a single plane. We suppose further that any radial motions are small and that radial pressure forces are negligible, so that the orbital motion of the disk is due entirely to equating the centripetal acceleration with gravity. Then, adopting cylindrical polar coordinates (R, ϕ, z), the circular velocity resulting from a gravitational potential $\Phi(R)$ is

$$\frac{v_\phi^2}{R} = \frac{d\Phi}{dR} . \tag{7.9}$$

The equation of mass conservation for an annulus of width ΔR at R, denoting the surface density of the disk again by Σ, is

$$\begin{aligned} \frac{\partial}{\partial t}(2\pi R \Delta R \Sigma) &= v_R(R,t)\, 2\pi R \Sigma(R,t) \\ &\quad - v_R(R + \Delta R, t)\, 2\pi (R + \Delta R) \Sigma(R + \Delta R, t) \end{aligned} \tag{7.10}$$

where v_R is the *net* radial velocity of the material. (In a turbulent viscosity model, the turbulent velocity w may be much larger than v_R, but the turbulent motions do not represent a net mass flux; §7.1.) The first term on the right-hand side of equation (7.10) is the flow of material into the annulus and the second term is the flow out. Taking the limit for small ΔR, one obtains

$$R \frac{\partial \Sigma}{\partial t} + \frac{\partial}{\partial R}(R \Sigma v_R) = 0 . \tag{7.11}$$

Similarly, the equation for conservation of angular momentum can be written as

$$R \frac{\partial}{\partial t}(\Sigma R^2 \Omega) + \frac{\partial}{\partial R}(R \Sigma v_R R^2 \Omega) = -\frac{1}{2\pi} \frac{\partial g}{\partial R} . \tag{7.12}$$

The usual fluid mechanics definition of viscosity ν_v is

$$g = -2\pi R \Sigma \nu_v R^2 d\Omega/dR\,, \tag{7.13}$$

so that

$$\frac{\partial}{\partial t}(\Sigma R^2 \Omega) \;+\; \frac{1}{R}\frac{\partial}{\partial R}(\Sigma R^3 \Omega v_R) \;=\; \frac{1}{R}\frac{\partial}{\partial R}\left(\nu_v \Sigma R^3 \frac{d\Omega}{dR}\right)\,. \tag{7.14}$$

The mass conservation equation can be used to eliminate v_R, with the result that

$$\frac{\partial \Sigma}{\partial t} \;=\; \frac{1}{R}\frac{\partial}{\partial R}\left[\left(\frac{d\Omega R^2}{dR}\right)^{-1}\frac{\partial}{\partial R}\left(-\nu_v \Sigma R^3 \frac{d\Omega}{dR}\right)\right]\,. \tag{7.15}$$

In many cases of interest most of the mass is contained in the central spherical star, so that the gravitational potential is that of a central point mass, and the angular velocity takes on its Keplerian value, $\Omega = (GM/R^3)^{1/2}$. Then the diffusion equation (7.15) becomes

$$\frac{\partial \Sigma}{\partial t} \;=\; \frac{3}{R}\frac{\partial}{\partial R}\left[R^{1/2}\frac{\partial}{\partial R}(\nu_v \Sigma R^{1/2})\right]\,. \tag{7.16}$$

It is convenient to have an equation for the mass flux as a function of radius; because

$$\frac{\partial \Sigma}{\partial t} \;=\; \frac{1}{2\pi R}\frac{\partial \dot{M}}{\partial R}\,, \tag{7.17}$$

we have

$$\dot{M} \;=\; 6\pi R^{1/2}\frac{\partial}{\partial R}(\nu_v \Sigma R^{1/2})\,. \tag{7.18}$$

Steady disk results

$$\nu_v \Sigma = \frac{\dot{M}}{3\pi}\left[1 - \left(\frac{R_*}{R}\right)^{1/2}\right].$$

or

$$\alpha c_s H \Sigma = \frac{\dot{M}}{3\pi}\left[1 - \left(\frac{R_*}{R}\right)^{1/2}\right]$$

$$D(R) = \dot{E} = \frac{1}{2}\nu_v \Sigma \left(R\frac{d\Omega}{dR}\right)^2 = \frac{3GM\,\dot{M}}{8\pi R^3}\left[1 - \left(\frac{R_*}{R}\right)^{1/2}\right]. \qquad (7.53)$$

Are there enough FU Ori objects to accrete most of the stellar mass - solving the "luminosity problem"?

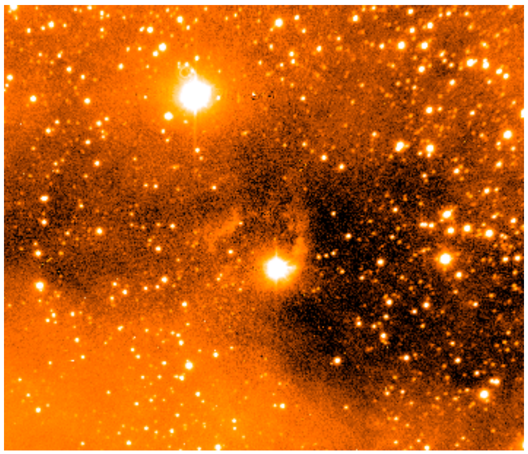
1. Current samples: ~ 10-15 objects, d < 1 Kpc;
   if all with $dM/dt \sim 10^{-4}\ M_\odot/yr$,
   $\sim 10^{-3}\ M_\odot/yr$ currently in high accretion phase;

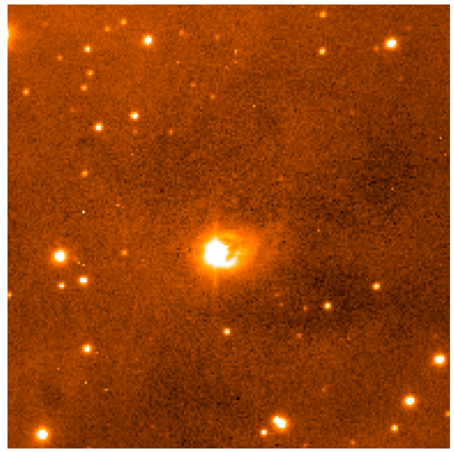
   Local star formation d < 1 Kpc;
   $dM_*/dt \sim 10^{-2}\ M_\odot/yr$,
   ~ 10 % of mass goes through FU Ori-type accretion

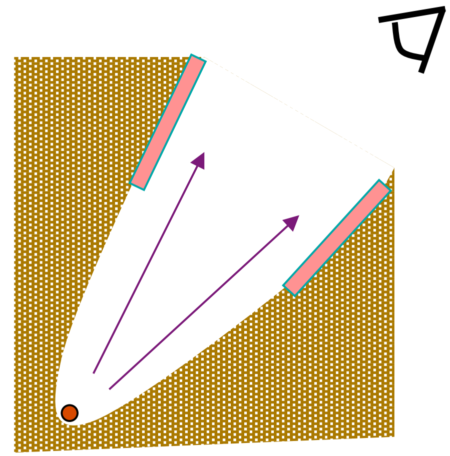
2. Source statistics (Orion Nebula Cluster);
   $\langle M \rangle \sim 0.3\ M_\odot$, $dM/dt \sim 10^{-4}\ M_\odot/yr \Rightarrow 3000$ yr
   $\langle t \rangle \sim 10^6$ yr $\Rightarrow$ 1/300 objects in accretion phase
   $N_* \sim 2000 \Rightarrow$ 7 FU Oris; where are they?

Possible solutions to FU Ori statistics:

1. dM/dt; we miss many heavily extincted (Class 0) objects



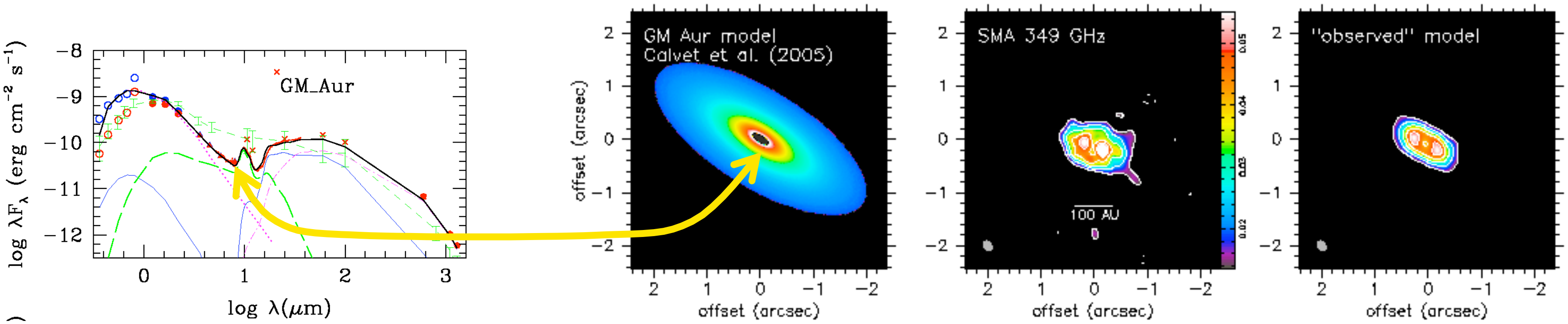




V1057, V1515 Cyg; nebulae suggest view down narrow (outflow) cone

2. Source statistics; only protostars (with envelopes) have FU Ori outbursts; O7 star evaporation! (could be some in embedded (BN/KL) region) Note; V883 Ori, Haro5a IRS appear to be candidates in L1641 (Reipurth & Aspin 1997)

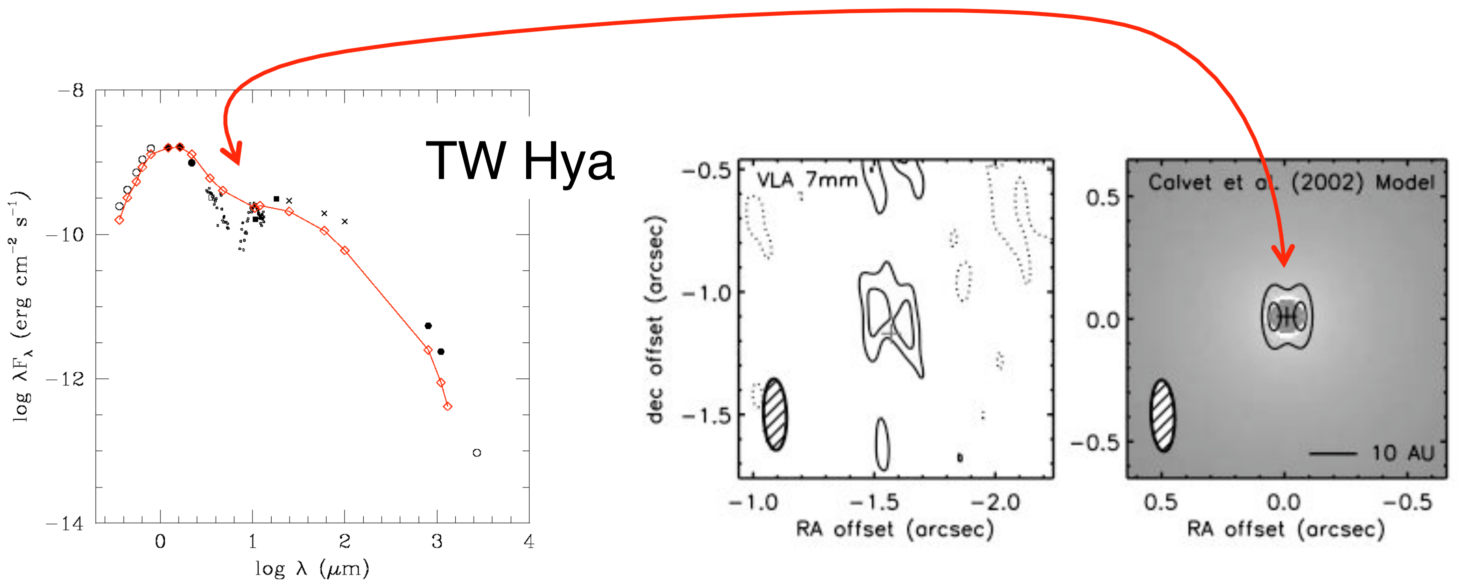
Inner disk holes: consequence of very rapid inner disk accretion?



Calvet et al. 2005

Hughes et al. 2009

TW Hya



D'Alessio et al. 2005