Accretion in low-mass stars

Lee Hartmann, University of Michigan

Michigan Star and Planet Formation

T Tauri, brown dwarf disks accrete… why?

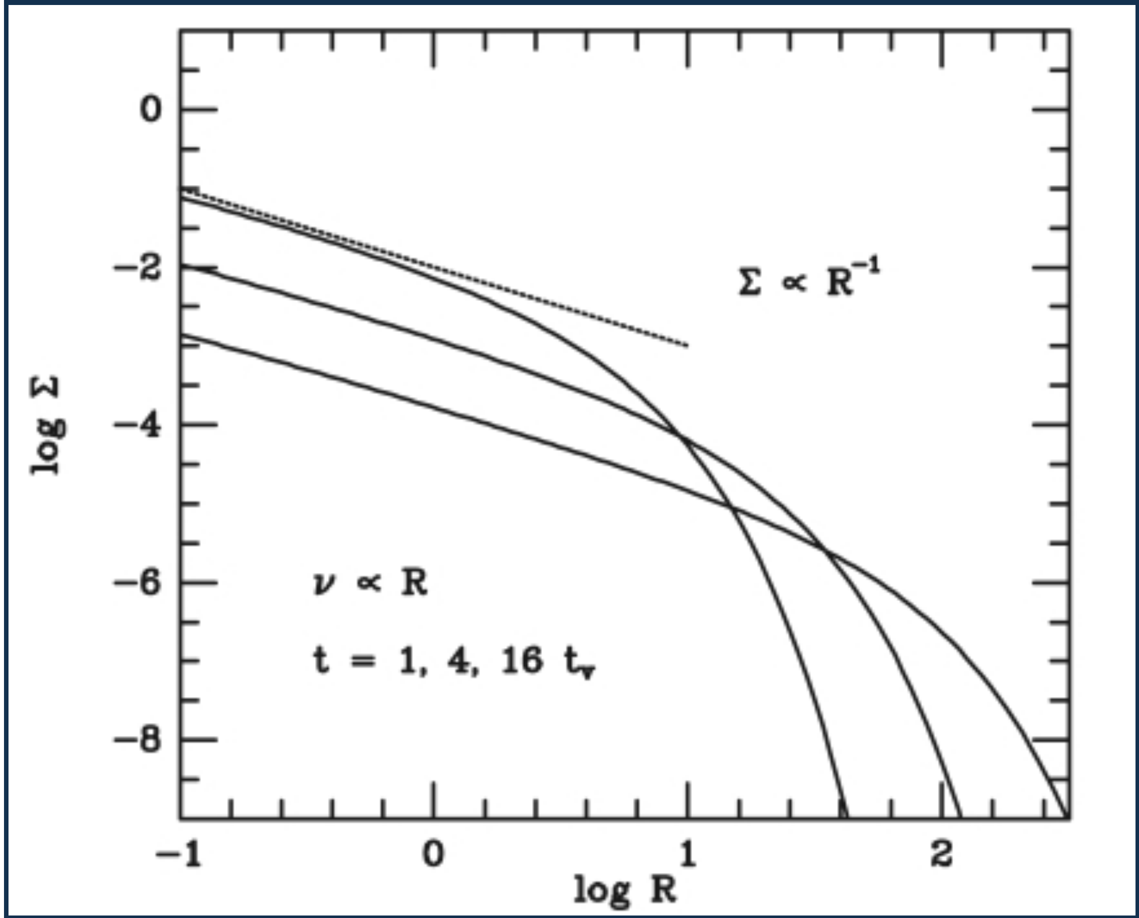
if viscous, no problem…

unfortunately, the only "viscous" process we know of is the magnetorotational instability, which requires ionization, which… protoplanetary disks don't have.

early on – gravitational instability (GI) should move MOST of the mass inward… but could "stall out" at large (~ 0.1 M_*) masses.

then what?

Disk accretion – purely viscous disk…



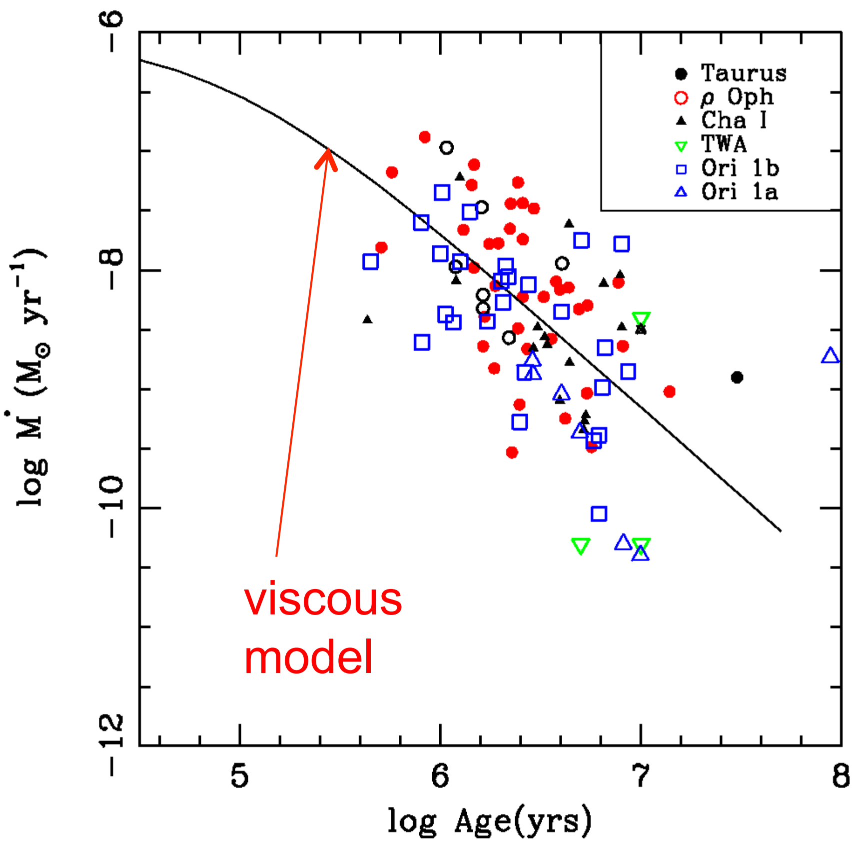
Hartmann 1998

For example,
similarity solutions

$$dM/dt \propto M_d/t_\nu$$

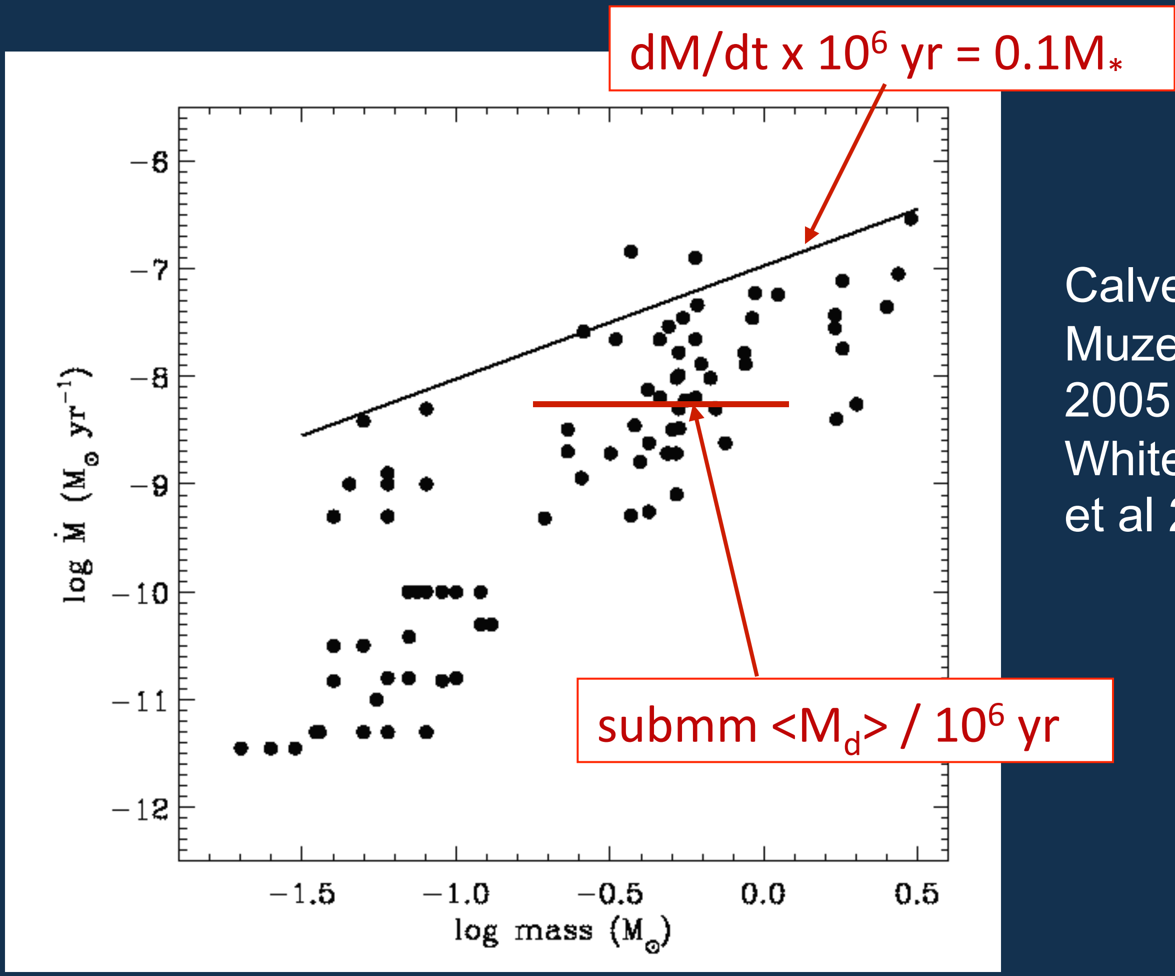
$$\propto M_d/R_d$$

dM/dt ↓ t, like viscous disks… but…



Sicilia-Aguilar et al. 2004

dM/dt ↓ as M* ↓



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

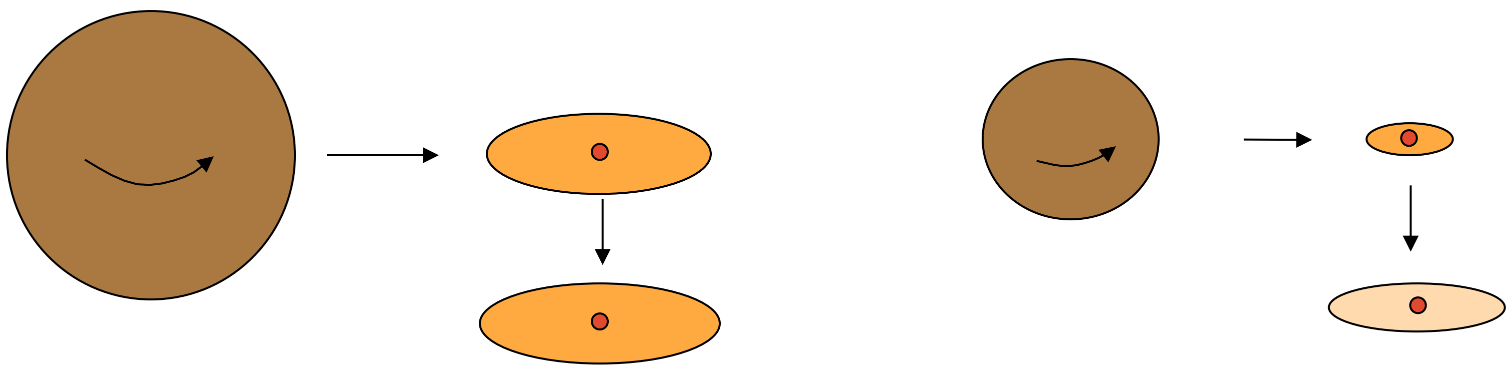
Viscous accretion disk dM/dt vs. M_*

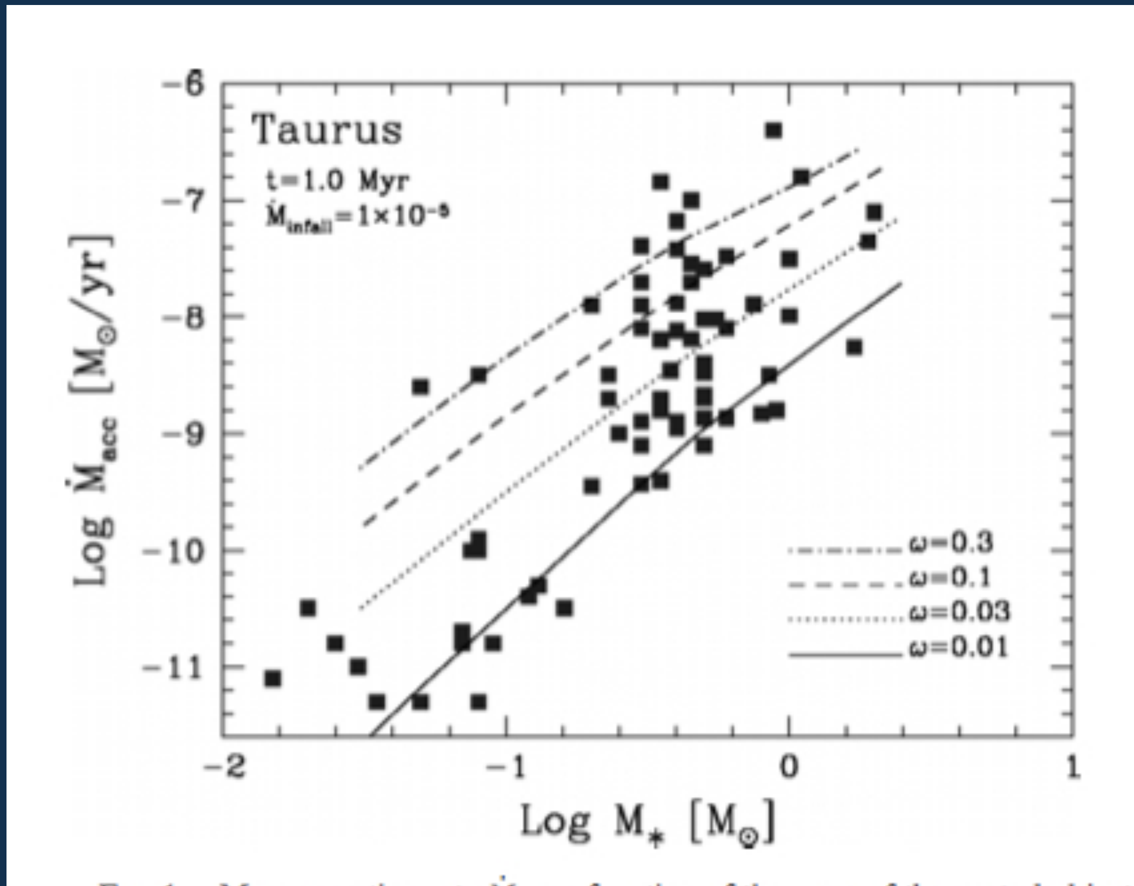
If $M_d(t=0) \sim 0.1\ M_*$ (GI limit) $\rightarrow$ $dM/dt(t=0) \propto M_*$

but; evolution:

small mass $\Rightarrow$ small initial cloud $\Rightarrow$ small initial disk radius $\Rightarrow$ faster viscous evolution

$\Rightarrow$ at the same age, lower mass stars have less disk mass, dM/dt depends more steeply on M_*





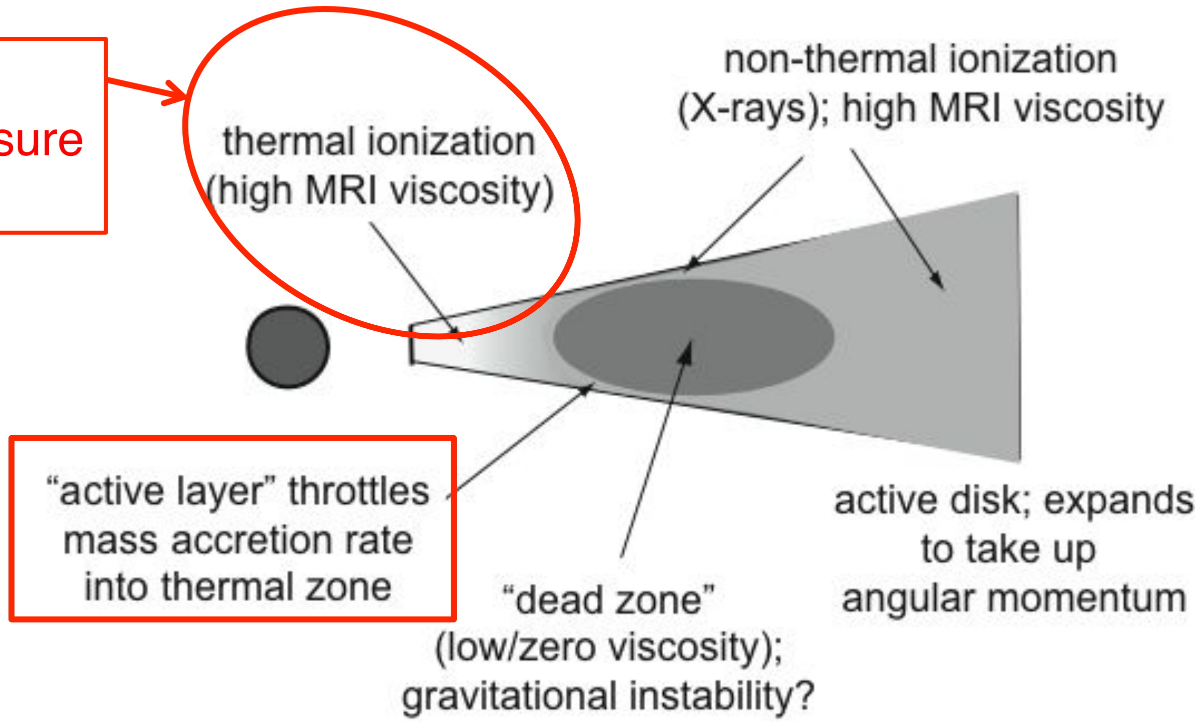
Dullemond, Natta, Testi 2006

Viscous disks with small disk sizes for small mass cores

unfortunately, disks are very unlikely to be fully viscous

“Dead zone” (Gammie 1996)

only can be reasonably sure about this



MANY complications and uncertainties

WHAT’S Σ_a?? *(Sano et al, Ilgner & Nelson, Turner, Bai)*

Gammie: pure viscous heating, constant Σ;

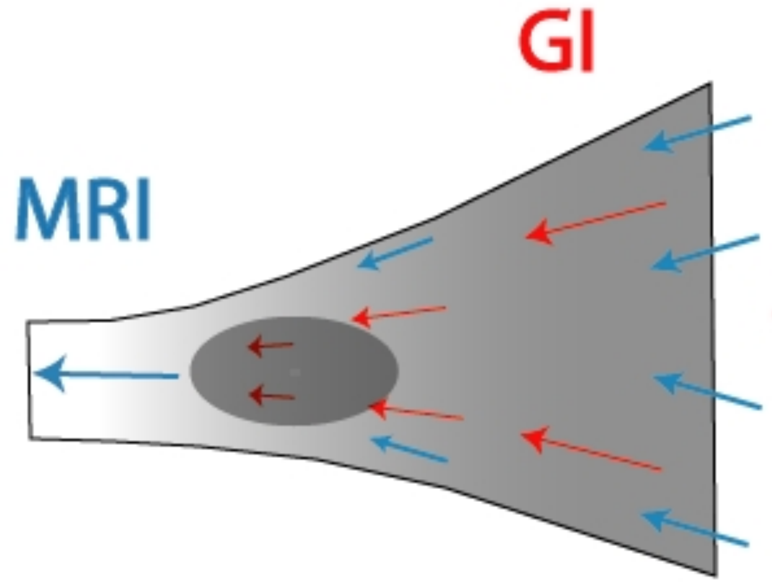
$\rightarrow$ NO dependence on time or disk mass!

dM/dt is set by the inner radius at which the MRI becomes THERMALLY activated.

We (H+06) suggested that irradiation heating, which depends upon L_*, might provide some dependence of dM/dt on M_*;

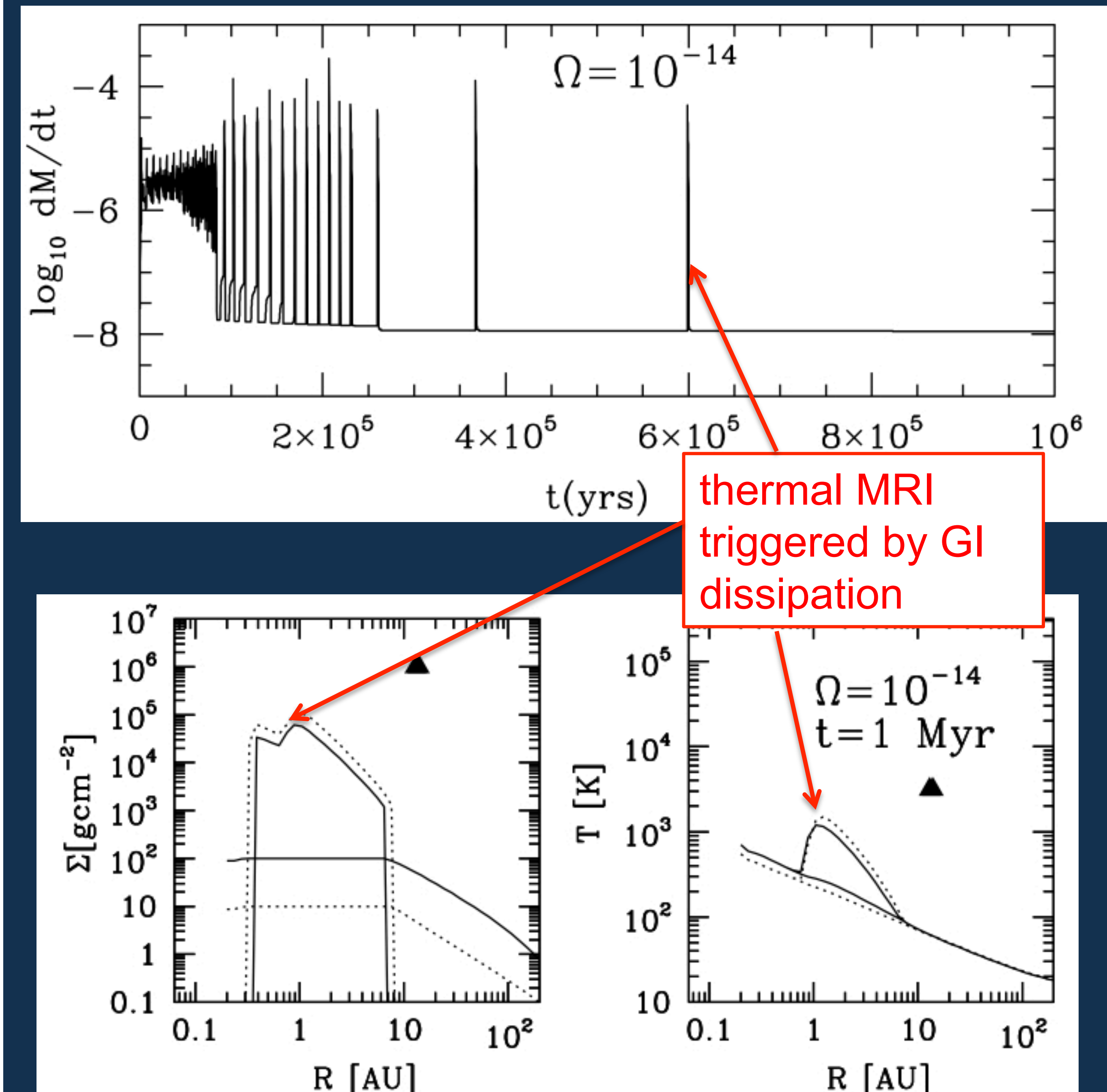
this hasn't been worked out yet in any detail

Mass addition from infall to disk; MRI+GI leads to instability



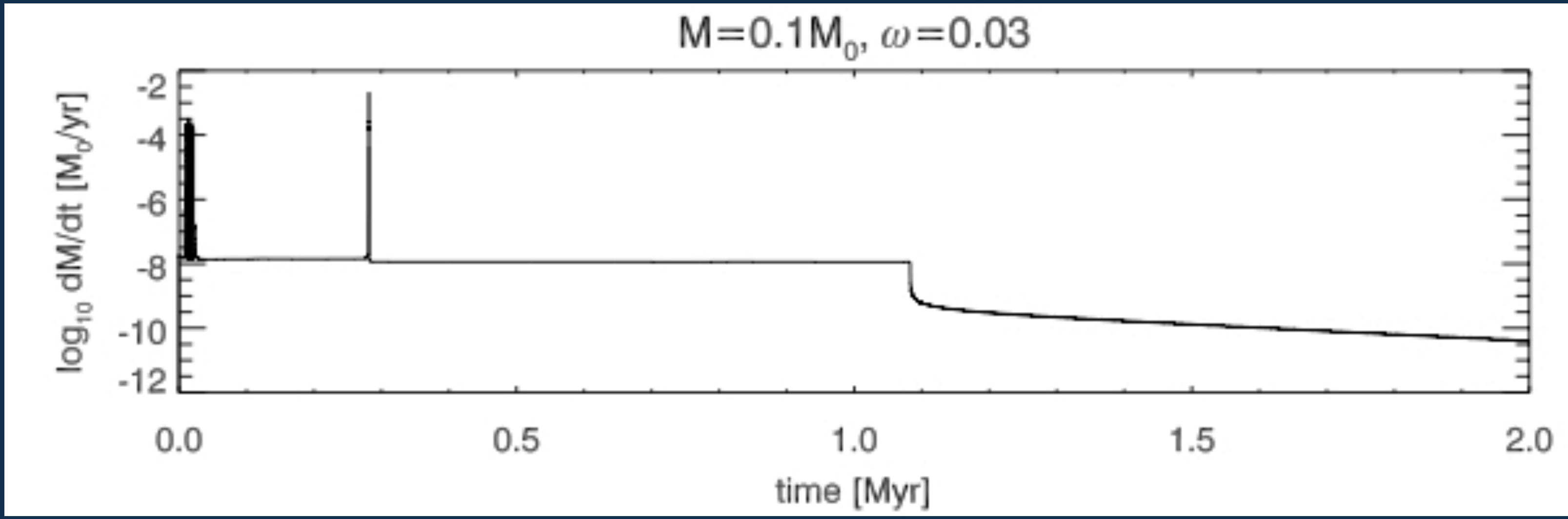
matter piles up at ~ 1-10 AU as
GI becomes less effective;
if dissipation -> thermal ionization,
MRI takes over;
-> outburst because viscosity ↑

(Armitage et al. 2001, Zhu, Hartmann, Gammie 2009 , 2010



Zhu et al 2010; outbursts because of mismatch between GI and thermal MRI

(works for FU Ori ouburst)



Jaehan Bae, UM, Zhaohuan Zhu (Princeton)

get low dM/dt, especially for brown dwarfs, for LO2 angular momentum/disk; like Dullemond et al. idea;

just takes LONGER because dead zone must be depleted by active layer accretion –
then acts just like a standard viscous disk.

So the test is: do low dM/dt -> low disk masses?

Summary 1: low dM/dt -> viscous disk + low disk masses??

I'm dubious.

I think there must be dead zones – rapid coagulation – form (dispensable?) planets – start starving the inner disk of mass to accrete. (note; even minimum mass solar nebula has 10^3 g/cm^{-2} @ 1AU; >> most estimates of Σ_a)

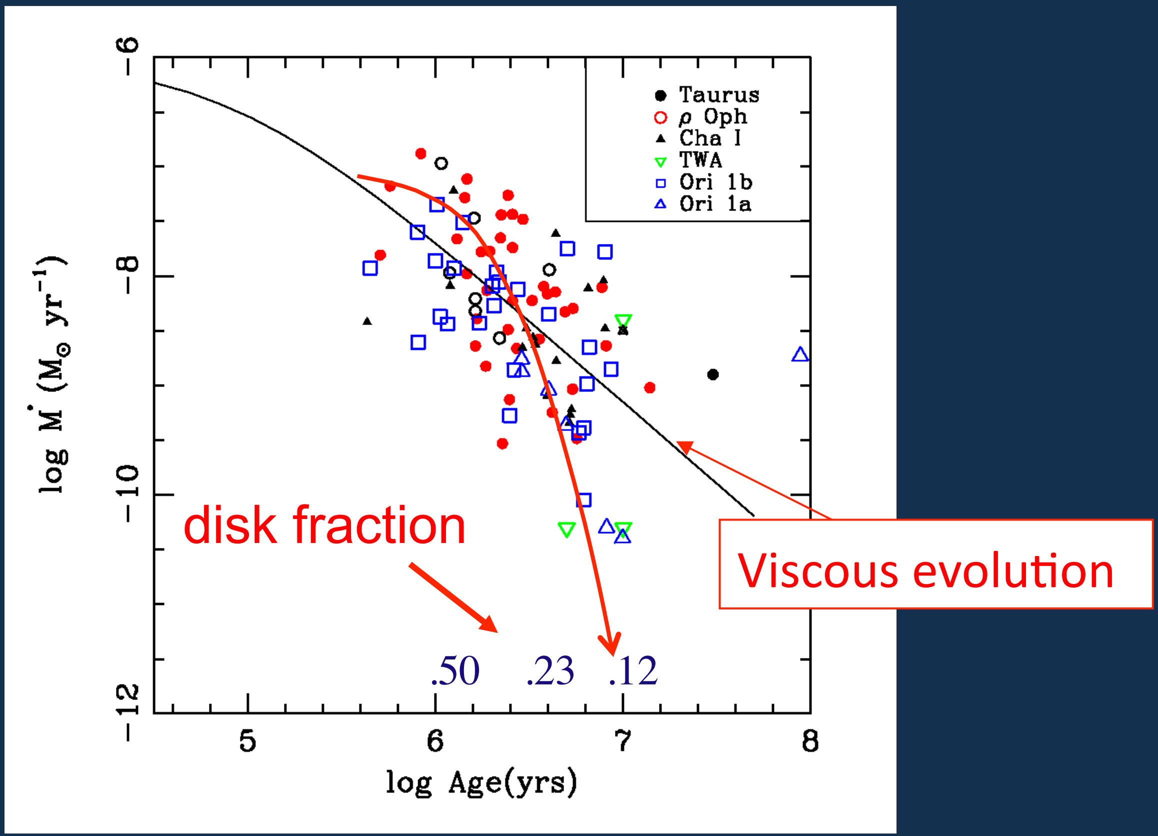
"Transitional" disks (big inner disk holes) cut both ways;

still have gas accretion with no small dust…

however, SOMETHING has vacuumed up the small dust, even it it didn't completely eliminate the gas (Zhu, Nelson, Hartmann, + 11)

FRACTION of accreting/IR excess objects decreases with time faster than viscous

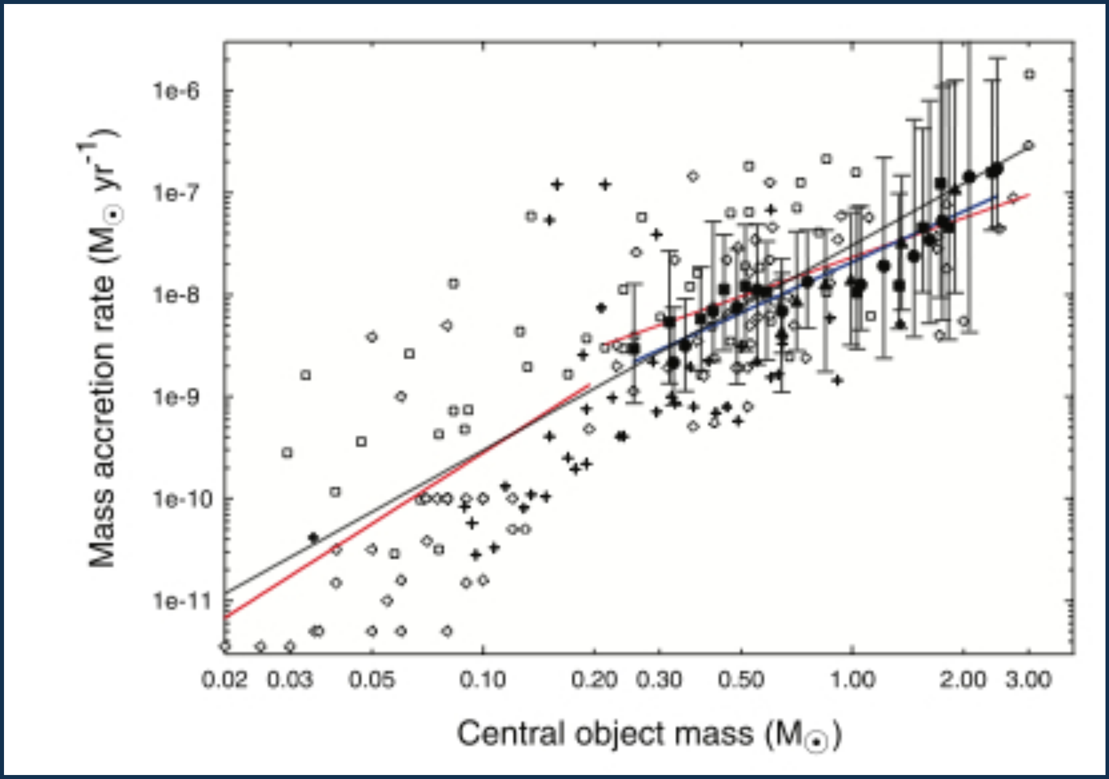
⇒ *can't all be viscous evolution!*



photoevaporation? (Clarke, Owen, Gorti, Hollenbach)

planets… IF dead zone, harder for PE to work, more likely to form massive bodies

Hartmann et al. (1998), Muzerolle et al. (2001), Calvet et al. (2005)



Vorobyov & Basu 08: just use pure GI?

$$\langle \dot{M} \rangle = 10^{-7.7} \langle M_* \rangle^{1.7}$$

$$\langle \dot{M} \rangle = 10^{-7.0} \langle M_d \rangle^{1.1}.$$

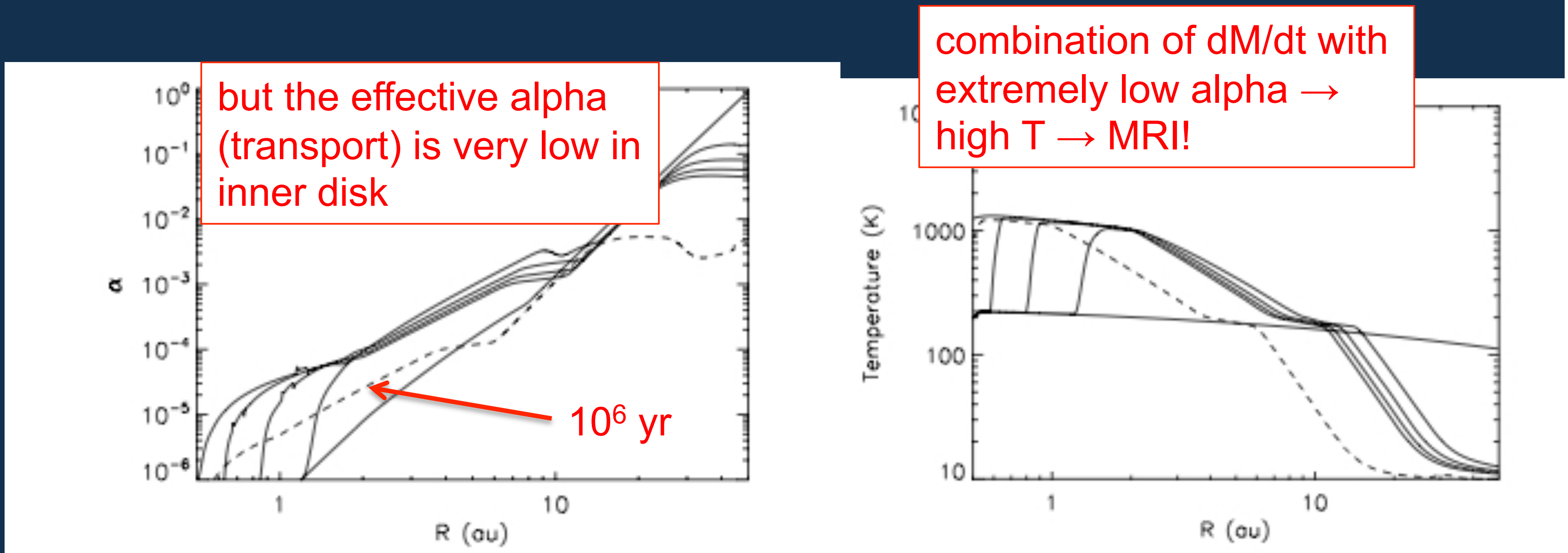
Use inner disk radius is 5 AU – outside where the dead zone and outbursts appear in our models.

GI works at large R;
MRI works at small R

compatible??

The accretion problem is in the INNER DISK

Rice & Armitage 09; pure GI (cooling approximation for transport)

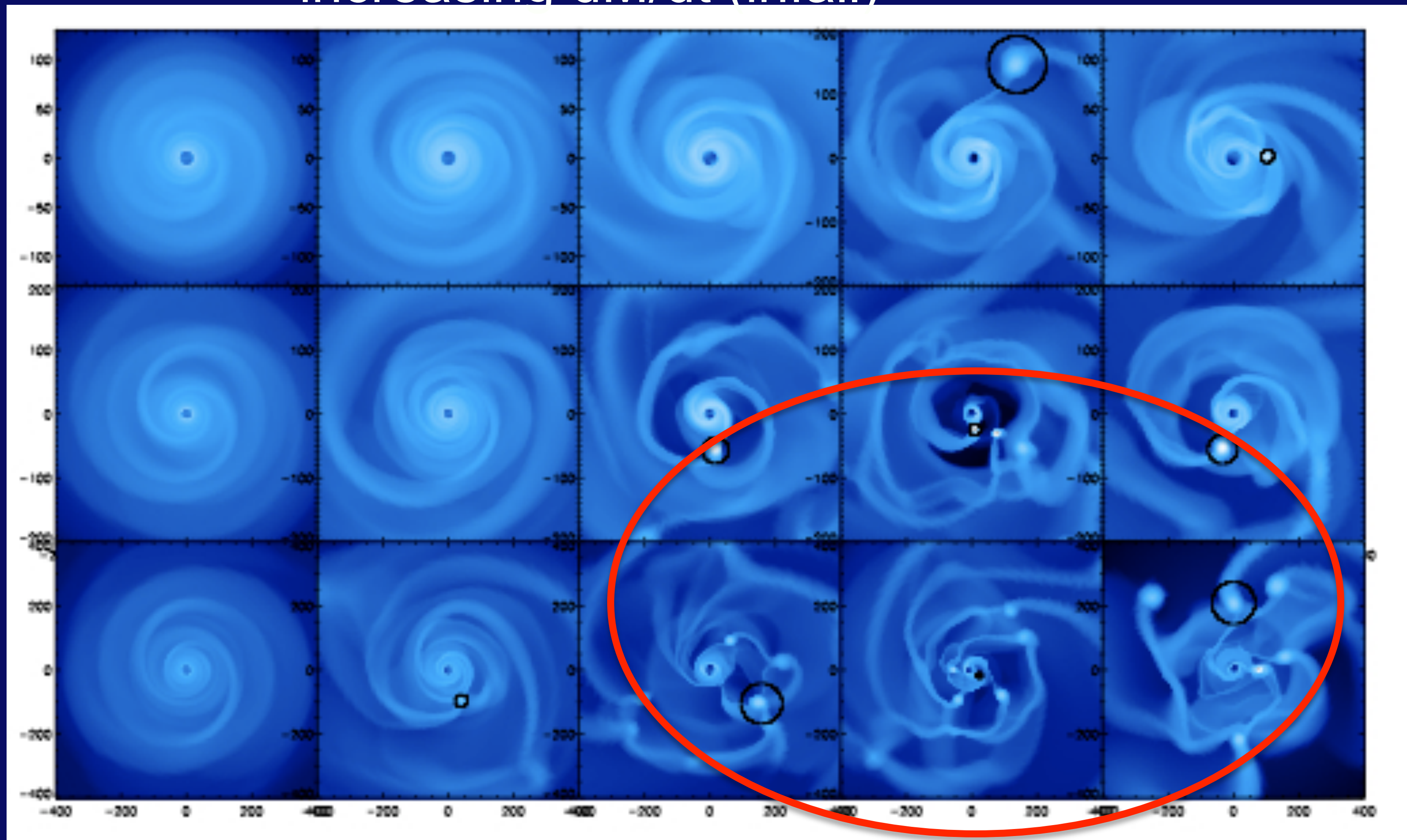


of course, clumps might pass through; if they survive

fragmentation?

increasing dM/dt (infall) →

← increasing infall radius

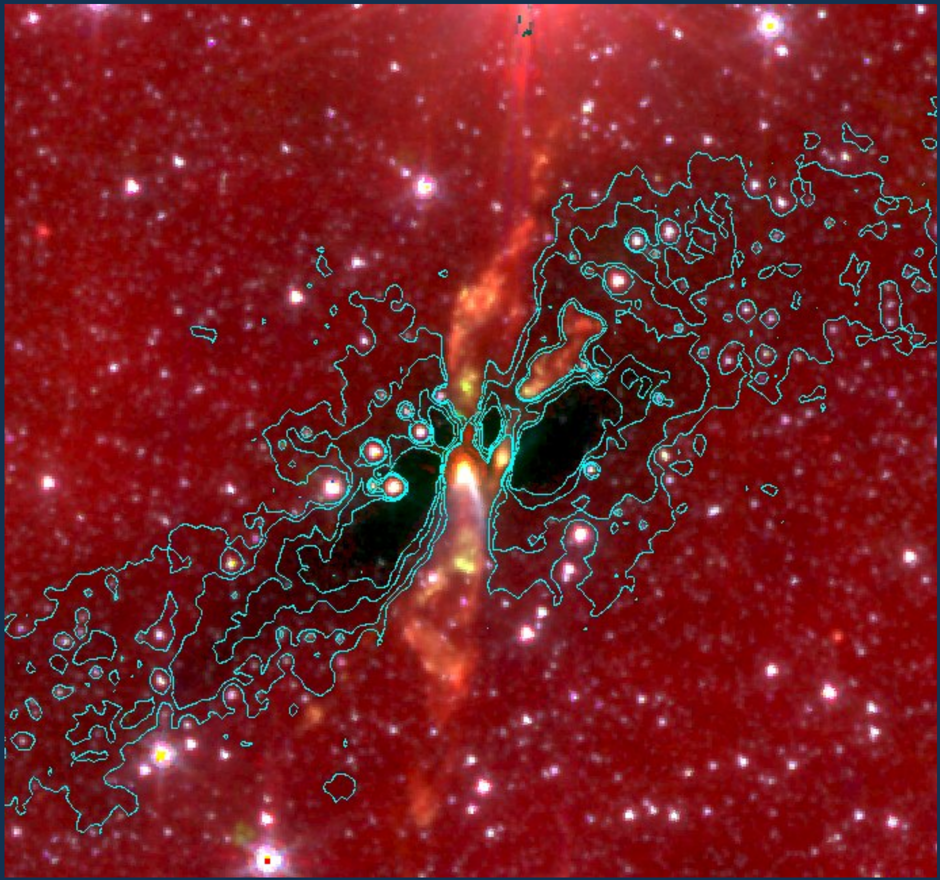


high J leads to FRAGMENTATION

Zhu et al. 2011, submitted

Protostellar collapse- filamentary and often non-axisymmetric and unaligned

BHR71

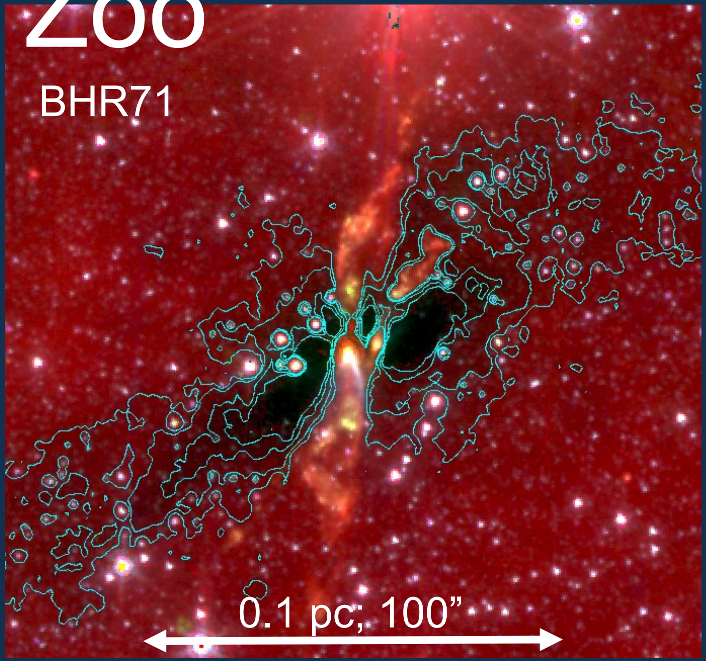


Visible (T. Bourke) *Spitzer 8 μm exinction*

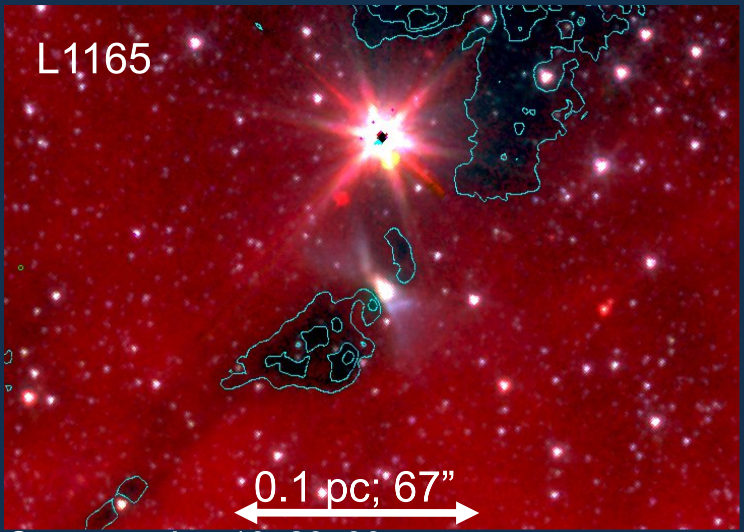
Tobin et al. (2010)

Protostellar Zoo

Contours: A_V =15, 22.5, 30



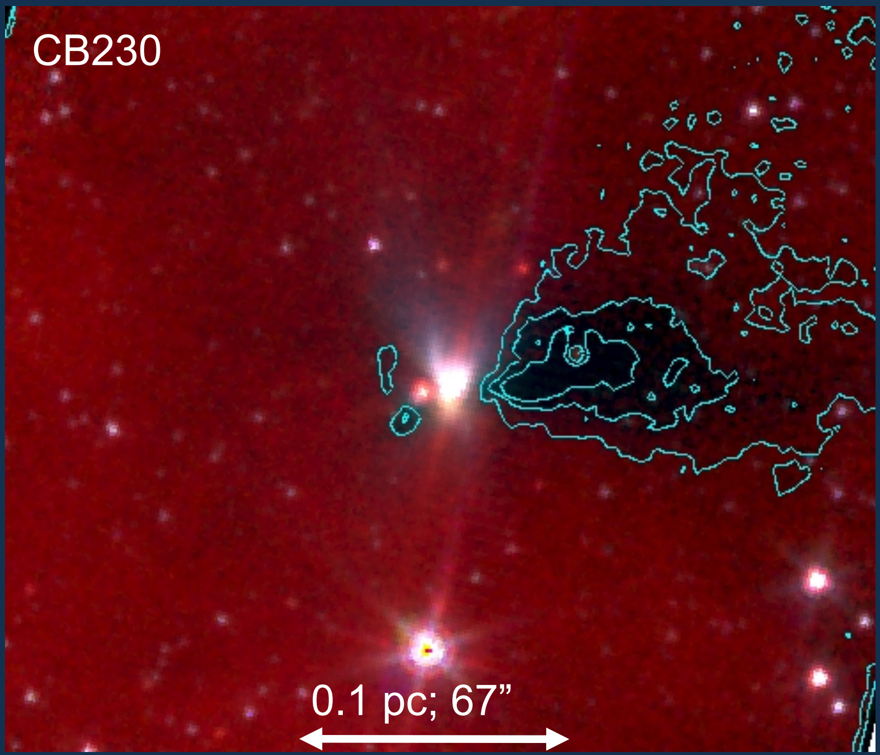
A_V =15, 20, 30, 40



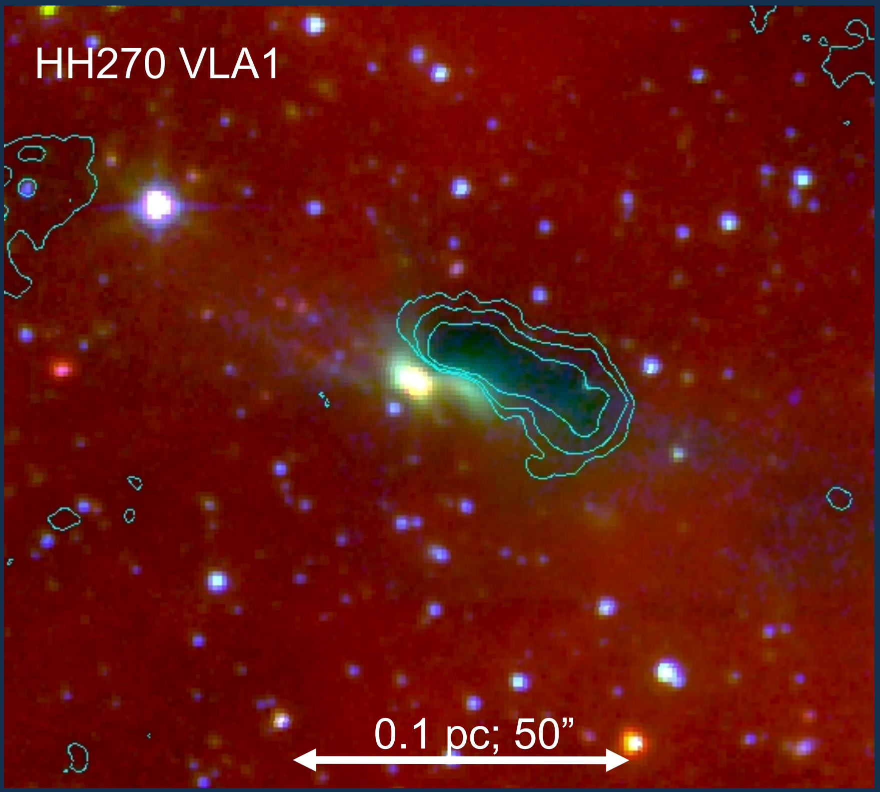
Contours: A_V =10, 20, 30

Tobin et al. (2010)

Protostellar Zoo

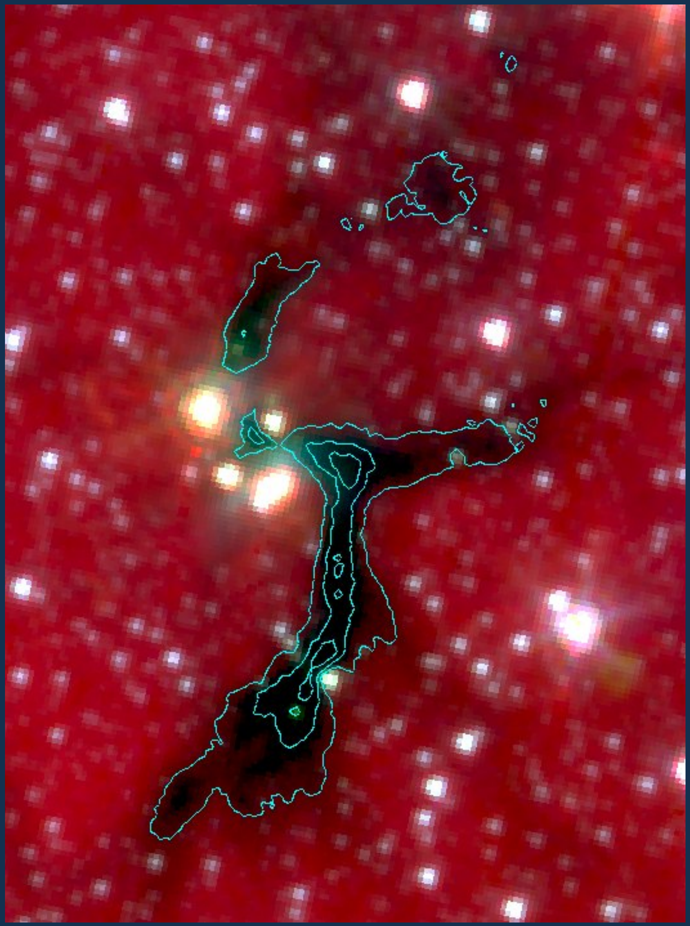


A_V =10, 20, 30



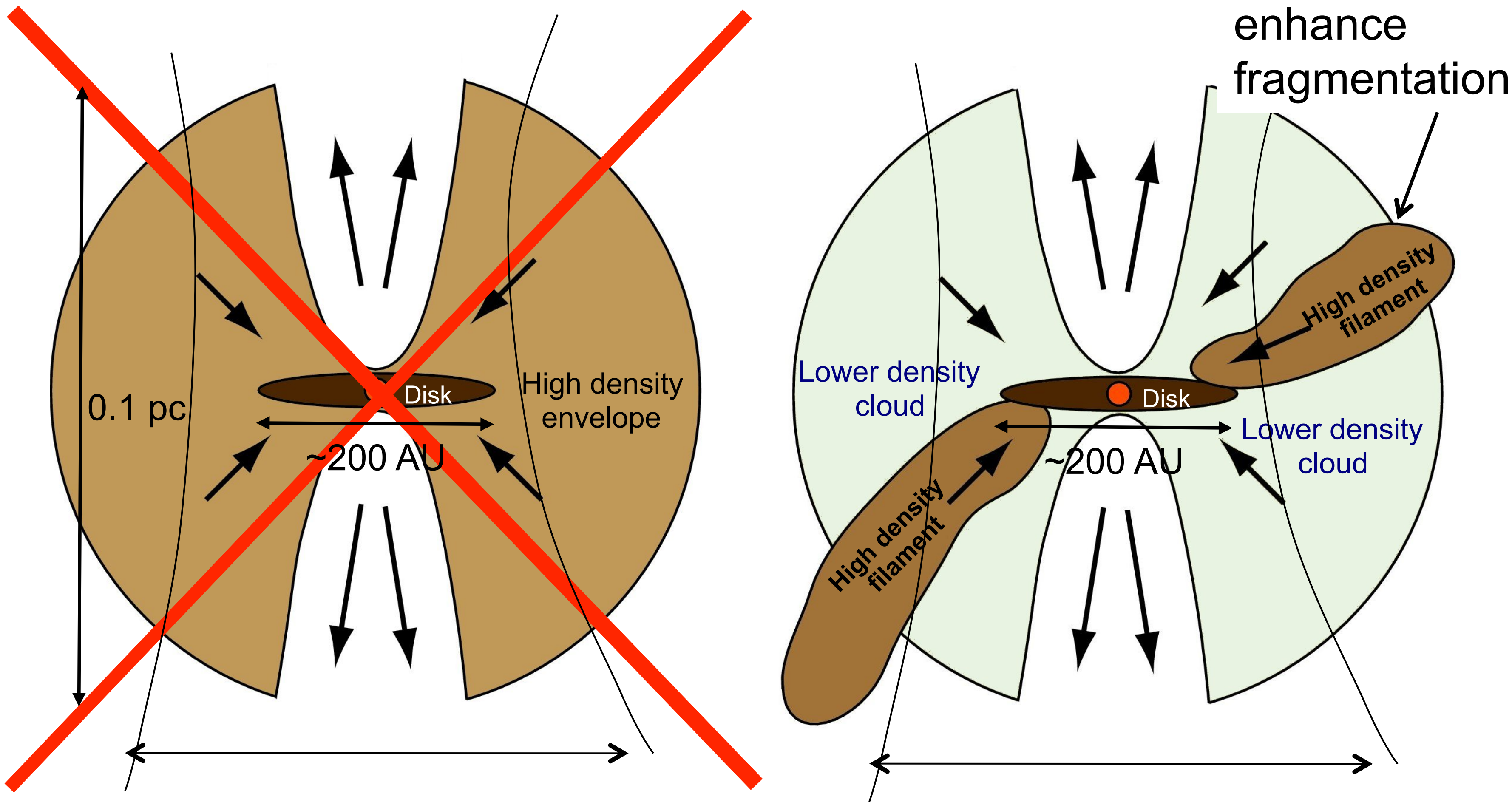
A_V =10, 20, 30

Tobin et al. (2010)



Many examples of complex, filamentary protostellar infall often not aligned well with outflows (rotation axis; magnetic field?)

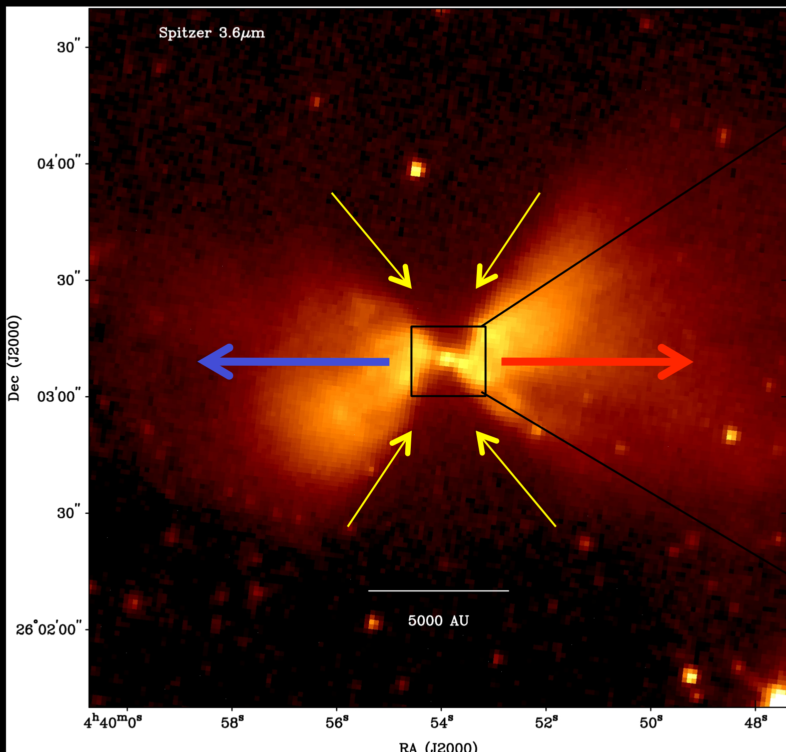
angular momentum transport by magnetic fields, only small disks? in addition to non-ideal MHD, geometry?



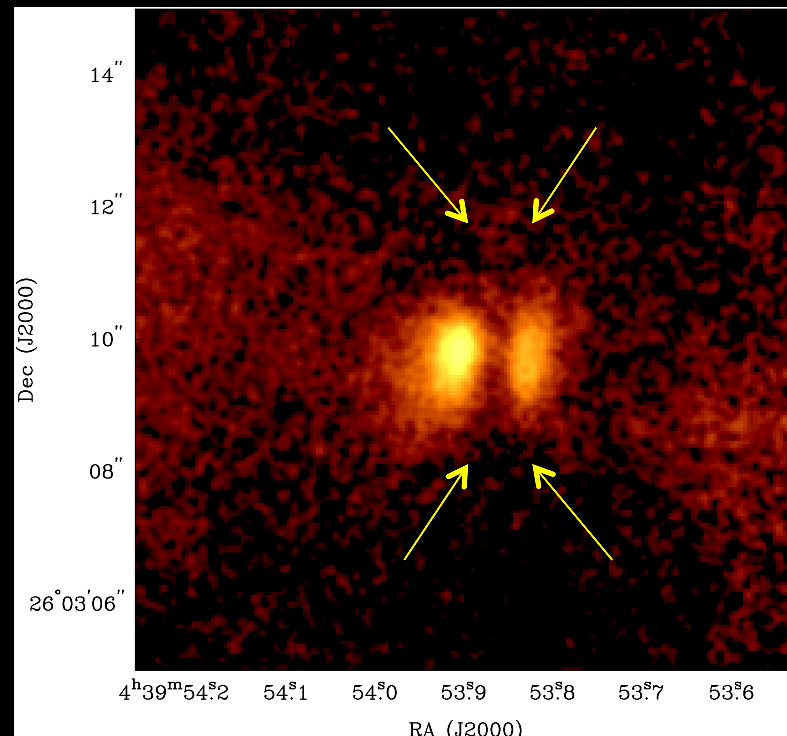
if collapse has already concentrated mass/flux, and if envelopes tenuous, can't couple enough to get rid of lots of angular momentum

Disk formation by infalling, rotating cloud in Class 0-I disk

L1527 Spitzer 3.6 micron



Gemini 3.8 micron 200 AU radius disk



scattered light images of bipolar outflow cavities and upper and lower surfaces of edge-on circumstellar disk; Tobin et al. 2010, ApJL

Fragmentation and small disks

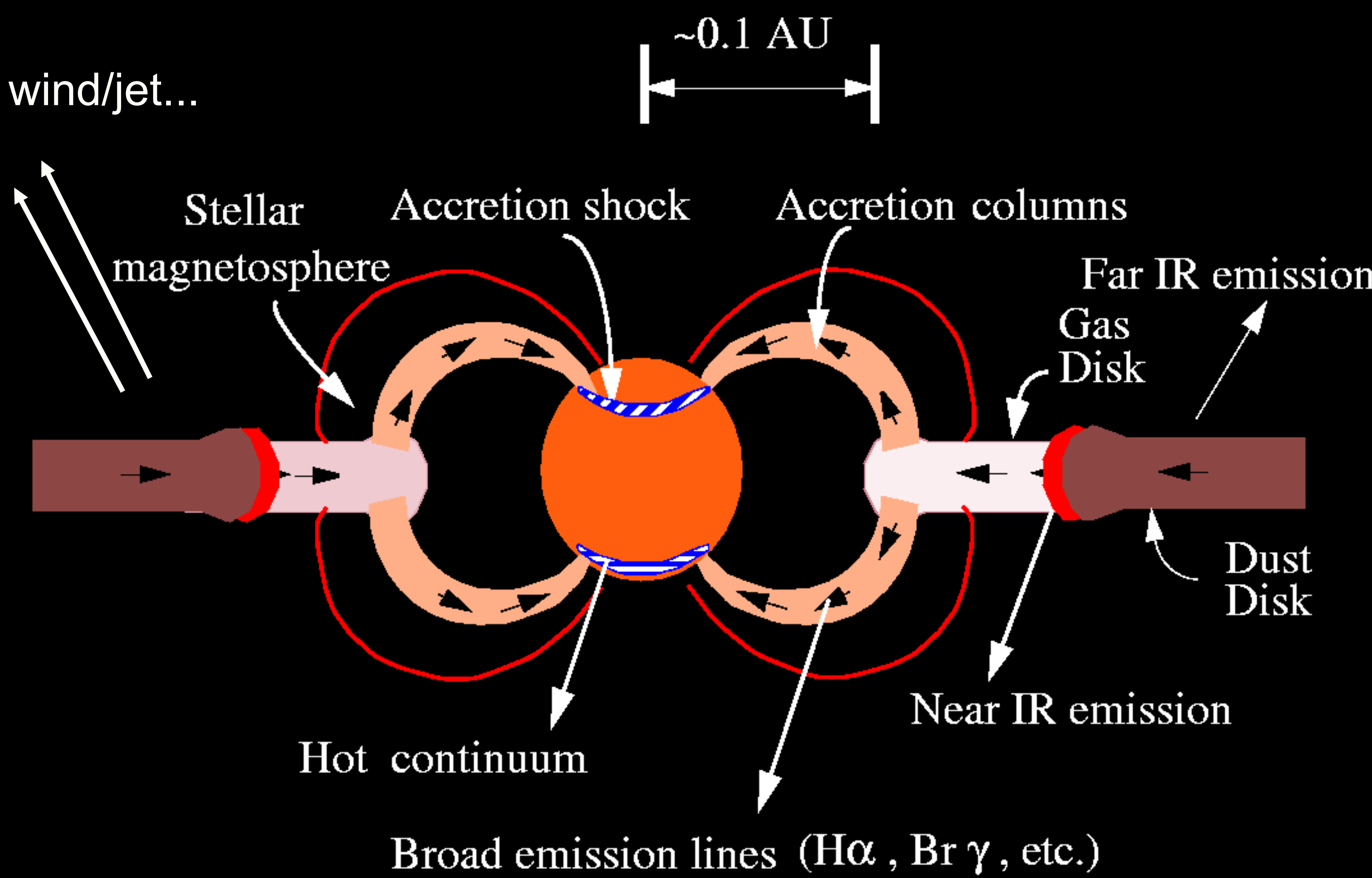
Why not fragmentation? highly non-linear perturbations by real infalling envelopes

Only small disks because of angular momentum transport by B? Depends not only on LOCAL mass to flux ratios but geometry (what does the field couple to?)

My two cents; I don't see the organization and orientation I would expect to see if B was dominating.

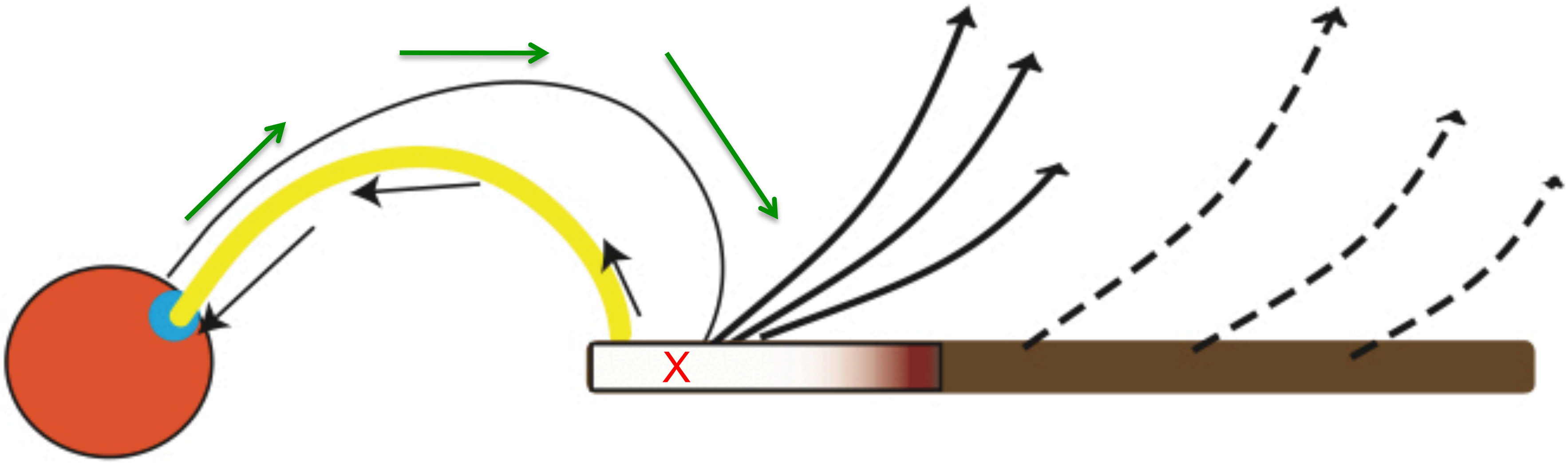
near the star is a different story…

T Tauri star - magnetospheric accretion



Ghosh & Lamb; J(in) ← is balanced by J(out)→

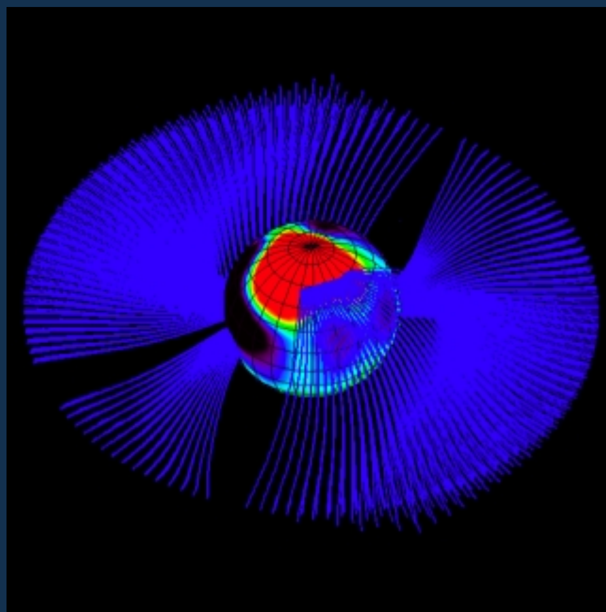
Wind from disk loses just the right amount of J



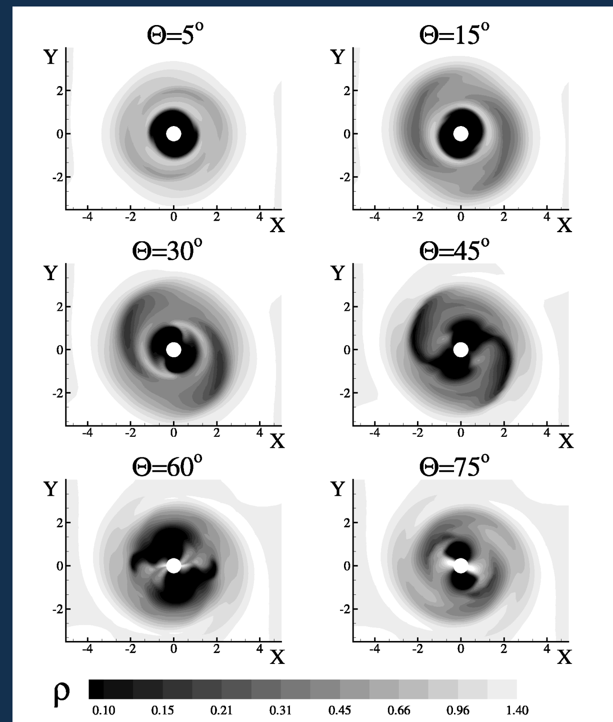
Shu et al; J(in) ← is balanced by J(out)→ at X point (no field line twisting)

Really? because…

because magnetospheres are complex



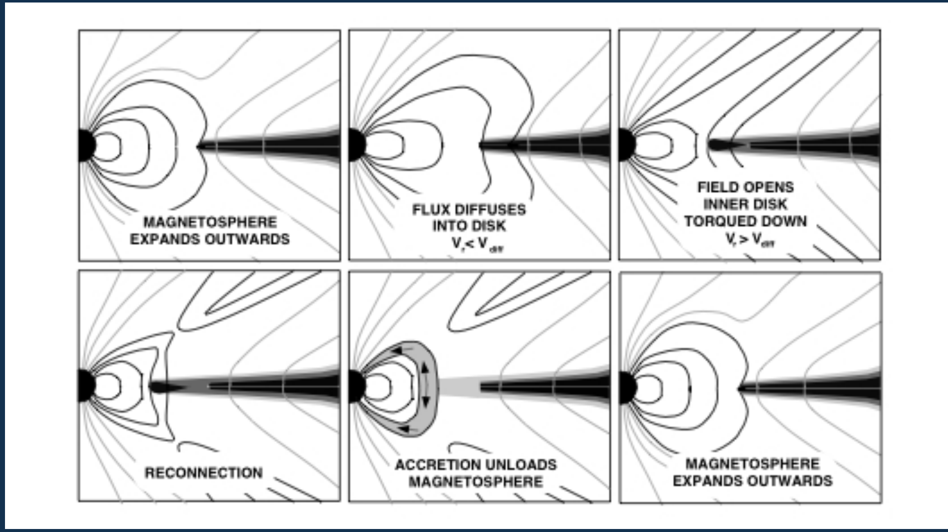
Jardine, Donati et al.

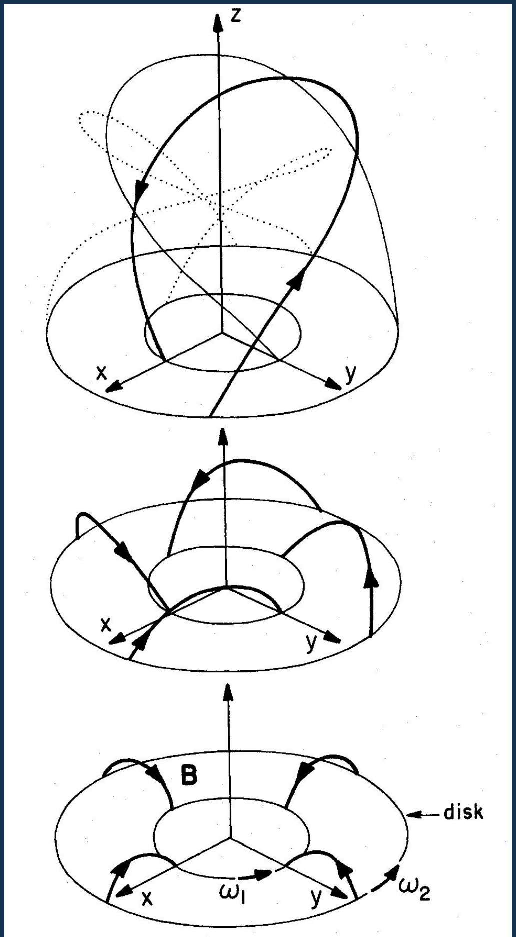


Romanova et al. 2003, 2004

- magnetic field lines can't all connect at co-rotation
- no reason to assume field lines slip through disk smoothly; *field lines must twist up*

General case: magnetic field lines twist up, balloon out as they are twisted - then reconnect





Goodson, Winglee, Böhm 1997; Goodson, Winglee 1999; Matt et al. 2002

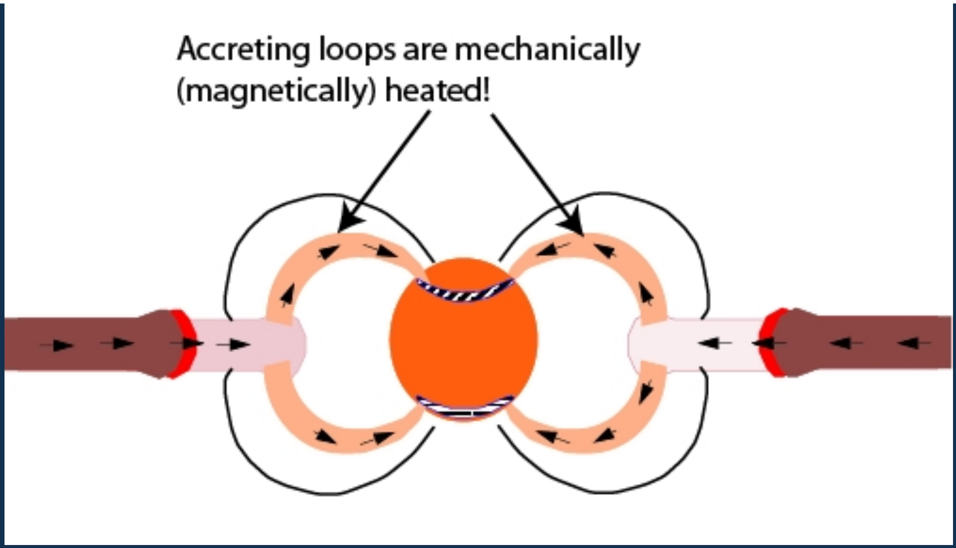
⇒mass ejection during inflation/reconnection of twisting field lines

⇒ angular momentum loss from B connected with both the disk AND the star

⇒taps into twisting energy (which is driven by accretion!)

⇒ reconnection limits spindown? (Matt & Pudritz)

Lovelace, Romanova, & Bisnovatyi-Kogan 1995

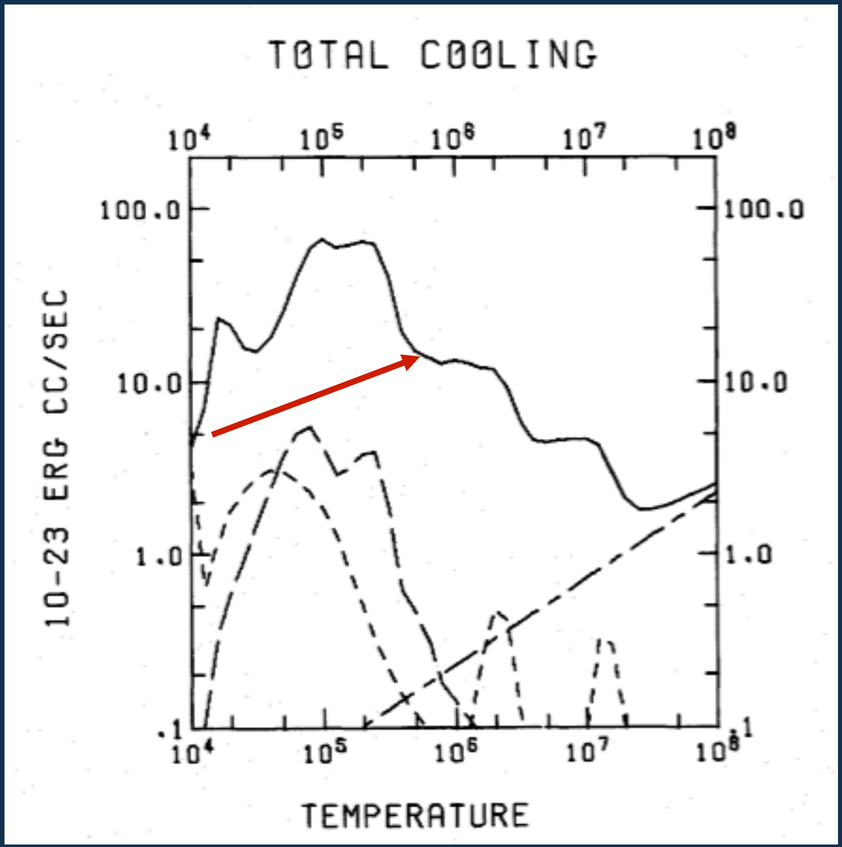


radiative energy loss ~ 1-10% L_{acc}

Our familiar accretion loops are heated to ~ 10^4 K (waves? reconnetion?)

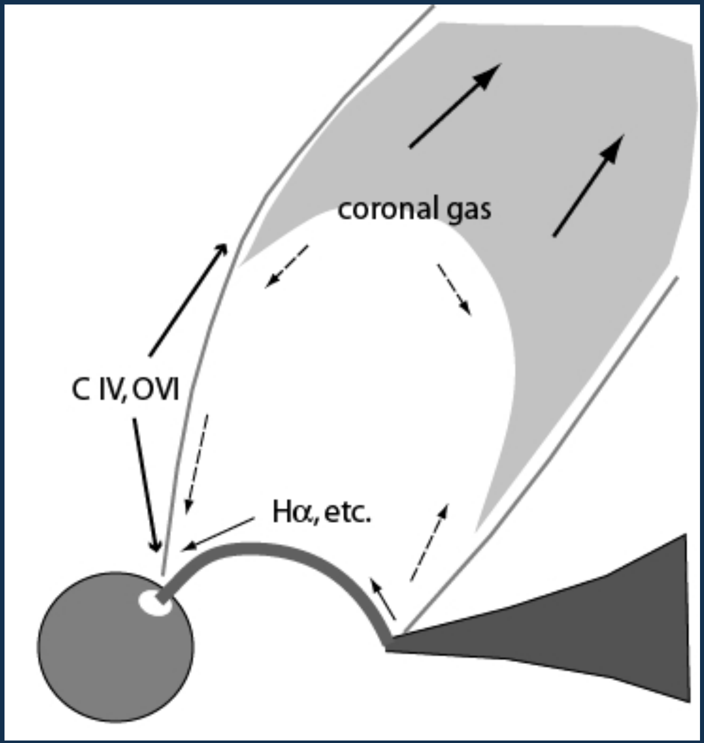
⇒ at SLIGHTLY lower density, can be heated to 10^6 K!

• Why not higher T (coronal) loops *filled with lower-density disk material*?

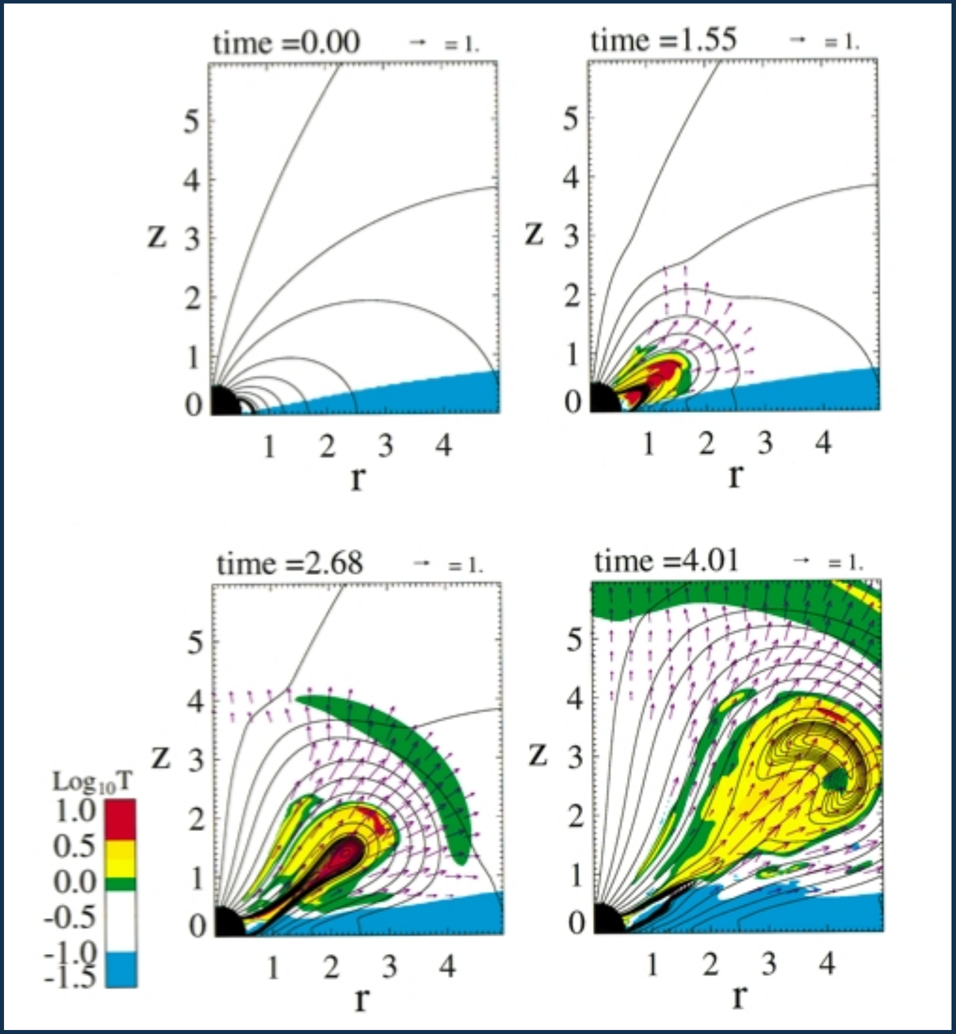


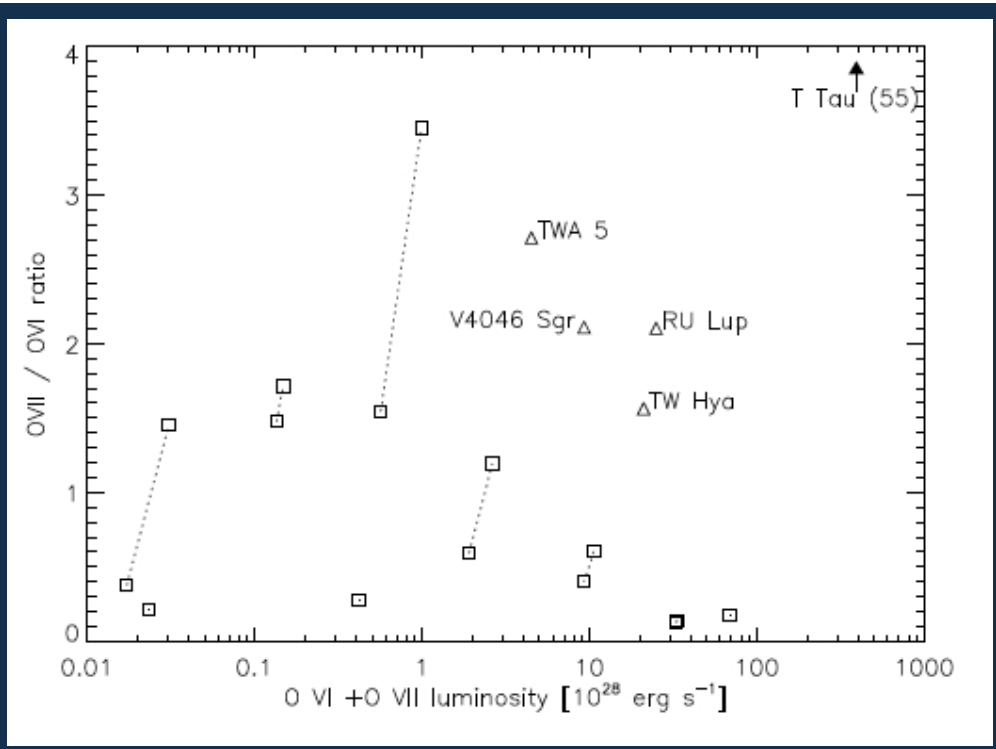
“Twister” idea for enhancing angular momentum loss: (H08)

• accretion starts, but field lines twist up, bulge out;
• density starts to drain out but gas heats up, can’t fall in
• field lines open out, ejecting coronal gas that was originally infalling disk gas
• large dM/dt because starts far out in potential well
• field lines connected to the star, spinning it down



Hayashi et al. 1996; coronal gas in twisted loop - heating to 10^8 K - outflow, flare...





Hot (closed AND expanding) loops:

- May explain OVII excess in CTTS (Gunther & Schmitt) (higher density loops due to mass accretion, lower T; also gas pressure?)
- Some stellar mechanical energy into accreting loops might explain slightly lower L_X in CTTS
- May explain hot winds/accretion (Dupree et al.)

Summary 2*: Stellar spindown and winds:*

• magnetic

• field lines connected to star; those to disk, accretion and spinup…

• most mass/angular momentum added during protostellar phase – therefore spindown then!

• during proto phase – high dM/dt -> small magnetospheres -> fast rotation favored in disk braking scenario

• Field lines MUST twist up

• “Twister” idea; ejection of disk material by CMEs (?)

• jets/outflows (the cool ones we see); clearly driven by accretion energy. Does dead zone limit the source region for jets?