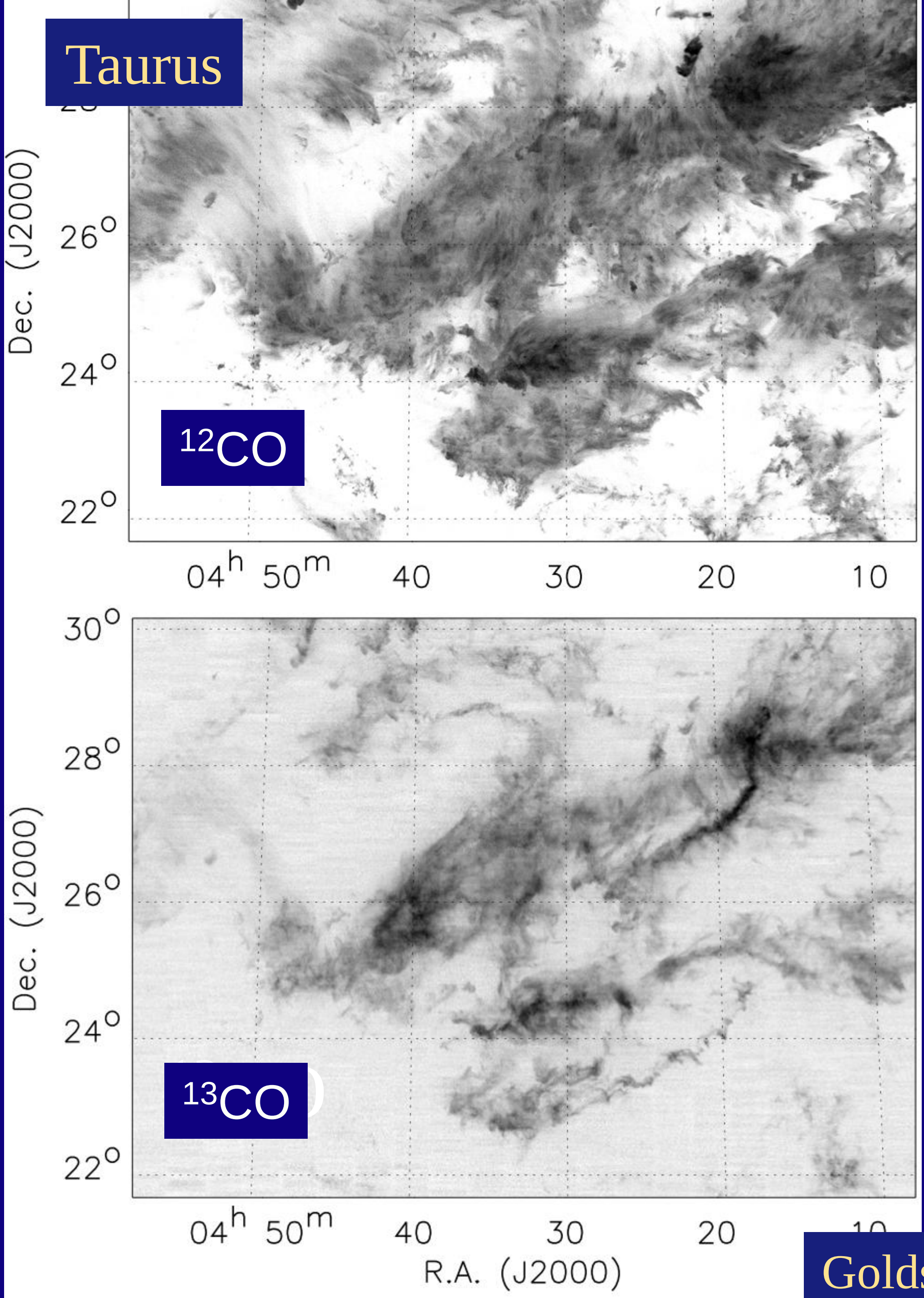
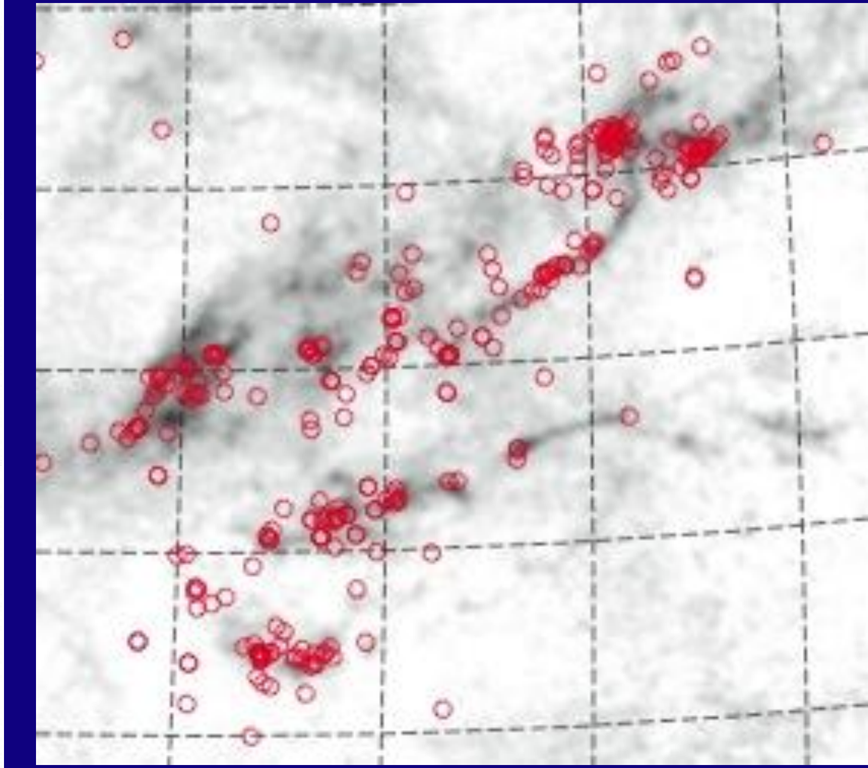
Formation of stars and their planets

Lee Hartmann
University of Michigan

The starting point: high-density regions of molecular clouds

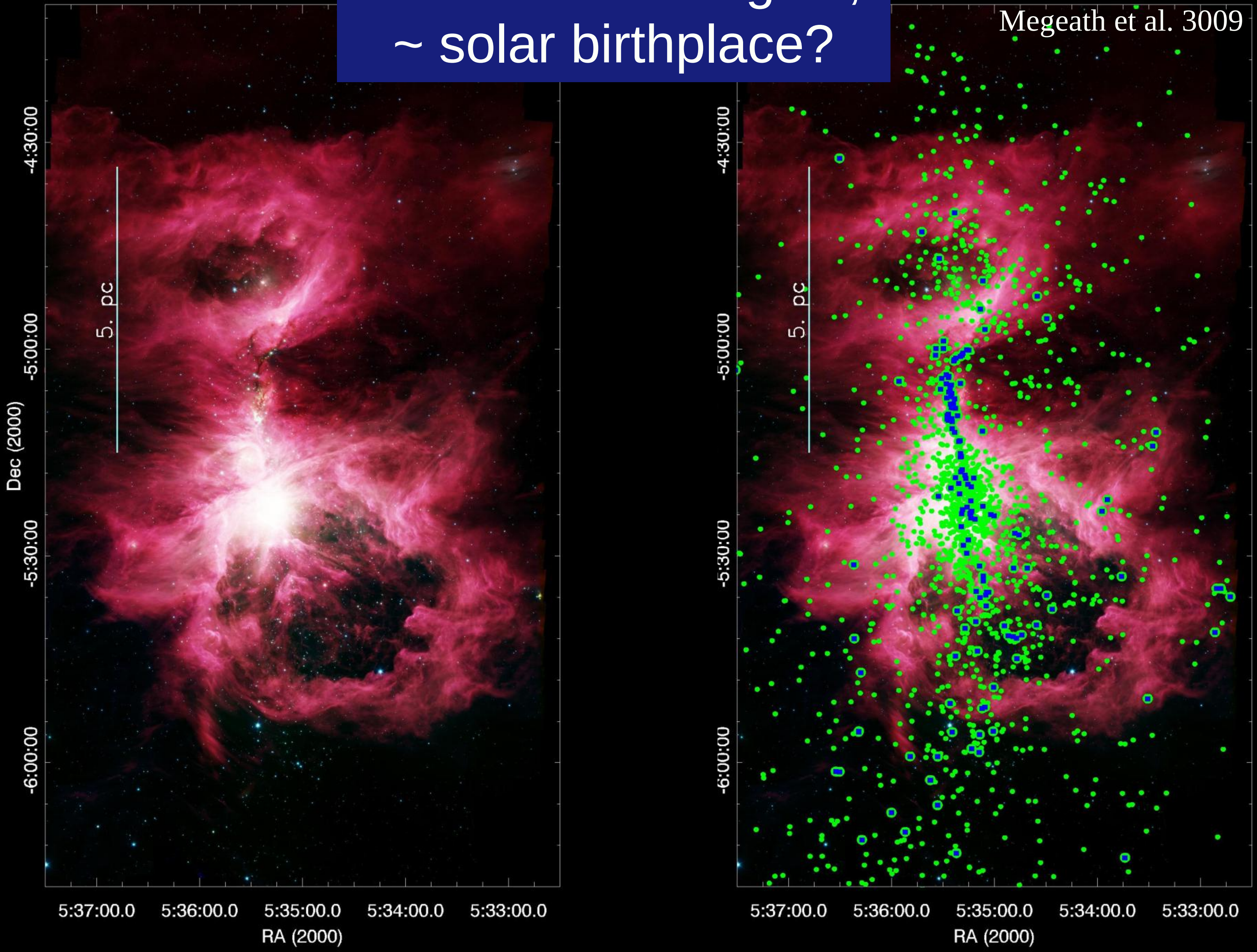


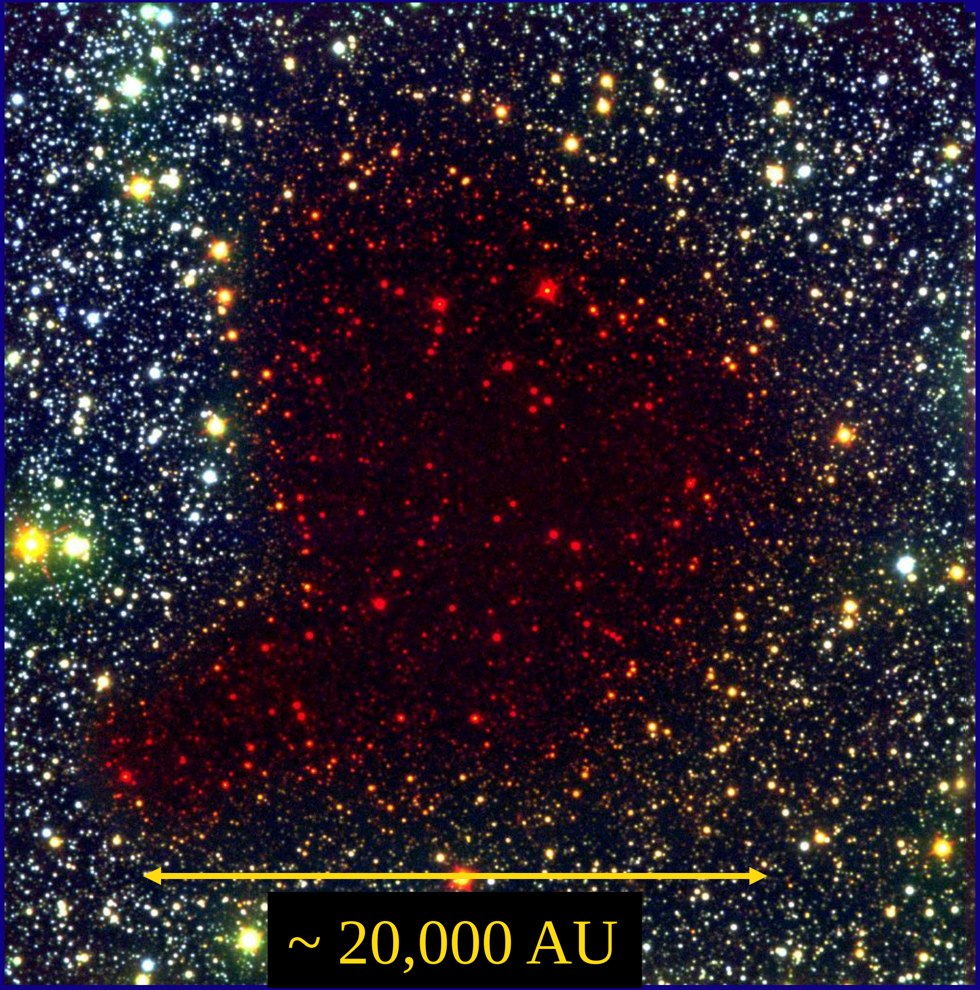


stars form in filaments

Goldsmith et al. 2008

Orion Nebula region; ~ solar birthplace?

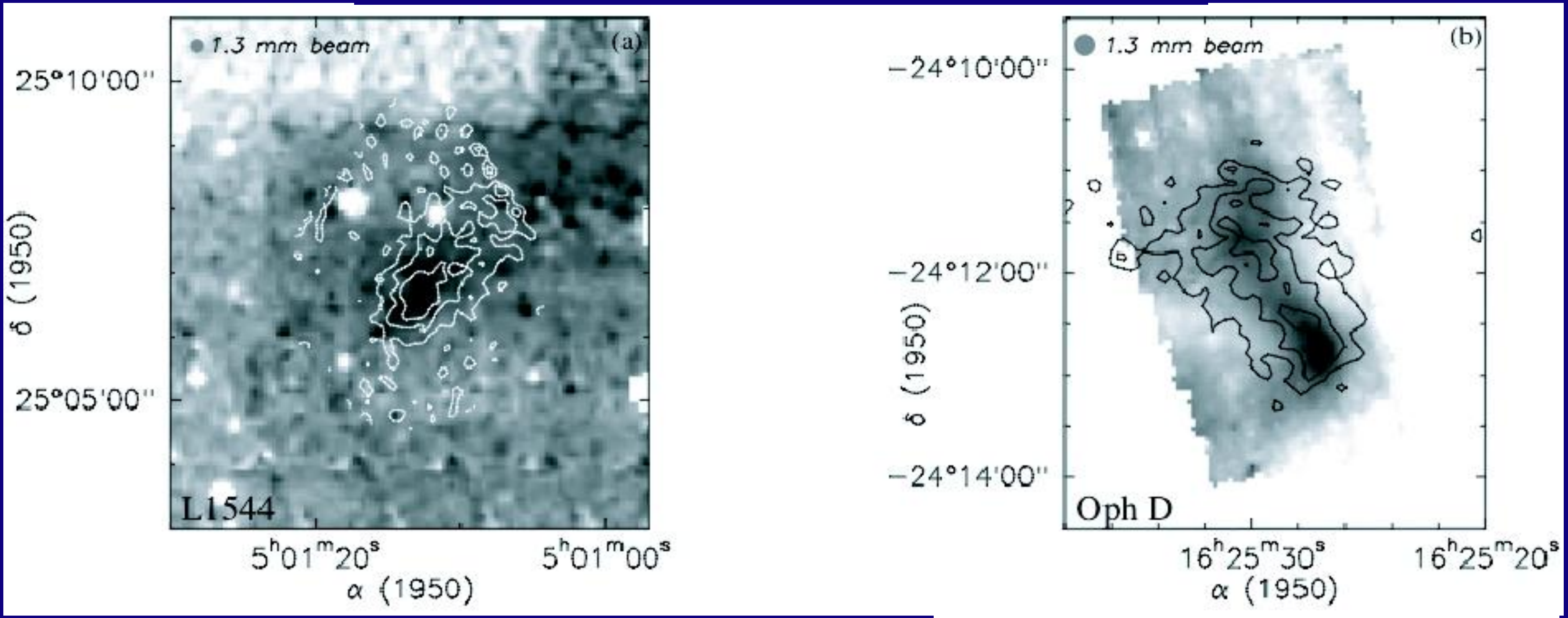


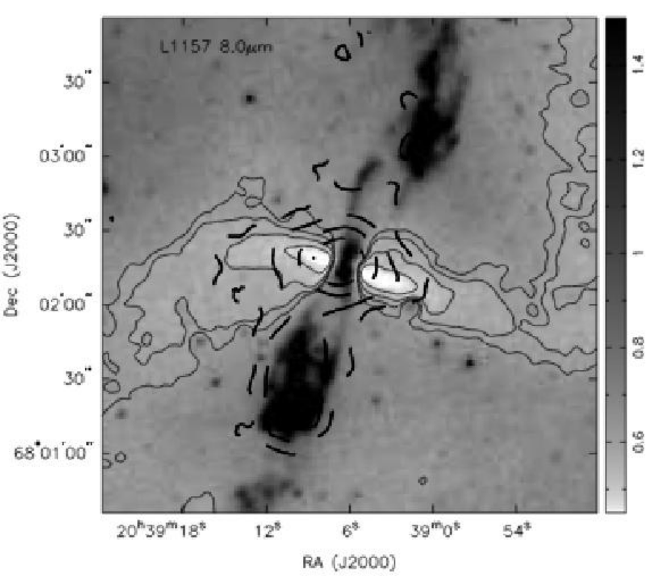


Alves, Lada & Lada 2001

Solar-type stars form from the collapse of LARGE protostellar gas clouds; conserving angular momentum ⇒ disk formation

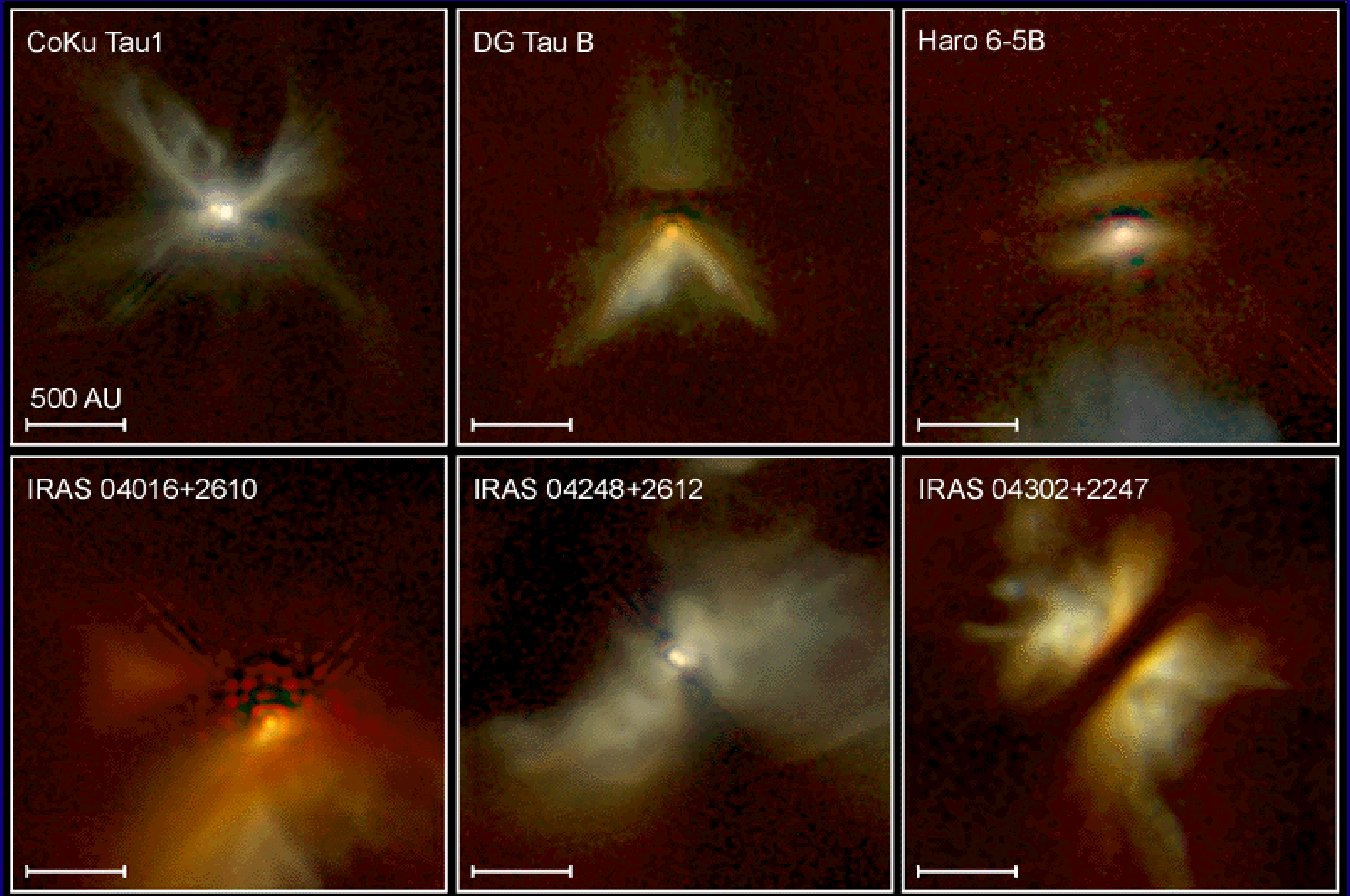
real cores are often irregular,
⇒ not controlled by magnetic fields;
asymmetry ⇒ binary formation





collapsing protostellar envelopes
are often highly structured;
implications for disk formation?

Protostars: images of (rotating) infall forming rotating disks

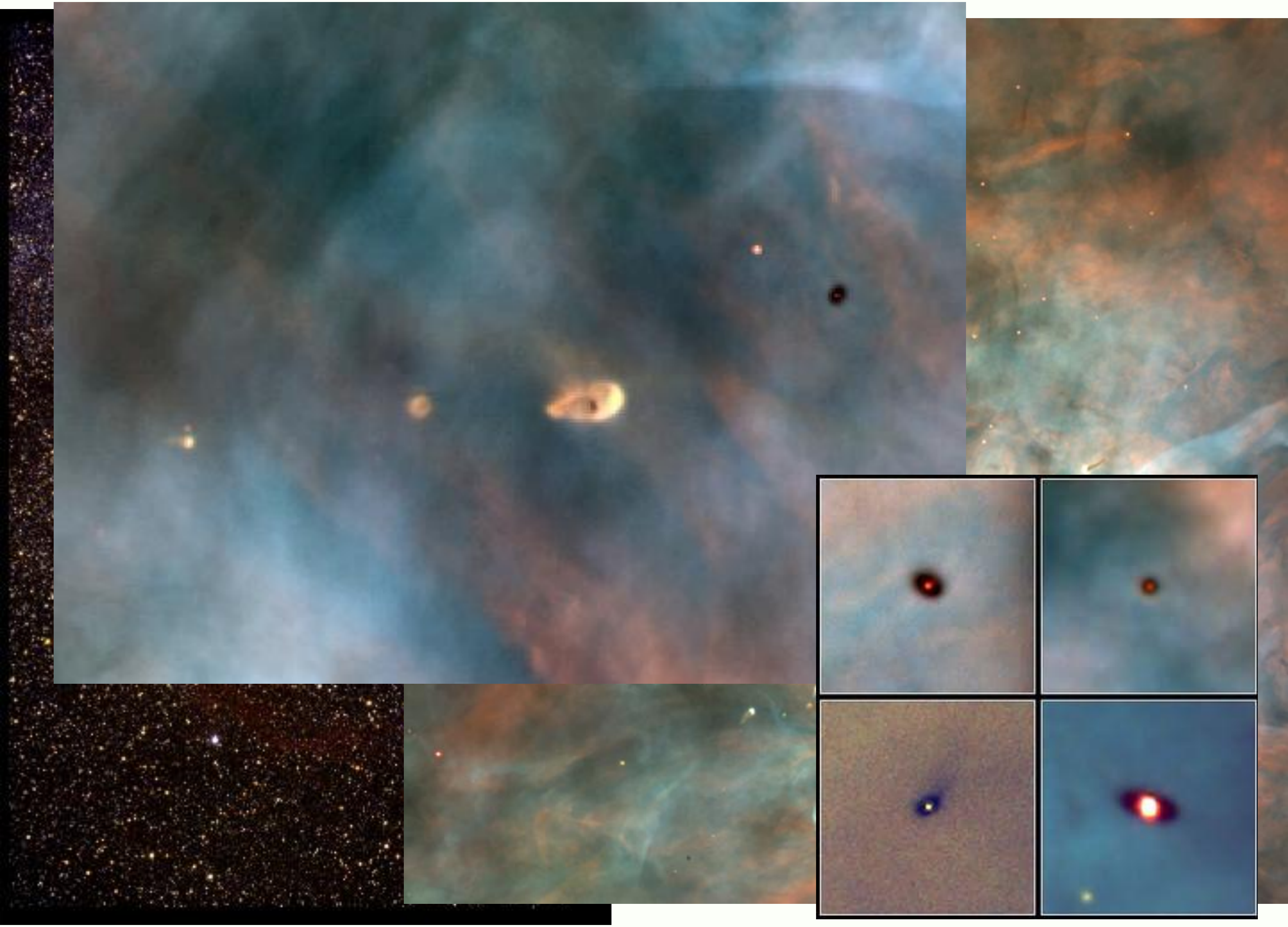


Young Stellar Disks in Infrared

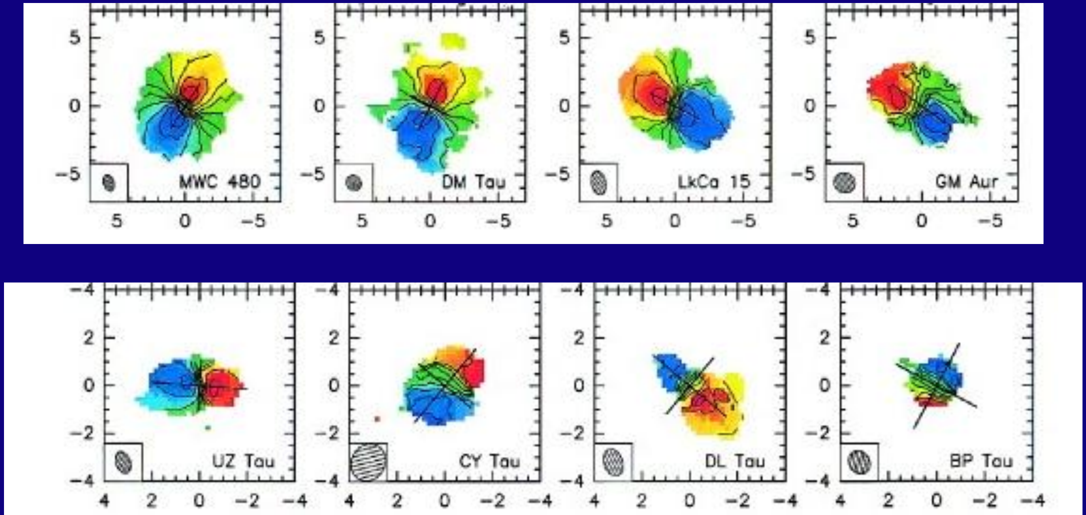
HST • NICMOS

PRC99-05a • STScI OPO

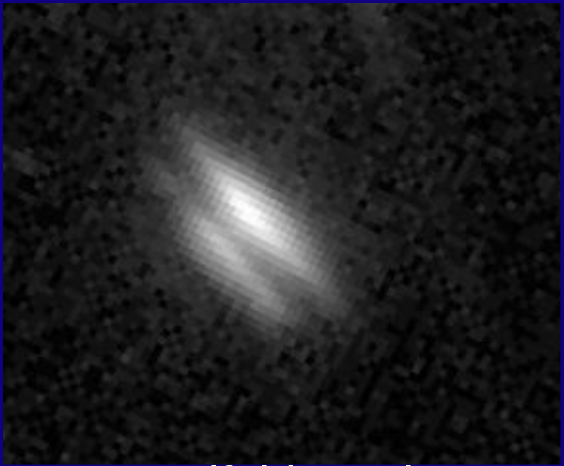
D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA



Rotating disks in mm-wave CO emission

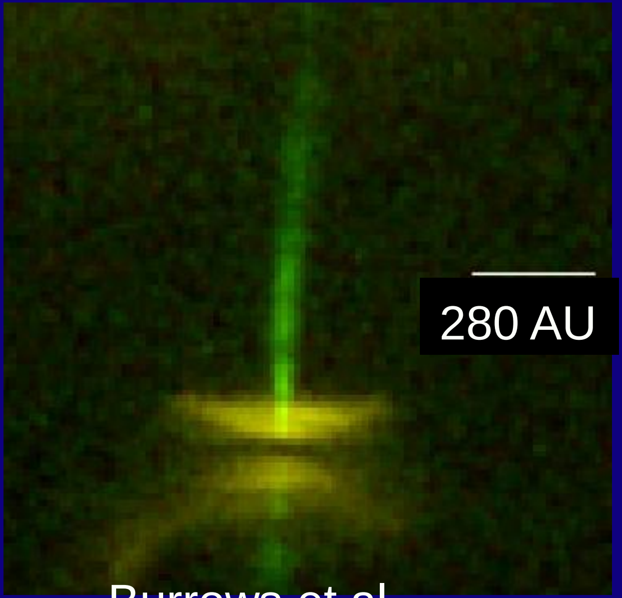


Simon
Dutrey
Guilloteau



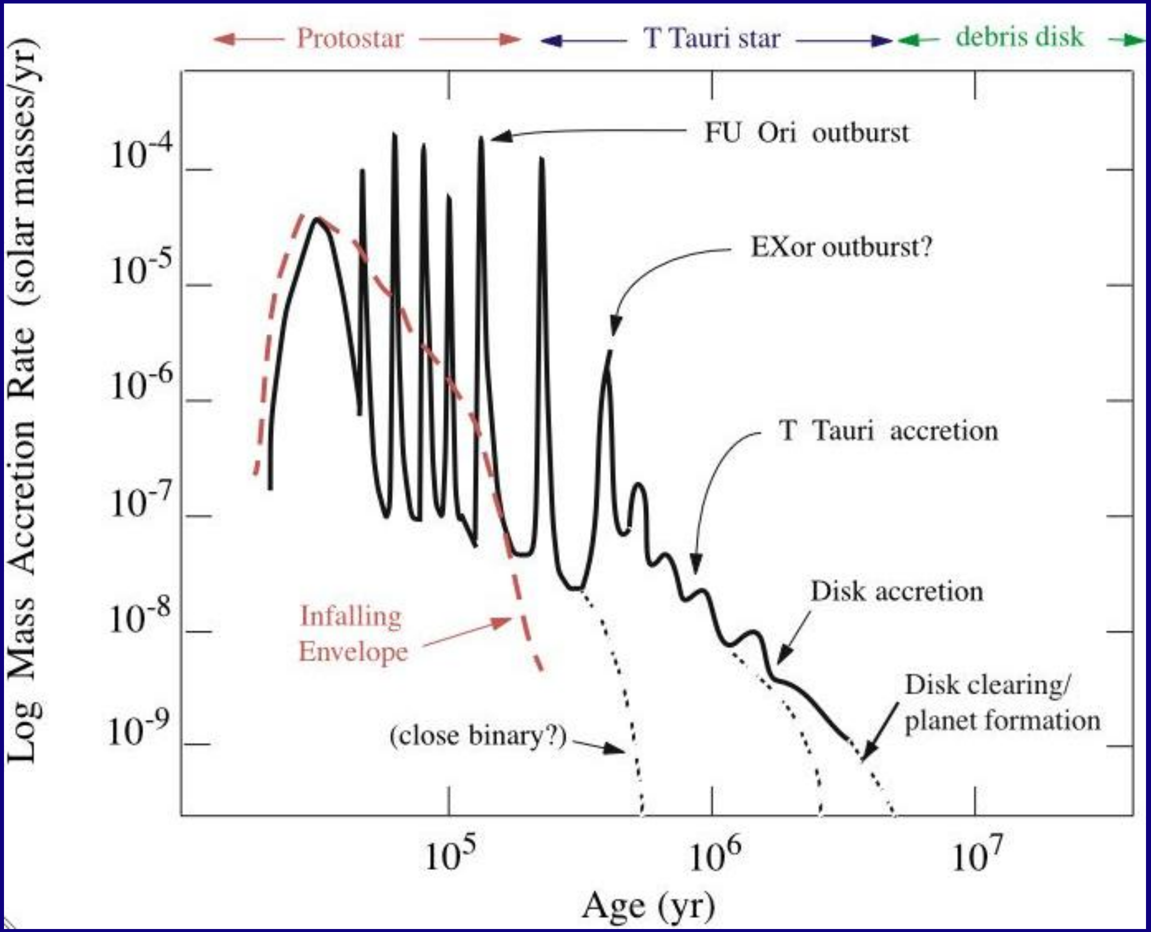
Stapelfeldt et al

disks seen in
scattered light

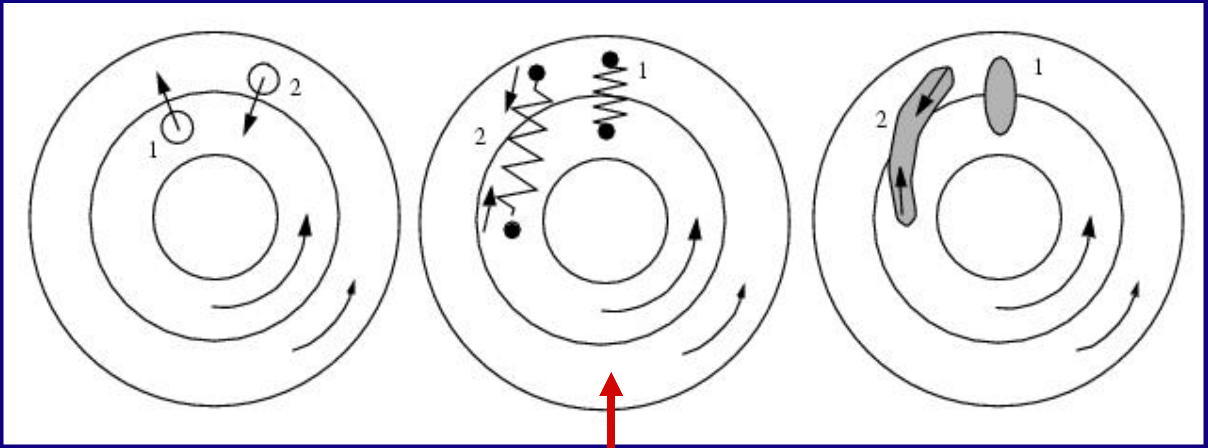


Burrows et al.

Most of the stellar mass is accreted in the protostellar phase - from disks! - in outbursts (?)

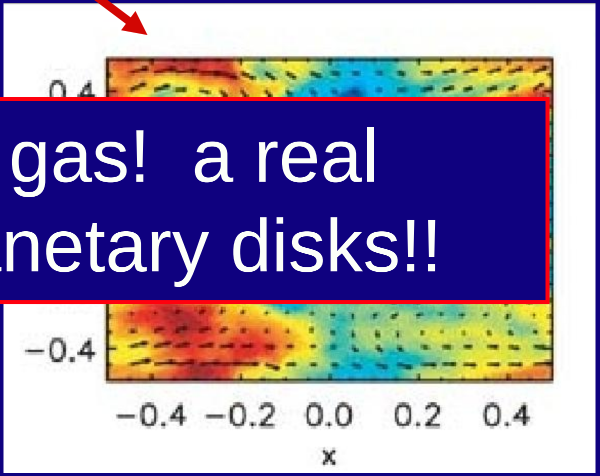


Why do disks accrete?



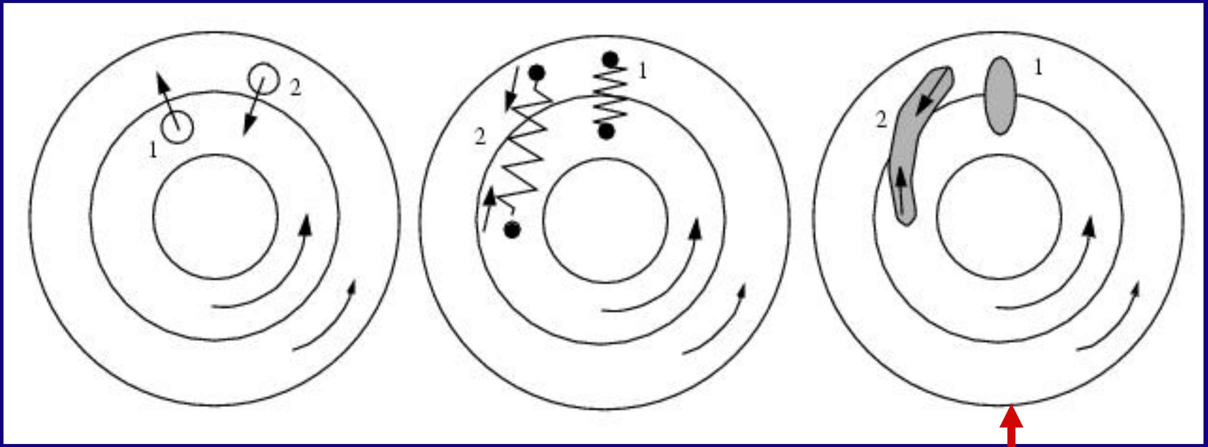
1. the magnetorotational instability (MRI)

side views



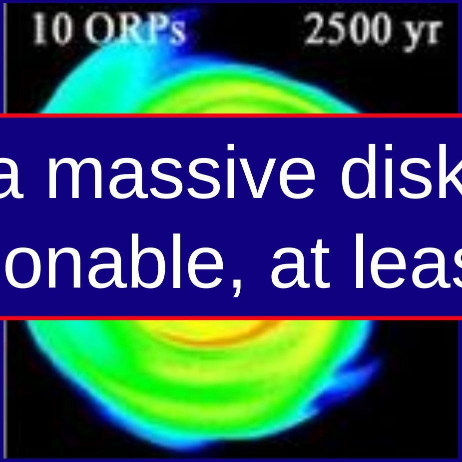
CAUTION! Need ionized gas! a real problem for cold protoplanetary disks!!

Why do disks accrete?



2. the gravitational instability (GI)

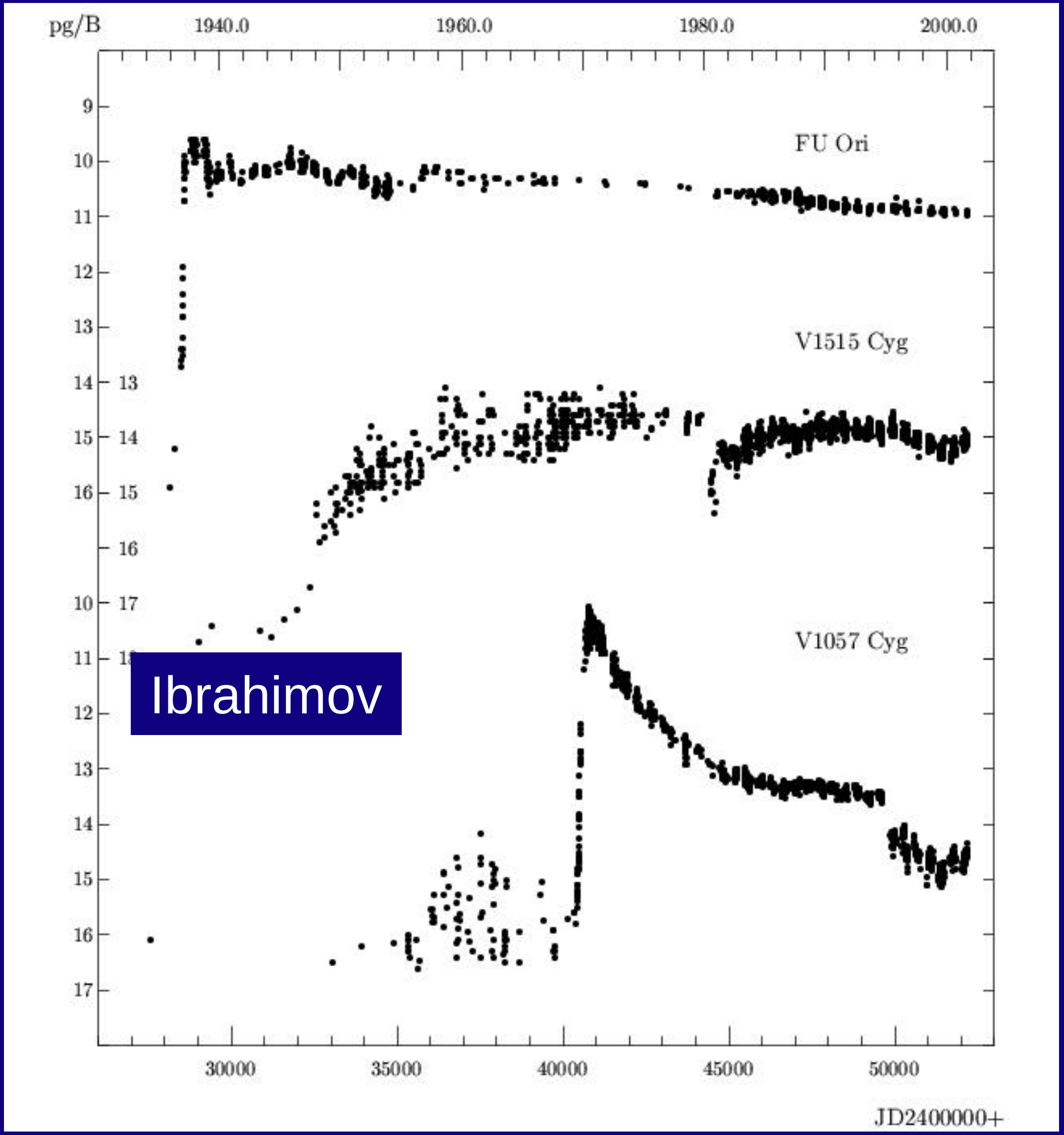
Need a massive disk, >~ 0.1 M(star)... but this is reasonable, at least in early evolution



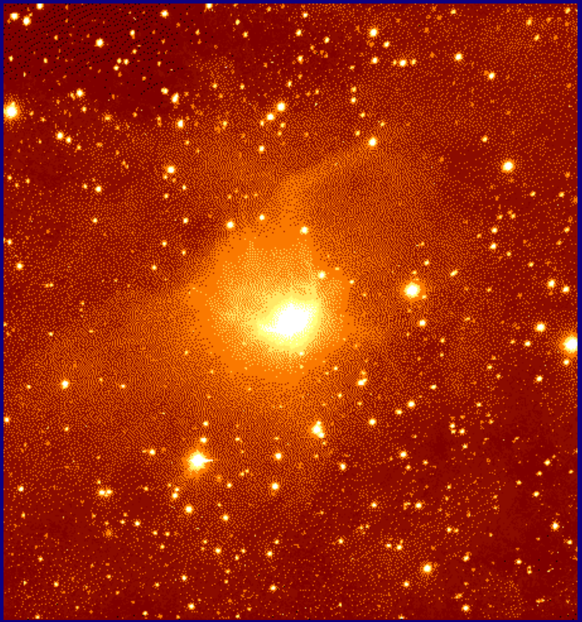
Boley et al.

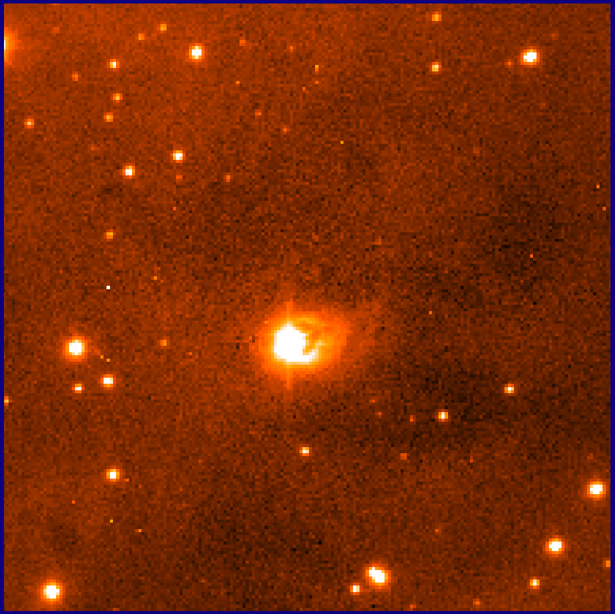
Fukagawa et al.

FU Ori objects - outbursts of disk accretion - ~ 10 M(Jup) in ~ 100 years

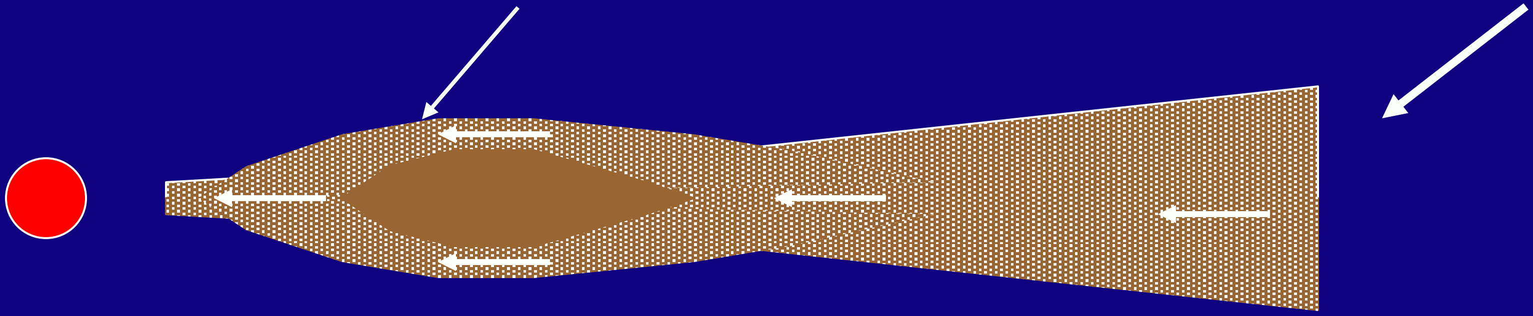


Ibrahimov





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



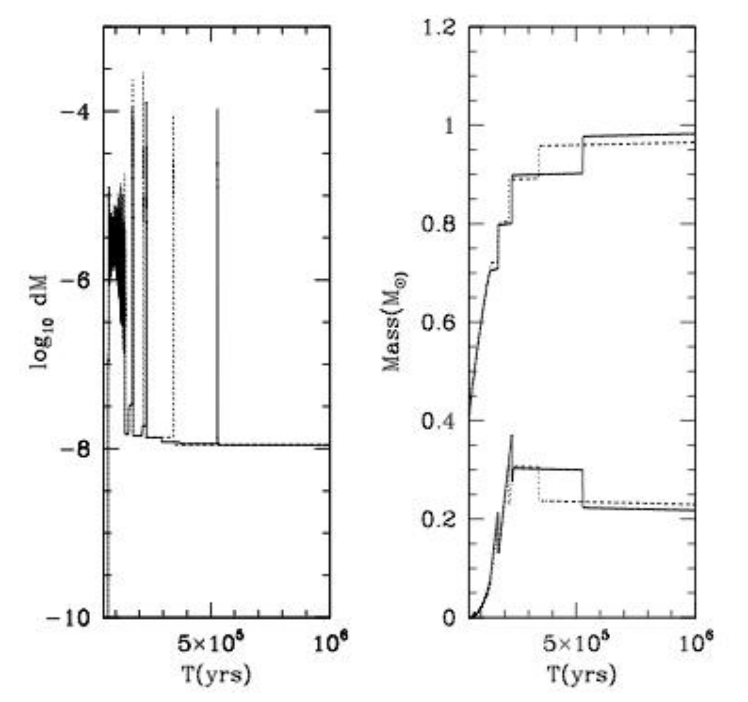
mass added at outer edge (infall)

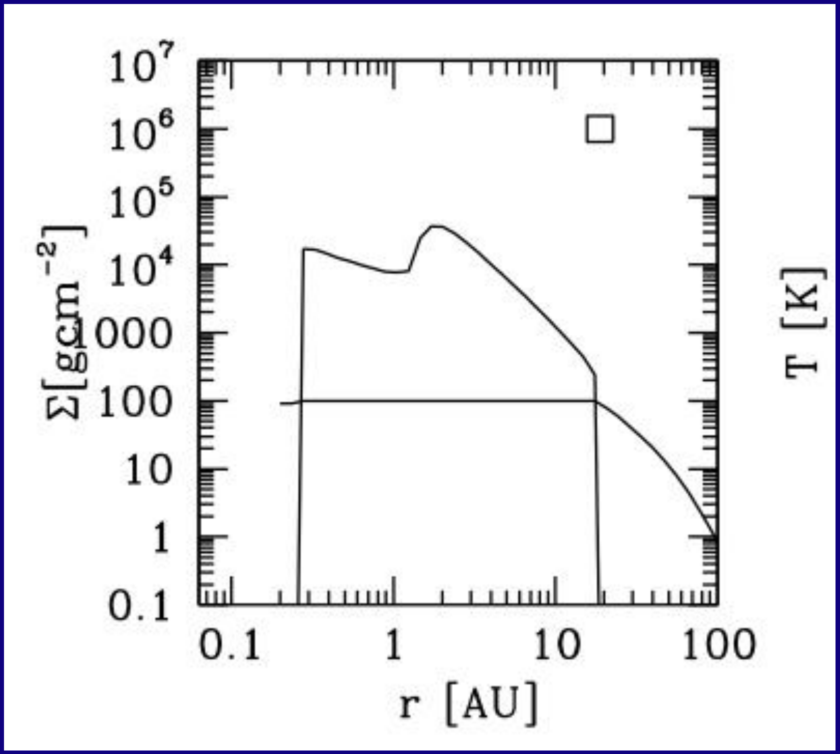
matter builds up in dead zone

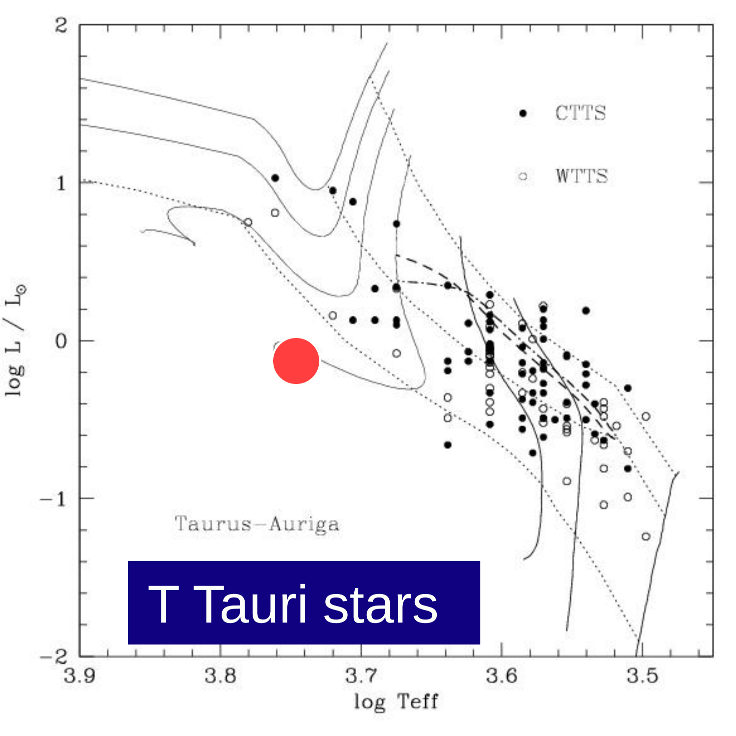
Steps:

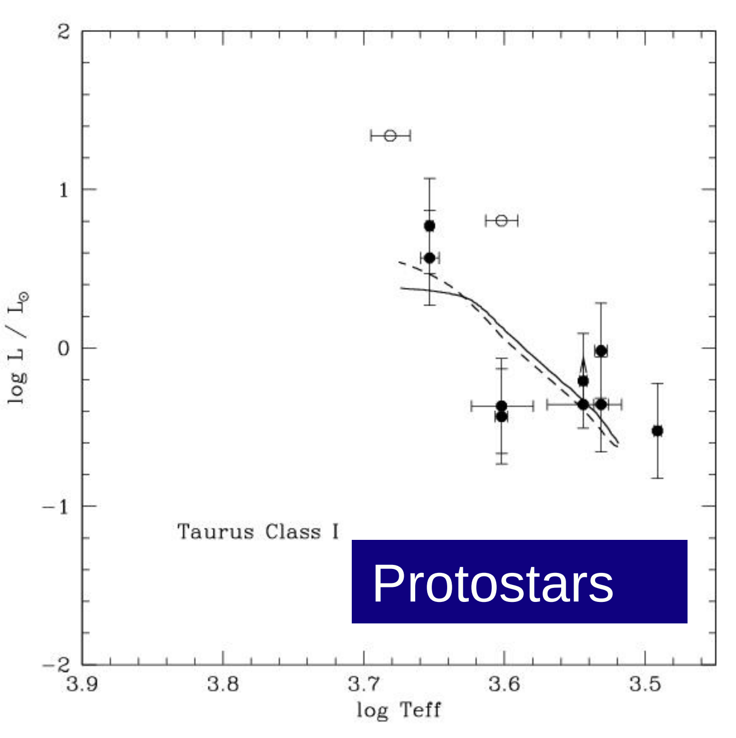
1. matter comes in from outer disk (via gravitational instability)
2. piles up in inner disk because MRI is not sufficiently active - too cold!
3. with some dissipation at high Σ, T increases - *thermal* activation of MRI
4. inward cascade of material driven by sudden increase in viscosity

Zhu, Hartmann, & Gammie 2009; dead zone + active layer; outbursts during infall, slow evolution after, very high surface density @ 0.3-5 AU





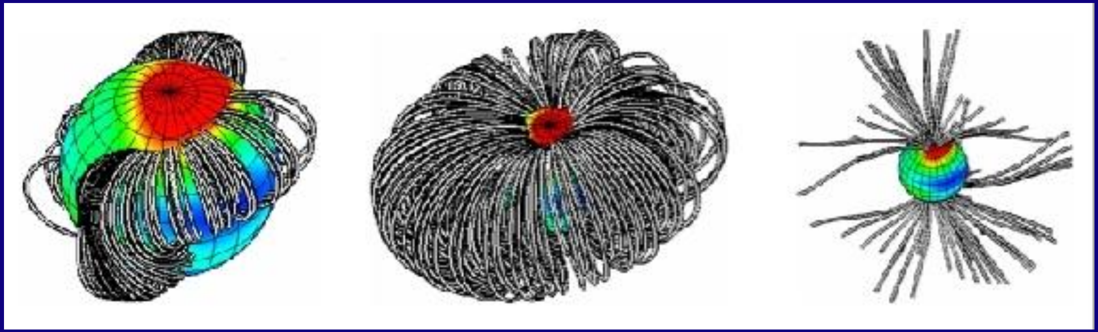

T Tauri stars

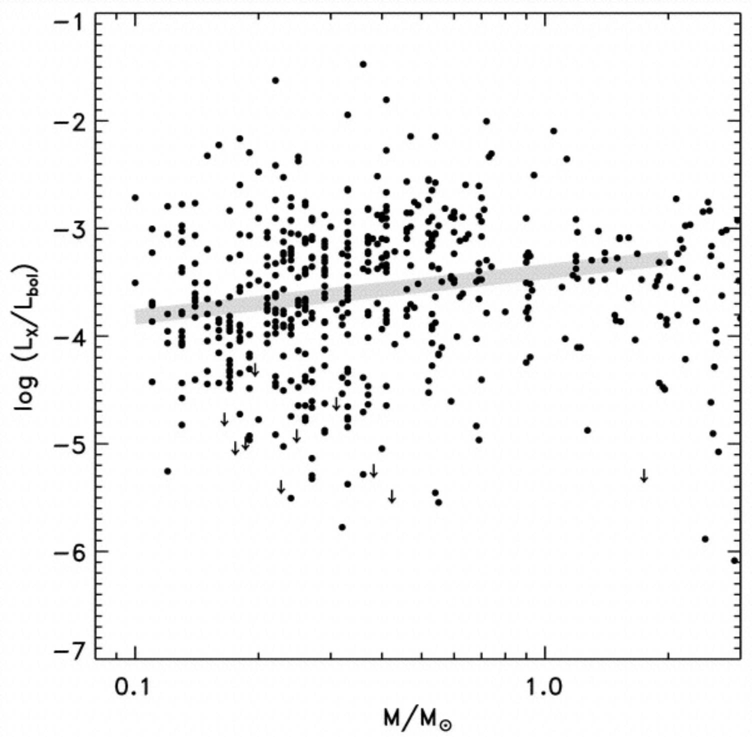

Protostars

Protostars ⇒ T Tauri stars (1 Myr-old solar-type stars); R (initial) ~ 2 Rsun

gravitational contraction slowed by D fusion ("birthline")

T Tauri stars are very magnetically active (Johns-Krull, Valenti, Donati, Jardine et al.)

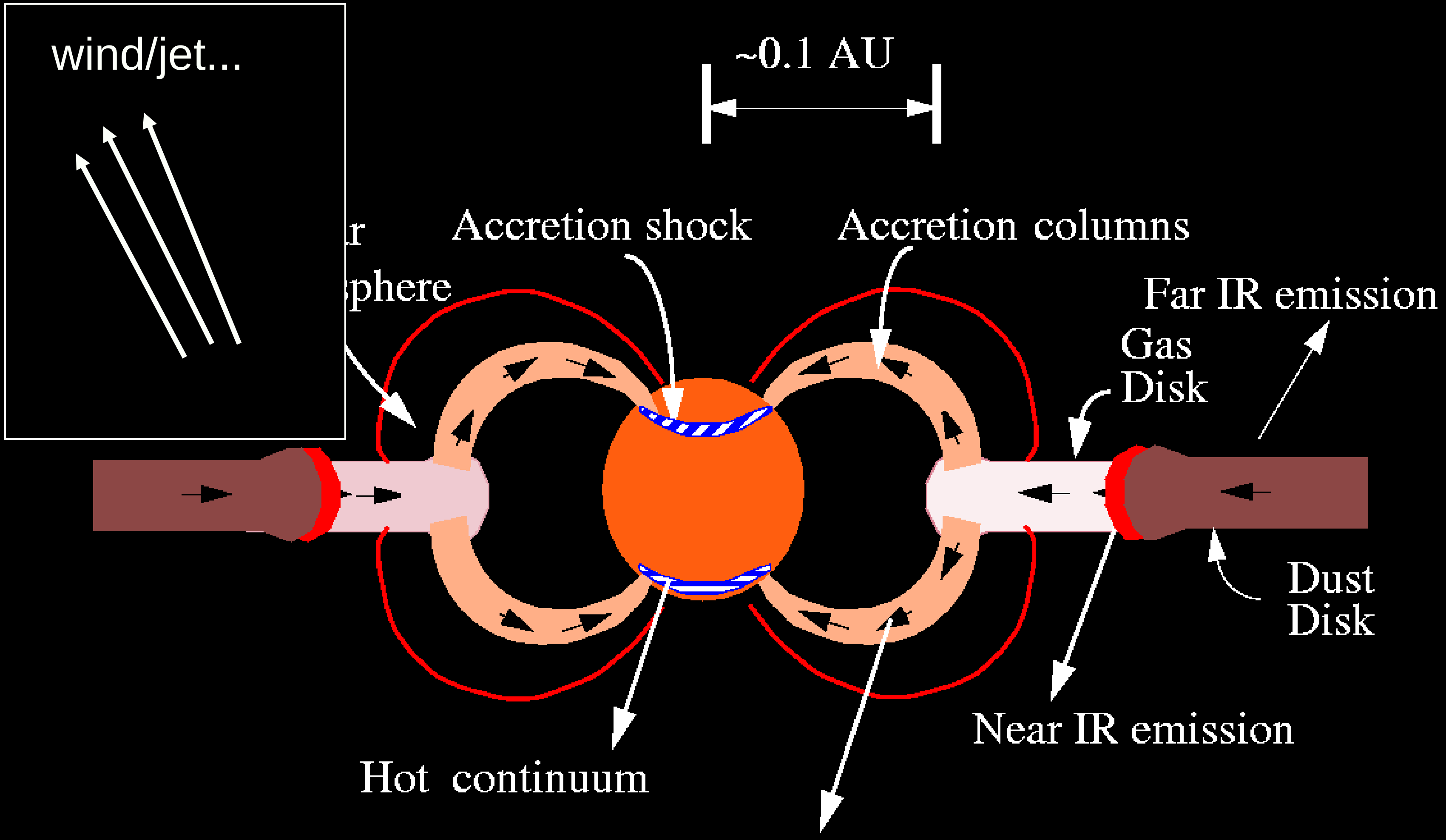




- Photospheric fields ~ 2 kG, covering factors 10-20% or more of stellar aurface
- X-ray emission ~ 10^{-3} L_*, about 1000 x solar

Preibisch et al. 2005

T Tauri star - magnetospheric accretion



wind/jet...

~0.1 AU

r

phere

Accretion shock

Accretion columns

Far IR emission

Gas Disk

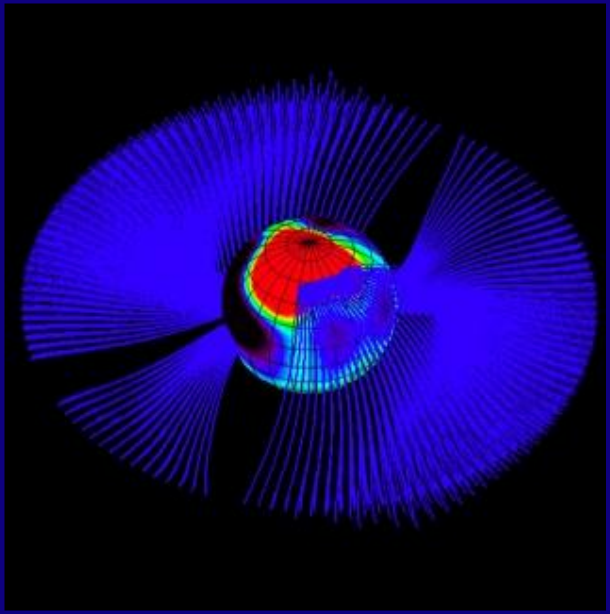
Dust Disk

Near IR emission

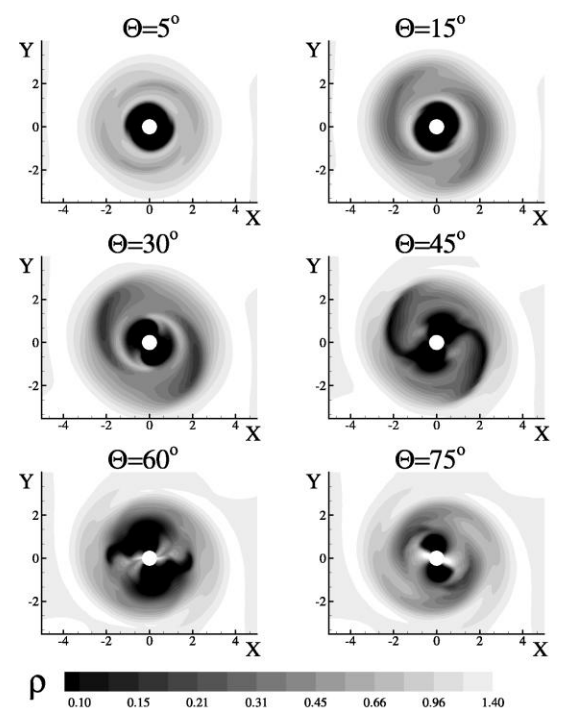
Hot continuum

Broad emission lines (Hα , Br γ , etc.)

Magnetospheres are complex



Jardine, Donati et al.



Romanova et al. 2003, 2004

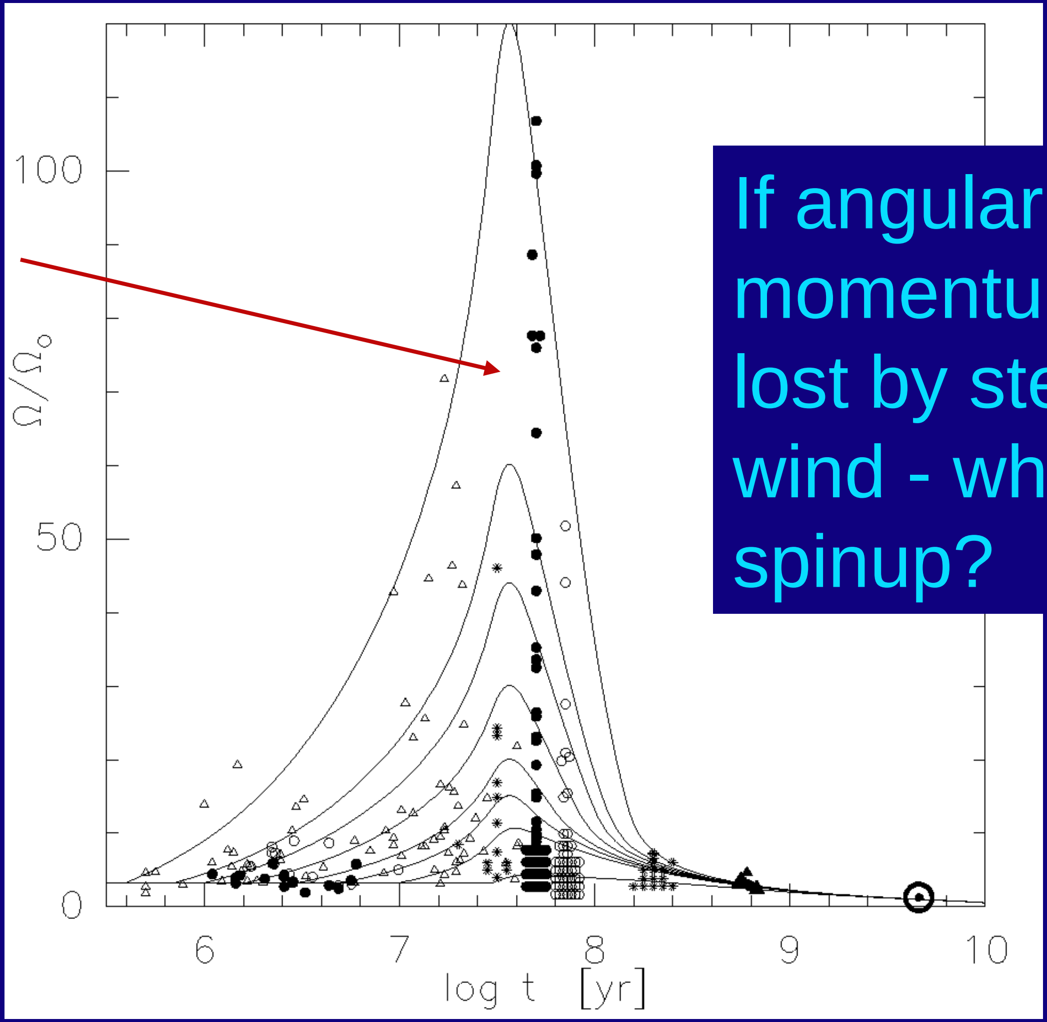
Continuum emission: (Calvet & Gullbring 1998)

- very small (~ 1%) covering factors
- Ingleby & Calvet (in prep); lower-mass flux tubes, f ~ 10%

⇒ ***accretion through many individual flux tubes***

T Tauri stars are SLOW ROTATORS despite formation by accretion of rapidly-rotating disk material

(spinup due to contraction toward MS



If angular momentum lost by stellar wind - why spinup?

Stauffer et al., Bouvier et al. 1997

The angular momentum (and energy!) problem

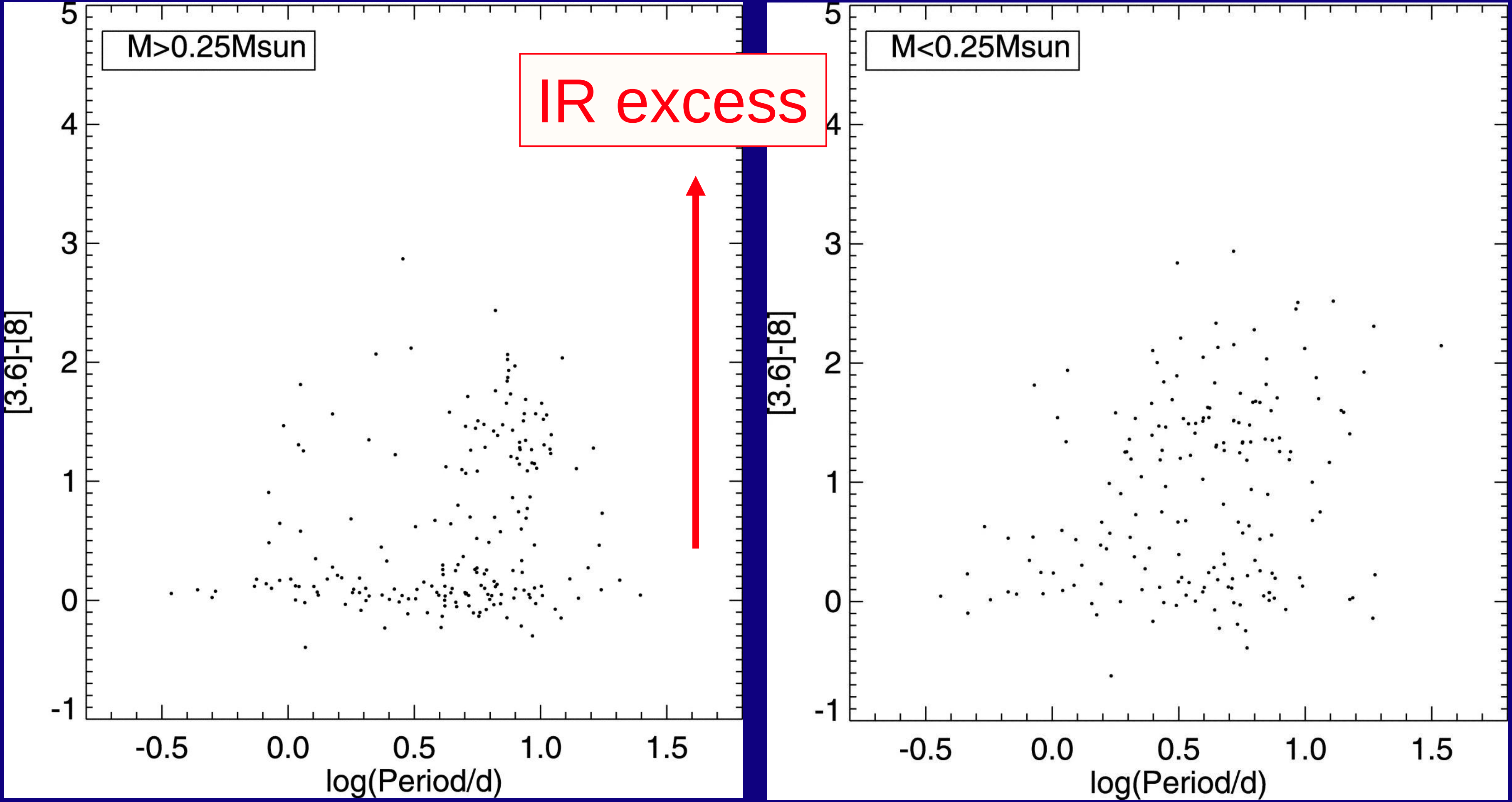
If stars accrete most of their mass from disks, they should be rotating rapidly

But they don't (~ 10% breakup for low-mass stars...)

This implies that a LARGE fraction of the accretion energy goes into whatever causes spindown ------- winds/jets! ($J = v_K r$; $KE = (1/2)\, v_K^2$)

Magnetosphere-disk spindown (?)

stars with disks rotate more slowly than those without...



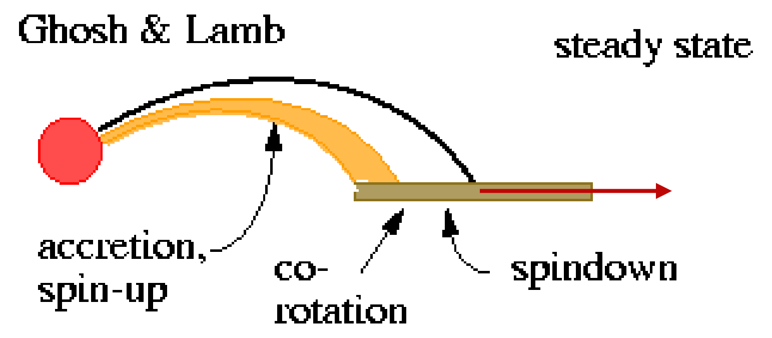
IR excess

Rebull et al. 2006

The angular momentum problem

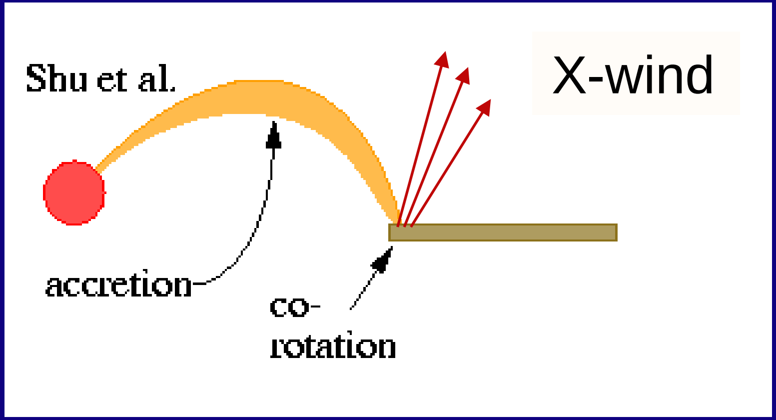
Accretion implies J(disk) ⇒ J(star); how to get rid of it?

Solution 1: different field lines
problem: field lines wind up unless perfect "slippage"

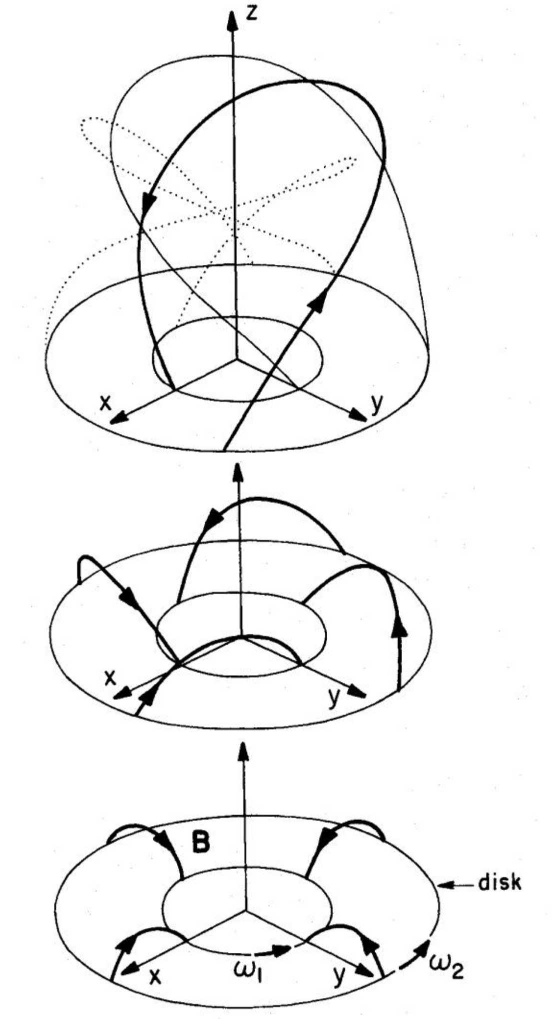


(Konigl, Collier Cameron & Campbell)

Solution 2: exact co-rotation, no winding
problem: unrealistic (axisymmetric, etc.)
detailed assumptions of angular momentum transfer?



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



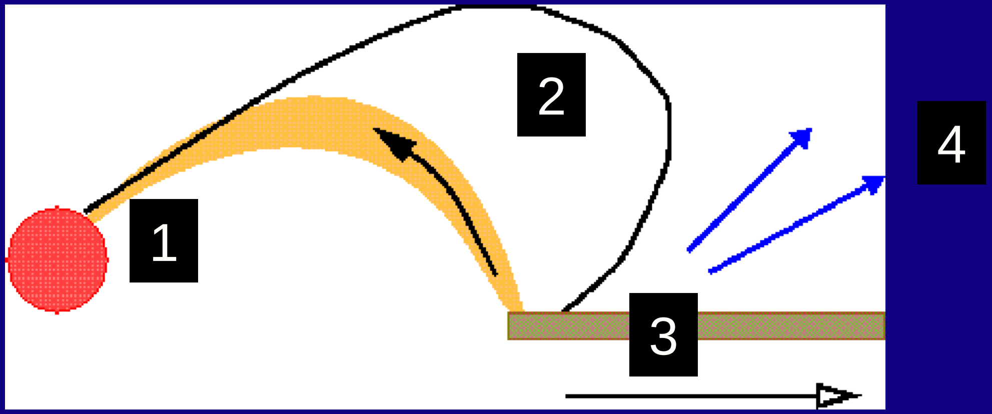
reconnection-

$\Rightarrow$ limits spindown (too much?)

(Matt & Pudritz 2004)

Lovelace, Romanova, & Bisnovatyi-Kogan 1995

Alternating cycles of accretion and disk braking?



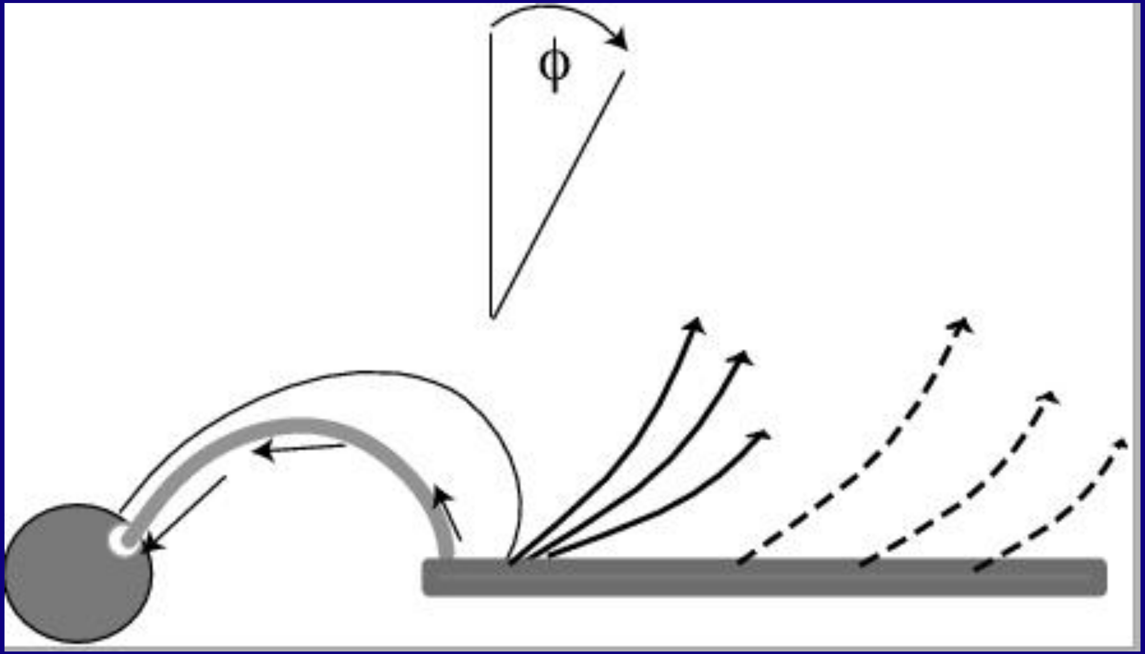
1. accretion

2. bulging field lines - material drains out onto star AND disk

3. accretion stops, field lines might move outside of corotation - disk braking

4. field configuration might assist disk outflow

When Φ > 30º, unstable equilibrium at Keplerian rotation - massive cold outflow (bead on a wire analogy)



Matt & Pudritz (2008a,b) suggest-
STELLAR WINDS! (again)

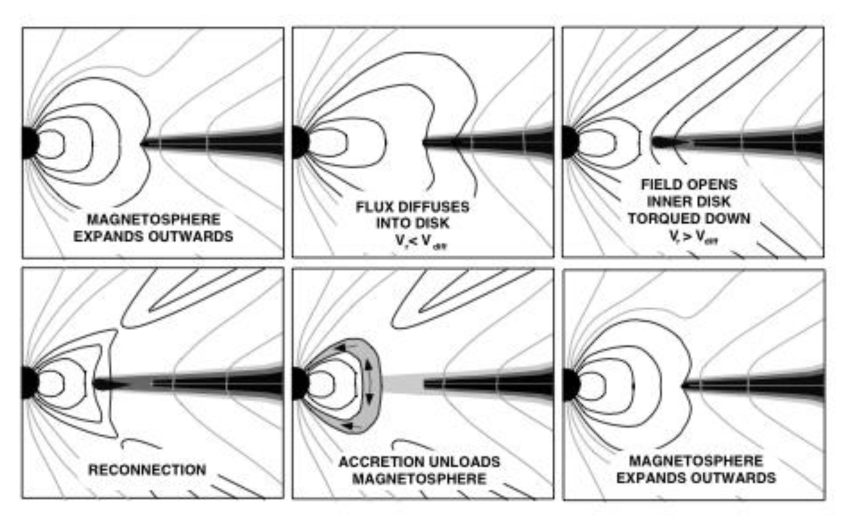
Advantages:

- field lines connect to star, so star is directly spun down
- don't need star to be spinning at breakup!

Disadvantages:

- stellar (magnetic activity) winds not powerful enough (otherwise, spindown to main sequence)
- need to tap into accretion energy! but HOW?

Wind driven by magnetic field inflation

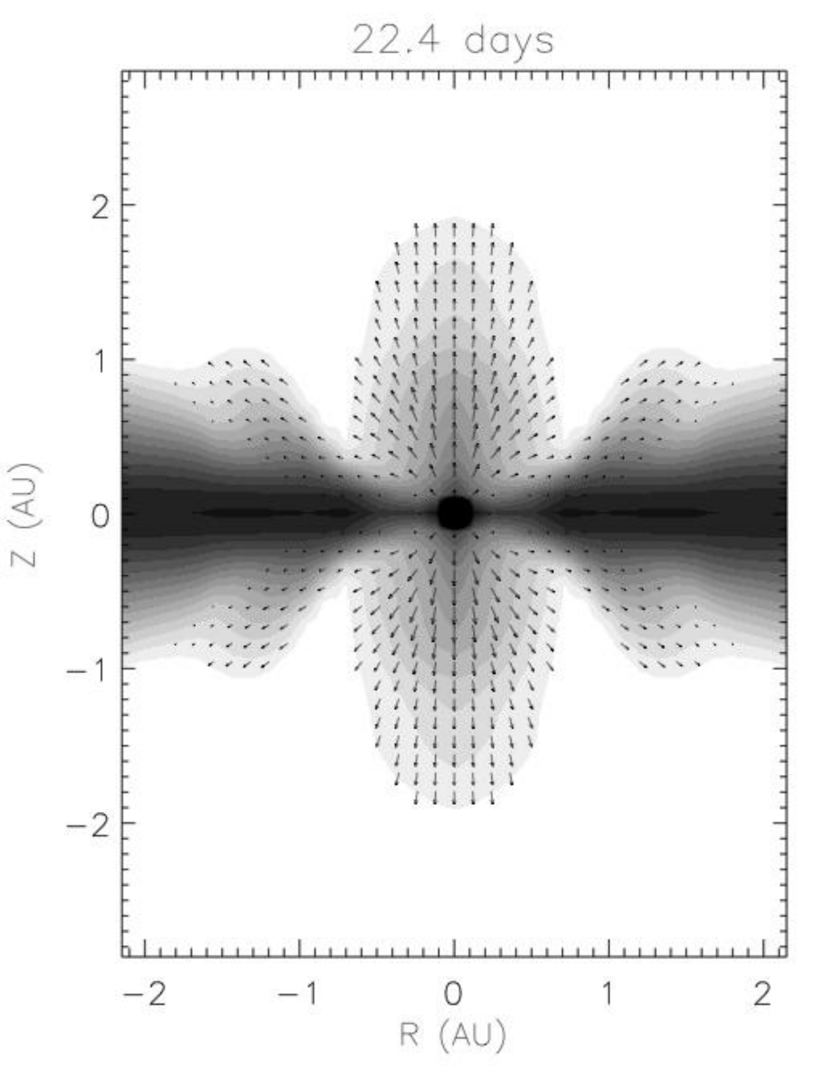


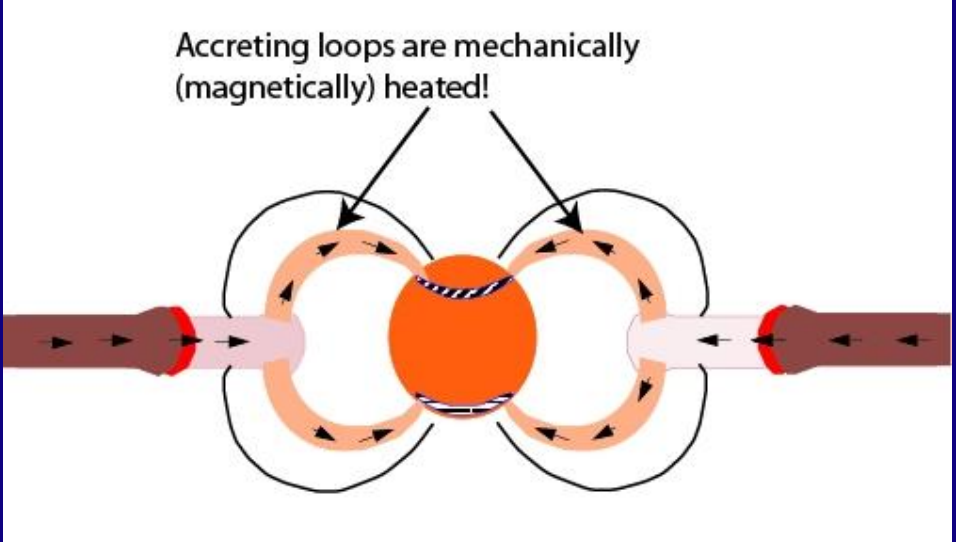
Goodson, Winglee, Böhm 1997; Goodson, Winglee 1999; Matt et al. 2002

⇒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!)



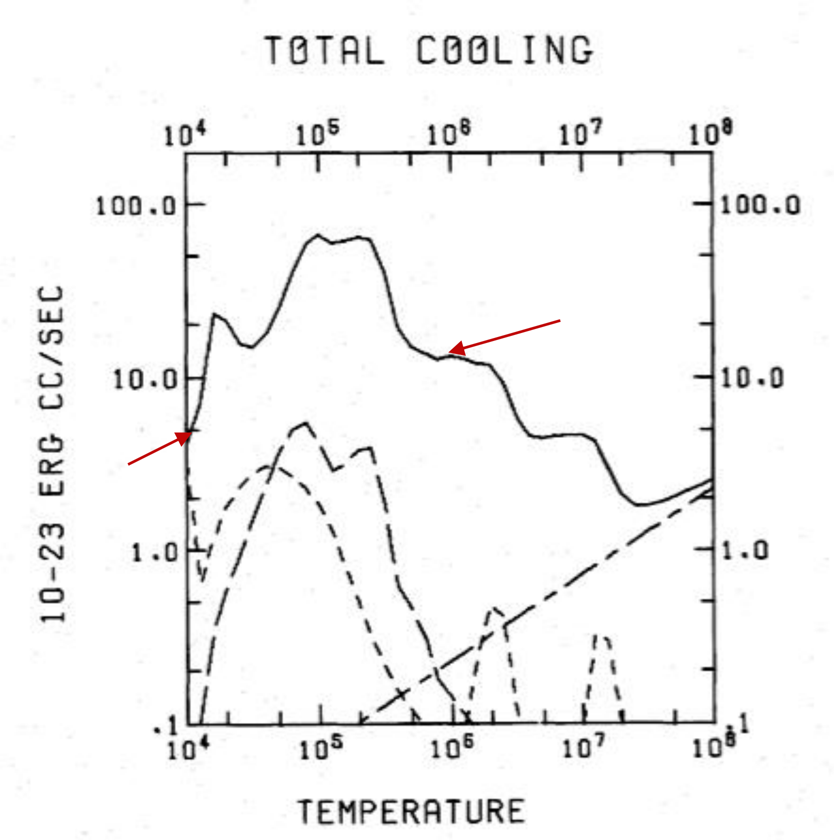


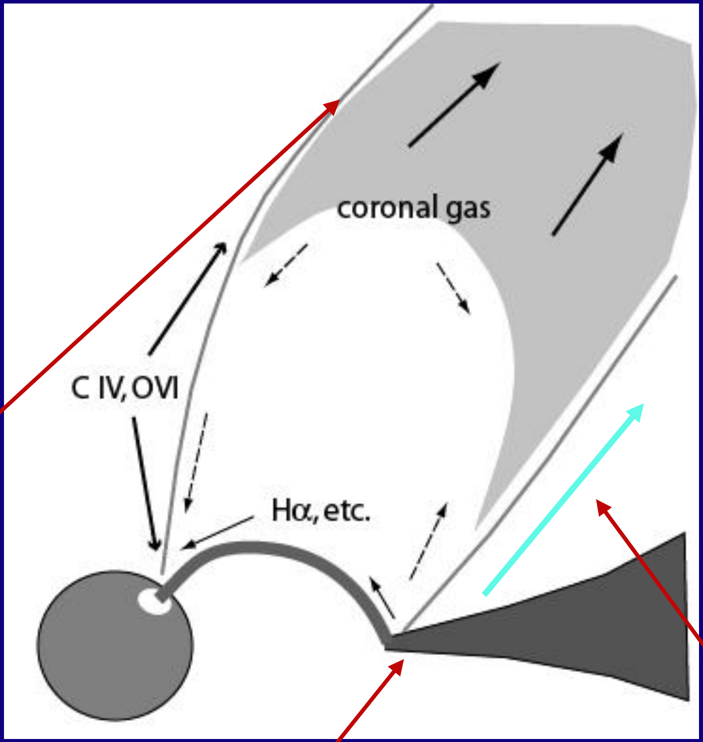
radiative energy loss ~ 1-10% L_{acc}

Loops are heated to ~ 10^4 K

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

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





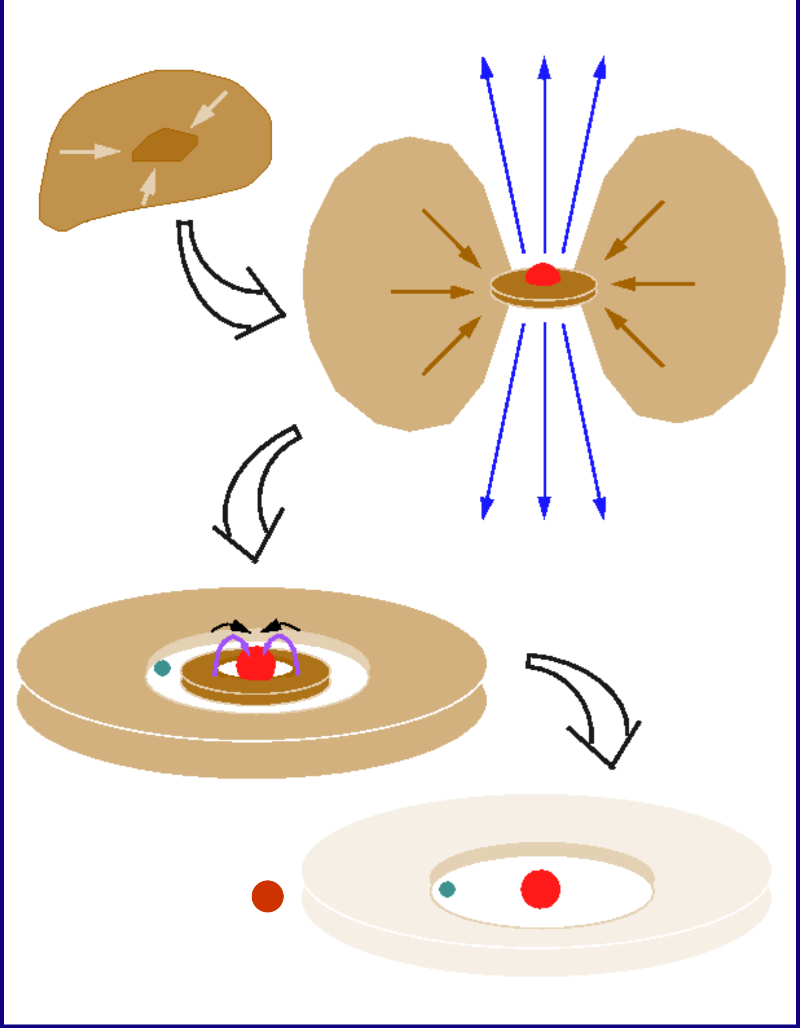
“Accretion-powered” stellar wind-not enough by itself(?)

Some disk braking from field lines tied to the disk outside of corotation?

Some disk wind angular momentum loss from inner disk?

Formation of the planets

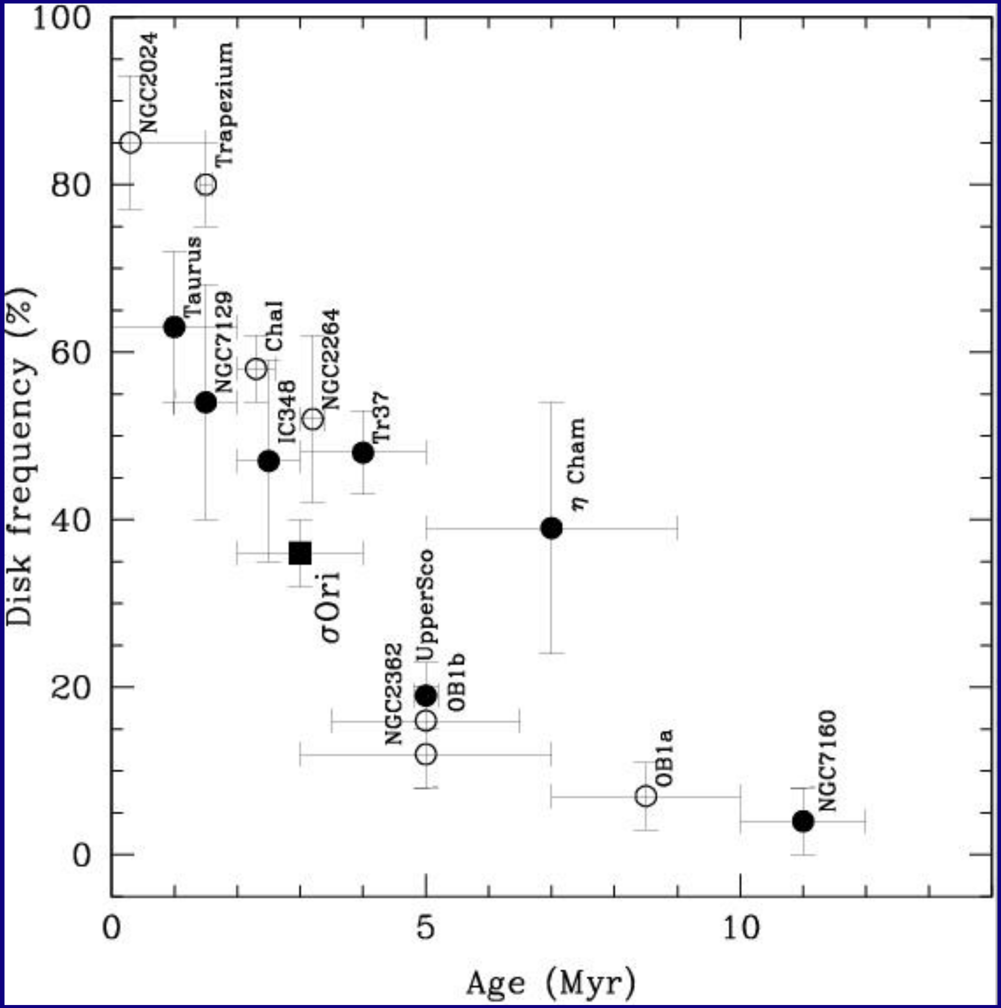
- cold gas cloud collapses under gravity to form
  - protoSun with disk and jet. accretes mass from disk - **THE SOLAR NEBULA**
- planets form in dusty rotating disk
  - dust gets “swallowed up” (accreted) in larger bodies



Disk “frequency” (small dust < 10 AU) decreases over few Myr

Current exoplanet statistics indicate ~ 15% of solar-type stars, << disk frequency at early ages

⇒ more to be found!

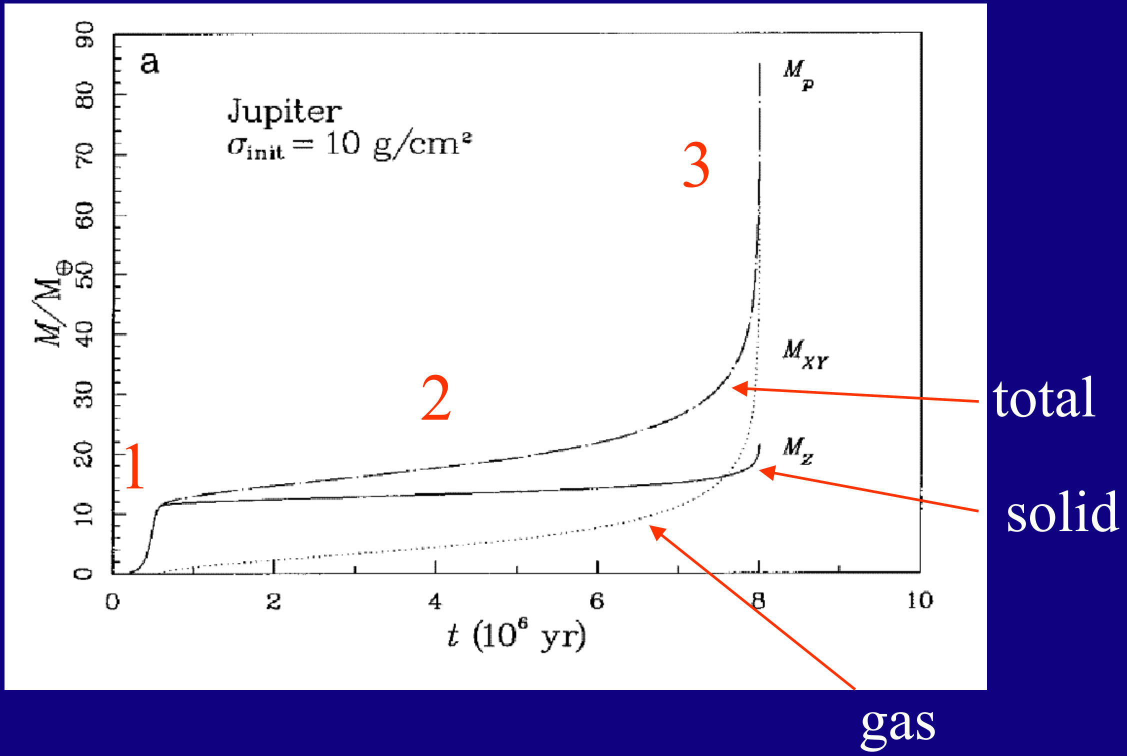


Giant planet formation theories

(core accretion)

- Phase 1: Runaway accretion of solids (crossing of planetesimal orbits)
- stops when feeding zone depleted
- Phase 2:Accretion of gas
- Phase 3: Runaway accretion of gas

Pollack et al. 1996



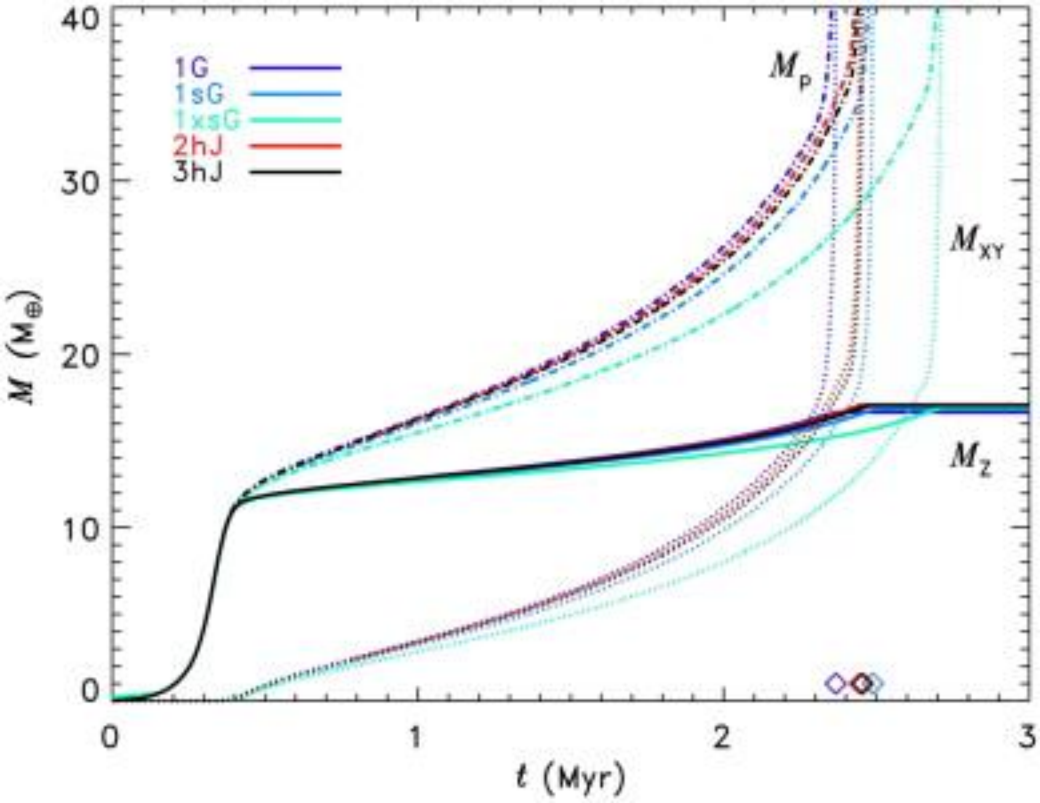
Giant planet formation takes too long?

Giant planet formation theories

- Lissauer, Hubickyj, D'Angelo, Bodenheimer 2009
- timescales ok

two effects:

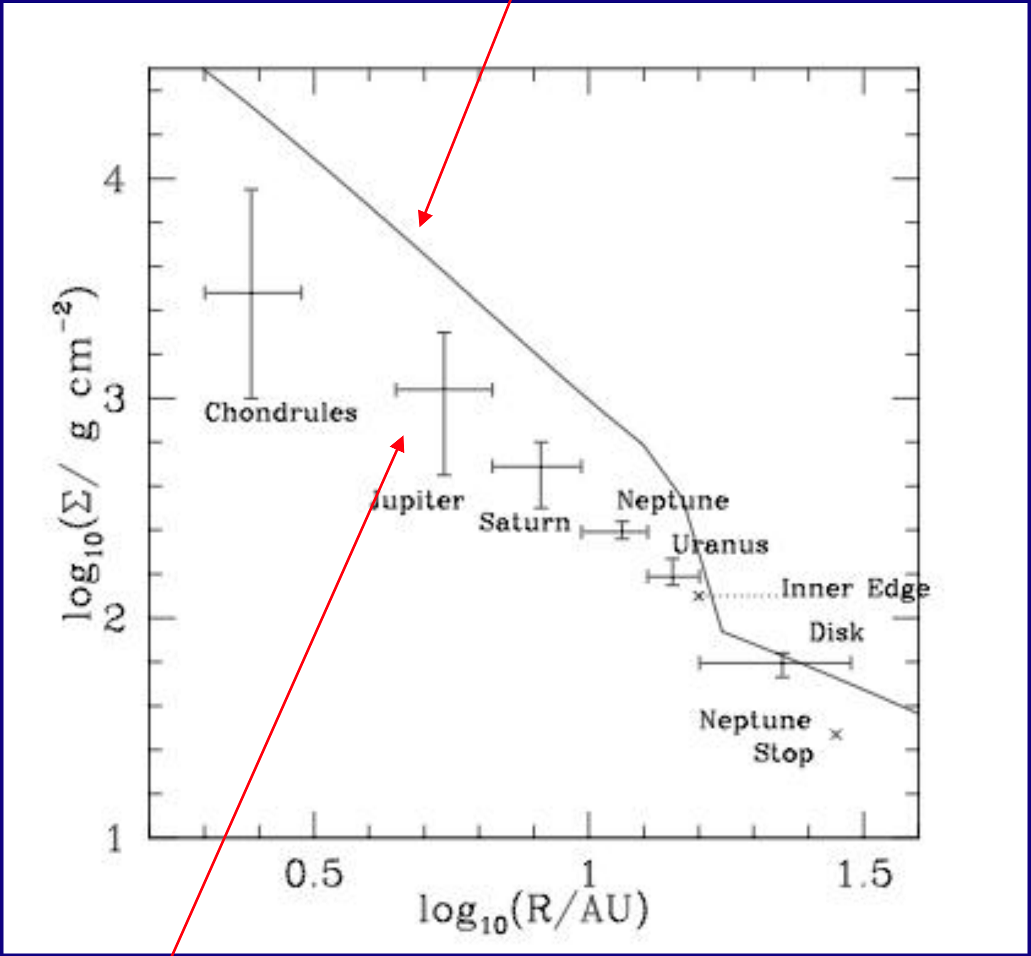
- 3 or more x the "minimum mass solar nebula" (MMSN)
- lower dust opacity - faster accretion (planet cools faster)



s

gas

Zhu et al. 2009 model w/dead zone; Σ >> MMSN!

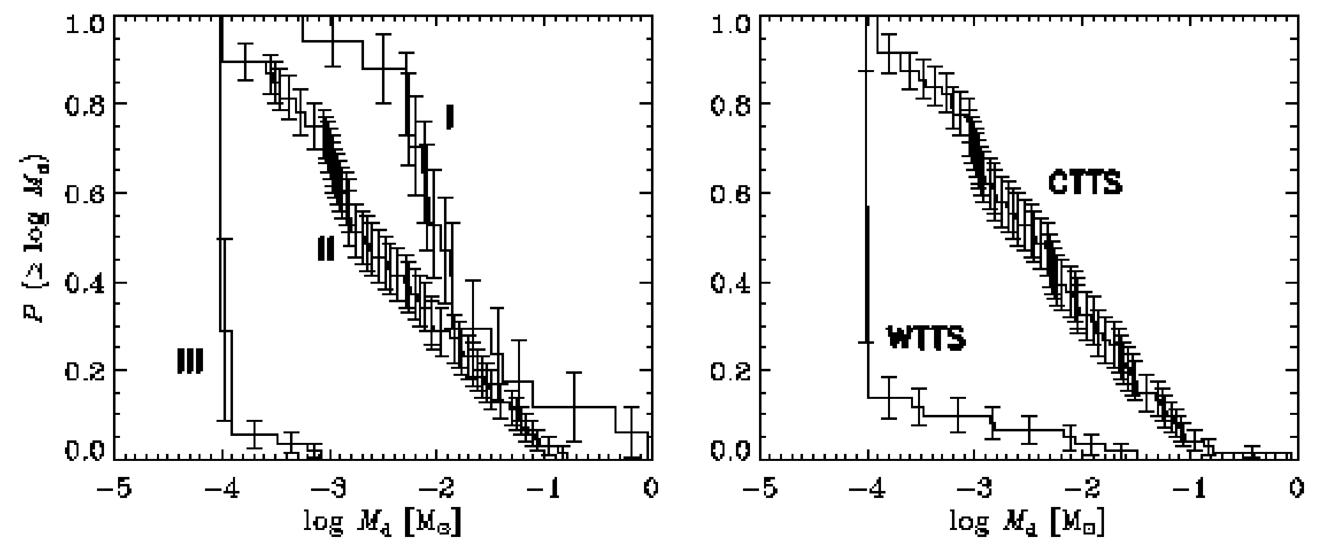


Compare with Desch reconstruction of solar nebula from "Nice" model (outward migration of giant planets)

Disk masses and dust emission

BUT: Median T Tauri disk mass in Taurus ~ 0.005 $M_{\odot}$ from 850μm fluxes- much lower than dead zone model!

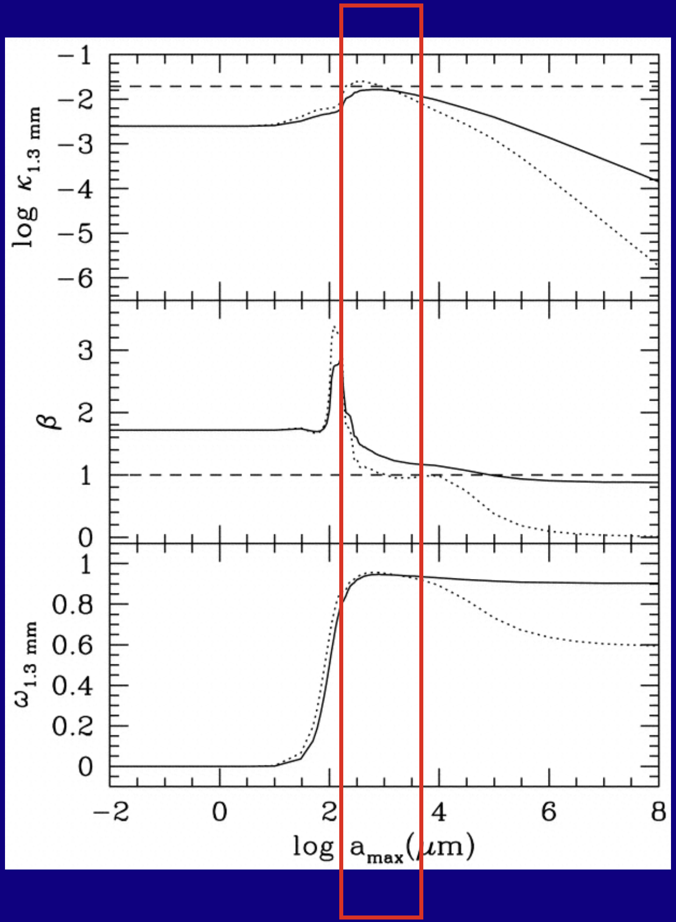
Andrews & Williams 2005



However, this assumes a specific dust opacity which is not that of the ISM ⇒ dust evolution

Disk masses?

Because dust MUST grow from ISM sizes - opacities are uncertain. If growth is does not stop at ~ 1 mm, opacities are LOWER than typically adopted.

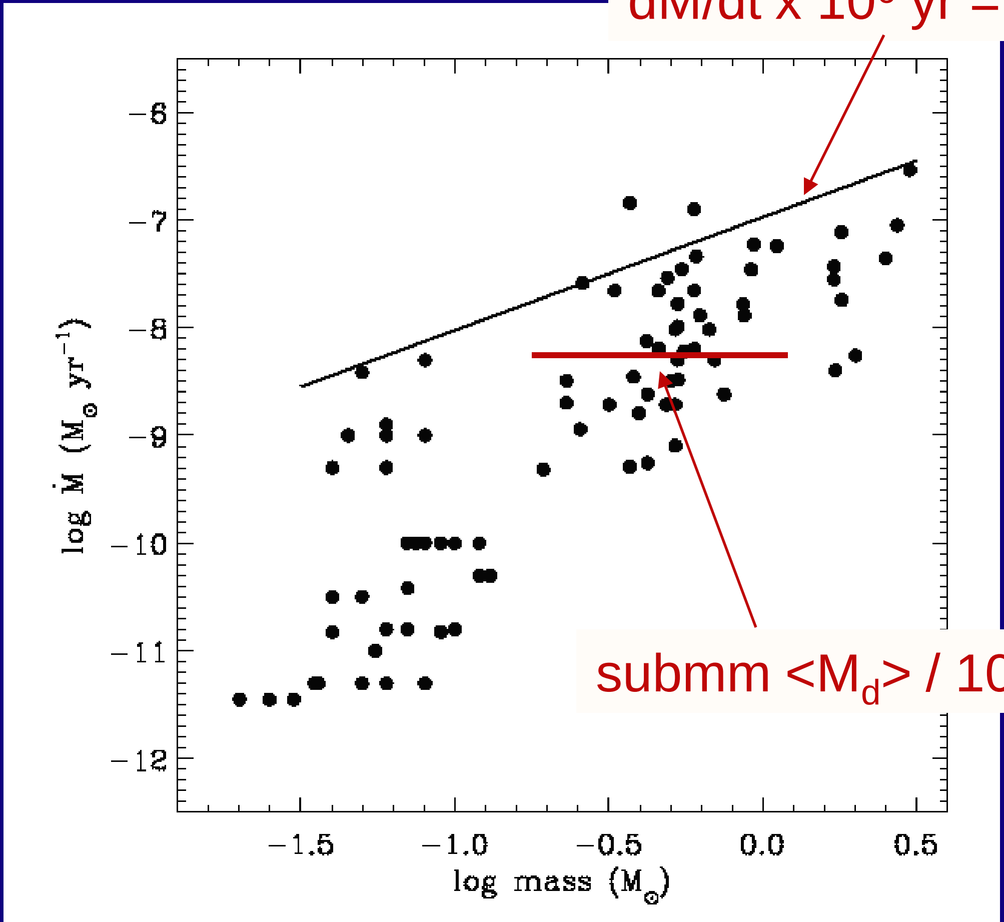


D’Alessio et al. 2001

Difficult to avoid the inference that disk masses have been systematically underestimated.

In addition, inner disks are unresolved and/or optically thick -

Accreted mass significant for solar-mass stars



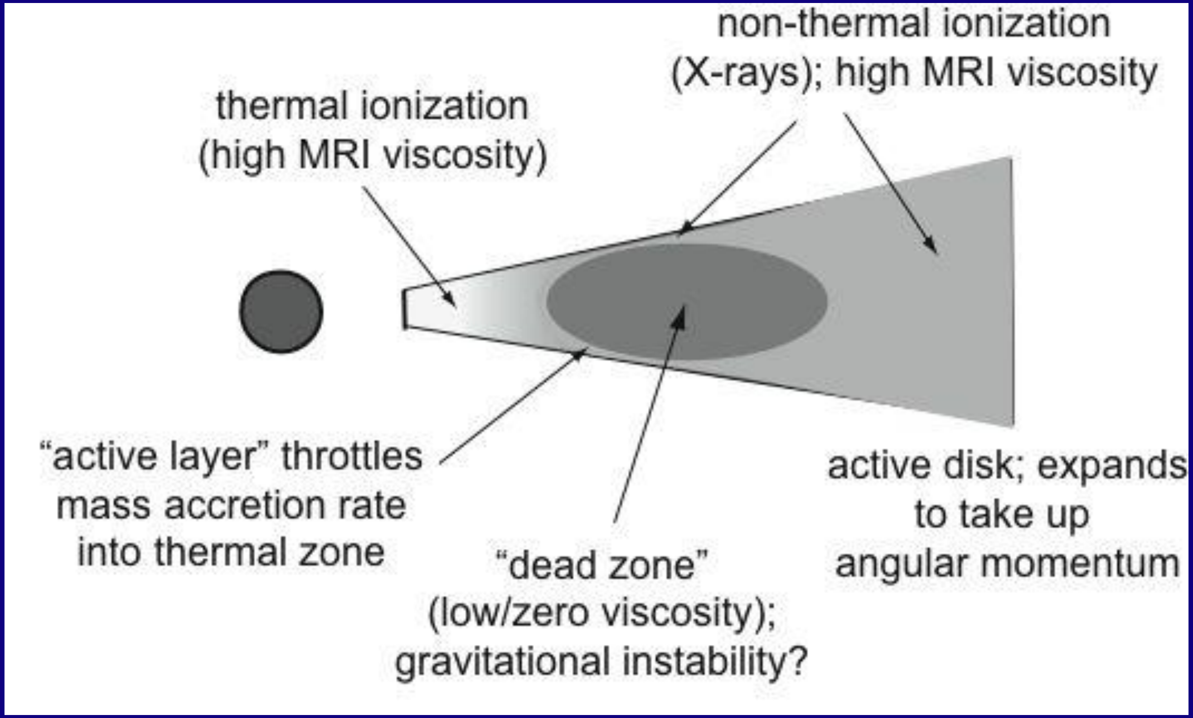
dM/dt x 10^6 yr = $0.1M_*$ - grav. instability?

submm $\langle M_d \rangle$ / 10^6 yr

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

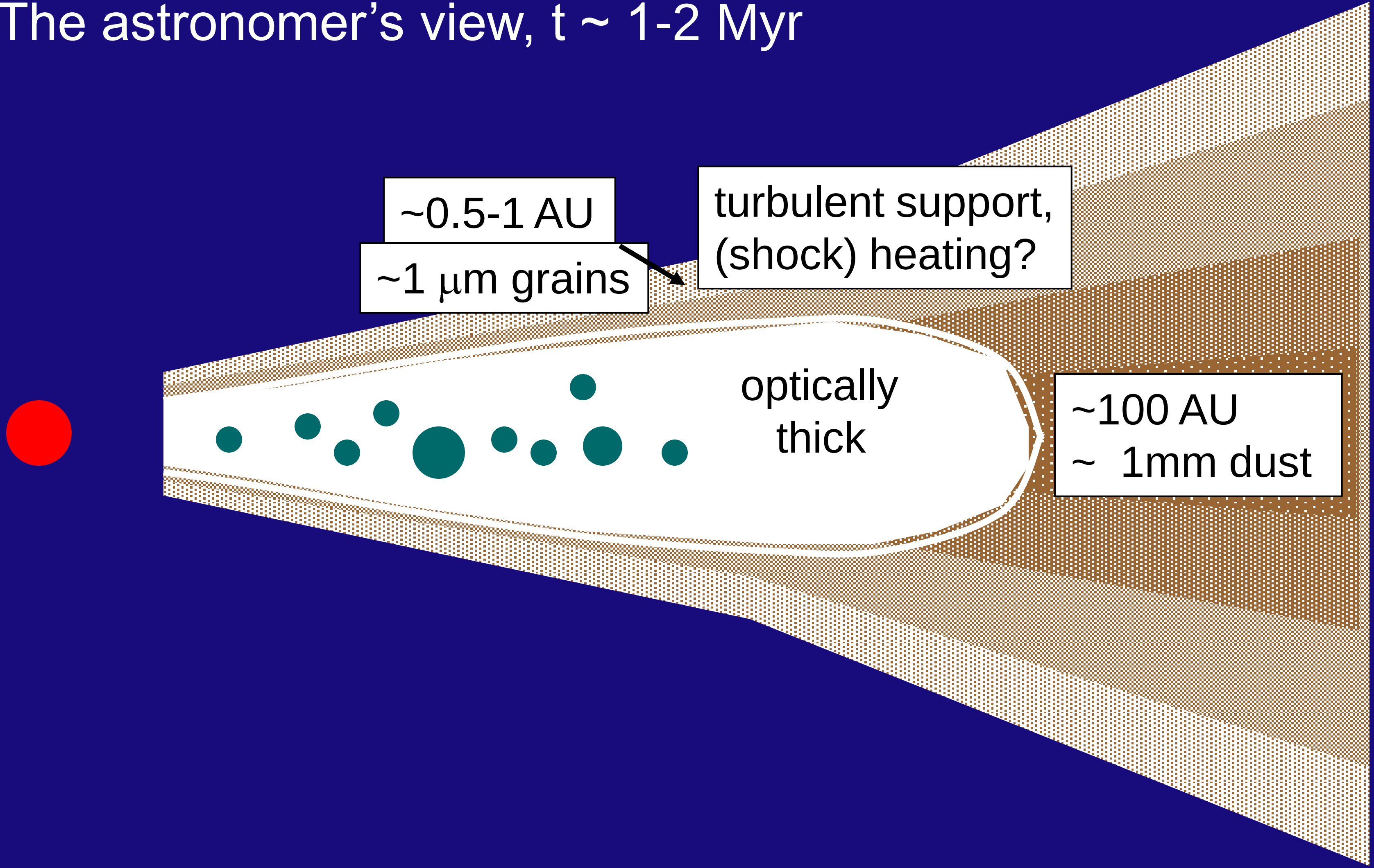
another argument why disk masses are underestimated by typical adopted mm opacities

“Dead zone” (Gammie 1996)



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

The astronomer’s view, t ~ 1-2 Myr



~0.5-1 AU

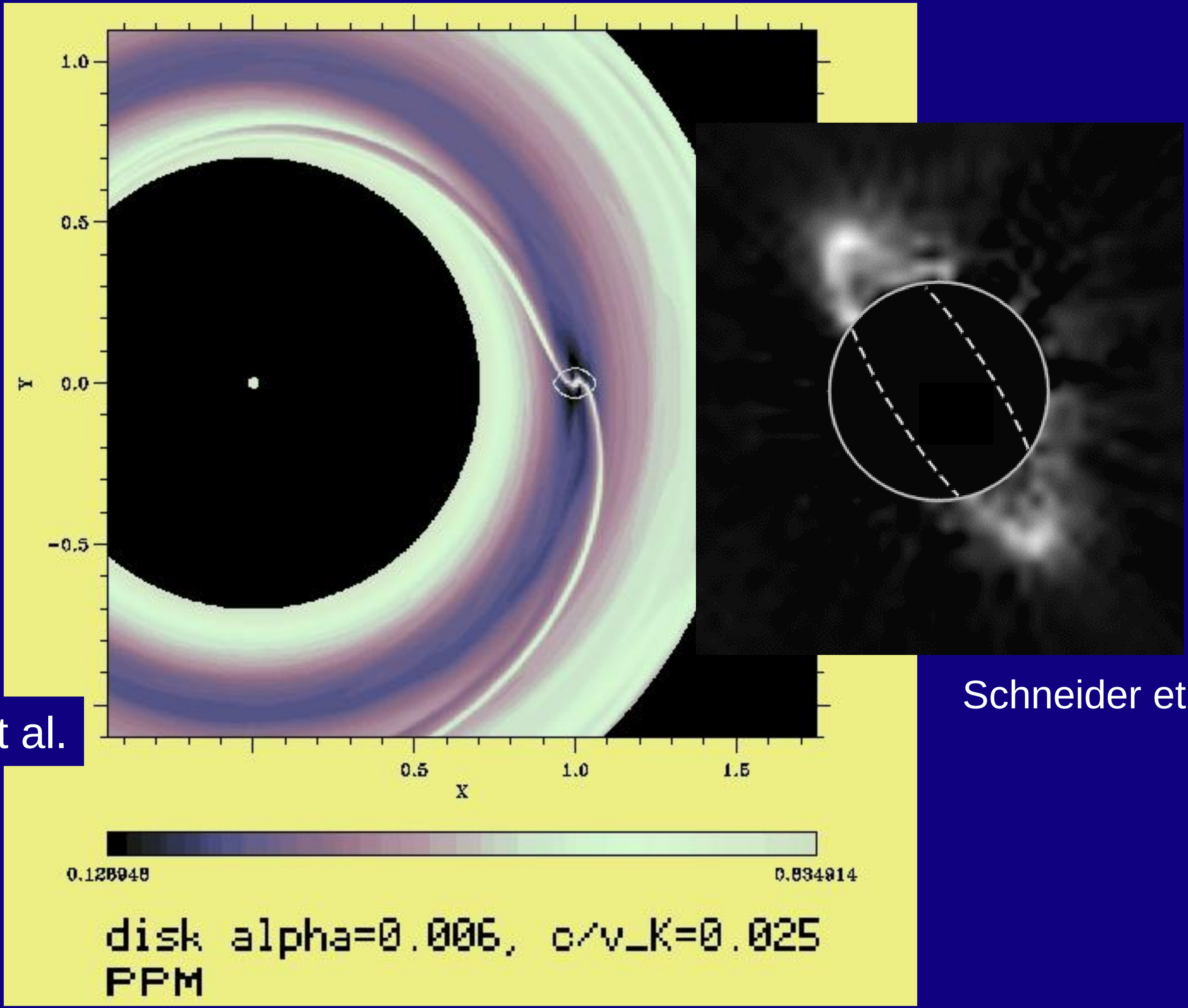
~1 µm grains

turbulent support,
(shock) heating?

optically
thick

~100 AU
~ 1mm dust

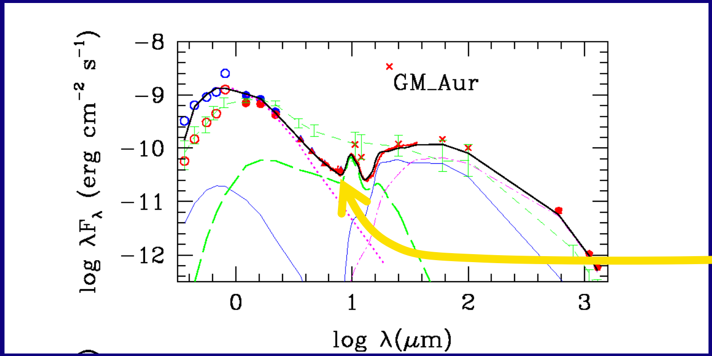
Planets open up gaps in disks

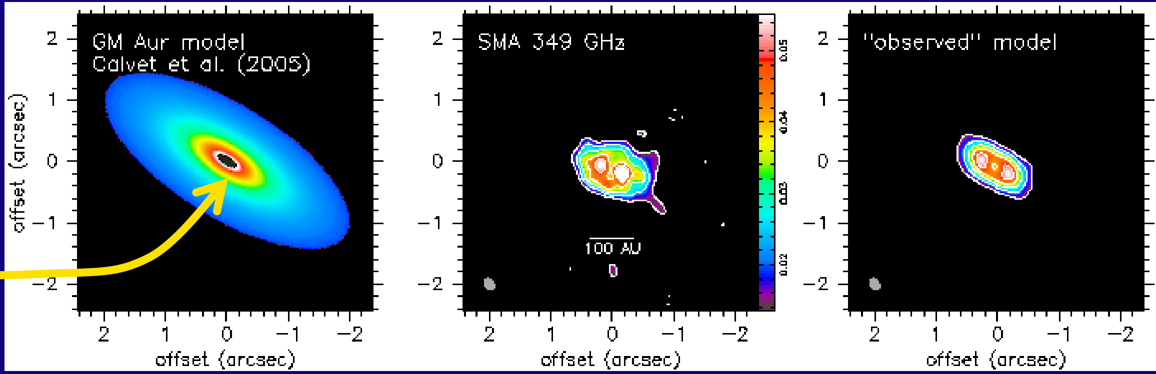


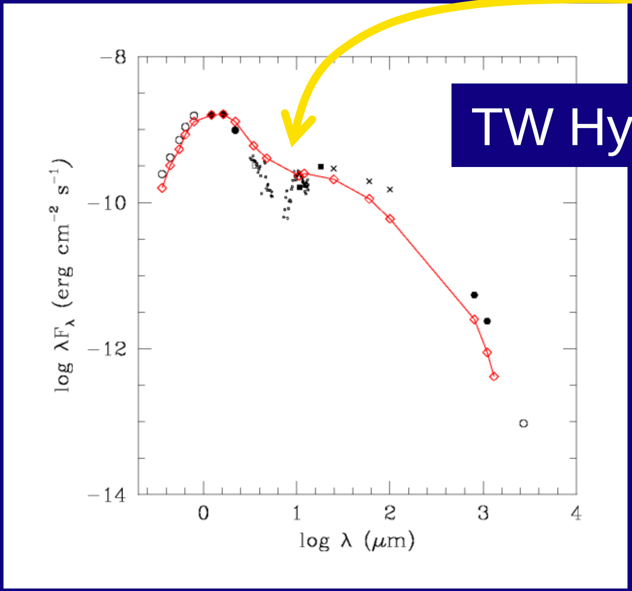
Rice et al.

Schneider et al.

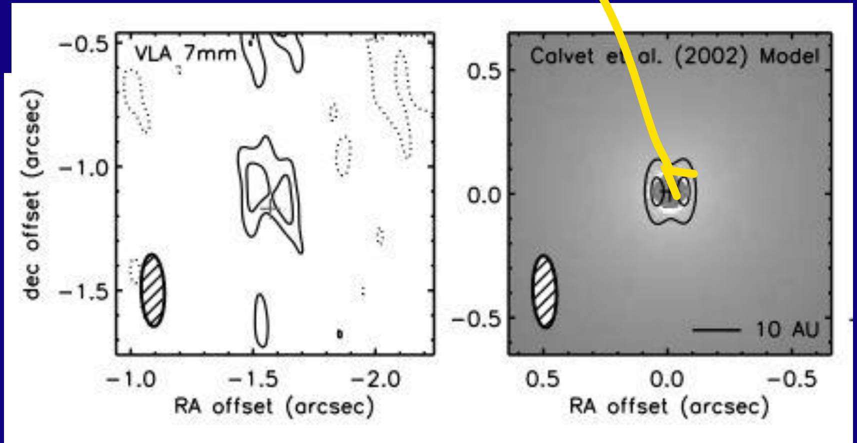
Inner disk holes? increasing evidence at few Myr...



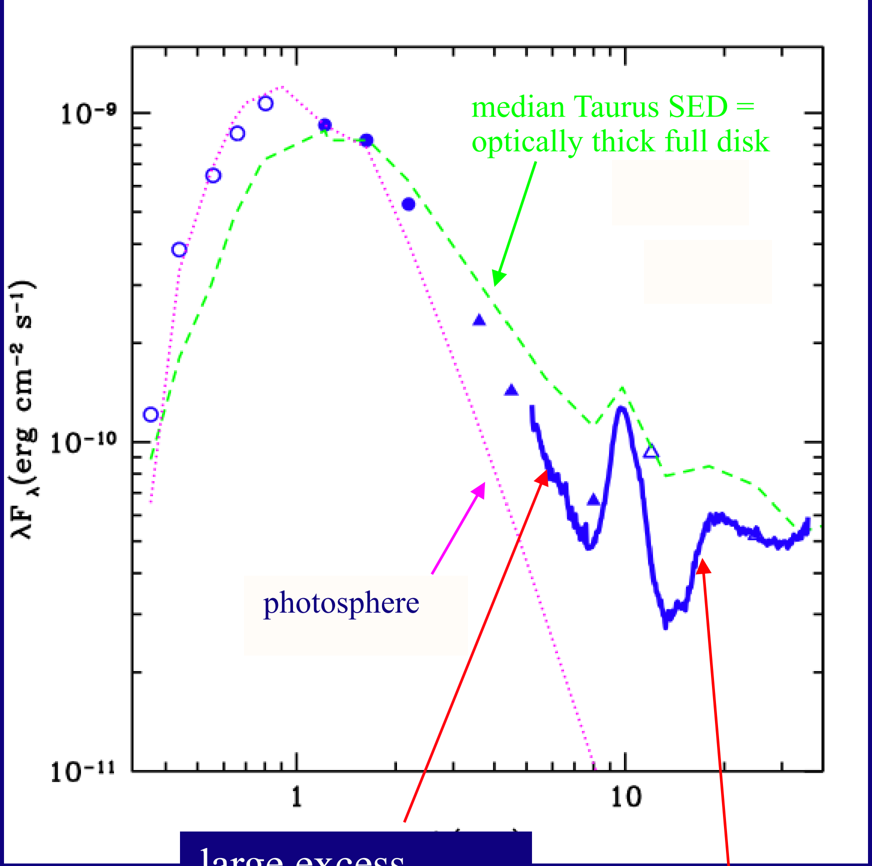




TW Hya



Pre-Transitional Disk; LkCa 15



median Taurus SED = optically thick full disk

photosphere

large excess, ~optically thick disk

Increasing flux/ optically thick disk

summary of disks...

- Disk frequencies (dust emission) not very different from 3μm - 24μm observations ⇒ evolution similar from 0.1 to ~ 10 AU; decay time ~~ 3 Myr
- Gas accretion ceases as IR excess disappears- clearing of inner disk
- “Transitional disks (holes, gaps)” ~5-10% @ 1-2 Myr
- Who knows what is happening at 1 AU @ 1 Myr (optically-thick, not spatially-resolved)
- Some evidence for dust settling/growth, increasing with age
- Disk masses probably are systematically underestimated ⇒ room for mass loss (migration, ejection)

Implications

Direct detection of gap in optically thick disk

Points to planet formation (Rice et al. 2003, 2007; Quillen et al. 2004; Alexander & Armitage 2007)

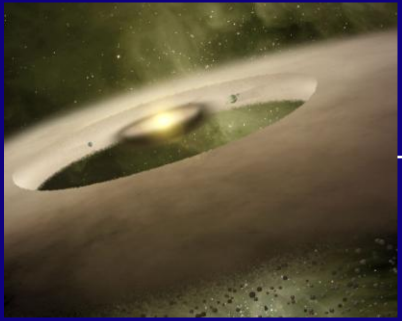
Suggests evolutionary sequence:

Gap opening (pre-TD) → inner disk clearing (TD)

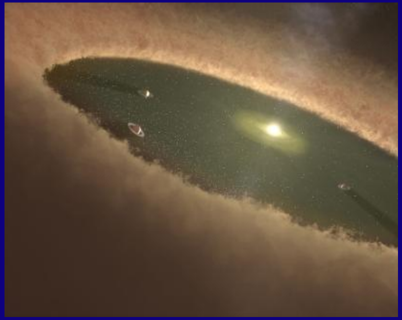
If so, evidence against inside-out clearing mechanisms: photoevaporation (Clarke et al. 2001; MRI erosion of wall (Chiang & Murray-Clay 2007)

“Full” optically thick disk

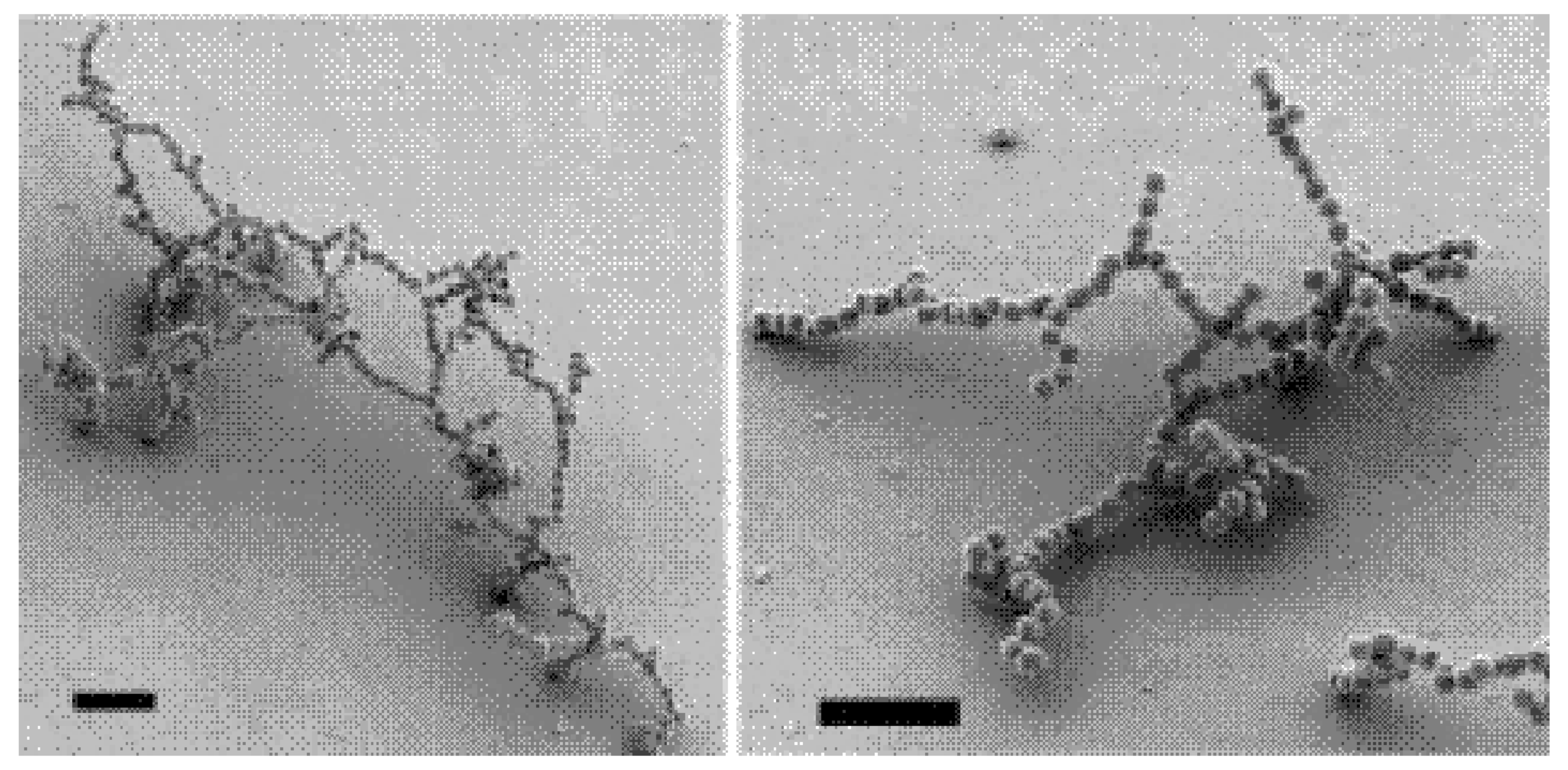
Disk Gaps:Pre-transitional disks



Inner Disk Holes: Transitional disks

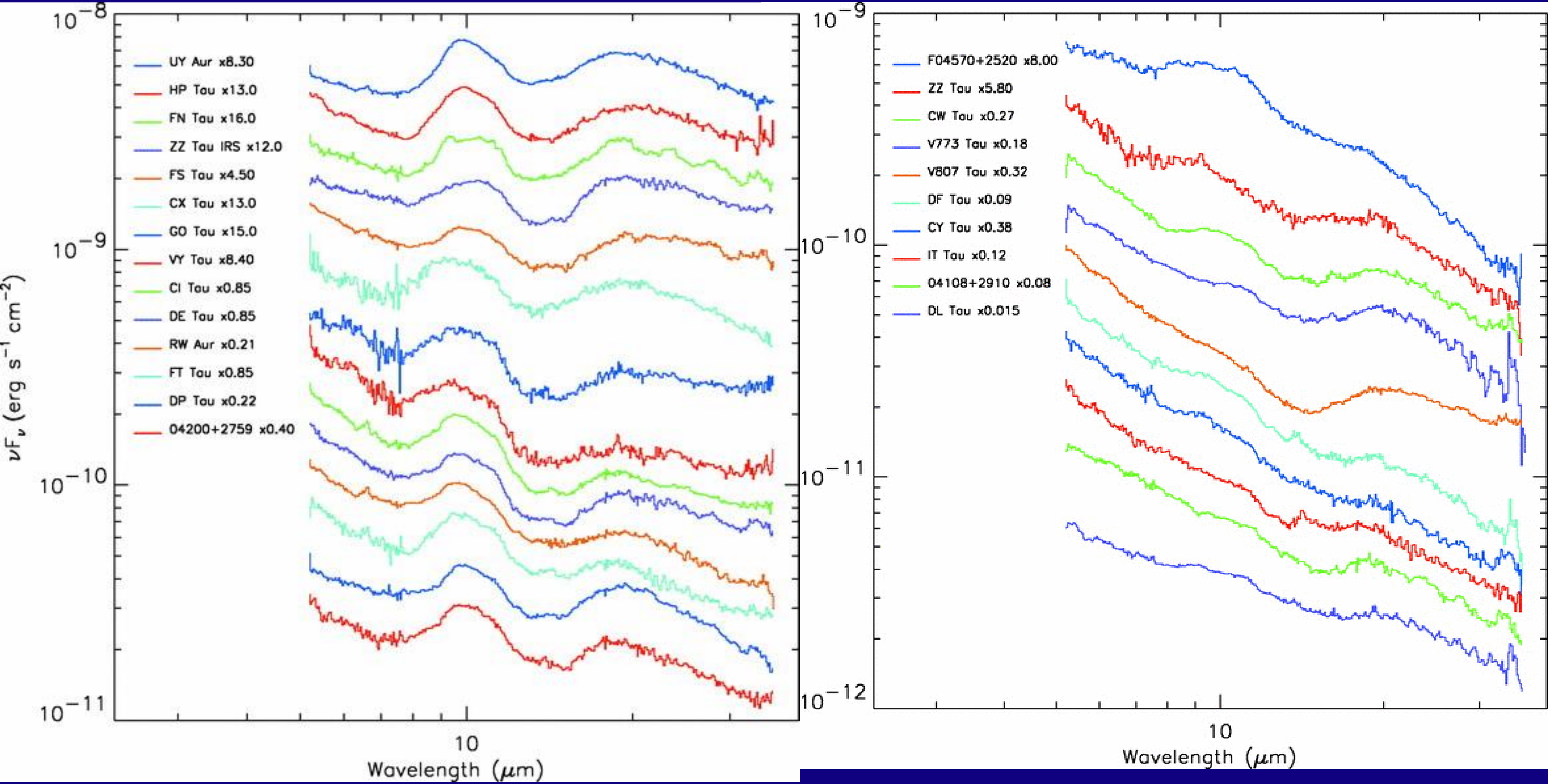


SSC



The beginning: (~ 1 micron) dust particles stick together

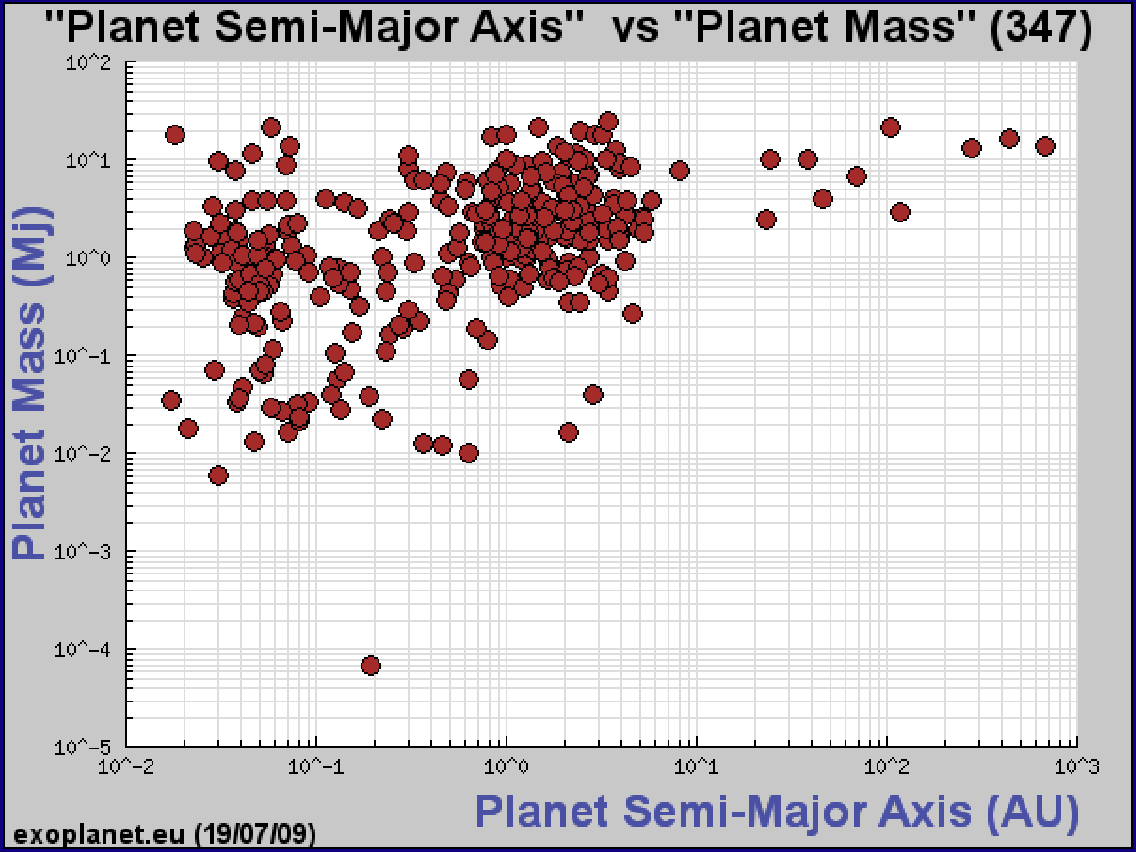
10 μm emission feature disappears when dust sizes >~ 5 μm; connected with dust growth/settling to disk midplane; first step in planet formation



Furlan et al. 2006

Exoplanets:

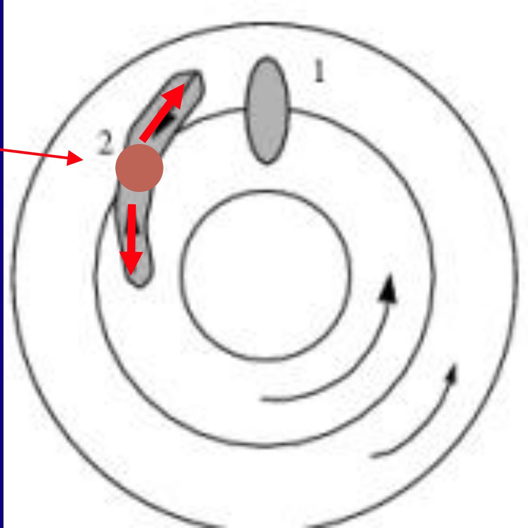
MIGRATION!

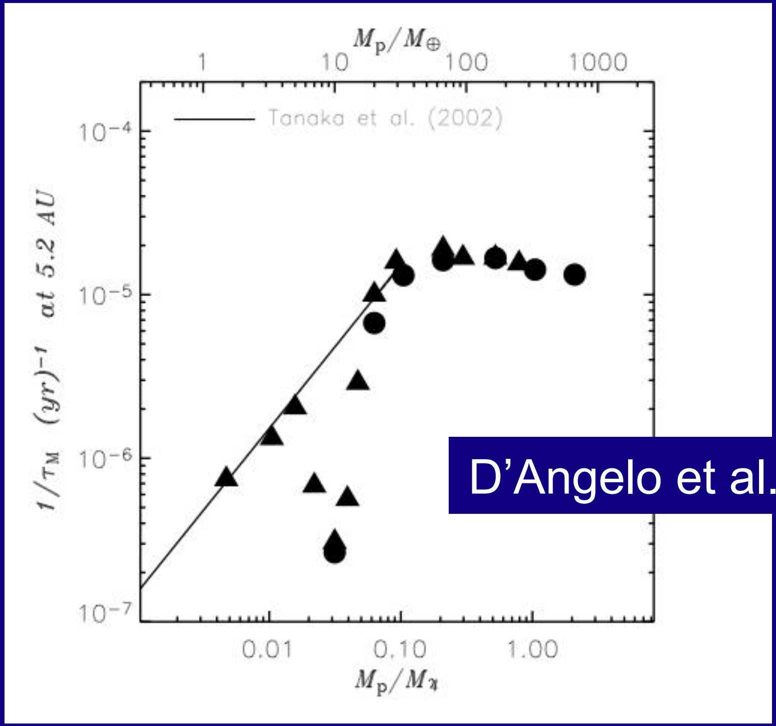


Planet formation: many problems to be solved

- micron size grains must stick; ✓
- can't grow too fast or must shatter ×
- "meter barrier"; bodies of this size migrate inward too fast because of gas headwind; also crash into each other × (solutions? turbulence, eddies, gravitational instability?)
- "Type I" migration; too fast ×

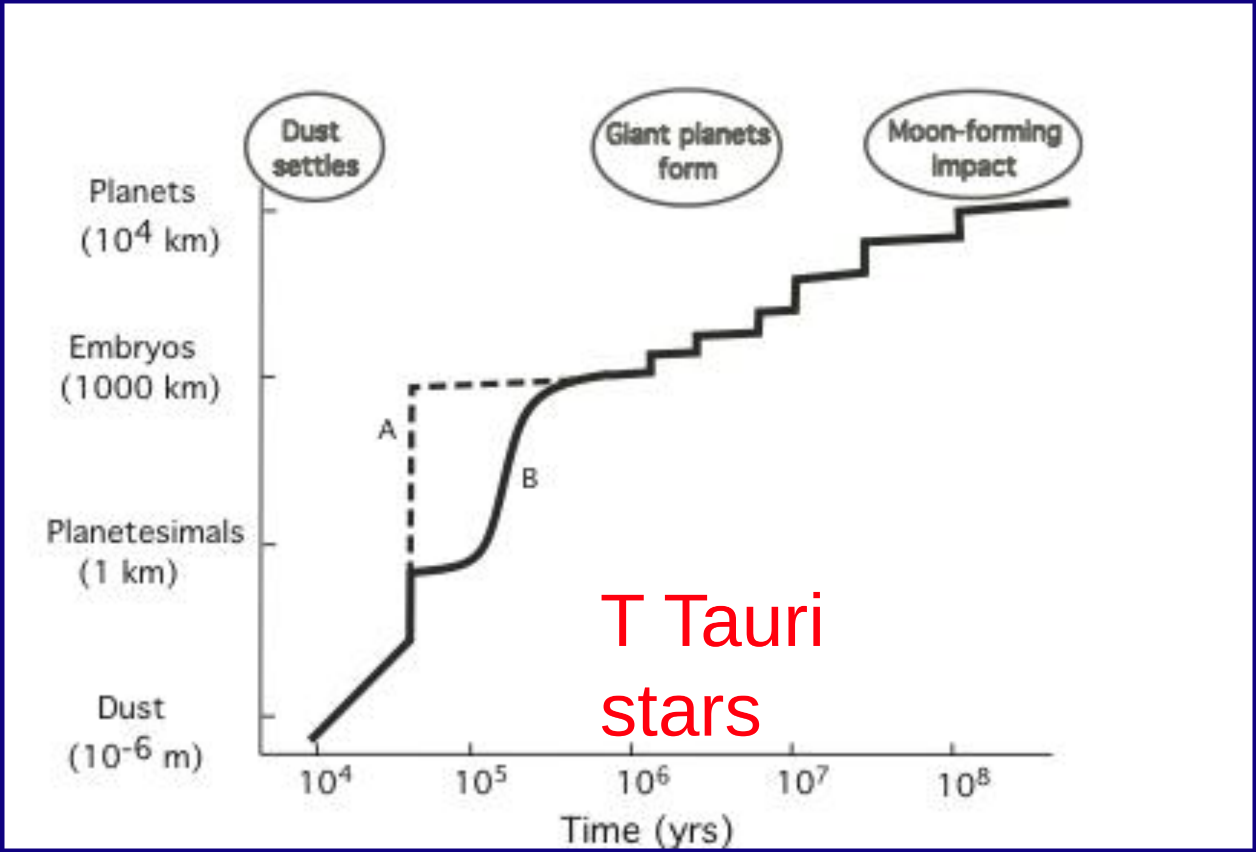
outer torque wins





D'Angelo et al.

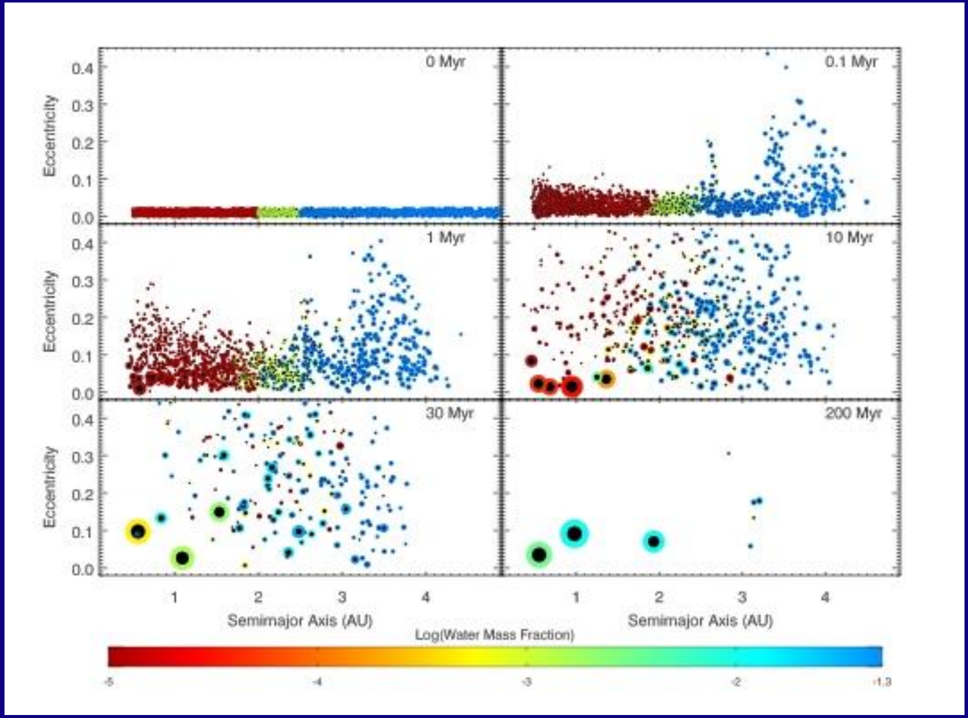
- are many planets lost into the central star?
- what is the nature of disk turbulence?
- is there a dead zone?

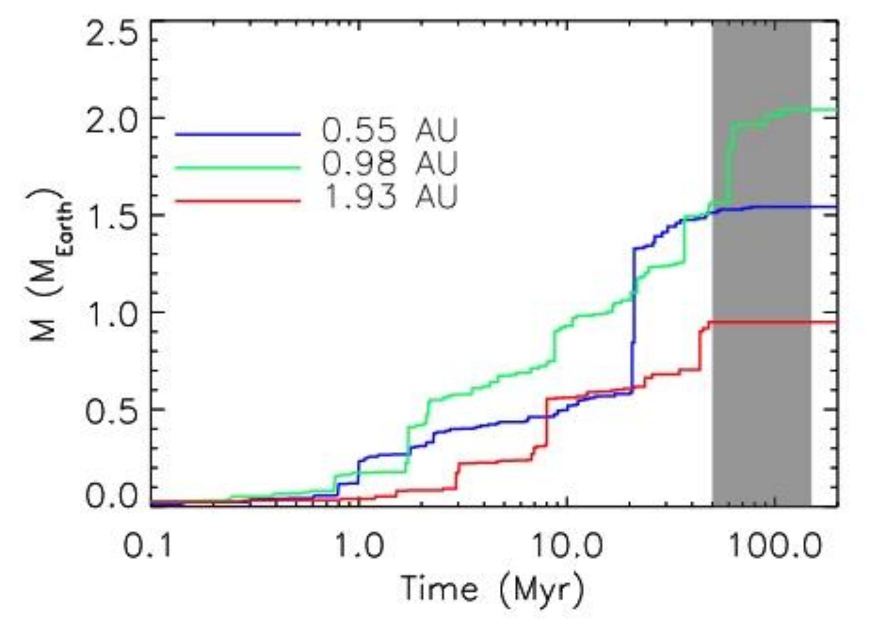


Raymond 2009

- make planetesimals somehow - get past the m barrier
- gravitational focusing- runaway growth(?)
- eccentricity “stirring” - “oligarchic” growth to embryos
- late stages - large collisions

Terrestrial planet simulations

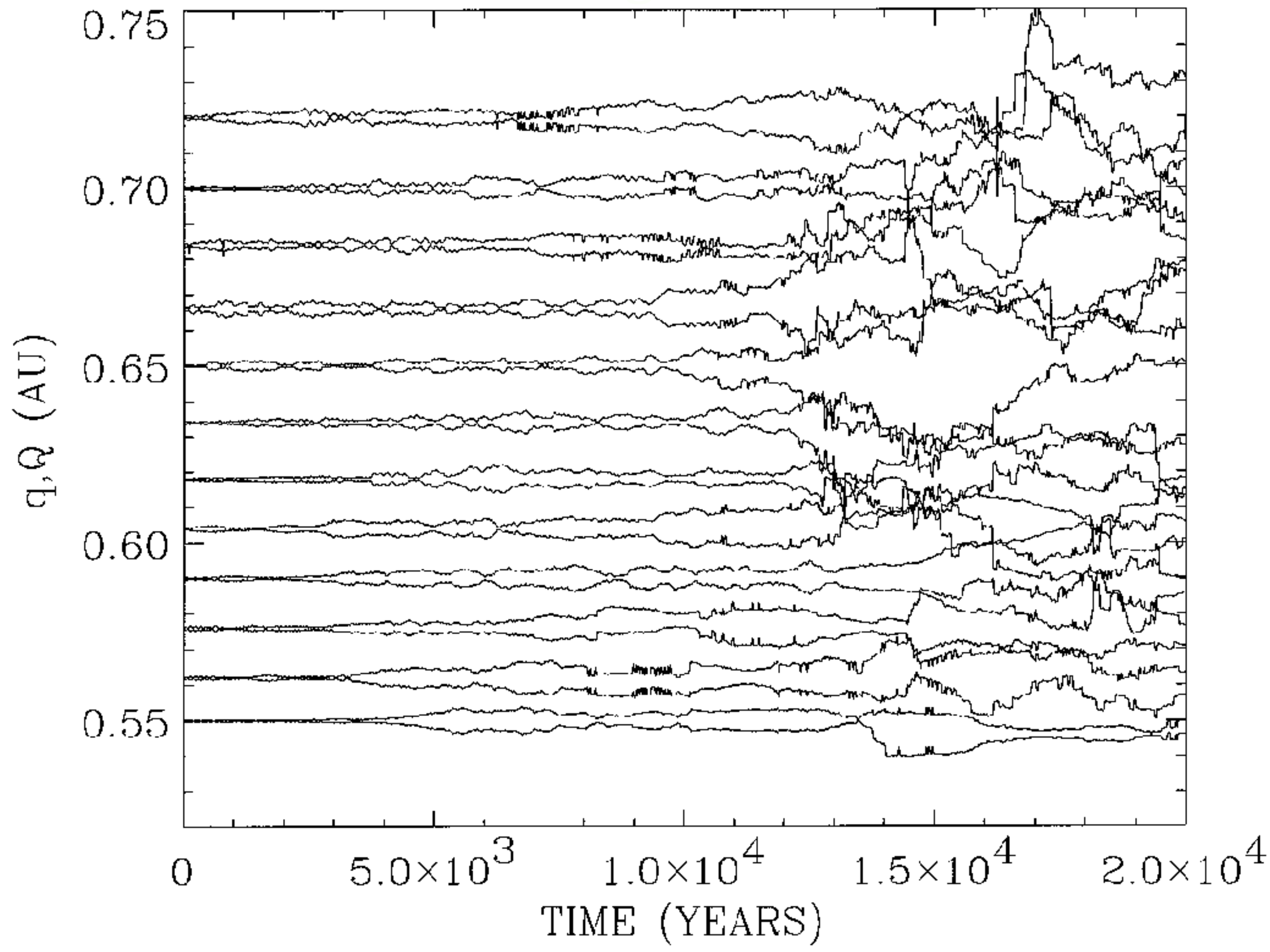




Raymond et al. 2006

maximum and minimum distances from Sun:

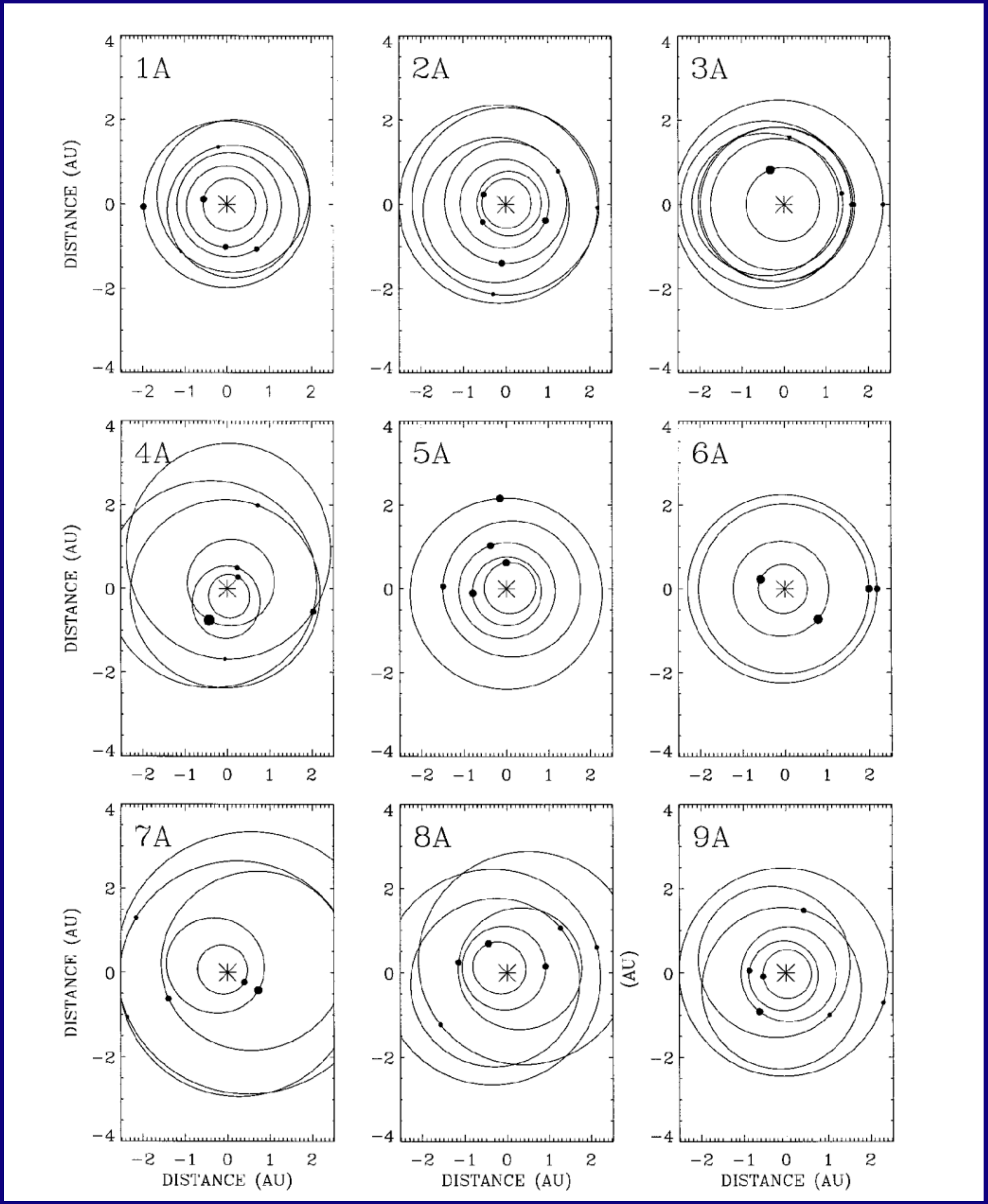
if too close together; CHAOS!



Chambers & Wetherill 1998

because of chaotic/random motions, different sets of planets result from slightly different initial conditions

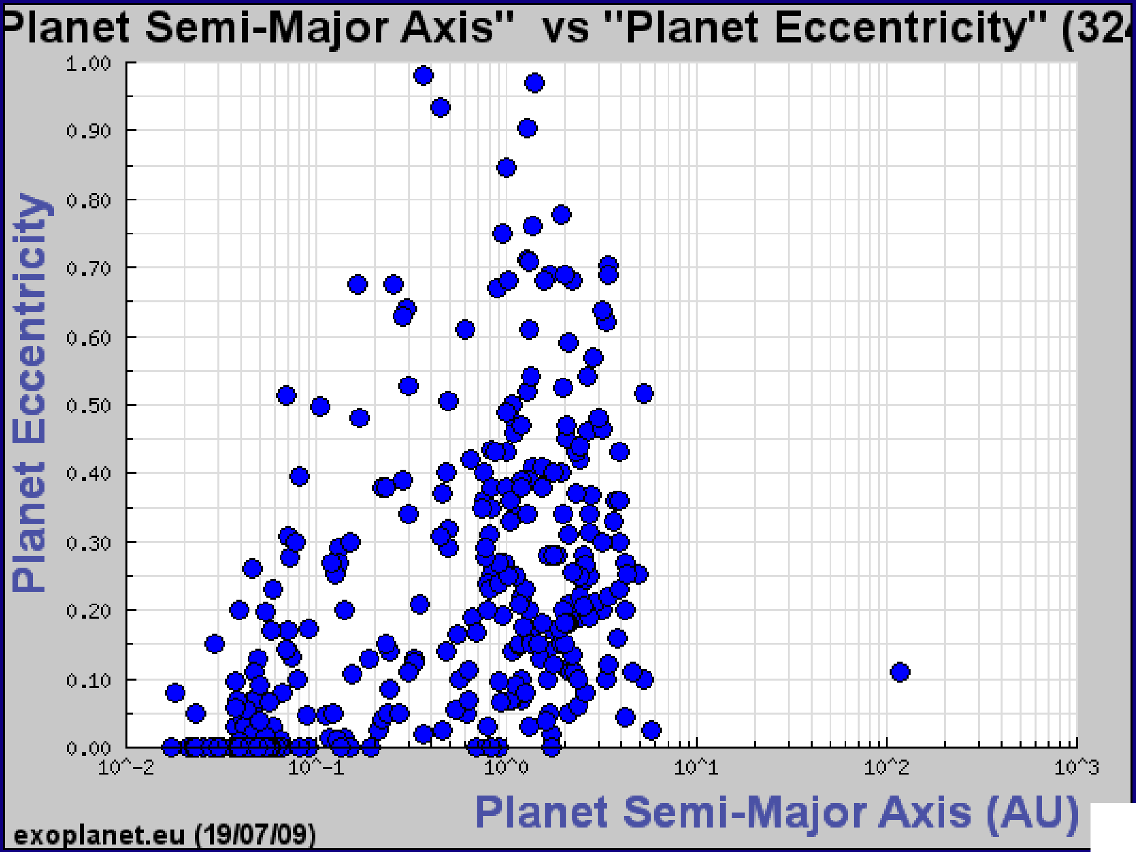
things “settle down” once the planets are spaced widely enough that their gravities don’t perturb their neighbors - much...

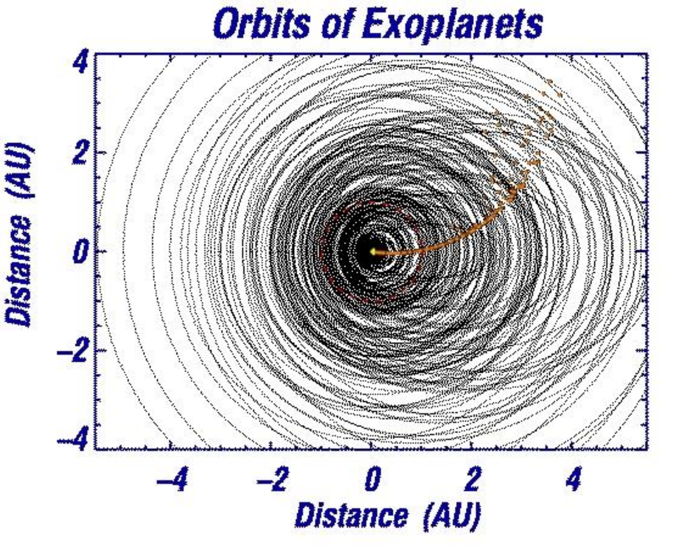


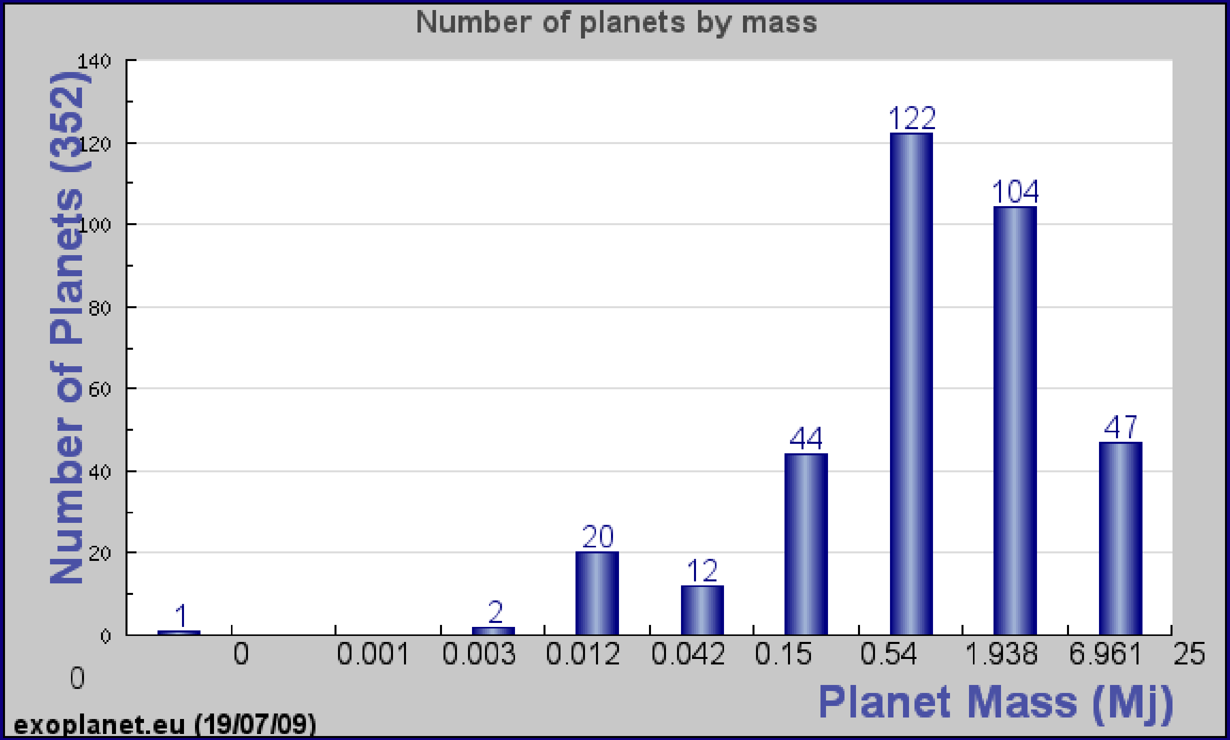
Chambers & Wetherill 1998

Terrestrial planets?

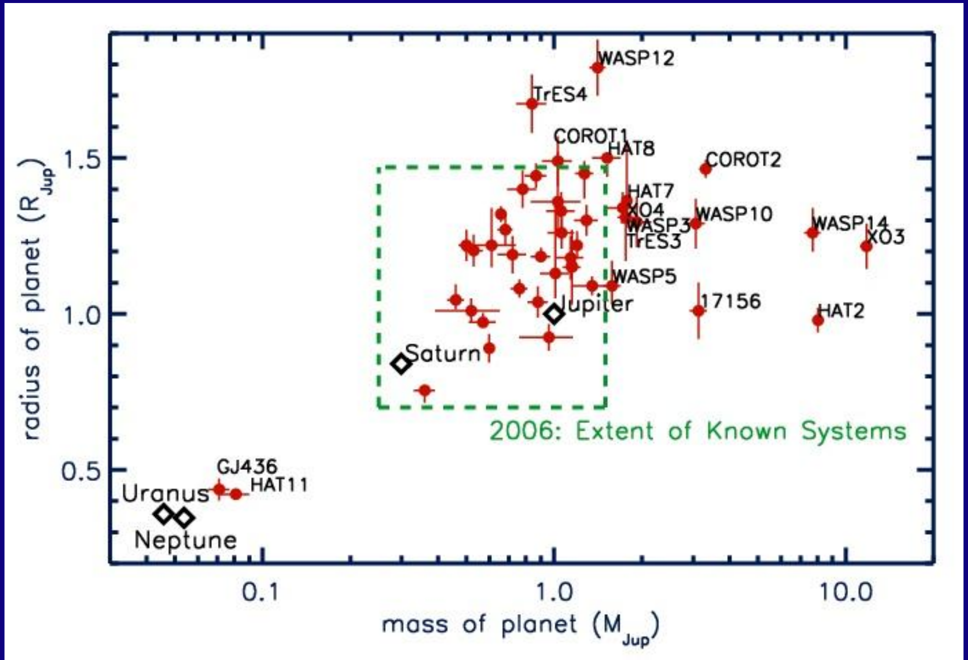
Kepler


Planet Semi-Major Axis" vs "Planet Eccentricity" (32
Planet Eccentricity
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
10^-2
10^-1
10^0
10^1
10^2
10^3
Planet Semi-Major Axis (AU)
exoplanet.eu (19/07/09)

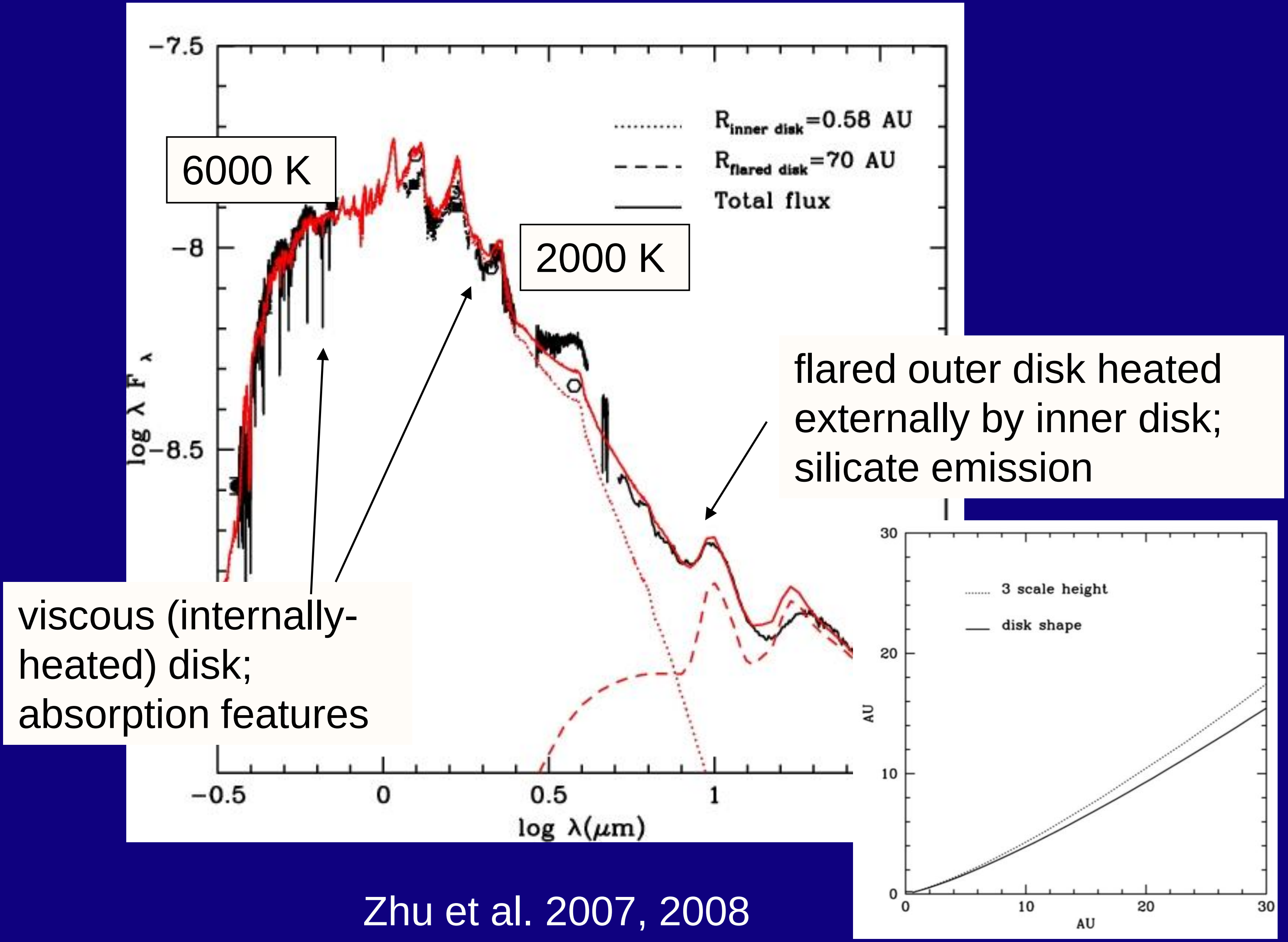

Orbits of Exoplanets
Distance (AU)
4
2
0
-2
-4
-4
-2
0
2
4
Distance (AU)


Number of planets by mass

exoplanet.eu (19/07/09)



Disk model explains variation of spectral type with λ



6000 K

2000 K

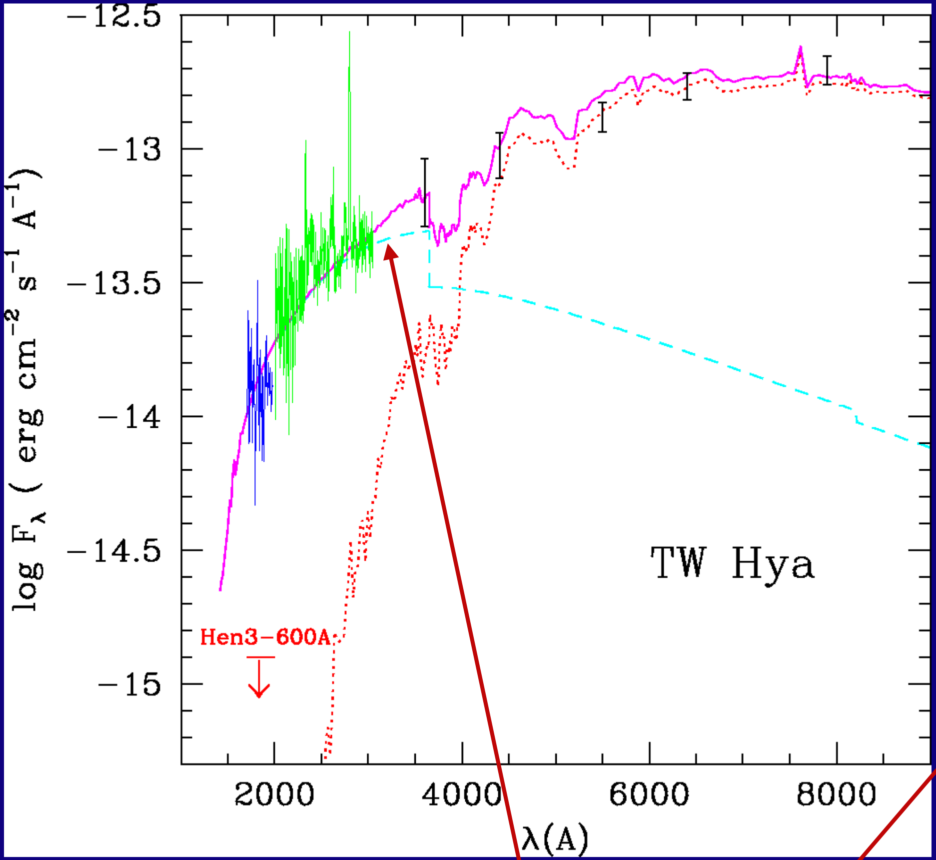
flared outer disk heated externally by inner disk; silicate emission

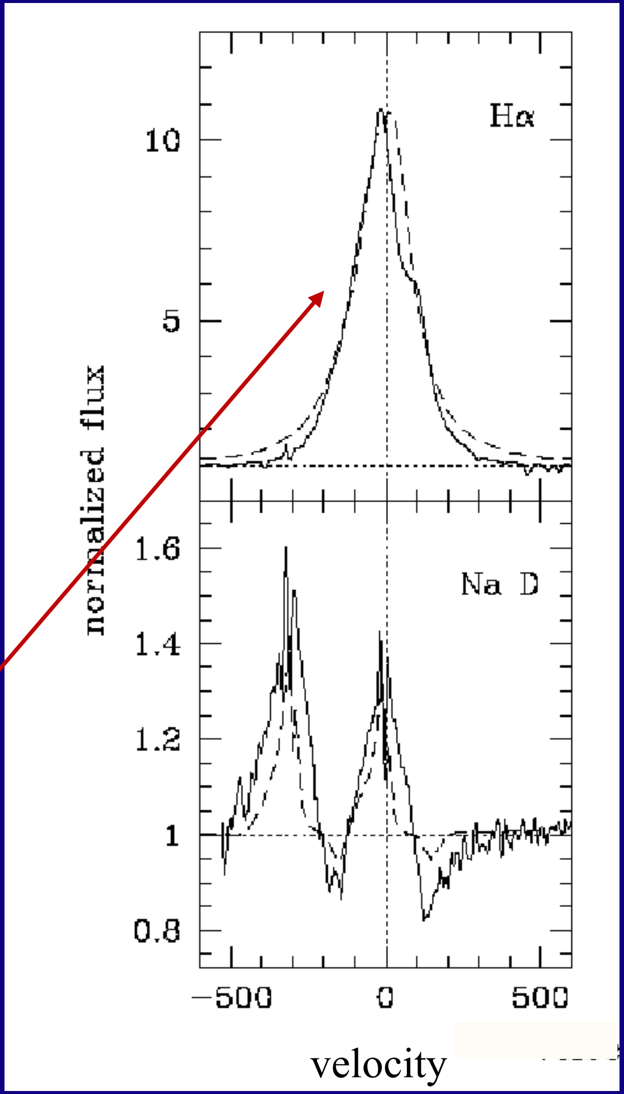
viscous (internally-heated) disk; absorption features

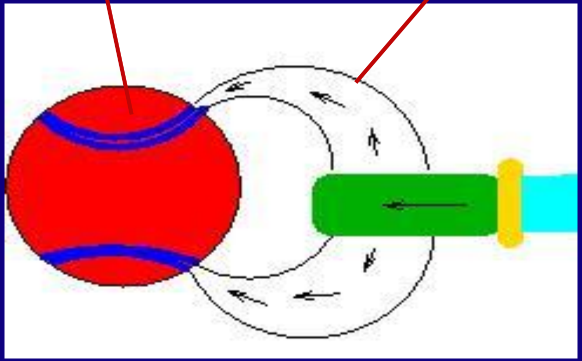
Zhu et al. 2007, 2008

Excess emission/veiling

Broad emission lines v ~ 250 km/s







Calvet et al.

Muzerolle et al.

Implications? Should be warm/hot loops: either

- magnetospheric infall @ 10^5 K (e.g., $c_s << v_{ff}$)
- outflow (T > 10^6 K and/or magnetic propulsion)

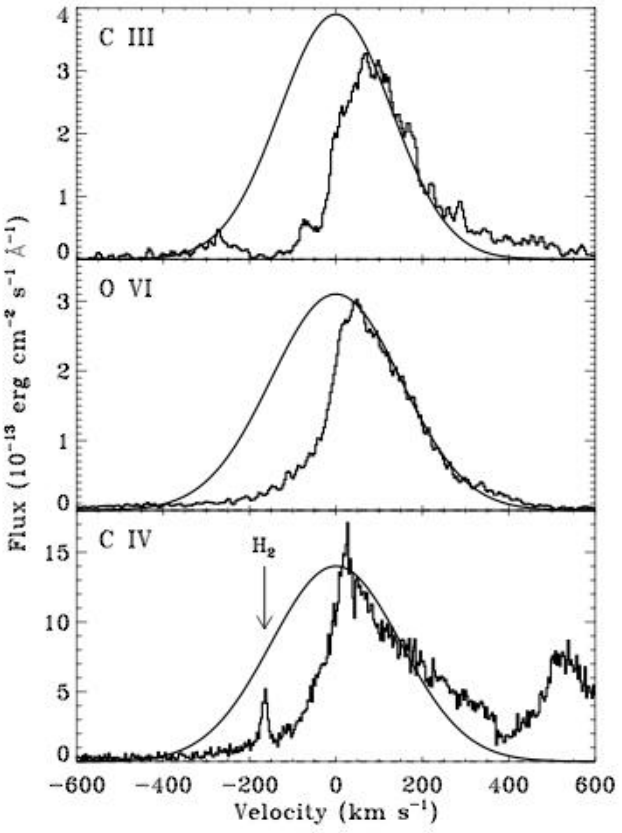
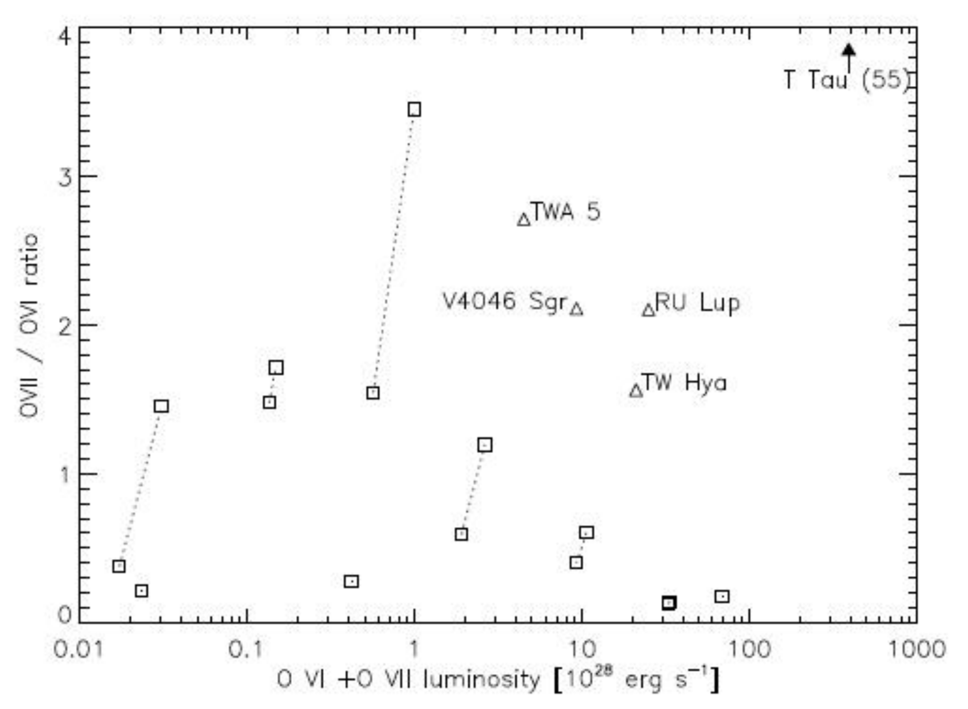


FIG. 2.—Line profiles of C III λ977, O VI λ1032, and C IV λ1548. Shown with each line is a Gaussian fit to the red side of the profile.

Line profiles too wide to be explained by accretion shocks

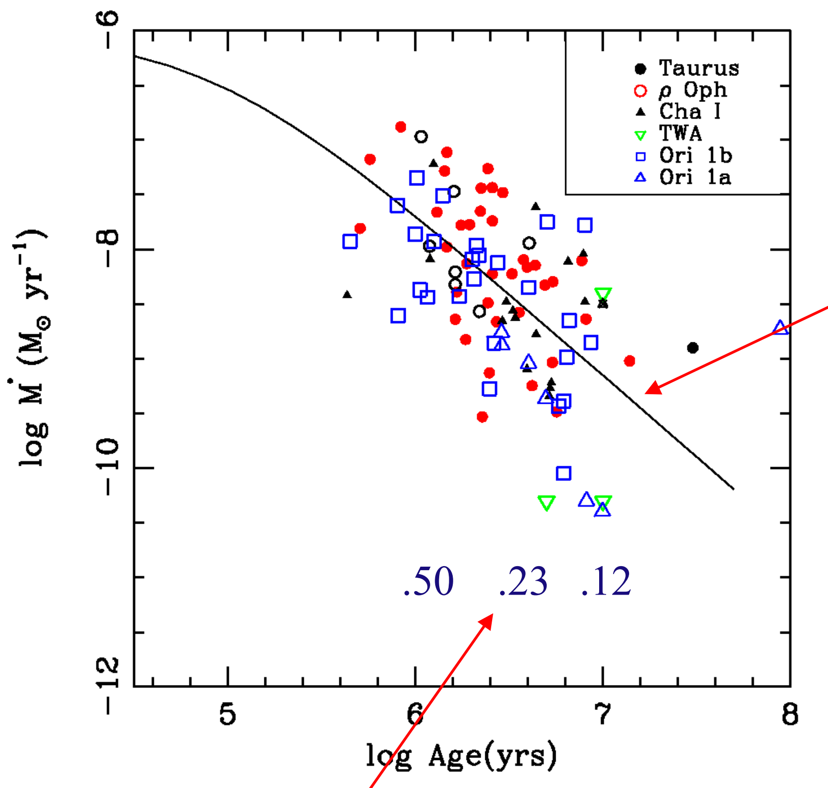
Dupree et al. 2005, Herczeg & Johns-Krull 2007, Gunther & Schmitt 2008, Lamzin et al. 2007



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.)

Mass accretion rate decreases with time



.50 .23 .12

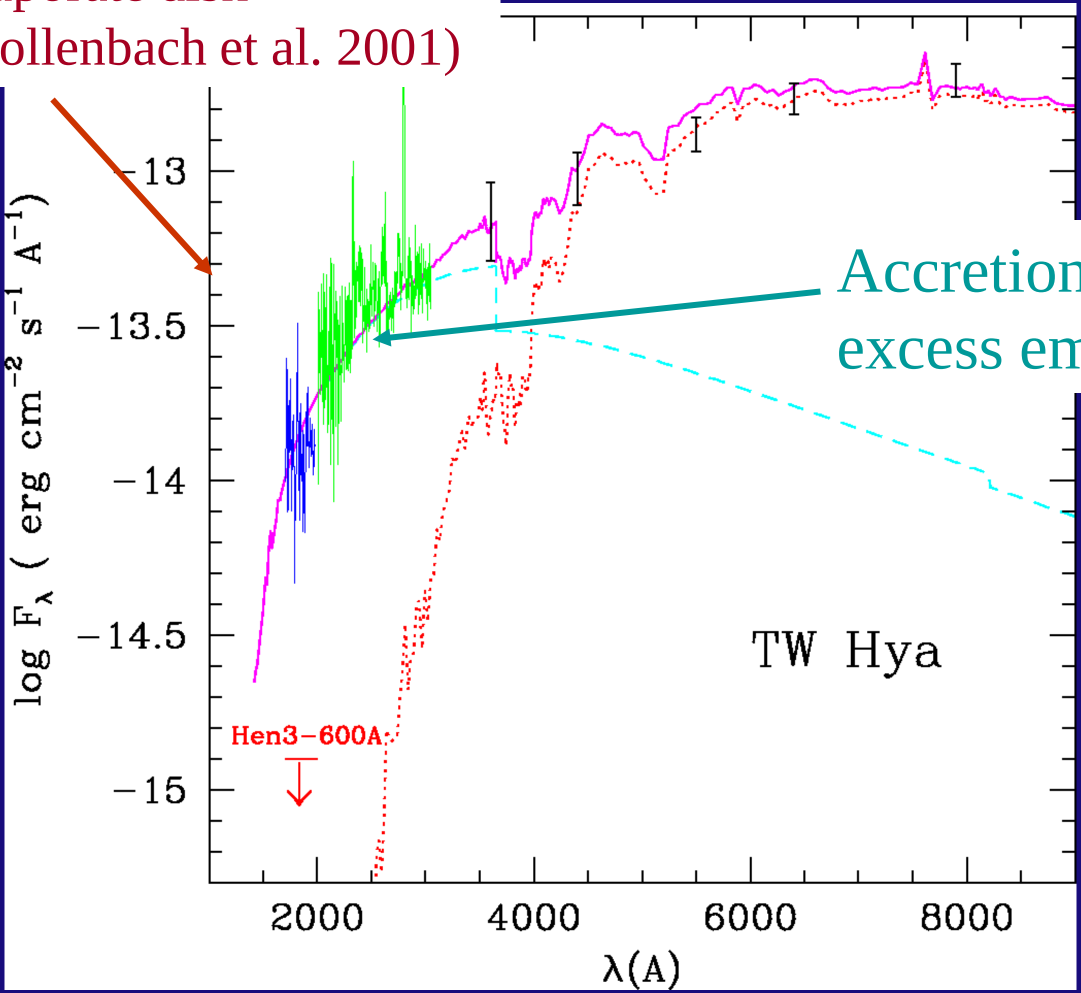
Viscous evolution - Gas

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

Fraction of accreting objects decreases with time

Photoevaporative fluxes?

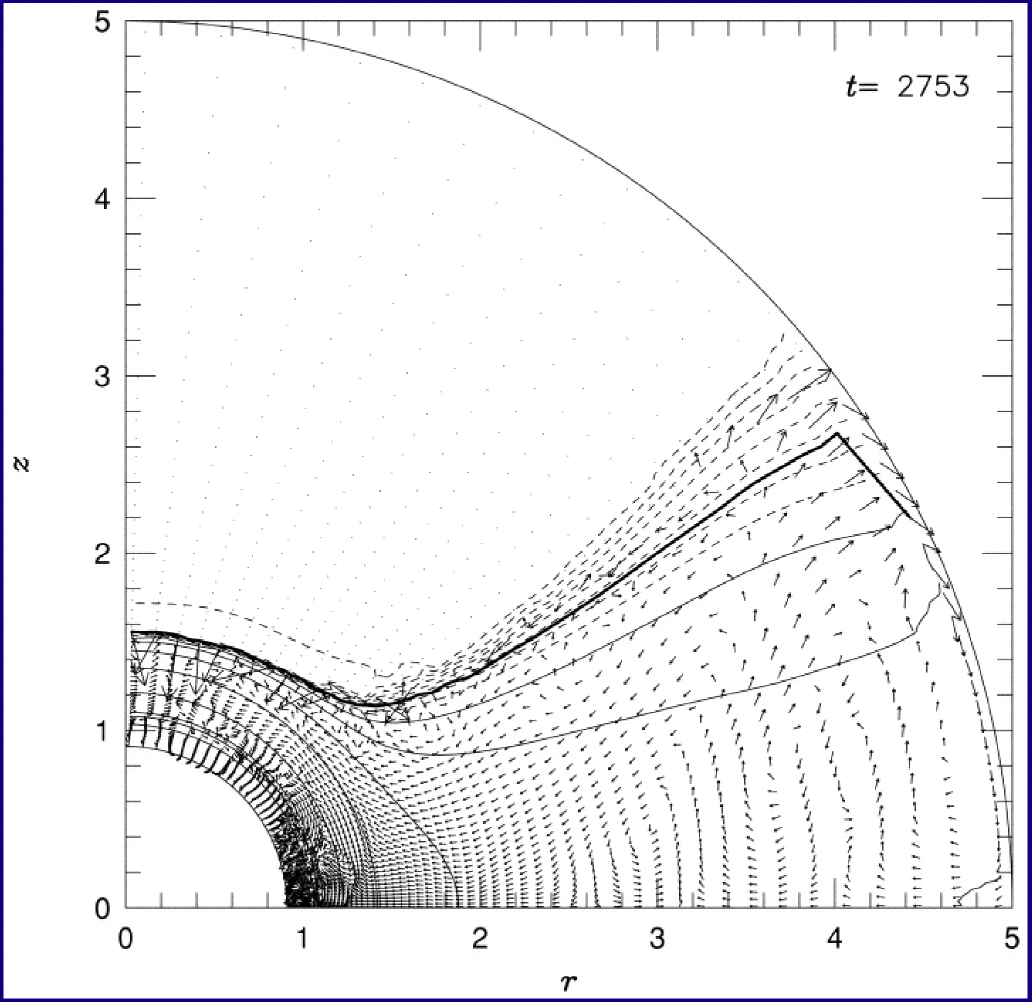
$\Phi \approx 10^{41}$ s^{-1} (typical EUV flux needed to evaporate disk in 10 Myr; Hollenbach et al. 2001)



Accretion-produced excess emission

Muzerolle, Calvet et al. 2000

high dM/dt? end of outburst might lead to enhanced stellar wind due to shears induced in the star by rapid accretion of material



Kley & Lin 1996

“Twister” scenario

- Most general case - no requirement of smooth field drift or interaction exactly at corotation
- May explain evidence for hot (stellar) winds connected with accretion
- Predicts some magnetospheric infall in transition-region (C IV, O VI) lines- maybe also outflows
- Helps explain OVII excess in CTTS