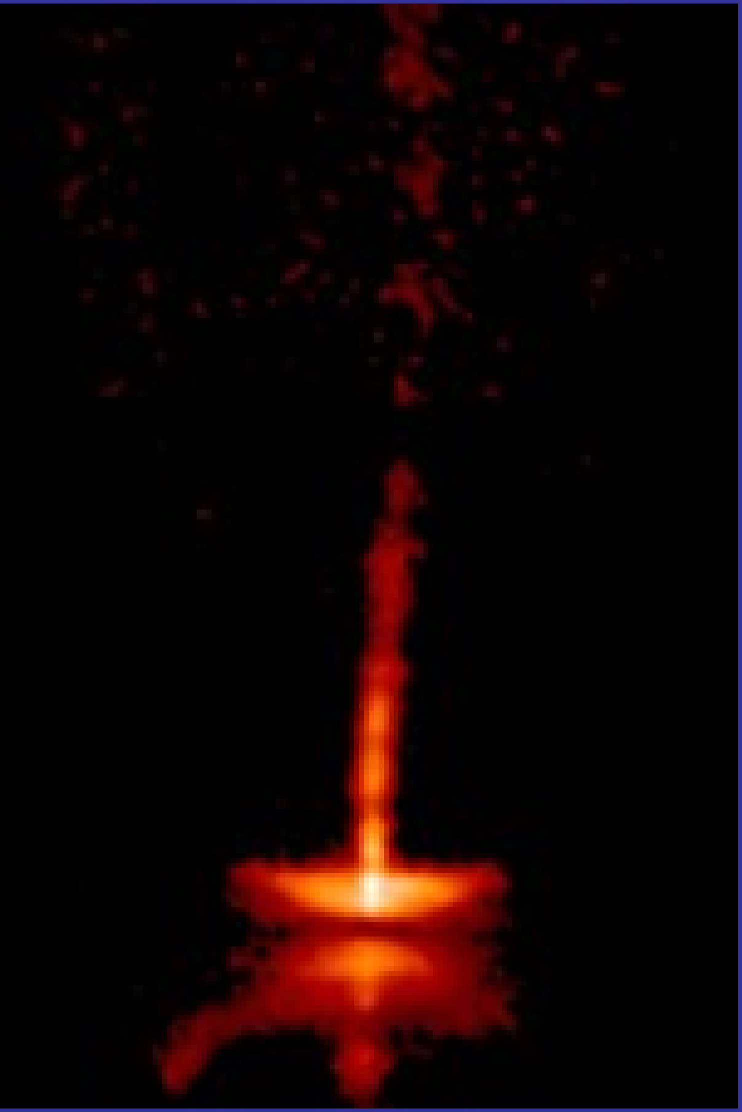

Observational challenges to ejection models in YSOs

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Outline

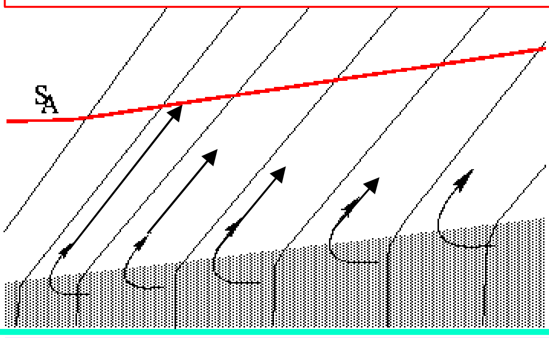
- Compare obs. with (steady) model predictions :
  - Jet width = density collimation
  - Wide angle kinematics
  - Sub-arcsec H2 jets/cavities
  - Jet rotation
  - Jet ejection/accretion ratio and jet power
- Conclusions
- Will concentrate on TTS since best linear resolution (0.1” = 0.15 AU @ 140pc), eg. compared to Class I/0 jets in Orion (0.3” = 150 AU @ 450pc) and better known stellar characteristics

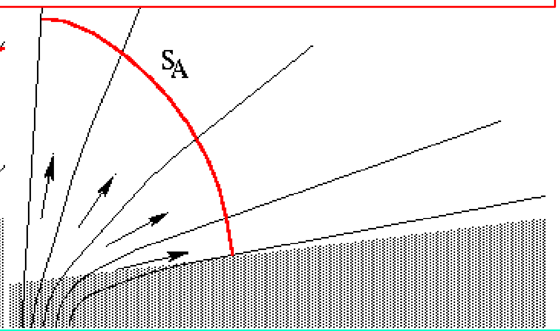
MHD ejection processes in TTS
(Fig. adapted from Ferreira et al. 2006)

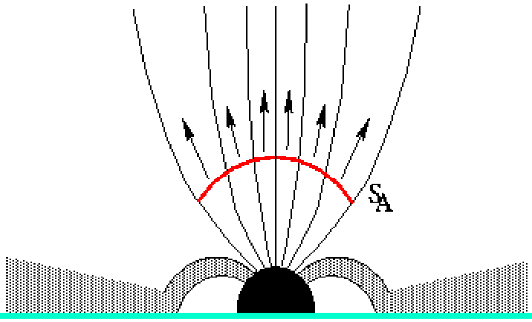
Cf. Ferreira's talk | Cf. Cai, Shu et al. | Cf. Sauty's talk

(1) Extended disk wind OR Inner disk X-wind | **(2) Stellar wind**

STEADY

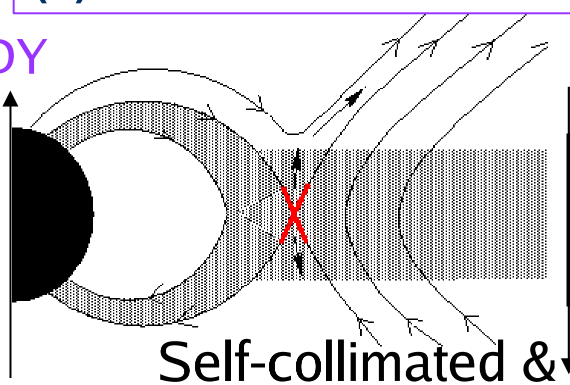




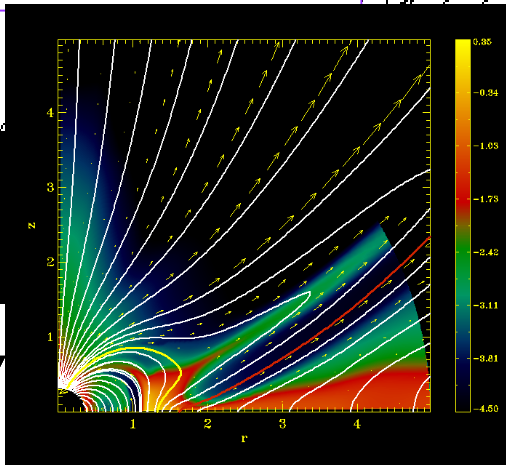


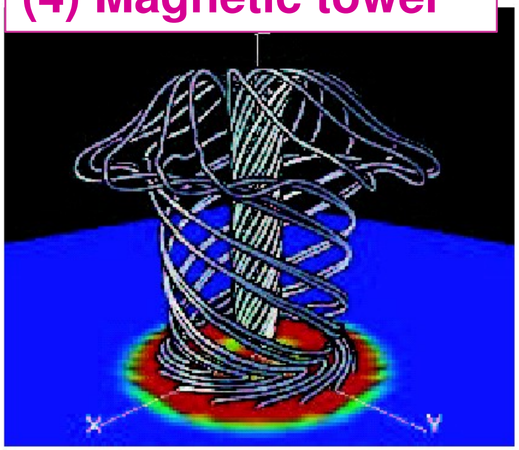
(3) Reconnexion X-wind OR CME-like | **(4) Magnetic tower**

UNSTEADY



Self-collimated &
stellar braking





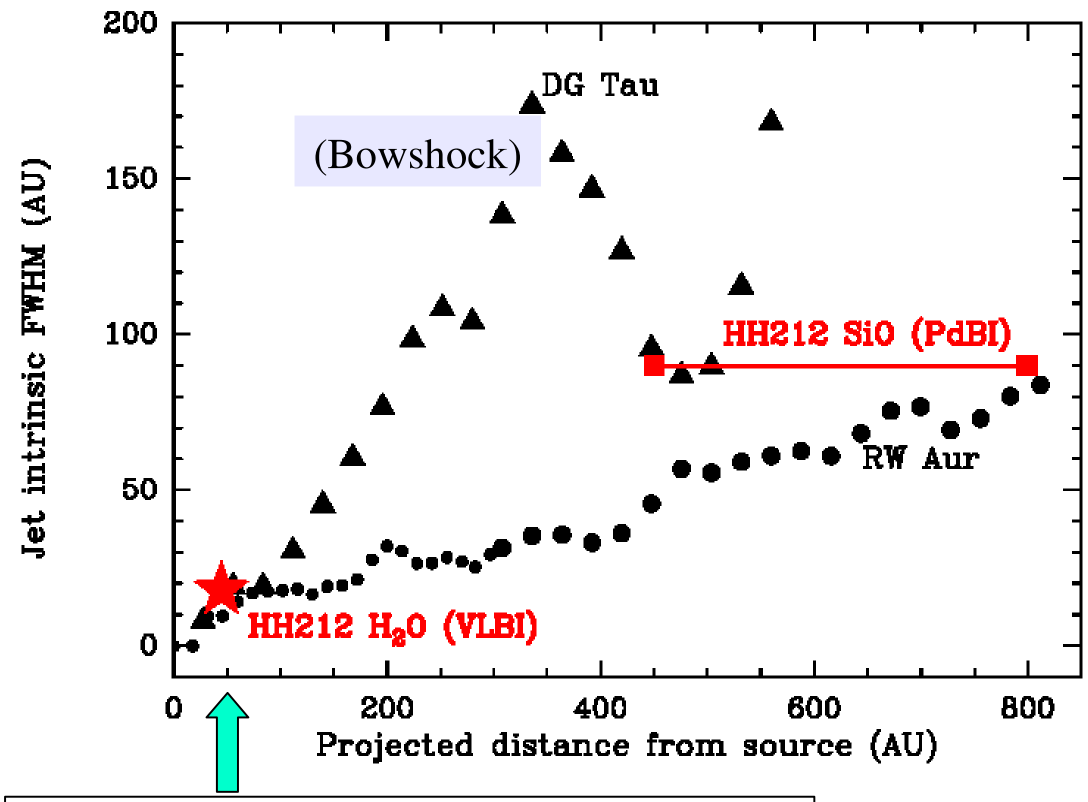
Cf. Ferreira's talk | Cf. Romanova, Zanni | cf. Matsumoto, Lebedev

Available predictions and constraints

- Theoretical predictions mostly for *steady jet models: disk-wind / stellar wind / X-wind*
- Little available yet on unsteady models: plasmoids/magnetic towers (studied by numerical means only)

  - Steady models predict n(r,z) and V(r,z) but we observe NLTE emissivities f(xe,Te) integrated along line of sight ➔ biases
    - cf. talks tomorrow by De Colle and by Gracia
  - Use synthetic maps / line profiles whenever possible:
    - unconvolved X-wind (Shang et al 98,02)
    - Convolved disk wind (Cabrit et al 99; Garcia et al 01; Pesenti et al 04)
    - Stellar wind + molecular Disk-wind in progress (Matsakos, Panoglou)
  - NB: Convolution by PSF further affects jet width and <V>
    - Essential for precise tests…

Need for magnetic jet collimation



Collimation scale ~ 50 AU
Opening angle drops from 30° to 4°
(**Hartigan et al. 04; Dougados et al. 00**)

- Same jet width in the HH212 protostar as in T Tauri stars despite a much denser envelope

➔ Definitely rules out jet collimation by (ram) pressure of infalling material (**Cabrit et al. 2007 A&A**)

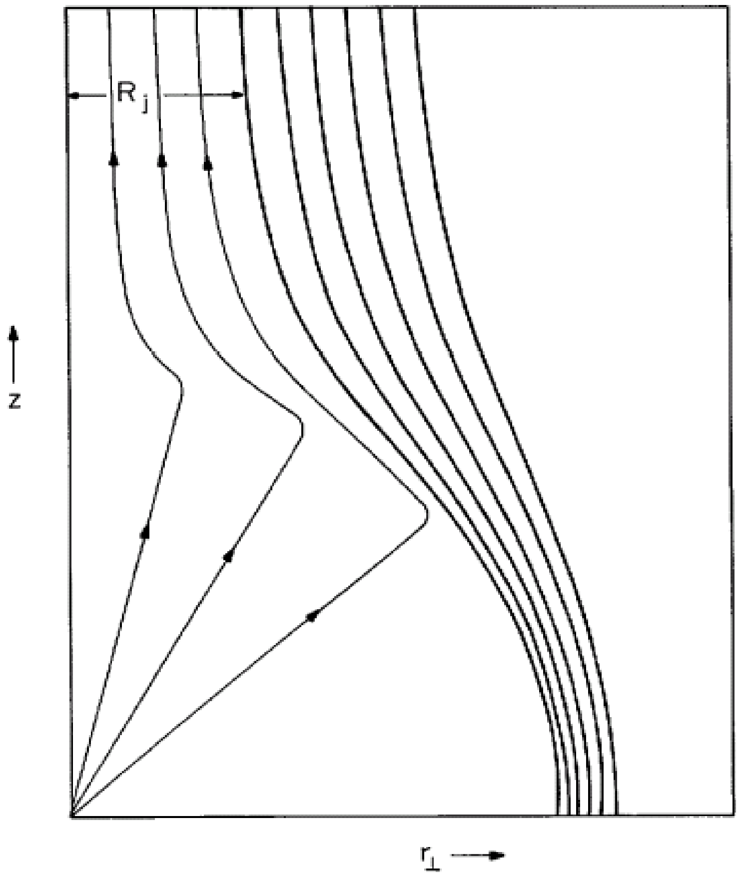
➔ Thermal pressure in disk also insufficient (Cabrit 2007 IAU 243)

➔ Requires (universal) magnetic collimation on disk scales

External magnetic jet collimation

- External magnetic collimation
  Criterion: magnetic pressure ~ Wind ram-pressure (cf. Kwan & Tademaru 88)
  - for Mw = 10^{-8} Mo/yr, Vw = 300 km/s , Z = 50 AU: B ~ 10mG over R ~ 100 AU

  ~ Advected B in disk models of Shu et al. 07
  - asymptotic opening angle ?
  - Two-component flow models (Matsakos et al 08; Meliani et al. 06)

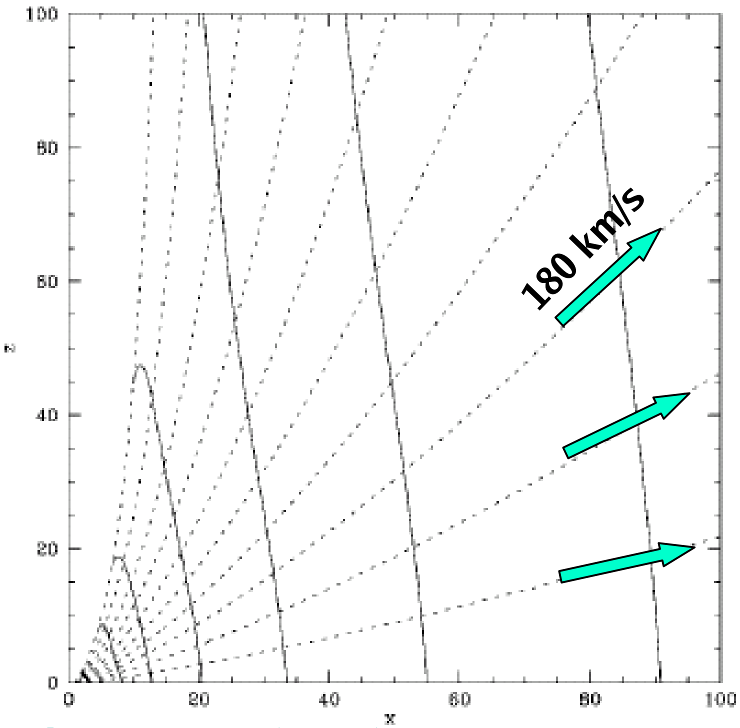


Kwan & Tademaru (1988)

Jet self-collimation: the « optical illusion »

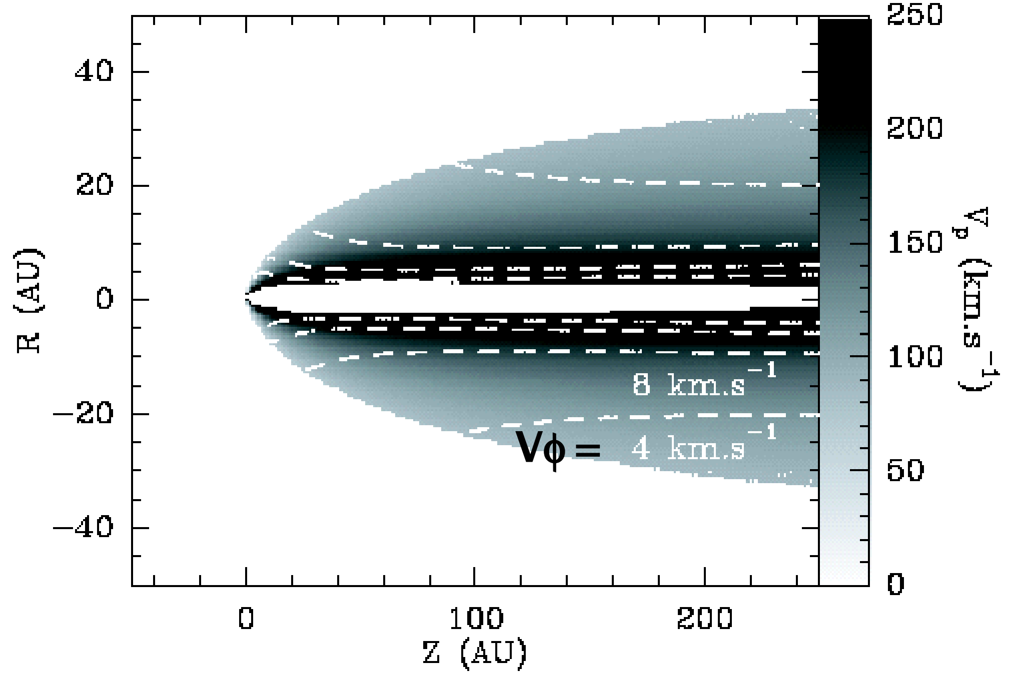
- Self-collimated MHD models predict on-axis density enhancement + wide-angle flow: fast in X-wind (and stellar wind), slow in D-wind

X-wind wide angle structure



Shang et al. (1998)

Disk wind wide-angle structure

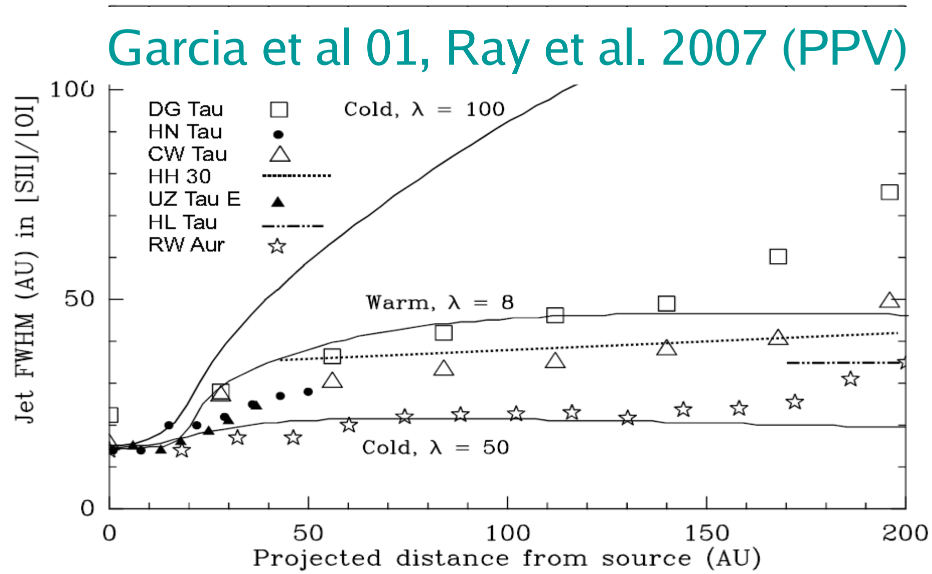


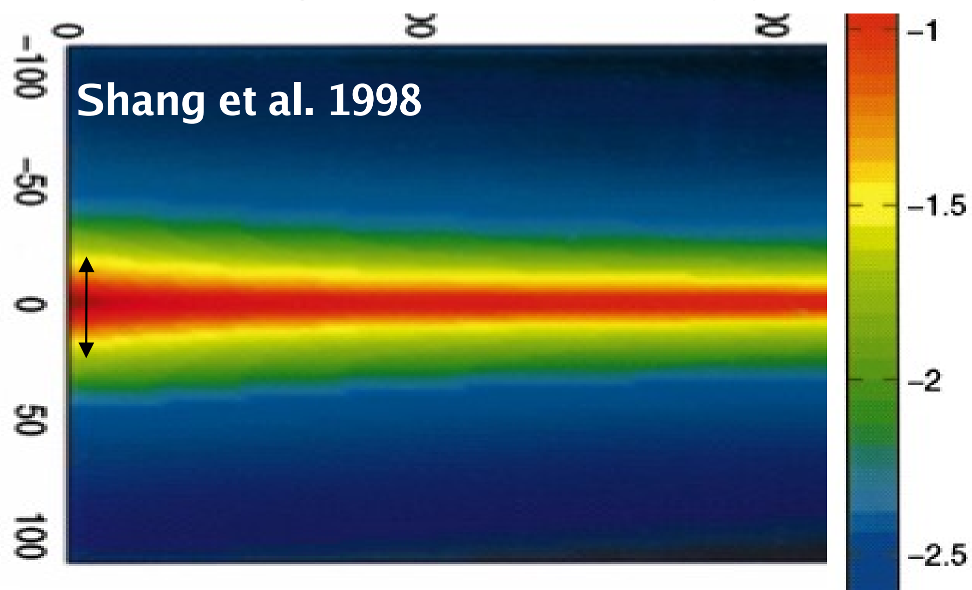
Pesenti et al. (2004)

Constraints from apparent jet widths
On-axis density enhancement

- Disk winds convolved by PSF: agree well for inner launch radius Rin ~ 0.1AU
- X-wind: unconvolved maps (Shang et al. 98; 02)
  - Too wide near jet base ?
  - Beam-convolution needed…
- Stellar winds (Sauty & Tsinganos 1994; Bogovalov & Tsinganos 00)
  - Maps in progress (Matsakos et al 08)…

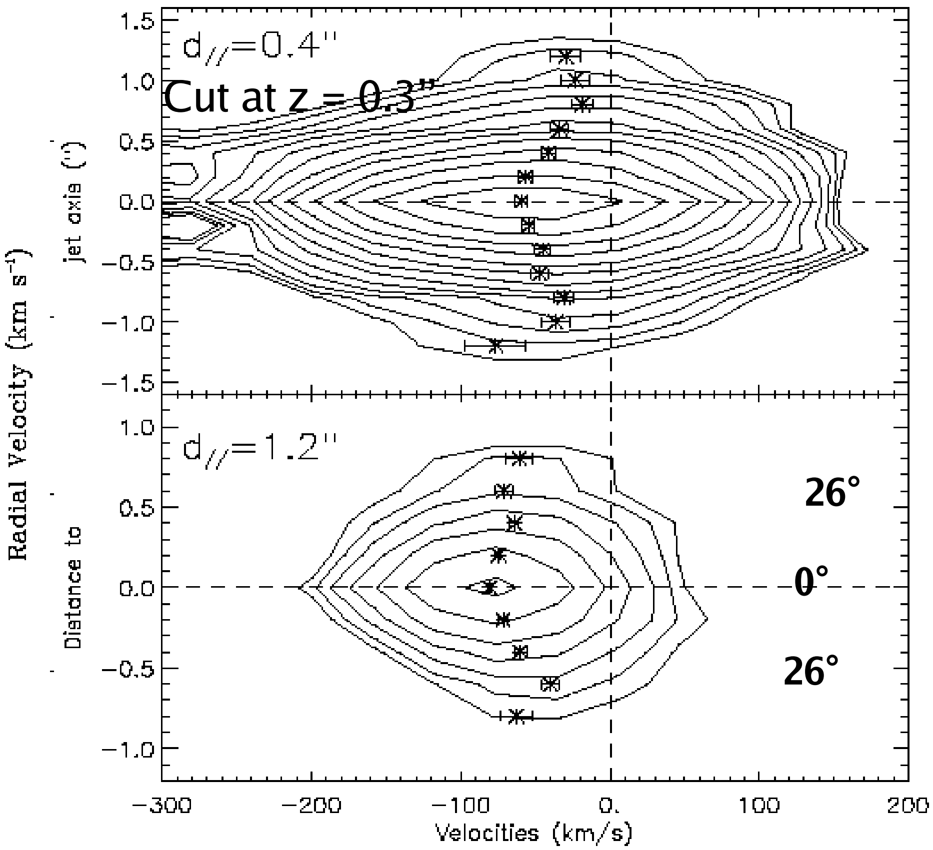
Garcia et al 01, Ray et al. 2007 (PPV)



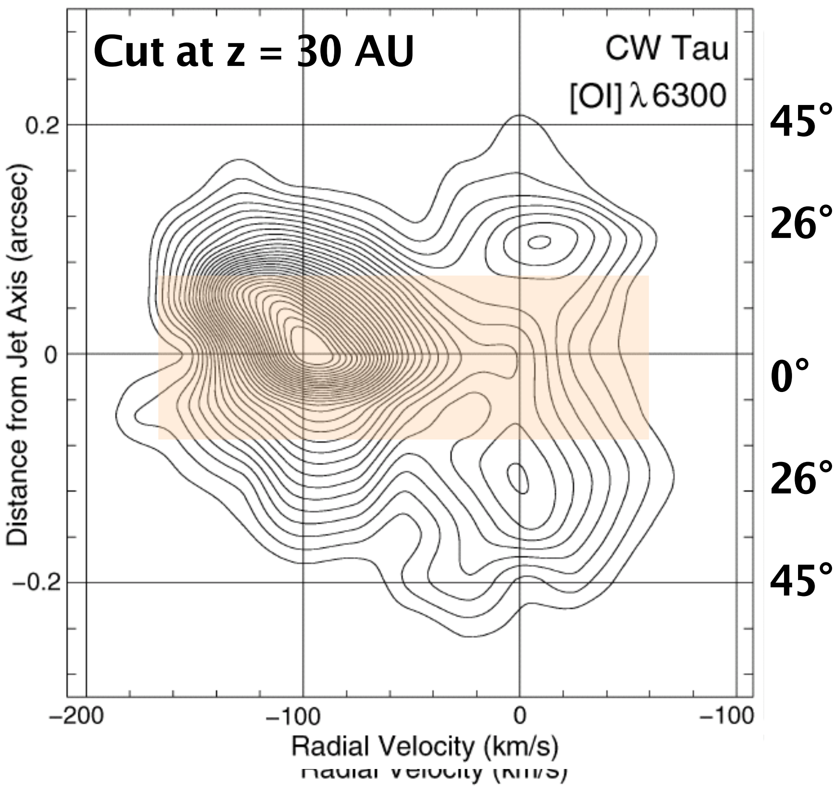


Obs. Constraints on wide-angle flow

- In resolved jets, radial velocity decrease away from jet axis
- drop to 0 km/s in CW Tau; Drop by factor 2-4 in DG Tau, RY Tau, Th28-R
- ➔ No fast-wide angle wind beyond θ > 30°



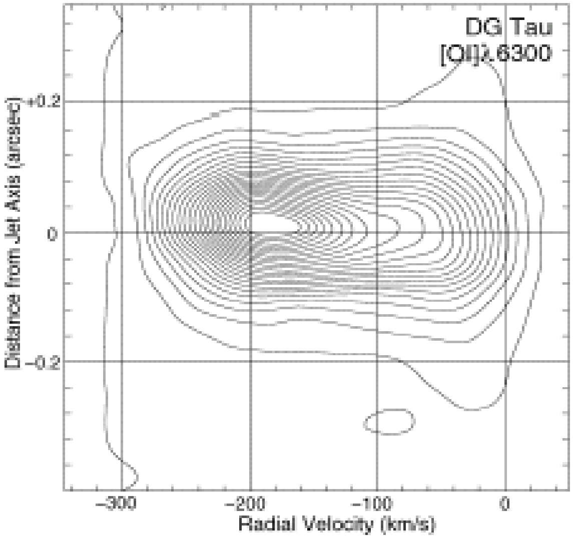
CFHT data from Amboage et al. (2008)



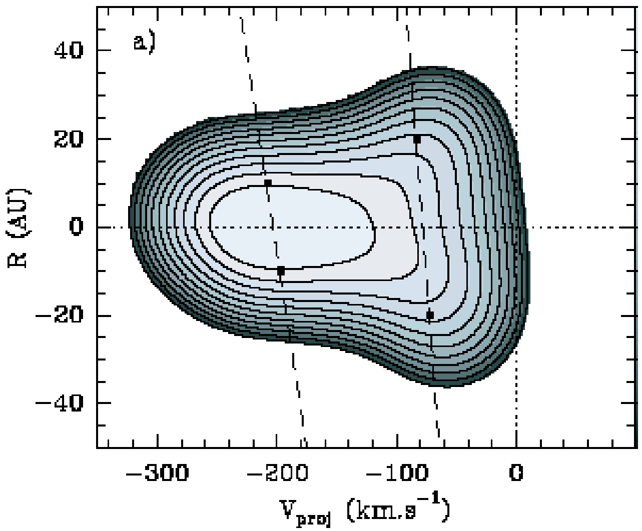
HST data from Coffey et al. (2007)

Transverse Velocity Decrease

- Transverse V(r) in DG Tau well reproduced by extended disk wind with Rout ~ 3 AU (value suggested by rotation)
    - Self-consistent extended Disk-wind model
- Alternative: « confined » narrow jet + slow bowshock wings



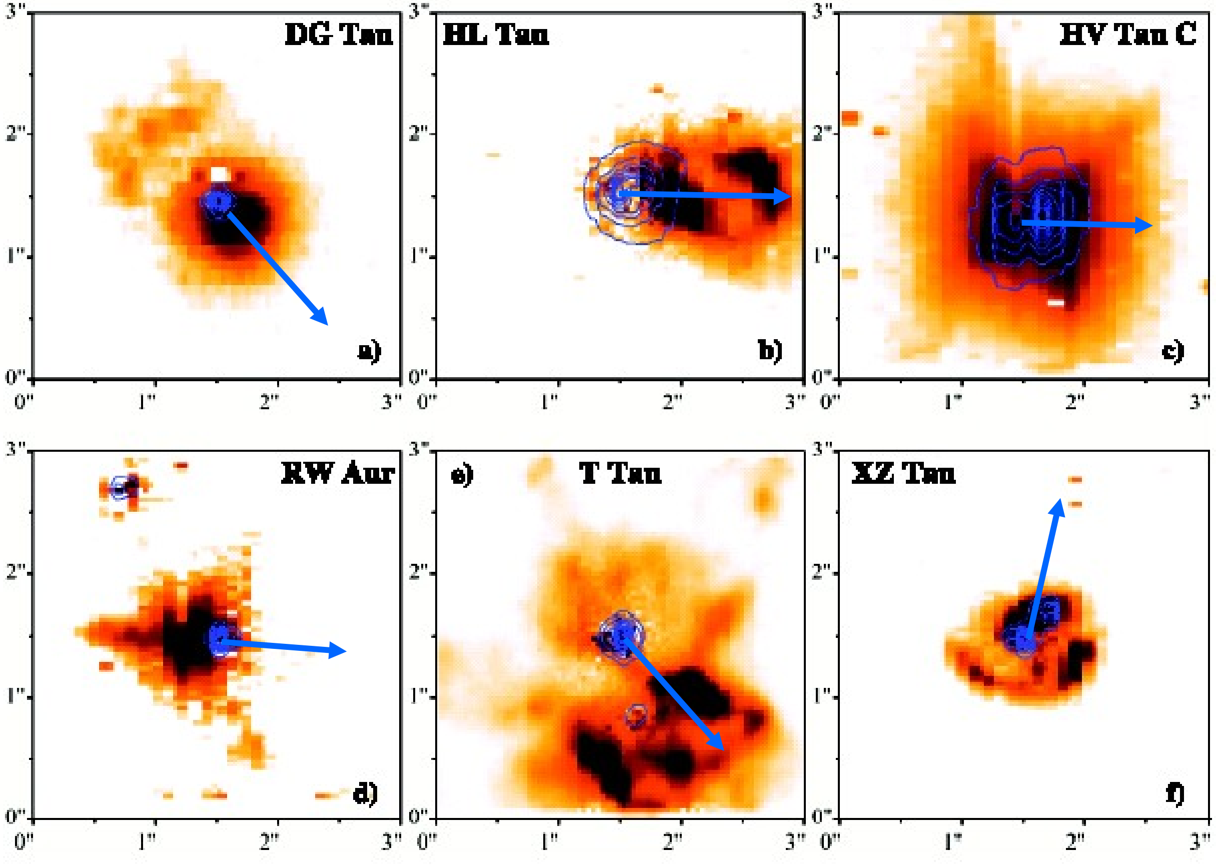
(Coffey et al. 2007)

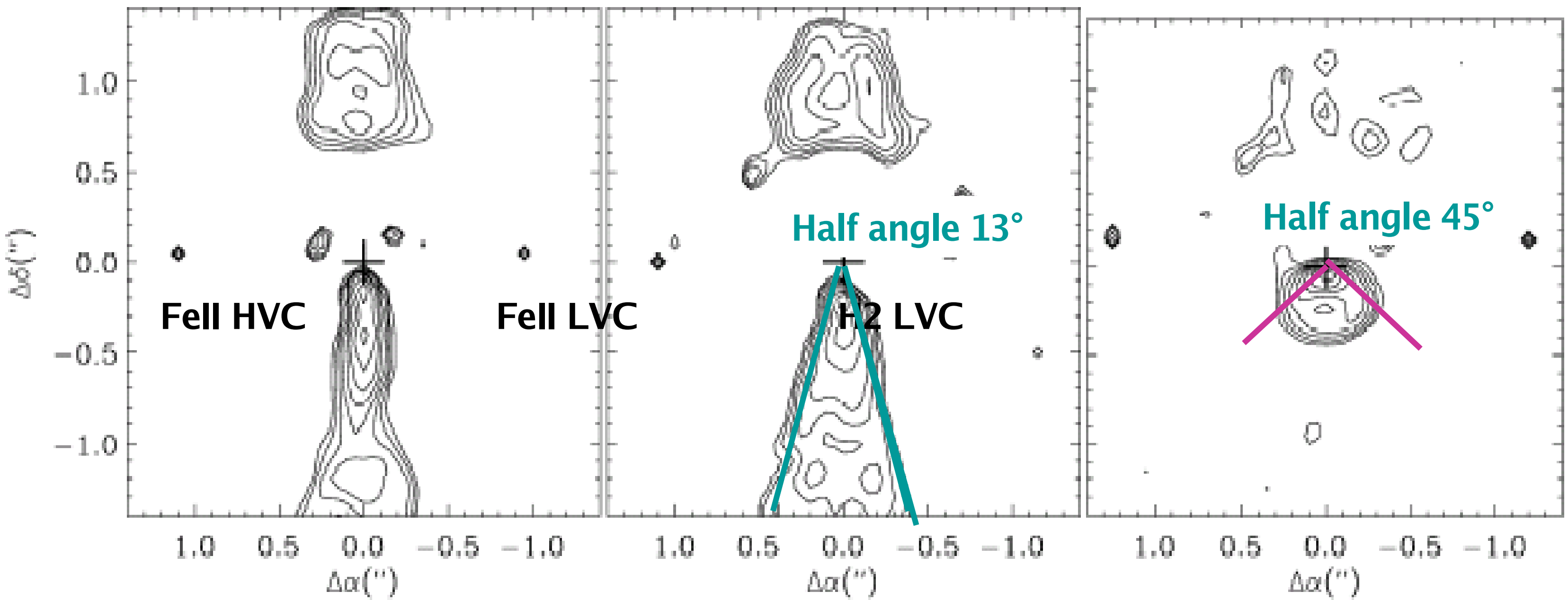


Warm disk wind model at
z = 50 AU for DG Tau
r0 = 0.07-3 AU, λ = 13
(Pesenti et al. 2004)

New: H2 around T Tauri jets

- Beck et al. (08): H2 slow cavities < -15 km/s + redshifted H2 jet in RW Aur (V > 100 km/s)

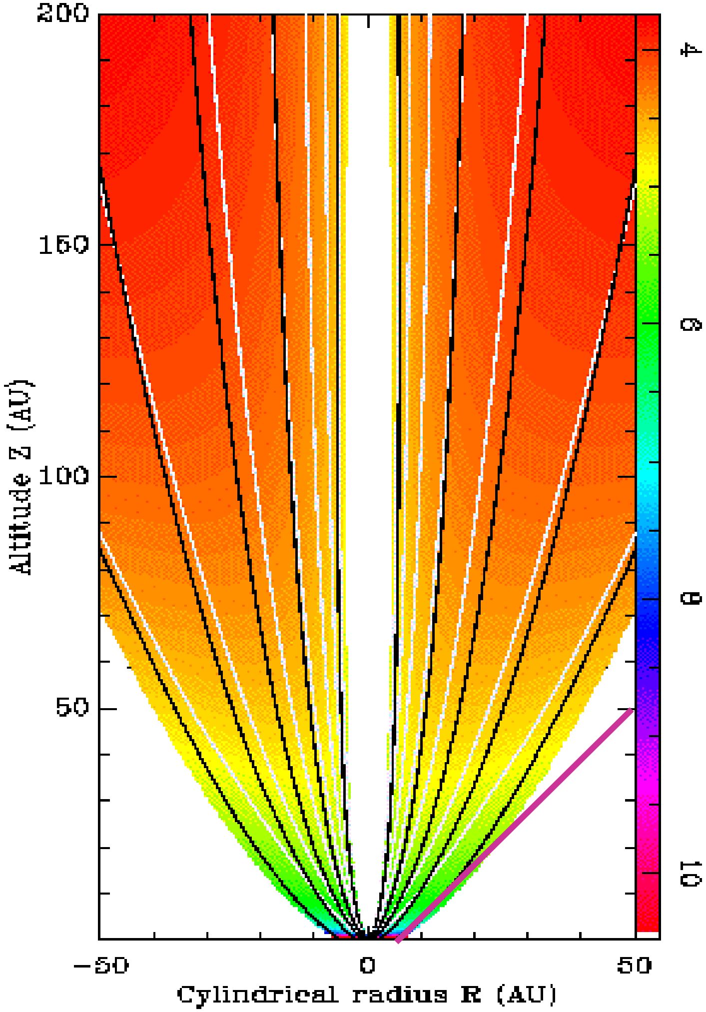




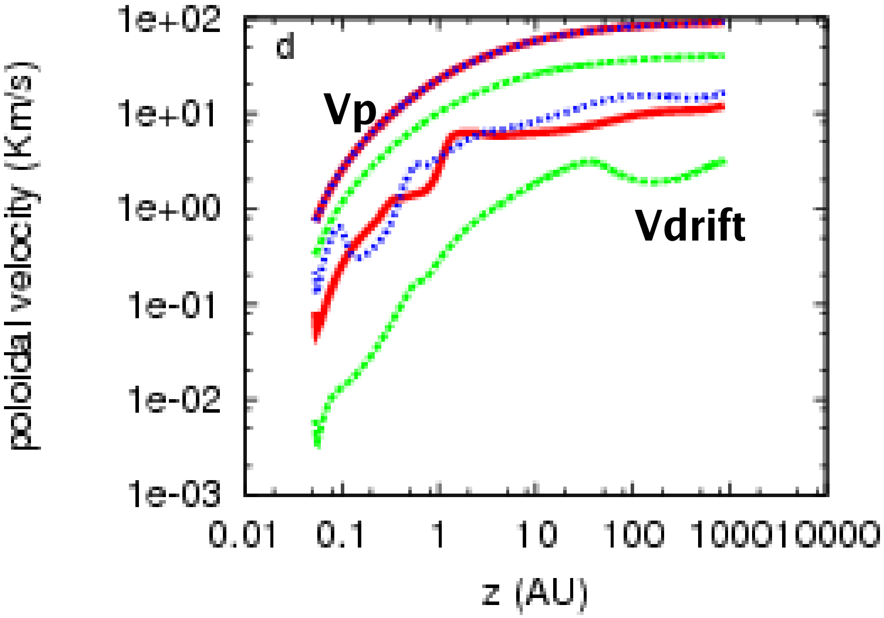
- H2 cavity vs. DG Tau blue atomic jet (cf. Agra-Amboage etal. Poster + talk Saturday) ;
  - Matches/extends transverse V decrease seen in atomic jet
  - Semi opening θ = 45°, Ro < 10 AU
  - Disk shocked by slow wide angle wind ?
  - Disk irradiated by strong FUV/Xrays ?
  - Molecular MHD disk wind from r0 < 10 AU ?

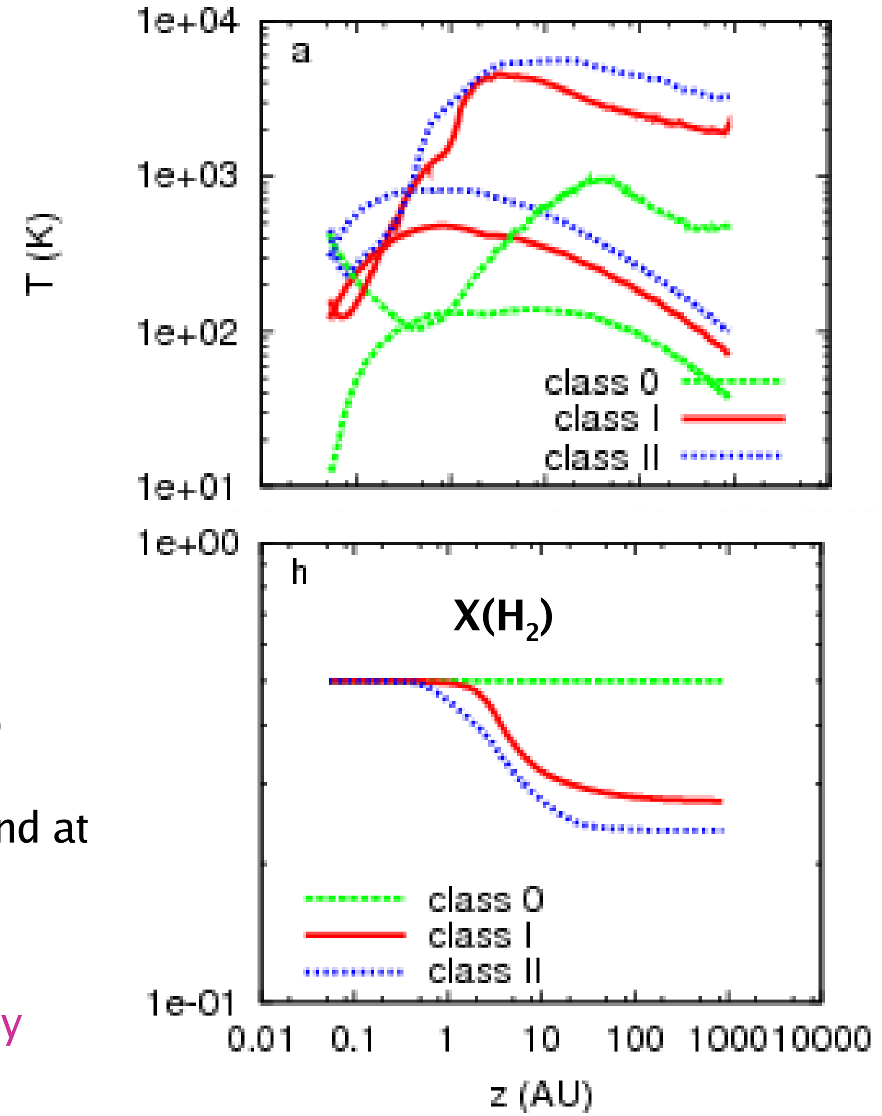
Molecules in MHD disk winds

- Time dependent chemistry in MHD disk winds (cf. Panoglou et al. 08; Poster #48 and talk saturday
  - Ionisation by X-rays and FUV
  - Vdrift from JxB (cf. Safier 93, Garcia etal. 01)
  - Chemistry/ ionisation/ heating/ cooling from C-shock model (Flower & Pineau des Forets 03)



Molecules in MHD disk winds





Launch radius = 1 AU and
Macc = 1e-7 to 5e-6 Mo/yr (Class II to Class 0)

- Enough charges to drag neutrals into MHD wind at V ~ 40-100 km/s
- T ~ 500-3000K, similar to observations
- 50% of H2 survives
- More details in Poster #48 and saturday talk by Panoglou

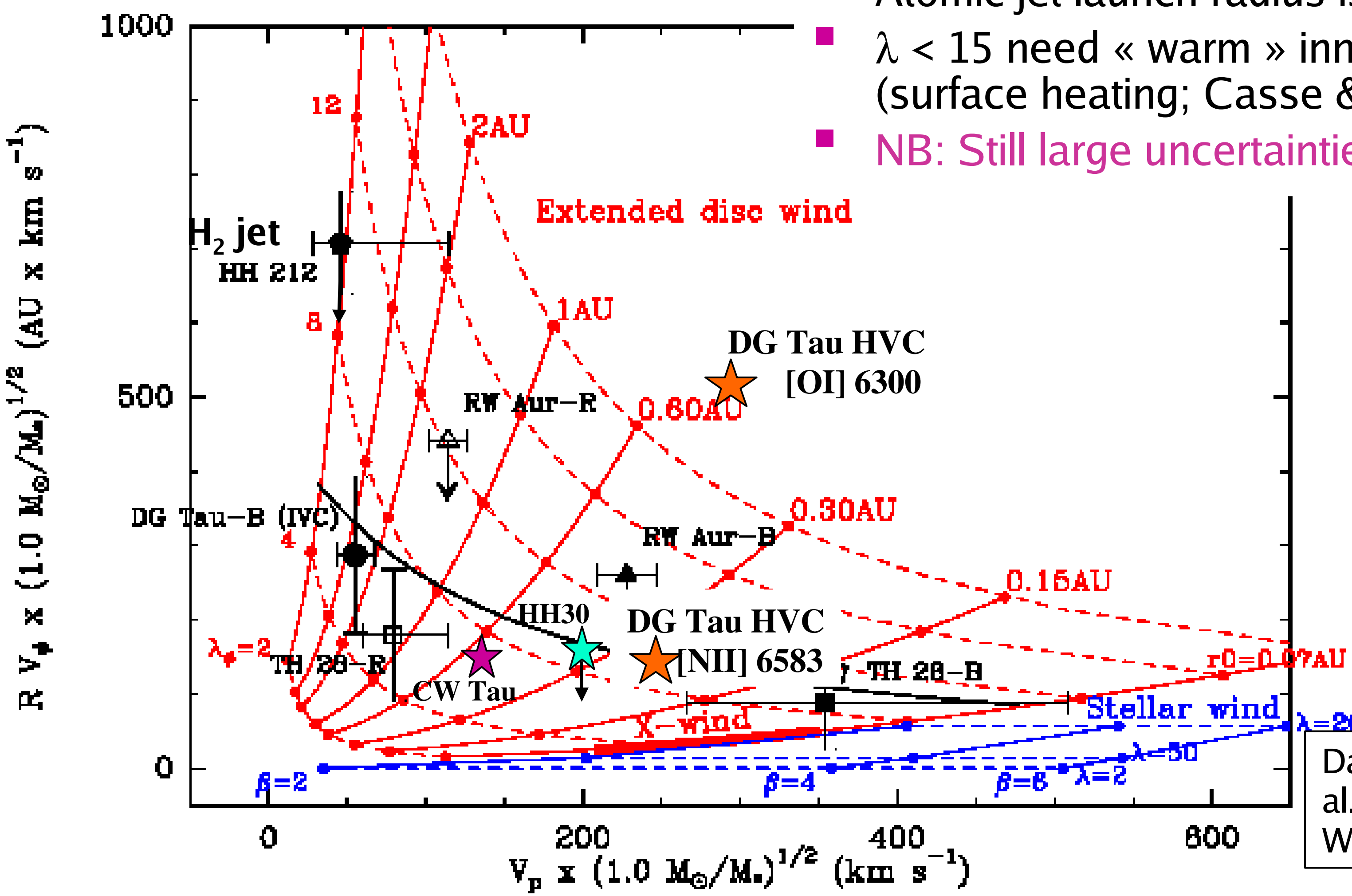
Predicted Kinematics: Vp vs. Vrot

- Poloidal speed Vp and angular momentum RVϕ in cold magneto-centrifugal disk winds depend on:
  - V_{K0} = Kepler speed at launch radius r0
  - Magnetic lever arm parameter $\lambda = r_A^2 / r_0^2$
  - RVϕ vs Vp gives r0 and λ (cf. Anderson etal 03)
- Generalize to all MHD steady models by including dependence on (cf. Ferreira et al. 2006):
  - Stellar rotation rate (stellar wind or X-wind)
  - Energy in form of enthalpy/waves (pressure-driven stellar wind) β = 2H /(GM*/r0)

Observed vs. Predicted Vp and Vrot

- Cold disk wind solutions (λ > 20) are ruled out
- Atomic jet launch radius is < 3 AU
- λ < 15 need « warm » inner disk winds (surface heating; Casse & Ferreira 00)
- NB: Still large uncertainties

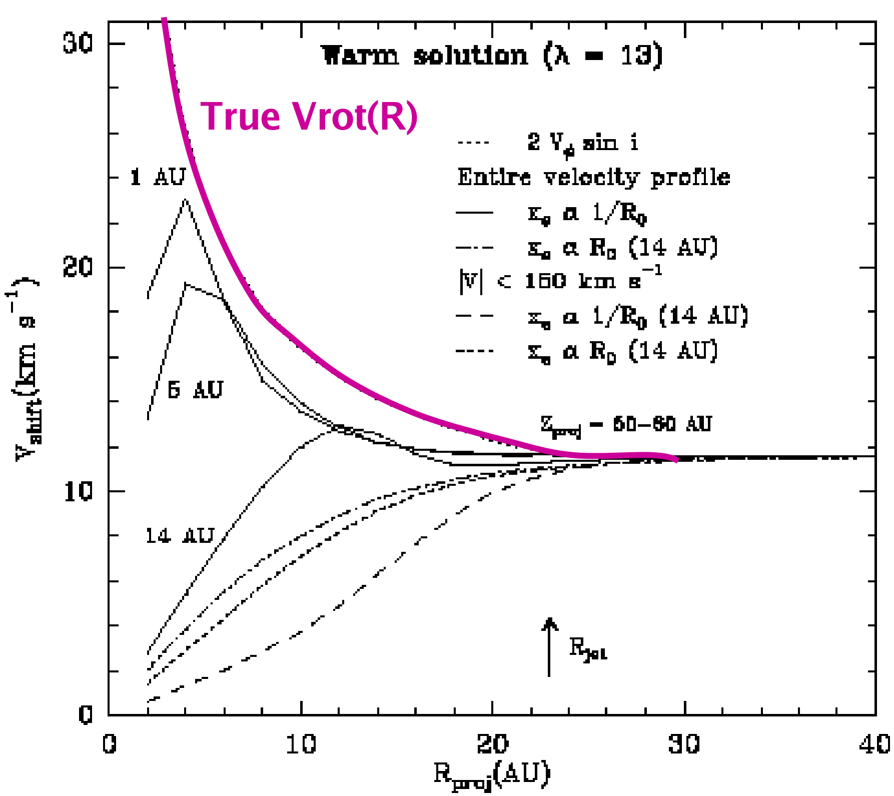
Updated from Ferreira et al. (2006)

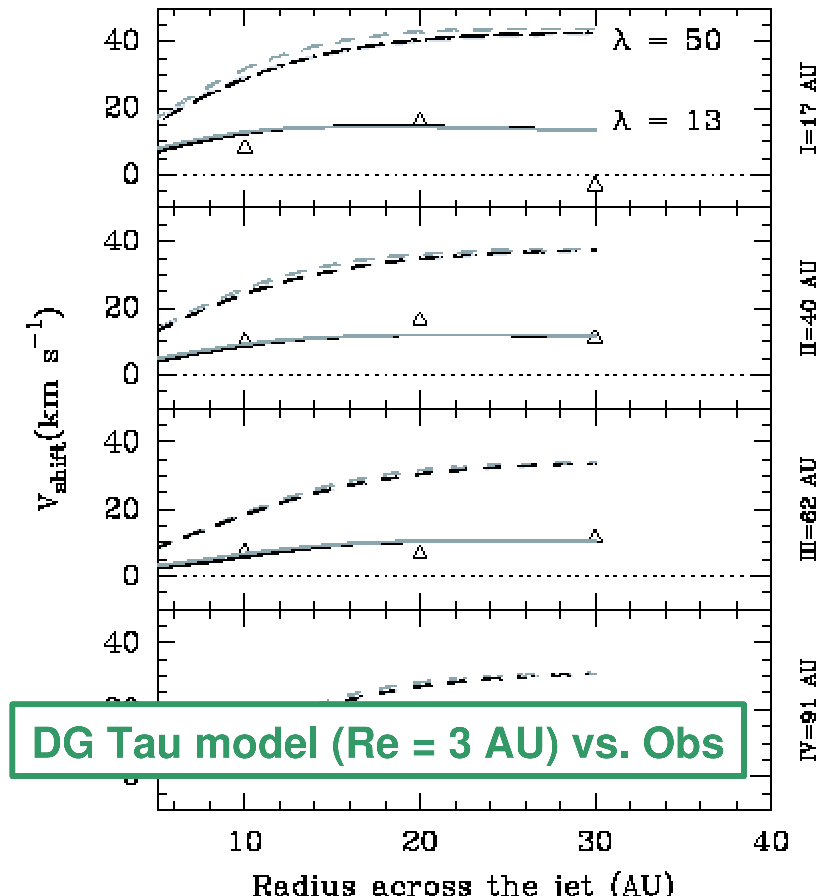


Data from Coffey et al. (04,07)
Woitas et al. (05)

Observational biases in jet rotation

- Projection + Beam smearing ➔ underestimate Vrot except at jet radius > PSF
- *Need to resolve jet beam to set reliable upper limit on Vrot : PB in many jets*



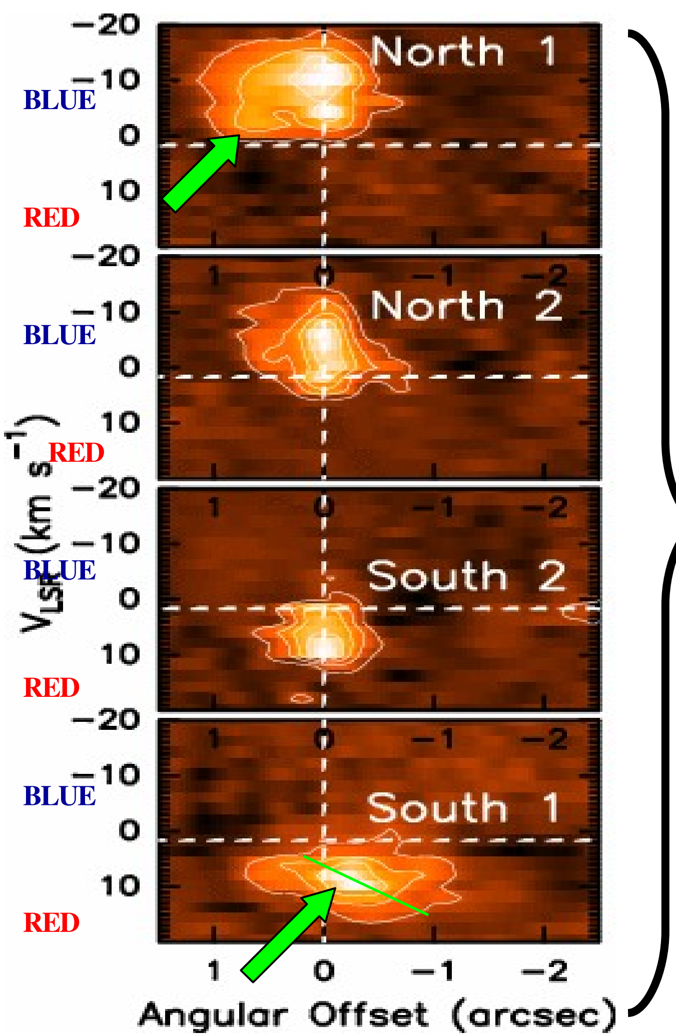


Pesenti et al. 2004 A&A
Synthetic PV cuts across warm MHD disk wind

Observational biases in jet rotation

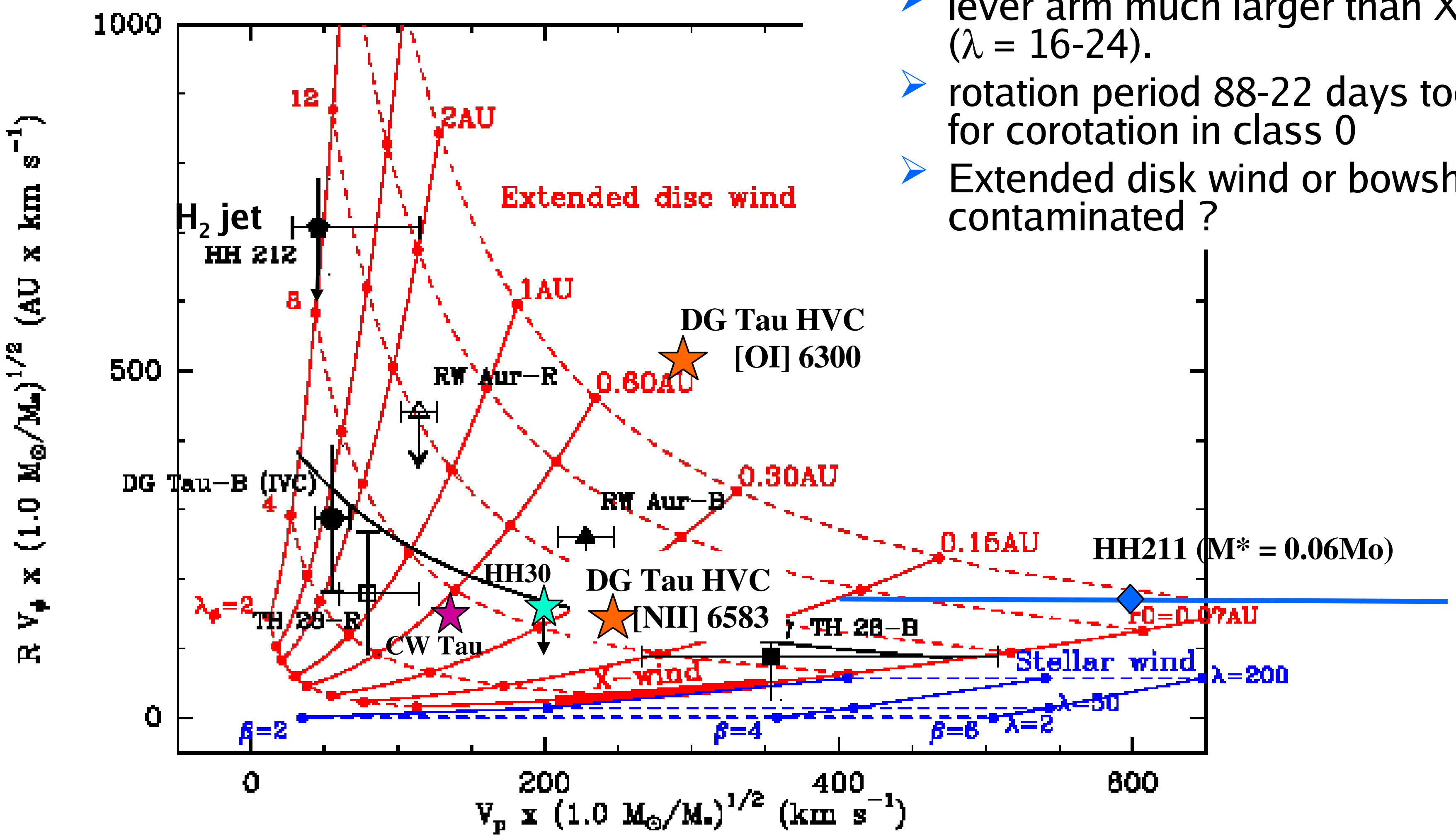
- Contamination by internal bowshocks
  - Mixing with non-rotating gas: diminish J
  - Asymmetries: create Vshift
  - May either under- or over-estimate J

- Possible examples
  - RW Aur: conflict between jet and disk rotation sense (Cabrit et al. 2006)
  - HH212: Vshift measured in component at Vrad ~ 2km/s but i = 4° (H_2O masers) ➔ V ~28 km/s: bowshock.
    - Fast jet with V ~150 km/s projected at Vrad ~ 10 km/s: unresolved, no Vshift (Codella et al 07).
    - See also Poster by S. Correia on H_2



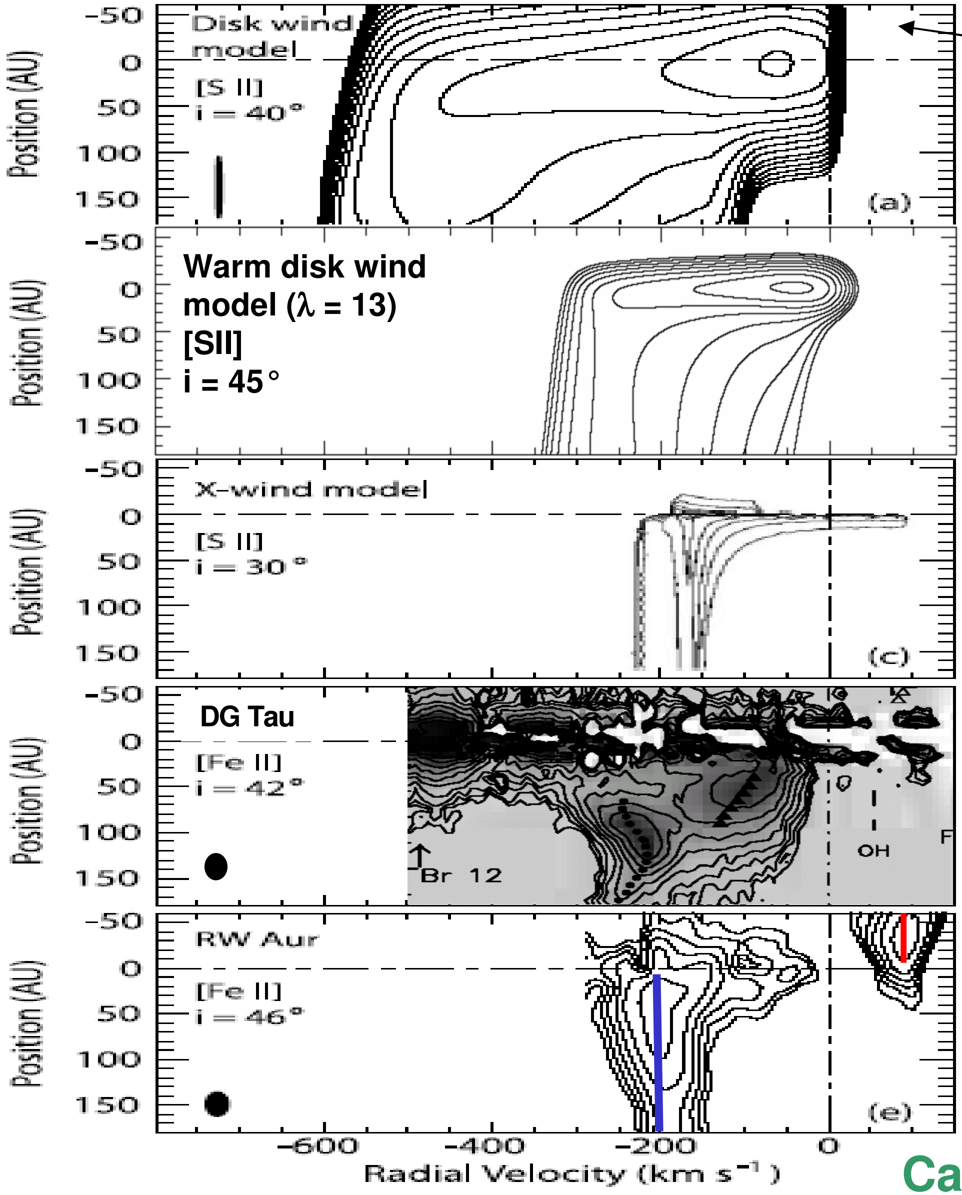
(Codella et al 07, A&A).

Observed vs. Predicted Vp and Vrot



- HH 211: Lee et al. (07) infer r0=0.15-0.06 AU for Vj = 100-200 km/s and M* = 0.06Mo, but:
  - lever arm much larger than X-wind (λ = 16-24).
  - rotation period 88-22 days too long for corotation in class 0
  - Extended disk wind or bowshock-contaminated ?

Poloidal Kinematics: along jet axis



- "Cold" Disk Wind Models λ ~ 50 (Ferreira 1997; Garcia et al. 2001): **too fast**
- "Warm" extended Disk Wind (r0 = 0.07-3AU, λ = 13: solution fitting rotation measurements)
  - HVC ok
  - IVC from outer disk radii
- X-wind model (Shang et al. 1998)
  - HVC ok with λ = 3
  - no IVC

➢Note jet asymmetry in RW Aur: different r0 or different λ ?

Cabrit (2007, IAU Symp 243)

Ejection to accretion ratio
Statistical value

- CTTS sample:
- Mdot from L[O I] (integrated)
- Macc from optical veiling + BC

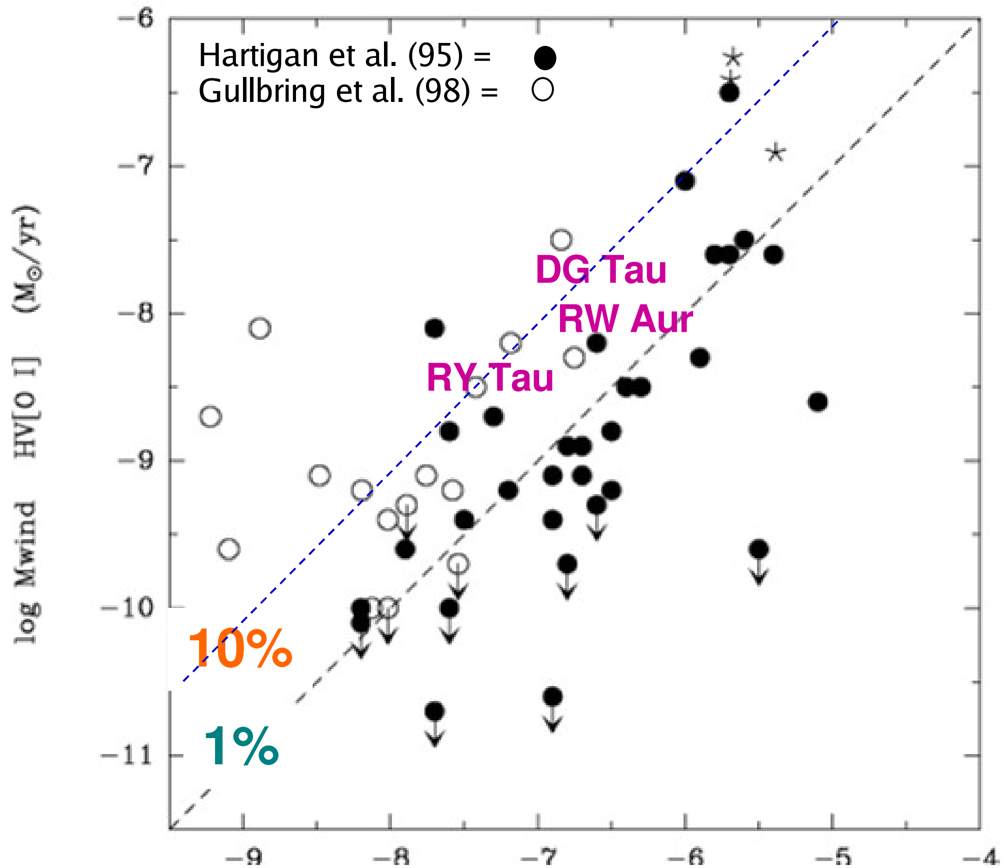
Mjet(one-sided)/Macc ~ 1%
(Hartigan et al. 95)

•updated accretion rates of Gullbring et al. (98, 01) ➔
Mjet(one-sided)/Macc ~ 10%
(Cabrit 2007,2008)

- Spatially resolved microjets: more precise Mjet in DG Tau, RW Aur, RY Tau, HN Tau (Lavalley et al 00, Woitas et al 05, Amboage et al 08, Hartigan et al 04)

Mjet(one-sided)/Macc ~ 1%-10%

- Similar ratio ~1%-10% for Class I jets (Hartigan et al. 94; Antoniucci et al 08)



Log Macc (M /yr)
from Cabrit (2008, 2007 IAU 243)

Jet mass flux vs. disk winds / X-wind

Reminder from J. Ferreira's review:

- Cold magnetocentrifugal disk winds powered mostly by Poynting flux α $B\phi$ (not by enthalpy/turb. pressure);
- The same $B\phi$ regulates angular momentum extraction from the disk, ie Macc
- In steady-state, Jet power = ½ Mj Vj^2 = energy liberated by keplerian accretion flow = GM*Macc/2 (1/Rin – 1/Rout)

- Magnetocentrifugal acceleration: $Vj^2 = (2\lambda-3)\ Vk^2(Rin)$
  - Self-similar D-wind: f = Mj/Macc = ln(Rout/Rin)/(2λ-2)
    - λ ~ 10 from rotation and Rout/Rin ~ 2-10 ➔ f ~ 4%-13%

  - X-wind: f = Mj/Macc = (Δr/Rin) /(2λ-3) < 1% for $\lambda > 2$

    wind torque / spin-up torque $f\lambda << 1$. Extra ingreedient ?

Jet mass-flux vs. stellar winds

- Mass-flux in hot wind (T ~ 10^5 - 10^6K) much lower than in optical jet
  - X-rays: Mw(10^6K) < 1e-10 Mo/yr (De Campli 1981, Matt & Pudritz 07):
    - cf. Xray jet in DG Tau (cf. Poster Günther etal.)
    - NB: Thermal pressure sufficient to broaden atomic jet (Güdel etal 08)
  - Si III] T ~ 6 10^4 K in RY Tau (Gomez de Castro & Verdugo 07): Mw ~ 1e-11Mo/yr < 1% of [OI] jet (Agra-Amboage et al. 08)
  - CIV: T < 20,000 K in wind acceleration region (cf. talk by C. Johns-Krull): cool stellar wind

- « Turbulent » power to overcome gravity from R*:
  - Lturb ~ GM*/R* Mjet ~ f Lacc ~ 2 Lkin (Ferreira et al. 06, Matt & Pudritz 08), but strict lower limit as never fully efficient
  - e.g. Alfven-wave driven wind (DeCampli 81): L(Alfven waves) ~ 5-10 Lkin; More if other waves + damping.
  - Lkin ~ 1%-10% Lacc ➔ Lturb ~ 2%-100% Lacc: challenging…

- More promising: thermo-magnetic launching close to corotation, eg. Plasmoid ejections (Romanova, Zanni, Hartmann)

Conclusions

- Jet collimation at Z ~ 50 AU is magnetic (internal or external): thermal pressure of disk/envelope is ruled out.

- Transverse velocity decrease: No fast wide angle wind beyond 30° of axis.
  - X-wind model needs modification…
  - Bowshock / expanding cavity around a confined jet ?
  - Extended disk wind ?

- Jet rotation searches: strongly limits parameter space for Disk-winds
  - $\lambda < 15$ ➔ heating at disk surface (Casse & Ferreira 00): origin ?
  - Rout < 0.5-3 AU for atomic jet: why ?
  - NB: Many uncertainties in Vrot, especially in class 0 jets

- H_2 in jets / slow cavities: disk winds as alternative to bowshocks/entrainment
  - H_2 at 120 km/s in RW Aur jet: not a stellar wind.
  - H_2 survives in MHD disk winds launched at a few AU

- Jet mass-flux and jet power :
  - Mj/Macc >> 1% seems challenging if ejection from R* or X-wind
  - Unsteady ejection driven by field relaxation in stellar magnetosphere very promising
  - Origin of jet velocity asymmetries ???