Jets, outflows, and disc winds

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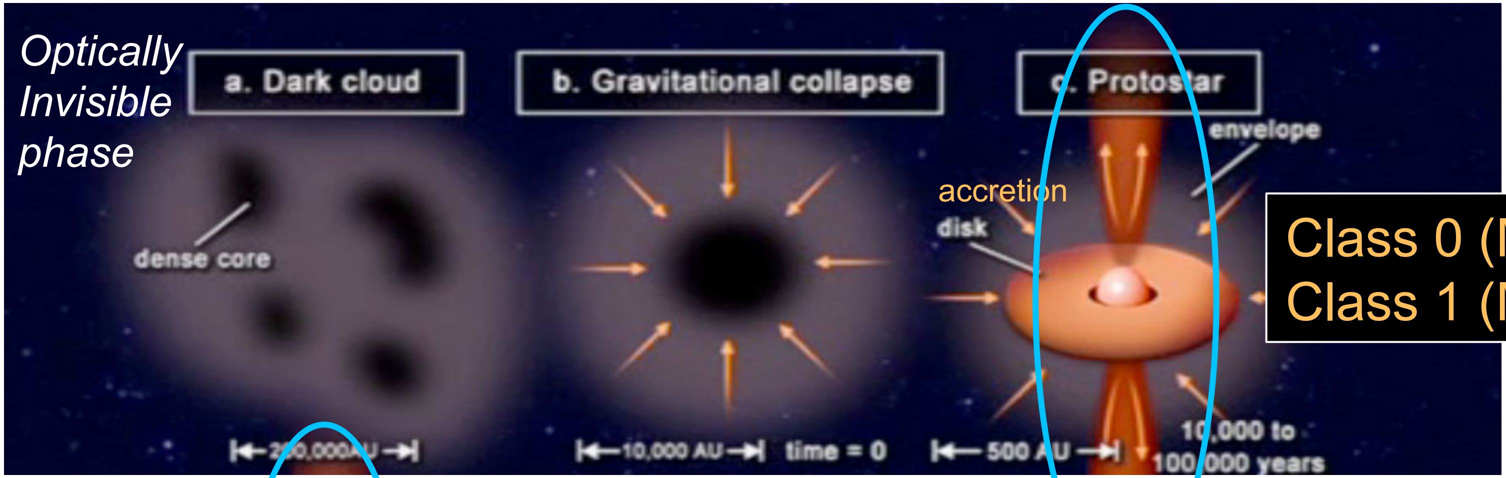
Jets, Outflows, and disk winds

- Jet and outflow signatures across star formation
- Jet collimation : evidence for a magnetic process
- Jet energetics : challenges for stellar winds
- Magneto-centrifugal disk winds: pros and cons
- Conclusions

Reminder: Stages of star formation

Strong accretion-driven outflows

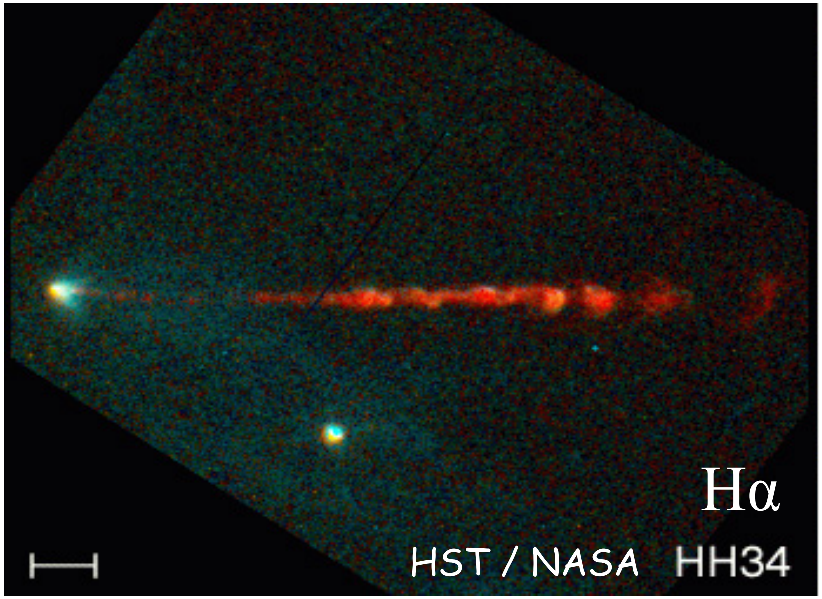


Optically Invisible phase

Class 0 ($M_* < M_{env}$)
Class 1 ($M_* > M_{env}$)

Resolved outflow signatures in young stars

Fast axial Jets
V = 100-800 km/s



- Ionic lines (O, S, S+, Fe+, Hα…)
- Free-free radio continuum
- Molecular lines (H_2, SiO, CO..)
- Water masers (jet base only)

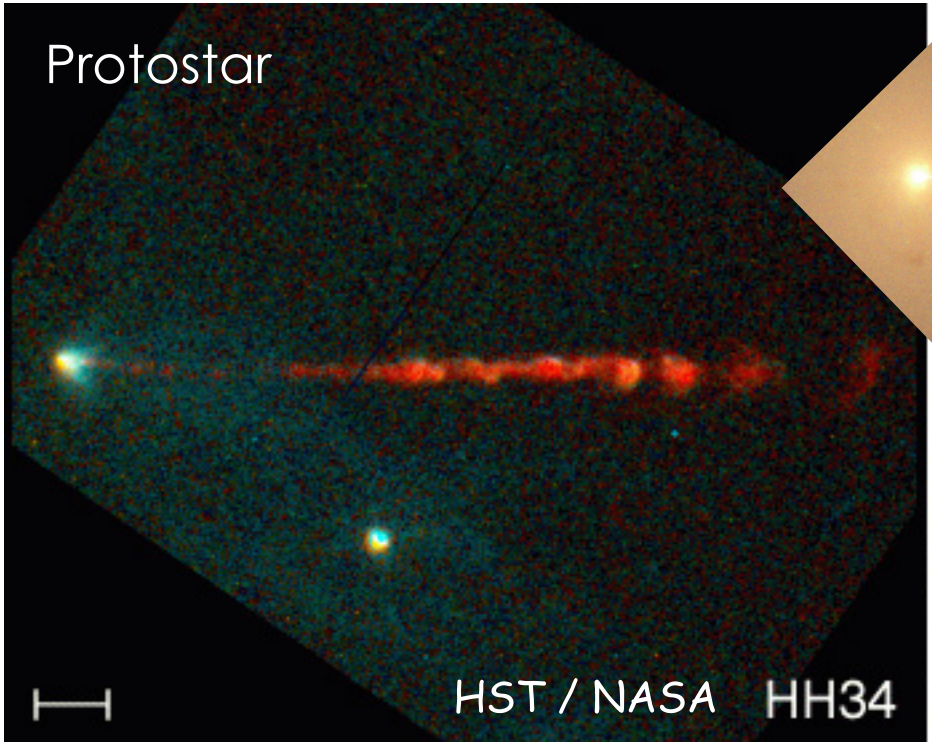
Low-velocity outflow cavities
V = a few 10 km/s

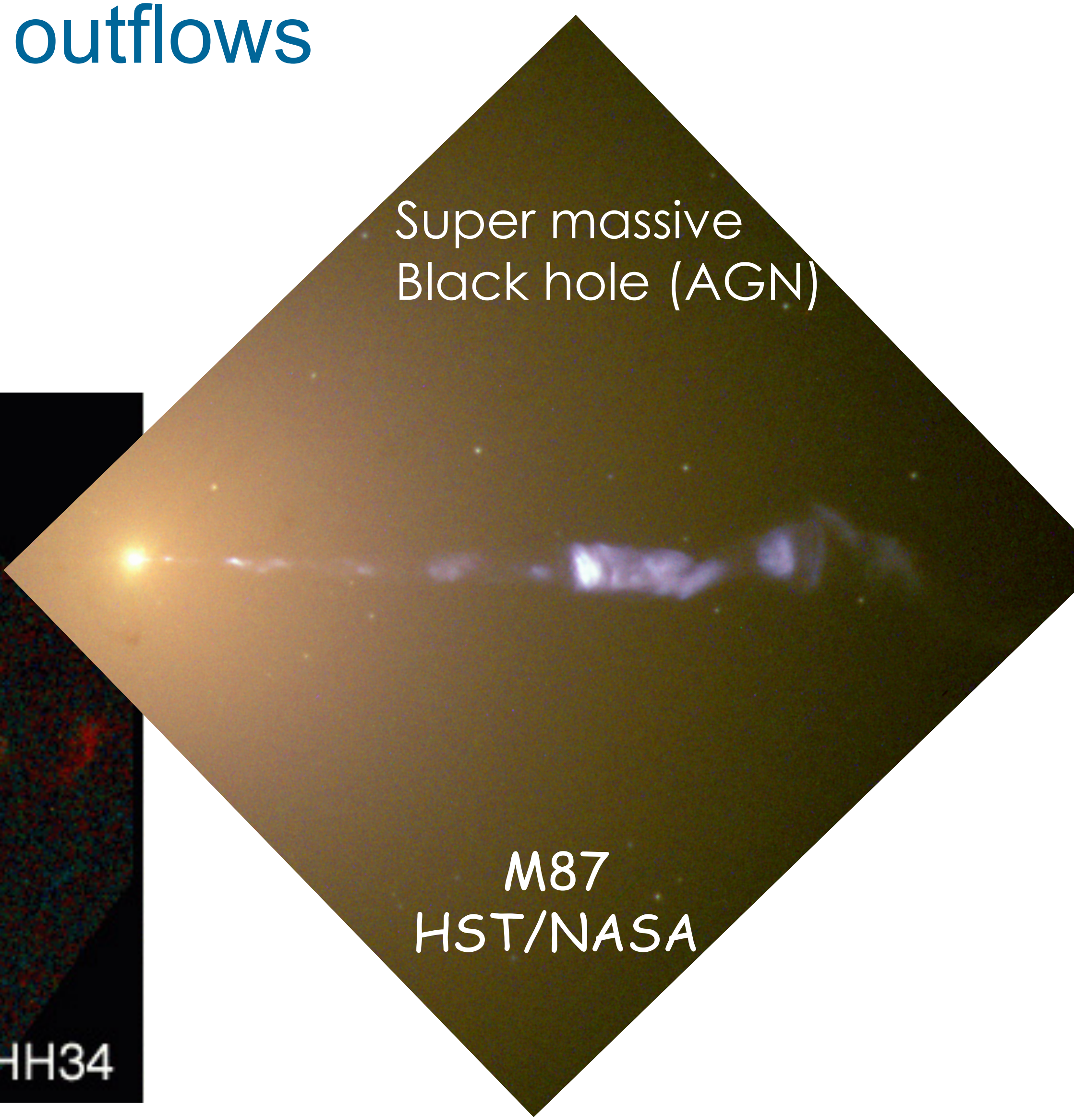
Spitzer NASA / Velusamy et al 2007

- Molecular lines: CO, H_2 (+ « ice » species CH_3OH, H_2CO …)

Reviews: Cabrit (2002, EDP Science), Arce+2007 (PPV)
Frank+2013 (Protostars & Planets VI)

Similarity to other astrophysical jets and outflows



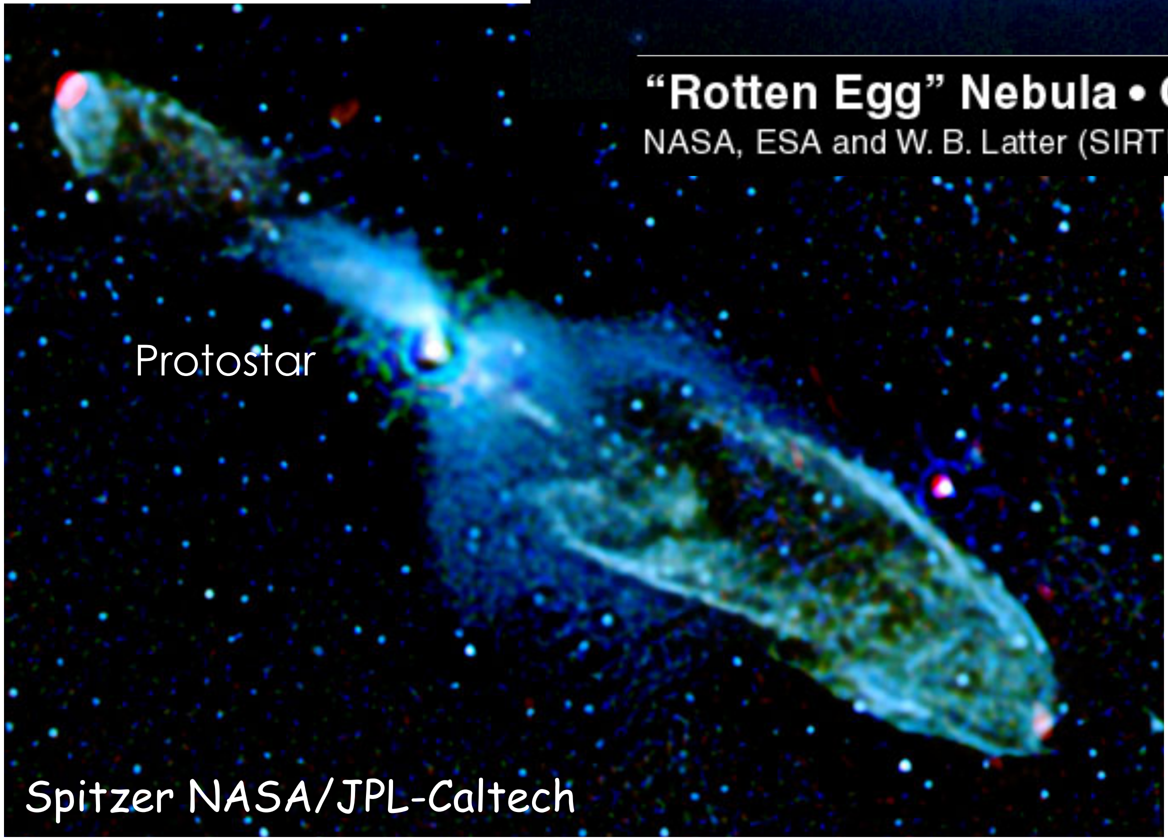


Similarity to other astrophysical jets and outflows


Dying star

“Rotten Egg” Nebula • OH231.8+4.2

NASA, ESA and W. B. Latter (SIRTF Science Center/Caltech) • STScI-PRC99-39

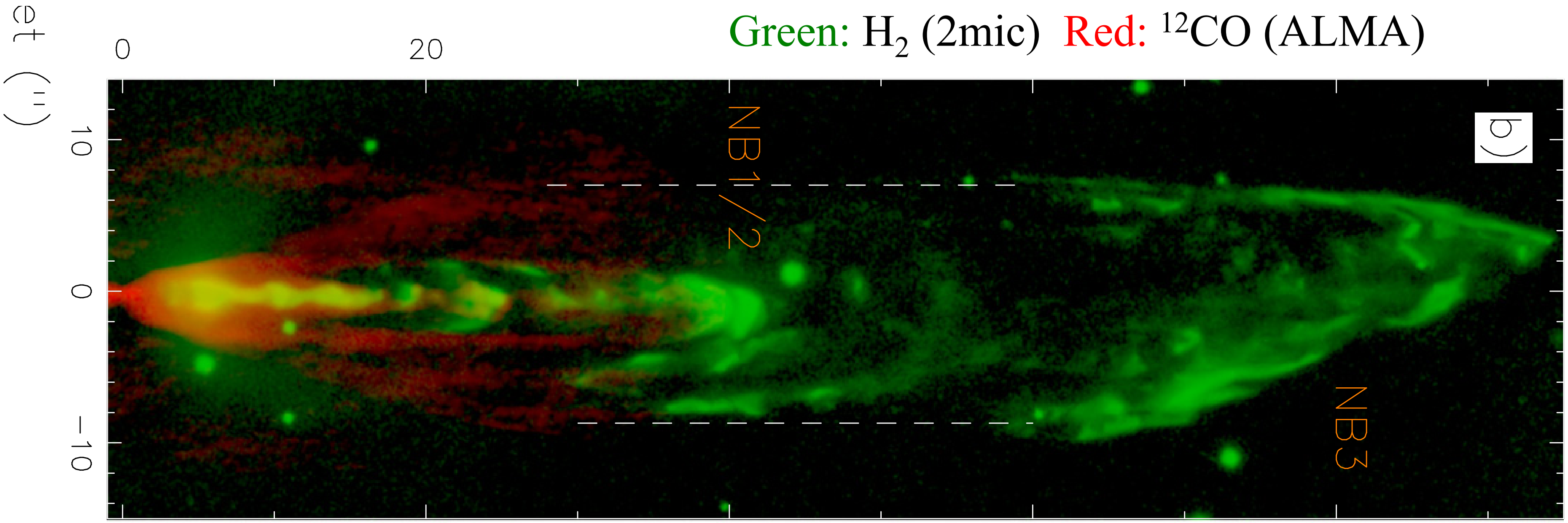

Protostar

Spitzer NASA/JPL-Caltech

Low velocity outflow cavities

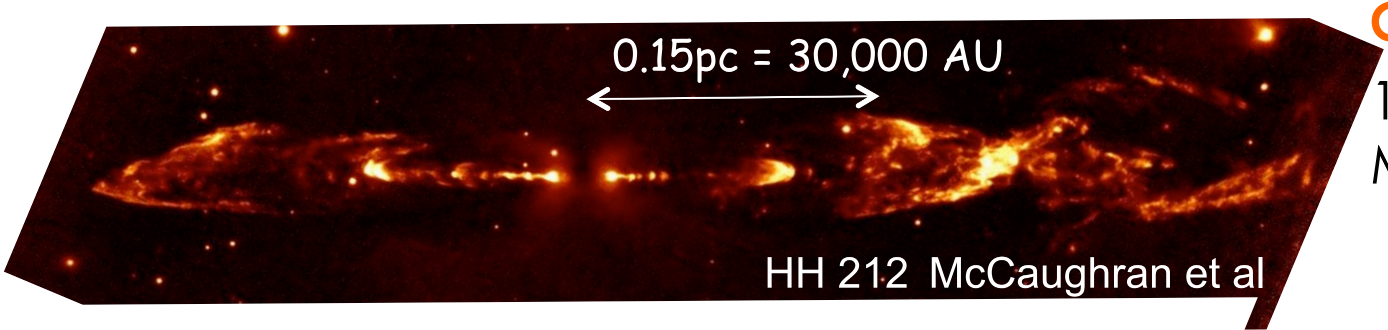
- First observed outflow signature in protostars (Snell+1980)
- Often Mass > M* ➔ mostly ambient gas swept-up by
  - jet bow-shocks see Cabrit, Raga & Gueth 1997
  - + wide angle wind ? See Arce+2007, Protostars & Planets V

ALMA: Nested CO jet bowshocks in HH212 (Lee+2015)



Green: H_2 (2mic) Red: ^{12}CO (ALMA)

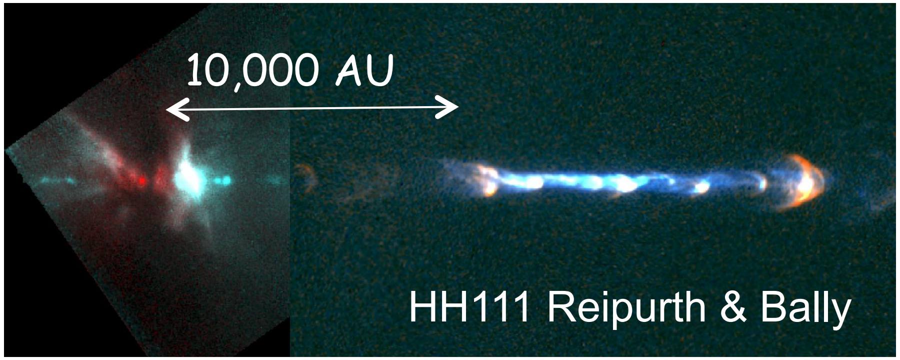
Universality of jets across ages



HH 212 McCaughran et al

Class 0 Protostars

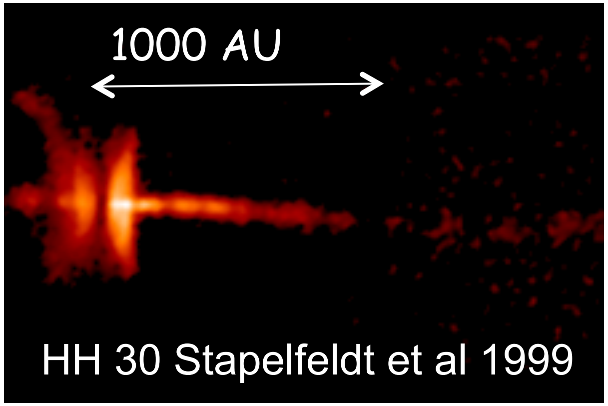
10^3-10^4 yr
M* < Menvelop



HH111 Reipurth & Bally

Evolved Class 1 Protostars

~ 10^5 yr
Residual infall, M* > Menvelop



HH 30 Stapelfeldt et al 1999

Class 2 = T Tauri Star with accretion Disk
~ 10^6 yr
No more obscuring envelope

A universal jet launching mechanism ?

- M* from 24 M_{Jup} to 15 $M_{\odot}$ (Whelan+04, Guzman+10)
- Mdot_acc from 10^{-10} to 10^{-5} $M_{\odot}$/yr
- Little influence of B*: Jets from young Herbig Ae/Be stars, (Gregory+14)

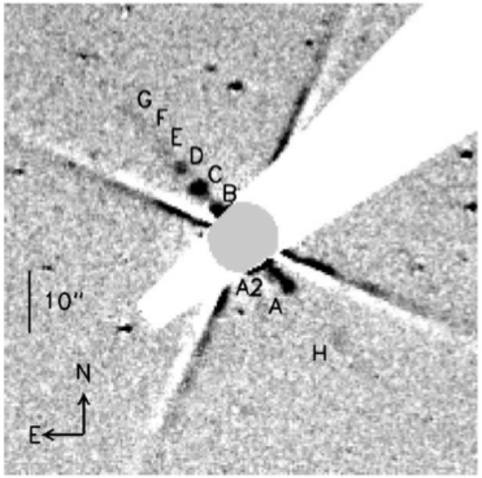
HD163296:

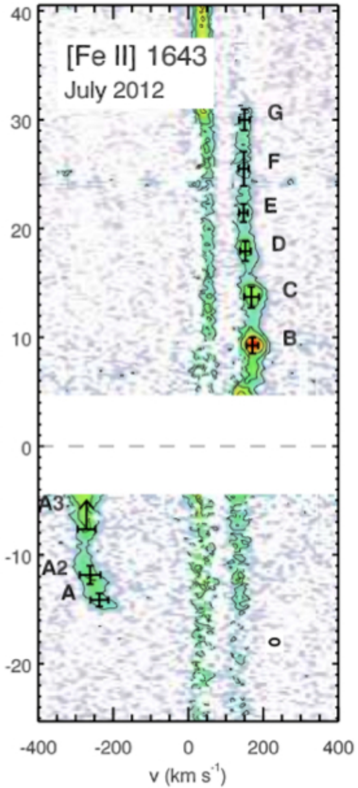
Ellerbroek+14:

similar to T Tauri jets

BUT no strong kG dipolar B* as in TTS

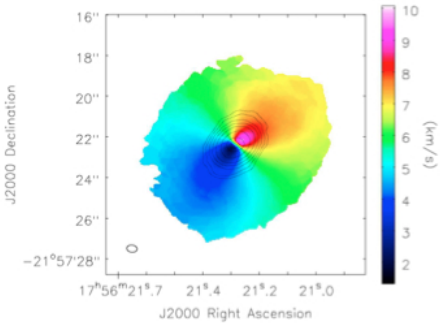
Jet HST
Wassell et al. 2006





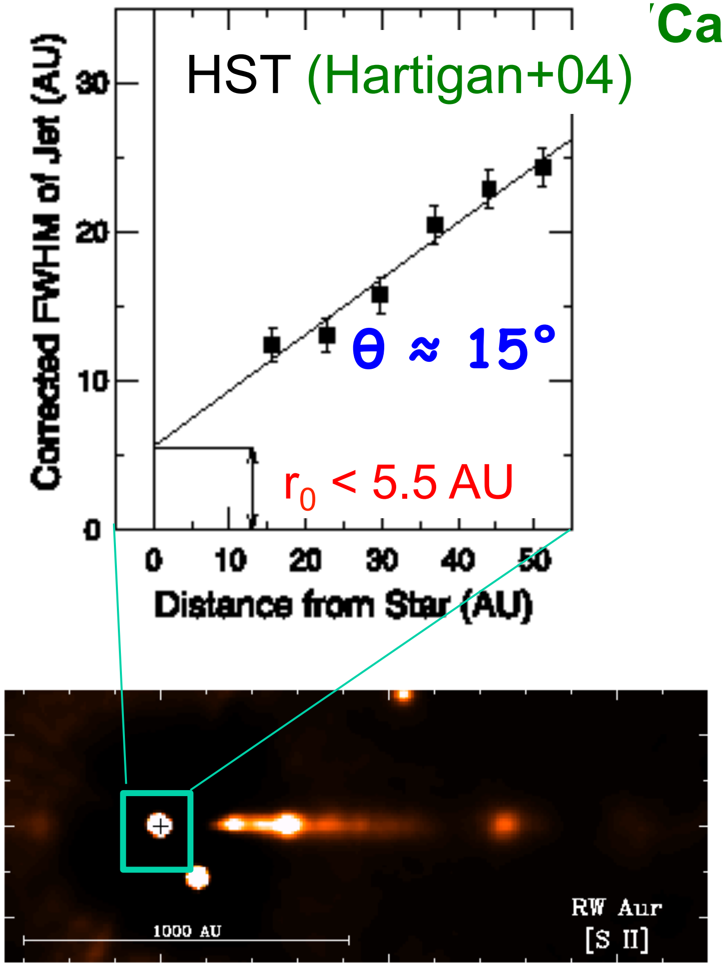
VLT / XSHOOTER

Disk CO(3-2) ALMA
de Gregorio-Monsalvo et al. 2013



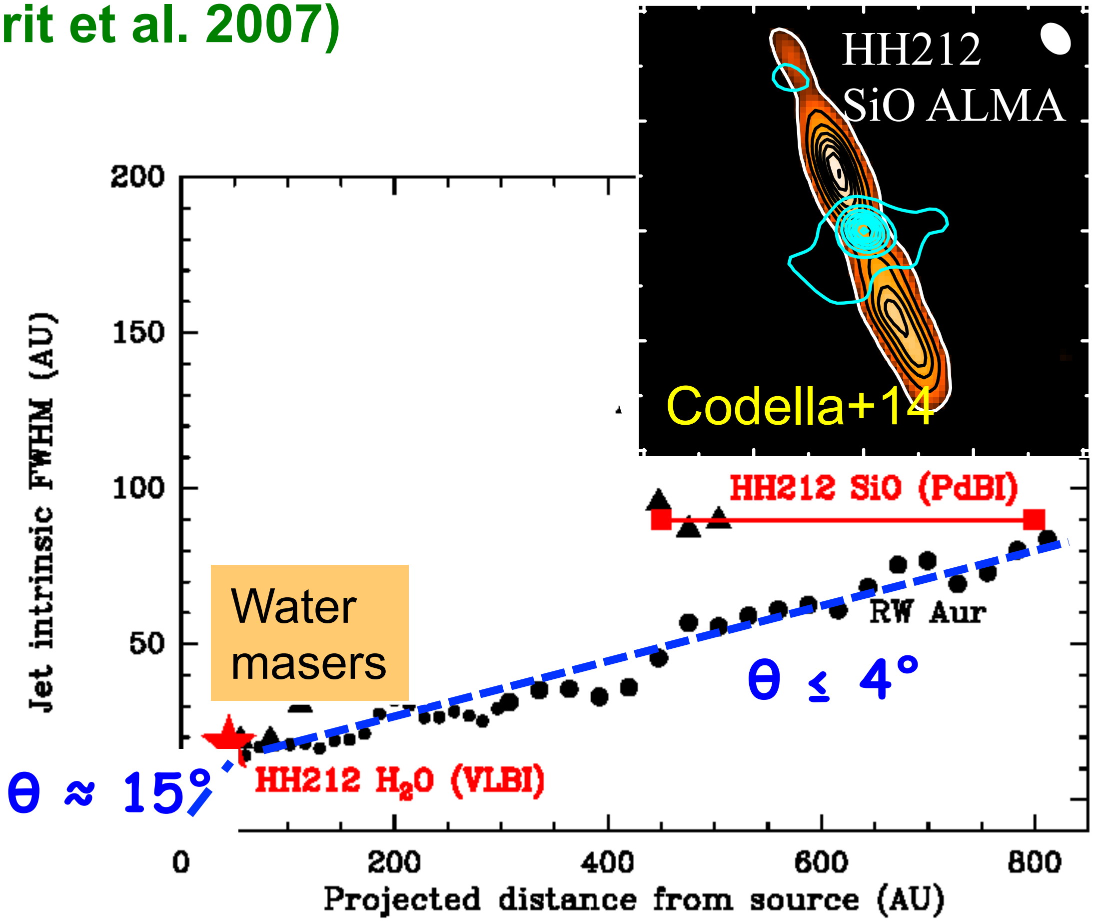
A universal collimation process

- collimation of atomic Class 2 jets into narrow cone at Z ~ 50 AU,R ~10 AU



- Same in molecular jets from Class 0 protostars

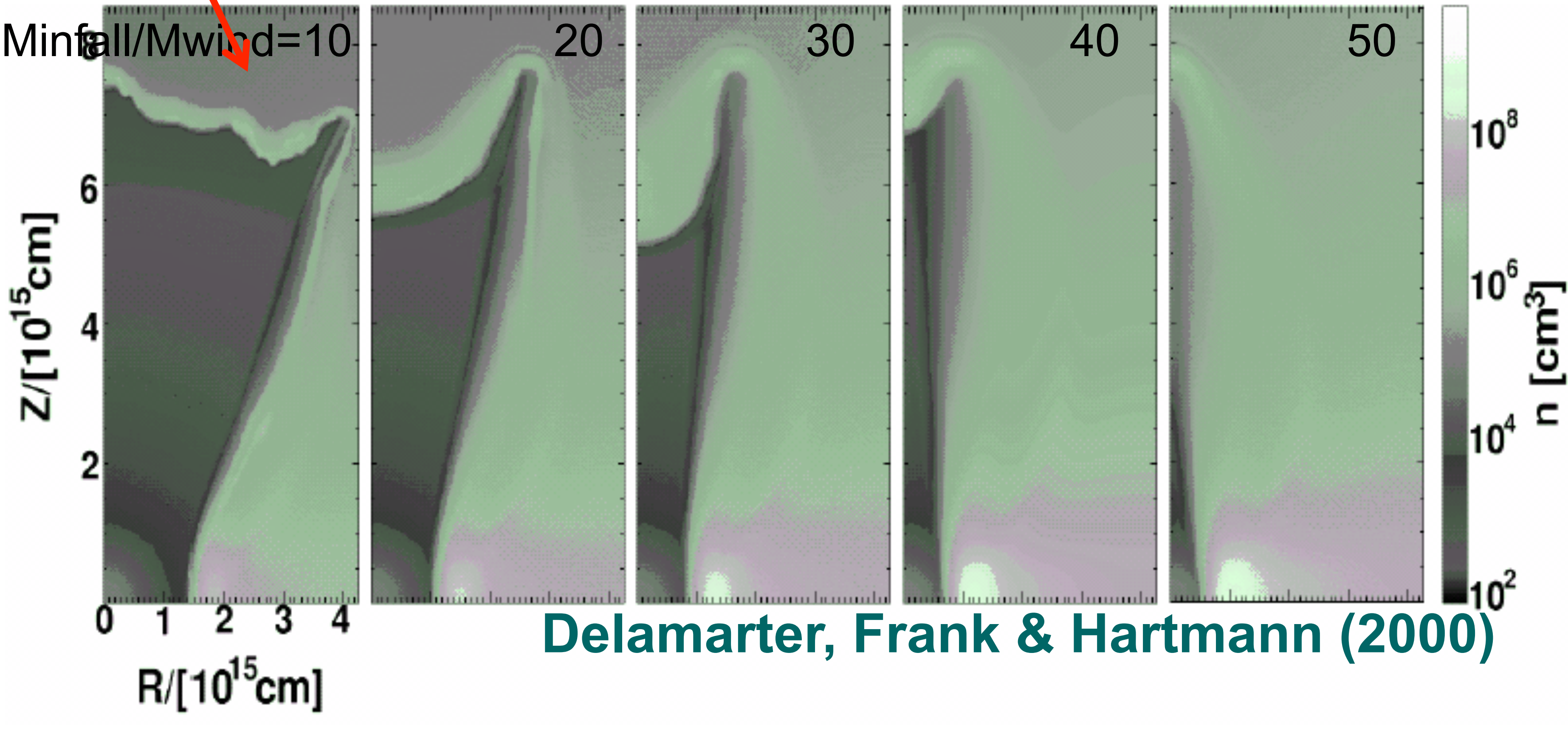
(Cabrit et al. 2007)



Cabrit et al. 2007

Inertial collimation by infalling envelope ?

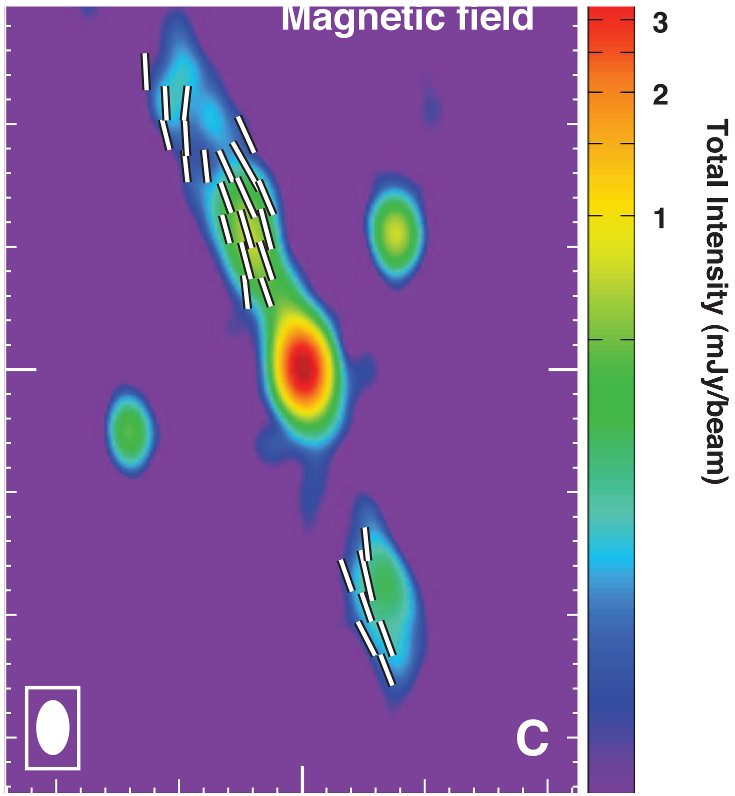
- Simulations for spherical wind:
  - opening angle strongly depends on ratio Mdot_infall/Mdot_wind
  - Observed ratio ≤ 10 ➔ cannot explain narrow jet
    - **Need Magnetic collimation (cf. Cabrit 2007, LNP)**



Delamarter, Frank & Hartmann (2000)

Evidence for magnetic collimation

- Synchrotron linear polarisation in HH80-81 jet from 10M$_\odot$ protostar
  - <B> aligned with jet
  - Polarization degree increases toward jet edges, like in AGN jets
    ➔ confining helical B ?



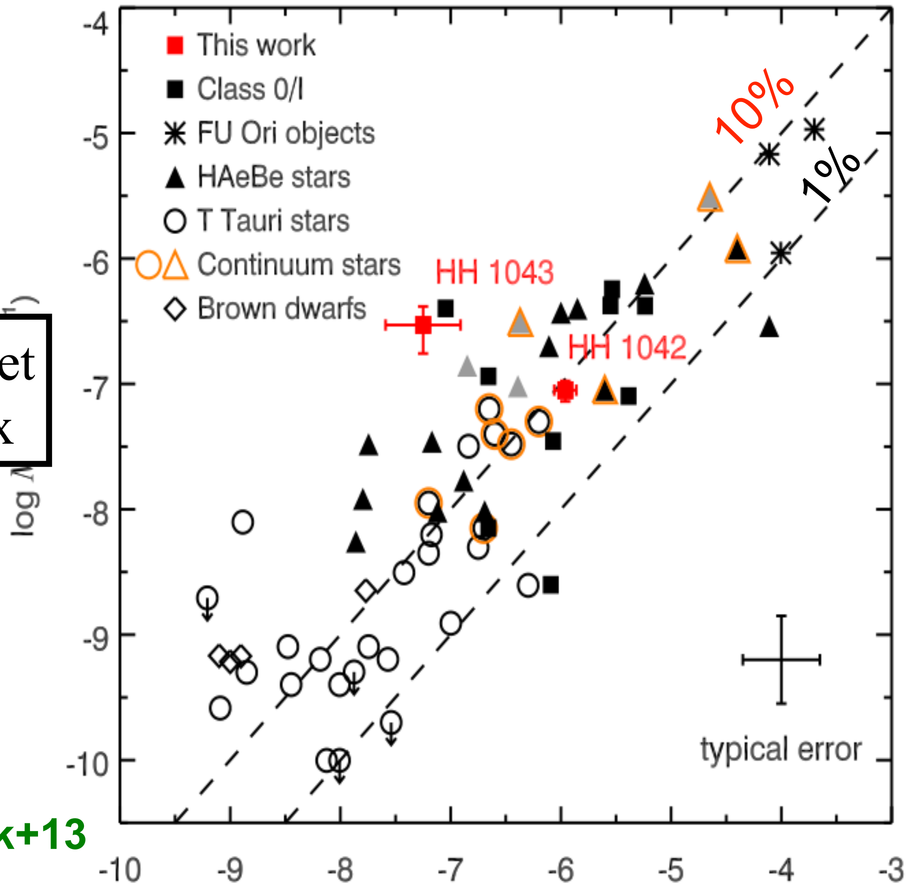
Carrasco-Gonzalez et al 2010, *Science* **330**, 1209

- Stationary Xray knot:

recollimation shock ?

Gudel+08,12

Atomic Jet mass fluxes vs accretion



Atomic Jet
Mass flux

Disk accretion rate
(from UV excess or L_{bol})

Elllerbroek+13 (with compilation of literature)

- Mjet/Macc ~ 10%
- Universal accross evolutionary stages and stellar masses (over 5 orders of magnitude in Macc)
- Force Fw = Mdot Vw ≥100 L_{acc}/c
  - Not radiatively driven stellar winds !
- Mechanical luminosity Lw ~ 1%-10% L_{acc}

Thermally driven stellar winds ?

- Needs thermal speed of order the escape speed
  - ✓ kT/μmH ~ 2GM*/R* ➔ T > 10^6 K in solar-mass T Tauri stars

- Problem:
  - Predicted X-ray flux exceeds observed Lx, and even Lbol (De Campli 1981)

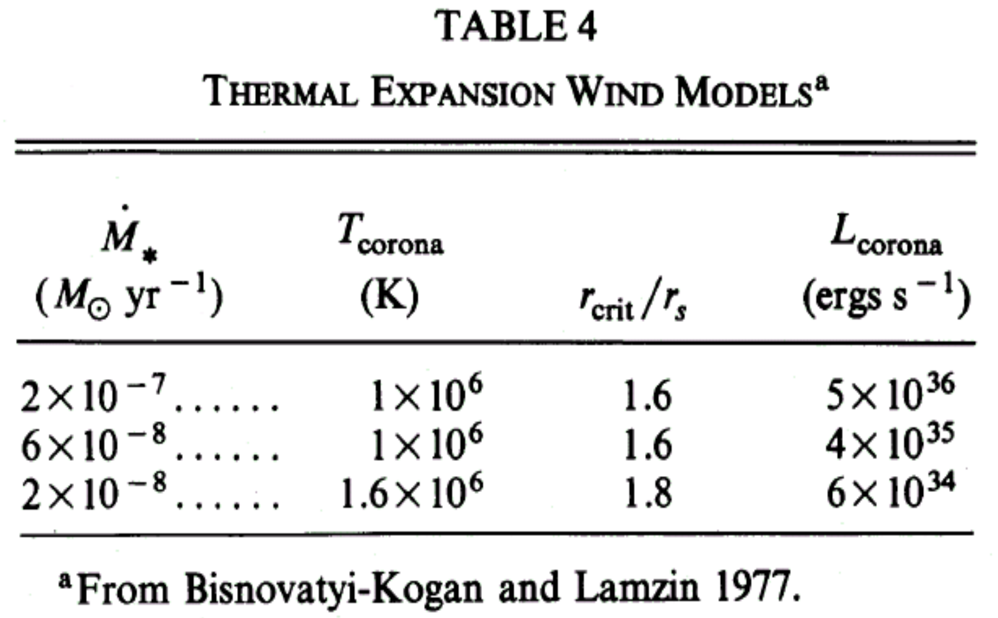


TABLE 4

THERMAL EXPANSION WIND MODELS[a]

$\dot{M}_*$ ($M_\odot$ yr^{-1})	T_{corona} (K)	r_{crit}/r_s	L_{corona} (ergs s^{-1})
2×10^{-7}......	1×10^{6}	1.6	5×10^{36}
6×10^{-8}......	1×10^{6}	1.6	4×10^{35}
2×10^{-8}......	1.6×10^{6}	1.8	6×10^{34}

[a] From Bisnovatyi-Kogan and Lamzin 1977.

Alfvén-wave driven stellar winds ?

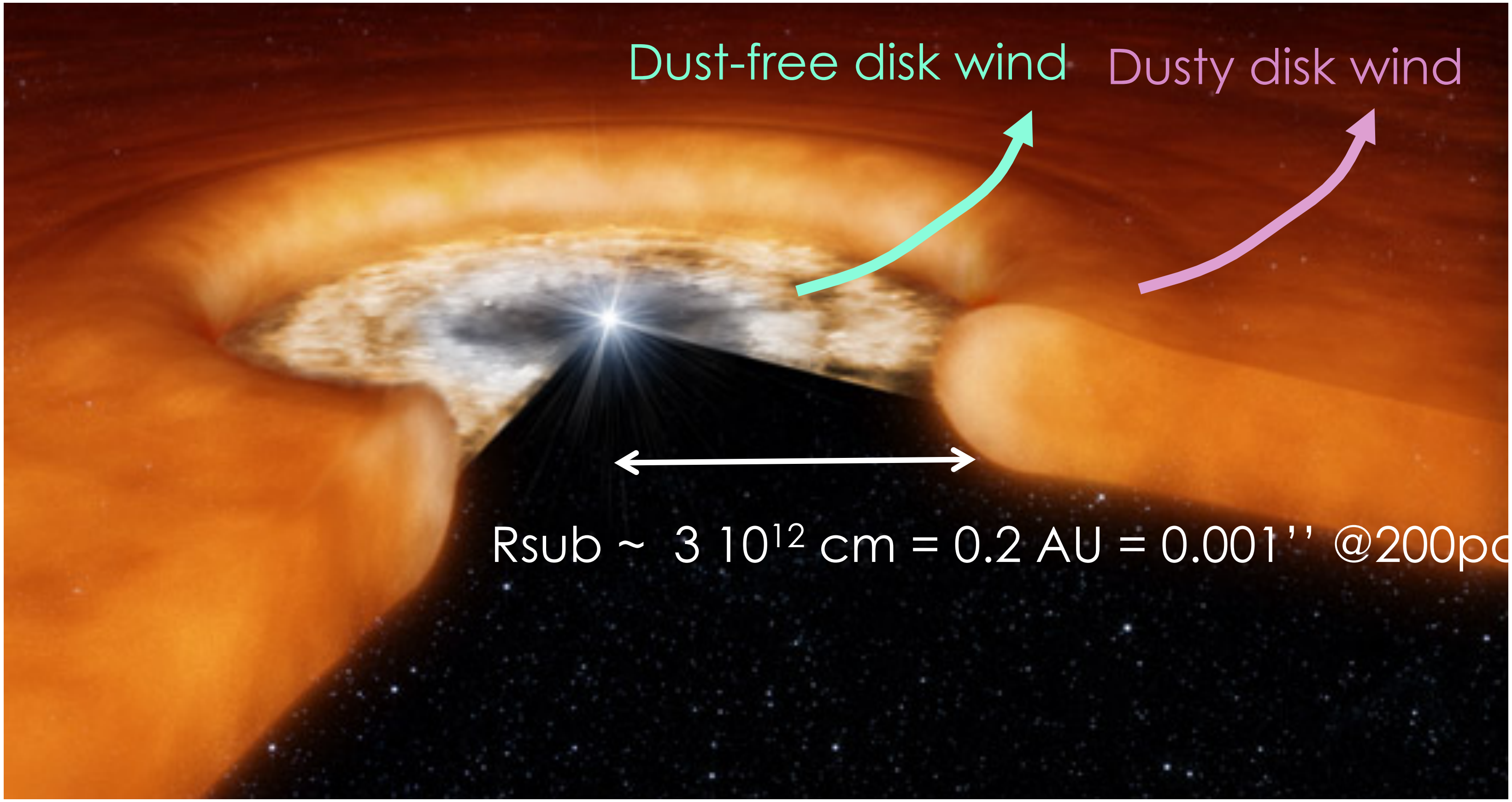
- Stellar B-field perturbed by accretion flow onto star
  - MHD waves could transfer momentum and drive *cold* stellar wind

- First Models (spherical, coherent waves, no damping, B* = 500G)
  - Lwind ~ 20% Lwave (De Campli 1981)
  - for young protostellar jets: Lwave = 5 x Lwind = 5%-50% Lacc : uncomfortably high fraction of accretion power into Alfvén waves

- Models for specific T Tauri star parameters (Cranmer+09)
  - Mw(model)/Mw(obs) ~ 0.1 (median)

➔ Strong stellar winds probably present but another contribution appears needed to explain jet mass-fluxes…

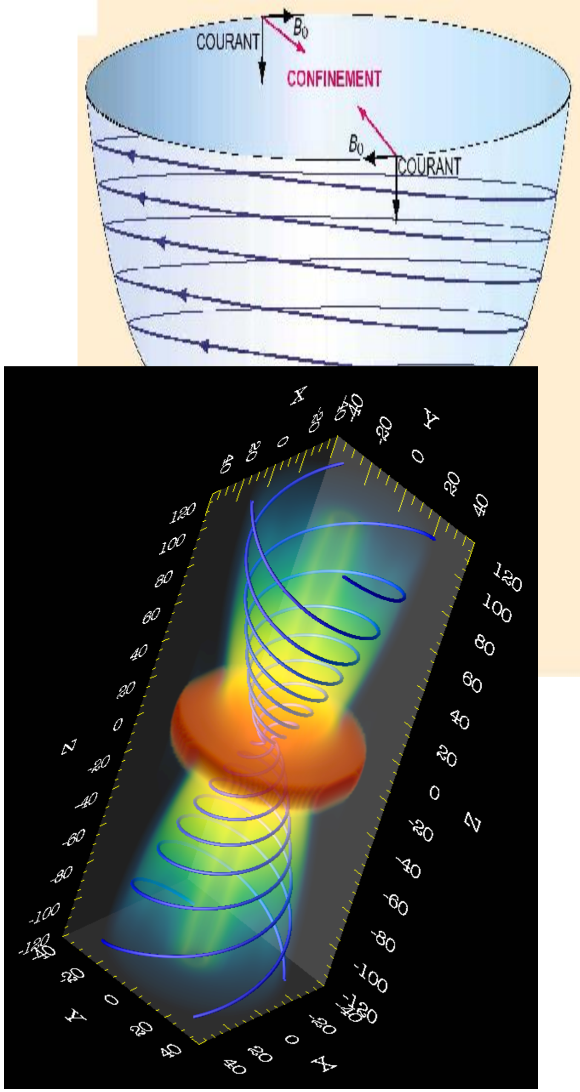
Possible jet/wind launching regions



Rsub ~ 3 10^{12} cm = 0.2 AU = 0.001'' @200pc

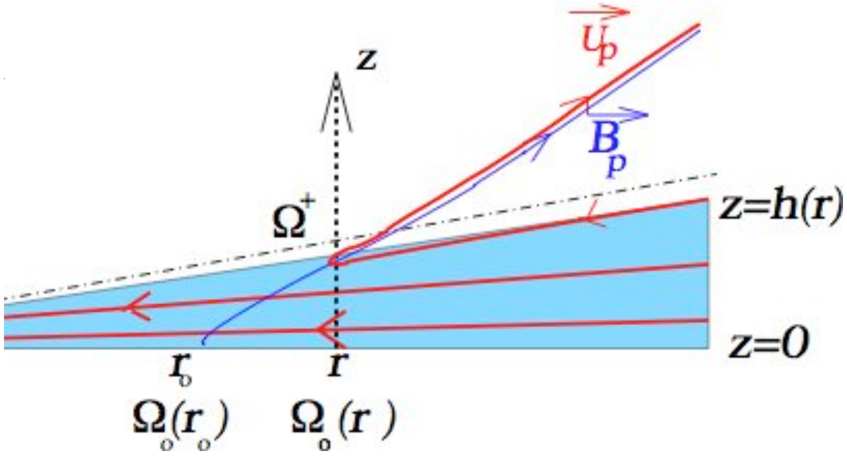
Magneto-centrifugal disk winds

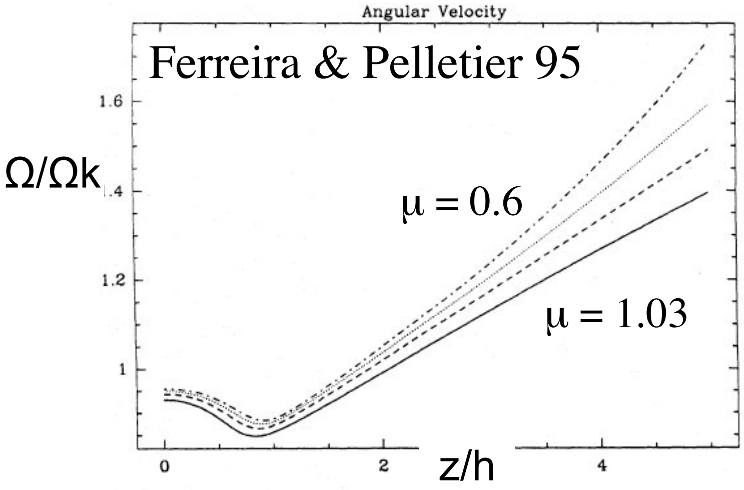
- Blandford & Payne 1982,
  - Poloidal B in disk extracts 100% angular momentum flux and accretion power
  - Self-collimation by “hoop stress” (Jz x Bφ)
  - Magnetic lever arm parameter $\lambda = (r_A/r_0)^2$ ➔ V∞ and Mass-flux
  - X-wind (review: Shang+00): r0 ~ 0.07 AU, λ ~ 3, Mw/Macc ~ 0.3; all assumed (mass-loading not yet solved).
  - D-wind (review: Pudritz+00) broad range of r0; λ and Mw/Macc solved from disk vertical equilibrium +B structure
- Numerical simulations of extended D-winds: Zanni+07, Stepanovs & Fendt 2014



Magneto-centrifugal disk winds how do they work ?

- Poloidal B twisted by rotation : creates B_φ and torque
- Full 2D steady solutions of accretion-ejection transition (Wardle & Konigl 93; Ferreira 97; Casse & Ferreira 00):
    - Inside disk, $F_\varphi < 0$: disk spun down and (slightly) subkeplerian
    - Above surface, $F_\varphi > 0$: matter is spun up: cold magneto-centrifugal ejection
    - Disk heating increases mass-flux ➔ decreases magnetic “lever arm” rA/r0 and V∞ (conserve ang.mom.flux)

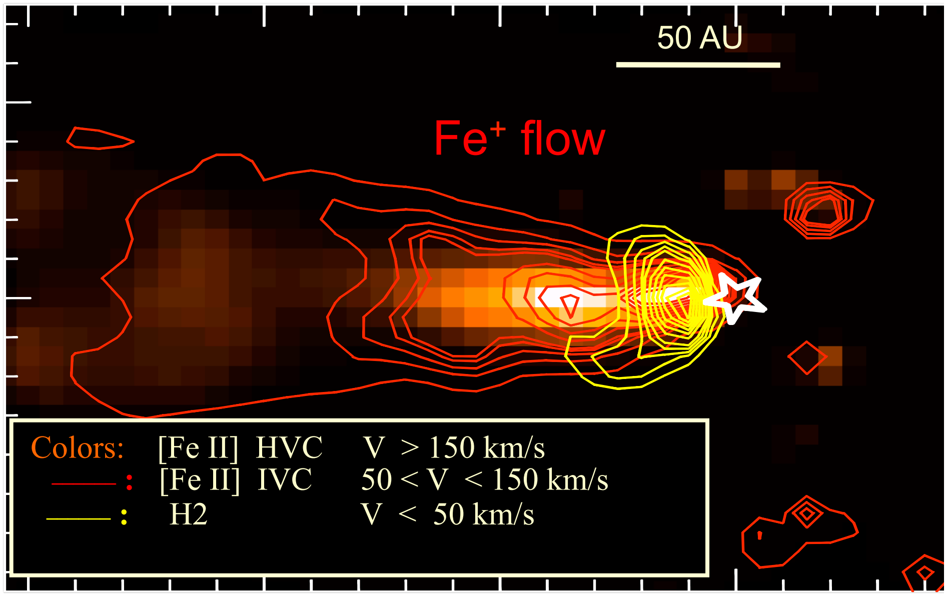




Observational constrains on MHD disk winds

- Comparison of synthetic predictions and observations
  - Apparent collimation scale: OK (Shang+98, Cabrit+99, Garcia+01,Ray+07)
  - “Onion-like” velocity structure ➔ suggest broad range of r0 ~ 0.1- 3 AU
  - but other explanations possible

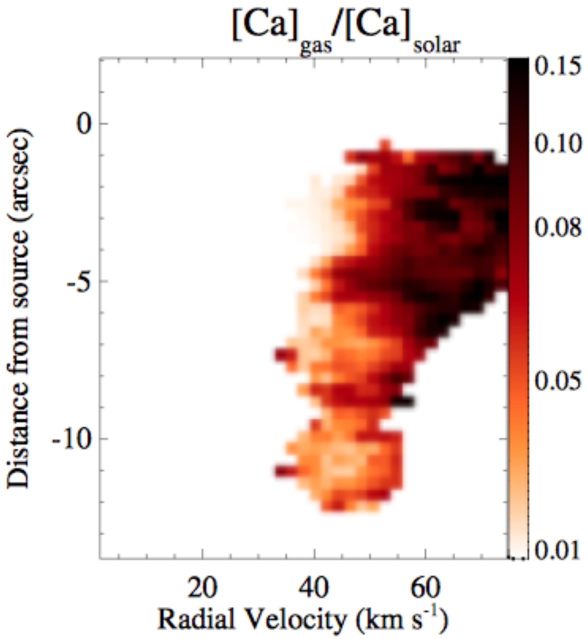
(Pyo+03, Agra-Amboage+11, White+16).



DG Tau Jet Agra-Amboage et al. (2011)

Dust in the launching regions of jets ?

Podio+11 DG Tau B

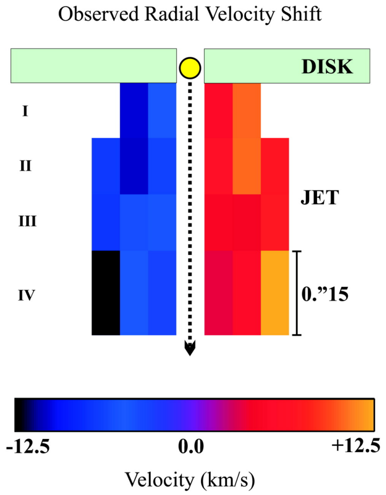


✧ Modeling of line ratios at base of atomic jets suggests under-abundance of refractory elements (Fe, Ca, Ni, Si…) vs less-refractory (O, S, P…) at all stages (Class 0, 1, 2 : Dionatos+10, Podio+11, Agra-Amboage+11)

- Depletion stronger at lower V
- Locked in dust grains ? → R_{launch} > Rsub = 0.2 AU
- Or dust grains trapped outside of Rlaunch ? (eg.disk dead zone)

Atomic jet rotation?

Class 2 DG Tau atomic jet



Transverse Vshift possibly due to rotation ~ 10-15 kms in 6 atomic jets (Bacciotti+02, Woitas +03, Coffey +04,07,11,12)

Steady, axisymmetric MHD disk wind predicts (Anderson+03)

$$2rV_\phi\Omega_0 = V_p^2 + 3\Omega_0^2 r_0^2$$

➔ would infer r0 ≈ 0.1 - 5 AU, λ ~10 for all candidates so far

➔ MHD disk wind with λ = 13 fits all spatial variation of DG Tau jet Vshift (r,z) (Pesenti+04)

Problem: optical « jet rotation » sense does not match disk rotation in 2 out of 4 cases (Cabrit+06, Louvet+16)

- non-steady MHD disk winds ? (Sauty+11, Fendt 2012) ?
- not jet rotation ? (eg. asymmetric shocks)
- Cannot infer r0 from such signatures…

Molecular Jets : disk winds ?

- Class 0 jets very bright in molecular lines (H_2, SiO, CO, SO) V ~ 60-150 km/s

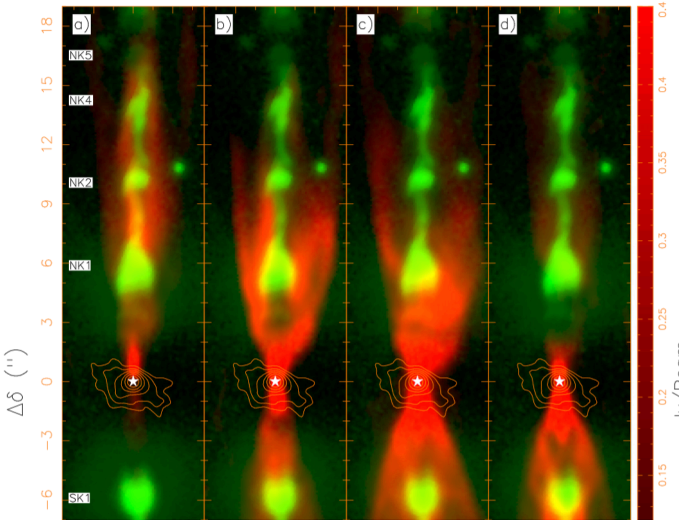
- Only H_2 left in Class 1 jets
  ➔ chemical evolution with age

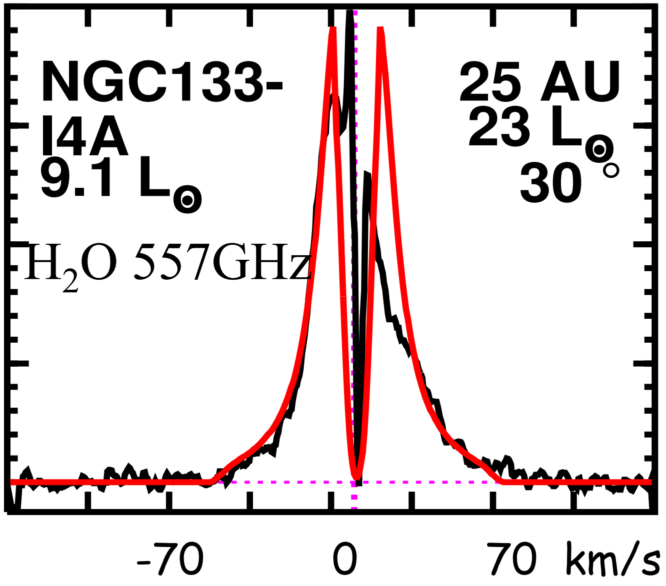
➔ Molecules ejected from the disk ?

- thermo-chemical model of dusty MHD disk winds with λ = 13 (Panoglou+2012)
  - ➢ agree with these trends
  - ➢ reproduce *Herschel* H_2O profiles in 20''-40'' beams (Yvart et al. 2016)

  - ➢ But challenged by ALMA/PdBI / VLBI observations !

Green: H_2 Red: ^{12}CO

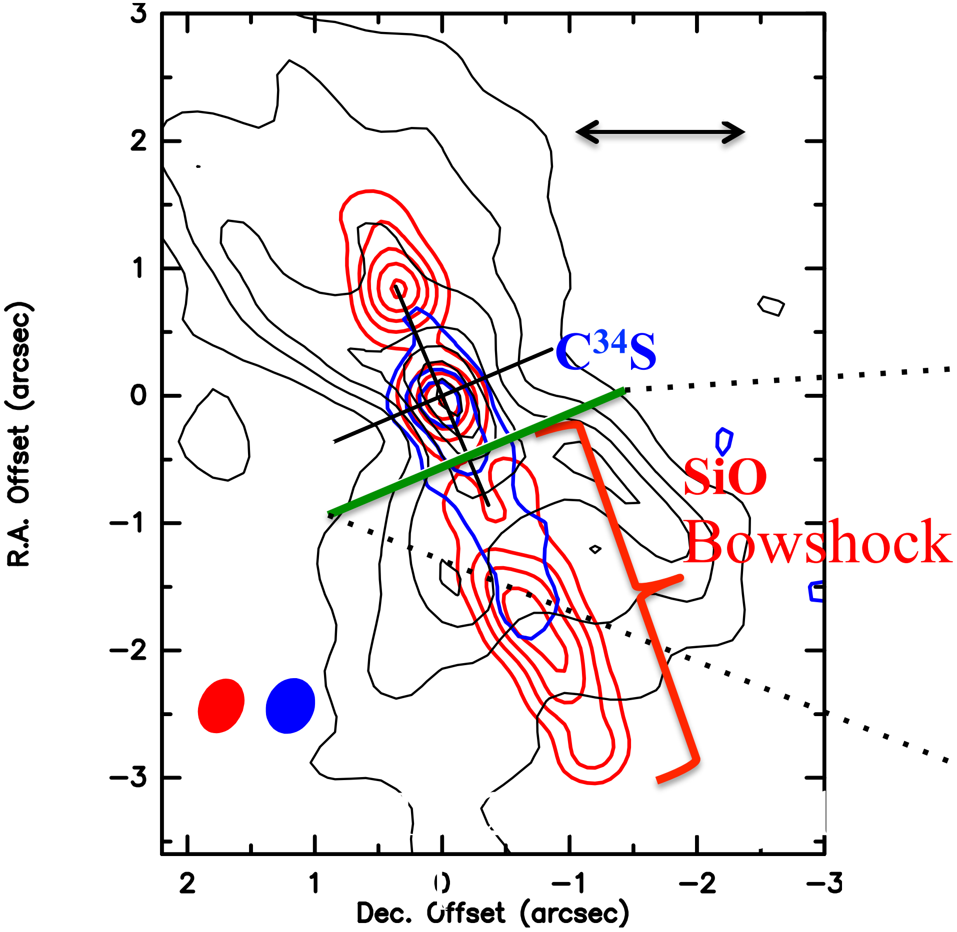




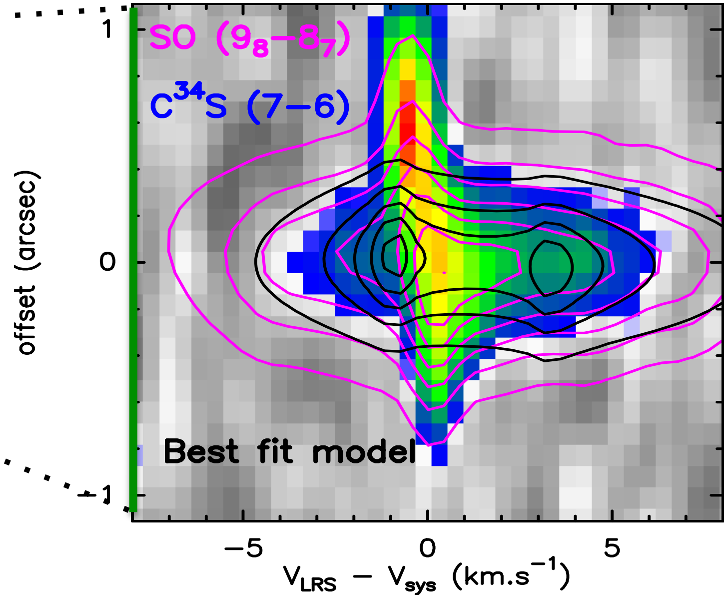
ALMA observations of HH212

Tabone et al 2016 in prep.,
ALMA 0.3'' resolution

No clear rotation in molecular jet.
➔ radial extent of MHD Disk wind < 10 AU and low angular momentum

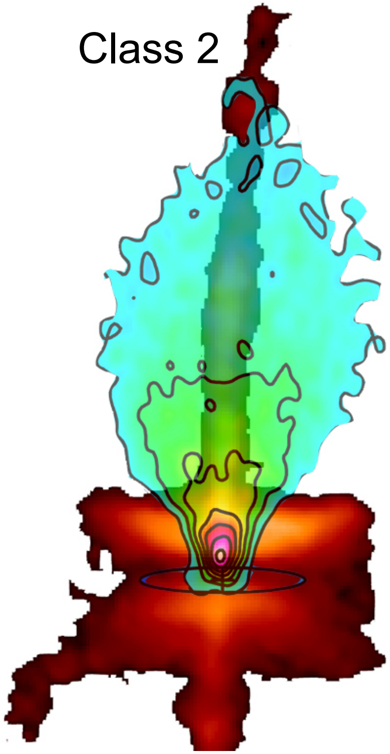


Example model:
r0 = 0.2 – 6 AU, λ = 5



Slow molecular «winds »

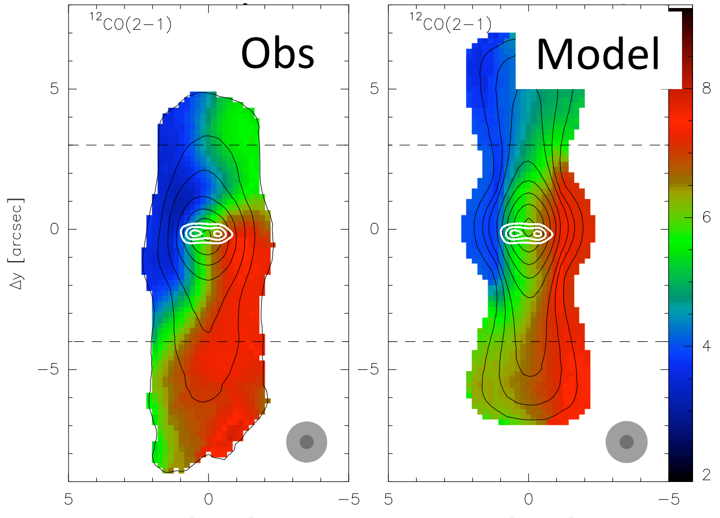
Class 2



HH30 in CO, Vφ ~ 0.5 km/s
(Louvet et al 2016, ALMA)
V ~10 kms ?

r0 ~ 2 -15 AU
λ < 2

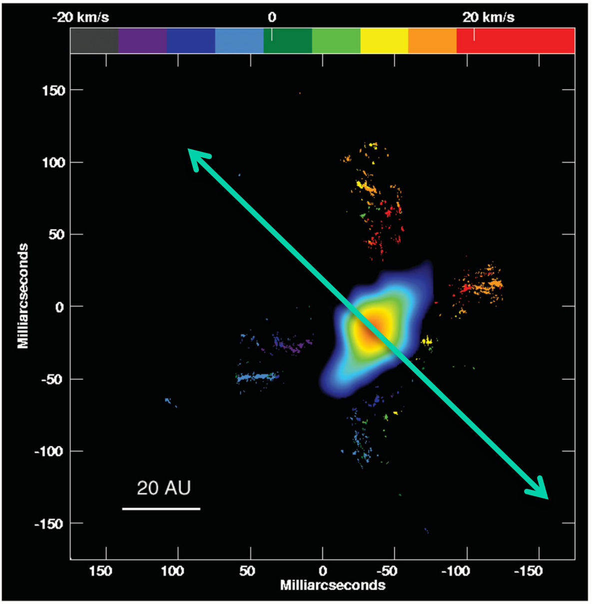
Class 1



CB 26 in CO, Vφ ~ 1 km/s
V ~10 kms ?
(Launhardt et al 2009, PdBI)

r0 = 10 to 30 AU
λ < 5 (Cabrit 08)

Class 0

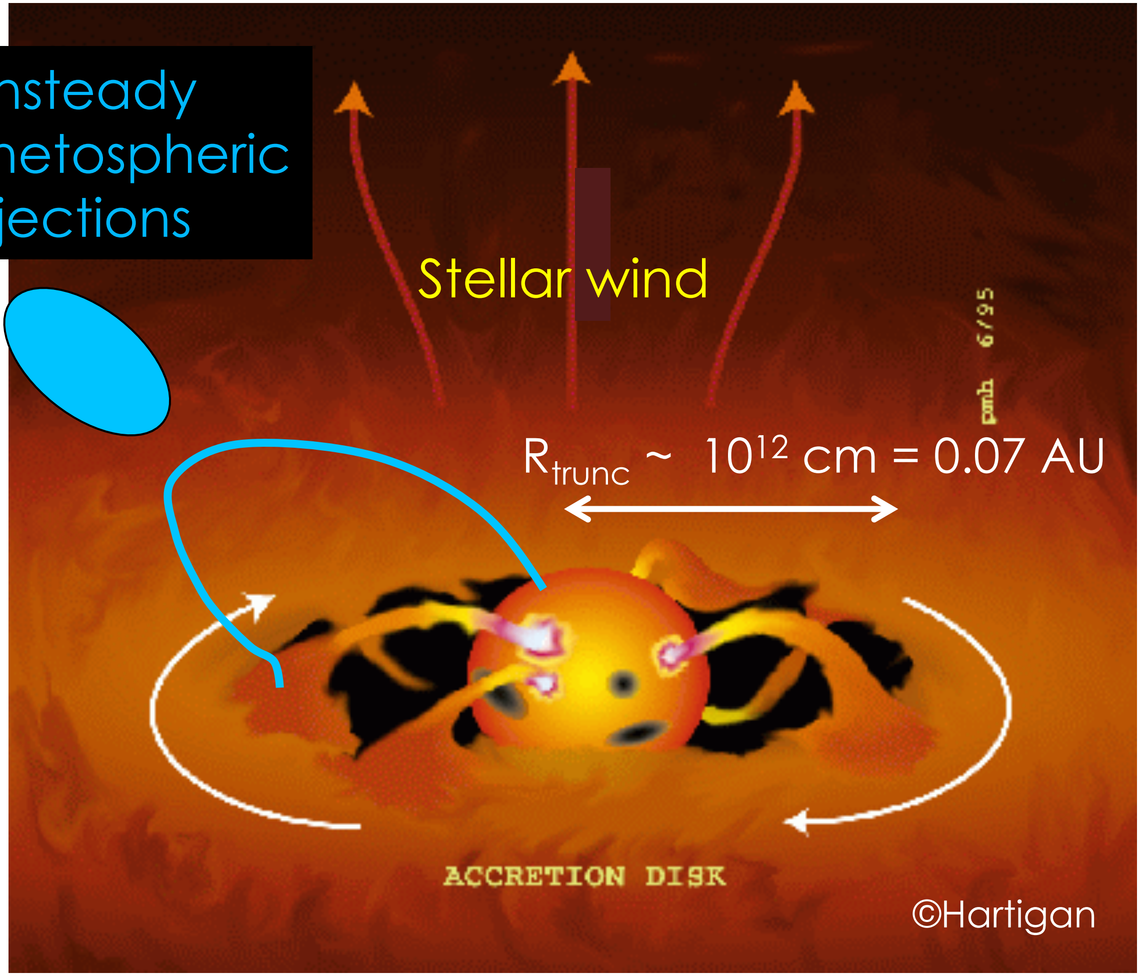


Massive protostar Source I
SiO masers VLBA
Vp and Vφ ~ 15 kms
(Matthews et al 2010)

Ejected ? Shocked ?
Entrained ?

MHD Disk-wind Model with
r0 = 3.5AU (Vaidya etal 2013)

Possible jet launching regions



Unsteady Magnetospheric ejections

©Hartigan

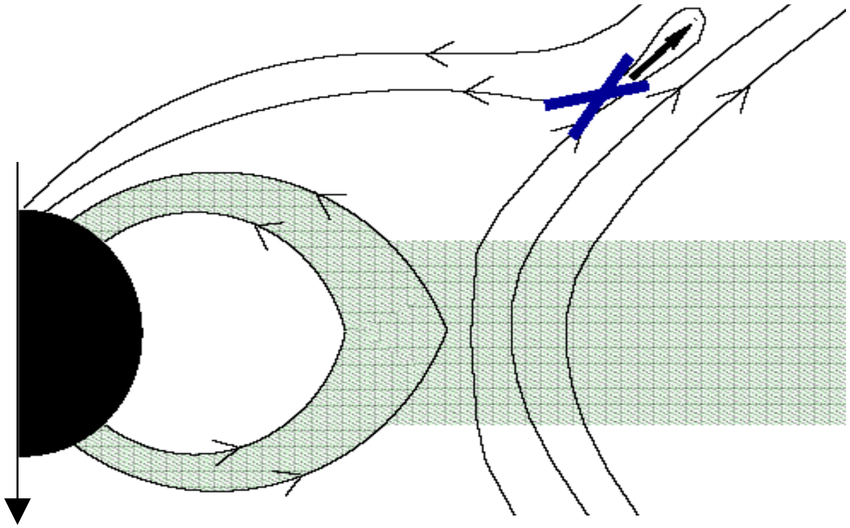
Characteristic speeds:

$V_{esc}(R^*) \sim 350$ km/s

$V_{kep}(R_{trunc}) \sim 100$km/s

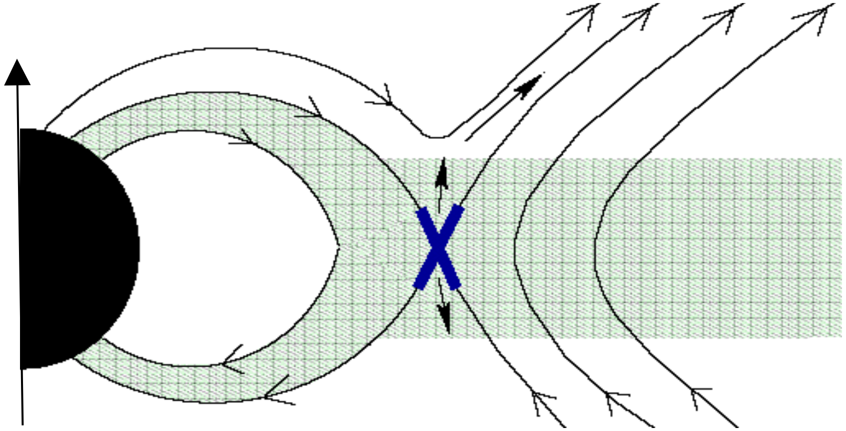
Sporadic Ejections by MHD relaxation

a) Stellar B antiparallel to disk B: Plasmoid ejections at 45°: need external collimation. too slow ? (~50 km/s)



Goodson et al. (1997, 1999)
Romanova (2009)
Zanni & Ferreira (2013)

b) Stellar B parallel to disk B: “Reconnexion” (ReX) winds self-collimated
Too much open B in star ?



Uchida & Shibata 84
Hirose et al.97
Ferreira et al. 2000

Conclusions

- Young stars still accreting from disk drive powerful jets, which sweep up large molecular outflow cavities
  - Wider angle winds also present at late stages > 0.1Myr ?
- Launch radius < 5 AU for atomic jet, < 15 AU for molecular
  - Information on milliarcsecond scale needed (cf. next talk)
- Jet collimation to narrow angle ~ 5° occurs within 20-50 AU ➔ magnetic collimation
  - disk B or opened stellar B-field ? Self-collimation or external ?
- Momentum flux > 100 Lbol/c and energy flux 1%-10%Lacc appear too high for stellar winds (radiative, thermal, or wave-driven)
  - Magneto-centrifugal disk winds with small Alfvén lever arm $r_A/r_0 < 3$?
  - Reconnexion winds from stellar magnetosphere ?
- ALMA and NOEMA bring new constraints on origin of molecular counterparts of atomic jets
  - Ejected from disk ? Entrained / swept-up ? More modeling needed !