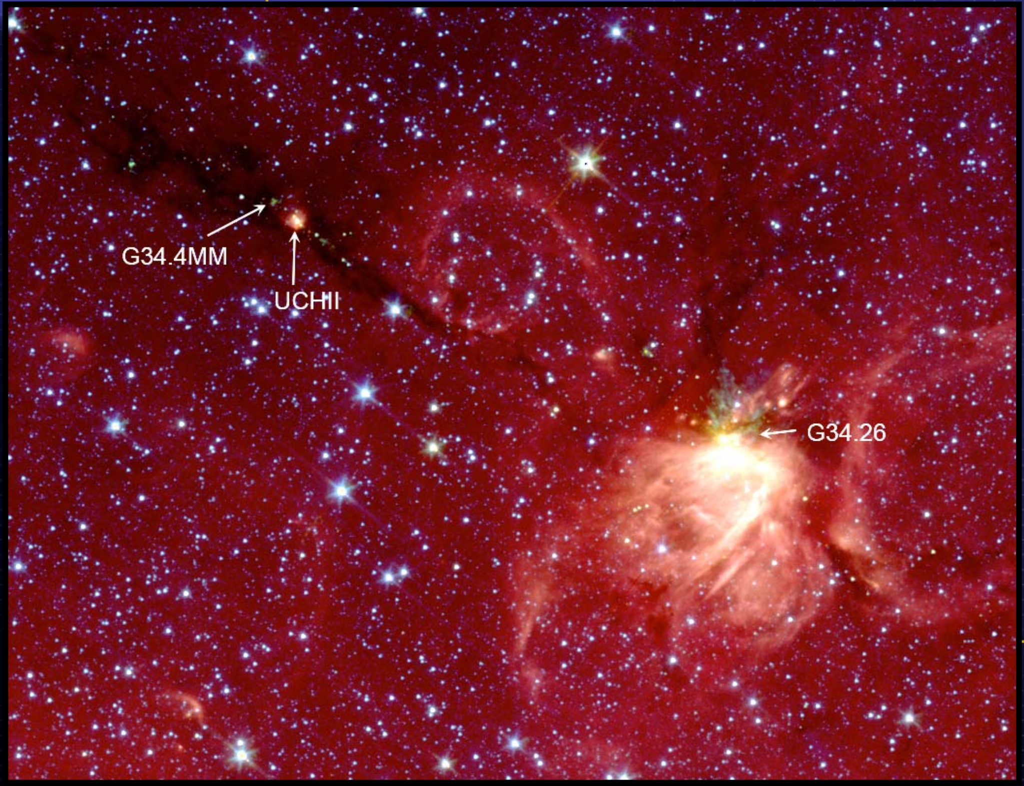
Massive Molecular Outflows and Outflow Clusters



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Star Formation, Then and Now

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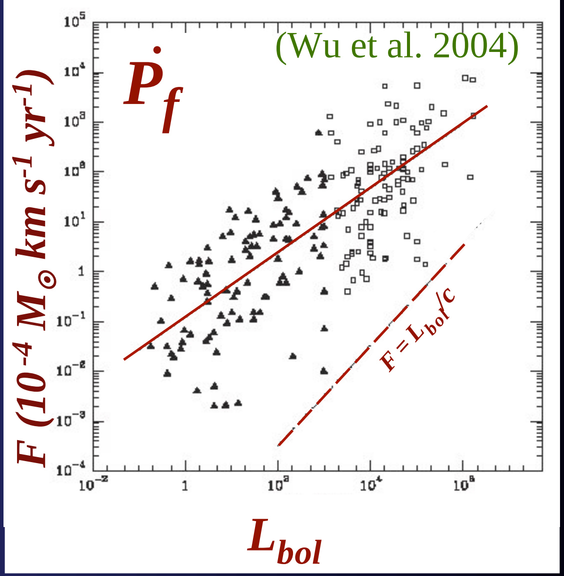
Contents

Concentrate on early B (proto)star clusters

- Brief introduction
- Review a few selected outflow clusters - an observational summary
- Comparison between high and low-mass cluster properties
- Star Formation Efficiency
- Feedback - high and low-mass mechanisms
- Summary

Outflow properties

	T Tauri stars	Early B stars	Mid to late O stars
L_{bol} $[L_\odot]$	~ 10^{0-2}	~ 10^{3-4}	~ 10^{4-5}
Outfow timescale [yrs]	~ 10^7	~ few x 10^5	~ few x 10^4
M_{flow} / M_{star}	~ few	~ 10-20	?
$\dot{M}_f$ $[M_\odot\, yr^{-1}]$	10^{-7} to 10^{-5}	$\lesssim 10^{-4}$ to 10^{-3}	$\lesssim 10^{-3}$ to 10^{-2}
$\dot{P}_f$ $[M_\odot\, km\, s^{-1}\, yr^{-1}]$	~ 10^{-5}	~ 10^{-3} to 10^{-2}	~ 10^{-2} to 10^{-1}



Feedback from outflows dominates over radiation at early times.

Early B star outflow clusters

Consider molecular outflow cluster properties as a function of time by examining selected clusters:

0.03 Myrs:	IRAS 05358+3542
0.1 Myrs:	G34.4
1 Myrs:	G173.58 (all early B stars formed)
~1-5 Myrs:	W75N (early B stars still forming)

Compare with cluster properties of a well-known low-mass star forming region: L1551 that appears to have been forming stars for ~ 25 Myr although most are less than 4 Myrs old.

IRAS 05358+3543 Protostar Cluster ~ 3.5×10^4 years old

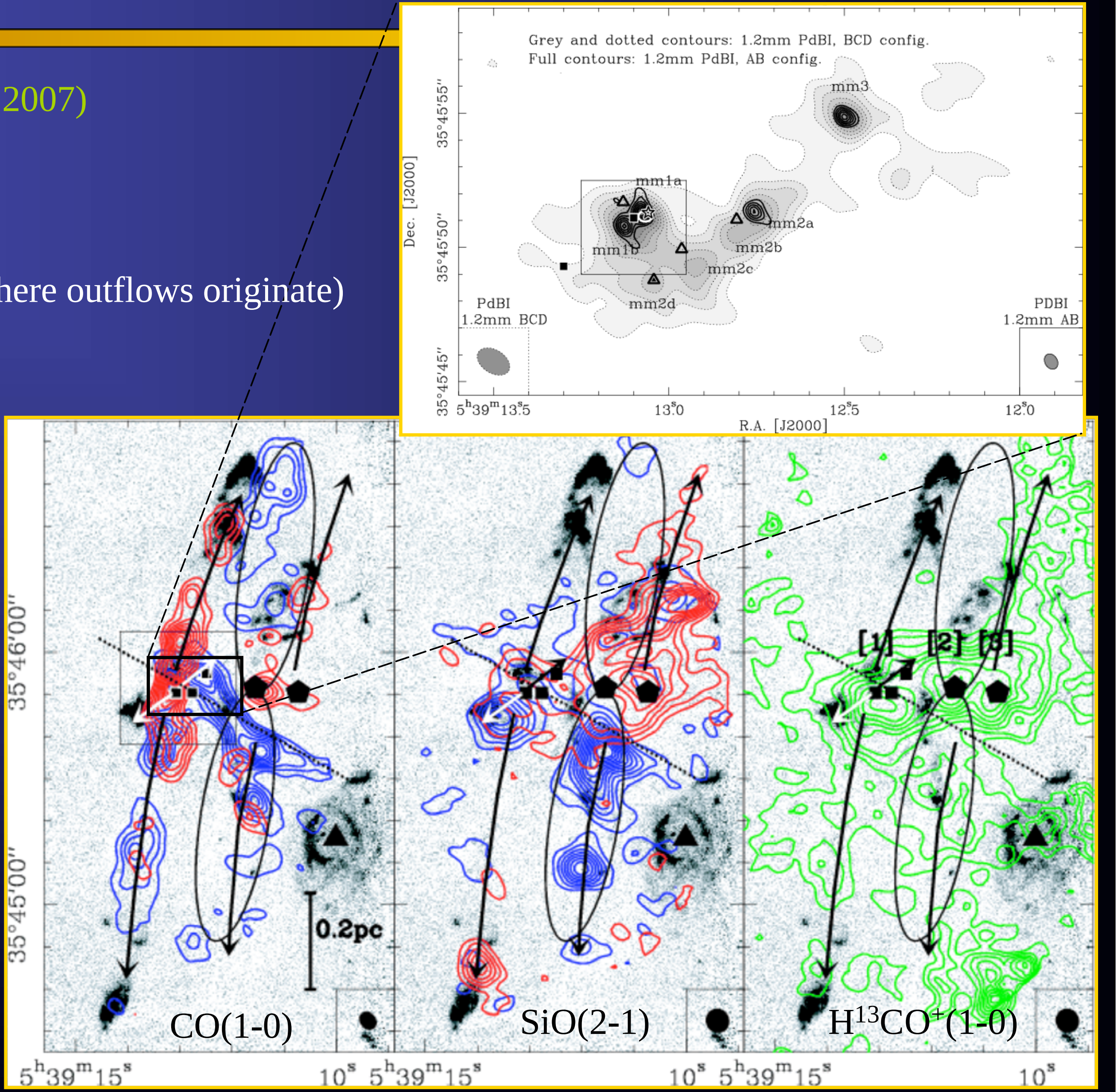
Beuther et al. (2002a,b,c, 2004, 2007)
Sridharan et al. (2002)

$M_{cl} \sim 610\ M_\odot$ (only clump where outflows originate)
$M_{outflows} \sim 20\ M_\odot$
$M_{stars} \sim$?
Current SFE ~ ?

Most massive star = B1 (13 $M_\odot$) MM1a which has a HC HII region, no cm cont. emission around other mm cores.

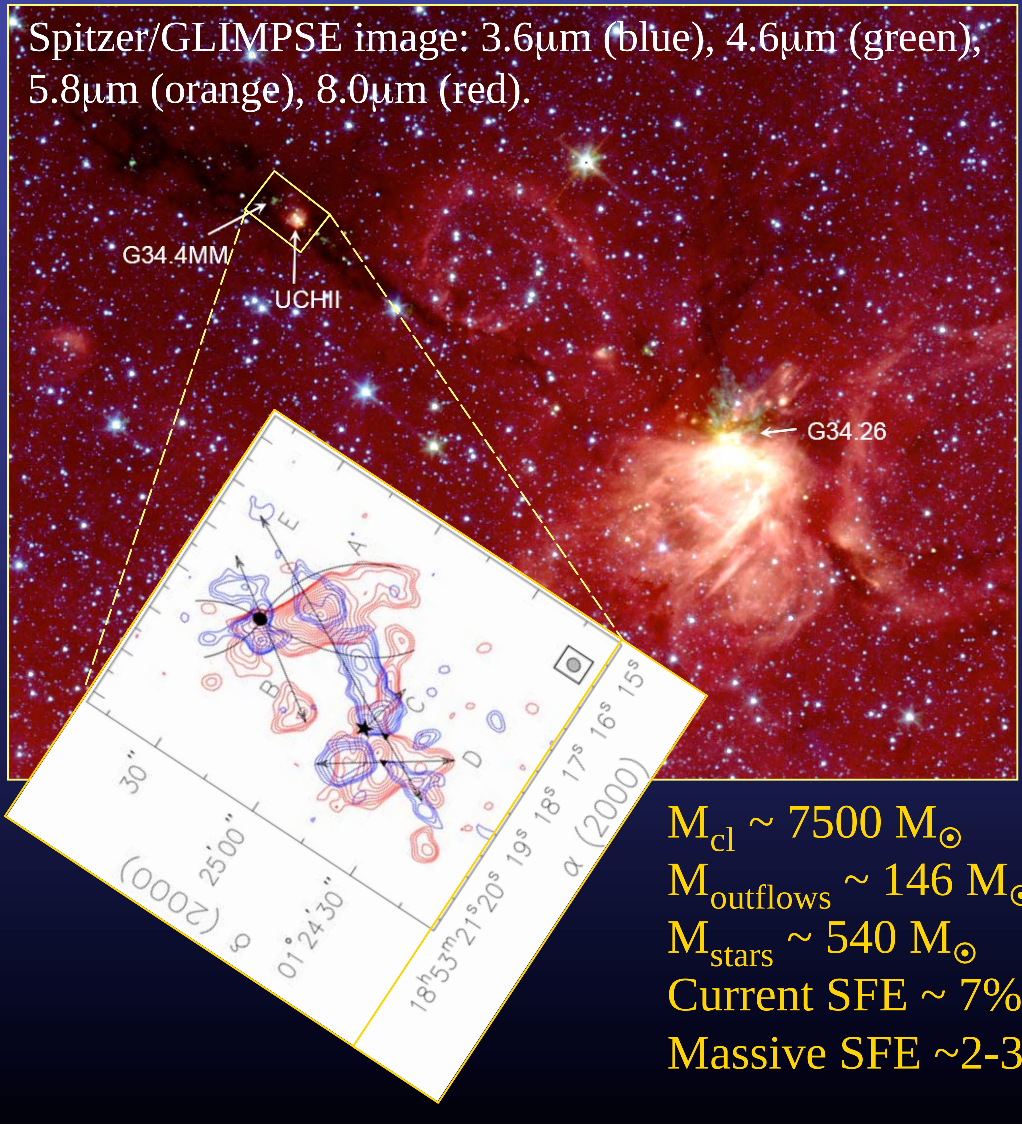
$E_{grav} \sim 4E_{outflows}$

Outflows will not disrupt core (yet).

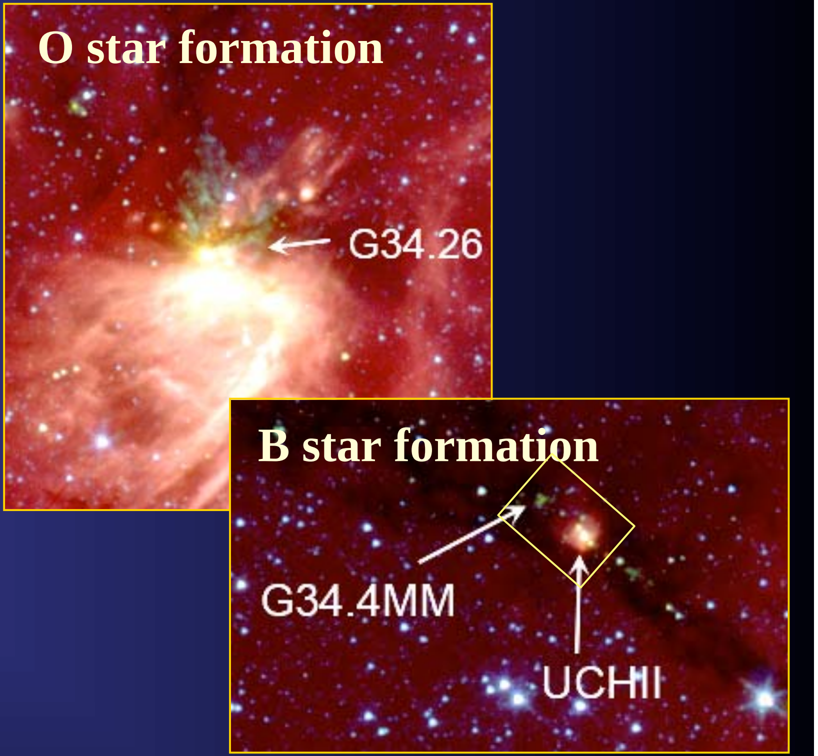


G34.4 - B (proto)star cluster ~ 10^5 years old

Shepherd et al. 2007, 2004; Rathborne et al 2005;
Churchwell et al. 2004



Spitzer/GLIMPSE image: 3.6µm (blue), 4.6µm (green), 5.8µm (orange), 8.0µm (red).



O star formation

B star formation

M_{cl} ~ 7500 $M_\odot$
$M_{outflows}$ ~ 146 $M_\odot$
M_{stars} ~ 540 $M_\odot$
Current SFE ~ 7%
Massive SFE ~2-3%

G34 MM: E_{grav} ~ $E_{outflows}$
Outflows will disrupt core.

G34 UCHII core: E_{grav} ~ $2xE_{outflow}$
Outflows will not totally disrupt core; future star formation possible

G173.58 - few x 10^6 year old B star cluster

Early B stars already formed, time to complete outflow/accretion & photoevaporate disks > few Myrs.

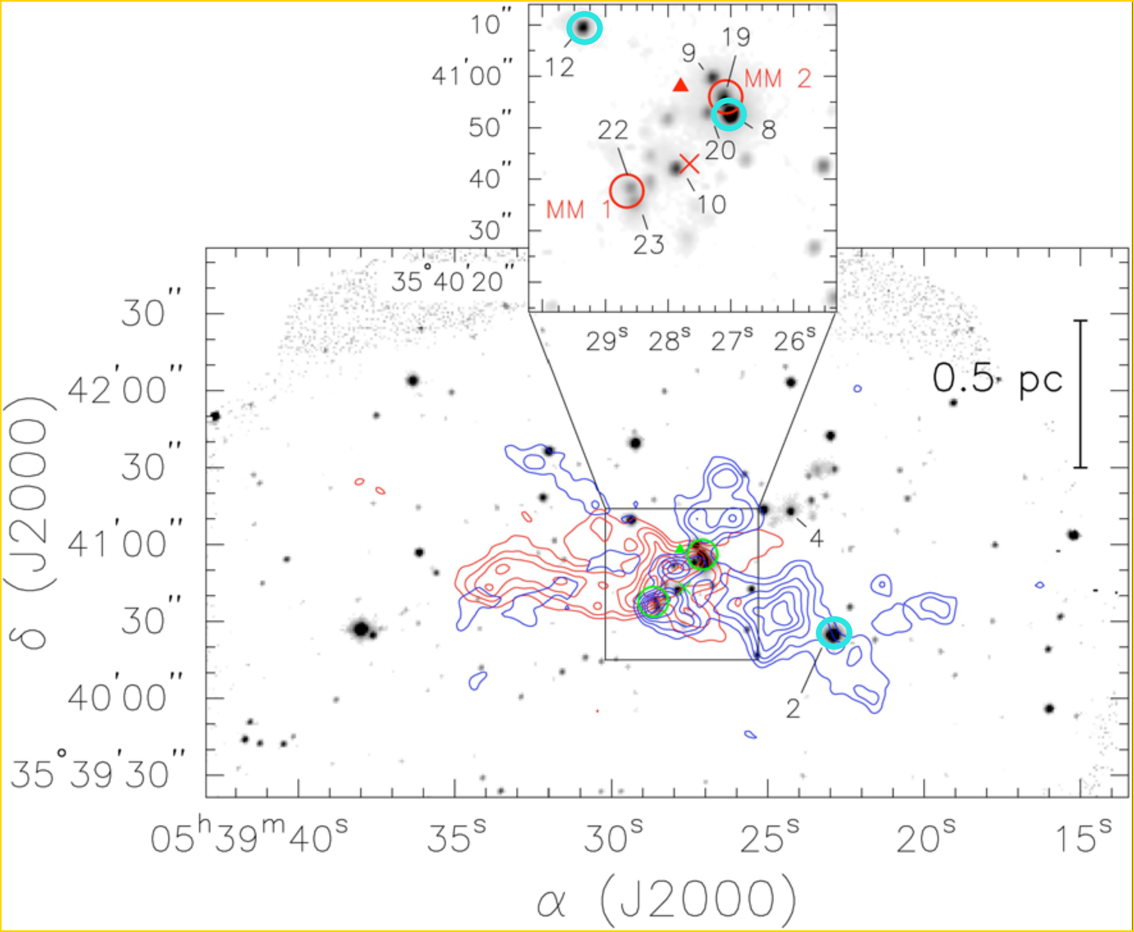
Current outflows powered by late B to A stars, ~ 0.3 Myrs old

Age distribution: 0.3 - few Myrs

$M_{cl} \sim 670\ M_\odot$
$M_{outflows} \sim 30\ M_\odot$
$M_{stars} > 85\ M_\odot$
Current SFE > 11%

$E_{grav} \sim 5\mathrm{x}E_{outflow}$

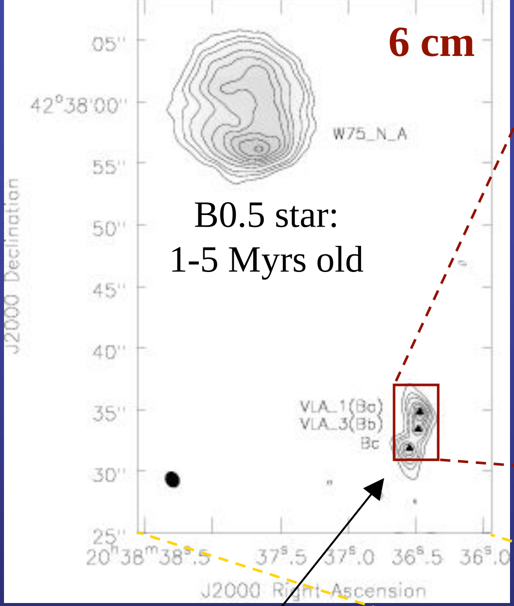
Outflows will not disrupt core; future star formation likely



○ B1/2 MS stars, little or no IR excess

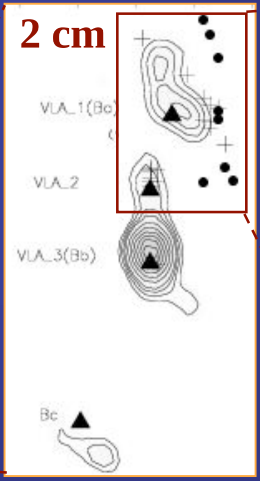
Shepherd & Watson (2002)

W75N Early B Star Cluster ~ 1-5 Myrs old



B0.5 star:
1-5 Myrs old

B1.5-B2 stars:
~0.1 Myrs old

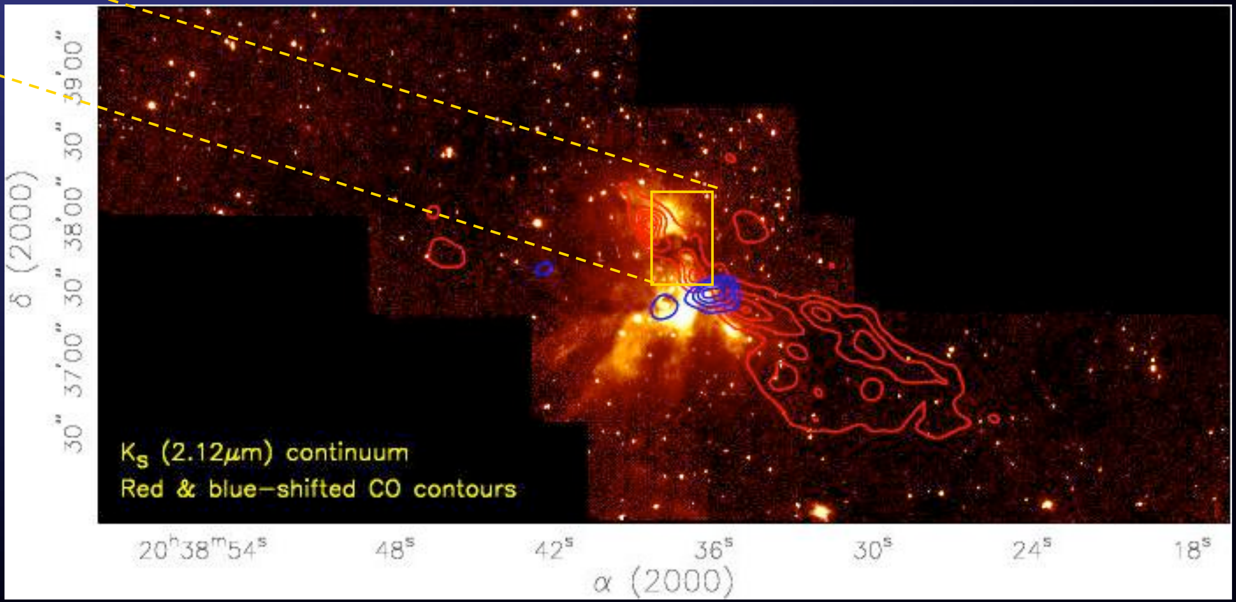


Wide-angle &
jet-like flows

$M_{cl} \gtrsim 2000\ M_\odot$
$M_{outflows} \sim 255\ M_\odot$
$M_{stars} \sim 415\ M_\odot$
Current SFE $\lesssim$ 16%

$E_{grav} \sim 2xE_{outflow}$

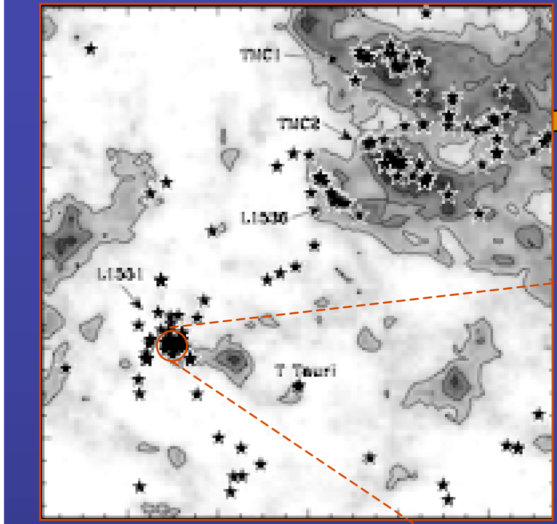
Outflows will not totally disrupt core; future star formation possible



B star age distribution:
0.1 to a few Myrs

Davis et al. 1998; Torrelles et al. 2003; Shepherd et al. 2003, 2004; Alakoz et al. 2005

L1551: Comparison with a Low-Mass Region



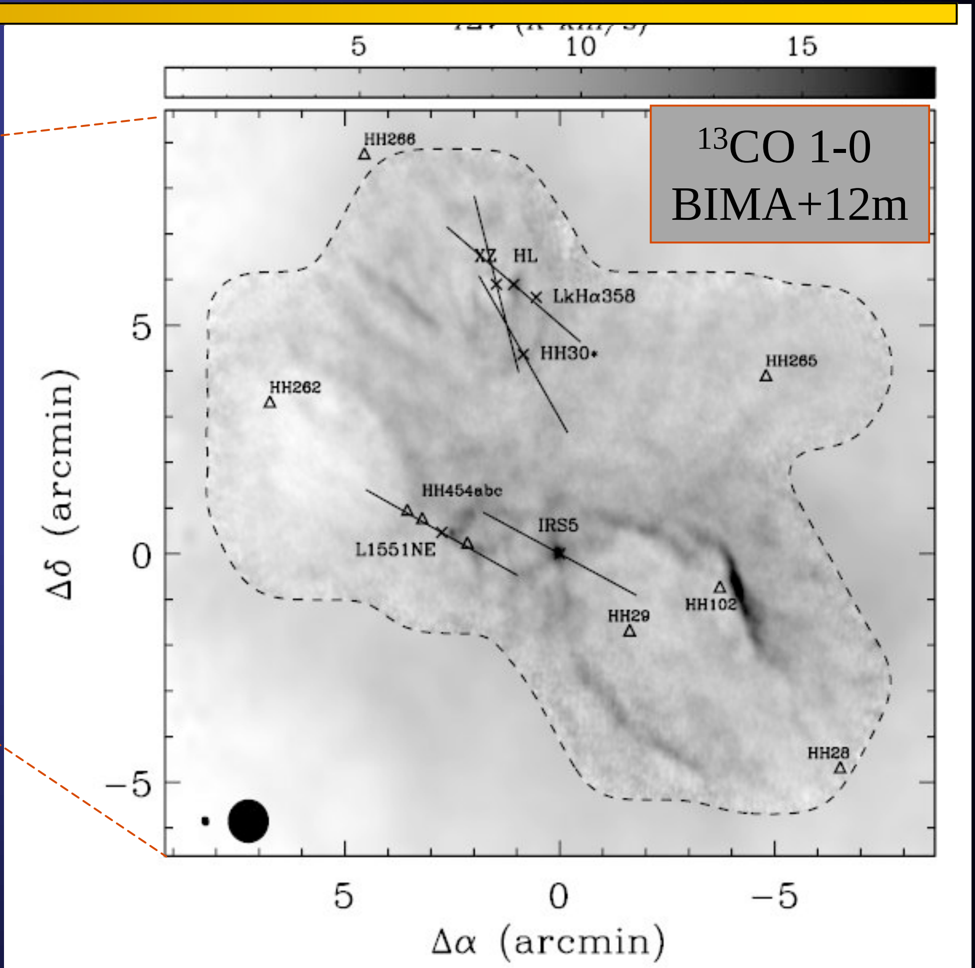
$M_{cl} \sim 160\ M_{\odot}$
$M_{outflows} \sim 6.9\ M_{\odot}$
$M_{stars} \sim 22\ M_{\odot}$
Current SFE ~ 12%

$E_{grav} \sim 0.5 \times E_{outflows}$

Outflows likely able to disrupt core.

Gas accelerated beyond gravitational confines of the cloud. At least 5-6 $M_{\odot}$ has been excavated from the cloud by current protostars.

Analysis suggests observed turbulent energy can be supplied by outflows only.



Swift & Welch (2007, Astro-ph 0706.2206)
Stojimirovic et al. (2006)

Most stars < 4 Myrs old
20% of stars > 6 Myrs old
Oldest protostar = 25 Myrs old

Cluster comparison

Name	**Age**	**Star Formation Size scale**	**M_{clump}**	**M_{stars}**	**SFE**	**E_{grav}**	**$E_{grav}/E_{outflow}$**
I 05358	0.03 Myrs	0.2 pc	630 $M_\odot$	?	?	~ 2×10^{47} ergs	4
G34.4	0.1 Myrs	0.7 pc	7500 $M_\odot$	540 $M_\odot$	~ 7%	~ 10^{47} ergs	1-2
G173.58	1 - few Myrs	0.5-1 pc	700 $M_\odot$	> 85 $M_\odot$	> 11%	~ 6×10^{46} ergs	5
W75N	1-5 Myrs	~ 0.5 pc	> 2200 $M_\odot$	~ 415 $M_\odot$	< 16%	$1\text{-}2 \times 10^{48}$ ergs	2
L1551	~ 25 Myrs	~ 0.3 pc	160 $M_\odot$	22 $M_\odot$	12%	~ 9×10^{44} ergs	0.5

Current SFE very similar across all mass ranges and ages sampled.
Consistent with Lada & Lada (2003): SFE ~ 10-30%

$E_{grav}/E_{outflow}$ similar in massive regions, significantly lower in low-mass region

Low vs high mass (early B stars)

Observtional differences that may affect feedback:

$M_{flow}/M_{\star}$ ~ a few for low-mass stars

~ 10-20 for early B stars (10-15 $M_{\odot}$)

Not understood - increased entrainment and/or disk +circulation model needed?

Outflow structure:

Low-mass = jet evolving into jet+wide angle wind

High-mass = jet evolving into wide-angle wind

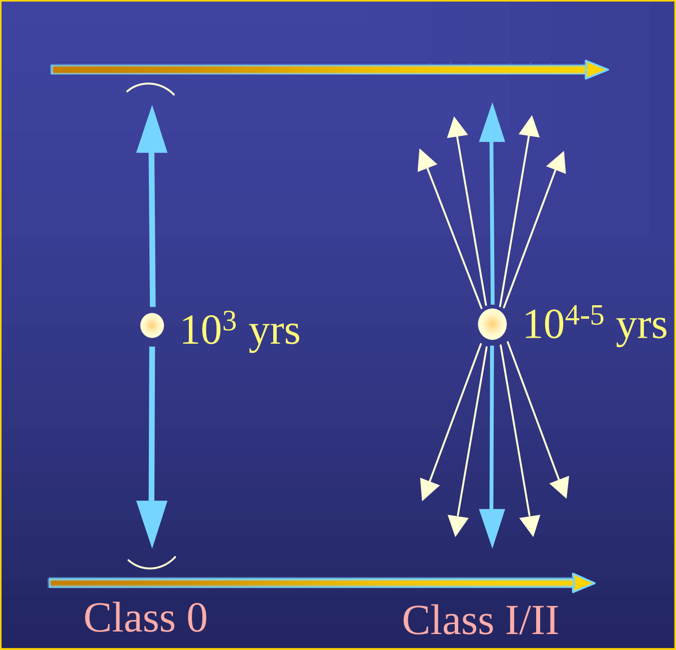
Presence of jet+wide-angle wind rare?

Precession can help but absence of well-collimated jets a mystery still.

Momentum distributed to wide angle most times.

Evolutionary scenarios

T Tauri star evolution (Fuller & Ladd 2002, Arce & Sargent 2006):

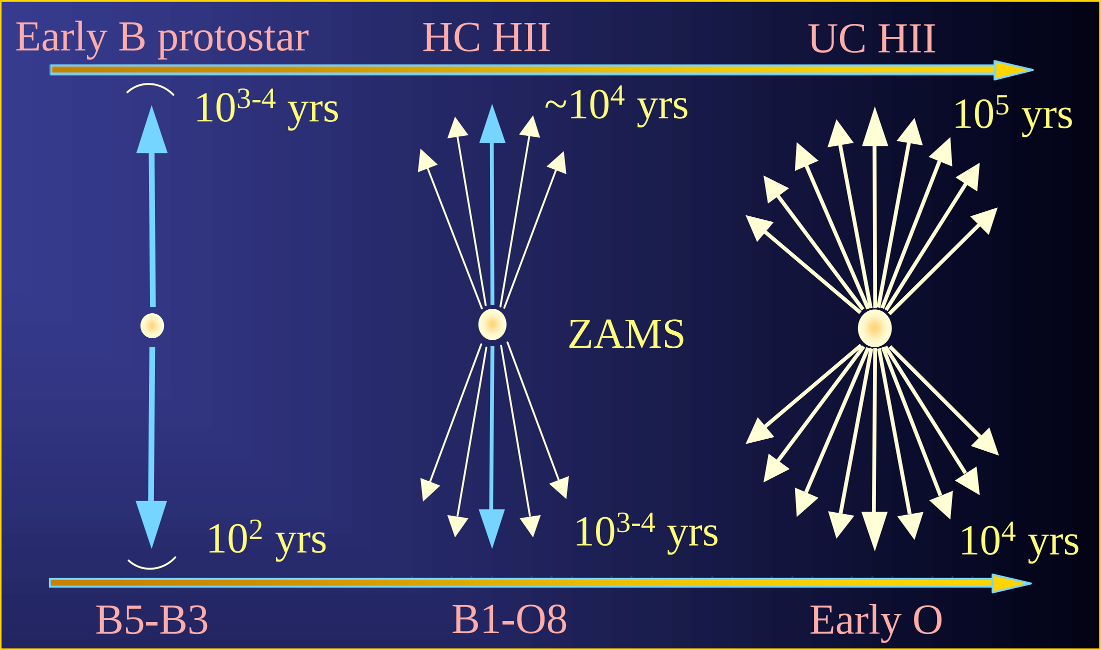


Begin very collimated in Class 0 phase.

Wide angle wind strengthens during Class I phase.

Fast, collimated jet becomes weaker but never disappears until accretion halts

Proposed OB star evolution (Beuther & Shepherd 2005):



Three morphologies produced by 2 possible sequences:

TOP: evolution of early B star from HM protostellar object via HCHII region to UC HII region

BOTTOM: evolution of an O star which transitions from B & late O-type stages to final $M_\star$ & $L_\star$

If final $M_\star$ independent of clump mass young O star can *look* like mid-B star.

Single vs clustered formation

- Matzner and McKee (2000) - low-mass clustered star formation
  - Clumps massive enough to form clusters of stars differ from isolated protostellar cores:
    - Stars with $M_\star < M_{\star,0}$ have outflows too weak to eject matter from the clump.

      $M_{\star,0} = X\,\Theta_0^2\,M_{cl}$

      where X = a star formation efficiency factor (for small X, $X \sim \varepsilon$, the SFE),

      M_{cl} = clump mass, Θ_0 = broadening angle of the outflow.

      For low-mass star forming clusters with jet-like outflows:

      $X \lesssim 1,\quad Q_0 \lesssim 10^{-2},\quad M_{cl} \lesssim 10^3\,M_\odot \rightarrow M_{\star,0} \lesssim 0.1\,M_\odot$

      for $M_{cl} \gtrsim 10^4\,M_\odot \rightarrow M_{\star,0} \gtrsim 1\,M_\odot$

      For clusters with high-mass, wider opening angle flows:

      $X \lesssim 1,\quad Q_0 \gtrsim 10^{-1},\quad M_{cl} > 10^3\,M_\odot \rightarrow M_{\star,0} \sim 10\,M_\odot$.

Thus outflows from solar type stars and/or with wider opening angles inject turbulence but material may remain bound to the clump.

Disk Turbulence - Impact on Outflows & Feedback

Gravitational instabilities induce spiral density waves; expected to be prevalent if $M_{disk\star} > 0.3\ M$, (Laughlin & Bodenheimer 1994). Toomre Q stability parameter (Yorke, Bodenheimer & Laughlin 1995):

$$Q = c_s\, \Omega\ /\ \pi G \Sigma = 56\ (M_\star/M_\odot)^{1/2}\ (R_d/AU)^{-3/2}\ (T_d/100K)^{1/2}\ (\Sigma/10^3\ g\ cm^{-3})$$

Where c_s = local sound speed, Ω = epicycle frequency of disk, Σ = disk surface density, R_d = disk radius & T_d = disk temperature.

For $Q < 1$ disk susceptible to local gravitational instability and axisymmertric fragmentation. Q = 1-2 disk susceptible to gravito-turbulence (Gammie 200 [illegible] Could be a significant angular momentum transport.

Early B (proto)stars appear to have $M_d/M_\star > 0.3$ [illegible] be as high as 1-10.

Consider examples of disks arou [illegible] accreting early B stars:

See: Kaitlin Krattler's poster on massive disk turbulence.

A few examples: Disks in accreting early B stars:

AFGL 490 - B2-B3 star

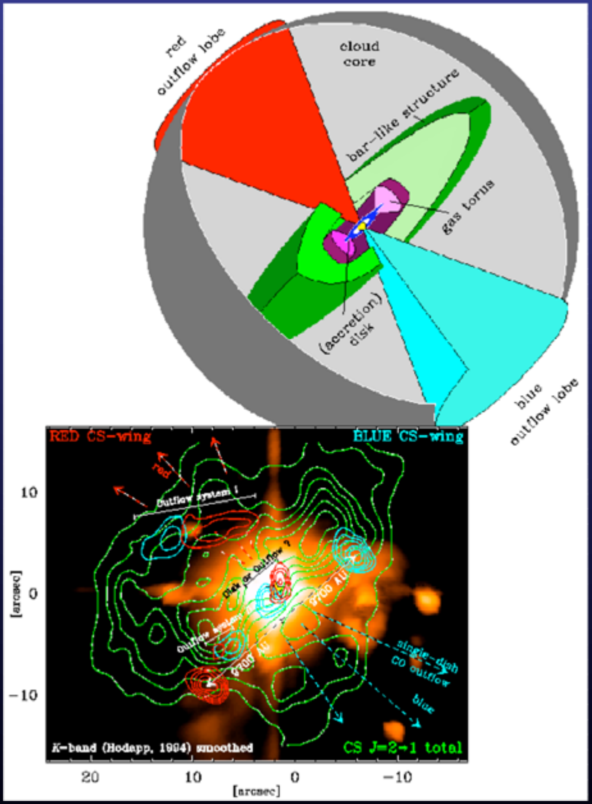
(Schreyer, Forbrich, & Henning 2005; Schreyer et al. 2002)

~20,000 AU CS torus,

<500 AU inner disk with:

$M_d \sim 8\ M_\odot$, $M_\star \sim 8\ M_\odot$

$M_d / M_\star \sim 1.0$



M17 – NowB9-B3 star

(Chini et al. 2004; **Sako et al 2005**)

~2,000 AU molecular torus:

$M_{torus} \sim 10\ M_\odot$, $M^\star \sim 3\text{-}8\ M_\odot$

$M_{torus} / M^\star \sim 2.0$

$M_{disk} / M^\star \sim 0.03$

G192.16-3.85 - B2 star

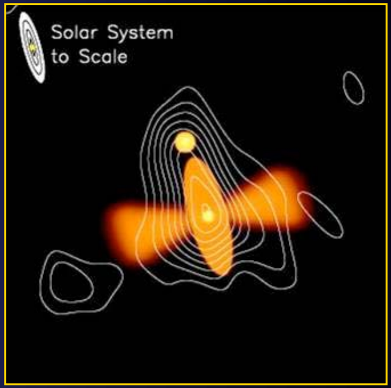
(Shepherd et al. 2001)

~10,000 AU $C^{18}O$ torus,

120 AU inner disk with:

$M_d > 3\ M_\odot$, $M_\star \sim 8\ M_\odot$

$M_d / M_\star > 0.3$



Growing list of early B stars with evidence for accretion disks actively powering outflow or flattened rotating tori, e.g.:

IRAS 20126+4104 (2,000 AU disk, 10,000 AU torus): Cesaroni et al. 1997, 1999, 2005, Zhang et al. 1998

G24.78+0.08 & G31.41+0.31 (3 unstable tori): Beltran et al. 2004

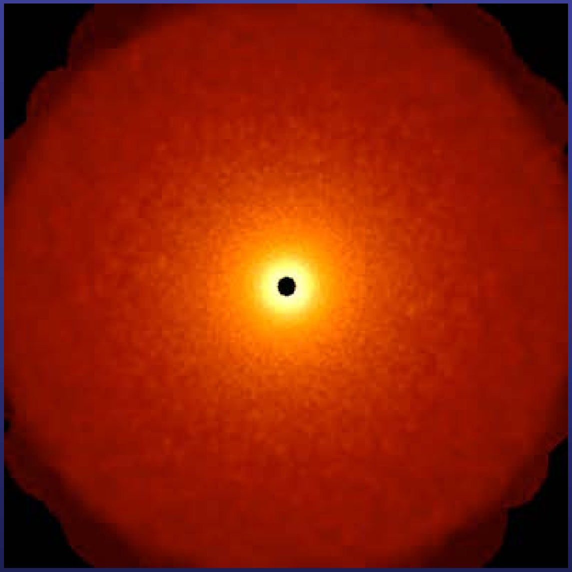
AFGL 5142 (>10,000 AU torus): Zhang et al. 1998, 2002

IRAS 18089-1732(2,000 AU disk): Beuther et al. 2004, 2005

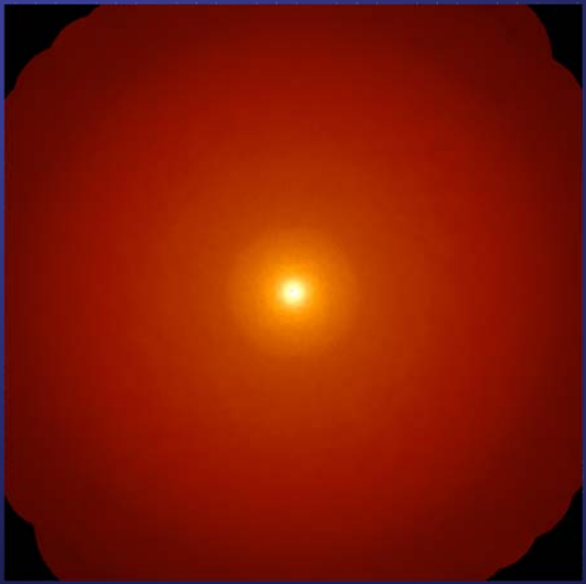
W33A, AFGL 2591, NGC 7538 IRS9 (evidence for ~50-100 AU dust disks & ionized accretion flows): van der Tak & Menten (2005)

Disk turbulence - impact on outflows

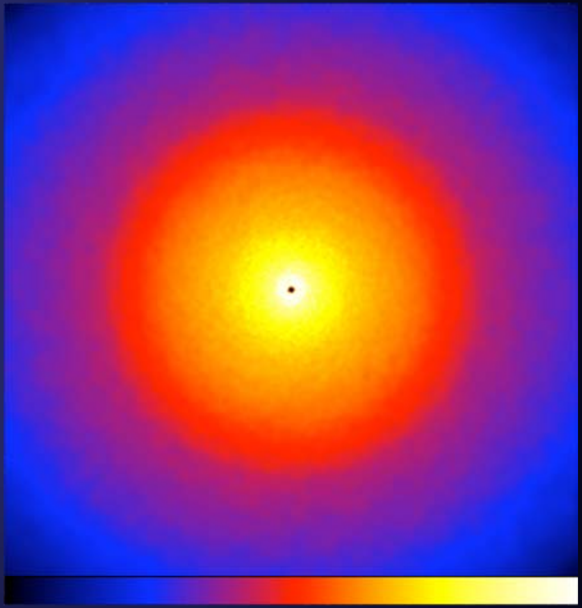
Mass of the disk dramatically changes the characteristics of spiral density waves that can transport angular momentum efficiently. Consider only the disk heating and cooling (no stellar heating, or heating due to ionized outflow or shocks produced by global infall onto the outer disk layers. Then for $M_{disk} = 0.1, 0.5\ \&\ 1.0\ M_{\star}$, (Lodato & Rice 2003,2005):



$M_{disk} = 0.1\ M_{\star}$



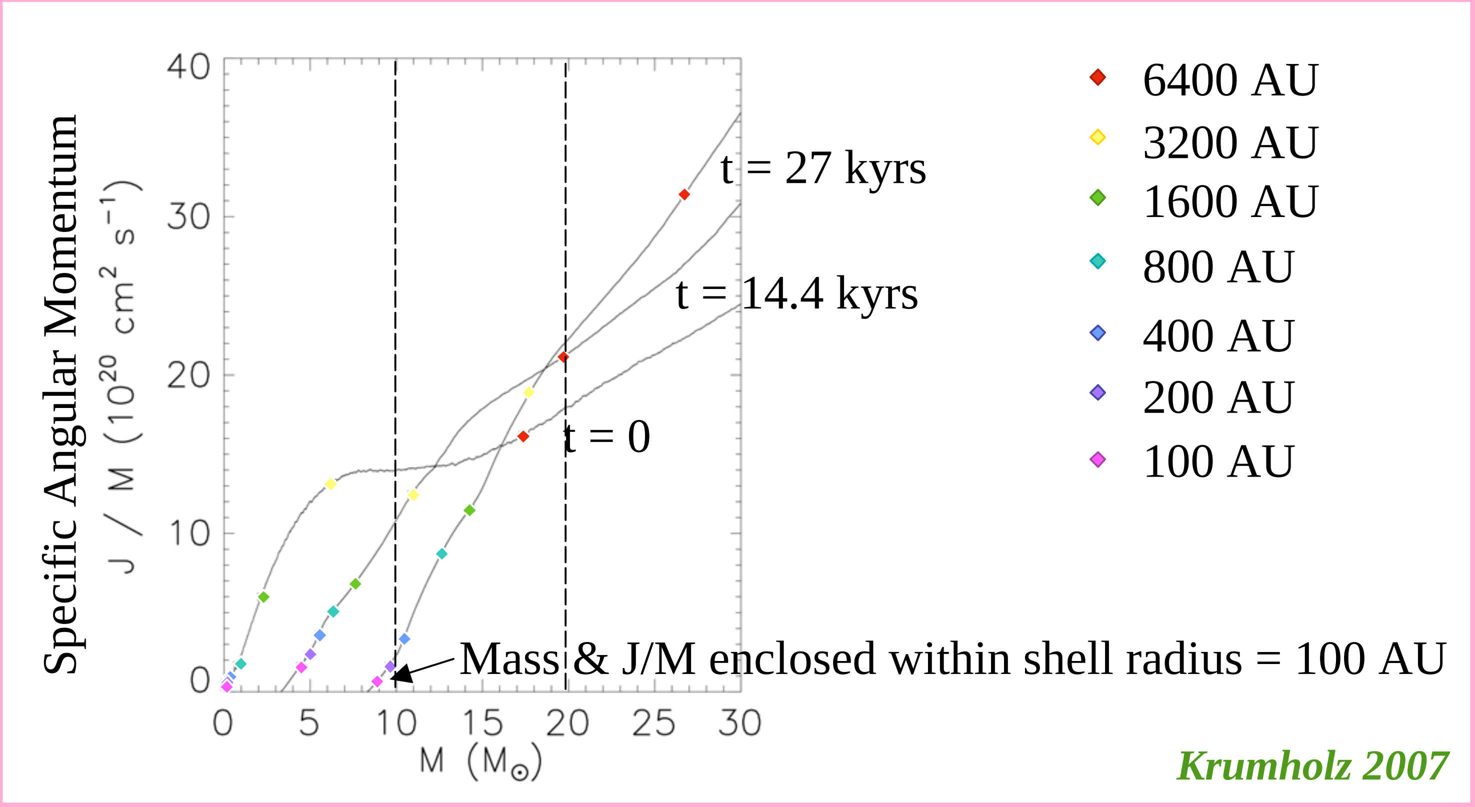
$M_{disk} = 0.5\ M_{\star}$



$M_{disk} = 1.0\ M_{\star}$

Matzner & Levin (2004) – Low-mass star formation: initial conditions and disk instabilities. Irradiation quenches fragmentation due to local instability because disk temperature is raised above parent cloud temperature.

Disks transport angular momentum to surrounding cloud?



Krumholz 2007

Disk appears to be transporting angular momentum outward.

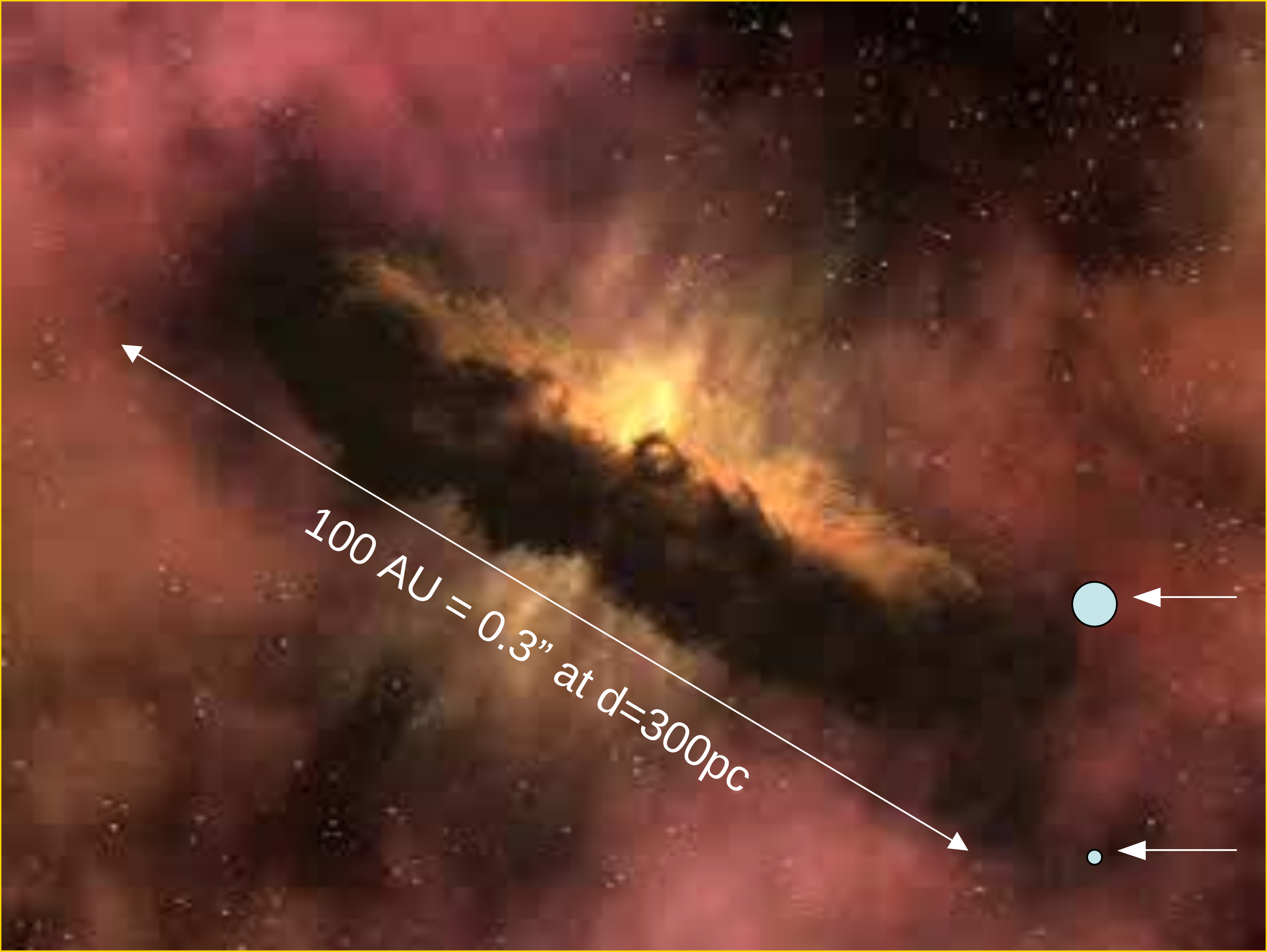
Within a shell of fixed mass, specific angular momentum decreases in time for small masses, increases at large masses, suggesting transport from inner mass shells to outer mass shells

Caveat: using Eulerian, not Lagrangian code: individual elements not followed. Can't distinguish between transport, when we give angular momentum from one mass element to another (via e.g. gravitational torques) from sorting, where gas elements that had initially low angular momentum migrate toward the center, while those born with high angular momentum migrate away from the star.

Feedback from Outflows & Disks

- For L1551, ~all outflows can break out of the cloud, feedback from outflows alone can explain observed cloud turbulence
- For massive star forming clusters several mechanisms appear to feed turbulence/energy in the cloud:
  - Outflows from lower mass YSOs may remain bound
  - Massive flows develop wide opening angles in less than 10^5 years which helps prevent entrained outflow gas from escaping cloud
  - Very massive disks transport angular momentum to surrounding cloud
  - HII regions heat surrounding cloud and expand into clump.
- Unknowns:
  - Balance between feedback mechanisms
  - How much angular momentum transported through disk to clump or torus
  - Is disk angular momentum removed only from outer regions (> 50 AU) or is it drained from the area of the disk where the outflow is launched (~0.1 to a few AU)? Could it change the balance between $\dot{M}_{flow}$ and $\dot{M}_{accretion}$?

Observations of disks with ALMA



ALMA band 7
300 GHz = 1 mm
resolution = 1.4” to 0.015”

~ Highest resolution
at 300 GHz = 1 mm
(0.015”)

~ Highest resolution
at 850 GHz = 350 μm

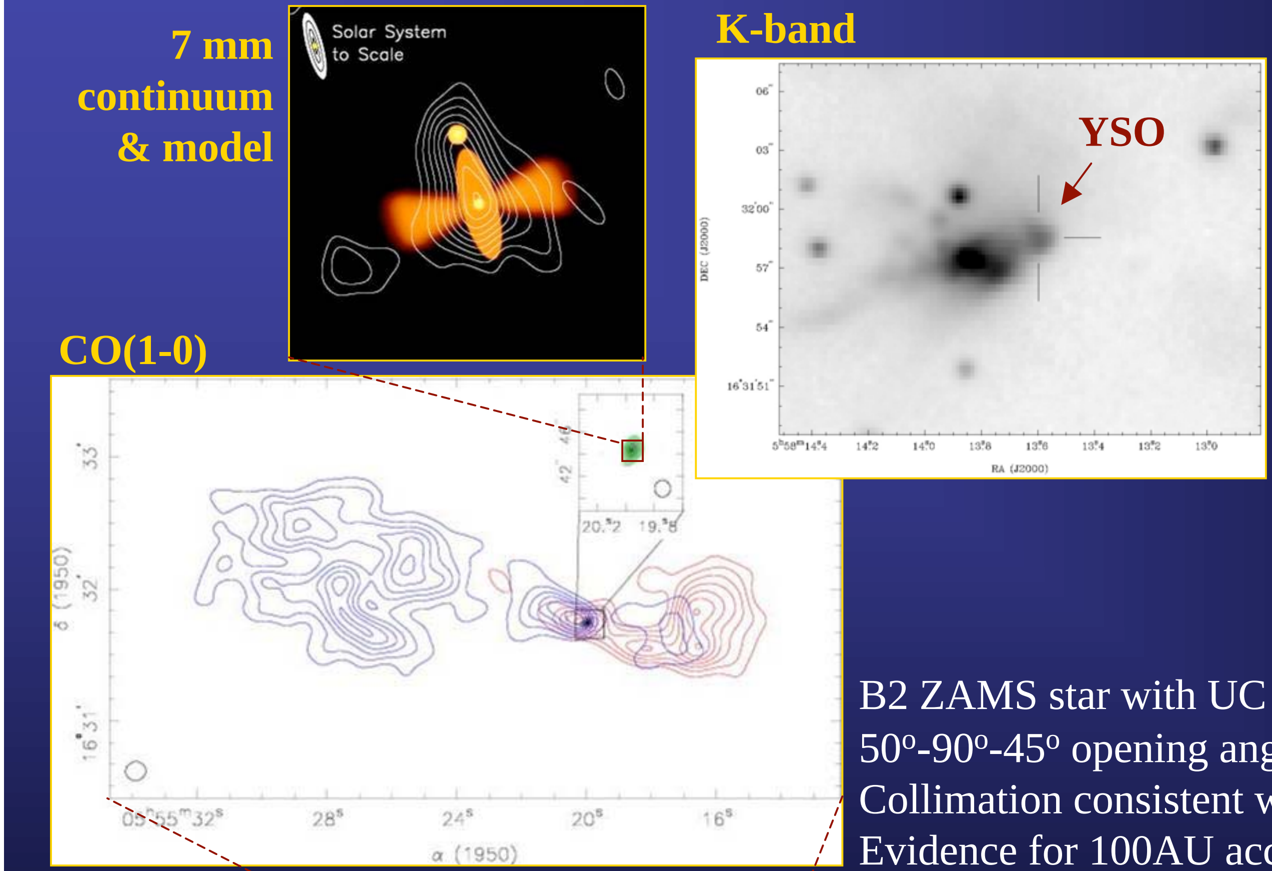
Summary

- Detailed studies of early B star forming clusters at different ages suggests:
  - SFE roughly constant (~10-15%) for low and high-mass regions. *Better estimates of stellar content needed - Spitzer modeling will help.*
  - During formation of massive stars, gravitational potential energy, E_{grav}, 2 to 5 times larger than kinetic energy in combined outflows.

    → Outflows alone not likely to disrupt cloud or halt star formation.
- For L1551, ~ all outflows can break out of the cloud, feedback from outflows alone may be enough to explain observed cloud turbulence.
- For massive star forming clusters several mechanisms appear to feed turbulence in the cloud:
  - Outflows from lower mass YSOs may remain bound.
  - Massive flows develop wide opening angles in less than 10^5 years (induced by precession and/or interaction with forming HII region).
  - Very massive disks may transport angular momentum effectively to surrounding cloud. *Need to estimate magnitude of angular momentum transport & whether it is drained from disk region producing outflow. ALMA will observe directly.*
  - HII regions expand into cloud and provide heating/ionization.

Discussion

G192.16: Early B Star ~ 10^5 years old


7 mm continuum & model

K-band

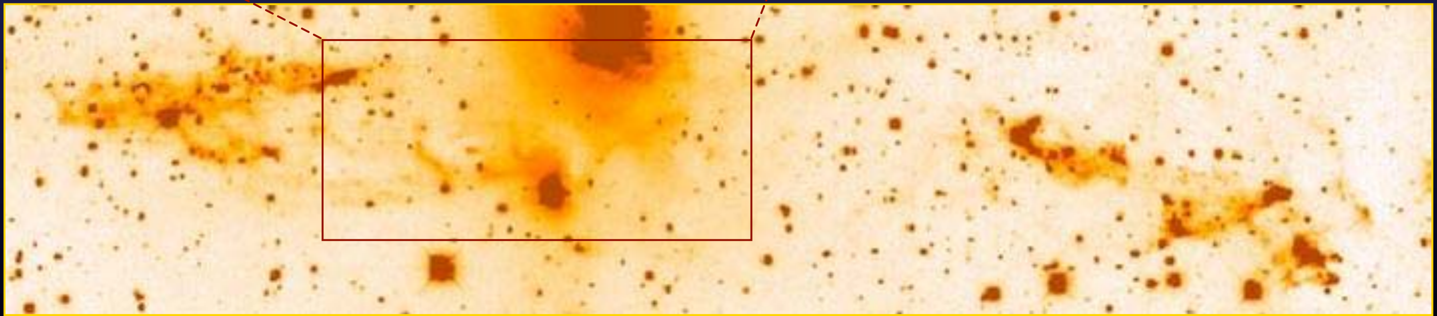
CO(1-0)

G192.16-3.82

Indebetouw et al. (2003)
Devine et al. (1999)
Shepherd et al. (1998,1999,2001)

$L_{bol} \sim 3 \times 10^{3} L_{sun}$
$T_{dyn} \sim 2 \times 10^{5}$ yrs
$M_{2.6mm} \sim 10 M_{sun}$
$M_f \sim 95 M_{sun}$
$\dot{M}_f \sim 6 \times 10^{-4} M_{sun}\, yr^{-1}$
$\dot{P}_f \sim 4 \times 10^{-3} M_{sun}\, km\, s^{-1}\, yr^{-1}$

B2 ZAMS star with UC HII region
50°-90°-45° opening angle outflow
Collimation consistent with wind-blown bubble
Evidence for 100AU accretion disk, 1000AU rotating torus



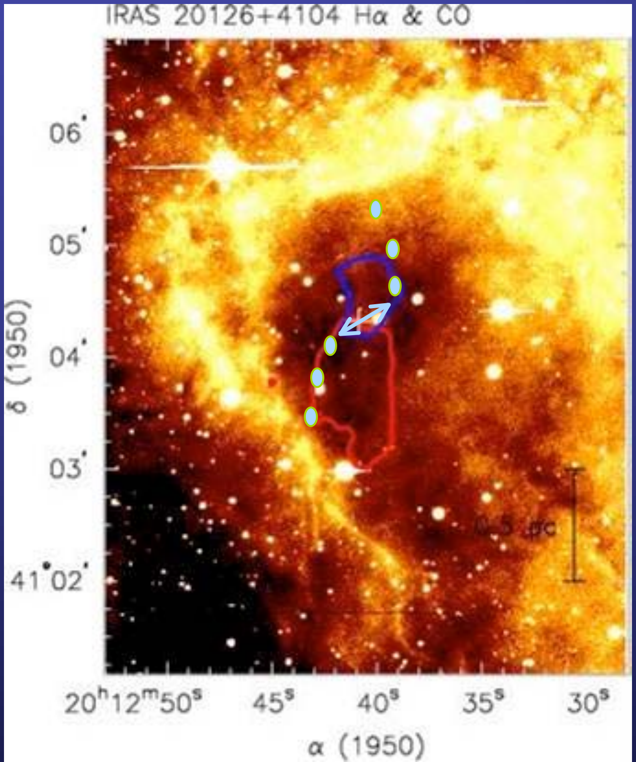
NH_3 core not gravitationally bound – near end of accretion phase

[SII]

I 20126: Early B Protostar ~ 10^4 years old

IRAS 20126+4104

Hα & CO(1-0)



Lebron et al. (in prep)
Cesaroni et al. (1999,2004,2005)
Hofner et al (1999,2001, in prep)
Moscadelli et al. (2000, 2005)
Shepherd et al. (2000)
Zhang et al. (1998, 1999)

$L_{bol} \sim 10^{4} L_{sun}$

$T_{dyn} \sim 2x10^{4}$ yrs

$M_{2.6mm} \sim 50\ M_{sun}$

$\dot{M}_f \sim 50\text{-}60\ M_{sun}$

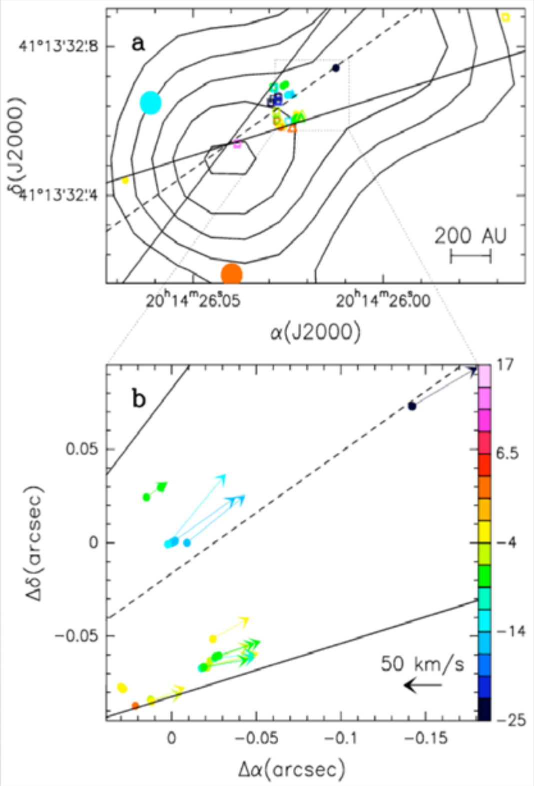
$\dot{M}_f \sim 8 \times 10^{-4}\ M_{sun}\ yr^{-1}$

$\dot{P}_f \sim 6 \times 10^{-3}\ M_{sun}\ km\ s^{-1}\ yr^{-1}$

B0.5 Protostar (*not* ZAMS but cm continuum detected)

Precessing jet may create wider angle CO outflow

2000 AU rotating torus & 10,000 AU rotating NH_3 core



Estimated jet full opening angle θ ~ 34º (from model of VLBI H_2O maser emission). Consistent with θ derived from SiO jet.

Compare: LM jets have θ ~ 10-30º within 10 AU of star that re-collimate to 1-3º within 100 AU.

No re-collimation obvious.

HH 80-81:Young Early B Stars

IRAS 18162-2048,
GGD 27, HH 80-81

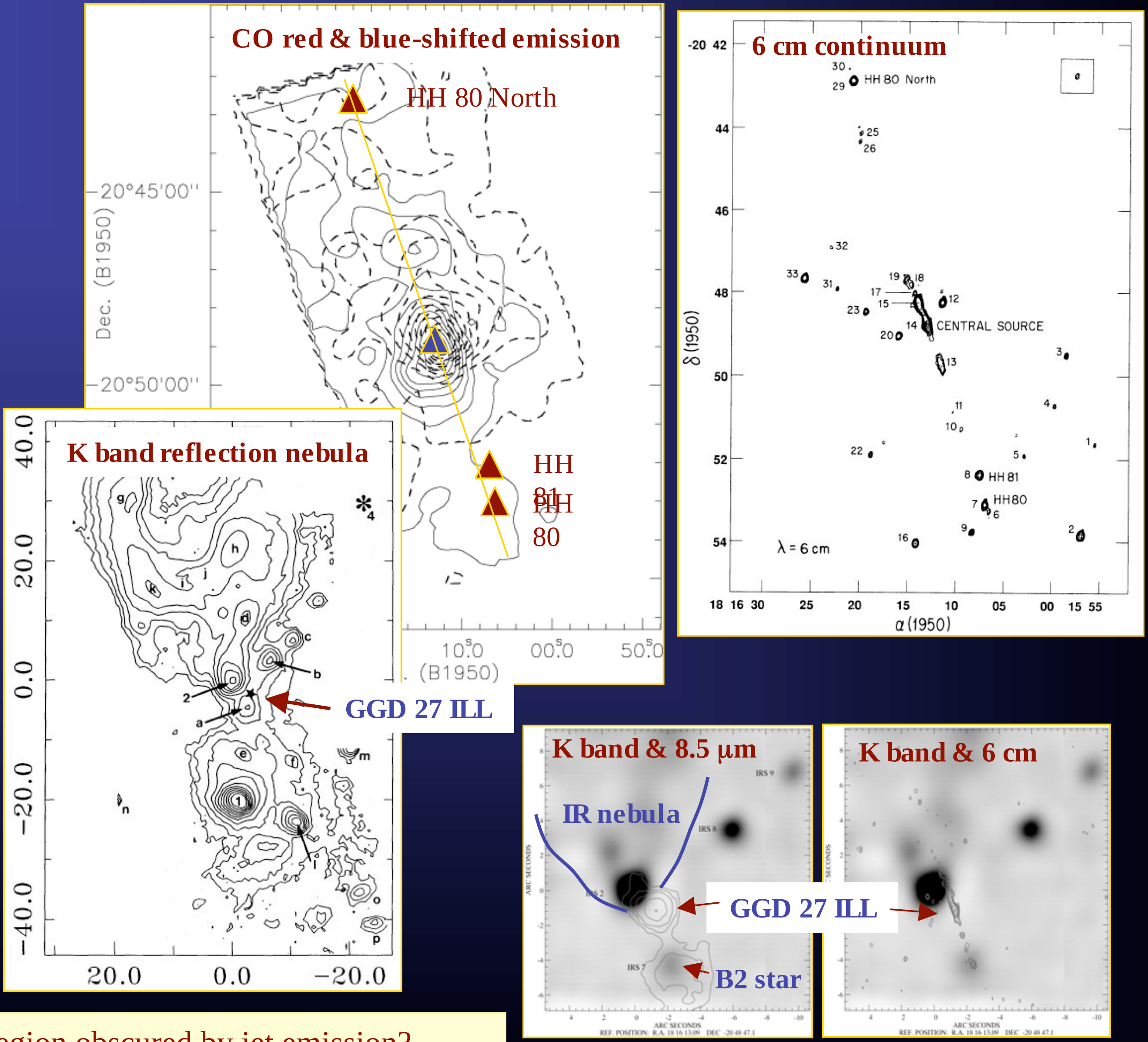
Yamashita et al. (1989)
Aspin et al. (1991)
Marti, Rodriguez, Reipurth (1993, 1995)
Gomez et al. (1995, 2003)
Stecklum et al. (1997)
Benedettini et al. (2004)

B star cluster with
$L_{bol} \sim 2 \times 10^{4} L_{sun}$
$T_{dyn} \sim 10^{6}$ *yrs*
$M_f \sim 570\ M_{sun}$
$\dot{M}_f \sim 6 \times 10^{-4}\ M_{sun}\ yr^{-1}$

GGD 27 ILL powers jet & illuminates reflection nebula, Sp. type < B1

CO opening angle > 40º

Collimated, ionized jet, no apparent UC HII region

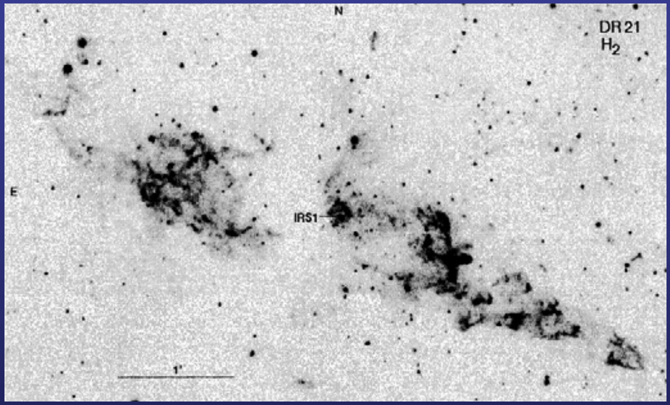


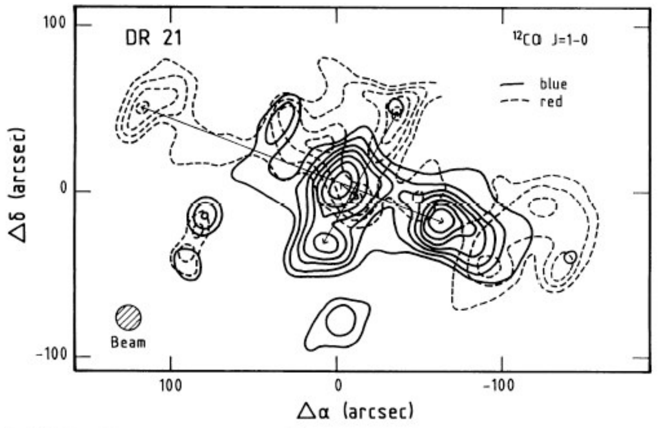
➔ Later than B3? Or is UCHII region obscured by jet emission?

DR 21: O Protostar cluster

DR21

Roelfsema et al. (1989)	$L_{bol} \sim 3 \times 10^{5} L_{sun}$
Garden et al. (1991)	$T_{dyn} > 5 \times 10^{4}$ yrs
Davis & Smith (1996)	$M_f \sim 3000\ M_{sun}$
Smith et al. (2005, in prep)	$\dot{M}_f < 6 \times 10^{-2}\ M_{sun}\ yr^{-1}$



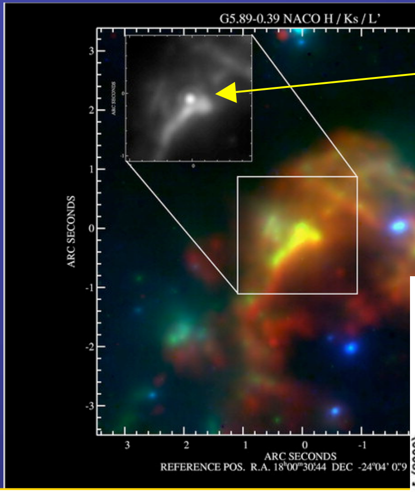


Spitzer image
Blue: 3.6μm
green: 4.5μm
orange: 5.8μ
m red: 8μm

DR21 outflow powered by mid-IR cluster of OB stars, most have no circumstellar material (Smith et al. in prep).

A newly discovered O star DR21:IRAC-4 appears to have a hot, accreting envelope: $L_{acc} > L_{\star}$

G5.89 - a Young O star



H, K, & L' NIR image

Feldt et al. (2003): ~ O5 star detected, no disk-like structure but small excess 3.5 μm emission → circumstellar material.

Cesaroni et al. (1991)
Acord et al. (1997, 1998)
Faison et al. (1998)
Feldt et al. (1999)

Watson et al. (2002): CO outflow larger than SiO. Outflow roughly ⊥ to UC HII region expansion.

$L_{bol} \sim 3 \times 10^{5} L_{sun}$

$T_{dyn} = 7.5 \times 10^{3}$ yrs

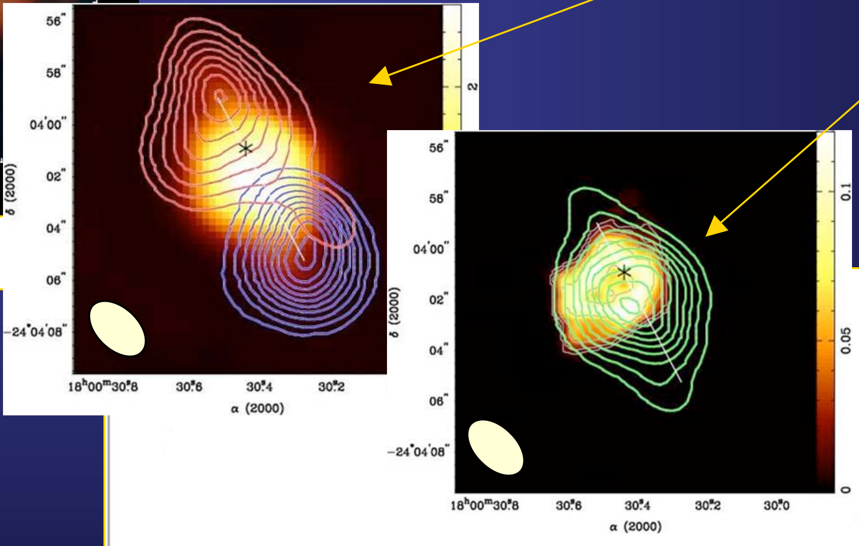
$M_f > 77\ M_{sun}$

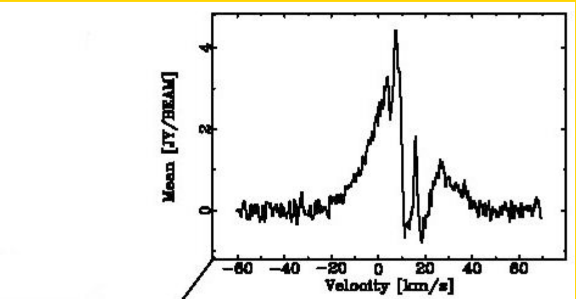
$\dot{M}_f > 10^{-3}\ M_{sun}\ yr^{-1}$

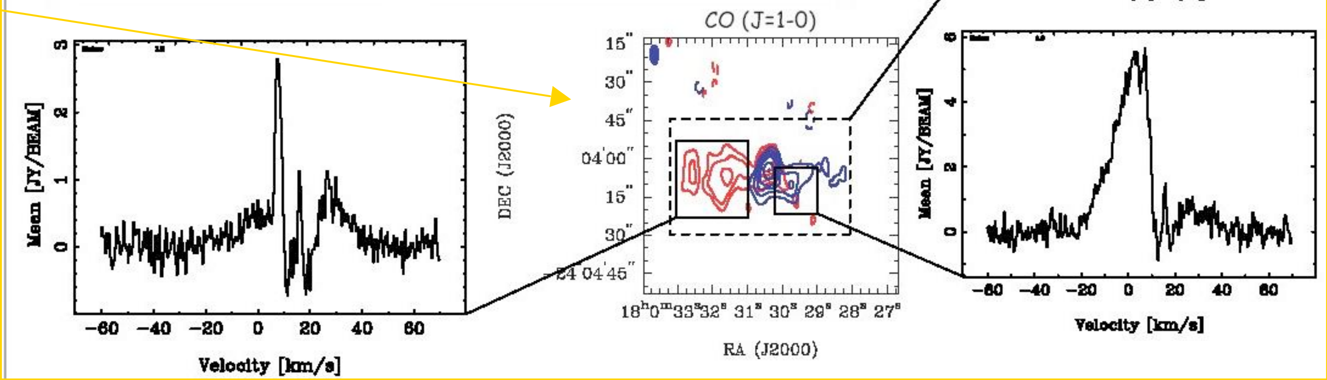
G5.89-0.39 New Results

Sollins et al. (2004): SiO(5-4) outflow opening angle ~ 90°. Outflow axis does not match axis found in $C^{34}S$ or CO/HCO+. Dust continuum extension along SiO outflow axis.

Multiple flows?

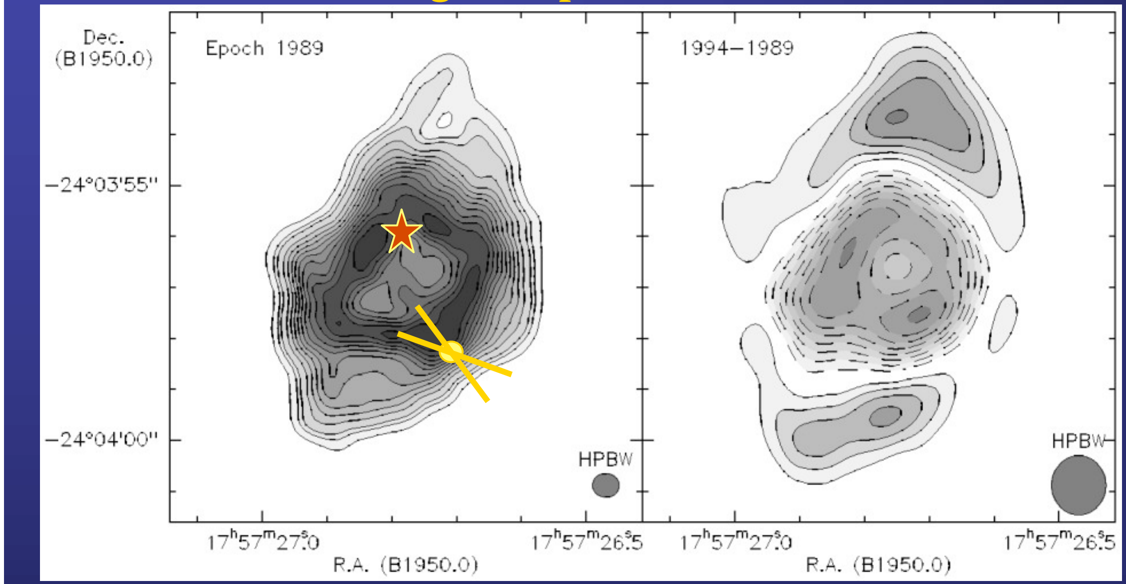






G5.89 - a Young O star

3.6 cm HII region expansion

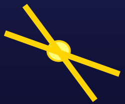


O5 (proto)star

C34S outflow detected along axis of UC HII region expansion – outflow affecting the ionized gas?

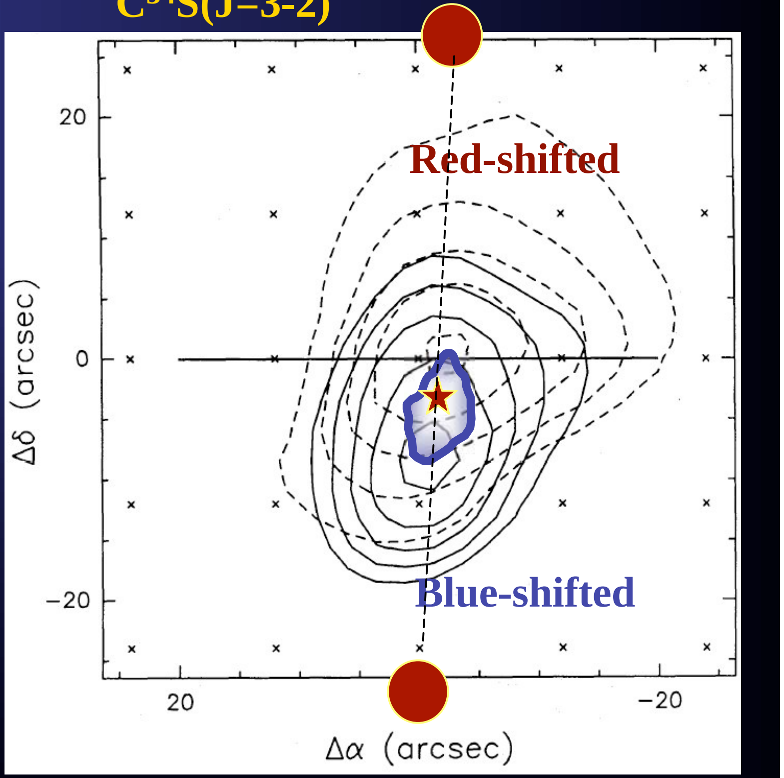
No accretion disk. Star located in a 10,000 AU dust-free cavity

Puga et al. (2005) – JUST OUT – O5 star ★ drives H2 knots along ionized gas expansion axis and C34S outflow?

Another source  drives SiO flow…

So what drives the E-W CO flow?

$C^{34}S(J=3-2)$



Massive vs Low-Mass Protostars

Kelvin-Helmholtz time scale (time to reach ZAMS):

$\tau_{KH} = GM^2/RL$

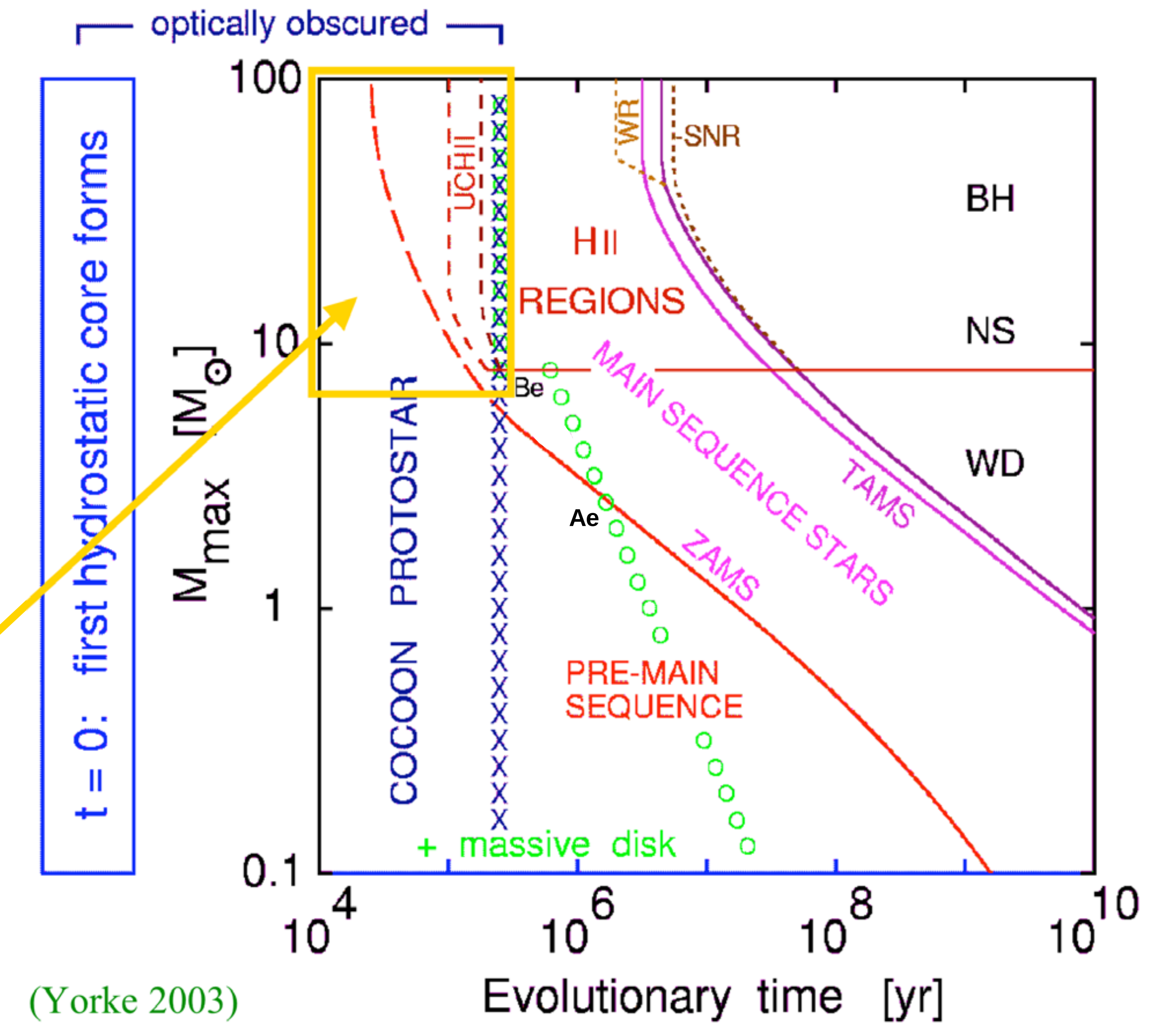
Accretion time scale:

$\tau_{acc} = M_\star/\dot{M}_{acc}$

For $M_\star \sim 8\ M_\odot$

$\tau_{acc} = \tau_{KH}$

And for $M_\star > 8\ M_\odot$ the star reaches the ZAMS while still accreting – ionizing radiation affects outflow & infall



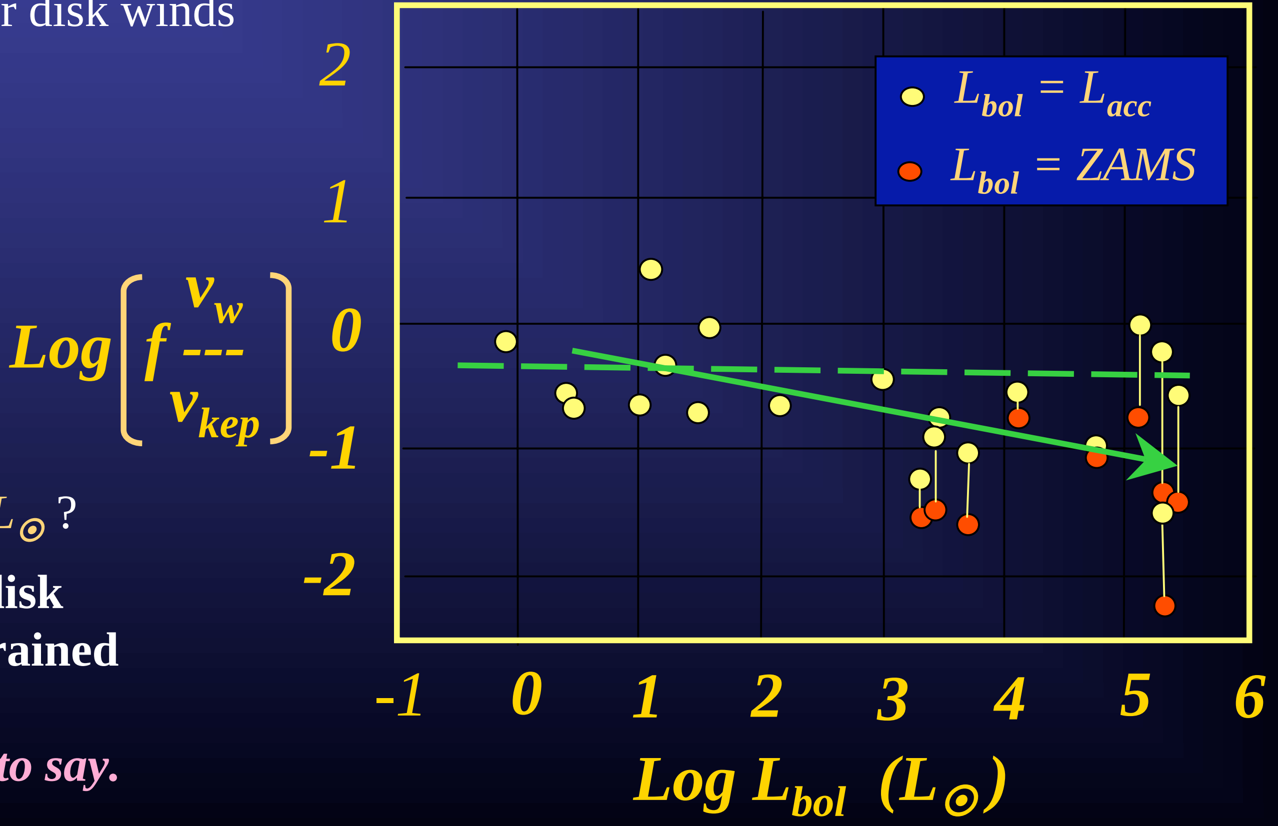
(Yorke 2003)

Disk angular momentum transport - possible impact on outflows?

Observations (Richer et al. 2000):

$$\frac{\textit{Outflow Force}}{\textit{Accretion Force}} = \frac{F_{co}}{\dot{M}_{acc}\, v_{kep}} = f\,\frac{v_w}{v_{kep}} \quad \text{where} \quad f = \frac{\dot{M}_w}{\dot{M}_{acc}}$$

$f\,\frac{v_w}{v_{kep}} \sim 0.03\ \ (10/1)$ for disk winds



Decrease in $\dot{M}_w / \dot{M}_{acc}$

between $L_{bol} = 1$ and $10^4\ L_{\odot}$?

If so, may indicate that disk angular momentum is drained from outflow footprint.

Errors are too large now to say.