Outflow Opening Angles in Early B (Proto)Stars

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With support from
NSF, Spitzer, The Origins Institute (McMaster U.) & Kavli Institute

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Santa Barbara, KITP stars07

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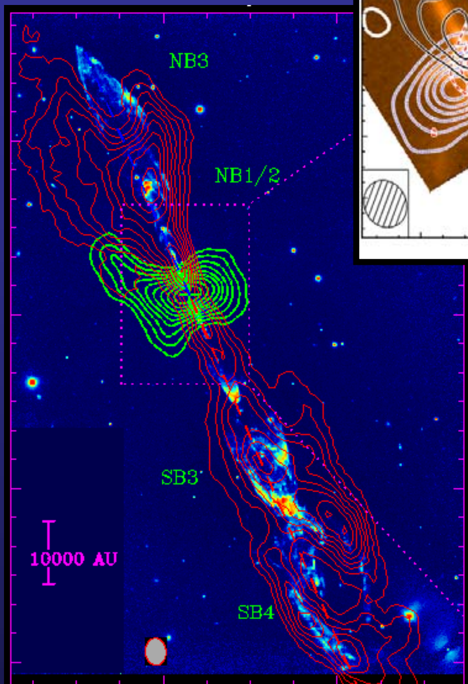
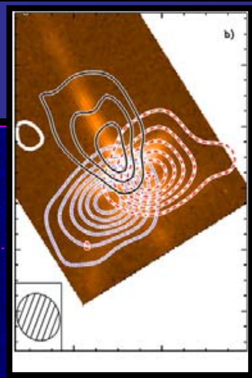
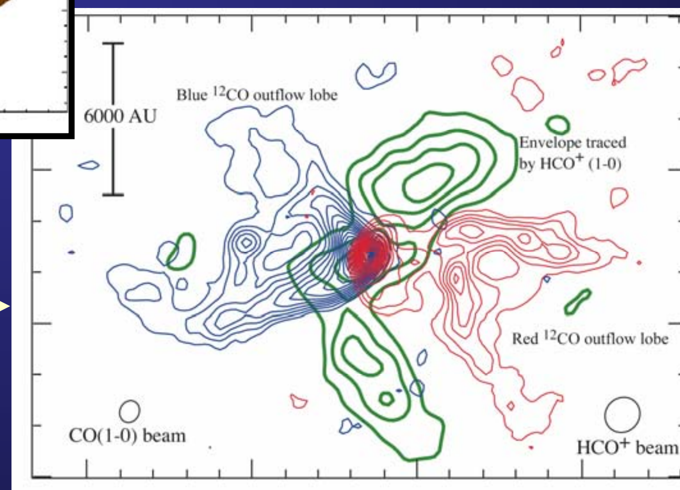
First: Low-Mass Outflow Evolution



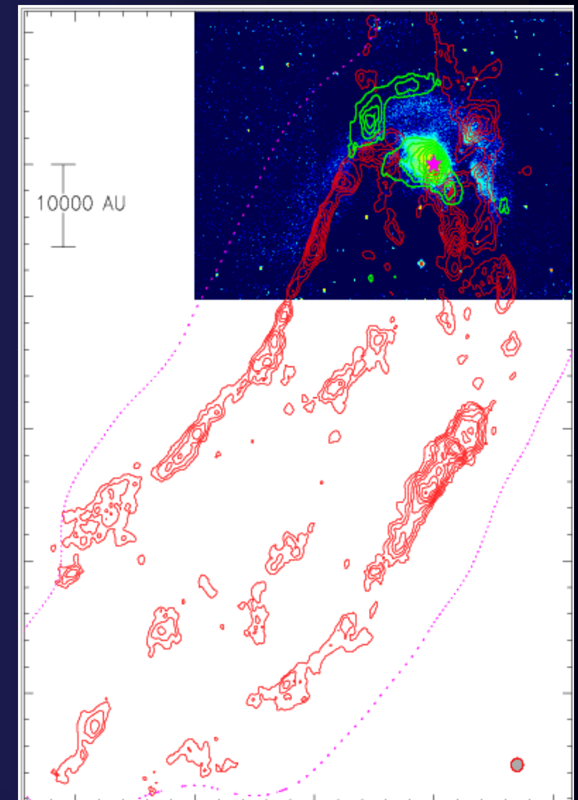


HH30
(Pety, Gueth et al 2006).



HH212 Lee et al. 2000
Wiseman et al. 2001

L1228 Arce & Sargent 2004



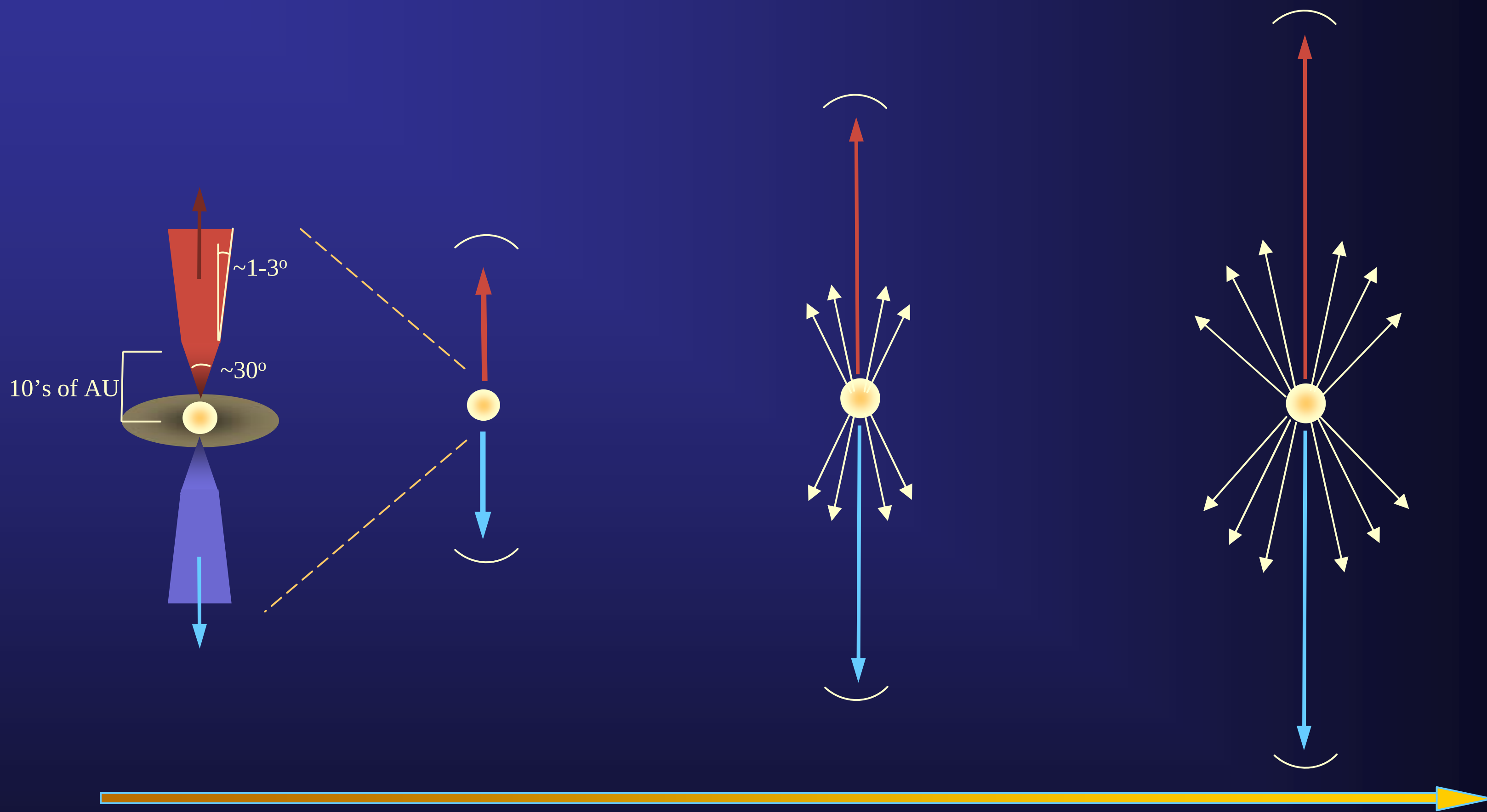
RNO91 Lee & Ho 2005

Class 0 Class I Class II

time

Red & blue contours: CO outflow
Green contours: Core emission (NH_3, HCO^+, N_2H^+)
Color: H_2 & IR reflection nebulae

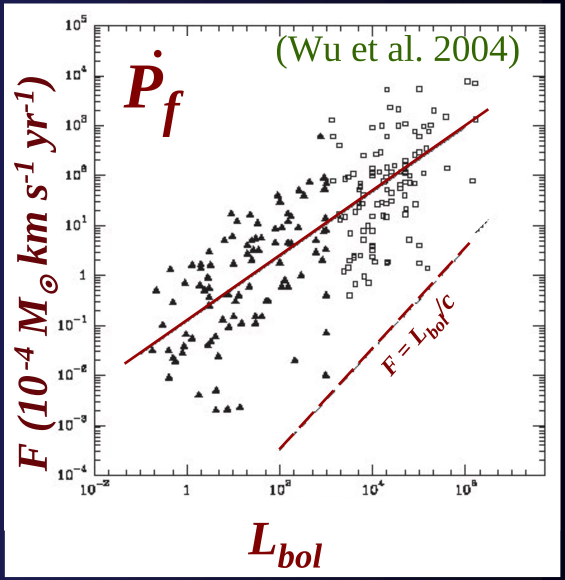
Low-Mass Outflow Evolution



Class 0	Class I	Class II - III
~10^{3-4} yrs	~10^{5} yrs	~10^{6-7} - 10^{8} yrs

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.

Massive vs Low-Mass Protostars

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

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

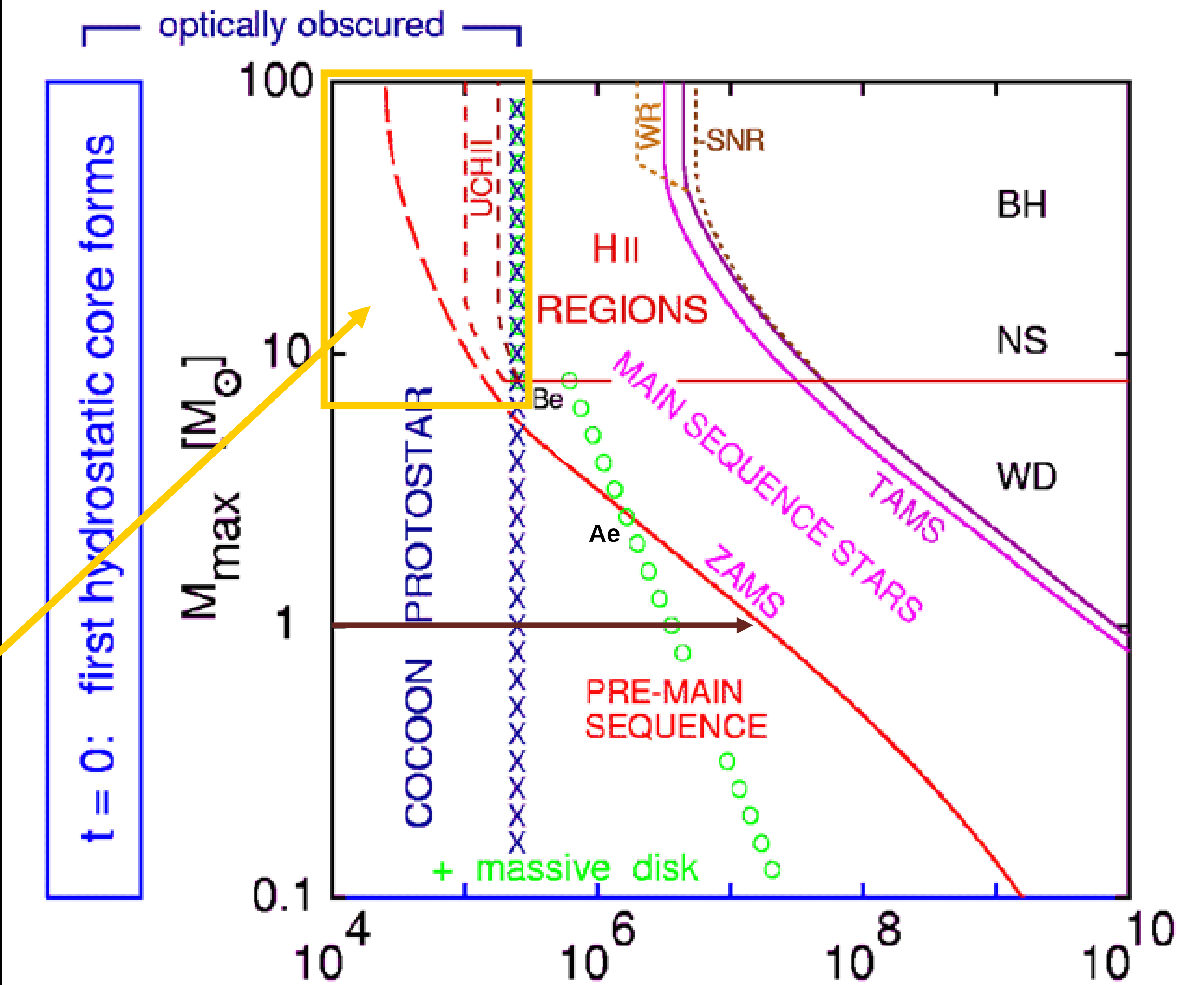
Accretion time scale:

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

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

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

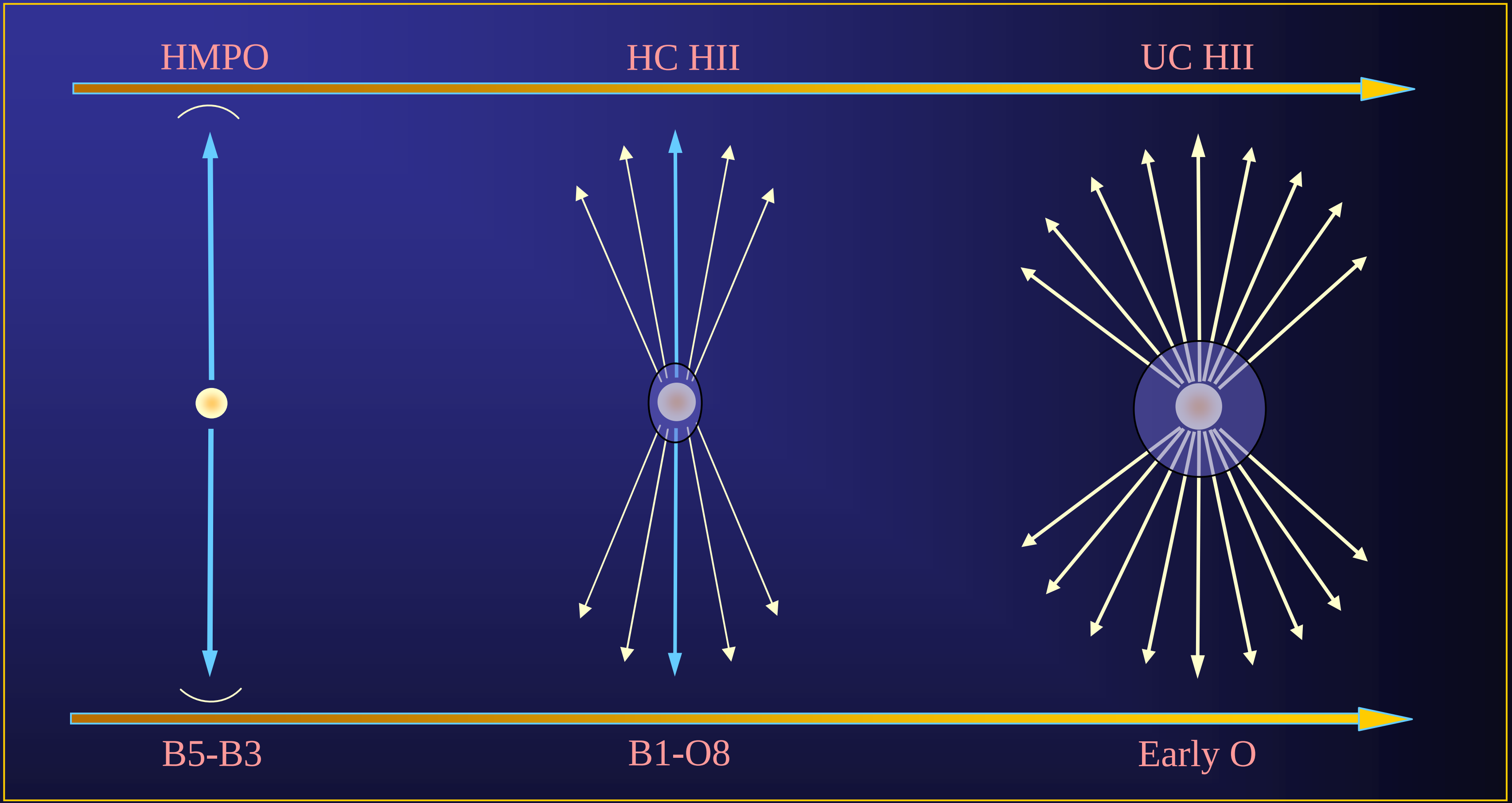
And for $M_\star > 8\ M_\odot$ the star reaches the ZAMS while still accreting – ionizing radiation affects outflow & infall



(Yorke 2003)

O & B star proposed evolution

Assume formation via accretion. Consider evolutionary scenario (Beuther & Shepherd 2005):



Three outflow morphologies produced by 2 possible evolutionary 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 and late O-type stages to final $M_\star$ & $L_\star$

Final $M_\star$ independent of initial clump mass: young early O star can *look* like mid-B star.

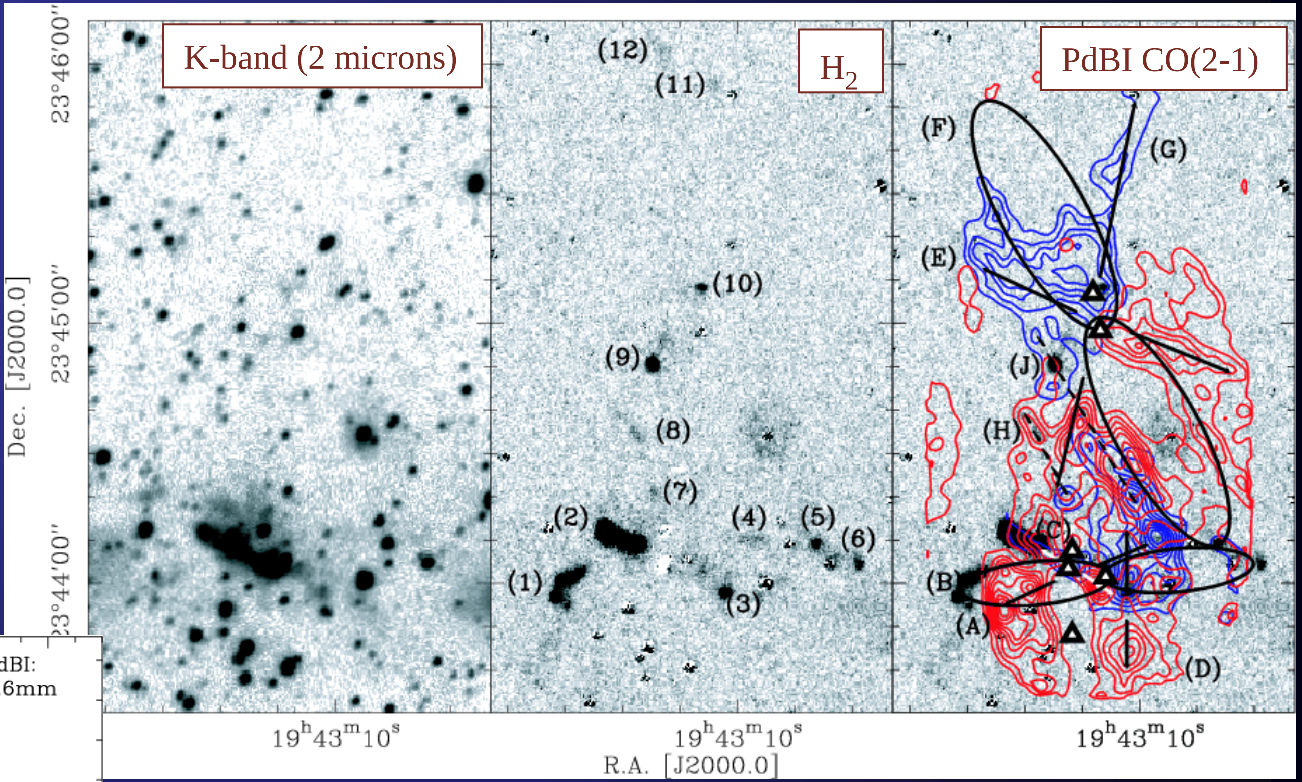
Early B (Proto)Stars

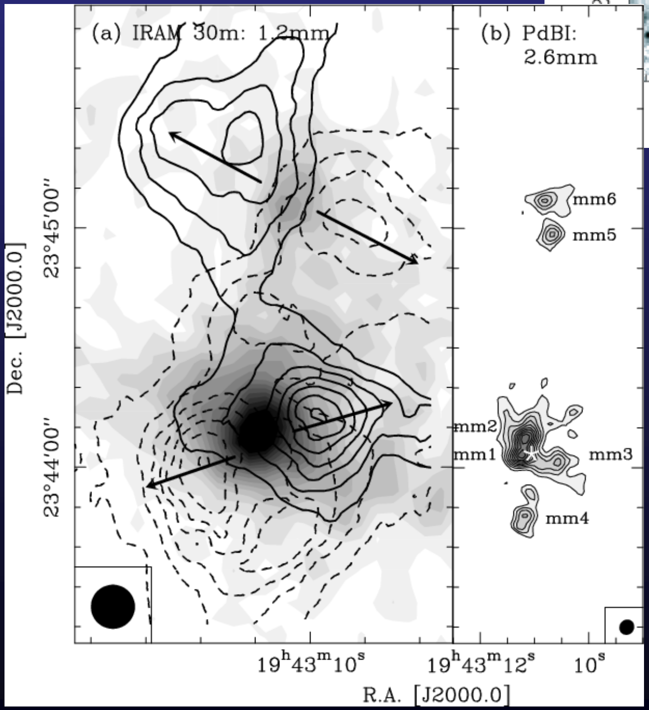
Source	RA (J2000)	Dec (J2000)	L [$\log_{10}(L_\odot)$]	D [kpc]	Age [years]
IRAS 20293	20 31 10.7	40 03 10	3.6	1.7	~ few x 10^3
IRAS 19410	19 43 11.4	23 44 06	4.0	2.1	≤ 10^4 ?
AFGL 5142	05 30 48.	33 47 54	3.5	1.8	~ few x 10^4
05358+3543	05 39 10.4	35 45 19	3.8	1.7	3-4 x 10^4
IRAS 20126	20 14 26.0	41 13 33	3.9	1.7	6 x 10^4
W75 N	20 38 36.5	42 37 34	3.0	2.0	2 x 10^5
G192.16	05 58 13.5	16 31 58	3.5	2.0	2 x 10^5
HH 80-81	18 16 13.0	-20 48 48	4.2	1.7	10^6

Focus here on highlighted sources

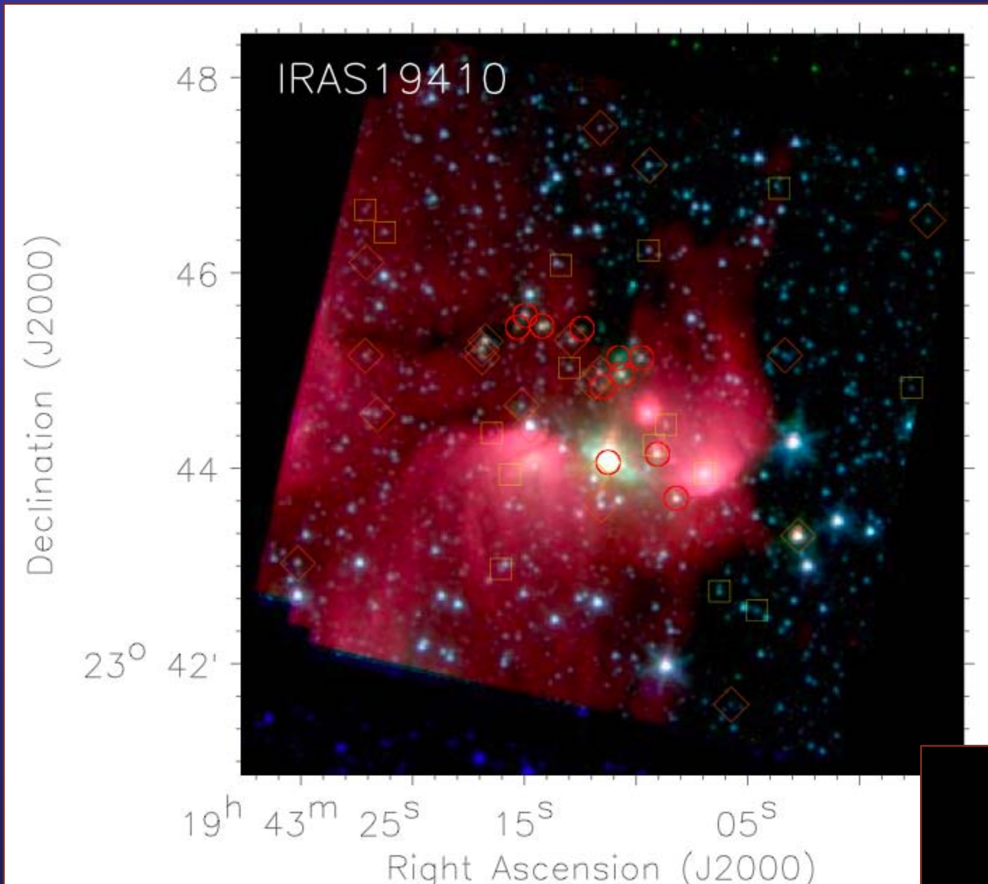
IRAS 19410+2336

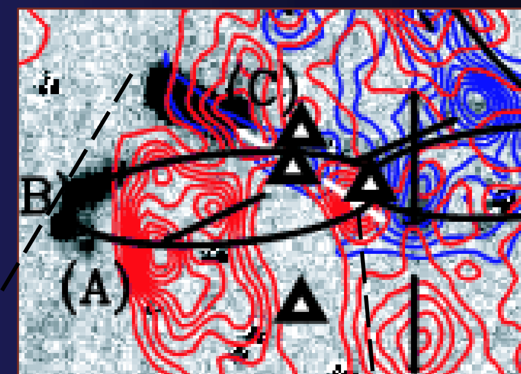
Beuther, Schilke & Stanke (2003)

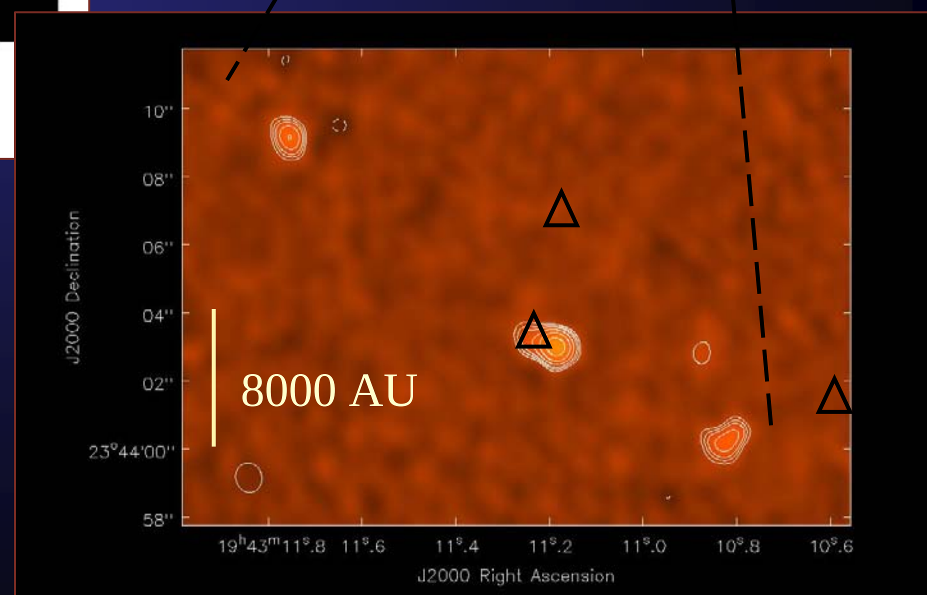




IRAS 19410 - Spitzer mid-IR & ionized outflow from MM1





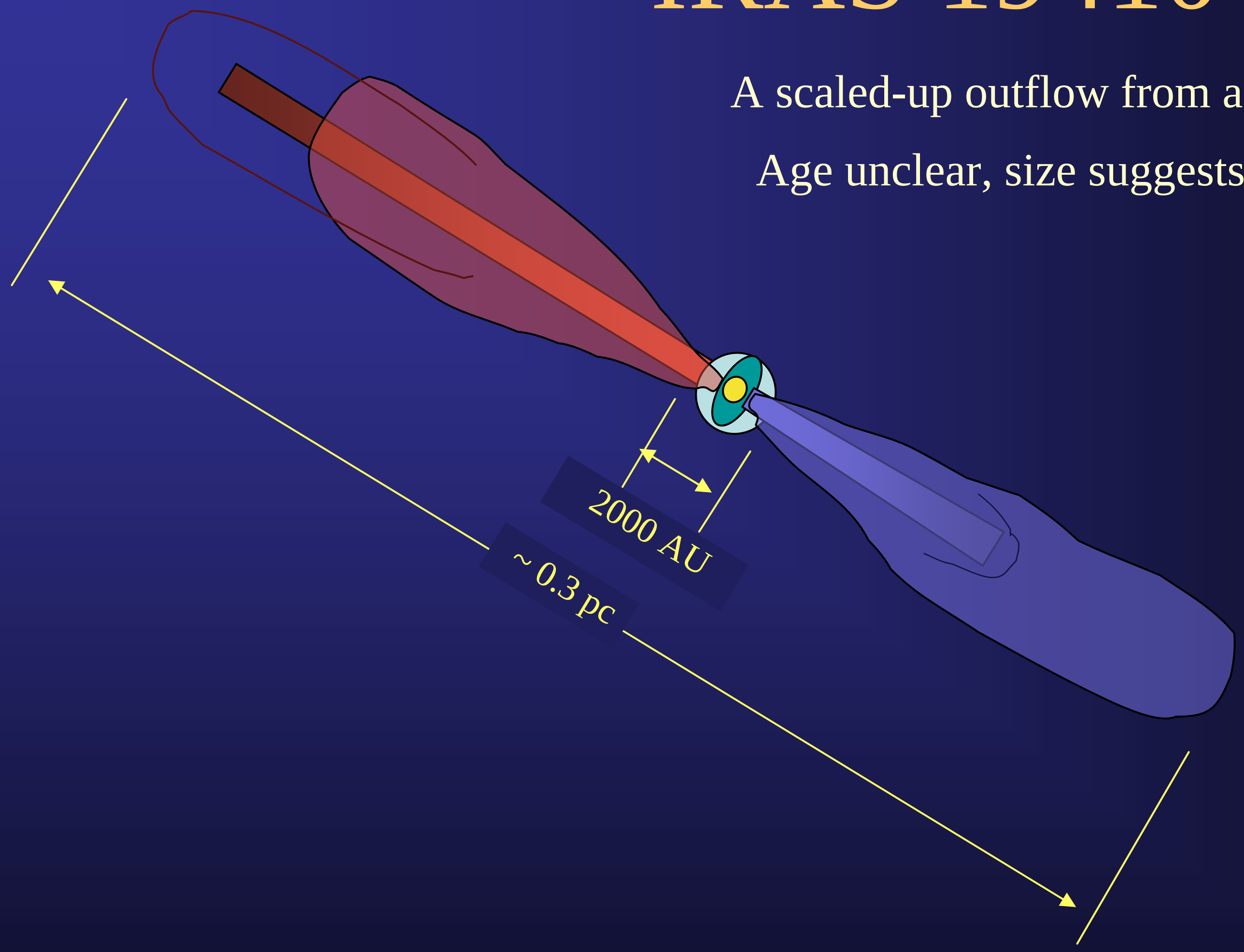


Oct 2007

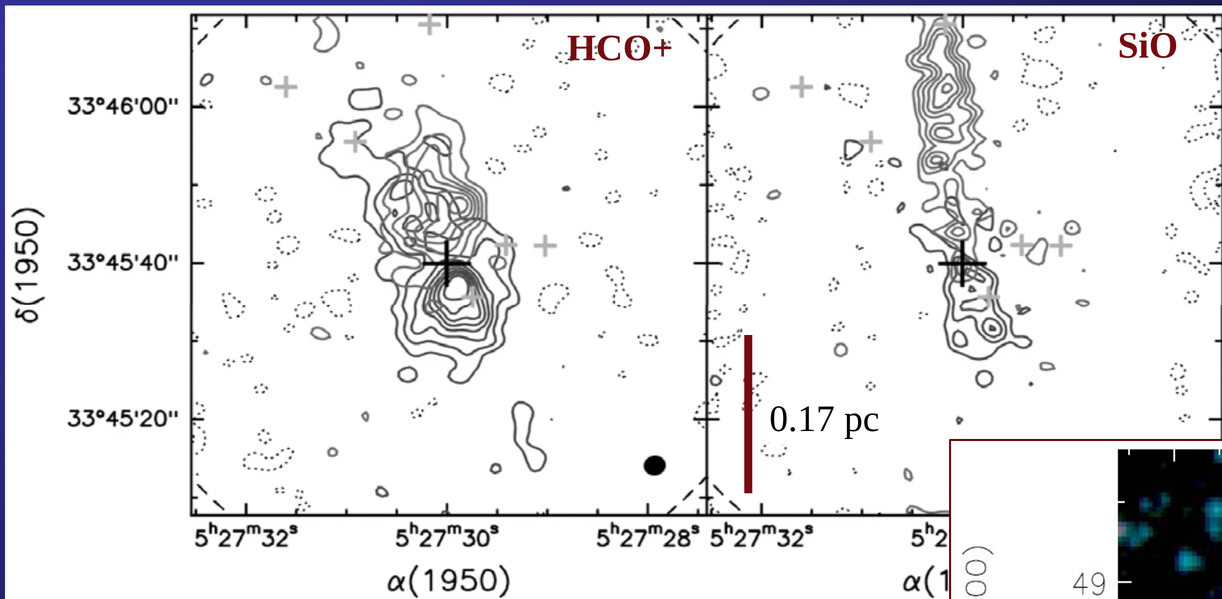
IRAS 19410 - MM1

A scaled-up outflow from an early B star

Age unclear, size suggests ≤ 10^4 years



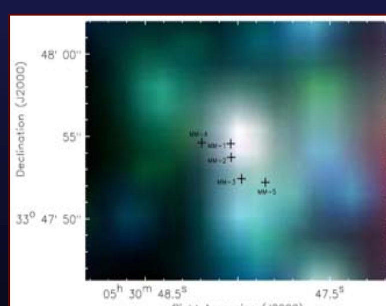
AFGL 5142 - ~few x 10^4 years old

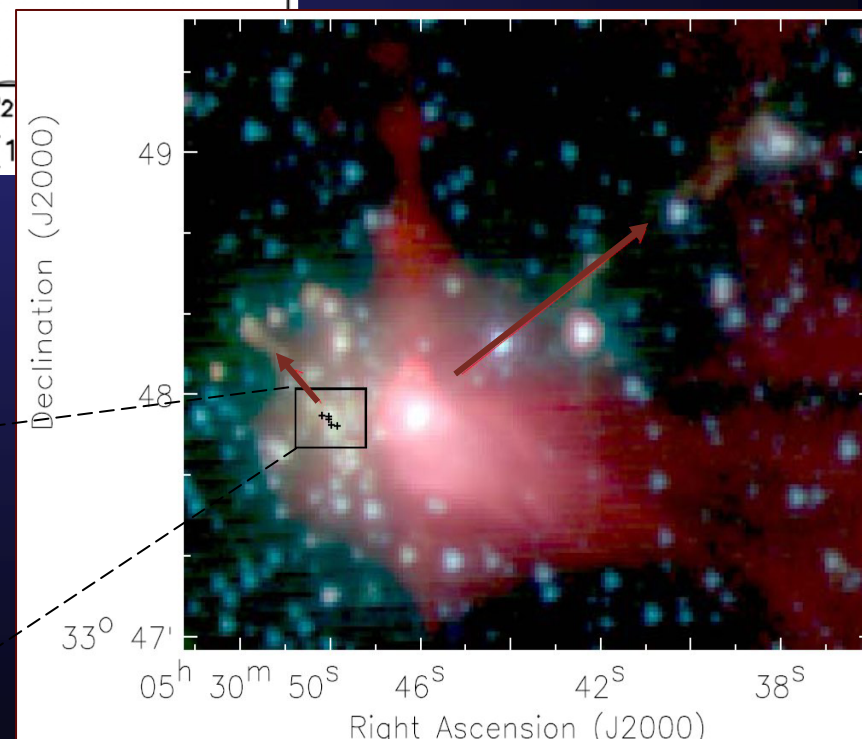


Early B protostar - No obvious UC HII region (not on ZAMS yet). Still accreting & producing outflow.

Hunter et al. (1999): HCO^+, SiO, young outflow. Spectral type unknown but mass of molecular cores suggests the formation of early B stars.

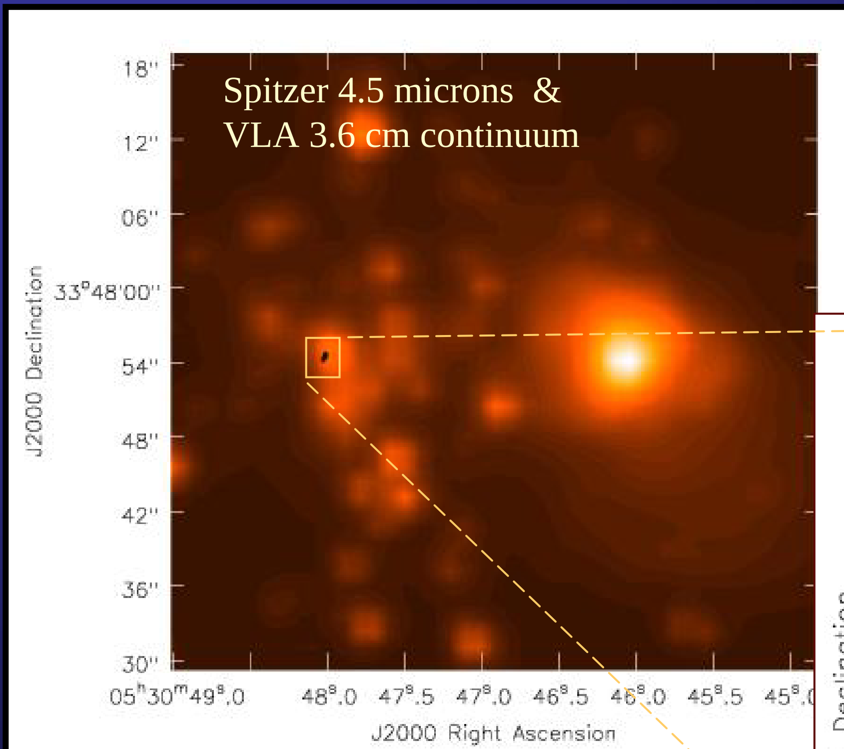
Spitzer (Qiu et al. 2007): shocked gas (green) beyond CO flow suggestive of collimated jets.



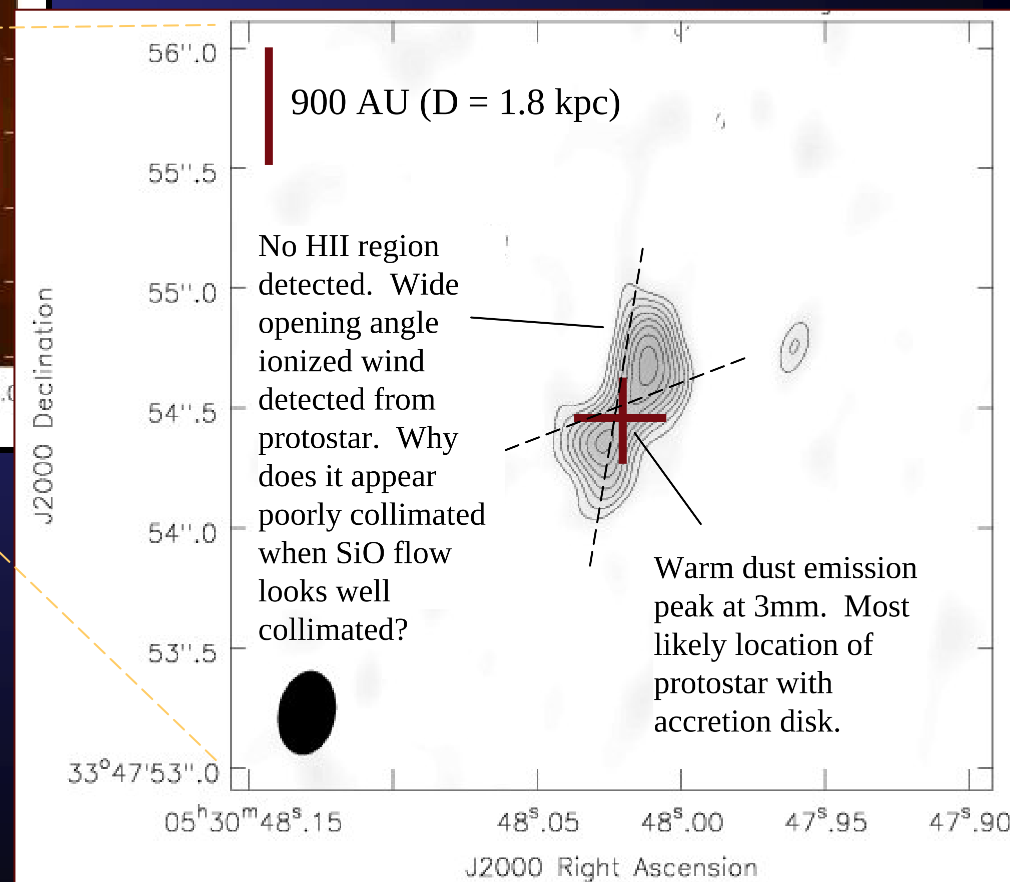


AFGL 5142

UC HII region not yet formed.
Wide-angle ionized wind detected



VLA observations: 3.6 cm continuum: A+B+C configurations with multi-scale clean deconvolution.

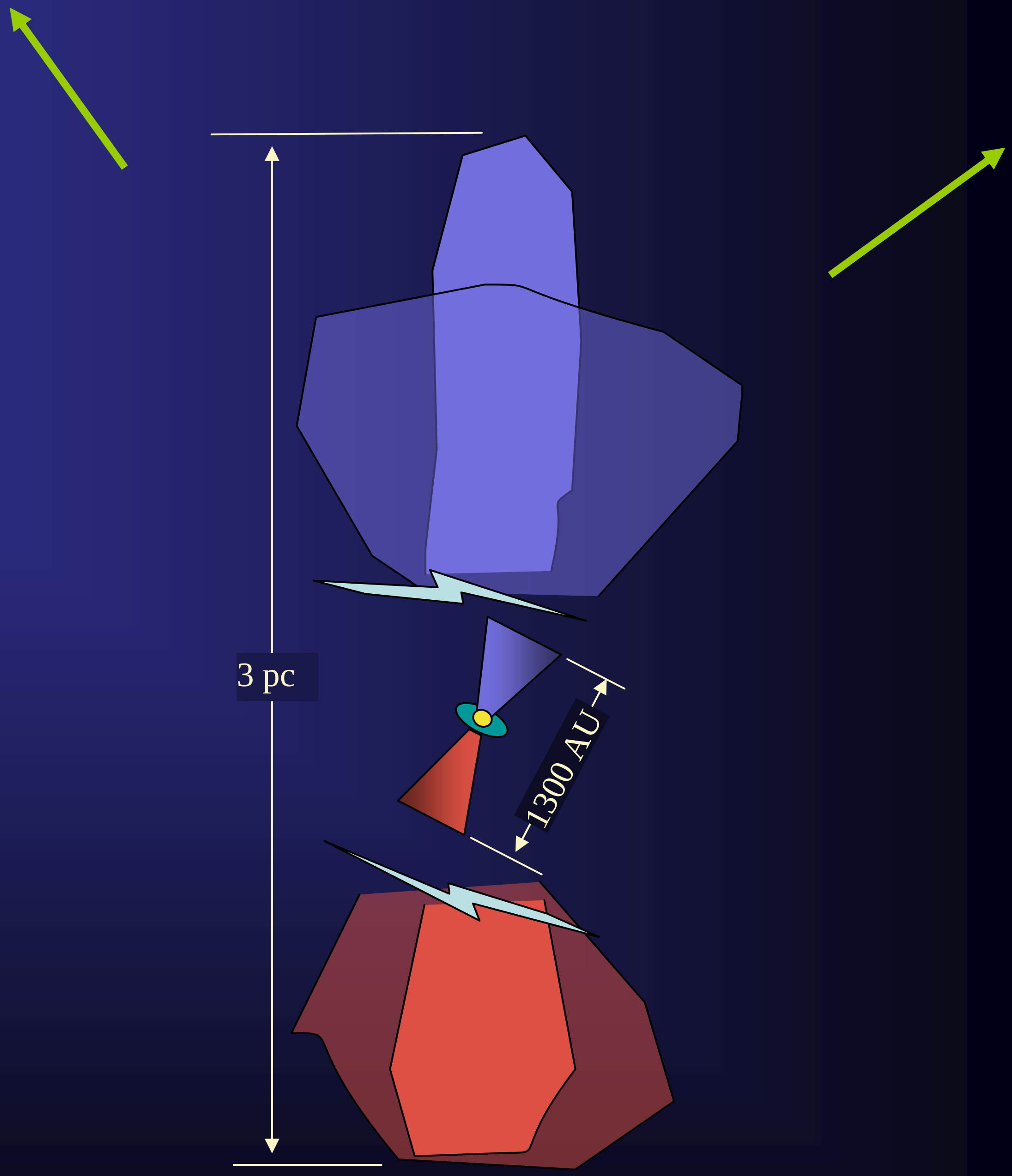


Resolution= 0.25”x0.3”
RMS = 25 microJy/bm,
Peak = 0.26 mJy/bm
Contours = -3,3,4,5,6,7,8,9 σ
Grey scale = 1σ to peak

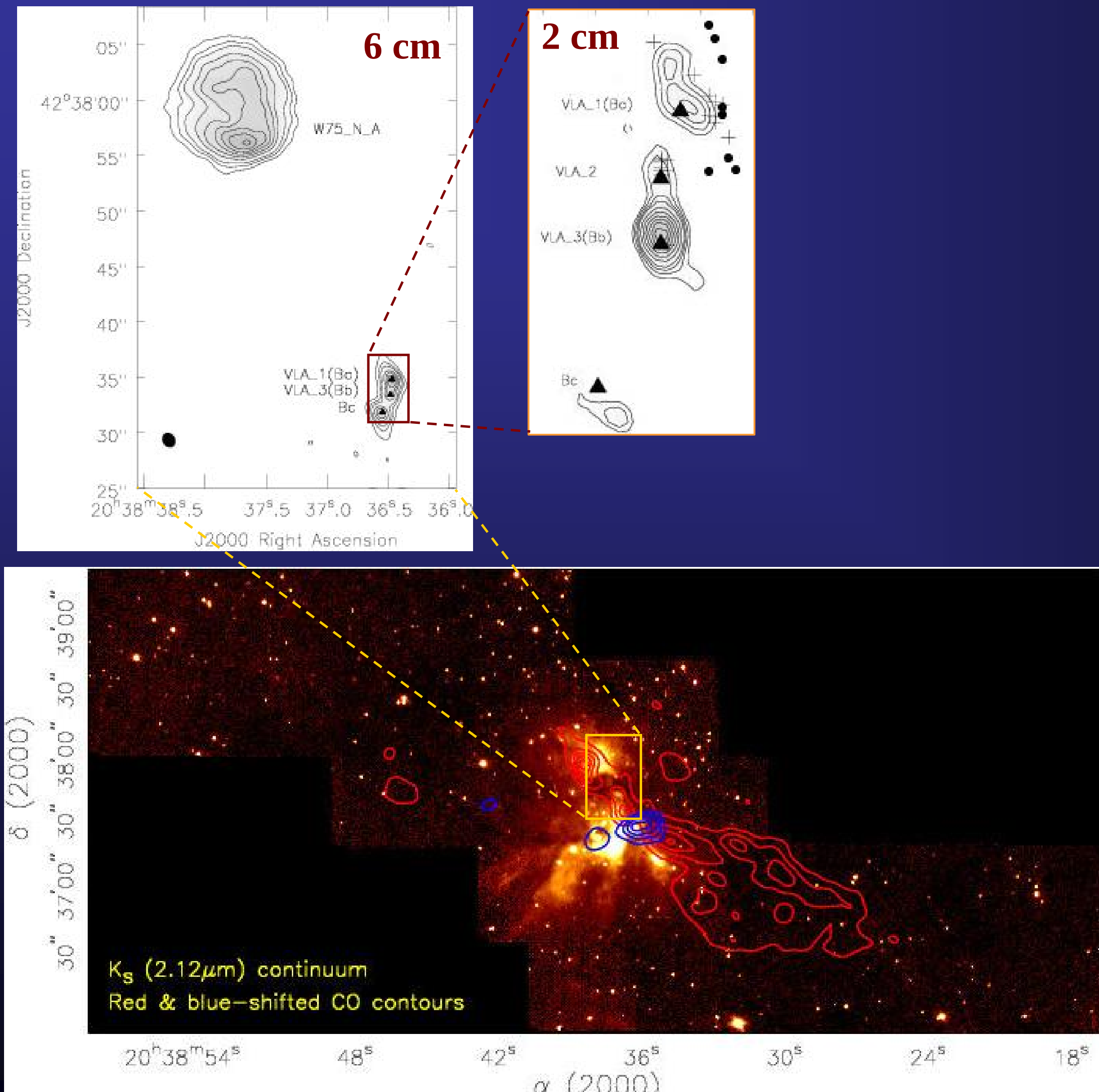
AFGL 5142

T_{dyn} ~ few x 10^4 years

Not So Simple…



W75 N early B, ~ 10^5 years old



W75 N B Star Cluster

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

Combined outflows:

L_{bol} ~ $4 \times 10^{4} L_{sun}$ *(combined)*

T_{dyn} ~ 2×10^{5} *yrs*

$M_{2.6mm}$ ~ $340\ M_{sun}$

M_f ~ $165\ M_{sun}$

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

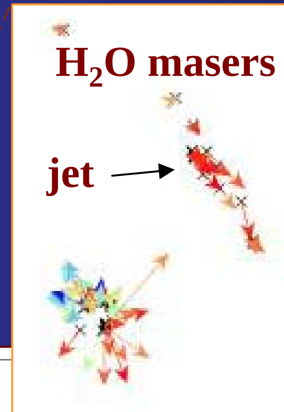
$\dot{P}_f$ ~ $2 \times 10^{-2}\ M_{sun}\ km\ s^{-1}\ yr^{-1}$

B0.5 – B2 ZAMS stars

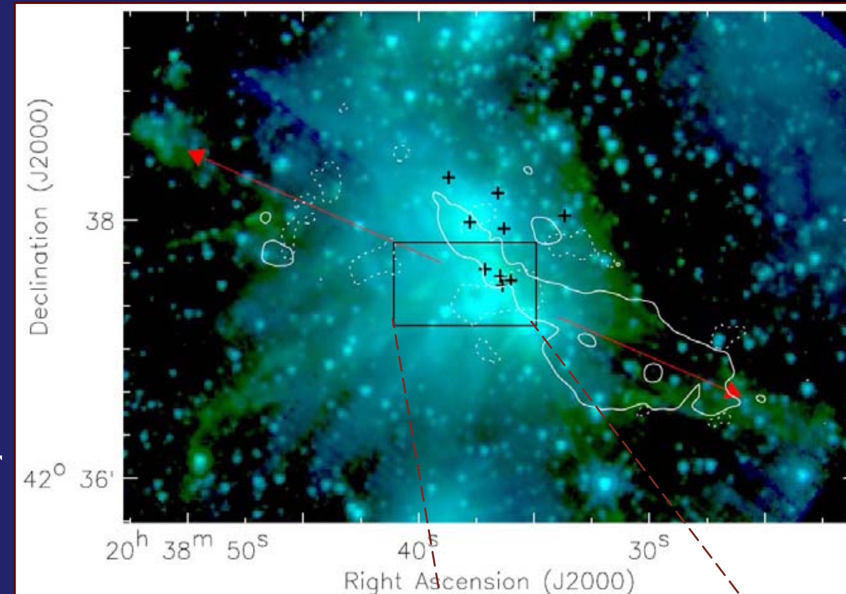
VLA 2: Wide-angle outflow from B2 ZAMS star with UC HII region.

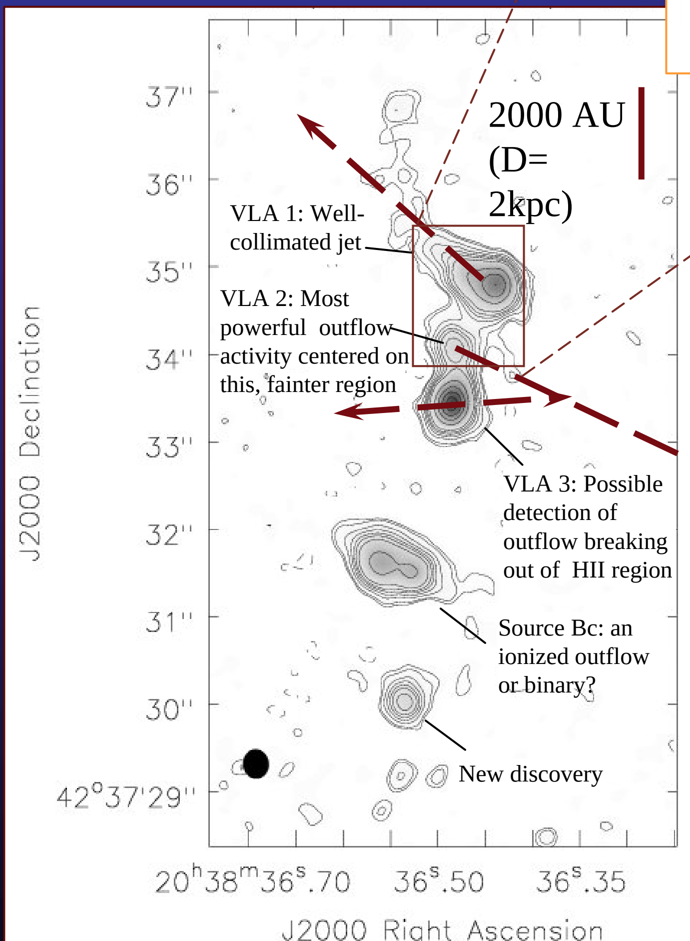
VLA 1: Jet – lower luminosity? Or is it younger/older? (Torrelles et al. 2003)

W75 N

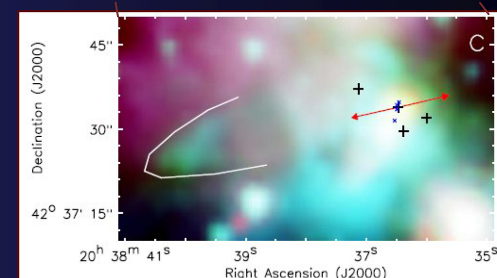


VLBA H_2O maser proper motions → Wide-angle flow
Torrelles et al (2003)





Qiu et al. 2007 - Spitzer shocked gas (green) beyond CO flow suggestive of remnant, collimated jet.

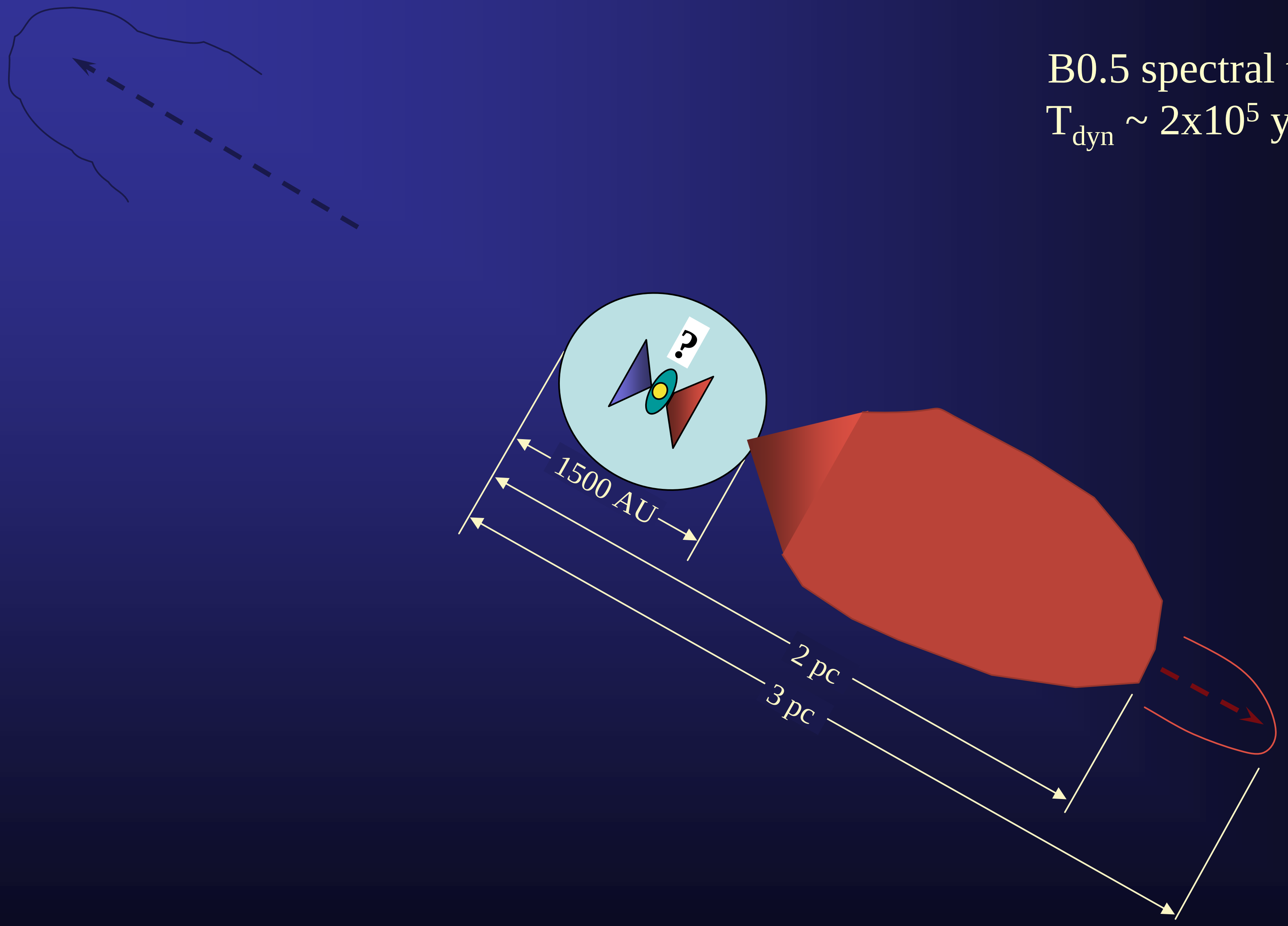


VLA observations: 3.6 cm continuum: A+B+C configurations with multi-scale clean deconvolution.

Resolution= 0.3", Grey scale = 1σ to peak
RMS = 26 microJy/bm, Peak = 2.9 mJy/bm
Contours = -3,2,3,6,9,12,15,20,40,60,80,100 σ

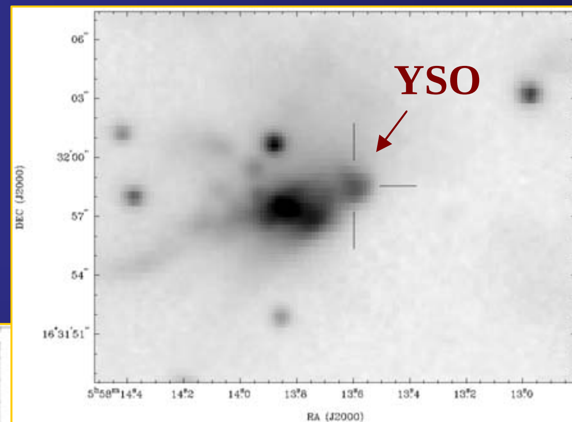
W75 N - VLA 2

B0.5 spectral type
$T_{dyn} \sim 2x10^5$ years

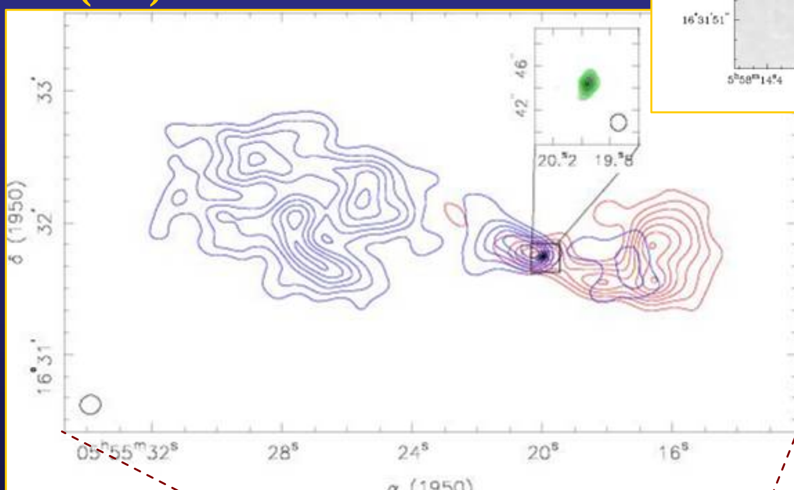


G192.16: B2 ZAMS ~ few x 10^5 years old

K-band



CO(1-0)



G192.16-3.82

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

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

$T_{dyn} \sim 1.7 \times 10^{5}$ yrs

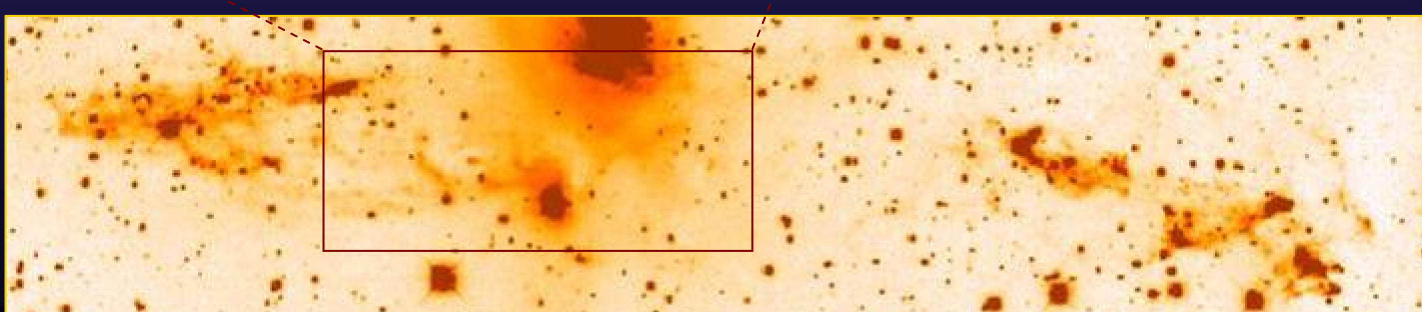
$M_{2.6mm} \sim 10\ M_{sun}$

$M_f \sim 95.3\ M_{sun}$

$\dot{M}_f \sim 5.6 \times 10^{-4}\ M_{sun}\ yr^{-1}$

$P_f \sim 594\ M_{sun}\ km\ s^{-1}$

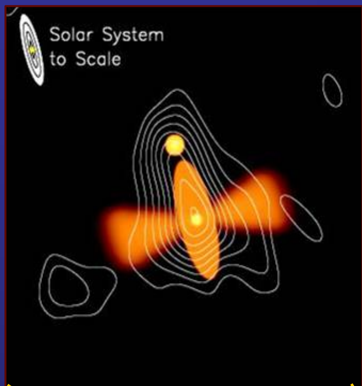
B2 ZAMS star with UC HII region
50^o-90^o-45^o opening angle outflow
Collimation consistent with wind-blown bubble
Evidence for 100AU accretion disk, 1000AU rotating torus



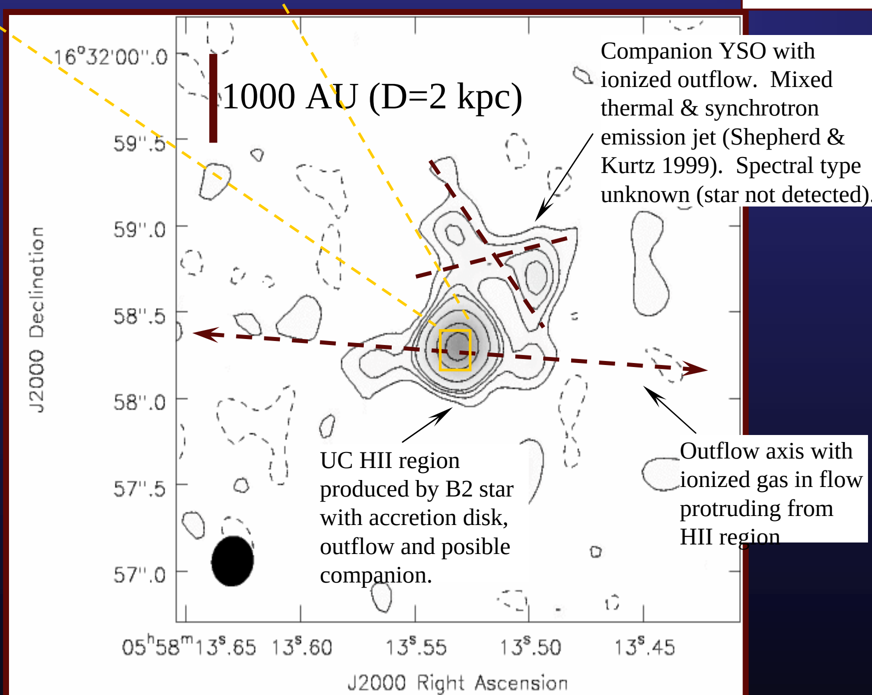
NH_3 core not graviatationally bound – near end of accretion phase

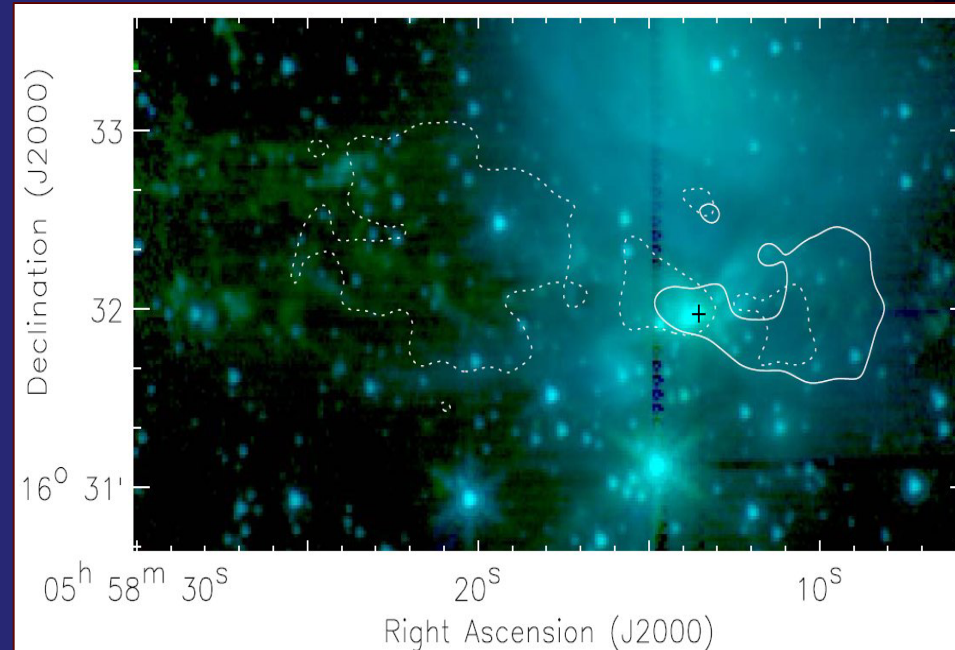
[SII]

G192.16



7 mm continuum (~100 AU res) & model. Ionized outflow opening angle ~ 40±10°





Qiu et al. (in prep) - Spitzer shocked gas (green) - *still* no sign of a jet (consistent with Davis et al. 1999)

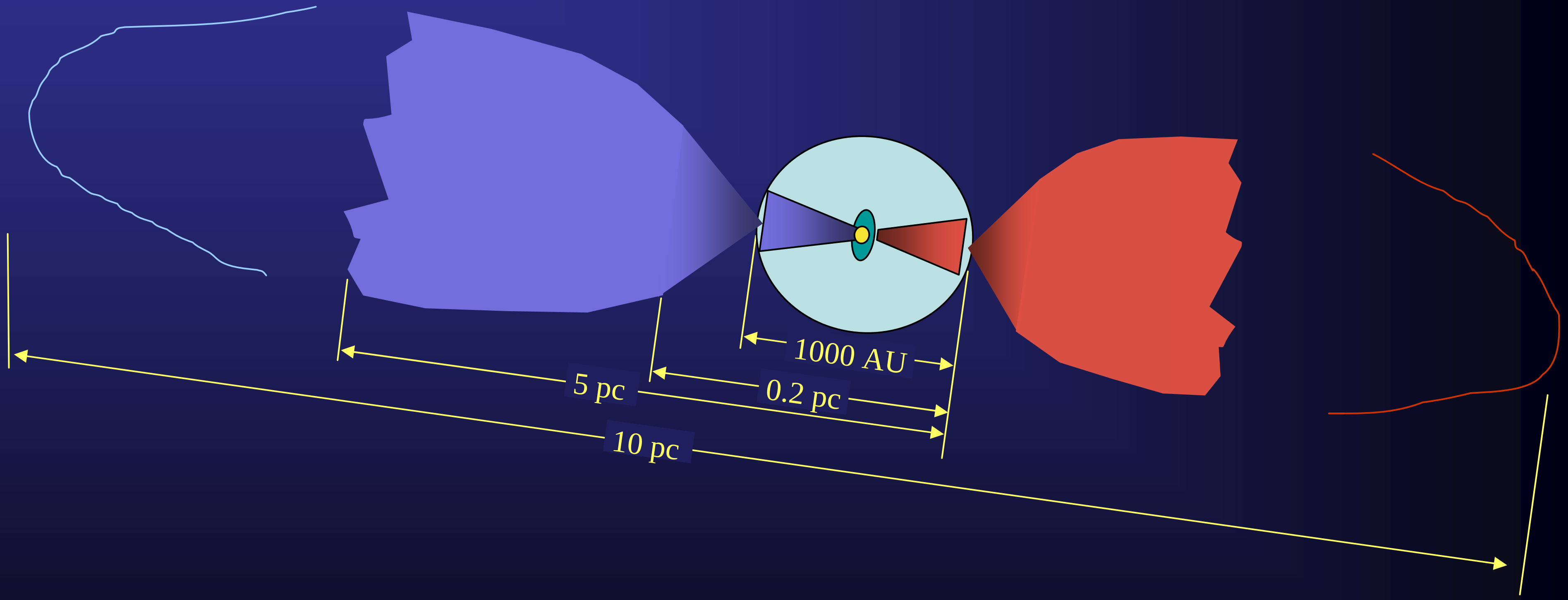
CO opening angle = 90°; narrows to ~50°

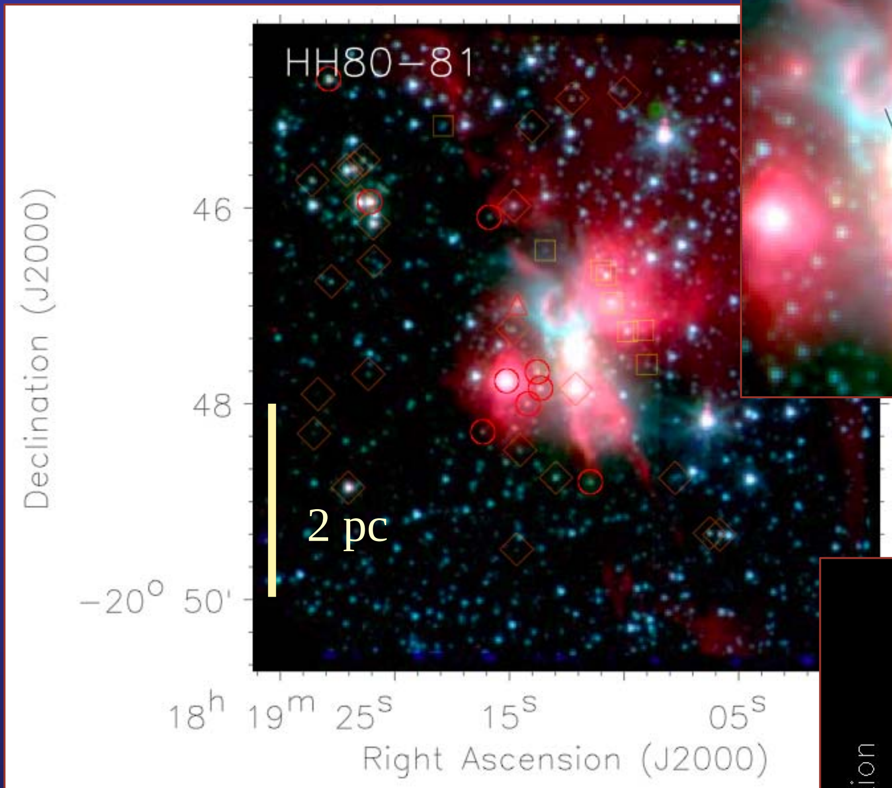
Resolution= 0.29"x 0.26"
RMS = 15 microJy/bm
Peak = 0.82 mJy/bm
Contours = -3,3,4,5,6,8,16,32,45 σ
Grey scale = 1σ to peak

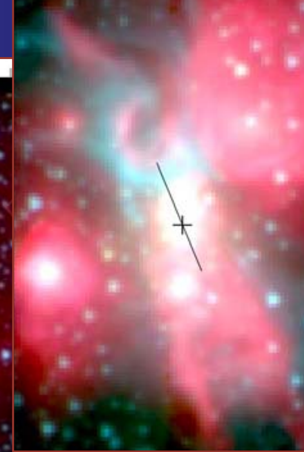
G192.19

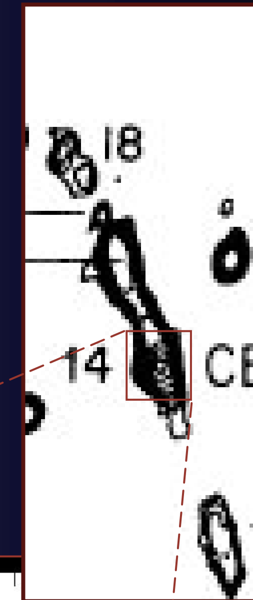
Tdyn ~ 2 x 10^5 years

Proposal:
HII region expands, creating molecular shell. Shell acts like a nozzle as outflow breaks through? Flow expands as a wind-blown bubble.

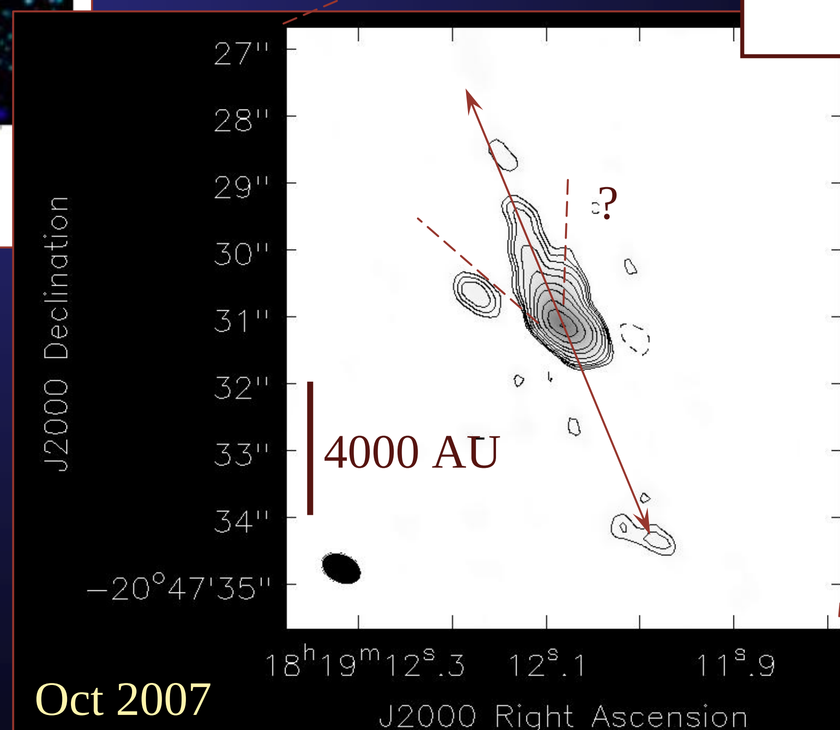








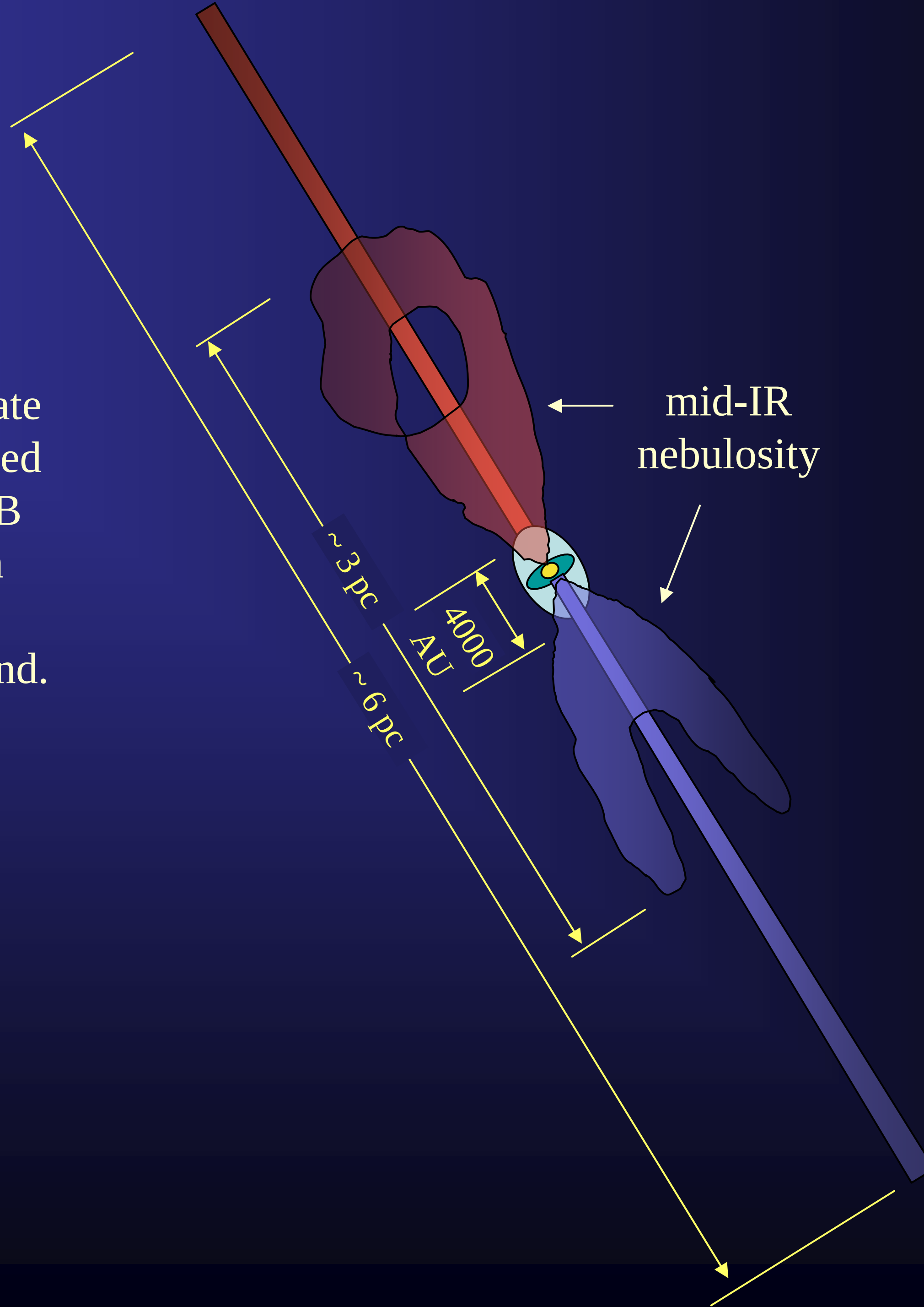
HH80-81 Spitzer
&
VLA continuum



HH 80-81

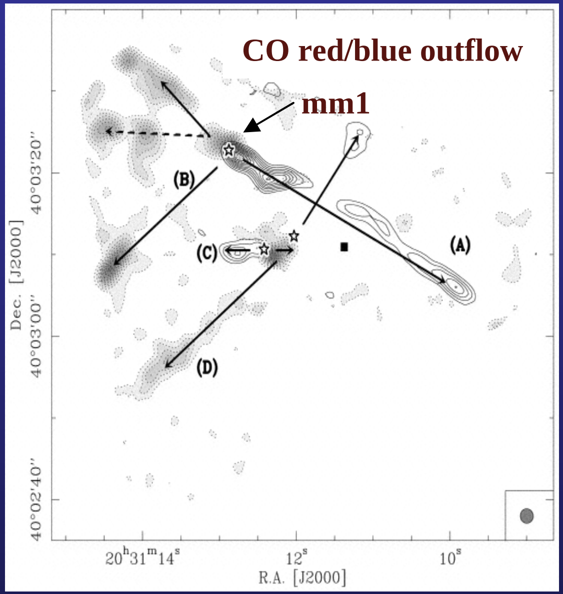
$T_{dyn} \sim 10^6$ years

Presence of collimated jet at late stage inconsistent with proposed outflow evolution of an early B star. Ionized outflow has both well-collimated jet and may have powerful wider angle wind.



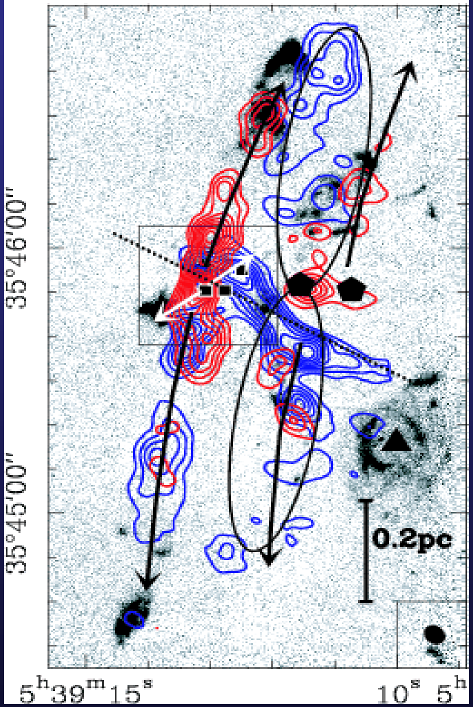
Early B star outflows still being imaged:

IRAS 20293



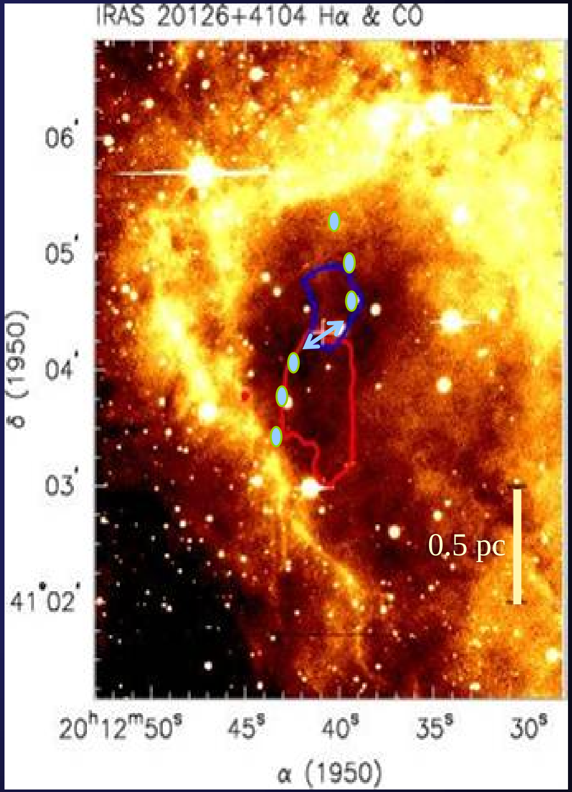
~ few x 10^3 years

IRAS 05358 - CO(1-0)



3-4 x 10^4 years

IRAS 20126 - Hα & CO(1-0)

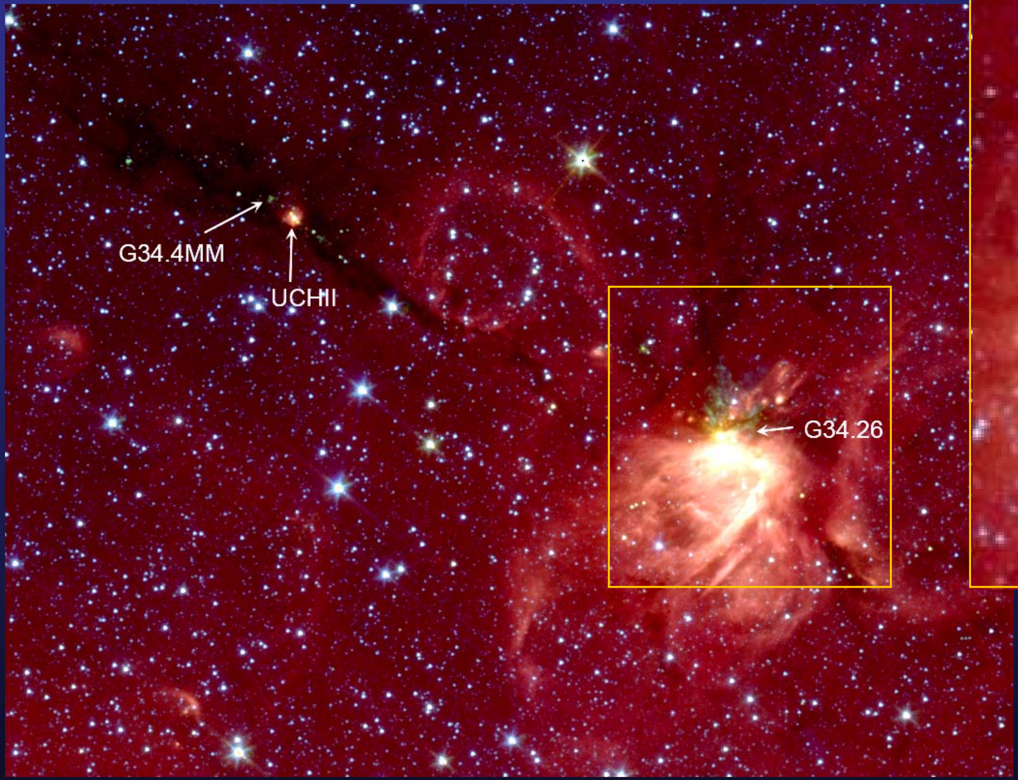


6 x 10^4 years

O star perspective

G34.26 & G34.4 Star Cluster

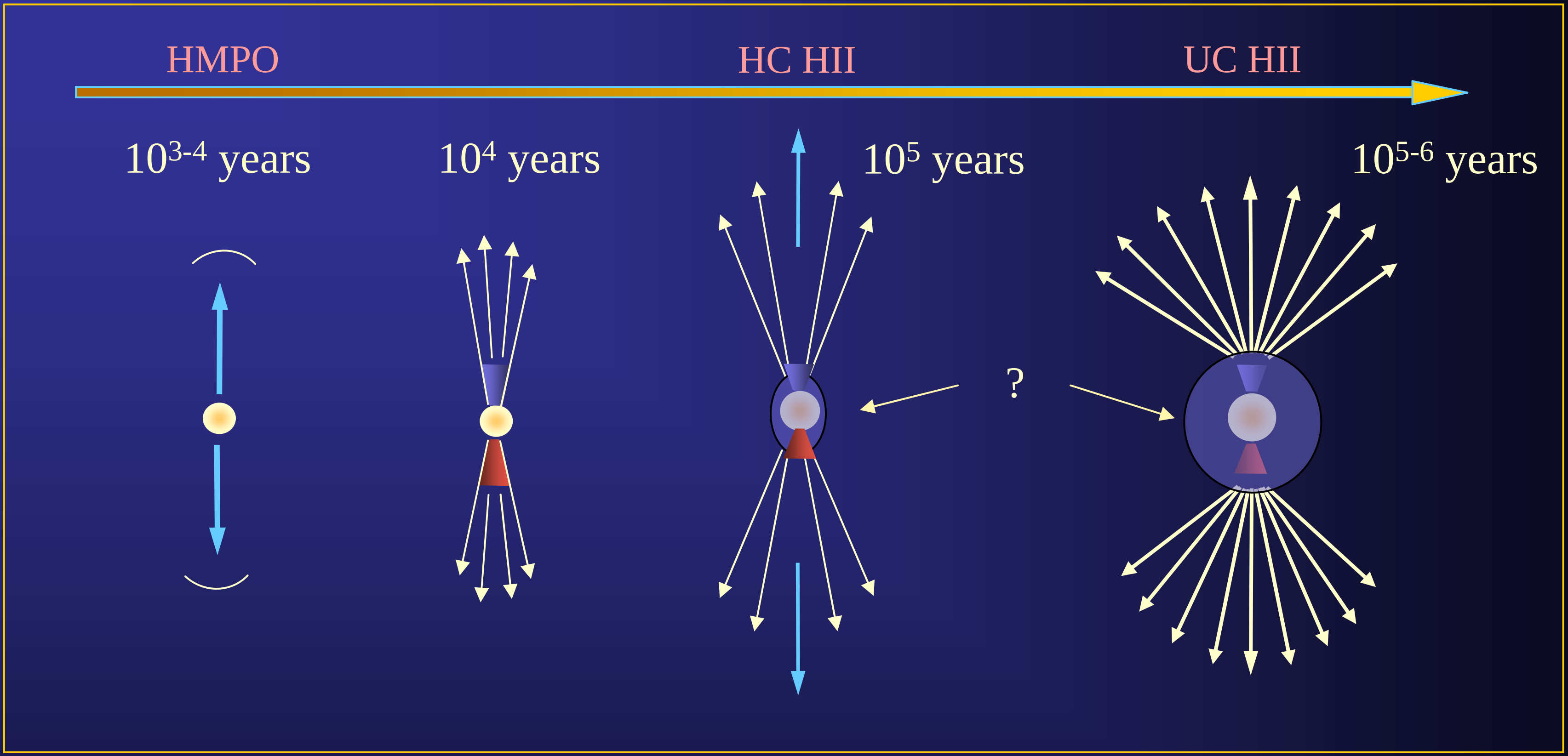
Churchwell et al. (2004),
Shepherd et al. (2007 ApJ, 1 Nov)



Green → shocks – similar to H_2 'fingers' in Orion.

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

Tenative Conclusions - early B star outflows



IRAS 19410
MM1

Transition
phase?

AFGL 5142
IRAS 20126

W75 N
VLA 2

/ ?

Conflicting examples:
HH 80-81 (~10^{6} years, jet)
G192.16 (≥ few x 10^{5} years, no jet)

Model constraints?

Age	**Outflow opening angle**
10^2 - 10^4 years	1°- few degree opening angle jet (scaled up low-mass flow)
Few x 10^4 years	20-30° “jet”
10^5 - 10^6 years	40-50° wind, widens to > 90° outside of UCHII region? Wind opening angle within 50 AU of star can be > 90°. Collimated jets can continue (one found).

Outflow Momentum/$M_\star$

For 2 sources we might know the momentum and stellar mass sufficiently to estimate $P_{flow}/M_\star$

- G192.16 - outflow has broken out of cloud, ➔ P = lower limit

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

  HII region ➔ B2 ZAMS ~ 8 $M_\odot$

  $P_f \sim 594\ M_{sun}\ km\ s^{-1}$

  $P_{flow}/M_\star \gtrsim 75$

- IRAS 20126 - outflow just reaching edge of cloud but high precession ➔ inclination correction not very accurate; ionized gas severely contaminated by jet emission

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

  HII region ➔ B0.5 ZAMS ~ 10 $M_\odot$

  $P_f \sim 403\ M_\odot\ km\ s^{-1}$

  $P_{flow}/M_\star \sim 40$