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Ionised and Molecular Gas Dynamics in High-Mass Star Forming Regions

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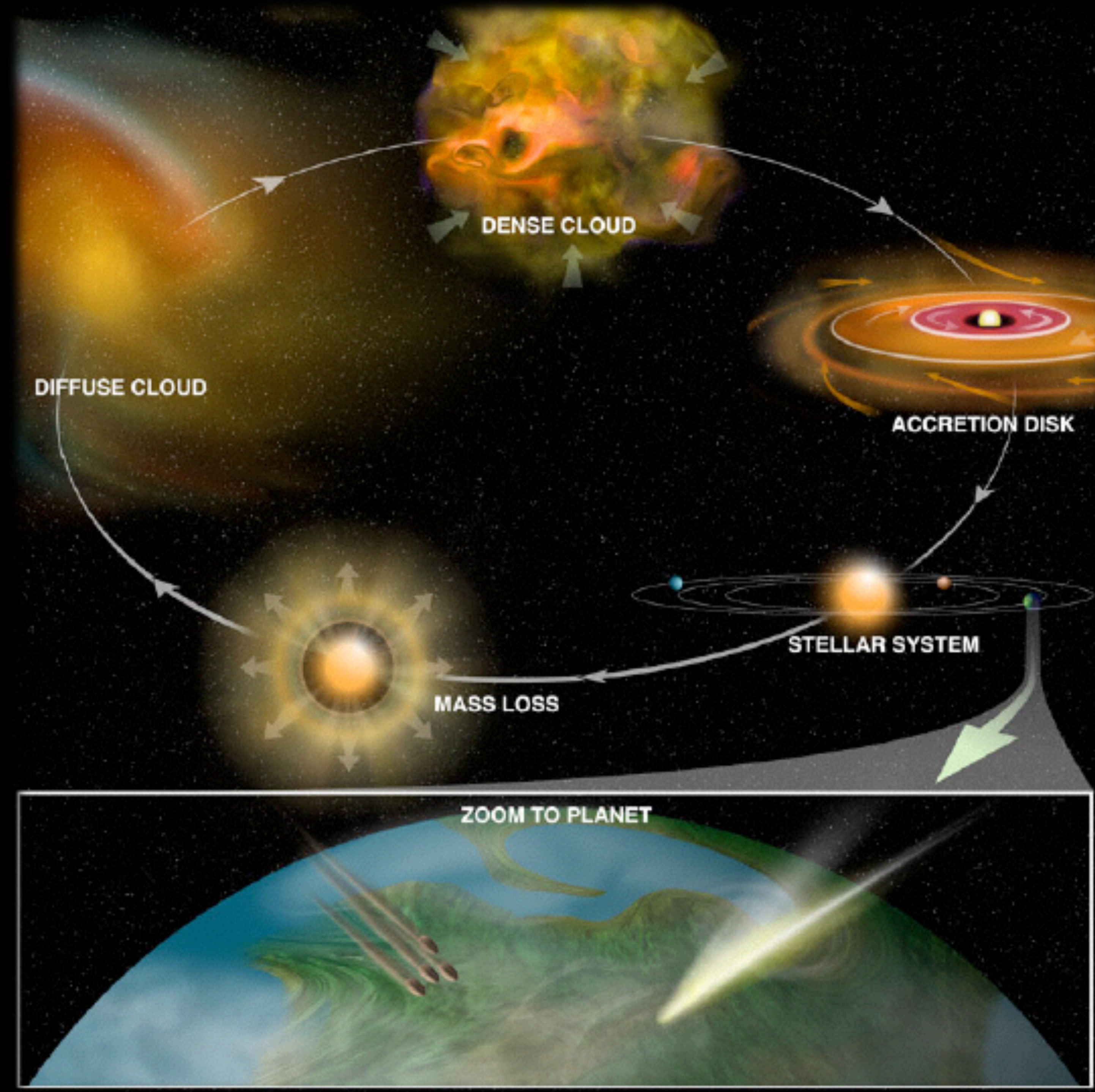
11 September, 2013

Outline

- (High-Mass) Star Formation
  - How do they get so massive?
- Gas Dynamics
  - Specifically, what can we get from the ionised gas
- A Few Case Studies
  - Rotation, Infall & Outflow
  - Future prospects

Star Formation

- Over-density in cloud
- Accretion through disk
  - Angular momentum builds up
- Powerful outflow
- Dispersal of envelope
- Stellar System emerges

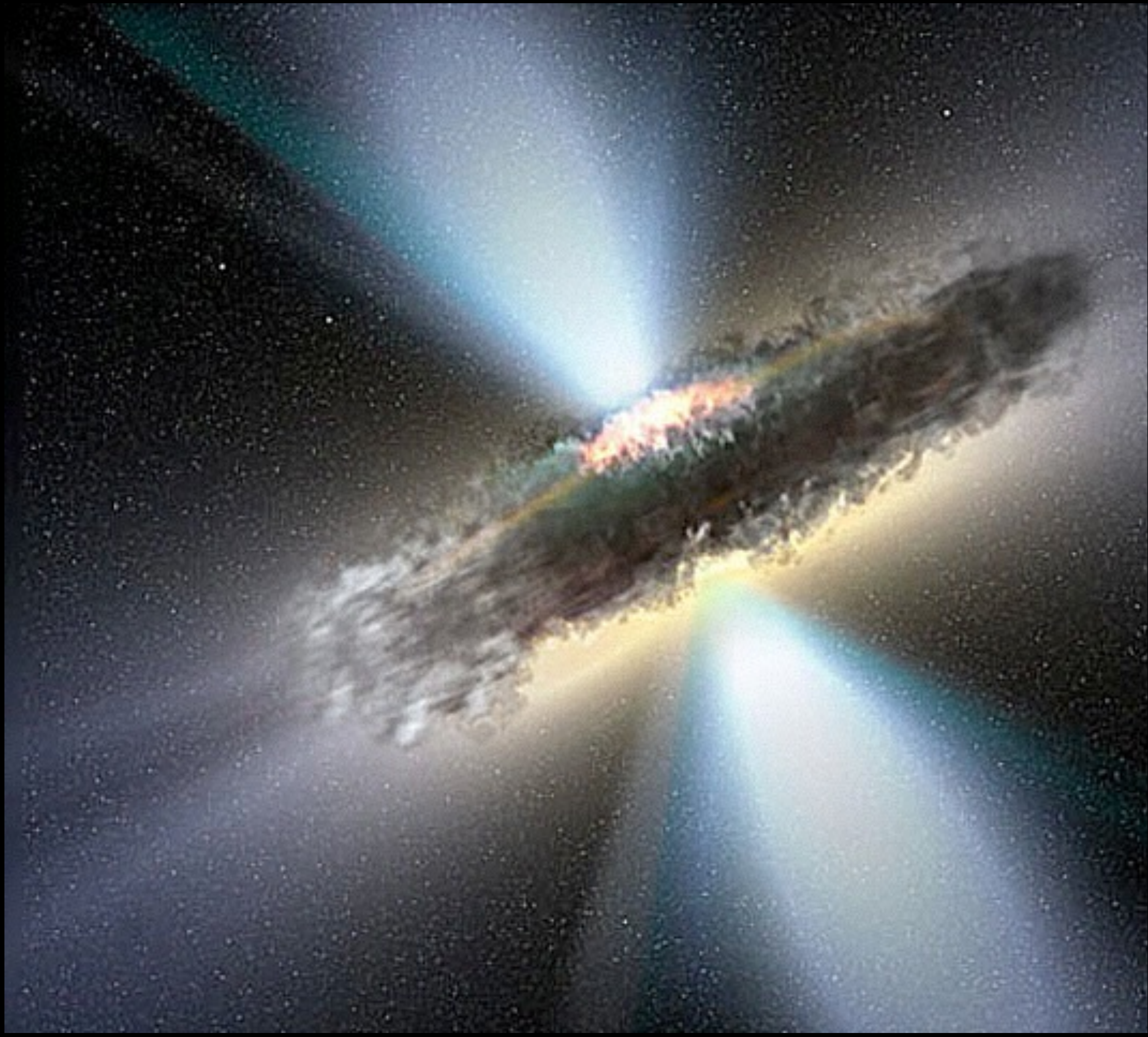


Bill Saxton, NRAO

Star Formation

For embedded sources,

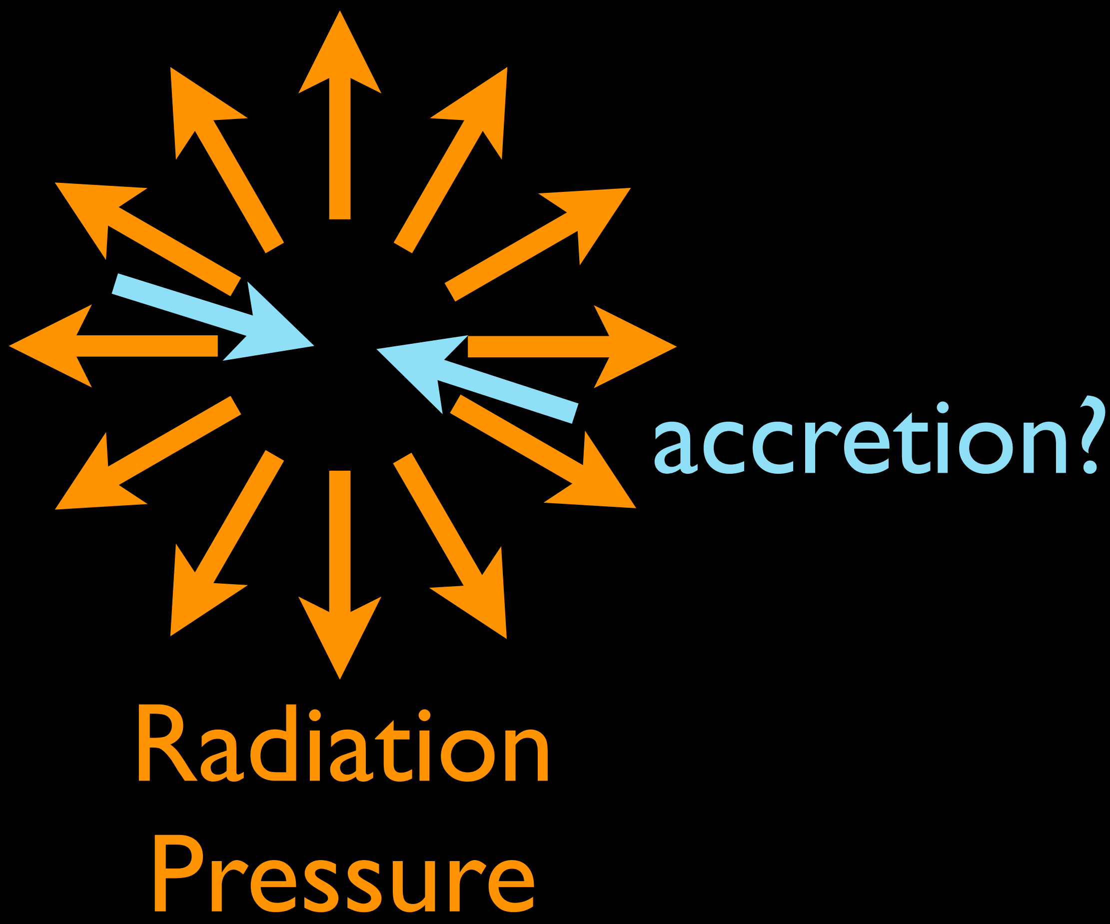
We don't see accretion itself, but use proxies to infer the presence of accretion



Infall onto a 'disc'
Rotation of the 'disc'
Outflow from the 'disc'

High Masses

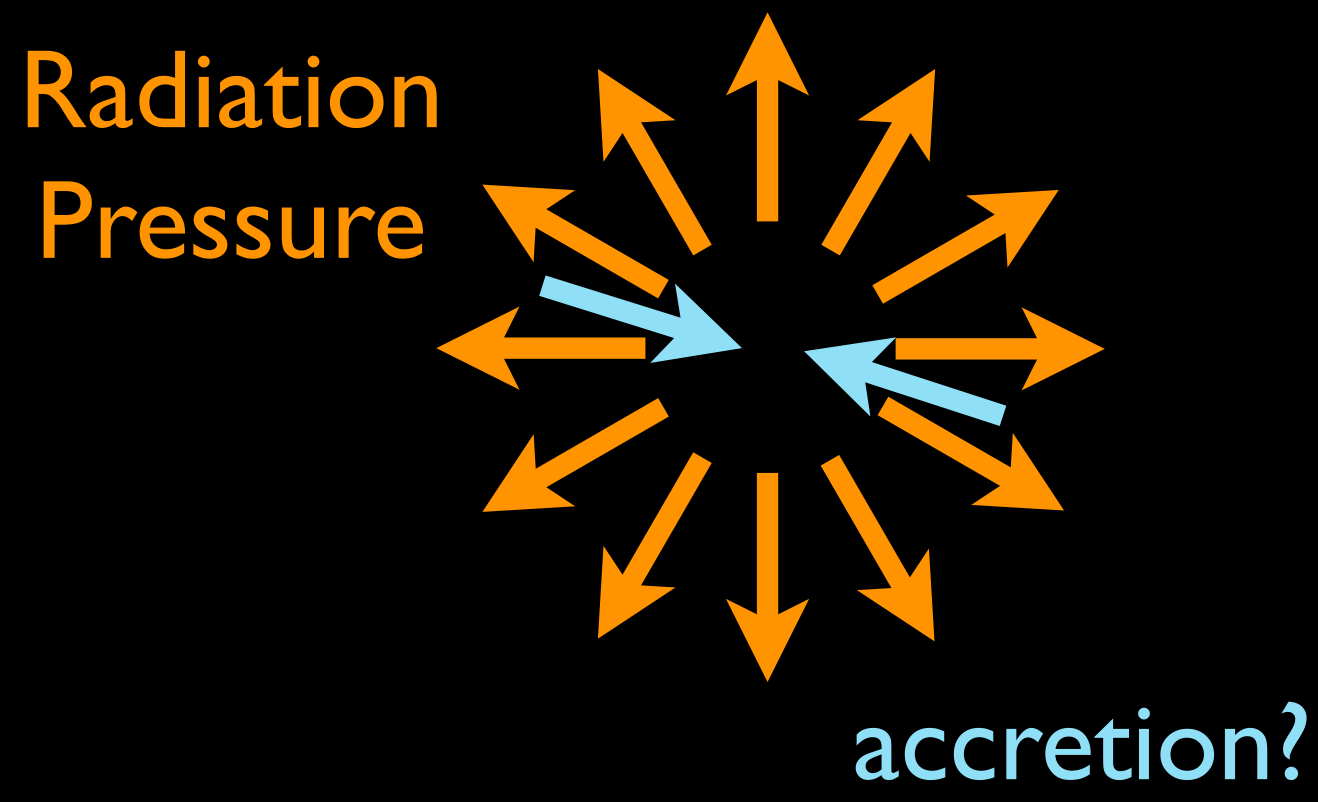
- Is it just scaled up?
  - Radiation pressure from the central star causes problems
- What happens above 8 $M_\odot$?
  - When does an HII region form?
  - How does accretion continue?



High mass stars are a prime driver of galactic evolution, yet we don't know how they get to be so massive

Radiation Pressure

Above ~ 8 $M_{\odot}$, the protostar continues to accrete up the main sequence



It was long believed that.....

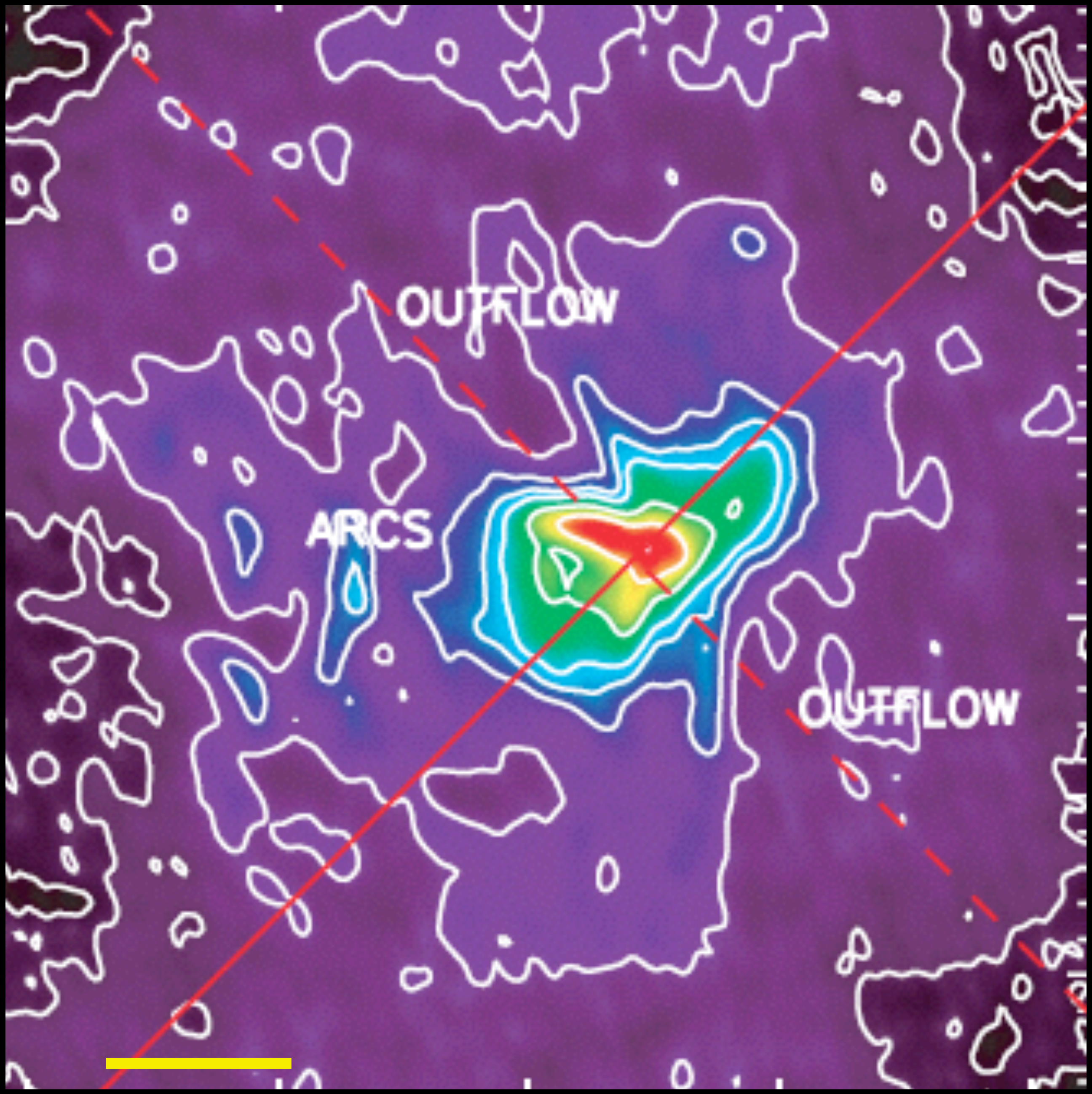
- Radiation pressure would halt accretion
    - assumes spherical symmetry

So, how do the most massive stars continue to grow?

Non-Spherical Accretion

- It's likely that accretion is non-spherical
  - RP escapes through lower density regions first
- Accretion can continue
  - if the infall momentum is high enough

1.3 cm continuum



G10.6-0.4

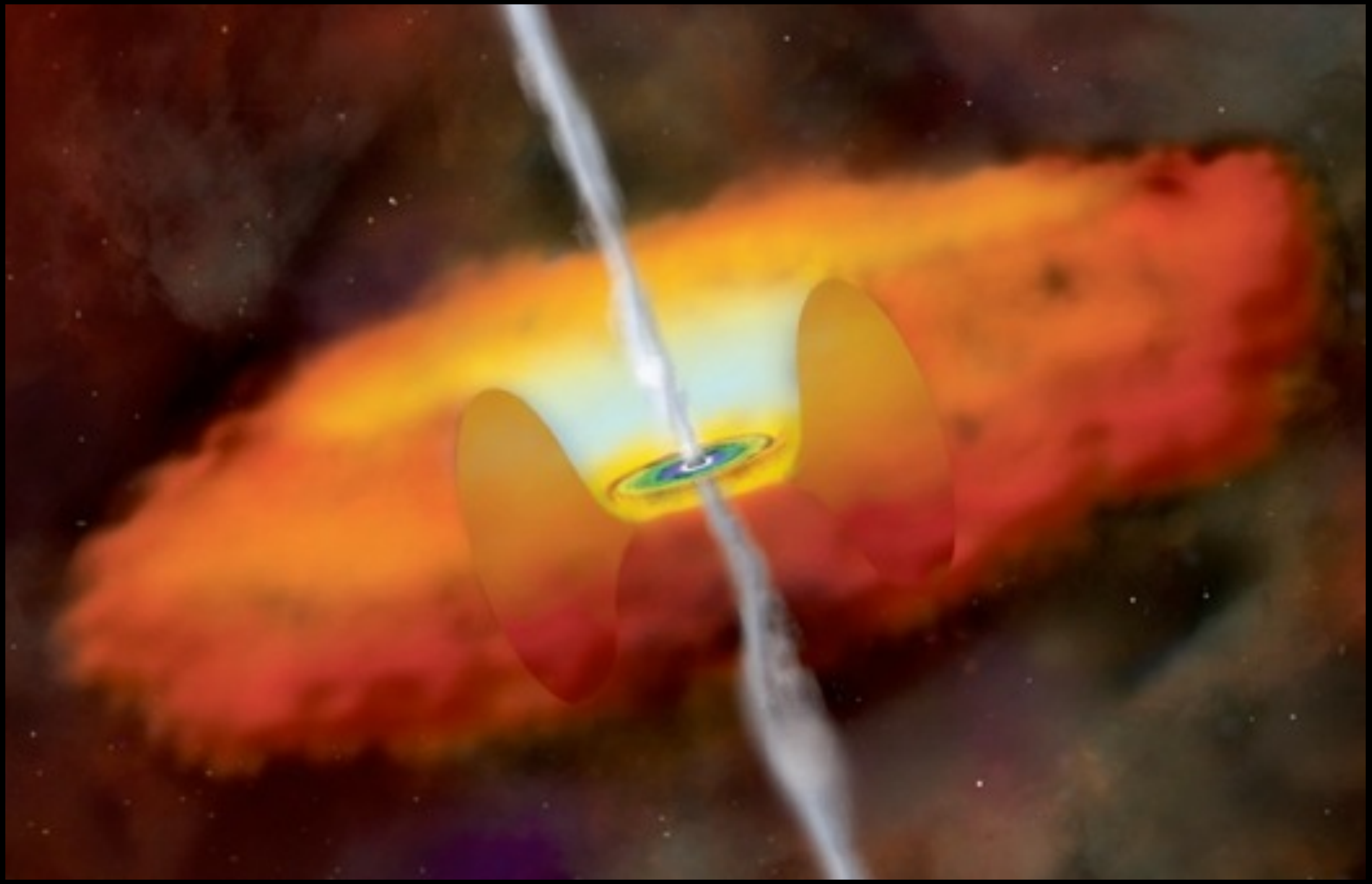
6000 AU

Keto & Wood 2006

Non-Spherical Accretion

- Accretion can be funneled through dense filaments

- An HII region has formed, but accretion continues

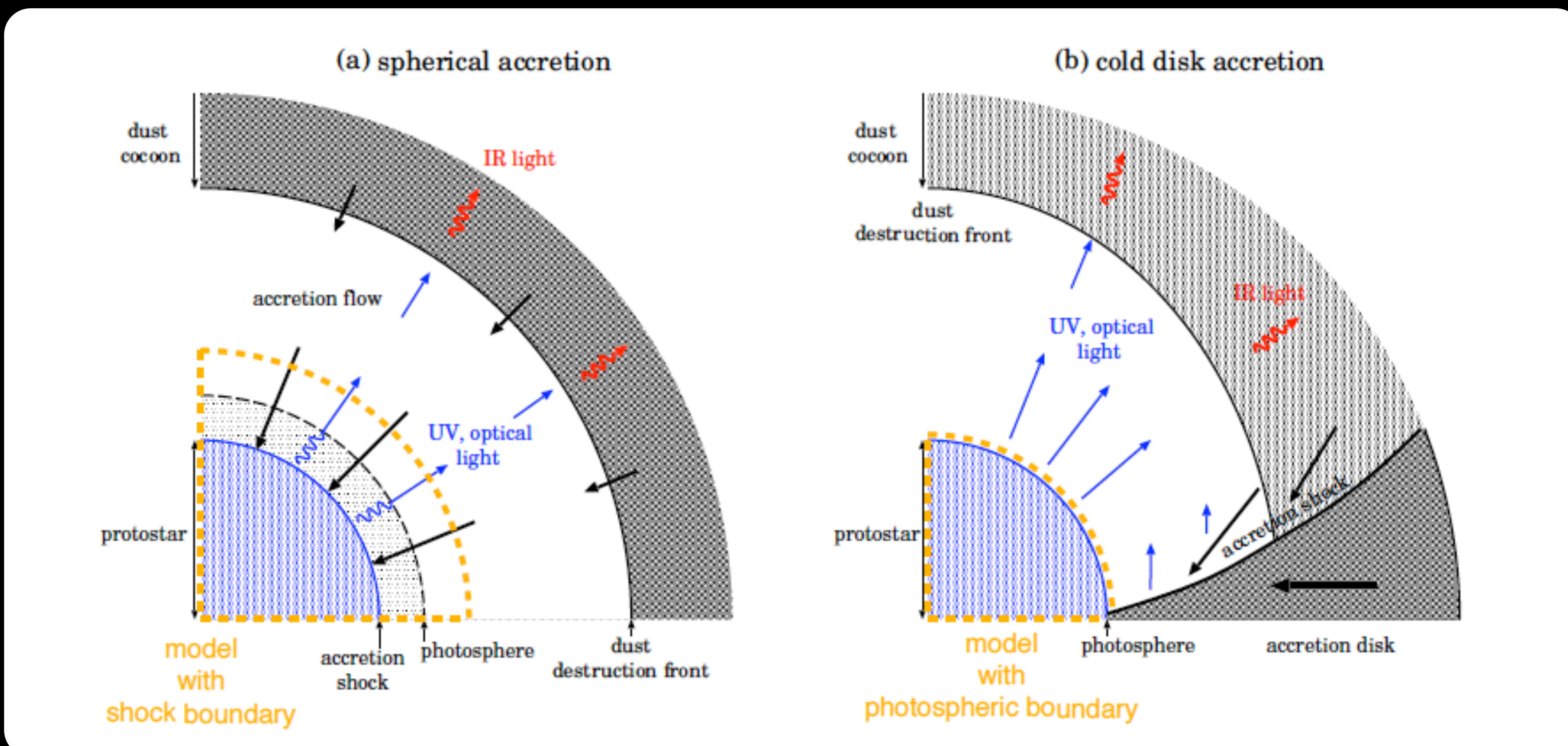


- In this case, is accretion still molecular?
    - we'll come back to this question later

NASA/CXC

Puffed up Protostars

- What happens if the infall rate onto the forming star is very high, and funnelled through a 'disc'



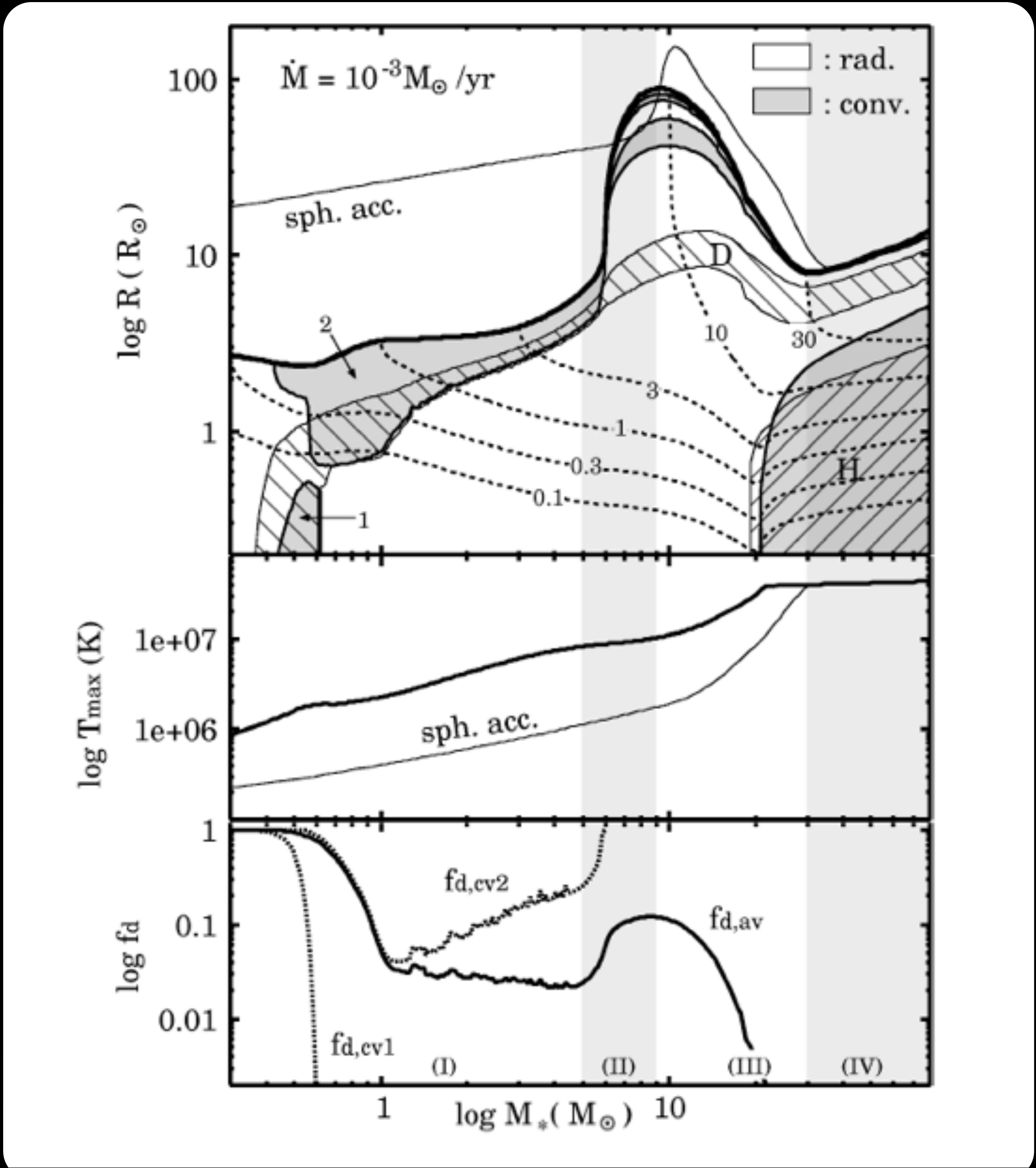
Hosokawa et al. 2010

High Accretion Rates

- With high accretion rates, and protostars that puff up, accretion can continue

Models still have trouble getting above ~ 30 M☉

What else needs to be accounted for?



Hosokawa et al. 2010

Accretion Tracers

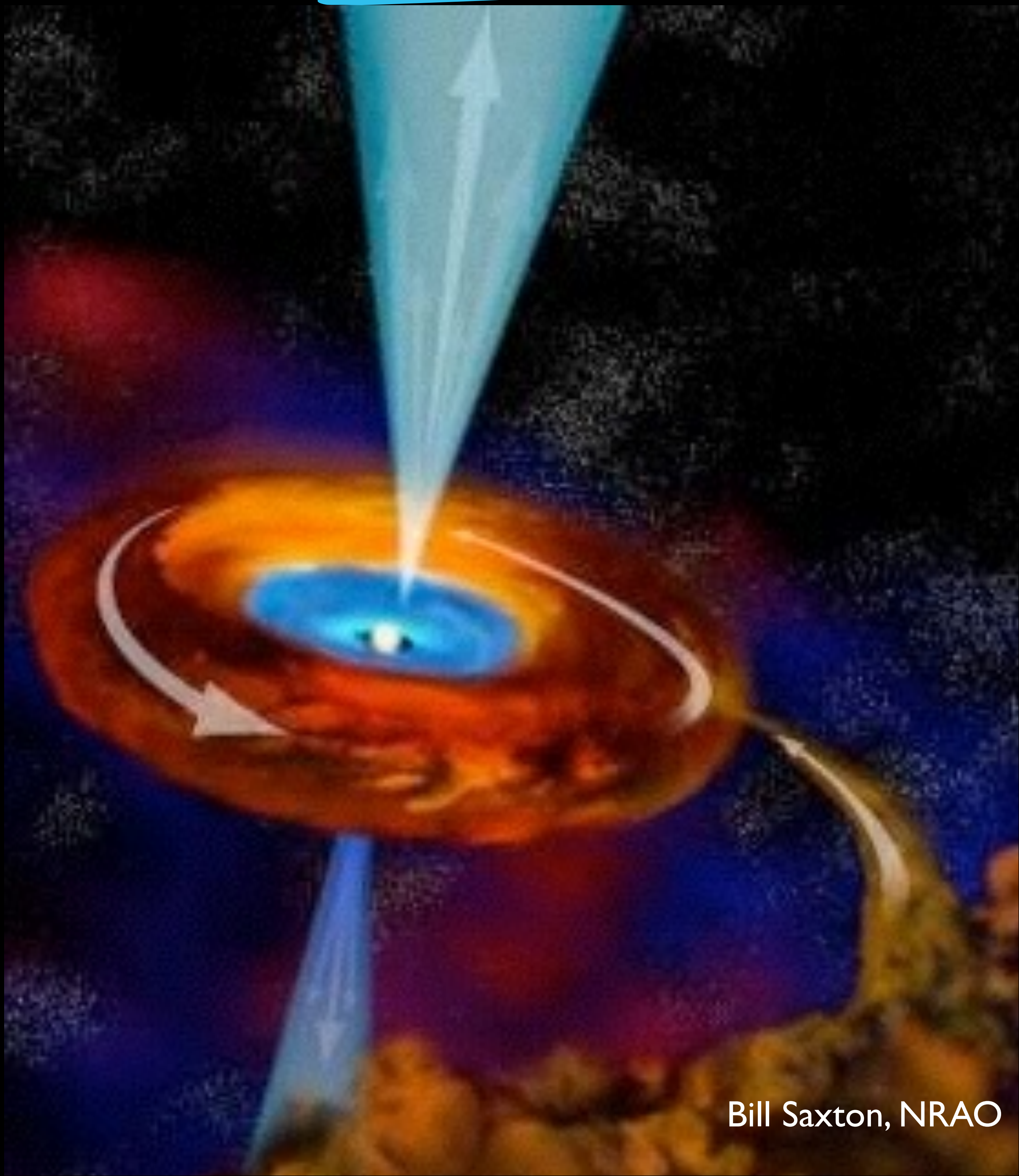
- Accretion onto the protostar is much too small to resolve

$$100R_\odot = 7 \times 10^{12}\mathrm{cm}$$

$$@6\mathrm{kpc} = 0.3\mathrm{mas}$$

- Look for larger scale dynamical tracers of accretion

Like we do in low-mass regions



Bill Saxton, NRAO

Tracing Accretion

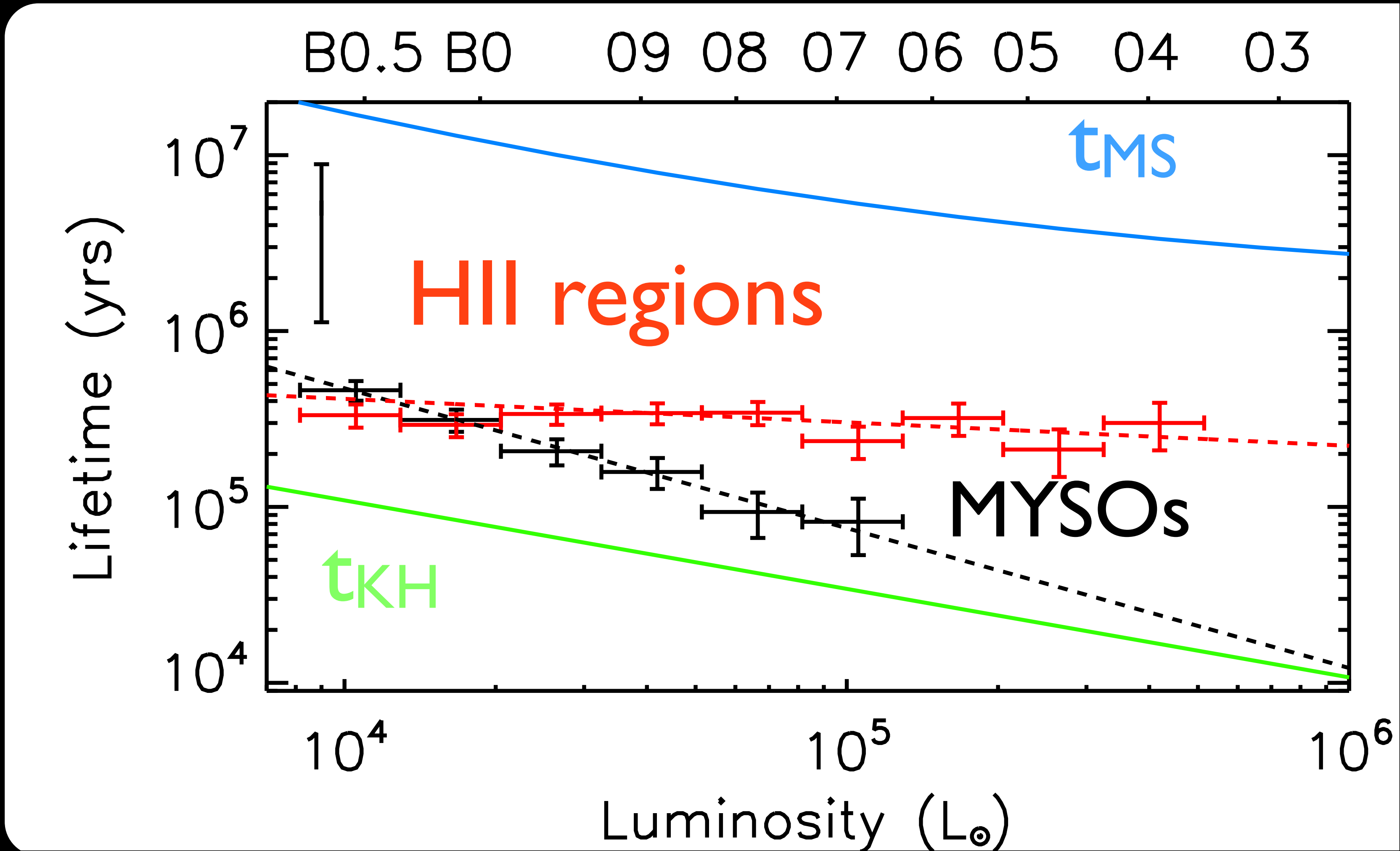
- To understand how the most massive stars form, we need to:
  - Look for the most massive star forming regions
  - Trace accretion proxies in the ionised and molecular gas

Where should we look?

- Only regions forming *the most* massive stars may be seen accreting after the formation of an HII region

$$L > 10^5 L_\odot$$

Below this, the star has gone through its main accretion phase well before forming an HII region



Davies et al. 2011 Mottram et al. 2011

What should we look for?

Outflow

- Separable Lobes on the Sky
- PV Diagrams

Infall

- Inverse P-Cygni Profiles
- PV Diagrams

Rotation

- Velocity Gradients
- PV Diagrams

How do we study gas dynamics?

Putting it all together, we get a scenario which explains the entire system...

... in both the molecular and ionised gas

Molecular Gas

- Can use chemistry to our advantage
  - Use many molecules to probe different conditions

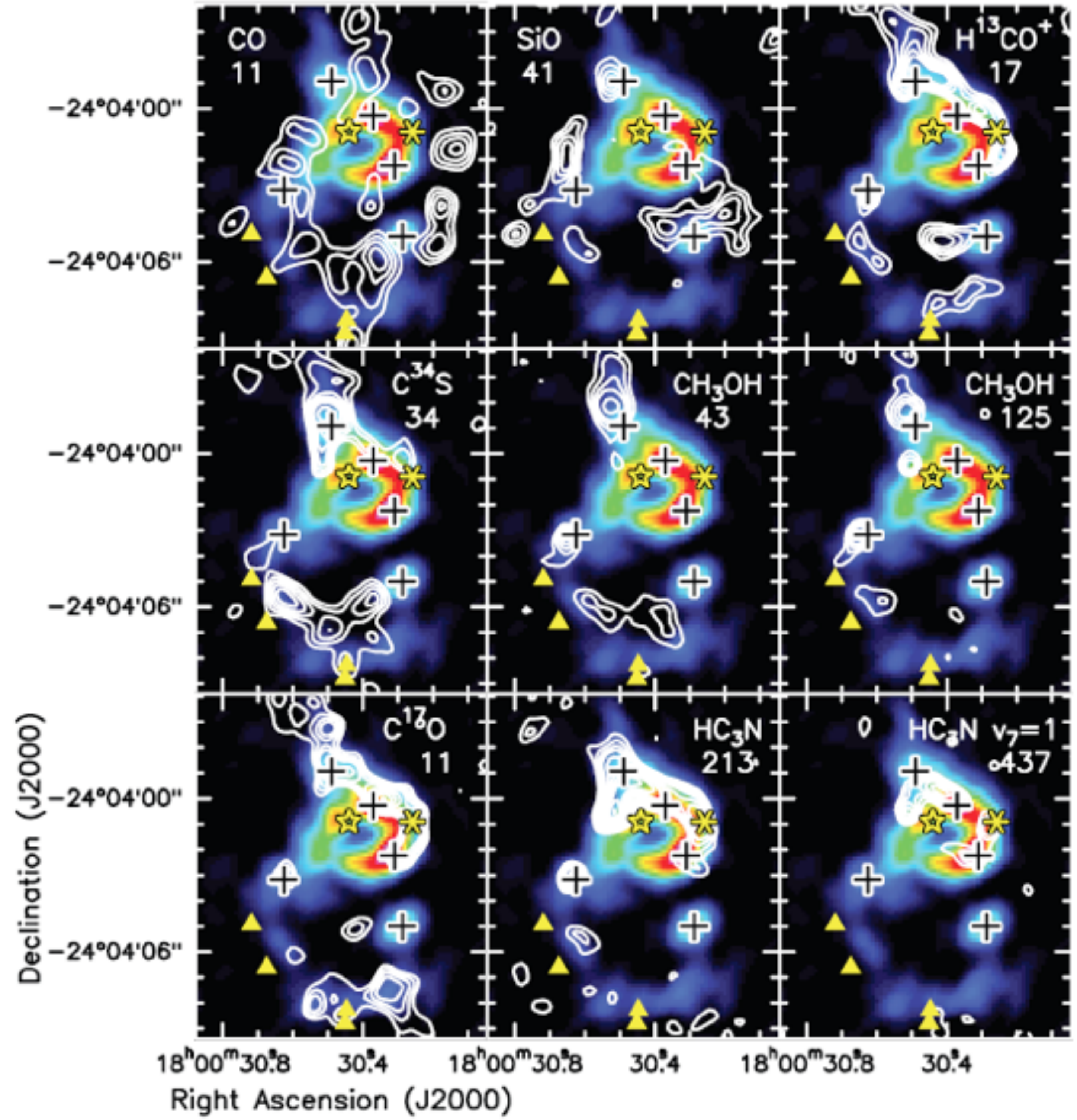
CO - bulk gas

HCO^+ - dense gas

SiO - shocked gas

CS - dense gas

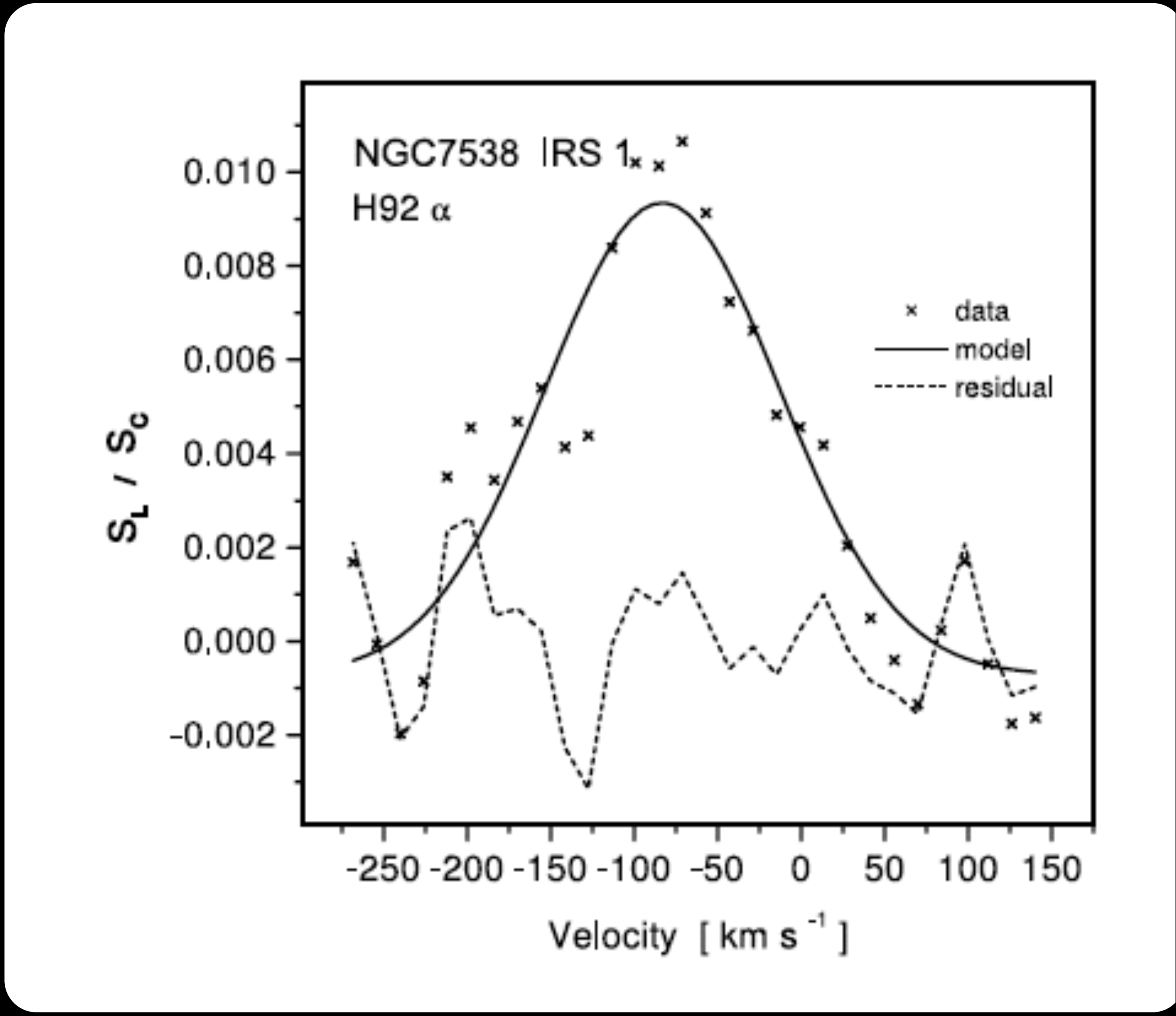
SO_2 - warm dense gas



Hunter et al. 2008

Ionised Gas

- Can use radio recombination lines to probe the ionised gas dynamics:
  - Shifts in line peak
  - must account for pressure broadening



Old VLA Correlator:
64 channels

New JVLA Correlator:
8000+ channels

Ionised Gas

- This has been problematic in the past because:
  - Could not get good spectral/spatial resolution & full line width
  - Line to continuum ratio is quite low at low frequencies

$$\frac{\Delta v^I}{\Delta v^D} = 0.142 \left(\frac{n}{100}\right)^{7.4} \left(\frac{N_e}{10^4}\right)$$

$$\frac{\int T_L dv}{Tc} \simeq 6.76 \times 10^3 \nu^{1.1} T_e^{-1.15}$$

Brockelhurst & Steaton 1972, Brown et al. 1978

Ionised Gas

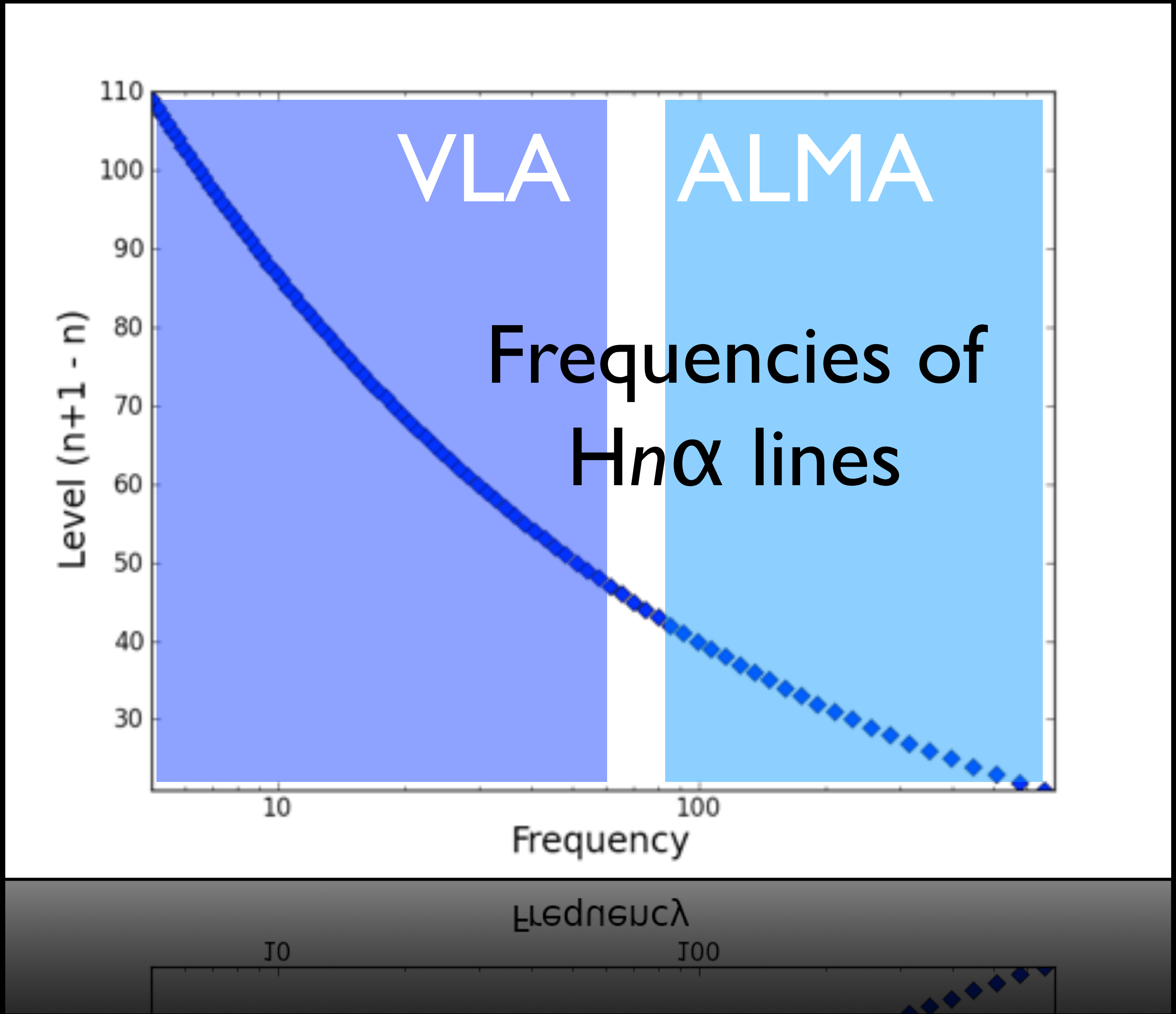
There are three ways to broaden a RRL

- Thermal Broadening — Fixed
- Pressure Broadening — Surmountable
- Dynamical Broadening — Interesting

Gas Dynamics

- Now we can begin to probe the dynamics on both sides of the ionization boundary!
  - with various molecular species
  - and RRLs for ionised gas

And we can do this on size scales where we can resolve the flows



Gas Dynamics

Outflow

- Separable Lobes on the Sky
- PV Diagrams
- Models of Bulk Flows

Infall

- Inverse P-Cygni Profiles
- PV Diagrams
- Models of Bulk Flows

Rotation

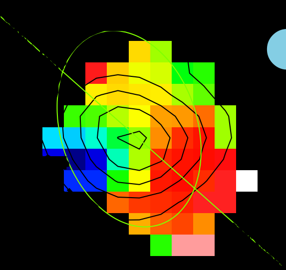
- Velocity Gradients
- PV Diagrams
- Models of Bulk Flows

Now that we know what we're looking for, and where....

Lets look at some examples!

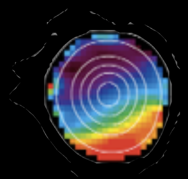
Rotation

- SO_2 (SMA 220 GHz)

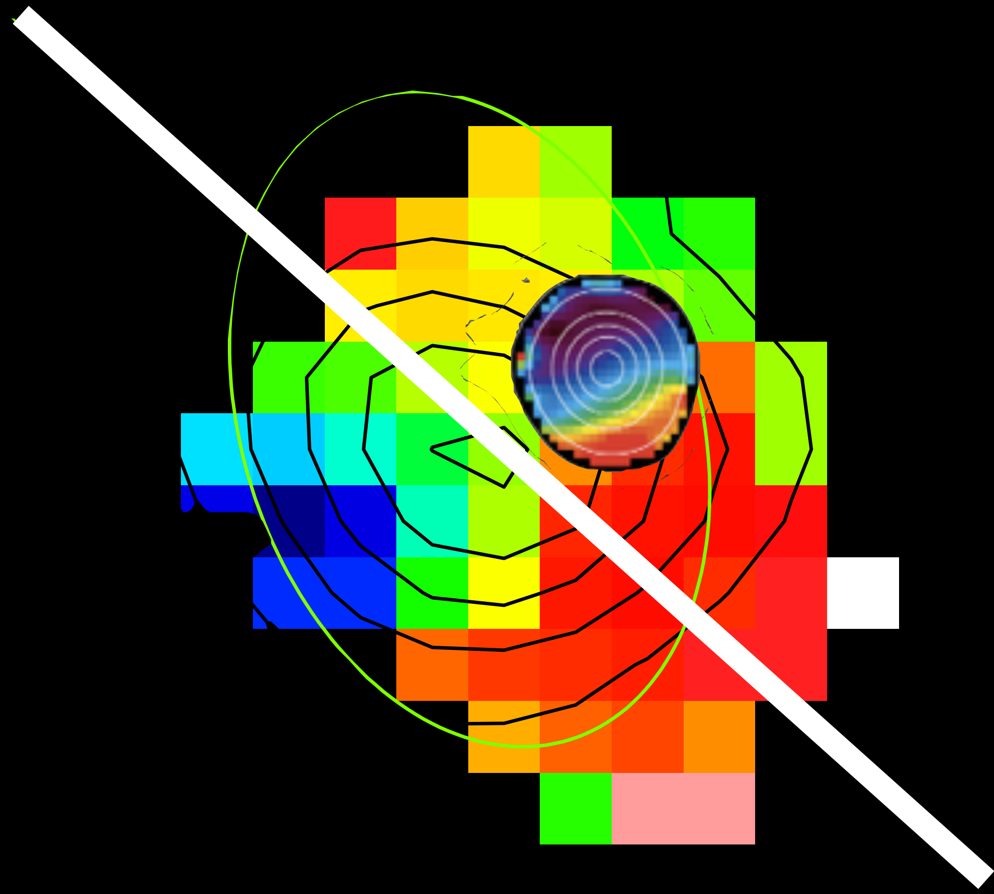


  - warm molecular gas is rotating around the HII region

- H53α (VLA 43 GHz)



  - the ionised gas within is rotating in the same direction

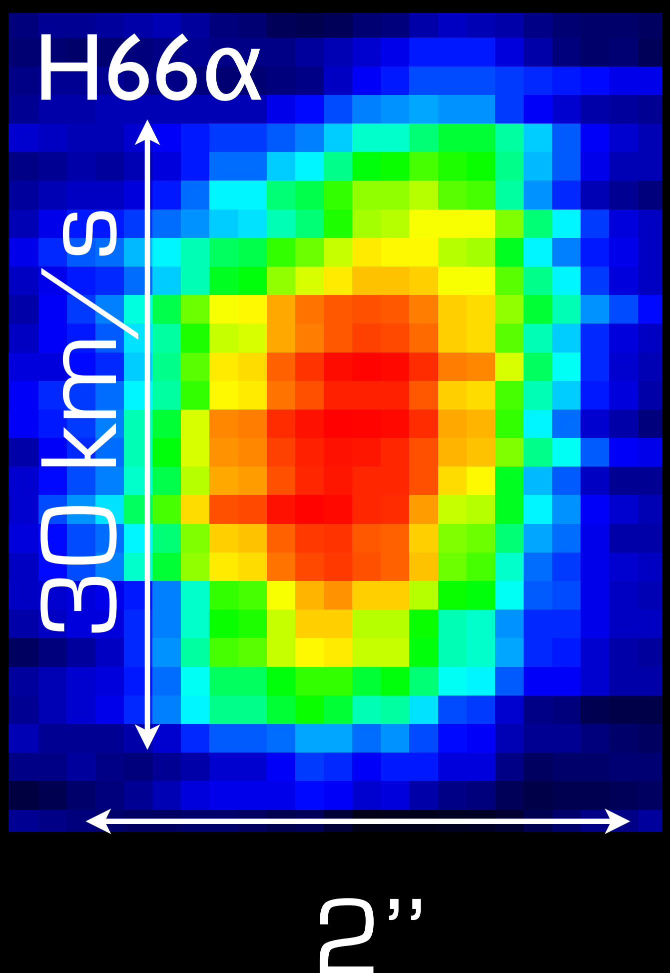


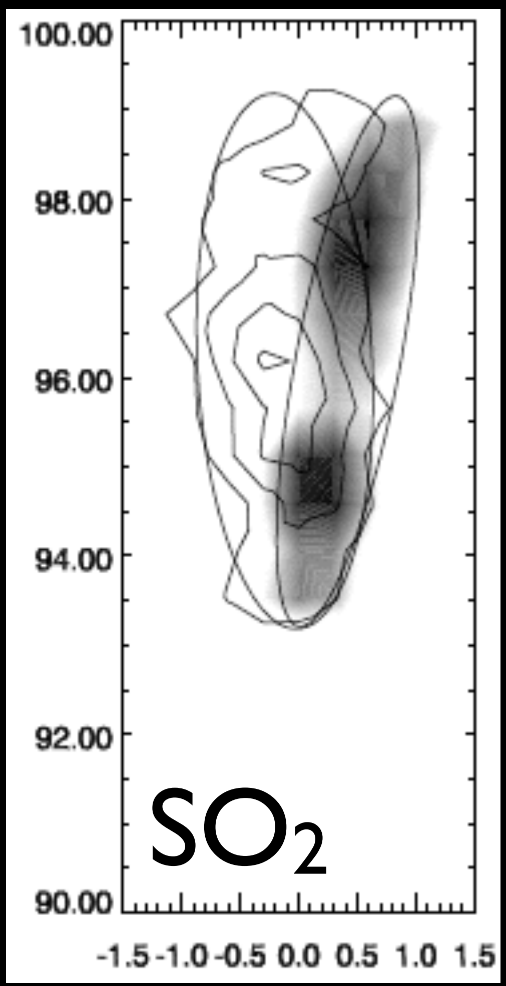
W51e2

Keto & Klaassen 2008, Klaassen et al. 2009

Rotation

- SO_2 (SMA 220 GHz)
  - warm molecular gas is rotating around the HII region
- H66α (VLA 22 GHz)
  - the ionised gas within is rotating in the same direction





G28.2

unpublished H66α, Klaassen et al. 2009

Rotation

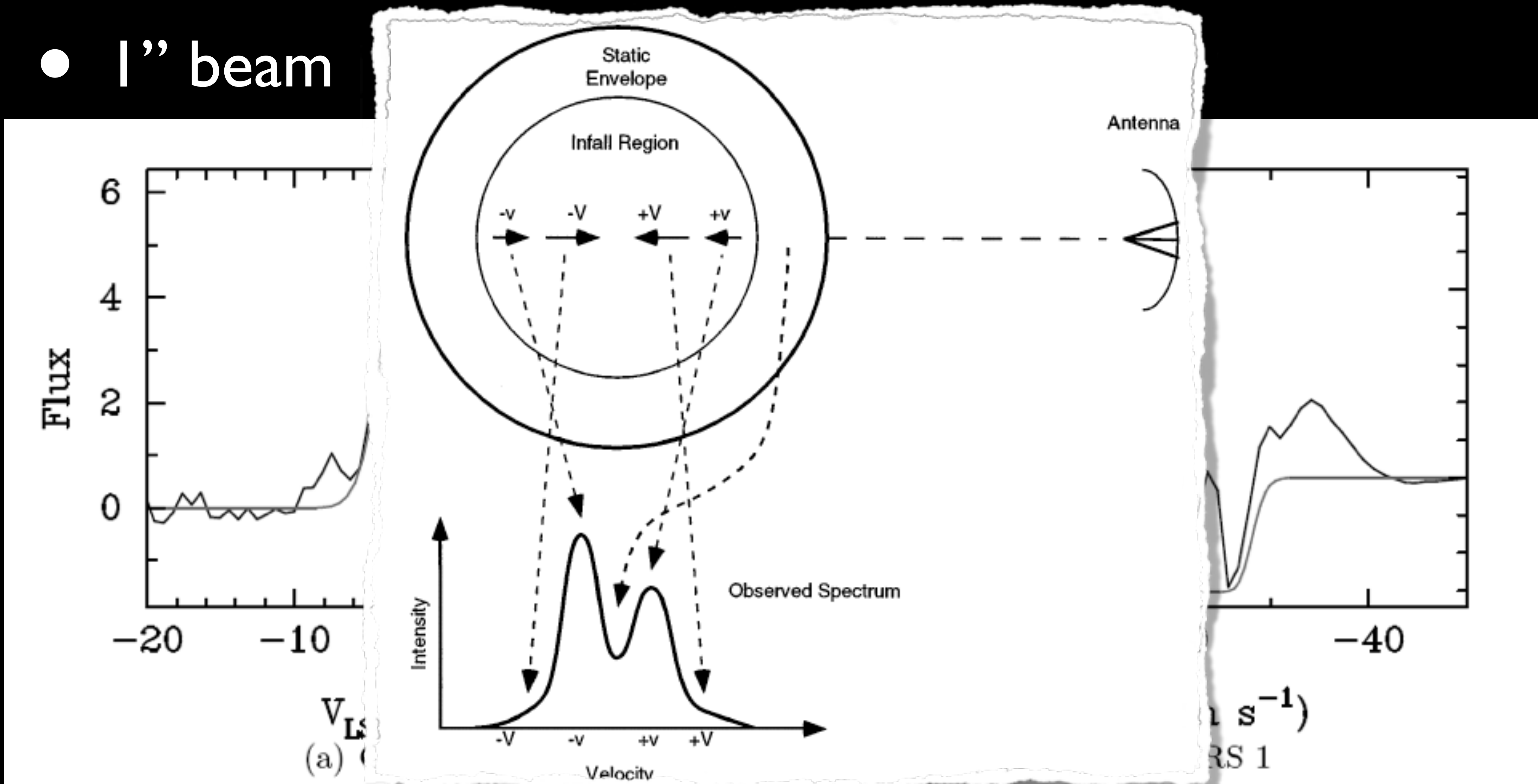
- SO_2 (SMA 220 GHz)
  - warm molecular gas is rotating around the HII region
- RRL (VLA)
  - the ionised gas within is rotating in the same direction

- For a given source, the velocity gradients are:
  - consistent with each other
  - along the same axis

This *suggests* they are caused by the same underlying physics

Infall

- Inverse P-Cygni Profiles (CO J=2-1)
- 1” beam



This shows the bulk infall, but on small scales

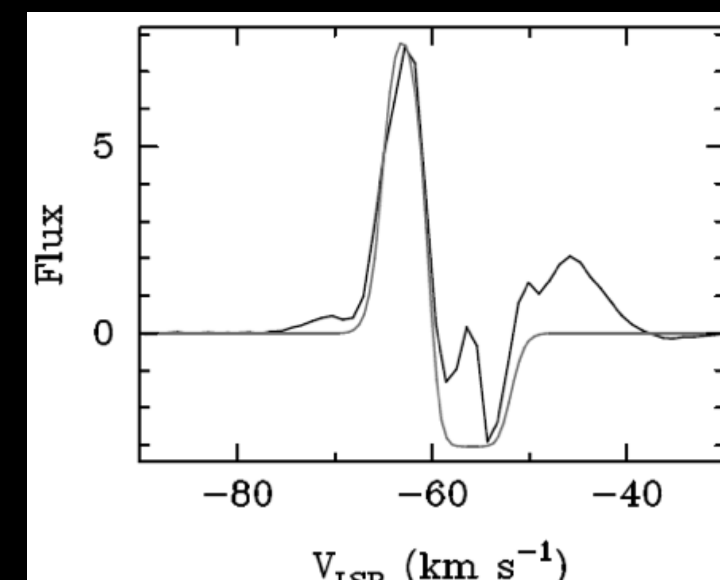
Klaassen et al. 2011

Klaassen et al. 2009,2011

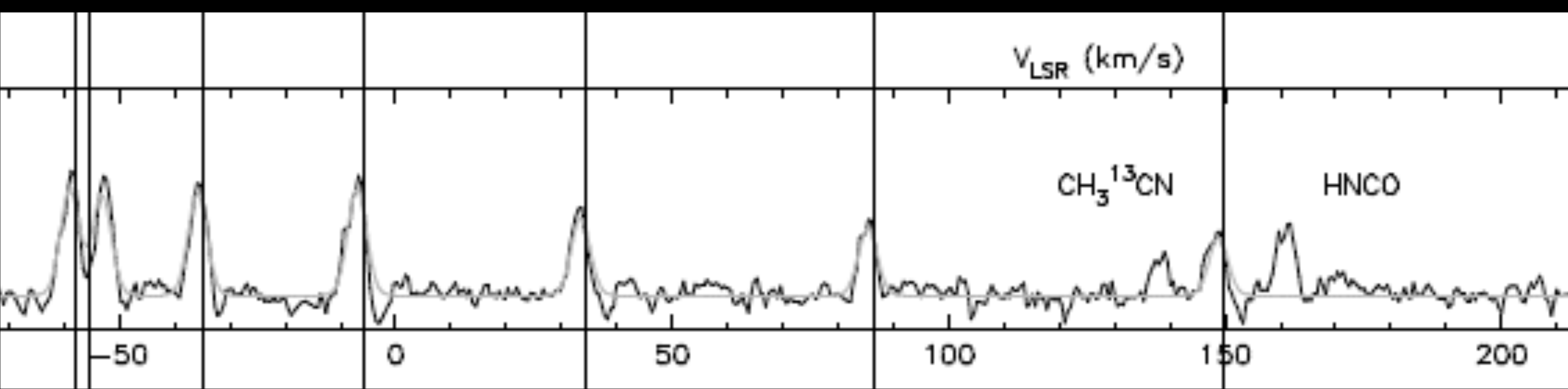
Infall

NGC 7538
IRS 1

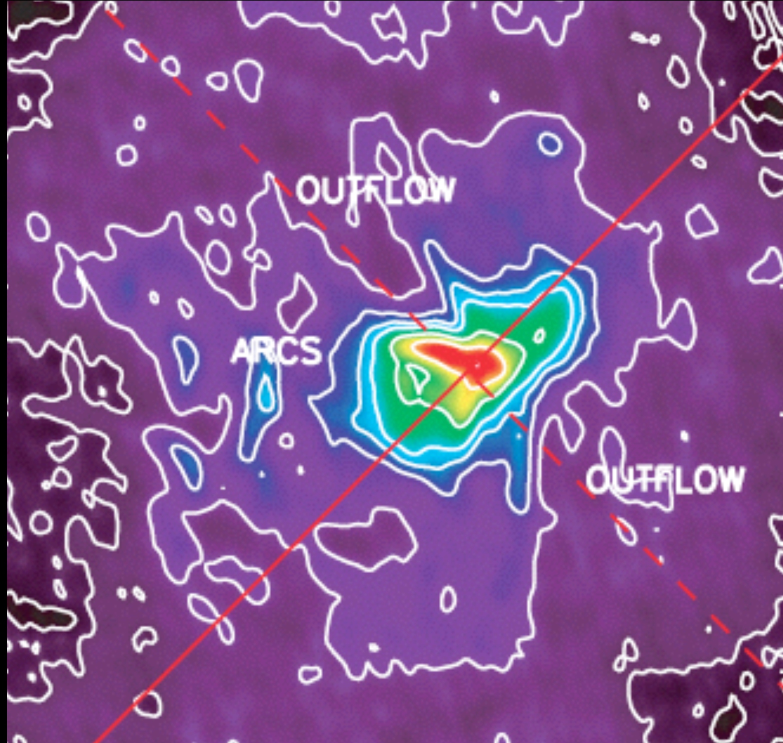
- CO Inverse P-Cygni profiles are not due to missing large scale structures.
  - We combined 2 SMA configurations + JCMT
  - The signature is also seen in the warm gas (as traced by CH_3CN)



Black lines indicate rest frequencies of CH_3CN lines



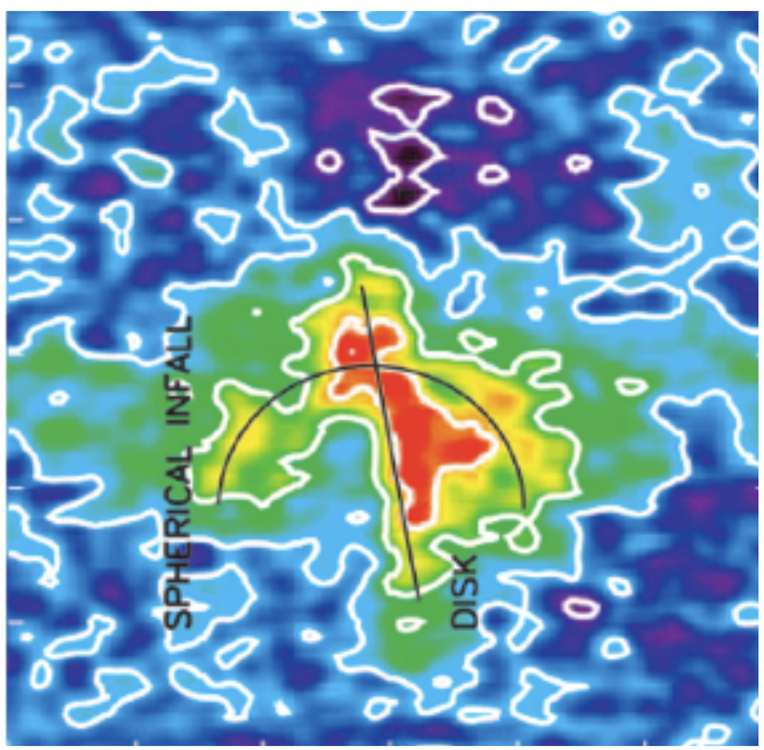
Infall



Molecular and ionised gas populations are again doing the same thing!

$$\dot{M}_{in} = 10 \times 10^{-4} M_{\odot}/yr$$

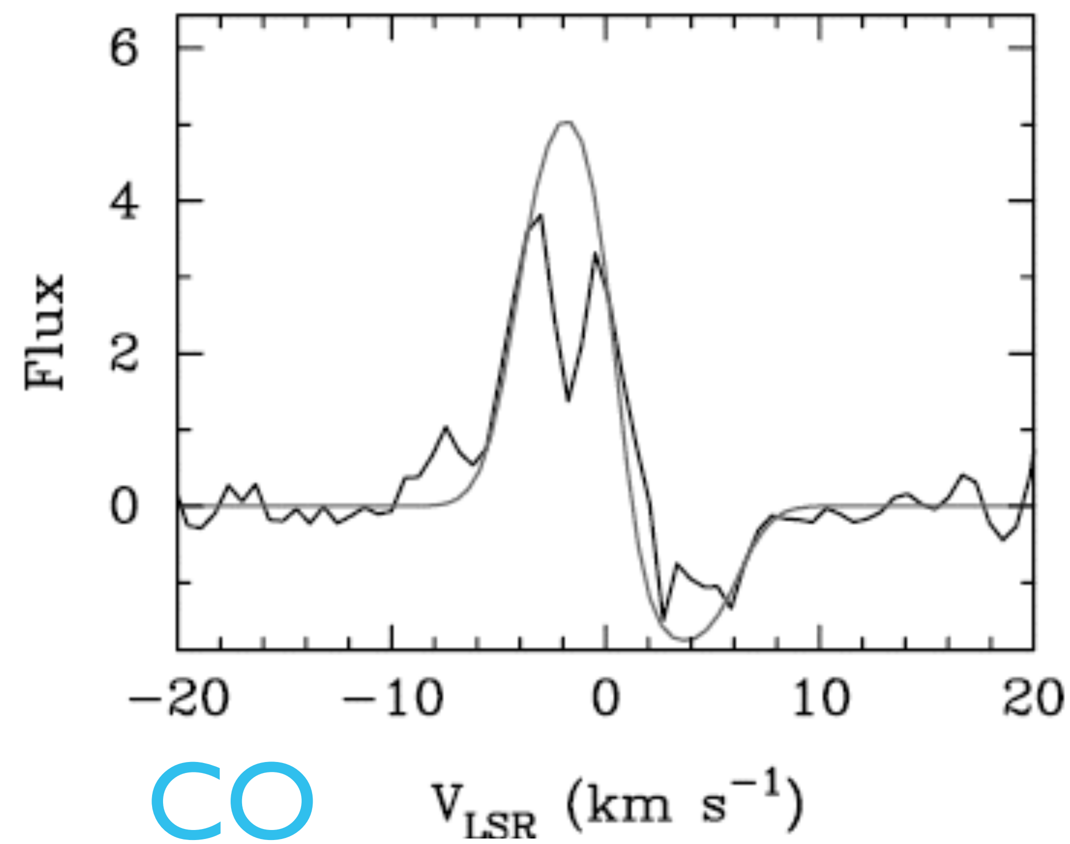
$$\dot{M}_{in} = 2 \times 10^{-4} M_{\odot}/yr$$



Velocity

Offset

H66α



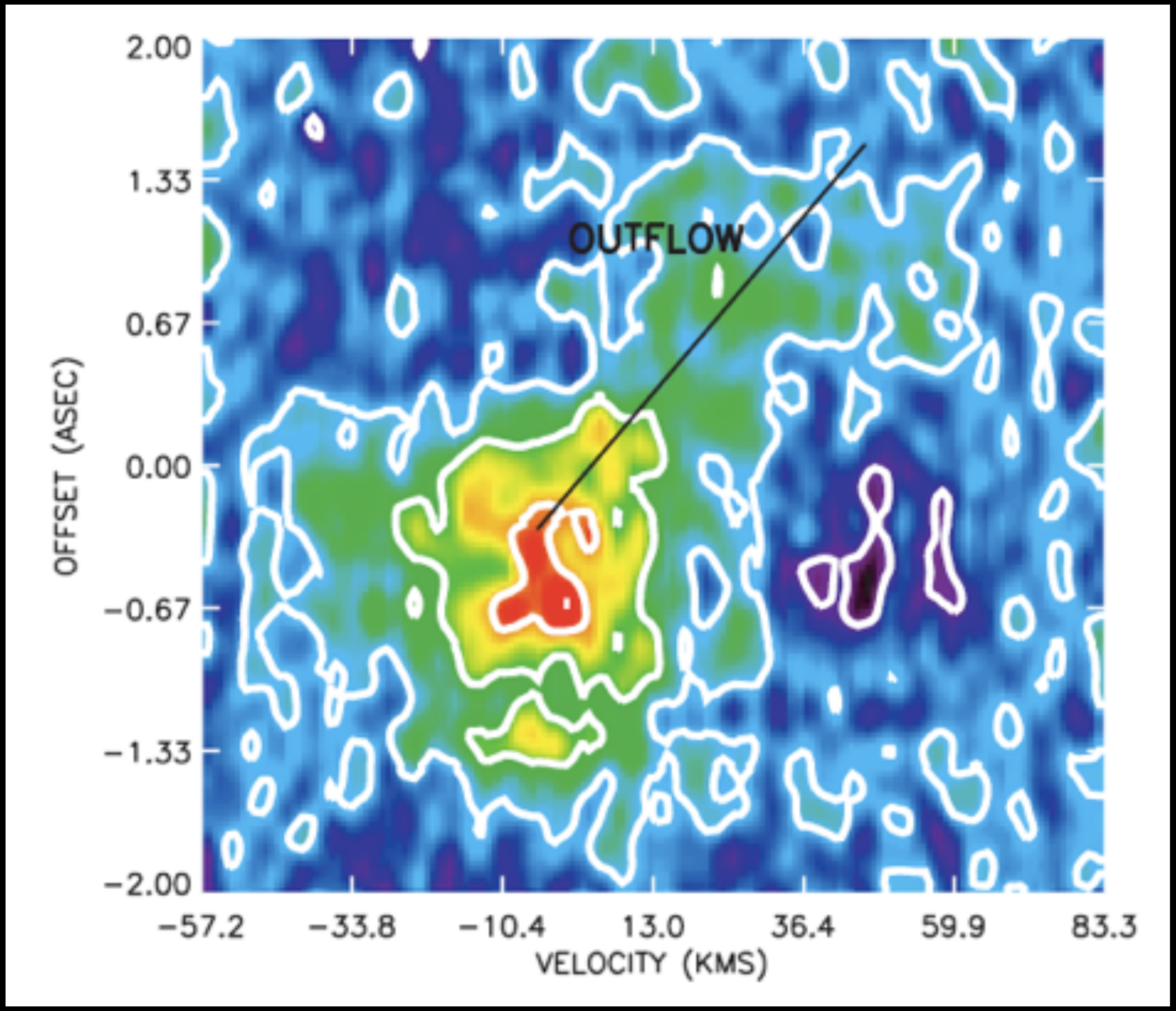
CO

G10.6-0.4

Keto & Wood, 2006, Klaassen et al. 2011

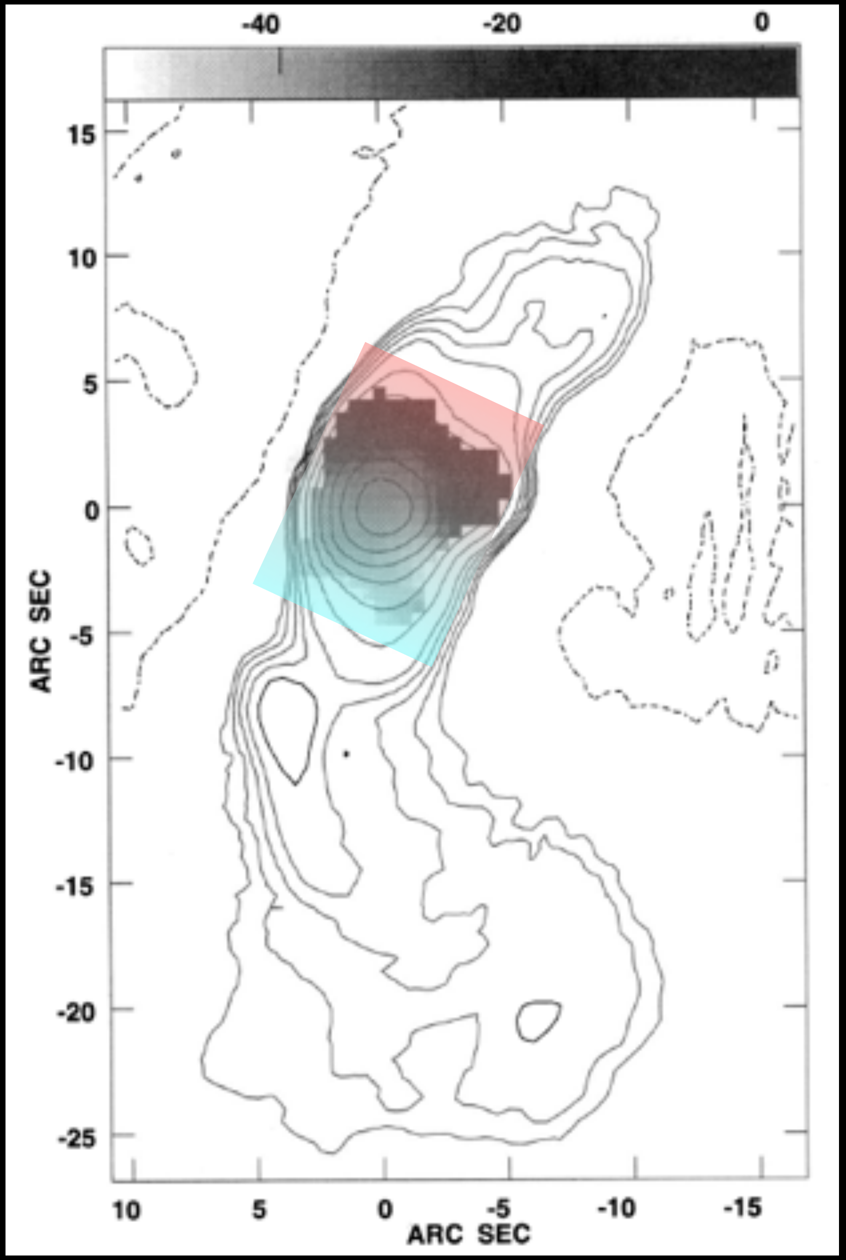
Outflow

Look at the molecular gas in regions with ionised outflows



Keto & Wood 2006

G10.6-0.4

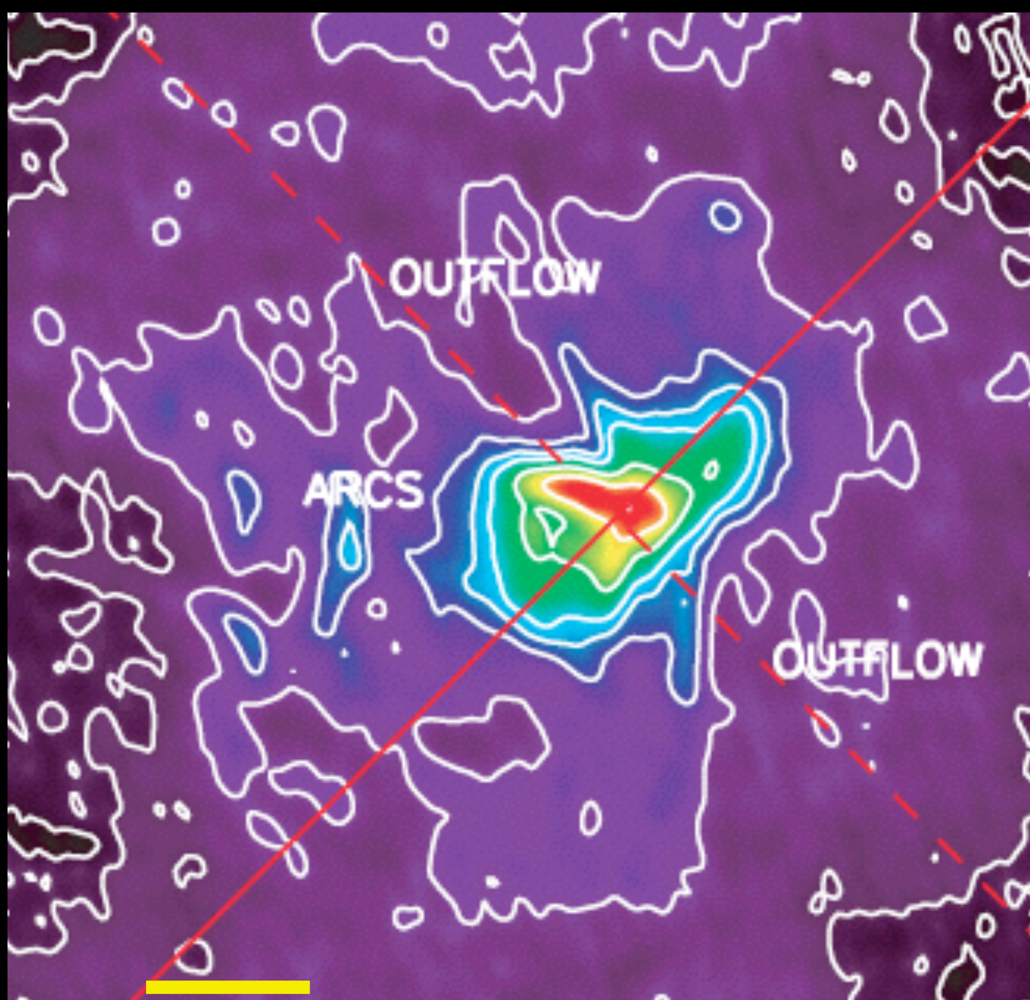


K3-50A

Depree et al. 1994

Outflow

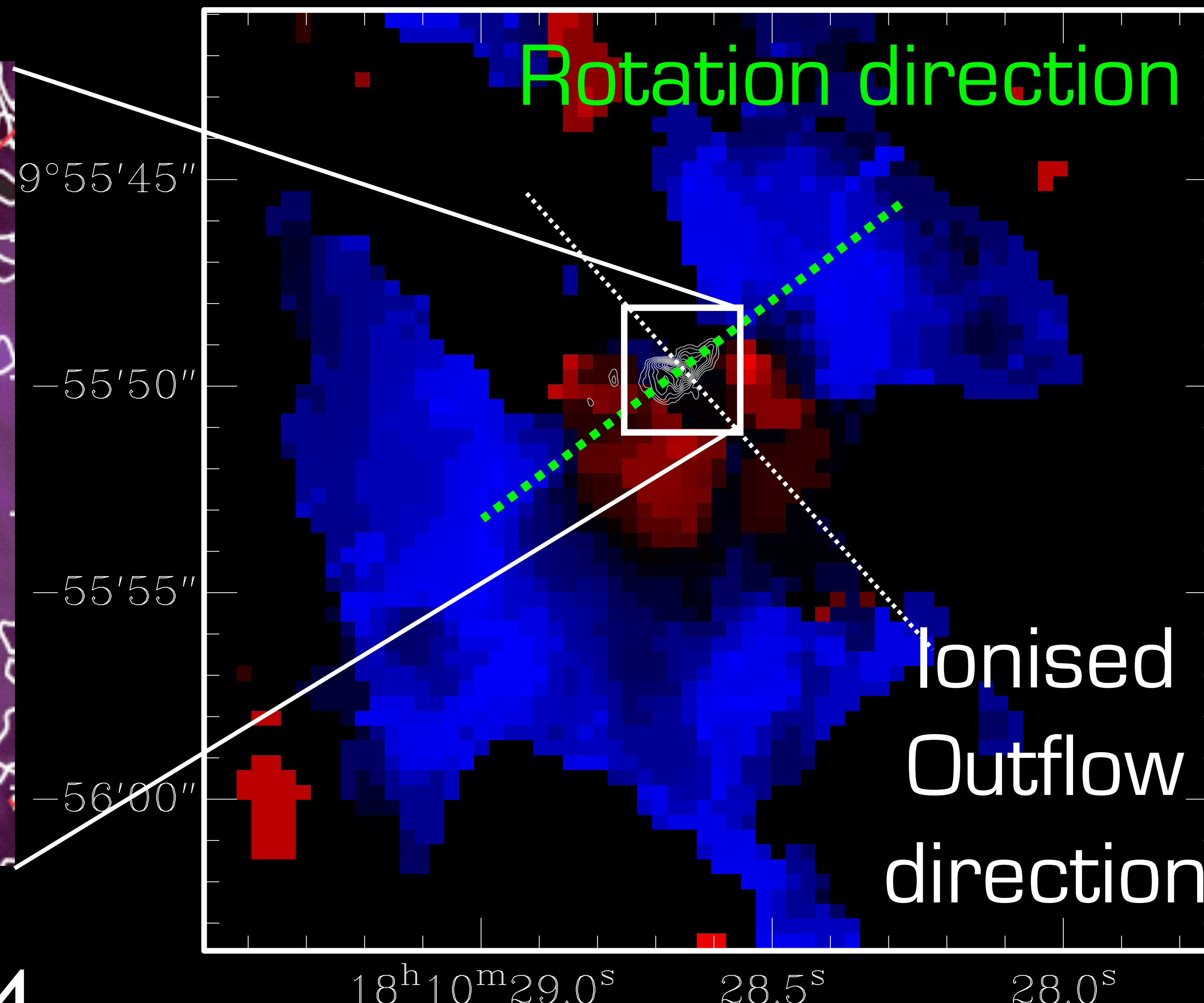
Look at the molecular gas in regions with ionised outflows



6000 AU

Keto & Wood 2006

G10.6-0.4



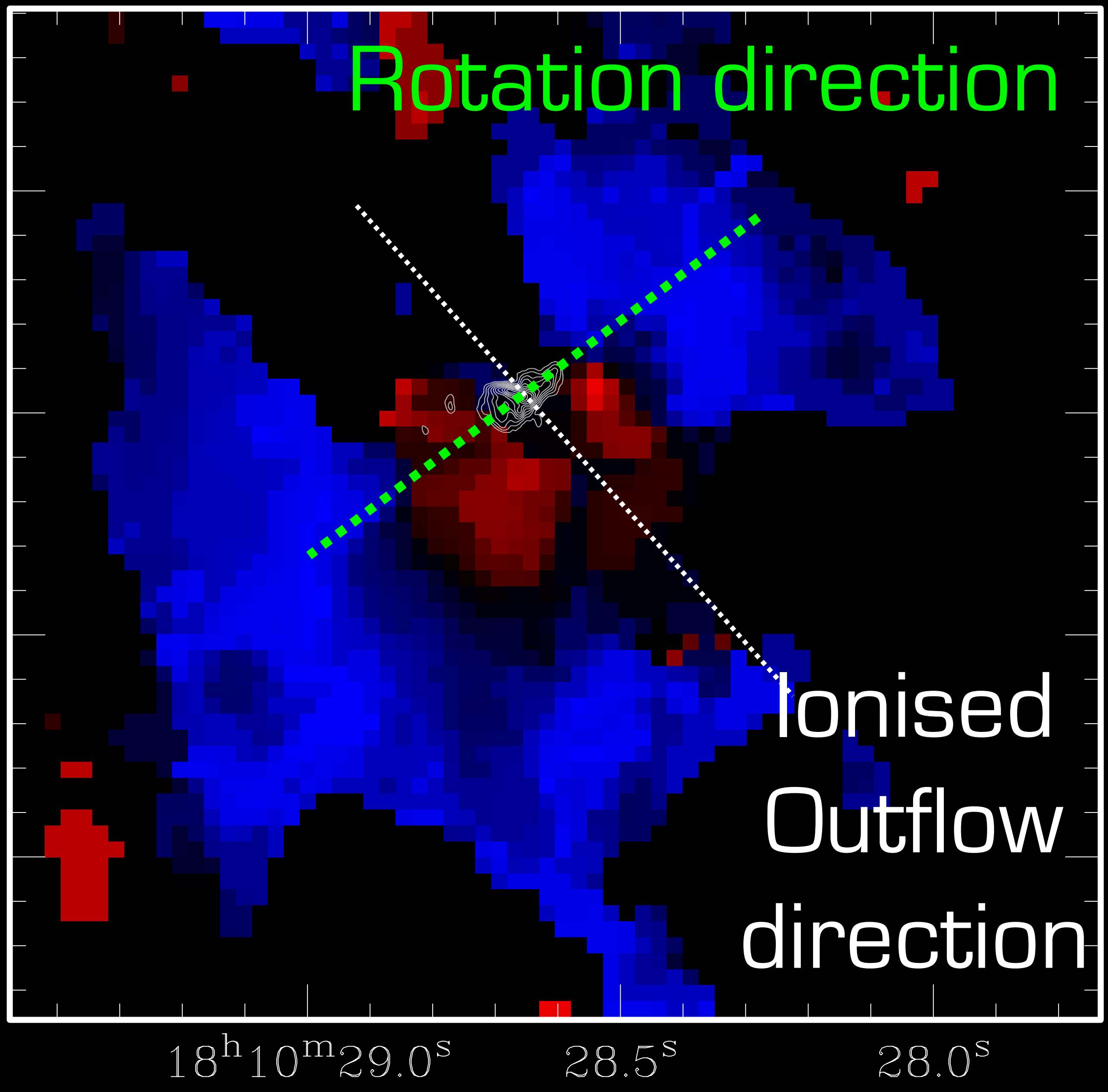
Klaassen et al. 2011

Outflow

Look at the molecular gas in regions with ionised outflows

- The CO does not show outflow motions
    - there are no ordered flows parallel or perpendicular to the suggested ionised outflow axis

G10.6-0.4



Klaassen et al. 2011

Outflow

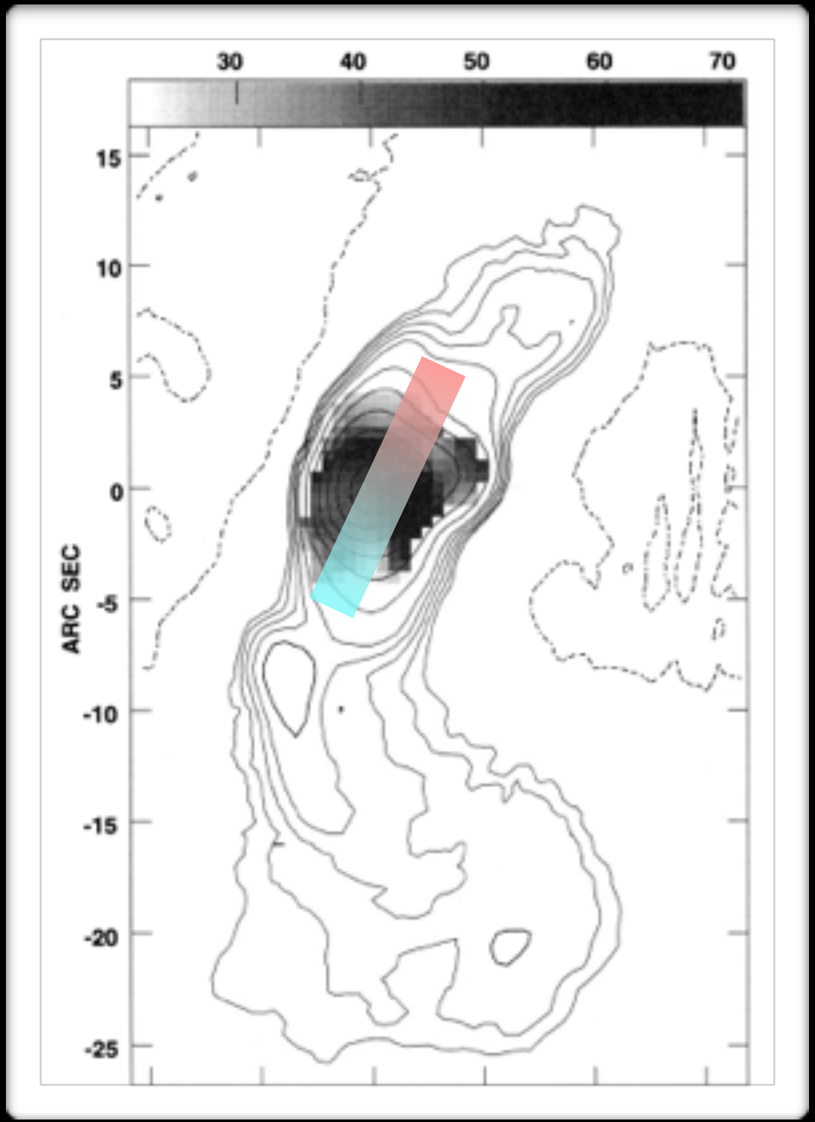
- In G10.6, why does CO not trace the molecular outflow?
  - Does the molecular outflow not exist?
  - is it not tracing the gas at the right densities?
- We don't know yet..

Current JVLA project to look closer at G10.6 (and 4 other sources) in H53α, SiO, CS, H_2CO and OCS

Outflow

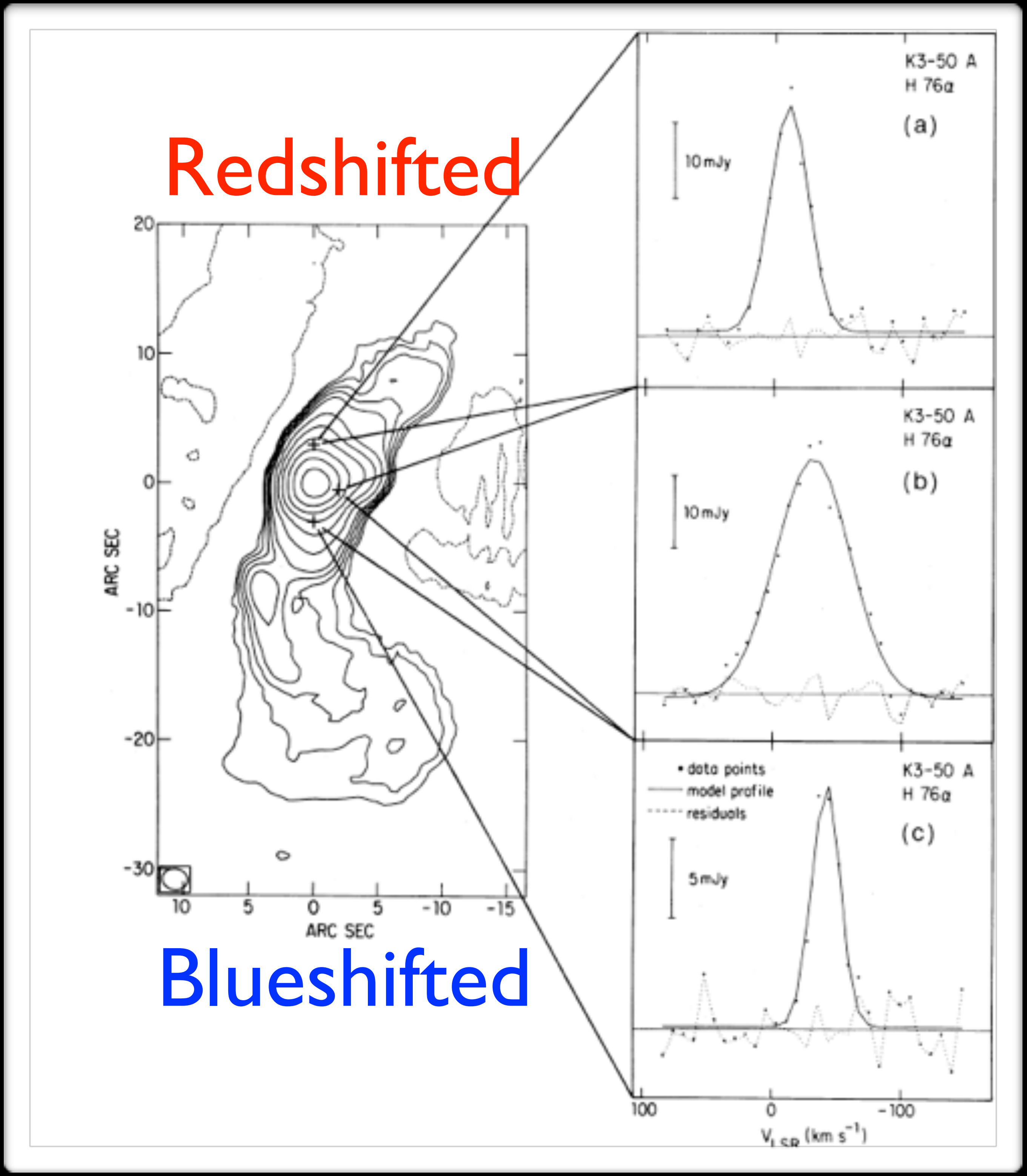
Lets try another source!

- 14.7 GHz Continuum
- H76α outflow?



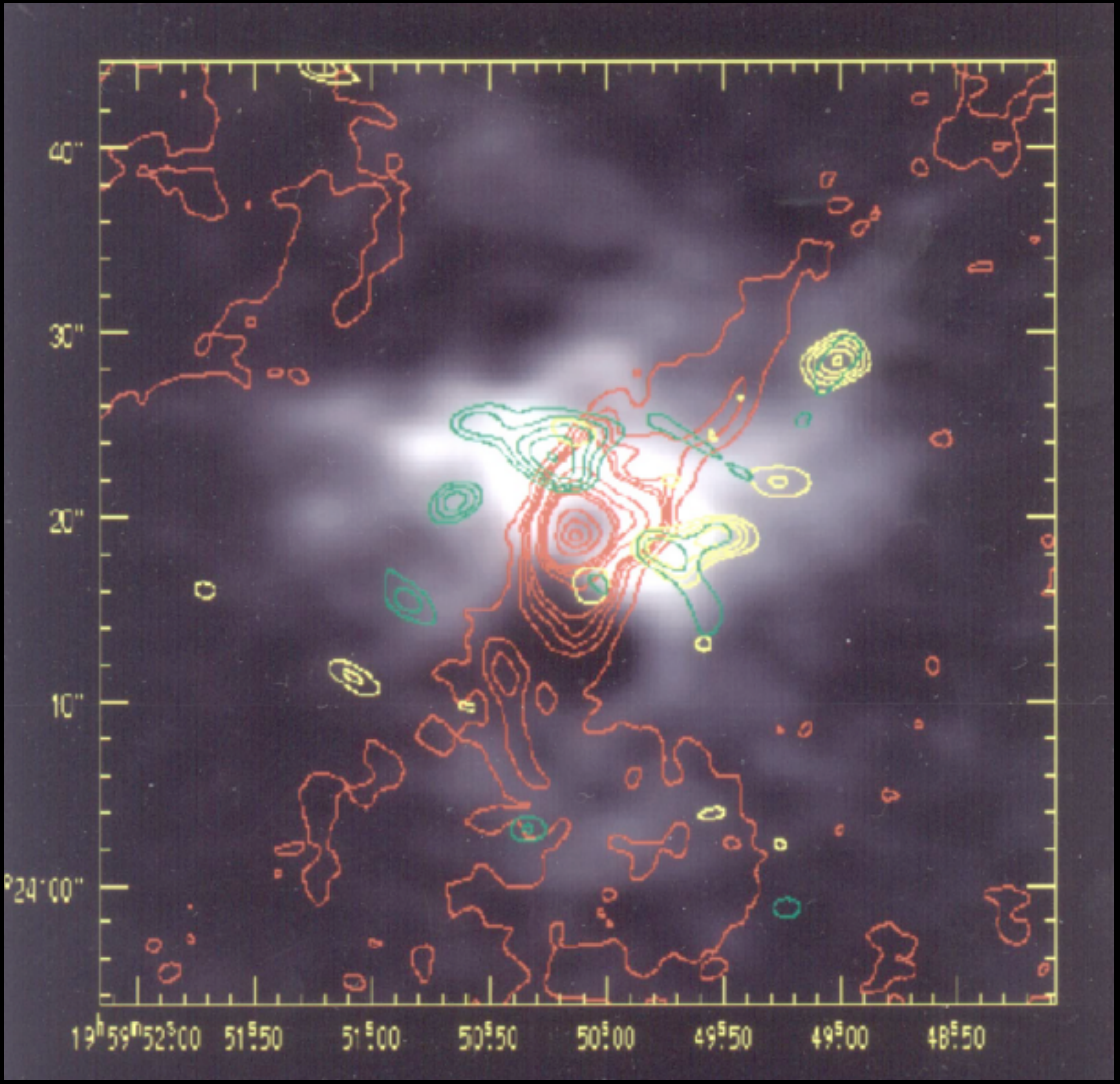
DePree et al. 1994

K3-50A



Outflow

- HCO^+ and SiO may be doing something interesting
  - greyscale = HCO^+
  - green=$H^{13}CO^+$
  - yellow = SiO
  - red = 14.7 GHz



Howard et al. 1997

Klaassen et al. 2013b

New Observations

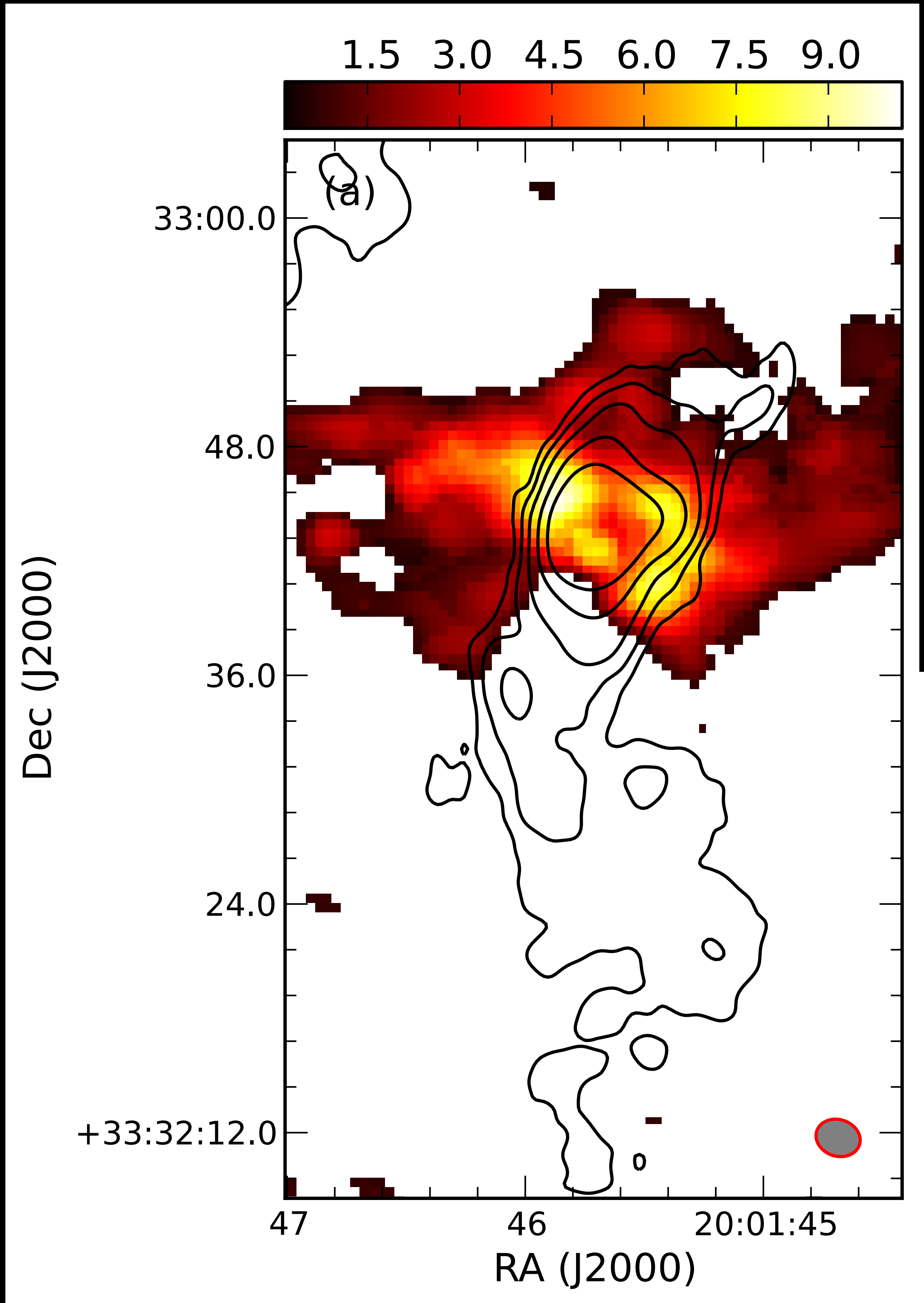
It's very encouraging! maybe we'll see a molecular outflow!!!

- CARMA C config
  - 90 GHz continuum
  - H41α
  - HCO^+ (J=1-0)
  - 1.8" spatial res. (0.07pc)
  - 1.7 km/s spectral res.
- VLA B config
  - 23 GHz continuum
  - 0.2" spatial res. (1740 AU)
  - ~31 channels averaged to obtain continuum

K3-50A is at a distance of 8.7 kpc

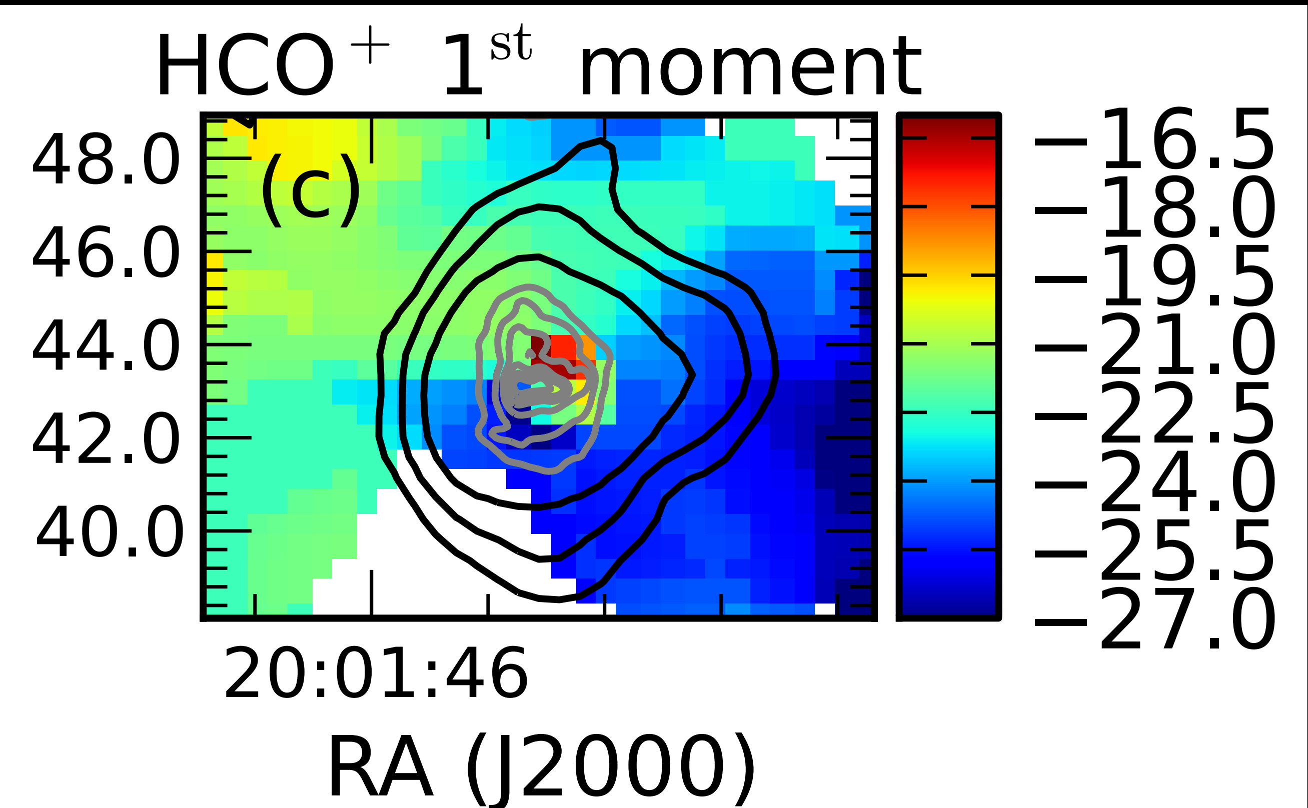
Klaassen et al. 2013b

HCO^+



HCO^+ emission superimposed on 15 GHz continuum

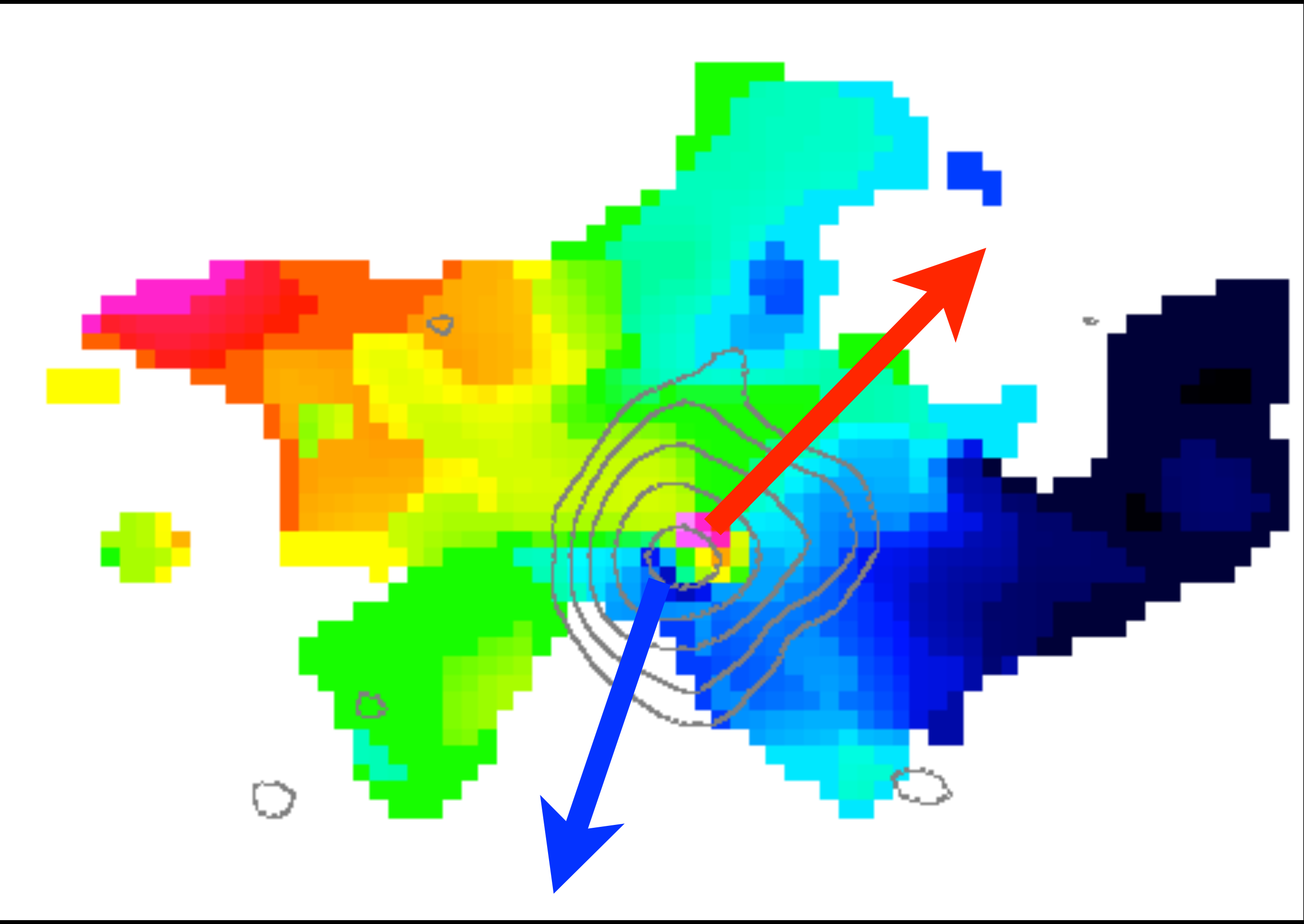
HCO^+ velocities on 23 & 90 GHz continuum



Klaassen et al. 2013b

HCO^+

- HCO^+ extends over a pc
- Bulk motions indicate large scale rotation (Howard et al. 1997)
- Does it look like outflow?
    - it is perpendicular to the ionised outflow



On the whole, no, it doesn't look like outflow

Klaassen et al. 2013b

HCO^+

We suggest *most* of the HCO^+ is rotating

$$\text{Size} \sim 1.1pc$$
$$M_{\text{gas}} \sim 2200 M_{\odot}$$
$$p_{\text{gas}} \sim 7000\,\mathrm{M_{\odot}\,km\,s^{-1}}$$

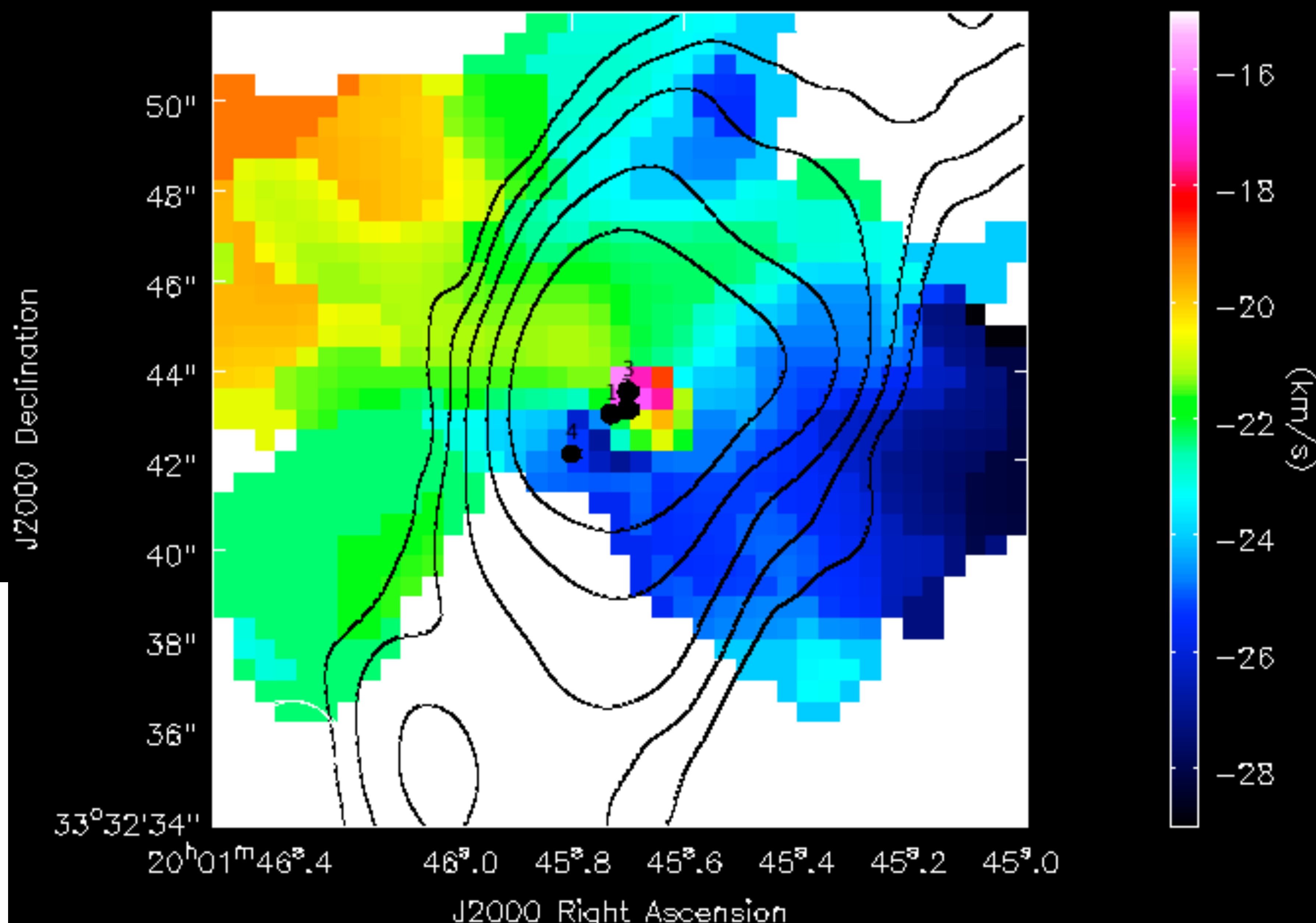
There's just too much stuff for an outflow

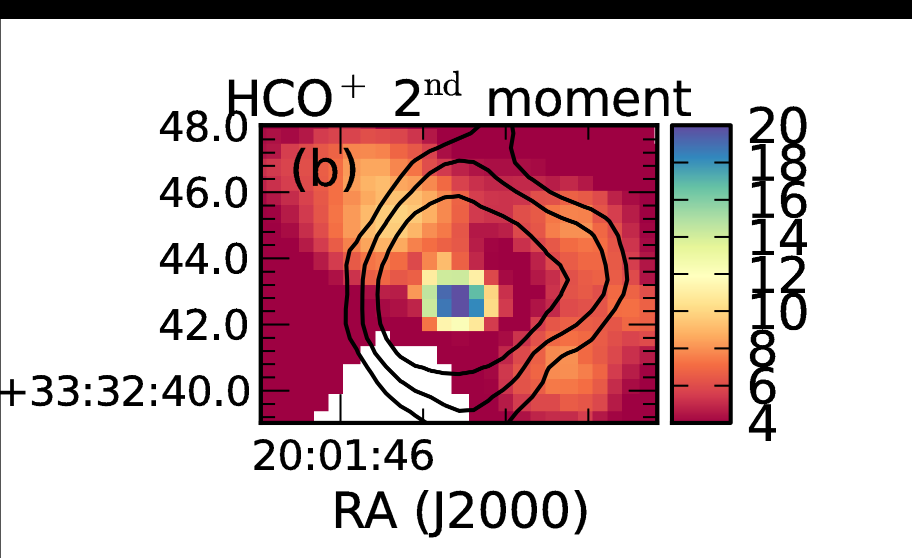
This is not what we were expecting (but what we got was way cooler!)

Klaassen et al. 2013b

HCO^+

- Motion is ⊥ to ionised outflow
- Too massive to be outflow
  2200 M⊙
- Rotating envelope!



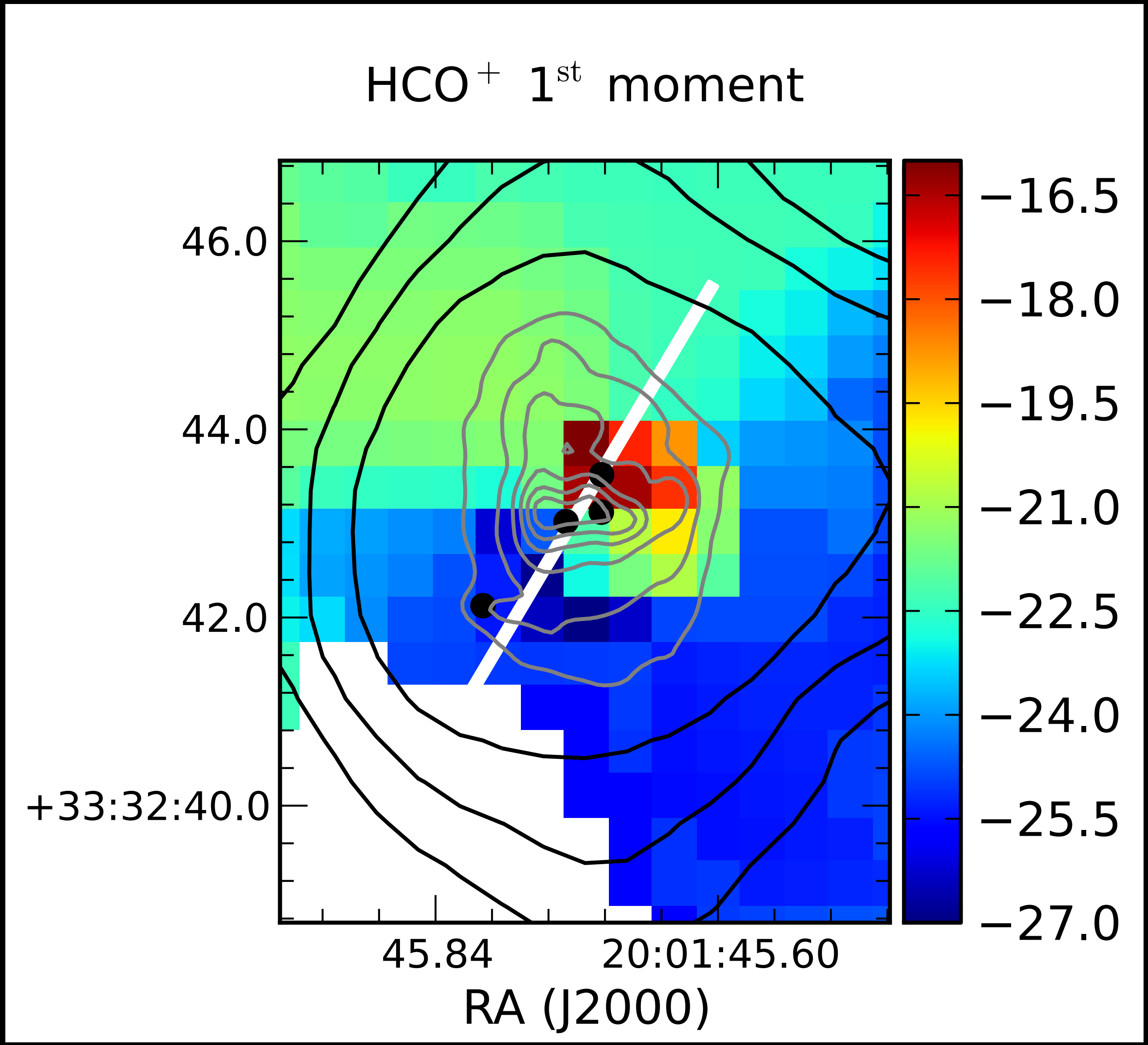


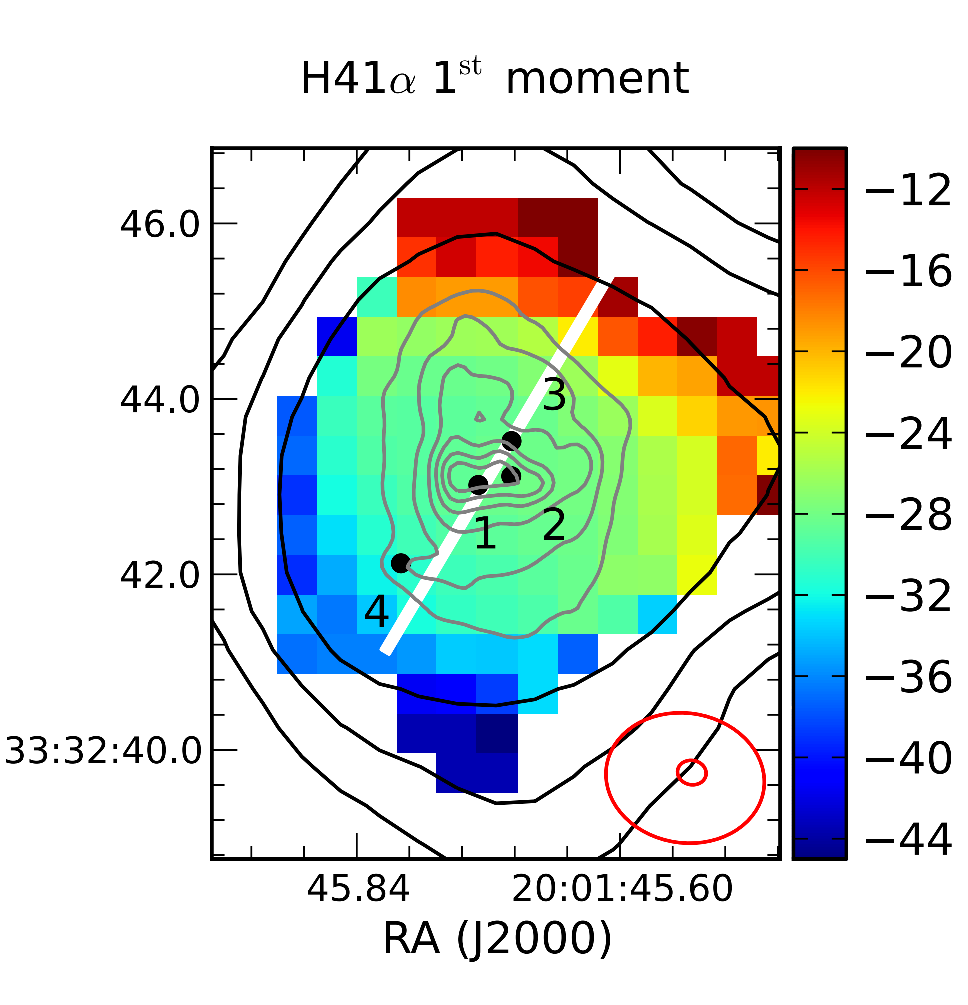
MIR sources from Okamoto et al. 2003

Klaassen et al. 2013b

HCO^+

- There seem to be high velocity spikes in the HCO^+ emission at the edges of the HII region

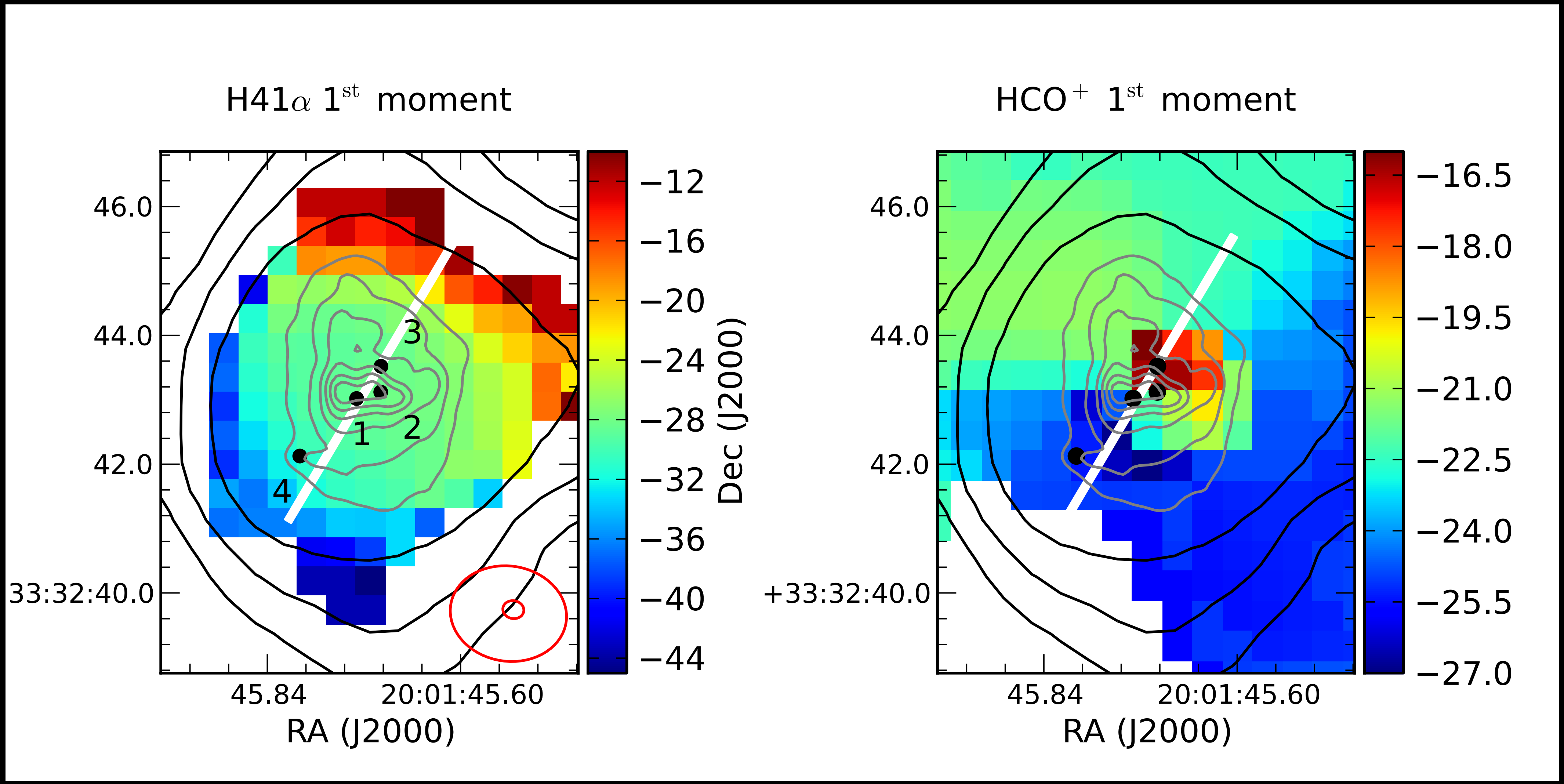




But remember the ionised gas?

Klaassen et al. 2013b

Entrained Outflow?



$$\frac{\Delta v}{\Delta r} = 145 \pm 13 \mathrm{km/s/pc}$$

$$\frac{\Delta v}{\Delta r} = 142 \pm 23 \mathrm{km/s/pc}$$

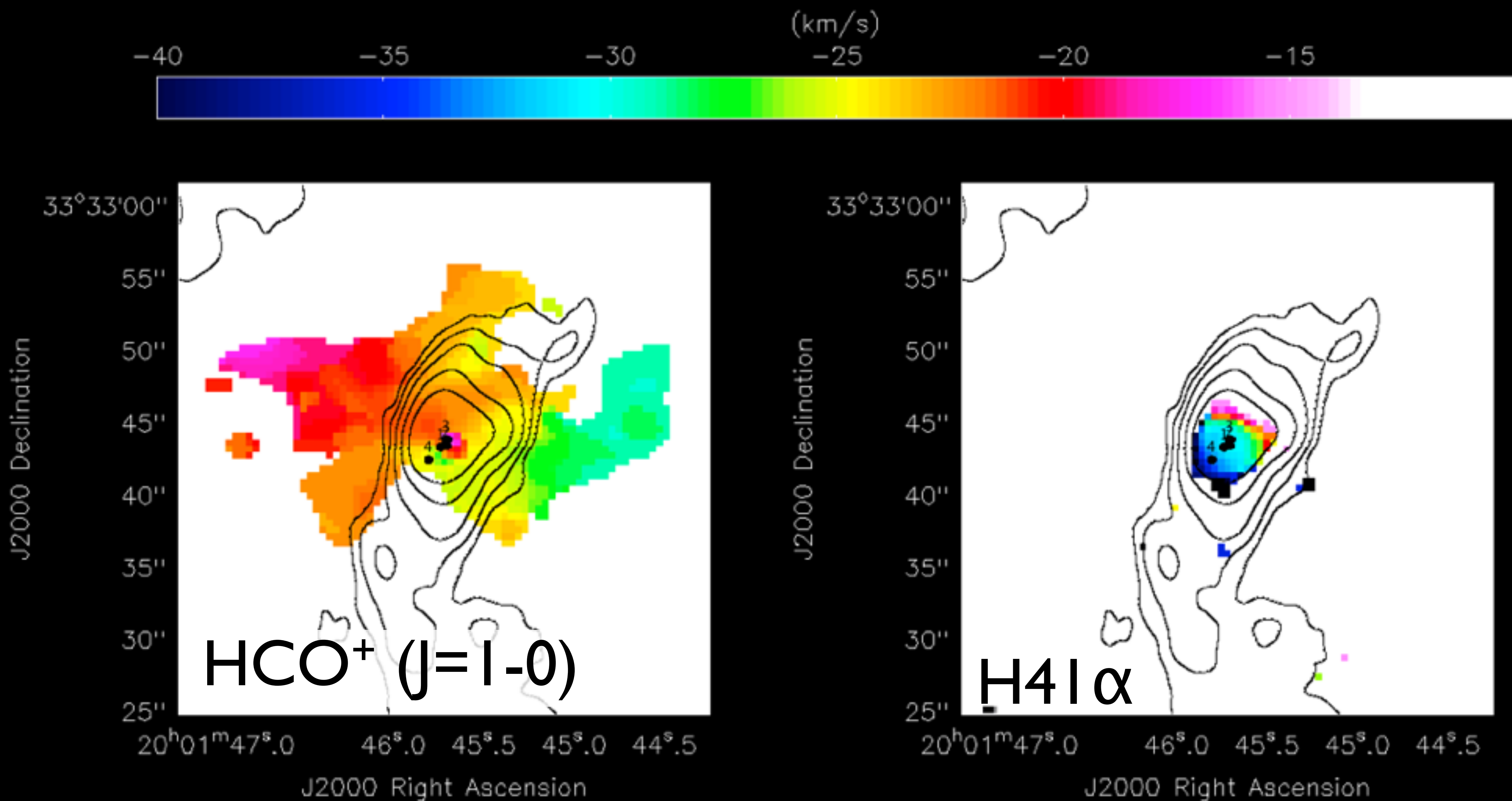
Is the ionised gas hitting the ionisation boundary, and continuing outward, taking the molecular gas with it?

HCO^+ velocity scale slightly compressed compared to H41α

Klaassen et al. 2013b

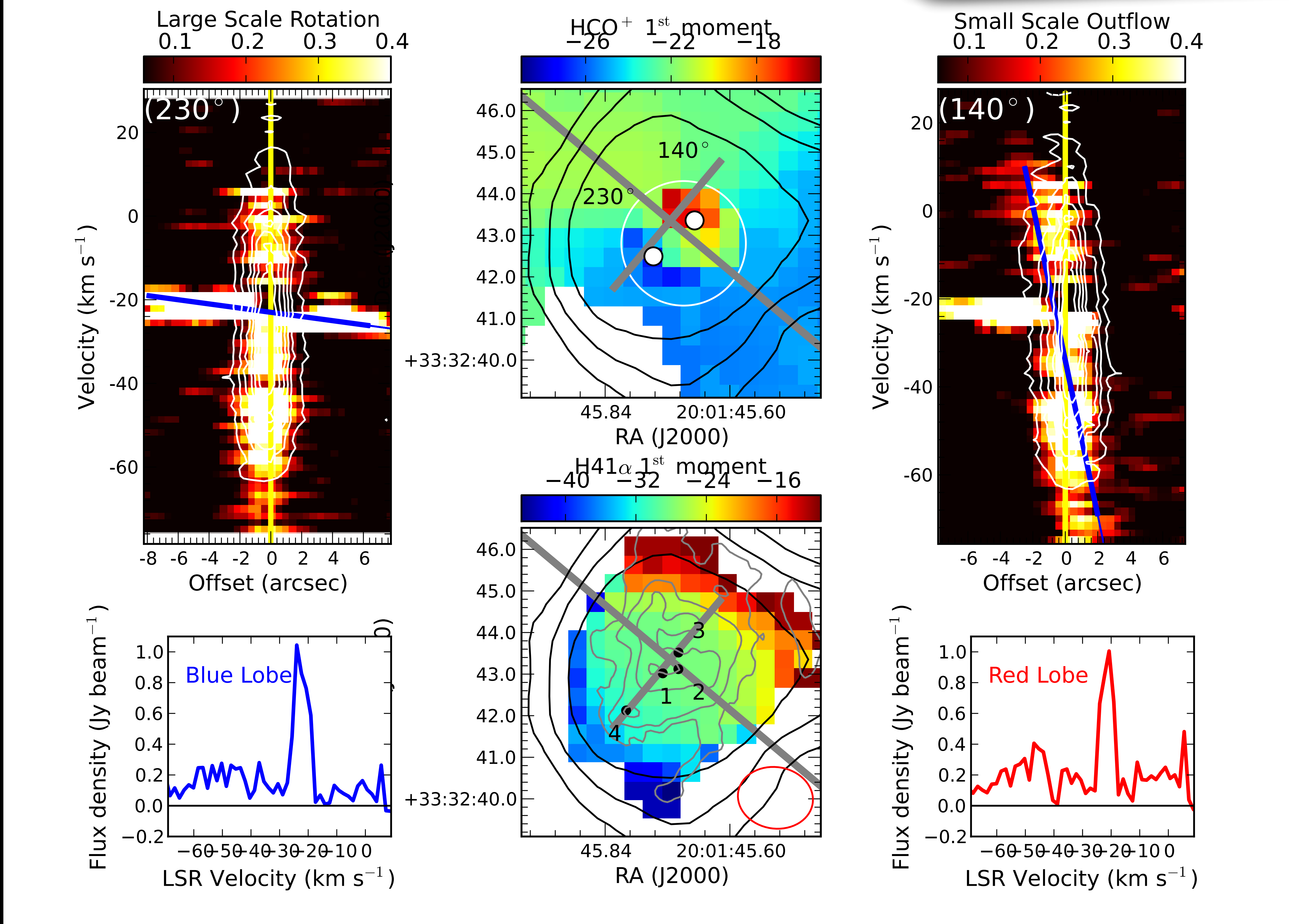
Gas Velocities

The HCO+ isn't being accelerated as much as the H41α



Klaassen et al. 2013b

PV Diagrams

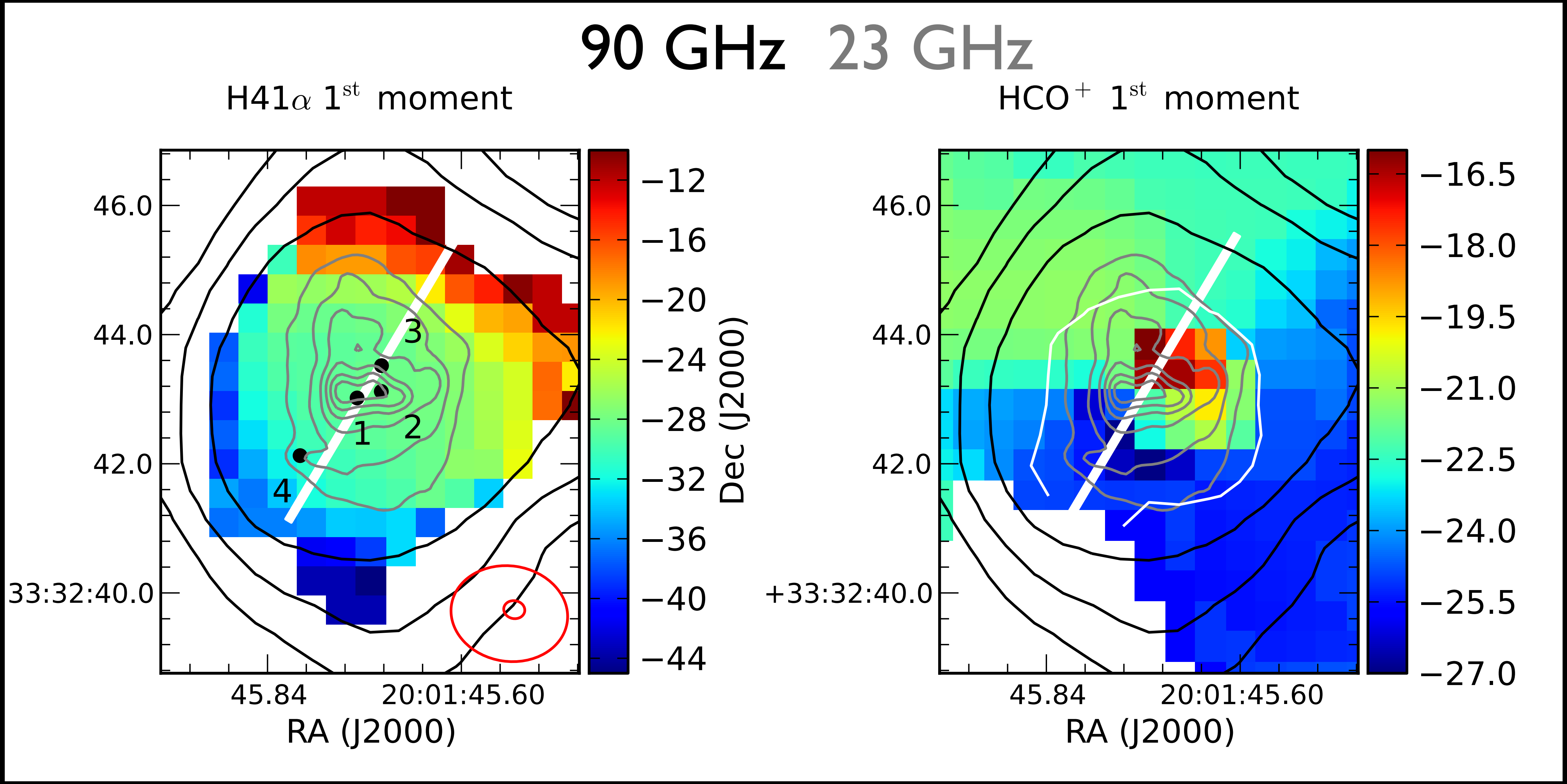


Klaassen et al. 2013b
Peters, Klaassen et al. 2012

Gas Velocities

Momenta of the ionised and molecular gas components

mv_{ion} = 100 M km/s mv_{molec} = 30 M km/s



White contour = 12 km/s velocity dispersion

These values are slightly scaled up from the simulations of Peters et al. 2010,2012 (who weren't trying to replicate this region, but one much smaller!)

Small Scale Outflow

- There appears to be a tiny molecular outflow here, being pushed outwards by the ionised gas

- What could be causing this you ask?

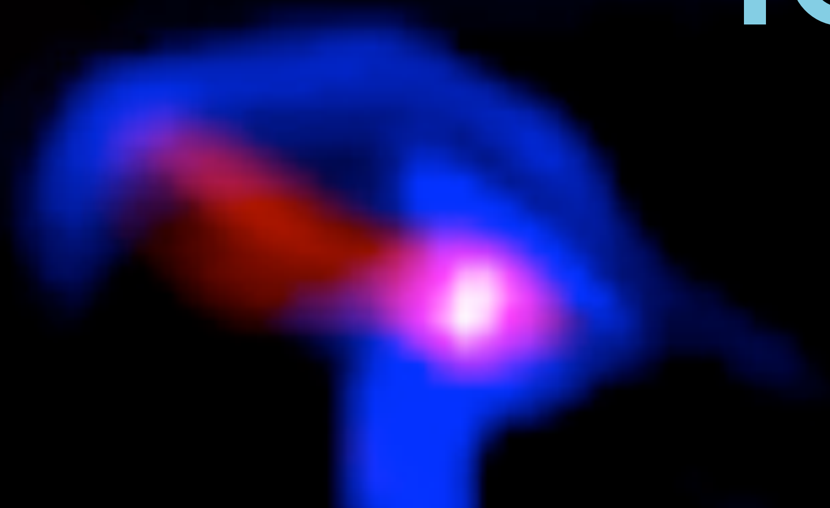
THE ASTROPHYSICAL JOURNAL, 760:91 (8pp), 2012 November 20 doi:10.1088/0004-637X/760/1/91

ARE MOLECULAR OUTFLOWS AROUND HIGH-MASS STARS DRIVEN BY IONIZATION FEEDBACK?

THOMAS PETERS[1,2,7], PAMELA D. KLAASSEN[3,4], MORDECAI-MARK MAC LOW[5], RALF S. KLESSEN[1], AND ROBI BANERJEE[6]

Ionisation Feedback

Peters, Klaassen et al. 2012



Ionisation Feedback

- Outflows driven by ionisation feedback have very different characteristics than the more traditional outflows
  - Smaller
  - Less massive
  - Less energetic

} By orders of magnitude!

Peters, Klaassen et al. 2012

Klaassen et al. 2013b

Ionisation Feedback

- K3-50A is a HUGE star forming region
- Yet its outflow properties are orders of magnitude smaller than those seen in comparable regions

Source	L_{Bol}	SiO	Molecular Outflow Properties		
		detection	Mass	Momentum	Energy
	(10^6 $L_\odot$)	(Y/N)	($M_\odot$)	($M_\odot$ km s^{-1})	(10^{45} erg)
K3-50A	2	Y[a,b,d]	4.6	28	0.24
G10.60−0.40	1.1[c]	Y[d]	90[c]	670[c]	50[c]
G10.47+0.03	1.4[c]	Y[a,d]	150[c]	1110[c]	81[c]
G48.61+0.02	1.3[c]	Y[e]	590[c]	2550[c]	118[c]
G19.61−0.23	1.7[c]	Y[d]	200[c]	1740[c]	150[c]

Summary

- Just because there's an HII region, doesn't mean the fun is over!
  - ionised and molecular rotation
  - ionised and molecular infall
  - ionised and molecular outflow

Studying both gas populations tells us about energy transfer through the ionization boundary

With ALMA nearing completion, and the upgrades to the VLA, this field is about to get *a lot* more interesting

‘My’ Recent ALMA Results

- IRAS 16293
  - Duality of the lines towards Source B
- HD 163296
  - Disk Wind
  - CO Snowline (via DCO^+)
  - Vertical structure of the disk