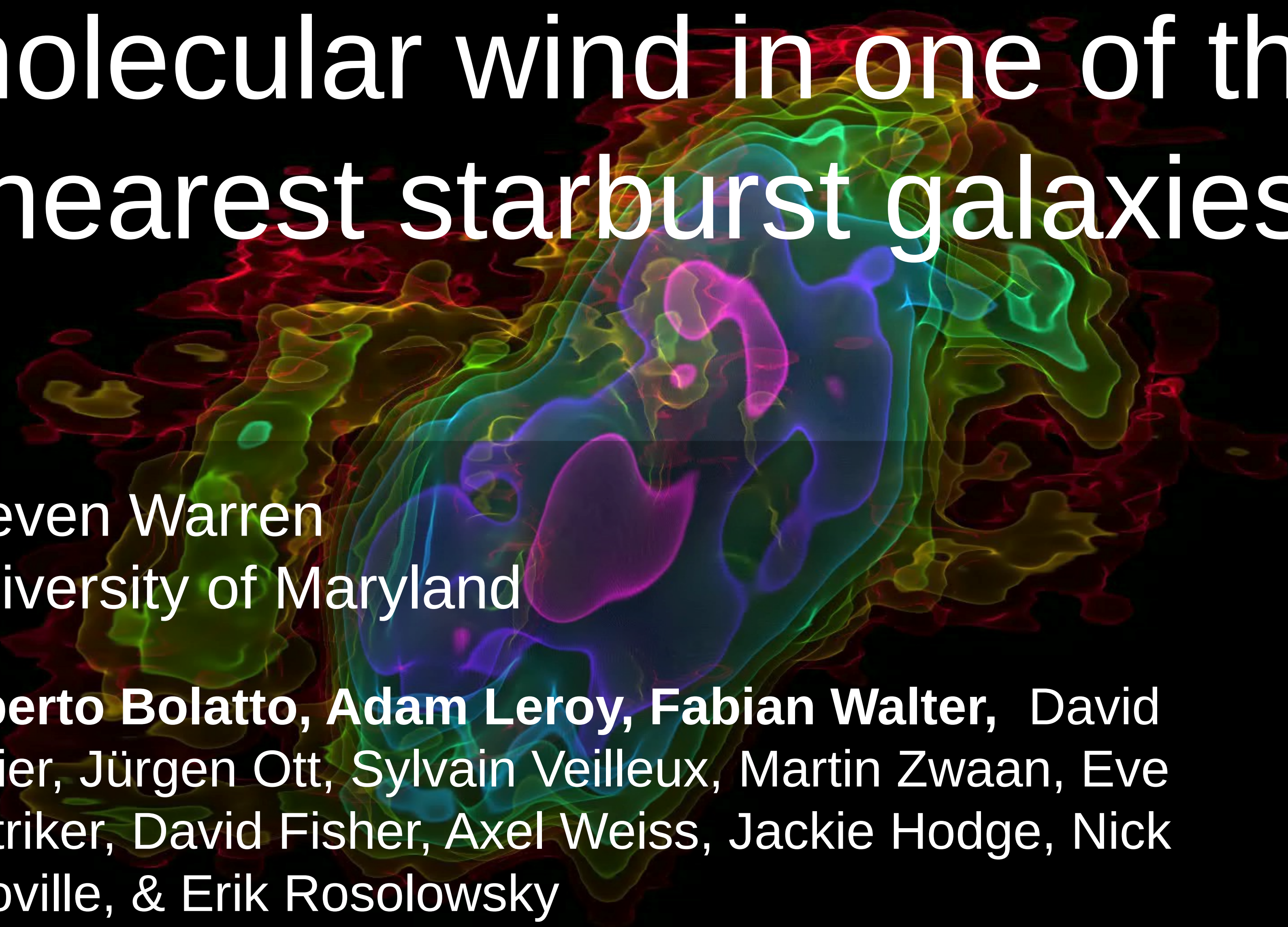
The ALMA view of the molecular wind in one of the nearest starburst galaxies



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The importance of "superwinds"

ON THE NATURE AND IMPLICATIONS OF STARBURST-DRIVEN GALACTIC SUPERWINDS

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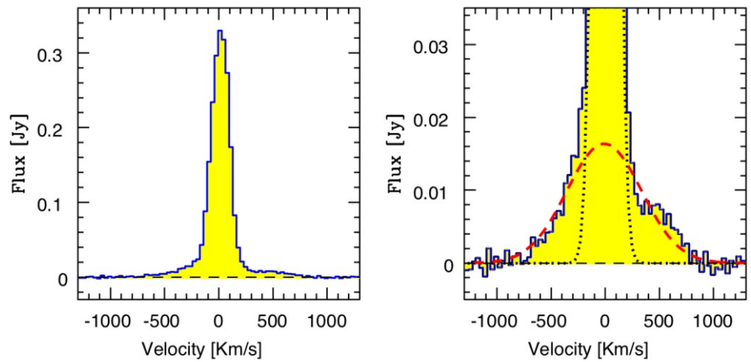
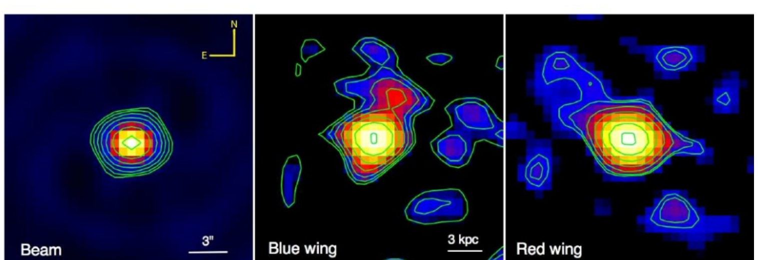
We discuss the possible astrophysical implication of superwinds. At the present epoch, a typical superwind may inject 10^8 $M_\odot$ of metals and 10^{58} ergs into the intergalactic medium (IGM) over its estimated lifetime of 10^7 yr. The local luminosity function for FIRGs implies that about 10^9 $M_\odot$ of metals and 10^{59} ergs could be injected, on average, per L_* galaxy over a Hubble time, even with no cosmic evolution in the superwind rate. Superwinds may play important or even dominant roles in the metal enrichment and heating of both the intracluster medium and general intergalactic medium. Superwinds may make an important contibution to the cosmic X-ray background, and their relationship to the QSO absorption-line phenomenon should be explored. We also speculate that superwinds may represent a phase in the evolution of a FIRG to a QSO/AGN and of a disk-disk galaxy merger to an elliptical galaxy. Finally, we emphasize that powerful FIRGs may be reasonable approximations to galaxies in formation. If so, then superwinds may be important during the process of galaxy formation, with particular relevance to the "explosions" or the "feedback" mechanisms suggested by Ostriker, Cowie, Ikeuchi, Dekel and Silk, White, and others.

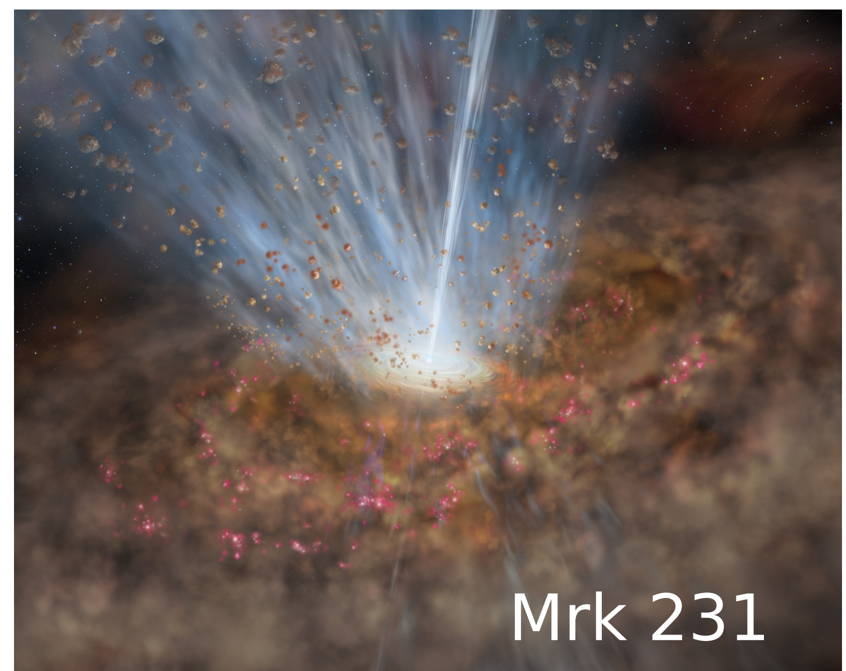
Context

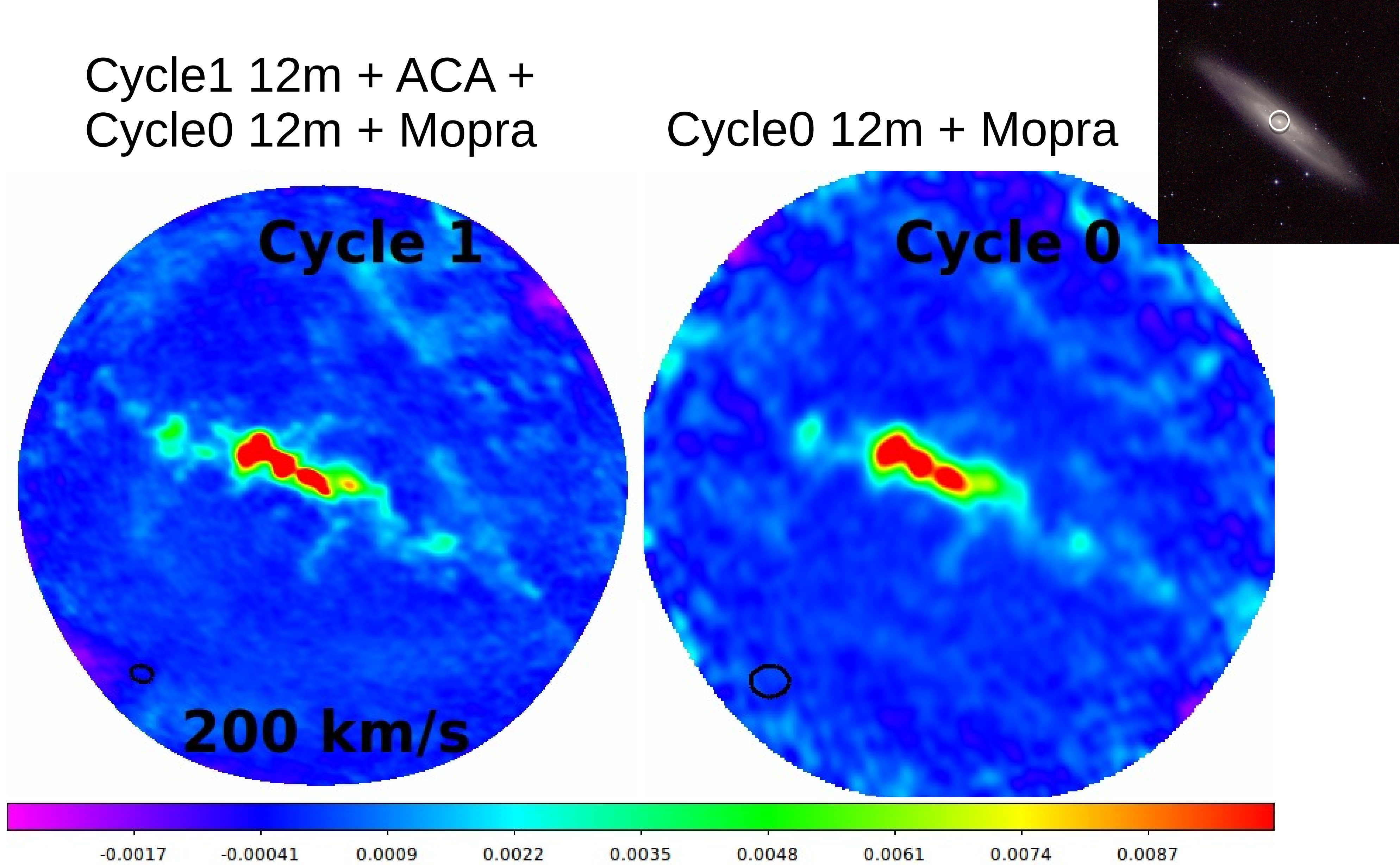
- Most of our understanding of galactic superwinds comes from unresolved observations
- Cold molecular gas is likely the **dominant mass component** (e.g., Rupke+2005)
- Key problems:
  - what is the mass-loading? η=(dM/dt)/SFR
  - How is momentum imparted efficiently to the cold gas?





Feruglio et al. (2010)

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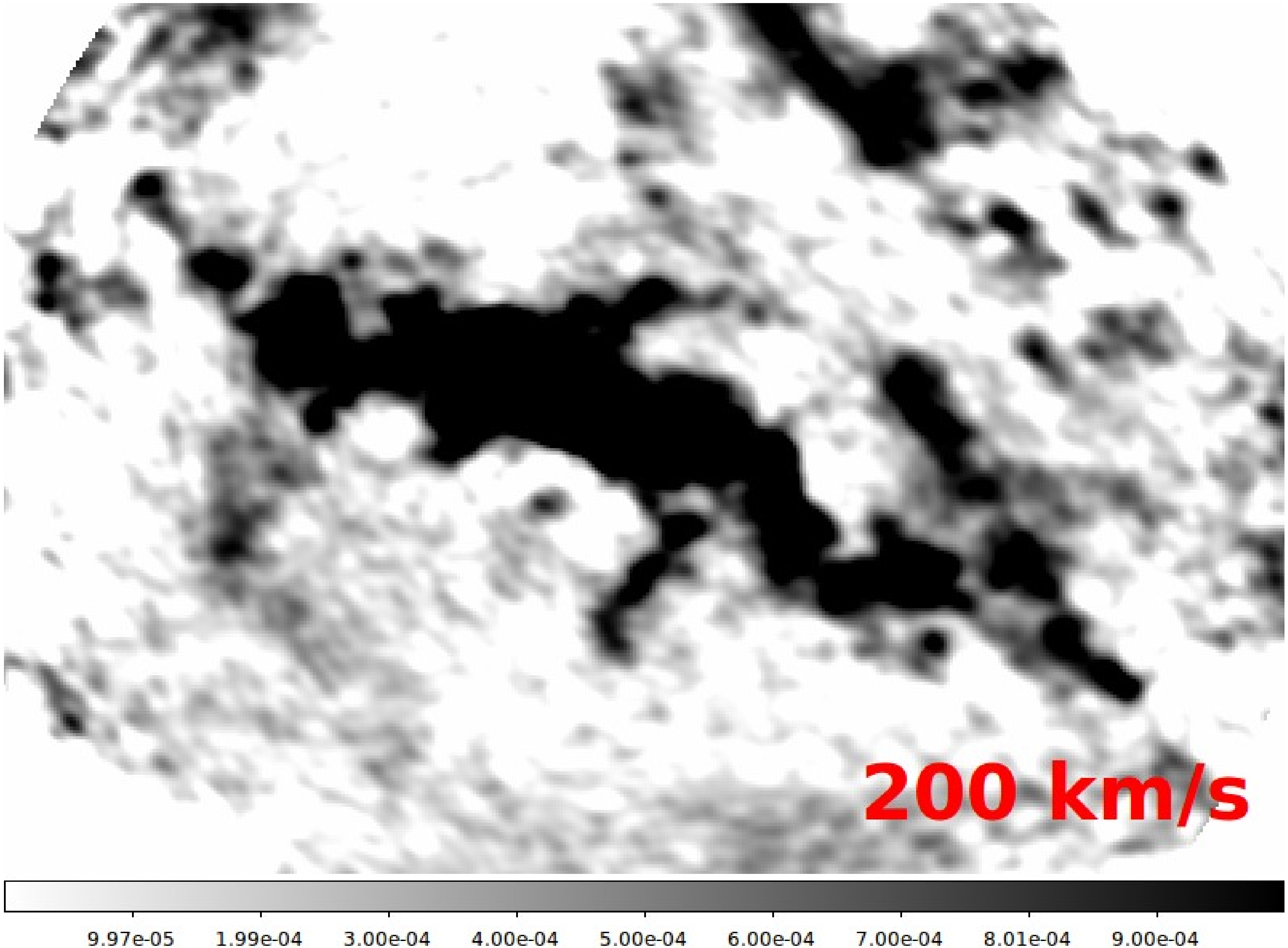
Cycle0 12m + Mopra
Cycle0 12m + Mopra
Cycle 1
Cycle 0
200 km/s
-0.0017
-0.00041
0.0009
0.0022
0.0035
0.0048
0.0061
0.0074
0.0087


200 km/s
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3.00e-04
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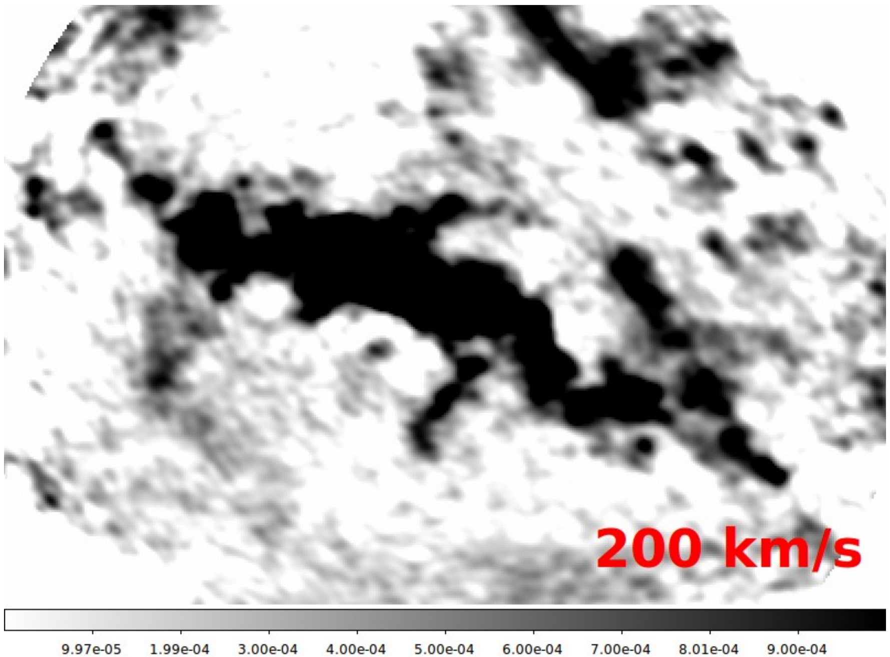
6.00e-04
7.00e-04
8.01e-04
9.00e-04

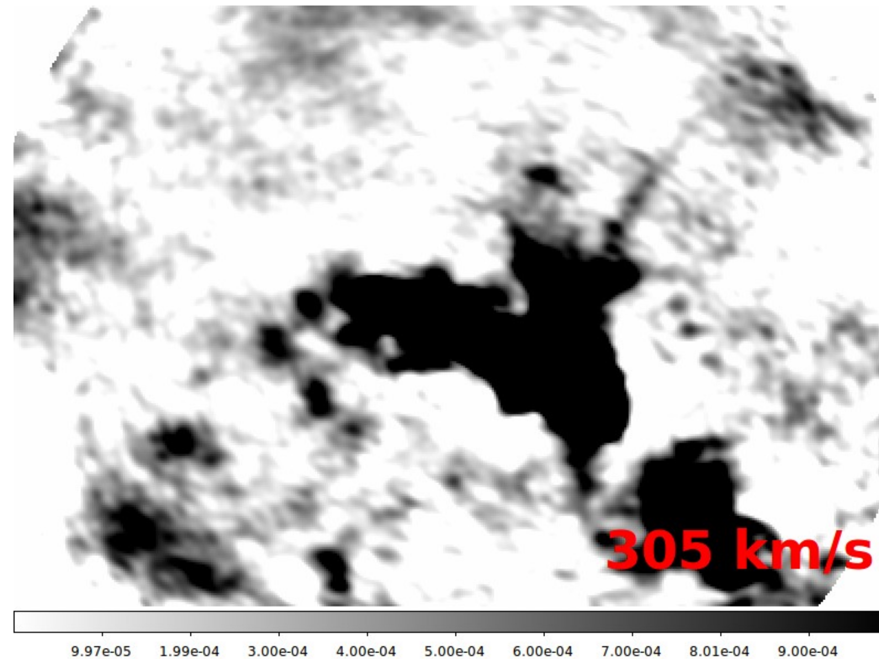
CO (J=1-0)

The Molecular Outflow

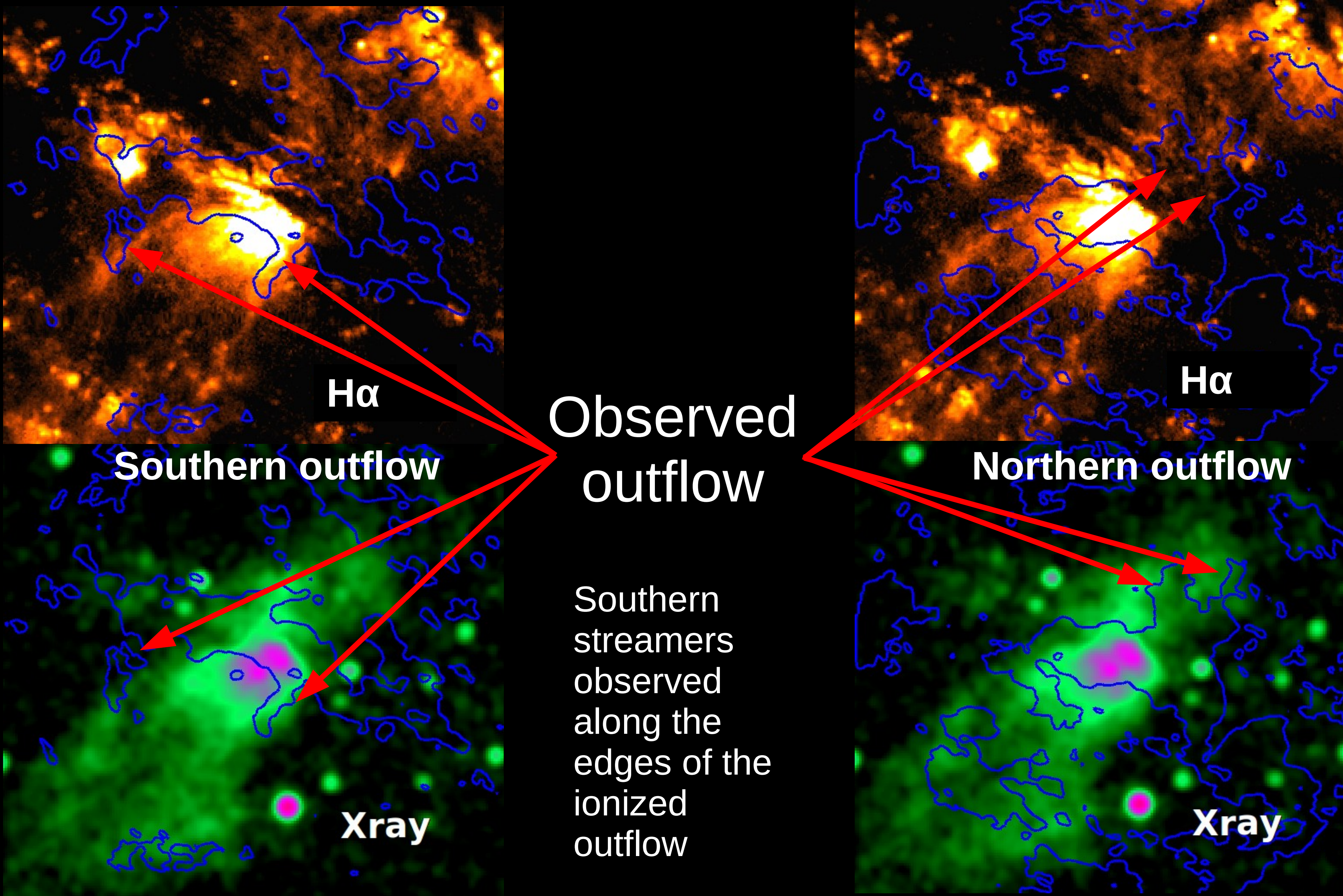
CO (J=1-0)



Approaching side

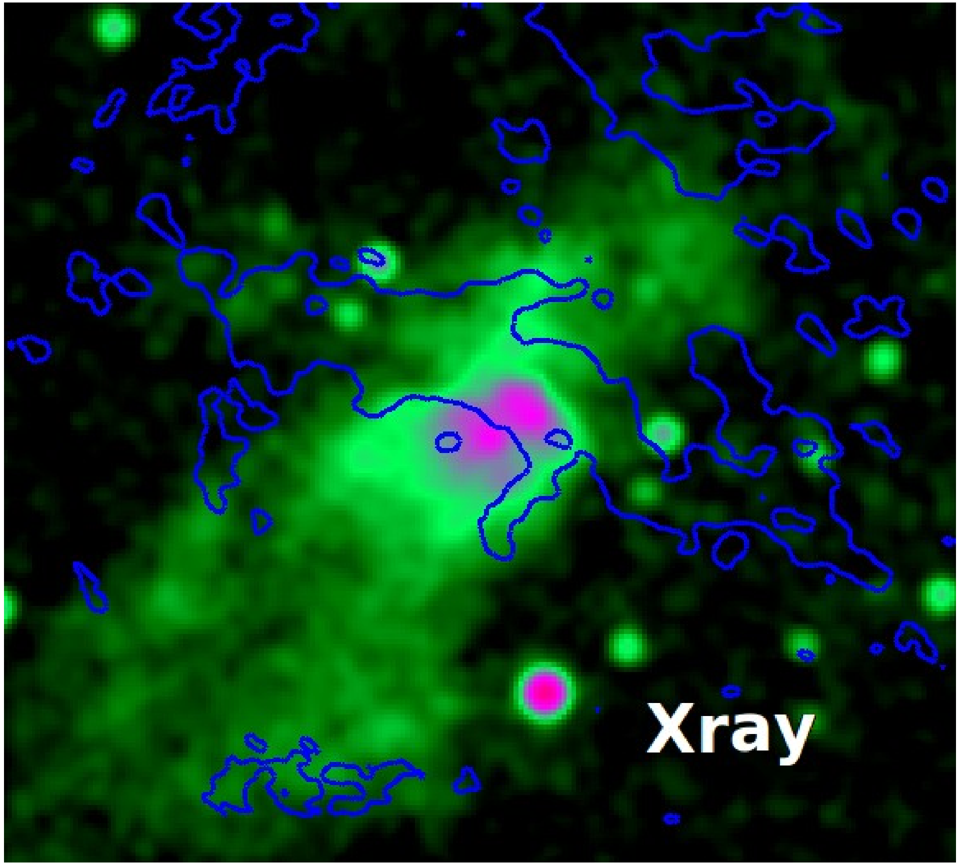


Receding side



Southern streamers observed along the edges of the ionized outflow

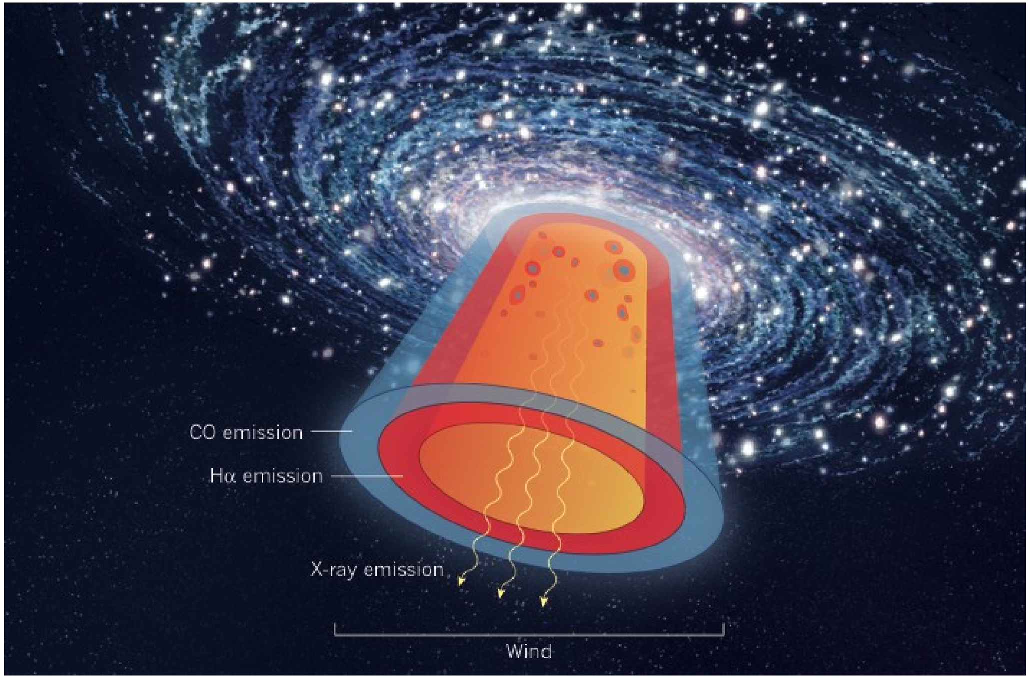
Wind Morphology



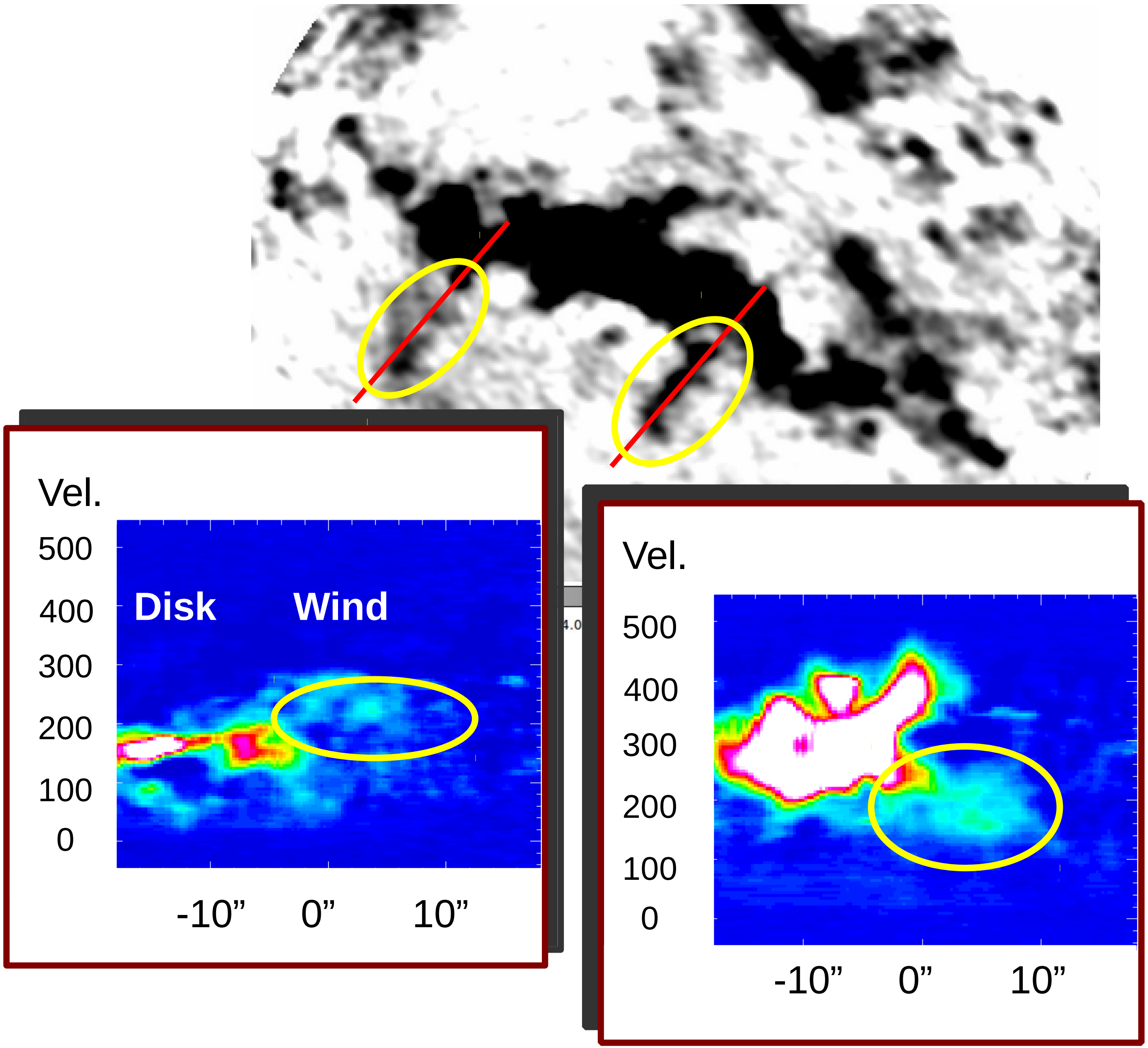
Xray: Strickland et al. 2000

Opening angle = 60^o
Inclination = 78^o

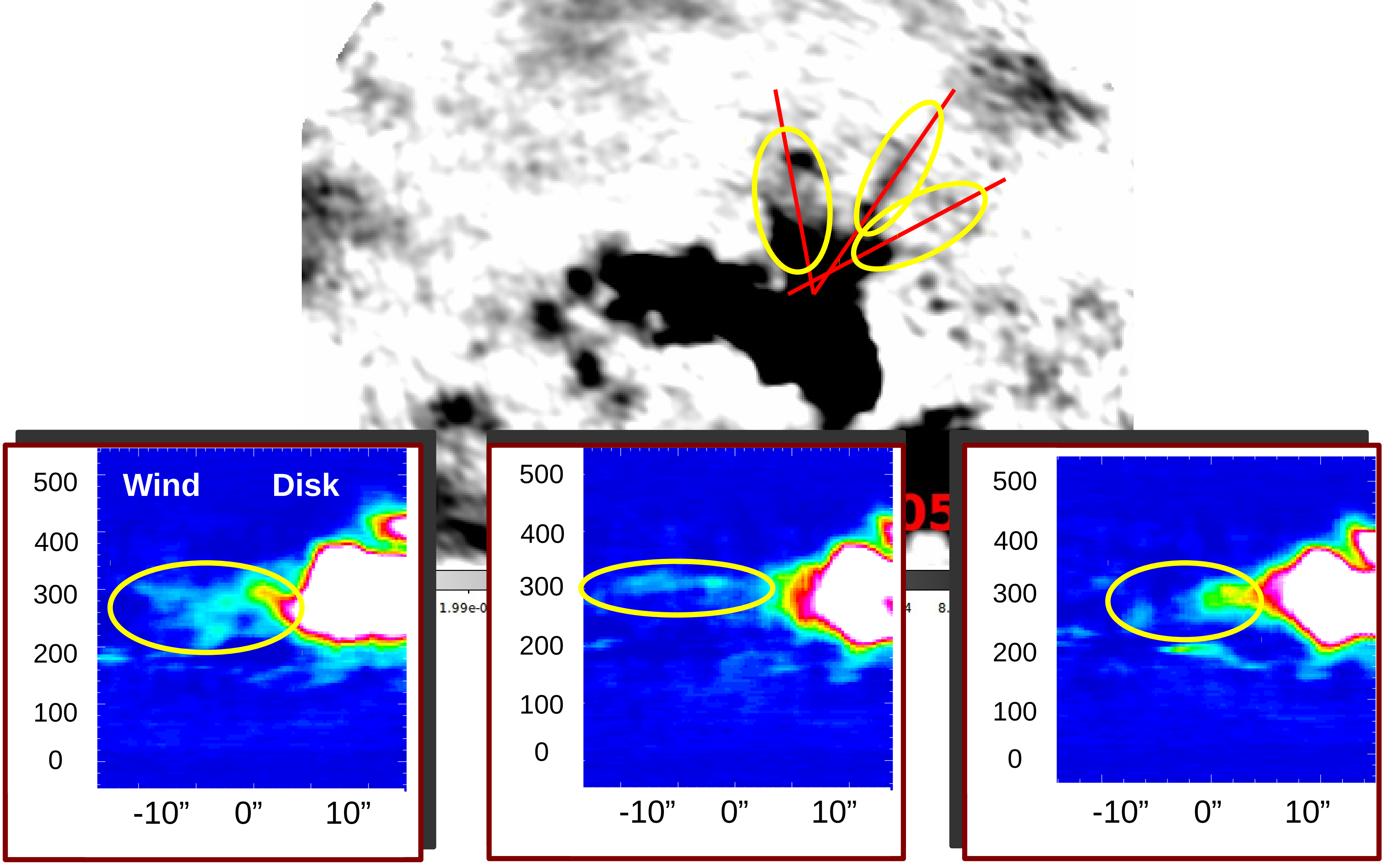
Westmoquette et al. 2011



Westmoquette et al. 2013



- The width of the most prominent streamer is unresolved
- Implying linear widths < 30 pc
- ~200 pc in length (projected)
- $V_{sh} \approx 60$ km/s (projected)
- $T_{dyn} \approx 3.25$ Myr
- Line width is large implying very turbulent motions



Wind
Disk
500
400
300
200
100
0
-10”
0”
10”
1.99e-0

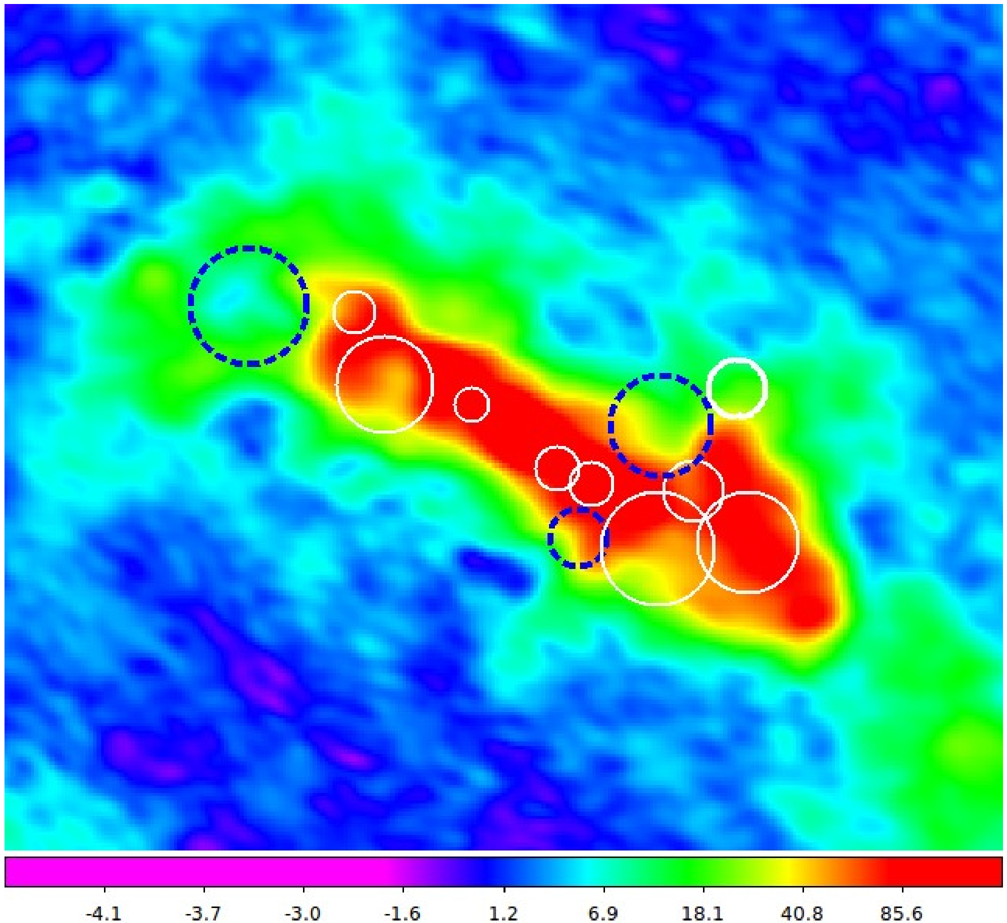
Outflow Results

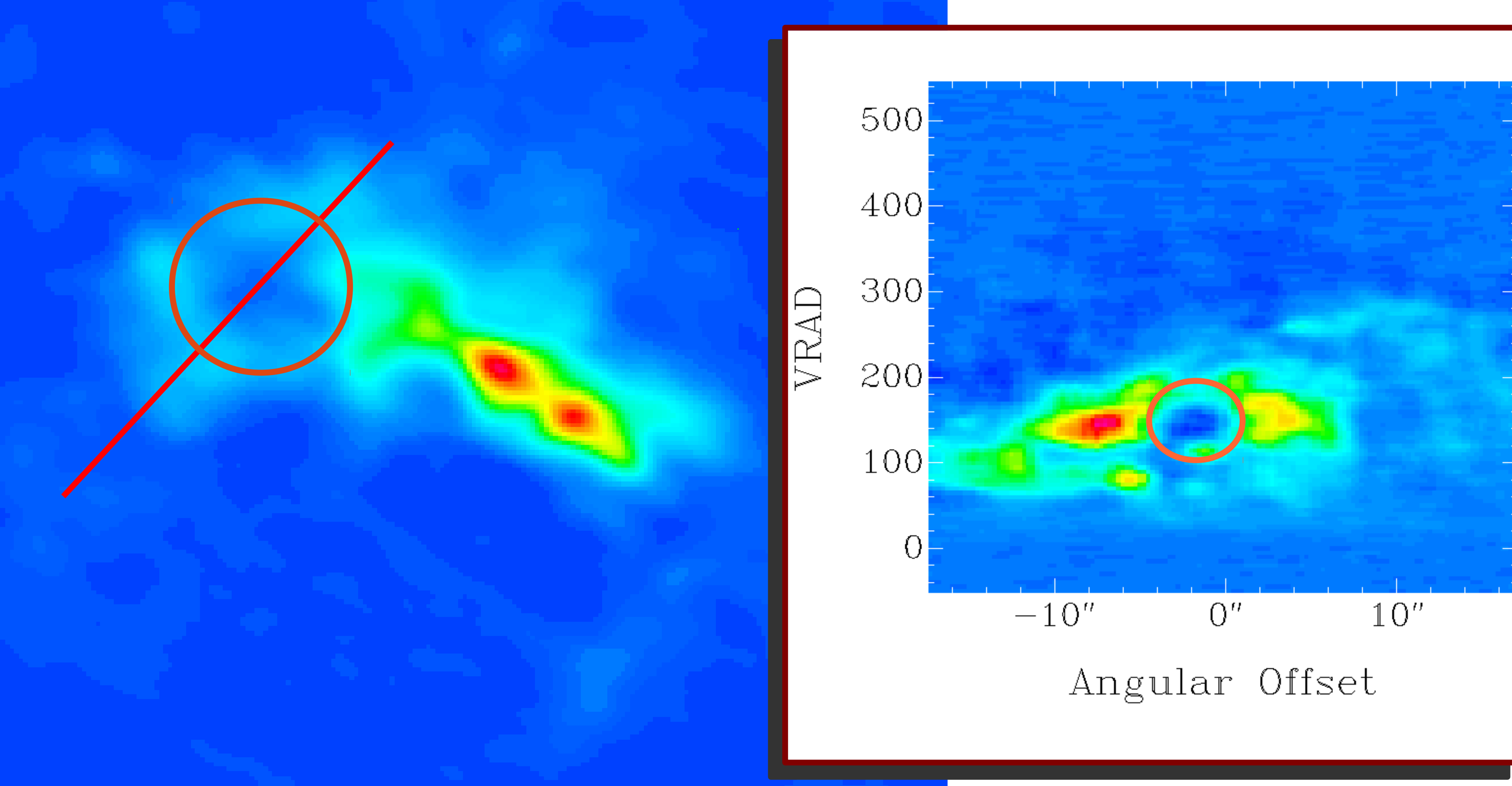
- Total outflow mass > 6 x 10^6 M_{sun}
  - α_{CO} assumption: these are not "virialized GMCs." Likely highly turbulent, suggesting low τ_{CO}.
  - Using optically thin calculation with a "reasonable" CO/H2 –

    $\alpha_{CO} \approx 0.3$ M_{sun}/(K km/s pc^2) (Bolatto, Wolfire, & Leroy 2013 ARAA)
- Mass outflow rate
  - Geometry is important
  - Projected outflow velocity ≈ 50 km/s
  - Projected streamer size ≈ 100 pc
- dM/dt ≥ 9 M_{sun}/yr (can push it to ~ 3 M_{sun}/yr with very pessimistic projection assumptions)
- SFR ~ 3 M_{sun}/yr
- η ~ 3
- Exhaust star formation in ≈ 60 Myr

Imprints of Stellar Feedback

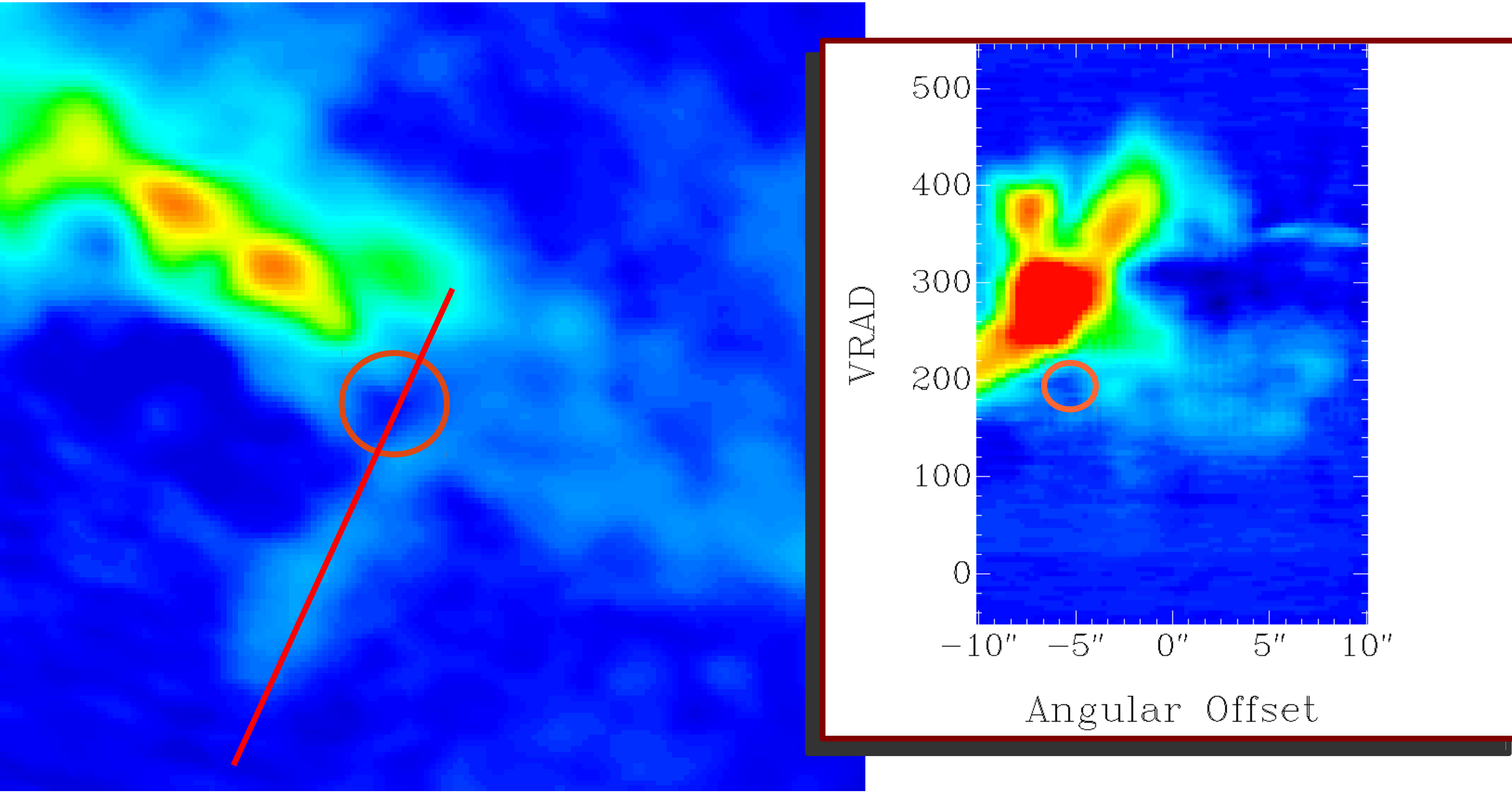
Sakamoto et al. 2006





$r_{sh} \approx 90$ pc $v_{sh} \approx 22.5$ km/s $E_{sh} \approx$ few x 10^{53} erg

$t_{dyn} \approx 4$ Myr momentum ≈ few x 10^{46} g cm/s $A_v \approx 9$



$r_{sh} \approx 45$ pc $v_{sh} \approx 20$ km/s $E_{sh} \approx 10^{53}$ erg

$t_{dyn} \approx 1.1$ Myr momentum $\approx 8 \times 10^{46}$ g cm/s $A_v \approx 2$

Conclusions

- ALMA has revealed the molecular outflow in NGC 253
- Expanding shells are imparting mechanical energy onto the gas, lifting the gas above the disk where the ionized outflow drags it away.
- Unclear what the final outcome of the wind material
- Search for other dense gas tracers in the wind.
  - Already hints in the HCN maps for dense gas in the outflow
- Upcoming deep HST IR observations may possibly reveal the central engines of the expanding shells (PI Leroy)