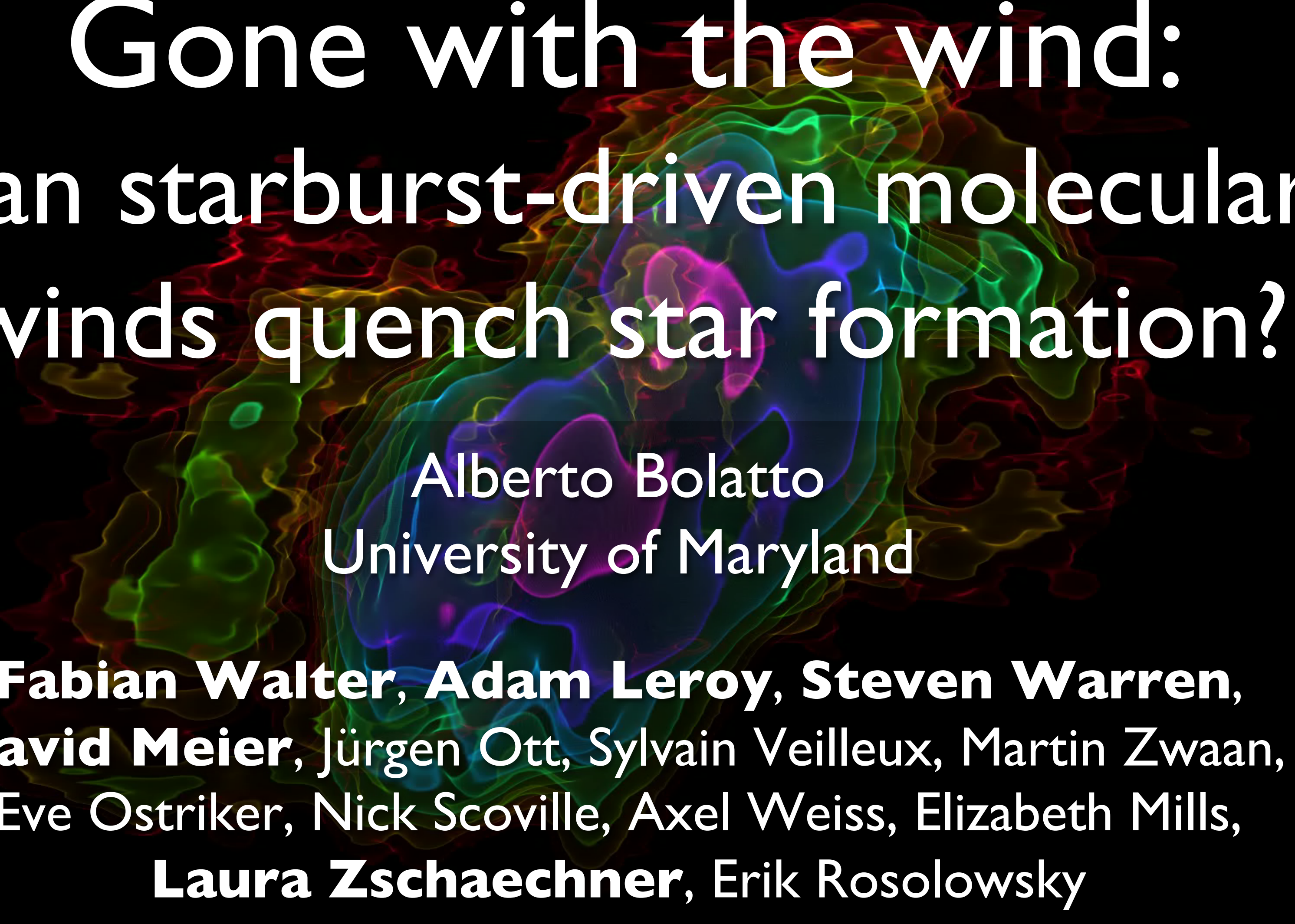

Gone with the wind: can starburst-driven molecular winds quench star formation?

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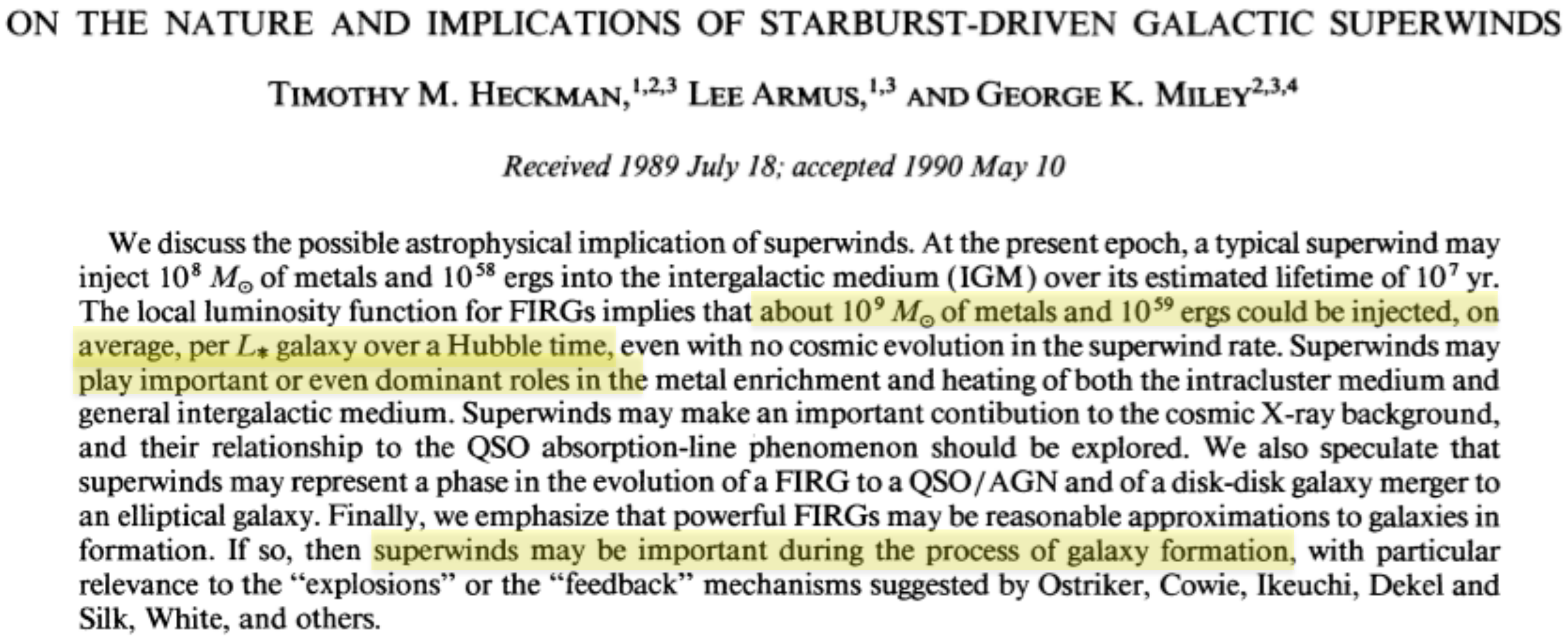
University of Maryland

Fabian Walter, **Adam Leroy**, **Steven Warren**,
David Meier, Jürgen Ott, Sylvain Veilleux, Martin Zwaan,
Eve Ostriker, Nick Scoville, Axel Weiss, Elizabeth Mills,
Laura Zschaechner, Erik Rosolowsky

Outline

- Motivation: why is this interesting?
    - Outflows and galaxy evolution
    - Molecular outflows at high and low redshift
- NGC 253 outflow
    - Filamentary structures, basic properties
    - Acceleration?
    - Deep HST imaging
    - Dense gas in the outflow
    - Can radiation pressure do it?
    - What's next?

The importance of “superwinds”



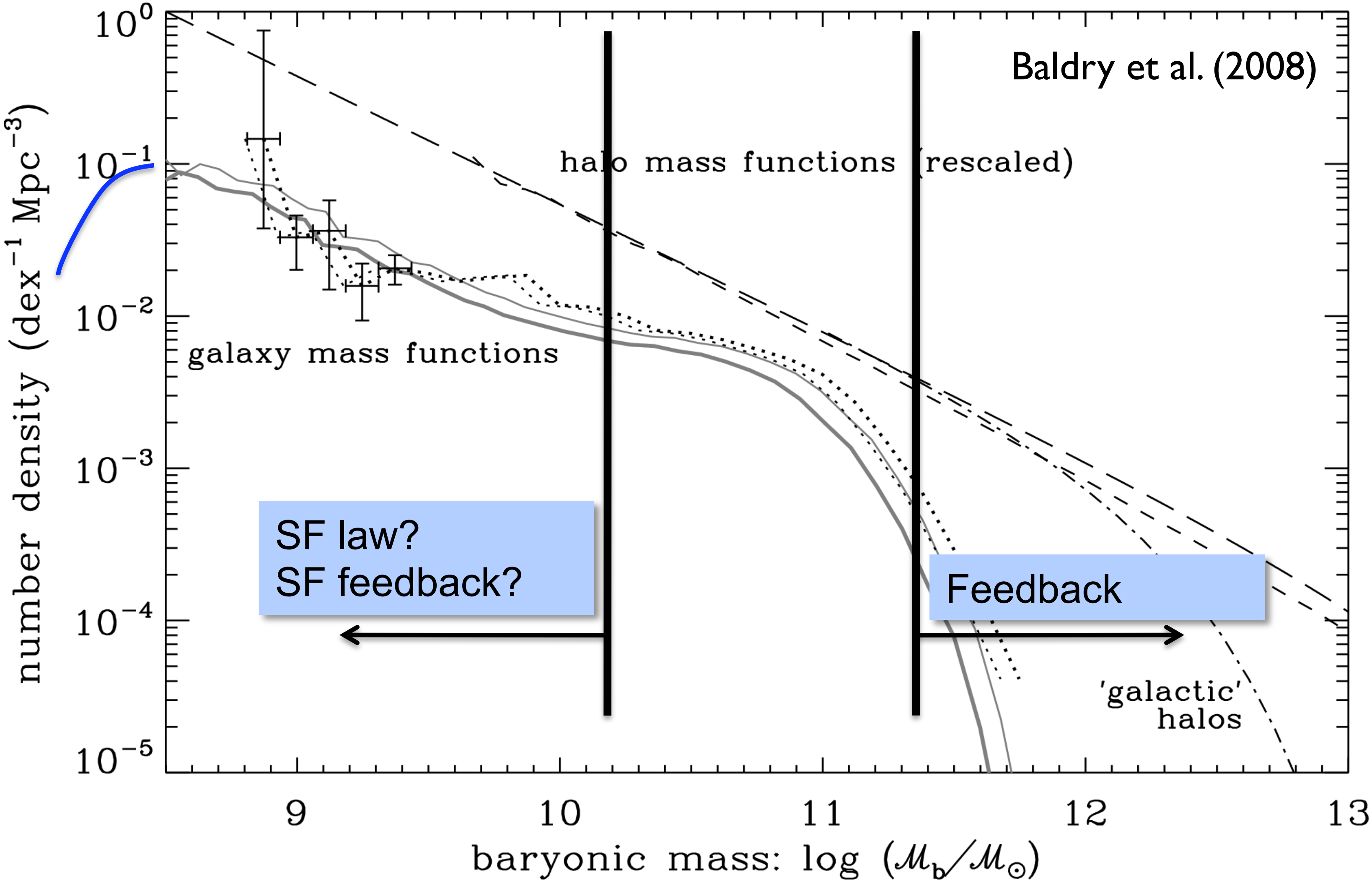
ON THE NATURE AND IMPLICATIONS OF STARBURST-DRIVEN GALACTIC SUPERWINDS

Timothy M. Heckman,[1,2,3] Lee Armus,[1,3] and George K. Miley[2,3,4]

Received 1989 July 18; accepted 1990 May 10

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.

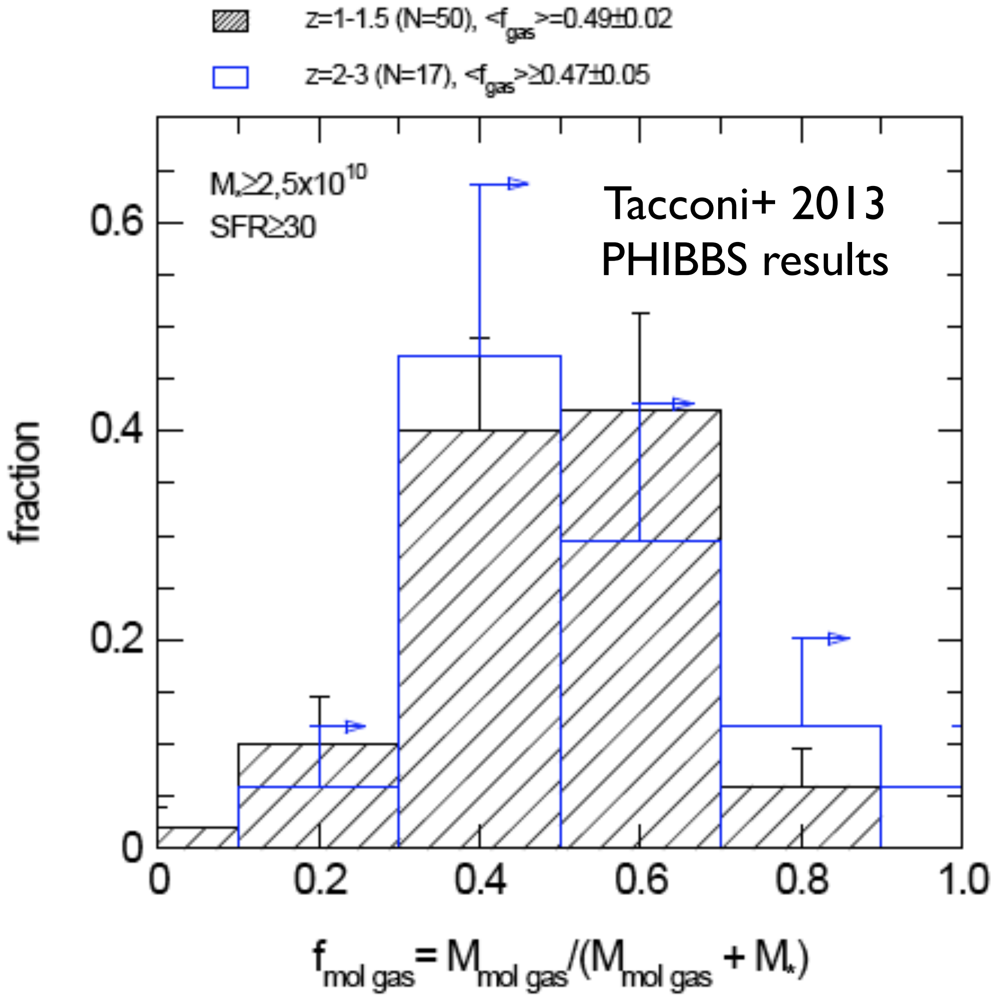
Shaping the galaxy mass function



Mismatch between halo and galaxy mass functions: particle physics or astrophysics?

Lengthening depletion timescales

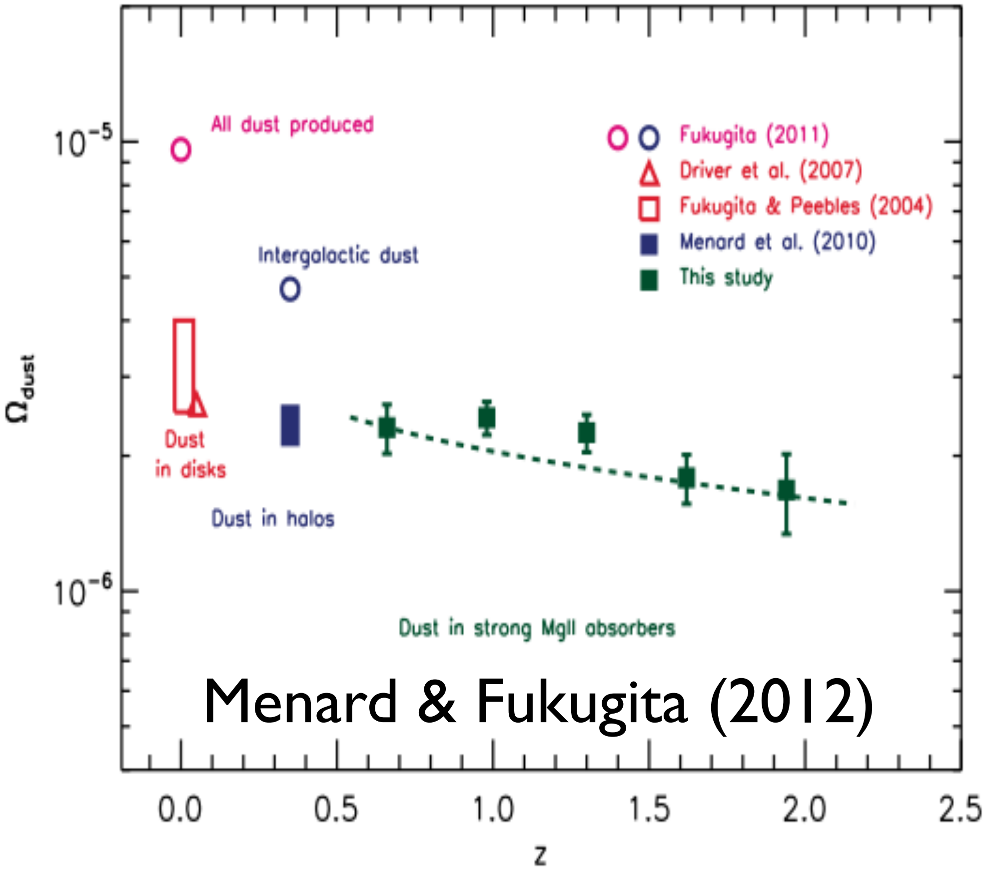
- Little variation in gas fraction between z~2-3 and z~1
- This requires "recycling"
- Baryons accreted at earlier times are thrown into the halo and re-accreted later (e.g., Davé et al. 2011)



Tacconi+ 2013
PHIBBS results

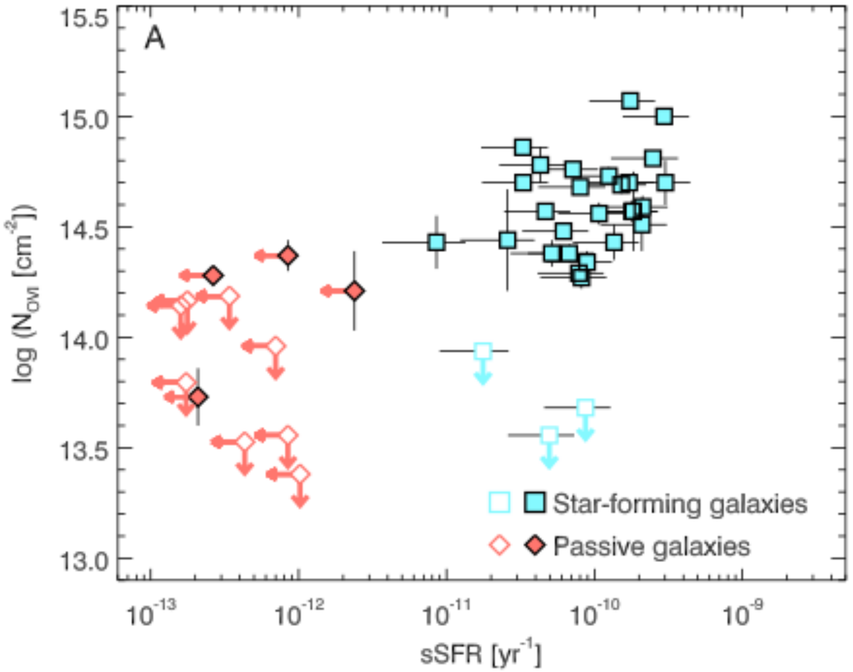
Enriching the IGM

- Halos are dusty (Menard & Fukugita 2012, Peek+ 2015)
- Dust can only be carried there by cool outflows
- Melendez+ 2015, Leroy+ 2015



Menard & Fukugita (2012)

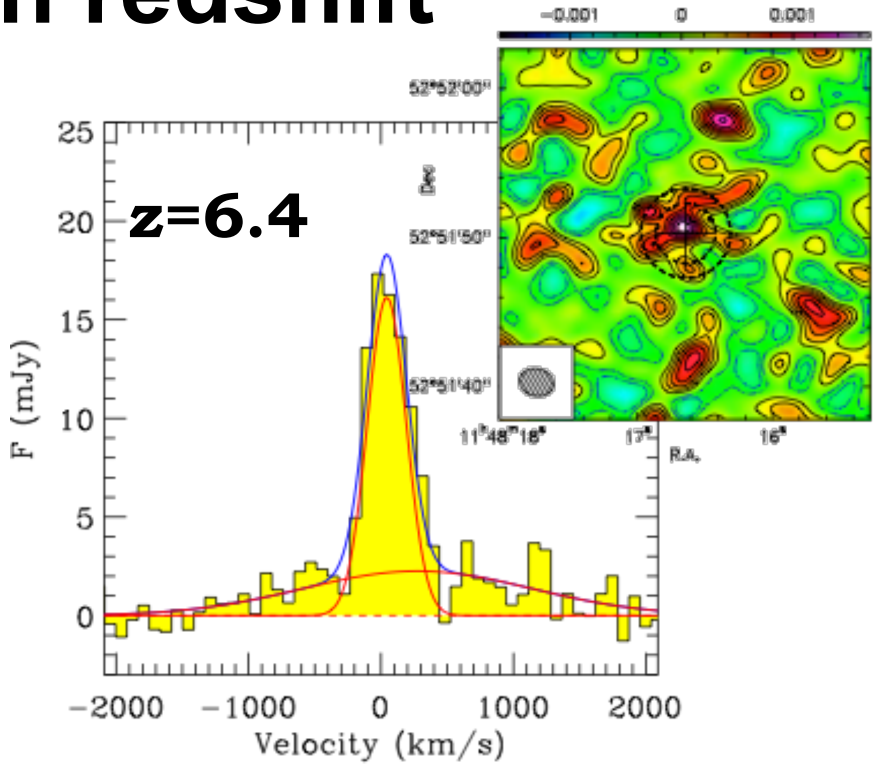
Tumlinson+ (2011)

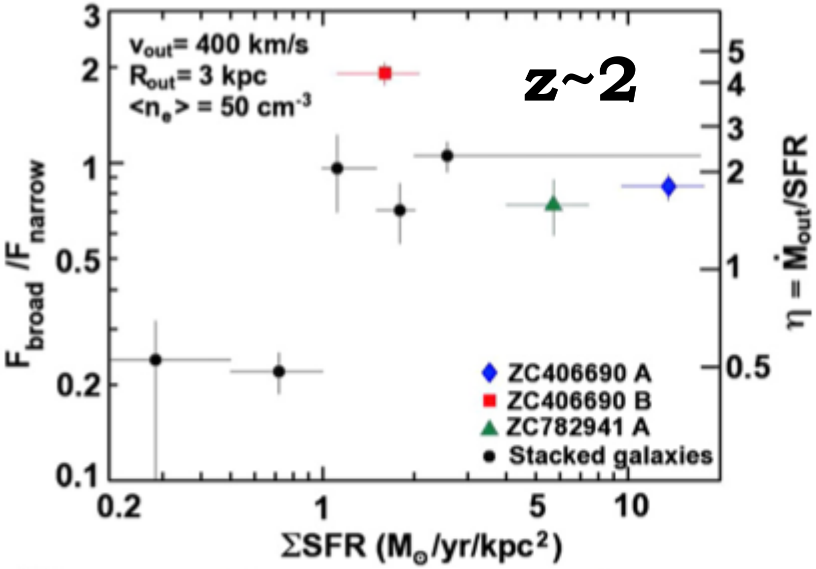


- ~15% of all the Oxygen resides in halos of SF galaxies, maybe even most of the Oxygen
- You see it around SF galaxies

Winds at high redshift

- Evidence early on for pervasive winds in LBGs (Pettini+ 2000)
- Maiolino+ (2012) find a fast, QSO driven wind in [CII] in the z=6.42 QSO J1148
- The mass outflow rate would be ~3500 $M_\odot$/yr

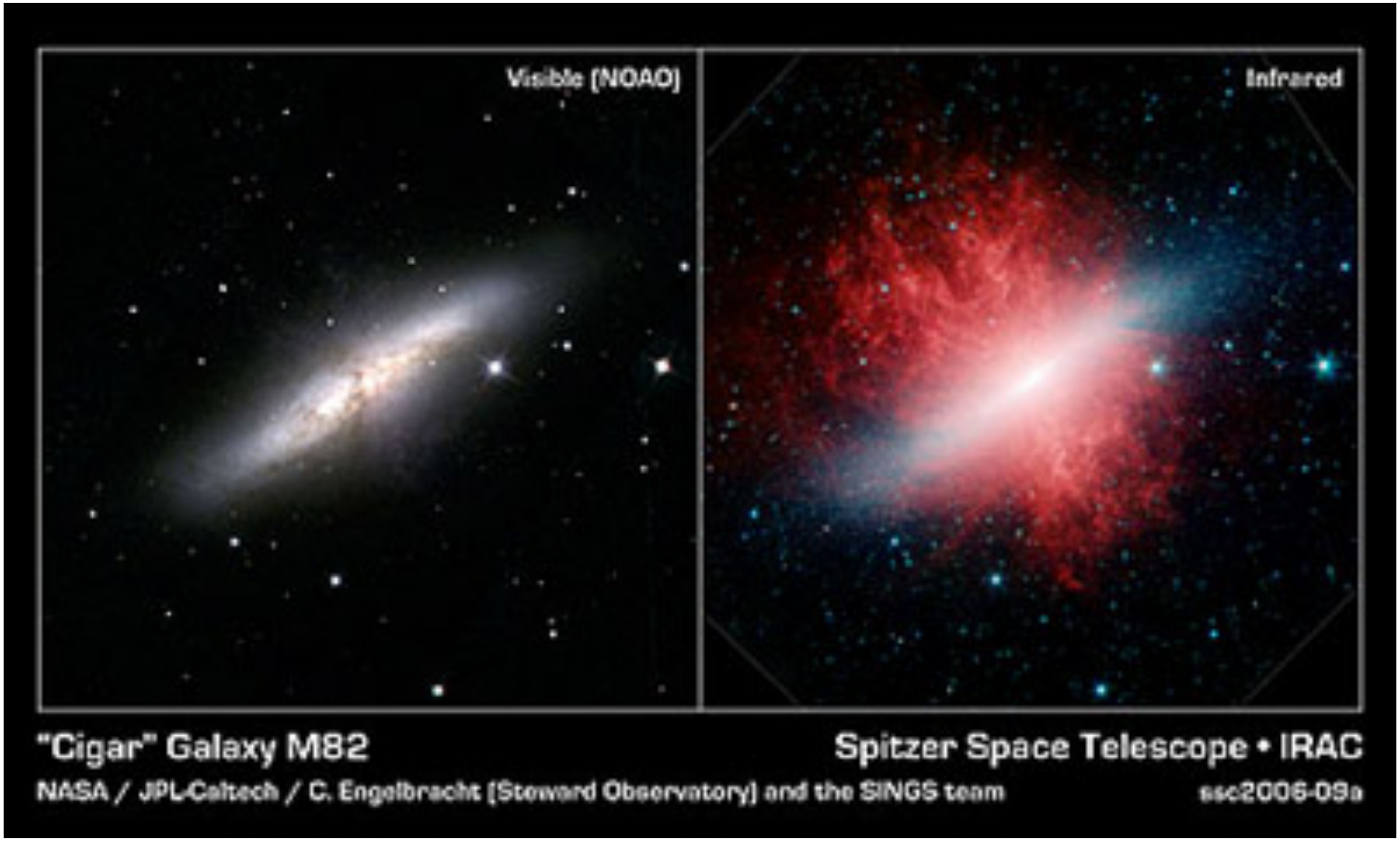




- Evidence for widespread wind activity in the SINS sample of main sequence galaxies (Shapiro + 2009)
- Broad lines correlated with SFR (Newman+ 2012)

Winds at low redshift

M82, the prototypical starburst, hosts a multiphase wind

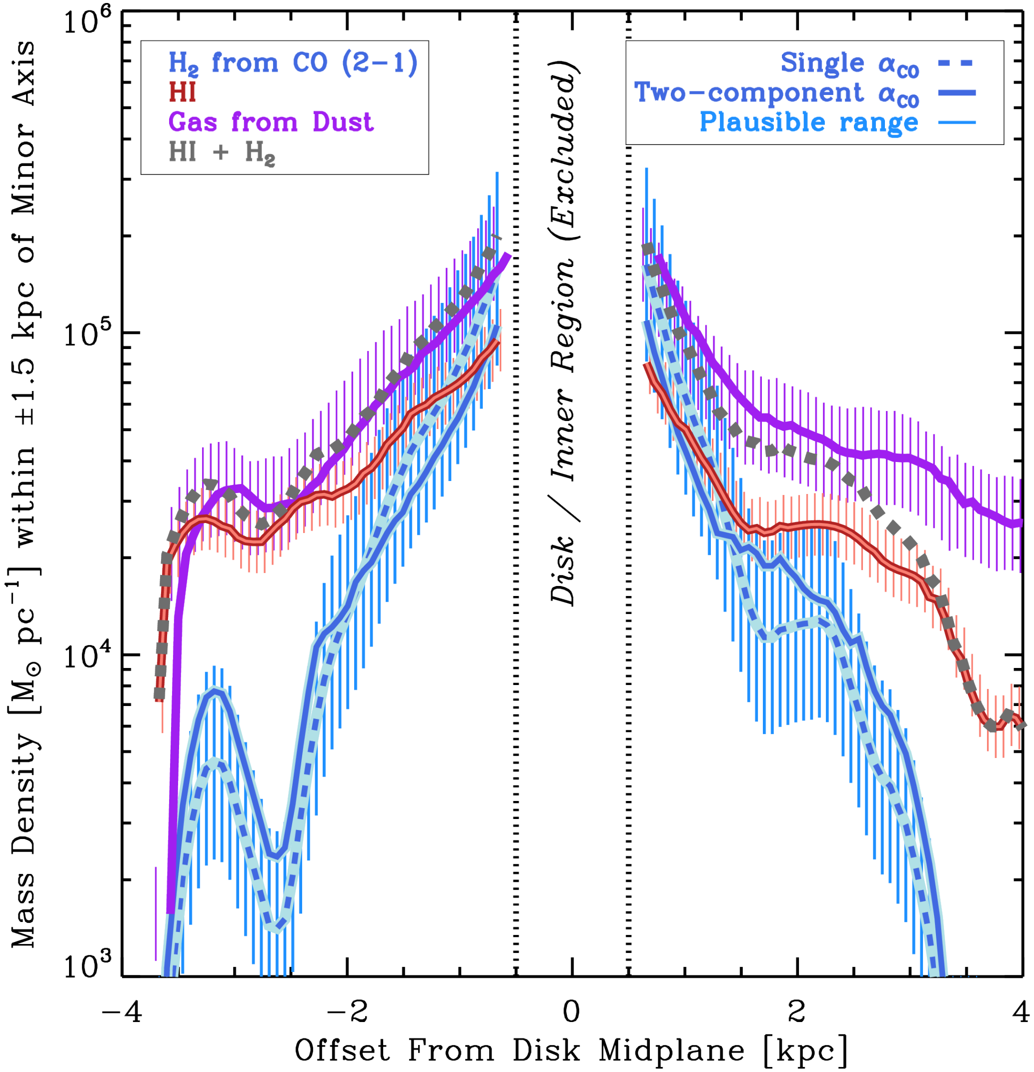


Walter+ 2002, Strickland & Heckman 2009, Engelbracht+ 2006

Multiphase structure

Mass profiles along the minor (outflow) axis show declining distribution and a changing phase of the cold gas. Dust tracks HI + H_2 with relatively little room for HII.

The mass dominant phase is cold gas



From Leroy, Walter+ (2015)

Mass profiles of H_2, HI, and gas from dust integrated around the minor axis.

Accelerating molecular clouds

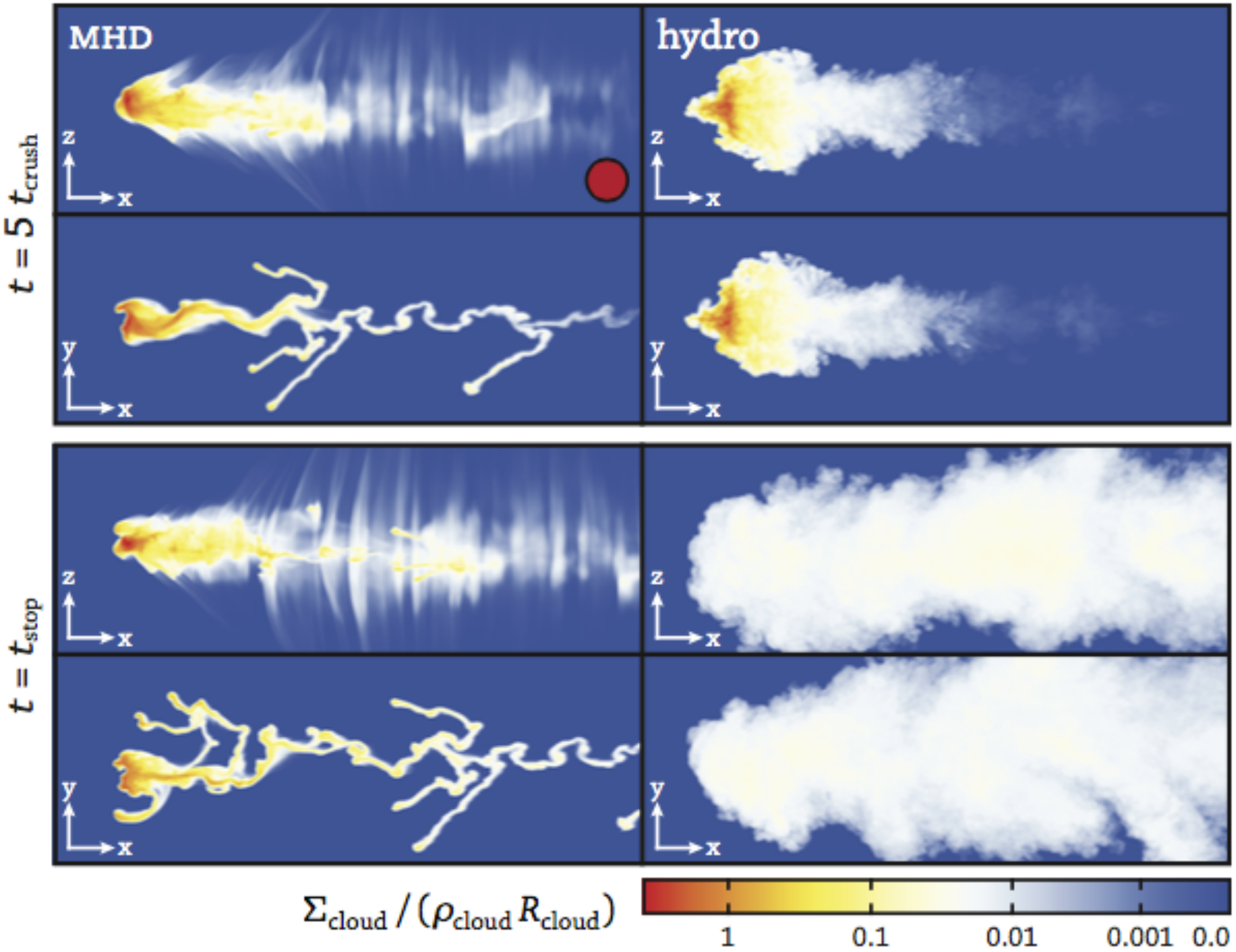
$\rho_{air} \sim 10^{-3}$ g cm^{-3}

$n_{plasma} \sim 10^{-1}$ cm^{-3}

$\rho_{iron} \sim 10$ g cm^{-3}

$n_{GMC} \sim 10^{3}$ cm^{-3}

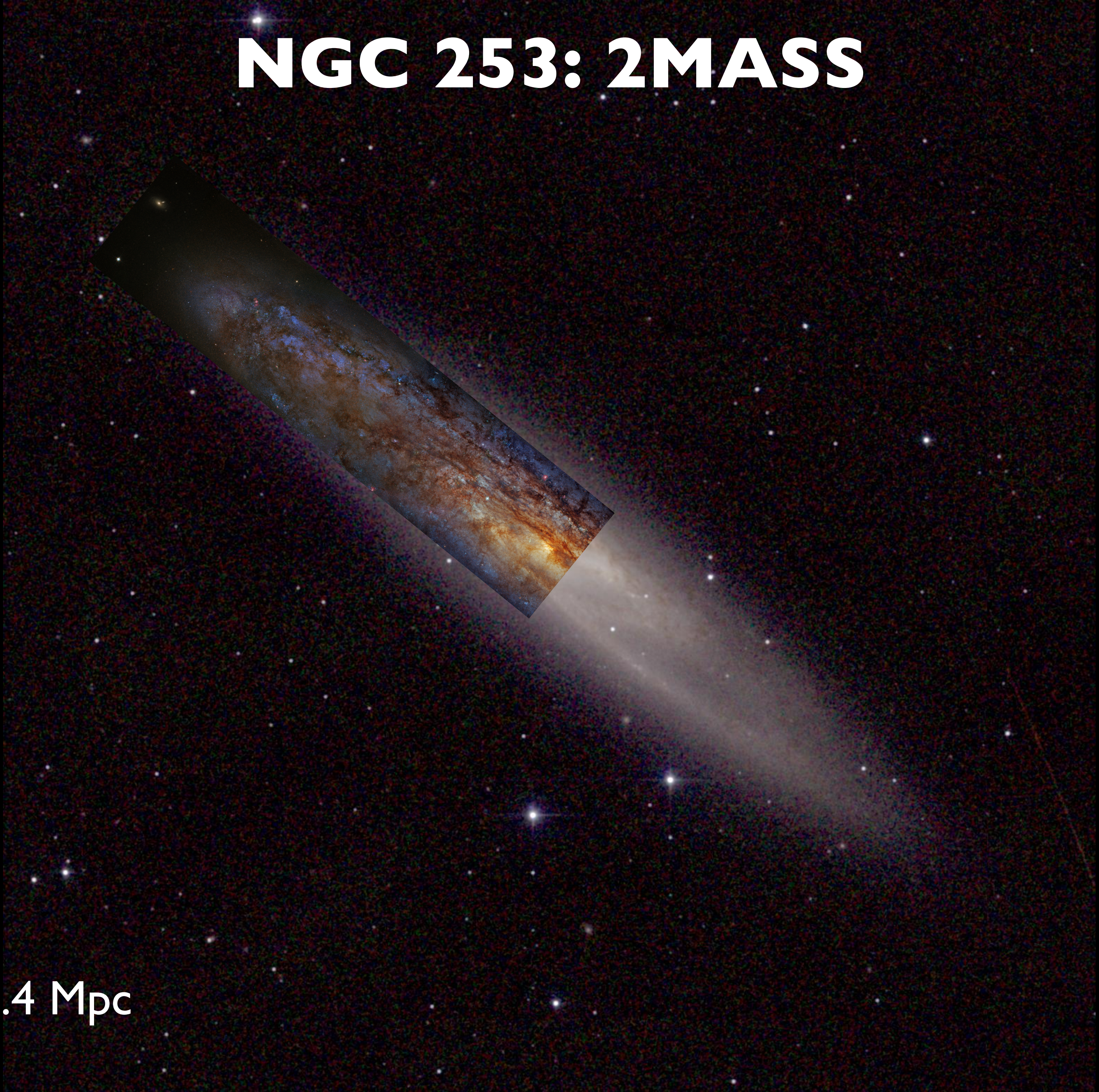
Keeping the cloud integrity



McCourt et al. (2015)

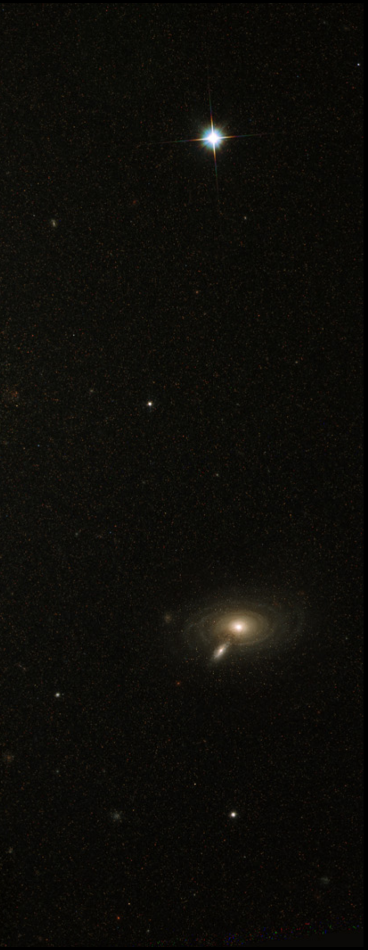
Magnetized clouds? McCourt+ 2015
Heat conduction stabilized clouds? Marcolini+ 2005
Radiative cooling stabilized clouds? Cooper+ 2009

NGC 253: 2MASS

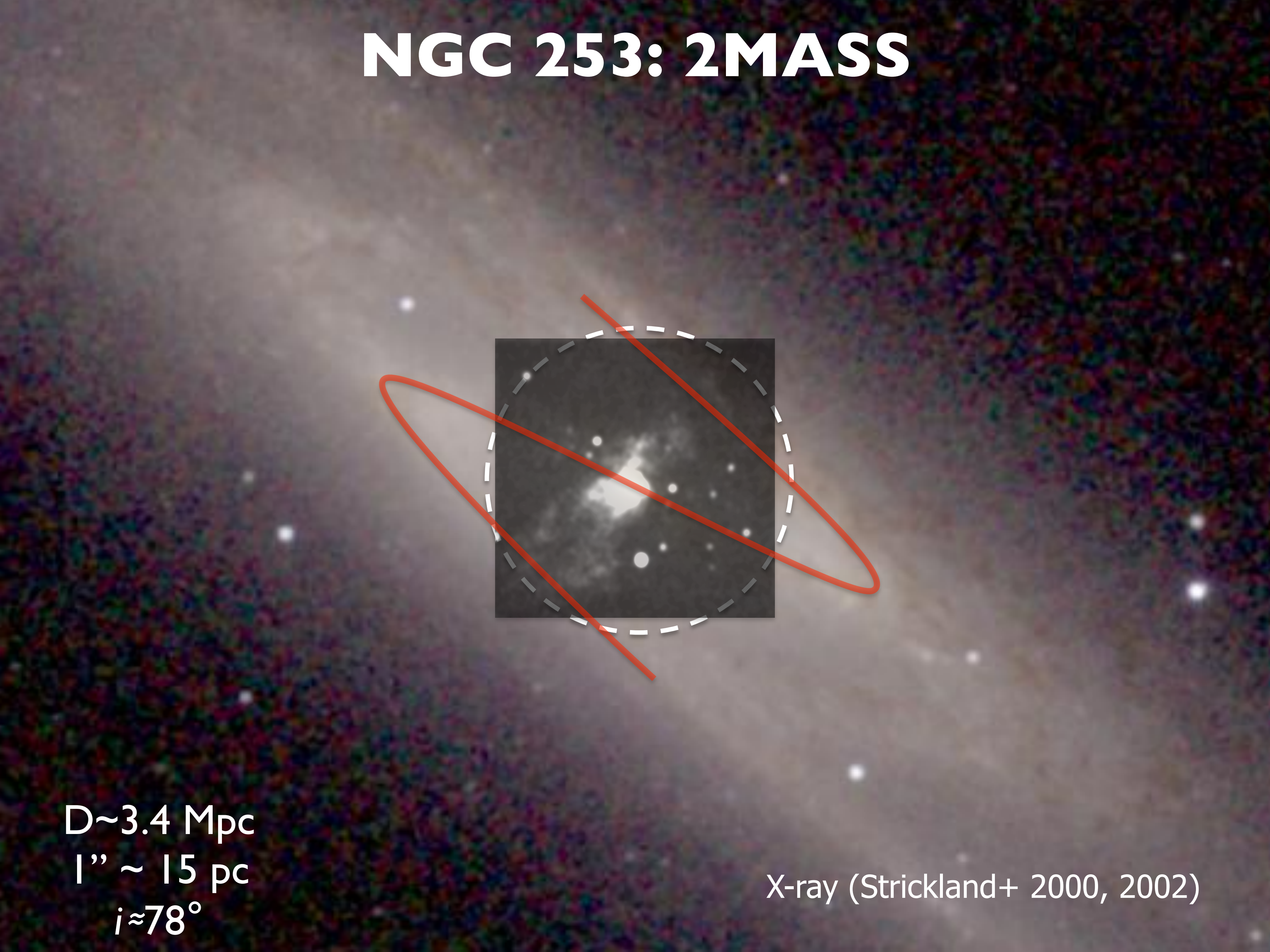


D~3.4 Mpc

NGC 253: HST



NGC 253: 2MASS



D~3.4 Mpc

1” ~ 15 pc

$i \approx 78^\circ$

X-ray (Strickland+ 2000, 2002)

CO data

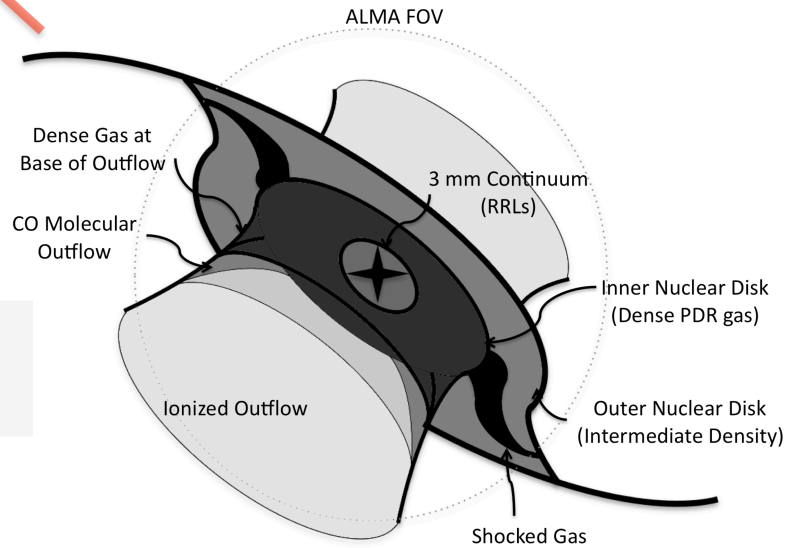
Sakamoto+ (2006)
superbubbles

cycle0+cycle1
+ACA+Mopra

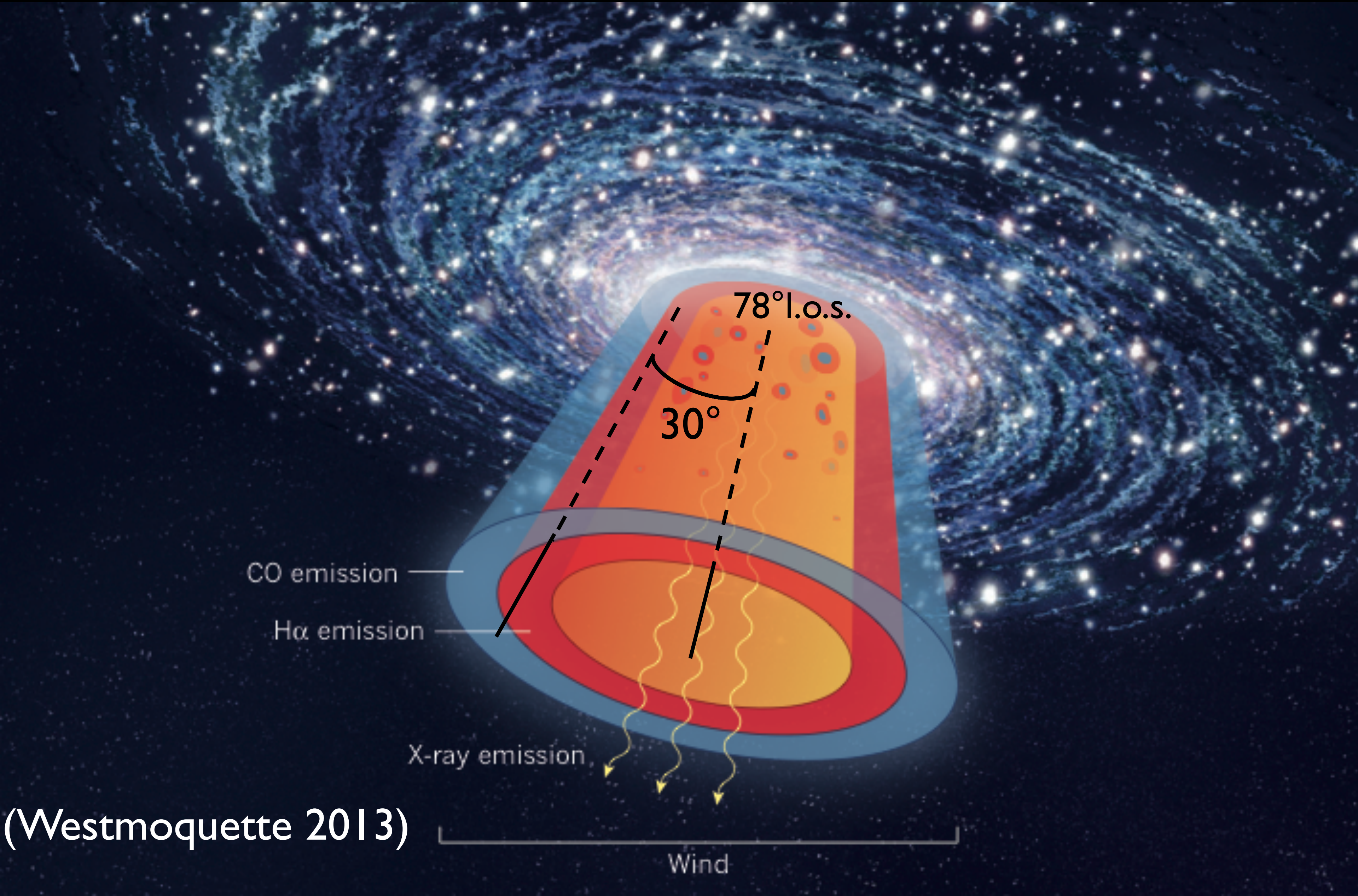
cycle0+Mopra

Bolatto+ (2013)

Sketch from Meier, Walter, et al., 2015



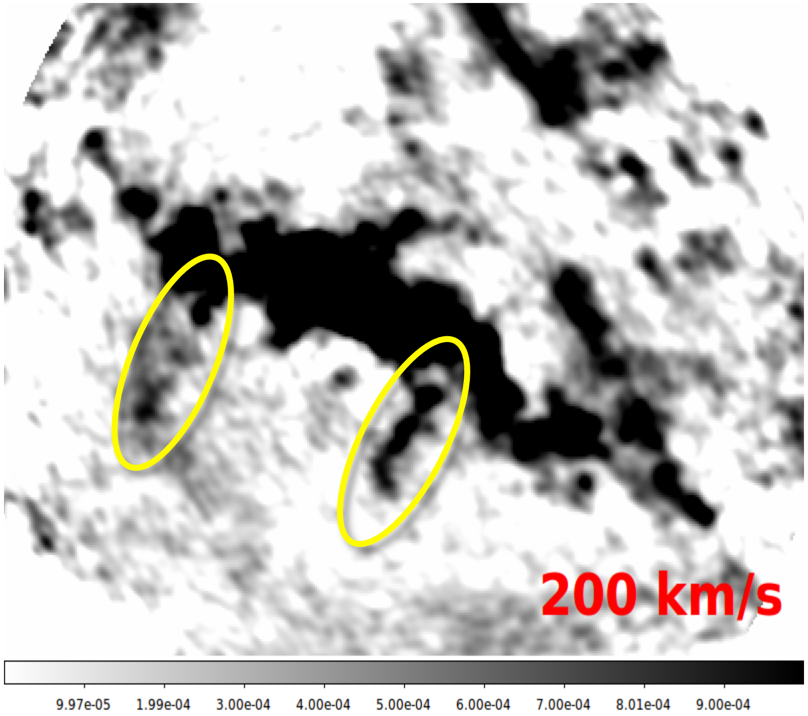
Outflow structure



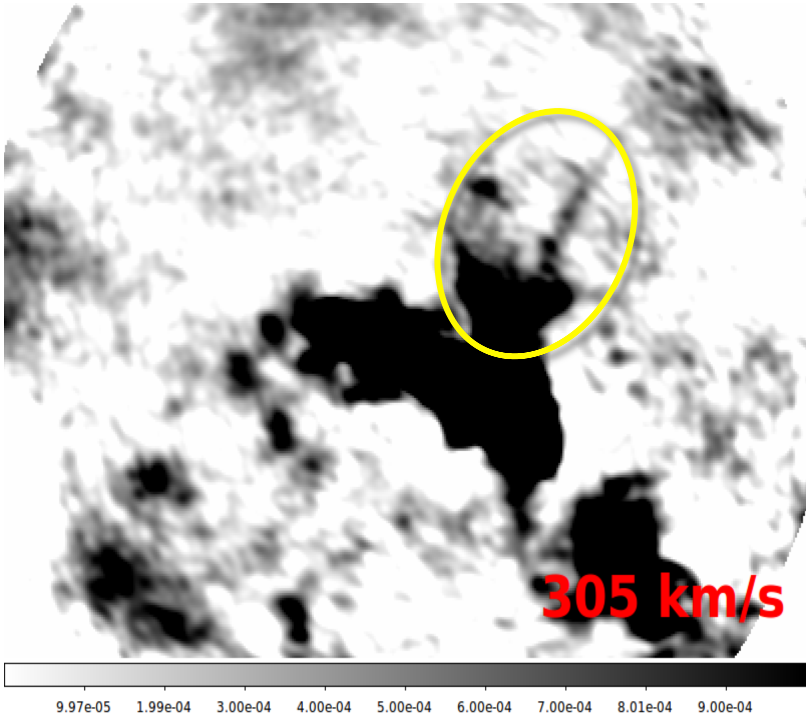
(Westmoquette 2013)

The Molecular Outflow

CO (J=1-0)

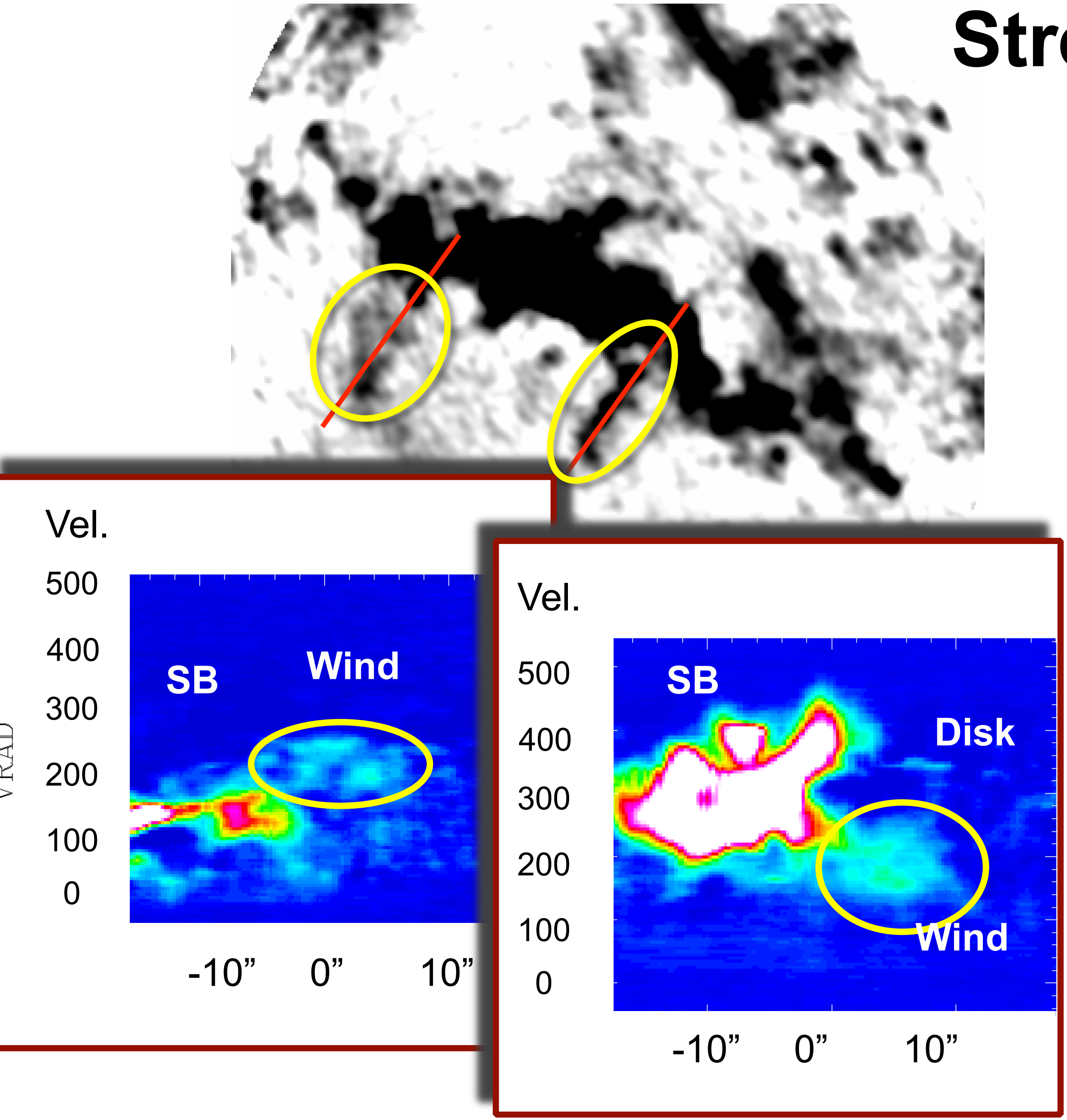


Approaching side
(in front of disk)



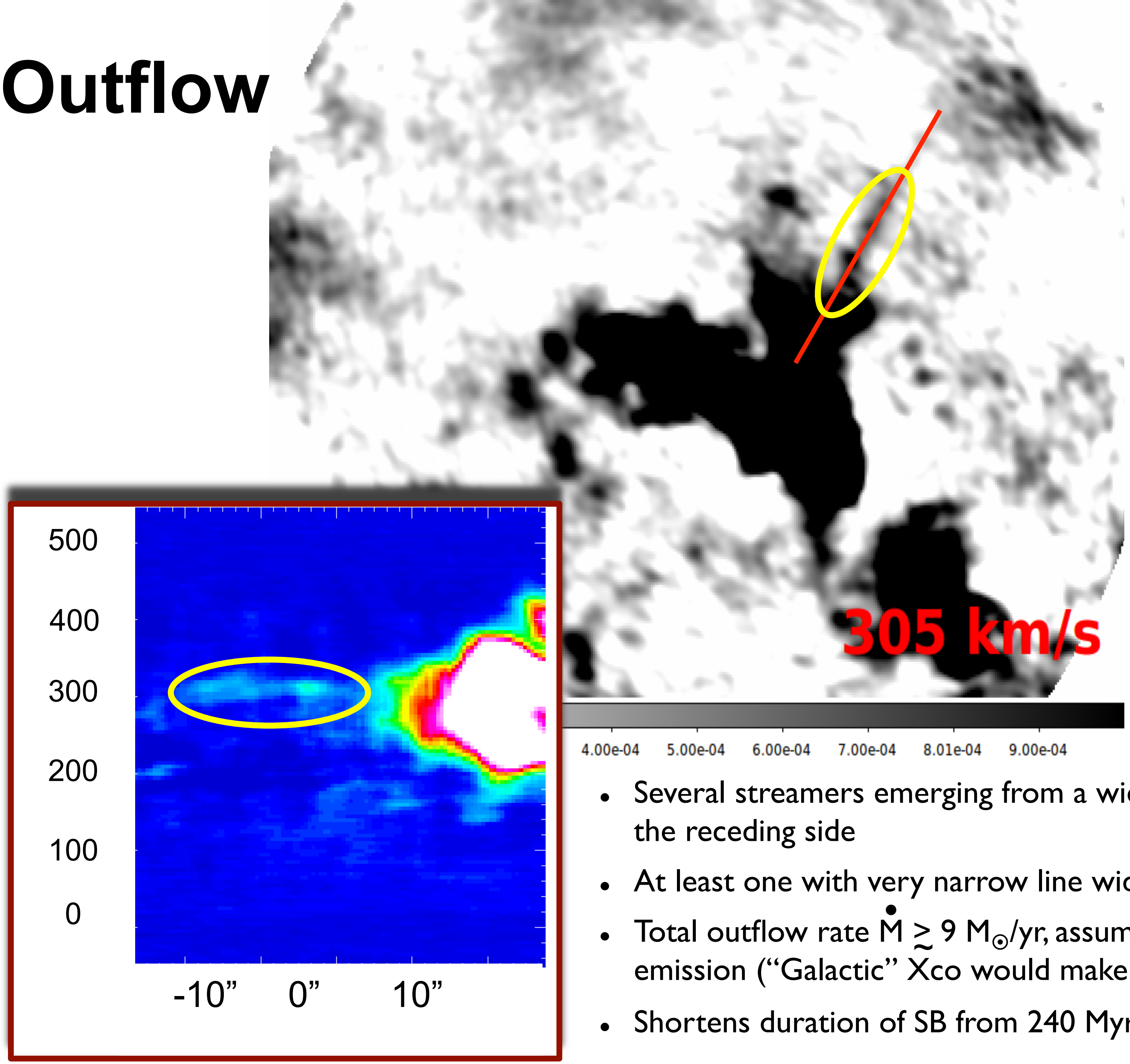
Receding side
(behind disk)

Streamers



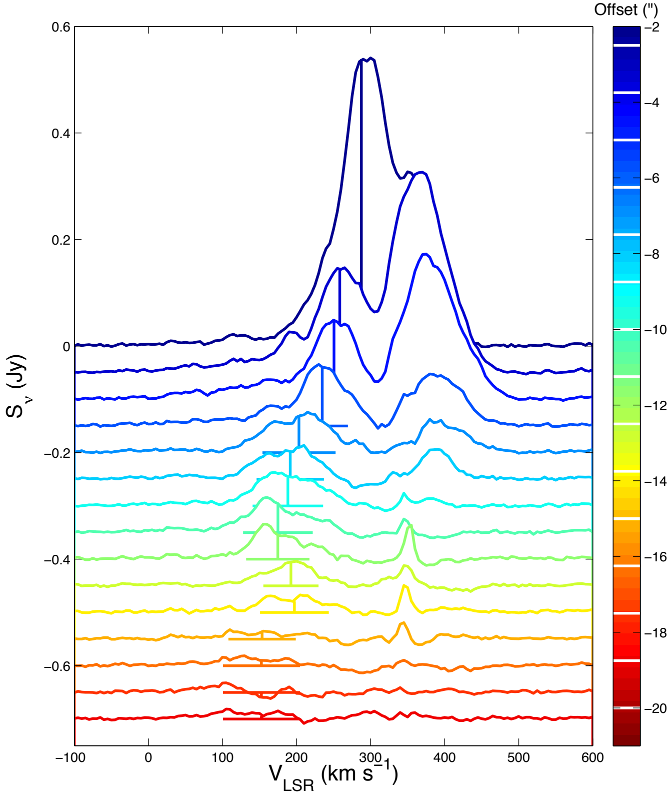
- Brightest streamer is barely resolved implying width < 30 pc
- Line width is ΔV~100 km/s implying very turbulent motions
- This is not self-gravitating gas!
- Optically thin mass: 10^6 $M_\odot$
- ~250 pc in length
- V_{ejecta} ≈ 30-60 km/s projected (90-300 km/s) deprojected
- T_{dyn} ≈ 1-3 Myr
- Some tension between high ΔV, age, and width

Outflow

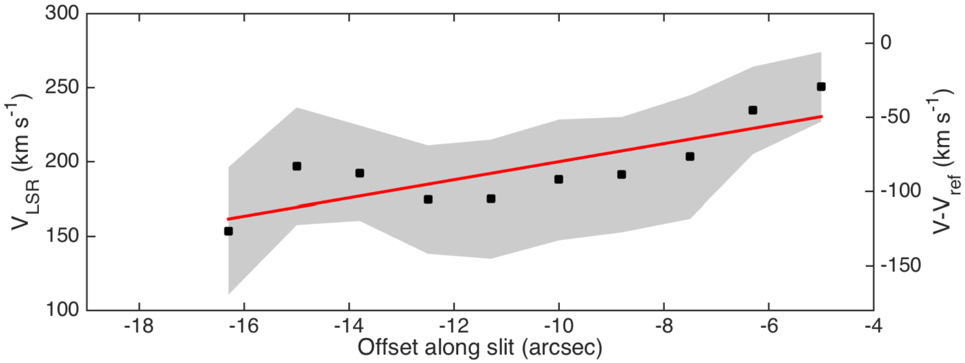


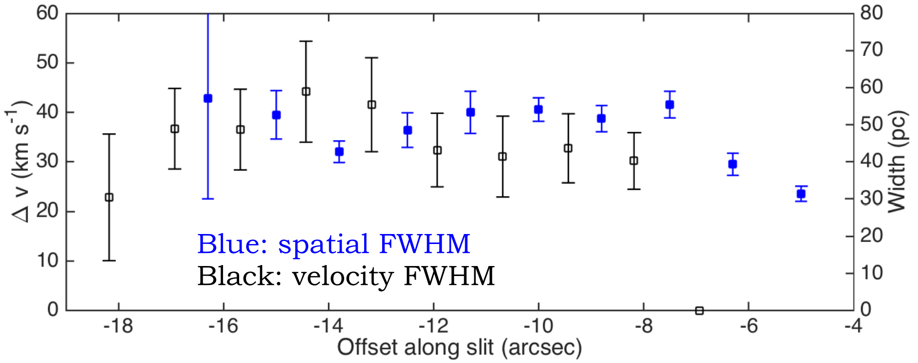
- Several streamers emerging from a wide structure on the receding side
- At least one with very narrow line width
- Total outflow rate $\dot{M} \gtrsim 9\ M_{\odot}/yr$, assuming optically thin emission (“Galactic” Xco would make it 10x larger)
- Shortens duration of SB from 240 Myr to 60 Myr

The brightest streamer

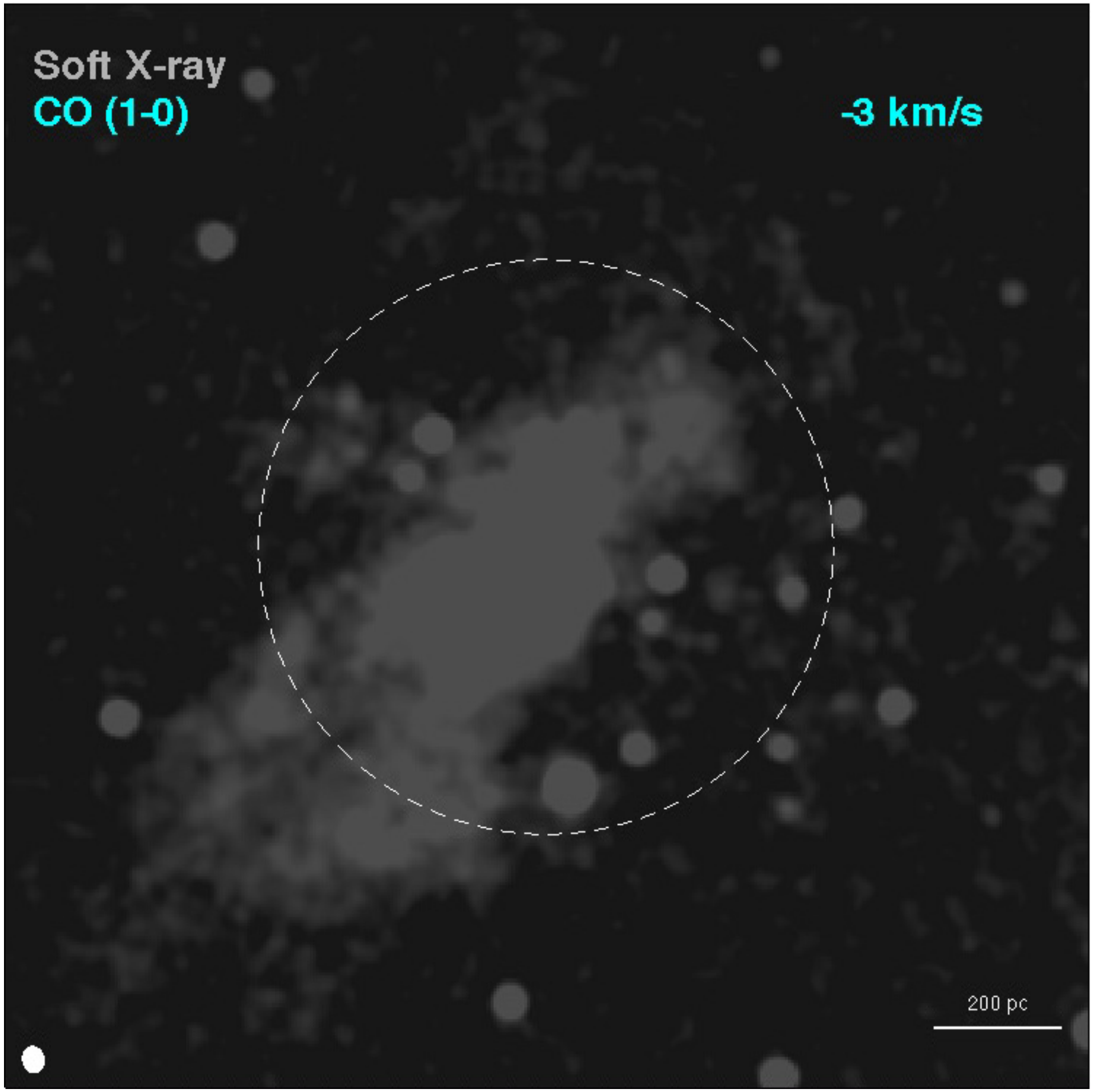


- There is a measurable velocity gradient along the SW streamer: ~1 km/s per pc, deprojected
- Acceleration? Self-sorting of velocities? Geometry (changing angle of outflow cone)?
- Gas at the end of the streamer is moving at ~360 km/s, approaching escape velocity, but projection is uncertain
- However, ΔV vs. width in streamer suggest it cannot be much older than 1 Myr unless confined, implying high outflow speed





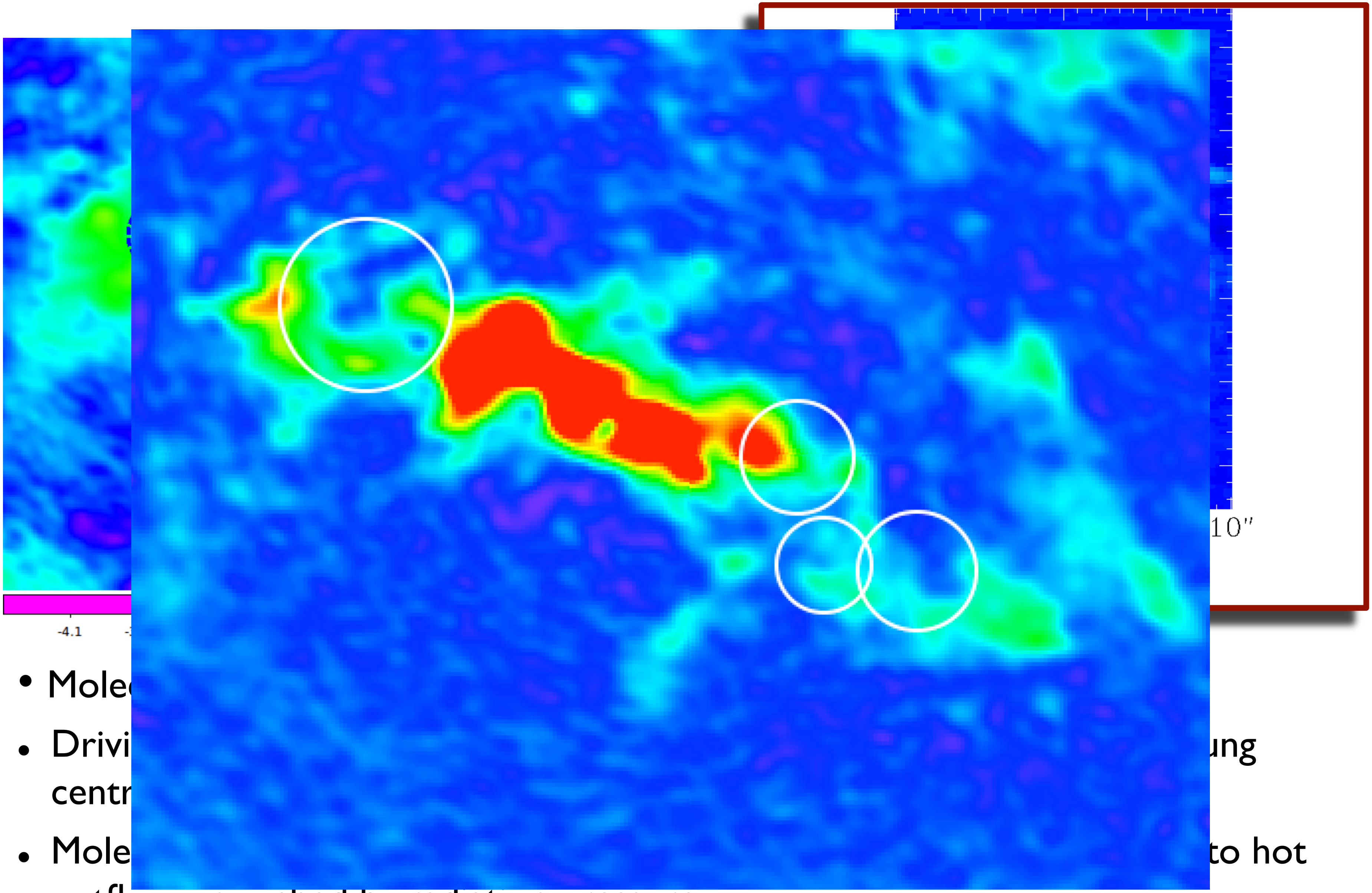
Imprints of stellar feedback?



- It was apparent in the first datasets that there are a number of “expanding molecular shell” structures in the starburst
- Sakamoto et al. (2004) already pointed out two “superbubbles” in SMA observations

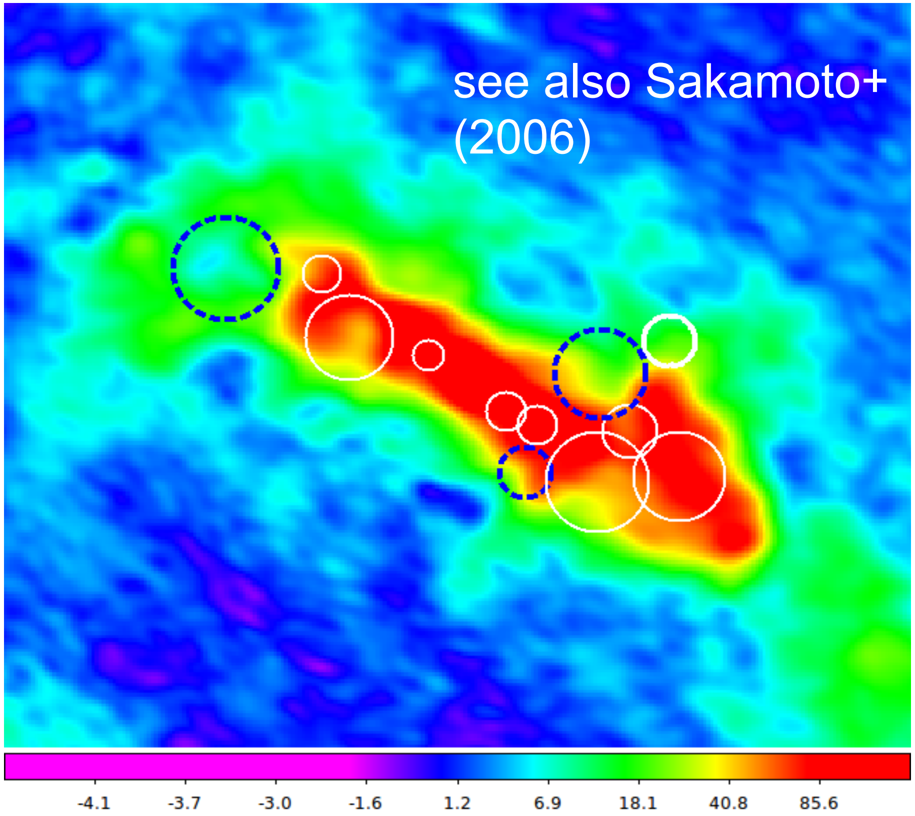
molecular expanding shells

Disk structures and streamers

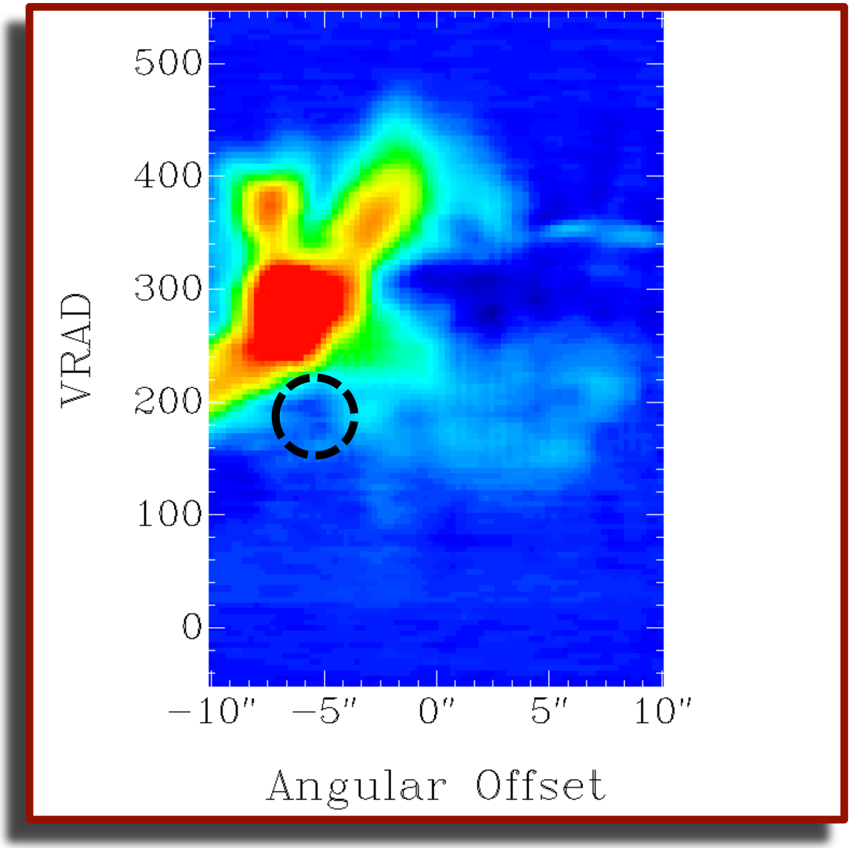


- Mole
- Drivi ung
  centr
- Mole to hot
  outflow or pushed by radiation pressure

Disk structures and streamers

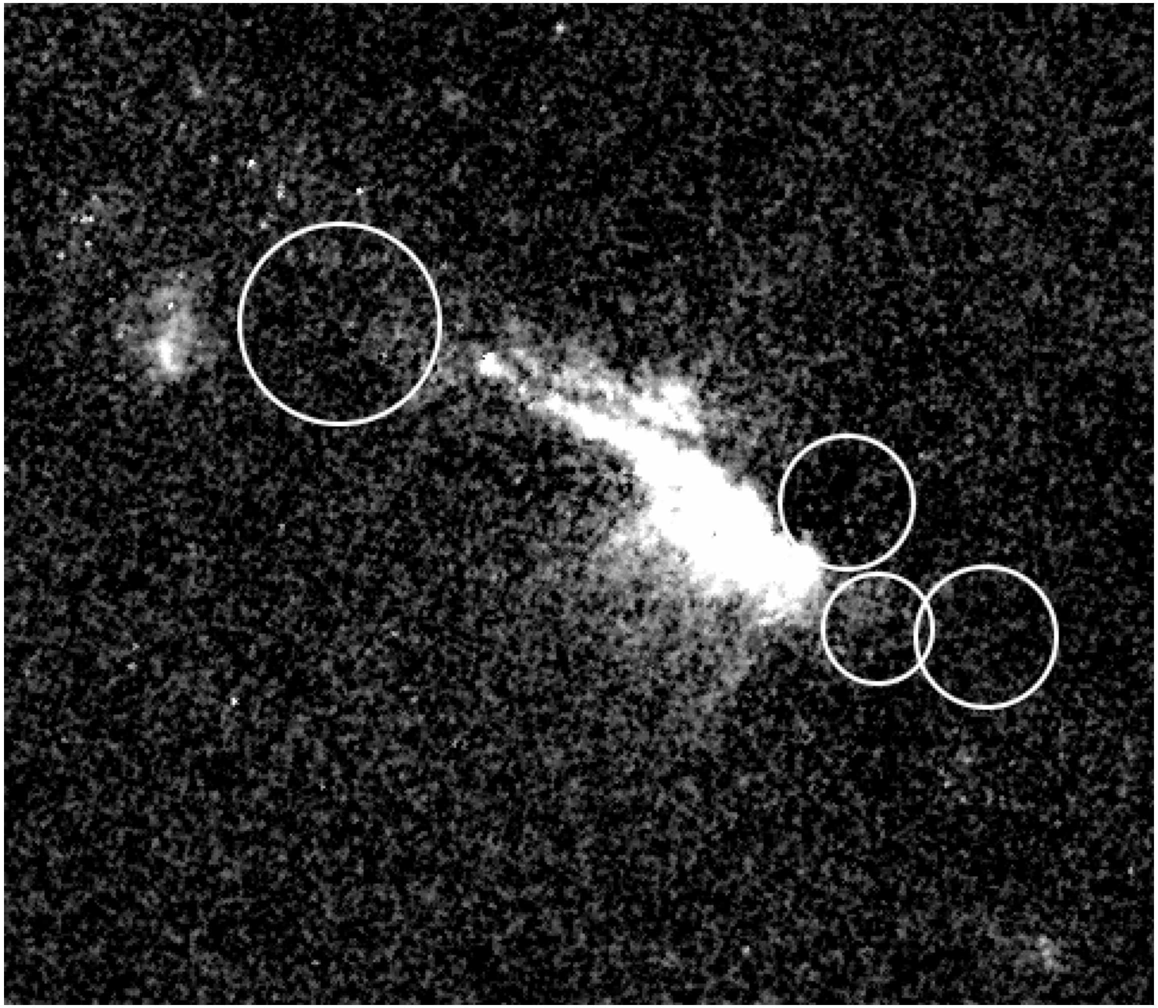


see also Sakamoto+ (2006)



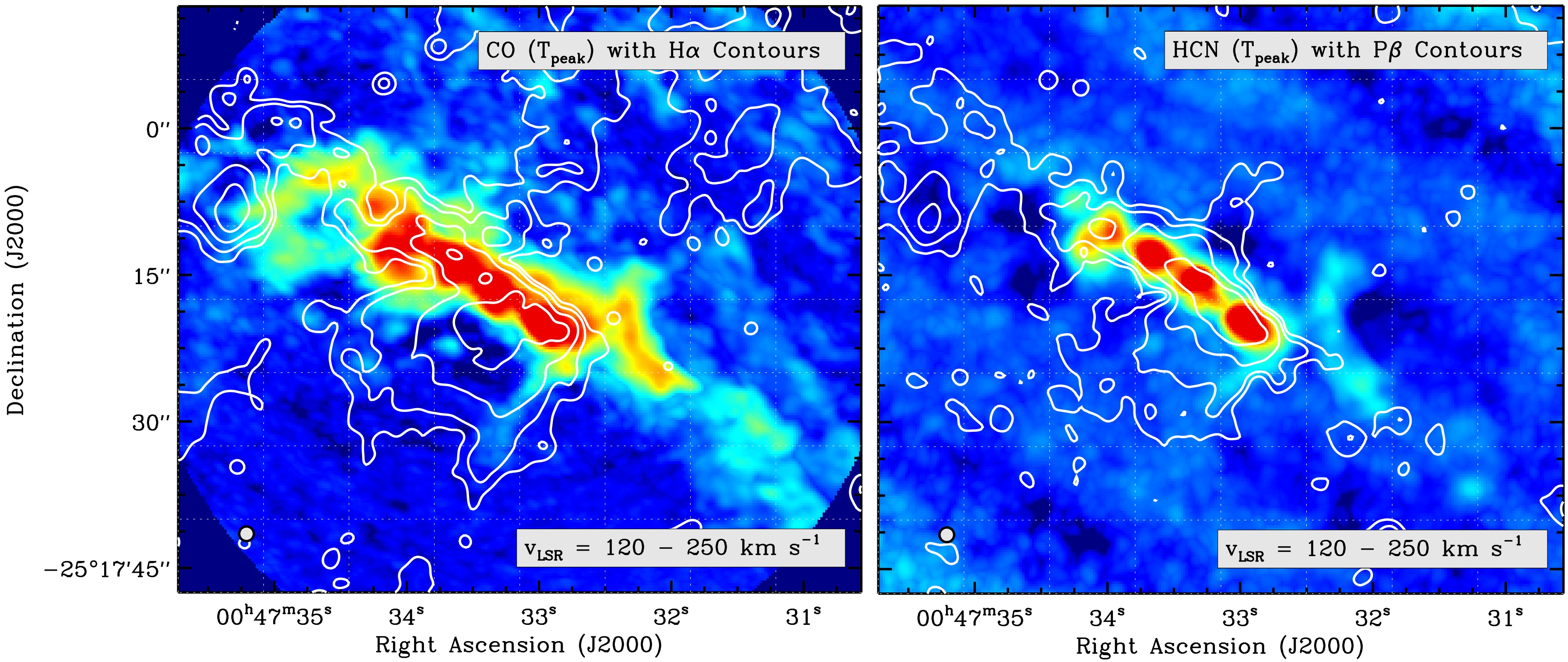
- Molecular shells with $V_{sh} \sim 23\text{-}42$ km s^{-1}, $M_{sh} \sim 10^{7}\ M_{\odot}$, $M_{sh} \sim 10^{52-53}$ erg
- Driving them through combination of stellar winds and SNe suggests young central clusters with $M_{\star} \sim 6\text{-}40 \times 10^{4}\ M_{\odot}$
- Molecular material may be initially accelerated this way, then advected into hot outflow or pushed by radiation pressure

Deep ionized gas imaging



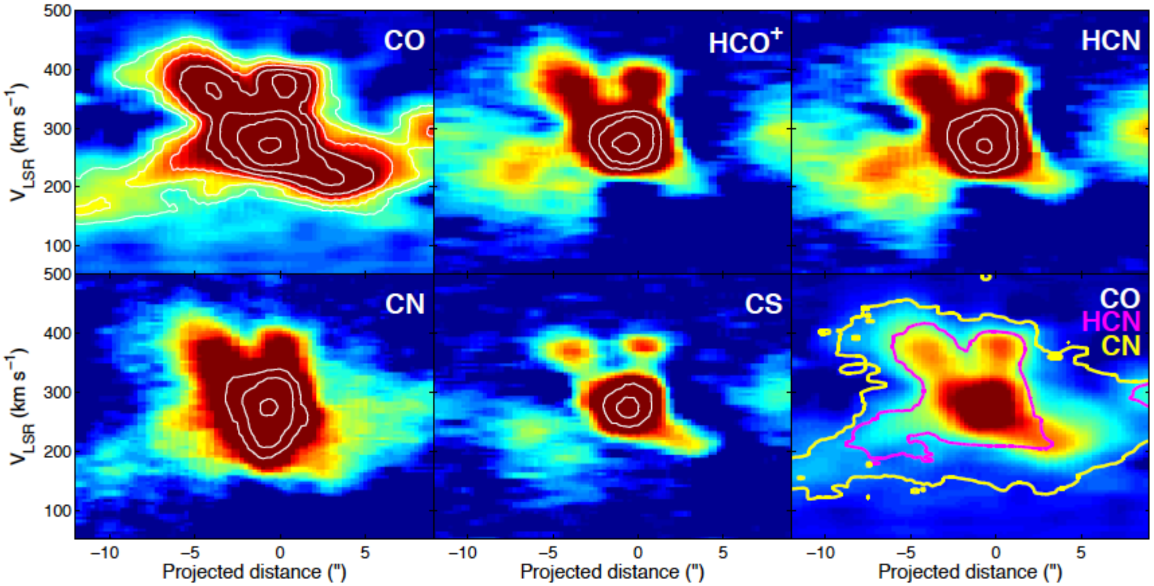
- New deep imaging in Paβ with narrow-band off, and new narrow-band off for existing Hα to improve continuum subtraction
- There is a hint of emission associated with near the base of the SW streamer
- But in other cases there is no association
- Lack of Hα emission shows the correction for extinction is likely very large even at Paβ
- Expect Av~13-18 from Σ~330-450 $M_{\odot}pc^{-2}$

Deep ionized gas imaging

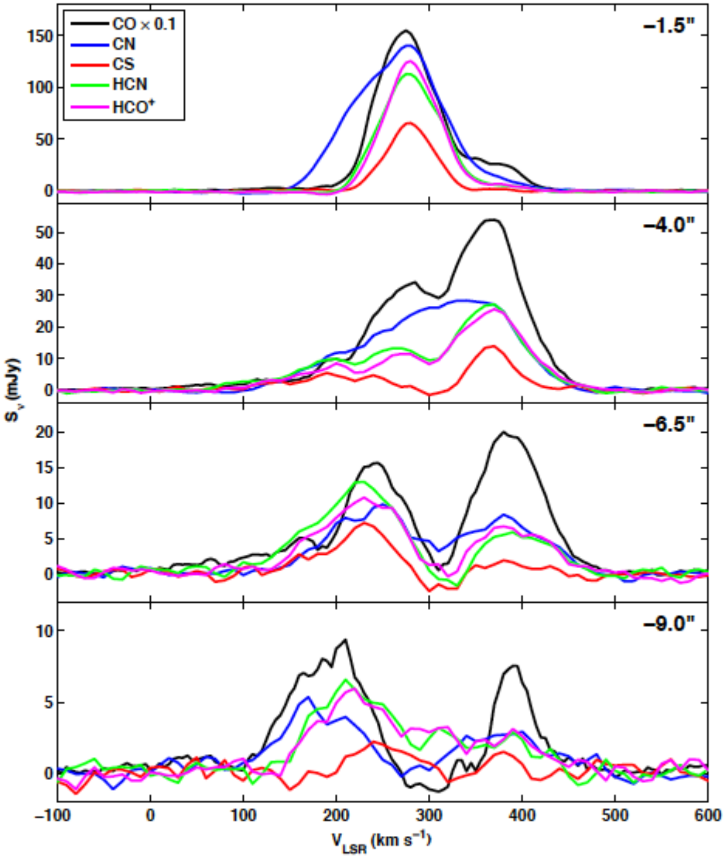


- Line ratios for the streamer suggest Av~2.5
- With a "double screen" geometry, $N(H_2)\sim5\times10^{21}$ cm^{-2}
- Consistent with optically thin "low mass" limit
- But beware of ionized gas emission in front

Dense gas in the SW streamer

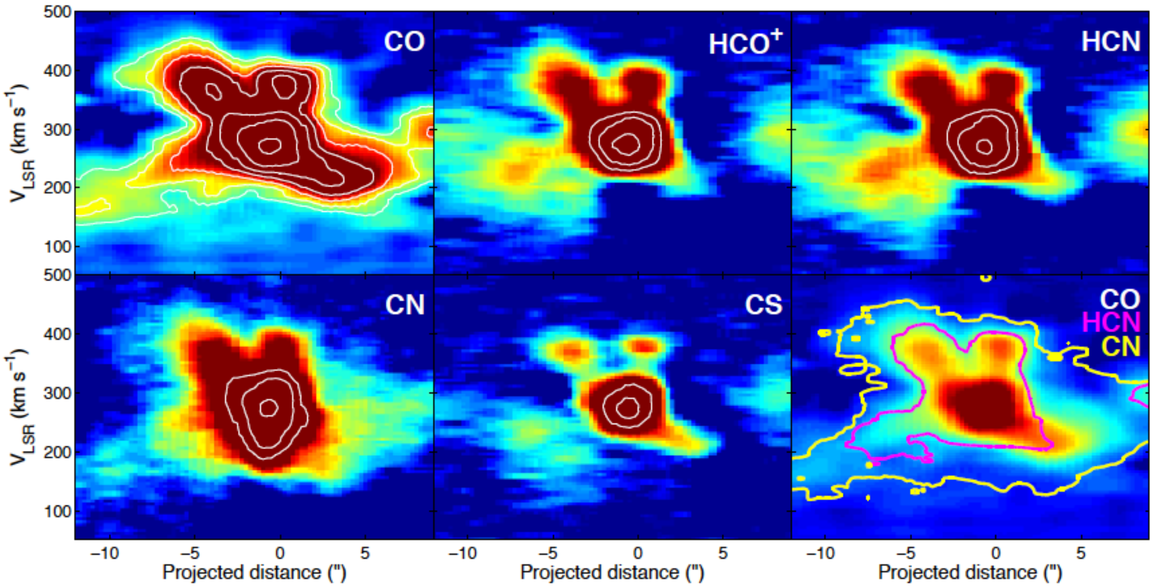


Walter+ in prep.

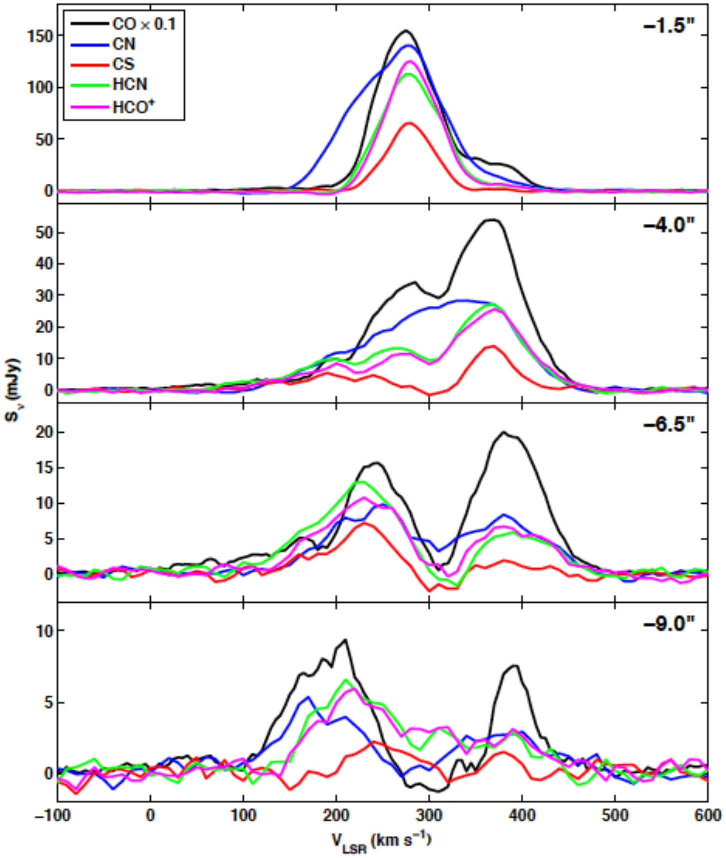


- The brightest streamer (SW) clearly has dense gas: HCO+, HCN, CS, and CN emission
- The ratios to CO are about constant and characteristic of the starburst region from which it originates. Very different from the disk!
- Clouds remain "intact" in the outflow for at least ~0.5-1 Myr as they are ejected?
- Strongly suggests optically thin dM/dt is an underestimate

Is HCN collissionally excited?



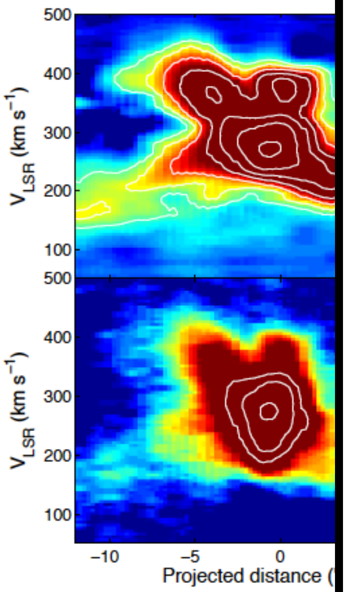
Walter+ in prep.

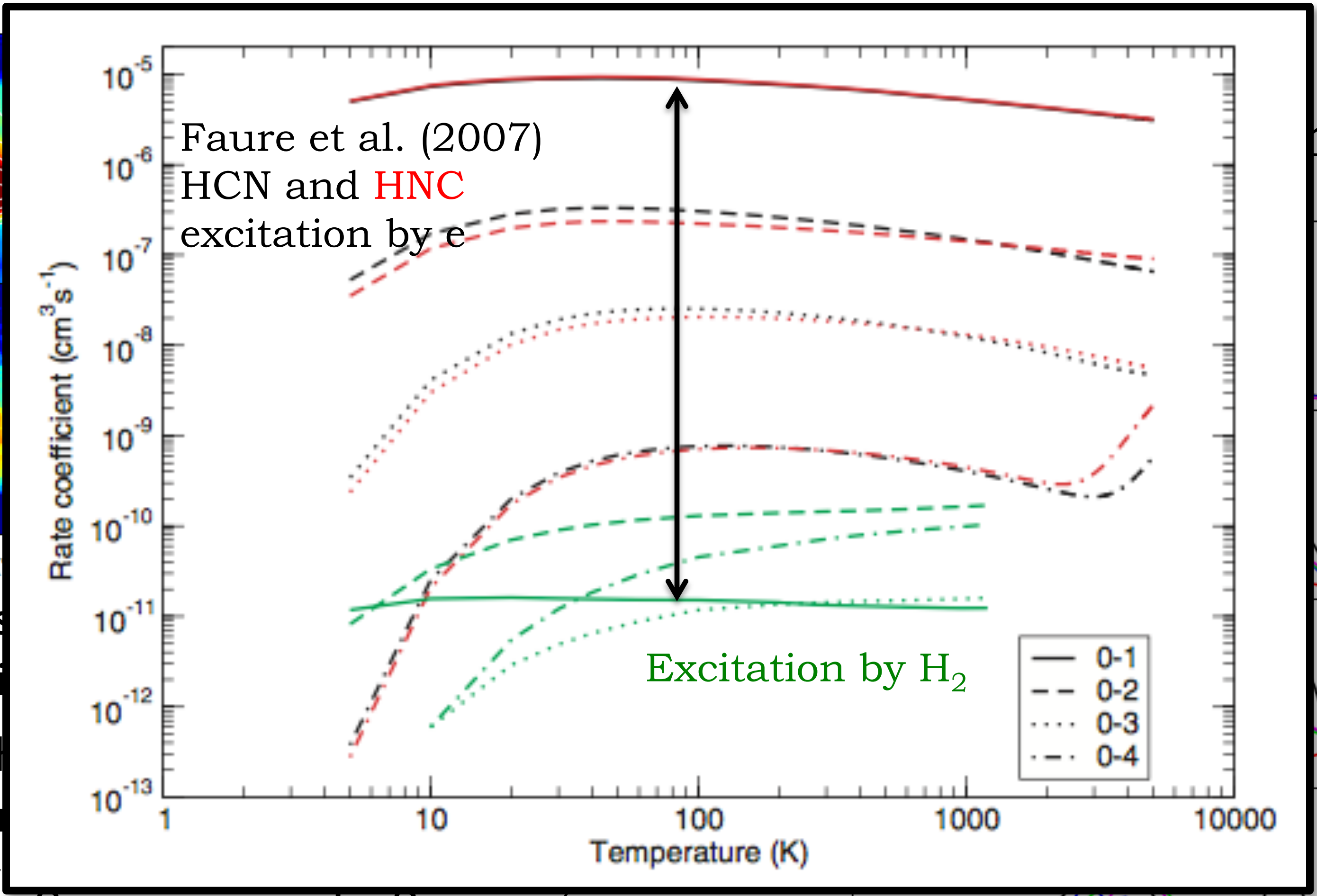


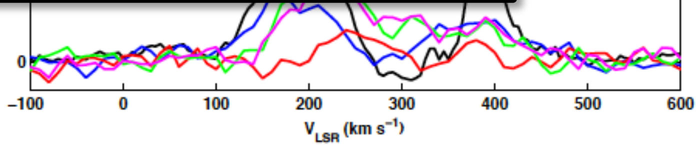
- Mean density from optically thin limit is n~40 cm^{-3}, consistent with limit from extinction
- From brightness temperature, if HCN physical temperature is ~100 K area clumping factor is ~50, implying volume clumping of 350, i.e. n~14,000 cm^{-3}
- Would need τ~70 for radiative trapping…
- If mass is larger by x10, it gets much easier

Is HCN collissionally excited?

rep.





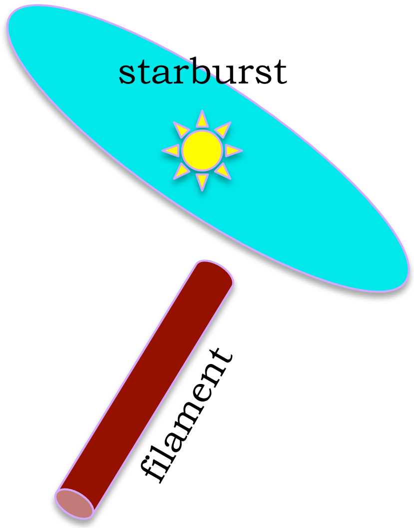


- Mean dens
  cm^{-3}, consi
- From brig
  temperatu
  ~50, imply
  n~14,000 cm^{-3}
- Would need τ~70 for radiative trapping…
- If mass is larger by x10, it gets much easier

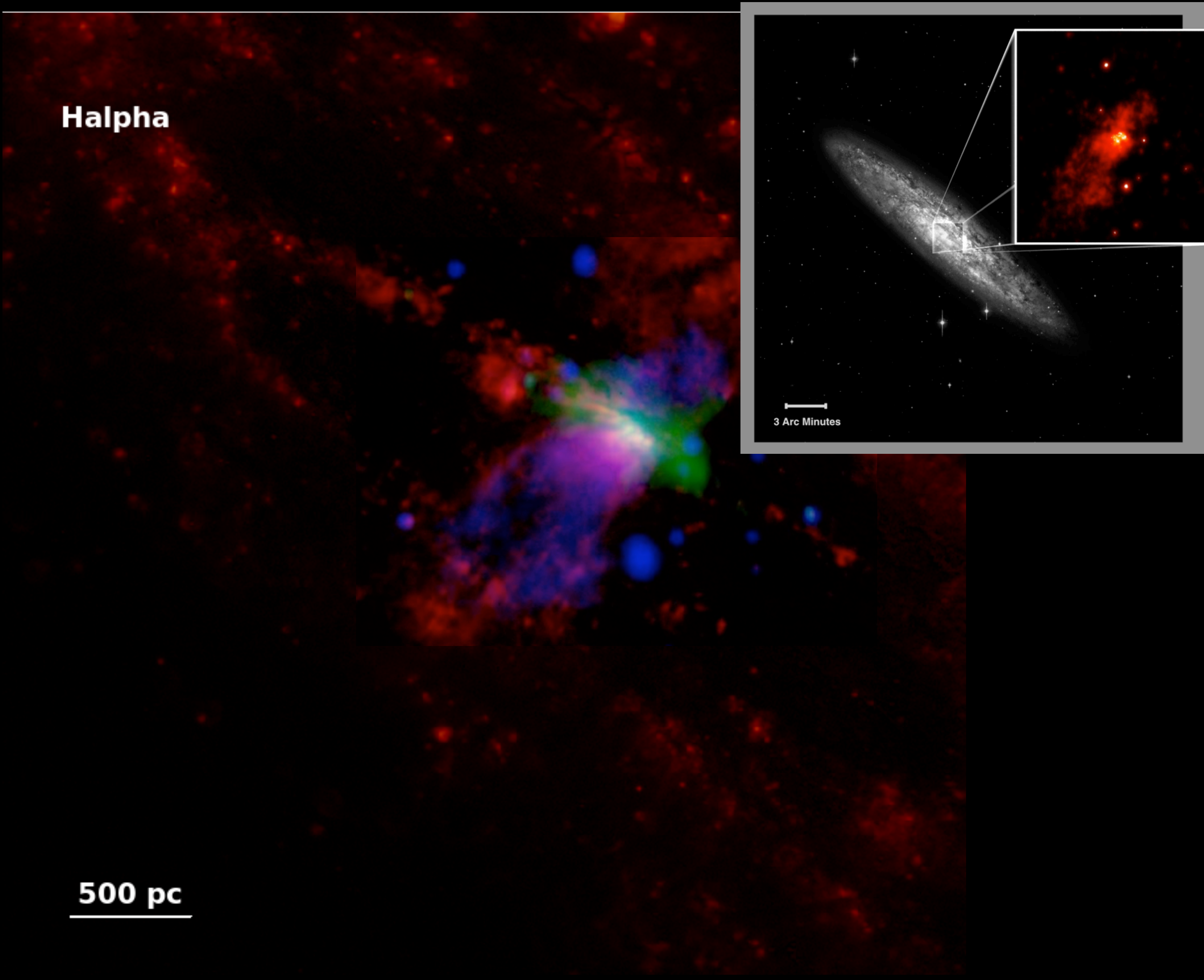
Can radiation pressure drive the streamers?

- L_{TIR}~$3.5x10^{10}$ $L_\odot$, about ½ in the 200 pc diameter starburst
- For the SW streamer, $M_{mol} \geq 10^6$ $M_\odot$ assuming optically thin emission
- The streamer is 60 pc wide by 250 pc long, distances 80 to 300 pc from disk
- Let us assume that the filament sees the “naked” starburst and is bathed mostly in FUV to get maximum efficiency
- “infinite plane” $F=(R_{fil}/R_{SB})^2 L_{SB}/2c$ ~$2x10^{32}$ dyn ➔ $a=F/M$~10^{-7} cm/s^2 (a factor of 2 worse for point source, and another for L fraction in SB)
- V=a t, ignoring gravity v~30 km/s after 1 Myr
- “Ballistic” $\frac{1}{2}v^2 = \int a\,dr$ yields v~60 km/s
- But all of this depends critically on “area” and mass
- And ignores gravity
- The observed dV/dr gradient seems also too large

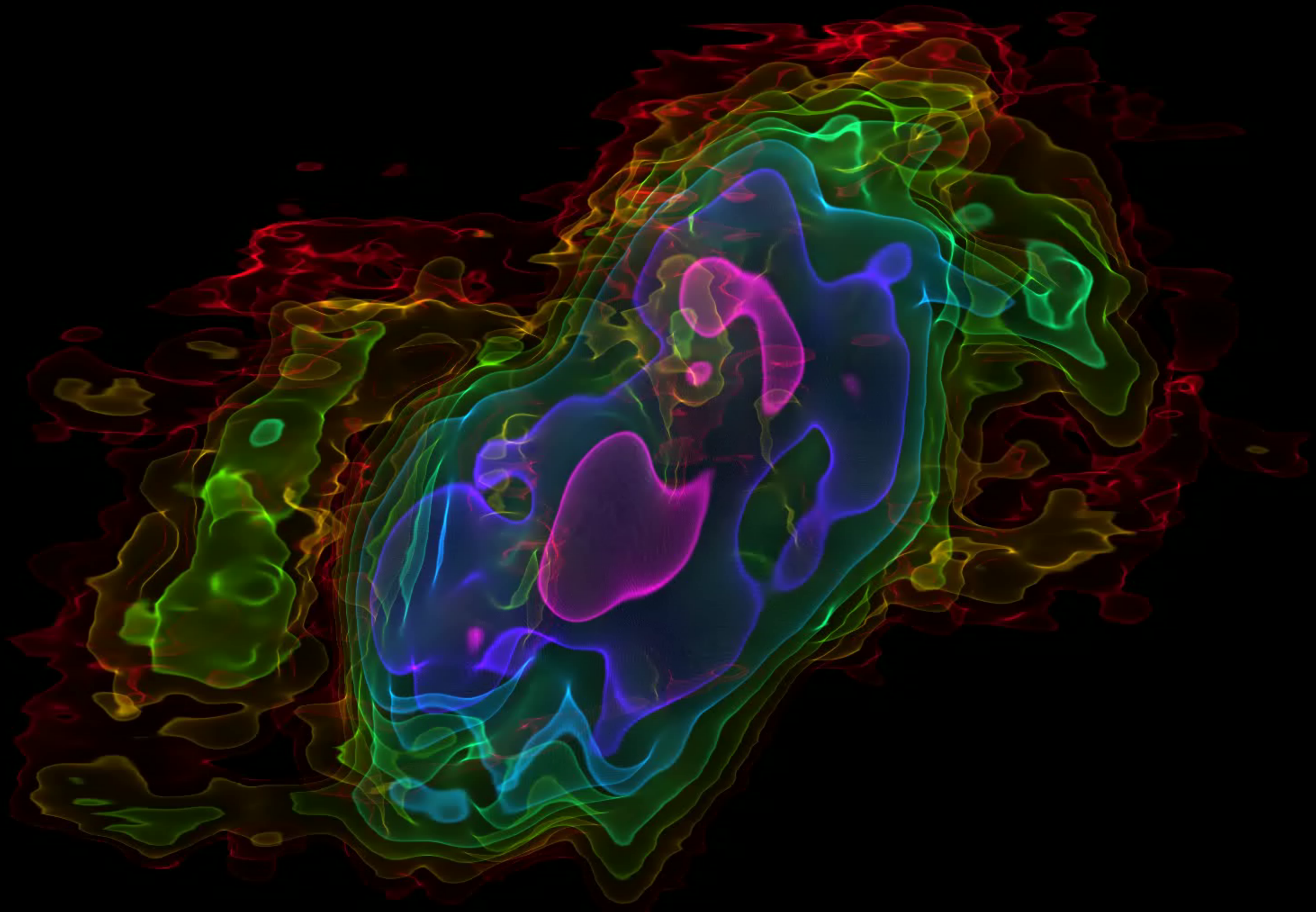
  by a factor of ~5



NGC 253: Hα, CO, X-ray



Can you find the outflow?



Isosurface rendered with YT
(E. Rosolowsky)

nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

Starburst galaxy NGC 253 mapped in unprecedented detail **PAGES 416 & 450**

ANATOMY OF A SUPERWIND

MICROBIOLOGY

RESISTANCE FIGHTING

The rise of superbugs — and fall of antibiotics

PAGES 394 & 398

CLIMATE WARMING

METHANE MENACE

Forecasting economic effects of melting Arctic ice

PAGE 401

REGENERATIVE MEDICINE

STEM CELL TO TRANSPLANT

Human 'liver bud' grows in mouse model

PAGE 481

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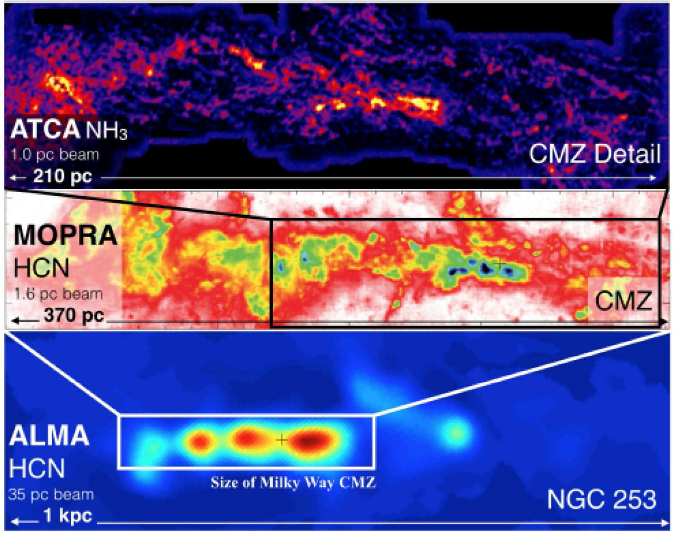
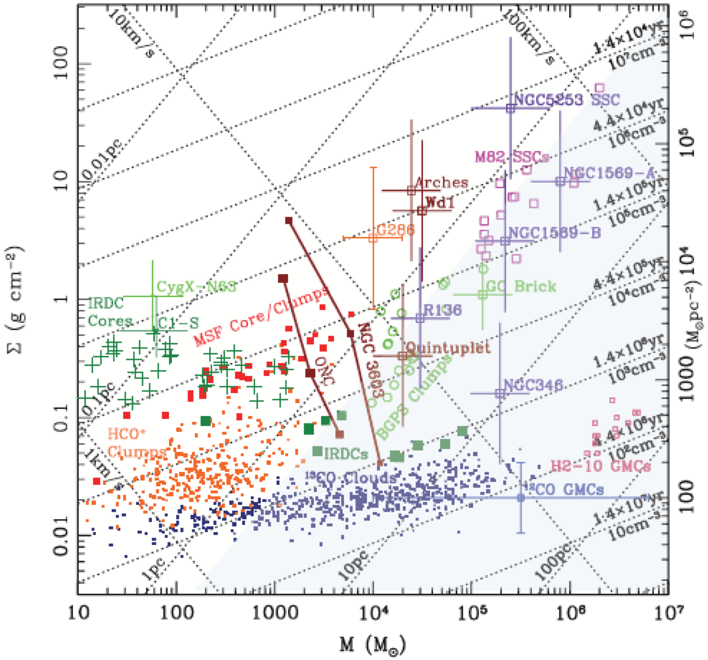
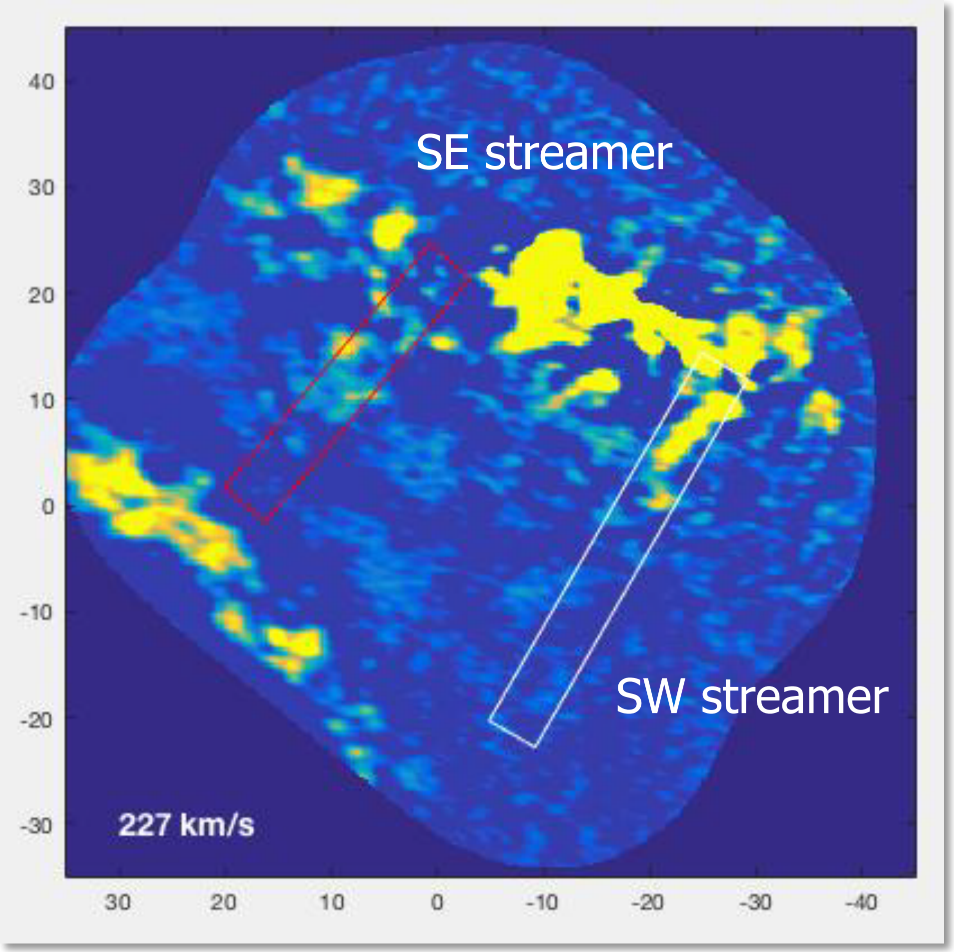
What's next?

- Cycle 2 A-ranked observations delivered: following the Southern streamers farther out and obtaining CO 2-1
  - Combination is not complete, but we think we clearly see them farther out: Accelerations? Escape fraction?
  - The CO 2-1/1-0 ratio will allow us to test the optical depth of the CO emission, refine mass outflow rate
  - Also studying Circinus, the nearest Seyfert, in separate proposal
- Cycle 3 A-ranked observations in the queue: ~1 pc resolution imaging of the starburst



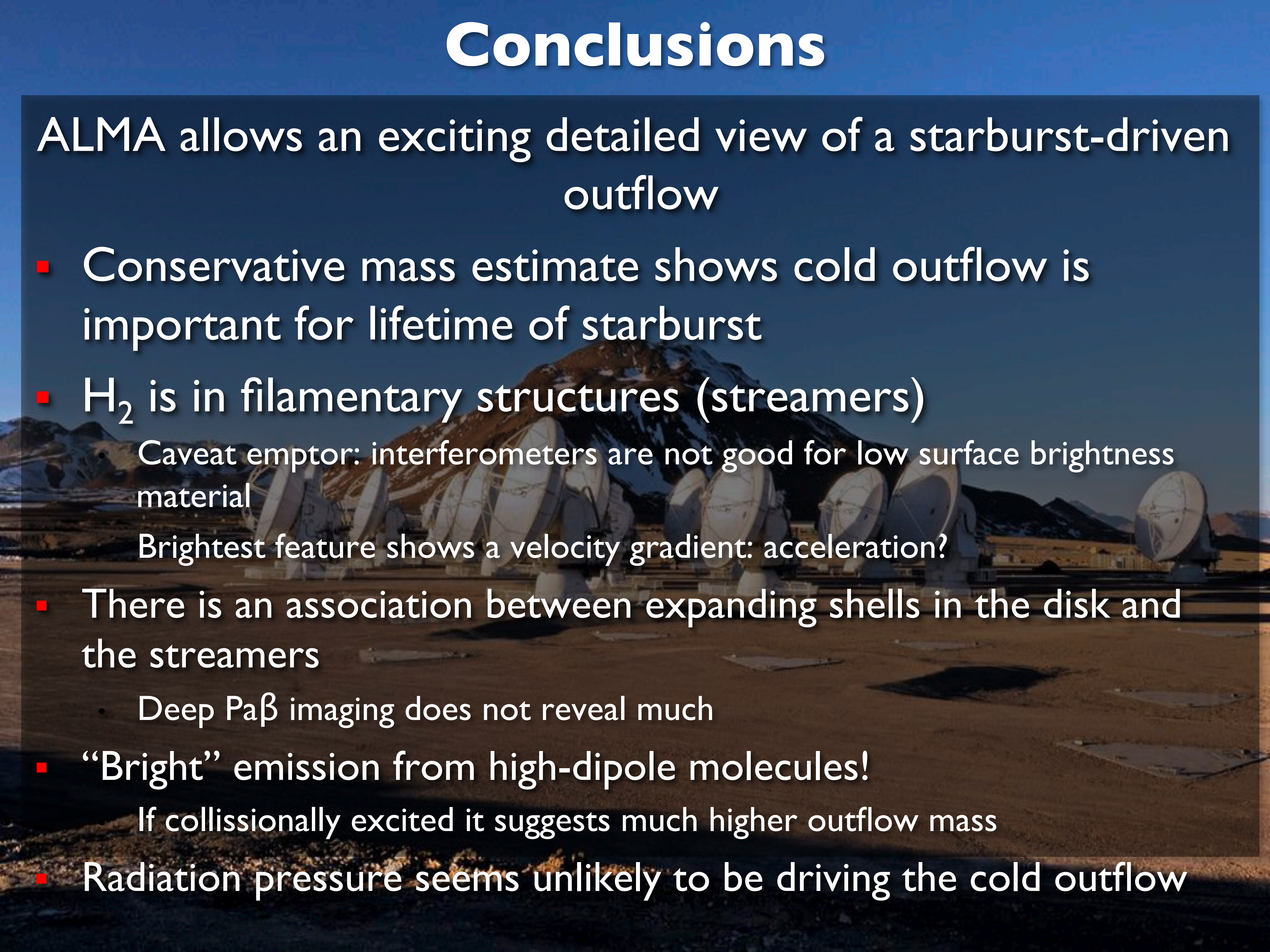
Top: SWAG Survey (PI: Meier, Ott, Mills) **Middle:** Jones et al. (2011) **Bottom:** Meier et al (2015)





Cycle 2 data still needs more work. But here is the approaching side of the outflow in CO 2-1

Conclusions



ALMA allows an exciting detailed view of a starburst-driven outflow

- Conservative mass estimate shows cold outflow is important for lifetime of starburst
- H_2 is in filamentary structures (streamers)
  - Caveat emptor: interferometers are not good for low surface brightness material
  - Brightest feature shows a velocity gradient: acceleration?
- There is an association between expanding shells in the disk and the streamers
  - Deep Paβ imaging does not reveal much
- "Bright" emission from high-dipole molecules!
  - If collissionally excited it suggests much higher outflow mass
- Radiation pressure seems unlikely to be driving the cold outflow