ALMA observations of 99 GHz free-free and Hα emission from star formation in the centre of NGC 253

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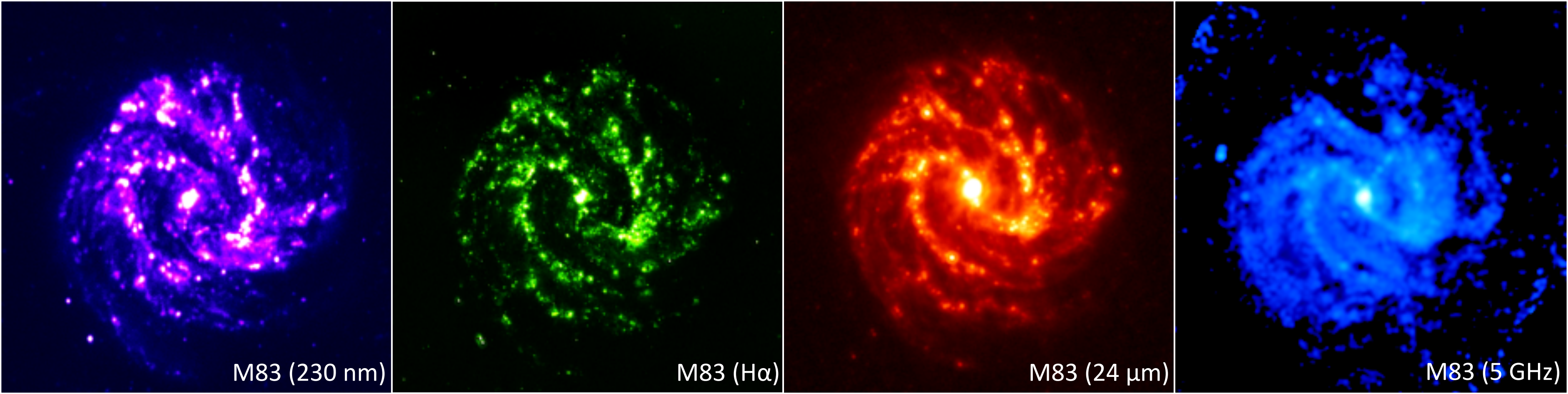
Star formation can be traced either by ultraviolet-luminous stars or by supernovae.

The wavebands commonly used to trace star formation each have drawbacks:

- Ultraviolet continuum emission from young stars is strongly affected by dust extinction.
- Optical/near-infrared recombination line emission from photoionized gas is also affected by dust extinction.
- Infrared emission from dust may include emission from dust heated by older stars.
- Synchrotron emission from supernovae appears more extended than the young stellar populations.



M83 (230 nm)

M83 (Hα)

M83 (24 μm)

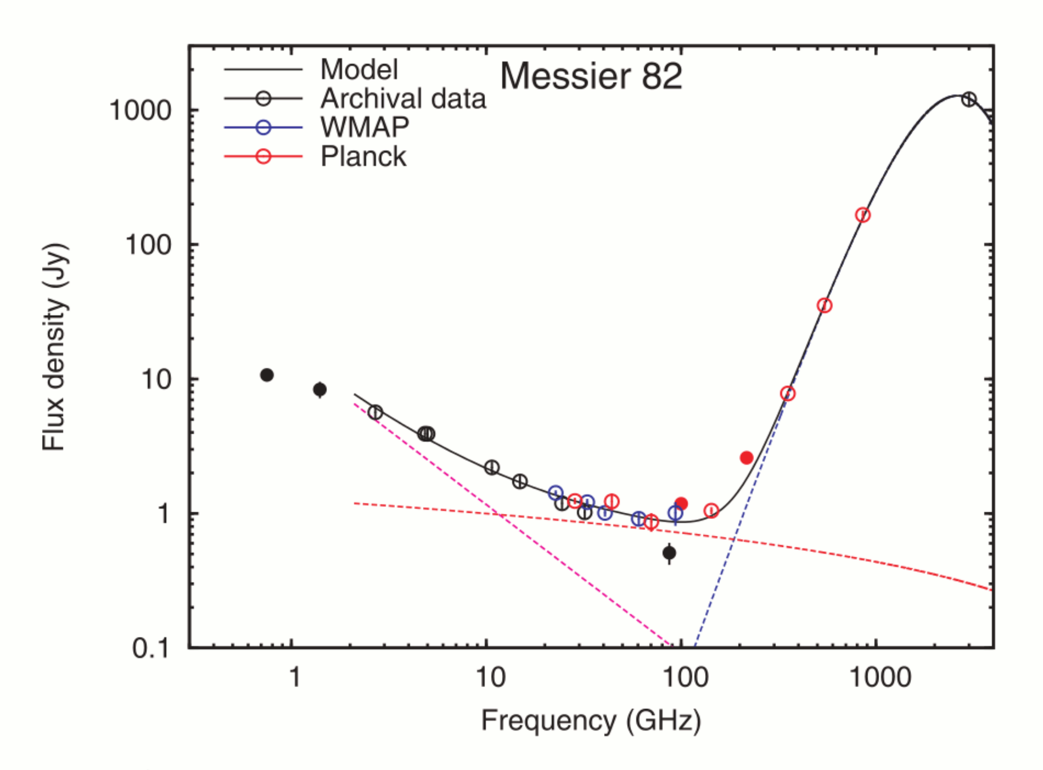
M83 (5 GHz)

ALMA can detect emission from photoionized gas in two forms:

- Free-free (or Bremsstrahlung) continuum emission
- Higher order recombination line emission

This emission has two advantages over other commonly-used star formation tracers:

- It directly traces young, photoionizing stars.
- It is unaffected by dust attenuation.

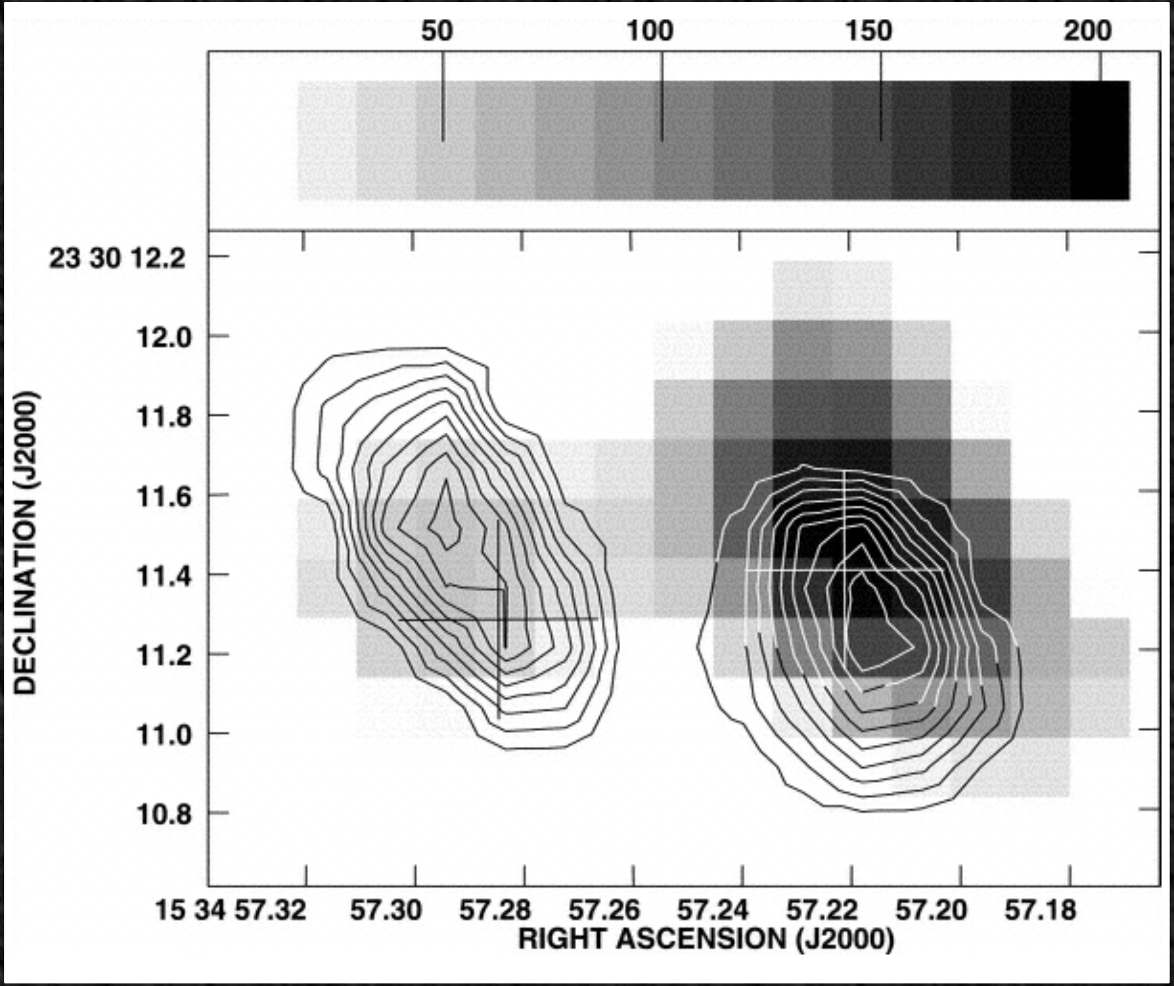


Peel et al. (2011, MNRAS, 416, L99)

Detection of radio/millimetre recombination line emission has been limited by sensitivity issues.

Most detections are radio lines at cm wavelengths that are affected by masing and opacity issues.

ALMA will have the capability to detect this emission at mm wavelengths in more galaxies, making it possible to analyze the line emission in larger samples of galaxies.



H53α, H92α in Arp 220 (Rodriguez-Rico et al., 2005, ApJ, 633, 198)

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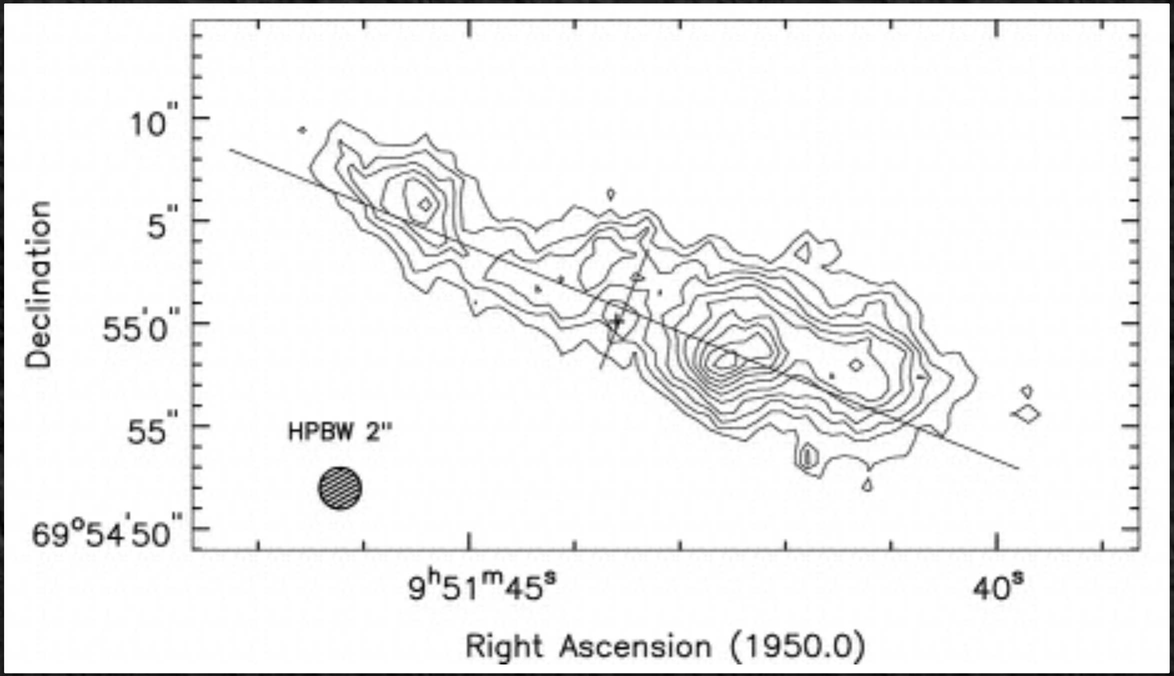

H92α in M82 (Rodriguez-Rico et al., 2004, ApJ, 616, 783)

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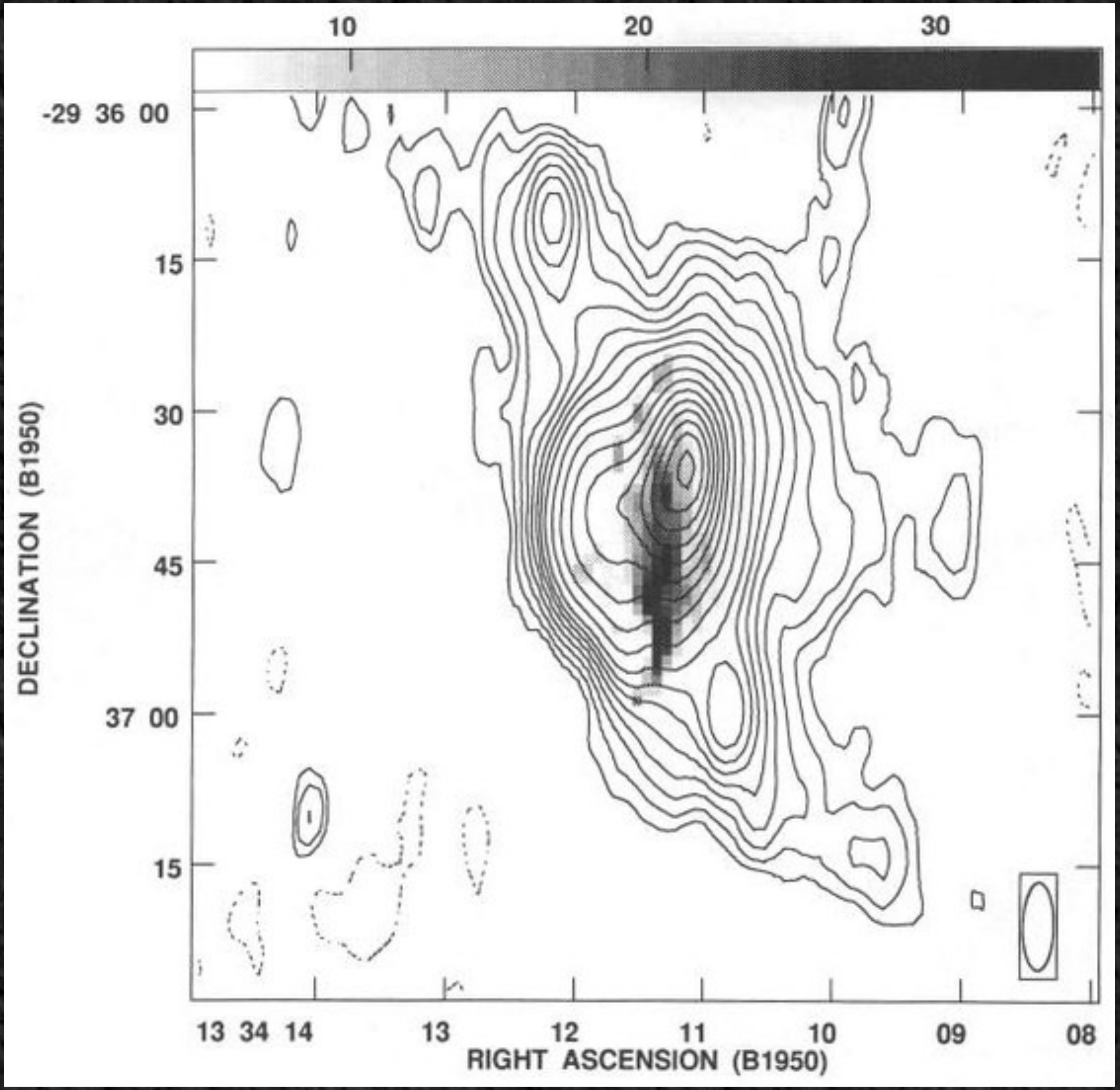


H92α in M83 (Zhao et al., 1996, ApJ, 472, 54)

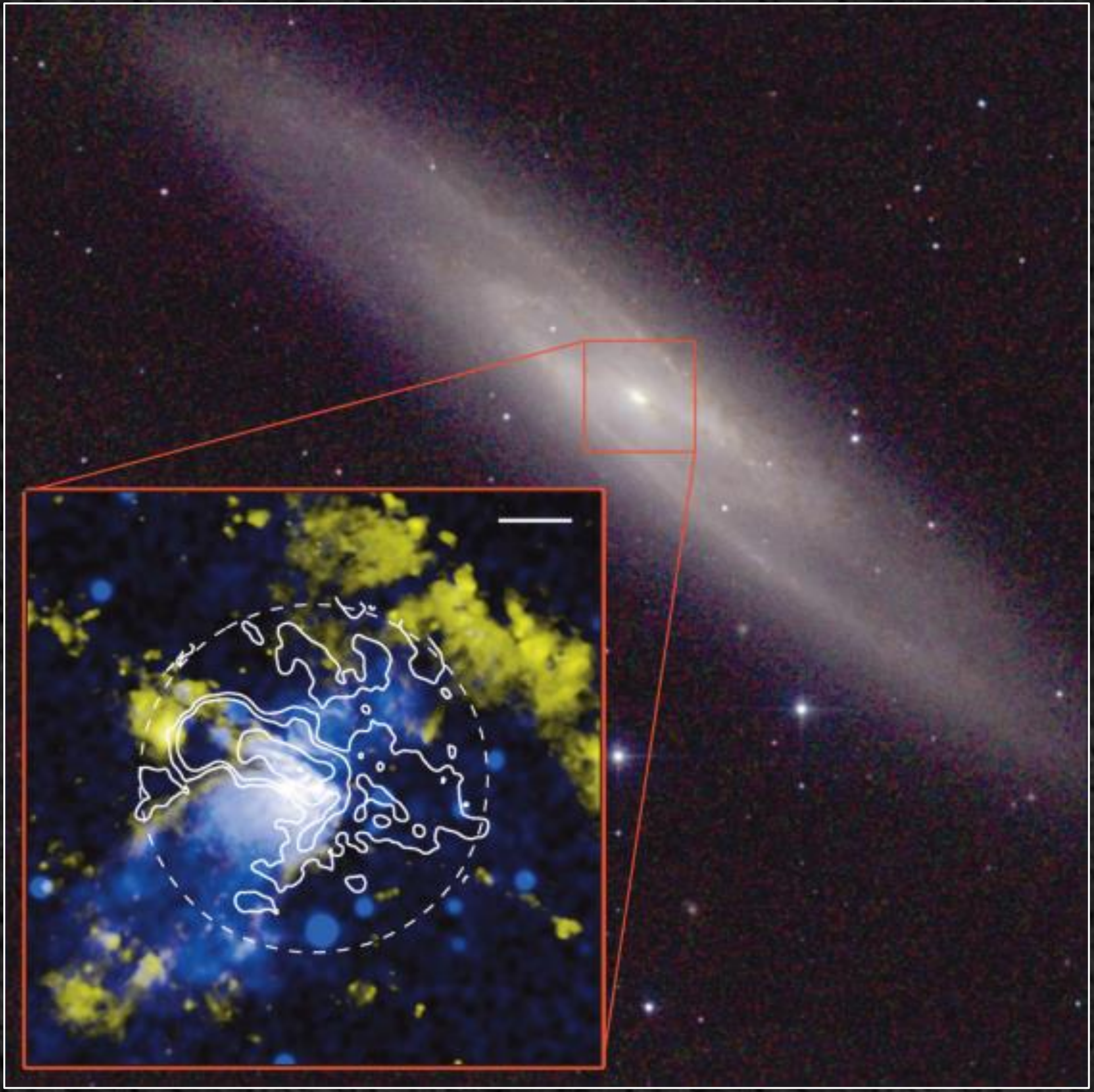
NGC 253 is a nearby spiral galaxy with starburst activity in its nucleus.

Multiple papers dating back to 1977 had reported radio recombination line emission from the nucleus of the galaxy.

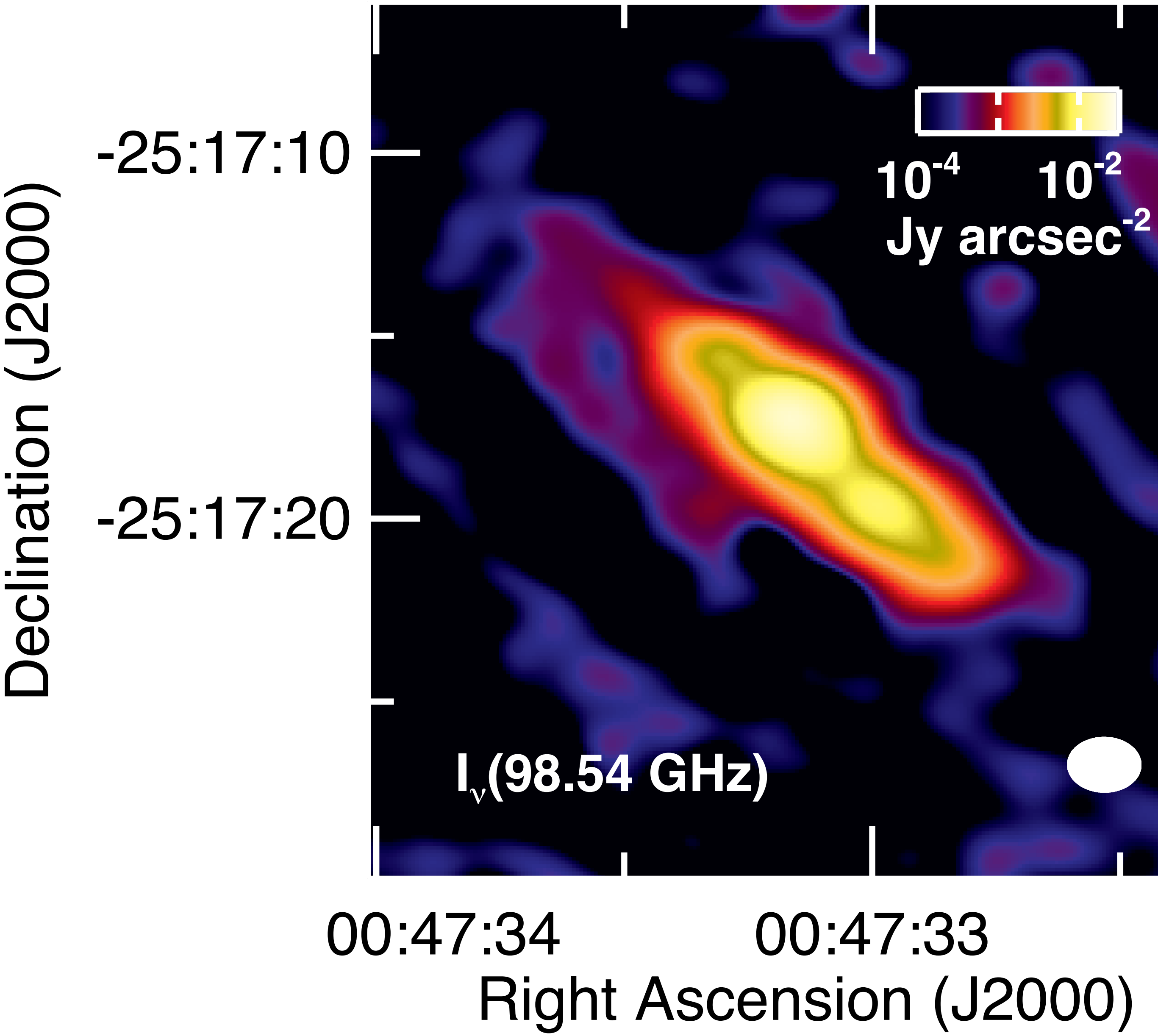
ALMA data have been published in the following papers:

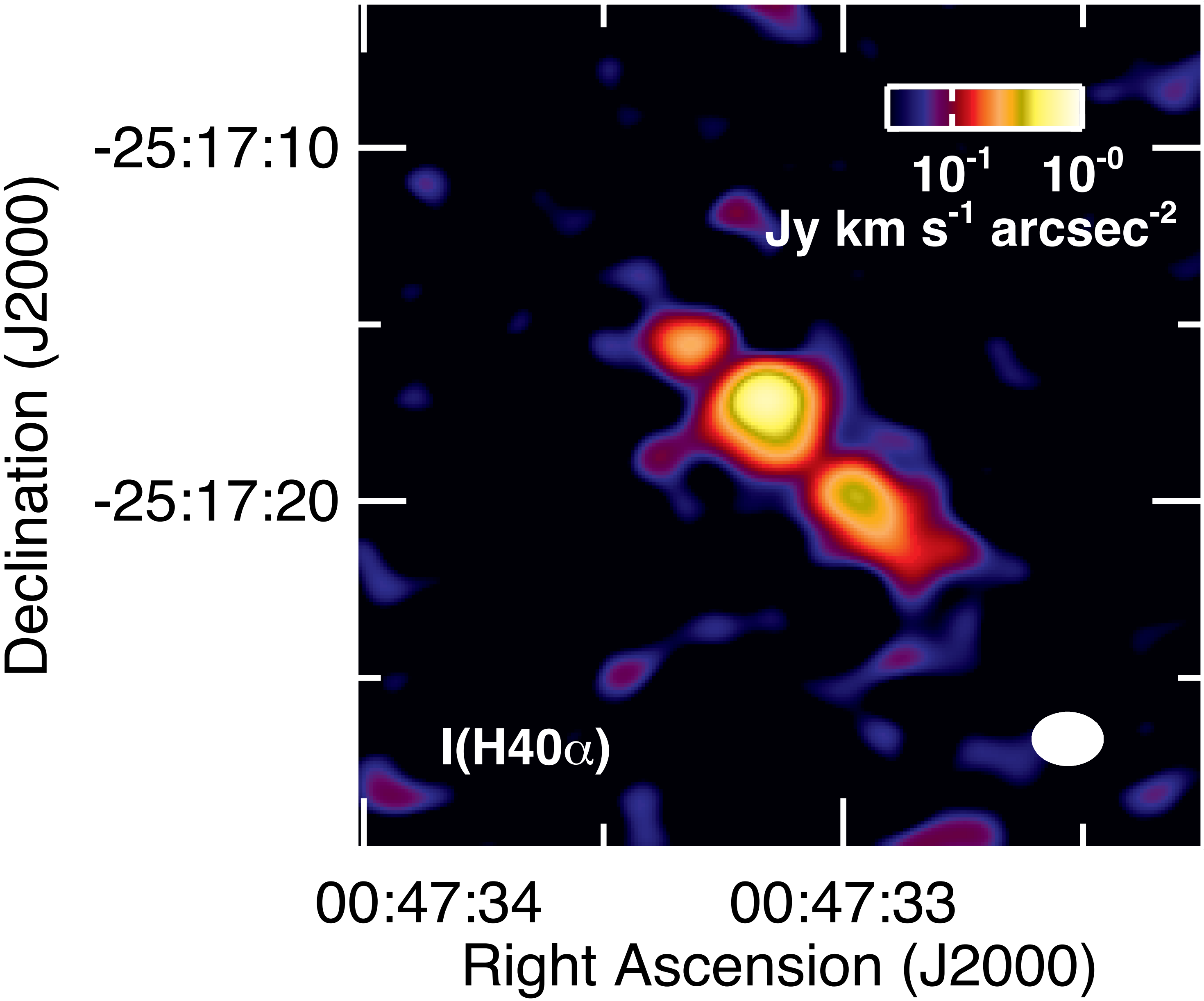
- Bolatto et al. (2013, Nature, 499, 450)
- Leroy et al. (2015, ApJ, 801, 25)
- Meier et al. (2015, ApJ, 801, 63)

However, most of the analysis of the ALMA data has focused on the molecular gas.



Bolatto et al. (2013, Nature, 499, 450)


-25:17:10
-25:17:20
Declination (J2000)
00:47:34
00:47:33
Right Ascension (J2000)
10^{-4}
10^{-2}
Jy arcsec^{-2}
I_ν(98.54 GHz)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Declination (J2000)
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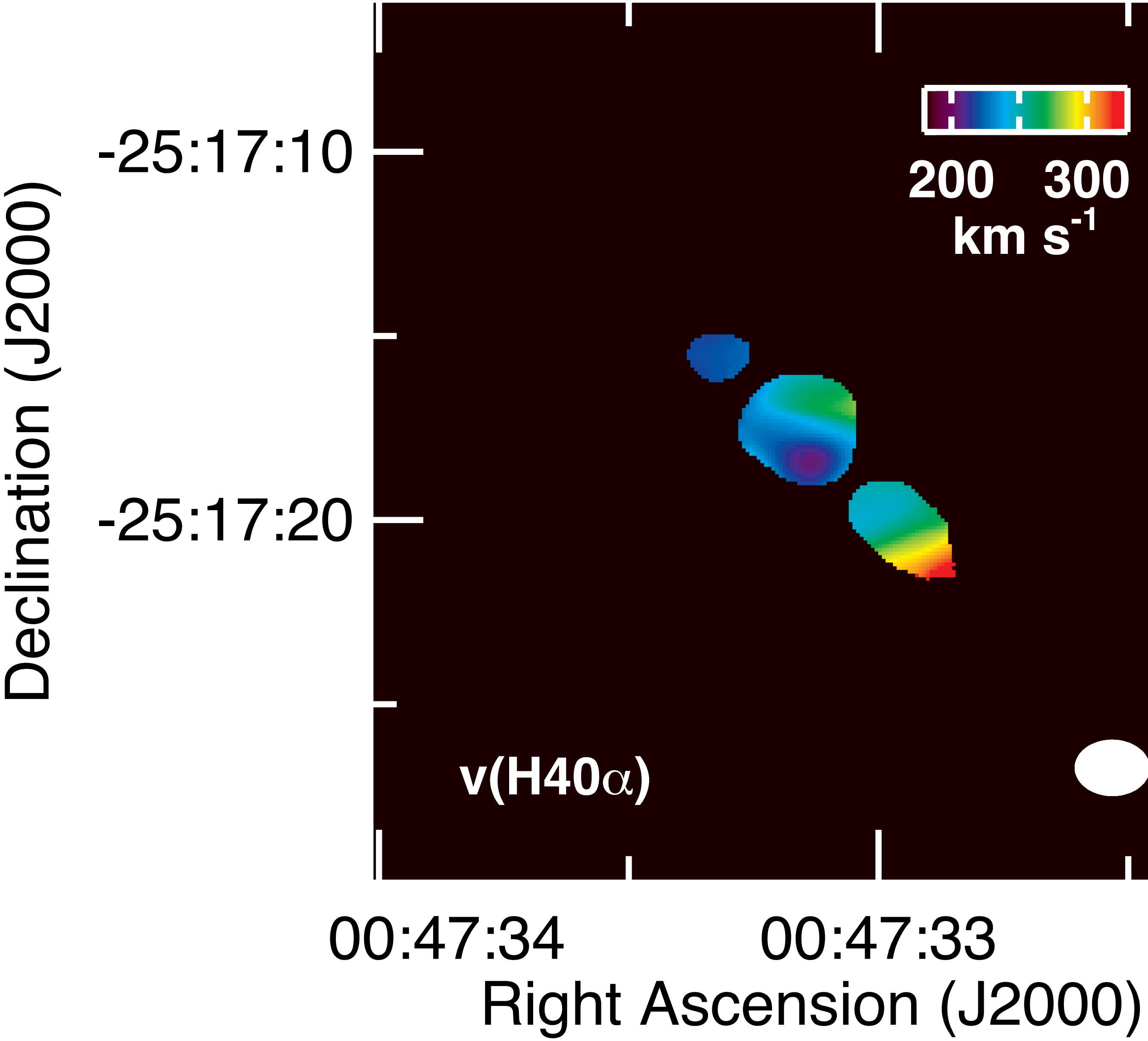
Right Ascension (J2000)
10-1 10-0
Jy km s-1 arcsec-2
I(H40α)


200
300
km s-1
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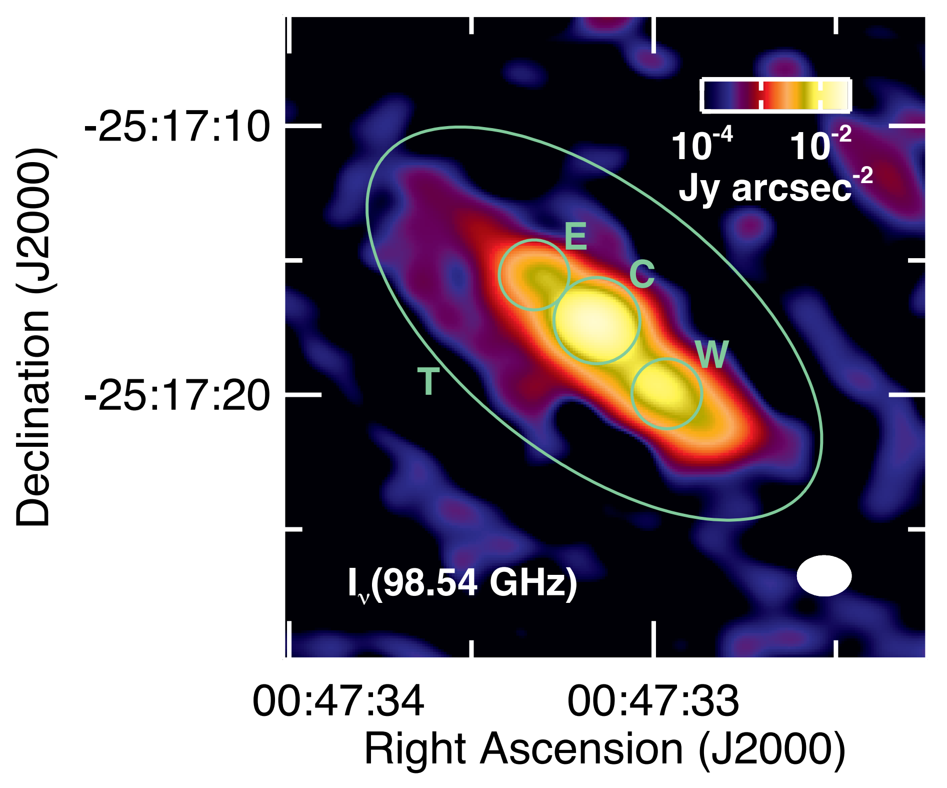
-25:17:20
Declination (J2000)
v(H40α)
00:47:34
00:47:33
Right Ascension (J2000)



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Declination (J2000)
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10^{-4}
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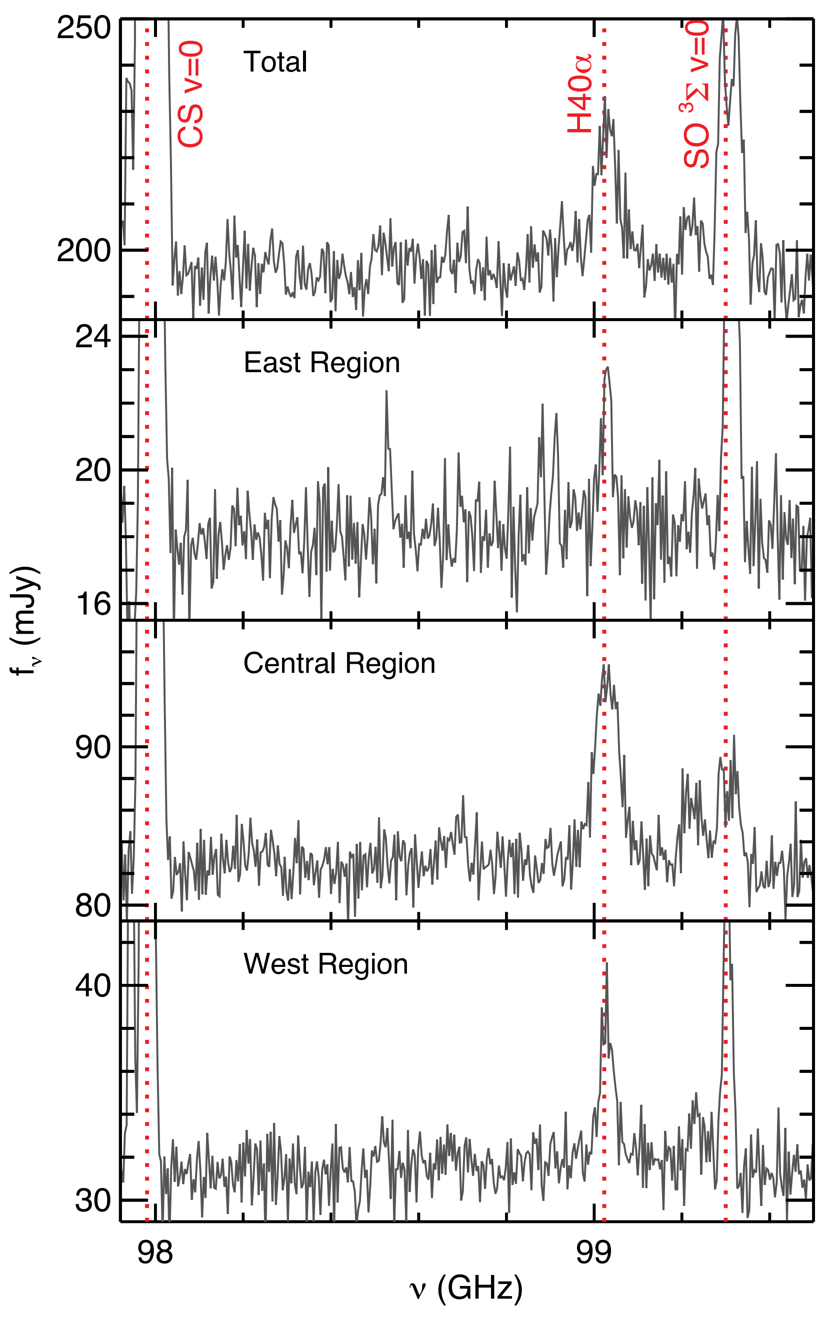
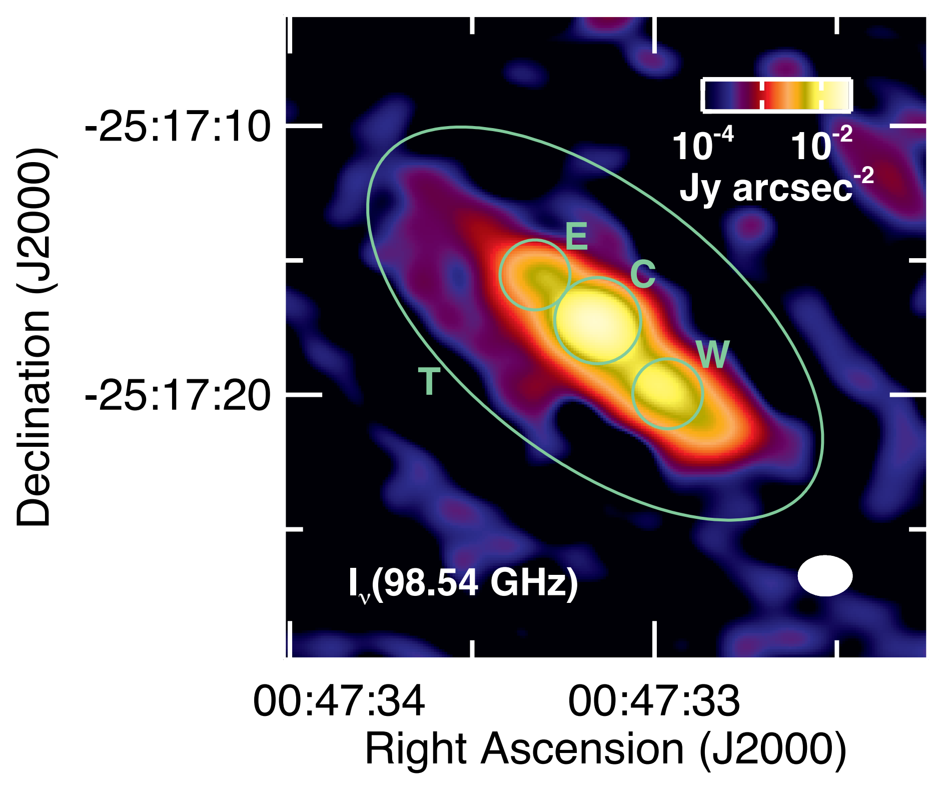
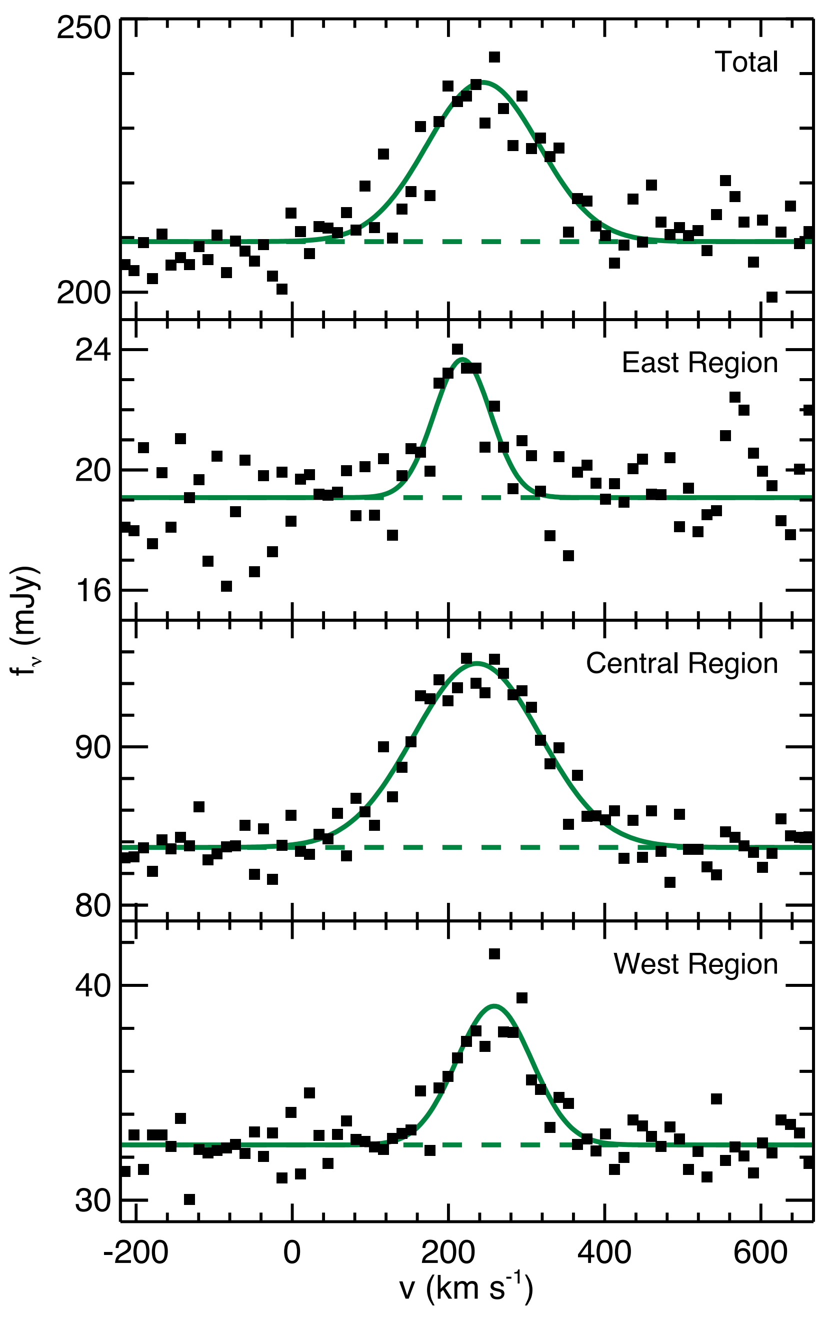
Jy arcsec^{-2}
E
C
W
T
I_ν(98.54 GHz)



Total
East Region
Central Region
West Region
CS v=0
H40α
SO $^3\Sigma$ v=0
250
200
24
20
16
90
80
40
30
f_ν (mJy)
98
99
ν (GHz)



-25:17:10
-25:17:20
Declination (J2000)
10^{-4}
10^{-2}
Jy arcsec^{-2}
E
C
W
T
I$_\nu$(98.54 GHz)
00:47:34
00:47:33
Right Ascension (J2000)



250
200
Total
24
20
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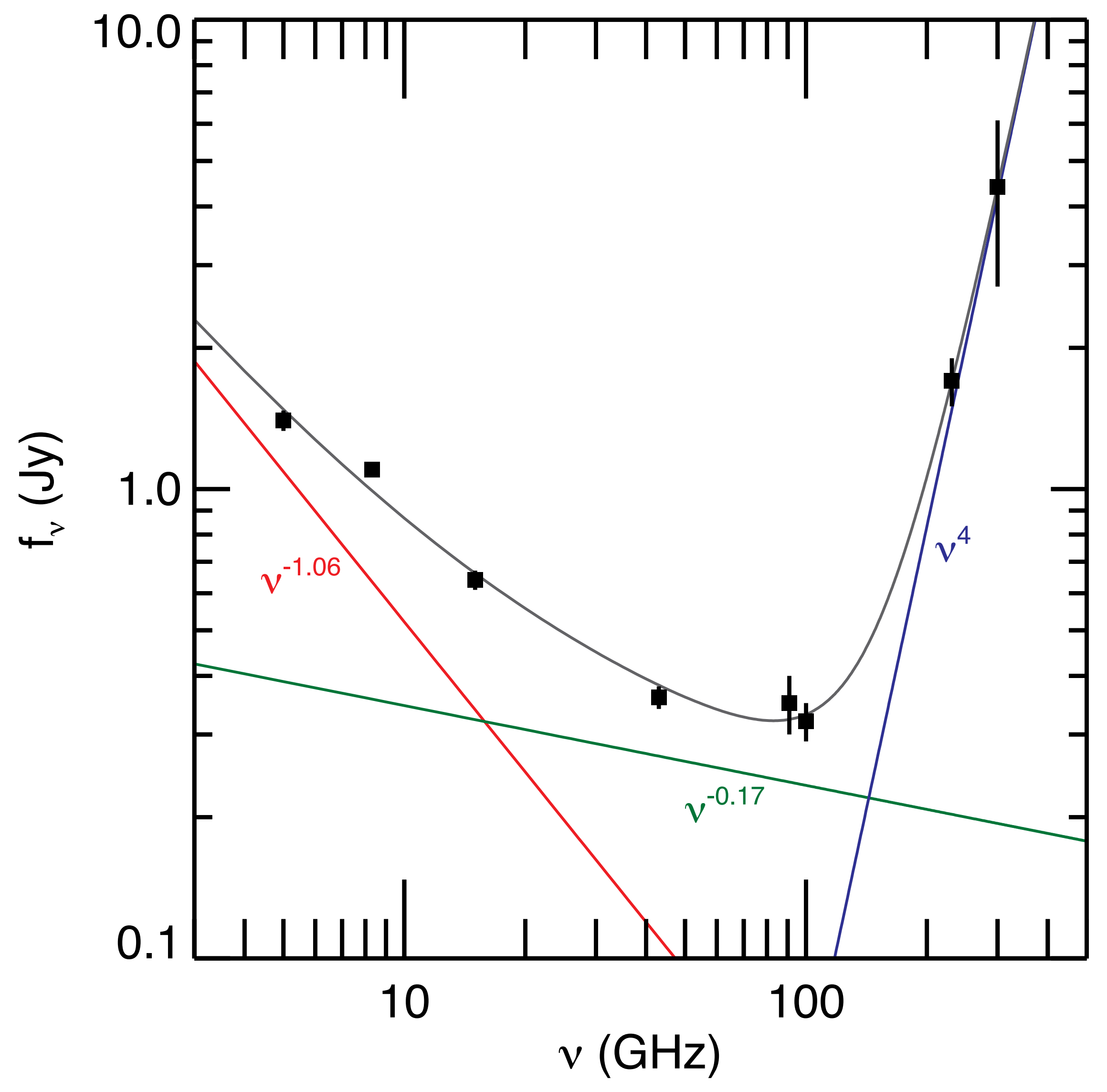
East Region
90
80
Central Region
40
30
West Region
f$_\nu$ (mJy)
-200
0
200
400
600
v (km s^{-1})

To use the continuum emission as a measure of free-free emission, we need to remove contributions from other sources.

We re-fit data from Rodriguez-Rico et al. (2006, ApJ, 644, 914) for the central 30” without fixing the slope of the synchrotron emission.

We estimate that 70±10% of the emission at 99.02 GHz is from free-free emission.

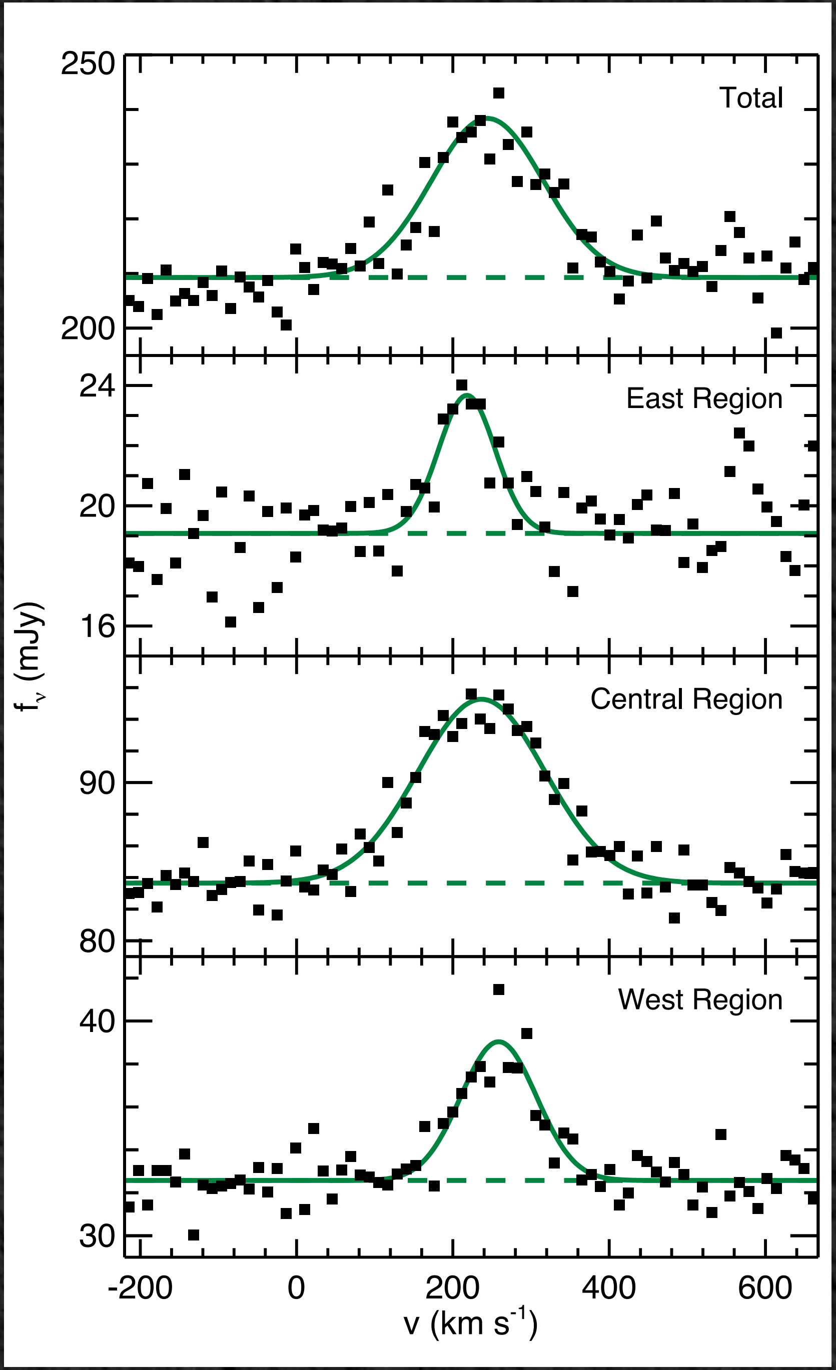


The ratio of recombination line emission to free-free emission can be used to measure the electron temperature (T_e) of the gas.

We first multiplied the continuum measurements by 0.70 to account for other sources of emission.

T_e (without adjustment):
5800-7100 K

T_e (with 0.70 adjustment):
3700-4500 K



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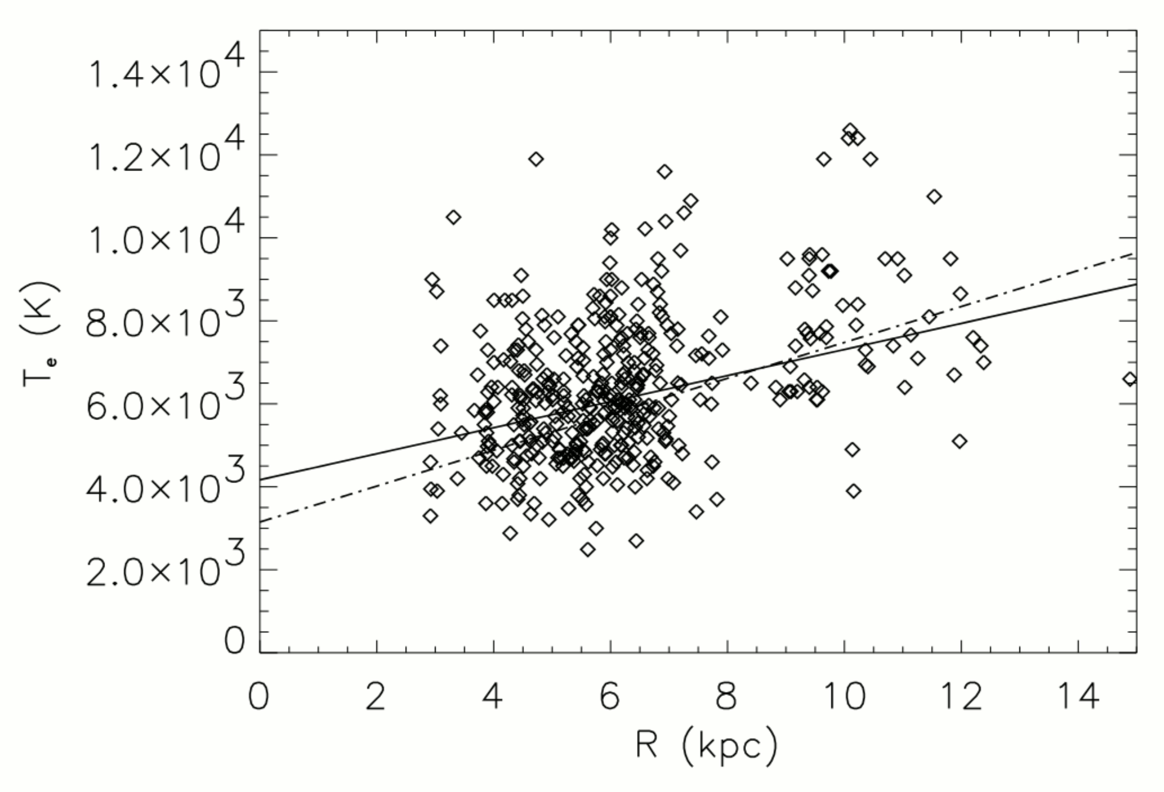
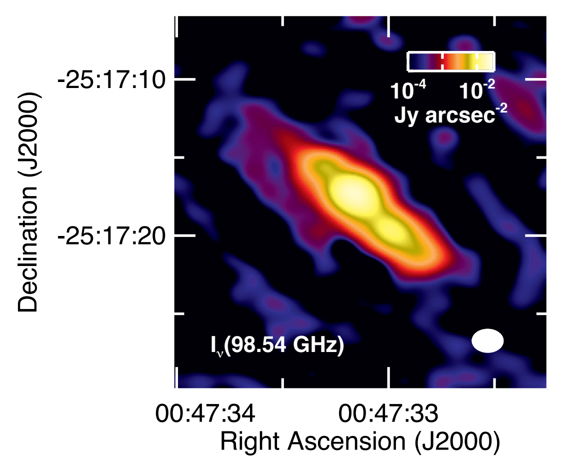


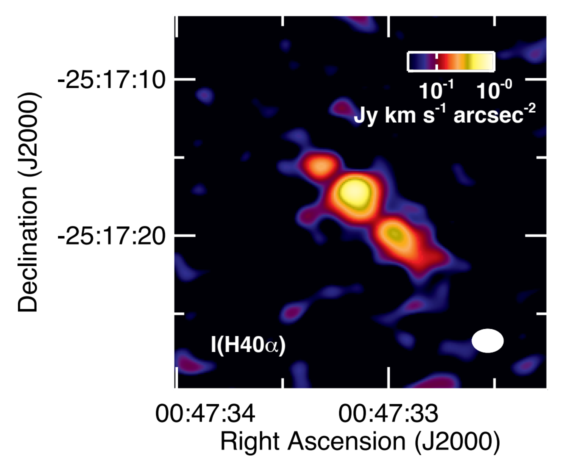
Paladini et al. (2004, MNRAS, 347, 237)

Both the free-free and recombination line emission can be converted to either photoionizing photon production rates (Q) or star formation rates (SFR).

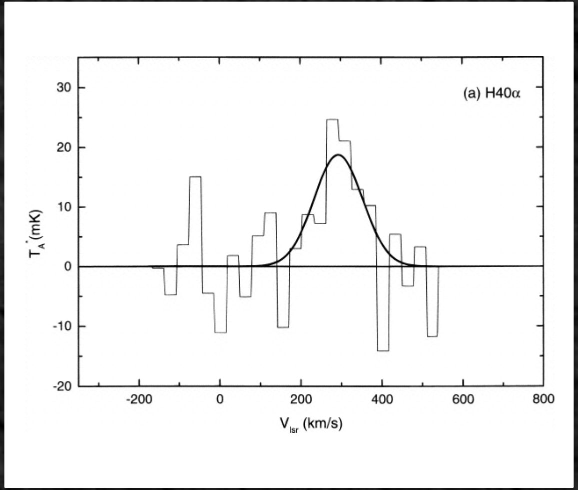
We compared these rates to other published values, which show significant scatter.



ALMA (99.02 GHz continuum)
SFR = 1.59 ± 0.16 $M_{\odot}$ yr^{-1}
Q = (3.0 ± 0.3) × 10^{53} yr^{-1}



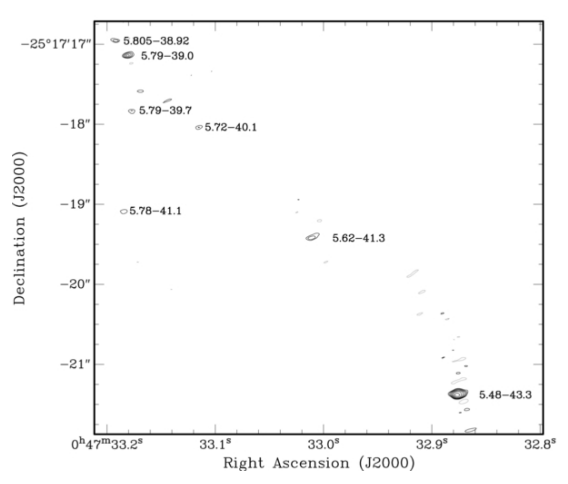
ALMA (H40α line)
SFR = 1.87 ± 0.18 $M_{\odot}$ yr^{-1}
Q = (3.5 ± 0.3) × 10^{53} yr^{-1}



NRO 45m Telescope (H40α line)
Puxley et al. (1997, ApJ, 485, 143)
Q = (7.0 ± 1.5) × 10^{53} yr^{-1} (adjusted)
Low S/N

1.2 cm continuum
(no picture shown)

ATCA (1.2 cm continuum)
Ott et al. (2005, ApJ, 629, 767)
SFR = 4.9 ± 0.5 $M_{\odot}$ yr^{-1} (adjusted)
Poor spectral decomposition



Australian LBA (SN at 2.3 GHz)
Rampadarath et al. (2014, AJ, 147, 5)
SFR < 4.9 $M_{\odot}$ yr^{-1}
Reached limits of methodology

Both the free-free and recombination line emission can be converted to either photoionizing photon production rates (Q) or star formation rates (SFR).

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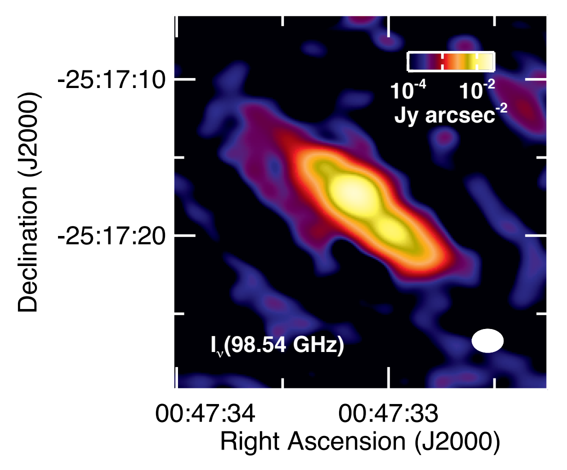
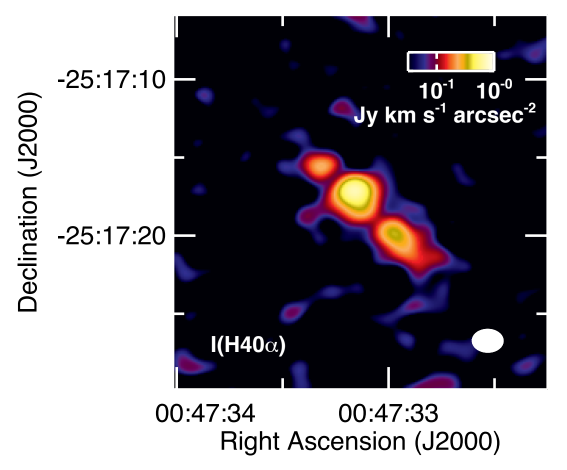
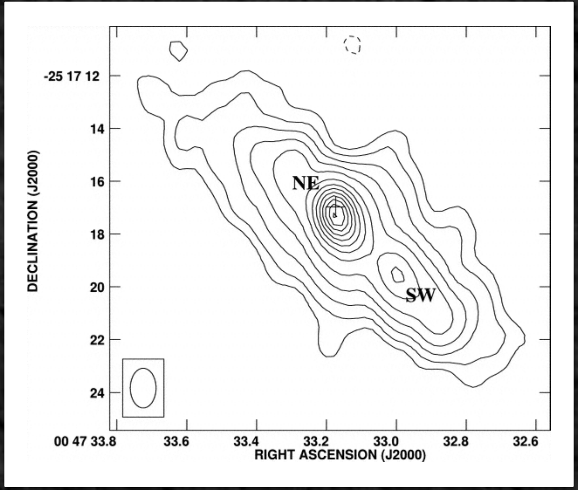


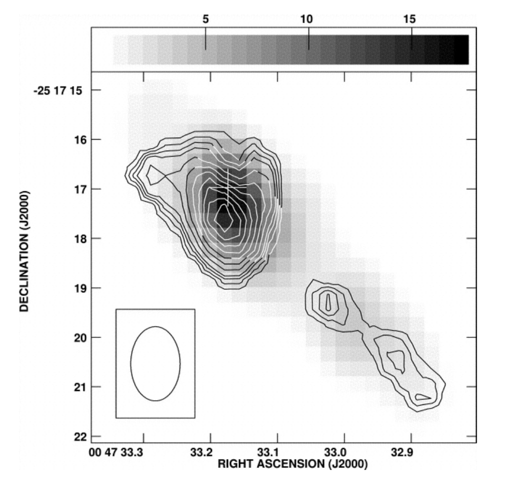
ALMA (99.02 GHz continuum)
SFR = 1.59 ± 0.16 $M_\odot$ yr^{-1}
Q = (3.0 ± 0.3) × 10^{53} yr^{-1}



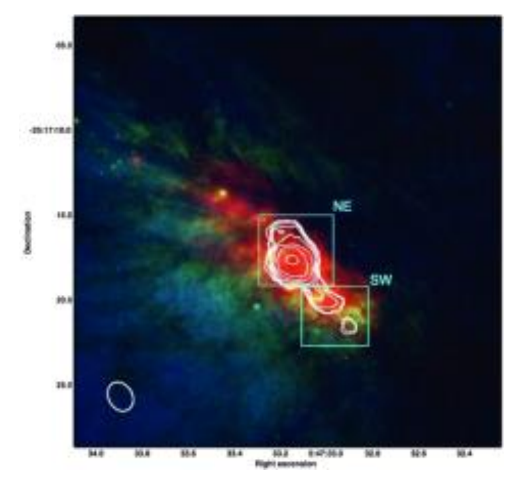
ALMA (H40α line)
SFR = 1.87 ± 0.18 $M_\odot$ yr^{-1}
Q = (3.5 ± 0.3) × 10^{53} yr^{-1}



VLA (43 GHz continuum)
Rodriguez-Rico et al. (2006, ApJ, 644, 194)
Q = 1.3 × 10^{53} yr^{-1} (adjusted)
Poor spectral decomposition



VLA (H53α, H92α line)
Rodriguez-Rico et al. (2006, ApJ, 644, 194)
Q = 1.1 × 10^{53} yr^{-1} (adjusted)
Poor sensitivity/RRL issues

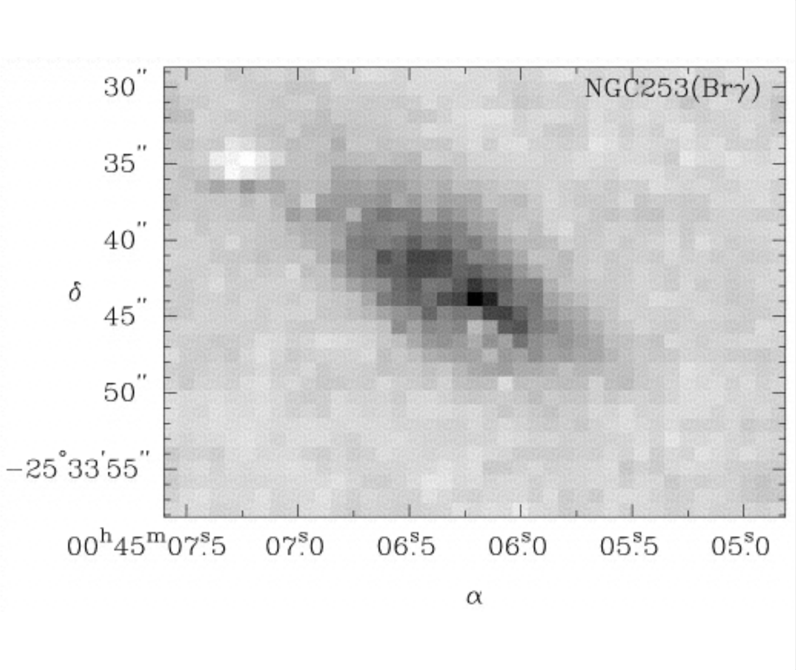


VLA (H58α line)
Kepley et al. (2011, ApJ, 644, 194)
Q = 1 × 10^{53} yr^{-1}
Poor sensitivity/RRL issues

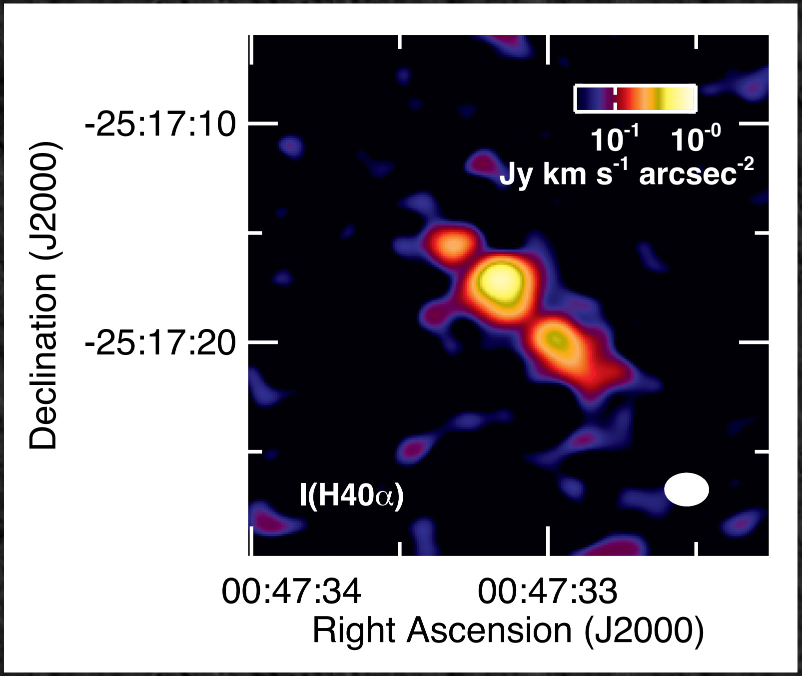
The central starburst in NGC 253 is heavily obscured in optical wavelengths, but near-infrared recombination lines (Paβ, Brγ) have been detected (Engelbracht et al., 1998, ApJ, 505, 639).

We can compare the H40α emission to the near-infrared lines to measure dust attenuation.

We measure attenuations that are ~3 dex higher than measured by Engelbracht et al.



Engelbracht et al. (1998, ApJ, 505, 639)
A_J = 2.00 ± 0.36
A_K = 0.87 ± 0.16



ALMA
A_J = 4.9 ± 0.2
A_K = 4.2 ± 0.2

Conclusions

- We detect both free-free and H40α emission from a three-lobed structure in the centre of NGC 253.
- The T_e measured in ALMA data are consistent with previous measurements in NGC 253 as well as with measurements in the Milky Way.
- The SFR measured with ALMA data fall within the broad range of SFR values reported in the literature, but the ALMA data should be better constrained.
- Combining the ALMA line measurements with near-infrared data, we measure dust attenuation that is ~3 dex higher than what was determined from the near-infrared data alone.

Future Work

- ALMA free-free and recombination line emission from other galaxies could be used to cross-calibrate other star formation tracers (e.g. infrared emission traced by Spitzer, WISE, and Herschel).
- Broad recombination line measurements could be used to identify the presence of AGN, including in situations where the AGN may be heavily obscured (e.g. LIRGs).
- Line emission from composite AGN/starburst objects can be used to identify the relative contributions of these components to the overall emission from these galaxies.