

ALMA observations of 99 GHz free-free and H40 α emission from star formation in the centre of NGC 253

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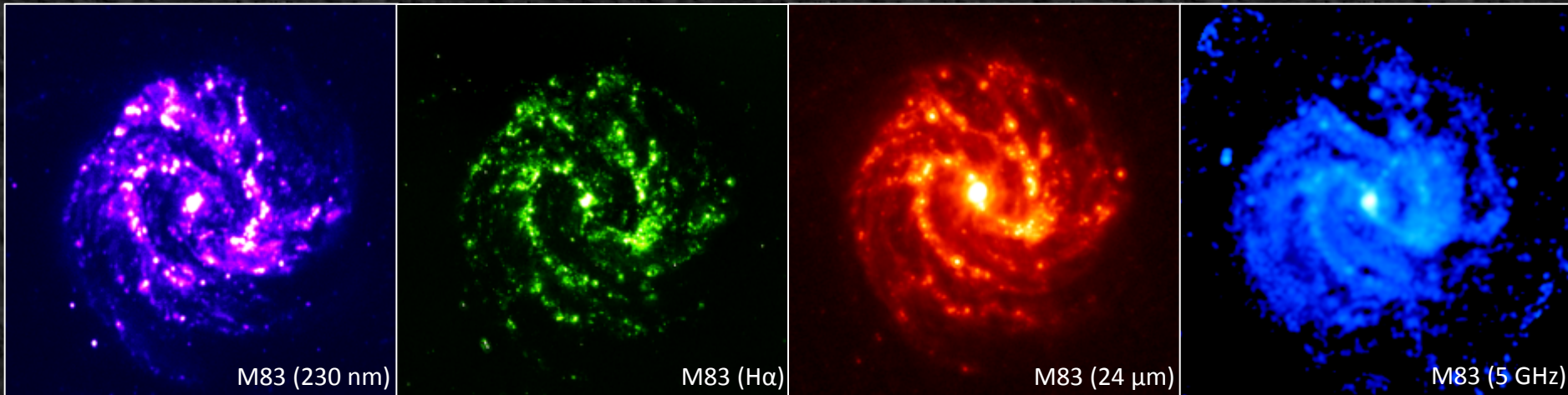
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2015, MNRAS, 450, L80

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.



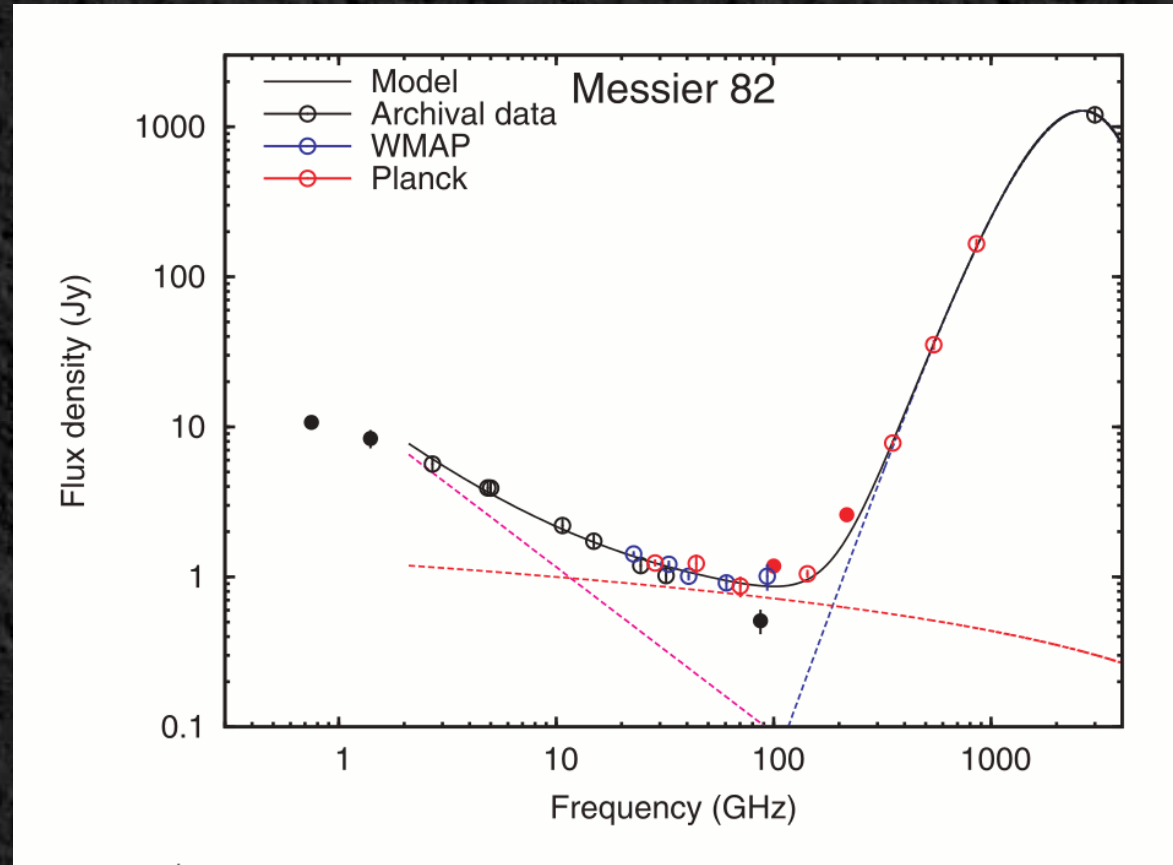
ALMA can detect emission from photoionized gas in two forms:

- Free-free 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.

See [Scoville & Murchikova \(2013, ApJ, 779, 75\)](#) for more background information on using these star formation tracers.

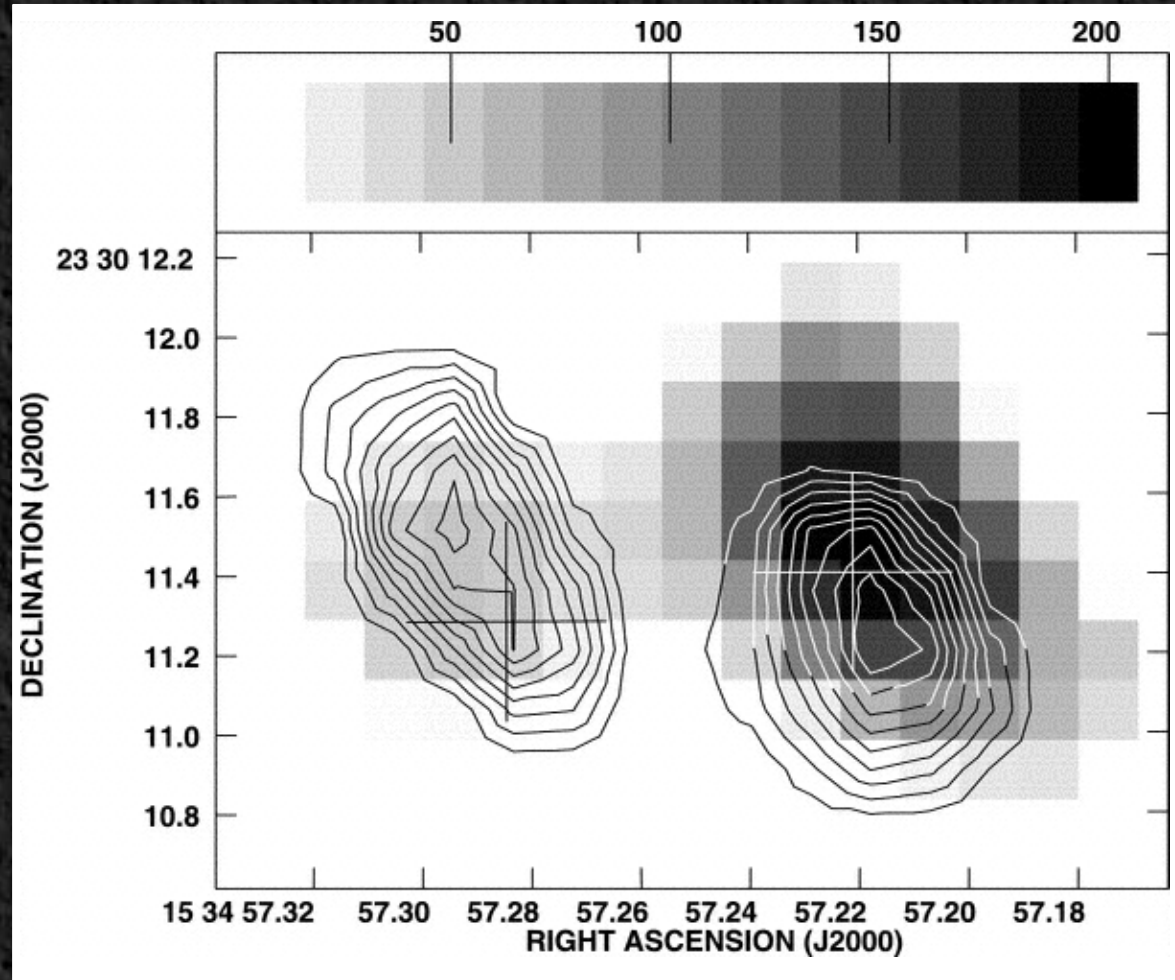


Peel et al. (2011, MNRAS, 416, L99)

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, where the recombination lines are not affected by these issues.

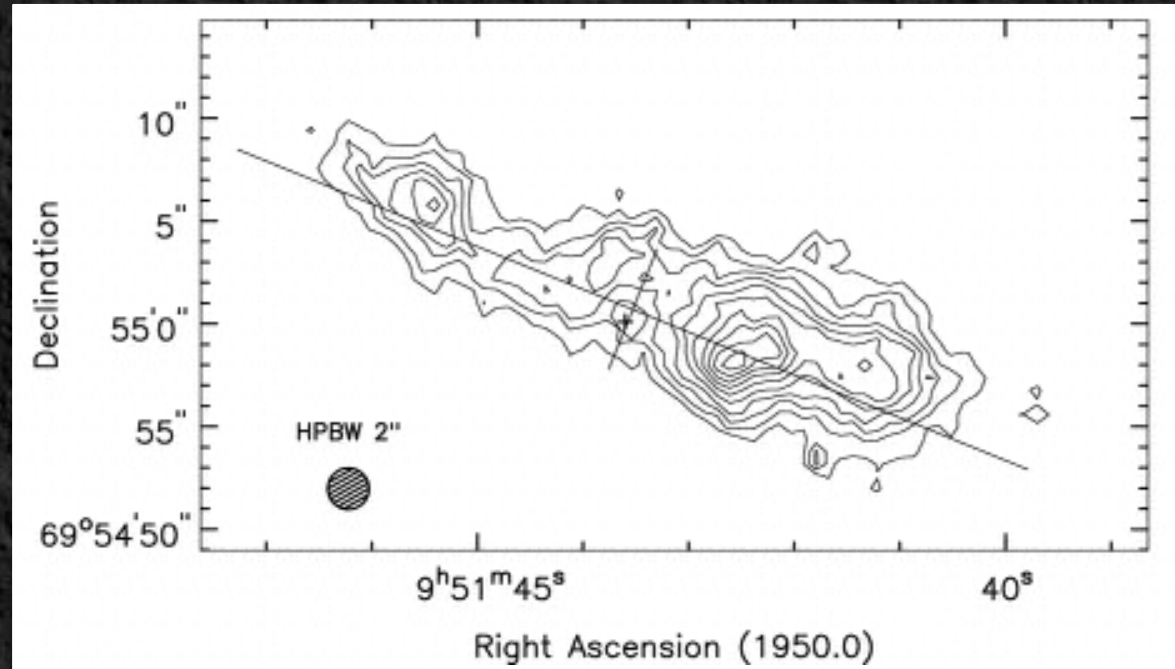


H53 α , H92 α in Arp 220 (Rodriguez-Rico et al., 2005, ApJ, 633, 198)

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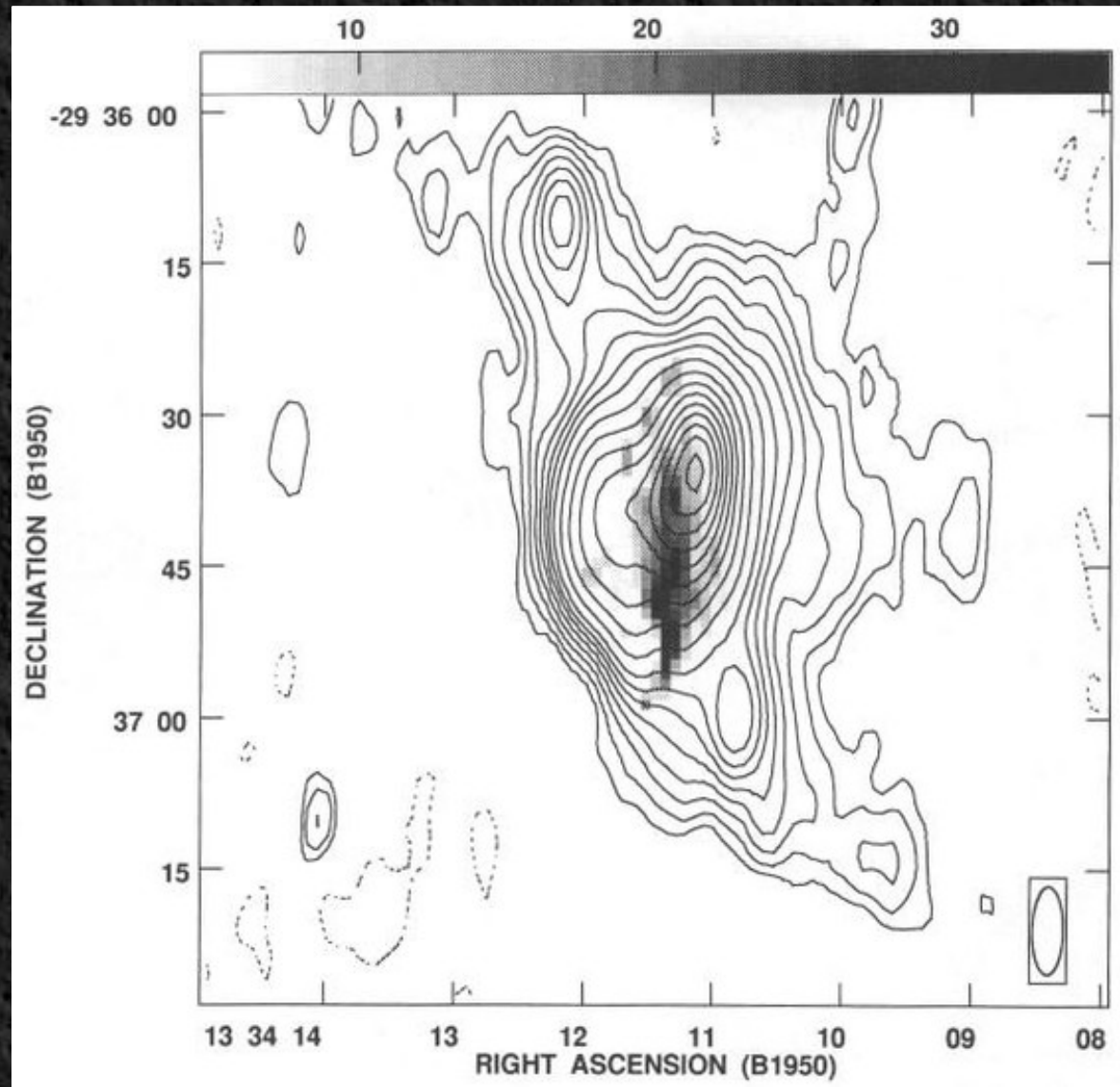


H92 α in M82 (Rodriguez-Rico et al., 2004, ApJ, 616, 783)

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

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H₂α in M83 (Zhao et al., 1996, ApJ, 472, 54)

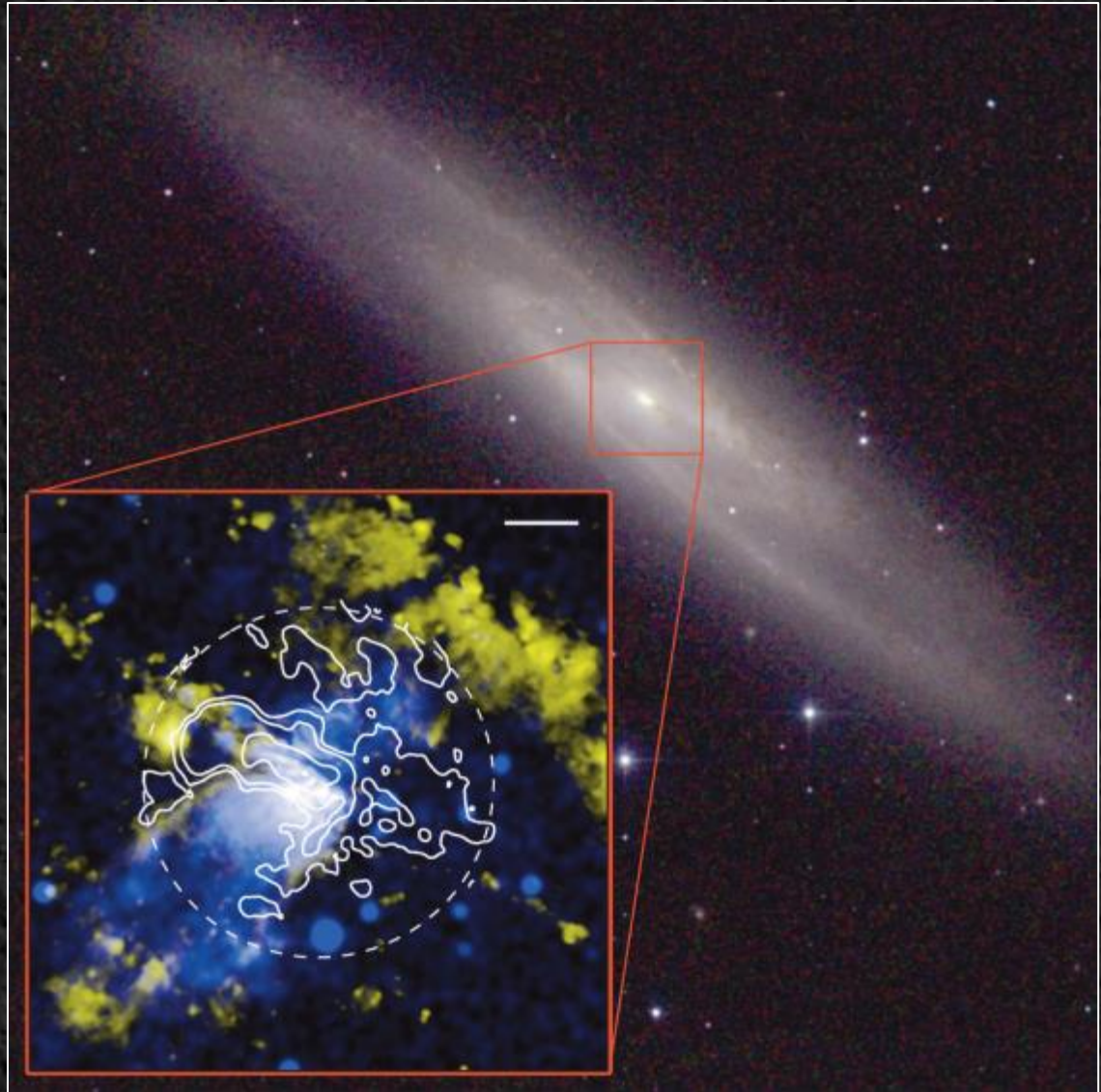
NGC 253 is a nearby spiral galaxy with starburst activity in its nucleus.

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.

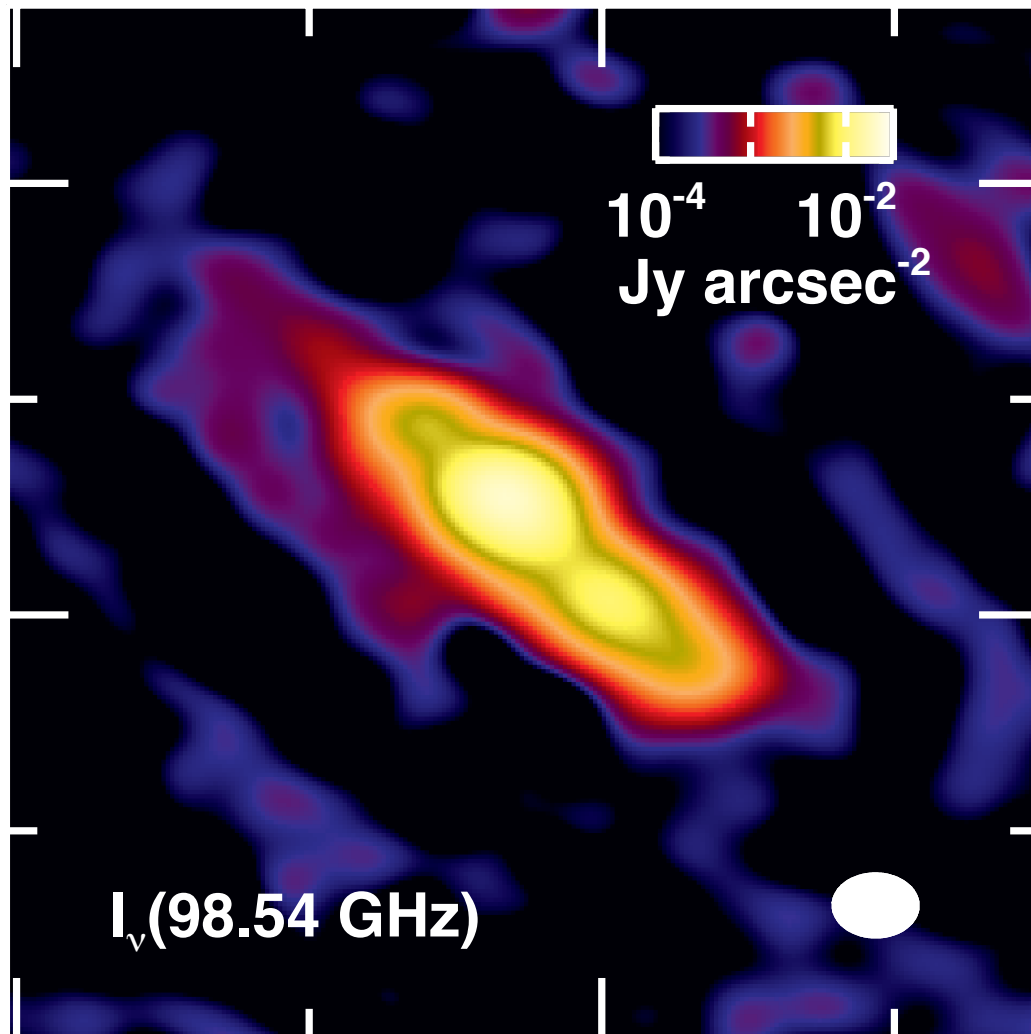


Bolatto et al. (2013, Nature, 499, 450)

Declination (J2000)

-25:17:10

-25:17:20



00:47:34

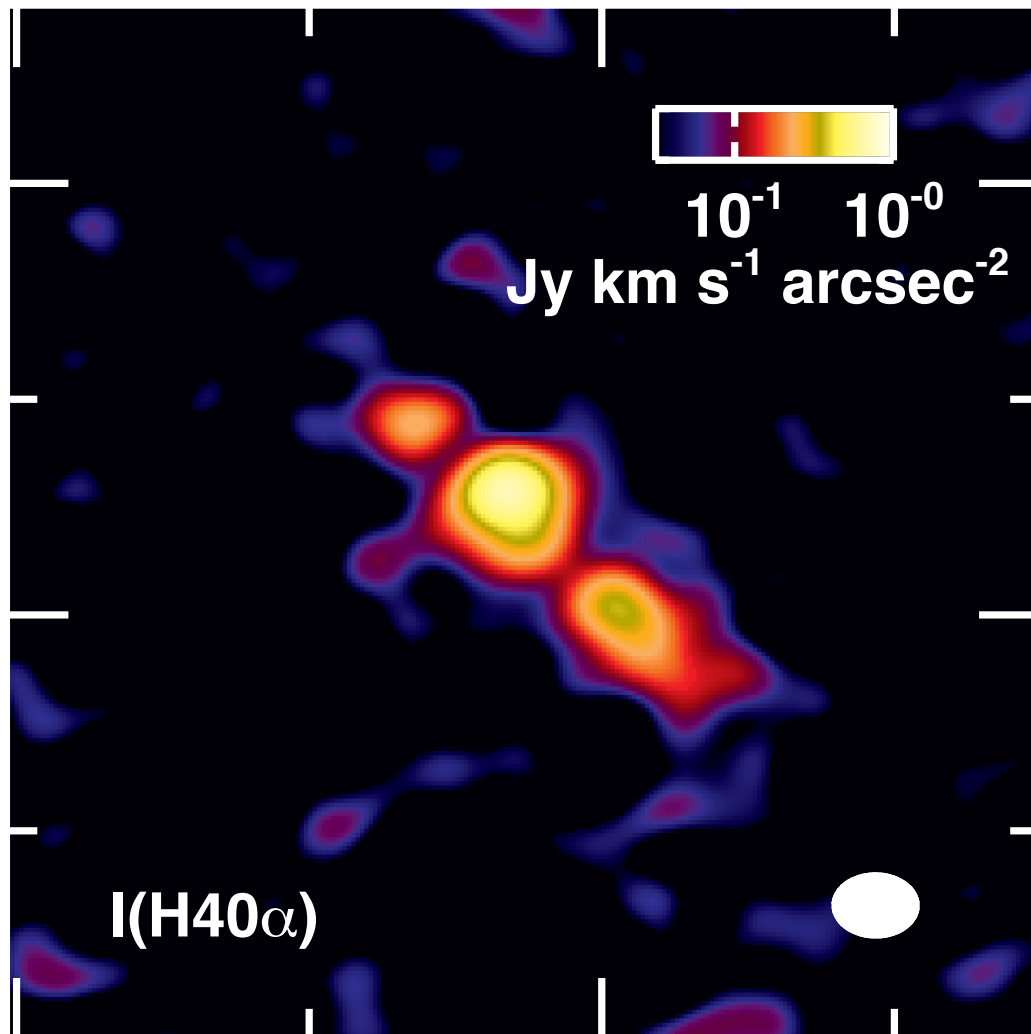
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Right Ascension (J2000)

Declination (J2000)

-25:17:10

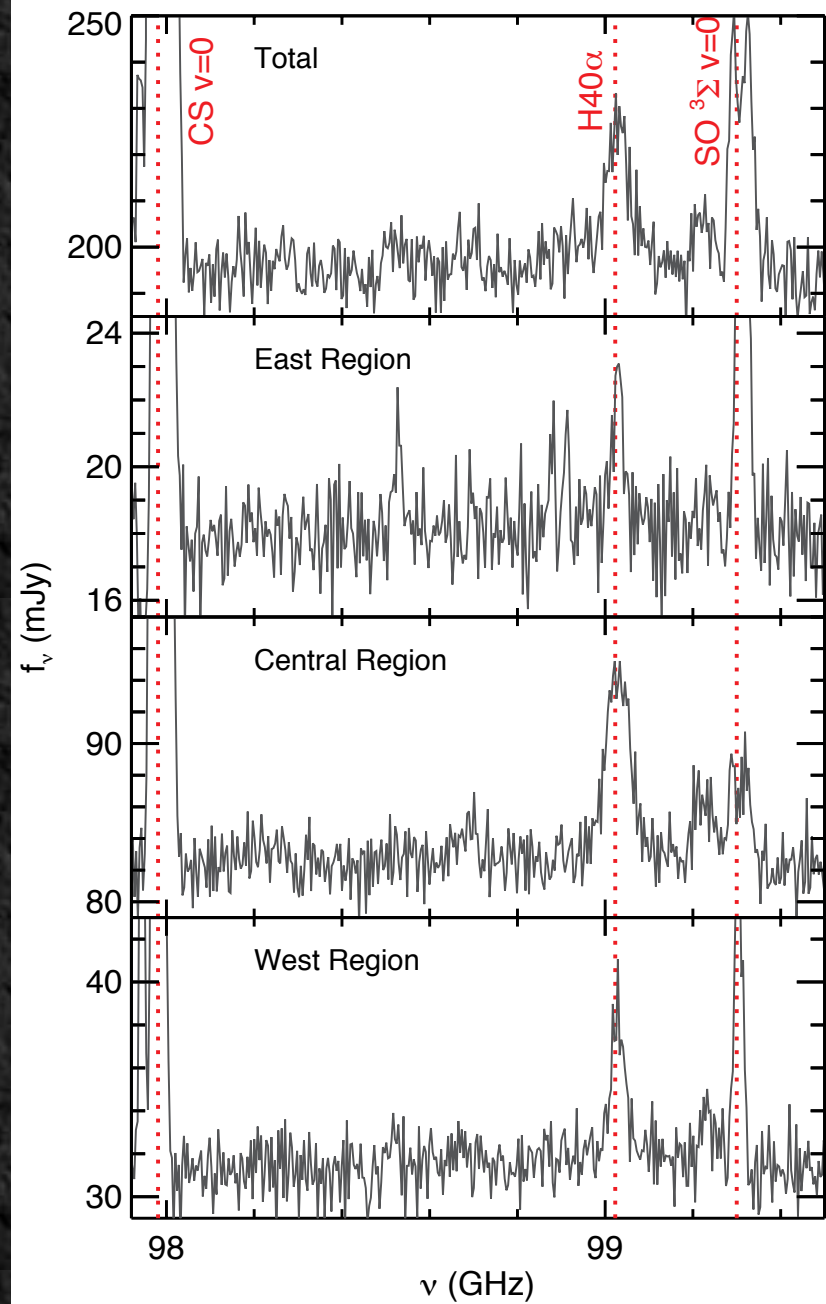
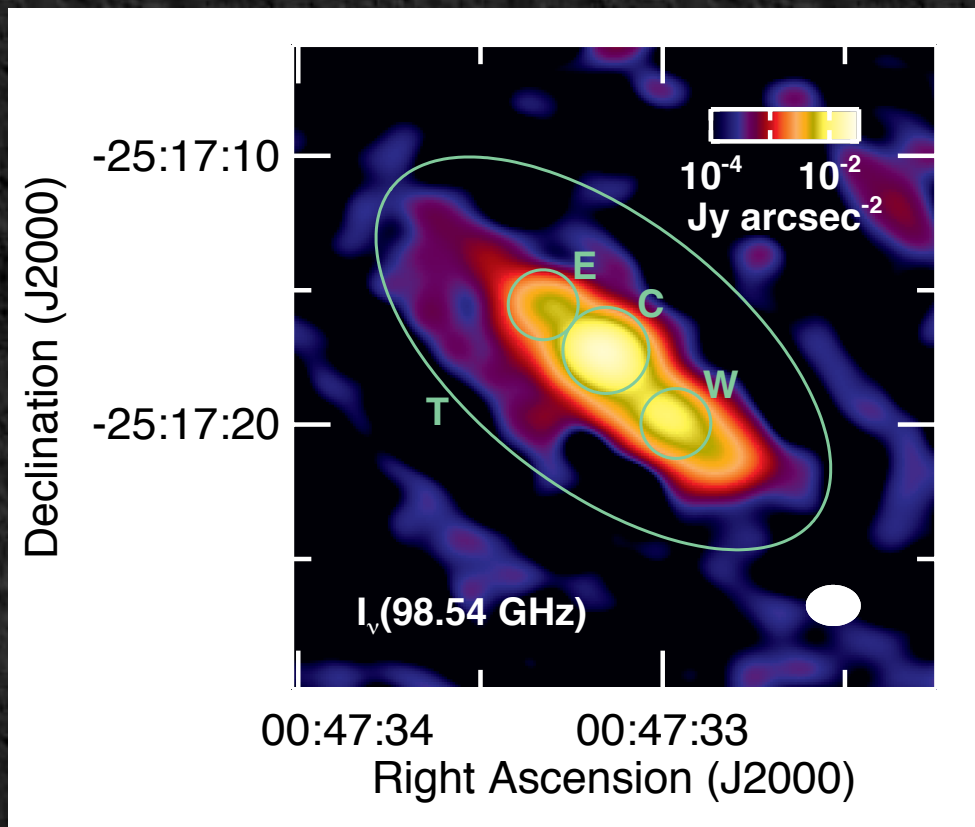
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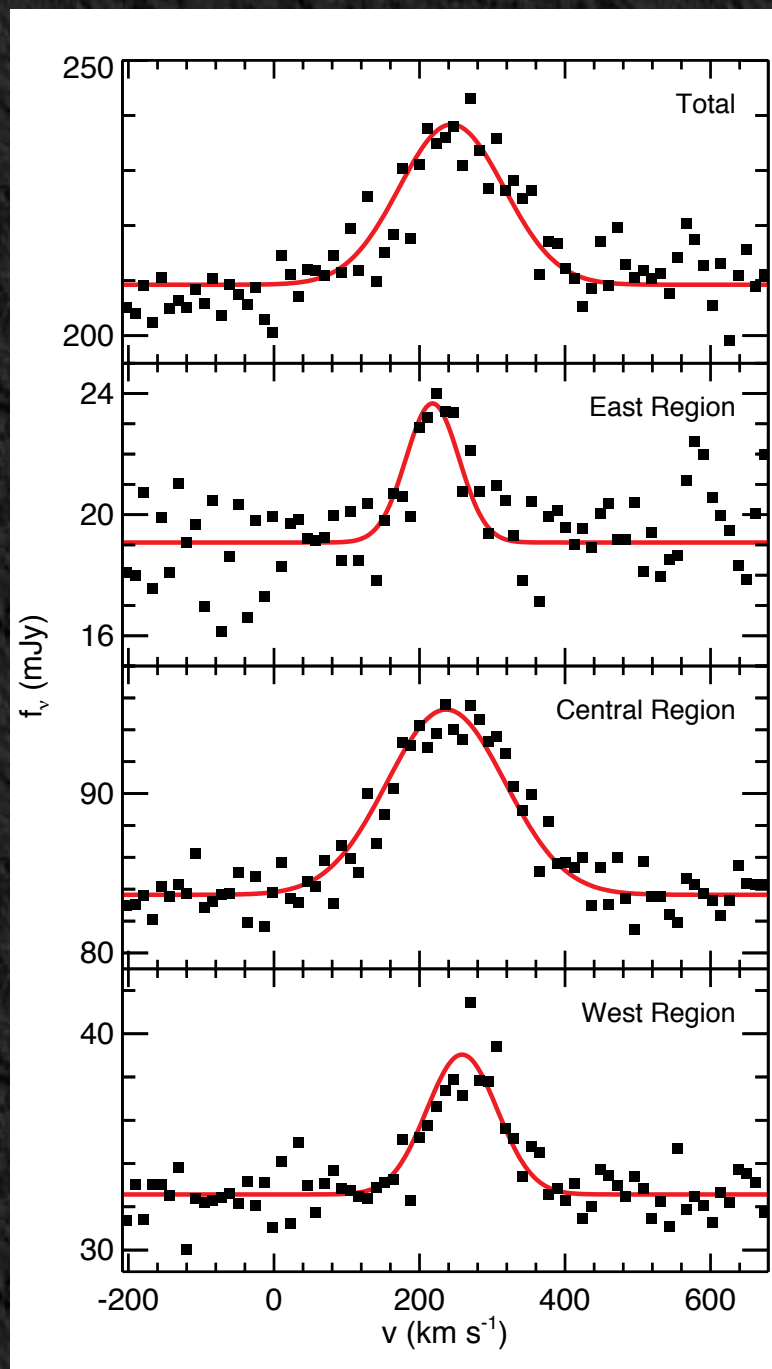
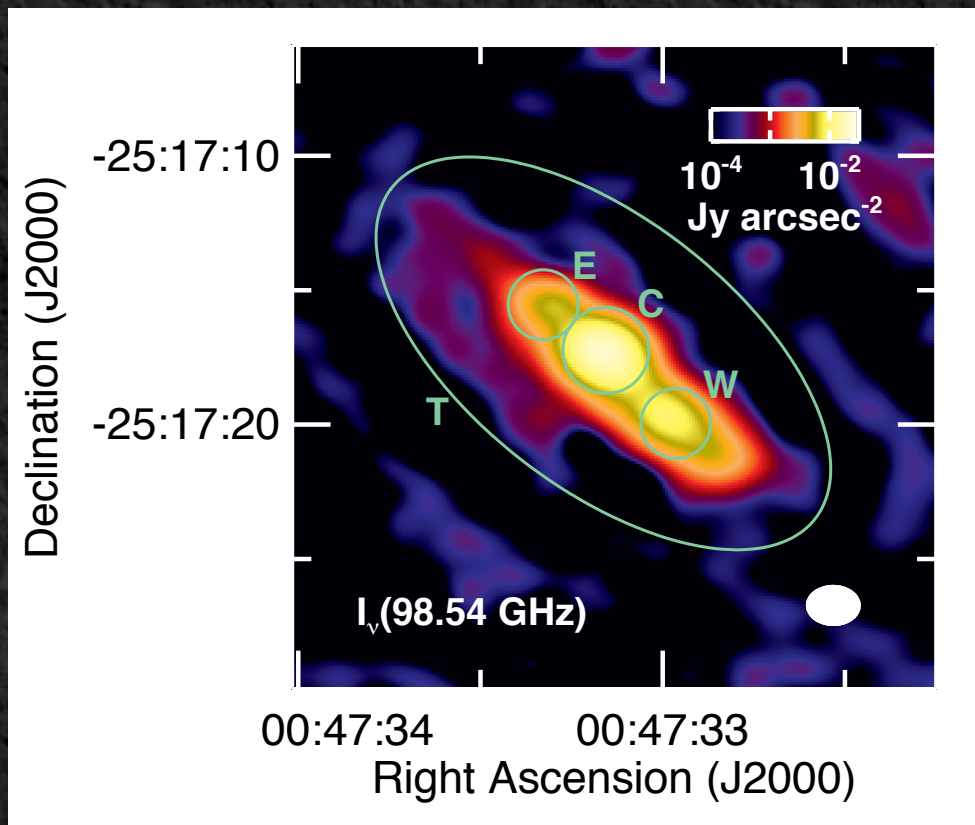


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Right Ascension (J2000)

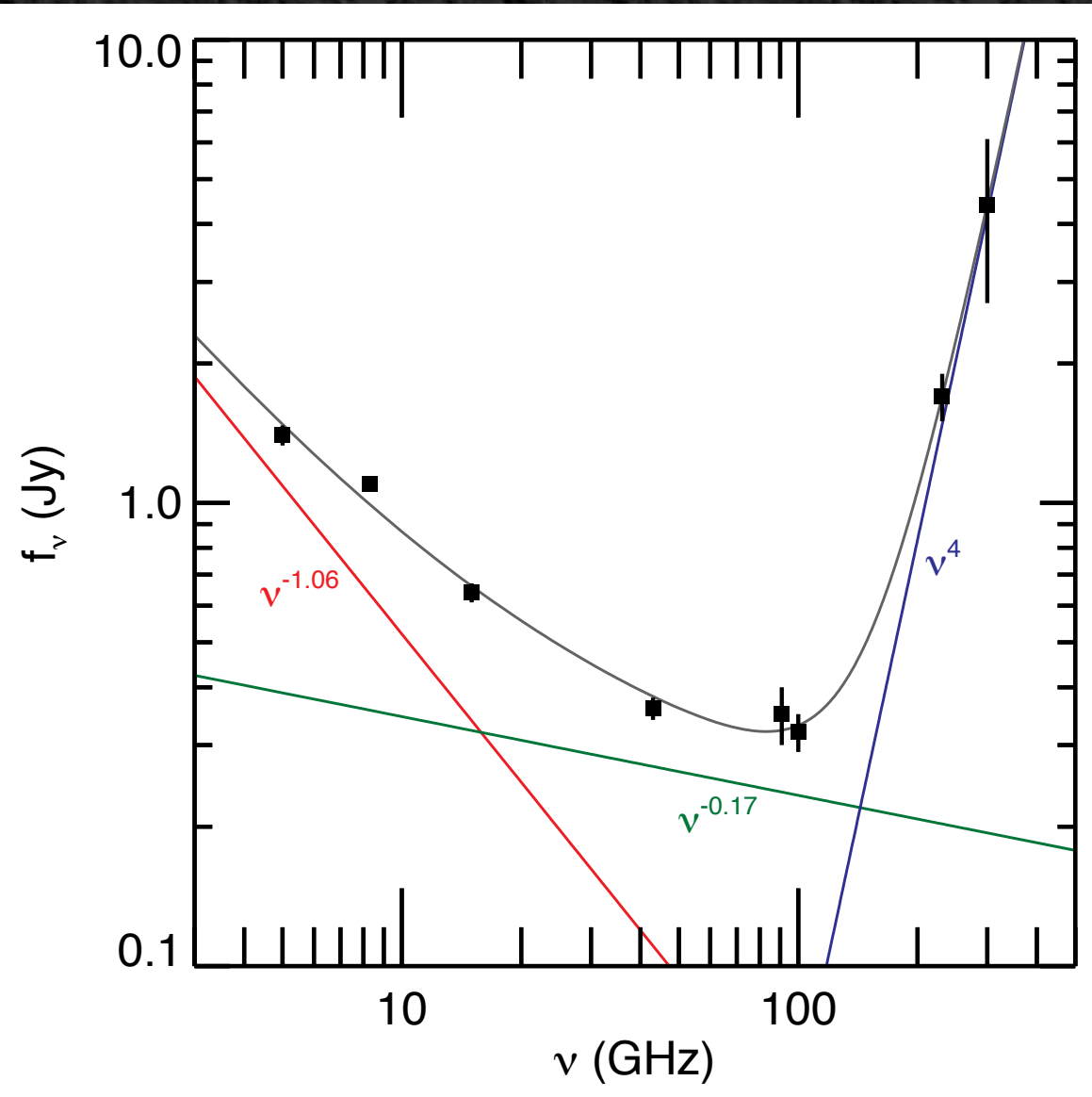




To use the continuum emission as a measure of free-free emission, we need to remove contributions from other sources.

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.

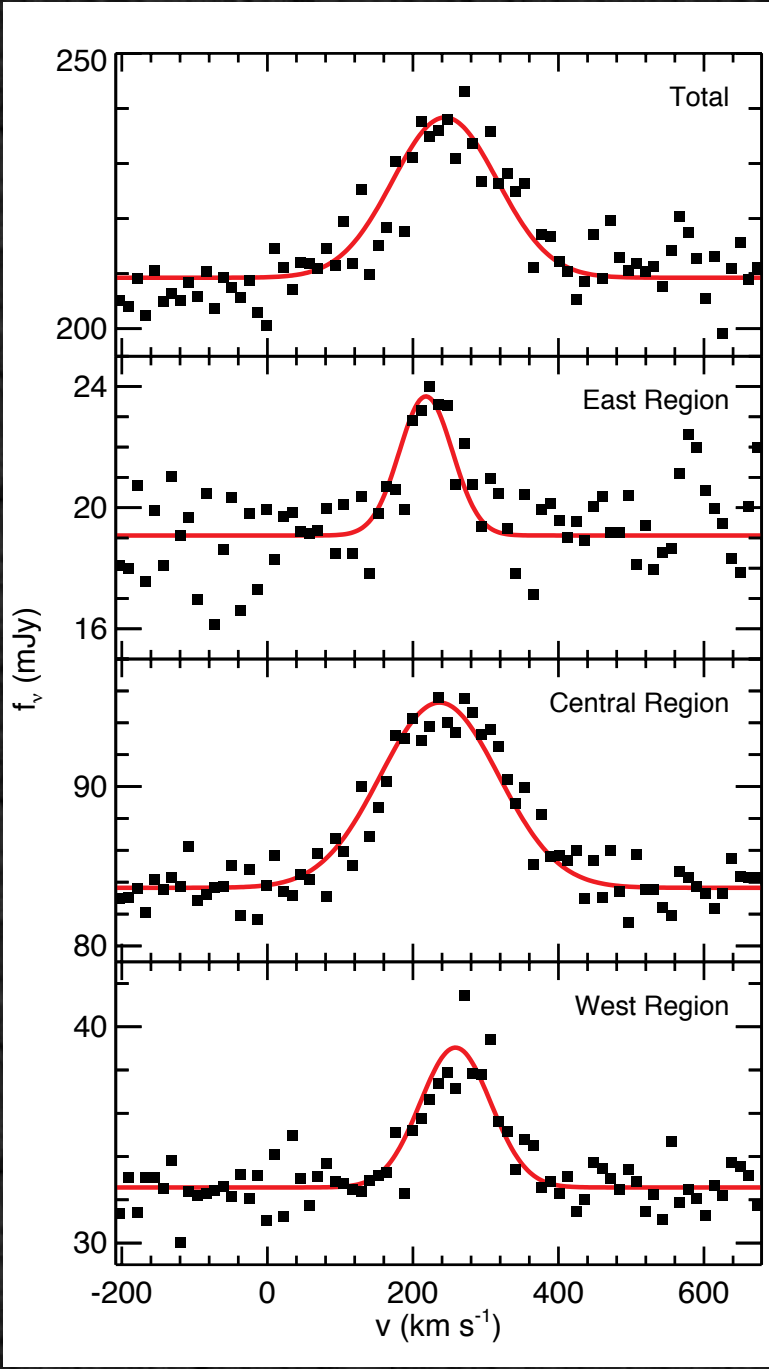


The ratio of recombination line emission to free-free emission can be used to measure the electron temperature (T_e) of the gas.

T_e (with 0.70 adjustment):
3700-4500 K

The T_e measured in NGC 253 are comparable to what is measured in the Milky Way Galaxy.

The ALMA-based T_e measurements are also comparable to previous T_e measurements.

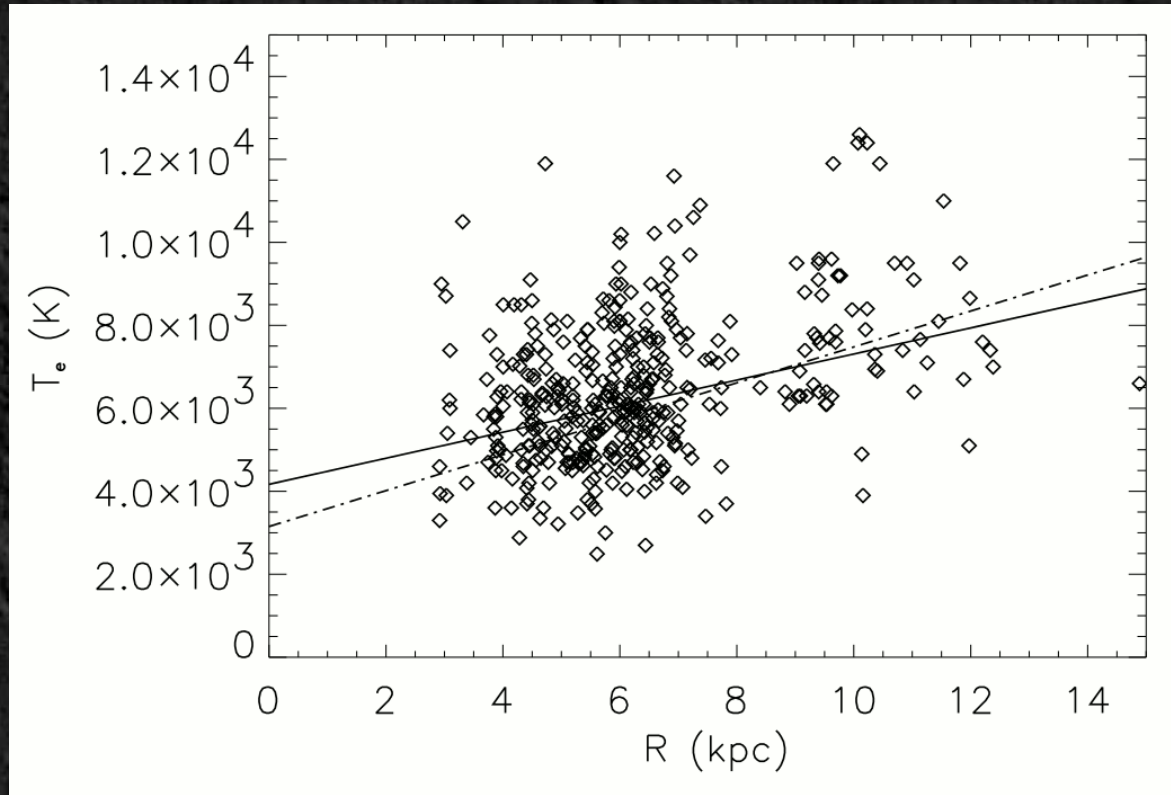


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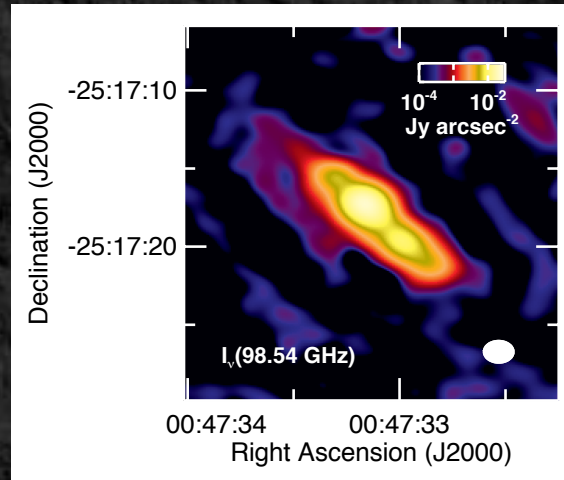
The ALMA-based T_e measurements are also comparable to previous T_e measurements.



Milky Way Galaxy (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).

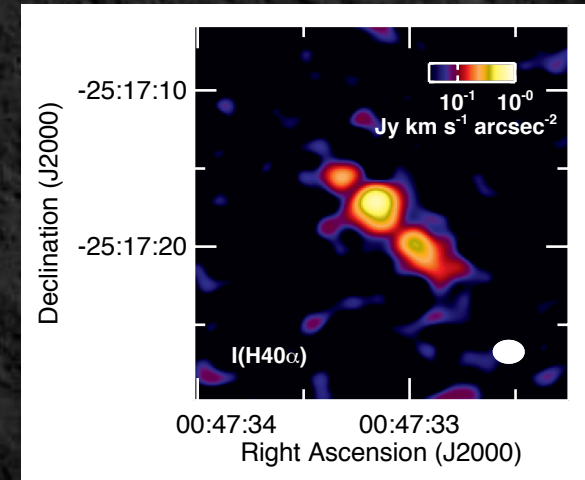
We compared these rates to other published values, which show significant scatter.



ALMA (99.02 GHz continuum)

$$SFR = 1.59 \pm 0.16 M_{\odot} \text{ yr}^{-1}$$

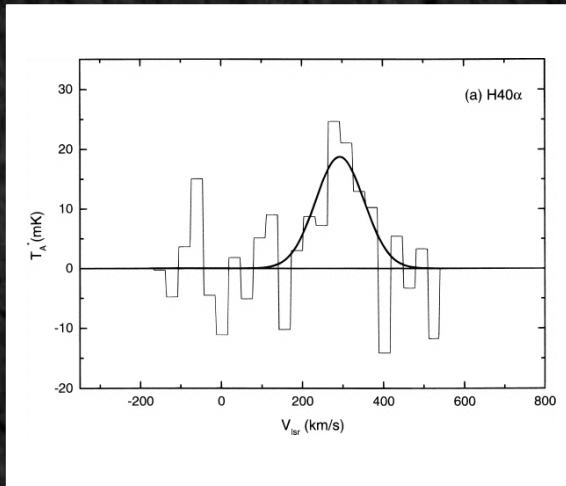
$$Q = (3.0 \pm 0.3) \times 10^{53} \text{ yr}^{-1}$$



ALMA (H40 α line)

$$SFR = 1.87 \pm 0.18 M_{\odot} \text{ yr}^{-1}$$

$$Q = (3.5 \pm 0.3) \times 10^{53} \text{ yr}^{-1}$$



NRO 45m Telescope (H40 α line)

Puxley et al. (1997, ApJ, 485, 143)

$$Q = (7.0 \pm 1.5) \times 10^{53} \text{ yr}^{-1} \text{ (adjusted)}$$

Low S/N

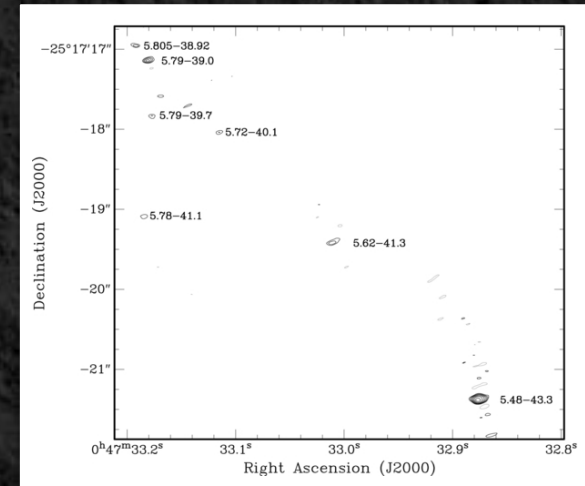
1.2 cm continuum
(no picture shown)

ATCA (1.2 cm continuum)

Ott et al. (2005, ApJ, 629, 767)

$$SFR = 4.9 \pm 0.5 M_{\odot} \text{ yr}^{-1} \text{ (adjusted)}$$

Out-of-date conversion to SFR



Australian LBA (SN at 2.3 GHz)

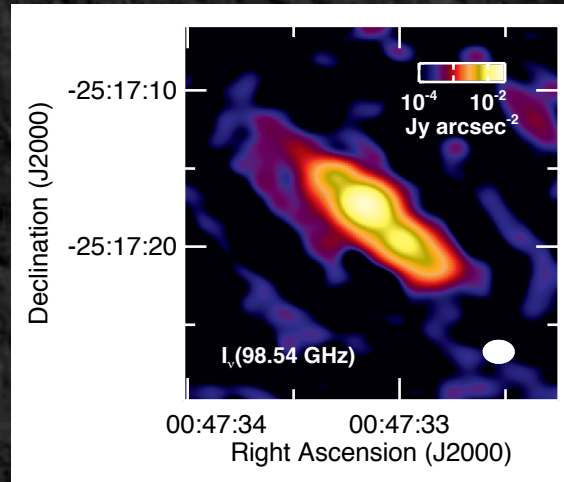
Rampadarath et al. (2014, AJ, 147, 5)

$$SFR < 4.9 M_{\odot} \text{ yr}^{-1}$$

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**).

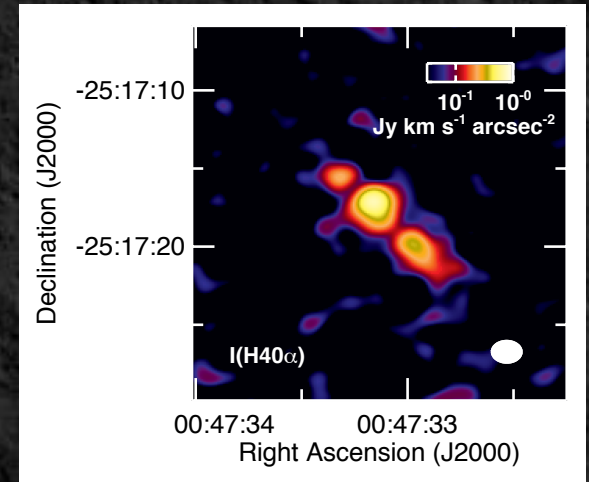
We compared these rates to other published values, which show significant scatter.



ALMA (99.02 GHz continuum)

$$\text{SFR} = 1.59 \pm 0.16 M_{\odot} \text{ yr}^{-1}$$

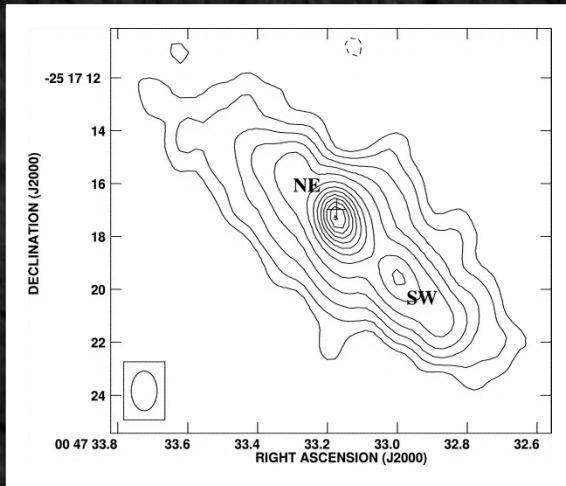
$$Q = (3.0 \pm 0.3) \times 10^{53} \text{ yr}^{-1}$$



ALMA (H40 α line)

$$\text{SFR} = 1.87 \pm 0.18 M_{\odot} \text{ yr}^{-1}$$

$$Q = (3.5 \pm 0.3) \times 10^{53} \text{ yr}^{-1}$$

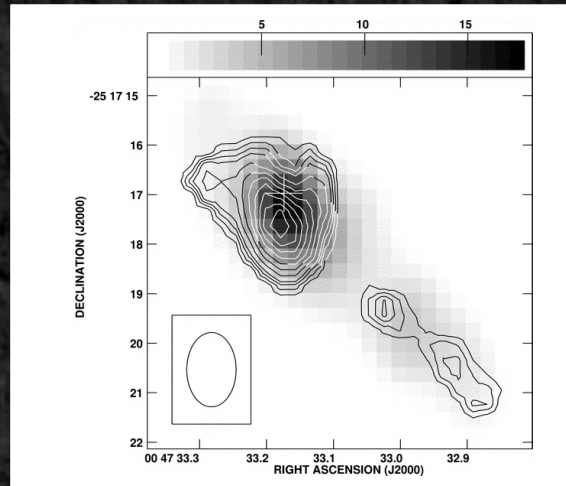


VLA (43 GHz continuum)

Rodriguez-Rico et al. (2006, ApJ, 644, 194)

$$Q = 1.3 \times 10^{53} \text{ yr}^{-1} \text{ (adjusted)}$$

Poor spectral decomposition

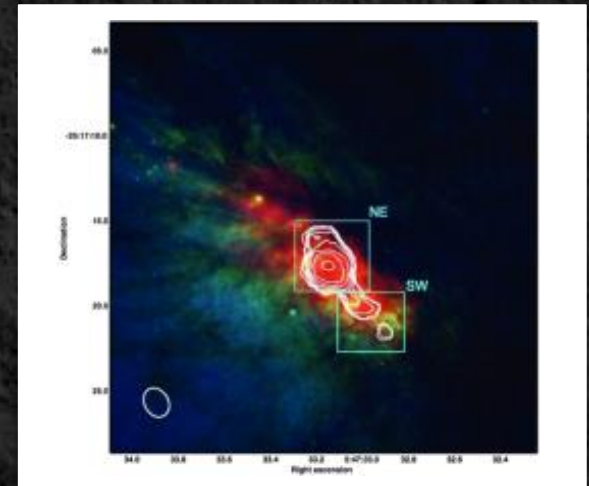


VLA (H53 α , H92 α line)

Rodriguez-Rico et al. (2006, ApJ, 644, 194)

$$Q = 1.1 \times 10^{53} \text{ yr}^{-1} \text{ (adjusted)}$$

Poor sensitivity/RRL issues



VLA (H58 α line)

Kepley et al. (2011, ApJ, 644, 194)

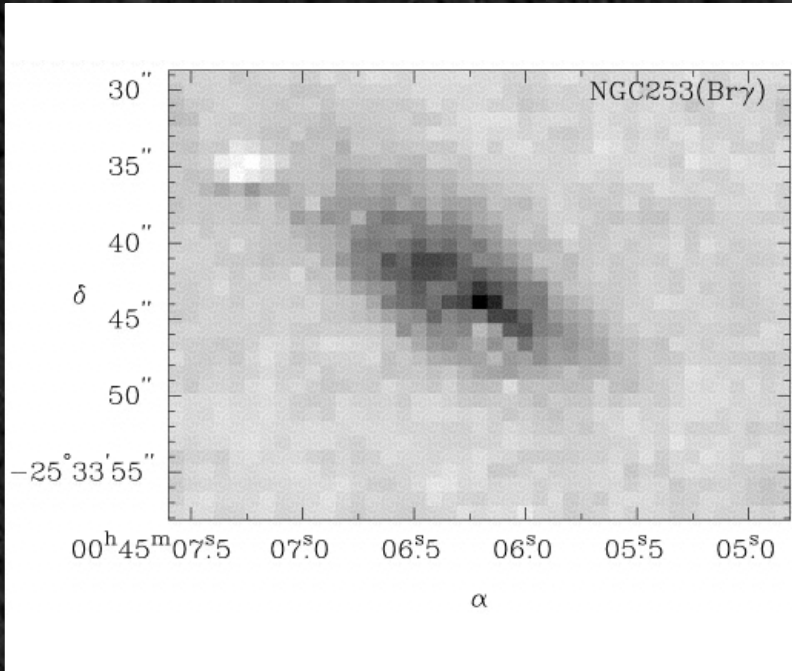
$$Q = 1 \times 10^{53} \text{ yr}^{-1}$$

Poor sensitivity/RRL issues

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

We can compare the H40 α emission to the near-infrared lines to measure dust attenuation.

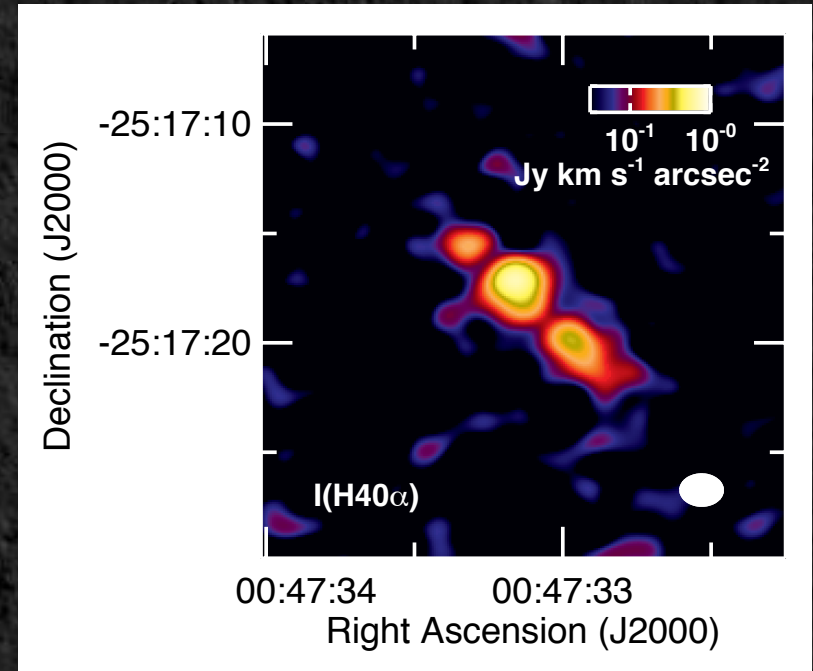
We measure attenuations that are ~ 3 dex higher than measured by Engelbracht et al.



Engelbracht et al. (1998, ApJ, 505, 639)

$$A_J = 2.00 \pm 0.36$$

$$A_K = 0.87 \pm 0.16$$



ALMA

$$A_J = 4.9 \pm 0.2$$

$$A_K = 4.2 \pm 0.2$$

Conclusions

- We detect both **free-free** and **H40 α** 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-based SFR 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.