Measuring star formation rates in nearby dust-obscured starbursts with ALMA

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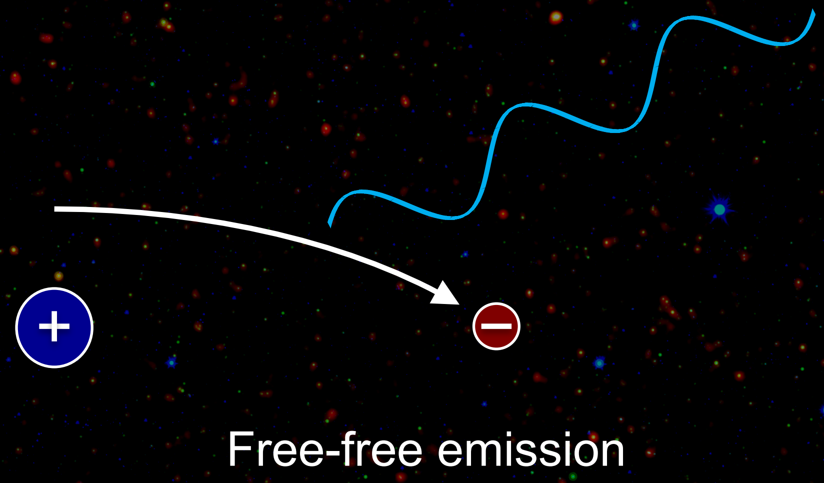
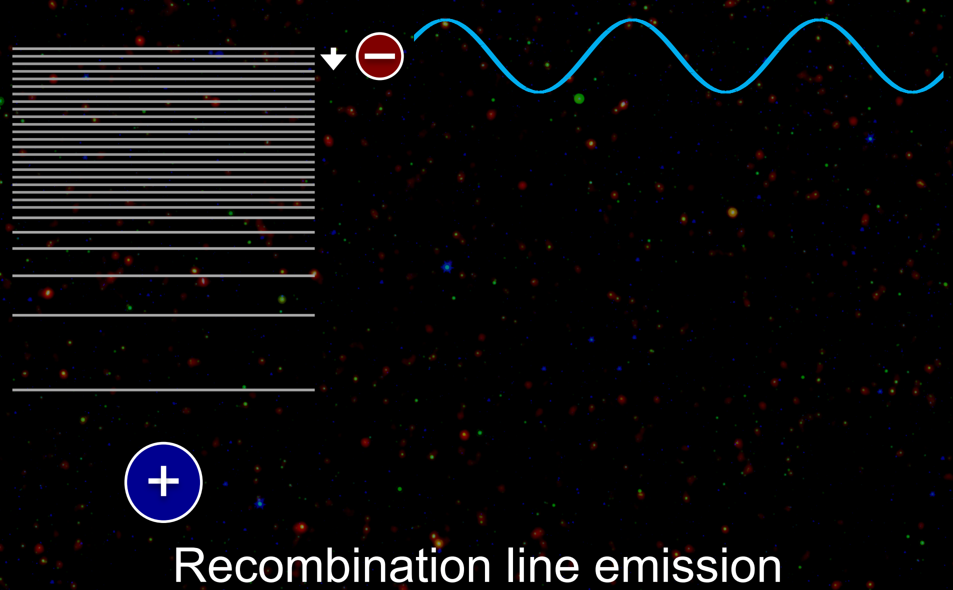
ALMA can detect emission from photoionized gas in two forms:

- Free-free continuum emission
- Higher order hydrogen 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.





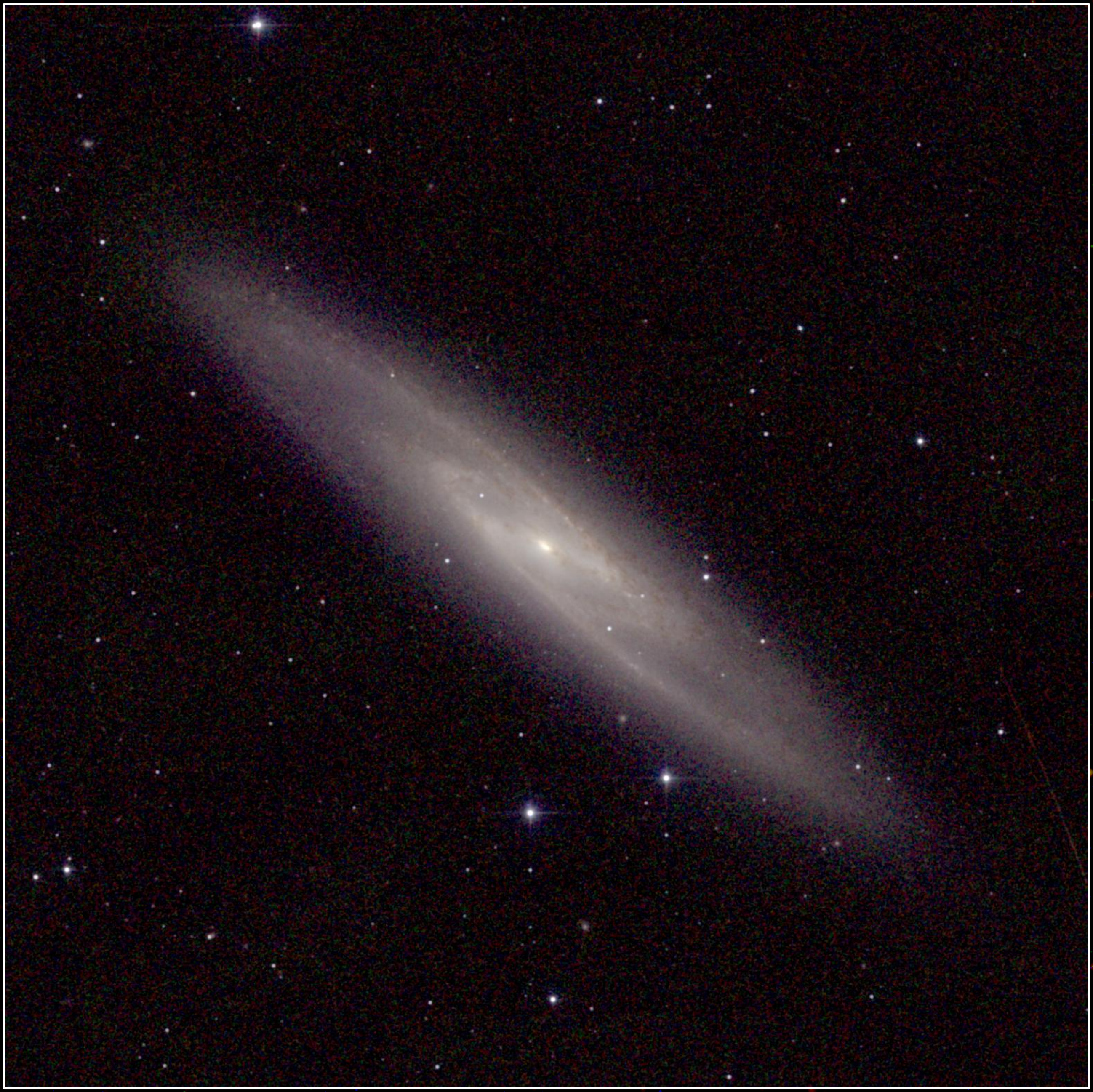
Three galaxies where ALMA has detected recombination line emission:

- NGC 253 (spiral galaxy with nuclear starburst)
  - Bendo et al., 2015, MNRAS, 450, L80
  - Meier et al., 2015, ApJ, 801, 63
  - Ando et al., 2017, ApJ, 849, 81
  - Nakanishi et al., 2018, in preparation

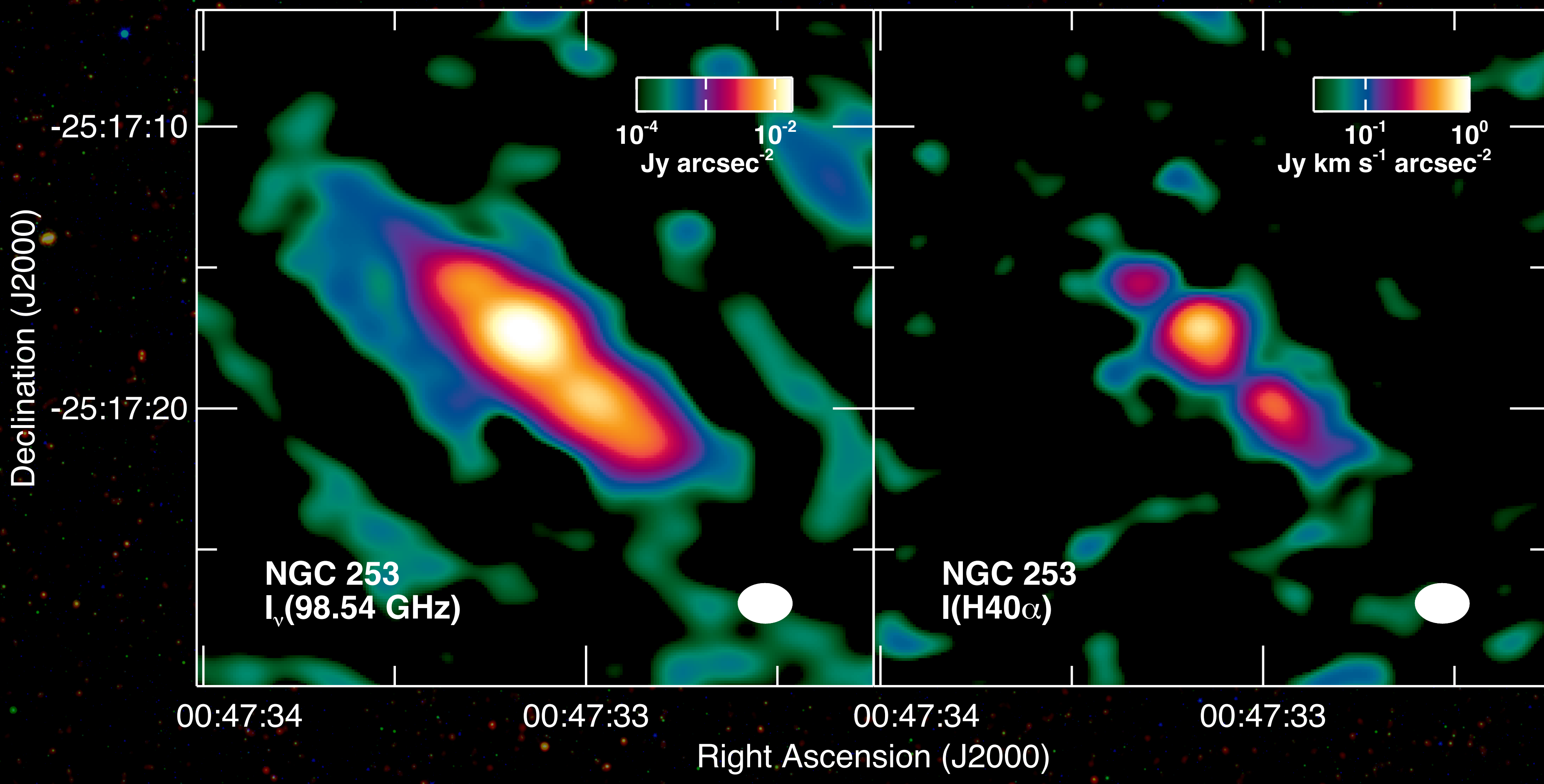
- NGC 4945 (spiral galaxy with starburst/AGN nucleus)
  - Bendo et al., 2016, MNRAS, 463, 252
  - Henkel et al., 2018, A&A, 615, A155

- NGC 5253 (low metallicity blue compact dwarf galaxy)
  - Bendo et al., 2017, MNRAS, 472, 1239
  - Miura et al., 2018, in press

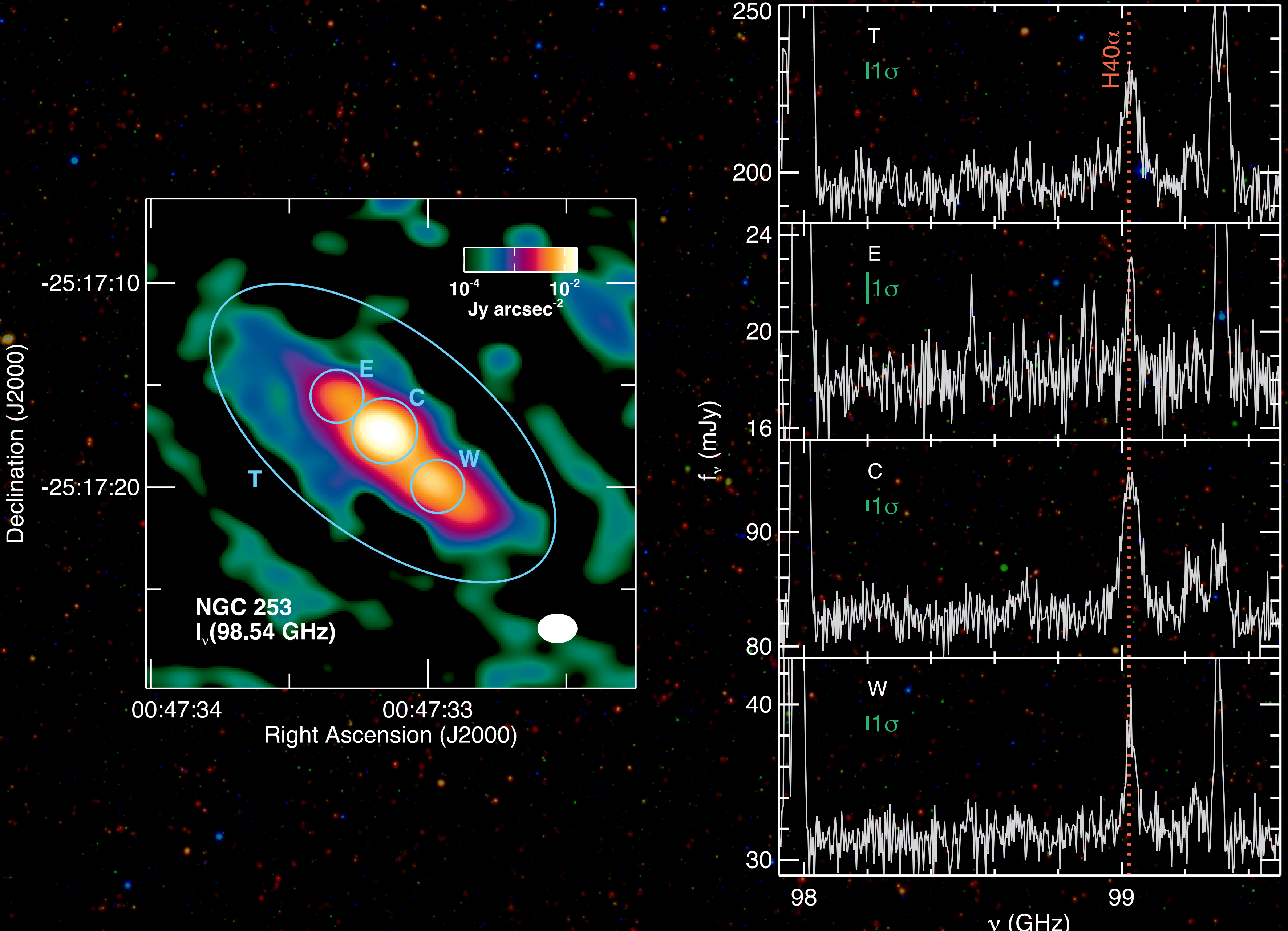

NGC 253



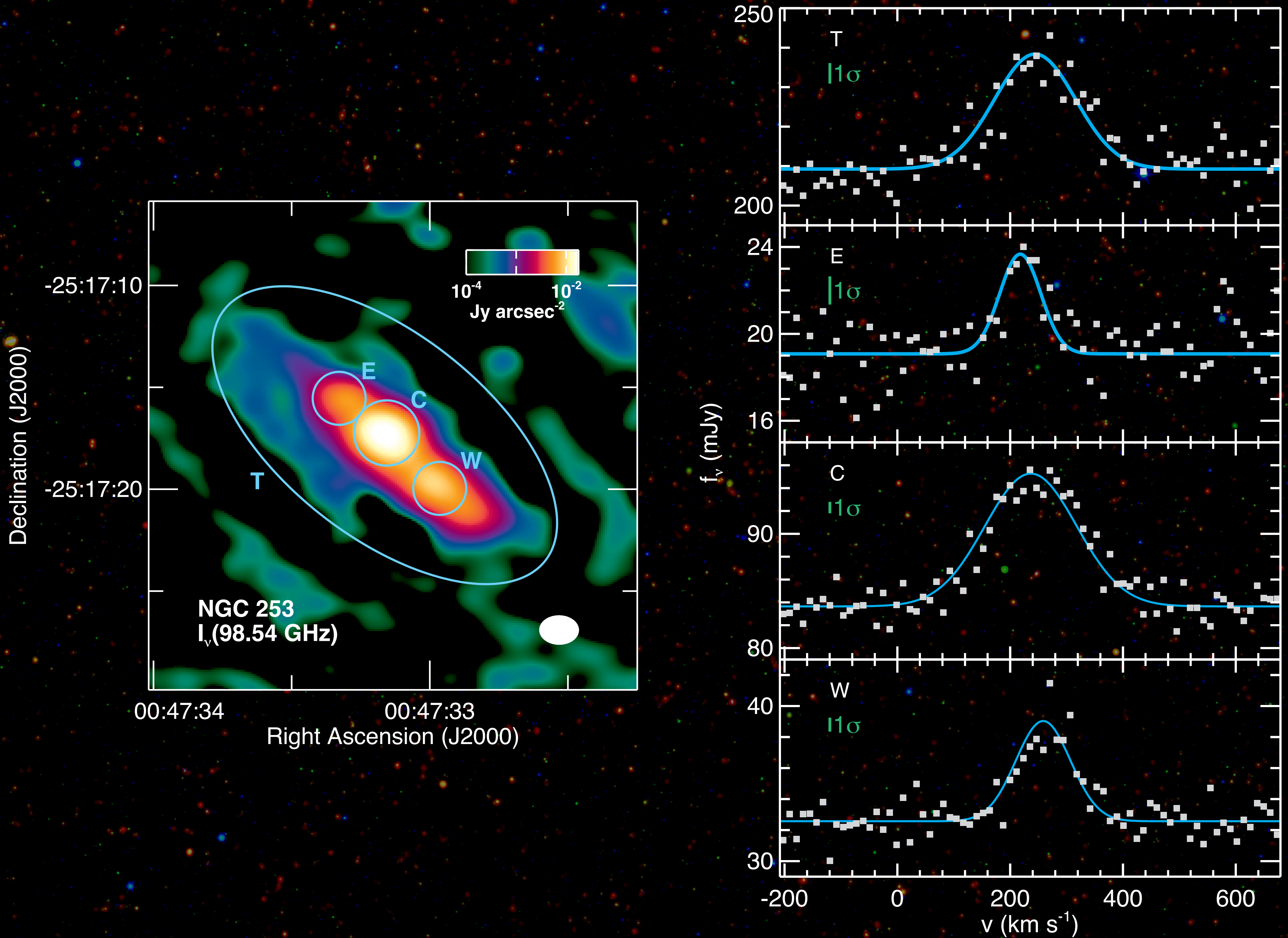
Near-infrared image (Jarrett et al. 2003)



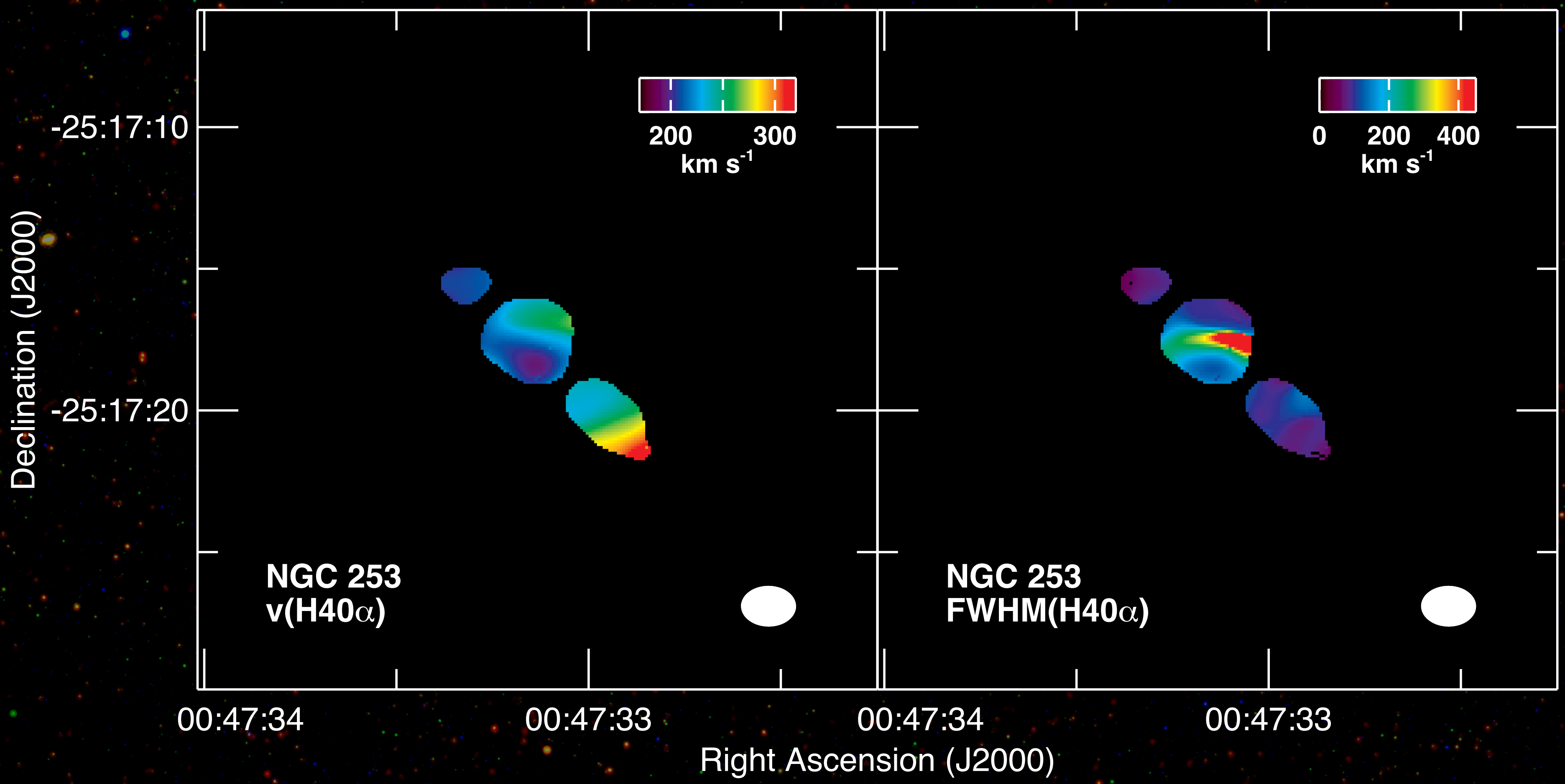
-25:17:10
-25:17:20
Declination (J2000)
00:47:34
00:47:33
00:47:34
00:47:33
Right Ascension (J2000)
10-4
10-2
Jy arcsec-2
10-1
100
Jy km s-1 arcsec-2
NGC 253
Iν(98.54 GHz)
NGC 253
I(H40α)



-25:17:10
-25:17:20
Declination (J2000)
00:47:34
00:47:33
Right Ascension (J2000)
10^-4
10^-2
Jy arcsec^-2
E
C
W
T
NGC 253
I_ν(98.54 GHz)
250
200
24
20
16
90
80
40
30
T
E
C
W
1σ
H40α
f_ν (mJy)
98
99
ν (GHz)

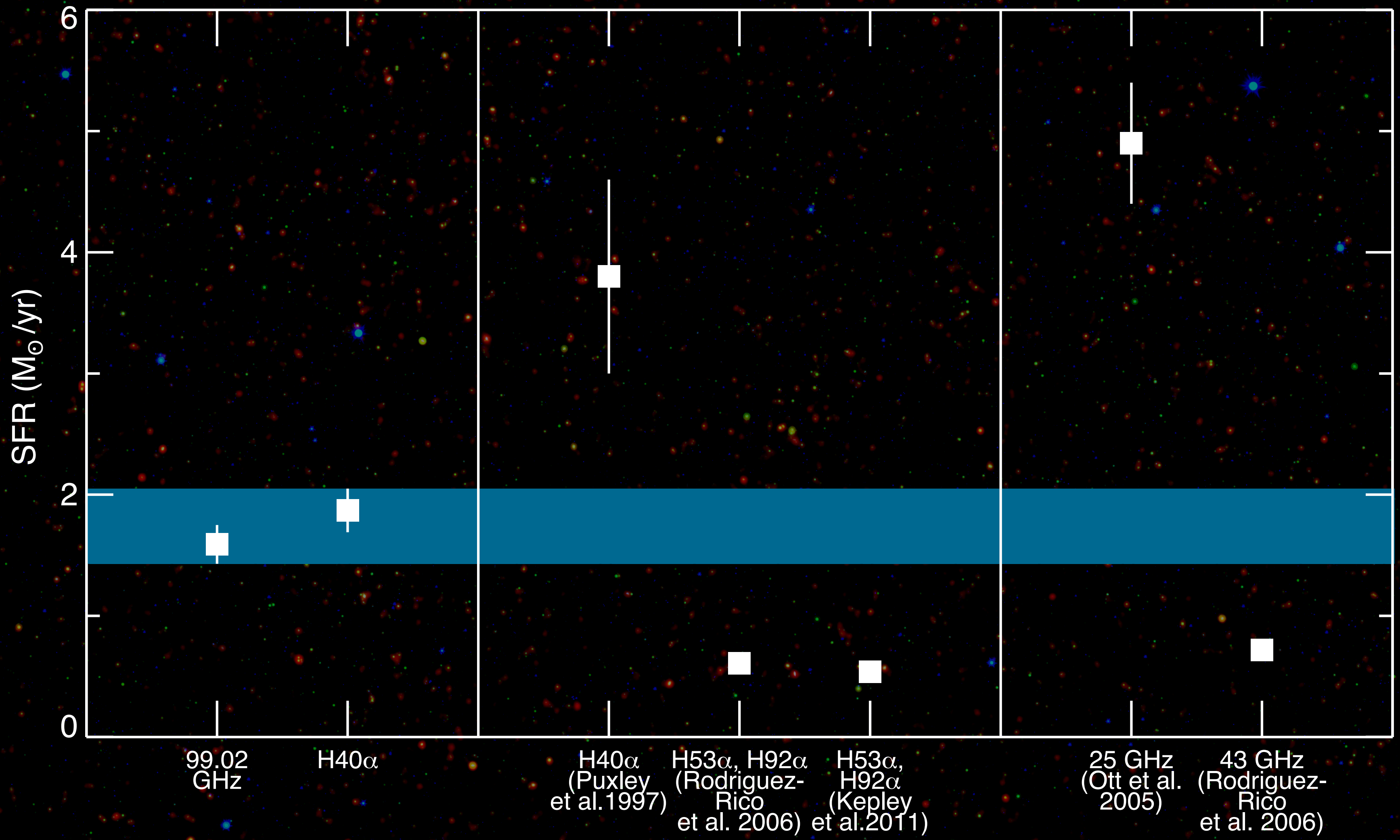


NGC 253
I_ν(98.54 GHz)
10^{-4}
10^{-2}
Jy arcsec^{-2}
E
C
W
T
-25:17:10
-25:17:20
Declination (J2000)
00:47:34
00:47:33
Right Ascension (J2000)
T
E
C
W
1σ
250
200
24
20
16
90
80
40
30
f_ν (mJy)
-200
0
200
400
600
v (km s^{-1})



200
300
km s-1
0
200
400
km s-1
-25:17:10
-25:17:20
Declination (J2000)
NGC 253
v(H40α)
NGC 253
FWHM(H40α)
00:47:34
00:47:33
00:47:34
00:47:33
Right Ascension (J2000)

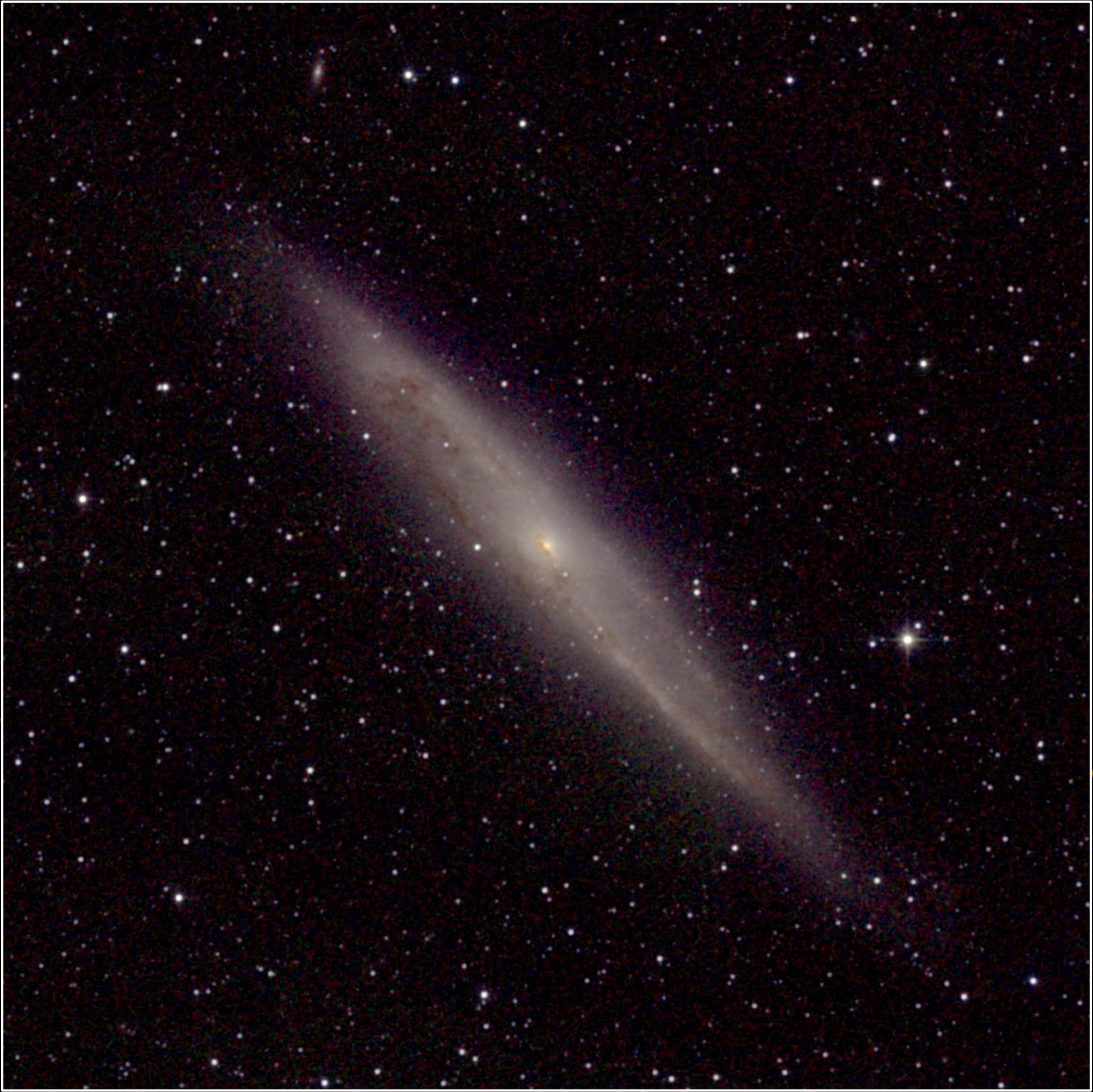
SFR Tracer	Measured SFR ($M_\odot$/yr)
99.02 GHz free-free (ALMA)	**1.59 ± 0.16**
H40α (ALMA)	**1.87 ± 0.18**
H40α (Puxley et al. 1997)	3.8 ± 0.8
H53α, H92α (Rodriguez-Rico et al. 2006)	0.60
H58α, H59α (Kepley et al. 2011)	0.54
Radio continuum (43 GHz; Rodriguez-Rico et al. 2005)	0.72
Radio continuum (25 GHz; Ott et al. 2005)	4.9 ± 0.5
Radio supernovae analysis (Rampardarath et al. 2014)	<4.9


SFR ($M_{\odot}$/yr)
6
4
2
0
99.02 GHz
H40α
H40α (Puxley et al.1997)
H53α, H92α (Rodriguez-Rico et al. 2006)
H53α, H92α (Kepley et al.2011)
25 GHz (Ott et al. 2005)
43 GHz (Rodriguez-Rico et al. 2006)

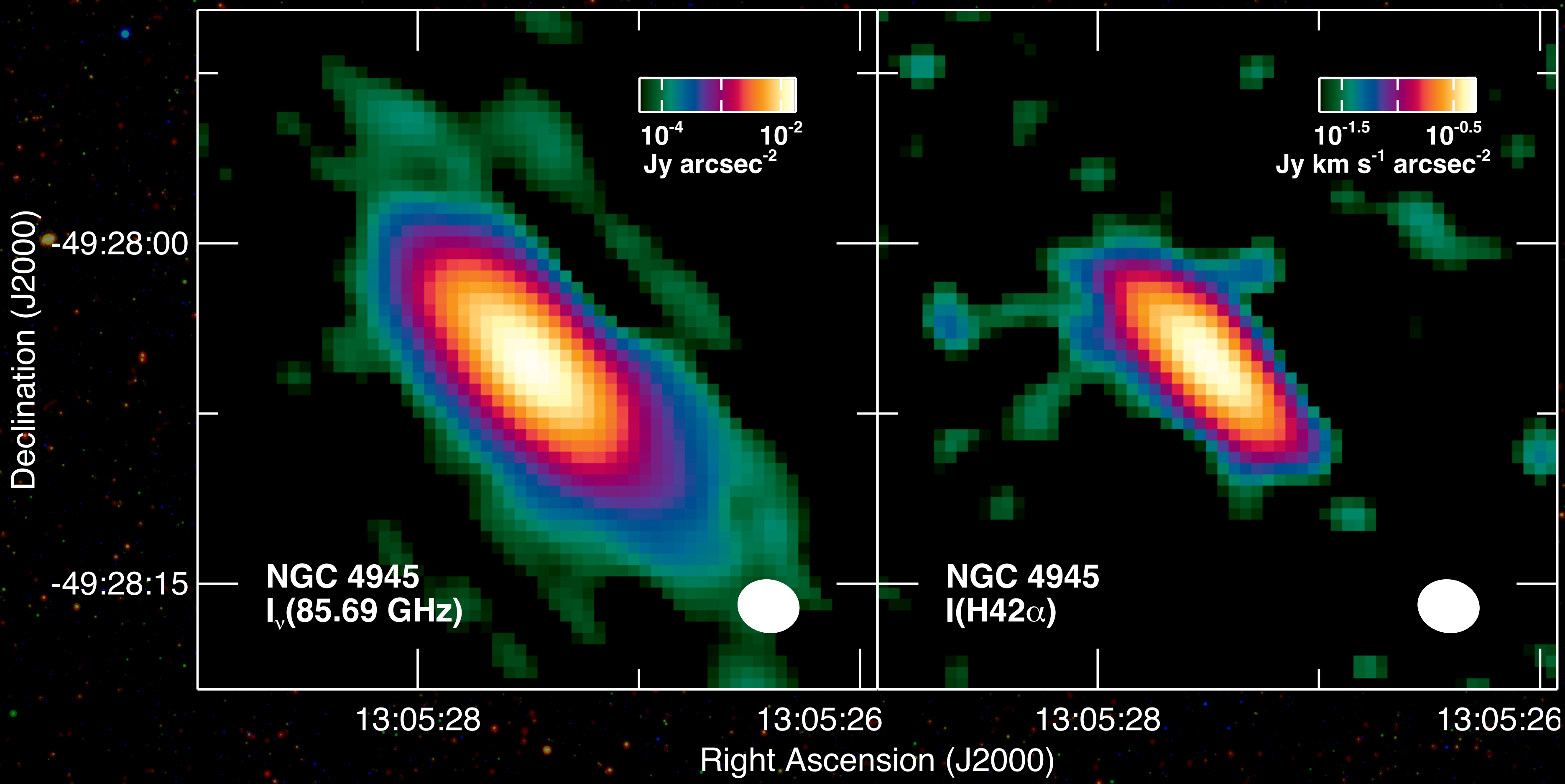
NGC 253 summary results

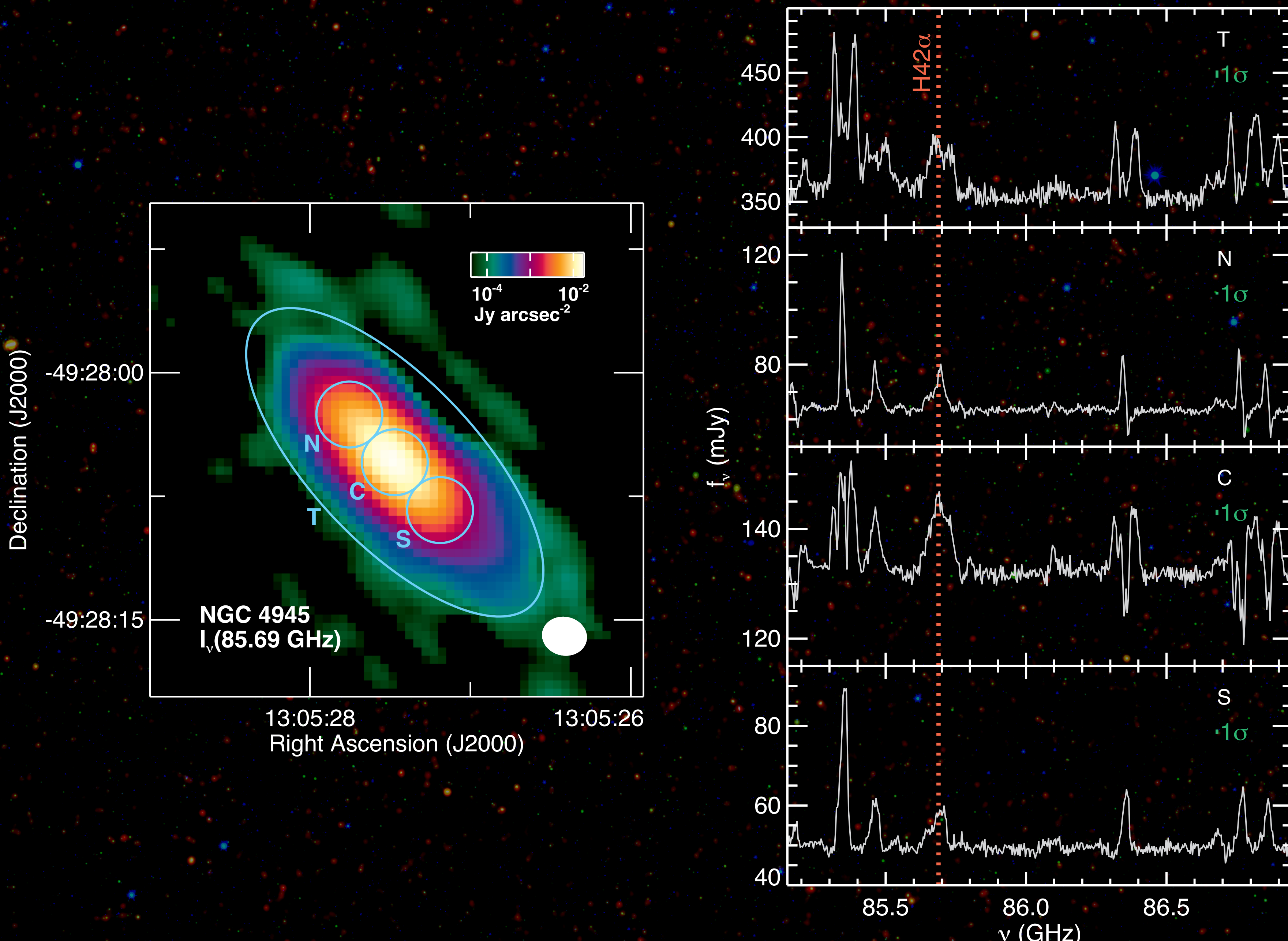
- SFR for central 20”x10” is $1.73 \pm 0.12\ M_\odot\ yr^{-1}$.
- Published range of values from mm/radio data is $0.5\text{-}4.9\ M_\odot\ yr^{-1}$.
- Lower frequency recombination-line emission and free-free emission potentially affected by gas opacity issues.
- Some problems with calibration of radio continuum emission as a star formation tracer.


NGC 4945

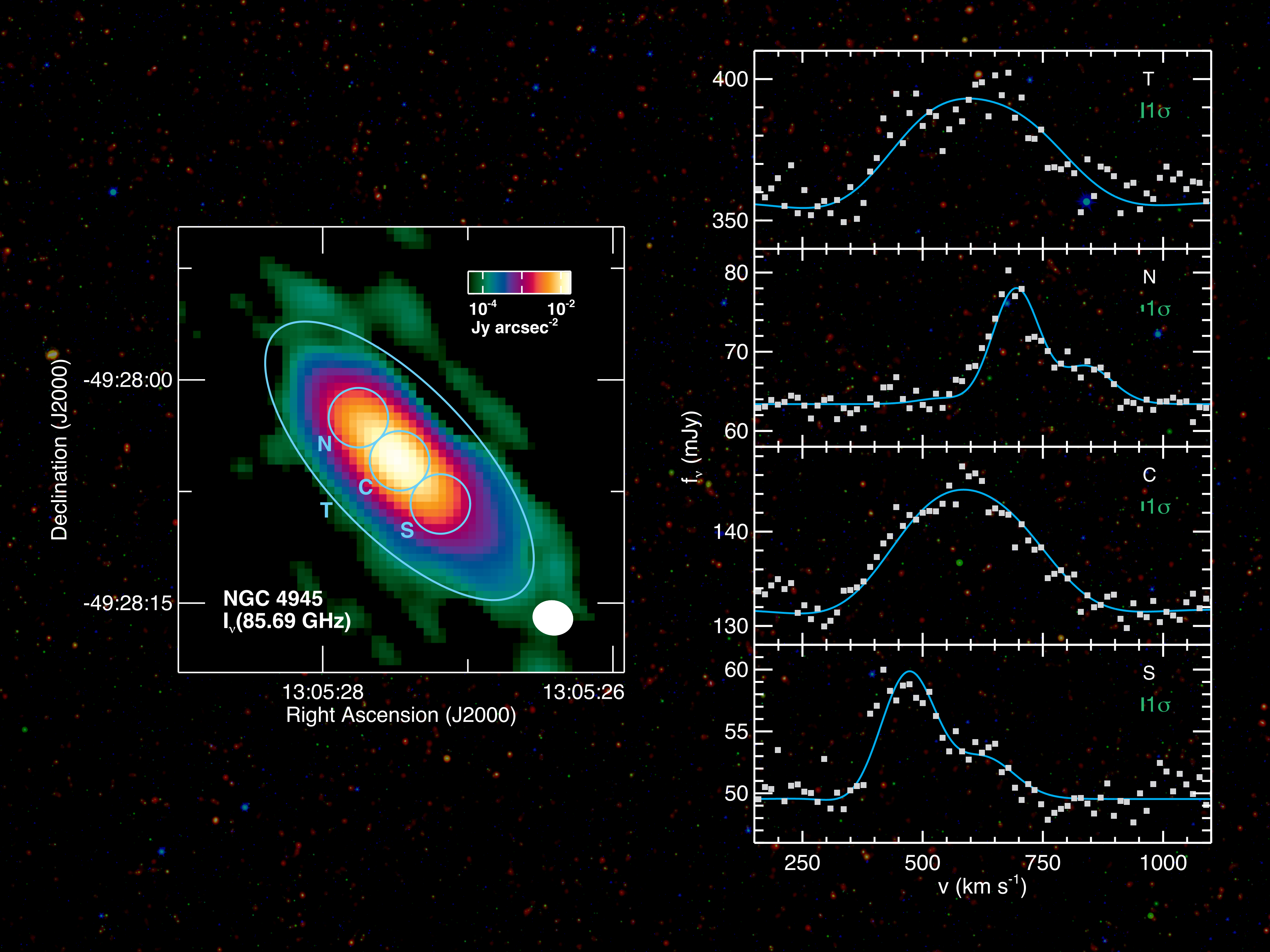


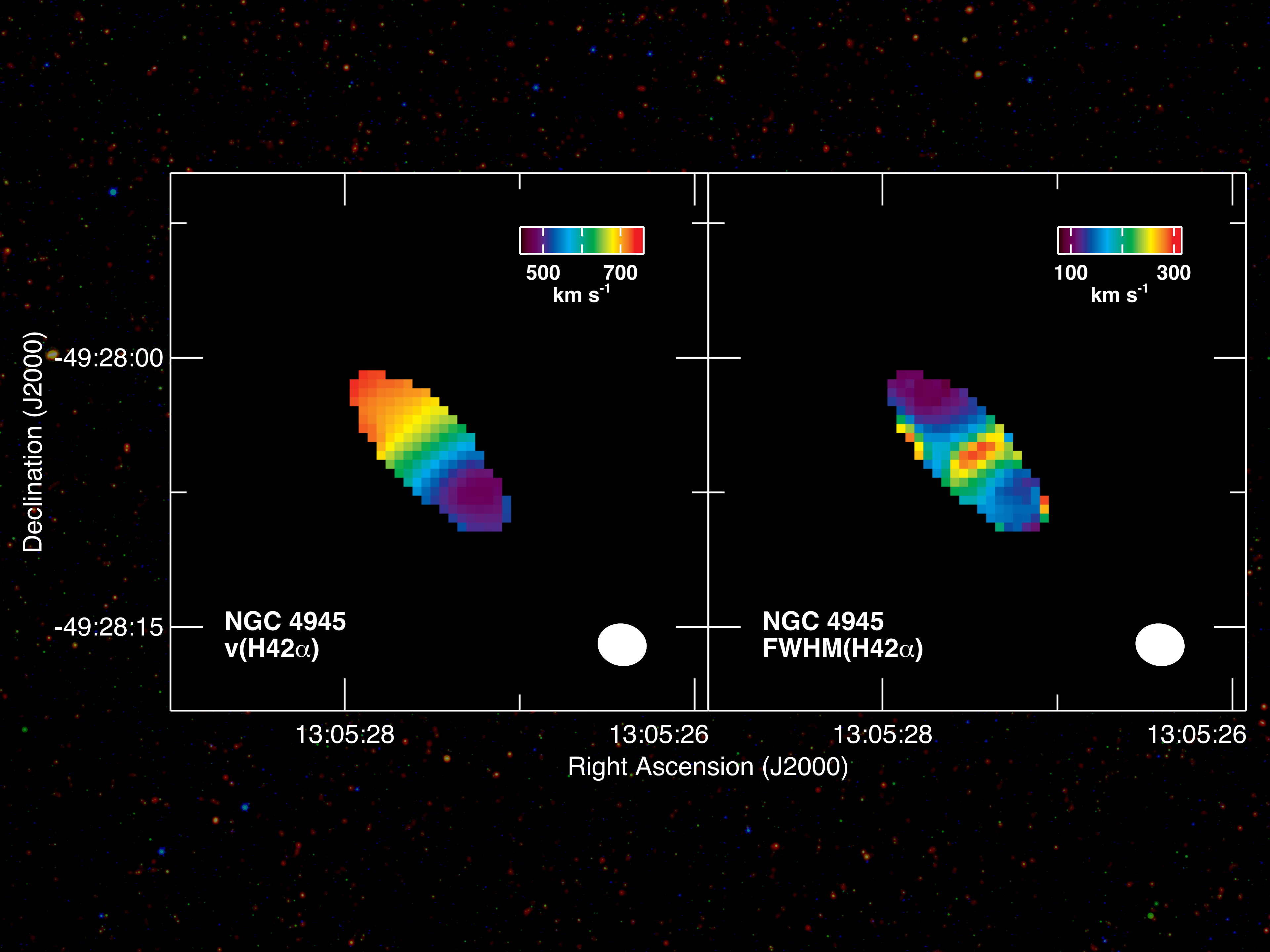
Near-infrared image (Jarrett et al. 2003)


10-4
10-2
Jy arcsec-2
10-1.5
10-0.5
Jy km s-1 arcsec-2
-49:28:00
-49:28:15
Declination (J2000)
NGC 4945
Iν(85.69 GHz)
NGC 4945
I(H42α)
13:05:28
13:05:26
13:05:28
13:05:26
Right Ascension (J2000)



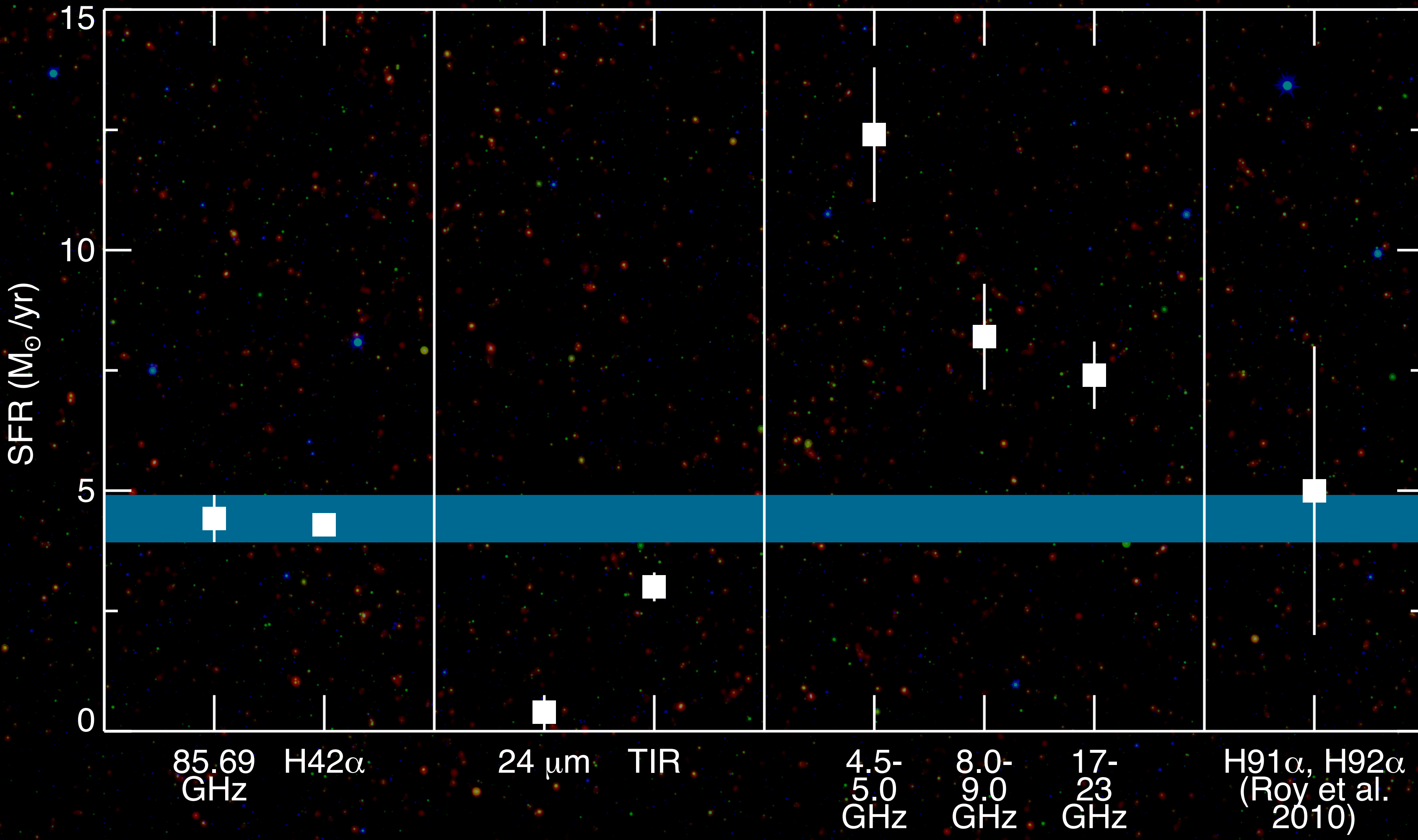
10^-4
10^-2
Jy arcsec^-2
N
C
T
S
NGC 4945
I_ν(85.69 GHz)
-49:28:00
-49:28:15
Declination (J2000)
13:05:28
13:05:26
Right Ascension (J2000)
H42α
T
1σ
N
C
S
450
400
350
120
80
140
120
80
60
40
f_ν (mJy)
85.5
86.0
86.5
ν (GHz)


NGC 4945
I_ν(85.69 GHz)
10^-4
10^-2
Jy arcsec^-2
N
C
T
S
-49:28:00
-49:28:15
Declination (J2000)
13:05:28
13:05:26
Right Ascension (J2000)
T
1σ
400
350
N
1σ
80
70
60
C
1σ
140
130
S
1σ
60
55
50
f_ν (mJy)
250
500
750
1000
v (km s^-1)



500
700
km s-1
100
300
km s-1
-49:28:00
-49:28:15
Declination (J2000)
NGC 4945
v(H42α)
NGC 4945
FWHM(H42α)
13:05:28
13:05:26
13:05:28
13:05:26
Right Ascension (J2000)

SFR Tracer	Measured SFR ($M_\odot$/yr)
Mid-infrared (22, 24 μm)	0.4
Total infrared (24-500 μm)	3.0 ± 0.3
85.69 GHz free-free (ALMA)	**4.42 ± 0.49**
H42α (ALMA)	**4.29 ± 0.07**
Radio continuum (4-23 GHz)	7 - 13
H91α, H92α (Roy et al. 2010)	2 - 8
Radio supernovae analysis (Lenc & Tingay 2009)	7.5 - 1170



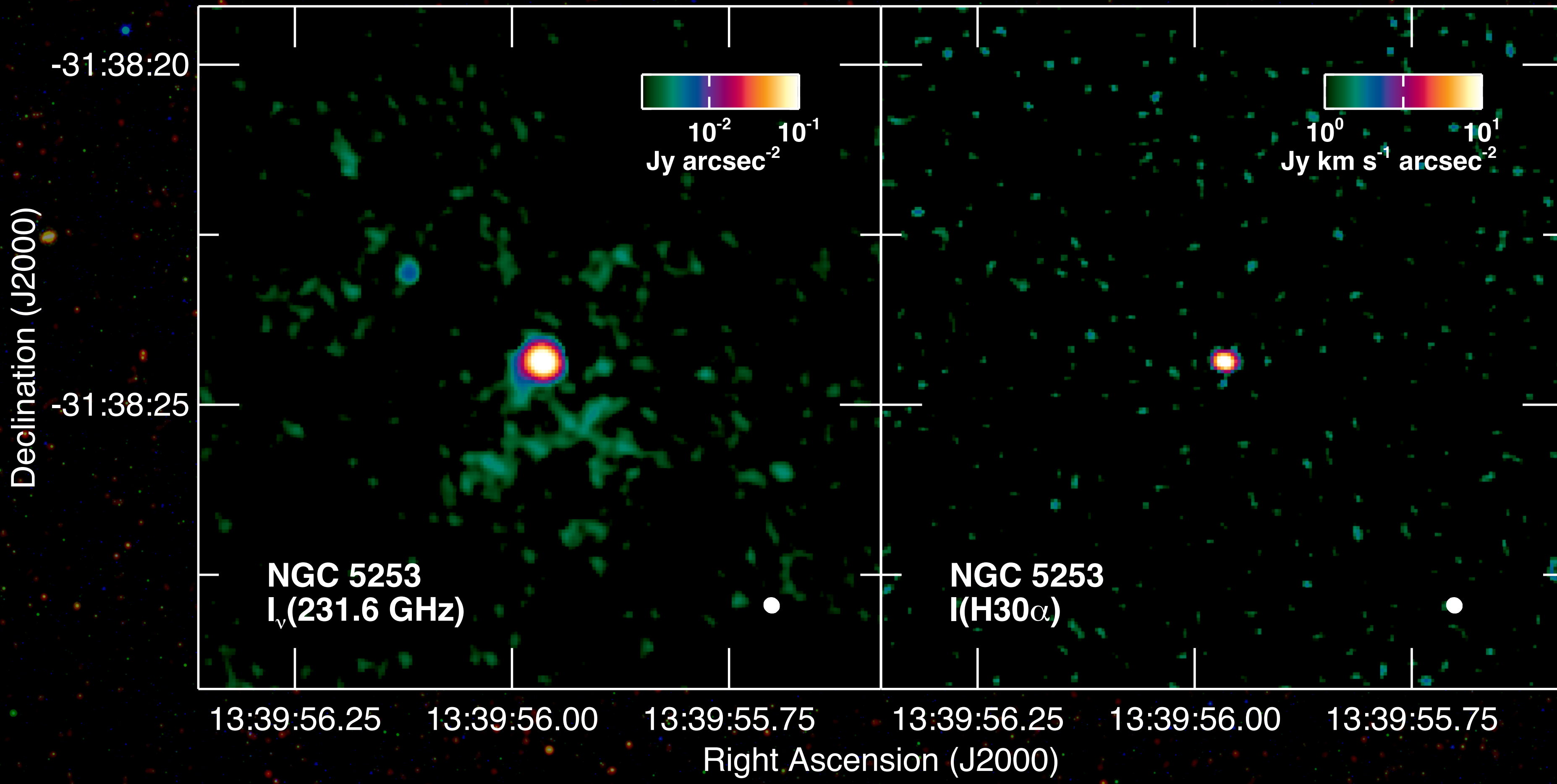
15
10
5
0
SFR (M⊙/yr)
85.69 GHz
H42α
24 μm
TIR
4.5-5.0 GHz
8.0-9.0 GHz
17-23 GHz
H91α, H92α (Roy et al. 2010)

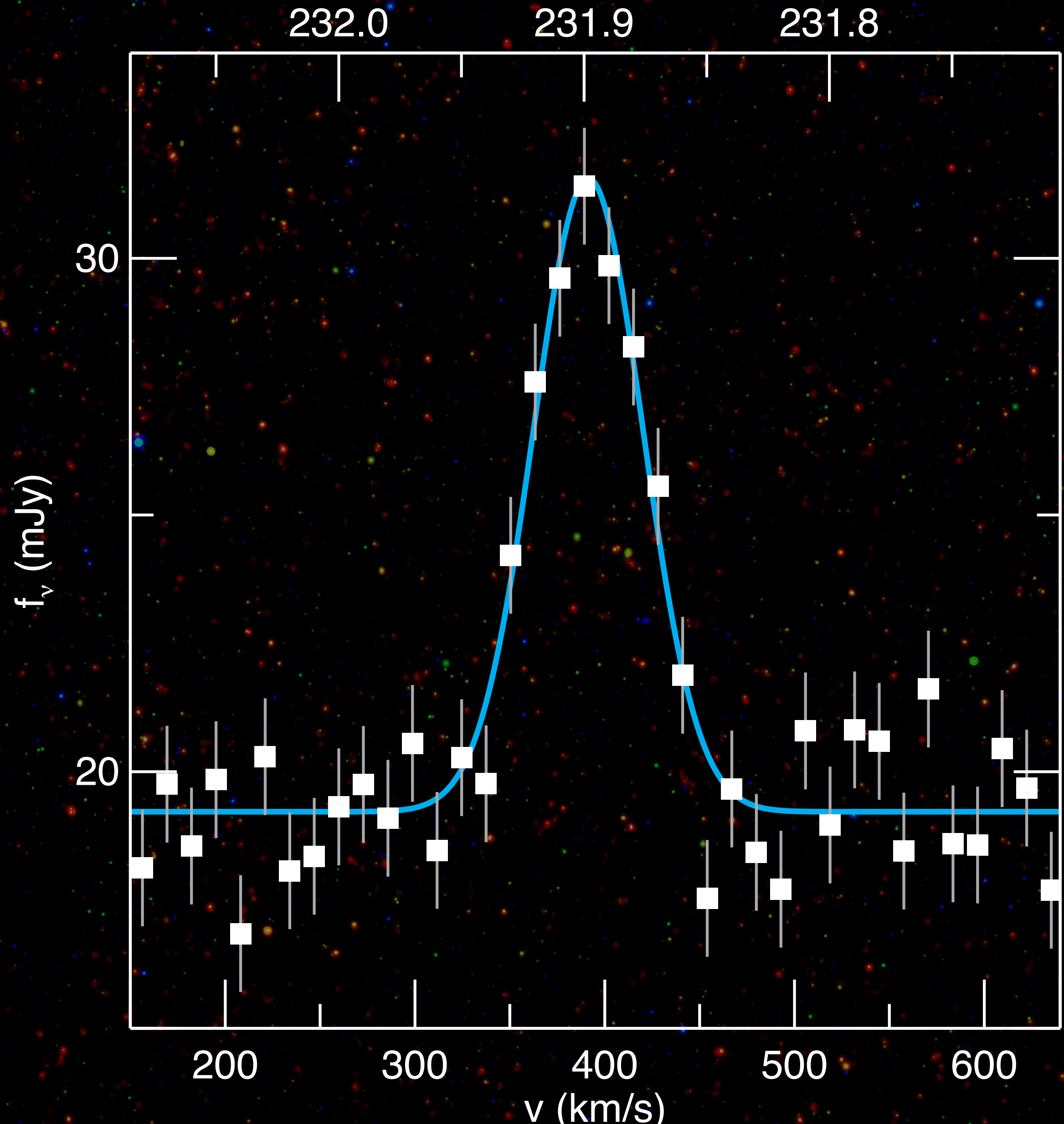
NGC 4945 results

- SFR for central disc is 4.35 ± 0.25 $M_\odot$ yr^{-1}.
- Total infrared flux gives SFR within ~30% of ALMA data.
- SFR from mid-infrared (22, 24 μm) flux densities are 10× lower than ALMA results.
  - Dust is optically thick in mid-infrared.
- SFRs from radio continuum data are higher than ALMA measurements.
  - Conversion from radio continuum emission to SFR affected by calibration problems related to assumptions about the spectral slope.


NGC 5253

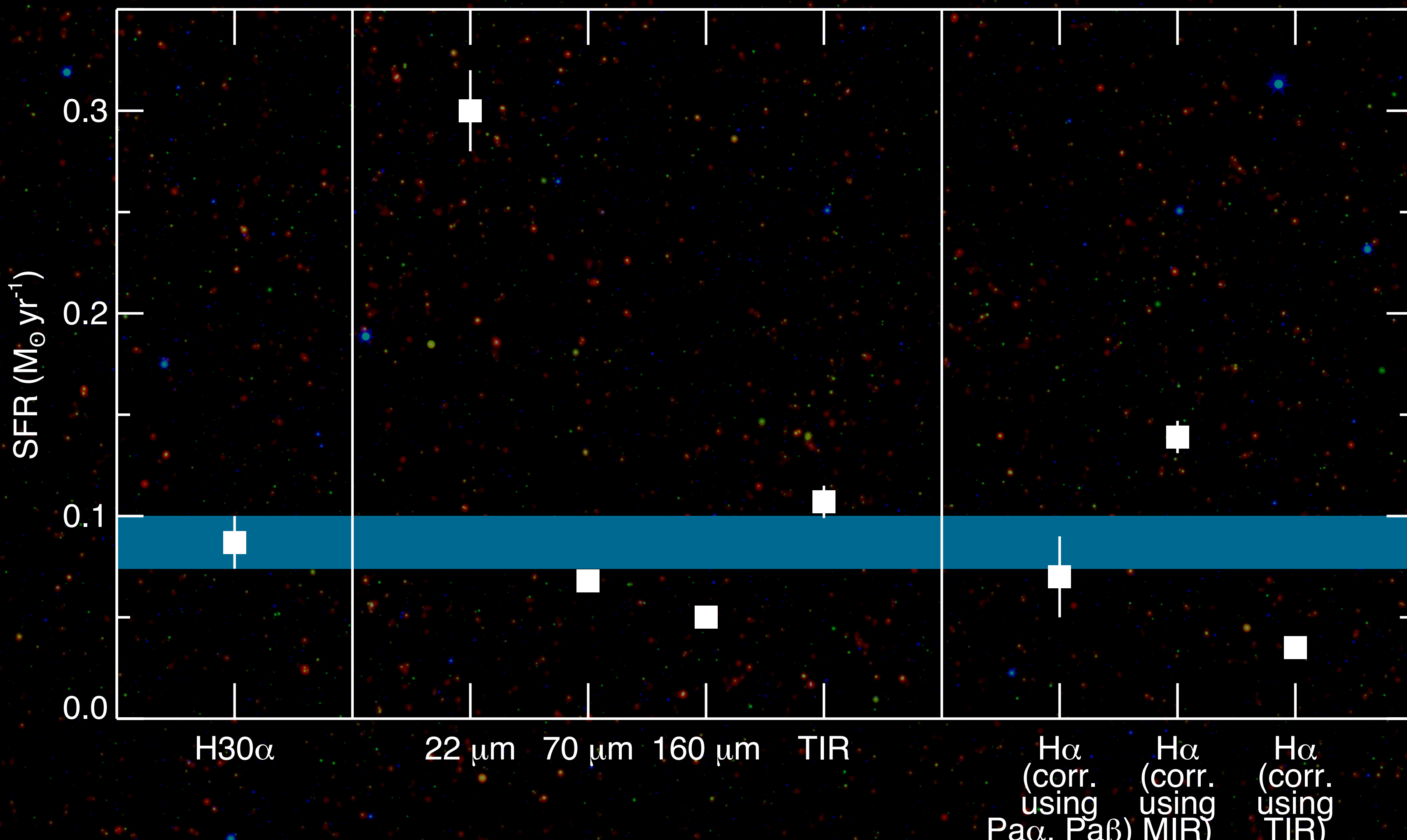
Near-infrared image (Jarrett et al. 2003)


-31:38:20
-31:38:25
Declination (J2000)
10^-2 10^-1
Jy arcsec^-2
NGC 5253
Iν(231.6 GHz)
10^0 10^1
Jy km s^-1 arcsec^-2
NGC 5253
I(H30α)
13:39:56.25
13:39:56.00
13:39:55.75
13:39:56.25
13:39:56.00
13:39:55.75
Right Ascension (J2000)



232.0
231.9
231.8
30
20
f_ν (mJy)
200
300
400
500
600
v (km/s)

SFR Tracer	Measured SFR ($M_\odot$/yr)
Hα (extinction corrected using Paα, Paβ)	0.07 ± 0.02
Mid-infrared (22 μm)	0.30 ± 0.02
Far-infrared (70 μm)	0.068 ± 0.004
Far-infrared (160 μm)	0.050 ± 0.003
Total infrared (22-500 μm)	0.110 ± 0.007
H30α (ALMA)	**0.079 ± 0.014**
Hα + 22 μm	0.139 ± 0.008
Hα + total infrared	0.0353 ± 0.0012



SFR (M$_\odot$ yr^{-1})
0.3
0.2
0.1
0.0
H30α
22 μm
70 μm
160 μm
TIR
Hα (corr. using Paα, Paβ)
Hα (corr. using MIR)
Hα (corr. using TIR)

NGC 5253 results

- Nuclear SFR is $0.087 \pm 0.013\ M_{\odot}\ yr^{-1}$.
- SFR from ultraviolet data are fairly consistent with ALMA result but slightly high.
    - Slightly higher SFR in past could explain this result.
- SFR from Hα + total infrared flux matches ALMA results.
- SFRs based on mid-infrared data are ~3× higher than other SFRs.
    - Low mertallicity results in low interstellar dust densities.
    - Low dust extinction causes the dust to be abnormally hot.
    - Mid-infrared flux is abnormally high.

Summary

- Millimetre free-free and recombination line emission can be detected from many nearby starbursts using ALMA.
- Early analyses with ALMA data have revealed problems with SFRs from lower-frequency radio data and mid-infrared data.
- Comparisons with ALMA data suggest that total infrared fluxes may be reliable star formation tracers in heavily obscured regions.
- Future ALMA observations will allow us to examine the efficacy of other star formation tracers more thoroughly.