ALMA observations of recombination line and free-free emission from nearby starbursts

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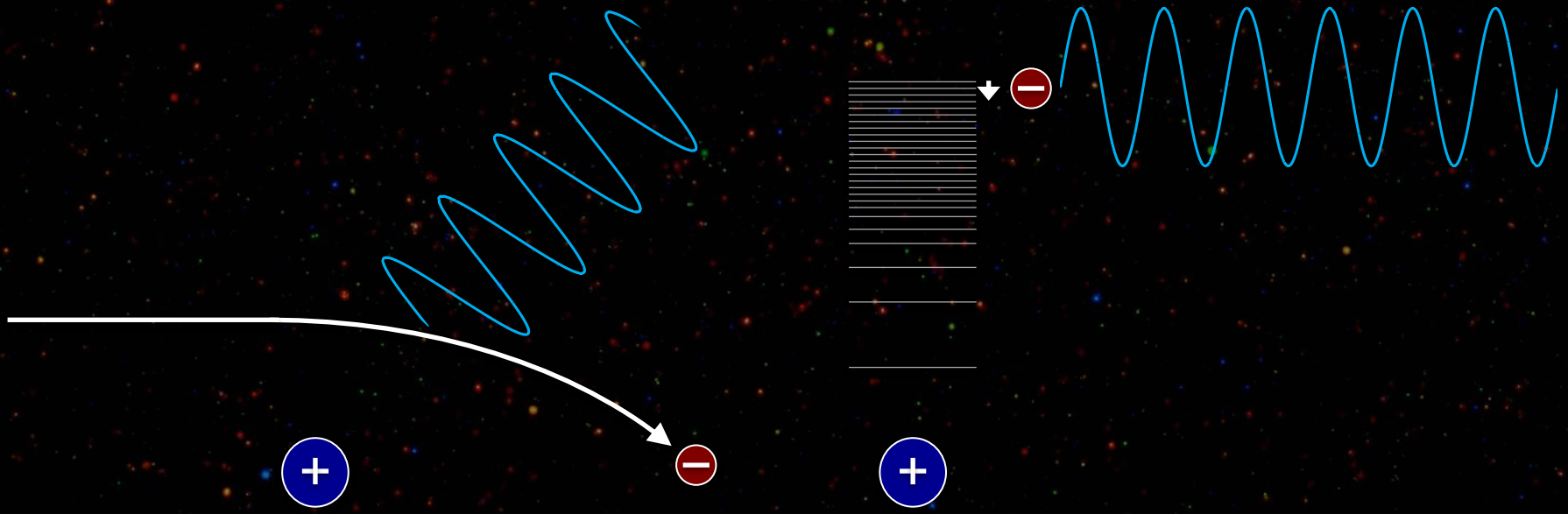
ALMA can detect emission from photoionized gas in two forms:

- 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.

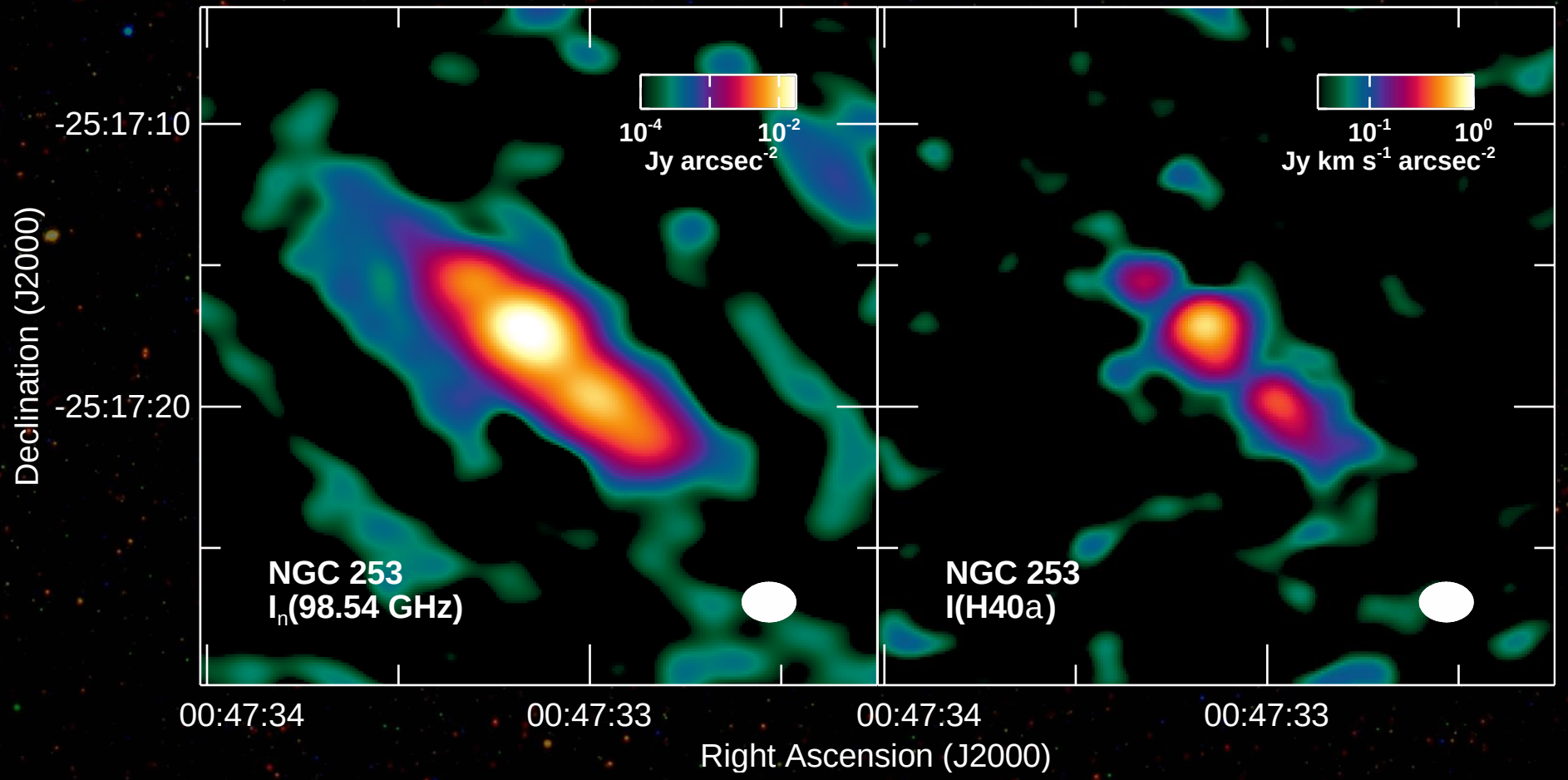


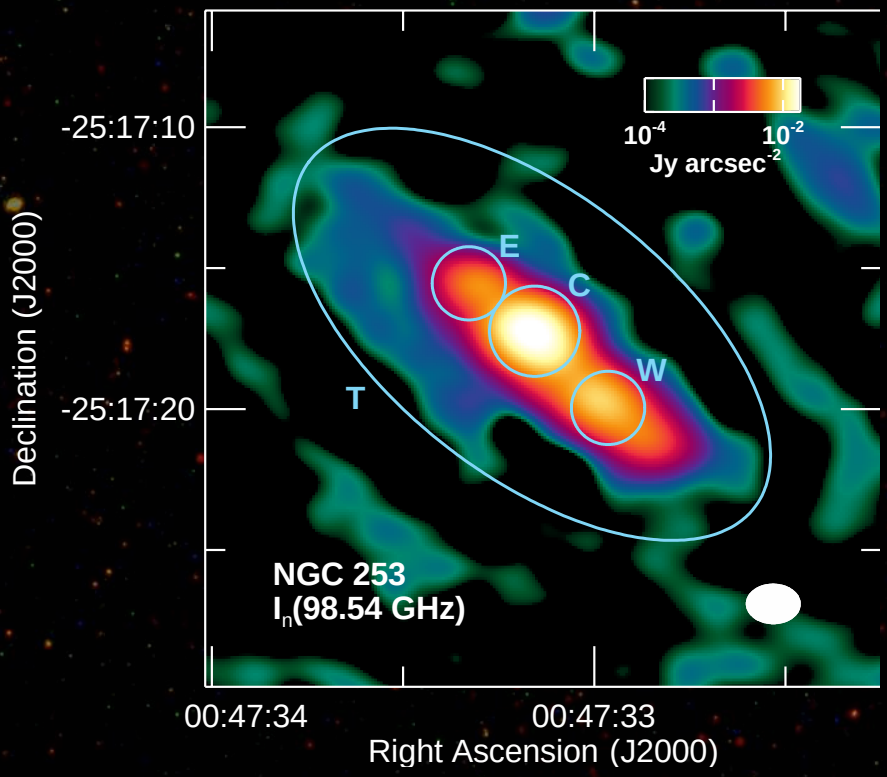
Free-free emission

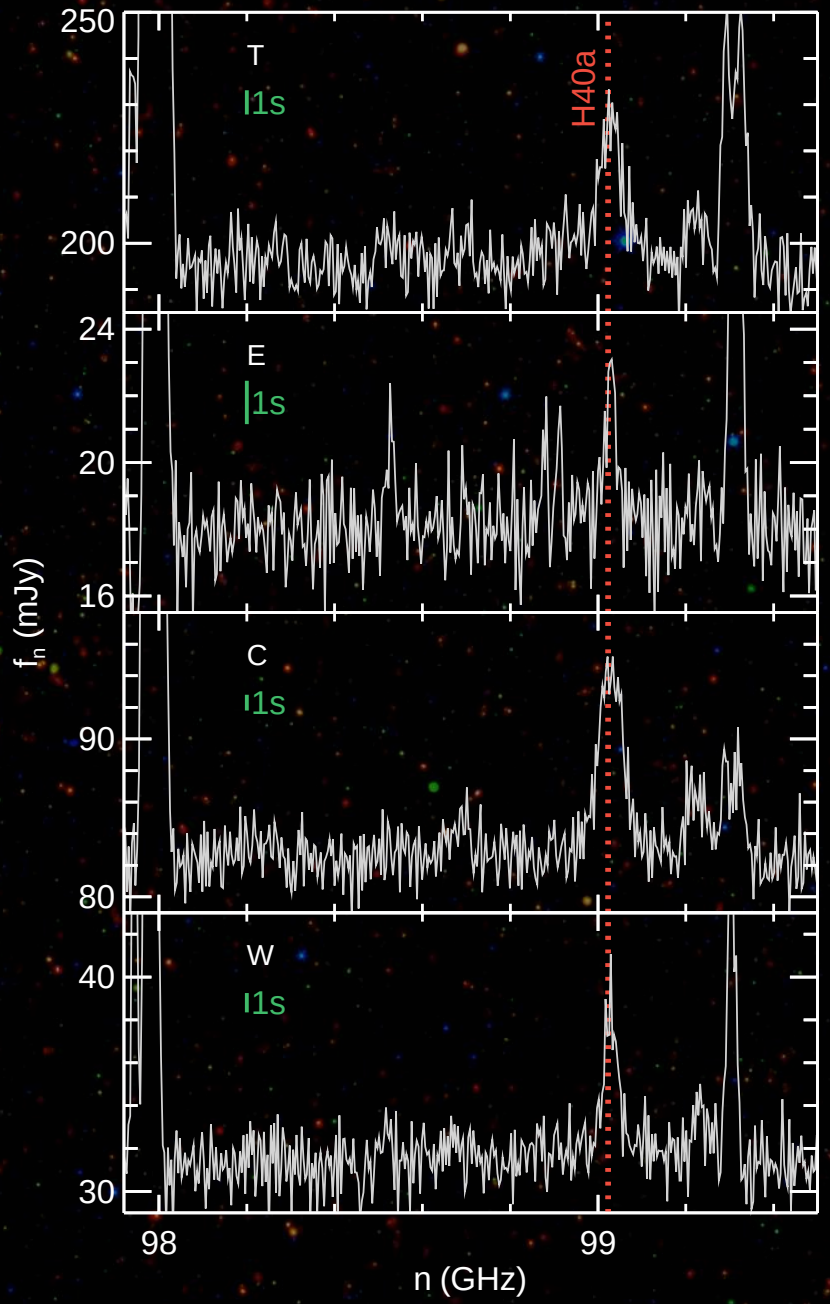
Recombination line emission

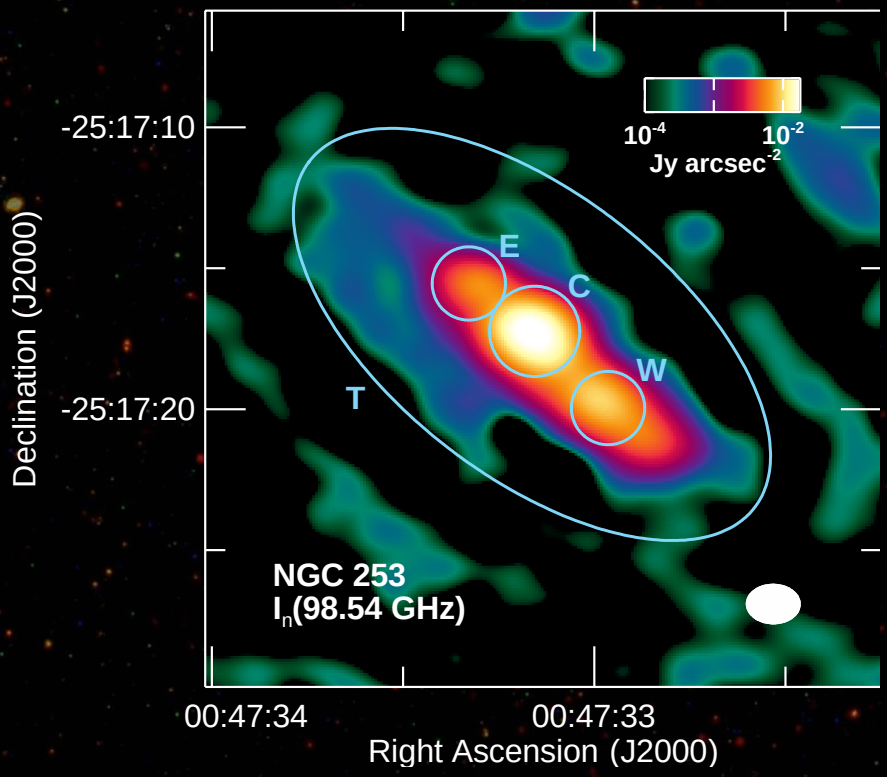
In this talk, I will talk about three galaxies where ALMA has detected recombination line emission:

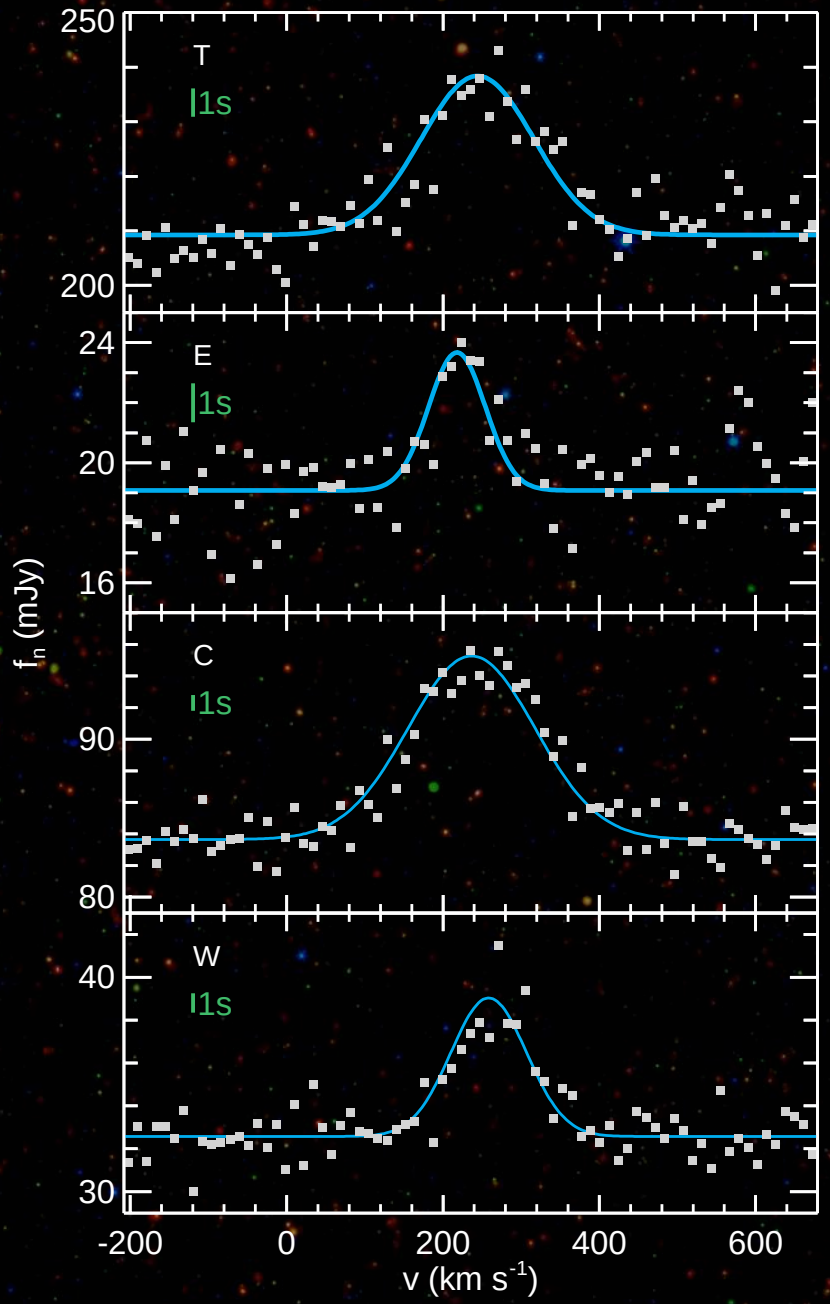
- NGC 253 (spiral galaxy with nuclear starburst)
  - Bendo et al., 2015, MNRAS, 450, L80
  - Meier et al., 2015, ApJ, 801, 63
  - Ando et al., 2017, submitted
  - Nakanishi et al., 2017, in preparation
- NGC 4945 (spiral galaxy with starburst/AGN nucleus)
  - Bendo et al., 2016, MNRAS, 463, 252
  - Hinkel et al., 2017, in preparation
- NGC 5253 (low metallicity blue compact dwarf galaxy)
  - Bendo et al., 2017, arXiv (1707.06184)
  - Miura et al., 2017, in preparation

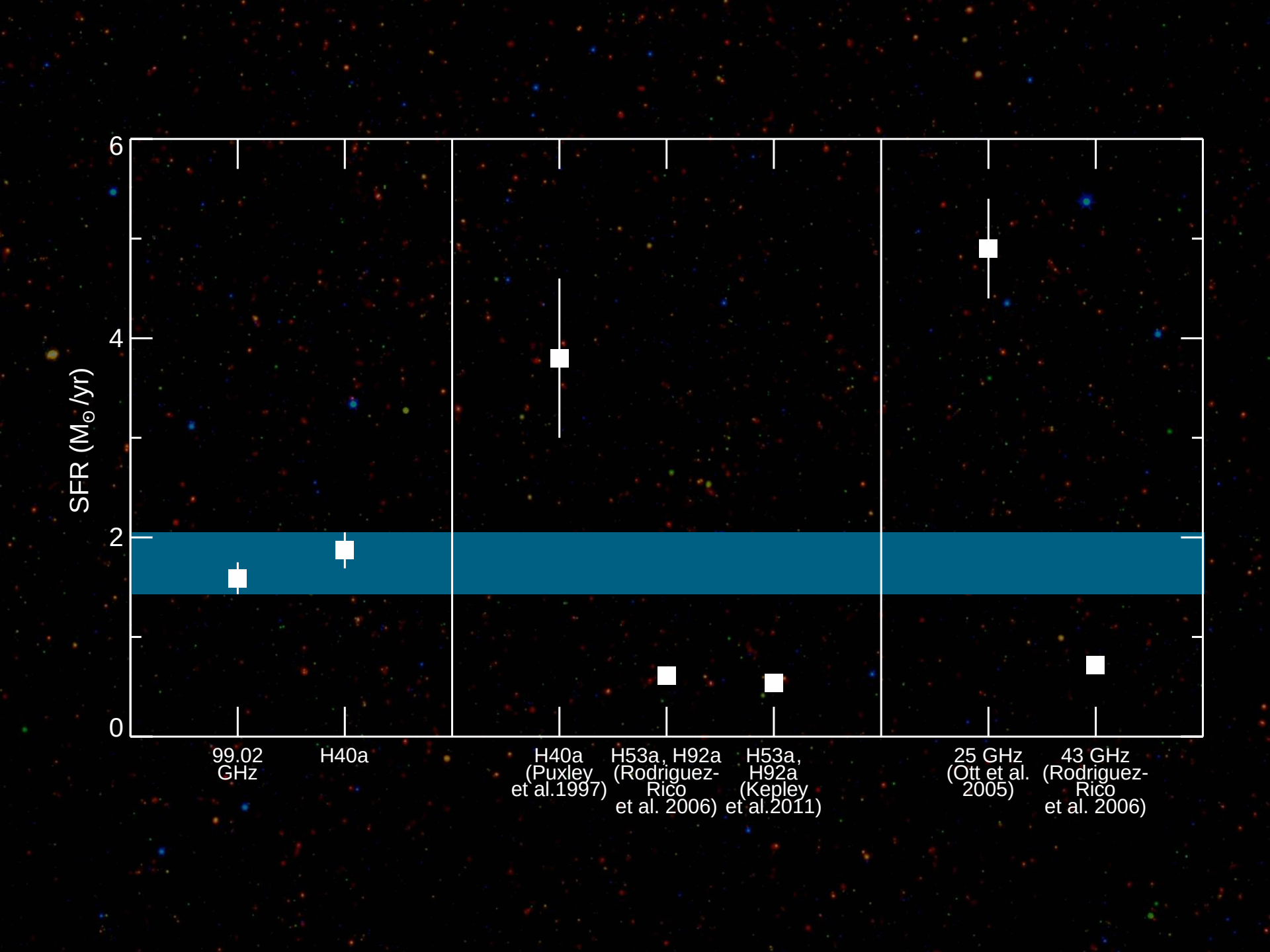

-25:17:10
-25:17:20
Declination (J2000)
10^{-4}
10^{-2}
Jy arcsec^{-2}
NGC 253
I_n(98.54 GHz)
10^{-1}
10^{0}
Jy km s^{-1} arcsec^{-2}
NGC 253
I(H40a)
00:47:34
00:47:33
00:47:34
00:47:33
Right Ascension (J2000)


-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_n(98.54 GHz)


250
200
24
20
16
90
80
40
30
T
1s
H40a
E
1s
C
1s
W
1s
f_n (mJy)
98
99
n (GHz)

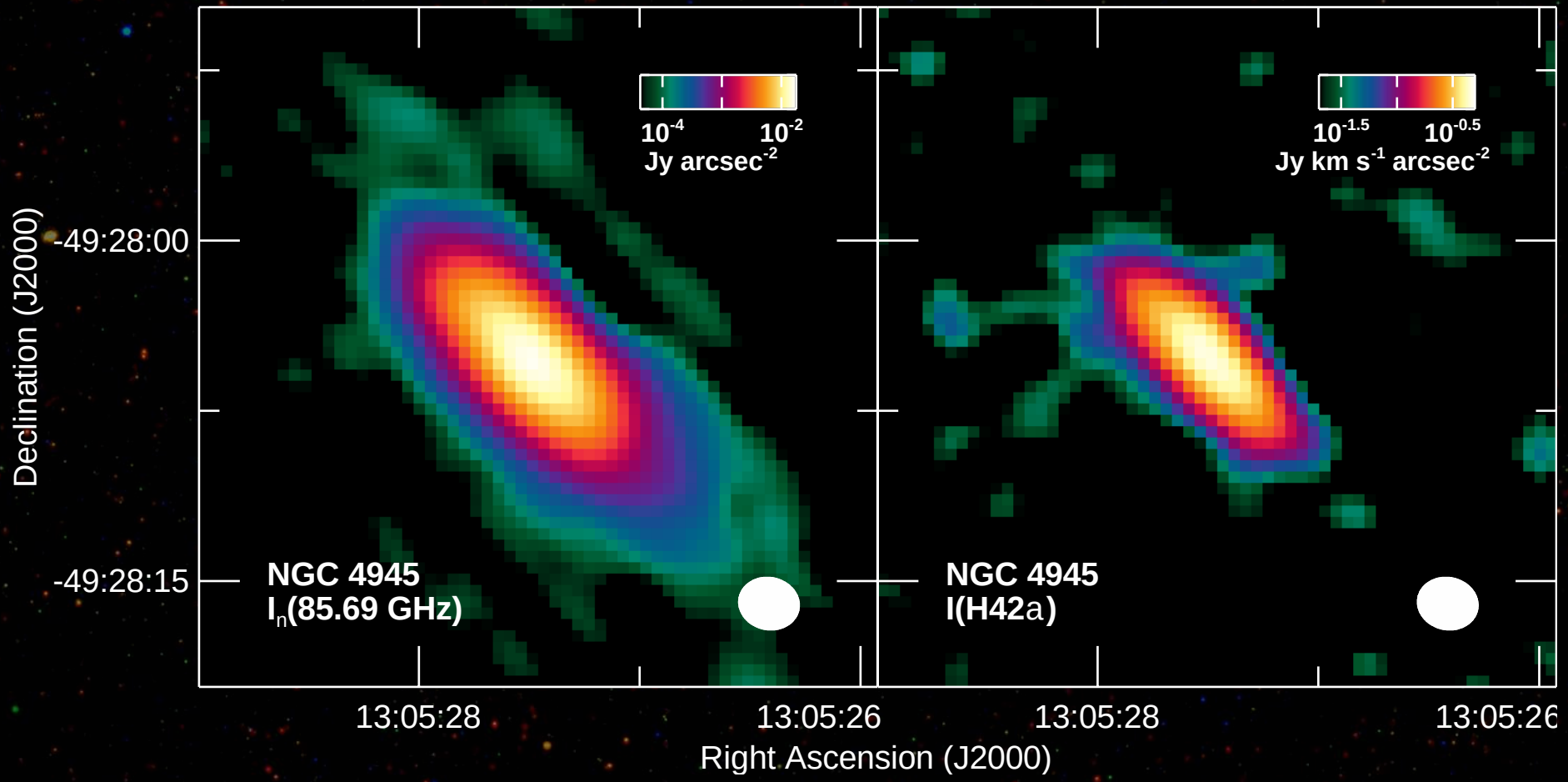

-25:17:10
-25:17:20
Declination (J2000)
00:47:34
00:47:33
Right Ascension (J2000)
10^-4
10^-2
Jy arcsec^-2
E
C
W
T
NGC 253
I_n(98.54 GHz)

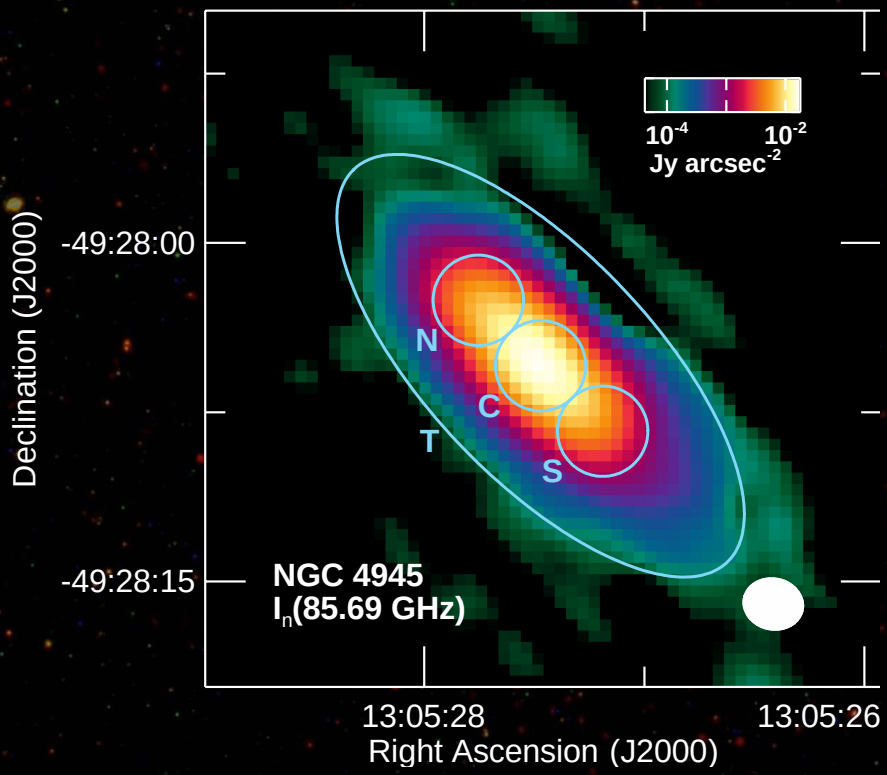

250
200
T
1s
24
20
16
E
1s
90
80
C
1s
40
30
W
1s
f_n (mJy)
-200
0
200
400
600
v (km s^-1)

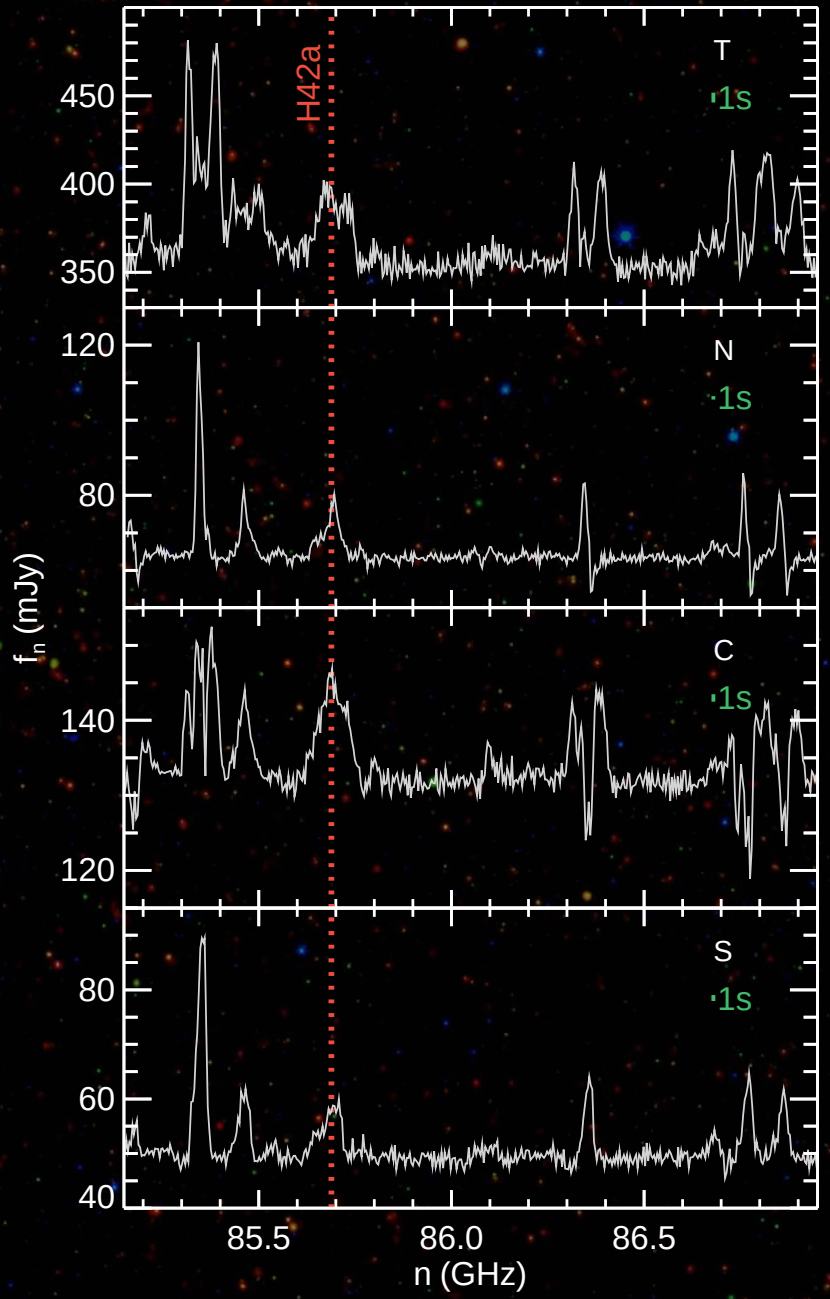

6
4
2
0
SFR ($M_\odot$/yr)
99.02 GHz
H40a
H40a (Puxley et al.1997)
H53a, H92a (Rodriguez-Rico et al. 2006)
H53a, H92a (Kepley et al.2011)
25 GHz (Ott et al. 2005)
43 GHz (Rodriguez-Rico et al. 2006)

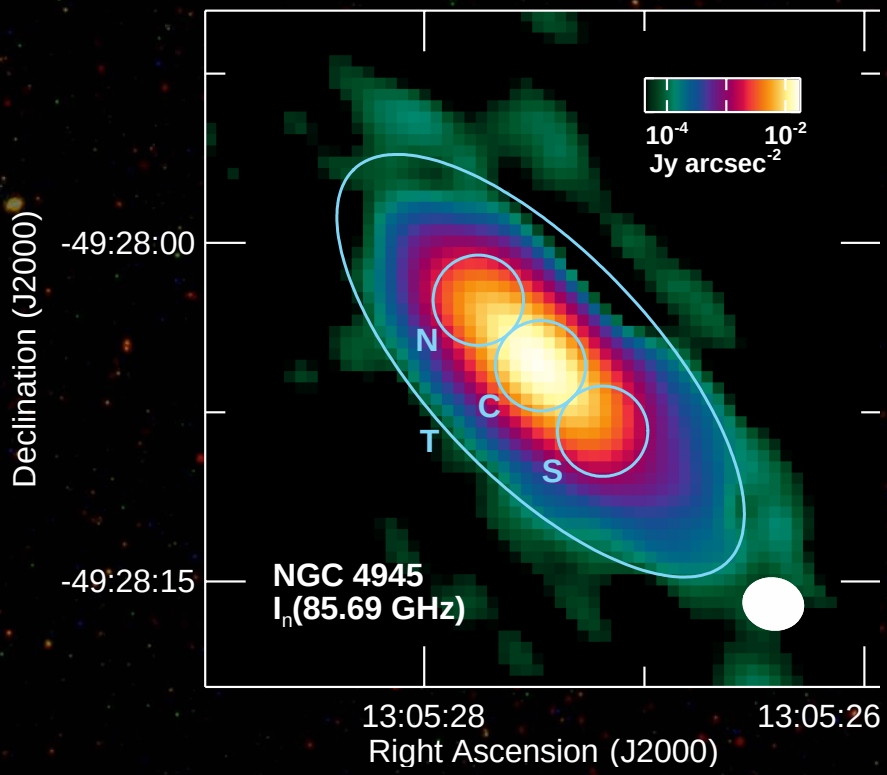
NGC 253 summary results

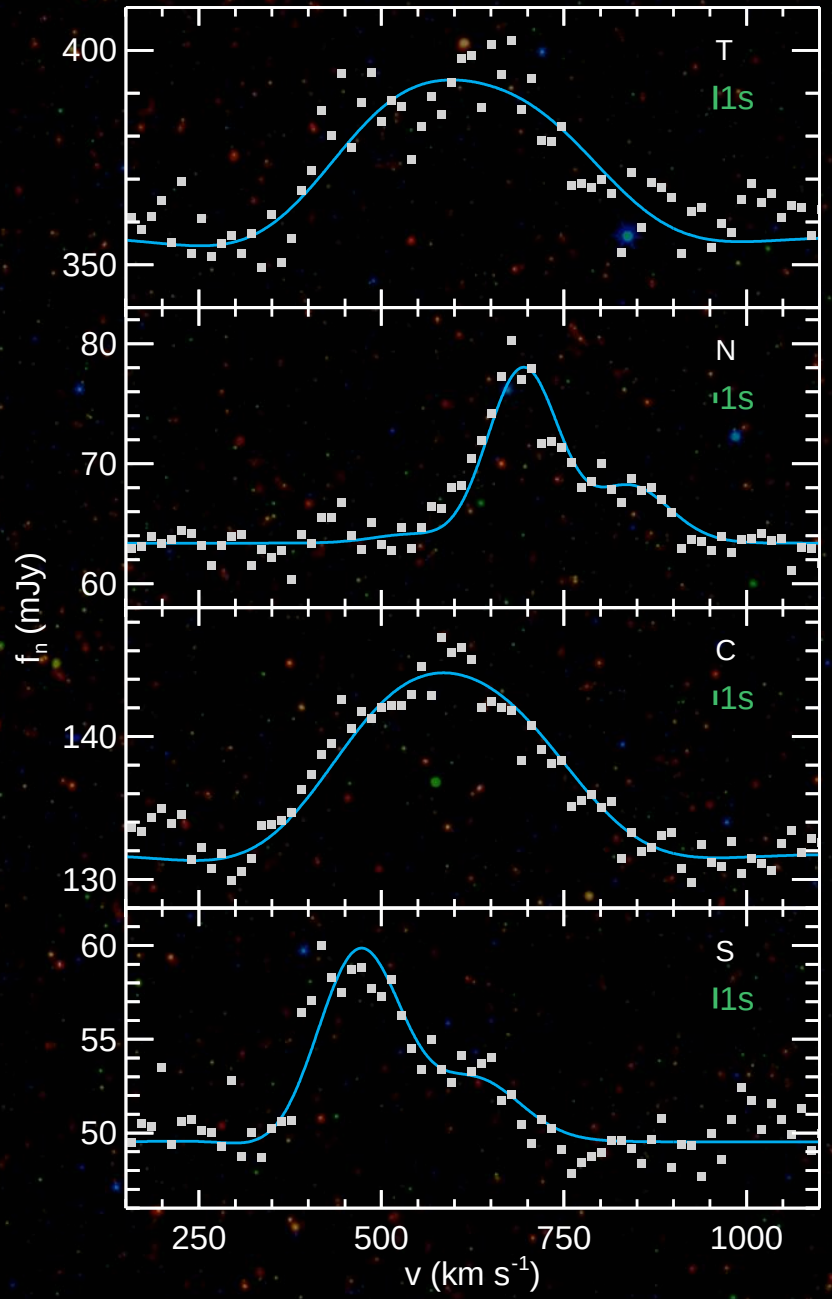
- Electron temperatures (from line/continuum ratio) is 3700-4500 K.
  - Matches measurements from inner regions of Milky Way Galaxy.
- SFR for central 20”x10” is $1.73 \pm 0.12\ M_{\odot}\ yr^{-1}$.
  - Other published SFRs from mm/radio data show a lot of scatter.
- Near-infrared dust attenuation is measured as $A_J = 3.4 \pm 0.2$ and $A_K = 2.1 \pm 0.2$.
  - ~1.5 magnitudes higher than previously-published measurements based on near-infrared data.

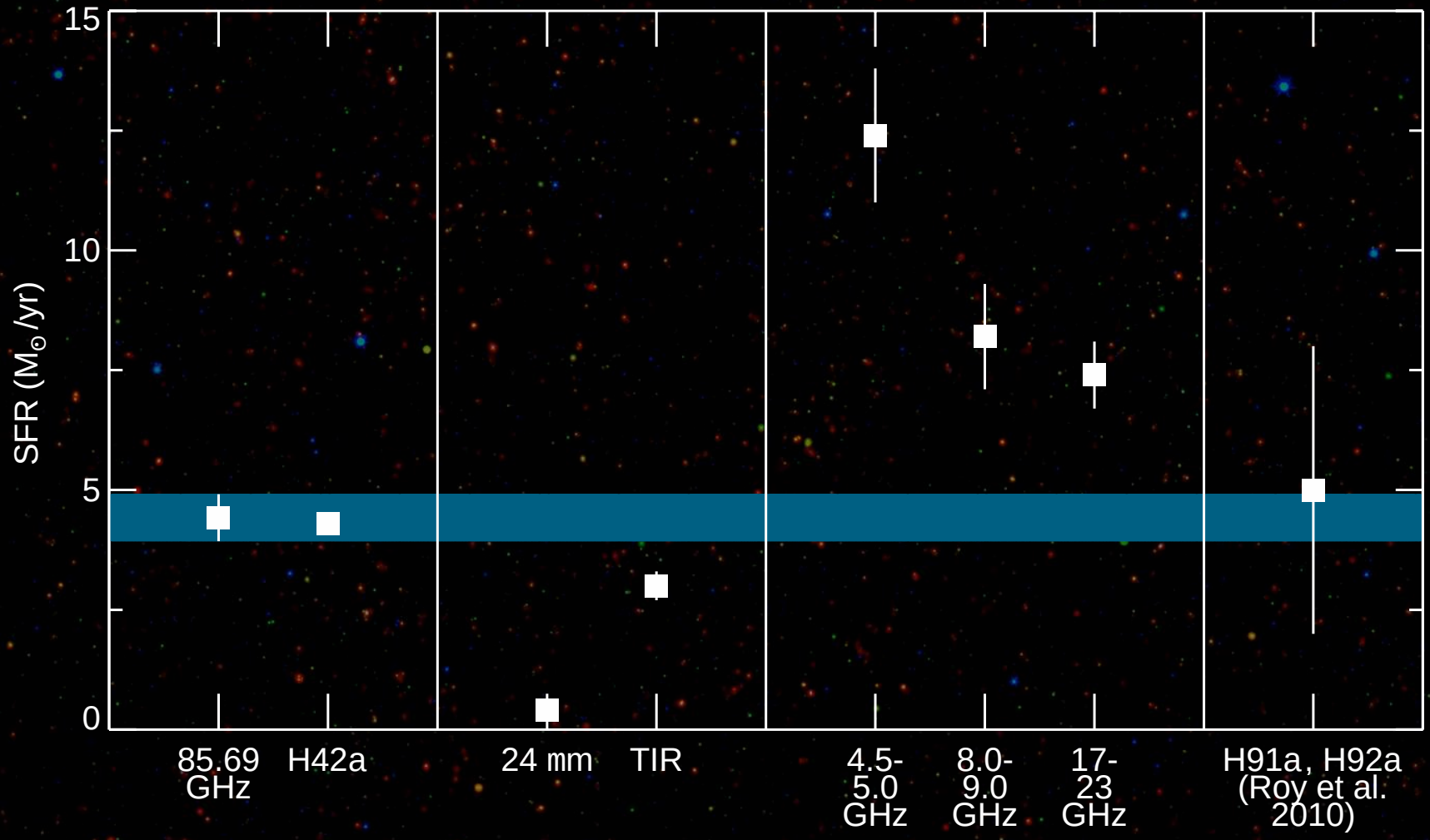

10^-4
10^-2
Jy arcsec^-2
NGC 4945
I_n(85.69 GHz)
10^-1.5
10^-0.5
Jy km s^-1 arcsec^-2
NGC 4945
I(H42a)
-49:28:00
-49:28:15
Declination (J2000)
13:05:28
13:05:26
13:05:28
13:05:26
Right Ascension (J2000)


10^-4
10^-2
Jy arcsec^-2
N
C
T
S
NGC 4945
I_n(85.69 GHz)
-49:28:00
-49:28:15
Declination (J2000)
13:05:28
13:05:26
Right Ascension (J2000)


H42a
T
1s
N
1s
C
1s
S
1s
450
400
350
120
80
140
120
80
60
40
f_n (mJy)
85.5
86.0
86.5
n (GHz)

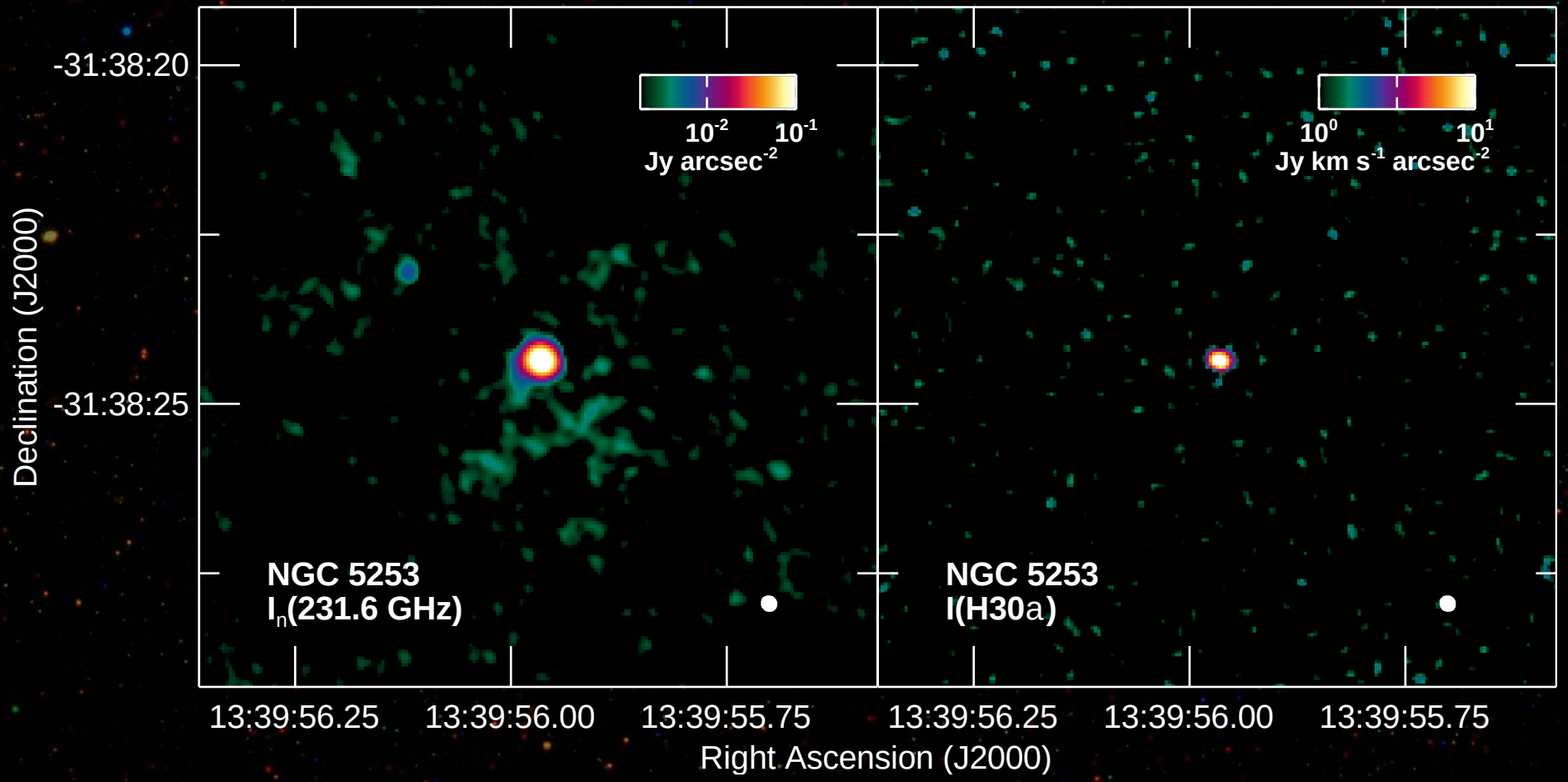

10^-4
10^-2
Jy arcsec^-2
N
C
T
S
NGC 4945
I_n(85.69 GHz)
-49:28:00
-49:28:15
Declination (J2000)
13:05:28
13:05:26
Right Ascension (J2000)

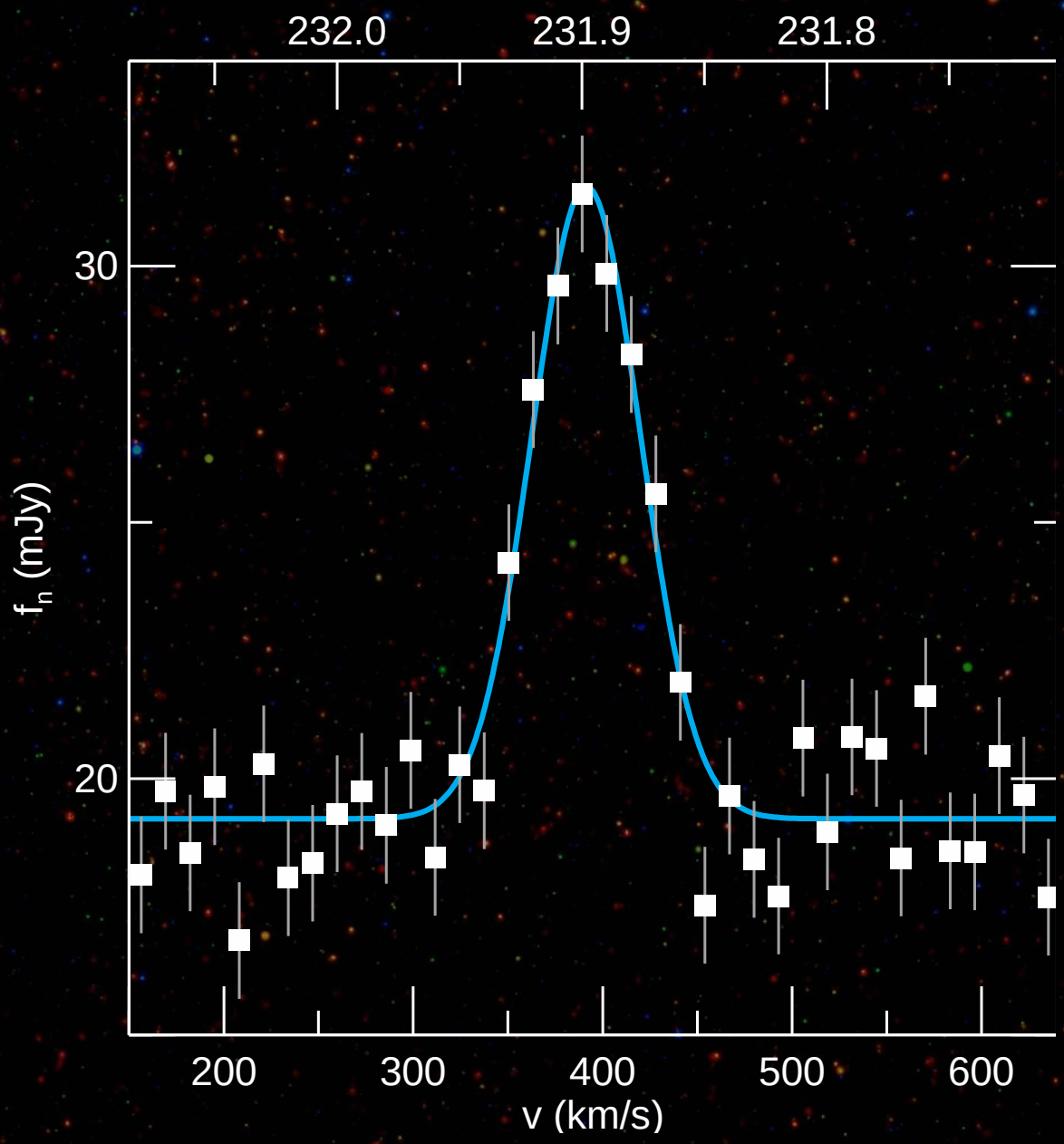

T
I1s
N
I1s
C
I1s
S
I1s
400
350
80
70
60
140
130
60
55
50
f_n (mJy)
250
500
750
1000
v (km s^-1)

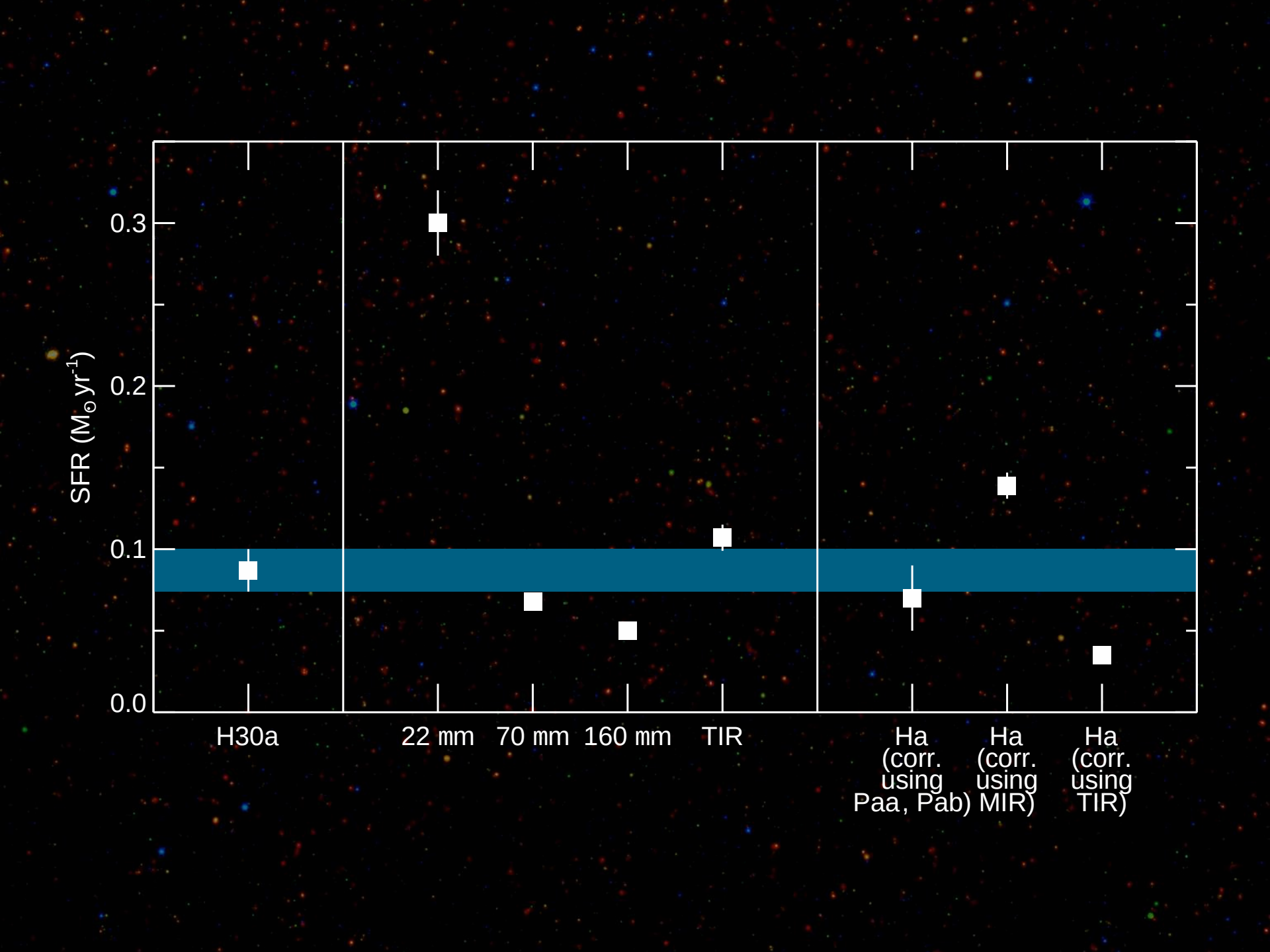

15
10
5
0
SFR ($M_\odot$/yr)
85.69 GHz
H42a
24 mm
TIR
4.5-5.0 GHz
8.0-9.0 GHz
17-23 GHz
H91a, H92a (Roy et al. 2010)

NGC 4945 results

- Free-free and recombination line emission primarily from exponential disc with scale length of ~2.1” (~40 pc).
  - No evidence of central peak associated with AGN.
- Electron temperatures (from line/continuum ratio) is 5400 K.
  - Matches measurements from inner regions of Milky Way Galaxy.
- SFR for central disc is $4.35 \pm 0.25\ M_{\odot}\ yr^{-1}$.
  - In comparison, mid-infrared flux densities (22, 24 μm) appear strongly affected by dust extinction.


-31:38:20
-31:38:25
Declination (J2000)
10^{-2} 10^{-1}
Jy arcsec^{-2}
NGC 5253
I_n(231.6 GHz)
10^{0} 10^{1}
Jy km s^{-1} arcsec^{-2}
NGC 5253
I(H30a)
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_n (mJy)
200
300
400
500
600
v (km/s)


SFR ($M_\odot$ yr^{-1})
0.0
0.1
0.2
0.3
H30a
22 mm
70 mm
160 mm
TIR
Ha (corr. using Paa, Pab)
Ha (corr. using MIR)
Ha (corr. using TIR)

NGC 5253 results

- All detected recombination line emission originates from central 0.6” diameter region.
- Nuclear star formation rate is $0.087 \pm 0.013\ M_{\odot}\ yr^{-1}$.
  - Abnormally hot dust temperatures cause SFR from mid-infrared (22 μm) data to be high and SFRs from far-infrared (70, 160 μm) data to be low.
  - SFRs from total infrared flux and from Hα data corrected with near-infrared lines match H30α result more closely.

Summary

- Millimetre free-free and recombination line emission can be detected from many nearby starbursts using ALMA.
- Early analyses with ALMA data have revealed the following:
  - SFRs from lower-frequency radio data lack accuracy and precision.
  - SFRs from individual infrared bands are affected by extreme dust effects.
  - SFRs from total infrared fluxes may be more reliable than other radio or infrared metrics in these types of starbursts.
- Future ALMA observations will allow us to examine the efficacy of other star formation tracers more thoroughly.