The Relation of Dust to Star Formation in Nearby Galaxies

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Outline

- Comparisons of Herschel-based infrared colour variations to dust heating sources in nearby galaxies
  - Qualitative approach
  - Quantitative approach (binned map data)
  - Quantitative approach (reproductions of infrared colour maps)
- Comparisons of ALMA observations of hydrogen line and free-free emission to infrared star formation tracers

Infrared Colour Variations

Infrared emission in any band is a function of both the dust temperature and dust mass, so the emission could be related to star formation because:

- The emission traces the energy absorbed by dust from star forming regions.
- The emission traces the amount of fuel available for star formation (the Kennicutt-Schmidt law).

Infrared colours are primarily sensitive to the dust temperature itself. Relating the infrared colours to dust healing sources indicates how the dust is heated.

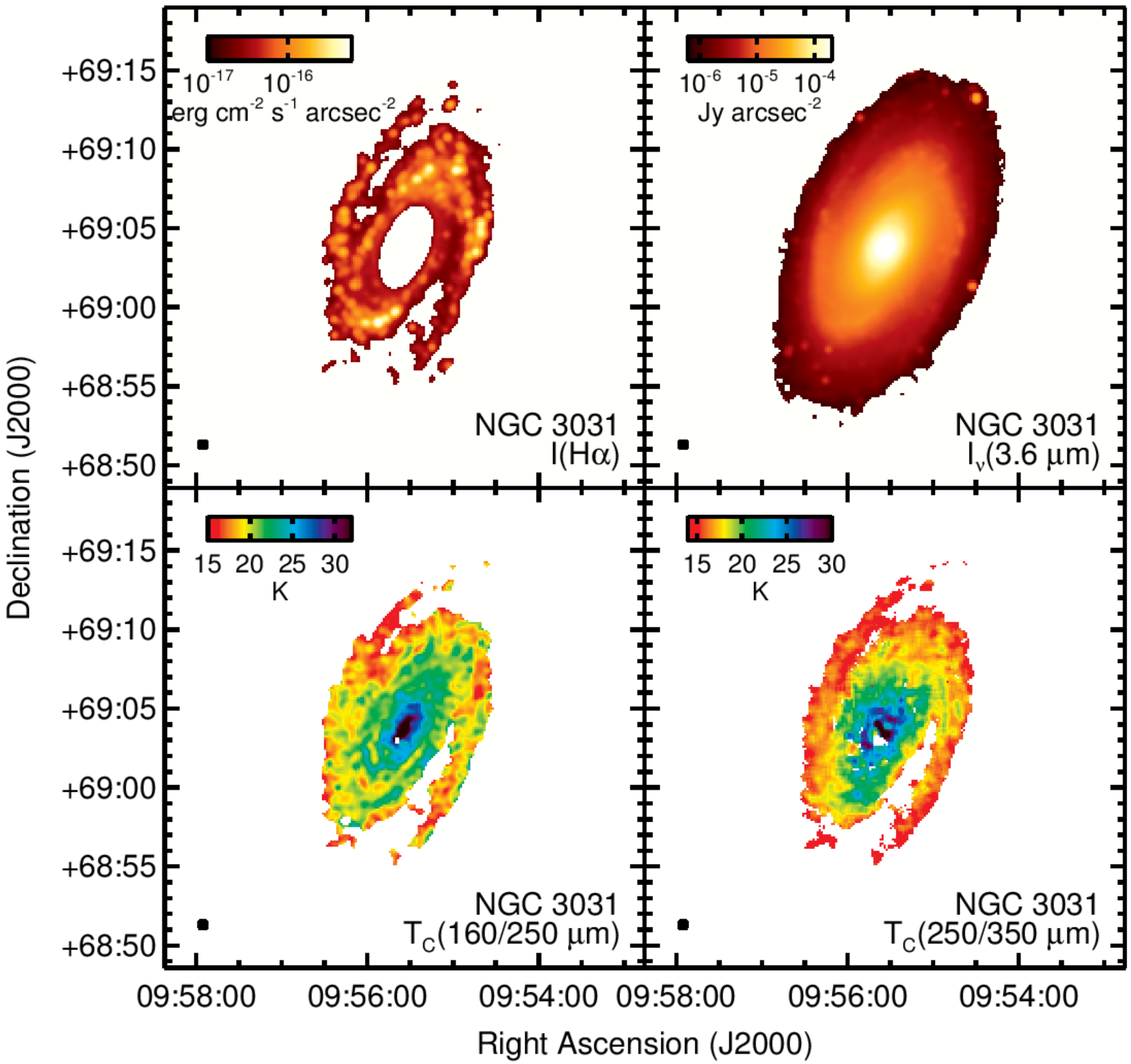
This is important for:

- Using dust emission as a star formation tracer.
- Modelling dust emission and radiative transfer correctly.

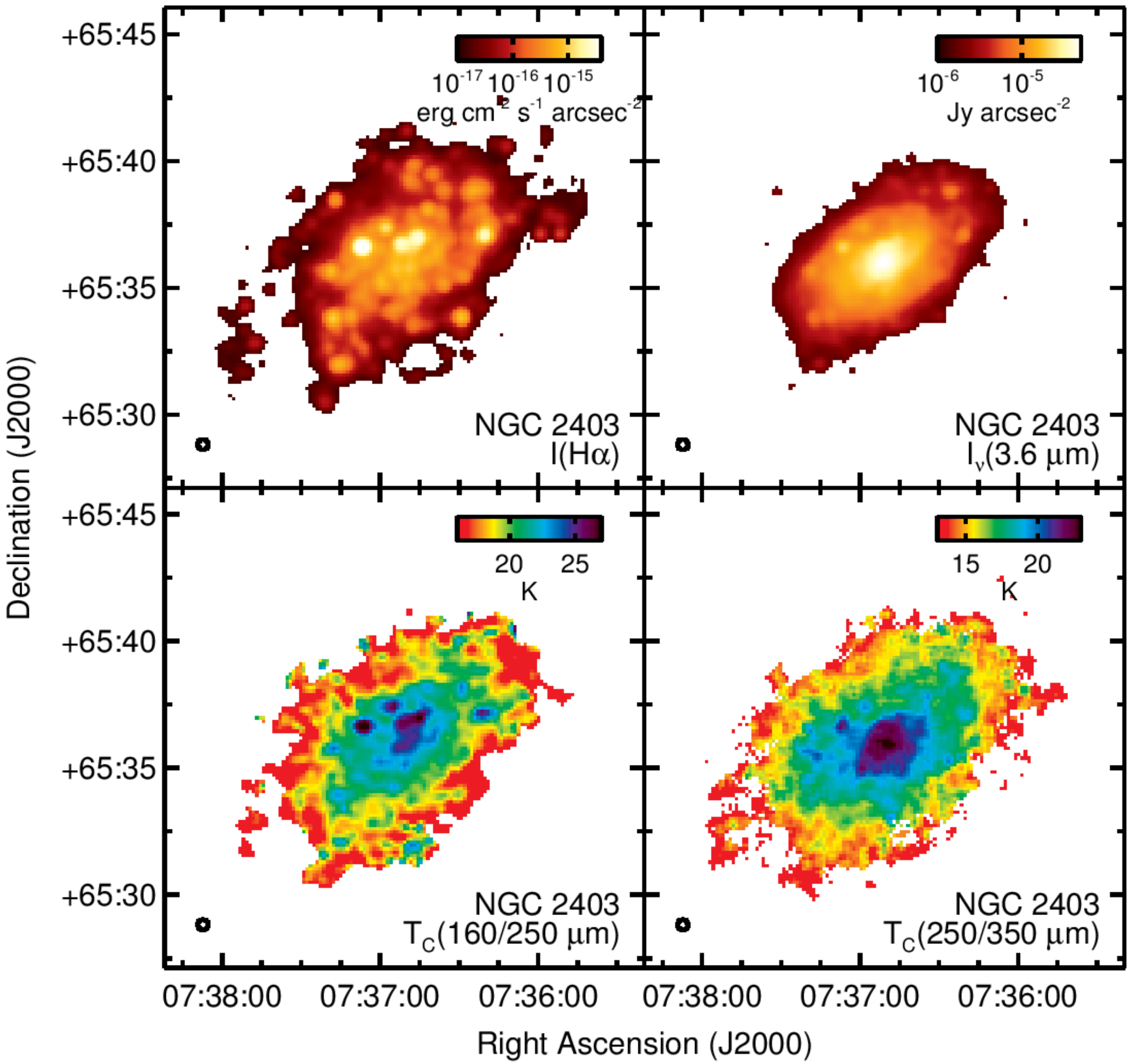
Qualitative Analysis

- Compare images of the infrared colour ratios to the following images:
  - Hα + 24 μm emission (star formation tracer)
  - 3.6 μm emission (evolved stellar population tracer)

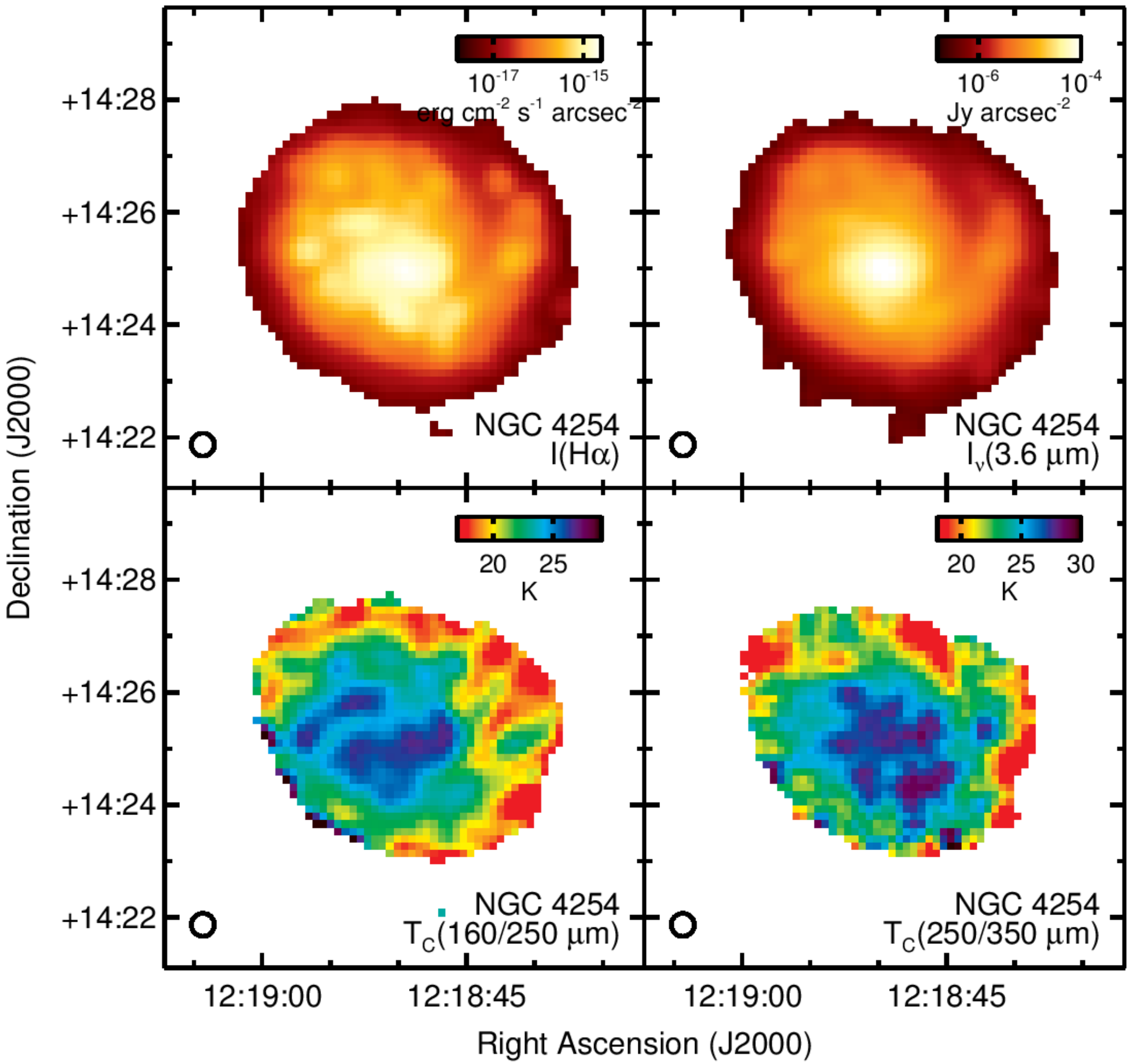
- Visual similarities will indicate which stellar population is heating the dust.



10-17 10-16
erg cm-2 s-1 arcsec-2
10-6 10-5 10-4
Jy arcsec-2
+69:15
+69:10
+69:05
+69:00
+68:55
+68:50
NGC 3031
I(Hα)
NGC 3031
Iν(3.6 μm)
15 20 25 30
K
NGC 3031
TC(160/250 μm)
NGC 3031
TC(250/350 μm)
Declination (J2000)
09:58:00
09:56:00
09:54:00
Right Ascension (J2000)



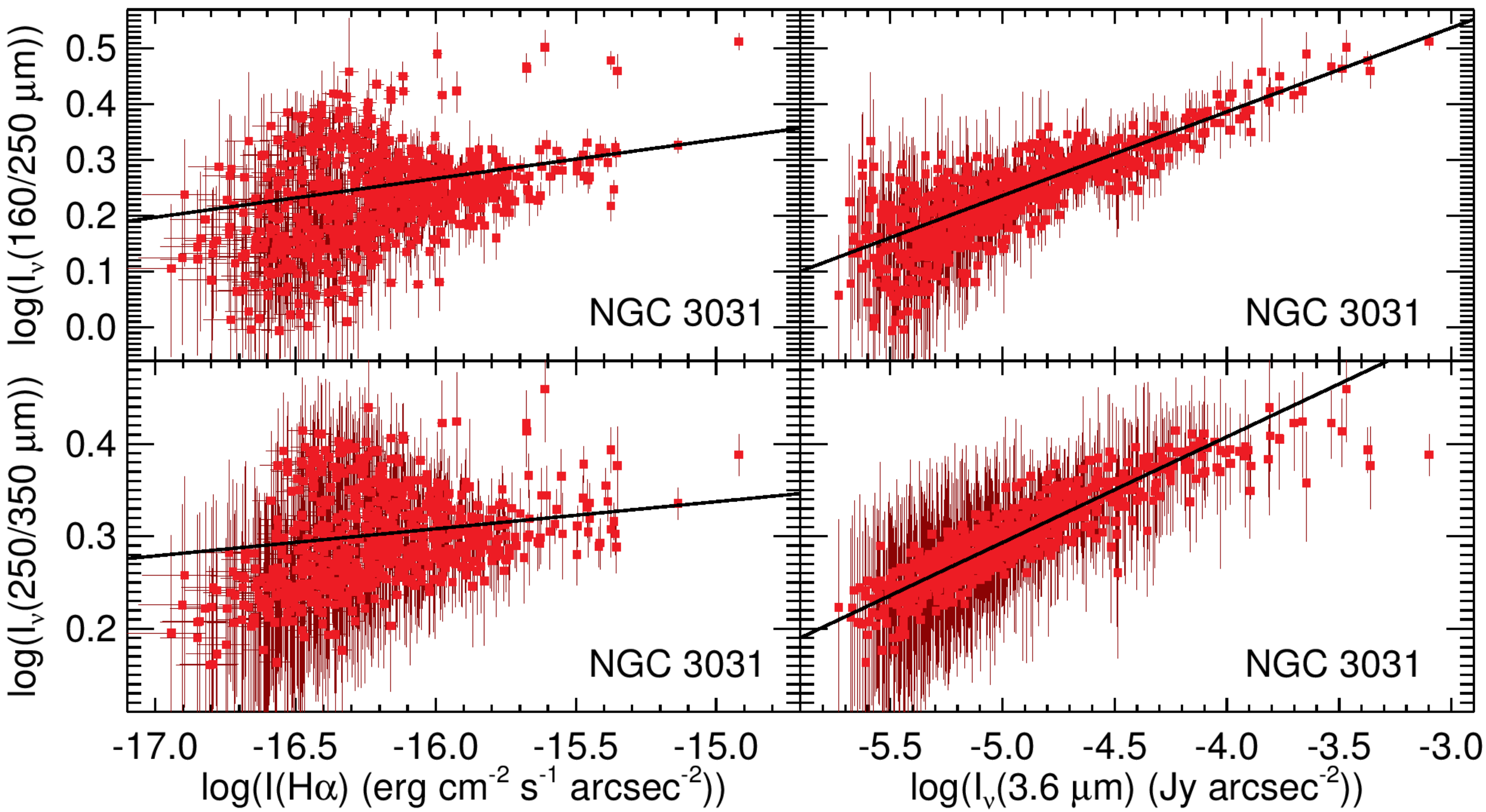
+65:45
+65:40
+65:35
+65:30
Declination (J2000)
10^{-17} 10^{-16} 10^{-15}
erg cm^{-2} s^{-1} arcsec^{-2}
NGC 2403
I(Hα)
10^{-6} 10^{-5}
Jy arcsec^{-2}
NGC 2403
I_{ν}(3.6 μm)
20 25
K
NGC 2403
T_C(160/250 μm)
15 20
K
NGC 2403
T_C(250/350 μm)
07:38:00
07:37:00
07:36:00
Right Ascension (J2000)



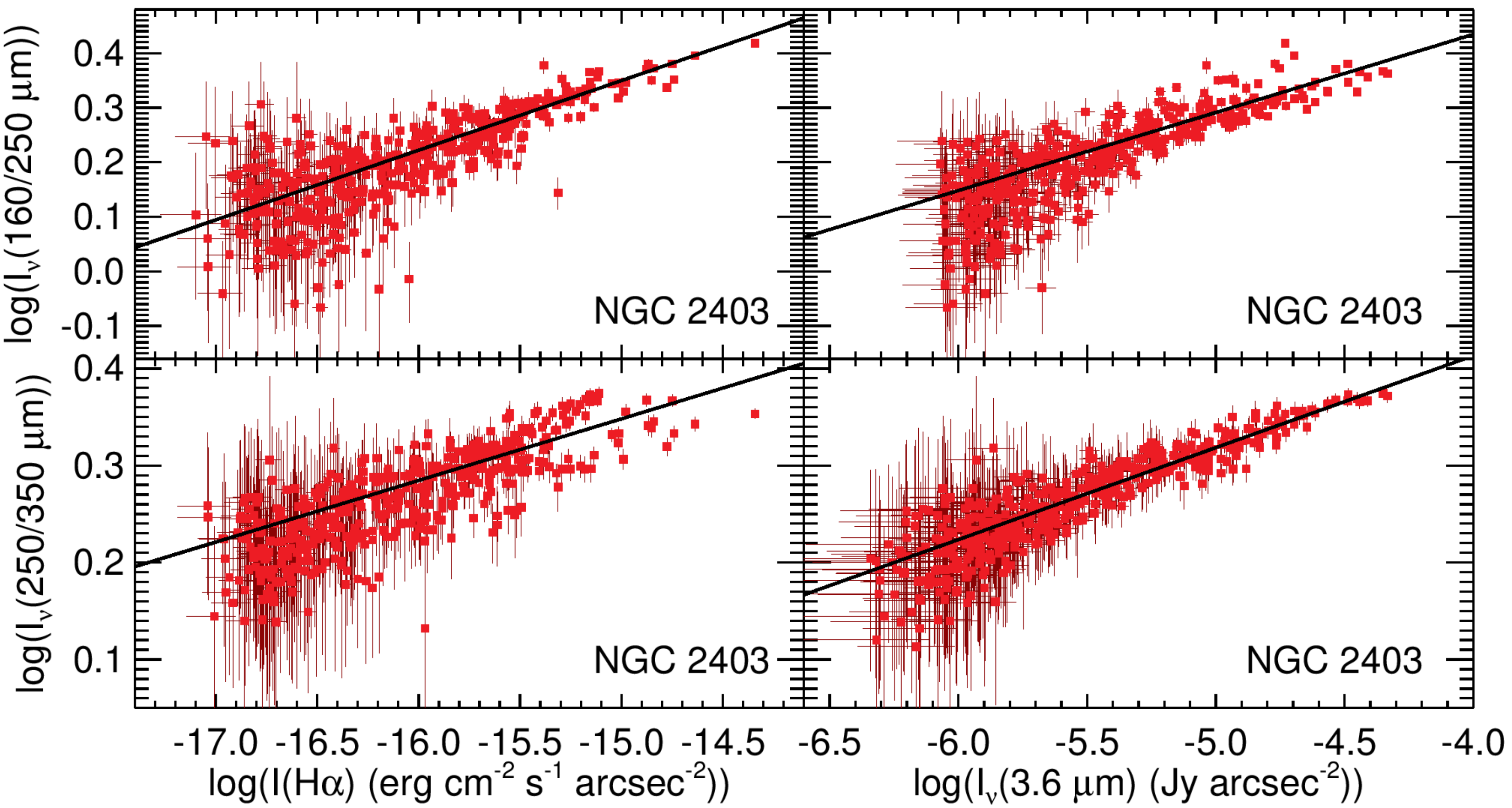
10^-17 10^-15
erg cm^-2 s^-1 arcsec^-2
NGC 4254
I(Hα)
10^-6 10^-4
Jy arcsec^-2
NGC 4254
I_ν(3.6 μm)
20 25
K
NGC 4254
T_C(160/250 μm)
20 25 30
K
NGC 4254
T_C(250/350 μm)
+14:28
+14:26
+14:24
+14:22
Declination (J2000)
12:19:00
12:18:45
Right Ascension (J2000)

Quantitative Analysis (binned map data)

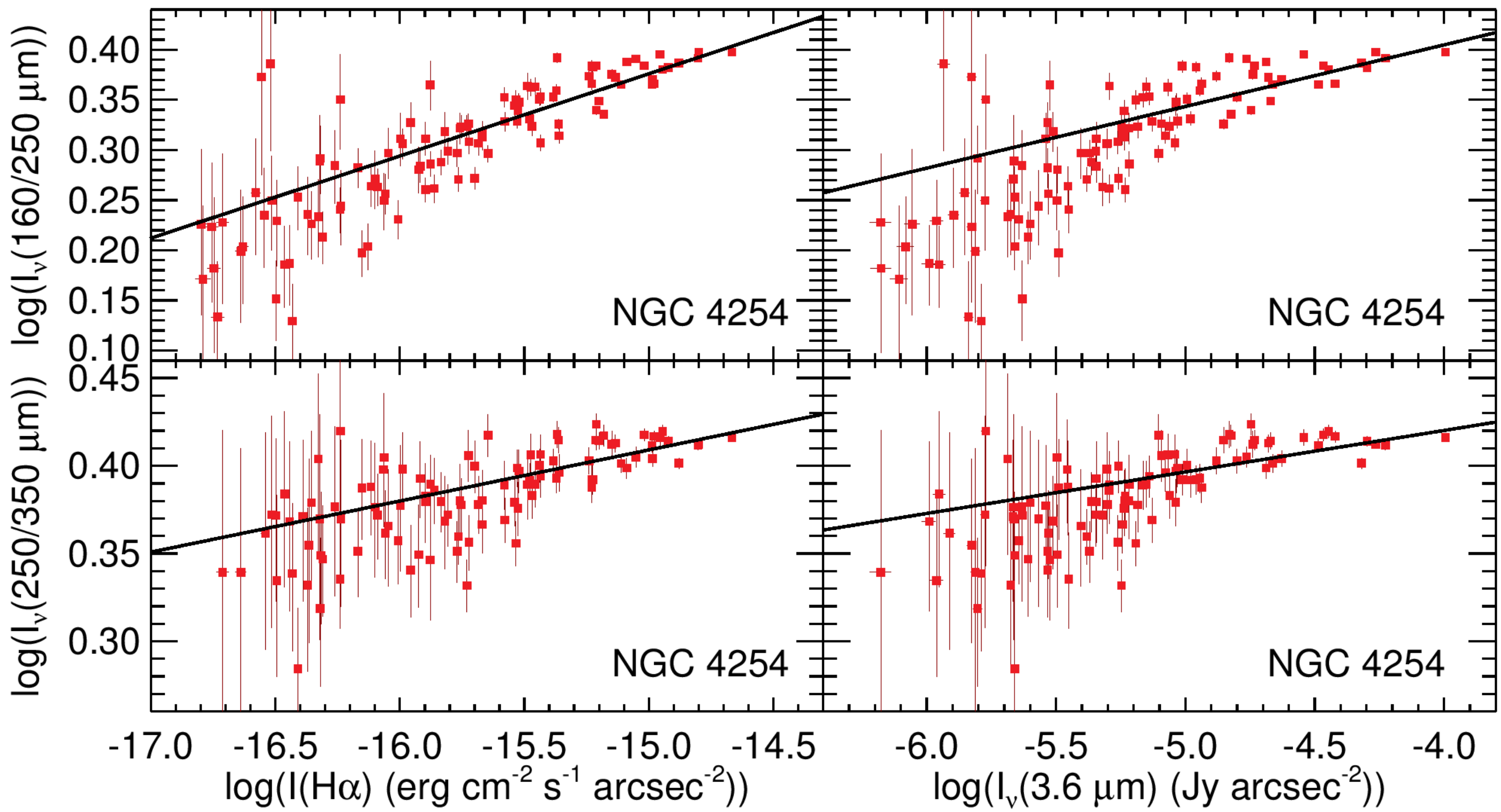
- Bin the data (using bins the size of the FWHM of the largest PSF).
- Plot the 160/250 and 250/350 μm ratios versus Hα + 24 μm emission and versus 3.6 μm emission
- The relations will indicate how the dust emission in the shorter band is related to the heating sources.



log(Iν(160/250 μm))
log(Iν(250/350 μm))
NGC 3031
NGC 3031
NGC 3031
NGC 3031
0.5
0.4
0.3
0.2
0.1
0.0
0.4
0.3
0.2
-17.0
-16.5
-16.0
-15.5
-15.0
-5.5
-5.0
-4.5
-4.0
-3.5
-3.0
log(I(Hα) (erg cm-2 s-1 arcsec-2))
log(Iν(3.6 μm) (Jy arcsec-2))



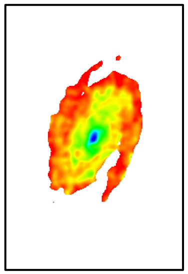
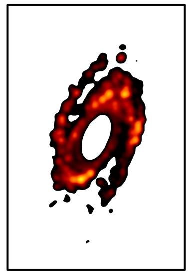
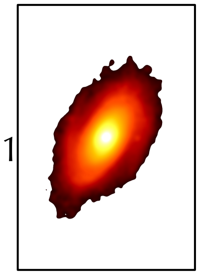
log(I$_\nu$(160/250 μm))
log(I$_\nu$(250/350 μm))
0.4
0.3
0.2
0.1
0.0
-0.1
NGC 2403
-17.0 -16.5 -16.0 -15.5 -15.0 -14.5
log(I(Hα) (erg cm^{-2} s^{-1} arcsec^{-2}))
-6.5 -6.0 -5.5 -5.0 -4.5 -4.0
log(I$_\nu$(3.6 μm) (Jy arcsec^{-2}))



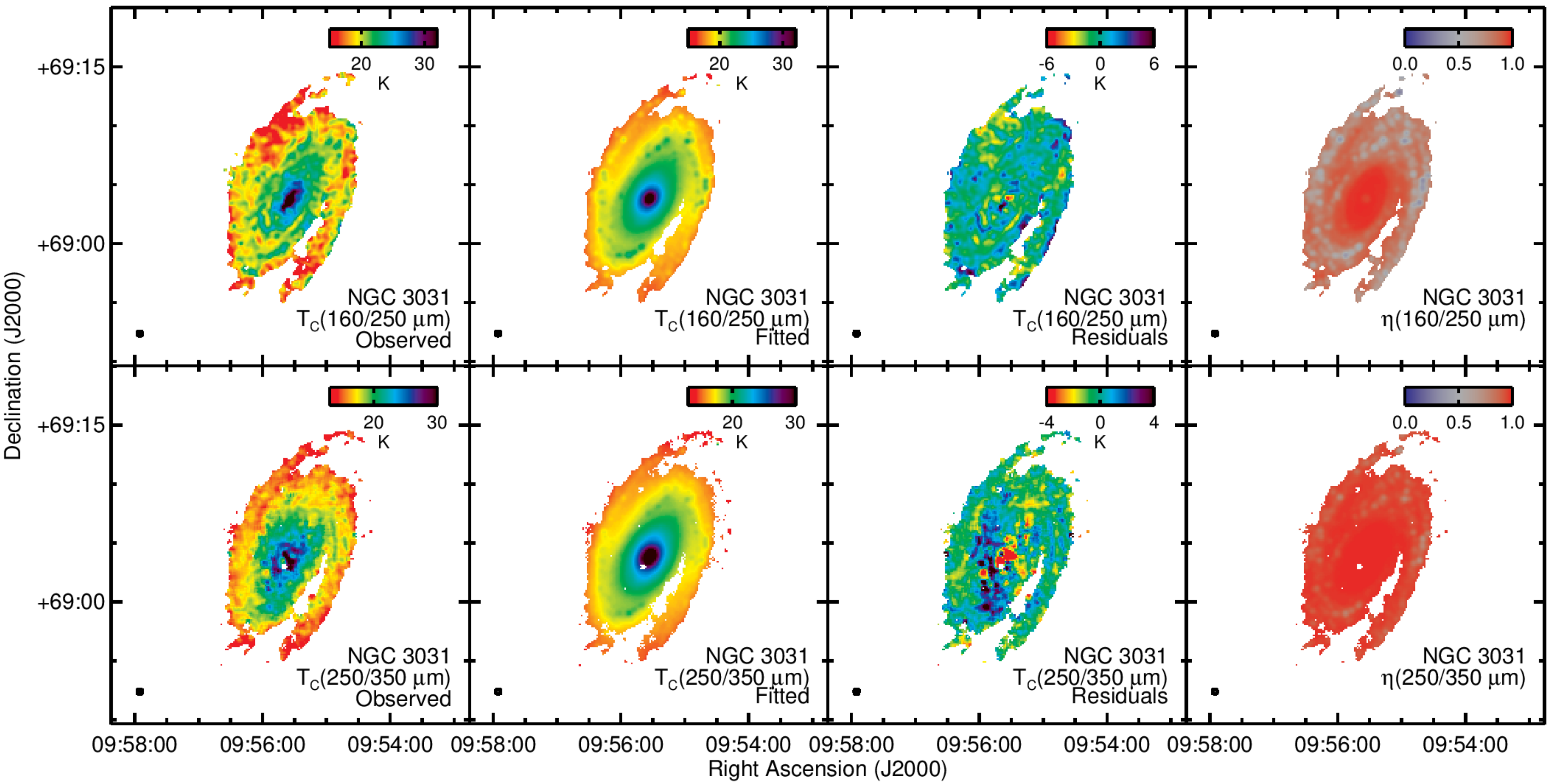
log(Iν(160/250 μm))
log(Iν(250/350 μm))
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.45
NGC 4254
NGC 4254
NGC 4254
NGC 4254
-17.0
-16.5
-16.0
-15.5
-15.0
-14.5
-6.0
-5.5
-5.0
-4.5
-4.0
log(I(Hα) (erg cm-2 s-1 arcsec-2))
log(Iν(3.6 μm) (Jy arcsec-2))

Quantitative Analysis (reproduction of infrared colour maps)

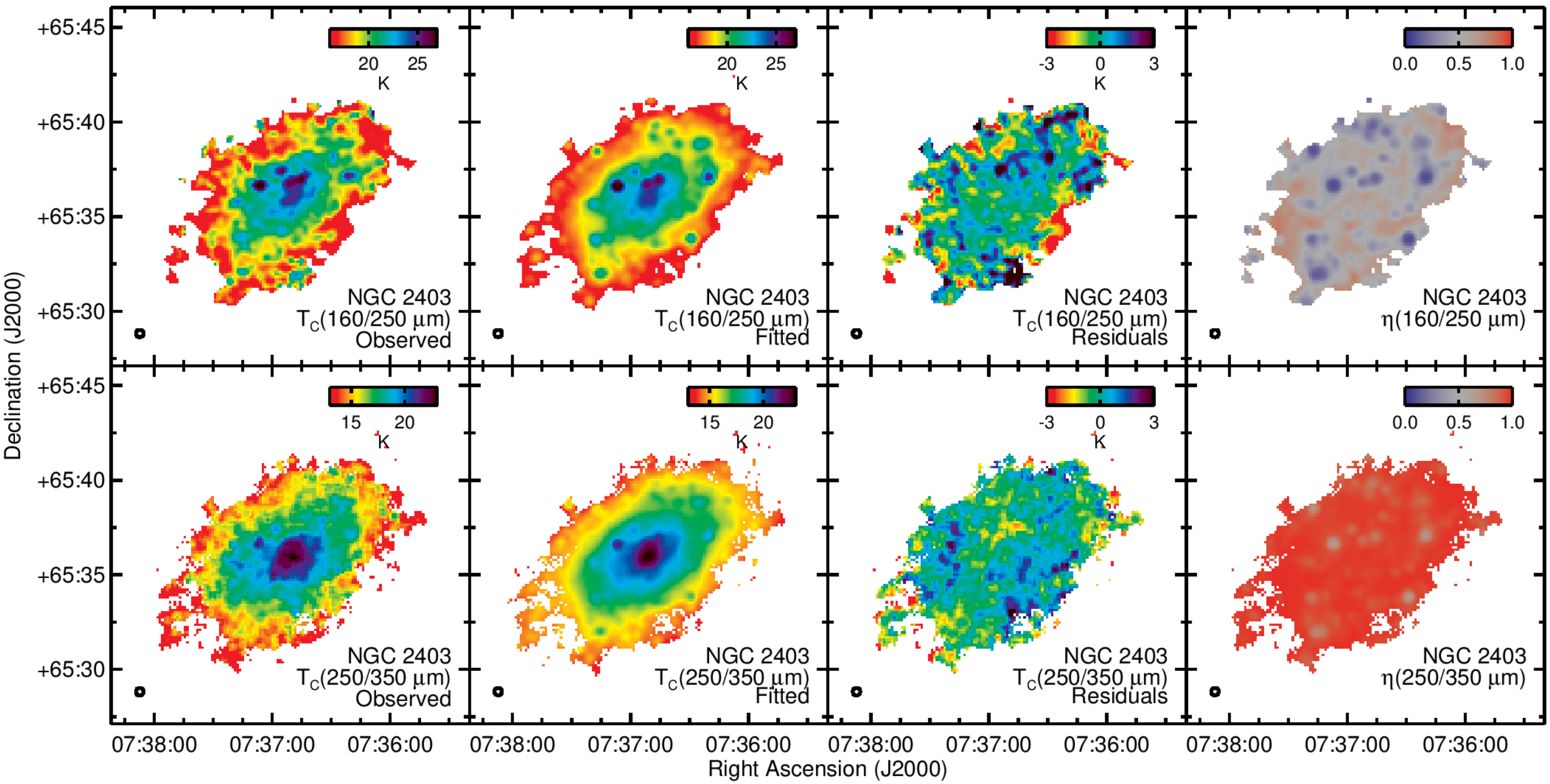
- The infrared colour data are fit with the following equation:

ln() = α ln( + A_1 ) + A_2

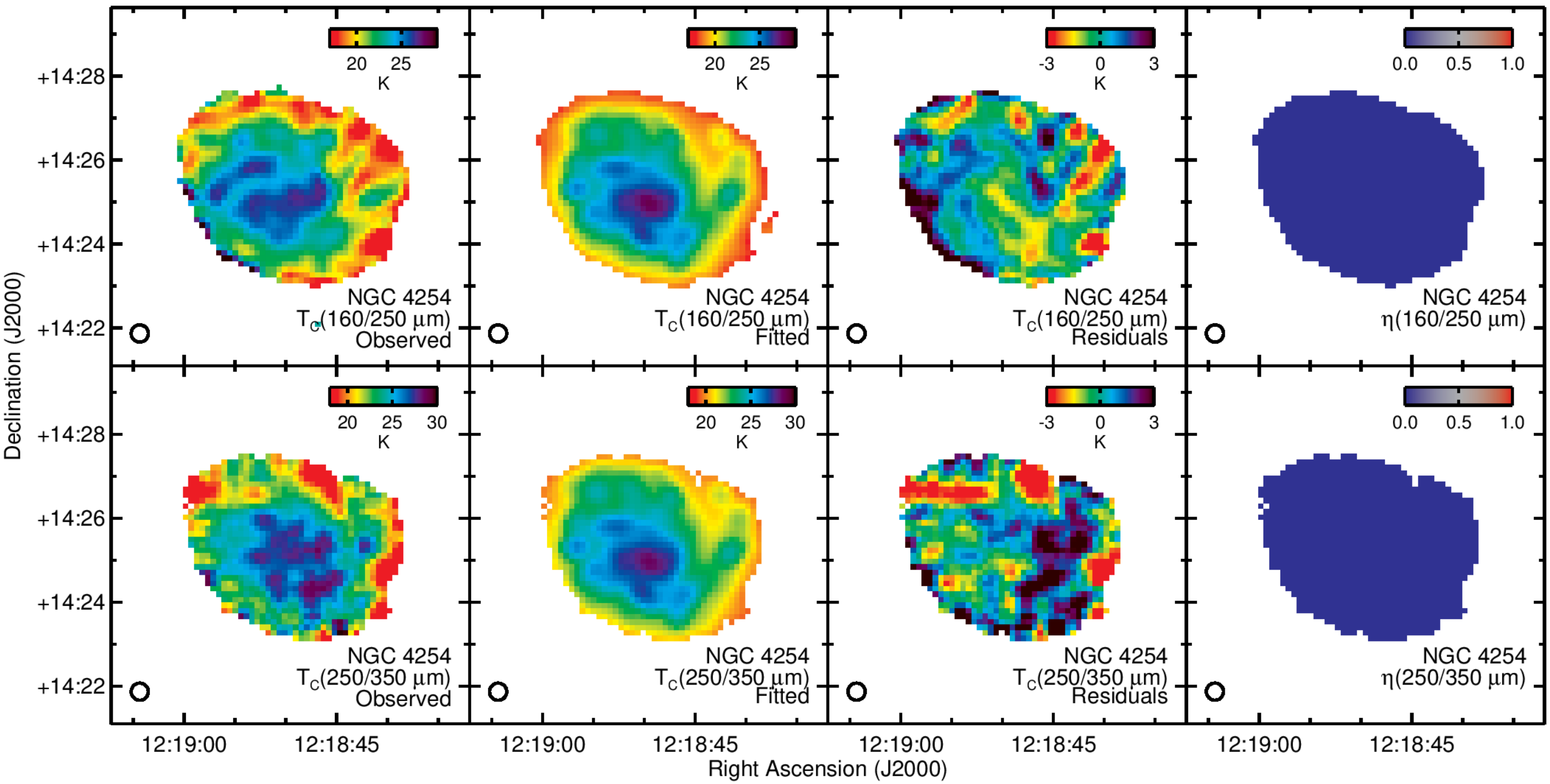
- The ratio of the star formation and evolved star components in the relation gives an indication of how the dust seen in the shorter waveband is heated.



Declination (J2000)
+69:15
+69:00
20 30 K
-6 0 6 K
-4 0 4 K
0.0 0.5 1.0
NGC 3031
T$_C$(160/250 μm)
Observed
Fitted
Residuals
η(160/250 μm)
T$_C$(250/350 μm)
η(250/350 μm)
09:58:00 09:56:00 09:54:00
Right Ascension (J2000)



NGC 2403
T_C(160/250 μm)
Observed
NGC 2403
T_C(160/250 μm)
Fitted
NGC 2403
T_C(160/250 μm)
Residuals
NGC 2403
η(160/250 μm)
NGC 2403
T_C(250/350 μm)
Observed
NGC 2403
T_C(250/350 μm)
Fitted
NGC 2403
T_C(250/350 μm)
Residuals
NGC 2403
η(250/350 μm)
K
Declination (J2000)
Right Ascension (J2000)
+65:45
+65:40
+65:35
+65:30
07:38:00
07:37:00
07:36:00



NGC 4254
T_C(160/250 μm)
Observed
NGC 4254
T_C(160/250 μm)
Fitted
NGC 4254
T_C(160/250 μm)
Residuals
NGC 4254
η(160/250 μm)
NGC 4254
T_C(250/350 μm)
Observed
NGC 4254
T_C(250/350 μm)
Fitted
NGC 4254
T_C(250/350 μm)
Residuals
NGC 4254
η(250/350 μm)
20 25 K
20 25 30 K
-3 0 3 K
0.0 0.5 1.0
+14:28
+14:26
+14:24
+14:22
Declination (J2000)
12:19:00
12:18:45
Right Ascension (J2000)

Conclusions from the Herschel colour analysis

- It is possible to identify nearby galaxies where the dust emitting in the far-infrared is:
    - Heated by evolved stars.
    - Heated by star forming regions.
    - Heated by one source or the other (depending on the wavelength).
    - Heated by both young and old stars equally (or ambiguously).

- It is difficult to predict which heating source is the dominant heating source in any specific galaxy without using this type of analysis or more complex modelling.

- However, emission from dust heated by evolved stars could still be related to star formation through the Kennicutt-Schmidt law.

ALMA Observations of Star Formation

ALMA can detect two different forms of emission from photoionized gas:

- Free-free continuum emission
- Millimetre/submillimetre hydrogen recombination line emission

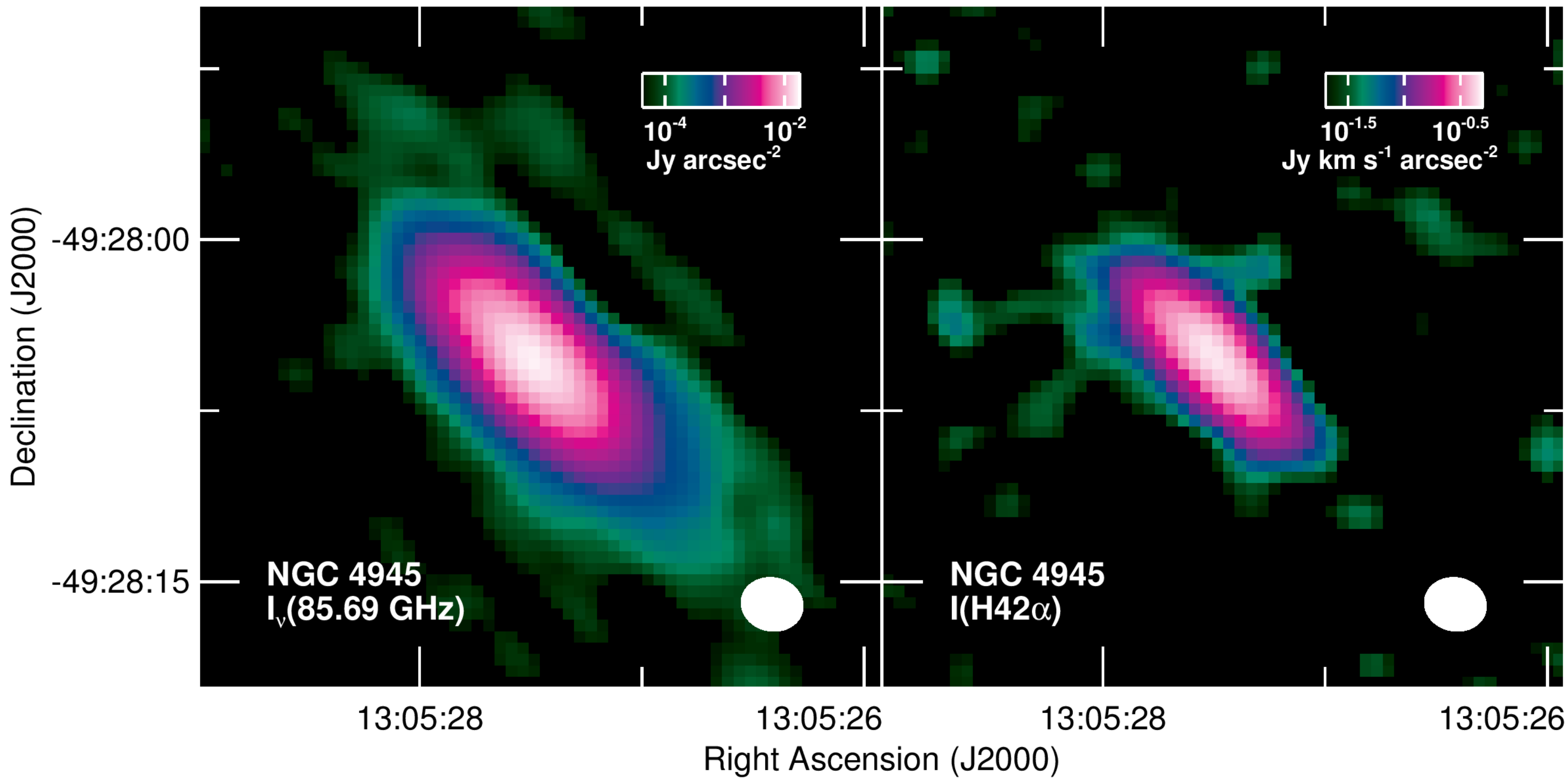
These forms of emission have two advantages over other star formation tracers:

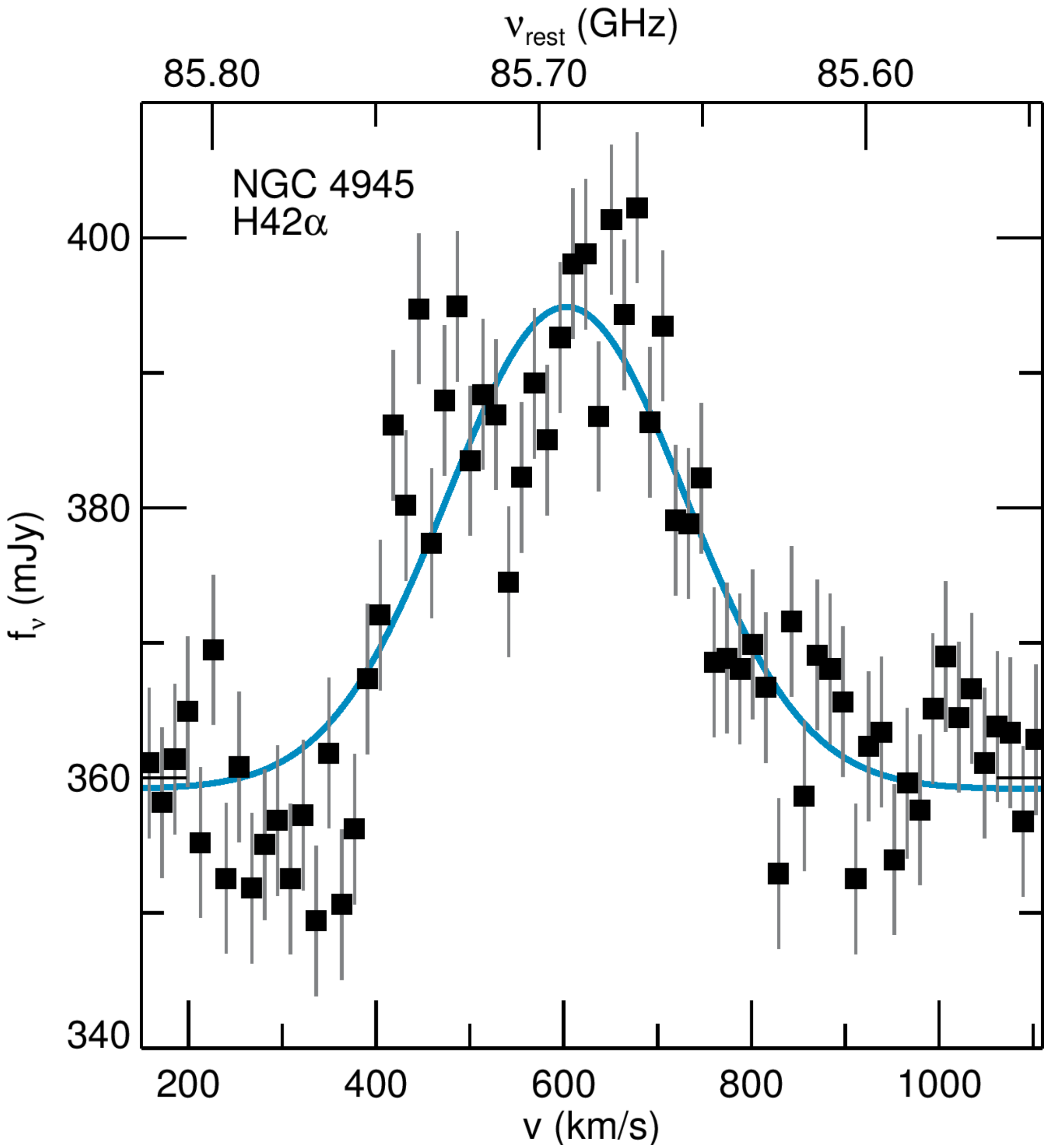
- They directly trace photoionizing stars.
- They are unaffected by dust extinction.

So far, ALMA has detected recombination line emission from three galaxies:

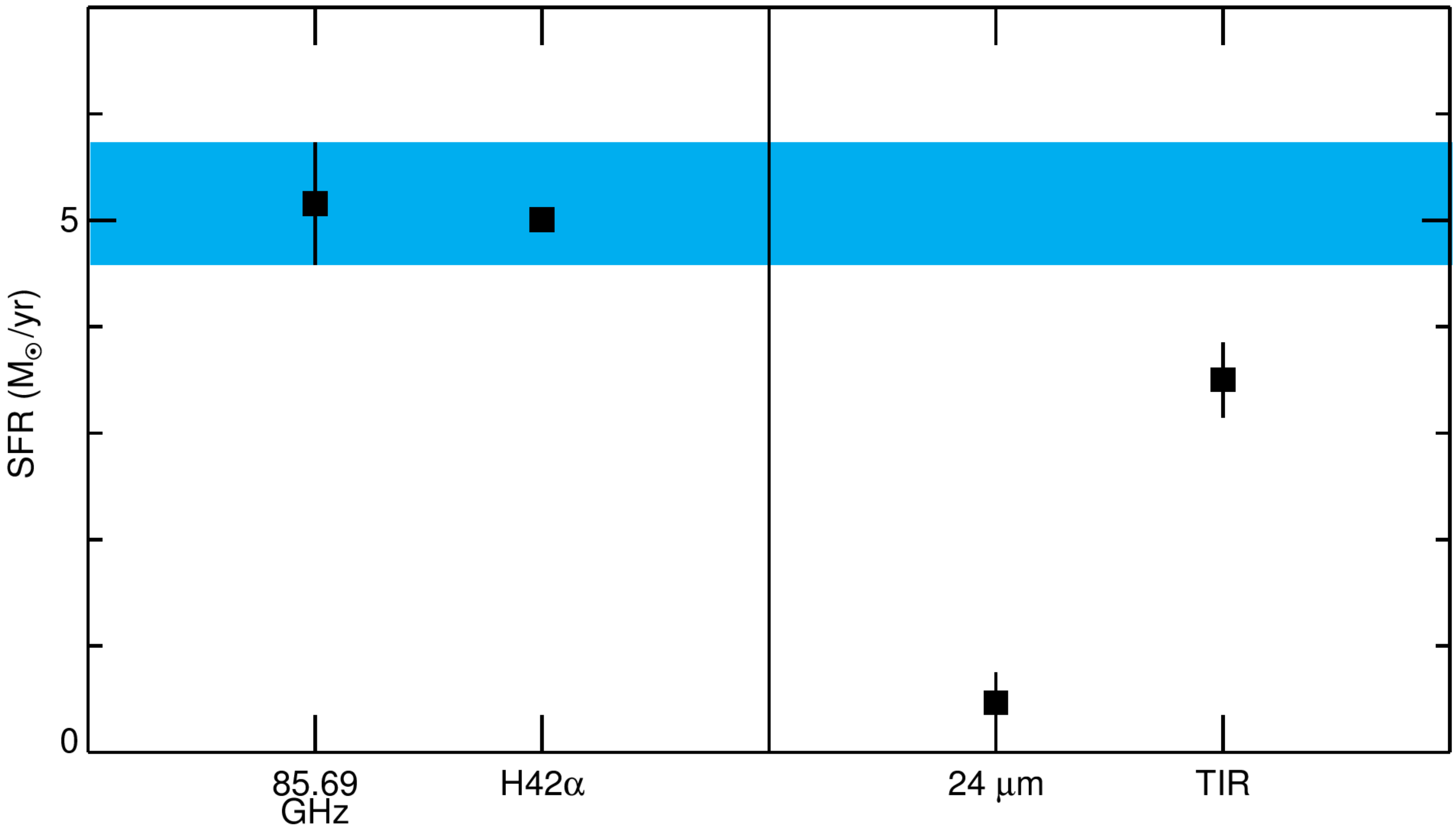
- NGC 253
- NGC 4945
- NGC 5253

The last two galaxies were useful for comparing ALMA-based SFRs to infrared-based SFRs.

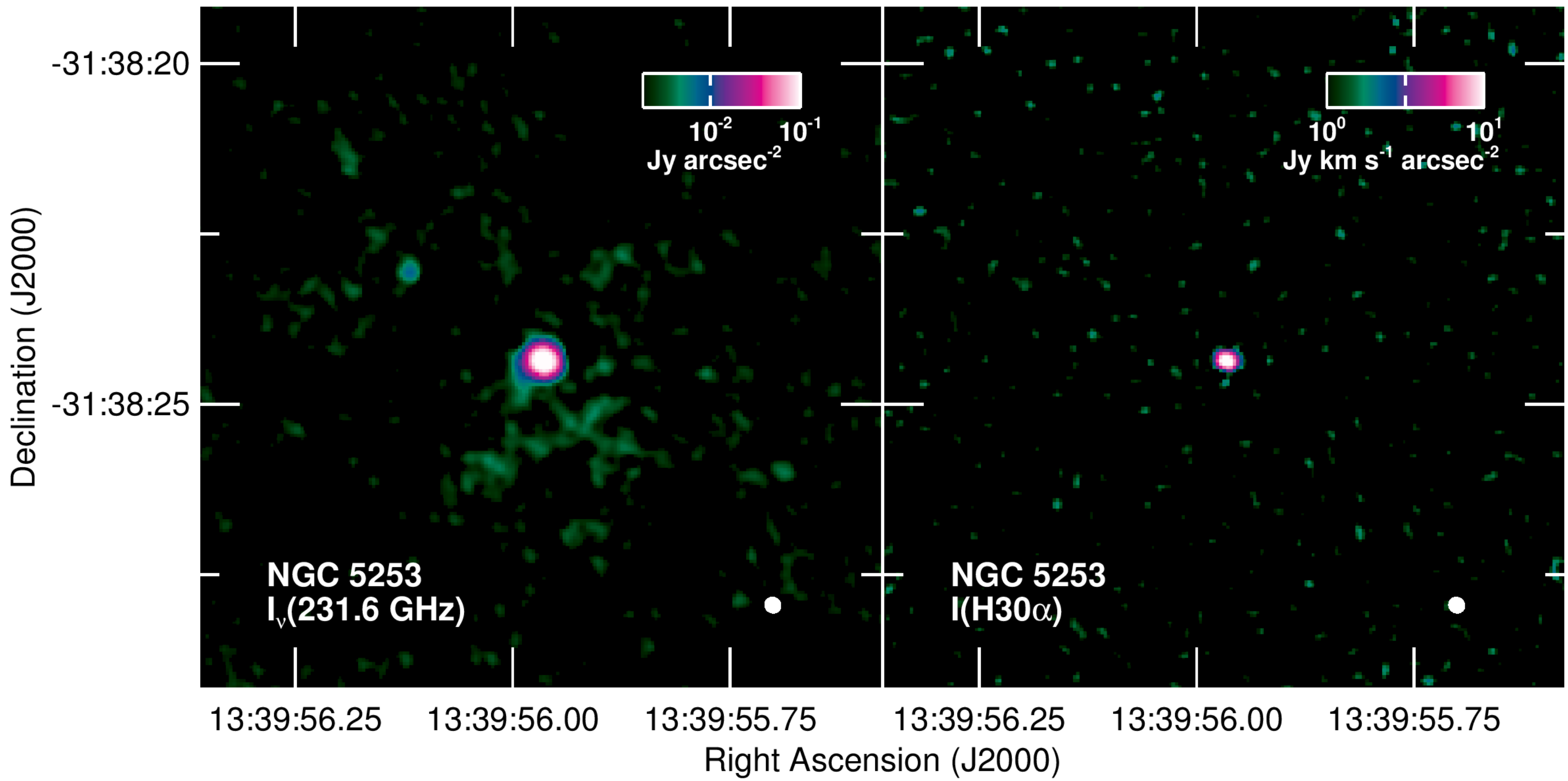

10^-4
10^-2
Jy arcsec^-2
10^-1.5
10^-0.5
Jy km s^-1 arcsec^-2
-49:28:00
-49:28:15
Declination (J2000)
NGC 4945
Iν(85.69 GHz)
NGC 4945
I(H42α)
13:05:28
13:05:26
13:05:28
13:05:26
Right Ascension (J2000)



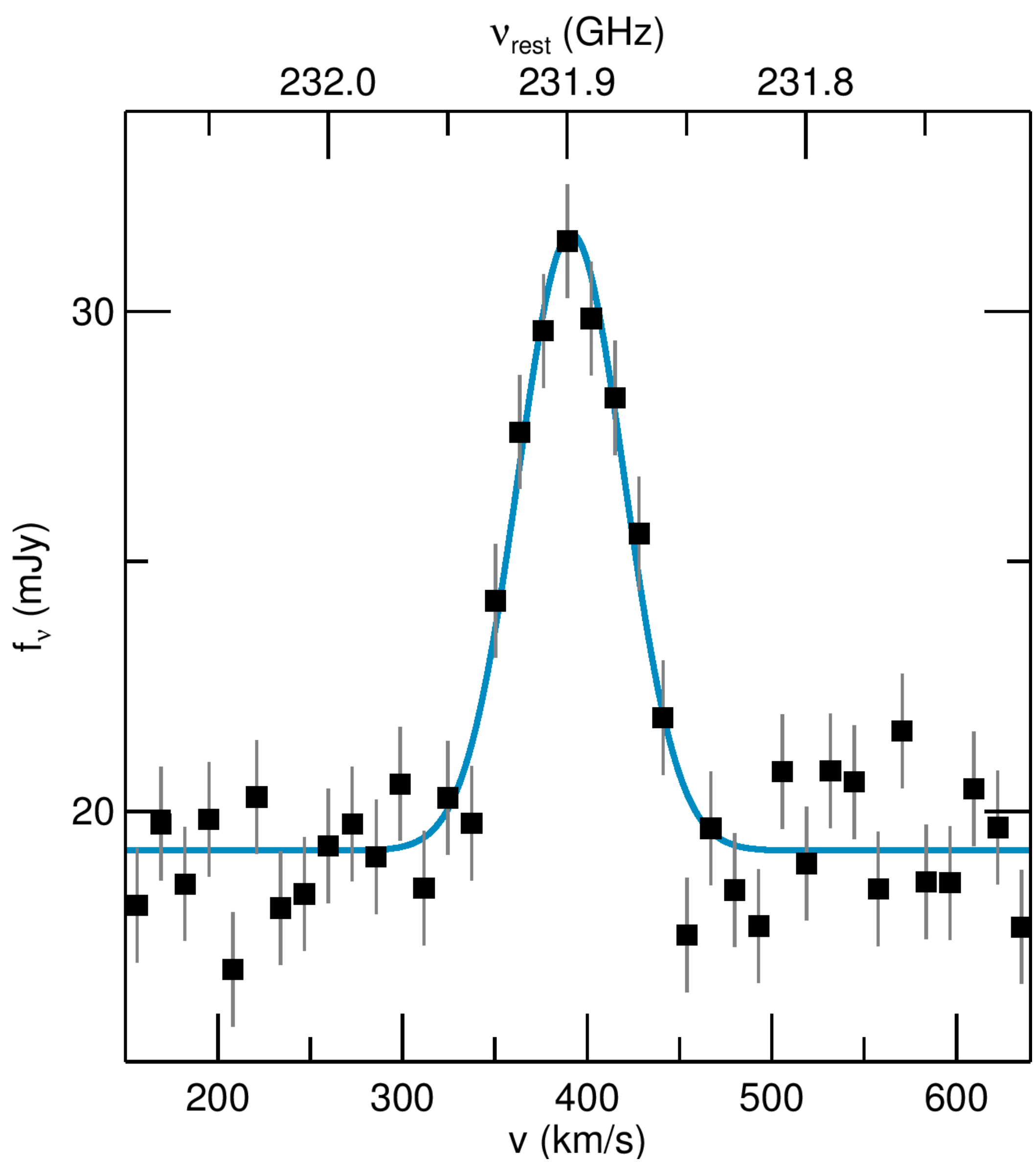
ν_rest (GHz)
85.80
85.70
85.60
NGC 4945
H42α
400
380
360
340
f_ν (mJy)
200
400
600
800
1000
v (km/s)



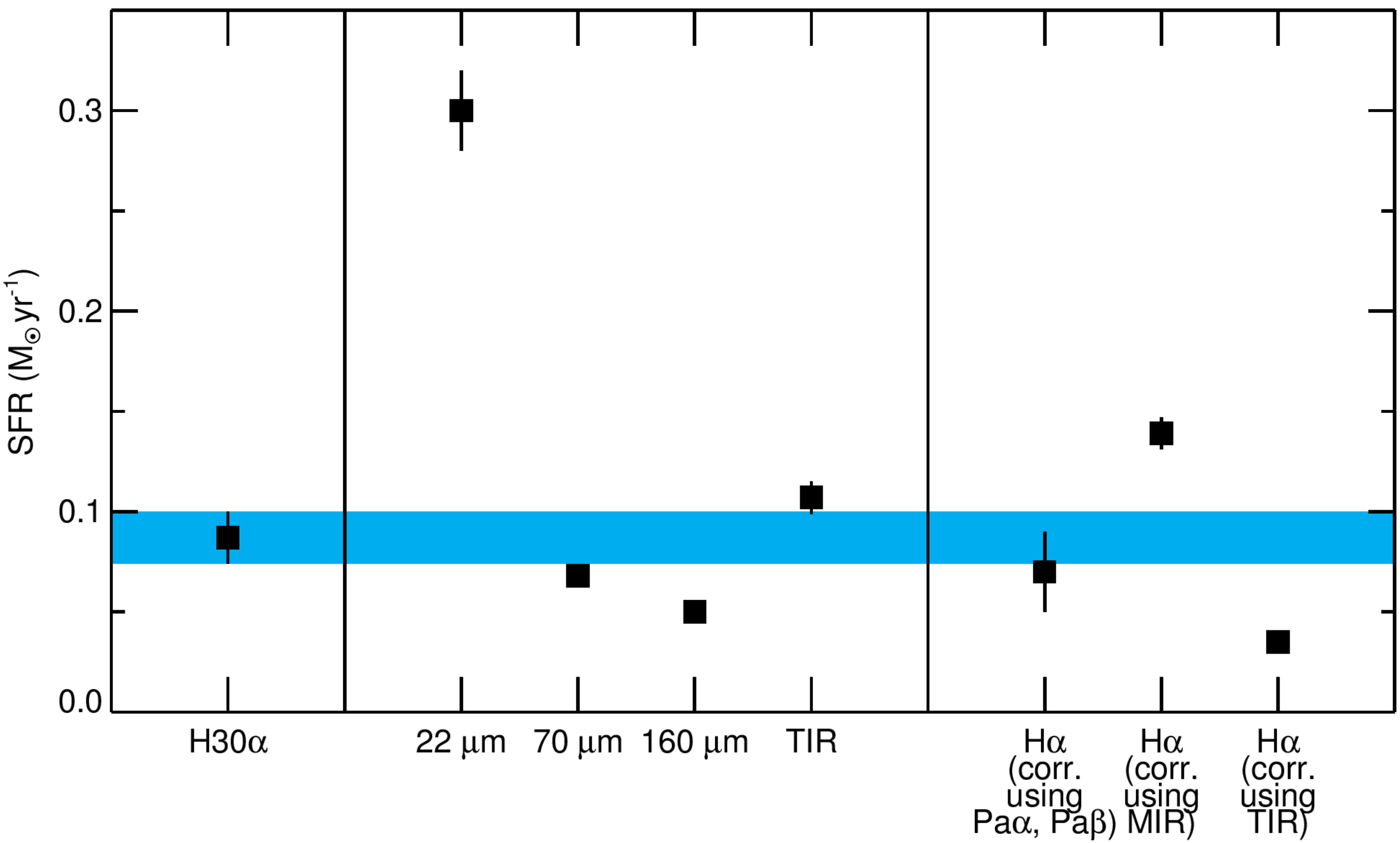
SFR (M$_\odot$/yr)
5
0
85.69 GHz
H42α
24 μm
TIR



-31:38:20
-31:38:25
Declination (J2000)
10^{-2} 10^{-1}
Jy arcsec^{-2}
NGC 5253
I_ν(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)



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



SFR (M☉ 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)

Conclusions from the ALMA analysis

- In dusty starbursts, the total infrared flux works reasonably well as a star formation tracer.
- Individual infrared bands do not necessarily trace very dust-obscured star formation effectively.
  - The mid-infrared flux works very poorly.
- Composite star formation tracers may not work well in heavily-obscured star forming regions.

Implications for Galaxy Quenching Studies

- The connection between infrared flux and star formation depends on the galaxy.
    - In normal or non-star-forming galaxies, the dust could just trace the fuel for star formation.
    - In extreme systems, the dust emission is reprocessed energy from star formation.
- Measuring star formation rates from a single infrared band may not be straightforward.
- The galaxy main sequence could be defined in part by the Kennicutt-Schmidt relation if the star formation rate is based on infrared flux.
- In heavily obscured starbursts, star formation could be more important for feedback than expected.