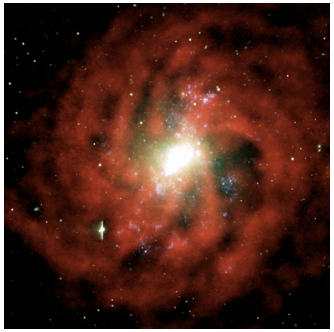
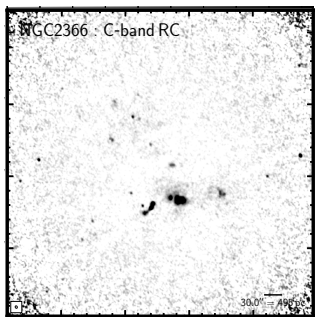
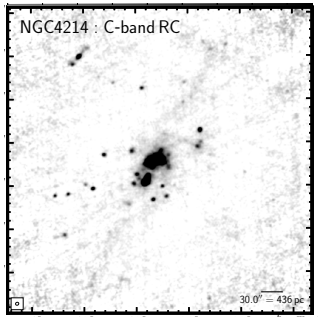
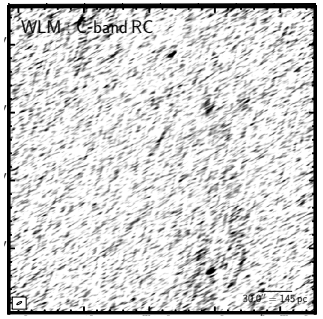



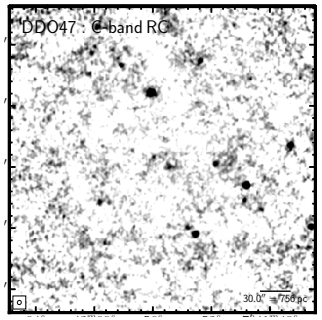

The Resolved Radio Continuum vs. Star Formation Rate in Nearby Dwarf Galaxies

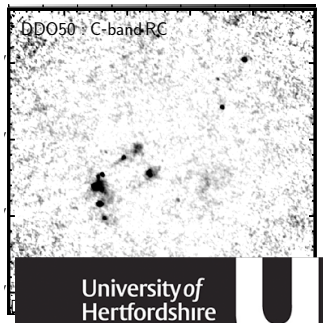
Luke Hindson, Elias Brinks, Jonathan Westcott,
Volker Heesen, Ged Kitchener et al.











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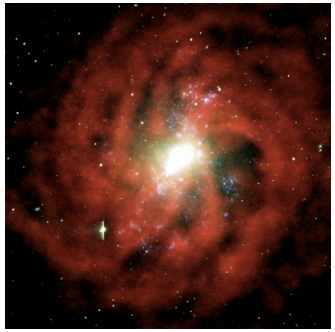
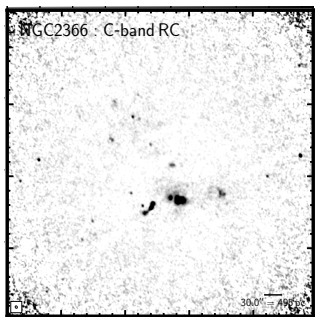
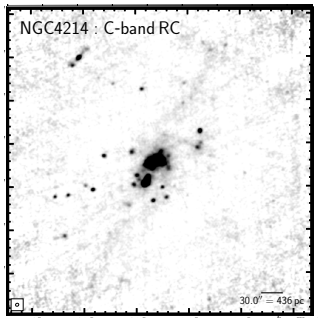
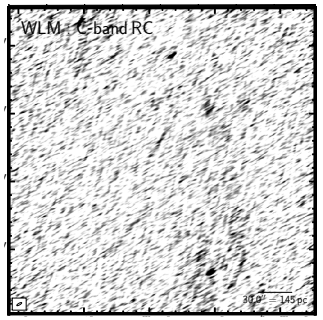


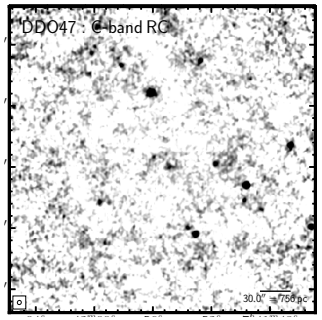

Integrated The ~~Resolved~~ Radio Continuum vs. Star Formation Rate in Nearby Dwarf Galaxies

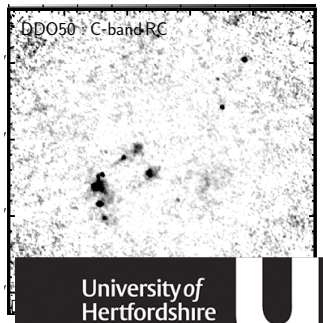
Luke Hindson, Elias Brinks, Jonathan Westcott,
Volker Heesen, Ged Kitchener et al.











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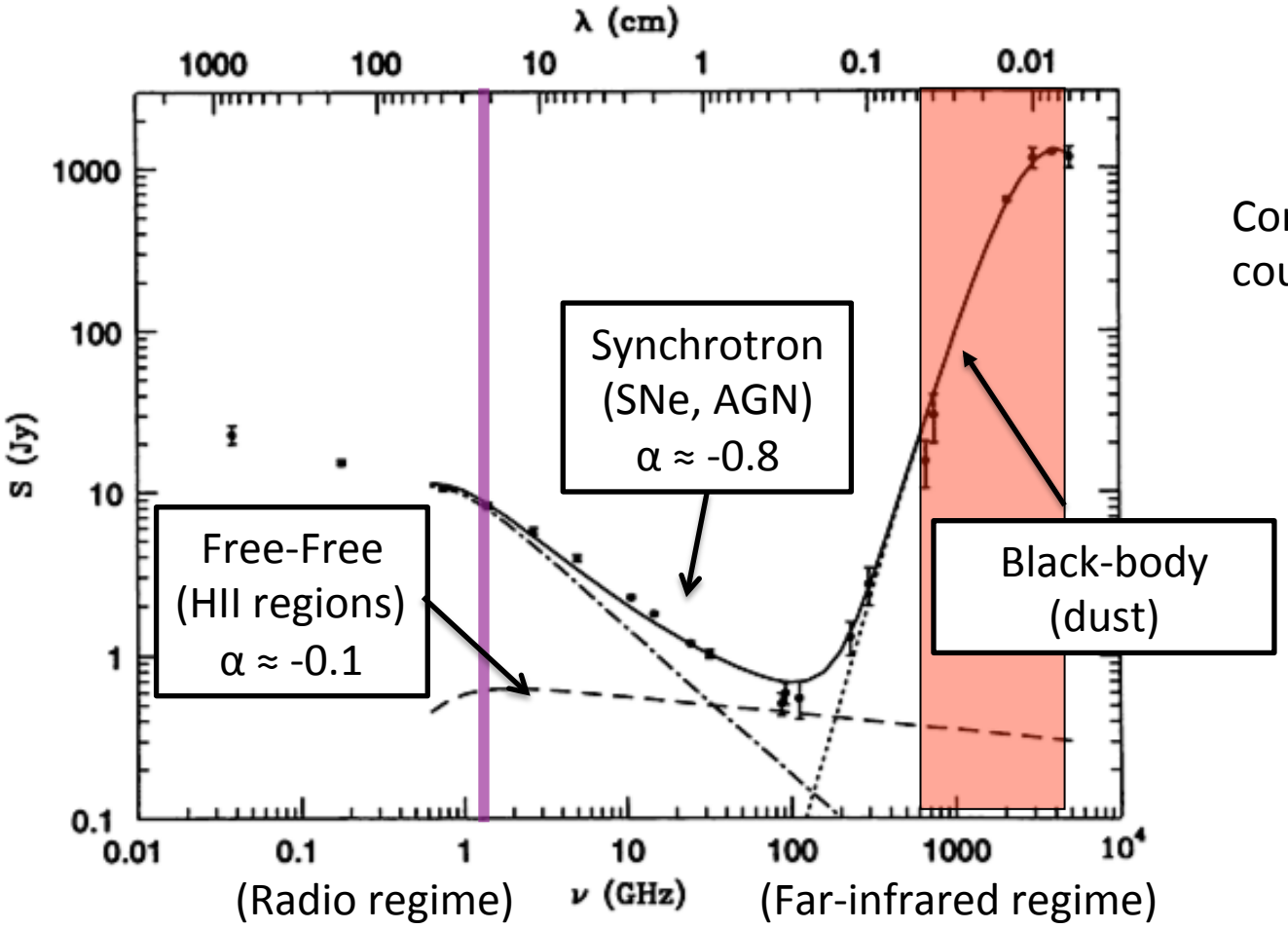
Continuum Emission in Galaxies

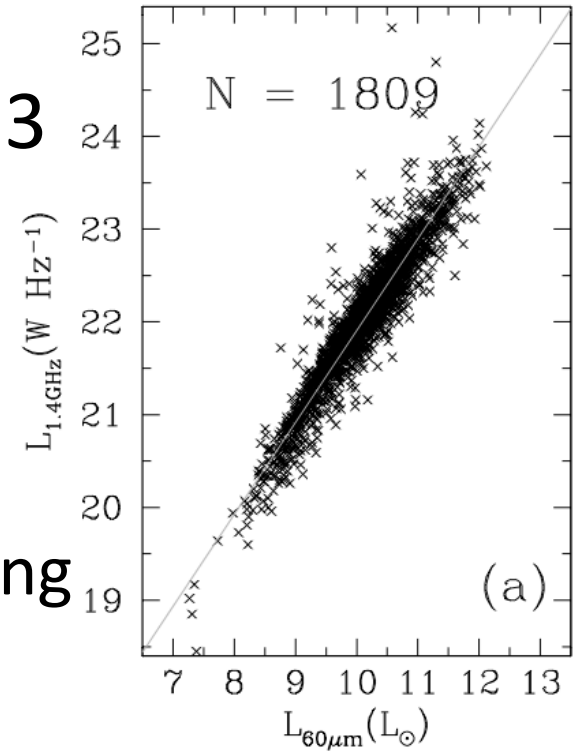


Condon plot count: 5

Condon 1992: The observed radio/FIR spectrum of M82 (Klein et al. 1988, Carlstrom & Kronenberg 1991)

RC—IR Relationship

- Holds over 5 orders of magnitude with only 0.2 dex scatter
- Holds out to a redshift of at least 3
- Calorimeter model
- The conspiracy
  - At low luminosity neither the IR or radio accurately trace the SFR leading



Yun et al. (2001): 60μm against 1.4GHz luminosity

Yun plot count: 2

The Sample

- Local Irregulars That Trace Luminosity Extremes, The HI Nearby Galaxy Survey
  - LITTLE THINGS (what an acronym)
- 40 dwarf irregular and Blue Compact Dwarf galaxies
- $0.8 < D[\mathrm{Mpc}] < 10.3$
- Extensive multi-wavelength data
  - FIR, UV, MIR, Optical (Hα)
- Low mass, low metallicity, early galaxy analogue and a test of the calorimeter model

Observations

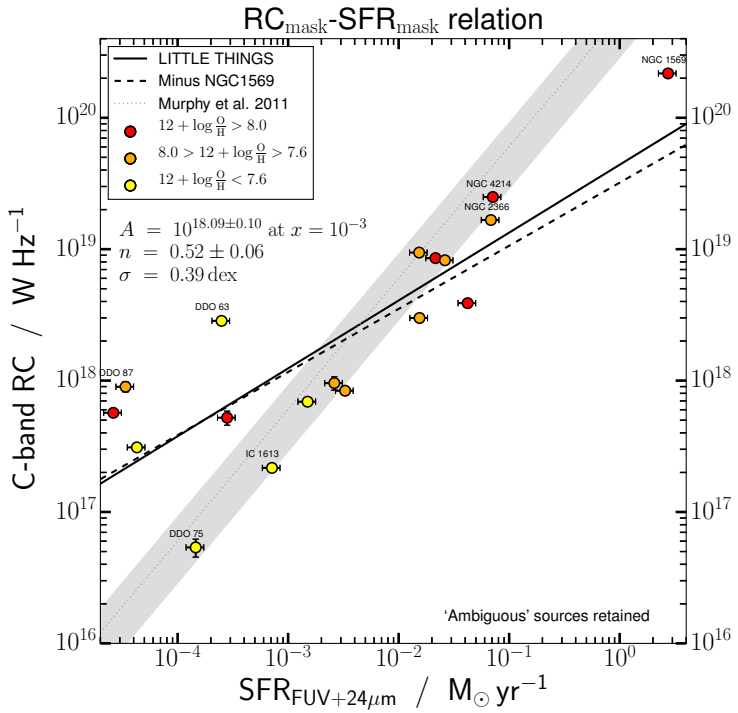
- VLA C-band (4—8GHz)
- 40 hours in C-configuration
- Resolution 3—8”
- Sensitivity 3—15μJy beam^{-1}
- 22 detections, 13 of which are new

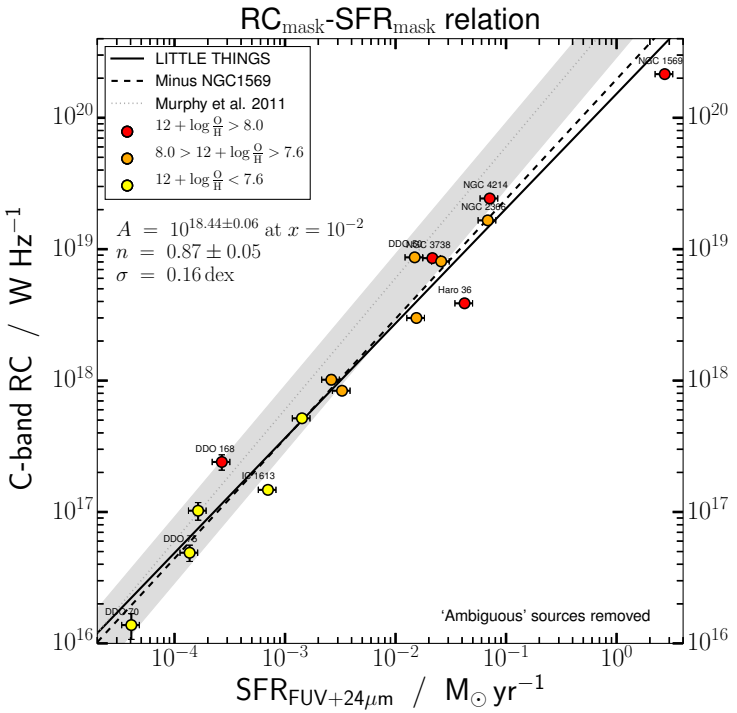
Analysis

- Remove background sources
- Define masks
- Estimate SFR
- Separate RC components
- Investigate the RC—SFR and RC—FIR relation
- Magnetic Fields

Removing Background Sources

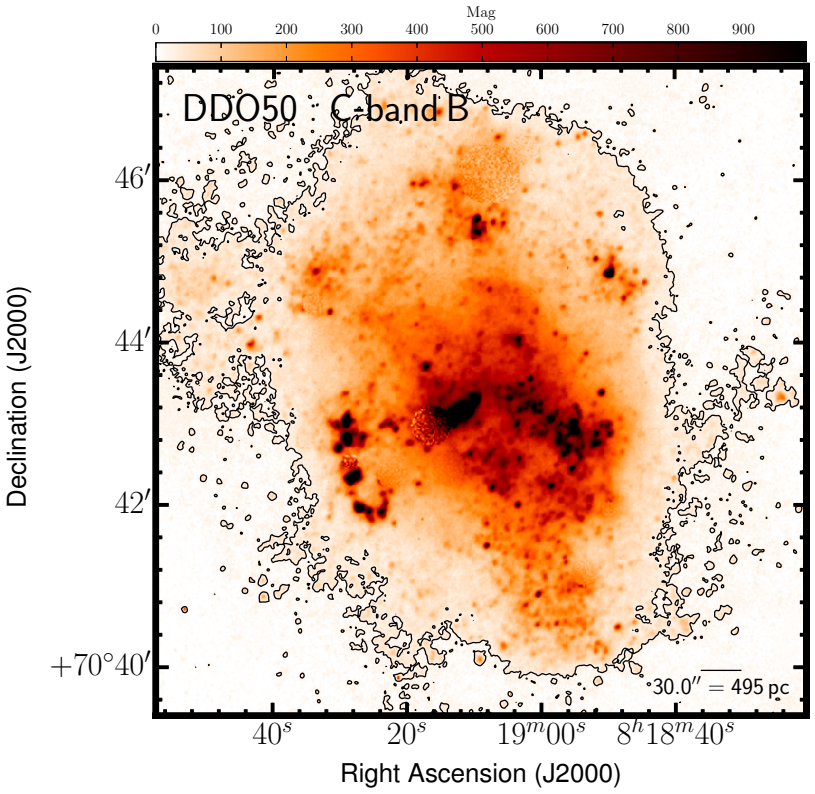
- Significant issue in these faint galaxies
- Identify through cross matching with NED and proximity of RC emission to Hα

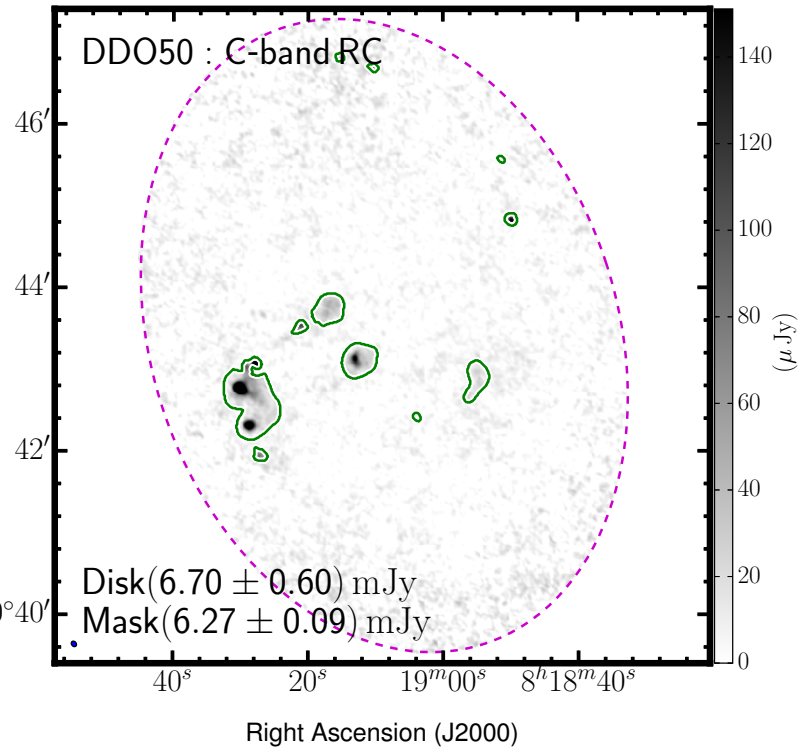




Masks

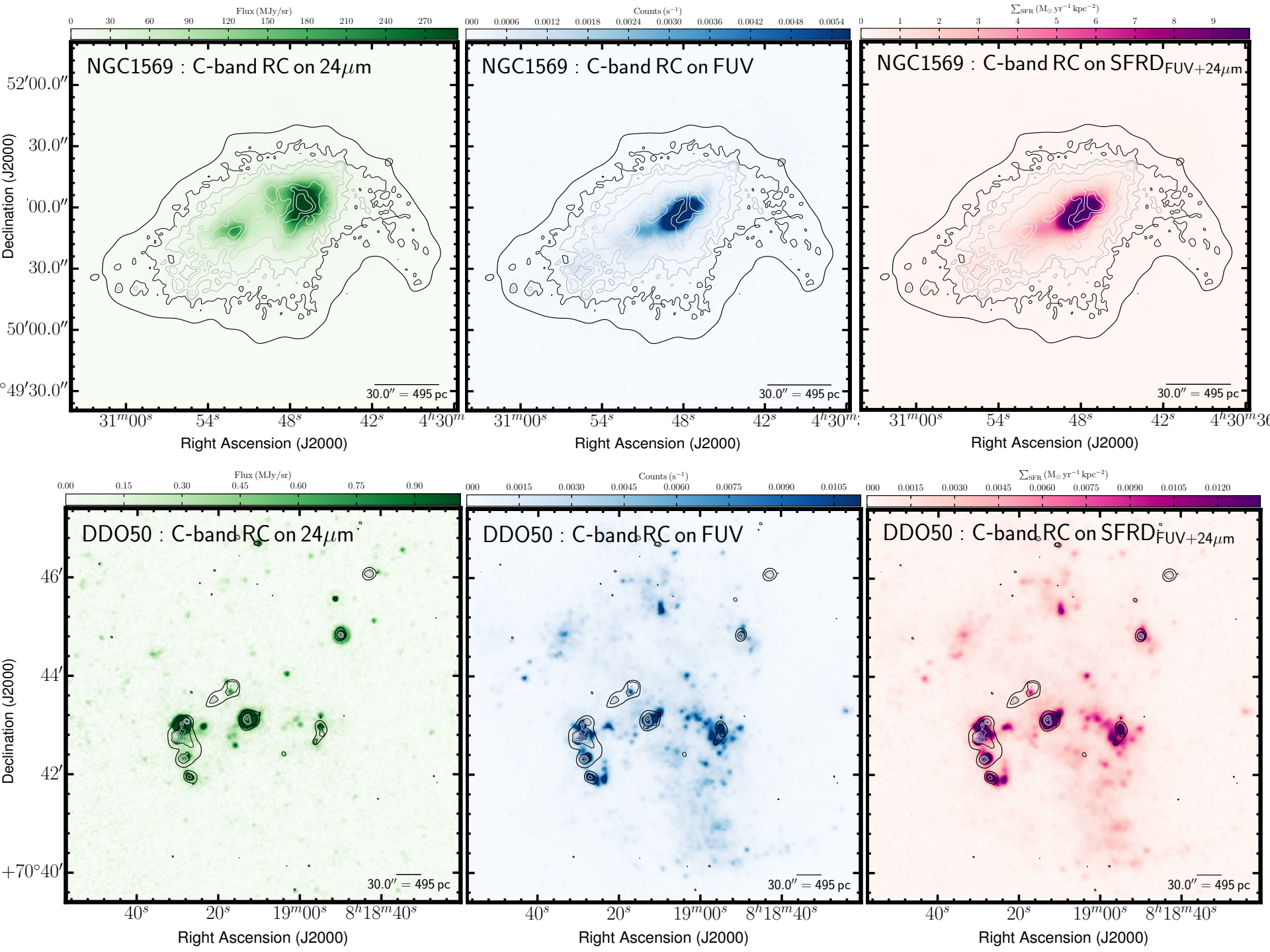
- Previous studies tend to either focus on unresolved observations or on bright galaxies
- RC emission in dwarfs is faint and patchy





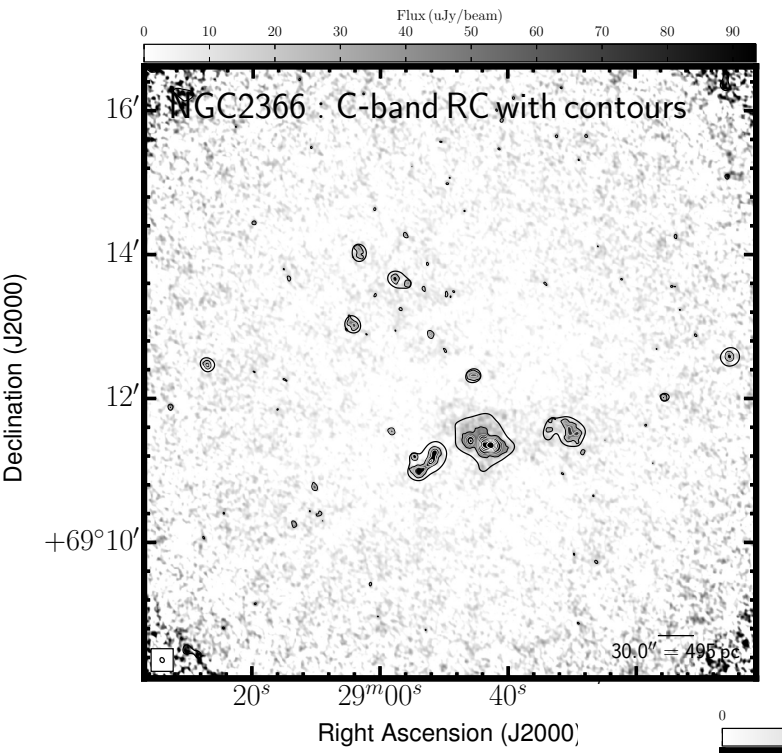
The SFR

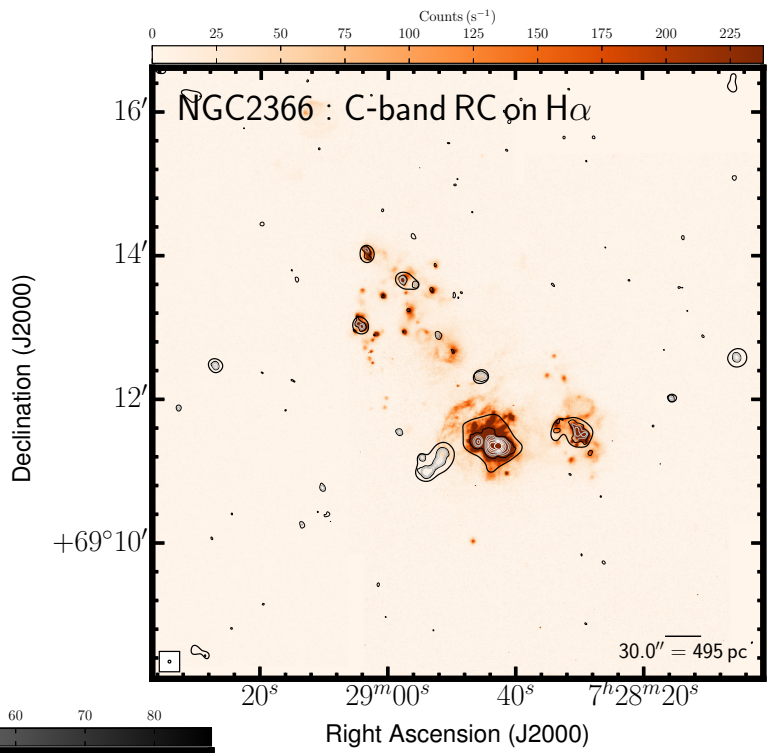
- Use combination of 24μm + FUV
  - Leroy et al. 2012
- The 24μm corrects the FUV for internal extinction
- Some uncertainty
  - Some MIR generated by older stars
- Issues regarding low star formation rate
  - Stochastic, not fully sampled IMF etc.

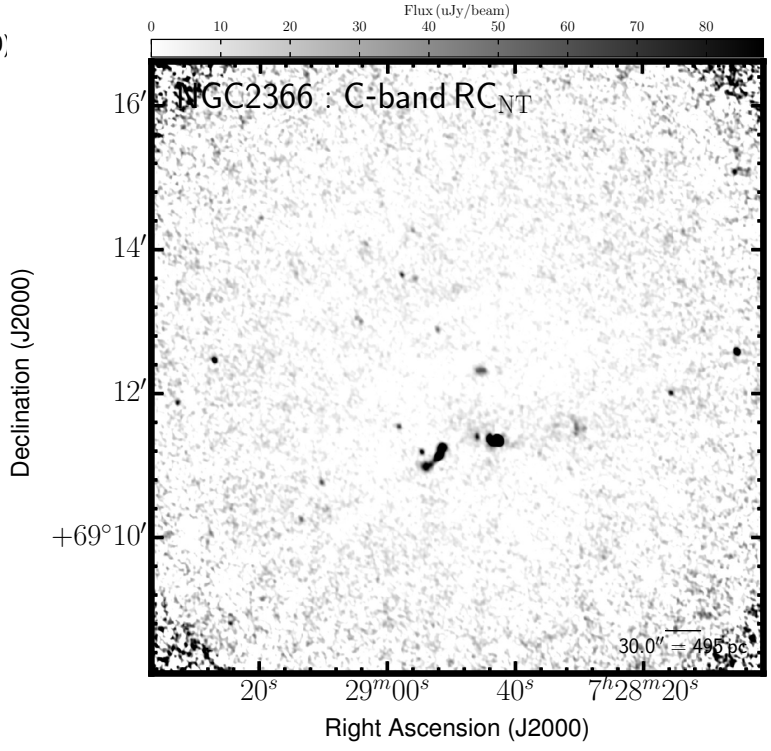

Flux (MJy/sr)
0 30 60 90 120 150 180 210 240 270
NGC1569 : C-band RC on 24μm
Counts (s^{-1})
000 0.0006 0.0012 0.0018 0.0024 0.0030 0.0036 0.0042 0.0048 0.0054
NGC1569 : C-band RC on FUV
$\sum_{SFR}$ (M$_\odot$ yr^{-1} kpc^{-2})
0 1 2 3 4 5 6 7 8 9
NGC1569 : C-band RC on SFRD$_{FUV+24\mu m}$
52′00.0″
30.0″
00.0″
30.0″
50′00.0″
°49′30.0″
Declination (J2000)
30.0″ = 495 pc
31^{m}00^s 54^s 48^s 42^s 4^{h}30^m
Right Ascension (J2000)
Flux (MJy/sr)
0.00 0.15 0.30 0.45 0.60 0.75 0.90
DDO50 : C-band RC on 24μm
Counts (s^{-1})
000 0.0015 0.0030 0.0045 0.0060 0.0075 0.0090 0.0105
DDO50 : C-band RC on FUV
$\sum_{SFR}$ (M$_\odot$ yr^{-1} kpc^{-2})
000 0.0015 0.0030 0.0045 0.0060 0.0075 0.0090 0.0105 0.0120
DDO50 : C-band RC on SFRD$_{FUV+24\mu m}$
46′
44′
42′
+70°40′
Declination (J2000)
30.0″ = 495 pc
40^s 20^s 19^{m}00^s 8^{h}18^{m}40^s
Right Ascension (J2000)

Separating the Radio Continuum

- Hα and RC_{Th} both originate in the hot (10^4K) plasma within HII regions
- Results in a tight spatial correlation that can be used to estimate the RC_{Th} emission
  - Deeg et al. 1997, Murphy et al. 2011
- The RC_{Th} can then be subtracted from the total RC to give the RC_{Nth}
- We do not correct the Hα for internal extinction
- A different Bayesian approach requires numerous samples of the radio SED (see Jonathans talk)

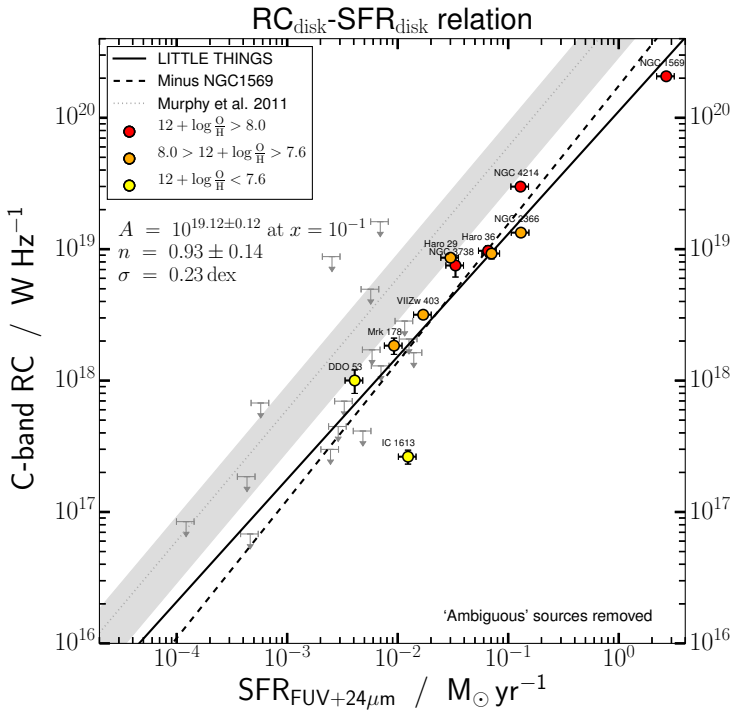

Flux (uJy/beam)
0 10 20 30 40 50 60 70 80 90
NGC2366 : C-band RC with contours
16′
14′
12′
+69°10′
Declination (J2000)
30.0″ = 495 pc
20s
29m00s
40s
Right Ascension (J2000)

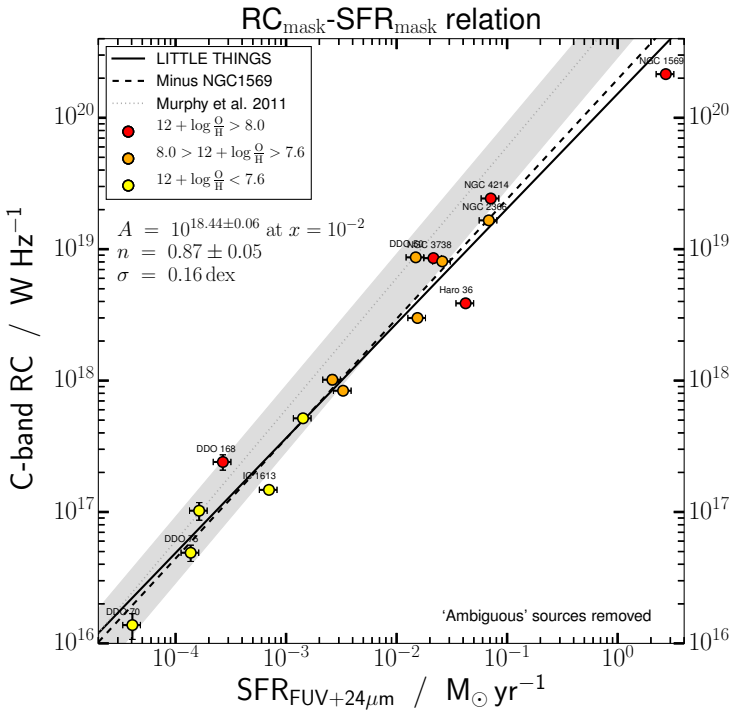

Counts (s−1)
0 25 50 75 100 125 150 175 200 225
NGC2366 : C-band RC on Hα
16′
14′
12′
+69°10′
Declination (J2000)
30.0″ = 495 pc
20s
29m00s
40s
7h28m20s
Right Ascension (J2000)

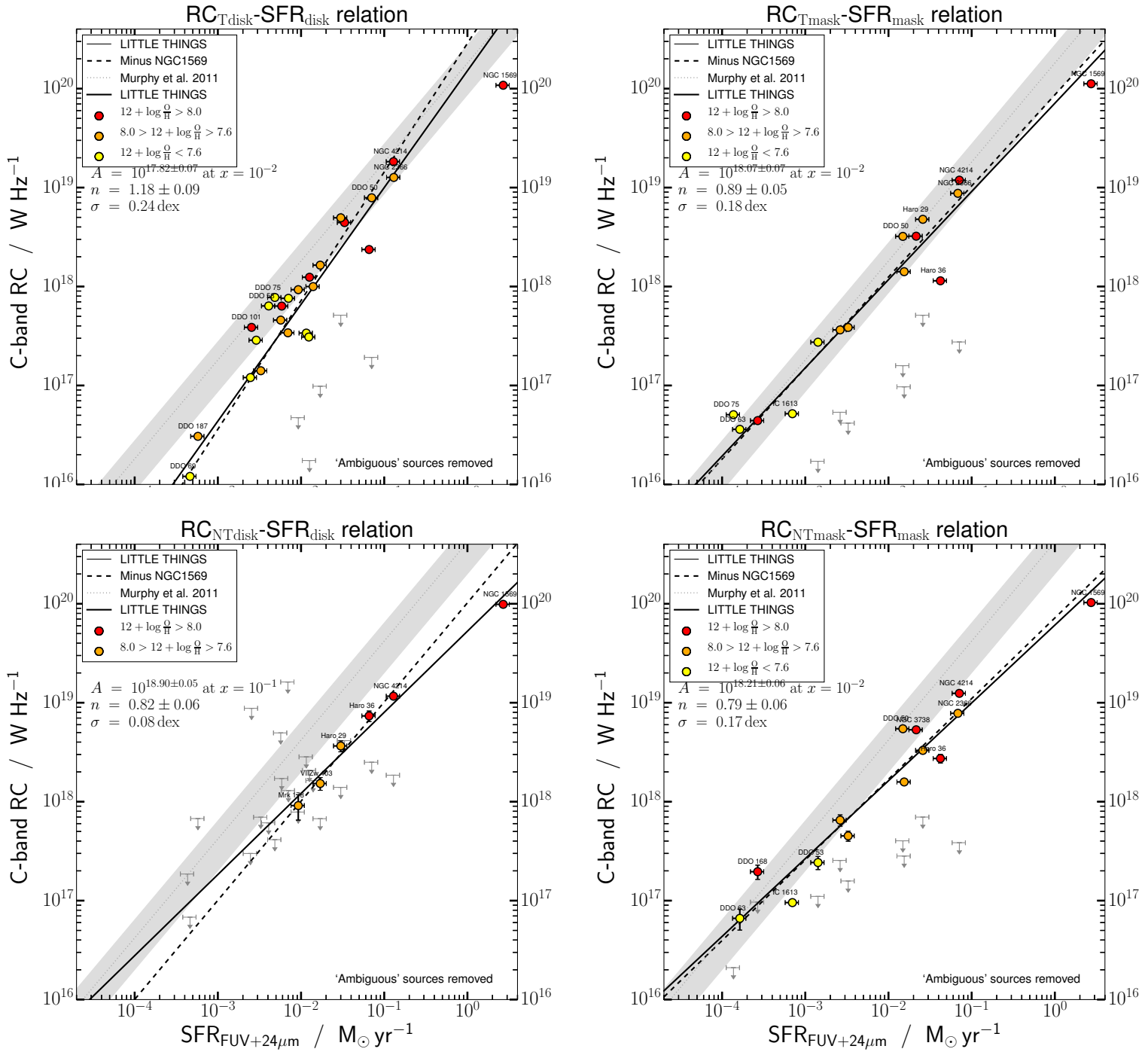

Flux (uJy/beam)
0 10 20 30 40 50 60 70 80
NGC2366 : C-band RCNT
16′
14′
12′
+69°10′
Declination (J2000)
30.0″ = 495 pc
20s
29m00s
40s
7h28m20s
Right Ascension (J2000)

The RC—SFR Relation

- Integrated over the RC-based mask results are consistent with theoretical
- Integrated over the disk-based mask show a suppression of the RC by a factor of 2—4

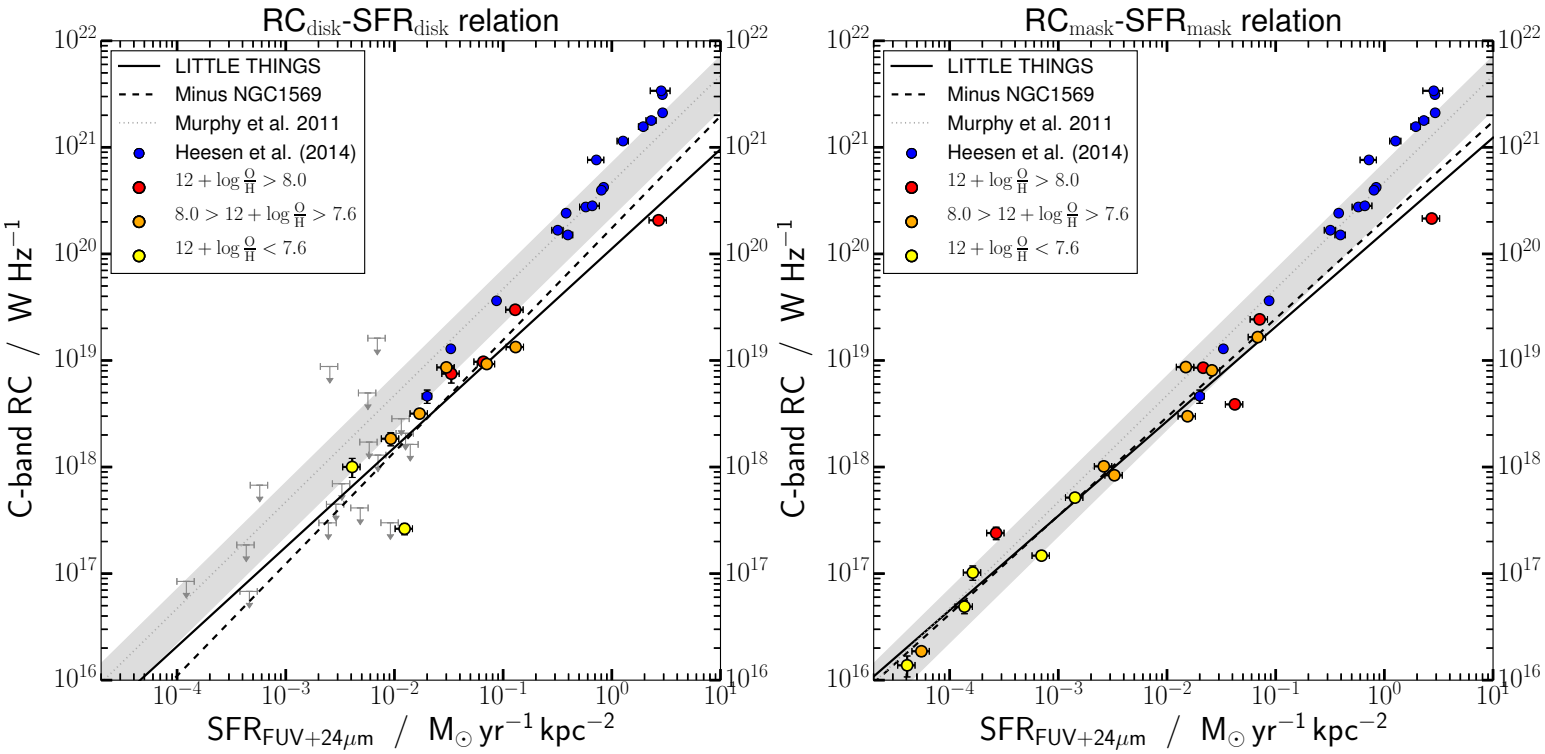





RC$_{\rm Tdisk}$-SFR$_{\rm disk}$ relation
RC$_{\rm Tmask}$-SFR$_{\rm mask}$ relation
RC$_{\rm NTdisk}$-SFR$_{\rm disk}$ relation
RC$_{\rm NTmask}$-SFR$_{\rm mask}$ relation
LITTLE THINGS
Minus NGC1569
Murphy et al. 2011
LITTLE THINGS
$12+\log\frac{\rm O}{\rm H}>8.0$
$8.0>12+\log\frac{\rm O}{\rm H}>7.6$
$12+\log\frac{\rm O}{\rm H}<7.6$
$A = 10^{17.82\pm0.07}$ at $x=10^{-2}$
$n = 1.18\pm0.09$
$\sigma = 0.24$ dex
$A = 10^{18.07\pm0.07}$ at $x=10^{-2}$
$n = 0.89\pm0.05$
$\sigma = 0.18$ dex
$A = 10^{18.90\pm0.05}$ at $x=10^{-1}$
$n = 0.82\pm0.06$
$\sigma = 0.08$ dex
$A = 10^{18.21\pm0.06}$ at $x=10^{-2}$
$n = 0.79\pm0.06$
$\sigma = 0.17$ dex
'Ambiguous' sources removed
C-band RC / W Hz^{-1}
SFR$_{\rm FUV+24\mu m}$ / M$_\odot$ yr^{-1}
NGC 1569
NGC 4214
NGC 2366
DDO 50
Haro 29
Haro 36
DDO 75
DDO 53
DDO 101
DDO 187
DDO 69
DDO 168
IC 1613
NGC 3738
Mrk 71

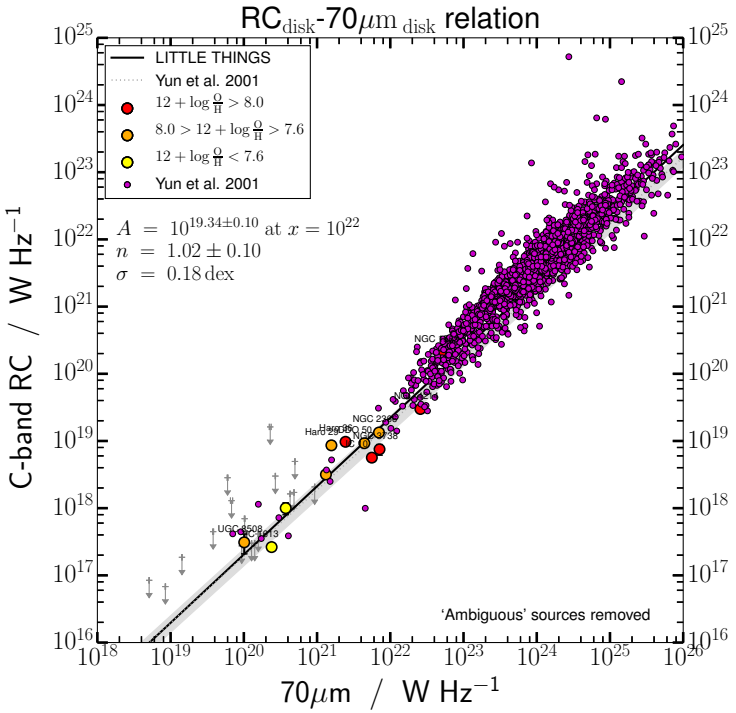
The RC—SFR Relation

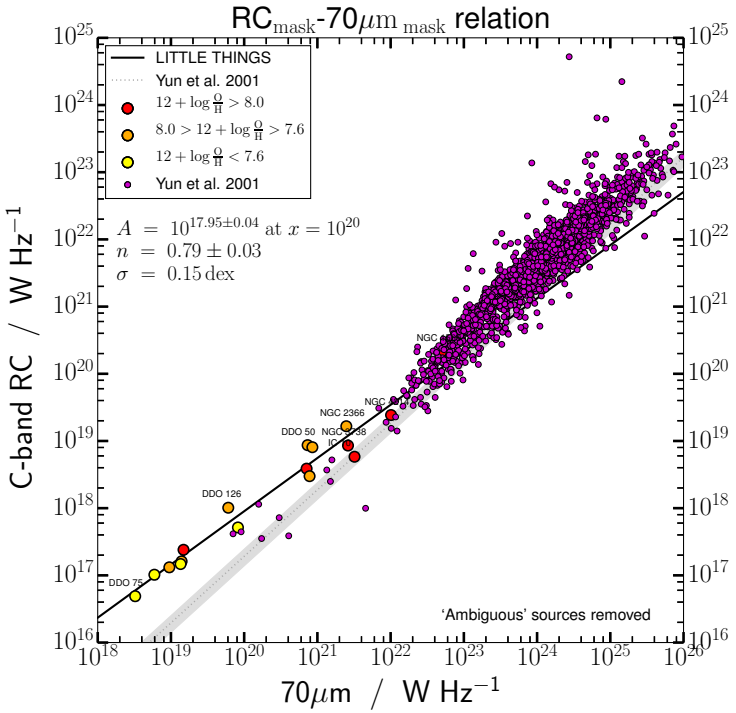
- Compared to the study of larger spirals by Heesen et al. (2014)

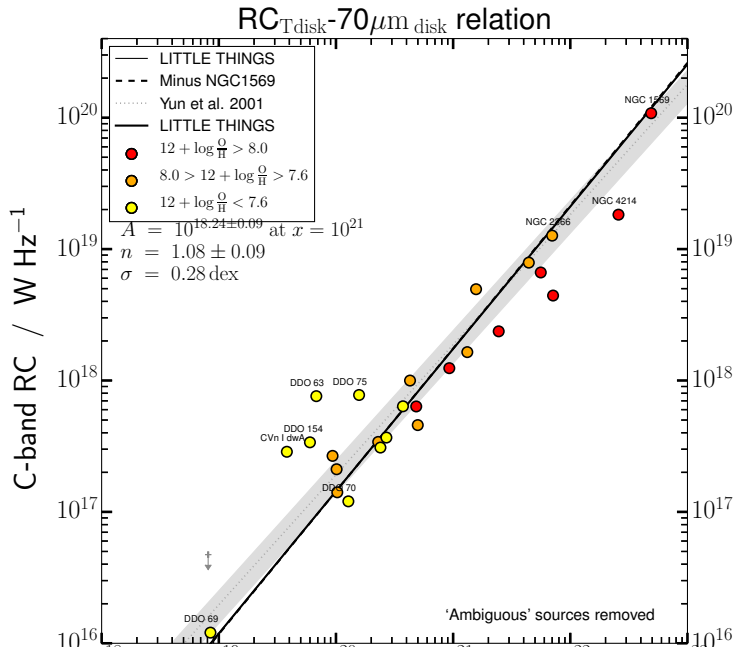


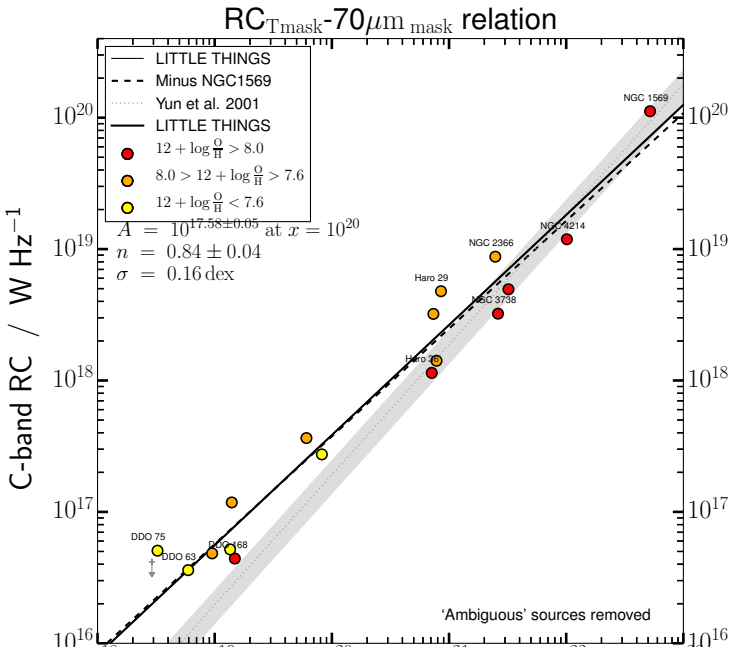
The RC—FIR Relation

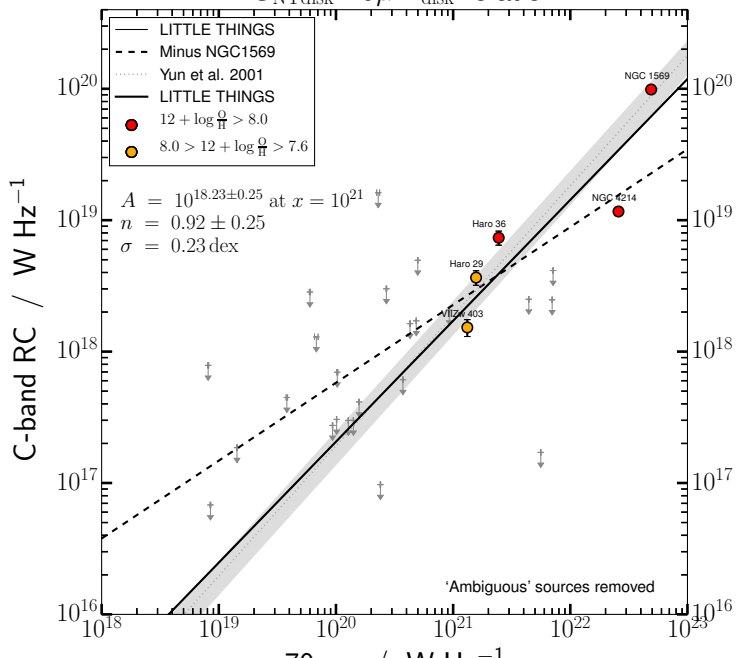
- RC excess when integrating over the RC mask
- Consistent when integrating over the disk

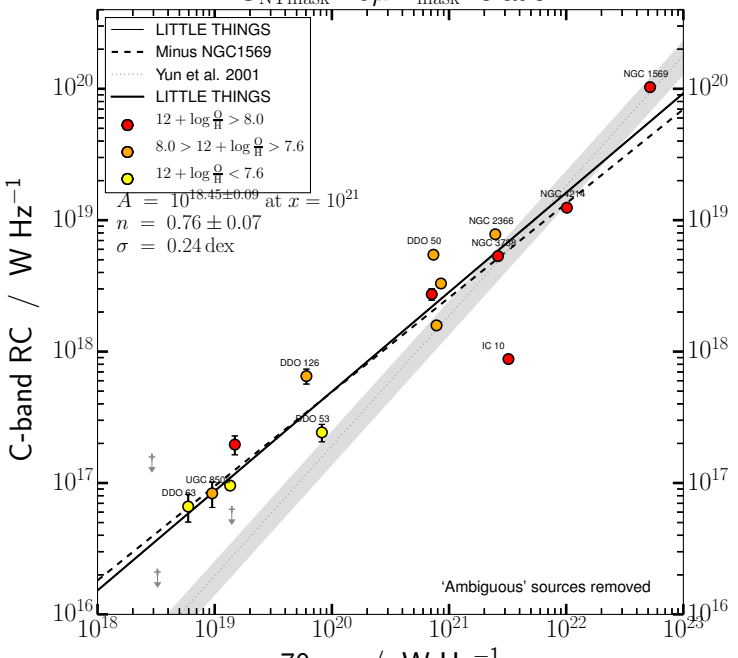





RC$_{\rm Tdisk}$-70μm $_{\rm disk}$ relation
LITTLE THINGS
Minus NGC1569
Yun et al. 2001
LITTLE THINGS
$12+\log\frac{\rm O}{\rm H}>8.0$
$8.0>12+\log\frac{\rm O}{\rm H}>7.6$
$12+\log\frac{\rm O}{\rm H}<7.6$
$A = 10^{18.24\pm0.09}$ at $x=10^{21}$
$n = 1.08\pm0.09$
$\sigma = 0.28$ dex
'Ambiguous' sources removed
C-band RC / W Hz^{-1}
NGC 1569
NGC 4214
NGC 2366
DDO 63
DDO 75
DDO 154
CVn I dwA
DDO 70
DDO 69

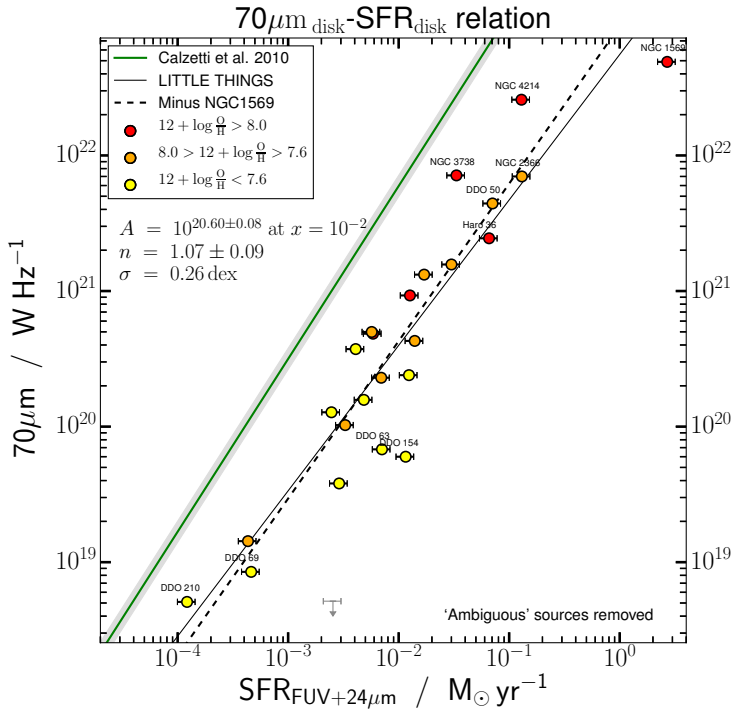

RC$_{\rm Tmask}$-70μm $_{\rm mask}$ relation
LITTLE THINGS
Minus NGC1569
Yun et al. 2001
LITTLE THINGS
$12+\log\frac{\rm O}{\rm H}>8.0$
$8.0>12+\log\frac{\rm O}{\rm H}>7.6$
$12+\log\frac{\rm O}{\rm H}<7.6$
$A = 10^{17.58\pm0.05}$ at $x=10^{20}$
$n = 0.84\pm0.04$
$\sigma = 0.16$ dex
'Ambiguous' sources removed
C-band RC / W Hz^{-1}
NGC 1569
NGC 4214
NGC 2366
Haro 29
NGC 3738
DDO 75
DDO 63
DDO 168

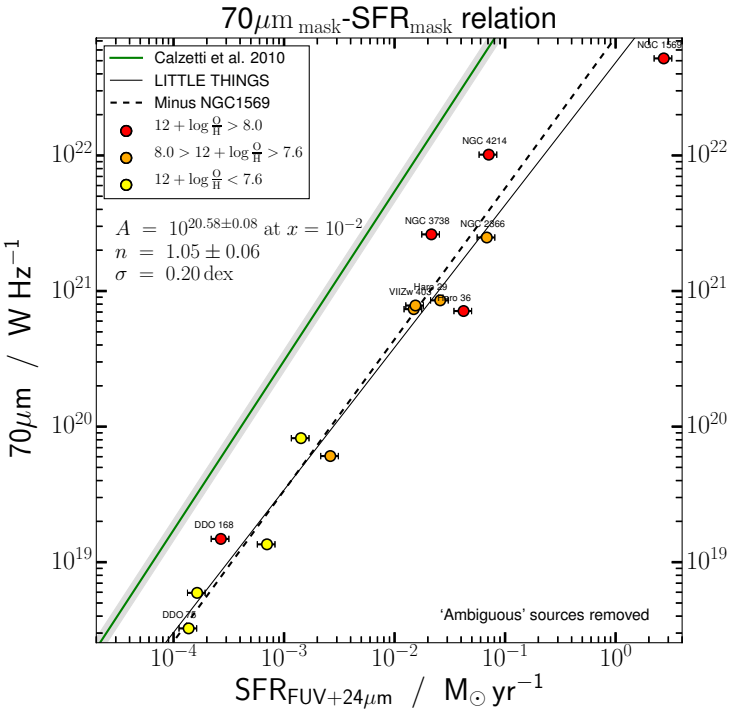

RC$_{\rm NTdisk}$-70μm $_{\rm disk}$ relation
LITTLE THINGS
Minus NGC1569
Yun et al. 2001
LITTLE THINGS
$12+\log\frac{\rm O}{\rm H}>8.0$
$8.0>12+\log\frac{\rm O}{\rm H}>7.6$
$A = 10^{18.23\pm0.25}$ at $x=10^{21}$
$n = 0.92\pm0.25$
$\sigma = 0.23$ dex
'Ambiguous' sources removed
C-band RC / W Hz^{-1}
70μm / W Hz^{-1}
NGC 1569
NGC 4214
Haro 36
Haro 29
VII Zw 403


RC$_{\rm NTmask}$-70μm $_{\rm mask}$ relation
LITTLE THINGS
Minus NGC1569
Yun et al. 2001
LITTLE THINGS
$12+\log\frac{\rm O}{\rm H}>8.0$
$8.0>12+\log\frac{\rm O}{\rm H}>7.6$
$12+\log\frac{\rm O}{\rm H}<7.6$
$A = 10^{18.45\pm0.09}$ at $x=10^{21}$
$n = 0.76\pm0.07$
$\sigma = 0.24$ dex
'Ambiguous' sources removed
C-band RC / W Hz^{-1}
70μm / W Hz^{-1}
NGC 1569
NGC 4214
NGC 2366
DDO 50
IC 10
DDO 126
DDO 53
UGC 8508
DDO 63

The FIR—SFR Relation

- Both the disk and RC masks integrated FIR underestimate the SFR compared to Calzetti et al. 2010





Magnetic Fields

- Assuming equipartition we can estimate the magnetic field strength
- Average of 6.0μG over disk mask and 12.7μG over RC mask
- Peaks towards regions of SF with values up to 30μG in NGC1569
- Consistent with larger spirals
  - 9.7μG in WSRT SINGS sample

Interpretation

- The RC is suppressed relative to the expected SFR over the disk
  - The RC_{Nth} is responsible
  - But the magnetic fields are strong so are CRes escaping?
- The FIR—SFR show the FIR underestimates the SFR in both masks
- The conspiracy continues
- More data obtained to improve S/N and allow radial, spectral, polarisation studies