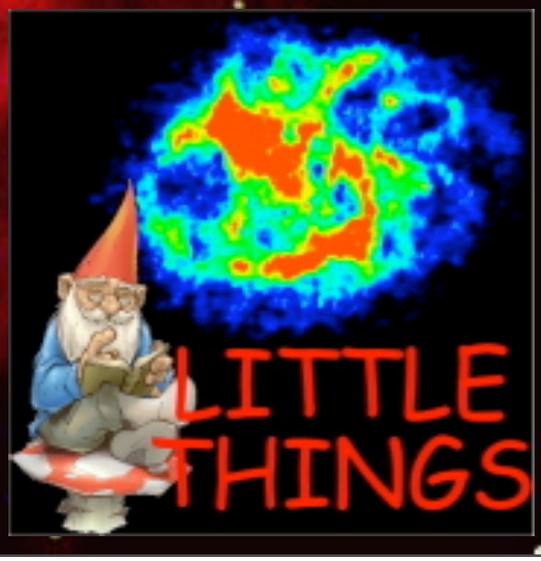
UNIVERSITY OF Southampton

The radio–FIR correlation in LITTLE THINGS dwarf galaxies

Volker Heesen
with contributions from
Ged Kitchener, Elias Brinks, Deirde Hunter and the LITTLE THINGS team

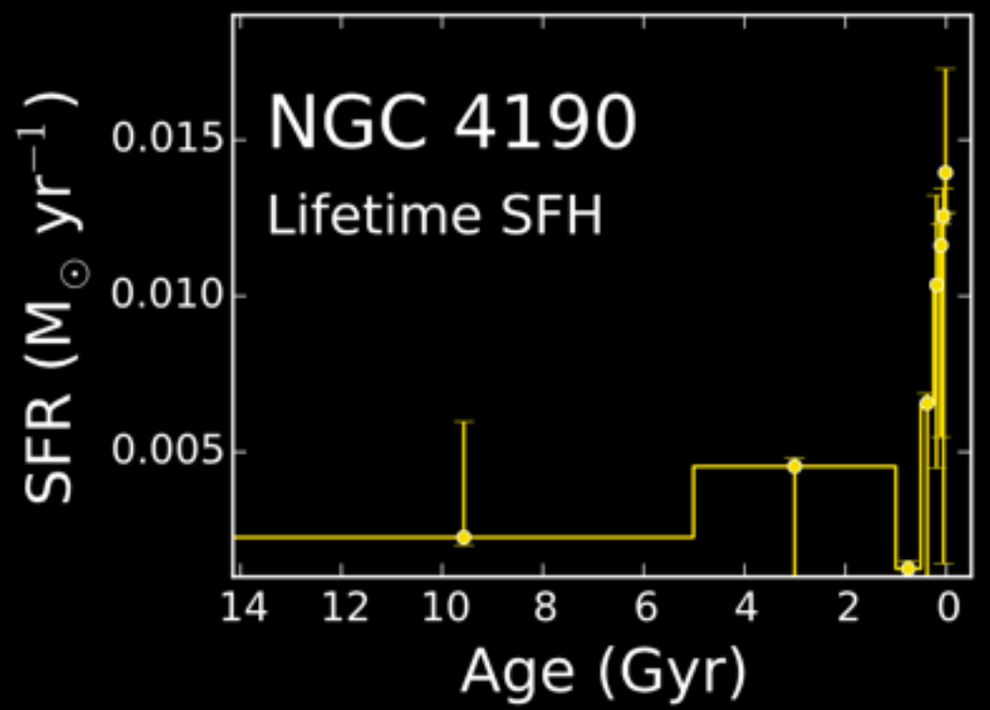


The BIG questions

- What regulates SF in small, gas-rich galaxies?
- What is the relative importance of sequential triggering?
- What is the role of turbulence for SF?
- What happens to the star formation process in the outer parts of disks?

Analoguoes to the "first galaxies"

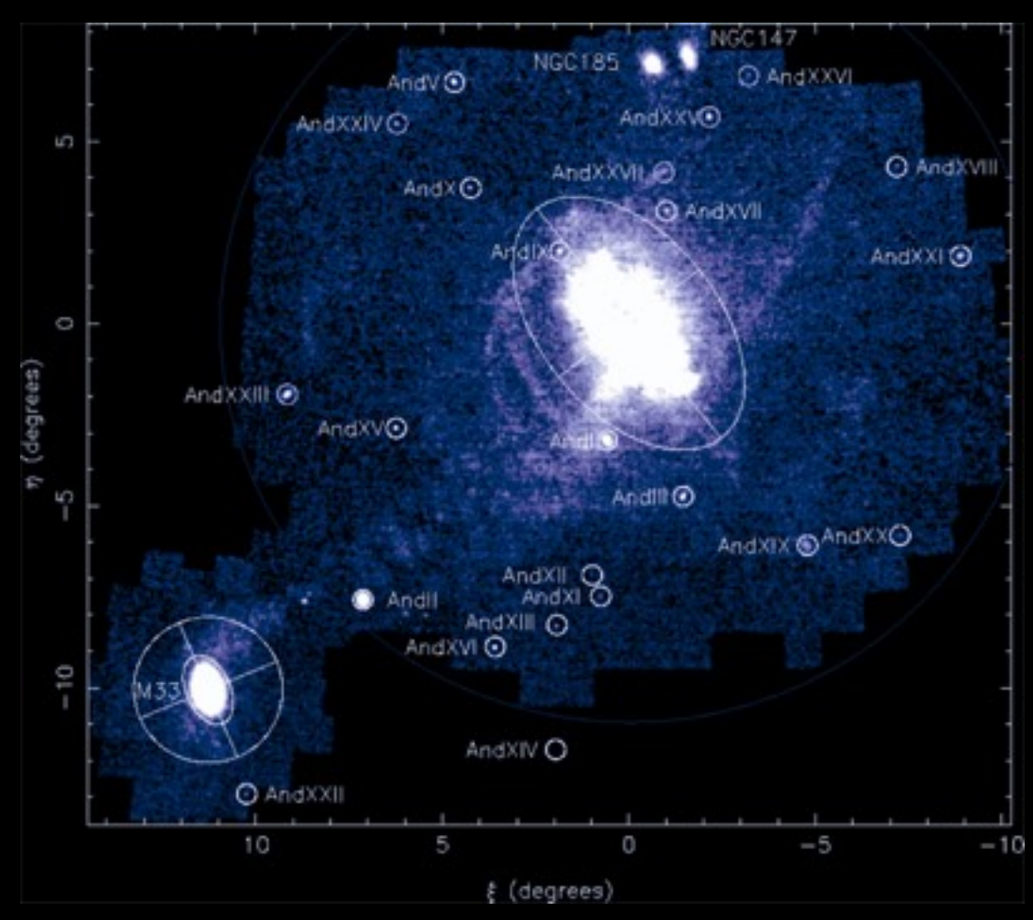
Burst-like SF history



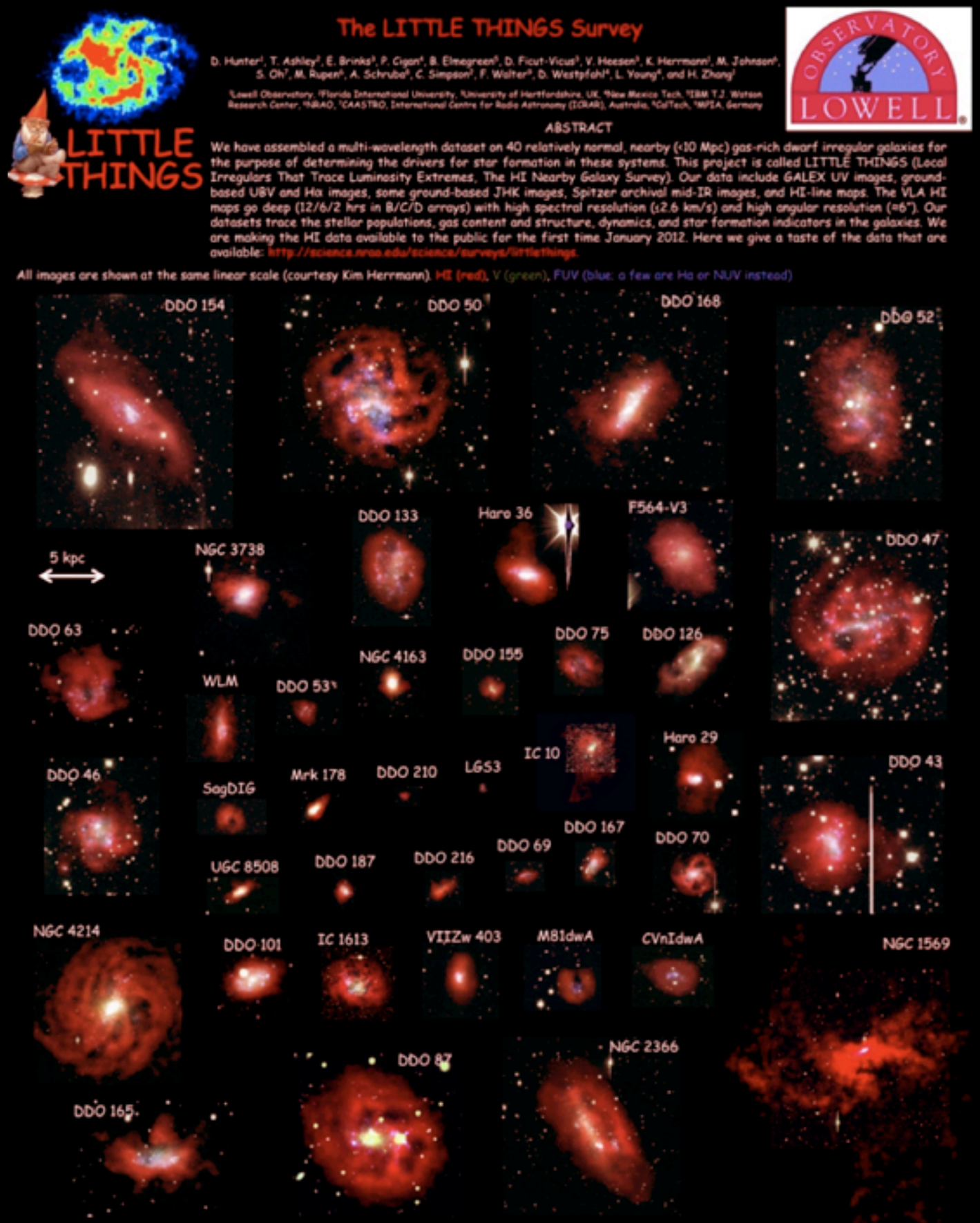
McQuinn et al. 2015

Stellar feedback: galactic winds

"Missing satellites" problem



Geraint Lewis (PAndAS)

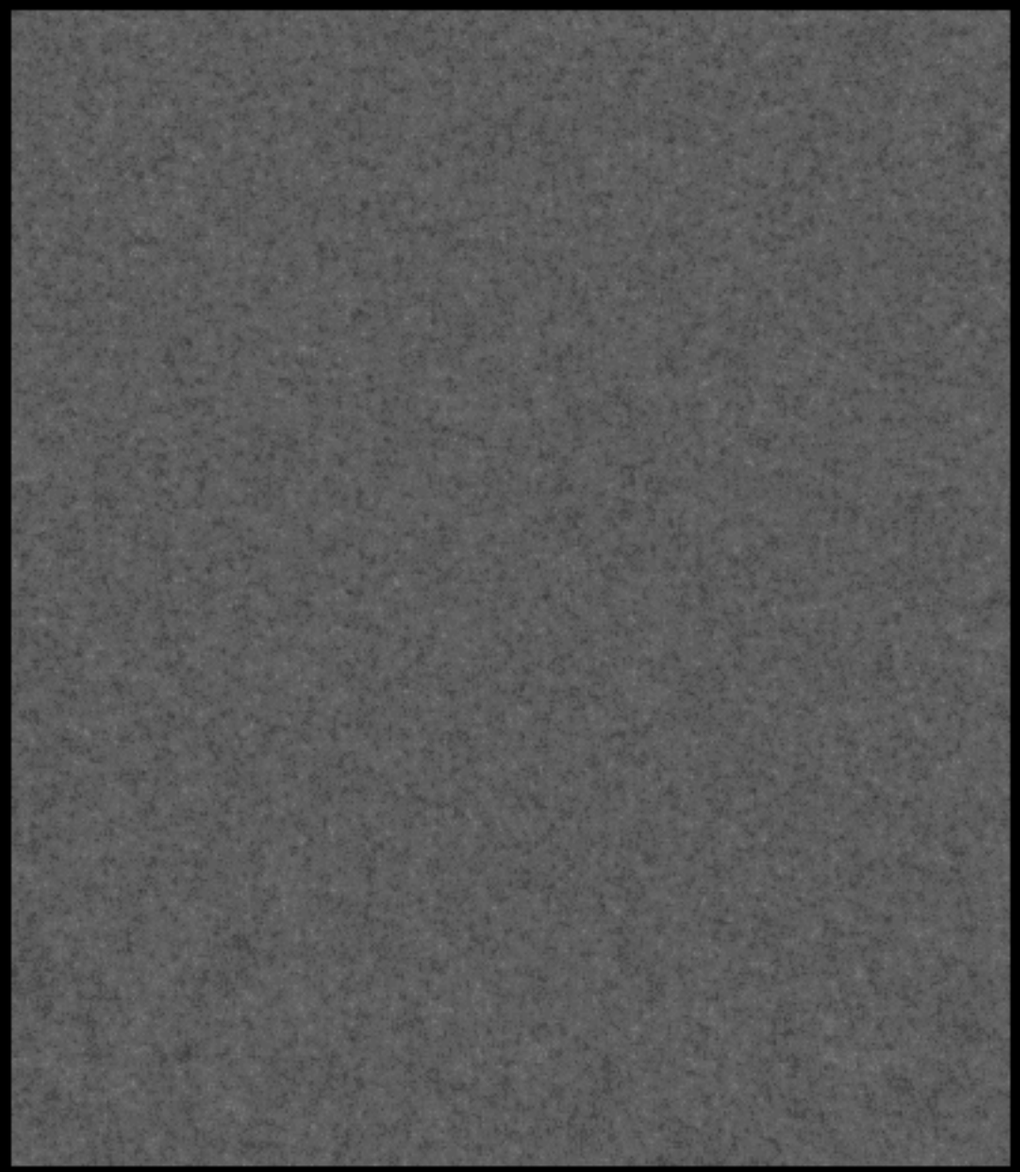


Local Irregulars That Trace Luminosity Extremes, The H I Nearby Galaxy Survey

- 41 irregulars
- 376 hr VLA time
- B, C, D-config
- 6–10" arcsec angular resolution
- 2.6 km s^{-1} velocity resolution

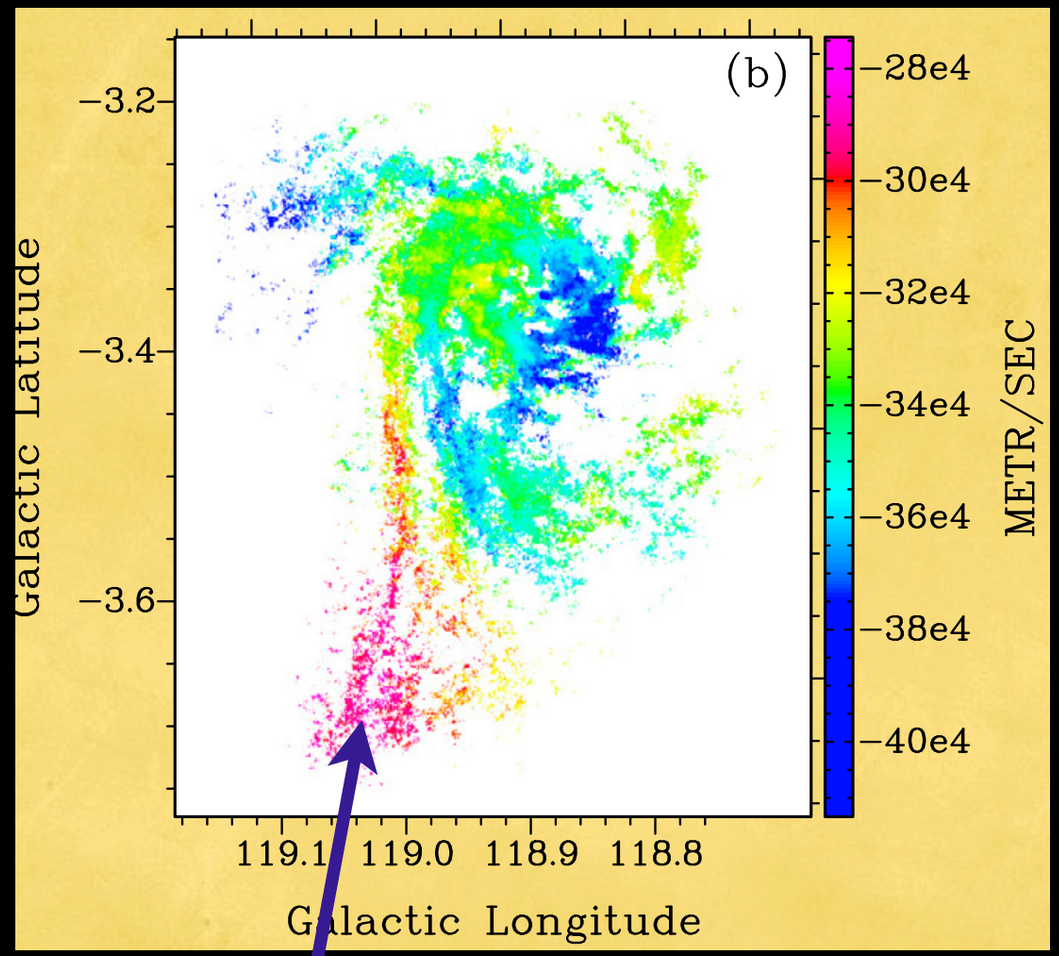
IC 10: infalling HI cloud

HI data cube



Hunter et al. 2012

HI velocity field

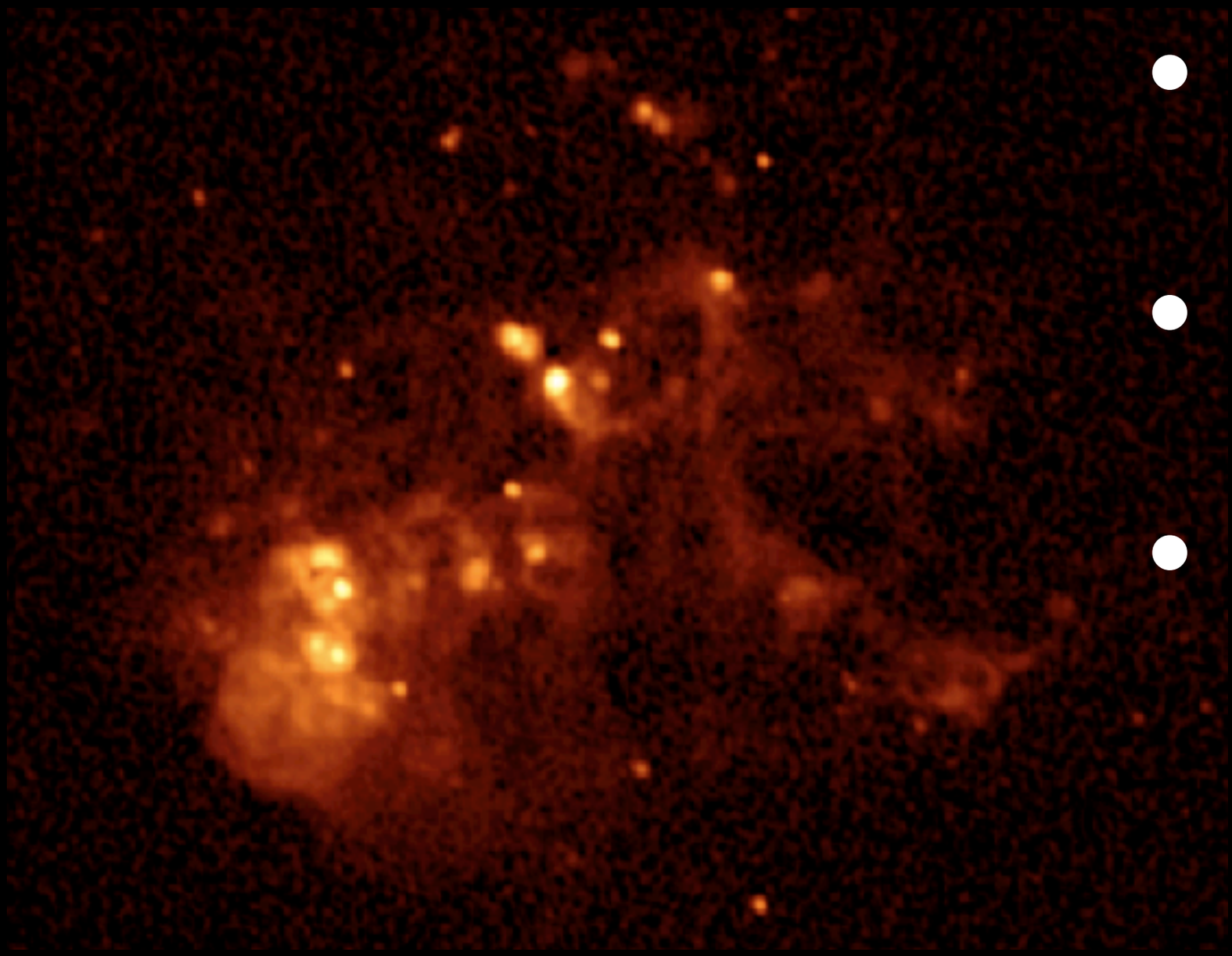


HI streamer
Infalling cloud

Ashley et al. 2014

VLA continuum survey

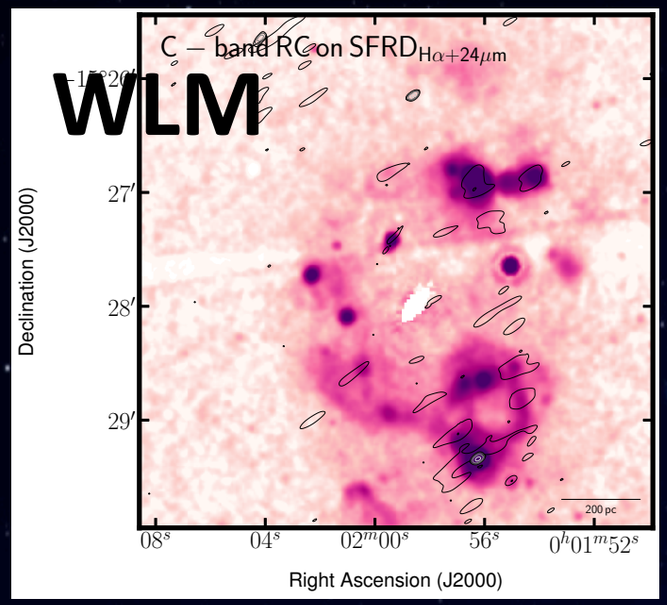
IC 10 6.2 GHz VLA + Effelsberg

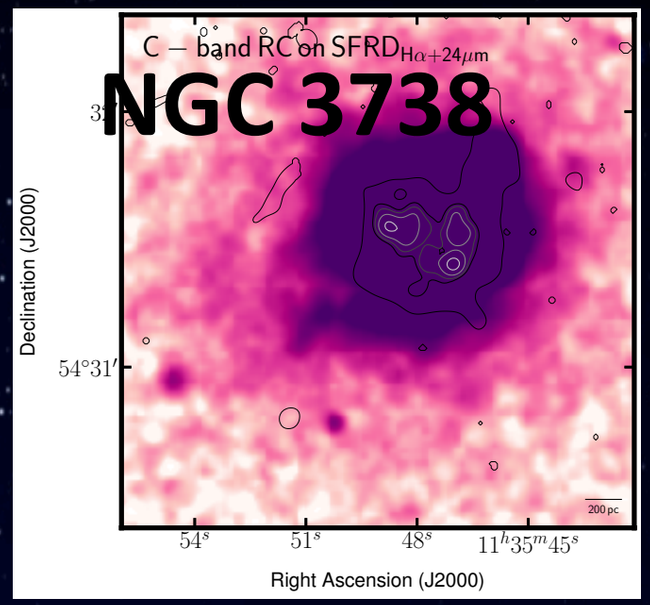


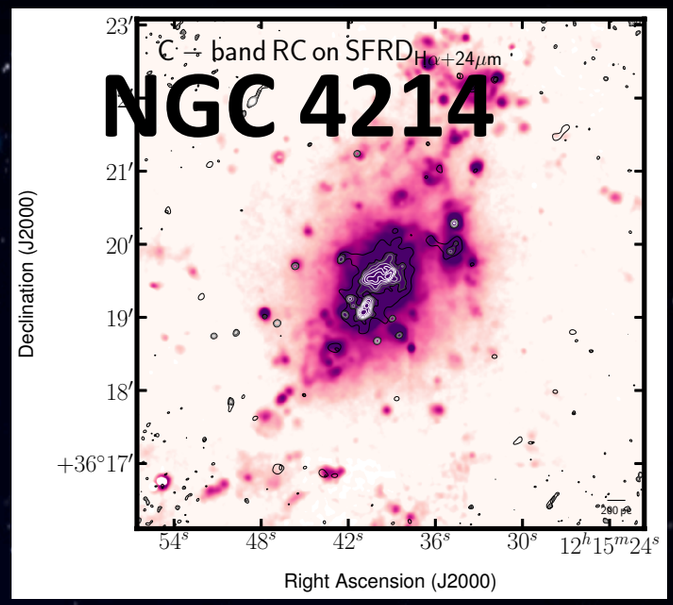
- 2010: IC10 + IC1613 (RSRO) VH11+,VH15+
- 2012: entire sample @6 cm Kitchener+, submitted
- 2014–now: subsample spectral index study 1–20 cm

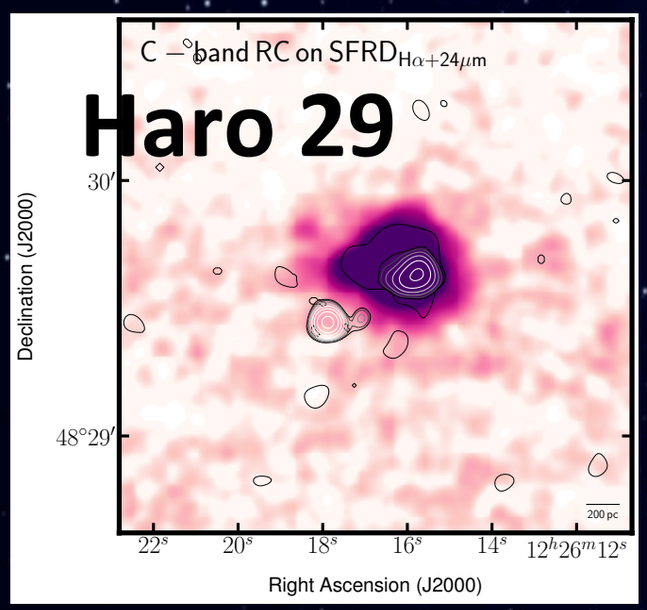
Motivation

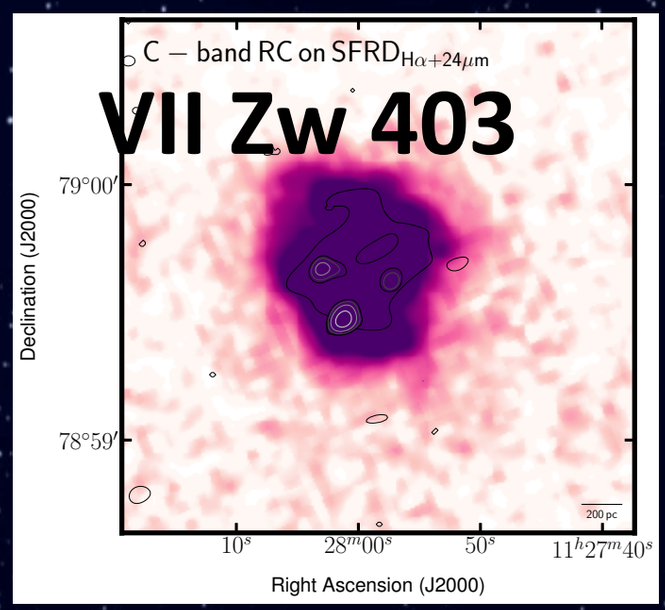
- Hardly anything known about RC in dwarfs
- Single-dish data are confusion dominated
- Interferometric data needed
- RC–FIR "conspiracy" Bell 2003, Lacki+10
  - CRe escape in galactic wind
  - Dust heating photons escape as well

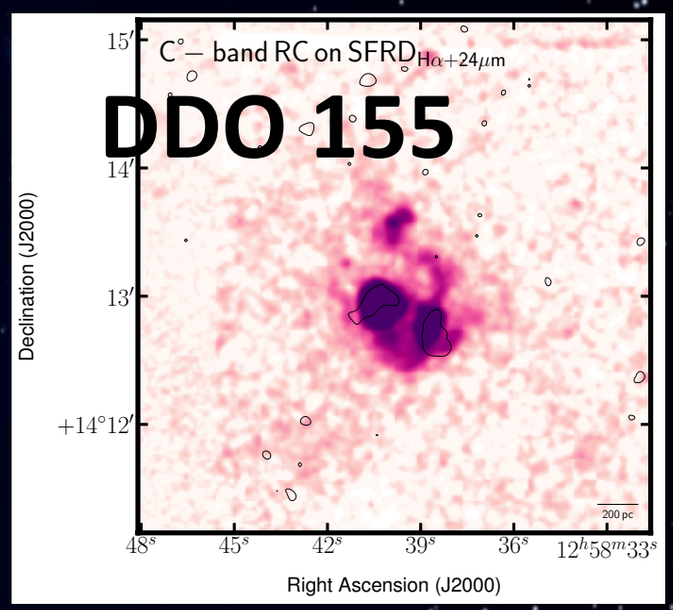

C − band RC on SFRD$_{H\alpha+24\mu m}$
WLM
Declination (J2000)
Right Ascension (J2000)
200 pc

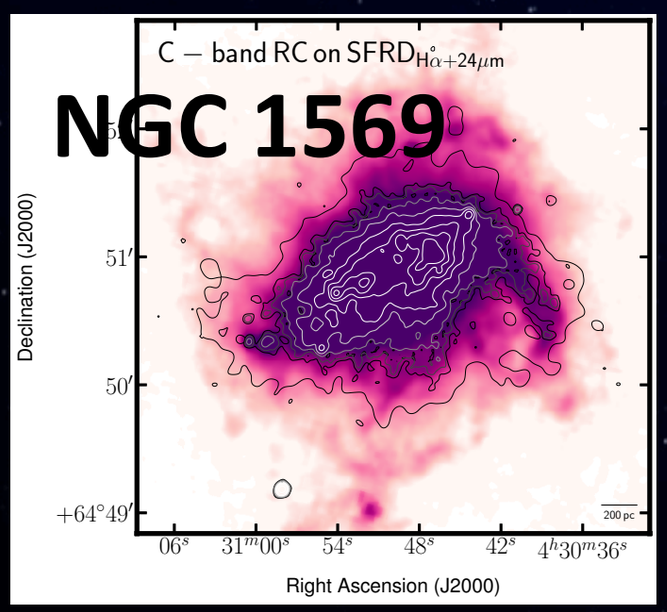

C − band RC on SFRD$_{H\alpha+24\mu m}$
NGC 3738
Declination (J2000)
Right Ascension (J2000)
200 pc

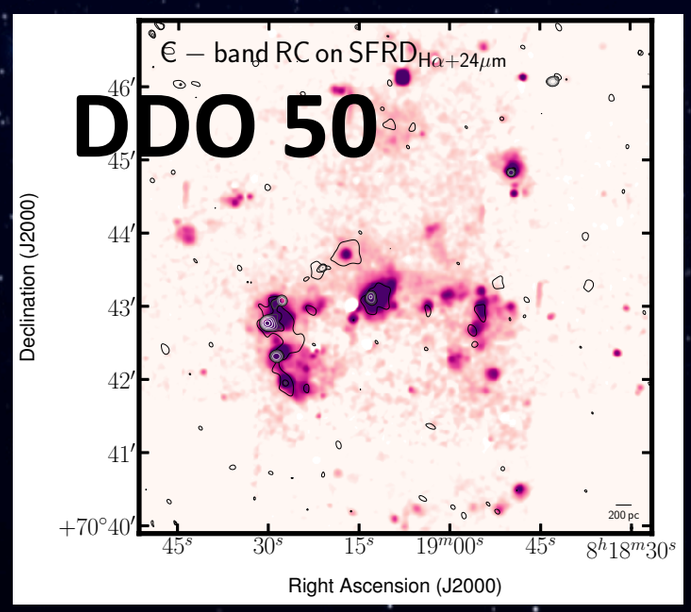

C − band RC on SFRD$_{H\alpha+24\mu m}$
NGC 4214
Declination (J2000)
Right Ascension (J2000)
200 pc

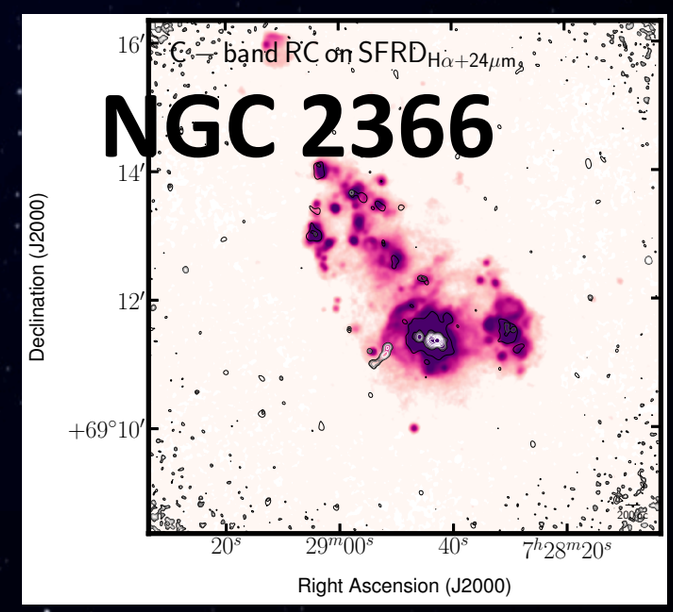

C − band RC on SFRD$_{H\alpha+24\mu m}$
Haro 29
Declination (J2000)
Right Ascension (J2000)
200 pc

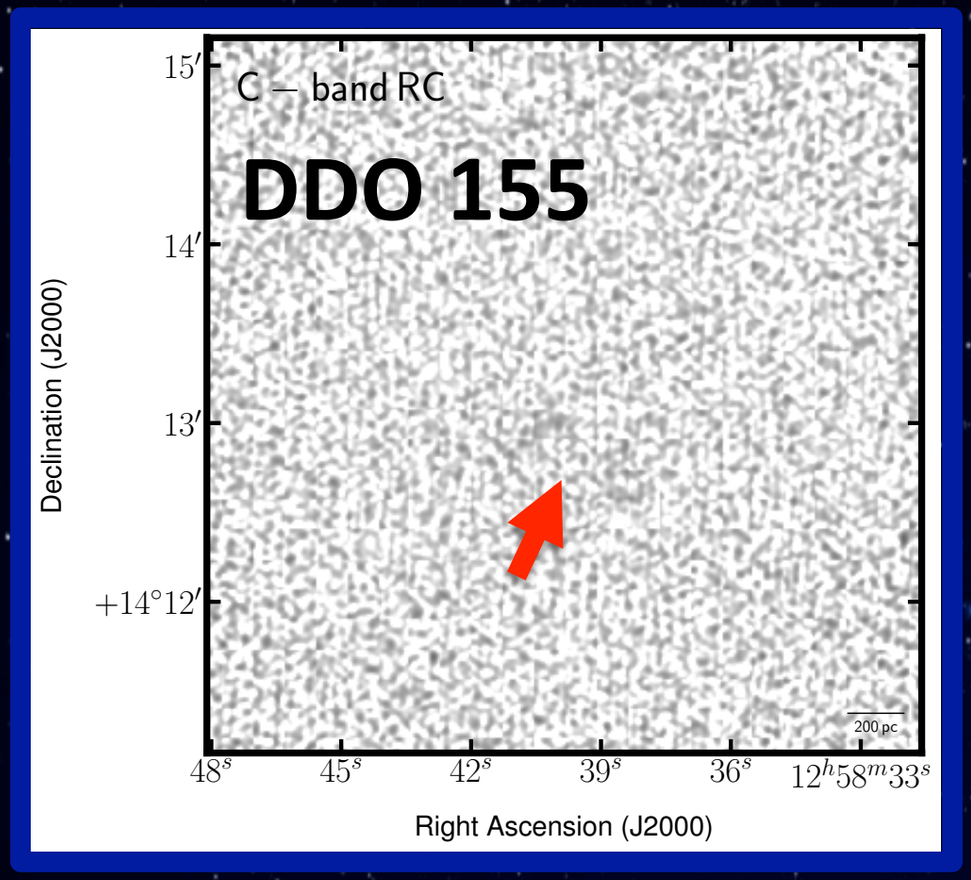

C − band RC on SFRD$_{H\alpha+24\mu m}$
VII Zw 403
Declination (J2000)
Right Ascension (J2000)
200 pc

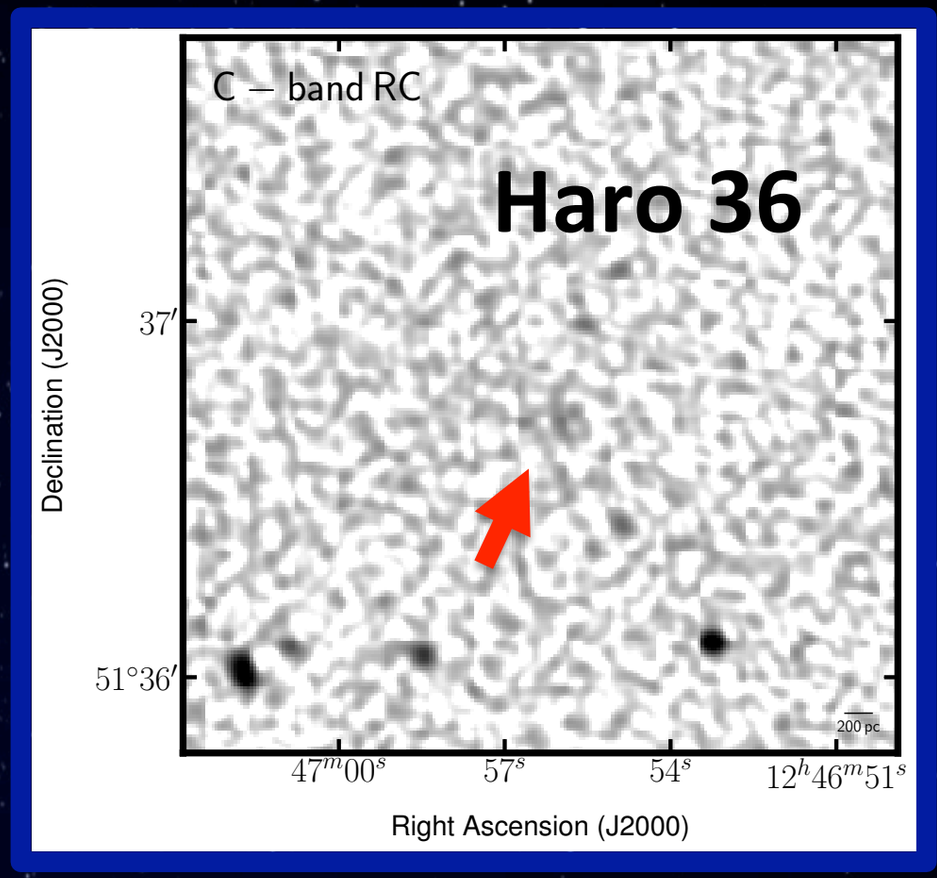

C − band RC on SFRD$_{H\alpha+24\mu m}$
DDO 155
Declination (J2000)
Right Ascension (J2000)
200 pc

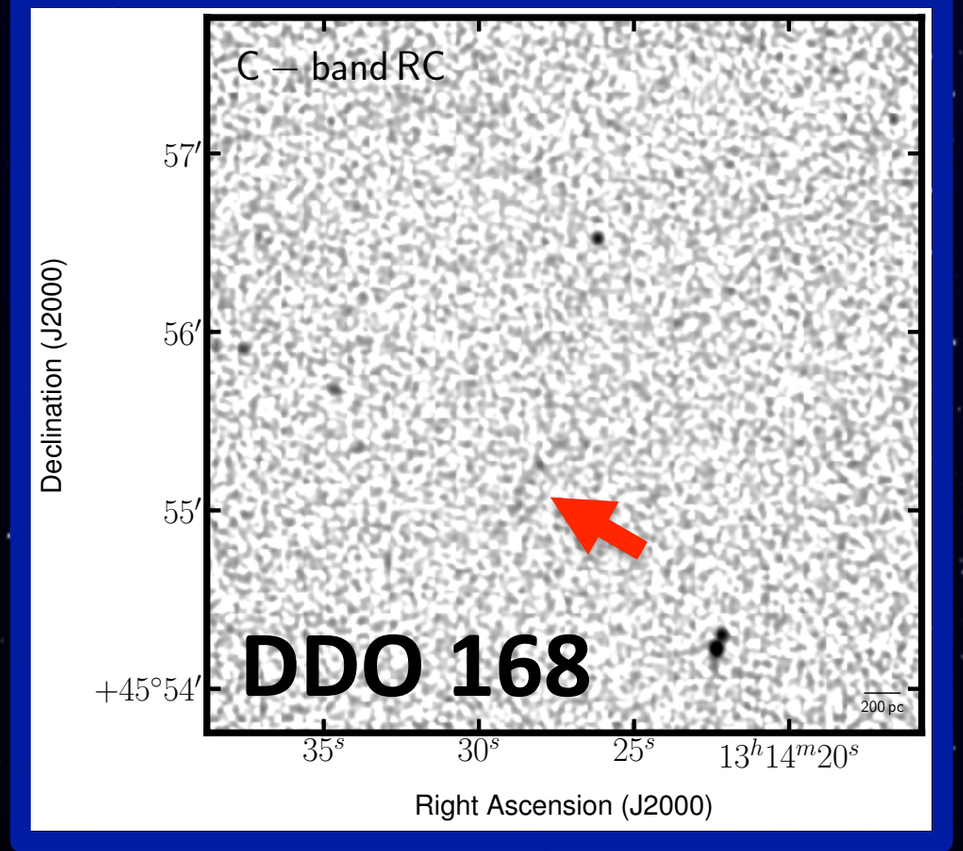

C − band RC on SFRD$_{H\alpha+24\mu m}$
NGC 1569
Declination (J2000)
Right Ascension (J2000)
200 pc

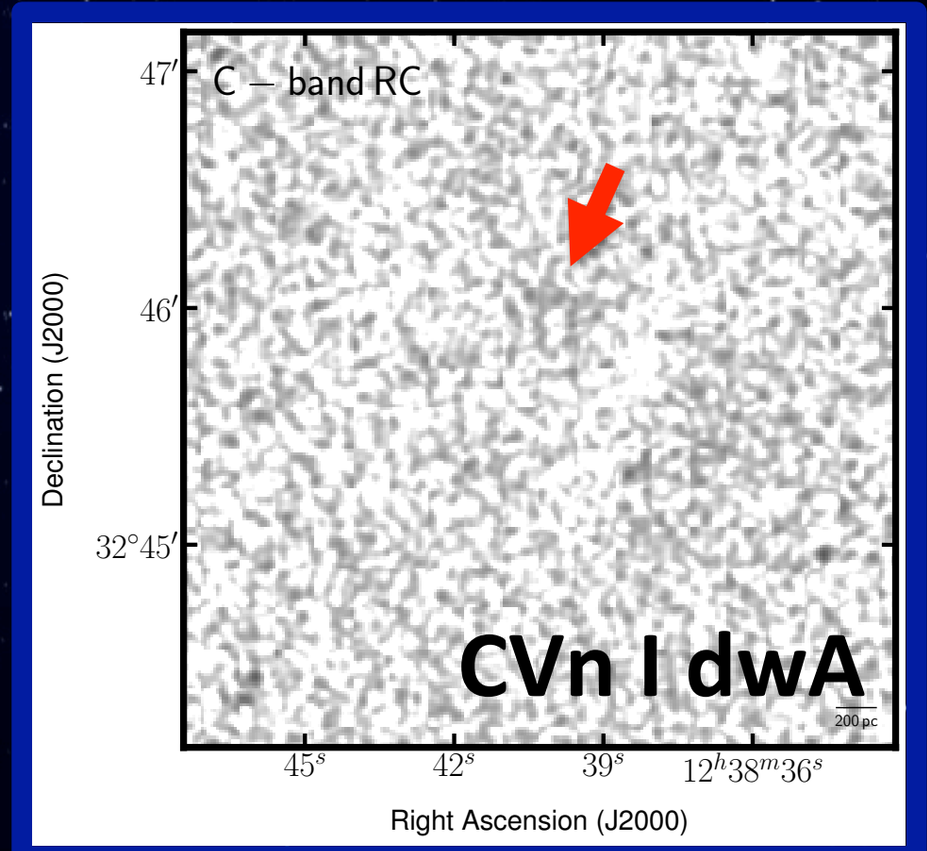

C − band RC on SFRD$_{H\alpha+24\mu m}$
DDO 50
Declination (J2000)
Right Ascension (J2000)
200 pc


C − band RC on SFRD$_{H\alpha+24\mu m}$
NGC 2366
Declination (J2000)
Right Ascension (J2000)
200 pc

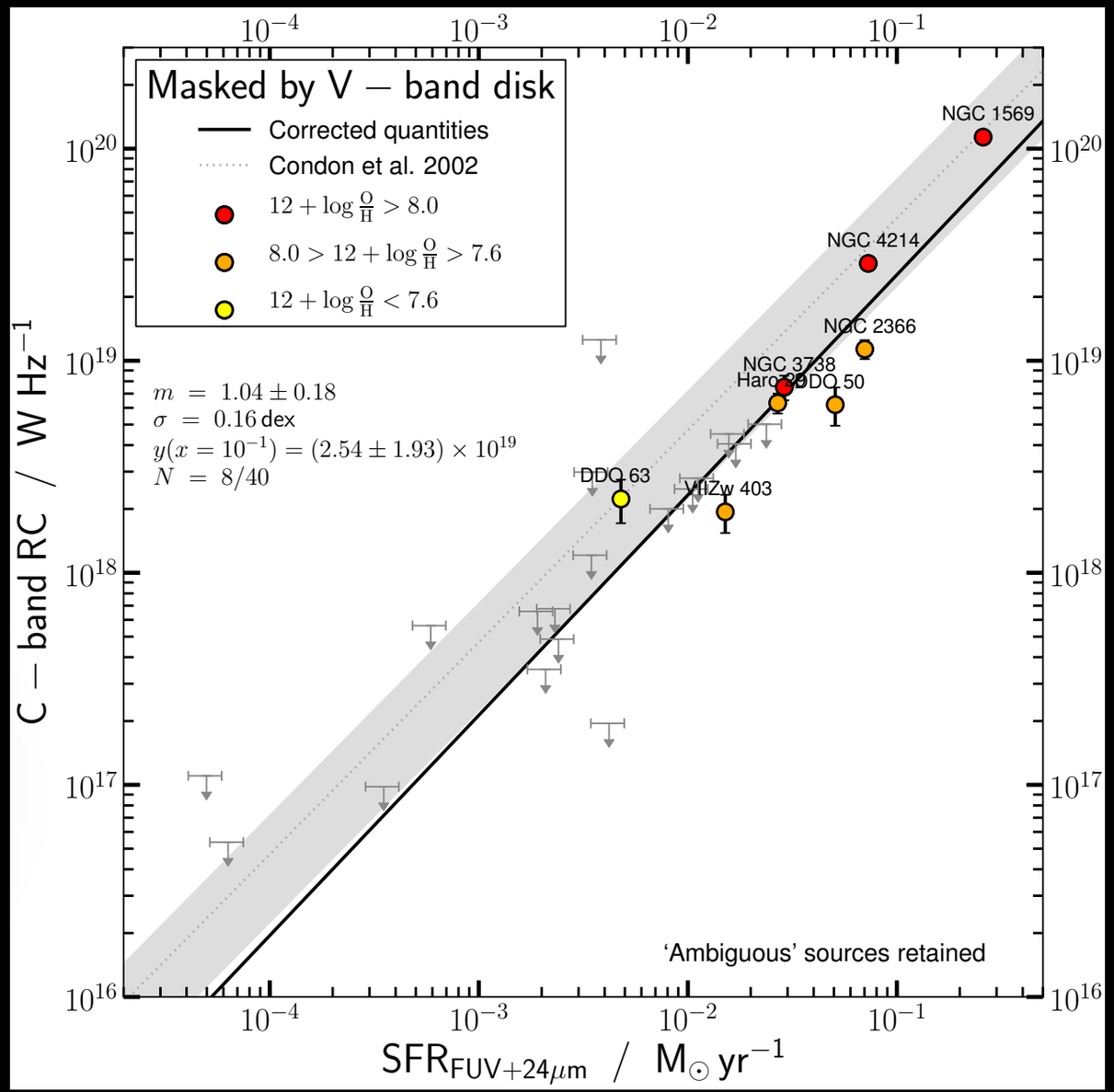

C – band RC
DDO 155
15′
14′
13′
+14°12′
48^s
45^s
42^s
39^s
36^s
12^h58^m33^s
Declination (J2000)
Right Ascension (J2000)
200 pc


C – band RC
Haro 36
37′
51°36′
47^m00^s
57^s
54^s
12^h46^m51^s
Declination (J2000)
Right Ascension (J2000)
200 pc


C – band RC
DDO 168
57′
56′
55′
+45°54′
35^s
30^s
25^s
13^h14^m20^s
Declination (J2000)
Right Ascension (J2000)
200 pc


C – band RC
CVn I dwA
47′
46′
32°45′
45^s
42^s
39^s
12^h38^m36^s
Declination (J2000)
Right Ascension (J2000)
200 pc

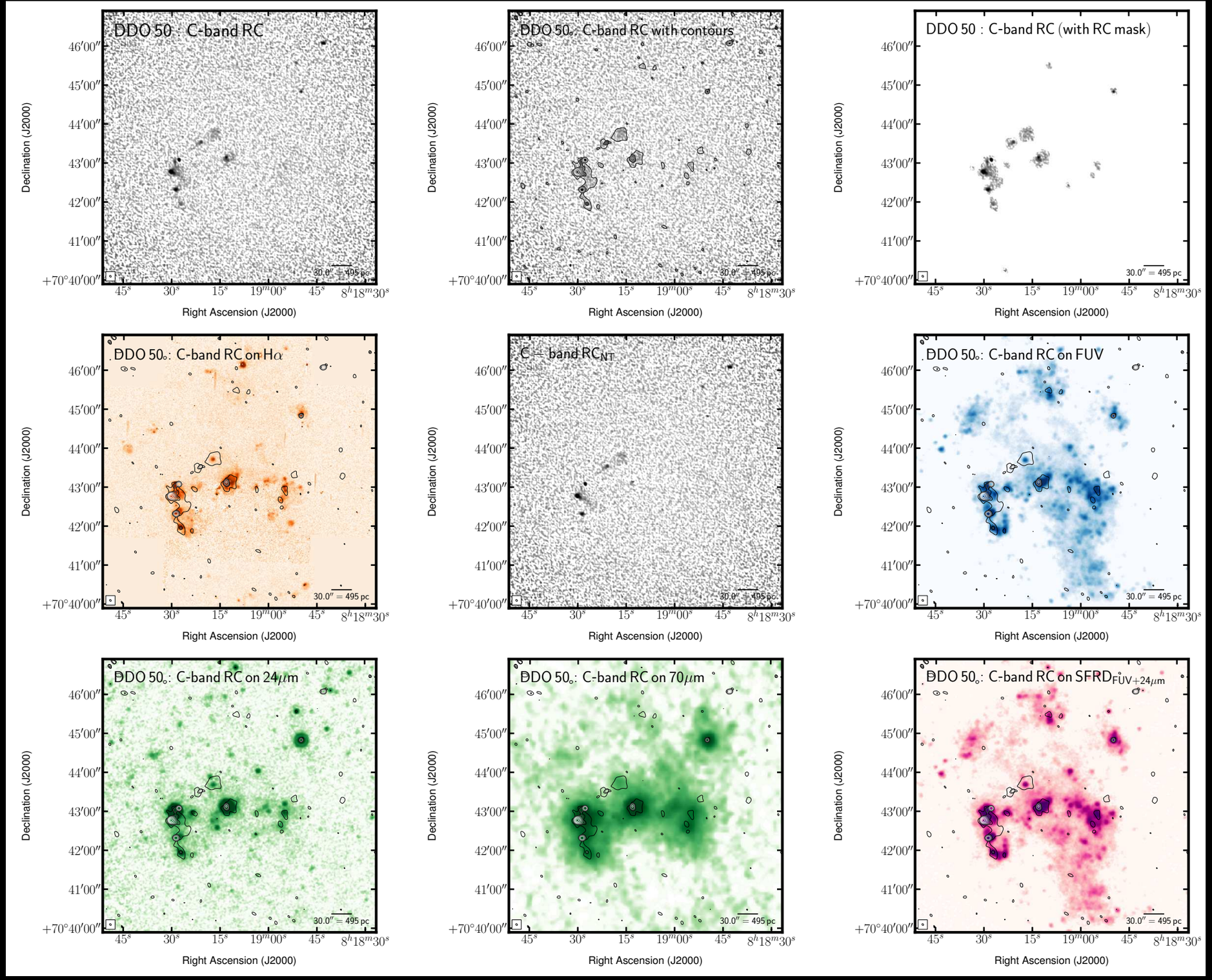
Disc integrated flux



- Integration over disc
- 40 galaxies @ 6cm
- 8 galaxies directly detected

Kitchener, Brinks, VH et al. 2015, submitted

Multi-wavelength picture

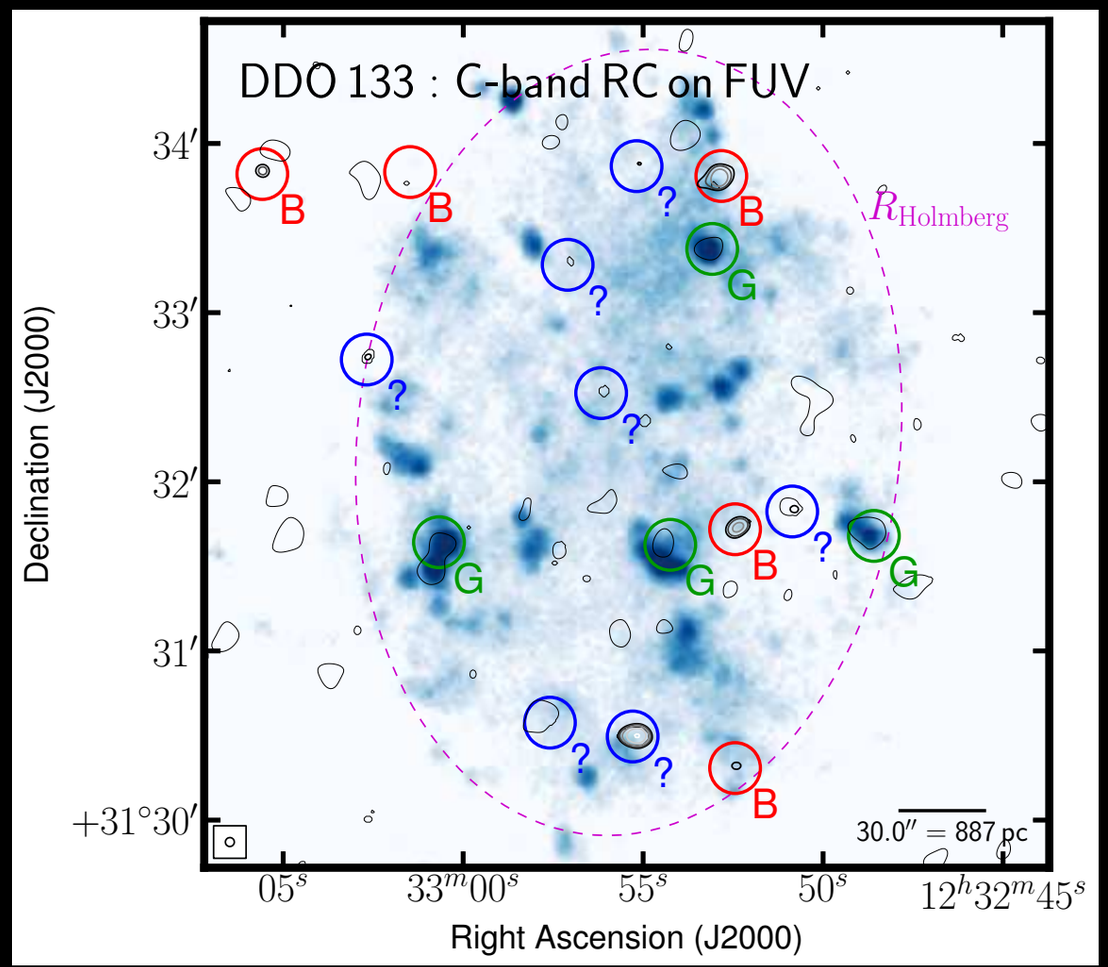


DDO 50
Holmberg II
H-alpha
GALEX FUV
Spitzer 24μm
Spitzer 70μm

Kitchener+15

Increasing the S/N

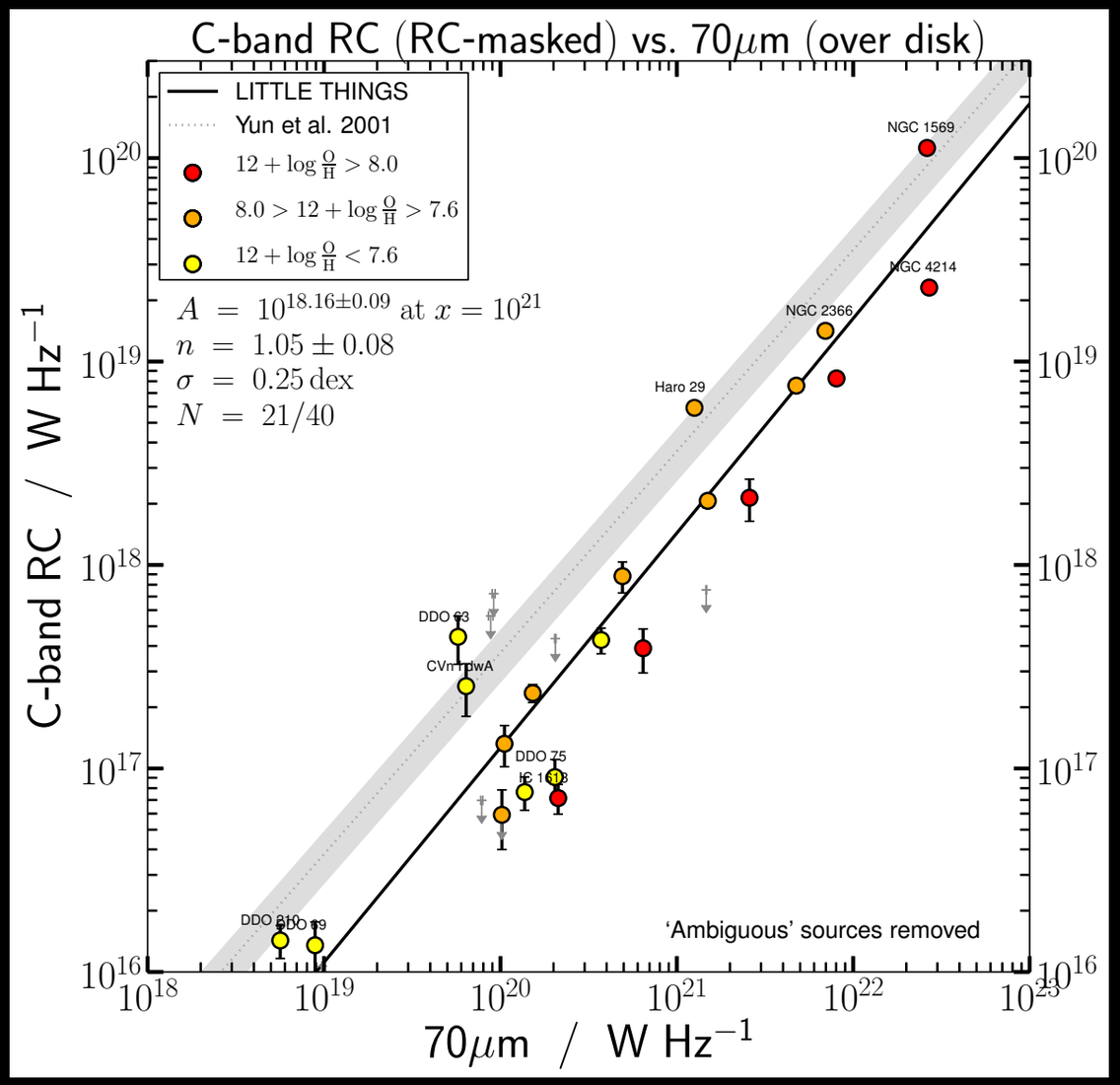
Radio 6 cm contours
+GALEX FUV



- Radio mask
- Remove background sources (2” cross match)
- Remove ambiguous sources
- Further 20 sources detected

Kitchener, Brinks, VH et al. 2015, submitted

RC–far infrared

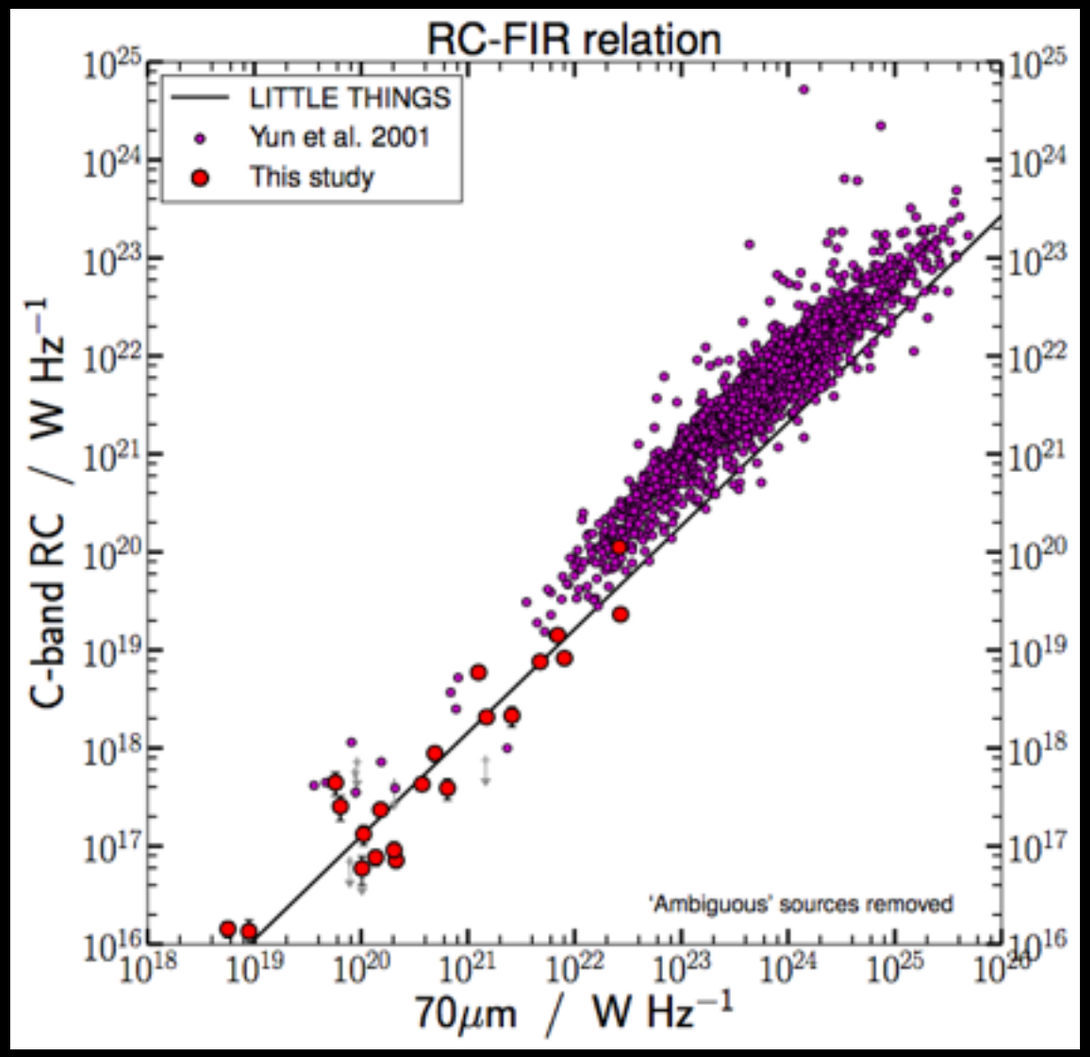


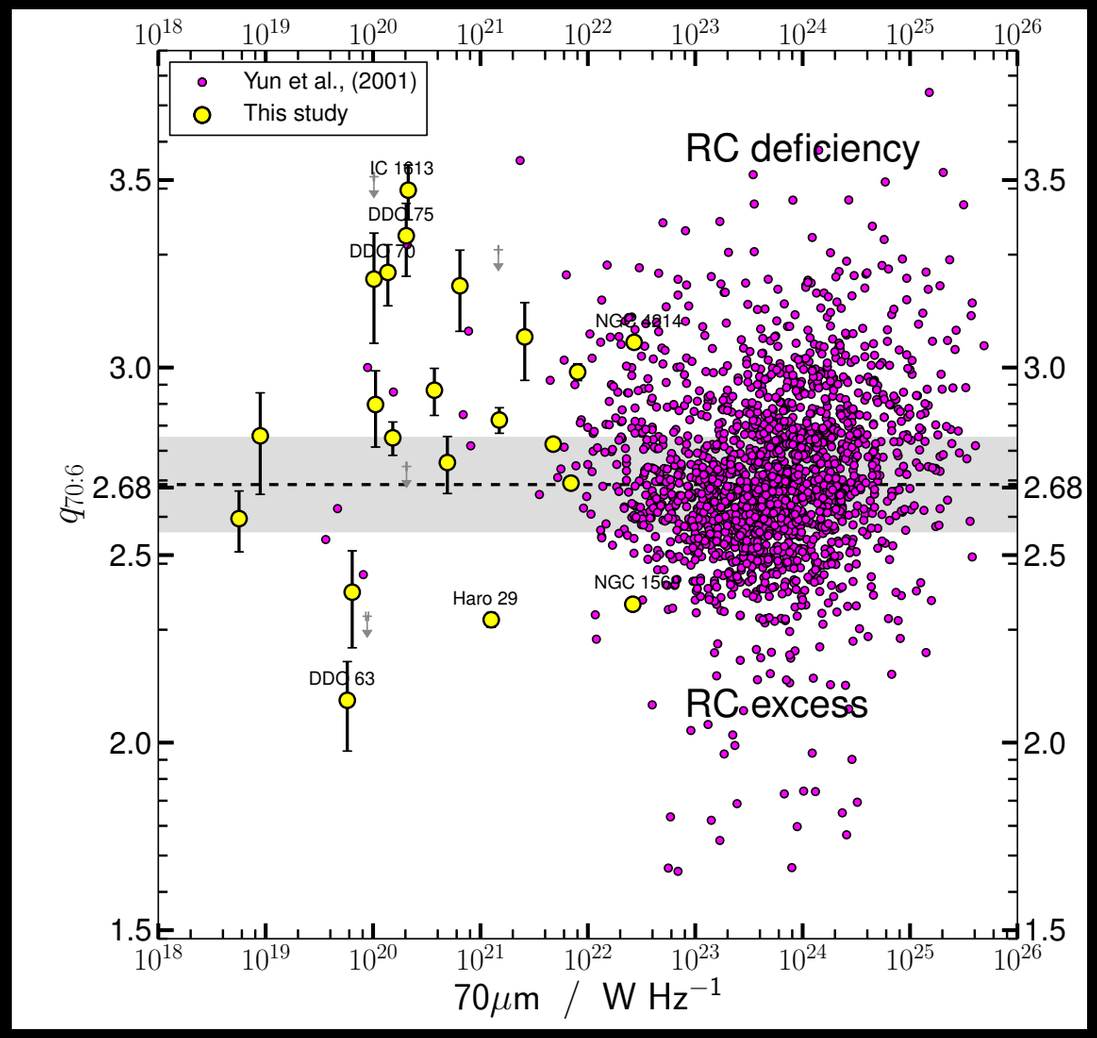
- Slope 1.05+/- 0.08 (slightly super-linear)
- Factor of 2 radio weak compared with spirals
- Conversion fct.:

$$\frac{\mathrm{RC}}{\mathrm{W\,Hz^{-1}}} = 10^{18.16\pm0.09}\left(\frac{70\mu\mathrm{mFIR}}{10^{21}\,\mathrm{W\,Hz^{-1}}}\right)$$

Kitchener, Brinks, VH et al. 2015, submitted

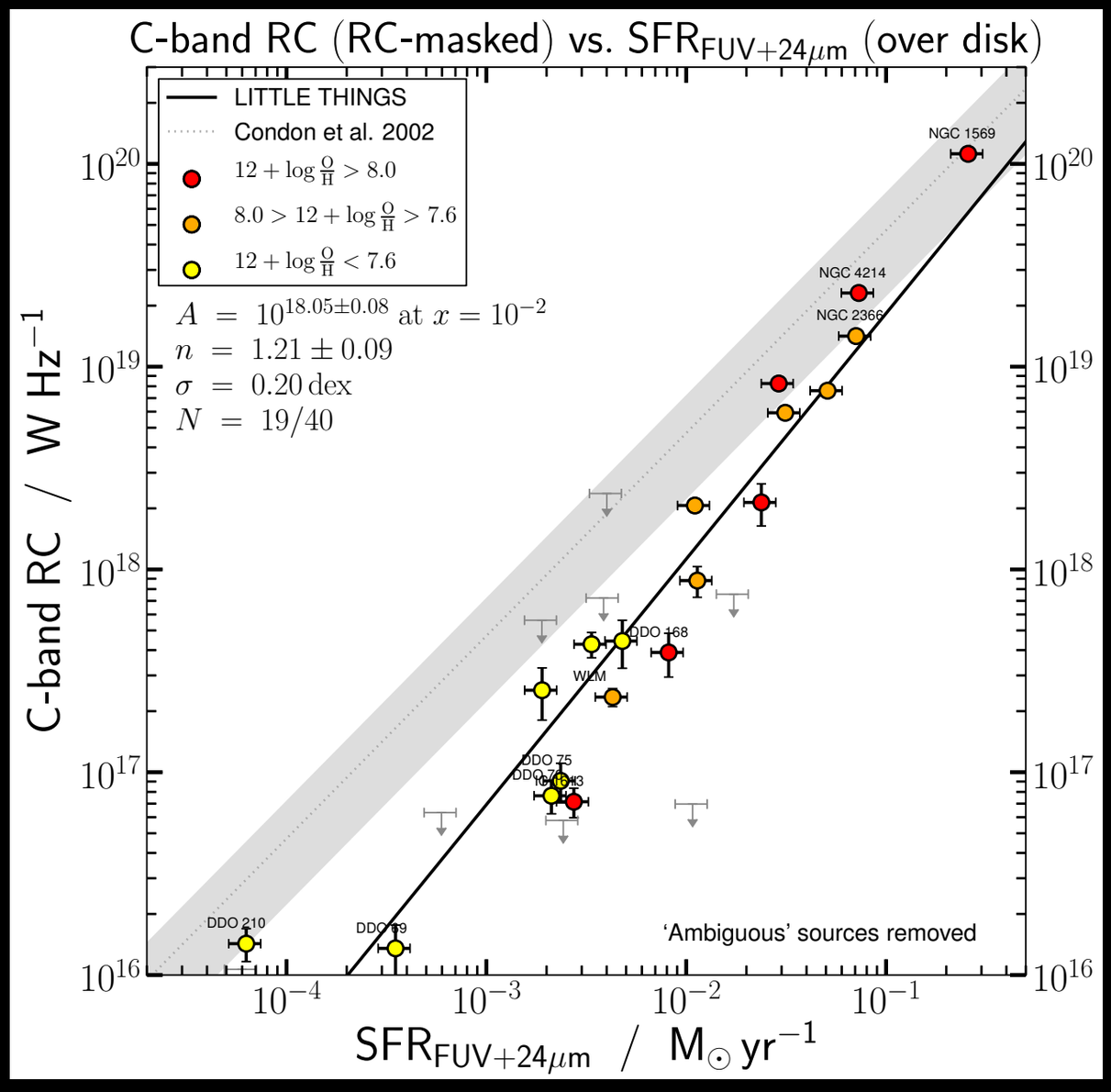
Comparison with spirals





Kitchener, Brinks, VH et al. 2015, submitted

Dwarfs are radio dim

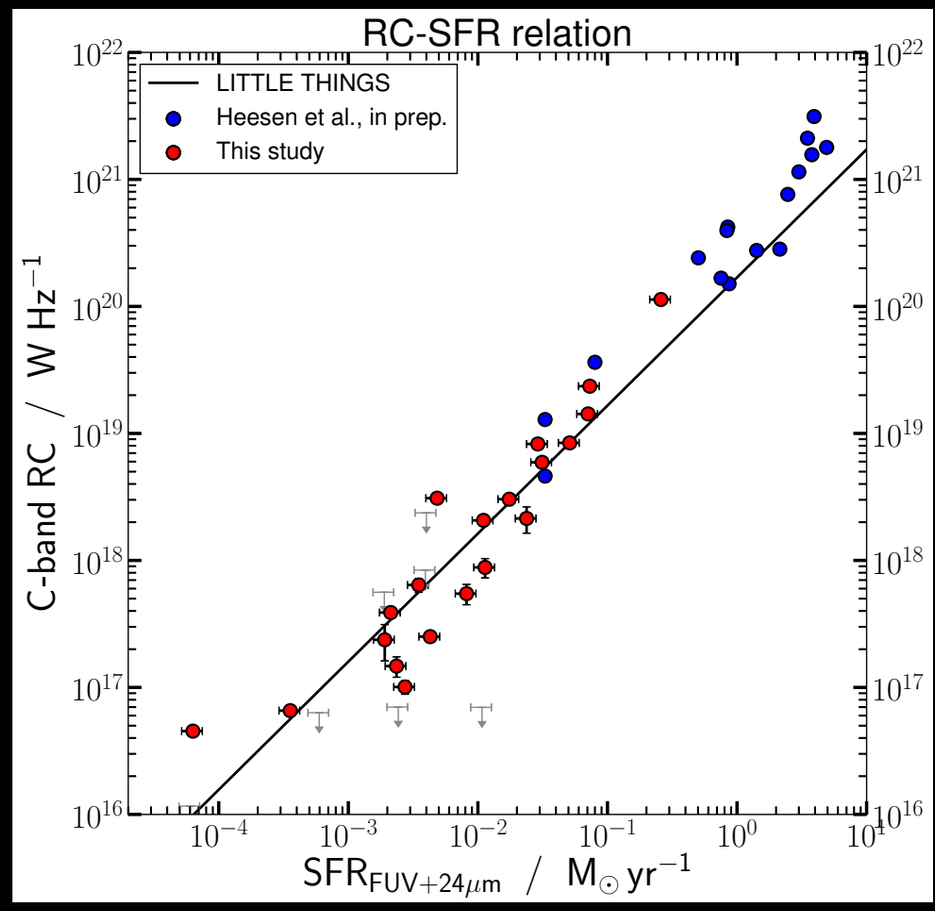


- Low magnetic field strengths (but B = 9μG)
- Cosmic ray electron escape
- Different IMF

Kitchener, Brinks, VH et al. 2015, submitted

Magnetic Field – SFR Relation

- Turbulent dynamo:
  B ~ $SFR^{0.33}$ Schleicher & Beck (2013)
  - Non-thermal: L ~ $B^{3+\alpha}$
  - RC_{nt}–SFR: RC_{nt}~$SFR^{1.33}$
- Weak B or CRs below SFR=0.1 M yr^{-1}



Kitchener, Brinks, VH et al. 2015, submitted

RC–SFR relation

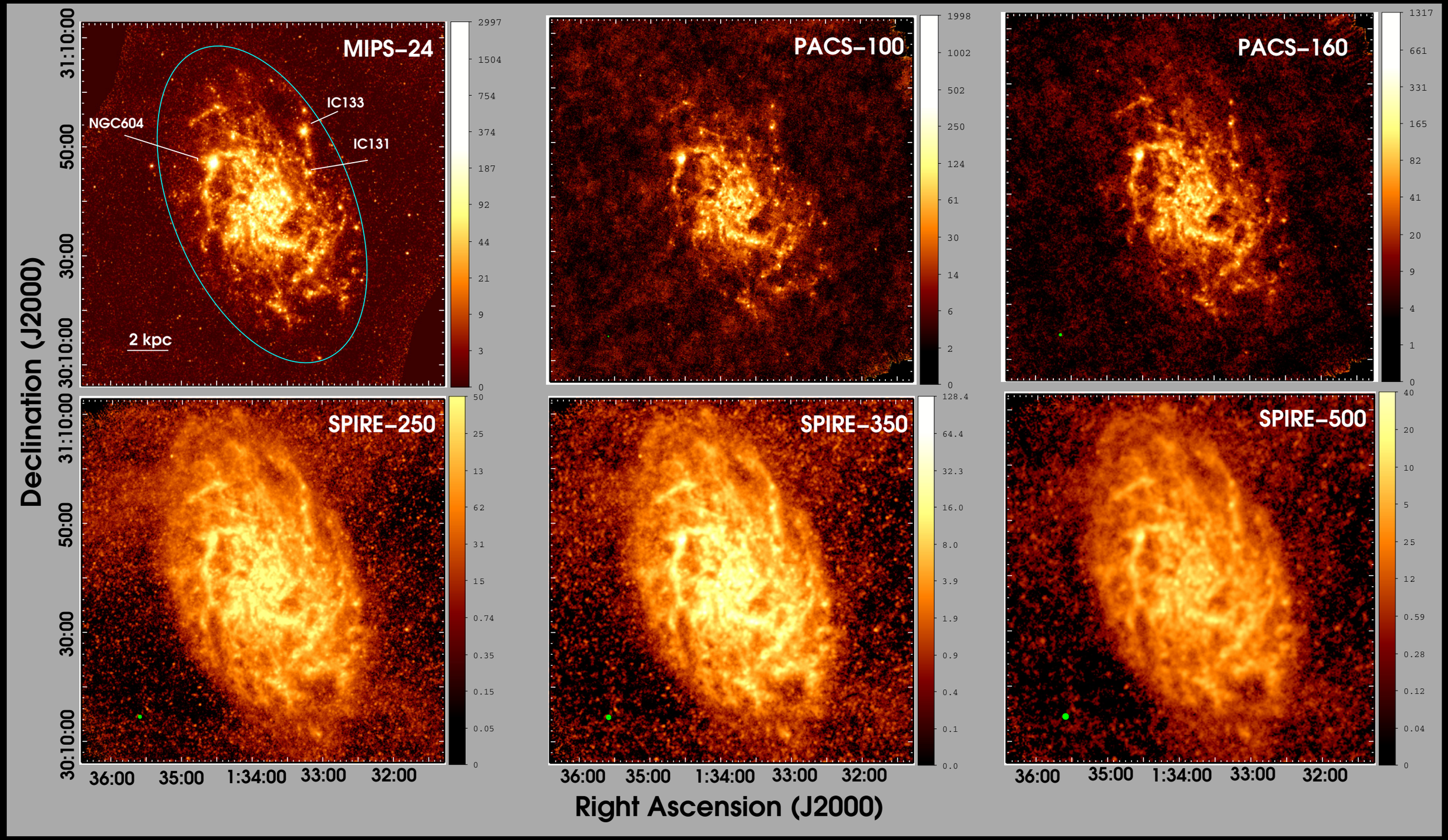
Why it may work:

- SFR ~ H-alpha (Kennicutt 1989)
- H-alpha ~ thermal RC
- SFR ~ Type II SN rate (> 8 M_{solar})
- Scale non-thermal luminosity to Milky Way SN rate

Complications:

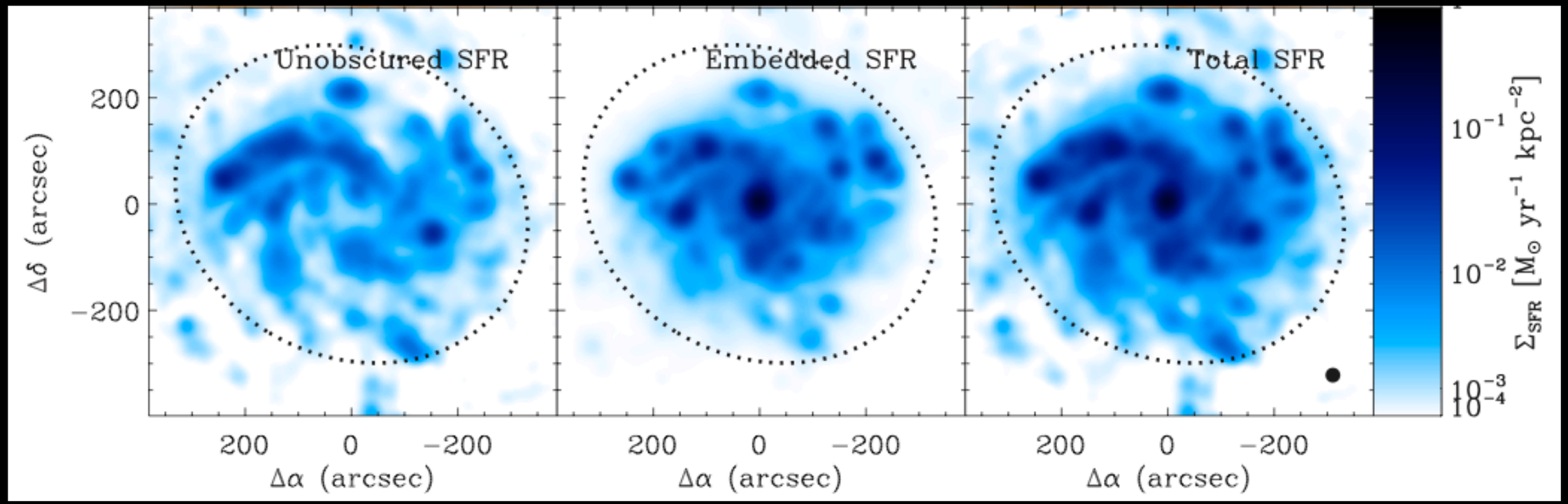
- need B–CR equipartition
- non-calorimetry
- weak B-fields
- time dependence

M33 far–IR: ISRF heating



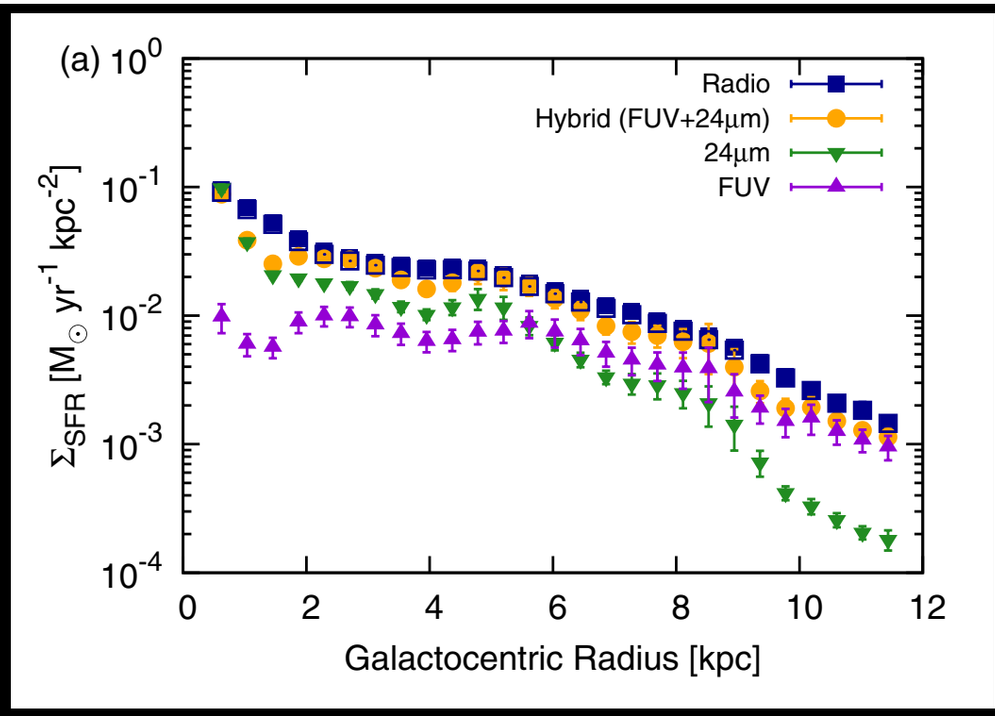
(Xilouris, Tabatabaei et al. 2012)

“Hybrid” star formation tracer



NGC 6946 (Leroy et al. 2008, 2012)

FUV is important in the outskirts of galaxies.



Heesen, Brinks, Leroy et al. 2014

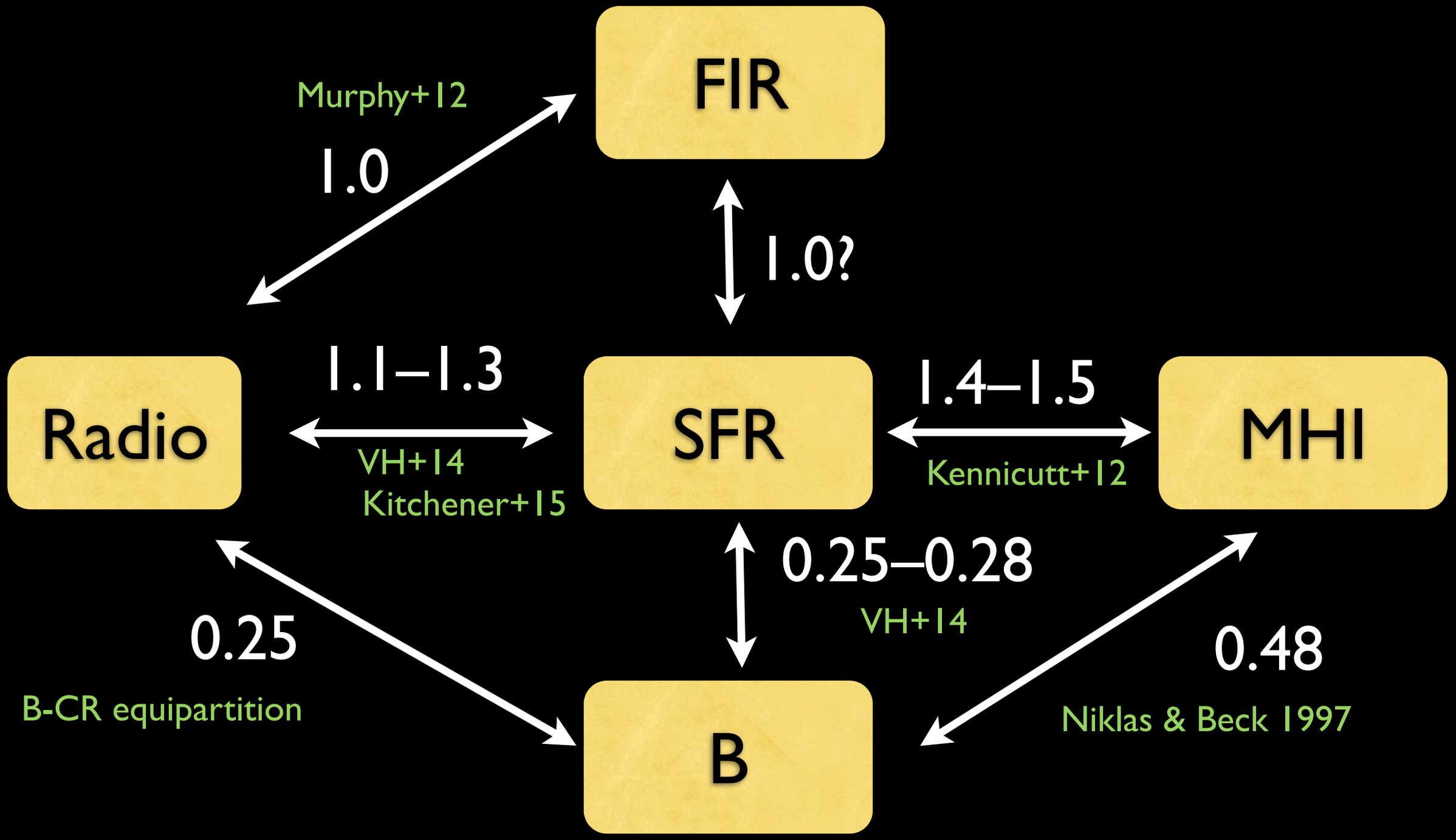
RC–FIR "conspiracy"

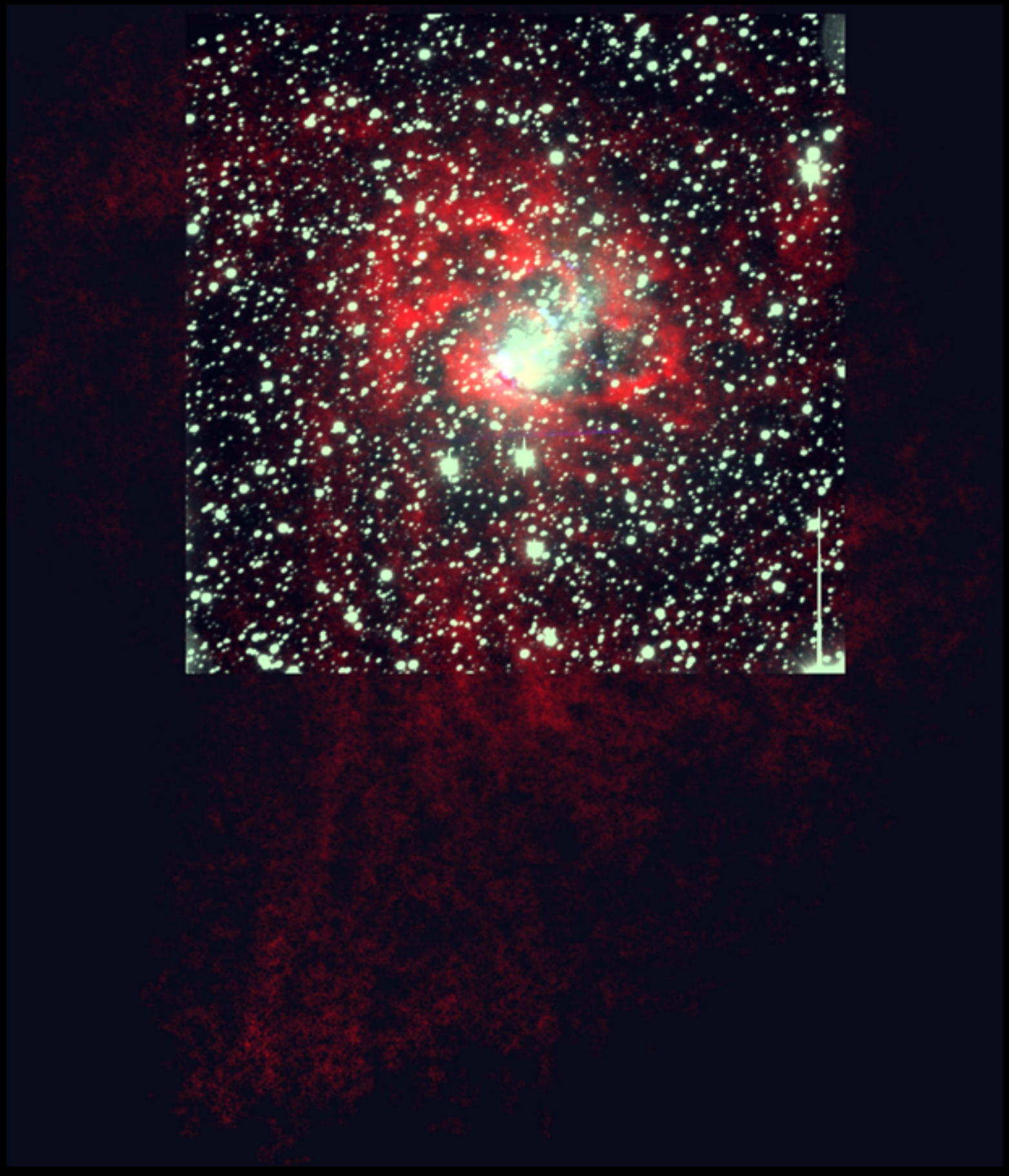
- Dwarfs lie a factor of 2 below the RC–FIR correlation
- Slope 1.05

- Dwarfs lie below the RC–SFR relation
- Slope 1.21
- Up to a factor of 10 radio weak

Radio deficiency is balanced by escaping dust heating photons

Global power-law relations

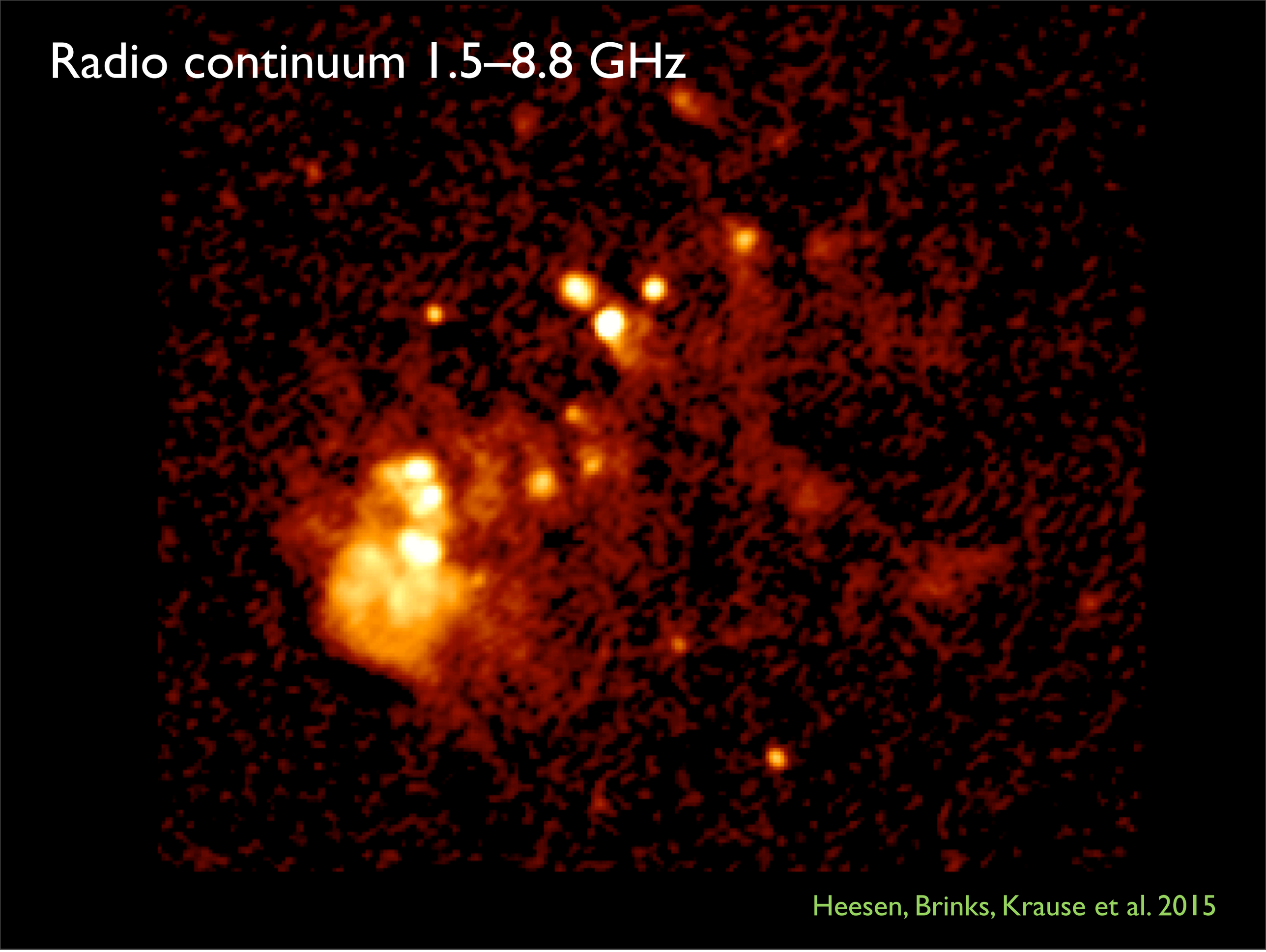




IC 10
D = 0.7 Mpc
SFR = 0.1 M yr^{-1}
Wolf-Rayet stars
Star burst
few Myr star clusters

Hunter et al. 2012

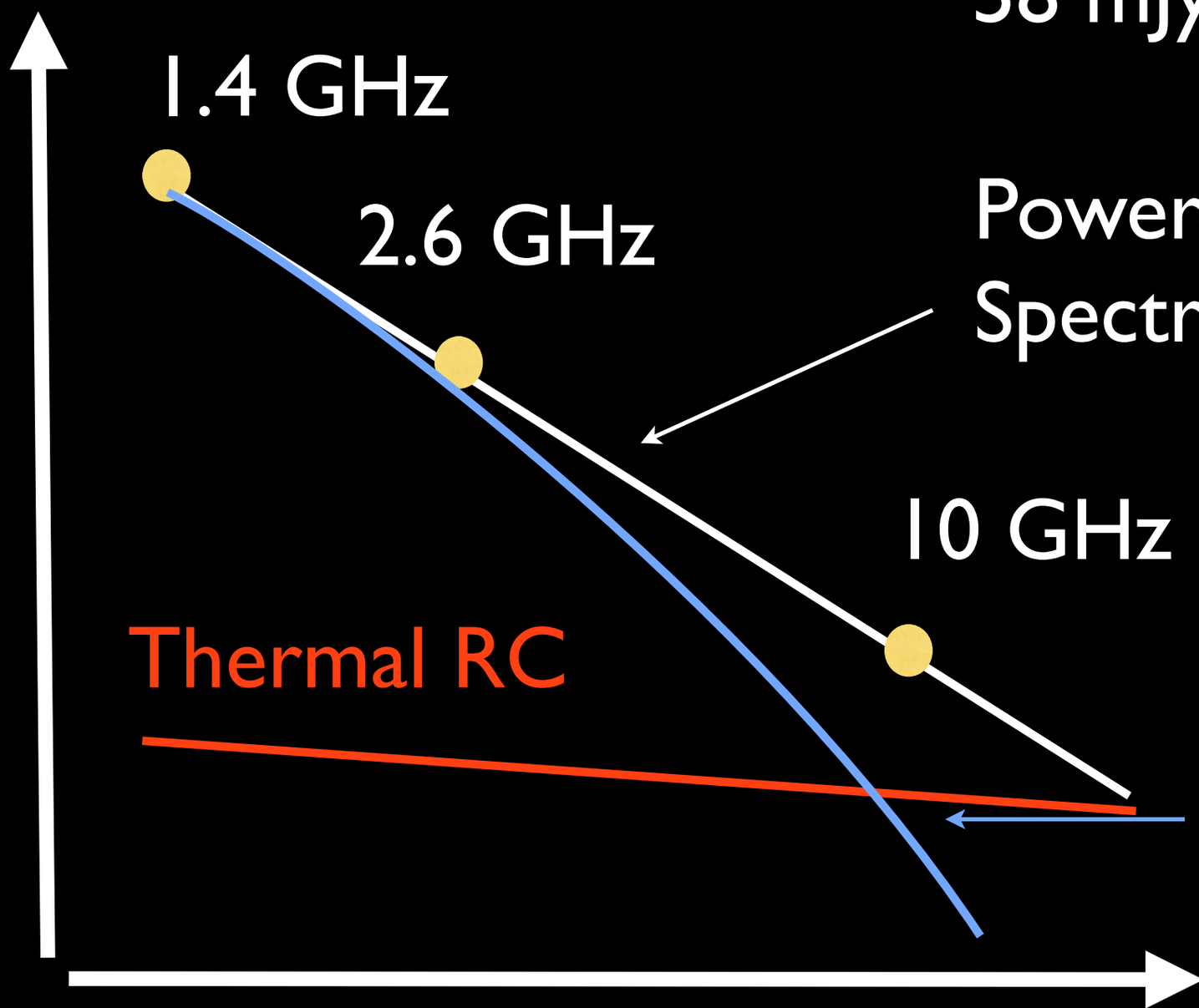
Radio continuum 1.5–8.8 GHz



Heesen, Brinks, Krause et al. 2015

“NT conspiracy”

Non-thermal flux density:
58 mJy (@6.2 GHz)



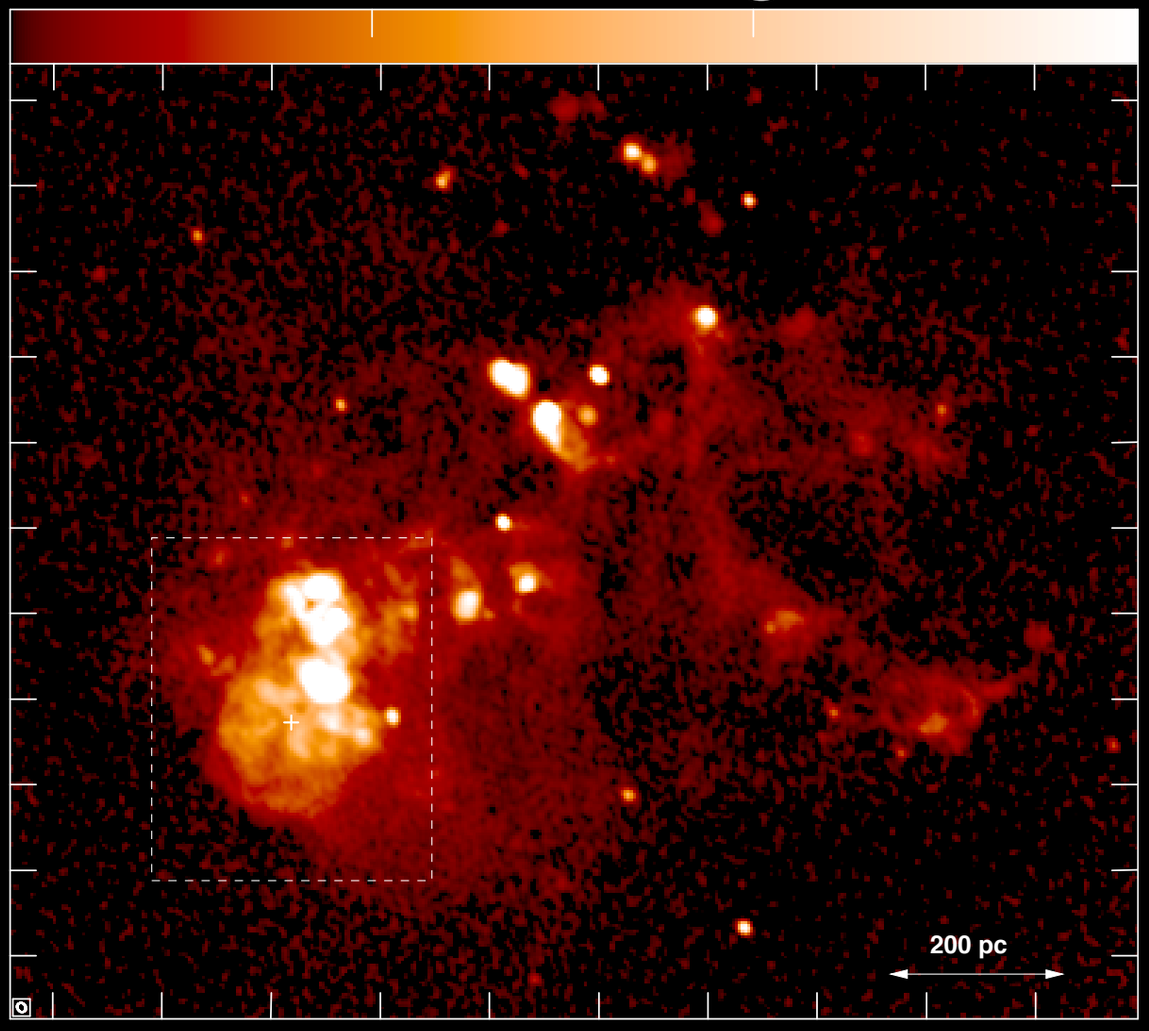
Power-law Chyzy et al. 2003
Spectral index: -0.41

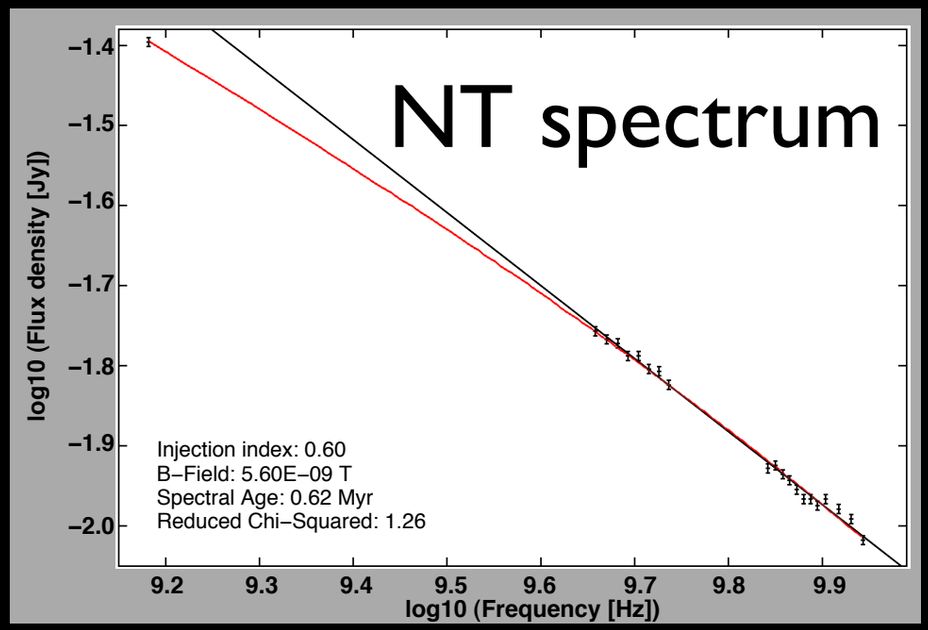
Non-thermal RC:
spectral curvature

Spectral ageing with the JVLA

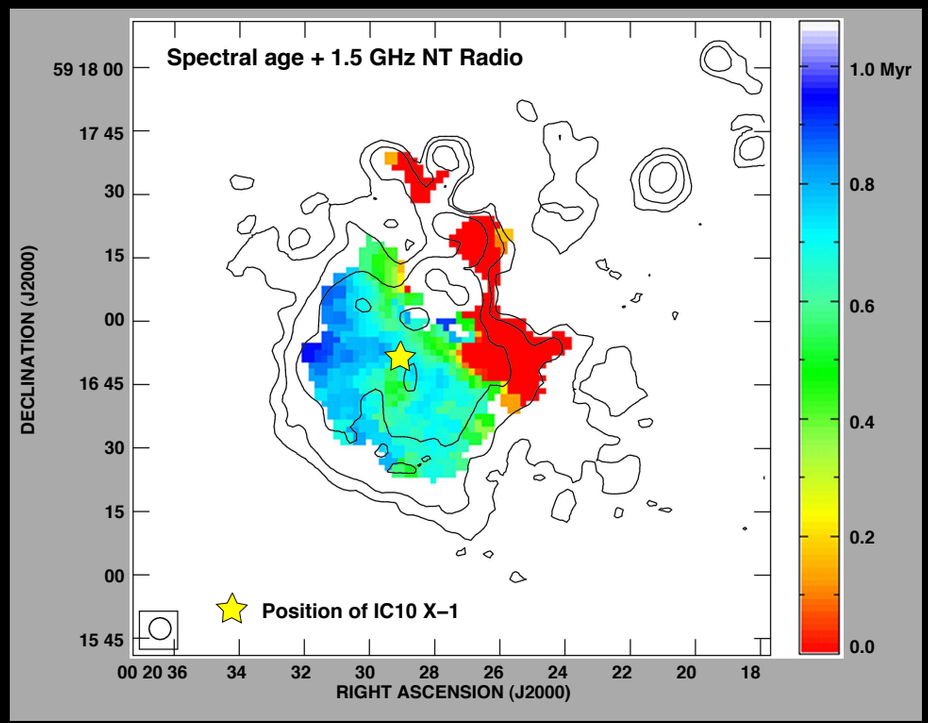
IC10 VLA+Effelsberg 6.2 GHz

(Heesen, Brinks, Krause et al. 2015)





Spectral age map



1.0 Myr

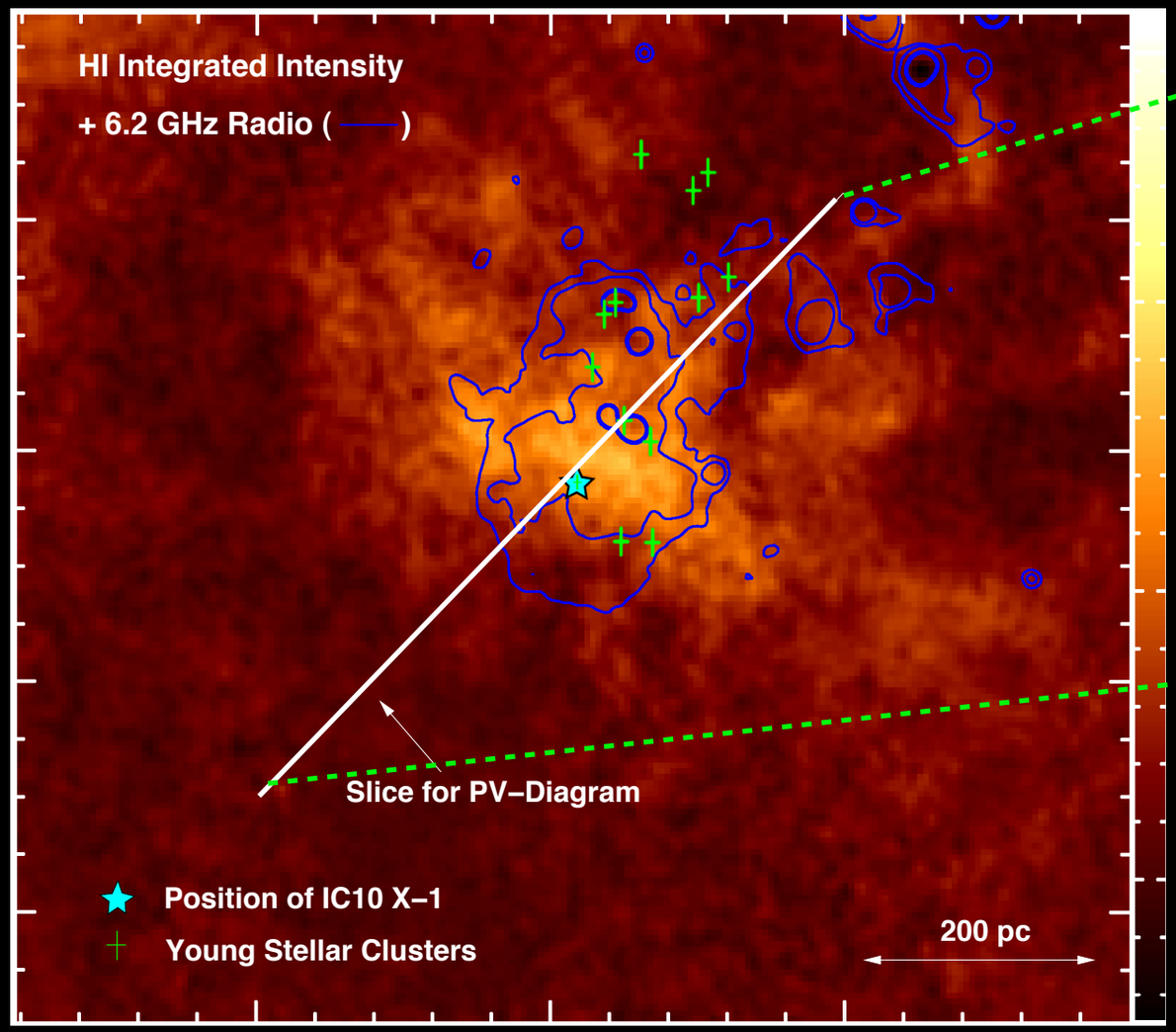
0.0 Myr

Some details:

- Subtract thermal RC w/ H–alpha
- Correct missing flux w/ Effelsberg
- Estimate B from equipartition

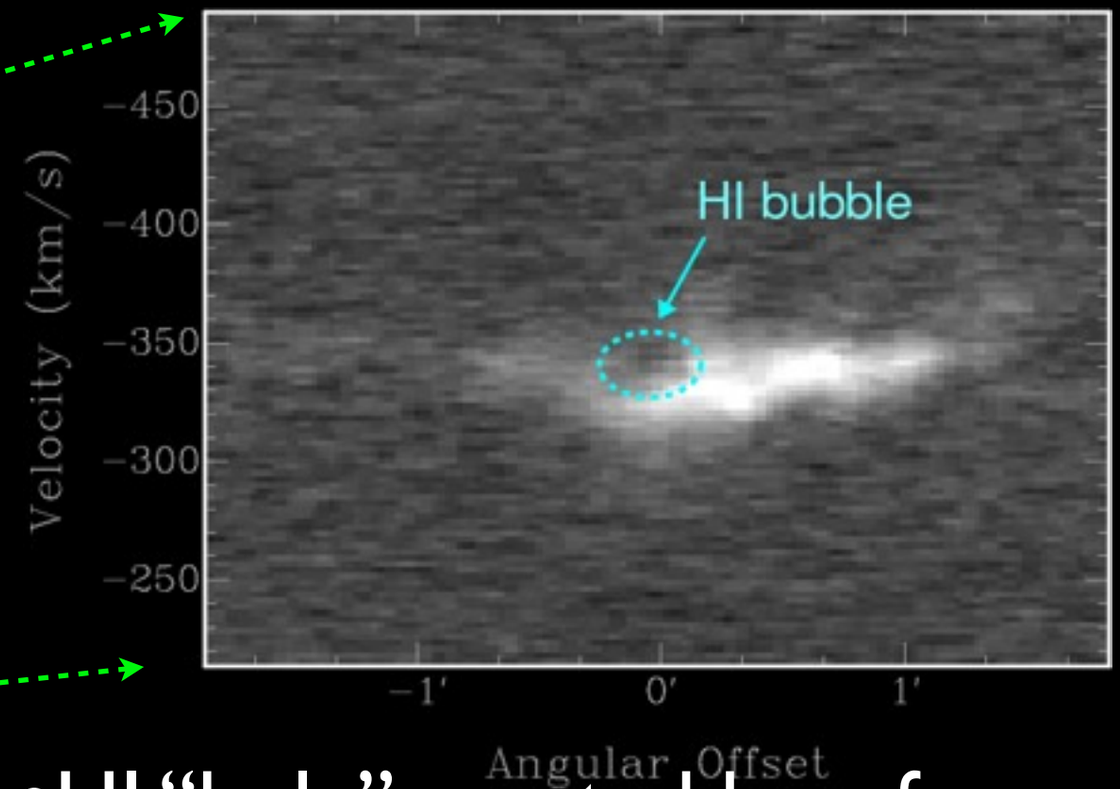
A young superbubble in IC10

HI emission + 6.2 GHz



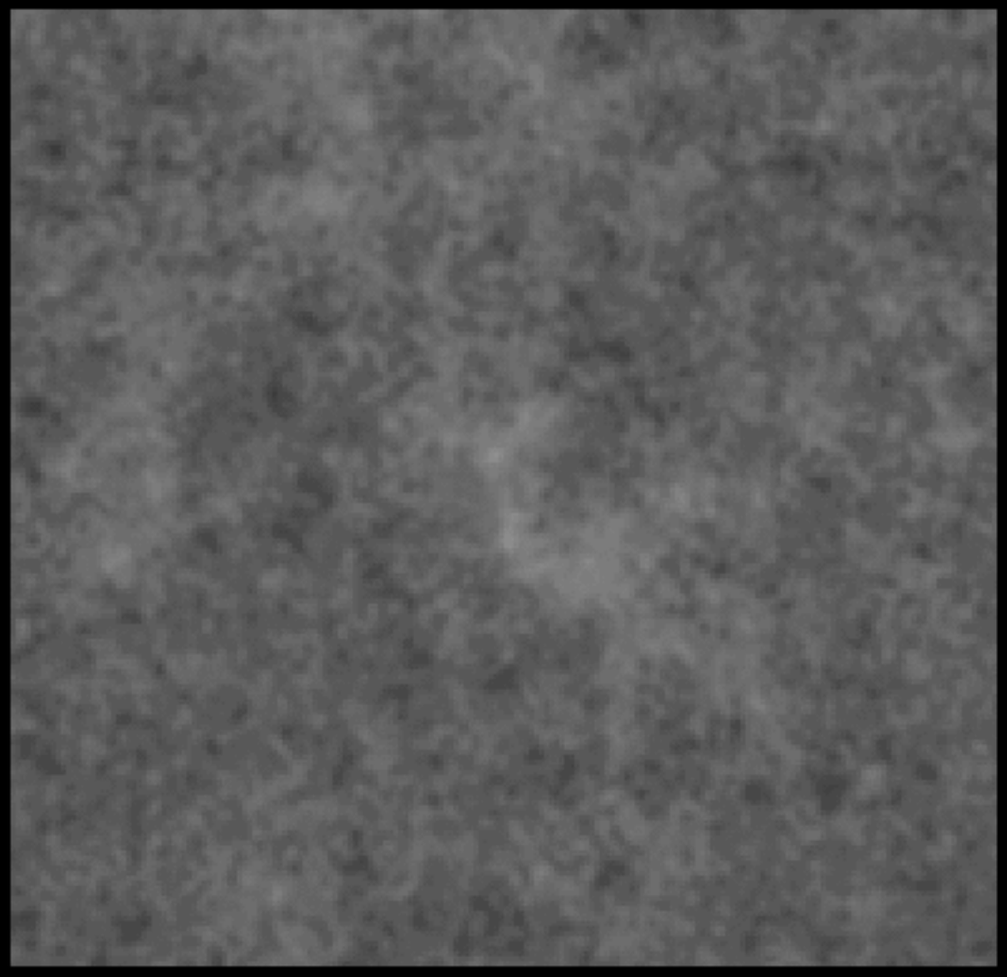
HI data cube from LITTLE THINGS
(Hunter et al. 2012)

Position–Velocity Diagram



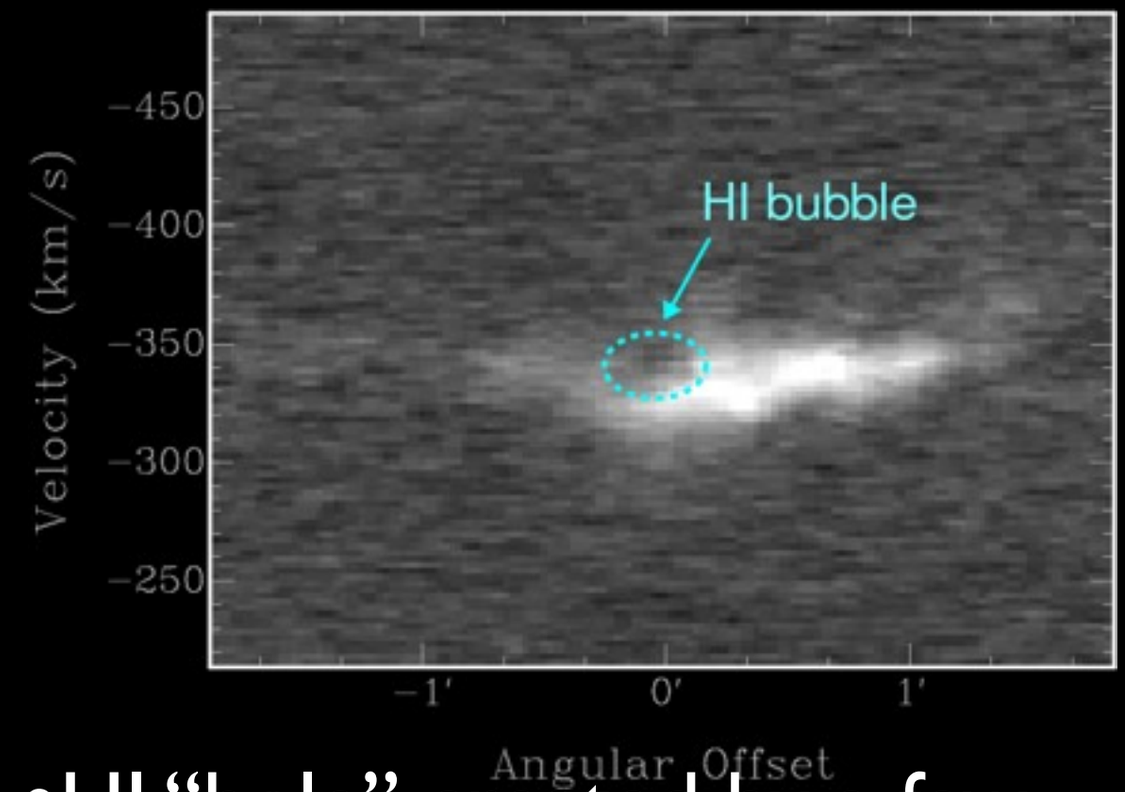
- HI "hole" created by a few massive Type Ic SNe
- IC10 X-1, 23–35 M_{solar} stellar mass black hole
- 'Hypernova' progenitor
  (Lozinskaya & Mosiiev 2007)

A young superbubble in IC10



HI data cube from LITTLE THINGS
(Hunter et al. 2012)

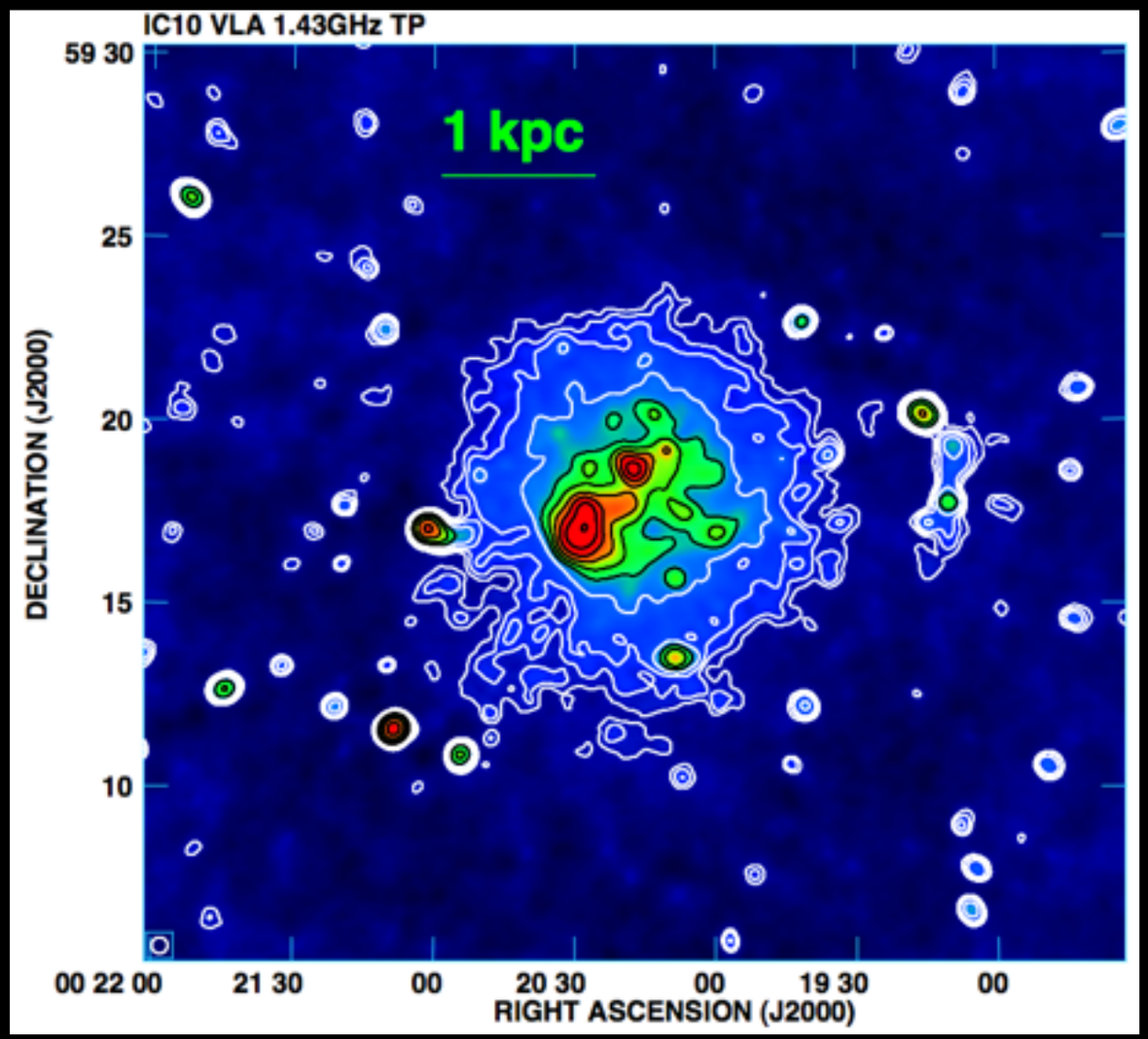
Position–Velocity Diagram



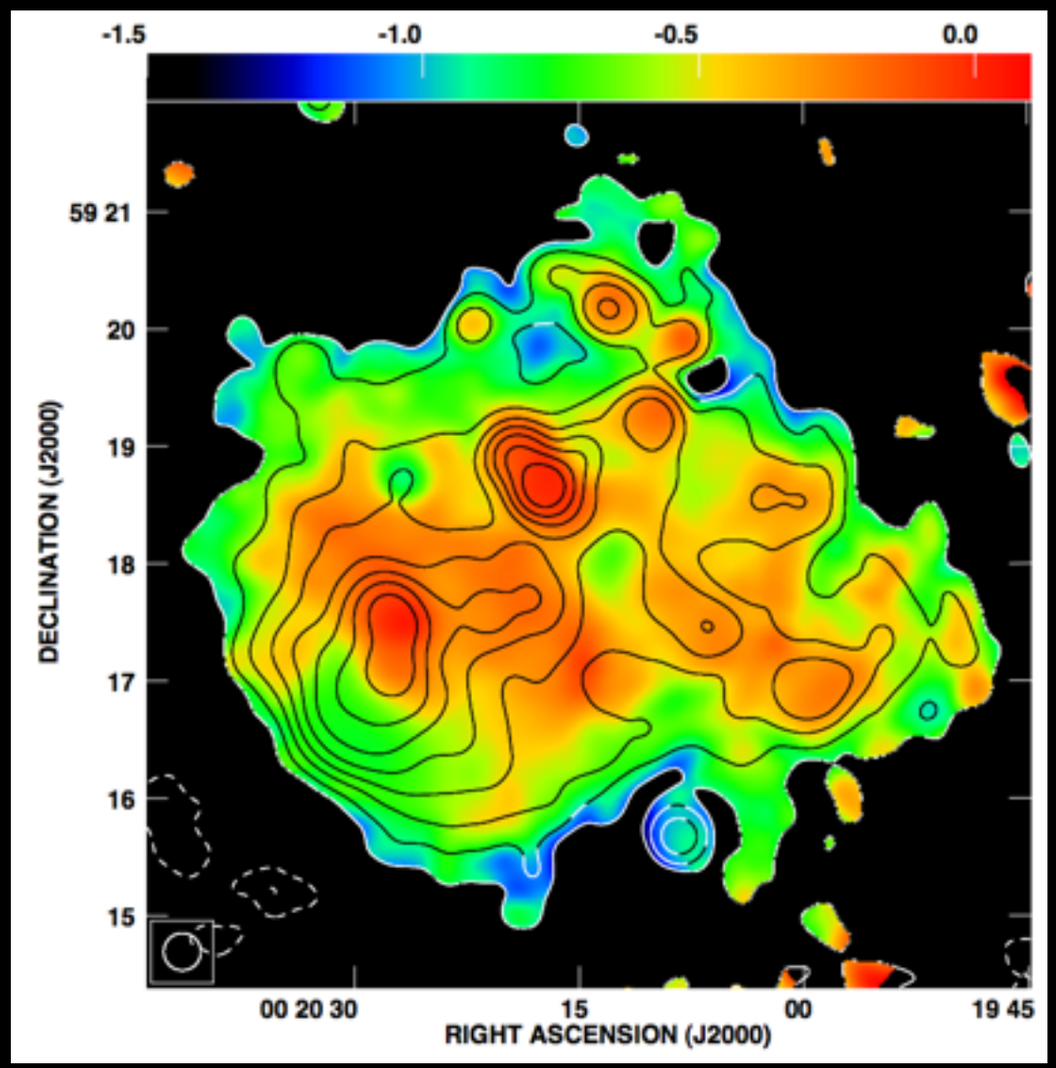
- HI "hole" created by a few massive Type Ic SNe
- IC10 X-1, 23–35 M_{solar} stellar mass black hole
- 'Hypernova' progenitor (Lozinskaya & Mosiiev 2007)

“Synchrotron envelope” in IC 10

1.4 GHz VLA + Effelsberg

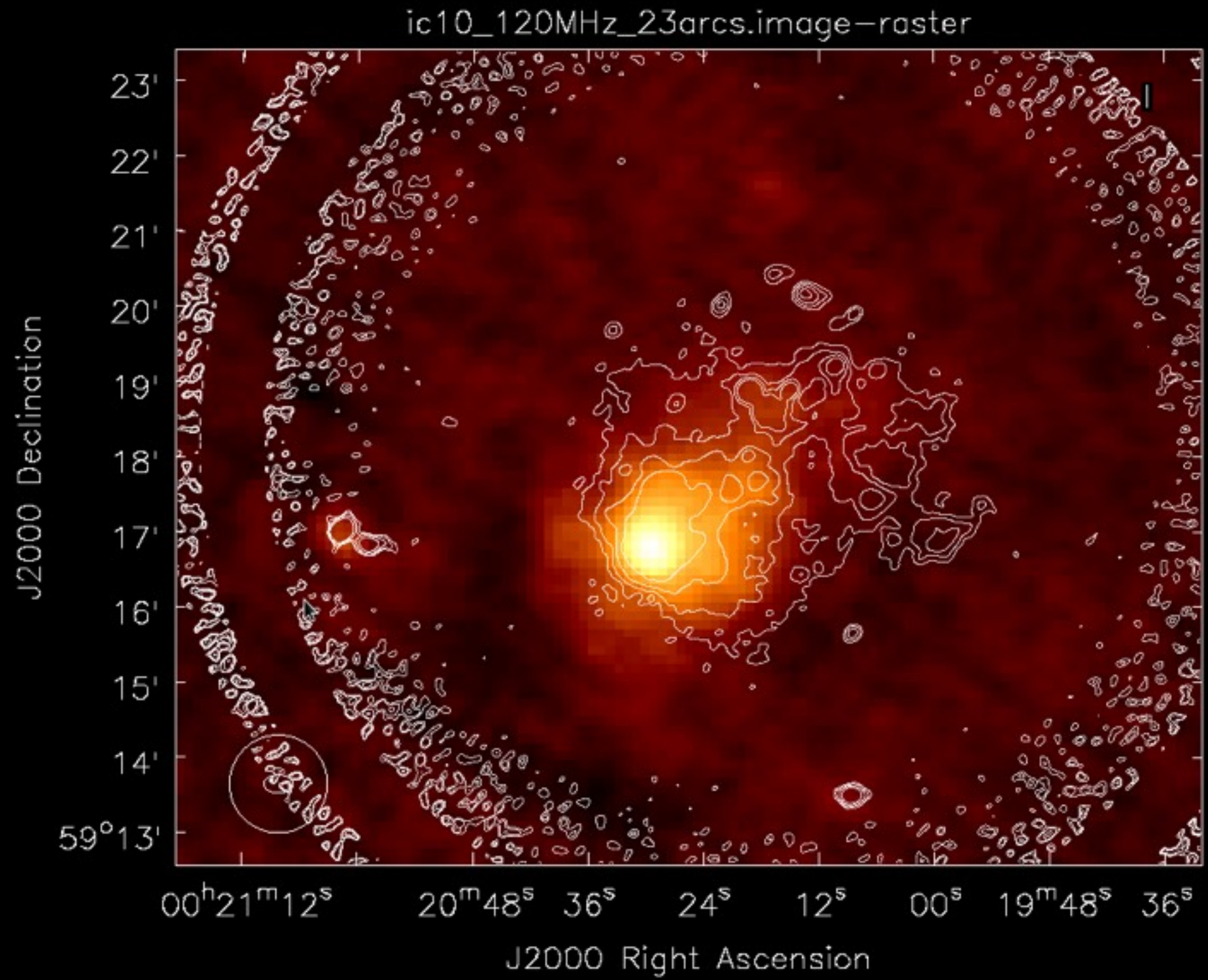


1.4–8.4 GHz spectral indx.



Chyzy, Drazgra, Beck, et al. 2015, in prep.

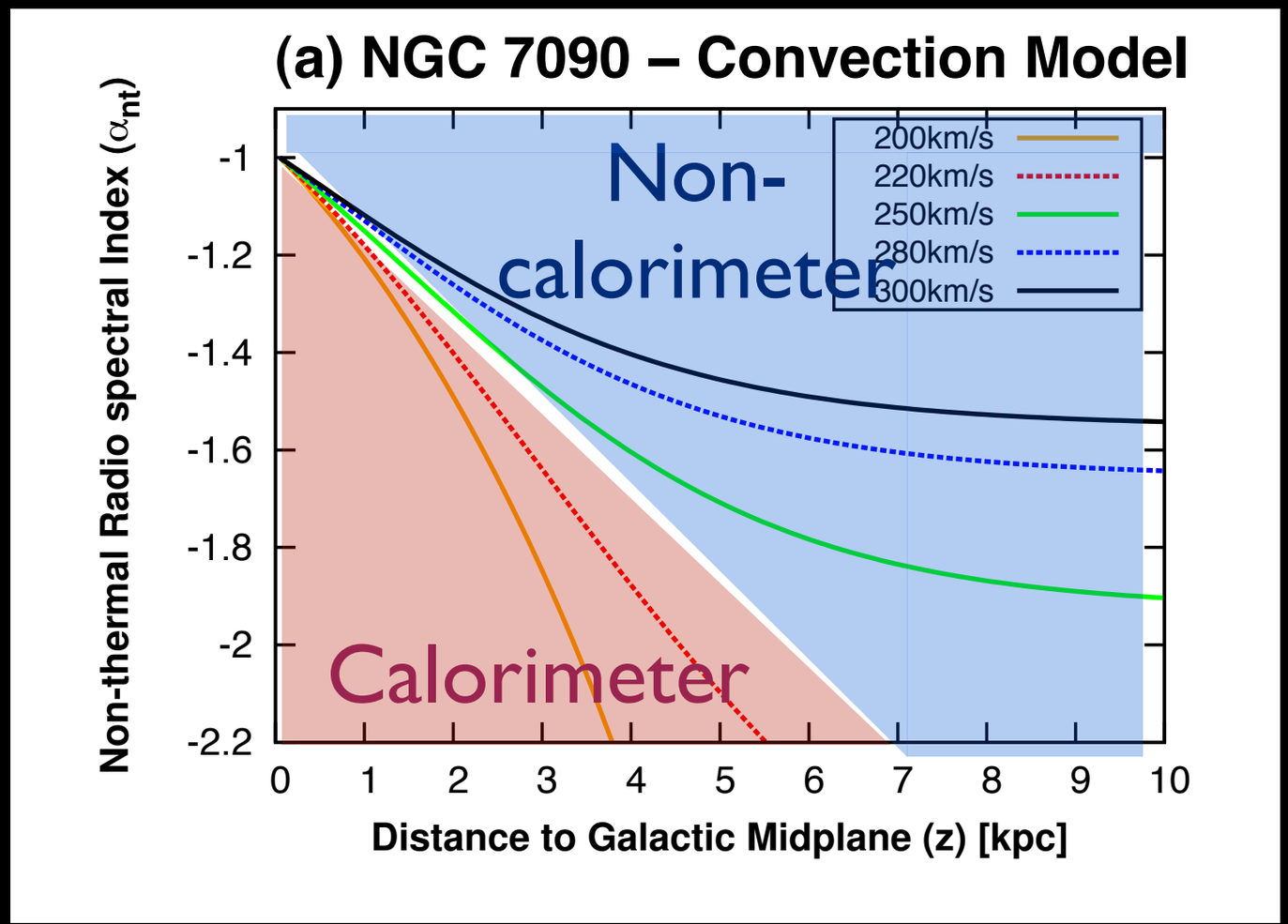
IC10 – 120 MHz LOFAR + 6 GHz VLA



LOFAR
FWHM = 23”
rms = 3 mJy/beam
BandWidt. = 3.6 MHz

VLA (contours)
FWHM = 9”
rms = 3 μJy/beam
BandWidt. = 2.0 GHz

Spectral index profile (z)



Assumptions:

- Exponential profile of B
- Constant wind speed V

Results:

- Concave profile

$V > V_{esc}$: CRe escape

- Convex profile

$V < V_{esc}$: CRe calorimeter

CR escape speed:

$$V_{\rm esc} \equiv \frac{h_{\rm B}}{2 \cdot t_{\rm rad}}$$

(Magnetic energy scaleheight: h_B / 2)

Heesen, Dettmar, Krause et al. 2015, submitted

Conclusions

- 26 out of 40 dwarfs RC detected
- 42% thermal RC fraction @6 cm
- 0.1–1.0 M yr^{-1} diverge from Condon's relation
- 10^{-3}–10^{-4} yr^{-1} factor of 10 radio deficient
- Radio factor of 2 deficient to FIR: "Conspiracy"
- Young (1 Myr) cosmic rays in IC 10
- Non-thermal outflows magnetize early Universe

Thank you!