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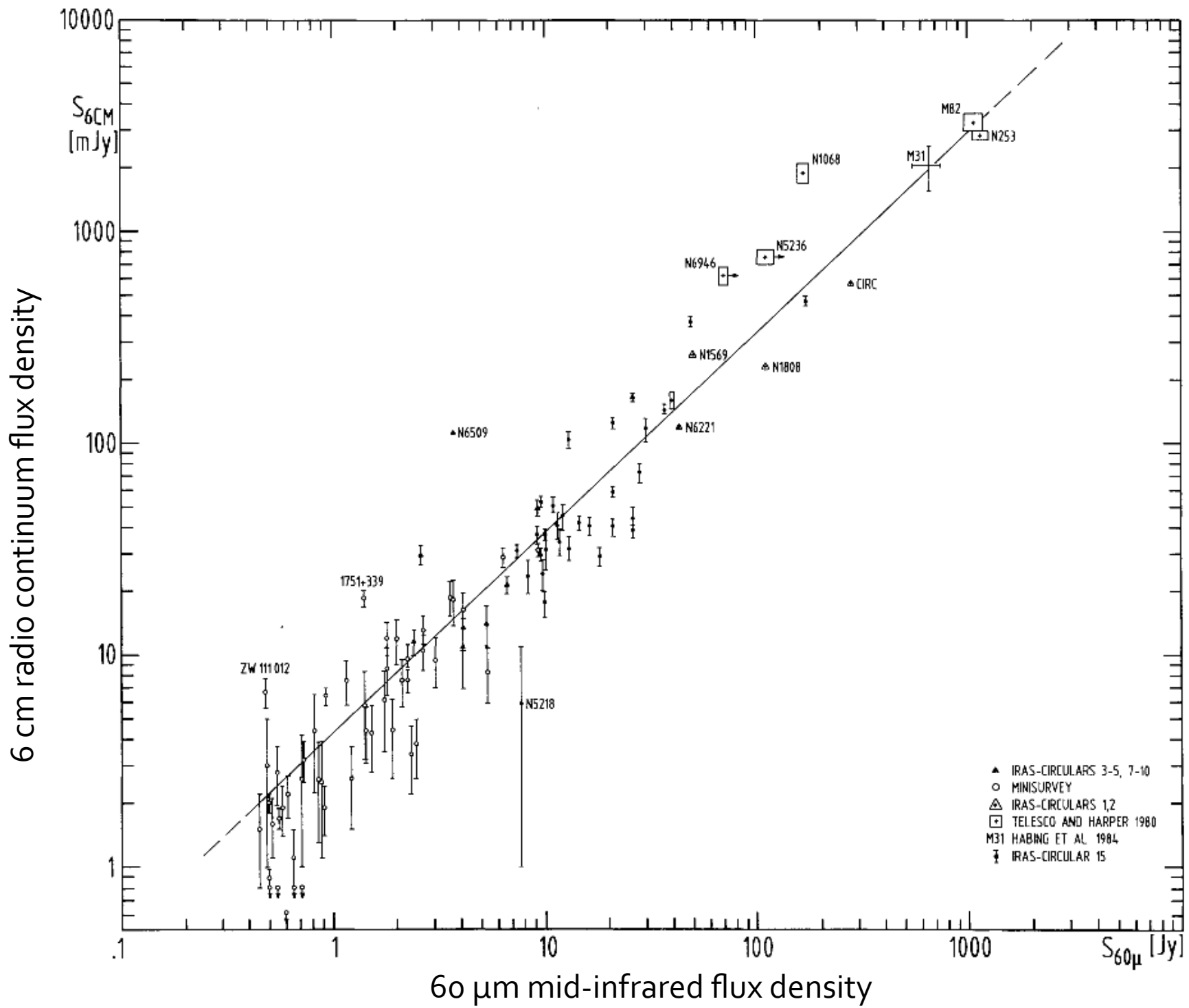
Probing cosmic rays in nearby dwarf irregular galaxies with deep radio continuum observations

Motivation

- RC as an extinction free SF tracer
 - Do dwarfs lie on the radio–FIR correlation?
- Do dwarfs have (ordered) magnetic fields?
 - Amplification by galactic dynamo
 - Thermally / non-thermally dominated?
- Dwarf galaxies as “building blocks”
 - Magnetization of the early Universe

Outline

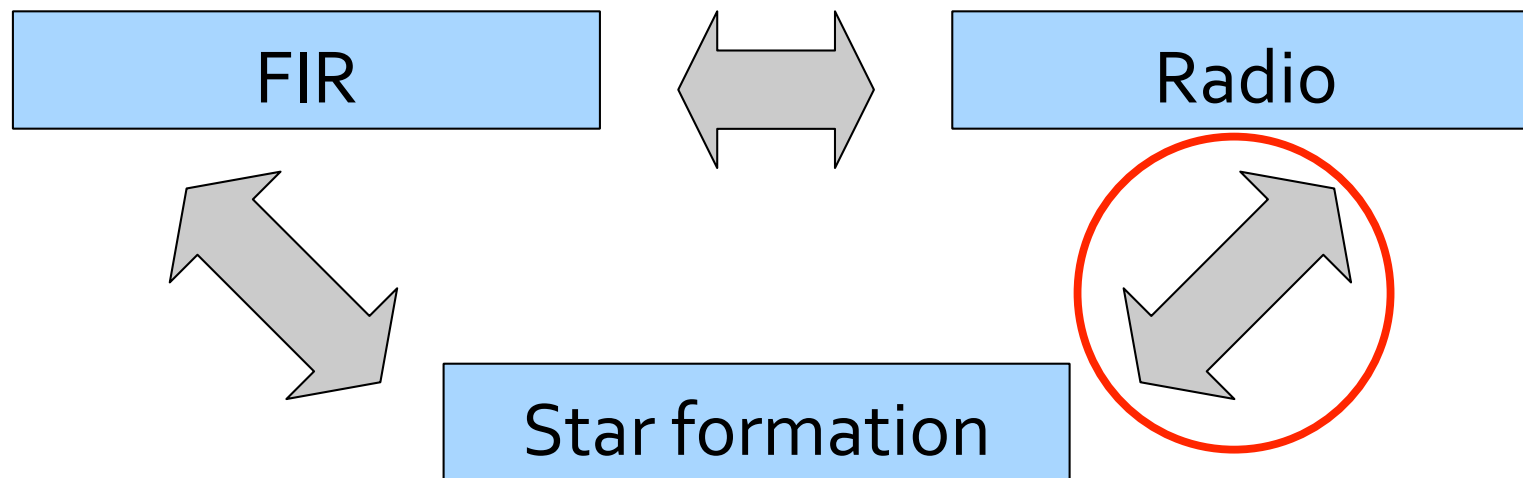
- Resolved RC–SFR correlation
- Dwarf irregular galaxy IC10
 - RC emission as SF tracer
 - Magnetic fields



de Jong et al. 1985

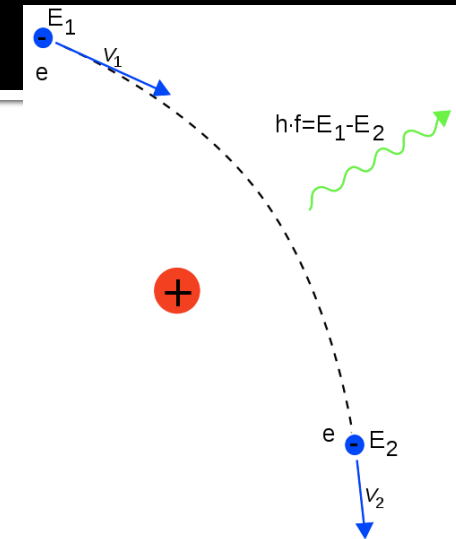
Radio–SFR correlation

- Break up the RC–FIR correlation into
 - RC–SFR correlation
 - FIR–SFR correlation



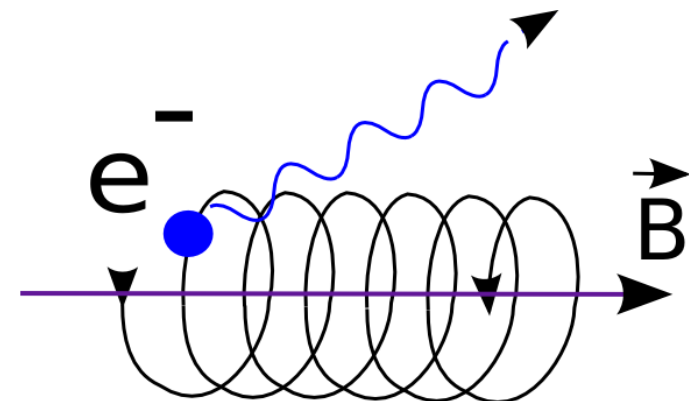
Radio emission in galaxies

- Thermal emission
 - UV-photons ionize gas
 - Free-free radio emission
 - Can use H α as tracer
- Non-thermal emission
 - Cosmic-ray electrons
 - Magnetic fields
 - Synchrotron emission



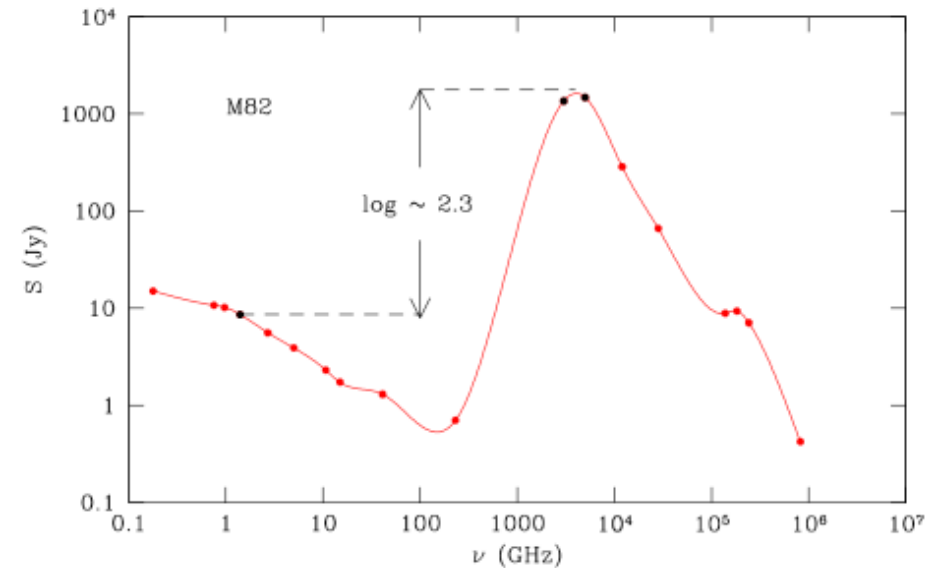
Massive stars

Wikipedia



RC–SFR correlation

- Radio continuum (RC)
- Thermal RC ideal SFR tracer
- Non-thermal emission dominates \propto SFR
- Resolved study
- Separate AGNs
- Condon's relation



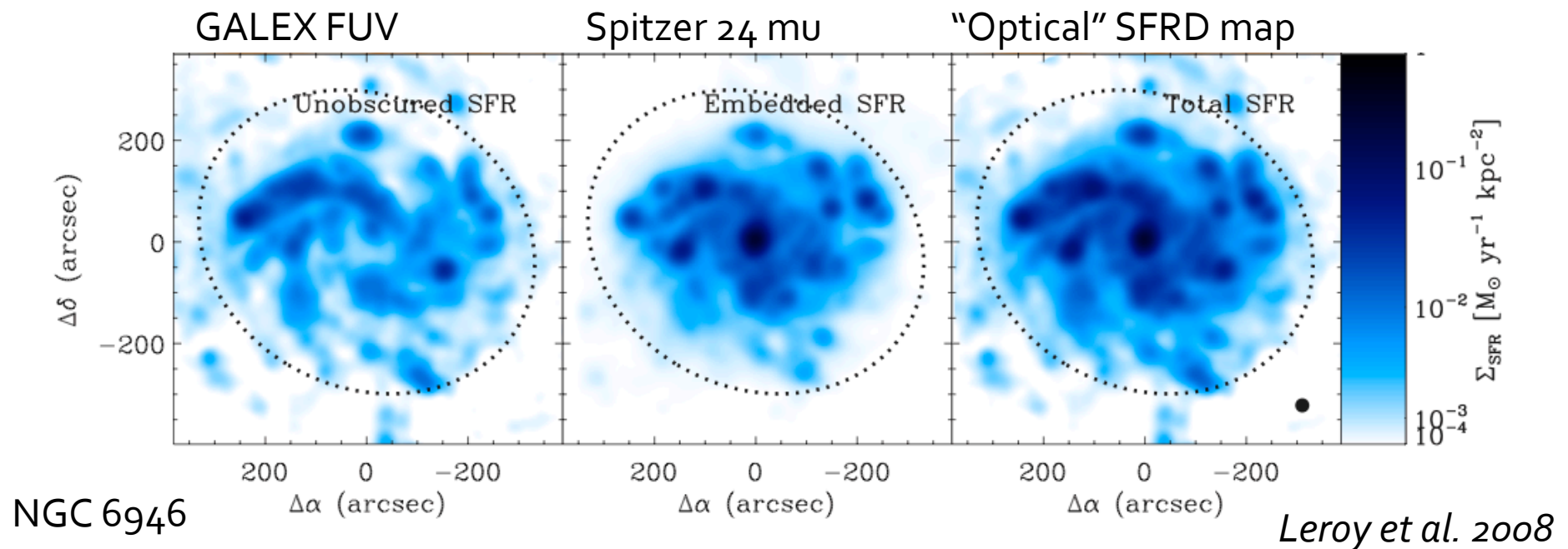
J. Condon

$$\left(\frac{\text{SFR}}{M_{\odot} \text{ yr}^{-1}} \right)_{>0.1 M_{\odot}} = 1.2 \times 10^{-21} \left(\frac{L_{1.4 \text{ GHz}}}{\text{W Hz}^{-1}} \right)$$

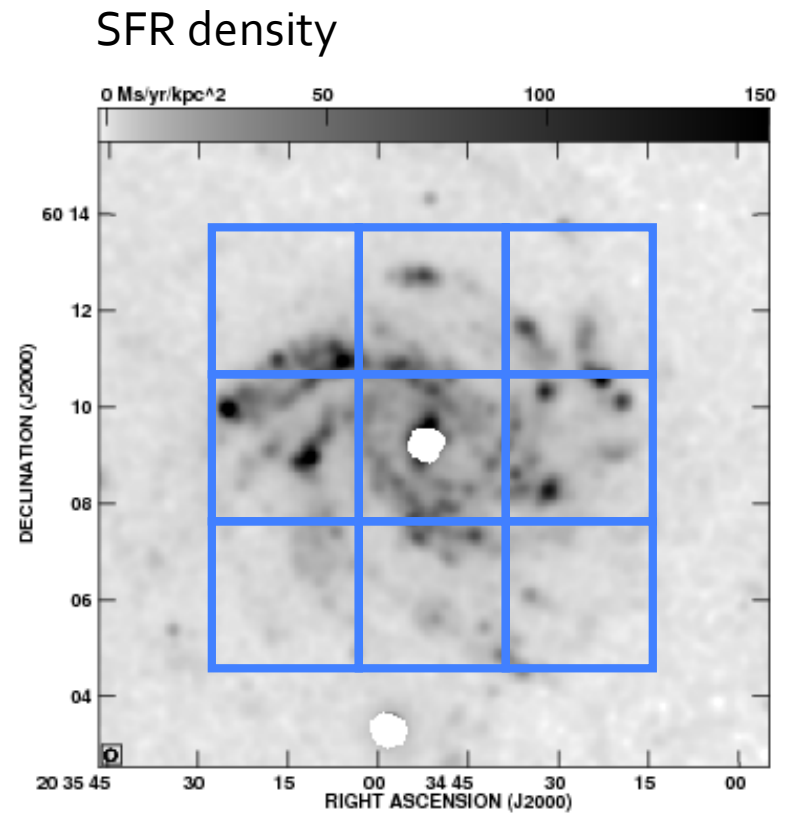
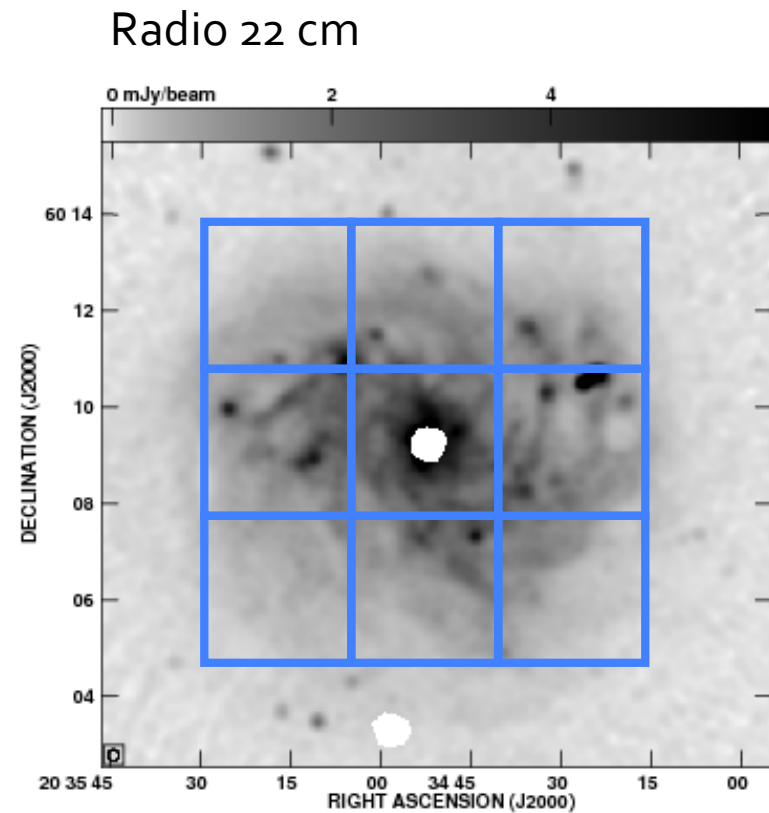
Condon (1992)

“Optical” star-formation tracers

- GALEX FUV: young massive stars
- *Spitzer* 24 μm : dust emission (SF regions)
- SFR density maps (Leroy et al. 2008, 2012)



Resolved SFRDs – NGC 6946



Grid not to scale!

- RC is smoothed SFRD map



y-axis: star formation rate per unit area

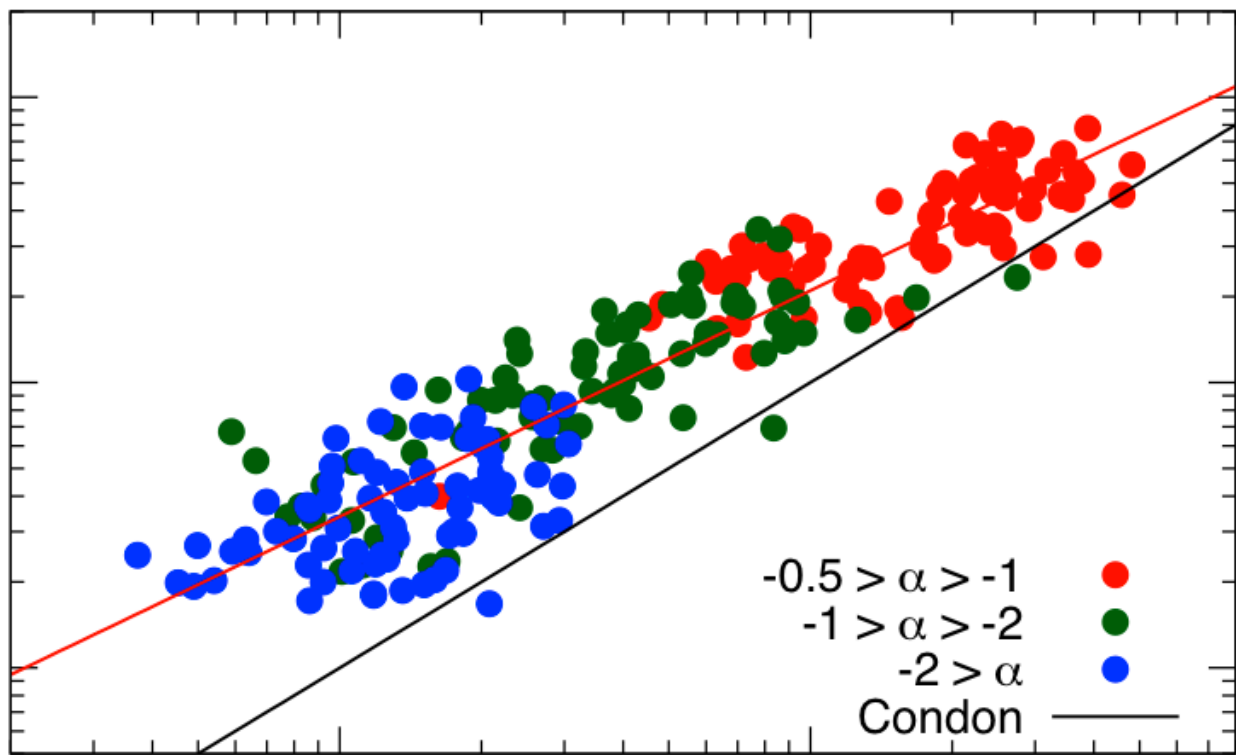
- Radio continuum emission at 22 cm

- Converted using Condon's relation

Non-thermal synchrotron and thermal free-free emission

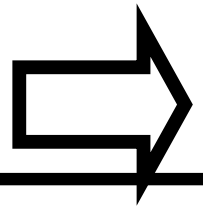
Radio SFRD [$M_{\text{solar}} \text{ yr}^{-1} \text{ kpc}^{-2}$]

10^{-1}
 10^{-2}
 10^{-3}



$-0.5 > \alpha > -1$
 $-1 > \alpha > -2$
 $-2 > \alpha$
Condon

Optical SFRD [$M_{\text{solar}} \text{ yr}^{-1} \text{ kpc}^{-2}$]



- Flat radio spectral index
- Intermediate radio spectral index
- Steep radio spectral index

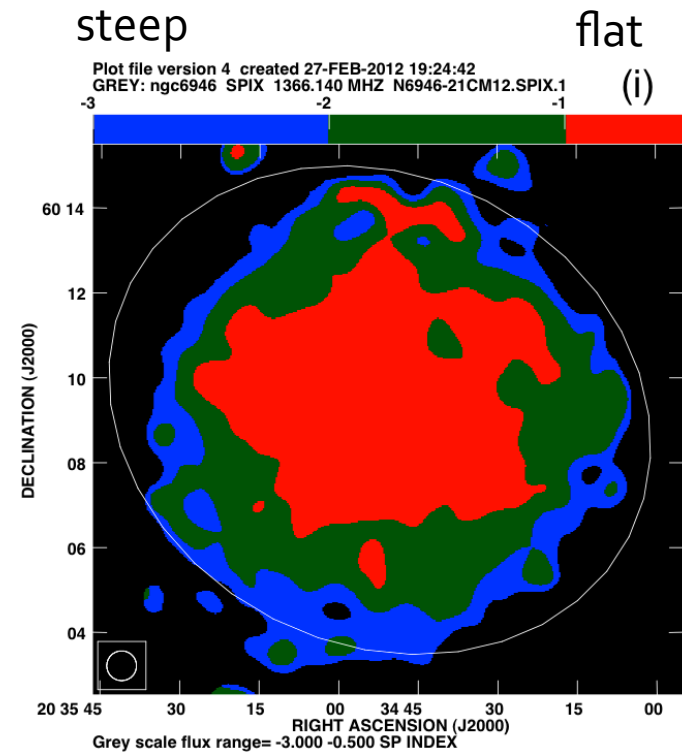
x-axis: star formation rate per unit area

Ultraviolet (GALEX FUV)
Unobscured young (O and B) stars.

Infrared (*Spitzer* $24\mu\text{m}$)
Dust enshrouded young stars.

Local RC–SFR correlation

- Local correlation
 - $\log(\text{RC}) = \zeta \times \log(\text{SFRD})$
($\zeta = 0.63 \pm 0.25$)
- Steep/flat spectral index
 - Radio bright/dim
- Cosmic-ray transport!



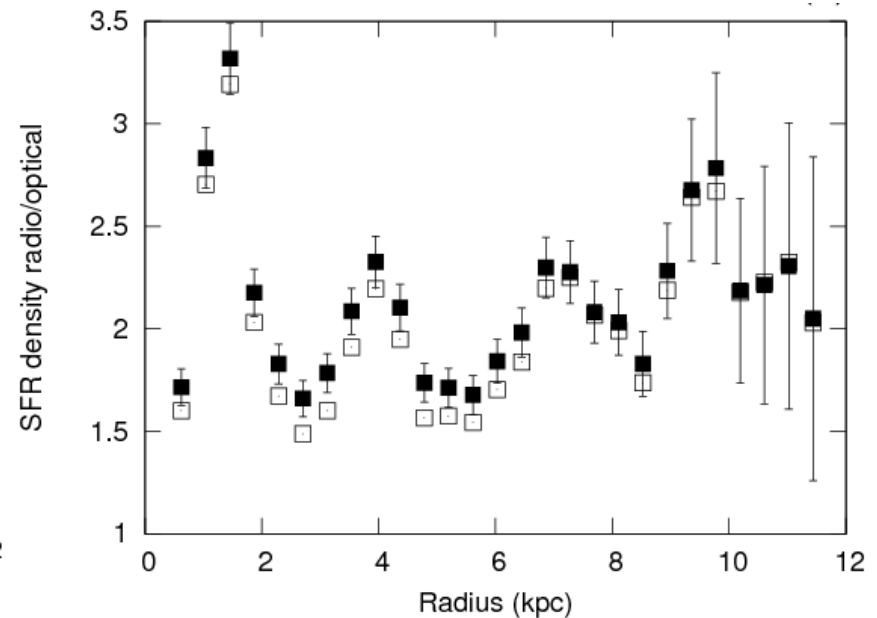
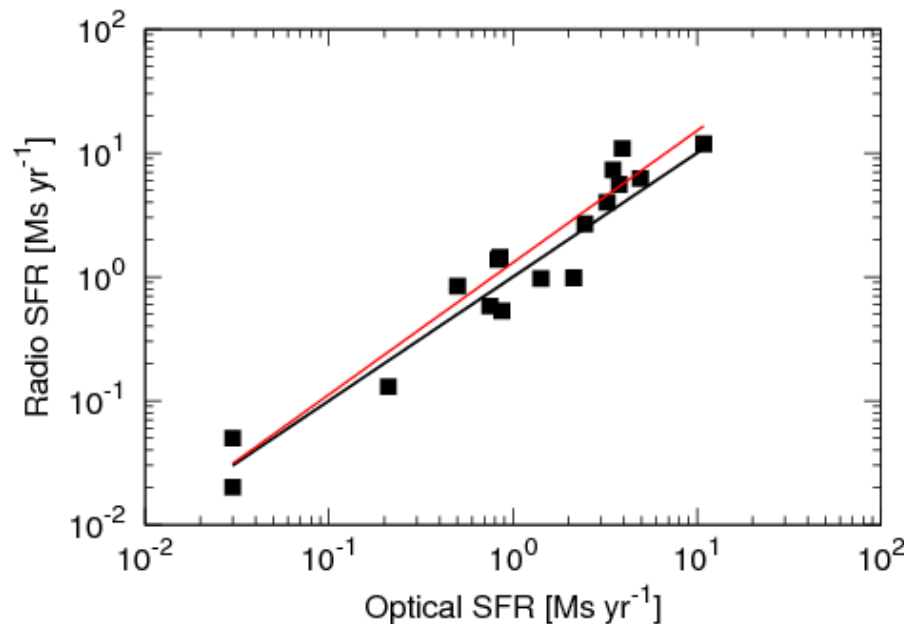
NGC6946

WSRT spectral index 22/18 cm

1.2 kpc resolution

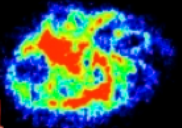
Resolved RC–SFR correlation

- Condon's relation confirmed
- RC/optical SFRD = 1.2 ± 0.6
- No strong correlation with global parameter
- Non-thermal RC is good SF tracer!



Outline

- Resolved RC–SFR correlation
- Dwarf irregular galaxy IC10
 - **RC emission as SF tracer**
 - Magnetic fields



The LITTLE THINGS Survey

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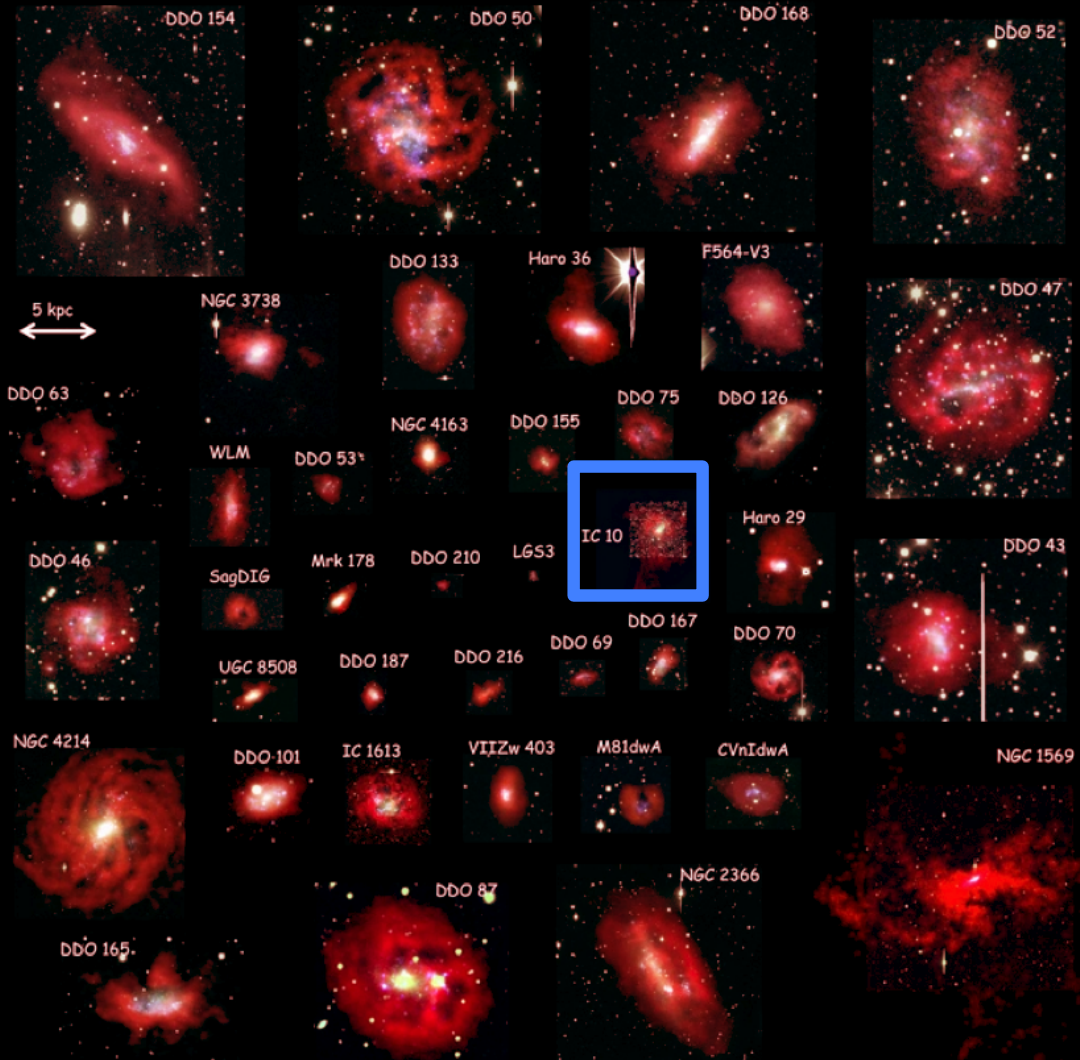
ABSTRACT

We have assembled a multi-wavelength dataset on 40 relatively normal, nearby (<10 Mpc) gas-rich dwarf irregular galaxies for the purpose of determining the drivers for star formation in these systems. This project is called LITTLE THINGS (Local Irregulars That Trace Luminosity Extremes, The HI Nearby Galaxy Survey). Our data include GALEX UV images, ground-based UB_v and H α images, some ground-based JHK images, Spitzer archival mid-IR images, and HI-line maps. The VLA HI maps go deep (12/6/2 hrs in B/C/D arrays) with high spectral resolution (± 2.6 km/s) and high angular resolution ($\approx 6''$). Our datasets trace the stellar populations, gas content and structure, dynamics, and star formation indicators in the galaxies. We are making the HI data available to the public for the first time January 2012. Here we give a taste of the data that are available: <http://science.nrao.edu/science/surveys/littlethings>.



LITTLE THINGS

All images are shown at the same linear scale (courtesy Kim Herrmann). HI (red), V (green), FUV (blue; a few are H α or NUV instead)



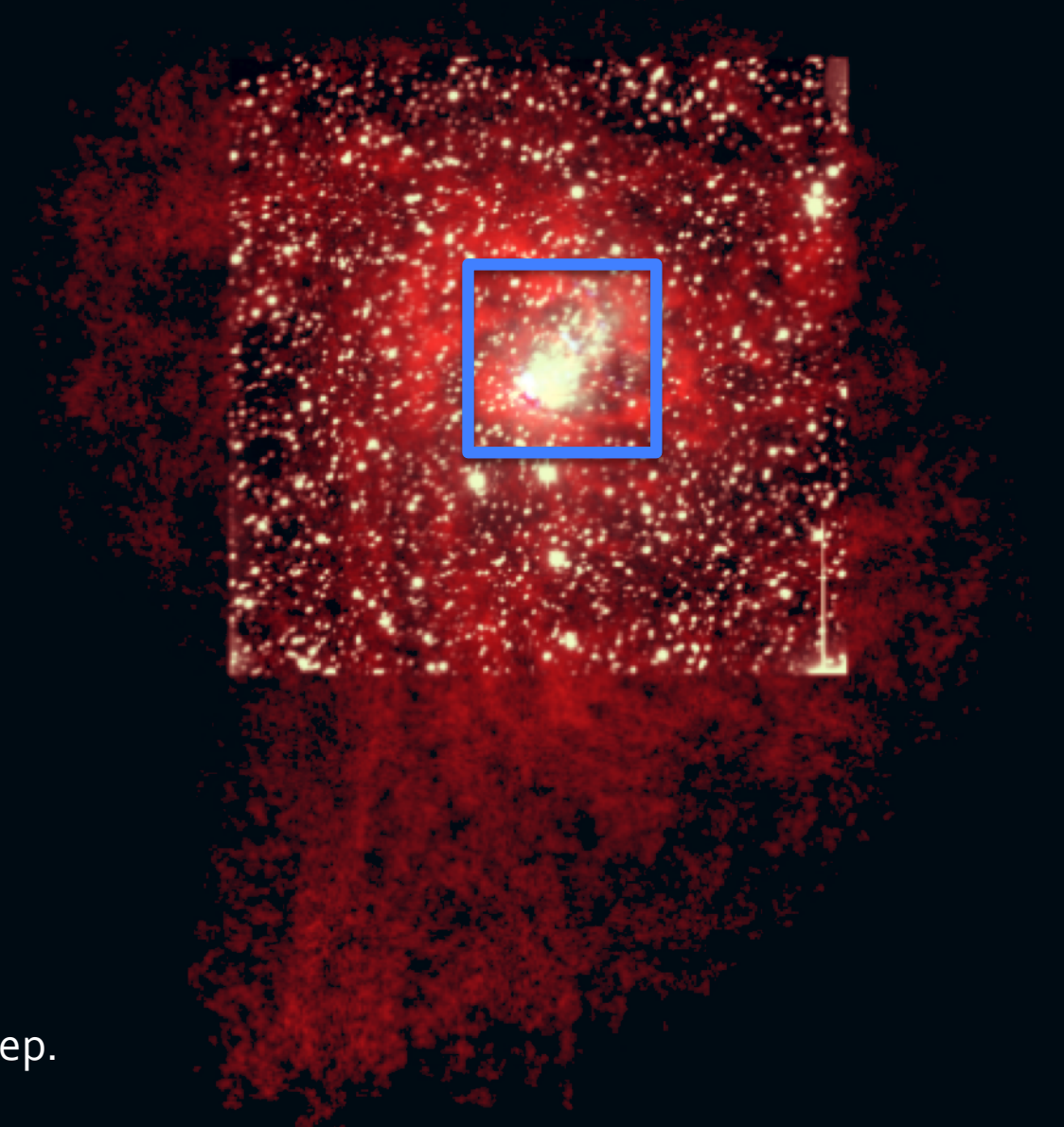
EVLA observations

IC10 + IC1613 at 20, 6, 3, 1 cm

Entire sample at 6 cm

See poster by Ged Kitchener

The LITTLE THINGS team is grateful to NRAO for telescope time and for support of team and public data access and to the National Science Foundation for funding through grants AST-0707563 (DAH), AST-0707426 (BGE), AST-0707468 (CES), and AST-0707835 (LMY). We thank Ms. Lauren Hill for producing the color images.



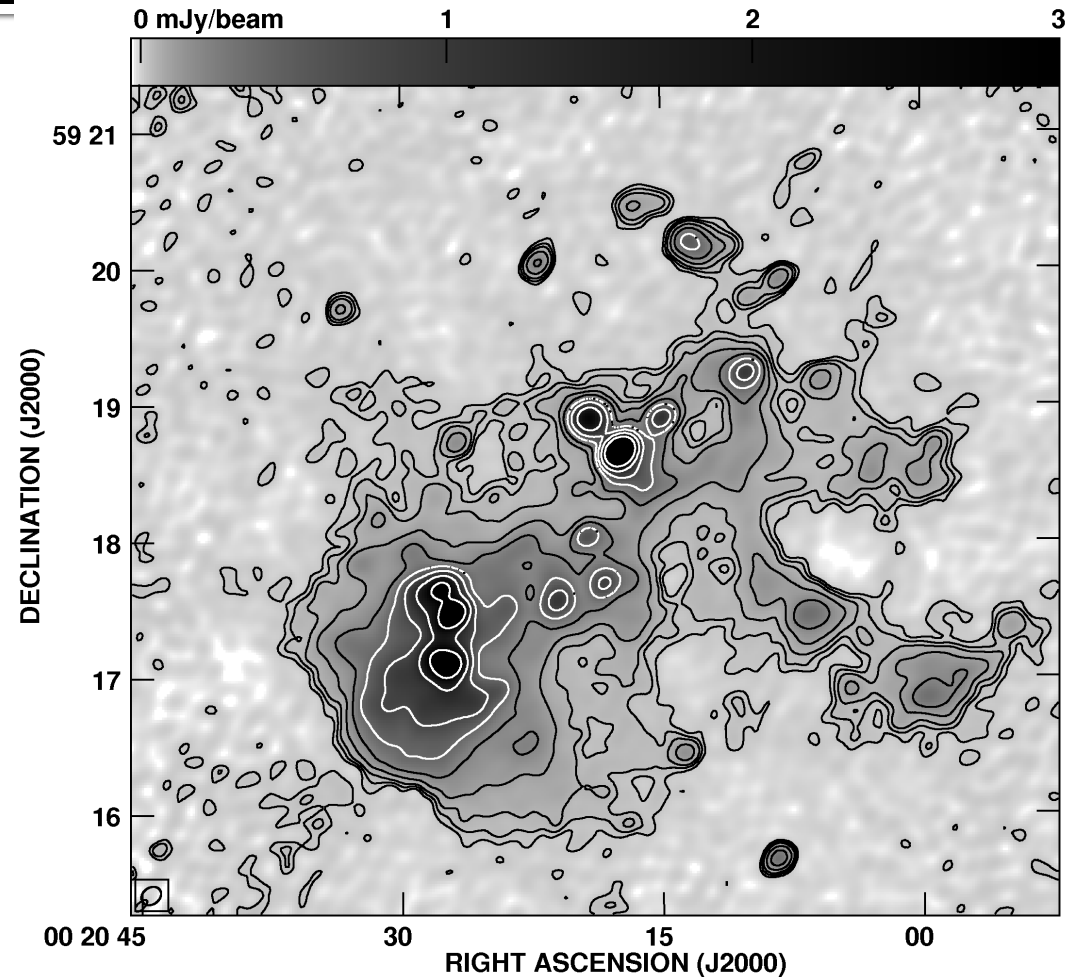
IC₁₀

HI emission

Hunter et al., in prep.

EVLA observations

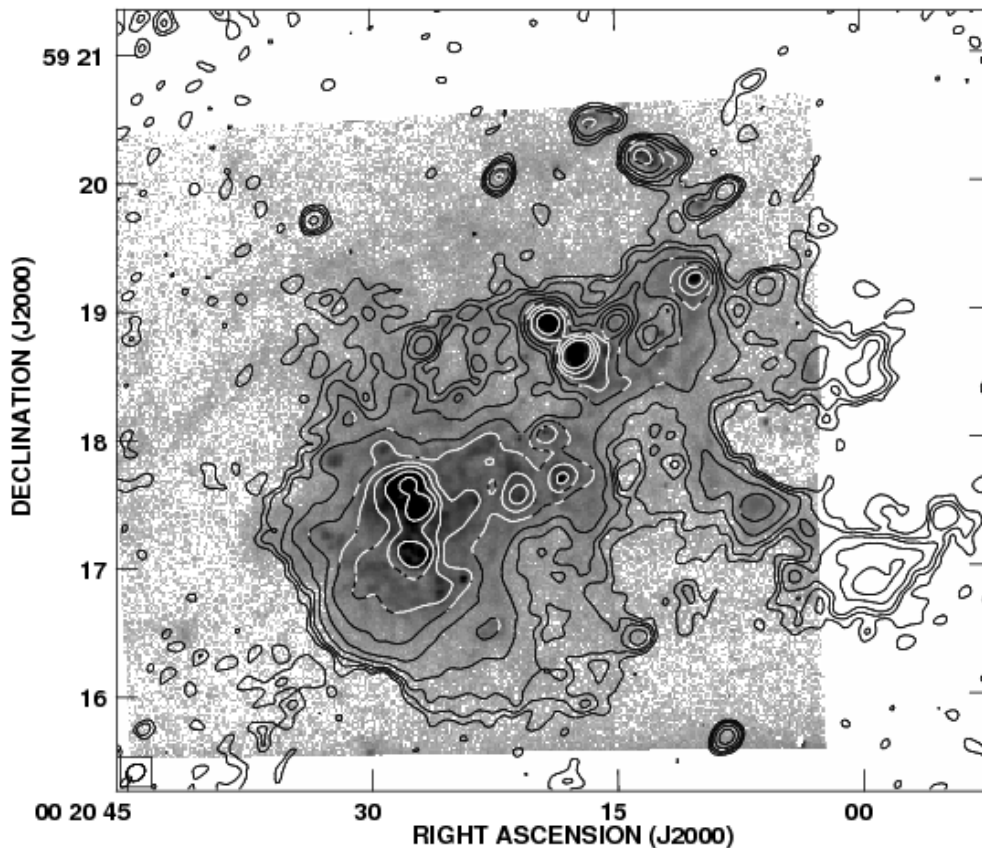
- 4h D-configuration at 6cm
- 5 $\mu\text{Jy}/\text{beam}$ rms noise
- Only 20% higher than theoretically expected



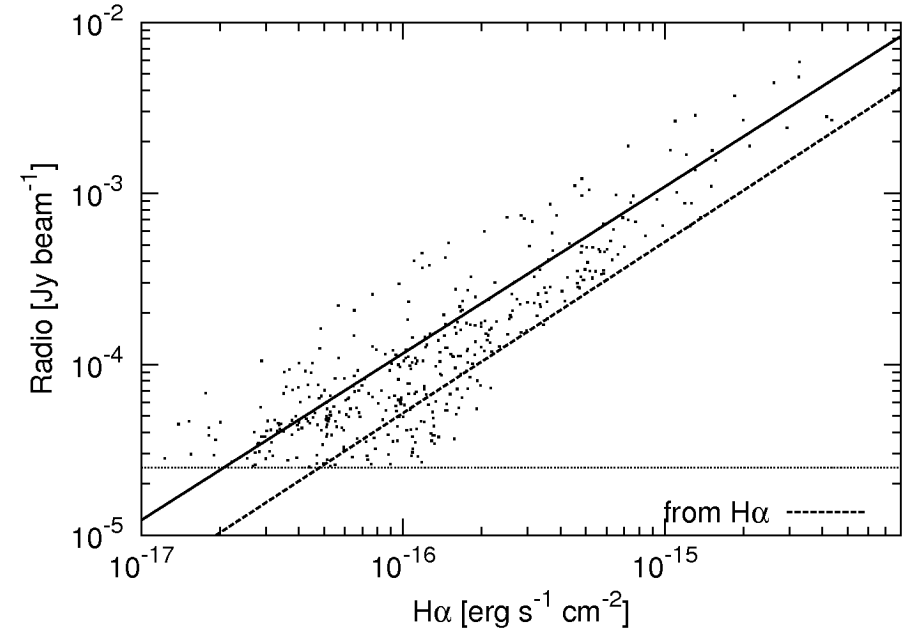
6 cm total power

Contours: $2^n \times 3$ sigma

RC – H α at 50 pc resolution



RC – H α correlation
50 pc resolution



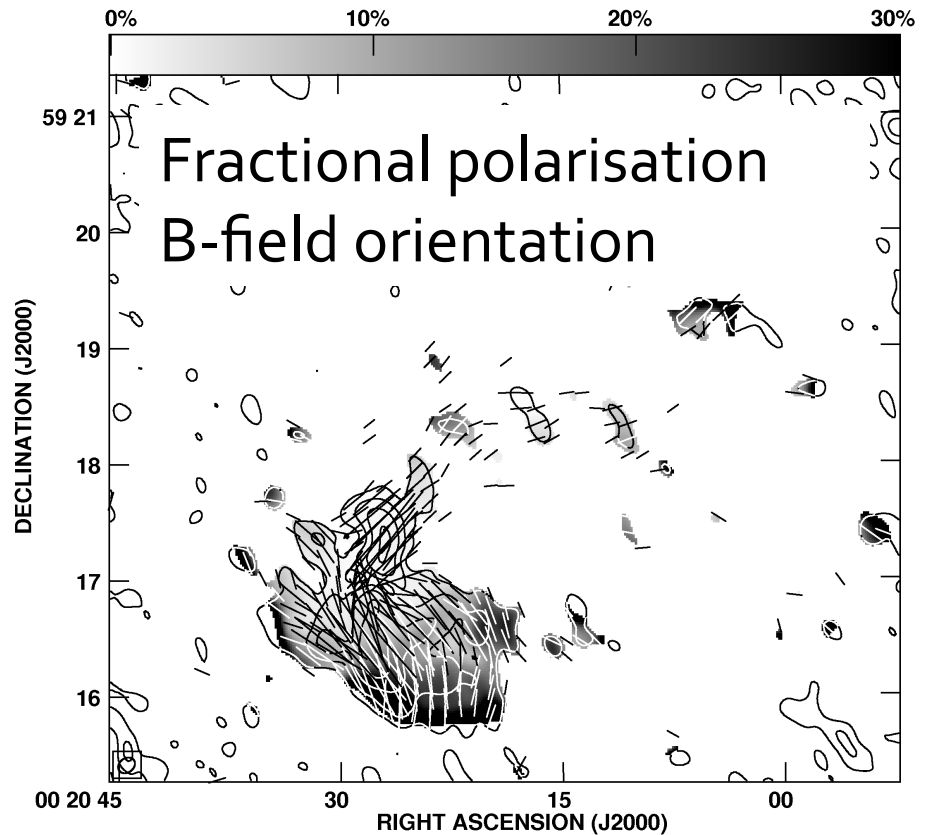
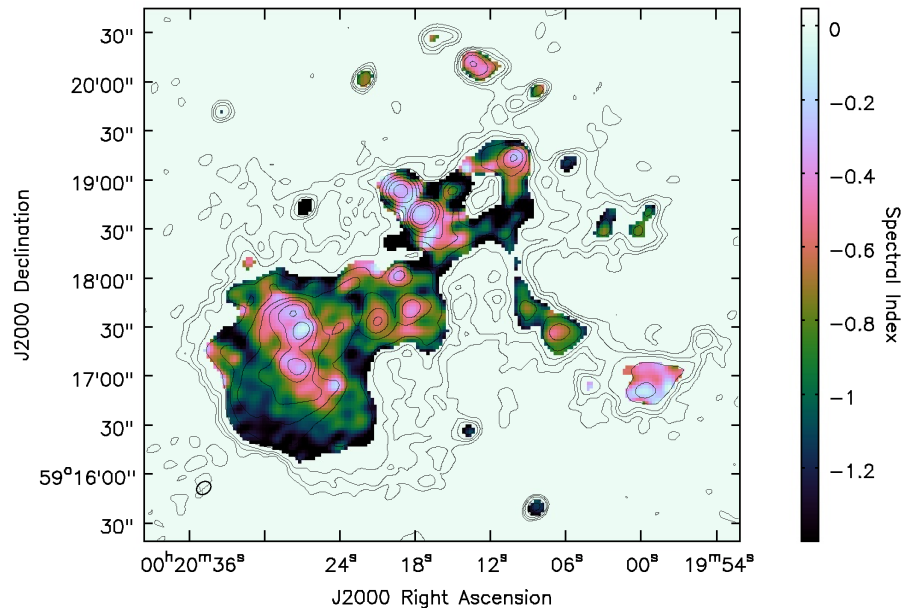
- 50% thermal RC emission
- Radio dim by factor 2–3 (Kennicutt 1998)

Outline

- Resolved RC–SFR correlation
- Dwarf irregular galaxy IC10
 - RC as SF tracer
 - **Magnetic fields**

Magnetic fields in IC10

Radio spectral index

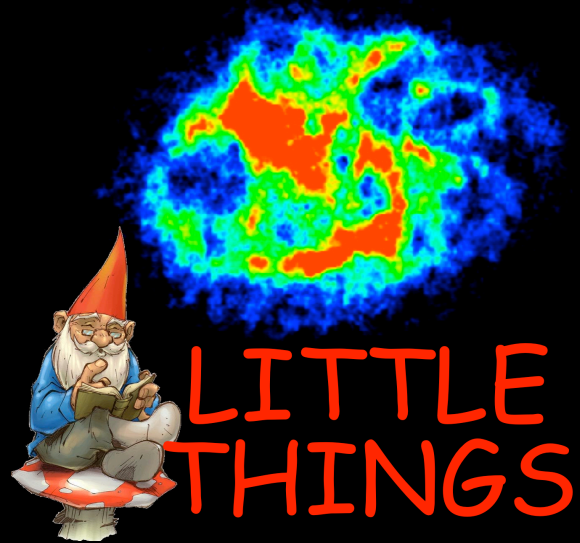


- Non-thermal bubble
- Fractional polarization 10–20%
- Possibly compression by shock waves

Conclusions

- Resolved RC–SFR correlation
 - Condon's relation works!
- Dwarf irregular galaxy IC10
 - High thermal RC fraction
 - Radio dim (compared to SFR)
 - Locally amplified B-fields

Thank you!



LITTLE
THINGS