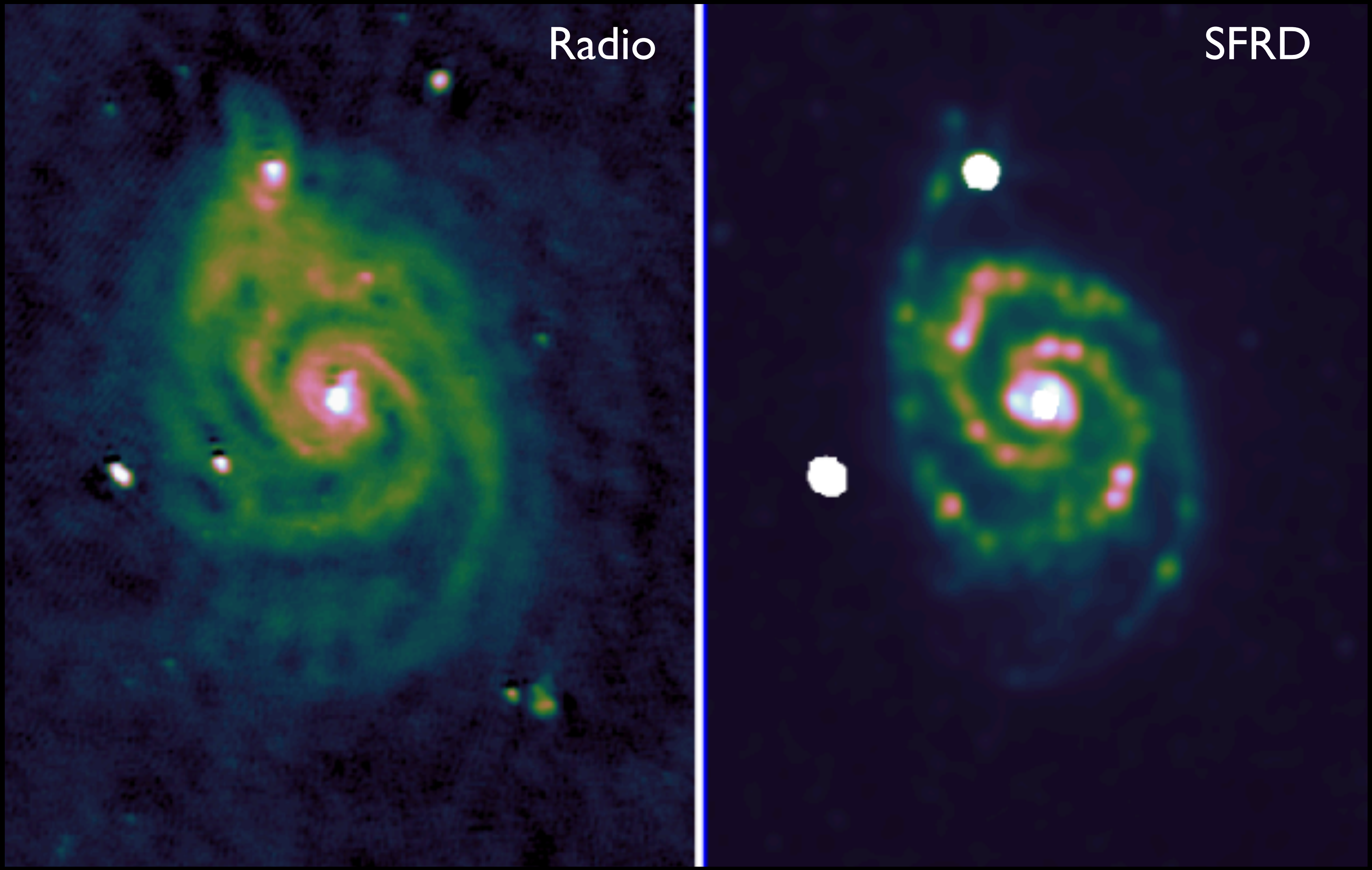
The low-frequency radio continuum—star formation rate relation in nearby galaxies with LOFAR

Volker Heesen
Hamburger Sternwarte



hamburger sternwarte
UHH Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

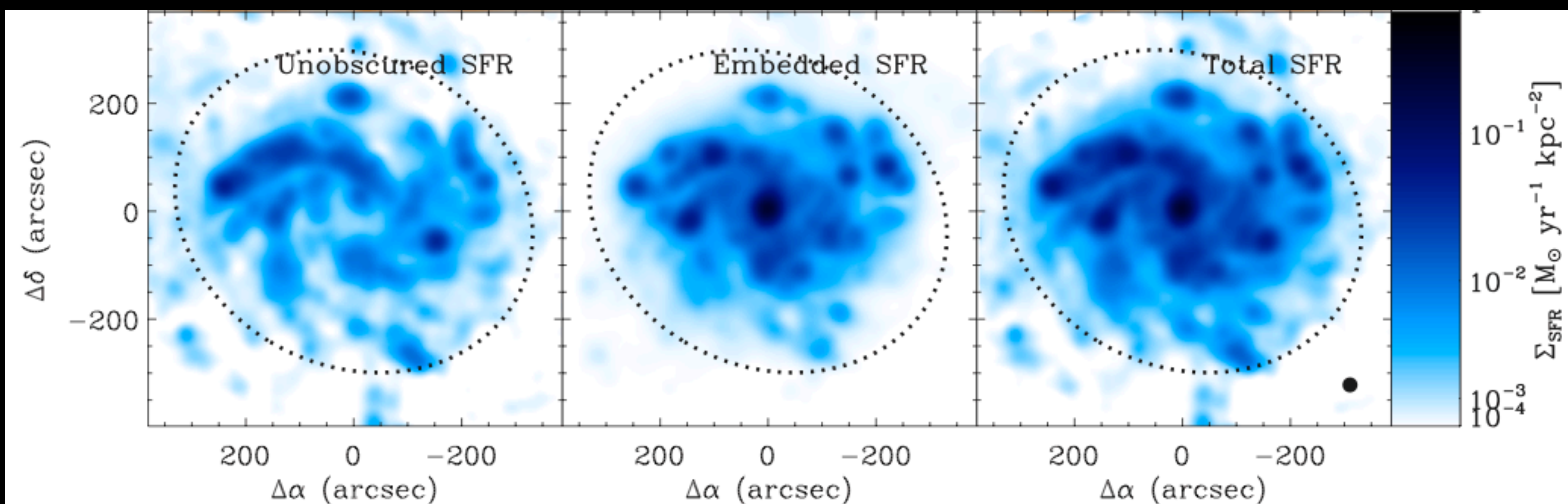
Motivation: radio–SFR relation

- Radio continuum as an extinction free SF tracer
  - No cryogenic satellites needed
- Physical reasons behind it
  - (1) CRE (cosmic-ray electrons) calorimetry
  - (2) Energy equipartition B–CR
- Cosmic-ray transport
  - Diffusion in the disc
  - Advection in the halo (galactic wind)

Star-formation surface density (SFRD)

(Leroy et al. 2008, 2012)

- GALEX FUV: young massive stars
- Spitzer 24 μm: dust emission (SF regions)
- Linear combination: FUV + 24 μm



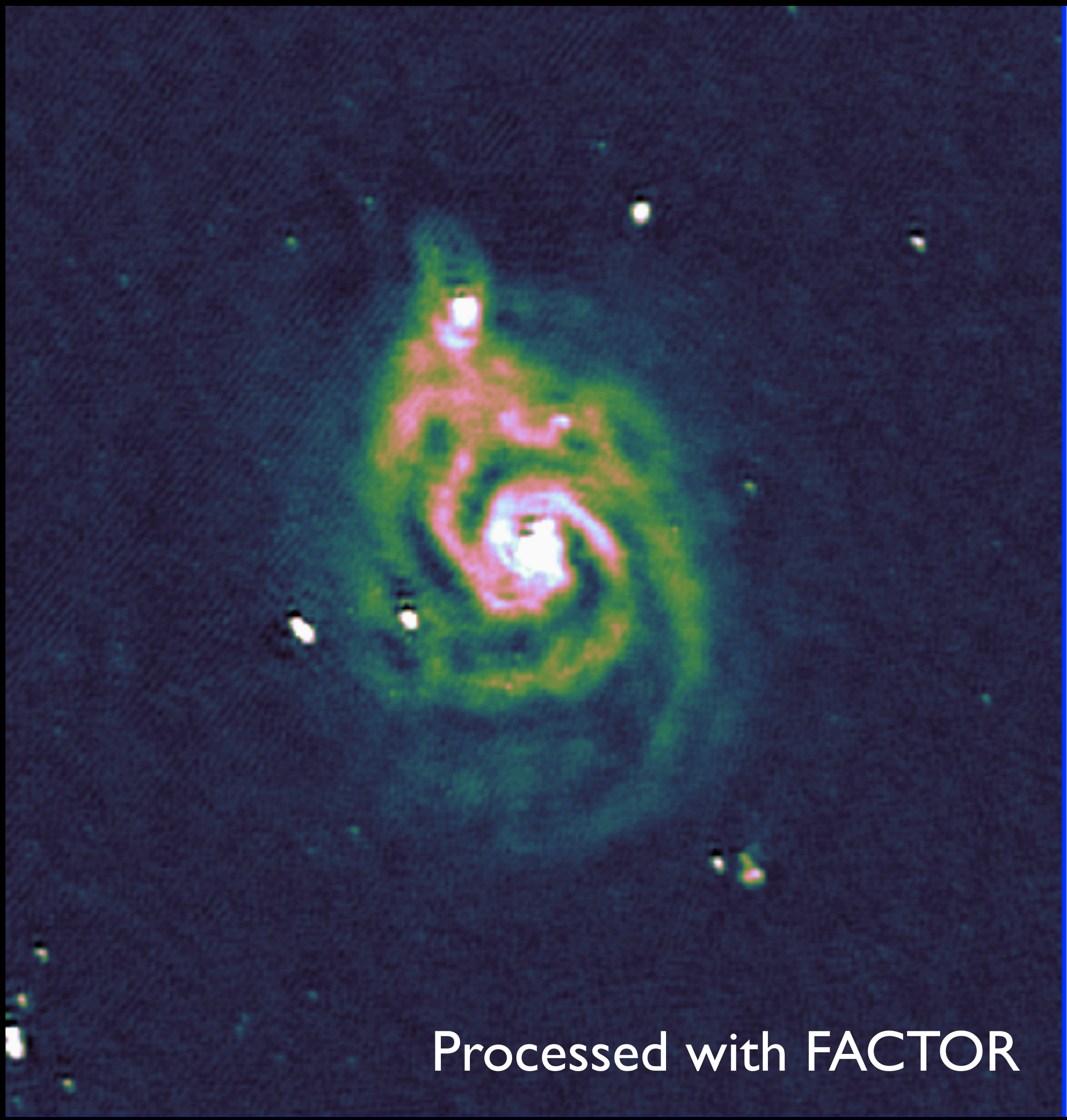
NGC 6946

ASU
ARIZONA STATE UNIVERSITY

NGC 5194 (The 'Whirlpool Galaxy')

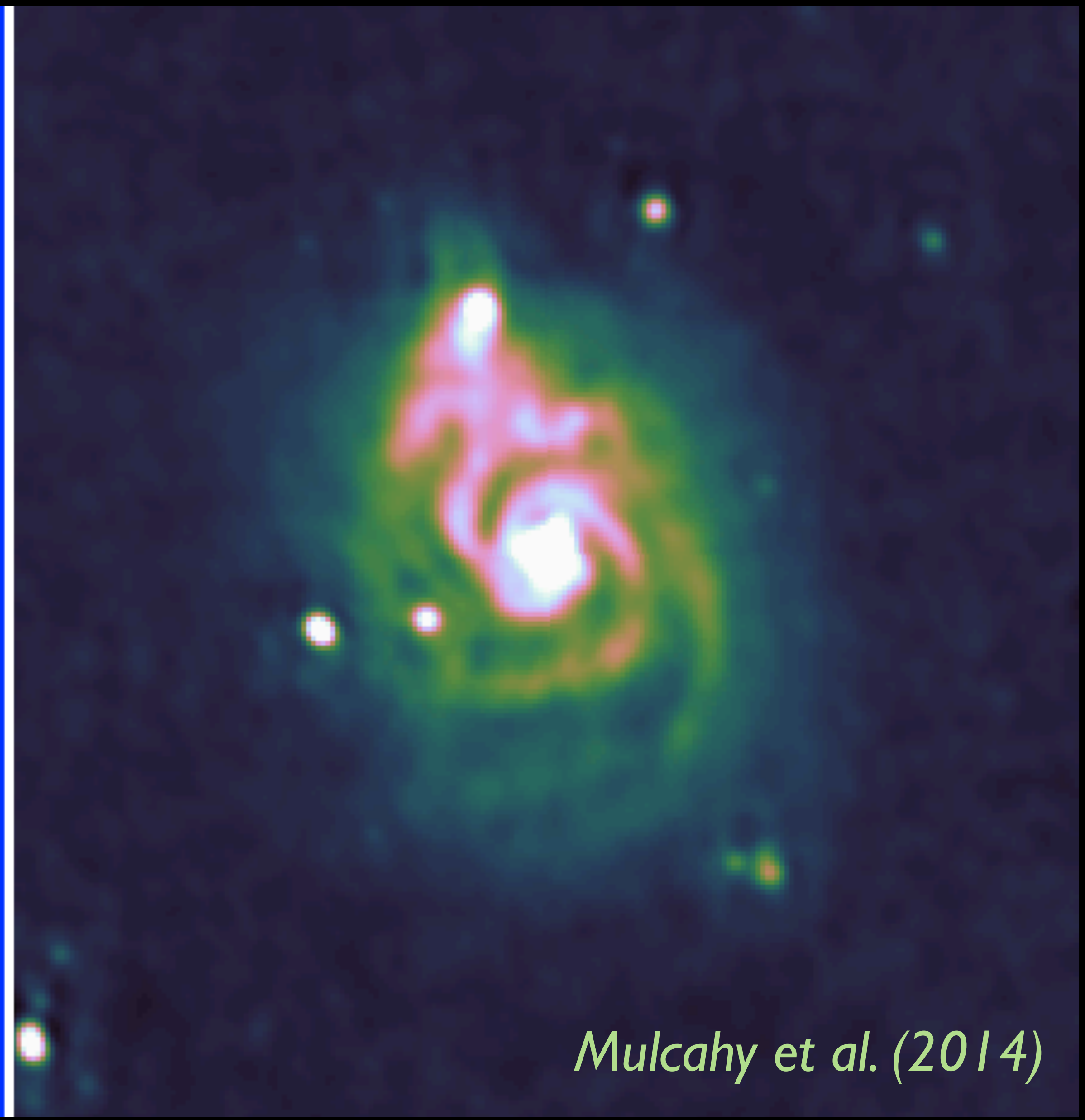
Lucia Perez

LOFAR 140 MHz



FWHM = 7 arcsec
rms = 130 μJy/beam

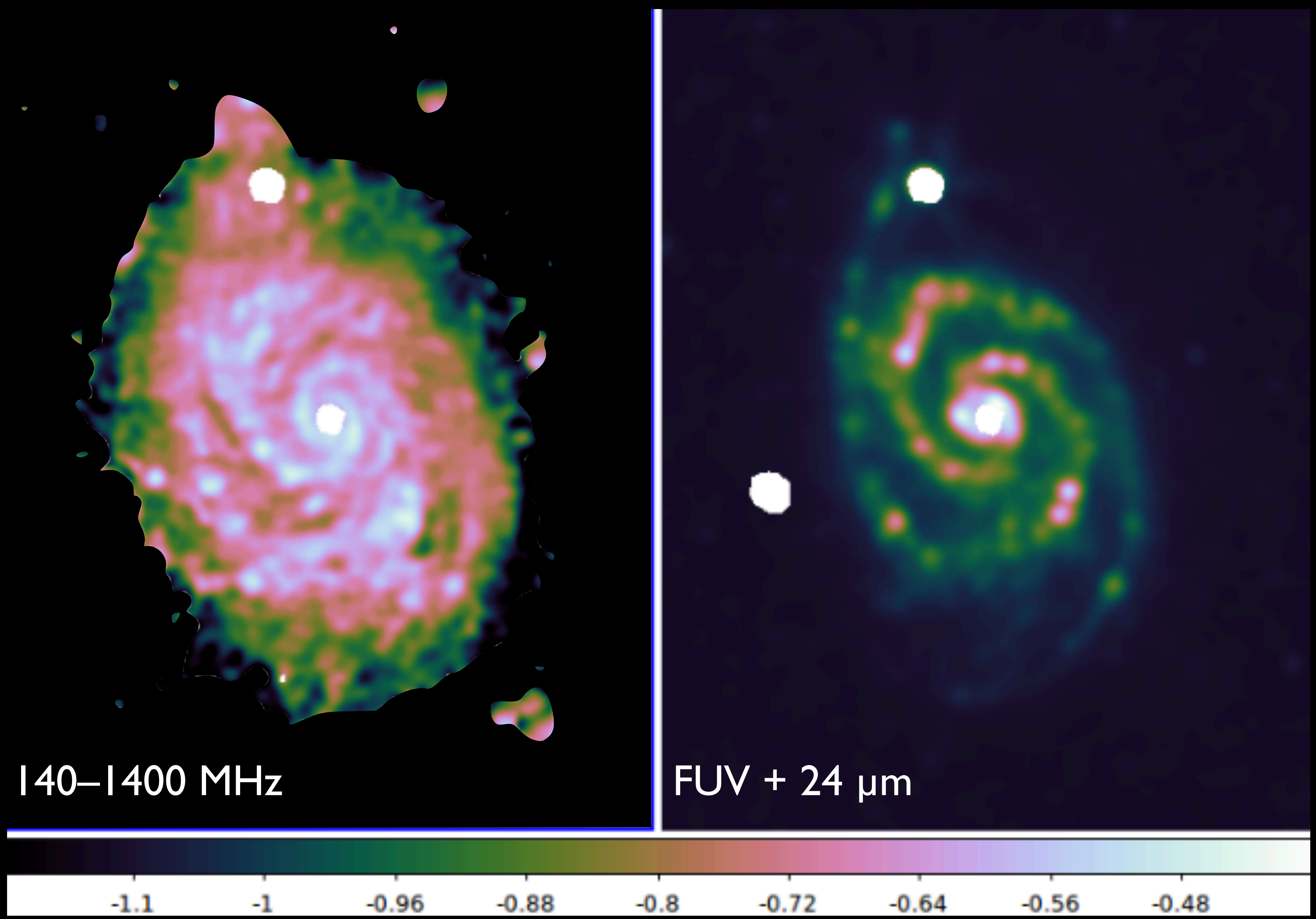
LOFAR 140 MHz



FWHM = 20 arcsec
rms = 350 μJy/beam

Spectral ageing of cosmic-ray electrons (CREs)

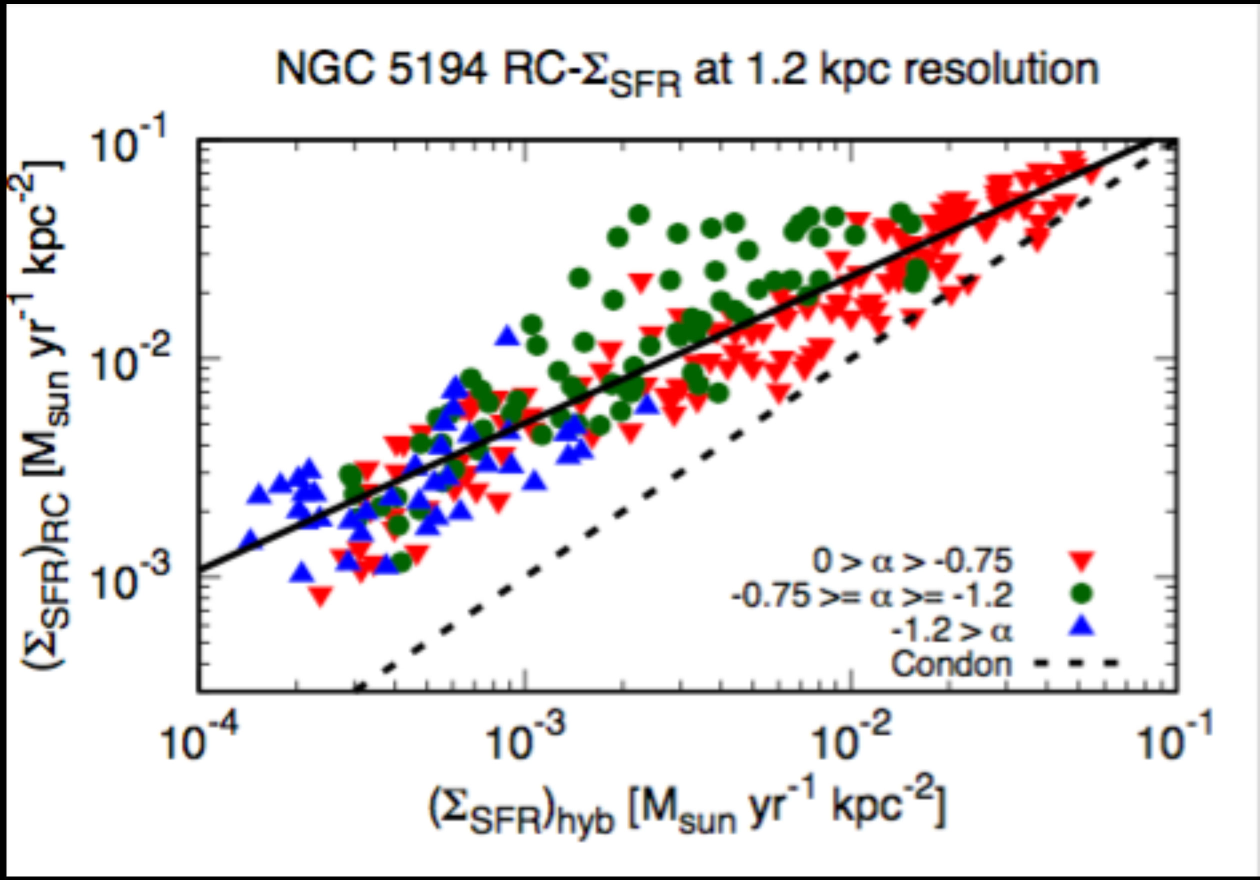
Radio spectral index SFRD

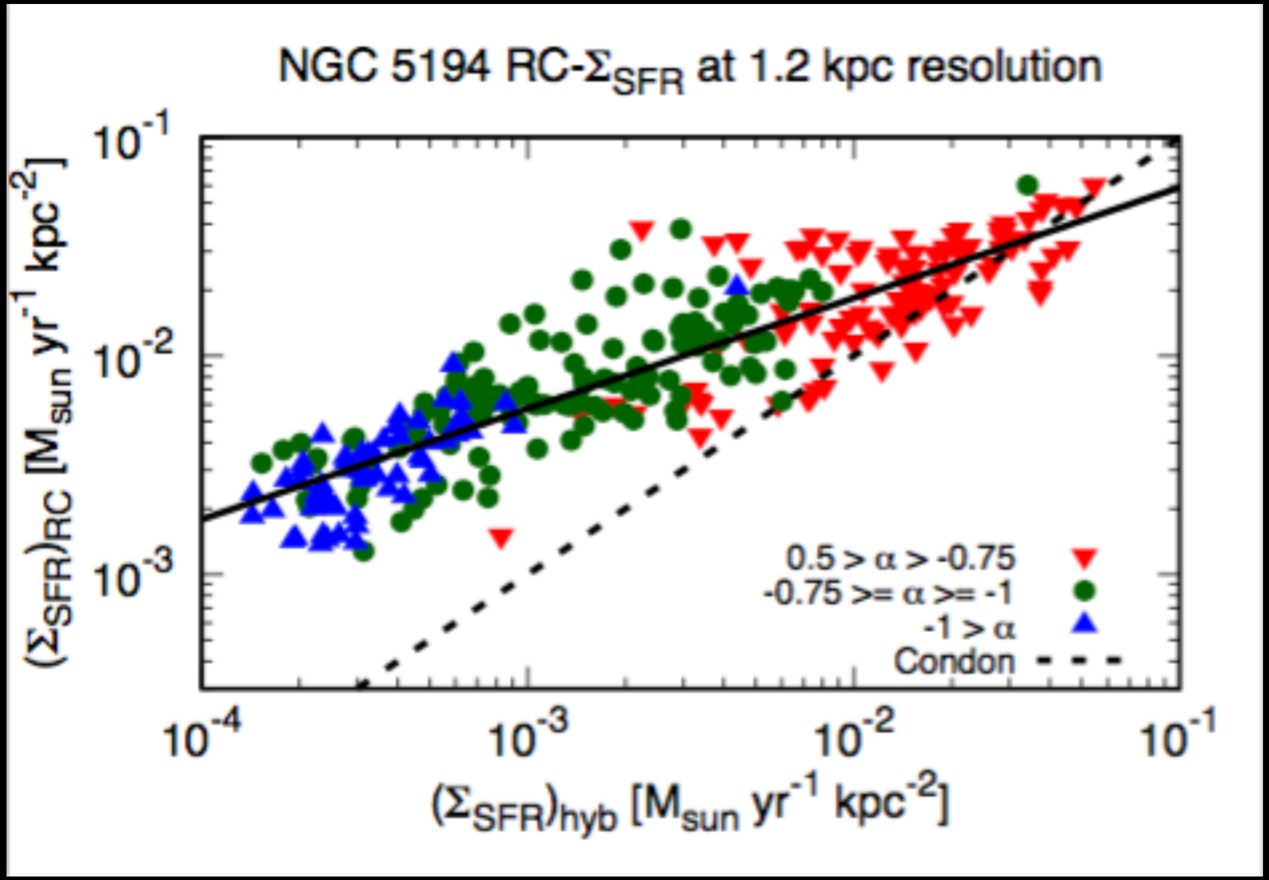


Young CREs in spiral arms, old CREs in interarm regions and outskirts

Radio–SFRD relation

WSRT 1.4 GHz Heesen et al. (2014) LOFAR 140 MHz





Spatially resolved relation (1.2 kpc):

$$\Sigma_{\rm SFR,hyb} \propto \Sigma_{\rm SFR,radio}^{0.67\pm0.02}$$

$$\Sigma_{\rm SFR,hyb} \propto \Sigma_{\rm SFR,radio}^{0.51\pm0.02}$$

CRE diffusion causes sub-linear radio-SFRD relation

Cosmic-ray diffusion

Star formation rate surface density

22cm radio continuum

Gaussian convolution kernel (at 1.4 GHz)

FWHM = 3.4 kpc ---> 1.7 kpc diffusion length

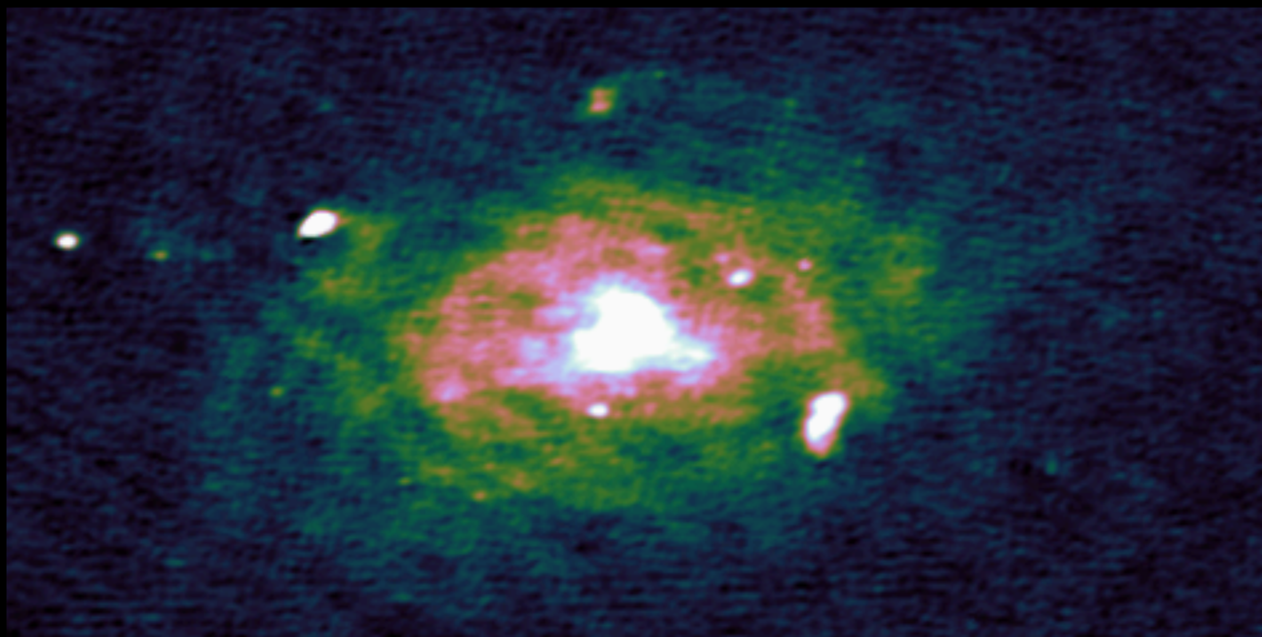
(Berkhuijsen et al. 2013; Tabatabaei et al. 2013; Heesen et al. 2014)

NGC 5055 (The 'Sunflower Galaxy')

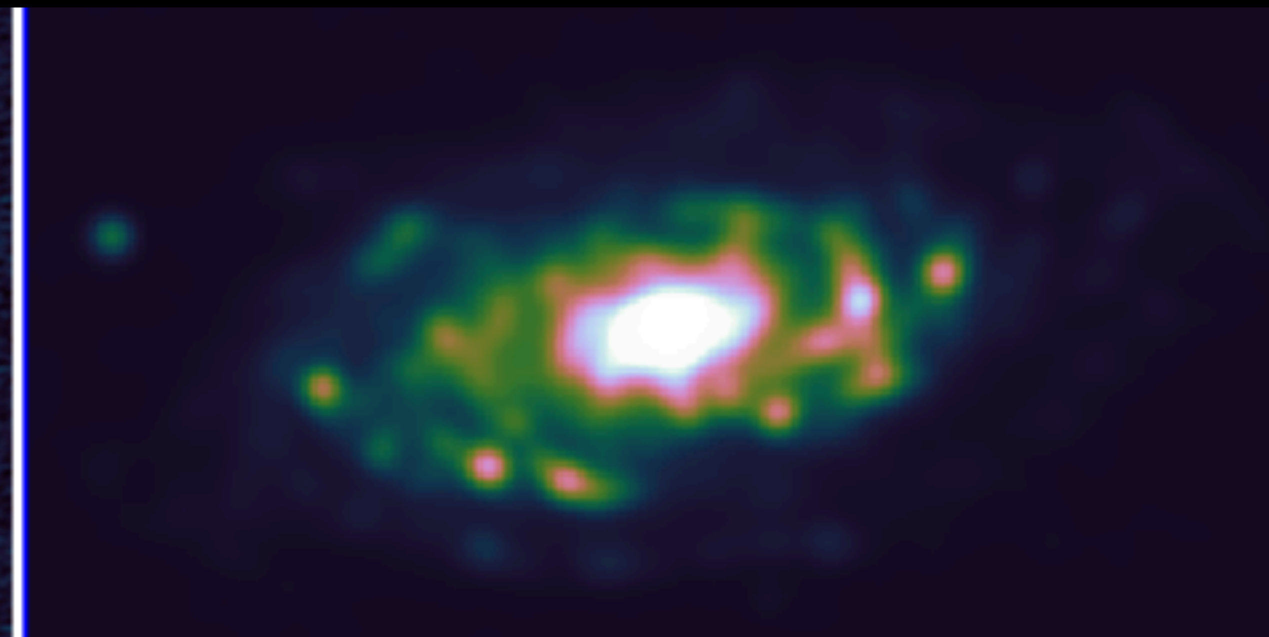
Cierra Huff

LOFAR

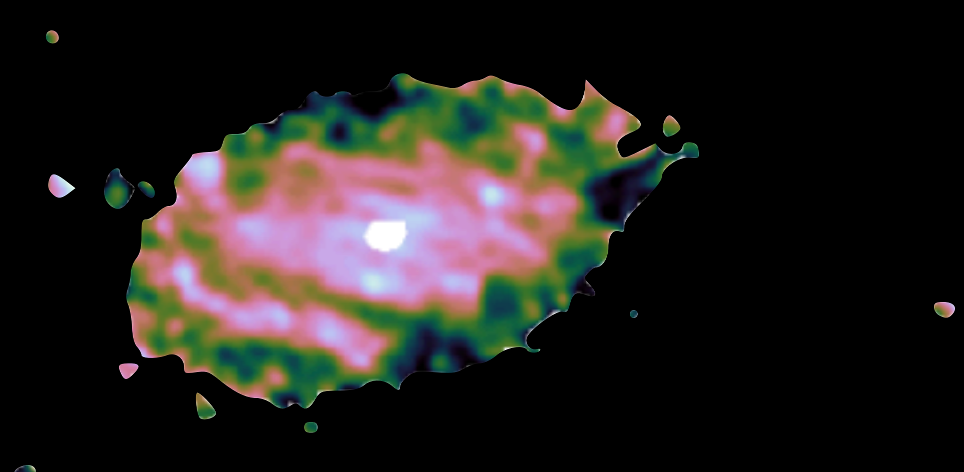
FWHM = 7 arcsec
rms = 100 μJy/beam



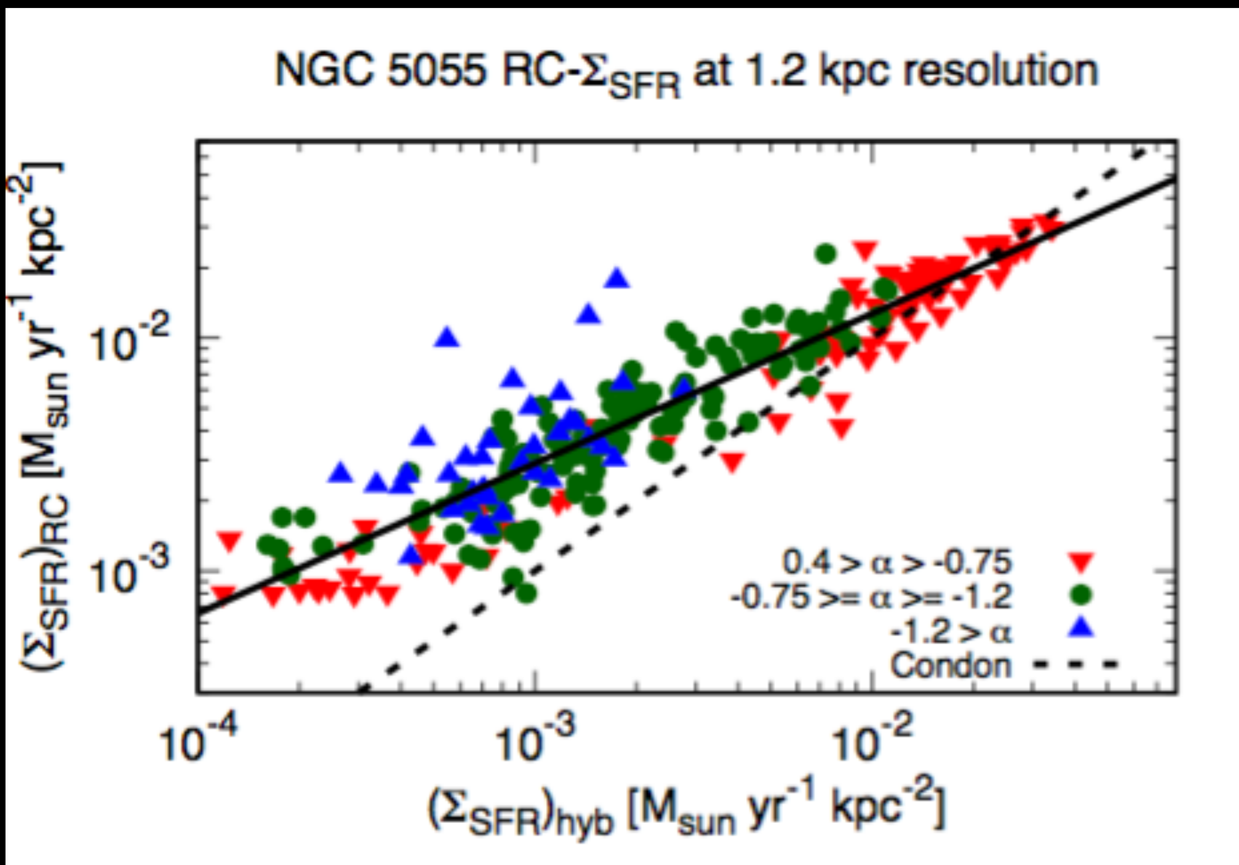
SFRD



Spectral Index



$$\Sigma_{\mathrm{SFR,hyb}} \propto \Sigma_{\mathrm{SFR,radio}}^{0.64\pm0.02}$$

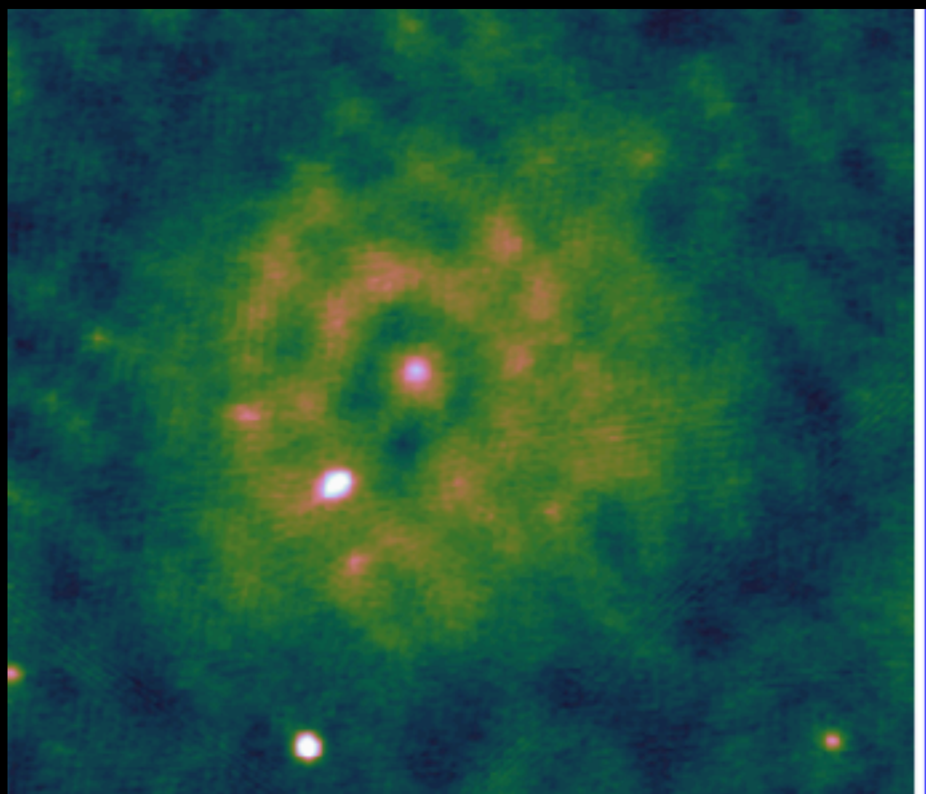


NGC 3184

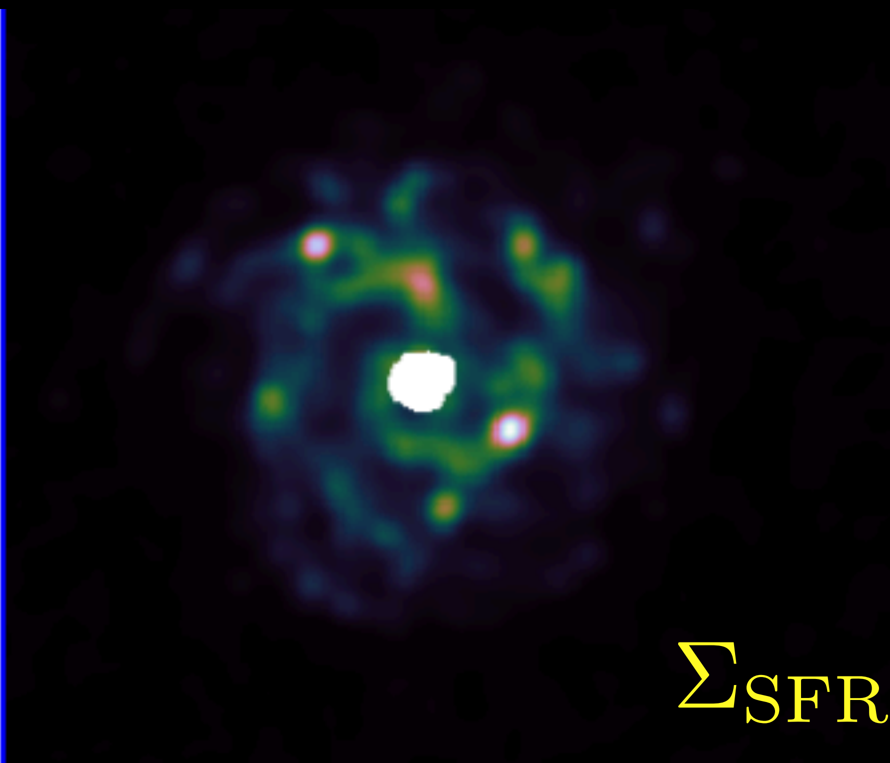
Jacob Woolsey

LOFAR

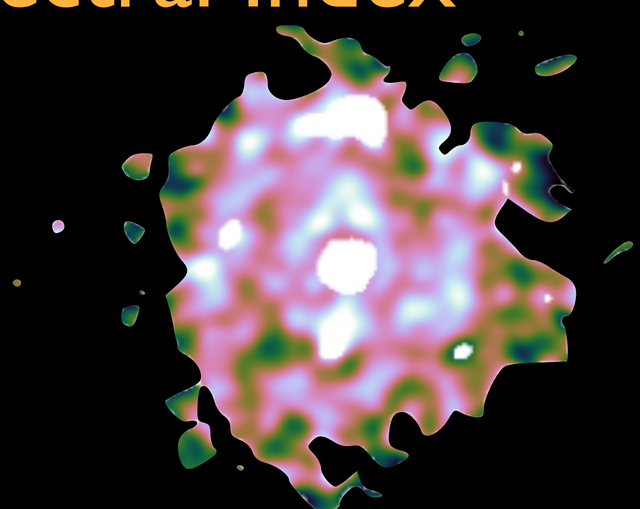
FWHM = 15 arcsec
rms = 300 μJy/beam



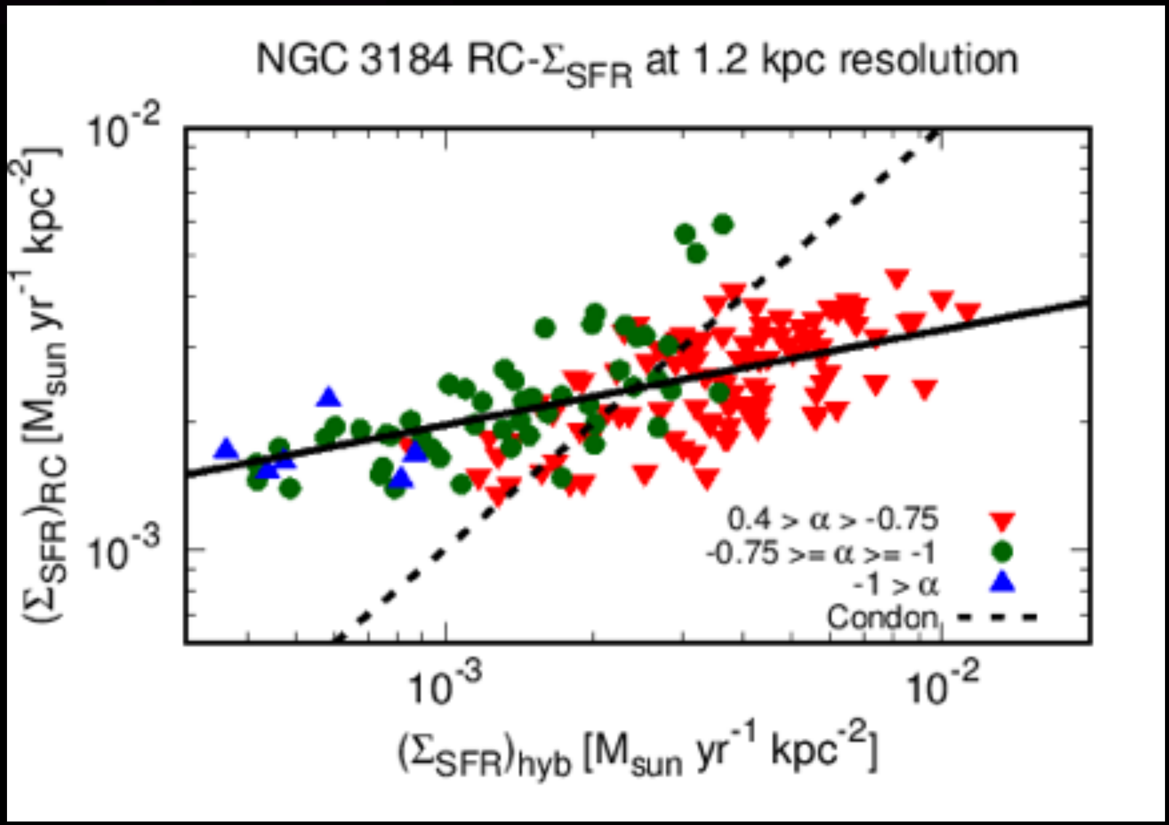
SFRD



Spectral Index



$$\Sigma_{\mathrm{SFR,hyb}} \propto \Sigma_{\mathrm{SFR,radio}}^{0.23\pm0.02}$$

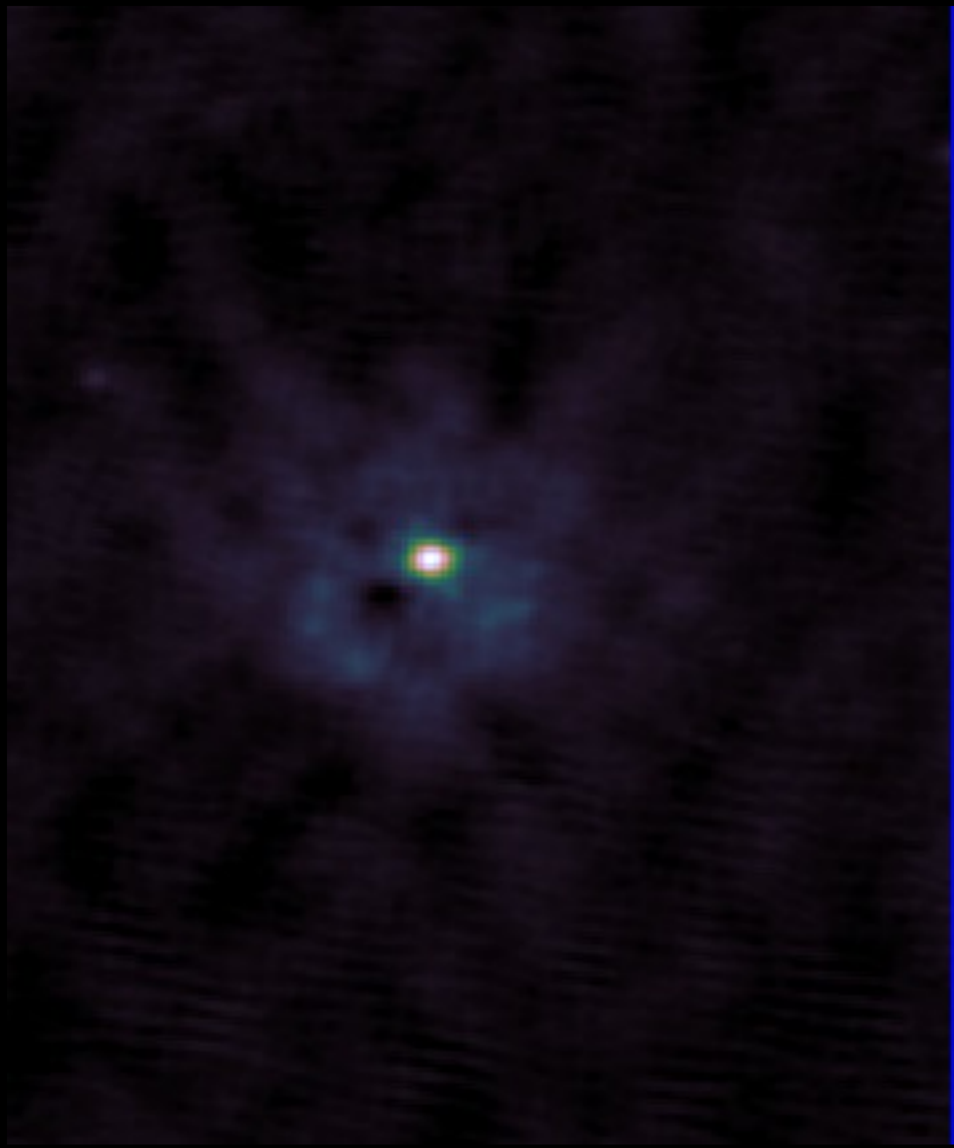


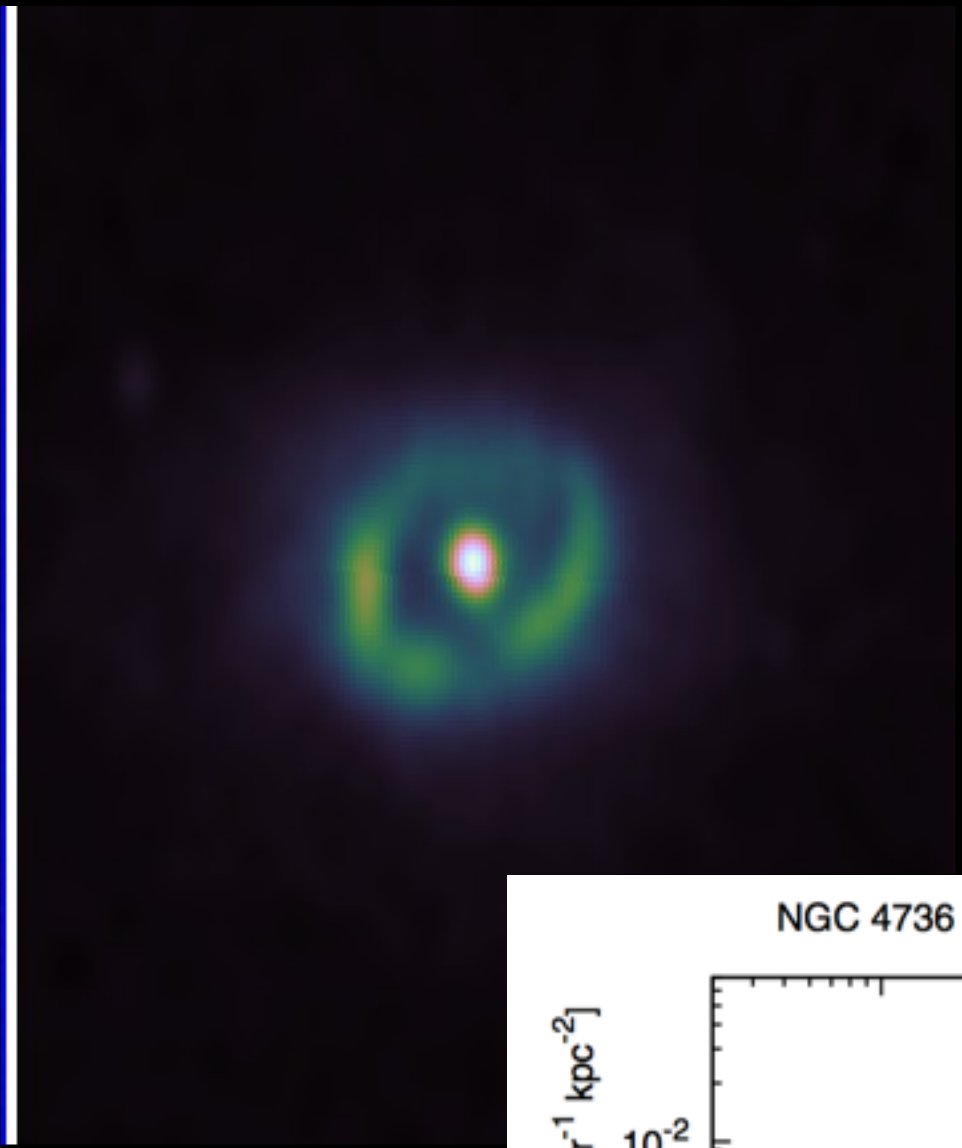
NGC 4736

Edward Buie II

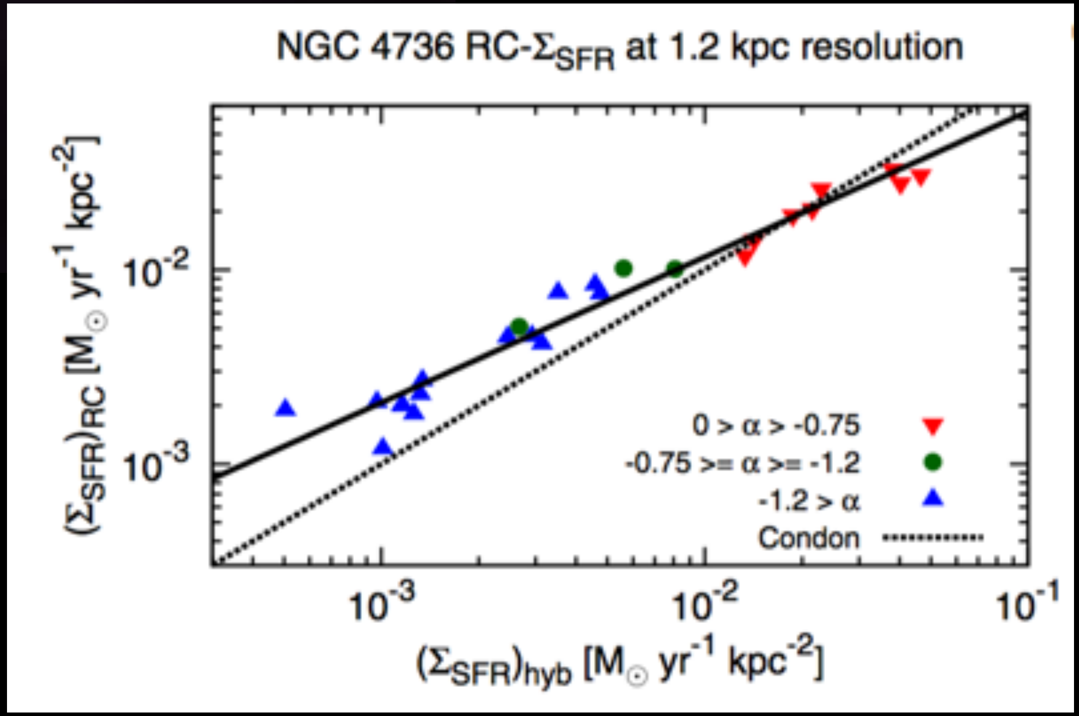
LOFAR

SFRD





LOFAR data currently analysed ...



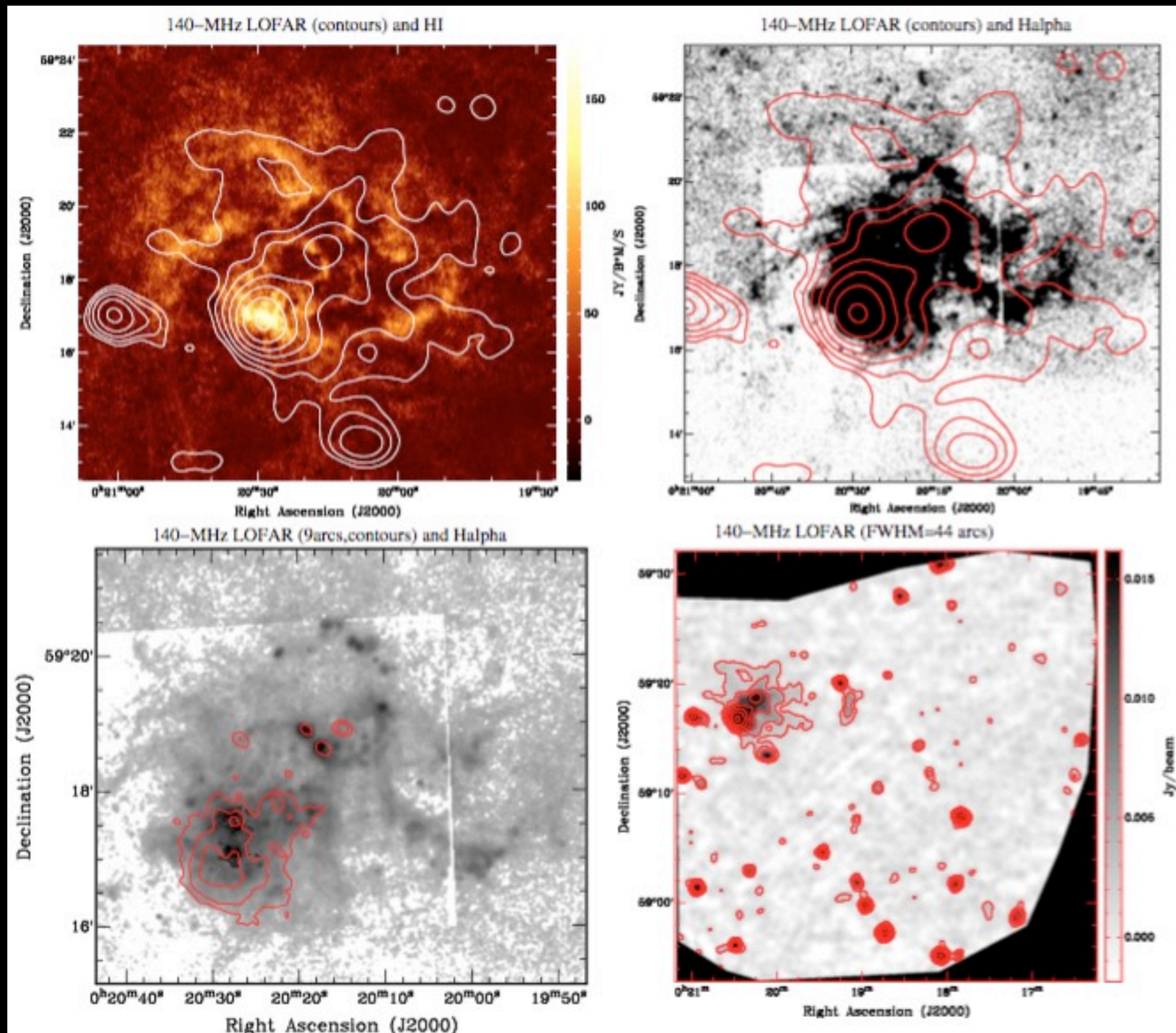
WSRT 1400 MHz:

$$\mathrm{SFR_{hyb}} \propto \mathrm{SFR}_{\mathrm{radio}}^{0.75\pm0.03}$$

IC 10: a starburst dwarf galaxy

HI

Halpha



Halpha

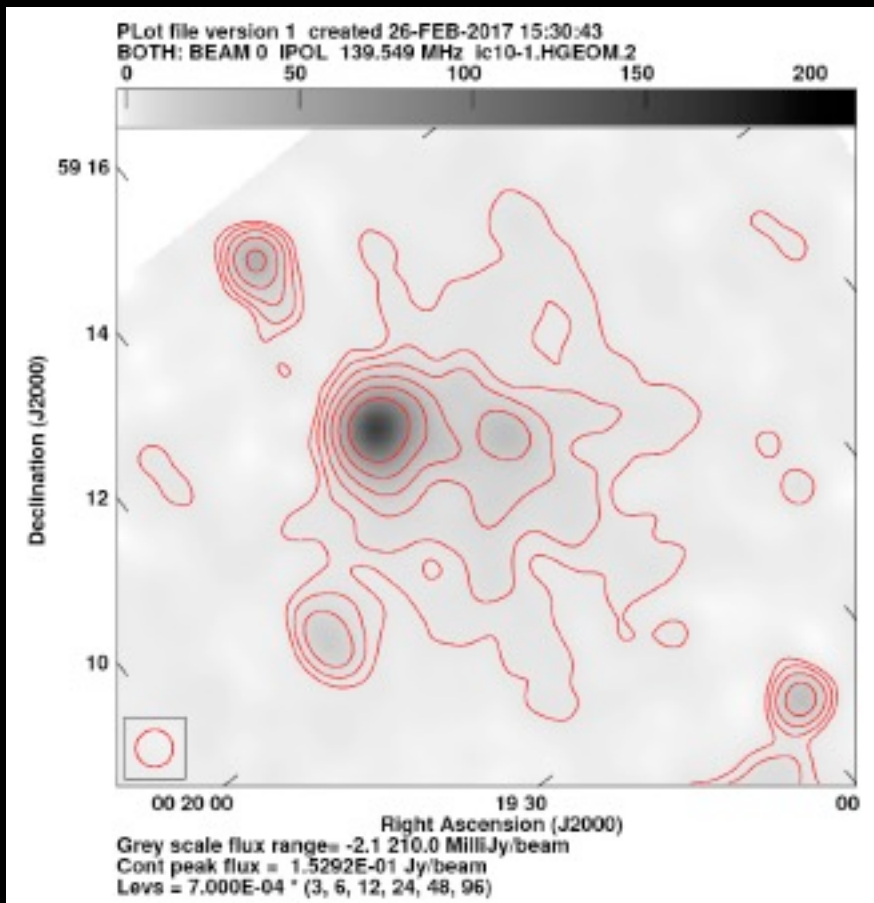
Facet

Heesen et al. 2017, in prep.

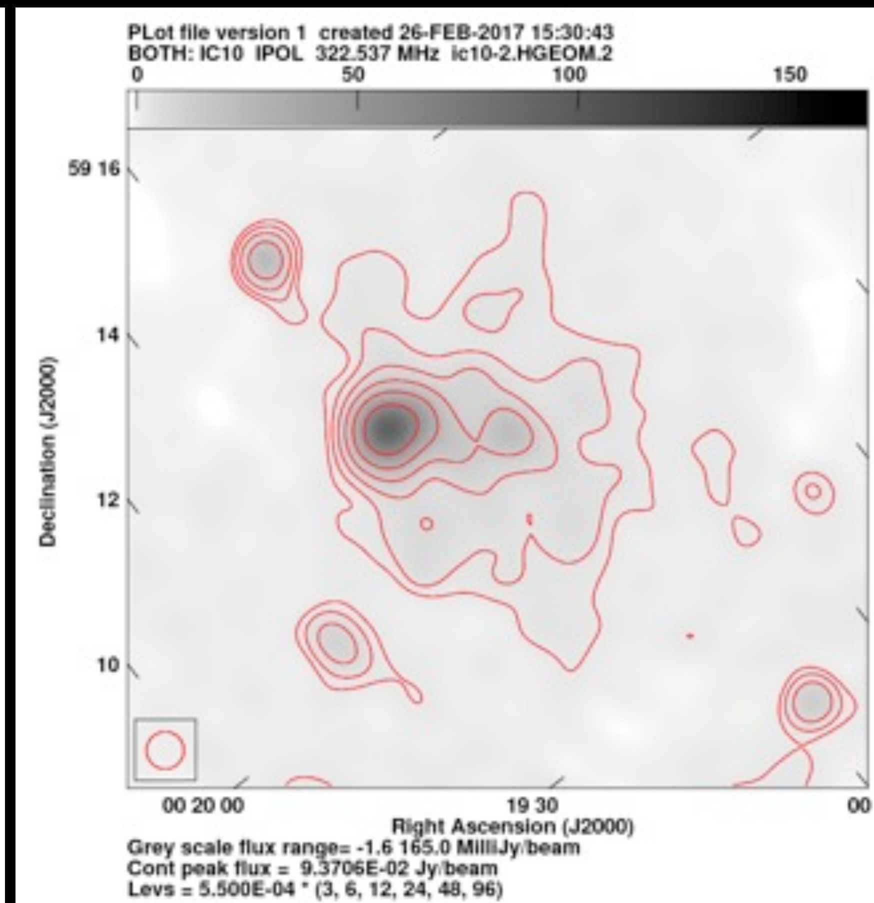
Consistency with other data

Heesen et al. 2017, in prep.

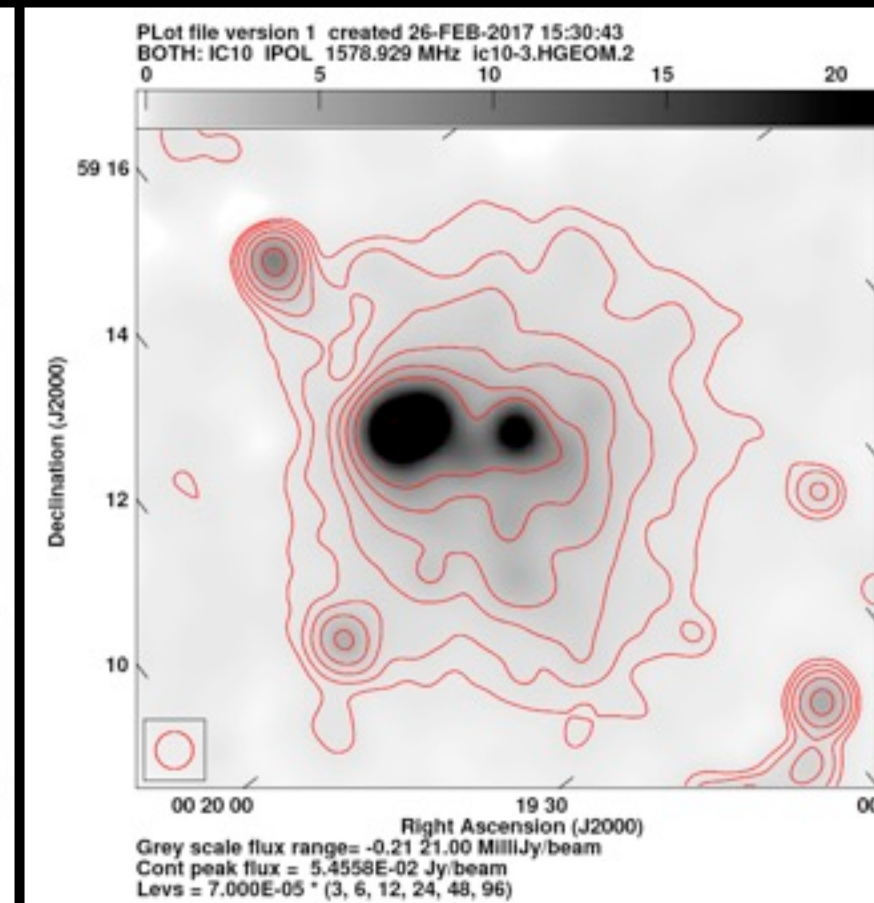
LOFAR 140 MHz



GMRT 325 MHz



VLA 1600 MHz



- Structure is broadly consistent with higher frequencies
- Very flat spectral index (alpha = -0.4)
- Halo is not spherical (like NGC 1569, Sridhar et al. in prep.)

Cosmic-ray transport models

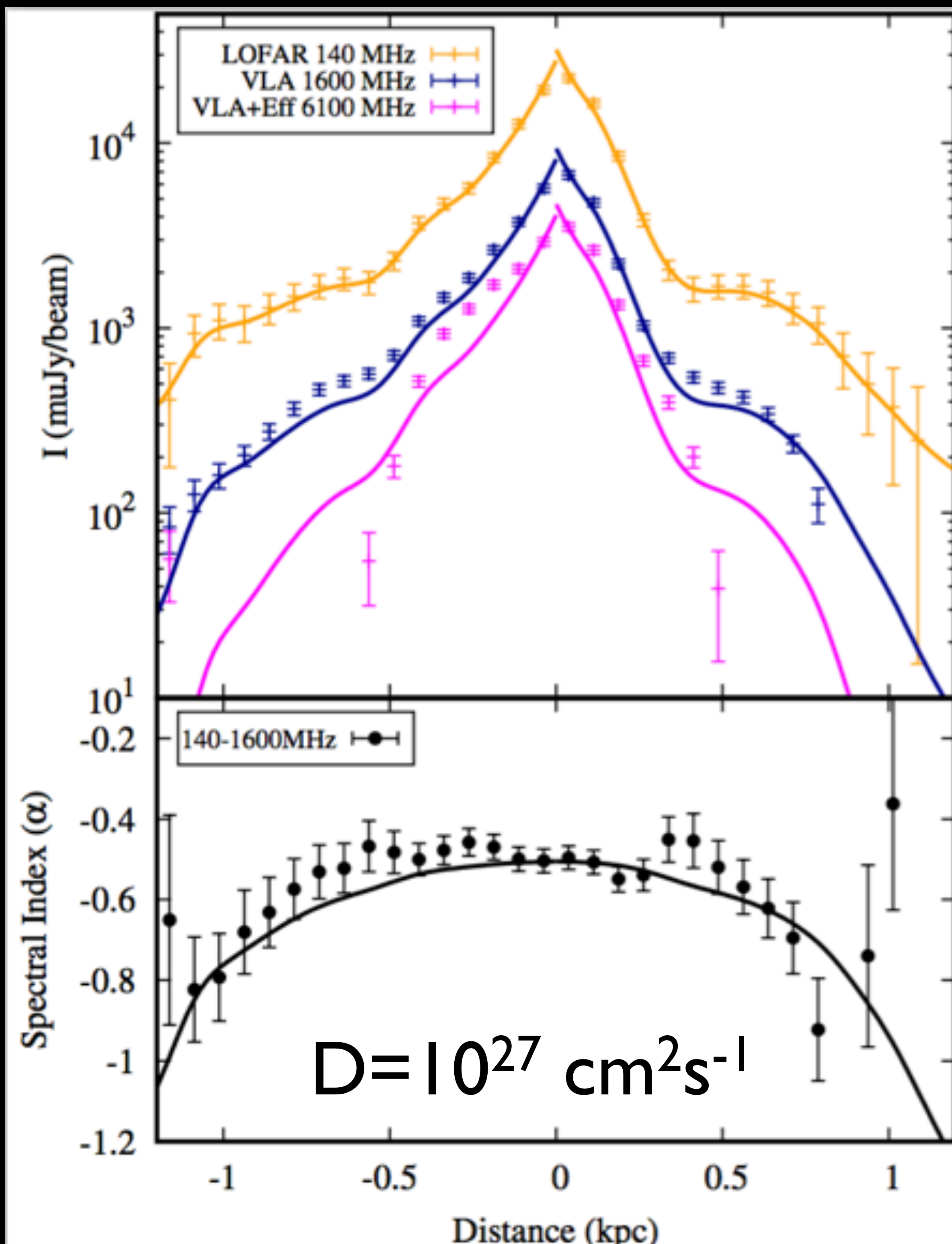
(SPINNAKER, Heesen et al. 2016)

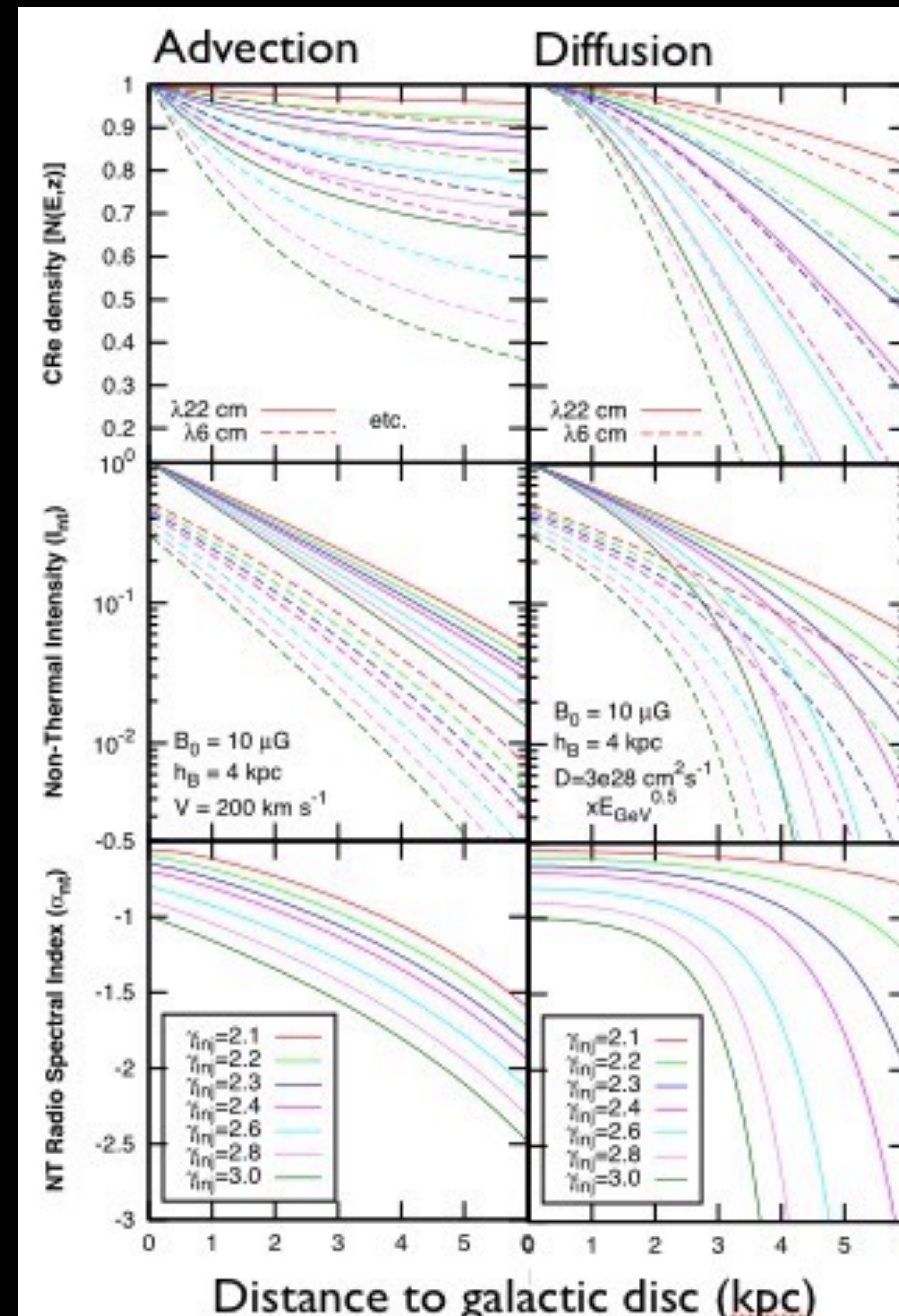
https://github.com/vheesen/Spinnaker

Minor axis profiles

Intensity

Spectral index



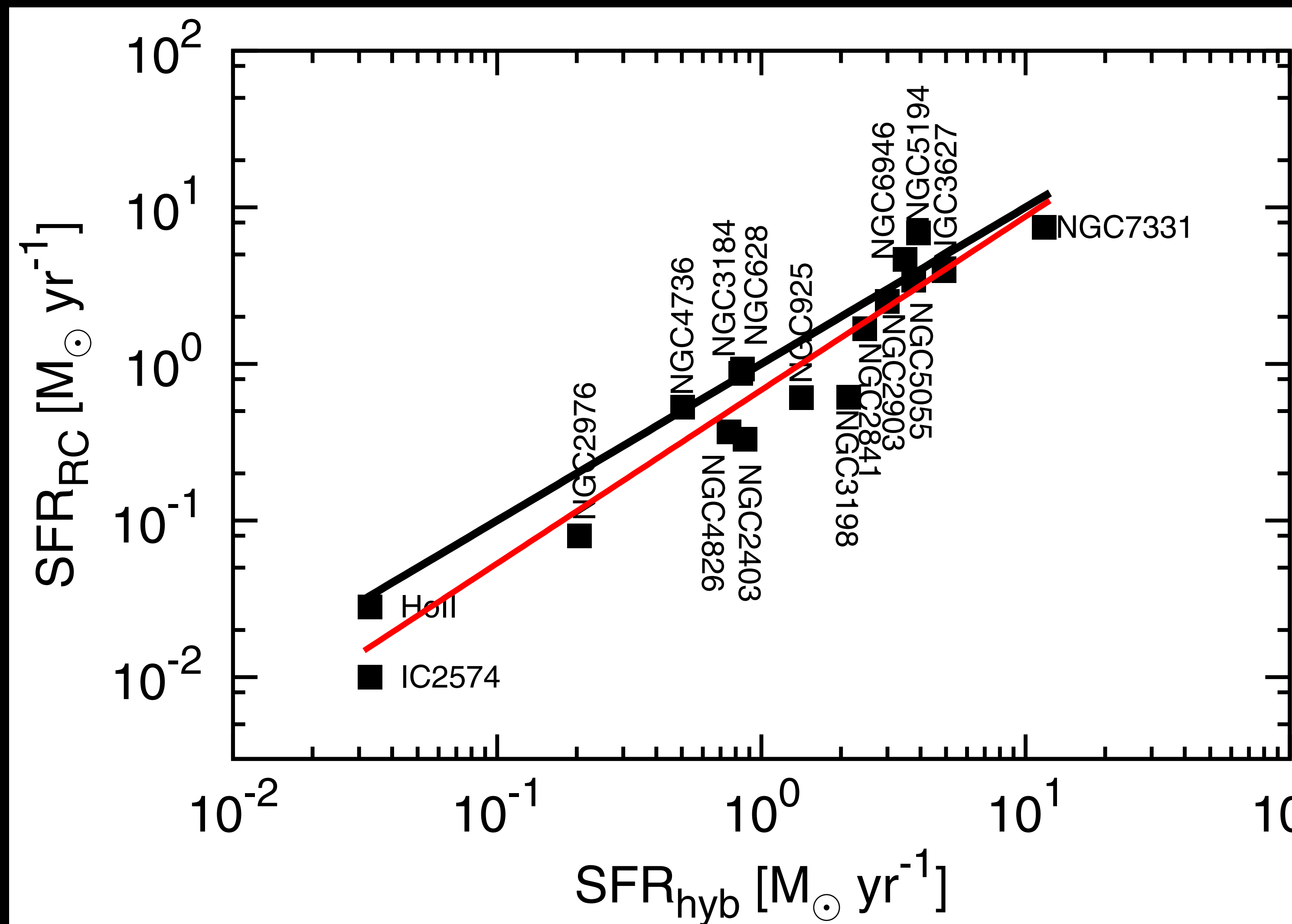


Conclusions

- Former results from WSRT
  - Integrated linear relation (slope=1.11+/-0.08)
  - Resolved RC–SFR relation (1 kpc scale)
  - Sub-linear resolved relation (slope 0.63+/-0.25)
  - Cosmic-ray transport (spectral ageing)
- New results from LOFAR
  - RC–SFR relation even more sub-linear
  - Improved non-thermal radio spectral indices

Integrated radio–SFR relation

(Heesen, Brinks et al. 2014)



y–axis:
– Use Condon relation to calculate SFR
– 22 cm radio

x–axis: SFR from GALEX FUV + Spitzer 24 μm

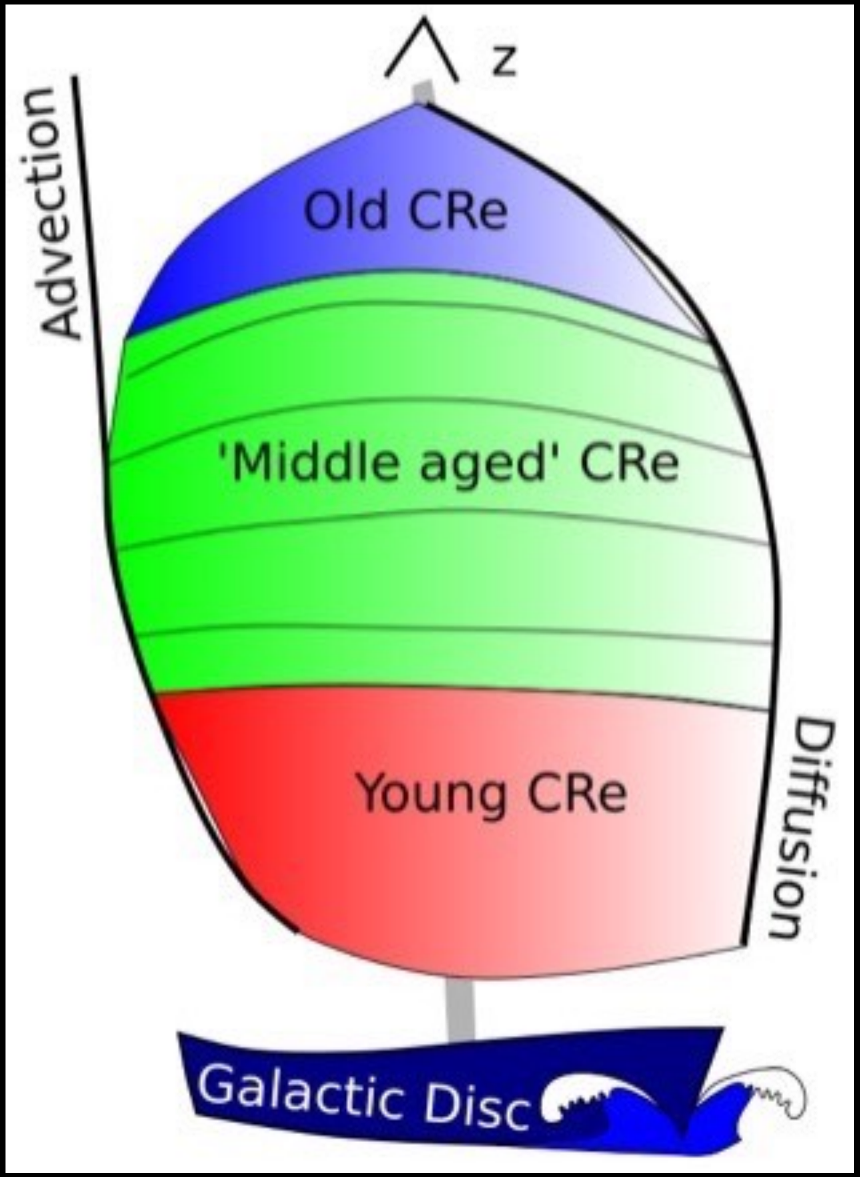
In the plot:
Black: Condon relation (1:1)
Red: Fit to data

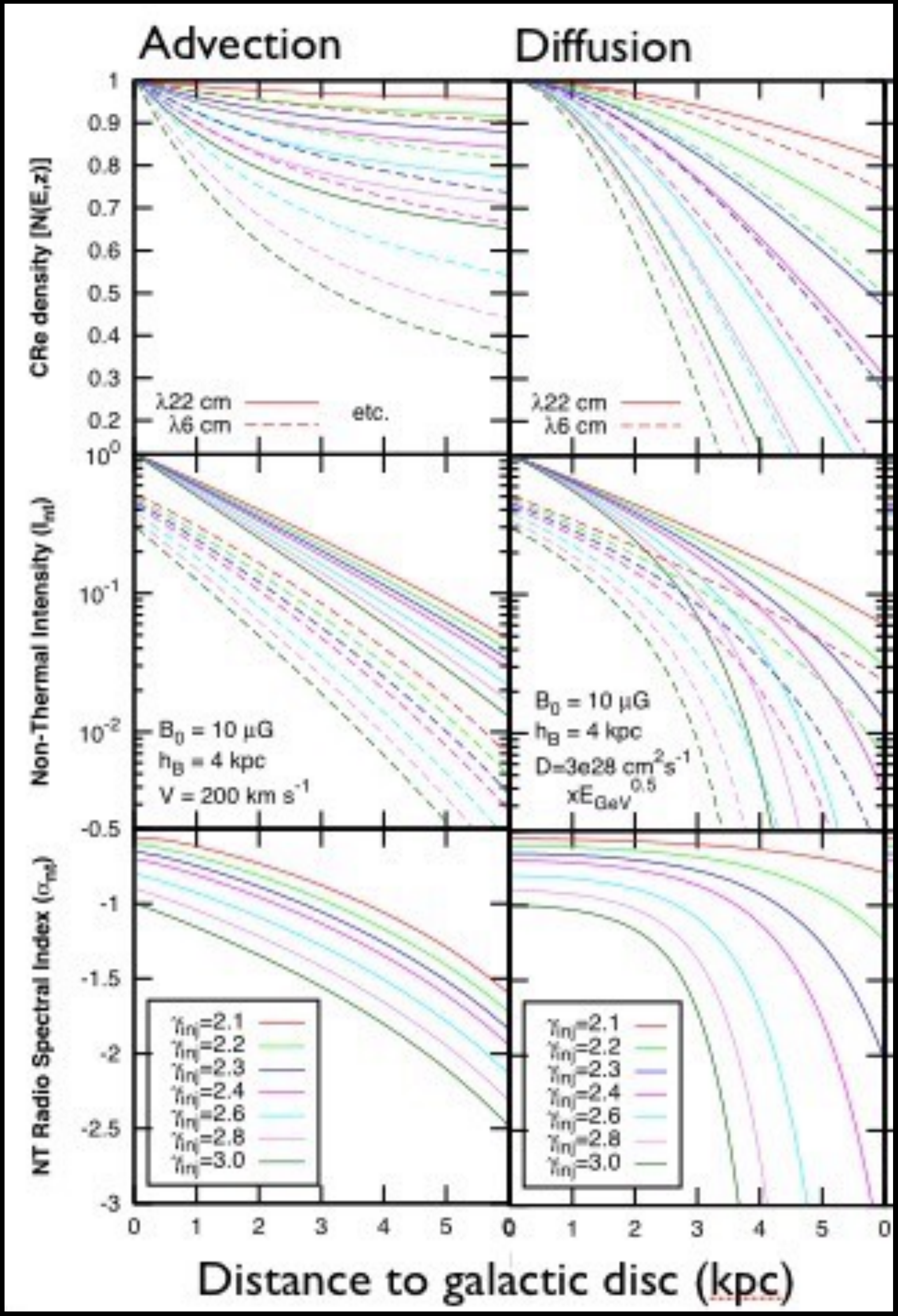
Integrated Ratio: $\Re = \frac{\mathrm{SFR}_{\mathrm{radio}}}{\mathrm{SFR}_{\mathrm{hyb}}} = 0.8 \pm 0.4$

RC–SFR slope: $\mathrm{SFR}_{\mathrm{radio}} \propto \mathrm{SFR}_{\mathrm{hyb}}^{1.11 \pm 0.08}$

SPINNAKER cosmic-ray transport models

https://github.com/vheesen/Spinnaker





Heesen et al. (2016)