

Star formation, galactic winds, and magnetic fields in nearby galaxies as probed with LOFAR

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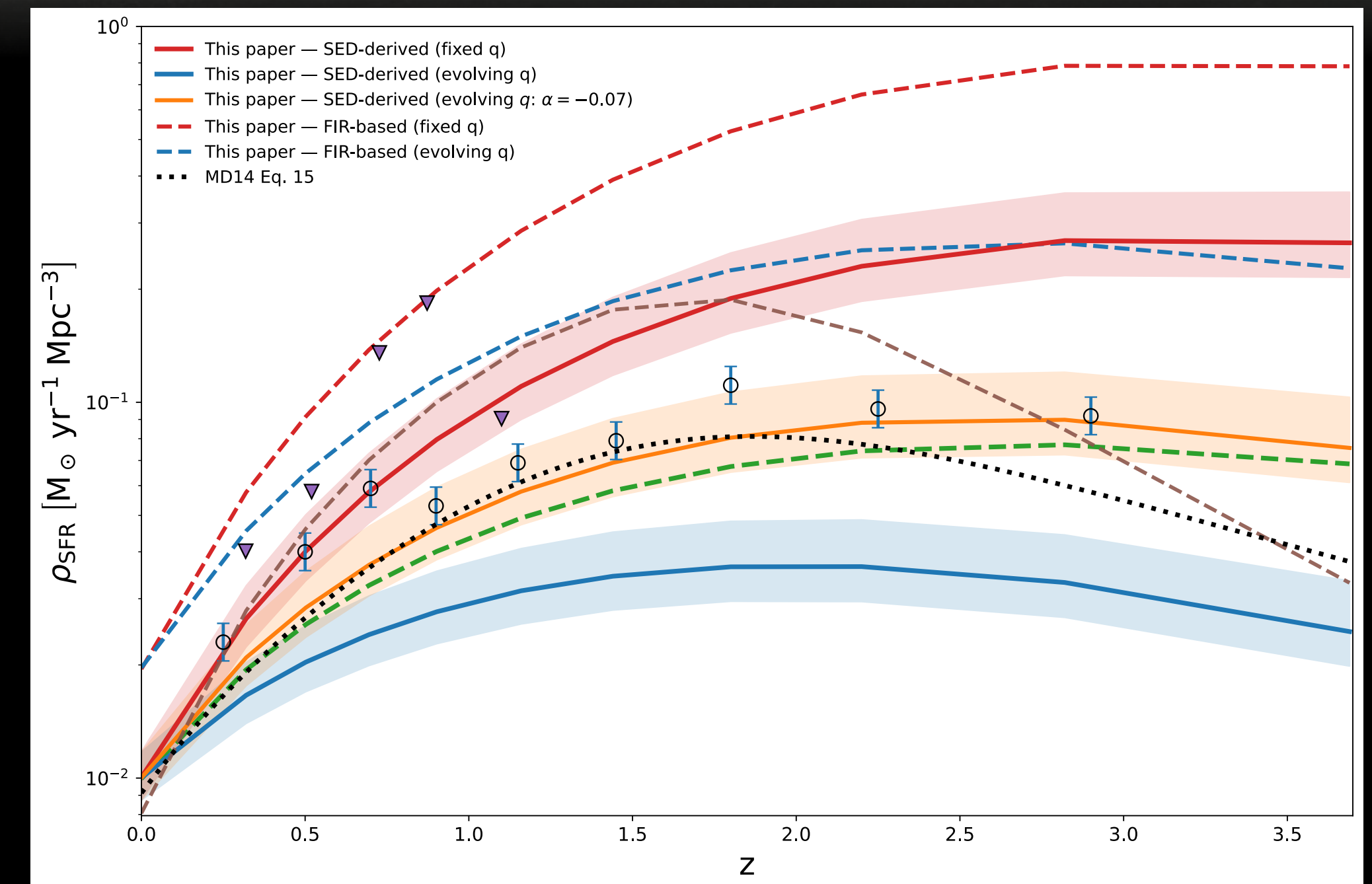
With contributions from the LOFAR Magnetism Key Science Project

Radio continuum as star-formation tracer

the radio-SFR relation

- Radio continuum observations are unaffected by dust and have high angular resolution
- However, many processes affect the radio-SFR relation such as cosmic-ray transport, magnetic fields, and electron energy losses
- Therefore, need for a reliable calibration

MIGHTEE: EvolvingRadioLuminosity Functions



Thykkathu +2026

Radio continuum emission from star-forming galaxies

Massive stars

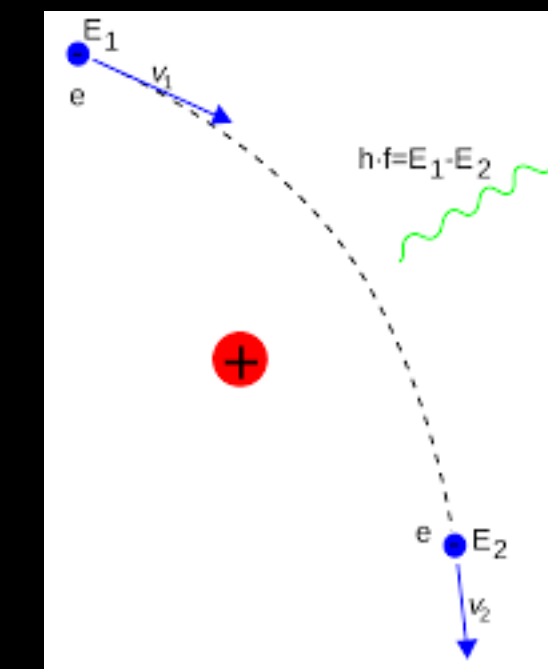


UV radiation

HII region



free-free radiation



R.I.P

supernova

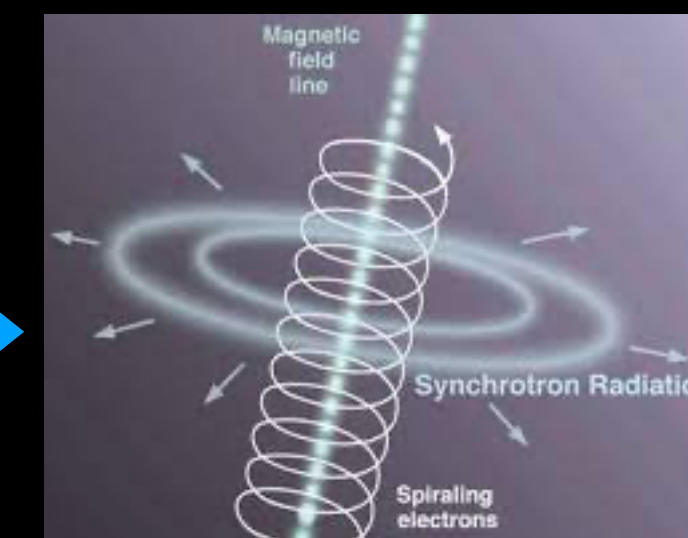


shock
acceleration

SNR



synchrotron
emission



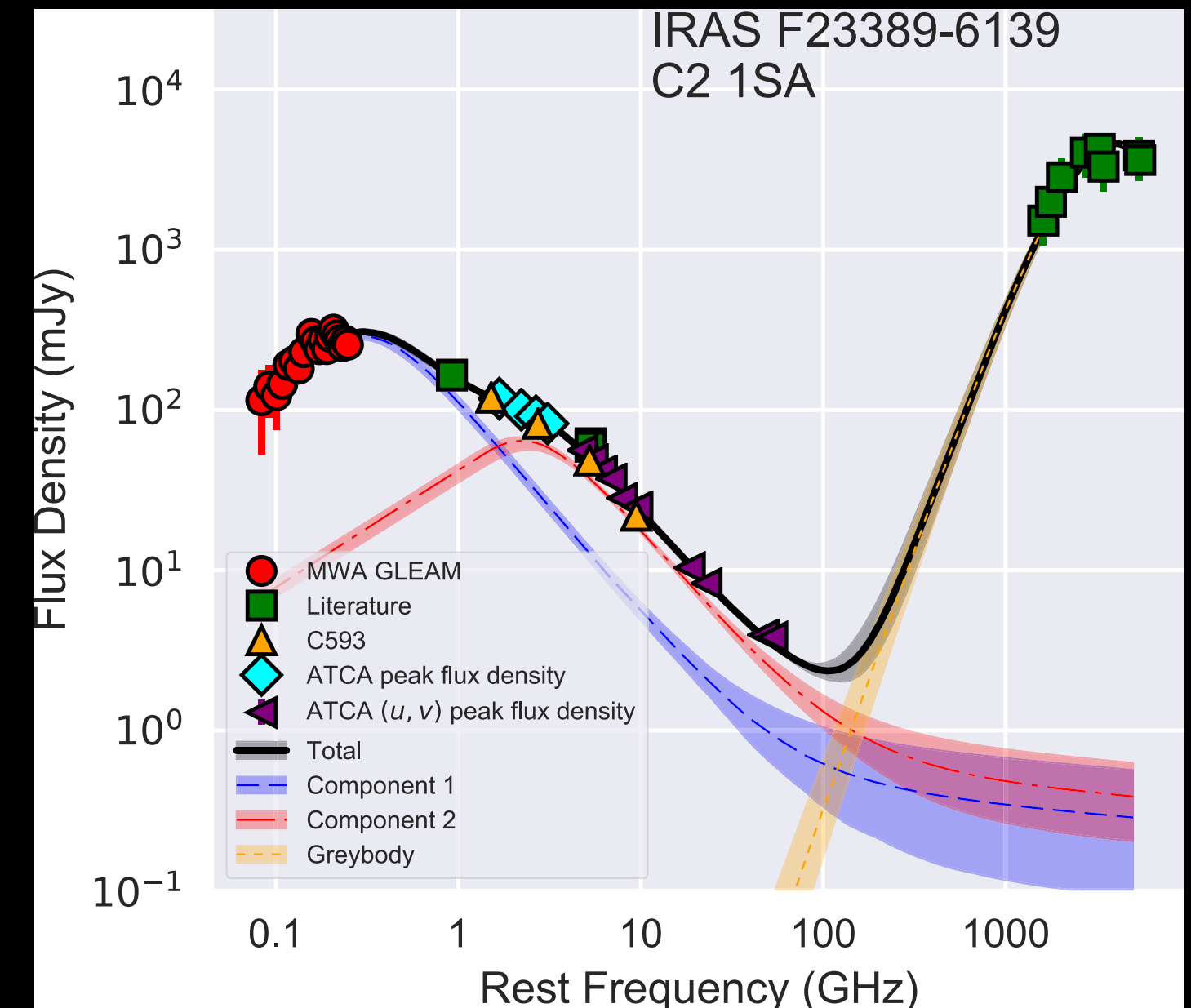
UHH / D. Engels

Radio-SFR relation

approximately linear relation

- Thermal radio continuum is ideal SFR tracer (Murphy + 2011)
- Non-thermal emission dominates below 10 GHz (e.g. Tabatabaei + 2017)
- Radio-SFR relation (Murphy et al. 2011):

$$\left(\frac{\text{SFR}_{1.4 \text{ GHz}}}{\text{M}_{\odot} \text{ yr}^{-1}} \right) = 6.35 \times 10^{-22} \left(\frac{L_{1.4 \text{ GHz}}}{\text{W Hz}^{-1}} \right)$$



Galvin + 2018

Observed radio–SFR relation

super-linear relation observed

- Observations show slightly to significantly super-linear relations

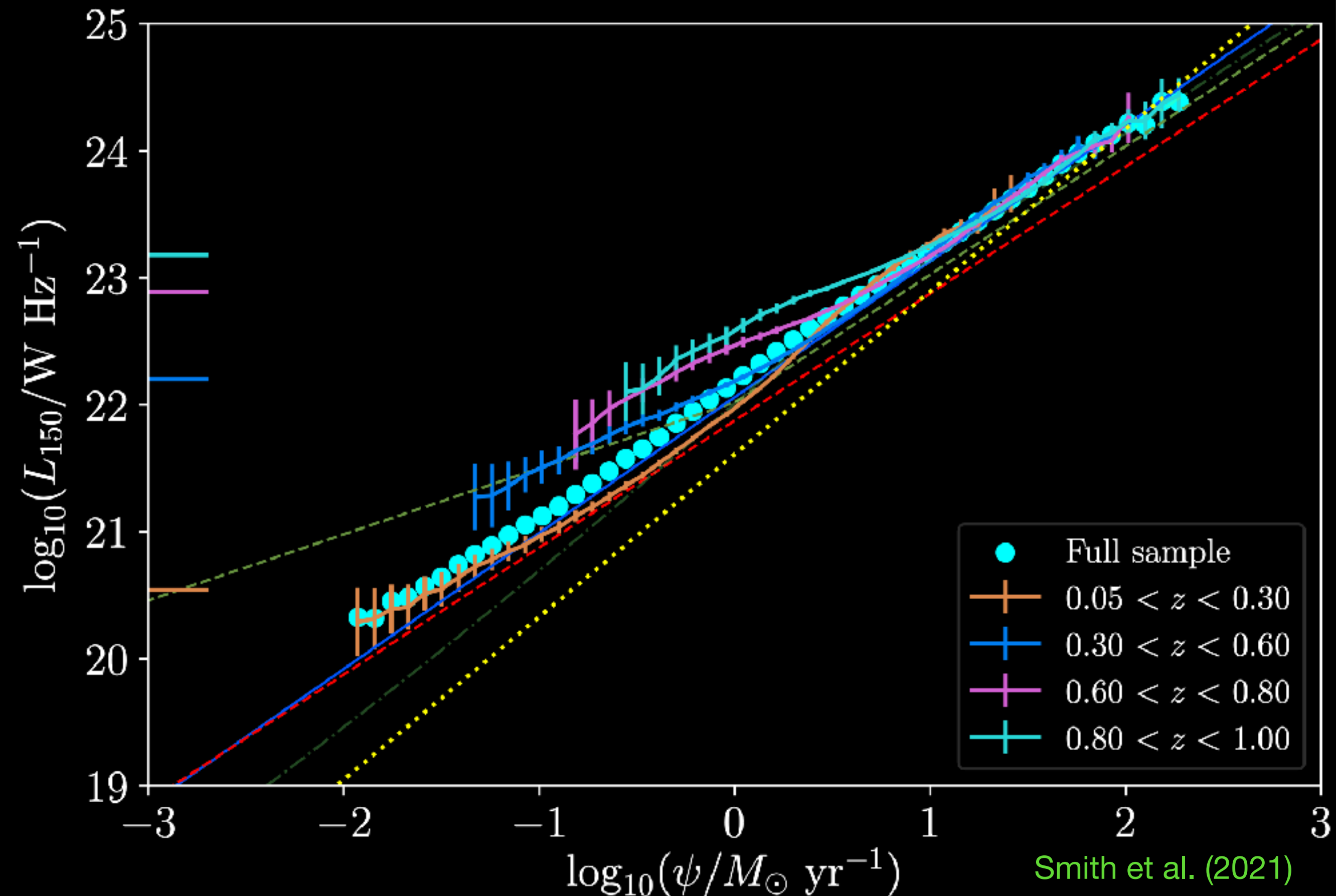
Other examples:

GAMA (Davies et al. 2017)

CHANG-ES (Li et al. 2016)

HERSCHEL-ATLAS (Gürkan et al. 2018)

Virgo Cluster (Edler et al. 2024)



Low-frequency Array (LOFAR)

a European radio interferometer

- 46 Dutch stations
- 16 international stations
- Low-band dipoles (30–85 MHz)
- High-band tiles (110–180 MHz)



van Haarlem et al. (2013)

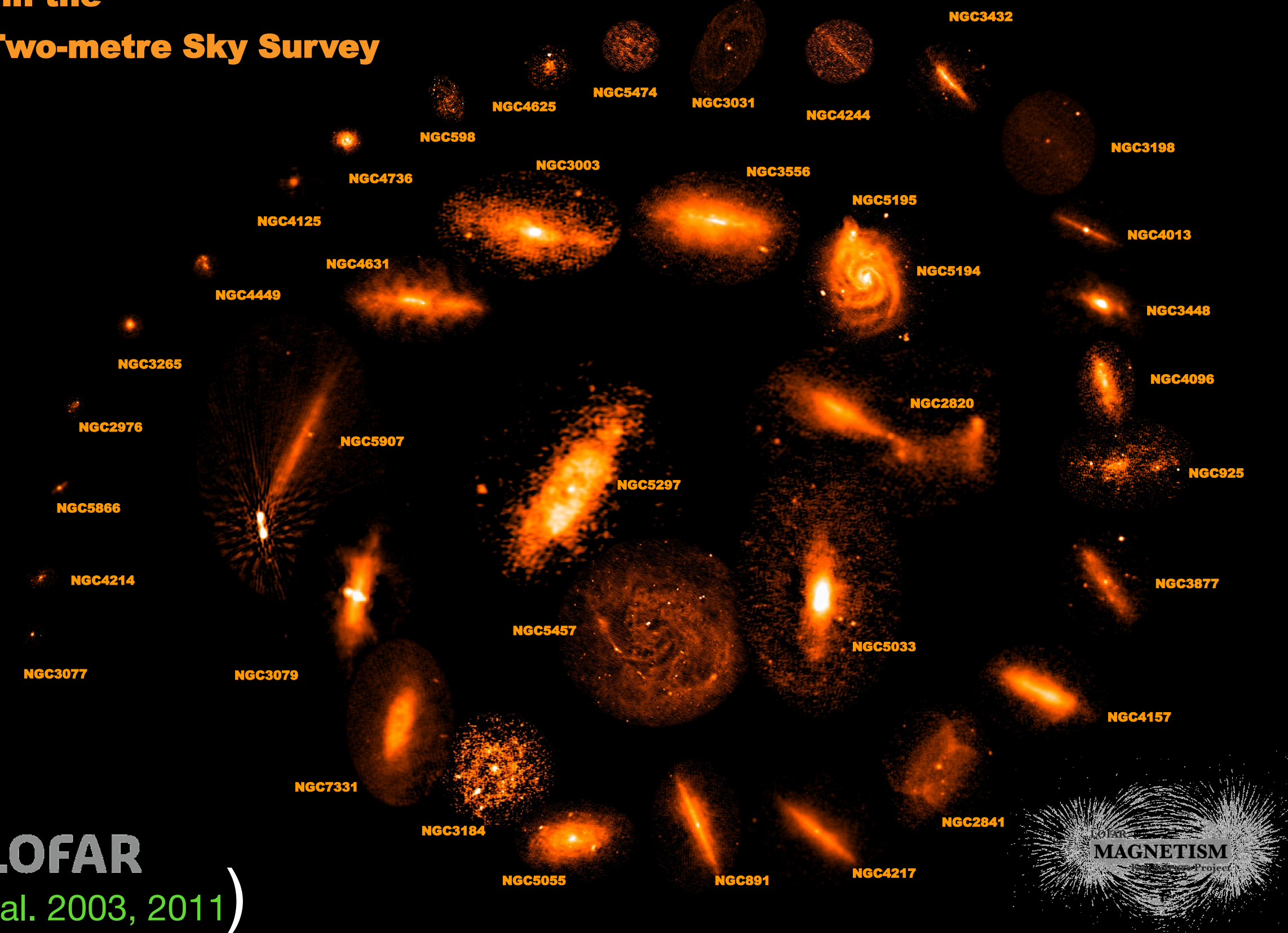


LOFAR observations

144 MHz data

- LOFAR Two-metre Sky Survey (LoTSS; [Shimwell et al. 2017, 2019, 2022, 2026](#))
- LoTSS data release 2 (45 galaxies)
- LoTSS data release 3 (70 galaxies)
- *Spitzer* and *Herschel* infrared data ([Kennicutt et al. 2003, 2011](#))
- High-frequency radio data from WSRT and JVLA ([Braun et al. 2007, Wiegert et al. 2015](#)) plot by F. Welzmüller

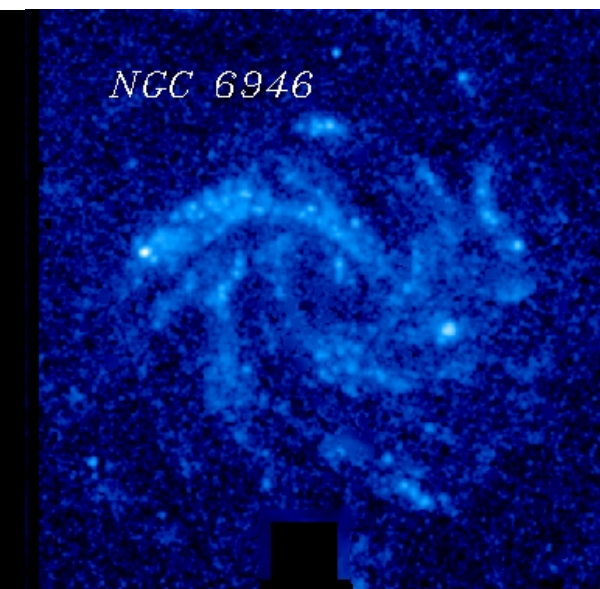
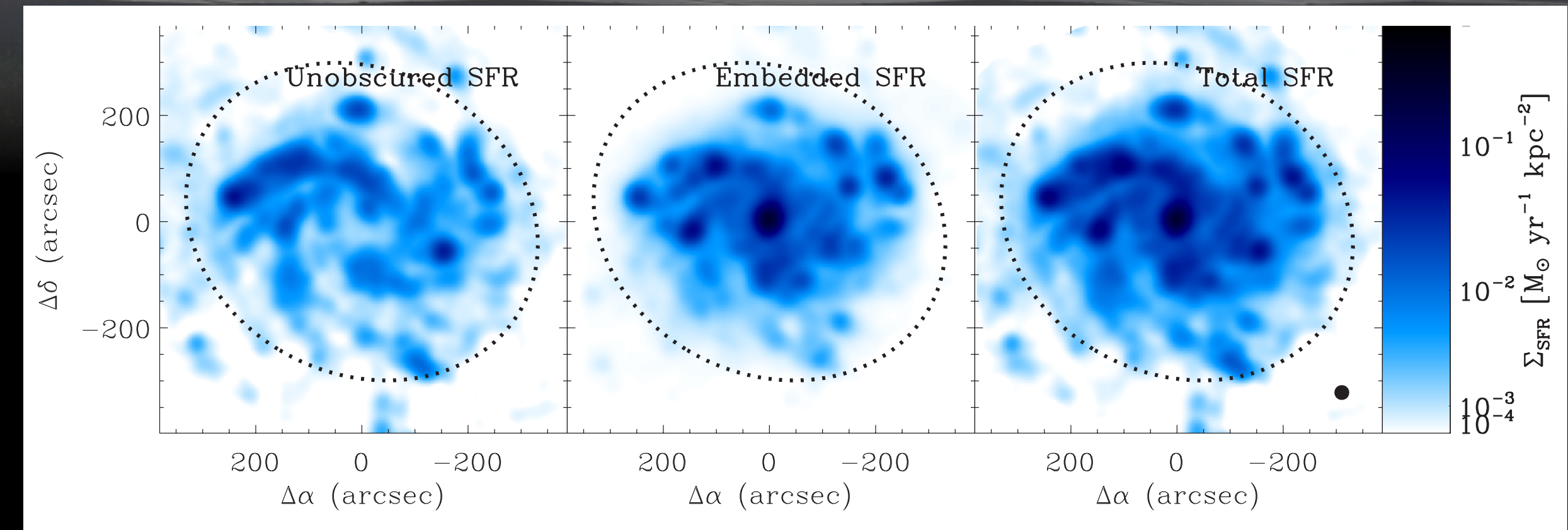
Nearby Galaxies in the LOFAR Two-metre Sky Survey



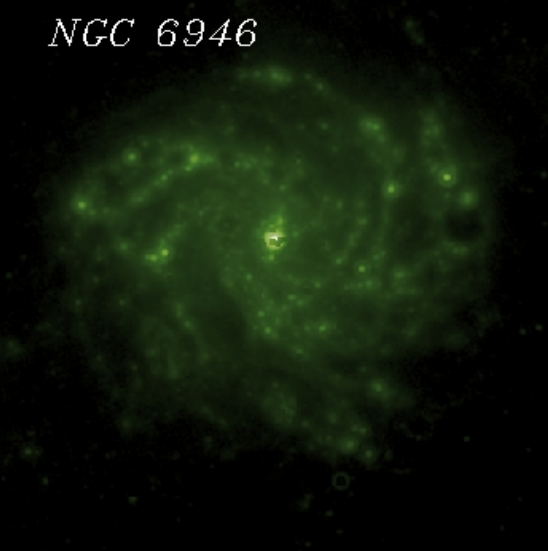
Star formation rates

two methods used

- Global data: dust-corrected H α luminosities
H α + mid-infrared (24 μ m)
- Local data: dust-corrected far-ultraviolet
FUV + mid-infrared (24 μ m)



FUV:
*The GALEX
Nearby Galaxies
Survey*

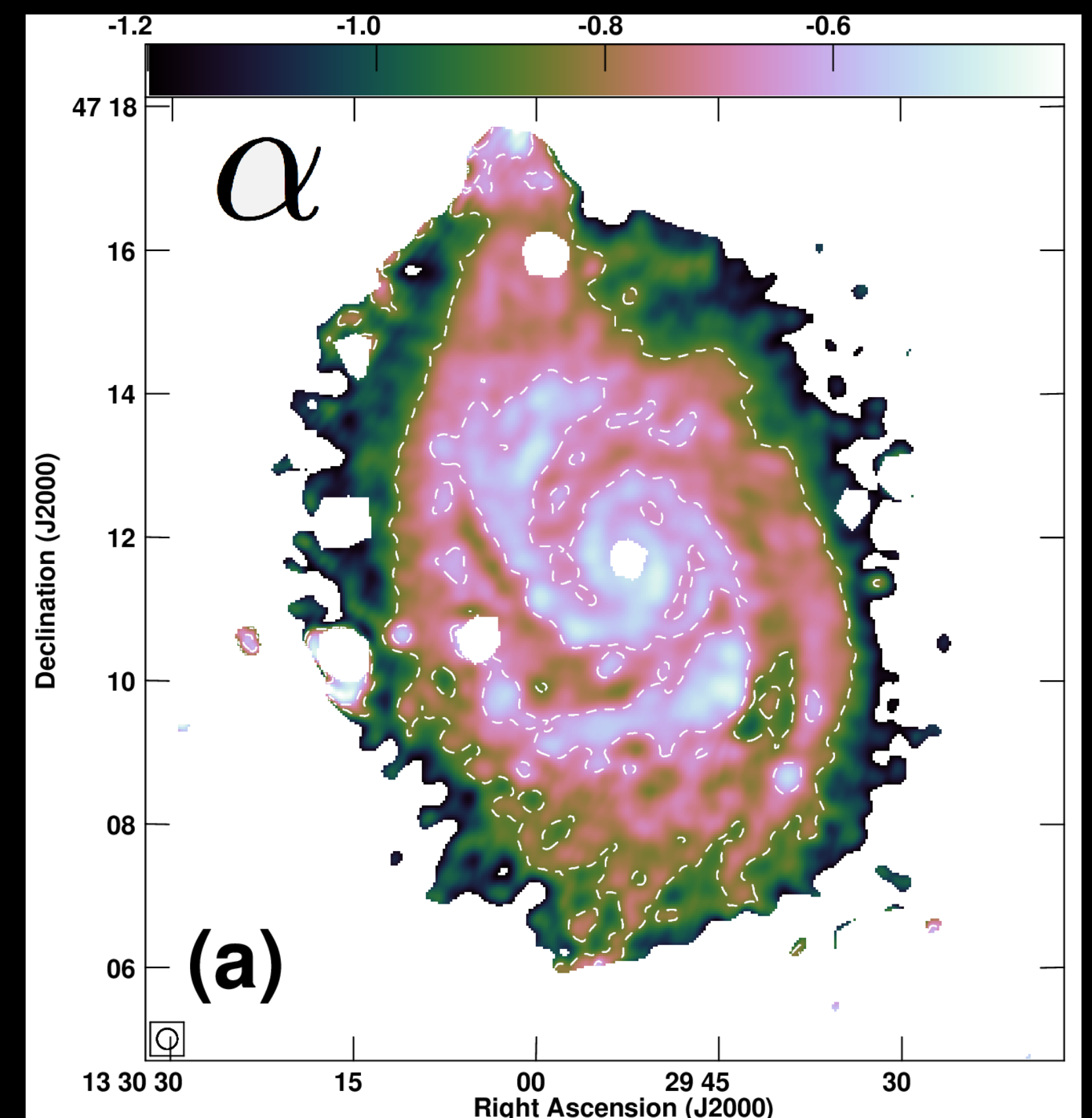
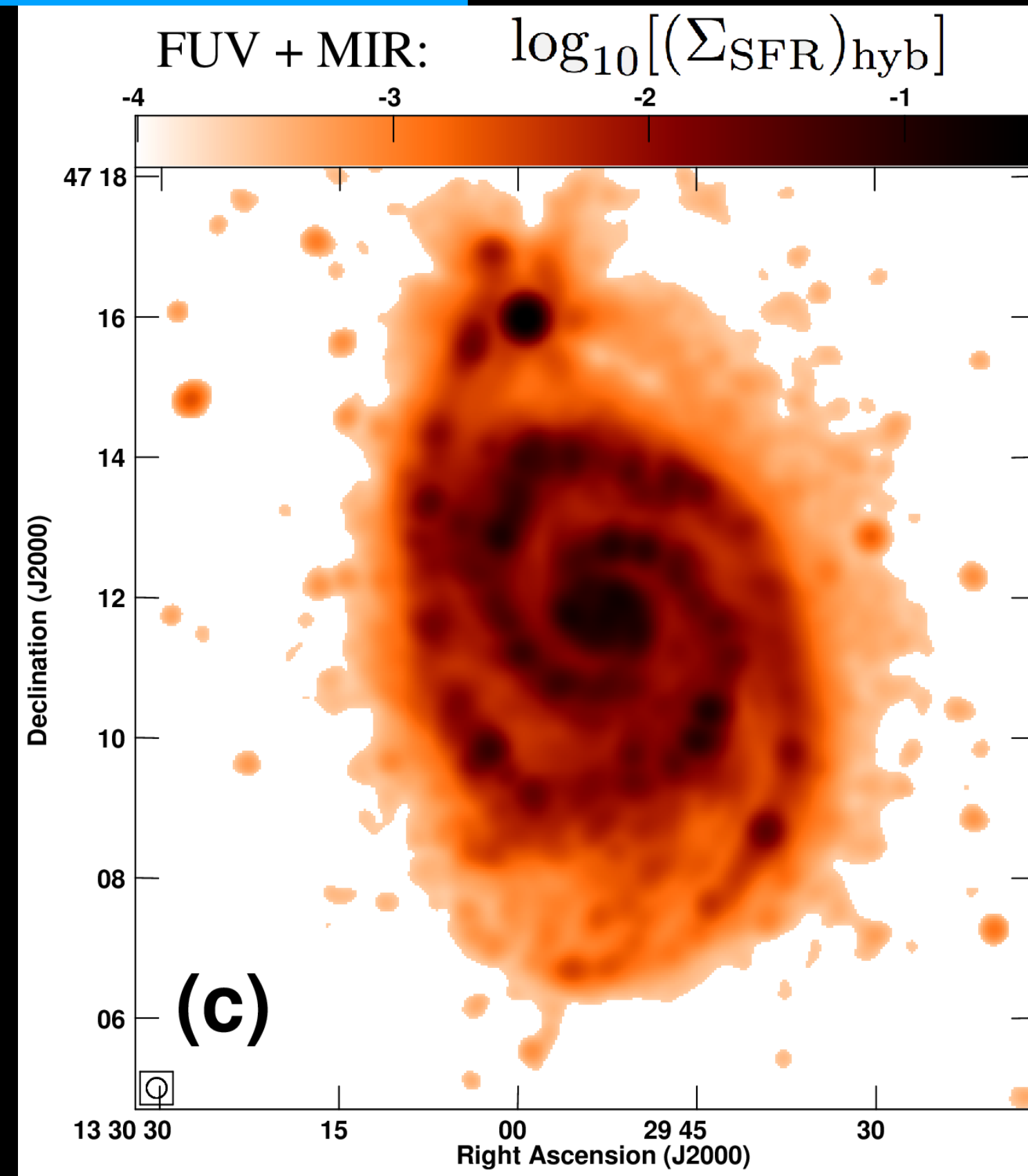
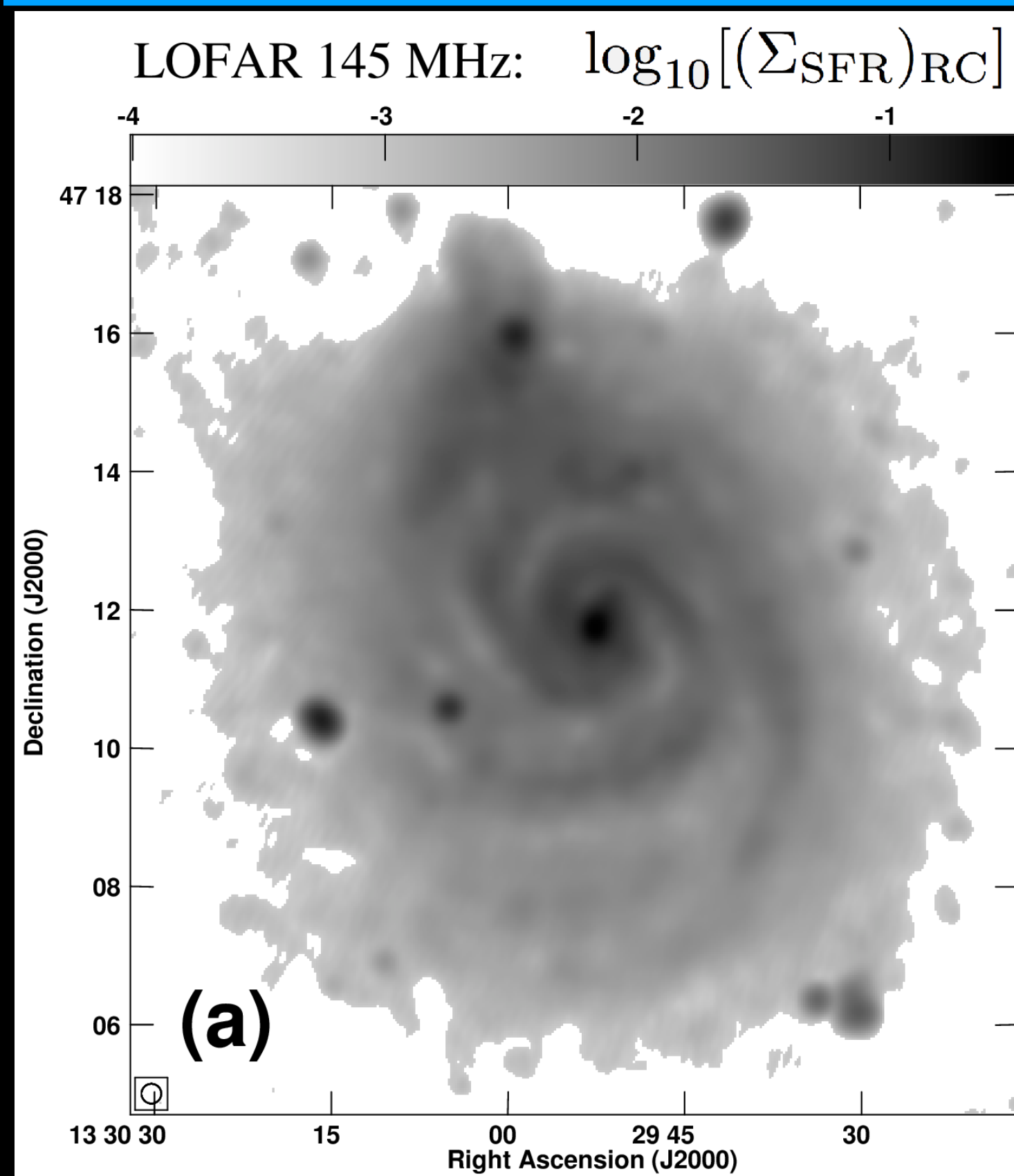


MIPS 24 μ m:
*The Spitzer
Infrared Nearby
Galaxies Survey*

Leroy et al, 2008

Comparison radio with star formation

spatial resolution of $1.2 \times 1.2 \text{ kpc}^2$



Semi-calorimetric radio–SFR relation

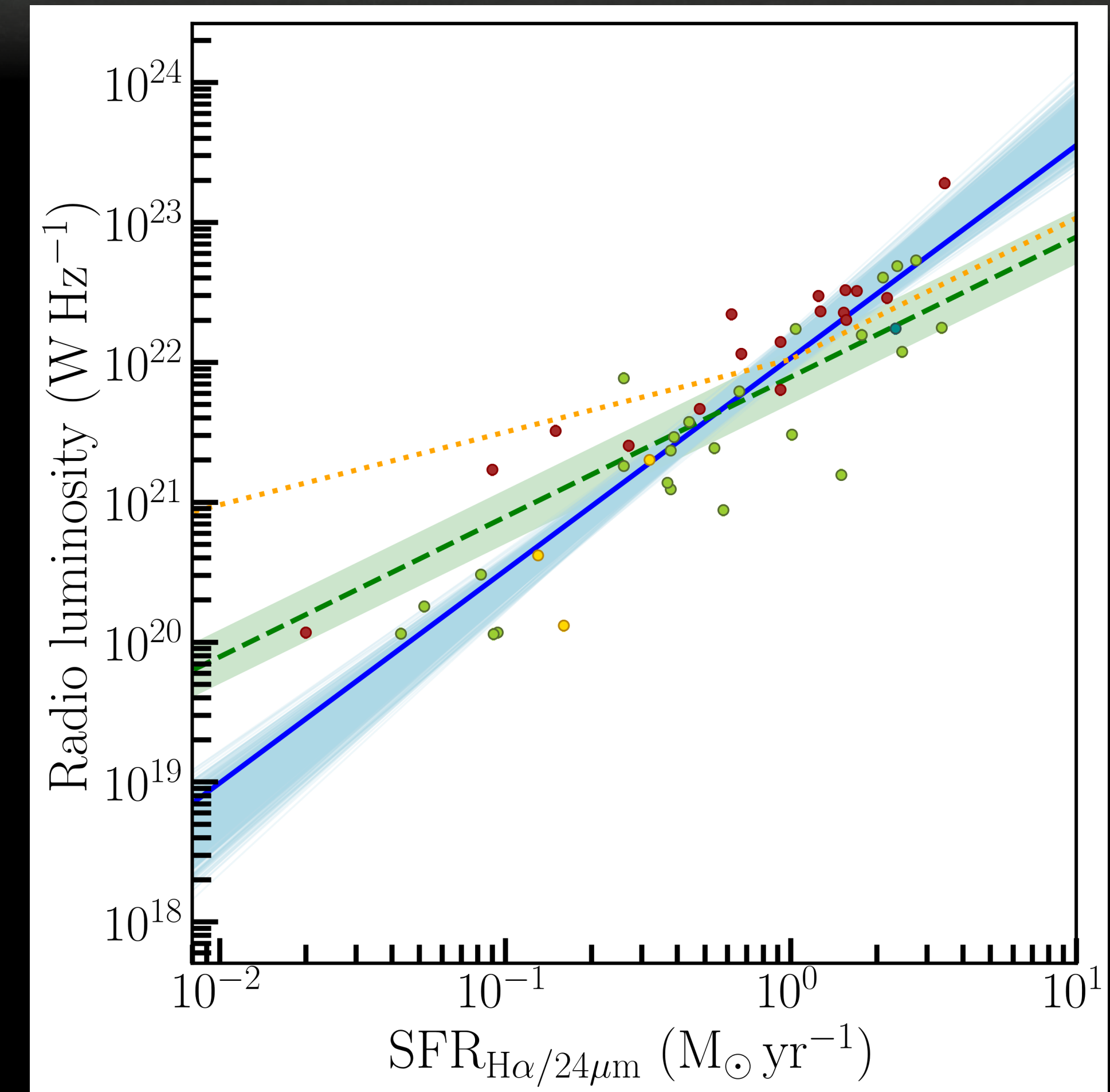
super-linear with $L_{144} \sim \text{SFR}^{1.2-1.4}$

Radio luminosity:

$$L_\nu \propto \eta \text{SFR}$$

calorimetric efficiency

CR injection



Heesen et al., 2022

How to estimate calorimetric efficiency?

use low-frequency radio spectral index!

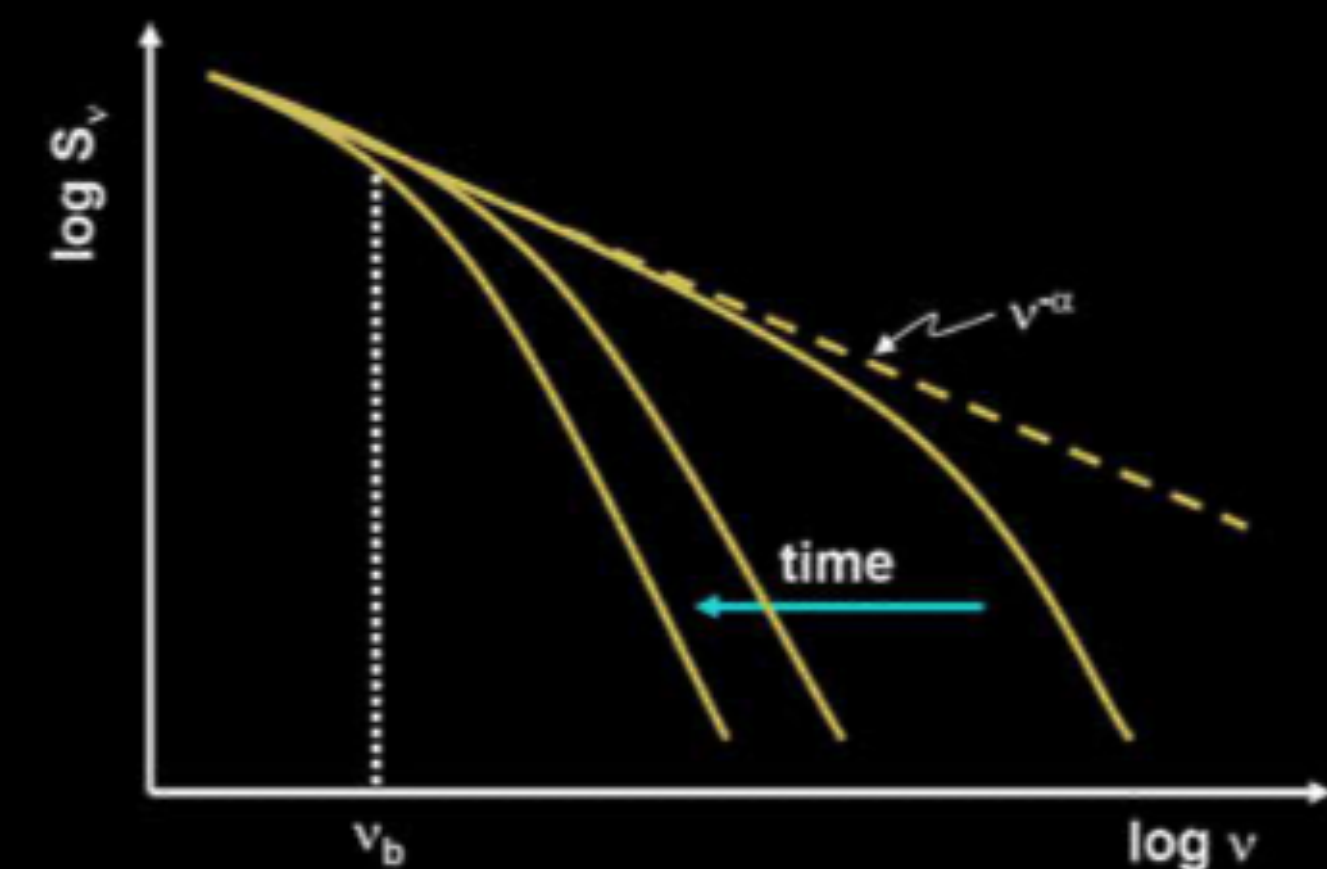
steep spectrum

Slow electron escape: $\eta = 1$ Radio spectral index: $\alpha = -1.1$

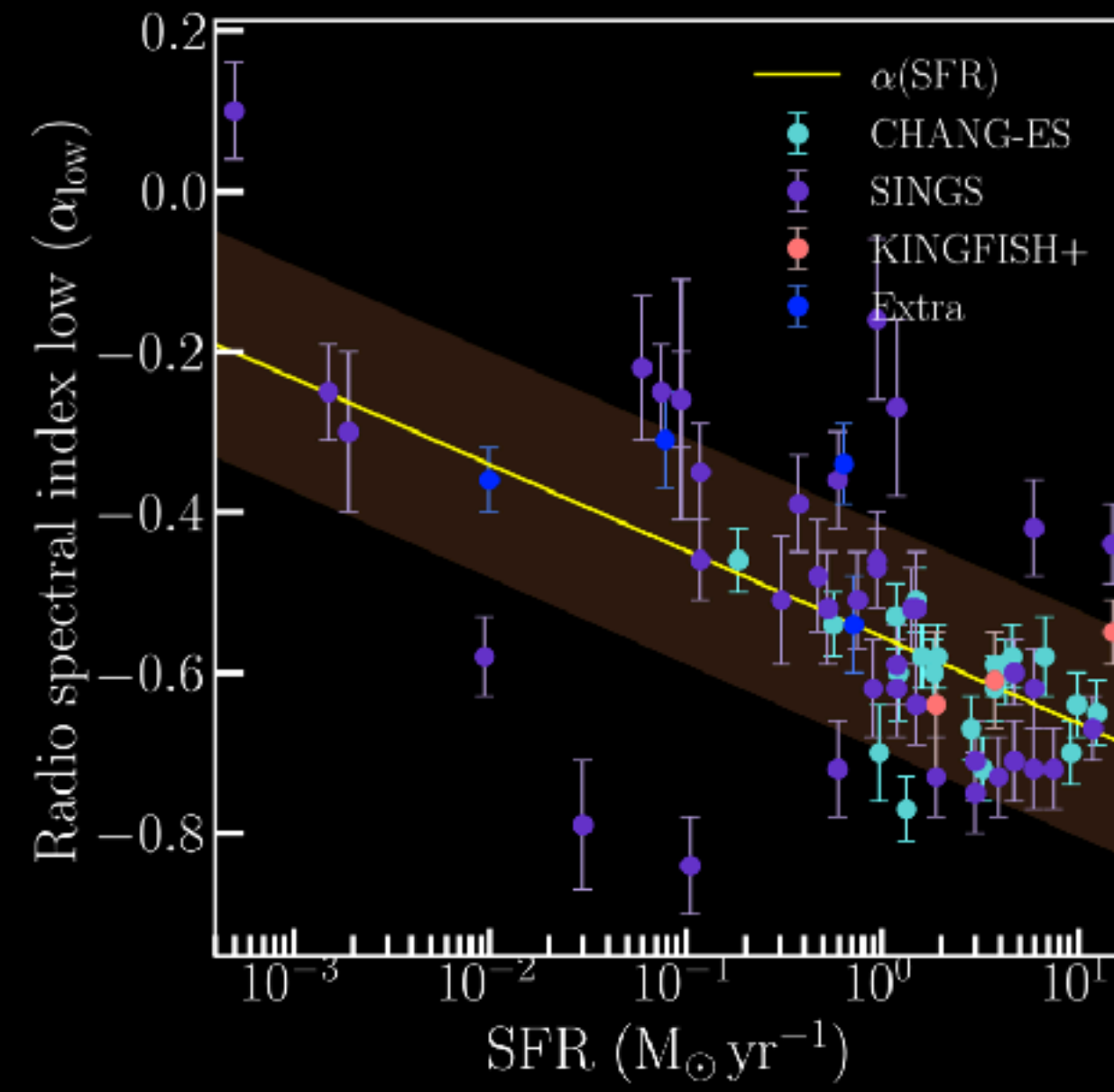
Fast electron escape: $\eta = 0$ $\alpha = -0.6$

flat spectrum

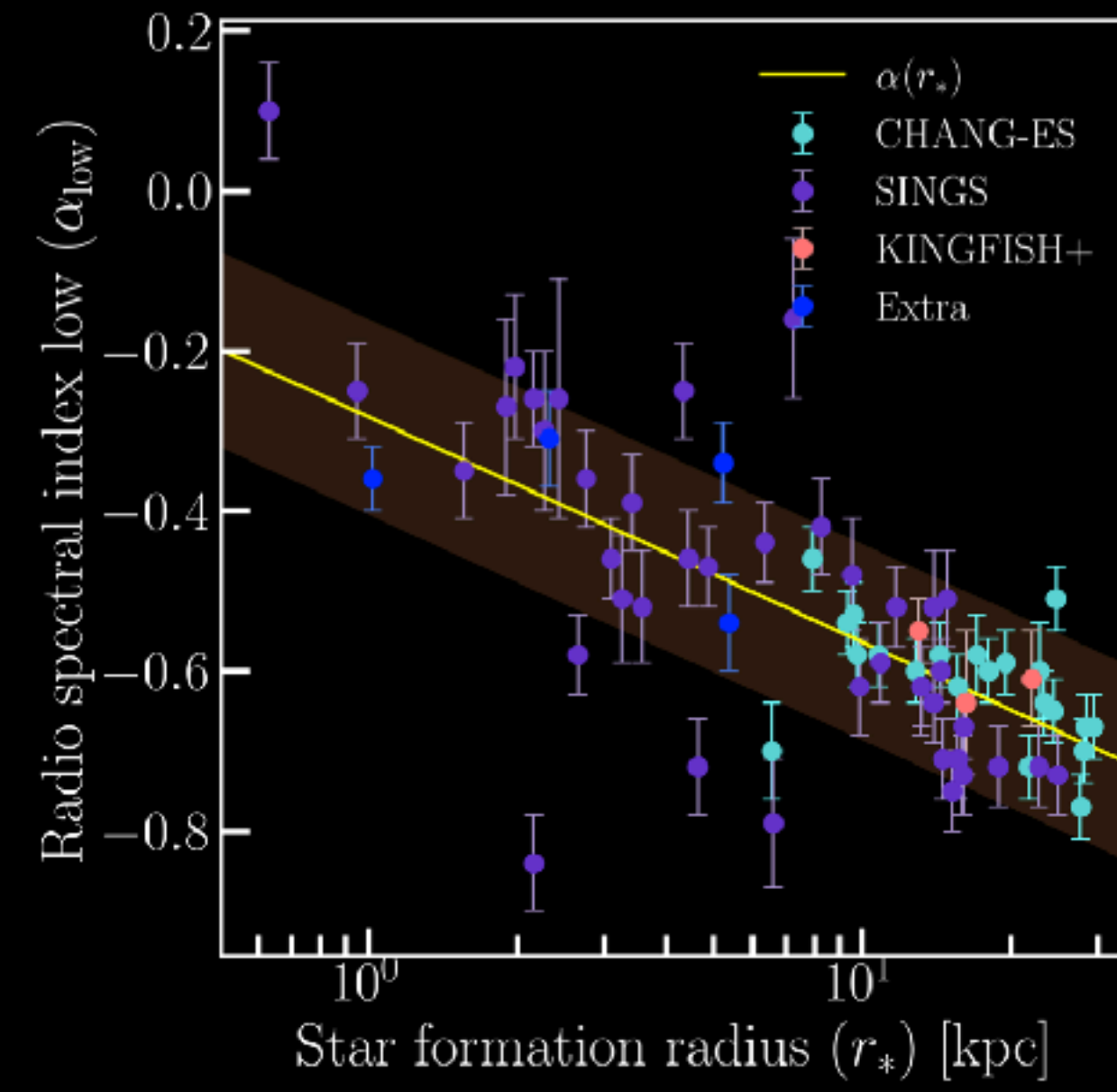
Spectral ageing



SFR

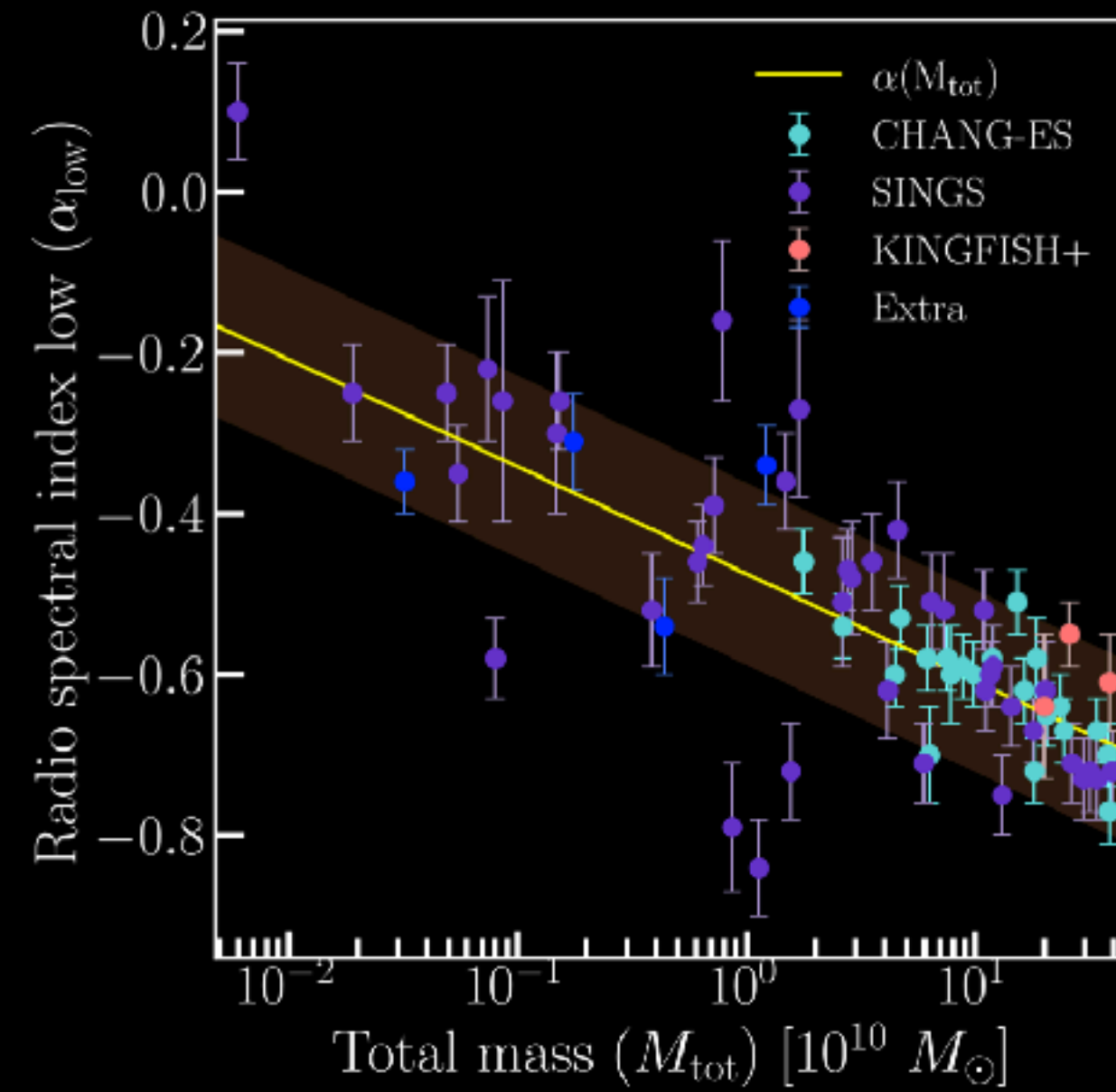


Size

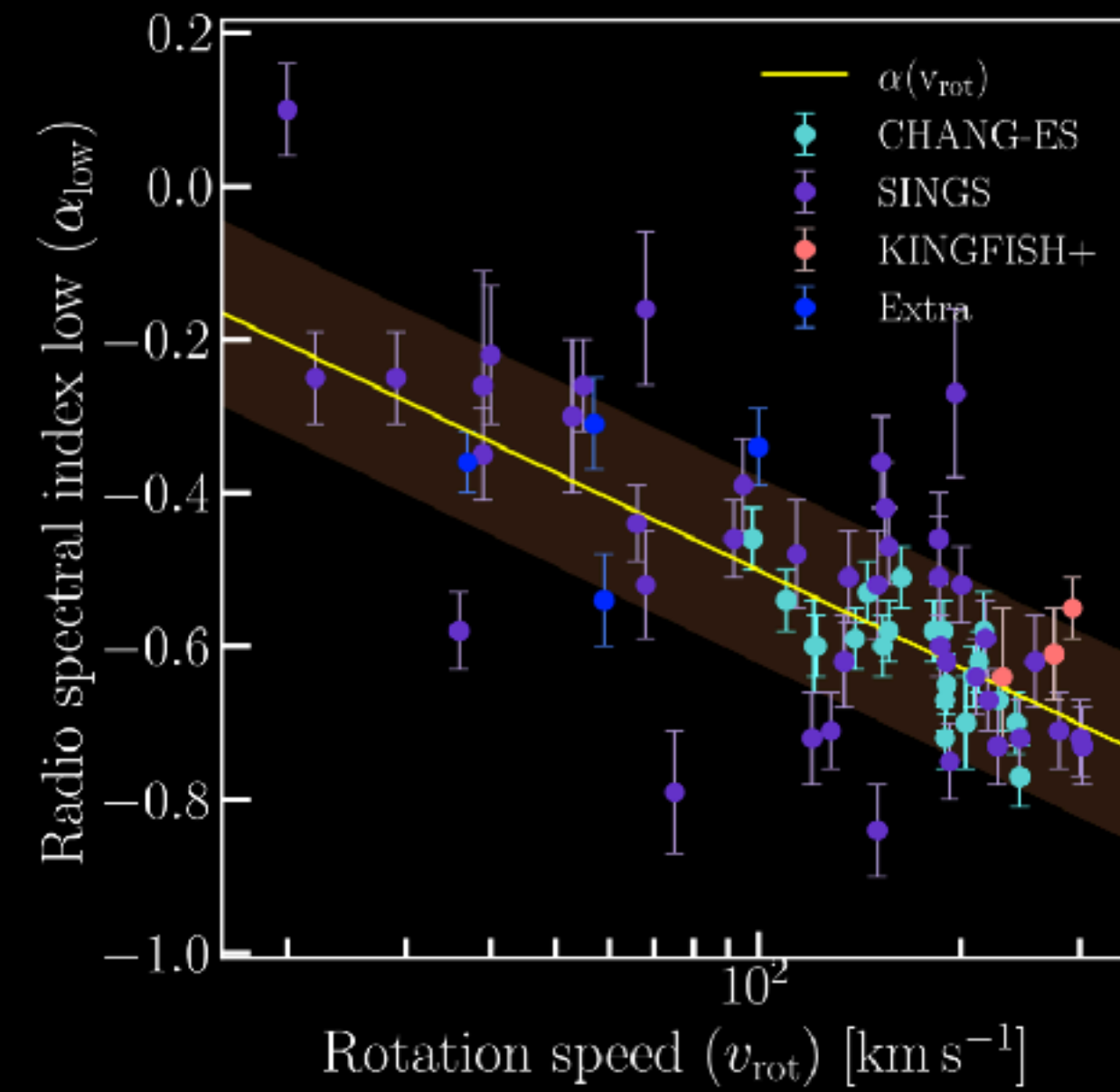


(d)

Mass

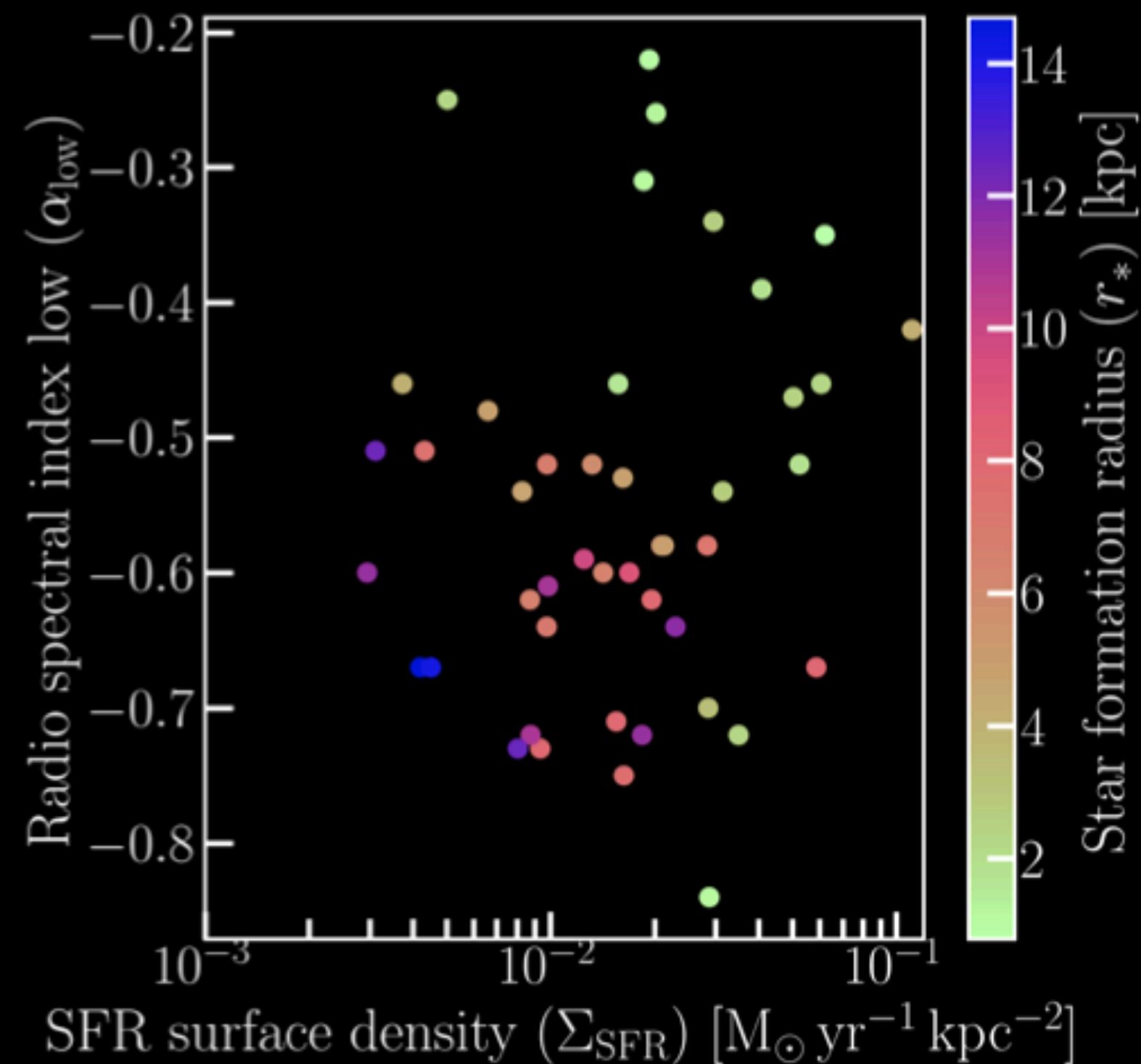


Rotation speed



Galaxy size determines radio spectral index

spectral index does not depend on Σ_{SFR}



h : scale height $\sim r_{\star}$
 (Krause et al. 2018)
 v : wind velocity $\sim \Sigma_{\text{SFR}}$
 (Heckman et al. 2015, Heesen et al. 2018)

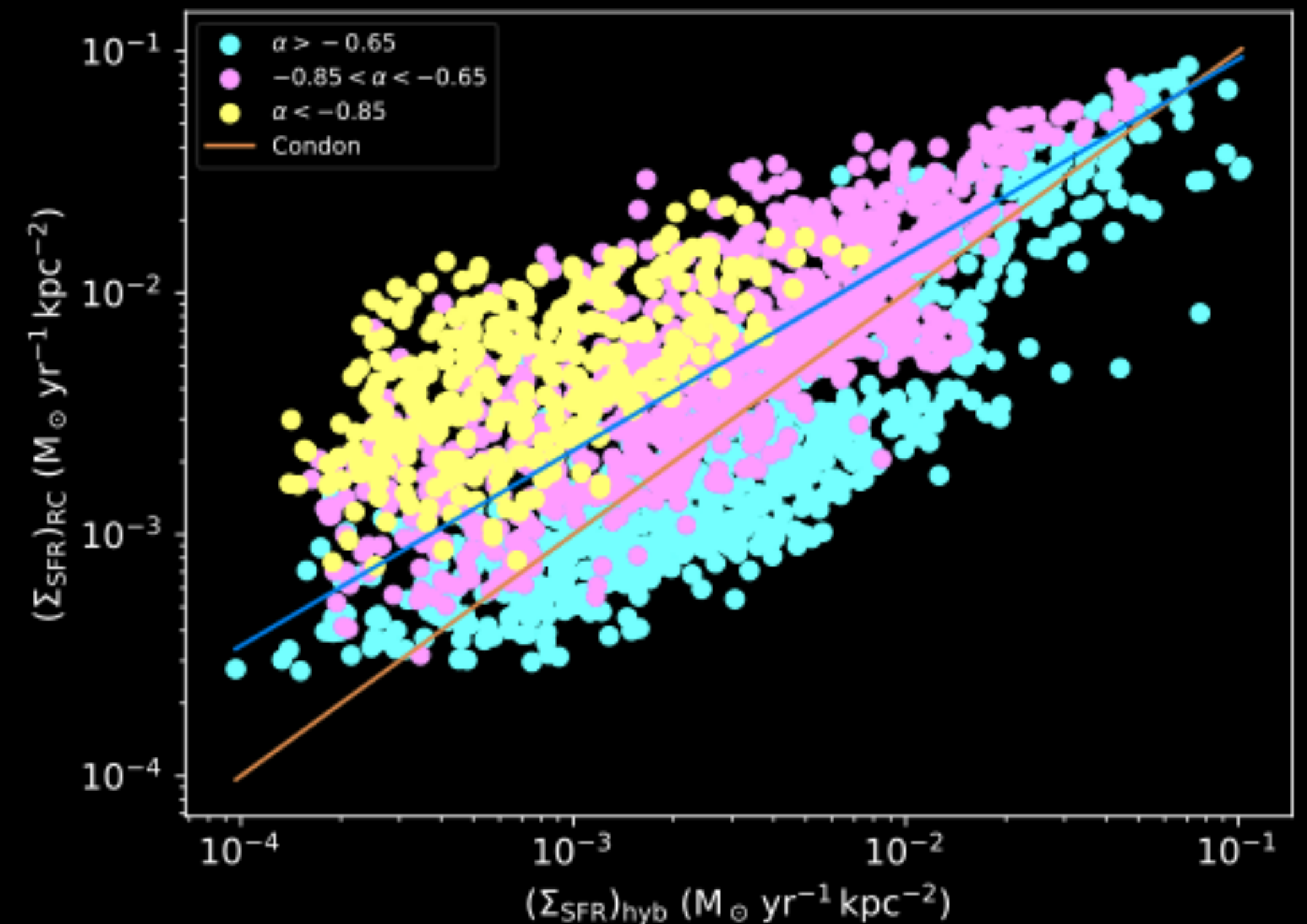
B : magnetic field strength
 $B \sim \Sigma_{\text{SFR}}^{1/3}$
 (Beck 2015, Tabatabaei et al. 2018)

radio spectral index

$$\frac{t_{\text{esc}}}{t_{\text{syn}}} \propto r_* \Sigma_{\text{SFR}}^{0.1}$$

Spatially resolved relation and radio spectral index

- Observed: $I_\nu - \Sigma_{\text{SFR}}^{0.6-0.8}$
- Integrated: $L_\nu - \text{SFR}^{1.1-1.5}$
- Radio spectral index dependence

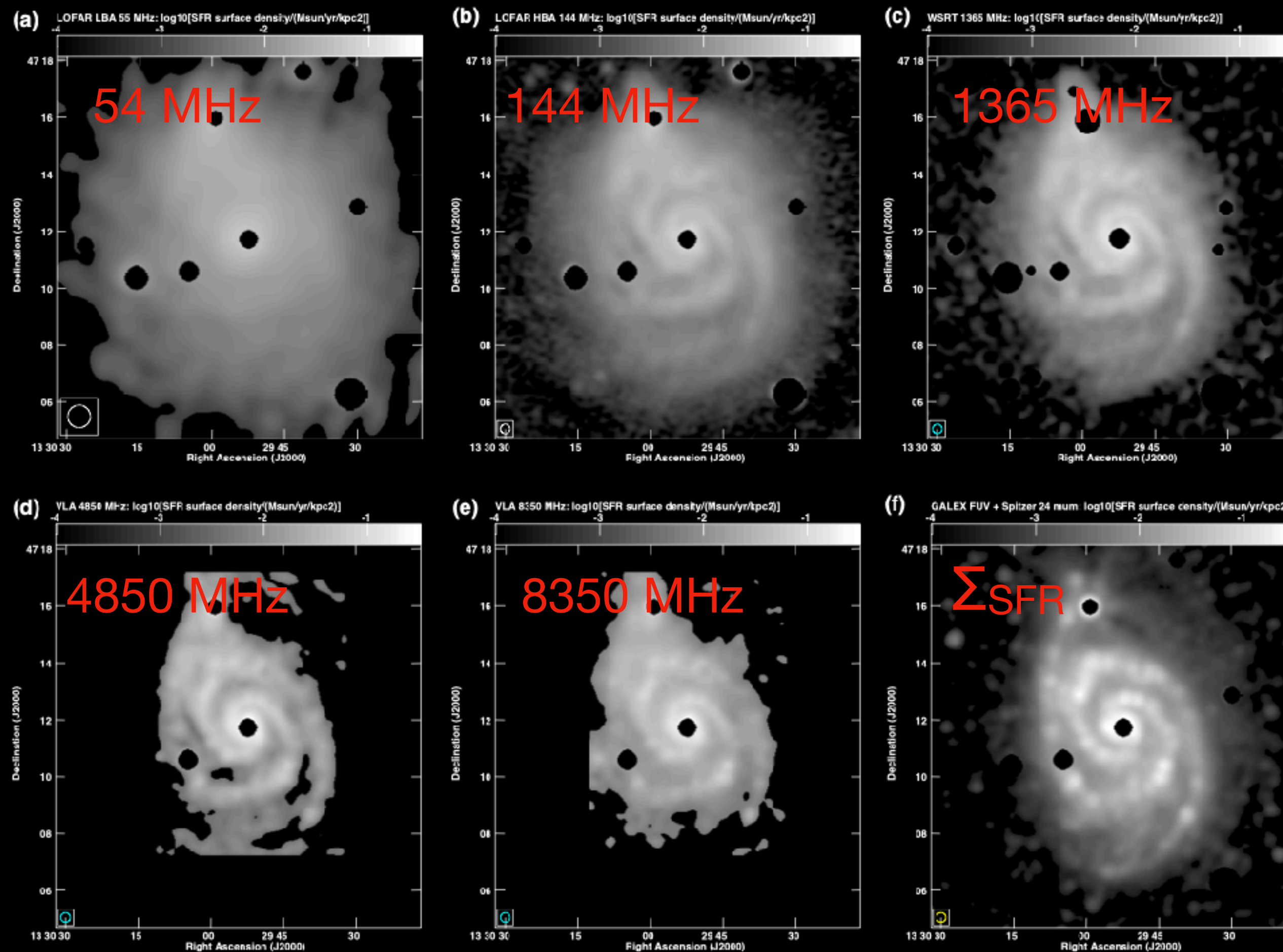


Heesen et al. (2024)

Smoothing experiment

diffusion length in face-on galaxies

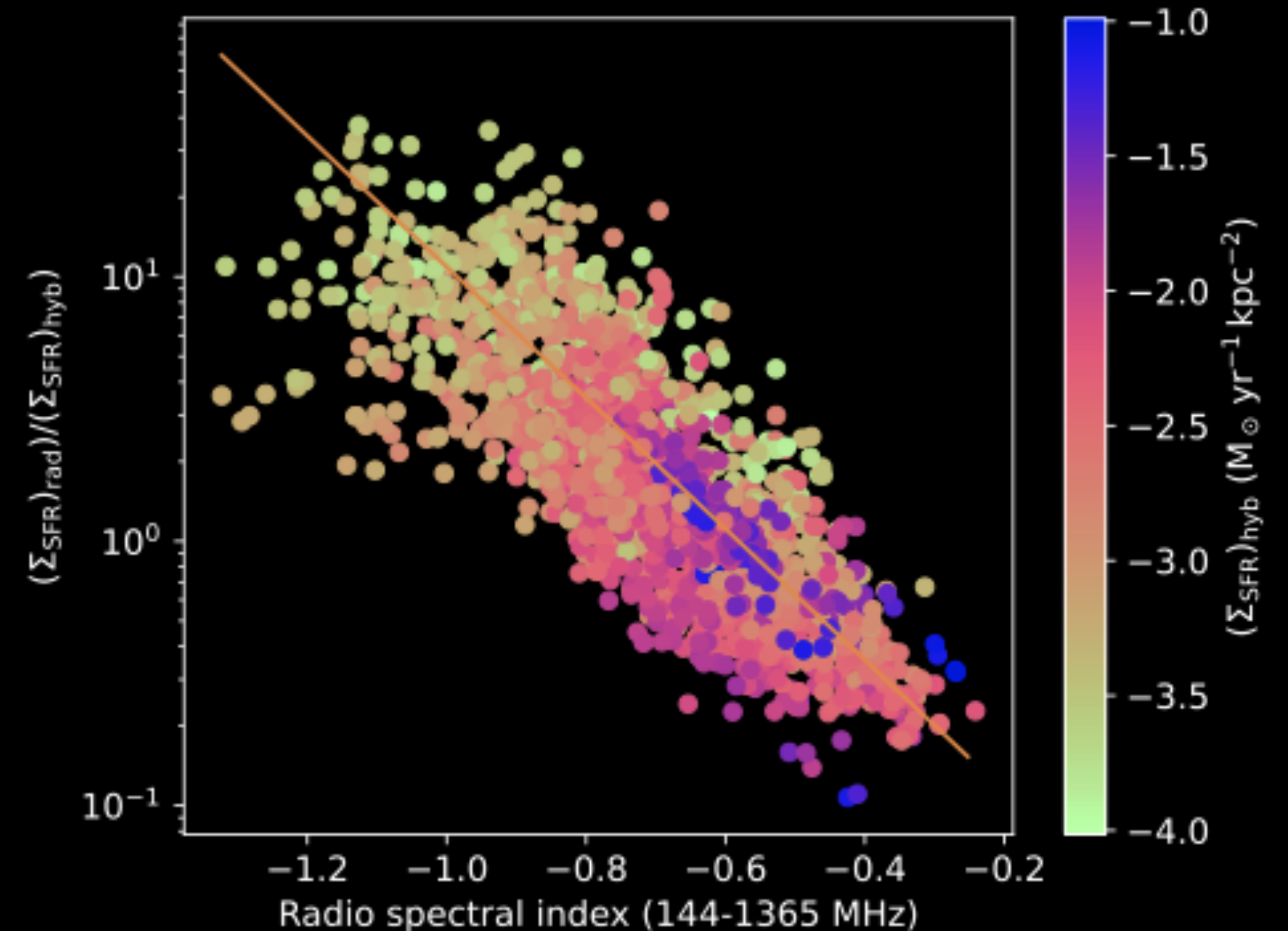
Lowest frequency



CRE injection

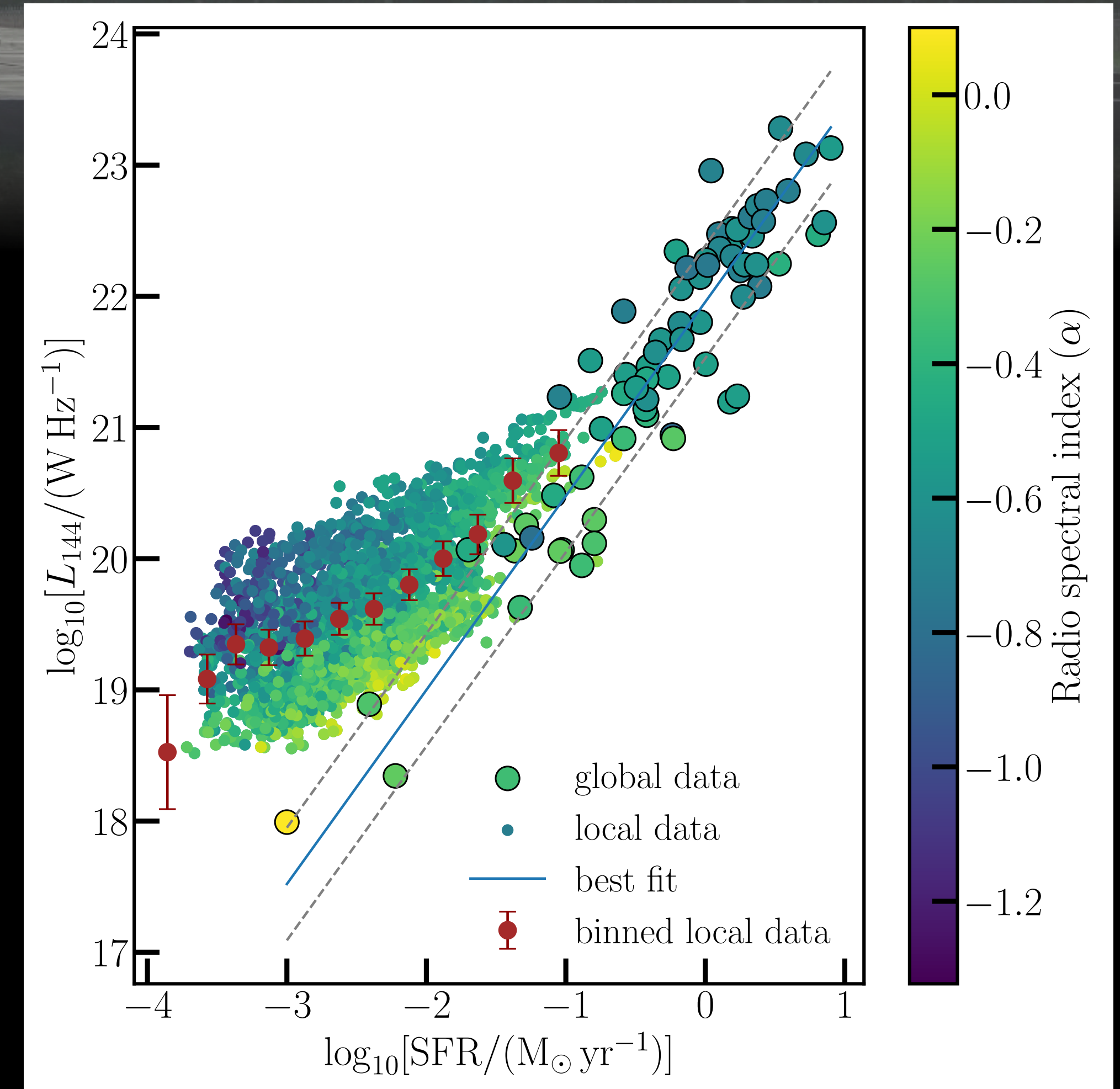
Calorimetric efficiency and the radio–SFR relation

- Ratio of radio-to-hybrid SFR
- Dependence on radio spectral index
- Old CRE are bright, young are faint



Global radio-SFR relation now including LoTSS-DR3 data

- Are under-luminous in the radio continuum
- Challenges radio-SFR relation at low masses
- Important to observe low mass systems

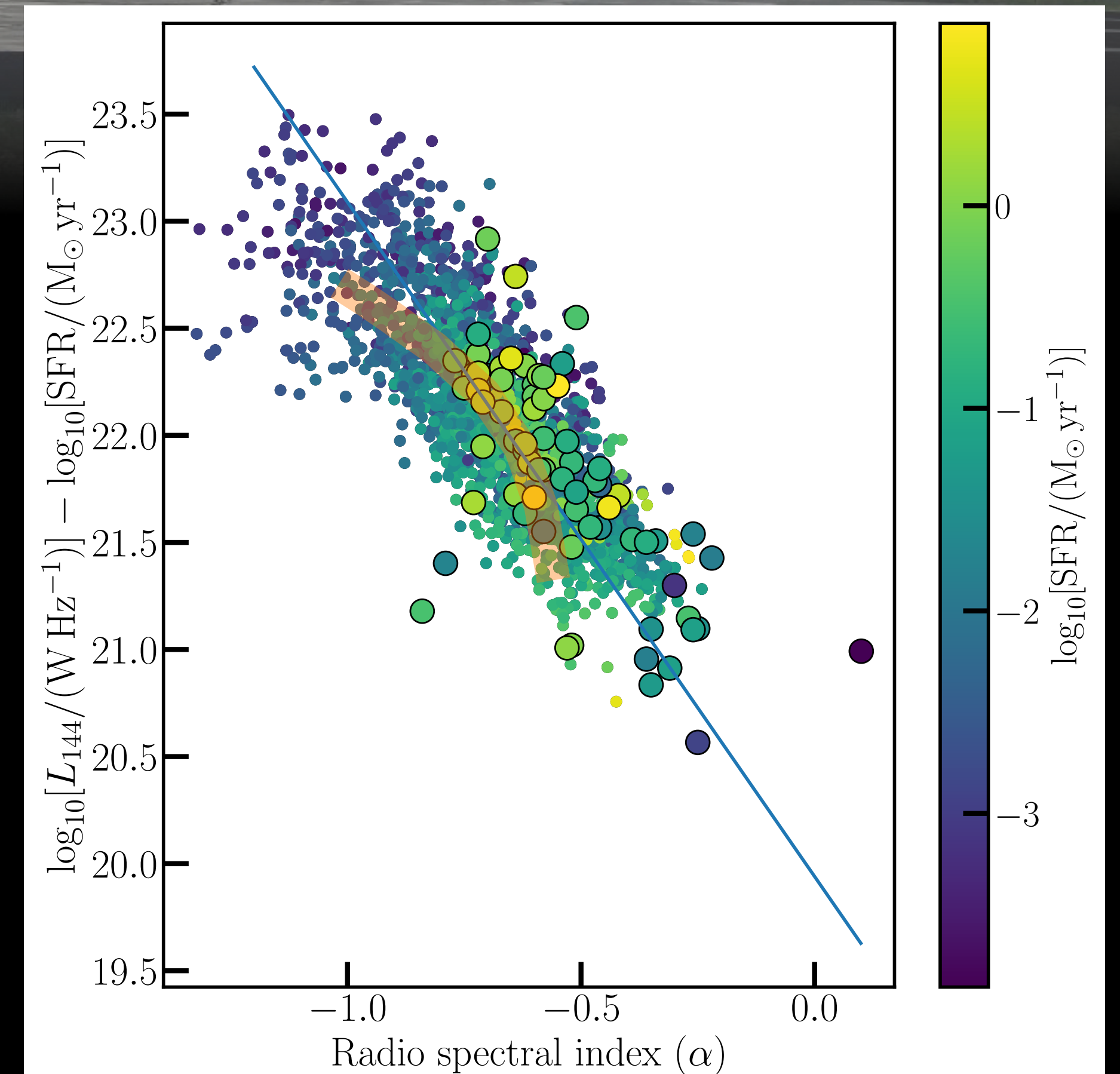


Heesen et al, accepted

Radio-to-SFR ratio

global and local data

- Global and local data follow approximately the same trend
- This means we may be able to define a unified global and local relation

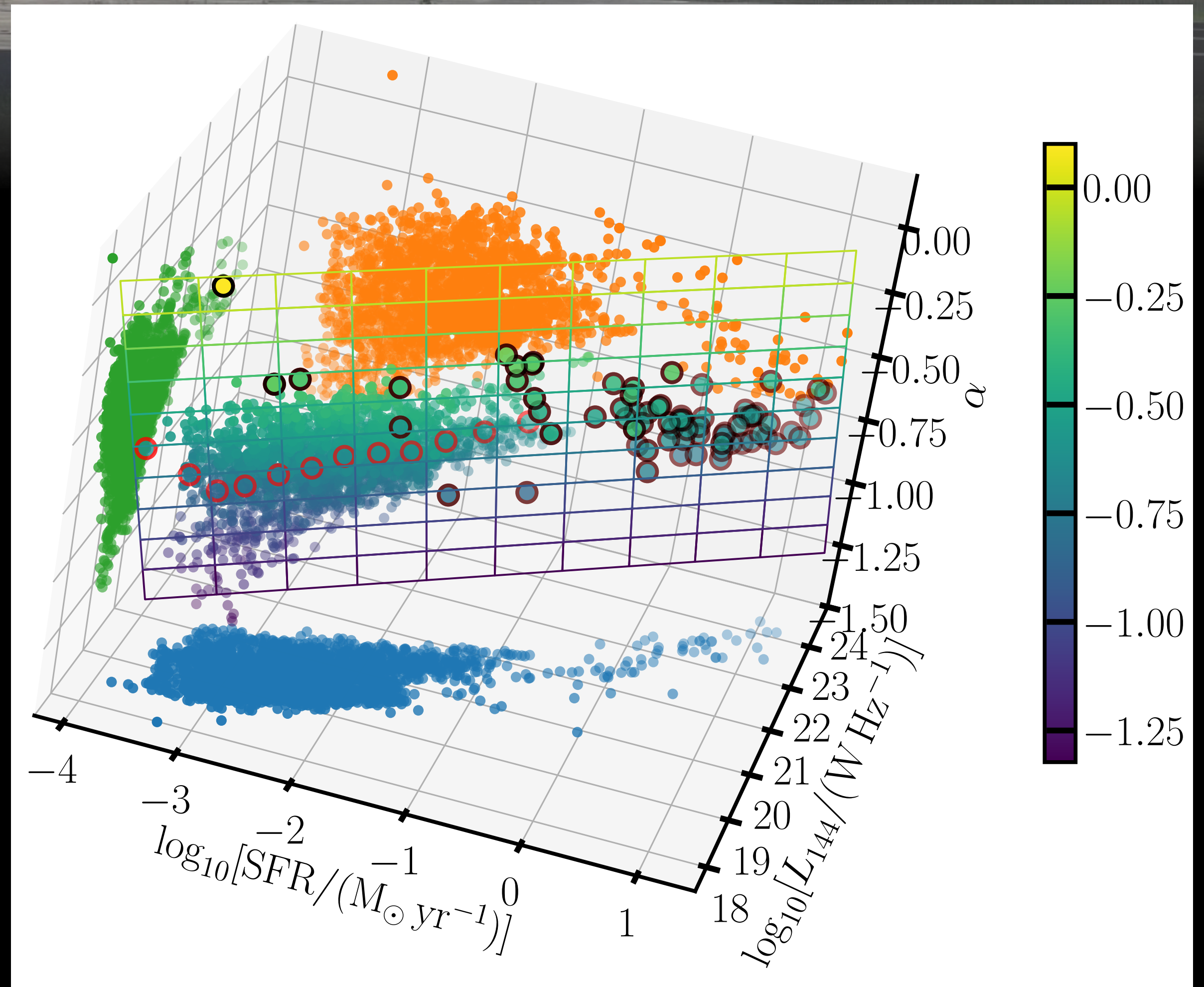


Heesen et al., accepted

Fundamental plane of the radio-SFR relation

- Parametrisation with radio spectral index
- Radio-SFR relation:

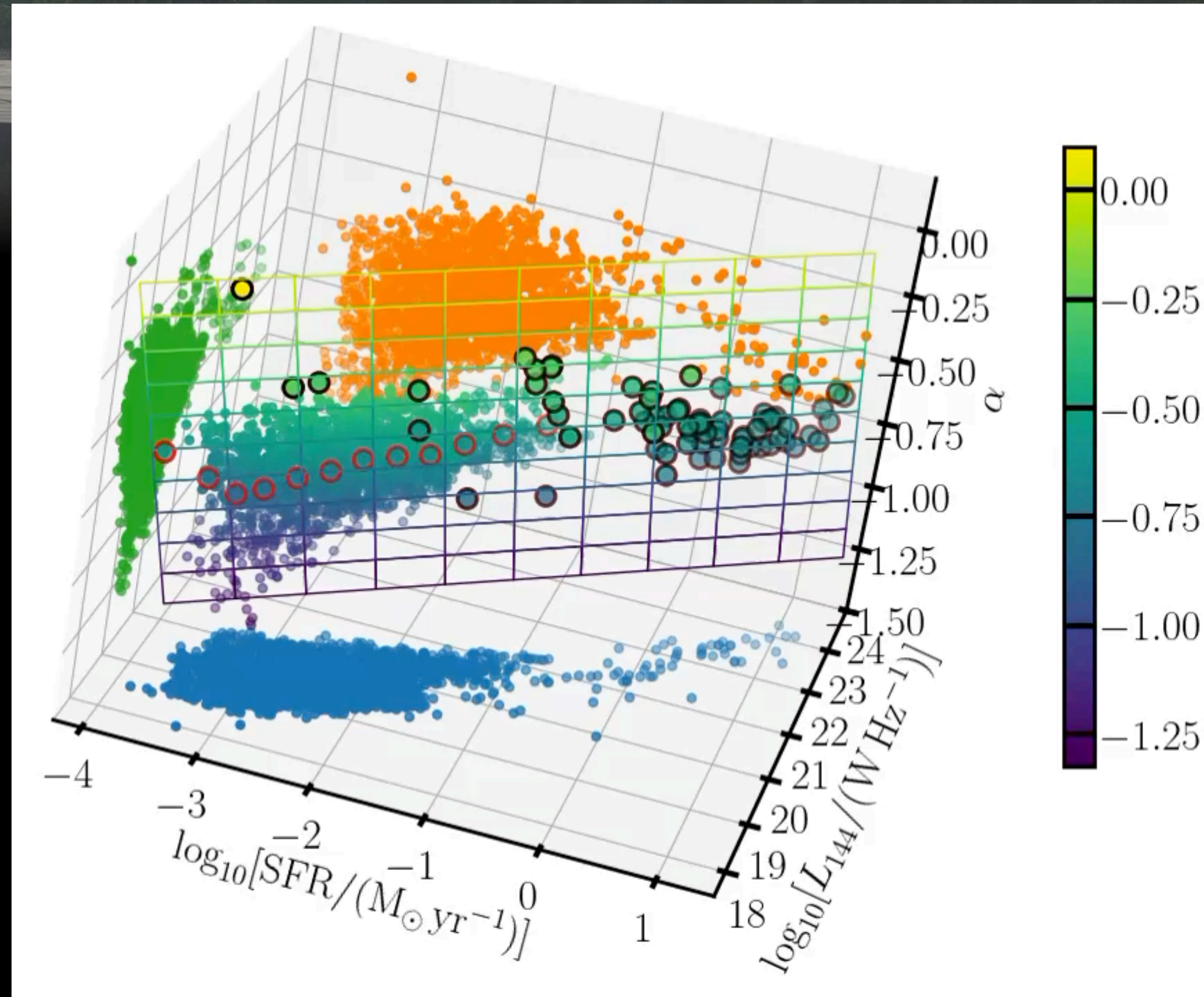
$$\log_{10}(L_{144}) = a \log_{10}(\text{SFR}) + b\alpha + c$$
- Global and local data points lie in a 'fundamental plane'



Heesen et al, accepted

Fundamental plane of the radio-SFR relation

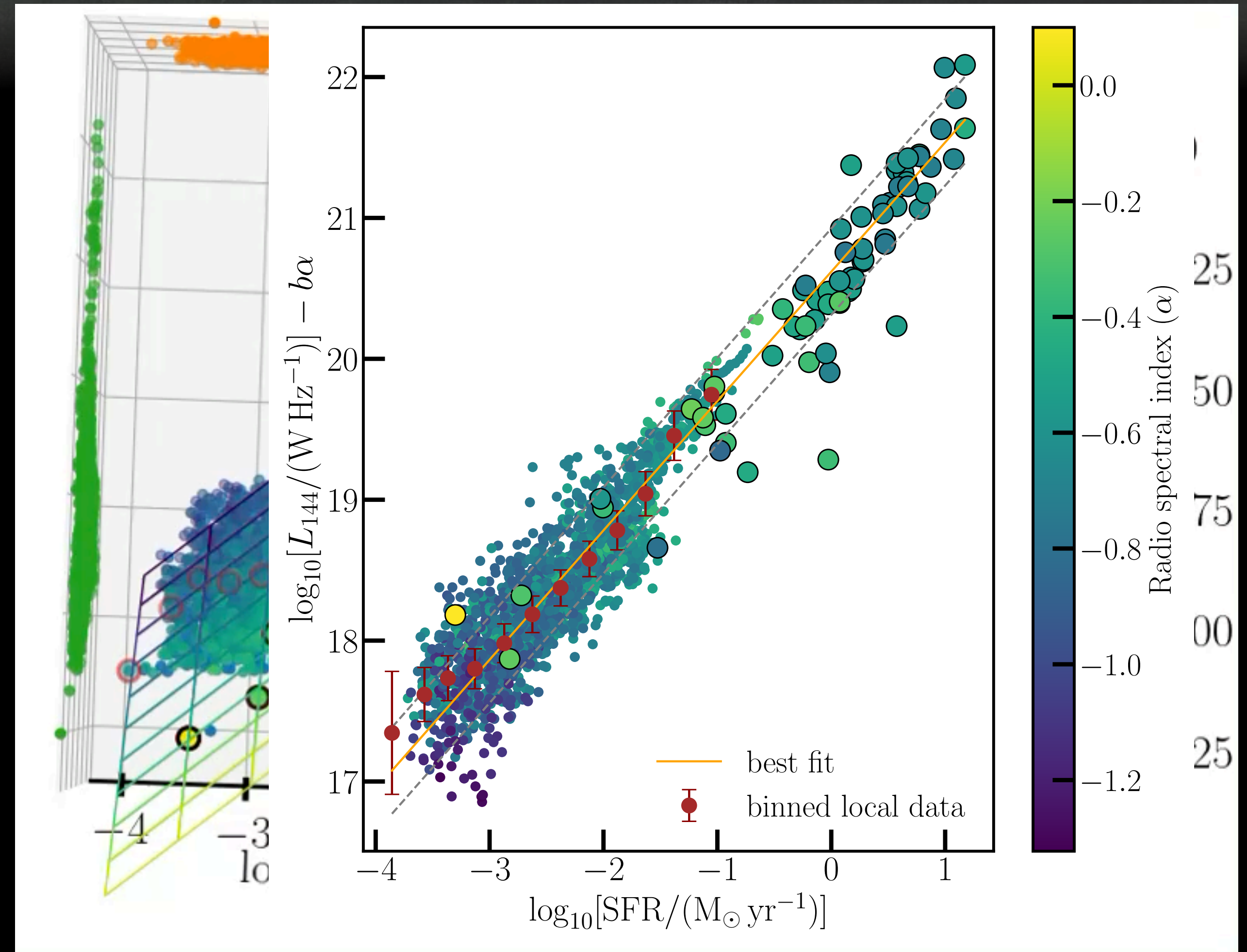
- Parametrisation with radio spectral index
- Radio-SFR relation:
 $\log_{10}(L_{144}) = a \log_{10}(\text{SFR}) + b\alpha + c$
- Global and local data points lie in a 'fundamental plane'



Heesen et al, accepted

Unified radio–SFR relation for global and local data

- Edge-on view of the fundamental plane
- Almost linear radio–SFR relation
- Scatter much reduced



Heesen et al., submitted

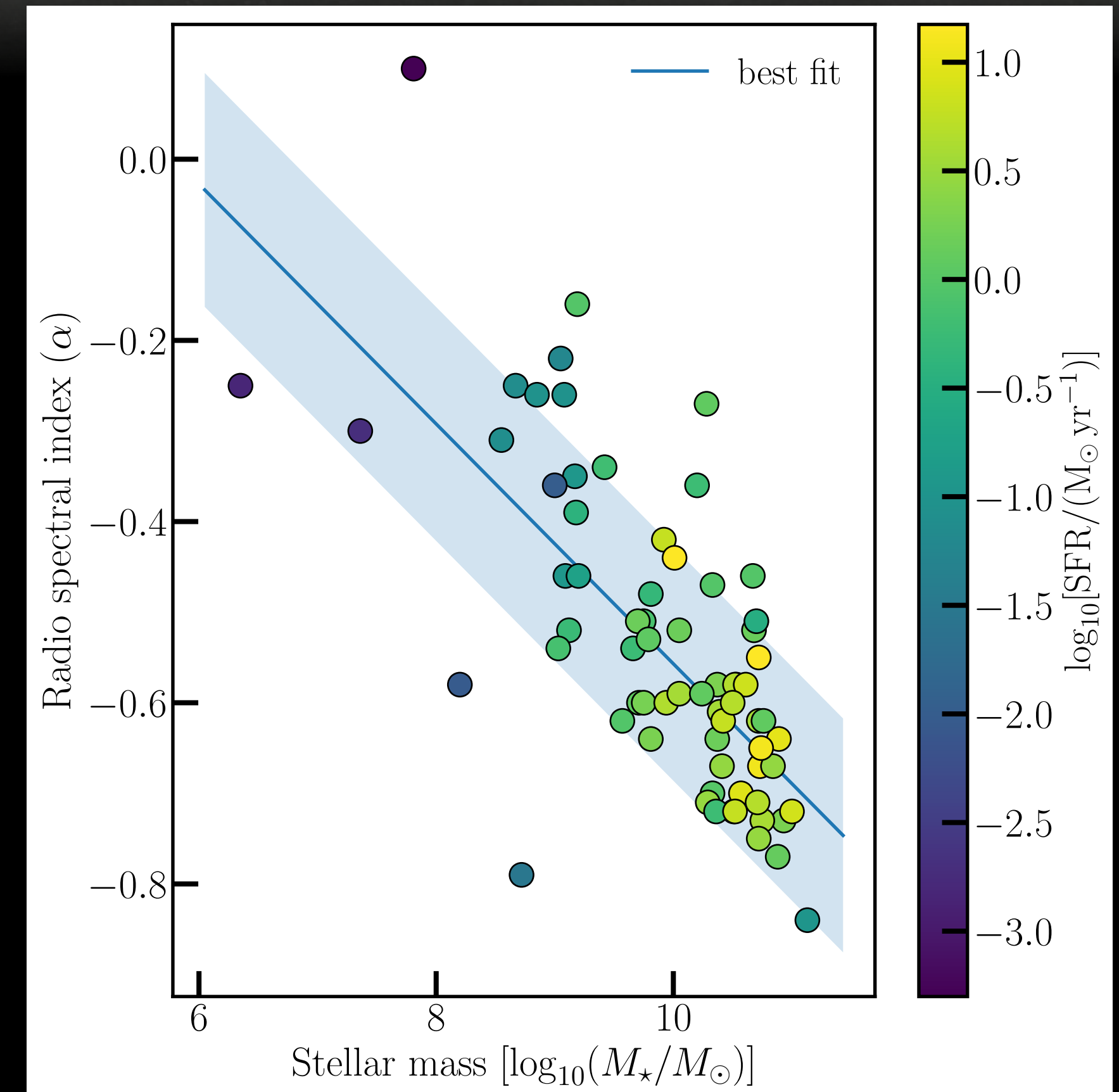
Mass dependency of radio–SFR relation

relation with stellar mass

- Radio spectral index depends on mass
- Mass parametrisation:

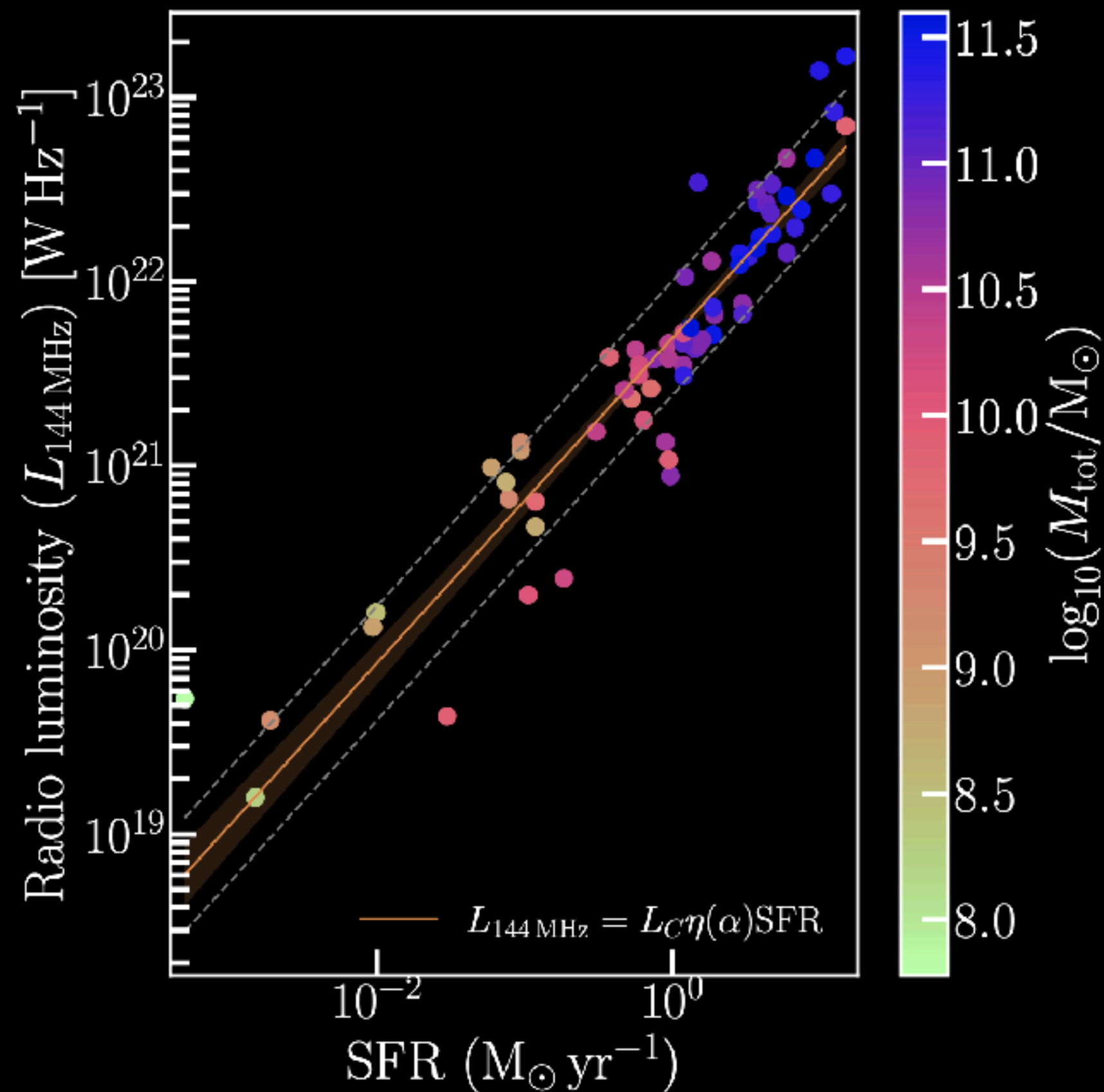
$$\frac{L_{144}}{\text{W Hz}^{-1}} = 10^{21.87 \pm 0.18} \left(\frac{M_*}{10^{10} M_\odot} \right)^{0.23 \pm 0.05} \left(\frac{\text{SFR}}{M_\odot \text{ yr}^{-1}} \right)^{1.10 \pm 0.06}$$

- Good agreement with LoTSS-DR2 wide-fields results (Shenoy+2026)



Mass dependency of radio–SFR relation

using the mass–size scaling relation



$$L_{144 \text{ MHz}} = L_C \text{SFR} M_{\text{tot}}^{\gamma}$$

(Gürkan et al. 2018, Smith et al. 2021)

$$\eta = \frac{1}{1 + \frac{t_{\text{syn}}}{t_{\text{esc}}}} \approx \frac{1}{2} \sqrt{\frac{t_{\text{esc}}}{t_{\text{syn}}}}$$

depends only on
galaxy radius

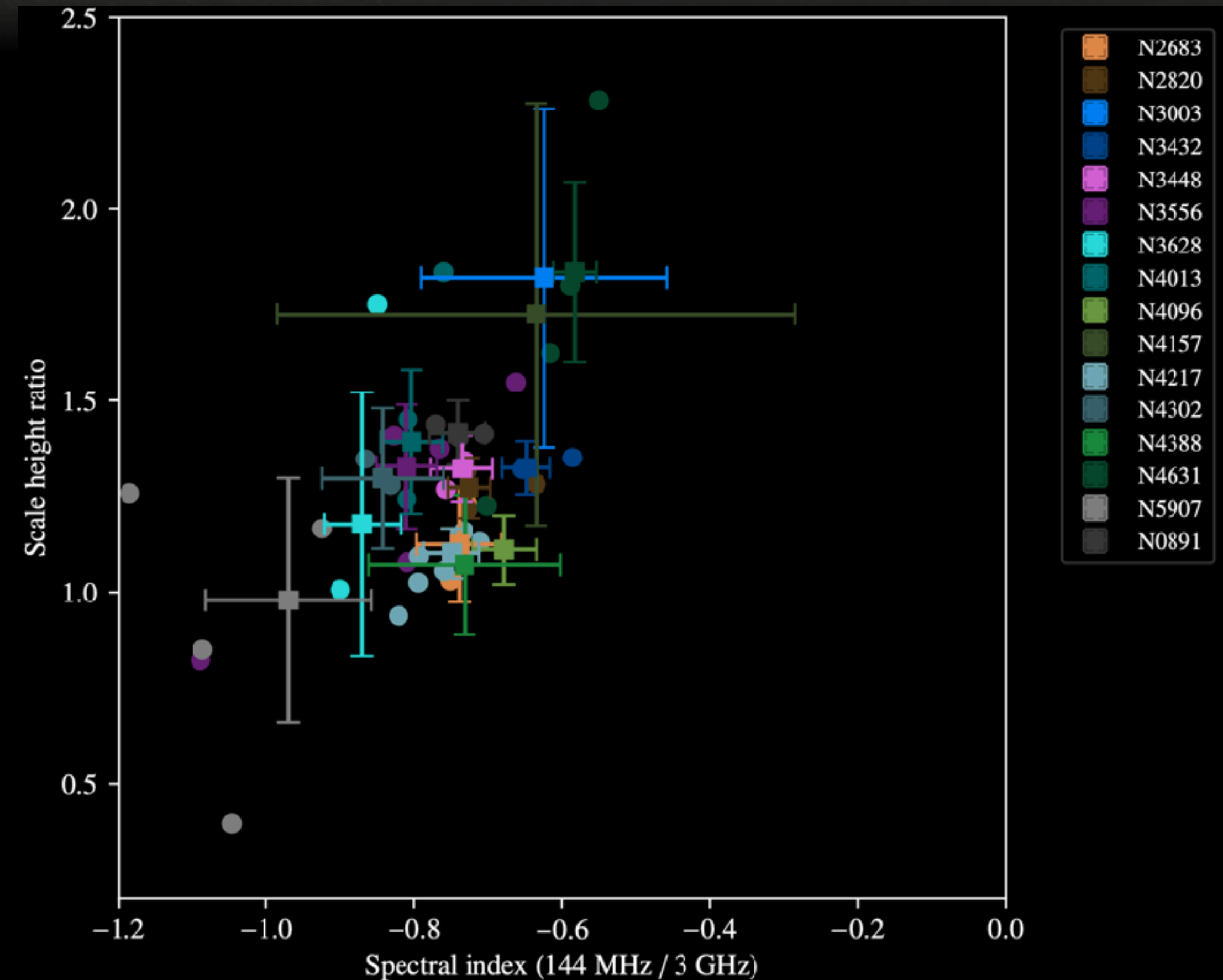
$$\eta \propto \text{SFR}^{0.05} M_{\text{tot}}^{0.27}$$

$$M_{\text{tot}} \sim r_{\star}^{1/3}$$

Cosmic ray escape in winds

radio spectral index

- Scale heights ratios (144 MHz / 3GHz)
- Large ratios in galaxies with flat spectra
- Cosmic-ray transport in galaxies with winds (Stein et al. 2023)



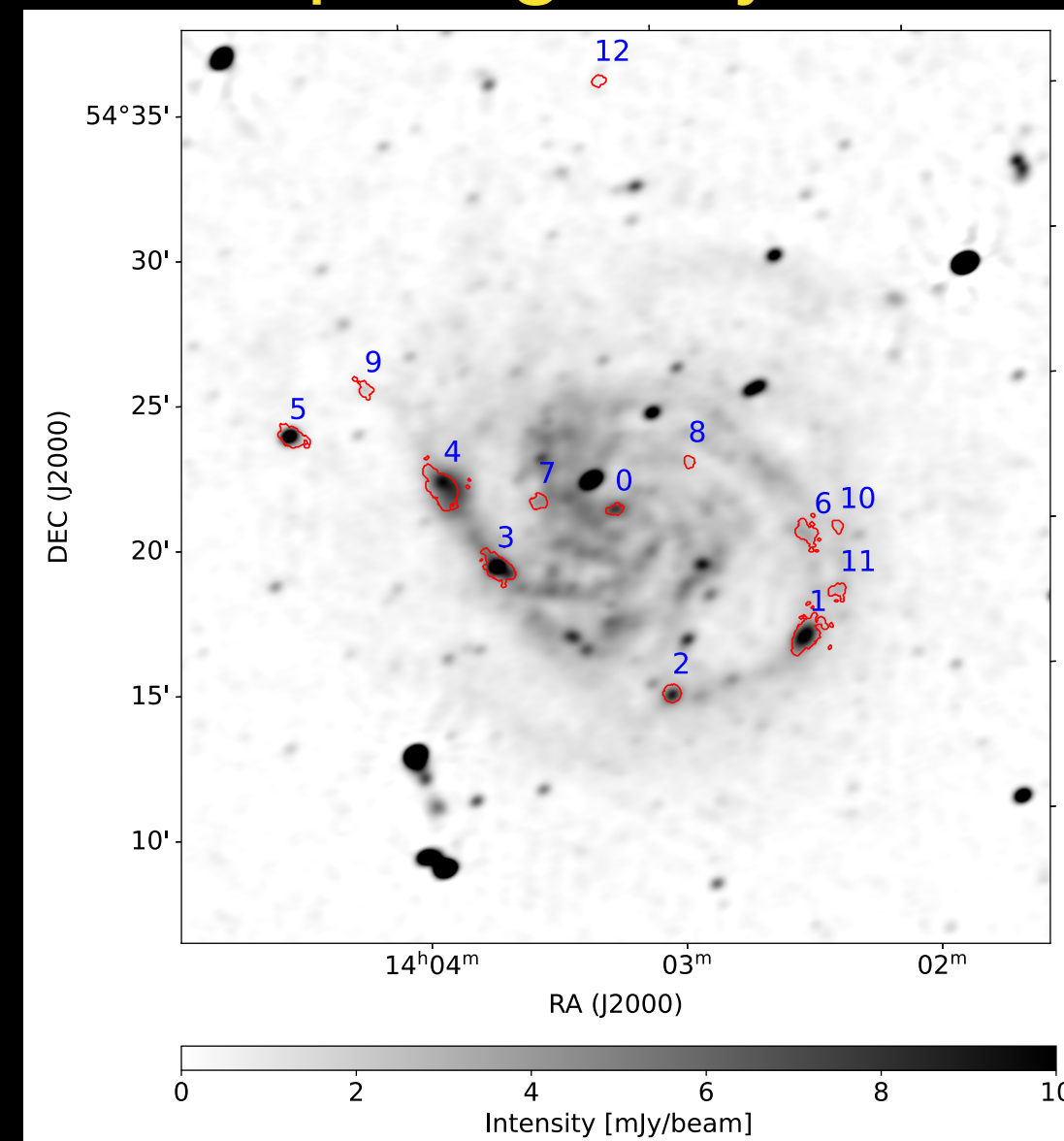
Smolinski et al, 2026

Other influences at low frequencies

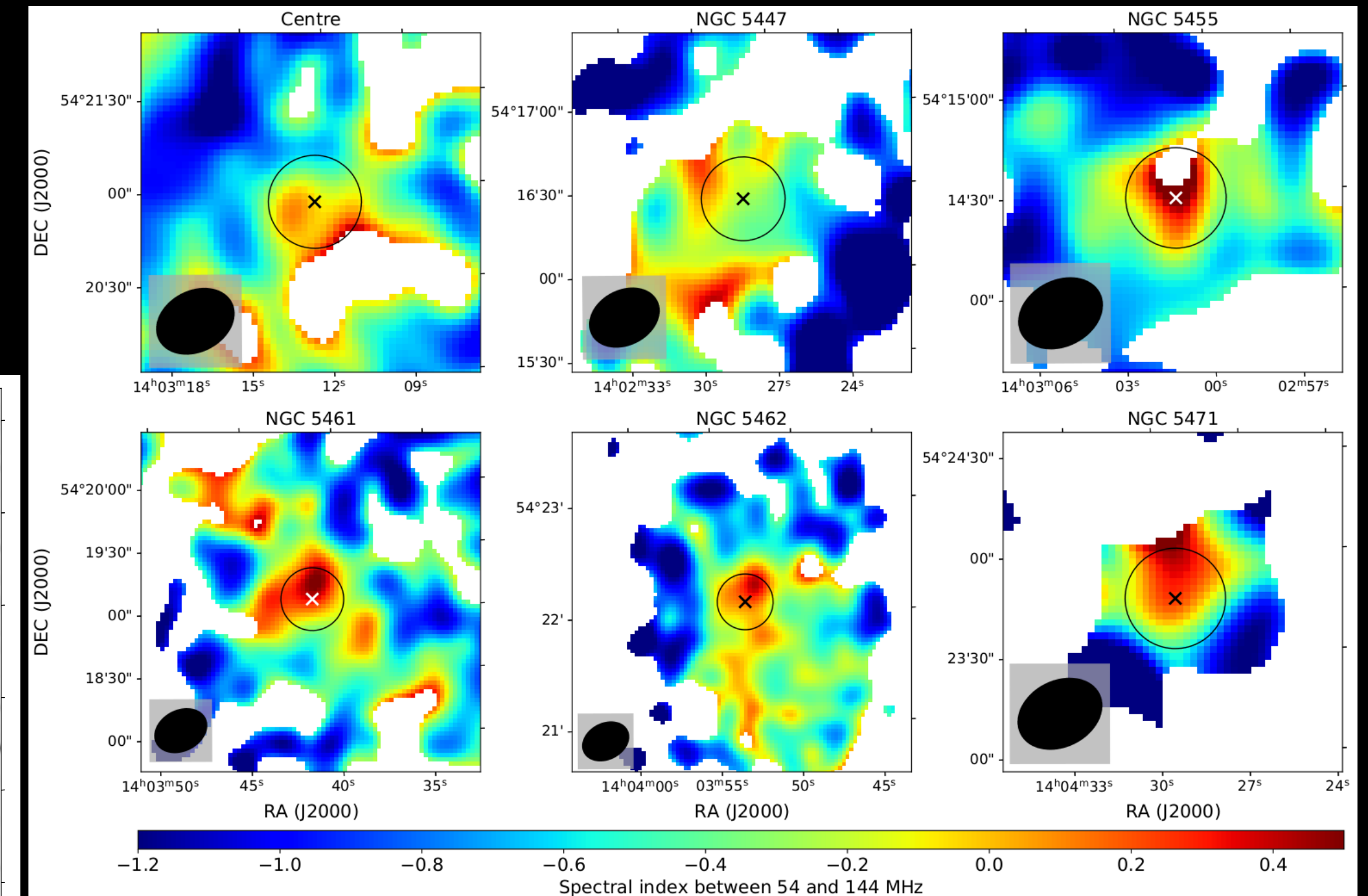
influence on the radio–SFR relation

- Free-free absorption
- Cosmic-ray ionisation losses
- Both flatten the spectrum

Spiral galaxy M101



Inverted radio spectra in H II regions

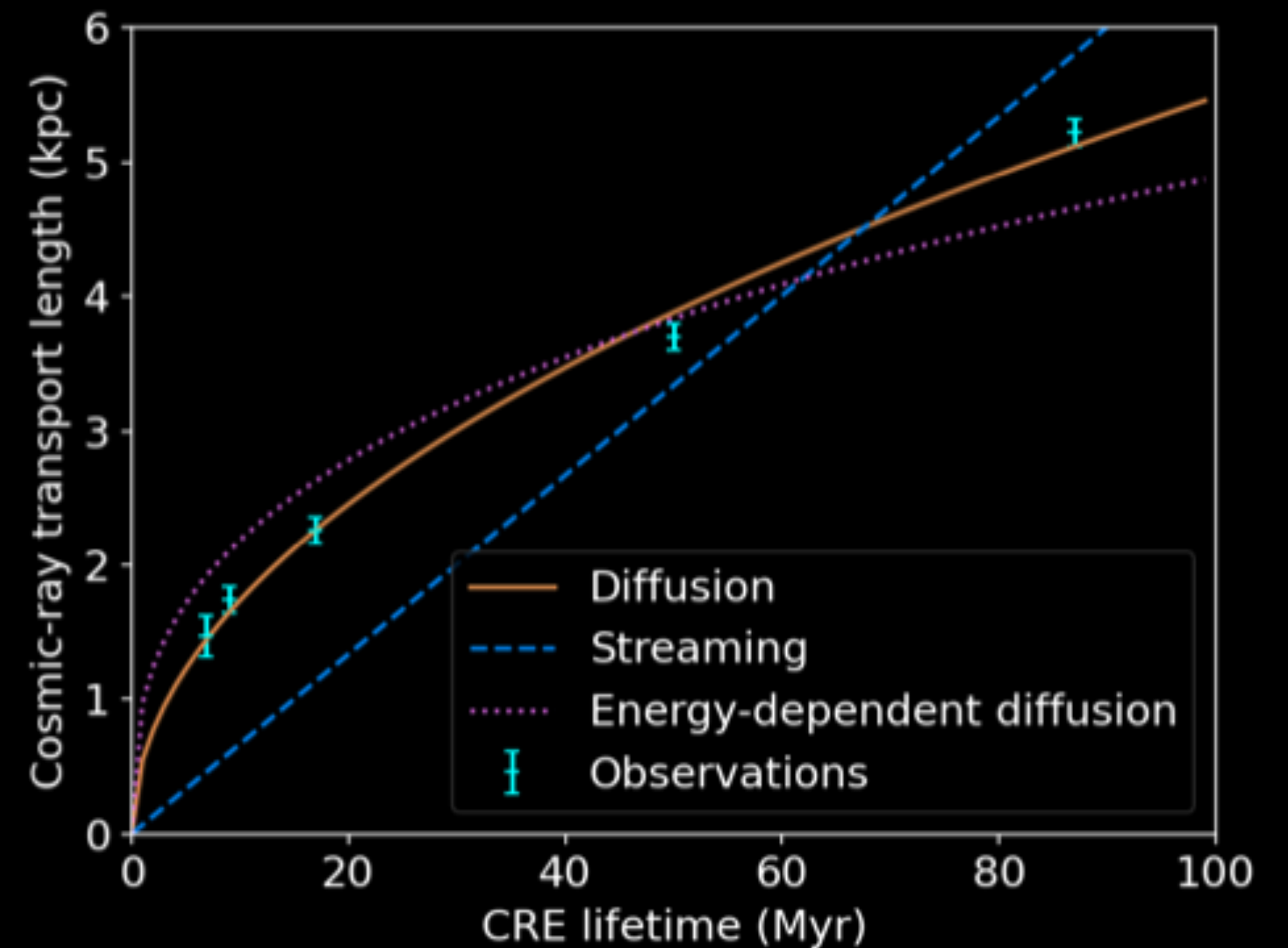


Gajovic et al. (2024, 2025)

Diffusion coefficients

Energy dependence

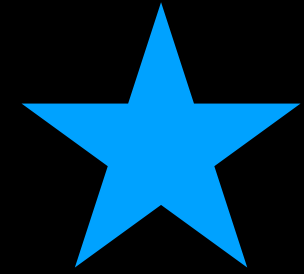
- Mostly non-energy dependent:
 $L \propto \gamma^{-0.25}$
- In radio haloes also non-energy dependent (*Schmidt et al. 2019, Stein et al. 2023*)
- Boron-to-carbon ratio supports this in the Milky Way ($E < 10$ GeV) (*Becker-Tjüs and Mertens (2020)*)



Circumgalactic B -fields

Experimental setup

Background source



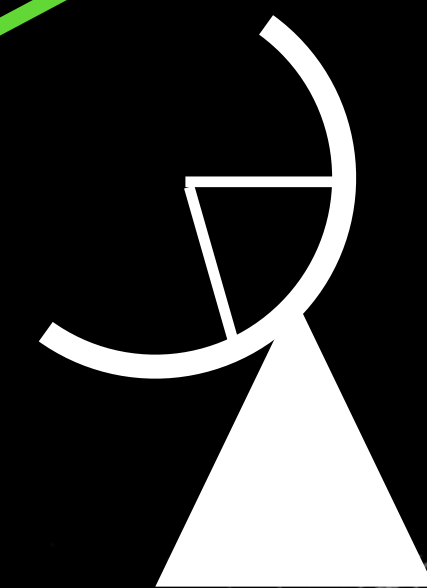
Polarised light

Impact parameter

Halo

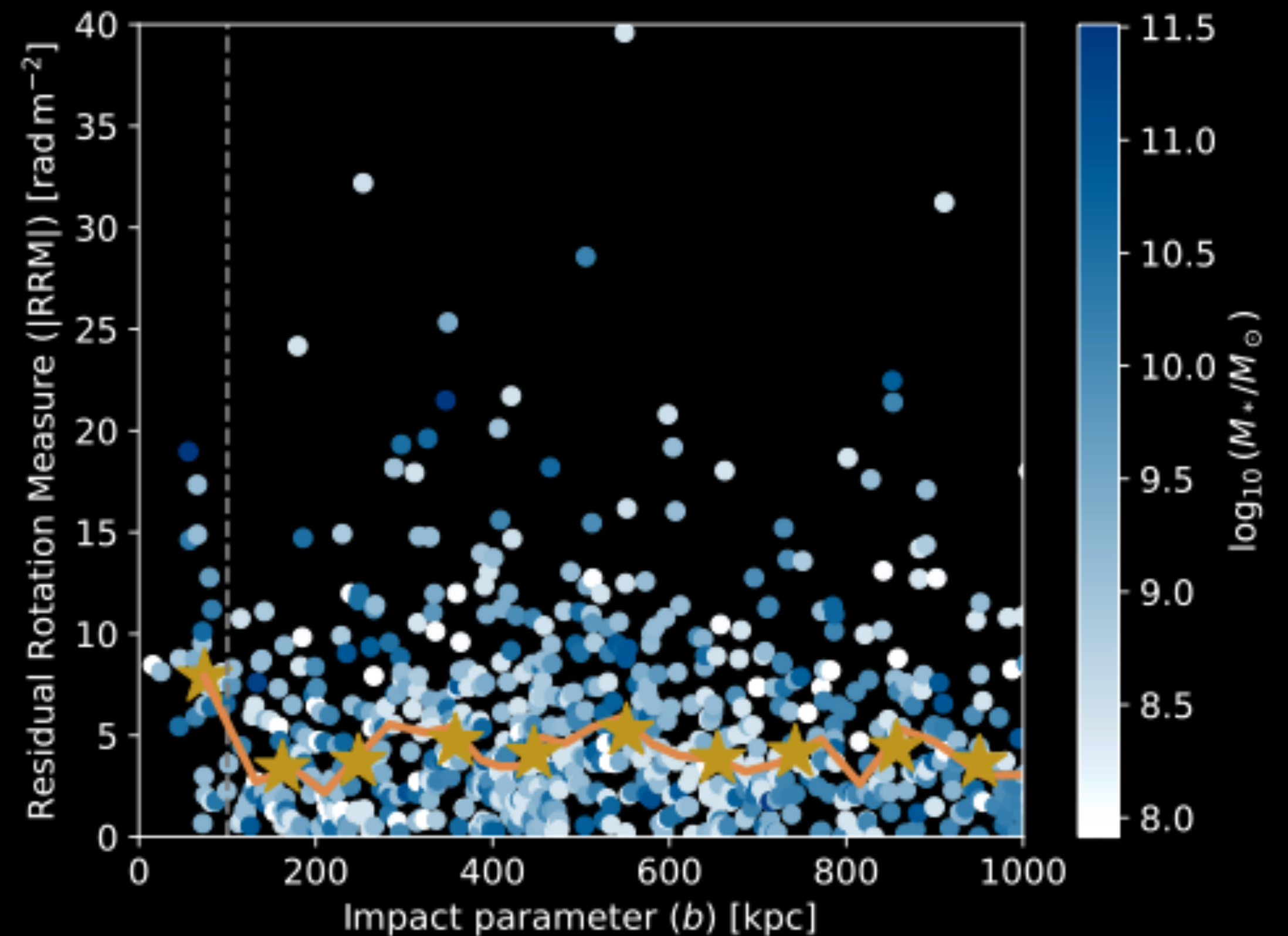
Galaxy

Radio telescope



Detection of circumgalactic B -fields consistent with bipolar outflows

- Excess rotation measure
- At impact parameters < 100 kpc near the minor axis
- $RM = 4 \text{ rad m}^{-2}$
- $B = 0.5 \mu\text{G}$



Conclusions and summary

- Super(sub)-linear global(local) radio–SFR relation
- Ratio radio-to-SFR depends strongly on radio spectral index (power-law slope of the radio continuum spectrum) for both global and local data
- Global and local data points form a fundamental plane defined by $[\log(L_{144}), \log(\text{SFR}), \alpha]$
- Unified global and local radio-SFR relation when using radio spectral index
- Mass dependency can be derived by spectral index parametrisation with mass

Questions?

