Cosmic Rays, galaxies and LOFAR

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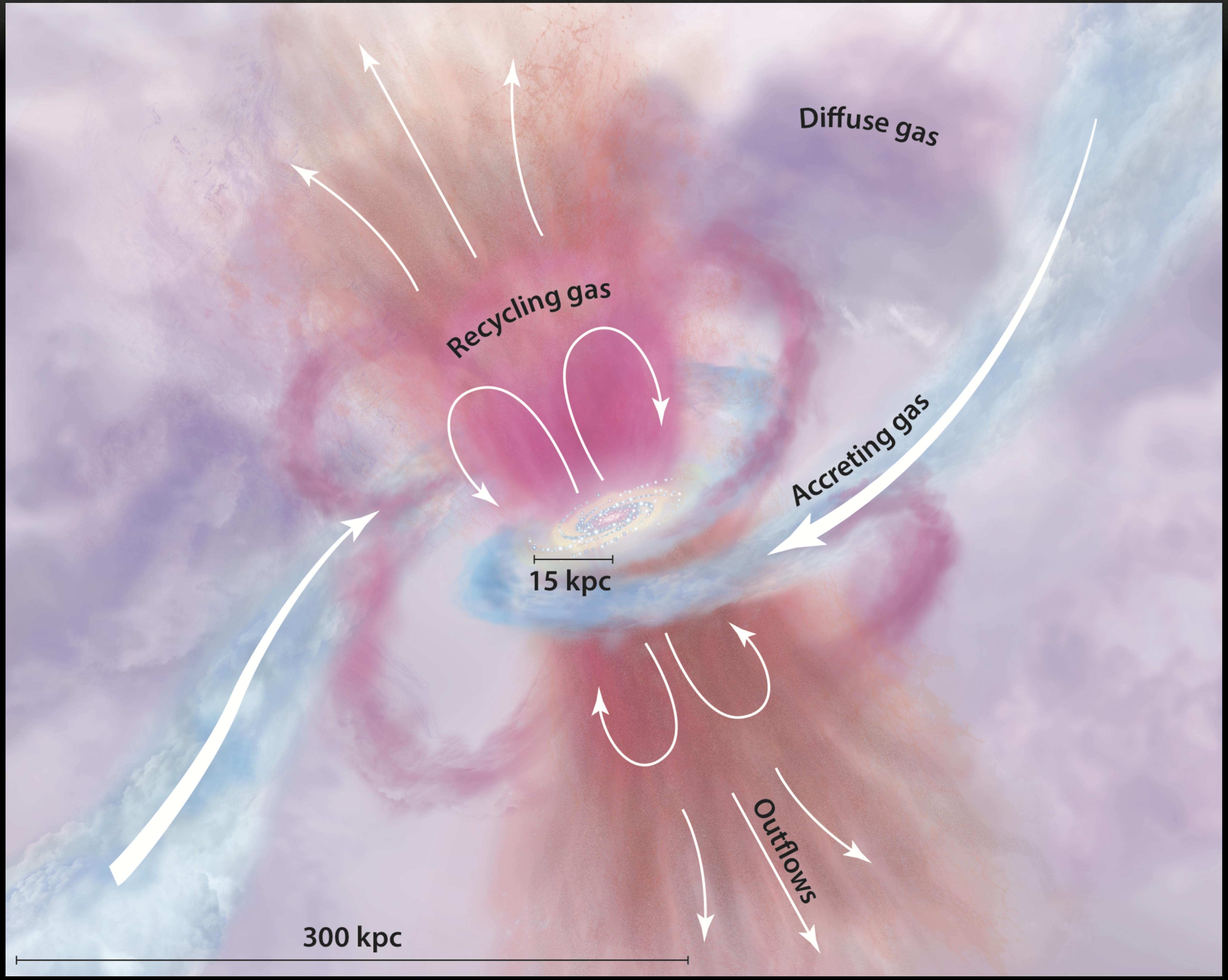
With contributions from Henrik Edler, Aritra Basu, Michael Stein, Julia Piotrowska, Lovorka Gajovic, and Krzysztof Chyży

Cosmic rays and magnetic fields in galaxies

why study them?

- Regulate outflows and accretion of matter
- Are important for galaxy evolution
- GeV-protons energetically most influential
- GeV-electrons are observed in the radio as cosmic-ray electrons (CREs)



Tumlinson et al. (2017)

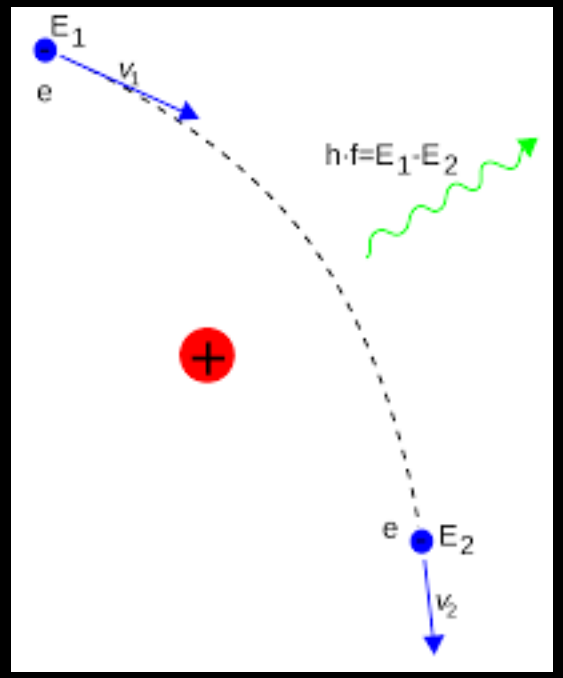
Radio continuum emission
from star-forming galaxies

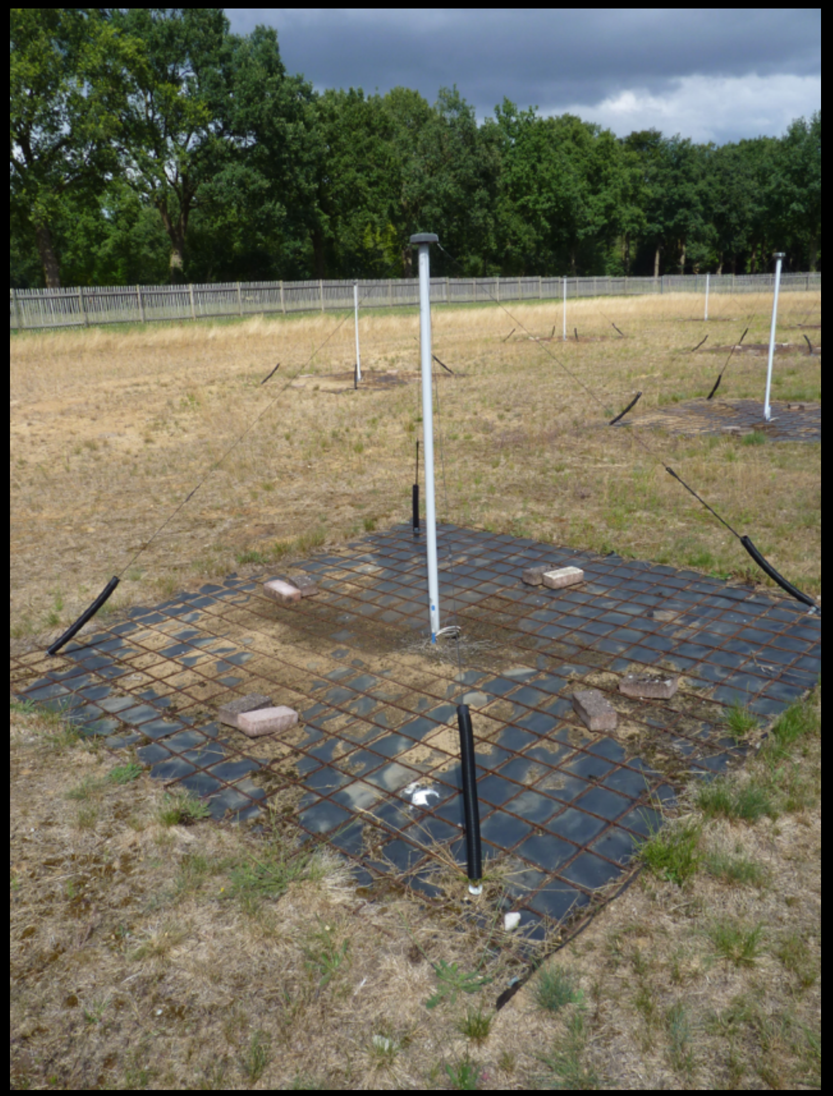
Massive stars

UV radiation

HII region

free–free radiation



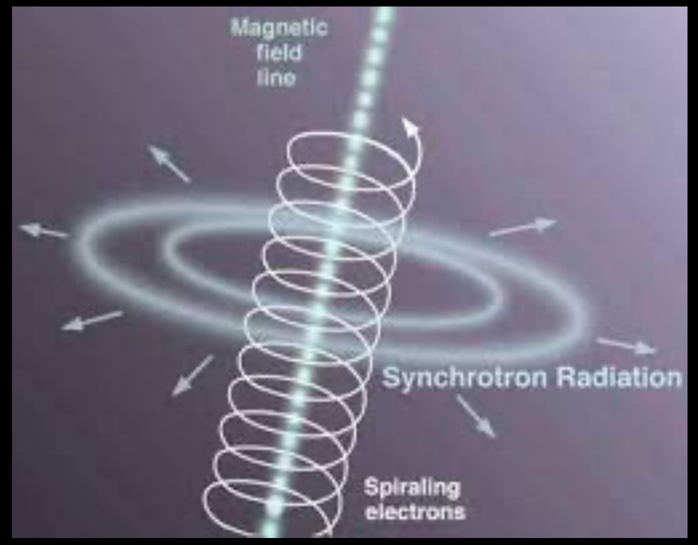


UHH / D. Engels

shock acceleration

SNR

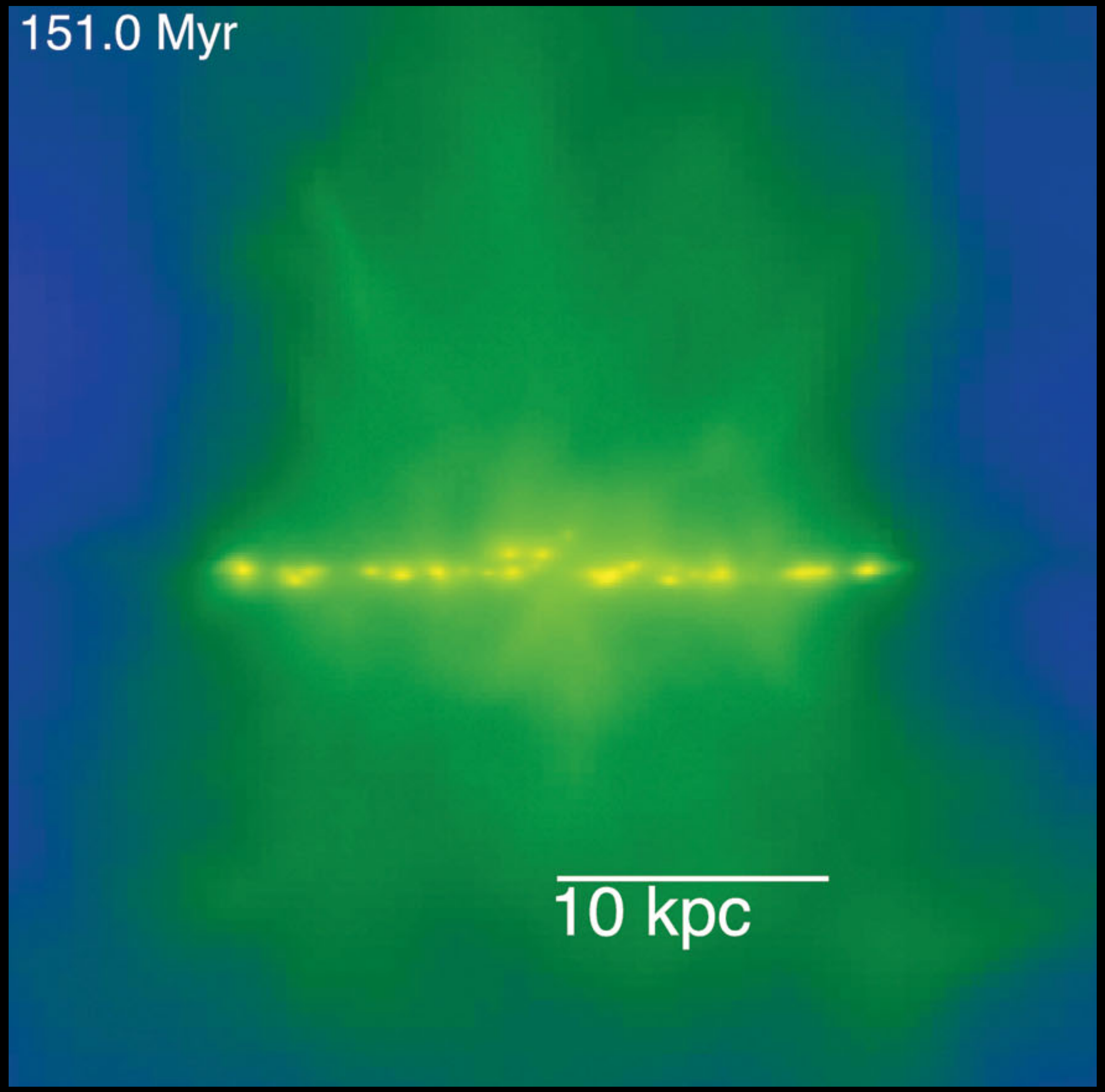
synchrotron emission



But there are some complications

with measuring radio star-formation rates

- Leakage of cosmic-ray electrons from galaxies
- Can be observed as radio haloes (*Heald et al. 2022; Stein et al. 2023*)
- Cosmic ray-driven winds (*Breitschwert et al. 1992, Everett et al. 2008, Recchia et al. 2016*)
- Thermal (free–free) absorption (talk by Gajovic)



Salem & Bryan (2014)

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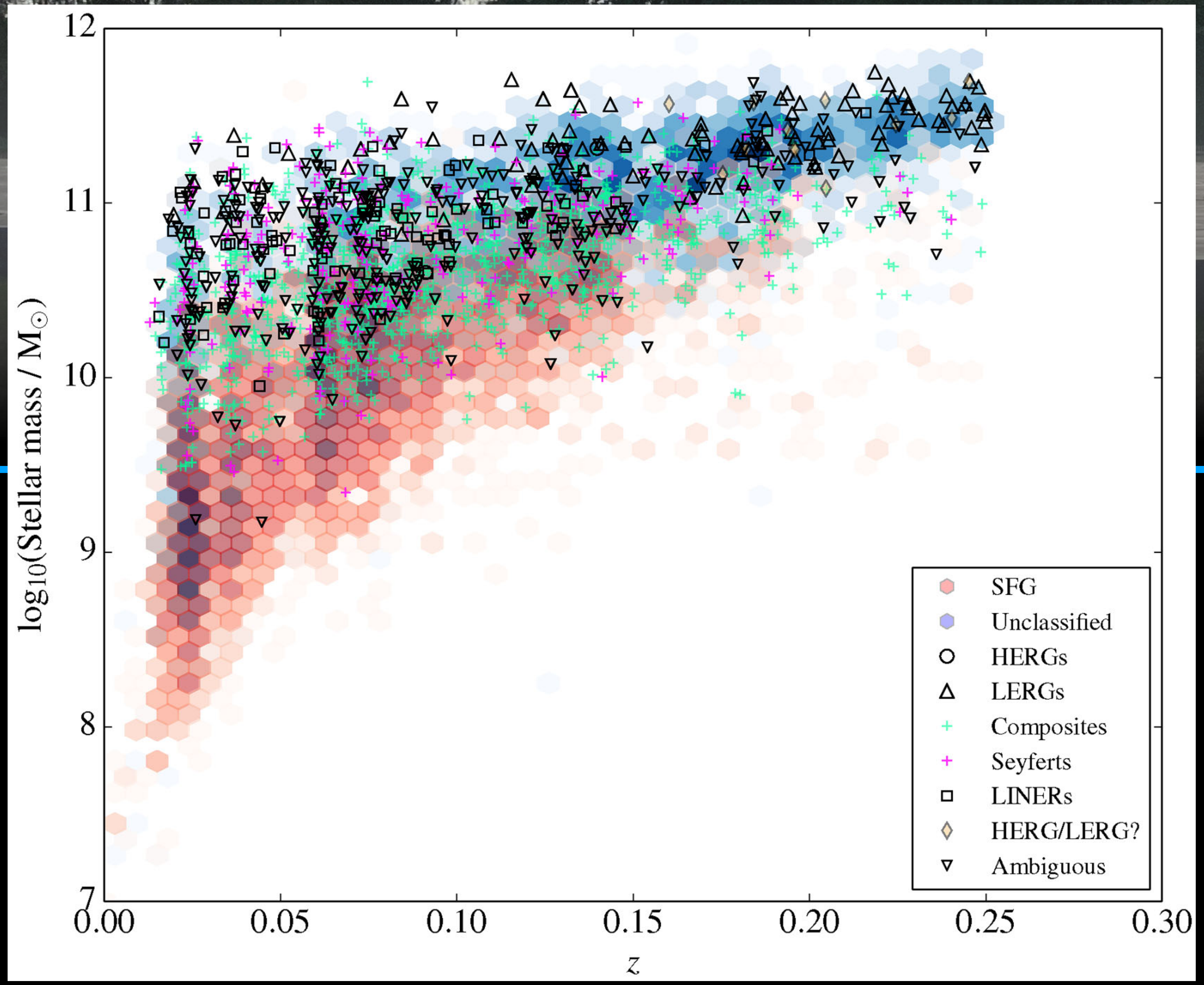
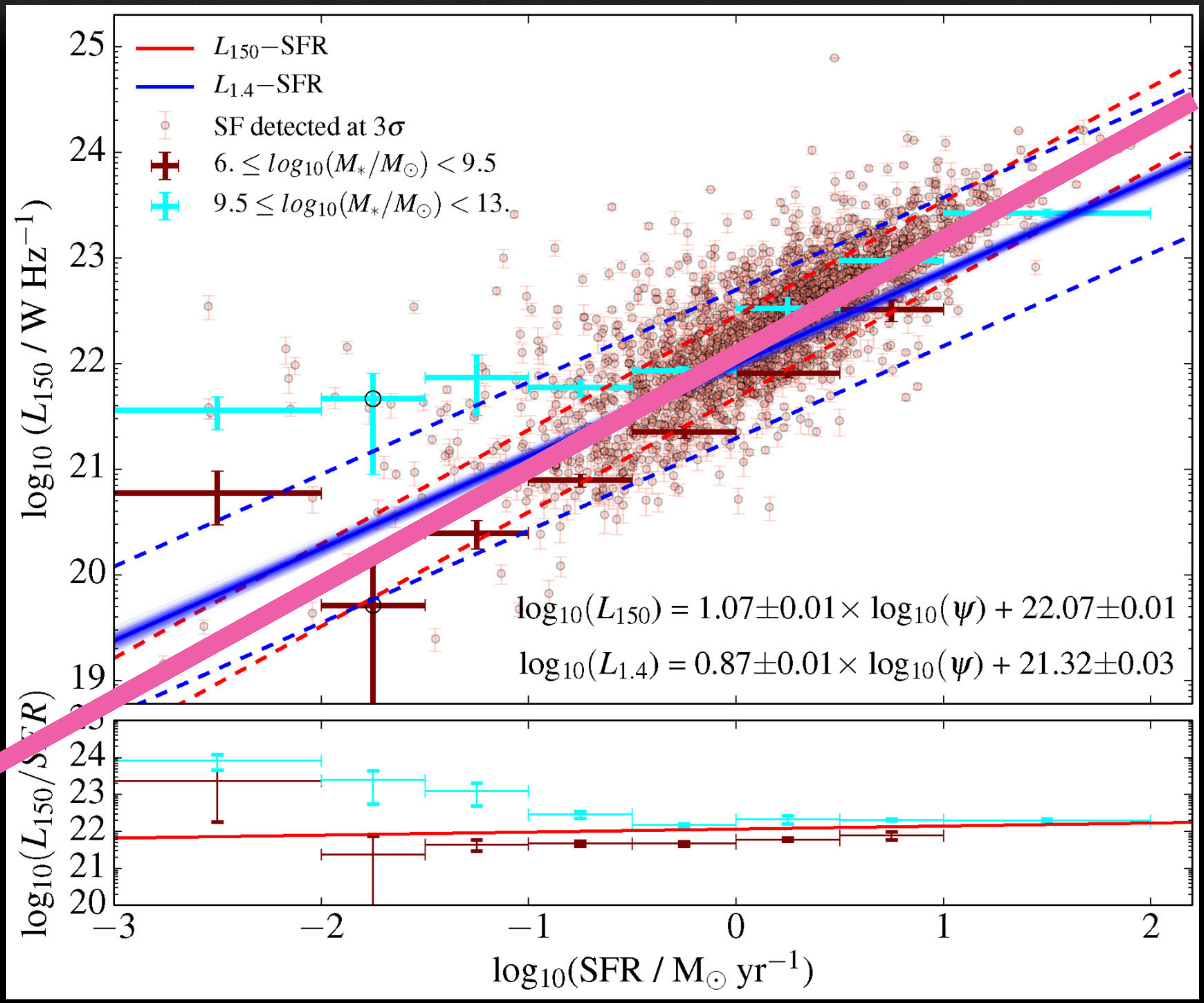


Gürkan et al. (2018)

Herschel ATLAS



Gürkan et al. (2018)

<u>Other examples:</u>

MANGA (talk by Jin)

GAMA (Davies et al. 2017)

CHANG-ES (Li et al. 2016)

ELAIS-N1 (Smith et al. 2021)

Virgo Cluster (Edler et al. 2023, and in prep)

super-linear radio-SFR relation

$$L_{150\,\mathrm{MHz}} \propto \mathrm{SFR}^{1.1}$$

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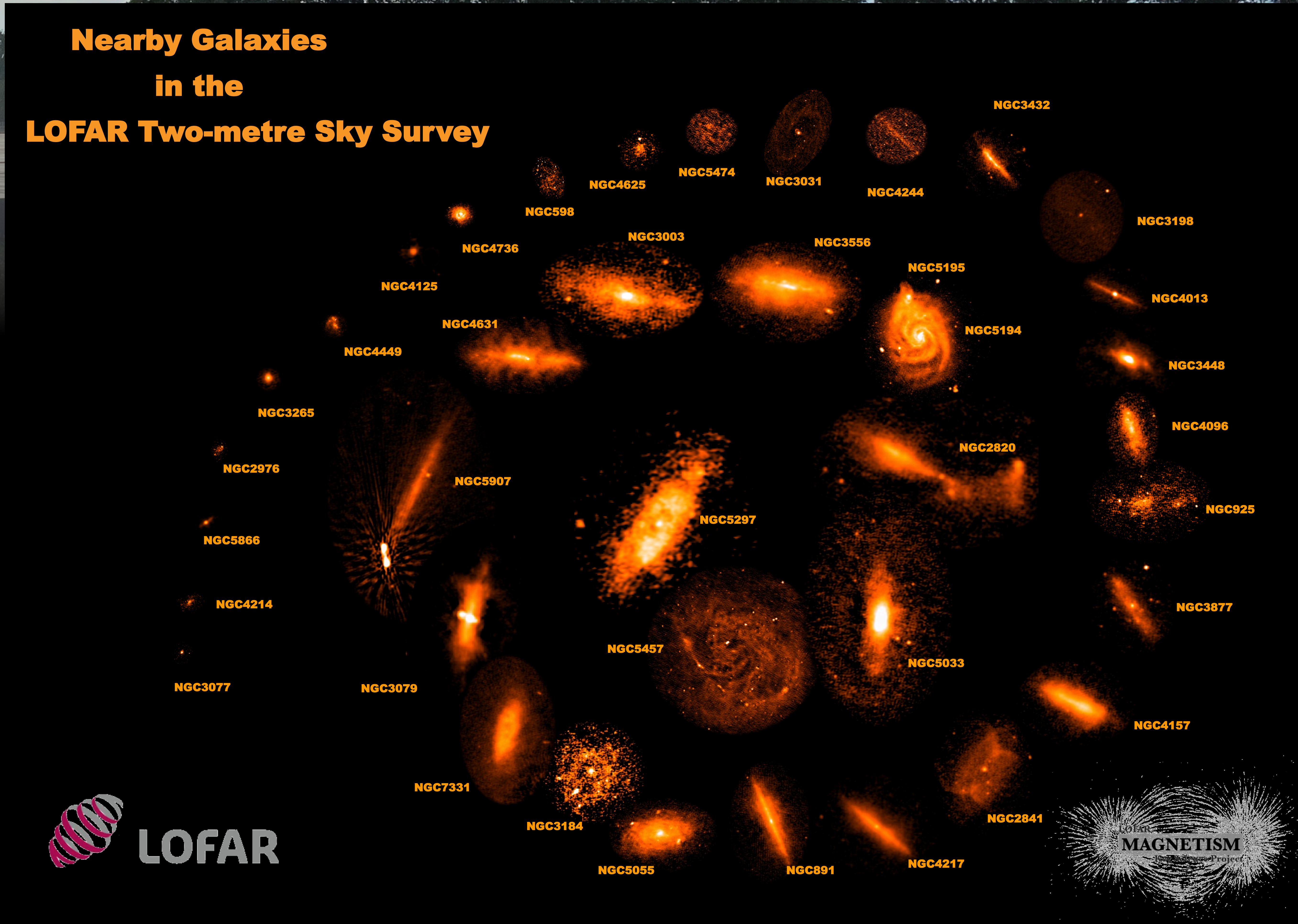
LOFAR observations

144 MHz data

- LOFAR Two-metre Sky Survey (LoTSS; Shimwell et al. 2017, 2019, 2022)
- 6 arcsec resolution is 300 pc at median distance of 11 Mpc
- Galaxies from KINGFISH, SINGS, and CHANG-ES
- *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)



LOFAR

Semi-calorimetric radio–SFR relation

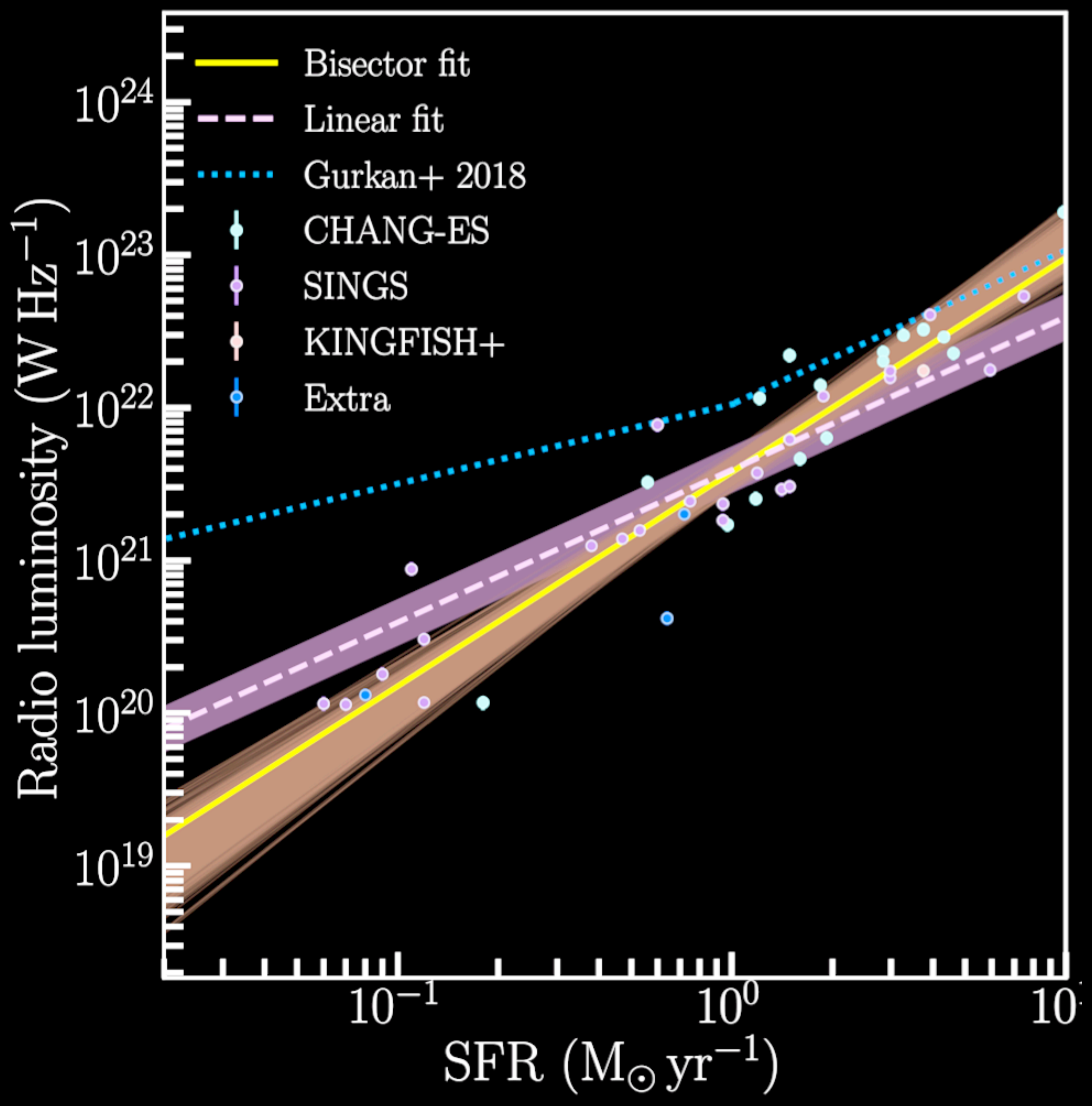
super–linear with L_{144} ~ $\mathrm{SFR}^{1.4\text{-}1.5}$

Radio continuum luminosity:

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

CRE calorimetric efficiency

CR injection



Heesen et al. (2022), plot by A. Basu

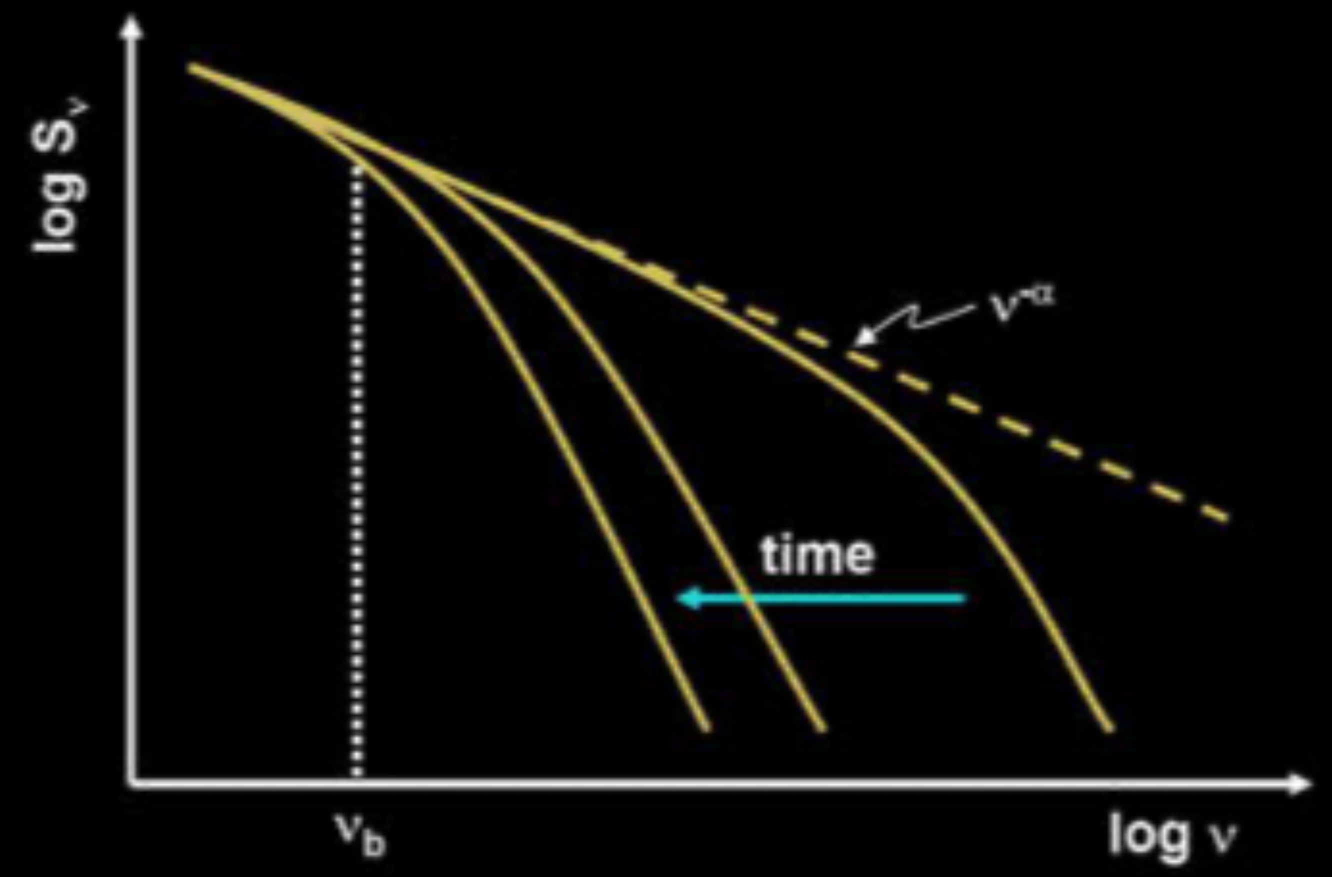
How to estimate calorimetric efficiency?

Use low-frequency radio spectral index!

steep spectrum

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

Spectral ageing



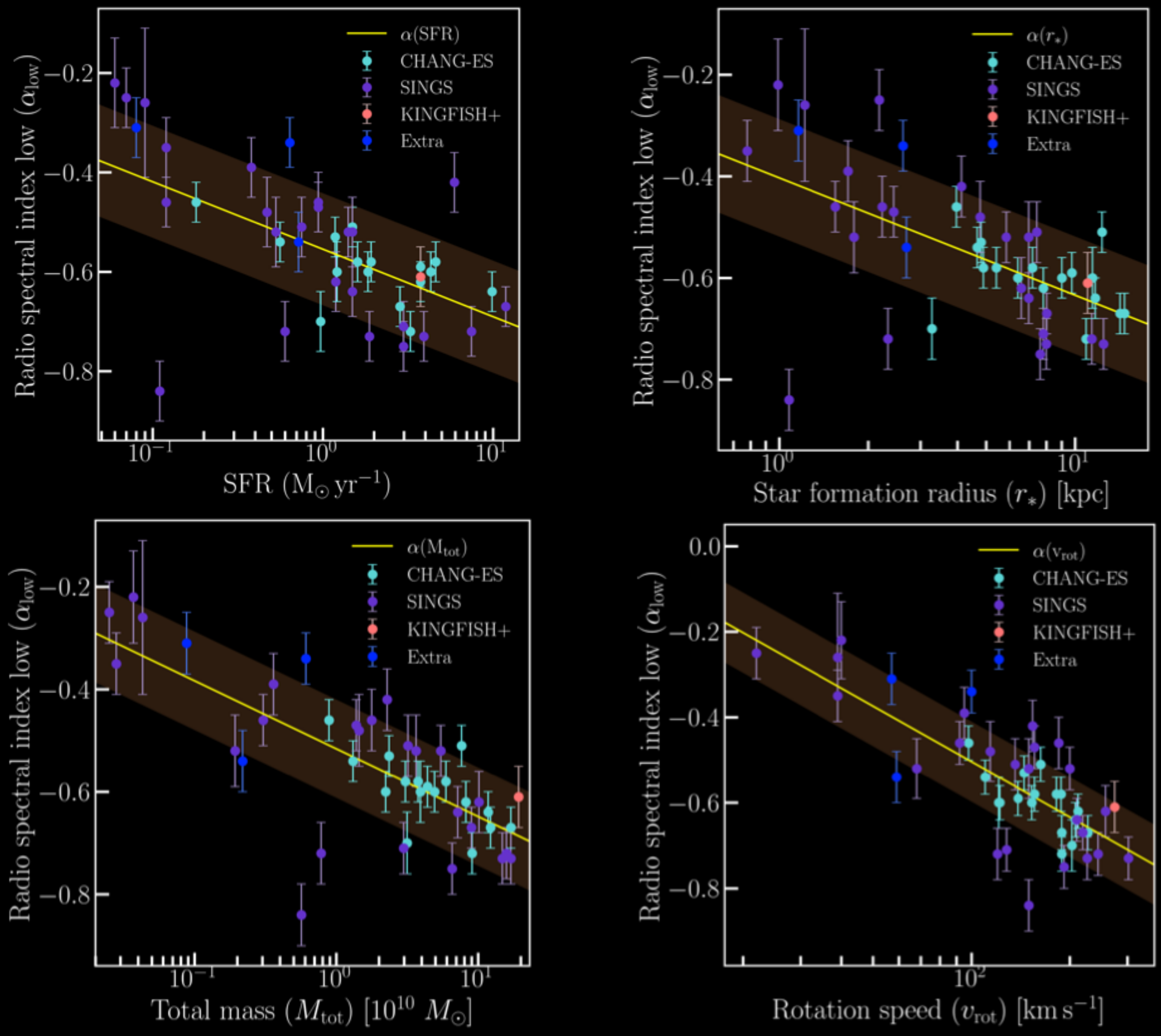
Fast electron escape: $\eta = 0$ $\alpha = -0.6$

flat spectrum

Klein and Fletcher (2015)

SFR from total infrared

star-formation radius from radio



Mass ~ v^2 r

Rotation speed from HI line width

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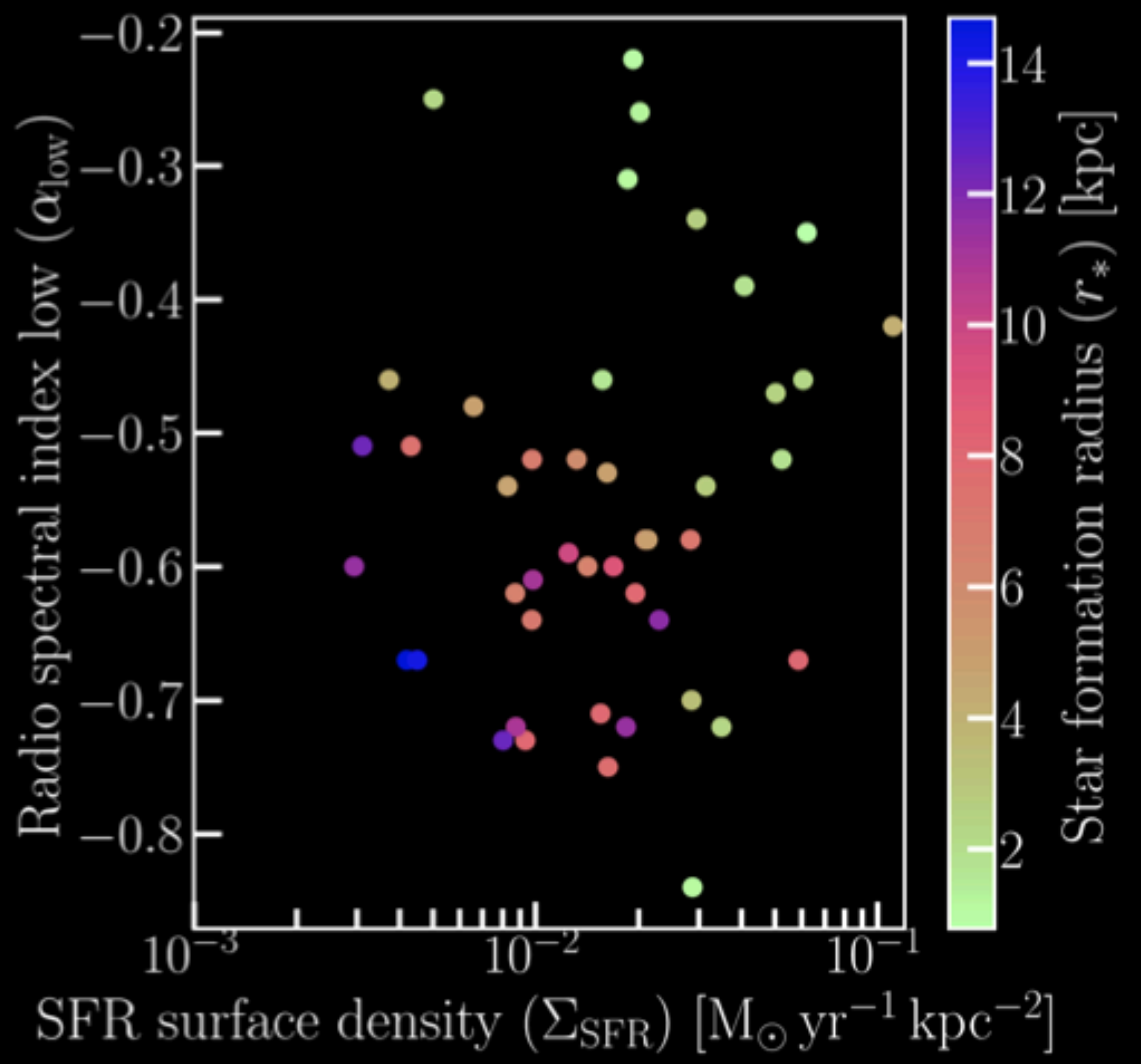
Galaxy size determines radio spectral index

Spectral index does not depend on Σ_{SFR}



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

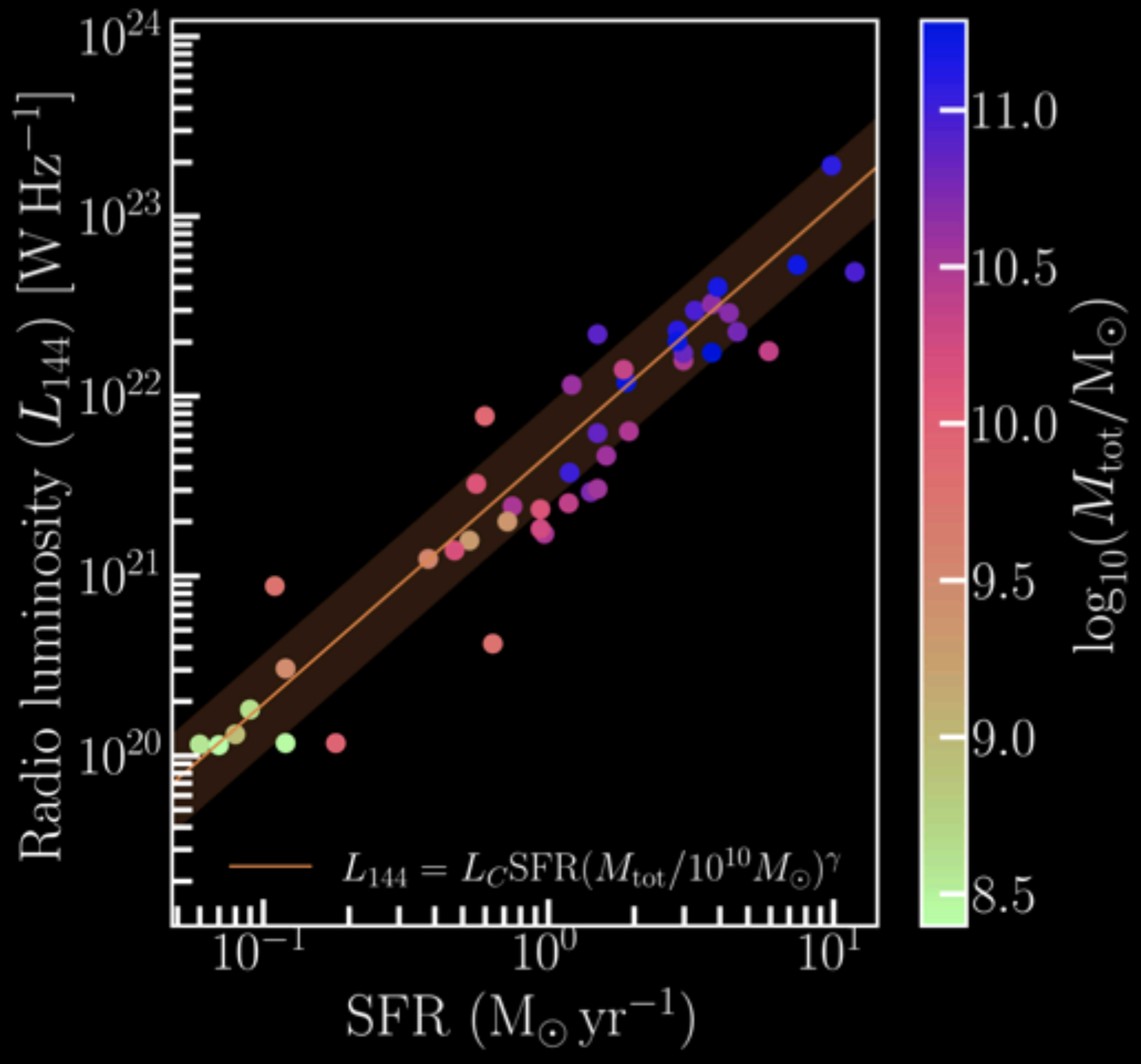
B: magnetic field strength
$B \sim \Sigma_{SFR}^{1/3}$
(Tabatabaei et al. 2018, Heesen et al. 2023)

radio spectral index

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

Mass dependency of radio–SFR relation

using the mass–size scaling relation



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

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

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

depends only on galaxy radius

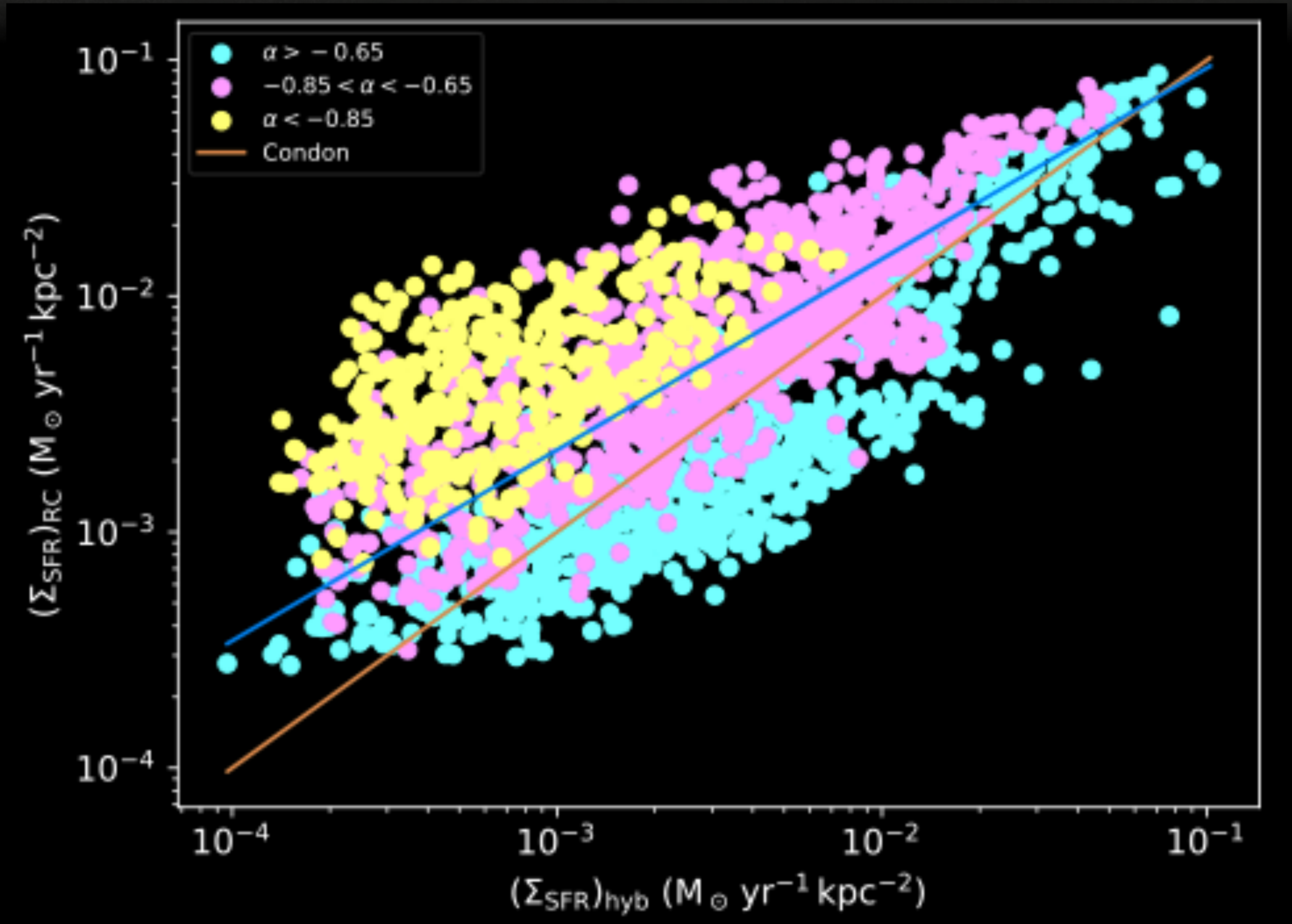
$$\eta \propto \mathrm{SFR}^{0.05}\, M_{\mathrm{tot}}^{0.27}$$

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

Spatially resolved radio–SFR relation

and radio spectral index

- Local radio–SFR: I_ν–$\Sigma_{\mathrm{SFR}}^{0.6\text{–}0.8}$
- Radio spectral index dependence
  - Steep spectrum: radio bright
  - Flat spectrum: radio faint
- Global radio–SFR: L_ν–$\mathrm{SFR}^{1.1\text{–}1.5}$



Heesen et al. (2023) in prep.

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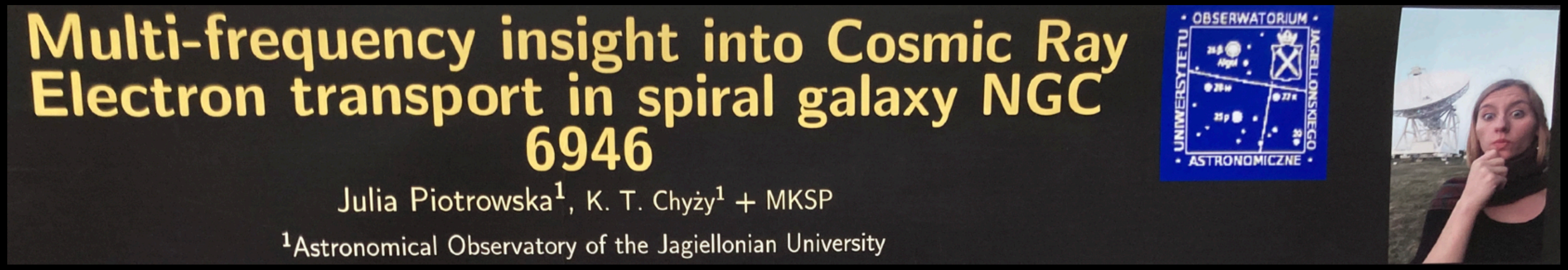
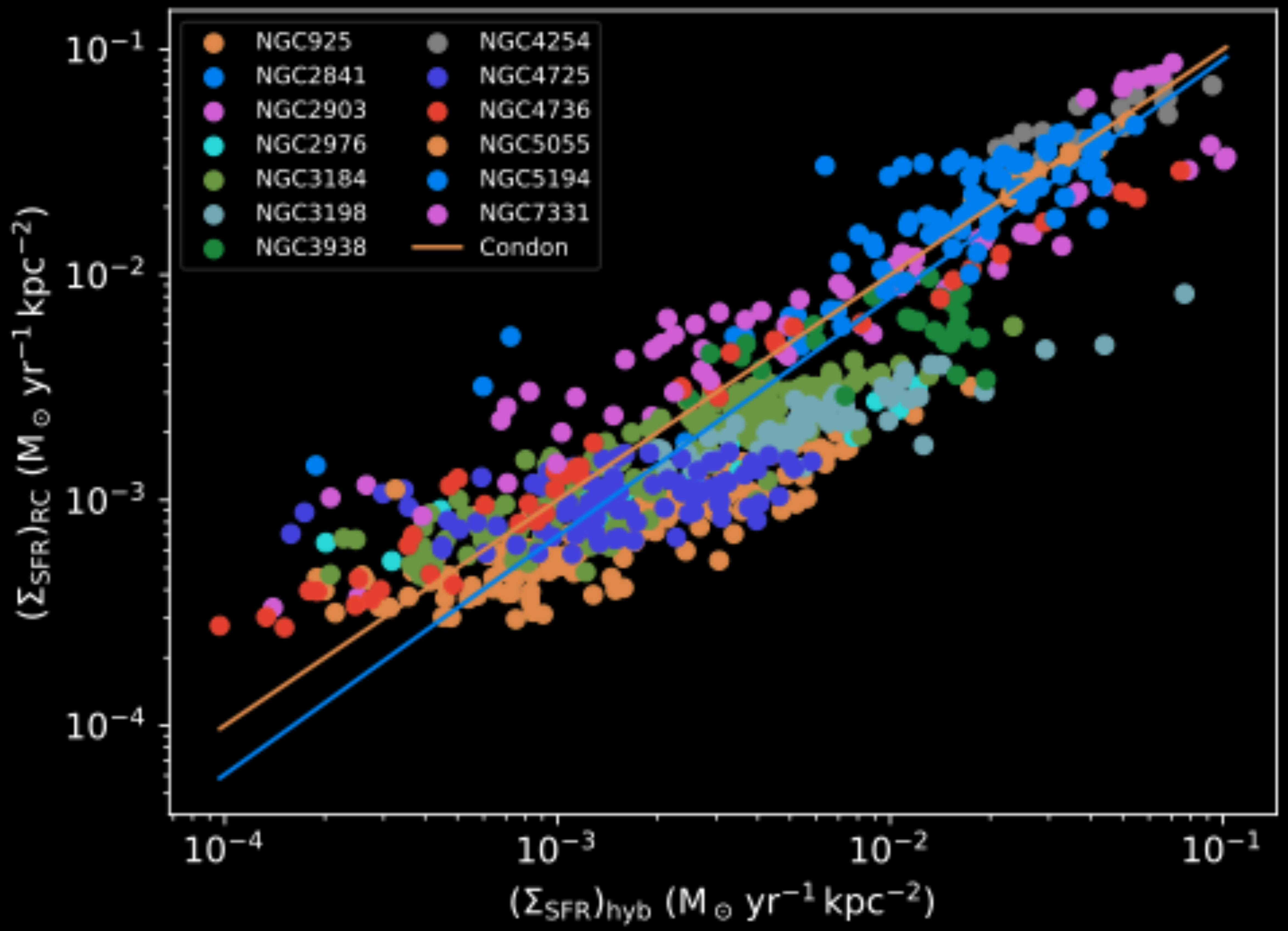
Influence of cosmic-ray transport

on the radio–SFR relation

- Young CREs near the sources not affected by transport
- radio–SFR relation is almost linear with I_ν–$\Sigma_{\rm SFR}^{0.9}$ (*Heesen et al. 2019*)
- Also observed in spiral arms of individual galaxies (*Dumas et al. 2011, Basu et al. 2012*)





Heesen et al. (2023) in prep.

Calorimetric efficiency

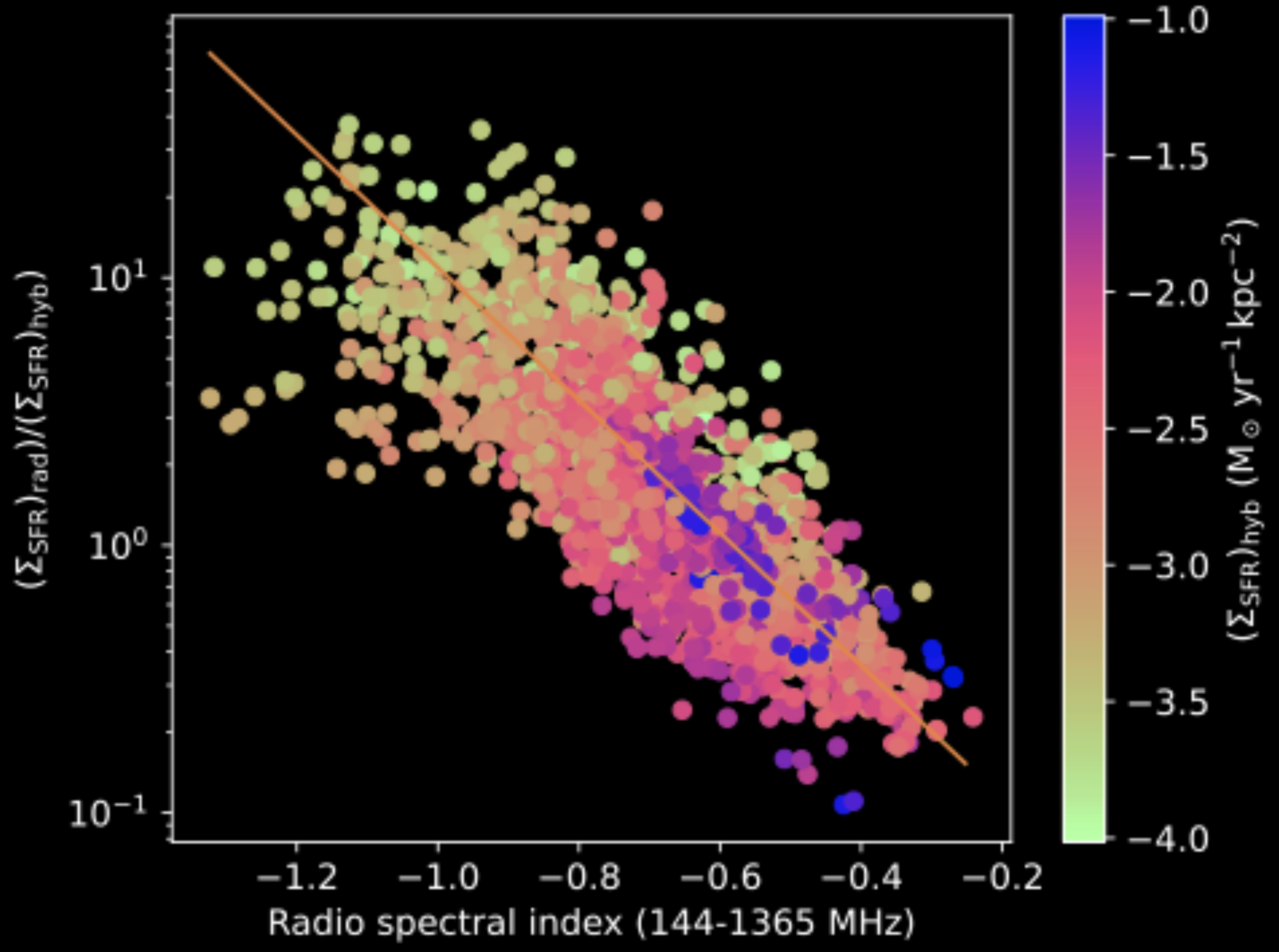
and the local radio–SFR relation

- Ratio of radio-to-hybrid SFR

$$\eta(\alpha) = (\Sigma_{\rm SFR})_{\rm RC} / (\Sigma_{\rm SFR})_{\rm hyb}$$

radio continuum / hybrid SFR surface density

- Dependence on radio spectral index
- Old CRE are bright, young are faint



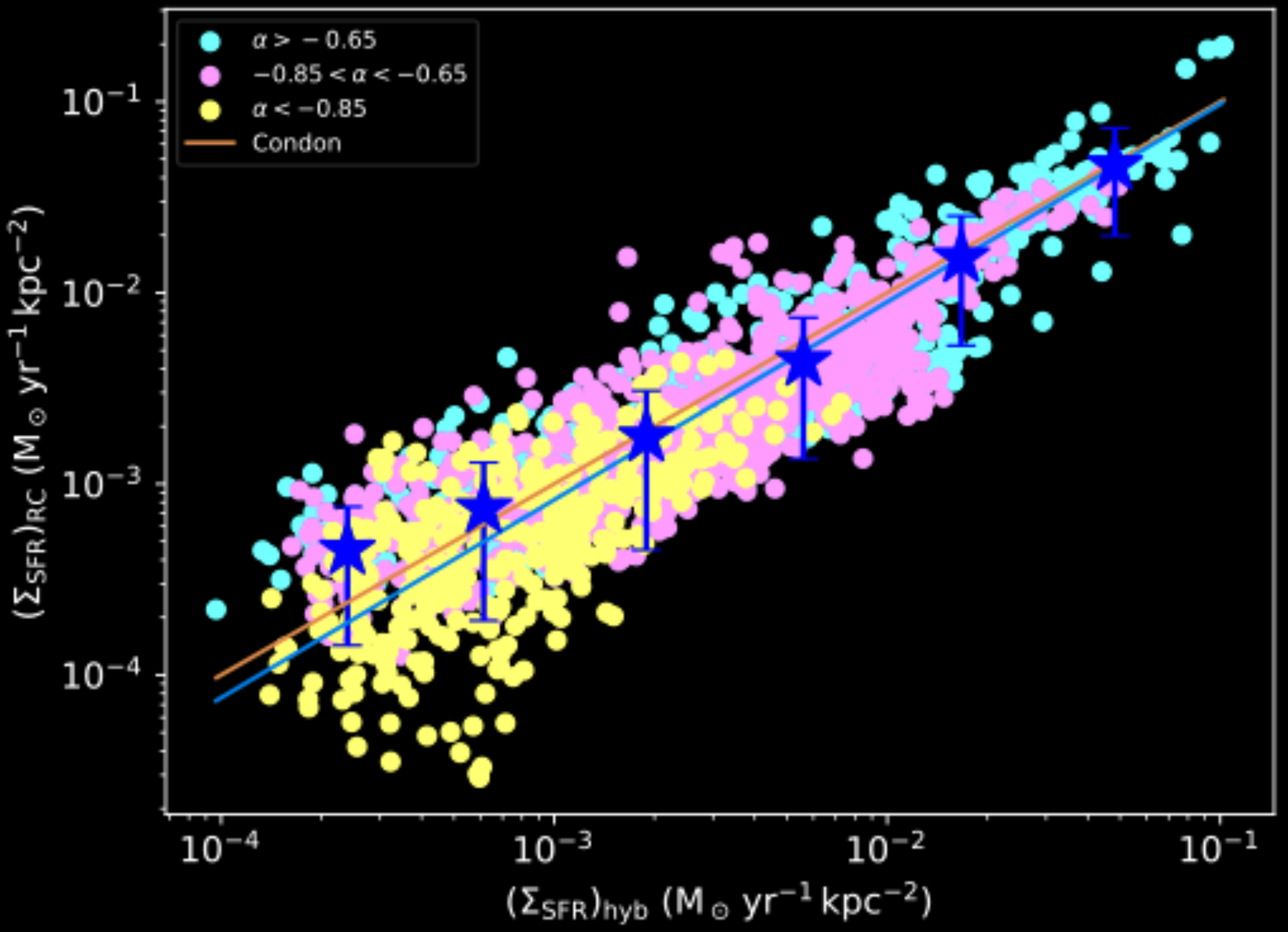
Corrected radio–SFR relation

on the radio–SFR relation

- Correct radio SFR for calorimetric efficiency
- Use parametrisation with radio spectral index

$$(\Sigma_{\mathrm{SFR}})_{\mathrm{RC}}/\eta(\alpha) \propto (\Sigma_{\mathrm{SFR}})_{\mathrm{hyb}}^{1.05\pm0.02}$$

- Almost linear radio–SFR relation



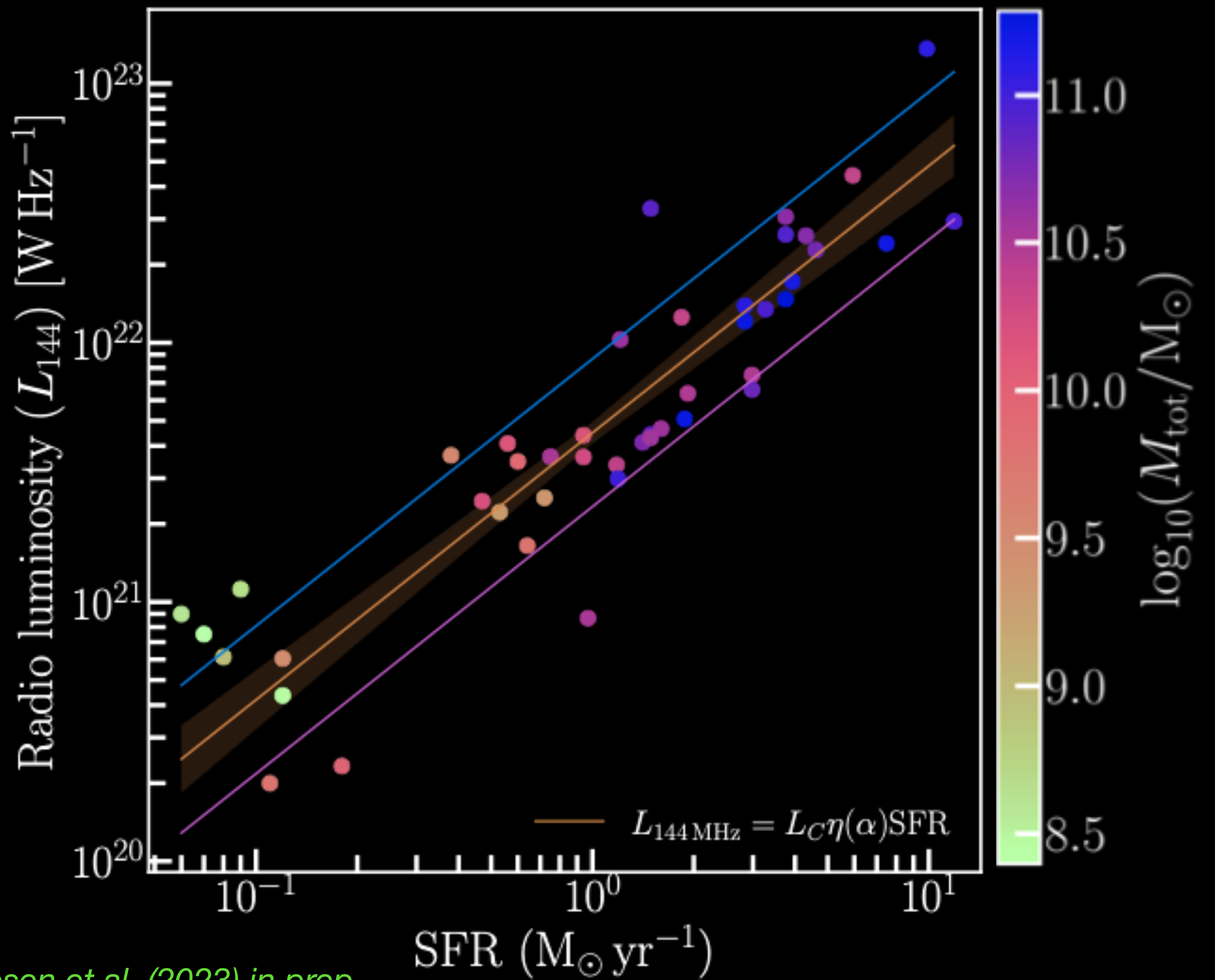
Heesen et al. (2023) in prep.

Universal radio–SFR relation

for both global and local measurements

- Correct global radio–SFR relation with CRE calorimetric efficiency
- Parametrisation with radio spectral index
- Same slope and normalisation as for local radio–SFR relation

slope = 1.03 +/- 0.07



Heesen et al. (2023) in prep.

Conclusions
and summary

- Non-linear global radio–SFR relation requires cosmic-ray escape such as observed as galactic winds in radio haloes
- Larger galaxies have to higher calorimetric efficiencies
- Sub-linear local radio–SFR relation requires cosmic-ray transport which is energy-independent diffusion
- Cosmic-ray electron calorimetric efficiency depends on radio spectral index
- Corrected radio–SFR relation is universal for both global and local SFRs