# **Cosmic rays and magnetic fields in galaxies**
# Frontend research at low radio frequency Radio astronomy: Science and technical challenges

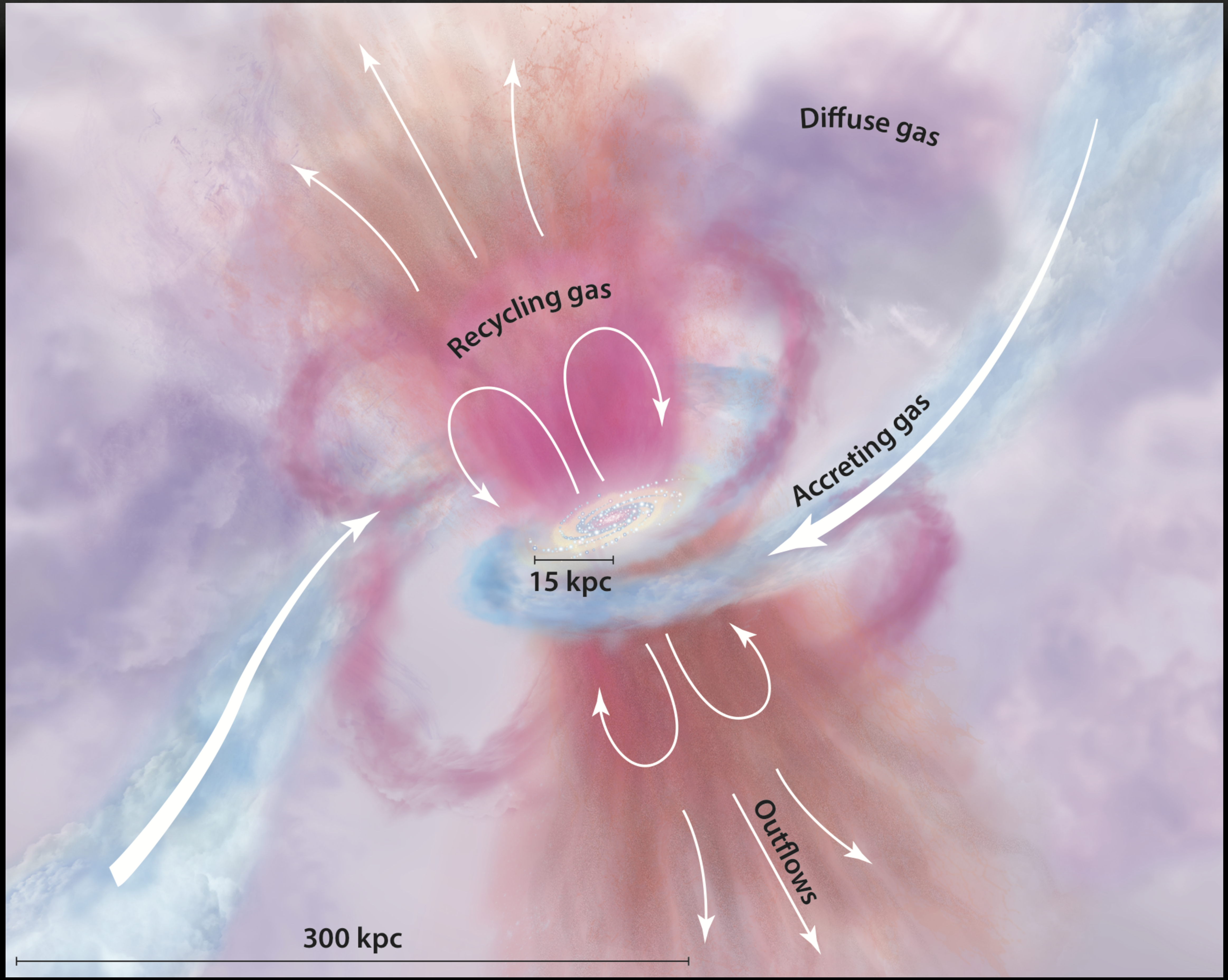
**Volker Heesen (University of Hamburg)**

**With contributions from Michal Stein, Arpad Miskolczi, Julien Dörner, Finn Welzmüller, Milan Staffehl, Tim-Leon Klocke, Sebastian Schulz, Henrik Edler, Ralf-Jürgen Dettmar and Shane O'Sullivan**

# Cosmic rays and magnetic fields in galaxies

## why study them?

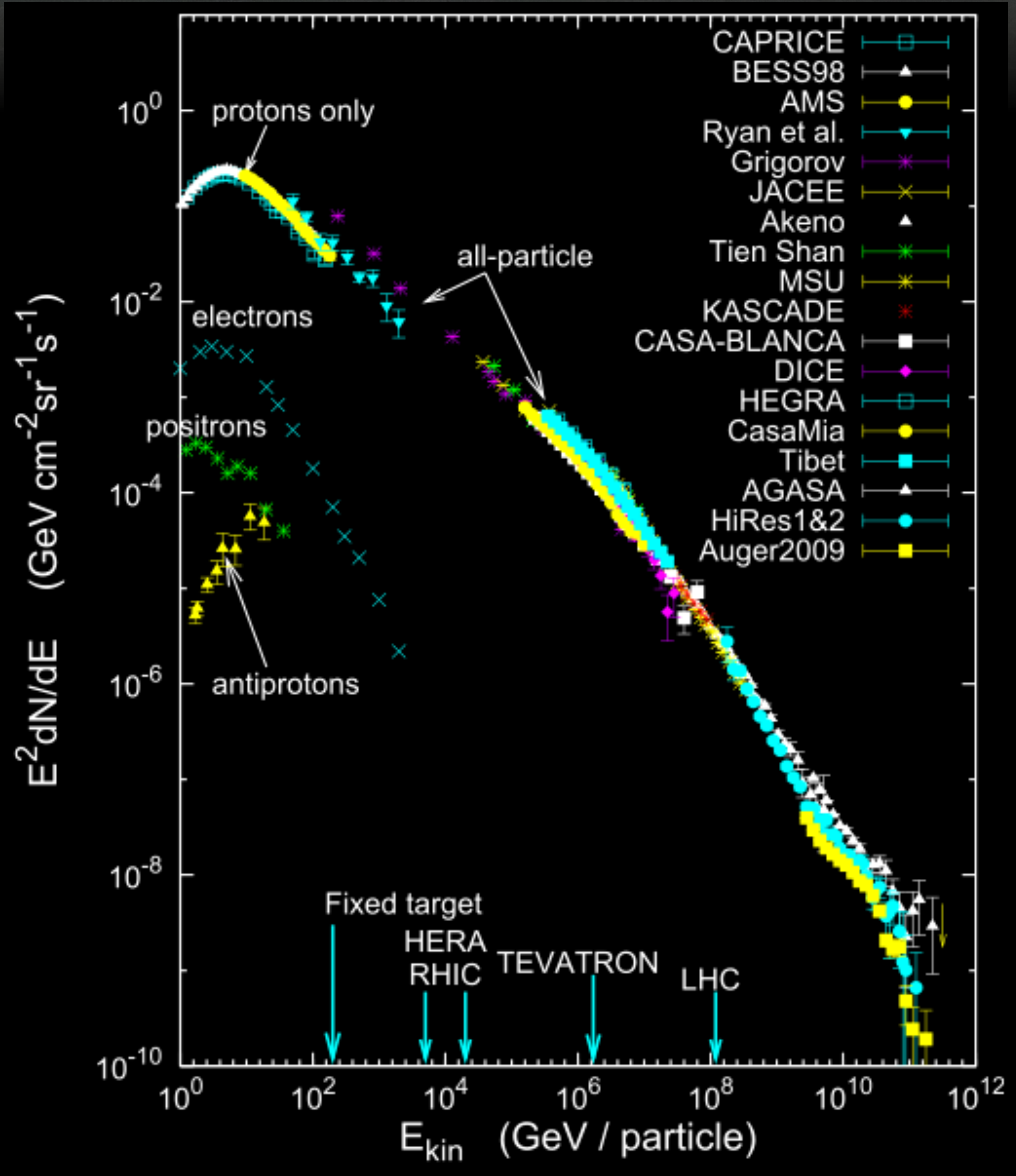
- Regulate outflows and accretion of matter
- Are important for galaxy evolution
- Cosmic rays follow magnetic field lines
- Magnetic fields play crucial role in star formation



# Cosmic rays

## and radio continuum emission

- Energy density ~ magnetic field (1 eV cm$^{-3}$)
- Small anisotropy ($10^{-4}$) => scattering on *B*-field
- GeV-protons energetically most important
- GeV-electrons are observed in the radio

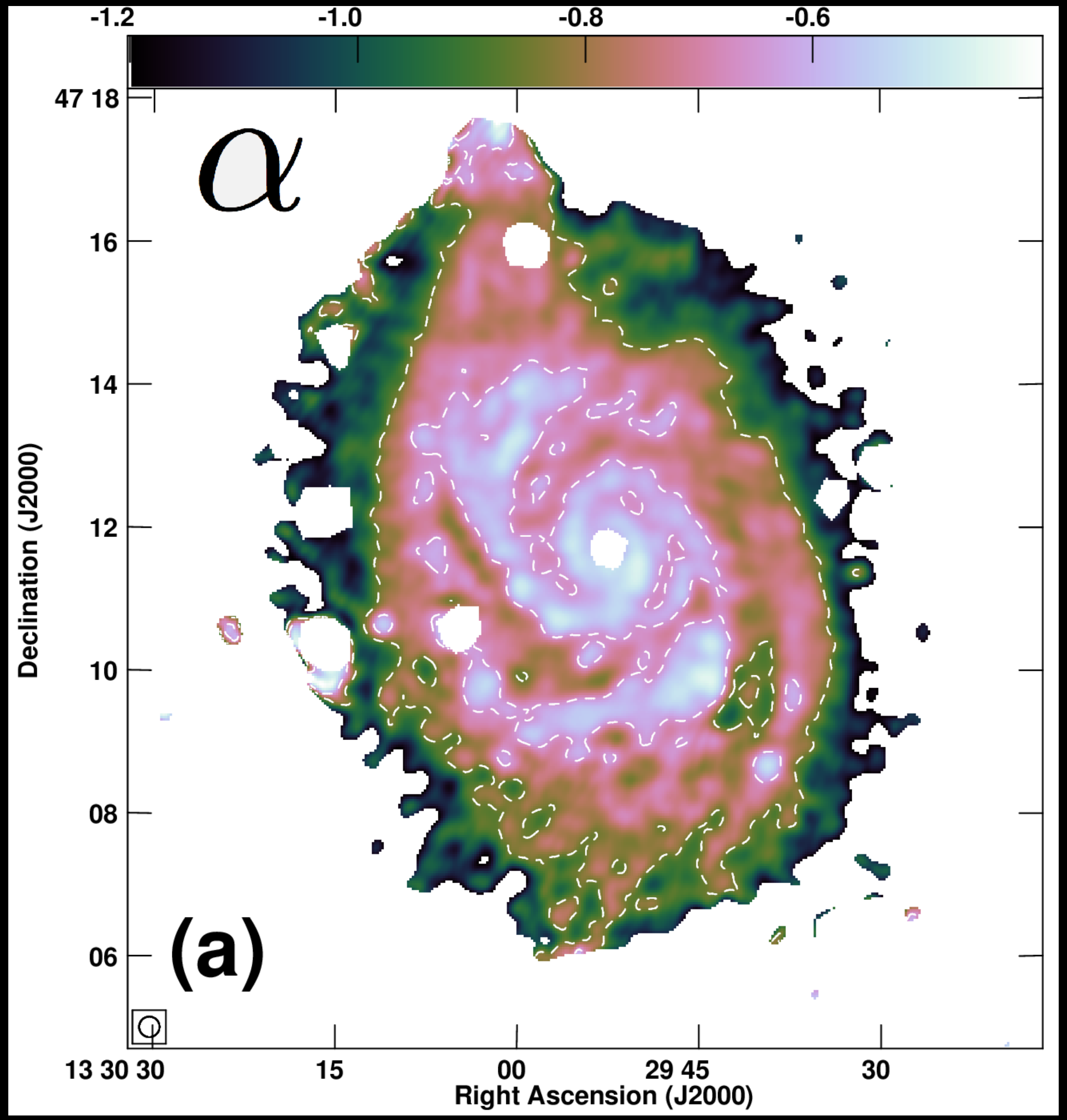



*Zweibel (2013)*

# Radio spectral index

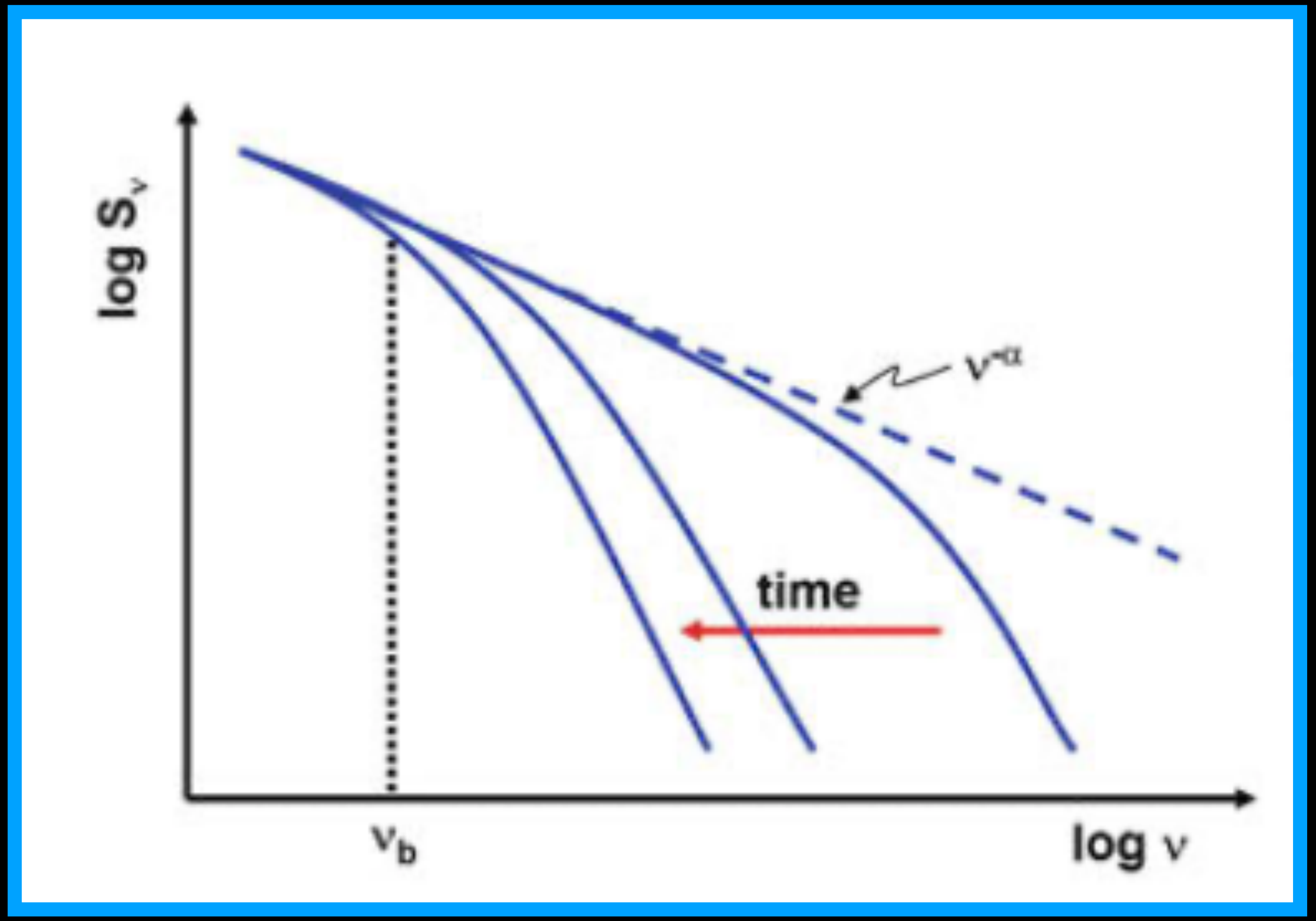
## as a proxy for cosmic-ray electron age

Radio spectral index: 144–1365 MHz




Young CREs in spiral arms, old CREs in inter-arm regions and outskirts

Spectral ageing

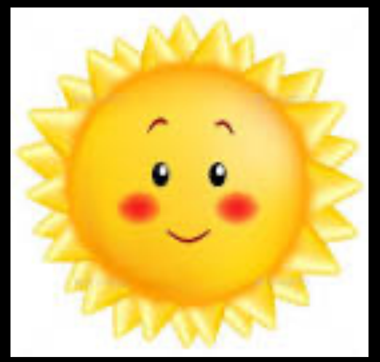



*Klein and Fletcher (2015)*

# Radio continuum emission

## from star-forming galaxies

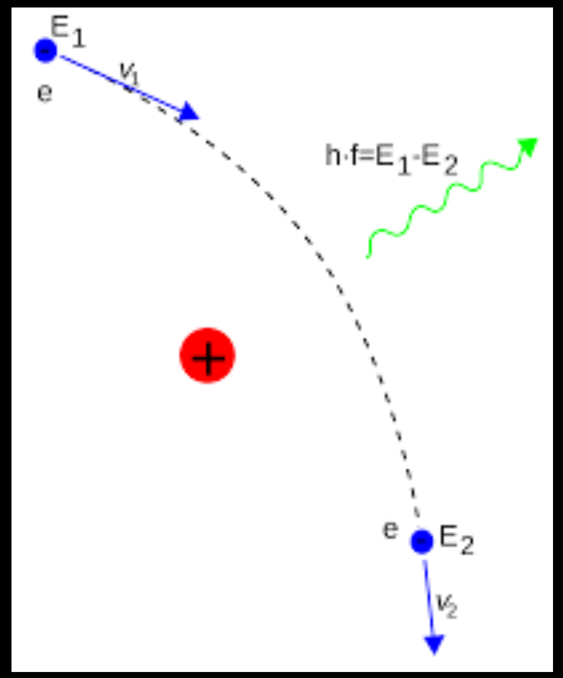
Massive stars

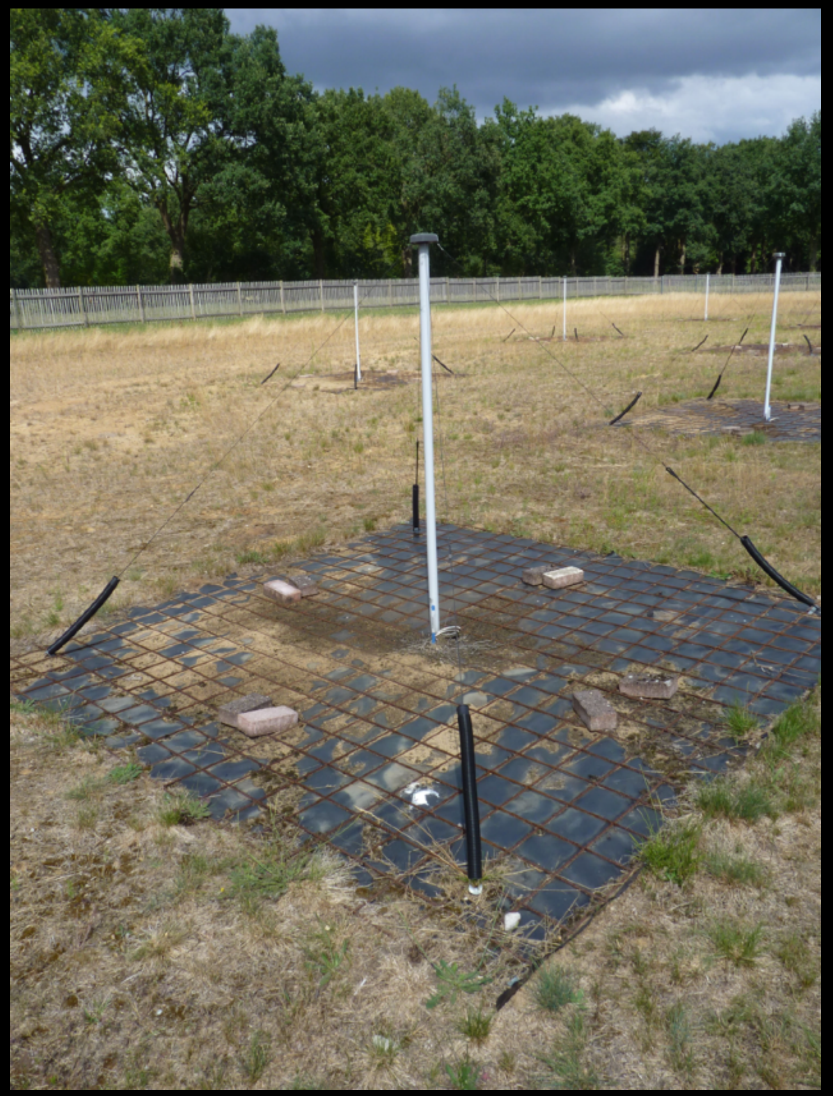


UV radiation

HII region

free–free radiation



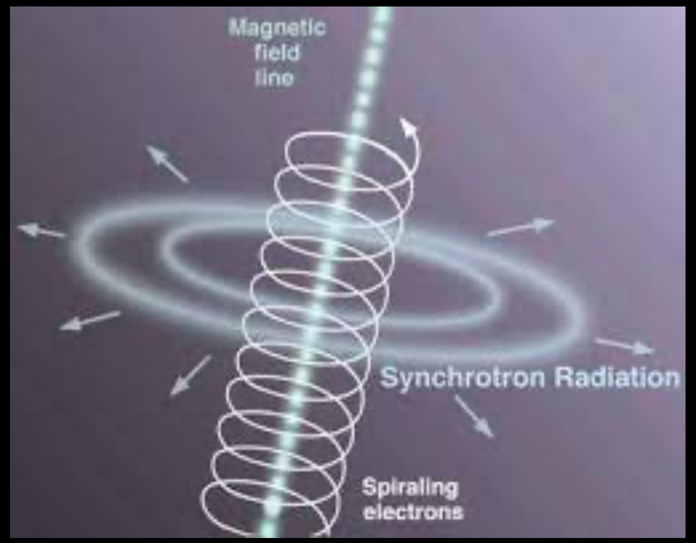
UHH / D. Engels


supernova

shock acceleration

SNR

synchrotron emission

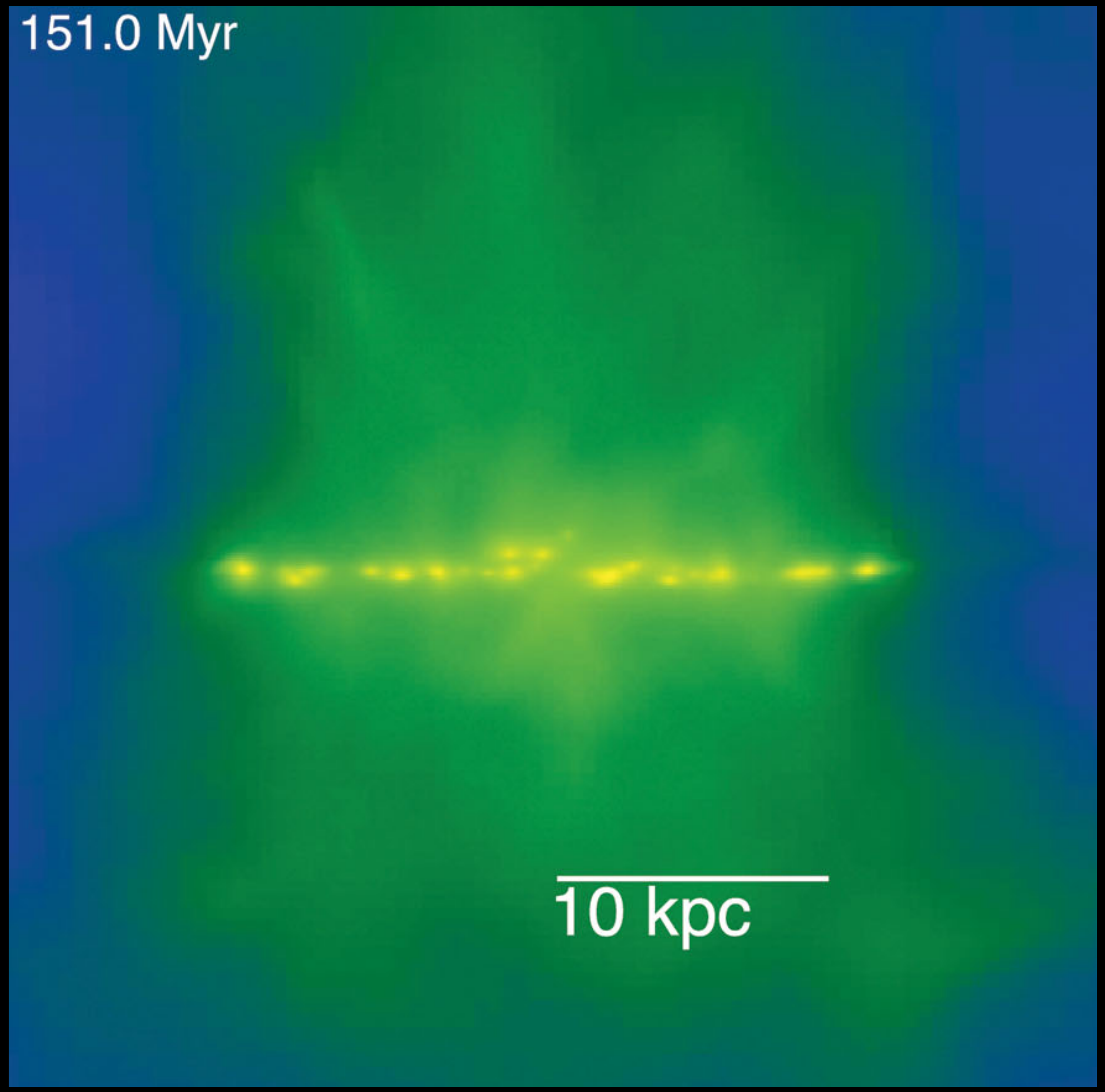



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

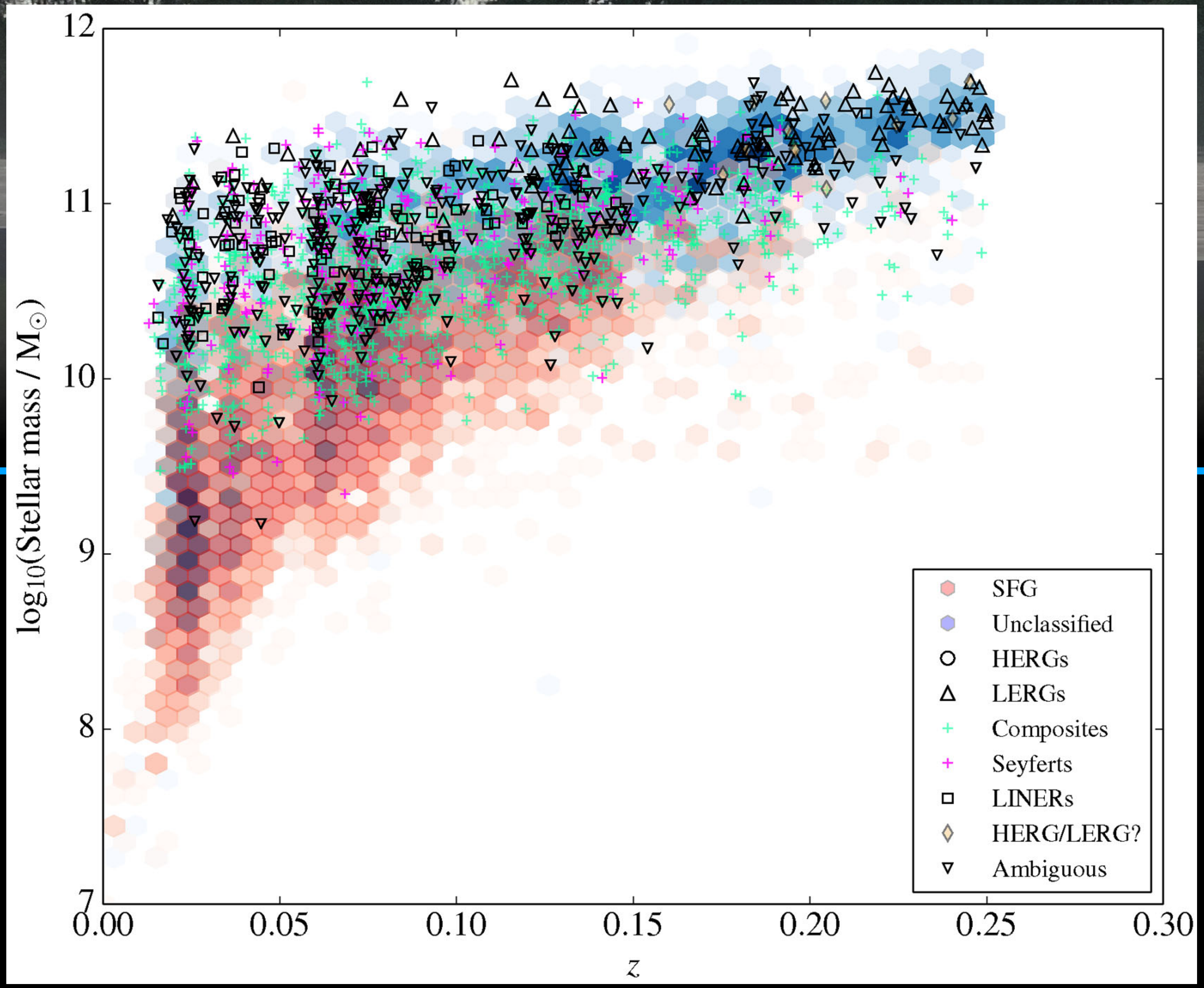
# But there are some complications

## with measuring radio star-formation rates

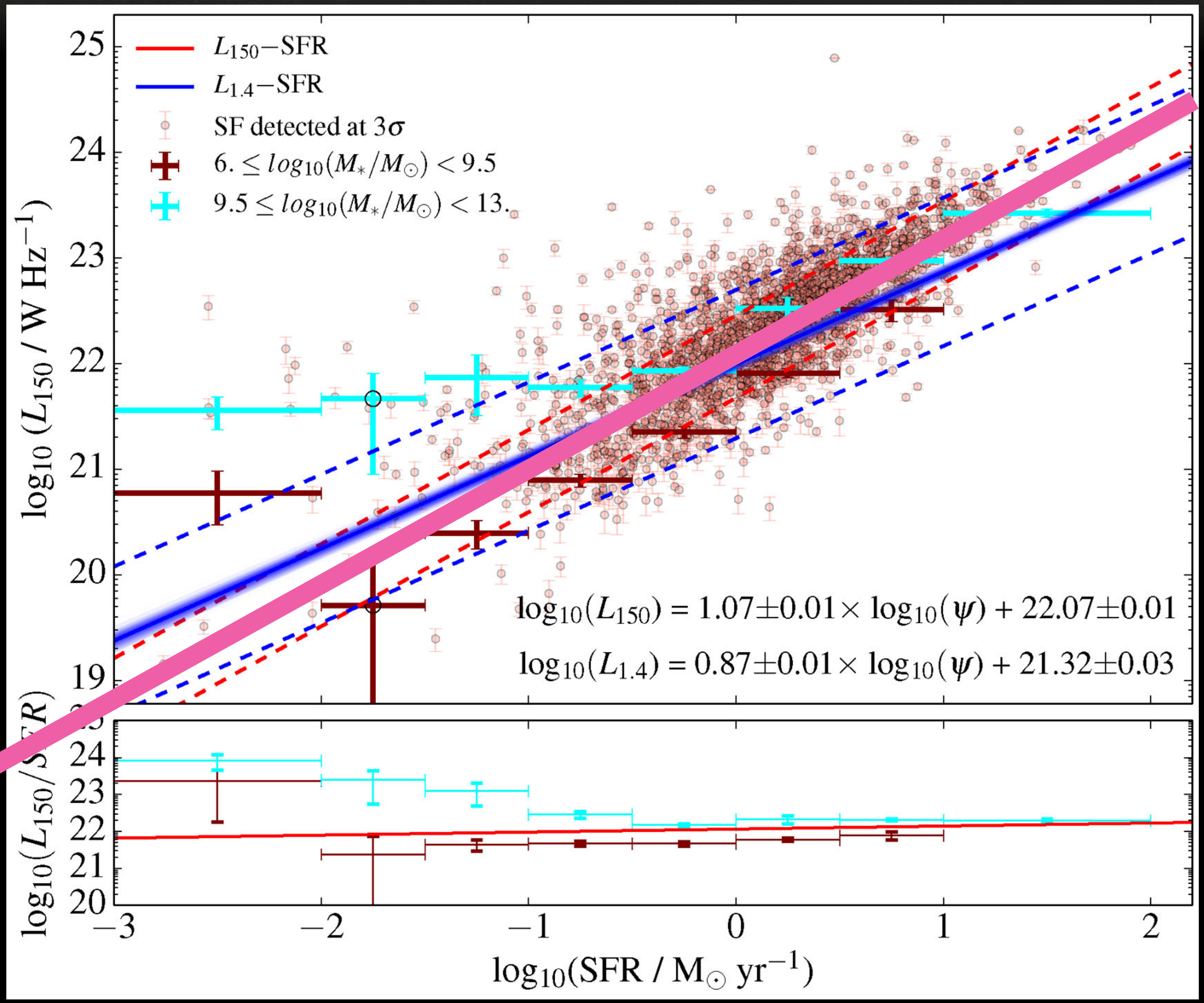
- Leakage of cosmic-ray electrons from galaxies
- Unknown, but may be larger than 50 per cent
- Cosmic ray-driven winds (*Breitschwert et al. 1992, Everett et al. 2008, Recchia et al. 2016*)




*Salem & Bryan (2014)*




Gürkan et al. (2018)




Gürkan et al. (2018)

**super-linear radio-SFR relation**

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

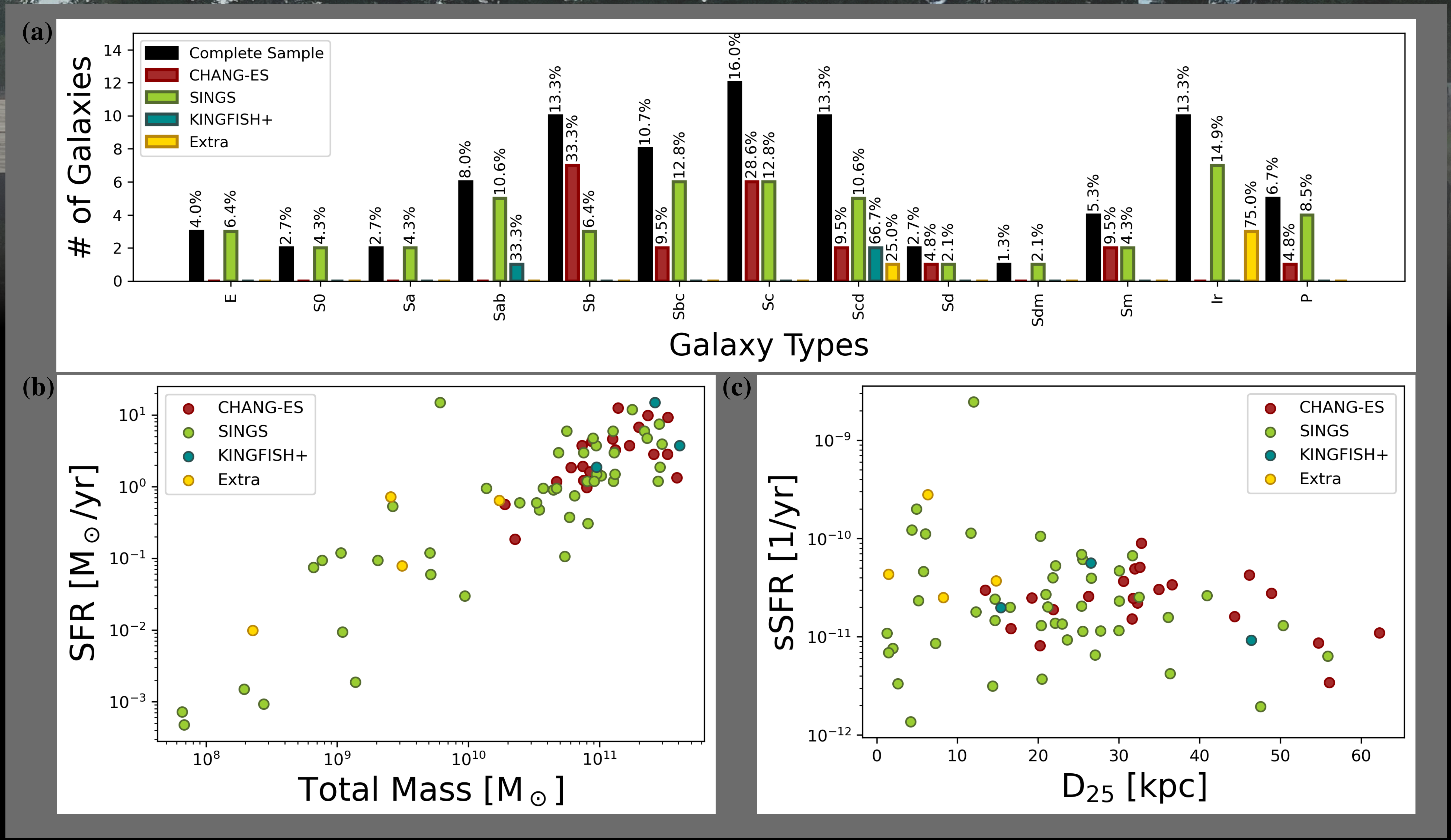
<u>Other examples:</u>

GAMA (Davies et al. 2017)
CHANG-ES (Li et al. 2016)
ELAIS-N1 (Smith et al. 2021)
Virgo Cluster (Edler et al. in prep)

# 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)




plot by M. Stein

# 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)

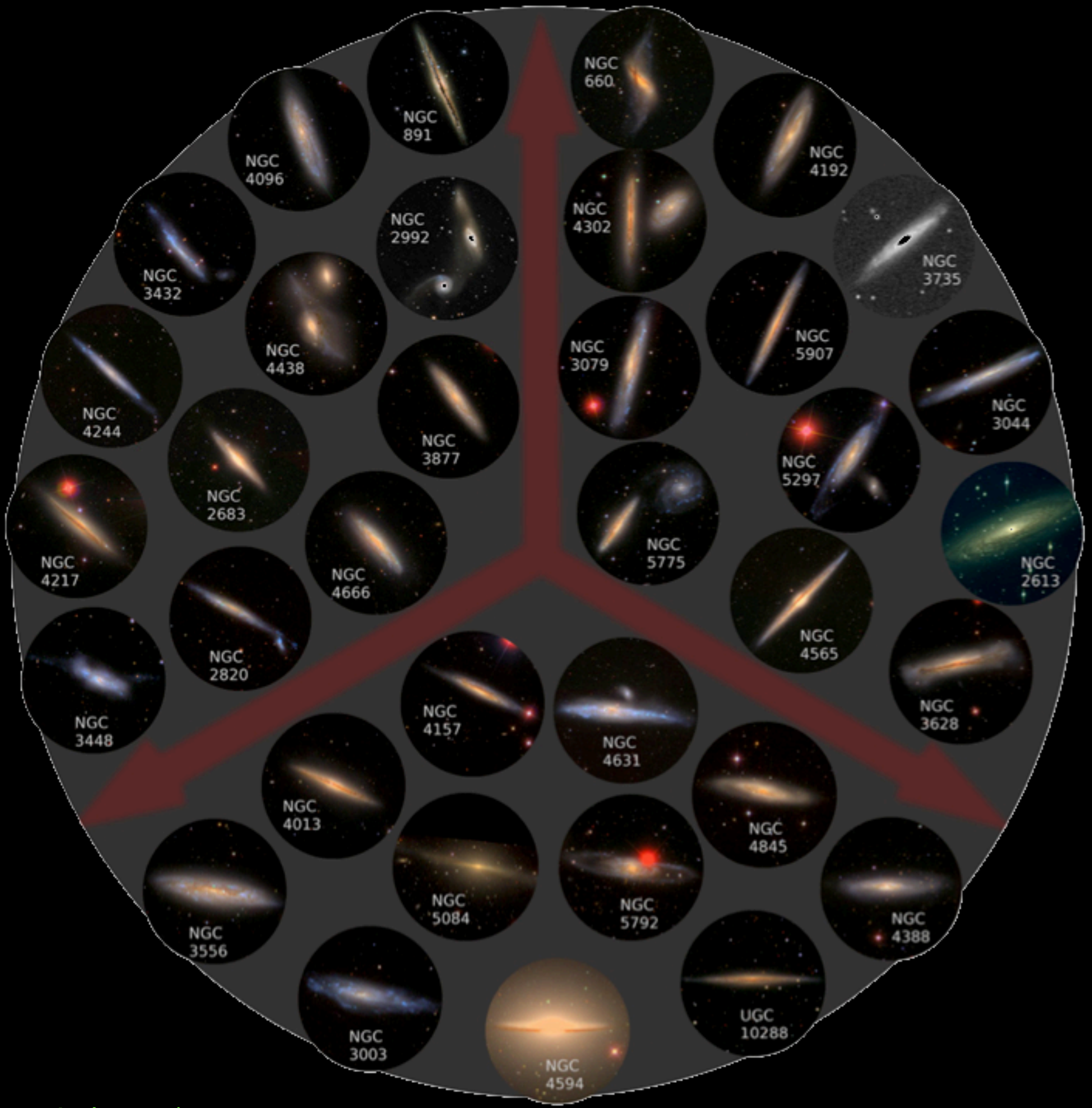

*van Haarlem et al. (2013)*

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

# Radio continuum observations

## LOFAR, JVLA, ATCA, Effelsberg, Parkes, WSRT

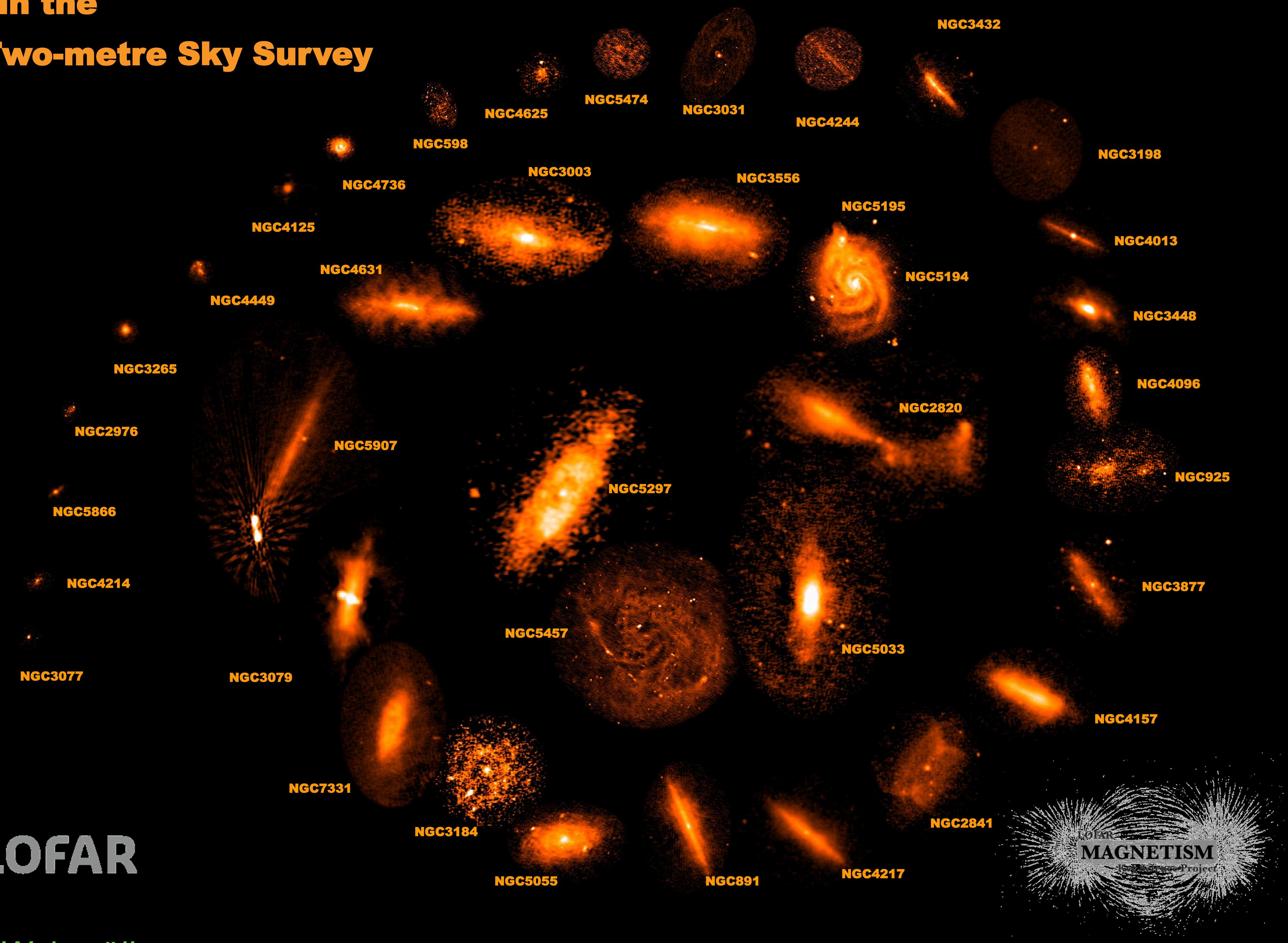
**CHANG-ES**
**Continuum HAlos in Nearby Galaxies - an EVLA Survey**




**EVLA**
Karl G. Jansky (Expanded) Very Large Array

*Irwin et al. (2012)*

**Nearby Galaxies in the .OFAR Two-metre Sky Survey**




LOFAR

*F. Welzmüller*

# Semi-calorimetric radio–SFR relation

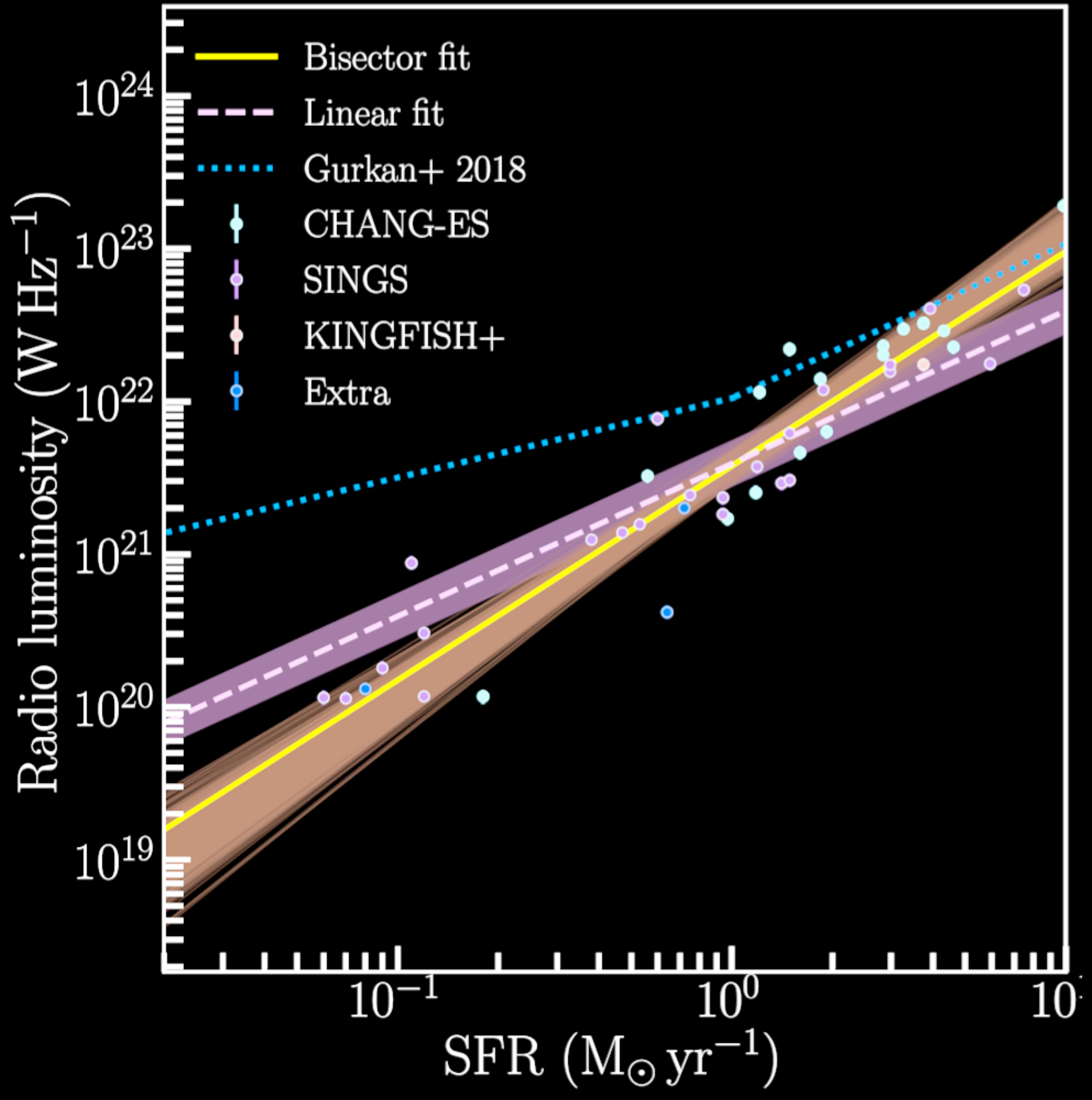
## super–linear with $L_{144}$ ~ SFR$^{1.4\text{-}1.5}$

Radio luminosity:

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

calorimetric efficiency

CR injection




plot by A. Basu

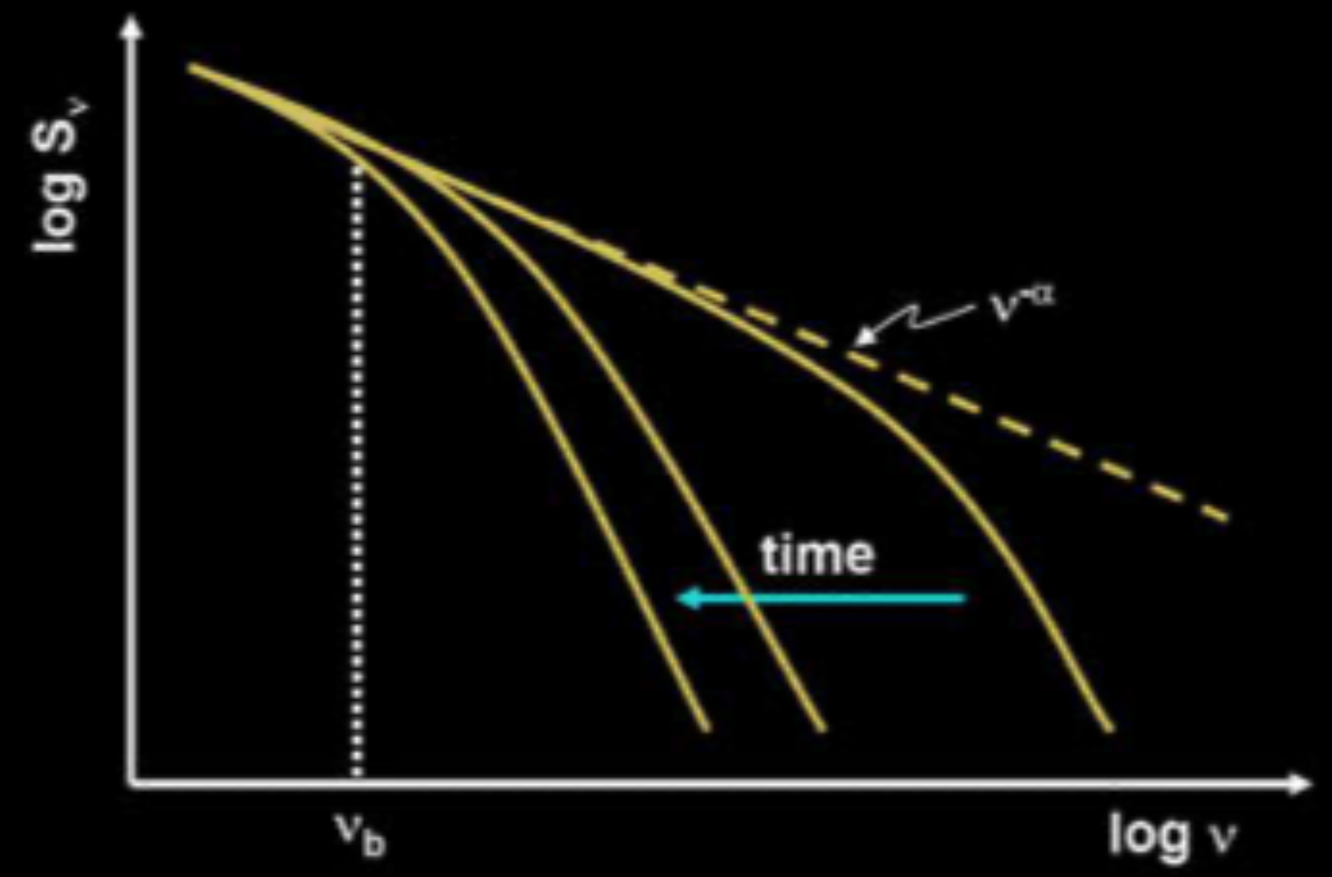
# How to estimate calorimetric efficiency?

## 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

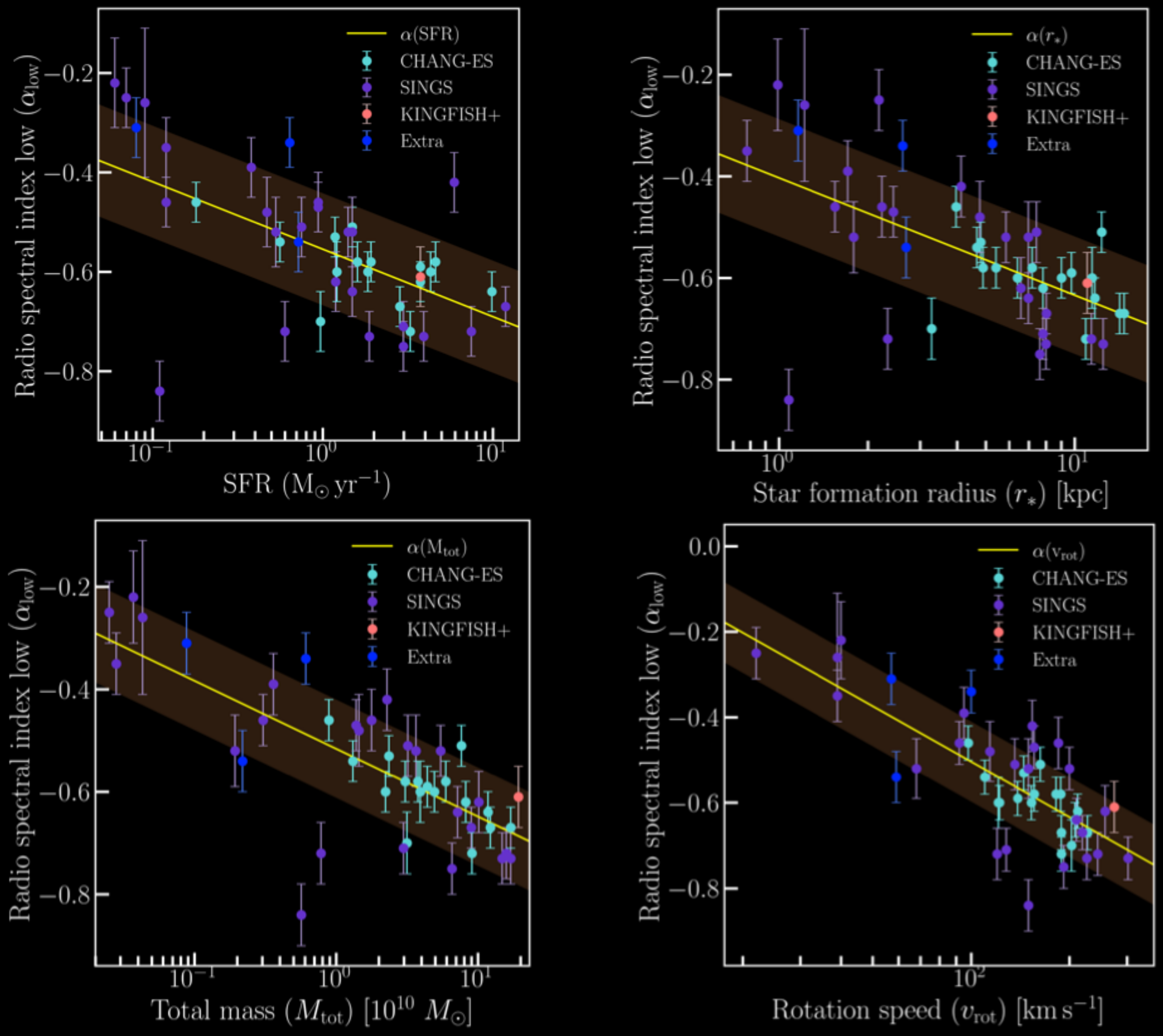
*Klein and Fletcher (2015)*

SFR from total infrared

star-formation radius from radio

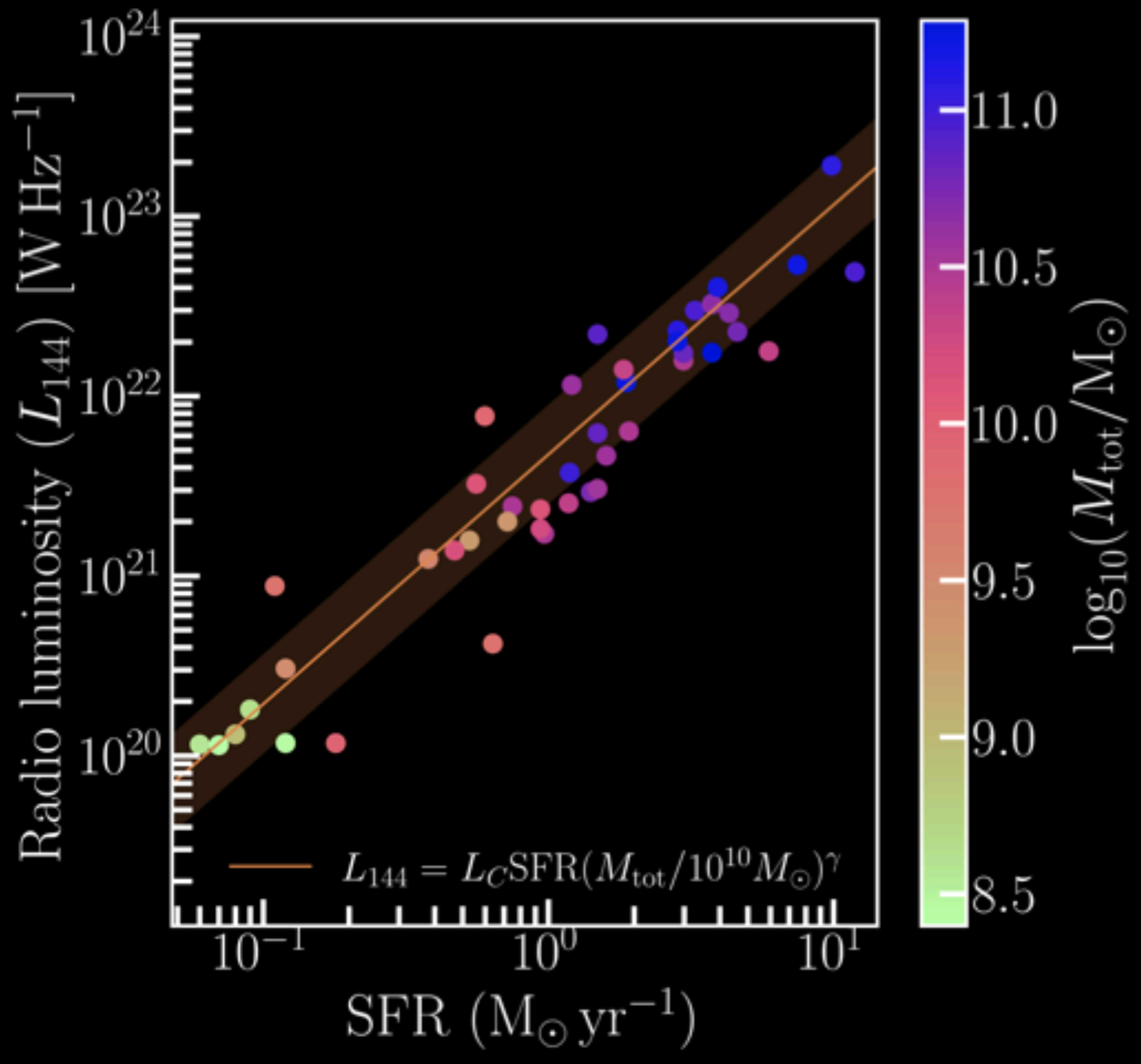
Mass ~ $v^2 r$

Rotation speed from HI line width



# 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

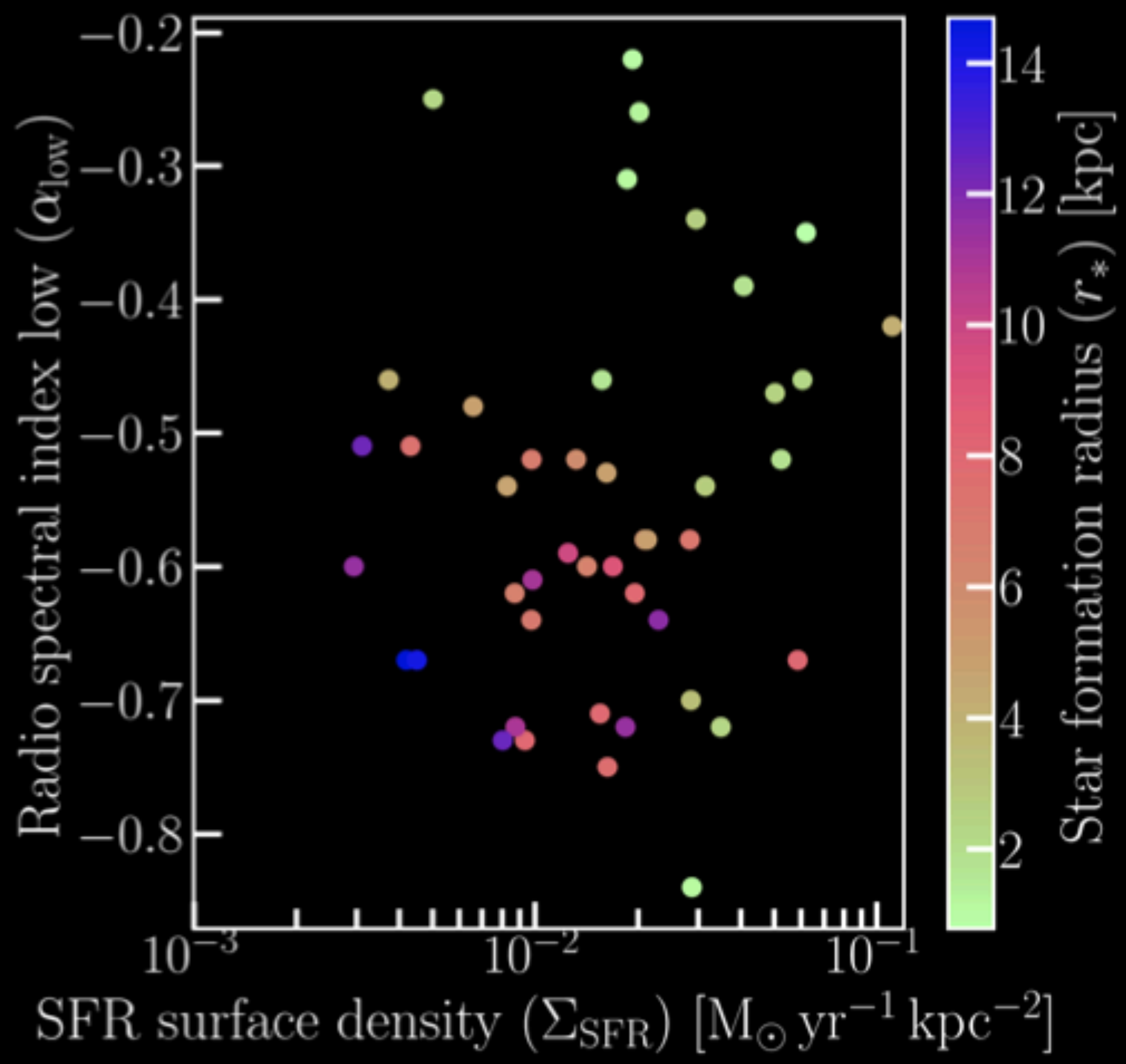
$$\eta \propto \mathrm{SFR}^{0.05}\, M_{\mathrm{tot}}^{0.27}$$

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

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

# Galaxy size determines radio spectral index

## Spectral index does not depend on $\Sigma_{SFR}$




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

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

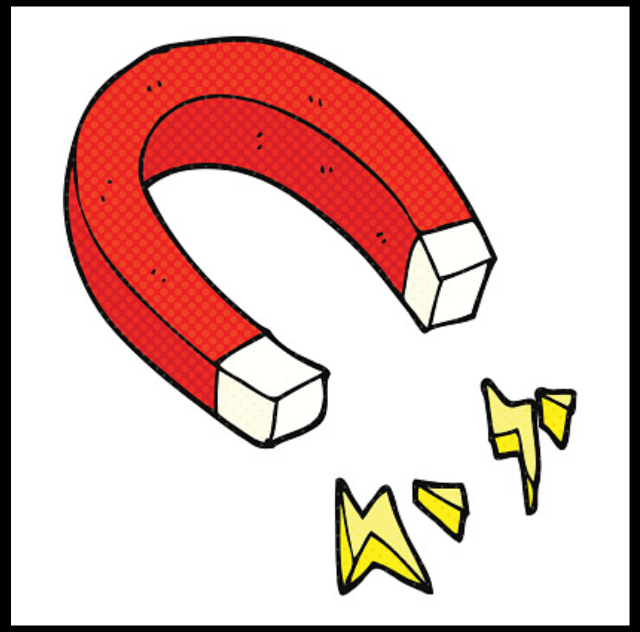
radio spectral index →

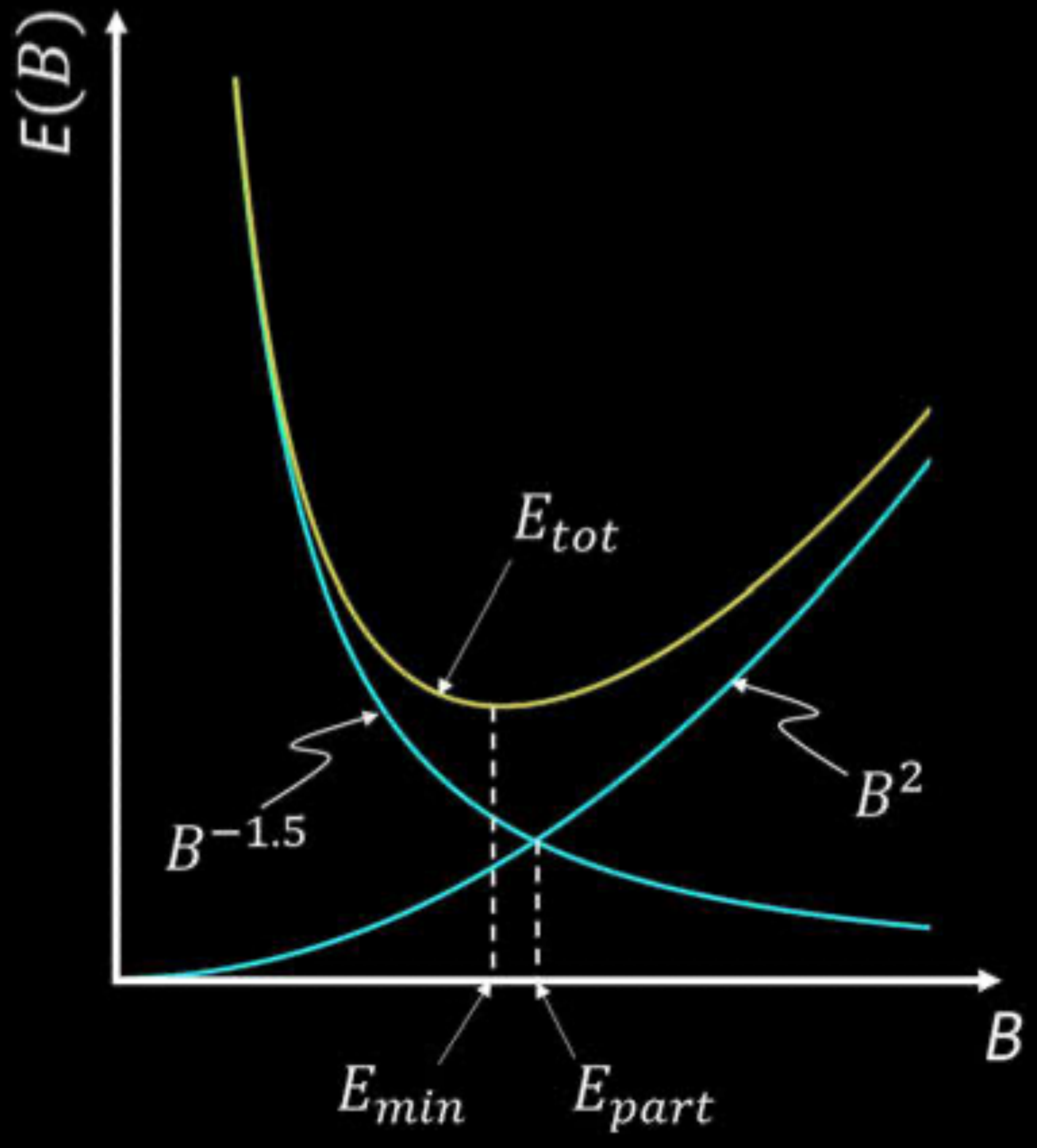
$$\frac{t_{esc}}{t_{syn}} \propto r_* \Sigma_{SFR}^{0.1}$$

# Magnetic field strength

## Estimated from energy equipartition

- Mean magnetic field strength: 7.9 +/- 2.0 µG
- Dependent on the radio spectral index
- Ordered magnetic field strength from polarisation



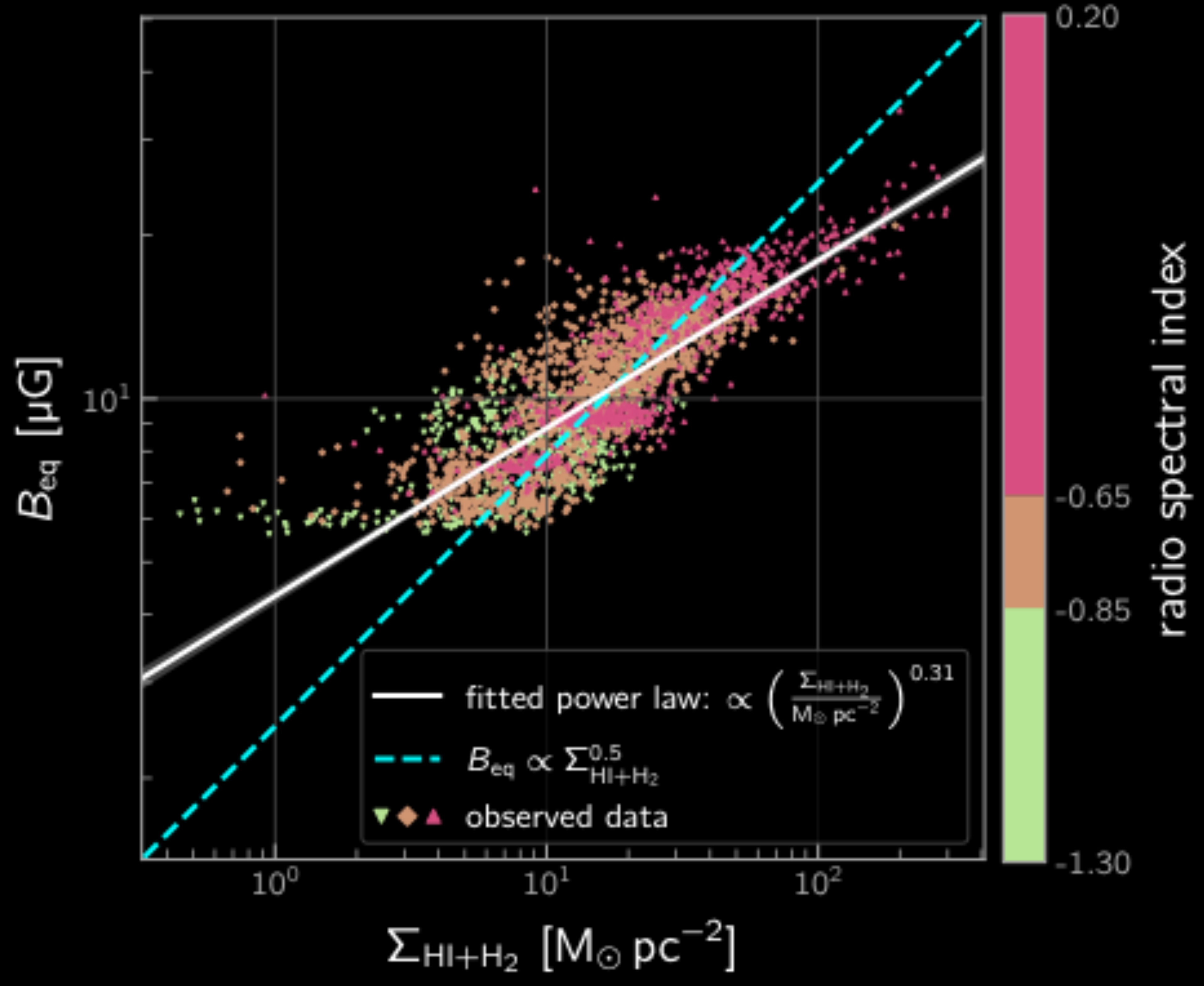



Klein & Fletcher (2015)

# Magnetic field–gas relation
## as estimated from energy equipartition

- Observed: $B$–$\Sigma_{\mathrm{gas}}^{0.3}$
- Theory: $B$–$\Sigma_{\mathrm{gas}}^{0.5}$ (constant velocity dispersion)
- Equipartition with kinetic energy density

$$\frac{B^2}{8\pi} = \frac{f}{2}\rho v_{\mathrm{t}}^2$$



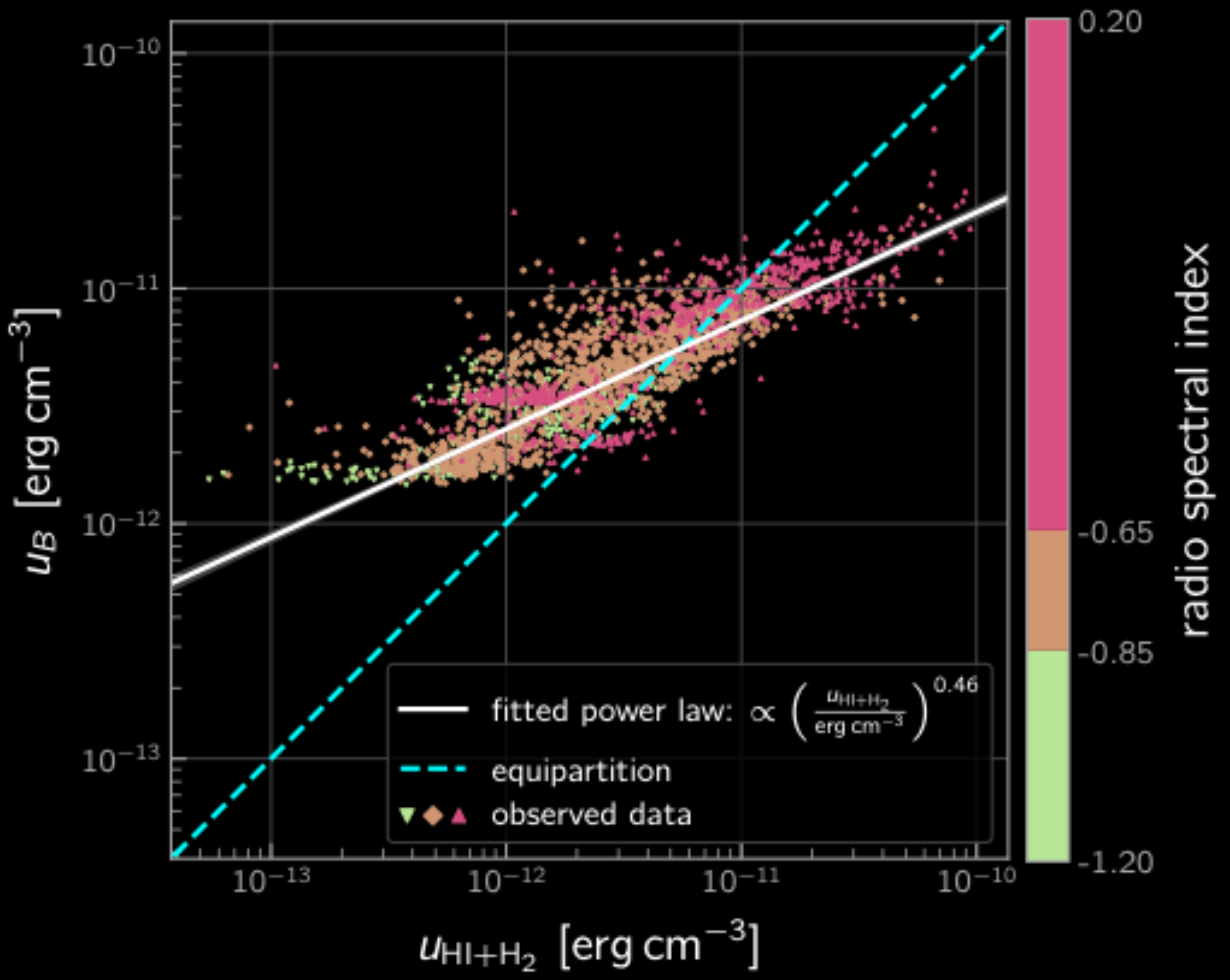

*Heesen et al. (2023)*

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

# Magnetic energy density
## and equipartition

- In approximate energy equipartition
- Amplification by small-scale dynamo
- Magnetic field weak in areas of high gas densities

Parker instability

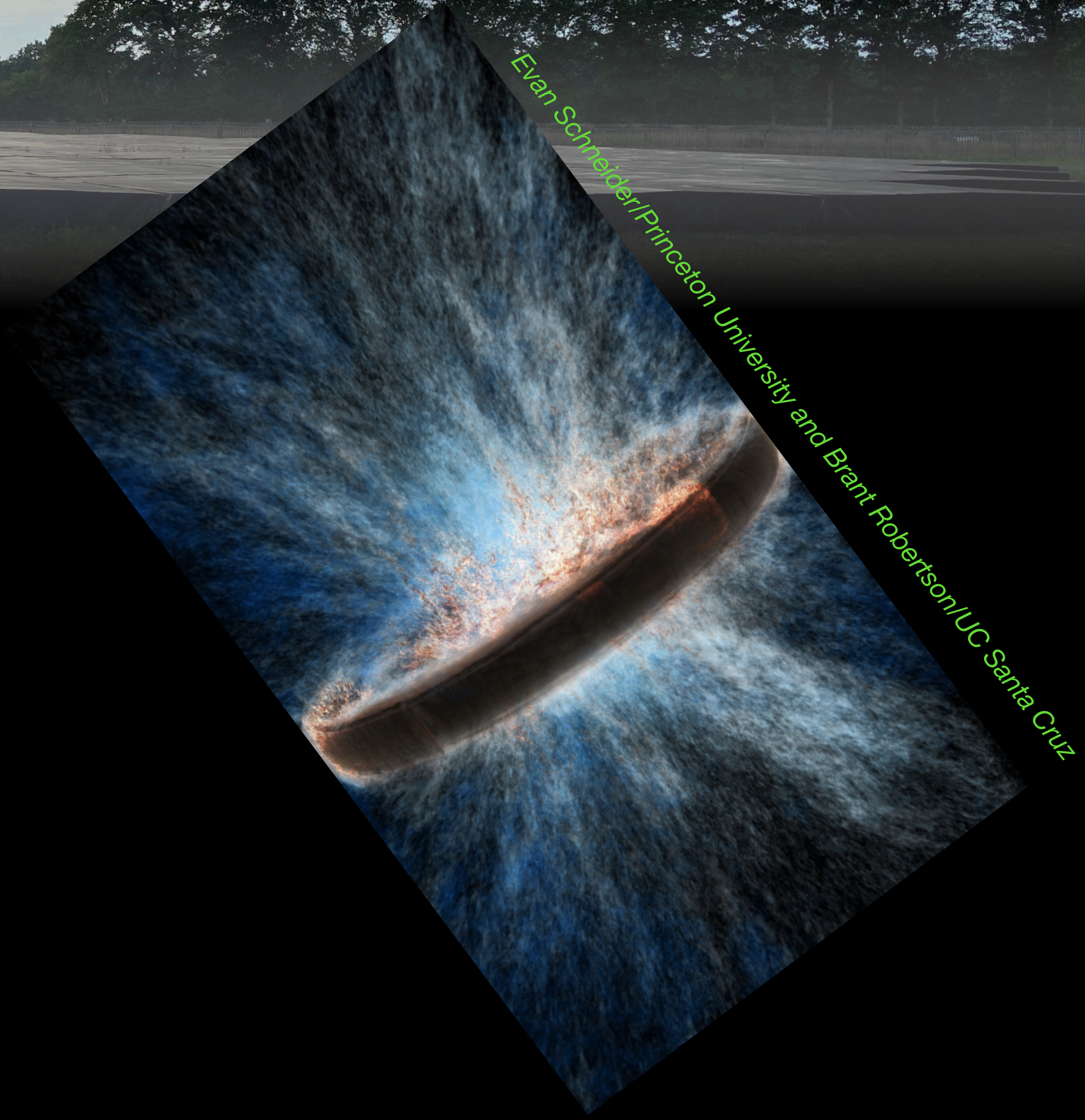




*Heesen et al. (2023)*

# Cosmic-ray transport

## and galactic winds

- Galactic winds play an important role in galaxy evolution
- Cosmic rays can be both <u>tracer</u> and <u>driver</u> for a wind
- Advection, diffusion and streaming contribute to cosmic-ray transport

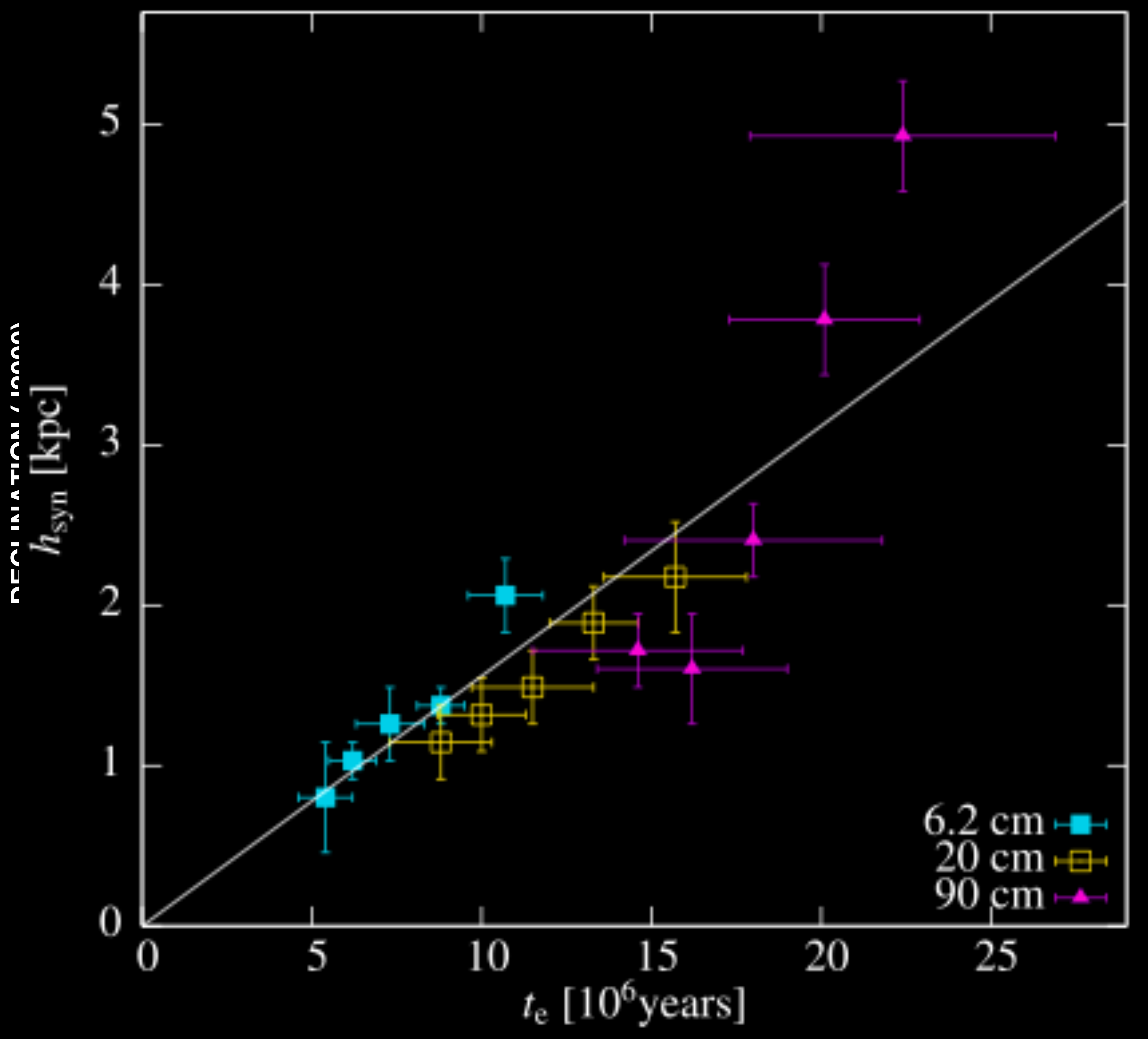


# How to detect galactic winds
## with radio haloes

- Diffusion dominated: no wind
- Advection dominated: wind

© NRAO

v = 300 km $s^{-1}$




Heesen et al. (2009)

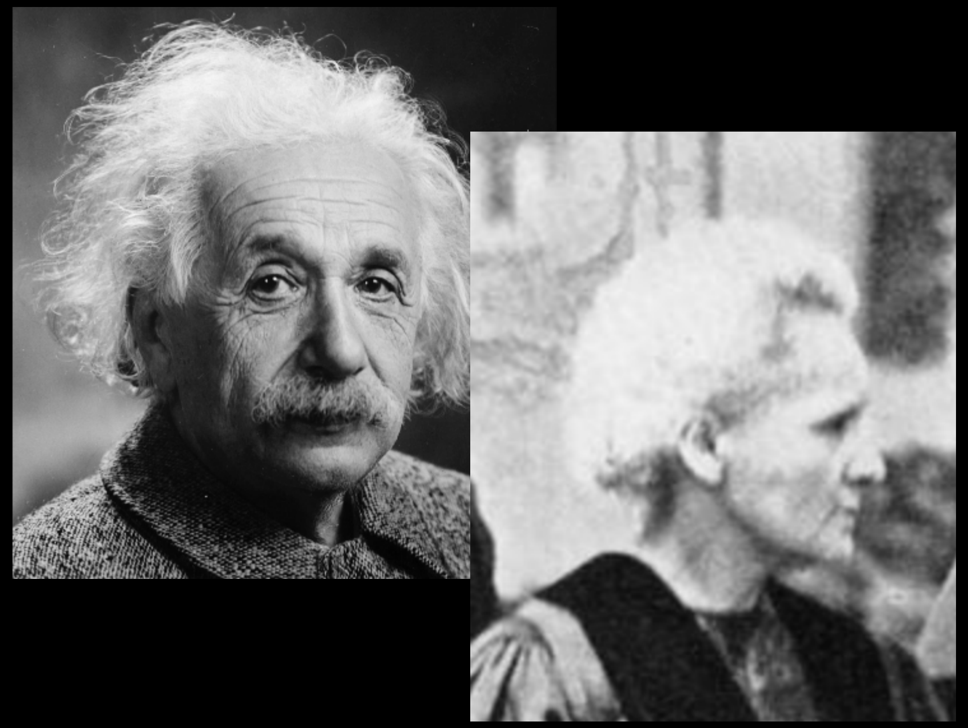
‘Young’ CRE


Ageing

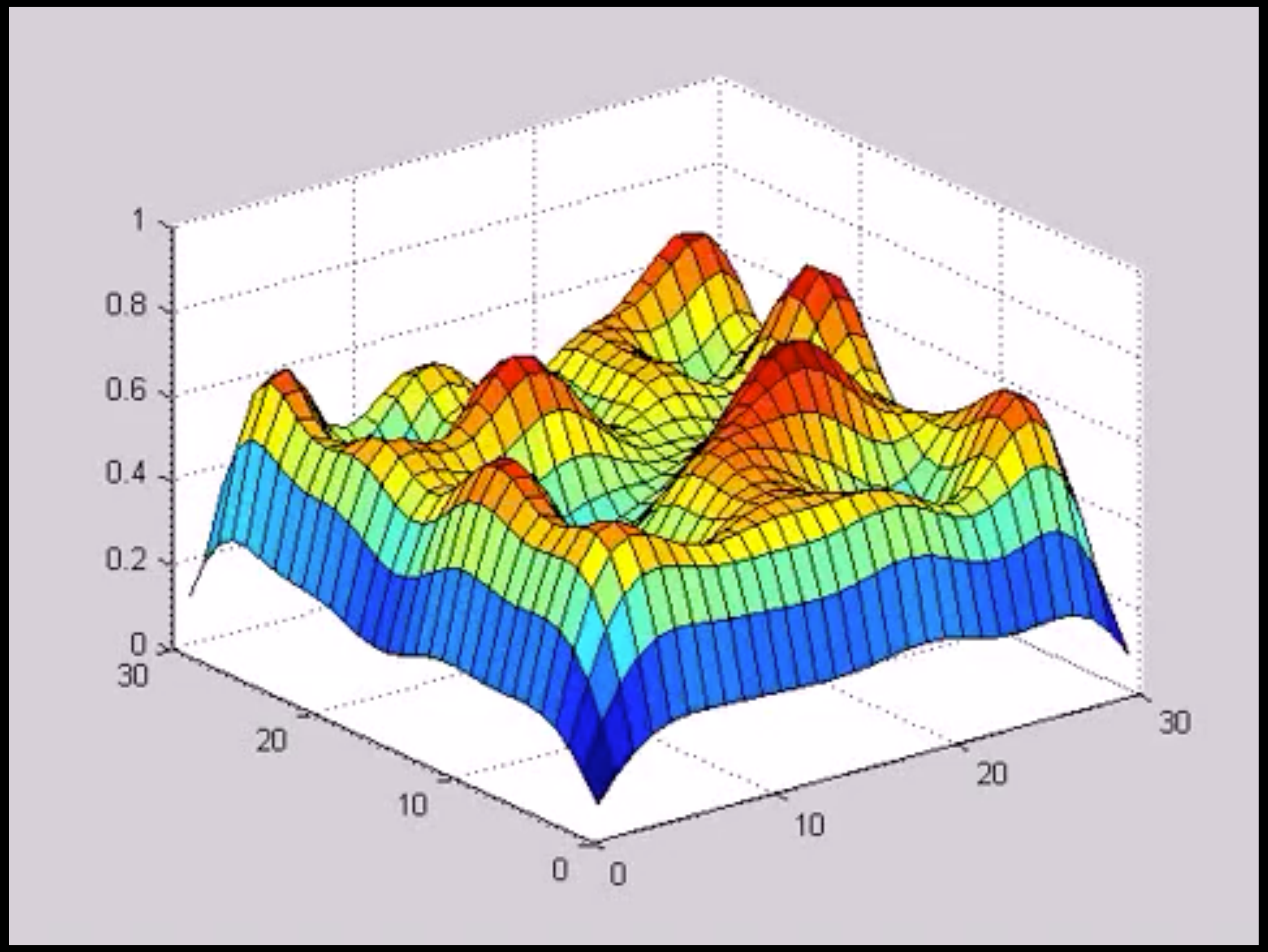
‘Middle-aged’ CRE

More ageing

‘Old’ CRE



Diffusion




Steady-state solution to heat equation with sources

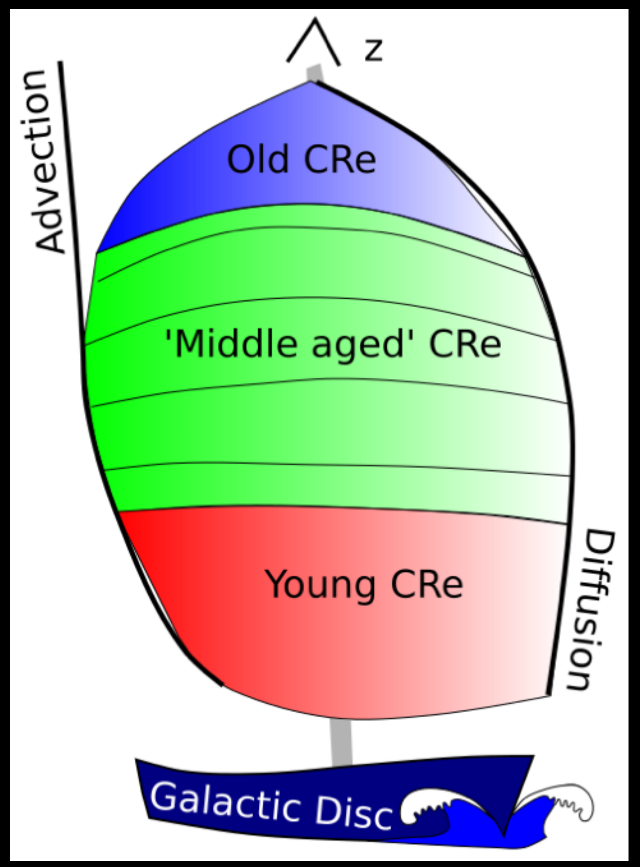
# Steady state solution

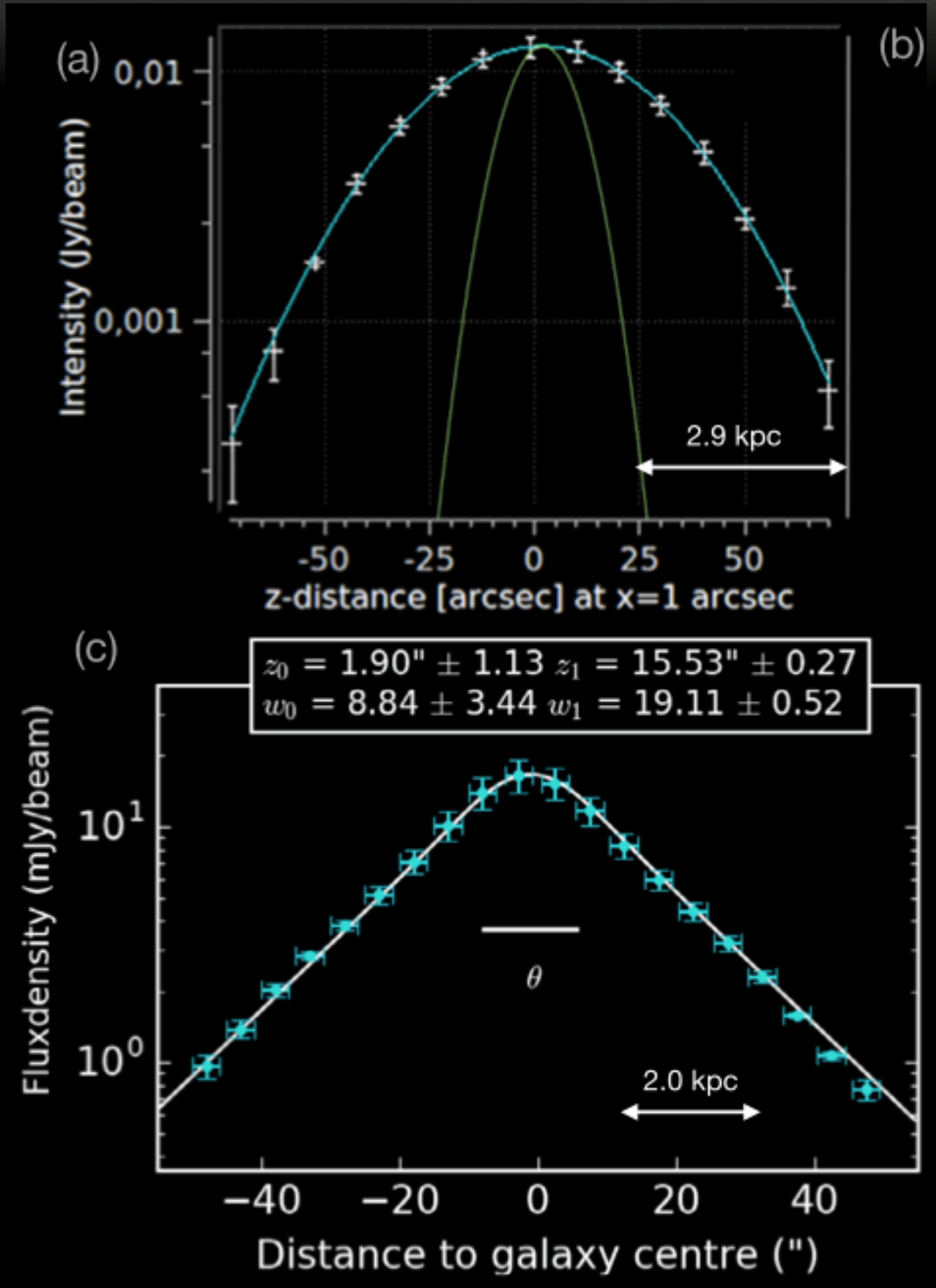
## with injection and losses

- Injection at z = 0; constant *B*-field
- Advection: linear decrease
- Diffusion: Gaussian decrease

**SPINNAKER**

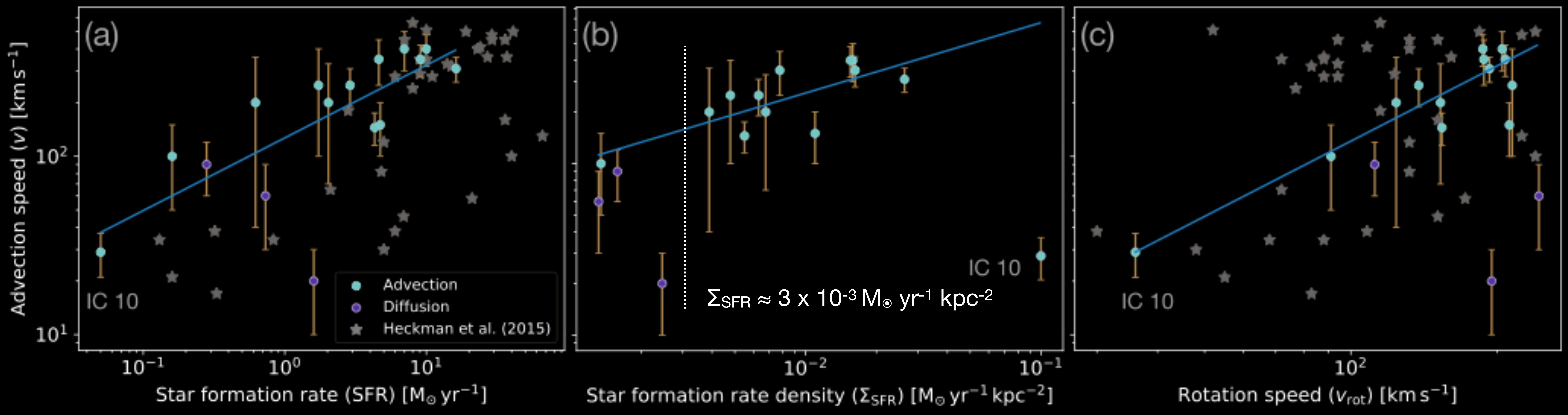
**S**pectral **IN**dex **N**umerical **A**nalysis of **K**(c)osmic-ray **E**lectron **R**adio-emission



# Advection speed scaling relations

## Star-formation rate




*Heesen (2021)*

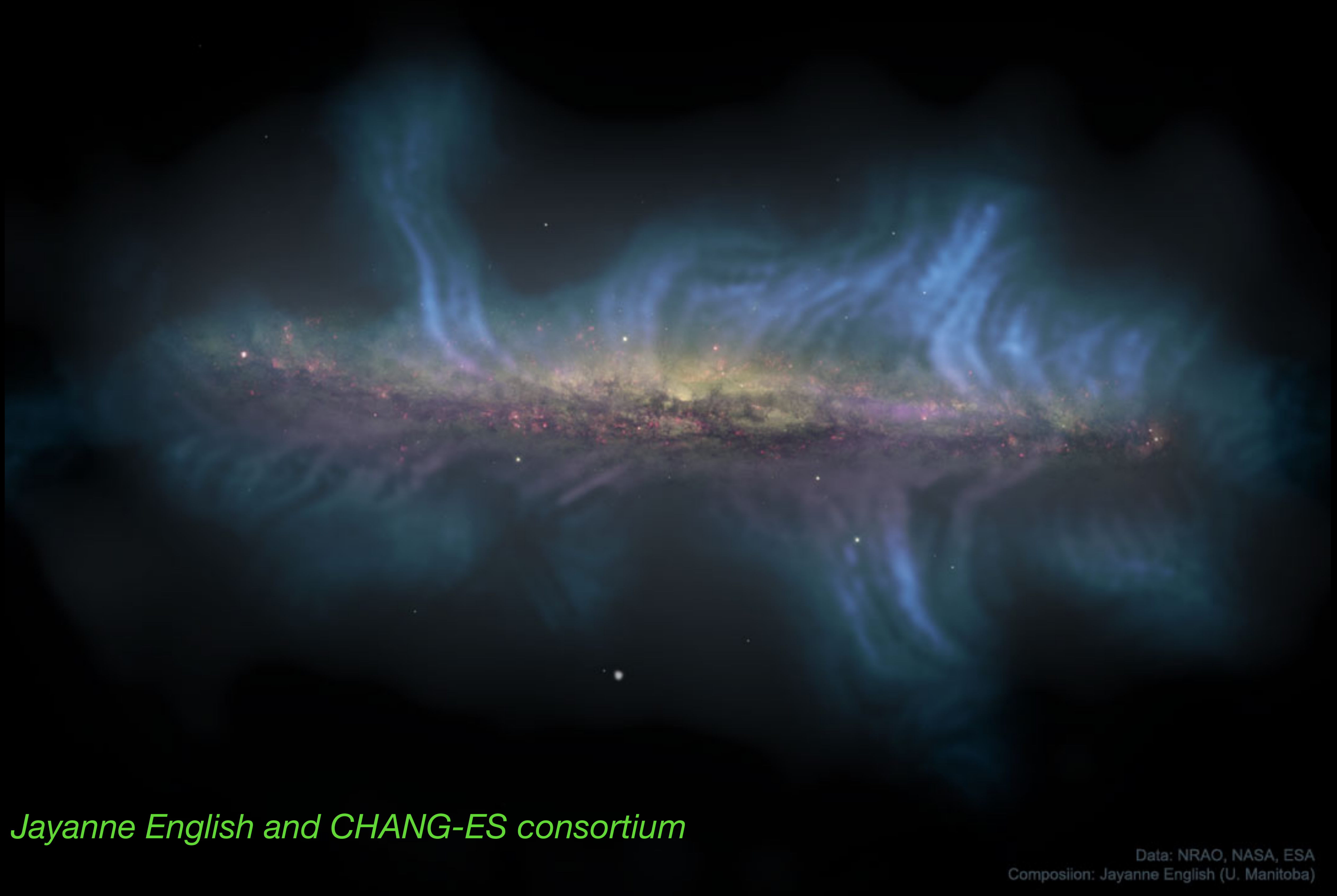
- Advection speed rises with SFR, $\Sigma_{SFR}$, and $v_{rot}$
- Correlations: $v \propto SFR^{0.4}$, $v \propto \Sigma_{SFR}^{0.4}$, $v \propto v_{rot}^{1.4}$

**Momentum-driven galactic wind (*Murray et al. 2005*)**

# The role of cosmic rays in galactic winds

## Relation with magnetic fields

- X-shaped magnetic fields in the halo
- Cosmic rays can stream along field lines
- Assume constant compound (gas + cosmic rays) sound speed




*Jayanne English and CHANG-ES consortium*

Momentum equation

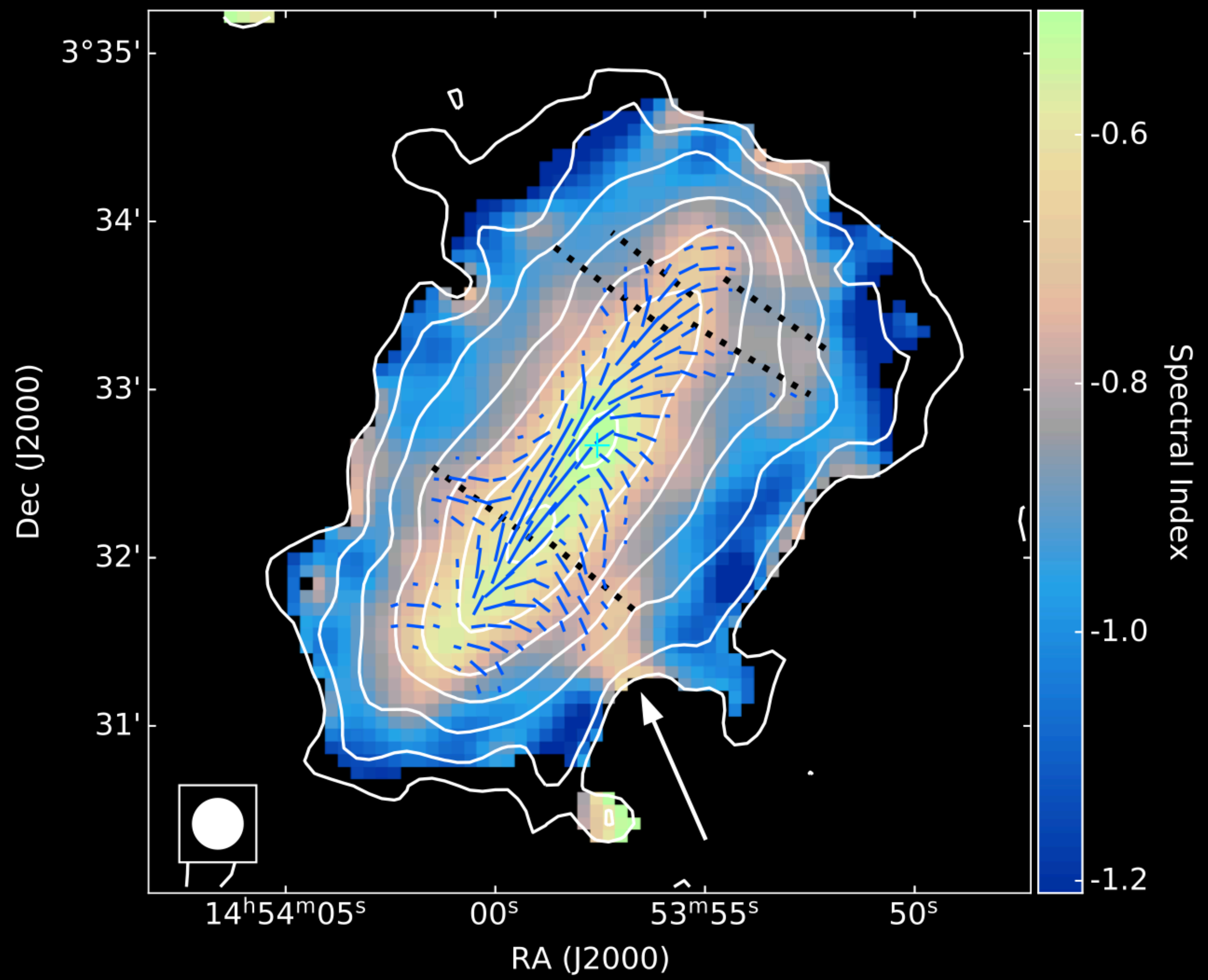
$$\rho v \frac{\mathrm{d}v}{\mathrm{d}z} = -\frac{\mathrm{d}P}{\mathrm{d}z} - \rho g$$

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

# Cosmic ray streaming

## as a means of transporting energy

- Transport length: L ~ $\nu^{-0.5}$ (as advection)
- Transport speed: similar to Alfvén speed
- Few cases so far for global streaming
- Possible localised streaming along vertical magnetic field lines

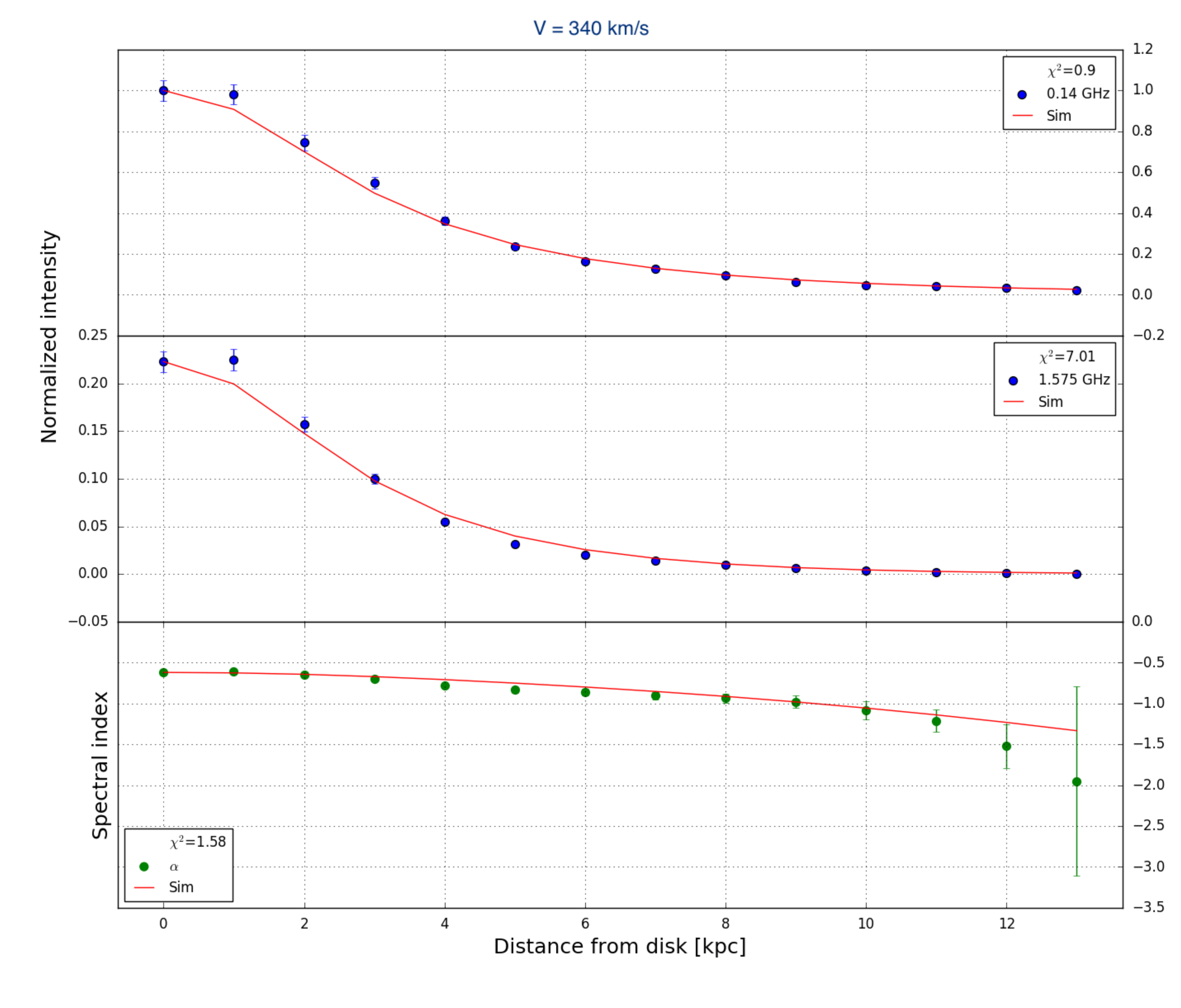



Heald et al. (2021)

# SPINNAKER fitting

## with Spinteractive

- Vary velocity until spectral index profile fits
- Magnetic field strength together with CRE density
- Best-fitting intensity profile




**code developed by Arpad Miskolczi**

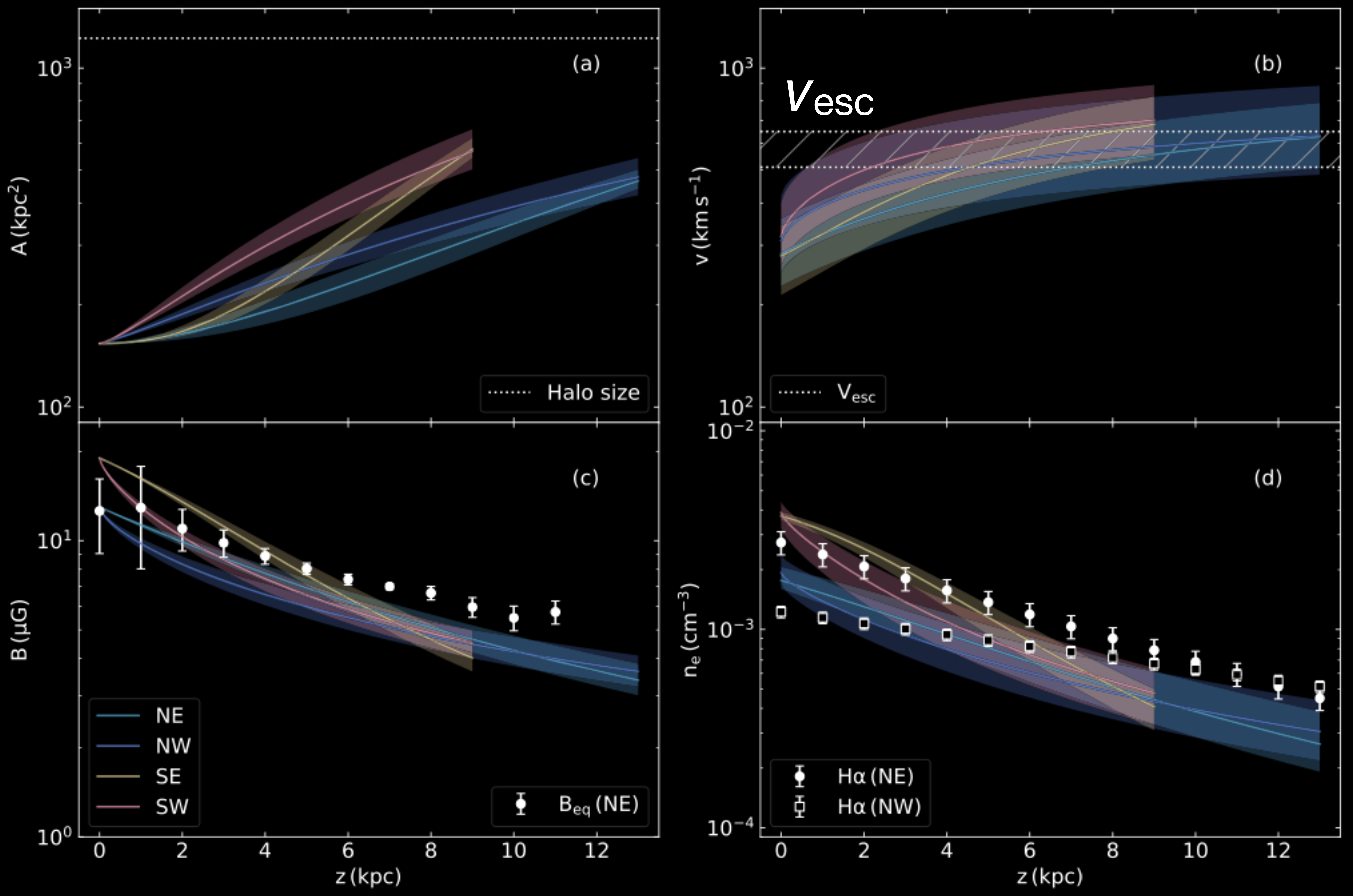
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

# Stellar feedback-driven wind

## Application to NGC 5775

Five more galaxies: paper by Michael Stein

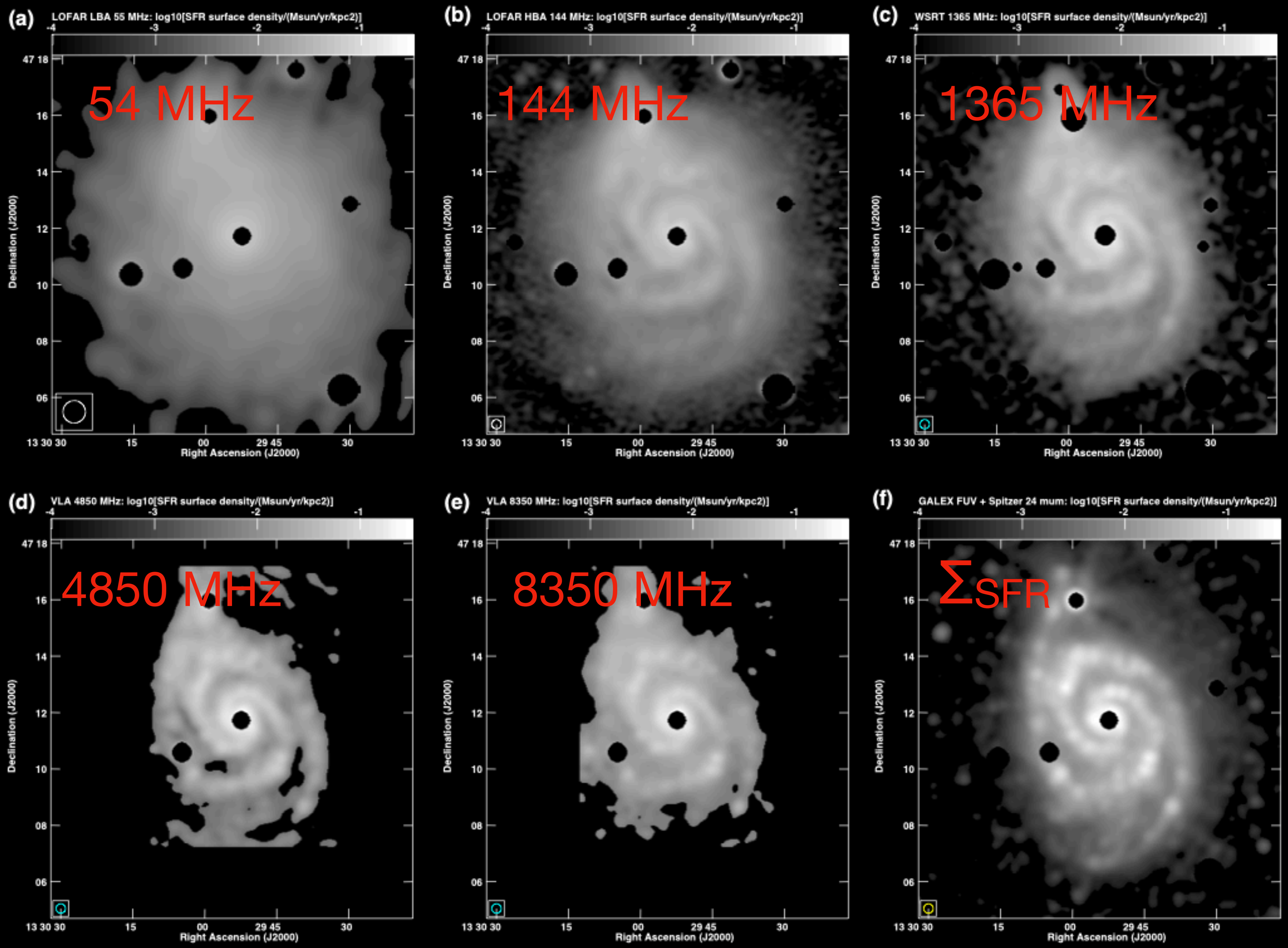
- Electron density of $10^{-3}$ cm$^{-3}$
- Wind velocity exceeds escape velocity
- Mass-loss rate of order $M_{\odot}$ yr$^{-1}$
- Mass-loading factor of order 1



# Smoothing experiment

## Diffusion length in face-on galaxies

Lowest frequency

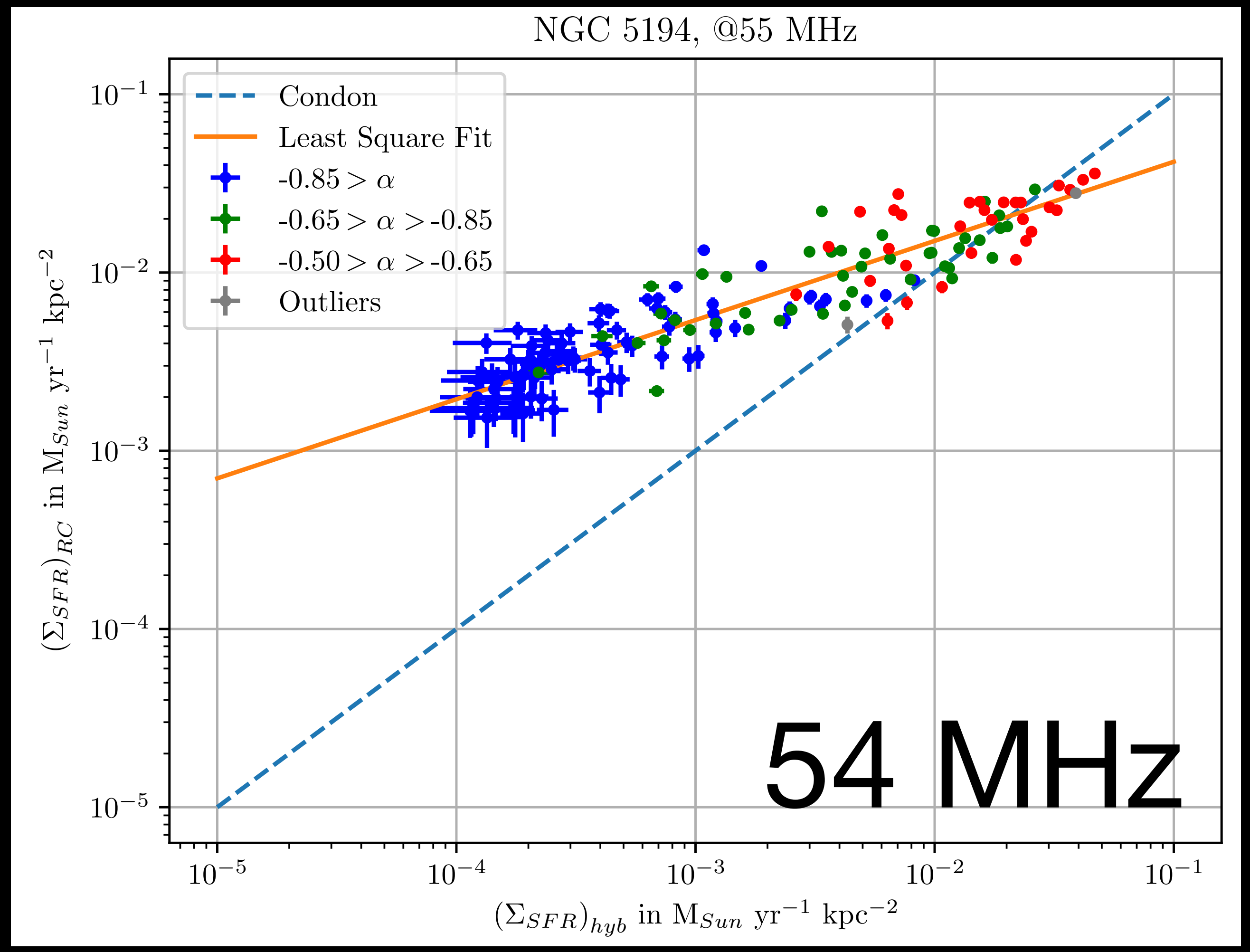


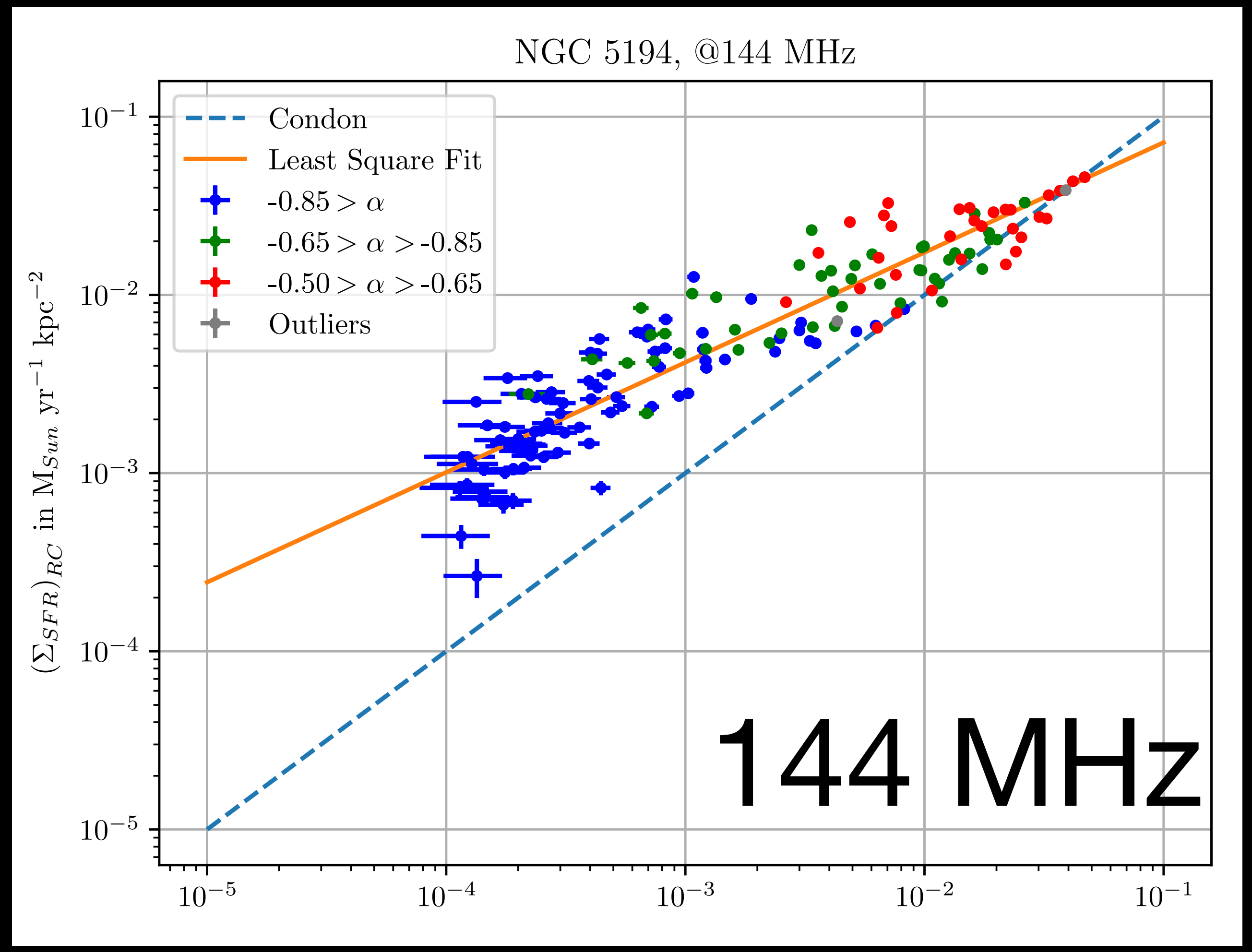

CRE injection

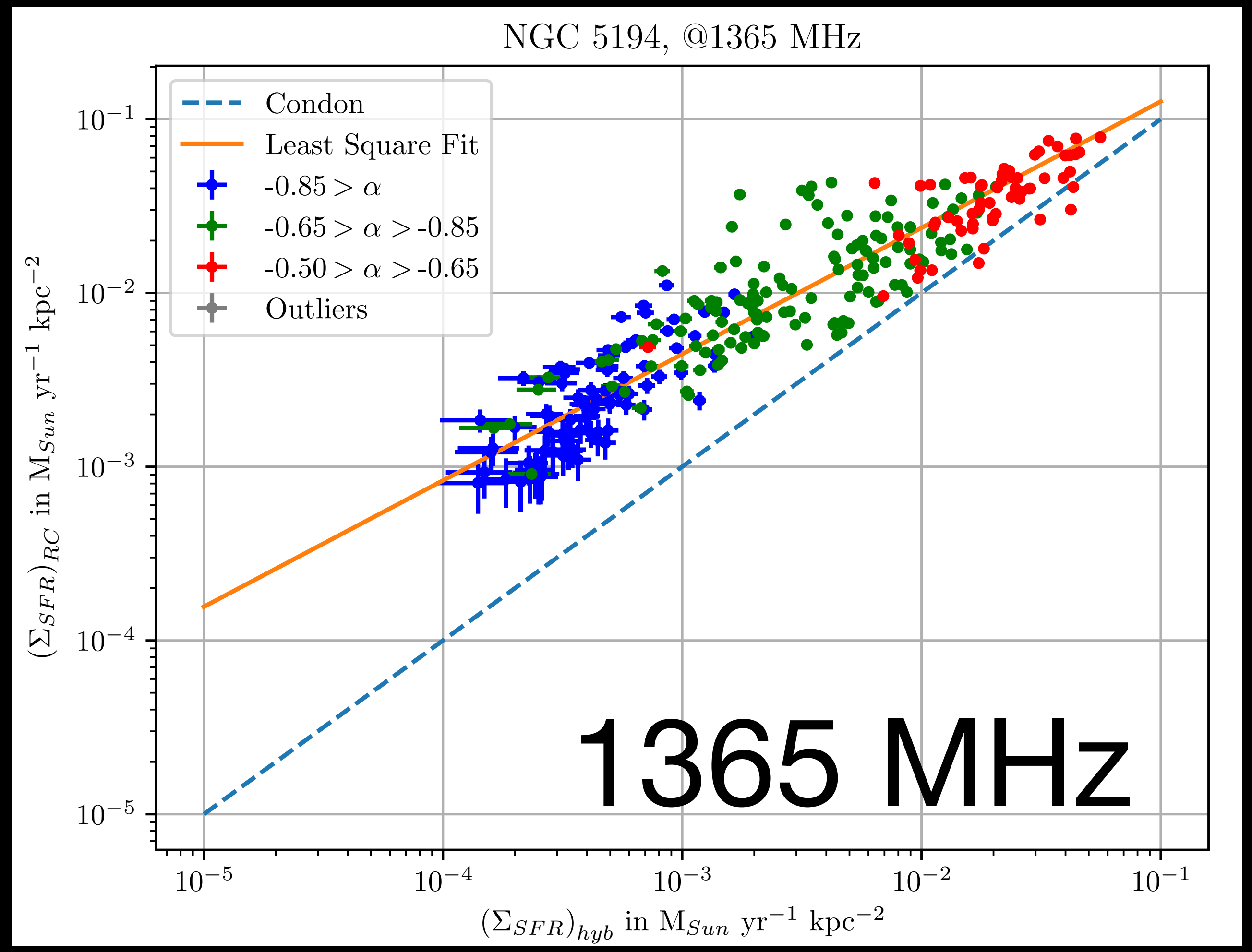
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

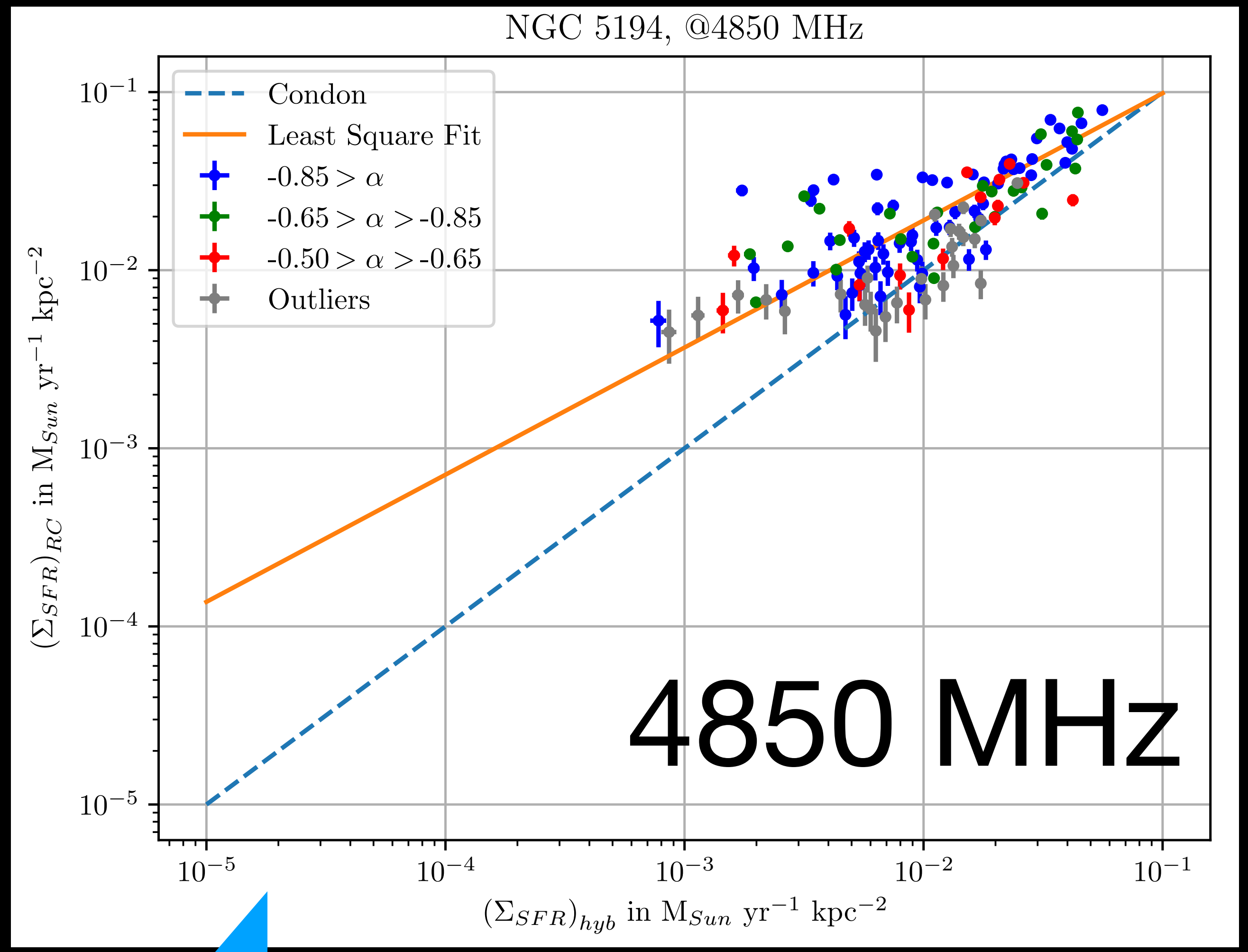
# Sub-linear radio–SFR relation for spatially resolved case

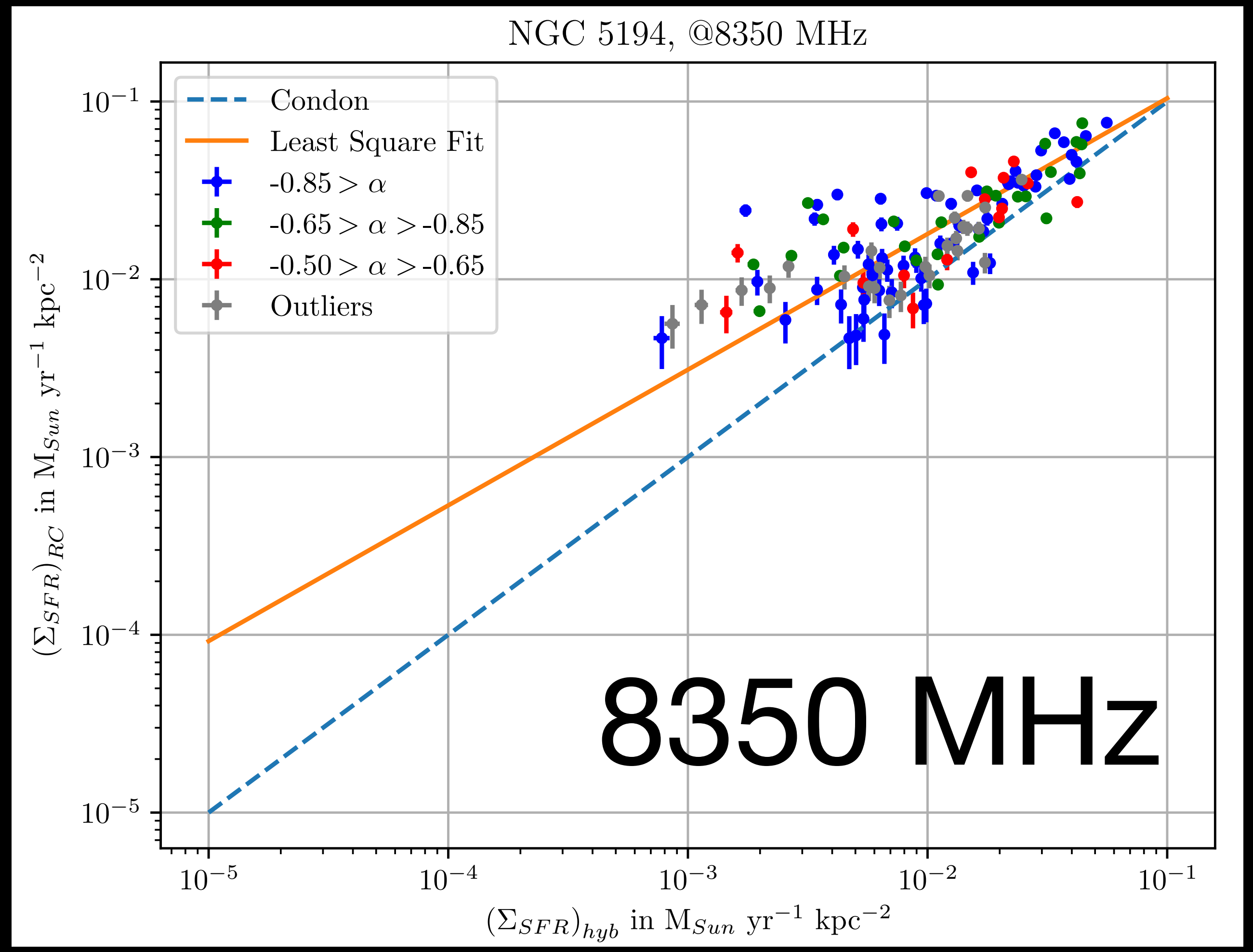
Lower frequencies, older CREs, decreasing slope




Slope decreases further for lower frequencies

CRE are older, so they can be transported further

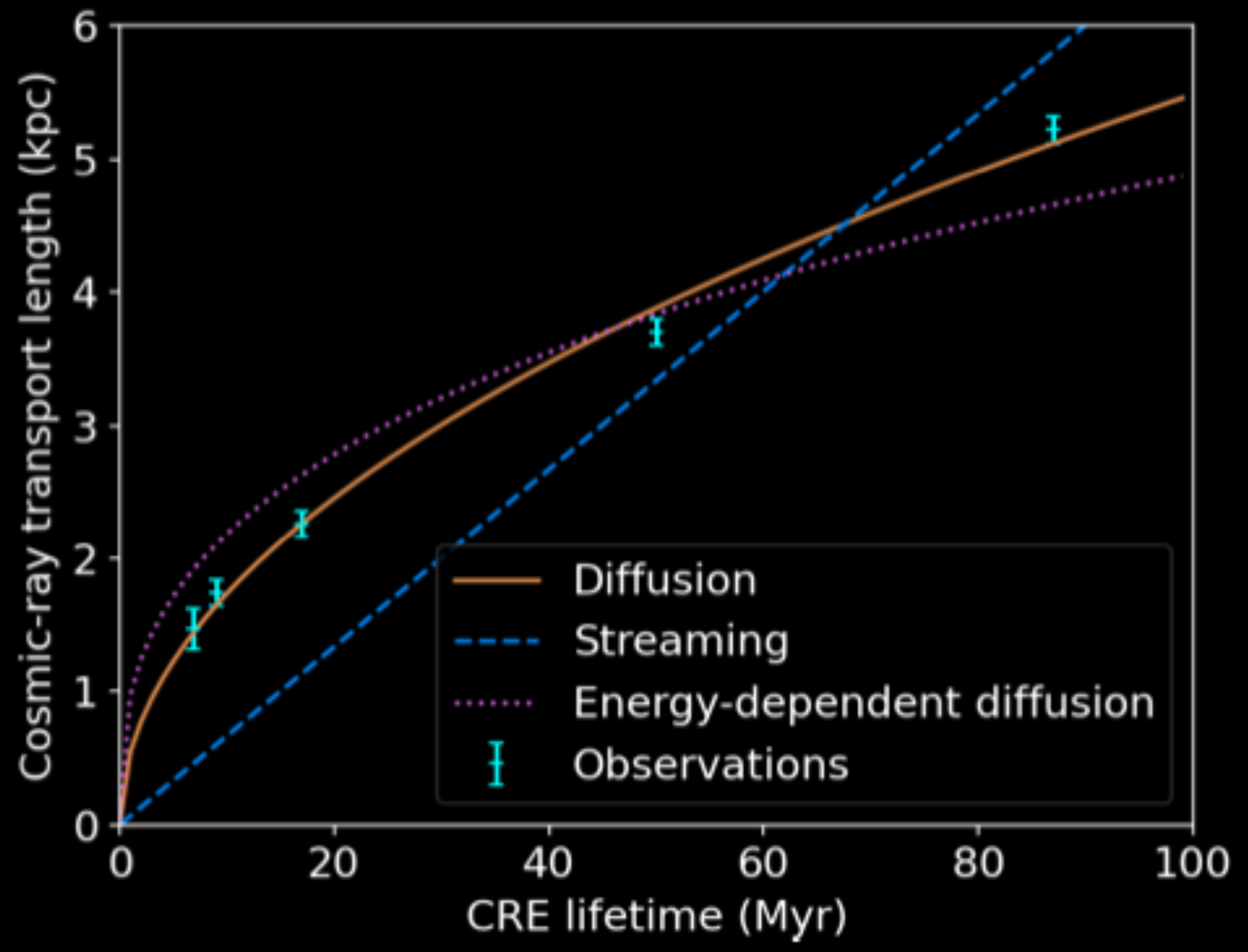
Lower frequencies, older CREs, decreasing slope

# Diffusion coefficients

## Energy dependence

$$D = \frac{L^2}{4\tau}$$

- $D = 10^{27}$-$10^{29}$ cm$^2$ s$^{-1}$
- Mostly non-energy dependent: $L \propto \nu^{-0.25}$
- In radio haloes also non-energy dependent (*Schmidt et al. 2019, Stein et al. 2022*)
- Boron-to-carbon ratio supports this in the Milky Way (E < 10 GeV) (*Becker-Tjus and Mertens (2020)*)

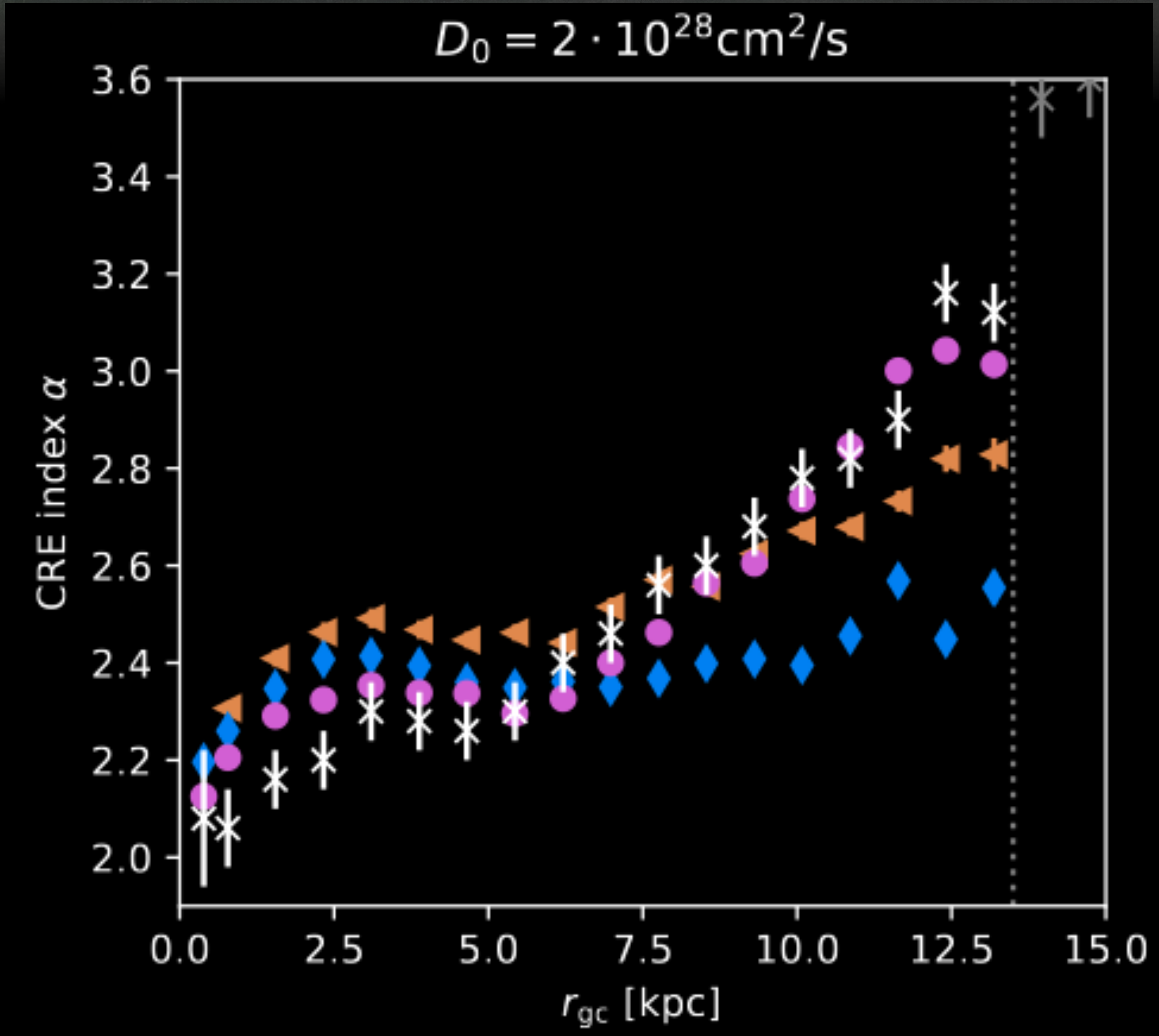


# 3D Simulation

## with wind and diffusion

- Diffusion coefficient confirmed
- No energy dependence
- Wind slower than estimated from radio haloes

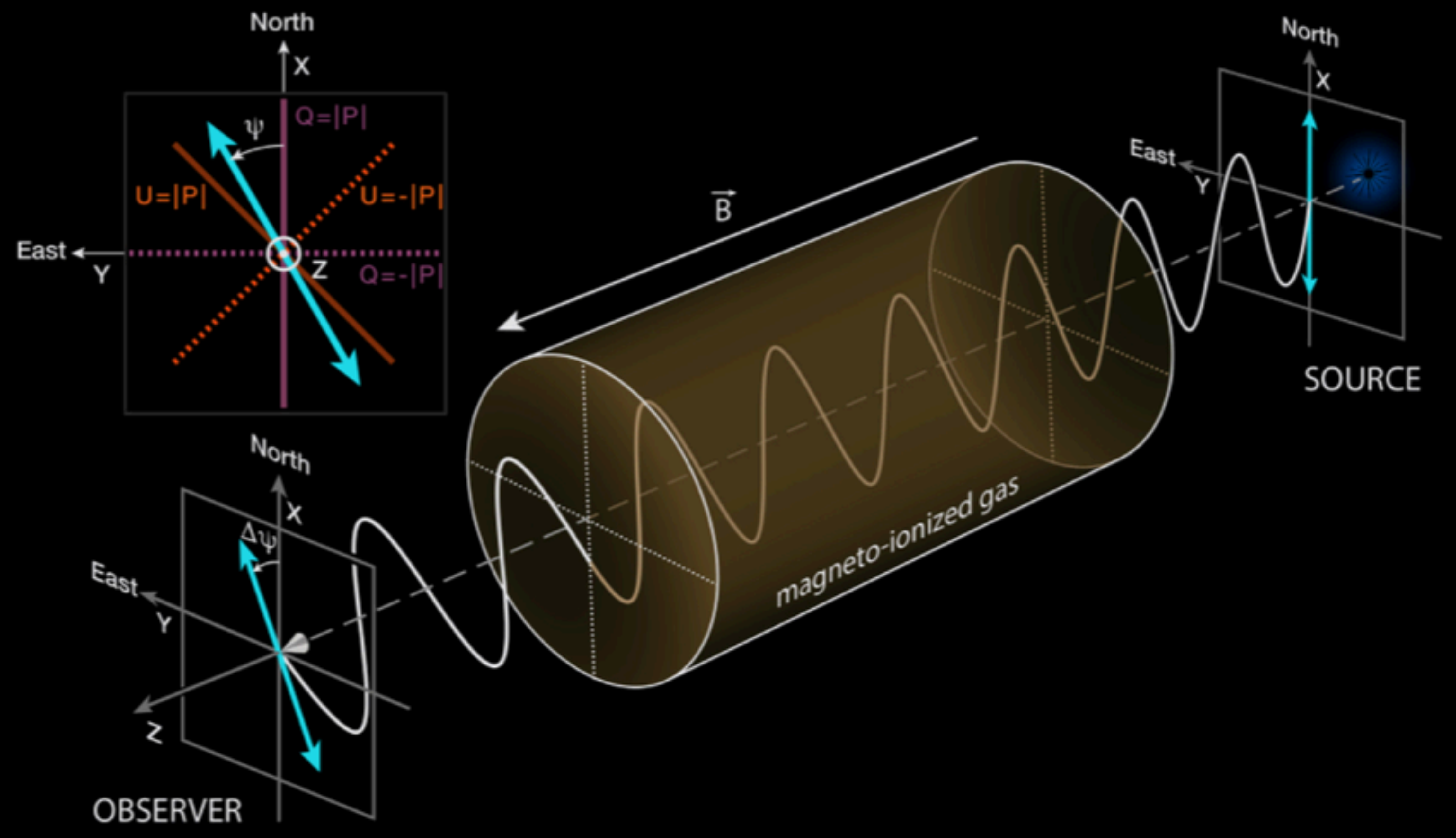
CRPropa v3.1




Dörner et al. (2023)

# Faraday rotation

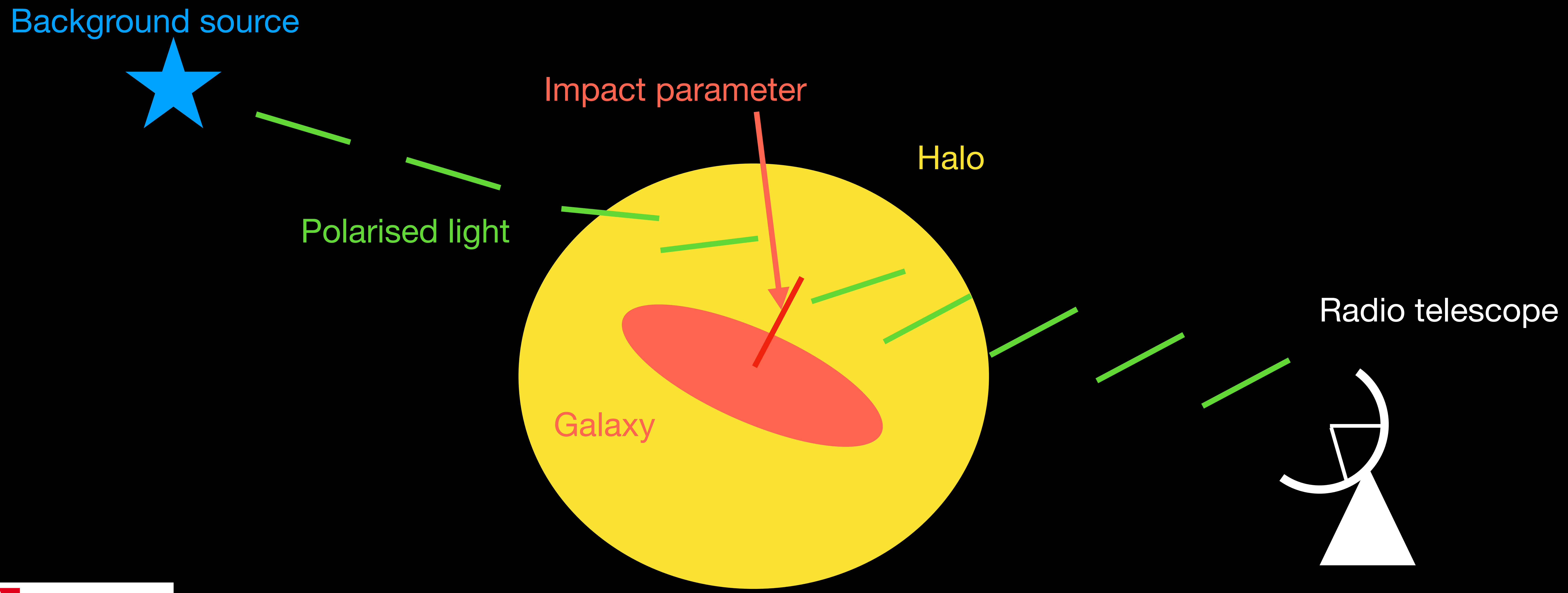
- Strongly wavelength dependent
- Foreground ‘screen’
- Background polarised sources
- Line-of-sight *B*-field




*NASA Goddard/Theophilus Britt Griswold*

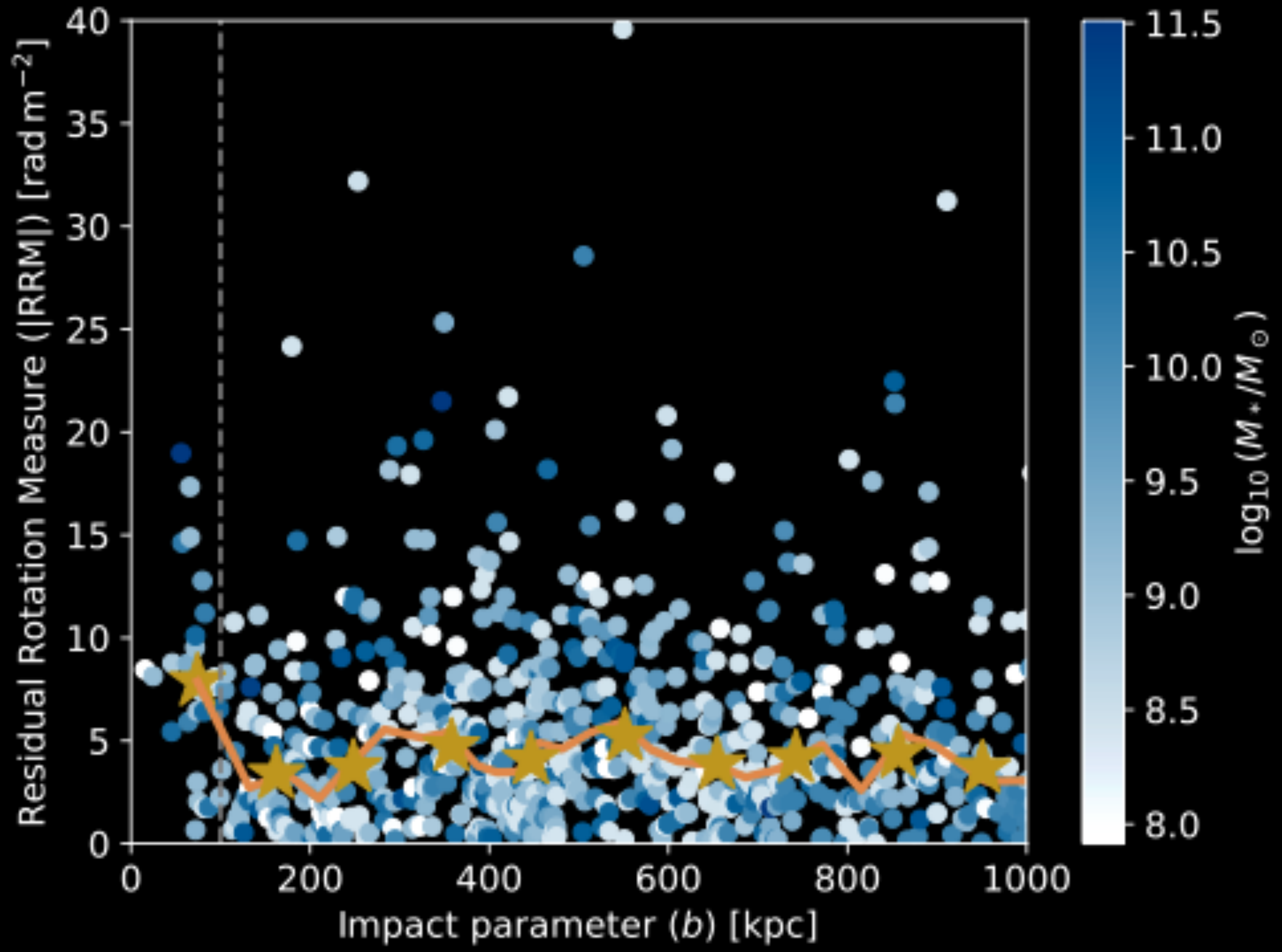
# Circumgalactic *B*-fields

## Experimental setup



# Detection of circumgalactic *B*-fields

- Excess rotation measure
- At impact parameters <100 kpc
- RM = 4 rad $m^{-2}$
- $B$ = 0.5 μG



# Conclusions
## and summary

- Non-linear Radio–SFR relation requires cosmic-ray escape
- Advection speed scaling relations in agreement with a momentum-driven wind, possibly cosmic-ray driven
- Magnetic field strength in equipartition with kinetic energy density
- Diffusion coefficients in agreement with Galactic values with no energy dependence
- Discovery of circumgalactic magnetic fields with Faraday rotation