Radio Observations
4th graduate school on Plasma-Astroparticle physics

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 Julia Tjus

Motivation

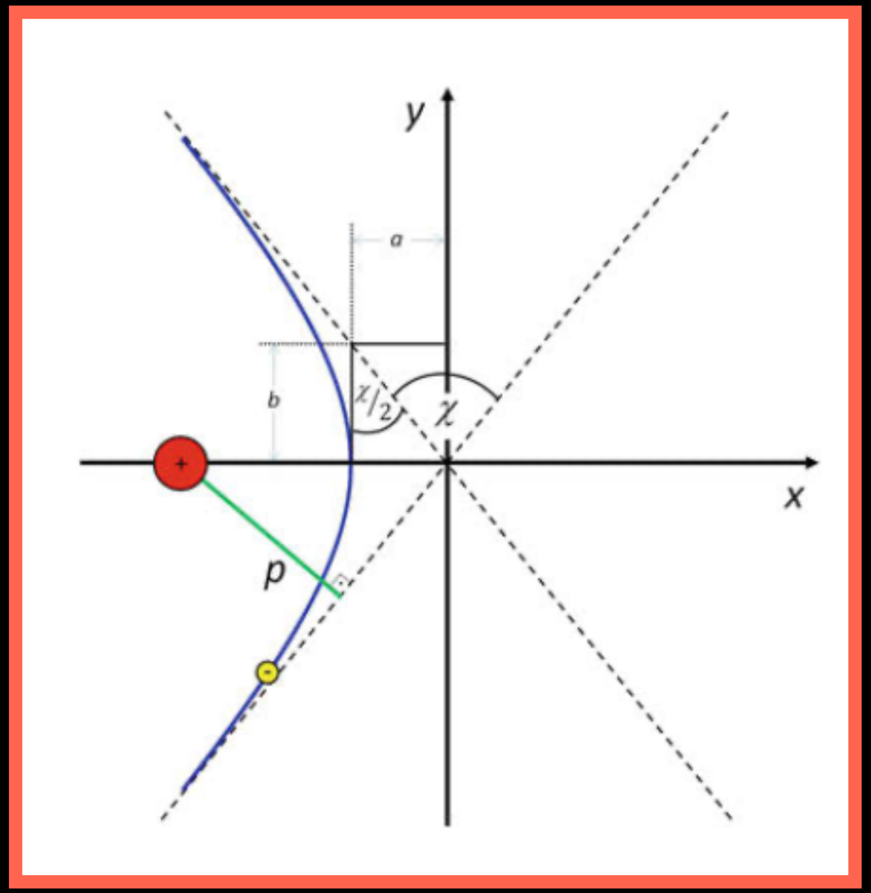
Radio continuum emission from star-forming galaxies

- Radio continuum is an extinction free star-formation tracer
- Ground-based astronomy in the `radio window'
- Interferometry allows us to obtain high resolution (few arcsec)
  (or even ~ 1 arcsec or better with LOFAR ILT)
- Low radio frequencies have low thermal contamination

Cosmic rays
and radio continuum emission

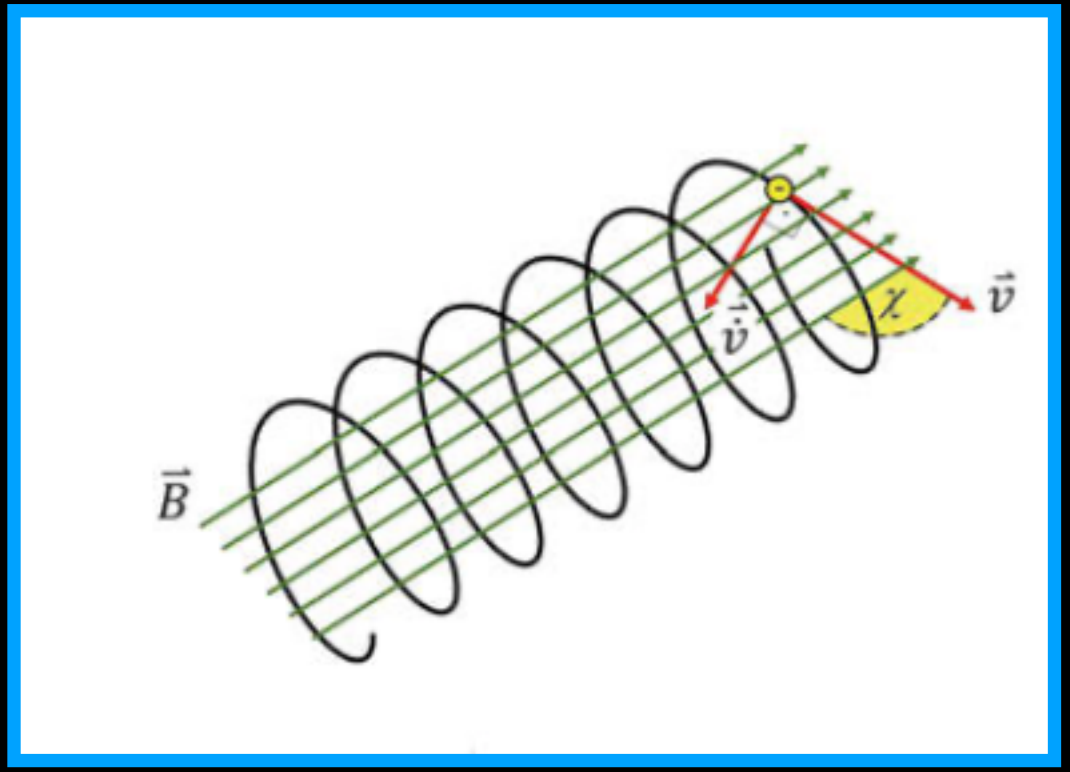
- Energy density ~ magnetic field (1 eV cm^{-3})
- Small anisotropy (10^{-4}) => scattering on *B*-field
- GeV-protons energetically most important
- GeV-electrons are observed in the radio

Free-free emission

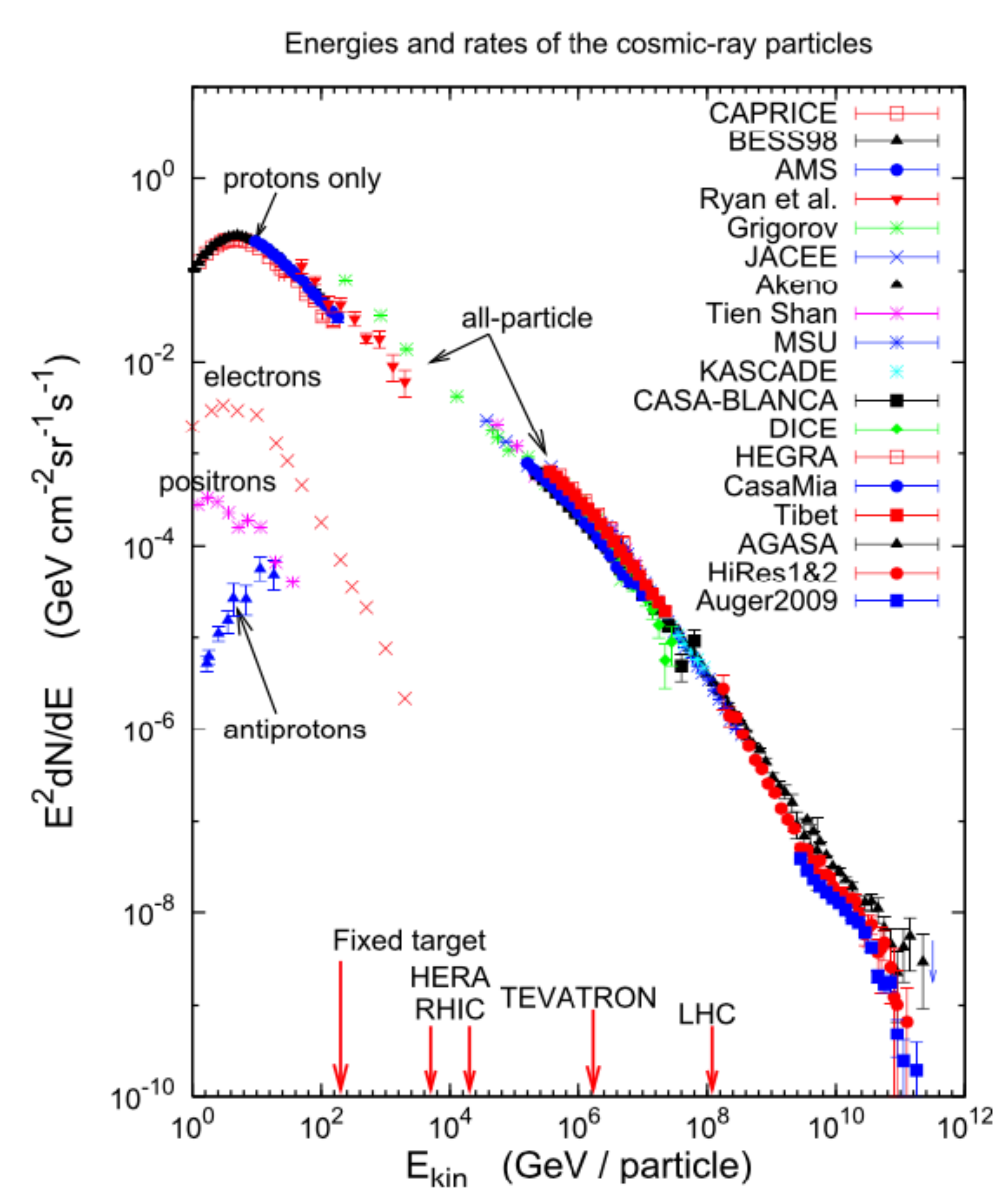


Klein and Fletcher (2015)

Synchrotron emission



Klein and Fletcher (2015)



Zweibel (2013)

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Cosmic ray electrons (CRE)

as observed in the radio continuum

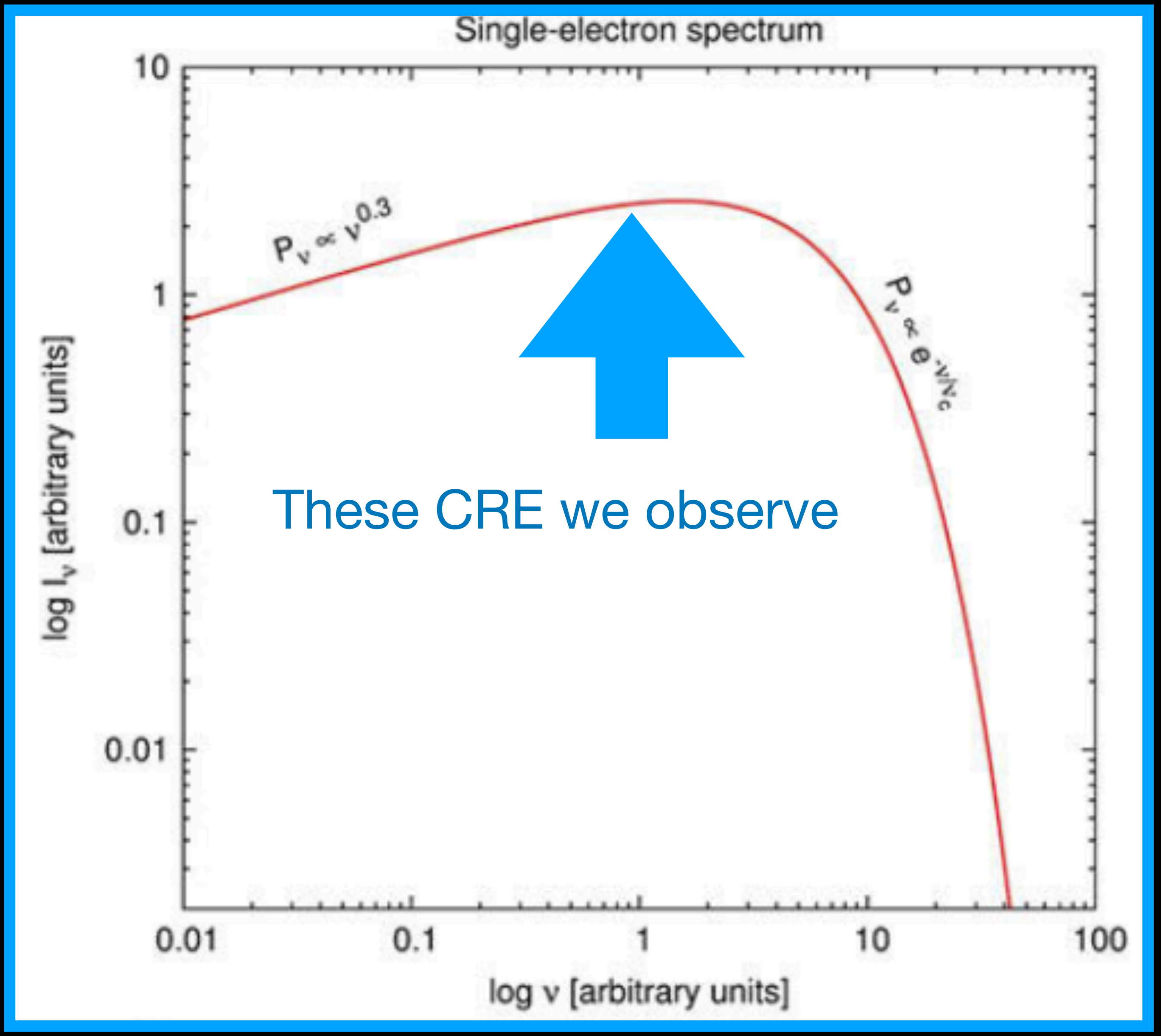
CRE energy: $$E(\mathrm{GeV}) = \left(\frac{\nu}{16.1\ \mathrm{MHz}}\right)^{1/2}\left(\frac{B}{\mu\mathrm{G}}\right)^{-1/2}$$

Synchrotron and inverse Compton losses: ~E^2

Spectral ageing (CRE with highest energy, lose energy faster)

CRE lifetime: $$\tau = 34.2\left(\frac{\nu}{\mathrm{GHz}}\right)^{-1/2}\left(\frac{B}{10\ \mu\mathrm{G}}\right)^{-3/2}\left(1+\frac{U_{\mathrm{rad}}}{U_{\mathrm{B}}}\right)^{-1}\ \mathrm{Myr}$$

Low-frequency: CREs are the oldest!

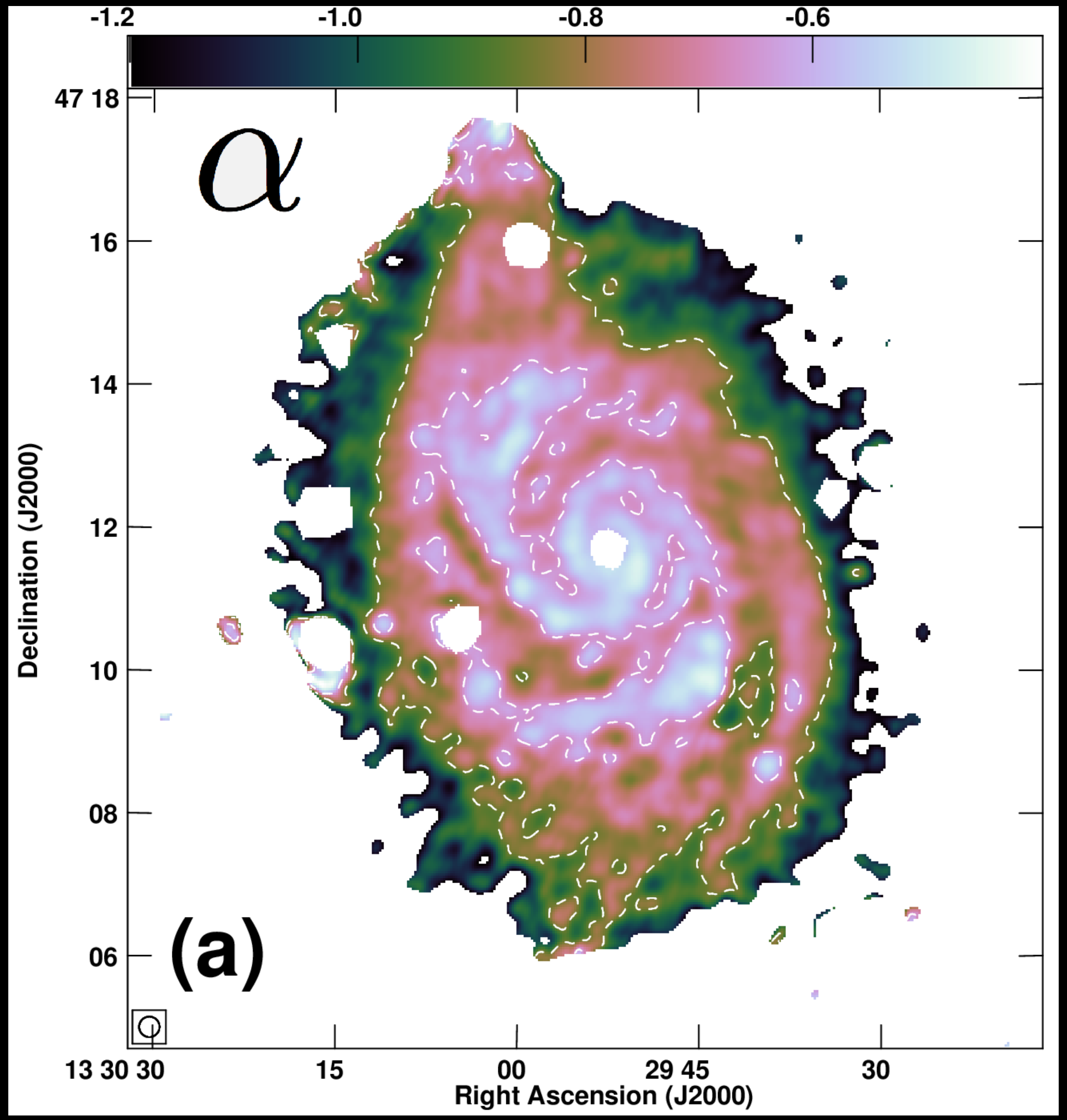


Klein and Fletcher (2015)

Radio spectral index

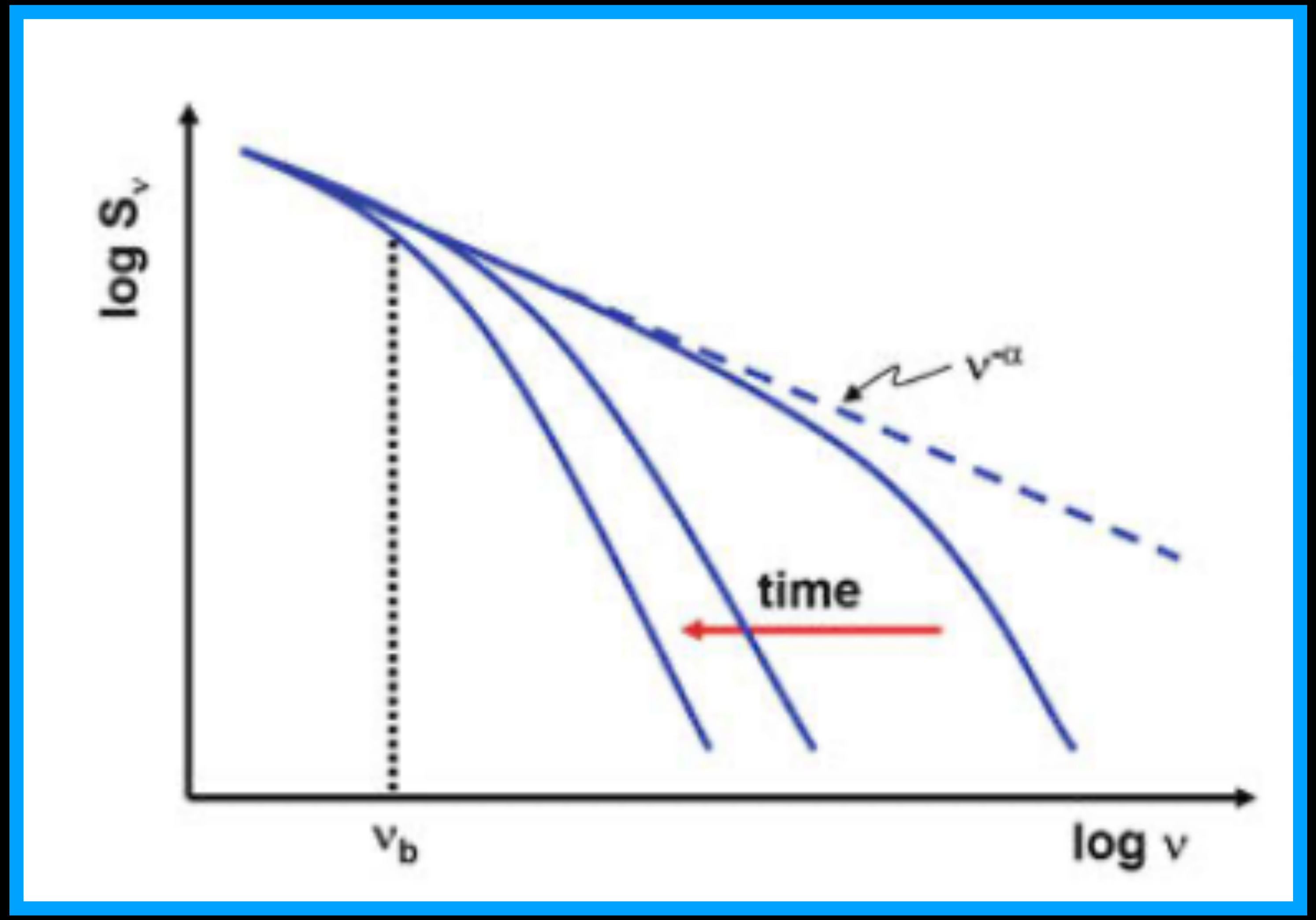
as a proxy for cosmic-ray electron age

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

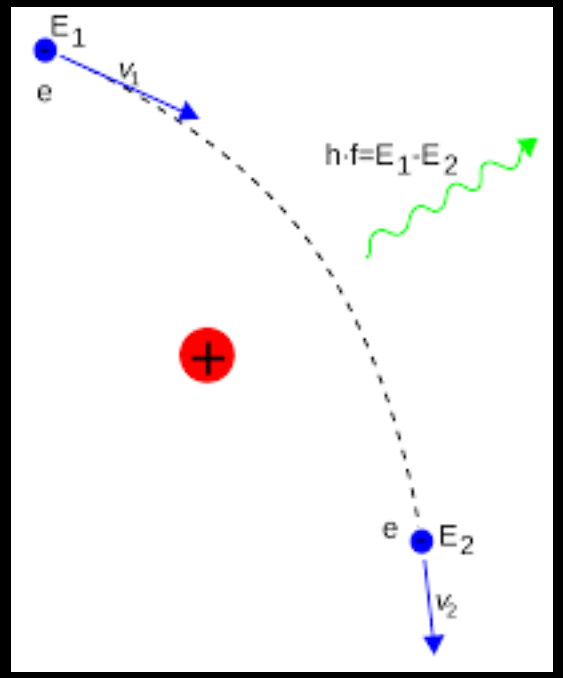
from star-forming galaxies

Massive stars

UV radiation

HII region

free–free radiation

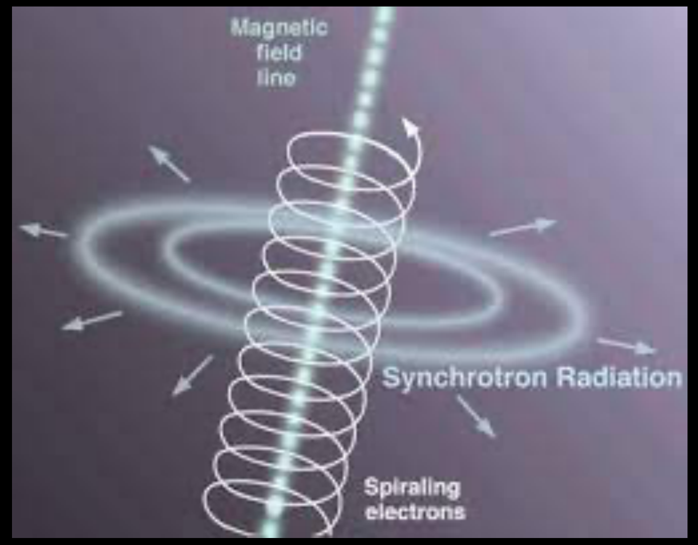


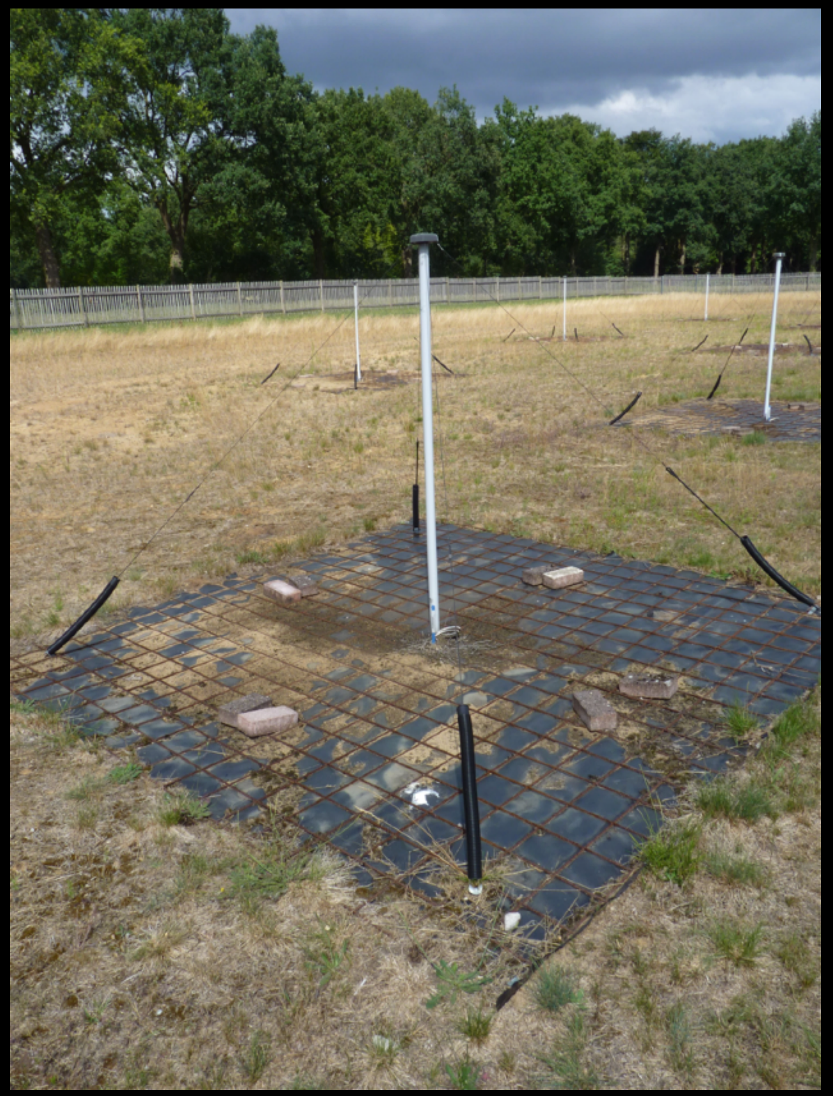
supernova

shock acceleration

SNR

synchrotron emission





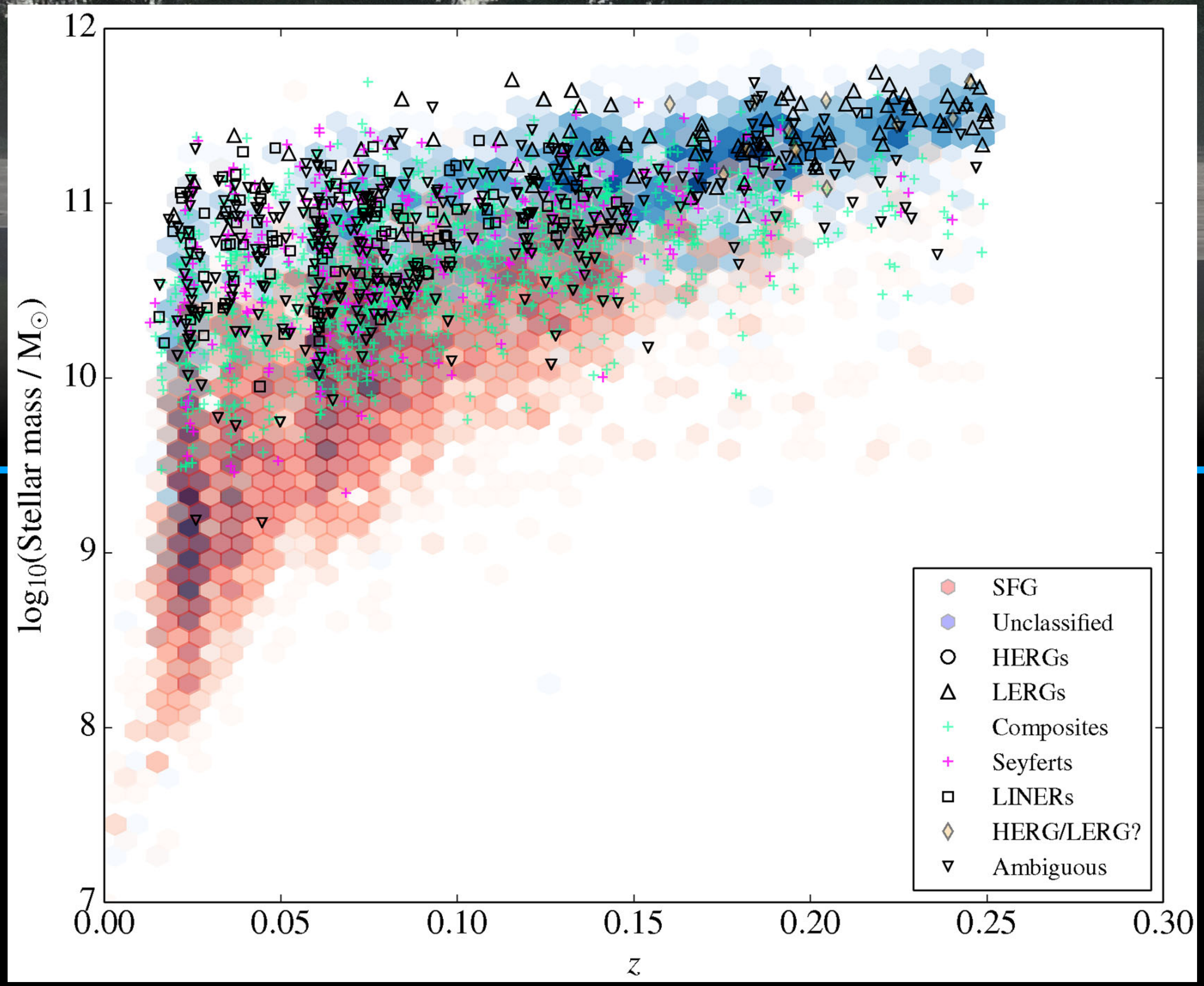
UHH / D. Engels

But there are some complications

with both methods of measuring SFRs

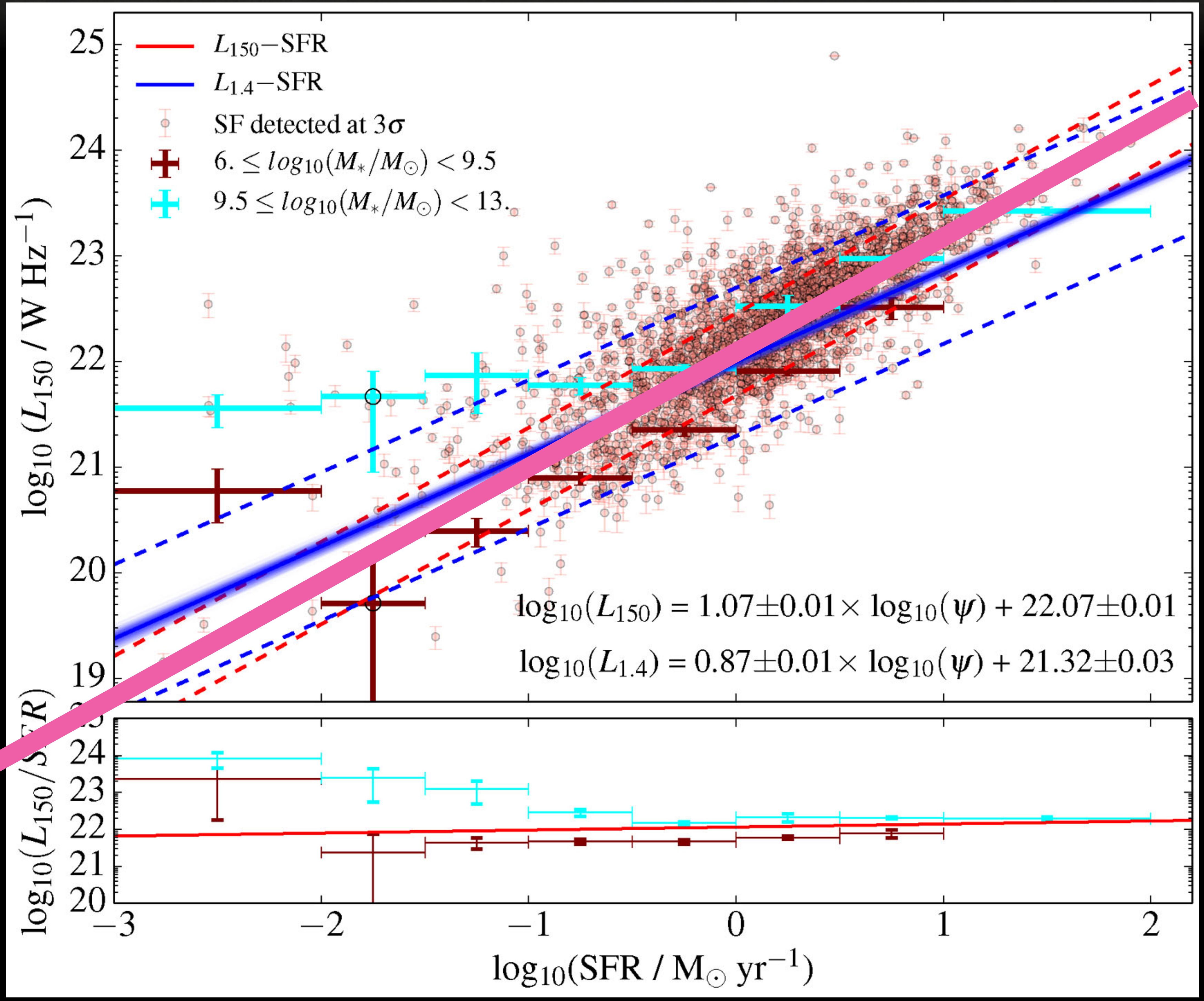
- Hybrid SFR
  - Leakage of Ly α photons from galaxies
  - Small effect (< 10 per cent)
- Radio SFR
  - Leakage of cosmic-ray electrons from galaxies
  - Unknown, but may be larger than 50 per cent

Phantom3Pix



Gürkan et al. (2018)

Herschel ATLAS



Gürkan et al. (2018)

Other examples:

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

super-linear radio-SFR relation

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

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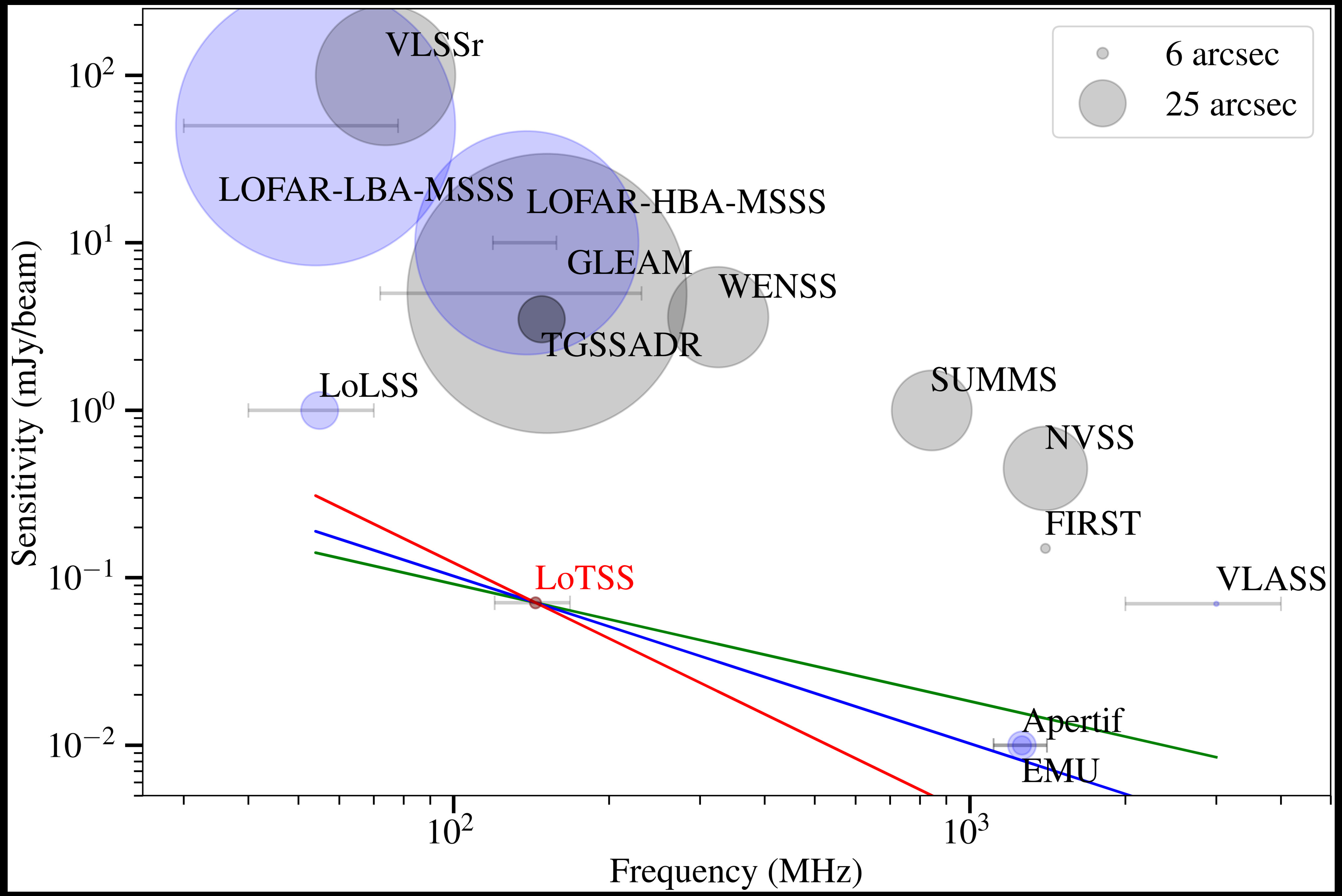
LOFAR Two-metre Sky Survey (LoTSS)

Data release 2

- 144 MHz effective frequency
- 6 and 20 arcsec resolution
- Sensitivity: 50–150 μJy beam^{-1}

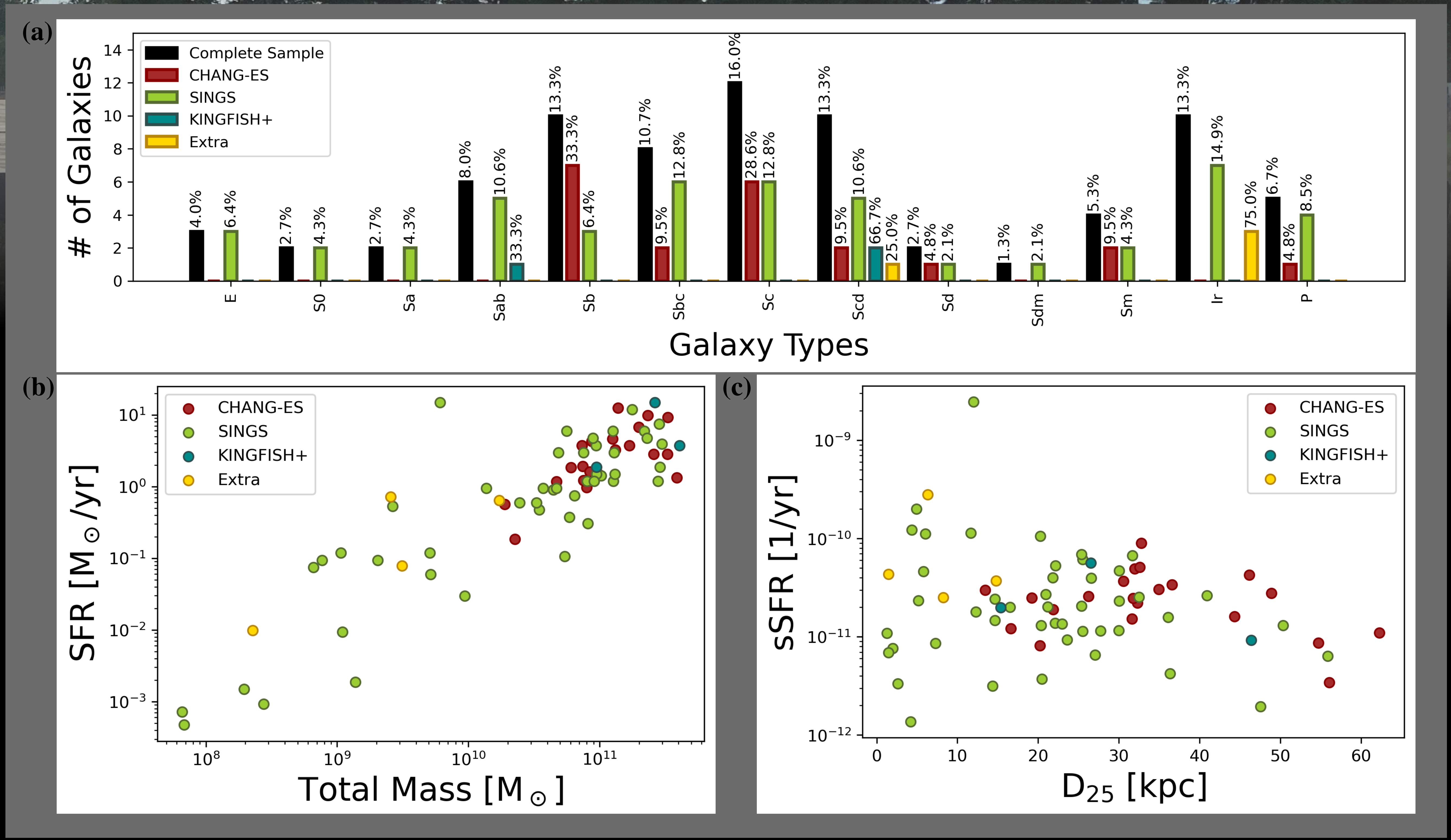


Shimwell et al. (2019)

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

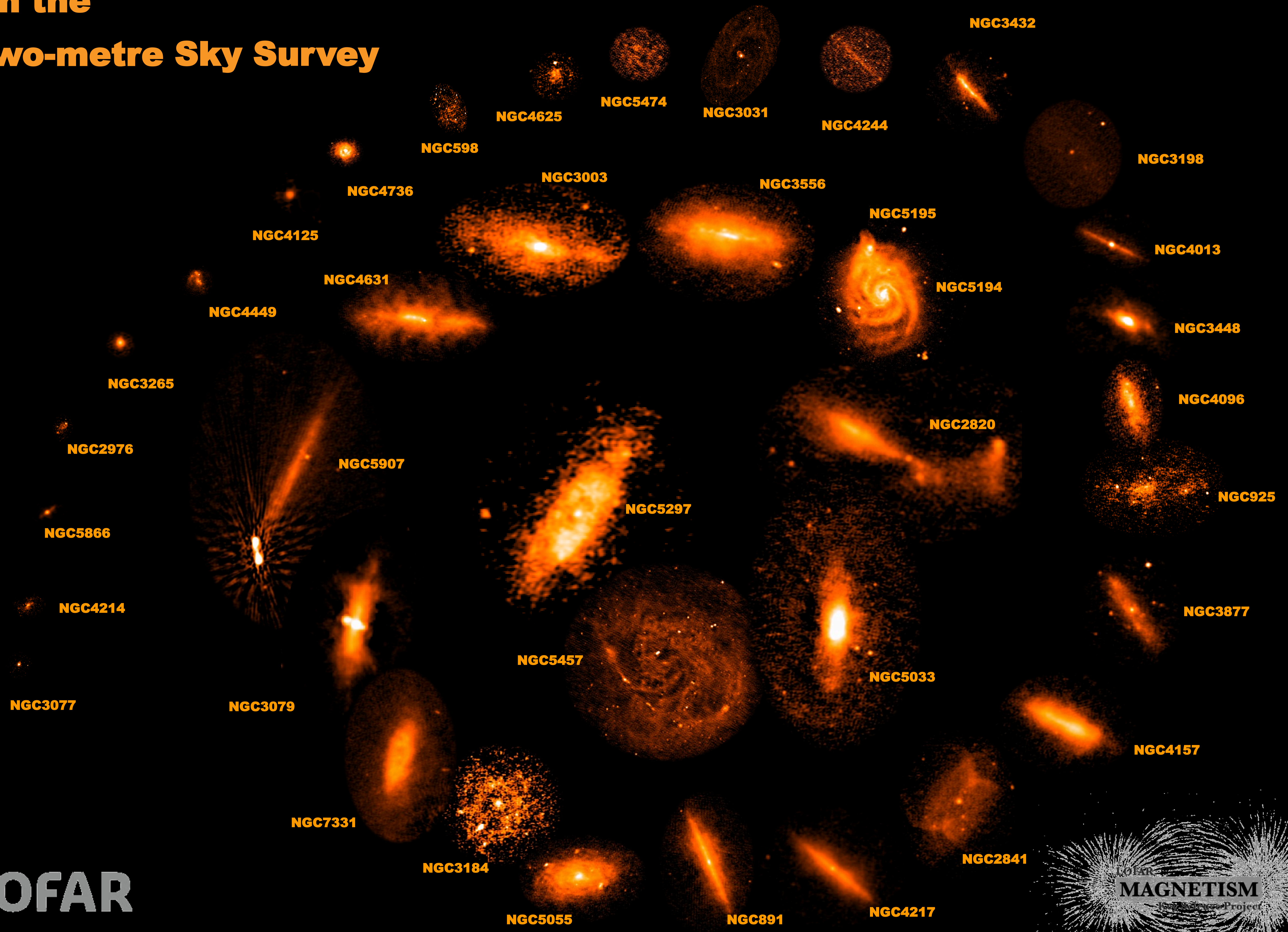
Low-frequency Array (LOFAR)

a European radio interferometer

- 46 Dutch stations
- > 10 international stations
- Low-band dipoles (30–85 MHz)
- High-band tiles (110–180 MHz)

van Haarlem et al. (2013)

Nearby Galaxies
in the
LOFAR Two-metre Sky Survey



DER FORSCHU

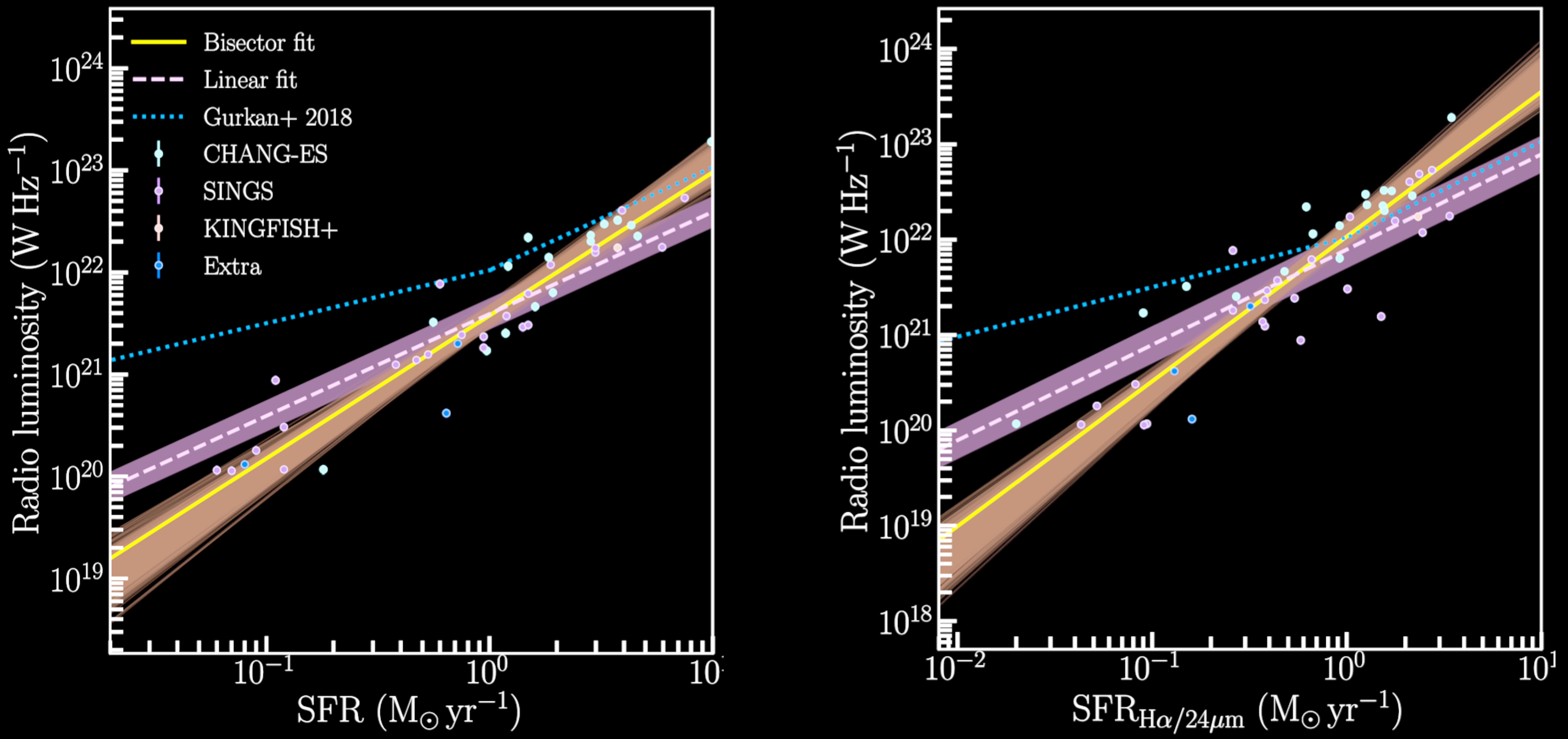
LOFAR

MAGNETISM

poster design by
F. Welzmüller

Radio–SFR relation for LOFAR

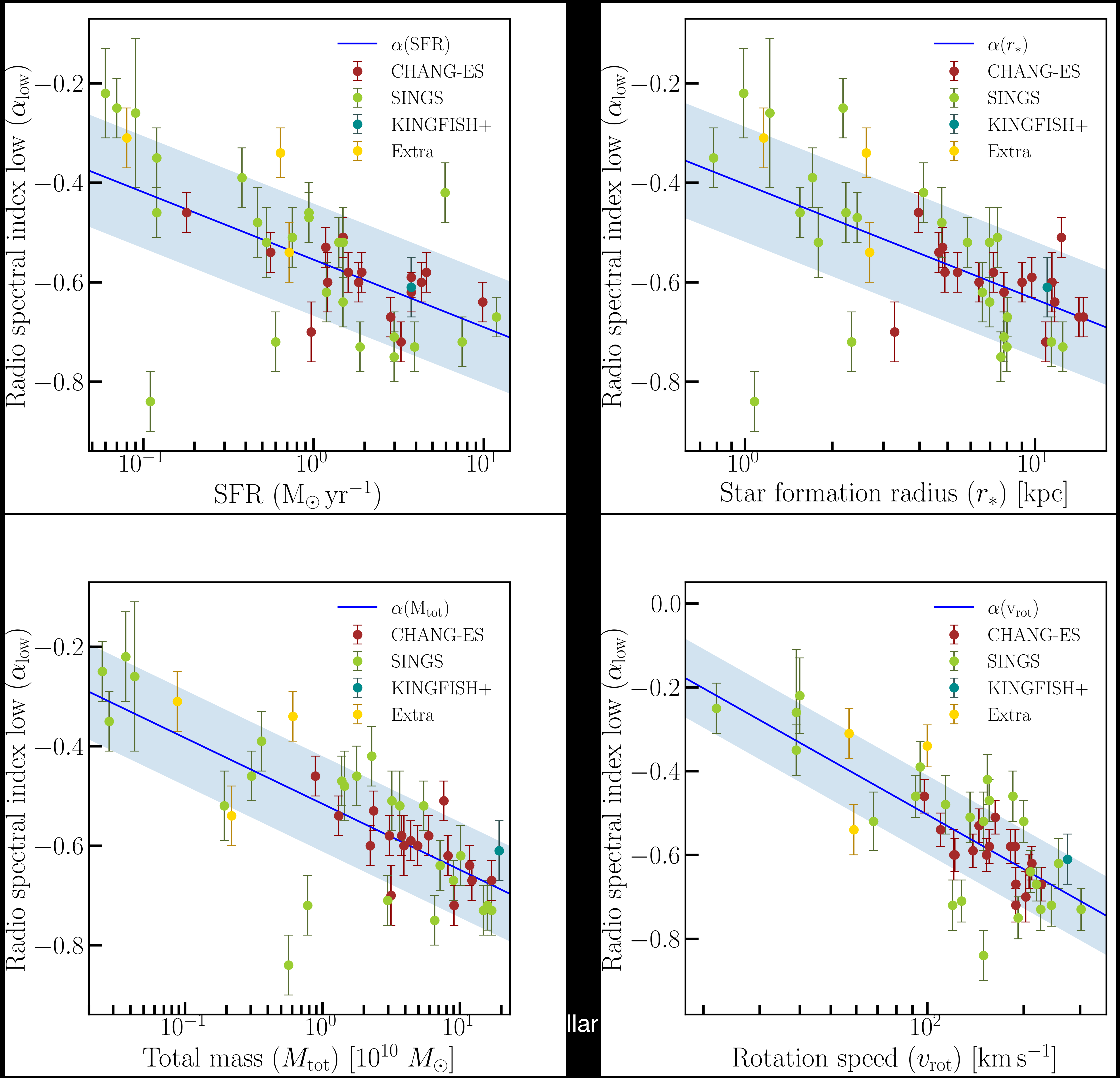
super–linear with $L_{144} \sim \mathrm{SFR}^{1.4\text{-}1.5}$



plot by A. Basu

SFR from total infrared

Mass ~ v^2 r



star-formation radius from radio

Rotation speed from HI line width

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Semi-calorimetric radio–SFR relation

Influence of cosmic-ray electron (CRE) transport

Radio luminosity: $L_\nu \propto \eta \mathrm{SFR}$

calorimetric efficiency

CR injection

How to estimate calorimetric efficiency?

Answer: compare loss and escape time-scales!

steep spectrum

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

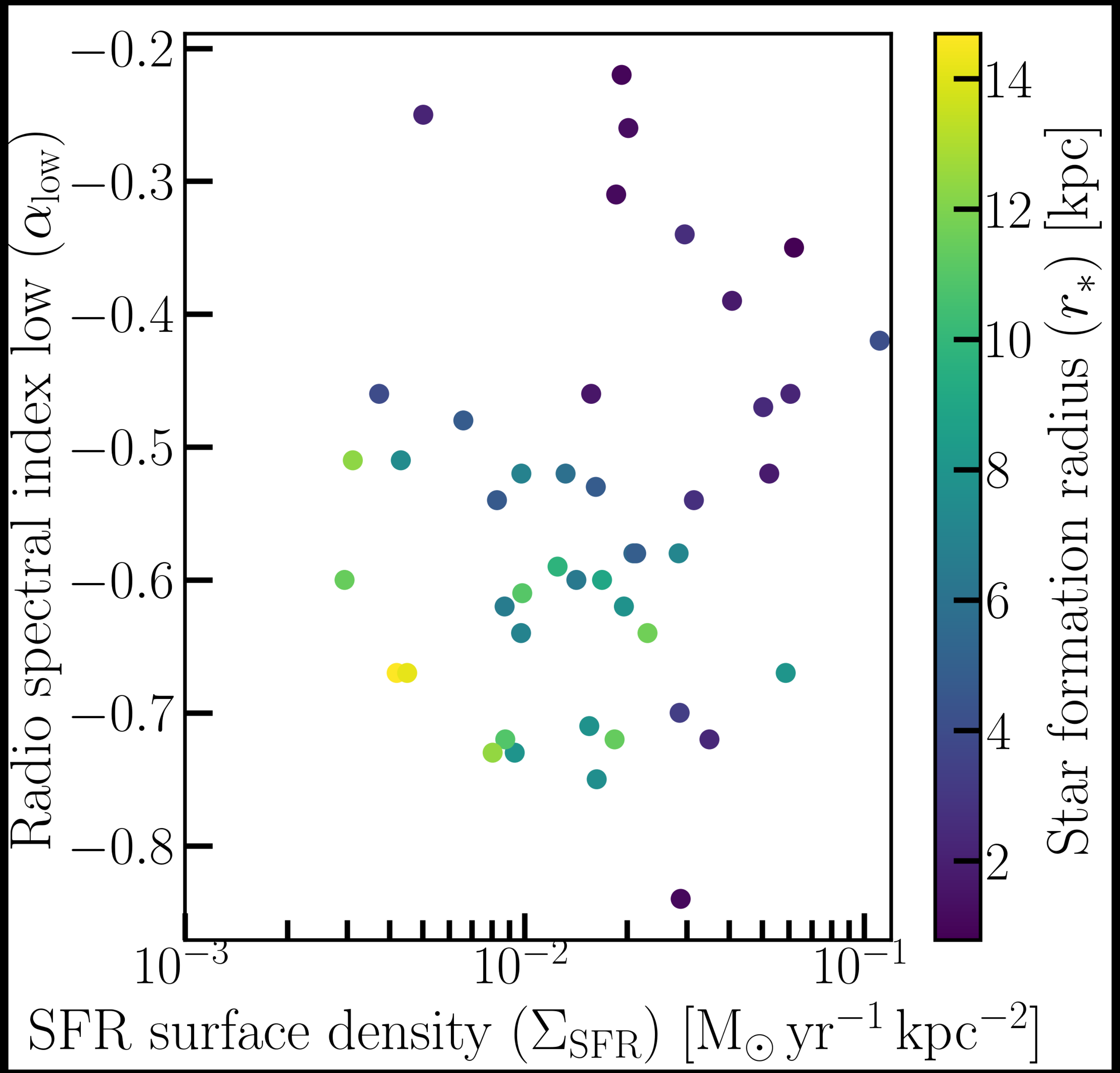
Semi calorimeter: $\eta = 0 \ldots 1$ $\alpha = -1.1 \ldots -0.6$

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

flat spectrum

Faster winds compensate stronger *B*-fields

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

radio spectral index

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

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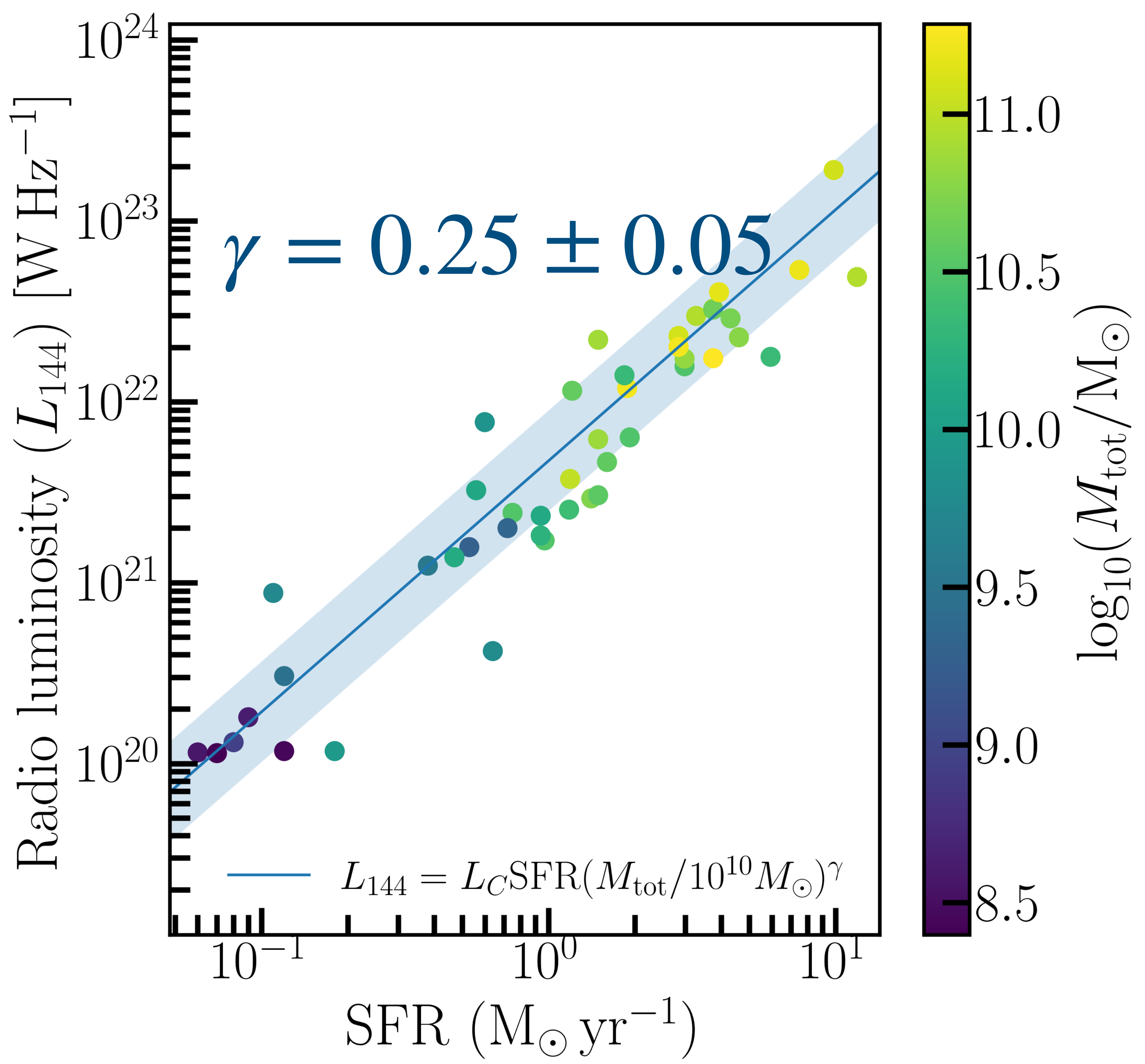
Mass dependency of radio–SFR relation

using the mass–size scaling relation



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

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

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

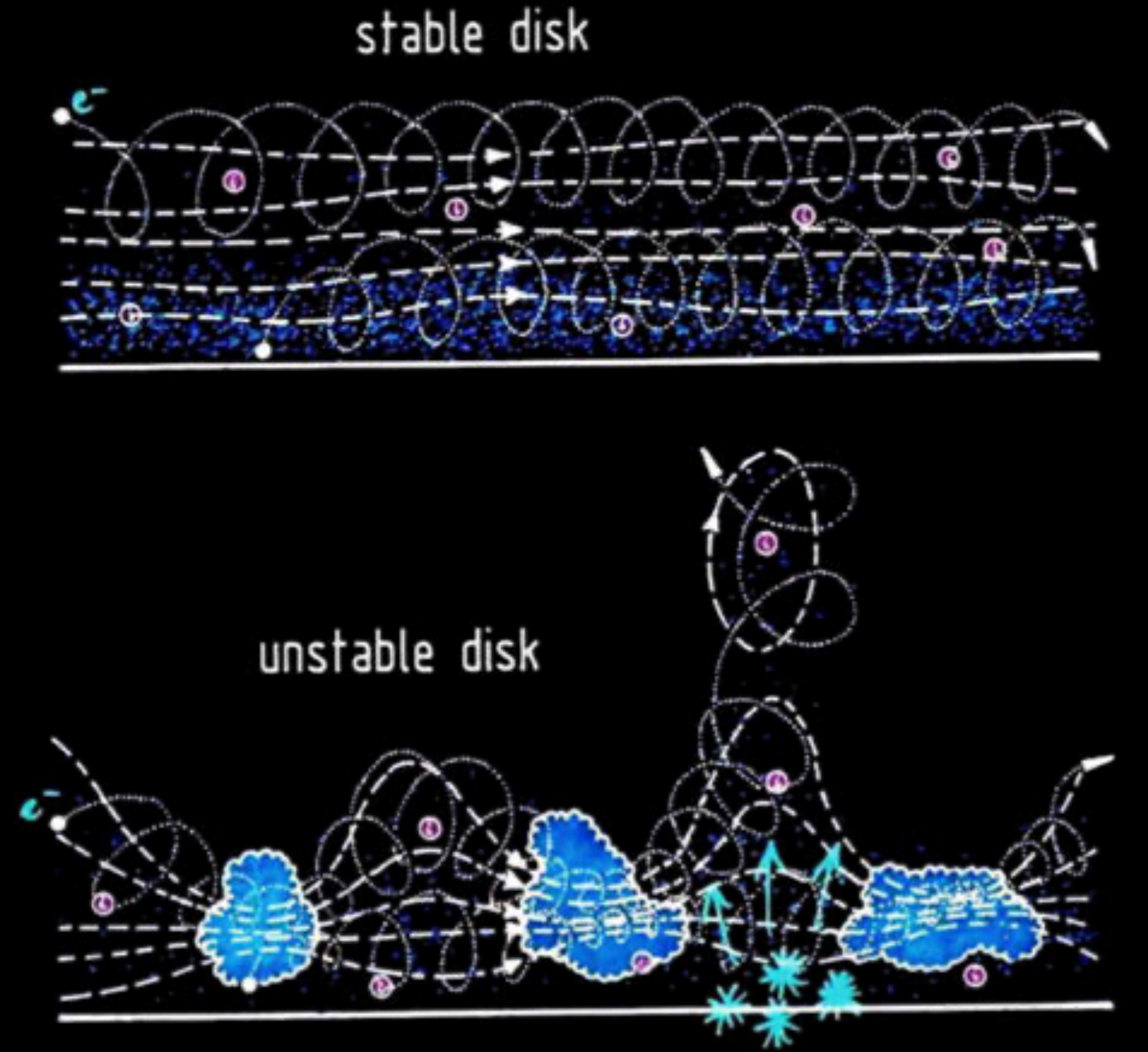
depends only on galaxy radius

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

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

What about magnetic fields?

Parker instability



Klein & Fletcher (2015)

$$B \propto \left(\frac{\Sigma_{\rm SFR}}{v}\right)^{1/2} \propto \Sigma_{\rm SFR}^{1/3}$$

Stability arguments suggest energy equipartition between cosmic rays and magnetic fields

$$\dot{E}_{\rm CR} t_{\rm esc} = \frac{B^2}{8\pi}\pi r_*^2 2h$$

cosmic ray injection

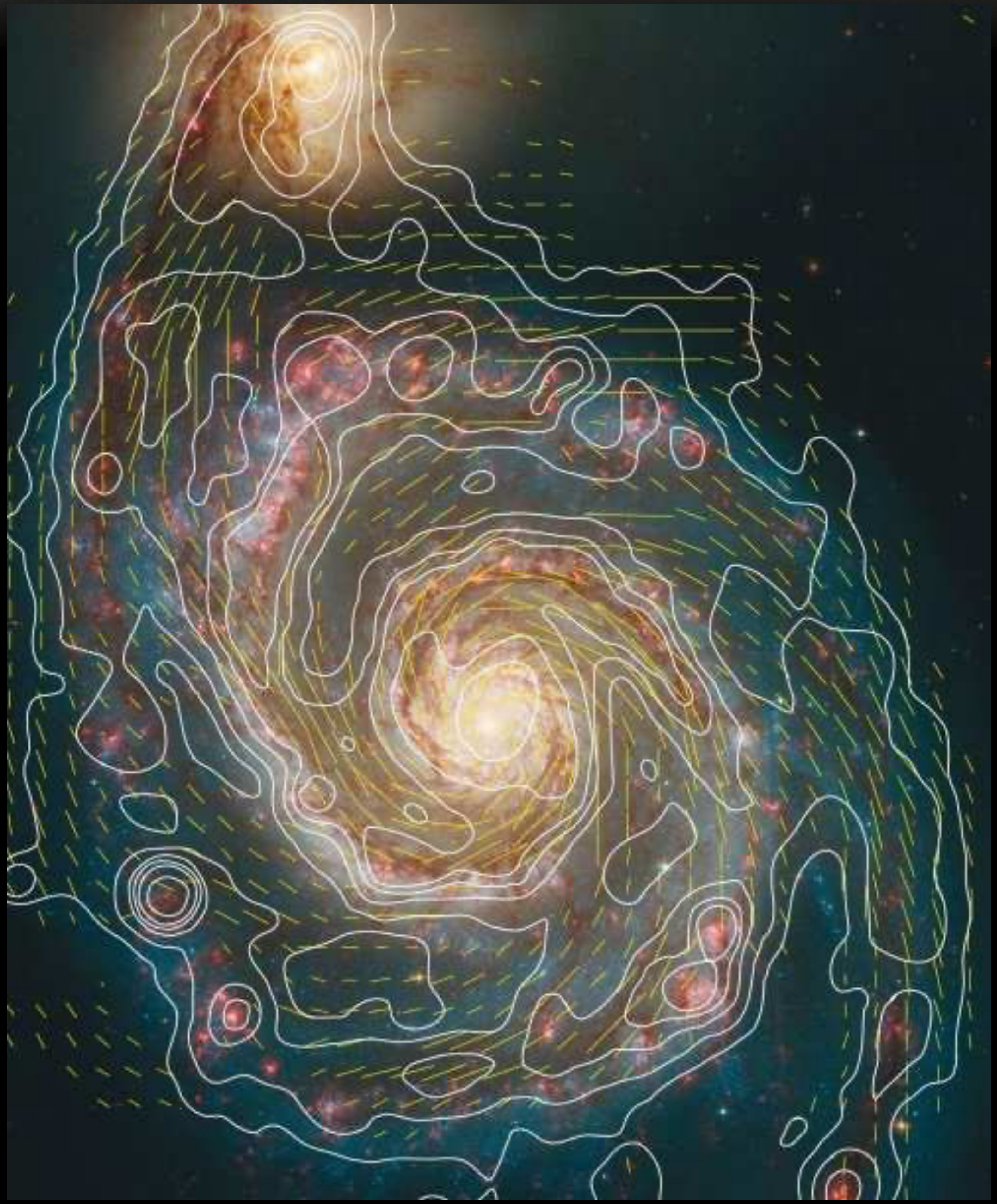
magnetic energy density

volume

Magnetic fields
and galaxy evolution

Lecture by Katja Ferrière

- Play an important role in galaxy evolution
- Regulate star formation
- Amplified by a dynamo either small or large-scale



Fletcher and Beck (2011)

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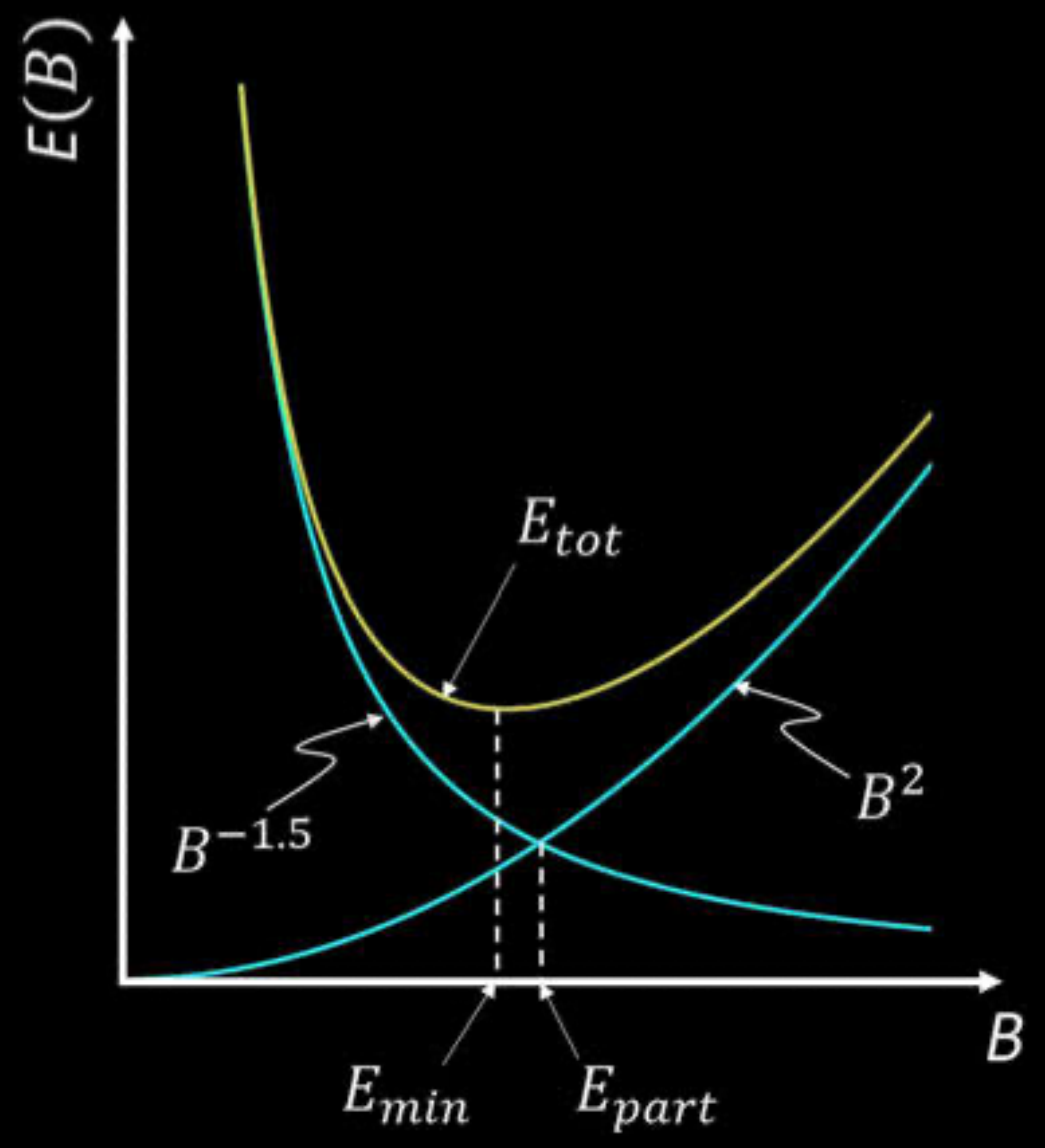
Magnetic field strength

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

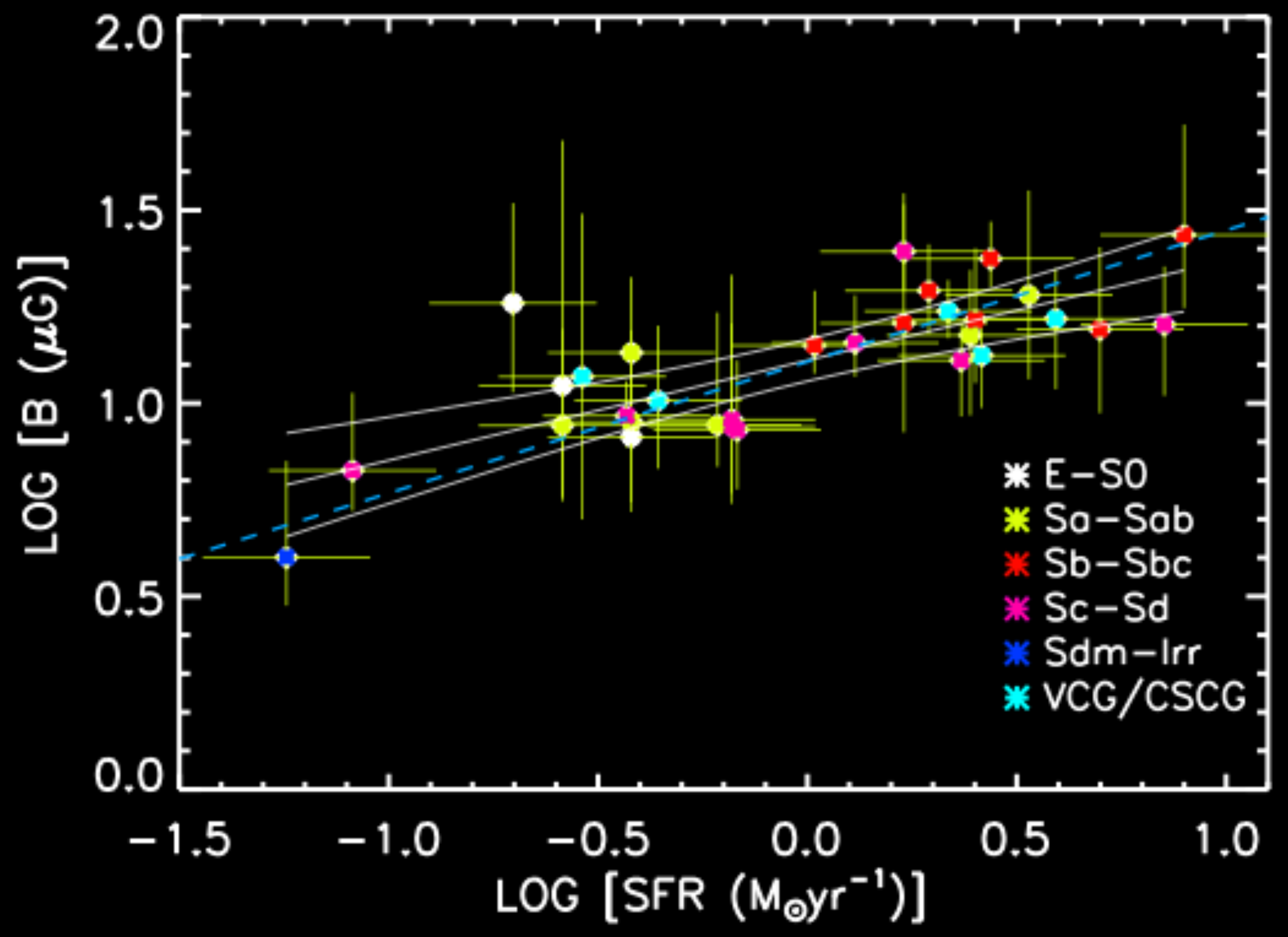


Klein & Fletcher (2015)

Magnetic field–SFR relation

Star-formation rate surface density

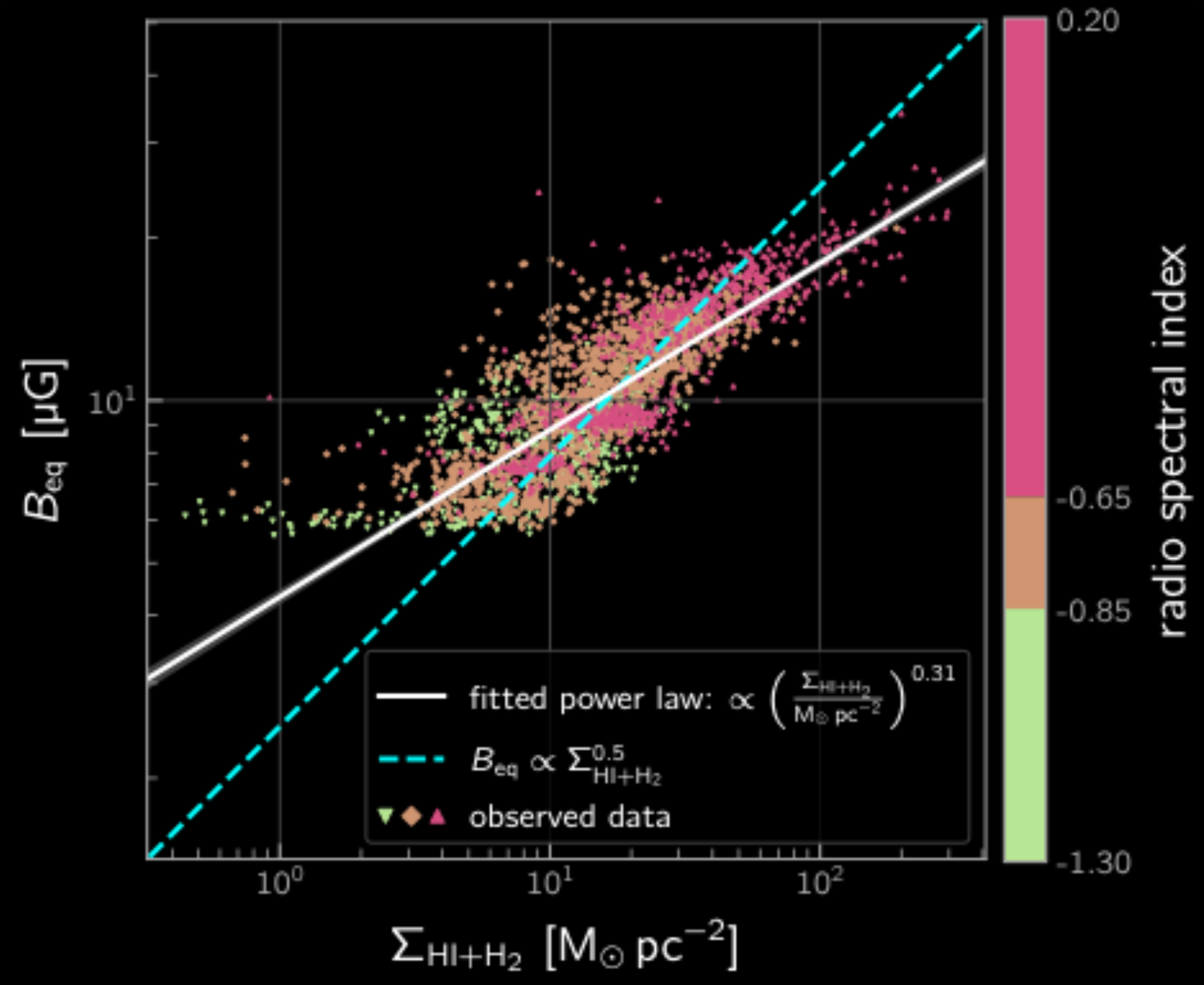
- Magnetic field strength rises with SFR
- *B* ~ $SFR^{0.34}$
- Consequence of the radio–SFR relation



Tabatabaei et al. (2017)

Magnetic field–gas relation

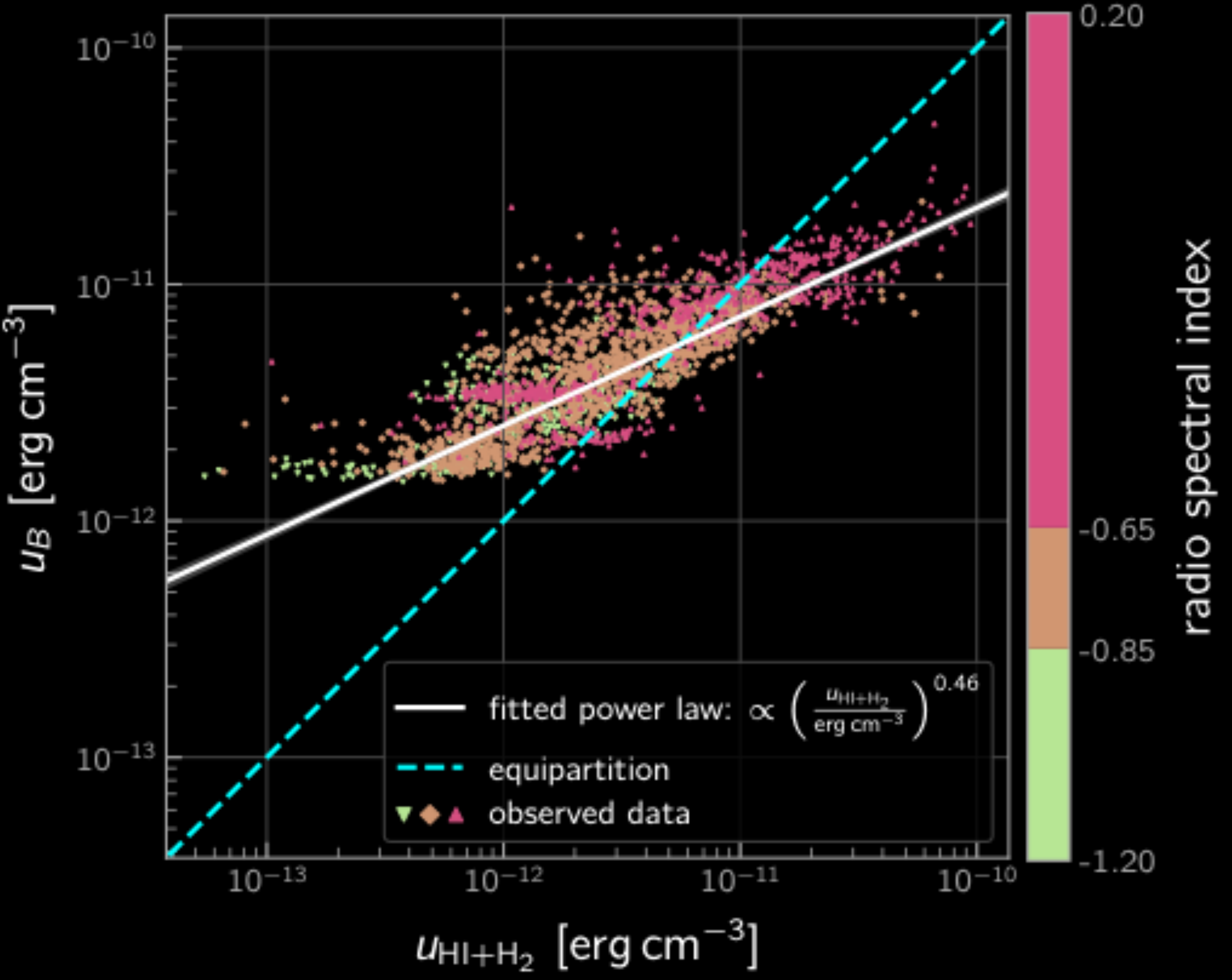
- B–$\Sigma_{gas}^{0.3}$
- Theory: B–$\Sigma_{gas}^{0.5}$
  - For a constant velocity dispersion
  - Equipartition with kinetic energy density



Heesen et al. (2023)

Magnetic energy density
and equipartition

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



Heesen et al. (2023)

What regulates magnetic fields in galaxies?

compression and amplification

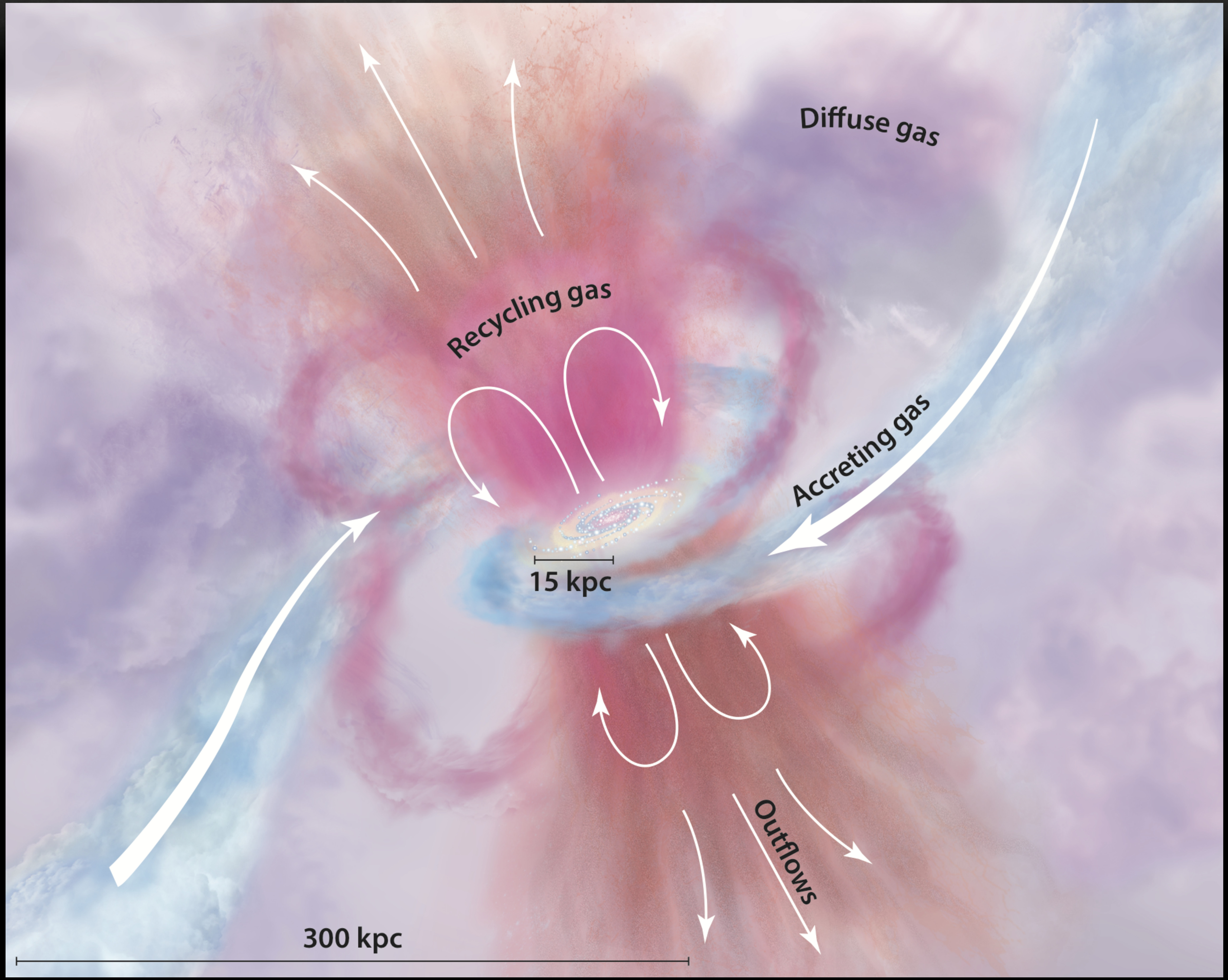
- Compression of B-fields
  - Isotropic compression: $\kappa = 2/3$
- Energy equipartition
  - Constant velocity dispersion: $\kappa = 1/2$

$$B \propto \rho^{\kappa}$$

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

Cosmic-ray transport
and galactic winds

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

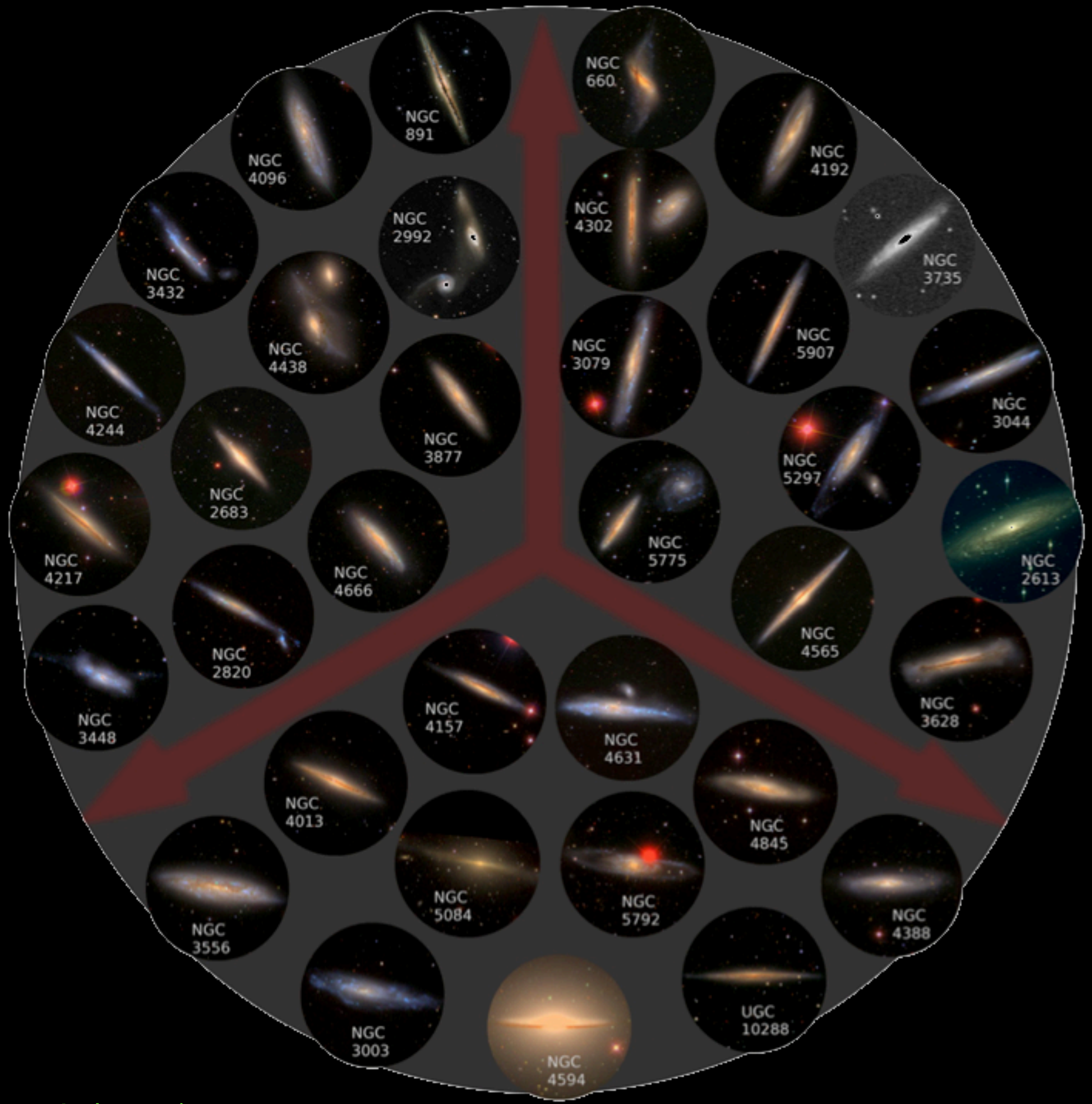


Tumliinson et al. (2017)

Radio continuum observations

LOFAR, JVLA, ATCA, Effelsberg, Parkes, WSRT

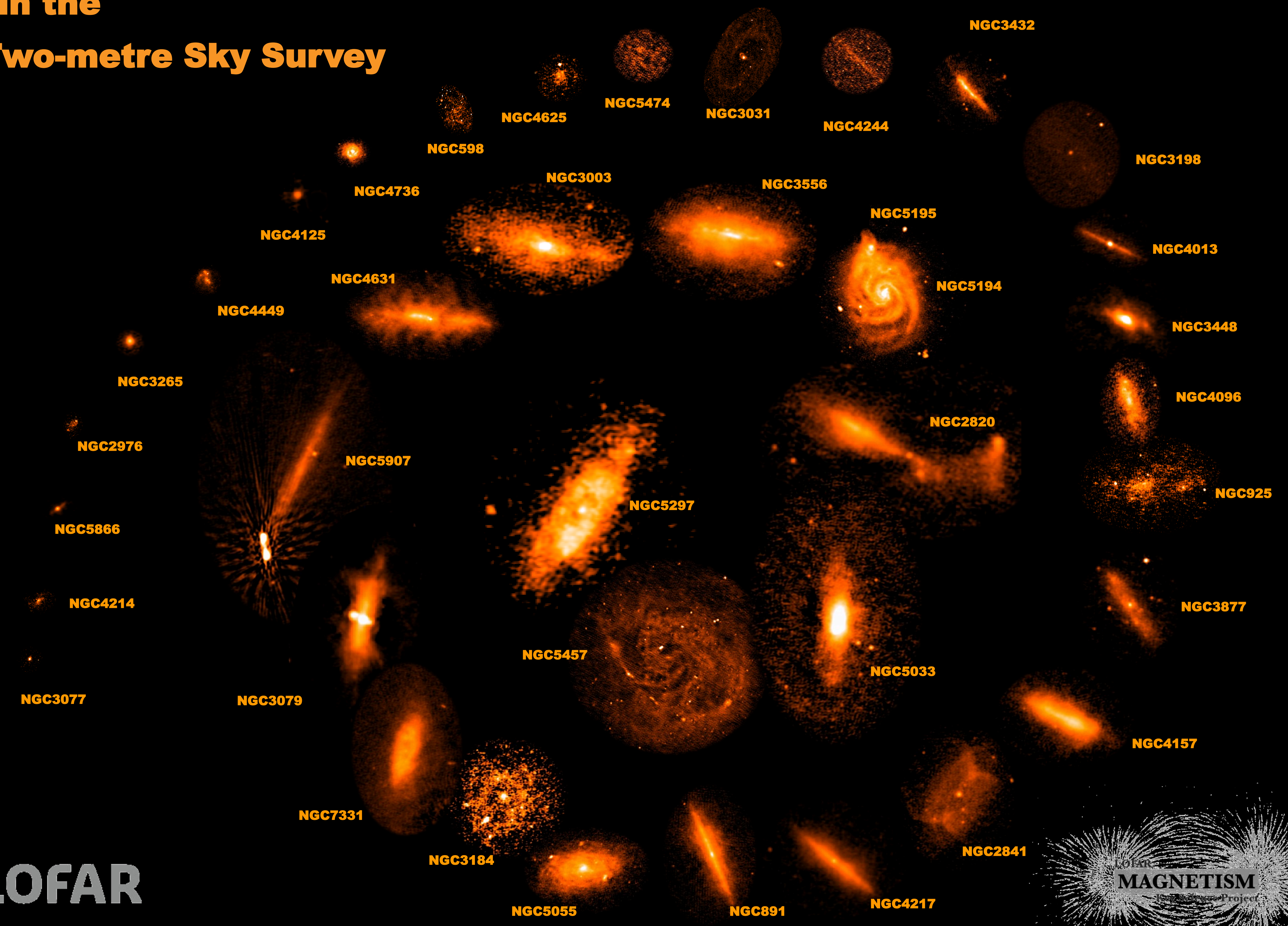
CHANG-ES
Continuum
HAlos in
Nearby
Galaxies
- an
EVLA
Survey



EVLA
Karl G. Jansky
(Expanded)
Very
Large
Array

Irwin et al. (2012)

Nearby Galaxies
in the
.OFAR Two-metre Sky Survey



LOFAR

MAGNETISM

F. Welzmüller

Gaseous haloes
FUV
UV-radion fro
O- and B-s
SF (100
Radio continuum
B-fields + CREs
SF (100 Myr)
O with ALMA
clear outflow of H2
or star formation
Hα
Ionized Hydroge
Star-formation (10
e)
ydrogen
or star formation

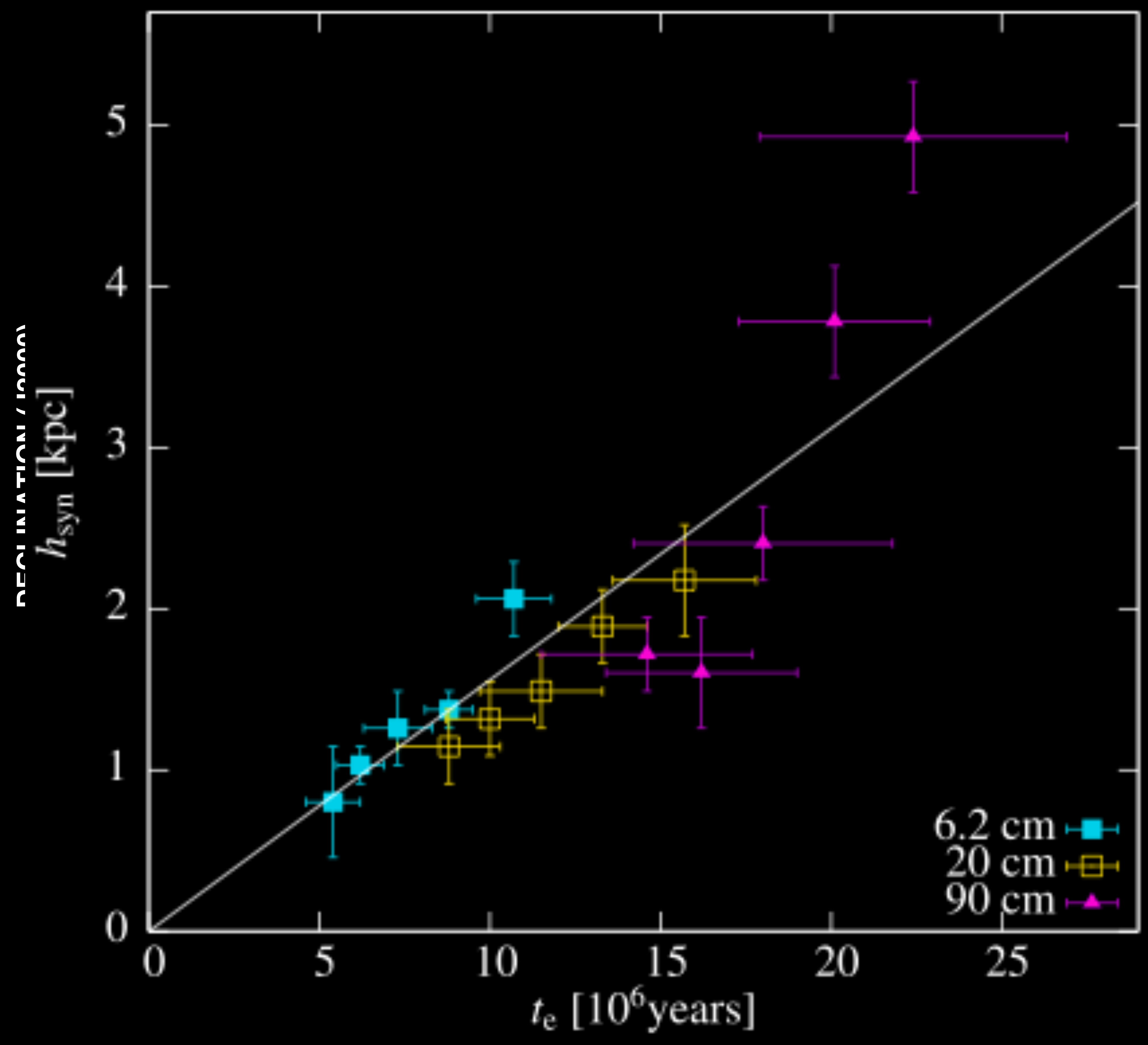
How to detect galactic winds

with radio haloes

- Diffusion dominated: no wind
- Advection dominated: wind

© NRAO

v = 300 km s^{-1}



Heesen et al. (2009)

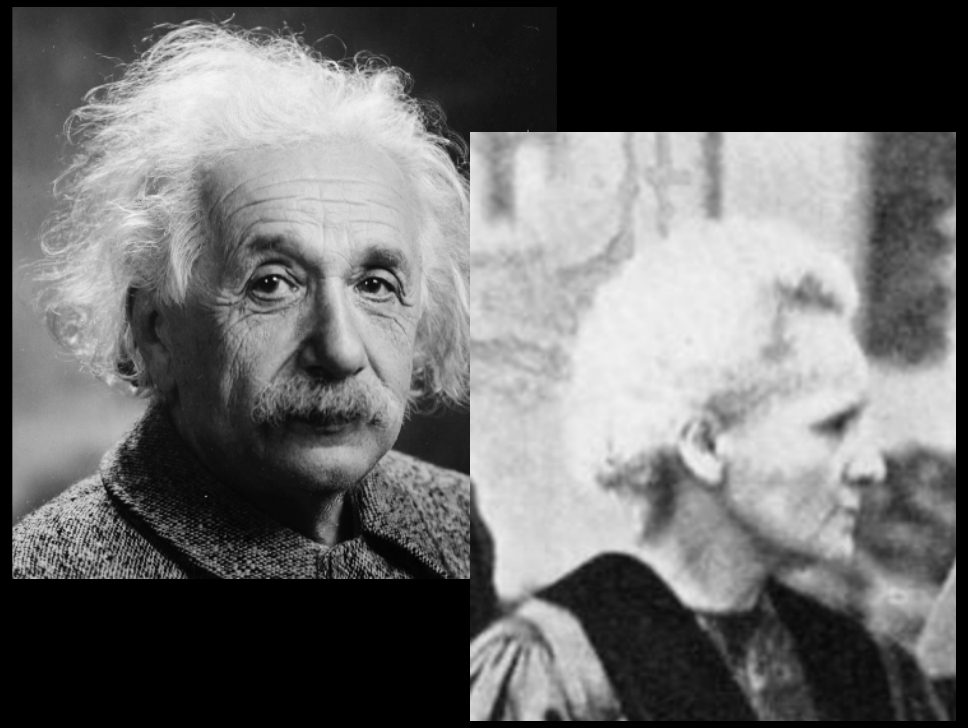
‘Young’ CRE

Ageing

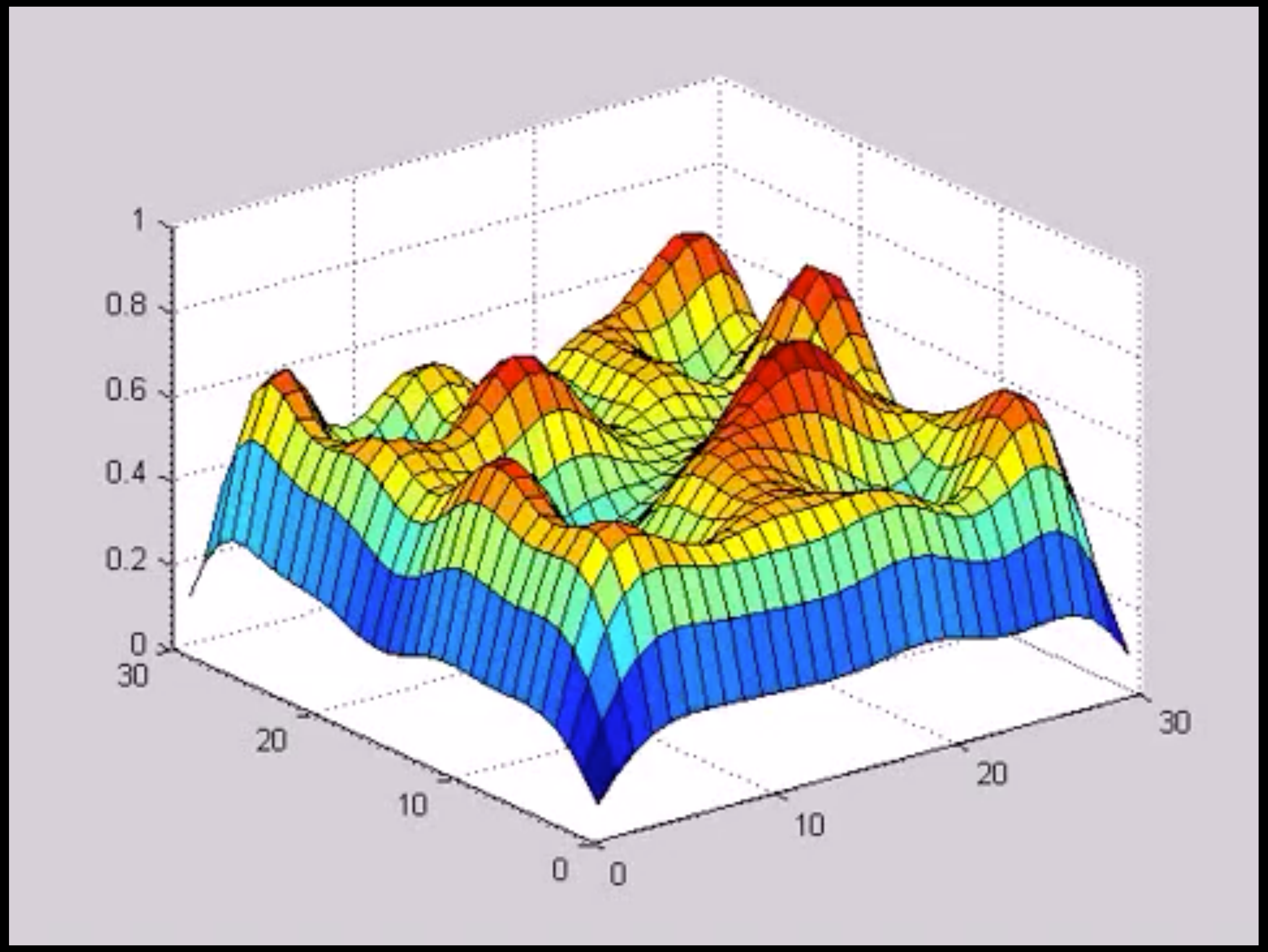
‘Middle-aged’ CRE

More ageing

‘Old’ CRE

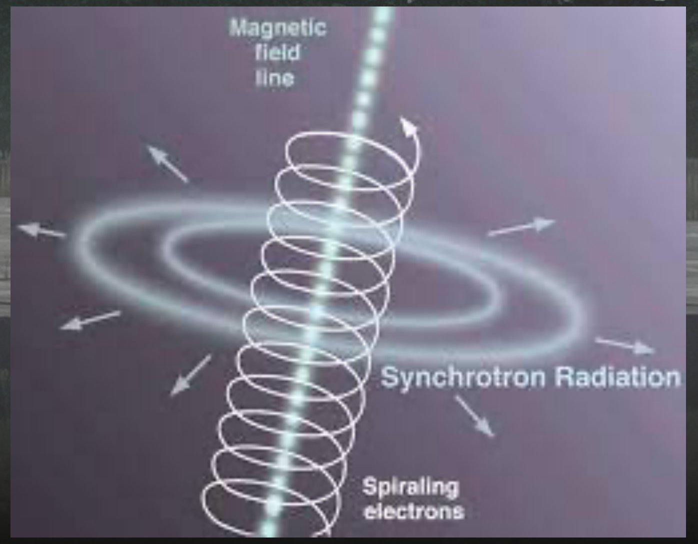


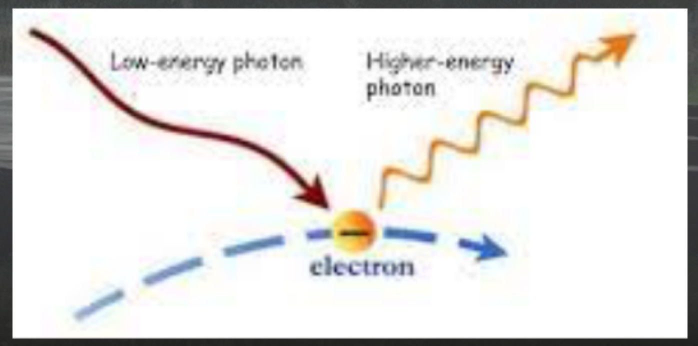
Diffusion



Steady-state solution to heat equation with sources

Steady state solution
with injection and losses

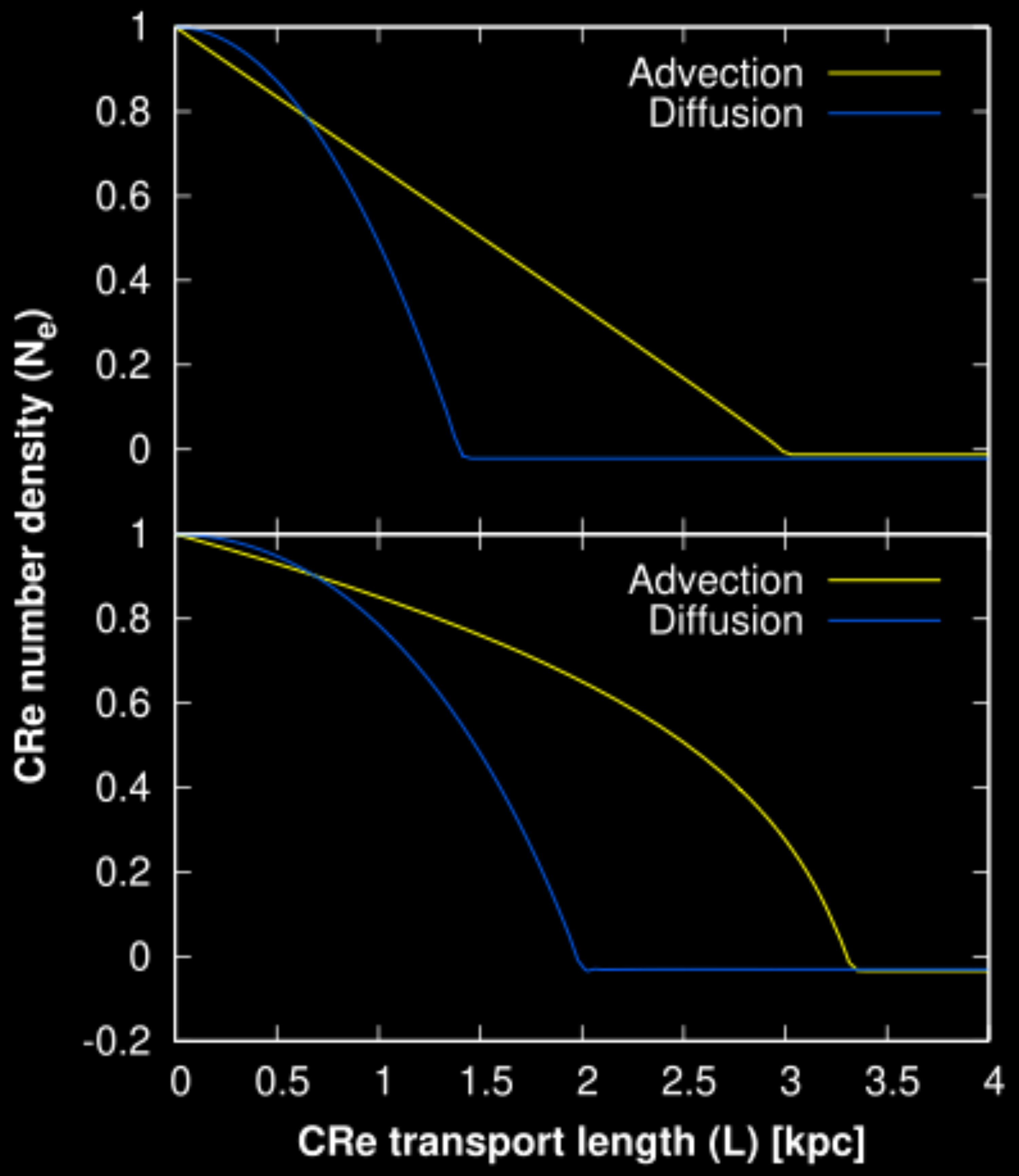




- Injection at z = 0; constant *B*-field
- Advection: linear decrease
- Diffusion: Gaussian decrease

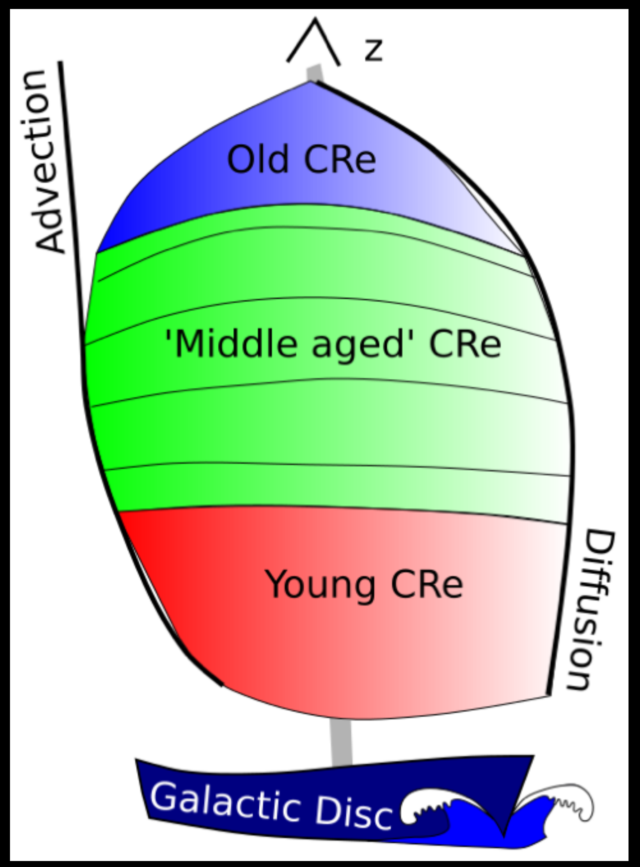
α = −1.0

α = −0.5



SPINNAKER

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

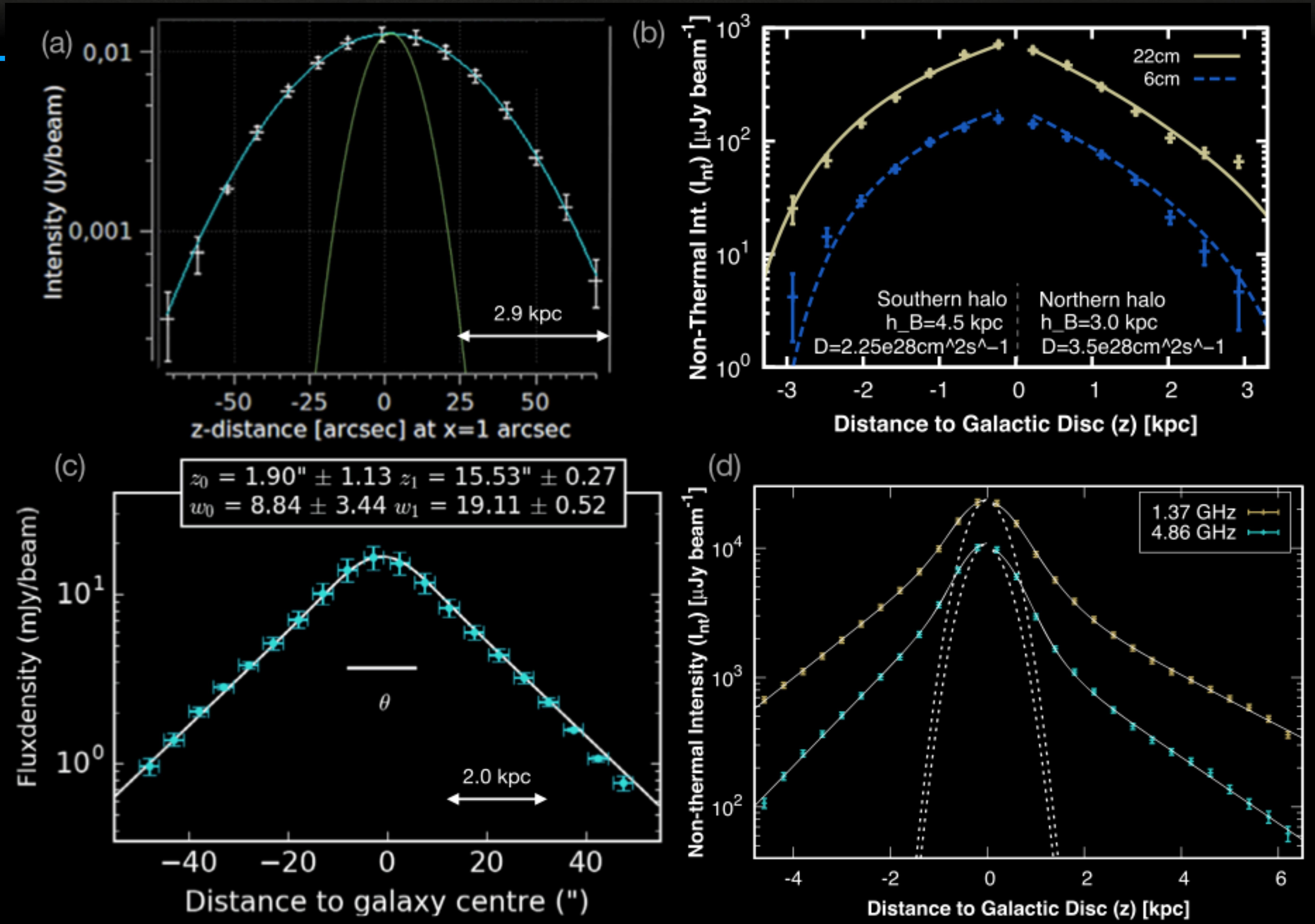


Diffusive and advective haloes

and their respective intensity profiles

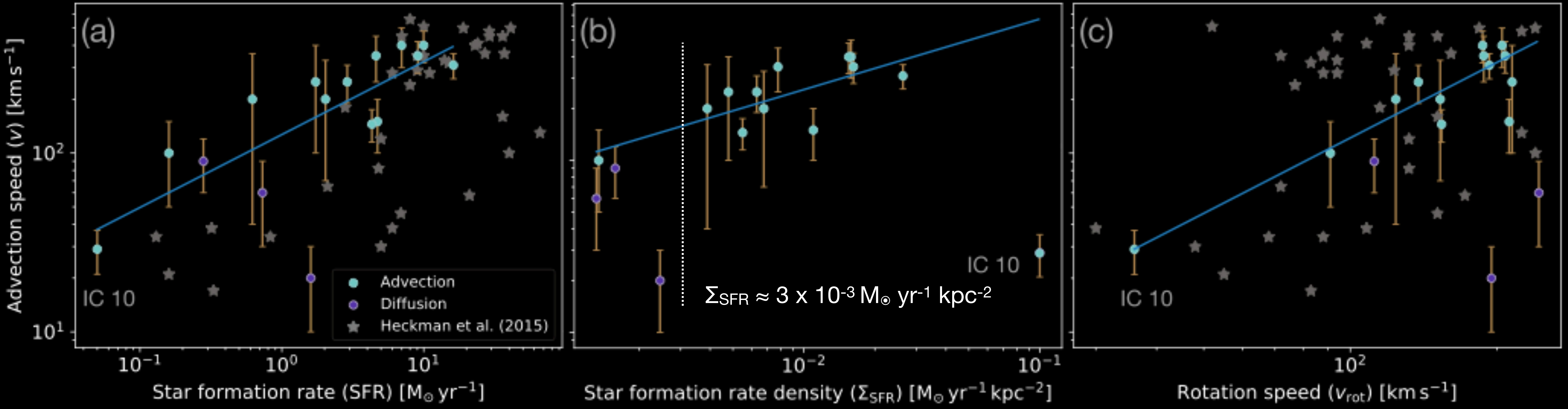
Diffusion

Advection



Advection speed scaling relations

Star-formation rate



Heesen (2021)

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

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

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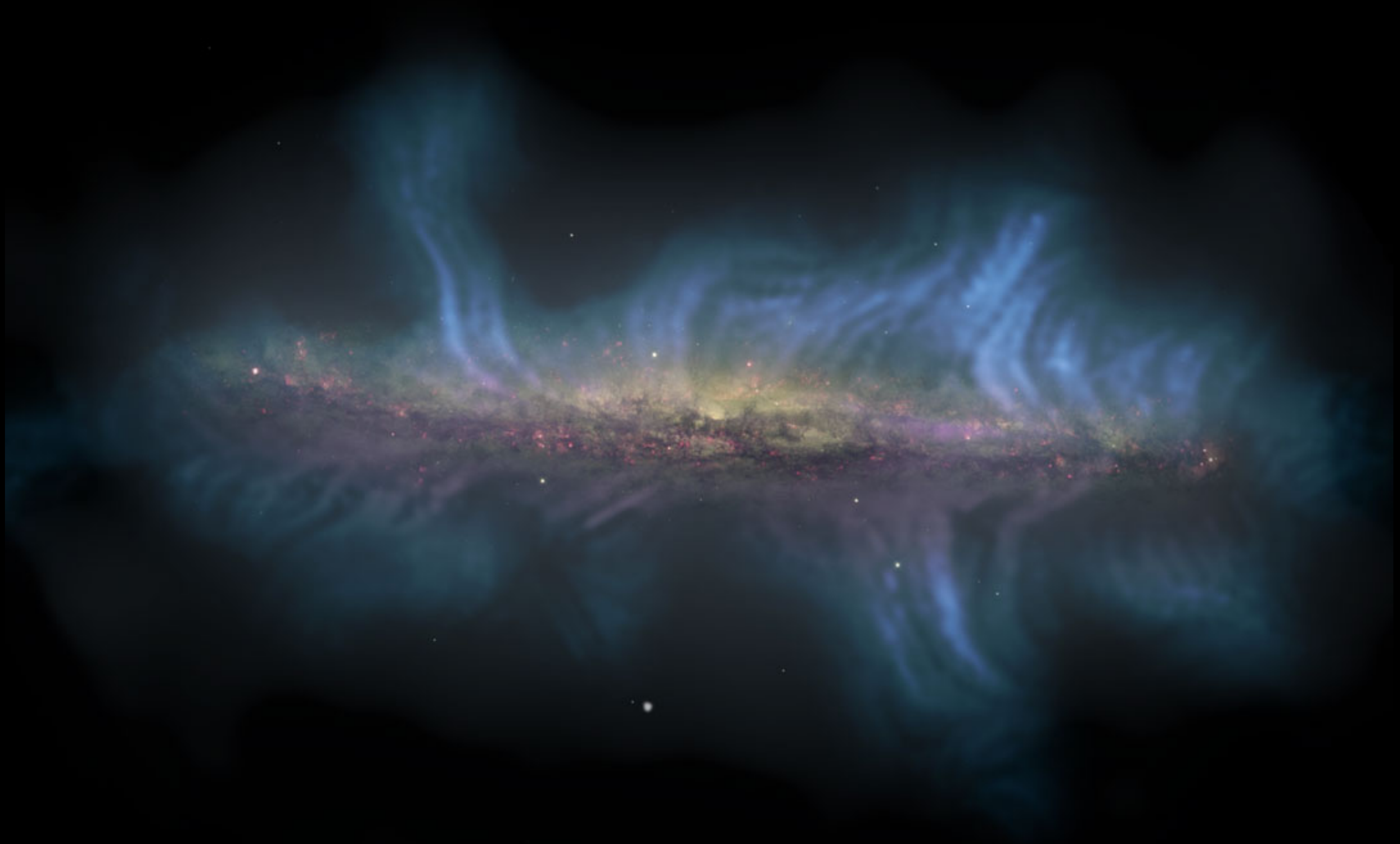
The role of cosmic rays in galactic winds

Relation with magnetic fields

- X-shaped magnetic fields in the halo
- Cosmic rays can stream along field lines
- Dynamic effect of magnetic field may be of importance too



Jayanne English and CHANG-ES consortium

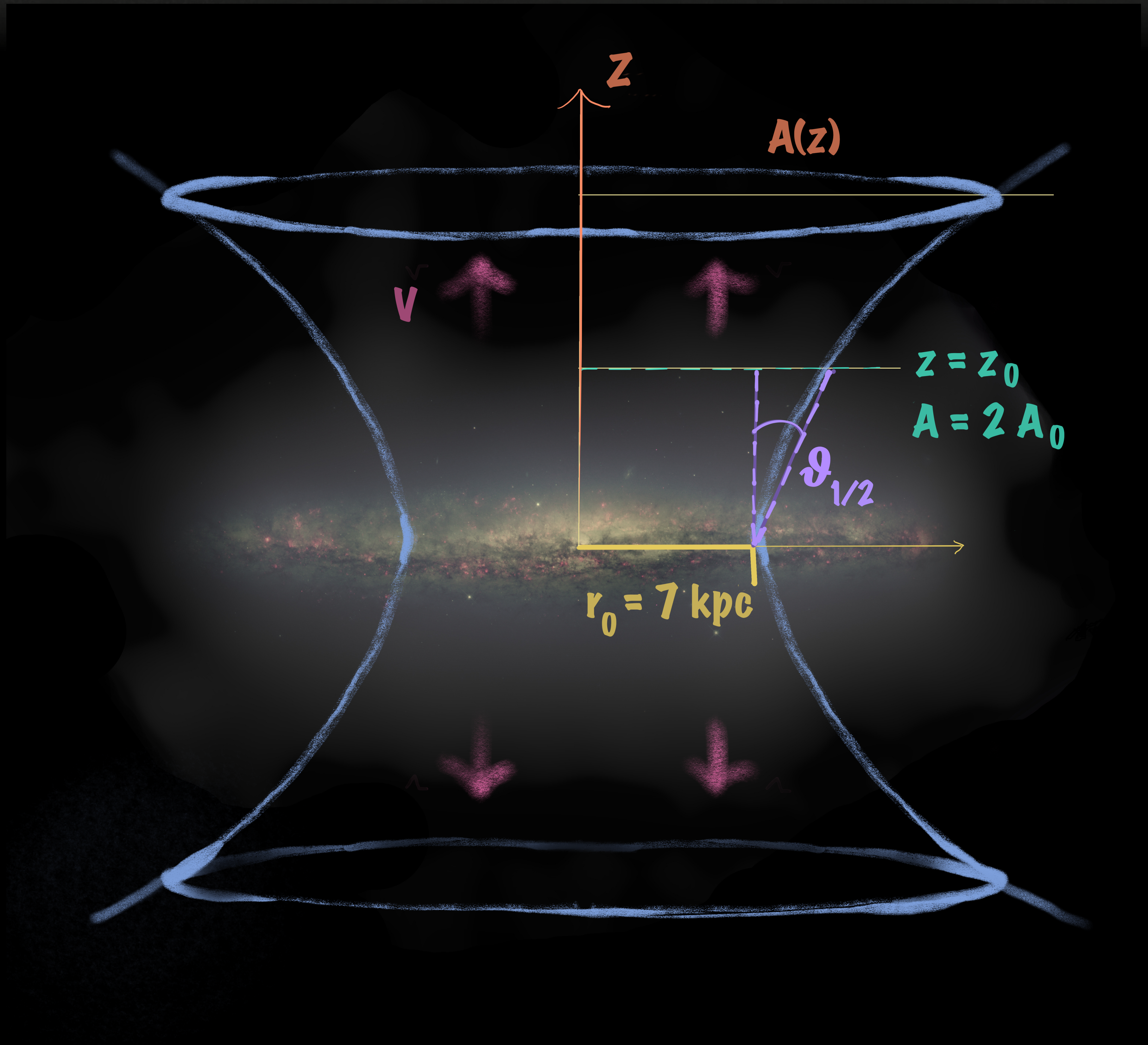
Data: NRAO, NASA, ESA
Composition: Jayanne English (U. Manitoba)

Stellar feedback-driven wind

Basic assumptions

- Flux tube geometry
- Used in previous cosmic ray-driven winds models
- Assume constant compound (gas + cosmic rays) sound speed

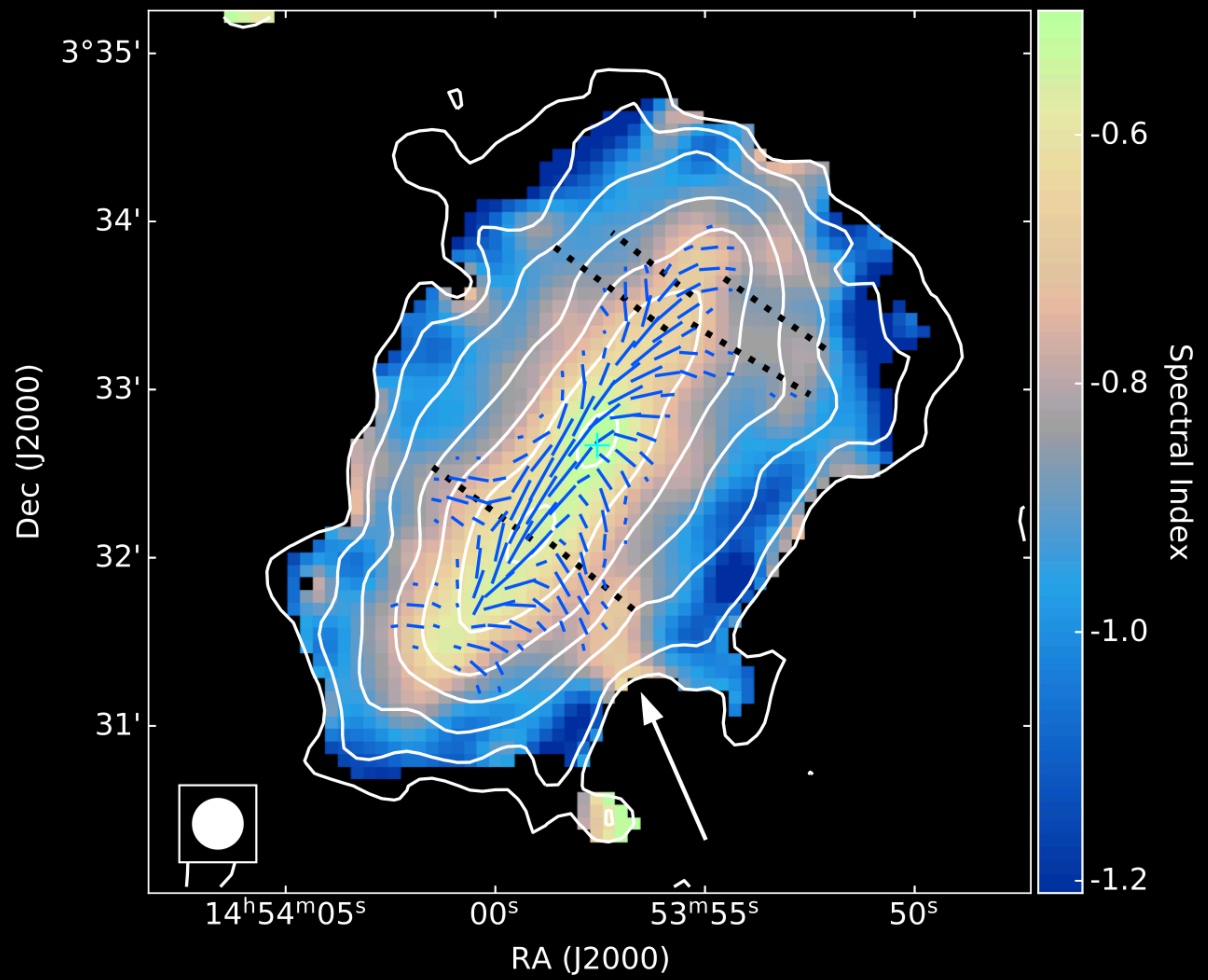
Momentum equation
$$\rho v \frac{\mathrm{d}v}{\mathrm{d}z} = -\frac{\mathrm{d}P}{\mathrm{d}z} - \rho g$$



Heald et al. (2022)

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



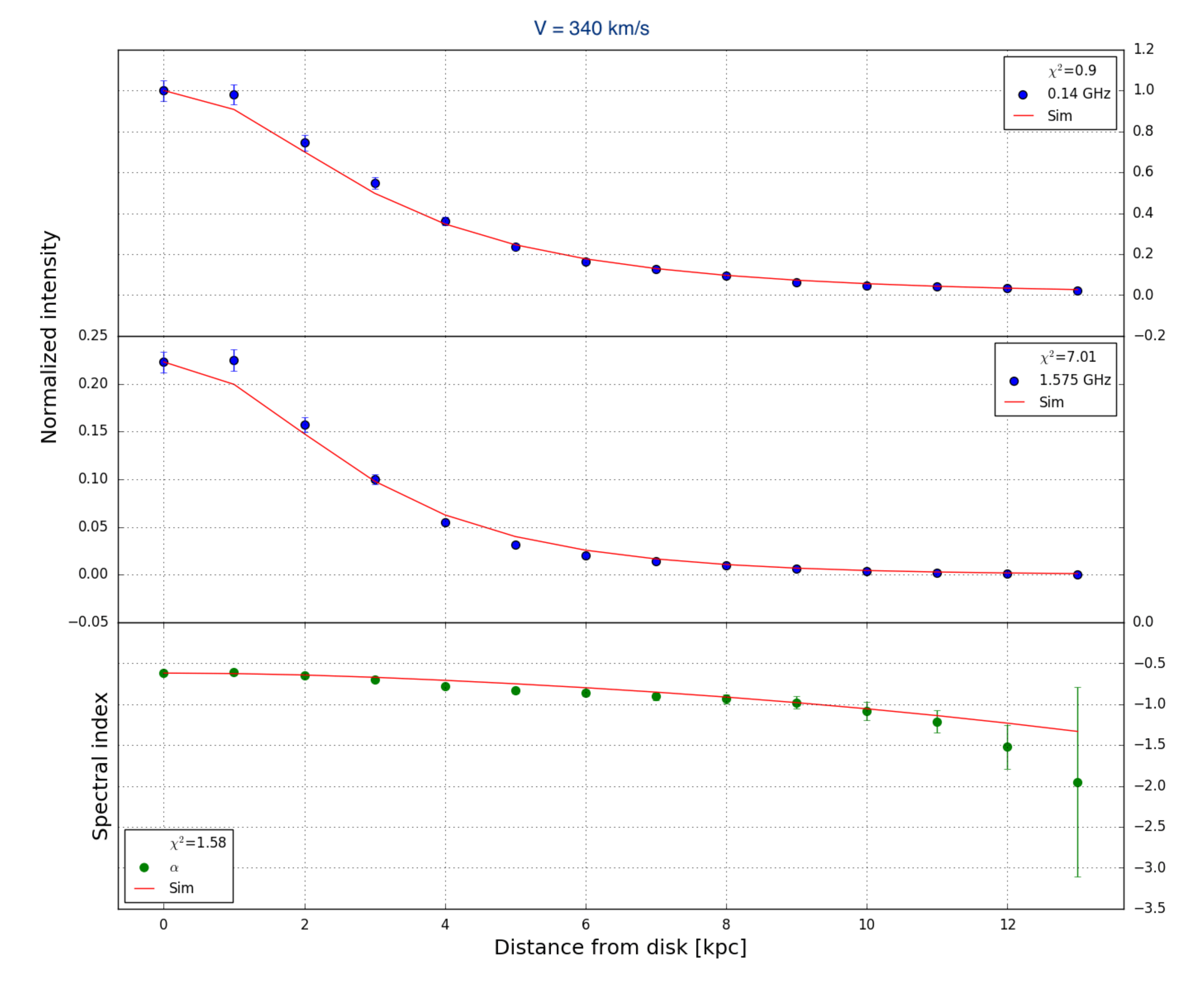
Heald et al. (2021)

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

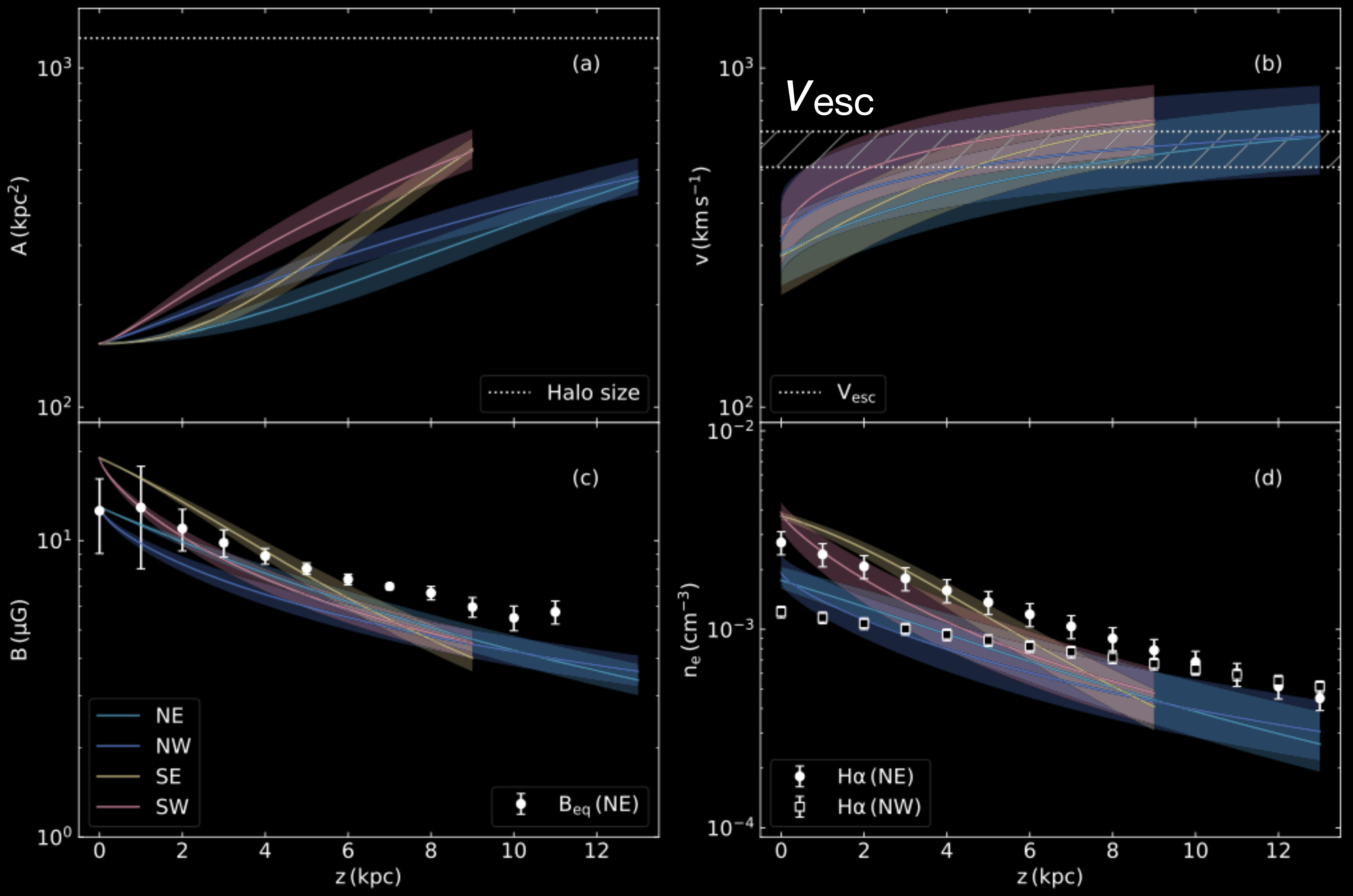


Stellar feedback-driven wind

Application to NGC 5775

Five more galaxies: paper by Michael Stein

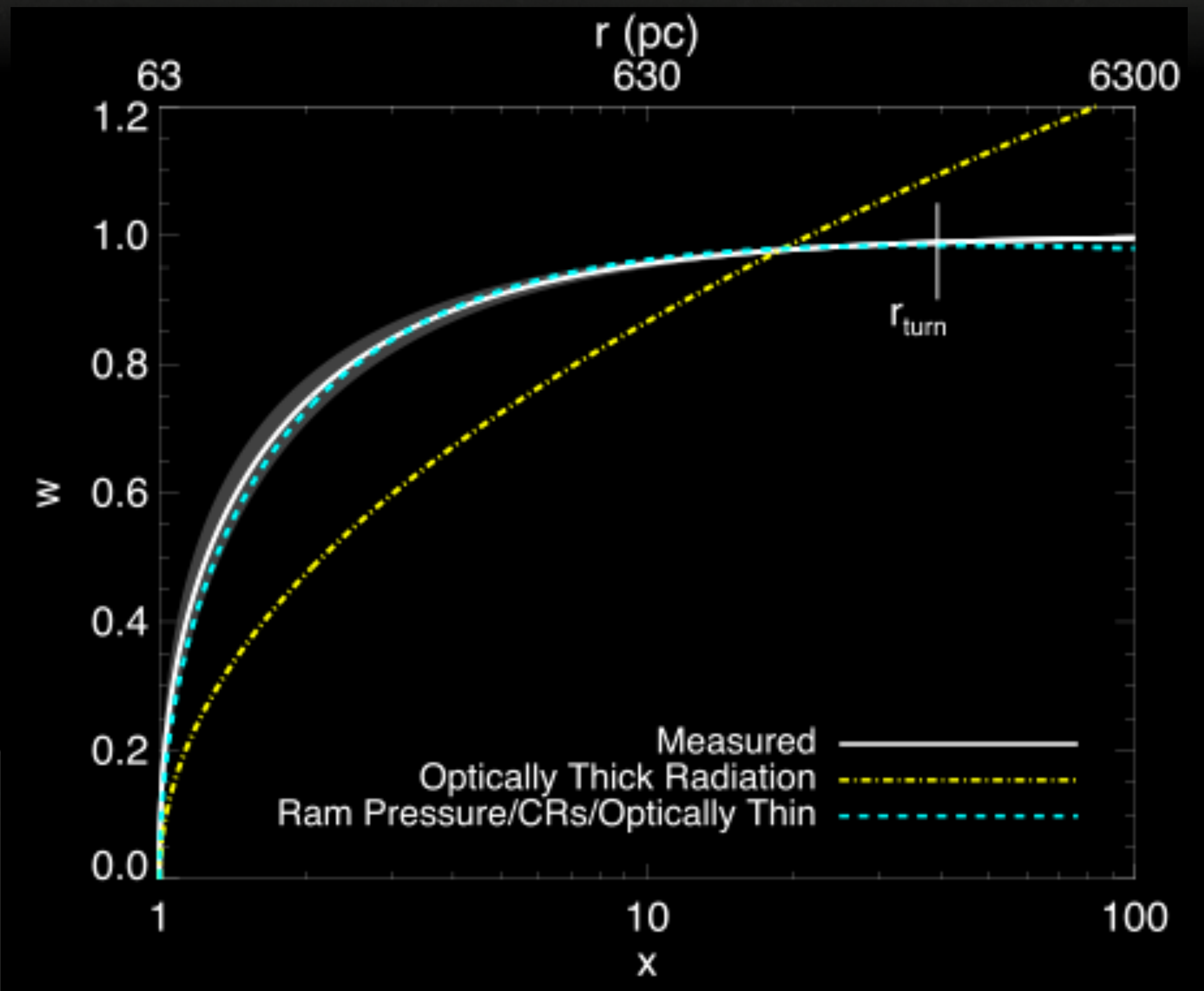
- Electron density of 10^{-3} cm^{-3}
- Wind velocity exceeds escape velocity
- Mass-loss rate of order $M_\odot$ yr^{-1}
- Mass-loading factor of order 1



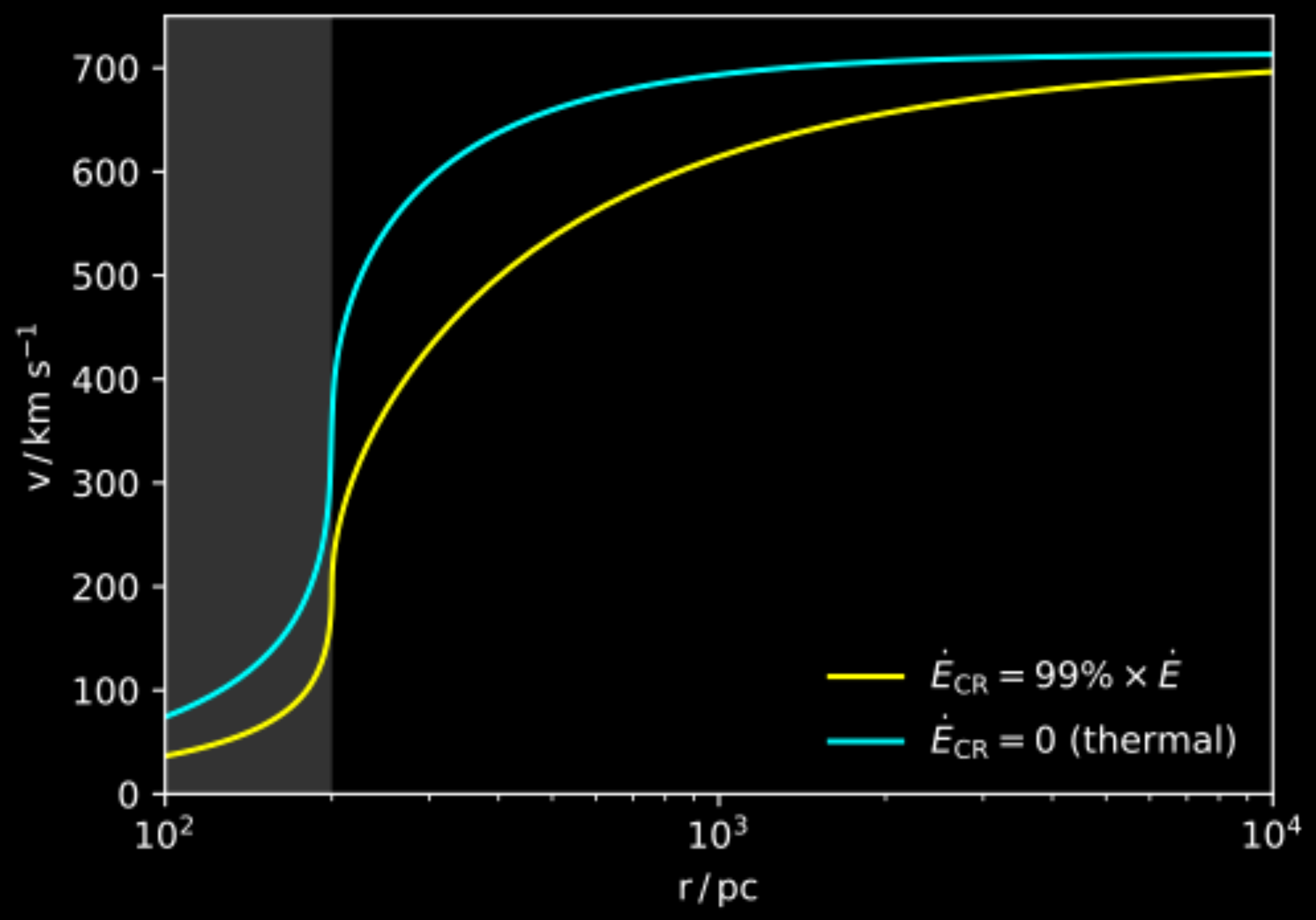
Wind velocity profile

Spectroscopic observations and theory

- Acceleration near the disc (< 1kpc) with a force ~r^{-2} (CRs, radiation pressure)
- Hydrodynamic wind models also have acceleration in 'driver' region



Chisholm et al. (2016)



Yu et al. (2020)

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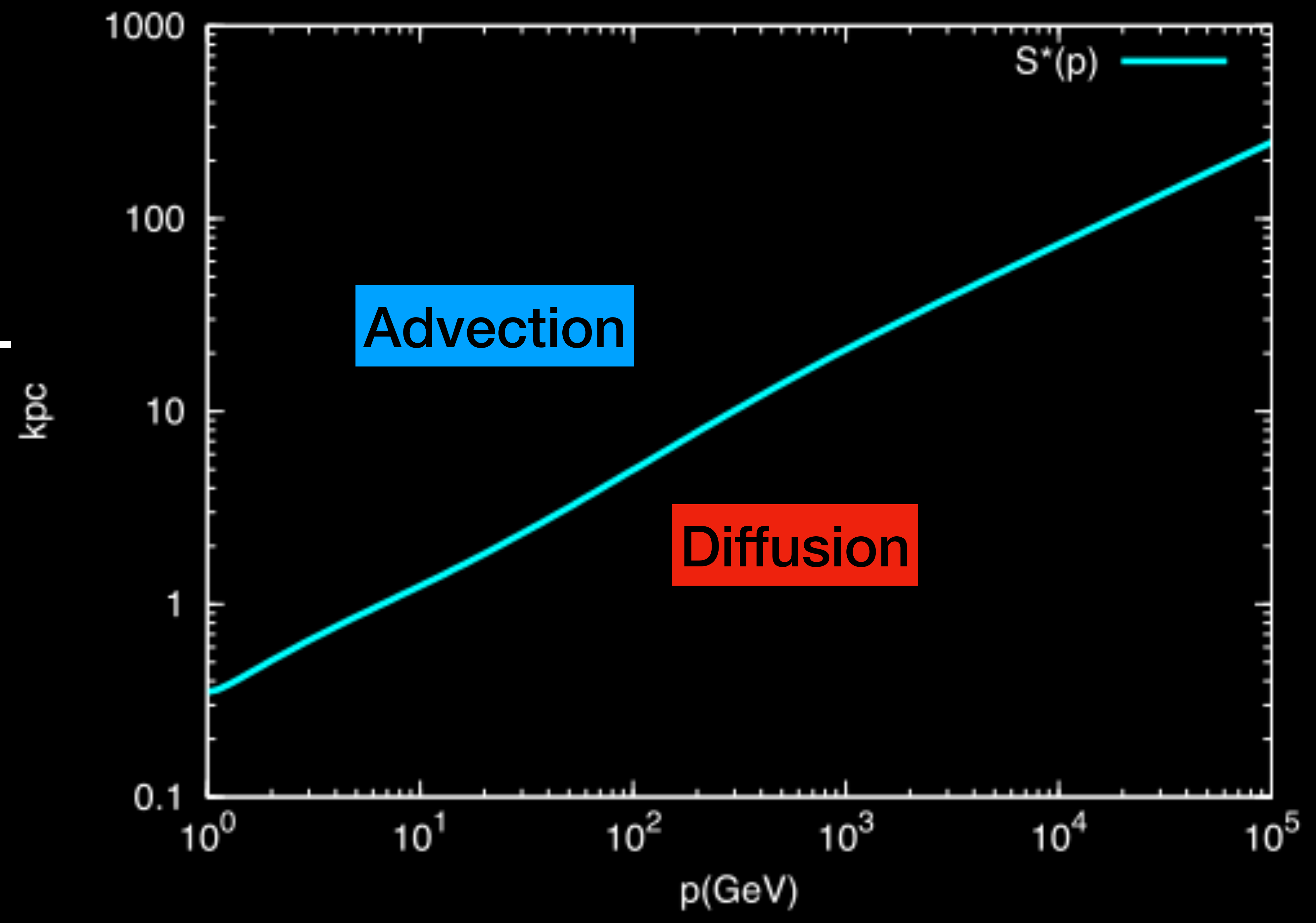
Diffusion-to-advection transition

Gaseous discs may be diffusive

- Diffusion-to-advection transition
- $z_\star = 1.2\ \mathrm{kpc} \frac{\mathrm{D}}{10^{28}\ \mathrm{cm^2\,s^{-1}}} \frac{\mathrm{v}}{100\ \mathrm{km\,s^{-1}}}$
- There is only a transition if there is a wind
- Diffusion-dominated haloes have no transition

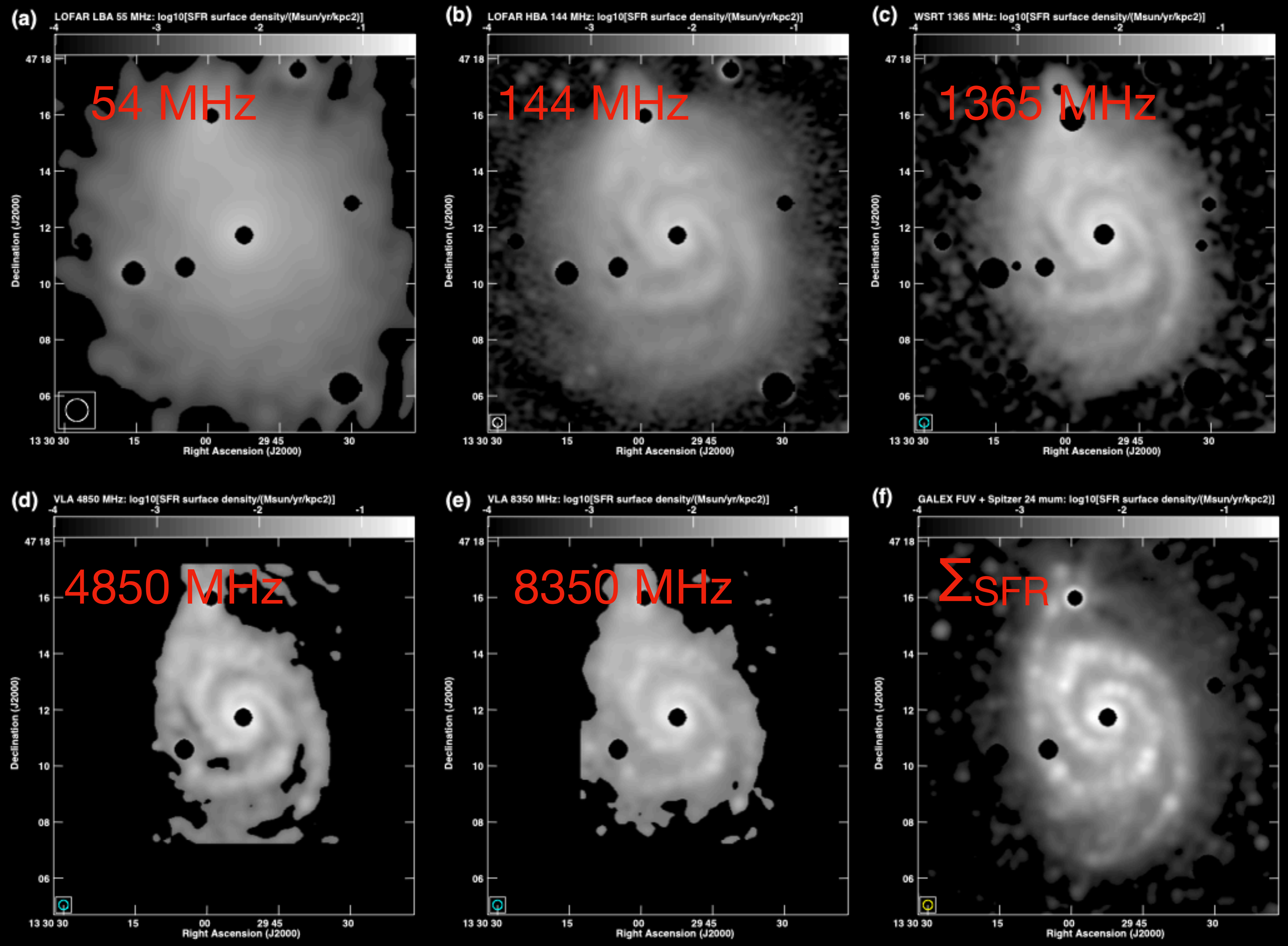


Recchia et al. (2016)

Smoothing experiment

Diffusion length in face-on galaxies

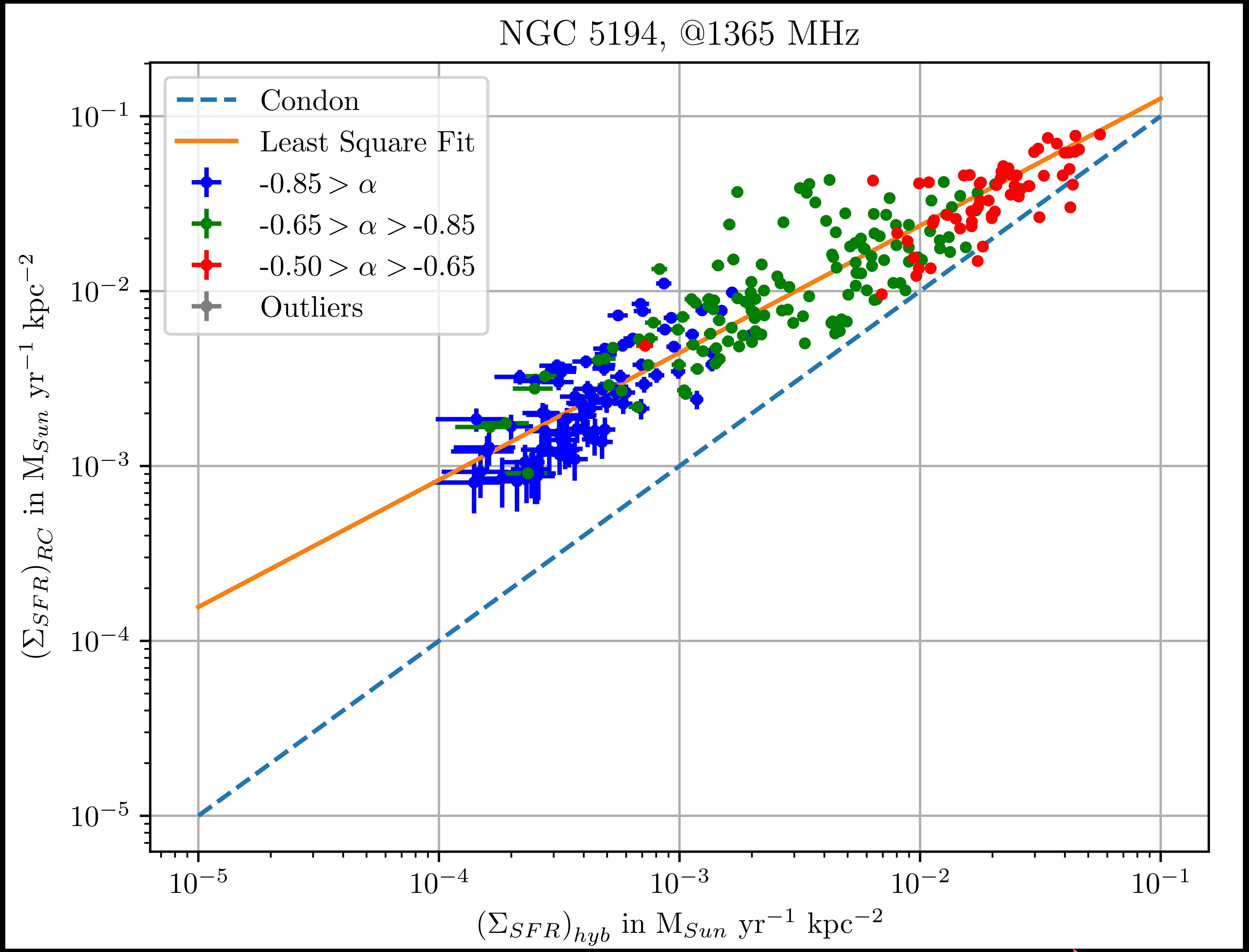
Lowest frequency



CRE injection

Spatially resolved radio–SFR relation

Radio star formation rate



Hybrid star formation rate

Radio spectral index

Red: Young CREs

Green: `middle aged' CREs

Blue: Old CREs

Condon relation:

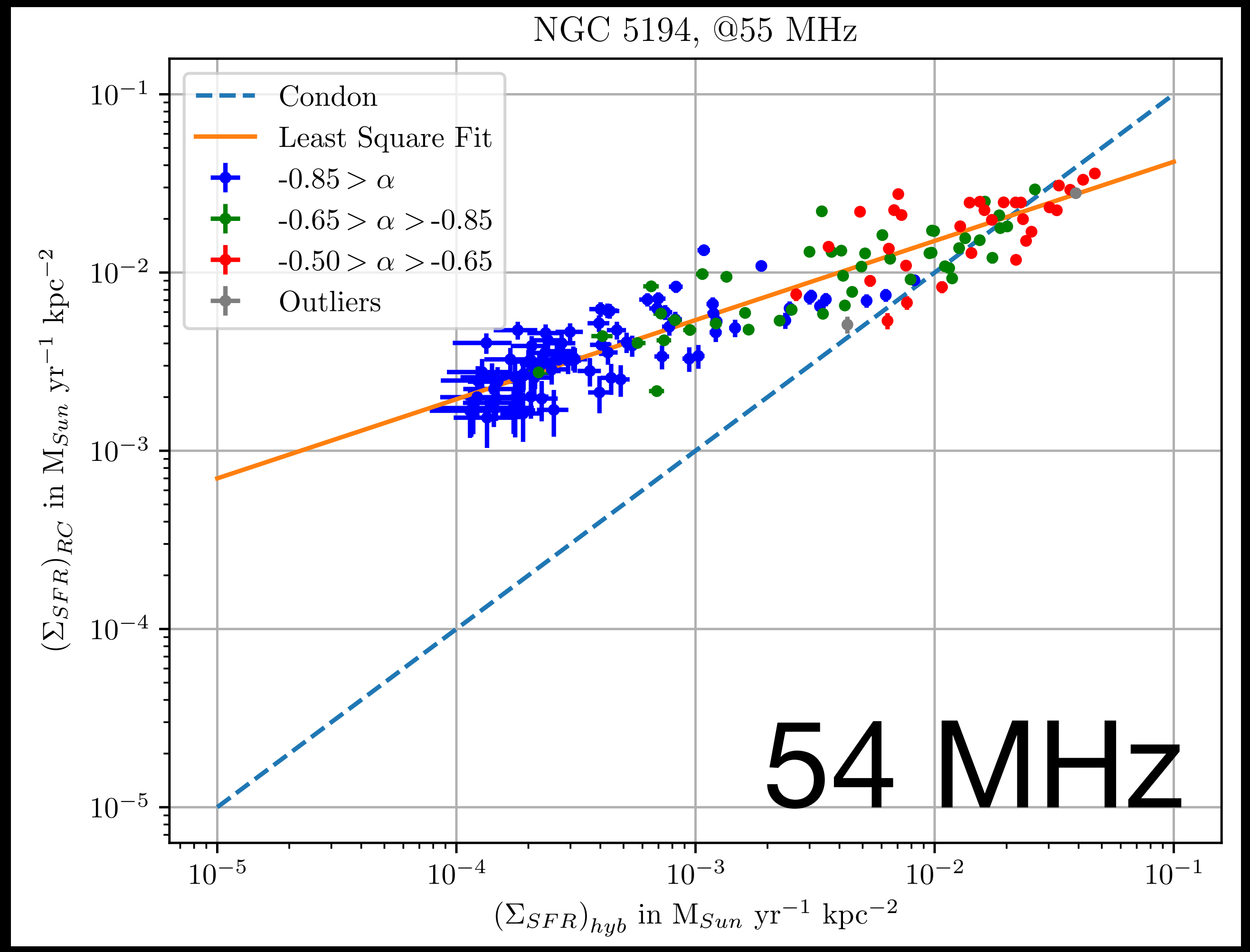
$$\left(\frac{\mathrm{SFR}}{M_\odot\,\mathrm{yr}^{-1}}\right)_{>0.1\,M_\odot} = 1.2\times10^{-21}\left(\frac{L_{1.4\,\mathrm{GHz}}}{\mathrm{W\,Hz}^{-1}}\right)$$

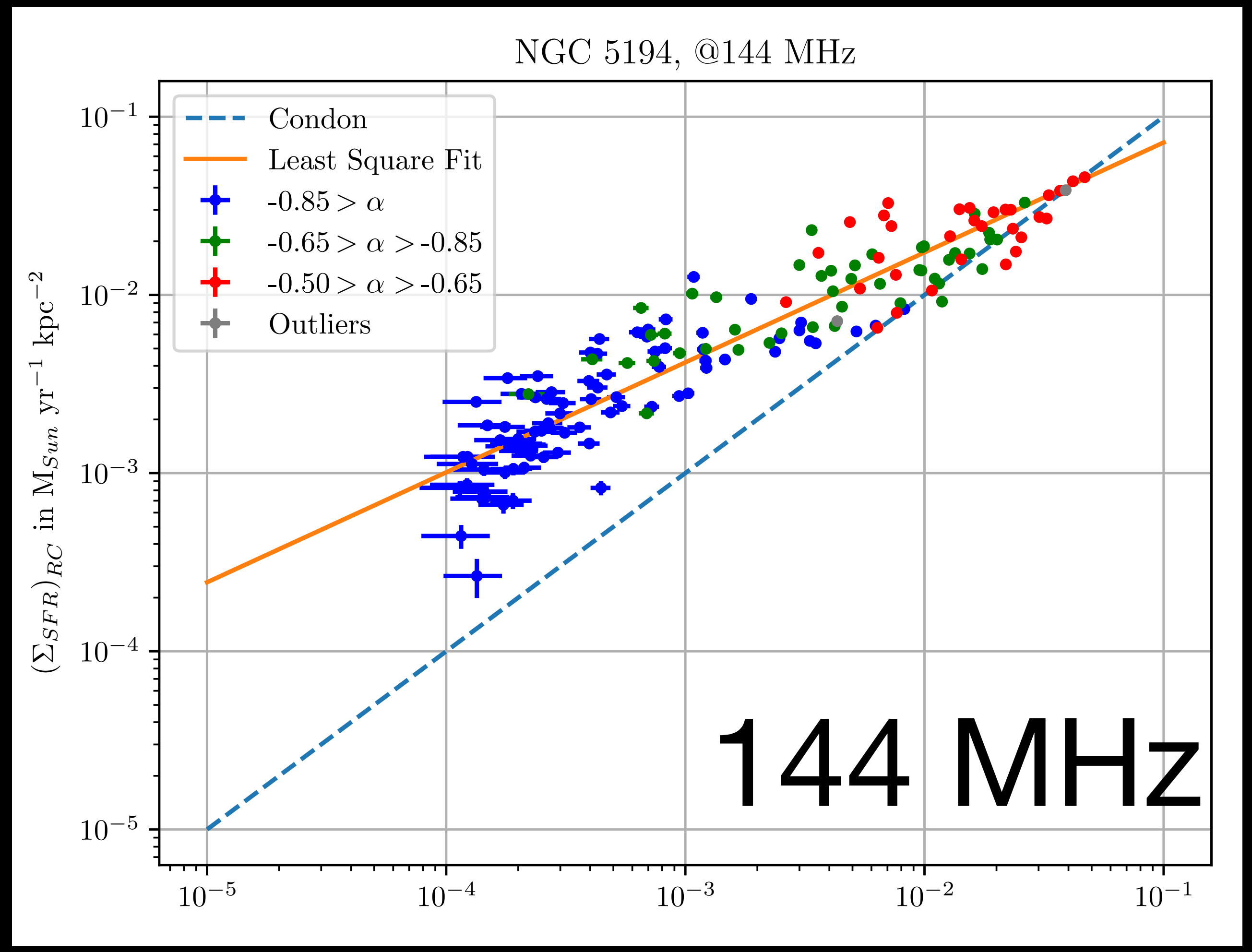
Results:

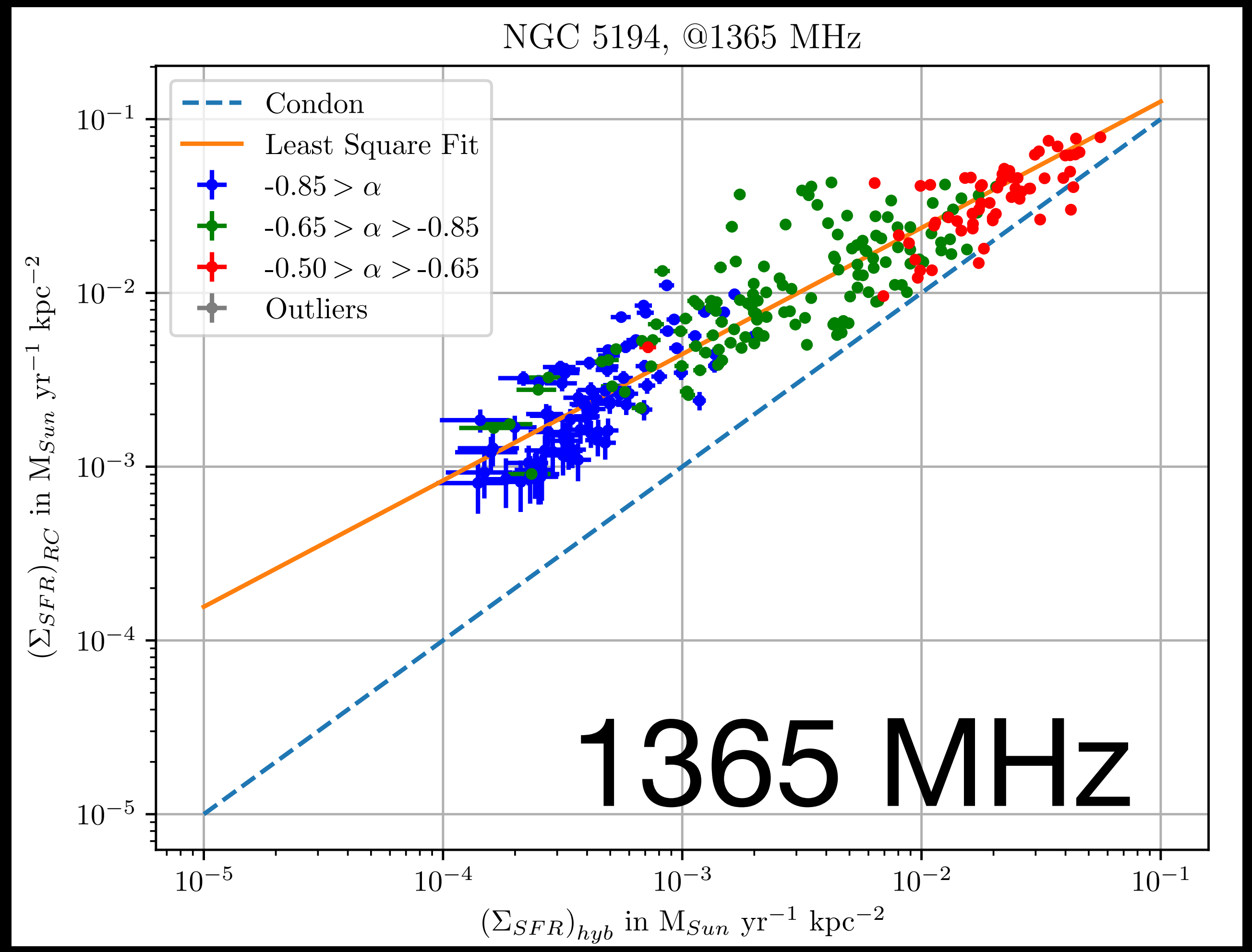
- Areas with young CREs agree with the theory
- But areas with old CREs lie above the 1:1 line
- Assumed to be the result of CRE transport

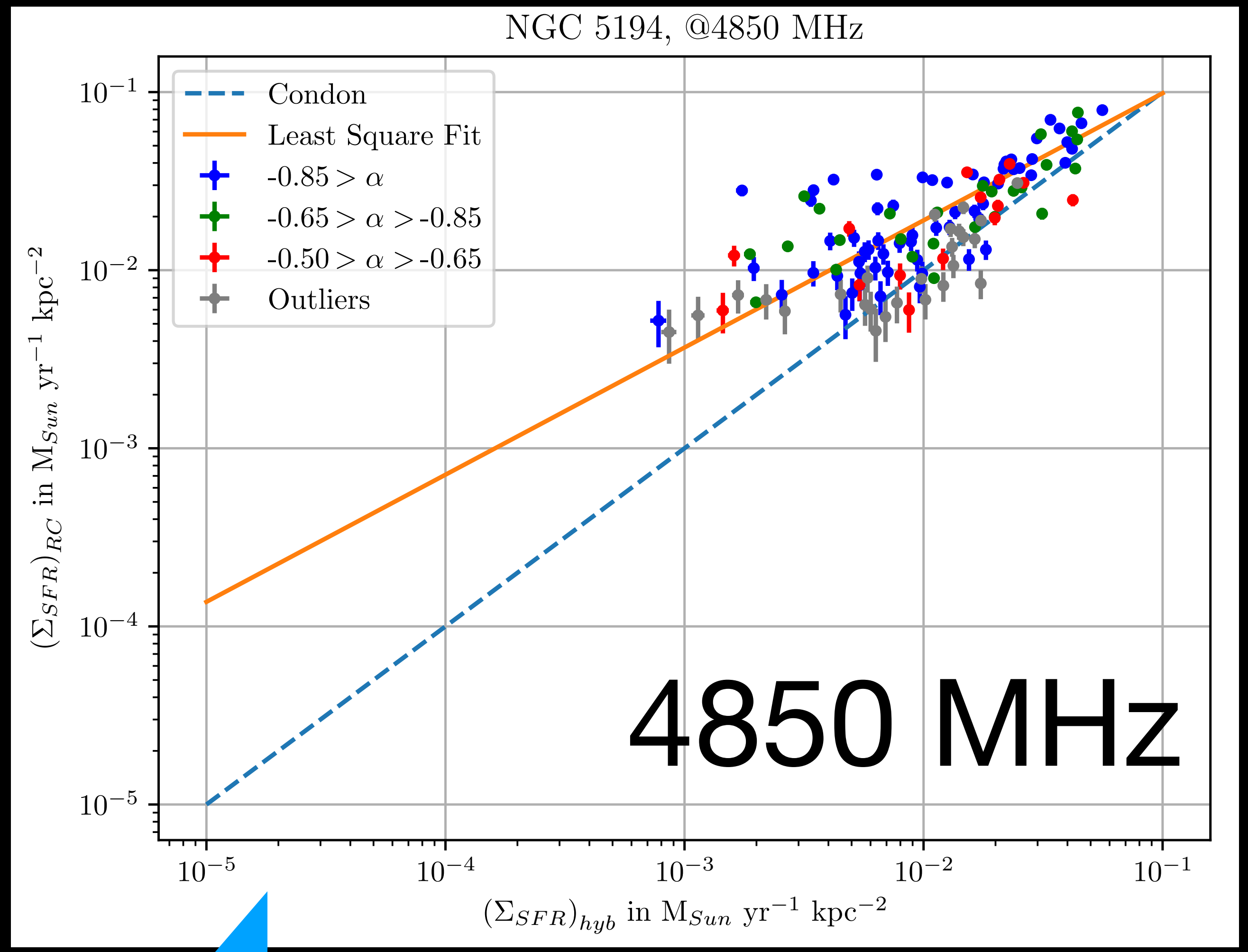
Sub-linear radio–SFR relation for spatially resolved case

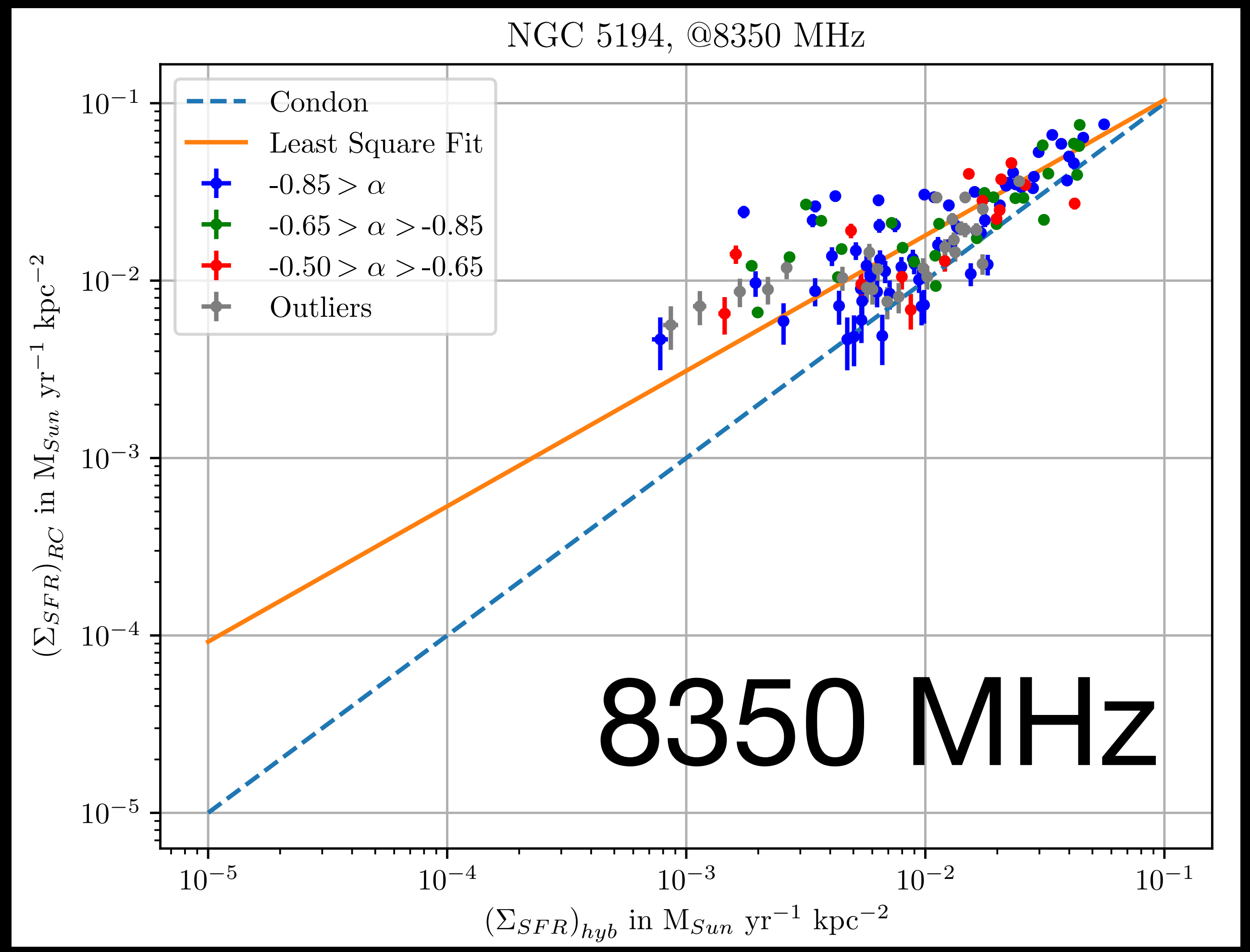
Lower frequencies, older CREs, decreasing slope











Slope decreases further for lower frequencies

CRE are older, so they can be transported further

Lower frequencies, older CREs, decreasing slope

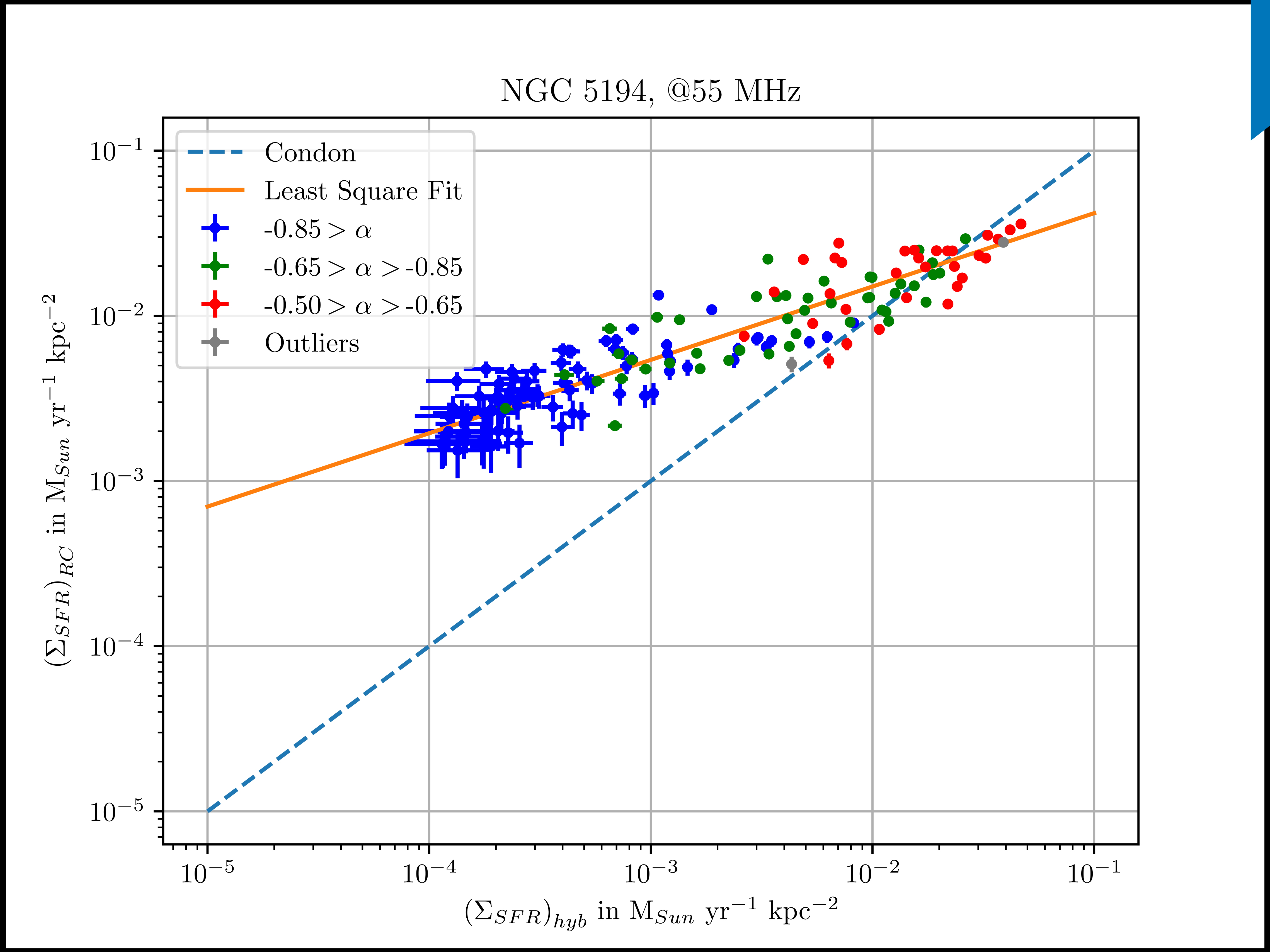
Linearise radio–SFR relation

Code developed by Sebastian Schulz

Convolve star formation map
estimate CRE transport

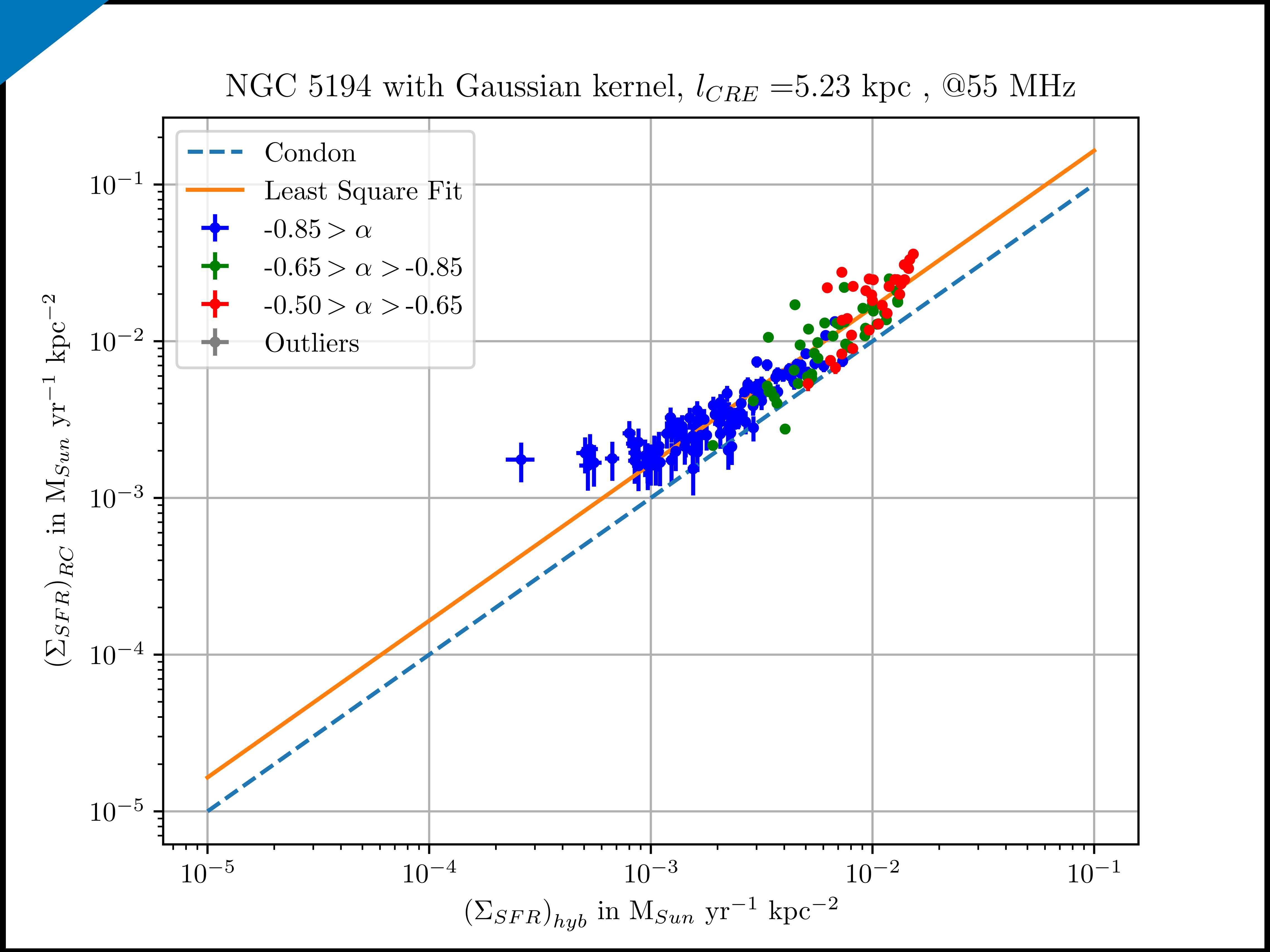
Radio continuum star formation rate

Radio-SFR relation



Hybrid star formation rate

Linearised radio-SFR relation



Hybrid star formation rate

Basic idea: *Berkhuijsen, Beck and Tabatabaei (2013)*

Code developed by Sebastian Schulz

GitHub

The hybrid SFR map is smoothed, until the radio–SFR relation is linear

Gaussian kernel: $$\exp\left(\frac{r^2}{2l_{\mathrm{CRE}}^2}\right)$$

Actually, a Gaussian is only accurate for a time-dependent model

We assume that CREs are in a steady state with injection = losses by synchrotron + inv. Compton

The CRE distribution is then approximately Gaussian

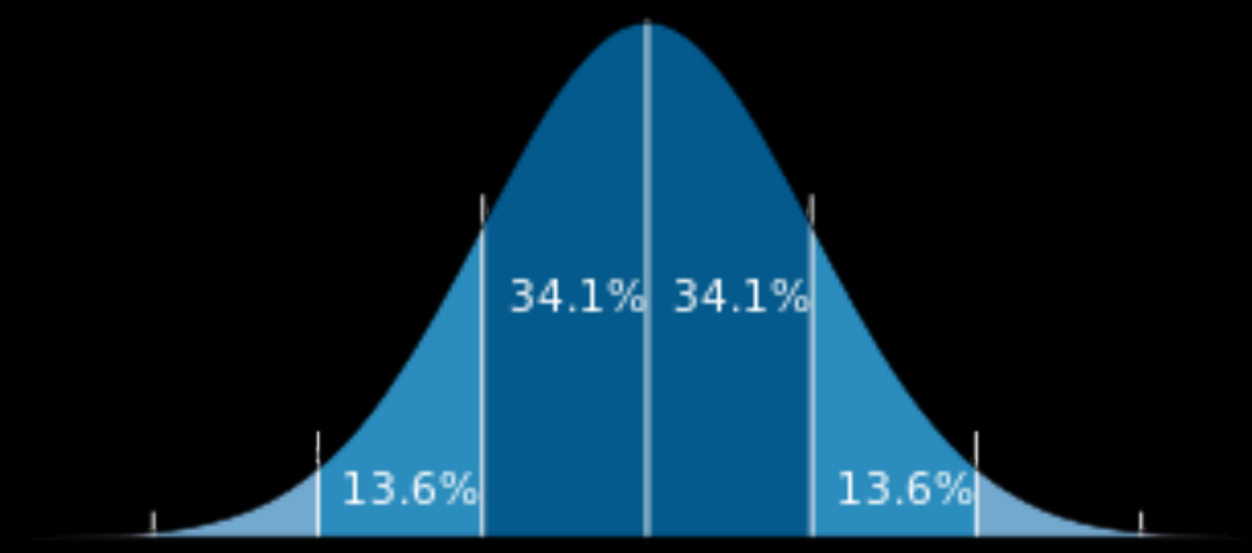
Heesen et al. (2019)

Random walk

Bronder (2020)

CRE transport length

Gaussian distribution

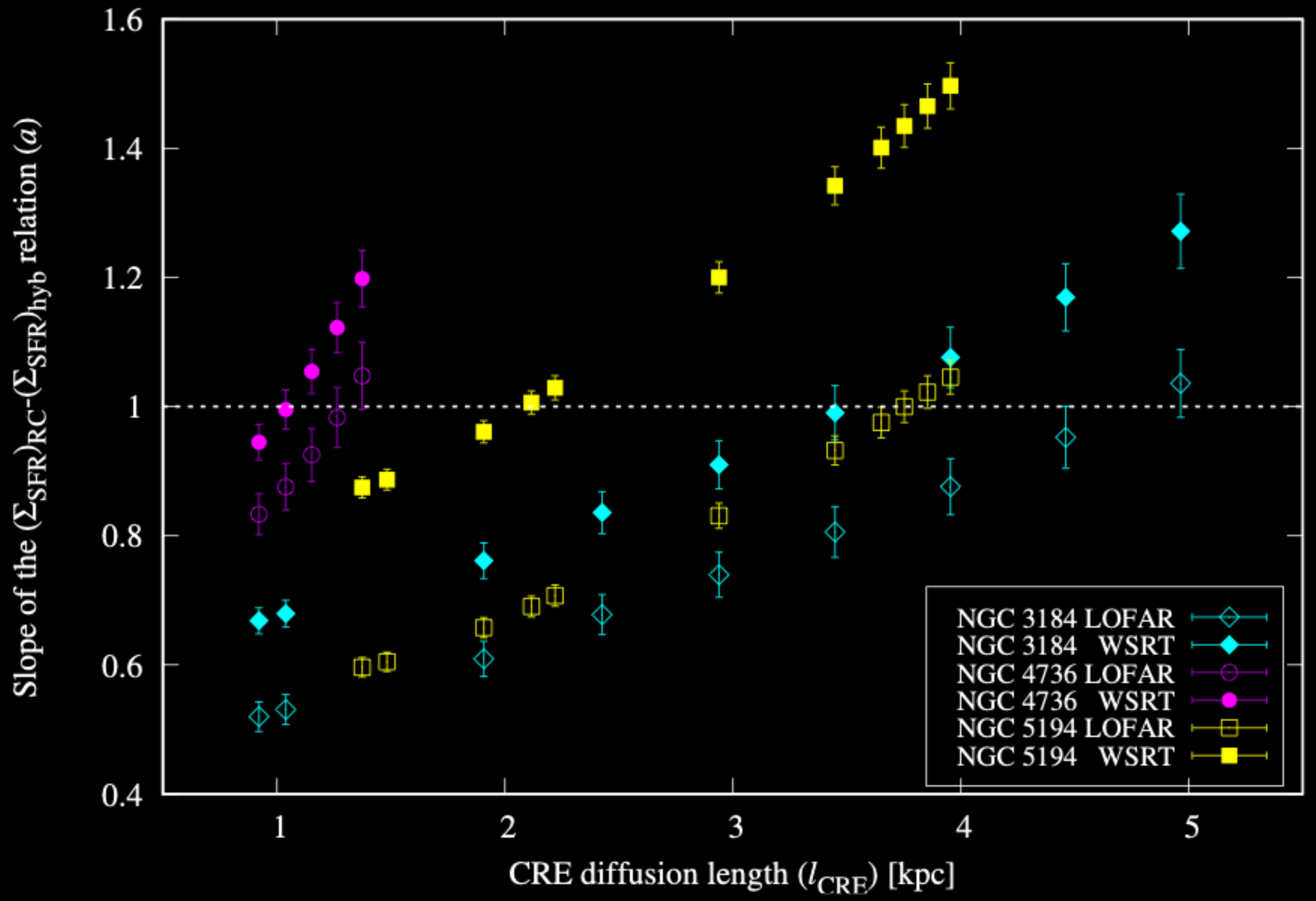


Smoothing experiment

- CRE diffusion length of 1-5 kpc
- Longer at lower frequencies
- Diffusion coefficient

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

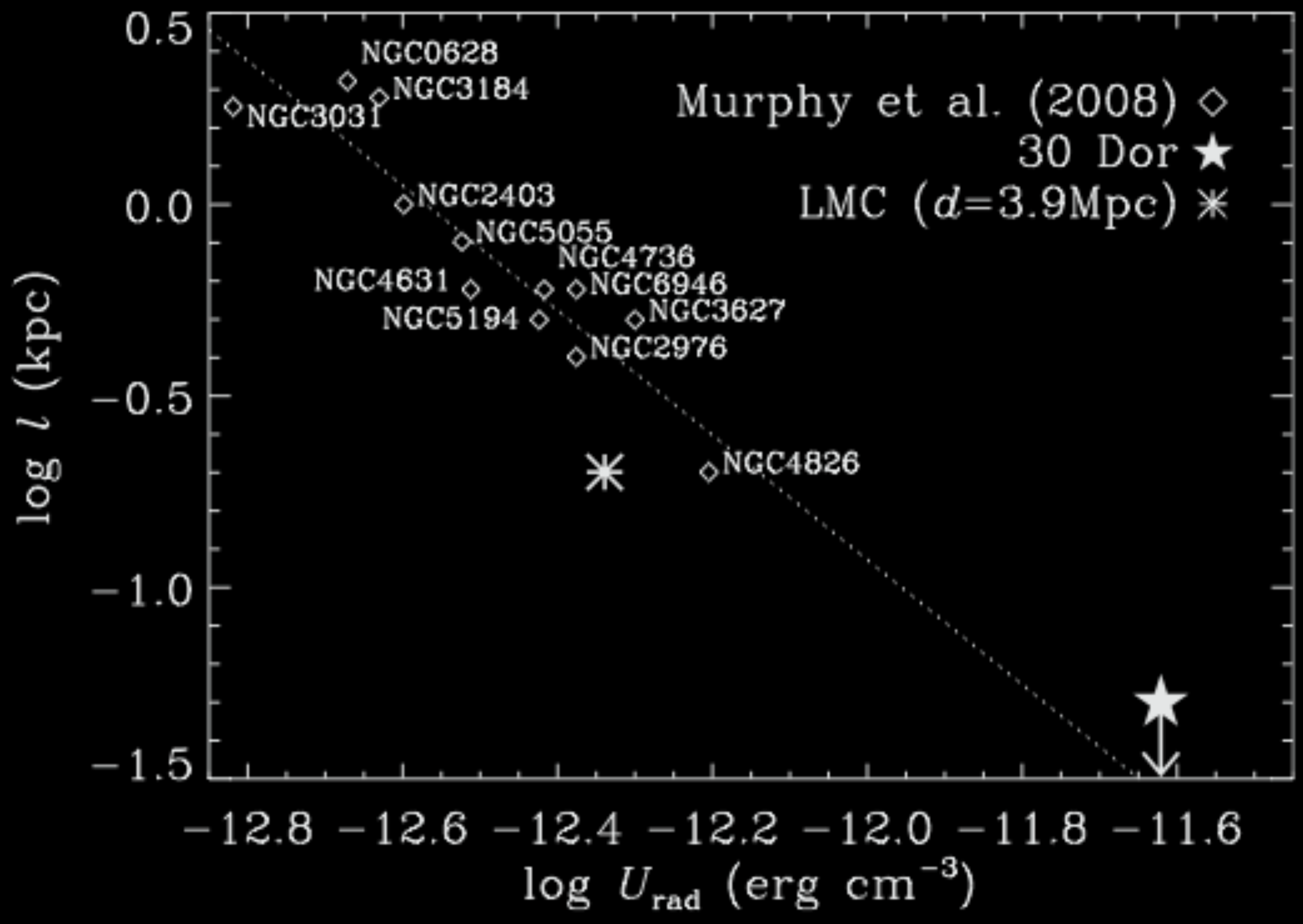
(isotropic 3D diffusion)



Diffusion coefficients

Measured values in galaxies

- $D = 10^{27}$-10^{29} cm^2 s^{-1}
- Most coefficients $D = 10^{28}$ cm^2 s^{-1}
- Low values in dwarf irregular galaxies
- High values in galactic haloes

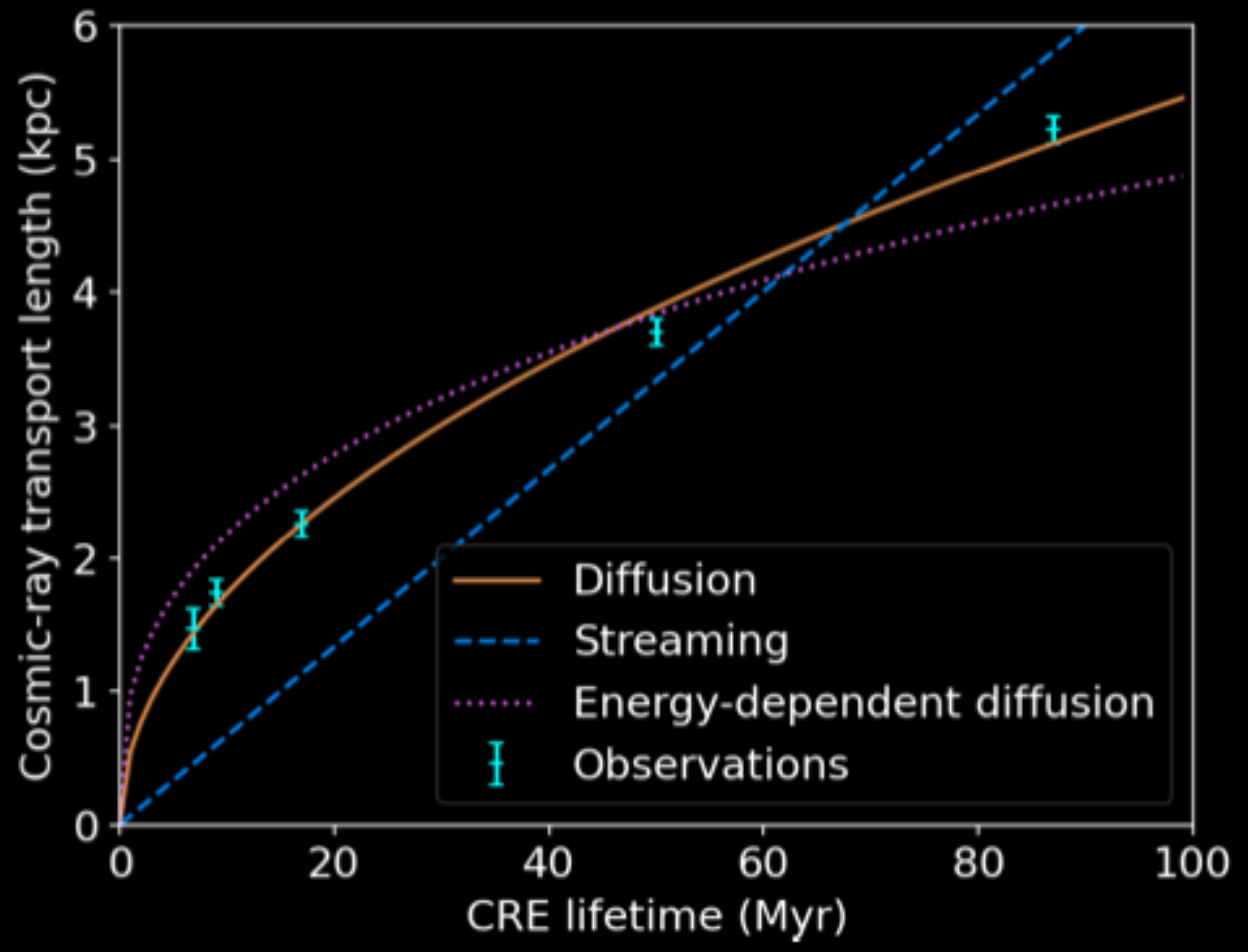


Murphy et al. (2012)

Diffusion coefficients

Energy dependence

- 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))

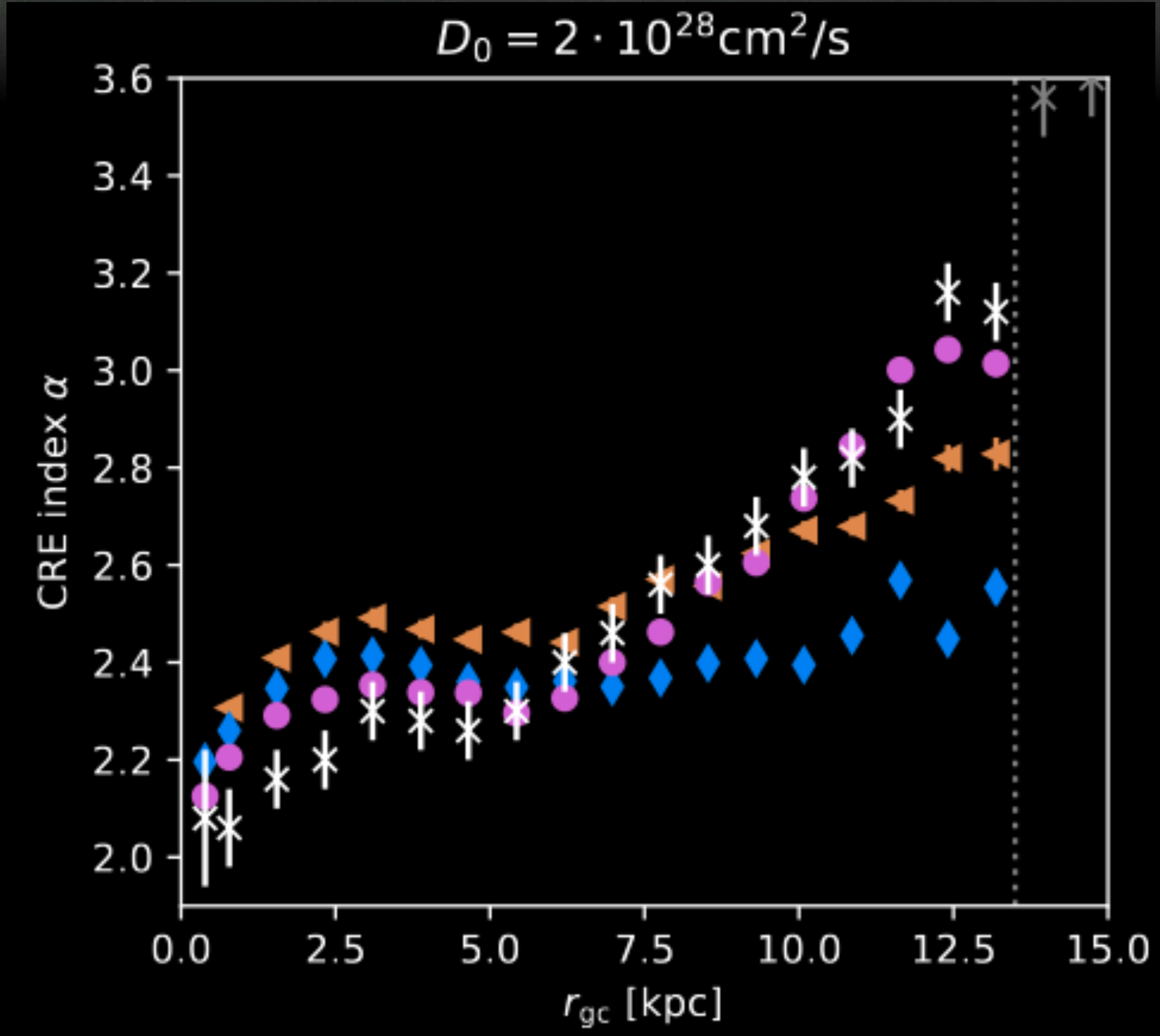


3D Simulation

with wind and diffusion

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

CRPropa v3.1



Dörner et al. (2023)

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