The LOFAR radio continuum view on galactic winds

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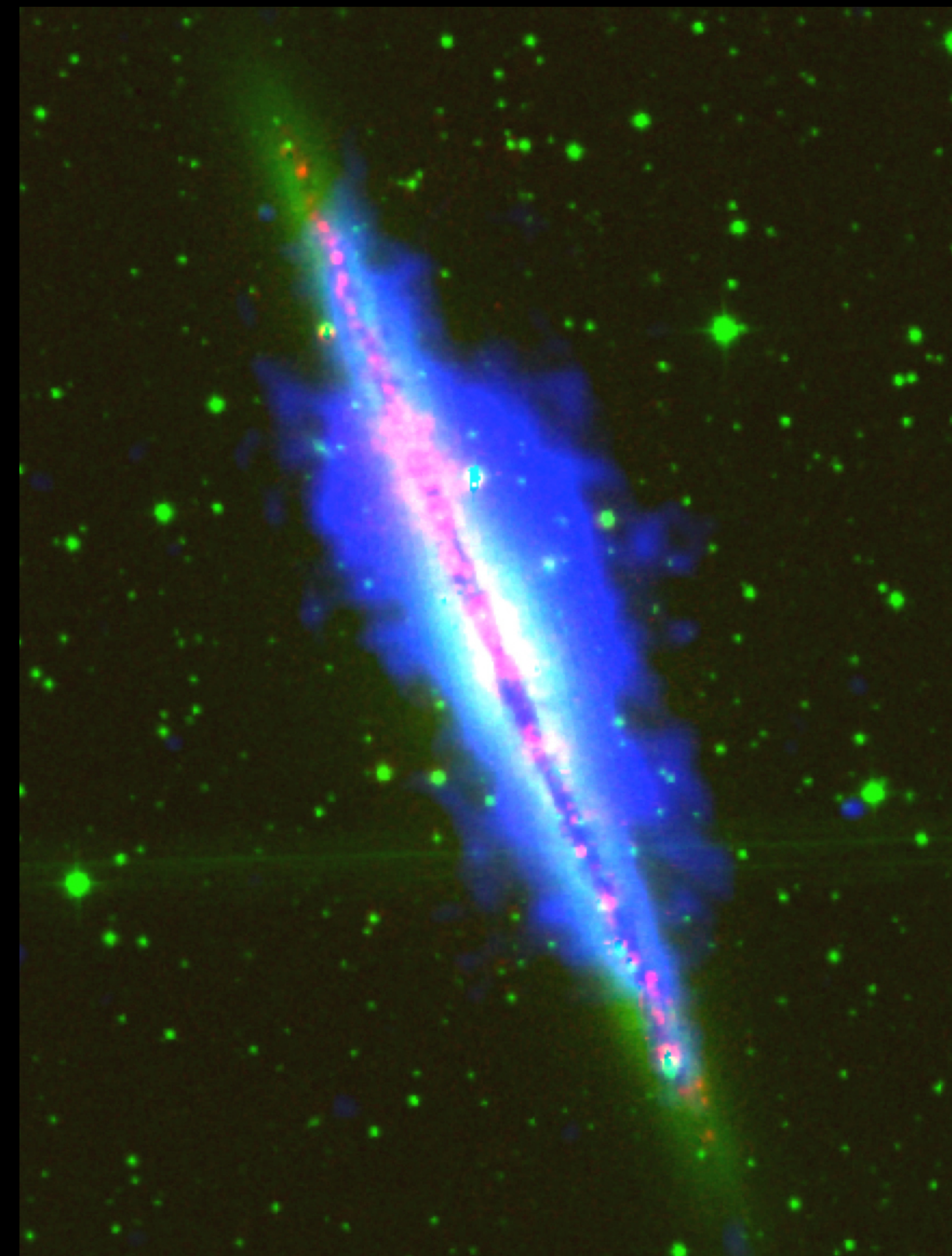
UHH Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

and the LOFAR Magnetism KSP

LOFAR MAGNETISM KEY SCIENCE PROJECT

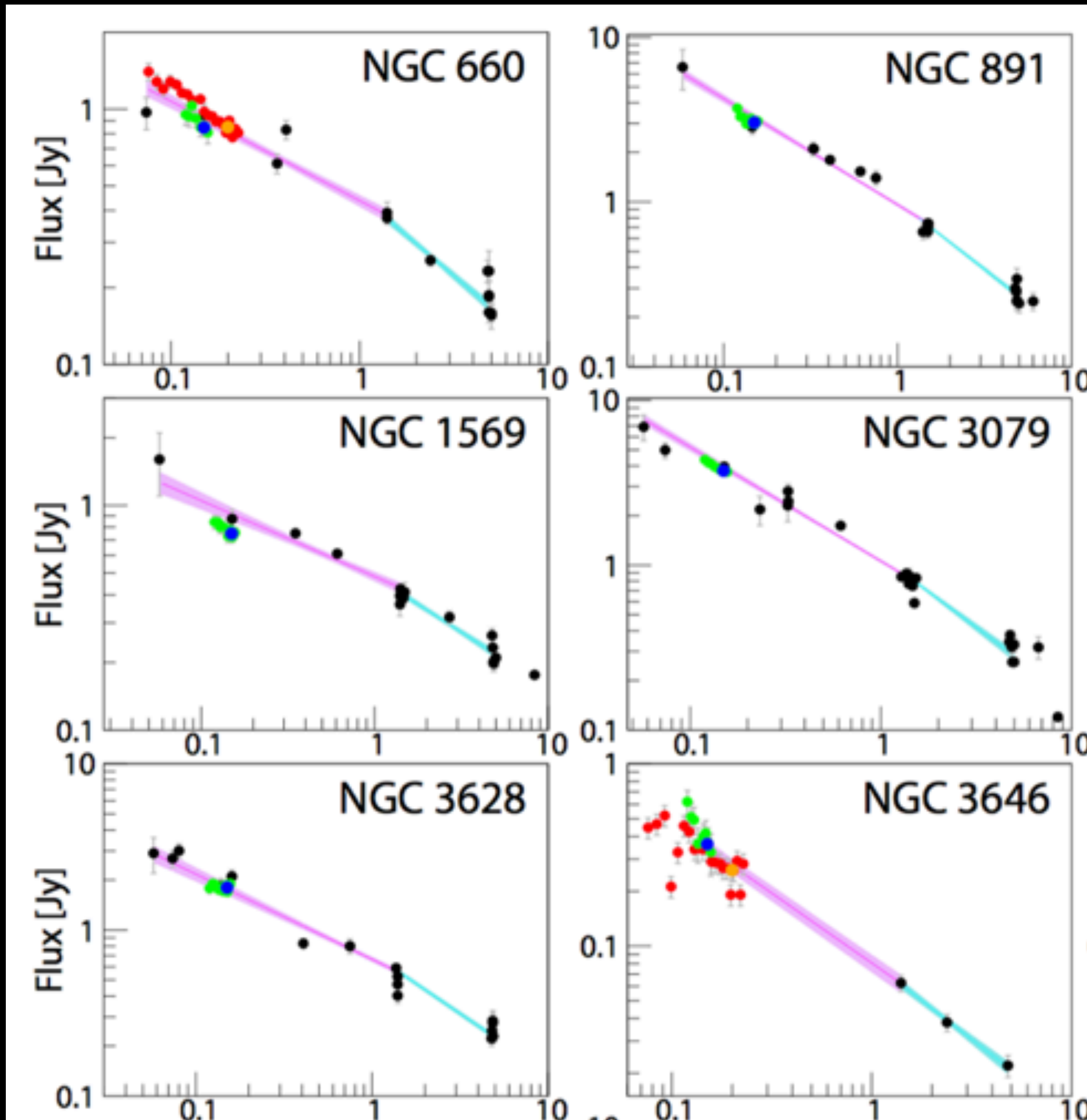


Mulcahy et al. (2018)

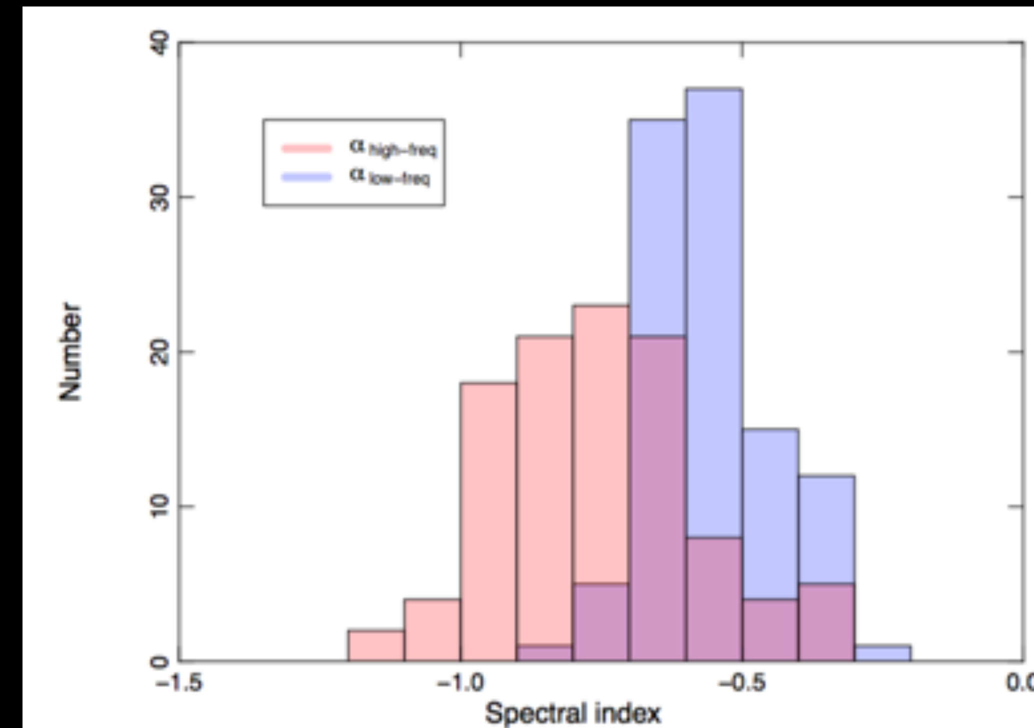
Motivation: cosmic-ray transport

- Stellar feedback plays vital role for galaxy evolution
- Cosmic ray-driven winds are:
  - cooler: 10^4 K rather than 10^6 K
  - denser: resulting in higher mass loading
- With radio continuum observations
  - we trace cosmic-ray electrons (CRe)
  - isotropic/ansiotropic diffusion in the disc
  - advection in the halo (galactic wind)

Flattening of the low-frequency radio spectrum

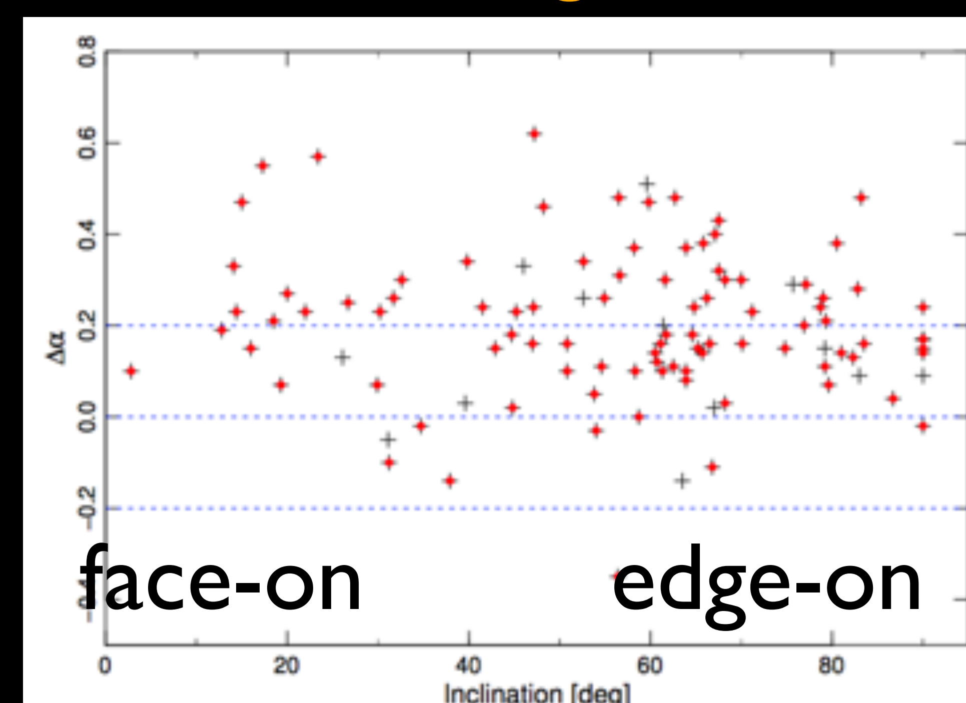


Frequency [GHz]



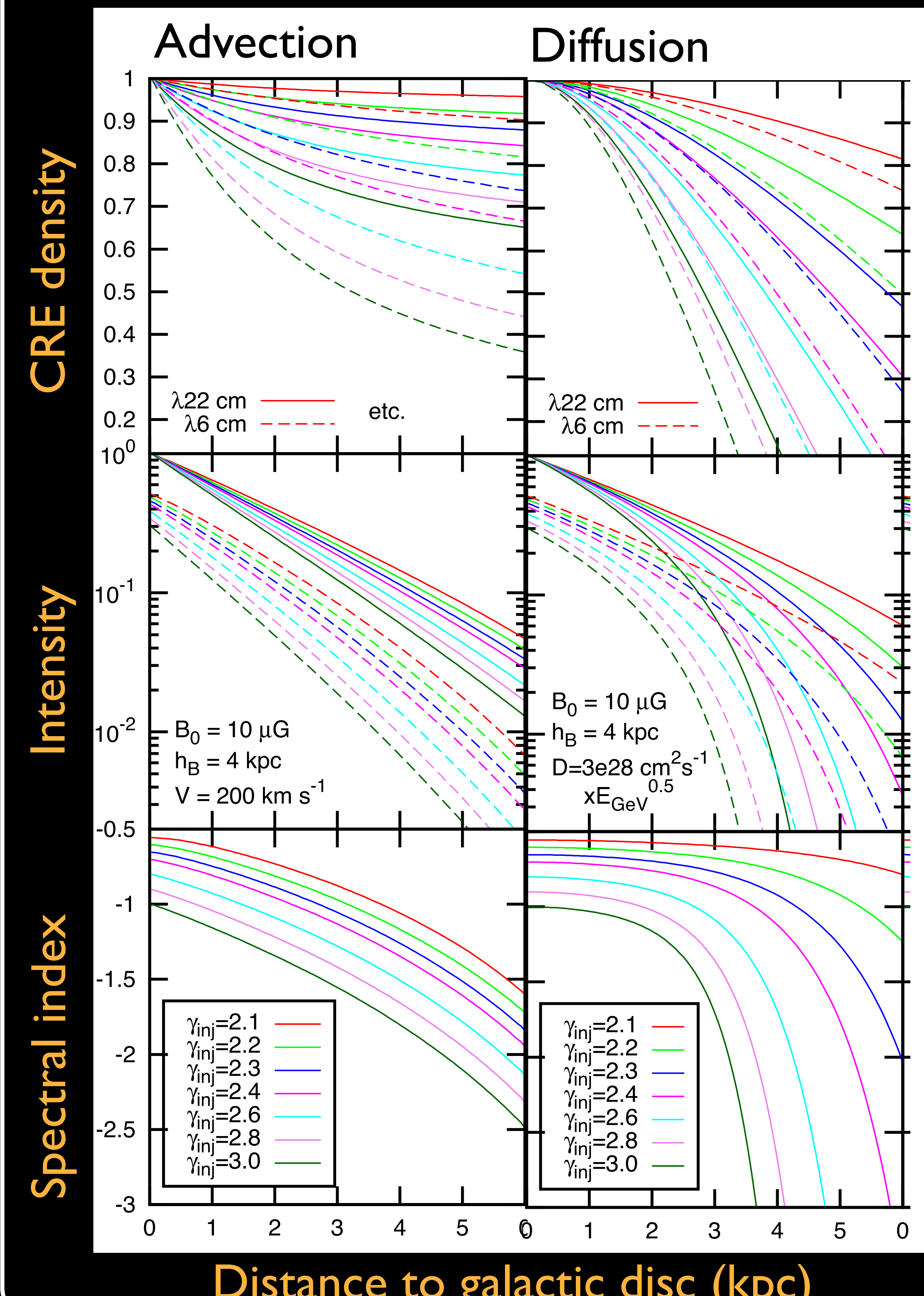
Spectral index difference

Inclination angle

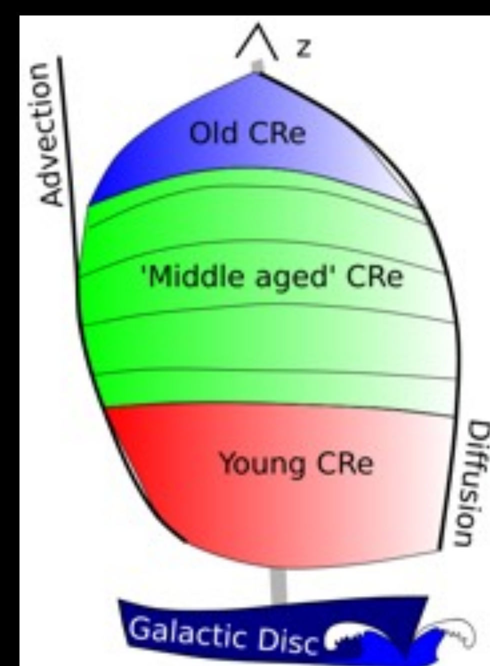


Chyzy et al. (2018)

1D CR-transport models



- Advection:
  - Exponential intensity and linear spectral index profiles
- Diffusion:
  - 'Gaussian' intensity and parabolic spectral index profiles

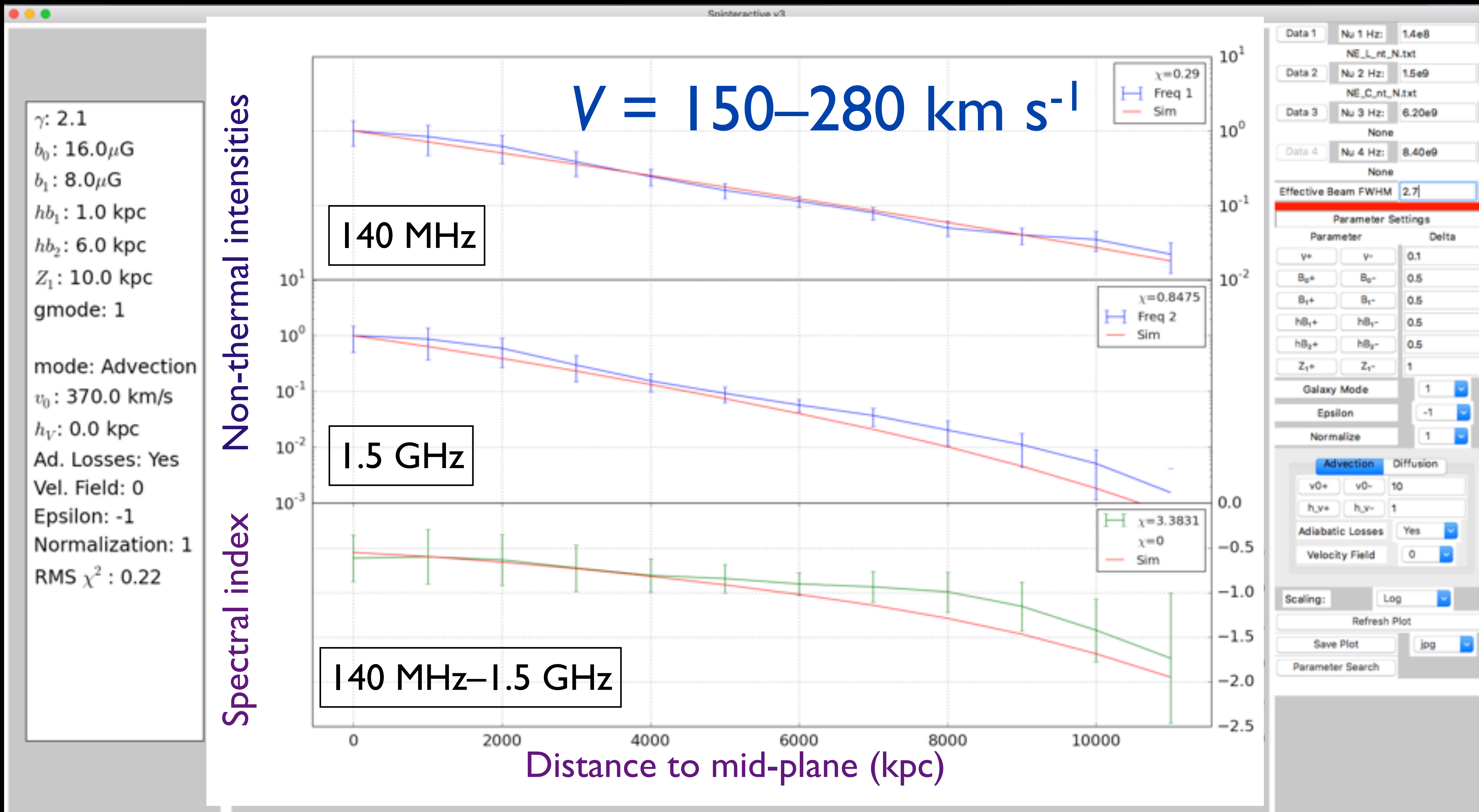


- **Sp**ectral **In**dex **N**umerical **A**nalysis of **K**(c)osmic-ray **E**lectron **R**adio-emission
- www.github.com/vheesen/Spinnaker

Heesen et al. 2016

SPINTERACTIVE

Developed by Arpad Miskolczi



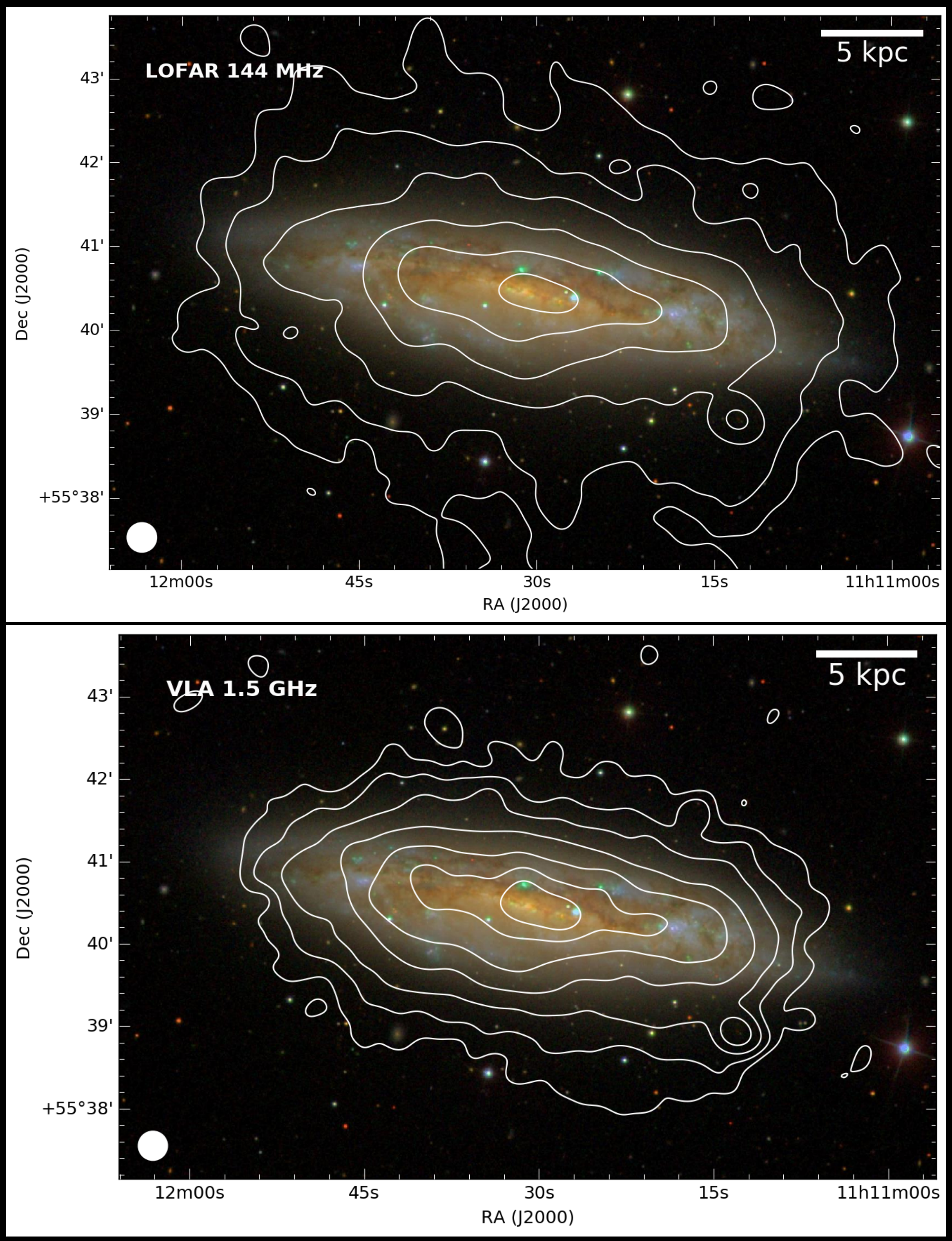
SPINNAKER & SPINTERACTIVE: https://github.com/vheesen/Spinnaker

The radio halo in NGC 3556 (M108)

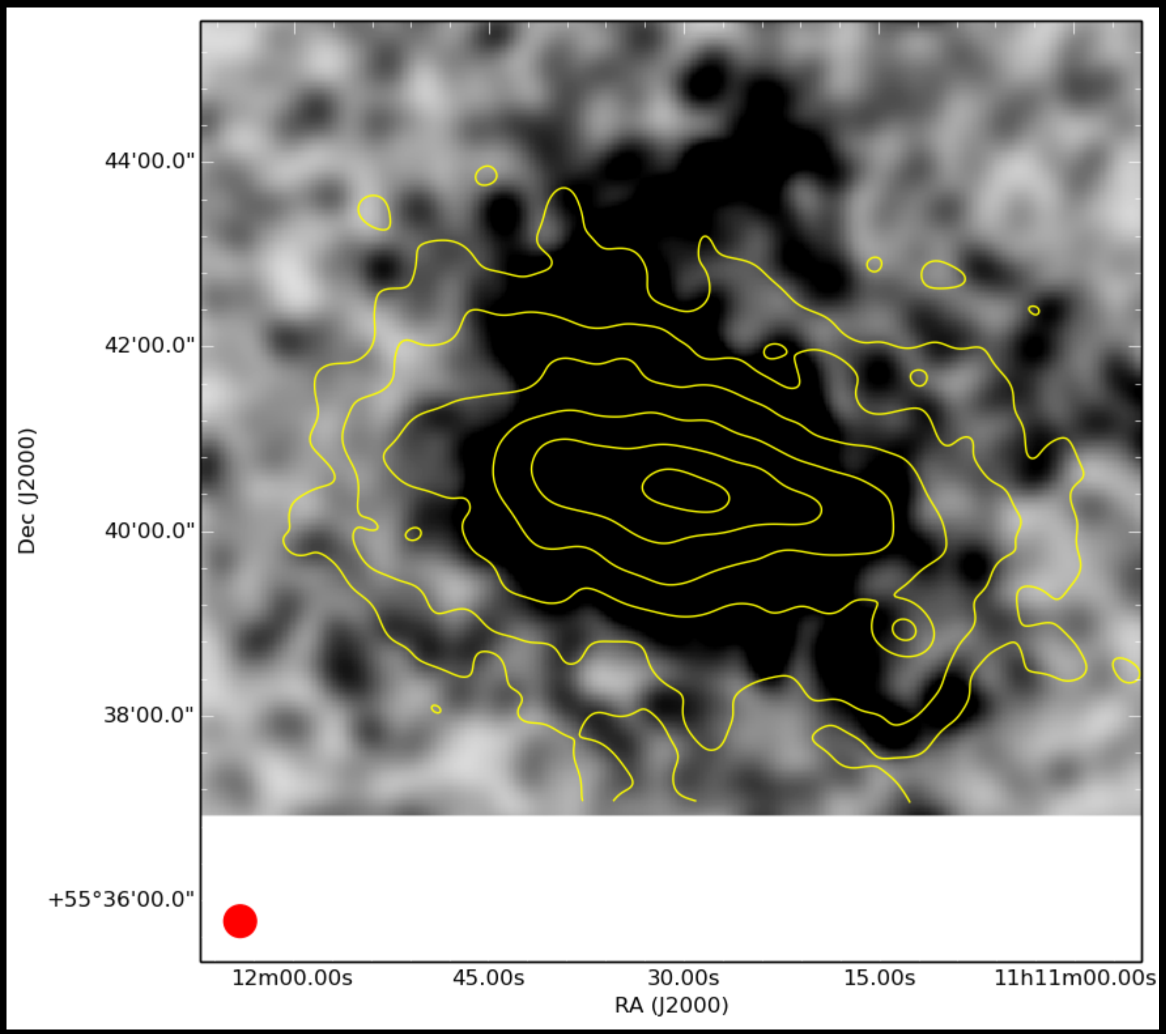
Miskolczi et al. (2019)

'Splash'

Detection of the radio halo



Overlay on X-ray



Radio halo much larger with LOFAR than with JVLA

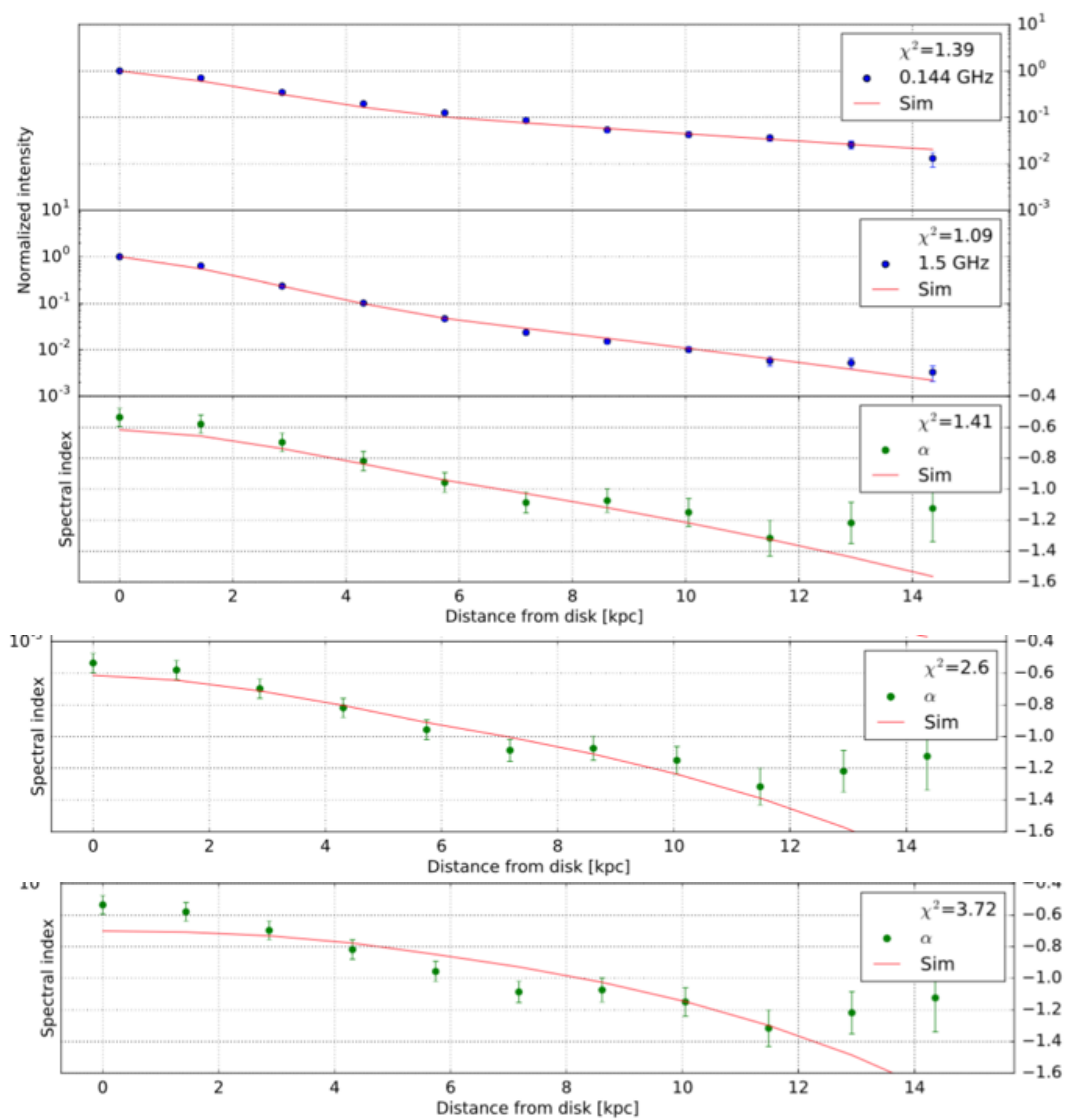
Intensity
140 MHz

1.6 GHz

Accelerated
wind

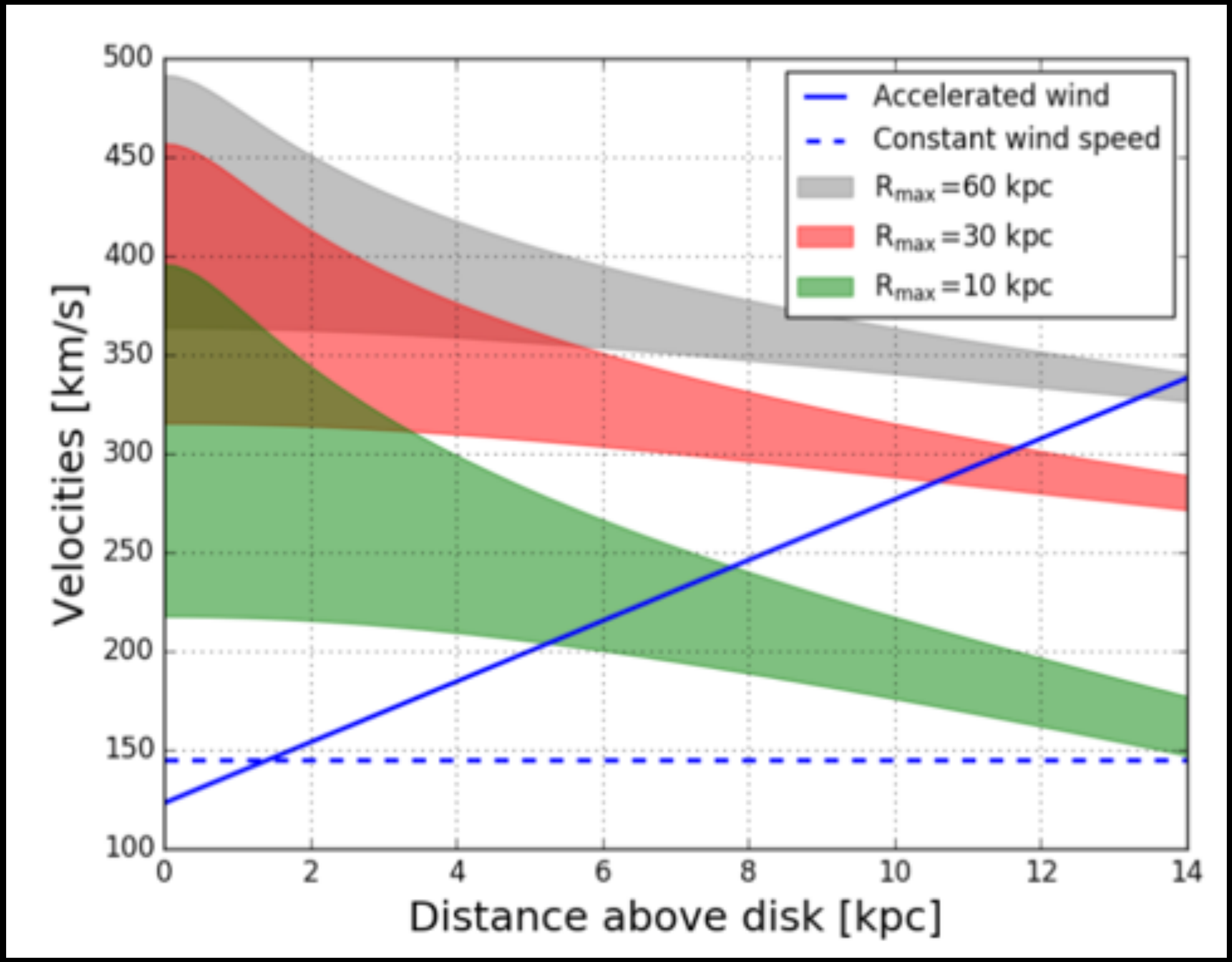
Constant
wind

Diffusion

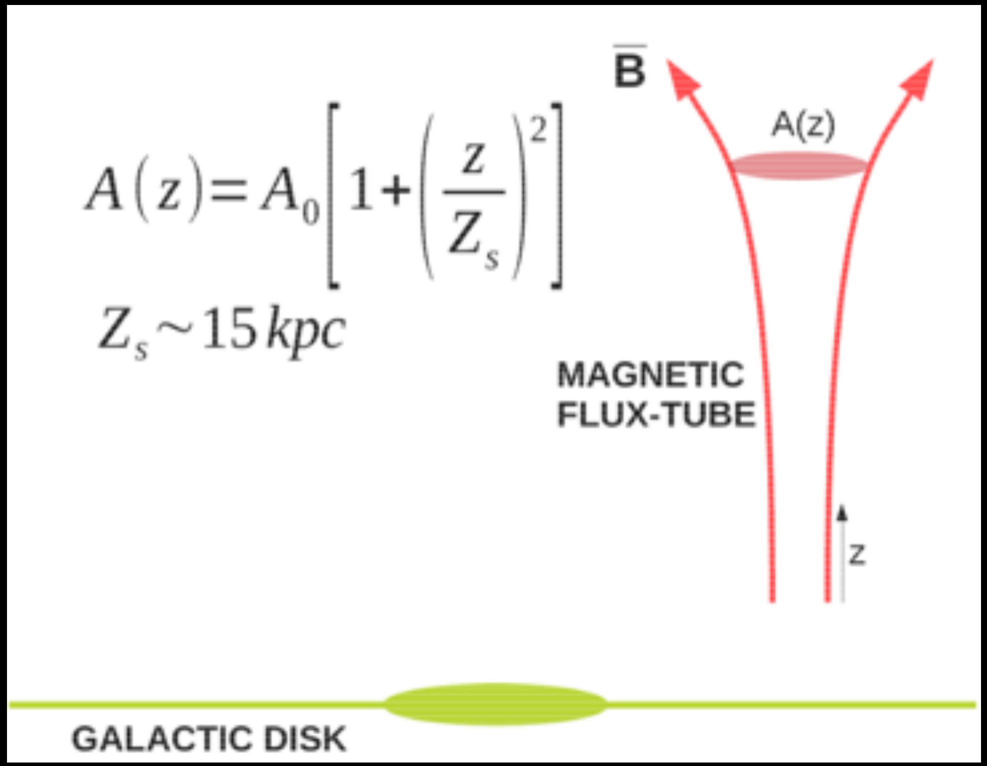


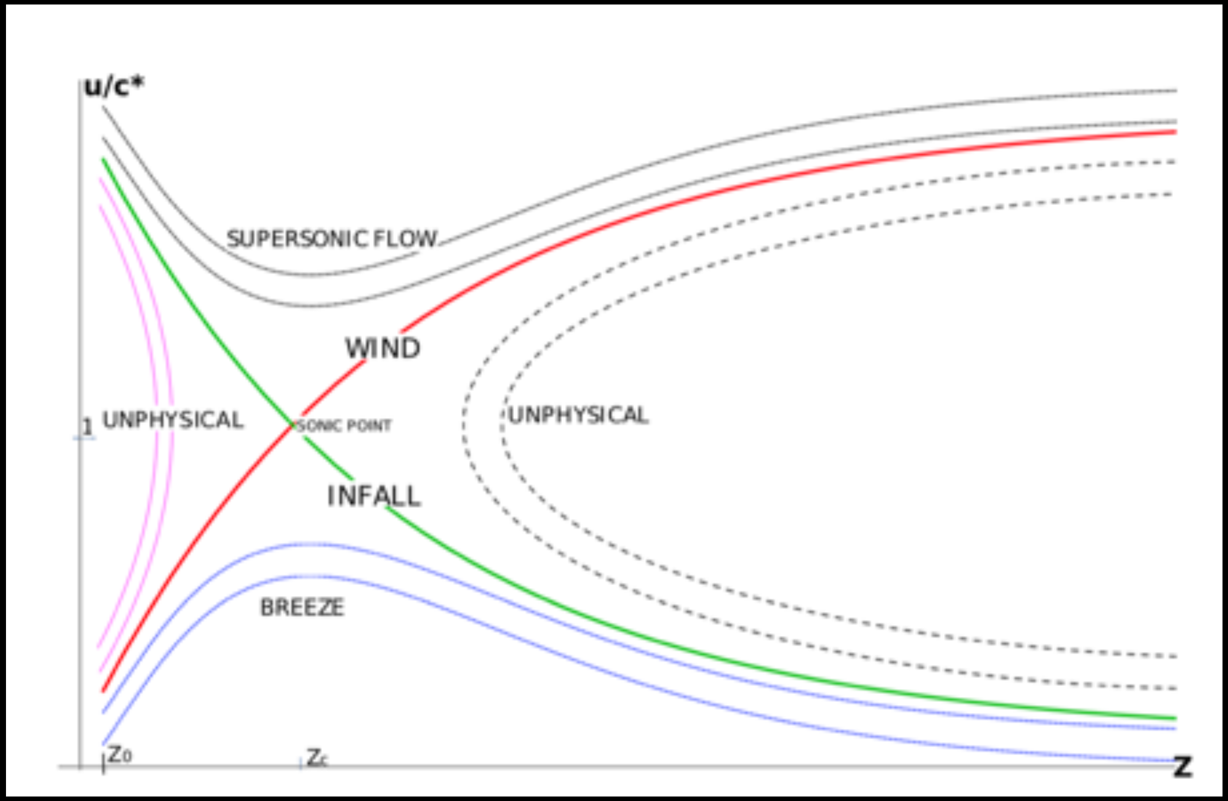
Volker Heesen, Galactic winds in the radio continuum with LOFAR

Accelerating advection speed



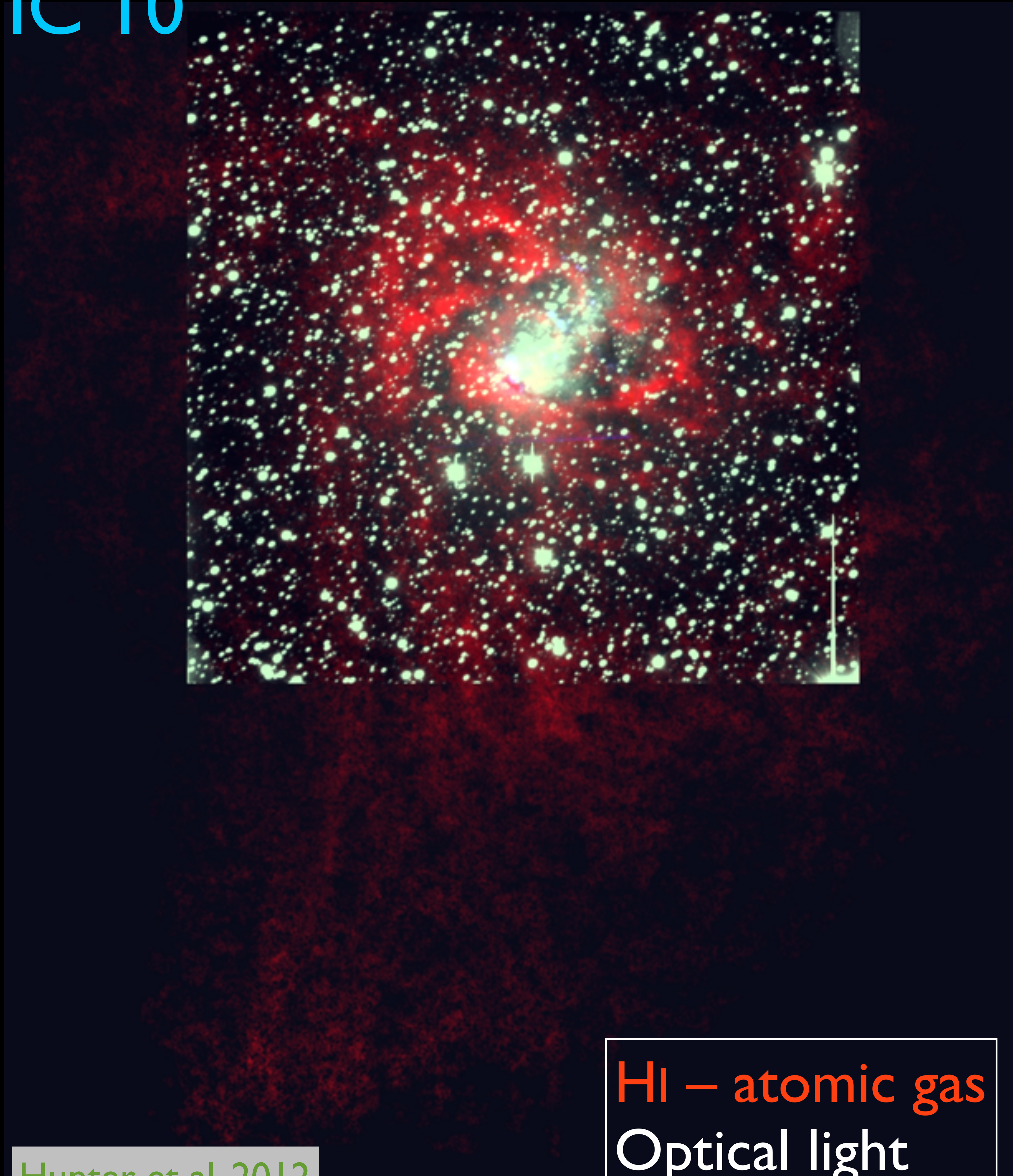
Miskolczi et al. (2019)





Recchia et al. (2016)

IC 10

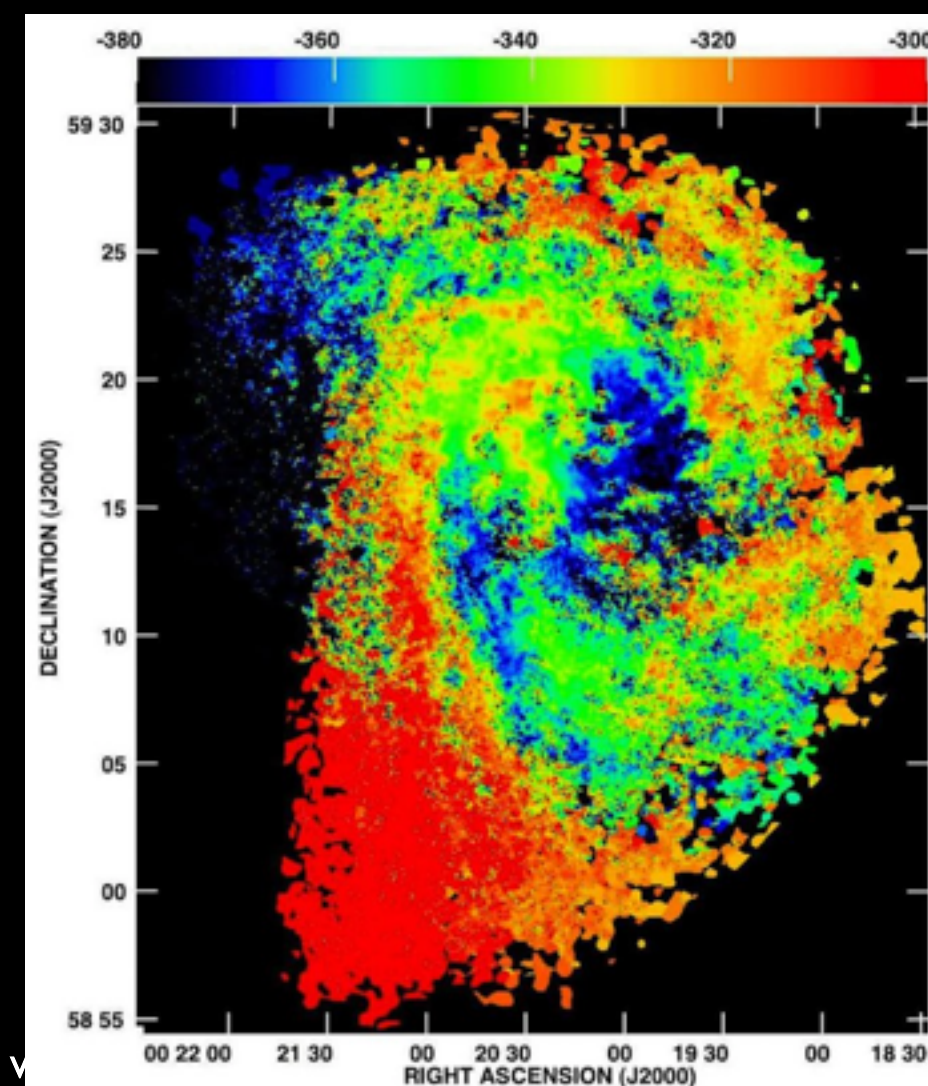


HI – atomic gas
Optical light

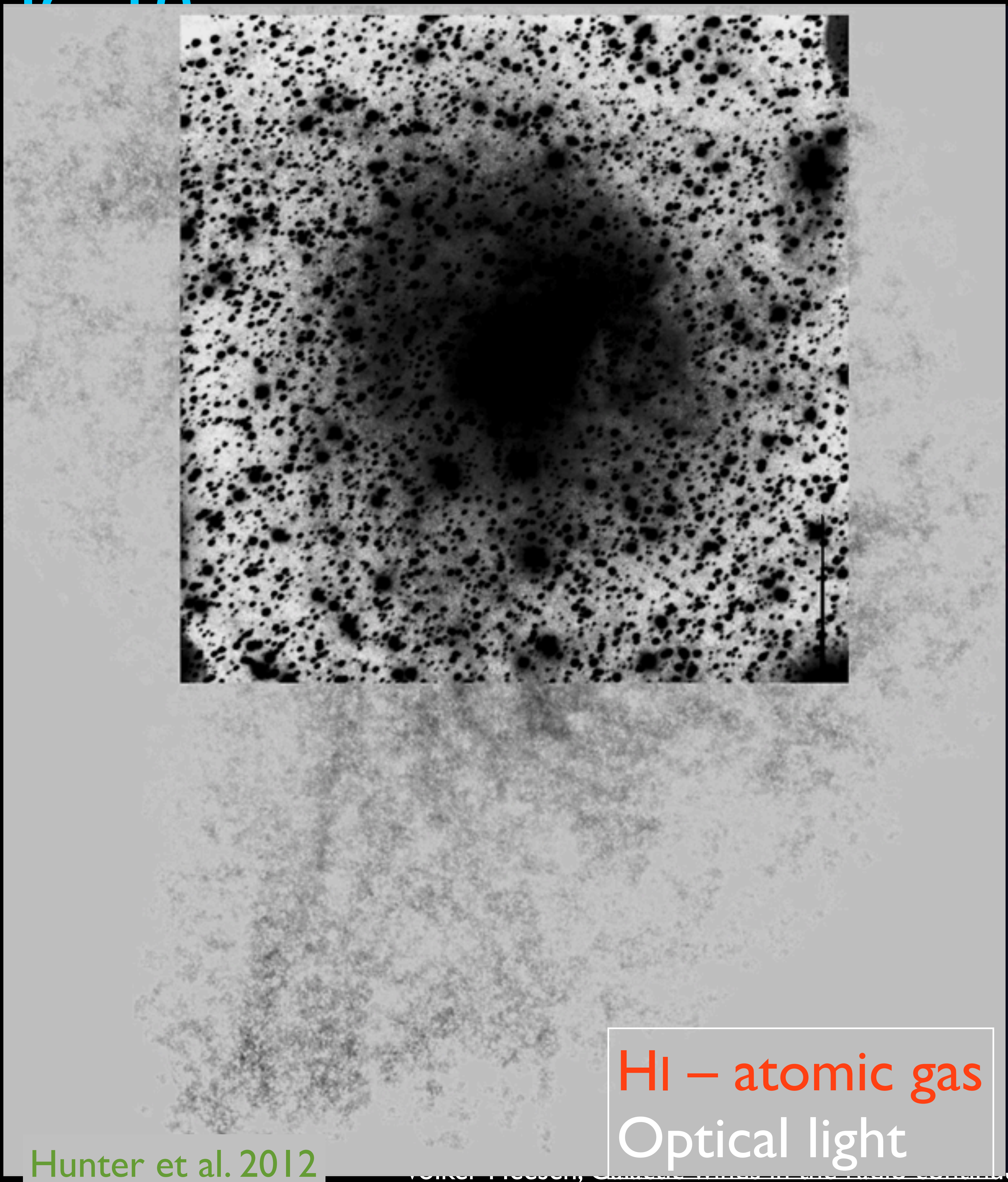
Hunter et al. 2012

D = 0.7 Mpc
SFR = 0.05 M yr^{-1}
SFRD = 0.1 M yr^{-1} kpc^{-2}
Wolf–Rayet stars
Star burst
Few Myr star clusters

HI velocity field



IC 10



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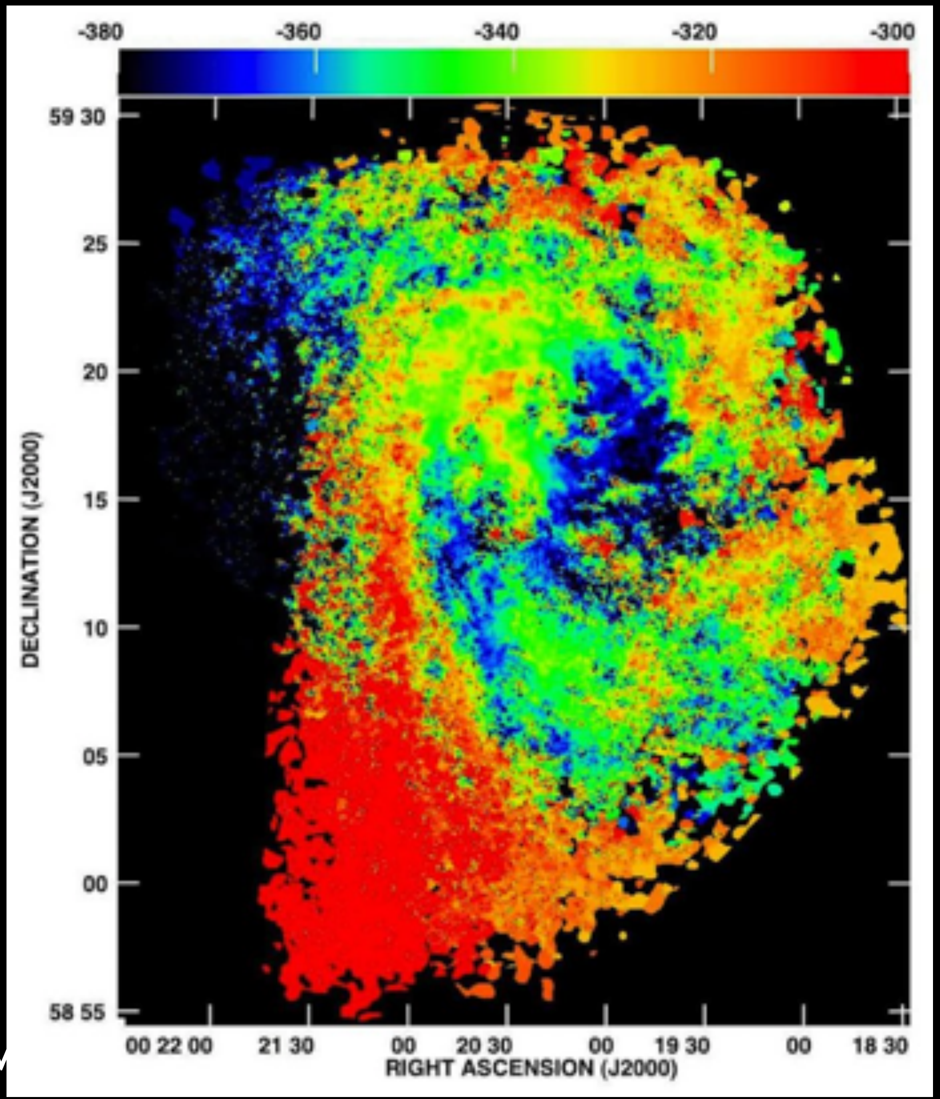


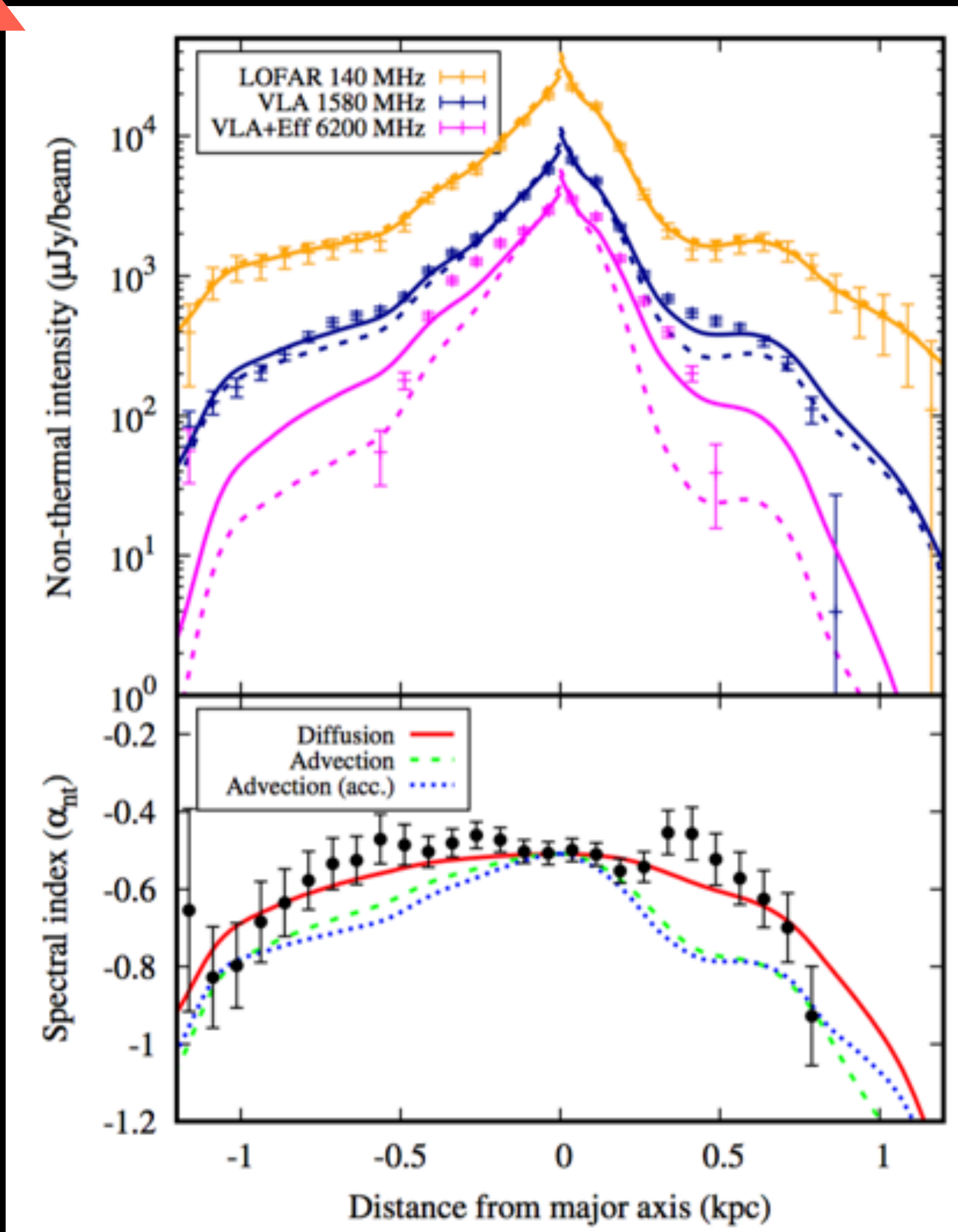
Cosmic-ray transport models

(Heesen et al. 2018a)

Minor axis profiles

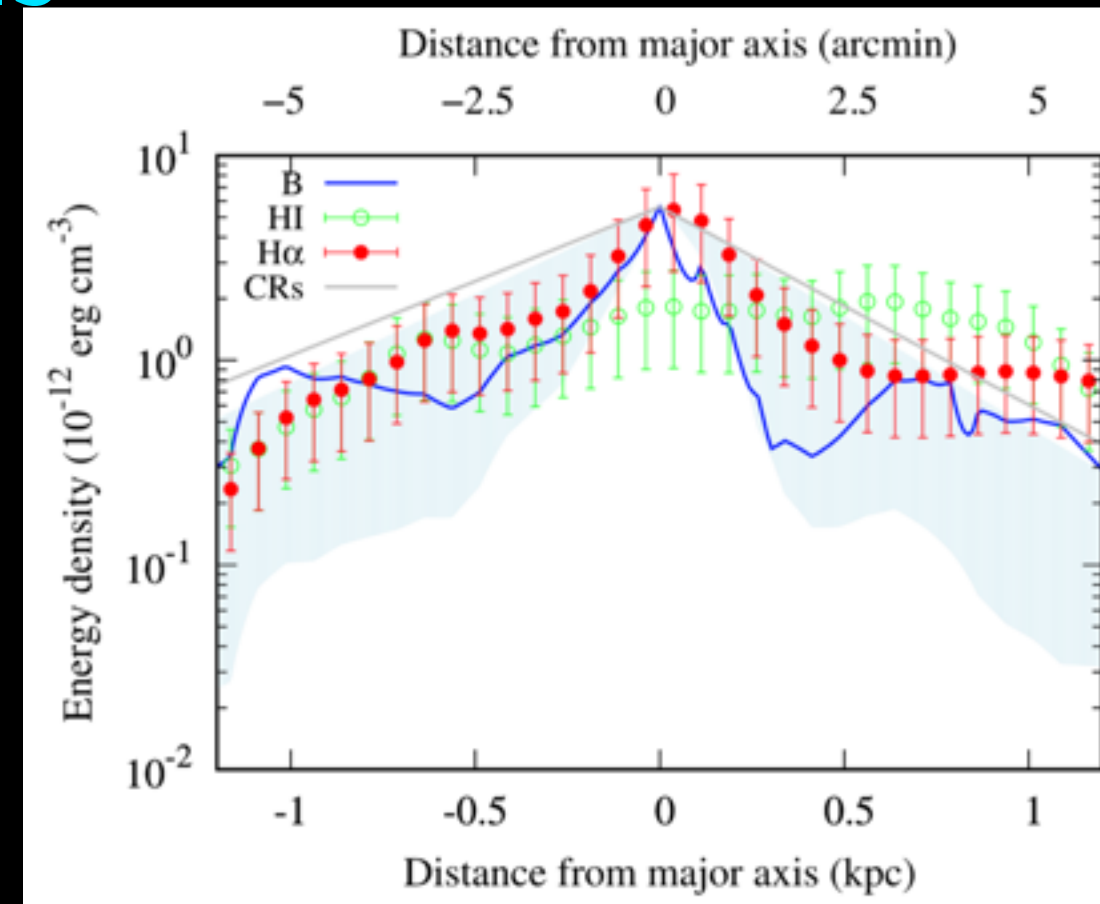
Intensity

Spectral index



Distance from maj. axis

Energy densities



<u>Accelerating wind:</u>

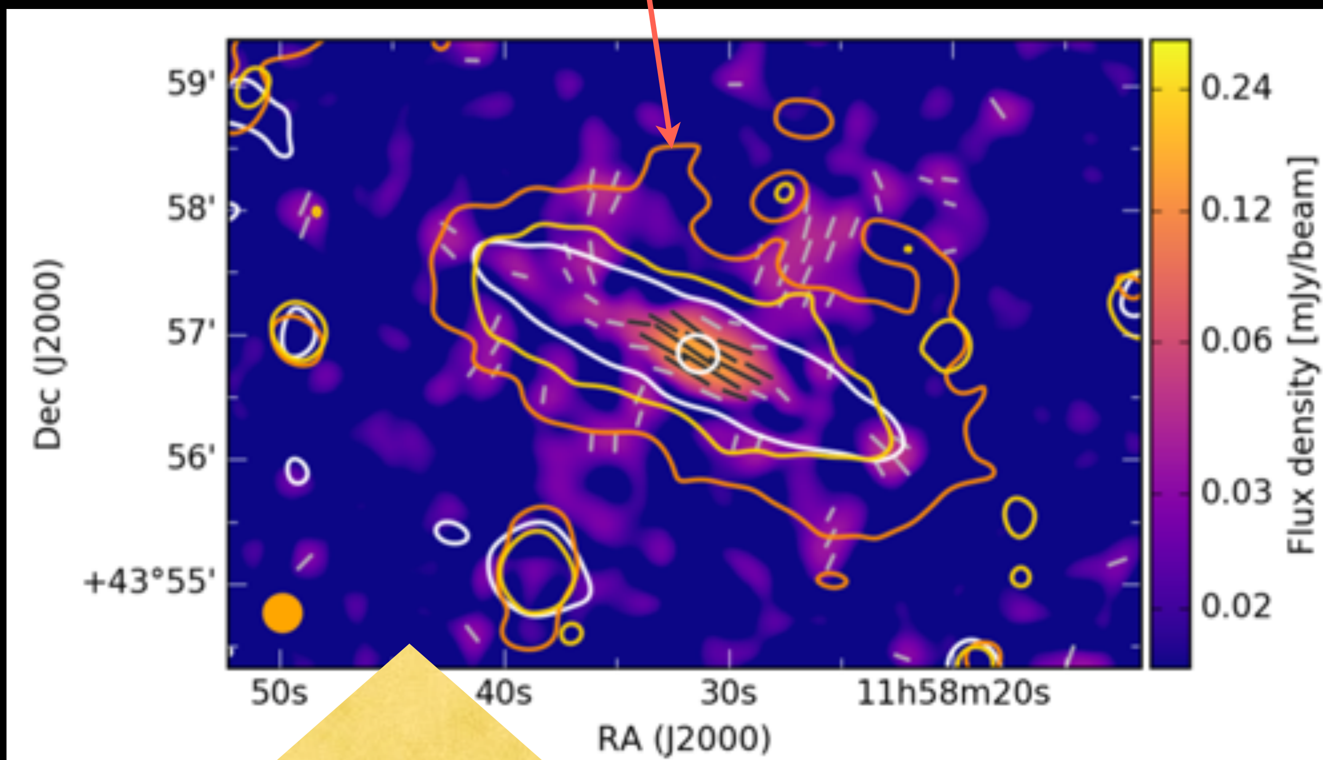
– Reaches V_{esc}
– Solution with equipartition:
  – Magnetic fields
  – Warm neutral medium
  – Warm ionized medium
  – Cosmic rays

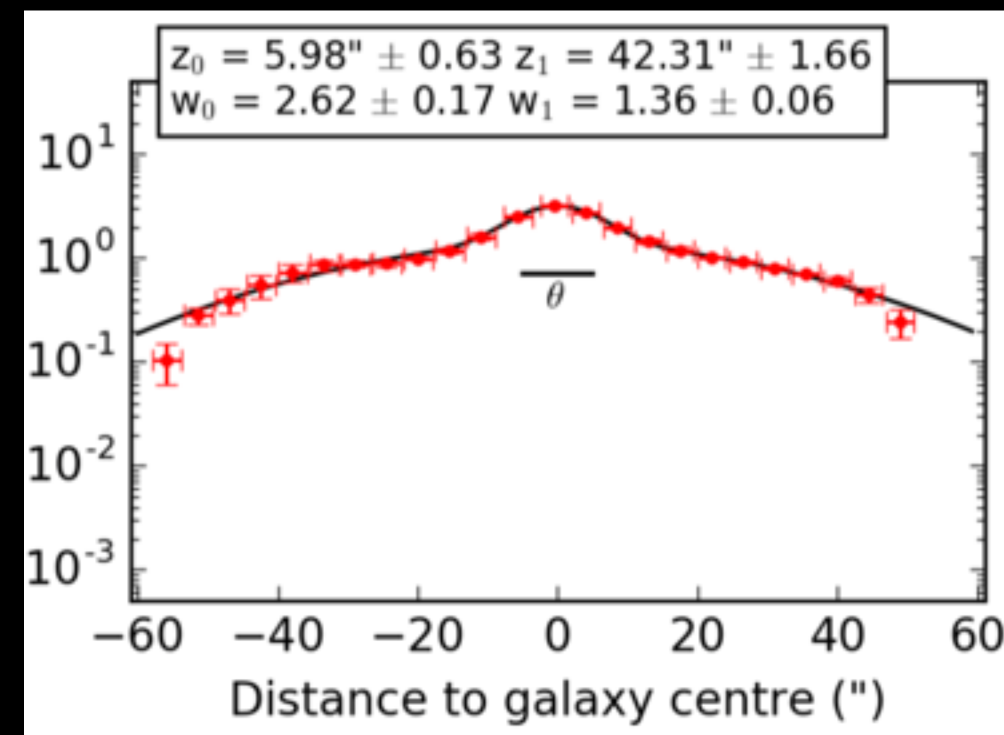
NGC 4013 – hybrid diffusion-advection halo

LOFAR 150 MHz (contours)

Stein et al. (2019, in prep.)

Gaussian intensity profile





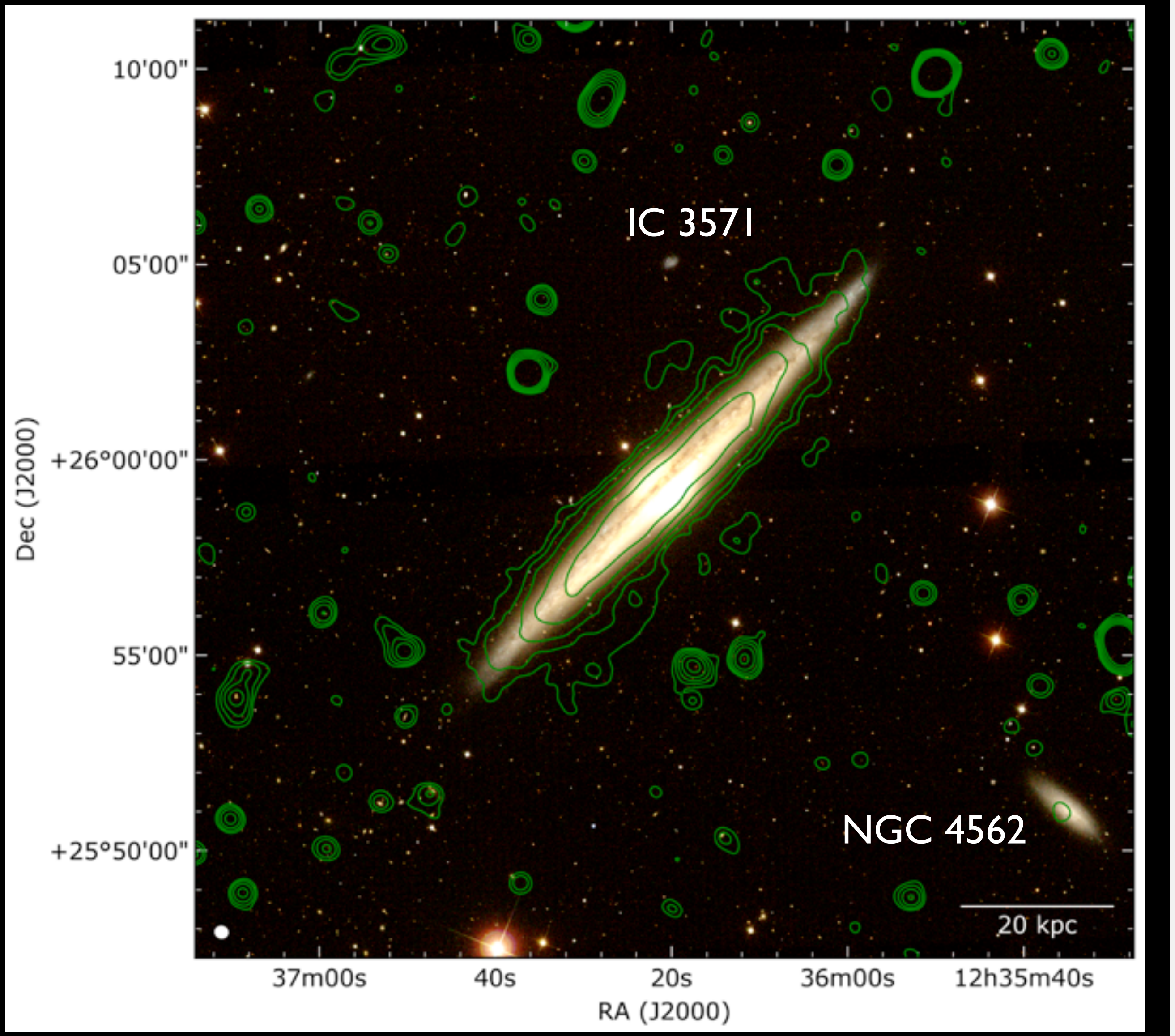
6-GHz B-field vectors

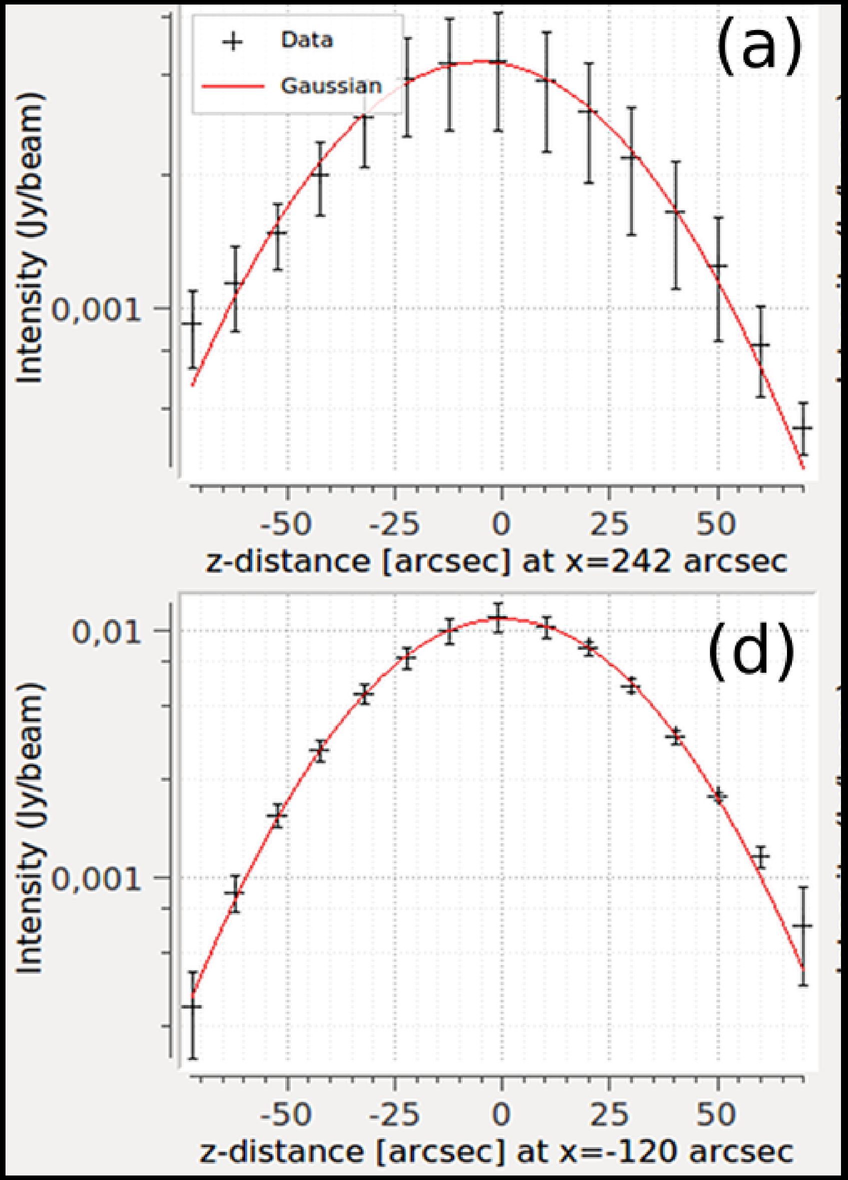
Slow wind (20–50 km s^{-1}); diffusion important

NGC 4565 – diffusion-dominated halo

Gaussian intensity profiles cannot be described by advection

- Low SFR and suface density
- High mass surface density
- No outflow?





Diffusion coefficients: D = (0.7–3.1) x 10^{28} cm^2 s^{-1} at 1 GeV (mostly not energy dependent)

(Heesen et al. in prep.)

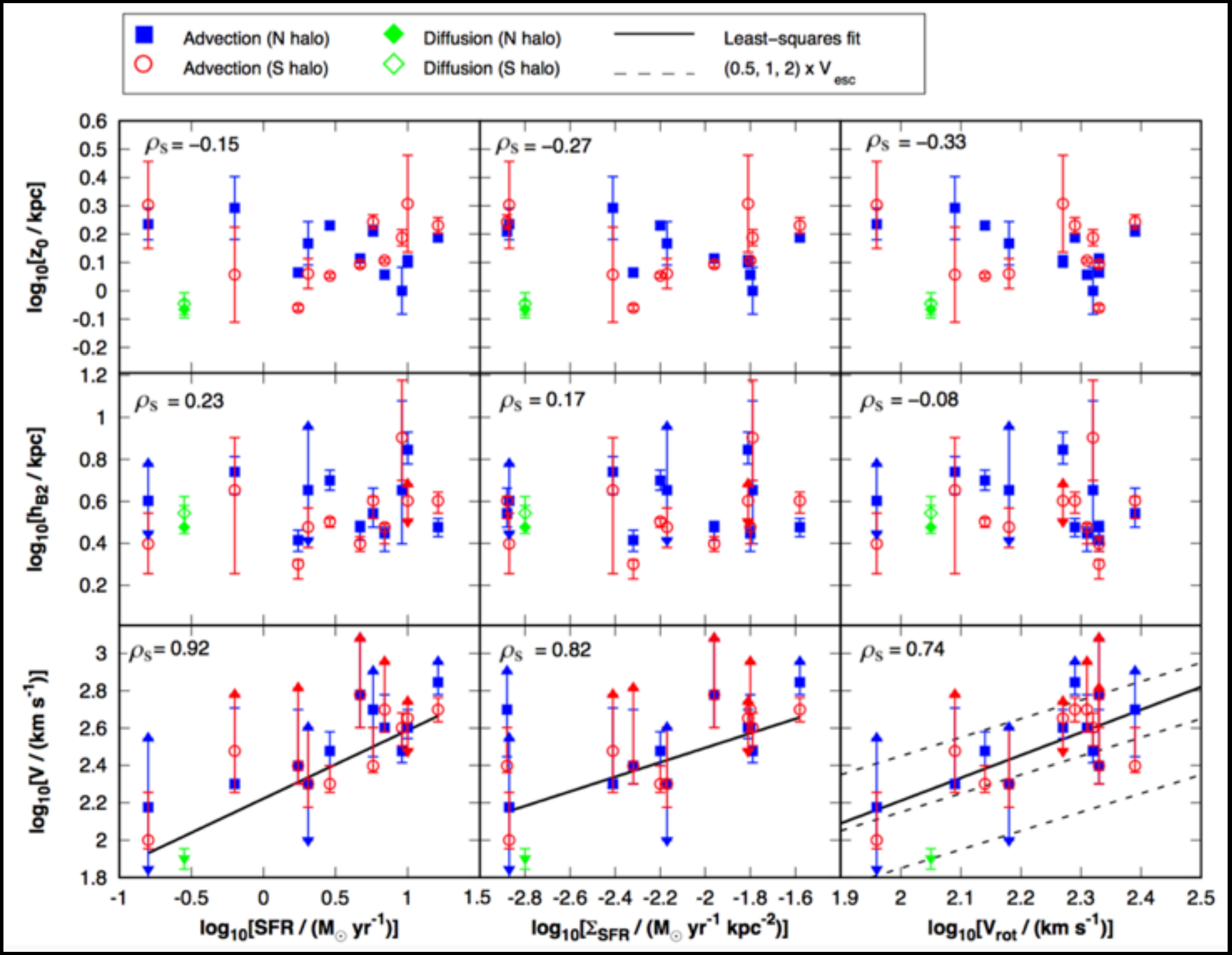
Parameter studies

Heesen et al. (2018b)

Intensity scale height

Magnetic field scale height

Advection speed



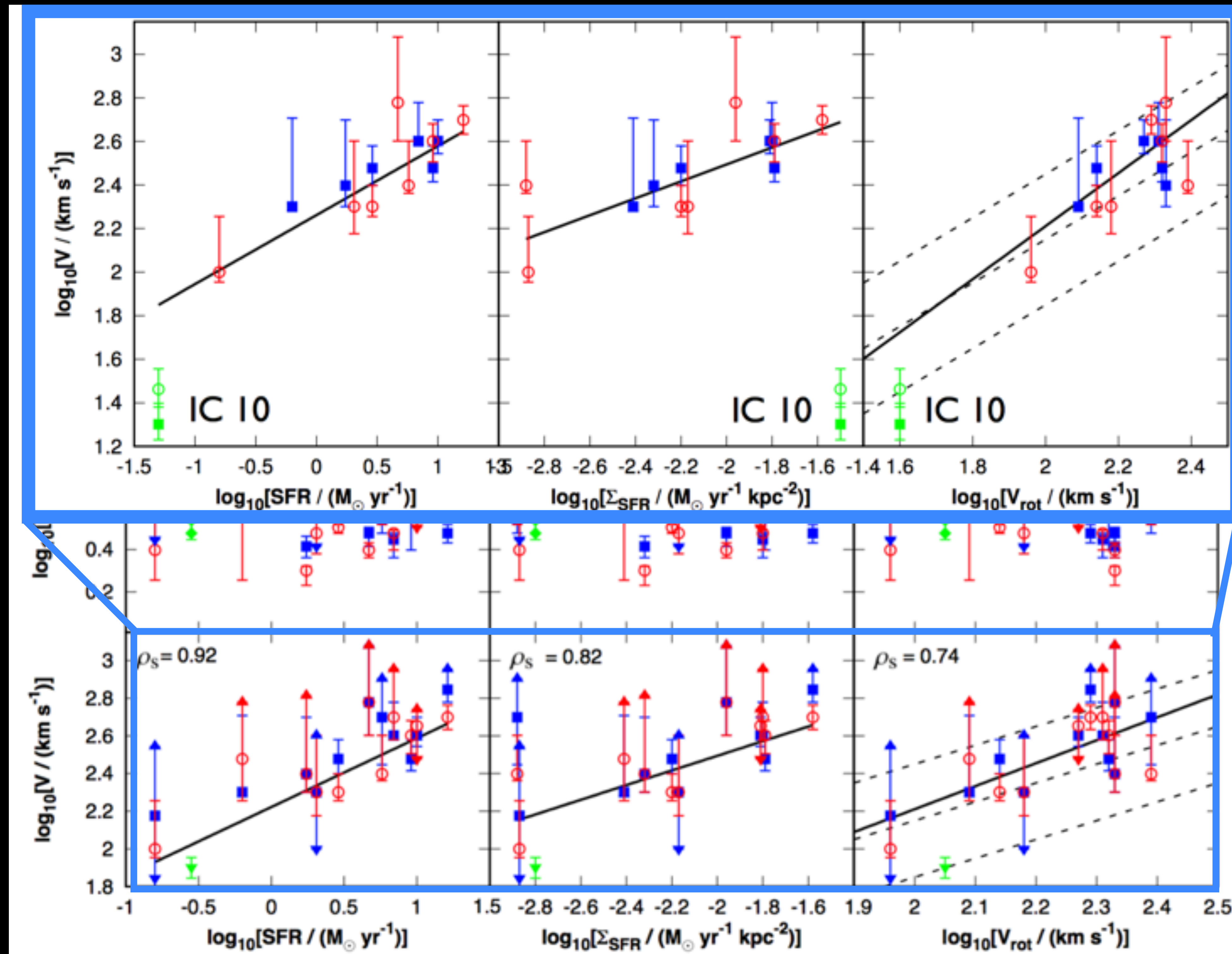
Star formation rate

Star formation rate surface density

Rotation speed

Parameter studies

Heesen et al. (2018b)



Intensity scale height

Magnetic field scale height

Advection speed

Star formation rate

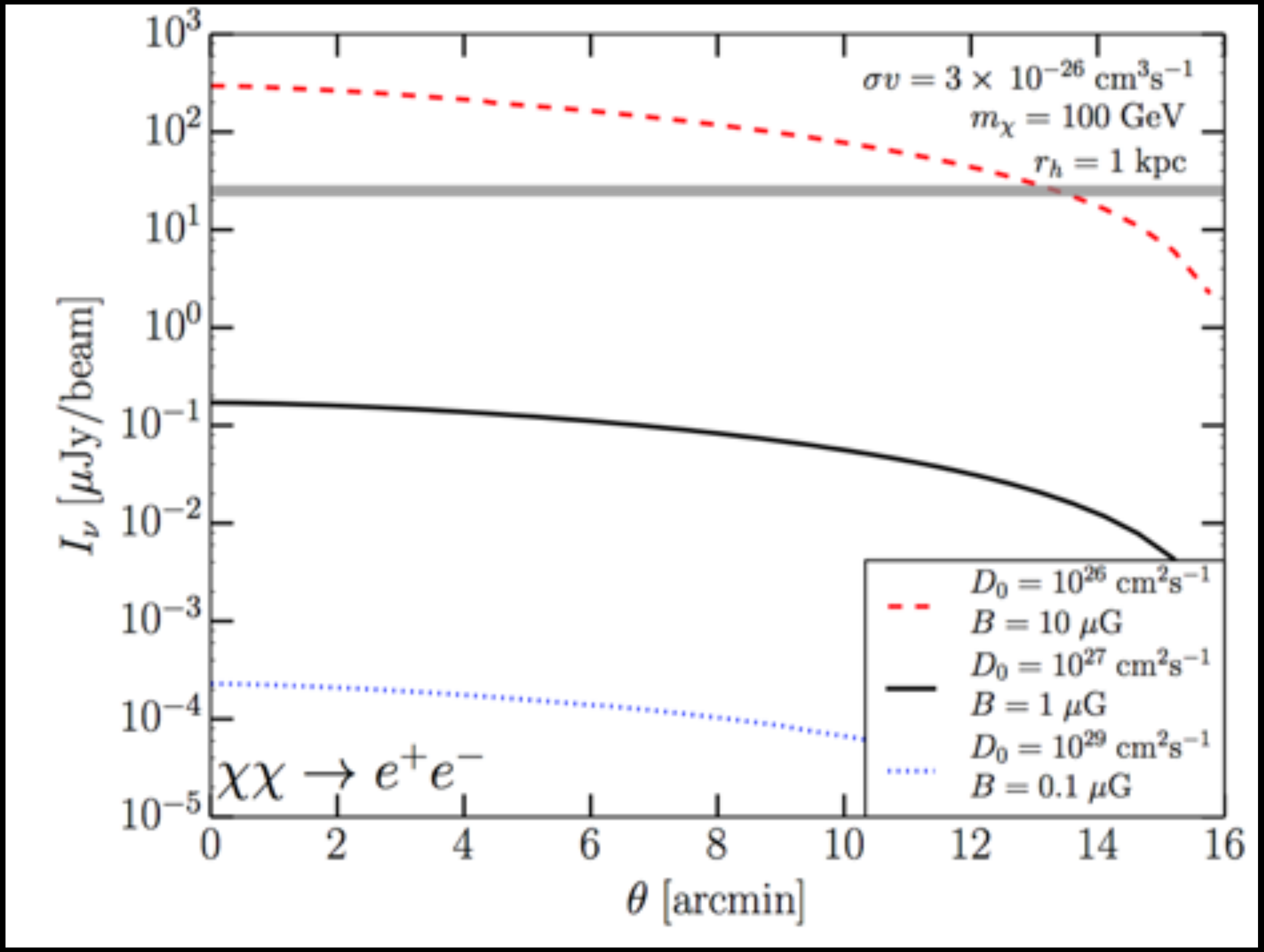
Star formation rate surface density

Rotation speed

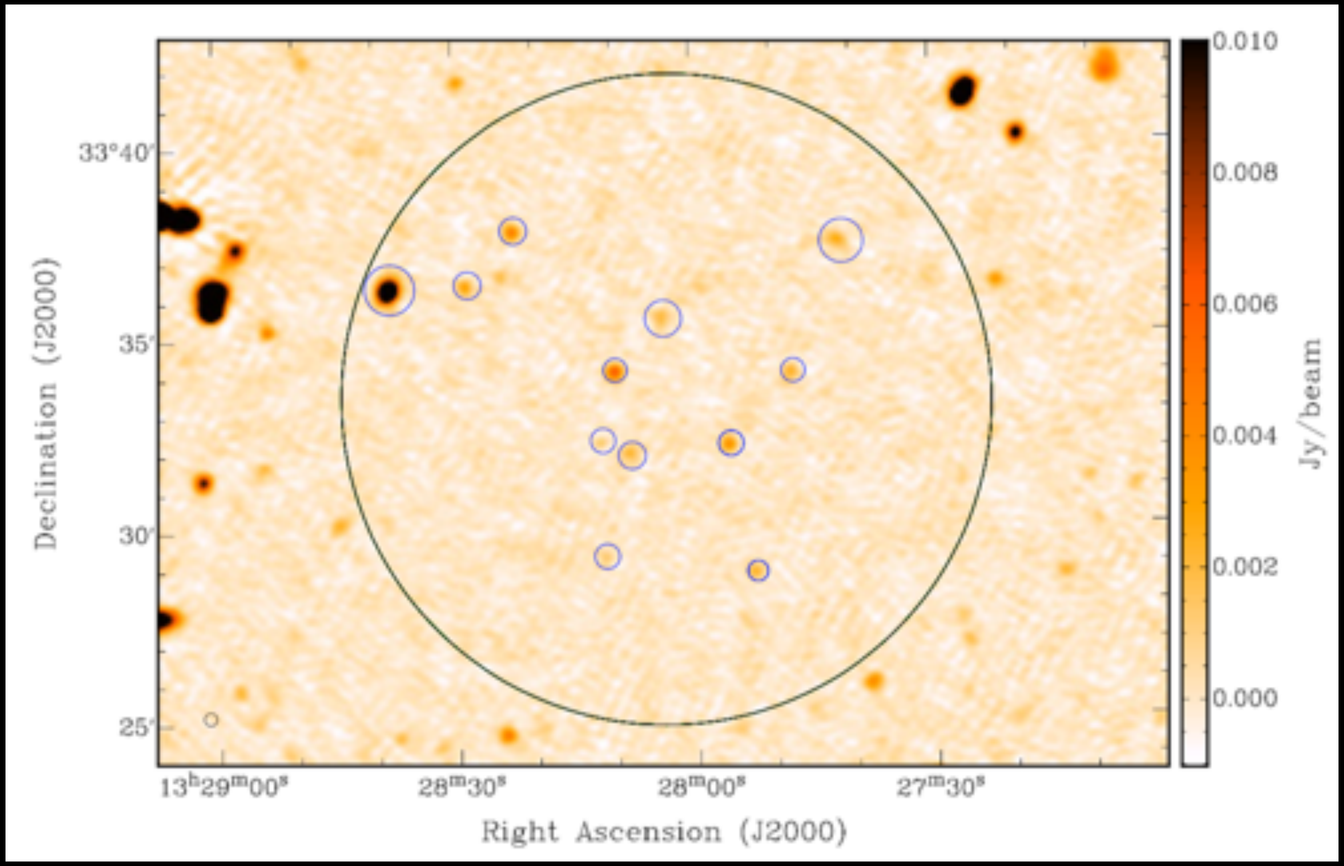
Dark matter in Canes Venatici I

Vollmann et al. (2019, in prep.)

Radial intensity profile



LOFAR 150-MHz

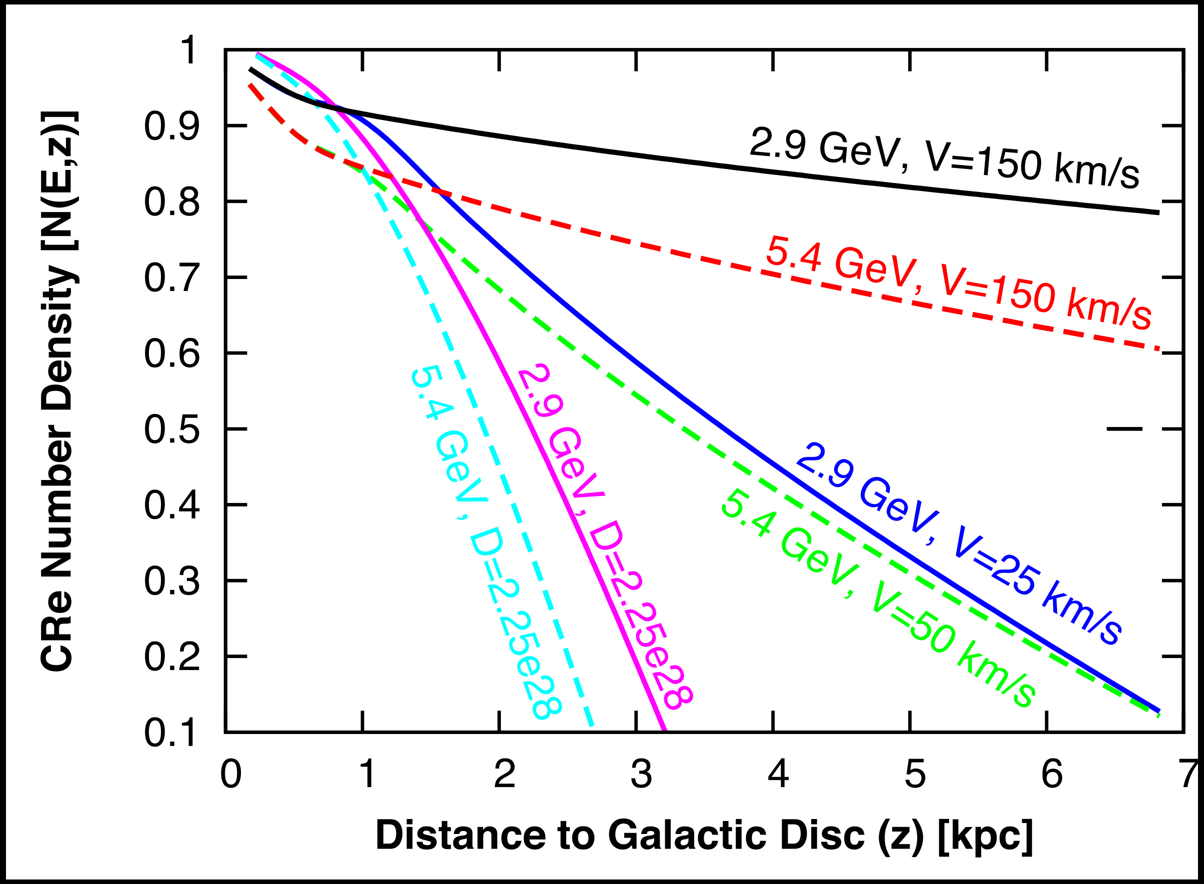


Upper limits comparable to *Fermi*–LAT in γ-rays!

Conclusions

- Radio haloes indicate presence of CRe
- Exponential intensity profile: advection
- Gaussian intensity profile: diffusion
- More important even: spectral index profile
- Accelerated outflow in M108 (NGC 3556)
- NGC 4565: diffusion-dominated
- IC10: possibly accelerated wind
- NGC 4013: hybrid diffusion-advection halo

1D modelling of cosmic-ray transport



Advection:

$$\frac{\partial N(E,z)}{\partial z} = \frac{1}{V}\left\{\frac{\partial}{\partial E}\left[b(E)N(E,z)\right]\right\}$$

Diffusion:

$$\frac{\partial^2 N(E,z)}{\partial z^2} = \frac{1}{D}\left\{\frac{\partial}{\partial E}\left[b(E)N(E,z)\right]\right\}$$

N(E, z): Cosmic Ray electron number (column) density

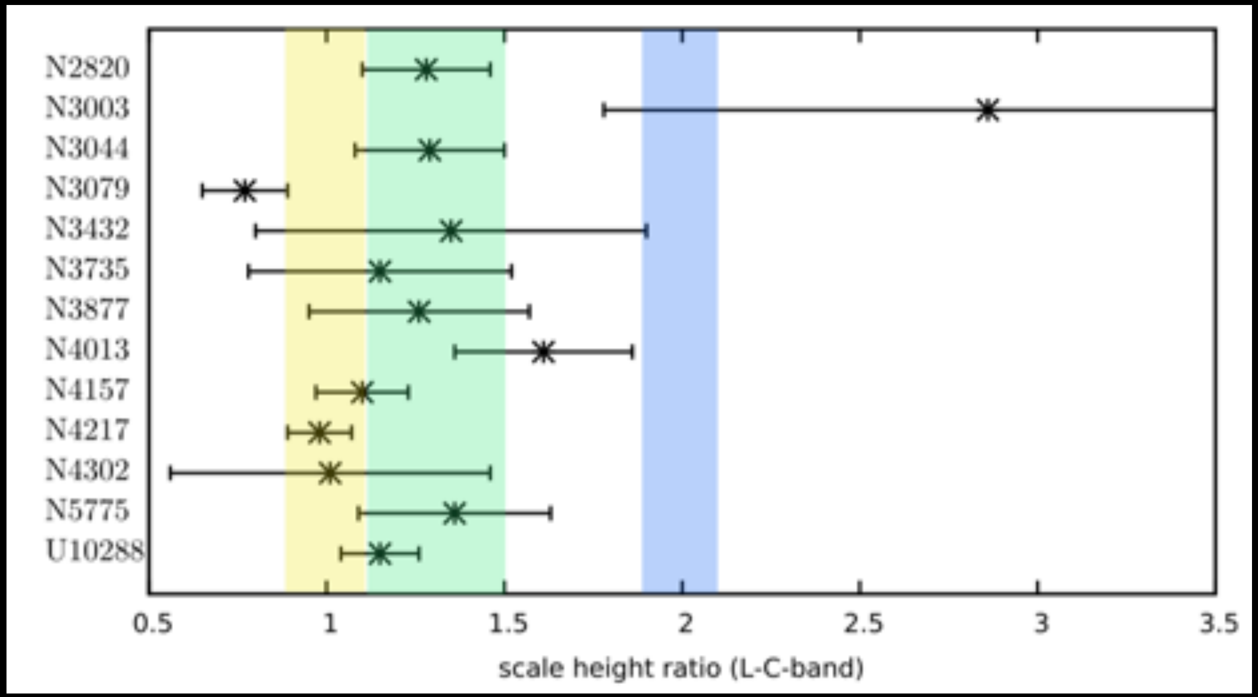
CRe losses: $-\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right) = b(E) = \frac{4}{3}\sigma_{\mathrm{T}}c\left(\frac{E}{m_{\mathrm{e}}c^2}\right)^2 (U_{\mathrm{rad}} + U_{\mathrm{B}})$

inverse-Compton losses

synchrotron radiation

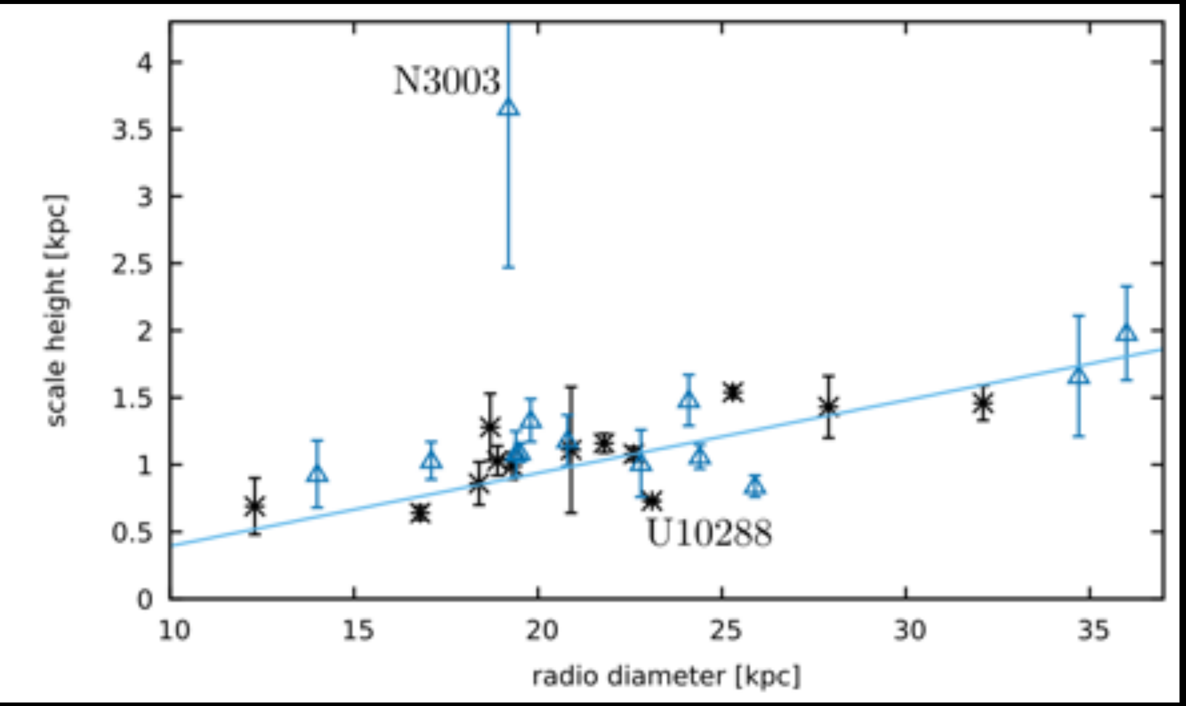
Scale heights in CHANG-ES galaxies

Krause et al. (2018)

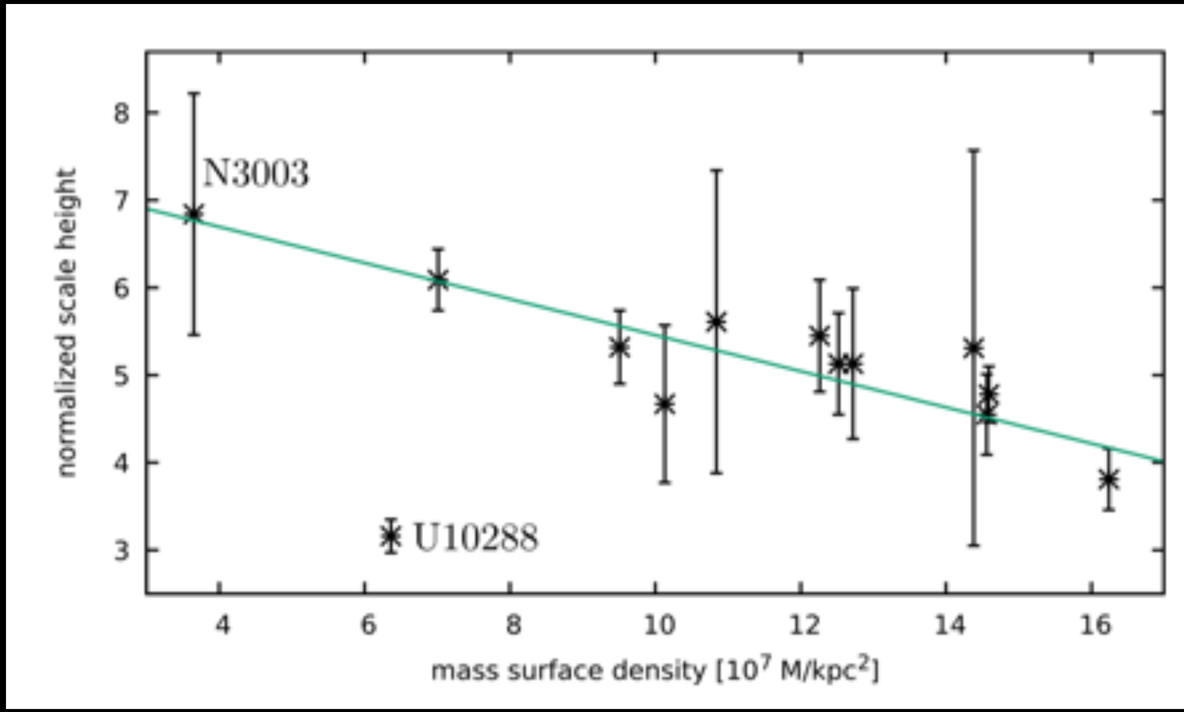


Yellow: advection (escape)
Green: diffusion
Blue: advection (no escape)

Trend with diameter

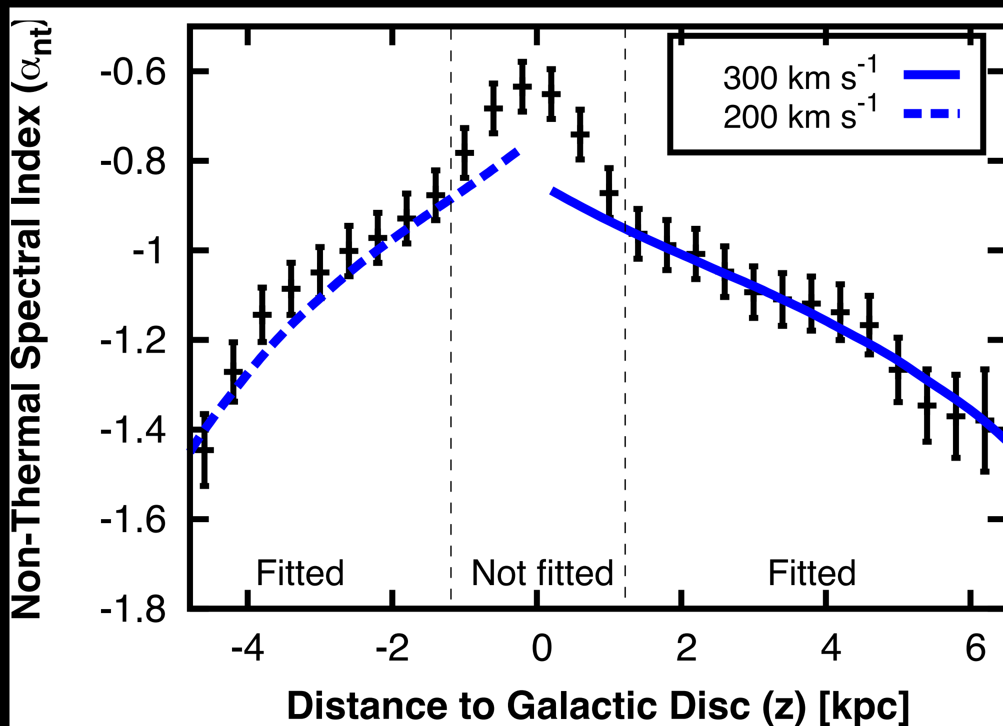


Trend with mass surface density

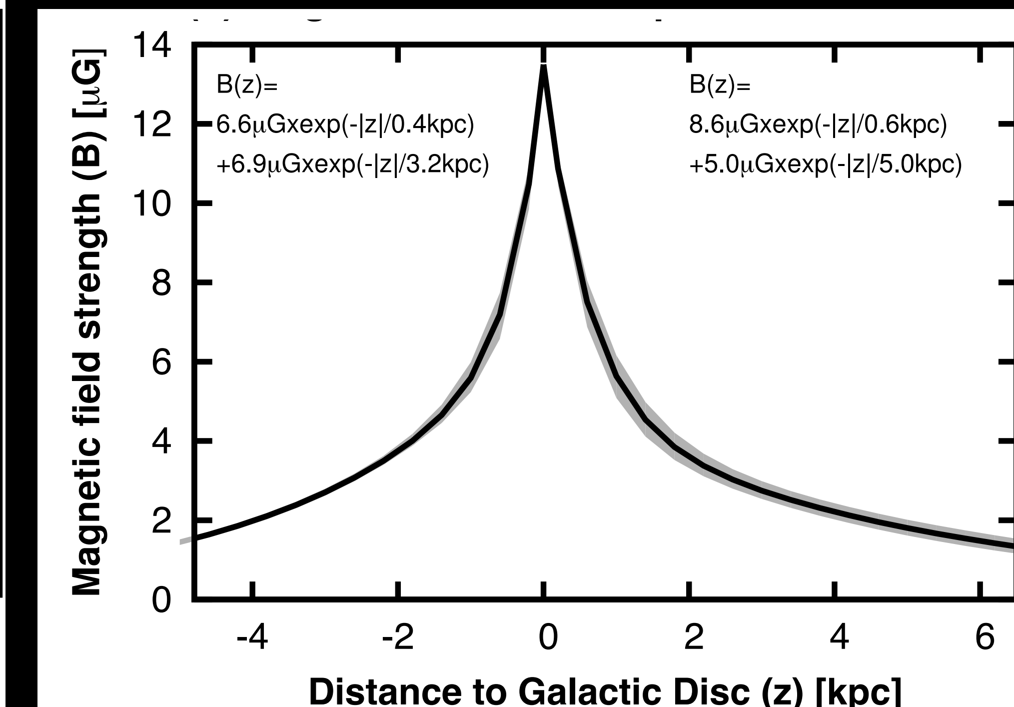


NGC 4631: Advection model

Radio spectral index profile

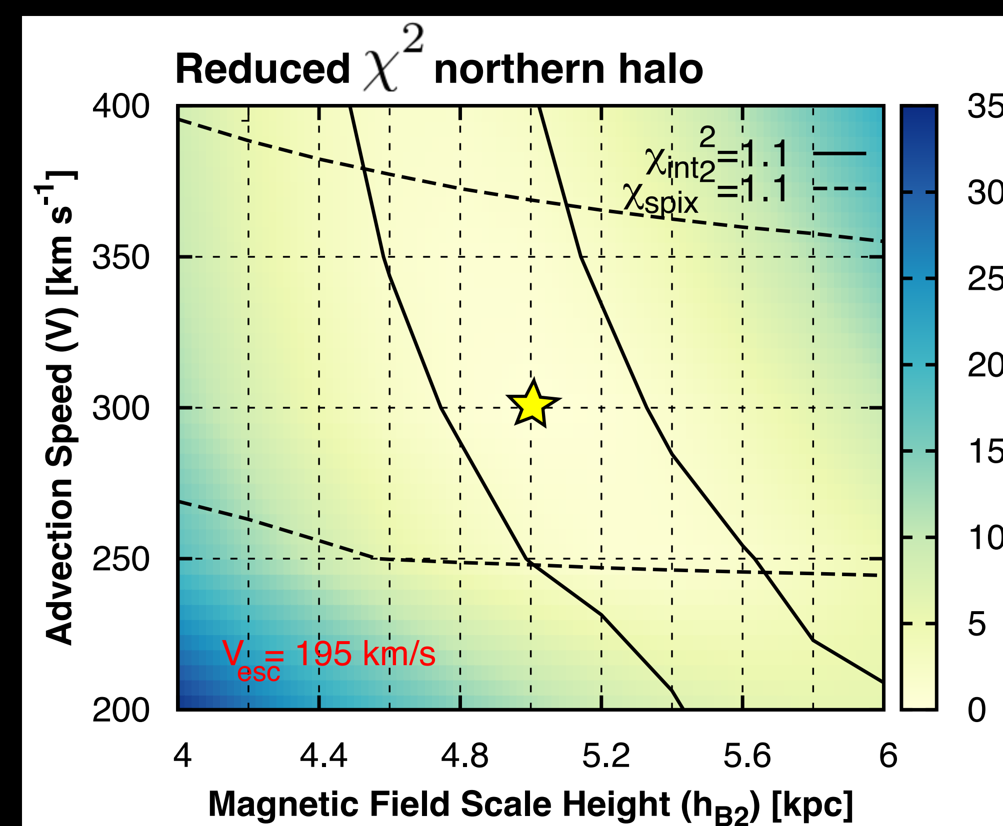


B-field model profile



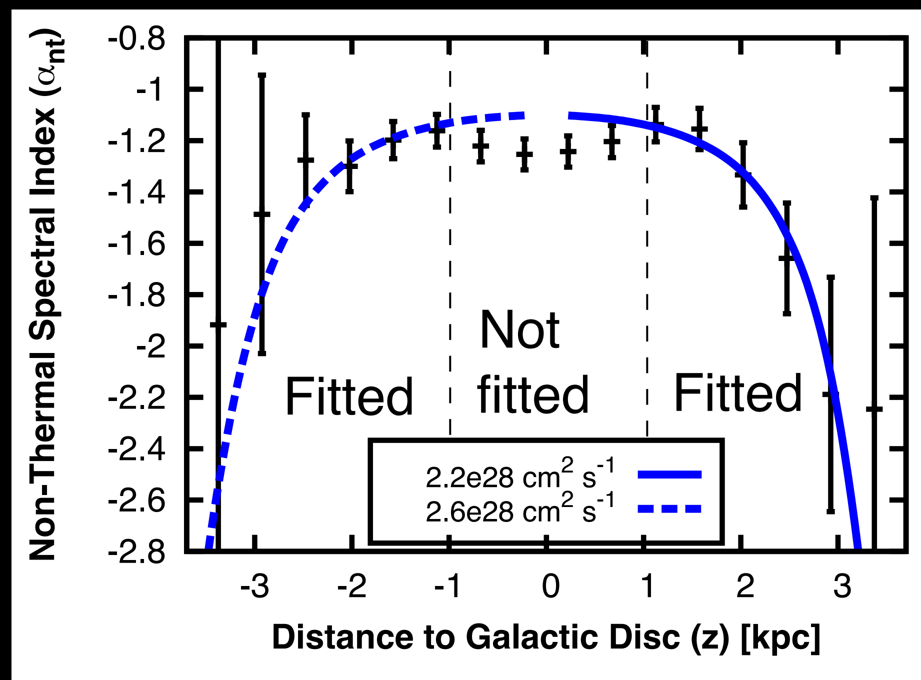
Exponential intensity profiles
+ linear spectral index profiles

Advection dominated halo

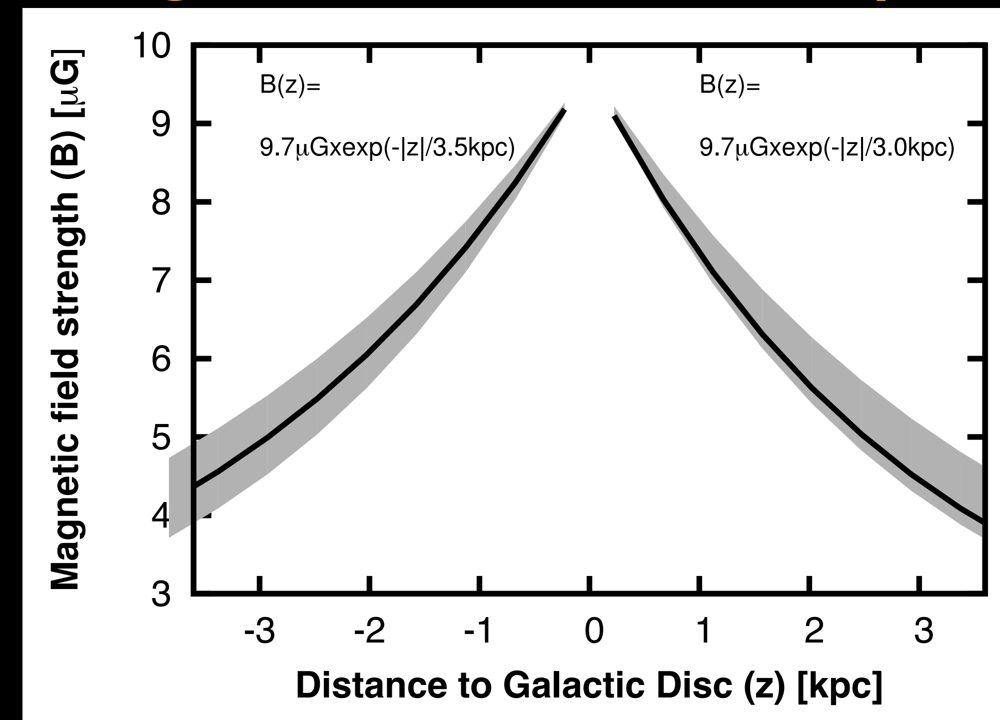


NGC 7462: Diffusion model

Radio spectral index profile

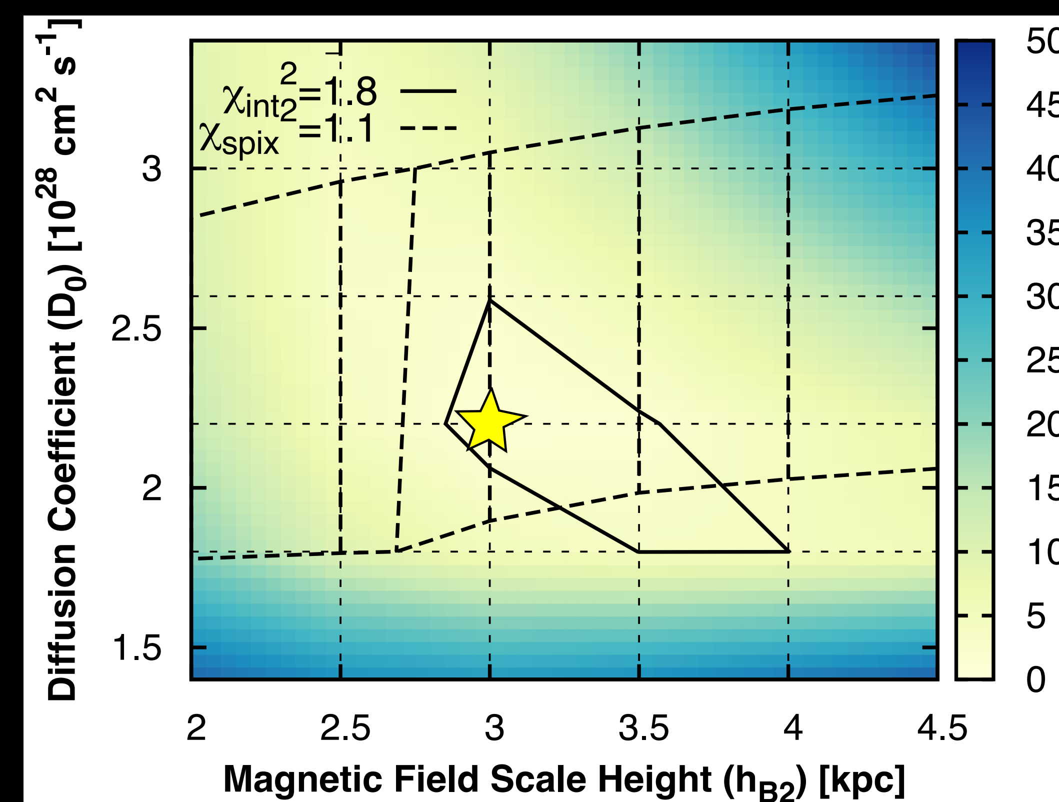


Magnetic field model profile



Gaussian intensity profiles
+ parabolic spectral index profiles

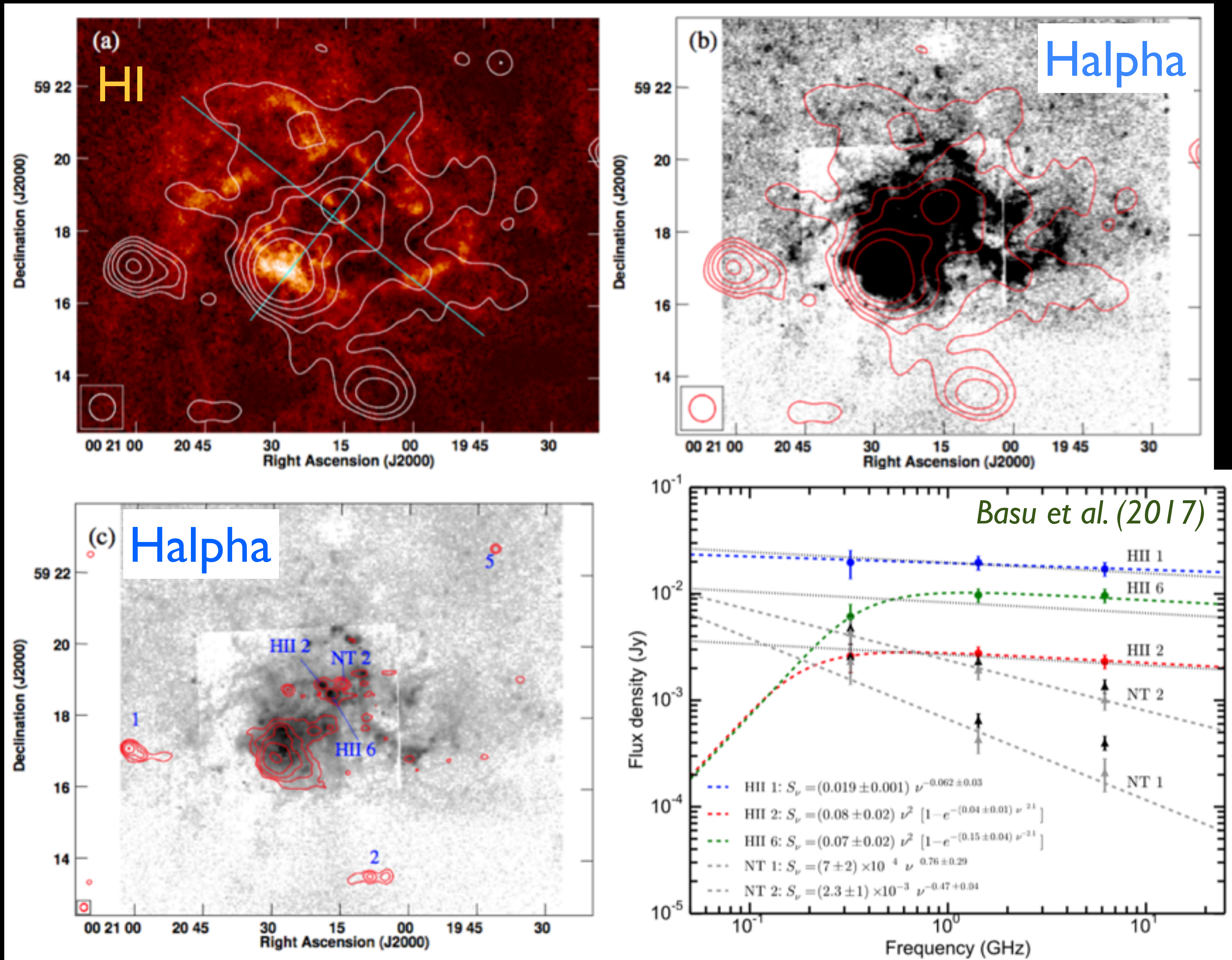
Reduced χ^2 northern halo



Diffusion dominated halo

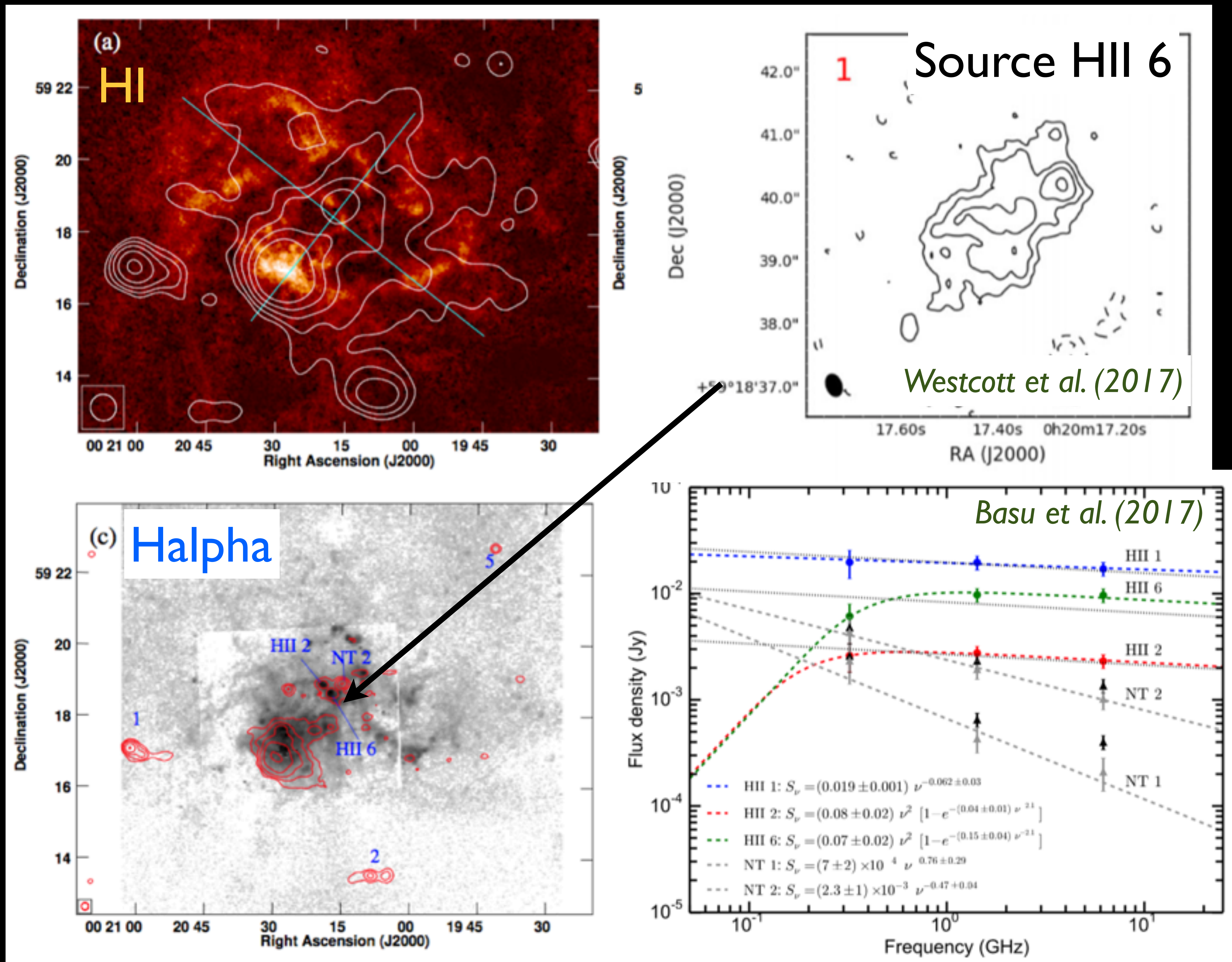
IC 10: a starburst dwarf galaxy

Heesen et al. (2018c)



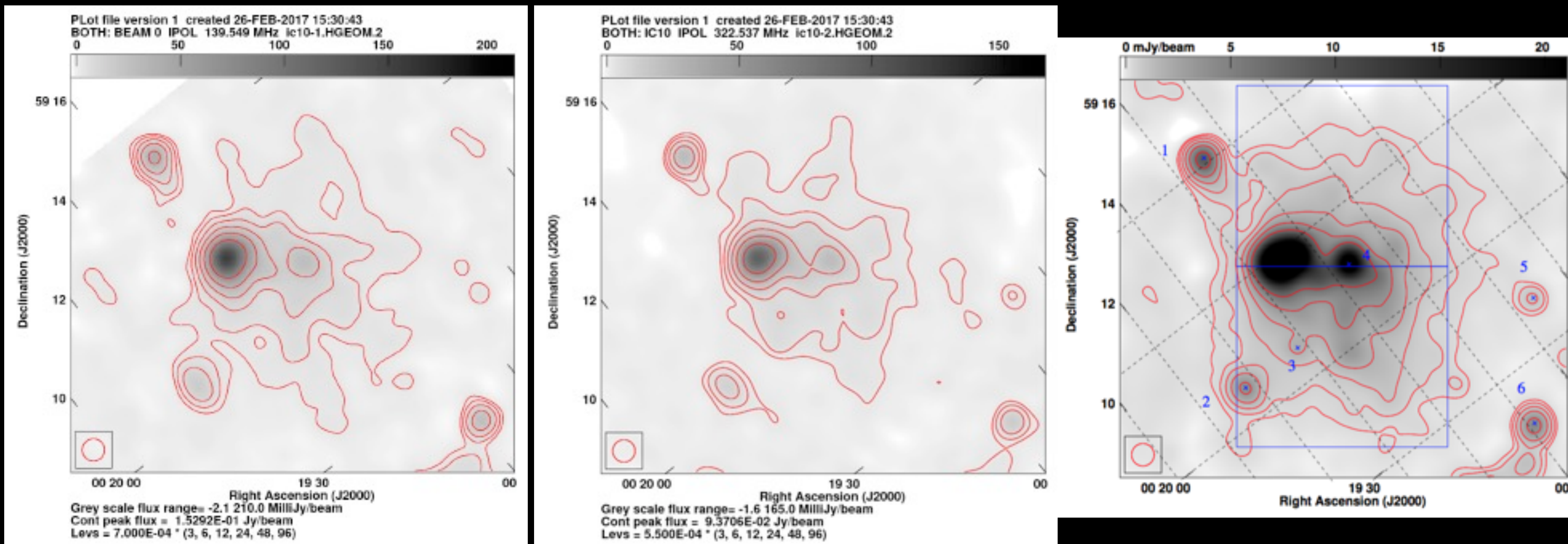
IC 10: a starburst dwarf galaxy

Heesen et al. (2018c)



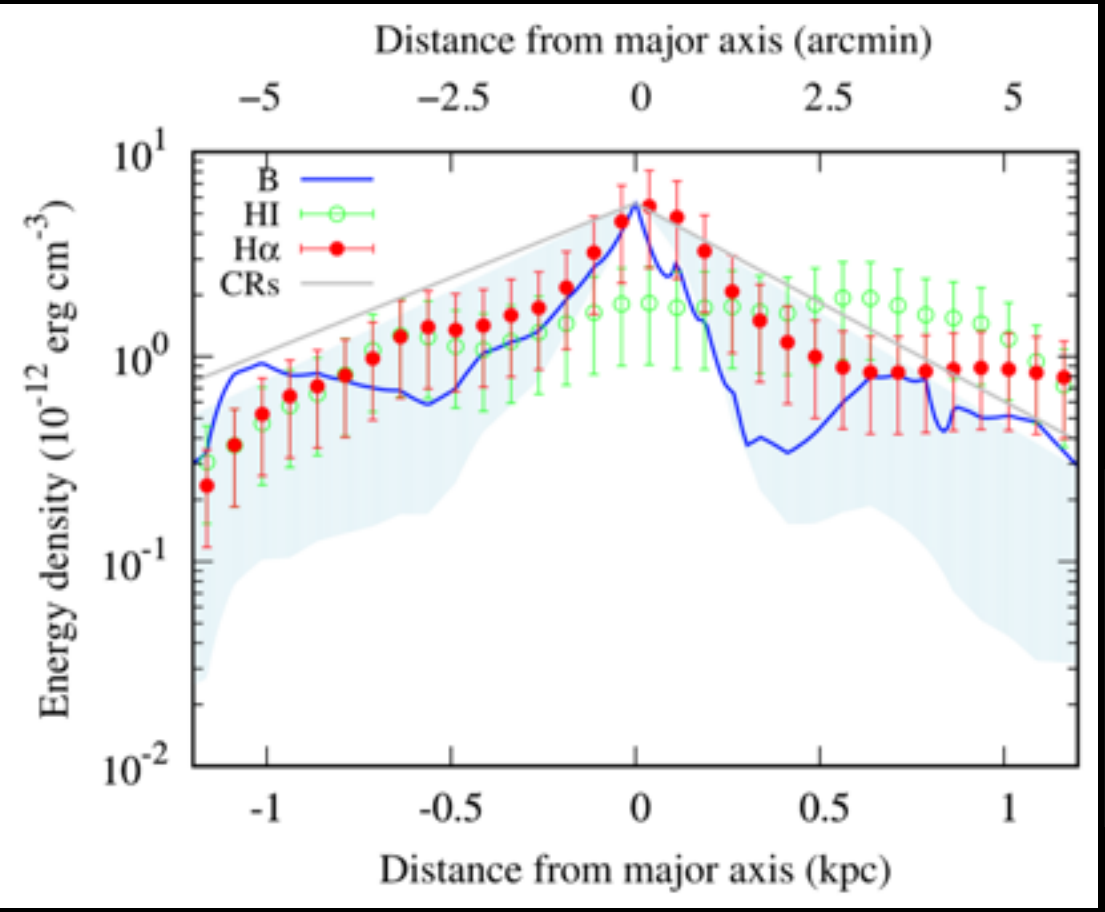
Radio halo

LOFAR 140 MHz GMRT 325 MHz VLA 1580 MHz



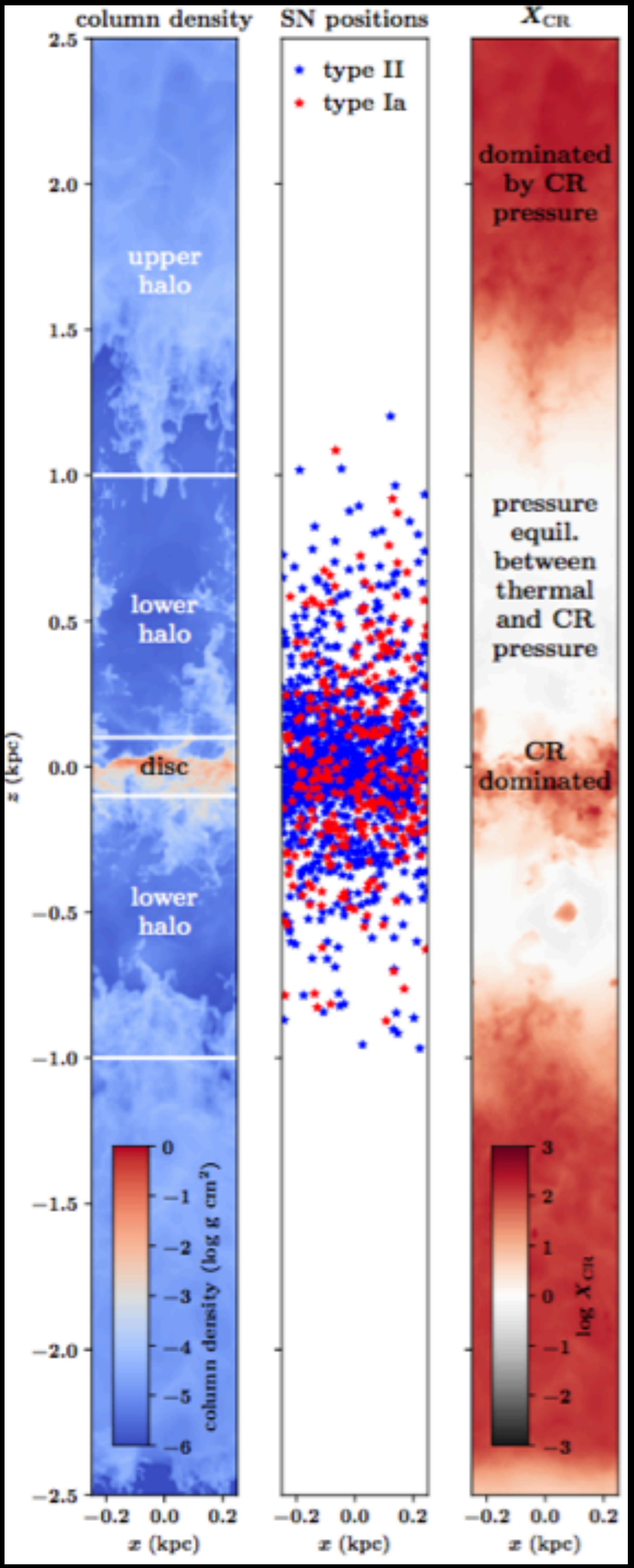
- Structure is consistent with higher frequencies
- Flat non-thermal spectral index ($\alpha_{nt} = -0.5$)
- Halo is not spherical, but boxy
- Similar to NGC 1569 (Sridhar et al. 2018, in prep.)

Cosmic ray-driven wind



Energy densities

Cosmic rays may dominate pressure in halo



Girichidis et al. (2018)

Model III (accelerating wind):

– Reaches V_{esc}
– Self-consistent solution with equipartition:
– Magnetic fields
– Warm neutral medium (HI)
– Warm ionized medium (Hα)
– Cosmic rays