The 20-kpc radio superbubble in the star-forming galaxy NGC 4217

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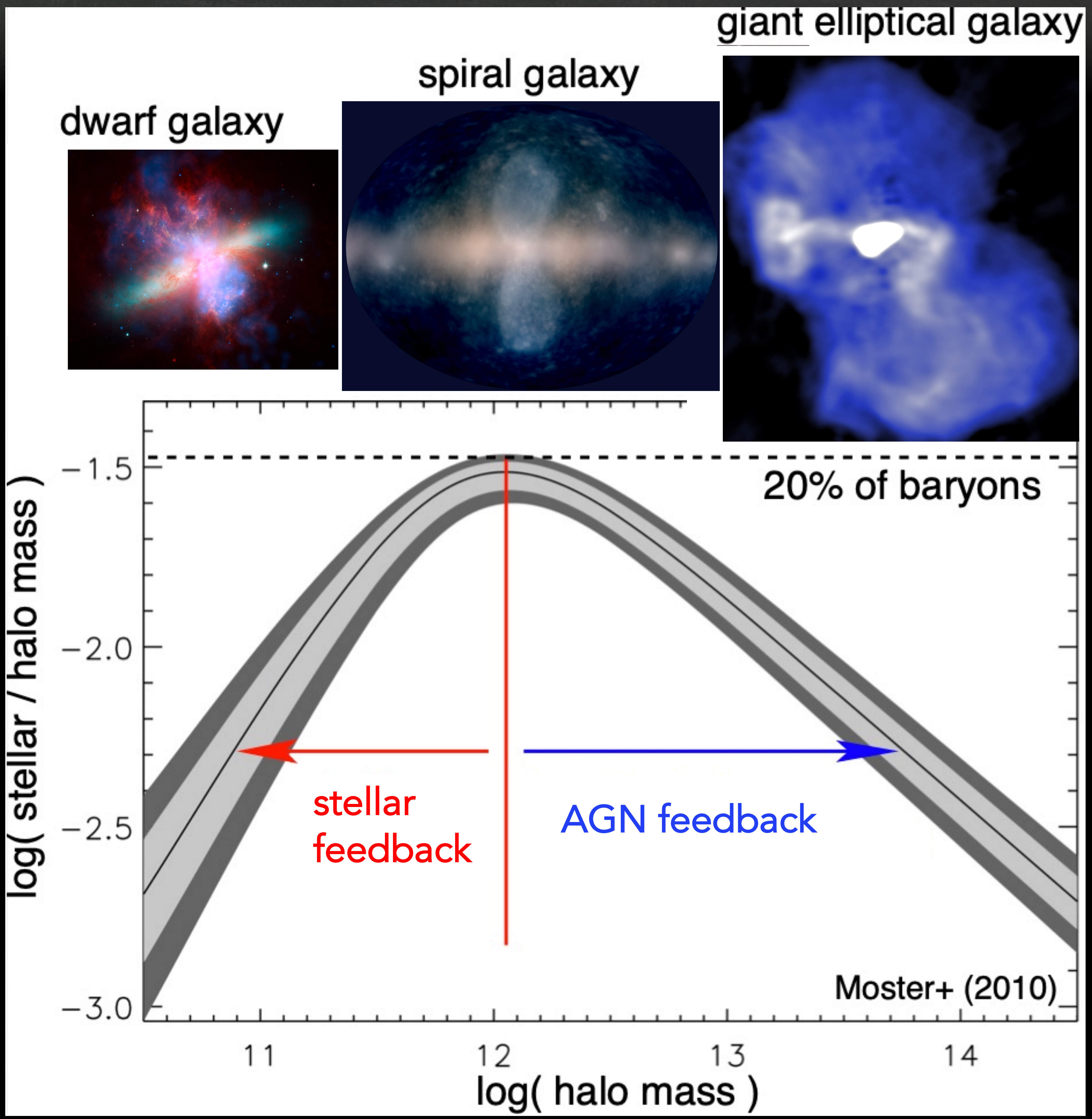
With contributions from the CHANG-ES consortium and the LOFAR Magnetism Key Science Project

Cosmic rays and magnetic fields in galaxies

why study them?

- Feedback in galaxies is very efficient
- Enhancement of outflows and suppression of accretion of matter
- Difficult to explain theoretically
- Cosmic rays may help, particularly in Milky Way-like galaxies

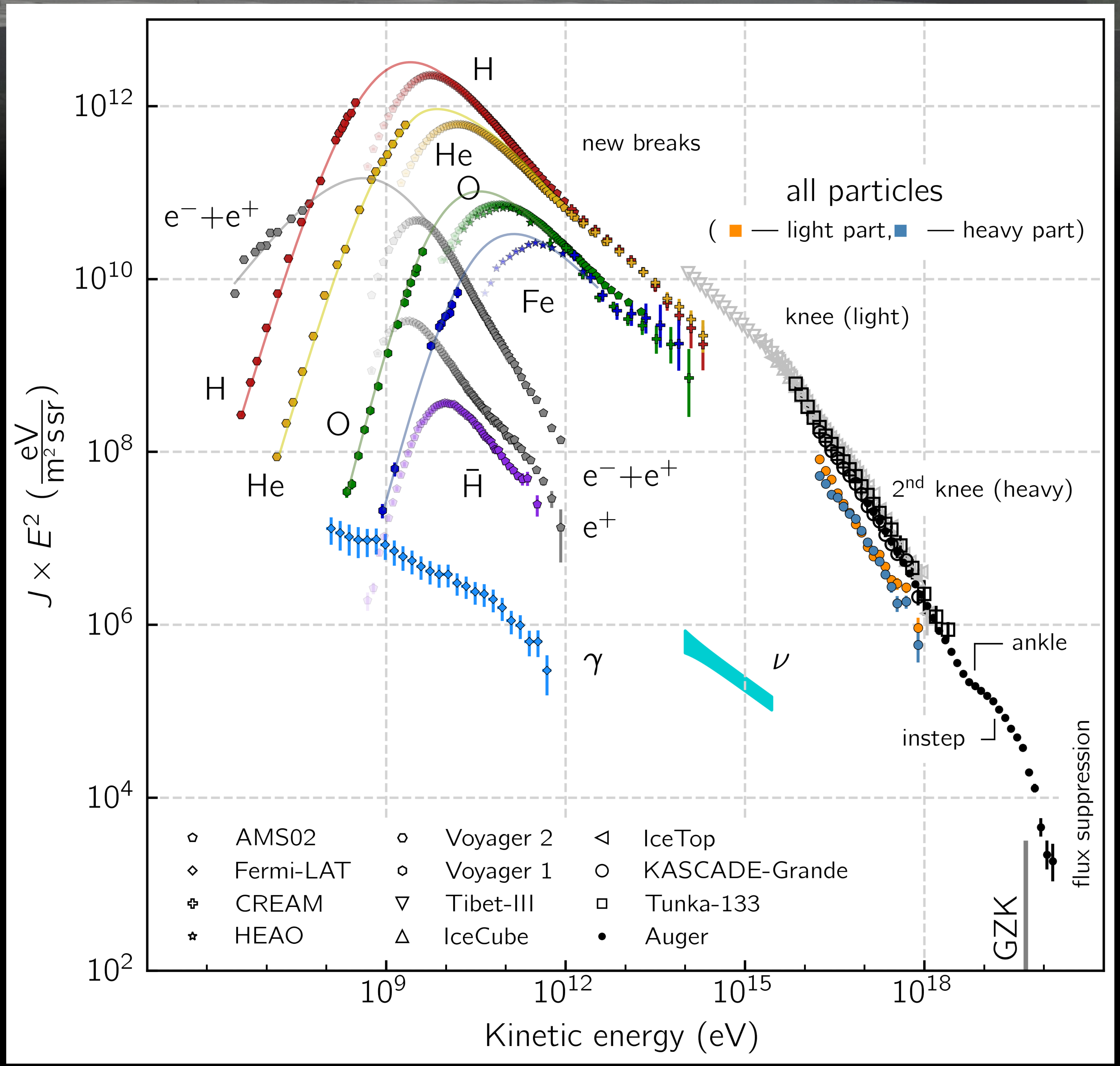


Ruszkowski & Pfrommer (2023)

Cosmic rays

and radio continuum emission

- Energy density ~ magnetic field ~ thermal gas ~ 1 eV cm^{-3}
- GeV-protons energetically most important
- GeV-electrons are observed in the radio
- But they are only at 1 per cent of the proton energy density

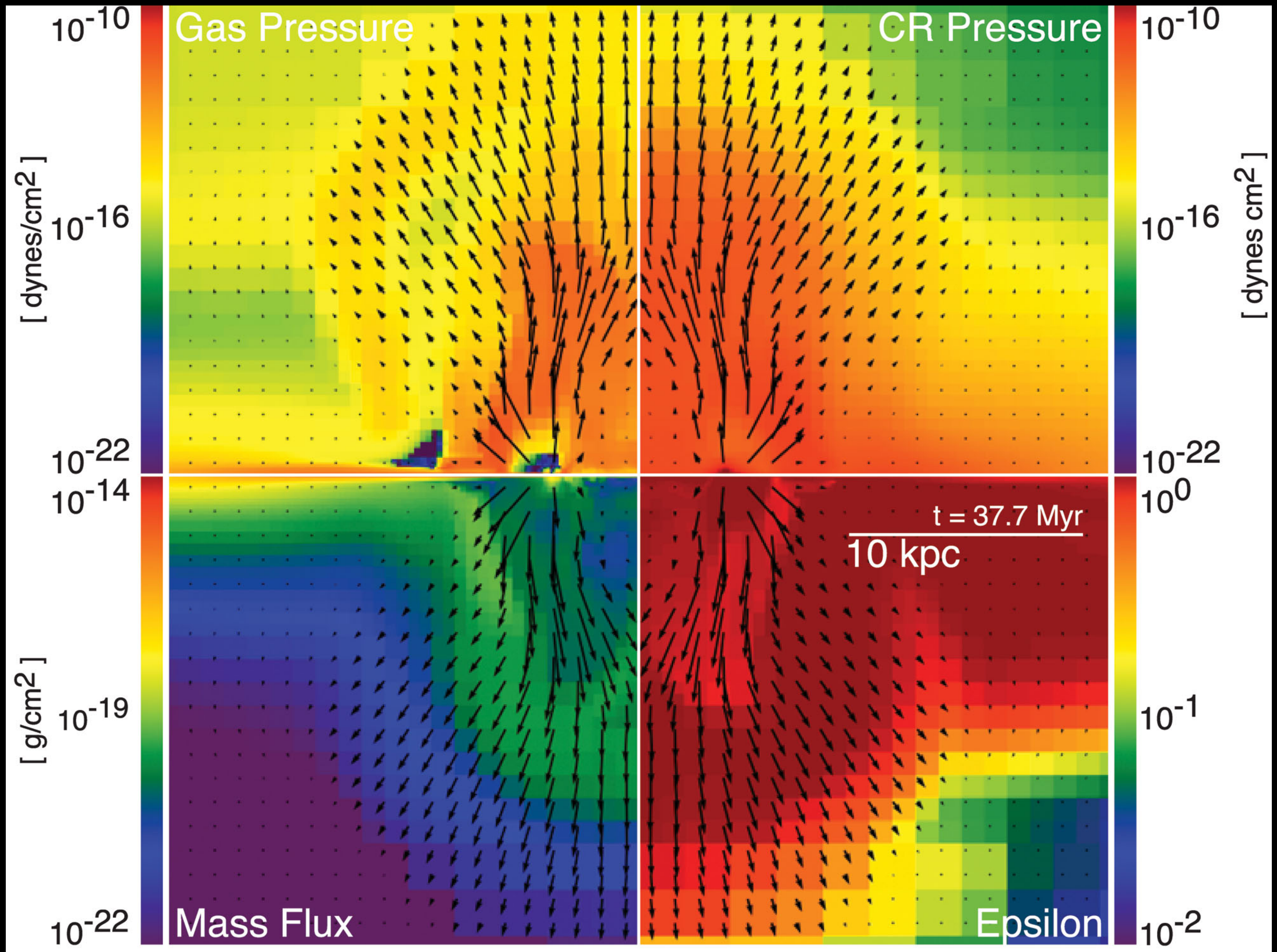


Lenok (2022), Ruszkowski & Pfrommer (2023)

Cosmic ray-driven winds

from theory and simulations

- Cosmic rays obtain only 10 per cent of the kinetic energy in supernovae
- Yet, the can accelerate gas in the halo
- Leads to bipolar outflow in post-starburst phase
- Cosmic ray-driven winds theory (*Breitschwert et al. 1992, Everett et al. 2008, Recchia et al. 2016*) and simulations (*Girichidis et al. 2018, Thomas et al. 2023*)



Salem & Bryan (2014)

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The prime example of a galactic wind

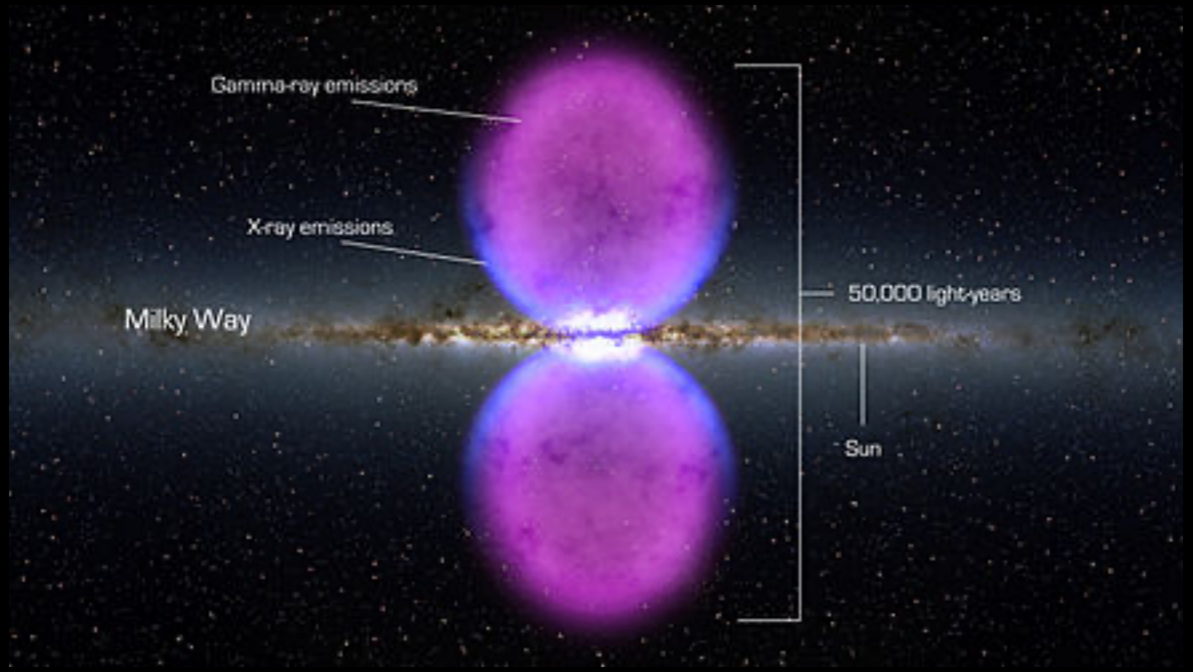
in the post-starburst galaxy M 82

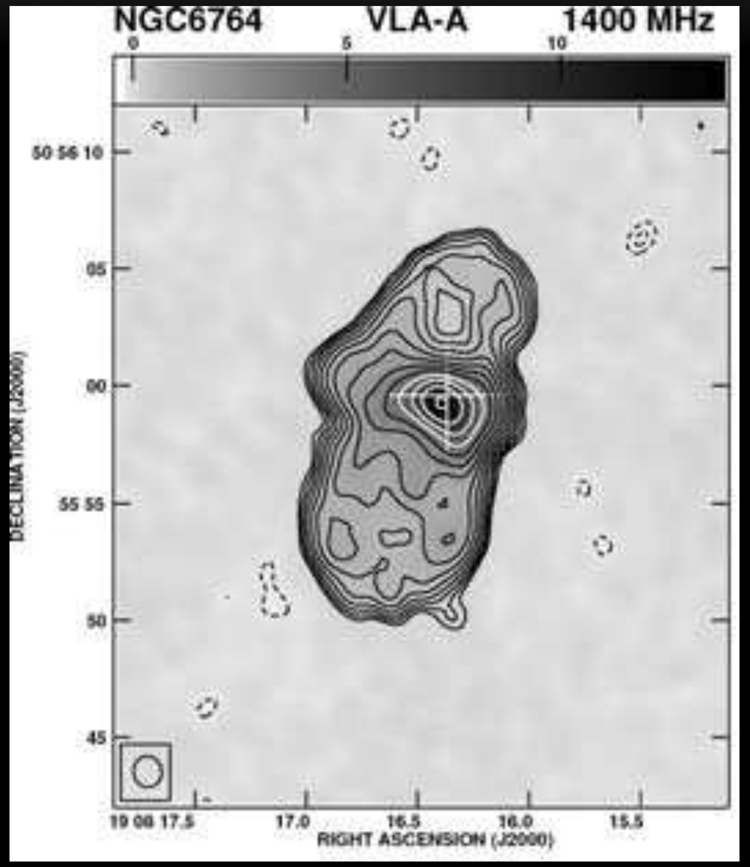
- Double-peaked emission-line profiles are observed along the minor axis
- Can be modeled as an outflow along a hollow biconical structure
- X-ray emission encompassed by Halpha emission

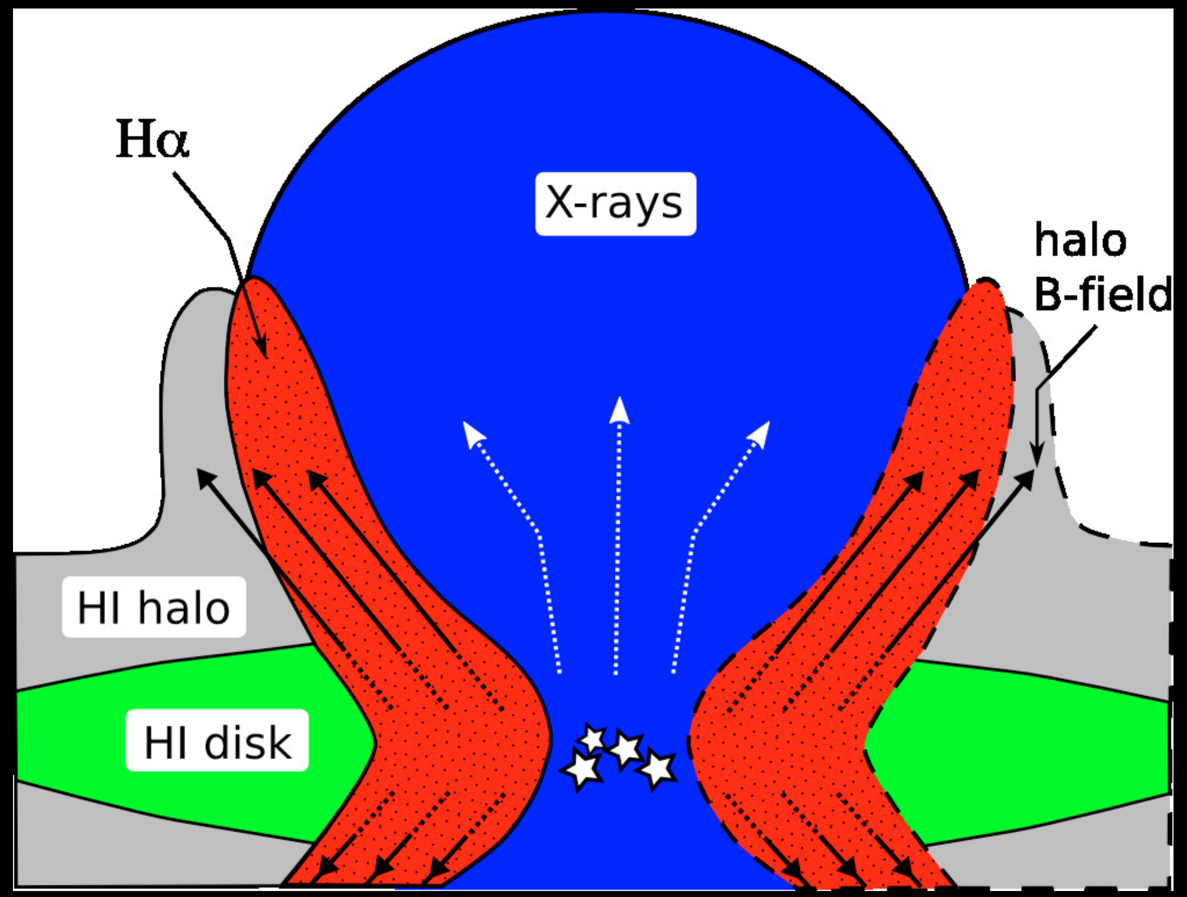
Why are no 10-kpc sized bubbles observed?

Spectral ageing, weak magnetic fields, sensitivity of radio images

- Fermi bubbles in the Milky Way
- kiloparsec-sized bubbles related to active galactic nuclei
- But flared radio haloes with X-shaped magnetic fields







Low-frequency Array (LOFAR)

a European radio interferometer

- 46 Dutch stations and16 international stations
- LOFAR Two-metre Sky Survey (LoTSS)
- High-band tiles (110–180 MHz)

van Haarlem et al. (2013)

CHANG-ES at the Jansky Very Large Array

JVLA survey of 35 edge-on galaxies

S-band data (2–4 GHz)
LOFAR data (144 MHz)

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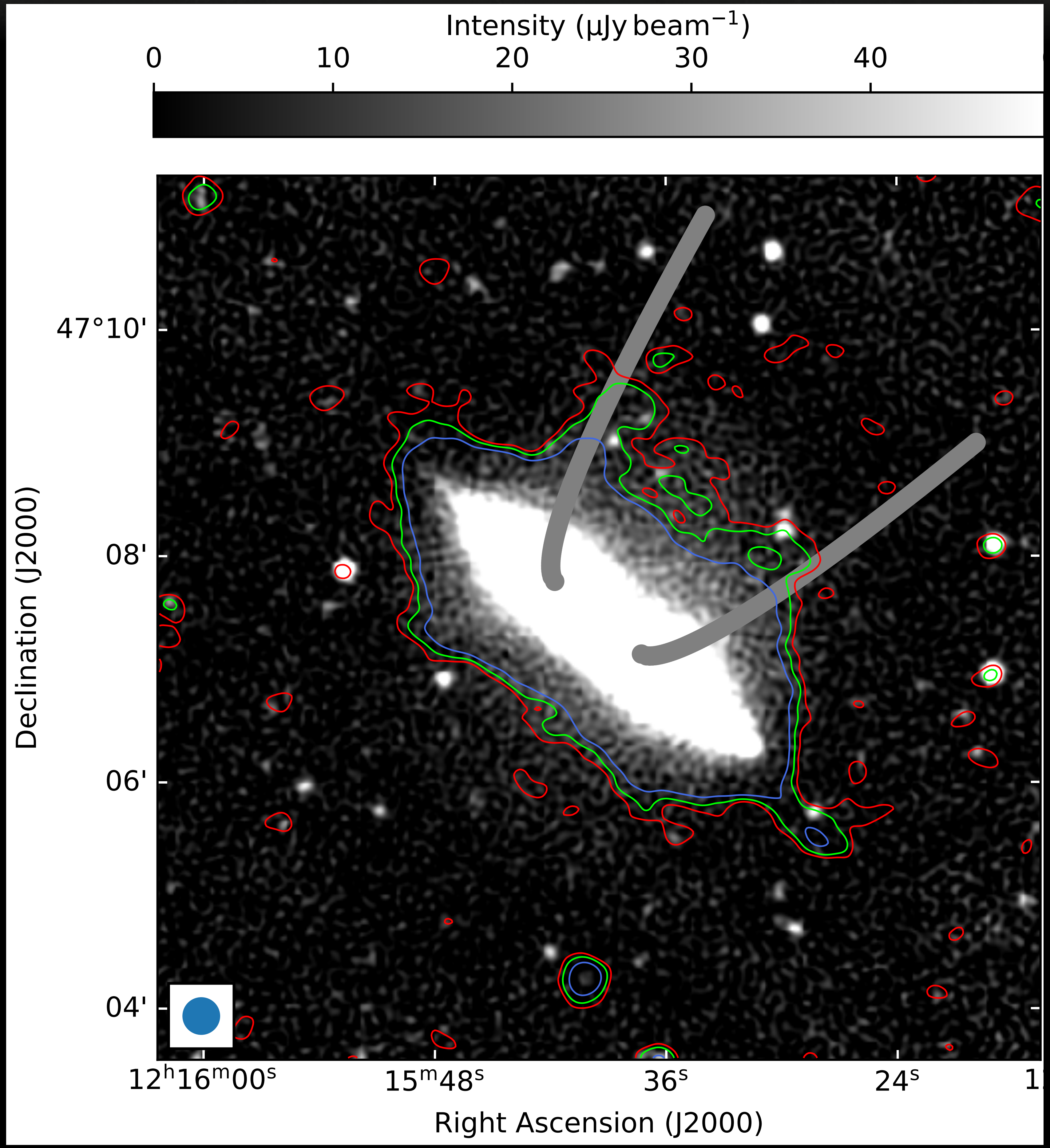
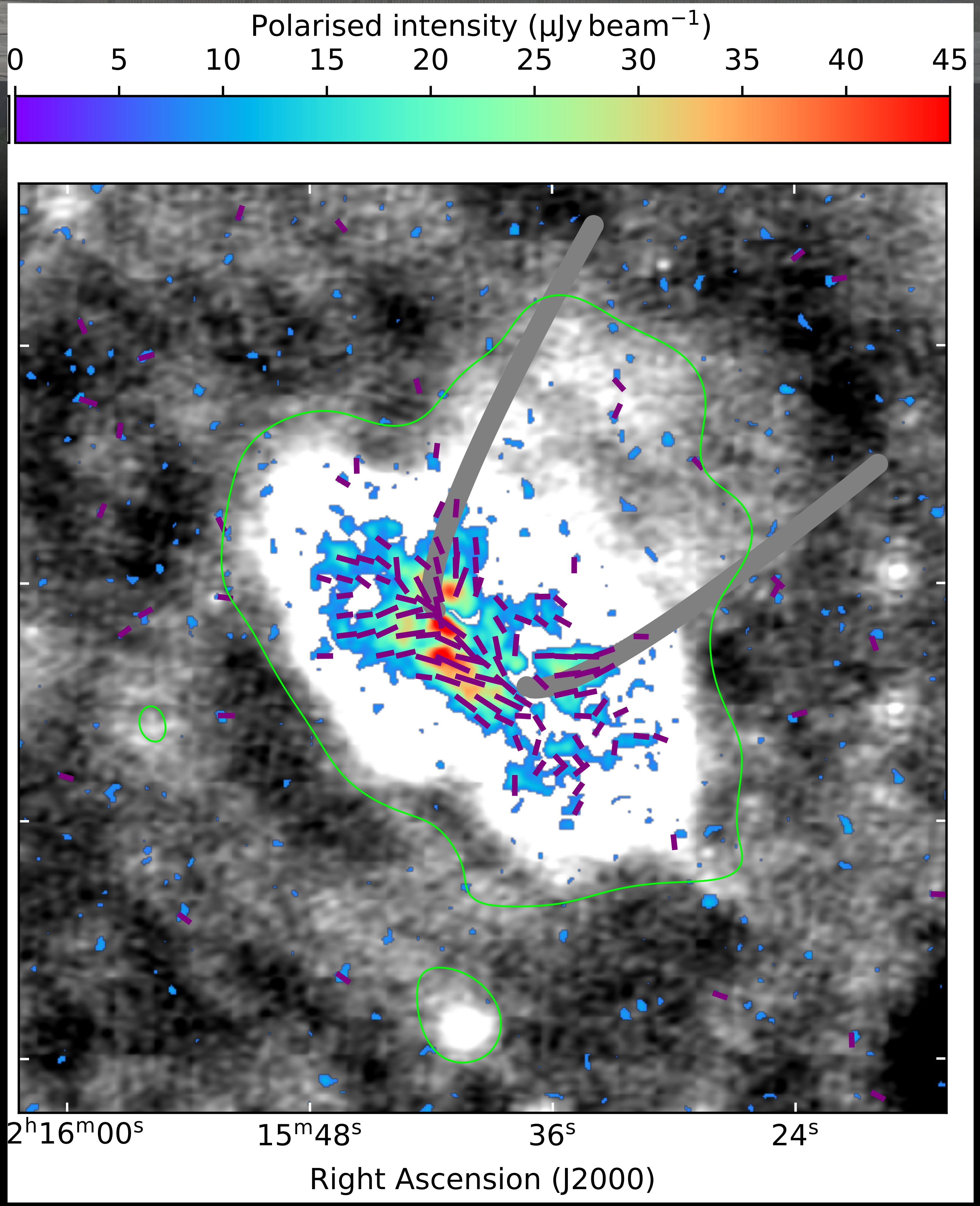


Heesen et al. (2024)

A 20-kpc sized bubble

re-imaged data from LoTSS

- Discovery with LOFAR
- Edge-brightended and aligned with X-shaped fields
- Edges seen with the JVLA at 3 GHz as flared halo

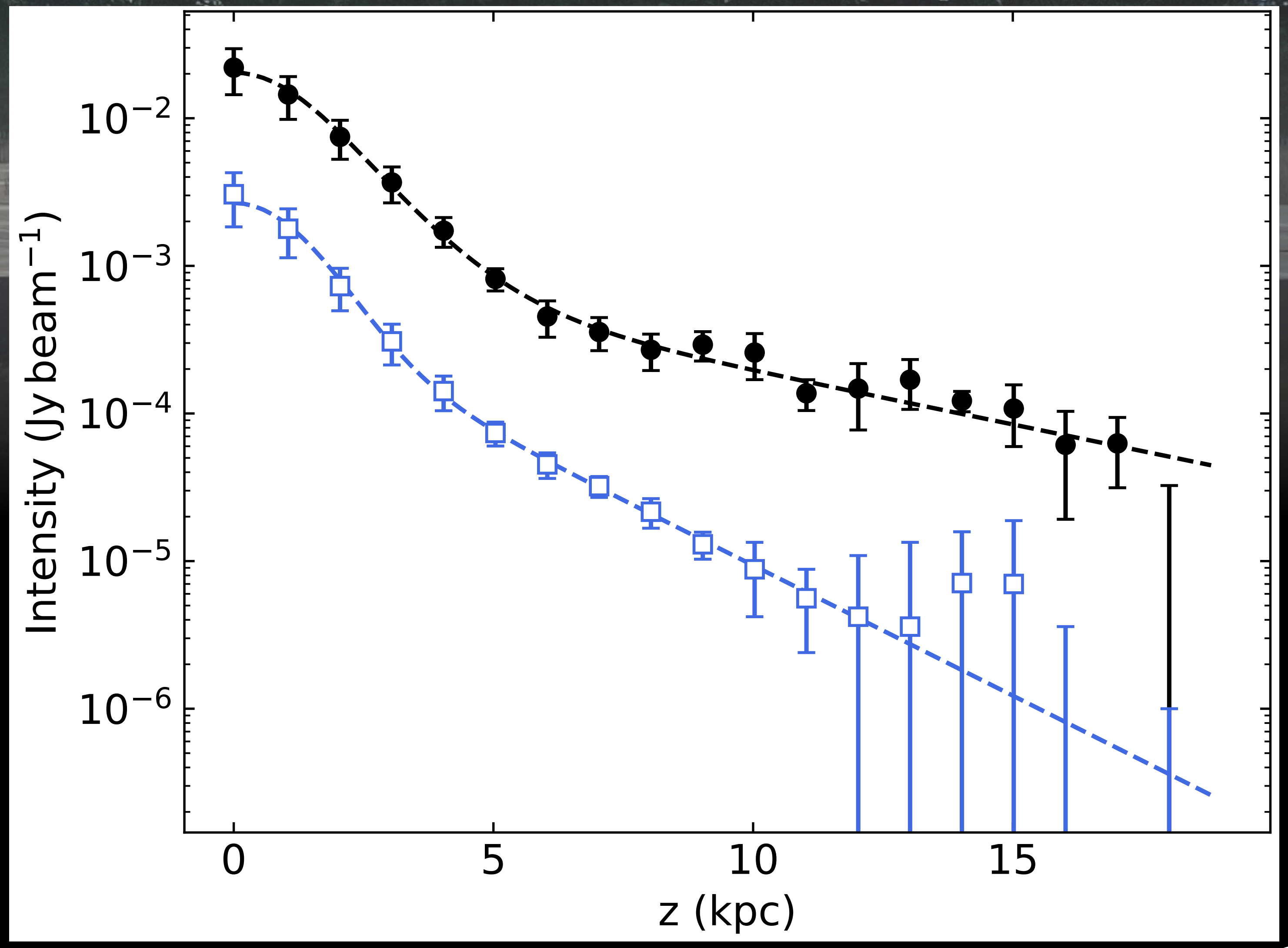


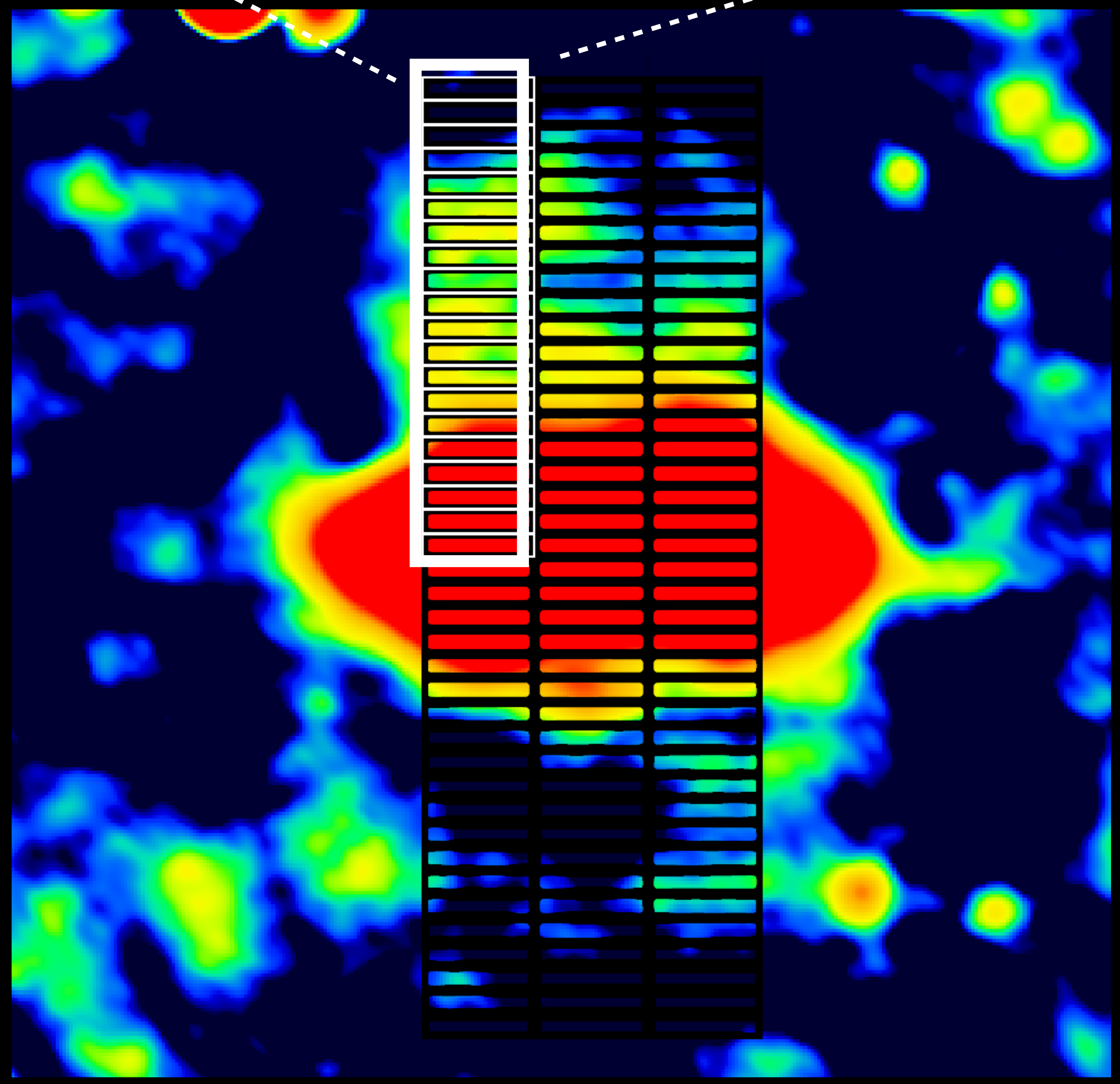
Heesen et al. (2024)

Vertical intensity profiles

in the north-western halo

- Break at 5 kpc distance
- Second very extended component
- Scale height of 6 and 3 kpc
- Vertical extent ~20 kpc

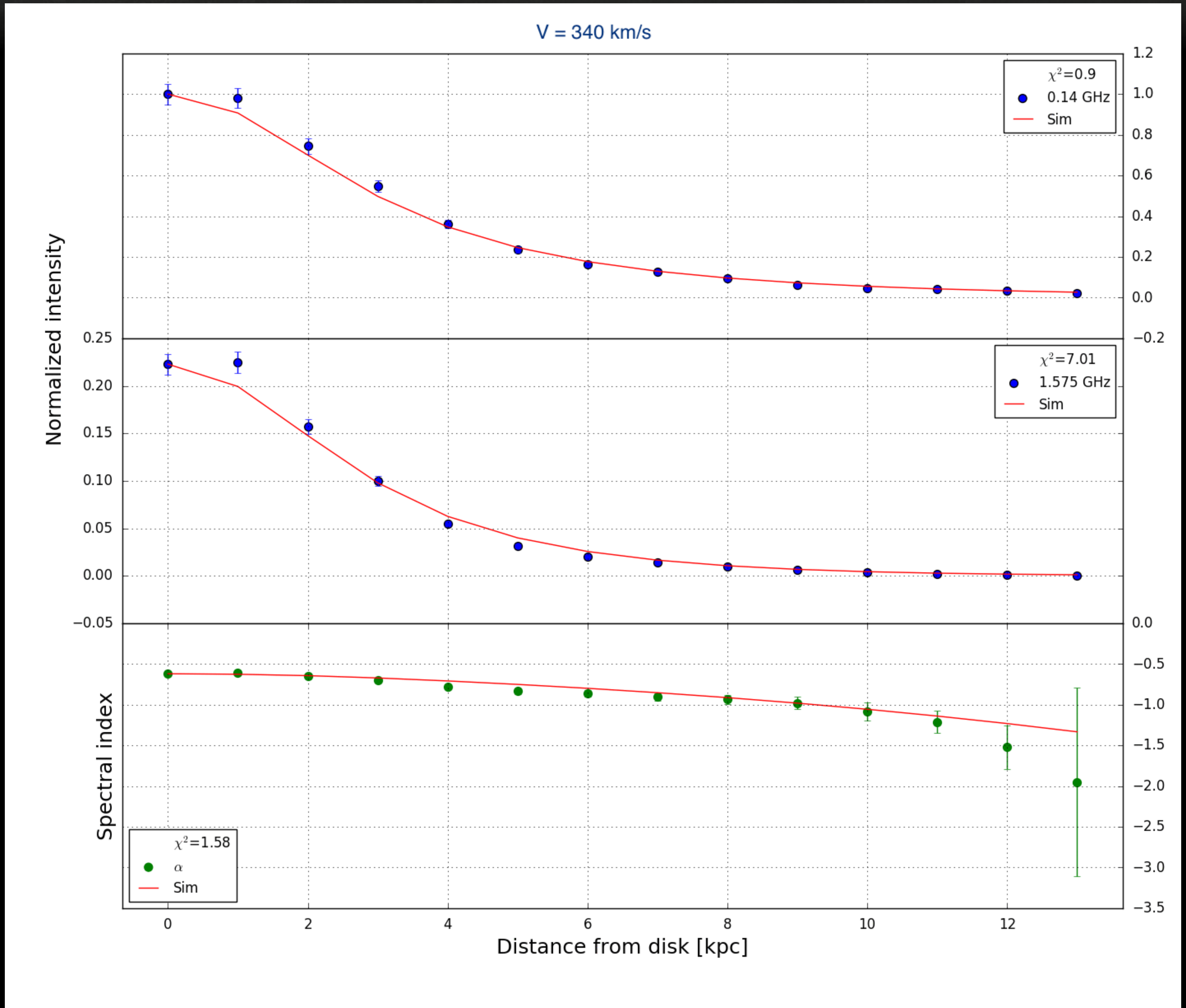




Cosmic-ray electron transport
with Spinteractive

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

code developed by Arpad Miskolczi



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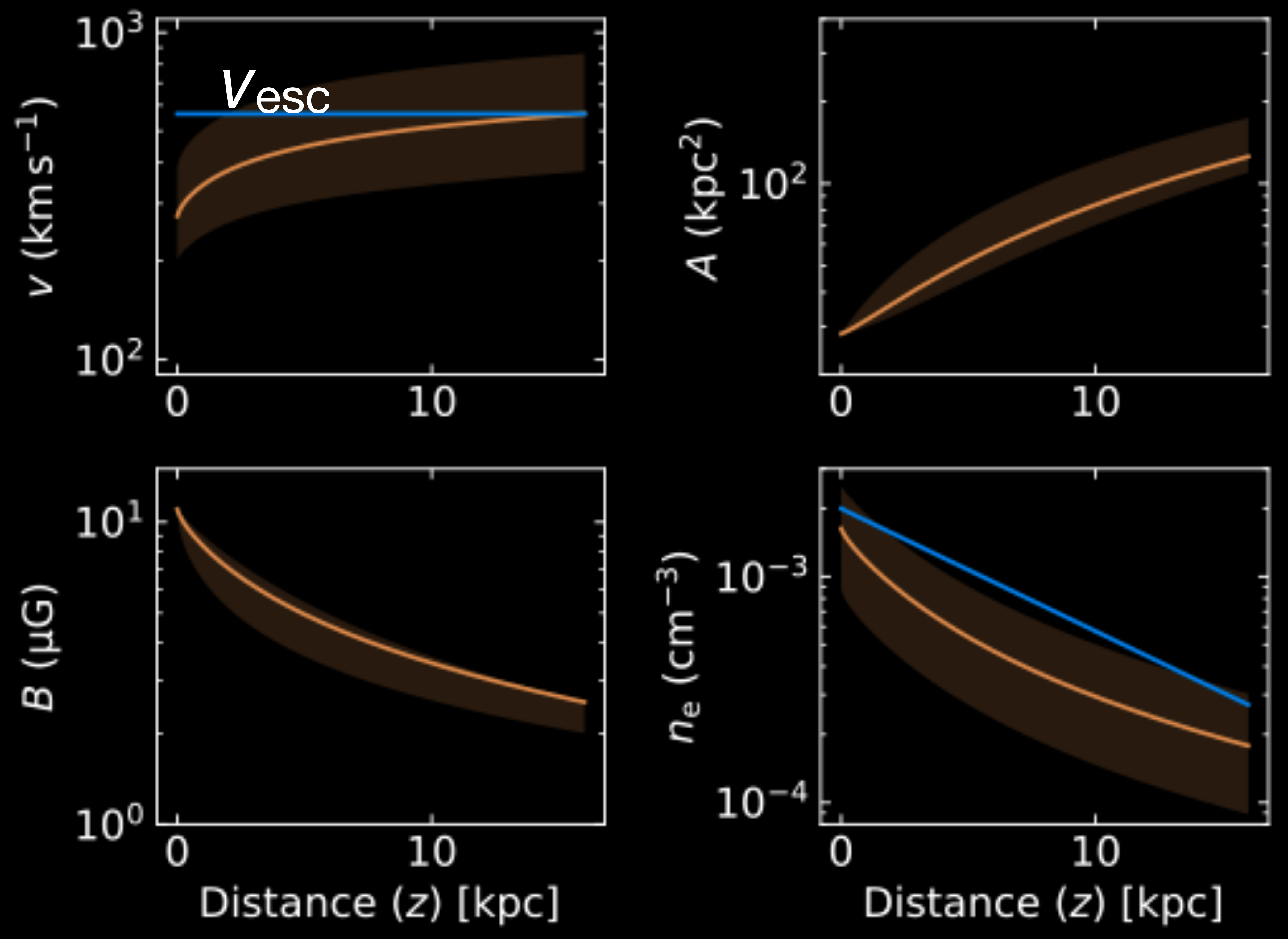
Stellar feedback-driven wind

Application to NGC 4207

Five more galaxies: Stein et al. (2023)

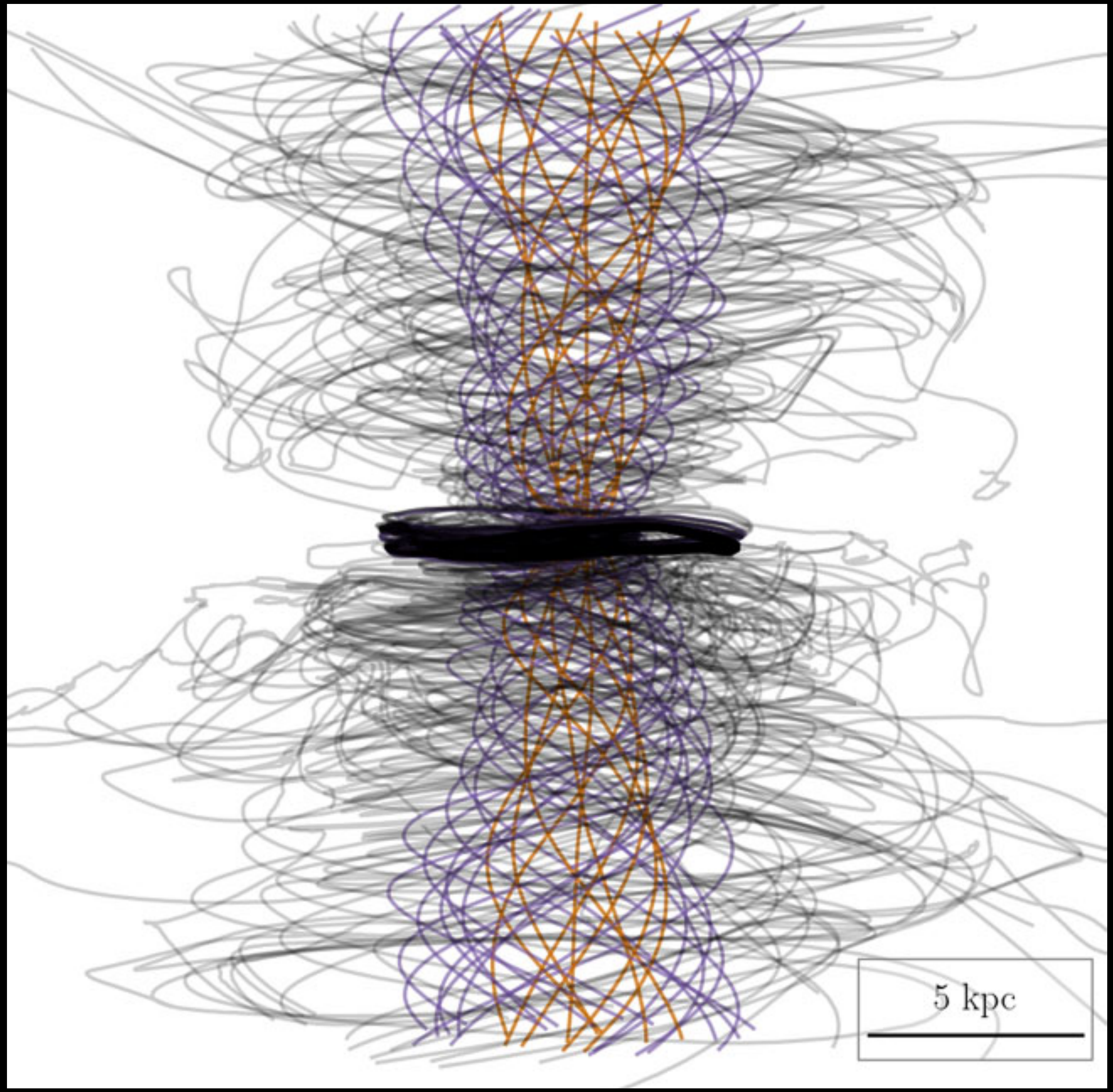
- Wind velocity rises to escape velocity
- Uncertainties due to assumption of magnetic field geometry
- Size of outflow in good agreement with bubble size



Heesen et al. (2024)

Helical magnetic field structure

- Magnetic fields follows gas particle trajectories
- Winding up of field lines expected
- Further observational tests in the future



Thomas et al. (2023)

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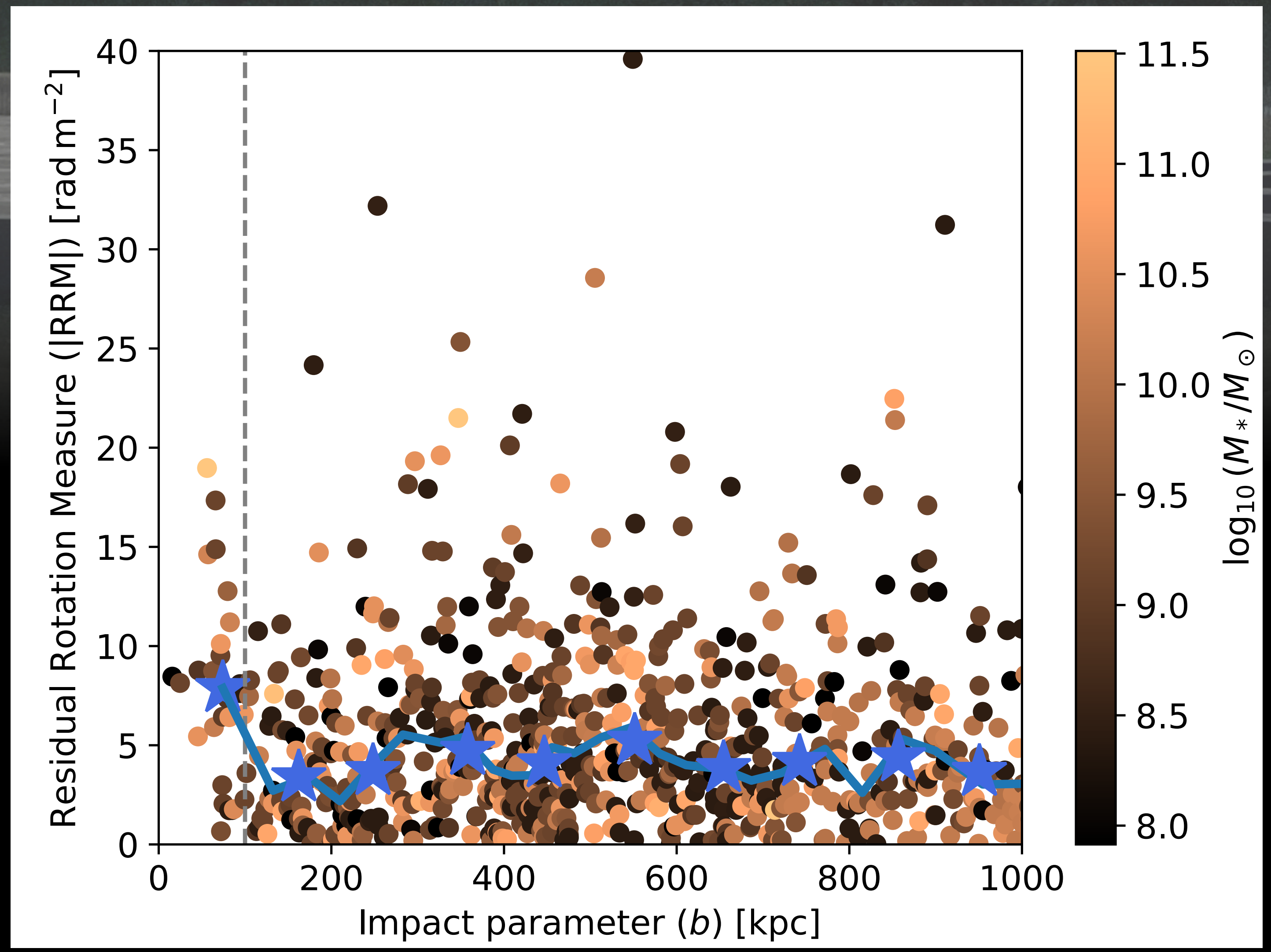
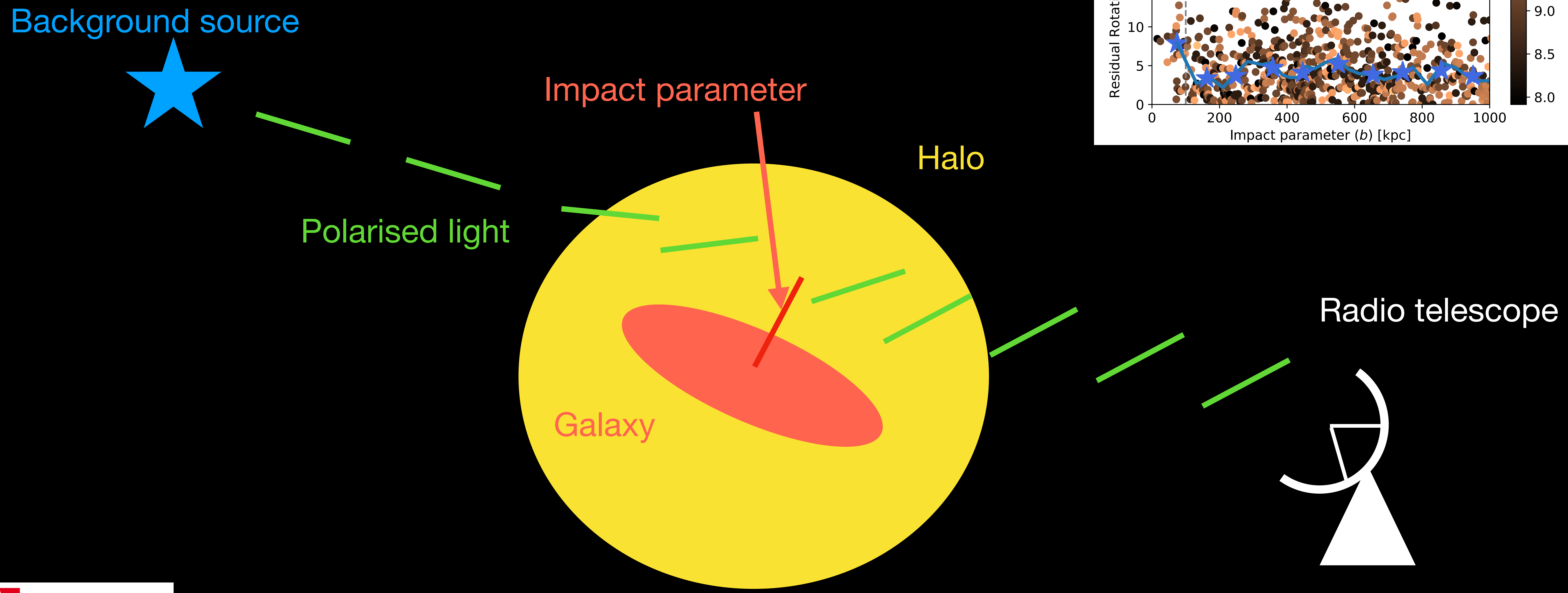
Circumgalactic *B*-fields

Experimental setup





Conclusions
and summary

- Cosmic ray-driven winds are predicted to be most important in Milky Way-sized galaxies
- Galactic winds are observed often as bipolar, but radio continuum morphology is different
- NGC 4217 is typical with a flared radio halo and X-shaped magnetic fields
- A new LOFAR maps reveals a 20-kpc bubble with its aligned with the X-shaped magnetic fields
- New observations are needed to measure 3D magnetic field structure