Nearby galaxies with LOFAR

Rosita Paladino (INAF-IRA Bologna)

on behalf of the LOFAR Nearby Galaxies WG

LOFAR Nearby Galaxies WG

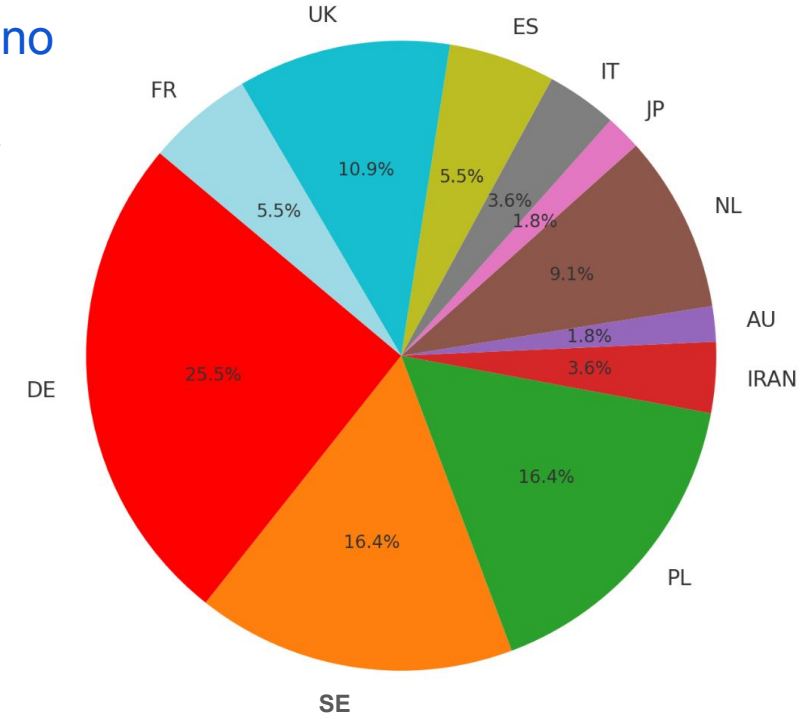
MKSP chairs: Krzysztof Chyzy - Rosita Paladino

SKSP chairs: John Conway - Krzysztof Chyzy

Members ~ 60 mailing lists subscribers

Monthly telecons

This talk is highly biased



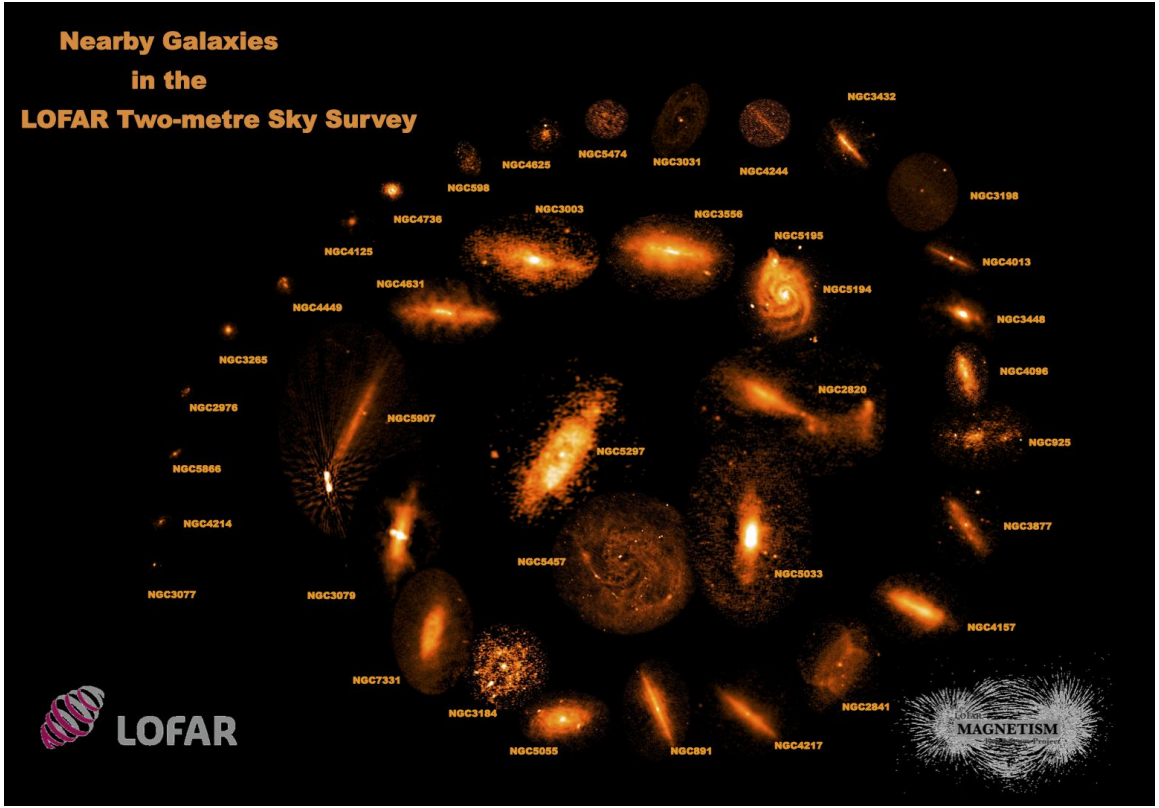
Why Nearby Galaxies @ low frequencies

“Nearby” @ < 30 Mpc

- Large scale + details

- Ideal to study multi-scale processes

- Multiwavelength coverage



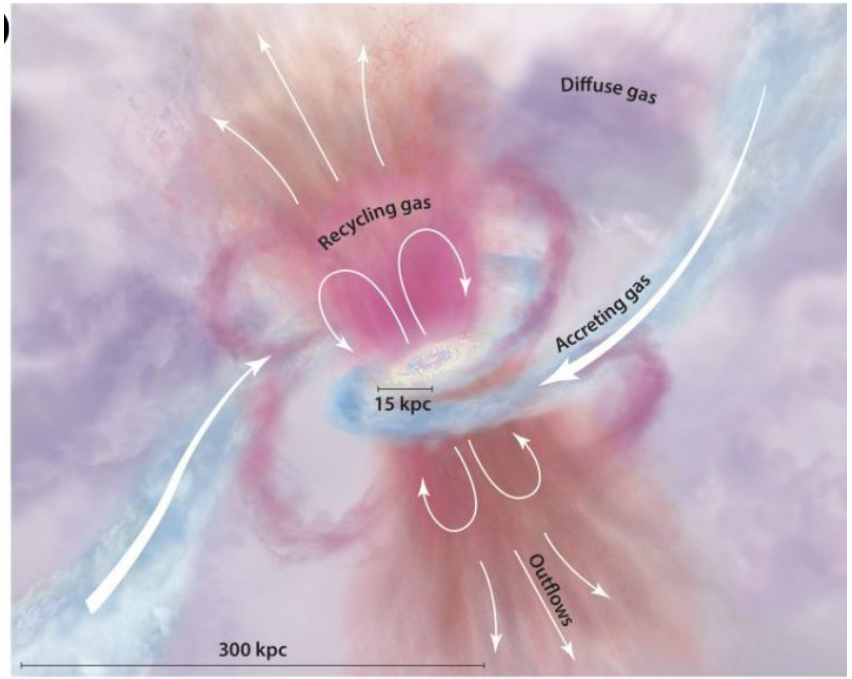
The role of relativistic phase (cosmic rays and magnetic field) in galaxy evolution

Need to add CR and B-field in this picture

Ruskowski & Pfrommer (2023):

“CRs accelerated at SNR shocks provide an efficient feedback mechanism [...]

CR cooling times are typically longer than those of thermal gas and CRs are well coupled to the plasma”

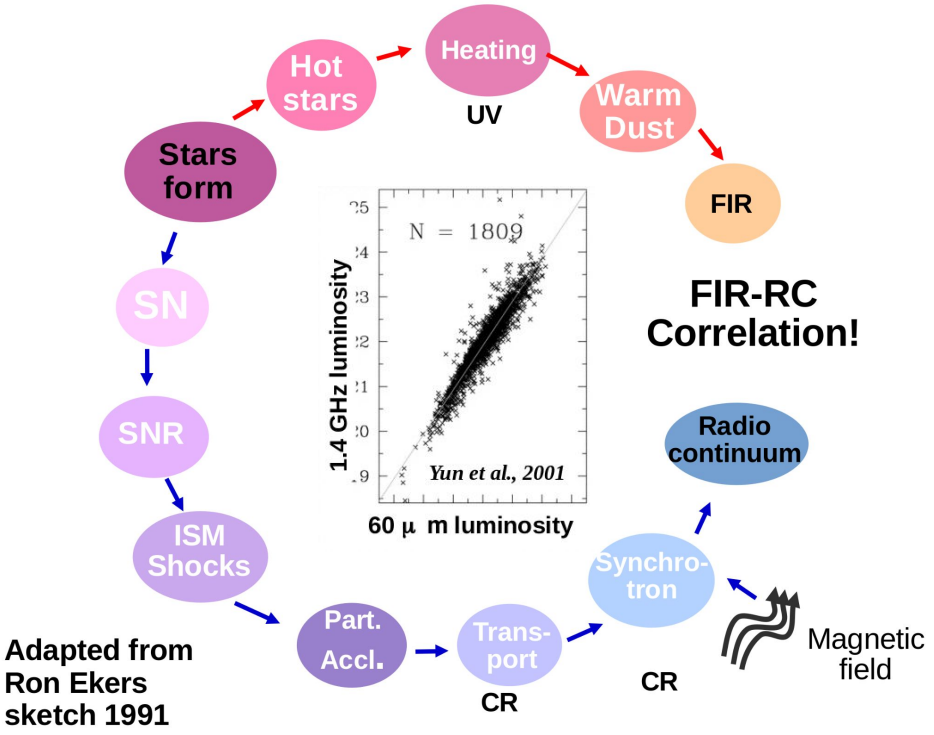


Tumlinson 2017

The role of relativistic phase (cosmic rays and magnetic field) in star formation processes

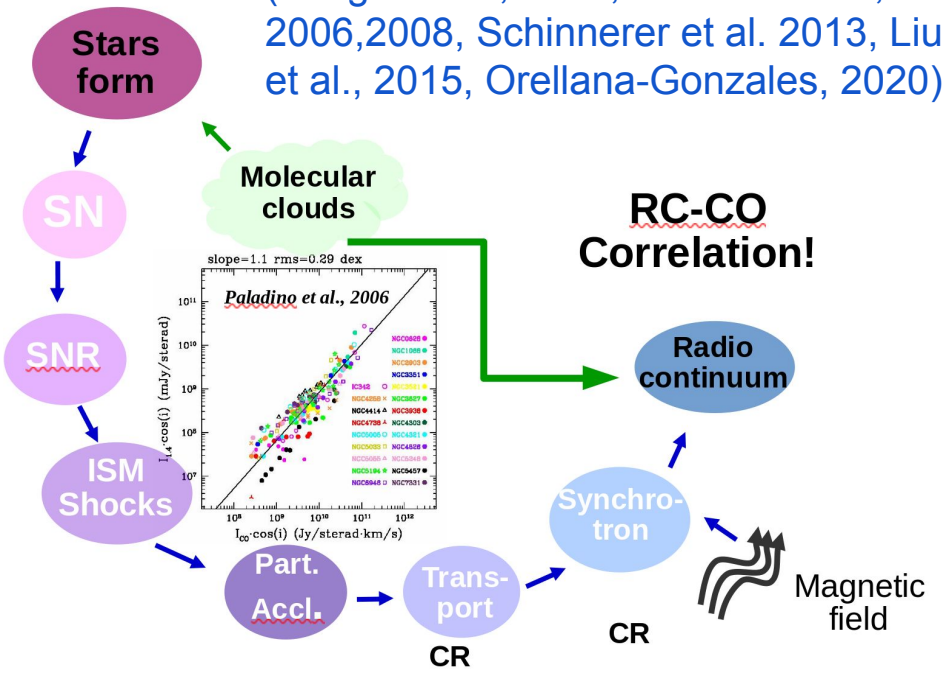
Radio continuum used as dust unnbiased SFR tracer (e.g. Condon, 1992; Tabatabaei et al 2007; Murphy et al, 2011)

The tight correlation between 1.4 GHz radio continuum and FIR emissions (e.g. Yun et al.2001)) motivated the use of RC as **dust unbiased SFR tracer.**



Further confirmation
global and spatially resolved correlations between RC and molecular emission

(Murgia et al., 2005, Paladino et al, 2006,2008, Schinnerer et al. 2013, Liu et al., 2015, Orellana-Gonzales, 2020)



Complex physics to be clarified

Calorimetric model (Voelk 1989, Lisenfeld 1996)

Magnetic field-gas coupling (Helou & Bicay, 1993, Niklas & Beck, 1997)

Hydrostatic pressure (Murgia 2005)

Proton calorimeter (Lacki, 2010)

$$I_{RC} \propto N_0 B^{\alpha+1} \nu^{-\alpha}$$

Observations at low frequency trace dominating synchrotron emission.

Further confirmation
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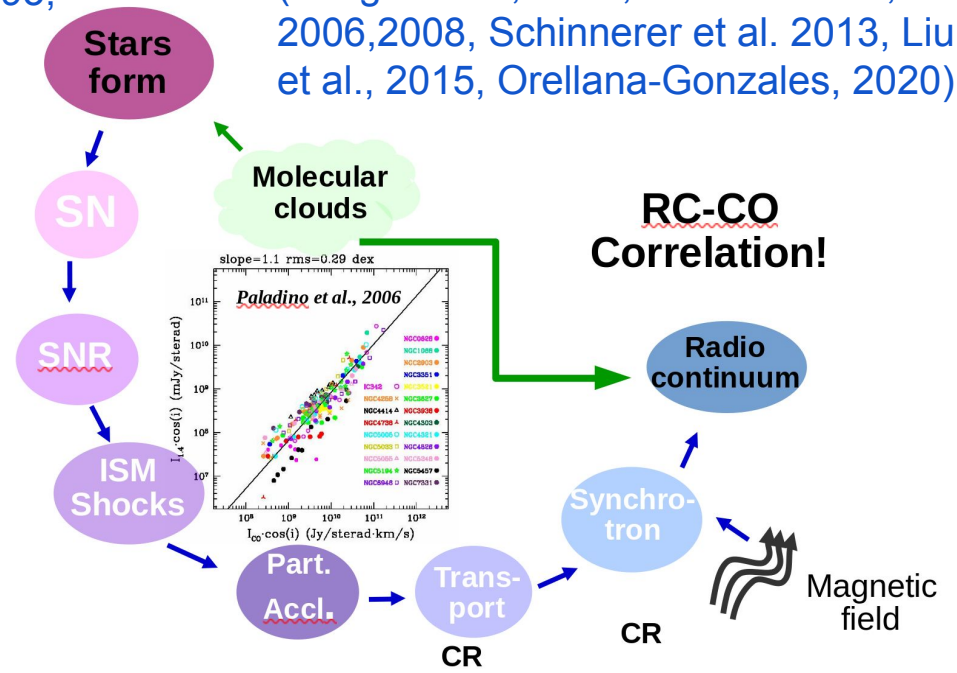
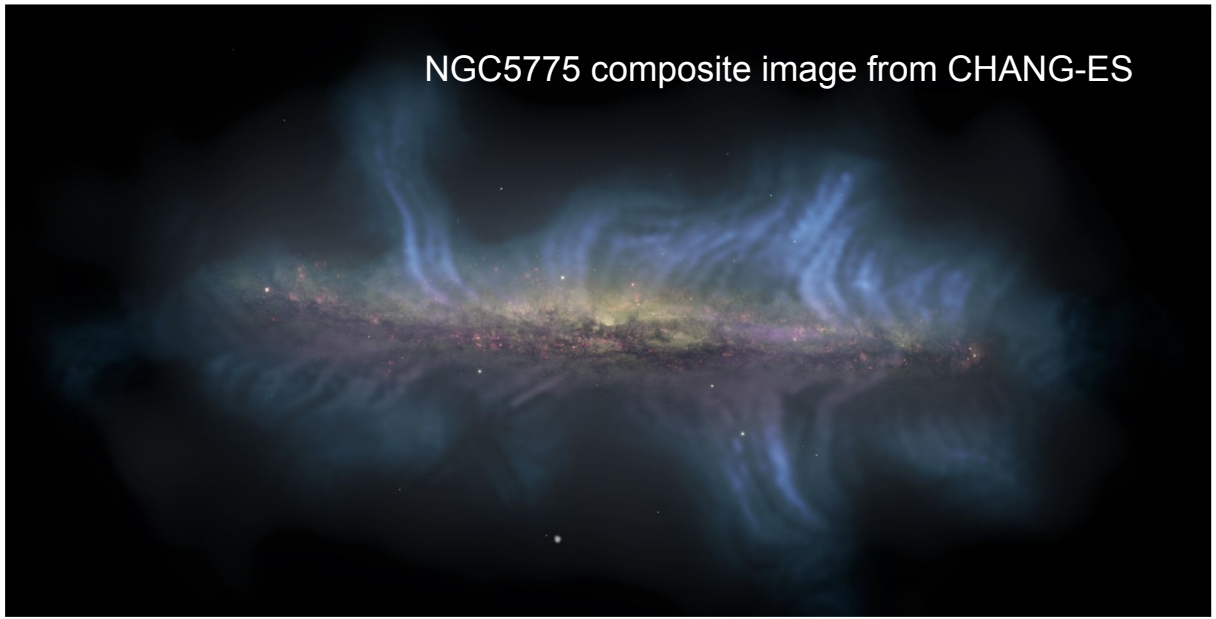


The role of relativistic phase (cosmic rays and magnetic field)

- in circumgalactic medium and winds

Polarized raido emission in edge-on galaxies show the poloidal fields connecting the disk to the galactic halo

(e.g. Tullman et al 2009;Heesen et al, 2009; Miskolczi et al. 2019; Irwin 2019; Stein et al. 2019; Krause et al 2020)



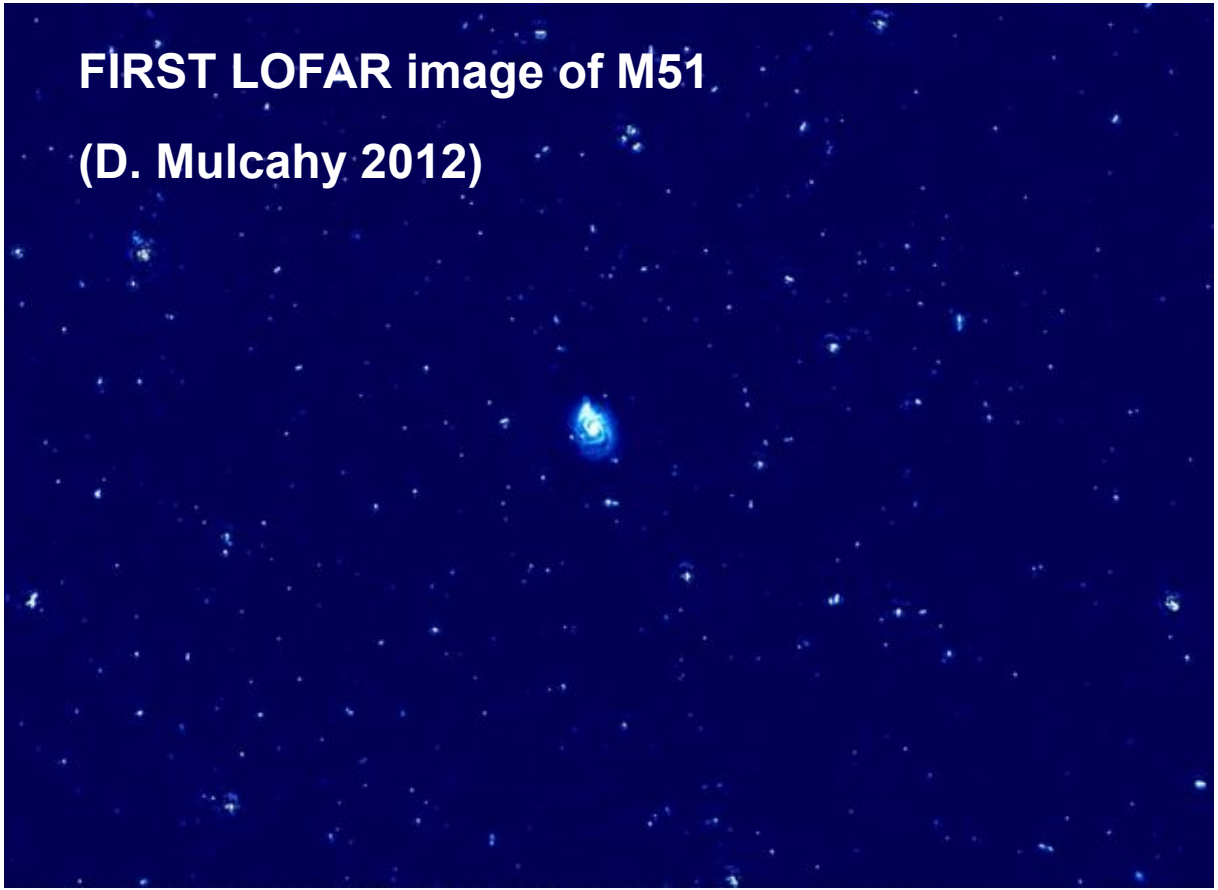
Ruzkowski & Pfrommer, 2023

LOFAR results sofar

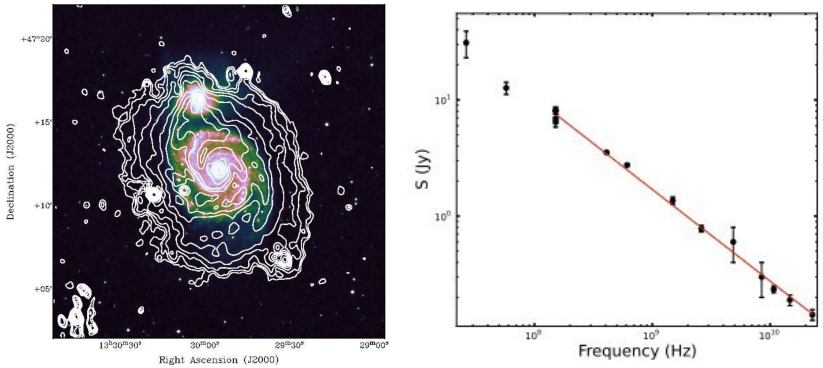
twofold approach

Individual galaxies
(Fatemeh's talk)

large sample
(Volker's talk)



Individual galaxies deep observations

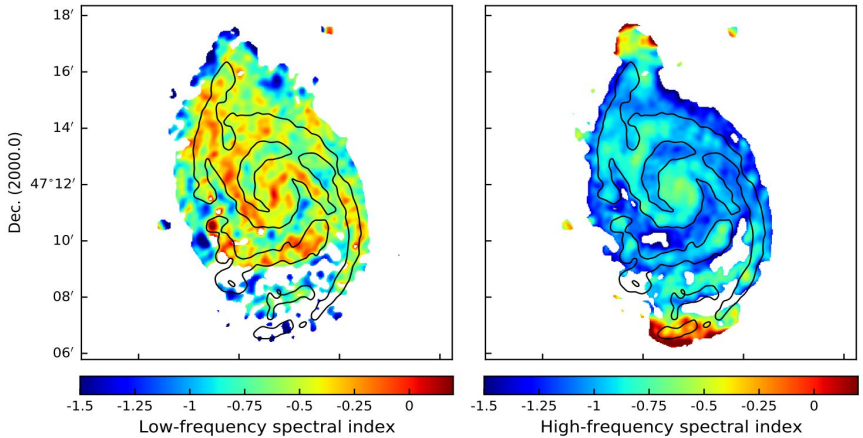


Mulcahy et al. 2014, 2016

- Larger extent than at high freq~16 Kpc
  CR propagation dominated by diffusion
- single power law to fit SED

Few background polarized sources found
(<0.5 sources/deg^2) **Neld et al. 2018**

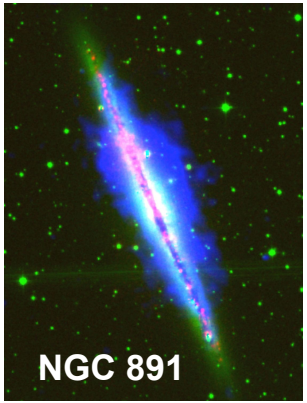
M51 observations with LBA
(**de Gasperin et al, 2021, Heesen 2023**)



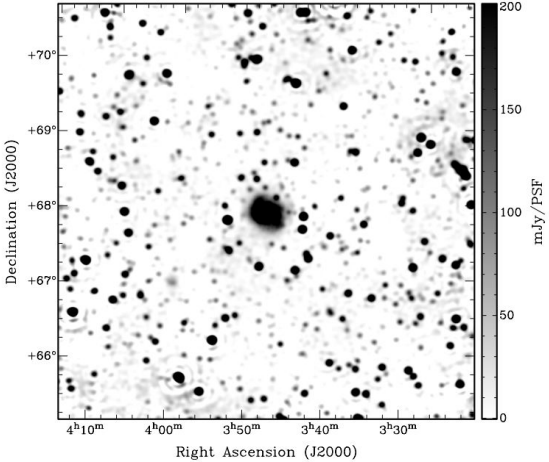
Gajovic et al. 2025

- Low-freq spectral index flatter than high-freq one
  in correspondence with HI high density regions
- Cosmic ray ionization losses in neutral gas

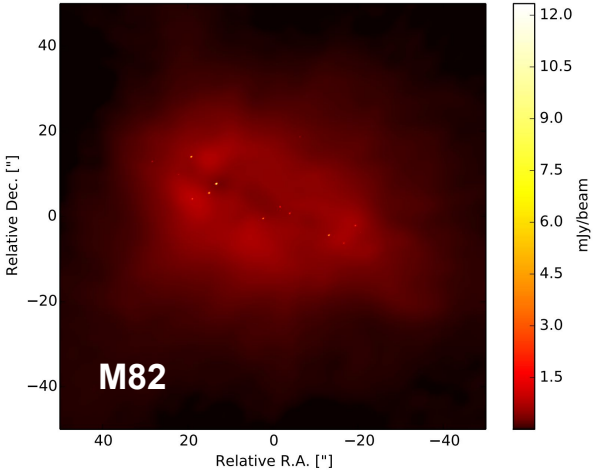
Individual galaxies deep observations



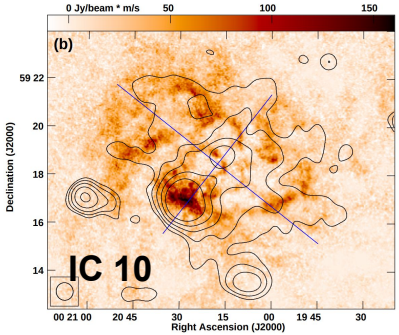
Mulcahy et al. 2018



Van Eck et al. 2017



Varenius et al. 2015

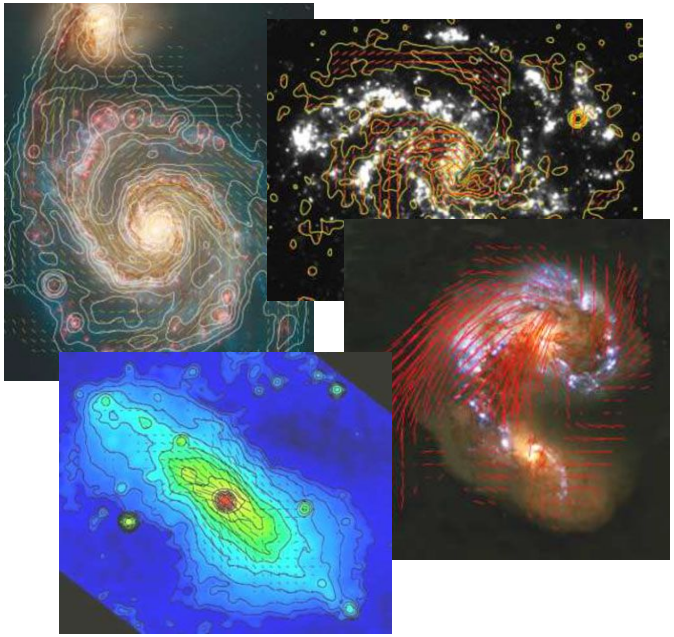


Heesen et al. 2018

Faraday tomography
to study the Galactic
foreground towards IC342

Sub-arcsecond image
both extended and compact
emissions are visible

Individual galaxies deep observations

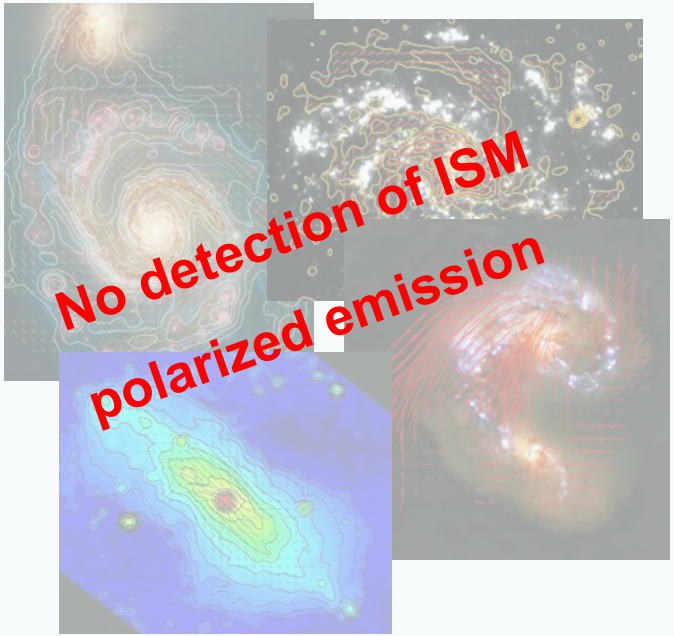


Beck & Wielebinsky et al. 2015

Individual galaxies deep observations

Depolarization

- Beam depolarization
- Internal Faraday dispersion
- Magnetic field strength
- thermal electron density
- pathlength along the line of sight



Beck & Wielebinsky et al. 2015

Individual galaxies deep observations

Depolarization

- Beam depolarization
- Internal Faraday dispersion
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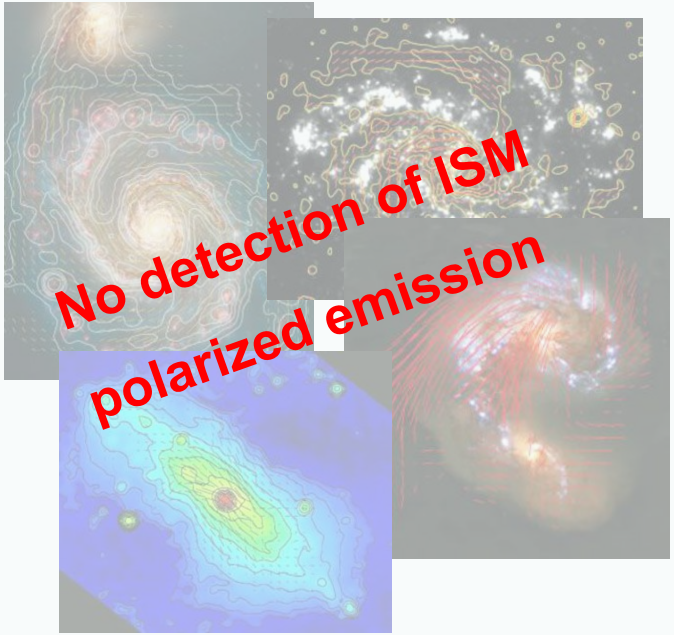
Using polarized background sources to probe the magnetic field of galaxies as a foreground screen could be more promising

BUT
the density of polarized sources in many nearby galaxies field is very low



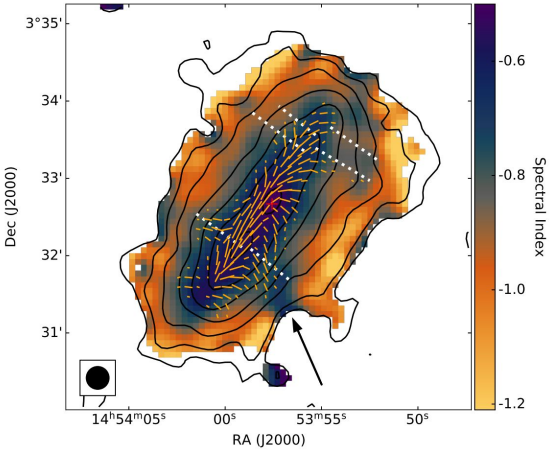
Beck & Wielebinsky et al. 2015

Edge-on galaxies: Synergy with CHANG-ES

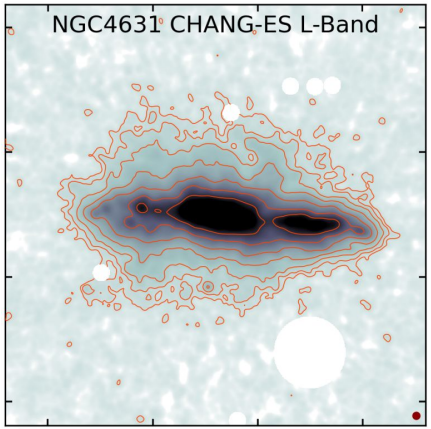
Continuum HAlos in Nearby Galaxies - EVLA Survey

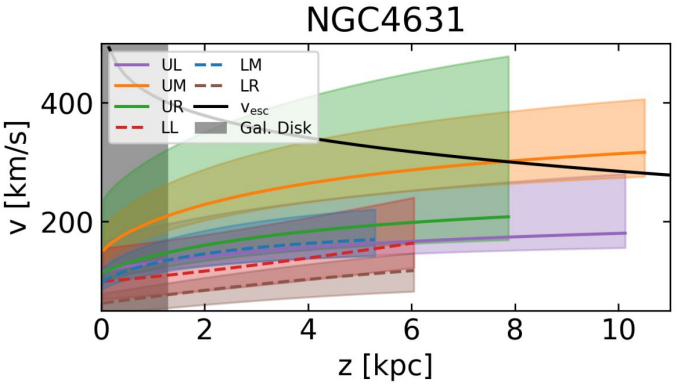
Irwin et al., 2012

- Galaxies with strong disk-halo flow: accelerated wind models (Heald et al, 2022, Stein et al., 2023)
- cosmic rays transport models (Heesen et al.,2016, 2024, Stein et al. 2023)



NGC 5775 - Heald et al, 2022





advection model - fitted wind velocity

NGC 4631 - Stein et al, 2023

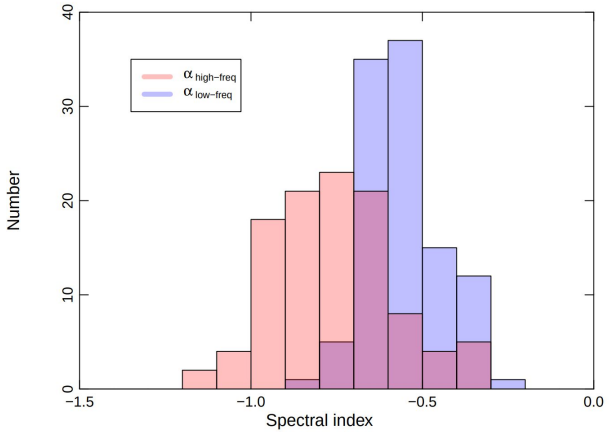
Large samples: MSSS

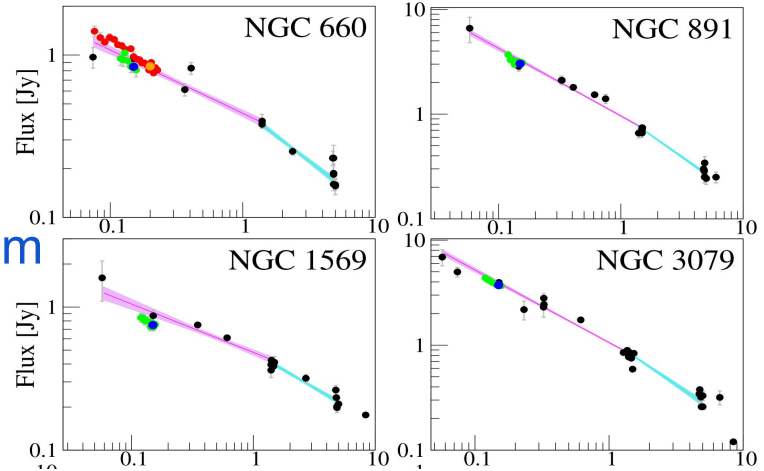
Multifrequency Snapshot Sky Survey

Chyzy et al., 2018

200 galaxies

Flattening of low-frequency radio continuum spectra





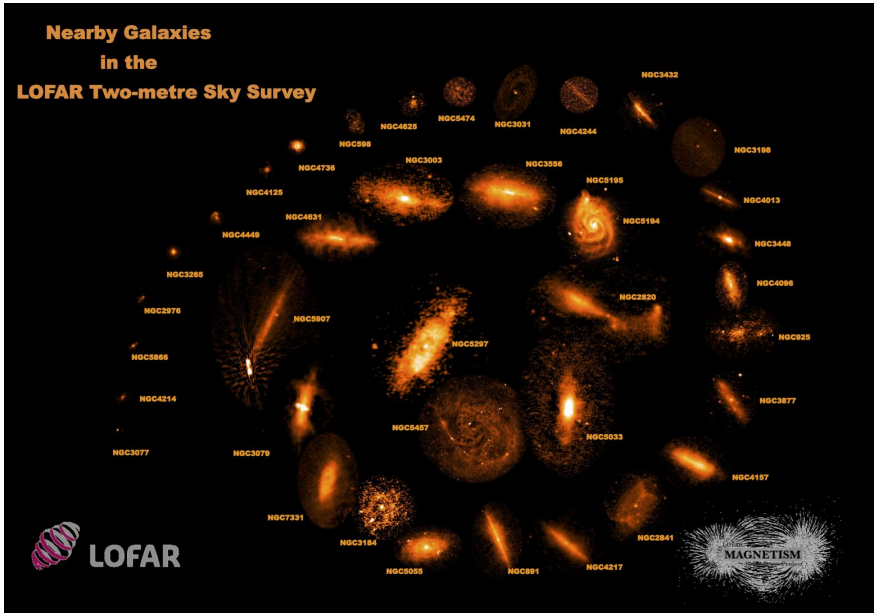
No dependence of flattening from galaxy inclination or morphology

Chyzy et al. 2018

Large samples: LoTSS

LOFAR two-metre Sky Survey

Shimwell et al., 2017, 2019



45 galaxies < 30 Mpc

Heesen et al.:

- I. Non linearity of RC-SFR relation (2022)

- II. Magnetic field - gas relation (2023)

- III. Influence of cosmic-ray transfer on the RC-SFR relation (2024)

- Detection of circumgalactic magnetic field (2023)

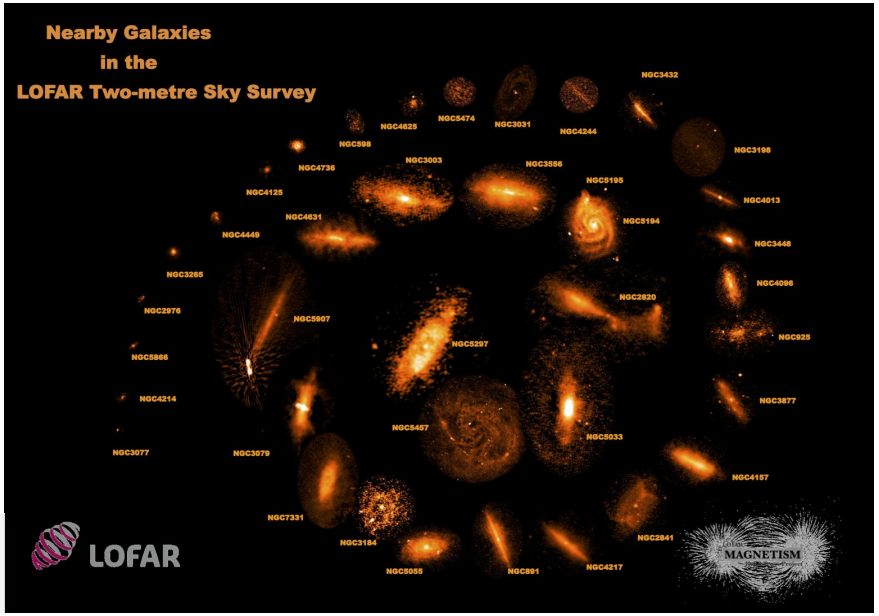
Large samples: LoTSS

LOFAR two-metre Sky Survey

Shimwell et al., 2017, 2019

DR2

45 galaxies < 30 Mpc



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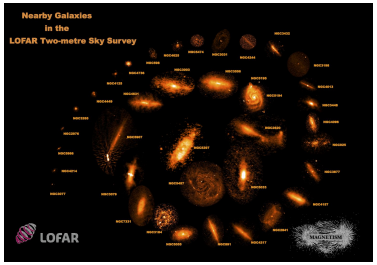
See Volker's talk

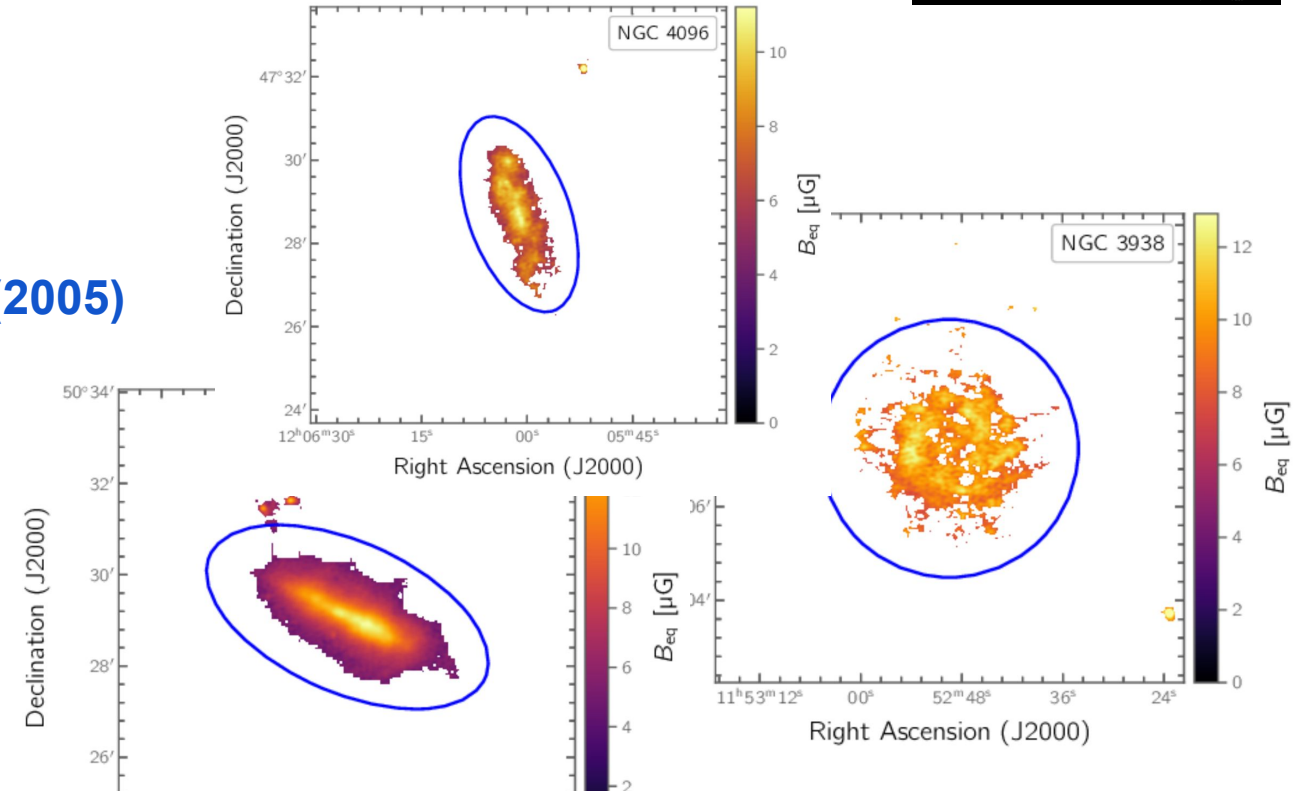
Magnetic field - gas relation

Spatially resolved equipartition B-field

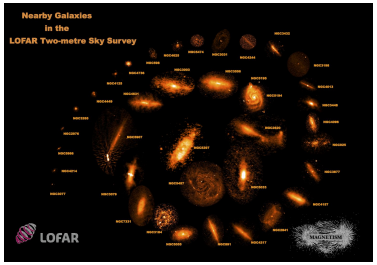


$B_{eq,\perp}$

using Beck & Krause (2005)
revised formula

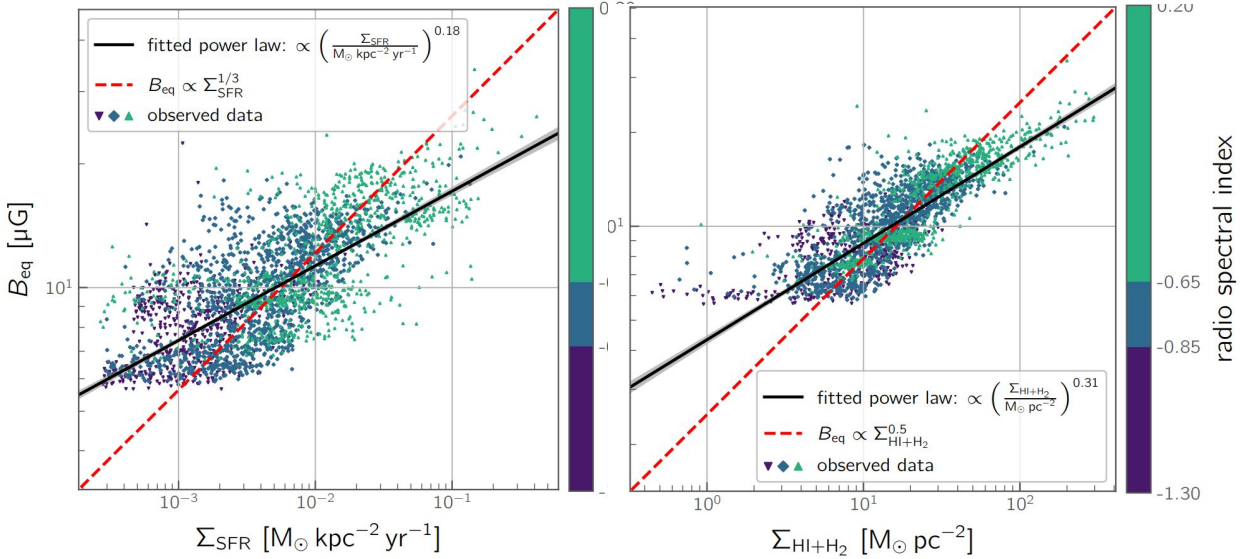


Magnetic field - gas relation



Spatially resolved comparison with

$$B_{eq} \approx \Sigma_{SFR}^{0.182} \qquad B_{eq} \approx \Sigma_{HI+HII}^{0.3}$$



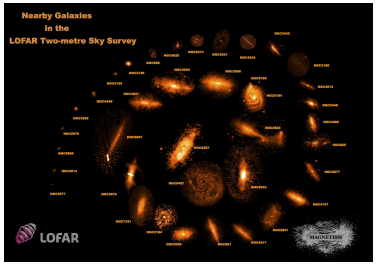
r=0.69 **r=0.80**

Both consistent with saturated small-scale dynamo

(Beck et al., 2015)

Magnetic field - gas relation

Spatially resolved comparison with



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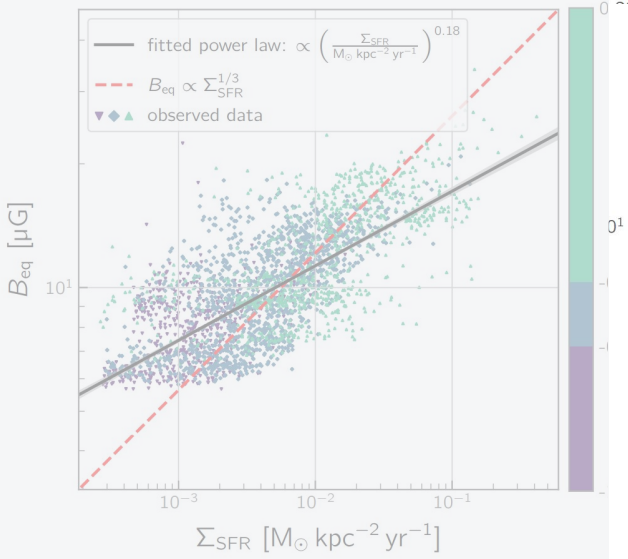

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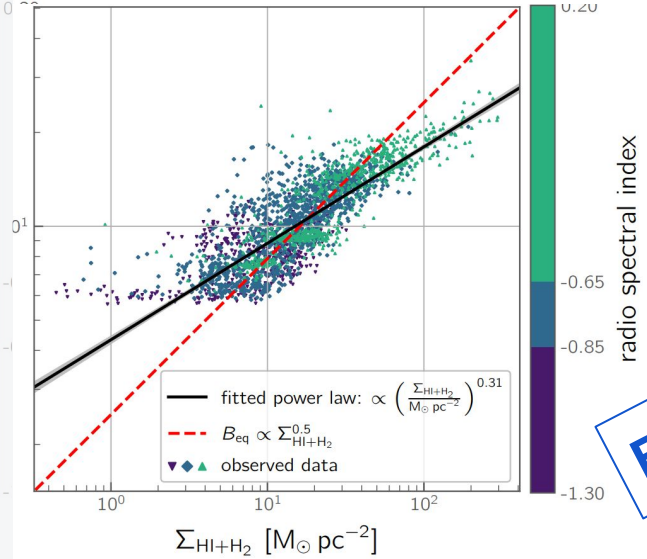

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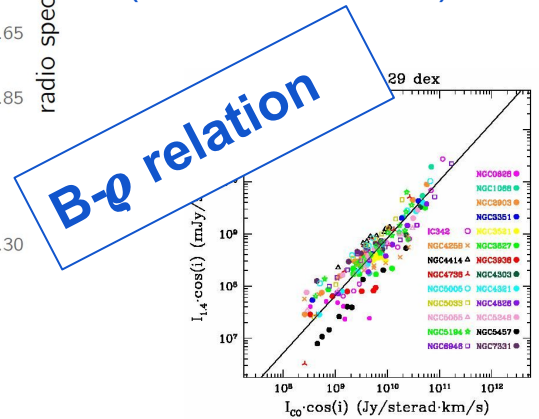
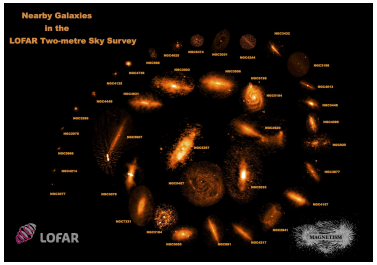


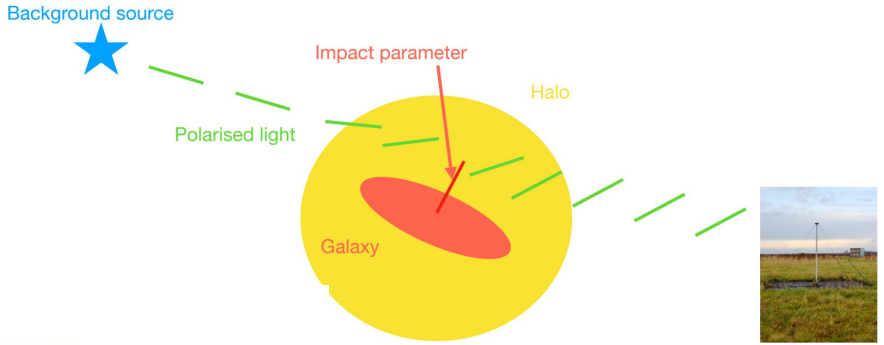
Detection of magnetic field in circumgalactic medium



Background sources from the high-precision RM extragalactic sources **(O'Sullivan et al., 2023)**
183 galaxies from Palomar sample (Ho et al., 1997)
with median dist =18 Mpc

Impact parameter =
⊥ distance between the LoS and the galaxy

ϕ = azimuthal angle with respect to the minor axis



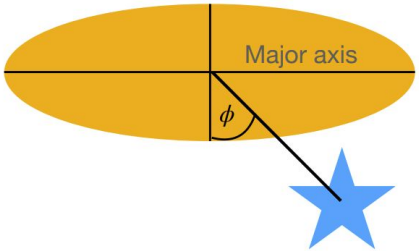
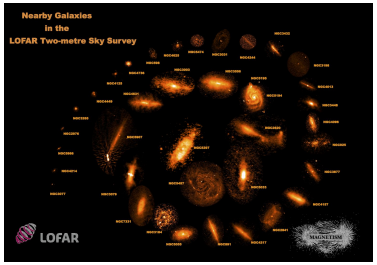
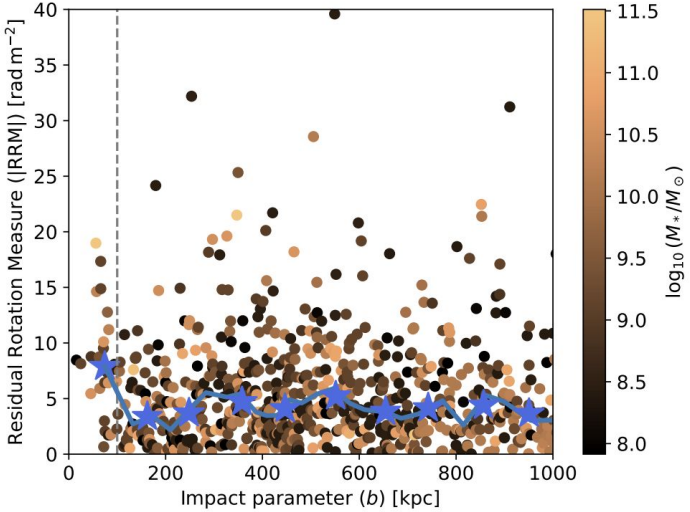
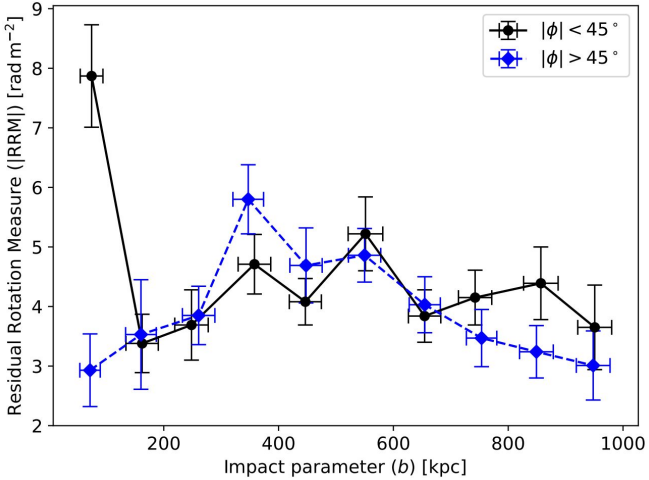


Fig from V. Heesen

Detection of magnetic field in circumgalactic medium

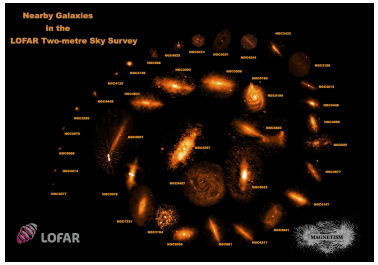


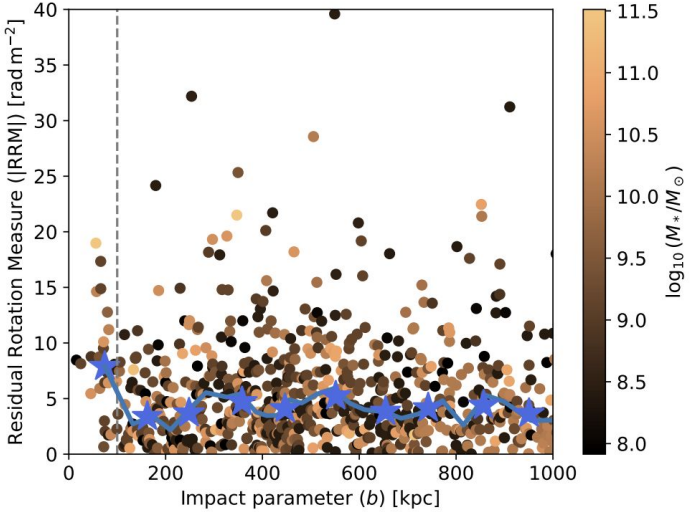


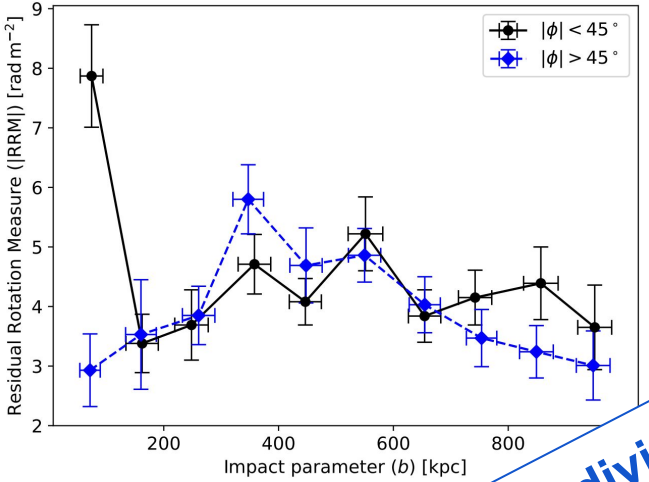


Statistical study.
Excess of RRM along sightlines around nearby galaxies
along the minor axis of inclined galaxies for impact parameter < 100 kpc.

Detection of magnetic field in circumgalactic medium







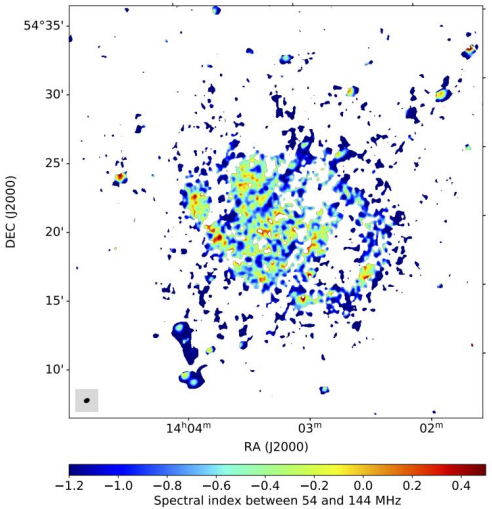
Statistical study.
Excess of RRM along sightlines around nearby galaxies
along the minor axis of inclined galaxies for impact parameter < 100 kpc.

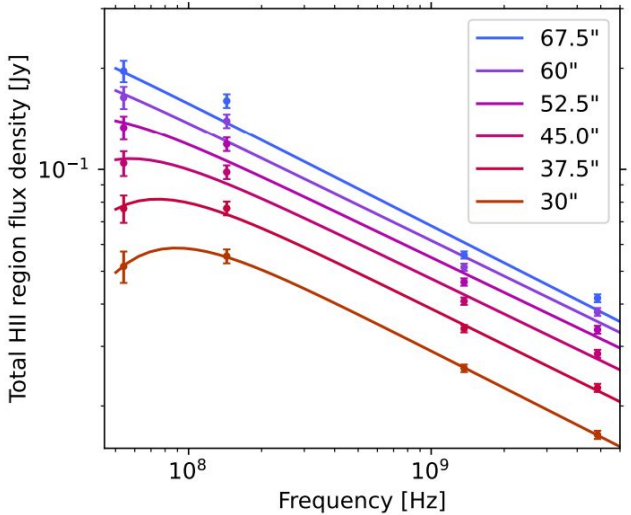
For individual galaxies source density is too low

LBA observations

M101 observations part of the LoLSS

(de Gasperin et al, 2023)





Flattening visible when measuring the flux in small area around the center of HII regions

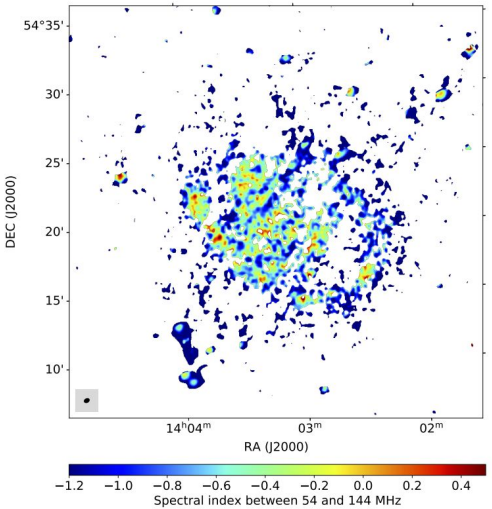
- Low-freq spectral index flatter in correspondence of HII regions

Gajovic et al. 2025

LBA observations

M101 observations part of the LoLSS

(de Gasperin et al, 2023)



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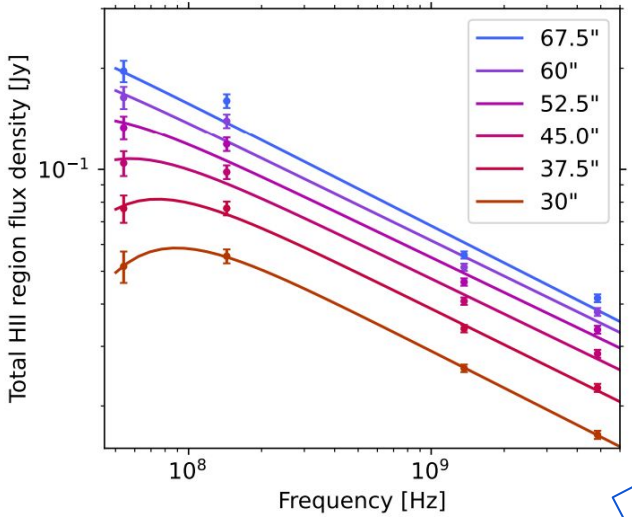


Gajovic et al. 2025

Flattening visible when measuring the flux in small area around the center of HII regions

Need of high resolution

Future perspective: synergies

EUCLID-LOFAR projects proposed

- The interplay between radio continuum emission, ionized gas and star formation in nearby galaxies, using (Heesen)

- Compact dwarf galaxies (Bomans)

- Role of thermal and non thermal pressure in ISM/IGM structure and star-formation (Tabatabaei)

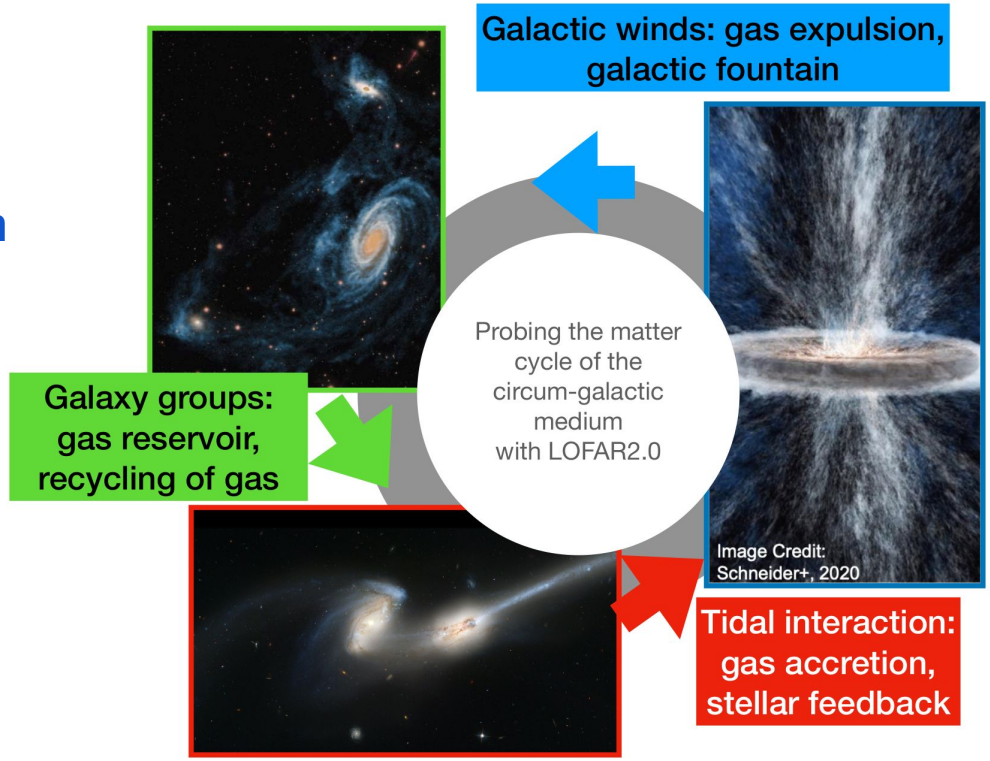
- Searching for SFR-radio luminosity relation and dust content of low surface brightness galaxies (Malek, Dabhade, Junais)

Future perspective: LOFAR 2.0

Nearby galaxies as laboratories for galaxy evolution with LOFAR2.0

Main goals:

- Role and fate of cosmic rays in galactic wind
- Structure of magnetic field in the circumgalactic medium



Future perspective with LOFAR 2.0

Nearby galaxies as laboratories for galaxy evolution with LOFAR2.0

Requested observations:

- **14 nearby galaxies: edge-on, face-on, groups and interacting**
- Deep HBA and LBA
- HBA polarization with only Dutch station
- International baselines to identify point sources to reduce confusion noise

Conclusions

Many results obtained with LOFAR 1.0

- RC-SFR relation
- Cosmic rays transport modelling
- Magnetic field - gas density relation

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LOFAR 2.0

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If interested join the Nearby Galaxies WG