Low-frequency radio emission from nearby galaxies

Sarrvesh S. Sridhar

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Overview

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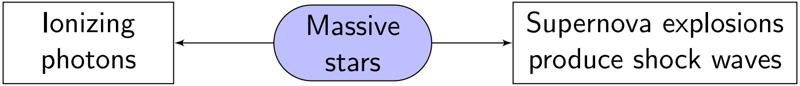
Radio continuum emission from galaxies

- Consider a normal, non-AGN star-forming galaxy



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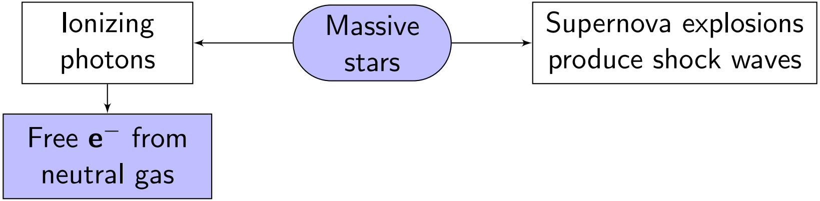

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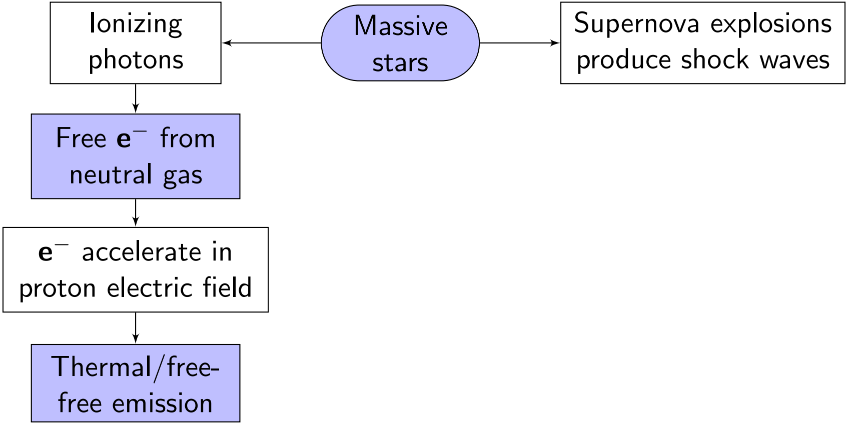

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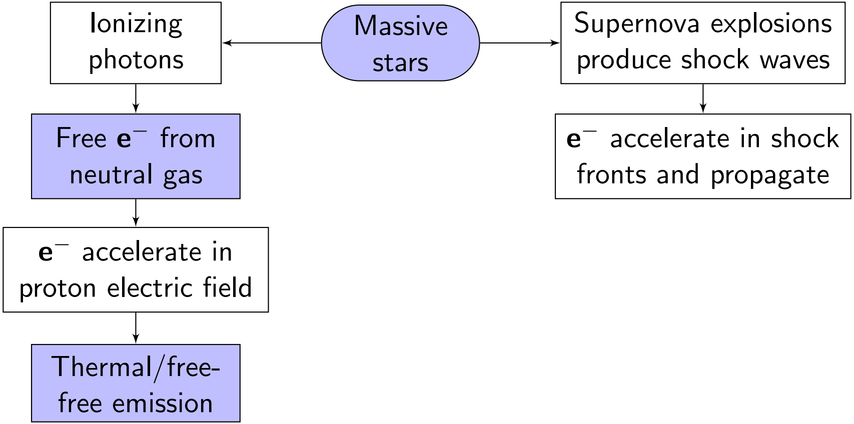

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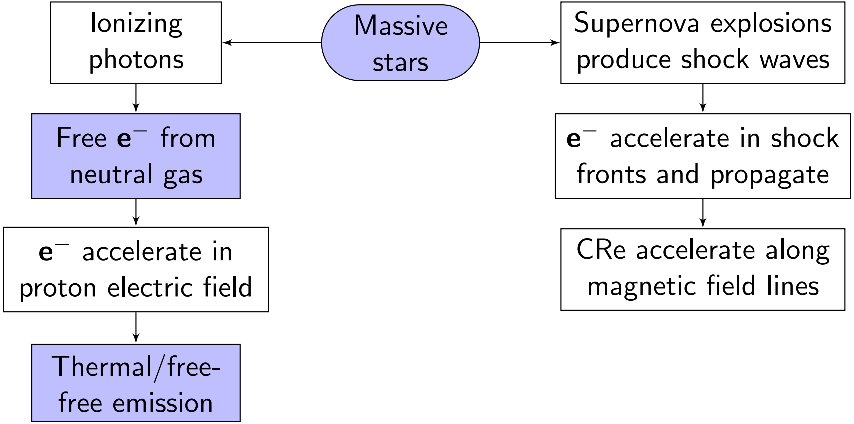

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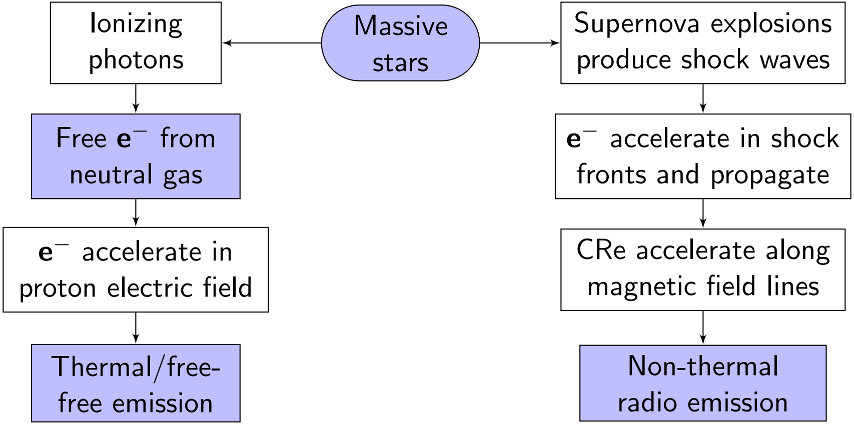

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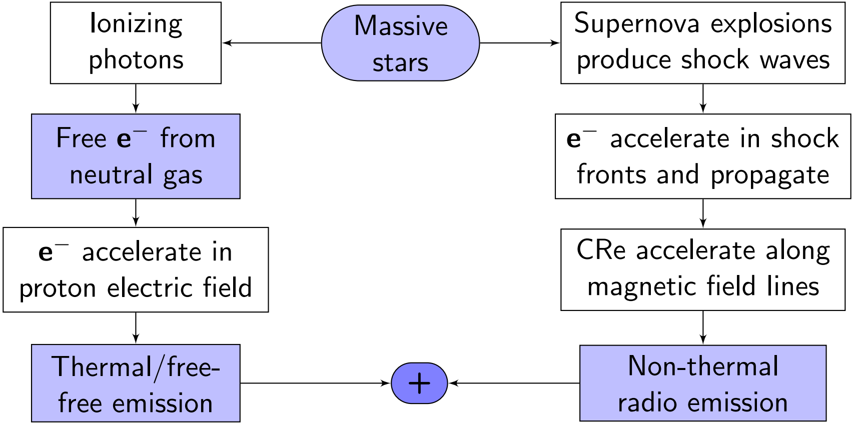
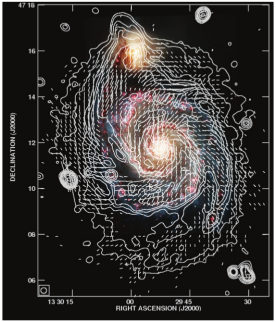
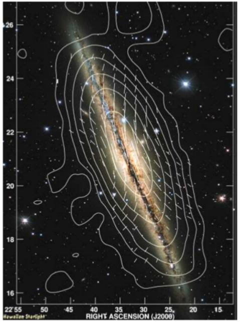
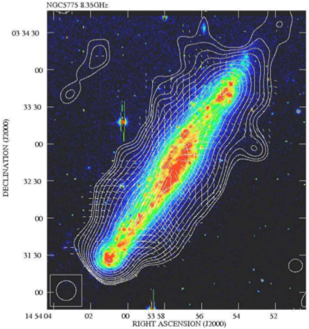


Magnetic fields in galaxies

- Contour lines trace total magnetic field
- Vectors trace ordered magnetic field







Images: Fletcher et al (2011); Krause (2009); Soida et al (2011)

Magnetic fields in galaxies

- planar spiral field in the disk + quadrupolar field in the halo

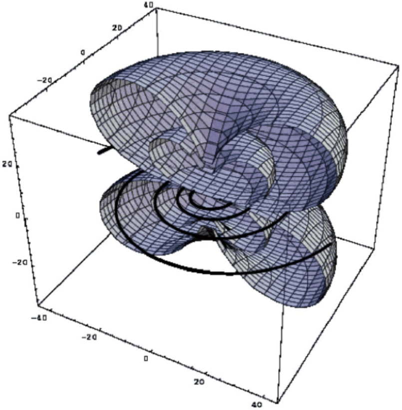


Image: Braun, Heald & Beck (2010)

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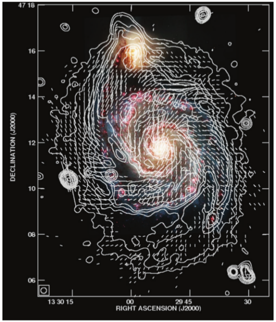
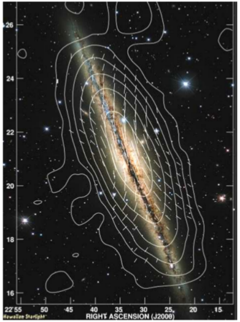
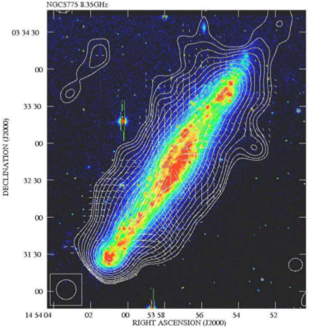
Magnetic fields in galaxies

- A consistent framework to explain **B** does not exist:
  - What is the physical extent of magnetic field lines in galaxies?
  - How does **B** interact with other ISM phases?
  - What are the dominant mechanisms that amplify **B**?







Images: Fletcher et al (2011); Krause (2009); Soida et al (2011)

Why observe at low radio frequencies?

- Cosmic ray electron (CRe) accelerating in magnetic field produce synchrotron emission.
- Lifetime and streaming velocity of CRe determine the distance they can travel in the ISM.
- At low ν, CRe have longer synchrotron lifetime.

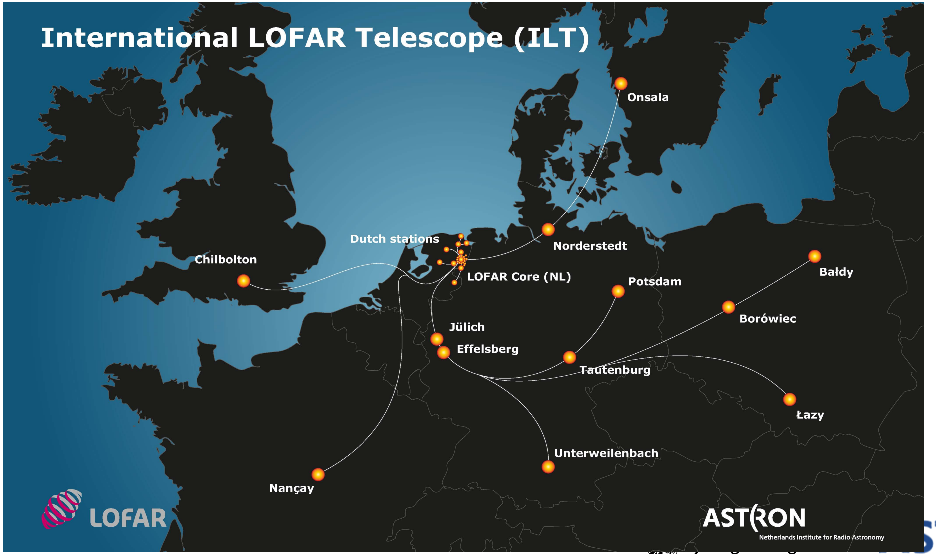
$$t_{\mathrm{syn}} \propto \nu^{-0.5} \qquad t_{\mathrm{syn}} \propto \mathrm{B}^{-1.5} \tag{1}$$

- **Low energy CRe can diffuse out to large radii**

Galaxy sample

- Observed a sample of nearby galaxies
  - M 101
  - NGC 4258
  - Four dwarf galaxies (NGC 1569, NGC 4214, NGC 2366, and DDO 50)
- Observed with LOFAR and WSRT radio telescopes
- Complemented by neutral hydrogen, UV, NIR, and Hα data

LOFAR - LOw Frequency ARray



LOFAR - LOw Frequency ARray

- Operates in 10 – 90 MHz (LBA) and 110 – 240 MHz (HBA) range.
- No moving parts – electronic telescope.

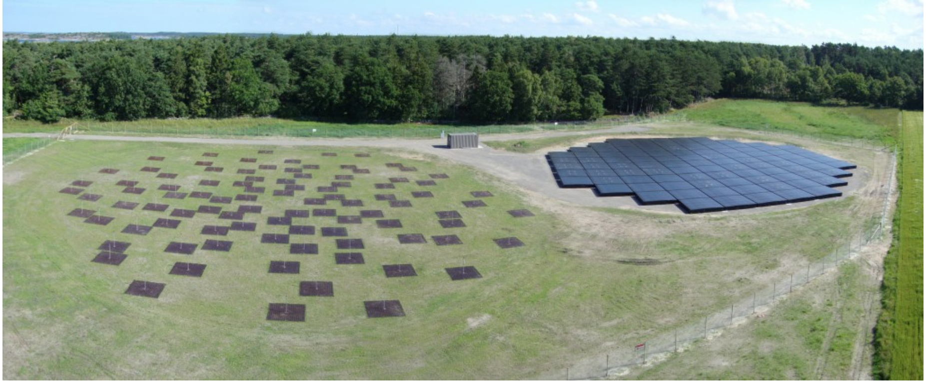


Image credit: LOFAR Sweden

Westerbork Synthesis Radio Telescope (WSRT)

- Began operations in 1970.
- 14 $\times$ 25 m dishes arranged East-West.
- 10 telescopes on fixed mounts and 4 on moveable rails.
- Not operational anymore – undergoing upgrades.
- Receivers:
  - 260 – 460 MHz
  - 310 – 390 MHz
  - 560 – 610 MHz
  - 700 – 1200 MHz
  - 1150 – 1750 MHz
  - 2215 – 2375 MHz
  - 4770 – 5020 MHz
  - 8150 – 8650 MHz
- After the upgrade, only 1.4 GHz will be supported.

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M 101

- Distance: 6.6 ± 0.5 Mpc
- Observed with LOFAR in 110 – 160 MHz band.
- With WSRT in 350, 1400, 2200 MHz bands.

Image credit: Oosterloo et al

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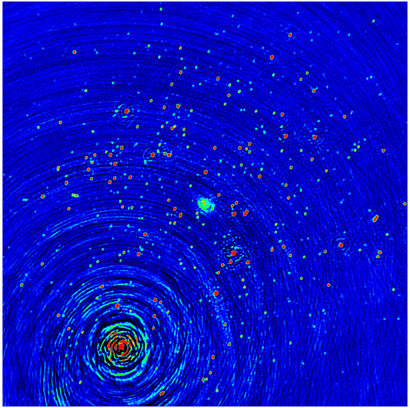

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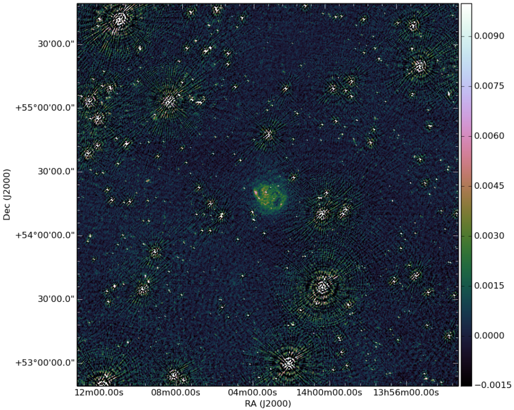

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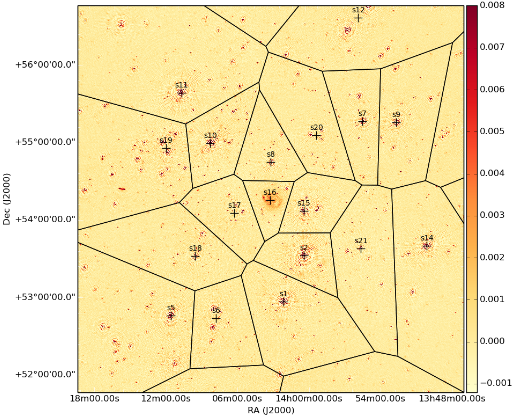

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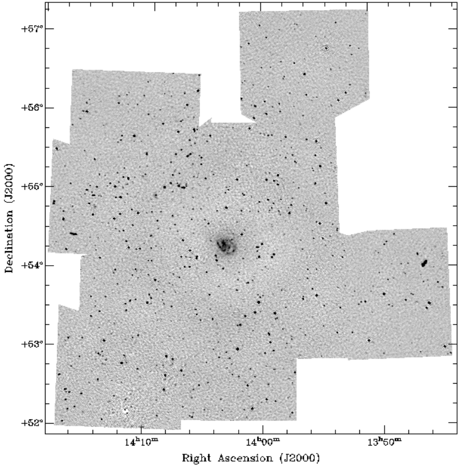
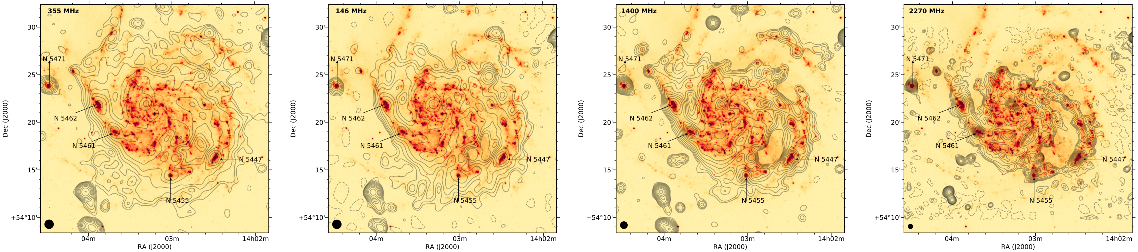
- Facet calibration: van Weeren et al (2006)



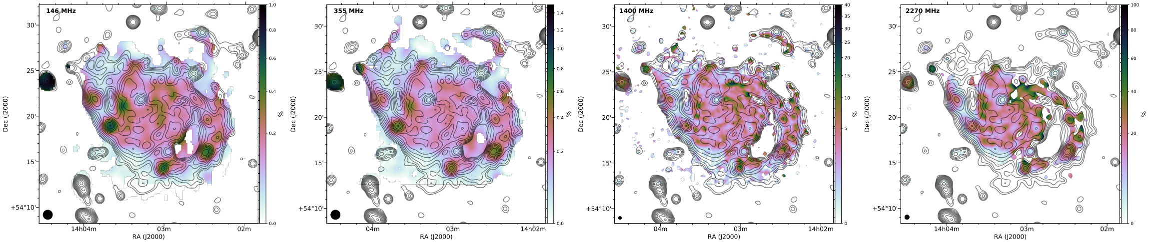
Radio continuum emission from M 101

- Radio continuum contours overlayed on *GALEX* UV image.
- Radial size increases with decreasing frequency (or increasing wavelength).



Thermal/non-thermal separation in M 101

- Recall that what we observe is a combination of thermal and non-thermal emission.
- We need to subtract thermal emission.
- We can use Hα + 24 μm maps to estimate thermal contribution.



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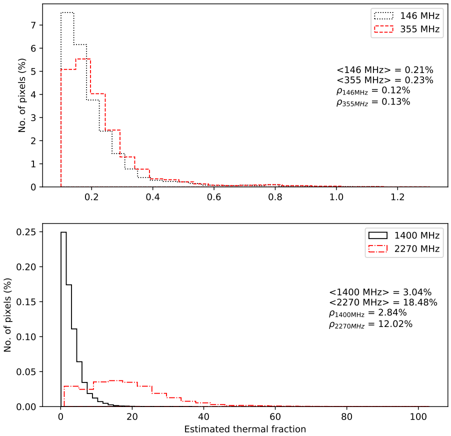
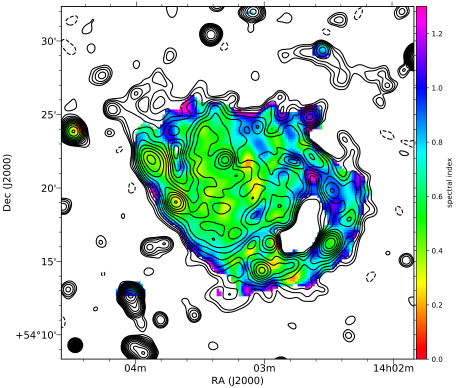
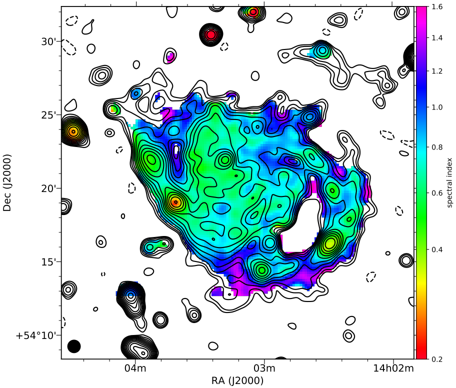


Non-thermal spectral index maps of M 101

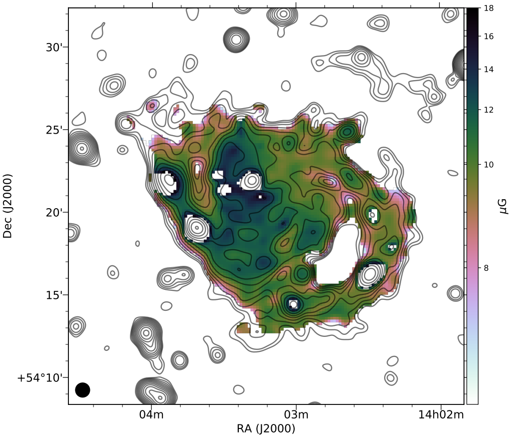
- Injection index, $\alpha \sim 0.5$





Magnetic field strength in M 101

- Assuming energy equipartition, **B** can be estimated from total radio continuum emission.
- See Beck & Krause (2005) for details.
- Peak strength: 15 μG.
- Decreases to about $8 - 9\mu$G in the outer disk.
- Mean magnetic field strength: 10.5 μG



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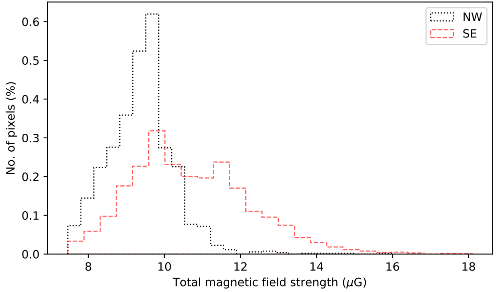
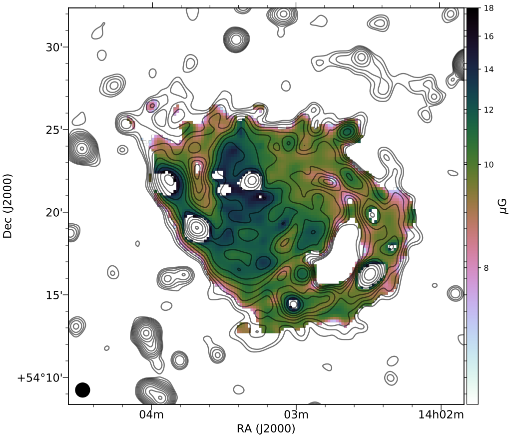
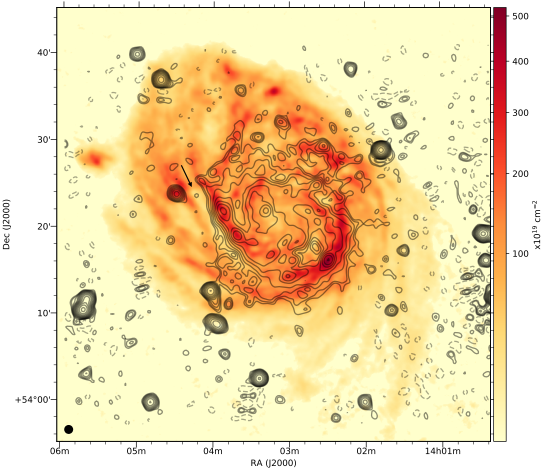




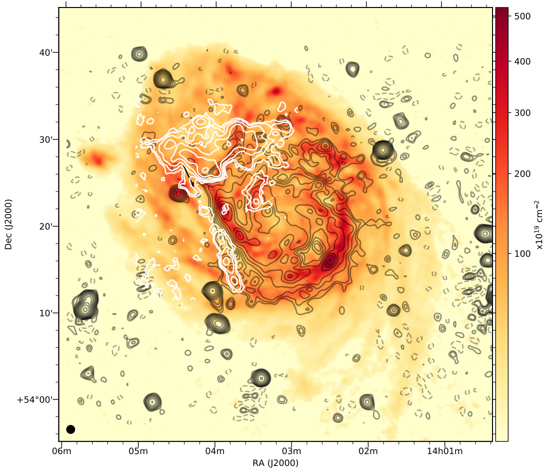
Relation between radio continuum and neutral hydrogen in M 101

- 92cm radio contours on HI
- RC coincides with HI arms
- Large "void" in HI along the eastern spiral arm.



Relation between radio continuum and neutral hydrogen in M 101

- 92cm radio contours on HI
- RC coincides with HI arms
- Large "void" in HI along the eastern spiral arm.
- Void in HI coincides with high velocity gas.

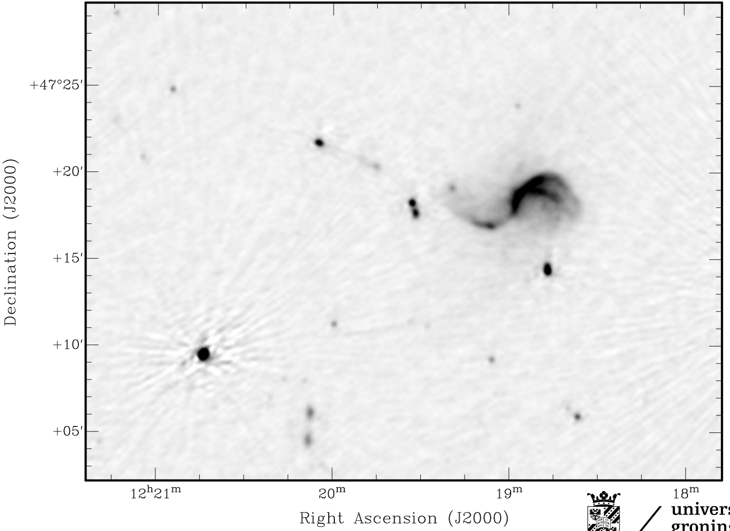


NGC 4258

- Distance: $7.60 \pm 0.17 \pm 0.15$ Mpc
- Unknown morphology!
- Anomalous arms first discovered in 1961 – in the disk or outside the disk?
- Previous studies did not detect RC from the disk
- LOFAR and WSRT observations

Image: X-ray: NASA/CXC/Caltech/P.Ogle et al; Optical: NASA/STScI; IR: NASA/JPL-Caltech; Radio: NSF/NRAO/VLA

NGC 4258 HBA image (14.2″ × 10.4″ 280 uJy/b)



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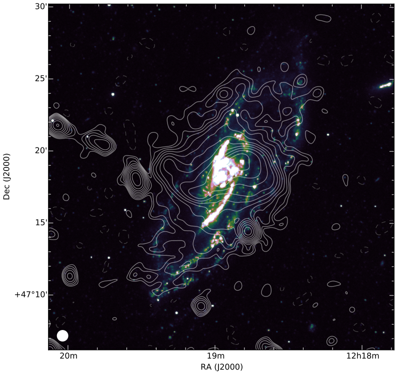
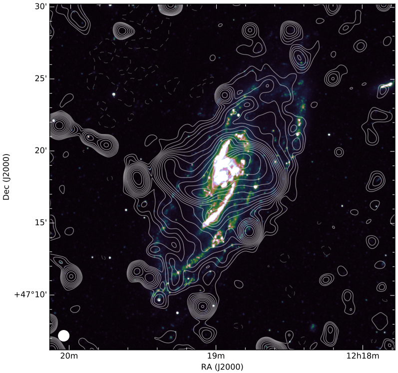
NGC 4258 Total intensity contours

- Smoothed to 40” resolution. Contours at 3×2^{n} mJy/b.
- Radio continuum emission detected out to a radius of $\sim$ 20 kpc.





Images: Sridhar et al (in prep)

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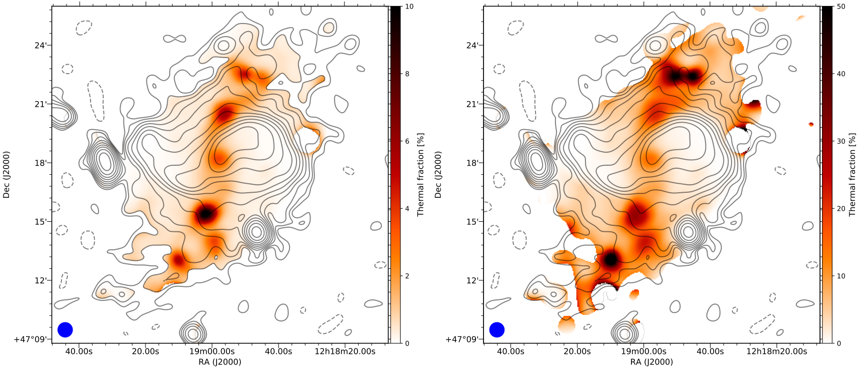
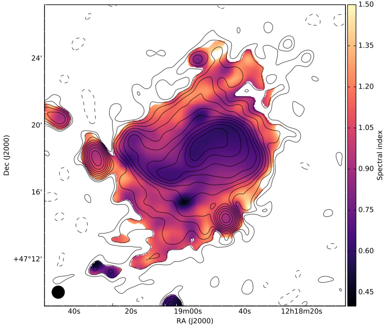
NGC 4258: Thermal contribution

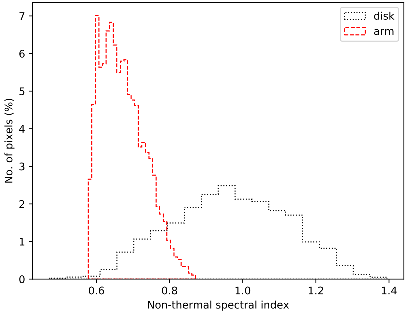
- Thermal estimation using extinction-corrected Hα map
- Less than a few % except towards HII regions.



Non-thermal spectral index

- $\alpha_{\rm nth}$ between 146 and 1400 MHz
- Clear distinction between the arm and the galactic disk
- Radial steepening of spectral index in the disk





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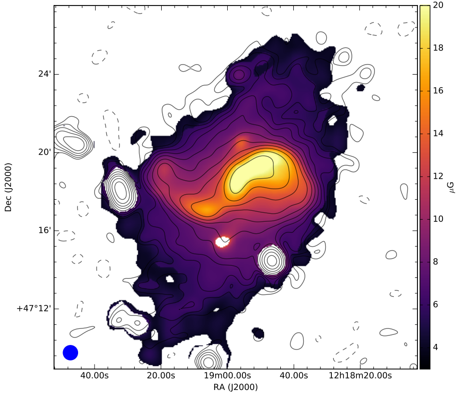
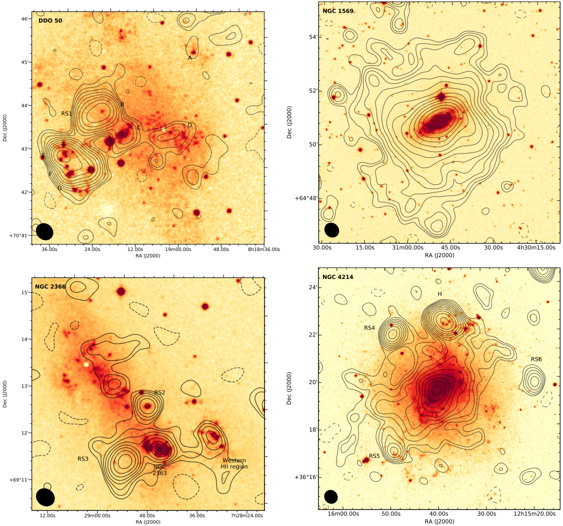
NGC 4258: Equipartition magnetic field

- Mean equipartition magnetic field stength, B= 7.6 μG
- Field strength in the arm could be an overestimate:
  - Unknown path length through the arm
  - Unknown proton-to-electron (K) ratio in the arm



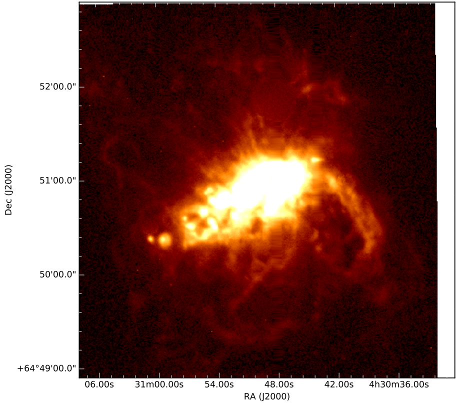
Dwarf galaxies

- Four dwarf galaxies:
  - NGC 1569
  - NGC 4214
  - NGC 2366
  - DDO 50
- 4 $\times$ 8-hours with LOFAR.



NGC 1569

- Post-starburst dwarf galaxy
- Distance: 3.36 Mpc
- Hα emission shows bubbles in the halo



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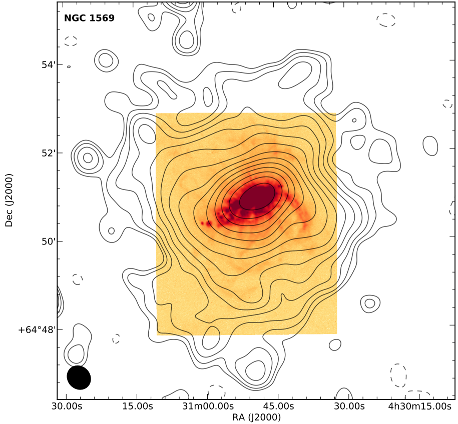
- LOFAR contours on Hα.



Summary

- Radio continuum emission can be used to probe large scale magnetic field in galaxies.
- Thermal subtraction is crucial.
- Low frequency radio emission helps probe the outer parts of galaxies.
- In the near future, we will have radio surveys with LOFAR, AperTIF, ASKAP, MeerKAT, ...
  - Large sample sizes.
  - Statistical study instead of looking at individual galaxies.