Cosmic ray electron propagation and the radio-IR correlation in IC 342

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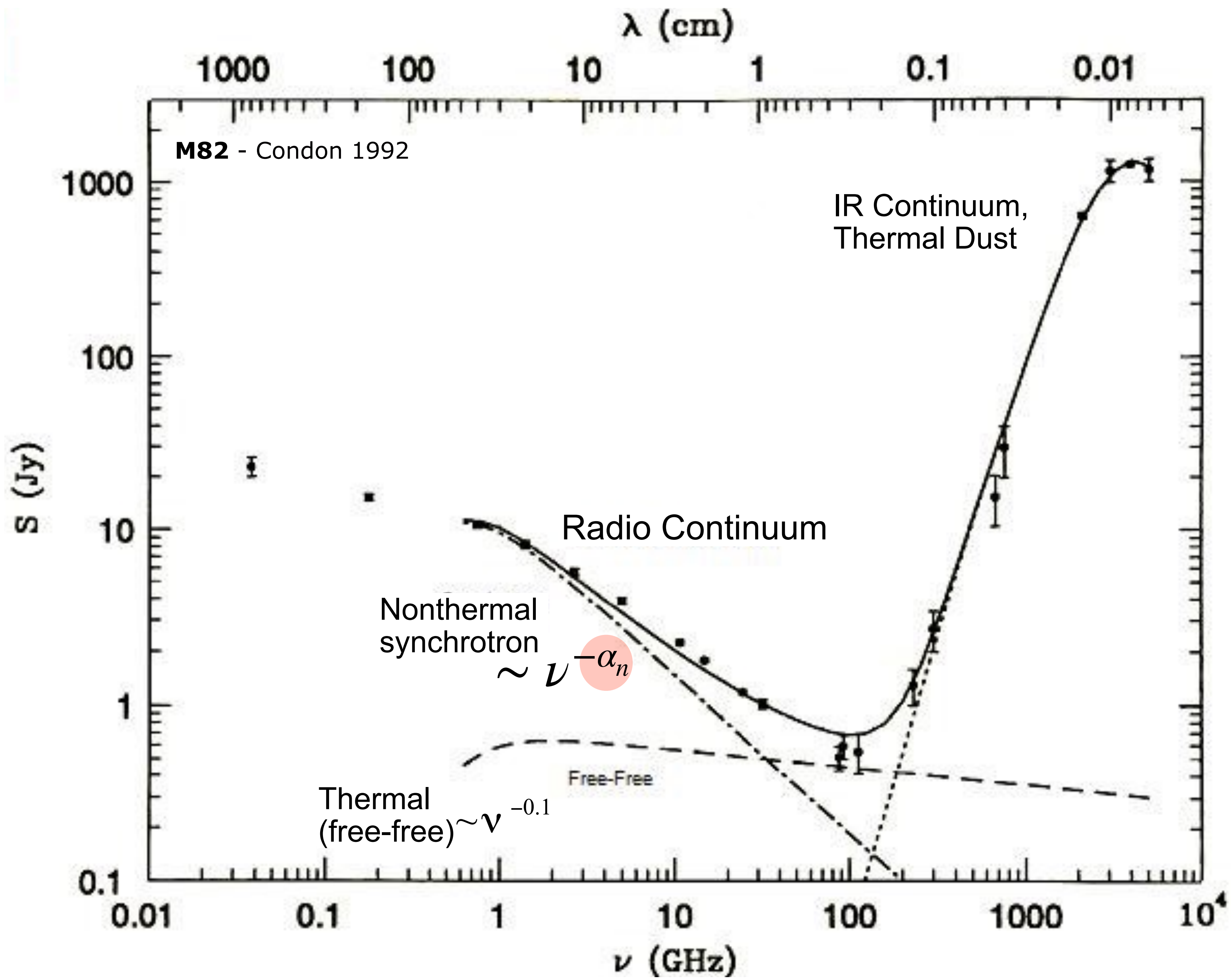
Credit: W4sm astro

Cosmic ray electrons (CREs) in galaxies

- Relativistic particles injected and accelerated in star forming regions, AGNs
- Important in ISM chemistry and pressure/energy balance studies
- A power-law (nonthermal) distribution of energy
- Power-law index varies due to interaction with ISM fields and matter
- Best traced in radio due to synchrotron cooling

CREs energy index ~ synchrotron spectral index α_n



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Details of CREs life cycle & impact:

- Acceleration/energy loss?
- Propagation: (diffusion/streaming/advection)?

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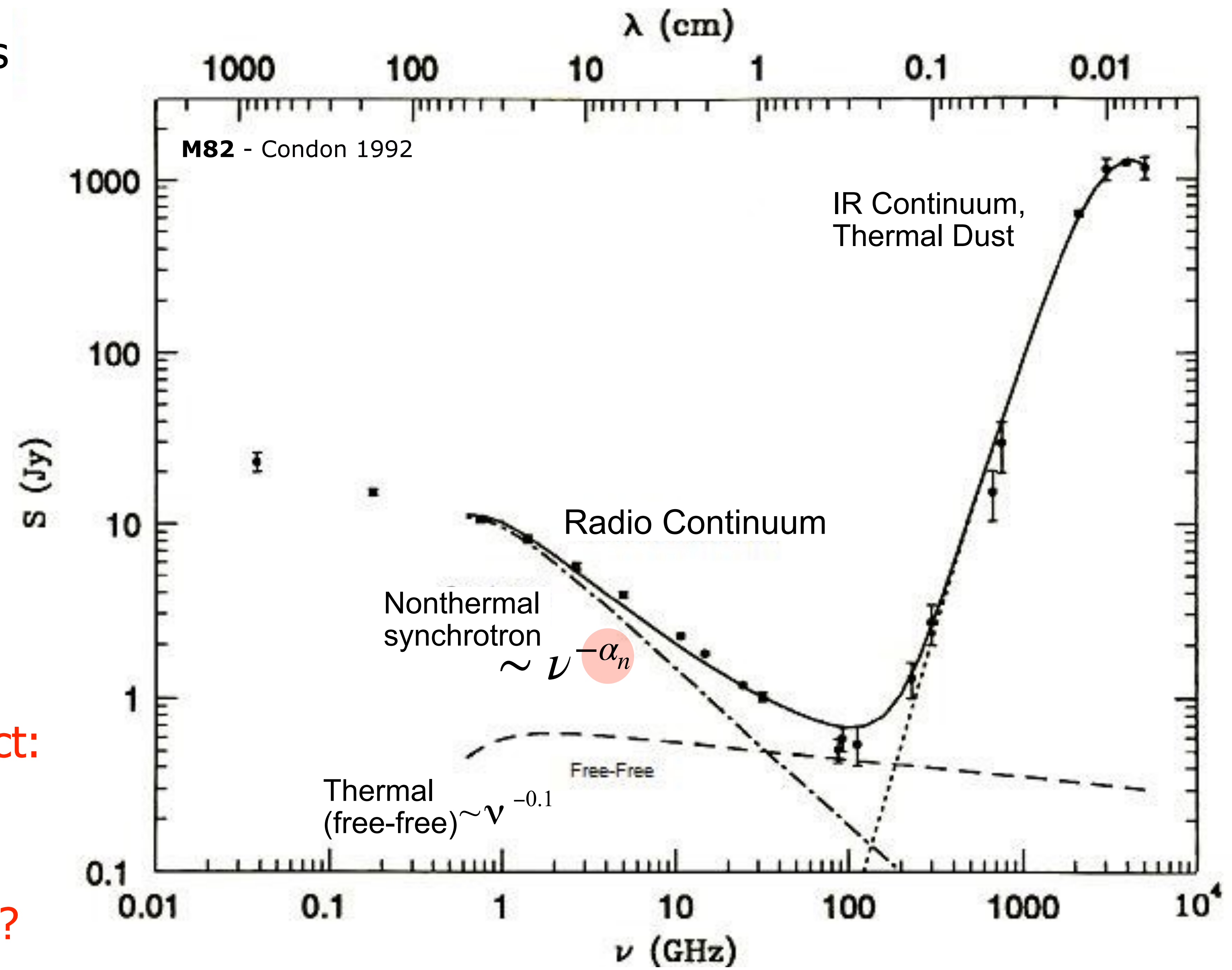
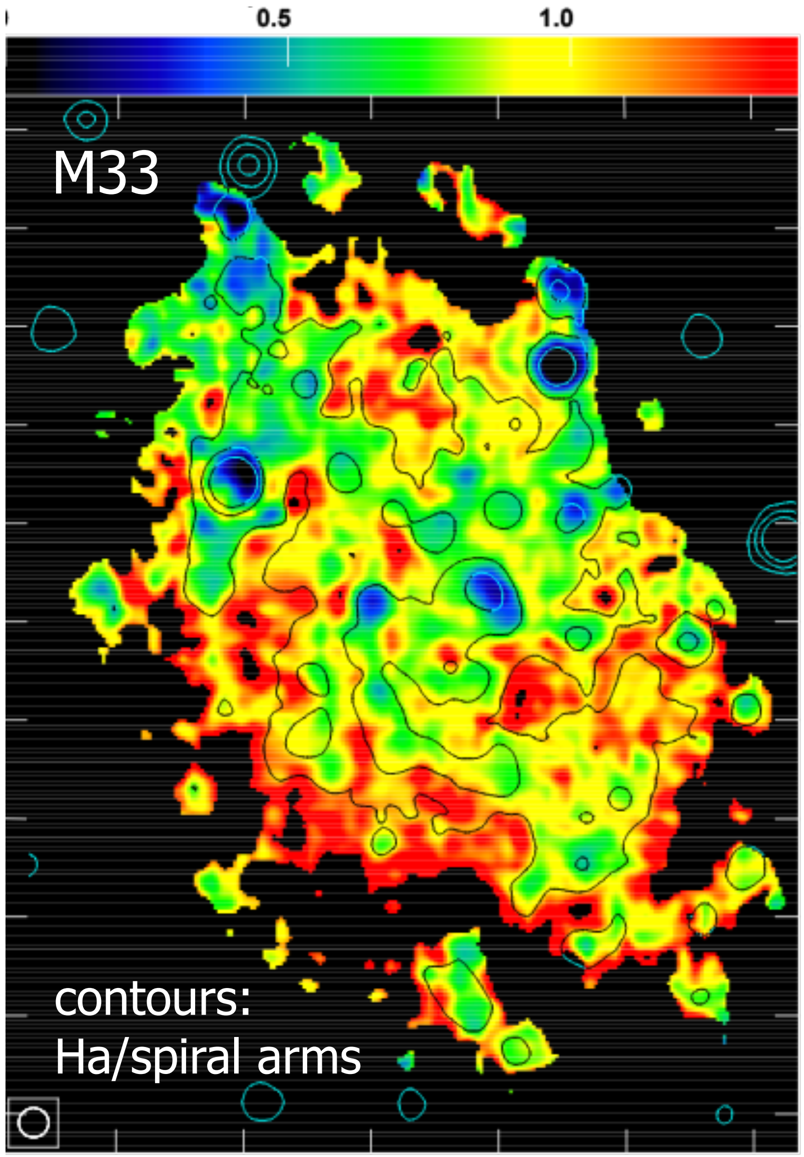


Acceleration & energy loss

Pure synchrotron spectral index in galaxies

α_n, $I_\nu^n \sim \nu^{-\alpha_n}$



- SF regions: injection and acceleration of CREs
- Diffuse ISM: synchrotron/IC cooling
- Spiral arms: LOS mixing of various losses

(Tabatabaei+ 2007)

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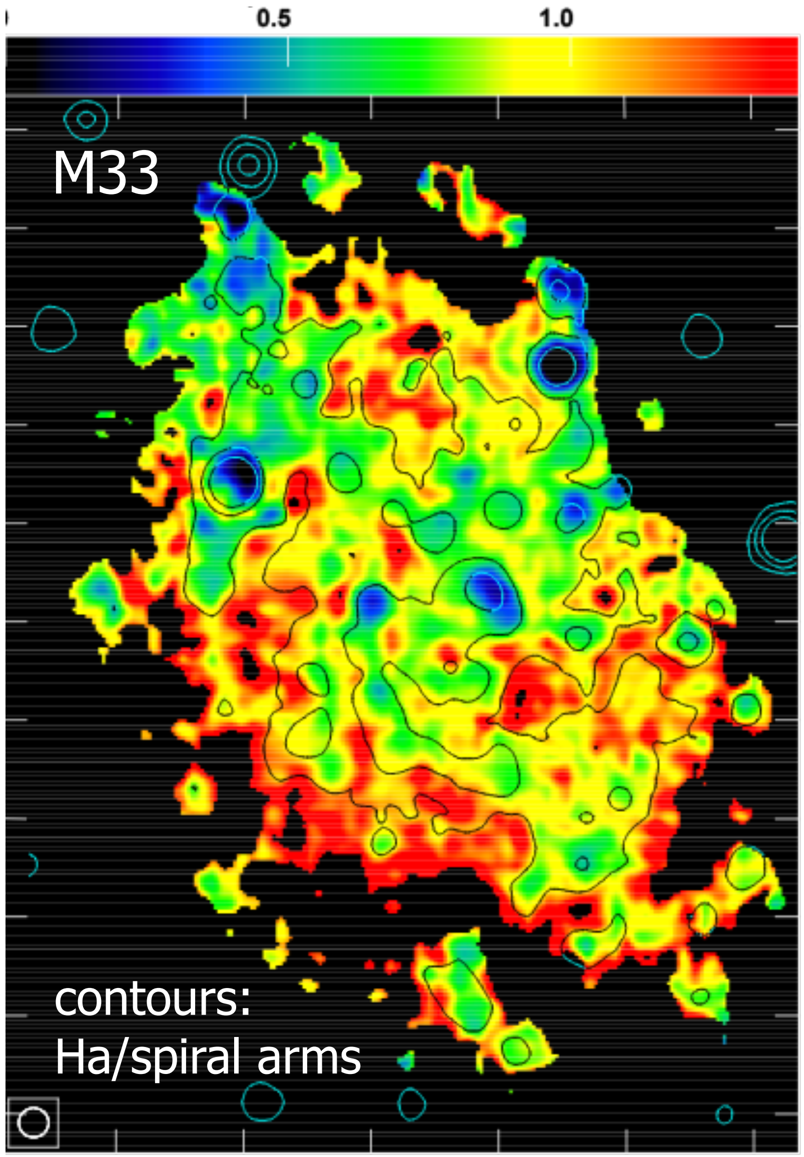

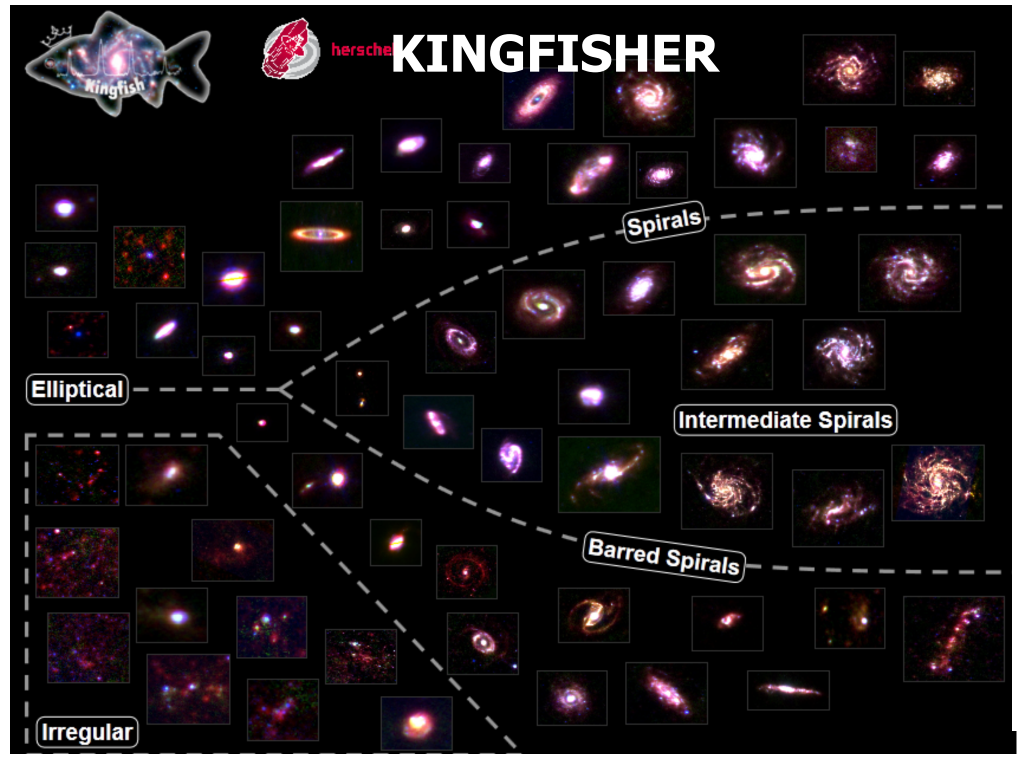

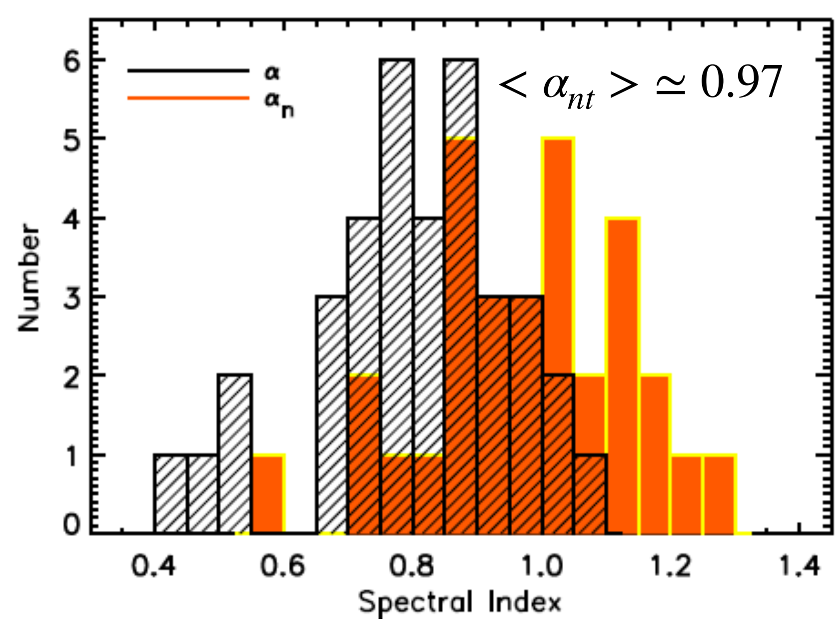

- SF regions: injection and acceleration of CREs
- Diffuse ISM: synchrotron/IC cooling
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(Tabatabaei+ 2007)

Nearby galaxies:
Synchrotron loss dominates
(Tabatabaei+ 2017)

Acceleration & energy loss

Pure synchrotron spectral index in galaxies

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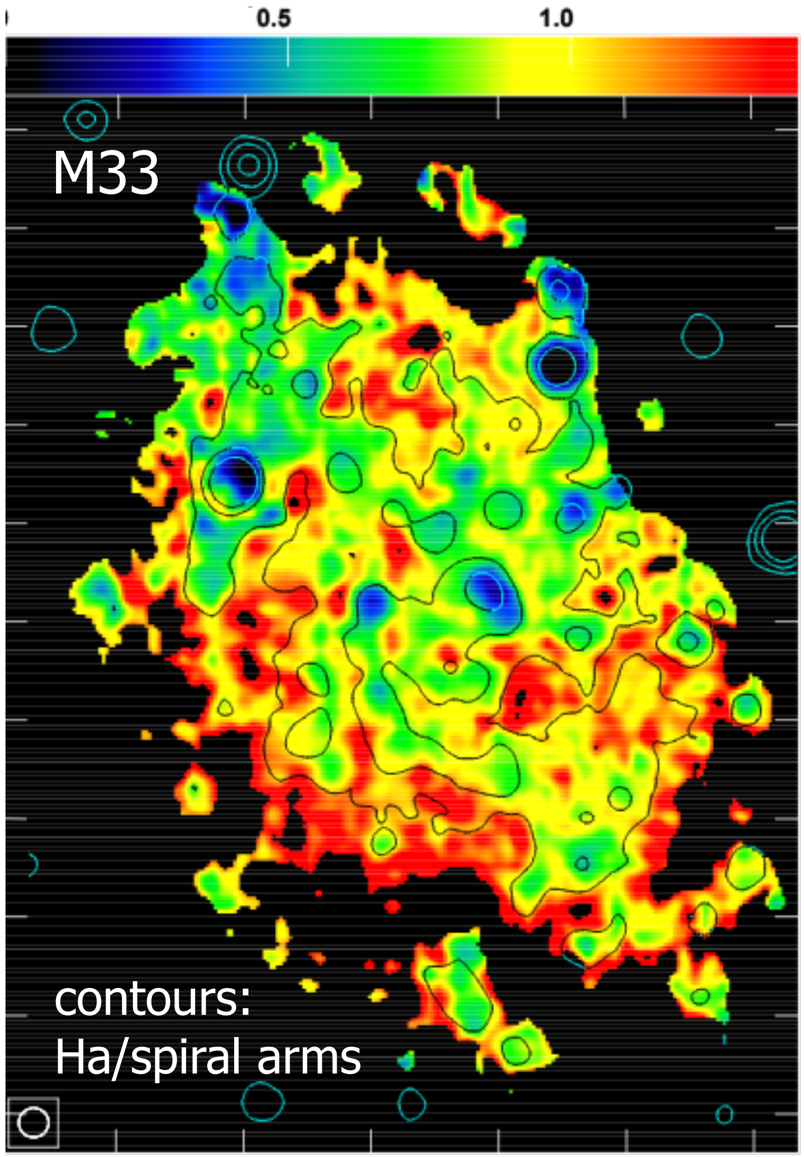

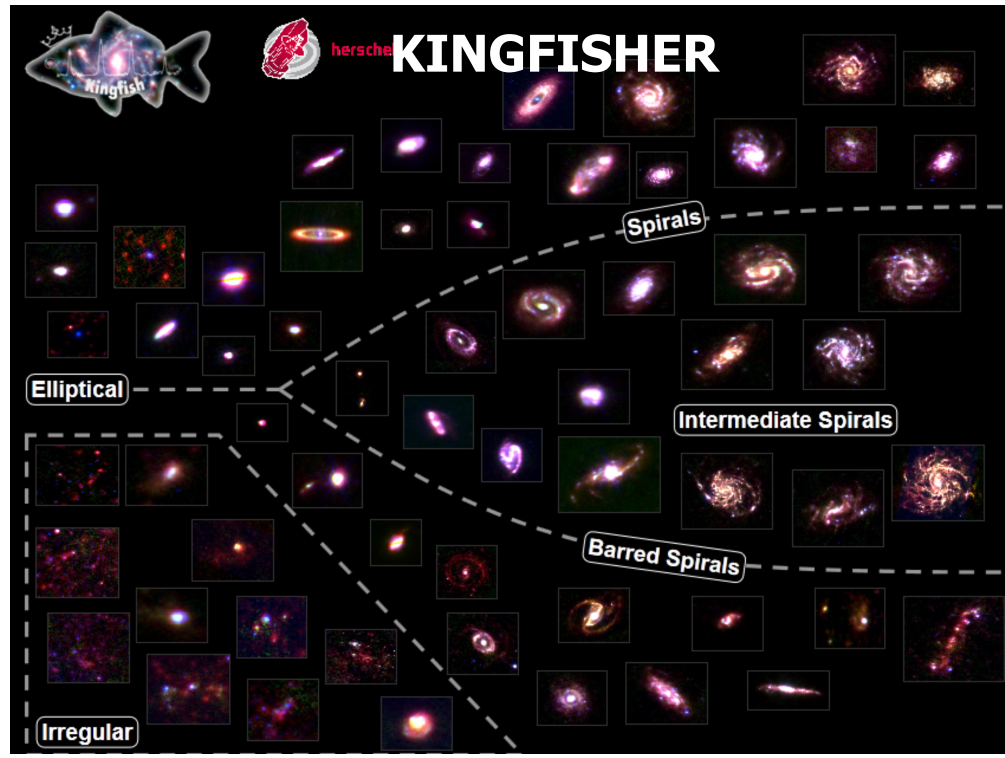

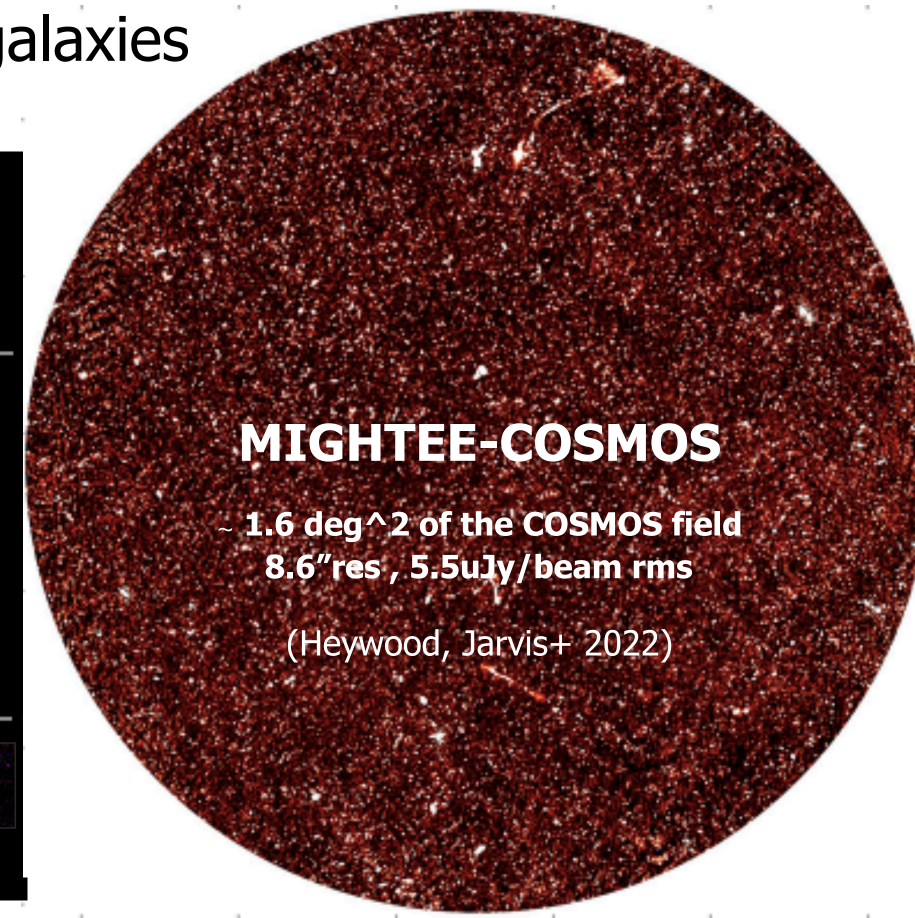

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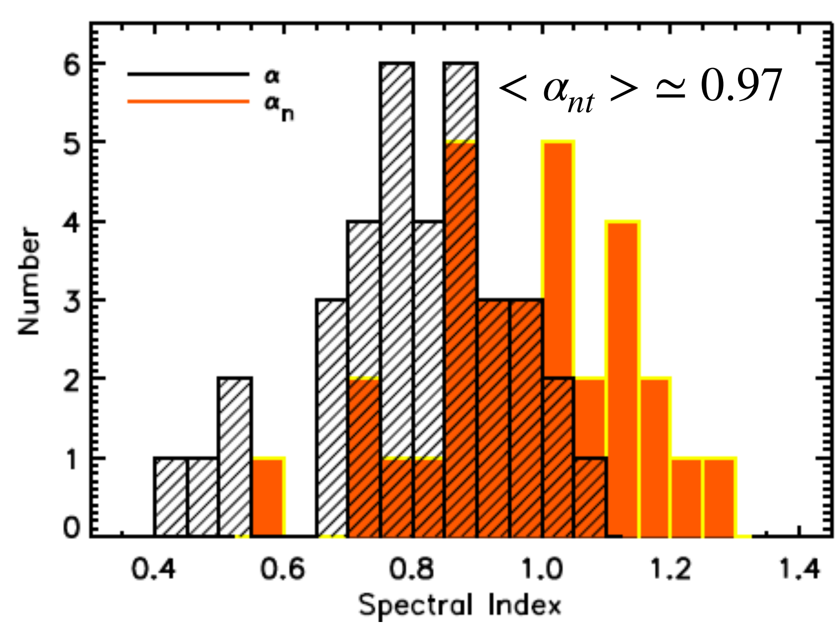
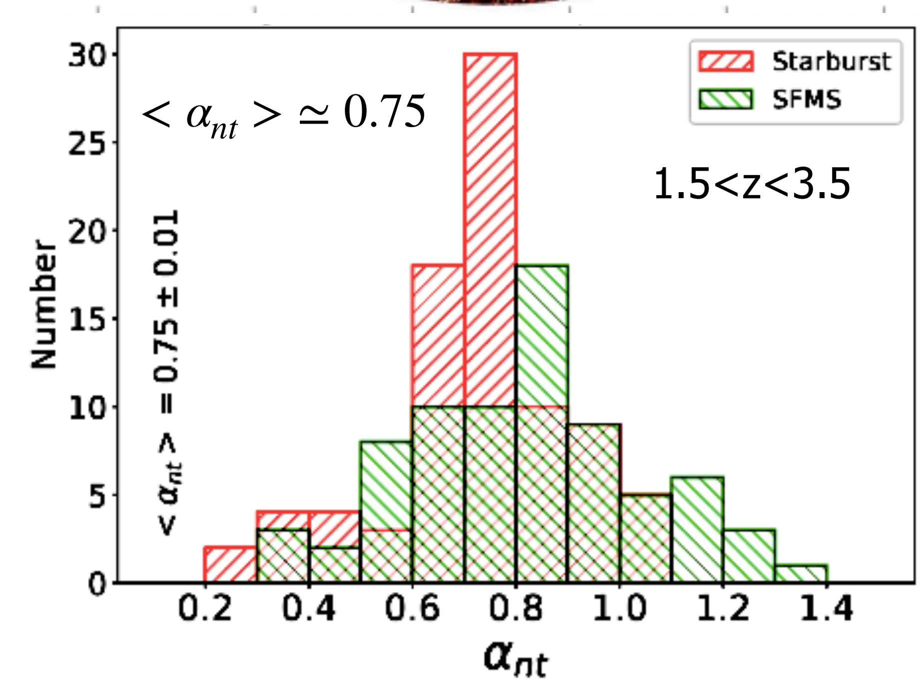


Nearby SF galaxies:
Synchrotron loss dominates
(Tabatabaei+ 2017)

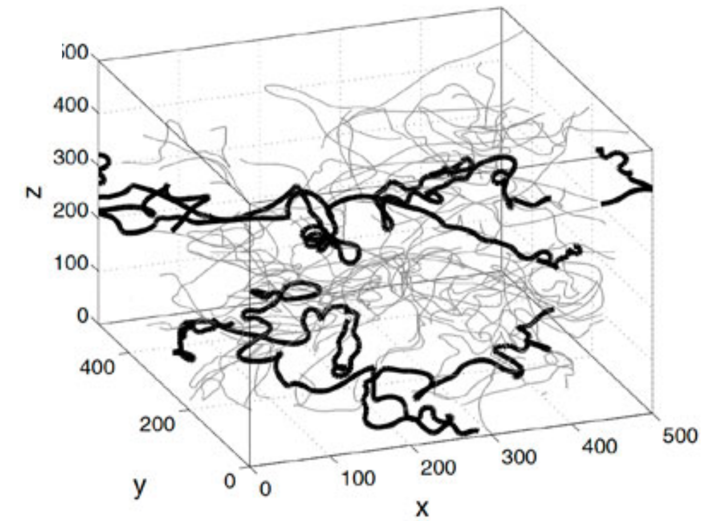


SF Galaxies at cosmic noon:
Winds + Fermi II acceleration
(Tabatabaei+ 2025)

CREs propagation: Theory

Characterized by a length which depends on uniformity of magnetic field

For CREs diffusion:



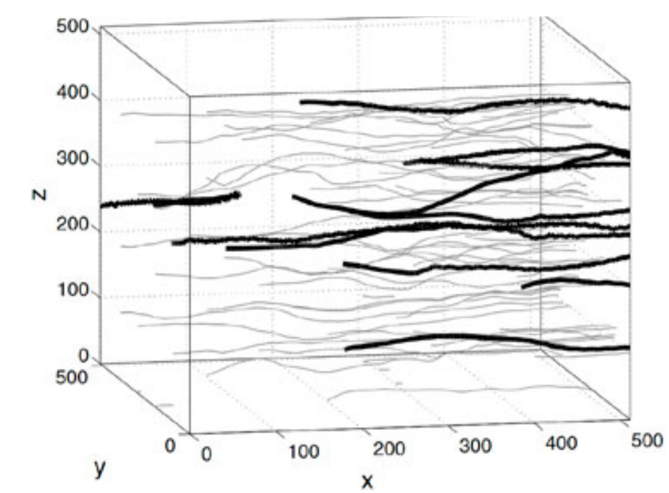
Xu & Yan (2013)

- if synchrotron loss dominates, $t_{\rm CRE} = t_{\rm synch}$ $\quad l_{\rm dif} \propto (B_{\rm ord}/B_{\rm tur})B_{\rm tot}^{-3/4}$
- if escape is important, $t_{\rm CRE} = t_{\rm escape}$ $\quad l_{\rm dif} \propto (B_{\rm ord}/B_{\rm tur})B_{\rm tot}^{-1/2}$
  (larger propagation length)

Ptuskin+ 1993, Breitschwerdt+ 2002, Dogiel & Breitschwerdt 2012, Shalchi+ 2009

For CREs Streaming:
(anisotropic & faster)

$$l_{\rm prop} \propto v_{\rm A} \propto B_{\rm ord}$$



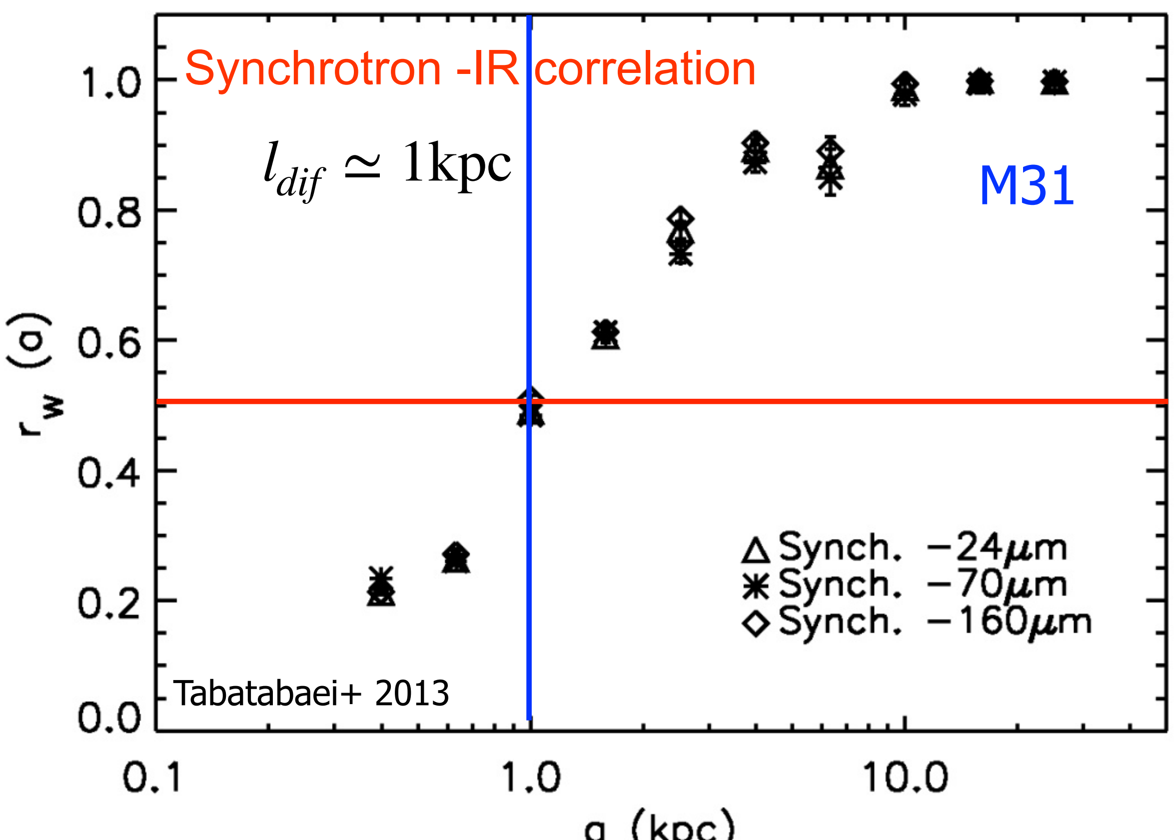
e.g., Kulsrud 2005; Enßlin et al. 2011

Propagation of CREs is isotropic on scales <1 kpc in the MW:
Strong et al. 2007; Tsap et al. 2012
—> favors diffusion models

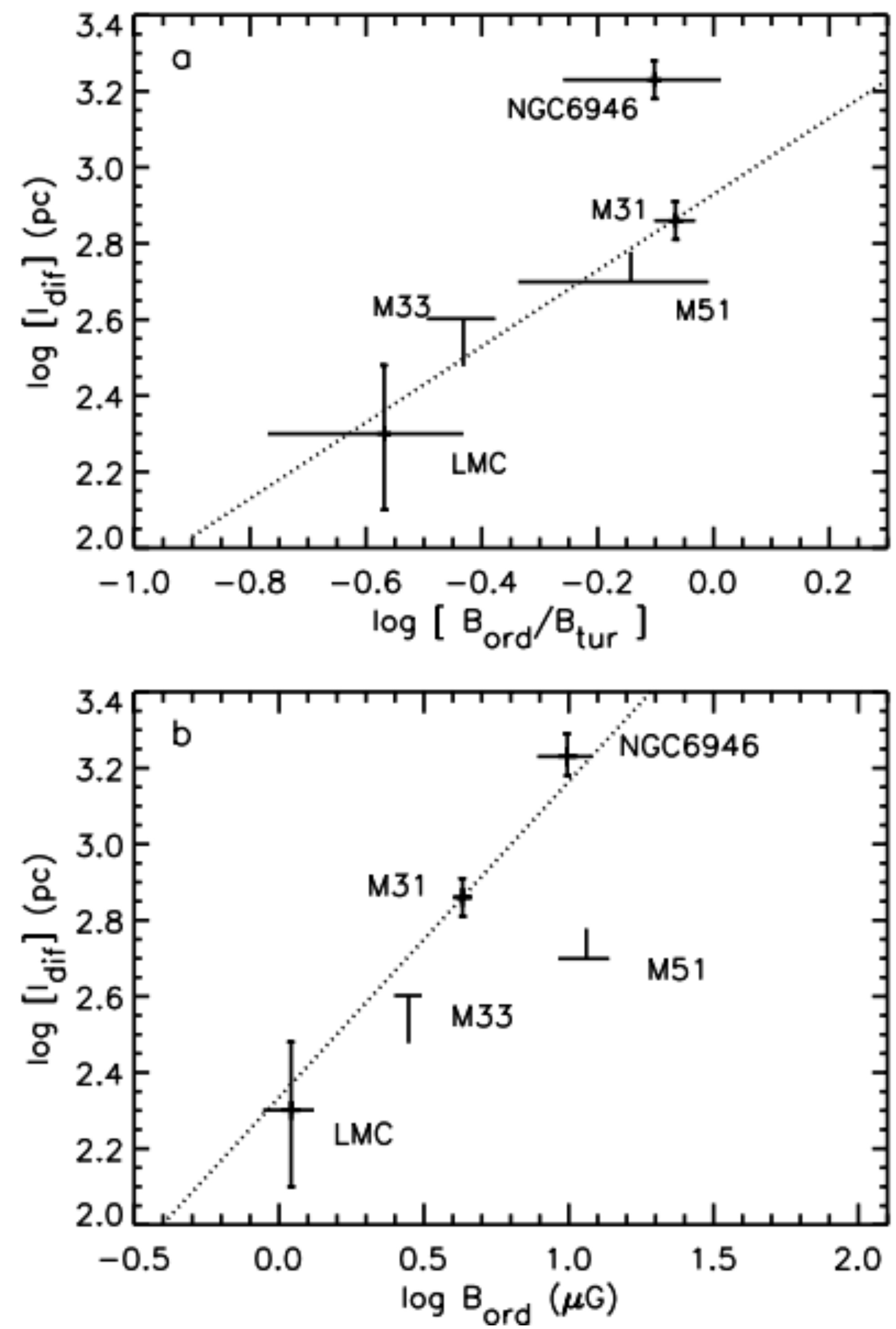
CREs propagation: Observation

l_{dif} ∝ Smallest scale of the synchrotron — IR correlation in galaxies
Taking into account complicated underlying physics:
CREs/magnetic field/gas pressure balance explains the correlation
(Tabatabaei et al. 2013a, b)

1) Thermal/nonthermal radio separation
2) Scale-decomposition of structures
3) Cross-correlation vs spatial scale
4) Break scale ~ propagation length

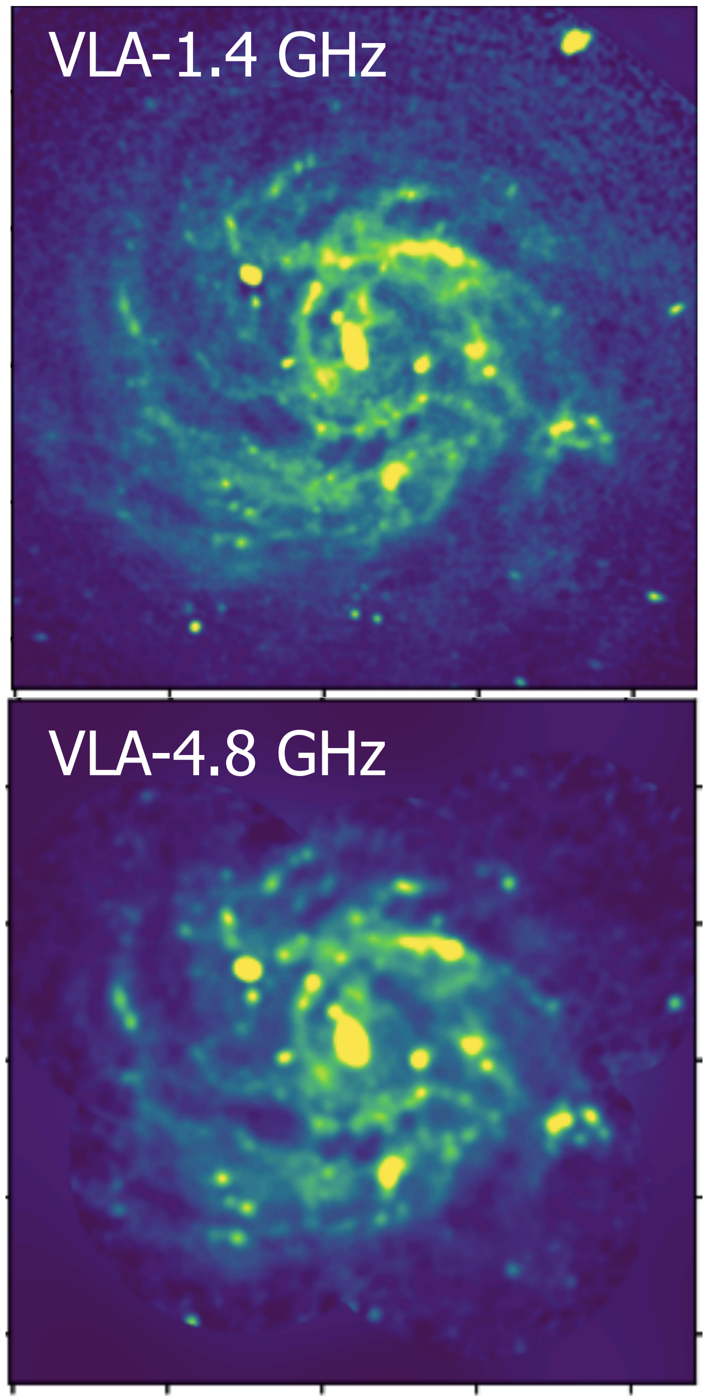


Which propagation model fits observations better?
—> More data points needed



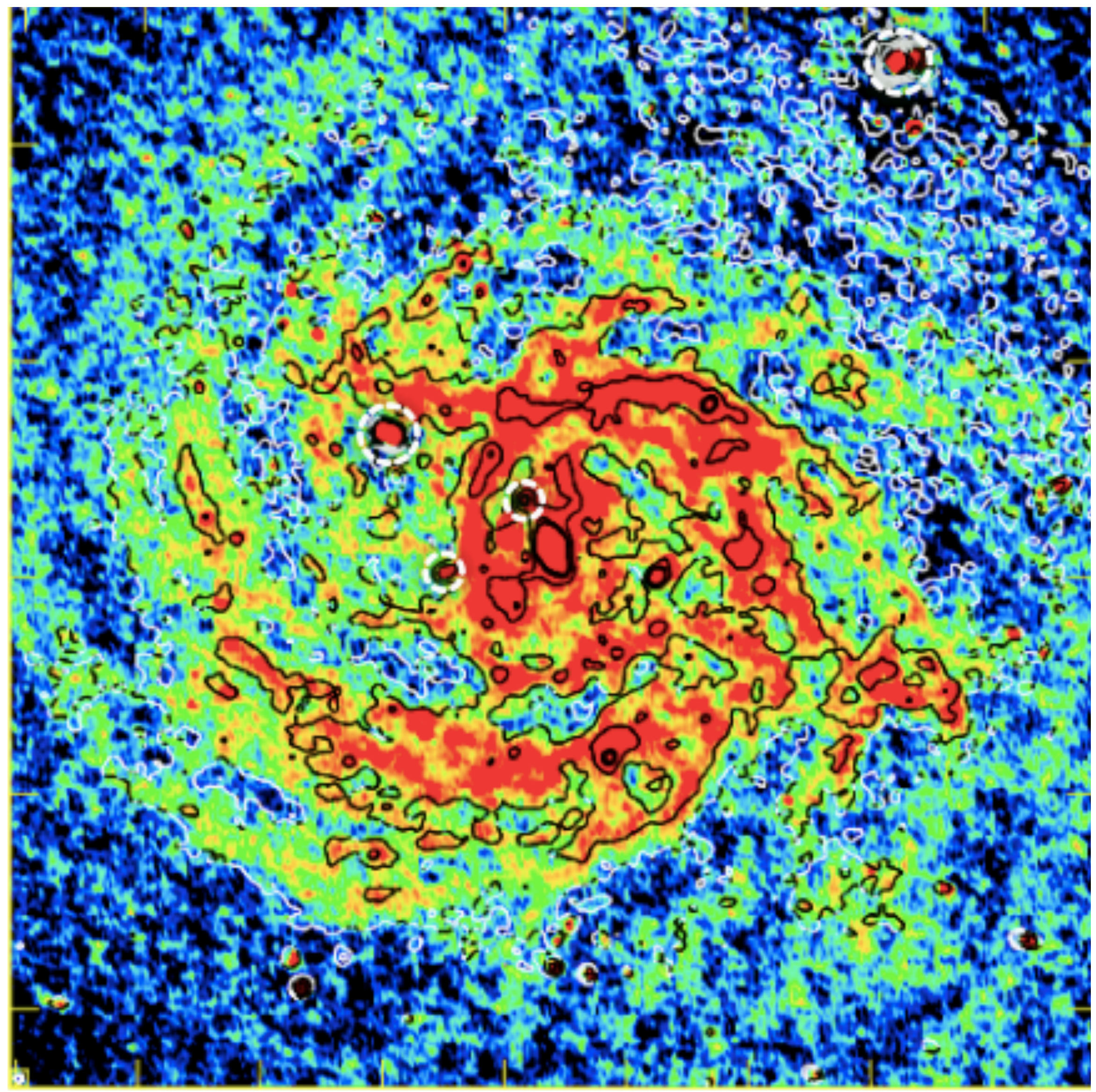
LOTSS nearby galaxy sample: Case of IC 342

M.R. Nasirzadeh



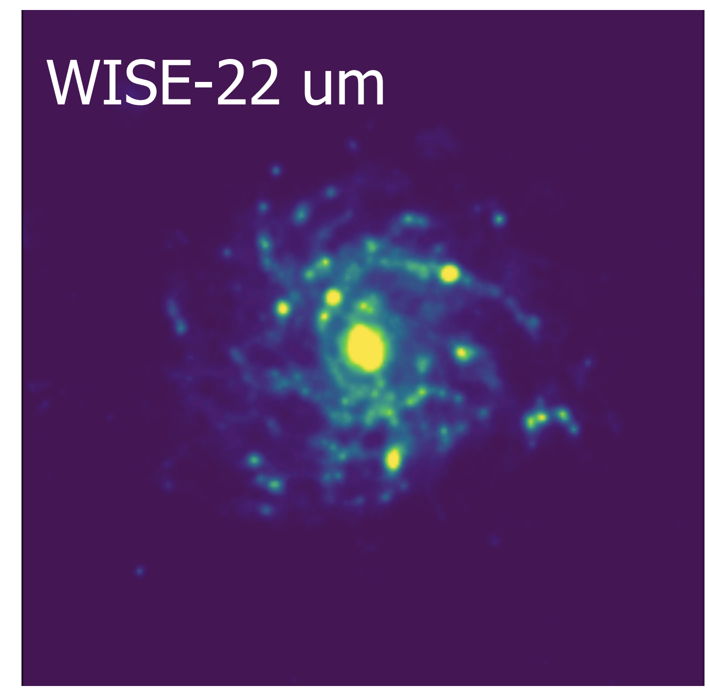
Beck 2015

LOTSS 144MHz
(DR2; Shimwell et al. 2022)



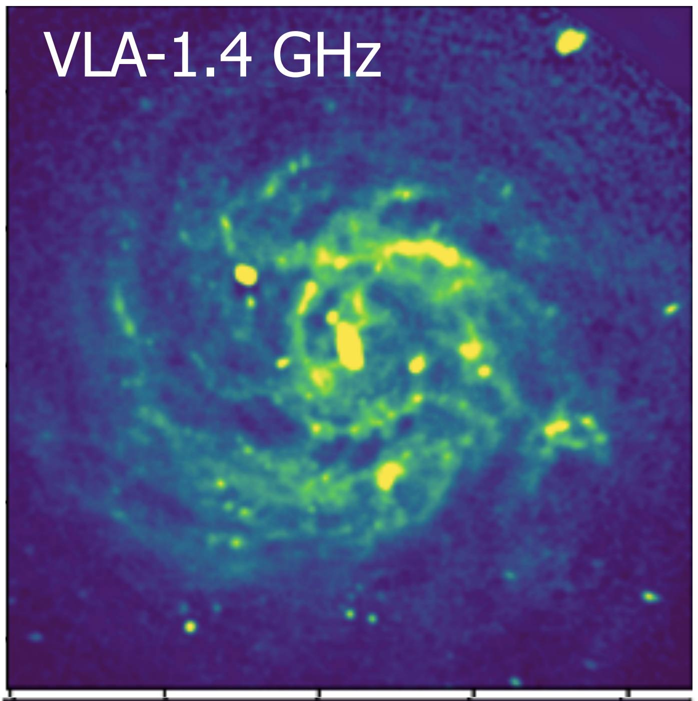
$\theta \simeq 10''$, rms = 180 μJy/beam

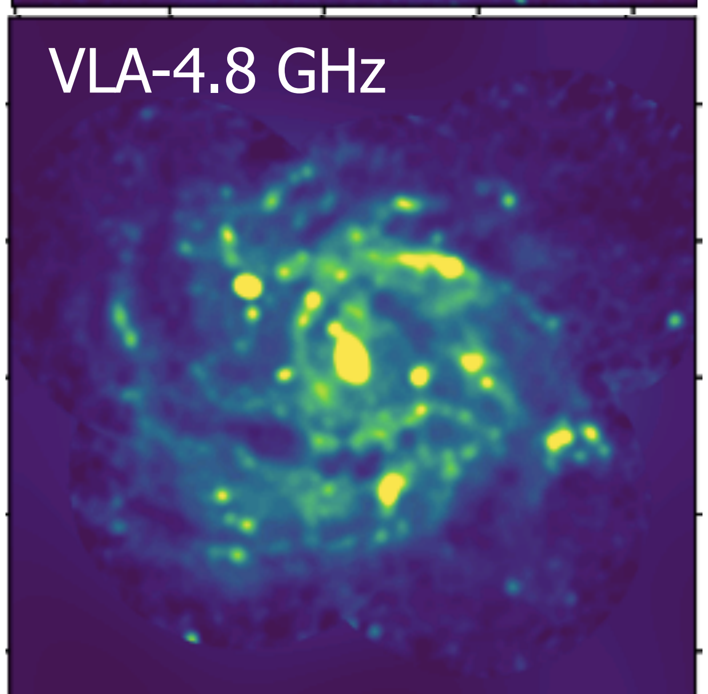
Source identification:
56% SF regions



LOTSS nearby galaxy sample: Case of IC 342

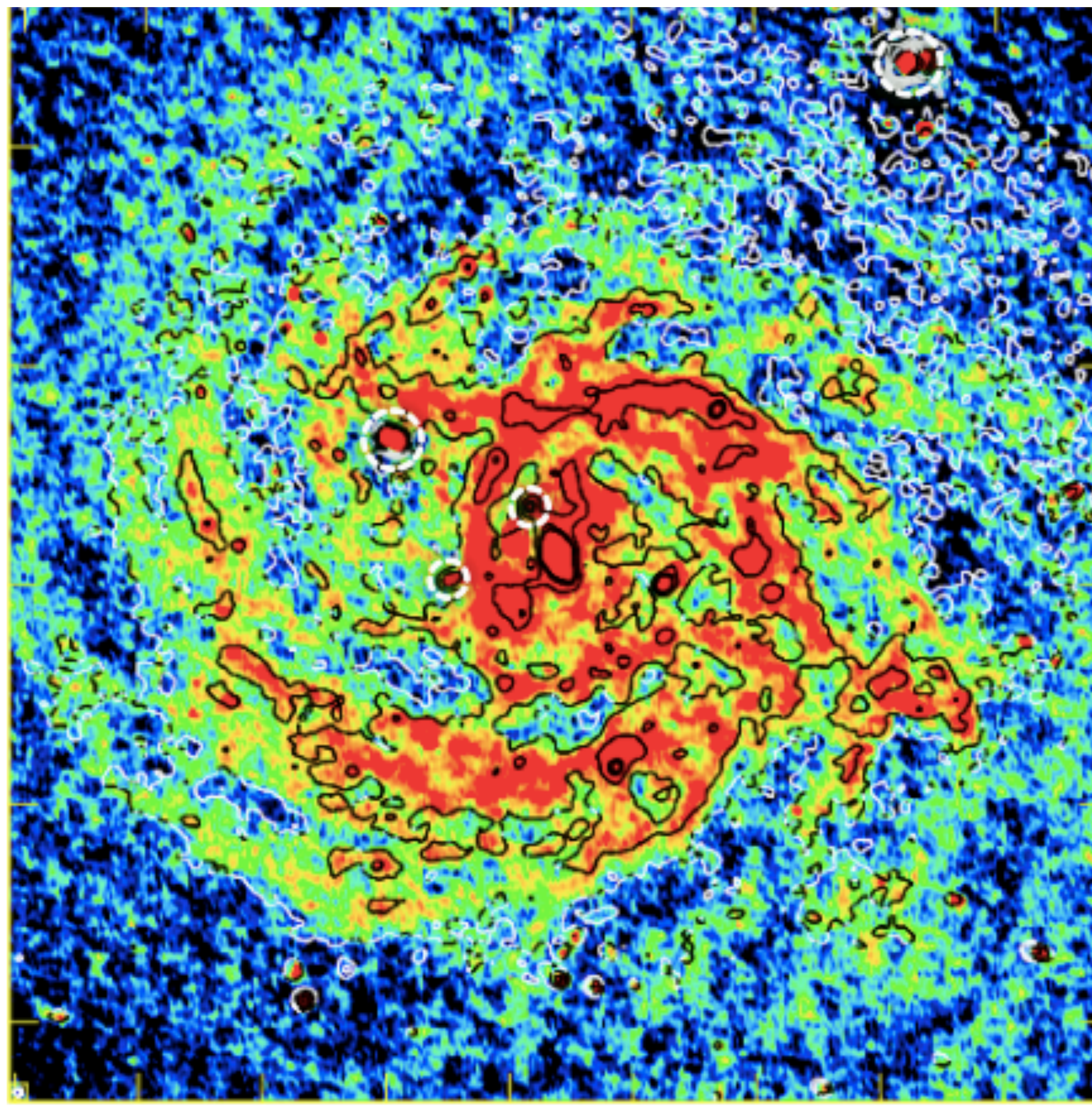
Thermal/nonthermal separation using MIR as thermal tracer
(Murphy+ 2006)





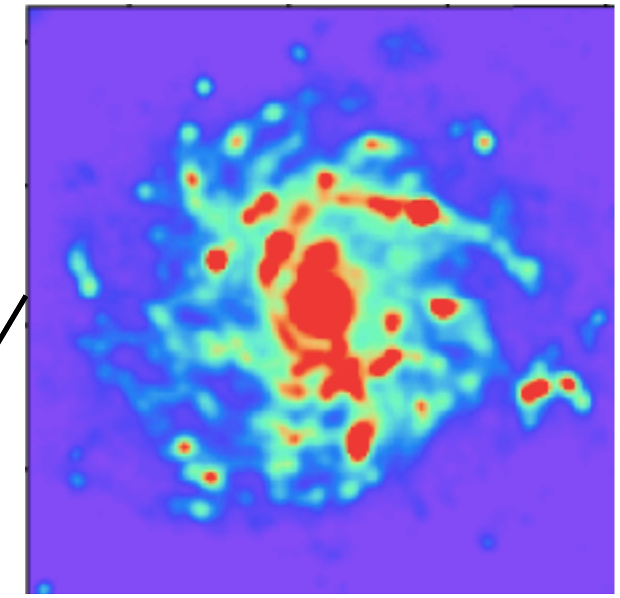
Beck 2015

$$\left(\frac{S_\nu^{\rm th}}{\rm Jy}\right) \sim 7.93\times10^{-3}\left(\frac{T}{10^4\,{\rm K}}\right)^{0.45}\left(\frac{\nu}{\rm GHz}\right)^{-0.1}\left(\frac{f_{24}}{\rm Jy}\right)$$

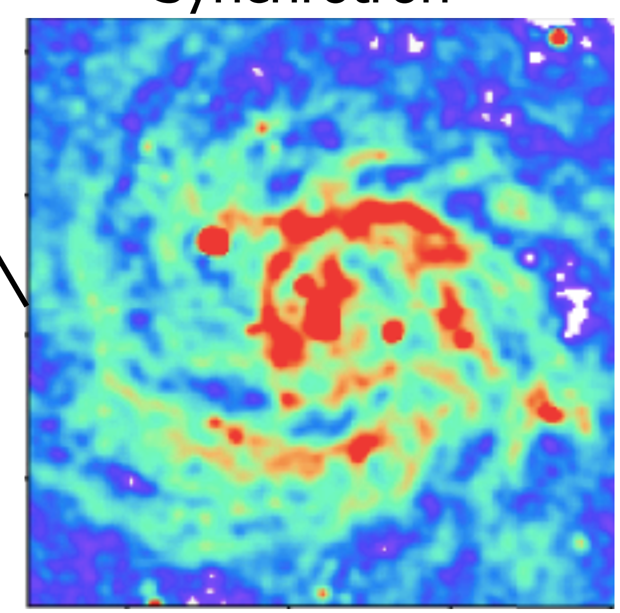


Although total thermal fraction is only~3% at 144MHz,
morphology changes locally after thermal correction.

Free-free



Synchrotron



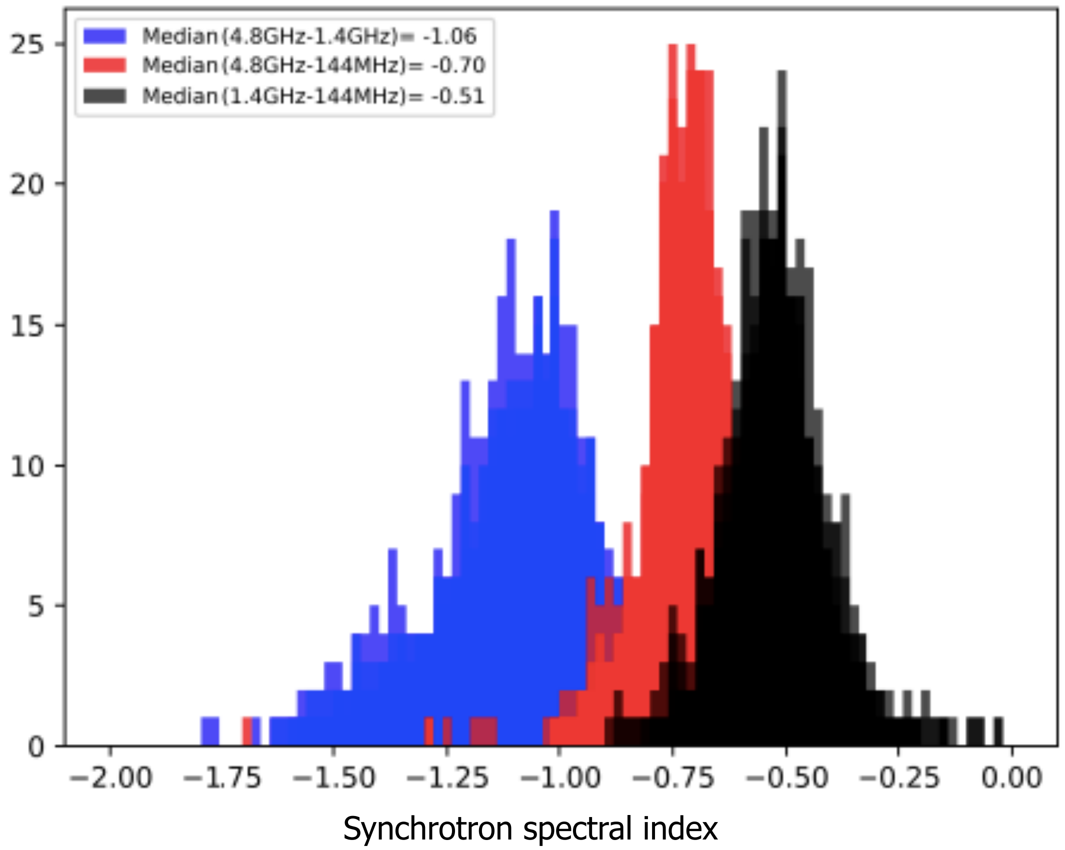
Nasirzadeh+ 2024

Synchrotron spectral index in IC342

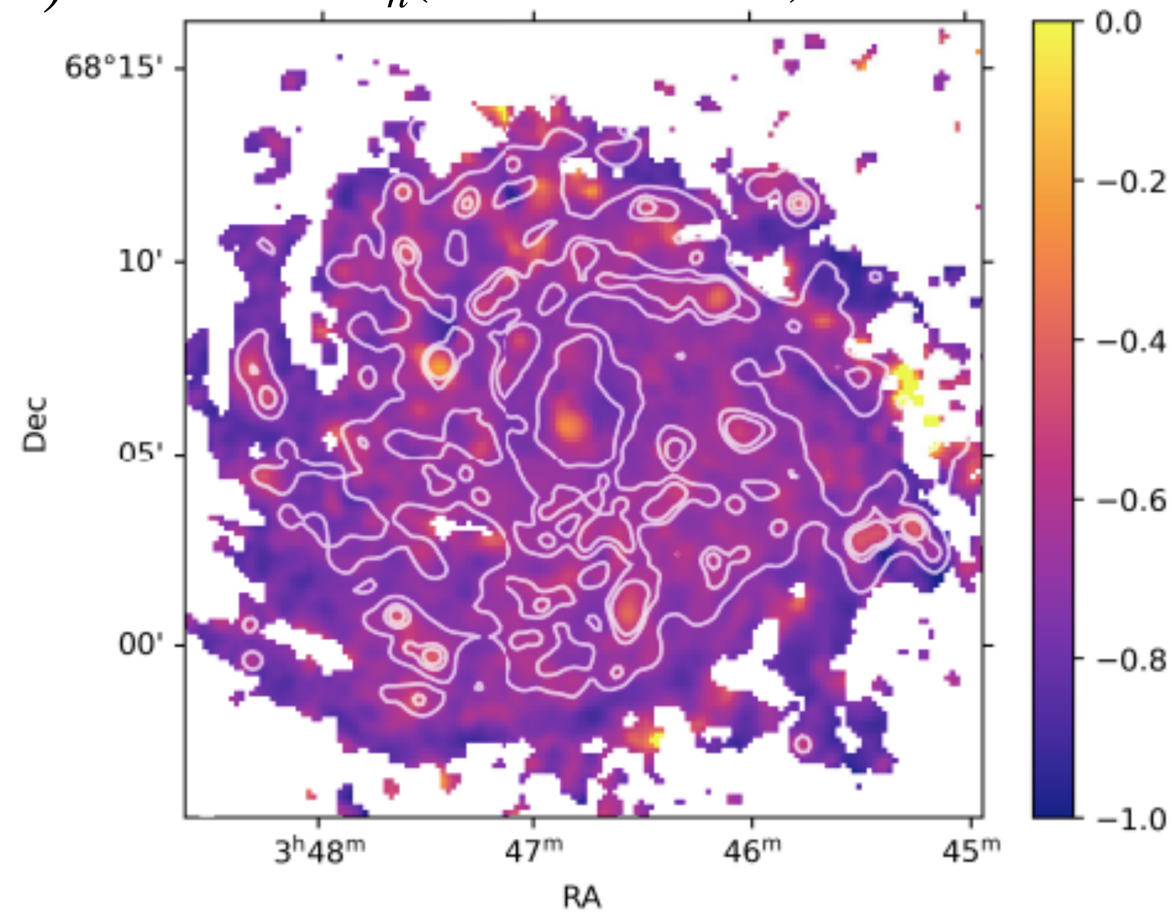
Nasirzadeh+ 2024:

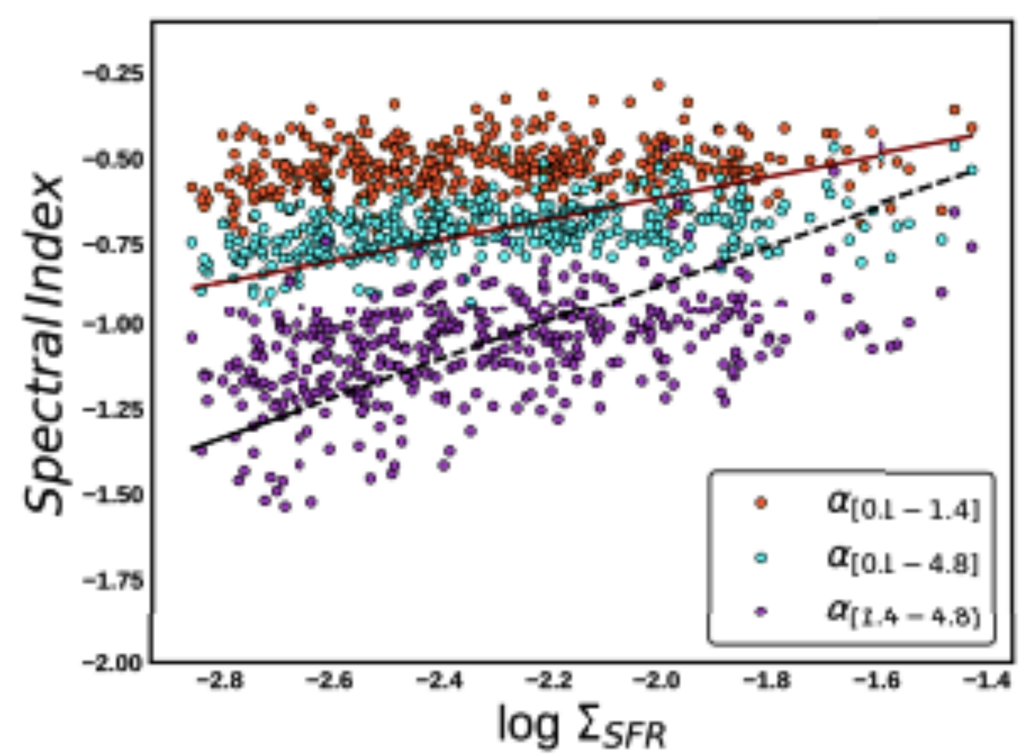
$(I_\nu^{\mathrm{n}} \sim \nu^{\alpha_n})$

Flattening toward low-frequencies occurs not only in SF but also in diffuse regions



$\alpha_n(0.1 - 4.8\ \mathrm{GHz})$

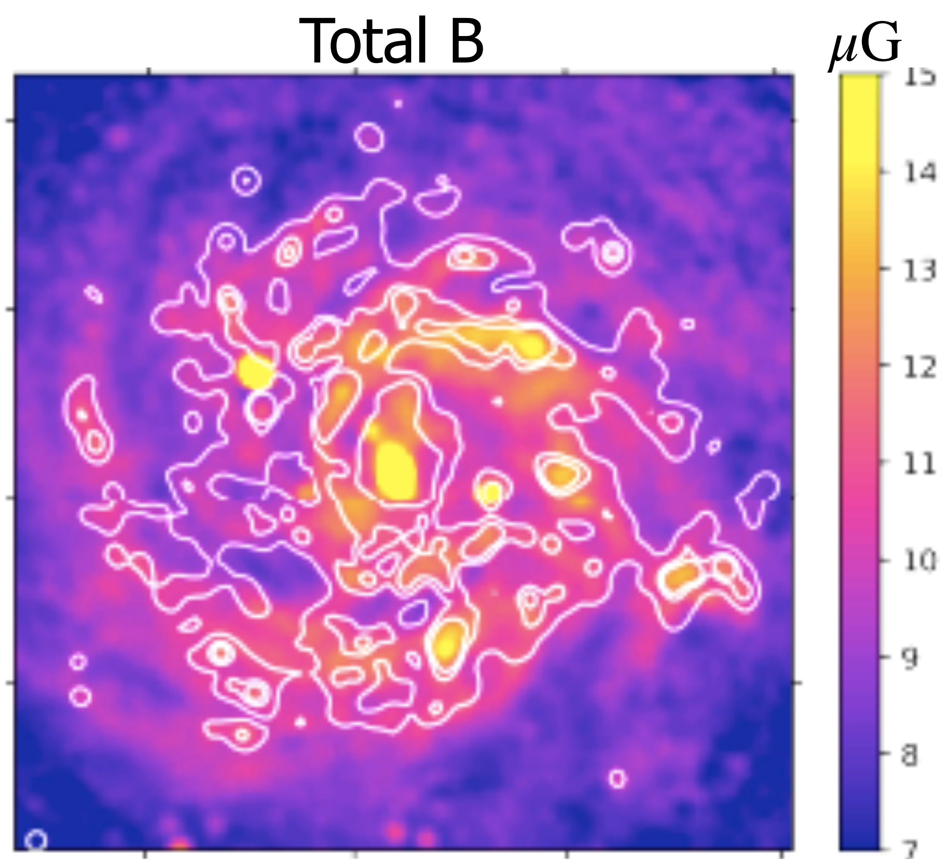


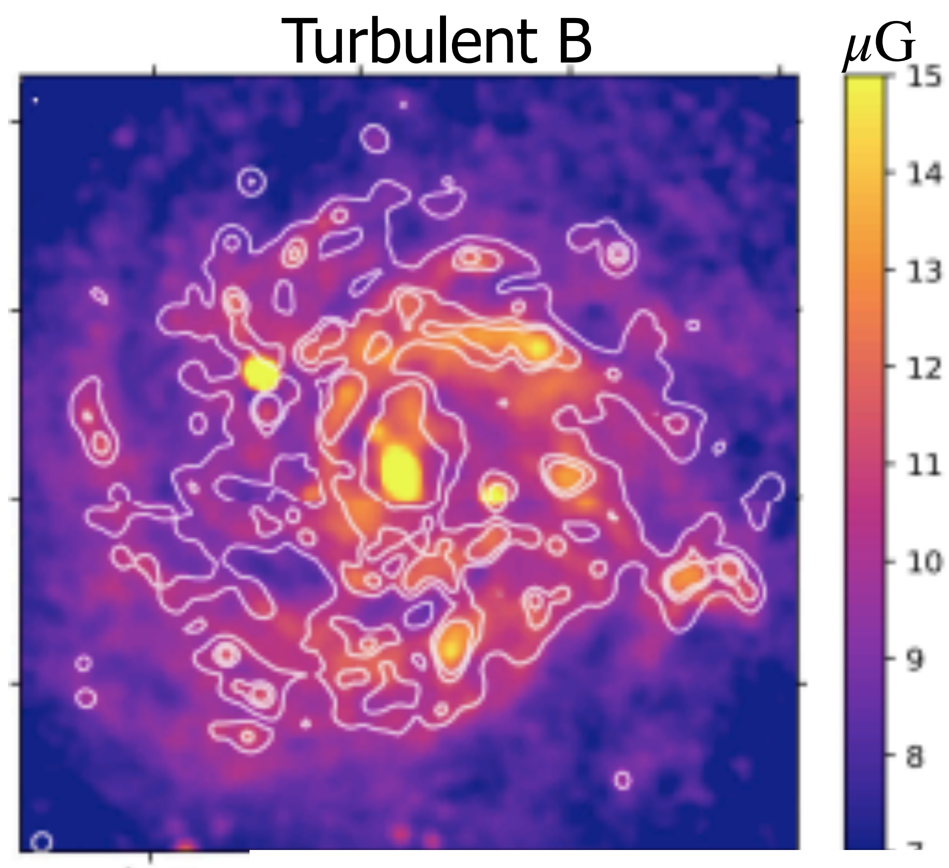


- Flatter in SF regions, agrees with previous works (Tabatabaei+ 2007, 2013, 2022, Hassani+2022)
- Between 0.1-1.4 GHz, no correlation with SFR (optically thickness/absorption effect?)

See also Heesen et al. 2022, Gajović et al.2025

Equipartition magnetic field strength in IC342

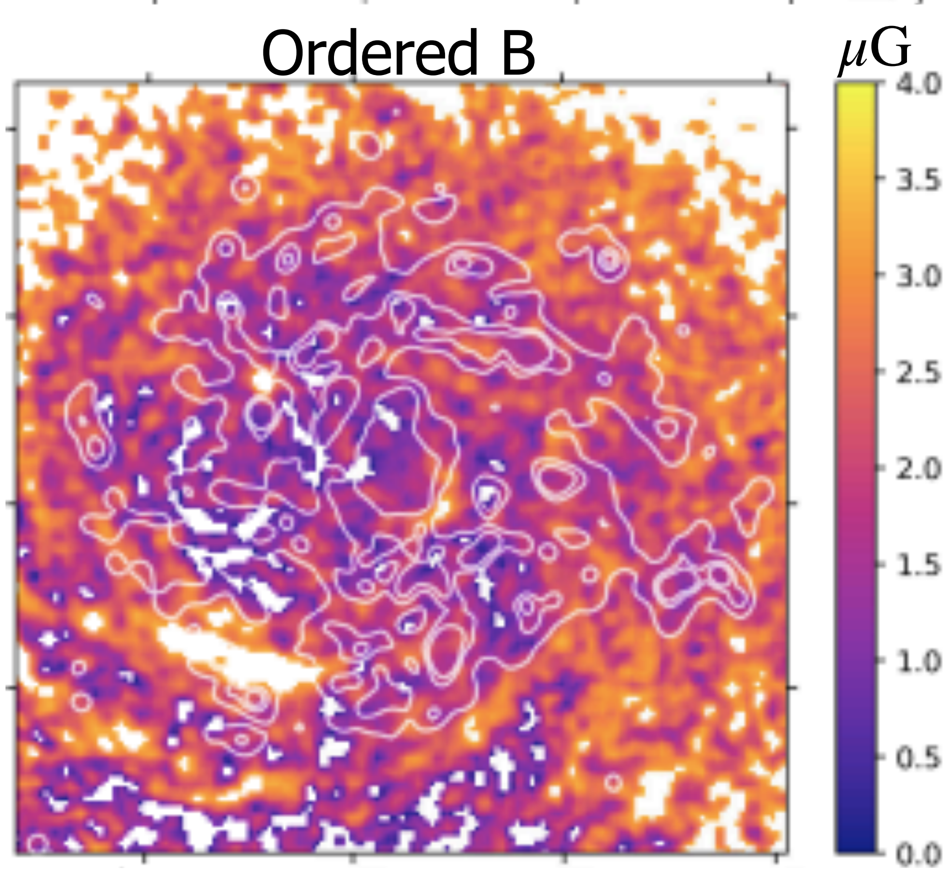


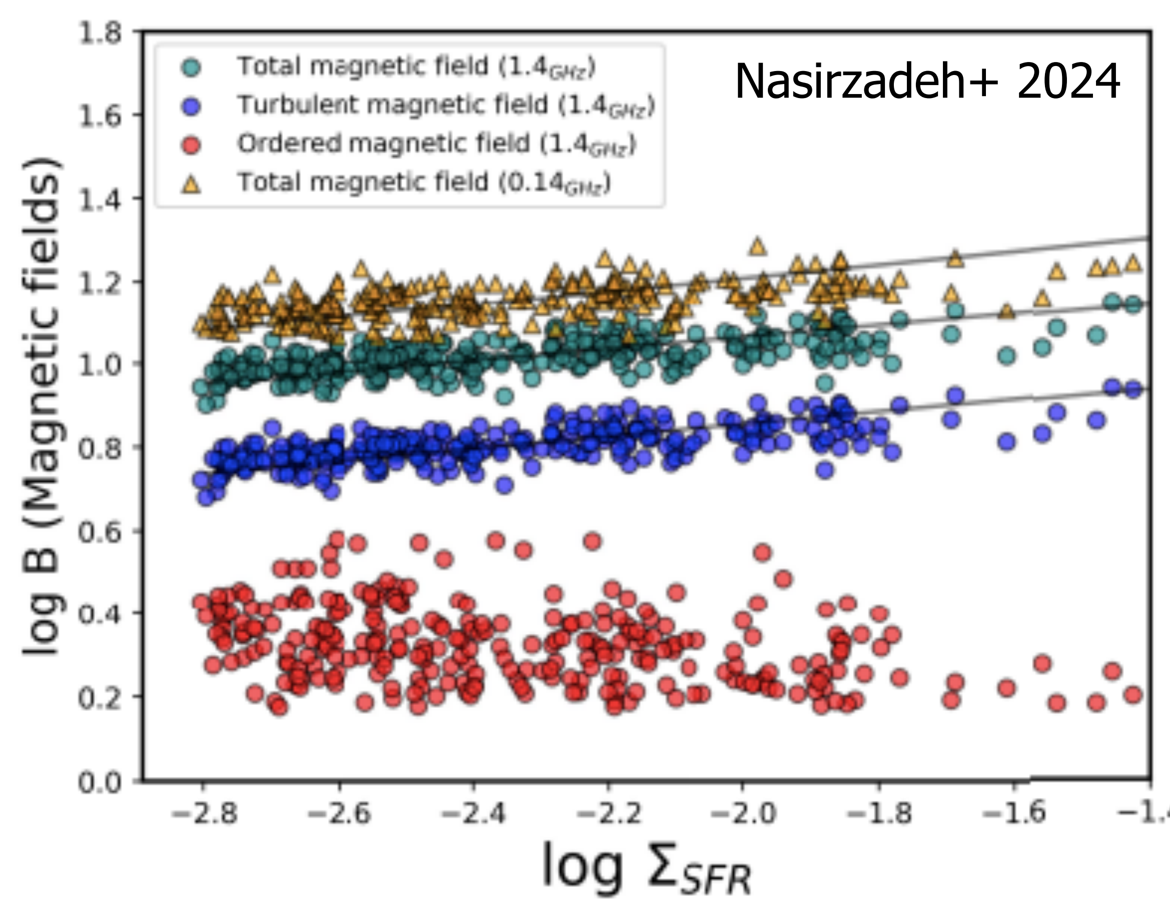


Total field~ 10uG

Total and turbulent fields stronger in SF regions

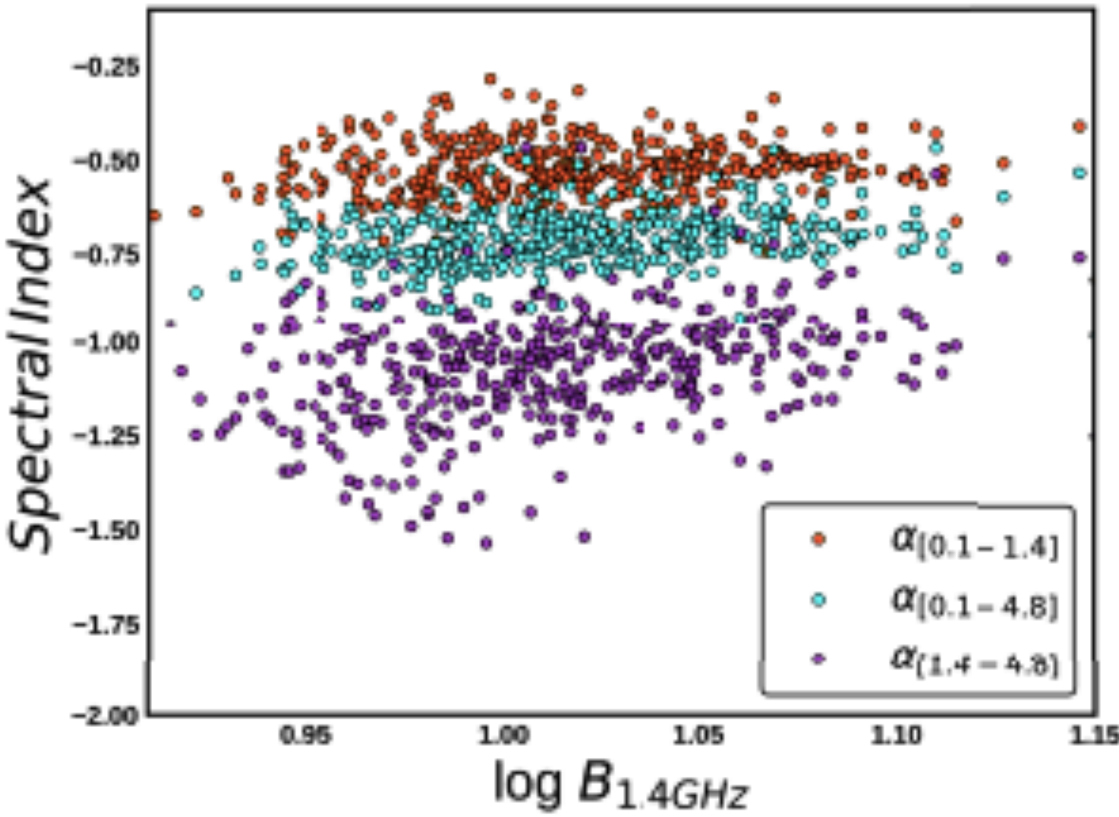
Ordered field~1/3 of turbulent field



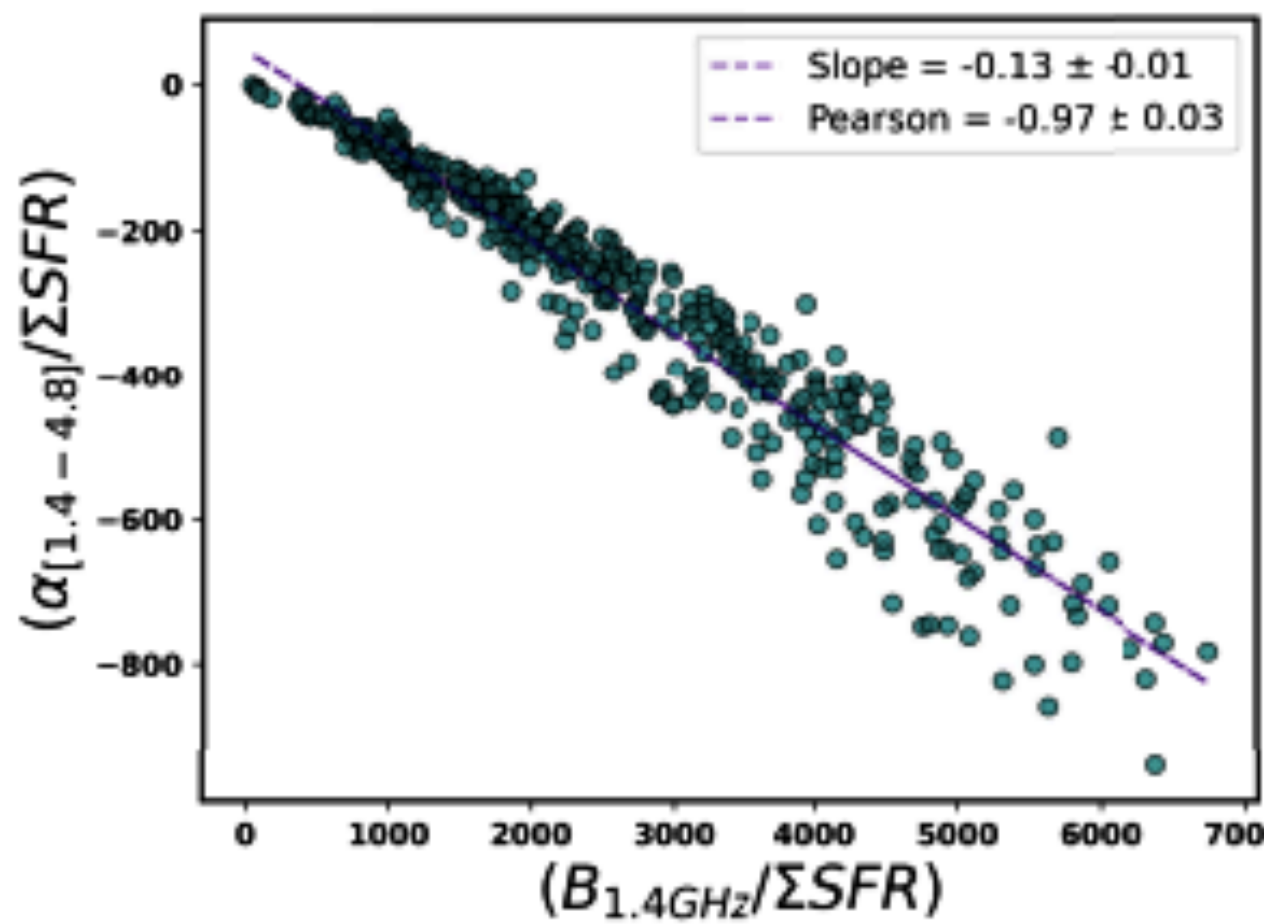


Impact of magnetic field on energy spectrum in IC342

Expectation: A steepening expected due to synchrotron cooling



No steepening w magnetic field: both spectrum and B depends on SFR



Steepening holds with total B per unit SFR surface density

Nasirzadeh+ 2024

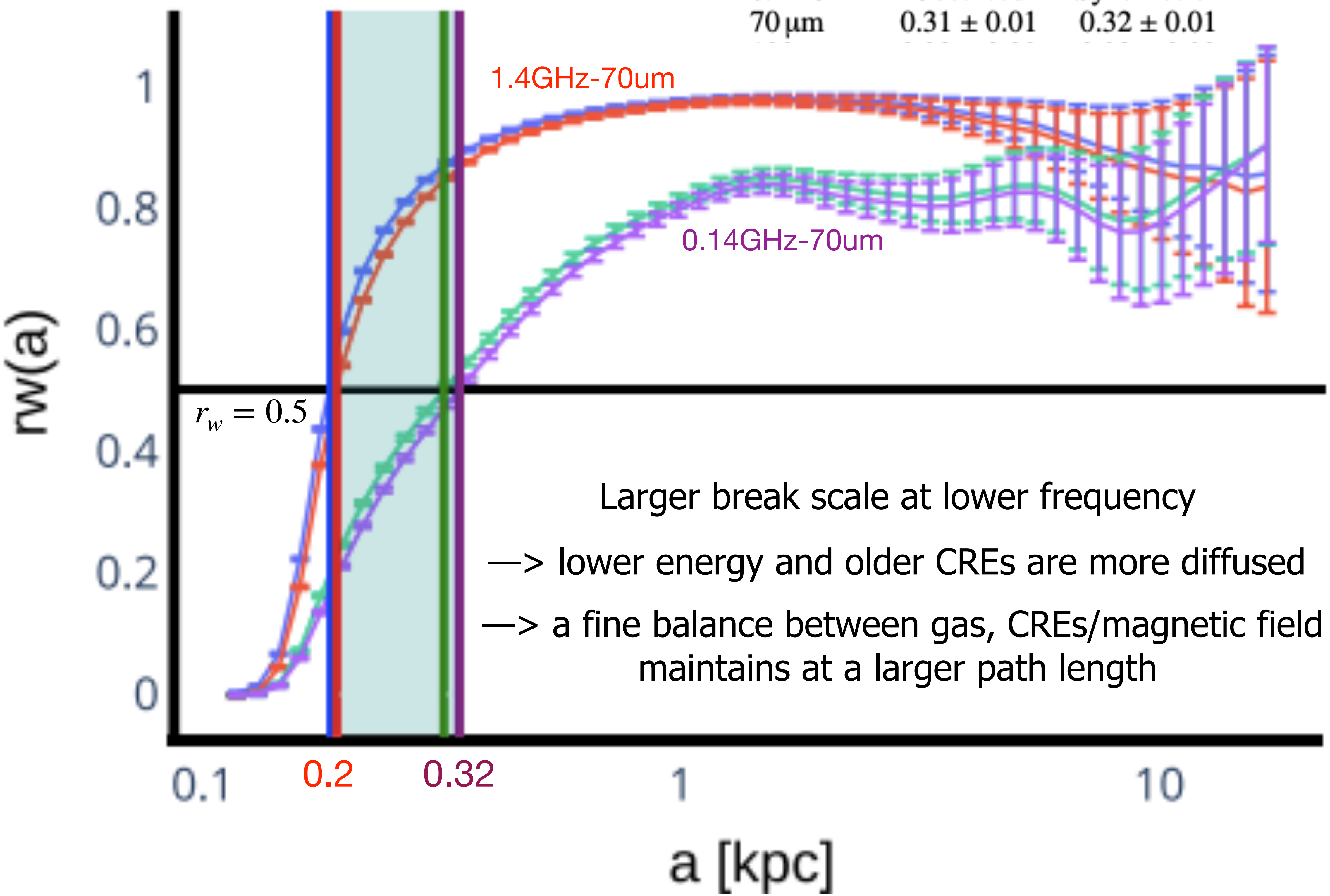
Radio-FIR correlation breaks down on a small scale

Nasirzadeh+ 2024:

Break scales in kpc

1.4 GHz 70 μm	Observed	Synchrotron
	0.18 ± 0.01	0.20 ± 0.01

0.14 GHz 70 μm	Observed	Synchrotron
	0.31 ± 0.01	0.32 ± 0.01

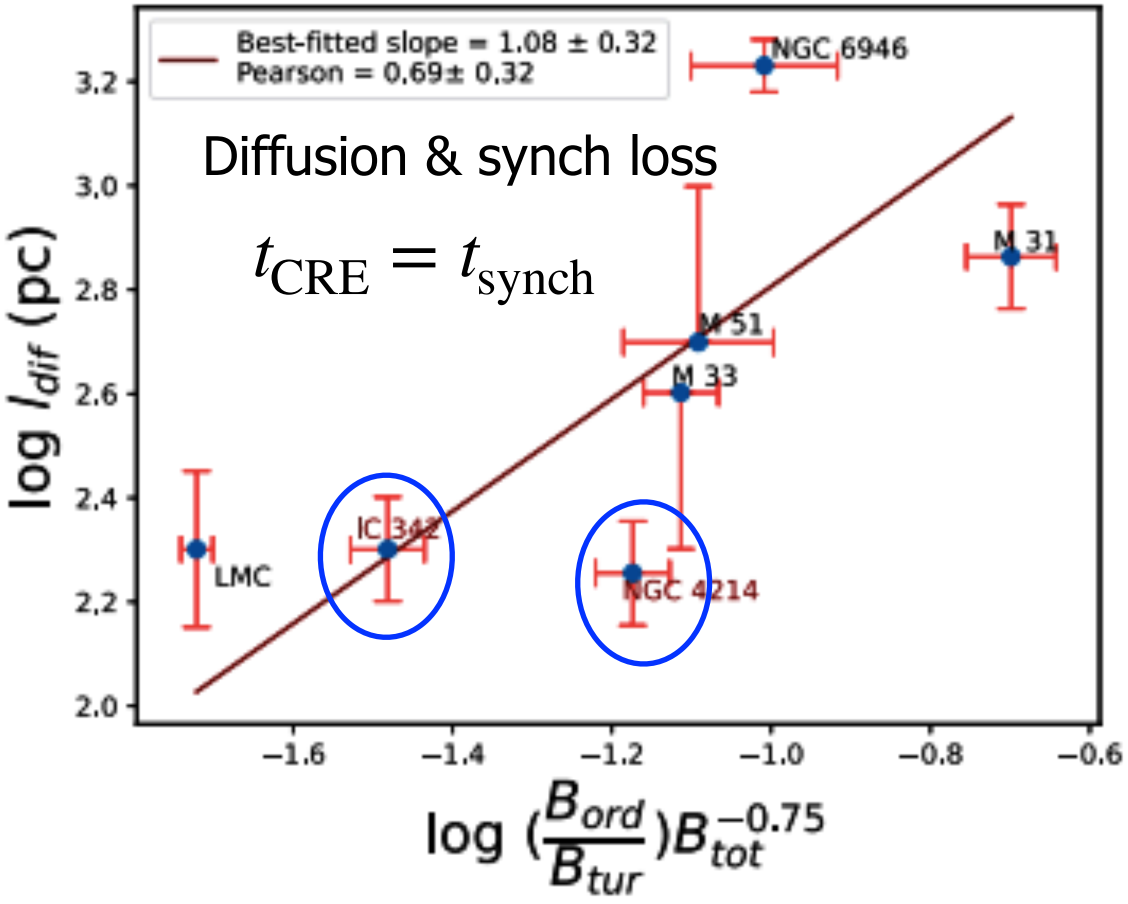


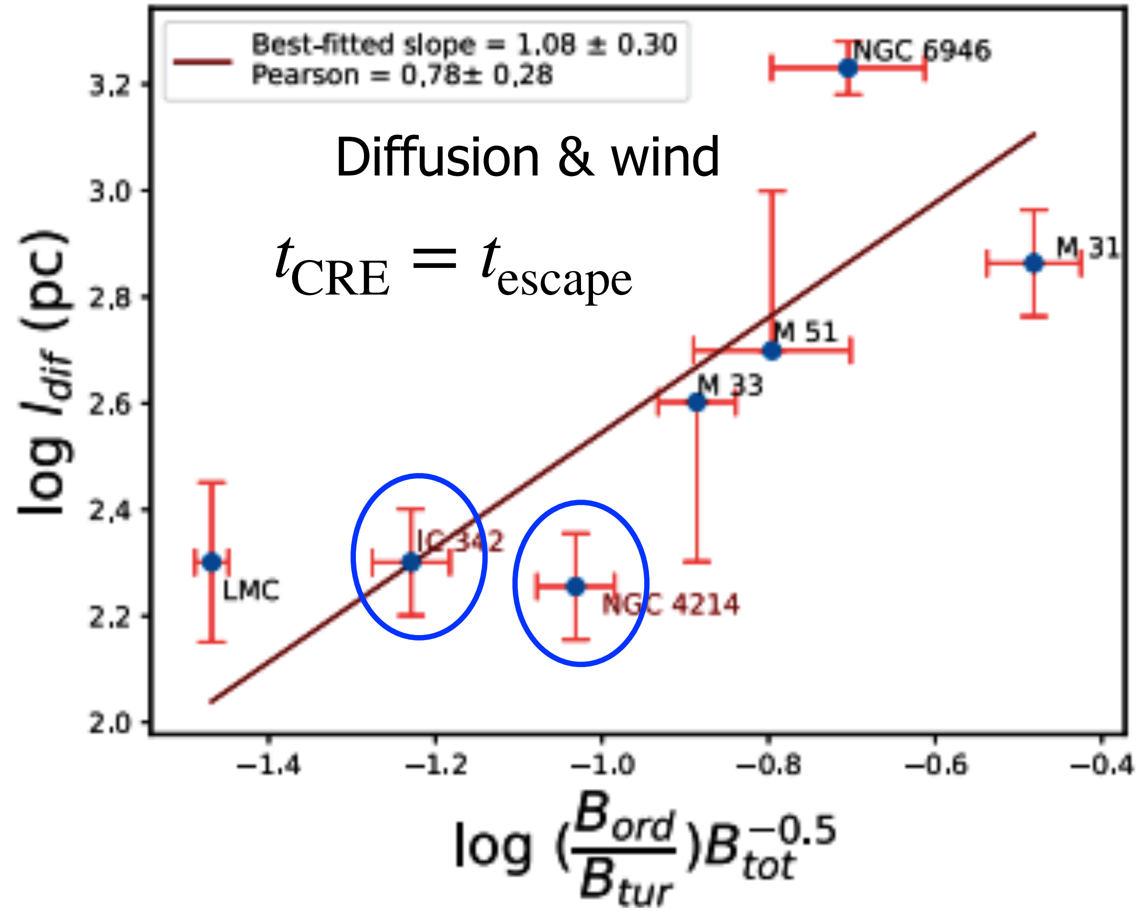
Larger break scale at lower frequency

—> lower energy and older CREs are more diffused

—> a fine balance between gas, CREs/magnetic field maintains at a larger path length

CREs propagation: Observations meet theory?





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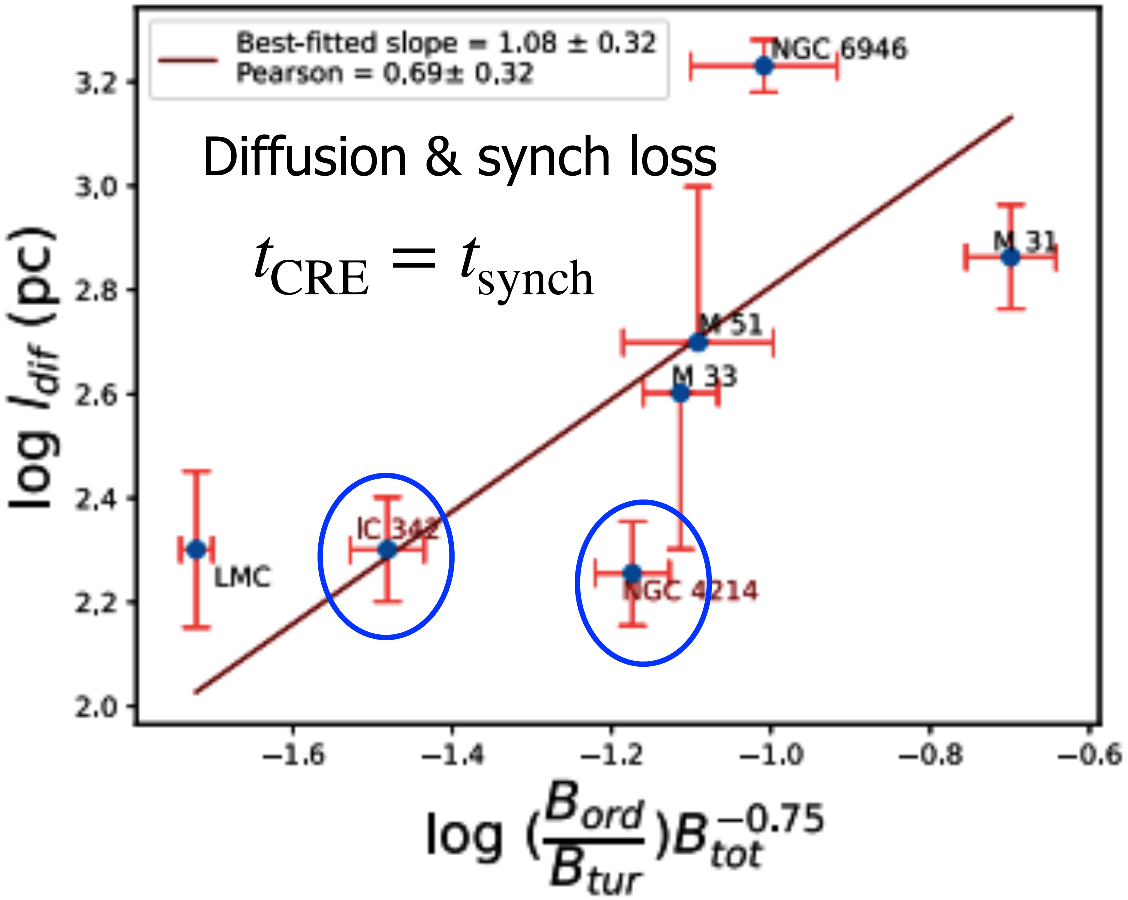

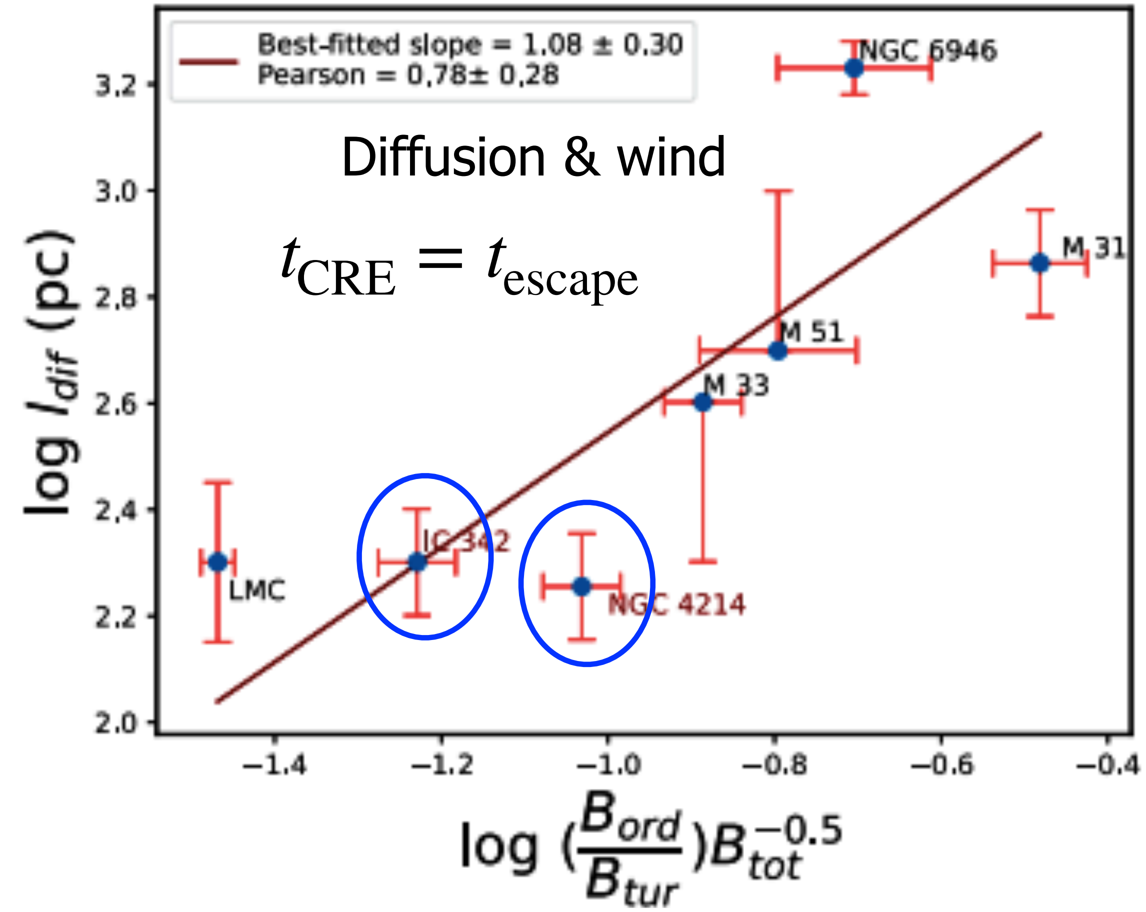

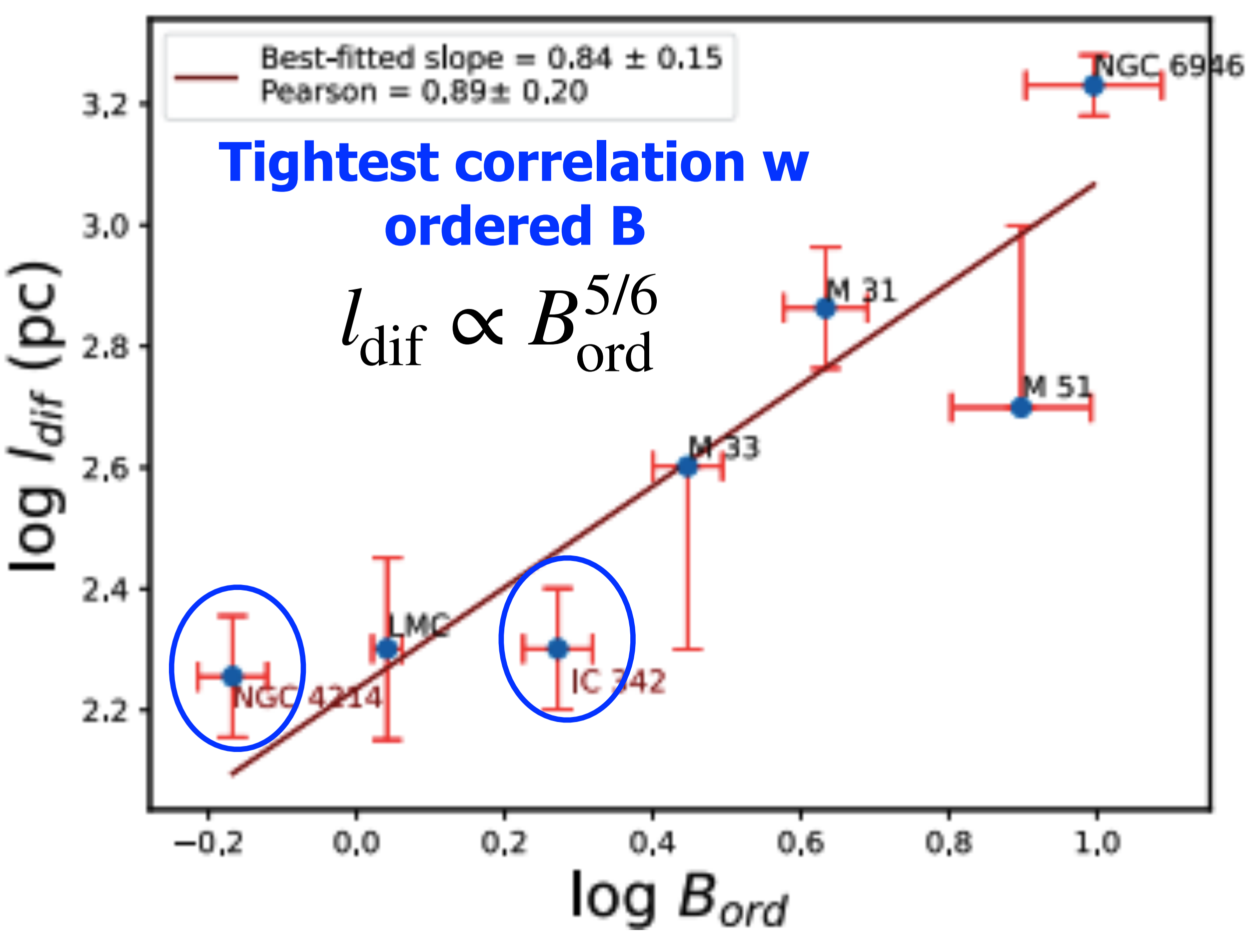

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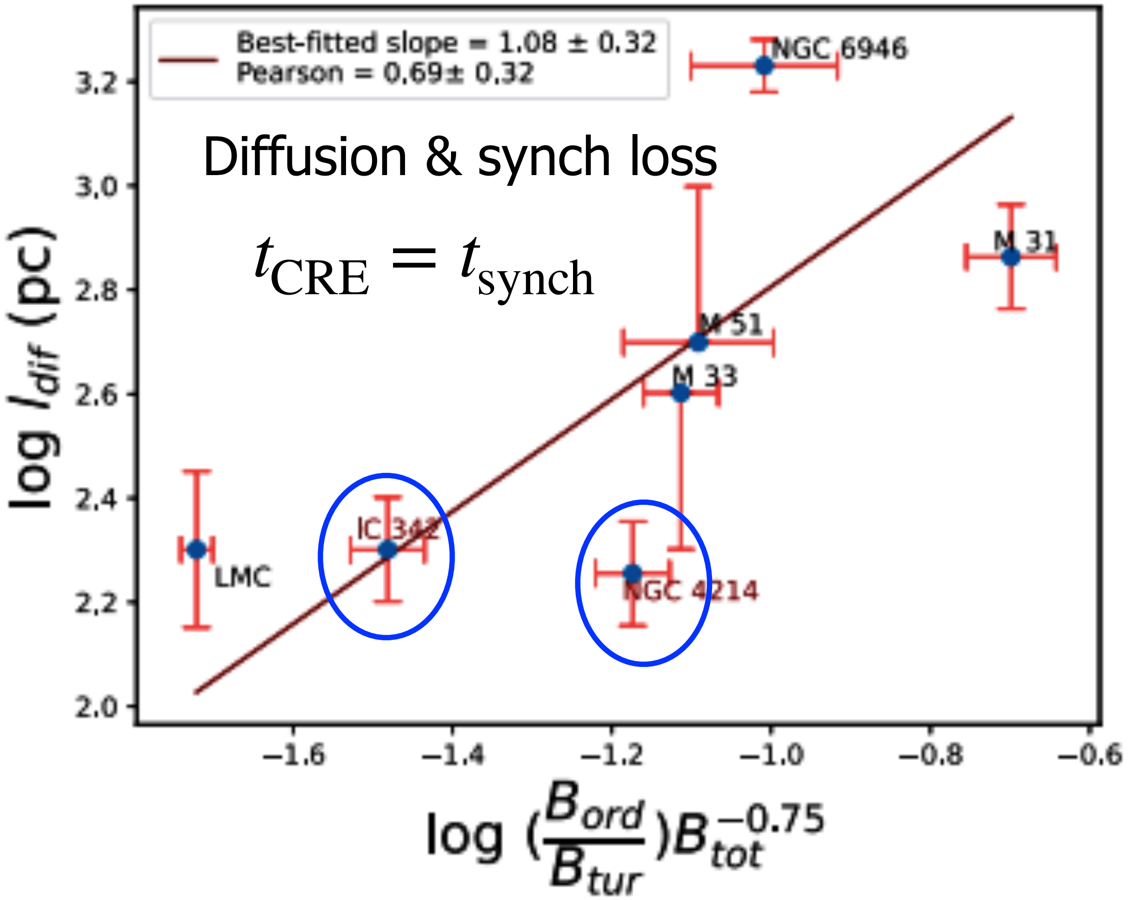

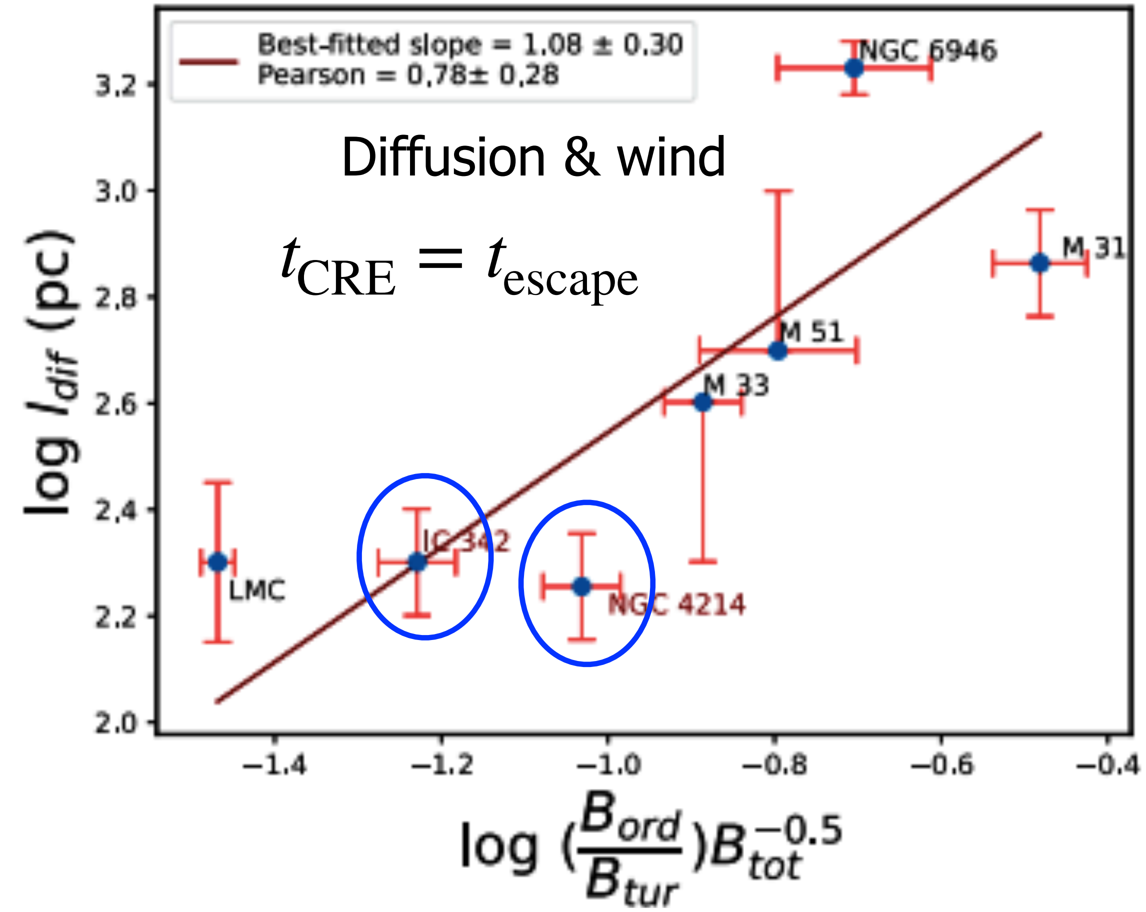

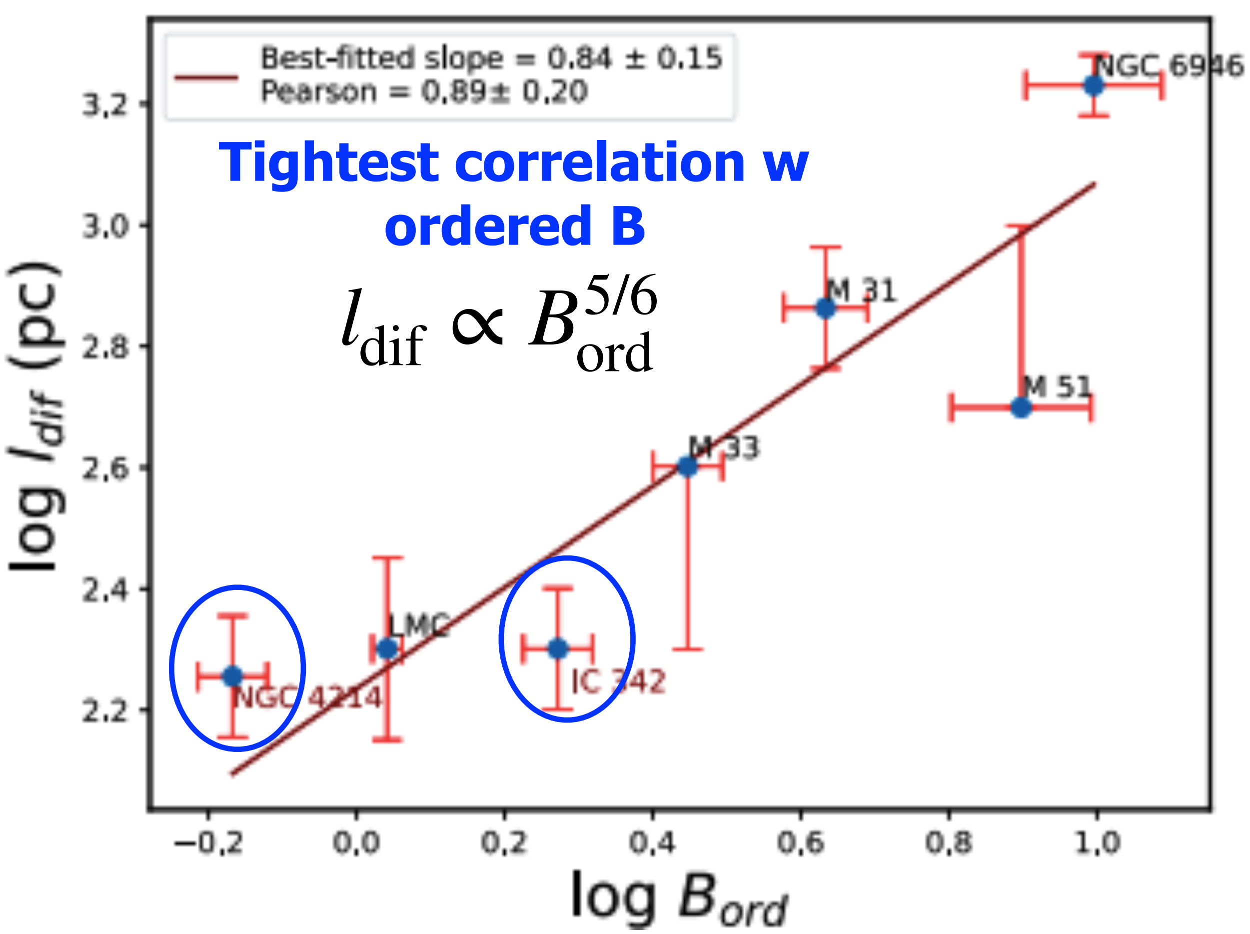

Expected if

- diffusion dominates along ordered field following Shalchi (2009):

$$l_{\mathrm{dif}} \propto (B_{\mathrm{ord}}/B_{\mathrm{tur}})B_{\mathrm{ord}}^{-1/6}t_{\mathrm{CRE}}^{1/2}$$

- CRE lifetime ~ a confinement time similar in different galaxies,
- turbulent field varies less than ordered field between galaxies

Nasirzadeh+ 2024

Summary

LOFAR LOTSS observations of IC342 combined with archival data:

- Multi-scale analysis of the correlation confirms that the correlation breaks down on a scale that is proportional to the diffusion length of the CREs, which is set by the regularity of the magnetic field.

- Scale length of CREs decreases with radio frequency, as expected theoretically.

- The steepening of CREs energy index in strong total magnetic field is only visible after removing the effect of SFR

- Diffusion length increases with the ordered magnetic field strength at a sublinear rate.

- The radio-IR correlation is insensitive to the FIR bands, indicating that warm and cold dust components are well mixed across IC342.