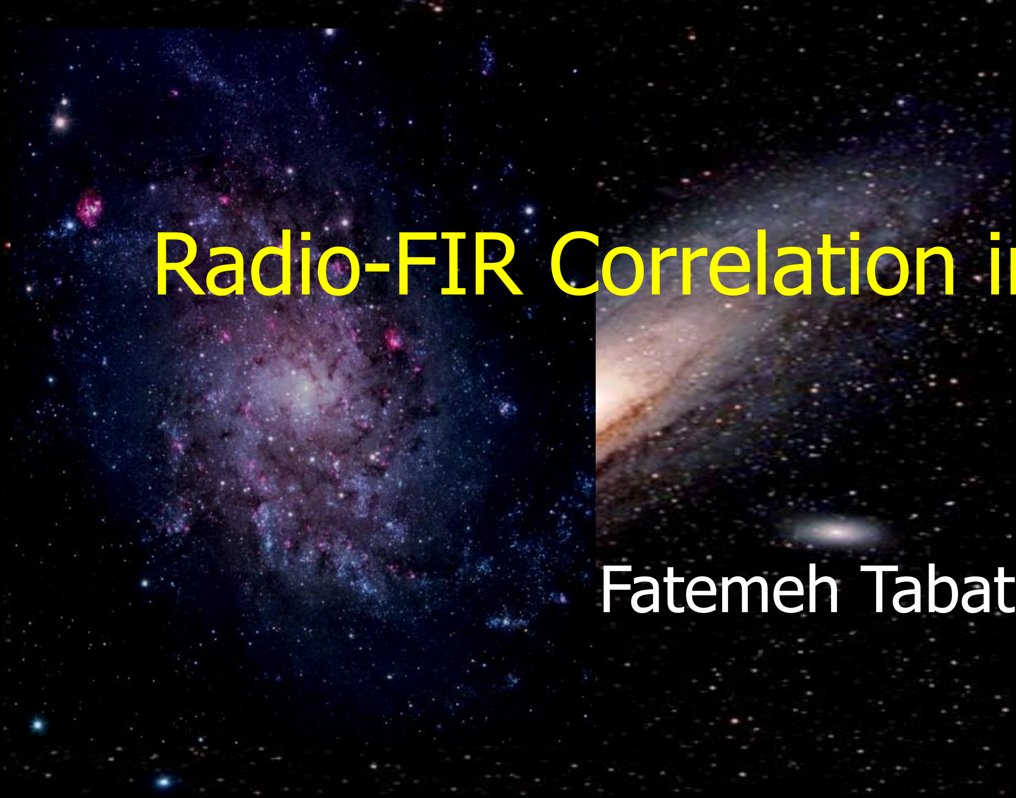

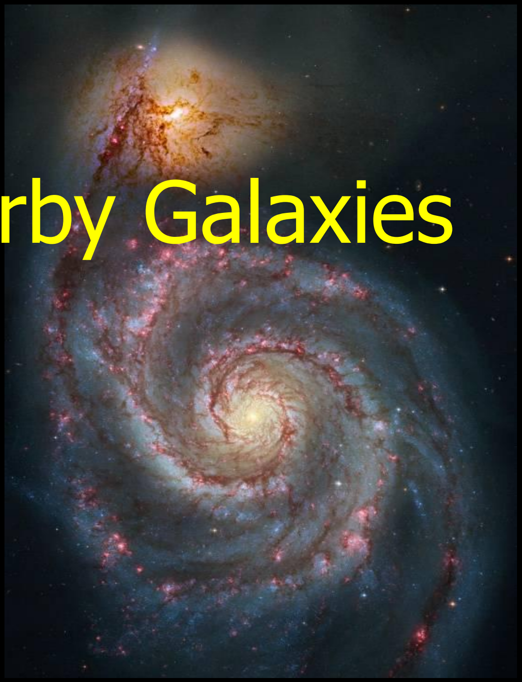

Radio-FIR Correlation in Nearby Galaxies

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Radio-FIR correlation:

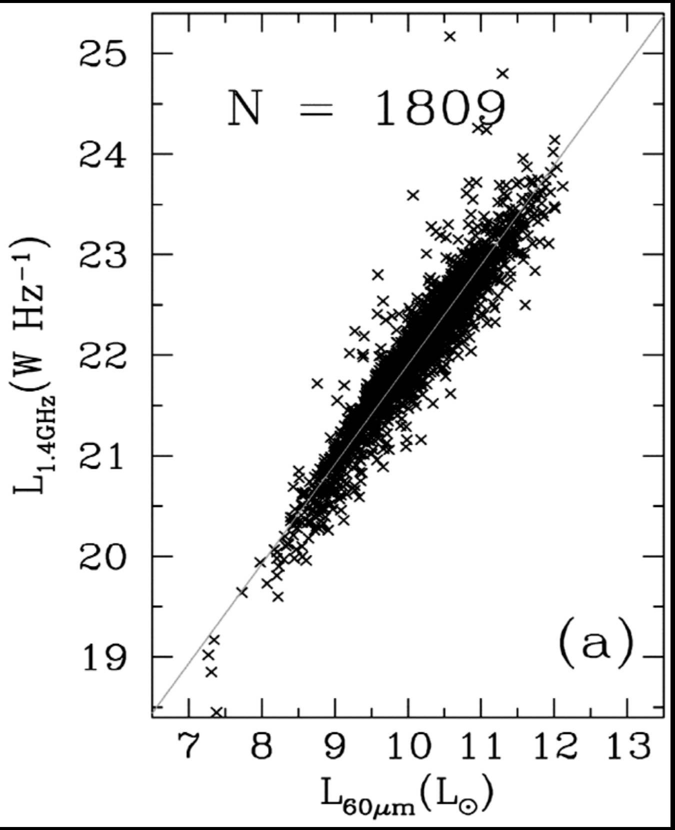
- first detection for a large sample of spirals based on IRAS data (e.g. Helou et al. 1985, de Jong et al. 1985)

- also holds on kpc scales within galaxies like M33 and M31 (e.g. Beck & Golla 1988, Hoernes 1998)

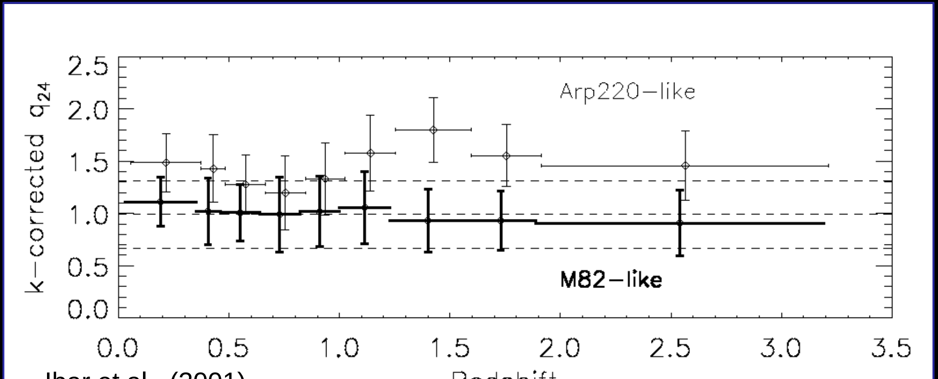
- invariant over 4 orders of magnitude (e.g. Hummel et al. 1988, Yun et al. 2001)

- applies to galaxies associated with star formation but not with AGNs (e.g. Roy et al. 1998)

- holds at high redshift z~1 (Frayer 2004) and possibly at z~3.5 (Ibar 2008)



Yun et al. 2001



Ibar et al. (2001)

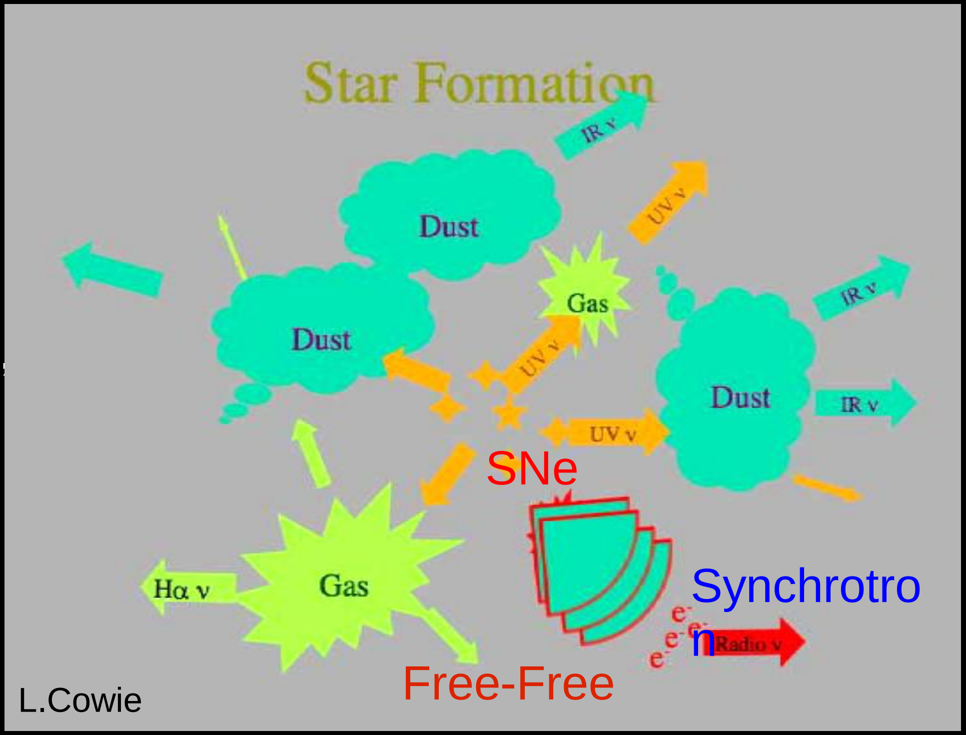
Radio-IR correlation explained as:

Young Massive star formation as common source
(e.g. Helou et al. 1985, Condon 1992)

- Calorimeter model
 (Völk 1989, Lisenfeld et al. 1996)

- Magnetic field-gas density coupling:
(e.g. Helou & Bicay 1993, Nicklas & Beck 1997,
Hoernes et al. 1998)

- Proton calorimeter model in starbursts
(Lacki 2009)



Other origins rather than massive stars:
- Intermediate mass stars as common source:
Xu et al. (1993)

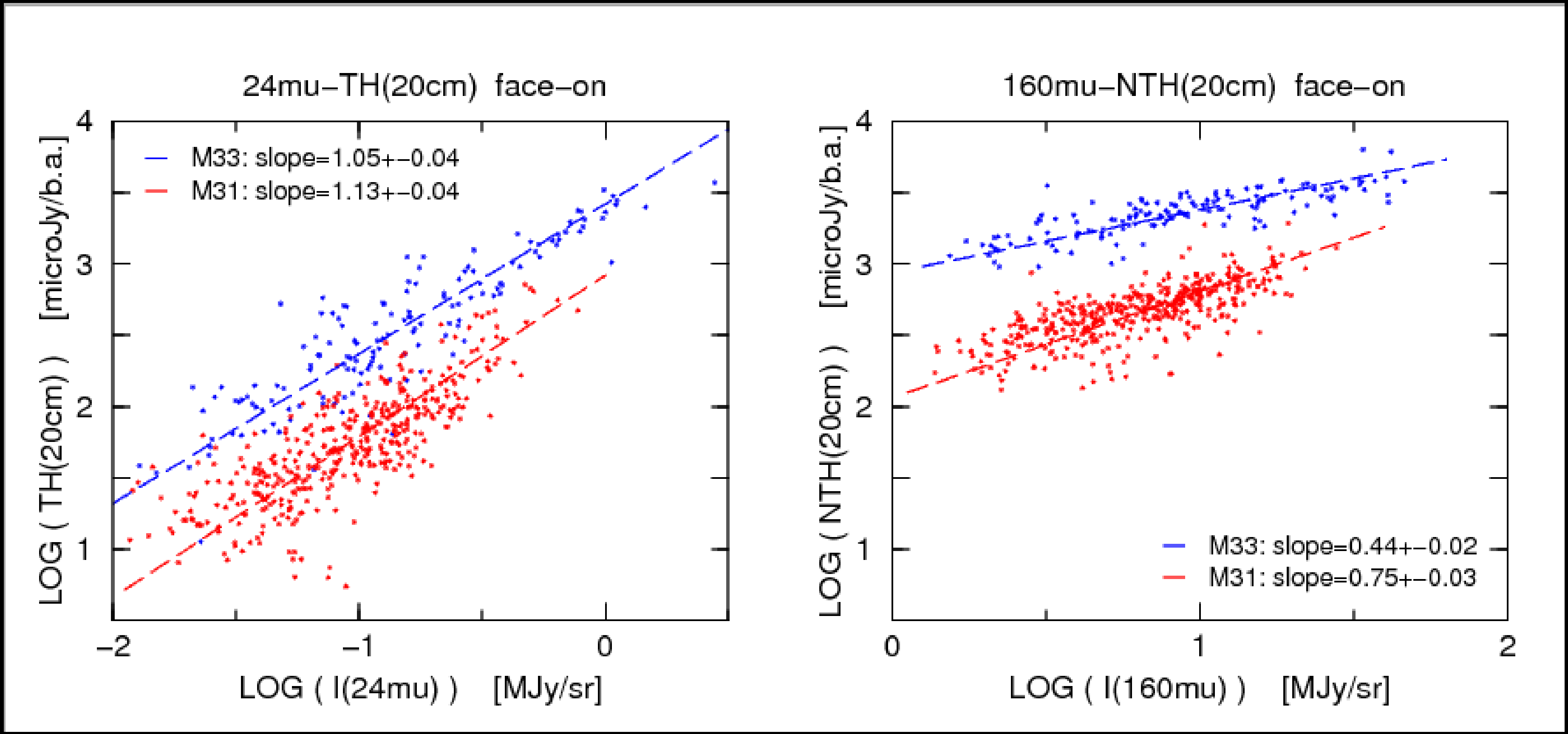
- Different origins, only B-gas density coupling:
Hoernes et al. (1998)

Non-linearity of Synchrotron-IR both locally and globally

- Golablly for a large sample of galaxies (Niklas et al. 1991)
- Inside galaxies: e.g. M31 (Hoernes et al. 1996)
  LMC (Hughes et al. 2006)

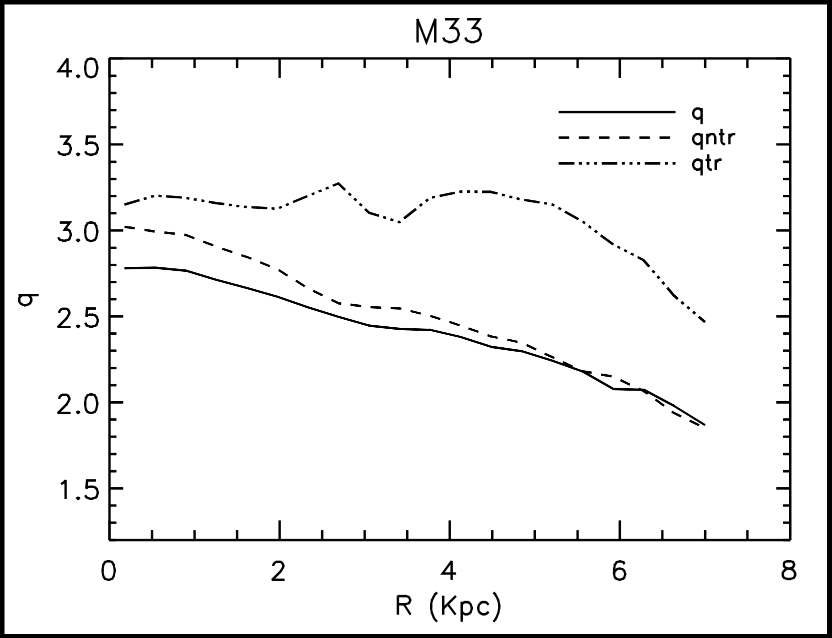
Thermal-24µm

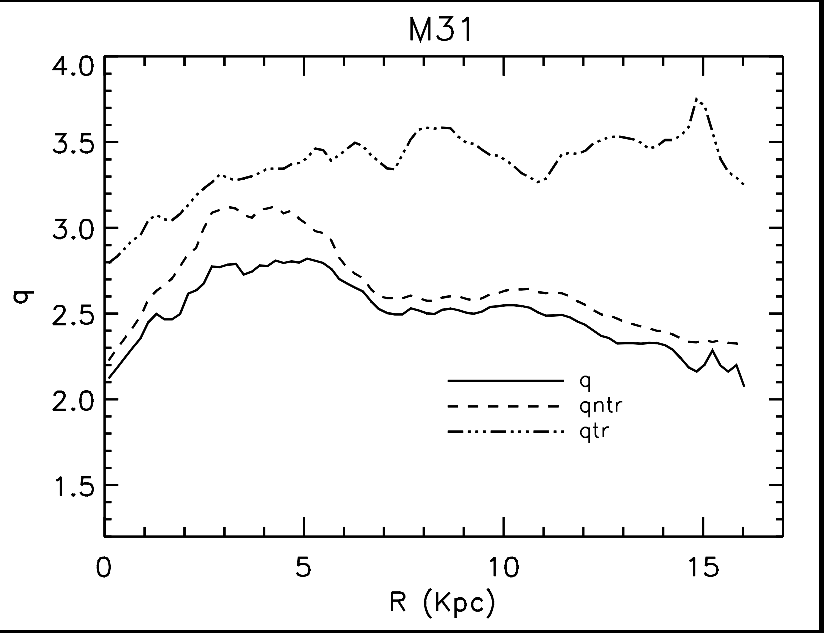
Synchrotron-160µm



Berkhuijsen et al. in prep.

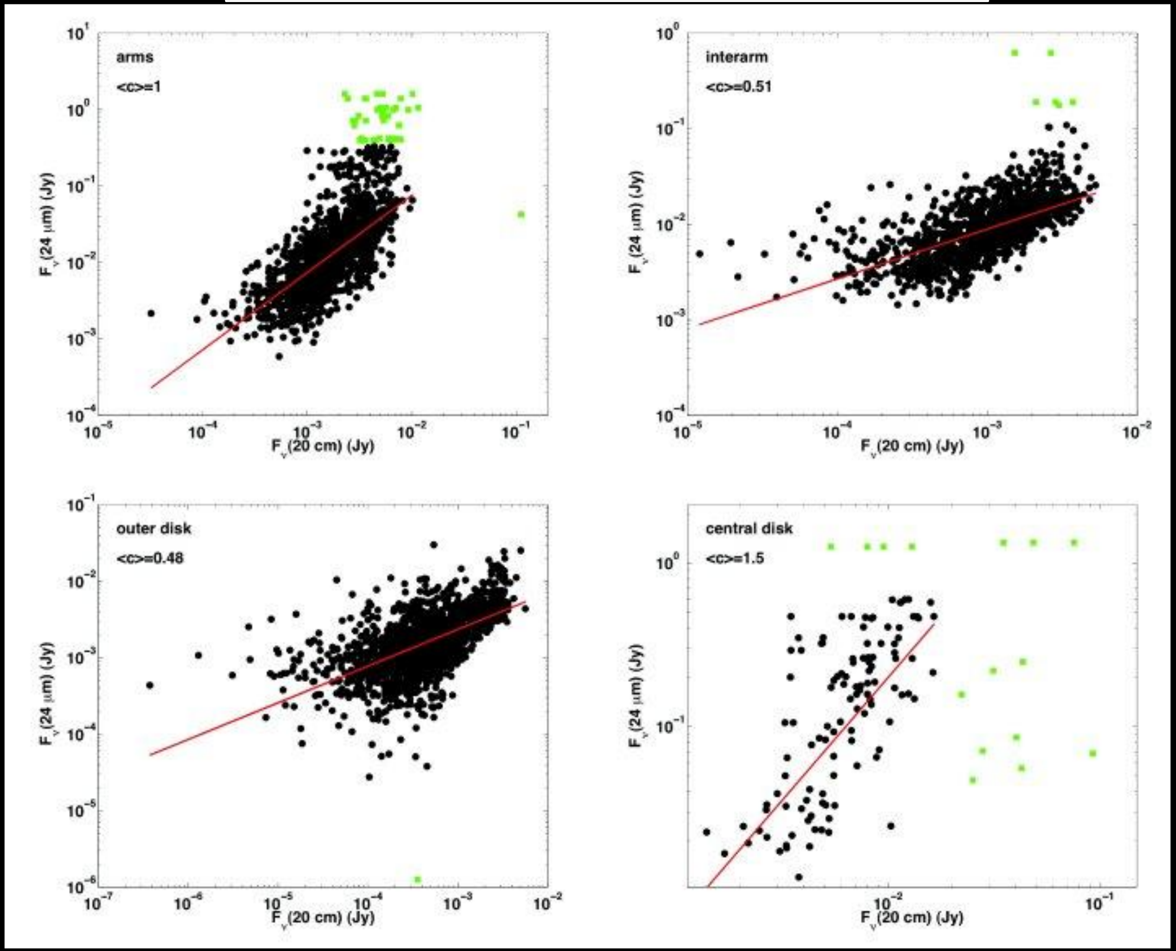
Non-linearity Inside Galaxies





Radio-IR in M33 and M31, Tabatabaei et al. in prep.

Radio-IR in M51, Dumas et al. 2011

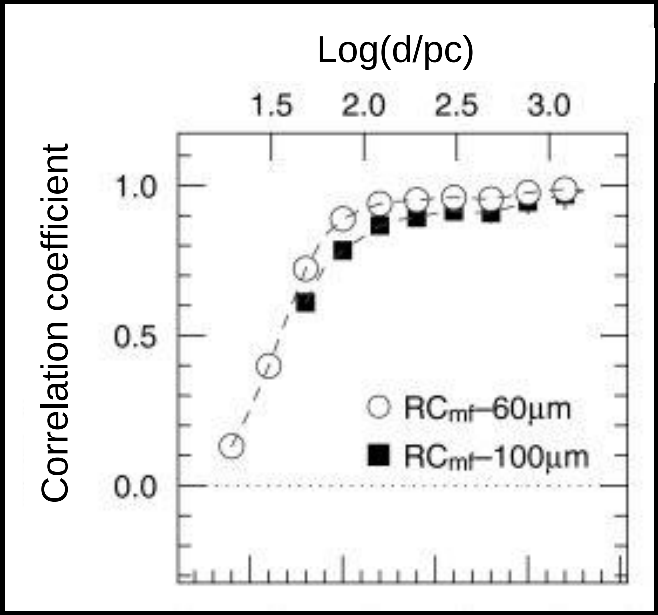


- M31 (Hoernes et al. 1996)
- M81 (Gordon et al. 2004)
- LMC (Hughes et al. 2006)

Break on Small Scales

- Our own galaxy: various observations: classical correlation:
e.g. no correlation in Orion (Boulanger & Perault 1988)

- Nearby galaxies : wavelet correlation:
The LMC, M51, M31 (Hughes_06, Dumas_11, Tabatabaei_in prep.)



Hughes et al. 2006

Massive star formation as the only reason?

Uncertainties:

- Connection of cold dust to massive SF?
- Connection of magnetic fields to dust (warm/cold)?
- Effects of cosmic-ray propagation?
- Smallest scale on which the correlation holds?
- Dependencies of other ISM characteristics like gas densities, metallicity,..?

→ Requires detailed studies within nearby galaxies including:

- Thermal/nonthermal radio separation
- Cold/warm dust differentiation
- Structural characteristics of IR and radio emission,….

Nearby galaxies:

- M31, M33, NGC6946, (M51, LMC,...)

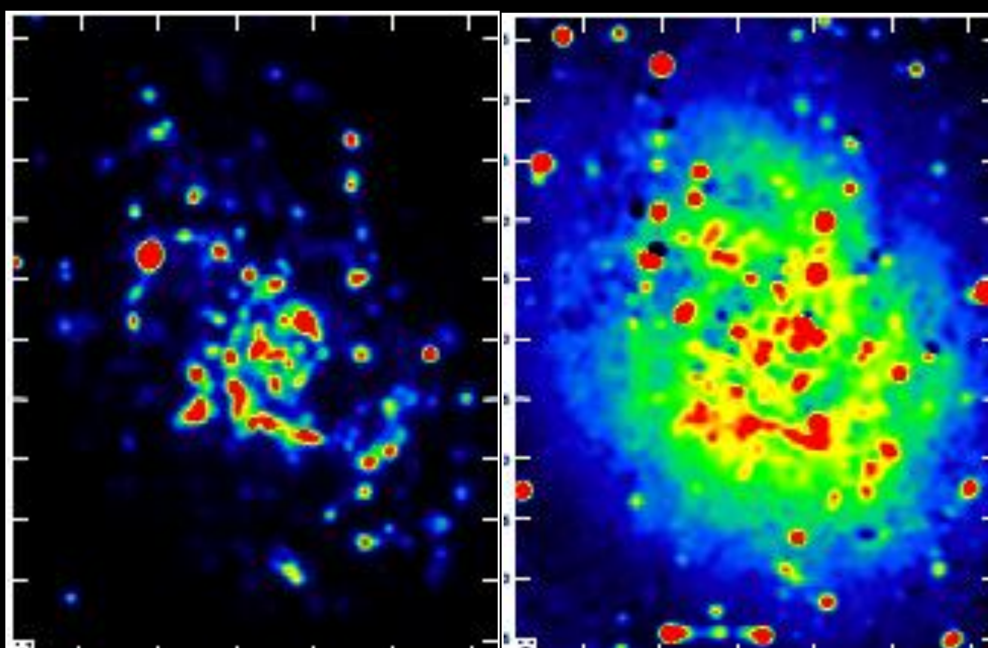
20cm Thermal/Nonthermal Separation

in M33

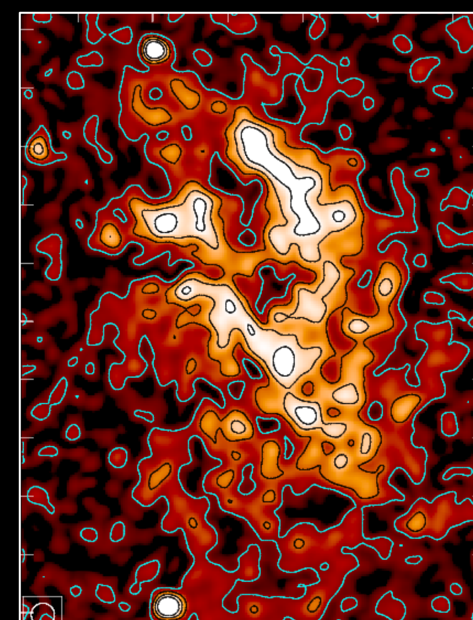
TRT Separation Method:
(Tabatabaei et al. 2007& 2008)

Synchrotron spectral index varies across the galaxies as CREs experience various energy losses

Free-free   Synchrotron



3.5cm-PI



Total thermal fraction in M33 = 24%   4%

Bright extended synchrotron emission , yet stronger close to the SF

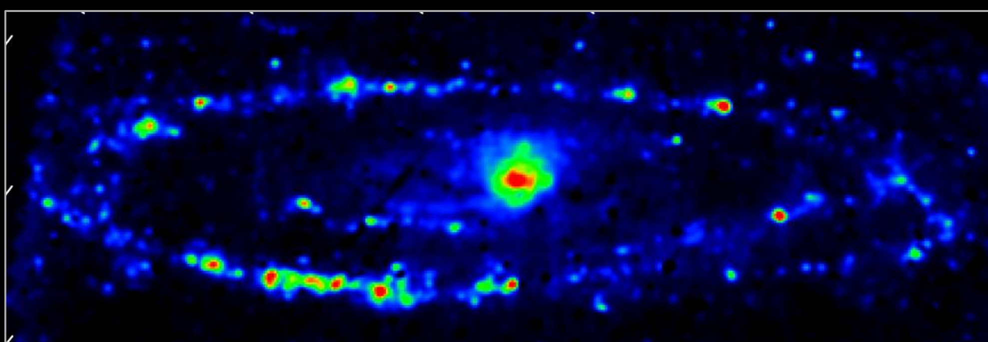
20cm Thermal/Nonthermal Separation

in M31

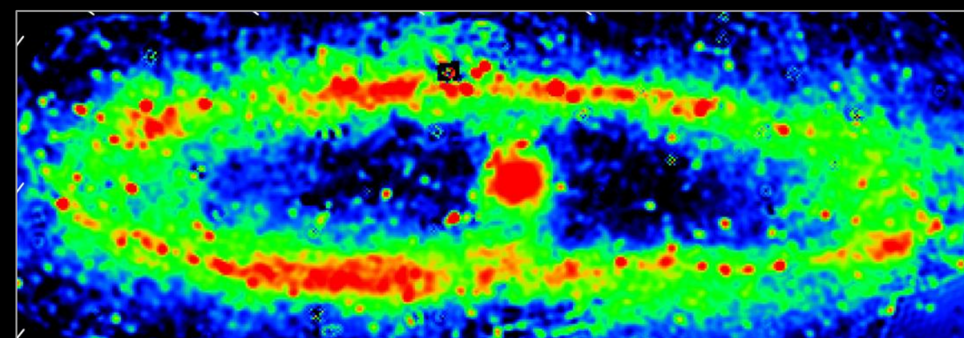
TRT Separation Method:
(Tabatabaei et al. 2007 & 2010)

Synchrotron spectral index varies across the galaxies as CREs experience various energy losses

Free-free



Synchrotron



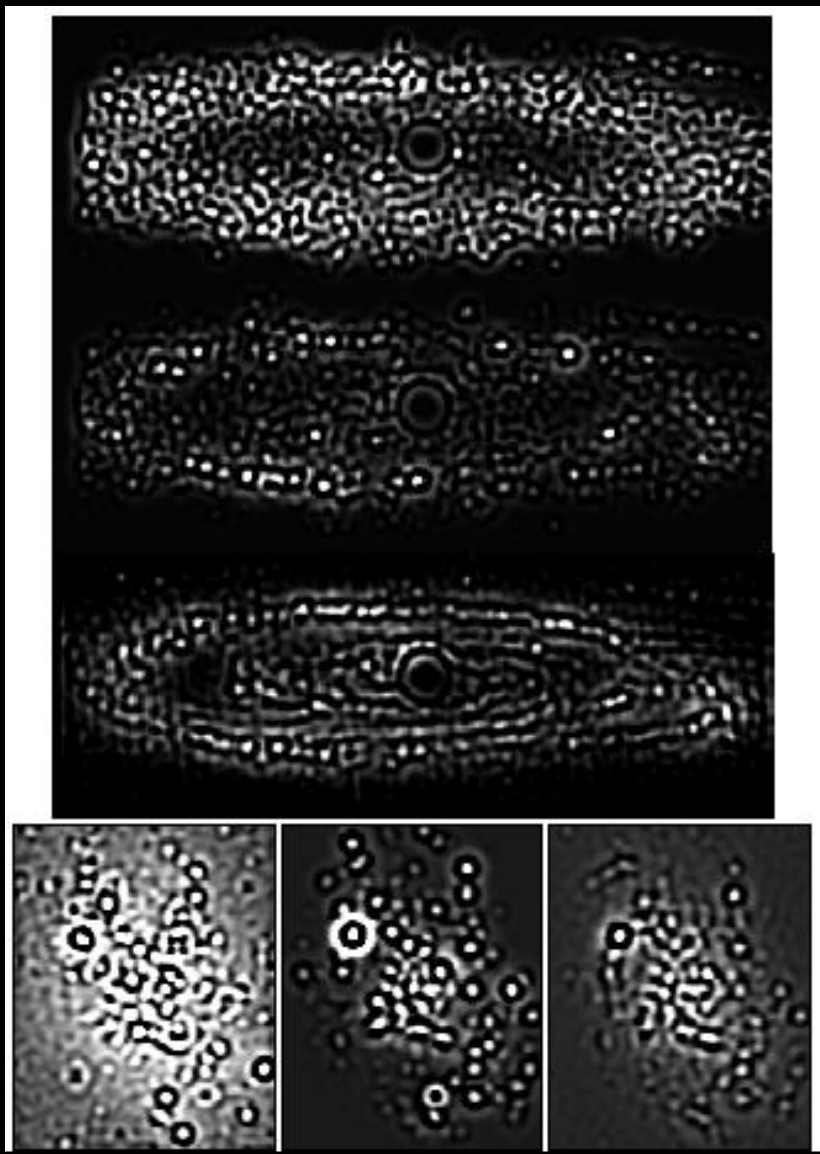
Total thermal fraction in M31 = 13%   1%

Bright extended synchrotron emission , yet stronger close to the SF

Wavelet Decompositions

Resolving differences on small scales in M31, on large scales in M33

spatial scale: 0.4 kpc



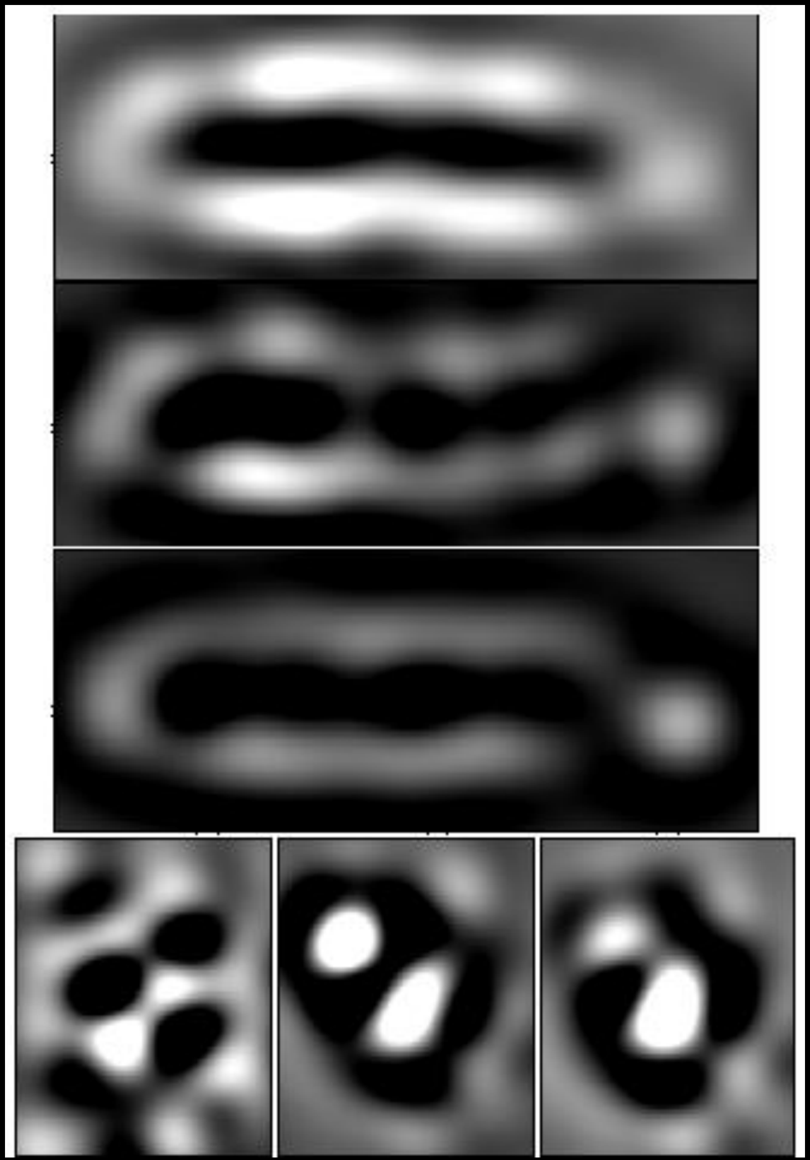
Sync Free-free 160 μm

20cm Synchrotron

20cm Free-free

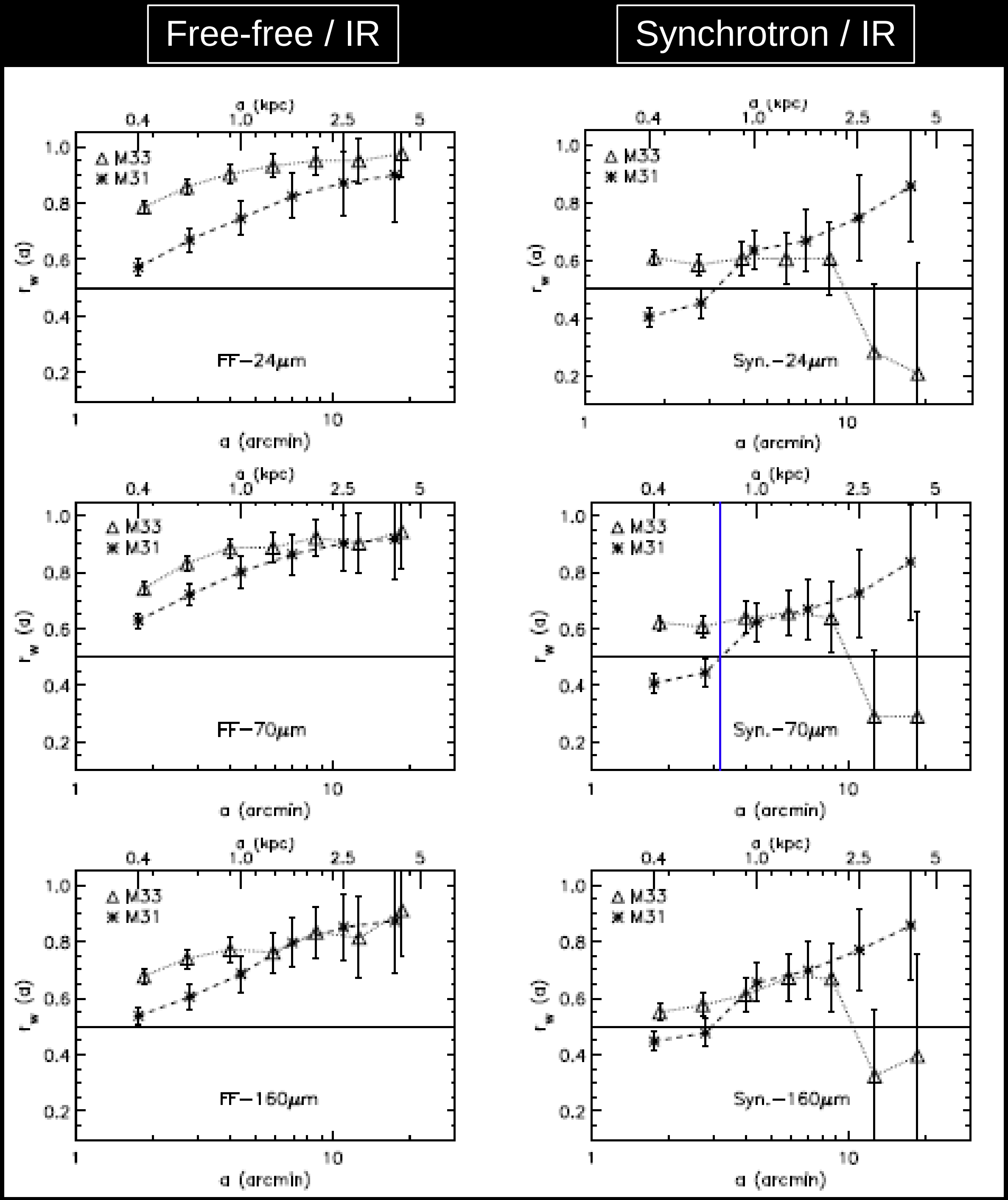
160 μm FIR

spatial scale: 2.7 kpc



Sync Free-free 160 μm

Radio-IR Correlation in M31 and M33



In M31:

- Synchrotron - IR breaks on **scale~800 pc** (r=0.5).

In M33:

- **No break** of the sync - IR correlation beyond 400 pc scale

- Sync-IR is higher than in M31 on small scales, but lower on large scales

What is the reason for different synchrotron-IR correlations in M31 and M33 ?

- Star-formation properties ?
- Dust heating ?
- Magnetic fields ?
- Cosmic-ray propagation ?

What is the reason for different synchrotron-IR correlations in M31 and M33 ?

- Star-formation properties ?

M33: 3 to 10 times higher SFR per area than M31
(Gardan et al. 2008, Tabatabaei & Berkhuijsen 2010)

↓

- Dust heating ?

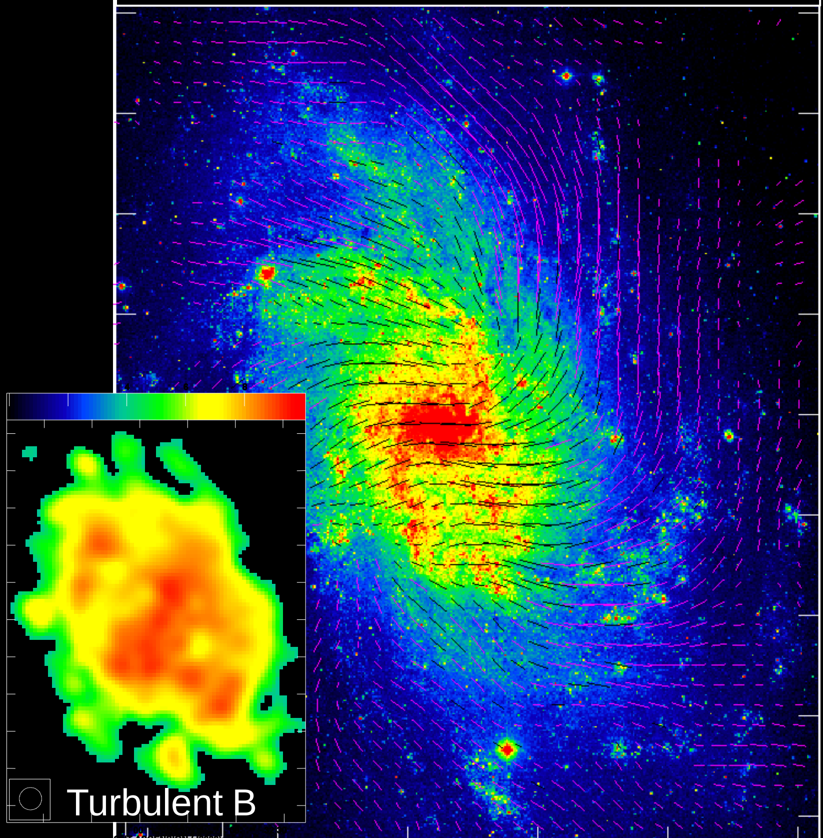
M33: young O/B stars
M31: ISRF (Xu 1990)

- Magnetic fields ?

- Cosmic-ray propagation ?

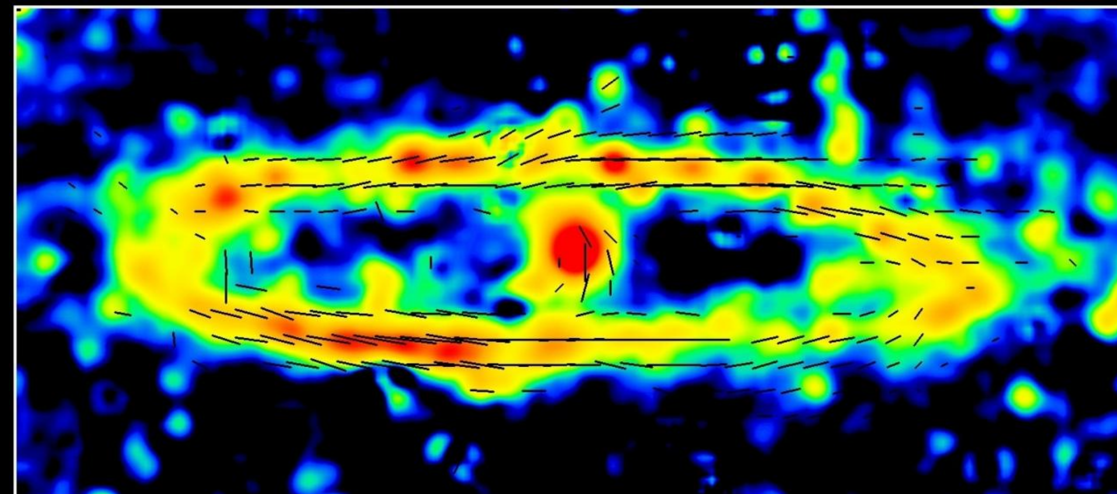
Magnetic Fields & CREs

B−vectors on optical image



Tabatabaei et al. 2008

Total radio emission and B−vectors



Fletcher et al. 2004

In M31:

- Total B ≈ 7 μG, regular B ≈ 5 μG
- Axisymmetric field in the ring, small pitch angle.

In M33:

- Total B ≈ 6.5 μG, regular B ≈ 2.5 μG
- Strong turbulent fields in SF regions
- Spiral field pattern, no correlation with arms, large pitch angle
- A vetical field component for R<4 kpc (halo field)

Theoretical expectation:

$$D_E \propto (\mathrm{B}_{\mathrm{turbulet}} / \mathrm{B}_{\mathrm{regular}})^{-2}$$

(e.g. Breitschwerdt et al. 2002)

What is the reason for different synchrotron-IR correlations in M31 and M33 ?

- Star-formation properties ?

M33: 3 to 10 times higher SFR per area than M31
(Gardan et al. 2008, Tabatabaei et al. 2010)

↓

- Dust heating ?

M33: young massive stars
M31: ISRF

- Magnetic fields ?

M33: strong small scale turbulent field
M31: strong large scale regular field

↓

- Cosmic-ray propagation ?

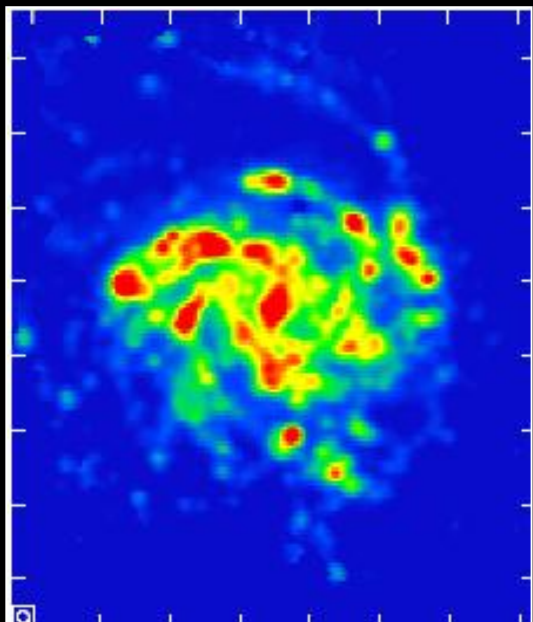
M33: younger CREs, close to SF regions or trapped in strong turbuent B field
M31: older CREs, easier propagation to large scales due to regular B

CREs are more diffused in M31 than M33 due to a larger diffusion length/ stronger B-regularity?

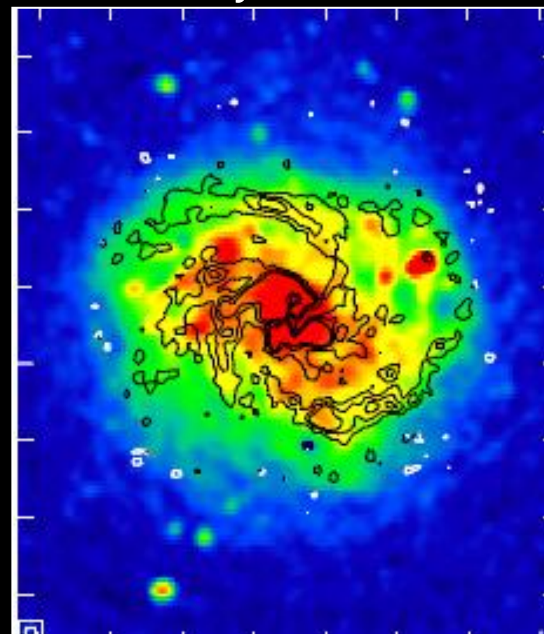
NGC6946 – High SF & Strong Regularity of B

Symphony of ‘magnetic arms‘ and giant HII regions

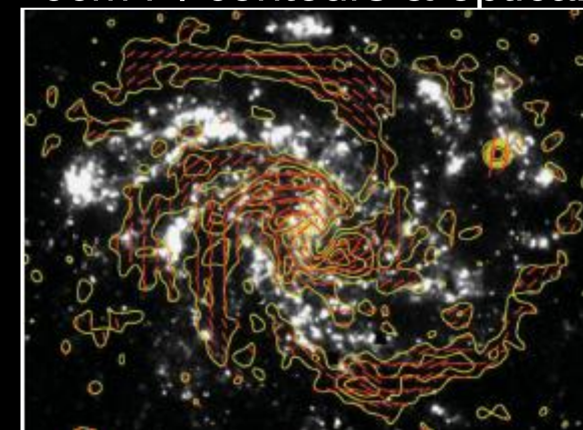
20cm Free-free



20cm Synchrotron



6cm PI-contours & optical



Beck et al. 1996, 2007

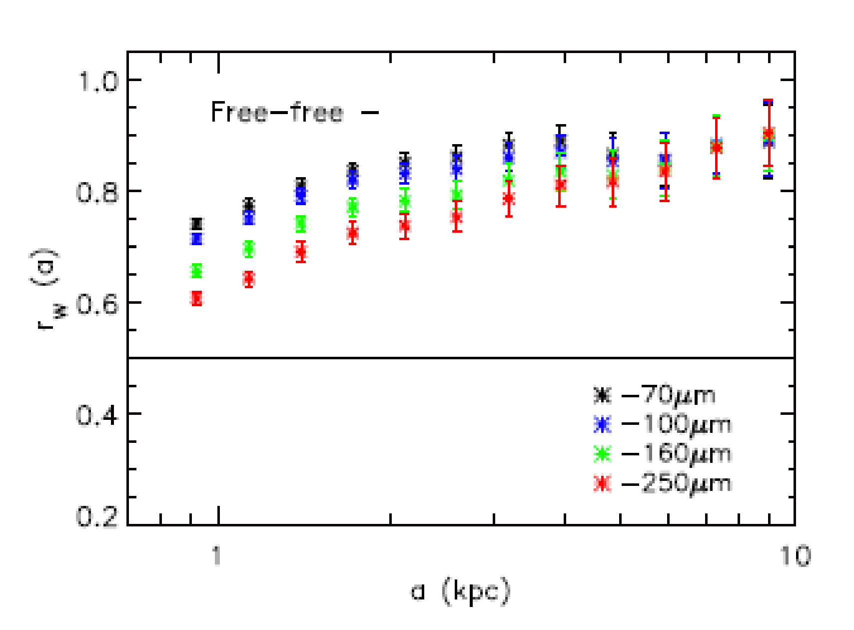
Total thermal fraction = 8% 1%

In NGC6946:

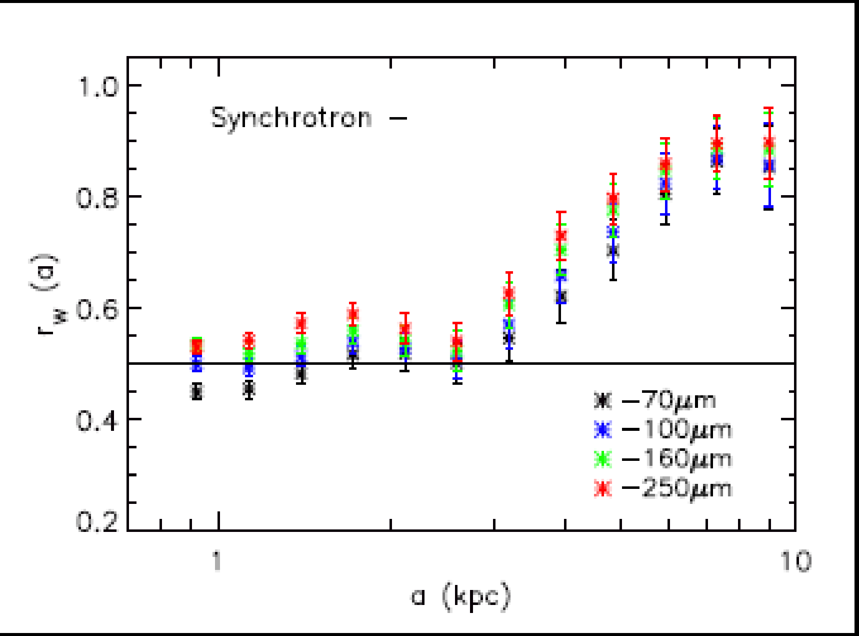
- Total B ≈ 12 μG, regular B≈ 7 μG
- Strong turbulent field in places of giant HII, strong regular B in its magnetic arms
- Fast diffusion of CREs in magnetic arms (regular/turbulent ~ 1)

Radio-FIR Correlation in NGC6946

Free-free



Synchrotron

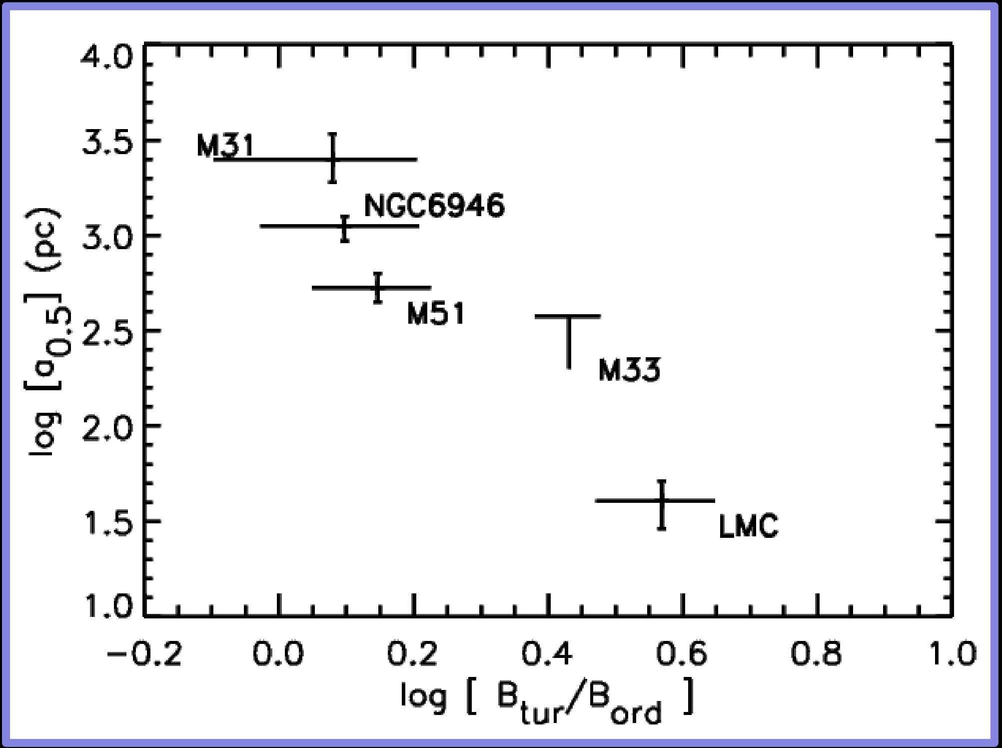


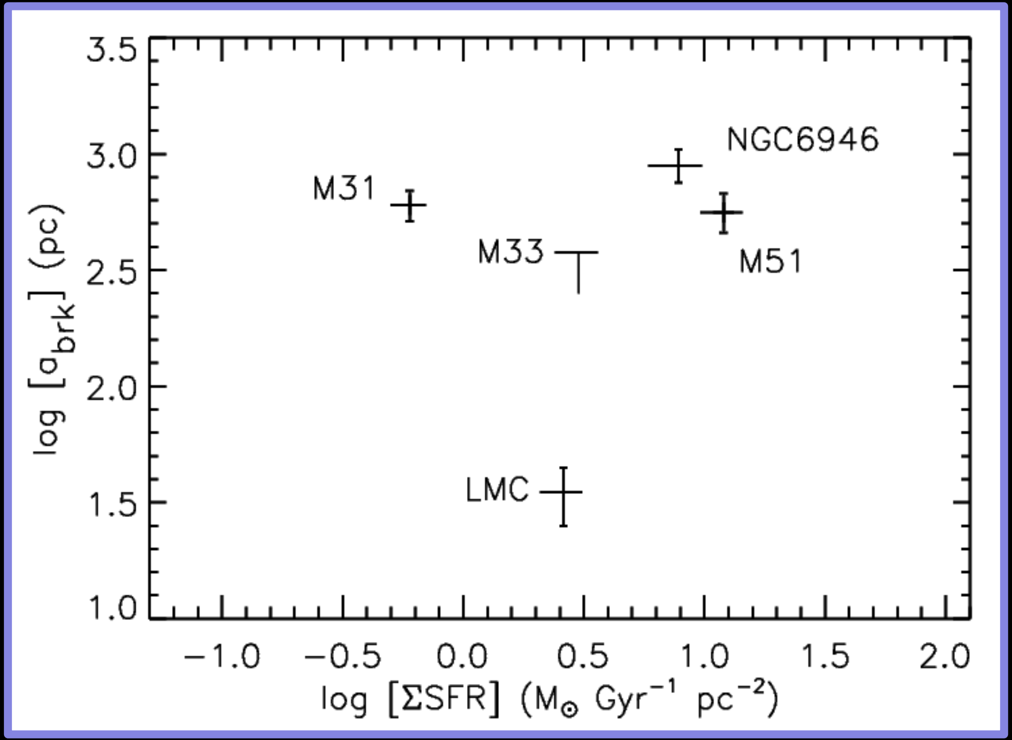
- Smallest scale the correlation holds **~ 0.9 kpc**
- Better synchrotron - colder than warmer dust (best with 250um)

What determines the smallest scale of Radio-FIR?

Star Formation or CRE Propagation?

~ 560 pc in M51 (Dumas et al. 2011)
~ 35 pc in the LMC (Hughes et al. 2006)





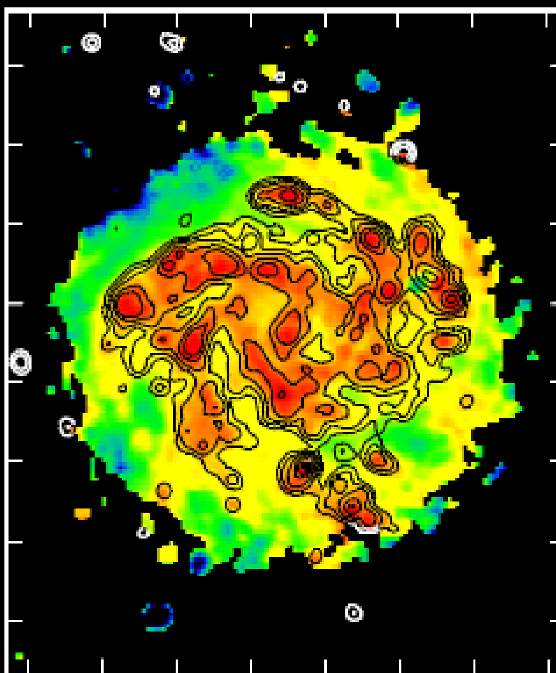
Tabatabaei et al. in prep.

- Break scale is larger for a larger regularity of the magnetic field → a(brk) ~ mean free path of CREs

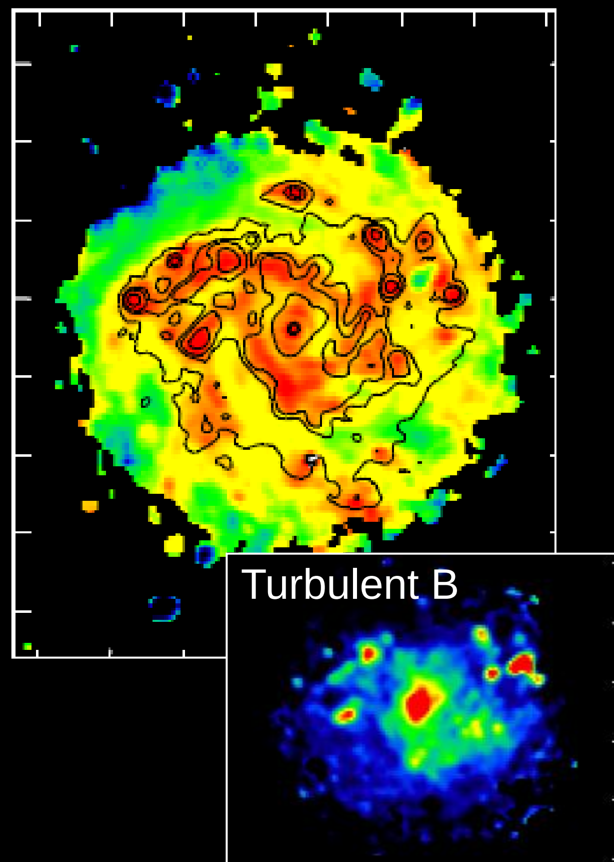
- Static pressure equlibrium is achived on smaller scales when the degree of field regularity is smaller

NGC6946: Variation of the FIR/radio ratio (q-parameter)

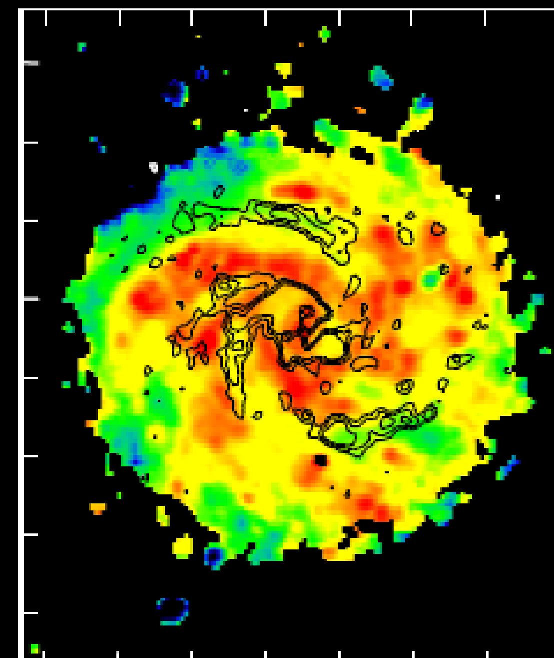
Contours:
Star formation density



Contours:
Turbulent magnetic field

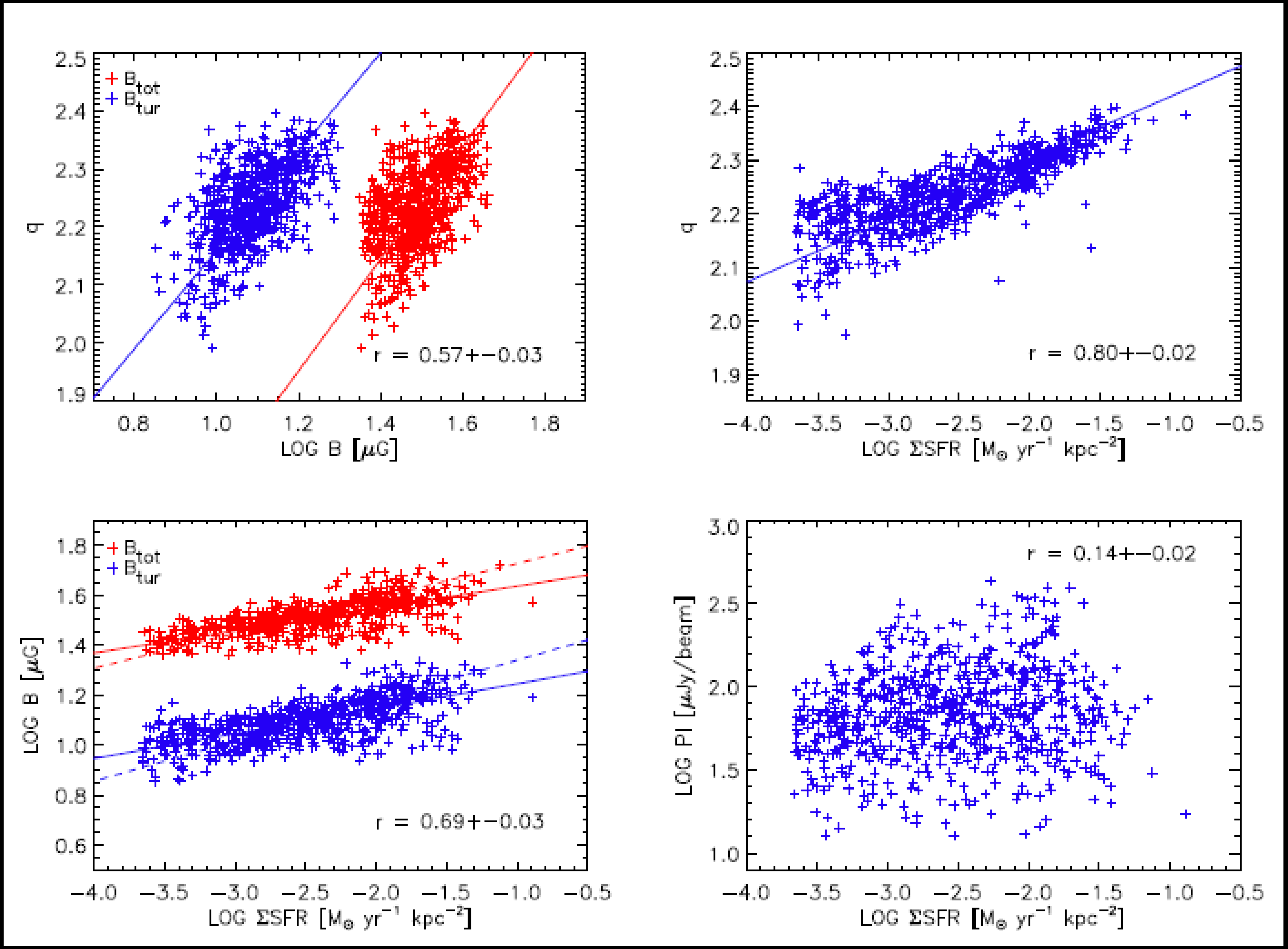


Contours:
Ordered magnetic field



- Larger q (or slope of correlation) in strong SF and strong turbulent B
- Smaller q along the magnetic arms.

Variation of the FIR/radio ratio (q-parameter)



$$q \propto (0.115 \pm 0.003) \log \Sigma_{\rm SFR},$$

$$q \propto (0.96 \pm 0.02) \log {\rm B_{tot}},$$

$$q \propto (0.85 \pm 0.02) \log {\rm B_{tur}},$$

$$\log B_{\rm tur} \propto (0.16 \pm 0.01) \log \Sigma_{\rm SFR},$$
$$\log B_{\rm tot} \propto (0.14 \pm 0.01) \log \Sigma_{\rm SFR}.$$

→In agreement with Chyzy (2008)

- Variations are a function of both star formation and magnetic fields.
- The total and turbulent B strengths are correlated with SFR.
- The ordered B and SFR are independent and partly anti-correlated.

Role of Radiation Field?

Table 7. Synchrotron–FIR/gas correlation in different regimes of radiation fields U_{ISRF} and U_{SF}.

Y	b^{ISRF}	r_c^{ISRF}	t^{ISRF}	n^{ISRF}	b^{SF}	r_c^{SF}	t^{SF}	n^{SF}
I_{70}	0.83±0.04	0.61±0.05	11.0	209	1.38±0.04	0.80±0.02	28.4	451
I_{100}	1.00±0.04	0.73±0.04	16.7	245	1.32±0.04	0.83±0.03	31.7	449
I_{160}	0.90±0.02	0.79±0.02	27.4	444	1.15±0.04	0.85±0.02	35.7	457
I_{250}	0.78±0.02	0.80±0.03	23.4	396	1.07±0.03	0.85±0.02	34.5	450
FIR	1.05±0.04	0.82±0.02	21.0	231	1.33±0.04	0.87±0.02	38.6	471
Σ_{Gas}	0.68±0.02	0.59±0.03	18.6	648	1.00±0.03	0.86±0.02	36.1	481
Σ_{SFR}-Σ_{Gas}	1.45±0.06	0.58±0.04	14.69	320	1.34±0.05	0.64±0.04	17.8	452
B_{tot}-Σ_{Gas}	0.27±0.05	0.48±0.05	9.7	314	0.23±0.01	0.75±0.03	23.6	429

- In ISRF, the synchrotron emission correlates better with the cold than warm dust

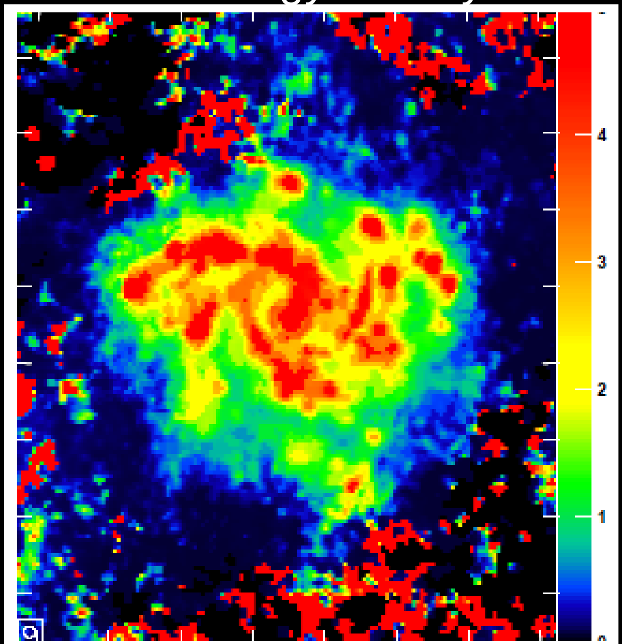
- In SF, no difference

→ warmer dust is mainly heated by SF
(where synchrotron produced by young CREs/turbulent B),

→ colder dust by a diffuse ISRF across the disk
(where synchrotron produced by diffused CREs/large-scale B).

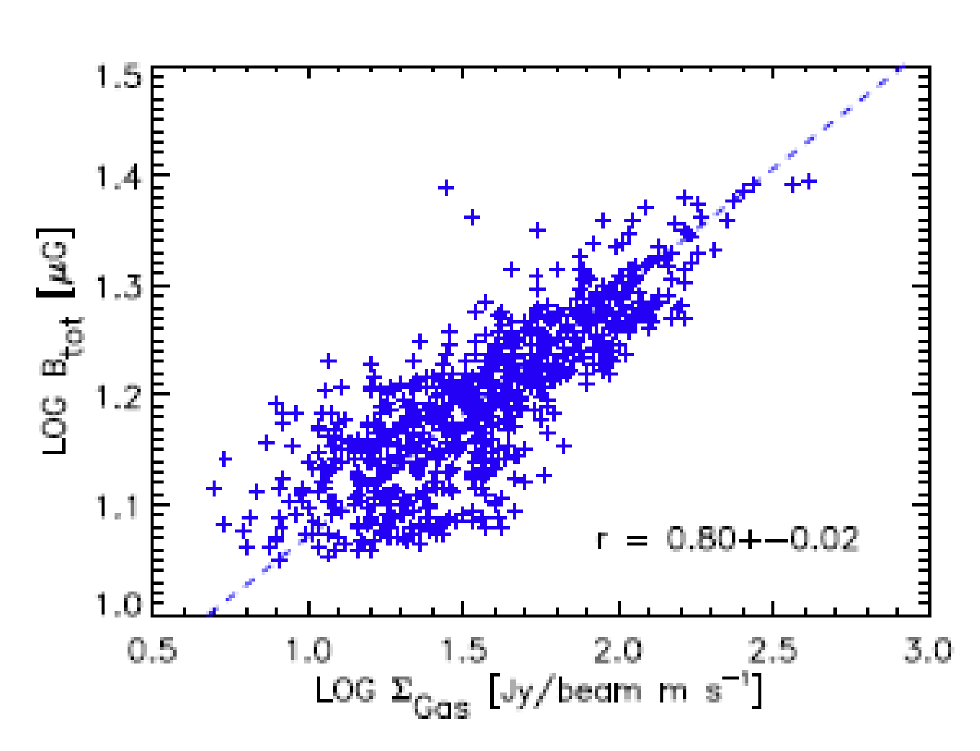
- FIR-Sync. is linear in ISRF , super linear in SF regime

Normalized radiation field energy density



Aniano et al. (2012)

Magnetic Field-Gas Density Coupling



• The synchrotron-FIR correlation can be well explained by the B-gas coupling models (Niklas & Beck 1997), particularly in SF regimes.

• The intermediate-mass stars seem to be a more appropriate origin in ISFR.

Tabatabaei et al. in prep.

Summary

- Synchrotron-FIR correlation breaks down on some scales, no unique warm/cold dust dependence.

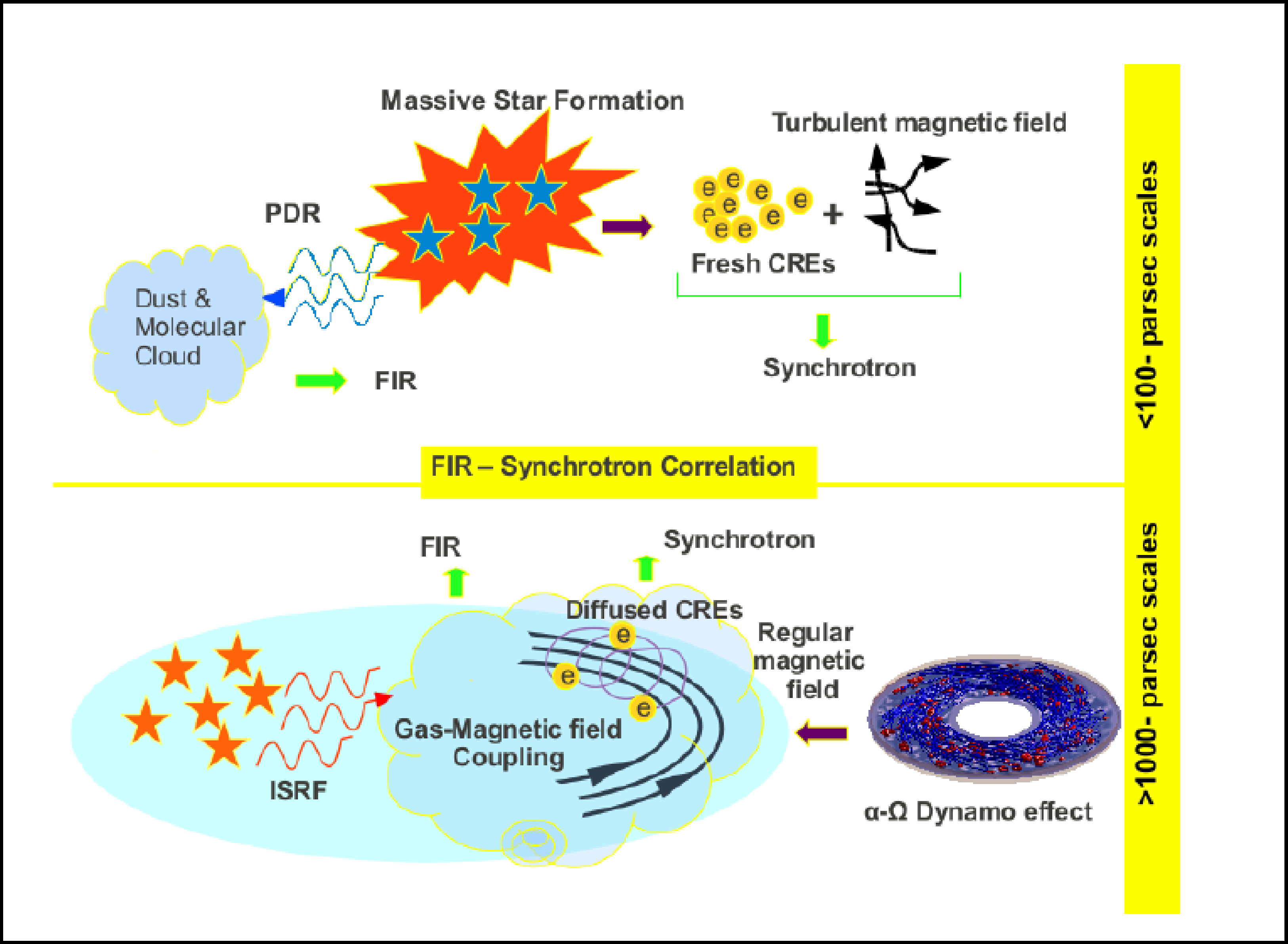
- In **general,** strong synchrotron emission emerges from shell- and filament-like features around star-forming regions. This is explained by the direct proportionallity between SFR and turbulent magnetic field/ fresh CREs.

- On large scales in M31, NGC 6946 the synchrotron emission is dominant, possibly due to the **fast diffusion of CREs** in the strong, ordered field.

- The break scale of the sync –FIR decreases with the ratio of turbulent -to- ordered magnetic fields which can be assigned to **CRE propagation in turbulent magnetic fields.**

Take away:

Synchrotron-FIR runs not only by SF but also by magnetic fields in galaxies.


Massive Star Formation
Turbulent magnetic field
PDR
Dust & Molecular Cloud
FIR
Fresh CREs
Synchrotron
FIR – Synchrotron Correlation
<100- parsec scales
FIR
Synchrotron
Diffused CREs
Regular magnetic field
Gas-Magnetic field Coupling
ISRF
α-Ω Dynamo effect
>1000- parsec scales