The FIR-Radio Correlation and Galaxy Halos

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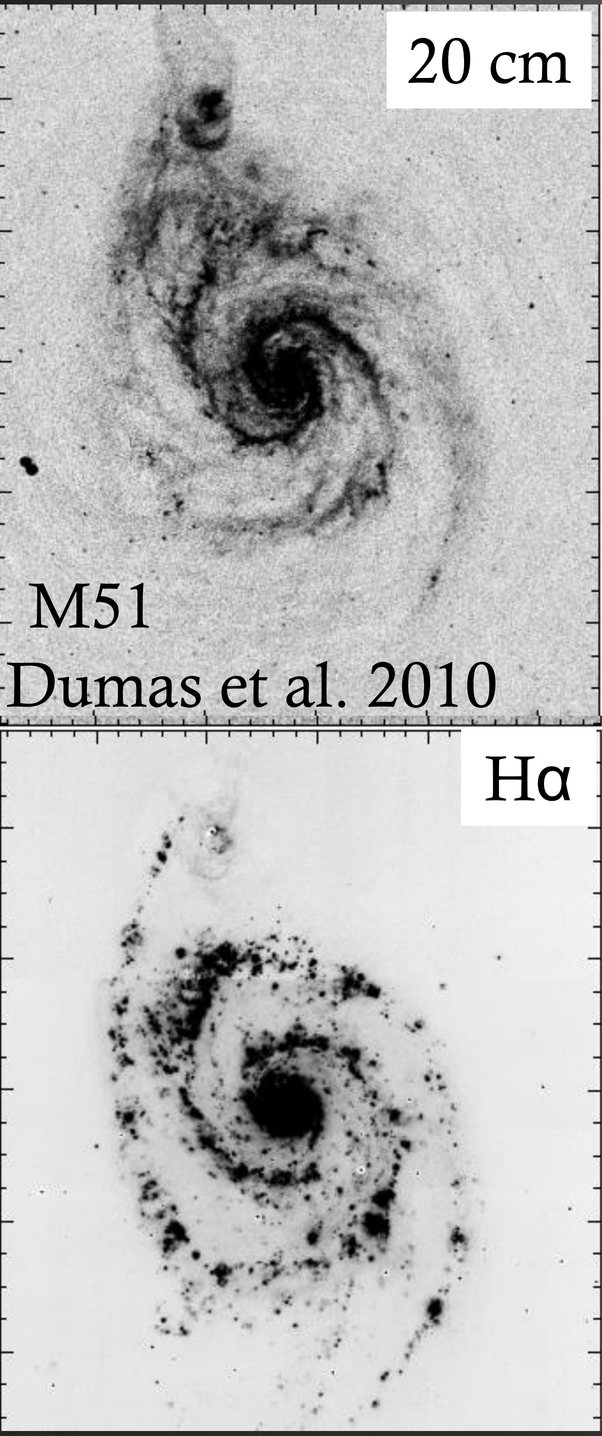
Far-Infrared (FIR) Emission from Galaxies

- Re-radiated starlight by interstellar dust grains
  - Traces massive star formation
- Super position of modified blackbodies
  - Temperature information
- PACS 3-color image
  - 70 μm BLUE
  - 110 μm GREEN
  - 160 μm RED

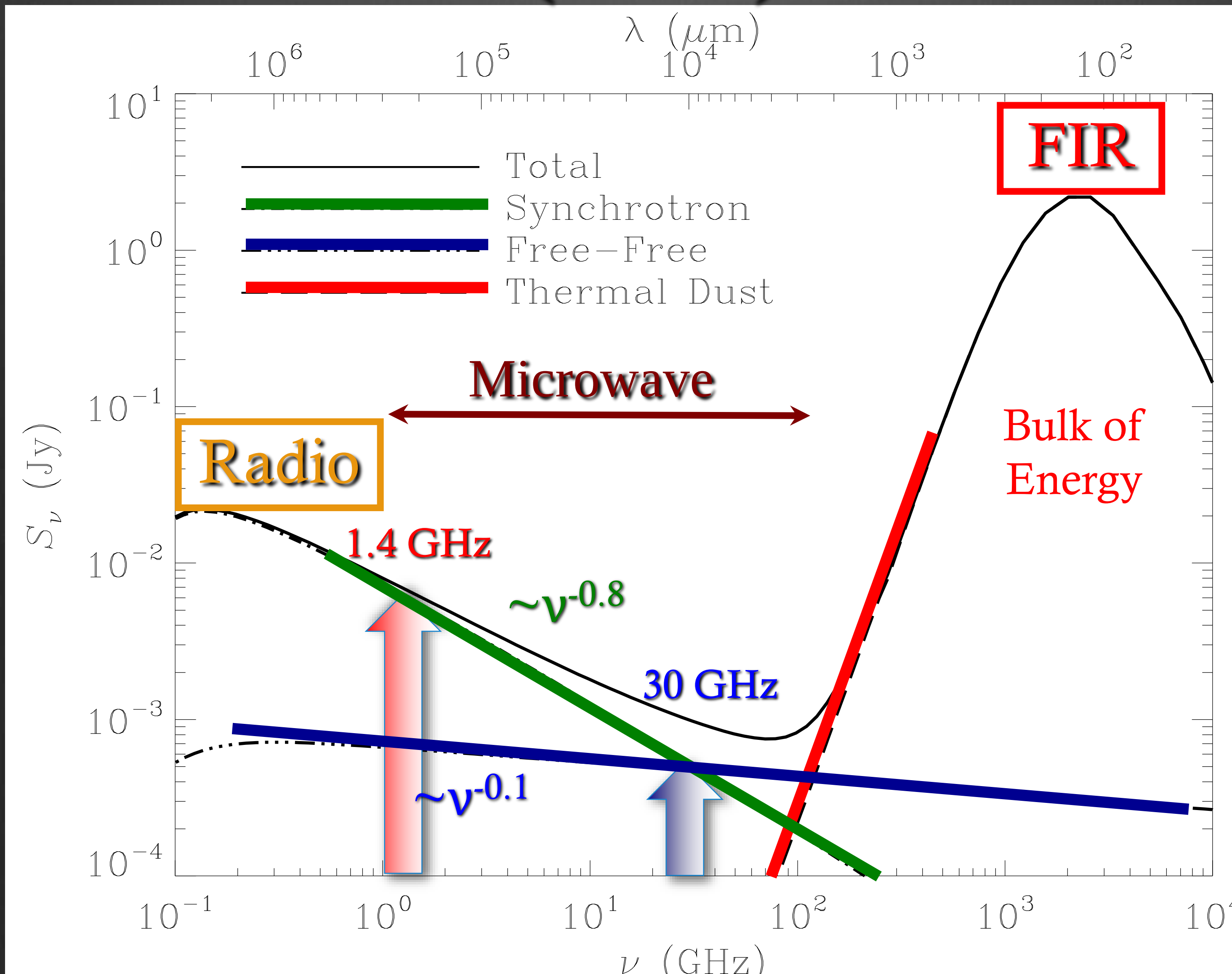


Radio Emission from Galaxies

- Combination of thermal and non-thermal radiation
  - Both arise from massive star formation
- 20 cm (globally ~90% non-thermal)
  - Synchrotron radiation from accelerated CR electrons by SNe
  - Discrete star-forming regions + SNRs on top of *diffuse disk.*
- 3.6 cm (globally ~30% thermal)
  - Bremsstrahlung (free-free) radiation from star-forming regions
  - Less of a diffuse component

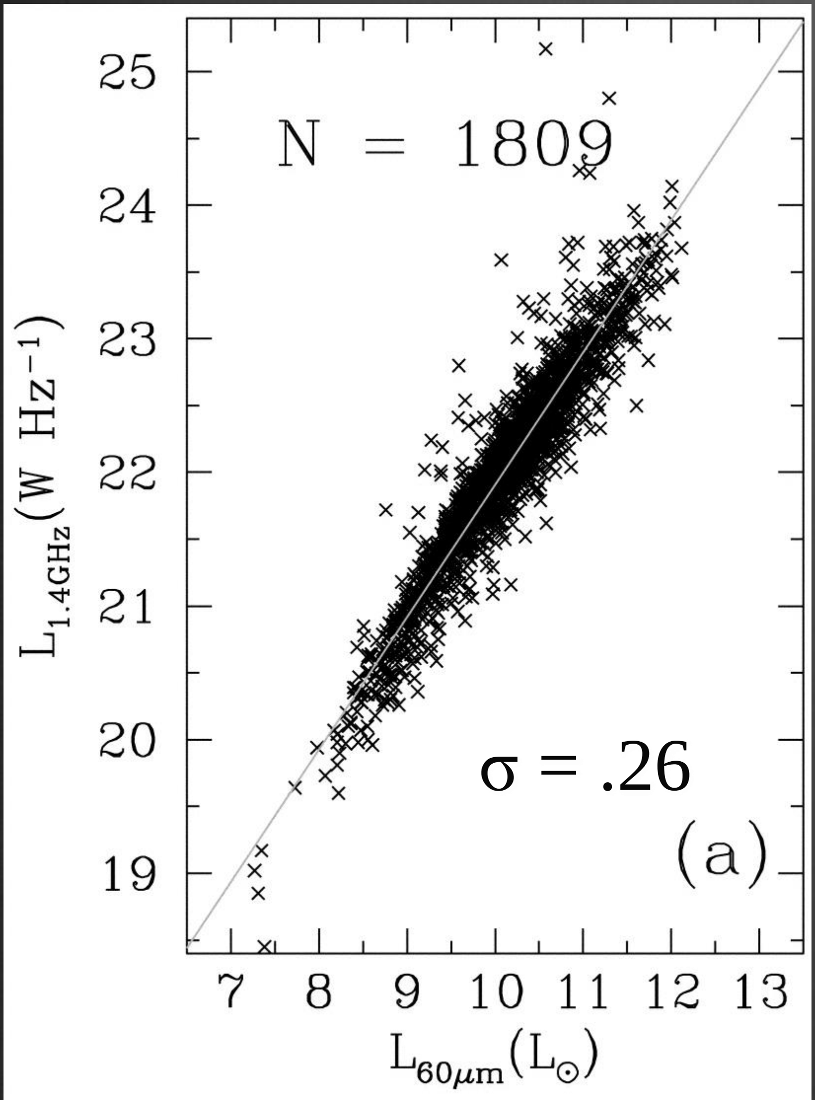
FIR to Radio Spectral Energy Distribution (SED) of a Galaxy

Flux Density

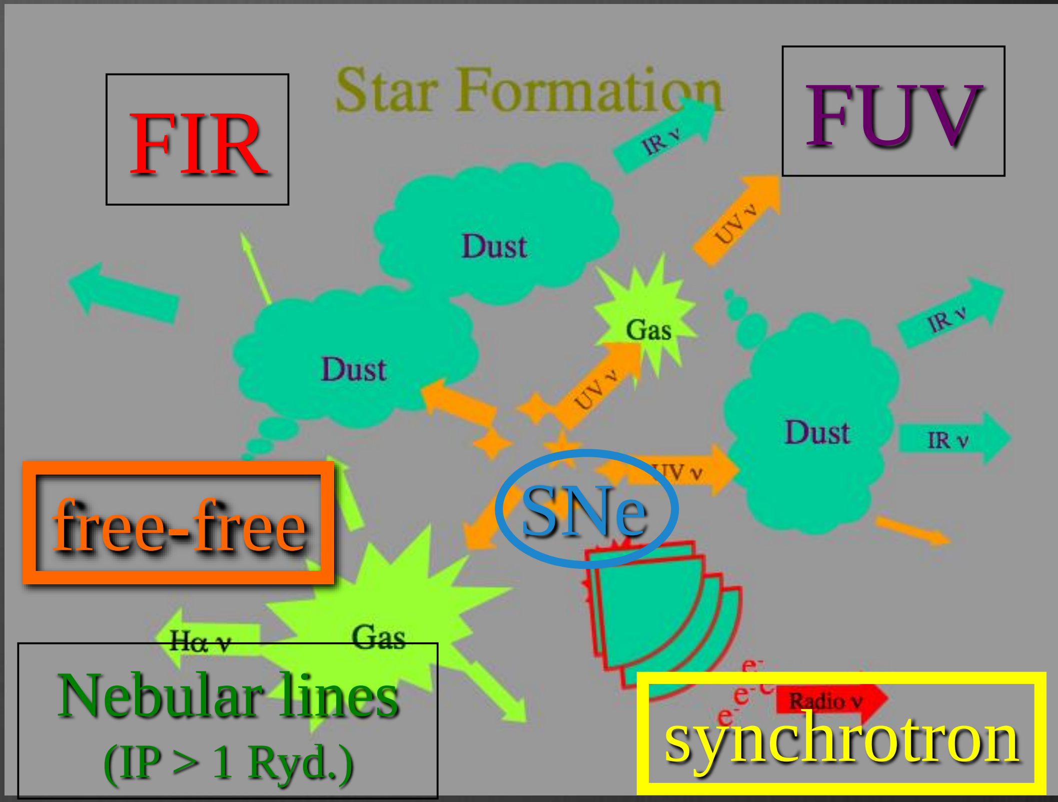


FIR – Radio Correlation: 1st order explanation

(van der Kruit 1971/1973; de Jong et al. 1985; Helou et al. 1985)



Yun, Reddy, & Condon. (2001)



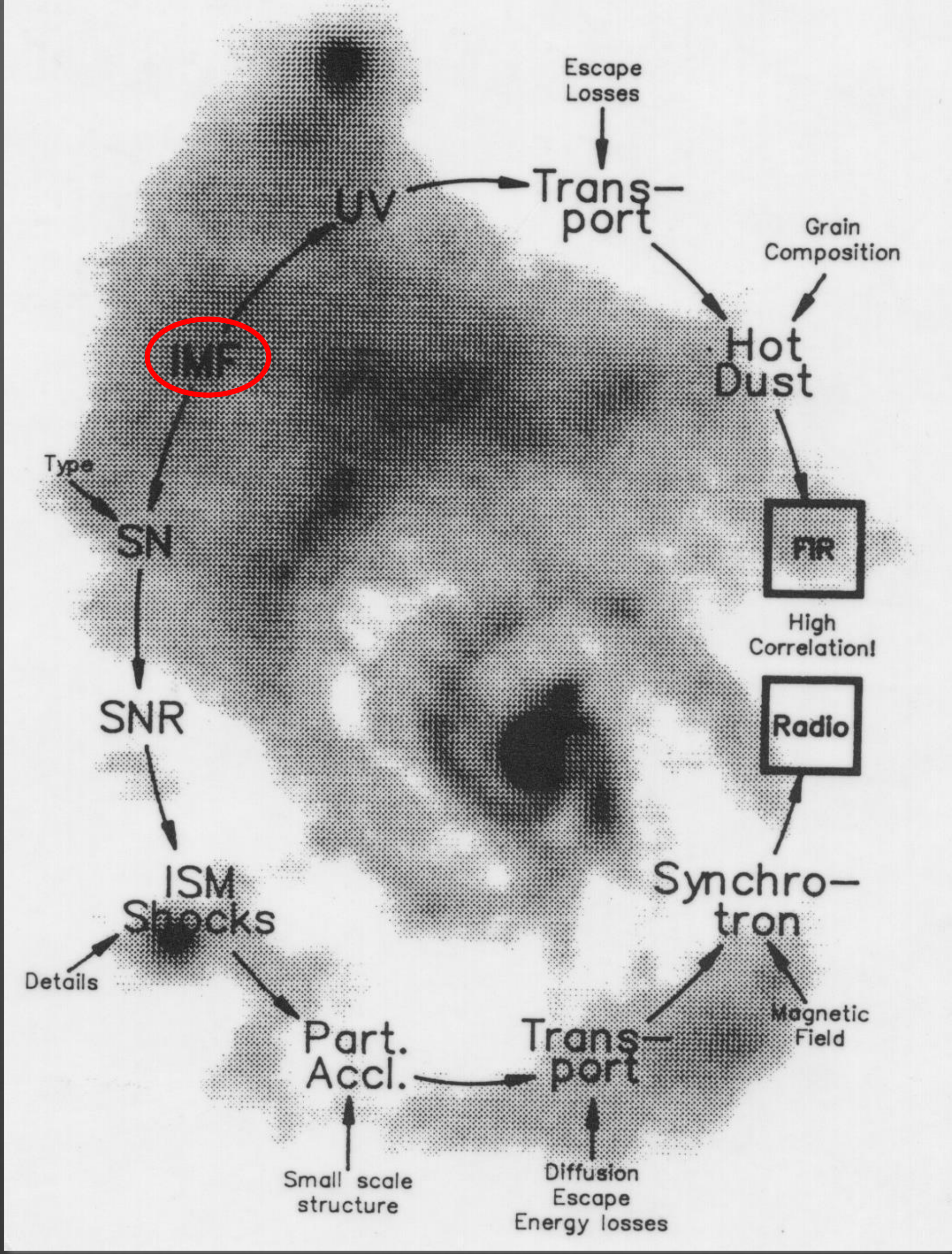
- Spans ~5 orders of magnitude in galaxy luminosity
- Driven by Massive Star Formation
  - FIR – Dust heated by Massive stars
    - mfp of dust heating UV photons ~100 pc
  - Radio – CR*e* accelerated by SNe in B-field
    - CR*e* diffuse ~1 kpc
- Radio image is *smoother* version of FIR image

(Some) of the Physics Involved

- FIR affected by:
  - IMF
  - UV photon transport
  - Optical depth
  - Grain distribution/composition

- Radio affected by:
  - IMF
  - Acceleration Mechanisms
  - Primary/Secondary e^-
  - Magnetic Field
  - Transport – diffusion & confinement

- How can FIR/Radio ratios of galaxies show such small scatter?



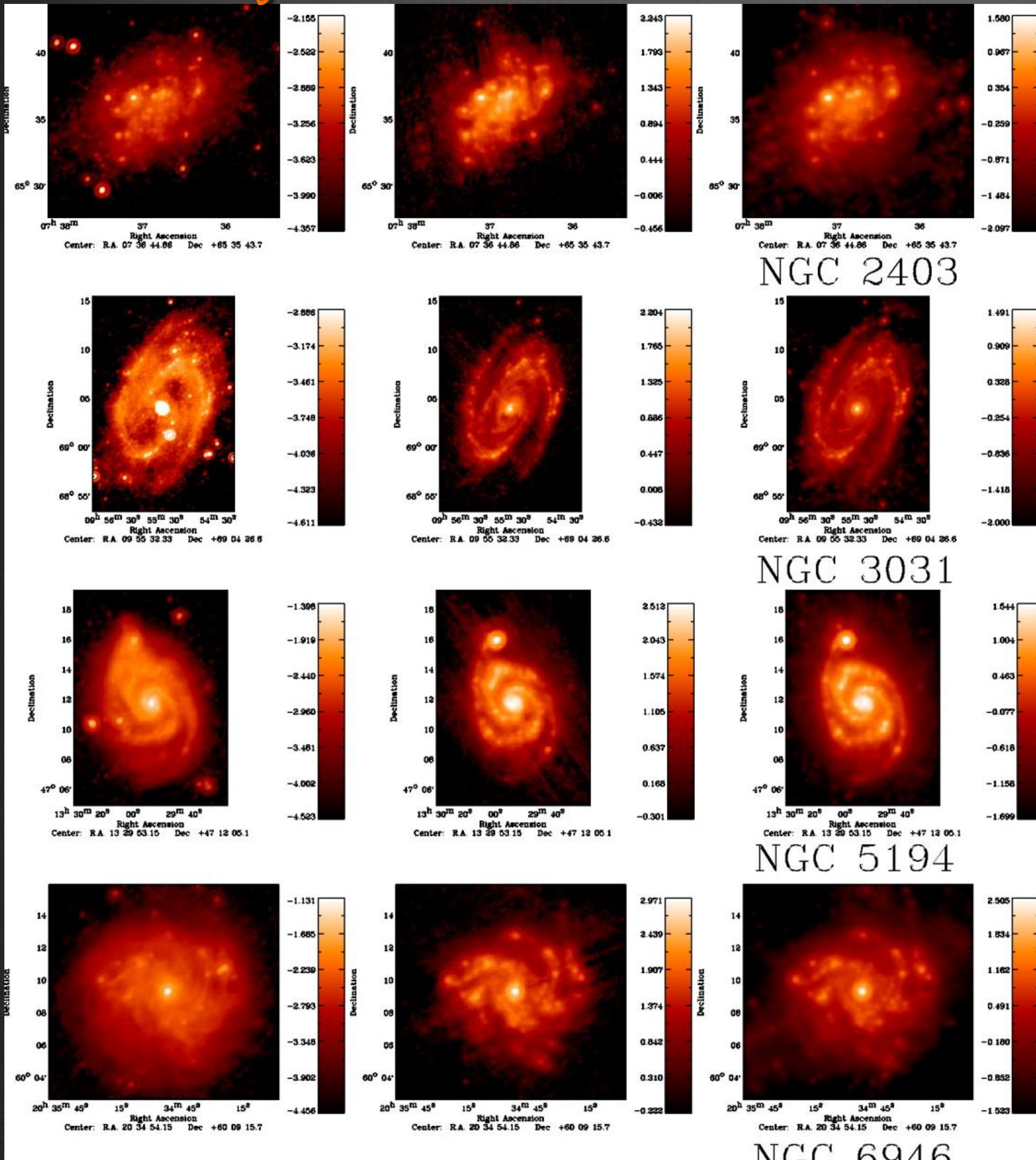
From Ekers (1991)

Using FIR/Radio Correlation to Characterize CR propagation

- Many studies on this topic, especially since *Spitzer* was launched:
  - SINGS Galaxies – Murphy et al. (2006, 2008)
    - Piggy-backing off of original phenomenological model of Helou & Bicay (1993).
  - LMC – Hughes et al. (2006), Murphy et al. (2012)
  - M51 – Dumas et al. (2011)
  - M31, M33, N6946 – Tabatabaei et al. (2007, 2010, 2013)
    - Above studies make use of wavelet cross correlations – power at different spatial scales as a function of frequency.

FIR and Radio Morphologies of Nearby *Field* Galaxies

Radio/Sync Cool Dust Warm Dust



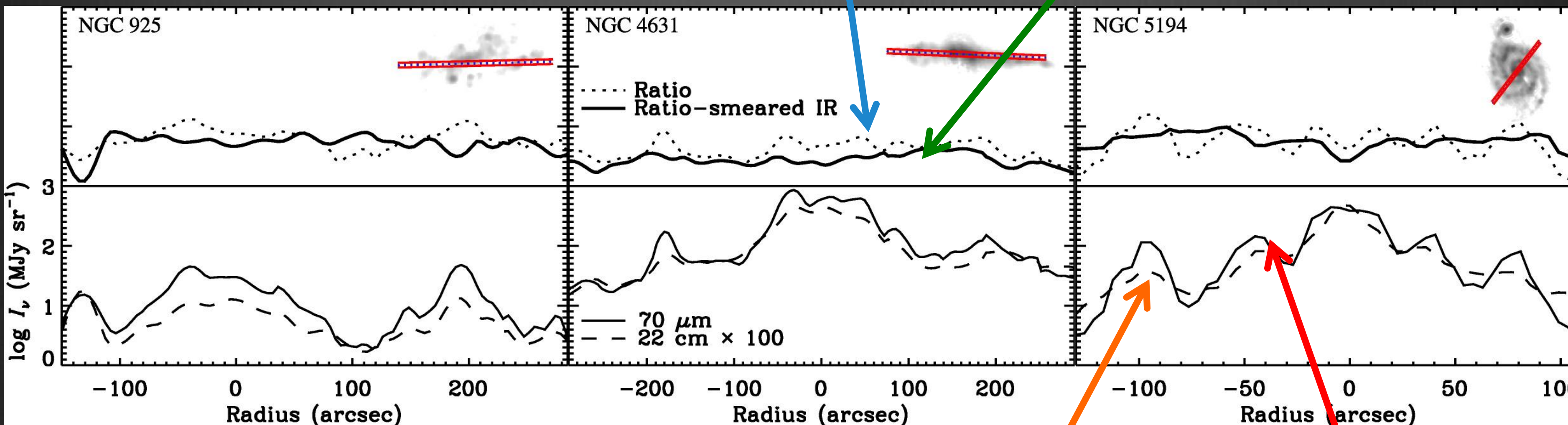
- With Spitzer, first time a resolved study of the FIR-radio correlation possible ***within*** a large number of nearby galaxies
  - Get at the physics driving the correlation!
  - Galaxies shown at matching resolution
- *Radio images have similar morphologies, but smoother due to diffusion of CR electrons.*

EJM+06a,b; EJM+08

Radial Cuts Across IR and RC Disks

Observed Residuals

Residuals after smoothing



EJM+08

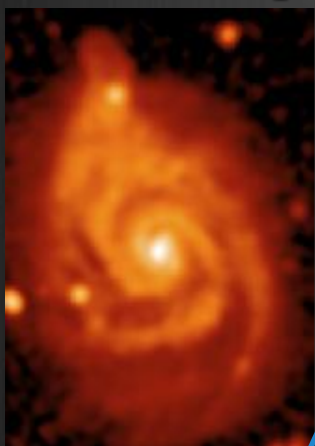
Radio

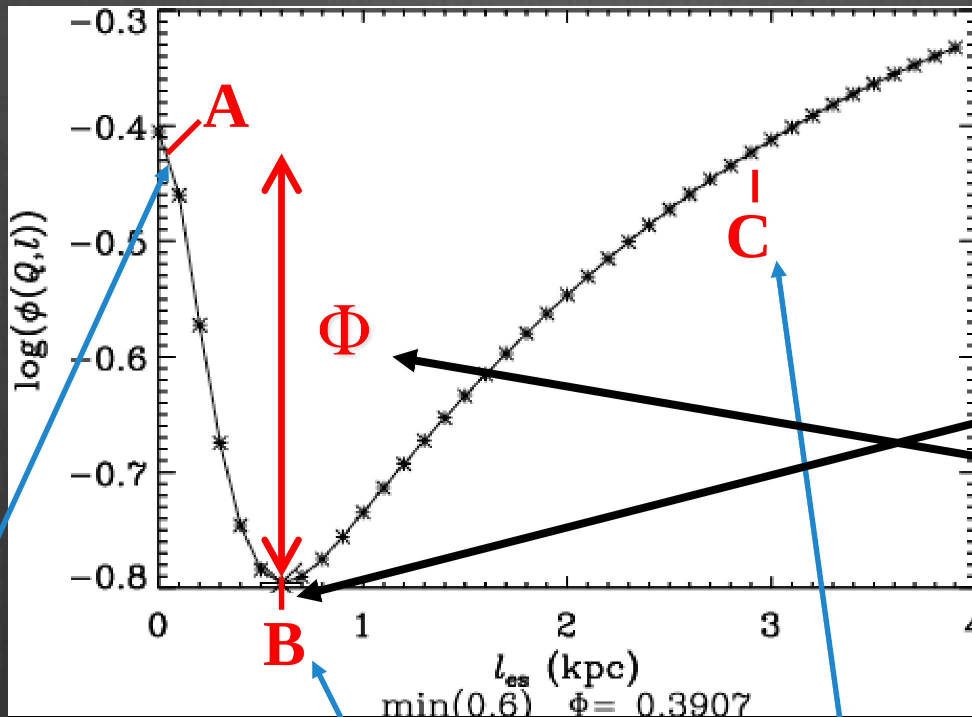
IR

- FIR emission more peaked than radio on arms/SF regions
  - *CR electrons diffuse further than mfp of UV heating photons.*
- Such signatures removed in residuals after smoothing the FIR disks appropriately!
  - ***Use smoothing kernel to infer physics of CR propagation in other galaxies!***

Image Smearing Analysis: (e.g. NGC 5194)

22cm Map





Residuals between Radio & Smeared FIR Images
(EJM+ 2006a,b)

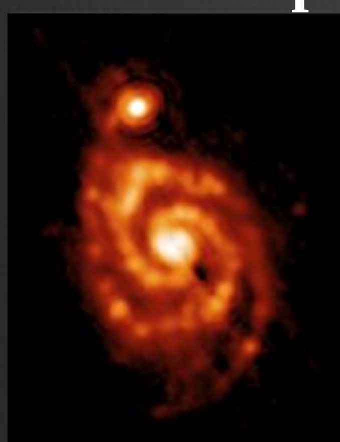
***B*: Best-fit Scale-length**

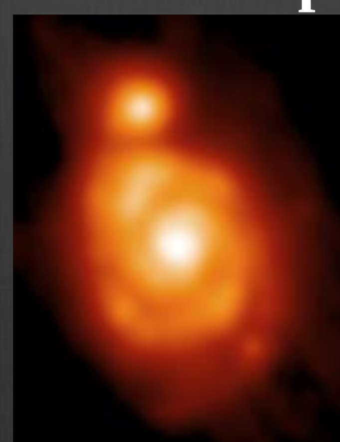
***Φ*: Improvement**

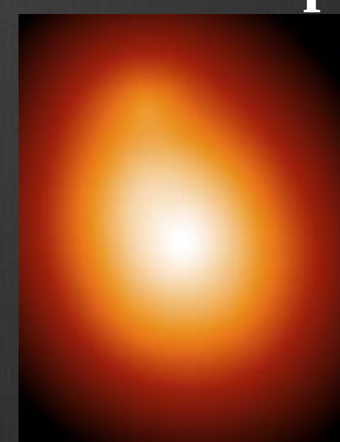
(~x2-3 on average)

A: *l* = 0.0 kpc **B: *l* = 0.6 kpc** **C: *l* = 3.0 kpc**

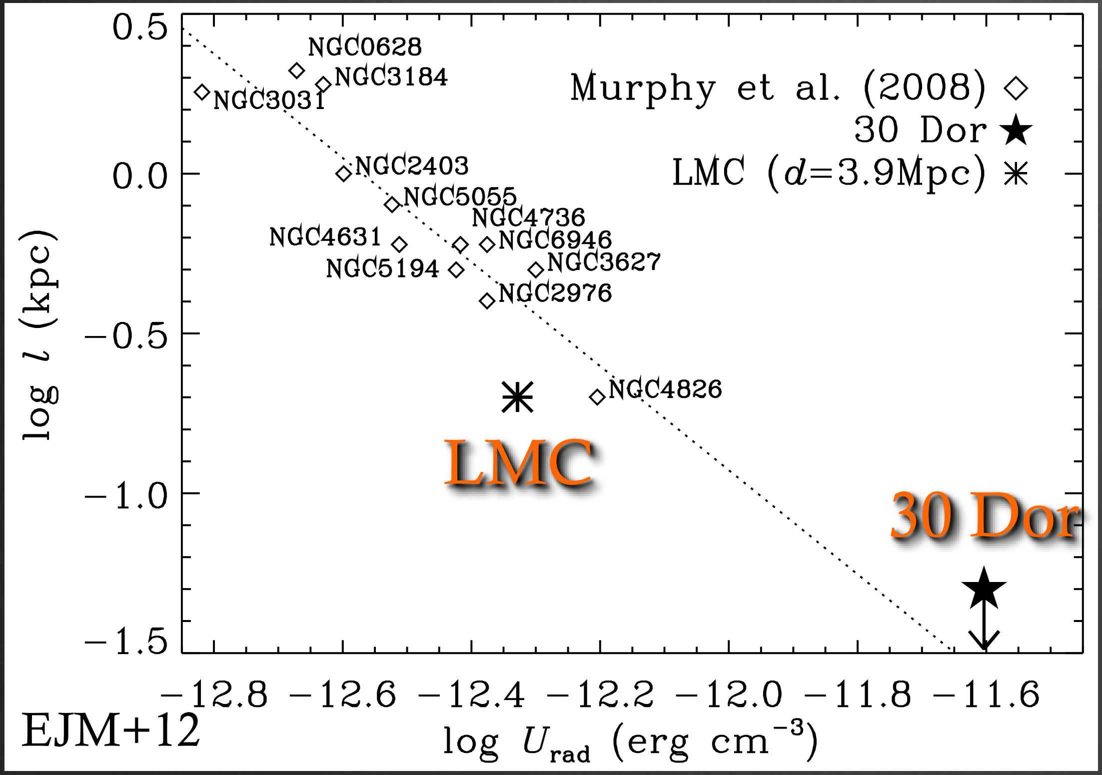
Smeared 70μm Maps







CR Propagation vs. Intensity of Star Formation



Star Formation Intensity

- Observed trend too steep to be explained by steady-state star formation
  - CRe⁻'s must be younger – *Galaxies with large values of Σ_{SFR} have likely undergone a recent episode of enhanced star formation*
  - *l is sensitive to SFHs*
- Including Irr galaxies suggestive of CR escape
  - Low *l* & SFR/area
- Edge-on's:
  - *Vertical diffusion similar to radial diffusion (e.g., N4631 → prominent halo)*

Order of magnitude diffusion estimates

Assume $U_{rad} \sim U_B = B^2/(8\pi)$

- **1.** $\langle U_{rad} \rangle \sim 4 \times 10^{-13}$ ergs/cm^3 from TIR SB
- **2.** $B \sim 9\mu$G → $\langle U_{rad} \rangle \sim 2 \times 10^{-12}$ ergs/cm^3

$$\left(\frac{\tau_{\rm cool}}{\rm yr}\right) \sim 5.7 \times 10^7 \left(\frac{\nu_c}{\rm GHz}\right)^{-1/2} \left(\frac{B}{\mu{\rm G}}\right)^{1/2} \times \left(\frac{U_B + U_{\rm rad}}{10^{-12}\ {\rm ergs\ cm^{-3}}}\right)^{-1}$$

Sync. losses

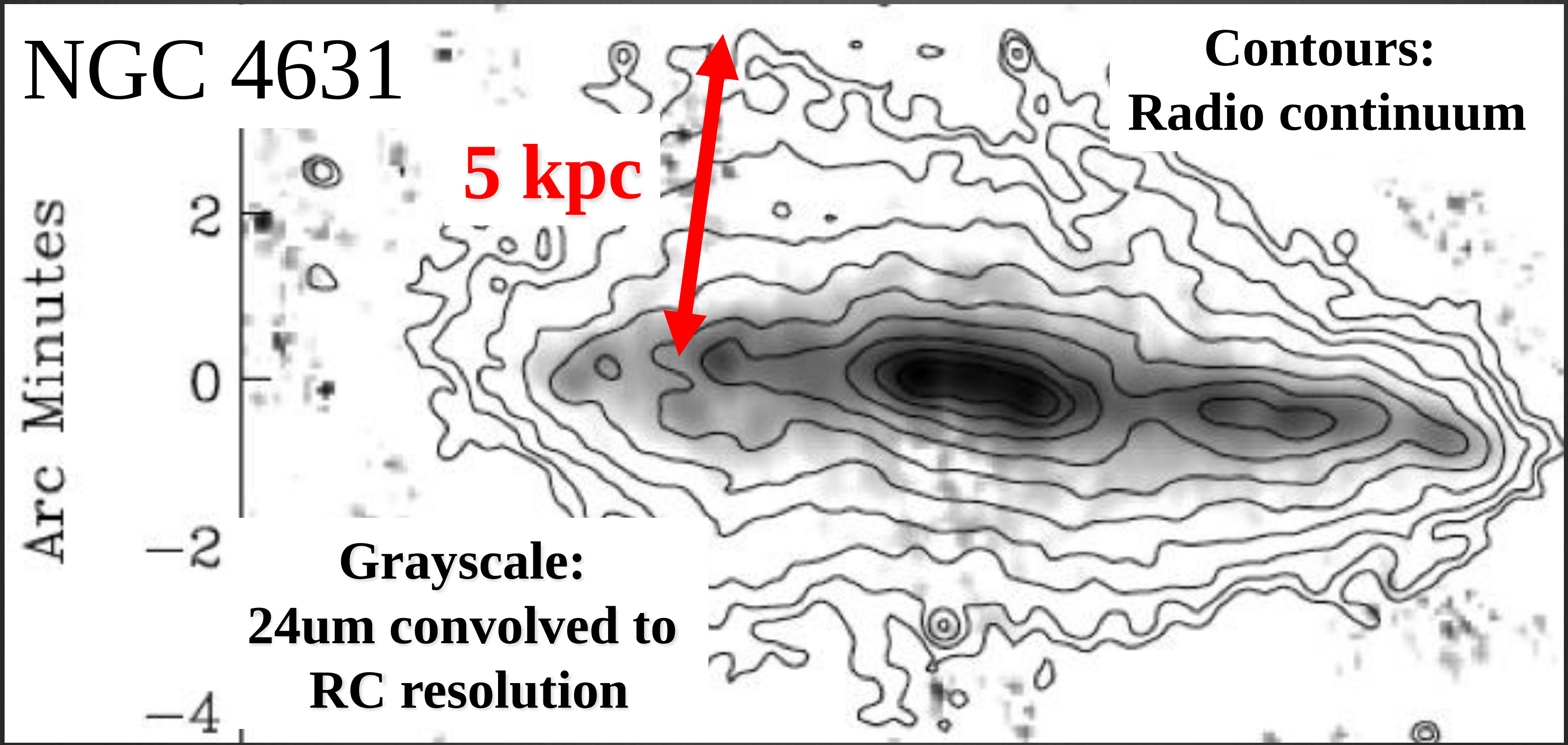
IC losses

$$\left(\frac{l_{\rm cool}}{\rm kpc}\right) \sim 7 \times 10^{-4} \left(\frac{\tau_{\rm cool}}{\rm yr}\right)^{1/2} \left(\frac{\nu_c}{\rm GHz}\right)^{1/8} \left(\frac{B}{\mu{\rm G}}\right)^{-1/8}$$

Random Walk Diffusion

- **1.** $\tau_{cool} \sim 110$ Myr; $l_{cool} \sim 6.8$ kpc
- **2.** $\tau_{cool} \sim 22$ Myr; $l_{cool} \sim 2.6$ kpc
- Both cases much *l_{cool} much (> x3) larger than what we measure.*
  - IC & synchrotron processes alone cannot explain structural differences between IR and RC maps
  - ***Differences in CR population Ages! Use to characterize SFHs***

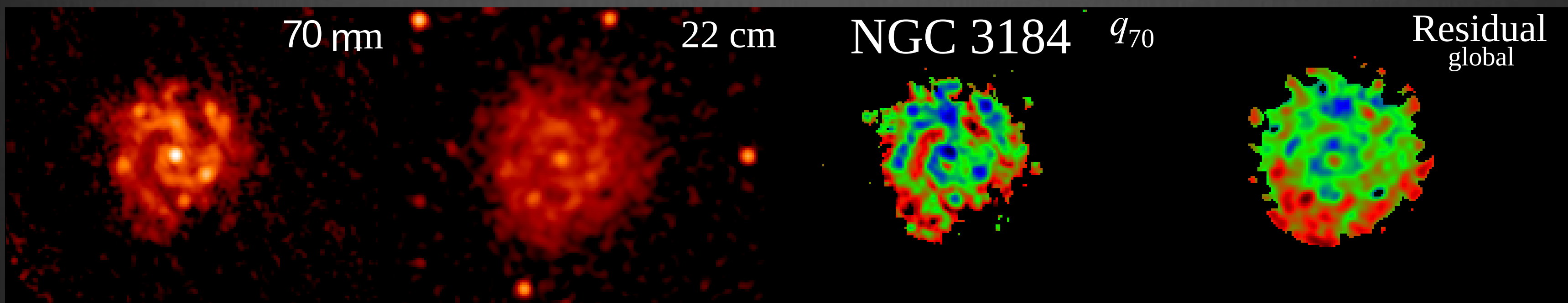
Edge-On Systems: Studying Negative Feedback



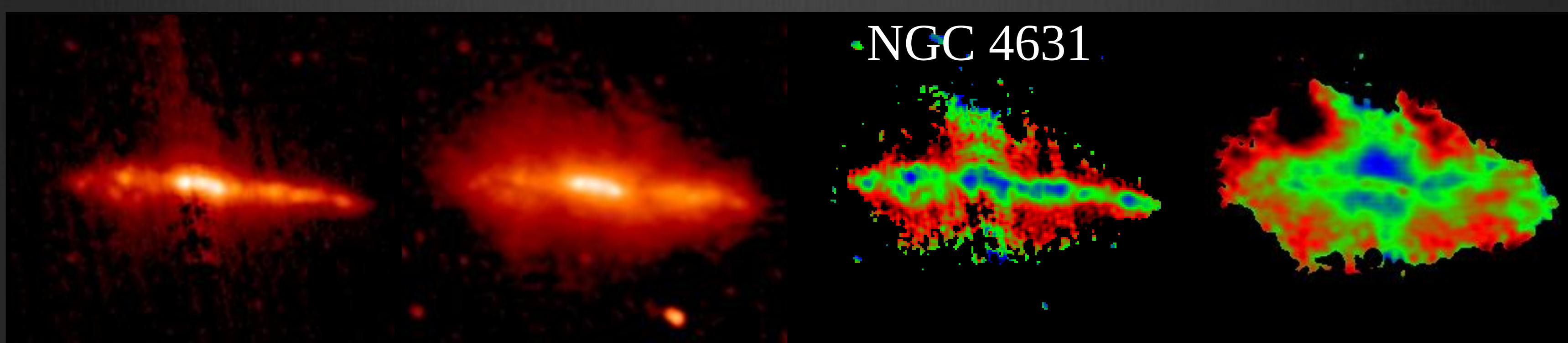
- Starburst winds are multiphase (e.g. Large synchrotron haloes):
  - Arise from advected cosmic-ray electrons in large-scale magnetic field
  - Implications for negative feedback effects: Is SF quenched by galactic CR winds (e.g. Socrates et al. 2008)?
    - Need direct comparison with distribution/kinematics of warm molecular gas
    - Implications for high-z ULIRGs where we cannot study these processes in detail

FIR/Radio Spatial Distribution

Face-On Spiral



Edge-On Spiral

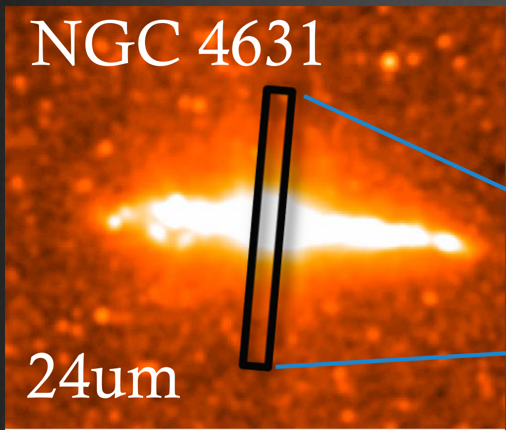


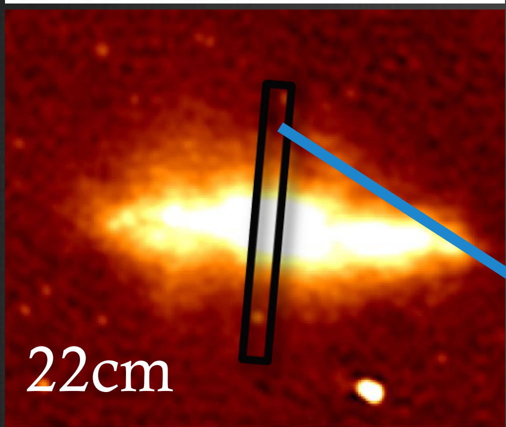
Vertical diffusion CRs occurs on similar timescale as those in disk

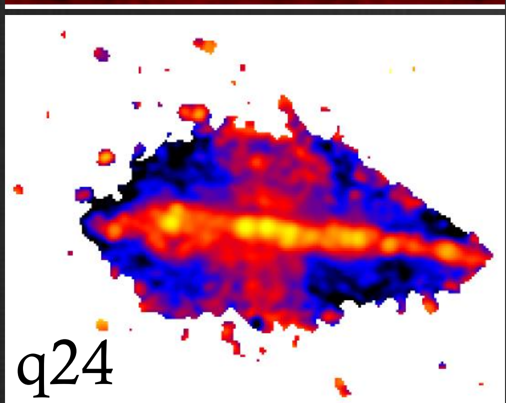
The Herschel EDGE on galaxy Survey (HEDGES)

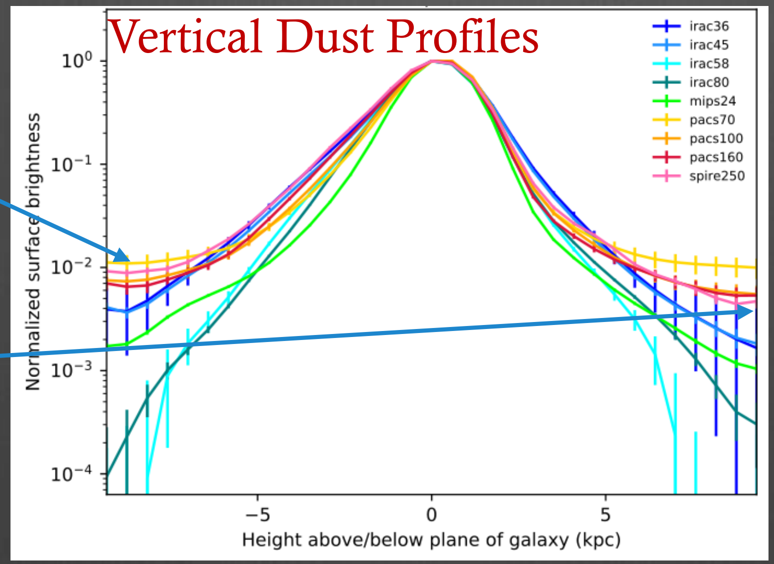
- Deep imaging in 6 bands between 70 – 500um, plus additional imaging from Spitzer IRAC and MIPS 24um, to measure dust halo SEDs.
  - Characterize dust content and processing in halos.
  - + CHANG-ES (Irwin et al.) → investigate vertical CR prop. : E ~3 & 8 GeV
  - ***Full dust SED in halo to compare with radio properties***
- All data taken before cryo ran out;
  - REU student (Jackie Pezzato – now at CIT) started analysis of FIR SEDs

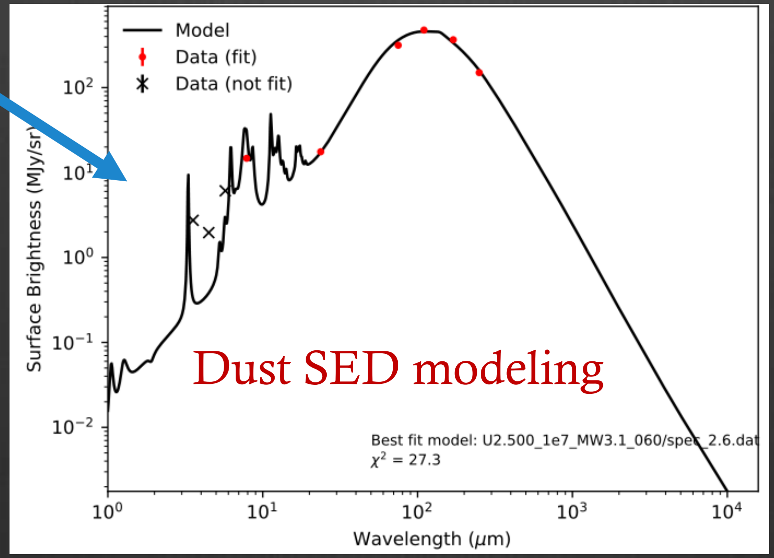
Full IR-Radio SED Halo Modeling











Instrument/Band	Standard Deviation (kpc)
IRAC 3.6 μm	0.717 ± 0.012
IRAC 4.5 μm	0.692 ± 0.011
IRAC 5.8 μm	0.642 ± 0.009
IRAC 8.0 μm	0.636 ± 0.008
MIPS 24 μm	0.558 ± 0.005
PACS 70 μm	0.611 ± 0.008
PACS 100 μm	0.641 ± 0.010
PACS 160 μm	0.662 ± 0.012
SPIRE 250 μm	0.709 ± 0.013

Initial Investigation

- Vertical profiles as function of FIR wavelength
- Full dust SED modeling
- To do: Incorporate Radio data in fits

Summary

- Pieces of galaxies do not behave like galaxies:
  - FIR-Radio correlation varies significantly within galaxies which appears mainly driven by propagation of CRs.
- Using FIR image as a source function for CRs, can smooth maps to match radio morphologies to glean CR propagation physics
  - Improvements in residuals by factors of ~x2 – 3.
  - Scale-length a dominant function of CR pop. age, rather than ISM conditions
- CR diffusion into the the halos of star-forming disks appears to occur on similar timescales as radial diffusion in the disk
  - However, much harder to account for CR diffusion into halo with single function compared with radially in disks.
- More work needed by full FIR-Radio SED analysis as function of vertical scale-height.
  - Such data now exists!