Relating the Propagation of Cosmic Rays to SFRs

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The Importance of the Relativistic phase of the ISM

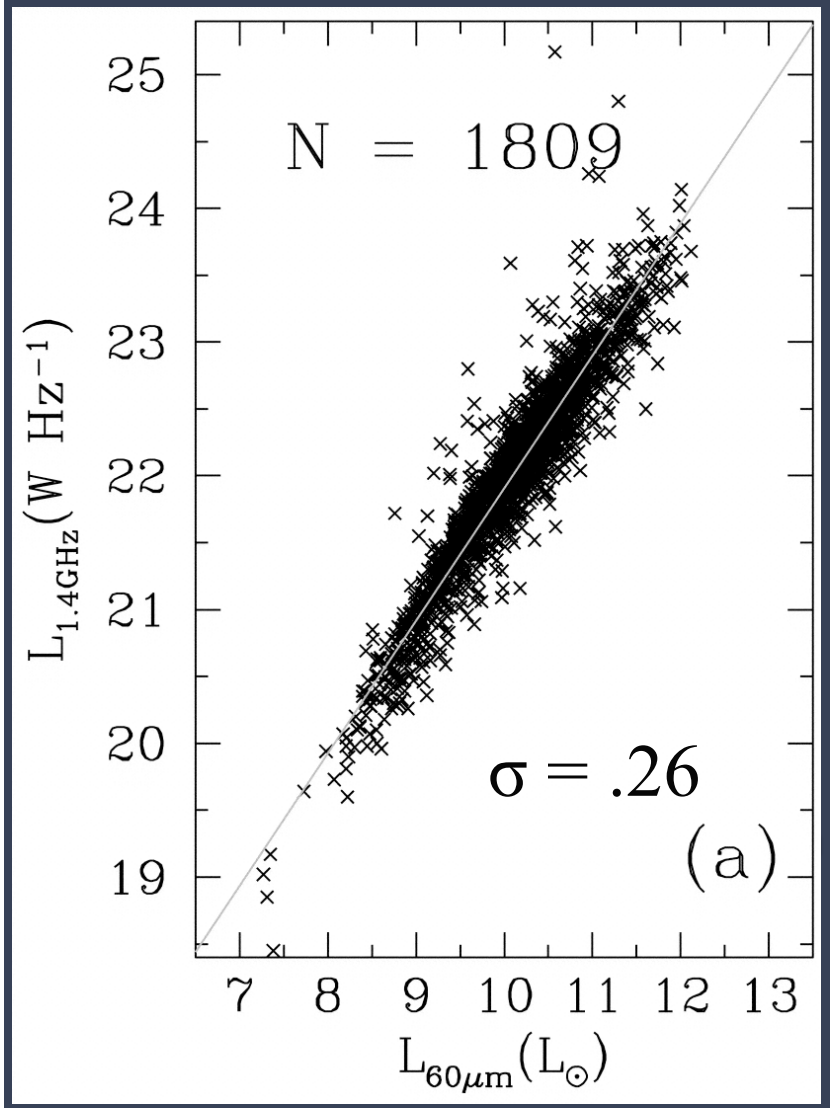
- RISM is composed of CR particles bathed in a large-scale magnetic field:
- Dynamically Important!

$$U_{CR} \sim U_B \sim U_{rad} \sim U_{turb} \sim 1\ eV/cm^3\ in\ MW$$

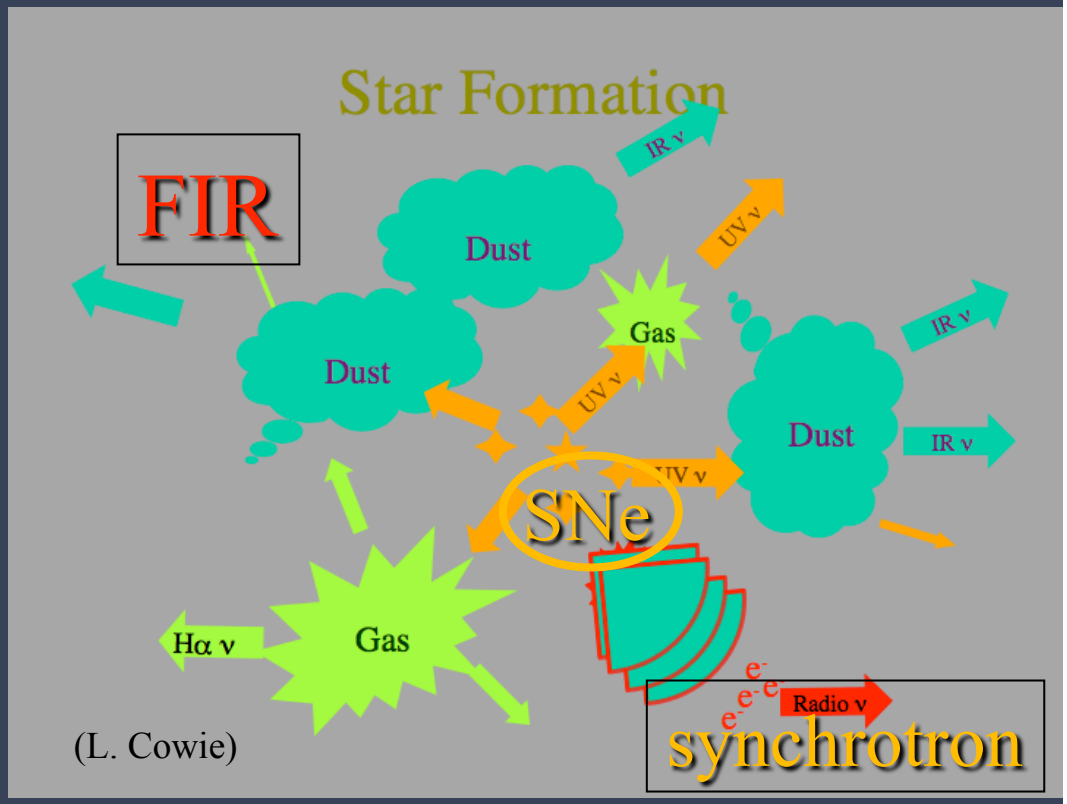
- Strong B-fields in place at high-z (e.g. Wolfe et al. 2008)
- CR's provide a possible means to couple energy from SF & AGN back into the ISM resulting *negative feedback* (e.g. Socrates et al. 2008).
- *CR electrons are a fundamental ingredient in the FIR-radio correlation*, so should tell us something about star formation
  - *Currently VERY LITTLE info. on CR propagation outside MW*

FIR – Radio Correlation: How it works… well, kind of

(de Jong et al. 1985; Helou et al. 1985)



Yun, Reddy, & Condon. (2001)

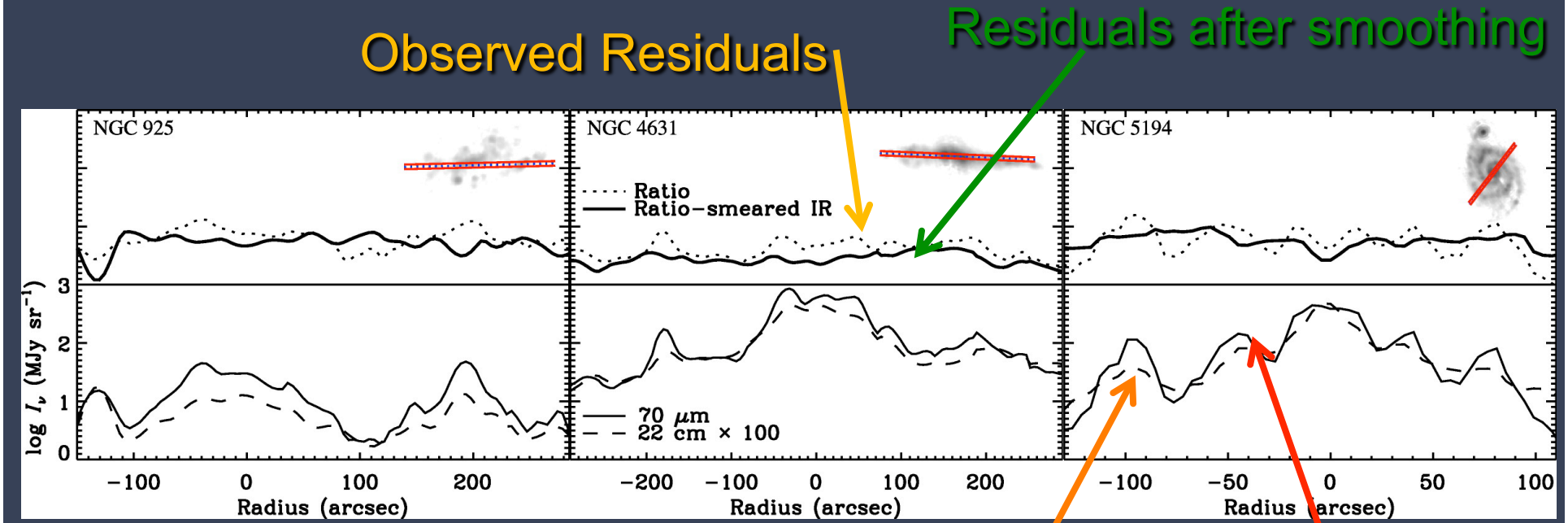


Driven by Massive Star Formation

- **FIR** – Dust heated by Massive stars
  - mfp of dust heating UV photons ~100 pc
- **Radio** – CRe$^-$ accelerated by SNe in B-field
  - CRe$^-$ diffuse ~1 kpc

➢ **Radio image appears as a smoother version of FIR image**

Radial Cuts Across IR and RC Disks

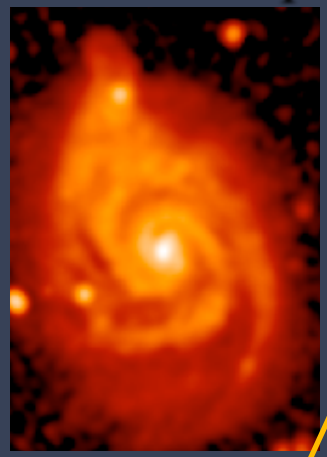


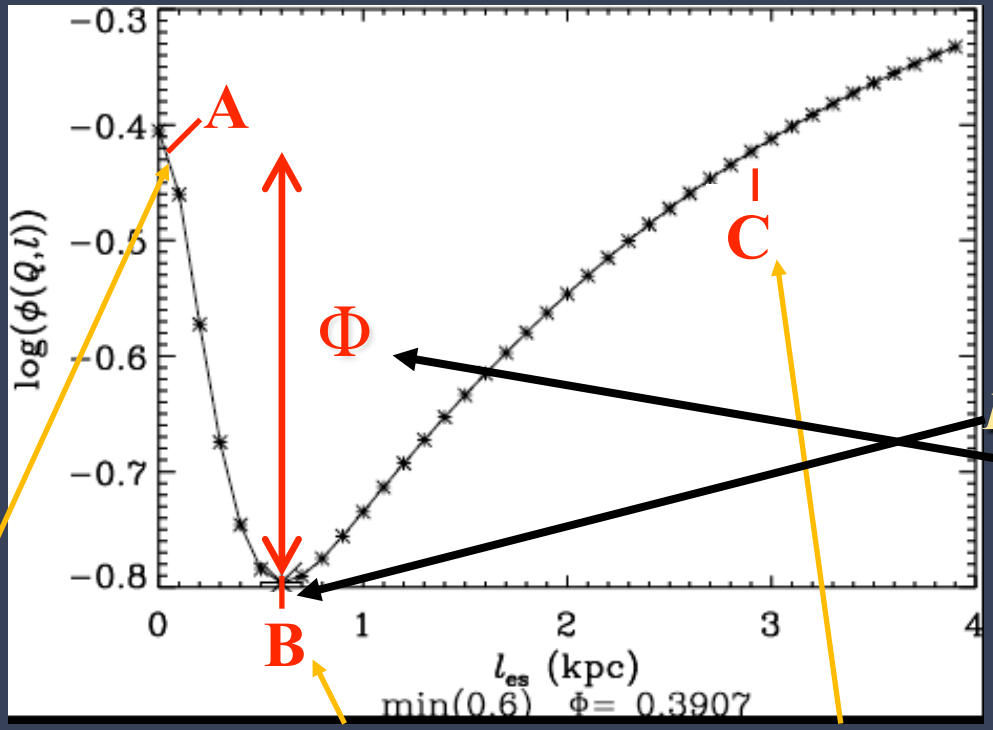
EJM08

- 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



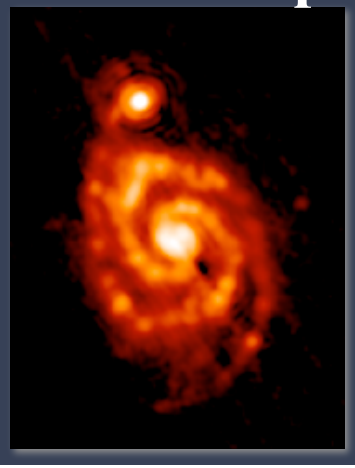


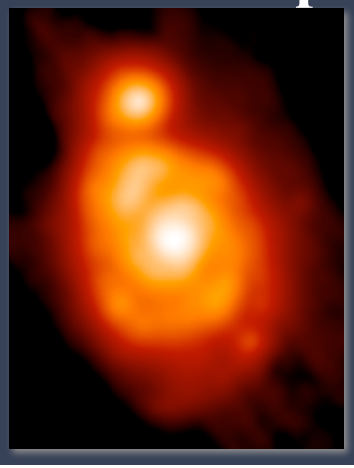
Residuals between Radio & Smeared FIR Images (Murphy et al. 2006a,b)

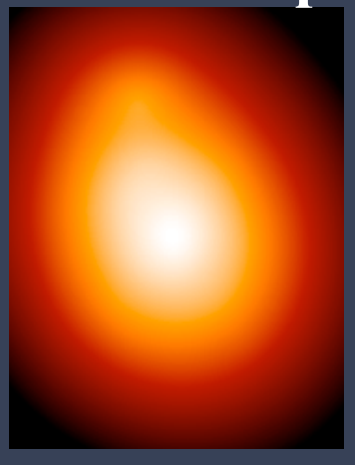
B: Best-fit Scale-length
Φ: Improvement
(~x2-3 on average)

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

Smeared 70μm Maps

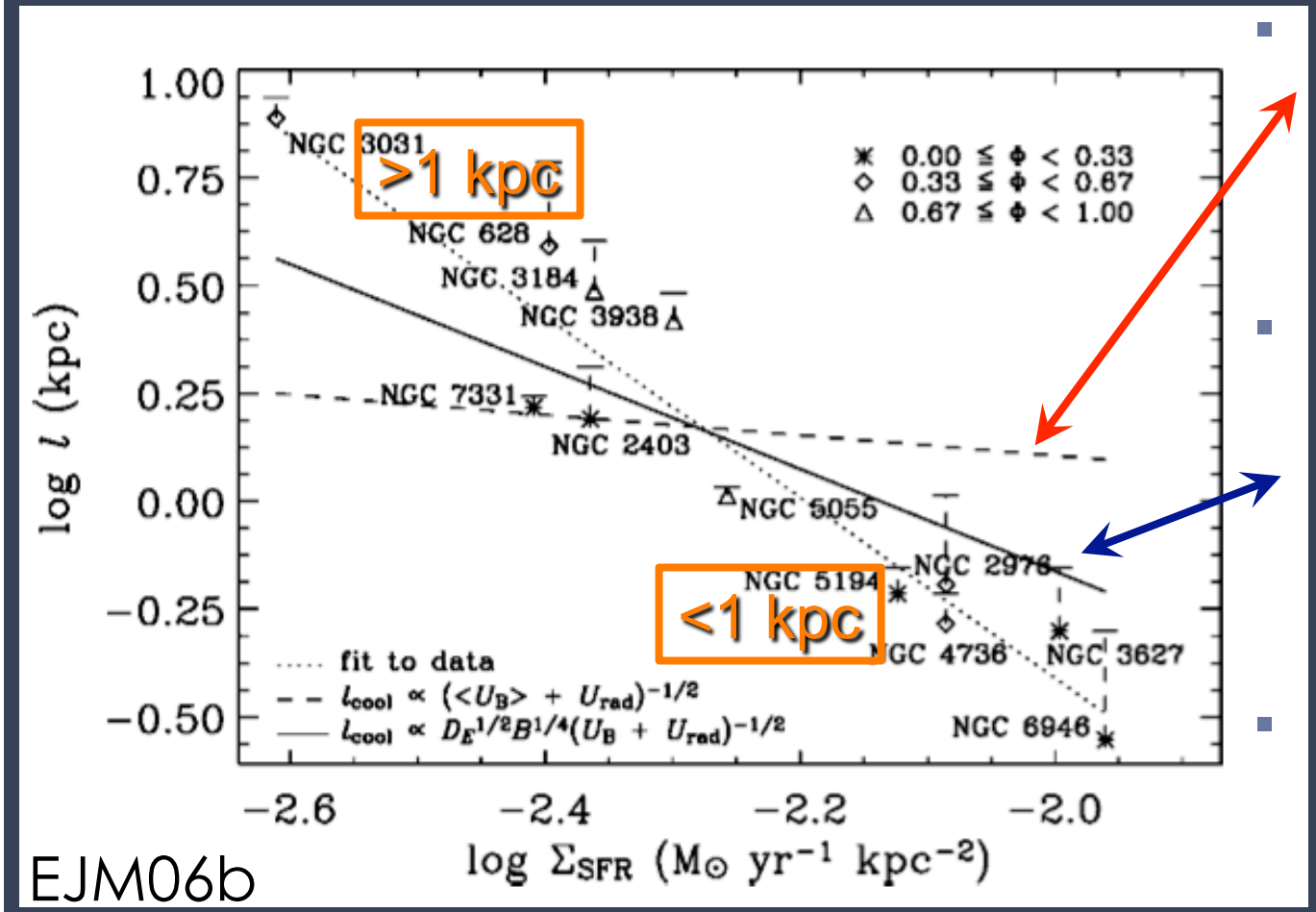






l_{diff} vs. Σ_{SFR}: Scaling-Relation Expectations

Can trend be explained by steady-state star formation?



EJM06b

- Scaling ***from synch + IC losses with fixed B***, D_E
  - Slope ~9x too shallow
- Scaling ***from synch + IC losses w/ non-fixed B***, D_E
  - β= 1/3, δ=-1
    - Extreme values
  - Slope ~ 2x too shallow
- Including Irr galaxies suggestive of CR escape
  - Low *l* & SFR/area

Conclusion: ***NO!*** CRe^-'s must be younger – *Galaxies with large values of Σ_{SFR} have likely undergone a recent episode of enhanced star formation*

Order of magnitude diffusion estimates

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

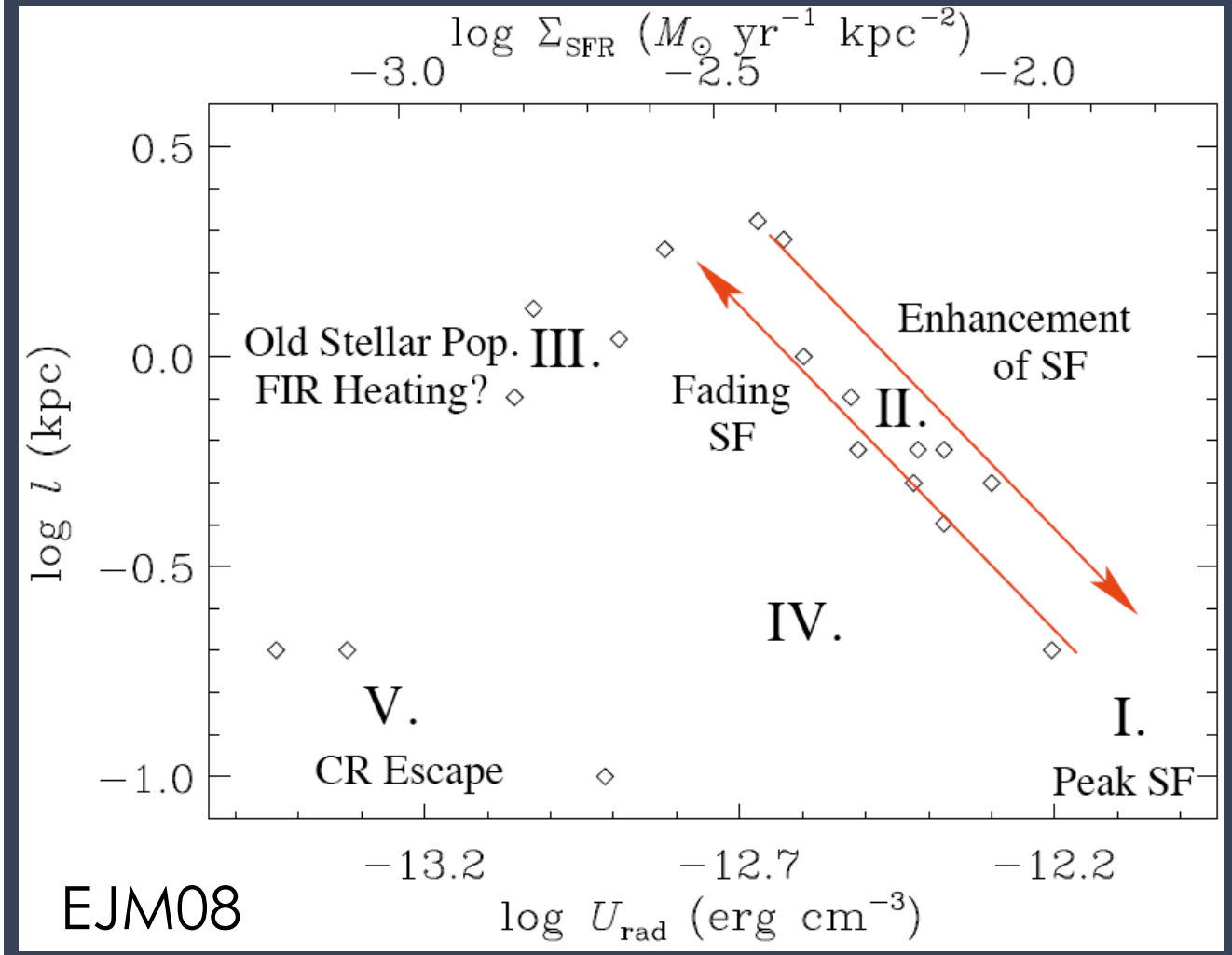
IC losses

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

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***

l_{diff} vs. Σ_{SFR}: Relating CR Propagation to SFHs



I. Peak SF: CRe's have yet to diffuse away from SF regions ***(< few Myr of recent SF)***

II. Galaxies move along this locus of pts as SF is enhanced or fades ***(>50 Myr to traverse after single burst)***

III. Low S/N? Old stellar pop. heating dust?

IV. No galaxies. In sample spirals ***SF does not completely cease*** for > 10 Myrs

V. All ***Dwarfs-Irr's*** in sample: likely scenario is enhanced ***CR escape (hi q's)***

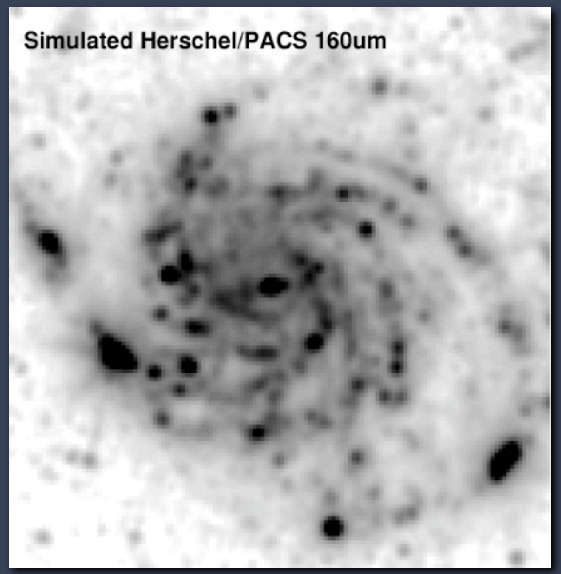
General Conclusions

- Smearing model is, empirically, the best description of FIR-RC correlation
  - Incorporates ***time-dependence*** of CRe^{-} diffusion
    - ***Sensitive to galaxy SFH***
  - For sufficiently large TIR SB, $\tau_{\text{enhancment}} \leq 100$ Myr
  - CRe's dominate SF regions/disk above/below $\log \Sigma_{SFR} \sim -2.3$
    - Galaxies w/ high SFR/area likely experienced recent enhancement of SF
- CR escape plays a significant role in Dwarf Irregulars
  - Open B-field lines allow CRs and metals stream into the IGM
- Future: ***Hershel*** will allow us to extend this work to individual star-forming complexes ***(KINGFISH; PI Kennicutt/Calzetti)*** and nearby LIRGs and ULIRGs, to *test validity of CRs in feedback models*

Future work: KINGFISH

(Key Insights on Nearby Galaxies: A Far-Infrared Study with *Herschel*)

- PI's. R. Kennicutt (EU); D. Calzetti (US)
- 526 hr approved *Herschel* OTKP
- Will build upon success of SINGS
- 61 nearby galaxies
- 2 Observational Components:
  - Imaging:
    - 6 bands from 70 - 500μm (5 - 35")
  - Spectroscopic Imaging:
    - 55 nuclear & 50 extra-nuclear star-forming regions
    - Principle atomic ISM cooling lines ([OI]63mm, [OIII]88mm, [NII]122,205mm, [CII]158mm)
- SINGS + *New* Ancillary Data:
  - *Spitzer*, optical + Hα, NIR, WSRT 22cm, THINGS (HI), BIMA-SONG (CO), IRAM-HERA (CO), CARMA (CO), Nobeyama (CO), SCUBA2 (sub-mm), *multi-frequency radio lacking!!!*

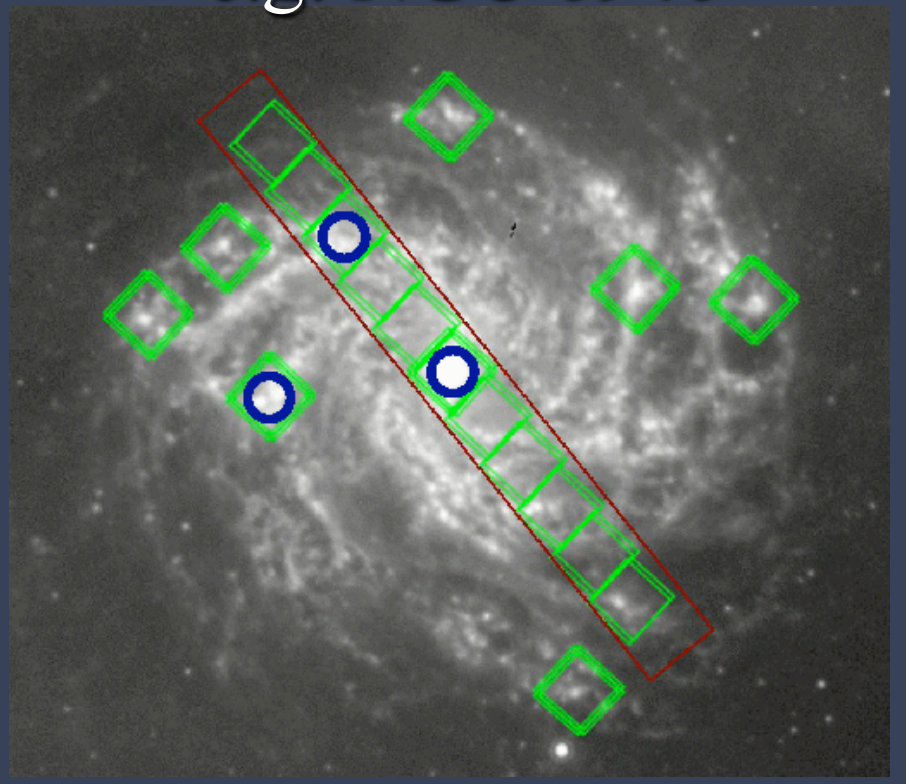


KINGFISH*ER*:

(KINGFISH - *Emission in Radio*)

- BIG THINKING for the EVLA
- PI's: E.J. Murphy & E. Schinnerer
- 3 – tiered program
  - Global spectral indices
    - ~5 bands: GBT + Effelsberg
  - Multi-frequency imaging of SINGS/KINGFISH spectroscopic-targeted star-forming regions
    - GBT + EVLA
    - RRL's as well? -- GBT Pilot Project
  - Complete multi-frequency imaging of 1 (or 2?) very nearby galaxies
    - GBT + EVLA

e.g. NGC 6946



SINGS+KINGFISH e-nucs

SINGS+KINGFISH Radial Strip

Pilot GBT RRL + 33 GHz