The FIR-Radio Correlation & Implications for GLAST Observations of Starburst Galaxies

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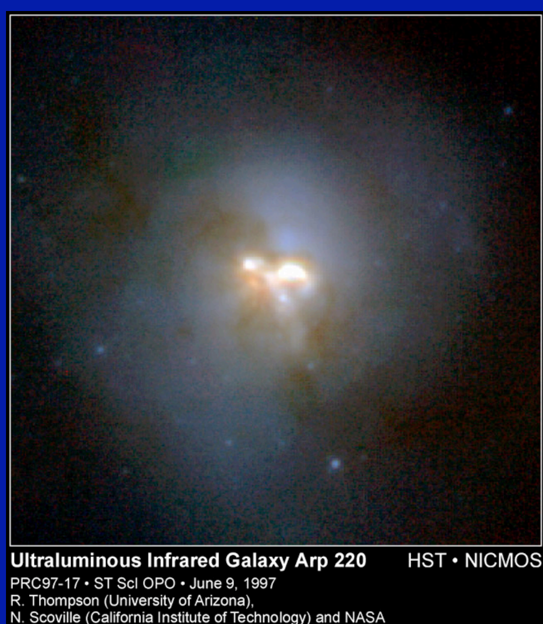
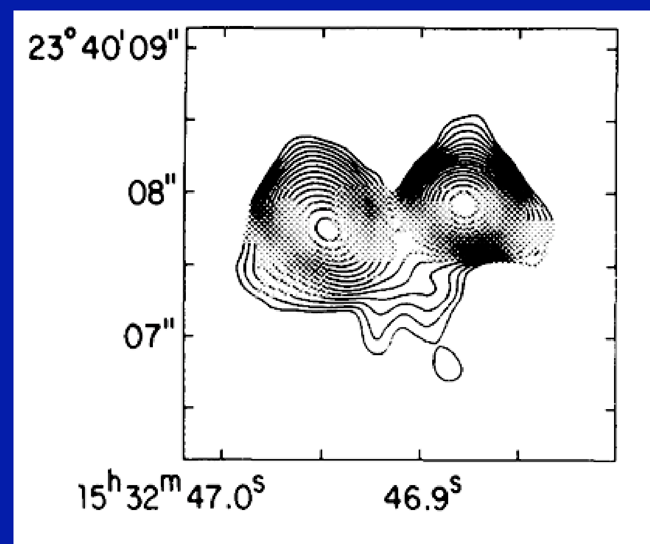
w/ Todd Thompson & Eli Waxman

Thompson, Quataert, & Waxman 2007, ApJ, 654, 219
Thompson, Quataert, et al, 2006, ApJ, 645, 186



Arp 220 w/ HST



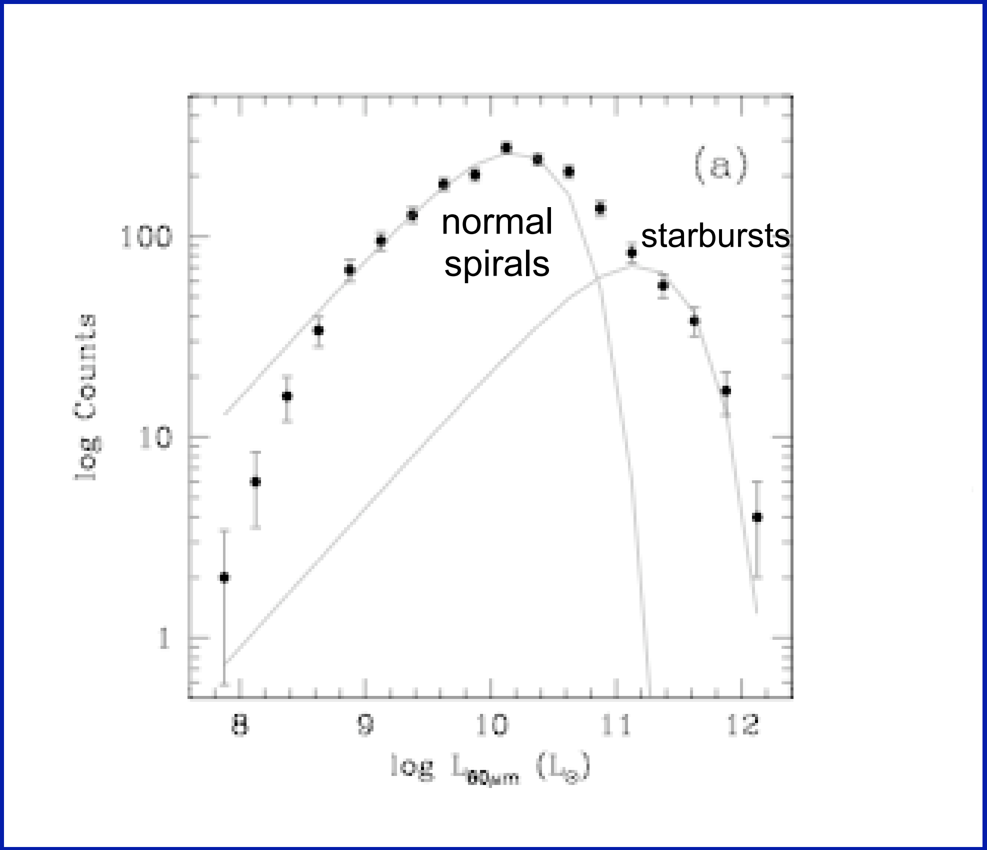
Arp 220 w/ the VLA

Outline

- Context: Starbursts & the FIR-Radio Correlation
- Direct Constraints on CRs & B-fields in Other Galaxies
  - Minimum Energy Argument (synchrotron emission)
- Rapid Electron Cooling in Starbursts
  - The Failure of the Minimum Energy Argument
  - The Origin of the FIR-Radio Correlation
- Implications for GLAST

Starbursts

Iras Number Counts



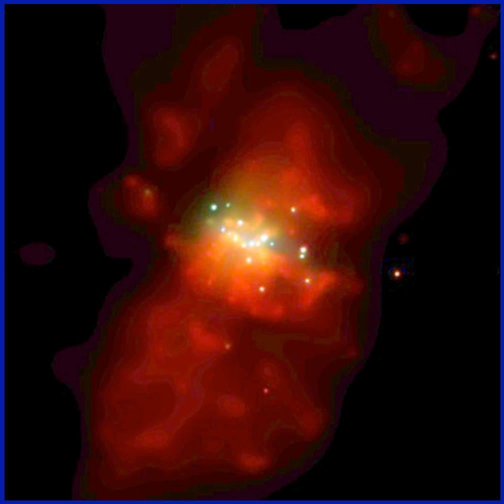
Yun et al. 2001

~ 10% of star formation at z ~ 0
majority at high z (ellipticals)

~ 10-10^3 $M_{\odot}$ yr^{-1}

often AGN activity present as well

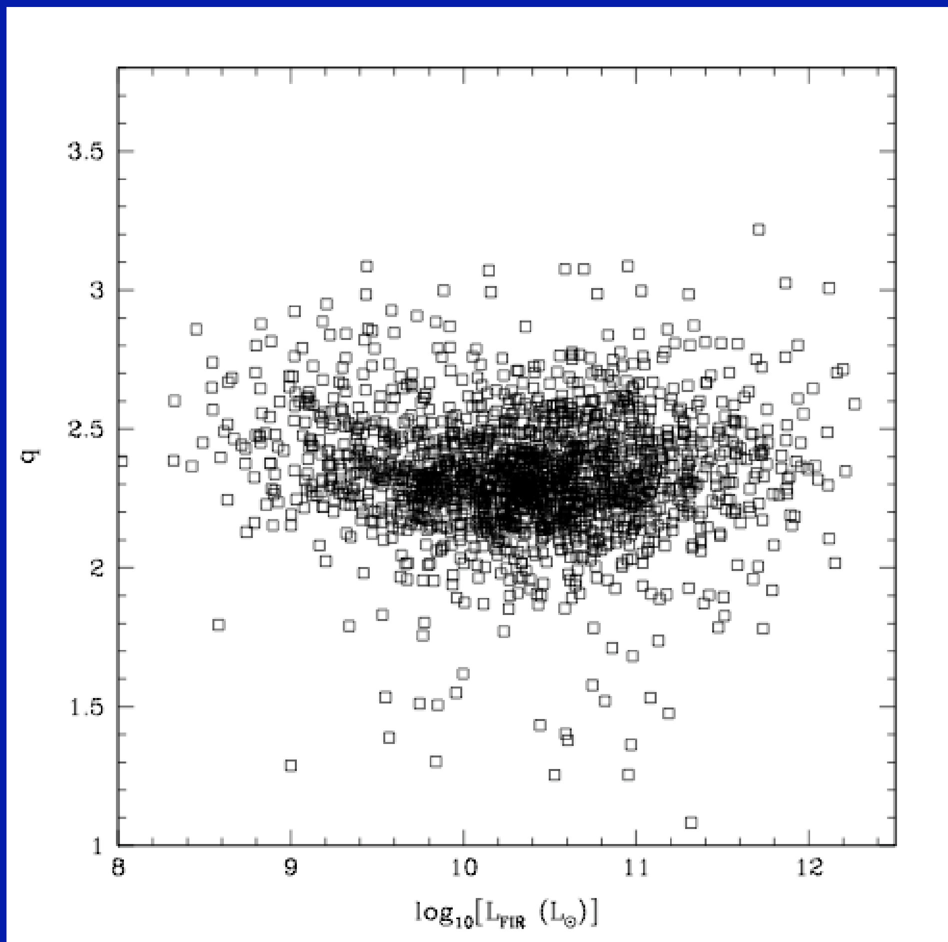
galactic winds -- thermal plasma & cosmic rays expelled (driven by SN, radiation, maybe CRs ...)



M82 w/ Chandra

The FIR-Radio Correlation

$\log_{10}[L_{FIR}/L_{radio}]$



Yun et al. 2001

$\log_{10}[L_{FIR}]$

$\nu L_\nu \approx$ **2 x 10^{-6} L_{FIR}**

(at ~ 1.4 GHz, where the radio emission is nonthermal)

UV → **FIR** (dust)

Massive Stars

supernovae

↓

cosmic rays

↓ **+ B-fields**

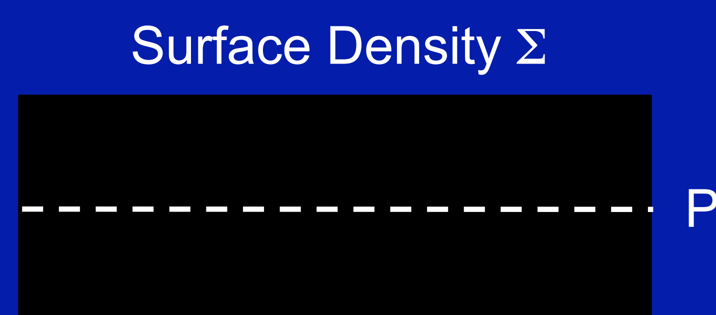
Radio (synchrotron)

Magnetic Fields & CRs in the Milky Way

(and other normal spiral galaxies)

- $\langle B \rangle \approx 5\text{-}10\ \mu G$: Faraday Rotation + Dispersion Measure, synchrotron
- energy density in CR ~ energy density in B-field

- $B^2/8\pi \sim \pi G \Sigma^2$
  - Applicable from $n \sim 1\text{-}10^7\ cm^{-3}$ (via Zeeman in molecular clouds)
  - B-field & CRs dynamically important compared to gravity (for hydro equil)



Hydro Equil: $P \approx \pi G \Sigma^2$

Estimating B-Field Strengths in Other Galaxies

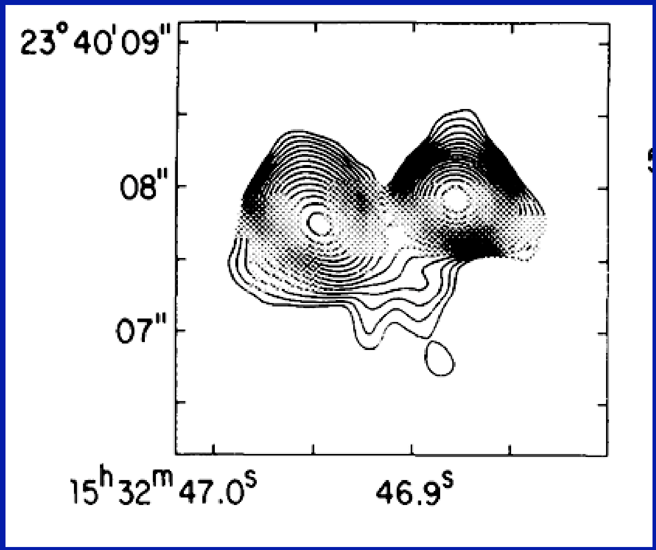
- There are (were) no Zeeman detections in other galaxies
    - Robishaw, Heiles, & Quataert (2008) detected 15 B-field components in 4 ULIRGs (OH masers)

- Use observed radio emission (synchrotron) to estimate B

- Two Observables: L_{rad} & R
  (+ radio spectrum)

  – e.g., Arp 220 ($L_{FIR} \sim 10^{12}\, L_{\odot}$):

  $L_{rad} \sim 10^{40}$ ergs/s & R ~ 100 pc



Arp 220 w/ the VLA

The Minimum Energy Estimate

$$\mathbf{P \propto \gamma^2 B^2 \quad t_{syn} \sim 10^9 B_{\mu G}^{-3/2} \nu_{GHz}^{-1/2}\ yr \quad \gamma \sim 10^4 \nu_{GHz}^{1/2} B_{\mu G}^{-1/2}}$$

$$\nu L_\nu \sim \frac{\epsilon_e V}{t_{syn}} \propto \epsilon_e V B^{3/2}$$

$$assume\ \epsilon_{tot} = \delta \epsilon_e \sim \frac{B^2}{8\pi} \quad (\delta \equiv \mathrm{p/e\ CR\ energy} \sim 10 - 100)$$

$$\rightarrow \nu L_\nu \propto \delta^{-1} B^{7/2} V \qquad \rightarrow \mathbf{B \equiv B_{min} \propto \delta^{2/7} \left(\frac{L_\nu}{V}\right)^{2/7}}$$

$$(\mathrm{minimum\ energy\ bec.}\ \epsilon_{tot} + B^2/8\pi\ \mathrm{minimized\ by}\ \epsilon_{tot} \sim B^2/8\pi)$$

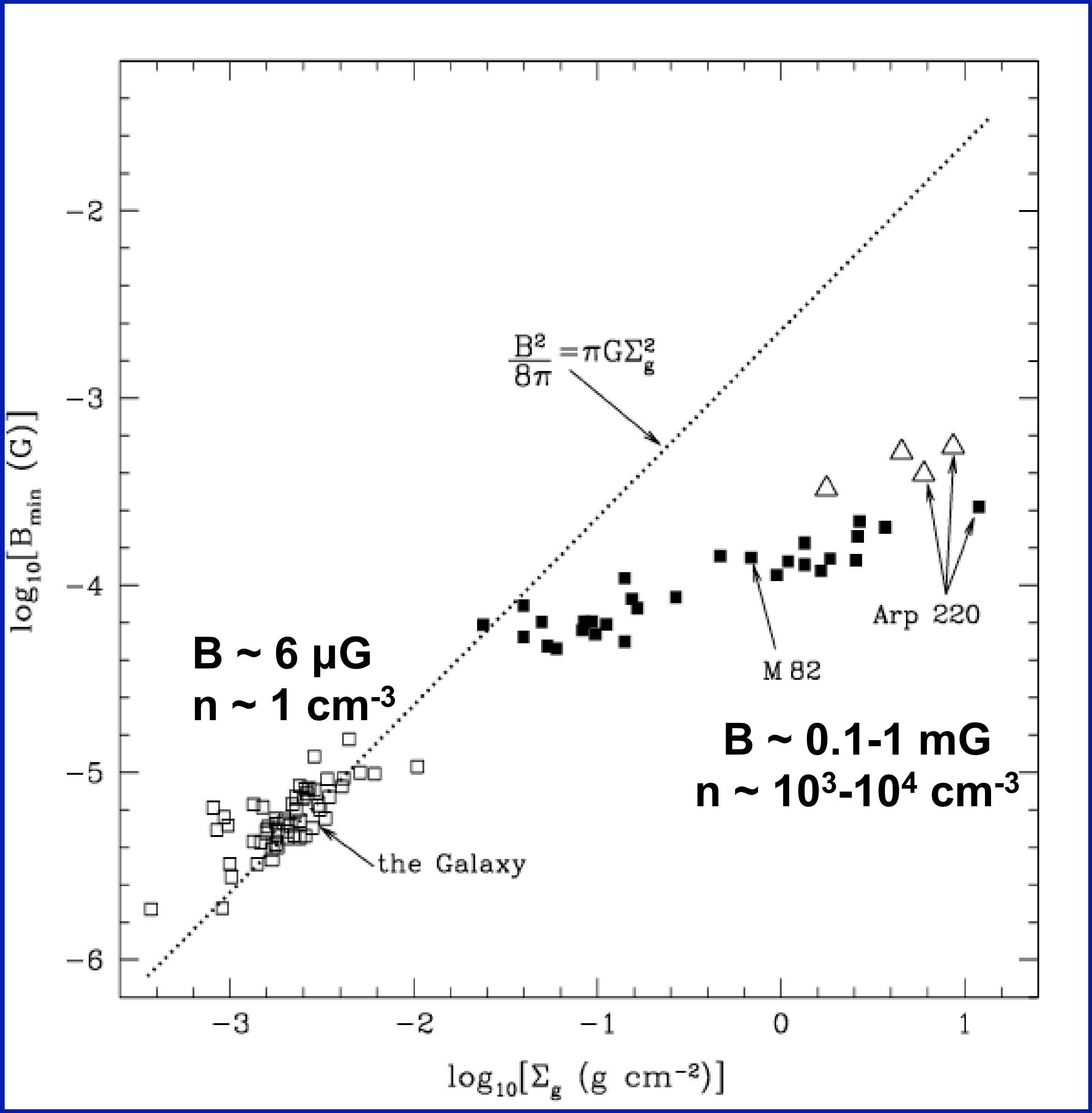
Milky Way: B_{min} ~ 5 μG, consistent with Faraday Rot.

ε_{tot} ~ $B^2/8\pi$ confirmed by γ-ray observations (pion decay from p-p interactions)

The Minimum Energy Field From Local Spirals to Luminous Starbursts

if B_{min} is correct,
B-fields & cosmic rays
are dynamically
weak compared to
gravity in starbursts

(and thus likely
unimpt. in regulating
star formation,
driving outflows, …)



The Failure of the Min. Energy Estimate

- $\varepsilon_e << B^2/8\pi$ if **$t_{cool} << t_{esc}$**

time for rel. e^- to radiate away its energy (synch & IC)

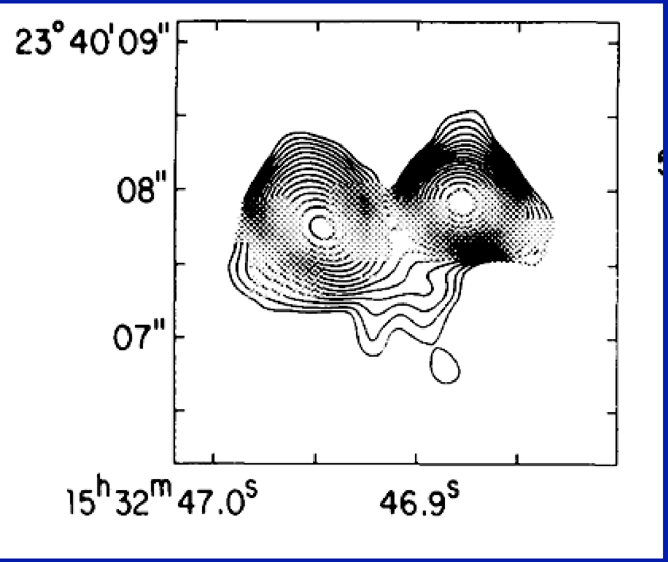
time for rel e^- to escape the galactic disk

- if **$t_{cool} << t_{esc}$, $B >> B_{min}$**
  - $L_{radio} \sim \varepsilon_e B^{3/2}$: $\varepsilon_e \downarrow \Rightarrow B \uparrow$
- MW: $t_{syn} \sim t_{IC} \sim t_{esc} \sim 10^7$-$10^8$ yr
- Arp 220: $t_{syn} \sim$? (B ~ ?)

  $t_{IC} \sim 5000$ yr

  $t_{esc} \sim$?; $t_{esc} > R/v_w \sim 3\times10^5$ yr

  $t_{IC} << t_{esc}$

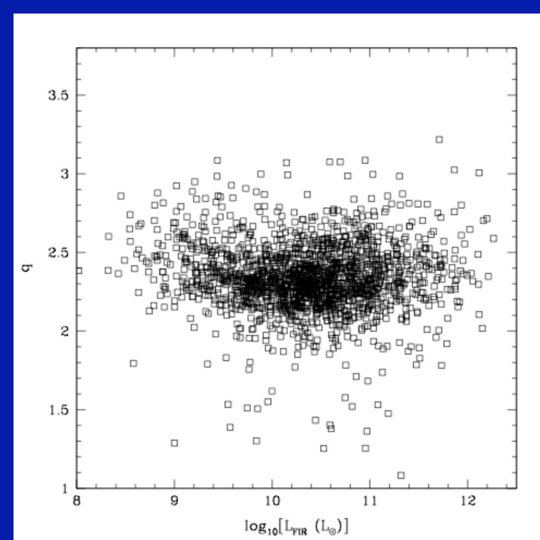


Implications of $t_{syn} << t_{esc}$

- $t_{syn} << t_{esc}$: e's radiate all the energy supplied by SN shocks

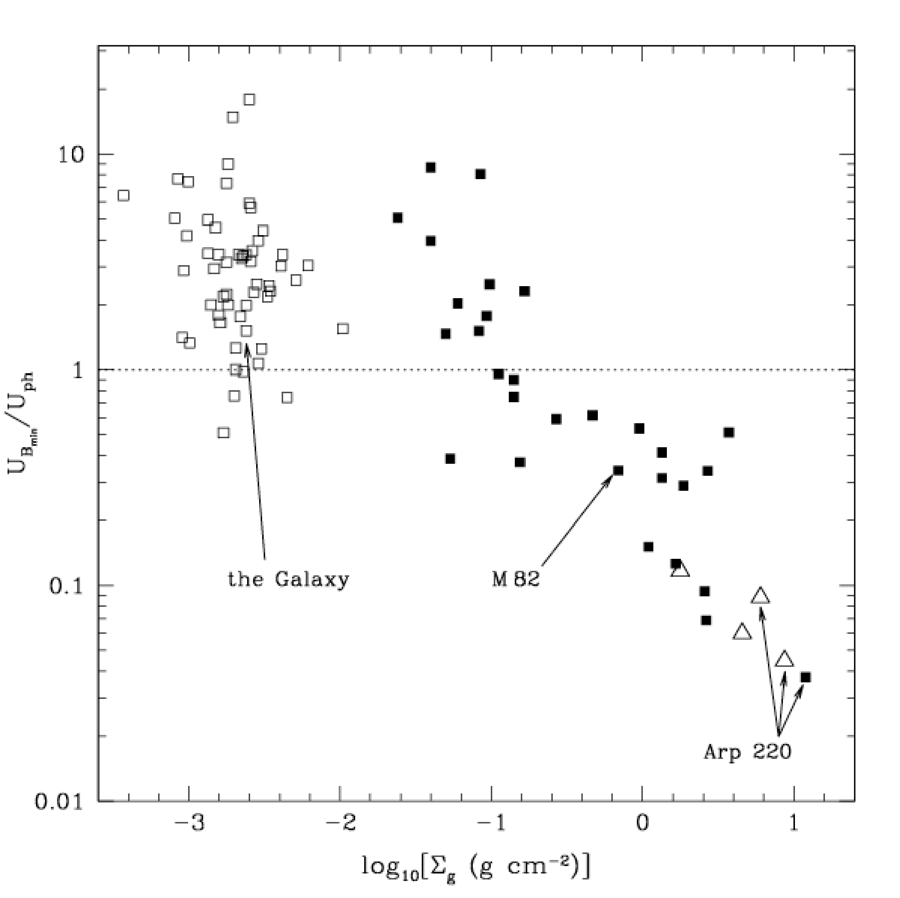
$$\nu L_\nu \sim \dot{\mathbf{E}}_{\mathbf{e}} \propto \mathrm{SN\ Rate} \propto \mathbf{L_{FIR}}$$

- Clean explanation for **linear** FIR-Radio Correlation
  - “calorimeter theory” (Volk 1989)
- $\nu L_\nu \approx 2 \times 10^{-6} L_{FIR}$ ***requires*** $t_{syn} \leq t_{esc}$
  - $\Rightarrow$ ~ 1% of SN energy supplied to CR e's
  - consistent w/ inferences from SN shocks
  - $t_{esc} > t_{syn}$ requires tremendous fine tuning



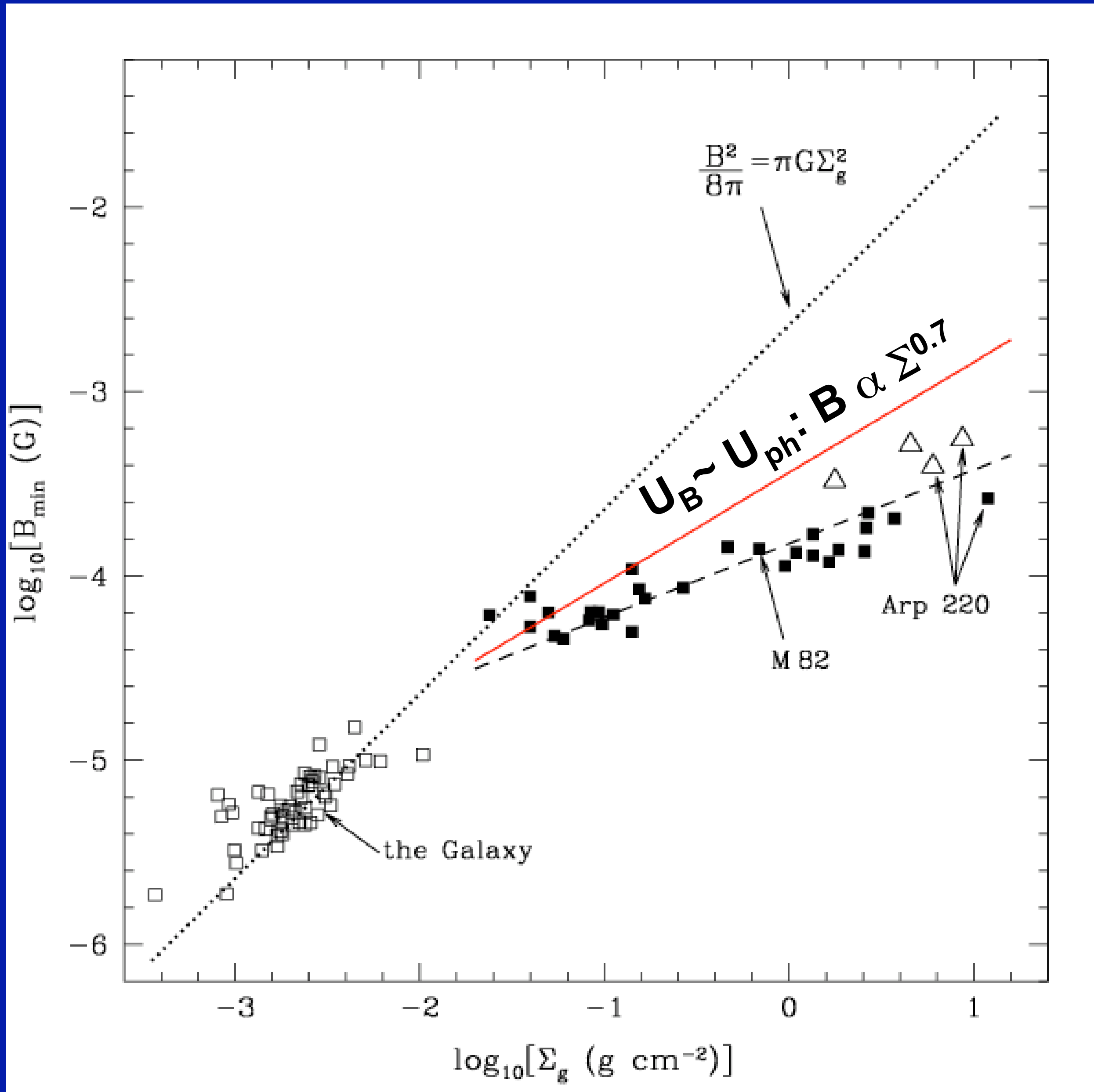
Synchrotron vs. IC cooling

- Conditions in Starbursts & FIR-Radio favor $t_{cool} << t_{esc}$
  - B_{min} is an underestimate



- FIR-Radio also Requires

  $t_{syn} < t_{IC}$, i.e., **$U_B > U_{ph}$**

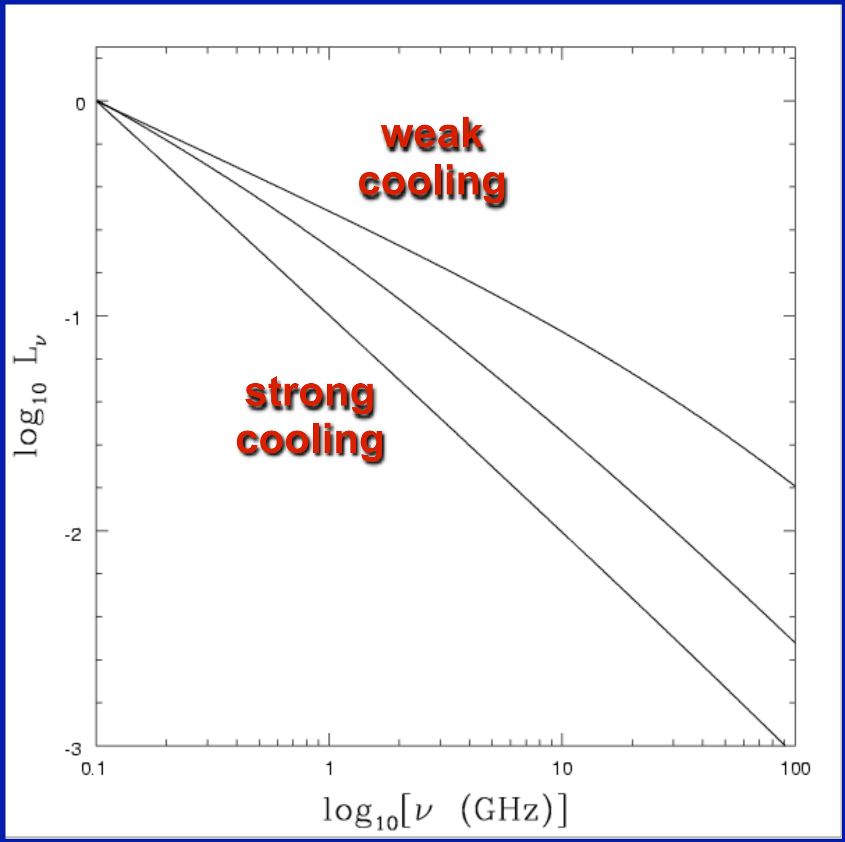


$\frac{B^2}{8\pi} = \pi G \Sigma_g^2$
$U_B \sim U_{ph}$: B α $\Sigma^{0.7}$
M 82
Arp 220
the Galaxy
$\log_{10}[B_{min}$ (G)]
$\log_{10}[\Sigma_g$ (g cm^{-2})]
−2
−3
−4
−5
−6
−3
−2
−1
0
1

Objection to $t_{cool} << t_{esc}$: Radio Spectra Do not Show Evidence of Strong Synchrotron Cooling

(e.g., Condon 1992)

- Injected: $dn/d\gamma \propto \gamma^{-2} \Rightarrow L_\nu \propto \nu^{-1/2}$ (weak cooling)
- Cooled: $dn/d\gamma \propto \gamma^{-3}$ ($t_{cool} \propto \gamma^{-1}$) $\Rightarrow L_\nu \propto \nu^{-1}$ (strong cooling)

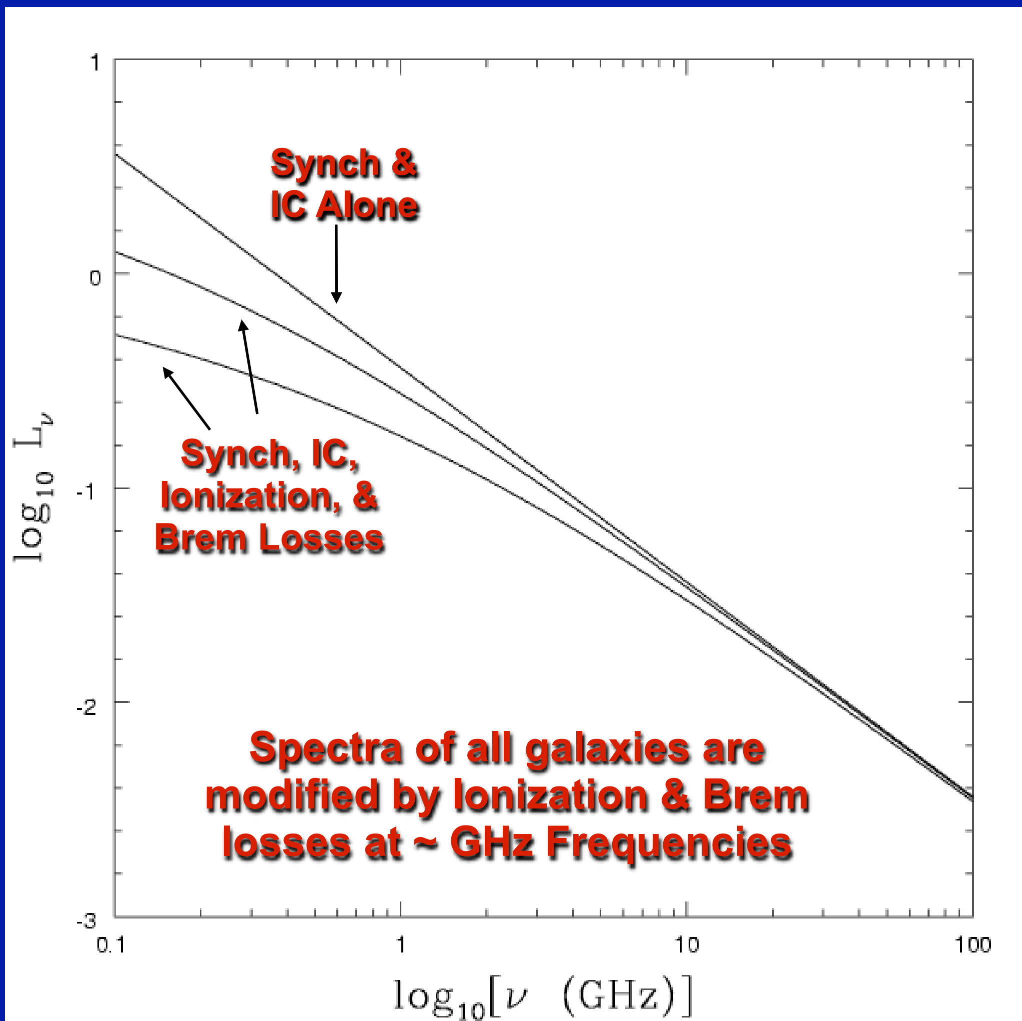


Observed

$L_\nu \propto \nu^{-\alpha}$

$\langle\alpha\rangle \approx 0.75$

at ~ GHz



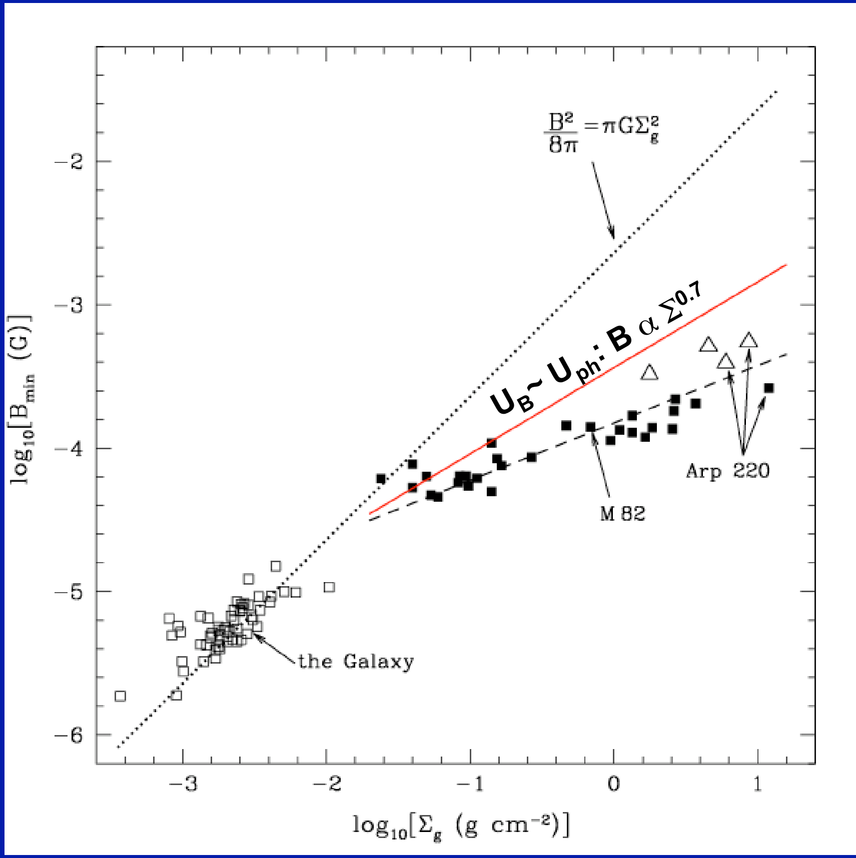
Simple Model: CR e's interact with gas at ~ mean ISM density

- lose energy to ionization of neutral H & relativistic bremssrahlung on nuclei, in addition to synch & IC

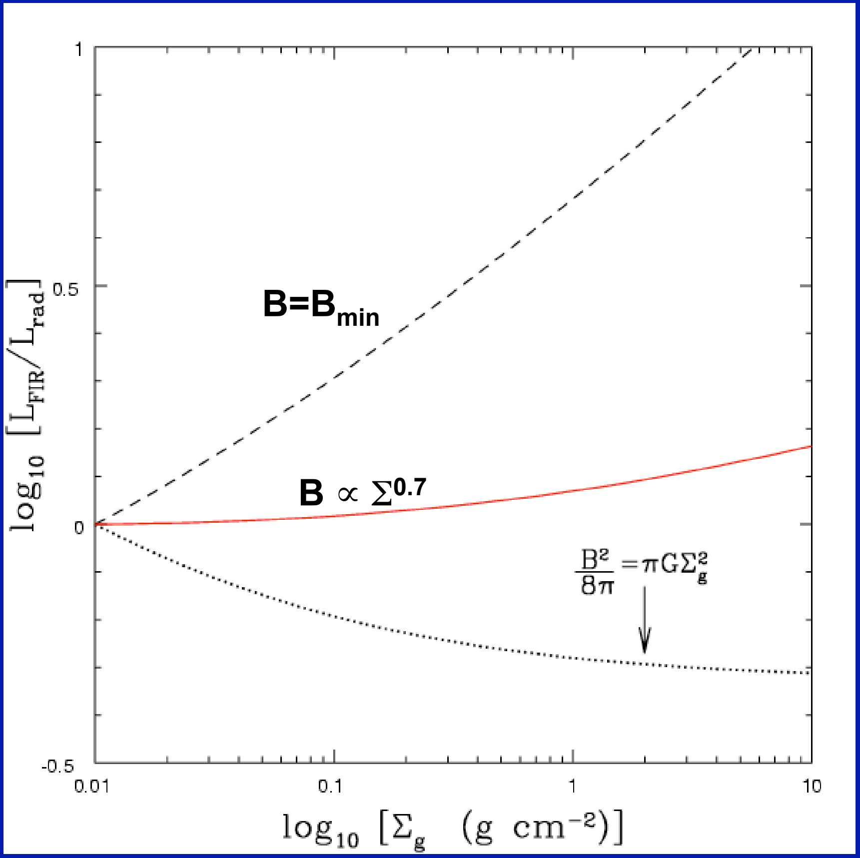
$$t_{\rm ion} \sim \mathbf{10^8 n^{-1}} \left(\frac{\gamma}{\mathbf{2000}}\right) \ \mathrm{yr}$$

$$t_{\rm brem} \sim 3 \times 10^7 \, n^{-1} \, \mathrm{yr}$$

Linearity of FIR-Radio?



assume CR e's interact with gas at ~ mean ISM density and escape is neglected



B > B_{min} & CR e-s interact w/ gas at ~ <n>: radio spectra in accord with observations and linear FIR-Radio correlation

Gamma-ray Emission

- Proton losses: **pion production** t_{pion} (protons) ~ t_{ion} (electrons): both ~ n^{-1}
- $p + p \rightarrow \pi^0 \rightarrow$ gamma-rays $\Rightarrow$ **strong > 100 MeV γ-ray sources**
- constraint: $p + p \rightarrow \pi^{+/-} \rightarrow e^{+/-}$ (secondary leptons)
- if **all** the radio emission is from secondaries, FIR-radio correlation $\Rightarrow$

$$\nu L_\nu \text{ (GeV)} \approx 10^{-5}\, L_{FIR}$$

(IC and brem likely smaller by a factor of ~ 4)

Glast Detection Limit

TABLE 1
PROPERTIES OF LOCAL STARBURST & STAR-FORMING GALAXIES

Object Name	D[a] (Mpc)	Σ_g[b] (g cm^{-2})	$S_{60\mu m}$[c] (Jy)	$S_{100\mu m}$[d] (Jy)	S_{TIR}[e] (Jy)	$S_{1.4GHz}$[f] (mJy)	νF_ν(GeV)[g] 10^{-11} GeV cm^{-2} s^{-1}	Data Refs.
NGC 3034 (M82)...	3.3	0.69	1313.5	1355.4	8302.4	7657.0	73	4,2,3
NGC 253...............	3.5	0.47	997.7	1857.8	7755.8	5594.0	68[h]	1,2,3
IC 342....................	4.4	0.02	255.9	660.7	2311.6	2250.0	20	1,2,3
NGC 2146.............	12.6	0.14	144.5	204.2	1009.8	1074.6	8.9	1,2,3
NGC 3690.............	42.2	0.04	119.7	118.6	748.0	678.3	6.6	4,2,3
NGC 1808.............	14.2	0.09	104.5	147.2	729.4	529.0	6.4	1,2,3
NGC 1365.............	18.6	0.09	84.1	185.4	704.2	530.0	6.2	7,8,3
Arp 220..................	76.6	12.0	107.4	118.3	691.9	326.9	6.1[i]	4,2,3
NGC 891...............	7.4	0.09	61.1	198.6	623.4	701.0	5.5	6,2,3
NGC 3627.............	10.2	0.04	56.2	144.9	507.3	458.0	4.5	4,2,3
NGC 660...............	12.0	0.08	65.5	103.8	477.4	387.0	4.2	4,2,3
NGC 3628.............	11.2	0.02	48.4	121.9	431.9	525.0	3.8	10,3
NGC 1097.............	18.0	0.10	46.7	116.1	414.0	415.0	3.6	4,2,3
NGC 3079.............	15.9	3.7	50.2	103.5	407.8	849.0	3.6	4,2,3

nearby starbursts are detectable with GLAST & perhaps HESS

NGC 253, M82, IC 342

(maybe NGC 1068)

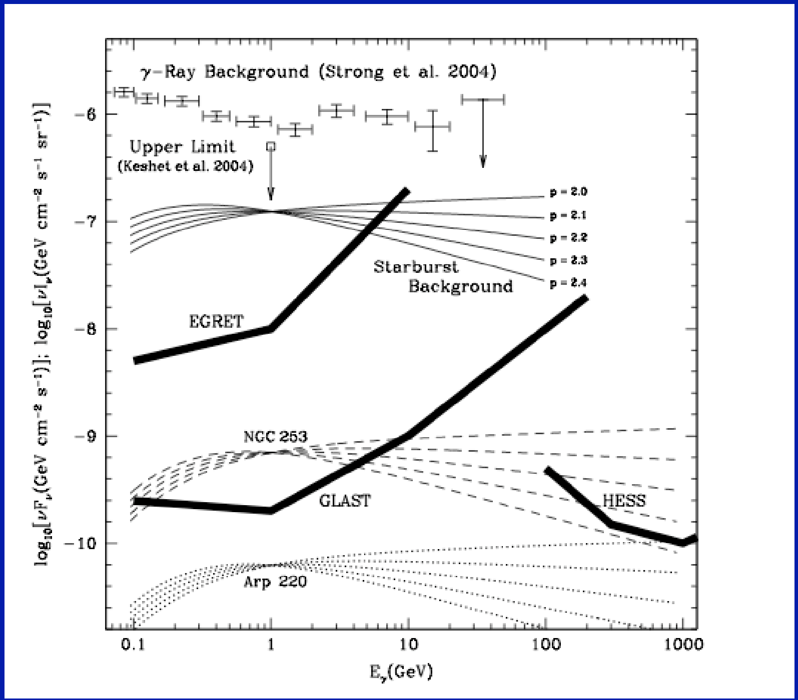
What GLAST will Teach us

- 1 GLAST detection ⇒ Secondary leptons impt for Radio

  ⇒ SN & CRs couple to Dense ISM

  - not all just vented by Galactic Winds
  - ionization & brem losses impt for e-

  ⇒ Starbursts acct for ~25% of γ-ray BG



Summary

- $B_{min} \Rightarrow B^2/8\pi << \pi G \Sigma^2$ in starbursts
  - suggests B-field & CR dynamically unimportant (compared to gravity)
- Rapid e^- cooling in starbursts invalidates B_{min}
  - $t_{cool} << t_{esc}$ (IC & synch)
  - Origin of the FIR-Radio correlation ("calorimeter theory")
  - B_{min} is an underestimate by at least a factor of ~ 3-5 ($U_B > U_{ph}$)
  - Ionization & Bremstrahlung losses modify radio spectra
- GLAST Observations Crucial Probe of ISM & CR Physics
  - Impt of secondaries?
  - M82, NGC 253, IC342 most promising sources