Radio, γ-Ray, and Neutrino Emission from Star-Forming Galaxies

M82 core
Marvil
JVLA 6GHz

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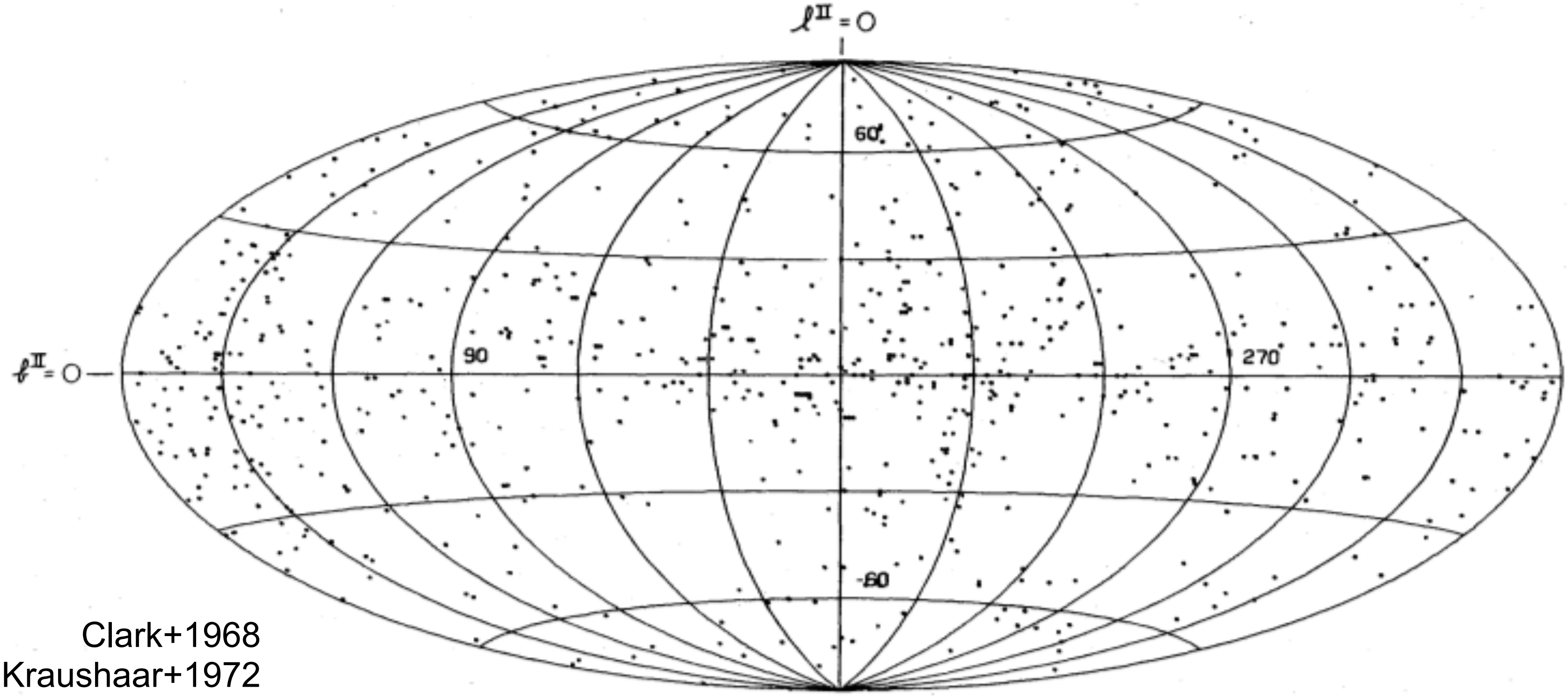
CRs are injected, emit, & escape.

- Primary CR *p* & *e* injected into the ISM by supernovae. ~10% & ~1% of 10^{51} ergs/SN, respectively.
- CRs scatter in the Galaxy ($\lambda \sim 0.1$-1 pc), diffuse outwards. May also escape via advection in a galactic wind.
- Collisions between CR *p* & ISM produce pions, decay to γ-rays, secondary $e^{\pm}$, and ν's. ~90% of CR *p*'s escape the Galaxy.
- Primary CR e^{-} and secondary $e^{\pm}$ cool in the ISM via synchrotron, IC of starlight (also bremsstrahlung & ionization).

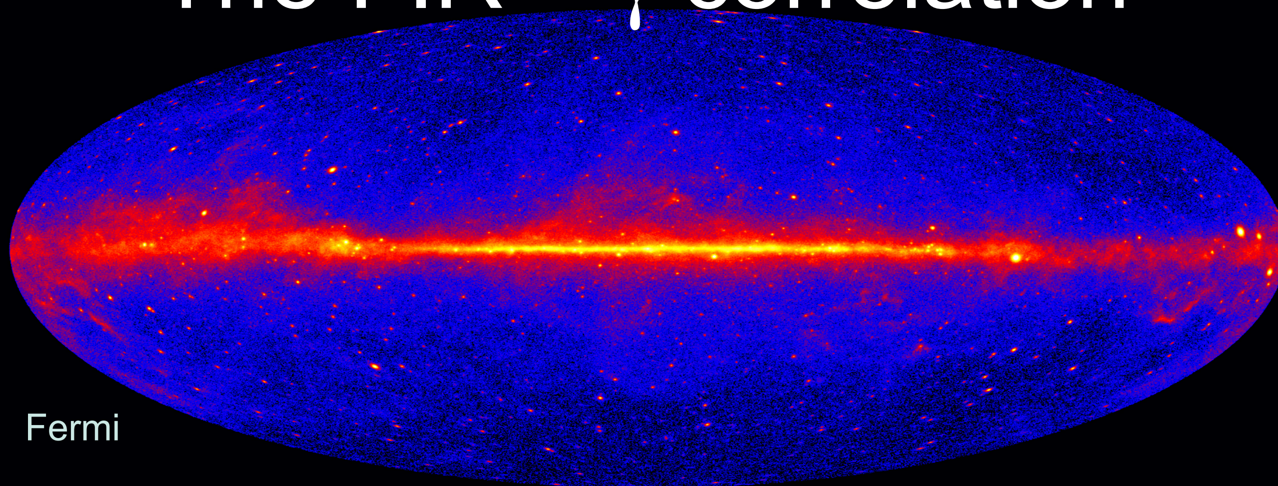
Orbiting Solar Observatory 3: 621 events, E > 50 MeV.

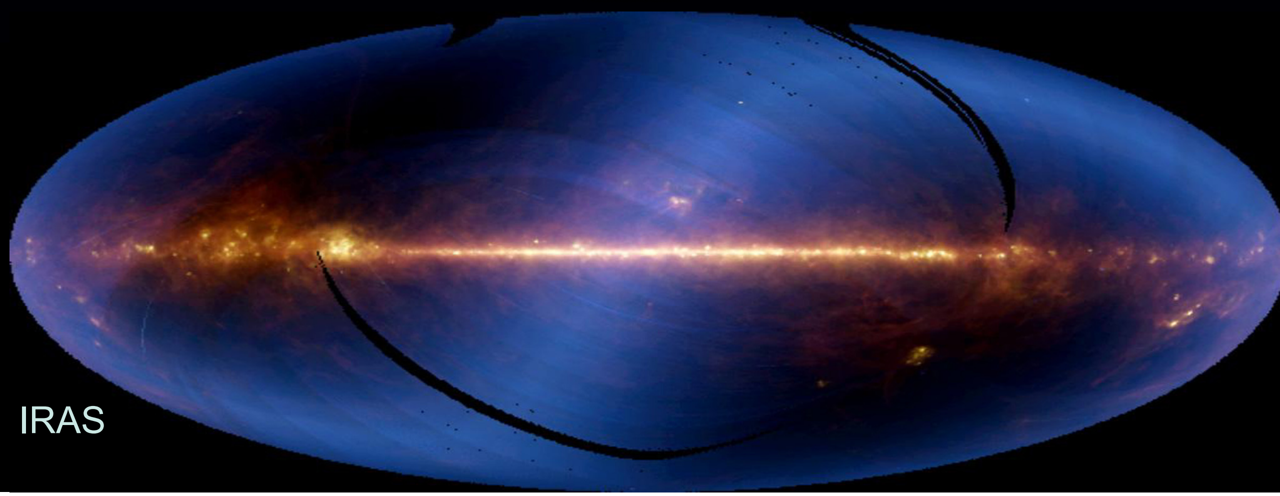


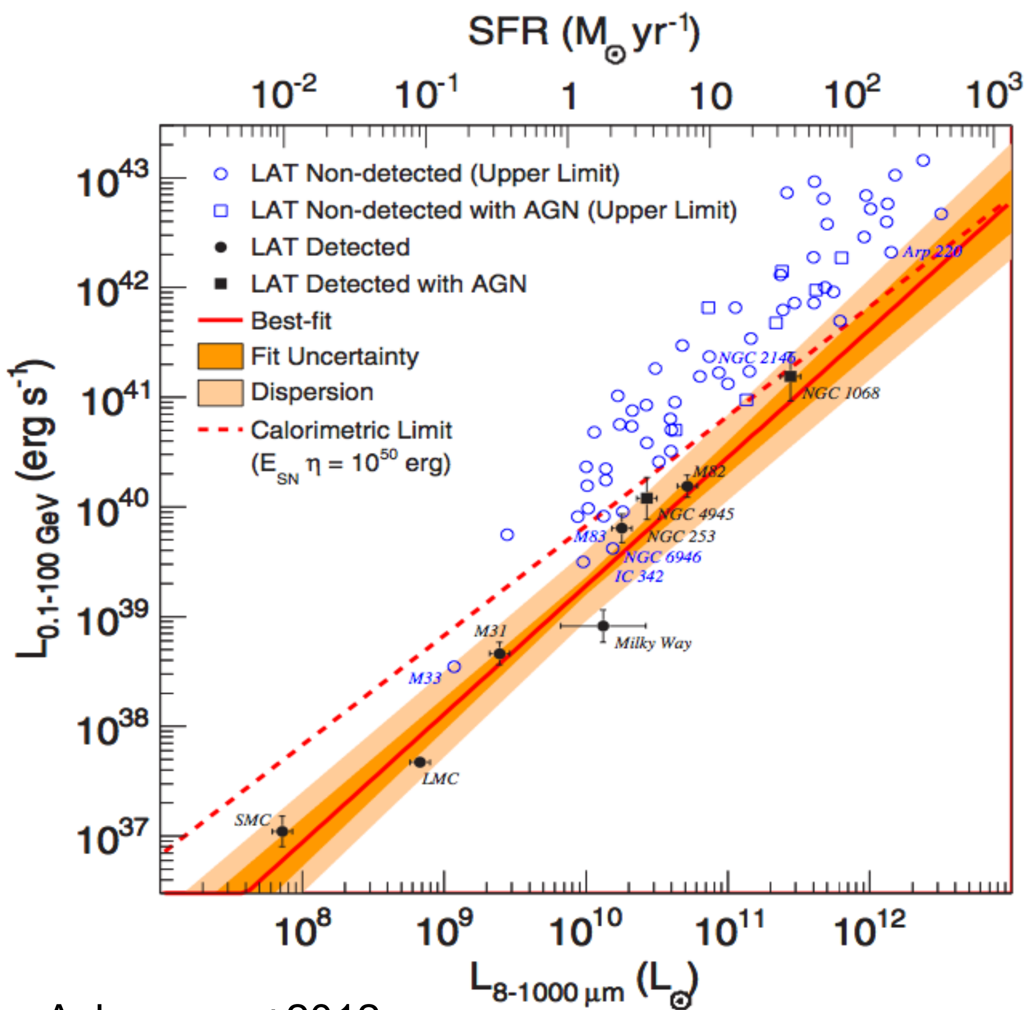
Clark+1968
Kraushaar+1972

Strong correlation with the Galactic Plane.

The FIR – γ correlation







Ackermann+2012

FIR – γ correlation

$$L_{\rm FIR} \sim L_{\rm GeV}^{1.15}$$

GeV photons from primary CR proton pion production (we think)

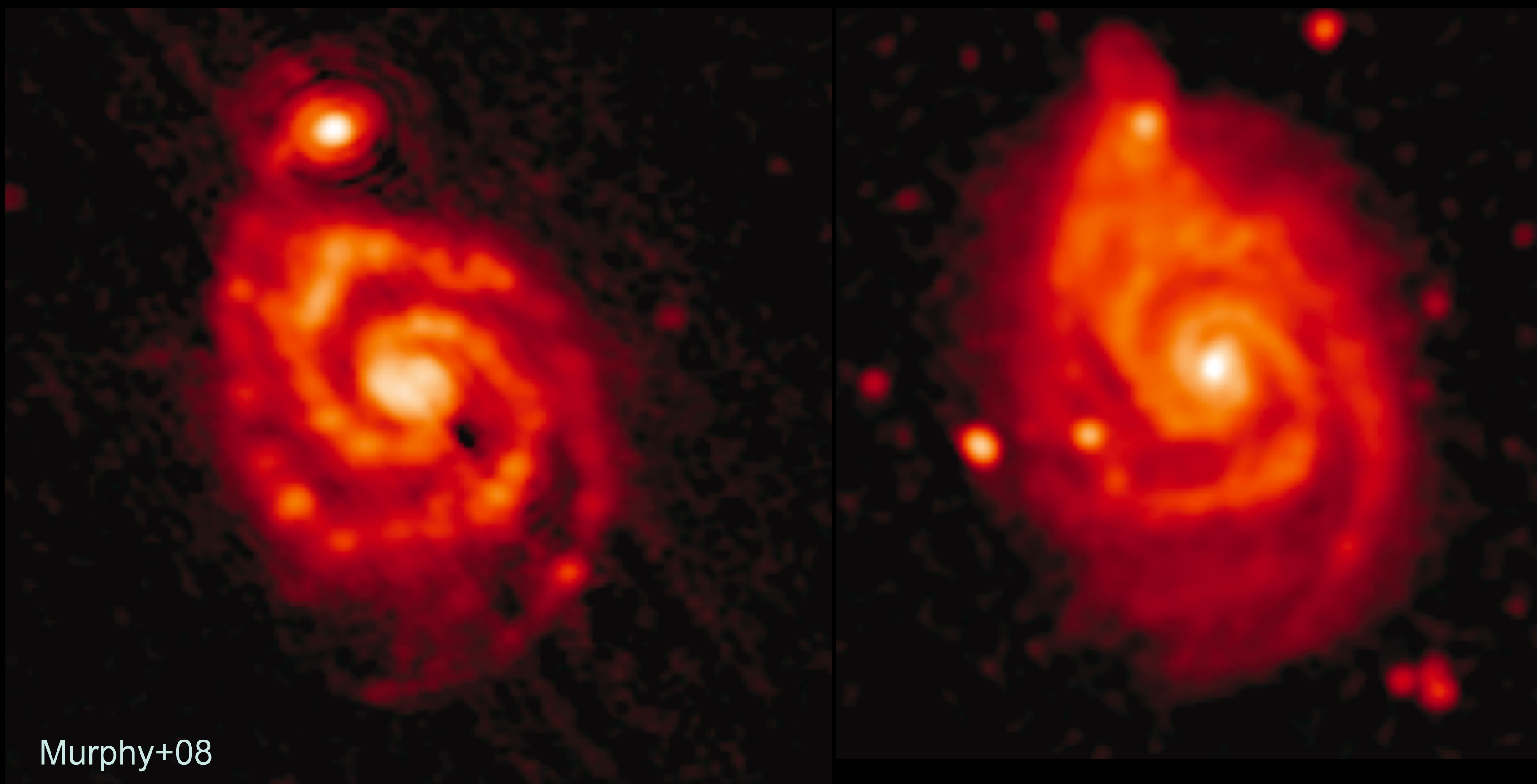
$$\pi^0 \rightarrow 2\gamma$$

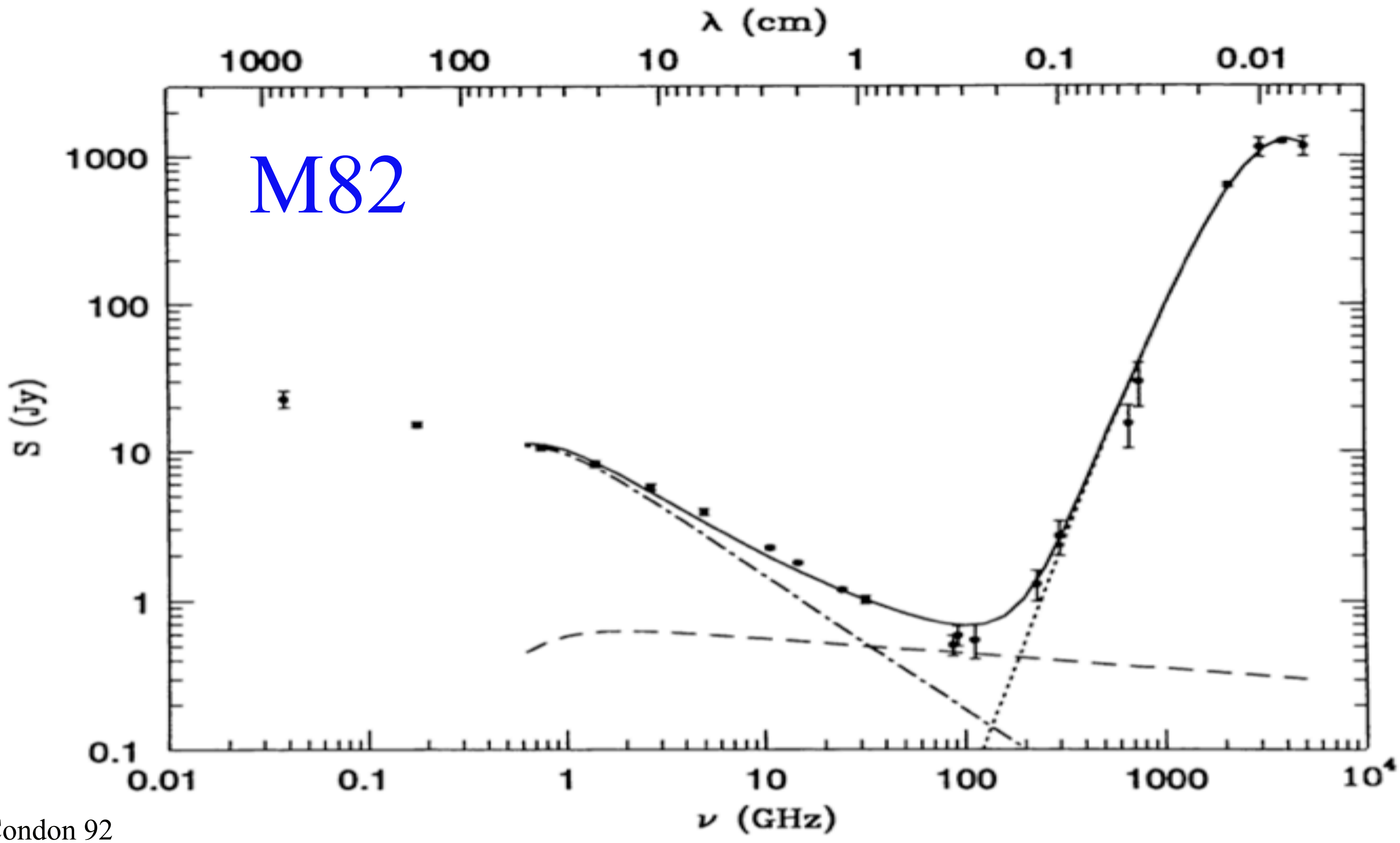
Some spatially resolved, some not.

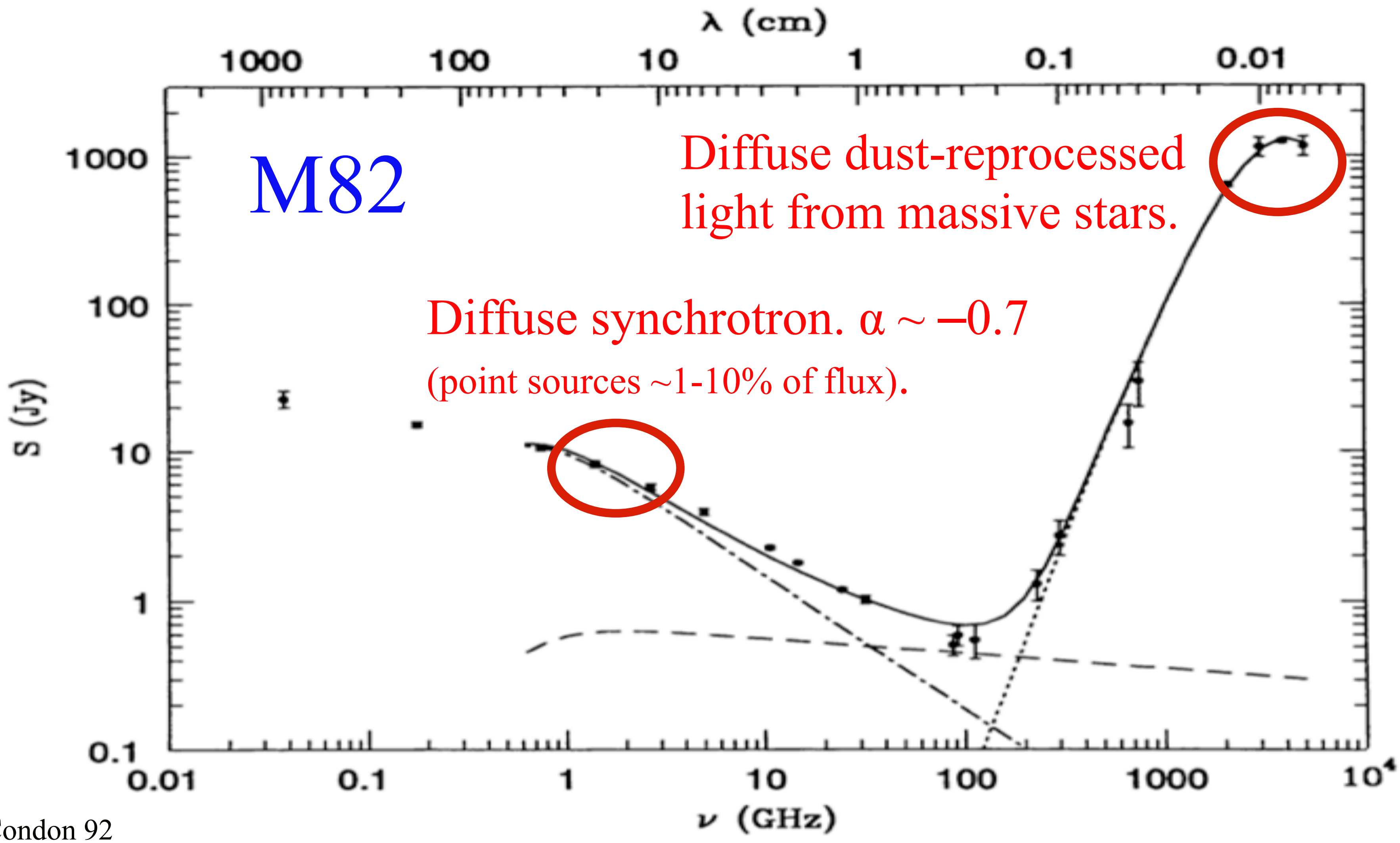
New detections: Arp 220, Circinus

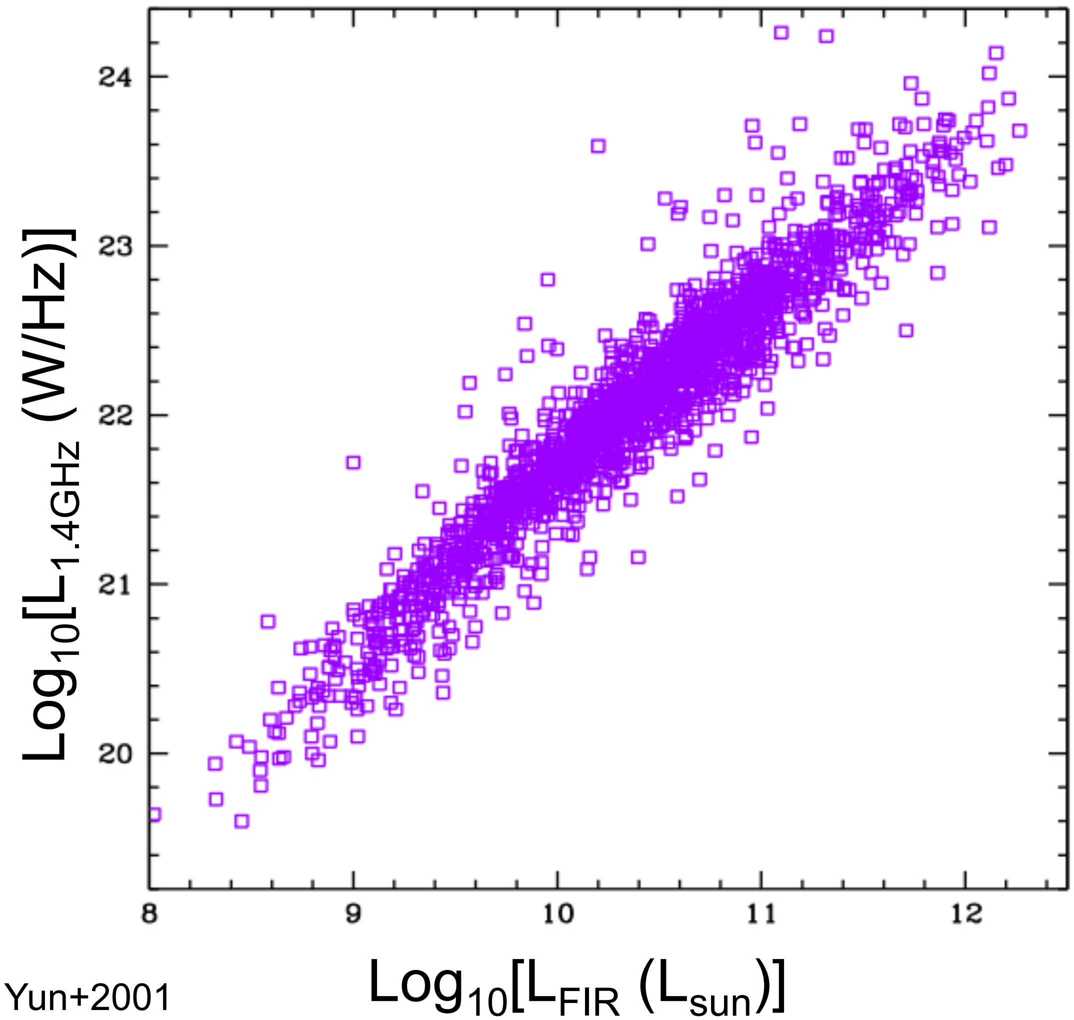
Veritas, HESS: M82, NGC 253

The FIR – radio correlation




λ (cm)
1000
100
10
1
0.1
0.01
M82
S (Jy)
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000
10⁴
ν (GHz)
Condon 92


λ (cm)
1000
100
10
1
0.1
0.01
M82
Diffuse dust-reprocessed light from massive stars.
Diffuse synchrotron. α ~ –0.7
(point sources ~1-10% of flux).
1000
100
10
1
0.1
S (Jy)
0.01
0.1
1
10
100
1000
10^4
ν (GHz)
Condon 92



Yun+2001

FIR – radio correlation

$$L_{\rm GHz} \sim 10^{-6} L_{\rm FIR}$$

GHz synchrotron from high energy leptons

$$E_e \sim 3\,{\rm GeV}\,\nu_{\rm GHz}^{1/2}\,B_{10\,\mu G}^{-1/2}$$

Holds locally on ~100 pc scales.
Holds at high-redshift.

Van der Kruit+71,73
De Jong+85, Helou+85
Yun+01, Bell 03, Murphy+08
Ivison+10, Smolcic+17

CRs, *B*, feedback, & other messengers

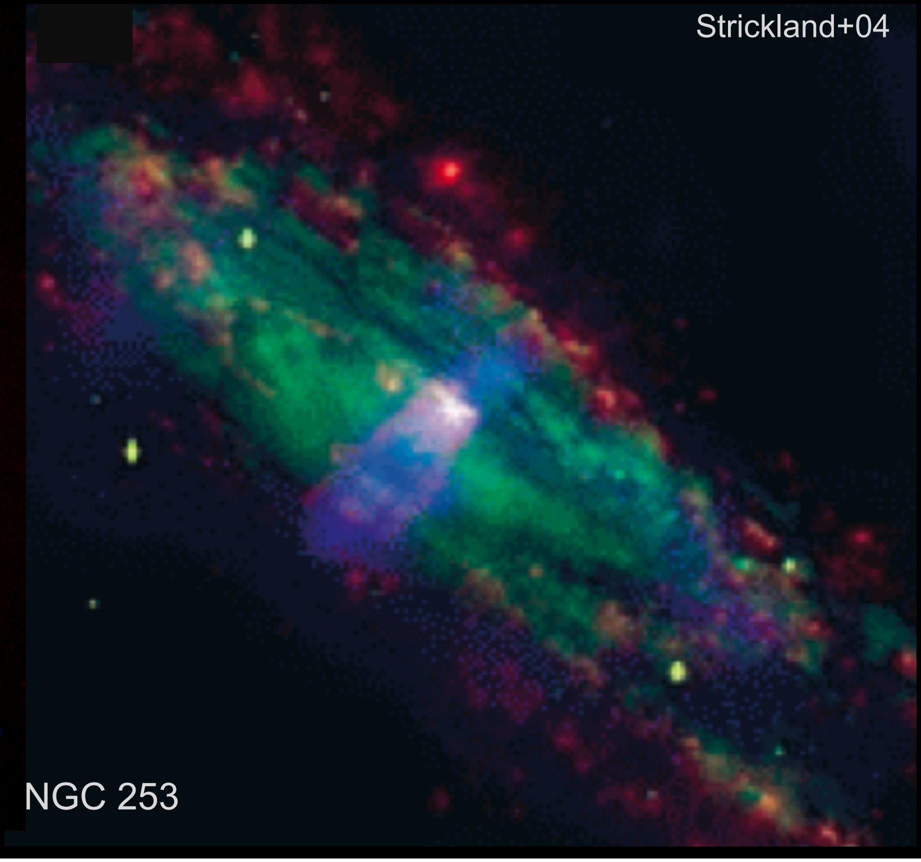
- The radio- and γ-ray – FIR correlations provide strong constraints on the CRs and magnetic fields of galaxies, from normal galaxies to starbursts.
- In the Milky Way (Boulares & Cox 1990)

$$\pi G \Sigma_g^2 \sim \rho \delta v^2 \sim U_{\mathrm{CR}} \sim U_B \sim F/c$$

Fundamental questions:

- Can CRs drive winds, affect galaxy formation? (Ipavich 1975; Breitschwerdt+1991)
- Is B dynamically important in all galaxies? (For Arp 220, B ~ 0.03G is needed!)
- Are the CR populations of other galaxies similar to MW?
- Do star-forming galaxies dominate the γ-ray background at 1 GeV?
- Can they be the source of the ~ PeV neutrinos?

Normal star-forming galaxies at high-z have winds and similar physical conditions to local starbursts (gas density, SFR/area).
Cosmic Ray Driven winds? (talks by Farber, Gianciti, Buckman, …)



Dynamic range.

4 – 5 dex in gas density.

$$t_{\rm brem}\,,\; t_{\rm ion}\,,\; t_{\pi} \sim n^{-1}$$

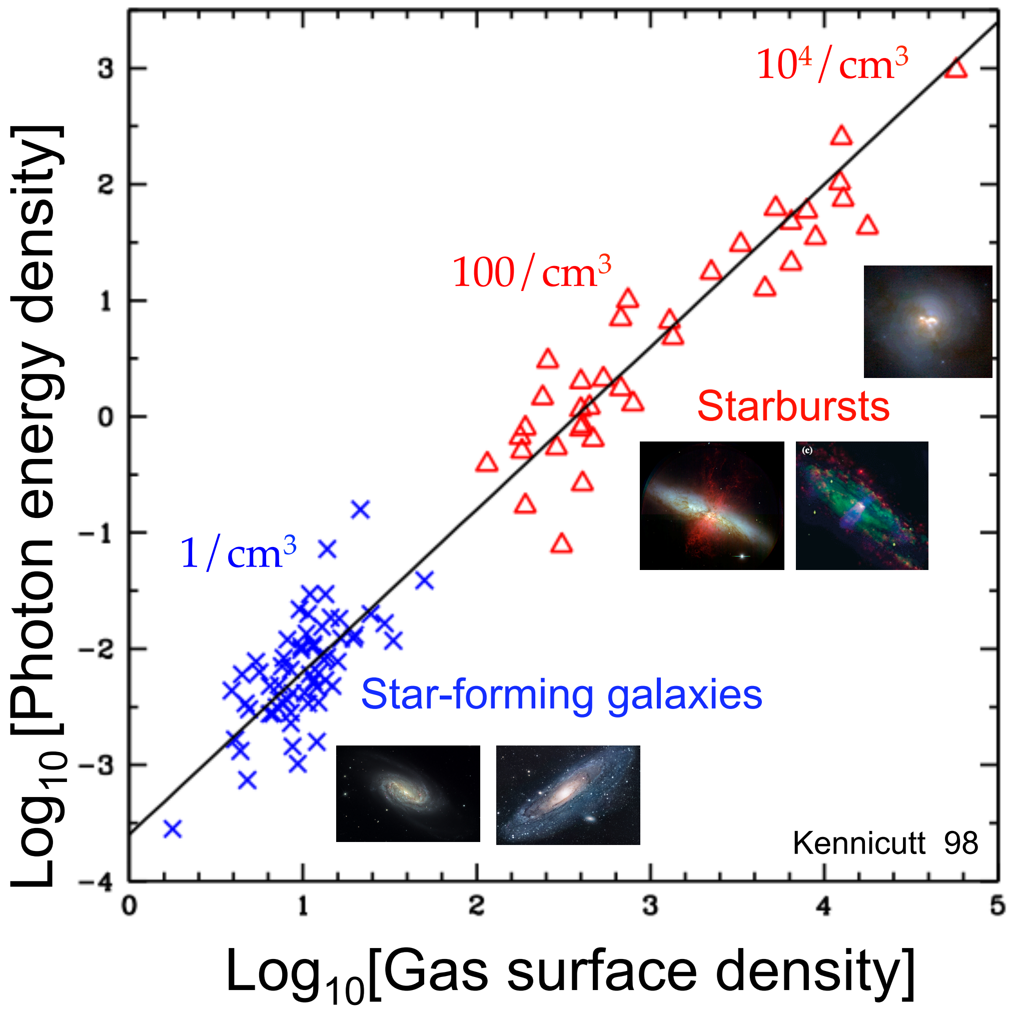
7 dex in photon and (probably) magnetic energy density

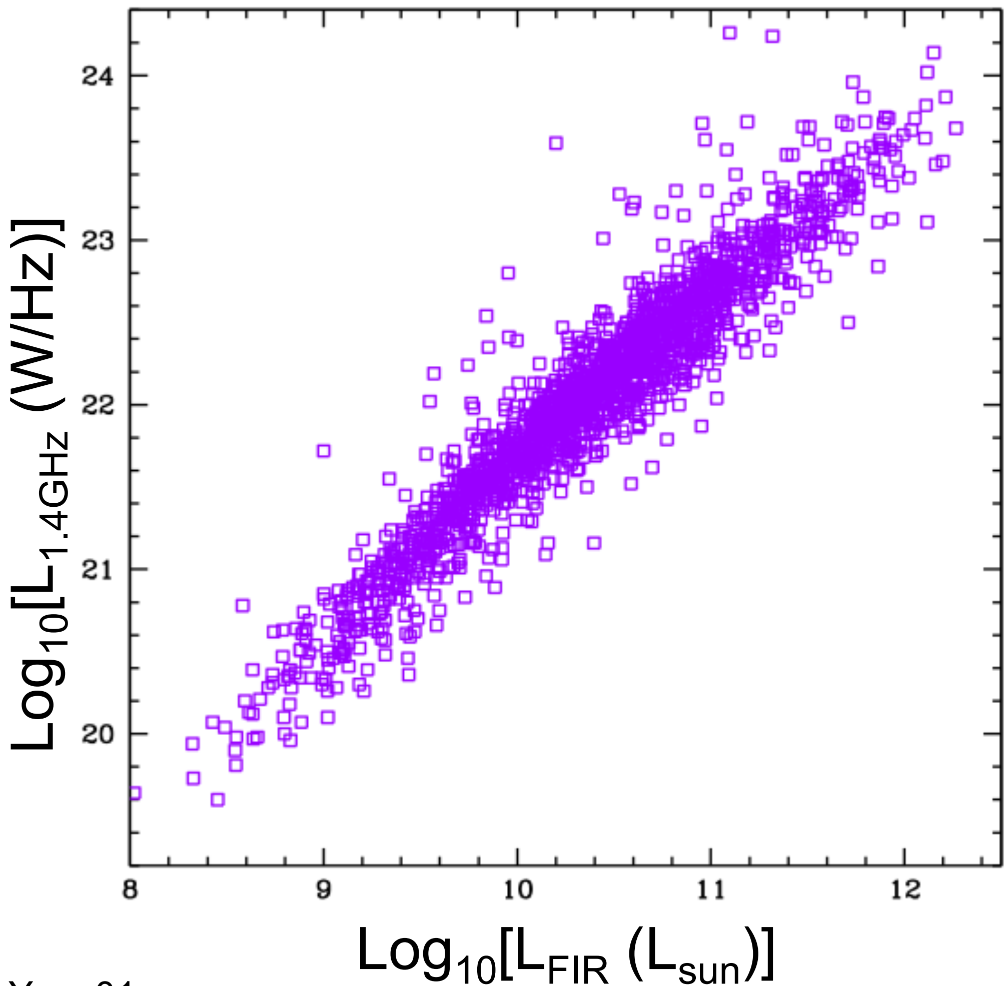
$$t_{\rm IC} \sim U_{\rm ph}^{-1}$$

$$t_{\rm synch} \sim U_{\rm B}^{-1}$$

6 dex in total pressure.

$$P_{\rm hydro} \sim \pi G \Sigma_g \Sigma_{\rm tot}$$





Yun+01

A first theory:

(Völk 89; Lisenfeld+96)

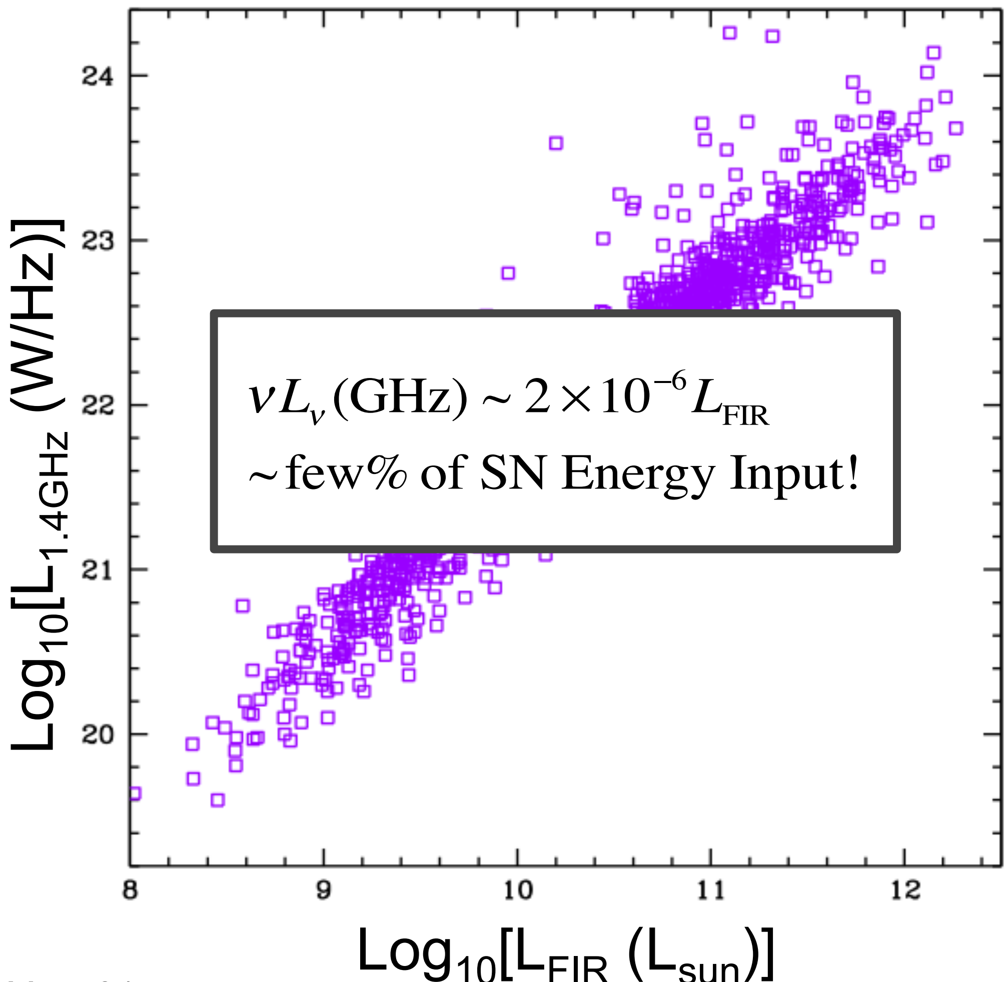
Massive stars dominate light:
UV → FIR.

Massive stars produce SNe, generate primary CRe's, suffer synchrotron losses, producing GHz continuum.

Electron Calorimetry: synchrotron cooling dominates and cooling time shorter than escape time:

$$t_{synch} << t_{escape}$$

Across the whole diversity of galaxies.



Yun+01

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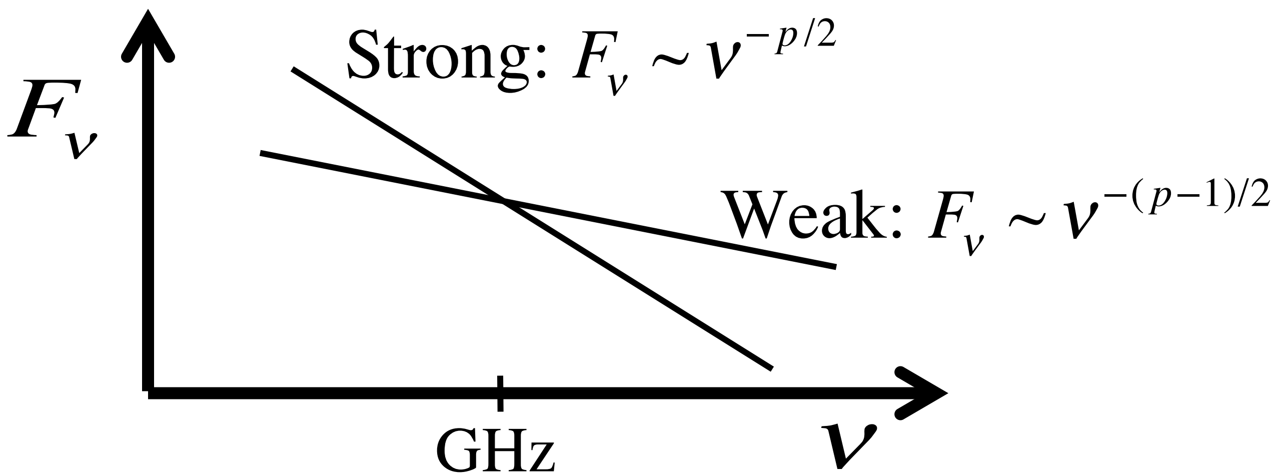
Across the whole diversity of galaxies.

But ...

e^- calorimetry predicts steep spectra.

If synchrotron (or IC) dominates cooling, the radio spectra of galaxies should be steep



Not observed. Typically, $F_\nu \sim \nu^{-0.7}$ not $\nu^{-1.1}$.

Yet, calorimetry must hold

(for some systems, anyway).

Calorimetry holds.

- Consider Arp 220. *B* is unknown, but photon energy density is known. The IC cooling time for GHz-emitting e^- is ultra-short:

$$t_{\rm IC} \sim 3\times 10^3\,{\rm yr}\left(\frac{10^{-6}\,{\rm ergs/cm^3}}{U_{ph}}\right)\left(\frac{B}{3{\rm mG}}\right)^{1/2}$$

- For $t_{escape} < t_{IC}$, CRs would have to be advected out of Arp 220 at velocity > 20,000 km/s. No. Thus, $t_{cool} \ll t_{escape}$.
- Electron Calorimetry! Rapid cooling limit. $U_{CRe} \ll U_{\mathbf{B}}$ (Thompson+06)
- Galaxy too: t_{cool} ~ few × 10^7 yrs ~ $t_{escape} = t_{diffusion}$. (Strong+10)
- **But, how do we then solve the spectral index problem?**

Bremsstrahlung & Ionization.

Bremsstrahlung & Ionization.

- Flatten the radio spectrum if t_{Brem}, t_{Ion} ~ t_{synch}, t_{IC}.

$$t_{\rm Brem} \sim 3\times10^{3}\,{\rm yr}\left(\frac{10^{4}\,{\rm cm}^{-3}}{n}\right) \qquad t_{\rm Ion} \sim 2\times10^{3}\,{\rm yr}\left(\frac{10^{4}\,{\rm cm}^{-3}}{n}\right)\left(\frac{3{\rm mG}}{B}\right)^{1/2}$$

- (Arp 220 has $\langle n \rangle \sim 10^4$ cm^{-3}, so CR e^- must interact with average density gas.)
- This flattens the radio spectra of galaxies (Thompson+06).
- **What about the FRC? Dense starbursts should be radio dim!** The power in e^- is going to bremsstrahlung & ionization!

Bremsstrahl

- Flatten the radio spectru

$$t_{\rm Brem} \sim 3\times10^3\,{\rm yr}\left(\frac{10^4\,{\rm cm}^{-3}}{n}\right)$$

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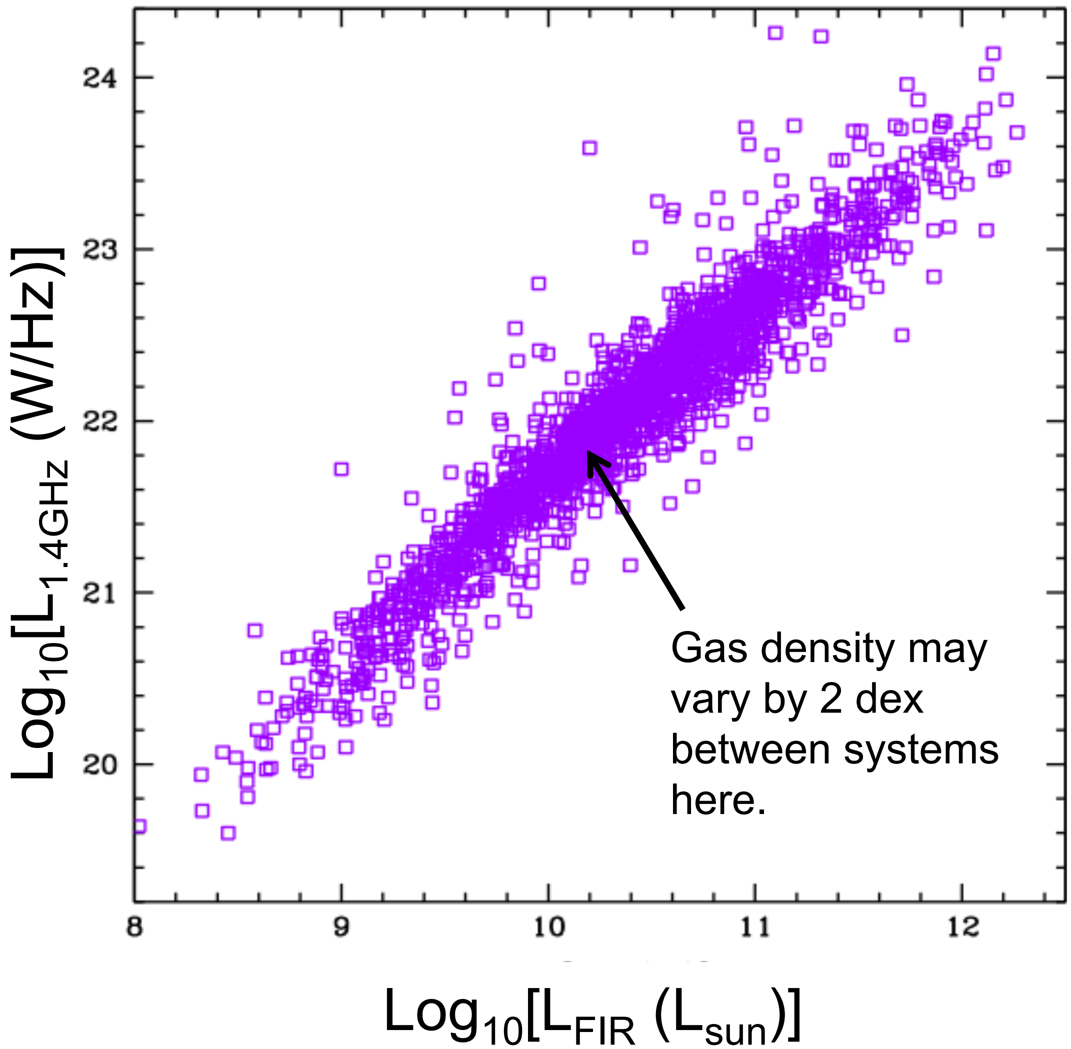


Secondary $e^{\pm}$ from CR protons.

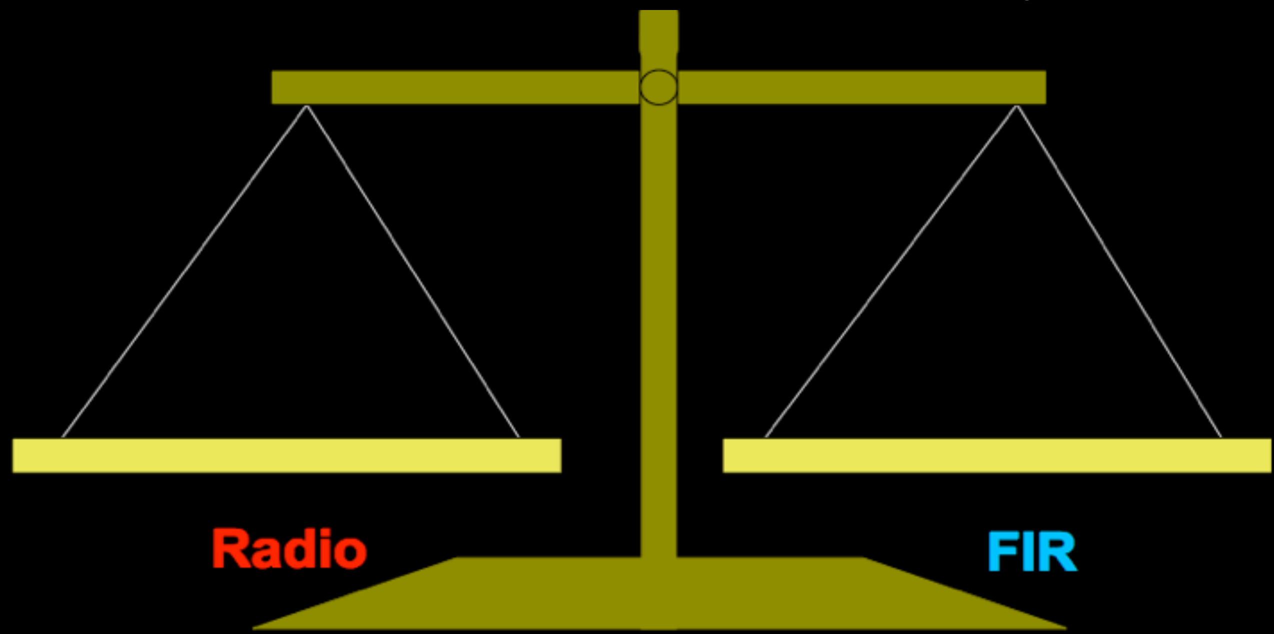
- If CR e^{-} interact with average density gas, so should CR *p*'s:

$$t_{\pi} \sim 5 \times 10^{3}\,\mathrm{yr}\left(\frac{10^{4}\,\mathrm{cm}^{-3}}{n}\right)$$

→ All CR protons "cool" before escaping a galaxy like Arp 220: **"proton calorimetry"** (Torres 04; Loeb & Waxman 06; Thompson+07; Lacki+10ab,11,12).

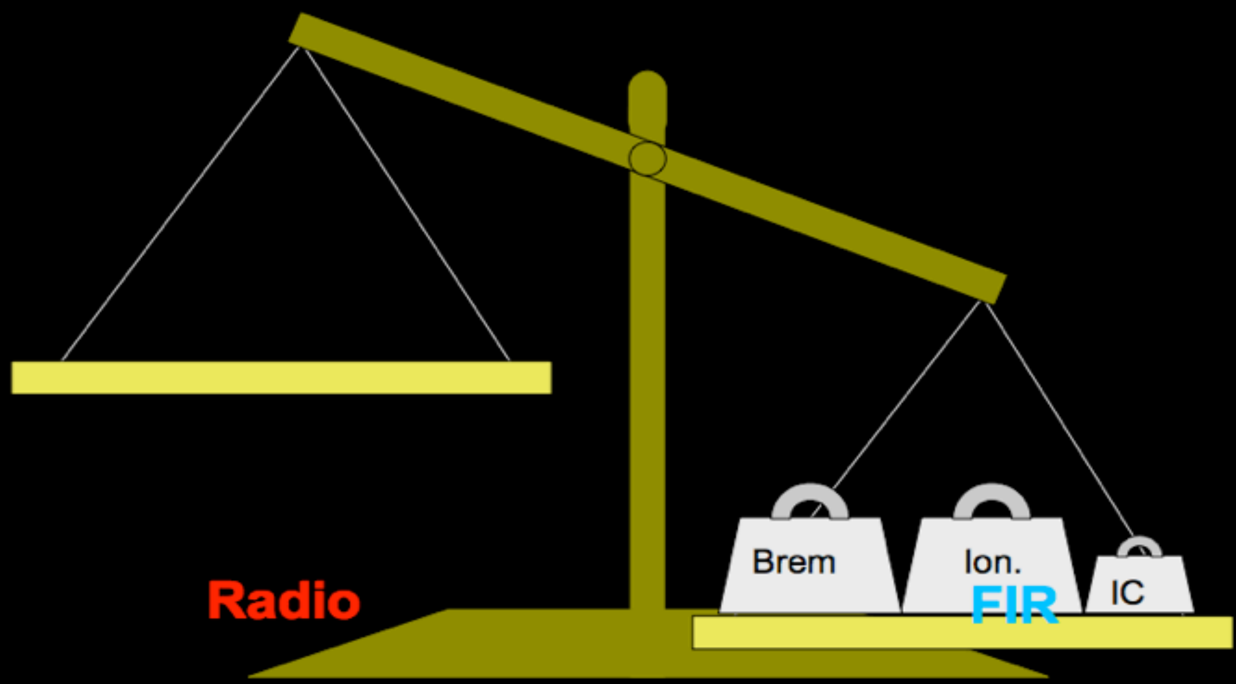
- Secondary $e^{\pm}$ cool. The "extra" radio makes up for the energy lost from primary e^{-} to bremsstrahlung and ionization (Lacki+10ab,11).
- Conclusion: Radio emission of starbursts is dominated by secondary $e^{\pm}$. Dense galaxies are on the FRC because of pion losses.

Pure CR e⁻ calorimetry.



All primary e⁻ power into synchrotron and all UV light into FIR would lead to a linear FRC with (essentially!) no free parameters.

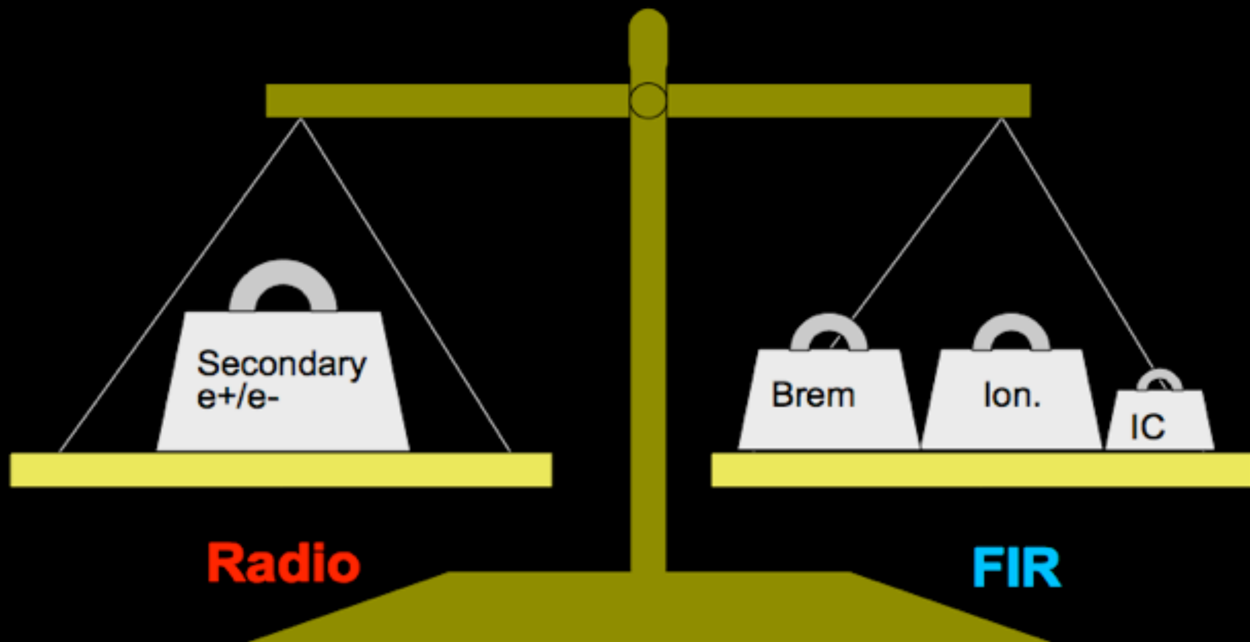
Slide from B Lacki; Lacki+2011



Considering only non-synchrotron losses fixes the radio spectral index, but breaks the FRC.

Slide from B Lacki; Lacki+2011

The high-density “conspiracy”



Secondaries make up the additional needed radio emission to maintain the FRC in dense galaxies.

Slide from B Lacki; Lacki+2011

Conspiracy or physics?

- Bremsstrahlung and ionization loss times go as 1/n.
- Pion production loss time goes as 1/n.

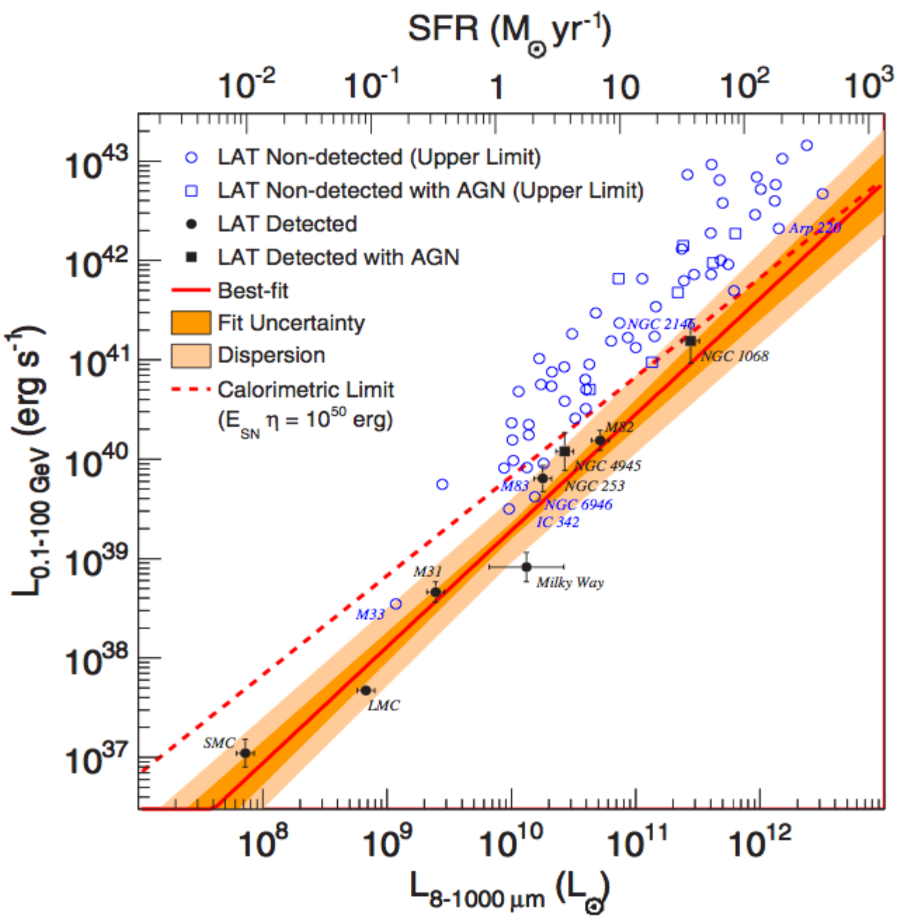
→ Physics, not conspiracy.

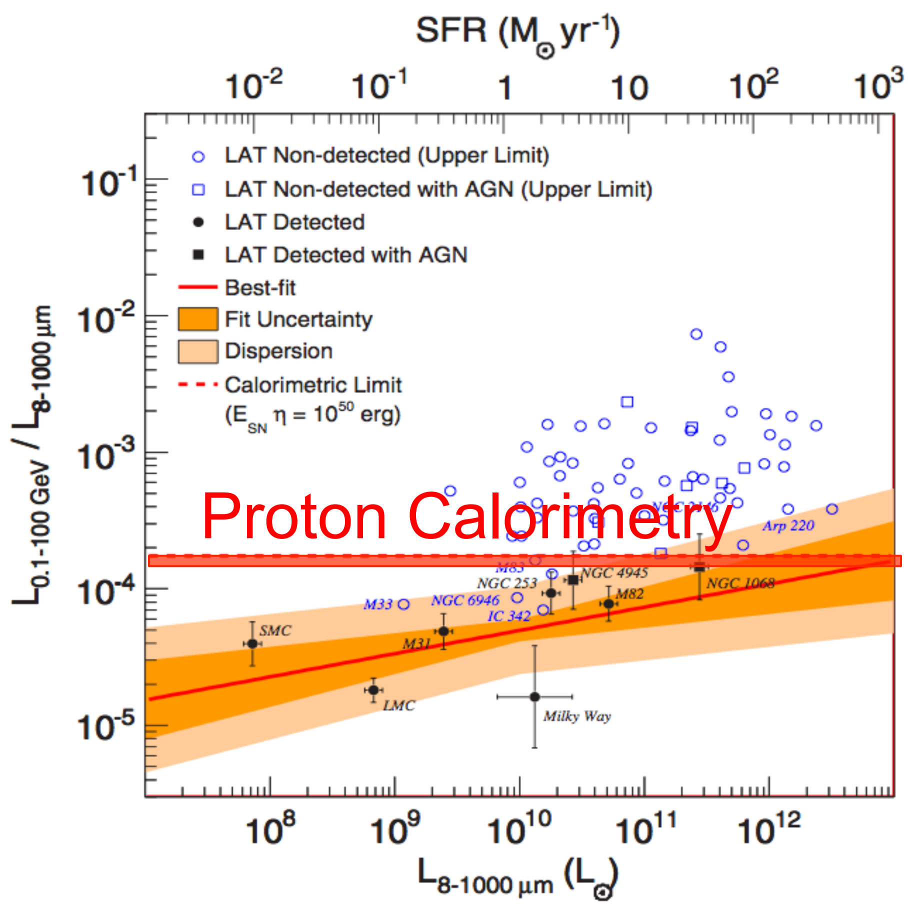
However, we **require** $E_e / E_p \sim 1/10$.

→ Physics, not conspiracy.

Predictions and consequences.

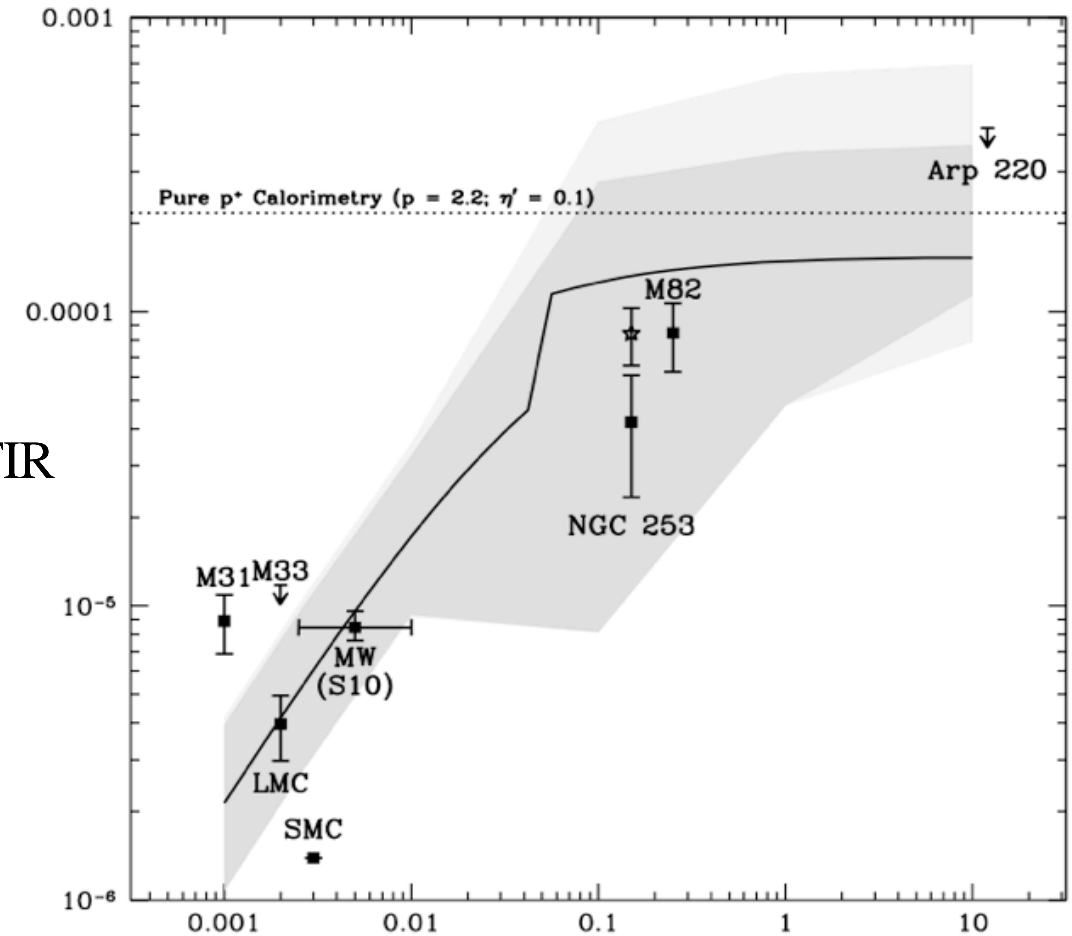
- Enhanced γ-ray and neutrino luminosities per unit SF for dense galaxies. **Proton calorimetry:** $L_\gamma \sim 2 \times 10^{-4} L_{FIR}$. $L(\nu_\mu) \sim L_\gamma$. (Wang, Yoast-Hull talks)
- GeV γ-ray & (maybe) ~PeV ν backgrounds (Pavlidou & Fields 02; Loeb & Waxman; Thompson+06; Murase+13; Tamborra+14; Ando+15, talk; Sudoh talk).
- Radio spectral index flattens as n increases. Negative curvature.
- High-z galaxies should maintain FRC, but not submm galaxies.
- $B^2/8\pi \neq U_{CR}$. No "equipartition/minimum energy".
- $B^2/8\pi$ is big in dense galaxies, but small compared to gravity. For Arp 220: B ~ 3 – 5 mG predicted. ~Confirmed (McBride+14).
- U_{CR} is big in dense galaxies, but small compared to gravity. Trouble for CR driven winds. Big γ-ray flux = small energy density.





Ackermann+2012

$F_\gamma / F_{\rm FIR}$

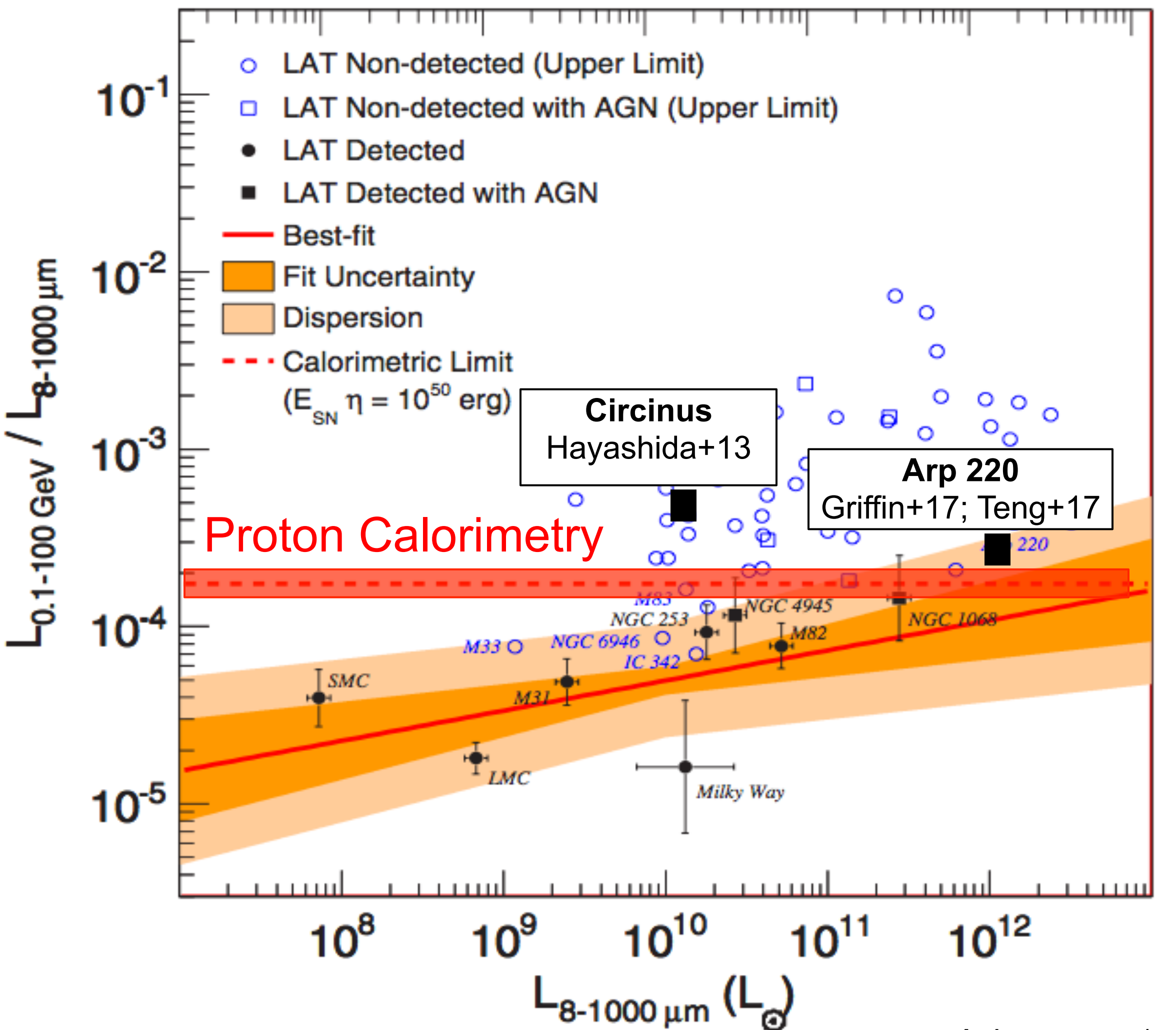


Log$_{10}$[Gas surface density]

Lacki+10ab,11

Super-Calorimetric Extra-galactic Gamma-Ray Sources!

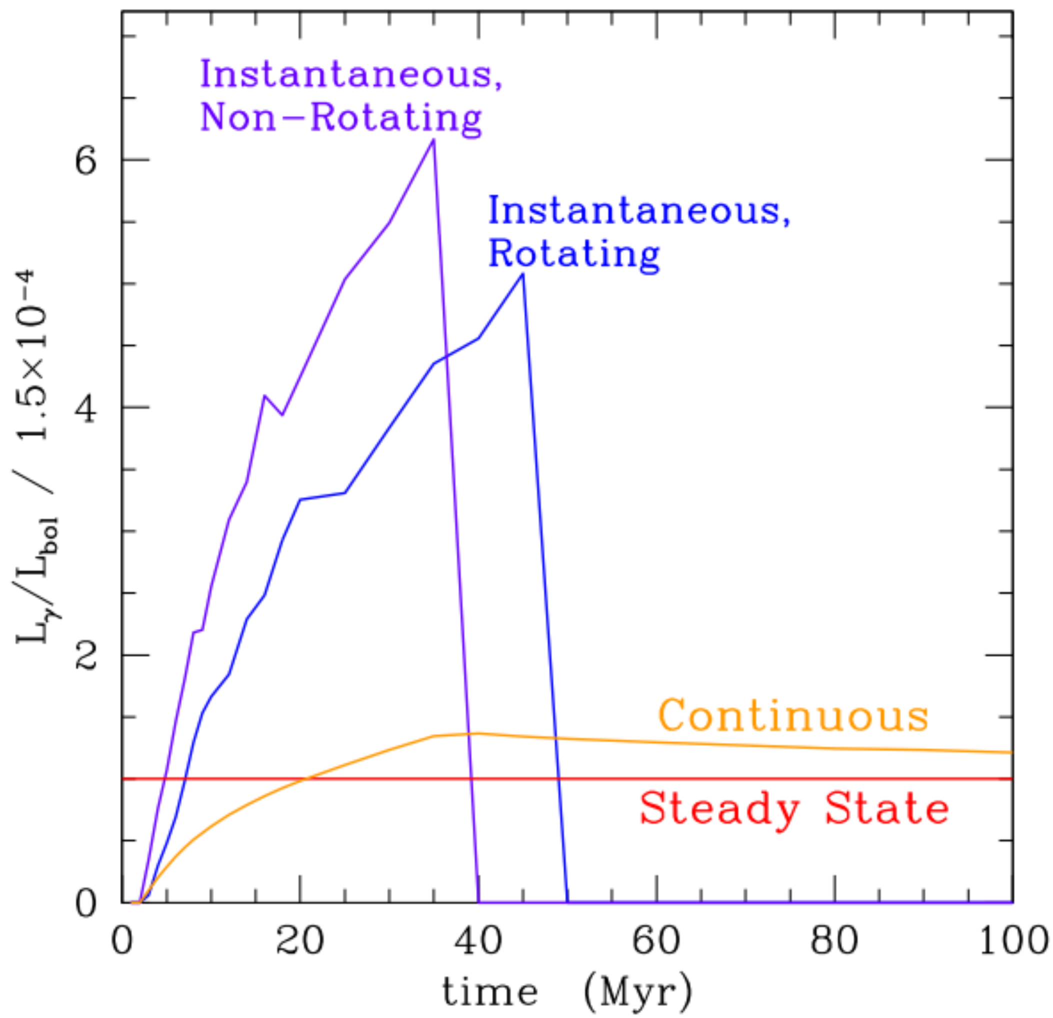
Scatter?



Ackermann+12

Non-steady star formation

- Linden & Thompson, in prep
- Spikes in star formation produce super- and sub-calorimetric ratios.
- Factor of 4 – 6 at maximum.
- **Circinus:** evidence for burst of central star formation ~10^7 year ago (Davies+07).



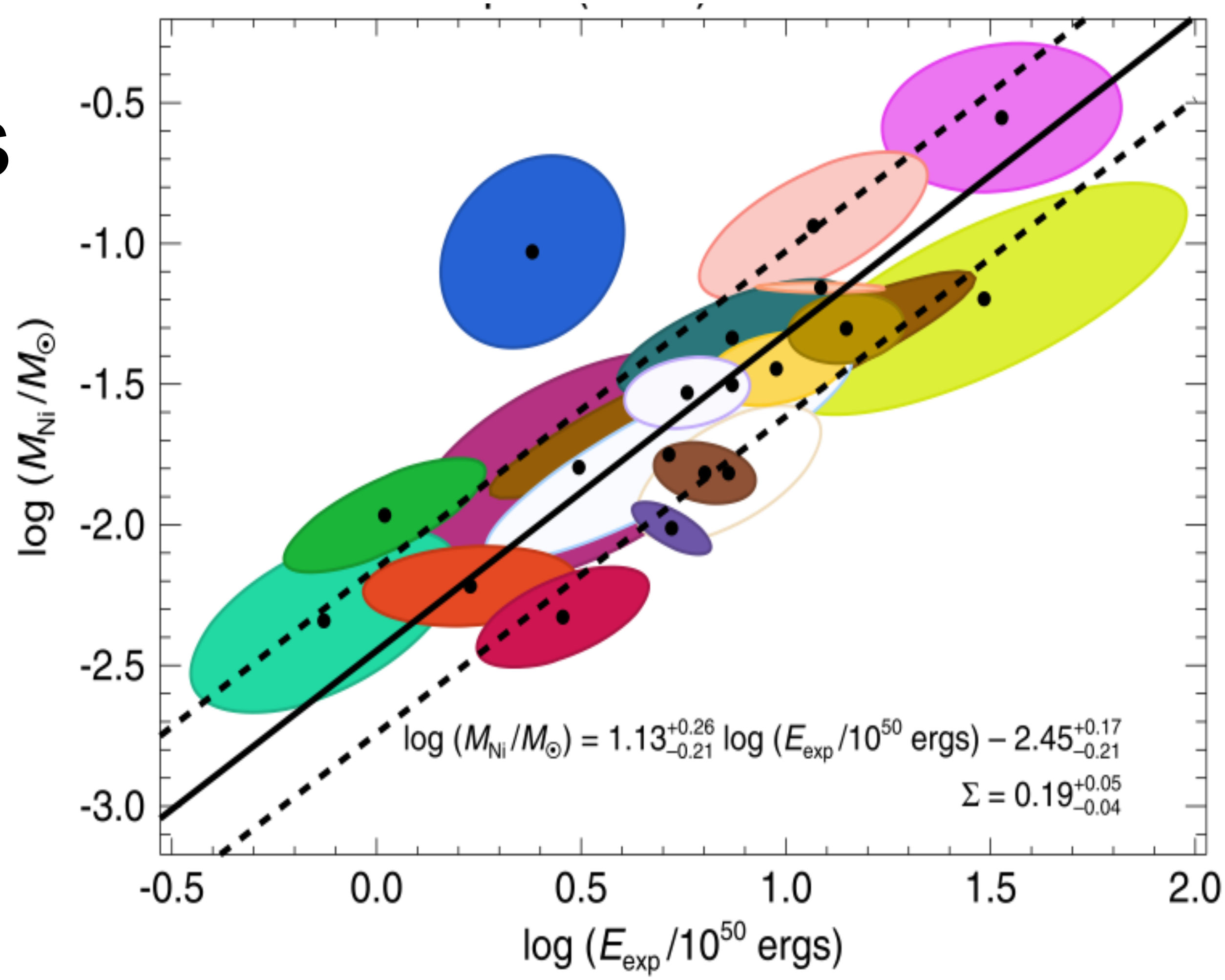
Not 10^{51} ergs

- Even for Type IIP SNe, energies vary widely.
- Population averaged energy per supernova?
- True rate per unit star formation as a function of galaxy type/metallicity?

Complete census:

ASAS-SN

Kochanek talk

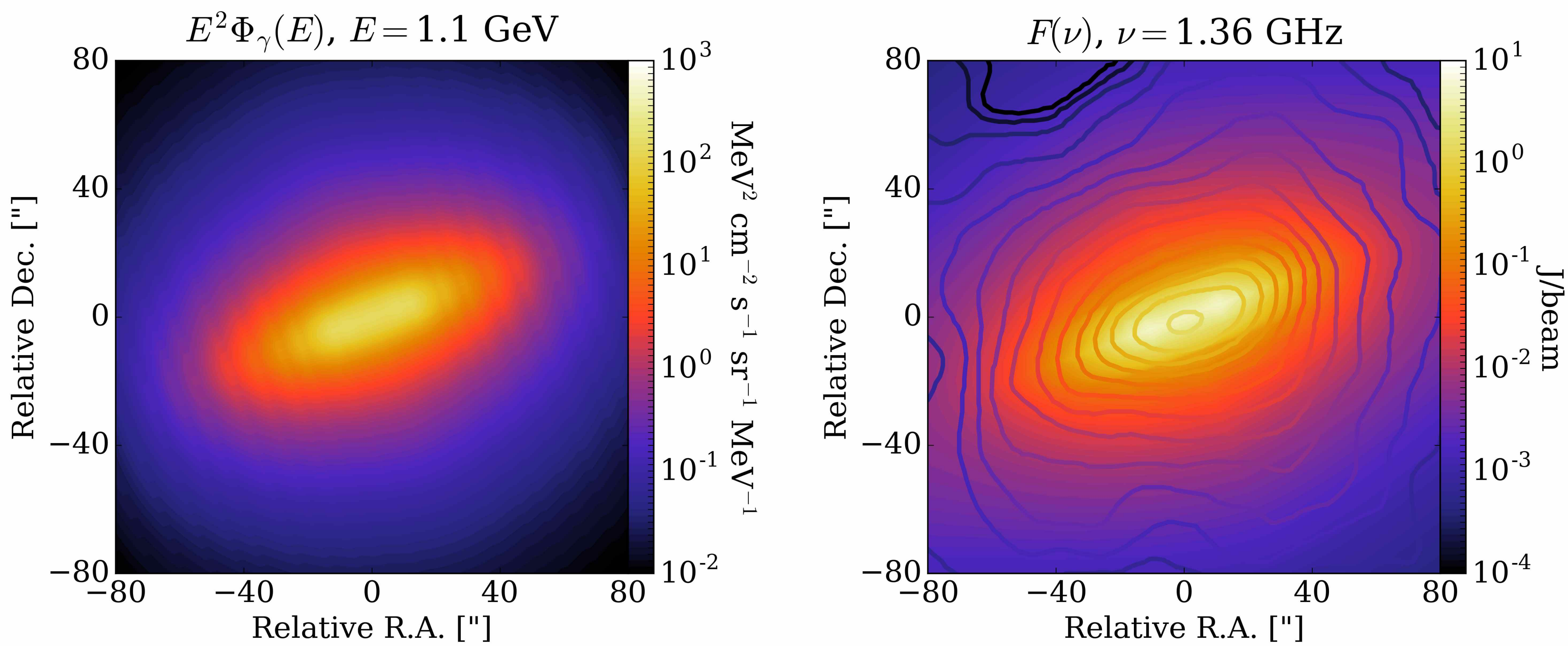


Pejcha & Prieto 15

Summary, Conclusions, Questions

- The radio-, neutrino-, γ-ray – FIR correlations provide strong constraints on the CRs, and B fields of star-forming galaxies.
- Star-forming galaxies are electron calorimeters.
- Calculations of the diffuse γ-ray & ν background should consider the FRC as a function of z.
- Radio spectral indices shaped by bremsstrahlung and ionization → γ,ν
- Dense galaxies approach proton calorimeter limit.
- Gas density predicts γ-ray and ν fluxes.
- “Low” CR energy density in dense galaxies → Winds?
- Secondary $e^{\pm}$ dominate synchrotron emission in dense galaxies.
- But, what is the “calorimetric fraction” of the Universe? PeV ν’s?

Beyond 1-zone models: minor axis radio emission



Buckman, Linden, Thompson, in prep


The End