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High energy emission from star forming regions

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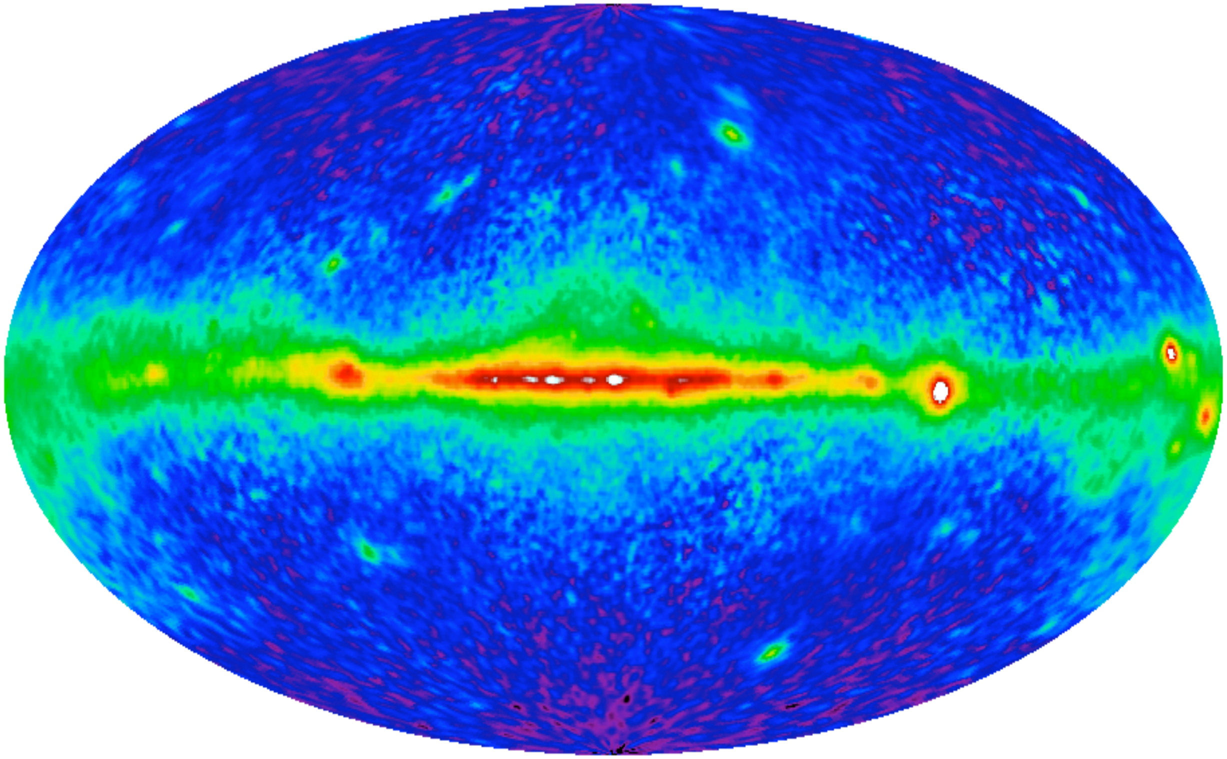
Gamma-ray emission from the interstellar medium



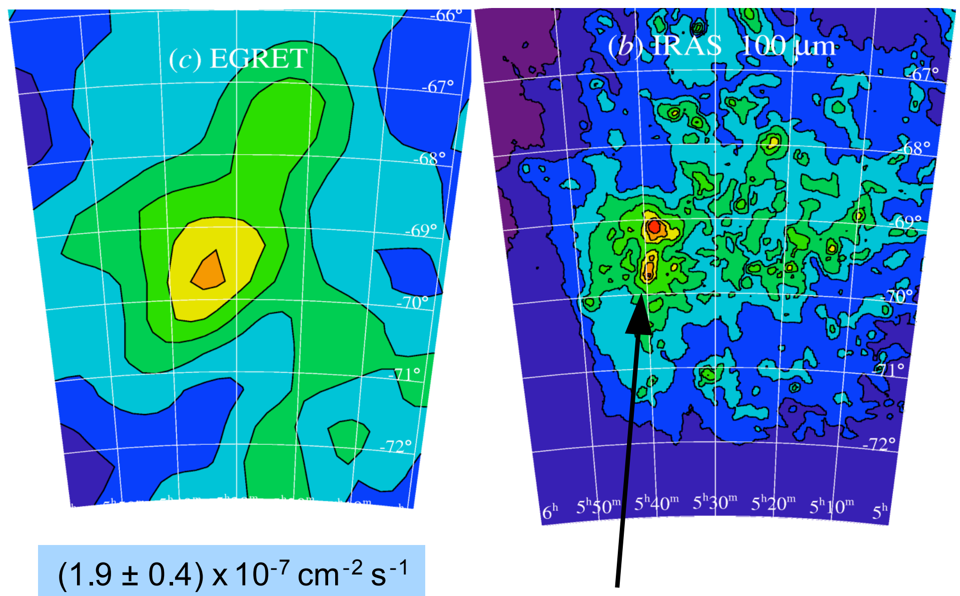
High-energy gamma-rays are produced in cosmic-ray interactions with interstellar gas and photons. Cosmic-ray production is associated with regions of massive star formation (e.g., SNRs, OB associations). This represents approximately 90% of the high-energy gamma-ray luminosity of the Milky Way (~10^6 solar)

~60% of all EGRET gamma-rays were diffuse emission from the Milky Way

Diffuse emission from external galaxies

LMC

EGRET IRAS



$(1.9 \pm 0.4) \times 10^{-7}\ cm^{-2}\ s^{-1}$

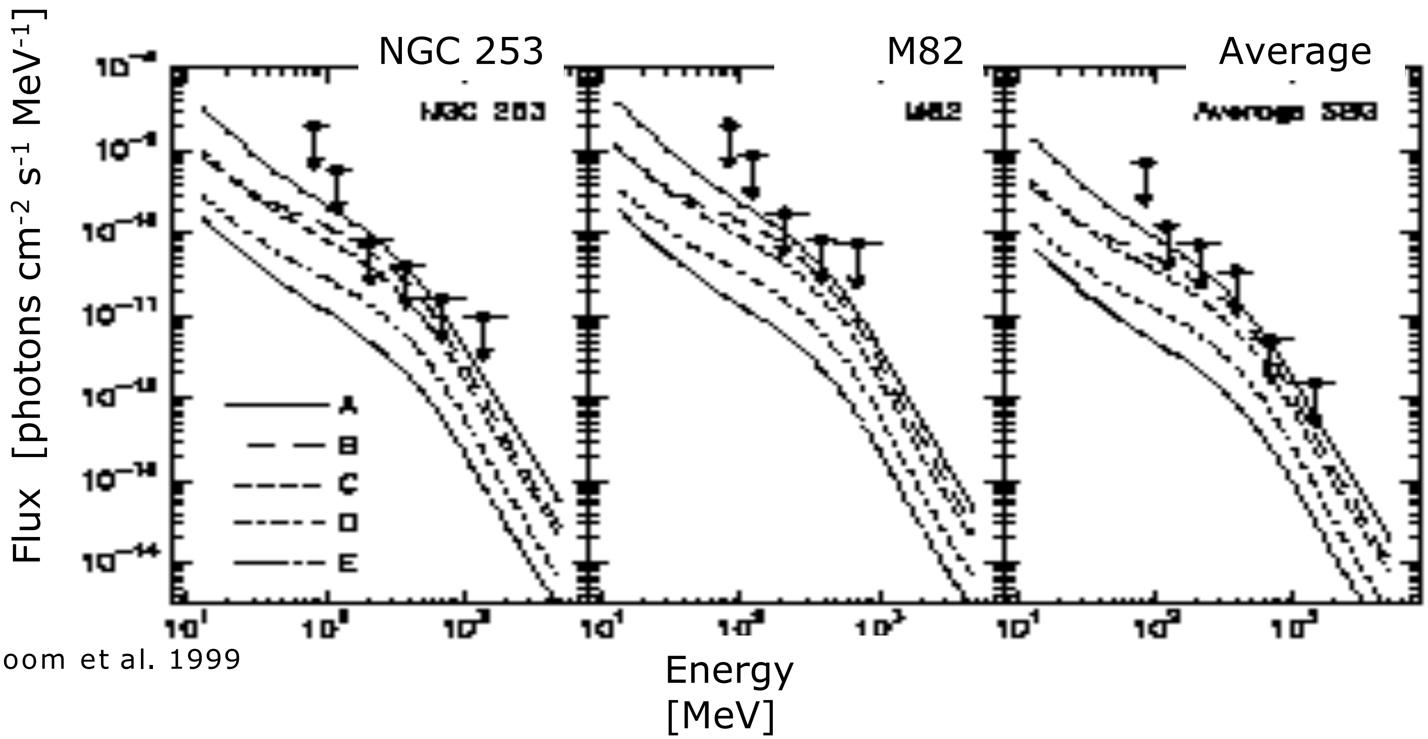
30 Doradus: extensive massive SFR and molecular clouds

- Only one other external galaxy detected in the light of its diffuse emission – LMC

The problem is distance: Milky Way at 1 Mpc would have a flux of about $2.5 \times 10^{-8}\ cm^{-2}\ s^{-1}$ (>100 MeV), well below EGRET's detection limit

[Akyuz et al. 1992, Volk et al. 1996, Paglione et al. 1996, Blom et al. 1999, etc.]

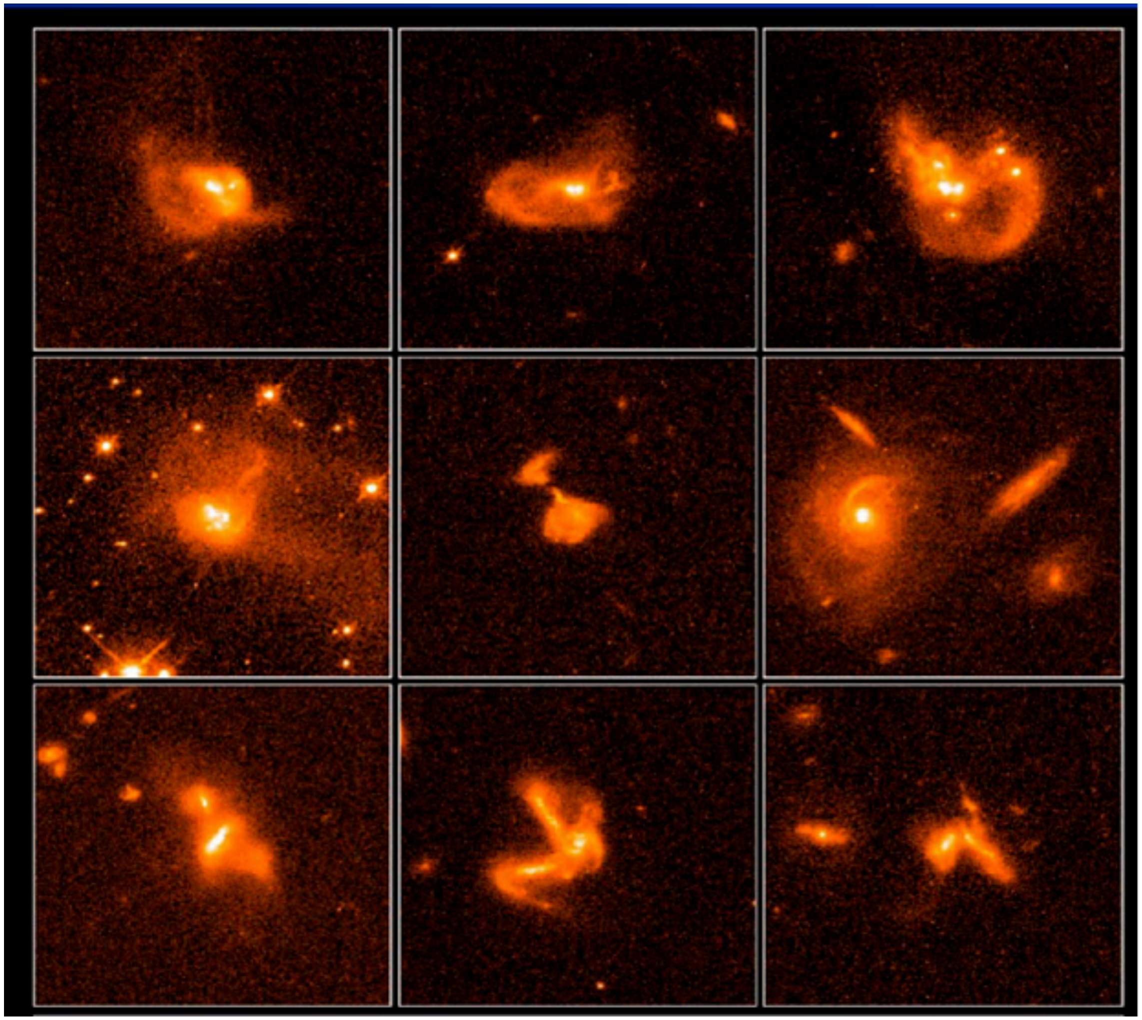
Nearby Starbursts: Upper limits with EGRET data
Early modeling suggest future detection by GLAST



Bloom et al. 1999

10 starbursts selected by distance (<10Mpc),
Infrared luminosity (>10^9 L_{solar}) at latitudes |b|>10.

Extreme regions of star formation: Almost all ULIRGs seems to be double or interacting



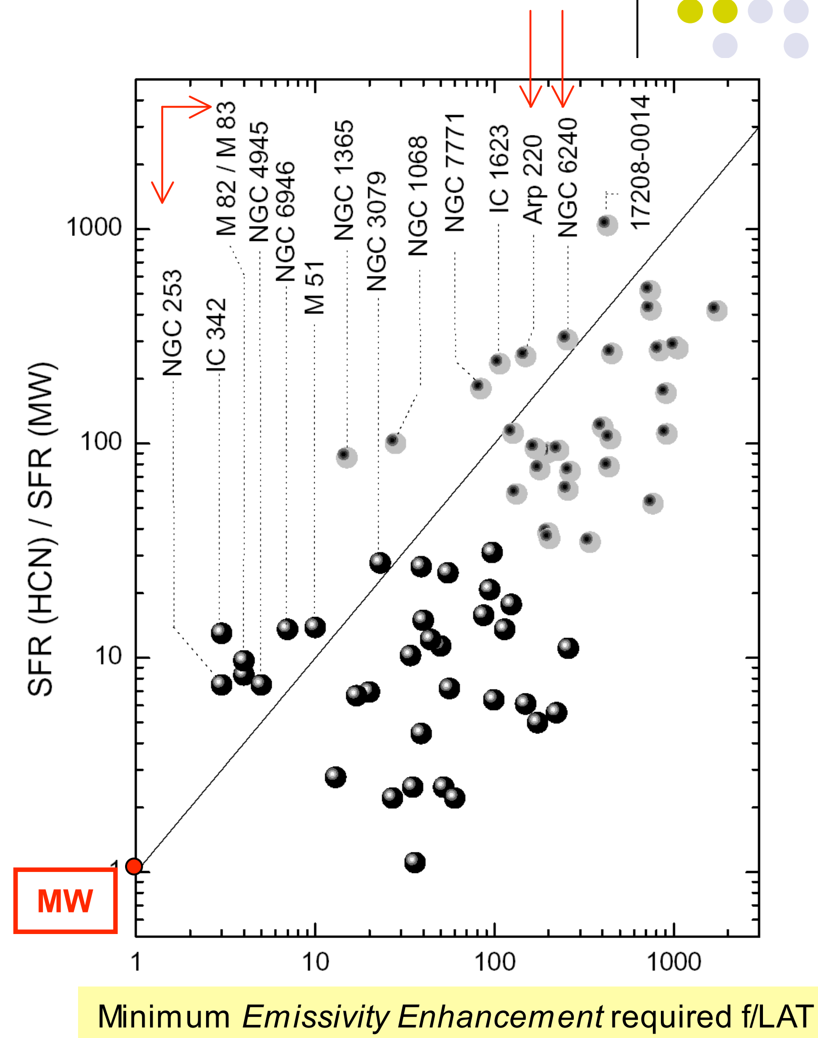
Only one within 100 Mpc [Arp 220]

Tens of LIRGs (luminosities >10^{11} L_{SUN}): detectability depends on the combined effect of distance and starburst activity.

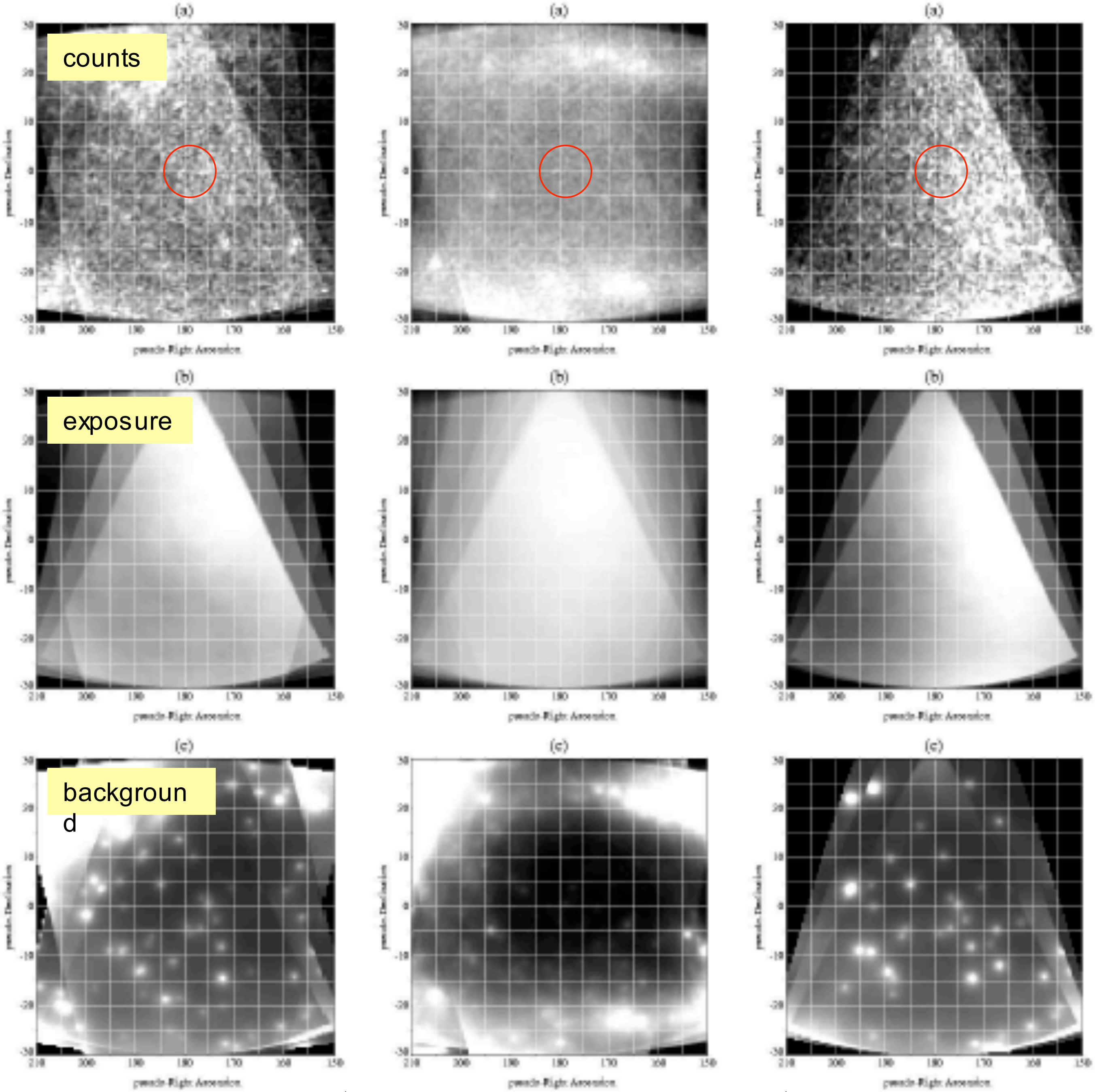
[review on LIRGs and ULIRGs: Sanders and Mirabel, ARA&A, 1996]

Detectability of LIRGs

- Gamma-ray detectability is favored in starburst galaxies (Akyuz, Aharonian, Fichtel, Volk, etc)
  - Large M_{gas} with high average density, enhanced cosmic ray density
- Recent **HCN-line** survey of Gao & Solomon (2004) of IR and CO-bright galaxies, and nearby spirals
  - Allows estimate of SFR (from HCN luminosity) and minimum required *k* for detection by LAT (from HCN + CO intensities and distance)
- Several nearby starburst galaxies and a number of LIRGs and ULIRGs are plausible candidates for detection



Torres, Reimer, Domingo-Santamaria, Digel ApJ Letters, 607, 99



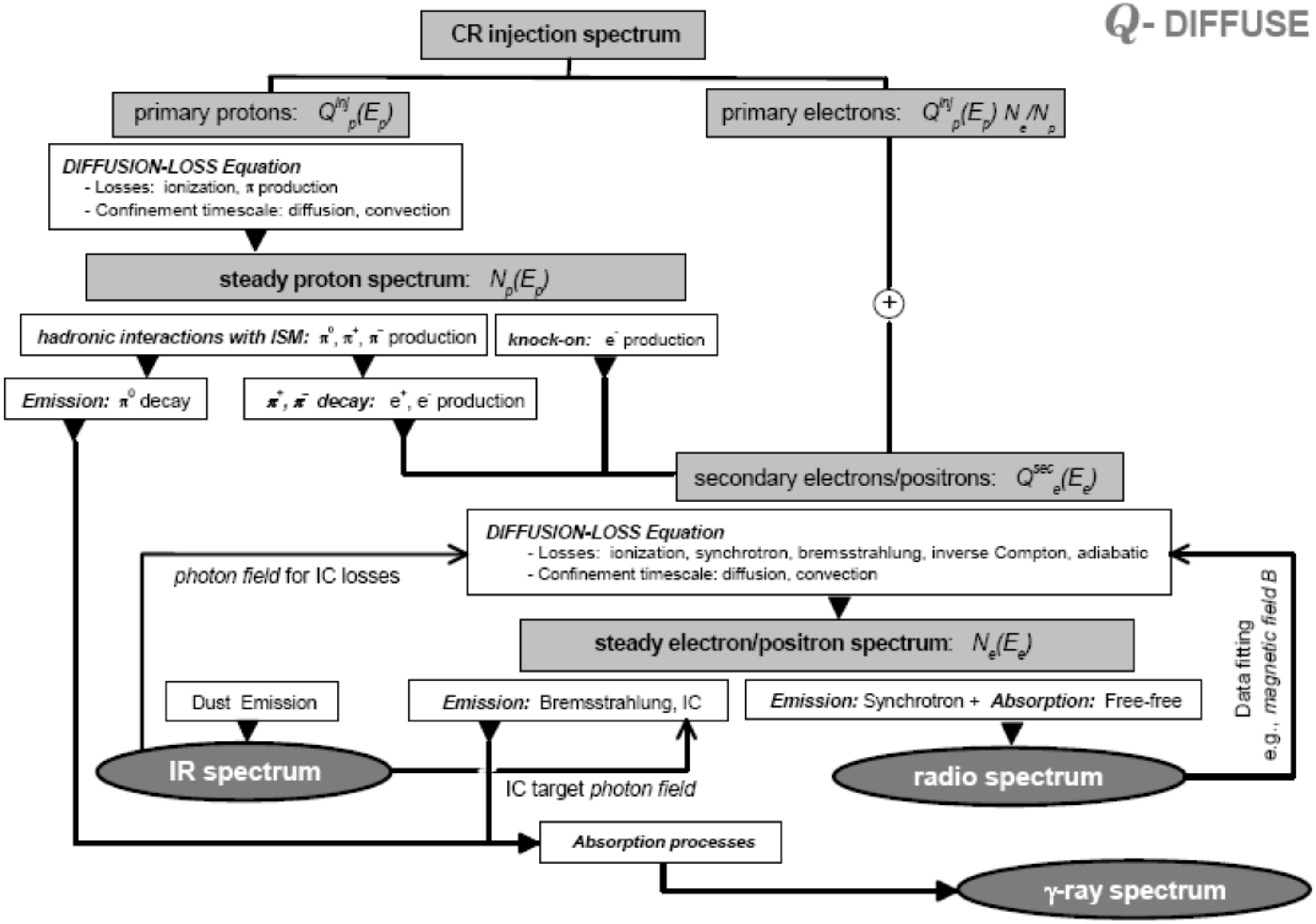
6 ULIRGs ordered by redshift	54 LIRGs ordered by L(HCN)/L(CO)	4 LIRGs ordered by L(HCN)/L(CO)

EGRET stacking searches: no added signal.

Cillis, Torres, Reimer
ApJ 621, 139, 2005

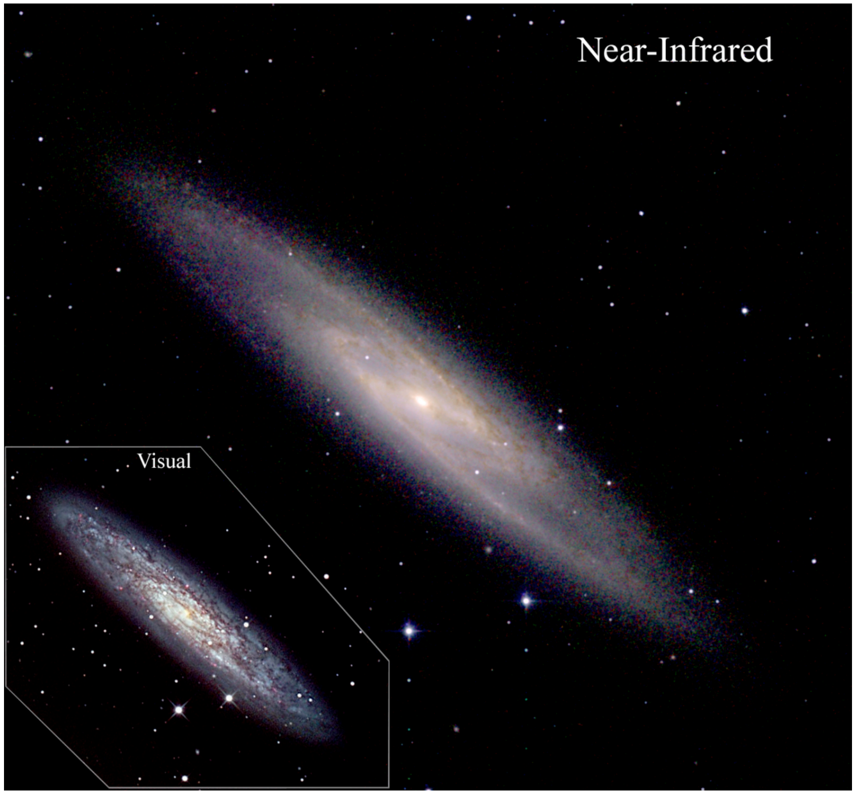
A more detailed computation

Q- DIFFUSE



Torres, ApJ, 617, 966 (2004)

Two applications: NGC 253 and Arp 220



Arp 220: main phenomenology

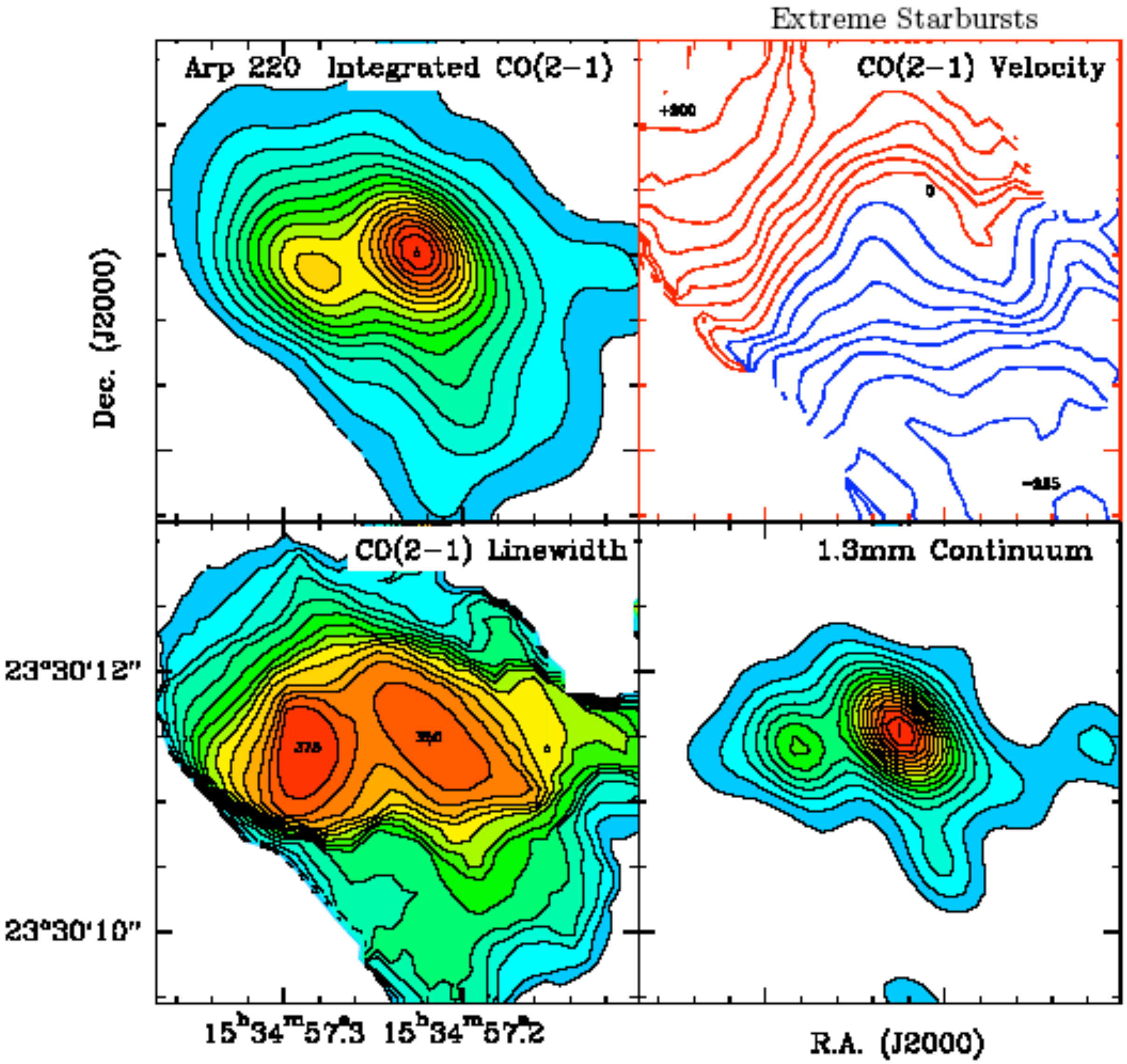
- The best studied and nearest ULIRG (72 Mpc)

  - Arp 220's center has two radio-continuum and two IR sources, separated by ~1 arcsec (e.g., Scoville et al. 1997, Downes et al. 1998, Soifer et al. 1999, Wiedner et al. 2002).

  - The two radio sources are extended and nonthermal (e.g., Sopp & Alexander 1991; Condon et al. 1991; Baan & Haschick 1995), and likely produced by supernovae in the most active starforming regions.

  - CO line, cm, mm-, and sub-mm continuum (e.g., Downes & Solomon 1998) as well as recent HCN line observations (e.g., Gao & Solomon 2004a,b) are all consistent with these two sources being sites of extreme star formation and having very high molecular densities.

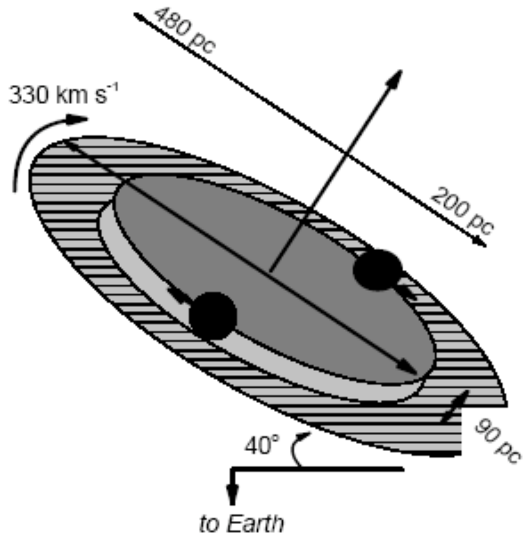
- Other less luminous candidates –if closer- can be detected.



~350 pc

Downes & Solomon 1998,
Gao & Solomon 2004

Fig. 4. Arp 220 : CO (2–1) integrated intensity, velocity, linewidth (FWHM), and the 1.3 mm continuum. CO integration limits: $(-320, +300\,\mathrm{km\,s^{-1}})$. Beam = $0''.7 \times 0''.5$. One arc second corresponds to 350 pc. The two sources of extreme starbursts can be seen in the integrated CO intensity and the 1.3 mm dust continuum where they completely dominate the emission.The strong deviations from circular rotation in the disk, indicated by the sharp twists in the velocity contours, are due to the West source which is rotating at an angle shifted by 110° from the main disk (from [3])



Arp 220: Geometry

Table 1. Some properties of Arp 220's extreme starbursts.

Property	West	East
Geometry	sphere	sphere
Radius [pc]	68	110
Average gas density (H_2) [cm^{-3}]	1.8×10^4	8.0×10^3
Luminosity (FIR) [$L_\odot$]	0.3×10^{12}	0.2×10^{12}

Table 2. Some properties of Arp 220's disk.

Property	Value
Geometry	cylinder
Thickness [pc]	90
Outer radius [pc]	480
Inclination from face-on	40°
Average gas density within the outer radius (H_2) [cm^{-3}]	1.2×10^3
Luminosity (FIR) [$L_\odot$]	0.7×10^{12}

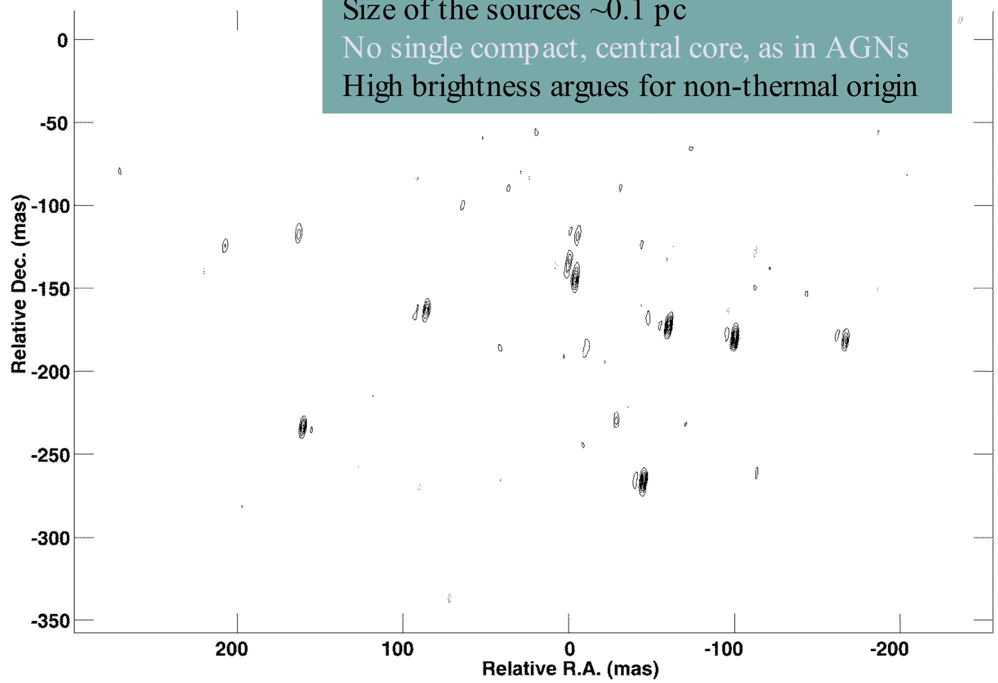
Arp 220: Supernova explosion rates

18 cm VLBI (3 *x* 8 milliarcsec resolution) continuum imaging of Arp 220: more than a dozen sources with 0.2-1.2 mJy fluxes (Smith et al. 1998), mostly in the western nucleus. In 2002, new observations with VLBI revealed 30 supernova remnants candidates, 20 in the western, and 10 in the eastern nucleus.

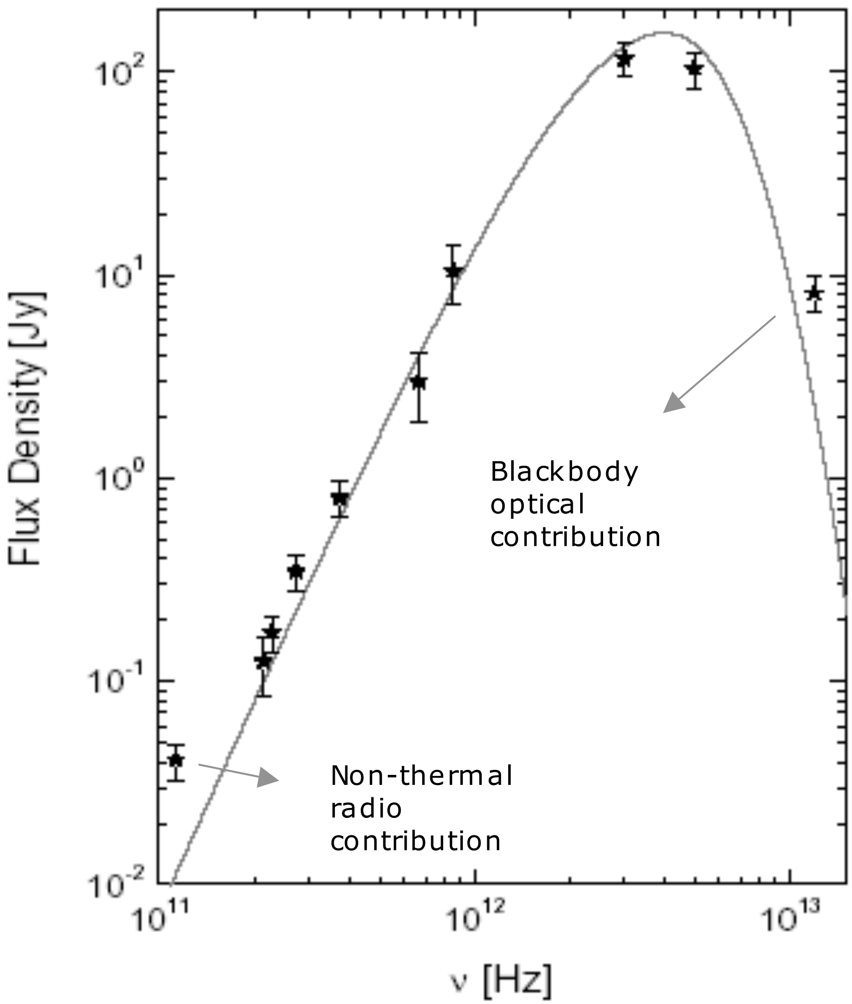
The previous result & models of the nuclei with Starburst99 (Shioya et al. 2001); and relationships between the IR luminosity and the rate of supernova explosions (Van Buren et al. 1994, Manucci et al. 2003) suggest that the rate is ~1-2 yr (!)

~300 times larger than the largest of the Local Group Galaxies (M31: ~0.9 SN/century)

7 hours, 17 telescopes.
Size of the sources ~0.1 pc
No single compact, central core, as in AGNs
High brightness argues for non-thermal origin



IR-FIR luminosity of Arp 220



the FIR emission is modelled by dust, having an emissivity law proportional to

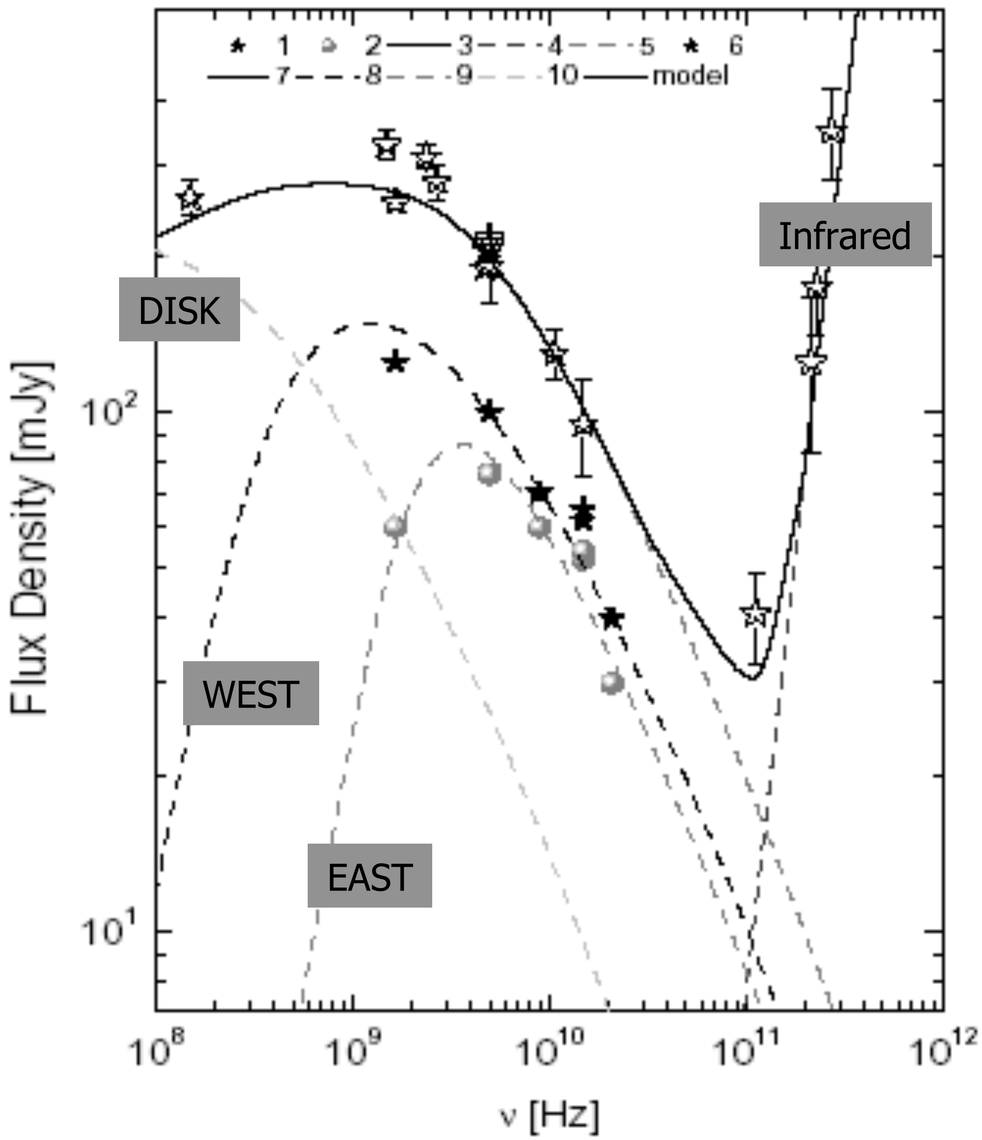
$$\nu^{\sigma} B(\epsilon, T).$$

Radiation is coming from each of the components of Arp 220, assuming that it is radiated with a single temperature and emissivity law.

The model (sum of the three contributions) derived to fit the data ($\sigma = 1.5$, $T = 42.2$ K)

Torres, ApJ, 617, 966 (2004)

Radio emission of the steady population of electrons

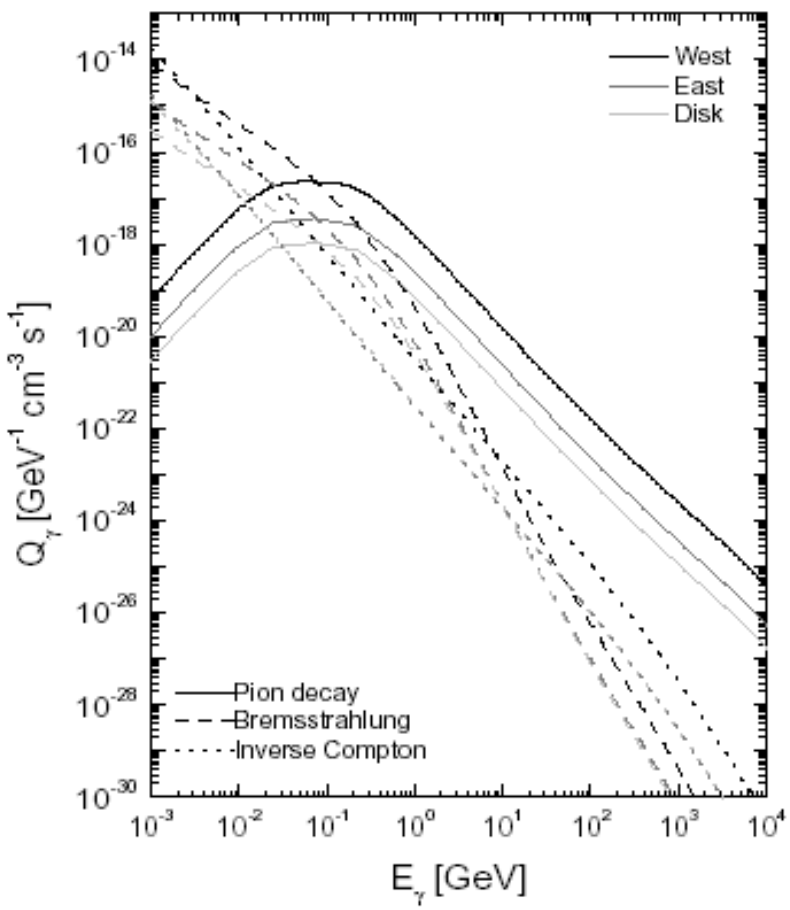


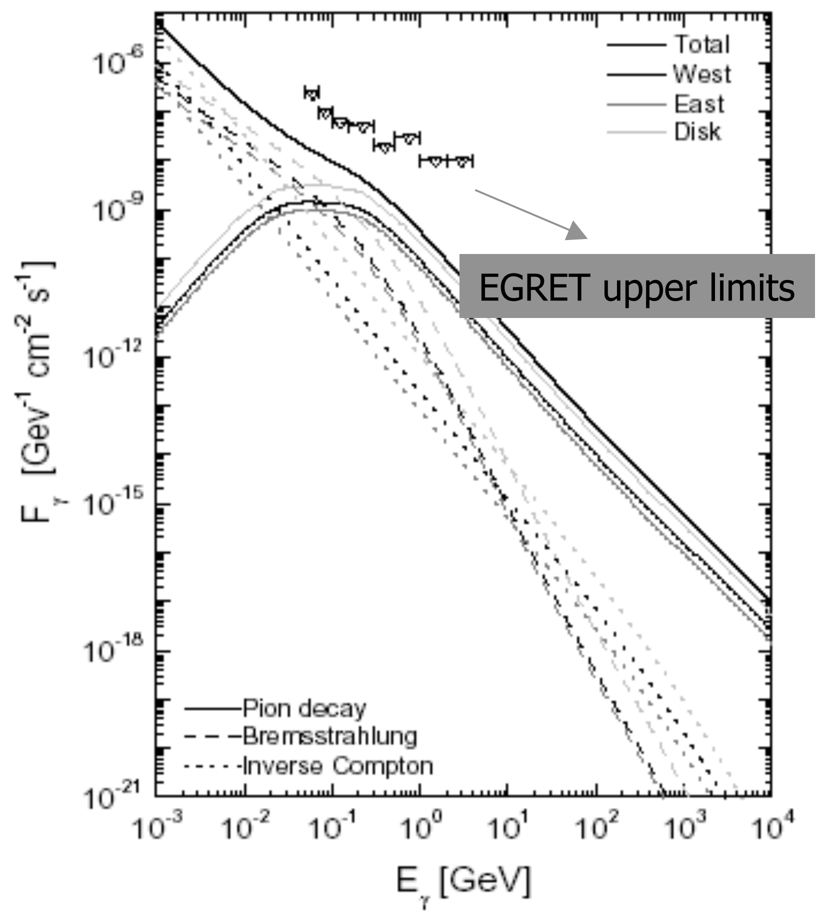
Lines are not fits to the data but predictions of the model for a particular choice of parameters.

Component	Magnetic Field	Critical Frequency
western starburst	6.5 mG	0.38 GHz
eastern starburst	4.5 mG	2.86 GHz
disk	280 μG	0.07 GHz

Torres, ApJ, 617, 966 (2004)

Arp 220 Gamma-ray predictions: just above GLAST 1yr sensitivity, more than 100 hs required for HESS/MAGIC





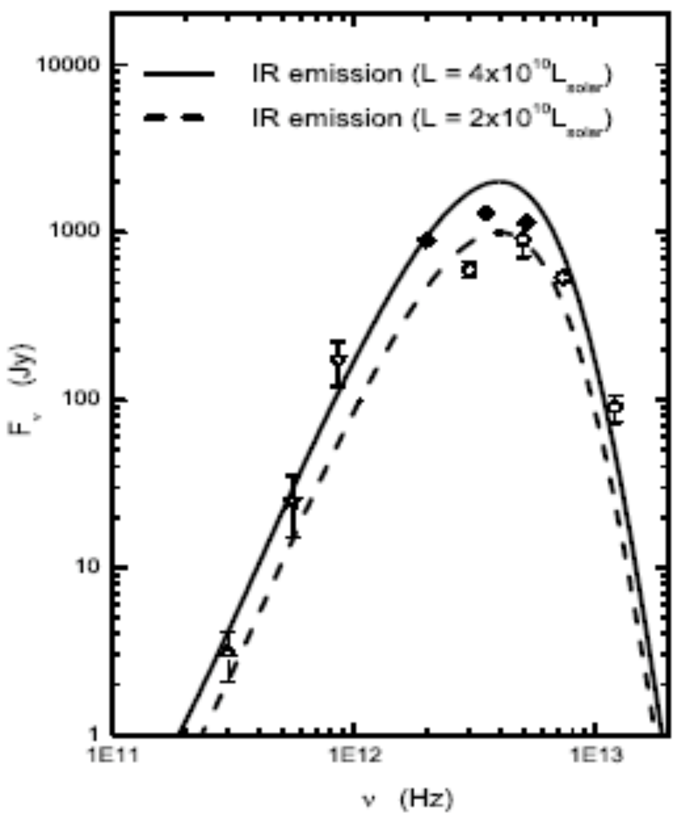
The emissivity is the largest in the western extreme starburst, the most active region of star formation. The differential flux shows the influence of volume. The disk flux is the largest, although just the western starburst provides more than one fourth of the total flux

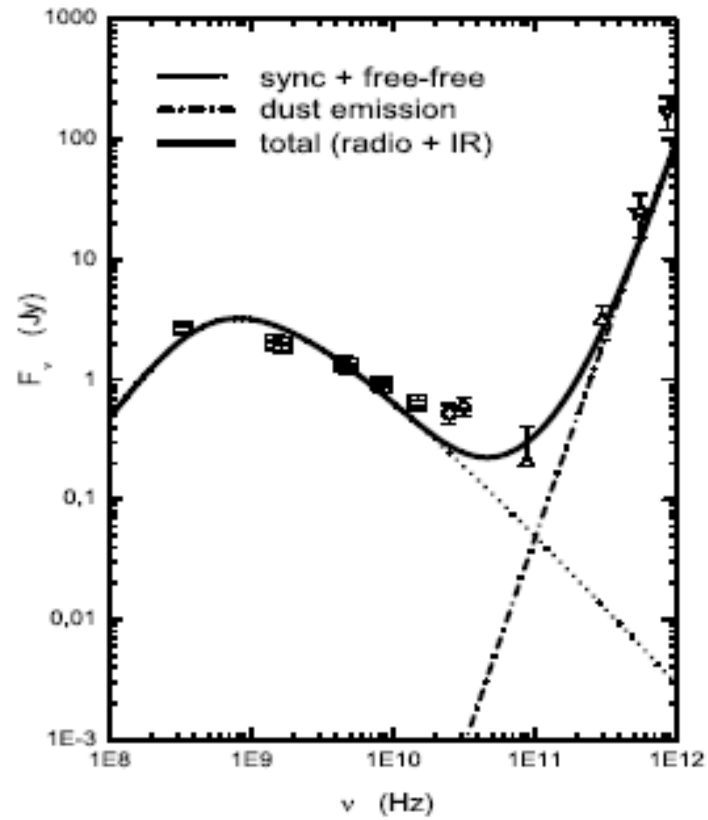
Parameters of the model for NGC 253

Physical parameters	Symbol	Value	Units	Comment
Distance	D	2.5	Mpc	
Inclination	i	78	degrees	
Infrared Luminosity of the innermost starburst (IS)	$L_{\rm IR}$	2×10^{10}	$L_\odot$	
Radius of the IS	–	100	pc	
Radius surrounding disk (SD)	–	1000	pc	
Uniform density of the IS	$n_{\rm IS}$	~ 600	cm^{-3}	Obtained or derived from observations
Uniform density of the SD	$n_{\rm SD}$	~ 50	cm^{-3}	
Gas mass of the IS	$M_{\rm IS}$	$\sim 3 \times 10^7$	$M_\odot$	
Gas mass of the SD	$M_{\rm SD}$	$\sim 2.5 \times 10^8$	$M_\odot$	
Supernova explosion rate of the IS	$\mathcal{R}$	~ 0.08	SN yr^{-1}	
Supernova explosion rate of the SD	–	~ 0.01	SN yr^{-1}	
Typical supernova explosion energy	–	10^{51}	erg	
SN energy transferred to cosmic rays	η	~ 10	%	
Dust emissivity index	σ	1.5	–	
Dust temperature	$T_{\rm dust}$	50	K	
Emission measure	EM	5×10^5	pc cm^{-6}	Obtained from modelling
Ionized gas temperature	T	10^4	K	
Magnetic field of the IS	B	300	μG	
Slope of primary injection spectrum	p	2.2–2.3	–	
Maximum energy considered for primaries	–	100	TeV	Assumed
Diffusion coefficient slope	μ	0.5	–	
Proton to electron primary ratio	N_p/N_e	50	–	
Confinement timescale	τ_0	1–10	Myr	

Domingo-Santamaria & Torres, A&A, astro-ph/0506240

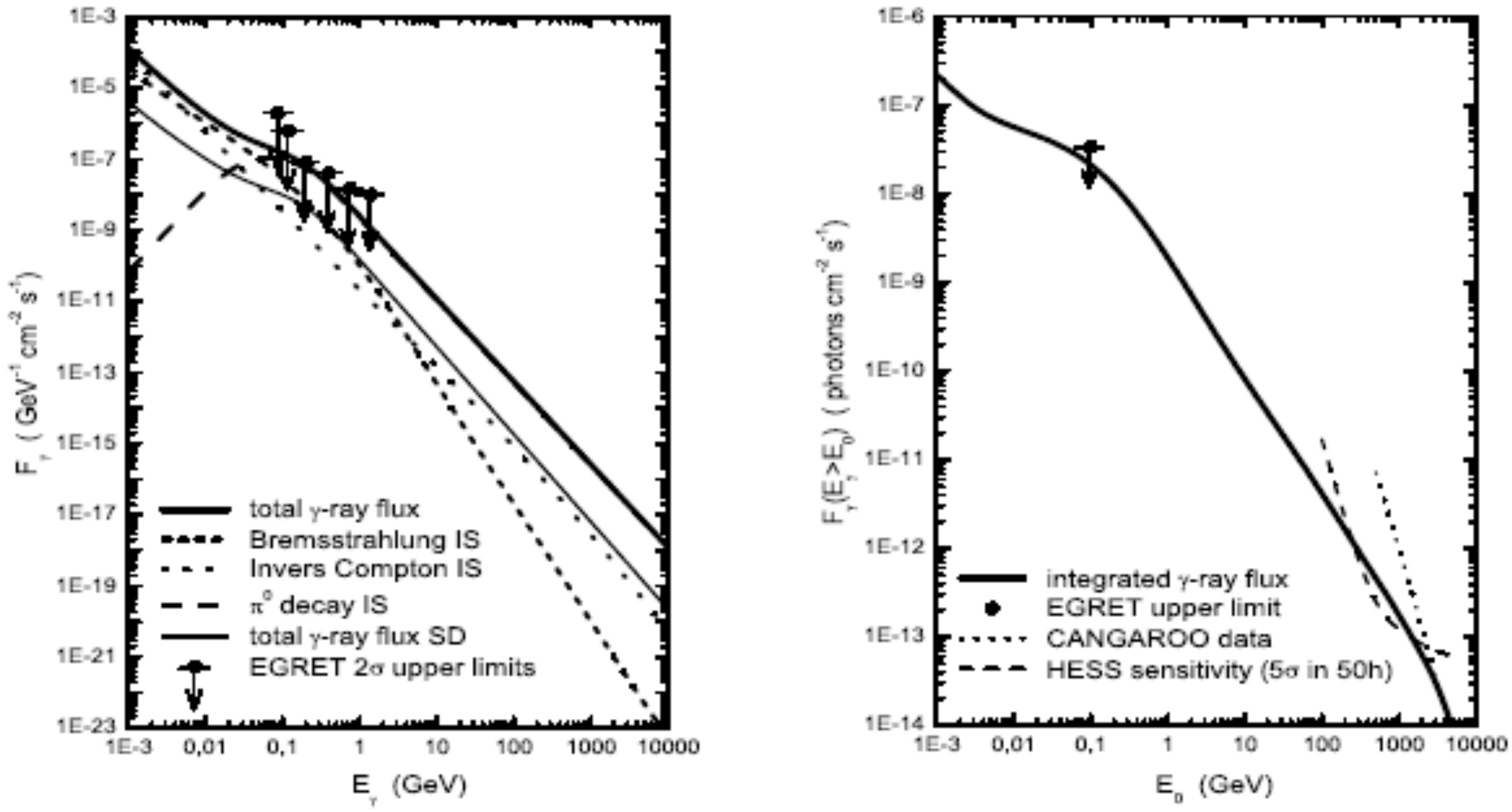
NGC 253: IR and radio modeling





Domingo-Santamaria & Torres, A&A, astro-ph/0506240

NGC 253 gamma-ray predictions: definitively a GLAST source, a HESS source if observed more than 50 hs. Our predictions are a few percent of CANGAROO claims



Domingo-Santamaria & Torres, A&A, astro-ph/0506240

Summary

- Extreme regions of star formation, following simple population analysis, are possibly detectable as gamma-ray sources
  - Starburst activity – cosmic ray populations
- Detailed analysis for ULIRG Arp 220 and NGC 253 show that they are expected as GLAST sources, and also as IACTs sources provided enough observation time is spent (>~100 hours for Arp, >~50 hours for NGC 253).
- Many other LIRGs (several tens) may appear in the forthcoming catalogs

Thank you.

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