Study of Cosmic Rays in Star Forming Galaxies Using GeV Gamma Rays by Fermi-LAT

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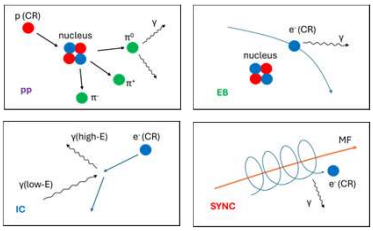
1. Background

- Star forming galaxy (SFG) produce intense cosmic rays (CR).
- CRs interact with interstellar medium and produce gamma rays.

We can study CRs by observing gamma-ray emission.

- Hadronic (CR proton) radiation
  - Pi0-decay (PP)
- Leptonic (CR electron) radiation
  - Bremsstrahlung (EB)
  - Inverse Compton scattering (IC)
  - Synchrotron (SYNC)



Contributions from EB and IC may be substantial in sub-GeV.

2. Purpose of the Study

1. Accurately determine CR e/p ratio & understand CRs and interstellar environments in other galaxies
2. Accurately model the Starburst(SB)-component, so that we can conclusively detect MeV emission from corona in Seyfert galaxies

3. Targets of analysis

- SFGs/SBGs individually detected by Fermi-LAT (excluding Seyfert galaxies)

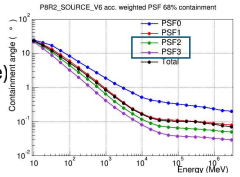
Name	R.A. (J2000) (deg)	Decl. (J2000) (deg)	Dist. (Mpc)
M82	148.97	69.68	3.7
NGC253	11.89	-25.28	3.3
M31	10.69	41.27	0.78
M33	23.47	30.67	0.85
Arp220	233.74	23.51	79.9
Arp299	172.13	58.57	47.7
NGC2146	94.66	78.36	18

4. Spectral analysis

Method

- We analyze 7 SFGs/SBGs spectra using 15 years of Fermi data form 50 MeV to 102.4 GeV.
- We defined the ROI of 15 x 15 deg^2 (0.1 deg bin-size).
- We combine different PSF types and energy bands.

Energy range (GeV)	PSF0	PSF1	PSF2	PSF3	Zmax (deg)
0.05-0.1	-	-	○	○	80
0.1-0.4	-	○	○	○	90
0.4-102.4	○	○	○	○	105



↑ Energy dependence of the Fermi-LAT angular resolution (for each PSF event type)

- BG = Galactic diffuse + isotropic emission+ 4FGL-based sources
- For all targets, we omitted the Sun/Moon emission templates (ecliptic lies outside the ROI).
- We test **Log-Parabola(LP)** and **PowerLaw(PL)** model in bright objects.

LogParabola:

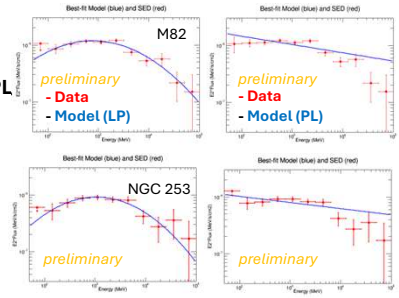
$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_b}\right)^{-(\alpha+\beta\ln(E/E_b))}$$

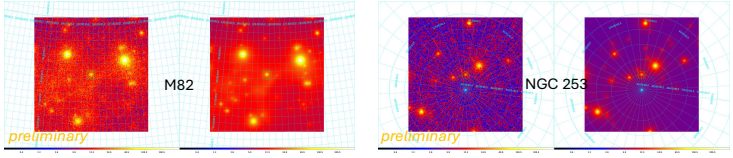
PowerLaw:

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\gamma}$$

Evaluation of SED in M82 and NGC 253 (LP vs. PL model)

- (right) SED data points and best-fit model
- **LP reproduces data better than PL.**
- Datapoints are likely biased by using PL.
- The spectrum is clearly curved, and **we will employ LP.**





↑ Data count map vs. model count map above 400 MeV centered on the objects

Result of other objects

- **Bright objects show curved spectrum, and we employed LP.**
- We employed PL for other weak objects.
- SFGs (M31 & M33) show softer spectrum than SBGs.
  → escape-dominated vs. calorimeter

Bright obj	TS	α	β	Eb(MeV)
M82	1752.9	2.046+/-0.044	0.106+/-0.023	956
NGC 253	903.9	1.997+/-0.064	0.128+/-0.035	1048
M31	159	2.17+/-0.11	0.172+/-0.078	1000

Weak obj	TS	Γ
Arp 220	53.9	2.19+/-0.16
NGC 2146	53.1	2.00+/-0.13
Arp 299	55.8	2.16+/-0.16
M33	44.6	2.20+/-0.12

5. SED Modeling of M82

Aim to constrain the CR proton (CRp) and electron (CRe) spectra of M82, with the aid of multiwavelength data.

Method

- We additionally use the Radio[1] and TeV data[2].
- We use **Naima** in SED modeling.

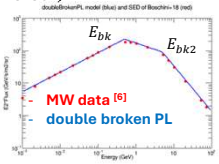
- **Photon field model for IC**
  - CMB: Implemented in NAIMA
  - IR: $T = 60\ K, U_{ph_IR} = 1340\ eV/cm^3$
  - Optical: $T = 3000\ K, U_{ph_IR} = 335\ eV/cm^3$

  (Derived L using the compilation of M82 interstellar radiation[3] and obtained U from the equation assuming $R = 250\ pc$[4])

$$U = \frac{L}{2\pi R^2 c}$$

- **Magnetic field strength for SYNC**
  - $MFD = 230\mu G$ [4], the same energy density as U_{ph_IR}
- **Target gas density for PP (Pi0-decay) and EB**
  - $N_{proton} = 400/cm^3$

  (Using $M_{H2} = 1.9 \times 10^8 M_\odot$ for $D = 3.25\ Mpc$ [5] and assuming $R = 250\ pc$ and $h = 100\ pc, V = 5.73 \times 10^{62} cm^3$)
- **Free-free emission**
  - Free-free emission is the dominant component at 100 GHz (radio)[7]. (assuming that 75% of the flux is free-free at 100 GHz and the index to be 0.1)
- **CR proton spectrum:** PL in momentum
- **CR electron spectrum:** Double broken PL
  - E_{bk1}: the balance between the ionization and EB (universal)
  - E_{bk2}: the balance between the EB, SYNC & IC (determined by gas density, ISRF energy density and MFD energy density)
  - $E_{bk1} \sim 0.5\ GeV, E_{bk2} \sim 5\ GeV$ (tentatively adopted the MW data[6])

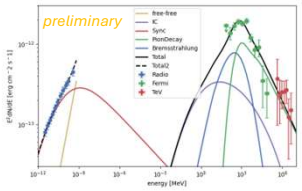


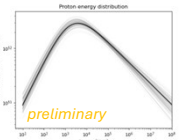
Four free parameters (normalization and index for CRp and CRe)

Result

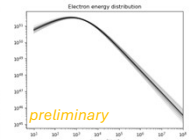
- The fit is converged successfully, and we obtained the best-fit parameters.
- The CR spectra were harder than MW.
- The spectral index of CRe and CRp were approximately the same.
- We obtained the CR electron-to-proton ratio (K_{ep}) ~1/30 @10 GeV. (Larger than the canonical 1/100 in the MW)
- In sub-GeV, the contribution from EB is substantial, while that from IC is smaller than PP or EB.

	index (M82)	index (MW)
proton	~2.39	~2.7
electron	~2.36	~3.1





↑ CRp spectrum



↑ CRe spectrum

↑ SED of radio, fermi, TeV and the components (PP, EB, IC, SYNC and free-free) and Total.

Reference

[1] A. Acharyya et al. (2025) [2] U. Klein et al. (1988), J. E. Carlstrom & P. P. Kronberg (1991), P. K. G. Williams & G. C. Bower (2010), A. Basu et al. (2012), and B. Adebahr et al. (2013) [3] Silva et al. (1998) [4] Lacki et al. (2013) [5] Weith et al. (2001) [6] Boschini et al. (2018) [7] Condon et al. (1992)

6. Summary and Future work plan

- We test both Log-Parabola and PowerLaw model for Bright objects to evaluate spectra.
- Bright objects show curved spectrum, and we employed LP.
- We constrained Kep, CR electron and proton spectral index in M82 through SED modeling with multiwavelength data.
  - We obtained $K_{ep} \sim 1/30$ @10 GeV in M82, it is larger than canonical value of MW.
  - The spectral index of CRe and CRp were approximately the same
- We plan to apply the same SED modeling approach to other galaxies. → discuss the production and propagation of CRs in other galaxies.