A hardronic Origin for the High-energy Gamma Rays from the Large-scale Disk of the Large Magellanic Cloud

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Outline

I. High-energy gamma rays from the star-forming galaxies
II. Templates for LMC field
III. Physical origin of gamma-ray emission from the LMC Disk
IV. Conclusion

Ⅰ. High-energy gamma rays from the star-forming galaxies

- Properties of Star-forming (SF) galaxies
  - Large and intensive star-forming regions
  - High gas density to form numerous stars

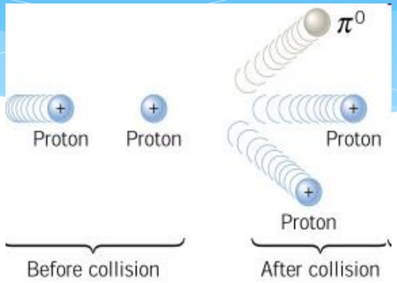
- Example
  - LMC, SMC
  - M82, NGC 253 (starburst galaxy)

M82 [Chandra-HST-Spitzer]

CR-induced HE gamma rays (>~100MeV) SFR∝Lγ

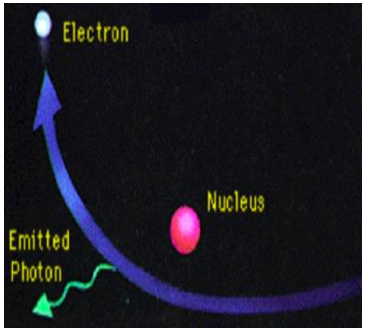
Hadronic gamma-ray emission

$$p^+_{\rm CR} + p^+_{\rm ISM} \rightarrow p^+ + p^+ + \pi^0, \pi^0 \rightarrow \gamma + \gamma. \quad (1)$$



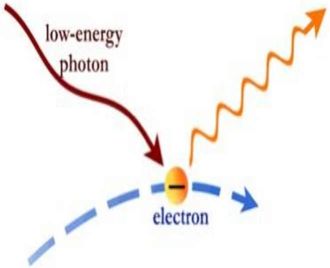
Bremsstrahlung radiation

$$e^-_{\rm CR} + p^+_{\rm ISM} \rightarrow e^- + p^+ + \gamma. \quad (2)$$



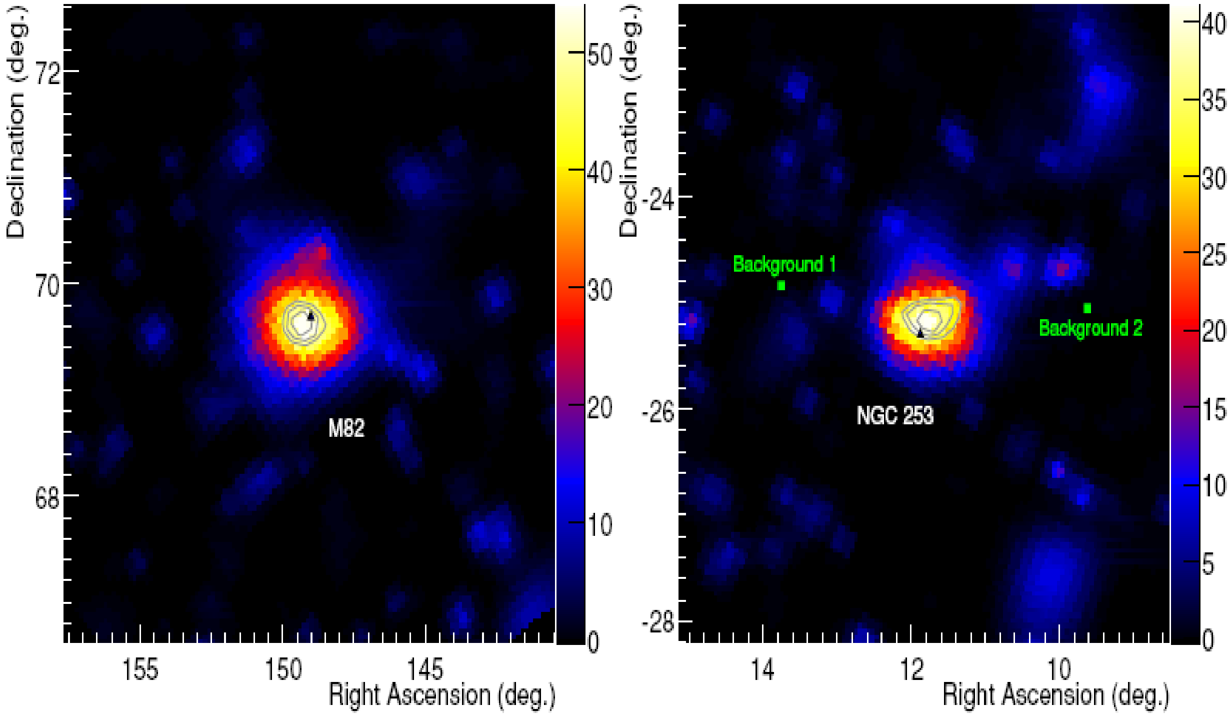
Up-scatter interstellar radiation

$$e^-_{\rm CR} + \gamma_{\rm ISRF} \rightarrow e^- + \gamma_{\gamma-{\rm ray}}. \quad (3)$$

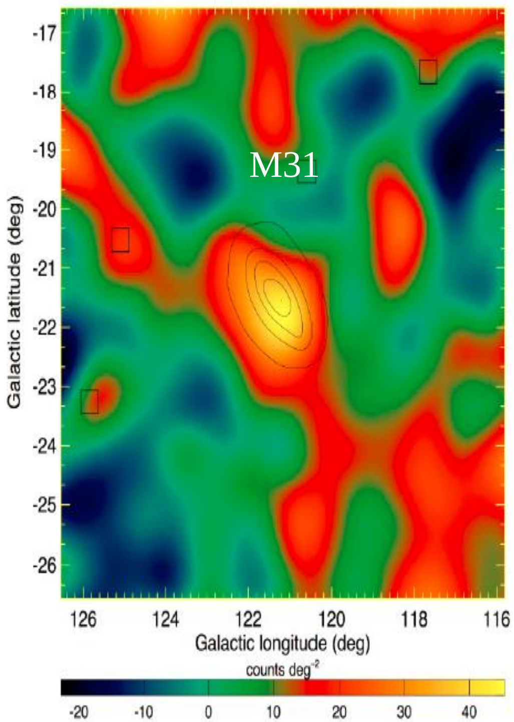


Foreman+2015 ApJ 808, 44

Detection of HE gamma rays in SF galaxies

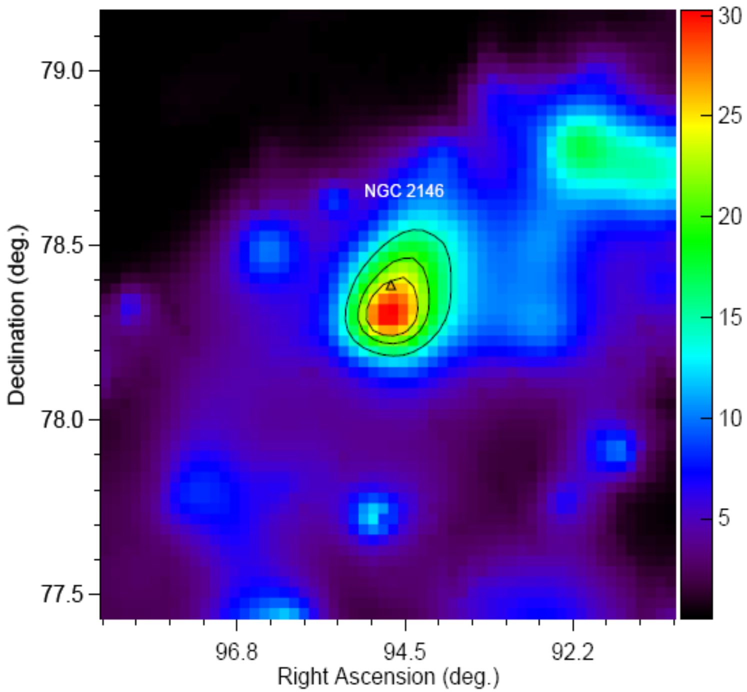


M82 and NGC 253 **Fermi LAT Collaboration (2010) ApJL 709, L152**

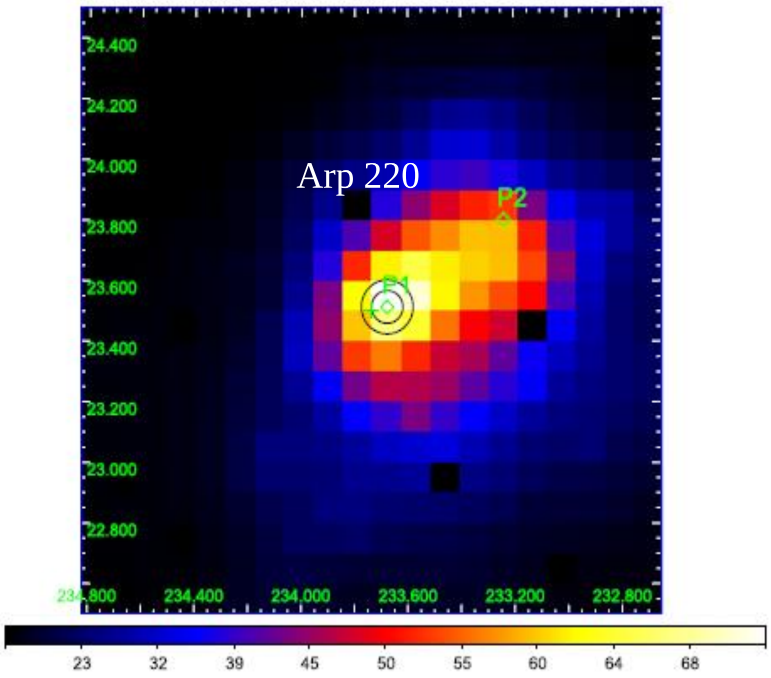


M31 **Fermi LAT Collaboration (2010) A&A 523, L2**

LIR and ULIR SF galaxies (SFR∝L_{IR})



NGC 2146 Tang+2014 ApJ 794, 26

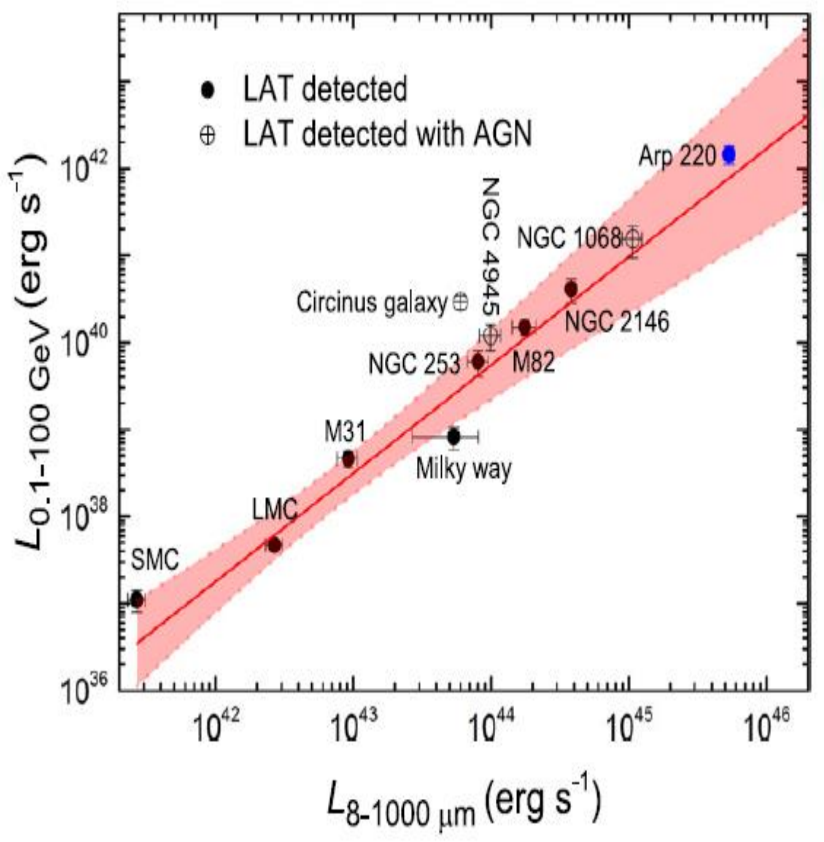


Arp 220 Peng+2016 ApJ 820, L20

Fermi LAT detection

L_{IR} and Lγ

Low energy break studies



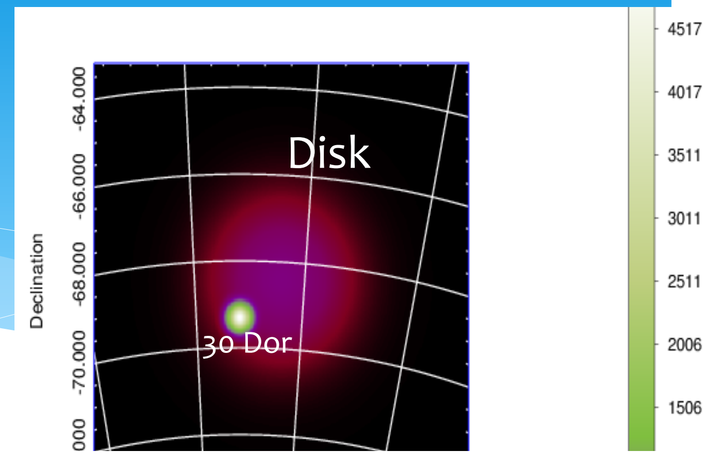
[Peng+ 2016 ApJL 820, L20](#)

LMC

- spatially resolved in GeV Band
- Far from the Galactic plane, less contaminated by diffusion background than IC 443 and W44

A good sample to resolve its components in gamma rays!

Ⅱ. Templates for LMC field



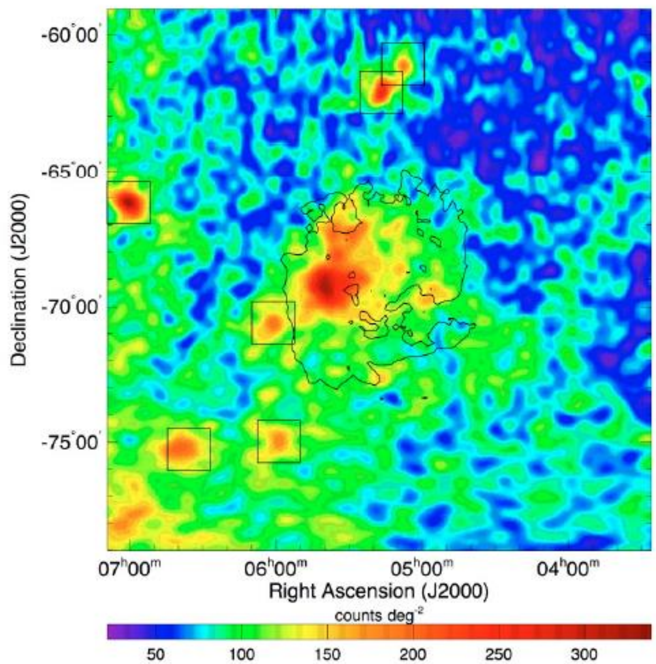


Table 3. Parameters of the 2D Gaussian sources model 2DG.

	Src.	ΔTS	α_{J2000}	δ_{J2000}	$r95$	σ	Flux
Disk ←	G1	1000.9	$05^h26.0^m$	$-68°16'$	$20'$	$73' \pm 5'$	19.6 ± 2.2
30 Dor ←	G2	121.7	$05^h38.8^m$	$-69°18'$	$7'$	$12' \pm 4'$	8.5 ± 2.2

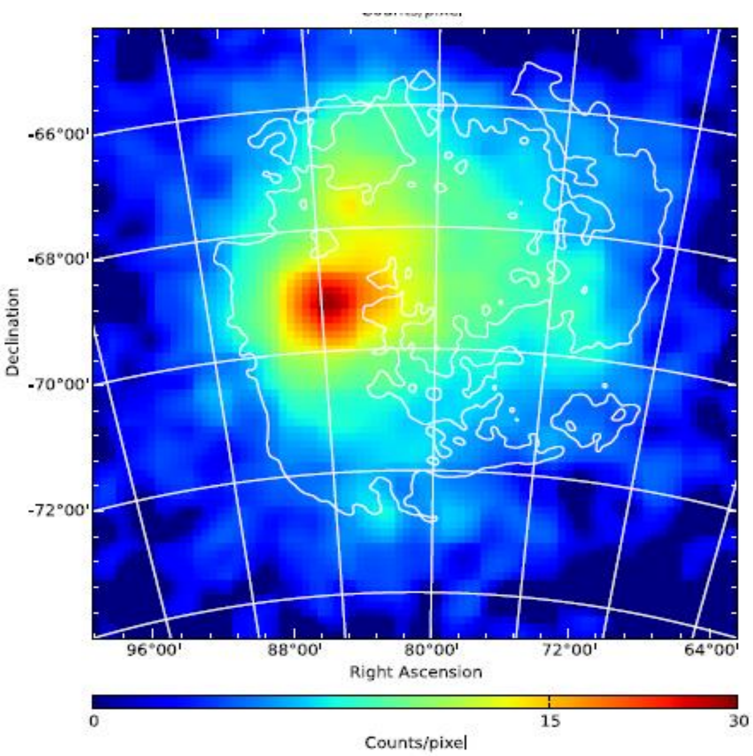
Abdo et al. (2010) A&A 512, A7

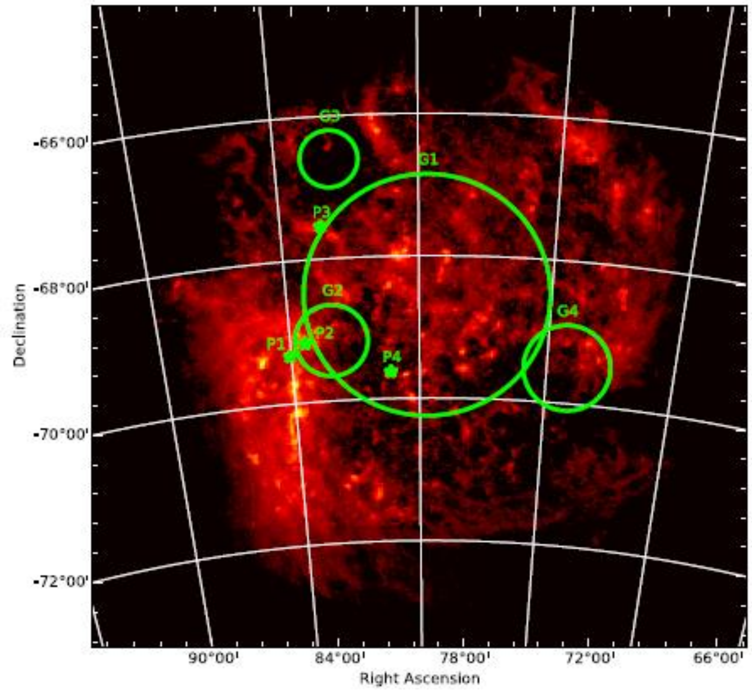
* **First 11 months** of Fermi-LAT observations

Template 1 +3FGL (T1)

Note: it is used in standard LAT analysis as of now.

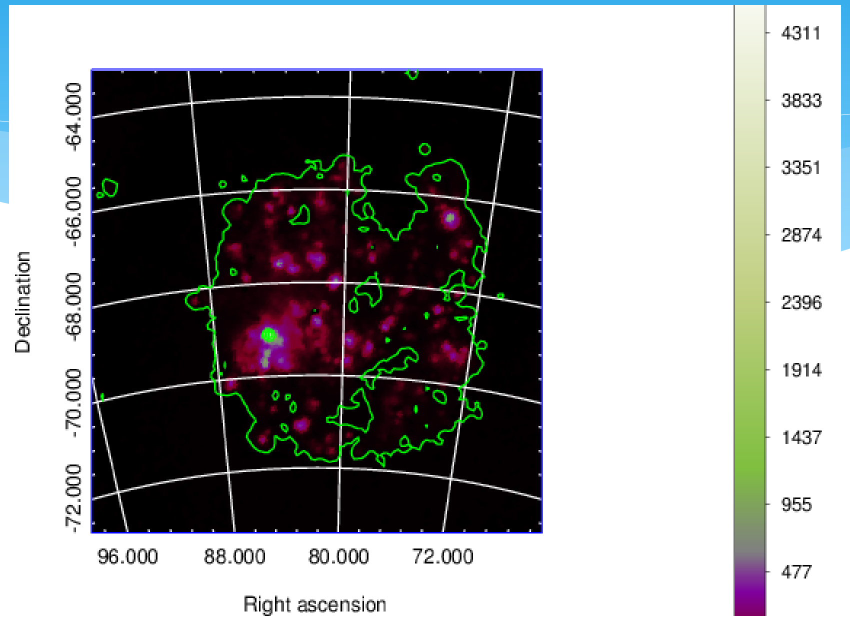
6 years' observations of Fermi-LAT



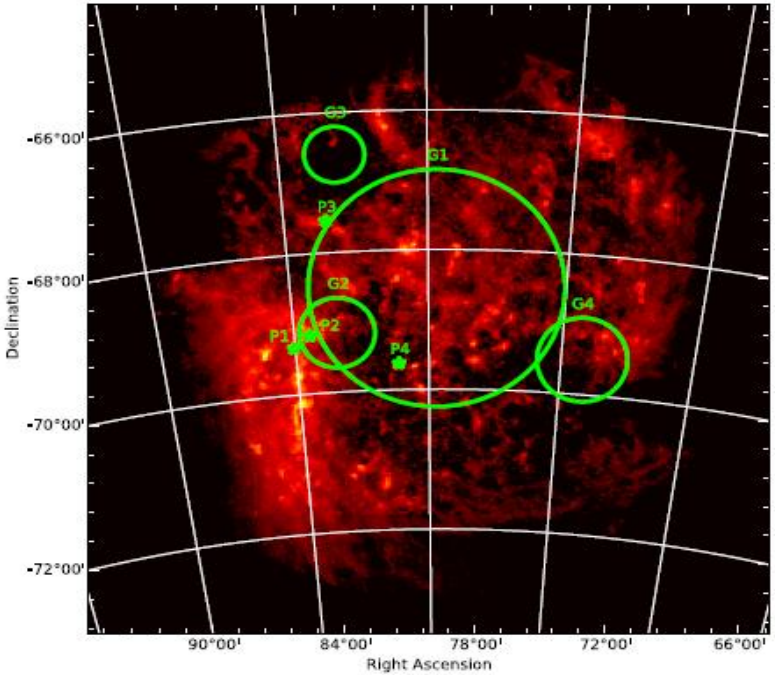


Ackermann et. al. (2016) A&A 586, A71

Template 2 (T2)



- Remove the LMC field source in the 3FGL (LMC H Ⅱ region)
- Add the P1 (PSR 0540-6919, N158A), P2 (PSR 0537-6910, N157B), P3 (Gamma-ray binary), P4 (SNR, N132D) and four extended sources (G1-G4)



Ackermann et. al. (2016) A&A 586, A71

Note: it is not employed in the standard LAT analysis.

Fermi-LAT analysis with 8 years' data

* Data coverage:
  1. 2008-2016, 8years
* Date base: P8_Source, 10°× 10° (ROI)
  1. 1-100 GeV
  2. 0.2-100 GeV
* Template for LMC region :
  1. T1
  2. T2

→ First, any new sources detected?

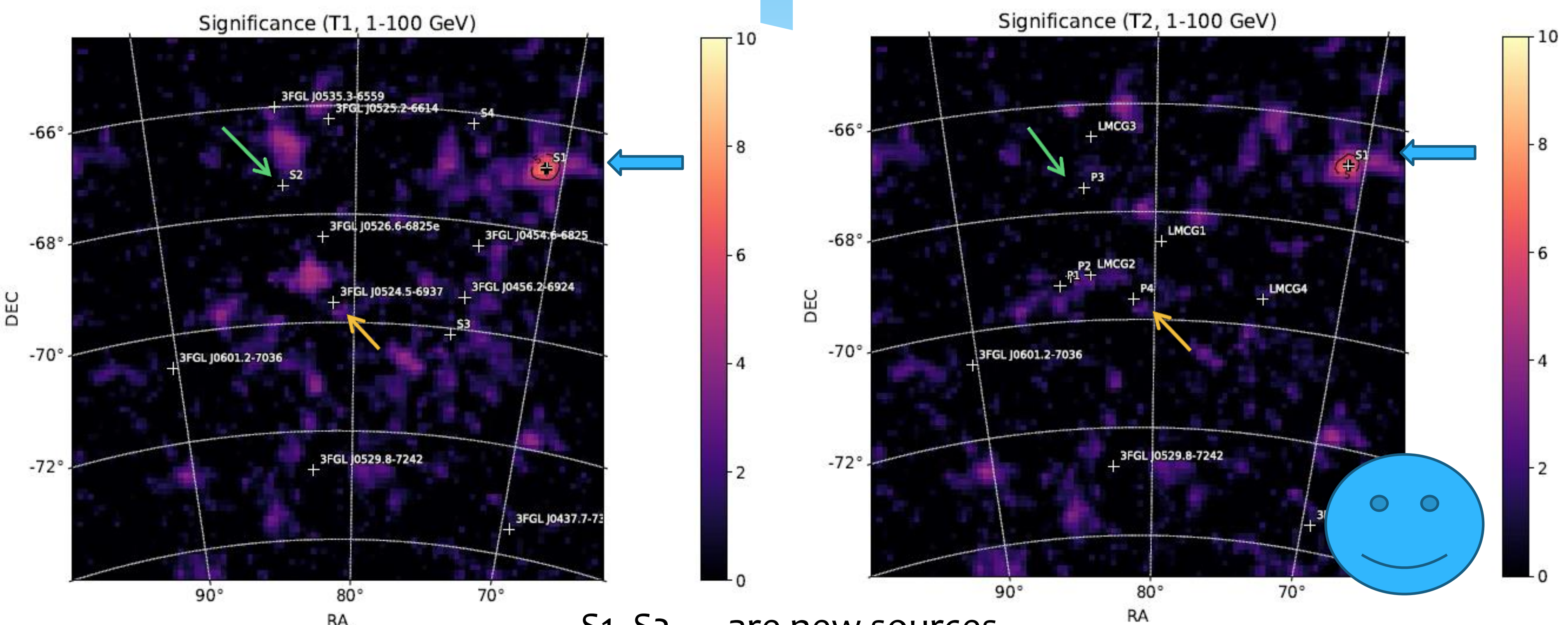
Second, which one is better?

Template comparison with data of 8 years

* T1: (Disk+30 Dor) + 3FGL sources
* T2: G1-G4+P1-P4 (LMC field) +3FGL sources (outer of the LMC field)

Which one is better? → Likelihood fit (L) + Residual TSmap→

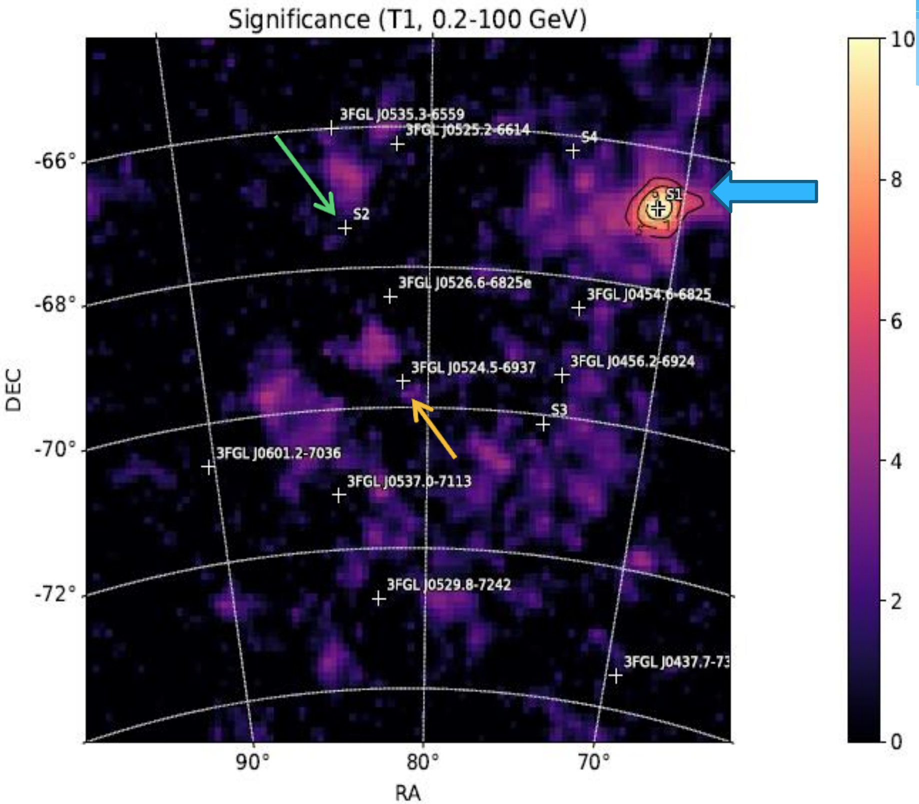
Comparison in 1-100 GeV

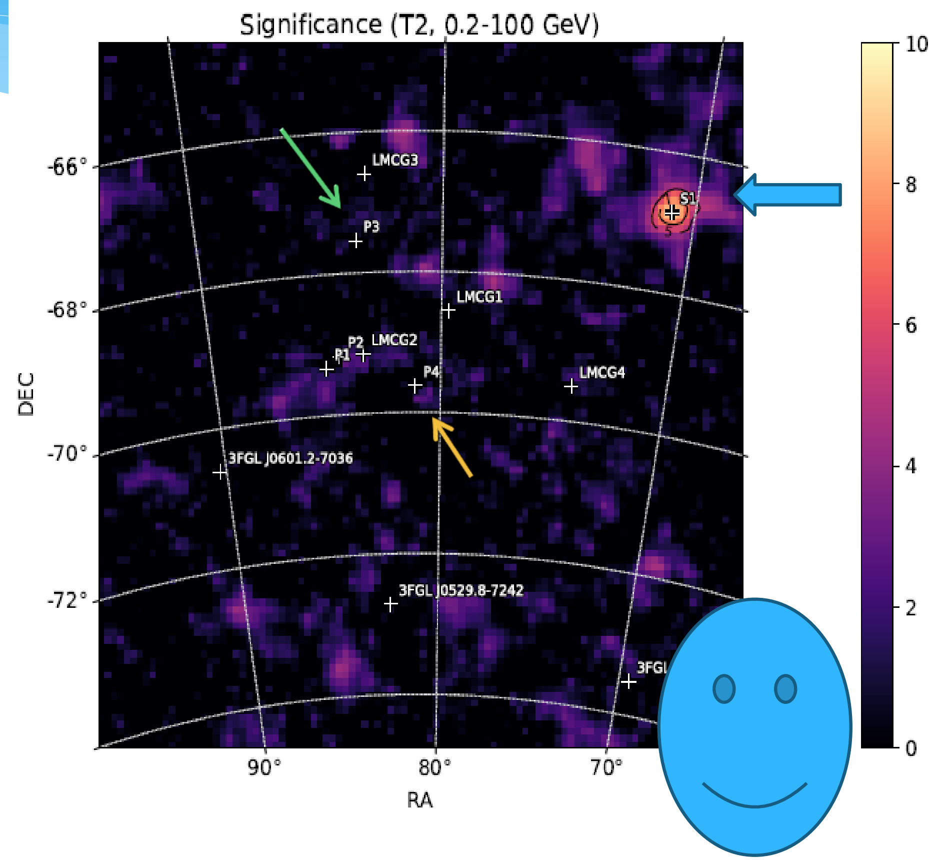


S1, S2… are new sources

* Significance maps, **1-100** GeV, **8** years. (Left) T1, (Right) T 2.

Comparison in 0.2-100 GeV

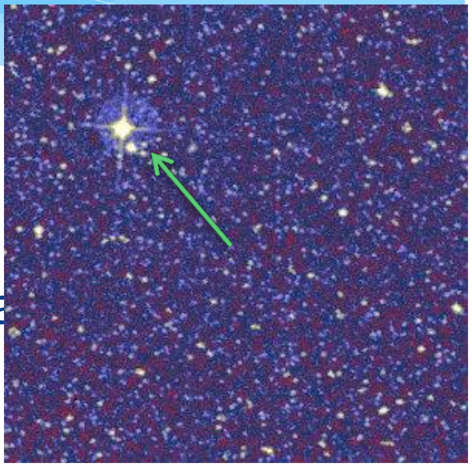




* Significance maps, **0.2-100** GeV, **8** years. (Left) T1, (Right) T2.

Candidates for the new point source S1

* Search four catalogs for the candidate source
  1. CRATES Flat-Spectrum Radio Source Catalog
  2. Veron-Cetty Catalog of Quasars & AGN
  3. Candidate Gamma-Ray Blazar Survey Source Cata
  4. The ATNF Pulsar Catalog version 1.56



0.14^2 degrees

* Only one source within r_{95}, **CRATES J044318-665155**.
* 0.037 degrees away from the new point source.

RA	Dec	r_68	r_95
70.856	-66.833	0.056	0.091

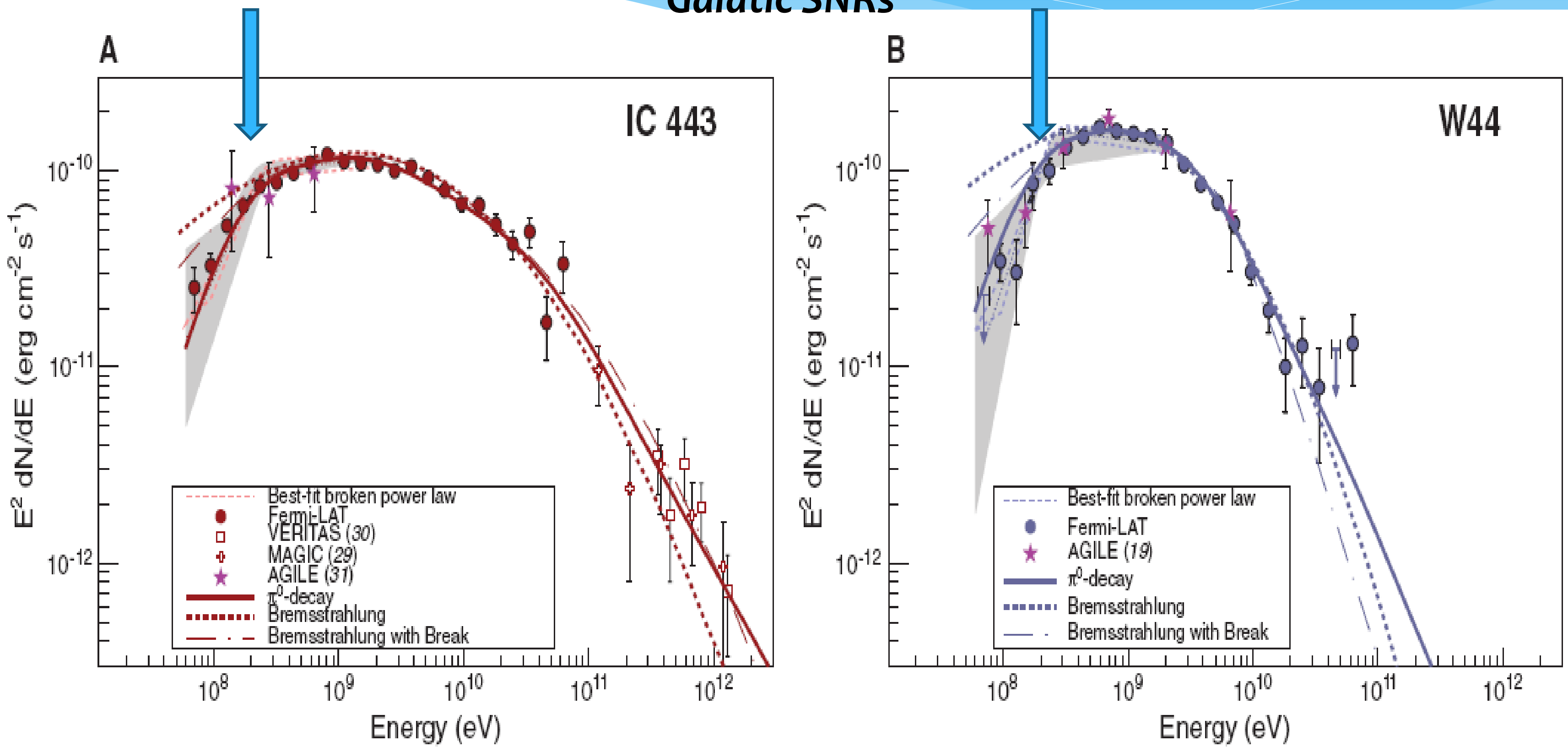
Results

I. T2 is a good template for modelling the gamma rays from the LMC observed by Fermi-LAT.

II. A new point source (S1) is detected near the LMC region.

Ⅲ. Physical origin of gamma-ray emission from the LMC Disk

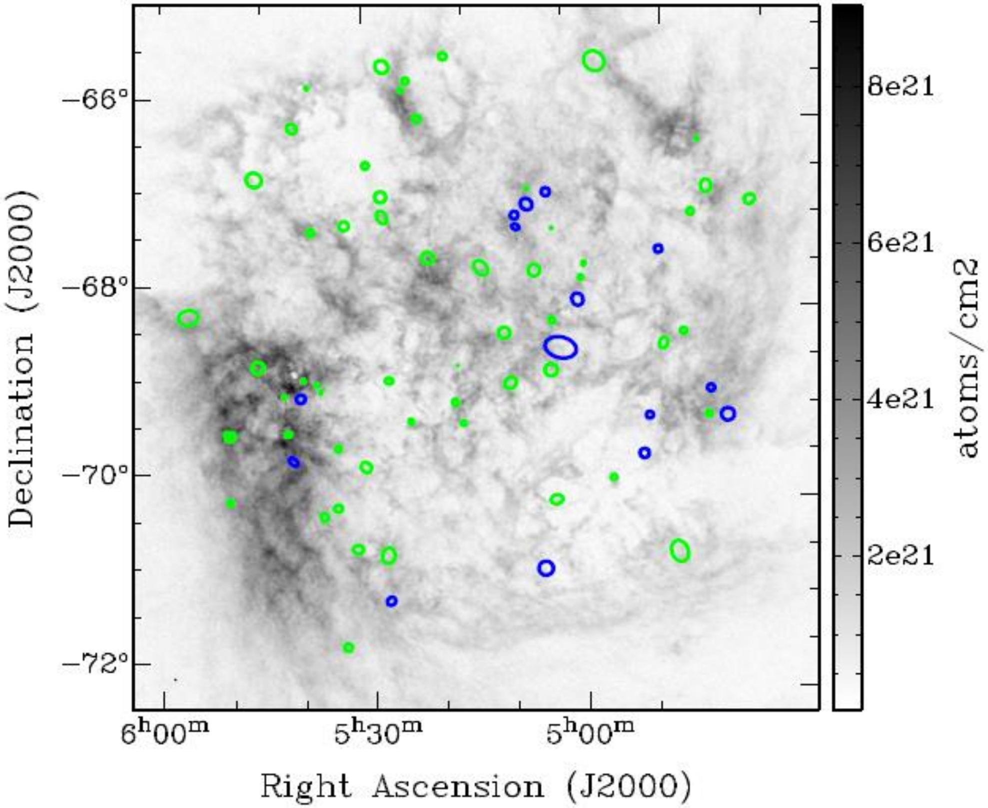
Galatic SNRs



- **Breaks between 0.06-2.0** GeV, evidence of pion-decay gamma rays.

Ackermann et. al. (2013) Science, 339

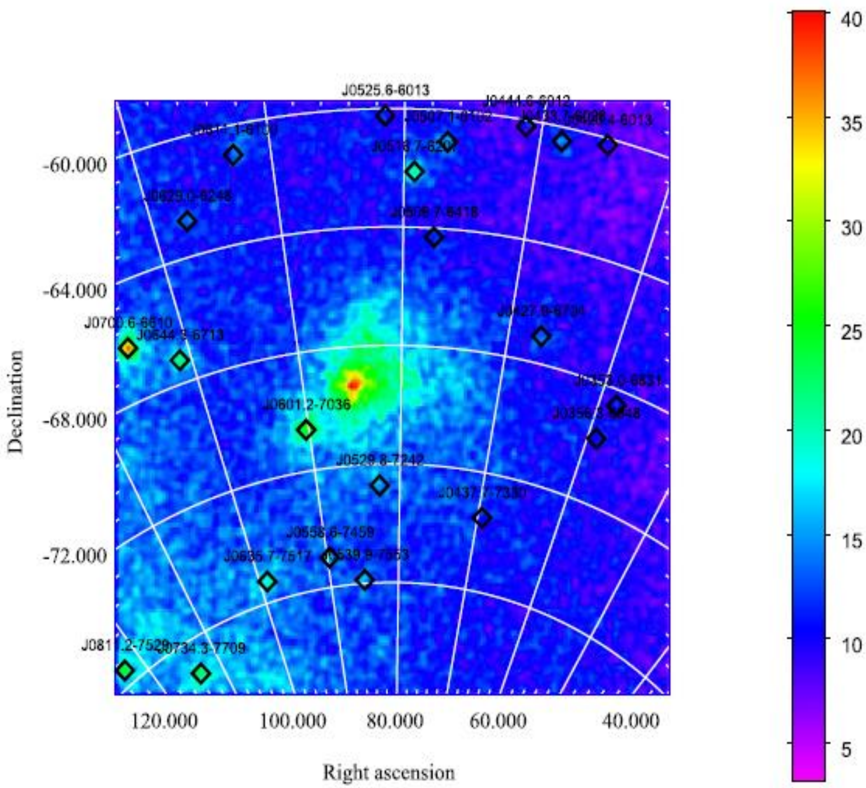
SNRs in the LMC region

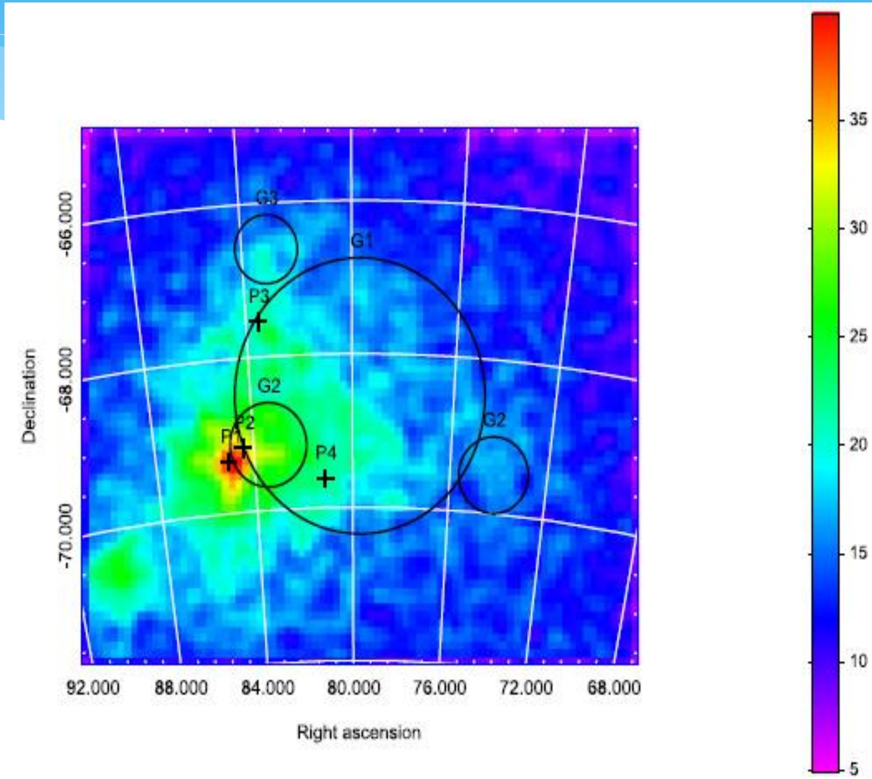


- Green: 59 confirmed
- Blue : 15 candidates

Bozzetto et. al. (2017) ApJS, 230,2

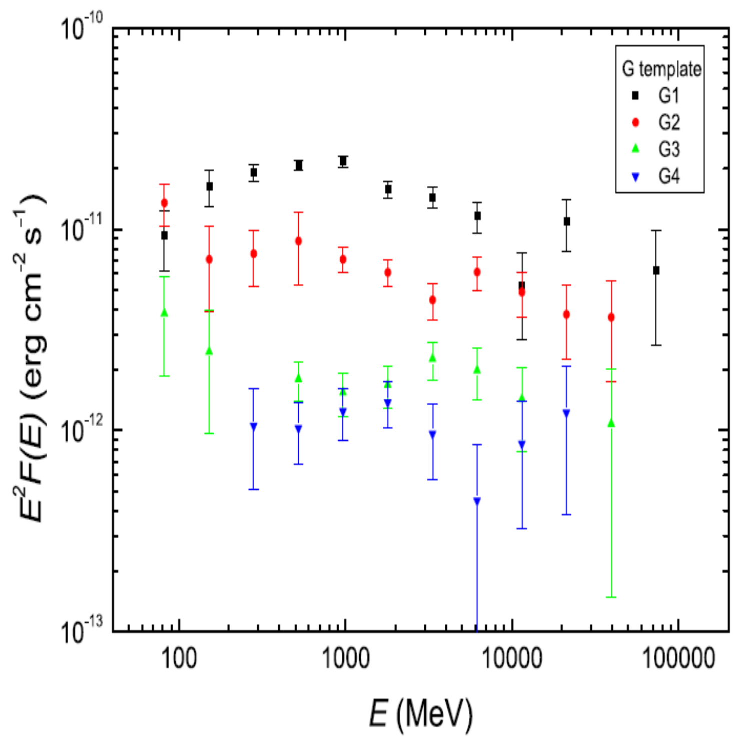
Low-energy data of LMC by LAT





* **0.06-2.45** GeV, with Model 2 **Tang+2017 ApJ, 843,42**

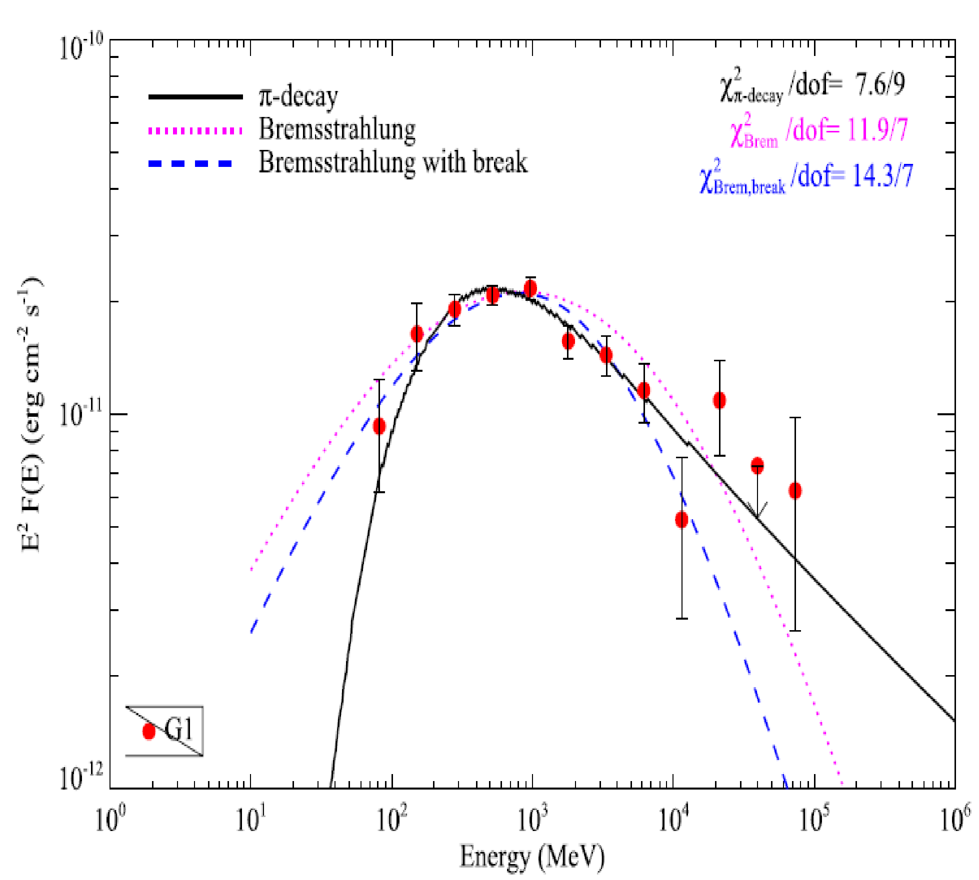
Detection of Low-energy Break



Broadband Analysis Results of the G1 Component

Model	E GeV	Component	K[a]	Γ_1[b]	Γ_2[c]	E_{br}[d] MeV	$\log L_0$[e]	$\log L_1$[e]	TS[e]	ΔTS[e]
PL	0.06–2.45	G1	4.0 ± 0.2	1.89 ± 0.03	...	...	−546725	−546350	750	...
BPL	...	...	3.8 ± 0.1	1.48 ± 0.09	2.35 ± 0.11	497 ± 78	...	−546317	816	66
PL	0.06–100	...	4.1 ± 0.2	2.06 ± 0.02	...	...	−261700	−261305	790	...
BPL	...	...	3.4 ± 0.1	1.39 ± 0.03	2.40 ± 0.03	532 ± 20	...	−261215	970	180

Modelling Results



* Pion decay model can be a better model!

Results

Table 3
Derived Parameters from the Physical Models for the G1 Component

Model	n_H cm^{-3}	$B\mu$G	U_{ph}eV cm^{-3}	s_{e1}[a]	s_{e2}[a]	$E_{e,b}$[a] MeV	s_p[b]	χ^2/dof	χ_r^2[c]
Bremsstrahlung[d]	$0.39^{-0.03}_{+0.03}$	$2.99^{-0.17}_{+0.20}$	$7.80^{-3.15}_{+6.73}$	$1.39^{-0.11}_{+0.12}$	...	...	...	7.7/6	1.28
...	$1.14^{-0.10}_{+0.10}$	$4.94^{-0.31}_{+0.34}$	$0.81^{-0.62}_{+1.18}$	2.00(fixed)	...	...	...	11.9/7	1.70
Bremsstrahlung with break[e]	$2.59^{-0.19}_{+0.19}$	$0.08^{-0.003}_{+0.004}$	0.01(fixed)	$1.45^{-0.74}_{+0.42}$	$2.41^{-0.06}_{+0.06}$	1318^{-382}_{+442}	...	6.7/5	1.33
...	$1.43^{-0.13}_{+0.14}$	$4.84^{-0.30}_{+0.35}$	$0.60^{-0.69}_{+1.34}$	1.80(fixed)	2.25(fixed)	4000(fixed)	...	14.3/7	2.04
π^0 decay[f]	...	...	...	...	...	...	$2.45^{-0.13}_{+0.14}$	7.6/9	0.85

* It favors for the pion decay model.

Ⅳ. Conclusion

* The template with 4 point sources and 4 extended sources is a good one to reproduce the LMC observations by Fermi-LAT.
* A new point source S1 is detected significantly and possibly linked with a AGN.
* The gamma-ray emission of the large-scale Disk of LMC favors for a hadronic origin, e.g., π^0 decay.

Thank you for your attention!