Contribution to the cosmic γ-ray background radiation from star-forming galaxies

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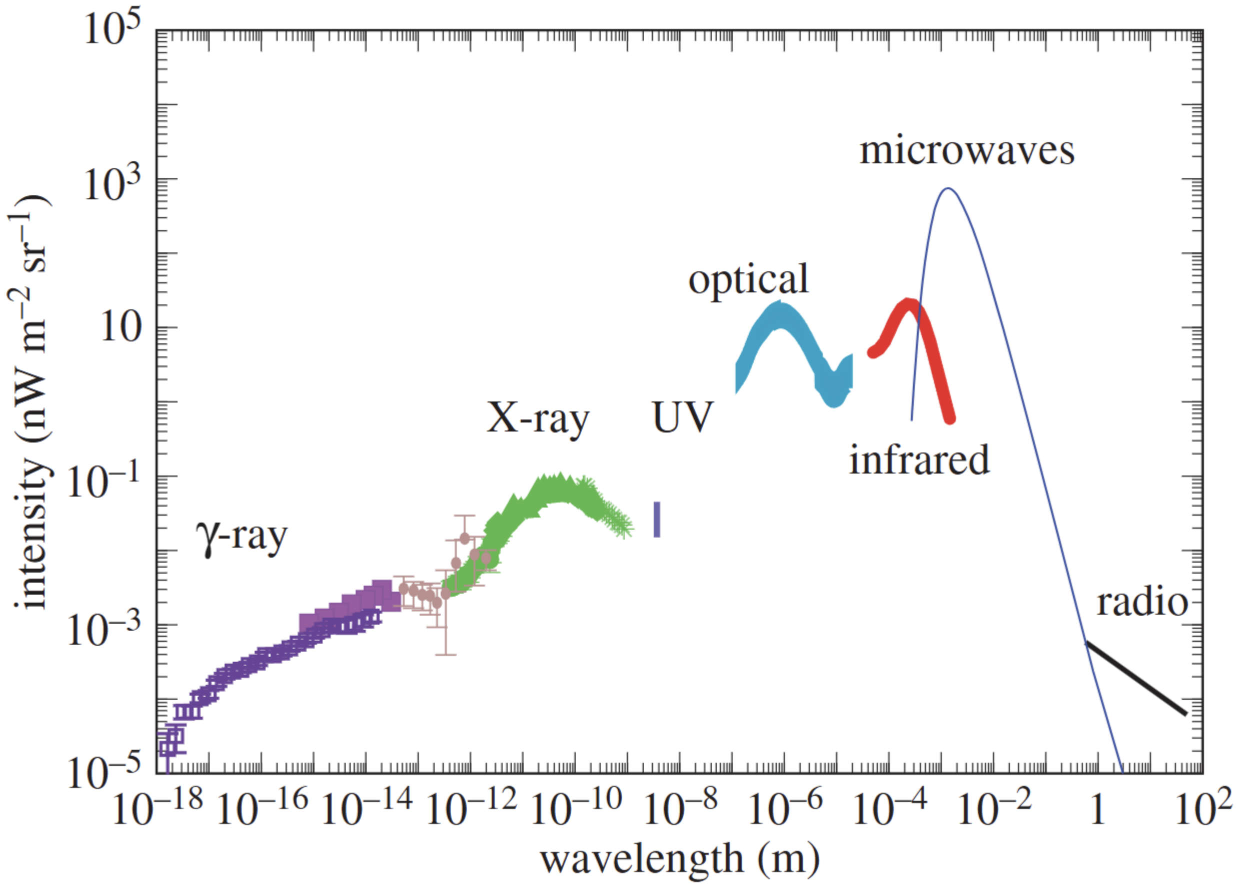
Cosmic Background Radiation



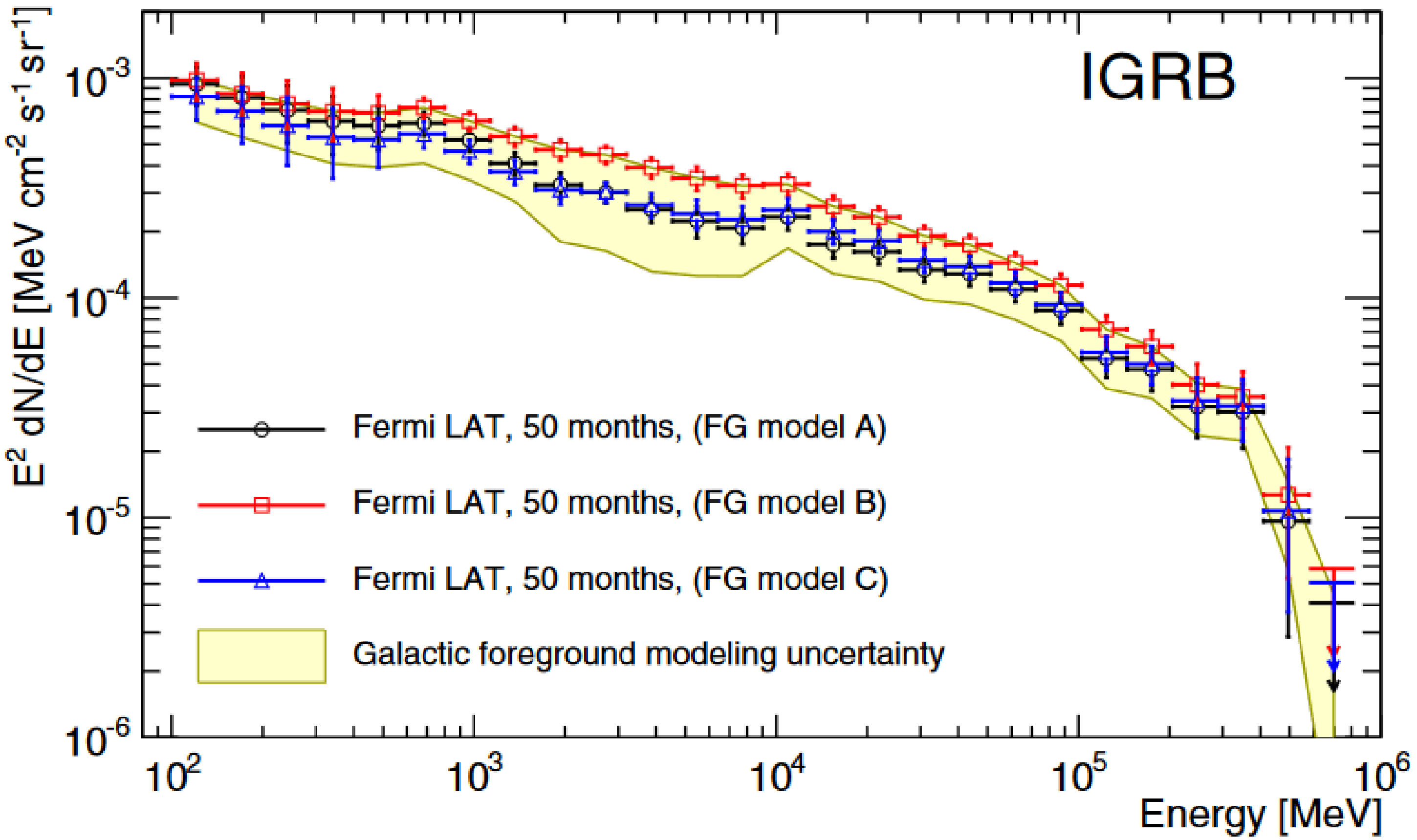
Spectrum of multi-wavelength cosmic background radiation

Cooray (2016)

Unresolved Isotropic Diffuse γ-ray Background (IGRB)

- Extragalactic γ-ray background (EGB or IGRB): contains both resolved and unresolved γ-ray sources, which is a constant.
- Unresolved IGRB: contains the diffuse unresolved extragalactic sources and potential unresolved Galactic emission.

Unresolved Isotropic Diffuse γ-ray Background (IGRB)



Ackermann et al. (2015)

Integrated LAT counts above 100MeV that used for the analysis of IGRB

Spectrum of derived IGRB by Fermi LAT

Candidate Sources

- Star-forming galaxies ← What we are interested in
- Active galactic nuclei
- Millisecond pulsars
- Dark matter annihilation

Review of Previous Works

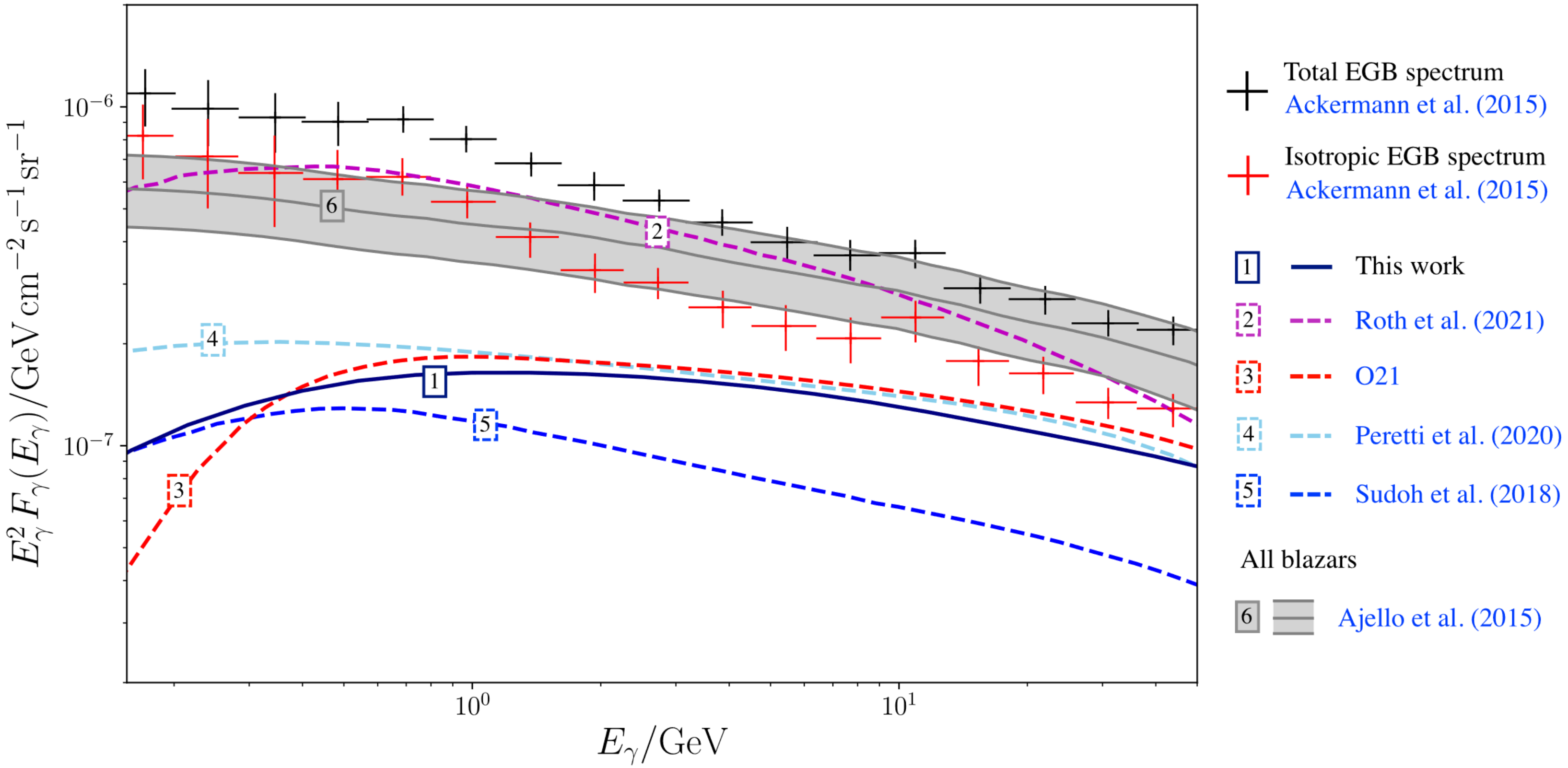


Figure A1. Total contribution from SFGs (starburst and main sequence) to the isotropic EGB, between 0.1 and 50 GeV. The fiducial result from this work is given by line 1, which is in agreement with the constraint imparted by the contribution from resolved and unresolved blazars (grey band, denoting the three models of Ajello et al. 2015) and the observed EGB with 50 months of *Fermi*-LAT data (Ackermann et al. 2015), determined using their foreground model A. Comparison is made with four recent works; Roth et al. 2021 (line 2), O21 (line 3), Peretti et al. 2020 (line 4), and Sudoh et al. 2018 (line 5).

25%

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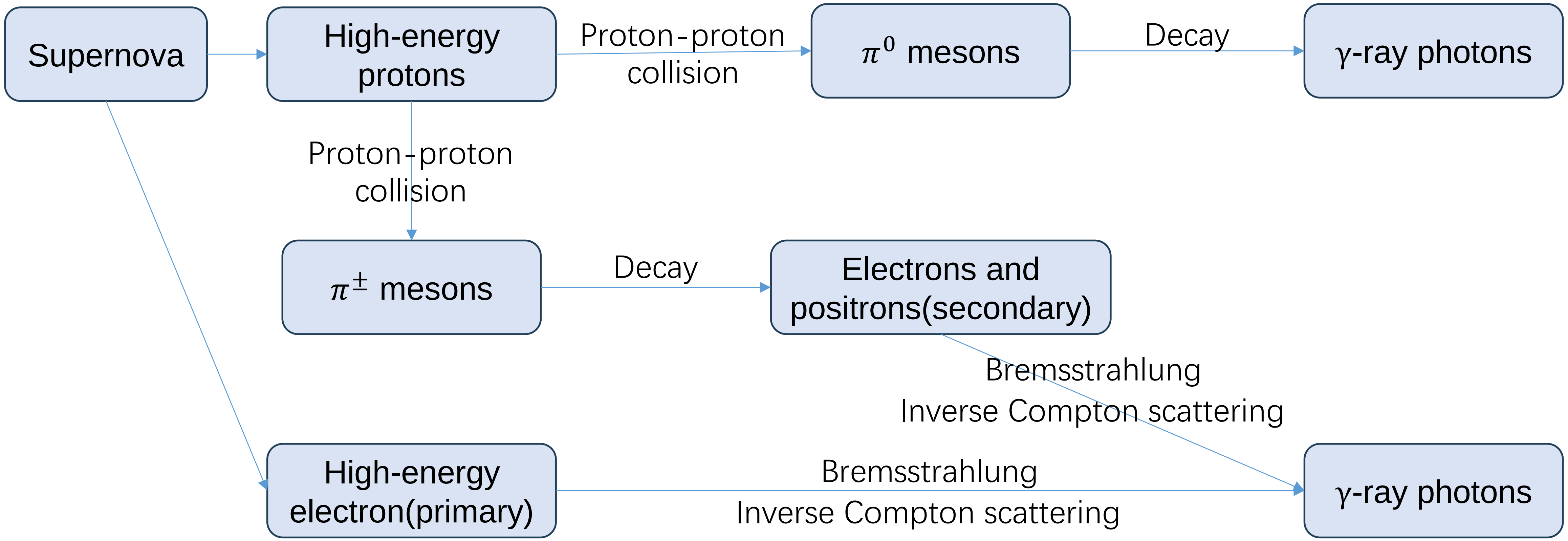
Owen et al. (2022)

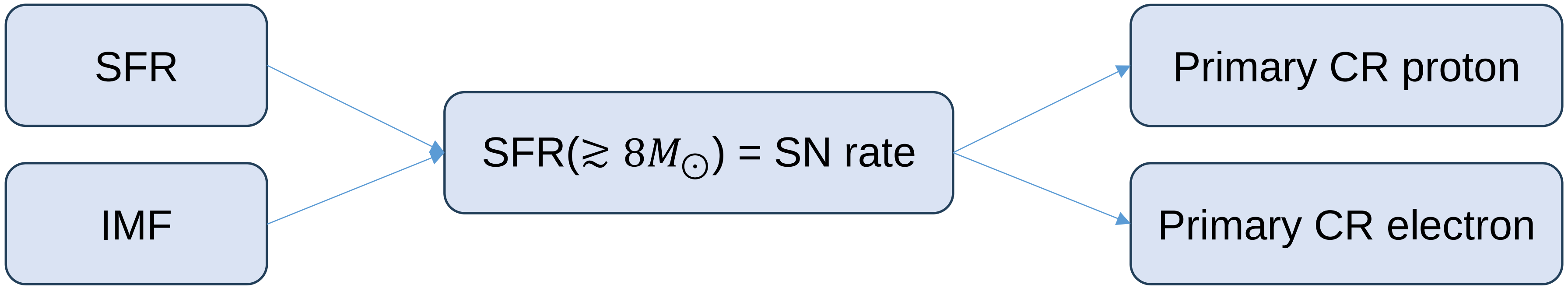
Basic Mechanism



Basic Mechanism

- What we need to know from galaxy properties:
- 1. Injection of cosmic rays from supernova events
    - Star-formation rate (SFR), injection fraction from supernova
- 2. Fraction of cosmic rays interacting with interstellar medium (ISM)
    - Gas & stellar mass, radius and scale height
- 3. Production rate of γ-ray photons
    - Radiation field (inverse Compton scattering)

Production of Primary Cosmic Rays



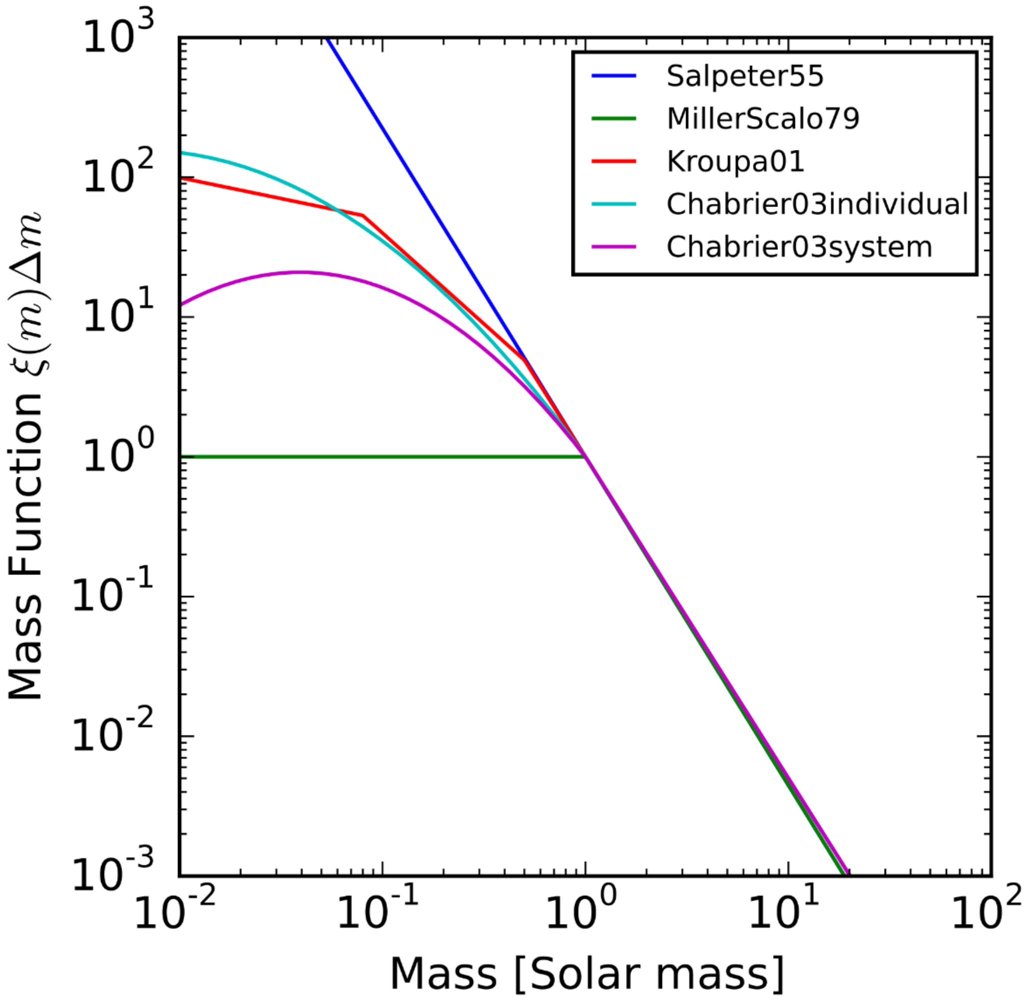
- Proton / Primary electron

$$\frac{dN_i}{dtdE_i} = C_i\left(\frac{SFR}{M_\odot yr^{-1}}\right)\left(\frac{E_i}{GeV}\right)^{-\Gamma_{inj}}$$

- $C_p = 3.83 \times 10^{45} s^{-1} erg^{-1}$
- $C_e = 0.012 C_p$
- $\Gamma_{inj} = 2.2$ (from observation)

Initial Mass Function (IMF)

- The initial distribution of masses for a population of stars during star formation.
- Necessary to determine galaxy properties! (SFR, mass…)



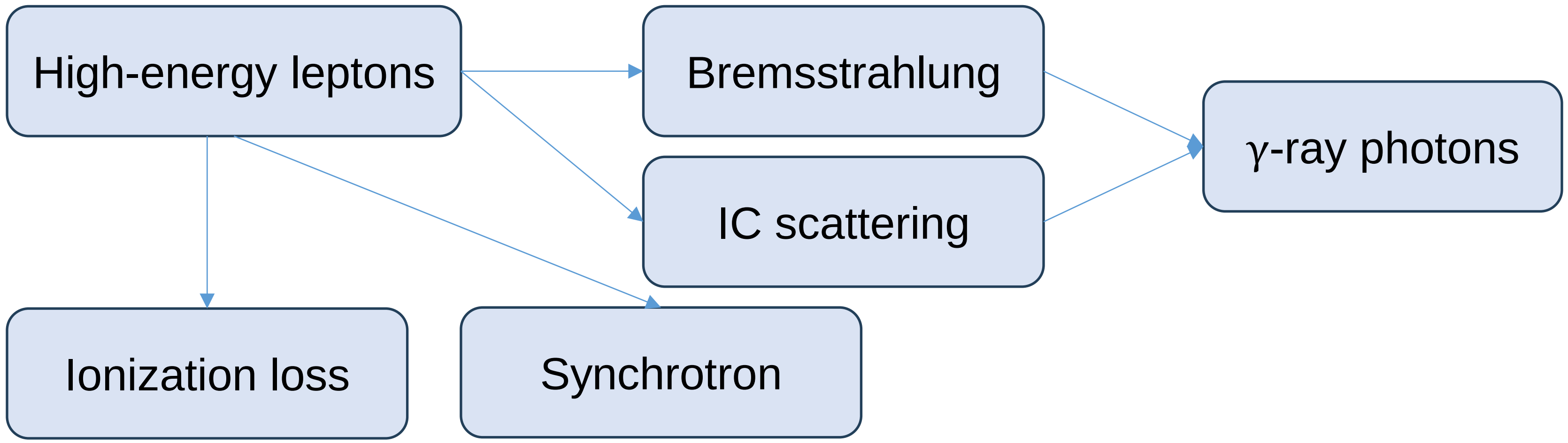
Propagation and Interaction of Cosmic Rays

- Fraction of cosmic rays interacting with ISM

$$f_{cal}(E_p) = 1 - exp(-t_{esc}/t_{pp})$$

- $t_{esc}(E_p) = min[t_{diff}, t_{adv}]$
- $t_{pp}(E_p) = (n_{gas}\sigma_{pp}c)^{-1}$

Cosmic ray lepton emission



- Bremsstrahlung: Radiation produced by the deceleration of high-energy leptons when deflected by ISM particles.
- Inverse Compton scattering: Low-energy photons scattered to higher energies by high-energy leptons.

γ-ray Flux at Earth

- γ-ray flux at earth:

$$\frac{dF_\gamma}{dE_\gamma} = \frac{(1+z)^2}{4\pi d_\mathrm{L}^2} \frac{dN_\gamma[E_\gamma(1+z)]}{dtdE_\gamma} e^{-\tau_\mathrm{EBL}}$$

d_L is the luminosity distance of the galaxy, $dN_\gamma[E_\gamma(1+z)]/dtdE_\gamma$ is the total γ-ray emission from a galaxy at energy $E_\gamma(1+z)$, τ_EBL is the optical depth from attenuation by EBL photons.

Application to Galaxy Samples

- We use the CANDELS GOODS-S sample from Roth et al. (2021). They select 22279 galaxies from 34930 galaxies in the full sample.
- Divide the sky into some slides ($\Delta z = 0.1$)
- Sum all fluxes of galaxies in the slide j

$$\sum_{i=1}^{n_{S,j}} \left(\frac{dF_{\gamma,i}}{dE_\gamma}\right)_{i,j}$$

- Here the $n_{S,j}$ is the number of CANDELS galaxies in the redshift bin
- Cosmic SFR best fitting function

$$\psi_{cosmic}(z) = 0.015 \frac{(1+z)^{2.7}}{1 + [(1+z)/2.9]^{5.6}} M_\odot year^{-1} Mpc^{-3}$$

Application to Galaxy Samples

- γ-ray flux from SFGs in the whole sky

$$\Phi(E_\gamma) = \frac{1}{\Omega_S} \sum_{j=1}^{n_{zbin}} f_{corr,j} \sum_{i=1}^{n_{S,j}} \left(\frac{dF_{\gamma,i}}{dE_\gamma}\right)_{i,j}$$

- $\Omega_S = 173 arcmin^2$ is the solid angle surveyed by CANDELS
- $f_{corr,j}$ is the ratio of total SFR to SFRs of CANDELS in a redshift bin

$$f_{corr,j} = \frac{\frac{4\pi}{3}(x^3(z+0.1) - x^3(z))\psi_{cosmic}(z)}{\sum_{i=1}^{n_{S,j}} \psi_{i,j}}$$

Verify models with nearby galaxies

Objects	D^{f} (Mpc)
MW	
LMC	0.05
SMC	0.06
NGC 253	3.5
M82	3.3
NGC 2146	17.2

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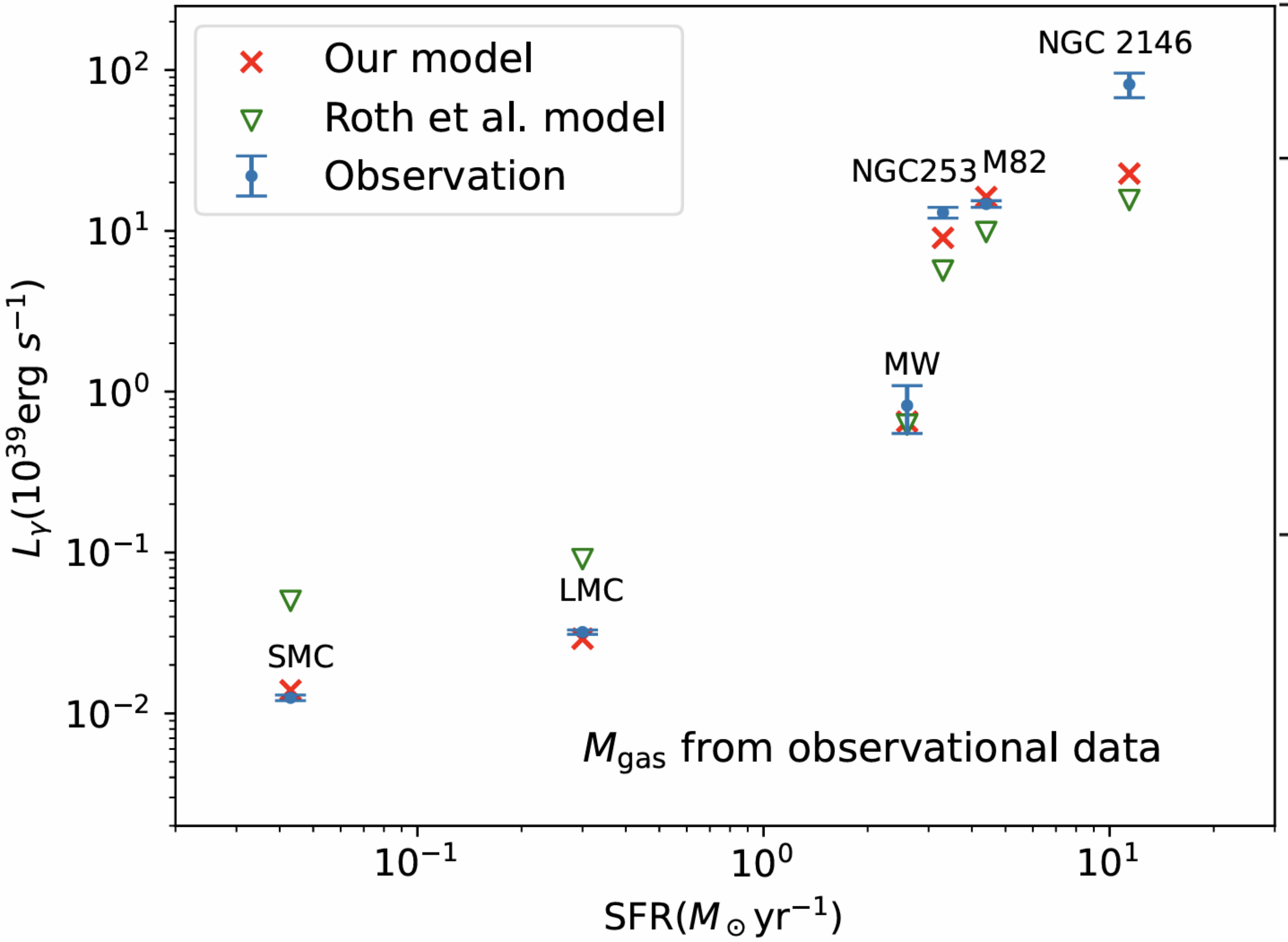


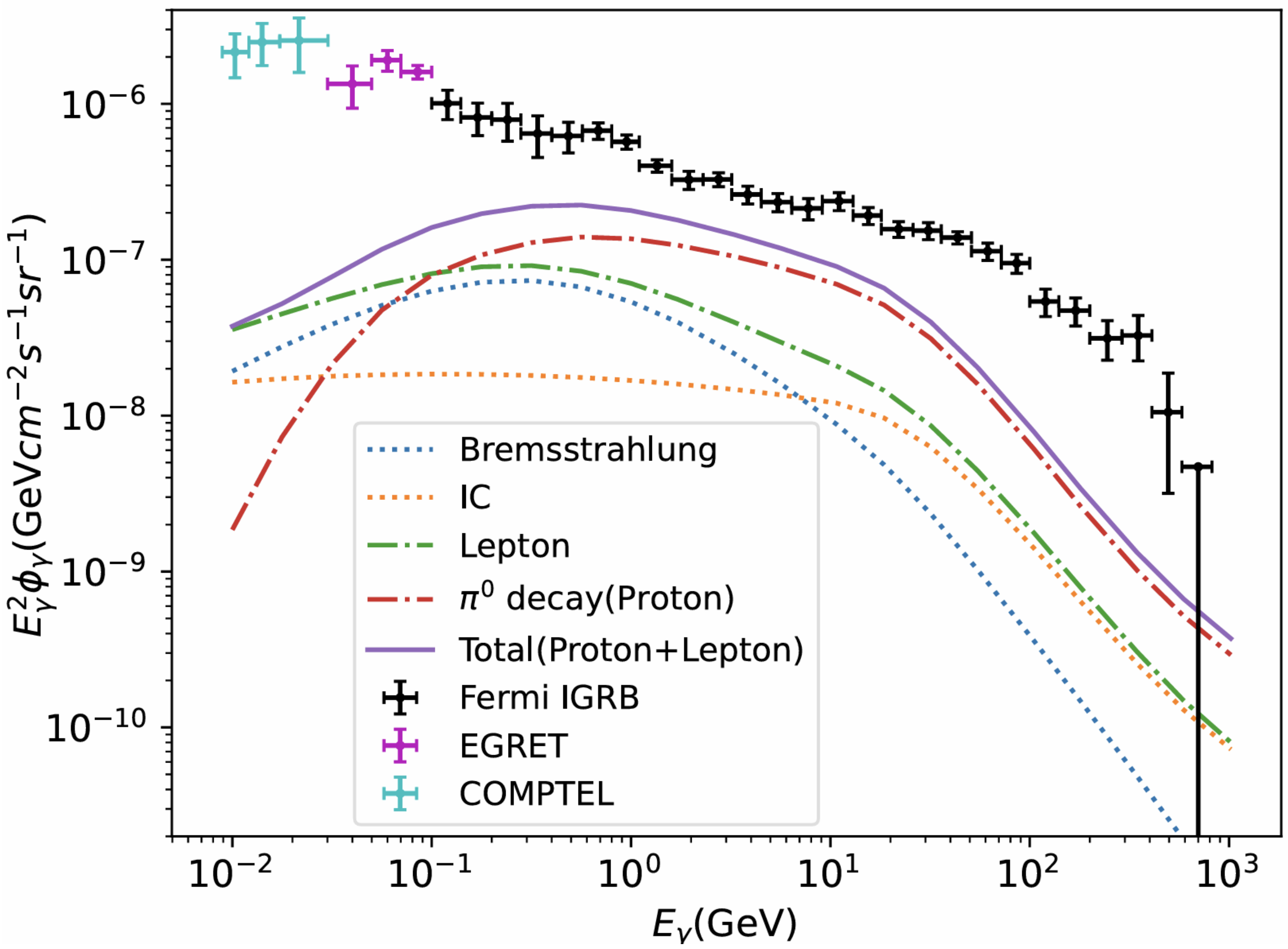
Our Result

Our Advantages

- In this work, we made some improvement compared with previous ones:

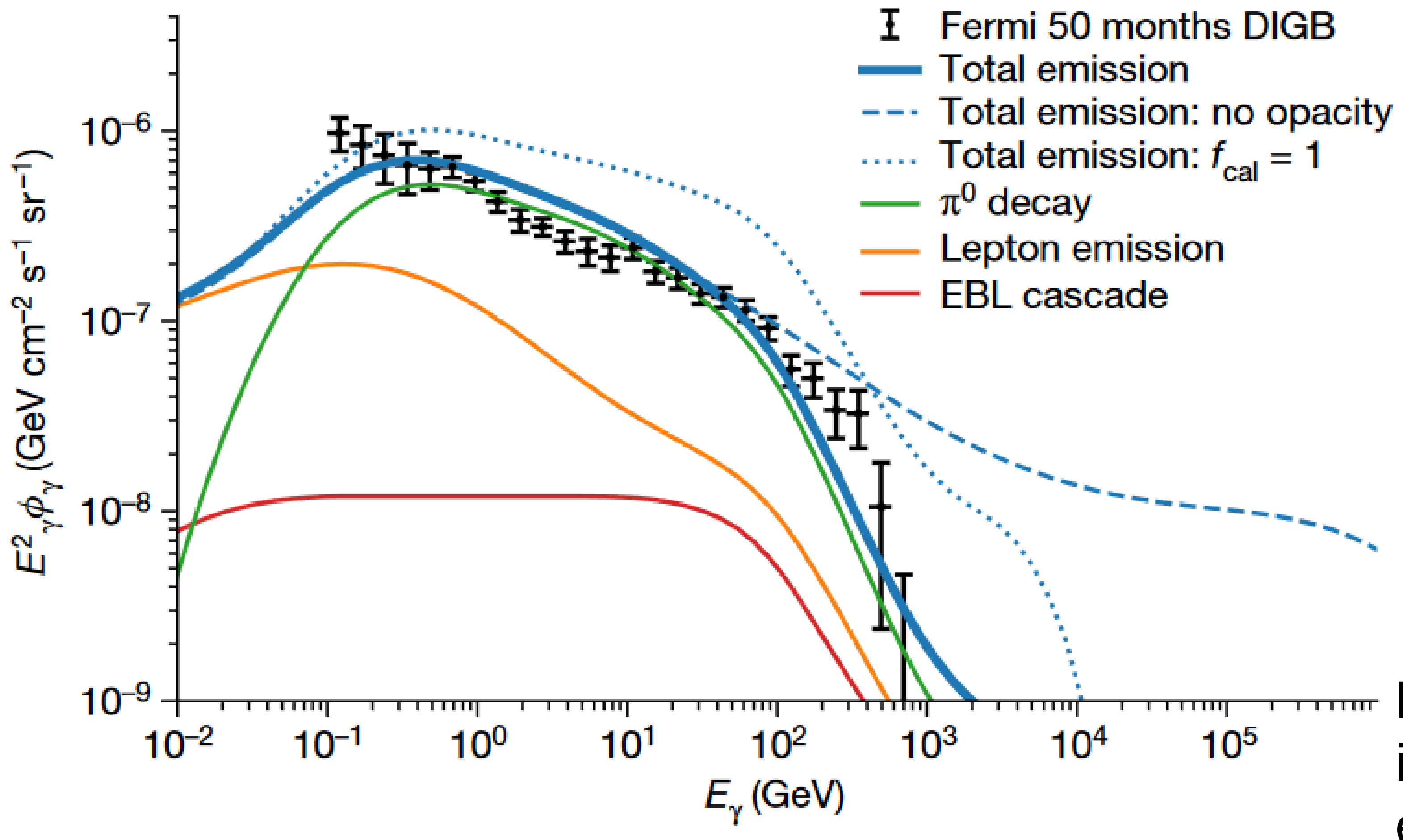
1. Use galaxy parameters of CANDELS, establish a comprehensive CR lepton emission model.
2. Base on careful normalization to nearby galaxies.
3. Keep consistency of initial mass function (IMF).
4. Describe lepton emission in more detail.
5. Up-to-date version of physical models.

Our Result



We apply the new model to calculate γ-ray luminosity from an SFG.
SFGs cannot explain the total unresolved background alone!

Research by Roth et al.



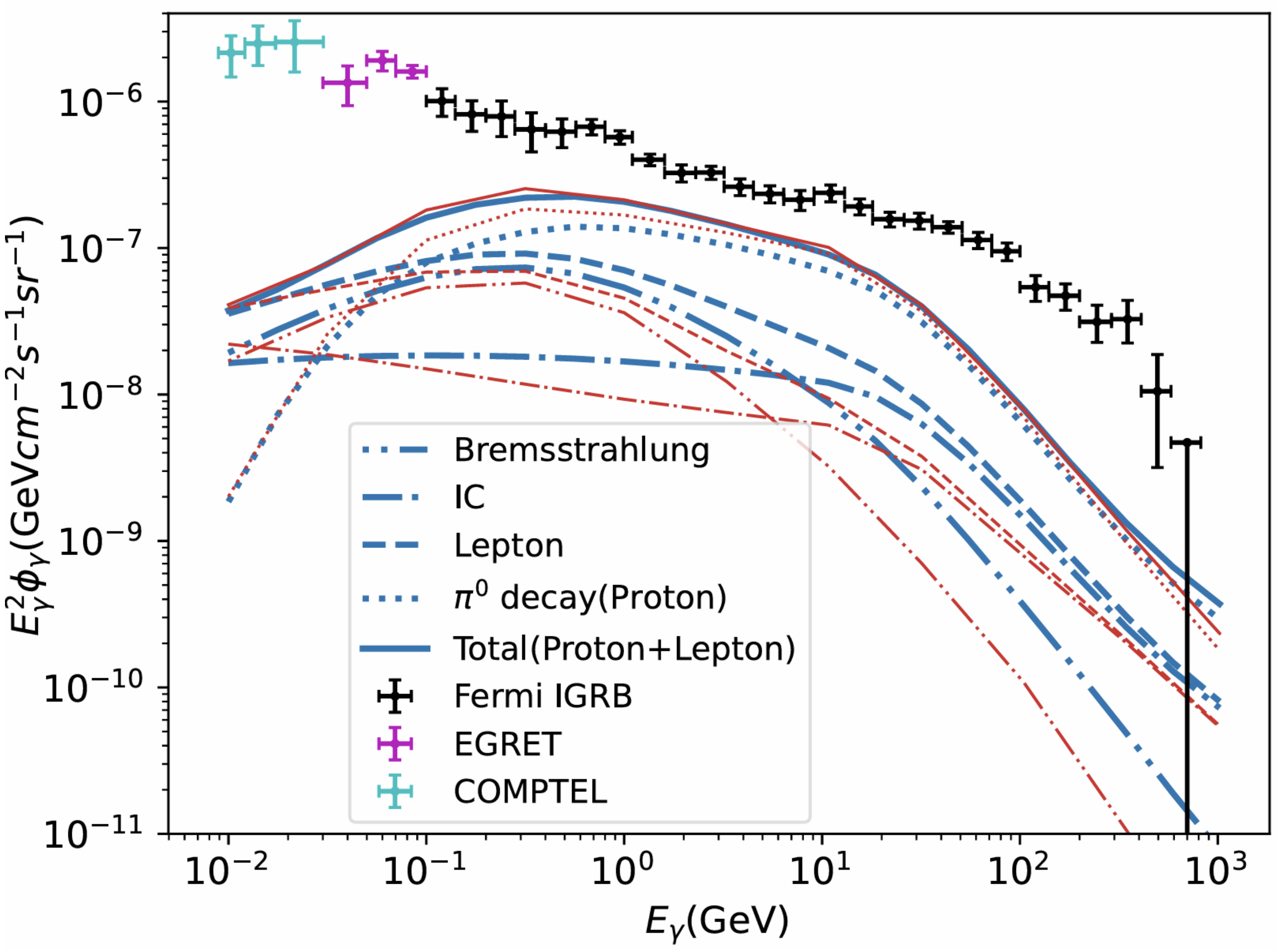
ELS, instead of

Roth et al. (2021), implies SFGs can explain the IGRB alone

What is the origin of the difference?

- In Roth+, the model flux is normalized by the factor “ϕ”, converting SFR into cosmic-ray production rate
  - $\phi = 7.15 \times 10^{42}\ \mathrm{GeV^{-1} s^{-1} (M_\odot/yr)^{-1}}$ in their paper
  - depends on IMF
    - their gamma-ray emission model uses Chabrier IMF
    - but their final background flux is re-calibrated by cosmic SFR evolution of Madau & Dickinson ‘14, which assumes Salpeter IMF
- We cannot reproduce the Roth+ ϕ value. By our own estimate,
  - $\phi = 5.40 \times 10^{42}$ assuming Chabrier IMF
  - $\phi = 3.45 \times 10^{42}$ assuming Salpeter IMF
- But we could reproduce the Roth+ background flux if we assume:
  - $\phi = 7.15 \times 10^{42}$ (the value in Roth+ paper)
  - cosmic SFR evolution assuming Salpeter
- However, the correct value of phi should be 3.45×10^{42}, according to our calculation
  - As a result, the background flux should be reduced by 3.45/7.15 = 0.48, roughly.

Comparison



Using the correct normalization factor (that we believe), Roth+ model flux is reduced, which becomes similar with our own background model flux using our emission model.

Future Work

- Current model considers few about the morphology, structure and other parameters of galaxies due to the lack of related information in deep field galaxy sample.
- The physical properties and gamma-ray spectra of nearby galaxies have been well observed and studied. We plan to establish a more detailed SFG gamma-ray emission model based on the nearby galaxies data in the future work.
- Open to any ideas about latest particle physics model knowledge!

Conclusion

- With our own estimate of the normalization factor, the Roth+ model gives a similar background flux with other previous studies including our own.
- It is unlikely that the background flux is explained 100% only by star-forming galaxies.
- SFGs are the major contributor (50-60%) to the unresolved IGRB in the energy band of 1-10 GeV.
- We established a comprehensive cosmic-ray lepton emission model.
- A more detailed SFG emission model will be established in future work.

Thank you for listening!