Cosmic Ray Interactions with Molecular Clouds Using GEANT4 Simulation

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Outline

- Introduction of Galactic Cosmic Rays
- Observation of γ-ray from GMCs
- GEANT4 MC Simulation
- Calculation and Result
- Summary and Future Works

Brief Introduction of Galactic Cosmic Rays

- CR distribution follows:
  $F(E) = AE^{-\alpha}$
- Changes of spectral index:
  3 PeV (Knee)
  5 EeV (Ankle)
- Sources of GCR:
  Supernova explosions
  Pulsar wind nebula, etc.
- Composition of CR:
  Protons [∼86%]
  α and heavy nuclei [∼12%]
  e^- and anti particles [∼2%]

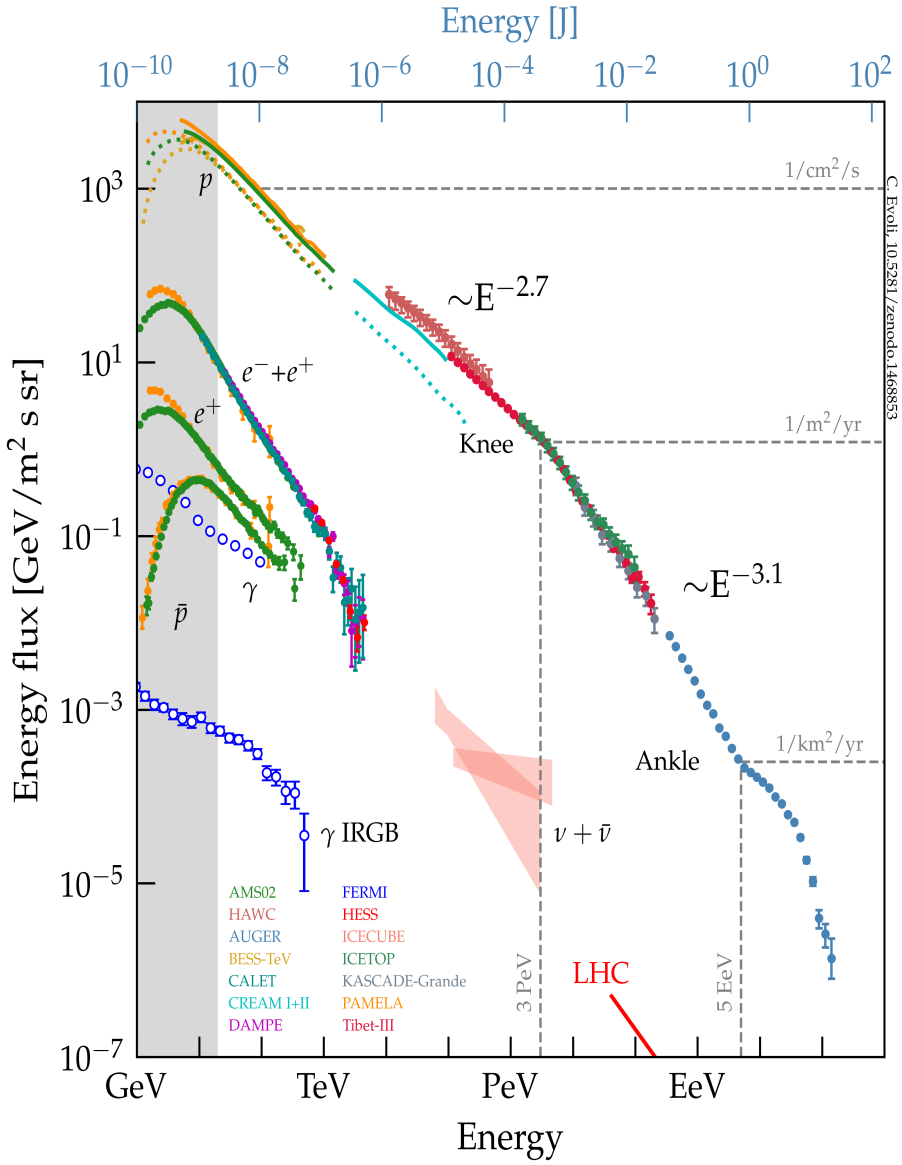

Fig: Observed CR flux near the Earth (*Evoli 2018*)

Interaction of Primary GCR in the Galaxy

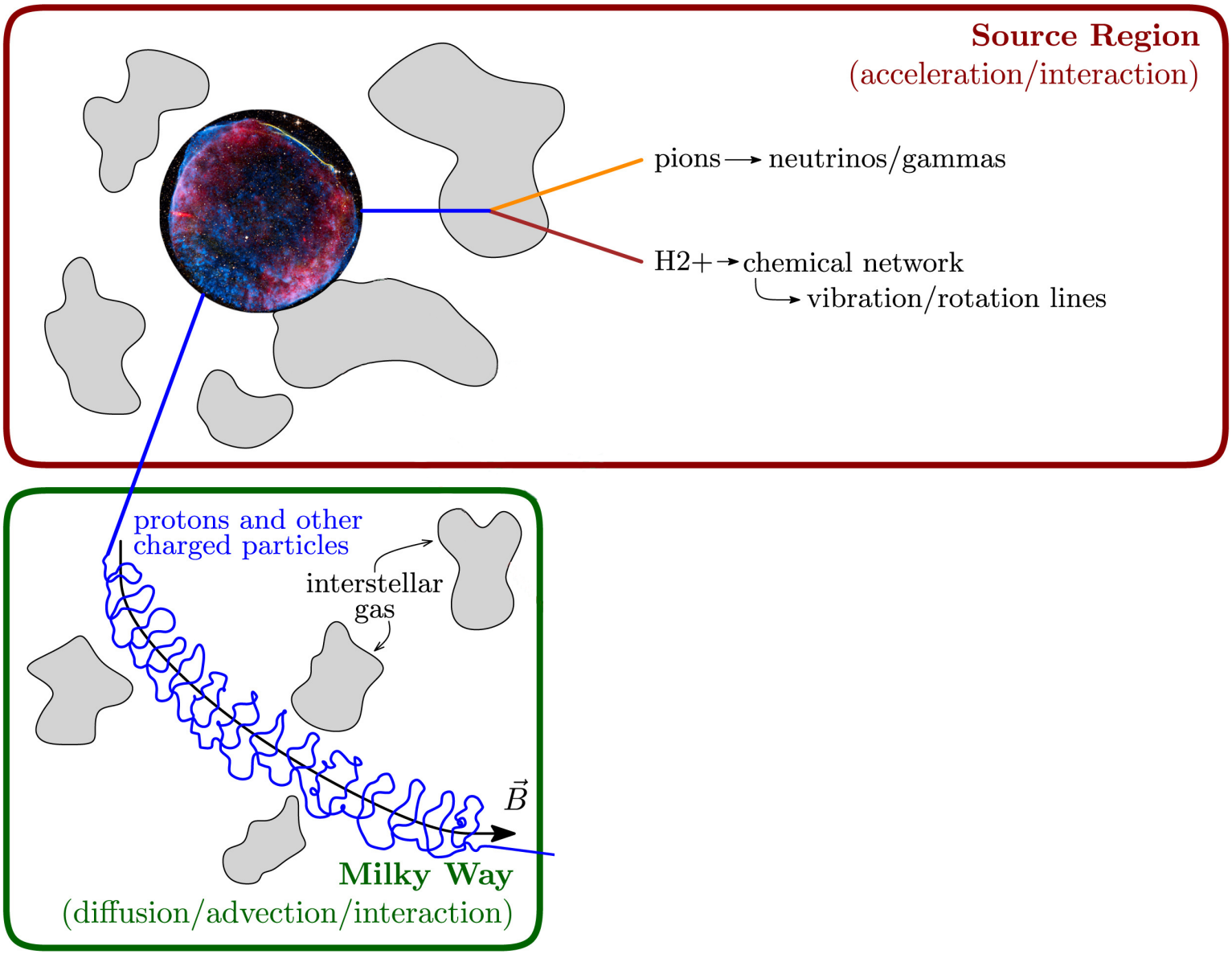

Fig: An illustration of the non-thermal multimessenger emission from hadronic cosmic-ray sources in the Galaxy (*Becker Tjus and Merten 2020*)

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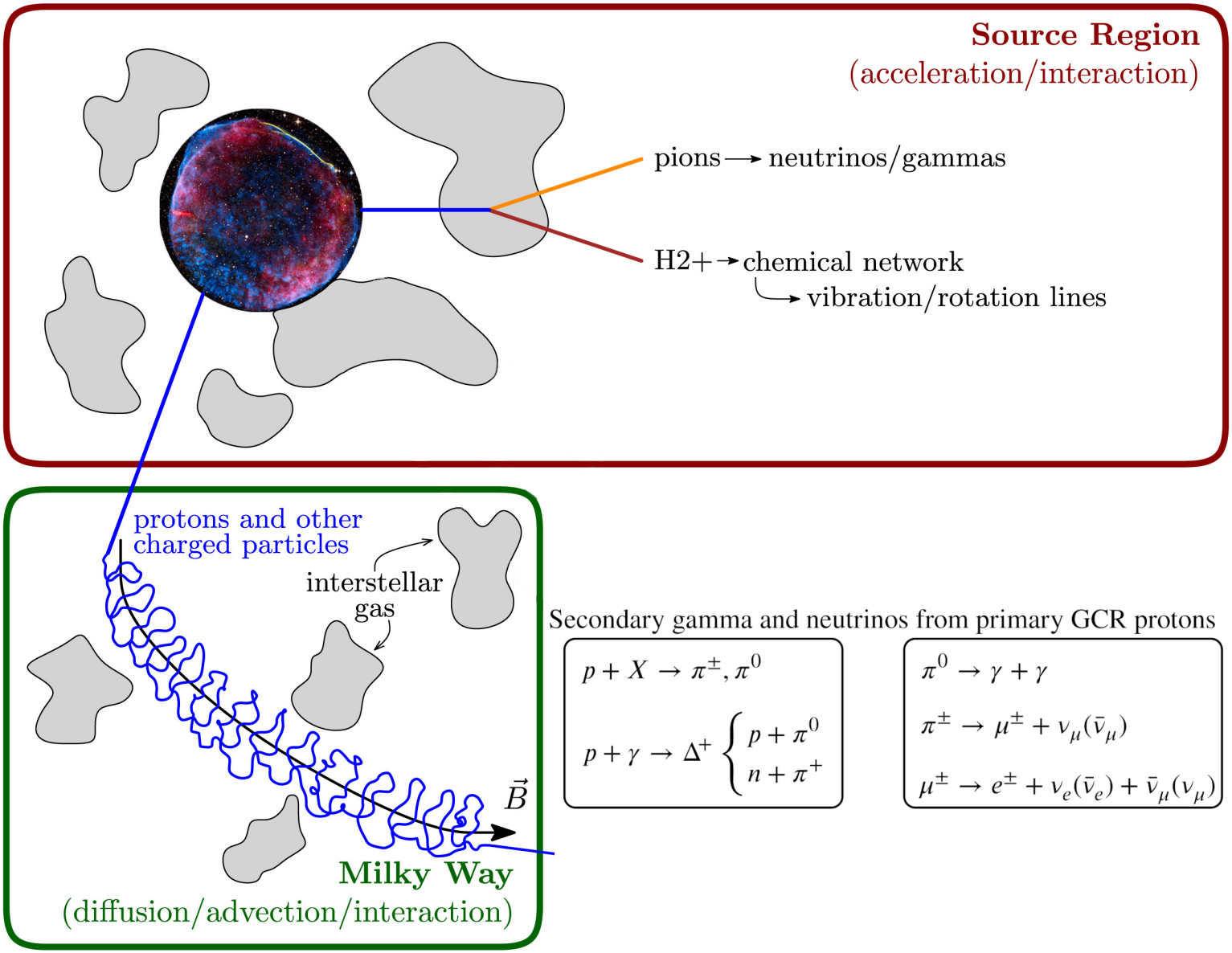

Secondary gamma and neutrinos from primary GCR protons

$$p + X \rightarrow \pi^{\pm}, \pi^{0}$$

$$p + \gamma \rightarrow \Delta^{+} \begin{cases} p + \pi^{0} \\ n + \pi^{+} \end{cases}$$

$$\pi^{0} \rightarrow \gamma + \gamma$$

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

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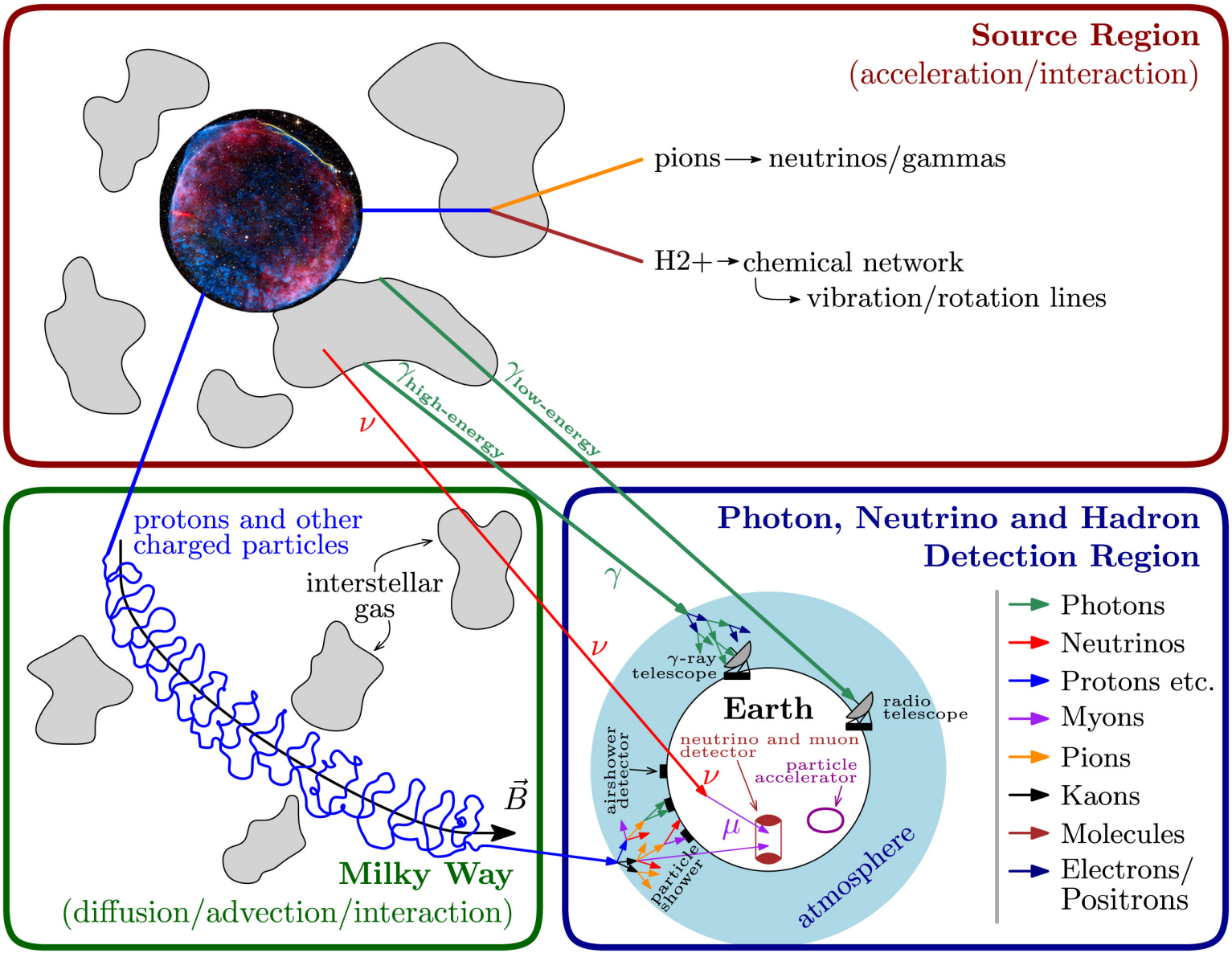

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Fermi-LAT observation of γ-ray from GMCs

Name	l (deg)	b (deg)	Distance (pc)	A ($10^5 M_\odot kpc^{-2}$)	Angular Area (deg^2)	Mass ($M_\odot$)	Radius (pc)
Aquila Rift	24.14	12.48	225	16.02	104	81101.25	22.59
Taurus	171.04	-15.32	135	5.63	32	10260.67	7.51
Rho Oph	354.34	16.82	125	3.98	24	6218.75	6.03
Orion A	211.83	-18.80	490	3.83	26	91958.29	24.60
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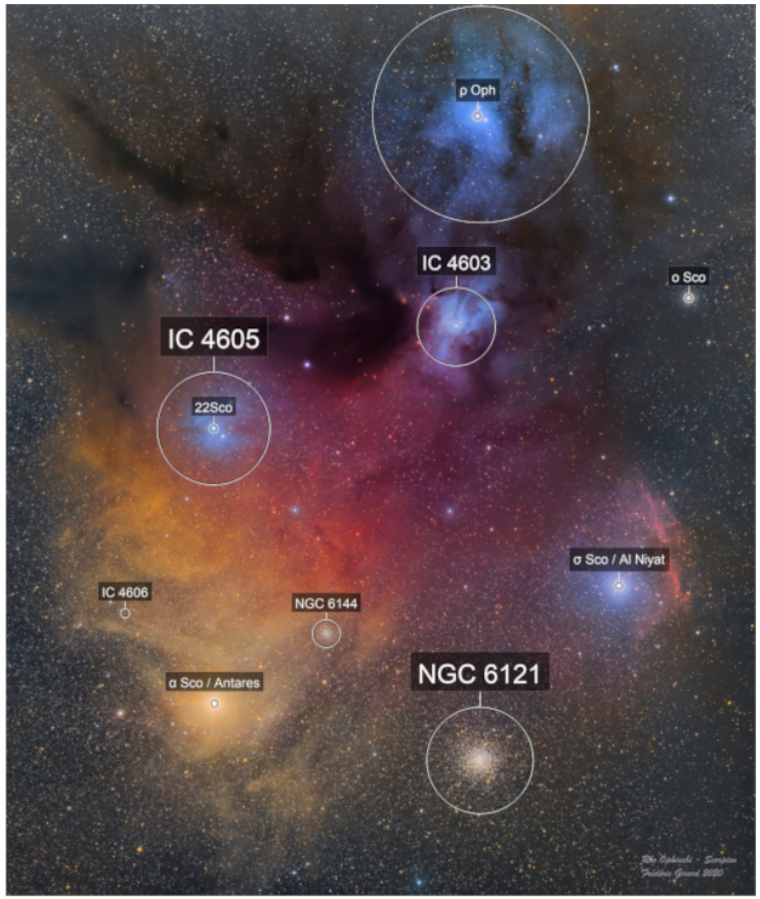

Fig: Observed γ-ray flux from Rho Oph GMC along with the flux derived from the direct CRs measurement by the AMS-02 experiment (black solid lines) (*Baghmanyan et al. 2020, www.astrobin.com*)

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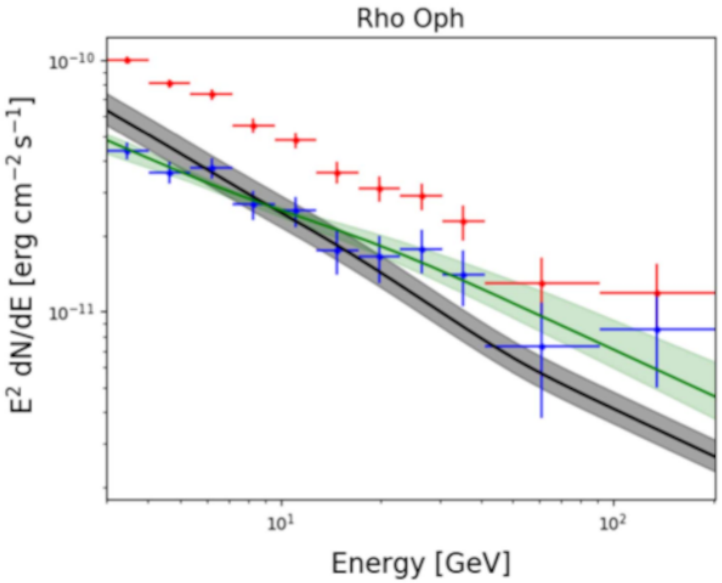

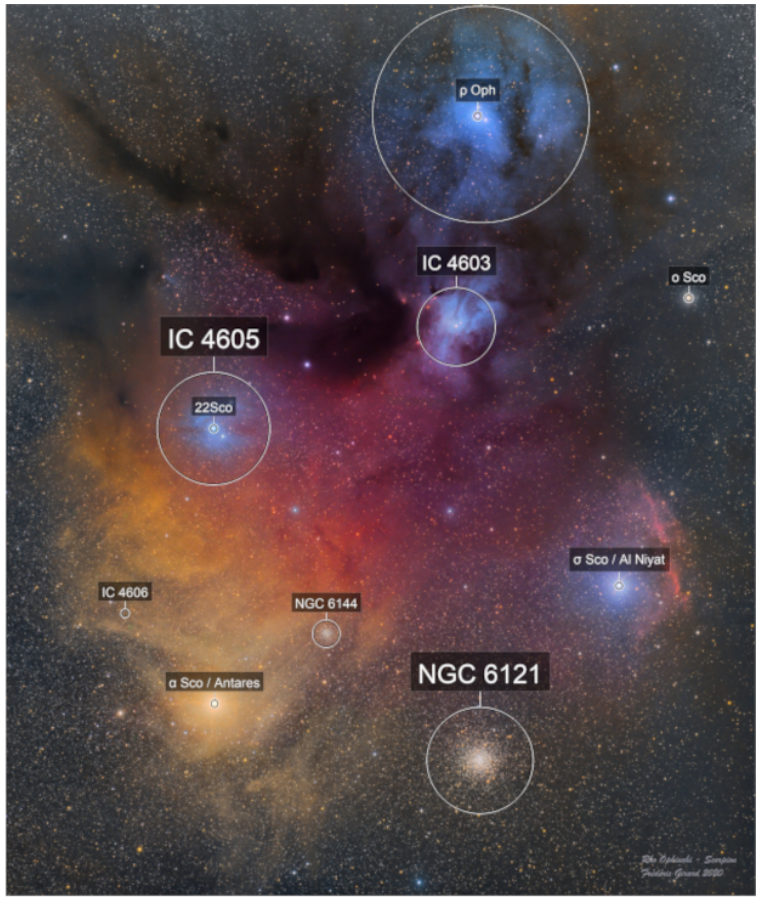

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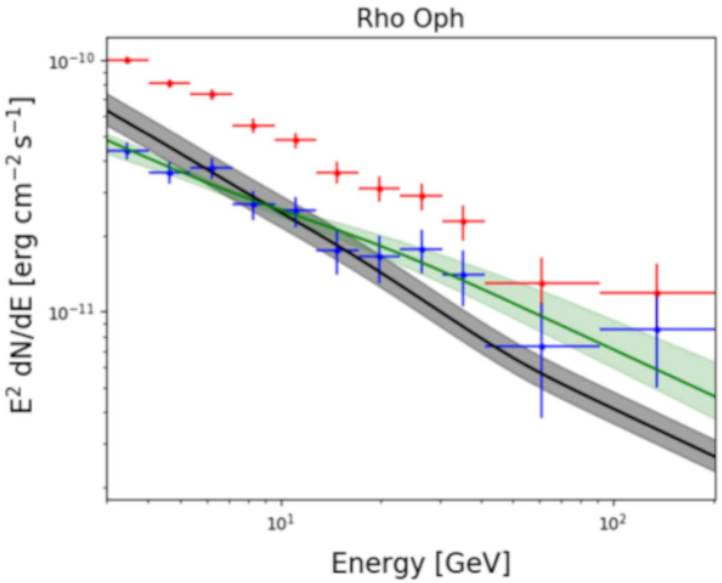
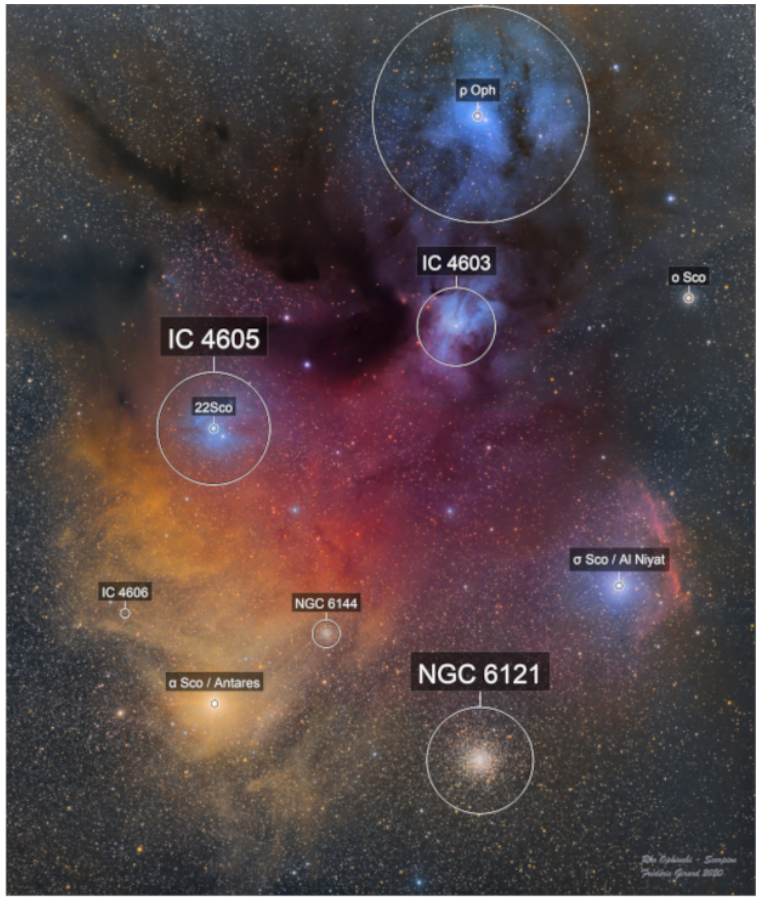
Fermi-LAT observation of γ-ray from GMCs

- The measured AMS-02 proton flux (*Aguilar et al. 2015*):

$$\Phi = C\Big(\frac{R}{45\ GV}\Big)^{\gamma}\Big[1+\Big(\frac{R}{R_0}\Big)^{\Delta\gamma/s}\Big]^{s}$$

- π^0-decay cross sections are taken from *Kafexhiu et al. 2014*





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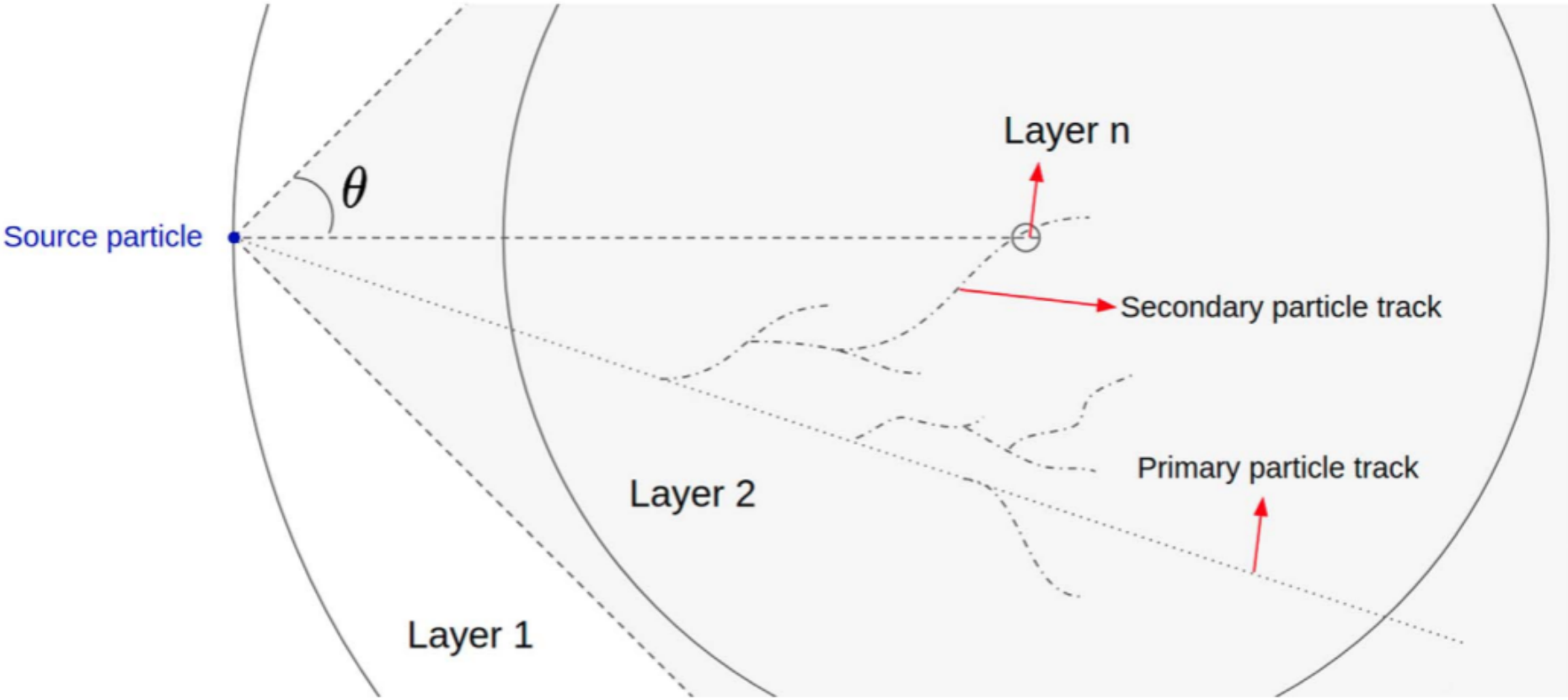

Fig: Propagation of primary GCR inside the cloud (*Pazianotto et al. 2021*)

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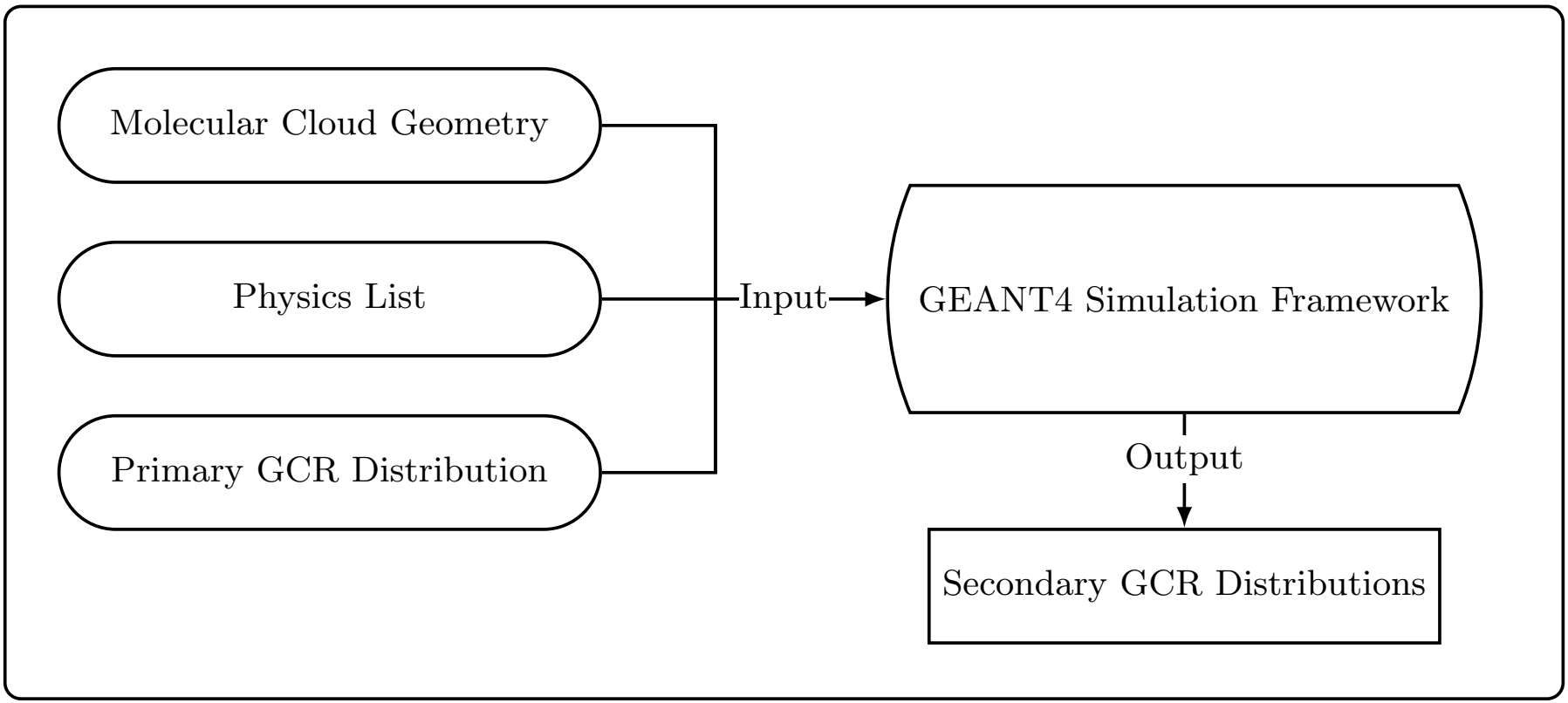

Fig: Simple flow chart diagram of our simulation framework

Particle Interaction Model

In GEANT4 the process are classified as:

- Hadronic (Elastic, Inelastic, Capture, Fission, etc.)
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GEANT4-CRMC interfacing used above 100 TeV to PeVs.

Calculation and Results

Molecular Cloud Geometry Model

The cloud is made out of H_2 molecules, where the density varies as:

$$n_H(R) = \frac{n_0}{1 + \left(\frac{R}{R_c}\right)^{\alpha}}$$

where n_0 is the central density $= 7.3 \times 10^3\ cm^{-3}$ and R_c the core radius, assumed to be 0.5 parsec *(Gabici, Aharonian, and Blasi 2007)*.

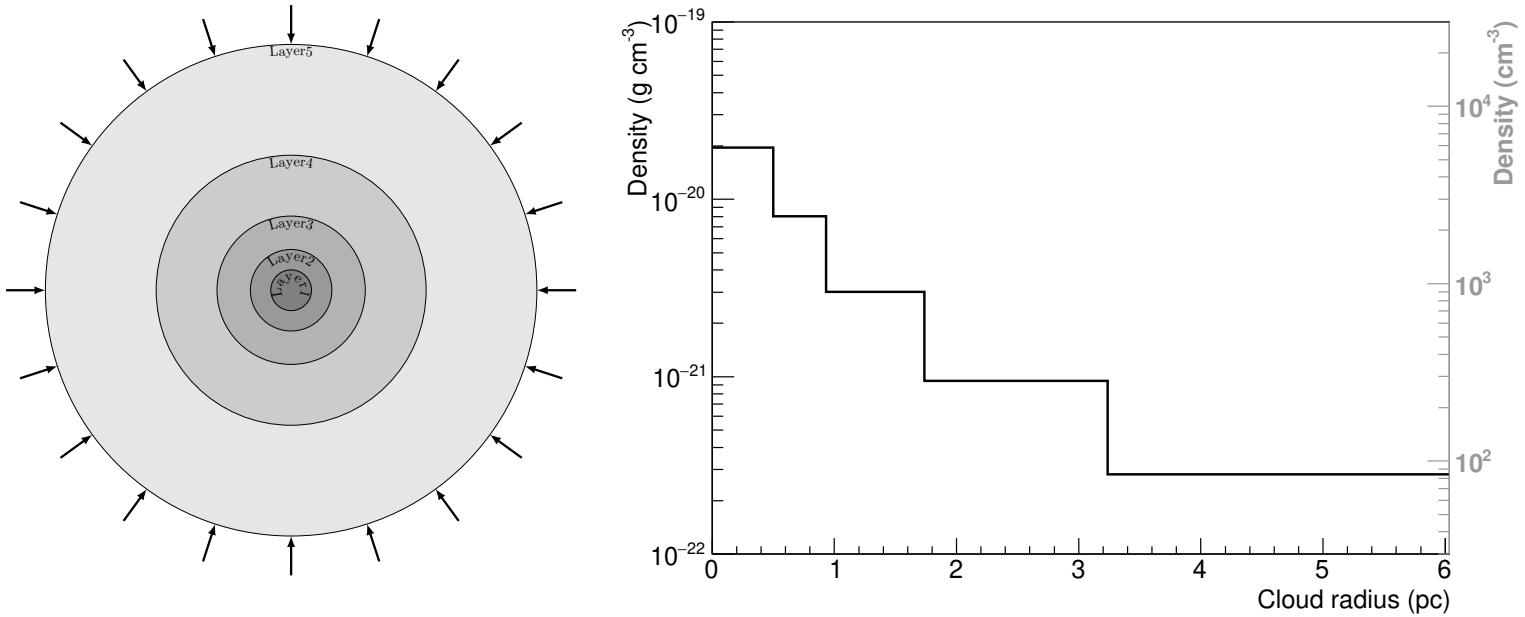

Fig: (left) Cross-sectional view of the molecular cloud, (right) Variation of cloud density in different layers.

Calculation and Results

Primary Particle Generation Model

Flux of primary particles:

$$J_{LIS}(E_k) = N \frac{E_k^{1.12}}{\beta^2} \left(\frac{E_k + 0.67}{1.67} \right)^{-\alpha}$$

where $\beta = \frac{v}{c}$, N is normalization factor $= 2.7 \times 10^3 \ m^{-2} sr^{-1} s^{-1} GeV^{-1}$, α is power law index $= 3.93$ (*Vos and Potgieter 2015*).

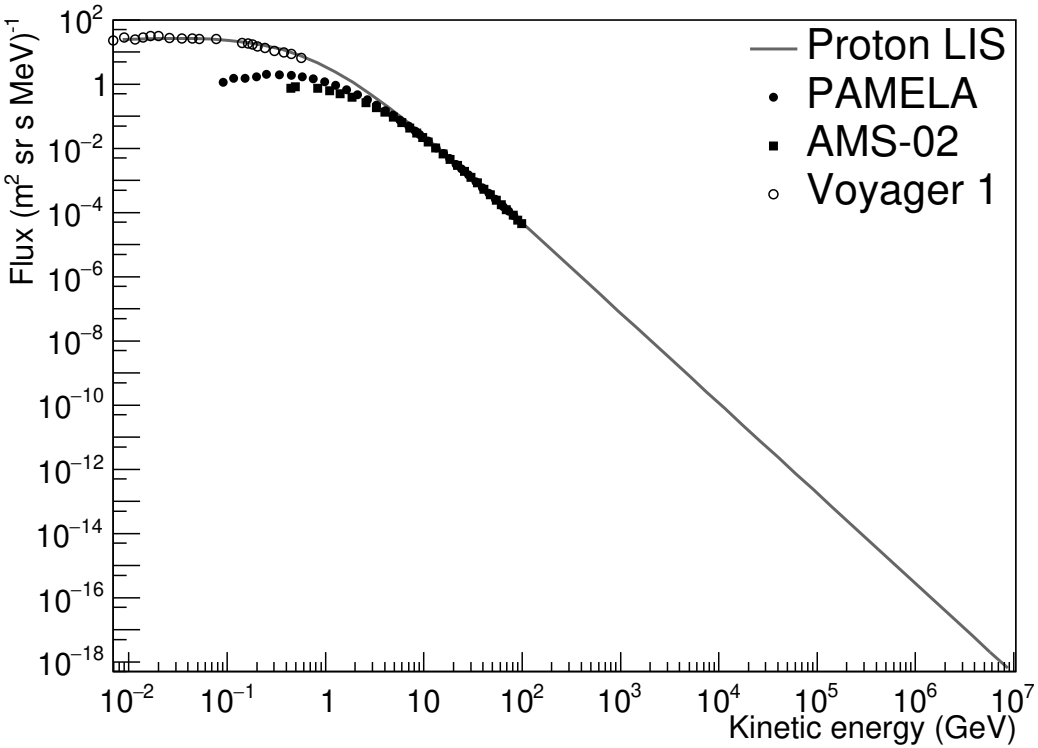

Fig: Unmodulated primary proton LIS according to which the molecular cloud was irradiated.

Calculation and Results

Simulated γ-ray Flux from Rho Oph Molecular Cloud

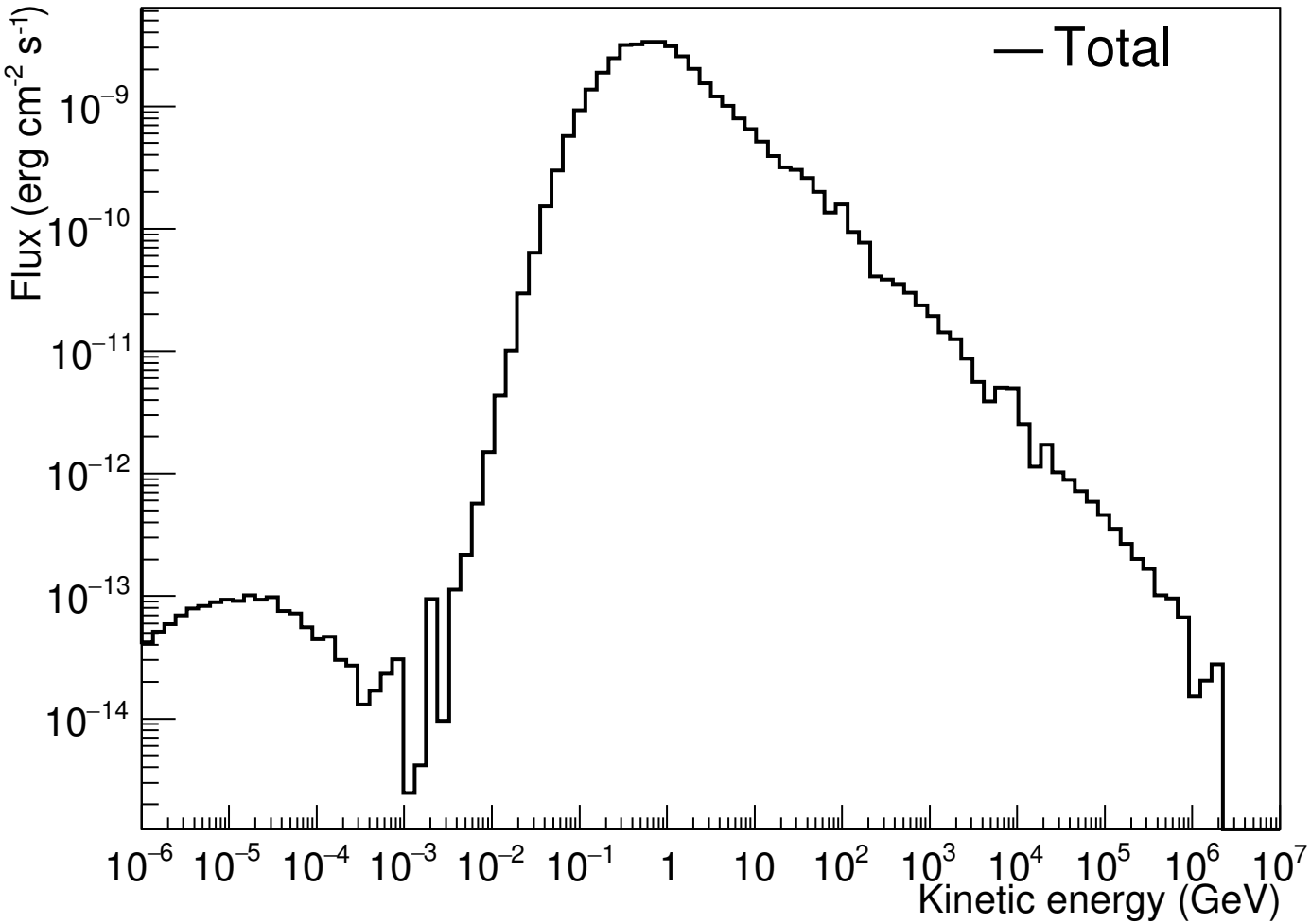

Fig: Total simulated γ-rays, originated from the interaction of LIS proton with the Rho Ophiuchi molecular cloud.

Calculation and Results

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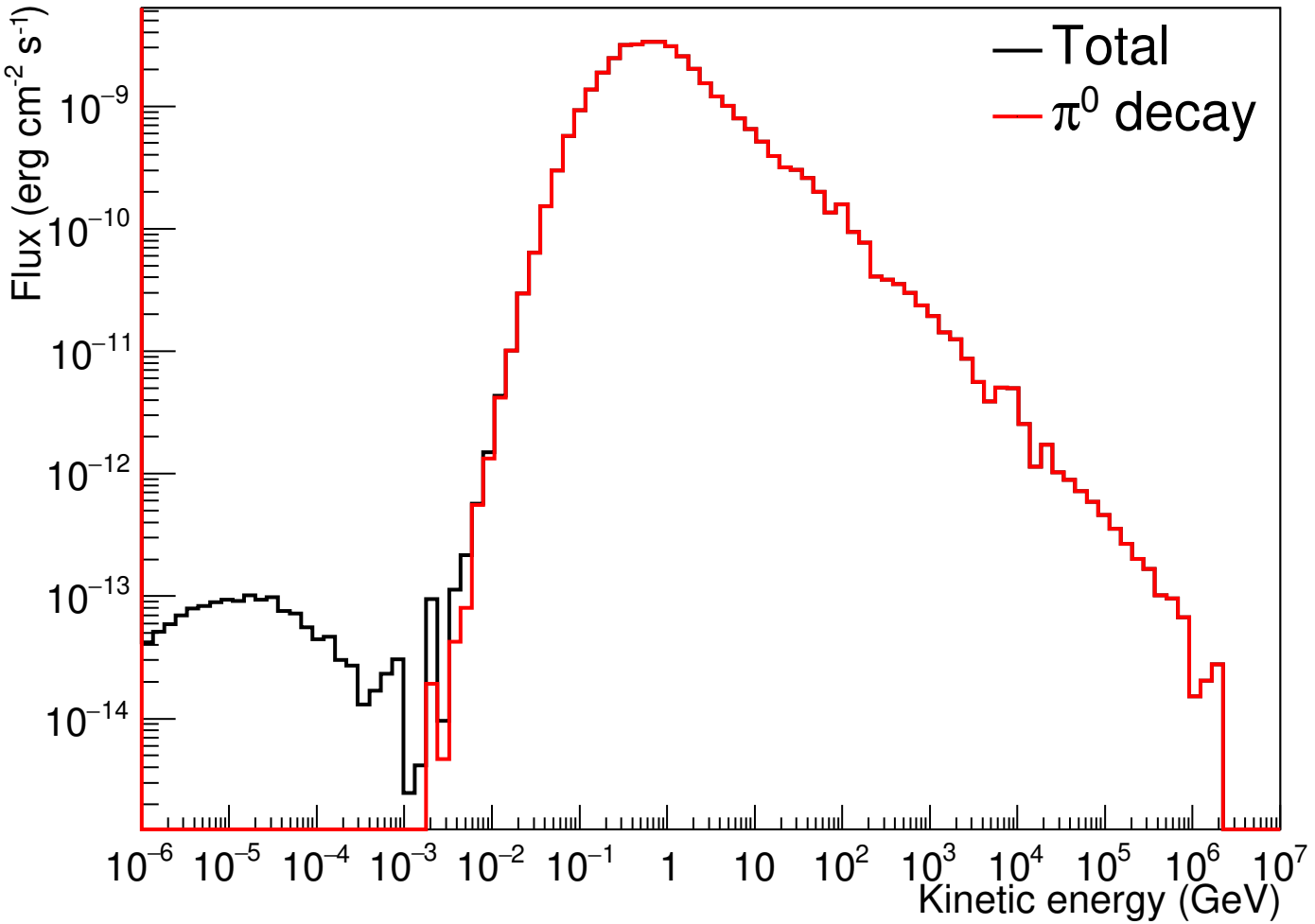

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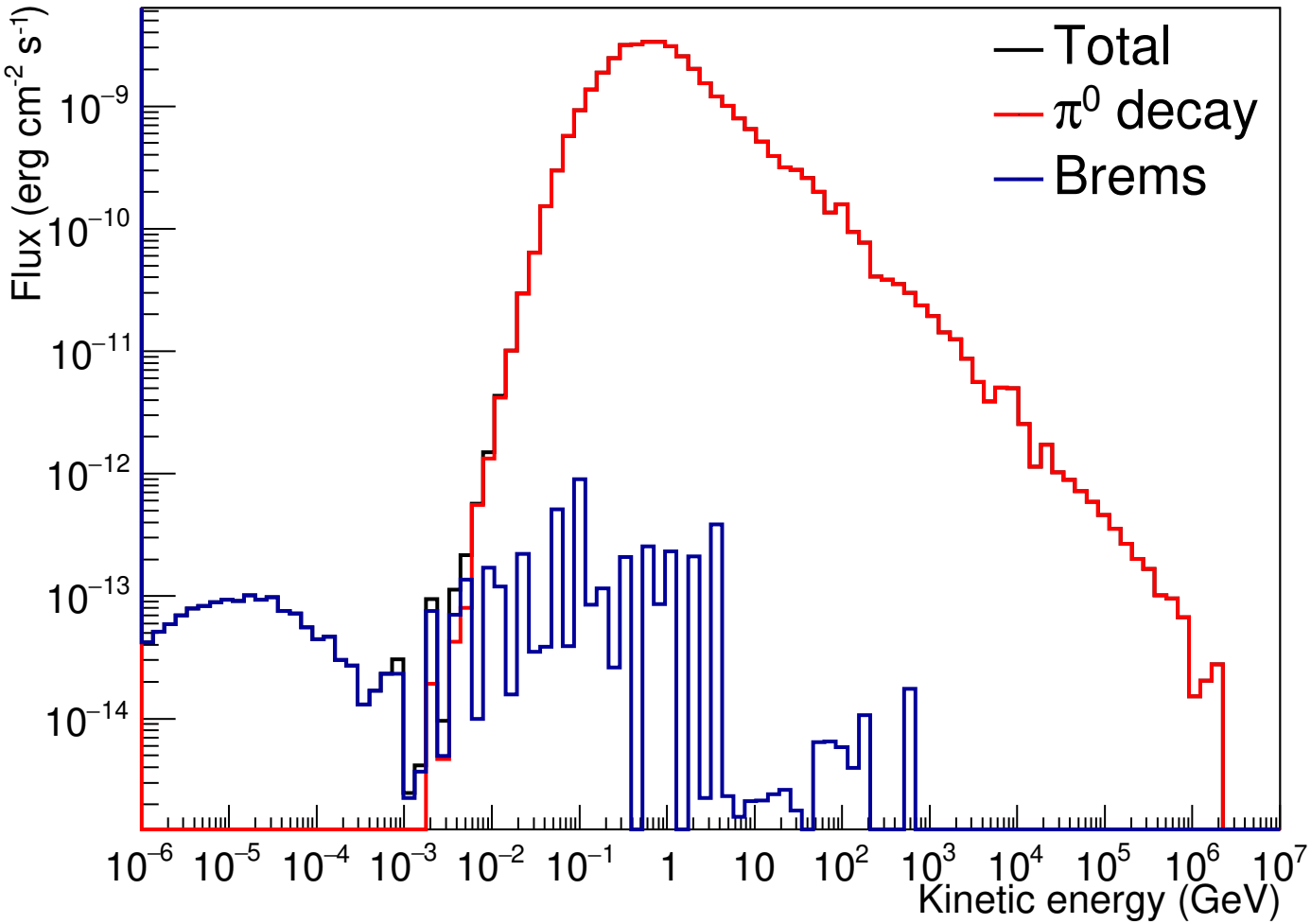

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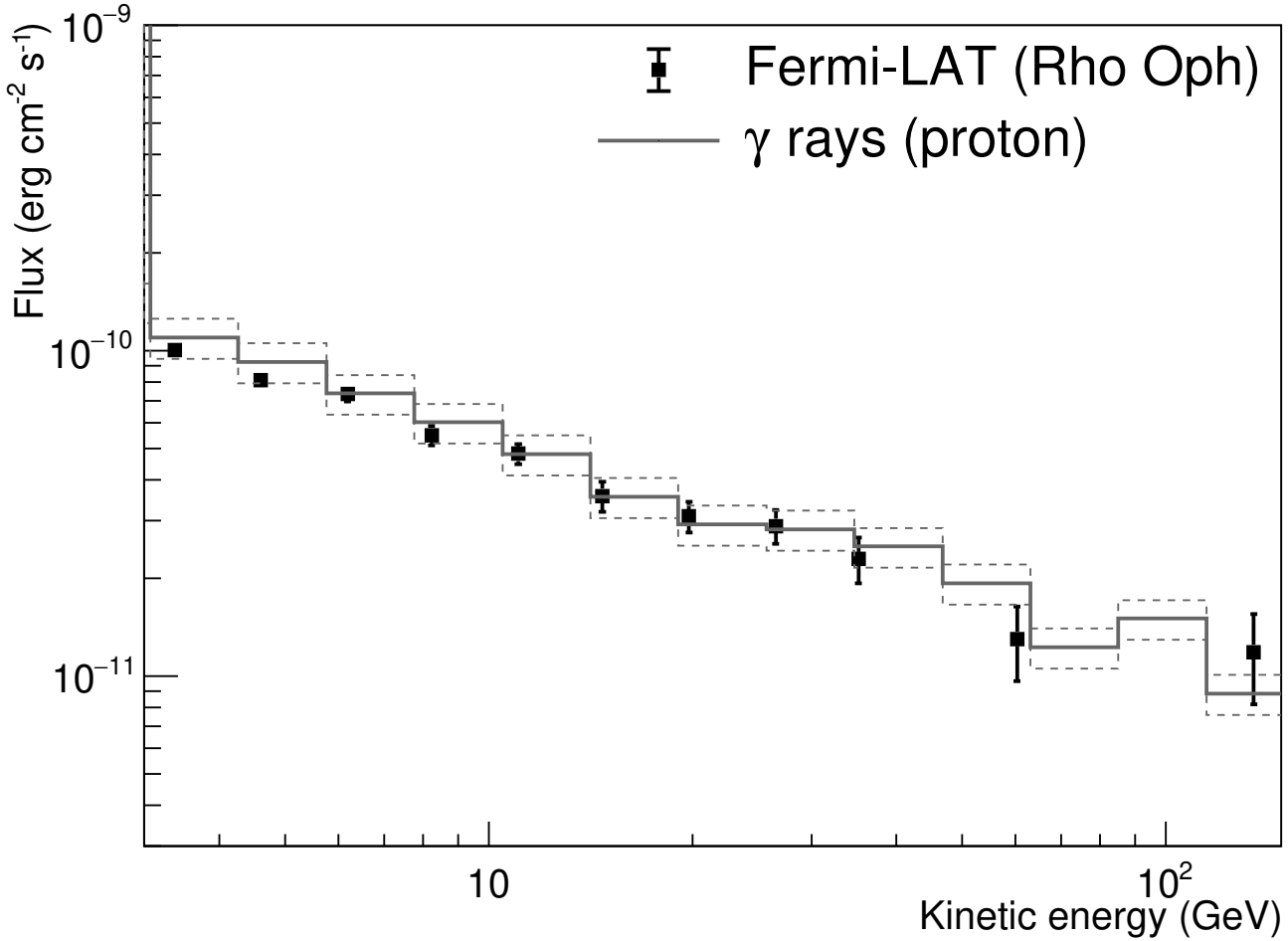

Fig: Spectral energy distribution of γ-ray flux as obtained by Fermi-LAT observation *(Baghmanyan et al. 2020)*, along with the simulated flux.

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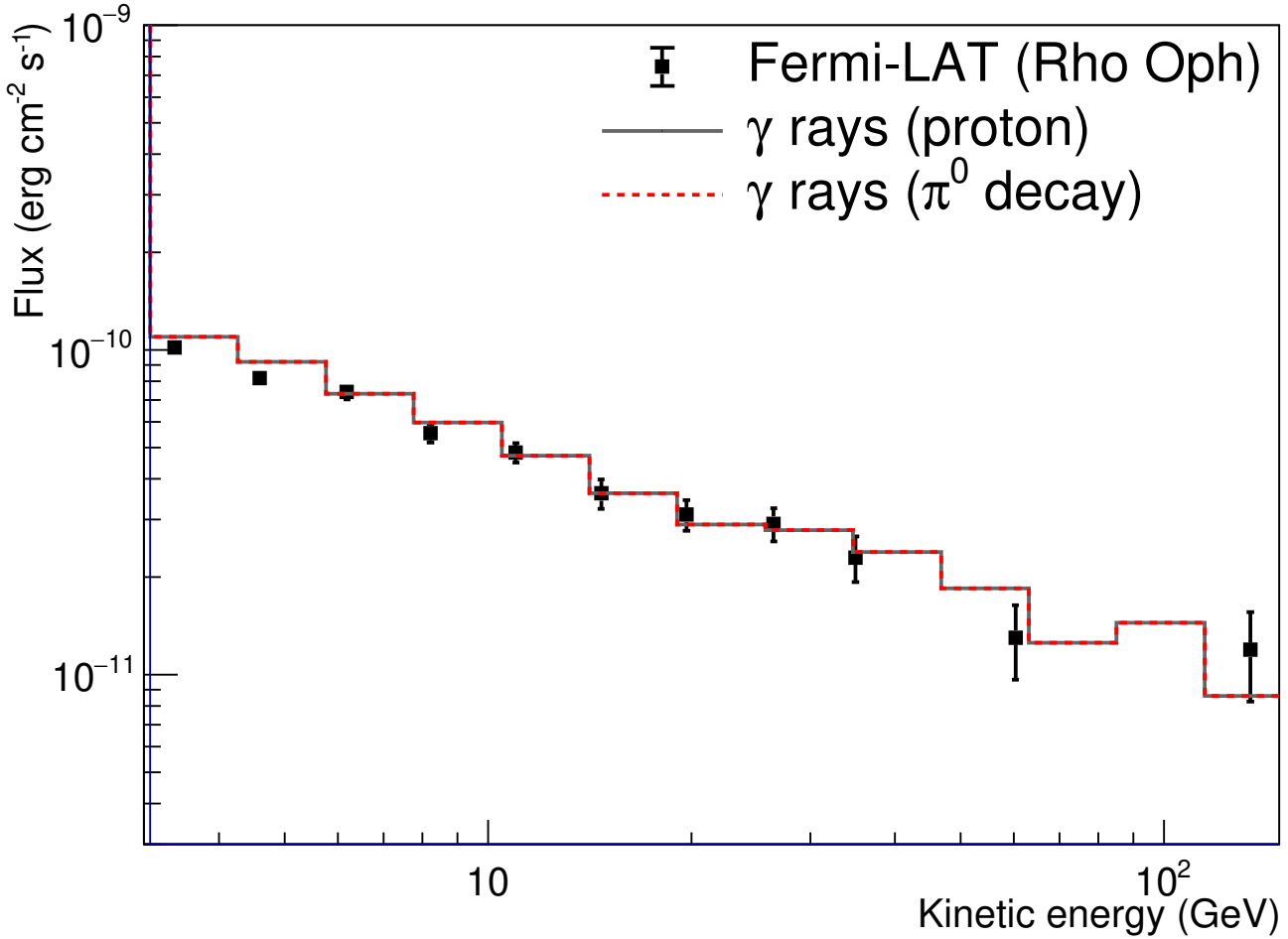

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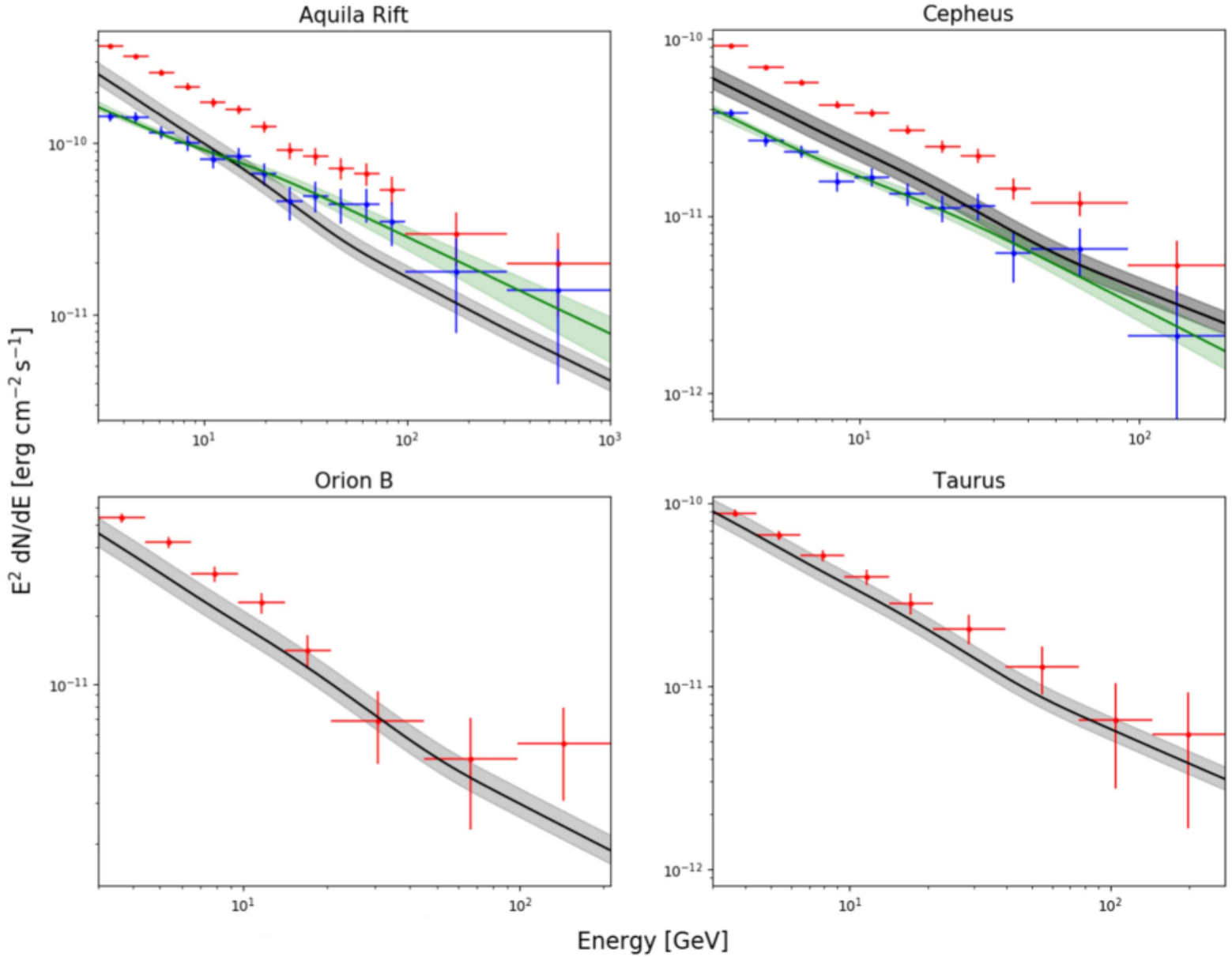
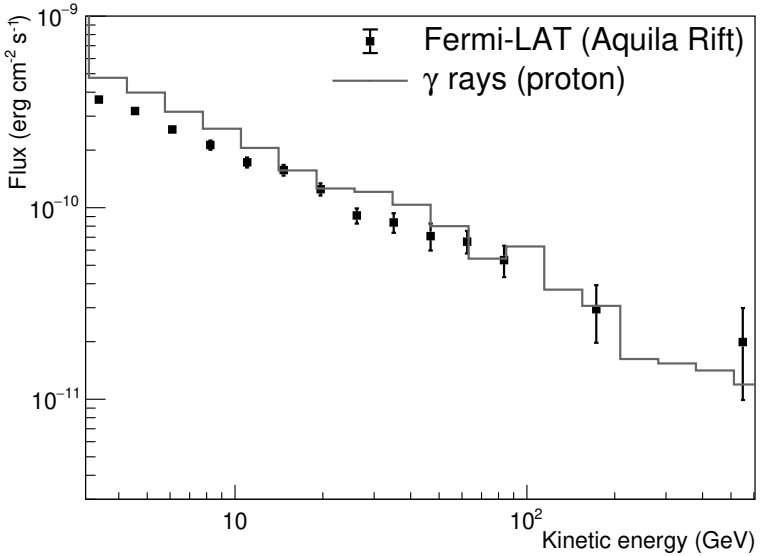
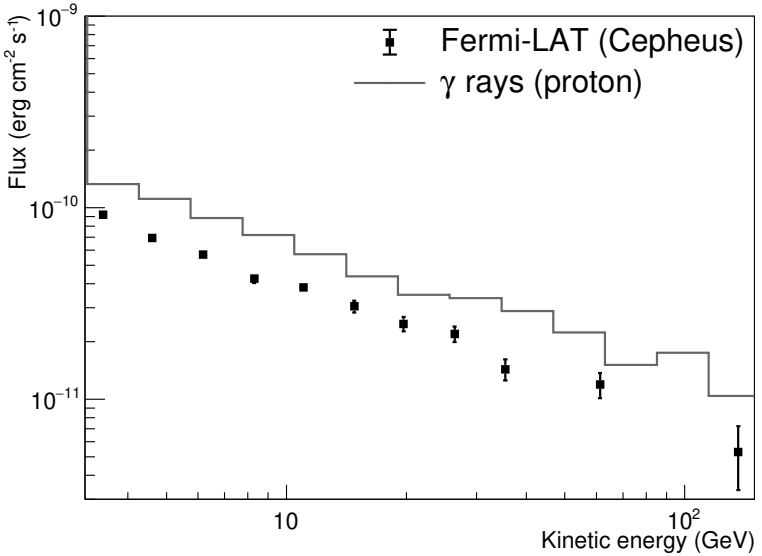


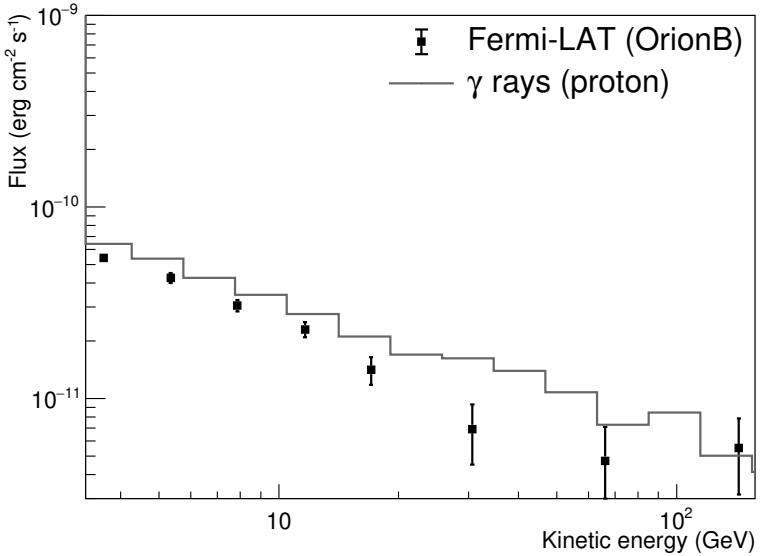
Fig: Observed γ-ray flux from different GMC along with the flux derived from the direct CRs measurement by the AMS-02 experiment (black solid lines) (*Baghmanyan et al. 2020*)

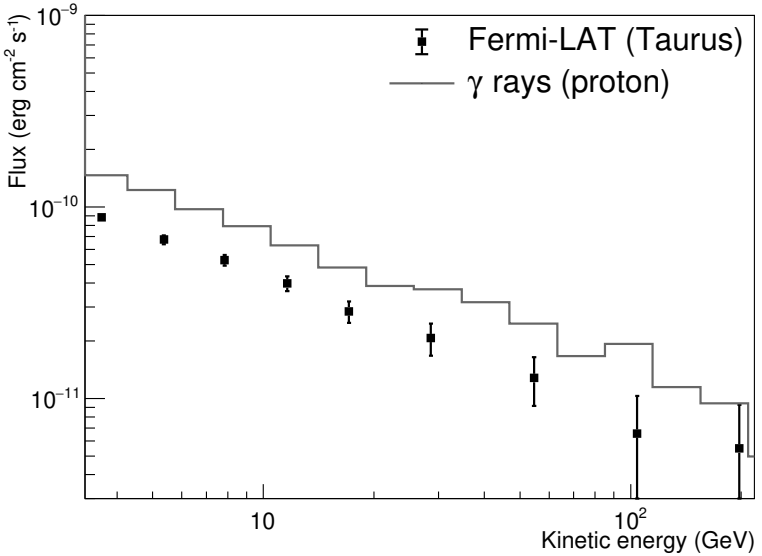
Calculation and Results

Preliminary Simulated γ-rays Along with Observation









Summary and Future Works

- We have developed a GEANT4 simulation framework to simulate non-thermal multimessenger emission from CR interactions.
- The upper energy limit of GEANT4 hadronic interaction model has been increased using GEANT4-CRMC interface.
- The excess in gamma ray flux seems to be due to the propagation effect of primary GCRs in the molecular cloud.
- From our calculation it also appears that the H_2 number density in GMC has significant effect in the observed γ-rays.
- In future we will simulate the contributions from CR heavy nuclies.

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Thank you.
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Normalising the Simulated Results

Given a simulation quantitative result X_s (e.g. particle flux), the value expected in the real world X_r is obtained with a **rescaling**.

$$X_r = X_s \frac{N_r}{N_s} \tag{1}$$

where N_s is the simulated events and N_r is the real events expected.

N_s is set by the user and N_r depends on the real source

So, the normalisation factor:

$$\frac{N_r}{N_s} = \frac{\int_{E_i}^{E_f} J_{LIS}(E_k) dE_k}{8.2 \times 10^8} \tag{2}$$

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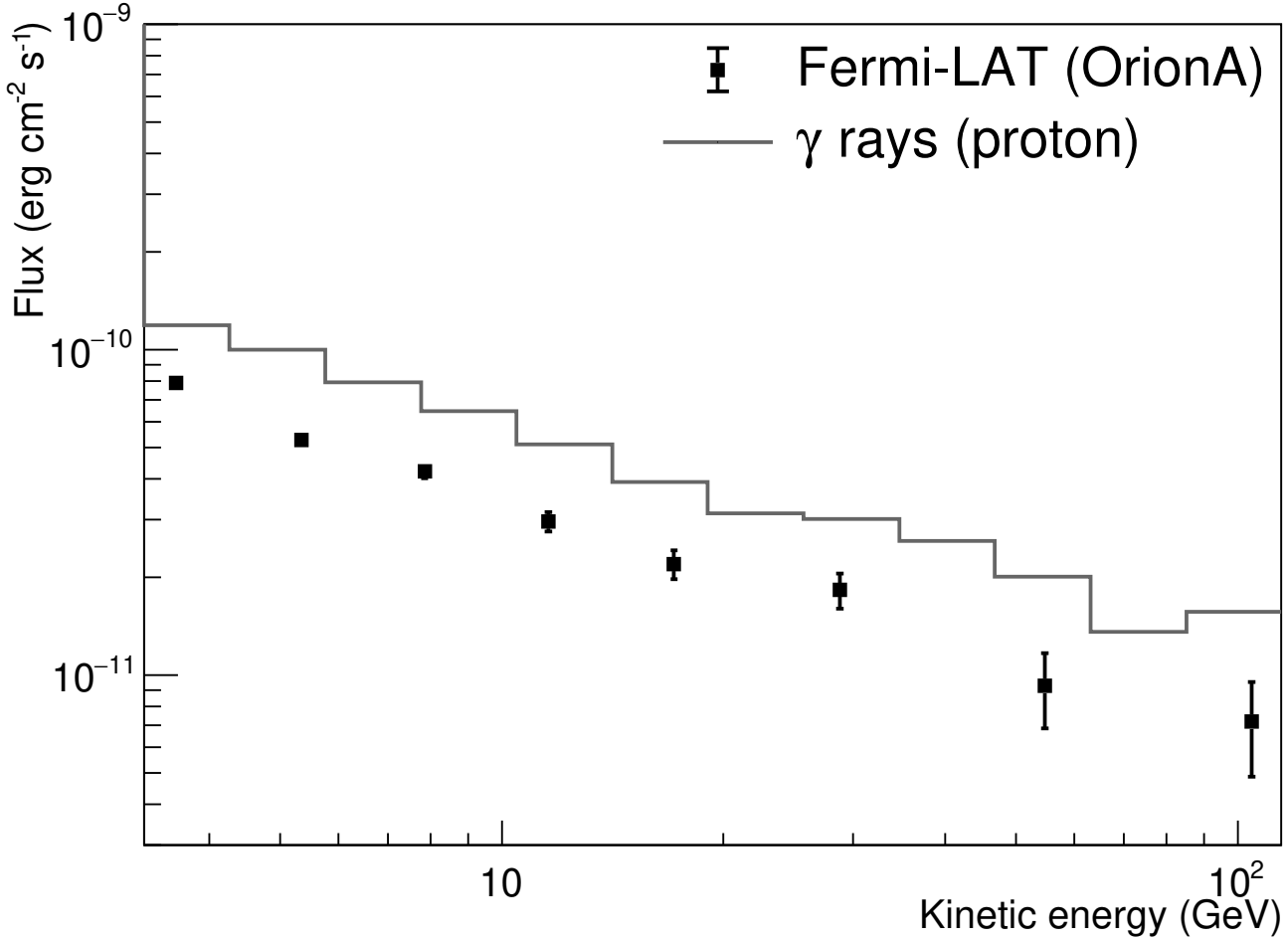
Comparison of Simulated γ-rays with Observation



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