Gamma-Rays Produced in Cosmic-Ray Interactions and the TeV-band Spectrum of RX J1713.7-3946

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Motives

- diffuse γ-ray emission in hadronic interactions generated by cosmic rays
  - Fact: multiplicity of non-π^0 secondaries with γ-rays as the final decay state is about 50% of π^0 multiplicity in hadronic interactions
  - Fact: CR and ISM compositions

    CR: p and α

    ISM: 90% protons, 10% heliums, 0.02% carbons, 0.04% oxygens

- Question: how important are these non-π^0 secondaries for the diffuse γ-ray emission?
- Question: what's the influence of heavier nuclei to the diffuse γ-ray emission?

Methodology

- High Energy Physics Event Generator DPMJET3.04

  by S. Roesler, R. Engel and J. Ranft

- full decay picture

- parametric method for $E \leq 20$ GeV

  (Kamae et al., ApJ 647, 692 (2006))

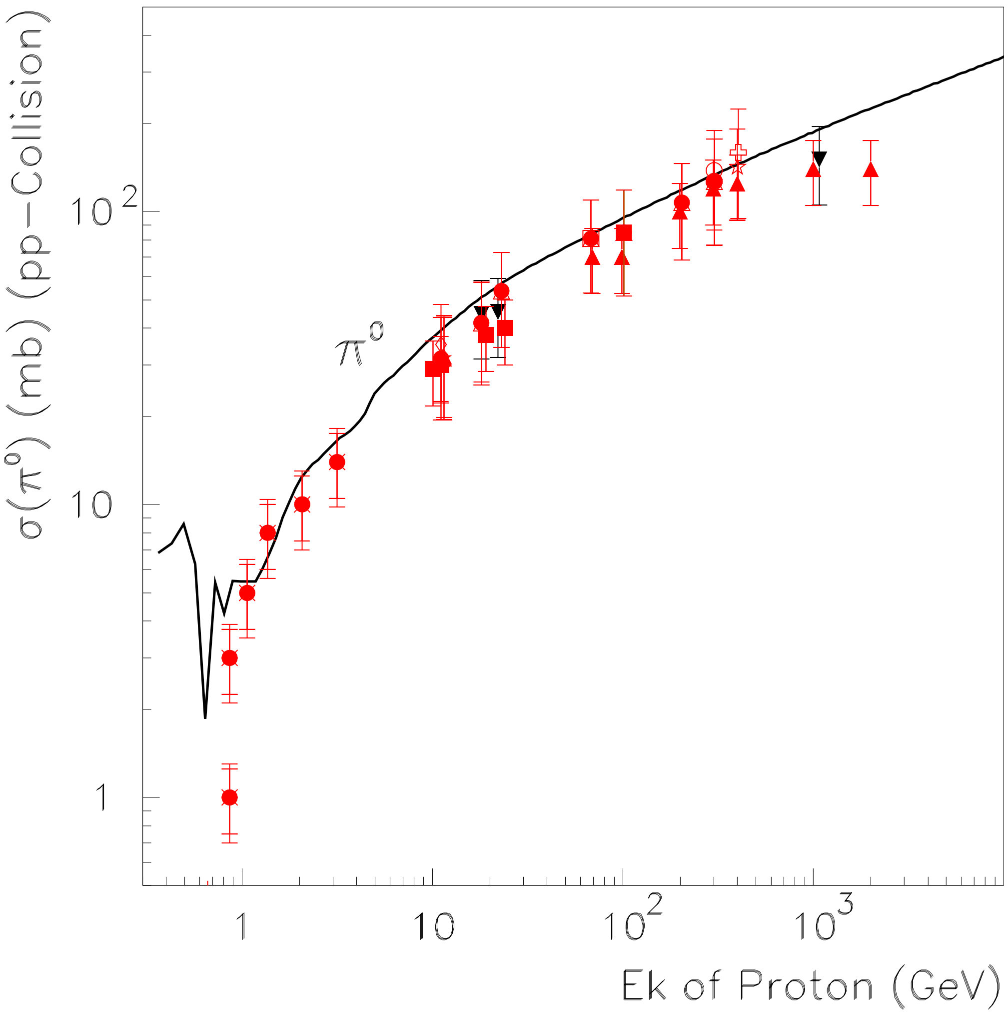
  $E < 2.5$ GeV: parametric

  $E > 20$ GeV: DPMJET

  $2.5 \leq E \leq 20$ GeV: transition

  (parametric + DPMJET)

- resonances included



Full Picture of γ-Rays of Hadronic Origin

- Resonance decays:

$\Delta(1232) \rightarrow p + \pi^0$

$\Delta(1600) \rightarrow p + \pi^0$

$\Delta(1600) \rightarrow \Delta(1232) + \pi^0$

$\Delta(1600) \rightarrow \mathrm{N}(1440) + \pi^0$

$\mathrm{N}(1440) \rightarrow p + \pi^0$

$\mathrm{N}(1440) \rightarrow \Delta(1232) + \pi^0$

$\mathrm{N}(1440) \rightarrow p + 2\pi^0$

- Baryonic decays:

$\Sigma^0 \rightarrow \Lambda + \gamma$

$\Sigma^+ \rightarrow p + \pi^0$

$\Lambda \rightarrow n + \pi^0$

$\bar{\Lambda} \rightarrow \bar{n} + \pi^0$

- Mesonic decays:

$\pi^0 \rightarrow 2\gamma$

$\pi^0 \rightarrow e^- + e^+ + \gamma$

$K^+ \rightarrow \pi^+ + \pi^0$

$K^- \rightarrow \pi^- + \pi^0$

$K_S^0 \rightarrow 2\pi^0$

$K_L^0 \rightarrow 3\pi^0$

$K_L^0 \rightarrow \pi^+ + \pi^- + \pi^0$

- Direct γ production:

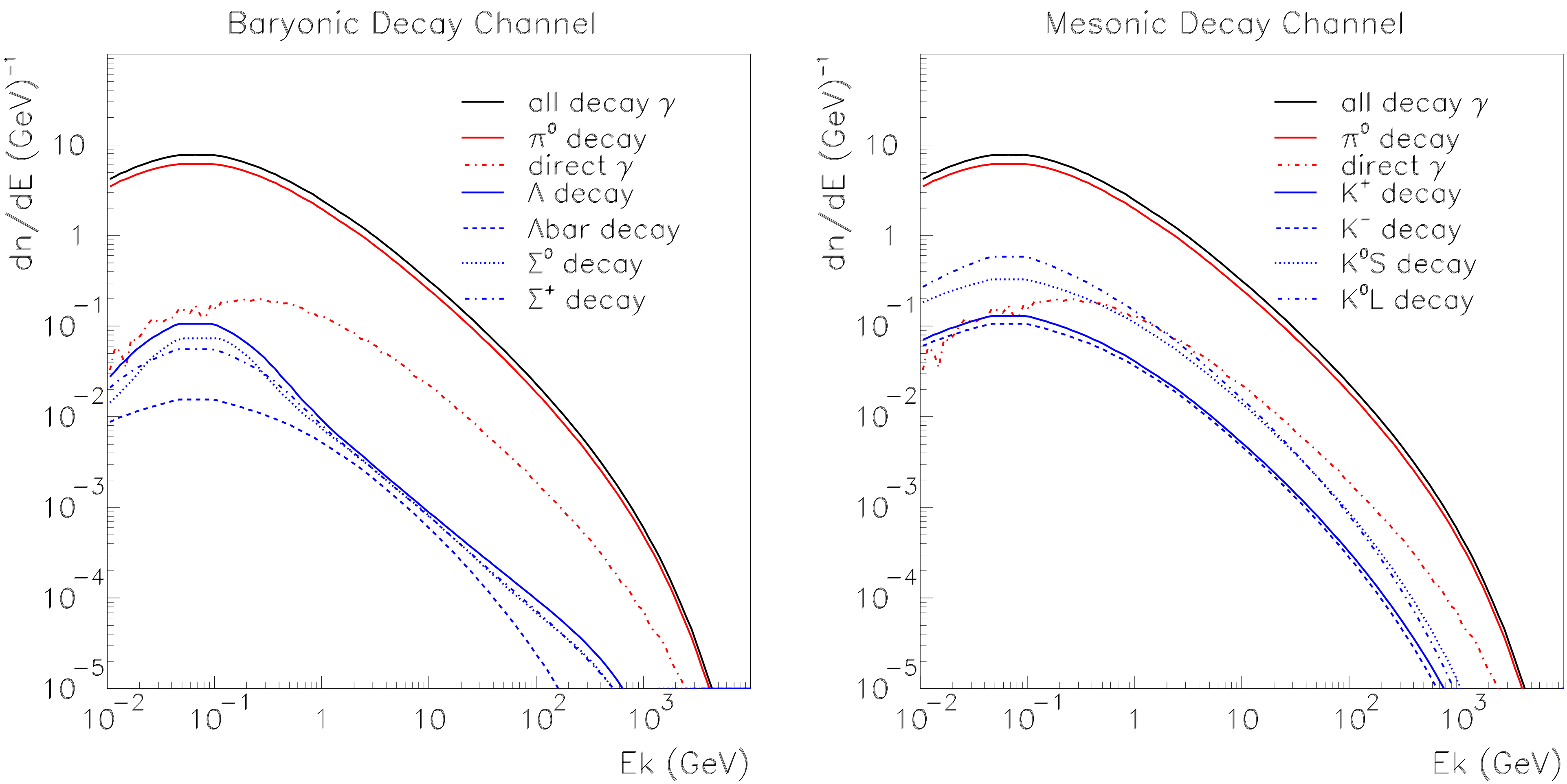
CR $(p, \alpha) + \mathrm{ISM} \rightarrow \gamma + \ldots$

- Where are η's?

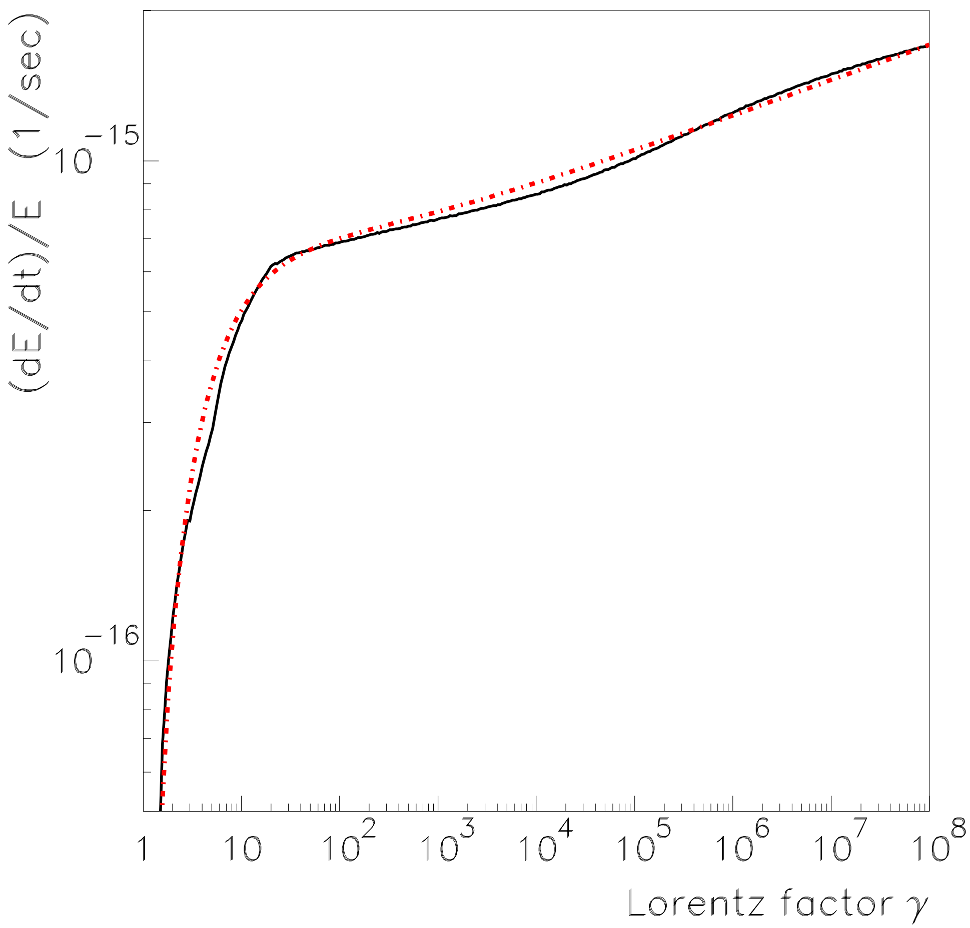
- η decay already treated by PYTHIA!

γ-Ray Energy Spectra of Hadronic Origin

- p+ISM at 10 TeV



Energy Loss in Production Collisions CR +ISM



- for CR protons + ISM
- energy loss rate per energy

- $\frac{\dot{E}}{E} \simeq 6.78 \times 10^{-16} \frac{(\gamma - 1)^2}{\gamma(\gamma + 1)} - 1.55 \times 10^{-17} \log(\gamma) + 1.80 \times 10^{-17} \log^2(\gamma)$

γ-Ray Production Matrix in CR Interactions

- spectrum of secondary particle produced in CR interactions:

$$Q_{2nd}(E) = \frac{dn}{dt \cdot dE \cdot dV} = n_{ISM} \int_{E_{CR}} dE_{CR}\, N_{CR}(E_{CR})\, c\beta_{CR} \left(\sigma \frac{dn}{dE} \right)$$

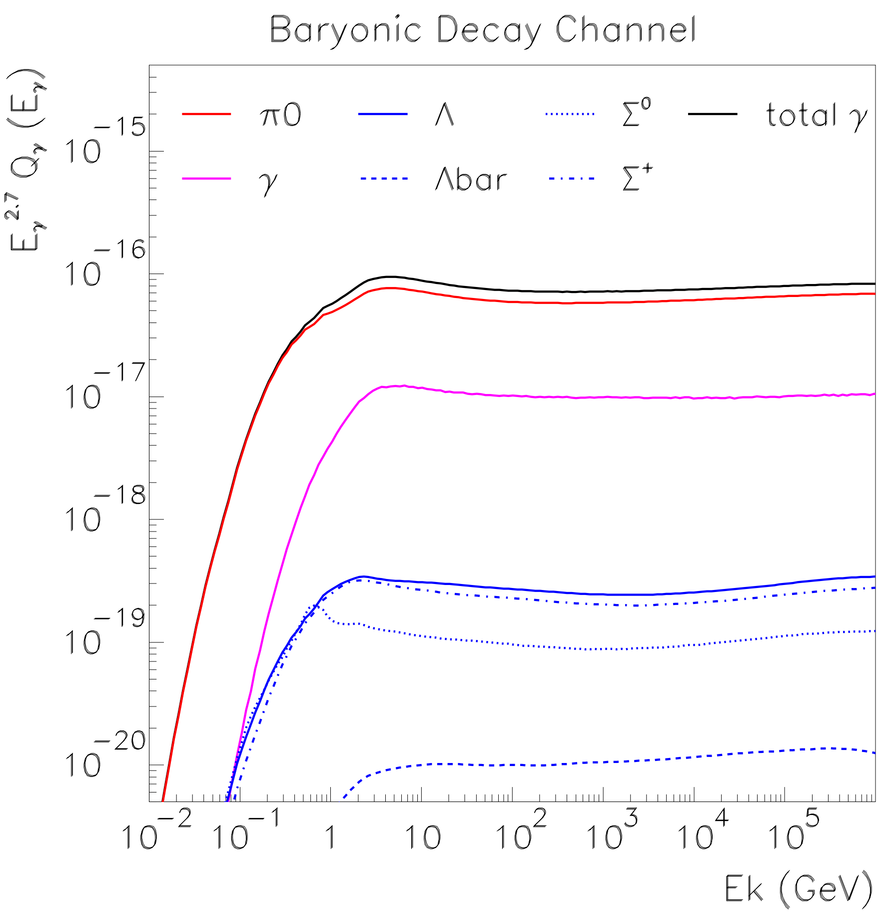
- γ-ray spectrum produced in CR interactions:

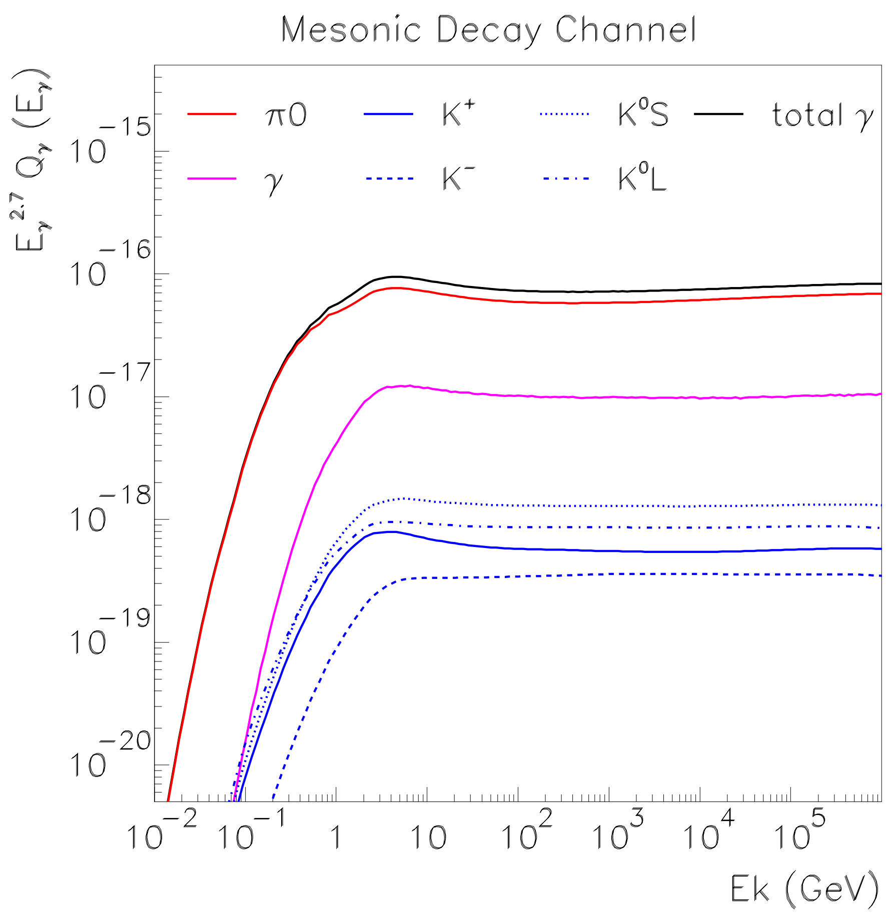
$$\begin{aligned} Q_\gamma(E_\gamma) &= \sum_k n_{ISM} \int_{E_{CR}} dE_{CR}\, N_{CR}(E_{CR})\, c\beta_{CR}\, \sigma(E_{CR})\, \frac{dn_{k,\gamma}}{dE_\gamma}(E_\gamma, E_{CR}) \\ \Longrightarrow Q_\gamma(E_i) &= \sum_j n_{ISM}\, \Delta E_j\, N_{CR}(E_j)\, c\beta_j\, \sigma(E_j) \sum_k \frac{dn_{k,\gamma}}{dE_\gamma}(E_i, E_j) \\ &= \sum_j n_{ISM}\, \Delta E_j\, N_{CR}(E_j)\, c\beta_j\, \sigma_j\, \mathbb{M}_{ij} \end{aligned}$$

- $\forall\ \mathbb{M}_{ij},\ \mathbb{M}_{ij} = \frac{dn}{dE}|_{E_\gamma = E_i, E_{CR} = E_j};$
- easy-to-use matrix operation for CR-generated diffuse γ-ray spectrum for arbitrary CR spectrum!

Hadronic γ-Rays in CR Generated Interactions

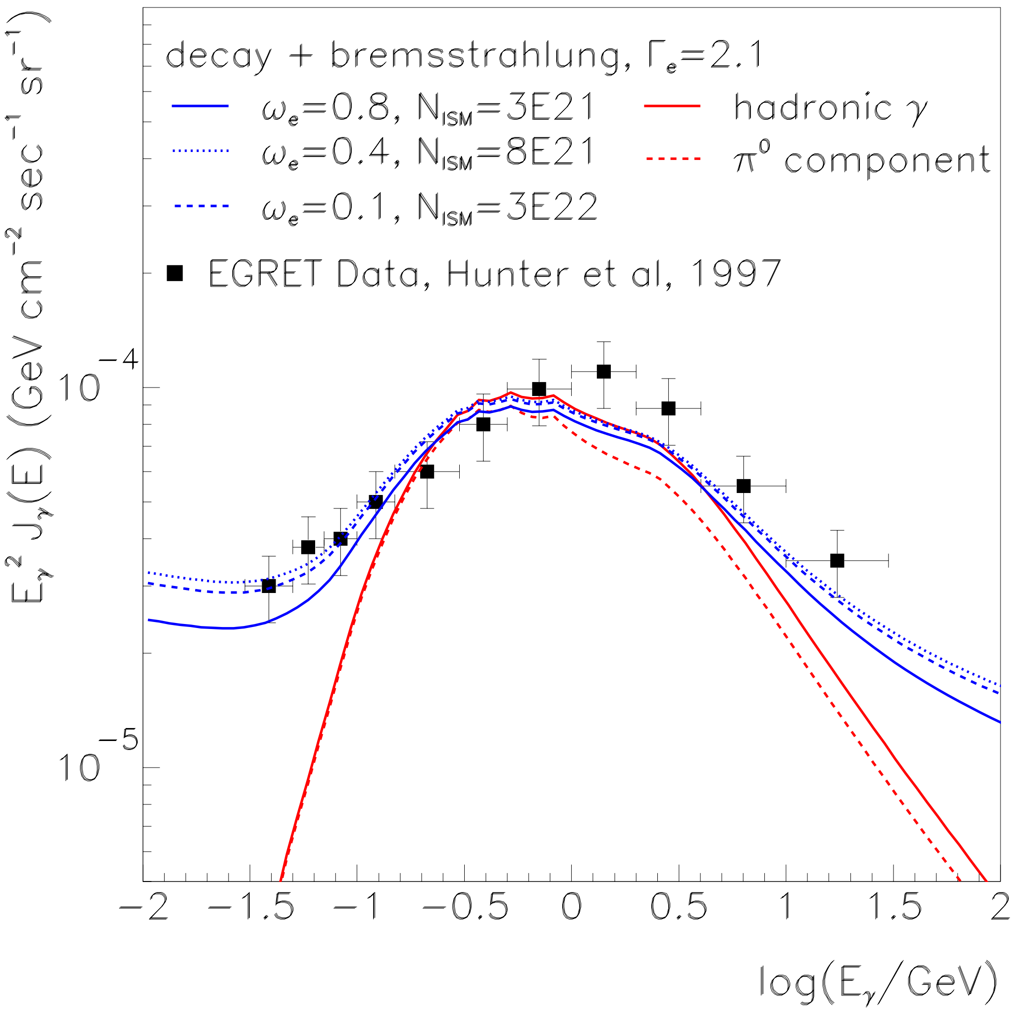
- CR+ISM: $N_{CR} \propto E_{CR}^{-2.75}$





- 20% γ-ray contribution from non-π^0 secondary particles in CR-generated interactions!

γ-Ray Spectrum in GeV Band



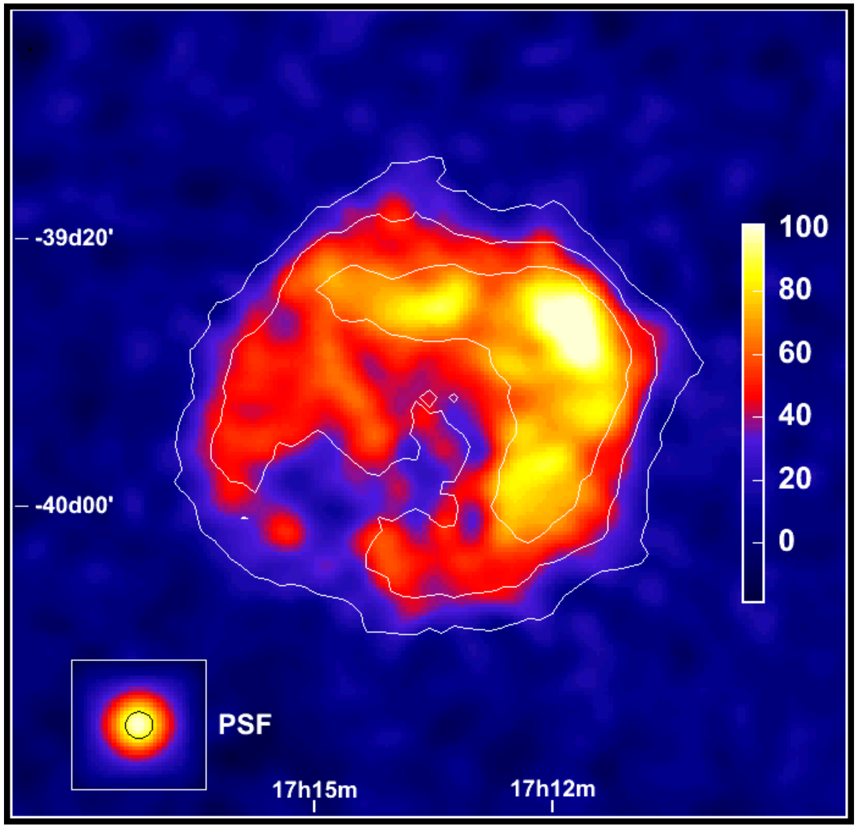
- generated by observed CR spectra
- γ-ray production matrix employed

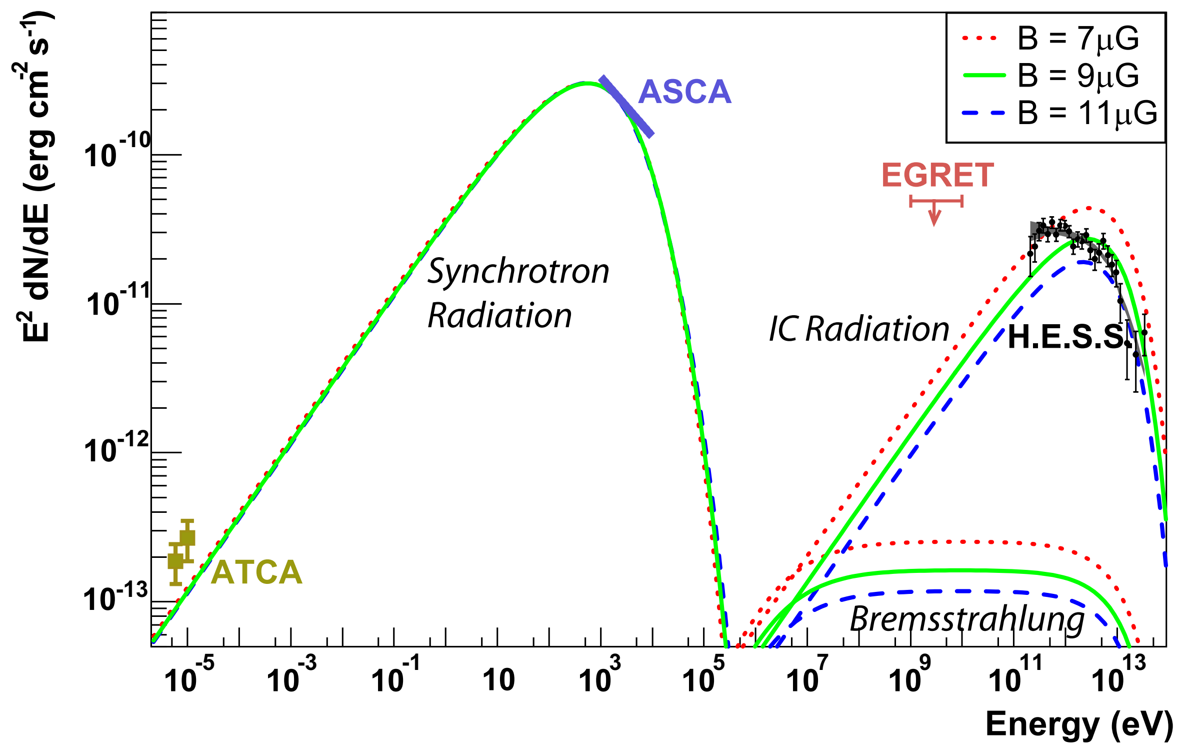
- for leptonic bremsstrahlung:
  - hard leptonic component applied
  - different normalizations

- GeV excess still remains!

- $\Phi_B(E) \simeq 1.3 \times 10^{-8} \frac{\omega_e}{0.1 \text{ eV/cm}^3} \cdot \frac{N_{ISM}}{10^{22} \text{ cm}^{-2}} \cdot \left(\frac{E}{100 \text{ MeV}}\right)^{2.0-\Gamma_e} \quad \frac{\text{erg}}{\text{cm}^2 \text{ sec sr}}$
- hadronic γ-rays insufficient to explain the GeV bump!

RX J1713.7-3946 Observation



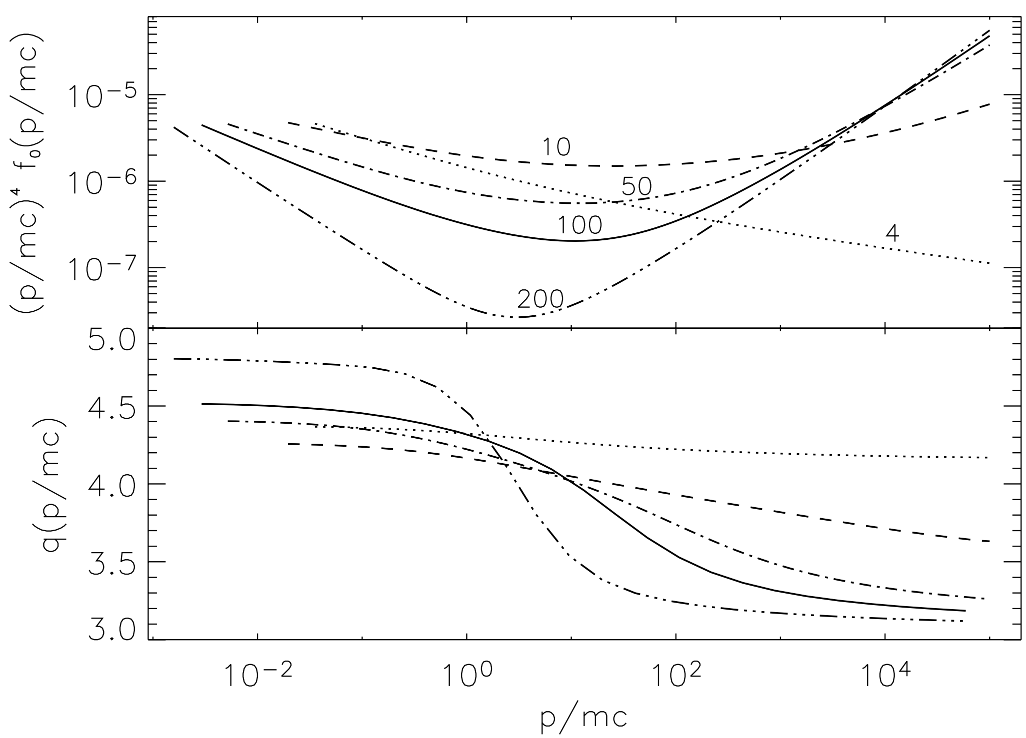


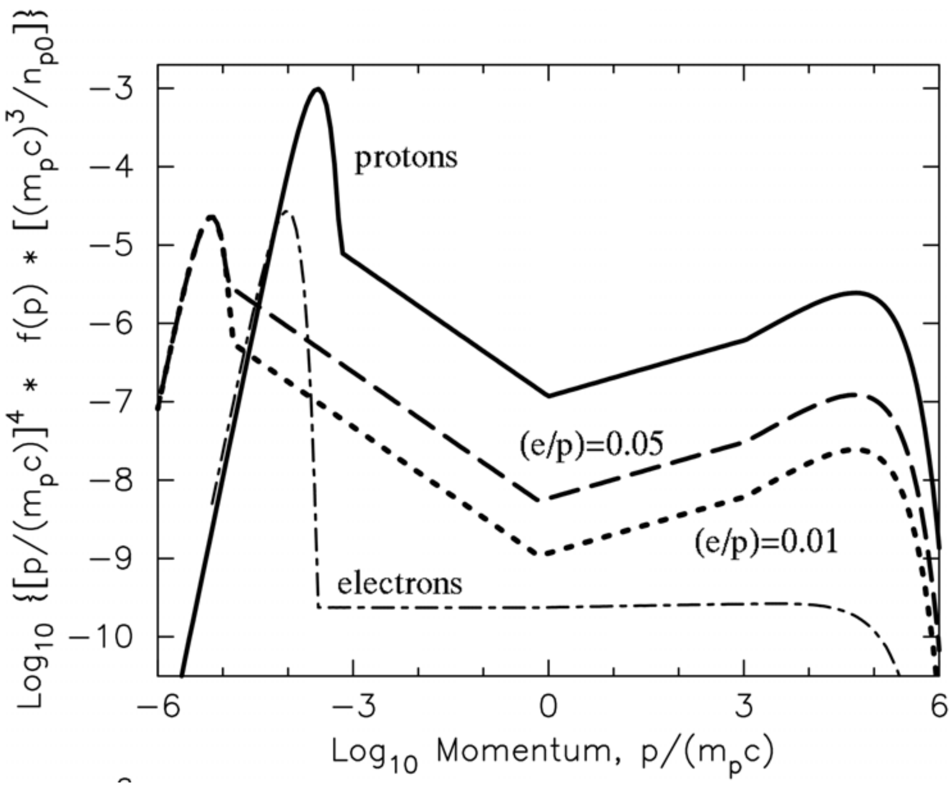
(HESS A&A 449, 223 (2006))

- Leptonic models (bremsstrahlung or Inverse Compton) requires unusually weak magnetic field!
- Shell-type SNR RX J1713.7-3946 may emit hadronic γ-rays!

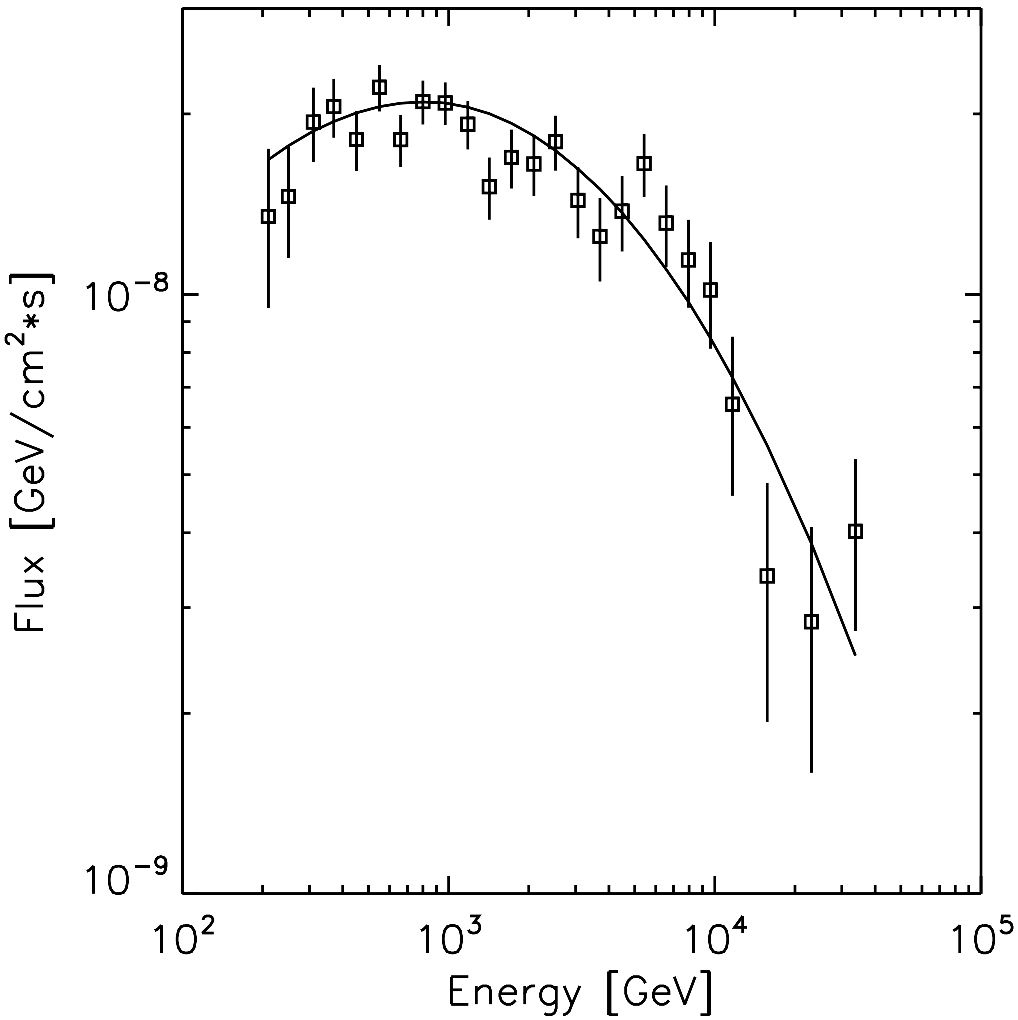
Shock Modification for Cosmic-Ray Acceleration

- shocks are efficient for particle acceleration;
- non-linear shock modification arises due to the dynamical reactions of accelerated particles on the shocks;
- Models predict continuous hardening spectra with a positive spectral curvature! (Amato & Blasi, MNRAS 371, 1251 (2006)) (Ellison et al., APJ 540, 292 (2000))





Best Fitted SNR RX J1713.7-3946 Spectrum



- parametrized particle spectrum:

$$N(E) = N_0 \left(\frac{E}{E_0}\right)^{-s+\sigma \ln \frac{E}{E_0}} \Theta\left[E_{\max} - E\right]$$

$E_0 = 15$ TeV

- γ-ray production matrix employed:

$\chi^2_{min} = 22.48$ for 22 DOF

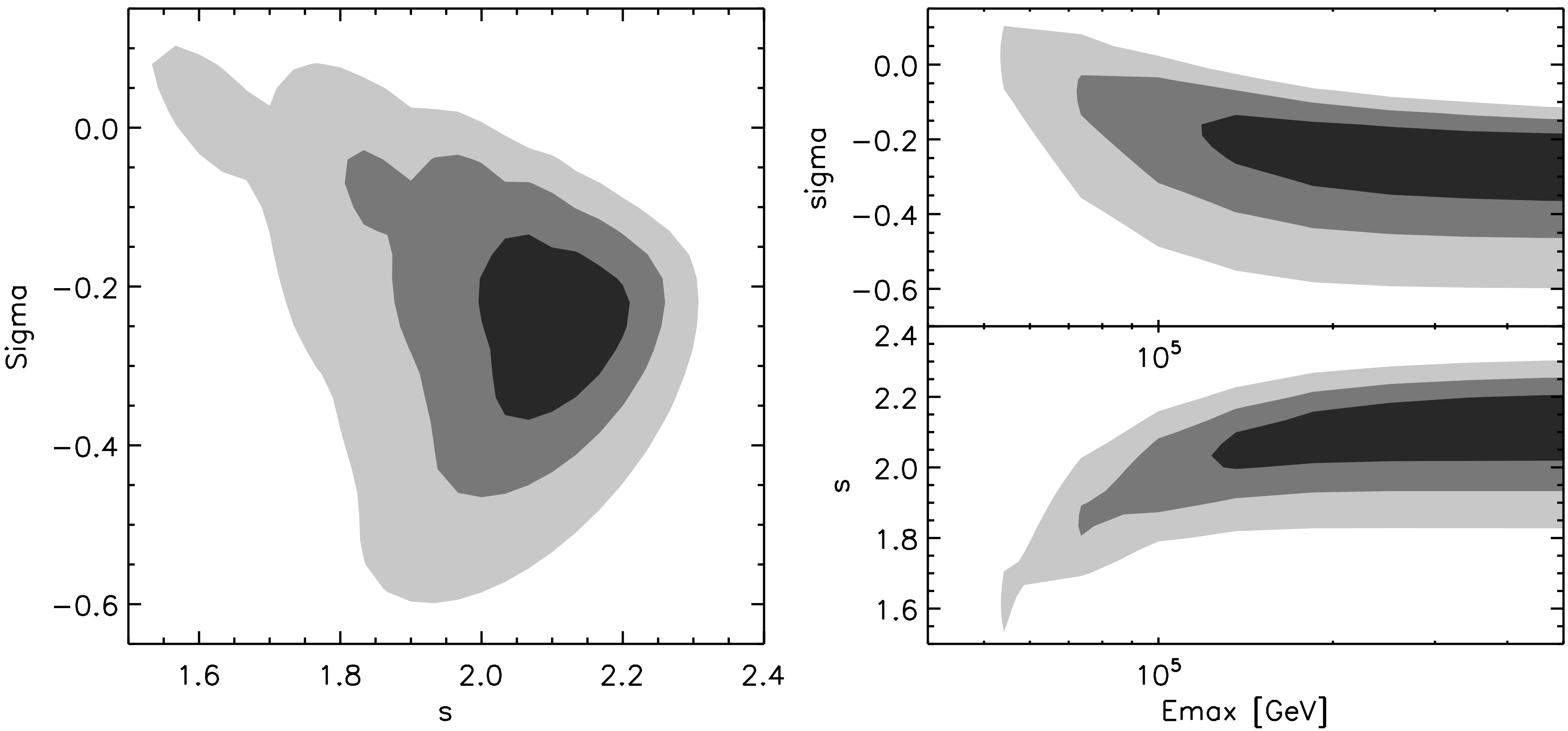
$\Longrightarrow s = 2.13$

$\sigma = -0.25$

$E_{\max} \gtrsim$ 200 TeV (No cutoff!)

- GLAST may provide information at $E \leq 200$ GeV!

Confidence Levels of Parameters



- areas of confidence levels: 68%, 95%, 99.7%;
- spectral curvature $\sigma > 0$ is ruled out (with CL > 95%)!
- negative spectral curvature strongly suggested!

Conclusions

- full picture of hadronic γ-rays in CR interactions;
- easy-to-use γ-ray production matrices;
- hadronic γ-rays insufficient to explain GeV excess;
- no evidence for standard models of CR modified shock accelerations;
- Hadronic scenario for RX J1713.7-3946 implies soft cutoff at $\sim$ 100 TeV!
- GLAST data is needed for better understanding!

† full article in press in Astroparticle Physics (or available in astro-ph/0611854)

‡ production matrices available at http://cherenkov.physics.iastate.edu/gamma-prod