ULTRA-HIGH-ENERGY COSMIC RAYS FROM ACCRETION SHOKS IN GALAXY CLUSTERS

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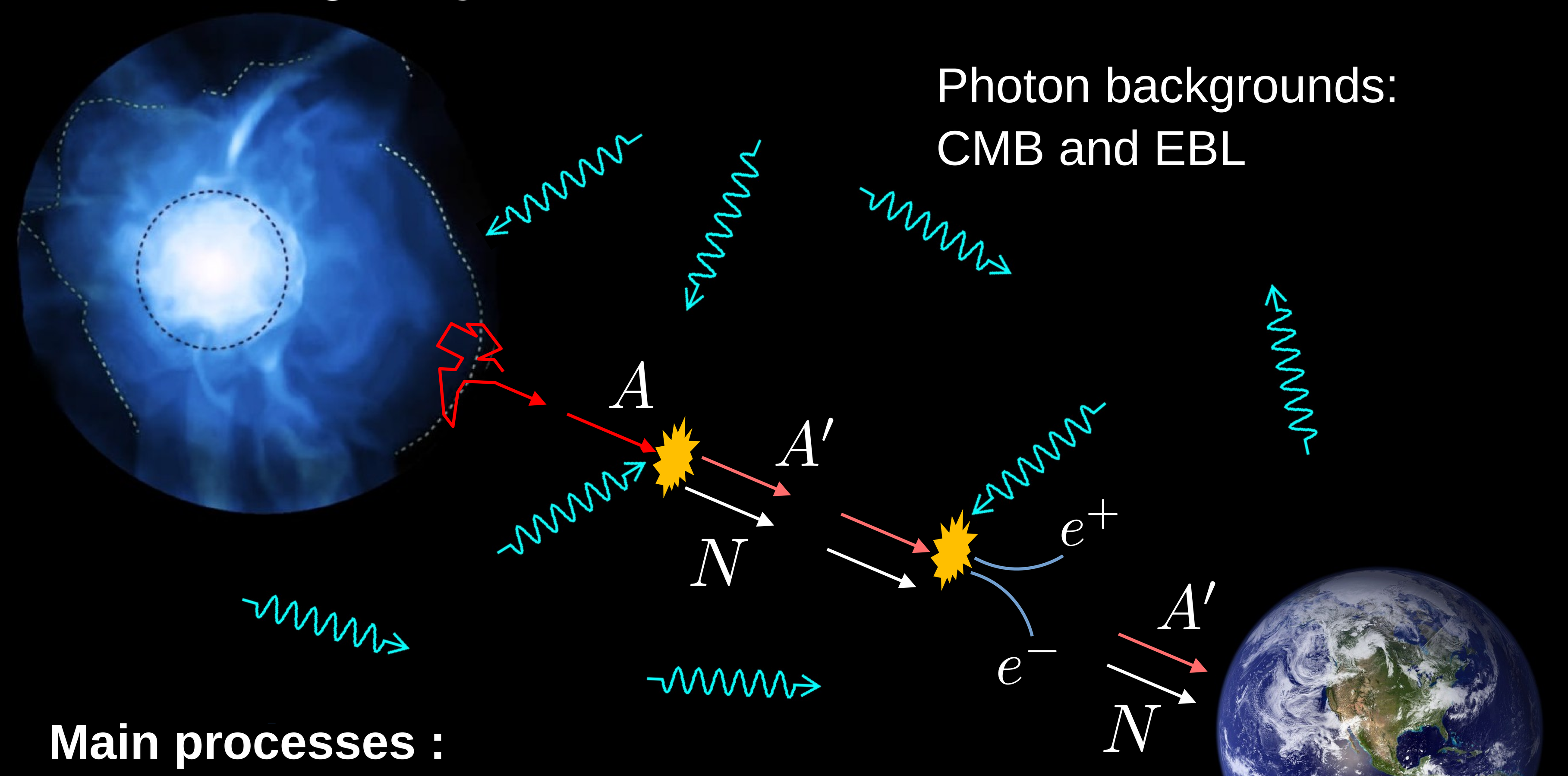
Abstract

The origin of ultra-high-energy cosmic rays is still unknown. Despite strong evidence suggesting an extragalactic origin of the sources that accelerate the most energetic cosmic rays, they have not yet been identified. Galaxy cluster accretion shocks have been considered as a possible acceleration site for cosmic ray particles. External accretion shocks in galaxy clusters arise from the inflow of material from the cosmic web into the cluster gravitational potential well. The size of these shocks can reach values on the order of megaparsecs, placing them among the largest shocks found in nature. In this work, we investigate the possibility that the ultra-high-energy cosmic rays are accelerated in galaxy cluster accretion shocks. For that purpose, we develop a model considering a set of discrete sources, corresponding to nearby massive clusters (including Virgo), superimposed to a continuous distribution of sources which considers both low-mass and non-local massive clusters. We fit the cosmic ray energy spectrum and the composition profile measured by the Pierre Auger Observatory in order to obtain a set of parameters corresponding to the injection spectrum assumed in the model. The possibility that the ultra-high-energy cosmic rays are accelerated in these astronomical objects is examined based on the results obtained.

Shocks in galaxy clusters as UHECR sources

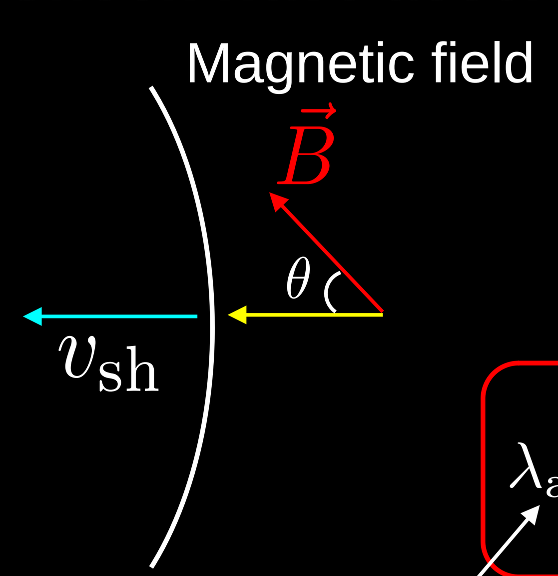


Main processes :

- Photopion production
- Pair production
- Photodisintegration

Acceleration and propagation

Shock wave acceleration



Gyroradius

$$r_g(E) = \frac{E}{ZeB}$$

Diffusion coefficient

$$k_{\|}(E) = \eta \frac{c\, r_g(E)}{3}$$

$\eta \in [1, 10]$

$$\lambda_{acc}(E) = \frac{4}{3}\left(\frac{c}{v_{sh}}\right)^2 r_g(E)\, \eta\, \mathcal{J}(\theta,\eta)$$

From Ref. [1]

$$\mathcal{J}(\theta,\eta) = \cos^2\theta + \frac{\sin^2\theta}{1+\eta^2} + 4\frac{\cos^2\theta + 16\,\frac{\sin^2\theta}{1+\eta^2}}{[\cos^2\theta + 16\sin^2\theta]^{3/2}}$$

Accretion shock parameters and injected spectrum

$$v_{sh} \cong 2.83 \times \left(\frac{M}{10^{15} M_\odot}\right)^{0.33} \frac{\text{km}}{\text{s}}$$

$$B \cong 1.71 \times \left(\frac{M}{10^{15} M_\odot}\right)^{0.31} \mu\text{G}$$

From cosmological simulations [2]

Cosmic ray luminosity of the galaxy clusters [3]:

$$\mathcal{L}_{CR}(M,z) = f_{CR}\, 1.98\times 10^{46}\left(\frac{M}{10^{15} M_\odot}\right)^{1.95} f(z)\,\text{erg}\,\text{s}^{-1}$$

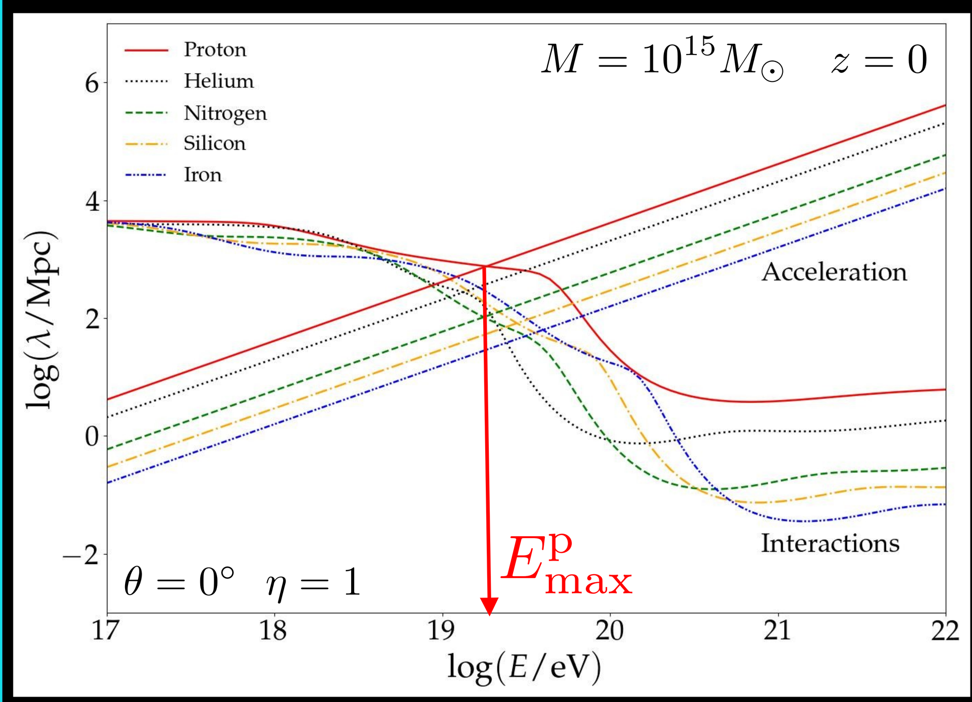
$$f(z) = (1+1.17\,z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

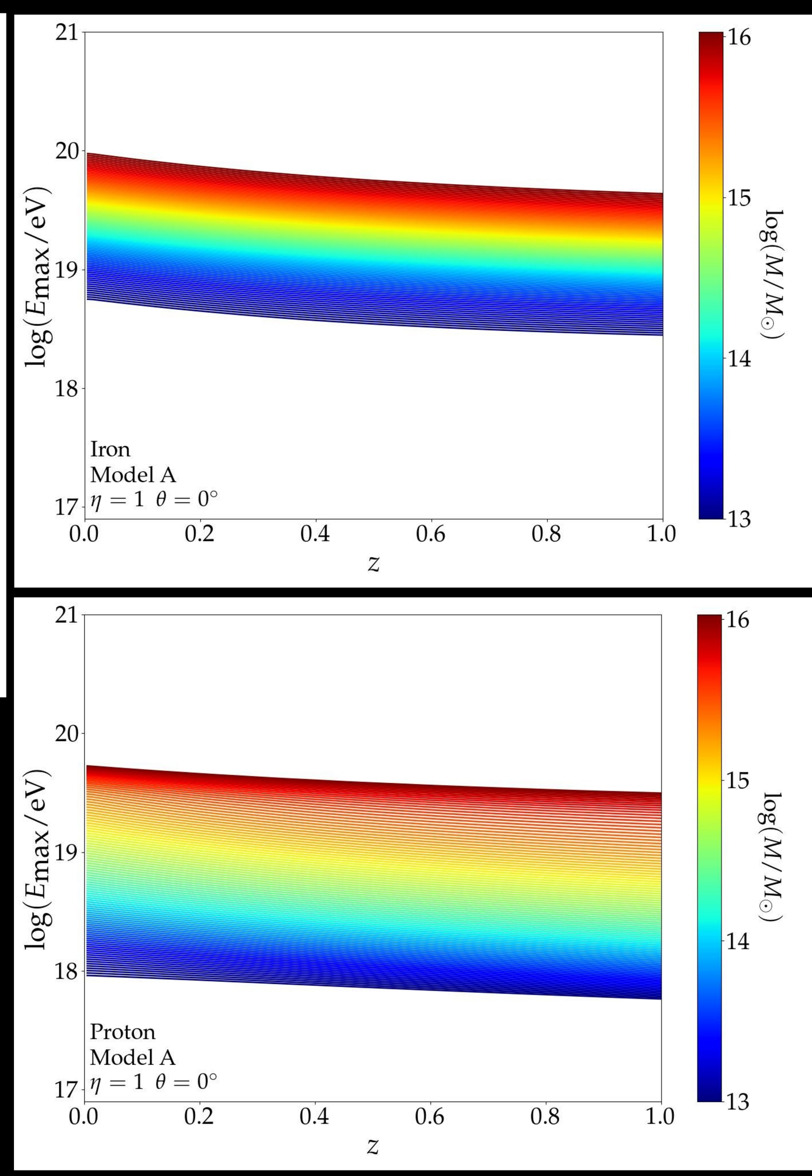
Constant

$$\mathcal{L}_{CR}(M,z,A) = I_A\, \mathcal{L}_{CR}(M,z)$$

$$\frac{dN_{CR,A}}{dt\,dE} = C(M,z,I_A,f_{CR},A)\left(\frac{E}{E_0}\right)^{-\gamma}\begin{cases} 1 & E < E_{max} \\ \exp(1 - E/E_{max}) & E \geq E_{max}\end{cases}$$

Maximum energy





Obtained by solving:

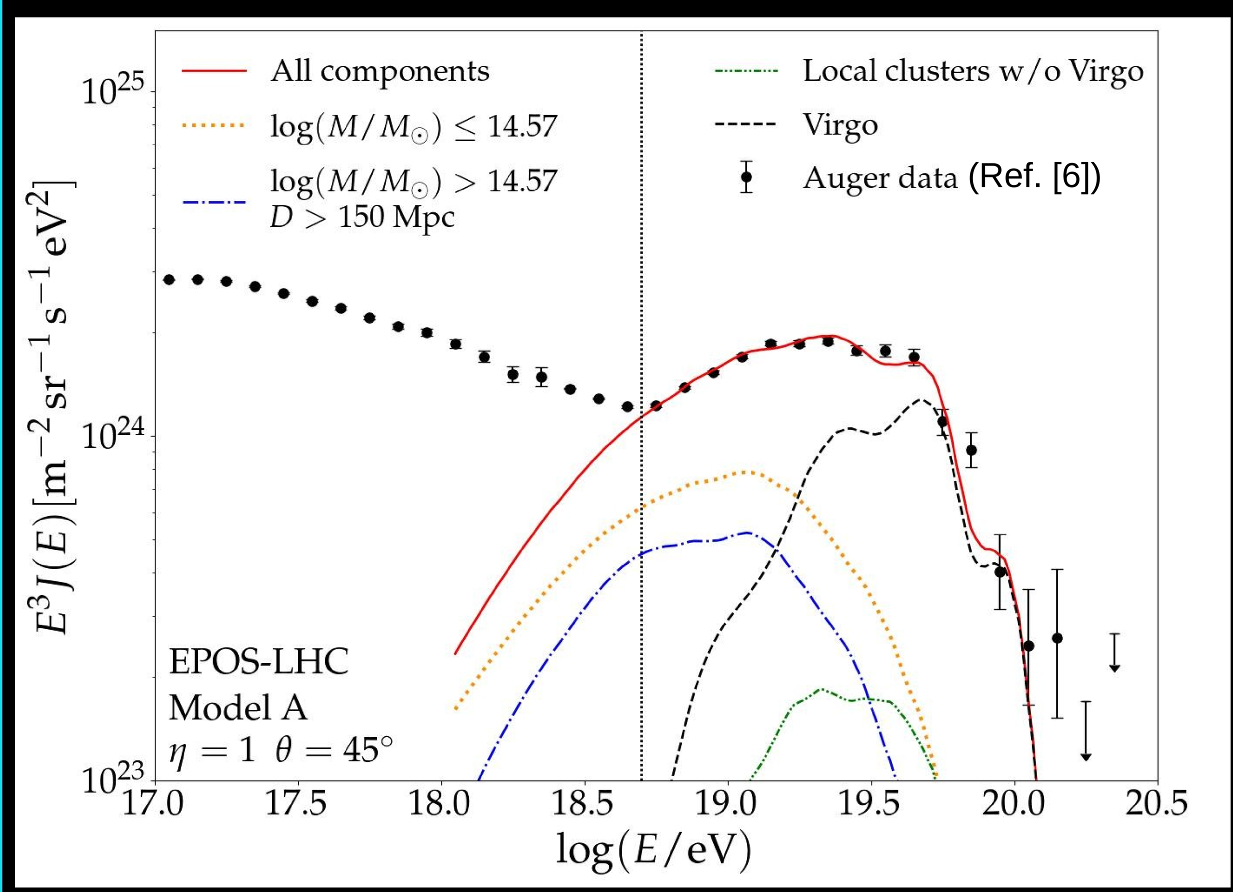
$$\lambda_{int}(E_{max}, z, Z) = \lambda_{acc}(E_{max}, Z, M)$$

$$E_{max}(A, z, M)$$

Fit of the flux and composition profile

- Discrete and continuous: $J(E) = J_D(E) + J_C(E)$
- Propagation: CRPropa 3 [4].
- Nearby clusters from catalog of Ref. [5].
- Cuts: D<150 Mpc and galaxy clusters in the field of view of Auger.

Cluster	D [Mpc]
A539	129.97
A1367	103.78
A2877	105.26
A3581	103.5
Centaurus	56.64
Fornax	20.68
Hydra	63.3
Norma	76.02
Virgo	**16.7**



Free fitting parameters:

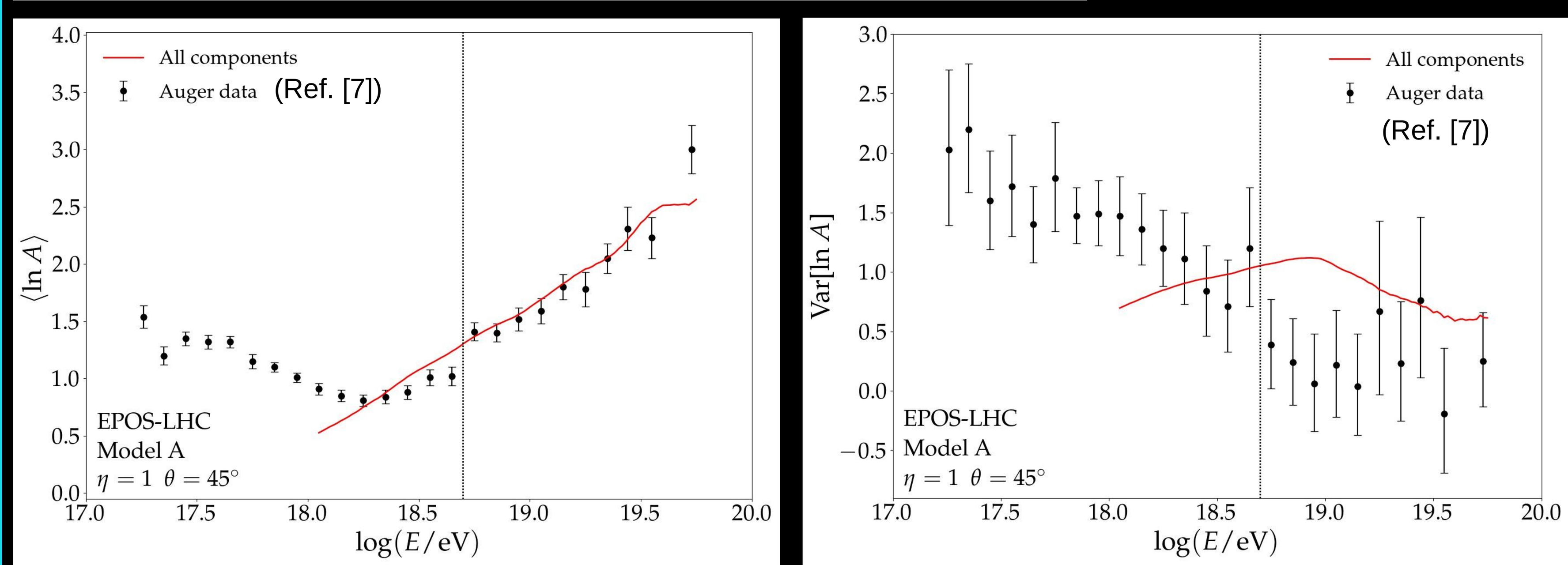
$$\{f_{CR}, \gamma\} \bigcup \{I_A\}$$

$$A \in \{\text{p, He, N, Si, Fe}\}$$

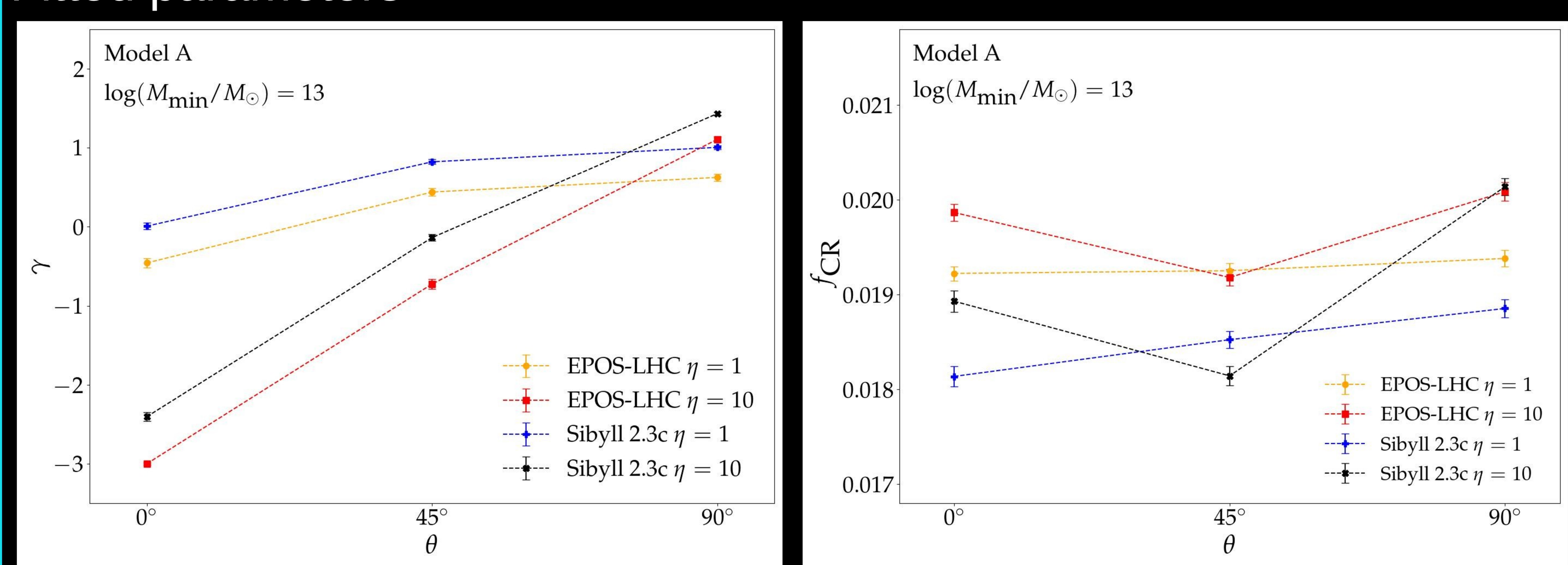
$$\sum_A I_A = 1$$

Energy cut:

$$\log(E/\text{eV}) \geq 18.7$$



Fitted parameters



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