Ultra-High energy cosmic rays acceleration at GRBs internal shocks

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Abstract

Relativistic jets are the seat of high energy emission mechanisms, that probably occur in relativistic shocks inside the jet (or when the jet encounter the ambiant medium). It is therefore interesting to consider internal shocks as sites for particle acceleration. We developed a numerical tool to compute the acceleration of particles at mildly relativistic shocks. This code includes energy losses and handles particle escape according to specific prescriptions, which can be adapted to different astrophysical environments and physical conditions. In a recent paper (arXiv:1409.1271), we applied our code to the case of GRBs internal shocks. We used the internal shock model of Daigne & Mochkovitch (1998), making different assumptions about the way the dissipated energy is redistributed between accelerated cosmic-rays, electrons and the magnetic field. We showed that particle acceleration can indeed be efficient in such environments, including for heavy nuclei, which survive photo-dissociation for a large range of gamma-ray bursts luminosities. However, only the models assuming that, (i) the prompt emission represent only a very small fraction of the energy dissipated at internal shocks, and (ii) that most of this dissipated energy is communicated to accelerated cosmic-rays, are able to reproduce the magnitude of the diffuse UHECR flux expected on Earth. For these models, we showed that the shape of the UHECR spectrum can be well reproduced above the ankle and the evolution of the composition is compatible with the trend suggested by Auger data.

Modeling a gamma-ray burst internal shock

We modeled internal shocks using the simple approach implemented by Daigne & Mochkovitch (1998), where the relativistic outflow emitted by the central engine is represented by a large number of shells that interact with one another, discretizing the propagation of a collisionless shock within the outflow. This treatment allowed us to estimate the key physical quantities at work during the internal shock phase and their evolution during the shock propagation. We assumed a given initial Lorentz factor distribution of the relativistic wind to obtain a single pulse lasting a few second in the lightcurve, which is typical in long GRBs. We discretize the evolution of the shock and make calculations at 18 different points representing 18 stages regularly distributed during the shock propagation (represented by full circles in the different graphs of Fig. 1). We considered three different models consisting in different combinations of the dissipated energy redistribution parameters. The first model (model A) assumed equipartition of the dissipated energy ($\varepsilon_e = \varepsilon_{CR} = \varepsilon_B = 0.33$) leading to an efficiency of the prompt emission of the order of 5%, independent of the burst luminosity L_γ. For models B and C, we made a different assumption on the dissipated energy redistribution parameters using much lower values ε_e, which implies that most of the dissipated energy is communicated to the accelerated cosmic-rays and the magnetic field (using $\varepsilon_{CR} \simeq 0.9$ (resp. 0.66) and $\varepsilon_B \simeq 0.1$ (resp. 0.33) for model B (resp. model C)). Therefore, the prompt emission efficiency is lower than in the case of model A and goes from approximately 0.01% for low values of L_γ to 1% for the highest prompt emission luminosities. It implies larger assumed values of the wind luminosity L_{wind} for a given prompt emission luminosity L_γ. Practically, to reproduce prompt emission luminosities between $5\ 10^{49}$ and $5\ 10^{53}$ erg s^{-1}, as in the case of model A, we assume wind luminosities between $3\ 10^{53}$ and $3\ 10^{55}$ erg s^{-1}. It may seem that the physical assumptions behind models B and C are somewhat extreme, from the energetics point of view, however, this does not increase the maximum power usually assumed for the GRBs by unreasonable factors. The highest luminosity GRBs ($L_\gamma > 5\ 10^{53}$ erg s^{-1}) require a wind power of only a factor of 3 for models B and C larger than for model A, while the difference in the power needed increases for lower luminosity GRBs, to reach a factor of 300 at the lowest luminosity. Consequently, the spread in the assumed intrinsic power of GBRs is smaller in the case of models B and C than in the case of model A (see Fig.1).

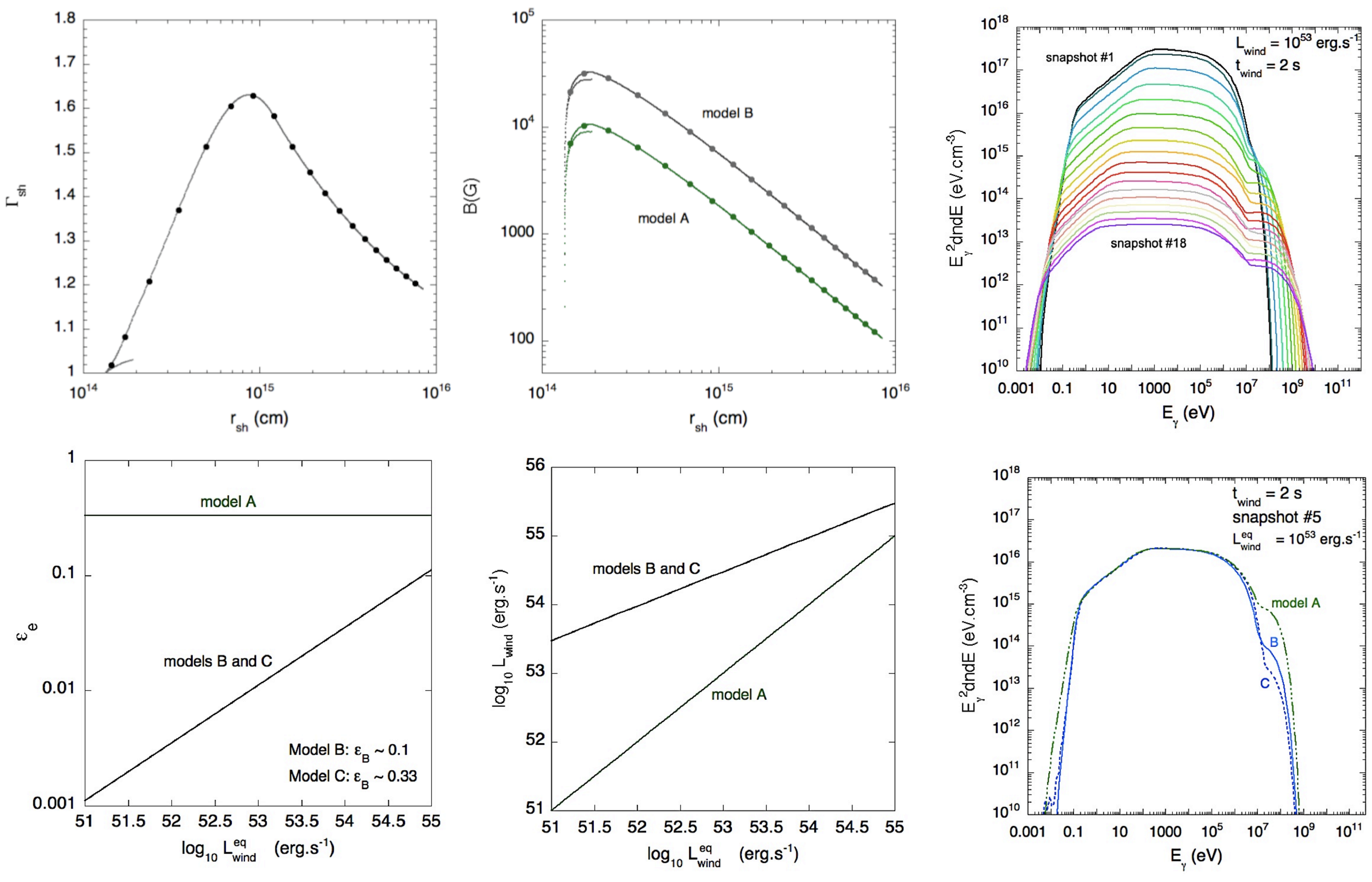

Fig.1 Top: Evolution of the shock Lorentz factor, the magnetic field and the emitted photon spectrum during the 18 stages of the single synthetic GRB pulse. ($L_{wind}=10^{53}$ erg s^{-1}, $t_{wind}=2$s). Bottom: Illustration of the different models of dissipated energy redistribution parameters and a comparison of the photon spectrum for stage 5.

Particle acceleration including energy losses

We performed numerical simulations of cosmic-ray acceleration at mildly relativistic shocks, using numerical tools inspired by the work of Niemiec & Ostrowski (2004). We considered Lorentz factors between 1 and 2, which is the typical range expected at GRB internal shocks. We tested various magnetic field configurations in the vicinity of the shock, assuming different turbulence power spectra, turbulence levels or regular field obliquities. **We calculated the spectra of particles escaping downstream and upstream as well as the energy evolution of the acceleration time for different magnetic field configurations.** Most of the spectra of particles advected downstream deviated significantly from single power laws, as already pointed out by Niemiec & Ostrowski (2004). In the cases of purely turbulent fields (assuming a Kolmogorov power spectrum), we found relatively hard spectra with a sizeable fraction of the available energy communicated to high energies. In the case of quasi parallel shocks with low turbulence level, the hardest spectra (well harder than E^{-2}) were found, while quasi-perpendicular "superluminal" shocks resulted in much softer spectra with sharp cut-offs below E_{max} (which is the energy at which the Larmor radius equals the largest turbulence length scale).

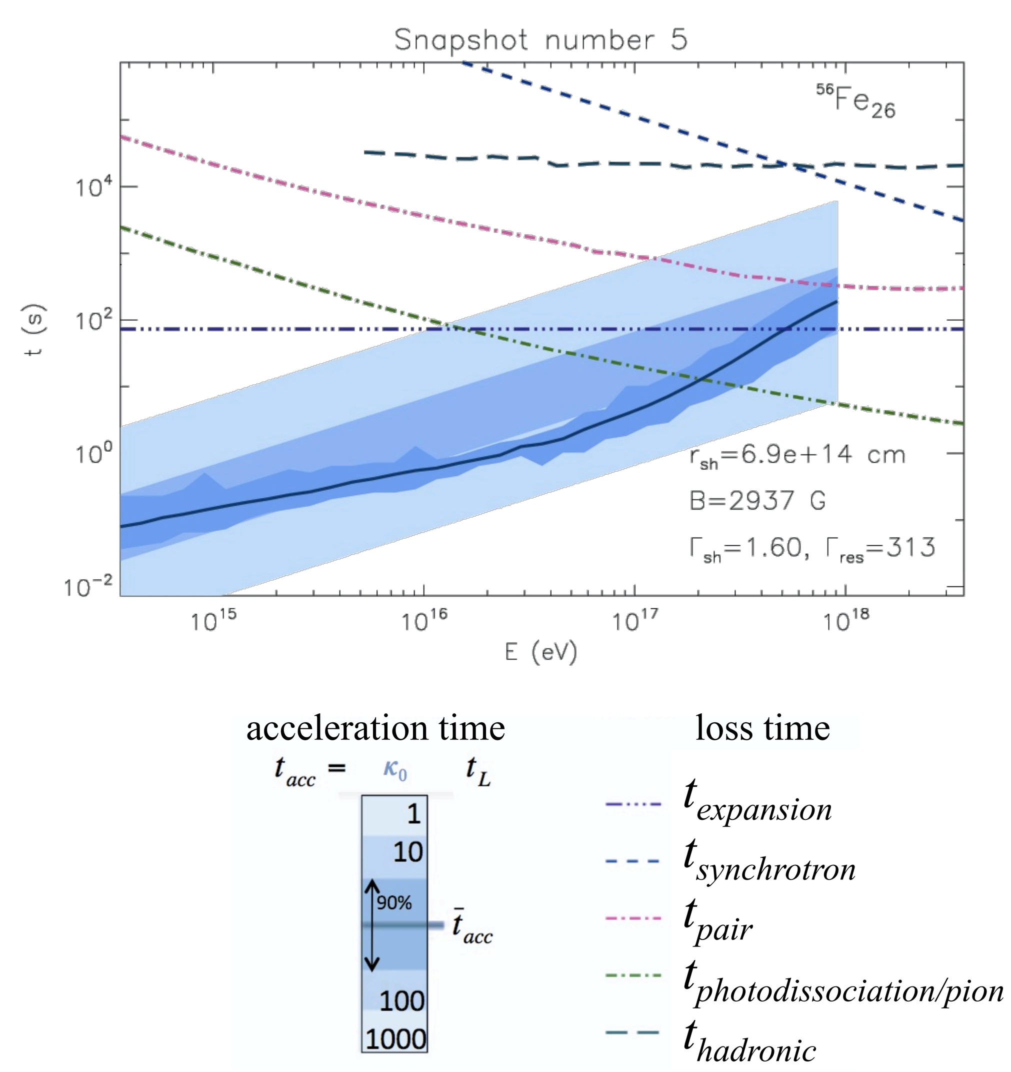

Fig.2 Comparison of the acceleration typical timescales with the energy loss timescales for stage 5 ($L_{wind}=10^{53}$ erg s^{-1}, t_{wind}=2s, model B).

Another important aspect of the problem is to properly take into account energy losses of the accelerated particles. For that purpose we simulated synthetic gamma-ray bursts using the model of Daigne and Mochkovitch (1998). This simple model allows to calculate the physical parameters of the internal shocks, such as the magnetic field strength, the electron density and characteristic energy, and gives values relatively close to more sophisticated hydrodynamic models. Using our own radiative code for synchrotron emission and inverse Compton scattering (in this case synchrotron self-Compton) We calculate the internal shock prompt emission (see example in Fig. 1) . Those photons will serve as targets for the accelerated cosmic-rays. We compared the acceleration typical timescales with the energy loss timescales (including interactions with the calculated prompt emission photons) to estimate the maximum energy that a cosmic ray can reach in the shock wave (see Fig. 2). We investigated different configuration and found that it is possible to accelerate heavy nuclei at energies larger than 10^{20} eV in some cases.

We included the energy loss mechanisms into the Monte-Carlo calculation of cosmic-ray acceleration at mildly relativistic shocks. We performed simulations reproducing the physical conditions (magnetic fields, baryon and photon densities, shock Lorentz factors) at different stages of the shock propagation. This treatment allowed us to estimate the cosmic-ray and secondary neutrino emission, for a GRB of a given luminosity, and its evolution during the shock propagation. We calculated cosmic-ray and neutrino outputs for different GRB luminosities and our three energy redistribution models, assuming a composition with ten times the metallicity of Galactic cosmic-ray sources (example in Fig.3).

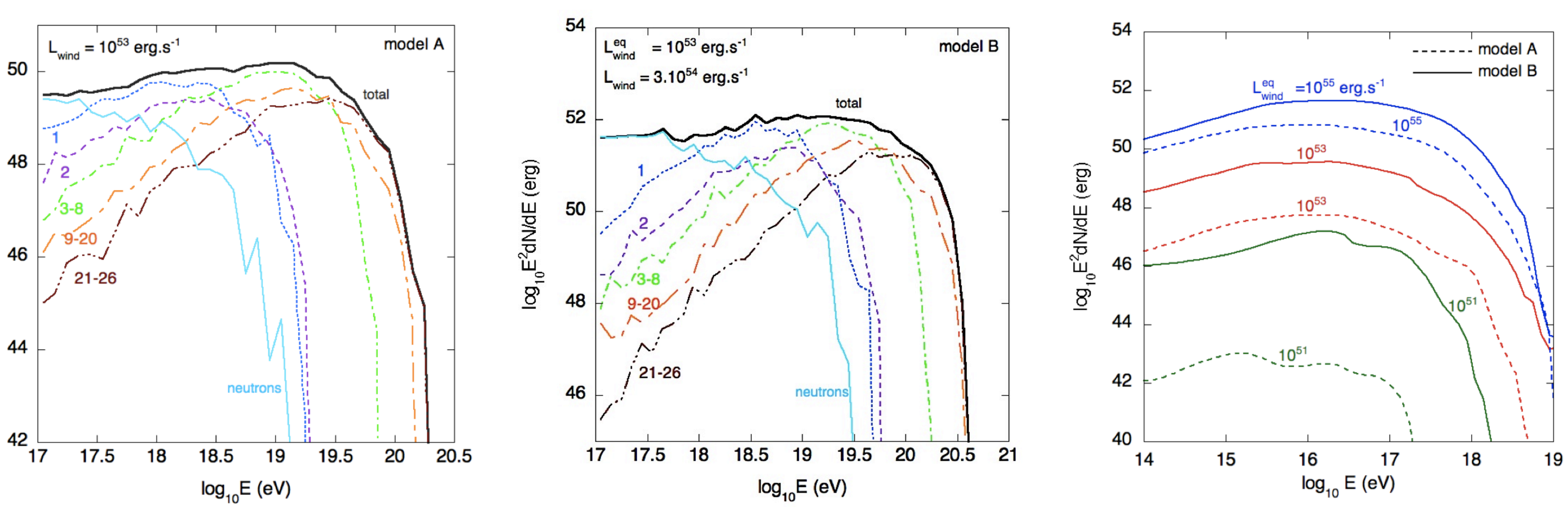

Fig.3 Cosmic-ray spectra, multiplied by E^2, emitted by GRBs, in the central source frame, assuming for illustration $L_{wind} = 10^{53}$ erg s^{-1}, in the cases of model A (left panel) and B (central panel). The contribution of different groups of nuclear species is shown (the labels refer to the nuclei atomic number Z). The normalization is obtained by integrating over the whole shock propagation.
Right panel: Neutrino spectra emitted by GRBs for different values of $L_{wind}{}^{eq}$: 10^{51}, 10^{53} and 10^{55} erg s^{-1}, for models A (dashed lines) and B (full lines).

Calculation of the diffuse UHECR fluxes expected on Earth

We calculated the expected UHECR and neutrino diffuse fluxes on Earth, by convoluting the cosmic-ray and neutrino release obtained for given GRB luminosities, with the distribution of GRB luminosities, taking also into account their luminosity function and cosmological evolution as recently derived by Wanderman & Piran (2010). In the case of model A, we obtained an integrated cosmic-ray luminosity density, above 10^{18} eV, of the order of 6 10^{42} erg Mpc^{-3} yr^{-1}, almost two orders of magnitude below that required to reproduce the observed UHECR flux. This means that GRBs are very strongly disfavored as the dominant source of UHECRs, if the dissipated energy is equally shared between accelerated electrons and cosmic-rays, as already concluded by several authors.
For models B and C, we found UHECR luminosity densities of 3.9 10^{44} and 3.2 10^{44} erg Mpc^{-3} yr^{-1} respectively, of the same order as those required. We then simulated the extragalactic propagation of UHECR from GRB sources, considering (i) different assumptions on the extragalactic magnetic field (EGMF) variance, (ii) the cases of isotropic or beamed GRBs, (iii) a large number of realizations of the history of GRB explosions in the universe. We found that the magnitude of the observed UHECR flux is well reproduced by models B and C, providing very moderate renormalizations of the predicted fluxes by ≃5% downward and ≃25% upward, respectively. The shape of the observed UHECR spectrum is also well reproduced above the ankle by both models, particularly by model C (see left panel of Fig. 4). Concerning the evolution of the composition, we found a good qualitative agreement with the trend suggested by the Auger data: a light composition at the ankle becoming gradually heavier with increasing energy. Because of the slightly higher maximum energies predicted, model C differs from model B by a slight shift in energy of the decrease of the proton component.
We finally calculated diffuse neutrino fluxes from GRB sources as well as cosmogenic neutrino and photon fluxes, and found that those fluxes were currently not constrained by any experimental measurement or limit (see right panel of Fig.4).

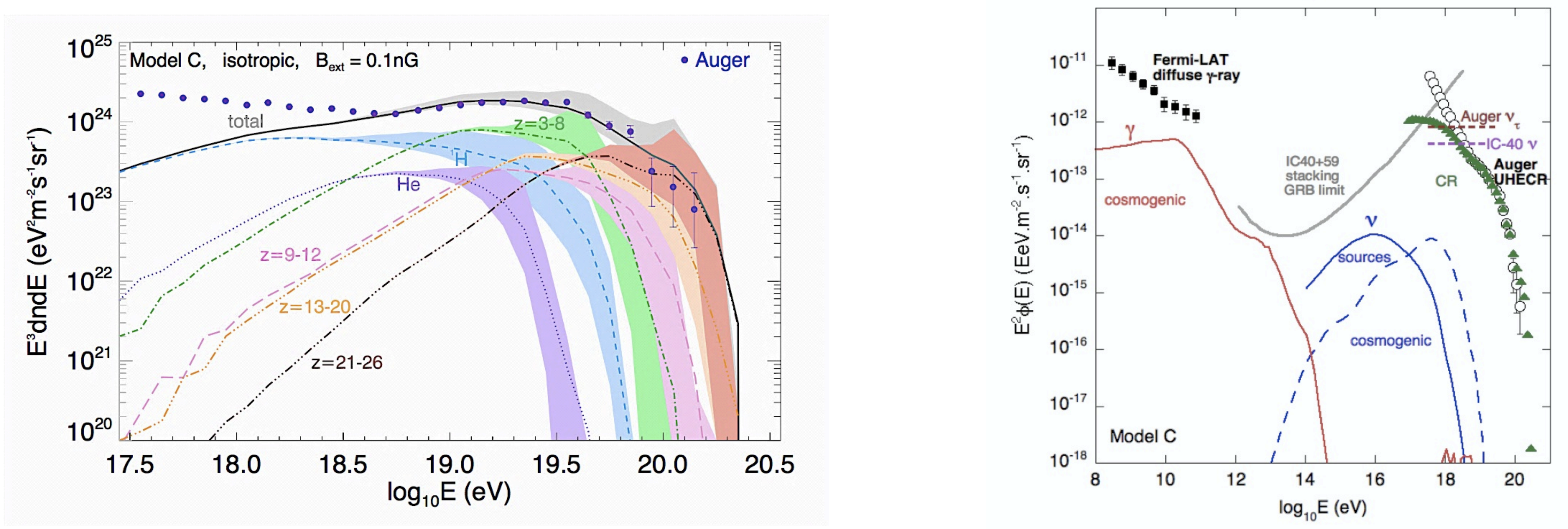

Fig.4 Left: Diffuse cosmique ray flux spectrum, expected on Earth, assuming an EGMF variance of 0.1 nG, in the case of model C. The contributions of different groups of nuclei are shown, the lines (plain lines for the total spectrum) represent the mean value calculated over 300 realizations of GRB history in the universe, the shaded areas represent the 90% intervals.
Right: UHECR spectrum, cosmogenic neutrinos and photons spectra and diffuse neutrino spectrum from GRB sources predicted for model C, compared to various experimental limits or measurements.