Extreme Energy Cosmic Rays: 
Bottom-up vs. Top-down scenarii

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Abstract

We present an overview on extreme energy cosmic rays (EECR) and the fundamental physics connected with them. The top-down and bottom-up scenarii are contrasted. We summarize the essential features underlying the top-down scenarii for EECR, namely, the lifetime and the mass imposed to the heavy relics whatever they be: topological and non-topological solitons, X-particles, cosmic defects, microscopic black-holes, fundamental strings. An unified formula for the quantum decay rate of all these objects was provided in hep-ph/0202249. The key point in the top-down scenarii is the necessity to adjust the lifetime of the heavy object to the age of the universe. The natural lifetimes of such heavy objects are, however, microscopic times associated to the GUT energy scale (\(\sim 10^{-28}\) sec. or shorter); such heavy objects could have been abundantly formed by the end of inflation and it seems natural they decayed shortly after being formed. The arguments produced to fine tune the relics lifetime to the age of the universe are critically analyzed. The annihilation scenario (‘Wimpzillas’) is analyzed too. Top-down scenarii based on networks of topological defects are strongly disfavored at the light of the recent CMB anisotropy observations. We discuss the acceleration mechanisms of cosmic rays, their possible astrophysical sources and the main open physical problems and difficulties in the context of bottom-up scenarii, and we conclude by outlining the expectations from future observatories like EUSO and where the theoretical effort should be placed.

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1 Introduction

Cosmic rays are one of the rare systems in the Universe which are not thermalized. Their energy spectrum follows approximately a power law over at least thirteen orders of magnitude. The understanding of the cosmic ray spectrum involves several branches of physics and astronomy.

First, to explain how cosmic rays get energies up to $10^{20}$eV according to observations and with such power spectrum. Then, to study the effect of galactic and extragalactic magnetic fields and explain the knee and the ankle effects. Furthermore, clarify whether the GZK effect is present or not in the cosmic rays events observed beyond $10^{20}$eV. Last and not least to understand the interaction of the cosmic rays with the atmosphere, the extended air shower formation, especially at extreme energies and the fluorescence effects. At the same time, one has to identify the astronomical sources of cosmic rays and relate the observed events, composition and spectra with the properties and structure of the sources.

The standard physical acceleration mechanism goes back to the ideas proposed by E. Fermi in the fifties. That is, charged particles can be efficiently accelerated by electric fields in astrophysical shock waves\cite{8, 10}. This is the so-called diffusive shock acceleration mechanism yielding a power spectrum with

$$n(E) \sim E^{-\alpha},$$

with $2.3 \leq \alpha \leq 2.5 - 2.7$. Such spectrum is well verified over thirteen orders of magnitude in energy.

2 Top-down scenarii

Top-down scenarii for extreme energy cosmic rays (EECR) are based on heavy relics from the early universe which are assumed to decay at the present time or from topological defects also originated in the early universe. For all relics, (whatever their nature: heavy particles, topological and non-topological solitons, black-holes, microscopic fundamental strings, cosmic defects etc.), one has to fine tune the lifetime of these objects to be the age of the universe.

It has been further proposed that stable heavy relics can produce EECR through annihilation by pairs\cite{23, 24}. This scenario suffer a different type of inconsistencies as we show below.

The second type of top-down scenarii rely on the existence of a network of topological defects formed during phase transitions in the early universe. Such topological defects should survive till nowadays to produce the observed EECR. In case they decay in the early universe we go back to the previous case. It must be first noted that only some grand unified field theories support topological defects\cite{11}. Moreover, recent CMB anisotropy measurements from Boomerang, Maxima, Dasi and Archeops\cite{19} have seen no evidence of topological defects strongly disfavoring their eventual presence in the present universe.
We provided in ref.\cite{1} an unified description for the quantum decay formula of unstable particles which encompass all cases above mentioned as well as the particle decays in the standard model (muons, Higgs, etc). In all cases the decay rate can be written as,

\[ \Gamma = \frac{g^2 m}{\text{numerical factor}} \]  

where \( g \) is the coupling constant, \( m \) is the typical mass in the theory (it could be the mass of the unstable particle) and the numerical factor contains often relevant mass ratios for the decay process.

The key drawback of all top-down scenarii is the lifetime problem. The ad-hoc requirement of a lifetime of the order the age of the universe for the heavy particles implies an operator with a very high dimension describing the decay, and/or an extremely small coupling constant (see below).

Heavy relics could have been formed by the end of inflation at typical GUT’s energy scales, but their natural lifetime would be of the order of microscopic times typically associated to GUT’s energy scales\cite{16}.

The problem in the top-down scenarii is not the formation of heavy particles or topological defects. They could all have been generated in the early universe. The key problem is their existence today (i.e. their imposed lifetime of the order of the age of the universe) and the value of their mass that must be adjusted to be \( \sim 10^{20} \text{eV} \).

Heavy particles with masses in the GUT scale can be produced in large numbers during inflation and just after inflation\cite{16}. The production mechanism is particle production by the expanding metric and parametric or spinodal amplification in the inflaton field. That is, linear resonance of the quantum modes of the heavy field in the background or condensate of the inflaton. In addition, non-linear quantum phenomena play a crucial role and can enhance the particle production\cite{16}. Such non-linear production is of the same order of magnitude as the gravitational production of particles by the time dependent metric.

Once these heavy particles are produced they must have a lifetime of the order of the age of the universe in order to survive in the present universe and decay into EECR. Only in the early universe the production of such heavy objects is feasible due to their large mass.

Moreover, in order to be the source of EECR, these particles must have a mass of the observed EECR, namely \( m_X > 10^{20} \text{eV} = 10^{11} \text{GeV} \).

The effective Lagrangian describing the X-relic decay contains a local monomial of dimension \( n \) (in mass units)

\[ \mathcal{L}_I = \frac{g}{M^{n-2}} X \Theta, \]  

here the field \( X \) is associated to the decaying particle of mass \( m_X \) and \( \Theta \) stands for the product of fields coupled to it.

Then, the decay rate for a particle of mass \( m_X \) takes the form\cite{11}

\[ \Gamma = \frac{g^2}{\text{numerical factor}} m_X \left( \frac{m_X}{M} \right)^{2n-8} \]  

\[ \]
and their lifetime will be given by
\[
\tau_X = \text{numerical factor} \frac{1}{g^2} \left( \frac{M}{m_X} \right)^{2n-8} = \text{numerical factor} \frac{1}{g^2} m_X 10^{6(n-4)}
\]
where we set a GUT mass \( M = 10^{15} \) GeV. The age of the universe is \( \tau_{\text{universe}} \sim 2 \times 10^{10} \) years
and we have to require that \( \tau_X > \tau_{\text{universe}} \). Therefore,
\[
10^{54} < \frac{\text{numerical factor}}{g^2} 10^{6(n-4)} \quad \text{or} \quad \log_{10} g < 3(n - 13) \tag{5}
\]
where we dropped the numerical factor in the last step.

For \( g \sim 1 \), eq. (5) requires an operator \( \Theta \) with dimension at least thirteen in the effective Lagrangian \( (3) \) which is a pretty high dimension.

That is, one needs to exclude all operators of dimension lower than thirteen in order to extremely suppress the decay. Clearly, one may accept lower dimension operators \( \Theta \) paying the price of a small coupling \( g \). For example: \( g = 10^{-9} \) and \( n = 10 \) fulfill the above bound still being a pretty high dimension operator. Notice that a moderate \( n \) as \( n = 4 \) lowers the coupling to \( g \sim 10^{-27} \).

In summary, a heavy X-particle can **survive** from the early universe till the present times if one chooses

- an extremely small coupling \( g \)
  and/or
- an operator \( \Theta \) with high enough dimension

None of these assumptions can be supported by arguments other than imposing a lifetime of the age of the universe to the X-particle. That is, the lifetime must be here **fine tuned**. That is, one has to built an ad-hoc Lagrangian to describe the X-particle decay. Indeed, a variety of ad-hoc lagrangians have been proposed in the literature together with the symmetries which can adjust a wide variety of lifetimes[5].

In order to cope with the lifetime problem a number of so called ‘solutions’ have been invoked, but all the ‘remedies’ replace an assumption by another one, namely:

- (1) an assumed new global symmetry to protect the X particle and which would be only broken non-perturbatively by quantum gravity wormholes [3] or instanton-type effects [4] to make \( \tau_X = \) age of the universe. However, these quantum gravity effects are poorly controlled, basic theoretical uncertainties remain, (the sign of the euclidean gravity action being only one of them), which would produce the opposite effect to the one claimed; thus \( \tau_X \) would be exponentially shortened (instead of increased) by wormholes.
• (2) discrete gauge symmetries to construct high dimensional operators [5]. As stated before, these are all ad-hoc lagrangians built on the assumption that such group symmetries could have a physical rôle. No fundamental physical reason exists to argue for them.

• (3) On the same line of thinking, fractionally charged particles (‘cryptons’) have been invoked [6] from some particularly chosen hidden sectors of particular effective string/M inspired models. Then, support to the assumption of a long lifetime for $\tau_X$ would come from a strongly interacting (bound state) sector and its non-pertubative dynamics (which is not controlled), in flipped $SU(5)$ for instance. But, as many ‘particle’ sectors appearing in string inspired phenomenology, no physical reason exists to choose for such states, in particular for fractionally charged (bound) state particles.

Finally, in the line of reasoning of (1)-(3) mentioned before, comparison with the stability or ‘metastability’ of the proton has been invoked in order to support for the stability (and decay) of the X-particles. In the standard model, in which baryon-lepton number is conserved, proton decay can be realized only by ad-hoc introducing non-renormalizable high dimensional operators; then, it is invoked that ‘a new global symmetry’ for the X-particle could exist, only broken by operators suppressed by $M^n$ with $M = M_{planck}$ and $n > 7$ [7].

In other words, ad-hoc proton decay is argued to support ad hoc X-particle decay. As is known, GUT models predict proton decay (which have not been found so far), placing a lower bound of the proton lifetime $\tau_{proton} > 1.6 \times 10^{25}$ yr. Proton decay is however a natural consequence of grand unification as lepton and quarks belong to the same multiplet.

A common feature to top-down approach is that the arguments trying to support a long lifetime for the X-particles successively call for more and more speculative explanations.

Still, the essential question in the top-down scenarii remain, i.e.: IF X-particles and topological defects in such scenarii have NOT decayed in the early universe, shortly after they formed, WHY they should decay JUST now?, i.e. the lifetime fine tuning remains.

The top-down scenarios are just tailored to explain the observed events. There is absolutely no physical reason to assume that relics have such a mass (and not any other value) and such a lifetime.

Moreover, the question of stability of topological solutions is a highly non trivial issue. The mere presence of a conserved topological charge does NOT guarantee their stability, the energy must be related to the topological charge and must be bounded from below by the topological charge. Otherwise, the topological defect is unstable.

Closed vortices from abelian and non-abelian gauge theories are not topologically stable in $3 + 1$ space-time dimensions. Static vortices in $3 + 1$ space-time dimensions just collapse to a point since their energy is proportional to their length. They do that in a very short (microscopic) time.
It must be noticed that only a restricted set of spontaneously broken non-abelian gauge theories exhibit vortex solutions. For example, there are no topologically stable vortices in the standard $SU(3) \times SU(2) \times U(1)$ model in $3 + 1$ space-time dimensions. Grand unified theories may or may not possess vortex solutions in $2 + 1$ space-time dimensions depending under which representations of the gauge group belong the Higgs fields.

Cosmic strings are closed vortices of horizon size. In $3 + 1$ space-time dimensions, strings collapse very fast except if they have horizon size in which case their lifetime would be of the order of the age of the universe. However, such horizon size cosmic strings are excluded by the CMB anisotropy observations and by the isotropy of cosmic rays.

Such gigantic objects would behave classically whereas microscopic closed strings (for energies $< M_{\text{Planck}} = 10^{19}$ GeV) behave quantum mechanically.

The existence of cosmic string networks is not established although they have been the subject of many works. In case such networks would have existed in the early universe they may have produced heavy particles $X$ of the type discussed before and all the discussion on their lifetime applies here. The discussion on the lifetime problem also applies to rotating superconducting strings which have been proposed as classically stable objects\[20].

In summary, a key point here is the \textbf{unstability} of topological defects in $3 + 1$ space-time dimensions. Unless one chooses very specific models \[21], topological defects decay even classically with a short lifetime. They collapse to a point at a speed of the order of the speed of light.

\subsection{Annihilation Top-down Scenarios}

There are top-down scenarii where, instead of decay, annihilation of the relic superheavy particles (wimpzillas) have been proposed\[23] \[24]. That is, in this scenario the relics with mass $M_X \sim 10^{12}$ GeV are stable and produce EECR through annihilation when they collide\[23] \[24]. Here, the lifetime free parameter is replaced by the annihilation cross section. These superheavy particles are assumed to be produced during reheating\[23]. Its annihilation cross section is thus bounded by the amount of dark matter in the universe: $\sigma_X \sim \alpha (M_X)^{-2}$ and $\alpha \leq 0.01$. In ref.\[24] the produced EECR flux is computed for several scenarii:

For a smooth dark matter distribution assuming a NFW singular profile it is required that $\sigma_X = 6 \times 10^{-27}$ cm$^2$ in order to reproduce the observed EECR flux\[24]. But this value for $\sigma_X$ is $10^{27}$ larger than the maximum value compatible with $\Omega \sim 1$ in the early universe (corresponding above to $\alpha \sim 0.01$).

In a second scenario, dark matter is assumed to form into clumps with NFW profiles. In this way, the EECR flux is about $\sim 2000$ times larger due to the increase of the dark matter density\[24]. However, that needs again a value for $\sigma_X \sim 10^{24}$ times larger than its value in the early universe.

Finally, isothermal clumps have been considered. There, the EECR flux turns to be independent of $\sigma_X$ but the internal radius of the clump $R_{\text{min}}$ is proportional to $\sigma_X$. For our galaxy, $R_{\text{min}}$ turns to be $\sim 10^{-42}$ times the size of the clump. For a 10 kpc clump this gives $R_{\text{min}} \sim 10^{-20}$ cm which is a high energy quantum microscopic scale. A further problem in this
scenario raised in ref. [24] is that the predicted EECR flux is too high by a factor 10^{15}. Then, in order to reduce the flux, it is proposed in ref. [24] that these wimpzillas amount only to 10^{-15} of the dark matter. This can be achieved by setting \( \alpha \sim 10^{-17} \) in the annihilation cross section. But such \( \sigma_X \) makes a problem for \( R_{\text{min}} \) which becomes then too small \( \sim 10^{-37} \text{cm} \sim 10^{-4} \text{Planck length} \).

2.2 Signatures of top-down scenarii

We have discussed above the main points from which the top-down approach can be theoretically criticized. Let us now mention some characteristic features of top-down models which can be taken as signatures to constraint or disclaim them from observational data:

- (1) Spectra of the particles generated in the top-down models are typically flatter than the bottom-up ones. Contrary to the acceleration mechanisms, the top-down generated spectra do not follow a power law.

- (2) The composition of the EECR’s at the source in the top-down scenarii is dominated by gamma rays and neutrinos (only 5% of the energy is in protons). Although propagation over cosmological distances modify the ratio of gamma rays to protons, still photons considerably dominate over protons. Top-down scenarii could be constrained by the cascade produced at low energies (MeV-GeV) by the gamma rays originated at distances larger than the absorption length [17].

- (3) Fluxes of EECR’s provided by topological defect models are much lower than required. Simulations of cosmic string networks including self-intersection, inter-commutation, multiple loop fragmentation, as well as cusp annihilation, all produce too low fluxes as compared with observations [17] [18]. (Some simulations of long strings networks claiming flux enhancement were recently discussed, but the typical distance between two such string segments being the Hubble scale, the EECR’s produced in this way would be completely absorbed [17] [18]. And, if by chance, a string as such would be near us (about few tens Mpc), it would imply a large anisotropy in EECR events, which is is not observed). In any case, simulations of the dynamics of cosmic string networks (with the cosmic expansion included) are not well controlled, making them not predictive.

Let us recall that the recent CMB anisotropy observations [19] strongly disfavor topological defects in the present universe. (We have discussed here topological defects since they are still considered in the EECR’s top-down literature).

3 Bottom-up scenarii

EECR may result from the acceleration of protons and ions by shock-waves in astrophysical plasmas (Fermi acceleration mechanism) [8]. Large enough sources or small sources with
strong magnetic fields can accelerate particles to the energies of the observed EECR. Sources in the vicinity of our galaxy as hot spots of radio galaxies (working surfaces of jets and the inter galactic medium) and blazars (active galactic nuclei with relativistic jet directed along the line of sight) as BL Lacertae can evade the GZK bound[11, 9, 8].

The acceleration of charged particles like protons and ions take place in astrophysical shock waves. In short, electric fields accelerate charged particles in the wavefront of the shock. Then, magnetic fields deviate and diffuse the particles. Charged particles take energy from the wavefront of macroscopic (astronomic!) size. Particles trapped for long enough time can acquire gigantic energies. This mechanism can accelerate particles till arbitrary high energies. The upper limit in energy is given by the time during which the particle stays in the wavefront which depends on the size of the source and on the magnetic field strength.

Particles gain energy by bouncing off hydromagnetic disturbances near the shock wave. Particles are both in the downstream and the upstream flow regions. Assume that a particle in the upstream crosses the shock-front, reaches the downstream region and then crosses back to the upstream region. This double crossing by the particle boosts its energy by a factor proportional to the square of the Lorentz factor of the shock \( \sim \Gamma^2 \) [8]. Such factor may be very large, indeed, the larger is the acceleration energy, the less probable is the process, finally yielding a power spectrum that decreases with the energy [see eq.(1)].

Accelerated particles are focalized inside a cone of angle \( \theta \leq \frac{1}{\Gamma} \). To rotate the particle momentum \( \vec{p} \) this angle takes a time \( \Delta t \sim r_g \theta = \frac{E}{Z e B_{\perp} \Gamma} \) where \( r_g = \frac{E}{Z e B_{\perp}} \) stand for the relativistic gyration radius of the particle in the magnetic field. It must be \( \Delta t < R_s \) where \( R_s \) is the radius of the spherical wave, otherwise the particle is gone of the shock front. Therefore, \( E < Z e B_{\perp} \Gamma R_s \). That is, one finds that the maximal available acceleration energy [8, 10] for a particle of charge \( Z e \) is,

\[
E_{\text{max}} = Z e B_{\perp} \Gamma R_s
\]  

There are other estimates but all have the same structure. The maximal energy is proportional to the the magnetic field strength, to the particle charge, to \( R_s \) which is of the order of the size of the source and to a big numerical factor as \( \Gamma \).

Further important effects are the radiation losses from the accelerated charged particles and the back-reaction of the particles on the plasma. That is, the non-linear effects on the shock wave.

Particle acceleration in shock-waves can be described at different levels. The simplest one is the test particle description where the propagation of charged particles in shock-waves is studied. A better description is obtained with transport equations. In addition, non-linear effects can be introduced in such a Fokker-Planck treatment [8, 10].
The distribution function for the particles in the plasma \( f(\vec{x}, \vec{p}, t) \) obeys the Fokker-Planck equation,
\[
\frac{\partial f}{\partial t} + \vec{u} \cdot \vec{\nabla} f - \frac{p}{3} \frac{\partial f}{\partial p} \text{div} \vec{u} - \text{div} (\kappa \nabla f) = Q .
\] (7)

Here, \( \vec{u} \) stands for the velocity field, the third term describes the adiabatic compression and it follows from the collision terms in the transport equation for small momentum transfer, \( \kappa \) describes the spatial diffusion and \( Q \) is a injection or source term. The energy spectrum follows from this equation irrespective of the details of the diffusion. It must be recalled that the coefficients in this Fokker-Planck equation are only sketchily known for relevant astrophysical plasmas. A microscopic derivation of the Fokker-Planck equation including reliable computation of its coefficients will be important to understand the acceleration of extreme energy cosmic rays (EECR).

Let us consider stationary solutions of the Fokker-Planck equation (7) for a simple one dimensional geometry. Let us consider a step function as velocity field\[8\]. That is,
\[ v(x) = v_1 \text{ upstream, for } x < 0 \quad \text{and} \quad v(x) = v_2 \text{ downstream, for } x > 0 . \] (8)

Eq.(7) then takes the form,
\[ v(x) \frac{\partial f}{\partial x} = \frac{\partial}{\partial x} \left[ \kappa(x, p) \frac{\partial f}{\partial x} \right] \quad \text{for } x \neq 0 . \]

Integrating upon \( x \) taking into account eq.(8) yields,
\[ v(x) f(x, p) = \kappa(x, p) \frac{\partial f}{\partial x} + A(p) , \]
where \( A(p) \) is an integration constant. Integrating again upon \( x \) gives the solution
\[ f(x, p) = \begin{cases} f_1(p) + g_1(p) e^{v_1 \int_0^x \frac{dx'}{\kappa(x', p)}}, & \text{upstream, } x < 0 \\ f_2(p), & \text{downstream, } x > 0. \end{cases} \] (9)

Matching the solutions at the shock-wave front at \( x = 0 \) yields,
\[ (r - 1)p \frac{\partial f_2}{\partial p} = 3 r (f_1 - f_2) , \quad g_1 = f_2 - f_1 \quad \text{and} \quad r \equiv \frac{v_1}{v_2}. \] (10)

Notice that the solution is independent of the diffusion coefficient \( \kappa(x, p) \). Eq.(10) has the homogeneous solution (no incoming particles),
\[ f_2(p) = A p^{-a} , \quad a \equiv \frac{3 r}{r - 1}. \]

For ultrarelativistic shock-waves we have \( r = 3 \) and \( a = 9/2 \)\[2\]. Therefore, the cosmic ray (CR) energy flux follows the law
\[ n(E) = p^2 f_2(p) = A p^{-\frac{5}{2}} , \]
in close agreement with the observations.

It must be stressed that this example is quite oversimplified. The geometry is not one-dimensional in astrophysical plasmas, the velocity field is not uniform, neither constant. However, the results obtained show the robustness of the approach\cite{8, 10}.

The particles back-reaction on the shock-wave can be neglected provided: (a) the shock thickness is much smaller than the CR mean free path and (b) the CR energy is much smaller than the shock energy. Otherwise, one has to take into account the back-reaction by coupling the transport equation for the CR with the hydrodynamic equations for the plasma including the CR pressure. The parameter that measures this non-linear effect is the so called injection parameter: \( \nu \equiv n_{CR}/N_1(\text{upstream}) \). For \( \nu \leq \nu_c \sim 0.001 \) the linear theory can be used. For \( \nu > \nu_c \) intrinsically nonlinear phenomena can show up as solitons and perhaps self-organized criticality. The non-linear effects predict a maximum CR energy and a hardening of the energy spectrum near this maximum\cite{8}.

### 3.1 Astrophysical Sources

Let us now discuss the possible astrophysical sources of EECR, both charged particles (protons, ions) and neutrinos.

- (1) According to eq.\((6)\) sources of large size and/or large magnetic fields are needed. For big sources natural candidates are active galactic nuclei (AGN). These are supermassive black holes (mass \( \sim 10^6 – 10^9 \) solar masses) in the core of quasars. They are powered by the matter accreting onto the core black hole. It has been found from X and \( \gamma \) ray detection that they are Kerr black holes near their extreme limit, that is with \( J = G M^2/c \). \cite{8, 12} These black-holes should have formed by rotating collapsing matter. Their angular momentum is large because it is just conserved during collapse; the excess should be radiated by gravitational radiation and what remains is an extreme or near extreme Kerr black-hole. They usually exhibit powerful jets identified through radio emission where shock-waves can accelerate CR’s. For example, acceleration may happen in radio lobes of radio galaxies\cite{8, 12}. The interaction regions may extend as much as a Mpc. The jet energy is dissipated into a bow shock inside the inter galactic medium and in shocks within the jet plasma itself. The characteristic size of the shock is about \( R_s \sim 10 \text{kpc} \) and the magnetic field is \( B \sim 10 – 100 \mu \text{G} \) which yields \( E_{\text{max}} \sim 10^{21} \text{eV} \)\cite{10}.

Shock-waves in the inner edge of accretion disks around supermassive black-holes in AGN can accelerate protons and ions to EECR energies. These particles interacting with the dense photon field yields extreme energy neutrinos. While neutrinos are emitted and can reach us, the protons and ions are absorbed there.

- (2) Blazars (quasars, with their jets pointing toward us) are good candidates like BL Lacertae. They have lower matter density that facilitates propagation of the CR.
There are a few known radio jets inside the GZK sphere. We have Centaurus A at about 3 Mpc away and M87 at 18 Mpc from us. Other highly luminous sources as Cygnus A are too far \( \sim 200 \text{Mpc} \). In order to explain the apparently isotropic distribution of detected events one needs an abundant and uniform distribution of sources or intergalactic magnetic fields able to isotropize the CR flux.

Radiou loud quasars are strong gamma emitters. If the gammas are produced by relativistic nuclei, high energy neutrinos can be produced too.

- (3) Extragalactic neutron stars, in particular magnetars (fastly rotating young neutron stars with \( B \sim 10^{15} \text{Gauss} \) and \( \Omega \sim 10^4 \text{s}^{-1} \)) may be small size sources of EECR. Galactic neutron stars would give a CR spectrum concentrated in the galactic plane unless strong galactic magnetic fields could isotropize the CR flux\[10,13\].

- (4) Sources of gamma ray bursts (GRB) may also accelerate CR since they have strong ultrarelativistic shock-waves\[25\]. However, the ability of GRB sources to provide enough energy input to account for EECR observed beyond \( 3 \cdot 10^{19} \text{eV} \) (from AGASA) is criticized in \[26\]. (See in addition \[27\]).

The present data from HiRes and AGASA seem incompatible above \( 10^{20} \text{eV} \) where AGASA has eight events beyond the GZK bound. Except for these AGASA events, the available EECR spectrum today seems compatible with the GZK effect showing up as predicted\[11,8\].

4 What should we expect from the forthcoming observatories like EUSO?

It is the task of the forthcoming experiments like Auger and EUSO to clarify the situation and show whether the GZK effect is present or not.

Furthermore, Auger and EUSO should be able to see or reject the pileup effect. The pileup effect is an enhancement of the CR spectrum just below the GZK cutoff due to CR starting out at higher energies and crowding up at or below the GZK energy\[11\].

In addition, the measurement of the CR spectrum at GZK energies will provide an unprecedented strong check of Lorentz invariance (or the discovery of its violation) since the Lorentz factor involved is extremely large\[11\] \( \sim 10^{11} \).

Last but not least, future observations should clarify the composition of the EECR. Neutrinos should be detected if present in the EECR. We have seen that there are potential astrophysical sources of extreme energy neutrinos. Besides that, extreme energy protons and ions yield neutrinos through the GZK effect.

All this information together should help to pinpoint the sources of EECR. Whether the EECR are isotropic or not and whether their incoming directions are correlated will be obviously a crucial information.
It would be then possible to decide whether the sources of EECR are big objects like galaxies and their AGN, medium size objects like the fireballs producing gamma ray bursts (GRB) or small objects like magnetars (see discussion above).

5 Where to place the theoretical effort?

We will place our effort in the Bottom-up context, for instance:

- 1) to extend the theory of Diffusive Shock Acceleration (DSA), (which explains well the power law spectrum of standard CR’s over at least thirteen orders of magnitude), in order to incorporate:

  Non-linear phenomena still poorly understood, i.e. back reaction of the particle on the plasma (on the shock wave), turbulence effects, careful derivation of the transport equations and the coefficients in them, resonant Alfven waves and dynamical instabilities; Confinement problem of the particles in the shock; gain of energy (minimal losses)

- 2) Astrophysical Sources of EECR.

  Our aim is to clarify the situation on the currently proposed models for EECR’s, (‘bottom-up’ and ‘top-down’ scenarii). The diffusive shock acceleration mechanisms allow to accelerate charged particles like protons and ions, till energies only restricted by the size and the magnetic field strength of the source. Active Galactic Nuclei, BL Lacs, fireballs associated to GRB’s, neutron stars appear as major candidates for EECR. Our task is to improve the research on the potential astrophysical sources, and to develop the theoretical research on the acceleration mechanisms involving plasma physics, magnetohydrodynamics, astrophysical shock waves and nonlinear phenomena still poorly understood. A crucial task will be to single out features of the EECR and prediction of its spectrum in order to discriminate among the different possible sources. Mainly to distinguish among ‘small’ sources with high magnetic field (magnetars-young neutron stars) and ‘medium’ size sources (fireballs producing GRB’s) from ‘large’ sources as radio galaxies and AGN.

In summary, the standard model of cosmic ray acceleration (diffusive shock acceleration) based on Fermi ideas explains the non-thermal power energy spectrum of CR over at least thirteen orders of magnitude. It is reasonable to extend such spectrum to EECR and this seems plausible. However, stimulating physical and astronomical problems remain to understand and explain the CR spectrum well below extreme energies.

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Figure 1: Cosmic ray spectrum[22].
Figure 2: Diagram illustrating current ideas concerning microquasars, quasars and gamma-ray burst sources (not to scale) extracted from ref.[14]. It is proposed in ref.[14] (see also ref.[15]) that a universal mechanism may be at work in all sources of relativistic jets in the universe.