Appendix A: PHYSICS MOTIVATION

Summary

After the three successful space missions in High Energy γ-ray astronomy at energies between 30 MeV and 10 GeV, SAS-2, COS B, and Compton GRO, there is a need to motivate a proposal for a major ground-based γ-ray observatory at Very High Energies $E \geq 100\,\mathrm{GeV}$. This is done in the following two sections.

Astrophysically the subject of γ-ray astronomy is the study of the Nonthermal Universe, i.e. diffuse cosmic matter and radiation with an energy distribution that has no characteristic energy scale attributable to a temperature. This implies that the dynamics of such matter is determined by nonthermal, collective processes rather than by two-body interactions which would always lead to a Maxwellian distribution. It is interesting and perhaps unexpected that from both measurements and theoretical considerations the Nonthermal Universe contains a significant part of the energy and is present in all regions of the Universe except in the dense interiors of stars and planets. The high energies of the individual particles which lie in the GeV range and far beyond preclude that we see them with the standard instruments of astronomy except for the case of energetic electrons in the radio continuum and - in very rare cases - the visible and even X-ray continuum of their synchrotron radiation. Therefore γ-ray astronomy is the appropriate energy range for observation.

There is one particle population, the Galactic Cosmic Rays, which also exists locally since it penetrates into the Solar System from Interstellar Space[1]. The local Cosmic Rays have been measured extensively *in situ* with ground-based and satellite detectors which could establish the nonthermal energy spectrum up to particle energies $E \geq 10^{20}$eV and also the chemical composition which, up to energies $\leq 10^{14}$eV, resembles to a certain extent solar abundances. However, even for the Galactic Cosmic Rays,

[1]The Cosmic Rays also penetrate into the Earth's atmosphere and produce secondary particles there. For very high energies the atmospheric secondaries reach the ground where they constitute an everpresent disturbing factor for sensitive detection devices. Interestingly, this is the only cosmic phenomenon originating clearly outside the Solar System that has a material influence on the Earth. The observed constancy of the Cosmic Ray intensity over the age of the Solar System makes this ionizing radiation also significant for the natural genetic mutations in living organisms; it is in fact considered as the essential motor of genetic evolution on Earth.

and in general for all remote particle populations, the spatial distributions and thus the sources and the production mechanisms can only be identified by the investigation of their γ-ray emission.

The in situ-measurements of the Galactic Cosmic Rays demonstrate in one example what should be true in general with few exceptions: the dominant nonthermal component is in the form of atomic nuclei whereas energetic electrons contribute at best a few percent by number and energy. However, despite the impressive source list of the Energetic Gamma-Ray Experiment Telescope (EGRET) on the Compton Gamma Ray Observatory [1], especially with regard to Active Nuclei of distant galaxies, no further nucleon-induced γ-ray emission apart form the Galactic Cosmic Rays has been unambiguously identified until now. All other High Energy γ-ray sources are compatible with Bremsstrahlung and synchrotron or inverse Compton emission from populations of ultrarelativistic electrons. Thus almost nothing is empirically known about the nucleonic component in general and even the sources of the Galactic Cosmic Rays are far from being clearly identified experimentally.

One concrete hope to separate γ-rays of nucleonic origin from the electronic γ-ray emission consists in the observation at Very High Energies. The strong radiation losses of electrons due to their large charge-to-mass ratio tends to limit the maximum energies electrons can reach in any particle acceleration region of finite lifetime and spatial extent compared to those of (fully ionized) nuclei. A very high energy nucleon can produce a pair of γ-rays of ten times lower energy in an inelastic collision with an atomic nucleus of the ambient thermal gas. Therefore, if the nonthermal nucleon spectrum amply encompasses the γ-ray observation energies, then Very High Energy γ-ray astronomy is not only possible but offers in addition basic advantages relative to the "satellite region" of GeV energies by preferentially observing γ-rays of nucleonic origin.

Section 1 of this Appendix A describes the spatial distribution and sources of nonthermal matter as well as its dynamical interaction with diffuse thermal matter and associated electromagnetic fields. It is then argued that the charged nuclear particle energy spectra should in most cases extend to particle energies of 10^{14} eV or beyond. This makes γ-ray astronomy at Very High Energies (VHE) not only feasible but in addition astrophysically extremely interesting. Since it can be done from the ground in a comparatively economic way, this possibility is also financially attractive. Moreover it is perhaps also the most promising possibility from an instrumental point of view, taking into account the dramatic development of the optical, so-called Imaging Atmospheric Cherenkov Telescope (IACT) technique in recent years.

It has been shown elsewhere (see Appendix C) that angular and energy resolutions of 0.1° and 25 percent, respectively, can be achieved with the array of telescopes proposed here. This allows powerful and versatile VHE γ-ray astronomy from the ground.

Dramatic instrumental developments have in the past always led to new scientific results. In order to get an idea about the astrophysical perspectives, the most important sources of VHE γ-rays are described in the light of the known instrumental capabilities in section 2. It is argued that within a number of years major and long-standing physics questions like the origin of the Galactic Cosmic Rays, the nonthermal characteristics of Active Galactic Nuclei and Quasars, the nonthermal history of galaxy formation in large galaxy clusters, the diffuse extragalactic Optical/Infrared photon background produced by the galaxies since their formation, as well as the absolute distance scale (the Hubble constant) to many extragalactic VHE γ-ray sources, can be resolved.

1 The Nonthermal Universe

High Energy γ-ray astronomy above about 30 MeV investigates the *Nonthermal Universe*, as distinct from the thermal world every physicist is familiar with. Such observations allow a determination of the spatial distributions of energetic nonthermal particle populations and a search for the positions and shapes of their sources. Well-known "localized" examples are Pulsar Nebulae and active nuclei of galaxies which have been studied extensively in the last years. In conjunction with observations at other wavelengths, from the radio to the hard X-ray domain, the interactions between thermal and nonthermal gas and especially the particle acceleration processes can be investigated as well. It is such a typical multi-wavelength approach which is generally needed to arrive at an overall physical picture.

This summarizes the role of High Energy γ-ray astronomy within astronomy as a whole. Its uniqueness lies in its capability to observe radiation with very high individual photon energies, especially due to the decay of secondary particles like π^0-mesons. They are produced by the dominant nucleonic component of nonthermal populations at energies up to 10^{13}eV, and possibly beyond. There is no other way to study this nucleonic component outside the Solar System.

The very fact that High Energy γ-rays with energies above about 30 MeV are produced by charged particles whose energies exceed that of the gamma photons shows that these particles can not be in thermal equilibrium with the thermal matter or with the low energy photons they interact with. This is also not true, not even approximately, amongst those particles themselves. In fact their momentum distribution shows no characteristic energy attributable to a temperature. Empirically those distributions are characterized by power-law distributions in momentum up to momenta corresponding to thousands of GeV and beyond. The best-known examples are the *Galactic Cosmic Rays*, a mainly nucleonic component of relativistic particles pervading the interstellar medium of our Galaxy.

The process of energization must therefore be a nonthermal one, distinct from the heating of a gas in a heat bath, as described in the textbooks of thermodynamics. Generally, energization is assumed to occur either in a stochastic process, whereby individual particles interact with macroscopic excitations of the system ("moving magnetic mirrors"), as considered in the Fermi process [2].

In perturbation theory these processes are described as wave particle interactions between charged particles and the electromagnetic fields of plasma waves like compressional or transverse magnetohydrodynamic waves. Alternatively it is more simply assumed that the macroscopic system, for example a Pulsar magnetosphere or an accretion disk with "frozen-in" magnetic field around a compact object, develops large-scale electric potential drops in the manner of a unipolar inductor. As a result test particles can gain energy in a one-shot process of gigantic strength. Typical voltage drops for such objects are in the 10^{12} GV range.

The phenomenon would be only of theoretical interest if these energetic particle populations merely represented a negligible contribution to the energy-momentum tensor of the diffuse medium which they pervade.

This is generally not true. For example, the *energy density* in the Cosmic Rays of our Galaxy is comparable to the internal and kinetic energy density of the interstellar gas, to the magnetic field energy density, and is even equal to the energy density of the interstellar photon field. Similar properties probably hold for the Cosmic Rays in the local intergalactic space outside our Galaxy and in the Intracluster Medium of rich clusters of galaxies, as well as for the synchrotron lobes of Active Galactic Nuclei (AGNs). To illustrate that statement consider a rich cluster with typically a few hundred large member galaxies like the Perseus cluster. The total internal energy of the thermal gas is about 10^{64}erg, the nonthermal energy exceeds 10^{63}erg, and the total thermal energy content of all the stars of all galaxies together amounts to 10^{62}erg! Since in our Universe the smaller mass scales evolve faster than the larger ones, such rich clusters may contain a few percent of all the baryonic mass in the Universe; it has in fact been argued recently that their mass fraction is rather as high as ten percent [3][2]. Their nonthermal energy content has to be compared with that of individual giant radio galaxies ($\sim 10^{60}$erg) and luminous Quasars ($\sim 10^{62}$erg). The combined thermal and nonthermal energy content of galaxy clusters and AGNs probably constitutes a significant fraction of *some tens of percent of the total random kinetic energy of the Universe*, despite a lower mass fraction.

It is even quite conceivable that matter in intergalactic space *beyond* galaxy clusters and the extended nonthermal lobes of galaxies with active nuclei shares its kinetic energy density *in general* more or less equally between and thermal and nonthermal gas. We shall not pause to go into the physical arguments here. *Energetically* this main part of intergalactic space is dominated by background photon fields, in particular the cosmological microwave background.

The large-scale *propagation* of nonthermal charged particles and γ-rays is not only governed by macroscopic electromagnetic fields as emphasized throughout this section. The energetically dominant intergalactic photon fields influence the propagation through inverse Compton collisions and gamma-gamma pair production processes on the one hand, and through gamma-nucleon pair production and photo-pion processes on the other, in a profound, strongly energy-dependent way. Thus intergalactic space

[2]This mass excludes the *dark matter* whose profound cosmological effects in the form of cold dark matter are responsible for the bottom-up scenario. The nonthermal component discussed here is an integral part of the baryonic matter even though some extremely high energy particle fractions might be due to the decay of leftovers from the very Early Universe, like weakly interacting massive particles or Topological Defects.

is not empty for nonthermal particles but rather acts as an absorbing screen in front of distant sources which permits their visibility only in the form of cascades of secondary particles with lower energy.

Defined in this sense the term Nonthermal Universe acquires a concrete astrophysical meaning. It is only explored in points and is in many ways *terra incognita*.

1.1 Dynamical coupling between nonthermal and thermal gas

For a study of the interaction between the nonthermal and the thermal matter we have to consider in more detail the *force density* of the nonthermal particles. It is not clear to which extent it is comparable to that in the thermal gas, since the force density depends on the gradient scale of the particle pressure. In the interstellar medium such a "dynamical equilibrium" is generally assumed to exist on a Galactic scale and across the magnetic field [4], and we have argued above that this should be more generally true on large spatial scales. It may not be so on small scales. These may be below the energetic particle scattering mean free path which couples the nonthermal particles to the thermal gas along magnetic flux tubes. The most dramatic decoupling occurs in weakly ionized regions where ion-neutral friction dissipates the magnetic field fluctuations necessary to isotropize the nonthermal particle component. Examples are the warm intercloud medium and the clouds of the interstellar medium of our Galaxy. Therefore much of the disk of our Galaxy will be characterized by an almost (within a factor ≤ 3) uniform Cosmic Ray distribution despite sizeable gradients in gas density. The γ-ray emission due to π^0-producing nuclear collisions is then proportional to the thermal gas density alone and was in fact successfully used to measure (neutral) gas densities (see e.g. [5]).

The situation is completely different in the *sources* of nonthermal particles, where by definition their pressure gradient length cannot possibly be larger than the source radius. These pressure gradients drive *self-excited* plasma instabilities whose magnetic fluctuations reduce the mean free path of the energetic particles to very small values close to their gyro radius. One will as a rule have to assume a strong influence of the nonthermal component on the overall system dynamics. This is at least true for the efficient sources which are of primary interest. Two often discussed examples are

Supernova Remnants and Pulsar Nebulae.

The investigation of the Nonthermal Universe should therefore have the particle sources as one of its main directions. Such an ideology is not very different from those in other areas of astronomy which primarily study stars, clouds, galaxies, and clusters of galaxies as sources of energy and radiation.

1.2 Gamma-ray emission

As far as *radiative phenomena* due to High Energy particles are used to diagnose the properties of the system, the synchrotron radiation from nonthermal electrons is a widely used means to estimate the strength and the directions of magnetic fields in extragalactic objects like normal galaxies, radio galaxies, and AGNs. Astrophysical synchrotron emission is usually confined to the wavelength range from the radio to the X-ray domain. An obvious stellar example is again the case of Pulsar Nebulae.

Gamma-ray emission is another and *independent* diagnostic tool, since for electrons it is most likely due to Bremsstrahlung and to Inverse Compton collisions with ambient low-energy photons. Even though the energy density of electrons may be small at any given time compared to that of the nucleons, their γ-ray emission is very strong due to these strong radiation mechanisms. Thus an electron-induced component of the High Energy γ-ray flux will always have to be suspected.

For the heavier hadronic particles like protons and heavier nuclei, γ-ray production is the only 'radiative' signature of practical importance. They collide with atomic nuclei of the thermal gas to produce in particular neutral pions which subsequently decay into two γ-rays. However, in the case of nucleons of very high energy in a high density photon field, the radiation lengths of the secondary electrons from collisional production or photo-production of charged pions may also be short enough to be counted as local nucleon-induced γ-ray emission. This can make the picture quite complex. For simplicity we shall attribute nucleon-induced γ-rays to π^0 decay in this discussion.

The diffuse γ-ray emission at energies above about 100 MeV from the disk of our Galaxy is assumed to be predominantly due to the rather uniform population of Cosmic Ray nucleons, mentioned above, which is consistent with the observations from the COS-B satellite [6] and proven in detail by the clearly visible broad "pion bump" centered at 67.5 MeV in the EGRET data [7]. The γ-ray flux and energy spectrum correspond to a ratio of nucleons to electrons $\sim 100 : 1$ by number in the GeV range as measured *in situ* by energetic particle detectors on a number of satellites. Therefore, nucleon-induced γ-rays are of great importance and should play a key role in the investigation of the sources, at least of the Galactic Cosmic Rays.

It is worth pointing out that the diffuse Galactic spectrum is the only case where High Energy nucleon-induced γ-rays have been identified. All other observations of γ-ray emissions up to now appear explainable in terms of electrons. However, as the Cosmic Ray observations show and also the theoretical considerations of the following subsection indicate, there can be little doubt about the general existence of a dominant nucleonic population. This should be even more dramatically so at very high particle energies where the radiative energy losses of electrons should diminish their number even further. Therefore a ground-based γ-ray detection system which concentrates on *Very High Energies* has the best qualifications to detect also the nucleonic nonthermal populations, the most important aim of γ-ray astronomy.

In this Very High Energy ($E \geq 100\,\mathrm{GeV}$) region the imaging atmospheric Cherenkov technique has seen a breakthrough which makes it in many ways competitive and in some ways even clearly superior to space-borne telescopes. It operates at energies around 100 GeV and above, with possible extensions down to threshold energies of 10 GeV. Apart from considerations of background and γ-ray absorption effects, we shall in fact show that in most cases the cosmic nonthermal particle spectra extend deeply into this Very High Energy (VHE) region, which makes VHE γ-ray astronomy feasible and highly interesting. For this purpose we need to consider the characteristics of cosmic accelerators and their upper energy cutoffs.

1.3 Acceleration of nucleons and electrons

As far as the γ-ray spectrum is concerned, it seems that nucleons can be accelerated to higher energies and in greater numbers than electrons.

The presently most favored form of a Fermi type acceleration mechanism is diffusive acceleration at shock fronts (see e.g. [8]). The hydrodynamic basis for this belief is that cosmic gas dynamics is largely dominated by supersonic flows which dissipate in strong shock waves. The ultimate explanation for this characteristic is the strong tendency of cosmic gas and dust to cool radiatively with the consequence of pressure loss, except possibly in the Early Universe when stellar nucleosynthesis had not yet enriched the gas with heavy elements. In such a fluid of low sound velocity almost any systematic flow tends to be supersonic. Examples for such processes are stellar mass loss in the form of winds, jets, or Supernova explosions, cloud collisions and stellar mass accretion flows, together with their analogs on the level of entire galaxies and galaxy clusters.

In these cases the accommodation of the flow to bordering media will as a rule require strong shock transitions and it is at this point where acceleration comes into the picture: energetic charged particles, scattered by magnetic field fluctuations, can diffusively cross a shock compression many times and gain energy each time before they are finally convected downstream. In the simplest case the resulting energy spectrum depends only on the shock compression ratio, i.e. for strong shocks this spectrum becomes almost universal with an energy dependence $\sim E^{-2}$. In addition the process can also be very efficient. It may convert a large fraction of the free flow energy into relativistic particles with roughly equal energy density per decade.

Nucleonic particles can be rather effectively *injected* into this acceleration process from the hot thermal particle distribution downstream of the shock. Spacecraft observations of accelerated protons in the Solar Wind are consistent with this picture. Despite some theoretical progress over the last years the situation is much less clear and more difficult for electrons because of their much smaller gyro radius at the same energy. Therefore, except in cases like Pulsar Nebulae, where the original particle source is hypothesized to be a relativistic wind of electron - positron pairs due to the neutron star nature of the stellar surface, one should normally expect the nucleonic particle component to dominate the nonthermal energy density.

From a more phenomenological point of view we can simply say that much: provided that the nucleon to electron ratio of 100:1 in the Cosmic Rays of our Galaxy is due to shock accelerators involving matter with roughly cosmic abundance, we should not be surprised to see a similar ratio in other shocks as well.

1.4 Upper energy cutoffs

Below the Zatsepin/Greisen cutoff on the cosmic microwave background, which is not our concern here, Very High Energy nucleons also have little energy losses except in extreme environments of high matter and photon densities. In contrast the synchrotron and inverse Compton loss rates for electrons of the same energy are usually high and increase with the square of the particle energy. And while it is true that for a given source strength the steady state emission from a population of relativistic electrons is independent of magnetic field and photon energy density, as far as the properties of the source itself are concerned its own radiative losses will compete with the energy gains in the acceleration process, limiting the maximum achievable energy of electrons relative to that of nucleons.

Such a consideration is most pertinent if we consider a slow stochastic acceleration process. The situation may be different in case of a direct one-shot acceleration in large-scale electric fields, say from AGN accretion disks (e.g. [9]). Here the electron losses may not strongly come into play.

From what we have said above it follows that the upper cutoffs of the nucleonic energy spectrum are basically limited by geometrical and system age constraints alone [10]. For most types of diffuse Galactic sources, in particular Supernova Remnants [11] or Pulsar-driven nebulae [12], investigated up to now, the energy spectrum extends at least to 10^{14}eV.

Accretion shocks around compact objects like Neutron Stars or stellar Black Holes have been suggested to yield maximum proton energies of the same order [13]. Extragalactic shock acceleration scenarios have led to much higher maximum energies $E_{\rm max}$. Thus the hypothetical accretion shock around a 10^9 solar mass Black Hole of an AGN was estimated to yield $E_{\rm max} > 10^{18}$eV, even including proton-proton collisions [14]. This is however the prime case where the extremely high photon densities in the neighborhood of the central object imply strong pair production and photo-pion losses for accelerating protons and nuclei, not to speak of the inverse Compton losses for energetic electrons. The corresponding limitations of upper cutoff energies and γ-ray transparency (due to $\gamma - \gamma$ absorption) are not yet fully clarified.

The extended galactic wind termination shocks, including those around normal late type galaxies like our own, have been argued to give $E_{\rm max} = 10^{19}$eV for protons [15], whereas the powerful jets from luminous radio galaxies may produce $E_{\rm max} \geq 10^{20}$eV in the Hot Spots of their termination shocks [16].

There are basically two provisos regarding these estimates. First of all the intensity of self-excited waves is assumed to approach that of the average magnetic field which implies that the scattering mean free path approaches the particle gyro radius. For strong shocks this so-called *Bohm limit* is probably a quite reasonable approximation. At least it is a popular assumption among theorists. Secondly the acceleration theory is implicitly also assumed to hold in rotating systems where at large distances the average magnetic field direction tends to become perpendicular to the shock normal. Both assumptions together give rise to an upper limit for $E_{\max}$. Their empirical disproof or verification would be a basic result of High Energy γ-ray astronomy.

Since the cutoffs $E_{\gamma,\max}$ for π^0-decay γ-rays lie roughly one order of magnitude below the cutoff of the proton energy distribution, we would have to expect $E_{\gamma,\max} \geq 10^{13}$eV for all of the types of sources mentioned above. We should also emphasize that particle acceleration to 10^{14}eV appears to be common in nonthermal sources, as shown *empirically* by the Cosmic Rays in our Galaxy and Pulsar Nebulae. We take this as an argument that the theoretical source models discussed above make it worthwhile to study the corresponding astronomical objects with suitable instruments of High Energy γ-ray astronomy. In fact the VHE region above 100 GeV, which is the region of ground-based γ-ray detectors, appears well suited for this type of investigation. The typical cutoffs are two orders of magnitude higher, and electron contributions are possibly not dominant.

1.5 The 100 GeV energy range

What are then the astronomical compromises and advantages of an energy threshold $E_{th} \sim 100\,\mathrm{GeV}$? They can be summarized as follows: In a Cosmic Ray nucleon background-limited situation the event statistics will decrease with increasing E_{th} for any γ-ray source spectrum with an integral spectral index roughly exceeding $1.7/2 \approx 0.9$. Also the intergalactic $\gamma - \gamma$ - absorption for distant extragalactic sources increases with E_{th}. Thus both effects call for low E_{th}. On the other hand there is the isotropic background of the Galactic Cosmic Ray electrons whose atmospheric showers are indistinguishable from γ-ray showers. For extended flat spectrum sources these backgrounds are much less important at high $E_{th} \sim 100\,\mathrm{GeV}$ than at $\sim 10\,\mathrm{GeV}$. Quite a few astrophysical γ-ray sources *are* extended and this makes low threshold detectors vulnerable to these backgrounds. Finally, the cutoff of any nonthermal electron spectrum produced in the same acceleration process as the nonthermal nucleons will be smaller or equal than the corresponding nucleon energy cutoff. As a consequence, for larger E_{th} there is a higher probability to see γ-rays from nucleons than from the electrons of the same source.

We shall discuss the astrophysical objectives in the next section.

2 Astrophysical Objectives

Figure 1 gives an overview over the potential sources of 100 GeV γ-rays, indicated by "γ" in the right lower corner of certain objects. Depending on their strength and their angular extent these objects may be observable by the proposed IACT array. In the following discussion we concentrate on localized sources of γ-rays. In addition there might be isotropic sources.

Although nonthermal particle populations are almost certainly not produced in the Early Universe before the decoupling of matter and radiation, its leftovers in the form of Topological Defects might ultimately decay into γ-rays. Such a source would be an isotropic one[3] and thus not be relevant for the present discussion. Electrodynamic generation of nonthermal particle populations occurs in the subsequent epochs of cosmic structure formation which entail more or less violent processes. This is even more true for the late phases of stellar evolution. Also dynamical processes, like AGNs, galaxy interactions, starbursts in galaxies, and galactic mass loss effects in the form of galactic winds, can lead to nonthermal particle production; on a stellar scale such processes are Supernova explosions and stellar winds, as well as accretion flows onto compact objects like neutron Stars and stellar Black Holes, along with Pulsars, that dissipate large scale reservoirs of free energy into thermal and nonthermal energy alike.

2.1 Probing the sources of Galactic Cosmic Rays

Historically, the interest in γ-ray astronomy arose in connection with the search for the origin of Galactic Cosmic Rays. Although the detection of diffuse Galactic γ-radiation above 30 MeV by EGRET has already made an important contribution to the current

[3]Like the Intergalactic Medium, and more or less also the Hot and the Cool Interstellar Medium of our Galaxy, except for localized massive clouds.

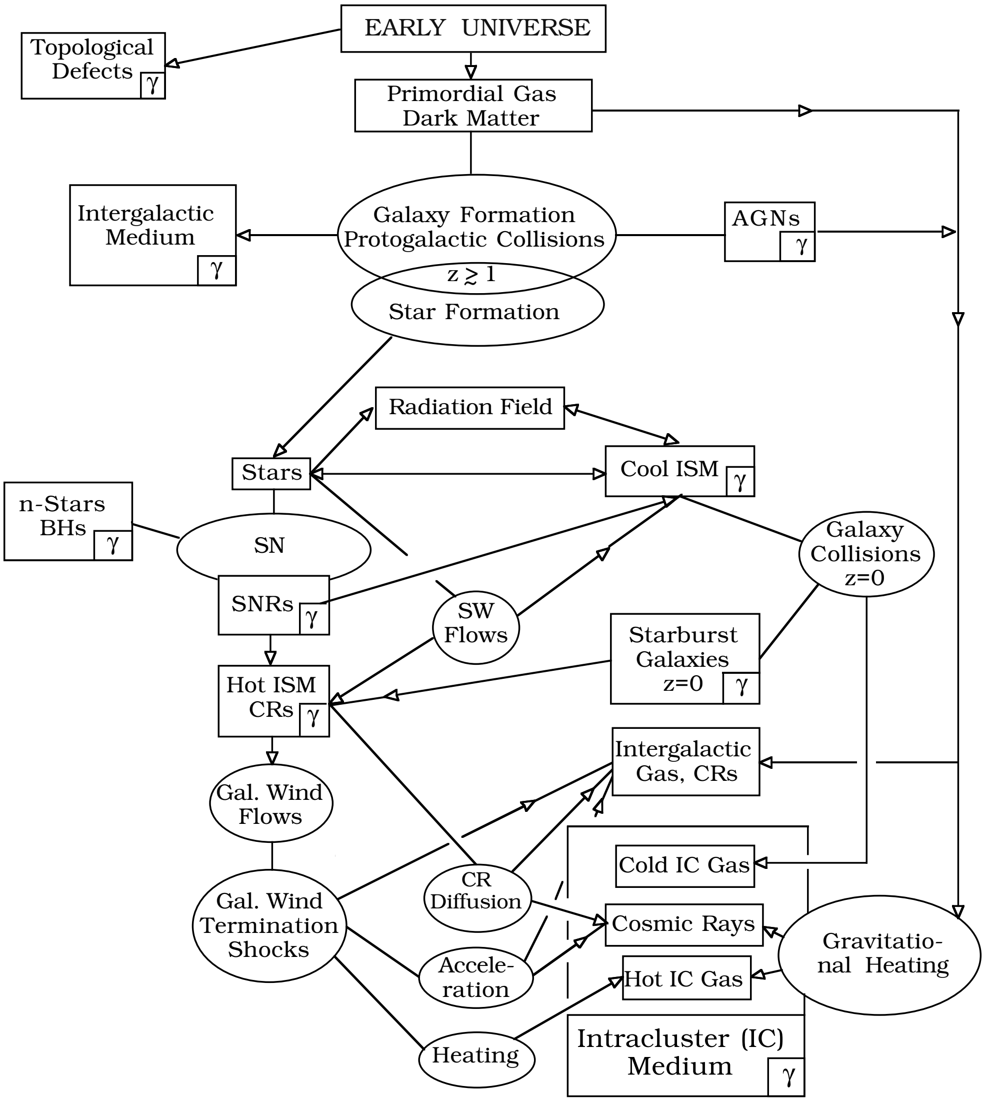


Figure 1: Known and possibly existing Very High Energy γ-ray sources (indicated by "γ" in the boxes for the related astrophysical objects), from Supernova Remnants (SNRs), neutron (n) Stars and Black Holes (BHs) to contemporary Starburst Galaxies, Galaxy Clusters, and Active Galaxies (AGNs). Connecting physical processes are designated by ellipses. Apart from speculative γ-rays from the decay of Topological Defects, also the diffuse Interstellar Medium (ISM), and the Intergalactic Gas are more or less isotropic γ-ray sources, not easily accessible with the IACT technique. All other types of γ-ray sources, at redshifts $z \leq 1$, could be observable with the proposed IACT system of the HESS project.

knowledge about the large scale distribution of the cosmic rays in the Galactic disk, this concerns only the low-energy, $E \ll 100\,\mathrm{GeV}$ protons and/or electrons. However, the *sources* of these particles and in particular of the higher energy Galactic Cosmic Rays up to energies of $10^{14} - 10^{15}\,\mathrm{eV}$ still remain highly uncertain. The suggested IACT array, with energy flux sensitivity 2 orders of magnitude better than the EGRET sensitivity, and with excellent angular resolution would be able to perform deep searches for the sites of acceleration of Galactic Cosmic Rays. We list here in particular three object classes:

- **Shell Type Supernovae Remnants**

  The detection of VHE γ-rays from shell-type Supernova Remnants (SNRs) in the energy range 0.1-10 TeV would be the first straightforward proof of the hypothesis of shock acceleration of Cosmic Ray protons and nuclei in SNRs up to ≥ 100 TeV. Before a SNR dissolves at the end of its evolution into the general Interstellar Medium, due to the fact that its internal pressure and the velocity of its outermost radiatively cooled shell have decreased towards the interstellar gas pressures and random velocities, essentially all accelerated Cosmic Rays remain contained in its interior (Fig. 2).

  Detailed theoretical models predict a resulting source spectrum $\propto E^{-2.1}$ [17]. Therefore such a SNR constitutes a well-defined γ-ray source which needs to be discriminated against the interstellar and the intergalactic γ-ray background along the same line of sight, as well as against the charged Cosmic Rays from the same directions which produce air showers in the atmosphere. Phenomenological estimates [18] show that more than 10 SNRs during the so-called Sedov phase at an age of $10^3 - 10^4\,\mathrm{yrs}$ in typical regions of the Interstellar Medium should be detectable above the level of sensitivity of the IACT array $J_\gamma(\geq 100\,\mathrm{GeV}) \sim 10^{-11}\,\mathrm{ph/cm^2 s}$. The GeV γ-ray fluxes of these SNRs are well below the flux sensitivity of EGRET. This can be seen from Fig. 3, if the modeled SNR spectra at 100 GeV are normalized to the above flux level, and if an EGRET limiting flux level of $\sim 10^{-7}\mathrm{ph\,cm^{-2}\,sec^{-1}}$ is used. In the case of a specific class of SNRs which are the results of Supernova explosions in dense interstellar regions with nearby massive molecular cloud(s), the expected γ-ray fluxes could be much higher. The possible hydrodynamic interaction of SNR shells with nearby giant molecular clouds (GMCs) could be the reason for enhanced GeV γ-ray fluxes from several SNRs, in particular from the objects γ Cygni and IC 443 recently observed

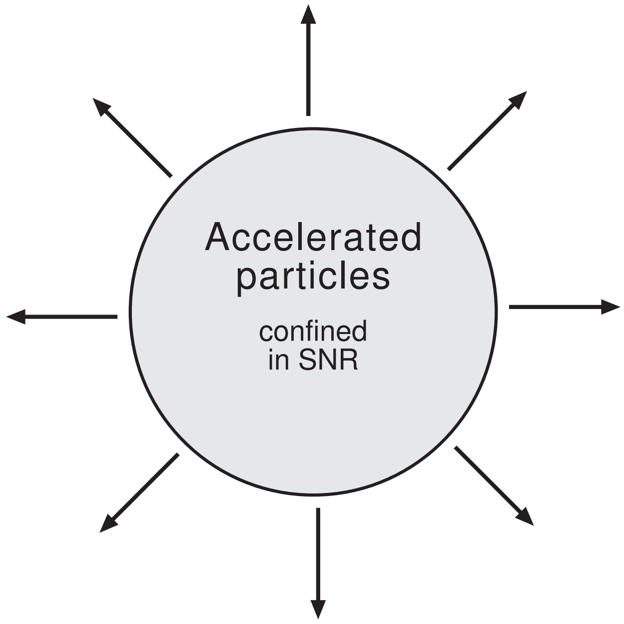
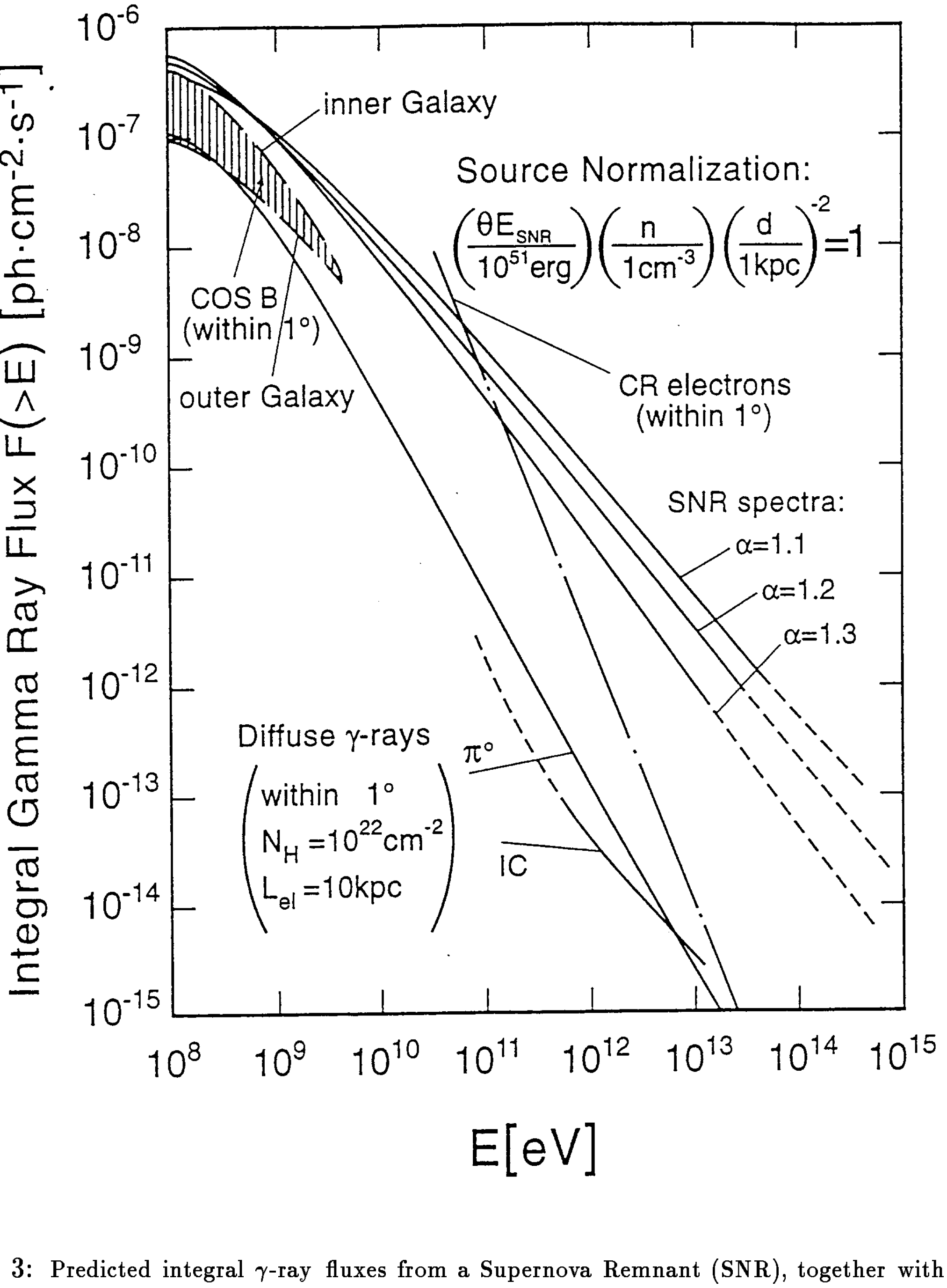


Figure 2: Schematic of a Supernova Remnant (SNR) as a Cosmic Ray source. The expanding SNR (shaded) continuously accelerates nonthermal particles in the shock wave at its outer boundary. The accelerated particles remain essentially confined inside, undergoing adiabatic expansion losses. They are finally released when the SNR is dissolving into the ambient Interstellar Medium.

by EGRET. If this hypothetical scenario is correct, the IACT array should be able to detect 100 GeV γ-rays from many more SNR/GMC interacting systems in the disk of our Galaxy. The ability of the IACT array to reveal "hot spots" of enhanced γ-ray flux within the approximately 1° size shells of nearby SNRs that are connected with relatively compact ($\approx 0.1^\circ$) molecular clouds would allow an estimate of the truly diffuse γ-ray component connected with the shell and thus, with rather good accuracy, a measurement of the total amount of energy in the accelerated protons. When extracting information about the shock accelerated protons, we have to take into account a non-negligible contribution to the γ-ray fluxes from the simultaneously accelerated electrons through their inverse Compton (IC) scattering on the the ambient photon fields [19]. Typically the contribution of IC γ-rays is well below the fluxes of the π^0-decay photons, except perhaps for SNRs with low gas density ($n \leq 1$ cm^{-3}), and low magnetic field ($B \sim B_{\rm ISM} \sim 5\mu$G) inside the remnant. However even in such cases, when the fluxes of IC and π^0 γ-rays may become comparable, the good spectroscopic ability of the IACT array would allow the separation of these two populations of VHE radiation which have very different spectral characteristics.

Detailed kinetic models for the particle acceleration at SNRs in a uniform Interstellar Medium predict peak luminosities which are higher by factors of a few as well as sizeable γ-ray emission with cutoff at a few tens of TeV during the late sweep-up phase with a progressive decrease of the γ-ray luminosity during the subsequent Sedov phase [20]. The reasons are shock compression ratios higher than 4 and therefore larger than average Cosmic Ray energy contents and gas target densities during early SNR phases, and stronger adiabatic energy losses at later phases. Stars with masses above about 20 solar masses modify their environment through their strong stellar winds. This leads to the prediction that for Red Supergiant progenitor stars the SNR γ-ray luminosity can be extremely large during the first weeks or months after the explosion [21]. The long-time decrease thereafter is finally stopped when the SNR reaches the interstellar shell swept-up by the progenitor star which results in a high γ-ray luminosity again.

Thus in detail the γ-ray emission picture of a SNR depends on its evolutionary phase and on the progenitor star's characteristics and is not straightforward for a given object. Nevertheless, the theoretical result that a SNR should at its dissolution release more nonthermal energy than thermal energy would be in stark contrast to a failure of the IACT array to detect positive γ-ray signals from a *number* of selected remnants where individual source idiosyncrasies could not counterfeit the picture any more. Such a failure would imply a strong constraint on the total amount of energy in accelerated protons $W_{\rm p} \leq 10^{49}$ erg, and would thus indicate the inability of the ensemble of SNRs in the Galaxy to explain the observed fluxes of the Galactic Cosmic Rays, in contrast to temporary beliefs. Thinkable alternatives are the pulsars, the termination shocks of winds from massive stars [22], the termination shock of the Galactic Wind, or the ensemble of accreting defunct Neutron Stars. Except for the latter [13] all such alternatives have difficulties to furnish the necessary nucleonic nonthermal energy release. Common to all these alternatives is that their energy input is *rather more distributed in space and time* compared to the Galactic SNRs, so that the identification of individual sources would be much more difficult, or even outright impossible for the proposed IACT system and even more so for any other detector.



$$\left(\frac{\theta E_{SNR}}{10^{51}\mathrm{erg}}\right)\left(\frac{n}{1\mathrm{cm}^{-3}}\right)\left(\frac{d}{1\mathrm{kpc}}\right)^{-2}=1$$

$N_H = 10^{22}\mathrm{cm}^{-2}$

$L_{el} = 10\mathrm{kpc}$

Figure 3: Predicted integral γ-ray fluxes from a Supernova Remnant (SNR), together with background γ-ray fluxes (adapted from [18]. Cosmic Ray (CR) electrons penetrating the atmosphere cannot be distinguished from γ-rays; the diffuse γ-ray background due to Galactic Cosmic Ray nucleons, denoted as "π^0", and the inverse Compton γ-ray background "IC" from the energetic electrons on the diffuse Galactic radiation field are less important. Their spectral index α is left as a parameter here; theoretically it might be as small as 1.0 during the early SNR evolution.

• **Giant Molecular Clouds**

SNRs are the most probable, but, as we have seen, still only one of the possible classes of potential Cosmic Ray accelerators. And, of course, it is quite possible that different classes of accelerators contribute to the observed Cosmic Ray flux in comparable amounts. This makes the problem very complicated; only direct identification of these sources as particle accelerators through their characteristic γ-ray emission can help to elucidate the origin of Galactic Cosmic Rays. In this context an additional requirement appears: the existence of an *accelerator* is by itself not enough for effective γ-ray production; one needs a second component, namely a *target*. The giant molecular clouds (GMCs) in the Galaxy seem to be ideal objects to play that role. These objects are genetically connected with star formation regions which are strongly believed to be the most probable settings (with or without SNRs) of Cosmic Ray production. The principal parameter which determines the visibility of GMCs in γ-rays is $M_5/d_{\rm kpc}^2$ where M_5 is the diffuse mass of a GMC in units of 10^5 solar masses. Passive GMCs submerged in the sea of Galactic Cosmic Rays can be detected by the IACT array if $M_5/d_{\rm kpc}^2 \geq 10$. Since there are only several GMCs in the Galactic disc with $M_5/d_{\rm kpc}^2 \sim 10$, one expects a very limited number of detectable passive GMCs. The search for VHE γ-rays from GMCs seems nevertheless very important due to the possible existence of high-energy Cosmic Ray accelerators nearby. Theoretical calculations show that at certain epochs, depending on the distance $R \leq 100\,{\rm pc}$ from a typical accelerator with $W_{\rm p} = 10^{50}\,{\rm erg}$, such a cloud may become visible both in GeV ($F_\gamma(\geq 100\,{\rm MeV}) > 10^{-7}\,{\rm cm^{-2}s^{-1}}$) and TeV ($F_\gamma(\geq 1\,{\rm TeV}) > 10^{-12}\,{\rm cm^{-2}s^{-1}}$) γ-rays, if $M_5/d_{\rm kpc}^2 \sim 1$. This increases the number of relatively low mass and/or distant GMCs which can be detected in γ-rays in a significant way [23]. Note that it is quite possible that some of the unidentified EGRET sources, located in the Galactic plane, are associated with objects of this type. As a result they should be chosen as Targets of Opportunity for observations with the IACT array. However, in the generally assumed case of energy-dependent propagation (diffusion) of Cosmic Rays the chance of simultaneous detection of a cloud in GeV and TeV γ-rays need not be very high. The higher energy particles propagate faster away from the accelerator and therefore reach the cloud earlier than the particles with lower energy. Thus the maximum of GeV γ-radiation tends to appear at an epoch when the maximum of the TeV γ-ray flux has already passed. Under these circumstances

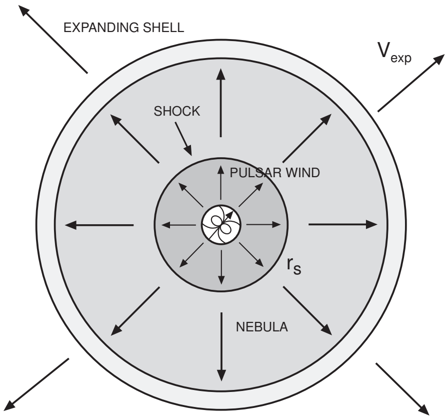


Figure 4: Schematic illustration of the Pulsar wind model of a Plerion [25]. The (innermost) rapidly rotating pulsar magnetosphere gives rise to a relativistic pulsar wind, mostly consisting of electron/positron pairs. This wind adjusts to the ambient pressure in a termination shock at r_s, thus producing an expanding nebula whose nonthermal particles are accelerated at the wind termination shock. This entire structure remains inside the Supernova Remnant shell produced by the ejected mass and its interaction with the ambient Interstellar Medium, cf. Fig. 2. In the case of the Crab nebula only the pulsar and its nebula are prominently visible.

a survey of the Galactic plane with the IACT array to search for GMCs irradiated by Cosmic Rays from relatively young Cosmic Ray accelerators nearby could be more informative.

- **Pulsar Driven Nebula**

The in situ-observed spectrum of Cosmic Ray electrons extends up to energies of a few TeV. The short life-time of TeV electrons in the ISM due to synchrotron and inverse Compton energy losses implies that these electrons are produced/accelerated in one (or few) nearby source(s) located at distances $d \leq 100\,\mathrm{pc}$. Thus, in situ particle observations do not tell us much about distant Galactic sources of VHE electrons. Synchrotron X-radiation and inverse Compton (IC) γ-radiation seem to be the most informative channels for searching of the accelerators of VHE electrons in the Galaxy. Recently, extended power-law X-ray radiation has been discovered by the ASCA and ROSAT spacecraft from many Pulsar driven nebulae (Plerions) [24]. The most probable interpretation of this radiation is in terms of synchrotron radiation of electrons with energy $\sim 100\,\mathrm{TeV}$ accelerated by the Pulsar or at the Pulsar wind termination shock in the nebula. Fig. 4 schematically illustrates the Pulsar wind model of a Plerion [25].

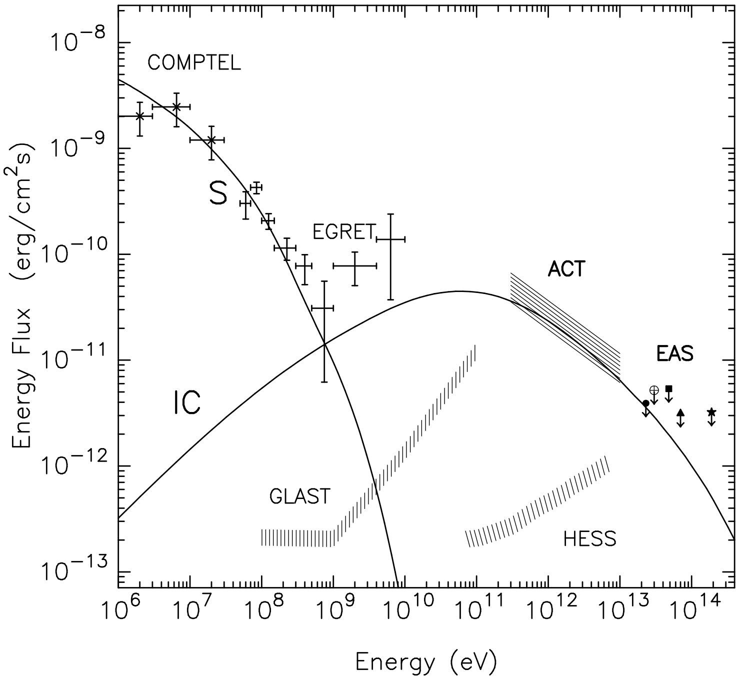


Figure 5: The energy flux spectrum of the Crab Nebula above 1 MeV. The Compton GRO data points from the COMPTEL and EGRET instruments below 10 GeV are continued with the measurements based on the Air Cherenkov Technique (ACT) and with the Extensive Air Shower (EAS) upper detection limits at energies $\geq$ 300 GeV and $\geq$ 300 TeV, respectively (see e.g. Cronin, Gibbs, Weekes, 1993, *Annu. Rev. Nucl. Part. Sci.*, **43**, 883). Below 1 GeV, and above 300 GeV the spectrum is consistent with a synchrotron (S) and an inverse Compton (IC) emission model [26]. Expected limiting flux levels for the GLAST (1 year all-sky survey) and HESS (100 h ON source observation) projects are at the level of a few milli Crab at threshold.

The shocked Pulsar wind and radial diffusion tend to fill the nebula behind the expanding Supernova ejecta ("shell") with VHE electrons/positrons from inside. The inverse Compton scattering of the same electrons on the ambient photon fields [26] results in γ-rays that are detectable, first of all, in the 0.1-1 TeV energy region. Three representatives of this class of sources, the Crab Nebula, the Vela Pulsar, and PSR 1706-44 have already been detected by the current single IACTs of the Whipple, HEGRA, and CANGAROO collaborations (see e.g. [27]). Fig. 5 shows the γ-ray fluxes of the Crab Nebula as measured by a wide variety of instruments.

The synchrotron X-ray nebulae discovered by ASCA and ROSAT have typical angular sizes $\leq$ few arcminutes and energy fluxes $f_x \sim 10^{-12} - 10^{-11}$ erg/cm^{2}s and surround more than 10 Pulsars with the highest values of the parameter L_0/d^2 (L_0 is the spin-down luminosity and d is the distance to the Pulsar). To the extent that the magnetic field on scales of a few parsecs from the Pulsar is indeed as low as $\bar{B}_{\rm ISM} \sim (3-5)\mu$G, we should expect also IC γ-ray nebulae to exist around these Pulsars with VHE energy fluxes at levels that are comparable to the X-ray fluxes, and thus detectable by the IACT array.

2.2 Extragalactic sources

- **Active Galactic Nuclei**

The discovery of γ-rays from numerous AGNs by the EGRET telescope testifies that High Energy γ-radiation above 100 MeV is a common feature of BL Lac objects (Blazars), radio-loud AGNs, and optically violent variable Quasars [28]. Presently two nearby BL Lac objects, Mrk 421 and Mrk 501, have been detected by the Whipple and HEGRA groups at TeV energies (see e.g. [29]). The enormous apparent (4π) γ-ray luminosities, the rapid variability of the EGRET AGNs as well as the requirement that the γ-ray production region be optically thin favor a strongly anisotropic character of the High Energy radiation from these objects. The radiation anisotropy may be naturally attributed to a relativistic bulk motion of the emitting nonthermal plasma jets ejected from the central object [30]. The synchronous flaring activity of these sources in the TeV and keV energy regions strongly supports the common belief that both components originate in the jets due to synchrotron and inverse Compton radiation of the same ≥ 1 TeV electrons [31]. This fact allows the prediction that the IACT array with its energy threshold around 100 GeV and flux sensitivity $\leq 10^{-12}$ erg/cm^{2}s will be able to detect numerous BL Lac objects (more than ten, in accordance with the recently published list of the 'The Einstein Slew Survey Sample of Bl Lac objects' [32]) with average X-ray fluxes exceeding $\geq 1\mu$J, and distances up to redshifts $z \sim 1$. One of the characteristic features of Blazars is their rapid time variability. Since the radiative cooling time of relativistic electrons due to synchrotron and inverse Compton processes is inversely proportional to their energy $E_{\rm e}$, the most prominent flares are expected at X-ray and VHE γ-ray energies produced by the same $E_{\rm e} \geq 1$ TeV electrons. Indeed, the recent detections of almost synchronous X-ray/TeV flares from Mrk 421 by ASCA and Whipple showed outbursts with durations of less than 1 hour. The good spectroscopic capability of the IACT array combined with its high detection rate should give very important (better than any other instrument in the different energy bands) measurements of the time evolution of the γ-ray spectra during these flares. This could give crucial insights into the difficult physics of the jets.

Predictions concerning the expected $\geq$100 GeV γ-ray fluxes from other EGRET AGNs, in particular from radio-loud quasars, are not conclusive. With some exceptions [33], most models predict cutoffs in the γ-ray spectra from distant Blazars between 10 and 100 GeV due to the intrinsic absorption in these sources [34]. However, this concerns the small scale ($\ll$ 1pc) jets where the observed GeV γ-rays originate. In fact, VHE γ-radiation could be very efficiently produced (and escape !) in sites different from those of the observed GeV radiation, for example in the large-scale optical/radio jets.

At present, all γ-ray AGNs detected by EGRET are Blazars. However, VHE γ-radiation can be expected also from AGNs which do not show jet-like features, e.g. Seyfert galaxies. Objects like NGC 4151, NGC 1275, 3C 120 could be good candidates for observations.

Finally, in the context of the γ-ray observability of blazars we should also mention the recently discovered Galactic superluminal objects GRS 1915+105 and GRO J1655-40, proposed to be scaled-down versions of AGNs ("microquasars") [35]. Note that these sources were first detected as transient soft γ-ray sources. The relativistic motion of the radio components in these sources may be a common phenomenon in many other luminous Galactic X-ray objects, in particular in Black Hole candidate X-ray transients. The possible link between relativistic motion and accretion phenomena in these objects might give a key insight into the nature not only of superluminal Galactic sources, but also of the central engines of AGNs and Quasars. Therefore, the Galactic superluminal sources should be considered as possible targets for future γ-ray observations with the IACT array.

- **Clusters of Galaxies**

VHE γ-radiation is not only expected from AGNs but also from other extragalactic objects which may contain accelerated particles and enough target material (in the form of gas, radiation and magnetic fields) for copious γ-ray production. Clusters of galaxies are of special interest in this context. A significant part of the energy of rich clusters of galaxies, the largest gravitationally bound objects in the Universe, may be in nonthermal form, i.e. in the form of accelerated particles which should be contained in the Intracluster Medium for times exceeding the age of the Universe. The Cosmic Rays may have been directly produced by SNRs and may then have diffused into the Intracluster Medium, or they may been predominantly accelerated at the termination shocks of the galactic winds from all early type galaxies presently filling the cluster. The average number density of the diffuse gas in rich clusters is estimated as $n_{\rm g} \sim 10^{-3} - 10^{-4}\,{\rm cm}^{-3}$. The π^0-decay γ-rays produced in interactions of relativistic protons with the ambient Intracluster Gas carry important information about *cosmological* Cosmic Rays accumulated over the entire galaxy formation history of the cluster. Due to the low density of the ambient Intracluster Gas, the efficiency of production of π^0-decay γ-rays is not high. However the enormous energy in relativistic protons (10^{63} erg in the Perseus cluster) partially compensates the low γ-ray production efficiency, leading to fluxes $J_\gamma(\geq 100\,{\rm GeV}) \sim 10^{-11}\,{\rm erg/cm^2 s}$ [36]. Since the angular size of several degrees of this or similar sources significantly exceeds 1°, the detection probability by the IACT array is marginal. The astrophysical significance is about inversely proportional to this probability.

- **Contemporary Starburst Galaxies**

While the γ-ray astronomy of rich galaxy clusters is concerned with the clusters' starburst history since formation, there exist several nearby contemporary starburst galaxies whose activity is presumably driven by recent interactions, like in the M81/M82-system. Estimates for the Cosmic Ray nucleon intensity in the starburst nucleus of M82 exceed that in our Galaxy by two orders of magnitude. Notwithstanding such an enormous nonthermal energy density, the π^0-decay γ-ray flux is estimated as $F_\gamma\,(>100{\rm GeV}) \leq 5\cdot 10^{-12}\,{\rm ph\,cm^{-2}\,sec^{-1}}$ from the central starburst region [36]. With a spatial extent smaller than a kpc this object would correspond to a γ-ray point source at the distance of 3.2 Mpc. The detection of the above flux would again be a challenge for the IACT array, but still within its capabilities if the theoretical estimates are realistic. The γ-ray flux could be significantly higher if a sizeable intensity of TeV electrons existed because it would produce an inverse Compton component in the intense Far Infrared radiation field of M82.

2.3 Observational cosmology

Radio galaxies, AGNs, and clusters of galaxies are considered as a potential class of Cosmic Ray sources with spectra extending to energies $E \geq 10^{20}\,\mathrm{eV}$, and they contain enough gas and photon target material for efficient γ-ray production. The detection of TeV γ-radiation from the BL Lac objects Mrk 421 and Mrk 501 is encouraging with regard to the future of extragalactic VHE γ-ray astronomy. As a consequence, γ-ray observations will be able to address several basic cosmological issues such as the intensity and time evolution of the diffuse extragalactic background radiation (DEBRA) fields [37] and a new method to determine absolute source distances on extragalactic scales [38, 39]. These exciting prospects are connected with the absorption and cascading of VHE γ-rays on the DEBRA fields.

- **Photon-Photon Absorption**

Assuming that γ-rays are emitted with initial spectrum $J_0(E)$ from a source at distance d, an observer looking within a narrow cone centered on the source will see an absorbed spectrum $J(E) = J_0(E)\exp[-\tau(E,d)]$, with a characteristic cutoff energy E^* given by $\tau(E^*, d) = 1$ (τ is the optical depth due to $\gamma - \gamma$ pair production on isotropically distributed photons of the DEBRA fields). No deviation from the intrinsic source spectrum at energy E implies $\tau(E) < 1$. For a low-redshift source ($z \ll 1$) this gives an upper limit on the current energy density of the DEBRA fields $n(\epsilon)$ at $\epsilon \approx 1\,(E/1\,\mathrm{TeV})^{-1}\,\mathrm{eV}$:

$$U_\epsilon = \epsilon^2 n(\epsilon) \simeq 3 \cdot 10^{-3}\,(z/0.1)^{-1}\,(E/1\,\mathrm{TeV})^{-1}\,(\mathrm{H}_0/100\,\mathrm{km/s/Mpc})\,\eta^{-1}\ \mathrm{eV/cm}^3\,,$$

where H_0 is the Hubble constant, and the coefficient $\eta \sim 1 - 2$ takes into account an uncertainty of the spectral shape of the DEBRA fields $n(\epsilon)$.

In principle, accurate spectroscopy in the expected cutoff region from *many* sources (to avoid the uncertainties connected with other probable reasons for the cutoffs) should allow one to derive not only upper limits but actually to measure the fluxes of the DEBRA fields. Thus model-independent information about the DEBRA fields requires proper spectral measurements and a good understanding of the intrinsic source spectrum. The suggested IACT array nicely suits these tasks, and could therefore give unique information about the era of formation and evolution of galaxies. Fig. 6 [40] shows the upper cutoff energies of the γ-ray spectra from objects at various redshifts,

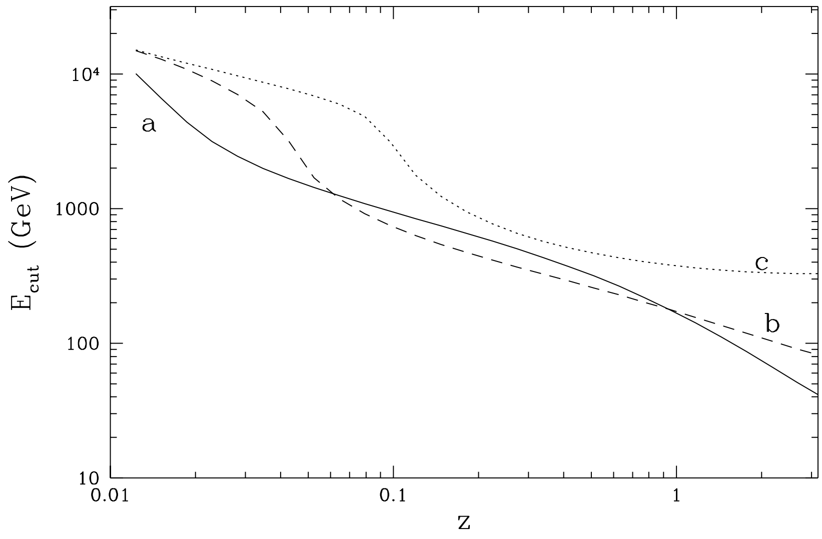


Figure 6: Cutoff energies for extragalactic γ-ray sources due to $\gamma - \gamma$ absorption, as a function of source redshift z, for three different cosmological models of the Infrared/Optical radiation background [40]. Curve (a) corresponds to a model in which galaxies and stars form very early ($z \sim 5$) in the Universe (e.g. Franceschini et al. 1994, *Astrophys.J.*, **427**, 140), whereas curves (b) and (c) show the cases of late ($z \sim 1$) and intermediate ($1 \leq z \leq 3$) galaxy formation which roughly correspond to the so-called Hot-Cold Dark Matter and Cold Dark Matter cosmological scenarios, respectively (e.g. Macminn and Primack, 1996, *Space Sci. Rev.*, **75**, 413).

as calculated for three currently popular cosmological models of galaxy formation. It is seen that at γ-ray energies of $\sim 100GeV$ the horizon lies at about $z = 1$. Note that measurements of cutoff energies E^* in the γ-ray spectra give model independent information only about the product of the DEBRA fields and the Hubble constant.

- **Formation of Pair Halos**

Because of absorption on the DEBRA fields, the γ-ray emission above E^* is not directly visible. However the electromagnetic cascades initiated by absorbed γ-rays may be observable. If the magnetic field near the source (within $\sim$ a few Mpc) is strong enough, $B \geq 10^{-9}$ G, the cascade (e^+, e^-) pairs will be promptly isotropized. This leads to the formation of extended Pair Halos ($R > 1$ Mpc) around VHE sources [39]. Schematically this is portrayed in Fig. 7, where a "primary" γ-ray of energy γ_0 produces an (e^+, e^-) pair on an Infrared /Optical DEBRA photon. The isotropized electron/positron then generates the observable γ-ray photon of lower energy γ by inverse

Compton scattering on a 2.7 K microwave background photon. The pair production length $\lambda(E_{\gamma_0})$ and the observable angle Θ determine the absolute source distance. Note that only in the case of an isotropically emitting source will the halo be centered on the source. If the primary VHE γ-ray emission is beamed at a large angle to the line of sight, the center of the Pair Halo can be displaced by an angle comparable to the typical angular size of the halo. However, the VHE γ-radiation of the halo is emitted isotropically and can be recognized by its distinct variation in spectrum and intensity with angular distance from the halo center. This variation depends weakly on the details of the central source configuration (in particular, the orientation and beaming/opening angle of a possible emitting jet), but depends on the level of the DEBRA fields, U_ϵ, and on the distance to the source, d. Thus, the resolution of a halo would give us *two* observables, the angular and the spectral distributions of γ-radiation, and would allow us to better disentangle the *two* variables, U_ϵ and d. It is important to note that if most of the source's VHE luminosity is initially carried by primary γ-rays with energy $E \gg 10\,\mathrm{TeV}$, the halo's radiation spectrum is insensitive to the source spectrum. In this case definite information about U_ϵ and d can be obtained on a *source-by-source* basis.

The γ-ray flux from a Pair Halo is proportional to the VHE luminosity of the central source. Given our current ignorance of the typical VHE luminosity of sources, one cannot make a precise statement regarding the observational requirements for the detection of a Pair Halo. However assuming an isotropic source luminosity from γ-ray energies $\gg 10\,\mathrm{TeV}$ of $L_0 = 10^{46}\,(d/1000\,\mathrm{Mpc})^2$ erg/s, (comparable to the intrinsic luminosities of many EGRET blazars with jet Doppler factors ~ 10), the γ-ray fluxes integrated within 1° above 100 GeV, are expected to be $\sim 10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Remarkably, numerical calculations show that this value changes only by a factor of a few despite the significant variation in n_ϵ and d. Thus we may assume that the discovery, mapping and spectroscopy of Pair Halos of distant extragalactic origin should be possible by the IACT array. This opens unique opportunities for doing *Observational Cosmology*, in particular:

1. Since the physical size of a halo is determined by the density of the DEBRA fields in the vicinity of the source (i.e, not the DEBRA fields we see today), one can probe directly the time evolution of the DEBRA by observing Pair Halo radiation from

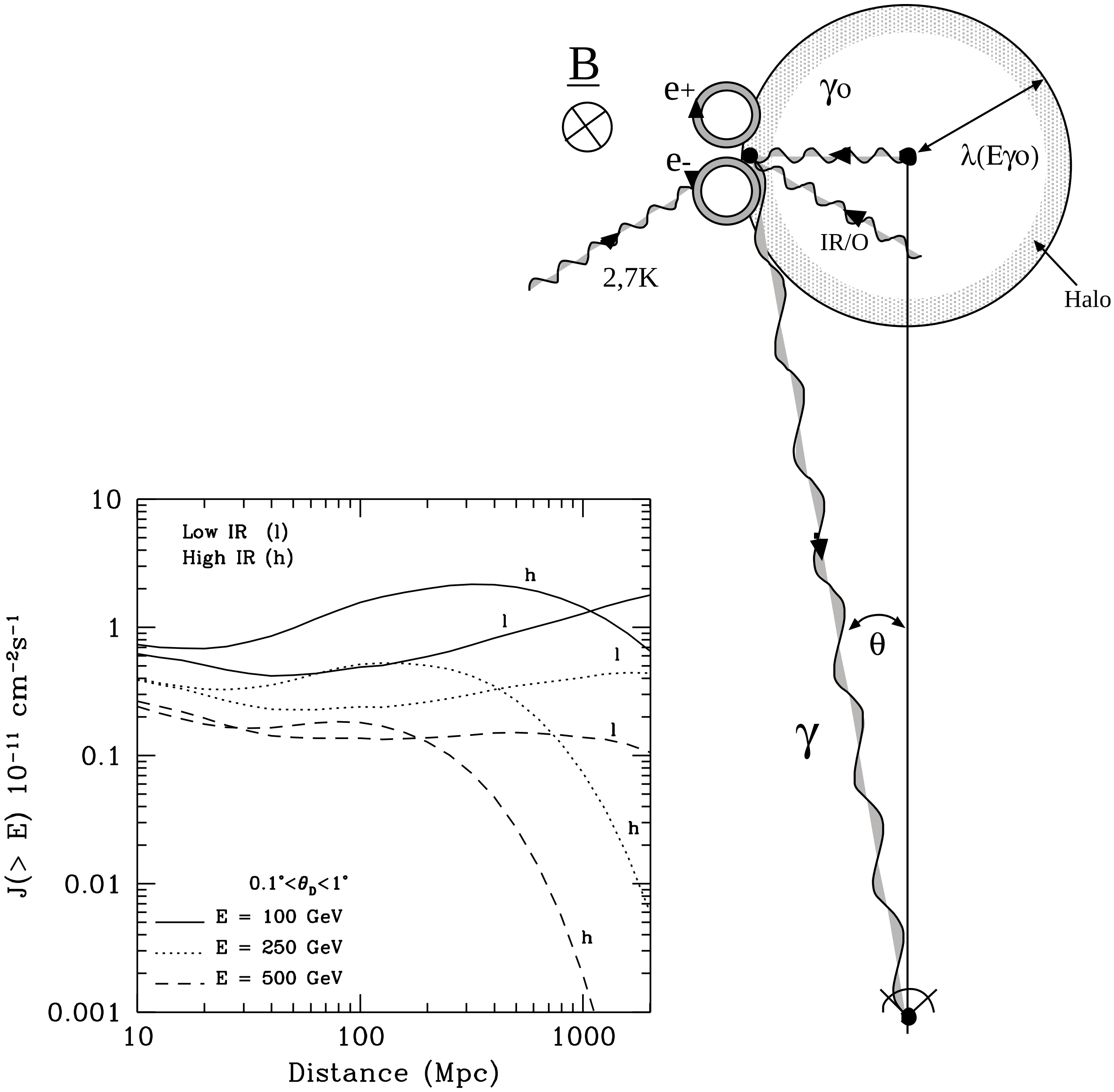


Figure 7: Physics of Pair Halos. In the right part the interaction processes of a "primary" gamma photons (γ_0), with high energy E_{γ_0}, with photons of the Infrared/Optical (IR/O) and the universal 2.7 K diffuse extragalactic background radiation (DEBRA) fields are shown. The (e^+, e^-) pairs from pair production on the IR/O background are isotropized in the magnetic field B. Their subsequent inverse Compton scattering on 2.7 K photons produces lower energy γ-rays. The angular size θ of the resulting pair halo is given by the mean free path $\lambda(E_{\gamma_0})$ and the absolute source distance. The left part of the figure shows the expected halo radiation fluxes integrated within $\theta = 1°$ above 100 GeV, 250 GeV , and 500 GeV as a function of the source distance for 2 different levels of the IR/O background: 'Low' ($n(\epsilon) = 10^{-3}\epsilon^{-3}$ ph/cm^{3}eV), and 'High' ($n(\epsilon) = 10^{-3}\epsilon^{-2}$ ph/cm^{3}eV). The assumed VHE luminosity of the central source above 10 TeV is $L_0 = 10^{46}(d/1\text{Gpc})^2$ erg/s [39].

sources at different redshifts. In contrast, the absorption cutoff in the primary γ-ray spectrum only contains information on the DEBRA that is averaged over redshift.

2. By comparing the characteristic physical sizes of the Pair Halos with their observed angular sizes one obtains information on source distances and the *redshift-distance* relation, i.e. on the value of the Hubble constant, that does not rely on a distance-ladder technique.

3. The intensities of the *primary* (point source-like and possibly variable) and the *halo* (extended and steady) components of VHE γ-ray emission from extragalactic sources allow one to determine the instantaneous and time integrated VHE-power of sources, and thus estimate the total nonthermal energy released by *individual* extragalactic sources during their active phases (thought to be $\sim 10^6 - 10^8$ years). Obviously, VHE radiation from Pair Halos might be detectable around many more objects than presently appear active.

2.4 Astroparticle physics

The conventional mechanisms of production of high energy gamma rays imply interactions of accelerated and stable charged particles, i.e. electrons, protons and nuclei, with ambient gas, low-frequency radiation, and magnetic fields. At the same time, different cosmological and particle physics scenarios allow the existence of cosmic γ-radiation of *non-accelerator* origin.

- **Topological Defects as Sources of the Highest Energy Cosmic Rays**

The existence of particles in Cosmic Rays up to energies $E \geq 10^{20}$ eV poses a serious challenge for any particle acceleration mechanism. This has recently motivated some astrophysicists and particle physicists to consider the possibility that the extremely high energy (EHE) Cosmic Rays may not have been electrodynamically accelerated at all, but instead may simply be the decay products of some massive particles surviving from an early cosmological epoch. One possible realization of such a non-acceleration ("top-down") origin of EHE Cosmic Rays is the annihilation and/or the collapse of so called *Topological Defects* (TDs) such as cosmic strings, monopoles, *etc.*, which could be formed in a symmetry-breaking phase transition in the very Early Universe [41].

A possible collapse of TDs in late cosmological epochs results in the production of "X" particles (gauge and Higgs bosons, superheavy fermions, etc) with a mass corresponding to the GUT (grand unified theory) energy scales, $m_{\rm X} \sim 10^{15}$ GeV. The "X" particles can then decay into quarks, gluons, and leptons. The quarks and gluons would quickly produce hadronic jets consisting of mostly pions with a small ($\approx 3\%$) fraction of nucleons. We thus obtain a natural mechanism for the production of high energy particles, nucleons, γ-rays, and neutrions with energies up to $\sim m_{\rm X} \sim 10^{24}$ eV, without invoking any acceleration mechanism. This very fact, as well as the serious theoretical problems with acceleration of particles to energies beyond 10^{20} eV, typical for many source and particle acceleration models, makes the TDs an attractive hypothesis for the explanation of the highest energy particles observed in the Cosmic Rays (see e.g. [42]). The distinct signature of the "TD" models of Cosmic Rays is a very high content of γ-rays at energies above 10^{20} eV [43], as well as high diffuse γ-ray background at energies between 10-100 GeV initiated by the cosmological electromagnetic cascading of the secondary products of TDs in the extragalactic photon fields [44, 40]. Detection of this radiation could provide robust constraints on the non-acceleration models of the highest energy Cosmic Rays. Unfortunately, the predicted fluxes are well below the fluxes of Cosmic Ray electrons, and therefore, even in the case of 100% rejection of the nucleonic component of Cosmic Rays, the VHE γ-ray "echo" of the TDs cannot be recognized by ground based detectors. This issue could be best addressed by satellite-borne instruments like GLAST that have anticoincidence shields against charged particles.

- **VHE gamma rays from Dark Matter**

It is almost undisputed that most (at least 90%) of the matter in the Universe is in the form of invisible dark matter. Neutral massive relic particles produced in the very Early Universe, with lifetimes exceeding the Hubble time, are considered as good candidates for such dark matter. There are several candidate particles with masses between 10 to 100 GeV, such as the lightest SUSY particles which satisfy the cosmological and astrophysical requirements. However, the recent measurements of the Z^0 decay width at LEP almost exclude this possibility. Nevertheless, yet more massive neutral relics may well provide the cosmological critical density if their lifetime exceeds

10^{16} yr [45].

Although invisible in the low-frequency bands, the dark matter consisting of weakly interacting massive particles (WIMPs) could be in principle observed through the characteristic gamma-ray line emission produced at the mutual annihilation of the supersymmetric (SUSY) particles. Due to nonrelativistic velocities of the dark matter particles (typically $v \sim 300\,\mathrm{km/s}$), we should expect almost monochromatic radiation with an energy $E_\gamma = m_\chi$. Thus detection of this radiation would unambiguously prove the existence of dark matter in the form of WIMPs, and tell us about the mass and density of the dark matter particles.

The annihilation rate of nonrelativistic WIMPs with a mass m_χ is estimated as (see e.g. [46])

$$< \sigma_{\mathrm{A}} v > \sim 10^{-25} \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^2 \mathrm{cm^3 s^{-1}}\,,$$

The channel of annihilation into two photons is suppressed by a factor of $\alpha^2 \sim 10^{-4}$ compared with the total annihilation cross-section. This is a rather slow process (compare, for example, with the two-photon annihilation rate of nonrelativistic thermal (e^+, e^-) pairs, $< \sigma_{\mathrm{A}} v > = \pi r_0^2 c \simeq 7.5 \times 10^{-15}\,\mathrm{cm^3 s^{-1}}$). Therefore, for any realistic mass concentration of dark matter in the Universe, the only promising region to search for annihilation radiation of dark matter seems to be our Galaxy. Possible larger masses of dark matter in other galaxies cannot compensate the loss in the "R^{-2}" factor (R is the distance to the source). The γ-ray fluxes expected from the halo of our Galaxy as a whole, is estimated at a level of $10^{-13}\,\mathrm{cm^{-2} sec^{-1} sr^{-1}}$ which is below the sensitivity of the current and planned detectors. However, in the case of a strong enhancement of the dark matter density towards the Galactic center, as it is predicted by some modern Galactic halo models, the radiation from *neutralino* annihilation from the direction of the Galactic center could be observable by IACTs [47]. Recent calculations by Buckley and Jungman [46] show that for a realistic halo model the monochromatic γ-ray fluxes within a solid angle 0.005 sr around the Galactic center could be as high as $10^{-9}\,\mathrm{cm^{-2} sec^{-1}}$, especially for $m_\chi \leq 200\,\mathrm{GeV}$. If one takes into account that the detection efficiency of 200 GeV γ-rays by a 4-IACT "cell" is almost 100%, the detection rate of 200 GeV monochromatic radiation with a flux $10^{-9}\,\mathrm{cm^{-2} sec^{-1}}$ is of about $R_\gamma \sim 0.1\,\mathrm{sec^{-1}}$. This is comparable with the detection rate of the background produced by Cosmic Ray electrons and protons within $\Omega = 0.005\,\mathrm{sr}$. Furthermore, the good energy resolution of the IACT array ($\sim$ 20%) would allow, in a search for monochromatic γ-ray emission, to reduce the Cosmic Ray background by another factor of a few. This implies that the minimum detectable fluxes of monochromatic VHE γ-ray emission ($E_0 \geq 100\,\mathrm{GeV}$) within $\Omega = 0.005\,\mathrm{sr}$ are

$$F_\gamma \sim 10^{-10}(t/1\,\mathrm{h})^{-1/2}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}\,.$$

Thus, 100 h observations of the Galactic center by the 4 IACT Array will be sufficient to reveal monochromatic $E_0 \geq 100\,\mathrm{GeV}$ VHE γ-ray fluxes down to a level of $F_\gamma \sim 10^{-11}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$, and thus to provide a test of different dark halo models of our Galaxy, and/or to put meaningful constraints on the SUSY parameter space.

References

[1] Fichtel C.E. et al., 1994, *Astrophys. J. Suppl.* **90**, 917; Thompson D.J. et al., 1995, *Astrophys.J. Suppl.* **101**, 259.

[2] Fermi E.,1949, *Phys. Rev.* **75**, 1169; Fermi E.,1954, *Astrophys. J.* 119, 1.

[3] White S.D.M. et al., 1993, *Nature* **366**, 429.

[4] Parker E.N., 1969, *Space Sci. Rev.* **9**, 651.

[5] Ramana Murthy P.V., Wolfendale A.W., 1993, *Gamma Ray Astronomy*, Cambridge University Press.

[6] Strong A.W. et al., 1988, *Astron. Astrophys.*, **207**, 1;

[7] Hunter S.D. et al., 1997, Âstrophys. J., in press.

[8] Axford W.I., 1981, *Proc. 17th Int. Cosmic Ray Conf.* **12**, 155; Drury L.O'C., 1983, *Rep. Prog. Phys.* **46**, 973; Blandford R., Eichler D., 1987, Phys. Rep. **154**, 1.

[9] Lovelace R.V.E., 1976, *Nature* **262**, 649.

[10] Völk H.J., 1987, *Proc. 20th Int. Cosmic Ray Conf.* **7**, 157.

[11] Lagage P.O., Cesarsky, C.J., 1983, *Astron. Astrophys.* **125**, 249.

[12] Arons J., 1996, *Space Sci. Rev.* **75**, 235.

[13] Cowsik R., Lee M.A., 1982, *Proc. R.Soc. Lond.* **A 383**, 409.

[14] Kazanas D., Ellison D.C., 1986, *Astrophys. J.* **304**, 178.

[15] Jokipii J.R., Morfill G.E., 1987, *Astrophys. J.* **312**, 170.

[16] Biermann P.L., 1997, J. Phys. G: Nucl. Part. Phys., **23**, 1.

[17] Berezhko E.G., Yelshin V.K., Ksenofontov L.T., 1994, *Astroparticle Physics* **2**, 215.

[18] Drury L. O'C., Aharonian F.A., Völk H.J., 1994, *Astron. Astrophys.* **287** 959; Naito T., Takahara J., 1994, *J. Phys. G: Nucl. Part. Phys.* **20**, 477.

[19] Mastichiadis A., 1996, *Astron. Astrophys.* **305**, L53.

[20] Berezhko E.G., Völk, H.J., 1997, *Astroparticle Physics*, in press.

[21] Kirk J.G., Duffy P., Ball L., 1995, *Astron. Astrophys.* **293**, L37.

[22] Montmerle T., 1979, *Astrophys.J.* **231**, 95; Casse M., Paul J.P., 1980, *Astrophys.J.* **237**, 236.

[23] Aharonian F.A., Atoyan A.M., 1996, *Astron. Astrophys.* **309**, 917.

[24] Kawai N., Tamura K., 1996, Proc. IAU Colloquium No. 160 (Sydney): *Pulsars: Problems and Progress*, 367.

[25] Harding A.K., 1996, *Space Sci. Rev.* **75**, 257.

[26] Gould R.J., 1965, *Phys. Rev. Lett.*, **15**, 577; Rieke G.H. and Weekes T.C., 1969, *Astrophys..J.* **155**, 429; Stepanyan A.A., 1980, *Izv. Kryms. Astrofiz. Obs.*, **62**, 79; De Jager O.C. and Harding A.K., 1992, *Astrophys.J.* **396**, 161; Atoyan A.M., Aharonian F.A., *MNRAS* **278**, 525.

[27] Kifune T., 1996, Proc. IAU Colloquium No. 160 (Sydney): *Pulsars: Problems and Progress*, 339.

[28] von Montigny C. et al., 1995, *Astrophys.J.* bf 440, 525.

[29] Weekes T.C., 1996, in Proc. Extremely High Energy Cosmic Rays: Astrophysics and Future Observations (Edt. M. Nagano), Tokyo, p. 160.

[30] Begelman M. C., Blandford R.D., Rees M.J., 1984, *Rev. Mod. Phys..* **56**, 255.

[31] Takahashi T. et al., 1996, *Astrophys.J* **470**, L89.

[32] Perlman E.S. et al., 1996, *Astrophys.J* **1034**, 251.

[33] Mannheim K., 1993, *Astron. Astrophys.* **269** 67.

[34] Dermer C. D., Schlickeiser R., 1993, Schlickeiser R., 1996, *Space Sci. Rev.* **75**, 299; *Astrophys.J* **415**, 458; Sikora M, Begelman M.C., Rees M.J., 1994, *Astrophys.J* **421**, 153; Bloom S.D., Marscher A.P., 1996, *Astrophys.J* **461**, 657; Ghisellini G., Maraschi L. *Astr. Soc. Pacific Conf. Ser.*, 1997, in press; Coppi P.S., 1994, in Proc. *Towards a Major Atmospheric Cherenkov Detector III* Tokyo (ed. T.Kifune), 139; Blandford R.D. and Levinson A., 1995, *Astrophys.J* **441**, 79; Inoue S., Takahara F., 1996, *Astrophys.J* **463**, 555.

[35] Mirabel I.F., Rodriguez L.F., 1995, in Proc. *17th Texas Symp. on Relativistic Astrophysics and Cosmology* (eds. H.Böhringer, G.Morfill, J.Trümper), p.21

[36] Völk H.J., Aharonian F.A., Breitschwerdt D., 1996, *Space Sci. Rev.* **75**, 279.

[37] Nikishov A. I., 1962, *Sov . Phys. JETP* **14**, 393; Gould R. J. and Schreder G. P. E., 1966, *Phys. Rev. Lett.* **16**, 252; Stecker F. W., De Jager O. C., Salamon M. H., 1992, *Astrophys. J.* **390**, L49; Biller S., 1995, *Astroparticle Physics* **3**, 385; Dwek E., Slavin L., 1994, *Astrophys. J.* **436**, 696; Macminn D., Primack J.R., 1996, *Space Sci. Rev.* **75**, 413.

[38] Salamon M. H., Stecker F. W., De Jager O. C., 1994, *Astrophys. J.* **423**, L1.

[39] Aharonian F. A., Coppi P. S., Völk H. J., 1994, *Astrophys. J.* **423**, L5; Aharonian F.A. et al., Proc. 24th Int. Cosmic Ray Conf. **2**, 511.

[40] Coppi P.S., Aharonian F.A., 1997, *Astrophys. J.*, to be published

[41] Hill C. T., Schramm D. N., Walker T. P., 1987, *Phys. Rev. D*, **36**, 1007; Bhatacharjee P., 1989, *Phys. Rev. D*, **40**, 3968.

[42] Sigl G., Schramm D.N., Bhatacharjee P., 1994, *Astroparticle Physics*, **2**, 401.

[43] Aharonian F.A., Bhatacharjee P., Schramm D.N., 1992, *Phys. Rev. D*, **46**, 4188; Lee S., 1997, Phys. Rev. D., submitted

[44] Protheroe R.J., Stanev T., 1996, *Phys.Rev Letters*, **27**, 3708; Sigl G. et al., 1997, *Phys.Rev Letters*, submitted.

[45] Ellis J et al., 1992, *Nucl. Phys. B*, **373**, 399.

[46] Buckley J.H. and Jungman G., 1995, *Towards a Major Atmospheric Cherenkov Detector-IV* (ed. M.Cresti), Padova, p.26.

[47] Urban M. et al., 1992, *Phys. Lett.*, **B293**, 149; Berezinsky et al., 1994, *Phys. Lett.*, **B325**, 136.