

Relativistic astrophysics and astroparticles

Keywords: *Relativistic compact stars (white dwarfs, neutron stars, quark stars, etc.) - Black holes at all mass scales – GRBs, Fast Radio Bursts, SN explosions, Novae, and other transient phenomena – Cosmic Rays and astroparticles -*

Key questions:

- *Physics of accretion and ejection onto/from compact objects*
- *Reveal and study the effects of GR in the strong field limit*
- *Measure the properties of BHs (mass, spin) and understand how energy is extracted from them*
- *Study the particle acceleration processes at all different scales*
- *Search for electromagnetic counterparts of gravitational waves and of neutrino sources*
- *Use the compact objects and high-energy observations to constrain fundamental laws of nature (e.g. Lorentz Invariance Violation, axion-like particles, dark matter)*

Probing Black holes and compact objects

Black holes (BH) are fully characterized by only three parameters: mass, angular momentum per unit mass ($a=J/M$) and electric charge. All additional information is lost inside the event horizon, and is therefore not accessible to external observers. Astrophysical BHs are even simpler, since their charge is expected to be zero in all situations of astrophysical interest. Despite much progress in the search for BHs over the last three decades, it is mainly through the mass argument (i.e. a mass larger than the maximum possible NS mass) that sources have been until recently identified as BHs. With the first detection of gravitational waves (GWs) in September 2015 and the identification of their source as a merger of two ~ 30 Msun black holes, stellar-mass BH existence has been finally proved. Although this unavoidably implies that also event horizons must exist, direct evidence of the latter is still missing. However, direct observations of effects related to the presence of the horizon are expected to be possible in the near future, though limited to the super-massive black hole (SMBH) at the centre of the Milky Way, through mm VLBI observations of the BH shadow (Event Horizon Telescope). The most precise observations performed up to now resolve regions of the size of the Earth orbit at the Galactic centre. An improvement by a factor of ~ 10 is needed to truly resolve the SMBH horizon. Currently, a few methods to identify the presence of a black hole in a systems have been proposed. One of these methods addresses directly the absence of a surface if the compact object. If the accretion flow is radiatively inefficient, as is observed at low accretion rates, in absence of a surface, energy can be lost inside the horizon, while in case of a neutron star the same energy would be radiated at the surface. This results in a difference in X-ray luminosity at low rates between NS and BH systems, which is observed but difficult to quantify, and in a difference in energy spectrum, hampered by the lack of statistics. Future high sensitivity high-energy observations can be used discriminate between radiatively inefficient flows on BHs and neutron stars. Other methods rely on effects from General Relativity (GR) in the strong-field regime. In particular, the presence of an innermost stable circular orbit around a compact object, whose value depends on the parameters of the object (such as spin and mass) is expected to effectively terminate the radiative accretion flow. This inner radius can be measured in different ways. Detailed modeling of the energy spectrum of an accretion disk, when present, can lead to the determination of its luminosity and therefore of its size. This has been applied to BH binaries, but requires high-sensitivity observations and broad-band coverage to determine the broad-band spectrum. The analysis of the relativistic deformation of the fluorescent iron Ka line is another way to determine how close to the compact object the accretion flow goes. Detailed observations of red-shifted, broadened and skewed iron line profiles allow one to measure the angular momentum per unit mass, since the inner stable orbit has a radius which depends on $a=J/M$. For a maximally rotating BH this radius is about six times smaller than for a non-rotating BH. This means that line profiles emitted by matter around a rotating BH are more relativistically distorted because matter feels a stronger field. Furthermore, if the line emission is produced within a relatively small 'hot spot' on the accretion disc, then the mass can be estimated, assuming Keplerian disc rotation, by determining the orbital period and the spot location from the line amplitude and energy. Finally, modeling of fast timing features such as quasi-periodic oscillations (QPO), originating in the inner accretion flow, can be connected to GR parameters and yield spin and mass measurements. A few measurements are available, but instruments with a much larger

effective area are required to confirm the applicability of the models.

X-ray polarimetry could also be used to probe strong-field GR effects. In AGNs, a rotation with time of the polarization angle of the Compton reflection component (produced with the iron line) is in fact expected and, more generally, a time-dependent polarization angle would be a clear signature of the presence of strong field GR effects. Analogously, a rotation with energy of the polarization angle of the thermal disc component is expected in BH X-ray binaries.

Binary compact objects

Double Neutron Star Binaries are excellent laboratories for Gravitational Physics. The discovery of PSR1913+16 in 1975 provided the first indirect evidence of gravitational radiation. PSR0737-3039, the first double pulsar, discovered in 2004, is an even better laboratory for high density matter and GR, allowing the determination of all the geometrical parameters of the system and the measurement of five Post Keplerian parameters (namely parameters that quantify the deviation from Kepler Laws). These results have yielded more extensive tests of GR than those derived in 30 years of observation of PSR1913+16. Further improvements of these tests, as well as the measurement of new parameters, have been achieved and are in publication. Continuing to monitor the system will allow us to constantly increase the precision of our measurements and, in particular, to determine the moment of inertia of a NS.

While Double NS binaries are the best test beds for GR, White Dwarf-Pulsar binaries in close orbits are the most promising targets for constraining alternative theories of Gravity. PSRJ1738+0333, for instance, currently places the strongest bound on the linear coupling constant $\alpha_0^2 < 0.5 \times 10^{-6}$ in the strong quadrature coupling regime ($\beta_0 \gg 0$), 10 times more constraining than the measurements of the Cassini spacecraft. At smaller values of β_0 , its current limit is only a factor of ≈ 1.7 less constraining than the Cassini limit, and it can improve and surpass the laser Solar System tests in the upcoming years.

The new planned surveys will also have the capability of unveiling a putative Pulsar orbiting a BH: such a system may probe relativistic gravity with a discriminating power surpassing all other methodologies.

Gravitational waves from binary compact objects

GWs in the ~ 10 -100 Hz range were first detected by the LIGO interferometers on 14 September 2015, signalling the merger of two compact objects of ~ 30 solar masses located at 410 Mpc. This almost unambiguously suggests a BH coalescence, although "gravastars" of this mass cannot be excluded (a gravastar is the result of the collapse of a very massive star, almost as compact as a black hole, but without an event horizon or a central singularity).

BH binaries are the ideal laboratory to probe GR in strong, relativistic conditions. By tracking the phase and amplitude of GWs along the phases of spiral-in, merging, and ring-down, one can extract extremely precise information about the stress-energy tensor. Binary waveforms depend, on the most general case, on 17 parameters, and, in principle, high signal-to-noise GW detections can provide measurements with unprecedented accuracy. As an example, binary mass, chirp mass, and reduced mass can be measured to a few parts in 10^5 with space interferometers. Compact binaries (NS-NS, NS-BH and BH-BH), and massive black hole binaries (MBHBs) fall in two different GW frequency domains, and will be targeted by both ground and space based interferometers. Coalescing NS-NS, NS-BH and BH-BH binaries are primary sources of high frequency gravitational radiation for ground based interferometers. The rate at which such events take place is highly uncertain for NS-NS binaries and completely unknown for stellar mass BH-NS systems. Similarly covered by uncertainty are the electromagnetic counterparts of compact stellar mergers: while coalescing binary systems containing at least one NS may have a nucleosynthetic signature ("kilonova"), merging black holes may produce relativistic outflows whose electromagnetic display is highly speculative. None of the few mergers detected recently by the LIGO interferometer has an identified electromagnetic counterpart.

Short GRBs are believed to originate from coalescing binaries and offer therefore a way to measure the rate of GW, alternative to that inferred from relativistic binary pulsars in our galaxy. However, also in this case significant uncertainties are involved, due for example to the unknown collimation angles, luminosity function and fraction of compact binaries producing a short GRB.

The possibility that deformed fast spinning NSs produce long lasting high frequency GW signals detectable with present or next generation ground based interferometers has received a great deal of attention. The two main scenarios involve old NSs in low mass X-ray binaries, which are spun up to millisecond spin periods by accretion torques, and newborn fast spinning magnetars.

If SMBH were common in the past as they are today, and if galaxies merge as implied by hierarchical clustering models of structure formation, then MBHBs must have been formed in large numbers during the cosmic history. GWs from MBHBs in the mass range $10e5$ - $10e7$ Msun are among the best targets for spaceborne interferometers, while high precision timing over a sample of some tens of millisecond radio pulsars (the so-called Pulsar Timing Array) can make a direct detection of the GW background at nano-Hz frequencies, most likely generated by SMBH in galaxy cores.

Detection of GW from MBHBs is interesting for two reasons: first, it will probe in situ strong gravity in the non-linear relativistic regime; second, GWs can complement electromagnetic observations to investigate the cosmic evolution of structures, such as galaxy interactions and mergers, and the demography of SMBH.

Theoretical predictions for the mechanisms of angular momentum loss, driving the evolution of low-mass close binaries (CBs) containing compact objects include magnetic braking, gravitational radiation and, for CVs also mass loss due to Nova explosions. The current observational evidence of their efficiency relies on the measured orbital period distribution only. The detection of GW from CBs with double and single degenerates will provide first observational support to the theory and will allow the identification of a large and hidden population of degenerate ultra-short period binaries, including WD systems which are thought to be the link to type SNIa progenitors.

Matter under extreme conditions

Neutron stars (NSs) are ideal laboratories to study matter in extreme conditions (densities, magnetic fields), not reachable in ground-based laboratories. Crucial insights on the equation of state and other properties of matter at nuclear densities can be derived from the following measurements.

If the highest frequency Quasi-Periodic Oscillations (QPOs) in the X-ray flux of accreting NSs corresponds to the frequency of motion of matter close to the star surface, then an upper limit on the NS radius can be inferred, therefore constraining the equation of state. This technique has already been applied to QPO data obtained with RXTE, but its full potential can only be exploited through higher throughput (large collecting area and band extended to higher energies) studies addressing the signal shape, its energy dependence and harmonic content in much greater detail.

Direct information on the redshift at the NS surface can be obtained from faint ion spectral lines originated on the surface itself. Detections of such lines (in particular Fe XXVI, Fe XXV and O VIII) have been reported in the past but again a systematic study awaits a much higher throughput X-ray observatory. Combined with the NS spin period inferred from pulsations and/or burst oscillations, the lines' profile obtained in this way would yield measurements of the NS mass and radius.

High precision pulsar timing is already providing us with the most precise determinations of the masses of neutron stars. As mentioned above, long term timing of the double pulsar system J0737-3039 will enable a precise measurement of its moment of inertia, and hence of the radius with enough accuracy for ruling out 90% of the proposed equations of state for nuclear matter.

Magnetars are (isolated) NSs which are powered mainly by magnetic energy (they include soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs)). Most of them are transients, implying a total population in the Galaxy much larger than the currently known sample (about 30, including candidates). There are by now different lines of evidence supporting the view that SGRs and AXPs host neutron stars with magnetic field strengths of at least $10e14$ - $10e15$ Gauss, including the detection of proton cyclotron lines in the phase-resolved X-ray spectra of these sources. Another evidence would come from phase and energy resolved polarimetry of SGRs that would show both proton cyclotron resonances and vacuum polarization resonances. The extension of the investigation of their very hard X-ray component to higher energies could shed some light on the phenomenology of the magnetosphere in such extreme fields. High throughput instrumentation with good spectral resolution would be ideally suited to reach this goal. SGRs sporadically emit giant flares during which enormous amounts of energy (up to $10e47$ ergs) are emitted in the initial subsecond-long spike. These events likely arise from sudden large-scale rearrangements of the extremely intense magnetic fields of these magnetars, possibly triggered by a major fracturing of the NS crust. An intense giant flare (such as that from SGR 1806-20 in 2004) occurring in a galaxy at tens of Mpc would appear as a short GRB. Therefore giant flares from SGRs might constitute a subclass of short GRB.

The study of isolated NSs (not powered by accretion and therefore offering in principle a much "cleaner" environment) can also be useful to probe the properties of matter in extreme conditions. The main tool in this respect is provided by X-ray observations of the thermal emission from the star's surface, which is affected by the internal structure and evolution, as well as by the composition and magnetization of the star's atmosphere. High resolution, time resolved spectroscopy over a broad energy range is essential to properly

identify lines and other spectral features (that can thus provide a gravitational redshift) and to derive the neutron star radius and surface temperature distribution, while spectrum and phase resolved polarimetry could test vacuum birefringence predicted by Quantum Electrodynamics.

Quantum Chromodynamics predicts that matter in extreme conditions could be in the form of a Quark-Gluon Plasma. It has been speculated that, due to accretion, a NS could temporarily be in this state before collapsing to a BH. The time spent by the star in this state depends on the properties of the Quark-Gluon Plasma. If this transition to Quark-Gluon Plasma occurs, then there should be in Nature NS more compact than could be expected on the basis of any equation of state for ordinary matter. Quark stars of this type would provide an unprecedented test bench for fundamental physics.

Physics of accretion and ejection

Accretion plays a fundamental role in powering the emission from compact objects at different scales, but the details of the processes through which gravitational energy is converted into radiation are still poorly known. The still widely adopted optically thick and geometrically thin α -disc (“standard Shakura & Sunyaev” model) is likely too simple to describe the complex observed phenomenology, especially at high and very low accretion rates. Much attention is being devoted to the investigation of the transport of angular momentum in accretion discs through magnetic turbulence and magneto-rotational instability. Although analytical studies can still provide invaluable progress, numerical simulations are necessary to quantify the importance of the physical effects generated in the non-linear evolution of these astrophysical scenarios. Near BHs, GR effects are also important. With the numerical tools currently available, it is now possible to move beyond the simple search for stationary or quasi-stationary solutions, while putting some of the original ideas of the pioneering works (such as Shakura-Sunyaev model) on a more quantitative level.

There is wide consensus that the observed X-ray emission is due to Comptonization of soft (optical-UV for AGN, soft X-ray for binaries) seed photons by a population of hot (10^9 K) electrons. Modeling the X-ray spectra with a proper Comptonization model would provide key information on the system geometry and physical status of the accretion flow (the thermal or non-thermal nature of the population of electrons). In galactic binaries, there is evidence that different processes are at work in different source states and hybrid thermal/non-thermal spectra have been observed. To make a significant advance in this field, a combination of theoretical and observational efforts is needed. More sensitive X-ray measurements, extending up to the energies where the spectra show a cutoff (tens or hundreds of keV), are needed, together with optical/UV and X-ray simultaneous monitoring. On the theoretical side, we stress the need to understand why systems with a stellar mass BH show noticeable differences compared to their bigger counterparts, despite the similarity in the physics of accretion that should be the same for both classes of objects.

The study of accretion onto neutron stars and white dwarfs provides a wealth of information on phenomena related to the presence of a “hard” stellar surface and of a magnetosphere. Such phenomena require an understanding of boundary layer physics, accretion torques, magnetospheric and column accretion, radiative transfer and resonant cyclotron scattering in strong magnetic fields, and unstable thermonuclear burning of freshly accreted material in the star’s surface layer. A complete comparison between properties of BH, NS and WD accretion is essential for the understanding of all classes of systems.

An important problem that remains currently unsolved is the observation that, although all galaxies host a SMBH in their central region, most of them do not appear to be currently active. The most striking case is that of our own Galaxy, whose BH at the Galactic Center has luminosity about ten orders of magnitude lower than the Eddington limit for a BH of its mass (i.e. 2.6×10^6 solar masses). Its X-ray emission exhibits two different states. In the quiescent state, weak emission appears to originate in an extended area around the BH, giving evidence for hot accreting gas in the environment of Sgr A*. Sgr A* itself displays X-ray flares which occur about once per day, during which the emission rises by factors up to 100 for several tens of minutes. The short rise-and-decay times of the flares suggests that the radiation must originate in a region within 10 Schwarzschild radii from the BH. Both the quiescent and the flaring states have been modeled in terms of radiatively inefficient accretion predicting a very hard spectrum, peaking around 100 keV. High sensitivity hard X-rays instruments in the 10-100 keV band are required to confirm this hypothesis. There is evidence that the Galactic center BH was much more active a few hundred years ago, based on the X-ray pure reflection spectrum of Sgr B2, a molecular cloud at a projected distance from Sgr A* of about 100 pc. It is then possible that Sgr B2 is echoing a past activity of Sgr A*. A polarimetric measurement would definitely confirm that the illumination is coming from Sgr A* (from the polarization angle), and help estimating the true distance of Sgr B2 (from the degree of polarization) and the epoch when the BH was

active.

A common feature of stellar size and supermassive BHs is the ejection of both winds and jets moving at relativistic speed. The presence of jets might be a key element to understand how the central engine works. While magneto-hydrodynamic processes are widely recognized to be involved in the collimation and acceleration of jets, the specific mechanisms of launching and fueling them are not known in detail. Moreover, we still do not know whether the jets are mainly made of leptons, or by Poynting flux. Advances in the understanding of these phenomena rely on multi-wavelength and polarization observations. The measure of the jet diameter can provide information on the size of the region where the jet is formed and initially accelerated. According to current models, the twisted magnetic field lines are anchored in the inner part of the rotating accretion disk. The last stable orbit then determines the minimum jet width. Present mm-VLBI provides a resolution of 15 gravitational radii, but in the near future the resolution can be significantly improved, thus allowing a direct test of whether BH rotation plays a role in jet formation.

According to Unified schemes the different classes of AGNs can be explained in terms of different viewing angles. Blazars, in which the jet is seen nearly face on, are extremely interesting because they possess a prominent high energy emission: $\sim 60\%$ of all gamma ray sources detected by Fermi/LAT belong to the Blazar class and ~ 70 Blazars have been detected at TeV energies by Cherenkov telescopes, constituting about 1/3 of all known TeV sources. This clearly indicates that particle acceleration must be taking place in these sources. Details of the spectra and temporal variability depends on the jet composition. As different energy bands in these variable systems test different emission components and jet scales, simultaneous observations across the whole electromagnetic spectrum (from radio waves to gamma-rays) are of paramount importance and should be pushed toward achieving higher sensitivity and spatial resolution across the spectrum.

Radio Galaxies (RGs) with the jet pointed away from the observer are considered the parent population of blazars. They are much fainter and difficult to detect at high energies because their non-thermal emission is not significantly Doppler-boosted. Indeed the number of observed RGs at high energies is small, about twenty in the 0.1-100 GeV and only five in the TeV band.

Nonetheless, Radio Galaxies are the most suitable class of extragalactic objects to explore the connection between jet and accretion flow. As jets in RGs are less biased by relativistic effects, the observer can have a direct view of the accretion processes. A sudden decrease in the X-ray flux shortly followed by the appearance of a superluminal radio emitting feature and a gamma-ray burst has been observed in at least two radio galaxies. This seems to relate instabilities in the accretion disk to the ejection of matter down the jet.

Finally, the jet misalignment in RGs favours the study of extended regions (lobes), usually overwhelmed by the jet emission in blazars, up to GeV energies, improving our comprehension of the acceleration processes occurring even at kpc distances from the black hole.

In stellar size BHs, episodes of ejection are clearly associated with particular source states as defined by spectral and time-variability properties; in particular, sharp state transitions, involving marked spectral changes and the appearance of particular features in the fast time variability appear to be correlated with the presence of jets. Therefore a broadband sensitive instrumentation as well as an efficient continuous monitoring of the sources is needed. Reaching a full understanding of the accretion/ejection properties in stellar-mass systems will directly connect to the models for AGN, since large-scale correlations have been found linking the two classes of systems, indicating that many properties of accretion and ejection are largely mass-independent.

Massive outflows at non-relativistic or trans-relativistic speeds are also common. The mass ejection from the most extreme AGNs can be prominent, close to the Eddington accretion rate. The velocities could be as high as 10-30% of the speed of light. These outflows are usually highly ionized and are investigated through both high ionization UV and X-ray lines. The mechanism for the launching of the outflow is largely an open issue, and presumably will require an intensive theoretical effort and some innovative ideas. On the observational side, the most relevant information is still missing: the geometric, kinematics and ionization structure of the flow, needed to determine the rate at which matter is ejected and the associated kinetic energy, cannot be probed in sufficient detail with present instruments. High spectral resolution, high sensitivity instruments are necessary to exploit the diagnostic capabilities of the iron absorption lines in the X-ray band.

AGN winds and jets can propagate in the ISM, ICM and IGM. Because of their large total energy, relativistic jets might play a crucial role in the energy balance of the media through which they propagate. The interaction of these large-scale ejections with the surrounding medium is of crucial importance for groups and clusters of galaxies. In these large, approximately virialized structures, phenomena of strong interactions

between radio-galaxy jets and the ICM are clearly observed in the form of bubbles and cavities, as well as in the form of particle acceleration to supra-thermal energies and related emissions.

The powerful natural gamma-ray beam of blazars can be used to measure the intervening astrophysical and cosmological radiation fields (the Extragalactic Background Light, EBL) and even probe the existence of the predicted tiny intergalactic magnetic field. Blazars have been also examined in view of the search for possible sources of ultra-high energy cosmic rays. In a possible scenario, the peculiar hard gamma-ray spectrum of some blazars could flag the re-processing of ultra-high energy photons emitted by UHECR interacting with the background radiation while propagating from the blazar to the Earth. In this case, the detection of photons of energies around 10-20 TeV from sources at $z > 0.1$ or even 1 TeV for $z > 1$ is expected, enormously enlarging the cosmological “gamma-ray horizon”. The same photomeson reactions involved in the production of photons result in the emission of high-energy neutrinos. Neutrinos could also be produced within the jet. Both FSRQ and BL Lacs have been considered as sources for the recent IceCube detection. The use of the blazar beams to uncover the spectral footprints of the interaction of high-energy photons with axion-like particles (very light particles predicted in several extensions of the Standard Model) is an exciting possibility actively discussed in the community. Similar effects are expected from the hypothesized breaking of the Lorentz invariance at high-energy, which would allow high-energy photons to acquire an “effective mass”, leading to the suppression of the photon-photon scattering and thus to the free propagation from large cosmological distances

Fast Radio Bursts

Fast Radio Bursts (FRBs) are enigmatic, short-duration (milliseconds) flashes of radio emission. The dispersion of their signal points towards an extragalactic origin and implies radio luminosities orders of magnitude larger than those of all other known short radio transients. Only very recently one such signal, FRB 121102, the only FRB for which multiple pulses were detected, has been firmly localised in a dwarf galaxy at redshift $z=0.2$. Another one, FRB 150418, has been tentatively associated with an elliptical galaxy at $z=0.5$, hosting a faint AGN. FRBs hence appear to be not only extragalactic, but cosmological and, as such, have the potential to be used as probes of the distant Universe. What powers FRBs radio emission remains, however, still undetermined. It is also unclear whether the repeating FRB 121102 is the same sort of signal as the other ones, for which, despite extensive follow-up observations, a single pulse only has been detected. FRBs could very well be the manifestation of different phenomena, as in the case of GRBs.

Gamma Ray Bursts and luminous supernovae

Gamma Ray Bursts (GRBs) are short (0.1-100 seconds) bursts of gamma-rays produced during the collapse of a very massive star or during the merger of two collapsed objects. Their cosmological origin could be inferred only after the observations with BeppoSAX in 1997, some 30 years after the discovery of GRBs. If isotropic, the energy emitted in the prompt gamma-ray phase corresponds to a luminosity $\sim 10e54$ erg/s, making GRBs the biggest cosmic explosions after the Big Bang.

GRBs are the most extreme special relativistic macroscopic objects in the universe, producing expanding shells of material moving with bulk Lorentz factors of order 100-1000. The related complex phenomenology can be explained in terms of creation of a fireball, due to the enormous initial energetic input and a transformation of the internal energy of this fireball into kinetic energy of expanding plasma. Part of this kinetic energy is later converted into accelerated particles, through mechanisms that are subject of active investigation, and then into radiation, the so-called GRB.

The scenario described above branches into several of the hottest problems of 21st century astrophysics:

- Understanding the GRB itself implies that we understand: the formation of a hot fireball, special and general relativity, particle acceleration processes, relativistic collisionless shocks, jet formation and collimation, particle acceleration, accretion processes, radiation mechanisms.
- GRBs emerge from regions of active star formation in galaxies. GRB being associated with massive stars can be used to investigate the star formation rate, and the initial stellar mass function as a function of redshift. Furthermore, they can be used as “lighthouses” to investigate the ISM of their host galaxies (metal abundances, dynamics, gas ionization, dust content).
- The reionization epoch. Because GRBs are so bright, they could be a suitable tool to probe the so-called

Dark Age of the Universe.

- The fate of the baryons. GRB can be used as lighthouses to light up the so called “oxygen forest”, thereby allowing us to map the web of dark matter induced filamentary structure of the Universe and possibly find the X-ray signal corresponding to the presence of a warm medium of ordinary matter, that is believed to hide the so-called missing baryons.

- Fundamental physics. GRBs can be used to constrain exotic effects of violation of fundamental symmetries such as the Lorentz invariance, possibly deriving from the phenomenology of some theories of quantum gravity.

Swift has detected 15 GRBs at $z > 5$, i.e. 1% of all Swift GRBs, with the farthest being at $z = 9.2$. These can be used to trace star formation, re-ionization and metal enrichment in high redshift galaxies. Furthermore, Swift has dramatically increased the sample of long-duration GRBs that are used to investigate the correlations between observables, that allow GRBs to be turned into standardizable candles and employed for precision cosmology.

The energy involved in GRB explosions is huge and it is released in a small region. Therefore, a quasi-thermal equilibrium (at relativistic temperatures) between matter and radiation is reached, with the formation of electron-positron pairs accelerated to relativistic speeds by the high internal pressure. This is a fireball. The presence of even a small amount of baryons makes the fireball opaque to Thomson scattering, so that the internal energy of the plasma is gradually transformed into kinetic energy of the fireball, which therefore accelerates until it reaches a coasting phase. At some point the fireball eventually becomes transparent. If the central engine works intermittently, the expanding fireball can contain inhomogeneities induced by shells moving with slightly different Lorentz factors. The occasional interaction between faster and slower shells is responsible for the formation of internal shocks and is expected to give rise to the observed temporal variability of the GRB emission. The whole fireball also interacts with the surrounding interstellar medium in the host galaxy, thereby snowplowing material and forming the external shock. Particle acceleration at these shocks and the following related radiative processes are seen to be responsible for the GRB and its afterglow emission. Though the general picture is rather well defined, there are numerous aspects of the processes of acceleration and radiation that are considered as hot topics for the theoretical research in the field.

One of the greatest unknowns in GRB science is the nature of the progenitor, though fortunately the general guidelines illustrated above can be discussed without specific assumptions on the nature of the progenitor.

Long GRBs follow the likely highly anisotropic collapse of the stripped core of a star more massive than $\sim 20 M_{\text{sun}}$ and may derive from a relativistic jet/outflow launched either by a rapidly accreting black hole (collapsar) or formed via “magnetic tower” mechanism by a highly magnetized rapidly spinning proto-NS (magnetar). In both cases, the energy budget is dominated by the kinetic energy of the core-collapse supernova ($1-5 \times 10^{52}$ erg), which is an order of magnitude larger than the collimation-corrected total energy of the GRB (10^{51} erg). Short GRB are produced after two compact stellar objects merge into a single BH surrounded by an accreting torus. In all progenitor scenarios, the central engine is a fast spinning compact star surrounded by a very dense torus. The energy should then be made available in the form of neutrinos, accretion of the material in the torus onto the compact object, rotation of both the torus and compact star and magneto-hydrodynamical processes. Observations of the GRB light curves, spectra and close environments confirm the association of the phenomenon with massive stars. In particular, nearly all low redshift GRB have an unambiguously detected accompanying stripped-envelope supernova, whose explosion epoch is compatible with being simultaneous with the GRB start time. However, the connection between the supernova explosion or compact star merger and the formation of the central engine and development of the GBR fireball remains subject of investigation.

Estimates of the amount of material close to the GRB site and its composition (metals) would shed light on the history of the pre-ejected material and thus on the evolution of the progenitor massive star. Short-lived absorption features and variable column densities would flag the presence of a nearby absorber affected by the burst prompt emission and early afterglow.

Emission features yield information on the kinematics of the ejection, abundances, and location of the reprocessing medium. High resolution, low energy spectra of X-ray afterglows are necessary to extract the relevant information from these features.

One crucial piece of information is the total energy budget of a GRB. Taking into account the collimation angle of the jet, it appears that the energy content of different bursts is universal, $\sim 10^{51}$ erg, so that the efficiency in converting the total energy into high-energy radiation, as well as the fireball baryon loading, should also be universal. In the collapsar scenario, where the fireball has to propagate through the stellar interior, this is unlikely to happen. On the other hand, if the fireball is magnetically dominated, rather than matter dominated, a high degree of polarization of the GRB radiation might arise and polarization measurements at early times could be of crucial importance.

In the internal shock scenario the colliding shells are both relativistic, and after the collision, the merged shell is still relativistic. The liberated energy is therefore a small fraction of the initial one. The efficiency of transformation of bulk kinetic energy into radiation is therefore small. On the other hand, efficient external shocks should produce the afterglow. Thus the afterglow should be more energetic than the prompt emission, contrary to what is currently observed. This paradox has not yet been solved.

Synchrotron radiation appears to be the most likely mechanism powering the afterglow at radio, optical and X-ray frequencies. However, the hardness of the spectrum seems to disagree with the predicted synchrotron-limiting slope. For GRBs at low to moderate redshifts, an extension of the measured afterglow spectra up to 50-100 keV (where the Compton component should dominate) would be crucial to test emission mechanisms. Observations of the early afterglow, expected to be bright at the high energies, have been carried out with Swift, that detected bright early ($t < 10^4$ s) flares presumably due to prolonged engine activity, and by Fermi-LAT in the MeV-GeV band where only $\sim 5\%$ of GRBs are detected. The MeV-GeV radiation exhibits a monotonic decay, in line with multiwavelength behavior, and its nature is compatible with synchrotron in an external shock. The present observational frontier is represented by TeV afterglow emission, never so far detected and possibly within the reach of the CTA experiment, at least for GRBs at $z < \sim 1$.

A variety of GRBs with softer spectrum, so called X-ray flashes, first discovered by BeppoSAX, have been studied by Swift that detected numerous members of this class. In two cases at particularly low redshift, accompanying supernovae were detected in the optical, similar in type to those connected with classical GRBs (i.e. stripped-envelope), but of lower energy and luminosity.

Noteworthy, stripped-envelope (i.e. hydrogen and helium poor) core-collapse supernovae with energies significantly larger than the canonical 10^{51} erg, although not as energetic as those accompanying GRBs, are now regularly detected by deep, high cadence, wide field optical surveys. They represent $\sim 5\%$ of all stripped-envelope supernovae and are the probable result of an asymmetric collapse; they often emit copiously at X-ray and radio frequencies and are good candidates both for TeV detection with CTA and, if very nearby, GW and MeV neutrino detection. Their observation will give fundamental information on the pre-supernova mass loss and its connection with the initial mass of the progenitor, core-collapse physics, and compact remnant formation. A further important result of the on-going un-targeted surveys is the big number of the exotic transients discovered (ranging from the ultra-faint up to the super-luminous ones, including the recently detected superluminous supernovae), whose observed properties are not yet fully studied and theoretical interpretation almost completely missing. The theory runs from electron capture SNe to stellar mergers, for the fainter transients, up to pair instability, shell-shell collisions, magnetars for the SLSNe.

The origin of Cosmic Rays

During the pioneering experiments of 19th century on electrostatic phenomena, scientists noticed the puzzling phenomenon of discharge of the gold leaves of electroscopes in the absence of external action. This indicated that there was some sort of ionization taking place in the air inside the electroscope, eventually leading to the electric discharge of the system. In 1912, V. Hess performed his pioneering first balloon flights that showed that this ionizing radiation, usually thought to be coming from the Earth surface, was in fact coming from outer space. This mysterious radiation was given the name of Cosmic Rays. Experiments aimed at unveiling the origin of Cosmic Rays proliferated and while their technical potential improved, people realized that this radiation was in fact made of charged particles (east-west effect), with energies that were higher and higher when measured with better and better experimental setups.

Much time and many experiments had to be done before we reached our most recent understanding of this phenomenon: cosmic rays are extremely energetic charged particles, with energy that ranges between 10^6 eV and more than 10^{20} eV. At the lowest energies their origin is related to and/or affected by phenomena taking place in the Earth-Sun surroundings. At energies of a hundred billion eV, cosmic rays start being generated

in distant sources inside our Galaxy. At these energies their flux at the Earth exceeds ~ 100 particles per square meter per second. At larger energies, their number decreases rapidly, and at the highest probed energies, $\sim 10^{20}$ eV, the flux corresponds to roughly one particle per square km per century! Such energy is only a few orders of magnitude below that corresponding to the so-called Grand Unification of Forces, where scientists expect that all fundamental forces but gravity unify in a single type of interaction.

The existence of cosmic rays forces us to envision new, quite violent places in the Universe in which Nature manages to transform other forms of energy to extremely energetic sub-nuclear particles, far from being in thermal balance with their surroundings. The investigation of the processes of particle acceleration in astrophysical environments has been mentioned many times in this document, to stress the fact that it is absolutely central to a variety of non-thermal phenomena, from GRBs to AGNs, from clusters of galaxies to supernovae.

As far as the origin of Cosmic Rays is concerned, the association of the bulk of Cosmic Rays with Supernova Explosions occurring in our Galaxy has been around for a very long time and become a paradigm. These cosmic explosions eject several solar masses of material into the interstellar medium, enriching it with heavy elements, such as Iron. The ejected material expands outward from the explosion site at supersonic speeds, forming a shock wave that heats up the gas and, at the same time, energizes a small fraction of particles to large supra-thermal energies: these will eventually become Cosmic Rays.

The relevant acceleration process, called diffusive shock acceleration, consists of repeated crossings of the surface of the shock generated as a consequence of the supernova explosion. At each crossing the particle gains a small energy and at the same time has a finite probability of escaping the system downstream of the shock. While the basic formulation of this shock acceleration mechanism has been in place since the '70s, important progress has come during the last decade from investigation of the dynamical reaction that accelerated particles exert on their accelerator: this reaction reflects in a change of the shock dynamics and thermodynamics and in the amplification of the ambient magnetic field. These phenomena affect in turn the properties of the system as an accelerator with crucial implications for the particle spectra and the maximum energy that can be achieved. This entire theoretical framework, known as "non-linear theory of particle acceleration at shock fronts", has provided a powerful tool to interpret the wealth of information that high-energy observations of Supernova Remnants have brought about, and has allowed to readily transform it into improved understanding. The synchrotron X-rays detected by Chandra and XMM from young and nearby Supernova Remnants have shown that these objects accelerate electrons up to energies of 1-10 TeV and host magnetic fields as high as a few hundreds of μG . Such high magnetic fields in turn are interpreted as produced by the instabilities induced by accelerated particles. The estimate of the acceleration efficiency that follows is about 10-20%, exactly what is needed for Supernova Remnants to be the primary contributors to the Cosmic Ray flux measured at Earth. At the same time such intense magnetic fields, being self-generated by the particles, would be tangled exactly on the appropriate scales to ensure efficient particle scattering, and as a consequence speed up the acceleration process so that very high energy can be reached, up to few PeV for protons and about 30 times higher for Iron nuclei.

Of course, most of the time, the particles that are seen emitting in SNRs are electrons rather than protons or nuclei, and their maximum energy is limited by radiation losses, which force it to be always much lower than 1 PeV. The best direct diagnostics for protons, which are the main constituents of CRs detected at Earth, comes instead from gamma-rays and neutrinos, the primary outputs of the interaction of energetic hadrons with the interstellar medium. The long sought evidence of gamma-rays from Supernova Remnants has finally come thanks to the gamma-ray space telescopes AGILE and Fermi and to the ground based Cherenkov arrays, HESS, MAGIC and VERITAS. Even after gamma-rays are seen, however, the issue of assessing whether they are of hadronic origin or rather the result of Inverse Compton scattering of the synchrotron emitting leptons is not trivial at all. In the case of gamma-rays from SNRs, however, the contemporary operation of all the above mentioned instruments, and the existence of a well established theoretical framework has been crucial for quick scientific progress, allowing to discriminate the origin of the emission in the different cases. We have found that what looked as the best candidate for hadronic emission at the time of the previous version of this document, RXJ1713-3946, is most likely dominated by leptons in gamma-rays; at the same time, we have indirect but strong evidence that in Tycho protons are being accelerated up to 500 TeV at least; finally we are fully confident that the gamma-ray emission from the SNRs W44 and IC443 is of hadronic origin. The last two sources are middle aged SNRs interacting with molecular clouds, which provide the ideal target for relativistic protons to produce gamma-rays through

neutral pion decay. The main question then becomes whether one is seeing emission from freshly accelerated hadrons or rather by cosmic rays from the galactic pool that are caught by the slow radiative shocks of these remnants and there compressed and reaccelerated. The answer to this question, which is in a way even more subtle than that concerning the leptonic or hadronic origin of the gamma-ray emission, has come, in the case of W44 at least, from a combination of broad band and multimessenger observations, and theory: while most of the gamma-ray emission detected from this remnant by AGILE and Fermi can be explained as due to reaccelerated particles, a fraction of freshly accelerated protons is likely required.

Needless to say that the advent of CTA, together with upcoming and existing neutrino telescopes such as IceCube, ANTARES and Km3Net, is promising to boost considerably our ability at detecting the emission of hadronic CRs directly from their accelerators. At the same time, recent theoretical achievements have finally provided us with a physically correct description of cosmic ray modified shocks propagating in a partially ionized medium, opening up new possibilities of investigating the acceleration of CRs through optical studies: 1) The width of the broad and narrow components of the Balmer line bears information on the energy density in the form of CRs at a supernova shock; 2) The spectrum of CRs accelerated at the shock is sensibly affected by the presence of neutral hydrogen near the shock. Comparison between theory and observations of SNR blast waves carried out with sufficiently high spatial and spectral resolution can provide a direct estimate of the shock acceleration efficiency. Such observations can be presently carried out e.g. with the GHaFaS spectrometer, mounted on the William Herschel Telescope in La Palma, or with the MUSE on VLT, and will in the future benefit of the GMT (Giant Magellan Telescope) and E-ELT (Extremely Large Telescope).

On their way from the sources to the Earth, cosmic rays interact with the gas and magnetic field in the interstellar medium, providing a glow of diffuse radio emission, X-ray radiation and gamma rays that we observe from the Earth. The observation of these radiations allows us to achieve a better understanding of the processes involved in the acceleration of cosmic rays and the random wandering that takes cosmic rays from their sources to Earth through diffusion in the magnetic field. During their journey, cosmic rays also ionize part of the medium that they cross, thereby allowing the regulation of the rate of formation of stars in the Galaxy. The ionization of neutral media affects the interplay of gas and magnetic fields, in particular in dense molecular clouds, where most stars form. The gravitational collapse that leads to the formation of stars happens with a rate that is regulated by the strength and structure of magnetic fields and by the gas itself that will end up in the star. Cosmic rays are the thermostat of all these complex phenomena. In a way, Cosmic Rays contribute to form those stars that will in turn return their energy to cosmic rays after their death. The death of these stars also returns to outer space those heavy elements and in particular those iron and carbon nuclei that are so fundamental for the development of life.

The interactions of these high-energy bullets hitting the interstellar medium induce spallation of heavy nuclei. This very important process pollutes the Galaxy with light elements such as Boron and Lithium that are very poor in the primordial soup that emerged from the Big Bang and that can be found in the Galaxy mainly as a result of the presence of cosmic rays and their interactions with the Galaxy. The measurements of the abundances of these elements, referred to as “secondaries” in the following, as well as of the positrons which are by-products of the same interactions, are precious to understand the processes responsible for diffusion in the Galaxy.

Extraordinary progress in this respect has come in the last decade from direct CR detection experiments. The Voyager spacecraft has finally provided us with the spectrum of Cosmic Rays outside the Sun termination shock, where particles are unaffected by the solar wind and their spectrum is hopefully representative of the galactic average. At the same time, PAMELA and AMS-02 have highlighted unexpected anomalies in the CR spectrum below the ‘knee’ that appeared so far featureless: there are breaks in the spectra of the most abundant species, protons and He nuclei, that are likely to be telling us that non-linear effects are not only important for CR acceleration but also to correctly describe their propagation. A fascinating possibility is that up to few hundred GeV the transport of CRs through the Galaxy is mostly determined by the turbulence they self-induce.

At larger energies, where CRs are too few to efficiently excite waves and simply propagate in the large-scale field that pervades the Galaxy, measurements of the ratio between the flux of secondaries and that of primary CRs (namely nuclei that are directly accelerated in the sources) has an energy dependence that is directly related to the turbulence spectrum. AMS-02 is extending the measurement of this ratio to high energy and

with sufficiently high precision so as to allow us to use it as the best available diagnostics of the underlying turbulence. In a similar way, the accurate AMS-02 measurement of the flux of antiprotons and the ratio of their flux to that of protons is being intensively studied by the community to reveal possible discrepancies to the standard view of CR propagation in the Galaxy.

Finally, direct detection experiments (PAMELA, AMS-02, Fermi-LAT) discovered the so called “rise in the positron fraction”, which attracted an enormous interest in the community. What these experiments found is that the ratio between CR positrons and electrons increases with energy above a few tens of GeV. Such a behavior might be due to some subtleties in CR propagation that we are still missing or to the contribution of some source of positrons in the Galaxy that has been so far neglected. The initial suggestion of a dark matter related origin of the excess positrons has progressively yielded to the idea that the “excess” positrons come from more standard astrophysical sources, pulsars, that are well known factories of leptonic antimatter. Pulsars, and more precisely Pulsar Wind Nebulae, thus enter now the realm of CR sources.

At energies of roughly 3×10^{15} eV the observed spectrum of cosmic rays shows a feature, known as the knee. The mystery of this feature has been haunting scientists for decades but experiments such as KASCADE (and previous observations carried out with EAS-TOP) have shown that the mass composition appears to change across the knee, getting heavier. This picture is consistent with lighter elements being accelerated to lower energies than heavier elements, namely all elements would be accelerated to the same maximum rigidity. On the other hand, recently other experiments such as ARGO-YBJ and Tibet Array, have shown that the knee in the light component (protons and helium nuclei) is rather at ~ 700 TeV, quite below the knee, thereby raising an issue on what is exactly going on.

This uncertainty also affects our understanding of the so-called transition region between Galactic CRs and extragalactic CRs, also referred to as ultra high energy cosmic rays (UHECRs). In the standard scenario, consistent with KASCADE data and further strengthened by KASCADE-Grande data, Galactic CRs end around a few times 10^{17} eV with a predominantly heavy composition, yielding to UHECRs that enter the game at energies around 10^{18} eV, where the mass composition starts becoming light again, a result confirmed by the two largest CR detectors operating at such high energies, Telescope Array (TA) and the Pierre Auger Observatory. The latter has, so far, collected the highest statistics of UHECR events.

The propagation of UHECRs over cosmological distances opens new questions of unprecedented interest: for protons with sufficiently high energy, the scattering with the photons in the cosmic microwave background gives rise to photopion production (pions appear in the final state). In 1966 two Russian scientists, Zatsepin and Kuzmin and an American scientist, Greisen, predicted independently that this particle physics interaction would cause the appearance of a feature in the spectrum of cosmic rays (the GZK feature), a flux suppression, which became thereafter the Holy Grail of Cosmic Ray Physics. For nuclei, the relevant interaction process is photodisintegration: a nucleus of mass A , colliding with photons in the background light (comprised of the fossil radiation of the Big Bang, the CMB, and the light produced by stars and reprocessed by dust) turns into a lighter element. For an Iron nucleus the photodisintegration process results in a spectral feature similar to but not identical to the GZK. The Auger measurements of the spectrum and mass composition of UHECRs have completely changed our way of looking at this field: these data have shown that a feature resembling the GZK does exist, but at the same time that the mass composition is mixed at energies $>10^{18}$ eV. While the mass composition is mainly light at 10^{18} eV, it becomes increasingly heavier at higher energies. Theoretical investigation of this surprising situation led to further surprise in that they showed that the injection spectra (at the sources) necessary to reproduce the data are extremely hard, quite unlike the once typically observed in astrophysical sources, with the possible exception of rapidly rotating pulsars and perhaps a handful of other possibilities. The future of the investigation in this field is bound to be filled with better and possibly complementary measurements of the mass composition and with compelling explanations of the wealth of observations that will become available.

In addition, the results of cosmic ray research indicate the importance of magnetic fields on several Mpc scales in galaxy clusters and cosmic filaments. Their evolution is an open problem, and the subject of multi-wavelength investigation (JVLA, ALMA, SKA precursors, Planck, Fermi, LBT and eROSITA).

