Multimessenger Astroparticle Physics

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5. Acceleration Sites and Sources

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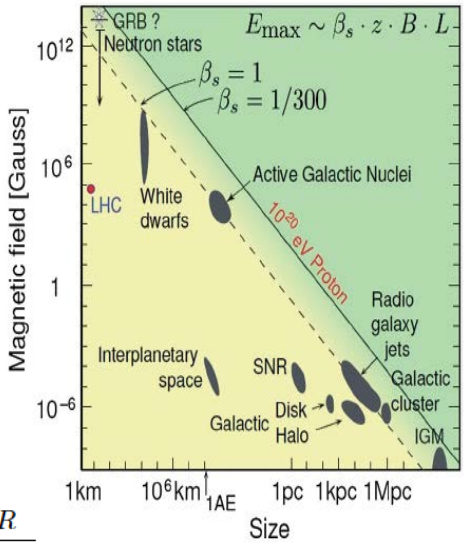
$$r_L = \frac{pc}{ZeBc}$$

- The particle acceleration in a magnetic field depends thus on the ratio of its linear momentum to its electric charge, parameter defined as the rigidity, measured in volt V and its multiples (GV, TV).

$$\mathcal{R} = r_L Bc = \frac{pc}{Ze}$$



$$\frac{E}{1\,\mathrm{PeV}} \simeq Z\frac{B}{1\,\mu\mathrm{G}} \times \frac{R}{1\,\mathrm{pc}} \simeq 0.2Z\frac{B}{1\,\mathrm{G}} \times \frac{R}{1\,\mathrm{AU}}$$

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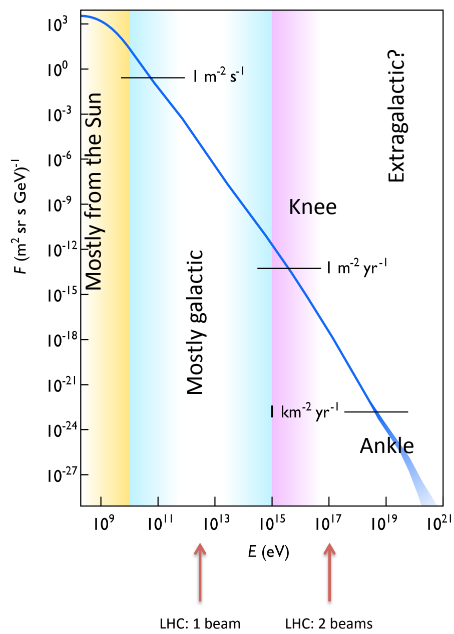
The paradigm for the sources of CR

- Galactic sources dominate below the knee
- Extragalactic sources dominate above the knee



Energy density of (Galactic) CR

The number density of CR with velocity v is given by $n(E) = \frac{4\pi}{v} I(E)$

And so **kinetic energy density** of CR, ρ_{CR} is therefore the integral of the **energy density flux**, $E \cdot n(E)$:

$$\rho_{CR} = \int En(E)\mathrm{d}E = 4\pi \int \frac{E}{v} I(E)\mathrm{d}E$$

assuming for the Galactic CR:

$$I(E) \approx 1.8 \times 10^4 (E/1\ \mathrm{GeV})^{-2.7} \frac{\mathrm{nucleons}}{\mathrm{m^2\ s\ sr\ GeV}}$$

the integral gives $\rho_{CR} \approx 0.8$ eV/cm^3 which is comparable with the energy density of the CMB $\rho_{CMB} \approx 0.25$ eV/cm^3

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SNR paradigm

If we assume this value to be the constant value over the galaxy, the power required (called *luminosity* in astrophysics) to supply all the galactic CR and balance the escape processes is:

$$\mathcal{L}_{CR} = \frac{V_D \rho_E}{\tau_{esc}} \sim 5 \times 10^{40} \text{erg s}^{-1}$$

where V_D is the volume of the galactic disk

$$V_D = \pi R^2 d \sim \pi (15\text{kpc})^2 (200\text{pc}) \sim 4 \times 10^{66} \text{cm}^3.$$

It was emphasized long ago (Ginzburg & Syrovatskii 1964) that supernovae might account for this power. For example a type II supernova gives an average power output of:

$$\mathcal{L}_{SN} \sim 3 \times 10^{42} \text{erg s}^{-1}$$

Therefore if SN transmit a few percent of the energy into CR it is enough to account for the total energy in the cosmic ray beam → **SNR paradigm**

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Stellar endproducts as acceleration sites

- Most VHE gamma-ray emissions in the Galaxy can be associated to SNRs
  - >90% of the TeV Galactic sources discovered up to now are stellar endproducts (we include here in the set of "SNR" also PWNe)
- 5 SNe have been recorded during the last millennium by eye (in 1006; in 1054 {this one was the progenitor of the Crab Nebula; in 1181; in 1572, by Tycho Brahe; and by Kepler in 1604); >5000 have been detected by standard observatories
  - Only one detected in neutrinos (SN1987A)
  - Nowadays, a few hundreds SNe are discovered every year by professional and amateur astronomers
- Two SNe classes:
  - Core-collapse supernovae (type II, Ib, Ic). A massive star burns the H in its core. When H is exhausted, the core contracts until the density and T conditions are reached such that the fusion 3He -> C can take place, which continues until He is exhausted. This pattern might repeat, leading to an explosive burning. Almost the entire gravitational energy of about 10^{53} erg is released in MeV neutrinos in a burst lasting seconds. A 25-solar mass star can go through a set of burning cycles ending up in the burning of Si to Fe in ~7 My
  - Type Ia supernovae, already discussed as "standard candles", occur whenever, in a binary system formed by a white dwarf and another star (for instance a red giant), the WD accretes matter from its companion reaching a total critical mass of ~1.4 solar masses. Beyond this, it re-ignites and can trigger a SN explosion.
- A SNR is the structure left over after a supernova explosion: a high-density neutron star (or a black hole) lies at the center of the exploded star, whereas the ejecta appear as an expanding bubble of hot gas that shocks and sweeps up the interstellar medium.

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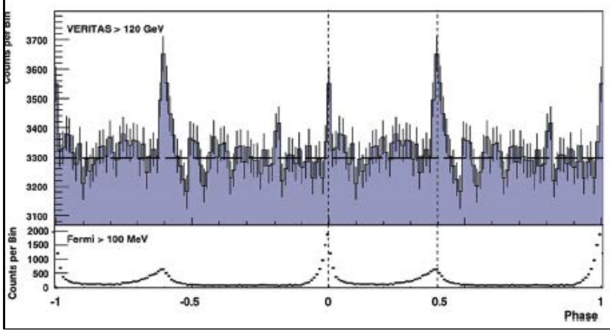
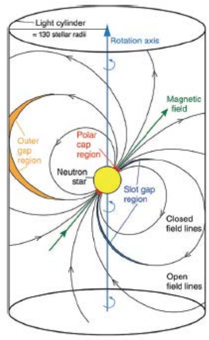
Neutron Stars; Pulsars

- When a star shrinks to a NS, it collapses to ~10-20 km, with density ~ 5 x 10^{17} kg/m^3
  - Since L is conserved, the rotation can become very fast
  - NSs in young SNRs are typically pulsars, i.e., emit a pulsed beam. Since the magnetic axis is in general not aligned to the rotation axis, for each period one has 2 peaks corresponding to either magnetic pole





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Neutron Stars; Pulsars

The rotating period for young pulsars can be estimated using basic physics arguments. A star like our Sun has a radius $R \sim 7 \times 10^5$ km and a rotation period of $T \simeq 30$ days, so that the angular velocity is $\omega \sim 2.5 \times \mu$rad/s. After the collapse, the neutron star has a radius $R_{NS} \sim 10$ km. From angular momentum conservation, one can write:

$$R^2\omega \sim R_{NS}^2\omega_{NS} \Longrightarrow \omega_{NS} = \omega\frac{R^2}{R_{NS}^2} \Longrightarrow T_{NS} \simeq 0.5\,\text{ms}\,.$$

The gravitational collapse amplifies the stellar magnetic field. As a result, the magnetic field B_{NS} near the NS surface is extremely high. To obtain an estimate of its magnitude, let us use the conservation of the magnetic flux during the contraction. Assuming the magnetic field to be approximately constant over the surface,

$$B_{\text{star}}R^2 = B_{NS}R_{NS}^2 \Longrightarrow B_{NS} = B_{\text{star}}\frac{R^2}{R_{NS}^2}\,.$$

For a typical value of $B_{\text{star}} = 1$ kG, the magnetic fields on the surface of the neutron star is about 10^{12} G. This estimate has been experimentally confirmed by measuring energy levels of free electrons in the pulsar strong magnetic fields. In a class of neutron stars called *magnetars* the field can reach 10^{15} G.

Typical pulsars emitting high-energy radiation have cutoffs O(a few GeV).

> 100 HE pulsars emitting at energies > 100 MeV have been discovered by the Fermi LAT.
They are very close to the Solar System, most < a few kpc away

They can be an important source of electrons/positrons

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Pulsars

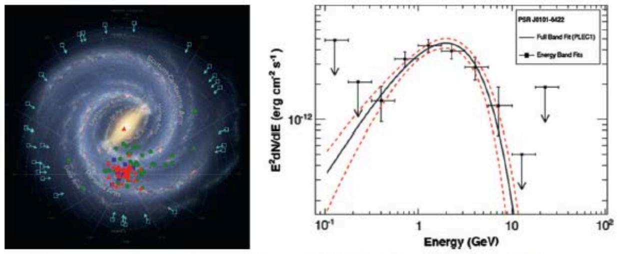


Fig. 10.11 Left: Map of the pulsars detected by the *Fermi*-LAT (the Sun is roughly in the center of the distribution). The open squares with arrows indicate the lines of sight toward pulsars for which no distance estimates exist. Credit: NASA. Right: Spectral energy distribution from a typical high-energy pulsar. Credit: NASA.

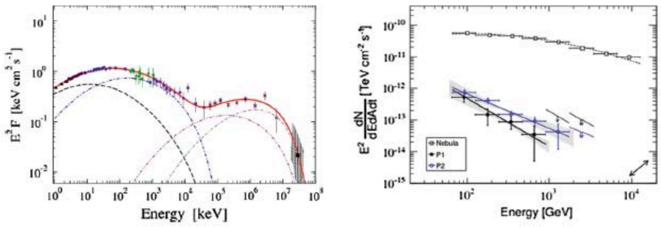
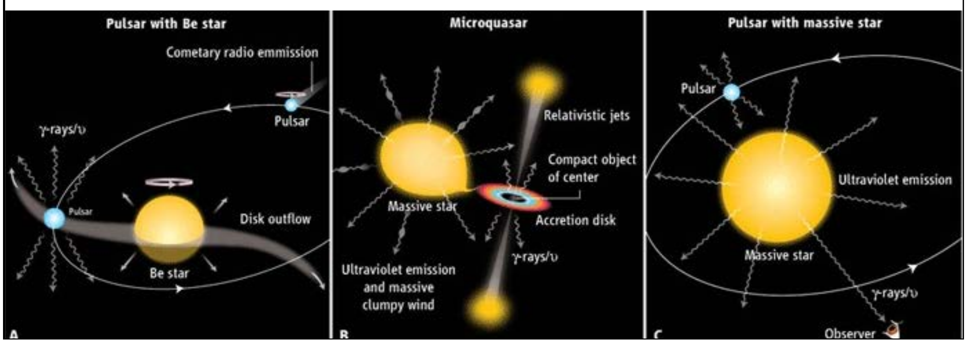


Fig. 10.12 Left: Spectral energy distribution of the Crab Pulsar. Right: The VHE energy emission, compared with the emission from the pulsar wind nebula powered by the pulsar itself. The two periodical peaks are separated. Credit: MAGIC Collaboration.

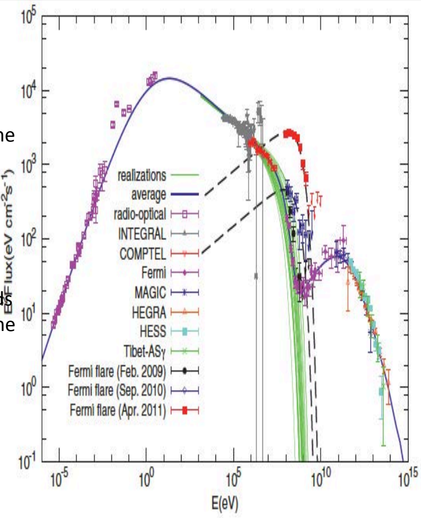
Binary Systems

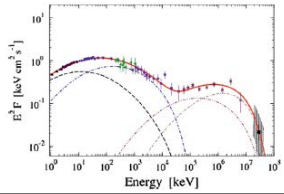
- NS and BHs and other compact objects are frequently observed orbiting around a companion compact object or a non-degenerate star (like in the binary system LS I +61 303). Mass can be transferred to the (more) compact object, accreting it. Shocks between the wind of the massive companion and the compact object can contribute to the production of non-thermal emission in X-rays or in gamma rays. Due to the motion of ionized matter, very strong electromagnetic fields are produced in the vicinity of the compact object, and charged particles can be accelerated to high energies, generating radiation.



Dynamics of SNRs

- SNRs are characterized by expanding ejected material interacting with ambient gas through shock fronts, with the generation of turbulent magnetic fields, O(10 µG - 1 mG).
- Typical velocities for the expulsion of the material out of the core are O(3000 km/s - 10 000 km/s) for a young (< 1000 yr) SNR.
- The shock slows down over time as it sweeps up the ambient medium, but it can expand over tens of thousands of years and over tens of pc before its speed falls below the local sound speed.
- Based on their emission and morphology (which are actually related), SNRs are generally classied under three categories:
  - Shell-type,
  - Pulsar wind Nebulae (PWN),
  - Composite (a shell-type SNR containing a PWN).
- The best known PWN is the Crab Nebula, powered by the central young (~1000 year) pulsar B0531+21. Crab Nebula emits radiation across a large part of the electromagnetic spectrum, and qualitatively one can see from the SED the SSC mechanism at work with a transition at 30 GeV between the synchrotron and the IC. One can separate the contribution of the pulsar from the PWN

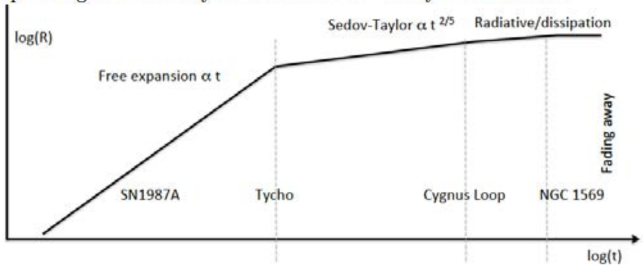




The evolution of a SNR can be described by a free expansion phase, an adiabatic phase, a radiative phase and a dissipation phase (Fig. 10.14).

1. In the free expansion phase, lasting up to few hundred years depending on the density of the surrounding gas, the shell expands at constant velocity and acts like an expanding piston, sweeping up the surrounding medium.
2. When the mass of the swept-up gas becomes comparable to the ejected mass, the Sedov-Taylor (adiabatic) phase starts. The ISM produces a strong pressure on the ejecta, reducing the expansion velocity, which remains supersonic for some 10^4 years, until all the energy is transferred to the swept-out material. During this phase, the radius of the shock grows as $t^{2/5}$. Strong X-ray emission traces the strong shock waves and hot shocked gas.
3. As the expansion continues, it forms a thin ($\lesssim$ 1 pc), dense (1-100 million atoms per cubic metre) shell surrounding the $\sim 10^4$K hot interior. The shell can be seen in optical emission from recombining ionized hydrogen and ionized oxygen atoms. Radiative losses become important, and the expansion slows down.
4. Finally, the hot interior starts cooling. The shell continues to expand from its own momentum, and $R \propto t^{1/4}$. This stage can be seen in the radio emission from neutral hydrogen atoms.

When the supernova remnant slows to the speed of the random velocities in the surrounding medium, after roughly 30 000 years, it merges into the general turbulent flow, contributing its remaining kinetic energy to the turbulence, and spreading around heavy atoms which can be recycled in the ISM.



SNRs and Particle Acceleration

A young supernova remnant has the ideal conditions for the Fermi 1st order acceleration. The maximum energy that a charged particle could achieve is given by the rate of energy gain, times the time T_e spent in the shock. In the Fermi first-order model,

$$\frac{dE}{dt} \simeq \beta \frac{E}{T_{cycle}} \qquad (10.35)$$

(Sec. sec:accfermi); $\lambda_{cycle} \sim r_L \simeq E/(ZeB)$ is of the order of the Larmor radius (see Sect. 10.2).

$$T_{cycle} \simeq \frac{E}{ZeB\beta c} \Longrightarrow \frac{dE}{dt} \simeq (\beta^2 c) ZeB \, . \qquad (10.36)$$

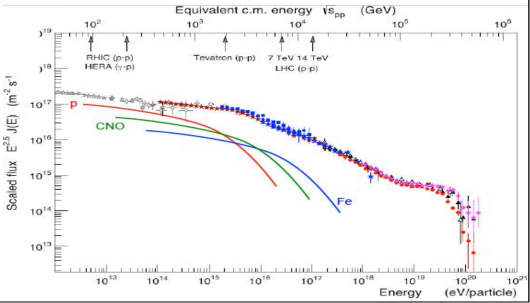
Finally

$$E_{max} \simeq T_S \frac{dE}{dt} \simeq ZeBR_S\beta \, . \qquad (10.37)$$

Inserting in Eq. 10.37 4 μG as a typical value of the magnetic field B, and assuming $T_e \simeq R_S/(\beta c)$, where R_S is the radius of the supernova remnant, we obtain:

$$E_{max} \simeq \beta \, Ze \, B \, R_S \simeq 300 \, Z \, \text{TeV} \, .$$

- E_{max} is proportional to Z. The knee is a structure due to the different maximum energy reached by nuclei with different Z. Note that the proportion to Z is an underestimate of the actual proportion, since the escape probability from the Galaxy also decreases with Z.



Extragalactic Acceleration Sources: AGN

- Among the extragalactic emitters, Active Galactic Nuclei (AGN) and Gamma Ray Bursts could fulfill the conditions (size, magnetic field) to reach the highest energies.
- SMBHs of 1M - 10G solar masses and beyond reside in the cores of most galaxies. The mass of BHs in the center of other galaxies has been calculated through its correlation to the velocity dispersion of the stars in the galaxy.
- In approximately 1% of the cases such BH is active, i.e., it displays strong emission and has signatures of accretion: we speak of an AGN.
- Infalling matter onto the BH can produce a spectacular activity. An AGN emits over a wide range of wavelengths from ray to radio: typical luminosities can be very large, and range from about 10^{37} to 10^{40} W (up to 10 000 times a typical galaxy).
  - The energy spectrum of an AGN is radically different from an ordinary galaxy, whose emission is due to its constituent stars.
- The maximum luminosity (in equilibrium conditions) is set by requirement that gravity (inward) is equal to radiation pressure (outward); this is called the Eddington luminosity - approximately, the Eddington luminosity in units of the solar luminosity is 40 000 times the BH mass expressed in solar units. For short times, the luminosity can be larger than the Eddington luminosity.

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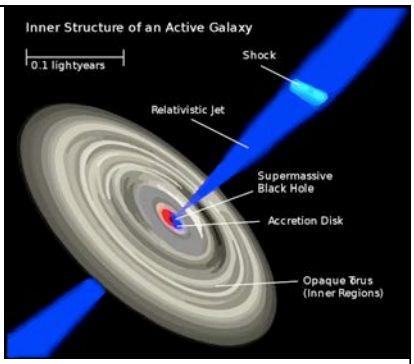
Structure of AGN



- Matter falling into the BH conserves angular momentum and forms a rotating accretion disk around it.
- In about 10% of AGN, the infalling matter turns on powerful collimated jets that shoot out in opposite directions, ~ perpendicular to the disk, at relativistic speeds.
- Jets have been observed close to BH with transverse size of ~0.01 pc, << than the radius of the BH
- Frictional effects within the disk raise the temperature to very high values, causing the emission of energetic radiation-the gravitational energy of infalling matter accounts for the power emitted.
- Typical values of B are O(10000 G) close to the BH horizon, quickly decaying along the jet axis.
- Many AGN vary substantially in brightness over very short timescales (days/minutes). The energy sources in AGN must be very compact, much smaller than their Schwarzschild radii (20 AU, about 3 light hours, for a SMBH of 1G solar masses).
- The so-called "unified model" accounts for all kinds of AGN within the same basic model.

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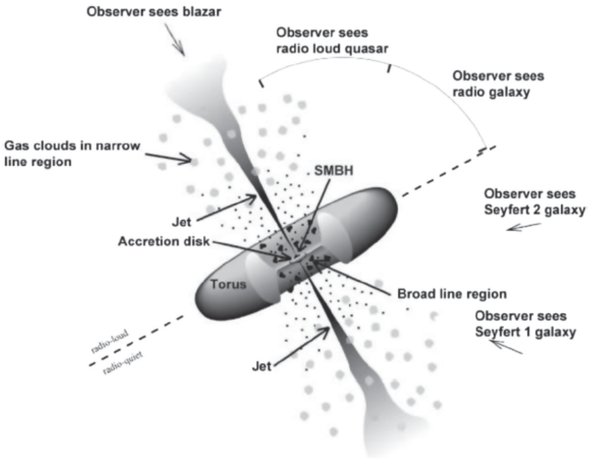
The Unified AGN Model

- The jet radiates mostly along its axis, also due to the Lorentz enhancement - the observed energy in the observer's frame is boosted by a Doppler factor Γ which is obtained by the Lorentz transformation of a particle from the jet fluid frame into the laboratory frame; in addition the Lorentz boost collimates the jet.



- An observer looking very close to the jet axis will observe essentially the emission from the jet, and thus will detect a (possibly variable) source with no spectral lines: this is called a blazar.
- As the angle of sight with respect to the jet grows, the observer will start seeing a compact source inside the torus; in this case we speak generically of a quasar.
- From a line of sight closer to the plane of the torus, the BH is hidden, and one observes essentially the jets (and thus, extended radio-emitting clouds); in this case, we speak of a radio galaxy (Fig. 10.16).

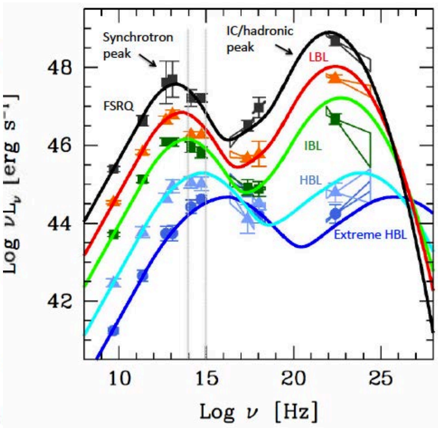
Blazars

Observationally, blazars are divided into two main subclasses depending on their spectral properties.

- Flat Spectrum Radio Quasars, or FSRQs, show broad emission lines in their optical spectrum.
- BL Lacertae objects (BL Lacs) have no strong, broad lines in their optical spectrum.
  Typically FSRQs have a synchrotron peak at lower energies than LBLs.
  BL Lacs are further classified according to the energies of the synchrotron peak $\hat{\nu}_S$ of their SED; they are called accordingly:
  - low-energy peaked BL Lacs (LBLs) if $\hat{\nu}_S \lesssim 10^{14}$ Hz (about 0.4 eV);
  - intermediate-energy peaked BL Lacs (IBL);
  - high-energy peaked BL Lacs (HBL) if $\hat{\nu}_S \gtrsim 10^{15}$ Hz (about 4 eV).

  (note that the thresholds for the classification vary in the literature).

Blazar population studies at radio to X-ray frequencies indicate a redshift distribution for BL Lacs peaking at $z \sim 0.3$, with only few sources beyond $z \sim 0.8$, while the FSRQ population is characterized by a rather broad maximum at $z \sim 0.6$–1.5.



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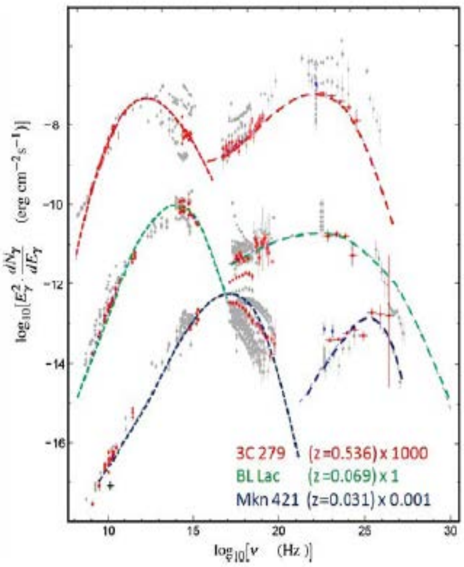
Blazars



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Non-AGN Extragalactic Gamma Ray Sources

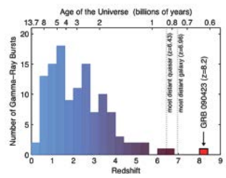
- At TeV energies, the extragalactic gamma ray sky is dominated by blazars. At present, > 60 emitters have been discovered and are listed in the online TeV Catalog. Only 3 radio galaxies have been detected at TeV (Cen A, M87 and NGC 1275).
- The two most massive closeby starburst (i.e., with an extremely large rate of star formation) galaxies NGC 253 and M82 are the only extragalactic sources detected at TeV energies for which the accretion disk-jet structure is not evidenced.
- At GeV energies, a significant number (about 1/3 ot the total) of unidentified extragalactic objects has been detected by the Fermi-LAT (emitters that could not be associated to any known object), and few non-AGN objects have been discovered.

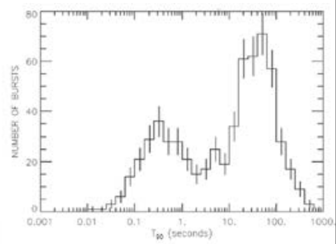
Gamma Ray Bursts

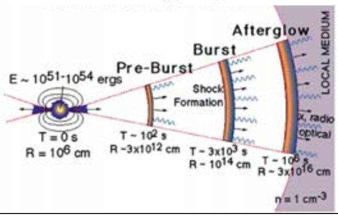
GRBs are of extragalactic origin. The distribution of their duration is bimodal, and allows a first phenomenological classification between “short" GRBs (T90 typically 0.3 s) and “long" GRBs (lasting more than 2 s, and typically 40 s). Short GRBs are on average harder than long

- sGRBs have been associated to the coalescence of pairs of massive objects, NS-NS or NS-BH. The system loses energy due to gravitational radiation, and spirals until tidal forces disintegrate it providing the jetted emission of an enormous quantity of energy during the merger (“kilonova”). This process can last ~ a few seconds, and has been recently proven by the simultaneous observation of gGW and gammas in a NS-NS merger.
- Long GRBs have been associated with a supernova from a very high mass progenitor, a “hypernova”. The connection between large mass supernovae (from the explosion of hypergiants, stars with a mass of between 100 and 300 times that of the Sun) and long GRBs is proven by the observation of events coincident both in time and space, and the energetics would account for the emission-just by extrapolating the energetics from a supernova. During the abrupt compression of such a giant star the magnetic field could be squeezed to extremely large values, of the order of 1 TG – 100 TG, in a radius of some tens of kilometers

  => The right energetics for UHE CR
- The detail of a possible acceleration process is ~ as for SNe
- Warning: IceCube observations => < 6% of CR come from GRBs



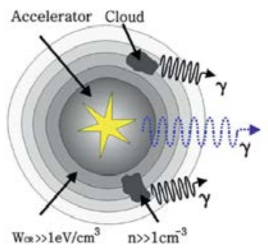


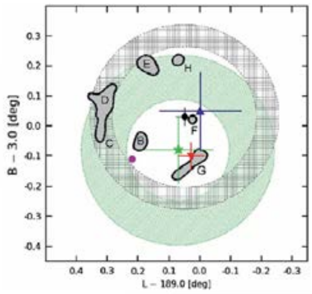


Gamma Rays and the Origin of CR

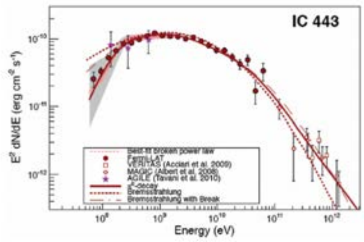
The right energetics, the right mechanism.

- Indications from morphology



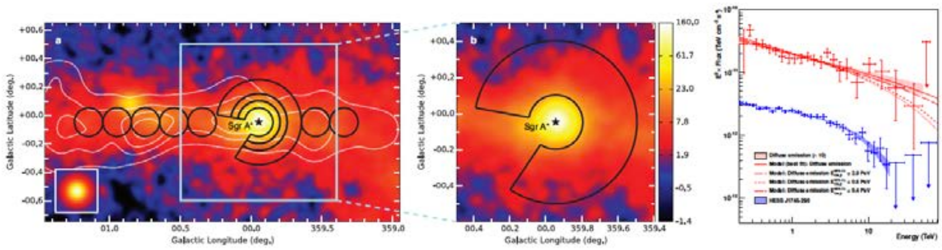


- Indications (could be improved with instruments at the MeV) of the presence of a π^0 peak



Where are the Galactic PeVatrons?

- The acceleration mechanism explains emission up to a few hundred TeV, close to the knee but not yet the knee
- Only 2 suspect Galactic PeVatrons have been found up to now: one is in the Galactic Center, the other is Crab Nebula (ssshhh)
- For both the interpretation is quite debated
- Remember the change of composition near the knee!
  - Neutrinos?



Testing if UHE CR originate from AGN

As the energetics of SNRs might explain the production of galactic CR, the energetics of AGN might explain the production of CR up to the highest energies. In the Hillas relation, the magnetic field and the typical sizes are such that acceleration is possible (Table 10.1).

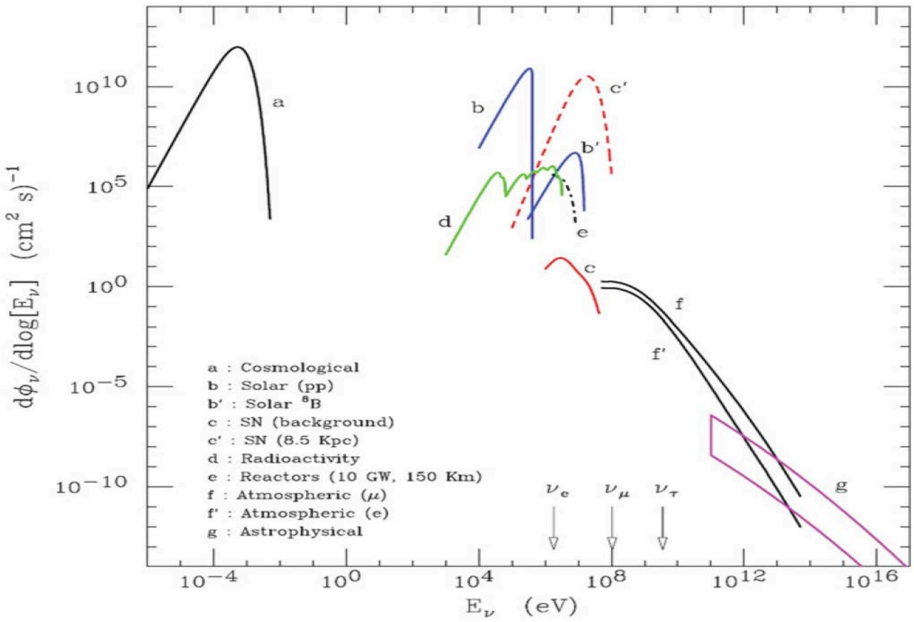
Where molecular clouds are not a likely target, as, for example, in the vicinity of supermassive black holes, proton–photon interactions can start the hadronic shower.

Although the spatial resolution of gamma ray telescopes is not yet good enough to study the morphology of extragalactic emitters, a recent study of a flare from the nearby galaxy M87 (at a distance of about 50 Mly, i.e., a redshift of 0.0004) by the main gamma telescopes plus the VLBA radio array has shown, based on the VLBA imaging power, that this AGN accelerates particles to very high energies in the immediate vicinity (less than 60 Schwarzschild radii) of its central black hole. This galaxy is very active: its black hole, of a mass of approximately 7 billion solar masses, accretes by 2 or 3 solar masses per year. A jet of energetic plasma originates at the core and extends outward at least 5000 ly.

Also Centaurus A, the near AGN for which some weak hint of correlation with the Auger UHE data exists, has been shown to be a VHE gamma emitter.

The acceleration of hadrons above 1 EeV has been proven very recently to correlate with the position of AGN, and in particular one blazar has been identified as a hadron accelerator at some tens of PeV. These

Neutrino Sources



Sources of Gravitational Waves

- At the largest scales (extremely low frequencies, 1fHz-1aHz) expected sources are fluctuations of the primordial Universe
- At lower scales (frequencies 0.1 mHz − 1 kHz expected sources are:
  - NS binaries (detected by LIGO/Virgo)
  - Stellar mass BH binaries, of the type detected already by LIGO
  - Supernova, gamma-ray bursts
  - Extreme mass-ratio inspirals, when a NS or stellar-mass BH collides with a SMBH
  - Supermassive black hole binaries, formed when galaxies merge.

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