Diffusive Shock Acceleration

The most popular way to accelerate particles in the Universe

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Syllabus

- **Lecture 1:** Introduction. Cosmic Rays. Gamma rays. Synchrotron radiation
- **Lecture 2:** Derivation of the *Universal* power law of accelerated particles.
- **Lecture 3:** The Fokker-Planck equation and its solutions. Phenomenology of efficient accelerators.

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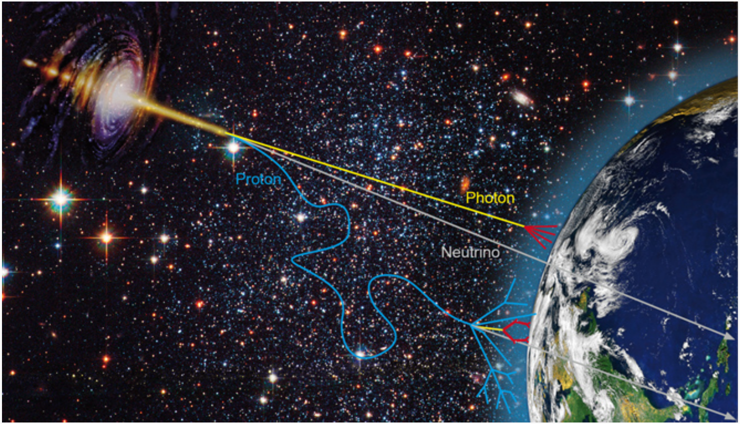
Introduction

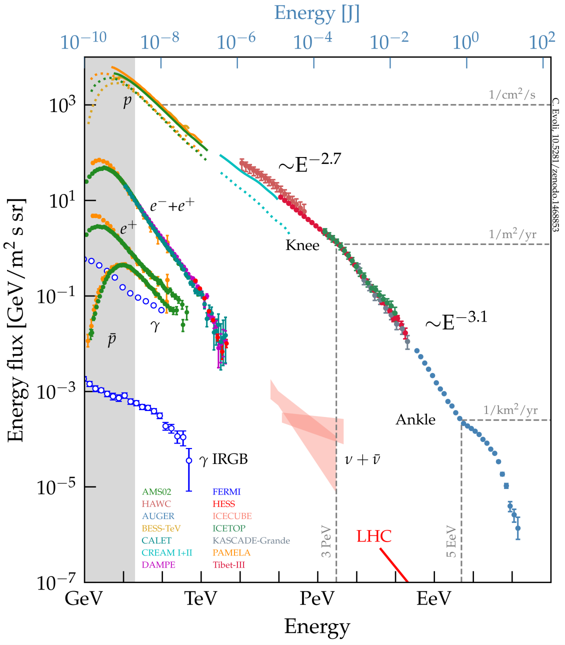
Photons • Cosmic Rays • Neutrinos • Gravitational Waves



The multi-messenger spectrum...

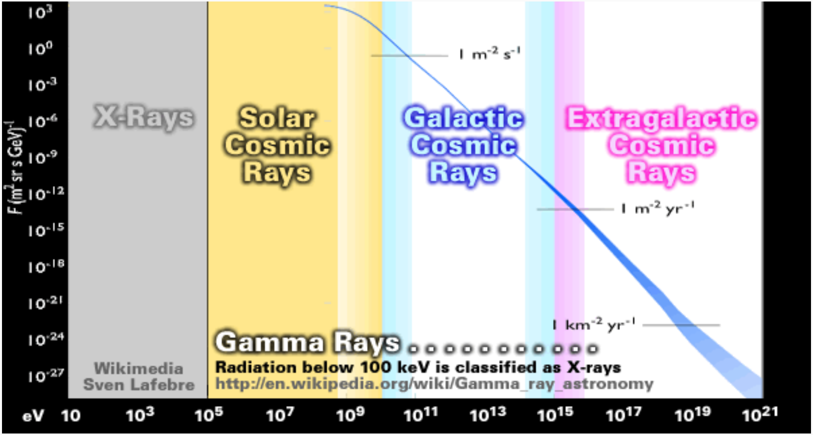
...of the **non-thermal** Universe

- Cosmic Rays
- Photons (γ rays)
- Neutrinos (ν)



Cosmic rays

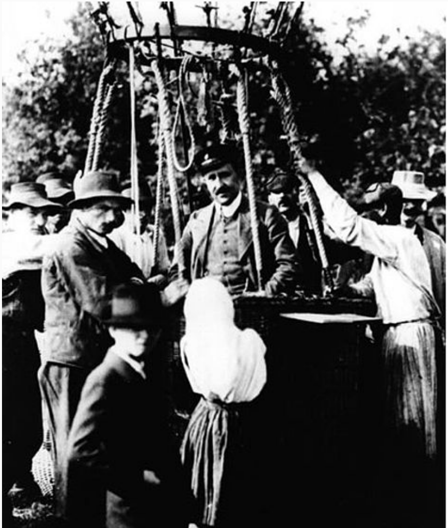
Charged particles arriving on Earth



Cosmic rays detection

Direct observation of cosmic rays is possible only above the Earth's atmosphere

- First detection by Hess in 1912
- Balloon at 5300 metres altitude
- Hess shared the 1936 Nobel prize for this discovery



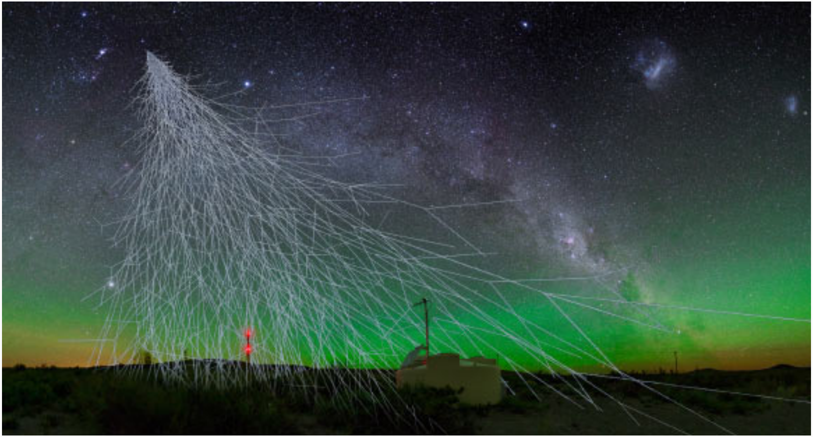
Detection of high energy cosmic rays

- About 200 low-energy cosmic rays strike every square meter of the Earth per second
- Above 10^{18} eV, only one particle/week falls on an area of 1 km^2
- Above 10^{20} eV, only one particle/century falls on a km^2
- To find and measure these rare events we need a giant detector

Because high-energy cosmic rays are very rare, it would be impossible to capture a significant number of them on a balloon, and therefore we detect them at the Earth's surface

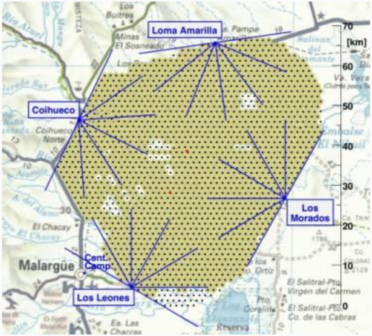
Air showers

- Cosmic ray collisions with Earth's atmosphere molecules initiate cascades of secondary particles



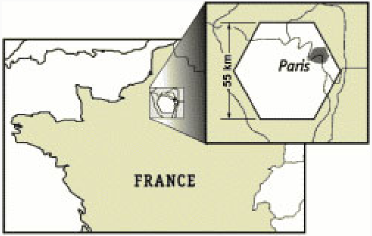
Cosmic ray detection

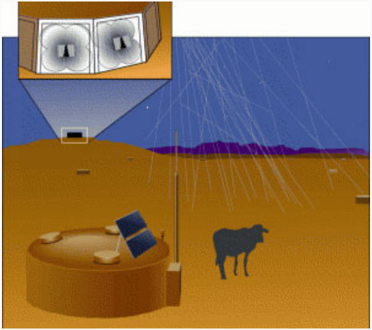
The Pierre Auger Observatory (Malargue, Argentina)



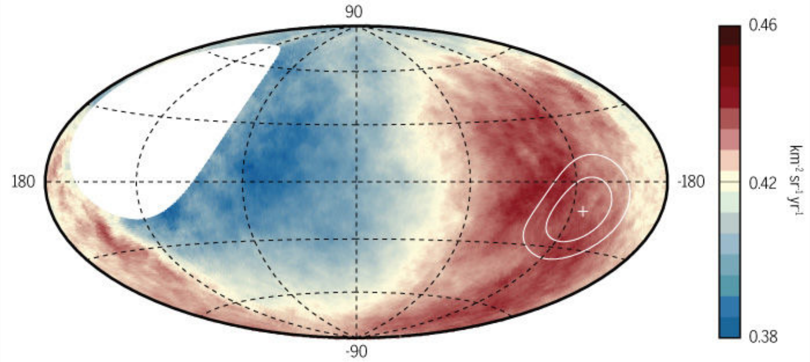
The Pierre Auger Observatory

- 1600 particle detector covering about 3000 km^2
- Each 11000-liter tank is filled with 12 tons of pure water





Cosmic Rays with $E > 10^{18}$ eV are extragalactic (no excess on the galactic plane)

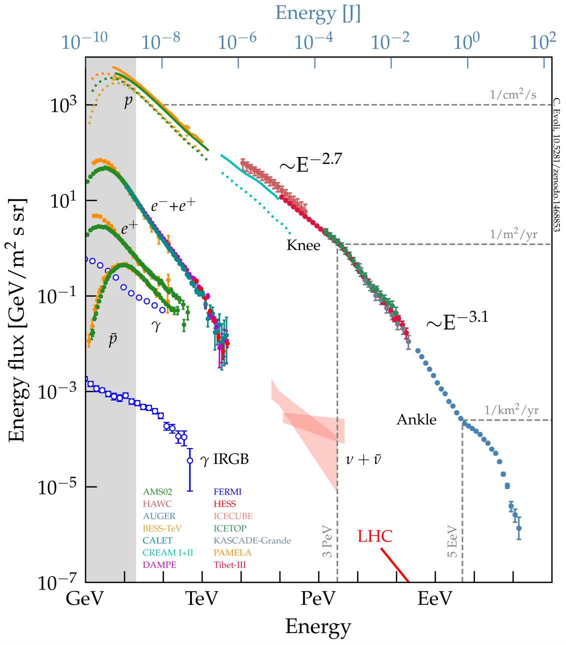


Pierre Auger collaboration (2017)

The multi-messenger spectrum: photons

Isotropic Diffuse Gamma-Ray Background (IGRB):

- Extragalactic emissions too faint or too diffuse to be resolved in a survey
- Residual Galactic foregrounds that are approximately isotropic



Gamma ray emission

Gamma ray emission

The gamma ray emission is non thermal!

- Black body $E_\gamma = 2.7\kappa T \Rightarrow \frac{E_\gamma}{\mathrm{GeV}} \sim \frac{T}{10^{13}\mathrm{K}}$

Emission processes

Hadronic

- Proton-proton collisions: $p + p \longrightarrow p + p + a\pi^0 + b(\pi^+ + \pi^-)$
- Proton-photon: $p + \gamma \longrightarrow p + a\pi^0 + b(\pi^+ + \pi^-)$

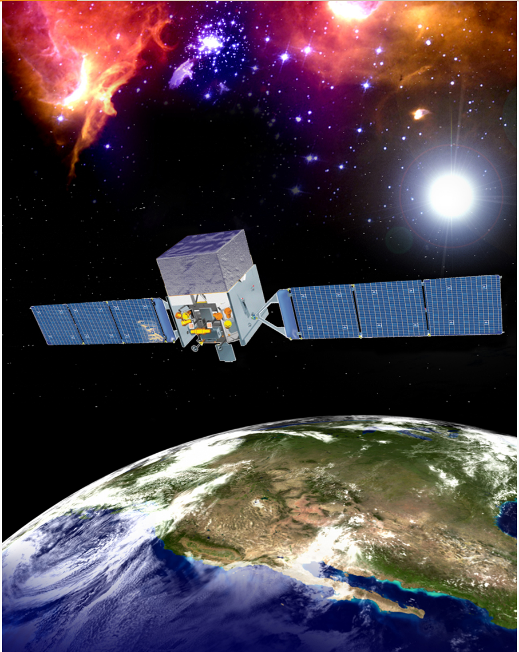
$$\pi^0 \longrightarrow \gamma + \gamma \qquad \pi^\pm \longrightarrow \mu^\pm + \bar{\nu}_\mu(\nu_\mu)$$

Leptonic

- Inverse Compton scattering: $e^- + \gamma \longrightarrow e^- + \gamma$
- Relativistic Bremsstrahlung

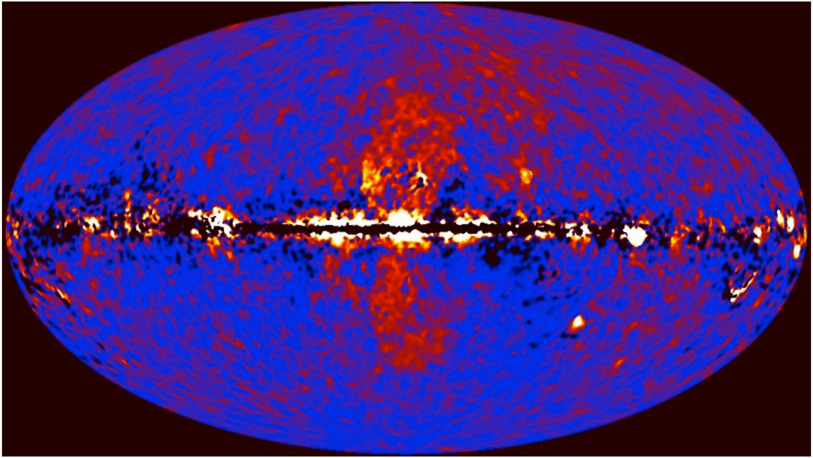
Gamma ray detection: from space ($E_\gamma < 100$ GeV)

The *Fermi* satellite was launched in 2008



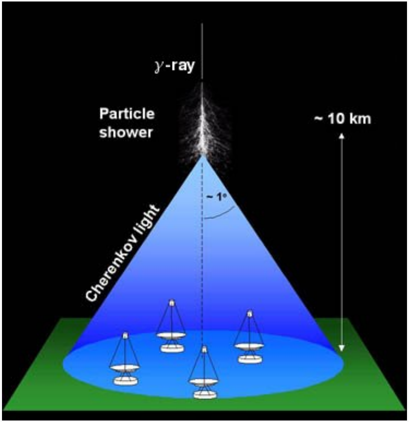
The Fermi bubbles

- *Fermi* satellite greatest discovery (the unexpected!)
- The origin of this emission is still unclear

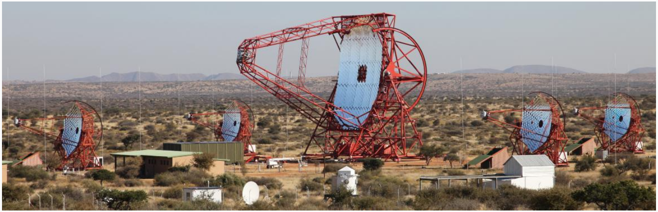


Ground-based gamma-ray astronomy ($E_\gamma < 100$ GeV)

- γ rays moves moves faster than the speed of light in the Earth atmosphere
- Production of air shower
- Optical Cherenkov light
- It's possible to track the γ-ray arrival direction

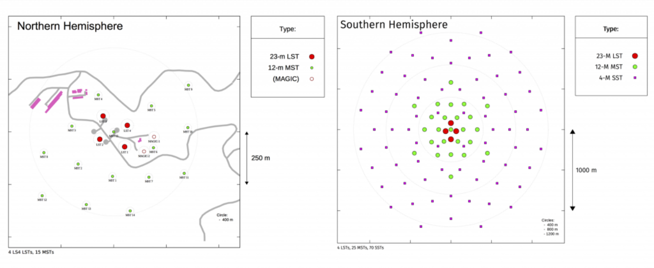


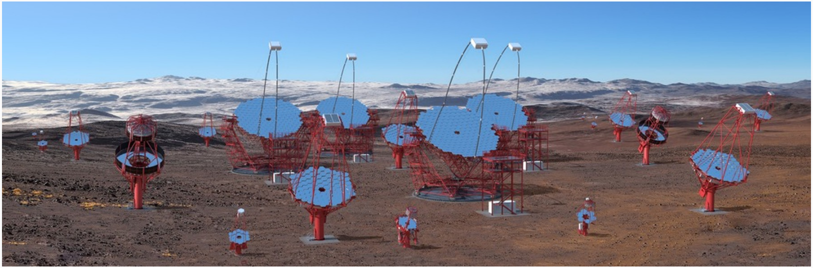
Ground-based gamma-ray telescopes



Veritas (Arizona) • MAGIC (La Palma) • HESS (Namibia)

The forthcoming CTA (Cherenkov Telescope Array)

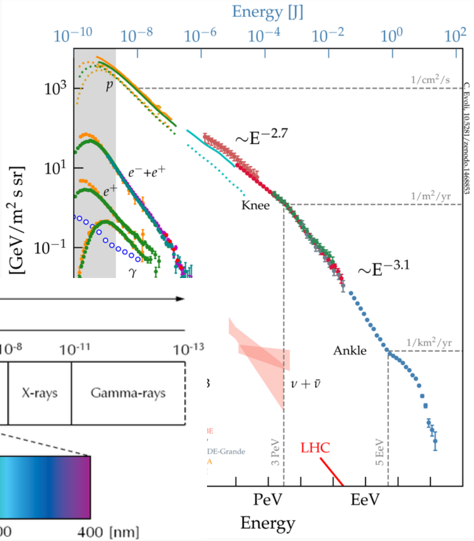


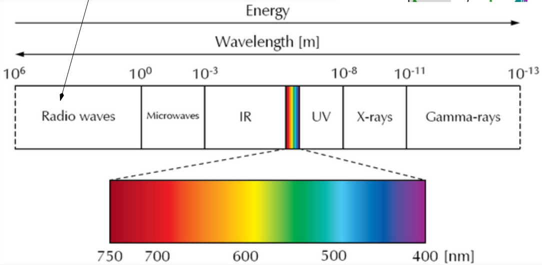


CTA Paranal (expected)

The electromagnetic spectrum

Synchrotron emission
is also non–thermal





Radio (synchrotron) emission

Radio astronomy

Development of radio astronomy after the second world war

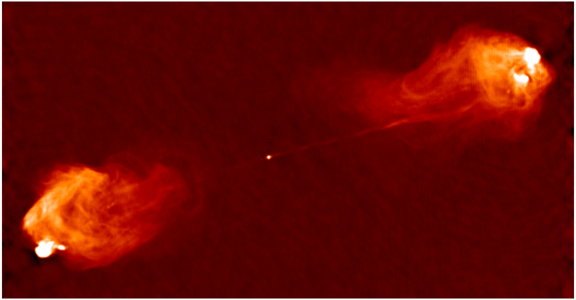
Radio data is an excellent tool to study the conditions in the plasma (magnetic and non-thermal energy content)

The Very Large Array (VLA)

Synchrotron emission basics

Synchrotron emission is produced by electrons and protons interacting with a magnetic field $\vec{B}$.

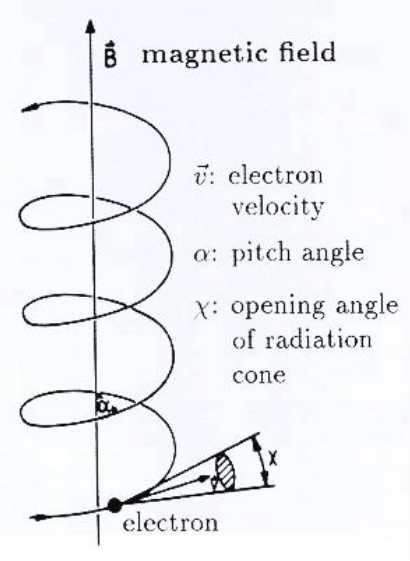
- Intensity $I \propto (m_e/m_p)^3 \sim 10^{-9} \Rightarrow$ **Leptonic synchrotron emission is more important than hadronic**
- $B > B_{\rm cr} \sim 4.4 \times 10^{13}$ G: quantum effects are important and synchrotron radiation from protons becomes relevant



Radioagalaxy Cygnus A

Synchrotron emission is beamed

Semi-opening angle $\chi/2 \sim 1/\Gamma, \qquad \Gamma = E/(m\,c^2)$



Synchrotron power

- Single electron's power:

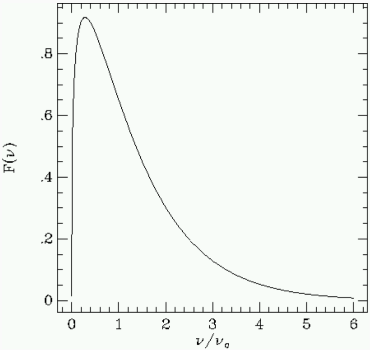
$$P_{\rm synchr}(E, E_{\rm ph}) = \frac{1}{h}\,\frac{\sqrt{3}e^3}{m_e c^2}\,B_\perp\,\frac{E_{\rm ph}}{E_{\rm c}}\int_{E_{\rm ph}/E_{\rm c}}^{\infty} K_{5/3}(\zeta)\,{\rm d}\zeta$$

- Modified Bessel function (second kind):

$$\frac{E_{\rm ph}}{E_{\rm c}}\int_{E_{\rm ph}/E_{\rm c}}^{\infty} K_{5/3}(\zeta)\,{\rm d}\zeta \sim 1.85\left(\frac{E_{\rm ph}}{E_{\rm c}}\right)^{1/3}\exp\left(\frac{-E_{\rm ph}}{E_{\rm c}}\right)$$

$P_{\rm synchr}(E_e, E_{\rm ph})$ peaks at
$E_{\rm ph} \sim 0.3 E_{\rm c}$

Photons characteristic energy:
$E_{\rm c}(E) = 5.1 \times 10^{-8}\,B\,E^2$ erg



Synchrotron cooling

- Energy losses:

$$\left.\frac{\mathrm{d}E}{\mathrm{d}t}\right|_{\mathrm{synchr}} \equiv -P_{\mathrm{synchr}}(E) = -\int P_{\mathrm{synchr}}(E, E_{\mathrm{ph}})\,\mathrm{d}E_{\mathrm{ph}}$$

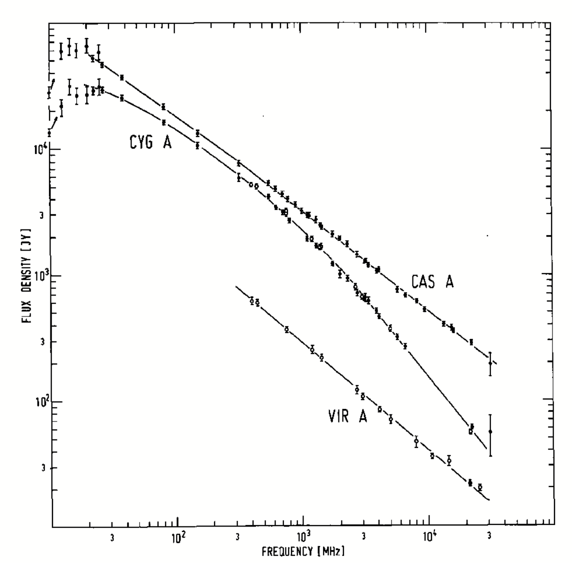
- Cooling time:

$$t_{\mathrm{synchr}} = \frac{1}{\mathrm{d}E/\mathrm{d}t} = \frac{2\,\pi}{3\,c\,\sigma_{\mathrm{T}}}\frac{(m_e c^2)^2}{E\,B^2} \sim \frac{4.1\times 10^2}{B^2\,E}\ \mathrm{s}$$

Synchrotron losses are not *catastrophic*!

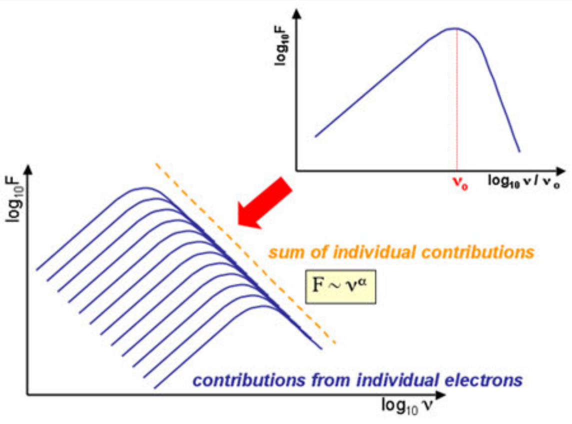
$$\frac{E_{\mathrm{c}}}{\mathrm{eV}} \sim 5\times 10^{-6}\left(\frac{B}{100\mu\mathrm{G}}\right)\left(\frac{E}{\mathrm{GeV}}\right)^2$$

Observed spectrum....is a power law!



Synchrotron emission from an ensemble of electrons N

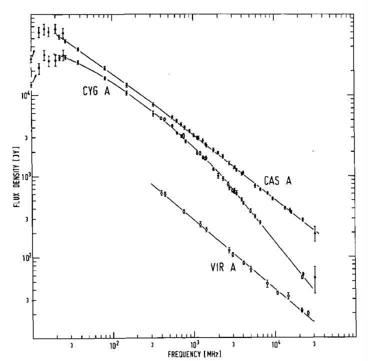
$$P_{\mathrm{synchr}}(E_{\mathrm{ph}}) = \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} P_{\mathrm{synchr}}(E, E_{\mathrm{ph}})\, N(E)\, \mathrm{d}E$$

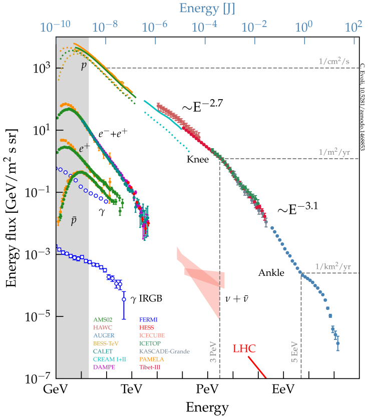


A power-law electron energy distribution produces a power-law spectrum

Power laws

- The spectrum of cosmic rays arriving on Earth is a (broken) power-law energy distribution
- The spectrum of relativistic electrons in the source is also a power law





Particle acceleration

FERMI'S ORIGINAL IDEA (1949)

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

- Two magnetized clouds moving to each other
- This scenario is not very common in the Universe
- Inefficient energy gain

$$\frac{\Delta E}{E} \propto \left(\frac{V}{c}\right)^2 \ll 1$$

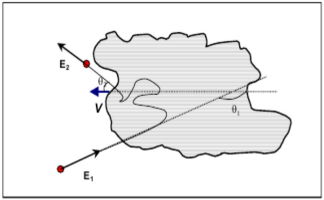


Figure 3.2: Sketch of a collision of a charged particle with moving magnetic cloud.

Including shocks (1954)

GALACTIC MAGNETIC FIELDS AND THE ORIGIN OF COSMIC RADIATION*

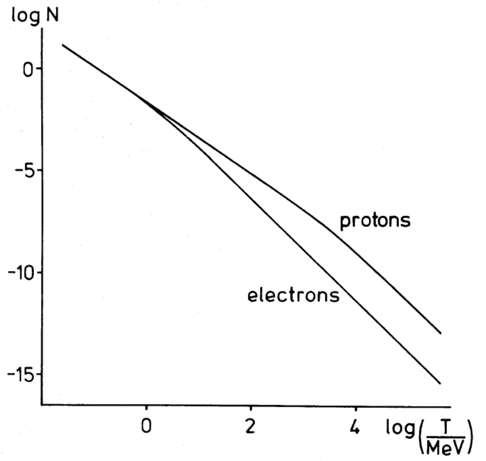
E. FERMI
Institute for Nuclear Studies, University of Chicago
Received September 11, 1953

Recently de Hoffmann and Teller[5] have discussed the features of magnetohydrodynamic shocks. They show, in particular, that at a shock front sudden variations in direction and intensity of the field are likely to occur. One is tempted to identify the boundaries of many clouds of the galactic diffuse matter with shock fronts. If this is correct, we have a source of magnetic discontinuities. Probably many of these discontinuities will be rather small. However, either their cumulative effect or the effect of some occasional major discontinuity will tend to convert the angle of pitch that a previous trap acceleration has reduced to a small value back to a statistical distribution corresponding to isotropy of direction. At this moment the particle is ready for a new trap acceleration.

But… he didn't perform the calculations

Derivation of the Universal power law (70's)

- Axford, Leer & Skadron 1977
- Krymskii 1977
- Bell 1978a,b
- Blandford & Ostriker 1978



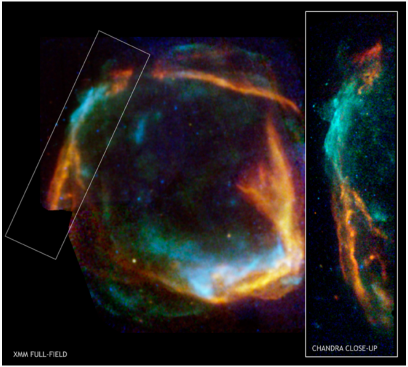
Bell 1978b

Shocks are very common in the Universe!

- Particles diffuse back and forth the shock due to magetic instabilities in the plasma
- Efficient energy gain

$$\frac{\Delta E}{E} \propto \frac{v_{\mathrm{shock}}}{c}$$

- Magnetic field amplification by Cosmic Rays itself! (Bell 2004)

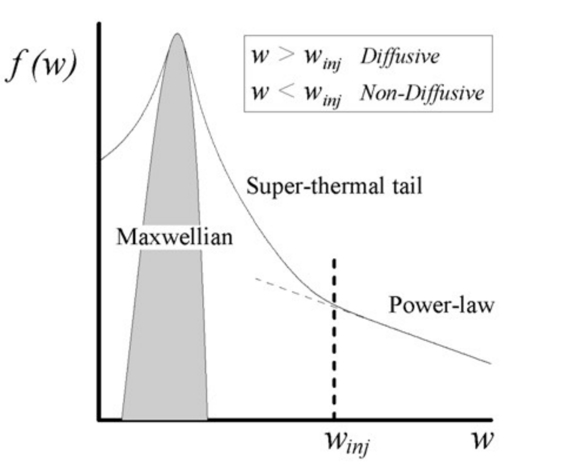


RCW 86 (Chandra and XMM-Newton X-ray data) - J. Vink

Particle energy distribution in astrophysical plasmas

Two main unknowns

- The minimum energy of electrons (injection problem)
- The maximum energy (Ultra High Energy Cosmic Rays)



Questions?