Multi Messenger Astrophysics

Paolo Lipari
INFN Roma Sapienza

ISAPP School 2019
Cosmic Ray Vision from the Southern Sky

Malargue, march 3rd 2019
“High Energy Universe”

The ensemble of astrophysical objects, environments and mechanisms that generate and store very high energy particles in the Milky Way and in the entire universe.

This field is one of the most significant and fascinating “Frontiers” in Science today.

1. Understanding the “COSMOS” where we live

2. The sources of the High Energy radiation can be the “laboratories” where we test (in conditions that are not achievable in “Earth based laboratories”) our Fundamental Laws of Physics.
Cosmic Rays, Photons, Neutrinos
Gravitational Waves

4 Messengers for the study of the “High Energy Universe”
Three messengers are “inextricably” tied together

[Cosmic Rays, Gamma Rays, High Energy Neutrinos can really be considered as three probes that study the same underlying physical phenomena]
Cosmic Ray Accelerator

Astrophysical object accelerating particles to relativistic energies

Contains populations of relativistic protons, nuclei, electrons/positrons

Emission of cosmic rays, photons, neutrinos
Fundamental Mechanism: Acceleration of Charged Particles to Very High Energy ("non thermal processes") in astrophysical objects (or better "events").

Creation of Gamma Rays and Neutrinos via the interactions of these relativistic charged particles.

"Hadronic"

\[ p + X \rightarrow \pi^+ \pi^- \pi^0 \ldots \]

\[ \pi^0 \rightarrow \gamma \gamma \]

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \]

\[ \quad \downarrow \quad \quad e^+ \nu_e \bar{\nu}_\mu \]

"Leptonic"

\[ e^\pm \gamma_{\text{soft}} \rightarrow e^\pm \gamma \]

\[ e^\pm Z \rightarrow e^\pm \gamma Z \]

\[ e^\pm \vec{B} \rightarrow e^\pm \gamma_{\text{syn}} \]
High Energy Source

\[ n_{\text{gas}}(\vec{x}, t) \]
\[ \tilde{B}(\vec{x}, t) \tilde{E}(\vec{x}, t) \]
\[ n_\gamma(\varepsilon, \hat{u}_\gamma, \vec{x}, t) \]  
Structure

Relativistic Particles

\[ N_p(E, \vec{x}, t) \]
\[ N_A(E, \vec{x}, t) \]
\[ N_e(E, \vec{x}, t) \]
\[ E_\gamma \geq 100 \text{ MeV} \] Gamma Ray Sky

Fermi two-year all-sky map

Credit: NASA/DOE/Fermi/LAT Collaboration
50% of flux +/- 5 degrees around equator

energy range 200 MeV to 100 GeV

Diffuse Emission

Fermi–LAT counts

Galactic coordinates

Cosmic Ray interactions in the Interstellar Medium
3rd FERMI Catalog

3034 sources

E > 100 MeV
TeV Sky 170 → 200 Sources

blue-to-red colors – > 0.1 GeV – Fermi gamma-ray sky
HESS survey of Galactic Plane
[ICRC 2015] 77 “firm identifications”
Extraordinary beasts in the sky
Gravitational Waves Studies
Entering a new exciting era with LIGO/VIRGO
Sources are transients
[with a variety of time scales
from a small fraction of a second to thousands of years]

Associated to Compact Objects
Neutron stars,
Black Holes (stellar and Supermassive)

FORMATION of Compact Objects
(very large acceleration of very large masses)

Natural connection to Gravitational Waves
Sources are transients
[with a variety of time scales
from a small fraction of a second to thousands of years]

Associated to Compact Objects
Neutron stars,
Black Holes (stellar and Supermassive)

FORMATION of Compact Objects
(very large acceleration of very large masses)

Natural connection to Gravitational Waves
The SUN: small scale laboratory: Solar Flare

7th March 2011. 20:02 UT
Binary Pulsars (PSR 1913+16) (discovery Hulse & Taylor (1978) (Nobel prize 1993) [Pulsar 17 rotation/second]

Orbit: 1.1 - 4.8 solar radii
Rotation period 7.75 hours
Period shorter
76.5 microsecond/year

300 Myr
two neutron star coalesce

Orbit smaller
3.5 m/year
“Analogy”

On a very different scale ...... GW 170817
GRB 170817A

GW 170817
Figure 8. Spectral fits of the count rate spectrum for the (left) main pulse (Comptonized) and (right) softer emission (blackbody). The blue bins are the forward-folded model fit to the count rate spectrum, the data points are colored based on the detector, and 2σ upper limits estimated from the model variance are shown as downward-pointing arrows. The residuals are shown in the lower subpanels.
Figure 1 | Optical/infrared and X-ray images of the counterpart of GW170817. a, Hubble Space Telescope observations show a bright and red transient in the early-type galaxy NGC 4993, at a projected physical offset of about 2 kpc from its nucleus. A similar small offset is observed in less than a quarter of short GRBs\(^5\). Dust lanes are visible in the inner regions, suggestive of a past merger activity (see Methods). b, Chandra observations revealed a faint X-ray source at the position of the optical/infrared transient. X-ray emission from the galaxy nucleus is also visible.
Victor Hess
before the balloon flight of 1912

Cosmic Rays
Discovery of Cosmic Rays
beginning of
High Energy Astrophysics
Observations at the beginning of 1900

Discharge of electroscopes

Why electroscopes are discharged?
Existence of IONIZING RADIATION

From where the ionization radiation is coming?
Radioactivity is the natural explanation.

1896 Bequerel discovers radioactivity in Uranium
1898 - 1900 Pierre and Marie Curie, E Rutherford ...
Relativistic charged particles.  [Latitude effect]

Mostly protons (+ ionized nuclei)  [East-West effect]
FIG. 1. Map showing location of our major stations for observing cosmic rays.
Fig. 5. Typical intensity vs. altitude curves for various latitudes.
A Geographic Study of Cosmic Rays

Arthur H. Compton, University of Chicago
(Received January 30, 1933)

LATITUDE EFFECT

Fig. 6. Intensity vs. geomagnetic latitude for different elevations.
Arthur Compton

Luis Alvarez

East-West effect
East-West Effect

More positive particles going East-ward
Relativistic charged particles. [Latitude effect]

Mostly protons (+ ionized nuclei) [East-West effect]

- 99% nuclei
- 1% electrons
- 1% Nuclei $Z > 2$
- 10% Helium
- 89% protons

Small quantities: positrons + anti-protons
ELECTRONS and POSITRONS
\[ \pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm \]

(1947) Powell, Occhialini and Lattes
\[
\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \\
\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \\
\pi^0 \rightarrow \gamma + \gamma
\]
Cloud Chamber Observations of Cosmic Rays at 4300 Meters Elevation and Near Sea-Level

Carl D. Anderson and Seth H. Neddermeyer, Norman Bridge Laboratory of Physics, California Institute of Technology

(Received June 9, 1936)
Hadronic Interactions

\[ p + ^{14}_N \rightarrow \pi^+ , \pi^- , \pi^0 , \ldots \]

\[ p , n , \bar{p} , \bar{n} \]

\[ K^+ , K^- , K^0 , \bar{K}^0 , \ldots \]
Extraordinary energy (!)

$(10^{15}, 10^{16}\text{ eV})$ now: $10^{20}\text{ eV}$

Pierre Auger

Phys. Rev. 1939

[Extensive Air Showers]
Acceleration of Cosmic Rays

[electrically charged particles]
Emission of Cosmic Rays from the Sources requires "escape"
COSMIC RAYS

Space and time integrated average of particles generated by many sources in the Galaxy and in the universe, also shaped by propagation effects.

Measurement at single point, and (effectively) single time.

[slow time variations, geological record carries some information]
MILKY WAY

Solar system

High energy sources
ExtraGalactic Space

Milky Way
ExtraGalactic Space

Milky Way
"Bubble" of cosmic rays generated in the Milky Way and contained by the Galaxy magnetic field.

Space extension and properties of this "CR bubble" remain very uncertain.
$E_\gamma \geq 100$ MeV  

Fermi two-year all-sky map

Credit: NASA/DOE/Fermi/LAT Collaboration
Diffuse Emission

Fermi–LAT counts
Galactic coordinates

Cosmic Ray interactions in the Interstellar Medium

50% of flux ± 5 degrees around equator

[Galactic gas]

energy range 200 MeV to 100 GeV
Galactic Cosmic Rays

\[ N_j(E) = Q_j(E) \times T_j(E) \]

Different particles:
- \( p, \) nuclei(\( Z, A \))
- \( \bar{p}, \ e^- \), \( e^+ \)

Injection of cosmic rays
Containment time

\[ N_j(E) = \int d^3x \ n_j(E, \vec{x}) \]

\[ \phi_j(E) = \frac{c}{4\pi} n_j(E) \]
Determination of the “confinement time” $T(p/Z)$

“Cosmic clock” (Beryllium-10)

$T_{1/2} \left[ ^{10}\text{Be} \right] = 1.39 \times 10^6$ years

$T \simeq 10$ Myr
Nuclear Fragmentation (collisions with the Inter Stellar Medium)

Composition compatible with a solar-like source, with secondary nuclei...

GCR

Solar system

relative abundance

Z (charge number)

NUCLEAR CHARGE NUMBER

Nuclear fragmentation at rest

proton

v
Column density

\[ X(E) = \langle \rho \rangle \ T(E) \]

Escape faster at higher E

\[ X(E) \propto E^{-\delta} \]

\[ \delta \simeq 0.4 \div 0.6 \]

\[ \frac{\langle \rho \rangle}{m_p} \simeq 0.2 \ \text{cm}^{-3} \]

(extended halo)
\[ N_j(E) = Q_j(E) \times T_j(E) \]

\[ L_j = \int dE \ E \ Q_j(E) \]

\[ L_{cr}(\text{Milky Way}) \approx 2 \times 10^{41} \ \text{erg/s} \]

\[ \approx 5 \times 10^7 \ L_\odot \]
The SuperNova “Paradigm” for CR acceleration

Energetics, Dynamics

CAS A
(1667)
Trinity Test  (1945)
“Fireball” of an Supernova explosion

Interstellar Gas

Strong Shock

Fermi 1\textsuperscript{st} order acceleration

\[ q(E) \propto E^{-(2+\varepsilon)} \]
Power Provided by SN is sufficient with a conversion efficiency of 15-20% in relativistic particles.
Diffusion approximation

Maximum energy for containment

\[ r_L = \frac{1.08 \text{ Kpc}}{Z} \left[ \frac{E}{10^{18} \text{ eV}} \right] \left[ \frac{\mu\text{Gauss}}{B} \right] \]

- \( r_{L_{\text{Larmor}}}(100 \text{ GeV}) \approx 3.6 \times 10^{-8} \text{ Kpc} \)
- \( r_{L_{\text{Larmor}}}(10^{20} \text{ eV}) \approx 36 \text{ Kpc} \)
- \( r_{\text{Fe}_{\text{Larmor}}}(10^{20} \text{ eV}) \approx 1.4 \text{ Kpc} \)
Fermi Acceleration
COSMIC RAY ACCELERATION

Very important paper of Enrico Fermi (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 magnetic 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.

The theory originally proposed by Fermi is NOT correct. But this work contains a fundamental idea that it is believed to be valid for cosmic ray acceleration.
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 magnetic 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.

A theory of the origin of the Cosmic Rays is proposed according to which cosmic rays are accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields [moving “clouds”]

One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays
FERMI ORIGINAL MODEL:

- General structure:

  Single acceleration event:
  Particle with Energy \( E \)
  in the event it gains an energy proportional to \( E \)

  \[ \Delta E = \xi E \]

- The events are iterated with probability \( 1-P \)
  The iteration is stopped with probability \( P \)

Two parameters \( \xi \) \( P \)
Problem:
We have a number $N$ of particles all with the Energy $E_0$ inside an “accelerator”. At regular intervals the particles acquire an energy $\Delta E = \xi E$, but with probability $P$ the particle will exit the accelerators, and the acceleration process stops.

What is the energy Spectrum of the particles that exit from the accelerator:

$$\Delta E = \xi E$$

$$E \rightarrow E (1 + \xi) \rightarrow E (1 + \xi) (1 + \xi) \rightarrow \ldots$$
\[ N \quad E_0 \]

[Image: Diagram of an accelerator with the notation \( dN_{out} \) and \( dE \) at the output.]
$E_0$

$E_1 = E_0 (1 + \xi)$

$E_2 = E_0 (1 + \xi)^2$

\[ \ldots \]

$E_k = E_0 (1 + \xi)^k$

The Probability to have energy $E_k$ is the probability of having received the acceleration exactly $k$ times:

$$P_k = (1 - P)(1 - P) \ldots (1 - P) P$$

$$= (1 - P)^k P$$
\[ E_k = E_0 (1 + \xi)^k \]

\[ n_k = N \quad P_k = N_0 \quad P(1 - P)^k \]

\[ k = \log_{1+\xi} \left[ \frac{E_k}{E_0} \right] = \frac{\ln\left( \frac{E_k}{E_0} \right)}{\ln(1 + \xi)} \]
\[ n_k \equiv n(E_k) = N_0 \ P \ (1 - P)^k \]

\[ = N_0 \ P \ (1 - P)^\frac{\ln(E_k/E_0)}{\ln(1+\xi)} \]

\[ = N_0 \ P \ \exp \left[ \frac{\ln(1 - P) \ \ln(E_k/E_0)}{\ln(1 + \xi)} \right] \]

\[ = N_0 \ P \ \left( \frac{E_k}{E_0} \right)^\frac{\ln(1-P)}{\ln(1+\xi)} \]
\[ n(E_k) = N_0 \, P \, \left( \frac{E_k}{E_0} \right)^{\frac{\ln(1-P)}{\ln(1+\xi)}} \]

\[ \frac{dn}{dE} \approx \frac{n(E_k)}{\Delta E_k} \propto E^{\frac{\ln(1-P)}{\ln(1+\xi)} - 1} \]

\[ \frac{dn(E)}{dE} \propto E^{-(\gamma+1)} \]
\[ n(E_k) = N_0 \, P \left( \frac{E_k}{E_0} \right)^{\frac{\ln(1-P)}{\ln(1+\xi)}} \]

\[ \frac{dn}{dE} \simeq \frac{n(E_k)}{\Delta E_k} \propto E^{\frac{\ln(1-P)}{\ln(1+\xi)} - 1} \]

\[ n(> E) \propto E^{-\gamma} \]

\[ \frac{dn(E)}{dE} \propto E^{-(\gamma + 1)} \]

\[ \gamma = -\frac{\ln(1-P)}{\ln(1+\xi)} \simeq \frac{P}{\xi} \]

Discrete Spectrum of the toy model

Differential Spectrum slope \( \alpha = \gamma + 1 \)

Integral Spectrum slope \( \gamma \)

\[ \ln(1+x) \simeq x + \frac{x^2}{2} - \frac{x^3}{3} + \ldots \]

\[ \ln(1-P) \simeq -P + \ldots \]

\[ \ln(1+\xi) \simeq \xi + \ldots \]
Collisions with a macroscopic Object moving with velocity $v$
Elastic scattering of a particle  

Wall at rest.
Elastic scattering: the particle is accelerated!

Moving Racket (velocity $V$)
Why the final velocity is $v_{\text{ball}} + 2 V_{\text{racket}}$?

2 Galilean transformations

1. Go to frame where
   The racket is at rest.
   The ball in this frame has velocity:
   $v_{\text{ball}} + V_{\text{racket}}$

2. Transform back to the Original frame adding $V_{\text{racket}}$. The result is.

   $v_{\text{ball}} + 2 V_{\text{racket}}$
“Drop Shot” slow down the ball

Elastic scattering: the particle is decelerated.

Moving Racket (velocity \(-V\))
Collision with moving Plasma Clouds in the Galaxy
Scattering on Plasma Clouds
Elastic Scattering of a particle of mass \( m \) on a “moving WALL” with mass \( M \gg m \)

Problem : A Particle scatters on a moving wall (a moving MACROSCOPIC OBJECT \( M \gg m \))
The particle has initial Energy \( E_i \) and initial direction (with respect to the wall velocity) \( \theta_i \).

Compute the final state energy \( E_f \) as a function of \( \theta_f \) (the scattering angle).
In the system where the wall is at rest (indicated by *) the problem is of course trivial: \( E_f^* = E_i^* \).

\[
E_i^* = \gamma (E_i - \beta p_{z,i})
\]

\[
\geq \gamma E_i (1 - \beta \cos \theta_i)
\]

\[
E_f = \gamma E_i^* (1 + \beta \cos \theta_f^*)
\]

\[
= \gamma^2 (1 - \beta \cos \theta_i)(1 + \beta \cos \theta_f^*) E_i
\]
\[ \langle E_f \rangle = E_i \gamma^2 (1 - \beta \langle \cos \theta_i \rangle) (1 + \beta \langle \cos \theta_f^* \rangle) \]

\[ \langle \cos \theta_f^* \rangle = 0 \]

The computation of \( \langle \cos \theta_i \rangle \) is a little more difficult, but it is obvious that “front” encounters are more likely that “back” encounters and therefore \( \langle \cos \theta_i \rangle < 0 \). In fact the probability of \( \theta_i \) is proportional to the relative velocity between the particle and the cloud.
\[ v_{\text{rel}} = |\vec{v}_{\text{cloud}} - \vec{v}_{\text{particle}}| \]

\[ = \sqrt{(c - v \cos \theta_i)^2 + v^2 \sin^2 \theta_i} \]

\[ = c \sqrt{(1 - \beta \cos \theta_i)^2 + \beta^2 \sin^2 \theta_i} \]

\[ = c \sqrt{1 + \beta^2 - 2\beta \cos \theta_i} \]

\[ \approx c \sqrt{(1 - 2\beta \cos \theta_i)} \]

\[ \approx c (1 - \beta \cos \theta_i) \quad \beta \ll 1 \]
\[
\frac{dN}{d \cos \theta_i} \propto \nu_{\text{rel}} \propto (1 - \beta \cos \theta_i)
\]

\[
\langle \cos \theta_i \rangle = \frac{\int_{-1}^{+1} d \cos \theta_i \cos \theta_i (1 - \beta \cos \theta_i)}{\int_{-1}^{+1} d \cos \theta_i (1 - \beta \cos \theta_i)} = -\frac{\beta}{3}
\]
\[
\frac{\langle E_f \rangle}{E_i} = \gamma^2 \left( 1 - \beta \langle \cos \theta_i \rangle \right) \left( 1 + \beta \langle \cos \theta_f^* \rangle \right)
\]

\[
\simeq \gamma^2 \left( 1 - \beta \left( -\frac{\beta}{3} \right) \right) \left( 1 + \beta \times 0 \right)
\]

\[
\simeq \frac{1}{1 - \beta^2} \left( 1 + \frac{\beta^2}{3} \right)
\]

\[
\simeq (1 + \beta^2 + \ldots) \left( 1 + \frac{\beta^2}{3} \right)
\]

\[
\simeq 1 + \frac{4}{3} \beta^2 + \ldots
\]

\[
\frac{\langle E_f \rangle}{E_i} \simeq 1 + \frac{4}{3} \beta^2 + \ldots
\]
In the original form of the Fermi acceleration, the accelerator is the entire Galaxy and therefore the probability $P_{\text{esc}}$ to “exit” from the accelerator is simply the probability to exit from the galaxy between one encounter with a cloud and the next or:

$$P_{\text{esc}} \sim \frac{(\Delta t)_{\text{encounters}}}{T_{\text{conf}}}$$

$$\Delta t \sim \left[n_{\text{clouds}} \left(\pi r_{\text{cloud}}^2\right) c\right]^{-1}$$

$$\gamma = \frac{P_{\text{esc}}}{\xi} \sim \frac{\Delta t/T_{\text{conf}}}{4/3 \beta^2}$$
\[ \beta \sim 10^{-4} \]
\[ T_{\text{conf}} \sim 10^7 \text{ years} \sim 10^{15} \text{ sec} \]
\[ \Delta t \sim 10^8 \text{ sec} \]

\[ \gamma = \frac{P_{\text{esc}}}{\xi} \sim \frac{\Delta t / T_{\text{conf}}}{4/3 \beta^2} \]

\[ \gamma \sim 10 \]

Spectrum too soft
MODIFICATION of the original FERMI Model

ACCELERATION at SHOCK FRONTS

FERMI 1st ORDER ACCELERATION
SHOCK in a fluid

Surface of discontinuity in the thermodynamics quantities

(Density, Temperature, Velocity)
After the passage of the shock wave, the gas is compressed and accelerated to velocity $v$. The gas at rest is indicated by the red line.
\[ \rho_1, T_1, v_1 = 0 \]

Fluid element in the fluid before the shock arrives
Fluid element
After the shock has passed:

- Set in motion
- Compressed
- Heated

\( \rho_2, T_2, v_2 \)
Shock arrive with velocity \( V_{\text{shock}} \)

\[
\rho_1, \ T_1, \ v_1 = 0
\]

Compute the fluid properties after the shock:

\[
\rho_2, \ T_2, \ v_2
\]

\( V_{\text{shock}} > v_{\text{sound}} \)

\[
M = \frac{V_{\text{shock}}}{v_{\text{sound}}}
\]

\( M \gg 1 \) Strong shocks

Mach Number
Kinematics Relation at the Shock

Rankine Huguniot Relations

Conservation of MASS (number of Particles), MOMENTUM, ENERGY

\[ \rho_1 v_1 = \rho_2 v_2 \]

\[ \rho_1 v_1^2 + P_1 = \rho_2 v_2^2 + P_2 \]

\[ \frac{1}{2} v_1^2 + \frac{P_1 + U_1}{\rho_1} = \frac{1}{2} v_2^2 + \frac{P_2 + U_2}{\rho_2} \]
\[
\begin{align*}
  r &= \frac{\gamma - 1}{\gamma + 1} \\
  \gamma &= \frac{2}{f} + 1
\end{align*}
\]

\[
\begin{align*}
  \rho_2 &= r \rho_1 \\
  M &\gg 1 \\
  \nu_2 &= \frac{V_{\text{shock}}}{r} \\
  T &\approx m V_s^2 \frac{(r - 1)}{r^2}
\end{align*}
\]
\[ r = \frac{\gamma - 1}{\gamma + 1} \quad \text{and} \quad \gamma = \frac{2}{f} + 1 \]

\[ \rho_2 = r \rho_1 \]

\[ v_2 = \frac{V_{\text{shock}}}{r} \]

\[ T \approx m \left( \frac{V_s^2}{r^2} \right) \frac{(r - 1)}{r^2} \]\n
\[ M \gg 1 \quad \text{Monoatomic gas} \]

\[ \gamma = \frac{5}{3} \quad r = 4 \]
\[ r = \frac{\gamma - 1}{\gamma + 1} \quad \gamma = \frac{2}{f} + 1 \]

\[ \rho_2 = r \rho_1 \]

\[ v_2 = \frac{V_{\text{shock}}}{r} \]

\[ T \approx m V_{s}^2 \frac{(r - 1)}{r^2} \]

\[ M \gg 1 \]

Biatomic gas

\[ \gamma = \frac{7}{5} \quad r = 6 \]
Unshocked material at rest

Piston

Shock Front

\( \rho_1 \)

\( v_1 = 0 \)

\( T_1 \)
**Strong Shock**

Unshocked material at rest

\[
\rho_2 = 4 \rho_1 \\
v_2 = v_{\text{piston}} \\
T_2 \gg T_1
\]

\[
v_{\text{shock}} = \frac{4}{3} v_{\text{piston}}
\]

\[
\rho_1 \\
v_1 = 0 \\
T_1
\]

**Compressed Material**

\[
r \rightarrow \frac{\gamma + 1}{\gamma - 1} = 4
\]
STRONG SHOCK

\[ \rho_2 = 4 \rho_1 \]

\[ v_2 = \frac{1}{4} v_1 \]

\[ T_2 \gg T_1 \]

Shock Rest Frame

\[ \rho_1 \]

\[ v_1 \]

\[ T_1 \]

Shocked material

Unshocked material
shocked material
More dense
Higher Temperature

Unshocked material
Fluid at Rest

$v < v_{\text{shock}}$

Shock Discontinuity
shocked material
More dense
Higher Temperature

\[ v < v_{\text{shock}} \]

\[ v_2 \]

Shock Rest Frame

Unshocked material

Upstream

\[ v_1 \]
Shock Discontinuity

Increase in energy Per double crossing

\[ \left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3} \beta_{\text{gas}} \]
Shock Discontinuity

$\langle \frac{\Delta E}{E} \rangle = \frac{4}{3} \beta_{\text{gas}}$

Increase in energy Per double crossing

$P_{\text{escape}} = \beta_{\text{shock}}$
\[ \alpha = 1 + \frac{P_{\text{esc}}}{\xi} \]

\[ \alpha = 1 + \frac{\beta_{\text{shock}}}{\frac{4}{3} \beta_{\text{gas}}} \]

\[ \alpha = 2 + \epsilon \]

Universal Spectral shape!
Demonstration that: \( \left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3} \beta_{\text{gas}} \)

\[
E_f = \gamma^2 \left[ 1 - \beta \cos \theta_i \right] \left[ 1 + \beta \cos \theta_f^* \right]
\]

\(-1 \leq \cos \theta_i \leq 0\)

\(0 \leq \cos \theta_f^* \leq 1\)

\[
\frac{dN}{d \cos \theta_i} \propto \cos \theta_i
\]

\[
\frac{dN}{d \cos \theta_f^*} \propto \cos \theta_f^*
\]
\[
\phi_{in} = n \ c \ \int_{-1}^{\beta} \frac{d \cos \theta}{2} \left[ -\cos \theta + \beta \right]
\]

\[
= \frac{n \ c}{2} \left[ -\frac{(\cos \theta)^2}{2} + \beta \cos \theta \right]_{-1}^{\beta}
\]

\[
= \frac{n \ c}{4} \left[ \frac{1 - \beta^2}{2} + \beta (1 + \beta) \right] = \frac{n \ c}{4} (1 + \beta)^2
\]
\[ \langle \cos \theta_i \rangle = \frac{\int_1^0 dz \, z \, z}{\int_1^0 dz \, z} = \frac{-1/3}{1/2} = -\frac{2}{3} \]

\[ \langle \cos \theta_f^* \rangle = \frac{\int_0^1 dz \, z \, z}{\int_0^1 dz \, z} = \frac{+1/3}{1/2} = +\frac{2}{3} \]

\[ \frac{E_f}{E_i} = \gamma^2 \left[ 1 - \beta \langle \cos \theta_i \rangle \right] \left[ 1 + \beta \langle \cos \theta_f^* \rangle \right] \]

\[ = \frac{1}{1 - \beta^2} \left( 1 + \beta \frac{2}{3} \right) \left( 1 + \beta \frac{2}{3} \right) \]

\[ \approx 1 + \frac{4}{3} \beta + O(\beta^2) \]
Demonstration \[ P_{\text{escape}} = \beta_{\text{shock}} \]

When a particle is on the “upstream” side of the shock, it will cross the shock with probability unity, however, when it is on the downstream side (shocked fluid region) it will have a finite probability \( P \) to be advected to the fluid without ever recrossing the shock.

To compute this probability we can consider a surface that moves at the same velocity of the shock in the down–stream region of the shock.

We can also assume that the relativisitc particles have a uniform density \( n \) and are isotropic in the rest frame of the shocked gas.

In the rest frame of the shocked gas the surface moves with velocity \( v = v_2 \).

The flux \( \phi_{\text{in}} \) that enters the surface corresponds to angles \( \theta \) (with respect to the velocity of the surface) corresponds to

\[
\phi_{\text{in}} \quad v_{\text{particle}} \leq v \\
cos \theta \leq v
\]

\[
\phi_{\text{out}} \quad v_{\text{particle}} \geq v \\
cos \theta \geq v
\]
\[ \phi_{\text{out}} = n c \int_{\beta}^{1} \frac{d \cos \theta}{2} \left[ \cos \theta - \beta \right] = \frac{n c}{4} (1 - \beta)^2 \]

\[ \frac{\phi_{\text{out}}}{\phi_{\text{in}}} = 1 - P_{\text{esc}} = \frac{(1 - \beta)^2}{(1 + \beta)^2} \simeq 1 - 4\beta \]

\[ P_{\text{esc}} = 4 \beta_2 = \beta_1 = \beta_{\text{shock}} \]
Fermi 2\textsuperscript{nd} order versus Fermi 1\textsuperscript{st} order
Fermi 1\textsuperscript{st} order
“shock in traffic”
"Fireball" of an Supernova explosion

Interstellar Gas

Strong Shock

Fermi 1st order acceleration

\[ q(E) \propto E^{-(2+\varepsilon)} \]
Power Provided by SN is sufficient with a conversion efficiency of 15-20% in relativistic particles.
Non accelerator sources of High Energy Particles

Dark Matter
(in form of WIMP's self annihilation or decay)

Super Massive Particles
[Very High mass scales ($M_{GUT}$, ...)]

Production of high energy particles of all types $\gamma, \nu, e^+, e^-, p, \ldots$
DARK MATTER

Dynamical evidence
Nature
Dynamical Evidence for Dark Matter

- Galaxies
- Clusters of Galaxies
- The entire Universe

The Dark Matter is “non baryonic” an “exotic” substance

A field that is not contained in the Standard Model of Particle Physics [!!]
COMA Galaxy Cluster

Optical
Fritz Zwicky 1933
First argument for Dark Matter
Virial theorem

X-ray
[hot gas confined by deep gravitational well]
Most of the baryonic mass in a Galaxy cluster resides in a hot (temperature $T \sim$ few KeV) intergalactic gas in hydrostatic equilibrium.
Keplerian circular motion:

\[
\frac{GM}{r^2} = \frac{v^2}{r}
\]

\[
v_{\text{rot}} = \sqrt{\frac{GM}{r}}
\]
Spiral galaxy NGC 3198 overlaid with hydrogen column density [21 cm] 

Expected from luminous Matter in the disk

Extra "invisible" component
M31: ANDROMEDA
Figure 1: The rotation curve of M31 by Roberts & Whitehurst (1975). The filled triangles show the optical data from Rubin & Ford (1970), the filled circles show the 21-cm measurements made with the 300-ft radio telescope (reproduced by permission of the AAS and the author).
\[ \rho_\odot \simeq 0.3 \frac{\text{GeV}}{\text{cm}^3} \]
Discovery of the Expansion of the Universe.

Velocity of Galaxies.

Edwin Hubble (1923)
Rescaling of all distances.

\[ t \quad : \quad \text{Universal time} \]

\[ a(t) \quad : \quad \text{Scale function} \]

\[ t_0 \quad : \quad \text{present} \]

\[ a(t_0) = 1 \]

\[ \vec{R}_{ij}(t) = a(t) \vec{r}_{jk} \]
Expansion and Redshift

\[ \lambda_{\text{emission}} \quad t \]

\[ \lambda_{\text{observed}} = \lambda_{\text{emission}} \frac{a(t_0)}{a(t)} \]

\[ \lambda_{\text{observed}} = \lambda_{\text{emission}} \frac{1}{a(t)} \]

\[ \lambda_{\text{observed}} = \lambda_{\text{emission}} (1 + z) \]

- Photon emitted at time \( t \)
- Wavelength "stretched" by the expansion
- \( p \approx \frac{1}{\lambda} \) all particles
- Definition of redshift \( z \)
- Relation between Redshift \( z \) and scale \( a(t) \)
Dynamics of the expansion:

\[
\left( \frac{da(t)}{dt} \right)^2 = \frac{8 \pi G \rho(t)}{3} a^2(t) - K
\]

Friedmann's equation.

[obtained from Einstein equations of General Relativity]

Constant \( K \)
Geometry of Space

\[
K = \frac{c^2}{R_0^2}
\]

\( K > 0 \)

\( K < 0 \)

\( K = 0 \)
Derivation from elementary Newtonian dynamics
[wrong motivation, but right answer]:

Spherical symmetry:
choose an arbitrary center point.
Energy = Kinetic + Potential

\[
\frac{1}{2} m \left( \frac{dr}{dt} \right)^2 - \frac{G M(r) m}{r} = E
\]

\[
M(r) = \frac{4\pi}{3} \rho(t) r^3
\]

\[
r = R_0 a(t)
\]

\[
K = \frac{2 E}{m R_0^2}
\]
\[
\left[ \frac{da(t)}{dt} \right]^2 = \frac{8 \pi G \rho(t)}{3} a^2(t) - K
\]

Substitute: \( t = t_0 \)

\[
H_0^2 = \frac{8 \pi G \rho_0}{3} - K
\]

\( K = 0 \)  \( \implies \rho_0 = \rho_{\text{critical}} = \frac{3 H_0^2}{8 \pi G} \)

Flat space
\[
1 = \frac{8\pi G \rho_0}{3 \, H_0^2} - \frac{c^2}{R_0^2 \, H_0^2}
\]

\[
1 = \frac{\rho_0}{\rho_c} - \frac{c^2}{R_0^2 \, H_0^2}
\]

\[\Omega_k = -\frac{c^2}{R_0^2 \, H_0^2}\]

Curvature term

Geometry defined by \( \Omega_0 \)
\[ \Omega_0 = \frac{\rho_0}{\rho_c} \]

- \( \Omega_0 > 1 \)
- \( \Omega_0 < 1 \)
- \( \Omega_0 = 1 \)
\[
\left[ \frac{da(t)}{dt} \right]^2 = \frac{8 \pi G \rho(t)}{3} a^2(t) - K
\]

\[\rho_0 = \rho_{\text{matter}} + \rho_{\text{radiation}} + \rho_{\text{vacuum}}\]

\[\rho(t) = \frac{\rho_{\text{matter}}}{a^3(t)} + \frac{\rho_{\text{radiation}}}{a^4(t)} + \rho_{\text{vacuum}}\]

Particle conservation

Particle conservation + momentum redshift

.... the vacuum is the vacuum...
\[
\frac{1}{H_0^2} \left[ \frac{da(t)}{dt} \right]^2 = a^2(t) \left[ \frac{\Omega_m}{a^3(t)} + \frac{\Omega_r}{a^4(t)} + \Omega_\Lambda + \frac{\Omega_k}{a^2(t)} \right]
\]

\[1 = \Omega_{\text{mat}} + \Omega_{\text{rad}} + \Omega_\Lambda + \Omega_k\]

\[\Omega_m = 1\]
\[\Omega_\Lambda = 0\]
\[\Omega_m = 0.3\]
\[\Omega_\Lambda = 0.7\]

\[H_0 = 70.2 \pm 1.4 \text{ Km/s/Mpc}\]

\[t_0 = 13.76 \pm 0.11 \text{ Gyr}\]
SuperNovae Ia are a standard candle. 

(universal light curve) [dimming + broadening]
SUPERNOVAE (Ia) STUDIES

\[ \alpha(t) \leftrightarrow \ell(z) \]

SN1a as standard candles

light-curve timescale “stretch-factor” corrected

\[ M_B - 5 \log h/60 \]

Kim, et al. (1997)
Dark Energy 73%  
(Cosmological Constant)

Ordinary Matter 4%  
(of this only about 10% luminous)

Dark Matter 23%

Neutrinos 0.1% 2%
The Universe is FLAT!

\[ \Omega_b = 0.0458 \pm 0.0016 \]

\[ \Omega_{\text{cold}} = 0.229 \pm 0.015 \]

\[ \Omega_\Lambda = 0.725 \pm 0.016 \]

\[ \Omega_k = 1 - \Omega_{\text{total}} = -\frac{c^2}{H_0^2 R_0^2} \]

\[-0.0133 \leq \Omega_k \leq 0.0084 \]

\[ |R_0| > 37 \text{ Gpc} \]

The Universe is FLAT!
Mysteries of the DARK UNIVERSE

DARK MATTER:
Holds together galaxies and other large scale structures
[A new elementary particle ?]

DARK ENERGY:
Drives apart galaxies and other large scale structures
[The energy of vacuum itself ?]

\[ \ddot{a}(t) = -\frac{4\pi G}{3} \left[ \rho(t) + 3p(t) \right] a(t) \]
Vacuum Pressure

\[ E_1 = \rho_v V_1 \]

\[ E_2 = \rho_v V_2 \]

\[ \Delta E = \rho_{\text{vacuum}} \Delta V \]

\[ W = -p_{\text{vacuum}} \Delta V \quad \text{Need to “pull” the piston} \]

\[ \rho_{\text{vacuum}} = -p_{\text{vacuum}} \]
Harmonic oscillator

\[ E_n = \left( \frac{1}{2} + n \right) \hbar \omega \]

Electromagnetic field vacuum E

\[ \langle \text{energy} \rangle = \left\langle \frac{E^2 + B^2}{8\pi} \right\rangle = \sum_k \frac{\hbar \omega_k}{2} \to \infty \]

\[ F_{\text{Casimir}} = \frac{\pi^2 \hbar c}{240 d^4} A \approx 1.3 \times 10^{-7} \left( \frac{1 \mu \text{m}}{d} \right)^4 \left( \frac{A}{1 \text{ cm}^2} \right) \text{ Newton} \]

Hendrik Casimir (1909, 2000)
The DARK MATTER is “Non Baryonic”

Nucleosynthesis

Structure Formation
BigBang
Nucleo-synthesis
constraints
on ordinary
(“baryonic”) matter
Discovery of the 2.7 Kelvin Cosmic Microwave Background Radiation
By Penzias and Wilson (1965), [Nobel 1978]
The "Rosetta stone"
Of the Early Universe

Angular power spectrum, $C_l$

$T_1(\theta_1, \phi_1)$  $T_2(\theta_2, \phi_2)$

$\langle T_1 T_2 \rangle = \sum a_{lm} Y_{lm}(\theta, \phi)$

$\langle |a_{lm}|^2 \rangle^{1/2} \equiv C_l$
Flat Universe from CMBR Angular Fluctuations

Spergel et al. (WMAP Collaboration) 
astro-ph/0302209

\[ \ell_{\text{max}} \approx 200/\sqrt{\Omega_{\text{tot}}} \]

\[ \Omega_{\text{tot}} = 1.02 \pm 0.02 \]

Triangulation with acoustic peak

- flat (Euclidean)
- negative curvature
- positive curvature

Known physical size of acoustic peak at decoupling \((z \approx 1100)\) 
Measured angular size today \((z = 0)\)
Power-law index (tilt) 
\( n = 1.0, 1.1, 1.2 \)

Hubble constant 
\( H_0 = 50, 60, 70 \)

Total density 
\( \Omega_{\text{tot}} = 1.0, 0.5, 0.3 \)

Baryon density 
\( \Omega_B = 5, 7.5, 10 \times 10^{-3} \)

Physics Today 1997:11, 32
GRAVITATIONAL INSTABILITY

Smooth

Structured
Big Bang

Big Bang Plus Tiniest Fraction of a Second
(10^{-43})

Inflation

COBE Sky Map

Big Bang Plus 300,000 Years

Light From First Galaxies

Big Bang Plus 15 Billion Years
Distribution of Galaxies in the SKY (XMASS)
2dF Galaxy Redshift Survey
Current power spectrum $P(k) [(h^{-1} \text{ Mpc})^3]$

- Cosmic Microwave Background
- SDSS galaxies
- Cluster abundance
- Weak lensing
- Lyman Alpha Forest

Wavelength $\lambda$ [h$^{-1}$ Mpc]

Wavenumber $k$ [h/Mpc]

Tegmark & Zaldarriaga, astro-ph/0207047 + updates
**NEUTRINOS**

\[ \sum m_{\nu} \gtrsim 0.05 \text{ eV} \]

Oscillation studies

\[ \sum m_{\nu} \lesssim 1.3 \text{ eV} \]

Structure formation

\[ \Omega_{\nu} \approx 0.021 \sum m_{\nu} \text{ (eV)} \]

Too much neutrinos erase Large Scale structure

\[ n_{\nu} = 6 \times \left( \frac{3}{4} \frac{\zeta(3)}{\pi^2} \frac{4}{11} T_y^3 \right) \]

\[ n_{\nu} = 6 \times 56 \text{ cm}^{-3} \]

\[ 0.001 \lesssim \Omega_{\nu} \lesssim 0.02 \]
A MODIFICATION OF THE NEWTONIAN DYNAMICS AS A POSSIBLE ALTERNATIVE TO THE HIDDEN MASS HYPOTHESIS

M. MILGROM
Department of Physics, The Weizmann Institute of Science, Rehovot, Israel; and The Institute for Advanced Study
Received 1982 February 4; accepted 1982 December 28
Uranus orbital anomalies
Prediction + Discovery of Neptune (23/24 September 1846)

Urbain Le Verrier
John Couch Adams

Mercury orbital anomalies
Extra 43''/century perihelion precession

New dynamics
General Relativity
(1916 Albert Einstein)
MOnodified Newtonian Dynamics \textbf{[MOND]}

\[ F_{\text{grav}} = \begin{cases} \mathbf{ma} & \text{for} \quad a \gg a_0 \\ \mathbf{m} \frac{a^2}{a_0} & \text{for} \quad a \ll a_0 \end{cases} \]

\[ a_0 \simeq 10^{-8} \text{ cm/s}^2 \]

Fundamental acceleration

\( a_0 \simeq c H_0 / 5 \)

Coincidence?

\[ \frac{G M}{r^2} = \frac{v^2}{r} \quad \text{“Newtonian”} \]

\[ v_{\text{rot}}^2 \rightarrow GM/r \]

\[ \frac{G M}{r^2} = \left( \frac{v^2}{r} \right)^2 \frac{1}{a_0} \]

Modified Newtonian (small acceleration)

\[ v_{\text{rot}}^4 \rightarrow GM \ a_0 \]

\[ v_{\text{rot}} \propto M^{1/4} \propto L^{1/4} \]
J. D. Bekenstein,  
“Alternatives to dark matter: Modified gravity as an alternative to dark matter,” 

1. Introduction

A look at the other papers in this volume will show the present one to be singular. Dark matter is a prevalent paradigm. So why do we need to discuss alternatives? While observations seem to suggest that disk galaxies are embedded in giant halos of dark matter (DM), this is just an inference from accepted Newtonian gravitational theory. Thus if we are missing understanding about gravity on galactic scales, the mentioned inference may be deeply flawed. And then we must remember that, aside for some reports which always seem to contradict established bounds, DM is not seen directly. Finally, were we to put all our hope on the DM paradigm, we would be ignoring a great lesson from the history of science: accepted understanding of a phenomenon has usually come through confrontation of rather contrasting paradigms.
Theoretical Objections: “Phenomenology, Not Theory”

Mordehai Milgrom (SciAmi August 2002).

Successful as it may be, MOND is, at the moment, a limited phenomenological theory. By phenomenological, I mean that it has not been motivated by, and is not constructed on, fundamental principles. It was born from a direct need to describe and explain a body of observations, much as quantum mechanics (and, indeed, the concept of dark matter) developed. And MOND is limited, because it cannot be applied to all the relevant phenomena at hand. [Cosmology, Structure formation]

The main reason is that MOND has not been incorporated into a theory that obeys the principles of relativity, either special or general. Perhaps it is impossible to do so; perhaps it is simply a matter of time.

After all it took many years for the quantum idea, as put forth by Max Planck, Einstein and Niels Bohr, to be encapsulated into the Schrödinger equation, and more time still to be made compatible with special relativity. Even today, despite long, concentrated efforts, theorists have not made quantum physics compatible with general relativity.
Theoretical Objections: “Phenomenology, Not Theory”

Mordehai Milgrom (SciAmi August 2002).

Successful as it may be, MOND is, at the moment, a limited phenomenological theory. By phenomenological, I mean that it has not been motivated by, and is not constructed on, fundamental principles. It was born from a direct need to describe and explain a body of observations, much as quantum mechanics (and, indeed, the concept of dark matter) developed. And MOND is limited, because it cannot be applied to all the relevant phenomena at hand. [Cosmology, Structure formation]

The main reason is that MOND has not been incorporated into a theory that obeys the principles of relativity, either special or general. Perhaps it is impossible to do so; perhaps it is simply a matter of time.

Recent Development of a covariant relativistic theory

Why is “DARK MATTER” the “prevalent paradigm”

1. Theoretical Difficulties in constructing a consistent, covariant theory.

2. Remarkable success of the “Dark Matter” paradigm in describing the structure formation in our universe. Relation between the Large scale galaxy distribution. Anisotropies in the Cosmic Background Radiation.

3. The “BULLET CLUSTER” (Cluster 1E0657-558: 2 colliding clusters at z=0.296) Clear separation between Baryons and Mass. [other similar objects discovered (MACS J0025.4-1222)]

Bullet CLUSTER (2 colliding clusters)
MASS DISTRIBUTION
(from gravitational lensing)
X-RAY Emission
(gas of ordinary matter)
In recent years a lot of attention has been given to the “train wreck cluster” [Abell 520] \( (z=0.21) \).

A “counter example” to the Bullet cluster.
DARK MATTER: we know a lot:

It exists (no modified gravity for the bullet cluster)

Good estimate of the cosmological average (~23%)

Most of it is non baryonic

Most of it is “cold”

It cannot be explained by the Standard Model in Particle Physics!
What is the Dark Matter?
Artists and Dark Matter

Cold Dark Matter
(Tate Gallery, London)

Cornelia Parker
What is the Dark Matter?

Possible theoretical ideas

Thermal Relic

Axion

Super-massive particles

Discuss only this idea
[perhaps the best motivated]
[offers the best chances of discovery]
Early Universe was HOT

[Adiabatic Compression Of a fluid]

“COSMIC SOUP”

\[ a + b \leftrightarrow c + d \]
Thermal equilibrium Distribution

\[ \frac{dN_j}{d^3x \, d^3p} = \frac{g_j}{(2\pi \hbar c)^3} \frac{1}{e^{E/T} \mp 1} \]

Boson

\[ n_j = n_{-j} \]

\[ n_j \neq n_{-j} \]

\[ \frac{dN_j}{d^3x \, d^3p} = \frac{g_j}{(2\pi \hbar c)^3} \frac{1}{e^{(E-\mu_j)/T} \mp 1} \]

fermion
\[ n(T) = \int d^3p \frac{dN}{d^3x \, d^3p} \]

\[ \rho(T) = \int d^3p \, E(p) \frac{dN}{d^3x \, d^3p} \]

High Temperature

\[ T \gg m_\chi \]

\[ n_{\text{boson}}(T) = g \frac{\zeta(3)}{\pi^2} T^3 \]

\[ n_{\text{fermion}}(T) = g \frac{\zeta(3)}{\pi^2} T^3 \times \frac{3}{4} \]

\[ \rho_{\text{boson}}(T) = g \frac{\pi^2}{30} T^4 \]

\[ \rho_{\text{fermion}}(T) = g \frac{\pi^2}{30} T^4 \times \frac{7}{8} \]
\[ n(T) = g \frac{e^{-m/T} (m T)^{3/2}}{2\sqrt{2} \pi^{3/2}} \]

\[ m < T \]

\[ \chi + \overline{\chi} \rightarrow q + \overline{q} \]
\[ \chi + \overline{\chi} \rightarrow g + g \]
\[ \chi + \overline{\chi} \rightarrow \gamma + \gamma \]
Annihilation cross section
Determines the "relic abundance"

\[ \Omega_j^0 \simeq 0.3 \left[ \frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma v \rangle} \right] \]

\[ \chi + \chi \leftrightarrow f + \bar{f} \]

\[ \chi + \chi \rightarrow f + \bar{f} \]
Particle anti-particle annihilation and the "Relic Density"

[Pedagogical discussion]

"box" of constant volume.

Equal distributions for particle and anti-particle

\[ dP_{\text{distruction}} = n_\chi \, \langle \sigma_{\chi\chi \rightarrow \text{anything}} \, v \rangle \, dt \]

Probability of disappearance per unit time

\[ \langle \sigma \, v \rangle = \int d^3v_1 \int d^3v_2 \, f_\chi(\vec{v}_1) \, f_\chi(\vec{v}_2) \, \sigma(|\vec{v}_1 - \vec{v}_2|) \, |\vec{v}_1 - \vec{v}_2| \]

Velocity averaged cross section

[in many cases \( \sigma(v) \, v = \text{constant} \)]
Particle anti-particle annihilation and the "Relic Density"

[Pedagogical discussion]
“box” of constant volume. Equal distributions for particle and anti-particle

\[ dP_{\text{disruption}} = n_\chi \langle \sigma_{\chi\chi\rightarrow\text{anything}} \nu \rangle \, dt \]

Probability of disappearance per unit time

\[ \langle \sigma \nu \rangle = \int d^3v_1 \, \int d^3v_2 \, f_\chi(\vec{v}_1) \, f_\chi(\vec{v}_2) \, \sigma(|\vec{v}_1 - \vec{v}_2|) \, |\vec{v}_1 - \vec{v}_2| \]

Velocity averaged cross section
[in many cases \( \sigma(\nu) \nu = \text{constant} \)]

\[ dn_\chi = -n_\chi \, dP_{\text{dist}} = -n^2_\chi \, \langle \sigma \nu \rangle \, dt \]

Evolution of the Particle density
\[
\frac{dn(t)}{dt} = -n^2(t) \langle \sigma v \rangle
\]

Time evolution of the density

Initial condition

\[
n(t_i) = n_i
\]

\[
\frac{dn}{n^2} = -\langle \sigma v \rangle \, dt
\]

Solution

\[
n(t) = \frac{n_i}{1 + n_i \langle \sigma v \rangle (t - t_i)}
\]

\[
\lim_{t \to \infty} n(t) = 0
\]

All particles annihilate.
Annihilation in an Expanding Universe

\[ n_{\text{comoving}} = n(t) a^3(t) \]
\[
\frac{d[n(t) a^3(t)]}{dt} = -n^2(t) a^3(t) \langle \sigma v \rangle
\]

Evolution equation for the comoving density

\[
n(t) a^3(t) = \frac{n_i a_i^3}{1 + n_i a_i^3 \langle \sigma v \rangle \int_{t_i}^{t} dt \ a(t)^{-3}}
\]

Solution

\[
(t - t_i) \rightarrow a^3(t_i) \int_{t_i}^{t} \frac{dt}{a(t)^3}
\]

Difference with respect to the case of constant volume
\[
\frac{d[n(t) a^3(t)]}{dt} = -n(t)^2 a^3(t) \langle \sigma v \rangle
\]

Evolution equation for the comoving density

\[
n(t) a^3(t) = \frac{n_i a_i^3}{1 + n_i a_i^3 \langle \sigma v \rangle \int_{t_i}^{t} dt \ [a(t)]^{-3}}
\]

Solution

\[
(t - t_i) \rightarrow a^3(t_i) \left( \int_{t_i}^{t} \frac{dt}{a(t)^3} \right)
\]

Difference with Respect to the case of constant volume

Possible convergent integral
For \( t \to \infty \) Finite relic density
\[ T(t) \propto \frac{1}{a(t)} \]

\[ T(t) \propto t^{-1/2} \]

\[ a(t) \propto t^{1/2} \]

\[ T^2(t) = \frac{K}{t} \]

\[ K = \left[ \frac{32}{3} G \left( \frac{\pi^2}{30 \hbar^3 c^5} \right) g^* \right]^{-1} \]

\[ g^* = N_{\text{bosons}} + \frac{1}{8} N_{\text{fermions}} \]

\[ a_i^3 \int_{t(M)}^{\infty} \frac{dt}{a^3(t)} = a_i^3 \int_{M}^{0} dT' \frac{dt}{dT} \frac{1}{a^3(T)} = \frac{2K}{m^2} \]

\[ \left[ n(t) a^3(t) \right]_{\text{asymptotic}} = \frac{n_i a_i^3}{1 + n_i \langle \sigma v \rangle} \frac{2K}{m^2} \]
Relation between time and temperature during the nucleosynthesis “the first three minutes”

\[ T^2(t) = \frac{K}{t} \]
Extrapolation to early time

\[ T^2(t) = \frac{K}{t} \]
Language of “freeze-out”

There is a time when the dark matter particles comoving density “freezes out”, remain constant.

\[ t_{\text{annihilation}} = \left( \langle \sigma v \rangle n_\chi \right)^{-1} \]

\[ t_{\text{expansion}} = \left[ \left( \frac{dL}{dt} / L \right) \right]^{-1} \]

\[ t_{\text{expansion}} = \left[ \frac{\dot{a}(t)}{a(t)} \right]^{-1} = 2t \]

\[ a(t) \propto \sqrt{t} \]

\[ t_{\text{annihilation}}(t^*) = t_{\text{expansion}}(t^*) \]

\[ t^* \equiv t_{\text{freeze}} \]

Annihilation stops.
\[ n_{\chi}^{\text{freeze}} \approx \frac{1}{\langle \sigma v \rangle 2t_{\text{freeze}}} \approx \frac{m_{\chi}^2}{\langle \sigma v \rangle 2K_g} \]

\[ n_{\chi}^{\text{today}} \approx n_{\chi}^{\text{freeze}} \frac{T_0^3}{m_{\chi}^3} \]

\[ = \frac{m_{\chi}^2}{\langle \sigma v \rangle 2K_g} \frac{T_0^3}{m_{\chi}^3} \]

\[ \rho_{\chi}^{\text{today}} \approx n_{\chi}^{\text{today}} m_{\chi} \approx \frac{T_0^3}{\langle \sigma v \rangle 2K_g} \]
\[
\rho_{\chi}^{\text{today}} \approx n_{\chi}^{\text{today}} \quad m_{\chi} \approx \frac{T_0^3}{\langle \sigma v \rangle \ 2K_g}
\]

\[
\rho_c = 3 \frac{H_0^2}{(8\pi G)}
\]

\[
\Omega_{\chi} \approx \left( \frac{16 \pi^{5/2}}{9 \sqrt{\pi}} \right) \frac{G^{3/2} \ T_0^3}{H_0^2 \ (\hbar c)^{3/2} \ c^3} \frac{\sqrt{g_{\text{eff}}}}{\langle \sigma v \rangle}
\]

\[
\Omega_{\chi}^{\text{analytic}} = 0.173 \left( \frac{3 \times 10^{-26} \ \text{cm}^3 \ \text{s}^{-1}}{\langle \sigma v \rangle_f} \right) \sqrt{\frac{g_{\text{eff}}}{106.75}}
\]
The "relic density" of a particle is determined by its annihilation cross section (several complications are possible).

\[
\Omega_j^0 \approx 0.3 \left[ \frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma v \rangle} \right]
\]

\[
\sigma(\chi\chi \to \text{anything}) \approx 10^{-36} \text{ cm}^2
\]

Weak interaction mass scale

\[
\sigma \approx \frac{\alpha^2}{M^2} (\hbar c)^2
\]

\[M \approx 200 \text{ GeV}\]
Weakly Interacting Massive Particles (WIMP's)

the WIMP's “miracle”

“Killing two birds with a single stone”

Dark Matter Puzzle

Direct observational problem

Theories Beyond the Standard Model (in particular Supersymmetry) predict new particles that have the right properties to form the DM

“Theoretical” motivation
Standard Model fields

fermions
quarks
leptons
neutrinos

bosons
photon
W
Z
gluons
Higgs
$H \ h$

2 Higgs
Weak (~100 GeV)
Mass scale ?

one stable
new particle
(R-parity conserved)

Super-symmetric extension

Squarks
Sleptons
Sneutrinos

New bosons (scalar)
spin 0 S....

New fermions
spin 1/2...ino

photino
Wino
Zino
gluinos
Higgsino
$\tilde{H} \ \tilde{h}$

$|\chi\rangle = c_1 \ |\tilde{\gamma}\rangle + c_2 \ |\tilde{\zeta}\rangle + c_3 \ |\tilde{H}\rangle + c_4 \ |\tilde{h}\rangle$
Three roads to the DM (WIMP) discovery

Efficient annihilation now (Indirect detection)

Efficient production now (Particle colliders)

Efficient scattering now (Direct detection)
\[ \chi + \chi \rightarrow q + \bar{q} \]

**Annihilation**

\[ q + \bar{q} \rightarrow \chi + \chi \]

**Creation**

\[ \chi + q \rightarrow \chi + q \]

**Elastic Crossing symmetry**
Overall view of the LHC experiments.
How do you see a Dark Matter (therefore invisible) particle?
Lowest mass, stable, (super-symmetric) Particle [LSP]

This particle interacts WEAKLY therefore (effectively always) traverse the detector invisibly.

Detection via 4-momentum conservation [“Missing energy and (transverse) momentum”]
“Direct” Search for Dark Matter

Elastic scattering

$$\chi + A \rightarrow \chi + A$$

Nucleus $A$ at rest
SUN – rotation around the galactic center.

\[ \nu_{\text{rotation}} \approx 200 \text{ Km/sec} \]
Predicted velocity distribution of DM particles
In the “Halo Frame”
Maxwellian form \( \langle v_{\text{wimp}} \rangle \approx 250 \text{ km/sec} \)
Velocity of Earth in the Halo rest frame

\[ \vec{w}_{\oplus}(t) = \vec{w}_\odot + \vec{v}_{\text{orbit}}(t) \]

\[ w_{\oplus}(t) \simeq w_\odot + \sin \gamma \, v_{\text{orbit}} \, \cos[\omega(t - t_0)] \]

“Halo rest frame”

[Co-rotation ?]
Velocity distribution in the Earth Frames

2nd June
2nd December
Expected flux of Dark Matter particles (here !):

\[ \phi_\chi = \frac{\rho_\chi}{m_\chi} \langle v_\chi \rangle \]

\[ \simeq 1000 \left[ \frac{100 \text{ GeV}}{m_\chi} \right] \text{(cm}^2 \text{ s)}^{-1} \]
"Direct" Search for Dark Matter

Non relativistic WIMP

\[ E_{\text{wimp}} \approx M_{\chi} + \frac{1}{2} M_{\chi} v^2 \]

\[ E_{\text{nucleus}} = M_A + \left[ \frac{1}{2} M_{\chi} v^2 \right] \frac{4 M_A M_{\chi}}{(M_A + M_{\chi})^2} \left( \frac{1 - \cos \theta^*}{2} \right) \]

\[ \chi + A \rightarrow \chi + A \]
\[ \frac{dR}{dE_{\text{recoil}}} (E_{\text{recoil}}, t) = R_0(E_{\text{recoil}}) + A(E_{\text{recoil}}) f(t) \]
DAMA-LIBRA (Gran Sasso underground Laboratory)

250 Kg NaI scintillator.

Observation of sinusoidal time-modulation of the Energy Deposition Rate

(controversial) claim of evidence of detection of Galactic Dark Matter

1.17 ton × yr
Period one year.
(... well obvious...)

“Phase”
Is centered
At the “right” value (!)

Maximum
The 2\textsuperscript{nd} june
day: \((146 \pm 7)\)

Fundamental discovery ?!

Unknown background
(with coincident phase) ?
First results from DAMA/LIBRA and the combined results with DAMA/NaI

Abstract

The highly radiopure $\simeq 250$ kg NaI(Tl) DAMA/LIBRA set-up is running at the Gran Sasso National Laboratory of the I.N.F.N.. In this paper the first result obtained by exploiting the model independent annual modulation signature for Dark Matter (DM) particles is presented. It refers to an exposure of 0.53 ton×yr. The collected DAMA/LIBRA data satisfy all the many peculiarities of the DM annual modulation signature. Neither systematic effects nor side reactions can account for the observed modulation amplitude and contemporaneously satisfy all the several requirements of this DM signature. Thus, the presence of Dark Matter particles in the galactic halo is supported also by DAMA/LIBRA and, considering the former DAMA/NaI and the present DAMA/LIBRA data all together (total exposure 0.82 ton×yr), the presence of Dark Matter particles in the galactic halo is supported at 8.2 $\sigma$ C.L..
New results from DAMA/LIBRA

Abstract

DAMA/LIBRA is running at the Gran Sasso National Laboratory of the I.N.F.N.. Here the results obtained with a further exposure of 0.34 ton × yr are presented. They refer to two further annual cycles collected one before and one after the first DAMA/LIBRA upgrade occurred on September/October 2008. The cumulative exposure with those previously released by the former DAMA/NaI and by DAMA/LIBRA is now 1.17 ton × yr, corresponding to 13 annual cycles. The data further confirm the model independent evidence of the presence of Dark Matter (DM) particles in the galactic halo on the basis of the DM annual modulation signature (8.9 σ C.L. for the cumulative exposure). In particular, with the cumulative exposure the modulation amplitude of the single-hit events in the (2 − 6) keV energy interval measured in NaI(Tl) target is (0.0116 ± 0.0013) cpd/kg/keV; the measured phase is (146 ± 7) days and the measured period is (0.999 ± 0.002) yr, values well in agreement with those expected for the DM particles.
$e^-/\gamma$: electronic recoil

n/WIMPs: nuclear recoil
Indirect searches for DARK MATTER in the Milky Way with DM halo
In the “WIMP paradigm” Dark Matter is NOT really dark point in the Milky Way with dark matter mass density

\[ \rho_{\chi}(\vec{x}) \]

Number density of DM particles

\[ n_{\chi}(\vec{x}) = \frac{\rho_{\chi}(\vec{x})}{m_{\chi}} \]

Release of energy

\[ (2m_{\chi}) \left[ \frac{1}{2} n_{\chi}^2(\vec{x}) \langle \sigma v \rangle \right] d^3x \, dt \]

[assume here DM particle is of Majorana nature \( \chi = \bar{\chi} \) ]
Density distribution determined by Rotation velocity measurements

“Cusp” at GC derived by N-body simulations

\[ \rho_{\text{isothermal}}(r) = \frac{\rho_s}{1 + (r/r_s)^2} \]

\[ \rho_{\text{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2} \]

\[ \rho_{\text{Einasto}}(r) = \rho_s \exp\left\{-(2/\alpha)[(r/r_s)^\alpha - 1]\right\} \]
Power generated by DM annihilations in the Milky Way halo

\[ L_{\text{DM}} \approx 3 \times 10^{37} \text{ erg s}^{-1} \left( \frac{\langle \sigma v \rangle}{3 \times 10^{-26} \text{ (cm}^3\text{s})^{-1}} \right) \left[ \frac{100 \text{ GeV}}{m_\chi} \right] \]

For comparison, for Cosmic Ray protons

\[ L_p \approx 10^{41} \frac{\text{erg}}{\text{s}} \]

small effect of “Cusp” on total luminosity
What is the final state of DM annihilations?

... well we do not know, we have to build a model (for example supersymmetry).

But it is plausible that the Dark Matter particle will (or could) produce all particles (and anti-particles) that we know.

Most promising for detection:

\[ \chi + \chi \rightarrow \gamma \quad e^+ \quad \bar{p} \quad \nu_\alpha \]

photons  Charged (anti)particles  Neutrinos
Photon emission from DM annihilation

\[ \phi_\gamma(E_\gamma, \Omega) = \frac{\langle \sigma v \rangle}{2 m_\chi^2} \left( \int d\ell \, \rho^2(\ell, \Omega) \right) \frac{dN_\gamma}{dE_\gamma} \bigg|_{\chi\chi \rightarrow \gamma} \]
No evidence for Dark Matter signal

1. Galactic Center

2. Dwarf Galaxies

3. Spectral lines

M. Ackermann et al. [Fermi-LAT Collaboration],
“The Fermi Galactic Center GeV Excess and Implications for Dark Matter,”

M. Ackermann et al. [Fermi-LAT Collaboration],
“Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data,”
Galactic Cosmic Ray Halo

Smaller CR density in the LMC and SMC
Charged particles: positrons and anti-protons

Trapped by the Galactic magnetic field

Extra contribution to the cosmic ray fluxes

Normal spectra for anti-proton/proton

Normal spectra $e^+/(e^- + e^+)$

Energy (GeV)
The “positron excess”: Evidence for DM or astrophysical effect?
Crucial ingredient: the MAGNET!

Flight data:
- 0.171 GV positron
- 0.169 GV electron
An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

“Positron Excess”!
Antiproton result

Agreement
With standard production mechanism
Cosmic Ray Spectra
AMS02

$\phi(E) E^{1.7} \text{ [GeV}^{1.7} \text{/(m}^2 \text{s sr)}]$

$E \text{ (GeV)}$

$p$ $e^-$ $e^+$ $\bar{p}$

$\gamma \times 10$

angle averaged diffuse Galactic gamma ray flux (Fermi)

CREAM p data
Do the positron and antiproton fluxes contain a DM component?

- Why the proton flux has its shape?
- Why the electron flux has its shape?
- Why the positron flux has its shape?
- Why the $\bar{p}$ flux has its shape?
Formation of the COSMIC RAYS spectra

Observable fluxes (directly at the Earth) <-> Propagation <-> Spectra released in interstellar space by the CR sources

\[ \phi_j(E, \vec{x}, t) \leftrightarrow q_j(E, \vec{x}, t) \]
“striking” qualitative features that “call out” for an explanation

4 spectra have approximately the same slope

[A] Proton and electron spectra are very different.
[a1] much smaller e- flux
[a2] much softer electron flux
[a3] evident “break” at 1 TeV in the (e^+ + e^-) spectrum

[B] positron and antiproton for (E > 30 GeV)
Have the same power law behavior
And differ by a factor 2 (of order unity)
Why? (for $E > 20-30$ GeV)

$$\gamma_{e^-} \approx \gamma_p + (0.41 \pm 0.02)$$

$$\gamma_{e^+} \approx \gamma\bar{p}$$

$$\gamma_{e^+} \approx \gamma\bar{p} \approx \gamma_p$$
Why?

(for E > 20-30 GeV)

\[ \gamma_{e^-} \approx \gamma_p + (0.41 \pm 0.02) \]

\[ \gamma_{e^+} \approx \gamma_{\bar{p}} \]

Is there a physical reason”, or it is “just a coincidence”?

\[ \gamma_{e^+} \approx \gamma_{\bar{p}} \approx \gamma_p \]
AMS02
FERMI-LAT
HESS
VERITAS
MAGIC

\( (e^+ + e^-) \)

very prominent spectral feature

**HESS fit**
\[ \gamma_1 \approx 3.0 \]
\[ \gamma_2 \approx 4.1 \]
\[ E_{\text{break}} = 900 \text{ GeV} \]

**MAGIC fit**
\[ \gamma_1 \approx 3.2 \pm 0.01 \]
\[ \gamma_2 \approx 4.1 \pm 0.01 \]
\[ E_{\text{break}} = 710 \pm 40 \text{ GeV} \]
New data release (ICRC-2017) by HESS
Publication of DAMPE (chinese satellite)
\textbf{proton versus electron spectra}

Standard explanation for the softer electron spectrum:

\[ \gamma_{e^{-}} \simeq \gamma_{p} + (0.41 \pm 0.02) \]

Astrophysical Accelerators generate identical spectra of electrons and protons (when ultra-relativistic) [Injection in the acceleration mechanism is mass dependent. Therefore different normalizations]

\textbf{Propagation effect}

due to the large rate of energy losses of relativistic electrons, their spectrum suffers more distortion
Energy losses
[synchrotron, Compton scattering] strongly depend on the particle mass

\[ \frac{dE}{dt} \propto \frac{q^4}{m^4} E^2 \]

Characteristic time for energy loss

\[ T_{\text{loss}}(E) \simeq \frac{E}{|dE/dt(E)|} \]

\[ T_{\text{loss}}(E) = \frac{E}{|dE/dt|} \simeq \frac{3m_e^2}{4c\sigma_{\text{Th}} \langle \rho_B + \rho_{\gamma}^*(E) \rangle} E \]

\[ \simeq 621.6 \left( \frac{\text{GeV}}{E} \right) \left( \frac{0.5 \text{ eV/cm}^3}{\rho} \right) \text{ Myr} \]

\[ \rho_b = \frac{B^2}{8\pi} \simeq 0.22 \left( \frac{B}{3 \mu\text{G}} \right)^2 \frac{\text{eV}}{\text{cm}^3} \]

\[ \rho_{\text{CMBR}} \simeq 0.26 \frac{\text{eV}}{\text{cm}^3} \]
Conventional interpretation for the proton/electron ratio [simplest discussion]

\[ N_p(E) = Q_p(E) \times T_p(E) \]
\[ N_{e-}(E) = Q_{e-}(E) \times T_e(E) \]

Accelerators generate spectra of electrons and protons of similar shape (but different normalization)

\[ Q_{e-}(E) \approx K_{ep} Q_p(E) \]

\[ \frac{N_{e-}(E)}{N_p(E)} \approx \frac{T_{e-}(E)}{T_p(E)} \approx E^{-0.4} \]

\[ K_{ep} \approx 0.01 \div 0.02 \]

Mass effect in acceleration injection
Conventional picture for the electron/proton ratio:

\[ T_p(E) = T_{\text{escape}}(E) \]

\[ T_e(E) = T_{\text{escape}}(E) \oplus T_{\text{loss}}(E) \sim T_{\text{loss}}(E) \]

\[ E \gtrsim 30 \text{ GeV} \]

\[ \frac{T_{\text{loss}}(E)}{T_{\text{escape}}(E)} \propto \frac{\phi_{e^-}(E)}{\phi_p(E)} \propto E^{-0.41} \]

\[ T_{\text{escape}}(30 \text{ GeV}) \gtrsim T_{\text{loss}}(30 \text{ GeV}) \sim 30 \text{ Myr} \]
“Conventional mechanism” for the production of positrons and antiprotons:
Creation of secondaries in the inelastic hadronic interactions of cosmic rays in the interstellar medium

\[ pp \rightarrow \bar{p} + \ldots \]

\[ pp \rightarrow \pi^+ + \ldots \]
\[ \quad \downarrow \mu^+ + \nu_\mu \]
\[ \quad \downarrow e^+ + \nu_e + \bar{\nu}_\mu \]

\[ pp \rightarrow \pi^0 + \ldots \]
\[ \quad \downarrow \gamma + \gamma \]

“Standard mechanism” for the generation of positrons and anti-protons

Dominant mechanism for the generation of high energy gamma rays

intimately connected
Straightforward [hadronic physics] exercise:

1. Take spectra of cosmic rays (protons + nuclei) observed at the Earth
2. Make them interact in the local interstellar medium (pp, p-He, He-p,...)
3. Compute the rate of production of secondaries

\[ q_j(E, \vec{x}_\odot) \]  

[cm³ s GeV]⁻¹
"Local" Rate of production of secondaries

Different low energy behaviors
(low energy antiproton production suppressed)

Power Law behavior at high energy

\[ \frac{\gamma}{e^+} \approx 5.5 \]
\[ \frac{e^-}{e^+} \approx 0.8 \]
\[ \frac{e^+}{\bar{p}} \approx 2.0 \]
Secondary spectra

Scaling behavior
Local production rates of secondaries

\[
\begin{align*}
  e^+ & \quad \overline{p} \\
  e^- & \\
  \bar{p} & \\
  \gamma \\
\end{align*}
\]

"striking" similarity

Observed fluxes
Local production rates of secondaries

"striking" similarity

Observed fluxes
The ratio positron/antiproton of the injection is \((within\ errors)\) equal to the ratio of the observed fluxes.

\[
\frac{\phi_{e^+}(E)}{\phi_{\bar{p}}(E)} \approx \frac{q_{e^+}^{\text{loc}}(E)}{q_{\bar{p}}^{\text{loc}}(E)}
\]

Does this result has a "natural explanation"?
There is a simple, natural interpretation that “leaps out of the slide”:

1. The “standard mechanism of secondary production is the main source of the antiparticles (and of the gamma rays)

2. The cosmic rays that generate the antiparticles and the photons have spectra similar to what is observed at the Earth.

3. *The Galactic propagation effects for positrons and antiprotons are approximately equal*

4. The propagation effects have only a weak energy dependence.
Relation between the production rate of a cosmic ray type and the observed flux at the Earth:

\[ \phi_j(E) = \frac{\beta c}{4\pi} Q_j(E) P_j(E) \]

 Flux

 Galactic Production Rate

 Propagation Function

\[ P_j(E) \approx \frac{T_j(E)}{V_j(E)} \approx \frac{\text{Average age}}{\text{Confinement volume}} \]
The study of the diffuse gamma ray flux allows to study the hypothesis that the shape of the CR spectra is approximately independent from position.

Flux: Integration of emission along the line of sight

\[ \phi_\gamma(E, \Omega) = \frac{1}{4\pi} \int_0^\infty d\ell \; q_\gamma[E, \vec{x}_\odot + \ell \hat{\Omega}] \]

\[ \Phi_\gamma(E) = \int_{4\pi} d\Omega \; \phi_\gamma(E, \Omega) \]

\[ = \frac{1}{4\pi} \int d^3 x \; \frac{q_\gamma(E, \vec{x})}{|\vec{x} - \vec{x}_\odot|^2} = \frac{Q_\gamma(E)}{4\pi L_{\text{eff}}^2(E)} \]

The angular distribution of the gamma ray flux encodes the space distribution of the emission.
Estimate of the space distribution of the emission

\[ q_{\gamma}(E, \vec{x}) = \frac{Q_{\gamma}(E)}{(2\pi)^{3/2} R^2 Z} \exp \left[ -\frac{z^2}{2 Z^2} - \frac{x^2 + y^2}{2 R^2} \right] \]

\[ Z \approx 0.22 \text{ kpc} \]
\[ R \approx 5.2 \text{ kpc} \]
Distortion of the source spectra created by propagation

\[ \frac{\phi_p(E)}{q_p^{\text{loc}}(E)} \approx \frac{\phi_{e^+}(E)}{q_{e^+}^{\text{loc}}(E)} \]

Weak energy dependence of the propagation effects!
Two crucial problems emerge:

[1.] The energy dependence of the propagation effects is significantly smaller than expectations (based on the B/C ratio) [theoretically motivated]

Problem also for antiprotons!

[2.] The propagation effects for positrons and antiprotons are approximately equal.

*Is this possible?*

\[-\frac{dE}{dt} \propto \frac{q^4}{m^4} E^2\]

Rates of energy losses for positrons and antiprotons differ by many orders of magnitude.
The much larger rate of energy loss for \( e^\pm \) is irrelevant in propagation if the time of residence of the particles is sufficiently short, so that a particle loses only a small fraction of its energy before escape from the Galaxy.

\[
\left| \frac{dE}{dt} \right| \ T_{\text{age}} \ll E
\]

\[
T_{\text{age}} \ll \frac{E}{\left| \frac{dE}{dt} \right|} \equiv T_{\text{loss}}(E)
\]
Characteristic times for the propagation of Cosmic Rays in the Milky Way

\[ T_{\text{esc}}(E) \quad \text{Time to escape from the Galaxy} \]

\[ T_{\text{loss}}^e(E) \quad \text{Time to lose a significant fraction of the initial energy (for electrons and positrons)} \]

\[ T_{\text{int}}^p(E) \quad \text{Interaction time (for protons)} \]
Energy losses negligible

Energy losses significant

$T_{\text{esc}} \propto E^{-\delta}$

$T_{\text{loss}} \propto E^{-1}$
"Standard picture"

Energy losses important for $E > \text{few GeV}$

"Alternative picture"

Energy losses become important at $E \approx 1 \text{ TeV}$
Use the electron spectrum as a "cosmic ray clock"

Where is the spectral feature associated to the critical energy?

Very smooth electron spectrum

Fit = \( K E^{-3.17} \)

FFA Solar Modulations (1.44GeV)
Where is the critical energy: $E^*$ in the electron spectrum?

Pull to very low energy
$E^* < 5$ GeV

Push to high energy
$E^* > 500$ GeV

$\langle \rho_B + \rho_\gamma \rangle = 0.5$ eV/cm$^3$
Possible (and “natural”) choice: identification of the sharp softening observed by the Cherenkov telescopes in the spectrum of \((e^+ + e^-)\) as the critical energy.

\[ E^* = E_{\text{HESS}} \simeq 900 \text{ GeV} \]

\[ T_{\text{confinement}}[E \simeq 900 \text{ GeV}] \simeq 0.7 \div 1.3 \text{ Myr} \]

Range depends on volume of confinement.

Propagation of positrons and antiprotons is approximately equal for

\[ E \lesssim E^* \simeq 900 \text{ GeV} \]
This solution is simple and natural but has a significant “theoretical” problem:

If: positrons and antiprotons have equal propagation properties.

Then: also electron and protons have also the same propagation properties.

But then why are the electron the proton spectra so different from each other?! (with electrons much softer).

The $e/p$ difference must be generated by the sources.
Can the sources release different spectra of e- and p without violating the "universality" of the acceleration mechanism? Yes!

Effects of Energy losses:
in the accelerators (perhaps SNR)

"Generation" =

- Injection in the acceleration process
- Acceleration
- Source Ejection (escape from accelerator)

- mass dependence
- mass dependence (energy loss)
- energy loss
Measurements of Beryllium 10

\[ T_{1/2} \approx 1.51 \pm 0.04 \text{ Myr} \]

\begin{equation}
\langle T_{\text{esc}} \rangle = 2 \text{ Myr}
\end{equation}

\begin{equation}
\langle T_{\text{esc}} \rangle = 15 \text{ Myr}
\end{equation}

N.E. Yanasak et al.

M. Kruskal, S. P. Ahlen and G. Tarlé,
Astrophys. J. 818, no. 1, 70 (2016)
What about secondary/primary nuclei?

[normally the “cornerstone” of most propagation models]

\[
\frac{\text{Boron}}{\text{Carbon}} \approx 0.21 \left( \frac{p/Z}{30 \text{ GV}} \right)^{-0.33}
\]
\[
\frac{\text{Boron}}{\text{Carbon}} \approx 0.21 \left( \frac{p/Z}{30 \text{ GV}} \right)^{-0.33}
\]

Approximation of constant fragmentation cross sections

Interpretation in terms of Column density

\[
\langle X \rangle \approx 4.7 \left( \frac{p/Z}{30 \text{ GV}} \right)^{-0.33} \frac{\text{g}}{\text{cm}^2}
\]

[Assuming that the column density is accumulated during *propagation in interstellar space*]

\[
\langle T_{\text{age}} \rangle \approx 30 \text{ Myr} \left[ \frac{0.1 \text{ g cm}^{-3}}{\langle n_{\text{ism}} \rangle} \right] \left( \frac{|p/Z|}{30 \text{ GV}} \right)^{-0.33}
\]
Residence time inferred from B/C ratio assuming that the column density crossed by the nuclei is accumulated in interstellar space is inconsistent [as it is too long] with the hypothesis that the energy losses of $e^\pm$ are negligibly small.

Possible solutions

1. [Energy dependence of fragmentation Cross sections]

2. Most of the column density inferred from the B/C ratio is integrated not in interstellar space but inside or in the envelope of the sources [Cowsik and collaborators]
Conventional (orthodox) description:

\[ P_{e^+}(E) < P_{\bar{p}}(E) \]

The result:

\[ \frac{\phi_{e^+}(E)}{\phi_{\bar{p}}(E)} \approx \frac{q_{\text{loc}}^{e^+}(E)}{q_{\text{loc}}^{\bar{p}}(E)} \]

is simply a (rather extraordinary) but meaningless numerical coincidence.

\[ Q_{e^+}(E) = Q_{\text{sec}}^{e^+}(E) + Q_{\text{new}}^{e^+}(E) \]

\[ Q_{\bar{p}}(E) = Q_{\text{sec}}^{\bar{p}}(E) \]

Positrons have an “extra source” (dominant at high energy).

New source sufficiently “fine tuned” (in shape and normalization)

\[ [Q_{e^+}^{\text{sec}}(E) + Q_{e^+}^{\text{new}}(E)] \ P_{e^+}(E) \approx Q_{e^+}^{\text{sec}}(E) \ P_{\bar{p}}(E) \]
Conventional propagation scenario:

A1. Very long lifetime for cosmic rays
A2. Difference between electron and proton spectra shaped by propagation effects
A3. New hard source of positrons is required
A4. Secondary nuclei generated in interstellar space

Alternative propagation scenario:

B1. Short lifetime for cosmic rays
B2. Difference between electron and proton spectra generated in the accelerators
B3. Antiprotons and positrons of secondary origin
B4. Most secondary nuclei generated in/close to accelerators
How can one discriminate between these two scenarios?

1. Extend measurements of e+- spectra
   Different cutoffs can confirm the conventional picture

2. Extend measurements of secondary nuclei [B, Be, Li]. Look for signatures of nuclear fragmentation inside/near the accelerators.

3. Study the space and energy distributions of the relativistic e+- in the Milky Way [from the analysis of diffuse Galactic gamma ray flux]

4. Study the populations of e- and p in young SNR (assuming that they are the main sources of CR)
Conclusions:

An understanding of the origin of the positron and antiproton fluxes is of central importance for High Energy Astrophysics.

This problem touches the cornerstones of Cosmic Ray astrophysics and it has profound and broad implications

[Possible new antiparticle sources, Spectra released by accelerators, Fundamental properties of propagation]

Crucial crossroad for the field.