Cosmic Rays, Photons, Neutrinos
Gravitational Waves

4 Messengers for the study of the “High Energy Universe”

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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]
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"

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

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

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

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

"Leptonic"

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

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

\[ e^\pm \vec{B} \rightarrow e^\pm \gamma_{\text{syn}} \]
Non accelerator sources

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

Super Massive Particles
[Very High mass scales]

Production of high energy particles of all types $\gamma, \nu, e^+, e^-, p, \ldots$
Gamma Astronomy has revealed a very rich, fascinating landscape

- Many sources have been identified [GeV, TeV ranges]
- Several classes of objects [SNR, Pulsars, PWN, AGN, GRB, ...]
- Probably different acceleration mechanisms.

Still developing an understanding, many questions remain open
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
Gravitational Waves Studies
Entering a new exciting era with LIGO/VIRGO
Essentially all gamma astronomy and neutrino astronomy can be seen as observations of Cosmic Rays in different astrophysical sites.

**Cosmic Ray Observations at the Earth:**

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

Single point, and (effectively) single time. 

[Slow time variations, geological record carries some information]

A “*Local Fog*” that is a terrible nuisance but also carries very important information.
Measurements of Cosmic Rays as Messengers at the Earth:

\[ \phi_p(E, \Omega), \quad \phi_{\text{He}}(E, \Omega), \quad \ldots, \quad \phi_{\{A,Z\}}(E, \Omega) \]

protons + nuclei

\[ \phi_{e^-}(E, \Omega) \]

electrons

\[ \phi_{e^+}(E, \Omega), \quad \phi_{\bar{p}}(E, \Omega) \]

anti-particles
High Energy CR flux (Indirect Shower Observations)

Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)

Scaled flux $E^{2.5} J(E)$ (m$^{-2}$ sec$^{-1}$ sr$^{-1}$ eV$^{-1.5}$)

Low energy EAS measurements (high-altitude)

Knee(s)

Galactic extraGalactic transition

Highest energy cosmic rays

Energy (eV/particle)
High Energy CR flux (Indirect Shower Observations)

$\gamma$-Astronomy $\rightarrow$ $\nu$-Astronomy

Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)

Scaled flux $J(E)$ (m$^{-2}$ sec$^{-1}$ sr$^{-1}$ eV$^{-1.5}$)

Low energy EAS measurements (high-altitude)

Knee(s)

Galactic extragalactic transition

Highest energy cosmic rays

100 TeV $\rightarrow$ Very High Energy
The CR spectra are *nearly perfectly* isotropic. but the **angular distribution** carries information of great importance

\[ \phi(E, \Omega) \simeq \phi(E) \]

[of course also when the angular distribution is consistent with exact isotropy ["The dog that did not bark"]

The energy spectra
their absolute and relative size,
their *different shapes* for different particle types
carry essential information that we want to understand.

Precision Measurements of AMS02 $E \lesssim 1$ TeV
AMS02 measurements: $p, e^-, e^+, \bar{p}$

(antiprotons from AMS days)
AMS02, PAMELA, CREAM, FERMI, HESS

Different shapes of the spectra

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

Low energy differences
Solar Modulations

$p/100$

$E_{\text{HESS}} = 900$ GeV

$(e^- + e^+)$
All electrons, Positron Spectra

Very Prominent spectral structure

$E^3 \phi(E)$ [GeV²/(m² s sr)]

$(e^+ + e^-)$

$e^+$

E (GeV)

AMS02
FERMI-LAT
HESS
VERITAS
MAGIC
HESS fit
\[ \gamma_1 \approx 3.0 \]
\[ \gamma_2 \approx 4.1 \]
\[ E_{\text{break}} = 900 \text{ GeV} \]

MAGIC fit
\[ \gamma_1 \approx 3.2 \pm 0.01 \]
\[ \gamma_2 \approx 4.1 \pm 0.01 \]
\[ E_{\text{break}} = 710 \pm 40 \text{ GeV} \]
- 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?
• Why the proton flux has its shape?

• Why the electron flux has its shape?

• Why the positron flux has its shape?

  Does the positron flux contain a DM component?

• Why the $\bar{p}$ flux has its shape?
Formation of the Cosmic Ray Spectra

Cosmic Ray Density at the Sun position =

“Release” in Interstellar Medium [Injection] \(\otimes\) Propagation from source to Sun

\[\phi = \frac{4\pi}{\beta c} n\]
Formation of the (proton) Cosmic Ray Spectrum

\[ n_p(E, \vec{x}_\odot, t_{\text{now}}) = \int_{-\infty}^{t_{\text{now}}} dt \int d^3x \int dE_i \ q_p(E_i, \vec{x}, t) \times \ P_p(E, \vec{x}_\odot, t_{\text{now}}; E_i, \vec{x}, t) \]

[General, explicit (but “formal”) expression]
Primary particles: (protons, electrons, Helium nuclei, ...)

Accelerated in Astrophysical Sources

“Release” =

- Injection in the acceleration process
- Acceleration
- Source Ejection (escape from accelerator)
Secondary particles:
positrons, antiprotons
[in the “conventional picture”:
no DM, no antimatter accelerators]]

Rare Nuclei (Li, Be, B, ....)

“born relativistic”

“Release” = Creation in the interaction of a higher energy particle
Cosmic Ray spectra: \( j = p, e^-, \ldots \)

\[
\phi_j(E) = q_j(E_i, \vec{x}_i, t_i) \otimes P_j(\text{source} \rightarrow \text{Sun})
\]

Problematic **Ambiguity:**

Parameters and structures (spectral indices, break points....) that determine the shapes of the spectra can have different interpretations with "release" and "propagation" playing different (complementary) roles.

\[
\phi_p(E) \propto E^{-\gamma_p}
\]

\[
\gamma_p = \gamma_0 + \delta
\]

- \( E_{\text{knee}} \) = Maximum acceleration Rigidity
- \( E_{\text{knee}} \) = Critical Rigidity for diffusion
SuperNova Remnants as possible main source of the Galactic Cosmic Rays

Do they provide sufficient Power?

Do they generate the “right spectra” [of p, He, ...., e] of the observed CR?

What are the right spectrum?
Different spectral shapes of relativistic particles in different SNR

From S. Funk (2015)
What does this mean?

The SNR sources contain a very large amount of Energy in relativistic Particles.
[adequate to supply the CR Galactic population]
Spectral shape?

Photon index [1-100] GeV

Possible interpretation: Time dependent spectra: SuperNova release *time integrated* spectra of approximately equal shape.
But what are the average spectra of the relativistic particles (protons, Helium, electrons, positrons [?]) released by the accelerators?

This is where the CR measurements become important [But requires to understand propagation]
New precision measurements (by AMS02) of anti-matter Cosmic Rays.

AMS02 +PAMELA data
New precision measurements (by AMS02) of anti-matter Cosmic Rays.

Approximately constant value for the ratio positron/anti-proton for \( E > 30 \text{ GeV} \)

Simple power law Fits (for \( E > 30 \text{ GeV} \))

\[
\gamma_{e^+} = 2.77 \pm 0.02
\]

\[
\gamma_{\bar{p}} = 2.78 \pm 0.04
\]

\[
\frac{e^+}{\bar{p}} \simeq 2.04 \pm 0.04
\]

\[
\left. \frac{\phi_{e^+}(E)}{\phi_{\bar{p}}(E)} \right|_{E \in [30,400] \text{ GeV}} \simeq (2.04 \pm 0.04) \times \left( \frac{E}{50 \text{ GeV}} \right)^{0.015 \pm 0.045}
\]
\[ \gamma_{e^+} = 2.77 \pm 0.02 \]

\[ \gamma_{\overline{p}} = 2.78 \pm 0.04 \]

\[ \frac{e^+}{\overline{p}} \approx 2.04 \pm 0.04 \]

Fitted slopes:

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

Approximately constant value for the ratio positron/anti-proton

\[ \frac{\phi_{e^+}(E)}{\phi_{\overline{p}}(E)} \bigg|_{E \in [30,400] \text{ GeV}} \approx (2.04 \pm 0.04) \times \left( \frac{E}{50 \text{ GeV}} \right)^{0.015 \pm 0.045} \]

Protons

\[ \gamma_p = 2.85 \pm 0.01 \]
\[ \gamma_p = 2.72 \pm 0.05 \]
\[ E_{\text{break}} \approx 330 \text{ GeV} \]

Does this "mean" something?
Rapid energy dependence for low E

Region where ratio is approximately constant
Different behavior: positron/anti-proton
electron/proton
Why?

(for E > 20-30 GeV)

\[ \gamma_{e^+} \approx \gamma_p \]

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

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

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

Why the electron and proton CR spectra have different shapes?

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

[Commonly accepted] ANSWER:

[1.] The electron and proton spectra have the same shape at injection.

[2.] The propagation effects are different, because electrons have a much larger energy loss rate.
Energy losses
[synchrotron, Compton scattering] strongly depend on the particle mass

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

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

Characteristic time for energy loss

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

\[\simeq 621.6 \left( \frac{\text{GeV}}{E} \right) \left( \frac{0.5 \text{ eV/cm}^3}{\rho} \right) \text{ Myr}\]
Conventional picture for the electron/proton ratio:

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

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

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

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

\[ T_{\text{escape}}(30 \text{ GeV}) \gtrsim T_{\text{loss}}(30 \text{ GeV}) \sim 30 \text{ Myr} \]
What I see as a “burning problem” (in a nutshell)

The fluxes of $\bar{p}$ and $e^+$ seem to be intimately related.

Let us assume:

[1.] *antiprotons are secondary* and therefore that there is an associated production of positrons.

[2.] Positrons propagate exactly as antiprotons.

Then: the calculated spectra of secondary positrons is consistent (within systematic uncertainties with the data).
“Conventional mechanism” for the production of positrons and antiprotons:

Creation of secondaries in the inelastic hadronic interactions of cosmic rays in the interstellar medium

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

\[ pp \to \pi^+ + \ldots \]

\[ \Downarrow \mu^+ + \nu_\mu \]

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

Injections of positrons and anti-protons are intimately connected
Calculation of the “Local injection” of secondaries by the “conventional mechanism”

\[ q_{p}^{\text{loc}}(E) = \phi_{p}(E) \otimes n_{\text{ism}}(\vec{x}_{\odot}) \otimes \sigma_{\text{hadronic}}[pp \rightarrow \bar{p} + \ldots] \]

\[ q_{e^{+}}^{\text{loc}}(E) = \phi_{p}(E) \otimes n_{\text{ism}}(\vec{x}_{\odot}) \otimes \sigma_{\text{hadronic}}[pp \rightarrow e^{+} + \ldots] \]

**Step 1:** Measure the spectra of CR near the Earth.

**Step 2:** Correct for Solar Modulation effects to obtain the spectra in interstellar space.

**Step 4:** Model the interaction to compute injection spectra of positrons + anti-protons.

\[ q_{j}^{\text{loc}}(E) = n_{\text{ism}}(\vec{x}_{\odot}) f_{p} \int dE_{0} n_{p}^{\text{loc}}(E_{0}) (\beta c) \sigma_{pp}(E_{0}) \frac{dN_{pp \rightarrow j}}{dE}(E, E_{0}) \]

\[ + (p + \text{He}) + (\text{He} + p) + (\text{He} + \text{He}) + \ldots \]
Nucleon Fluxes

Pamela, AMS02, CREAM
HEA0 (for nuclei)
Particle production in hadronic collisions

\[ pp \rightarrow \pi^+, K^+, \bar{p}, \ldots \]

\[ E_0 = 10^4 \text{ GeV} \]

Example of a Montecarlo calculation with Pythia
Injection

Observed Fluxes

"Striking" similarity

Particle Fluxes
**Injection of positrons and antiprotons**

At *high energy* approximately constant ratio (consequence of scaling)

\[
\frac{q\overline{p}}{q_{e^+}} \approx 1.80 \pm 0.5
\]

\[
\frac{\phi_{e^+}(E)}{\phi_{\overline{p}}(E)} \bigg|_{E\in[30,350] \ GeV} \approx 2.04 \pm 0.04
\]

\[p + p \rightarrow p + p + p + \overline{p}\]

**Low energy:**
kinematical suppression of antiproton production

\[
E_{i,\text{threshold}} = 7 \ m_p
\]

\[
E_{f,\text{threshold}} = 2 \ m_p
\]
The ratio positron/antiproton of the injection is (within errors) equal to the ratio of the observed fluxes.

Does this result have a "natural explanation"?
\[ n_\overline{p}(E, \vec{x}_\odot, t_{\text{now}}) = \int_{-\infty}^{t_{\text{now}}} dt \int d^3x \int dE_i \ q_\overline{p}(E_i, \vec{x}, t) \times P_\overline{p}(E, \vec{x}_\odot, t_{\text{now}}; E_i, \vec{x}, t) \]

\[ n_{e^+}(E, \vec{x}_\odot, t_{\text{now}}) = \int_{-\infty}^{t_{\text{now}}} dt \int d^3x \int dE_i \ q_{e^+}(E_i, \vec{x}, t) \times P_{e^+}(E, \vec{x}_\odot, t_{\text{now}}; E_i, \vec{x}, t) \]

“natural explanation” for the ratio:

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

1. Energy dependence of the local injection is valid in most of the source volume.

2. Negligible energy distortions during propagation (Energy remains approximately constant)

3. Equal propagation for antiprotons and positrons (!!!)
Two “scenarios” seem to emerge:

### Scenario 1 ("Conventional picture")

1a. We assume (from the study of e-, p spectra) that propagation effects suppress electrons versus protons [with a marked energy dependence].

1b. If both positrons and antiprotons have a secondary origin, their ratio must strongly depend on energy.

1c. The ratio e+/pbar is constant, therefore, a **NEW POSITRON SOURCE** is required to compensate for the suppression of positrons (due to energy losses).

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

[the equality \( \frac{\phi_{e^+}(E)}{\phi_{\bar{p}}(E)} \approx \frac{q_{e^+}(E)}{q_{\bar{p}}(E)} \) is “just a coincidence”.]

Alternative possibility

Scenario 2.

2a. Positrons and antiprotons are both of secondary origin.

2b. The observed positron/anti-proton ratio is approximately equal to the ratio at source. Therefore positrons and anti-protons propagate in approximately the same way. Escape is rapid, and energy losses negligible.

2c. The energy dependence of the e-/p fluxes is NOT the effect of propagation, but is formed at injection, in the CR accelerators. [Perhaps because of energy losses inside the accelerators]
Critical Energy $E^*$

$$T_{\text{loss}}(E^*) = T_{\text{confinement}}(E^*)$$

[For electrons with $E > E^*$ energy losses are important]

Identify the softening in the all electron spectrum and 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
Constraints on the residence time of $e^\pm$

Beryllium-10 Measurement

$\tau_{esc} = 15.0 \pm 1.6$ Myr

Critical energy where residence time and energy-loss time are equal

Excluded region

Constraints on the residence time of $e^\pm$

Beryllium-10 Measurement

$\tau_{\text{esc}} = 15.0 \pm 1.6$ Myr

CRIS measurement Of Beryllium isotopes

Excluded region

Critical energy where residence time and energy-loss time are equal

Antiproton/proton ratio

Claims in the recent literature that the recent data AMS02 data is consistent with the "standard scenario"

Significant tension between data and models
Secondary nuclei: Li, Be, B

A complex scenario is emerging

Probably production in sources is important

Fit of Lithium flux

Same model as the one used for proton and helium (double power law with smooth transition) between 45 GV and 3 TV:

$$\Phi = C \left( \frac{R}{45 \text{ GV}} \right)^\gamma \left[ 1 + \left( \frac{R}{R_0} \right)^{\Delta \gamma/s} \right]^8$$

Change of slope at the same range than for the one found for Proton and Helium.
An understanding of the origin of the positron and antiproton fluxes is [seems to me] of central importance for High Energy Astrophysics. 

**Crucial crossroad for the field.**

Most commonly accepted view:
The hard positron flux requires an "extra component"
Sources of relativistic positrons [Pulsars, DM annihilation] exist.

The similarity of the antiproton and positron fluxes:

[Constant ratio $e^+/\bar{p} \approx 2$ at high energy (E > 30 GeV]
[Kinematical suppression of antiprotons at low energy] suggests a secondary origin for both fluxes.
Viable solution, but the implications are profound.

*It is very important to clarify what is the correct explanation*
High Energy CR flux

Galactic extragalactic transition

Low energy EAS measurements (high-altitude)

Knee(s)

Highest energy cosmic rays
Structures in the Cosmic Ray Energy Spectrum

1. The “Pamela hardening”

2. The break in the \((e^- + e^+)\) spectrum observed by the Cherenkov Telescope

3. The “KNEE” \[\log_{10}[E(\text{eV})] \approx 15.5\]

4a. The “Iron Knee” of Kascade Grande

4b. The “proton (+Helium) Ankle” \(16.92 \pm 0.08\)

4c. The “Second Knee” \(17.08 \pm 0.05\)

5. The “ANKLE” \(17.6 \pm 0.2\)

6. The UHECR suppression \(18.6\)

6. The UHECR suppression \(19.4–19.8\)
The Nature of the “KNEE” in the Cosmic Ray Spectrum

Accelerator feature
[Maximum energy of acceleration. implies that all accelerators are similar]

Structure generated by propagation
[implies that the (main) Galactic CR accelerators must be capable to accelerate to much higher energy]
The CR "KNEE" as a propagation effect
[Associated to the maximum length scale of turbulence of the random Galactic Magnetic field]
Galactic versus Extra-Galactic CR

Possibility to explore new classes of sources

Transition Energy $E^*$

$\phi_{\text{galactic}}(E^*) = \phi_{\text{extra galactic}}(E^*)$
Piece of extragalactic space: non MilkyWay-like sources

Milky Way “bubble” of CR confined by $B_{\text{gal}}$

AGN

Galaxy

Milky Way
Piece of extragalactic space:

Nature and distribution of extragalactic sources.

Milky-Way-like non Milky-Way like (AGN) sources

Structure and intensity of extragalactic magnetic field.
The distinction Galactic / extra-Galactic is conceptually clear.

... but how is it possible experimentally to disentangle the Galactic and extragalactic populations?

Non trivial

Crucial observation: **ANGULAR DISTRIBUTIONS**

Galactic CR production most likely from a disk region (with the Sun close to one border)

**ISOTROPY**

1. Sufficiently “scrambled” particles produced in the Milky Way

2. Extragalactic particles emitted from a (sufficiently large portion) of an isotropic universe
The possibility of "proton Astronomy" (at sufficient high magnetic Rigidity)

\[ \Delta \theta \approx 0.53^\circ \ Z \left( \frac{10^{20} \text{ eV}}{E} \right) \left( \frac{\sqrt{D \, d}}{\text{Mpc}} \right) \left( \frac{\langle B \rangle}{nG} \right) \]
Significant interest in Cen A [closest AGN]

Points: Auger events $E > 58$ EeV
Red lines: [3, 20] degrees circles around Cen A

Is this the first “image” of an astrophysical object taken with protons?!
Kascade-Grande results

All particles

Iron nuclei

Protons

KASCADE-Grande

$\frac{d\sigma}{dE} \times E^{2.7}$ (m$^{-2}$sr$^{-1}$s$^{-1}$eV$^{-1.7}$)

$10^{17}$eV $\rightarrow$ $10^{18}$eV

$\gamma = -2.95 \pm 0.05$

$\gamma = -2.76 \pm 0.02$

$\gamma = -3.24 \pm 0.08$

$\gamma = -3.25 \pm 0.05$

$\gamma = -3.24 \pm 0.05$

$\gamma = -2.79 \pm 0.08$

PRD 87(2013)081101
PRL 107(2011)171104

log$_{10}$ (E/eV)
Kascade-Grande results

"Iron Knee"

$$E_{\text{knee}}(Z) = Z \ E_{\text{knee}}(p)$$

Extragalactic Cosmic Rays become dominant at lower energy

$$E^* < E_{\text{ankle}}$$
Interpretation of the **Ankle** as the "**DIP**"

\[ p + \gamma_{\text{cmbr}} \rightarrow p + e^+ e^- \]

V. Berezinsky, P. Blasi

Extra-Galactic

DIP STRUCTURE

Galactic
Interpretation of the **Ankle** as the "**DIP**"

\[ p + \gamma_{\text{cmb}} \rightarrow p + e^+ e^- \]

V. Berezinsky, P. Blasi

"**ANKLE models**" versus "**DIP Models**"

- Different Transition energy
- Different spectral shape
- Different Power requirement

Very important constraints for the sources
Auger composition study:

**Average position of shower Maximum**

- Average of $X_{\text{max}}$

**Dispersion of shower Maximum**

- Std. Deviation of $X_{\text{max}}$

\[ p \quad \text{(proton)} \quad \text{Fe} \quad \text{(iron)} \]

\[ \log_{10}(E/\text{eV}) \]

\[ (X_{\text{max}}) \quad (\text{g/cm}^2) \]

\[ \sigma(X_{\text{max}}) \quad (\text{g/cm}^2) \]

AUGER, PRELIMINARY

ICRC 2015
Model dependence QGSJetII-04
[description of Shower development]

\[ \langle \ln A \rangle \]

\[ \sigma^2 [\ln A] \]

Very light CR population
for \( E \approx 10^{18} \text{ eV} \)
and becoming heavier!

Small dispersion:
small range of \( A \) contributing to the CR population
Possible Interpretation  (Auger at ICRC-2015)

1. Very hard spectra

2. Cutoff is the maximum energy of acceleration in the sources

$$E_{\text{max}}(Z) = Z \cdot E_p$$
The HiRes detector suggest for their Data (smaller statistics) a different interpretation consistent with pure proton for all energies $E \gtrsim 10^{18}$ eV.

The AUGER results (if correct) have very important implications for the sources of extragalactic CR.

Several attempts of building a physical mode that also describe the “sub-ankle” region.
Gravity

Gravitational Waves

and

High Energy Particles

Multi-messenger High Energy Astrophysics as:

“Einstein Richest Laboratory”
The *merger of binary neutron-stars* systems combines in a single process:

- extreme gravity,
- *copious emission of gravitational waves*,
- complex microphysics,
- and electromagnetic processes that can lead to astrophysical signatures observable at the largest redshifts.

* black-hole formation,
* torus accretion onto the merged compact object,
* *connection with gamma-ray burst engines*,
* ejected material, and its nucleosynthesis.

*... This phenomenon* could be considered Einstein's richest laboratory.
Numerical Simulation [35 msec] of merging of 2 neutron stars


THE MISSING LINK: MERGING NEUTRON STARS NATURALLY PRODUCE JET-LIKE STRUCTURES AND CAN POWER SHORT GAMMA-RAY BURSTS
7.5 msec
Figure 1. Snapshots at representative times of the evolution of the binary and of the formation of a large-scale ordered magnetic field. Shown with a color-code map is the density, over which the magnetic-field lines are superposed. The panels in the upper row refer to the binary during the merger ($t = 7.4$ ms) and before the collapse to BH ($t = 13.8$ ms), while those in the lower row to the evolution after the formation of the BH ($t = 15.26$ ms, $t = 26.5$ ms). Green lines sample the magnetic field in the torus and on the equatorial plane, while white lines show the magnetic field outside the torus and near the BH spin axis. The inner/outer part of the torus has a size of $\sim 90/170$ km, while the horizon has a diameter of $\sim 9$ km.
Figure 3. Magnetic-field structure in the HMNS (first panel) and after the collapse to BH (last three panels). Green refers to magnetic-field lines inside the torus and on the equatorial plane, while white refers to magnetic-field lines outside the torus and near the axis. The highly turbulent, predominantly poloidal magnetic-field structure in the HMNS ($t = 13.8$ ms) changes systematically as the BH is produced ($t = 15.26$ ms), leading to the formation of a predominantly toroidal magnetic field in the torus ($t = 21.2$ ms). All panels have the same linear scale, with the horizon diameter being of $\approx 9$ km.
The simulation shows that the magnetic field is organized in a structure that is consistent with the emission of a jet and then a Gamma Ray Burst.
The simulation shows that the magnetic field is organized in a structure that is consistent with the emission of a jet and then a Gamma Ray Burst.

**GRB 130427A**

\[ \Gamma \gtrsim 1200 \quad !! \]

Lorentz factor of the jet

Many questions:
- What is the jet made of?
- Which particles are accelerated?
- What is the maximum energy?
- What particles emerge?
The development of the understanding of neutron star mergers will likely need to be guided by DATA

[and surprises (phenomena beyond what we now know) are certainly possible!]

I will tell you a secret.... I hope very much that the GBM event in coincidence with GW150914 is a genuine coincidence, and that it is teaching us something important.....

The understanding will come together with a better understanding (and observations) of other phenomena (AGN, binary systems, and also SNR)
Heber Curtis (1918)  
[Lick Observatory]  

“Descriptions of 762 Nebulae and Clusters ....”  

“...curious straight ray ... apparently connected with the nucleus by a thin line of matter.”
Superluminal Motions

Source moving on the celestial sphere

\[ c \beta_{\text{app}} = L \dot{\omega} \]

\[ \beta_{\text{app}} \approx 6 \]

\[ \beta_{\perp,\text{app}} = \frac{\beta \sin \theta}{(1 - \beta \cos \theta)} \]

\[ \Gamma \geq \sqrt{\beta_{\text{app}}^2 + 1} \]

\[ \theta \approx \Gamma^{-1} \]
Observations of M87

2005
2008
2010

HESS
MAGIC
VERITAS

$E \geq 350$ GeV

Figure 2. VHE light curve of M 87 of the flaring episodes in 2005 (top), 2008 (middle), and 2010 (bottom). Integral fluxes are given above an energy of 350 GeV. The lengths of the gray bars correspond to the length of the gray shaded areas in Figure 1. A time of 0 days corresponds to MJD 53460, MJD 54500, and MJD 55270 for 2005, 2008, and 2010, respectively. Flux error bars denote the 1 s.d. statistical error. Horizontal error bars denote the time span the flux has been averaged over. Note that in the case of time spans longer than one night the coverage is not continuous.
VLBA radio images of M87 at 43 GHz

Radio Imaging of the Very-High-Energy γ-Ray Emission Region in the Central Engine of a Radio Galaxy

DOI: 10.1126/science.1175406

The VERITAS Collaboration, the VLBA 43 GHz M87 Monitoring Team, the H.E.S.S. Collaboration, the MAGIC Collaboration
GRS1915+105

Superluminal Motions in microQuasars in our Galaxy

Observations in radio

$\lambda = 3.5$ cm

“Two pairs of bright radio condensations”
Angular velocities

\[ \mu_a \approx 17.6 \pm 0.4 \frac{\text{mas}}{\text{day}} \]

\[ \mu_r \approx 9.0 \pm 0.1 \frac{\text{mas}}{\text{day}} \]

\[ \mu_{a,r} = \frac{\beta \sin \theta}{1 \pm \beta \cos \theta} \frac{c}{D} \]

\[ \beta = 0.92 \pm 0.08 \]

\[ \theta = (70 \pm 2)^\circ \]

\[ D = 12.5 \pm 1.5 \text{ kpc} \]
Concluding remarks:

The Study of Cosmic Rays at the Earth remains an essential tool to develop our understanding of the “High Energy Universe”

Understanding of the mechanisms that shape the detailed form of the spectra of anti-particles is of crucial importance.

Understanding the “Knee”, the “Ankle” and the structures in between is a very important task.

Perhaps the Galactic accelerators can reach much beyond the PeV-range

Cosmic Rays give “time and space integrated” information on an energy region than spans 6 orders of magnitude in energy beyond current gamma-astronomy $10^{14} \div 10^{20}$ eV

The scientific potential multi messenger studies with GW is extraordinarily interesting