Astroparticle physics

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Outline

Session I:

- Survey: extreme energies, extreme densities.
- Relics from the early Universe: freeze-out.

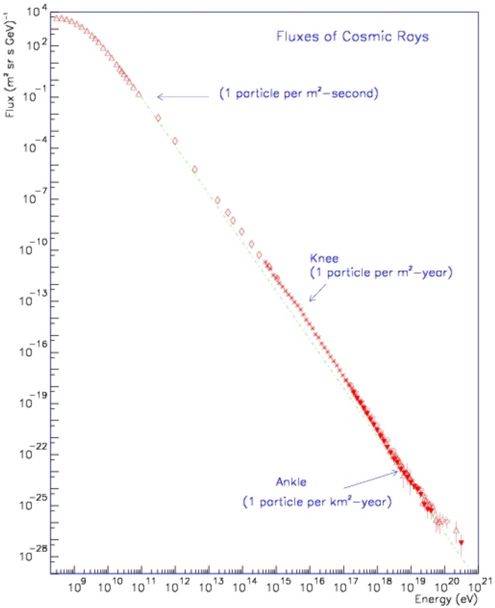
Session II:

- The most energetic particles: ultra-high energy cosmic rays.

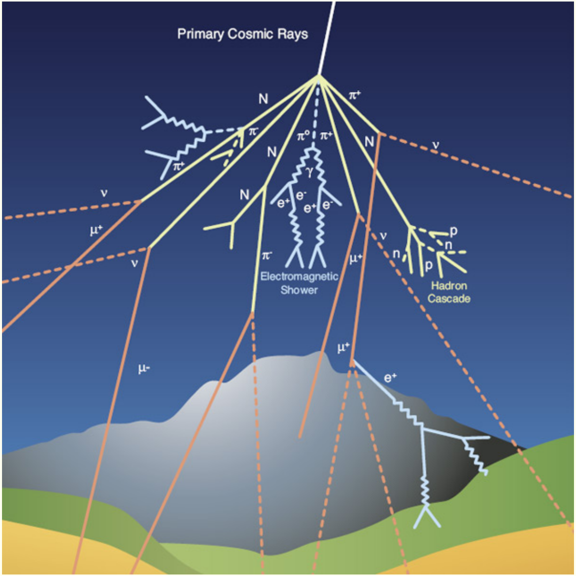
Session III:

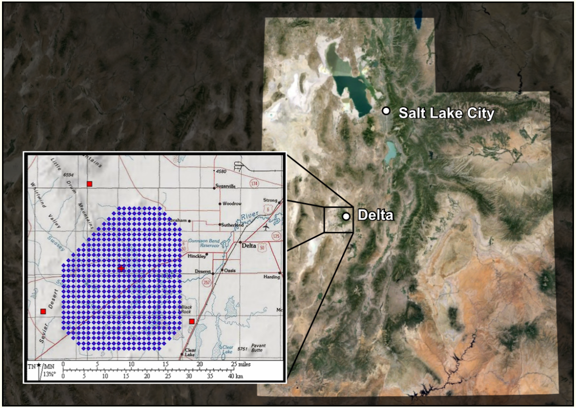
- Gamma-ray astronomy.
- Cosmological magnetic fields.

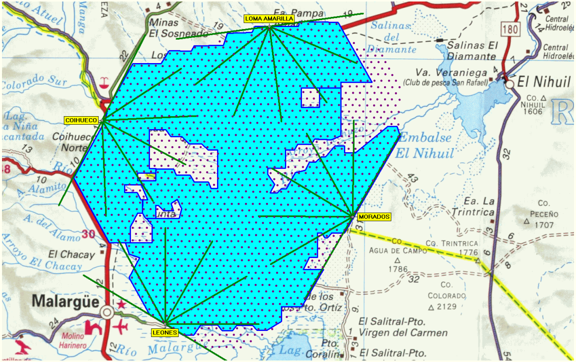
Extreme energies and extreme densities



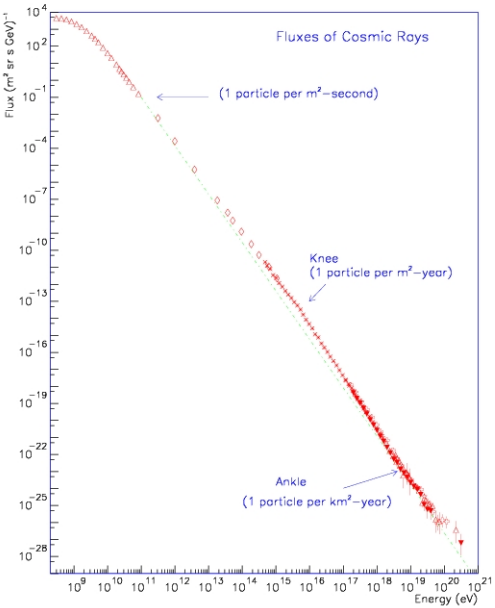
Fluxes of Cosmic Rays
(1 particle per m²−second)
Knee
(1 particle per m²−year)
Ankle
(1 particle per km²−year)
Flux (m² sr s GeV)⁻¹
Energy (eV)


Primary Cosmic Rays
N
π⁺
π⁻
π⁺
N
π°
π⁺
N
ν
γ
ν
e⁺
e⁻
e⁺
e⁻
N
μ⁺
ν
ν
p
n
n
p
π⁻
μ⁺
Electromagnetic
Shower
Hadron
Cascade
μ⁻
μ⁺
e⁺


Salt Lake City
Delta
Sugarville
Woodrow
Strong
Sutherland
Abraham
River
Gunnison Bend Reservoir
Delta
Hinckley
Deseret
Oasis
Harding
Black Rock
Clear Lake
Pavant Butte
5751
4580
6594
Little Drum Mountains
Whirlwind Valley
Swasey
Sevier Desert
TN
MN
13½°
0 5 10 15 20 25 miles
0 5 10 15 20 25 30 35 40 km



LOMA AMARILLA
COIHUECO
MORADOS
LEONES
Malargüe
El Nihuil
Embalse El Nihuil
Salinas del Diamante
Salinas El Diamante
Va. Veraniega
(Club de pesca San Rafael)
Minas El Sosneado
Ea. Pampa
Coihueco Norte
El Chacay
Arroyo El Chacay
A. del Alamo
A. Alamito
Colorado Sur
Río Malargüe
Molino Harinero
Ea. La Trintrica
Co. Agua de Campo 1786
Cq. Trintrica 1776
Co. Colorado 2129
Co. Peceño 1707
Co. Nihuil 1606
Central Hidroeléc
El Salitral-Pto. Virgen del Carmen
El Salitral-Pto.
Pto. Coralin
Lag.
180



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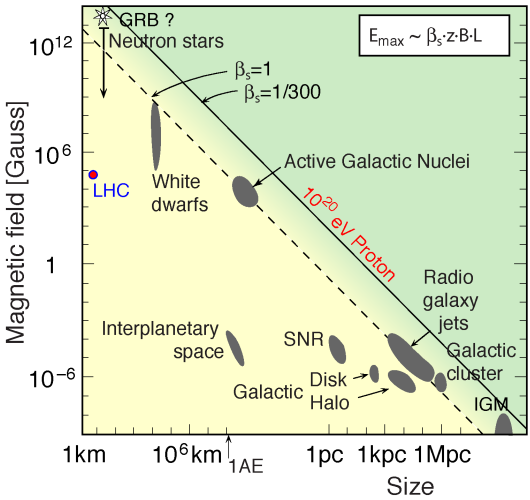

GRB ?
Neutron stars
$E_{max} \sim \beta_s \cdot z \cdot B \cdot L$
β_s=1
β_s=1/300
Active Galactic Nuclei
10^{20} eV Proton
White dwarfs
LHC
Radio galaxy jets
Galactic cluster
Interplanetary space
SNR
Disk
Halo
Galactic
IGM
10^{12}
10^{6}
1
10^{-6}
Magnetic field [Gauss]
1km
10^{6}km
1AE
1pc
1kpc
1Mpc
Size

Energy budget

Assume:

- Bulk is of galactic origin
- Copernican principle: local population is the same throughout most of the Galaxy
- Propagation is by diffusion in a magnetised halo tracking the disc

Gamma-rays track pions produced by interactions between CR nuclei and interstellar gas.
Also isotropic within 10^{-3} due to B-fields.

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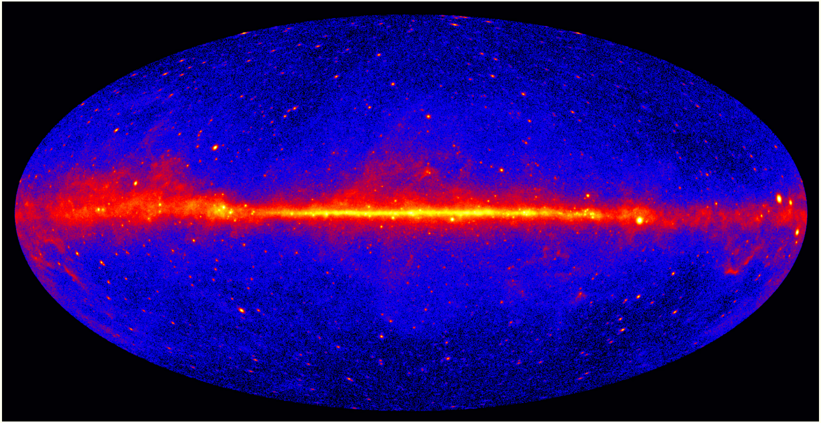

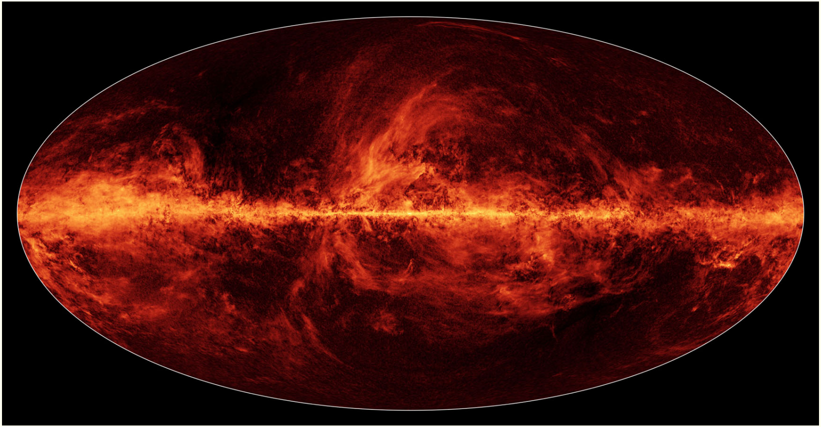

Energy budget

The flux is broadly described by a power law:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} \approx \left.\frac{\mathrm{d}\Phi}{\mathrm{d}E}\right|_0 \left(\frac{E}{E_0}\right)^{-2.7},$$

with $E_0 \approx 10^{10}$ eV and $\left.\frac{\mathrm{d}\Phi}{\mathrm{d}E}\right|_0 \approx 10^2/\mathrm{m}^2\mathrm{sr\ s\ GeV}$.

The energy density can be estimated as:

$$\mathscr{E}_{CR} = \frac{4\pi}{c}\int_{E_0}^{E_{max}} E\frac{\mathrm{d}\Phi}{\mathrm{d}E}\,\mathrm{d}E \approx 1\mathrm{ev/cm}^3,$$

which is dominated by the GeV nuclei and does not depend on the high-energy cutoff.

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Energy budget

Observations of the ratios of secondary spallation nuclei to primaries (e.g. Boron to Carbon ratio) tell us that these CRs have traversed a grammage of $g \approx 5$ g/cm^2.
If they have been confined in a volume V containing a target mass M for a time τ,

$$g \approx \frac{\tau c M}{V}.$$

It follows that the CR luminosity is

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Baade & Zwicky '34, Ginzburg & Syrovatskii '64, Drury '83

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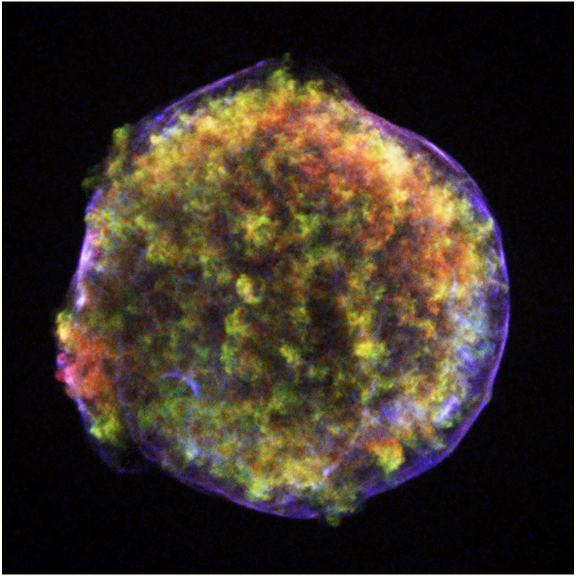
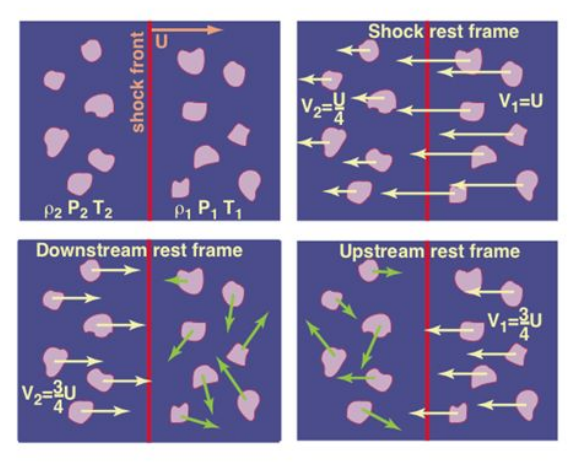


First order Fermi acceleration



Up to $\approx 10^{15}$ eV and E^{-2} injection spectrum.

The GZK cuttoff

- The first event above 10^{20} eV was recorded by Linsley in 1962.
- The CMB was discovered in 1965.

$$\gamma_{\mathrm{CMB}} + p(E > 5 \times 10^{19} eV) \rightarrow \Delta(1232) \rightarrow \pi^0 + p \text{ or } \pi^+ + n$$

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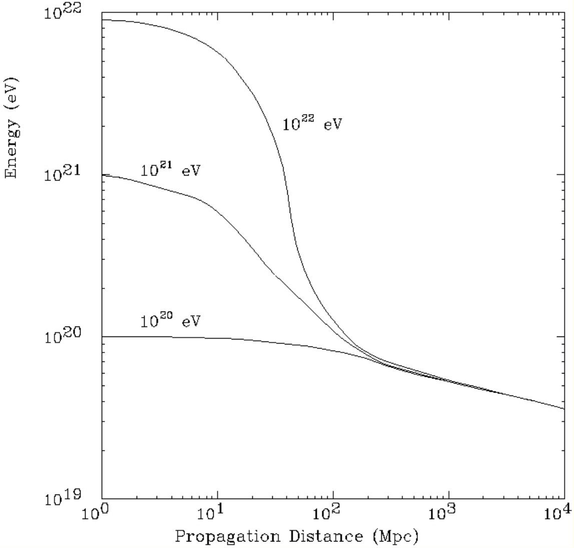

Super-heavy dark matter

One way to avoid the GZK cutoff is to create the CRs in the galaxy.

- Dark matter with $m_\chi \gtrsim 10^{13} GeV$ and $\tau_\chi \sim 10^{22}$ yr.
- Cannot be a thermal relic (Griest & Kamionkowski 91).
- Could be generated by the time-varying gravitational potential at the end of inflation.

Several predicted signatures: anisotropy, composition, isocurvature and tensor modes.

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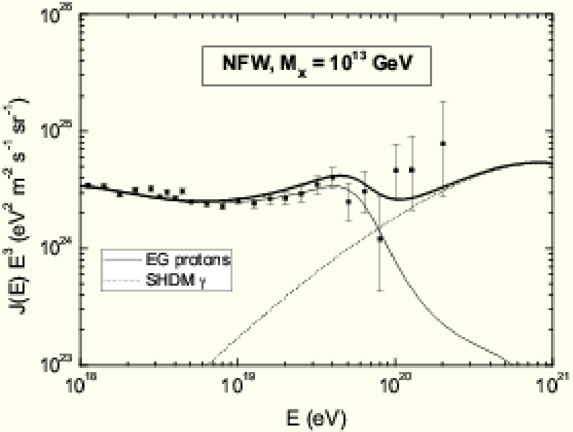
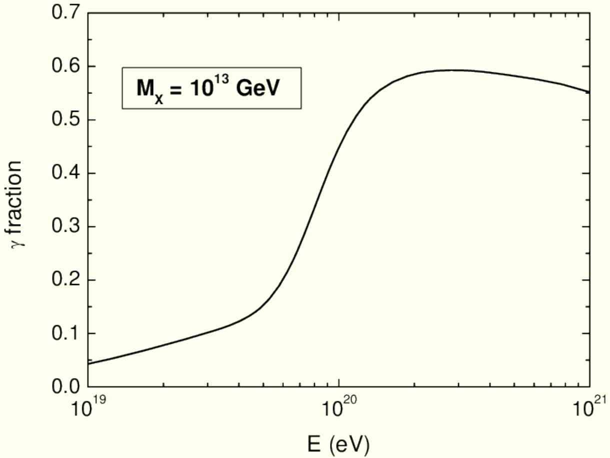


Aloisio & Tortorici 08

Super-heavy dark matter



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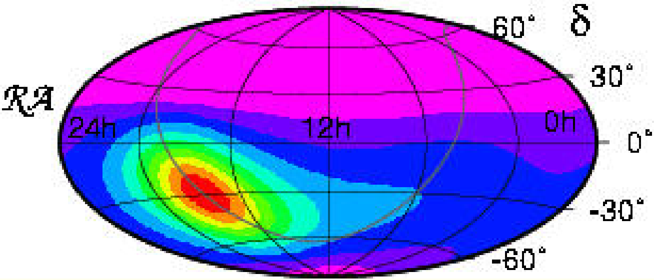
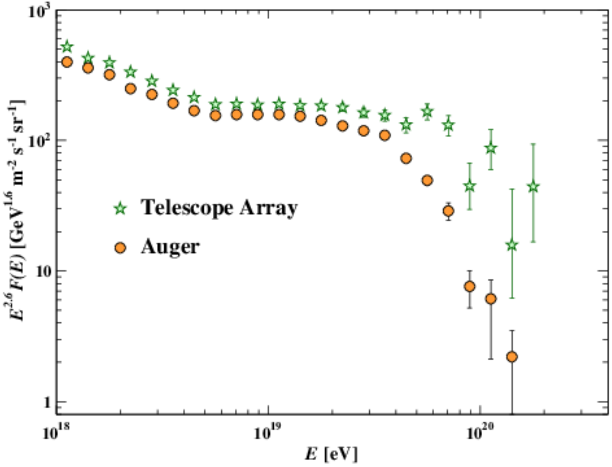
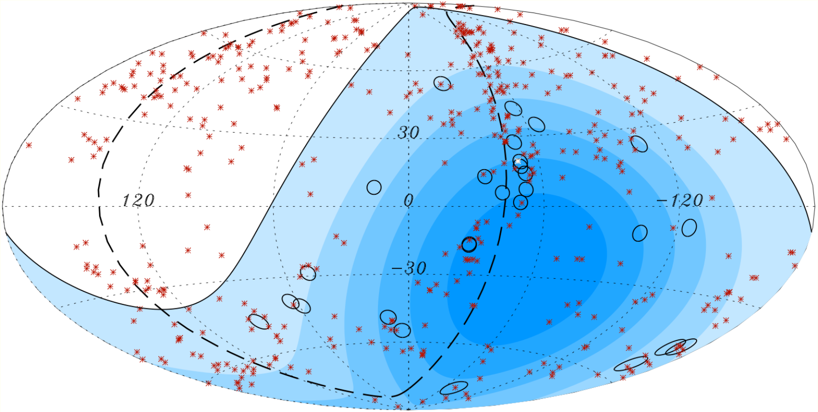


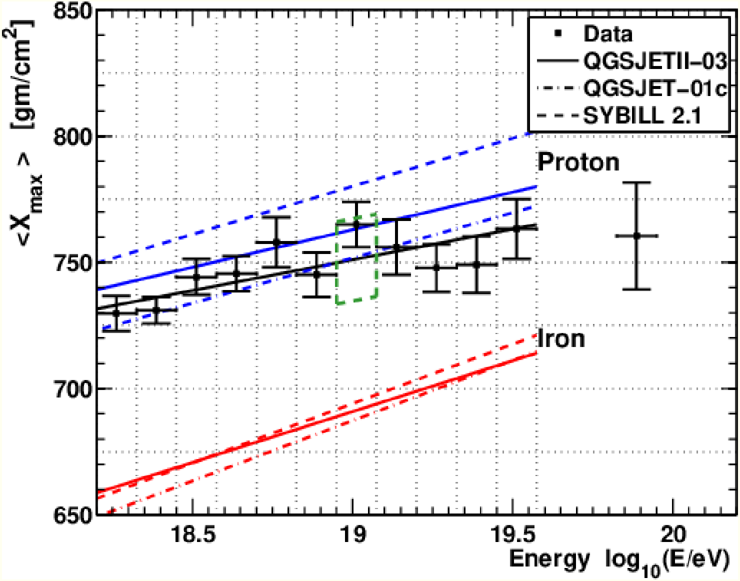
Evans, FF & Sarkar 02



Telescope Array
Auger
$E^{2.6} F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]
10^3
10^2
10
1
10^{18}
10^{19}
10^{20}



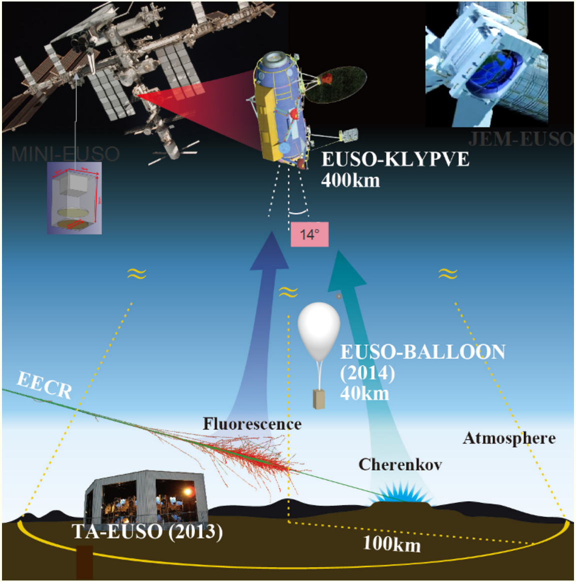
PAO 08



850
800
750
700
650
<Xmax> [gm/cm2]
Data
QGSJETII-03
QGSJET-01c
SYBILL 2.1
Proton
Iron
18.5
19
19.5
20
Energy log10(E/eV)

Open questions:

- GZK cutoff or source power limit
- Do we understand particle interactions at the highest energies?
- Is CR astronomy viable?
- Associated HE νs?



MINI-EUSO
JEM-EUSO
EUSO-KLYPVE
400km
14°
EUSO-BALLOON
(2014)
40km
EECR
Fluorescence
Atmosphere
Cherenkov
TA-EUSO (2013)
100km