Origin of the most energetic particles in the Universe

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Particles and Cosmology – 2025

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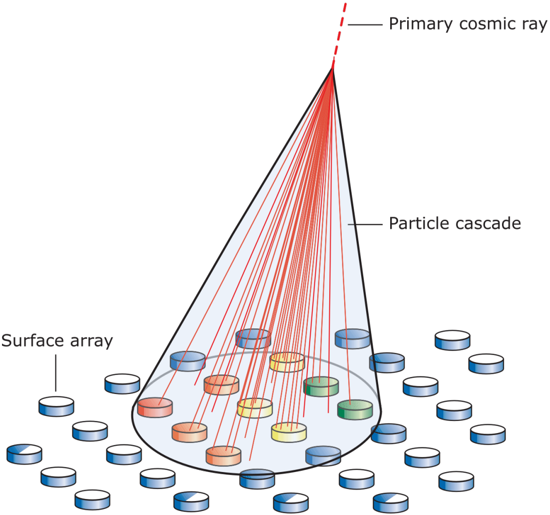
Lecture 1

1. Review of observational data
2. Cosmic ray propagation
3. Common acceleration mechanisms

Extensive air shower



from Bauleo & Martino, Nature 2009

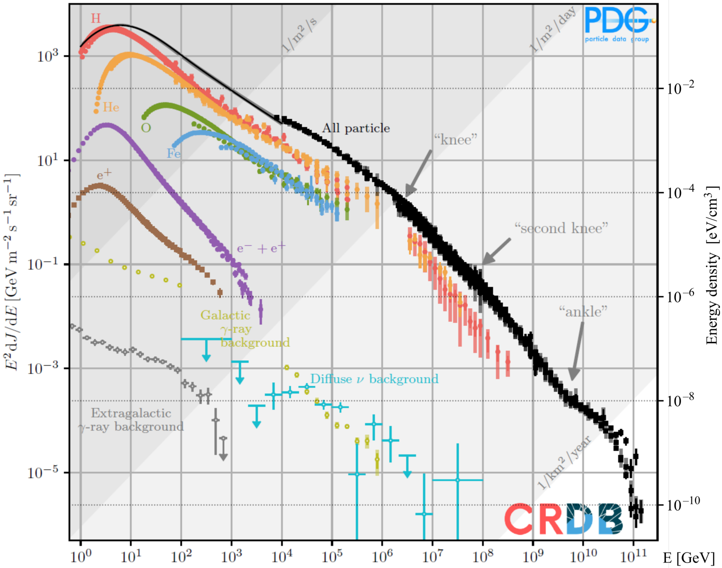
Cosmic Rays discovered
by Victor Hess in 1912

Primary particle
hits atmosphere

lots of secondaries
detected on ground

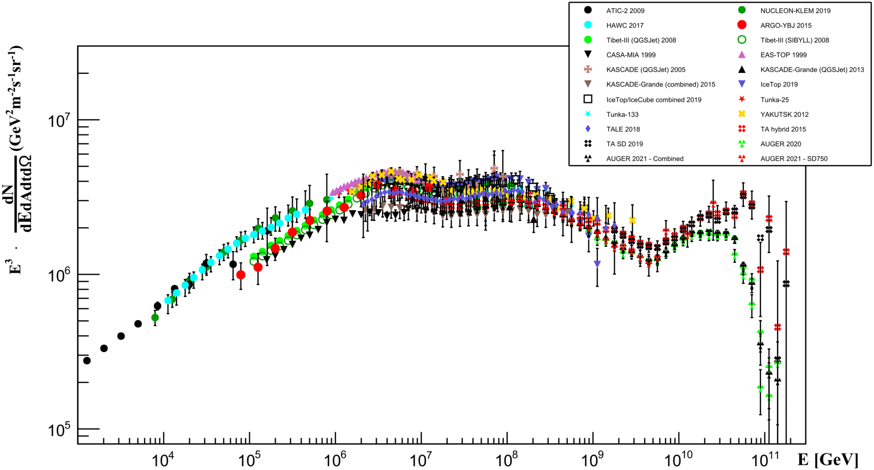
Pierre Auger Observatory

Cosmic Ray spectrum (all species)



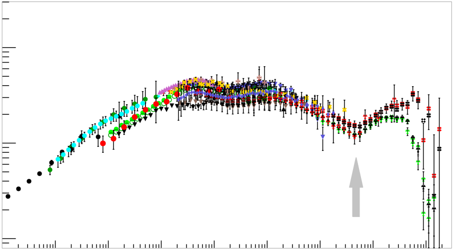
S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)

Cosmic Ray spectrum (baryons and nuclei)



Di Sciascio, Appl. Sci. 2022

Two components in the Cosmic Ray distribution



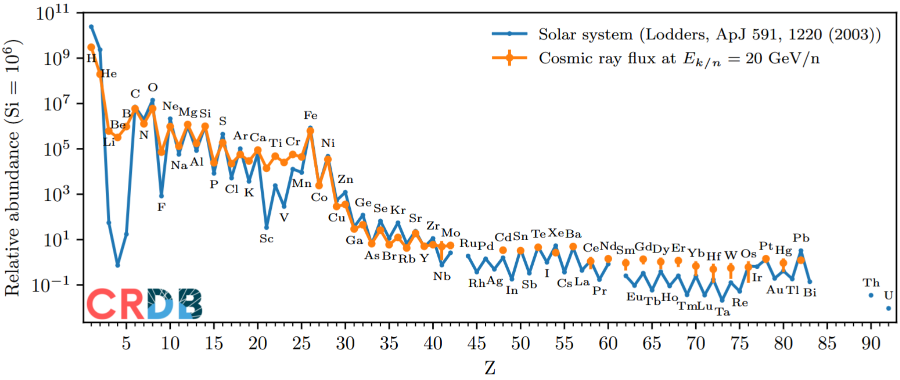
Lower-energy (likely galactic)

- $E < 5 \times 10^{18}$ eV
- energy density ≈ 0.3 eV/cm^3

Higher-energy (likely extragalactic)

- $E > 5 \times 10^{18}$ eV
- energy density $\approx 10^{-8}$ eV/cm^3

Cosmic Ray abundances



D. Maurin et al., The European Physical Journal C (2023)

Lithium, Beryllium and Boron nuclei in Cosmic Rays
are almost entirely of secondary origin

Nuclei spallation and CR isotopic clocks

$$^{12}C,^{16}O + p \;\rightarrow\; ^{9}Be,^{10}Be + \text{fragments}$$

^{9}Be is stable

^{10}Be half-life is $T_{1/2} = 1.39 \times 10^{6}$ yr (decays into ^{10}B)

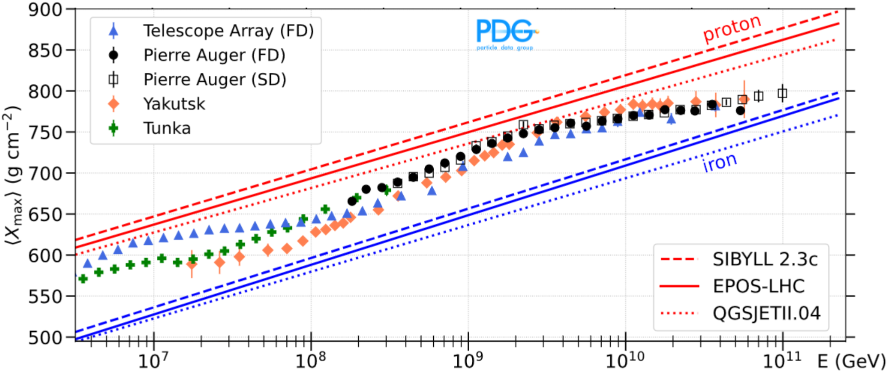
Be/O (or Be/C) ratio measures *grammage*, $X = \int \rho \, \mathrm{d}\ell$

- traversed garammage $X = 5 \div 7 \ \mathrm{g/cm^2}$ (at ~ 250 MeV/nucleon)

$^{10}Be/^{9}Be$ (or $^{10}Be/^{10}B$) ratio measures age

- residence time $t_{\mathrm{res}} \sim 15$ Myr ($2.5 \div 50$ Myr)

Cosmic Ray composition at highest energies



S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)

Note:
direct measurement of cross-sections is possible only up to 10^8 GeV (LHC)

Confinement by Galactic magnetic field

Lower-energy Cosmic Rays diffuse out of the disc

The diffusion is governed by small-scale turbulent magnetic field

Injection spectrum at the galactic sources $N_E \propto E^{-\gamma}$

transforms into observed spectrum $N_E \propto E^{-\gamma-\delta}$ $(\gamma + \delta \approx 2.7)$

if escape time scales as $t_{esc} \propto E^{-\delta}$

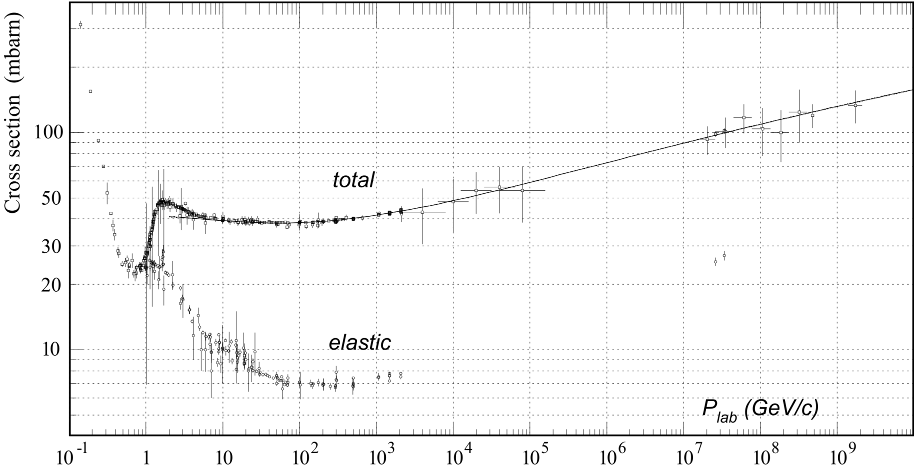
- Bohm-type $\delta = 1$
- Kolmogorov-type $\delta = 1/3$
- Kreichnan-type $\delta = 1/2$

Deflection by Galactic magnetic field

- large-scale magnetic field strength in Galactic disk $\sim 3\mu$G
- thickness of Galactic disk ~ 300 parsec
- above $\sim 2 \times 10^{19}$ eV all Cosmic Rays are not confined in the disc
- extragalactic Cosmic Rays deflect by an angle $\theta_{\rm defl} \sim Z/E_{18}$

Arrival directions of the highest-energy CRs ($\gtrsim 10^{20}$ eV)
point towards sources with less than 15° deviation even for iron nuclei
(less than 1° for protons)

proton-proton cross-section



Olive et al. (Particle Data Group), Chin. Phys. C (2014)

Interaction of Cosmic Rays with matter

pp reaction

$p + p \to$ 2 nucleons $+$ pions (main channel)

cross-section $\approx$ 30 mbarn, almost independent of energy in GeV-TeV range

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Three branches with approx. equal probabilities, π^0, π^+, π^-

$\pi^0 \to 2\gamma$

$\pi^+ \to \mu^+ + \nu_\mu$
$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$

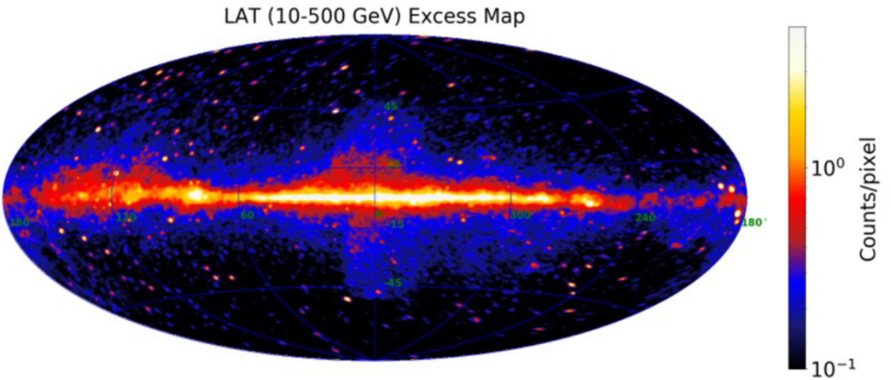
$\pi^- \to \mu^- + \bar{\nu}_\mu$
$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$

energy shares in secondaries

- (1/6): electrons and positrons
- (1/3): photons
- (1/2): neutrinos $\longleftarrow$ source of astrophysical neutrinos (1 of 2)

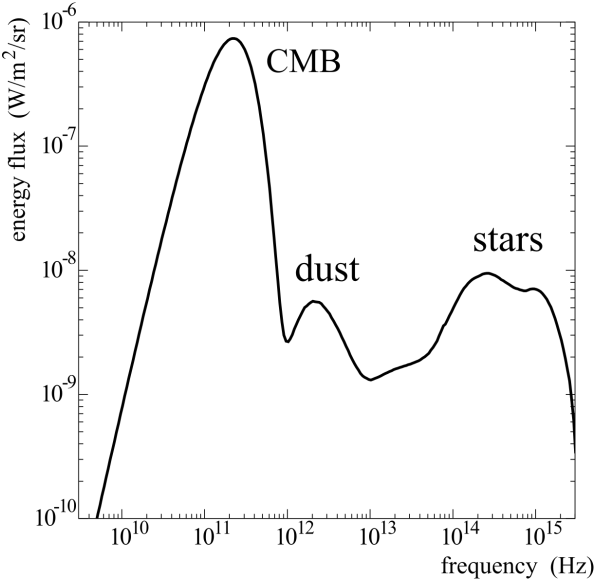
Each of these particles has energy ~ 0.1 of the primary's energy

GeV sky map



Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. (2022)

Extragalactic background light



Stecker & Salamon, ApJ 1999

Energy loss channels

$e^- e^+$-pair production (Bethe-Heitler process)

$\gamma + \text{El. field} \rightarrow e^- + e^+$

cross-section $\sigma_{\rm pp} \approx 1.5\ Z^2$ mbarn

inelastisity $\epsilon \approx 10^{-4}\ A^{-1}$

photodisintegration

$\gamma + {}^{56}Fe \rightarrow$

$\rightarrow$ lighter nucleus + nucleon(s)

cross-section $\sigma_{\rm dis} \approx 100$ mbarn

inelastisity $\epsilon \approx 0.02$

photo-pion reaction

$p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0$

$\rightarrow n + \pi^+$

cross-section $\sigma_\pi \approx 0.6$ mbarn

inelastisity $\epsilon \approx 0.2$

Inelastisity ϵ — fraction of energy lost per interaction

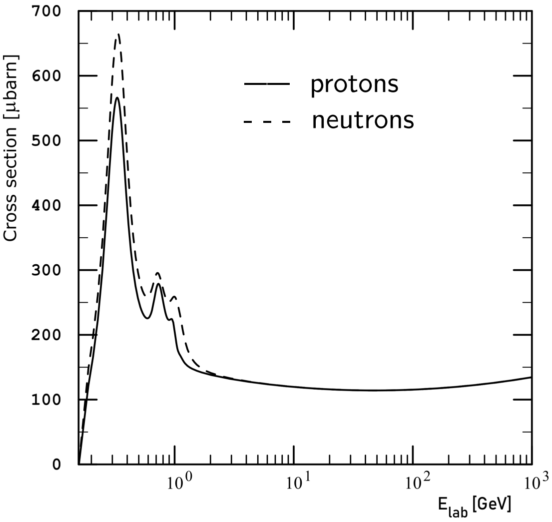
Photo-pion reactions

$$p + \gamma \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$

$$n + \gamma \rightarrow \Delta^{0} \rightarrow n + \pi^{0}$$
$$\rightarrow p + \pi^{-}$$

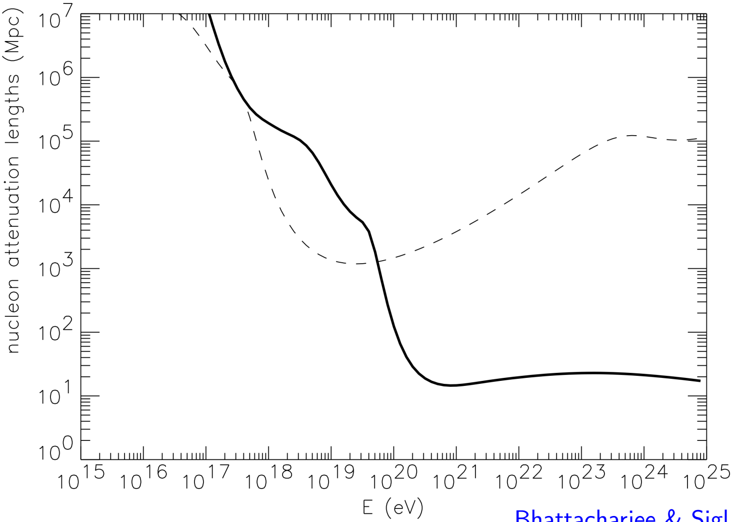
decay of charged pions
$\longrightarrow$ 2nd source
of astrophysical neutrinos

$E_\nu \sim 0.05 E_p$



Bhattacharjee & Sigl, Phys. Rep. 2000

GZK (Greisen–Zatsepin–Kuzmin) horizon

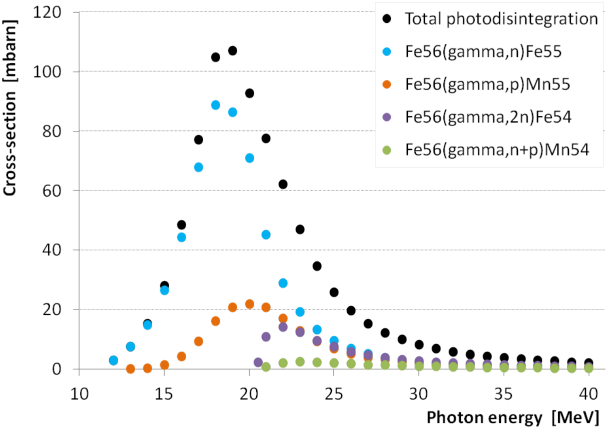


Bhattacharjee & Sigl, Phys. Rep. 2000

nucleon attenuation lengths: solid line — photo-pion production

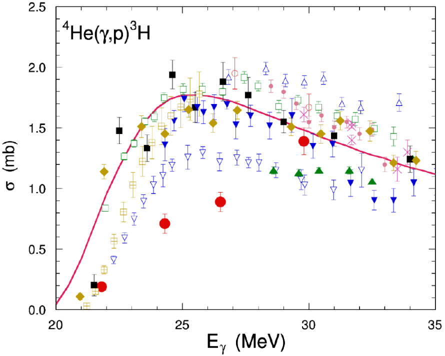
dashed line — pair production

Giant Dipole Resonance photo-disintegration

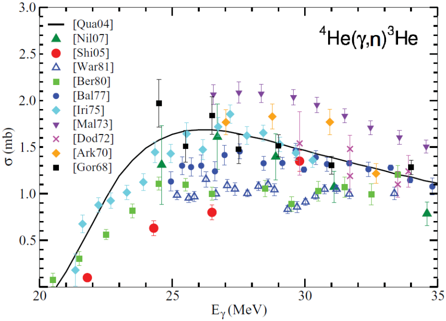


Borodina et al. (2000)

Photo-disintegration of Helium



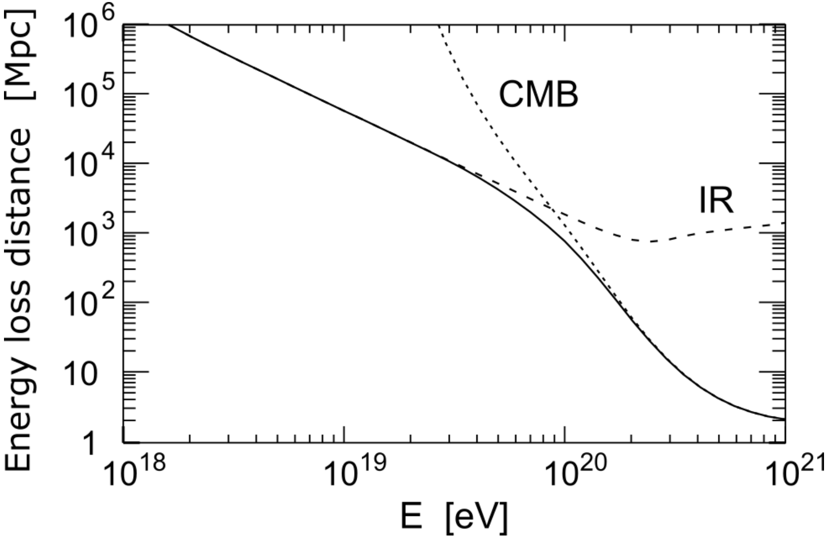
Raut et al., Phys Rev Lett (2012)



Tornow et al., Phys Rev C (2012)

For He nuclei, photodisintegration dominates over pair production losses

Iron nuclei losses



Epele & Roulet, Phys. Rev. Lett. 1998

Cosmic Ray horizon at $E = 10^{20}$ eV

protons

Attenuation distance ~ 100 Mpc (due to photo-pion losses)

- ~ 30 AGNs and a few galaxy clusters are within this distance

Helium nuclei

Attenuation distance ~ 2 Mpc (due to photodisintegration)

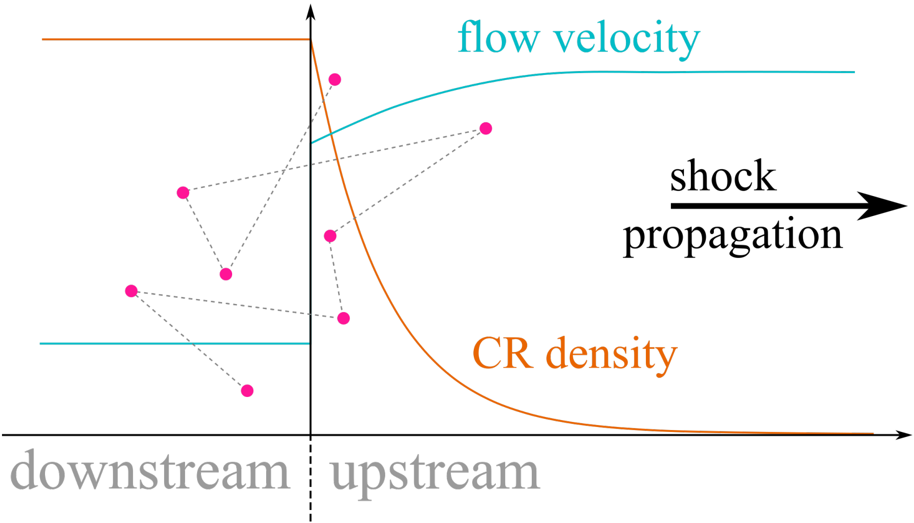
- the nearest *currently active* AGN (Cen A) is at $3 \div 4$ Mpc
- the nearest galaxy cluster (the Virgo Cluster) is at $15 \div 20$ Mpc

Iron nuclei

Attenuation distance ~ 700 Mpc (due to photodisintegration)

- $\sim 10^4$ AGNs and ~ 300 galaxy clusters are within this distance

Schematic view of particle-accelerating shock



Diffusive shock acceleration

Flow's work done on CRs

$$P_{flow} = \left(\frac{1}{3} E\, N_{\rm E}\, {\rm d}E \right) V_{\rm sh}$$

=

Power of acceleration

$$P_{acc} = \dot{E}\, (N_{\rm E}\, {\rm d}E\ \lambda)$$

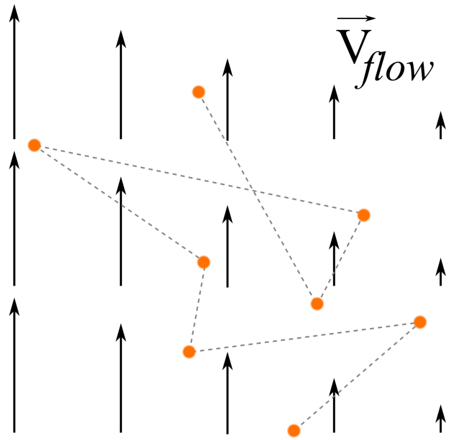
Acceleration rate

$$\dot{E} = \frac{1}{3} \frac{E V_{\rm sh}}{\lambda} = \frac{1}{3} \frac{E V_{\rm sh}^2}{\mathcal{D}} \left(= \frac{V_{\rm sh}^2}{c^2} qBc \ \text{ with Bohm diffusion} \right)$$

Energy distribution — power-law $N_{\rm E} \propto E^{-\alpha}$ with index $\alpha = \dfrac{(V_u/V_d)+2}{(V_u/V_d)-1}$

In strong non-relativistic shocks compression ratio is $V_u/V_d = 4$ and $\alpha = 2$

Acceleration in shear flows



Acceleration rate

$$\dot{E} \sim \frac{(\nabla V_{\rm fl} \lambda)^2}{c^2} qBc \propto E^2$$

innate problem:
acceleration takes too long
at lower energies $\left(t_{\rm acc} \propto E^{-1} \right)$

more like an energy-boost process
rather than
standalone acceleration mechanism

Summary 1

- Cosmic Rays extend in energy beyond 10^{20} eV.
- There are two components:
  lower-energy, likely Galactic, with $E_{\rm CR} < 5 \times 10^{18}$ eV
  higher-energy, likely extragalactic, with $E_{\rm CR} > 5 \times 10^{18}$ eV
- The highest-energy cosmic rays ($E_{\rm CR} \gtrsim 10^{20}$ eV) must come from nearby sources
- There are two common (diffusive) acceleration mechanisms:
  shock acceleration
  shear-flow acceleration acceleration (energy boost)
- *One more mechanism will be discussed later*