Cosmic Rays, Fermi acceleration, Ultra-High-Energy Cosmic Rays (UHECRs), and Ultra-High-Energy (UHE) neutrinos:

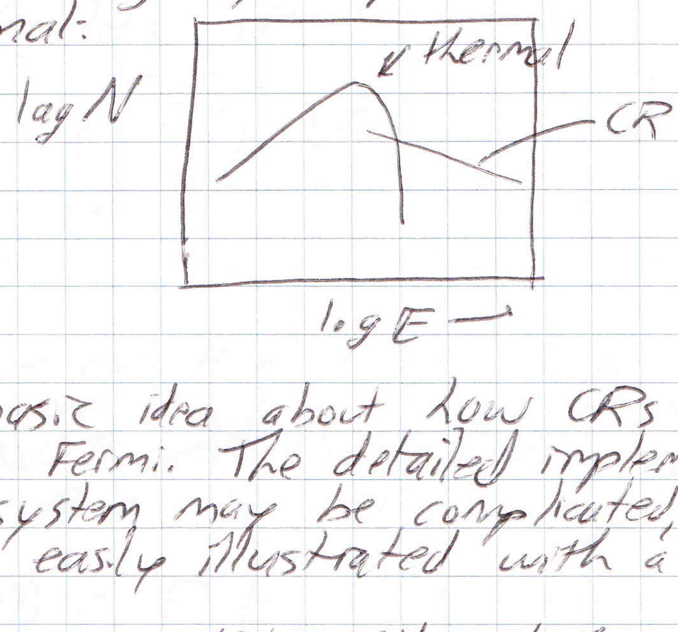
Everywhere that there are astrophysical plasmas, there are <u>cosmic rays</u> which I here define to be high-energy particles (e.g., protons and electrons) with non-thermal power-law spectra,

$$\frac{dN}{dE} \propto E^{-p} \quad \text{with } p \cong 2.2-2.7 \text{ typically.}$$

E.g., CR e^-'s are inferred through the synchrotron emission they emit in SNRs, radio lobes, AGN jets, the MW, GRBs, ~~etc~~ cluster shocks, ...

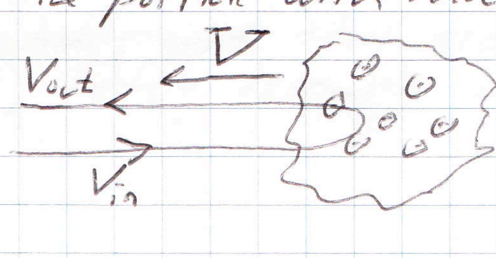
CR protons are seen in the Milky Way; they are also ~~acce~~ seen in the solar wind.

Thermal processes produce thermal energy distributions which are exponentially (Boltzmann) suppressed, $\exp[-E/kT]$ at high energies; the power laws must therefore be nonthermal:



The basic idea about how CRs are accelerated is due to Fermi. The detailed implementation in any given system may be complicated, but the basic idea is easily illustrated with a toy model.

Suppose a particle with velocity v_{in} is incident on a cloud of plasma, with $\vec{B}$ fields out of the page, moving toward the particle with velocity V



The magnetized cloud acts like a moving mirror that reflects the particle. Since it is moving, the particle receives an energy kick, much like a ping-pong ball when you hit it with a paddle.

If the reflection is elastic in the mirror frame, then the reflected particle has energy

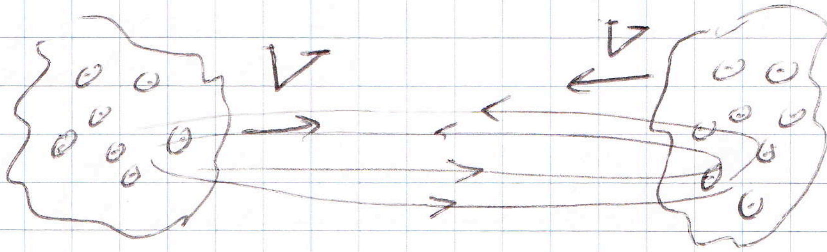
$$E_{out} = \Gamma^2\left(1 + 2\frac{v}{c}\frac{V}{c} + \frac{V^2}{c^2}\right)E_{in} \quad \text{where} \quad \Gamma = \frac{1}{\sqrt{1-V^2/c^2}}$$

Thus, if the particle is relativistic, ($\frac{v}{c} \simeq 1$), then

$$E_{out} = \left(1 + 2\frac{V}{c} + \frac{V^2}{c^2}\right)\Gamma^2 E_{in}$$

(which recovers $E_{out} = 4\Gamma^2 E_{in}$ familiar from inverse-Compton scattering by a relativistic e^- in the $\Gamma >> 1$ limit, and $1 + 2V/c$ in the NR limit).

Now suppose that there are two clouds approaching with velocities V:



The particle can then keep bouncing off the clouds, increasing its energy by a multiplicative factor,
$P = \cancel{1+2V/c+V^2/c^2}\ (1+V/c)^2\Gamma^2$ each time. After bouncing n times, it will have an energy

$$E(n) = P^n E_{in}$$

Suppose that after each scatter, there is a chance f that the particle escapes the system. If so, then the number of particles with that scatter n times (to an energy $E(n)$) before escaping is

$$N(n) \propto (1-f)^n$$

Writing $n = \frac{\ln(E/E_0)}{\ln \beta}$, and with some algebraic rearrangement, the number of particles with energy E is

$$N(E) \propto E^{1-p} \quad \text{with} \quad 1-p = \frac{\ln(1-P)}{\ln \beta}$$

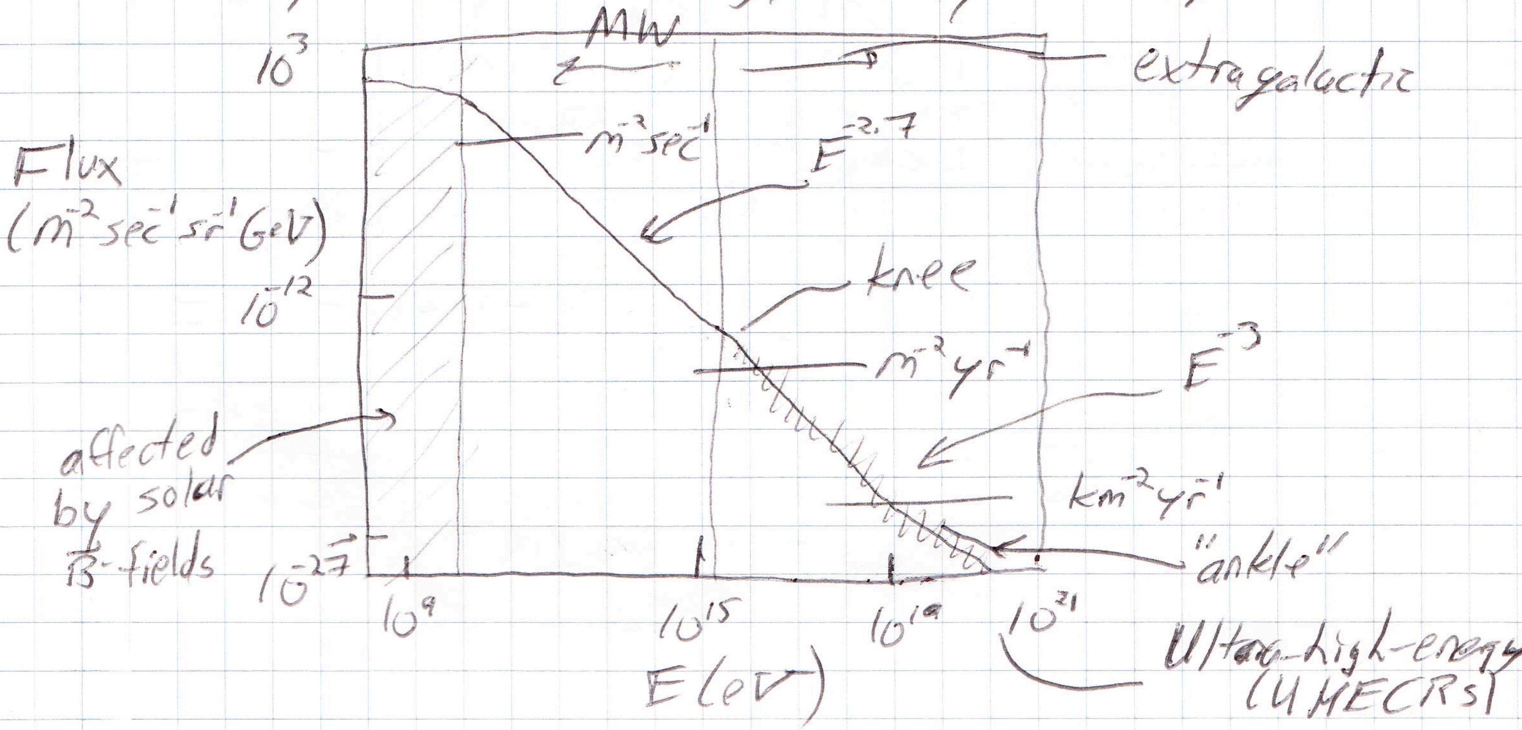
or $$\frac{dN}{dE} \propto E^{-p},$$

and this is how a power-law spectrum arises.
A little more work shows (e.g., see Longair for NR case) why $p \simeq 2$–2.5 may be expected.

More realistically, these "clouds" may be magnetic-field irregularities or (more likely) the magnetized fluid in front and behind a shock.

Conceptual question: How are such large non-thermal energies consistent with equipartition? Answer: CR acceleration can be viewed as approach to equipartition between particles (mass m) and motions of bulk flows of fluids with macroscopic masses $M \gg m$. Even if $v_{bulk} \ll c$, will have $Mv^2 \gg mc^2$.

Local CR flux (contains e^-, e^+'s, $\bar{p}$'s, heavier elements, but most of energy density is in protons)



One more fact about acceleration:

The maximum energy to which a CR can be accelerated is limited by the (Larmor radius) $\lesssim$ (size of accelerating region):

or

$$R_L = \frac{\gamma m v}{eB} \overset{\gamma \gg 1}{\simeq} \frac{E}{ceB}$$

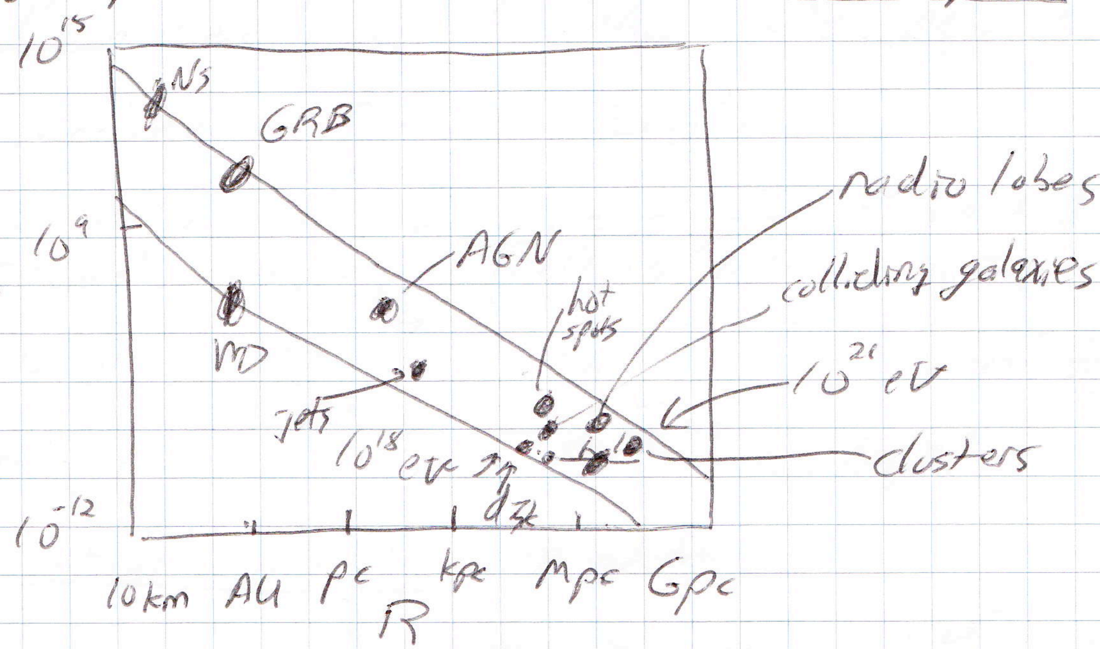
$$\Rightarrow \quad E_{max} \simeq 10^{21}\,\mathrm{eV}\left(\frac{B}{G}\right)\left(\frac{R}{pc}\right).$$

E.g., a SNR ($R \sim 10\,pc$, $B \sim 100\,\mu G$) $\Rightarrow$ $E_{max} \simeq 10^{15}\,\mathrm{eV}$

$\Rightarrow$ subankle CRs thought to be accelerated in SNRs.

Also MW ($\sim 10\,kpc$, μG) can contain CRs up to $\sim 10^{18}\,\mathrm{eV}$ $\Rightarrow$ $E \gtrsim 10^{18}\,\mathrm{eV}$ are <u>extragalactic</u>

Can put potential accelerators on <u>Hillas plot</u>:



UHECRs ($E \gtrsim 10^{[illegible]}$ eV $- 10^{[illegible]}$ eV; extragalactic):

If CR proton has energy above

$$E_{GZK} \simeq \frac{m_\pi^2}{E_{CMB}} \simeq \frac{(140\ \mathrm{MeV})^2}{3\times10^{-4}\ \mathrm{eV}} \simeq 10^{20}\ \mathrm{eV}$$

(the GZK — Greisen-Zatsepin-Kuzmin) bound, it can produce a pion through $p + \gamma_{CMB} \to p + \pi^0$, $\to n + \pi^+$.

with the mean-free-path for this is

$$\lambda = \frac{1}{n_\gamma \sigma} \approx \frac{1}{(411\ \mathrm{cm}^{-3})\,\cancel{(10^{-14}\ \mathrm{cm})^2}\,\cancel{(3\times10^{-13}\ \mathrm{cm})^2}\,(3\times10^{-15}\ \mathrm{cm})^2} \sim$$

~ 100 Mpc.

Thus any sources producing $\gtrsim 10^{20}$ eV particles <u>that we see</u> must be within ~ 100 Mpc distance.

$\Rightarrow$ Expect decline in flux at $\gtrsim 10^{20}$ eV;

is now seen by <u>Auger</u>, a 3000-km^2 ground array in Argentina (Nov. 2007)

Energy density in $\gtrsim 10^{19}$ eV CRs is $\overset{?}{\sim} 5\times10^{52}\ \mathrm{erg}/\mathrm{Mpc}^3$

Energy production rate $\sim 5\times10^{44}$ erg/Mpc^3/yr

<u>Waxman-Bahcall limit to UHE neutrinos:</u>

If UHECR protons lose energy in source and through $\gamma p \to n\pi^+$ or ~~pp~~ $p + p \to p + p + \pi^\pm + \ldots$, the charged pions decay to ν's: $\pi^\pm \to \mu^\pm + \nu_\mu$, $\mu \to e^\pm \nu_\mu \nu_e$.

The maximum intensity of such ν's is

$$I_{max} \simeq 10^{-8}\ \mathrm{GeV/cm^2/s/sr} \qquad E_\nu \simeq E_p/20$$

Constrains models where $\pi^0 \to \gamma\gamma$ produces large gamma-ray background