Astroparticle Physics
- an introduction with a focus on galactic cosmic rays

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Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten

Von V. F. Hess
(Physik. Zeitschr. **14**, 1084, 1912)

[...]

Die Ergebnisse der vorliegenden Beobachtungen scheinen am ehesten durch die Annahme erklärt werden zu können, daß eine eine Strahlung von sehr hoher Durchdringungskraft von oben her in unsere Atmosphäre eindringt und auch noch in den untersten Schichten einen Teil der in geschlossenen Gefäßen beobachteten Ionisation hervorruft.

[...]

The fifth ballon flight

1 Introduction

Cosmic rays is all radiation consisting of charged relativistic particles impinging on the Earth' atmosphere

High energy cosmic rays: $E > 1$ GeV

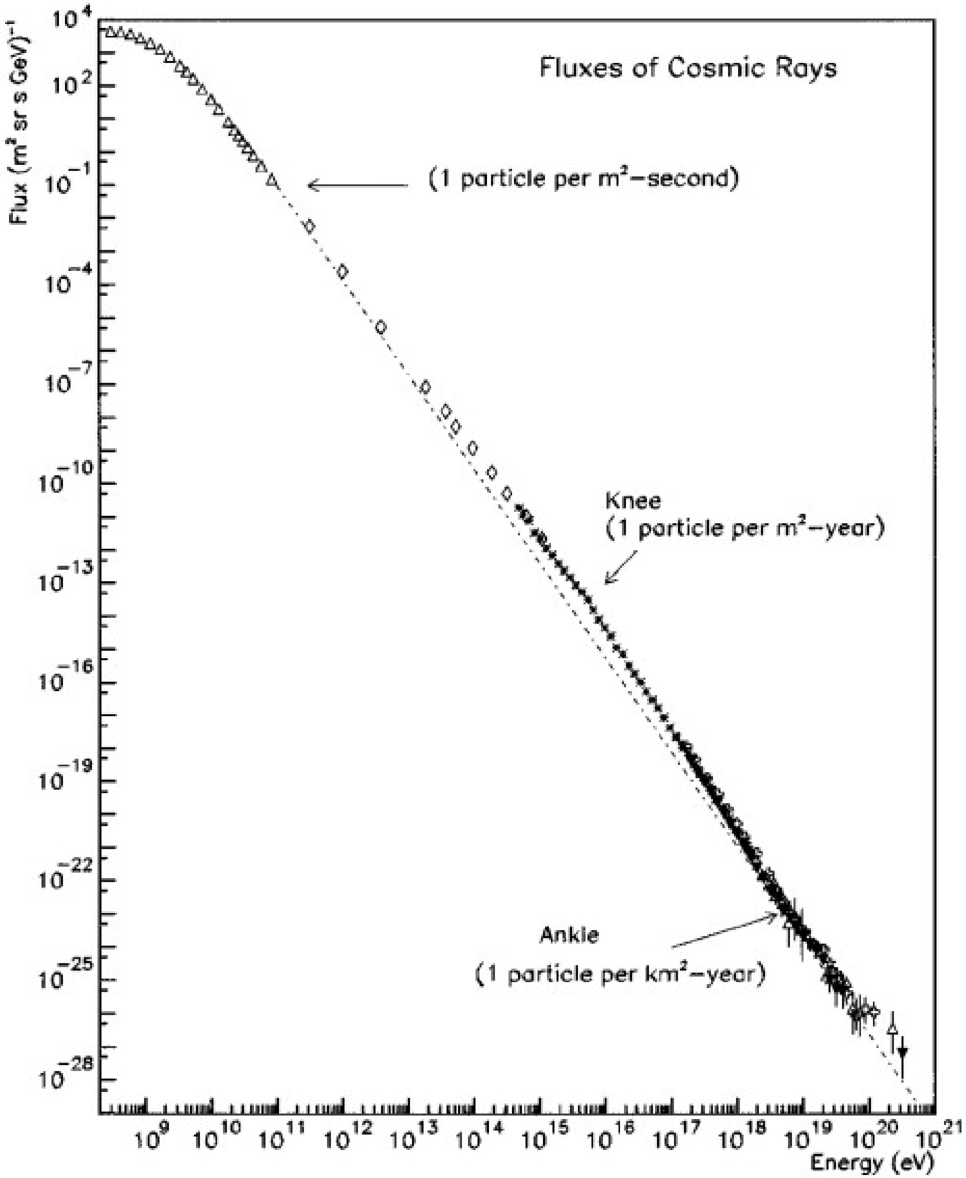
Gamma-ray and neutrinos

- created as secondaries of high energy cosmic rays
- help to learn more about cosmic rays and their sources (“multi-messenger”)

Cosmic Ray Spectrum

- nearly featureless
- extending over eleven orders of magnitude from
  a few GeV to a few · 10^{20} eV

Many more known (later)



Historical Remarks

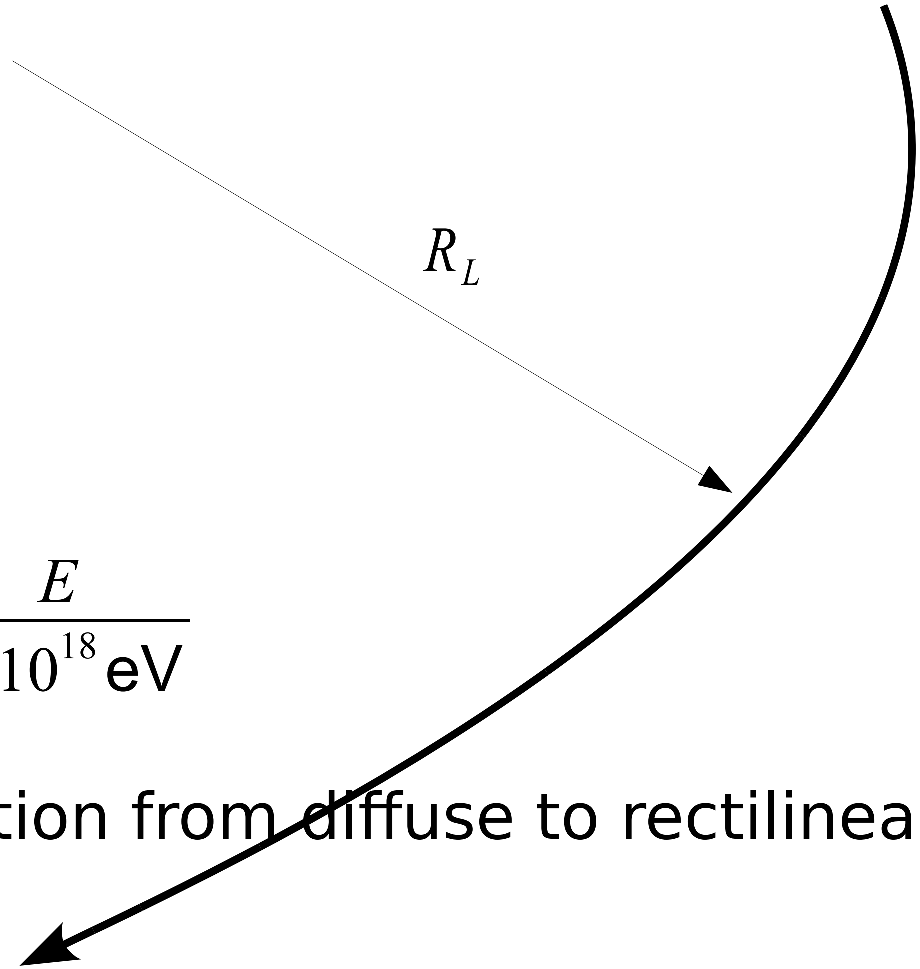
1912 Victor Hess discovered cosmic rays
1929 Skobelzyn observed first cosmic ray in cloud chamber; Bothe & Kohlhörster showed that tracks are curved in a magnetic field
1928 Clay observed latitude effect
1932 Anderson discovered the positron in cosmic rays
1932 Raged debate in USA about sources of cosmic rays
1934 The sign of the east-west asymmetry showed that cosmic rays are positively charged
1934/1938 Rossi and Auger discovered extensive air showers
1934 Bethe and Heitler developed the electromagnetic cascade theory
1949 Fermi proposed that cosmic rays are accelerated by bouncing off magnetic clouds
1952/1954 First human accelerator reaching $p > 1$ GeV
1972 Launch of the SAS-2 satellite marked the start of high energy gamma-ray astronomy
1976 Start of the first prototype of a large scale underwater detector for high energy neutrino astronomy, DUMAND, in Hawaii
1989 First detection of the Crab Nebula in very high energy gamma-rays ($E>100$ GeV)
1998 Superkamiokande found first convincing evidence for massive neutrinos
...

Aspects of Cosmic Ray Physics

- Astrophysical aspects
  - What are the sources?
  - How do they accelerate cosmic rays?
  - What happens during the journey of cosmic rays to Earth?
- Interactions of particles in the atmosphere
- Experimental methods to detect cosmic rays, gamma rays, neutrinos
- Connections between cosmic ray physics and searches for physics beyond the Standard Model

Our Milky Way

Our Milky Way



- Average magnetic field

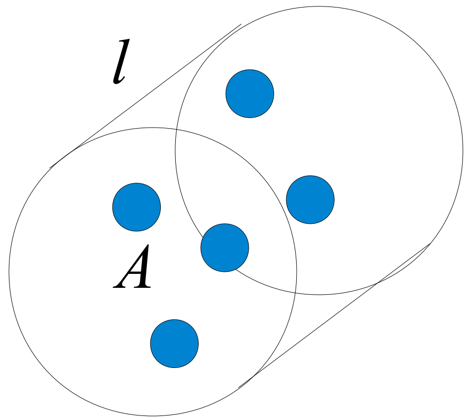
$$B = 3\,\mu\text{G}$$

- Lamour radius

$$R_L \;=\; \frac{c\,p}{z\,e\,B} \;\approx\; 100\,\text{pc}\,\frac{3\,\mu\text{G}}{B}\,\frac{E}{Z\cdot 10^{18}\,\text{eV}}$$

- $E = 10^{18}\,\text{eV}$ marks the transition from diffuse to rectilinear propagation of cosmic rays

Basic notation of particle physics – a reminder



- **Optical/interaction depth**

$$\frac{N\sigma}{A} = n\,l\,\sigma = \tau = \text{optical depth}$$

- **Absorption**

$$dI = -I\,d\tau = -I\,n\,\sigma\,dl$$

$$I = I_0 \exp(-\tau) \quad \text{or} \quad I(l) = I_0 \exp\left(-\int_0^l dl\,n\,\sigma\right)$$

- Slant depth

$$X(l) = \int_0^l dl'\,\rho(l')$$

measures the weight per area of the material crossed

Galactic Cosmic Rays – Basic observations

- Integral intensity $I(>E)=\int_E^\infty dE'\, I(E')$
- Flux $\Phi = \int d\Omega\, I(E)\cos\theta = I(E)\int_0^{2\pi} d\phi \int_0^{\pi/2} d\theta \sin\theta\cos\theta$

$$= \pi I(E)\int_0^{\pi/2} d\theta \sin 2\theta = \pi I(E)$$

  for isotropic intensity

- (differential) number density of particles with velocity v

  $n(E)=\frac{4\pi}{v} I(E)$

More general

$$I = \frac{d^4 N}{d\,A\,dt\,d\,\Omega\,dE}$$

$$d\,N = f(\vec{x}, \vec{p})\,d^3 x\,d^3 p$$

with $f(\vec{x}, \vec{p})$ = phase space distribution

$$\Rightarrow \quad I(\vec{x}, p, \theta, \phi) = v\,p^2 \frac{dp}{dE} f(\vec{x}, \vec{p}) = p^2 f(\vec{x}, \vec{p})$$

Abundances

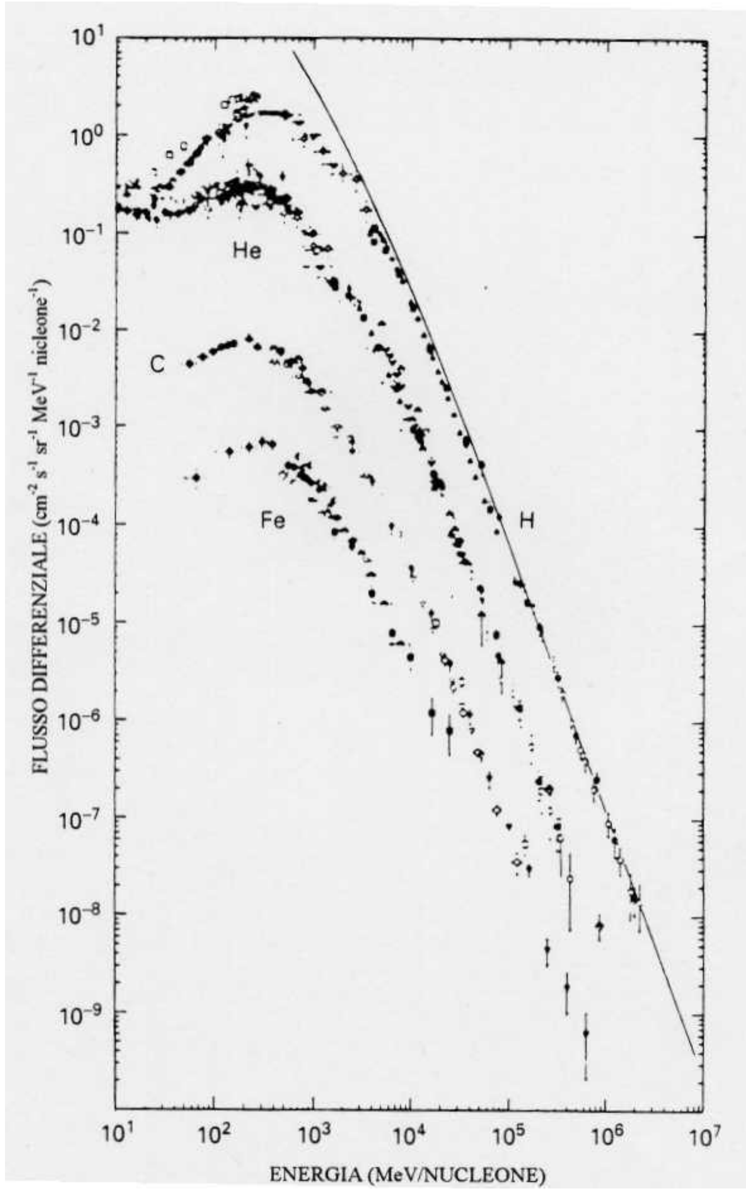
- Nuclei 98%
- Electrons 1%

Nuclei

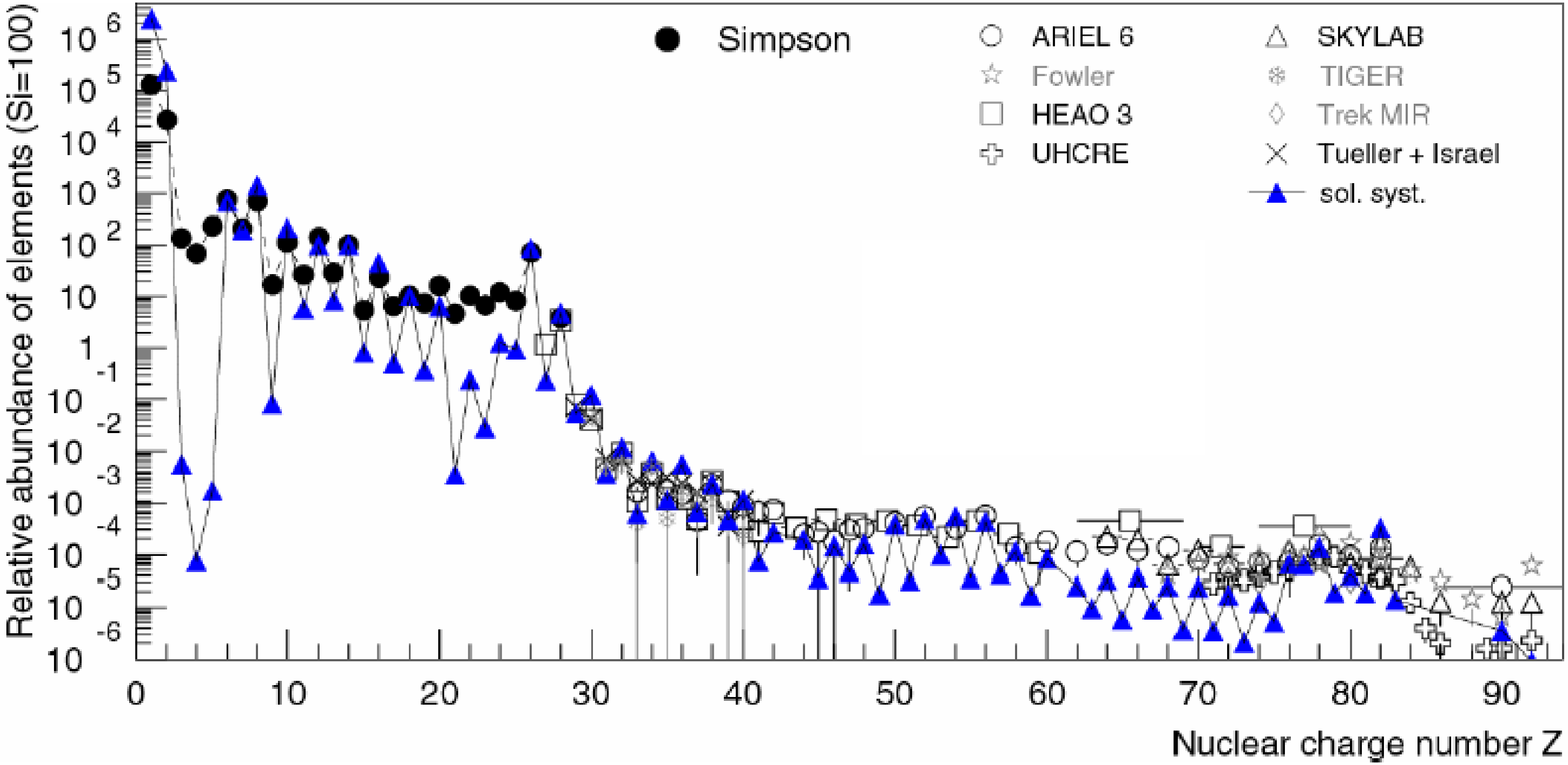
- Protons 87%
- He 12%
- heavier nuclei ~1%

Above a few GeV

$$I(E) \sim 1.8\, E^{-\alpha} \frac{\text{particles}}{\text{cm}^2\,\text{s}\,\text{sr}\,\text{GeV}}$$



Abundances



measured ratio $\frac{n_{LiBeB}}{n_{CNO}} \approx 0.25$

Cascade equation for two species of particles

$$\frac{d\,n_p}{d\,X} = -\frac{n_p}{\lambda_p} \text{ and } \frac{d\,n_s}{d\,X} = -\frac{n_s}{\lambda_s} + p_{sp}\frac{n_p}{\lambda_p}$$

$X = \int dl\,\rho(l)$ measures the amount of transversed matter

$\lambda_i = m/\sigma_i$ interaction lengths (in gr/cm^2)

$p_{sp} = \sigma_{sp}/\sigma_{tot}$ spallation probability

Solution $\frac{n_s}{n_p} = p_{sp}\frac{\lambda_s}{\lambda_s - \lambda_p}\left[\exp\left(\frac{X}{\lambda_p} - \frac{X}{\lambda_s}\right) - 1\right]$ for $n_s(0) = 0$

$$\frac{n_s}{n_p} = p_{sp} \frac{\lambda_s}{\lambda_s - \lambda_p} \left[\exp\left(\frac{X}{\lambda_p} - \frac{X}{\lambda_s} \right) - 1 \right]$$

$s =$ LiBeB with $\lambda_s \approx 10\, g/cm^2$

$p =$ CNO with $\lambda_p \approx 6.7\, g/cm^2$ and $p_{sp} = \frac{\sigma_{sp}}{\sigma_{tot}} \approx 0.35$

$$\left(\frac{n_s}{n_p} \right)_{meas} \approx 0.25$$

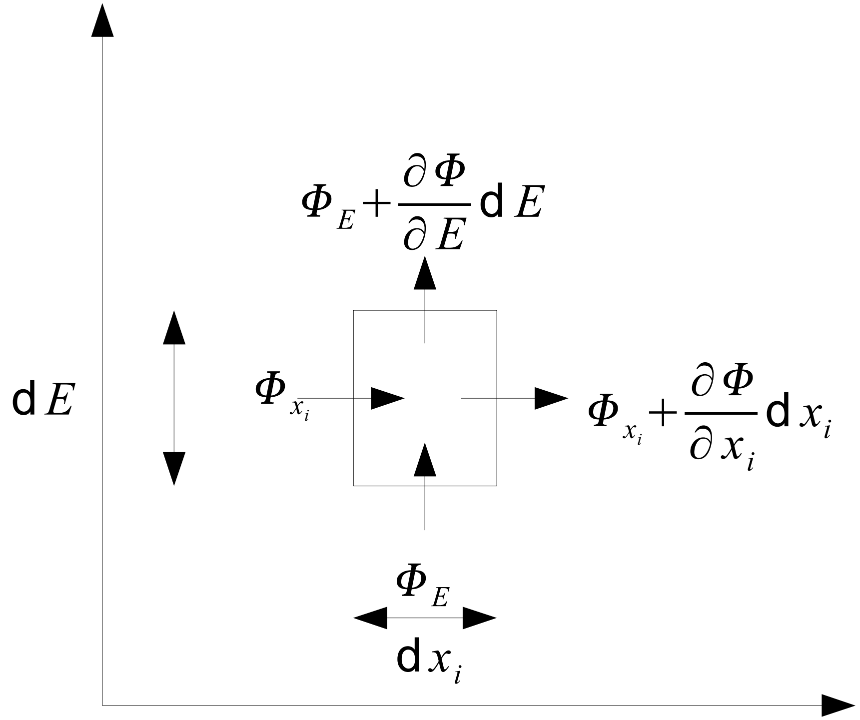
⇒ fits for $X \approx 0.56\, g/cm^2$

Slant depth of the Milky Way $X = m_H n_H h \approx 10^{-3}\, g/cm^2$

⇒ propagation of cosmic rays resembles a random-walk.

We can describe Cosmic Rays in the Milky Way as fluid!

Diffusion-equation



$n_i(E, \vec{r}, t)$ = electron density

$$= \frac{\mathrm{d}^2 N}{\mathrm{d}V\,\mathrm{d}E}, \quad \mathrm{d}V = \mathrm{d}x_1\,\mathrm{d}x_2\,\mathrm{d}x_3$$

$\Phi_E(E, \vec{r}, t)$ = energy flux per volume

$\Phi_{x_i}(E, \vec{r}, t)$ = spatial flux per energy interval

$Q(E, \vec{r}, t)$ = production rate of $e^{\pm}$ per volume per energy interval

$$
\begin{aligned}
\frac{\partial}{\partial t} n(E, \vec{r}, t)\,\mathrm{d}E\,\mathrm{d}V &= Q(E, \vec{r}, t)\,\mathrm{d}E\,\mathrm{d}V \\
&+ \left[\Phi_E(E, \vec{r}, t) - \left(\Phi_E(E, \vec{r}, t) + \frac{\partial \Phi_E}{\partial E}\mathrm{d}E\right)\right]\mathrm{d}V \\
&+ \sum_{i=1}^{3}\left[\Phi_{x_i}(E, \vec{r}, t) - \left(\Phi_{x_i}(E, \vec{r}, t) + \frac{\partial \Phi_{x_i}}{\partial x_i}\mathrm{d}x_i\right)\right]\mathrm{d}E\,\frac{\mathrm{d}V}{\mathrm{d}x_i}
\end{aligned}
$$

$$
\Rightarrow \frac{\partial n}{\partial t} = -\vec{\nabla}\vec{\Phi}_{\vec{r}} - \frac{\partial \Phi_E}{\partial E} + Q
$$

Flux ~ gradient of the concentration $\Rightarrow \quad \Phi_{x_i} = D_{ij}\frac{\partial n}{\partial x_j}$

$$
\Rightarrow \frac{\partial n}{\partial t} = \vec{\nabla}(D\vec{\nabla} n) - \frac{\partial \Phi_E}{\partial E} + Q. \qquad D = (D_{ij}) = \text{Diffusion tensor}
$$

Loss rate due to energy loss mechanisms

$$
-\frac{\mathrm{d}E}{\mathrm{d}t} \equiv b(E) \quad \Rightarrow \quad n(E)\frac{\mathrm{d}E}{\mathrm{d}t} = \Phi_E = -b(E)\,n(E)
$$

Diffusion loss equation

$$\frac{\partial n}{\partial t}=\vec{\nabla}(D\vec{\nabla}n)+\frac{\partial}{\partial E}\left[b(E)n(E)\right]+Q(E)$$

Isotrope medium $\Rightarrow$ $D=$ Skalar, no spacial extension

$\Rightarrow$ $\vec{\nabla}(D\vec{\nabla}n)=D\vec{\nabla}^2 n$

Energy loss mechanisms for electrons

Energy loss rate $\dfrac{\mathrm{d}E}{\mathrm{d}t}$,

Cooling times $\tau = \dfrac{E}{(\mathrm{d}E/\mathrm{d}t)}$

Ionisation

Hydrogen $\left(-\dfrac{\mathrm{d}E}{\mathrm{d}t}\right)_{\mathrm{ion}} = 7.64 \cdot 10^{-15} \left(\dfrac{n_H}{\mathrm{m}^{-3}}\right)(3 \quad \ln\gamma + 19.8)\,\mathrm{eV\ s}^{-1}$

↑

relativistic rise (Bethe-Bloch)

Thus $\left(\dfrac{\mathrm{d}E}{\mathrm{d}t}\right) \approx 10^{-5} \left(\dfrac{n_H}{\mathrm{m}^{-3}}\right) \mathrm{eV\ Jahr}^{-1}$ and $\tau \sim E\, n_H^{-1}$

Bremsstrahlung (interaction with nuclei)

Hydrogen $$\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\text{brems}} = 3.66\cdot 10^{-22}\left(\frac{n_H}{\mathrm{m}^{-3}}\right) E\,\mathrm{s}^{-1}$$

H-plasma $$\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\text{brems}} = 7.0\cdot 10^{-23}\left(\frac{n_H}{\mathrm{m}^{-3}}\right)(\ln\gamma + 0.36)\, E\,\mathrm{s}^{-1}$$

$\Rightarrow \quad \tau \sim n_H^{-1}$

Adiabatic losses

Adiabatic extension of a source (e.g. SNR)

$\mathrm{d}U = -p\,\mathrm{d}V$

(Expansion of a volume → work → loss of inner energy)

e.g. homogenously expanding sphere $\left(-\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\text{ad}} = \left(\frac{1}{R}\frac{\mathrm{d}R}{\mathrm{d}t}\right) E$

$\Rightarrow \quad \tau \sim const$

Synchrotron-radiation

Source: high energy electrons/positrons in B-field

Basics: Radiation in rest frame of the charge (Lamor Formula)

$$-\frac{\mathrm{d}E}{\mathrm{d}t}=\frac{q^2|\ddot{\vec{r}}|^2}{6\pi\epsilon_0 c^3} \quad \left(\frac{\mathrm{d}E}{\mathrm{d}t} \text{ is lorentz-invariant}\right)$$

Dipol-radiation: $|\vec{E}|\sim|\sin\theta|$

$$I(\theta)\sim\sin^2\theta$$

Polarisation: $\vec{E}\|\vec{r}$ at large distance $\perp$ diplo axis

Example: Motion in a constant B-field

$$v_\perp=v\sin\theta, \quad v_\|=\cos\theta$$

Cyclotron-frequency $(\gamma m\dot{\vec{v}}=q\vec{v}\times\vec{B})$

$$\nu_g=\frac{1}{2\pi}\frac{qB}{\gamma m}$$

$q = e\,, \quad m = m_e$

$\nu_g = 2.8\,\gamma^{-1}\,\mathrm{MHz}\,(B/1\,\mathrm{G}) \rightarrow$ Radio

$|\vec{a}| = |\dot{\vec{v}}_\perp| = \dfrac{eB}{\gamma\, m_e}\, v \sin\alpha$ Zentripetal acceleration in B-System (Laboratory)

$|\vec{a}\,'| = \gamma^2 |\vec{a}|$ in current rest frame

Lamor-Formula

$$-\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{e^2 |\ddot{\vec{r}}|^2}{6\pi\epsilon_0 c^3} = s \underbrace{\left(\frac{e^4}{6\pi\epsilon_0^2 c^4 m_e^2}\right)}_{\sigma_T} \left(\frac{v}{c}\right)^2 c \underbrace{\left(\frac{B^2}{2\mu_0}\right)}_{U_{\mathrm{mag}}} \gamma^2 \sin^2\alpha$$

$$\sigma_T = \frac{e^4}{6\pi\epsilon_0^2 c^4 m_e}\,, \quad U_{\mathrm{mag}} = \frac{B^2}{2\mu_0}\,, \quad \epsilon_0 \mu_0 = 1/c^2$$

$$\Rightarrow \quad \boxed{\left(-\frac{\mathrm{d}E}{\mathrm{d}t}\right) = 2\,\sigma_T\, c\, U_{\mathrm{mag}} \left(\frac{v}{c}\right)^2 \gamma^2 \sin^2\alpha}$$

Average over isotropical velocity distribution

$$\langle \sin^2\alpha \rangle = \frac{1}{2}\int_{-1}^{1} \mathrm{d}\cos\alpha \sin^2\alpha = \frac{1}{2}\int_{-1}^{1} \mathrm{d}u\,(1-u^2) = \frac{2}{3}$$

$$\begin{aligned}\left\langle -\frac{\mathrm{d}E}{\mathrm{d}t}\right\rangle &= \frac{4}{3}\sigma_T c\, U_{\mathrm{mag}} \left(\frac{v}{c}\right)^2 \gamma^2 \\ &= 1.058\cdot 10^{-14} (B/\mathrm{T})^2 \gamma^2 \beta^2\,\mathrm{W}\end{aligned}$$

for particles with an isotropical velocity distribution

Cooling time $\tau_{\mathrm{sy}} = \frac{3\, m_e^2 c^3}{4\sigma_T U_{\mathrm{mag}} E} = 4\cdot 10^{10} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-2} \left(\frac{E}{1\,\mathrm{TeV}}\right)^{-1}\mathrm{s}$

Cooling is more efficient for higher energies $\Rightarrow$ steepening of the electron spectrum

Inverse Compton-effect

Compton effect

Kinematics

$$\frac{\Delta\lambda}{\lambda}=\epsilon(1-\cos\alpha),\quad \epsilon=\frac{\hbar\omega}{m_e c^2}$$

Dynamics: Klein-Nishima

$$\sigma_{\mathrm{KN}} = \frac{\pi r_e^2}{\epsilon}\left\{\left[1-\frac{2(\epsilon+1)}{\epsilon}\right]\ln(2\epsilon+1)+\frac{1}{2}+\frac{4}{\epsilon}-\frac{1}{2(2\epsilon+1)^2}\right\}$$

$$\approx\begin{cases}\sigma_T(1-2\epsilon) & \epsilon\ll 1 \text{ (Thomson-Grenzfall)}\\ \pi r_e^2\frac{1}{\epsilon}(\ln(2\epsilon)+\frac{1}{2}) & \epsilon\gg 1 \text{ (ultrarelativistisch)}\end{cases}$$

Inverse Compton-effect

Energy loss rate of electrons

$U_{\text{rad}} \equiv$ energy density of the isotropical radiation field with $\gamma \hbar \omega \ll m_e c^2$

$$\left\langle -\frac{\mathrm{d}E}{\mathrm{d}t} \right\rangle = \frac{4}{3} \sigma_T c U_{\text{rad}} \left(\frac{v}{c} \right)^2 \gamma^2$$ (see sychrotron radiation)

Cooling time $\tau_{\text{sy}} = \frac{3 m_e^2 c^3}{4 \sigma_T U_{\text{rad}} E} = 4 \cdot 10^{13} \left(\frac{E}{1\,\text{TeV}} \right)^{-1} \text{s}$ for $U_{\text{CMB}} = 0.25\,\text{eV/cm}^3$

Diffusion lost equation

$$\frac{\partial n}{\partial t} = \vec{\nabla} (D \vec{\nabla} n) + \frac{\partial}{\partial E} [b(E) n(E)] + Q(E)$$

How to solve?

- define source distribtution
- define boundary conditions

Most simple example

- infinite, homogeneous source distribution
- Injection spectrum $Q(E)=K\cdot E^{-x}$
- steady state

$$\Rightarrow \quad \frac{\partial n}{\partial t}=0, \quad \vec{\nabla} n=\vec{0}$$

$$\Rightarrow \frac{\mathrm{d}}{\mathrm{d}E}[b(E)n(E)]=-Q(E)$$

$$\Rightarrow n(E)=-\frac{1}{b(E)}\cdot\frac{K}{1-x}E^{-x+1}+\underbrace{const}_{=0,\text{ because }\lim_{E\to\infty} n(E)=0}$$

$$\boxed{\Rightarrow n(E)=\frac{K}{x-1}\frac{E^{-(x-1)}}{b(E)}}$$

Ansatz for $b(E) = -\frac{\mathrm{d}E}{\mathrm{d}t}$: (leading orders in E)

$$b(E) = A_1 \left(2 \ln \frac{E}{m_e c^2} + 19{,}8\right) + A_2 E + A_3 E^2$$

↑	↑	↑
Ionisation	Bremsstrahlung (+adiabatic losses)	Synchrotron, I.C.

Ionisation dominates $\Rightarrow n(E) \sim E^{-(x-1)} \sim E \cdot Q(E)$

Bremsstrahlung dominates $\Rightarrow n(E) \sim E^{-x} \sim Q(E)$

Synchrotron radiation + I.C. dominates $\Rightarrow n(E) \sim E^{-(x+1)} \sim \frac{Q(E)}{E}$

Simple description of the diffusion („Leaky box type“)

$\tau(E)$ = life time in „galactic confinement volume“

- D = 0 in confinement volume
- loss term = $\dfrac{n(E)}{\tau(E)}$

Comparison of cooling times

$$\underbrace{\tau_1 < \tau_2 \ldots}_{} \ll \tau(E) \ll \underbrace{\tau_k < \ldots < \tau_n}_{}$$

relevant energy	not relevant
loss mechanisms	particles escape
→ steady state solution	before loosing energy
without diffusion	

Example

Typical for nuclei: $\tau \simeq (1 \cdots 3) \cdot 10^7$ years

Assumption: τ similar for $e^{\pm}$

$E = 300$ MeV , $n_H = 10^6$ m^{-3} $\rightarrow \tau_{\text{ionisation}} \simeq 3 \cdot 10^7$ Jahre

$\rightarrow$ Ionisation relevant for $E \leq 300$ MeV

$\rightarrow n(E) \sim E^{-(x-1)}$

$E = 3$ GeV , $n_H = 10^6$ m^{-3} $\rightarrow \tau_{\text{brems}} \simeq 5 \cdot 10^7$ Jahre

$\rightarrow$ Bremsstrahlung relevant around $E \simeq 1$ GeV

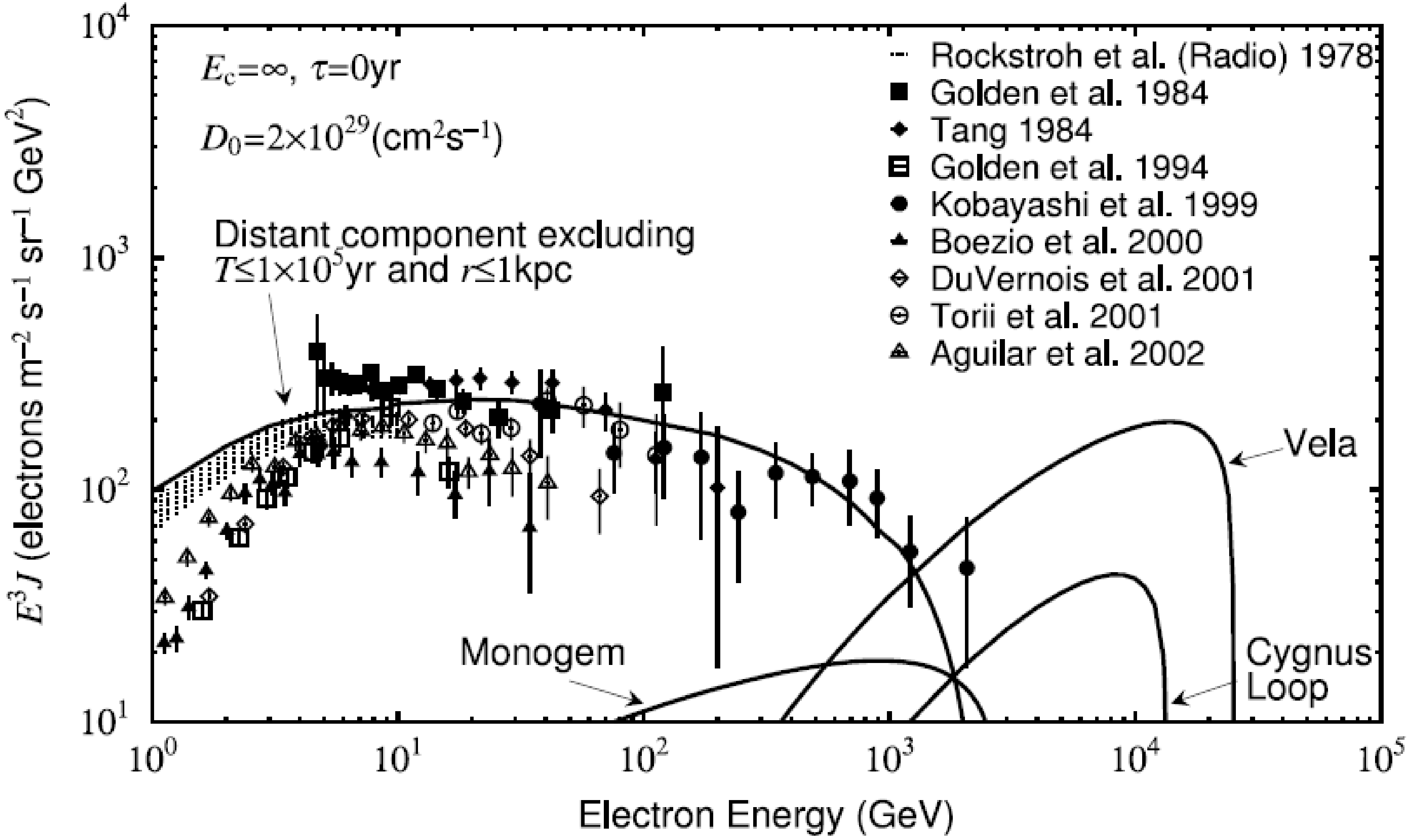
$\rightarrow n(E) \sim E^{-x}$

$E = 10$ GeV , $B = 6 \cdot 10^{-10}$ T $\rightarrow \tau_{\text{synchr}} \simeq 3 \cdot 10^5$ Jahre $\simeq O(\tau_{\text{IC}})$

$\rightarrow$ Synchr. + I.C. relevant for $E > 10$ GeV

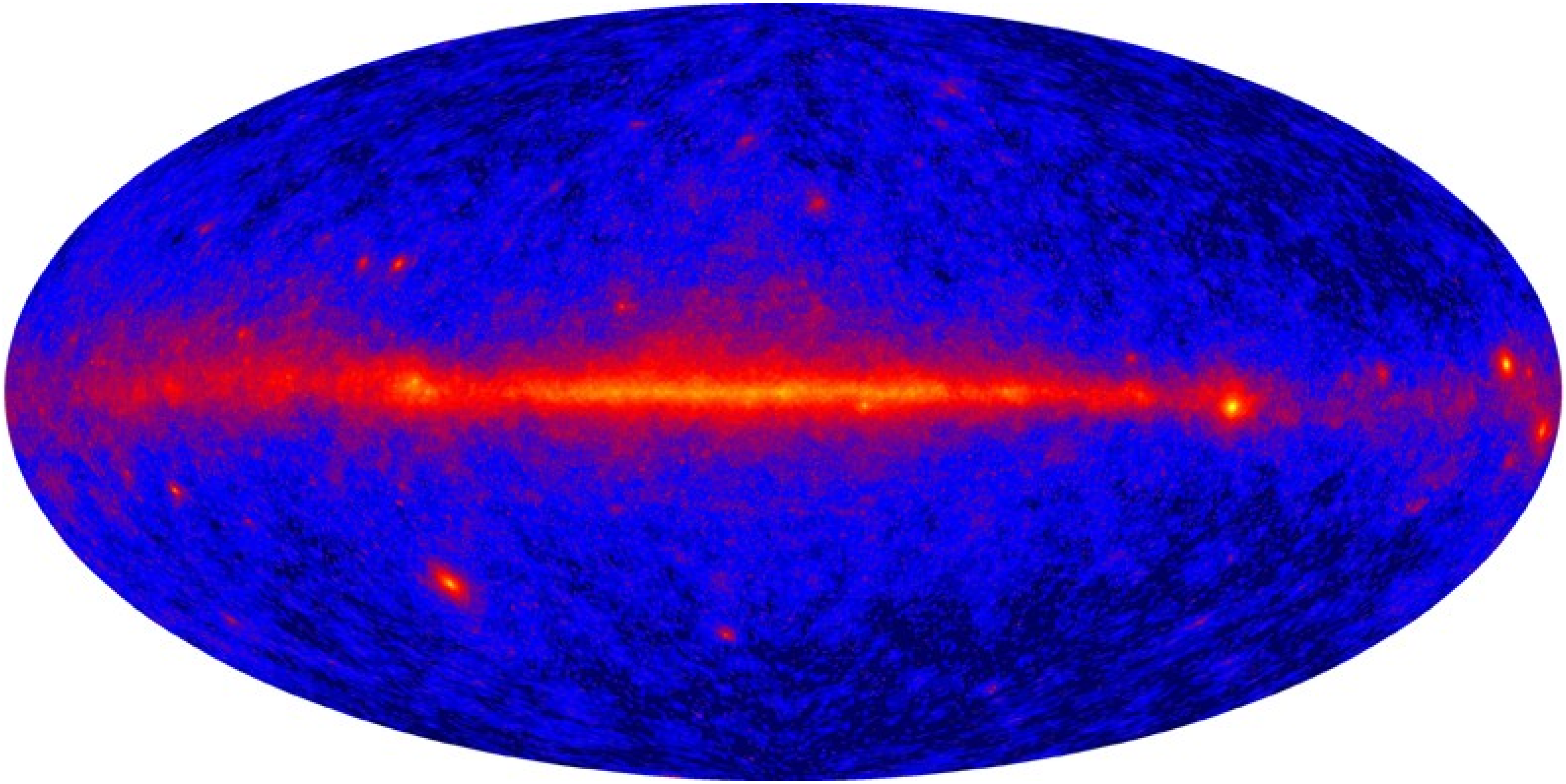
$\rightarrow n(E) \sim E^{-(x+1)}$

$\rightarrow O(100\,\text{pc})$


$E_c=\infty$, τ=0yr
$D_0=2\times10^{29}$(cm^{2}s^{-1})
Rockstroh et al. (Radio) 1978
Golden et al. 1984
Tang 1984
Golden et al. 1994
Kobayashi et al. 1999
Boezio et al. 2000
DuVernois et al. 2001
Torii et al. 2001
Aguilar et al. 2002
Distant component excluding
$T\leq1\times10^5$yr and $r\leq$1kpc
Vela
Monogem
Cygnus
Loop
$E^3 J$ (electrons m^{-2} s^{-1} sr^{-1} GeV^2)
Electron Energy (GeV)
10^0
10^1
10^2
10^3
10^4
10^5

Diffusion of nuclei

Galactic gamma-rays



Direct measurement of the radiation power in the Milky Way $L_\gamma(E_\gamma > 100\,\text{MeV}) \approx 10^{32}\,\text{W}$

Inelastic cross-section for $p\,Nuclei \rightarrow X$

$$\sigma_{pp} \approx \left[31.5 + 0.46 \ln^2(E/50\,\mathrm{GeV})\right] \mathrm{mb} \qquad (1\,\mathrm{mb} = 10^{-31} m^2)$$

$$\sigma_{pA}/\sigma_{pp} \approx A^{2/3}(1.3 + 0.15 \log_{10} A) \qquad (\text{good for } A > 7)$$

Interaction probability $P = \frac{N\sigma}{A} = n\,dl\,\sigma \overset{!}{=} \frac{dl}{\lambda}$

Interaction length $\lambda = \frac{1}{n\sigma}$ $\qquad (n_H = 1 \ldots 2 \cdot 10^6\, 1/\mathrm{m}^3)$

Interaction rate $\nu_{WW} = c/\lambda = \sigma\, n\, c$

$pp \rightarrow \quad \pi^{\pm}, \quad \pi^0, \ldots$

$\rightarrow \gamma\gamma$ dominant for γ-Spectrum for $E < 100\,\mathrm{MeV}$

$\rightarrow$ Neutrino source

Isospinsymmetrie $\Rightarrow$ $\approx \frac{2}{3} E$ in $\pi^{\pm}, \approx \frac{1}{3}$ in π^0 $(\rightarrow \gamma\gamma)$

Test of the $\pi^0 \to \gamma\gamma$ hypothesis

$$L_\gamma \approx \nu_{WW}(pp) \cdot \sum_{i\ \text{(CR in Galaxy)}} \frac{E_i}{3} = \frac{1}{3} \sigma_{pp} n_H c \epsilon_{CR} \cdot V_{\text{Galaxy}}$$

ϵ_{CR} $= \text{energy density of charged CR} \approx \text{protonen}$

$\approx 10^6 \, \text{eV m}^{-3}$

n_H $\approx 10^6 \, \text{m}^{-3}$

σ_{pp} $\approx 32 \cdot 10^{-31} \, \text{m}^2$

V_{Galaxy} $\approx 400 \, pc \cdot \pi \cdot (8 \, \text{kpc})^2 \approx 2 \cdot 10^{60} \, \text{m}^3$

$\Rightarrow$ $L_{\pi \to \gamma\gamma} \approx 1.3 \cdot 10^{32} \, \text{W}$

Measured

$$L_\gamma (E_\gamma > 100 \, \text{MeV}) \approx 10^{32} \, \text{W}$$

Diffusion equation for nuclei

$$\frac{\partial n_i}{\partial t} = \vec{\nabla}(D\vec{\nabla} n_i) + \frac{\partial}{\partial E}\left[b(E) n_i(E)\right] + Q(E) - \frac{n_i}{\tau_i} + \sum_j P_{ij} \frac{n_j}{\tau_j}$$

n_i = Number density of nuclei i

$\tau_i(E)$ = Lifetime for spallation from nuclei i

$P_{ij}(E)$ = Mean number of nuclei i per spallation from nuclei j
($P_{ij} \neq 0$ only for $A($ nuclei $i) < A($nuclei $j)$

Simple approximation for light nuclei in isotropic medium

- diffusion small compared to spallation loss $\Rightarrow$ $D \approx 0$
- $m_{\text{nuclei}} \gg m_e \Rightarrow n$ no energy losss $\Rightarrow$ $b(E) \approx 0$
- light nuclei: Li, Be, B rare $\Rightarrow$ $Q_i(E) \approx 0$

Where are we – a short summary

- Cosmic rays are messengers from the high energy Universe
- The cosmic rays we measure on Earth are typical for the cosmic rays population in our Milky Way
- Cosmic-ray propagation can be described by a diffusion equation, i.e. cosmic rays behave like a fluid in a box

- Next steps (today)
    - Age of cosmic rays → sources must be active now
    - Energy dependent propagation → source spectra are power laws $dn/dE \sim E^{-2}$
    - Acceleration of cosmic rays
    - Source detection?

Simplest assumption

All CR have the same fixed age ξ after injection when observed on Earth

$$\Rightarrow \quad \Rightarrow \quad \frac{\mathrm{d}n_i}{\mathrm{d}\xi} = -\frac{n_i(\xi)}{\xi_i} + \sum_j P_{ij} \frac{n_j(\xi)}{\xi_j}$$ with $n(\xi)$ observed on Earth

<u>L-Kerne</u> (L = light): Li, Be, B; $n_L(0)=0$ Injection time (there are no sources

<u>M-Kerne</u> (M = medium): C, N, O most abundant primary nuclei, $n_M(0) \neq 0$

Spallation M→L, M $P_{\mathrm{ML}} \approx \overbrace{0.28}^{\text{Fragmentationswahrscheinlichkeit}}$ $P_{\mathrm{MM}}=0$

L/→M,L $P_{\mathrm{LM}}=P_{\mathrm{LL}}=0$

$$\frac{\mathrm{d}n_{\mathrm{M}}}{\mathrm{d}\xi} = -\frac{n_{\mathrm{M}}(\xi)}{\xi_{\mathrm{M}}}$$ no refill

$$\frac{\mathrm{d}n_{\mathrm{L}}}{\mathrm{d}\xi} = -\frac{n_{\mathrm{L}}(\xi)}{\xi_{\mathrm{L}}} + \frac{P_{\mathrm{ML}}}{\xi_{\mathrm{M}}} n_{\mathrm{M}}(\xi)$$

X-section $\Rightarrow$ $\xi_{\mathrm{M}} \approx 60\,\mathrm{kg/m^2}$, $\xi_{\mathrm{L}} \approx 84\,\mathrm{kg/m^2}$ (from known X-sections)

Age of Cosmic Rays

Estimate of the confinement volume

$\xi = \bar{\rho} c \tau$ with $\bar{\rho} =$ mean density, $\xi = 48\,\mathrm{kg/m^2}$ $\Rightarrow$ $\tau = 3 \cdot 10^6$ years

Extension of a galaxy 1-10 kpc $\Rightarrow$ escape after $3 \cdot 10^3 - 3 \cdot 10^4$ years

$\Rightarrow$ confinement volume

Improved estimate of the age (confinement time):

Measure radioactive isotopes, half life time $\tau_{1/2}$

$\Rightarrow$ additional loss term: $\dfrac{u_i}{\tau_{\mathrm{dec}}(i)}$

$\tau_{\mathrm{dec}}(i) = \gamma_i \tau_{1/2} / \ln 2,$ γ_i $\Leftrightarrow$ time dilatation

Example

C,O $\overset{\text{spallation}}{\rightarrow}$ ^{7}Be, ^{9}Be, ^{10}Be 10% at birth

$^{10}\text{Be} \rightarrow {}^{10}\text{B} + e^{+} + \nu_e$

$\tau_{1/2} = 3.9 \cdot 10^{6}$ years

Measurement

$n(^{10}\text{Be})/n(^{7}\text{Be})$, $n(^{10}\text{Be})/n(^{9}\text{Be})$ $\Rightarrow$ only 28% ^{10}Be

$\Rightarrow$ mean age at arrival on Earth= $O(10^{7})$ Jahre

Simplified model

Leaky Box:

- $D = 0$
- loss term = $-\dfrac{n_i}{\tau_e(i)}$ τ_e = local escape time in galaxy

Steady state:

- $\dot{n}_i = 0$
- no source terms $Q_i = 0$, Be produce alone in spallation of C,O,N
- no energy loss $b(E) = 0$

$$\Rightarrow \qquad 0 = -\frac{n_i}{\tau_e(i)} - \frac{n_i}{\tau_{\text{Spal}(i)}} + \underbrace{\sum_{j \in \{\text{C,N,O}\}} \frac{P_{ij}}{\tau_{\text{Spal}(j)}} n_j}_{C_i}$$

for $i \in \{{}^7\text{Be}, {}^9\text{Be}\}$

and $$0 = -\frac{n_k}{\tau_e(k)} - \frac{n_k}{\tau_{\text{Spal}(k)}} + C_k - \frac{n_k}{\tau_{\text{dec}}(k)}$$

für $k = {}^{10}\text{Be}$

$$\Rightarrow \quad \boxed{\frac{n_k}{n_i} = \frac{C_k}{C_i} \frac{1/\tau_e(i) + 1/\tau_{\text{Spal}}(i)}{1/\tau_e(k) + 1/\tau_{\text{Spal}}(k) + 1/\tau_{\text{dec}}(k)}}$$

Measurement of $\frac{n_k}{n_i}$ $\Rightarrow \tau_e \approx 10^7$ years

with $\xi = 48\,\text{kg/m}^3$

$\Rightarrow \rho_{\text{IS}} \approx 3 \cdot 10^5\,\text{m}^3$

Die GZK Grenze

Magnetische Einschlussgebiete ↔ Gyroradius

$$r = R_B \frac{\sin\theta}{Bc}, \quad R_B = \frac{pc}{Ze}$$

Galaktisch: $B \approx 3 \cdot 10^{-10}$ T

Protonen

- $E \approx 10^{15}$ eV ⟶ $r \leq 0.36$ pc
  $\approx$ Skala der Diffusionsgleichung
  $\Rightarrow$ Isotropie
- $E > 10^{15}$ eV ⟶ Anisotropie steigt, Entweichzeit sinkt, Diffusion verliert an Relevanz
- $E \approx 10^{18}$ eV ⟶ $r \leq 3.6$ kpc ≈ Halo-Radius
- $E \approx 10^{21}$ eV ⟶ nicht galaktisch eingeschlossen

  $B \approx 3 \cdot 10^{-12}$ T $\Rightarrow r \leq 36\ Mpc \Rightarrow$ lokale Gruppe

Dominate Verlustprozesse höchstenergetischer Strahlung

Kollisionen mit CMB (+IR, V, ...) $\Rightarrow$ Photoproduktion

a) Schwelle

$$p+\gamma_{\text{CMB}}\rightarrow\begin{cases} n\pi^{+} \\ p\pi^{0}(\rightarrow\gamma\gamma)\end{cases}$$

$$\sqrt{s}\geq(m_p+m_\pi)c^2\approx 1.1\,\text{GeV}$$

Labor

$$\sqrt{s}\approx\sqrt{2\,p_p p_\gamma}\approx\sqrt{2\,E_p E_\gamma(1+\cos\theta)}\approx\sqrt{2\,E_p E_\gamma}$$

$$\Rightarrow E_p\approx\frac{s}{2\,E_\gamma}\geq\frac{(1.1\,\text{GeV})^2}{2\,E_\gamma}$$

Planck-Spektrum für $T\approx 2.73\,\text{K}$ $\Rightarrow$ $\boxed{E_p\geq 5\cdot 10^{19}\,\text{eV}}$

b) Erste Resonanz $\Rightarrow$ GZK-Cut-Off (Greisen, Za....)

$$p\,\gamma_{\text{CMB}}\rightarrow\Delta^{+}\rightarrow\begin{cases} n\pi+ & 33.3\,\% \\ \pi^{0}p & 66.7\,\%\end{cases}$$

$$(\uparrow\uparrow\downarrow)\,J^P=\left(\frac{1}{2}\right)^{+} \qquad (\uparrow\uparrow\uparrow)\,J^P=\left(\frac{3}{2}\right)^{+}$$

$$L=0 \qquad L=0$$

$$m_p=938\,\text{MeV}/c^2 \qquad m_\Delta=1232\,\text{MeV}/c^2$$

Schwelle

$$\sigma_{\gamma p}\approx 0.1\,\text{mb} \;\rightarrow\; \text{Resonanz}\,\sigma_{\gamma p}\approx 0.6\,\text{mb}$$

Resonanzlage

$$\sqrt{s}=m_\Delta c^2,\quad E_p\geq\frac{(m_\Delta c^2)}{2\,E_\gamma}\;\underset{T=2.73\text{K}}{\Rightarrow}\;E_p>6\cdot 10^{19}\,\text{eV}$$

Reichweite

$$\lambda = (\sigma_{\gamma p} n_\gamma)^{-1}$$
$$n_\gamma \approx 5 \cdot 10^8 \,\text{m}^{-3}, \quad \langle \sigma_{\gamma p} \rangle \approx 0.75 \,\text{mb}$$
$$\Rightarrow \lambda \approx 3 \,\text{Mpc}, \quad \tau_{\text{propagation}} \approx 10^7 \text{ Jahre}$$

- Höchstenergetische Protonen (>10^{20} eV) stammen aus lokaler Gruppe → Abfall des Spektrums (GZK Cut-Off)
- Beobachtung “Knöchel”, d.h. Ausflachung, Widerspruch? **(Spektrum Auger, Skymap Auger)**
- Beschleunigung in AGN?
- Exotische Alternative: Primordiale schwere Teilchen, $m > 10^{20} \,\text{eV}/c^2$
- das wird in den nächsten Jahren noch sehr spannend!!!!

z