High Energy Astrophysics: COSMIC RAYS

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OUTLINE OF THE LECTURES

- INTRODUCTION
  - SOME HISTORY
  - BASIC INFORMATION AND DATA
    - Spectrum
    - Chemical Composition

OUTLINE OF THE LECTURES

- COSMIC RAY TRANSPORT
  - Basic treatment of diffusion in a magnetic field
  - Interaction of particles and waves
  - Transport equation in the presence of diffusion, advection and energy losses
  - Specialization to acceleration and transport in the Galaxy

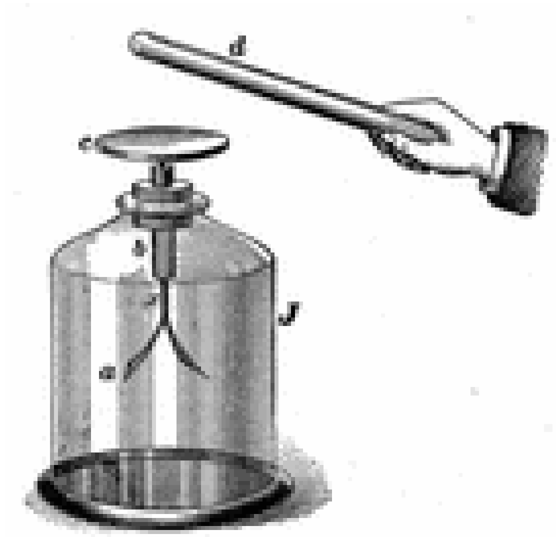
OUTLINE OF THE LECTURES

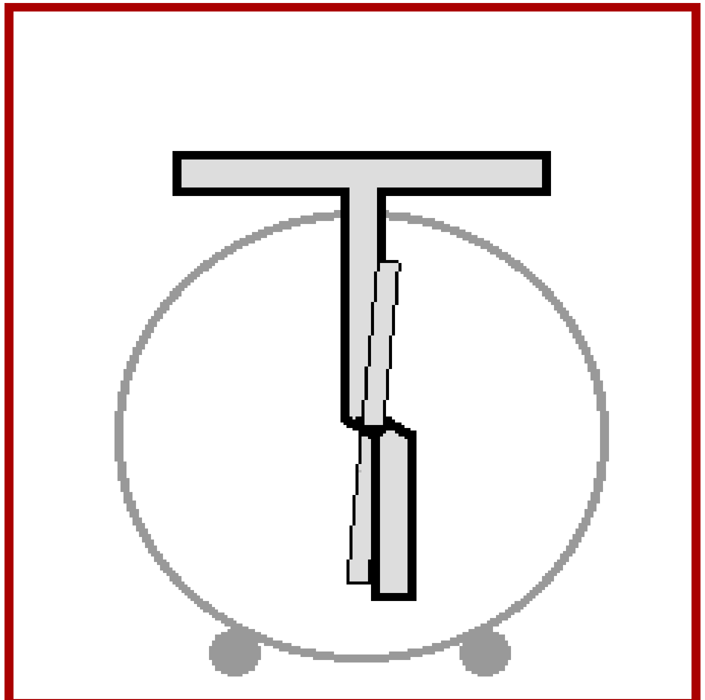
- **COSMIC RAY ACCELERATION**
  - **Particle Acceleration at non relativistic (NR) shocks: Test particle Theory**
  - **Particle Acceleration at NR shocks: the non linear (NL) theory**
    - Non linear dynamical reaction of accelerated particles
    - Magnetic field amplification and reaction
    - Maximum energy of accelerated particles
    - Escape of particles from the accelerator
  - **Particle Acceleration at relativistic shocks**
    - Basic elements
    - The spectrum
    - A general approach

OUTLINE OF THE LECTURES

- FROM GALACTIC TO EXTRAGALACTIC CR
  - The End of the Galactic CR spectrum
  - The origin of the first knee
  - …and of the second knee
  - An Ankle, a broken ankle or a dip?
  - Extragalactic cosmic rays
    - Protons, iron nuclei…
  - Ultra High Energy Cosmic Rays
    - Spectrum
    - Anisotropy
    - Chemical composition
    - Sources

Early History of Cosmic Rays



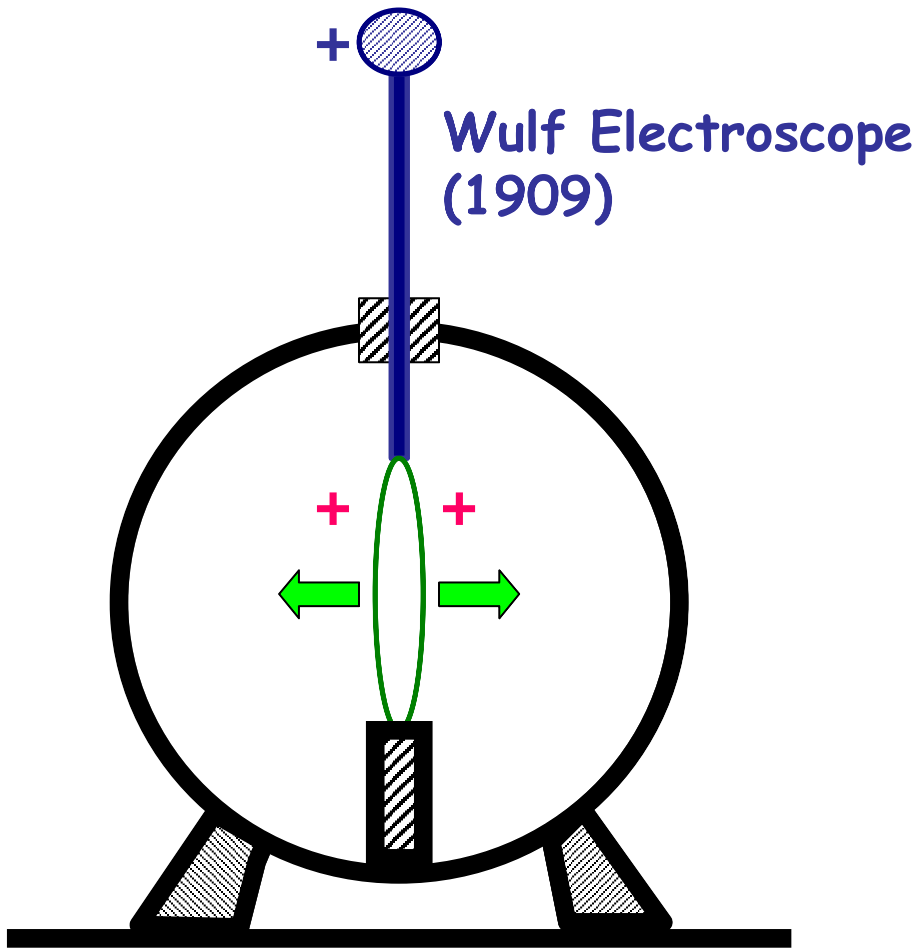


The electroscope is neutral as evidenced by the needle in a relaxed position.

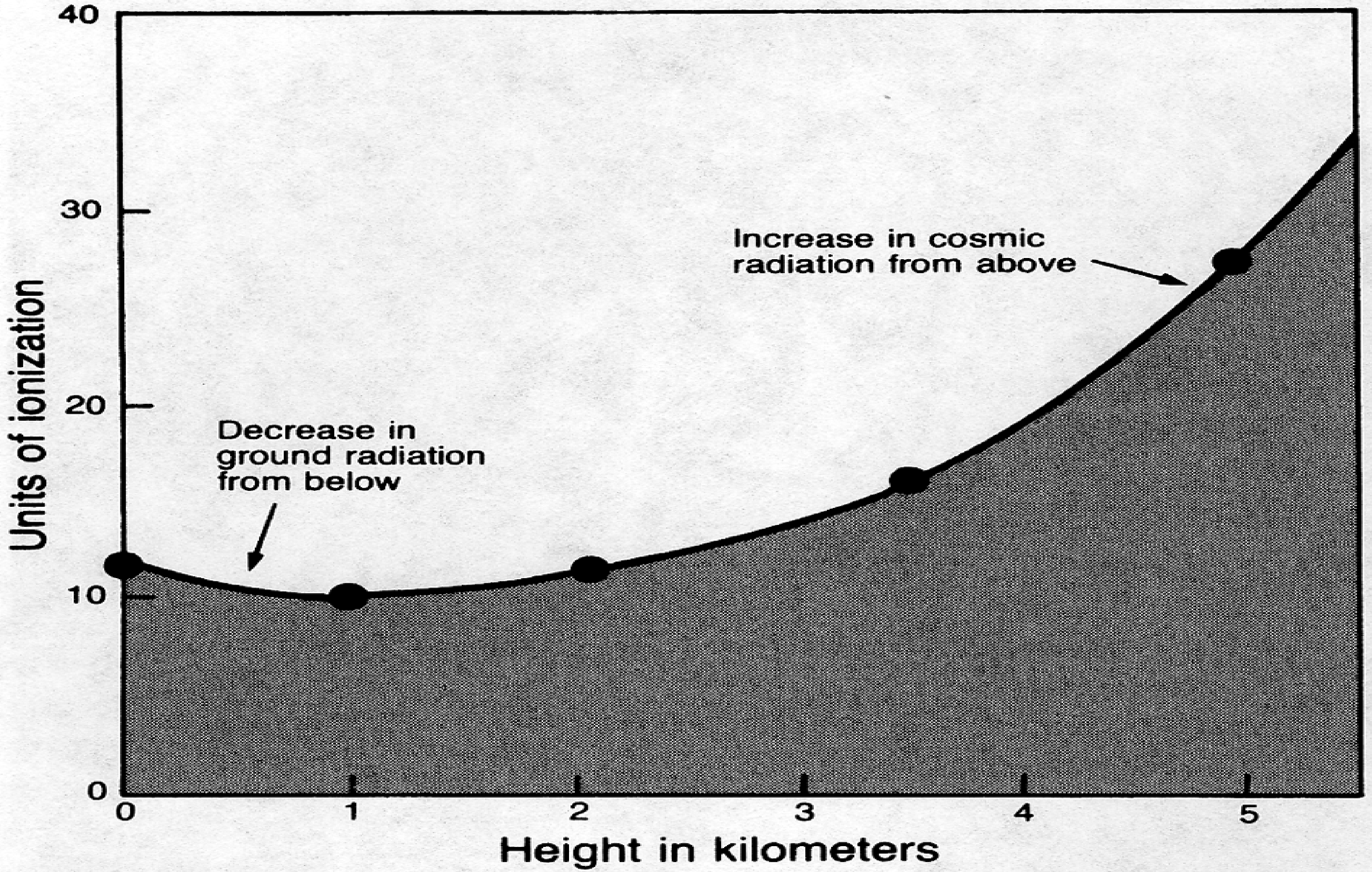
Ionized by what?

- 1895: X-rays (Roengten)
- 1896: Radioactivity (Becquerel)
- But ionization remained, though to a lesser extent, when the electroscope was inserted in a lead or water cavity

Victor F. Hess: the 1912 flight



COSMIC Rays


Units of ionization
40
30
20
10
0
0
1
2
3
4
5
Height in kilometers
Decrease in ground radiation from below
Increase in cosmic radiation from above

Millikan Theory

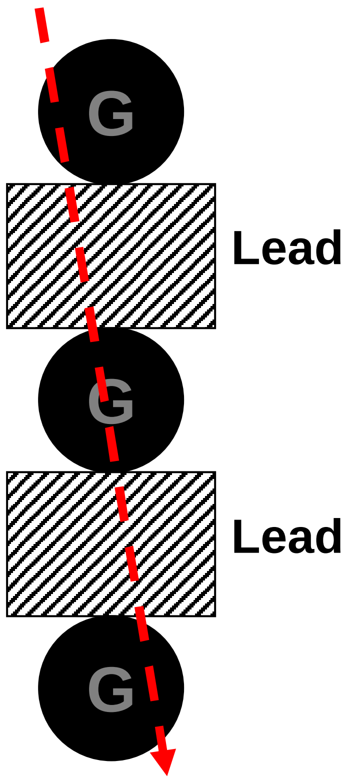
Cosmic Rays (as Millikan called them) are gamma rays as the birth cry of elements heavier than hydrogen

Millikan found that the absorption curve of CR was not compatible with one absorption length, but rather could be fit with a combination of three absorption lengths: 300, 1250 and 2500 g/cm^2, corresponding, according to Compton Theory to gamma ray energies of 26, 110 and 220 MeV

4 p → He	ΔM=27 MeV	**OK**
14 p → N	ΔM=108 MeV	**OK**
12 p → C	**ΔM=85 MeV**	**?**
16 p → O	ΔM=129 MeV	**OK**
28 p → Si	ΔM=150 MeV	**May be**

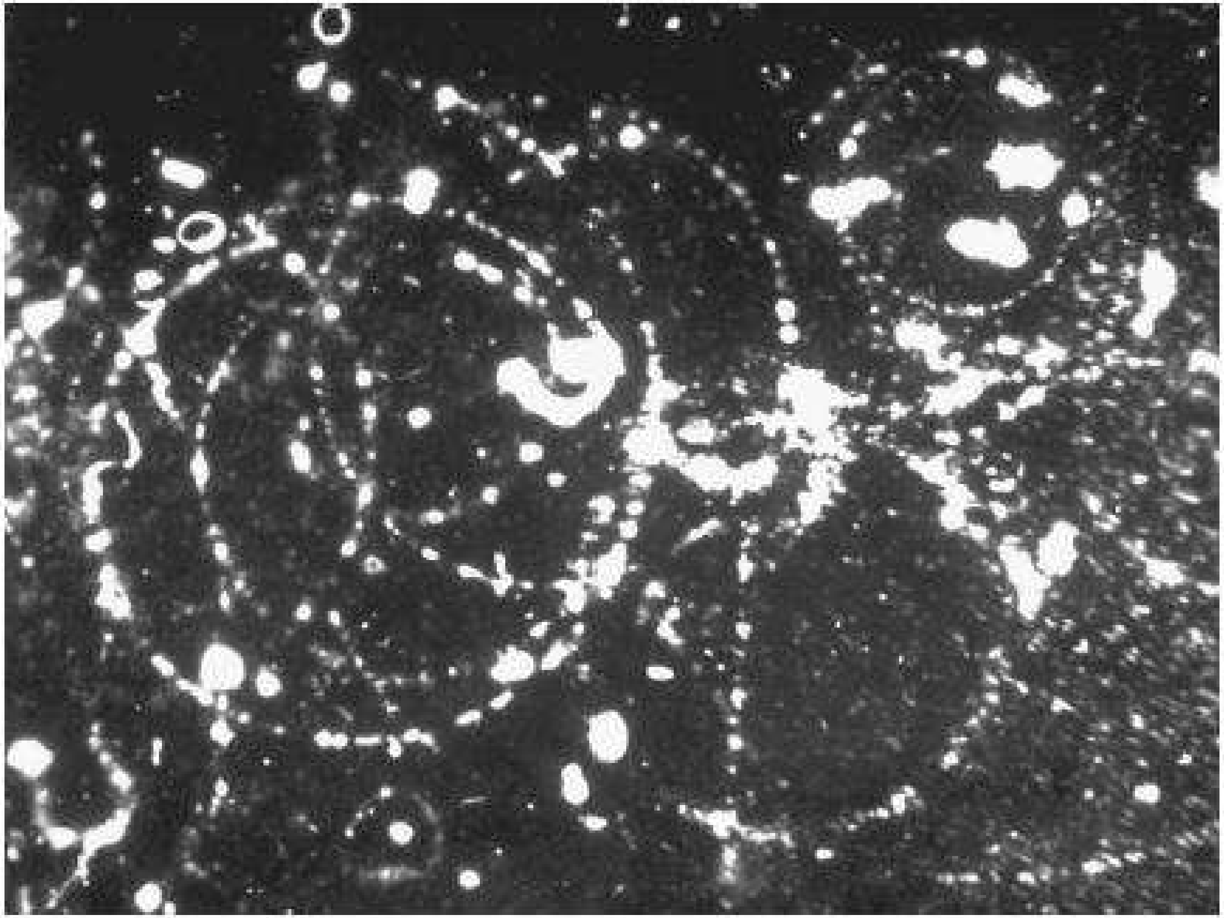
But birth cries do not go through lead!

Bruno Rossi had performed several experiments with his coincidence Geiger counters and found that CR could penetrate even 1m of lead



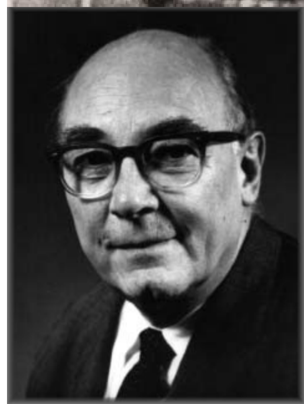
COSMIC RAYS
ARE
NO GAMMA RAYS
And
THEIR ENERGY IS
> GeV

Definitely charged...

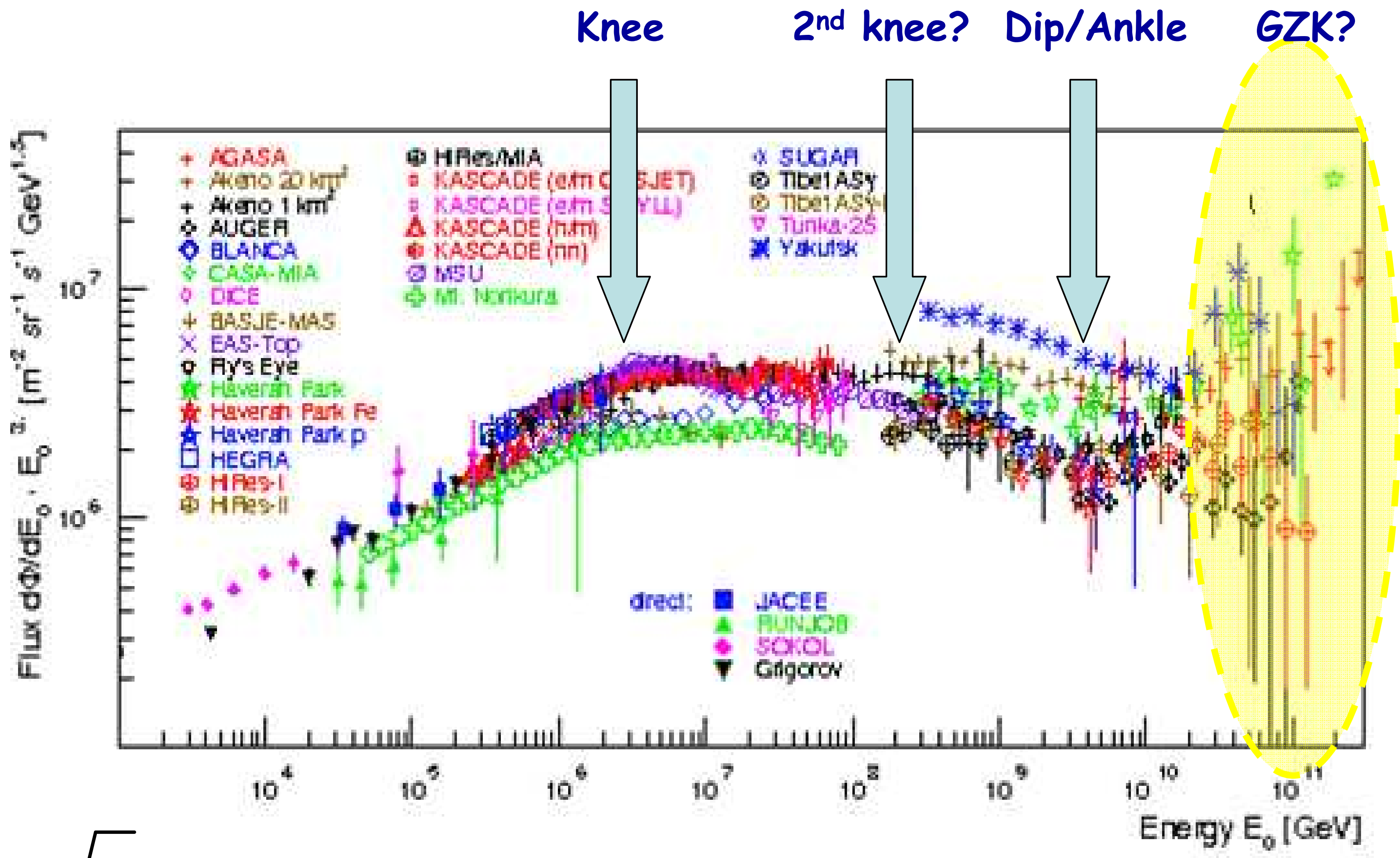


Dimitr Skobelzyn: picture of cosmic ray event in cloud chamber with B-field (1927)

- 1930: B. Rossi in Arcetri predicts the East-West effect
- 1932: Carl Anderson discovers the positron in CR
- 1934: Bruno Rossi detects coincidences even at large distance from the center...first evidence of extensive showers!
- 1937: Seth Neddermeyer and Carl Anderson discover the muon
- 1938-39: Auger detects first extensive air showers with energy up to 10^{13-14} eV
- 1940's: Boom of particle physics discoveries in CR
- 1962: UHECRs by Linsley & Scarsi

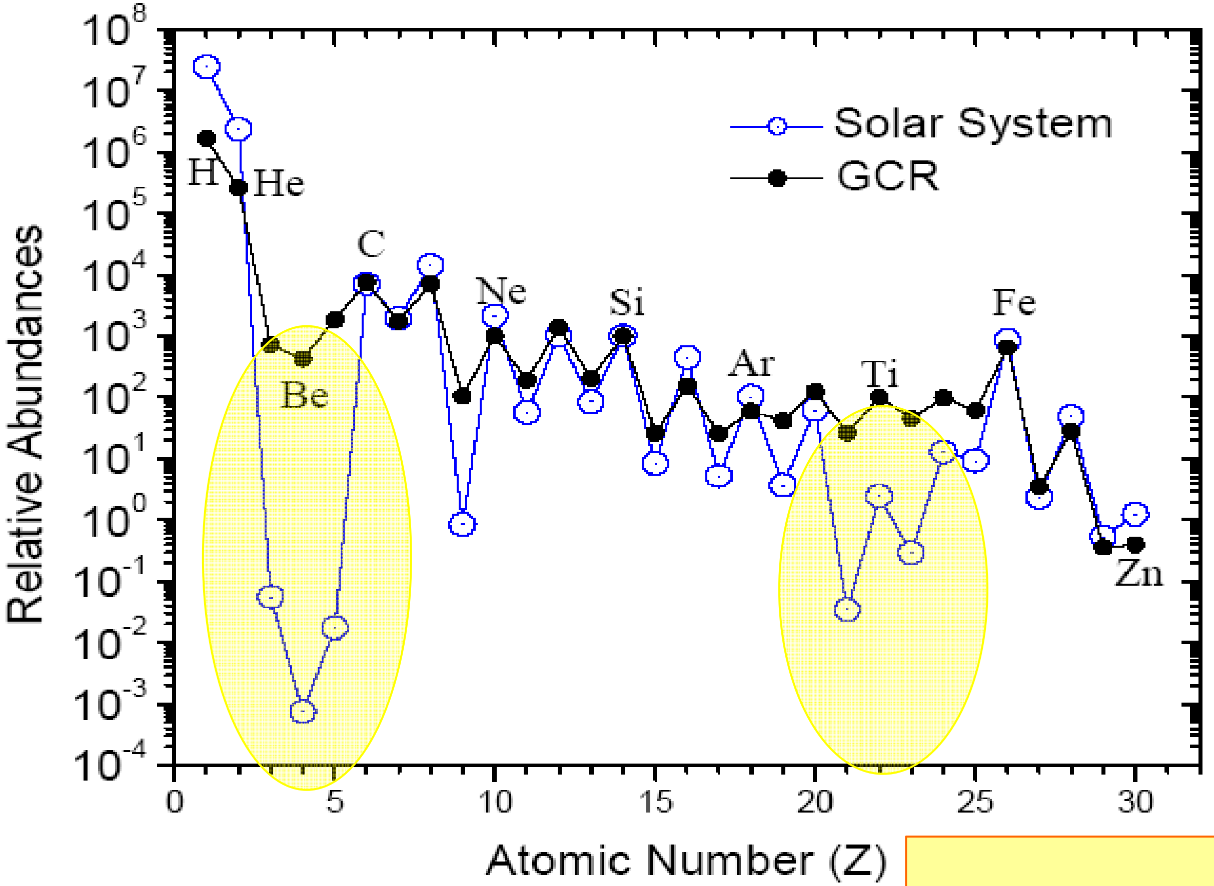


The Spectrum of Cosmic Rays



$\sqrt{s}$ **140 GeV** **2.5 TeV** **20 TeV** **100 TeV** **450 TeV**

The Chemical Composition of Cosmic Rays



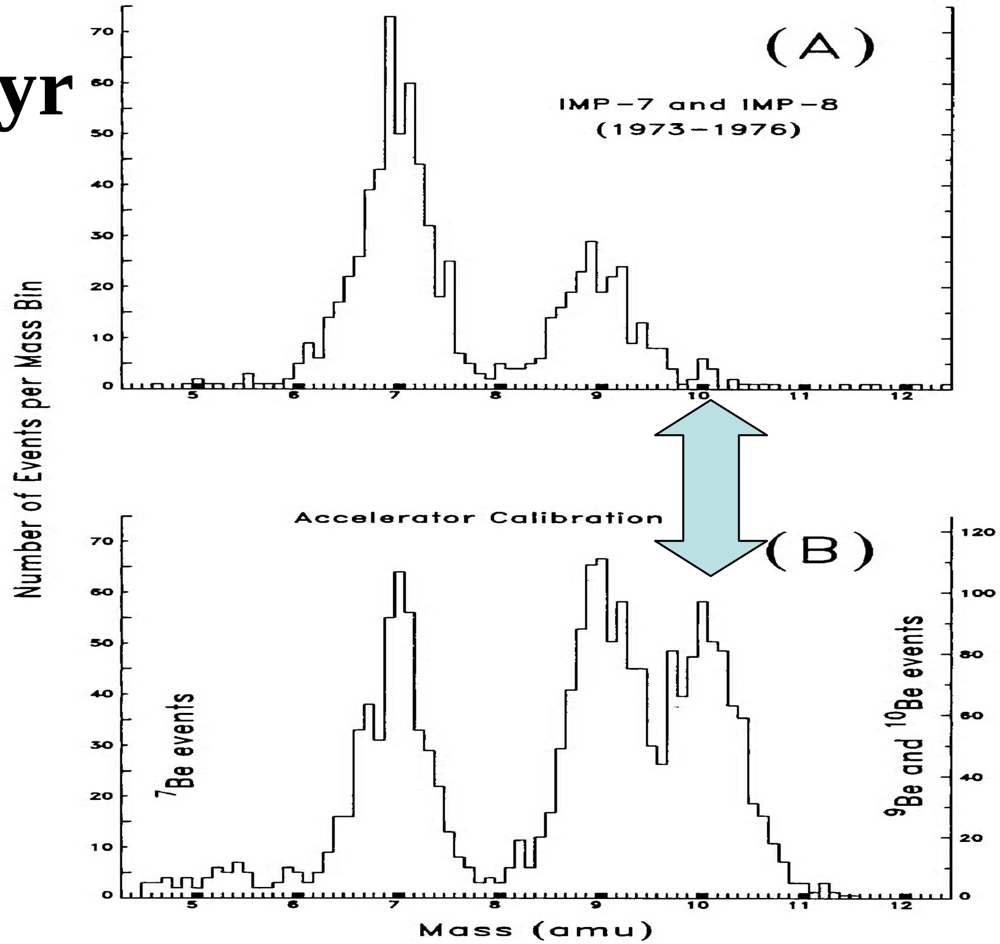
$$\tau_{\mathrm{int}} \approx \frac{1}{n_{\mathrm{gas}} c\, \sigma_{\mathrm{spall}}} \approx \text{few Myr}$$

Unstable Elements

Simpson and *Garcia*-Munoz 1988

$$\tau_{^{10}\mathrm{Be}} = 1.5 \times 10^6 \ \mathrm{yr}$$

Age of Cosmic
Rays about
10-15 million years



Balloon flights
For Cosmic Rays

Laboratory
Experiment

PROPAGATION OF COSMIC RAYS

$$\tau_{DISC} = \frac{300\,\mathrm{pc}}{(1/3)c} \approx 3000\ \mathrm{years}$$

PROPAGATION TIME IN THE DISC

$$\tau_{GAL} = \frac{15\,\mathrm{kpc}}{(1/3)c} \approx 150{,}000\ \mathrm{years}$$

PROPAGATION TIME ALONG THE ARMS OF THE GALAXY

$$\tau_{HALO} = \frac{3\,\mathrm{kpc}}{(1/3)c} \approx 30{,}000\ \mathrm{years}$$

PROPAGATION TIME IN THE HALO

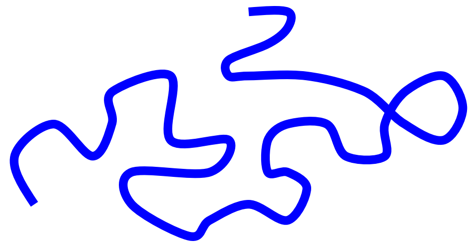
ALL THESE TIME SCALES ARE EXCEEDINGLY SHORT TO BE MADE COMPATIBLE WITH THE ABUNDANCE OF LIGHT ELEMENTS

DIFFUSIVE PROPAGATION

A qualitative look at the diffusive propagation of CR

If λ is the mean distance between two scattering centers, then the time necessary for a particle to travel a distance R is

$$\tau_{\mathrm{diff}} = \left(\frac{\lambda}{c}\right)\left(\frac{R}{\lambda}\right)^2 = \frac{R^2}{c\lambda}$$



Mean distance between
Scattering centers

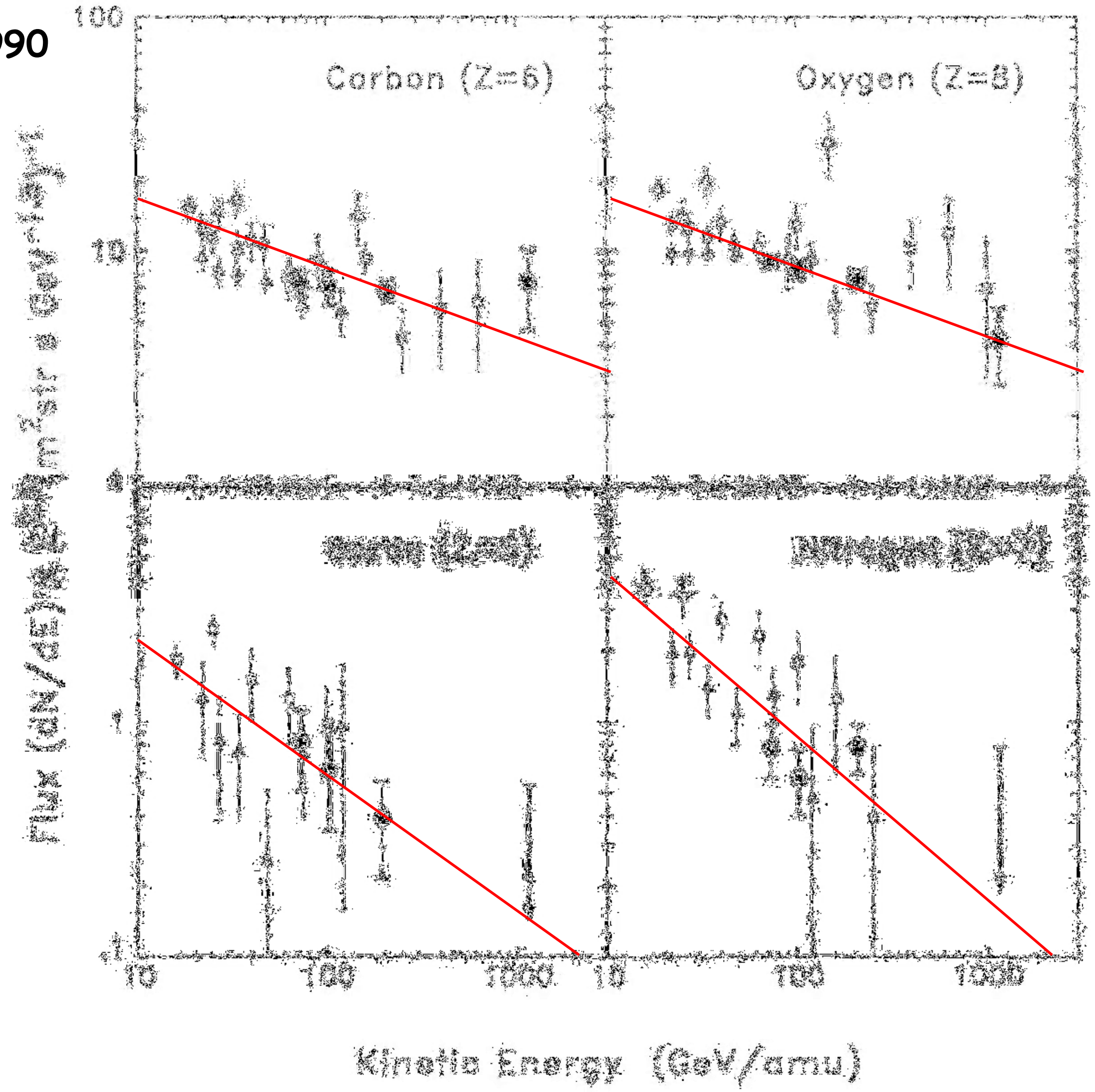
From the measured abundance of light elements and from the decay time of Unstable elements we know that the diffusion time on scales of about 1 kpc Must be about 5 million years. It immediately follows that

$$\lambda \sim 1\,\mathrm{pc} \quad \Longrightarrow \quad D = c\,\lambda = (5\text{-}10)\times 10^{28}\ cm^2 s^{-1}$$

Diffusion Coefficient

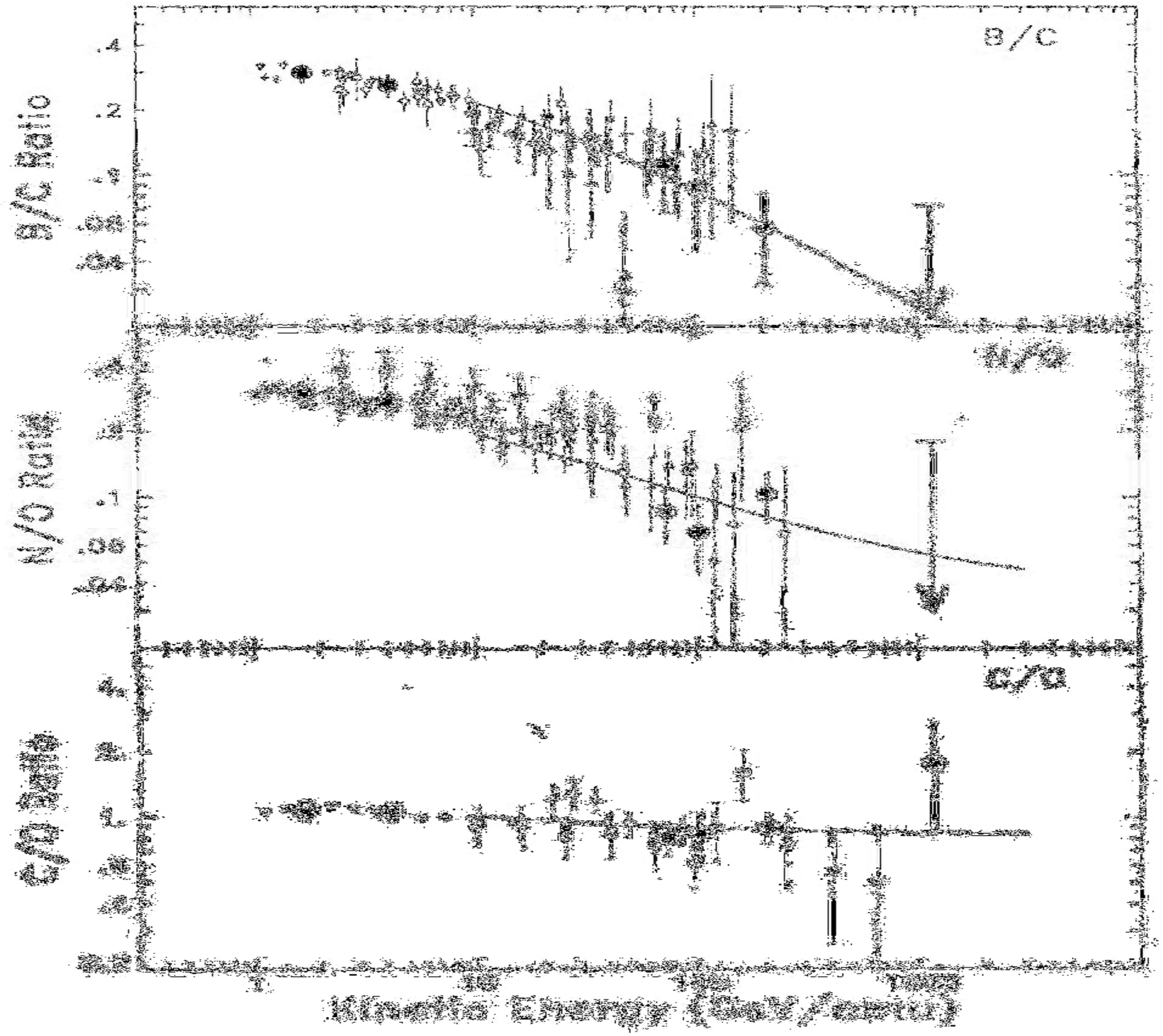
More detailed measurements

Swordy et al. 1990

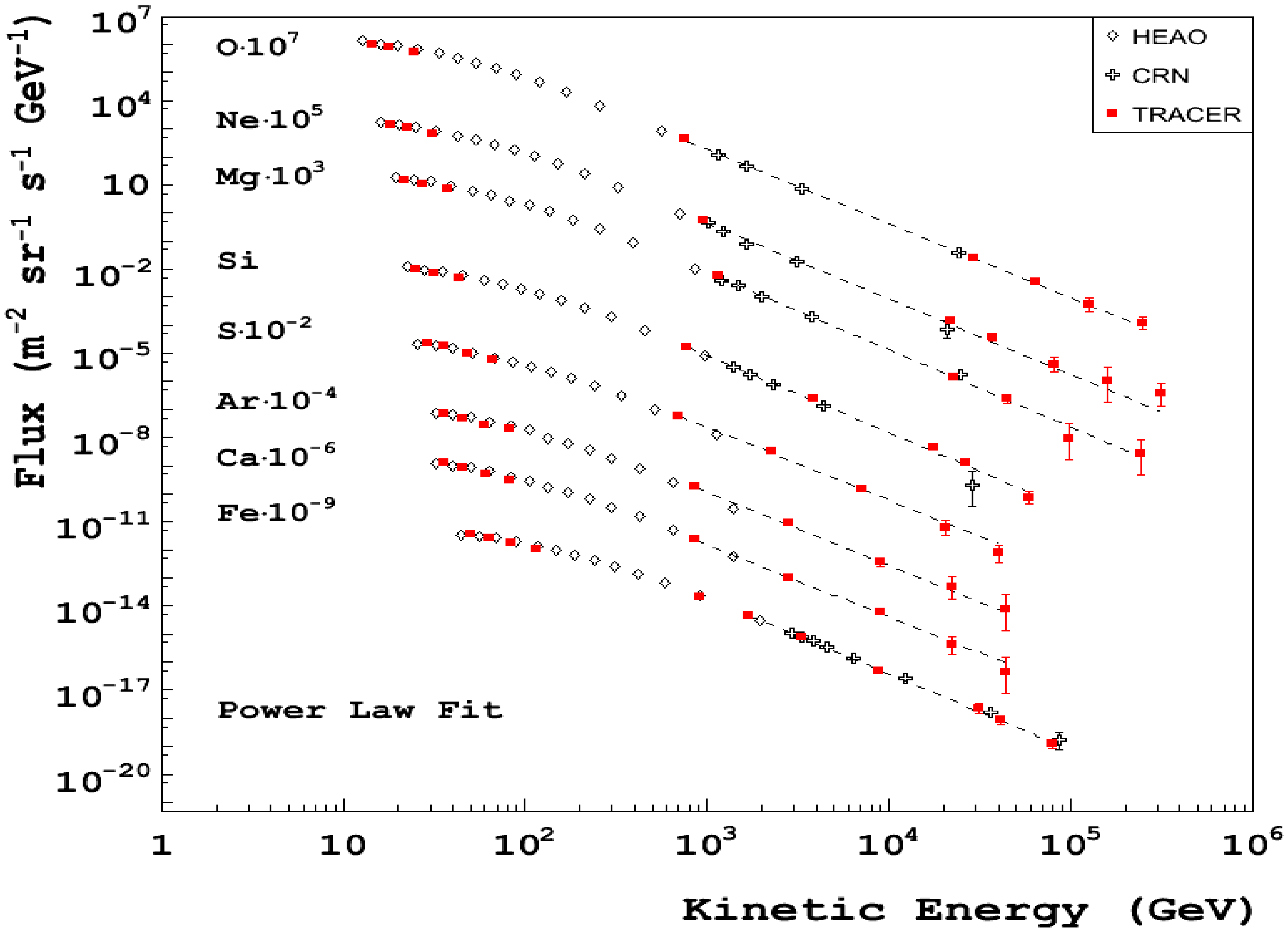


Swordy et al. 1990

RATIO SECONDARY/PRIMARY AND PRIMARY/PRIMARY

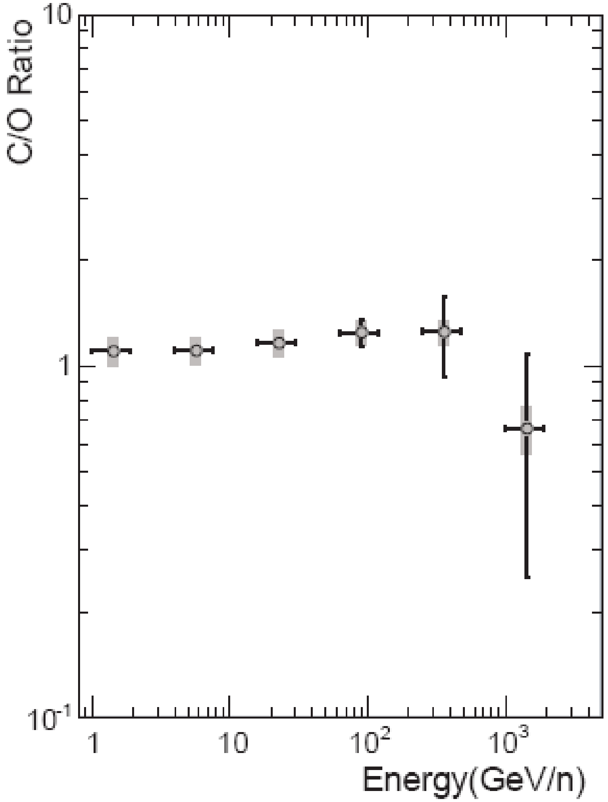


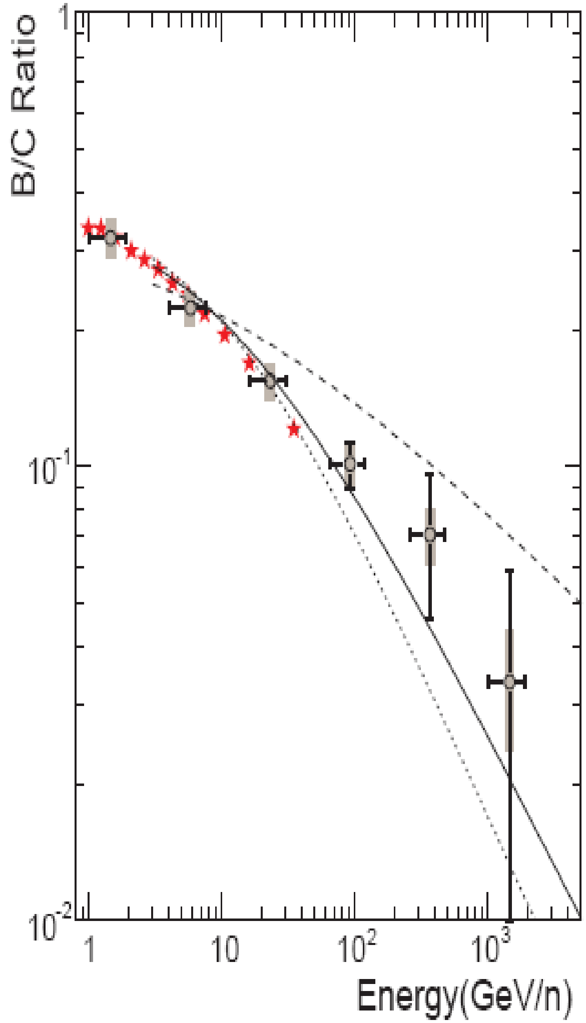
RECENT DATA

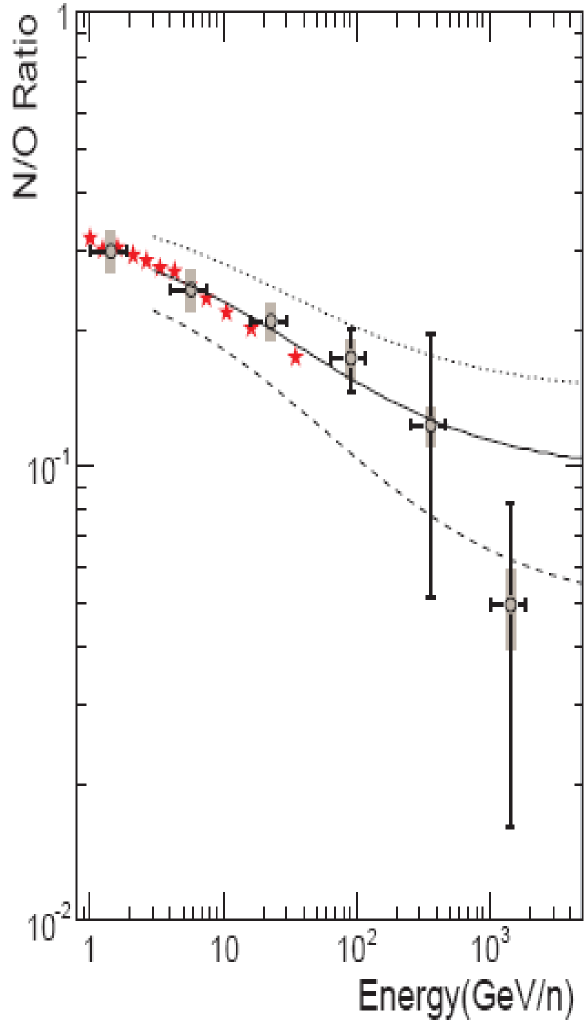


HEAO
CRN
TRACER
O·10^7
Ne·10^5
Mg·10^3
Si
S·10^-2
Ar·10^-4
Ca·10^-6
Fe·10^-9
Power Law Fit
Flux (m^-2 sr^-1 s^-1 GeV^-1)
Kinetic Energy (GeV)

CREAM data (2008)







Dependence of the Diffusion Coefficient on energy

$$q_s(E) = n_p(E)\, Y\, \sigma\, n_{gas}\, c$$

$$n_s(E) = q_s(E)\,\tau_{conf}(E)$$

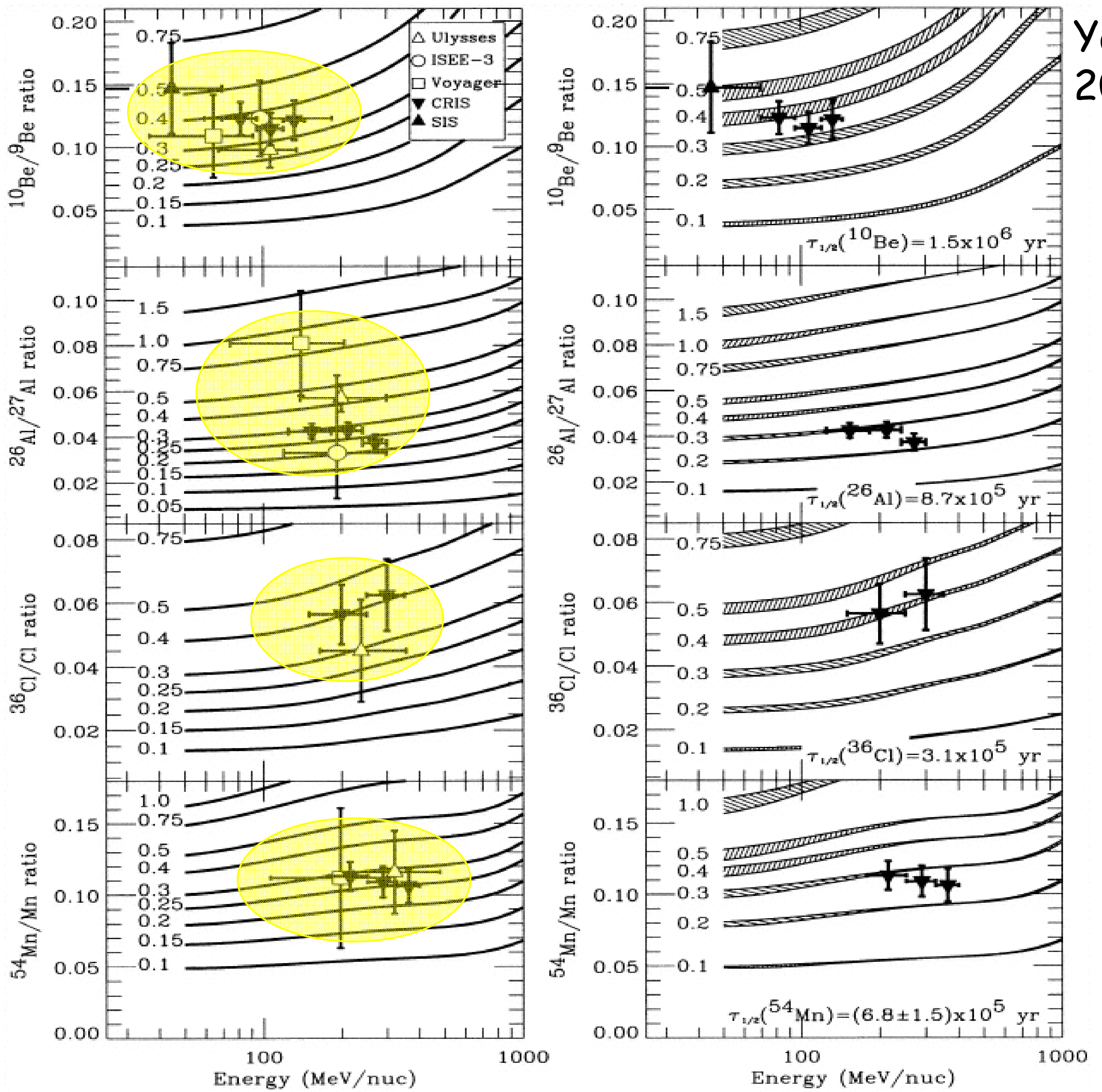
$$\frac{\text{Secondary}}{\text{Primary}} = \sigma\, Y\, n_{gas}\, c\, \tau_{conf}(E) \approx \frac{x(E)}{x_{nucl}} \qquad x_{nucl} \approx 50\ \mathrm{g\ cm^{-2}}$$

$$x(E) = n_{gas}\, m_p\, c\, \tau_{conf}(E)$$

From the previous plot we see that at low energies P/S ~ 0.1 which implies
X(E) ~ 5 g cm^{-2}

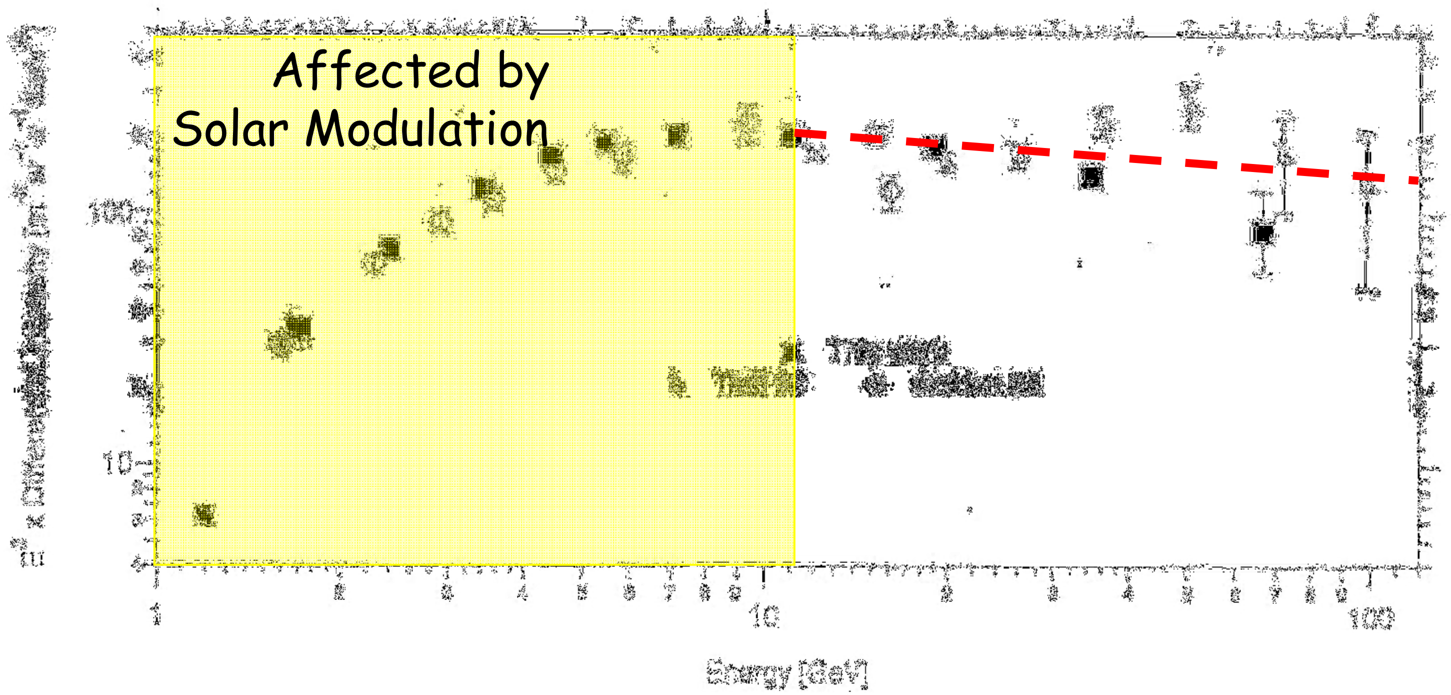
As a function of energy: $D(E) \propto (1/X(E)) \propto E^{\delta} \qquad \delta \sim 0.5$

Dependence on the mean density of the target gas

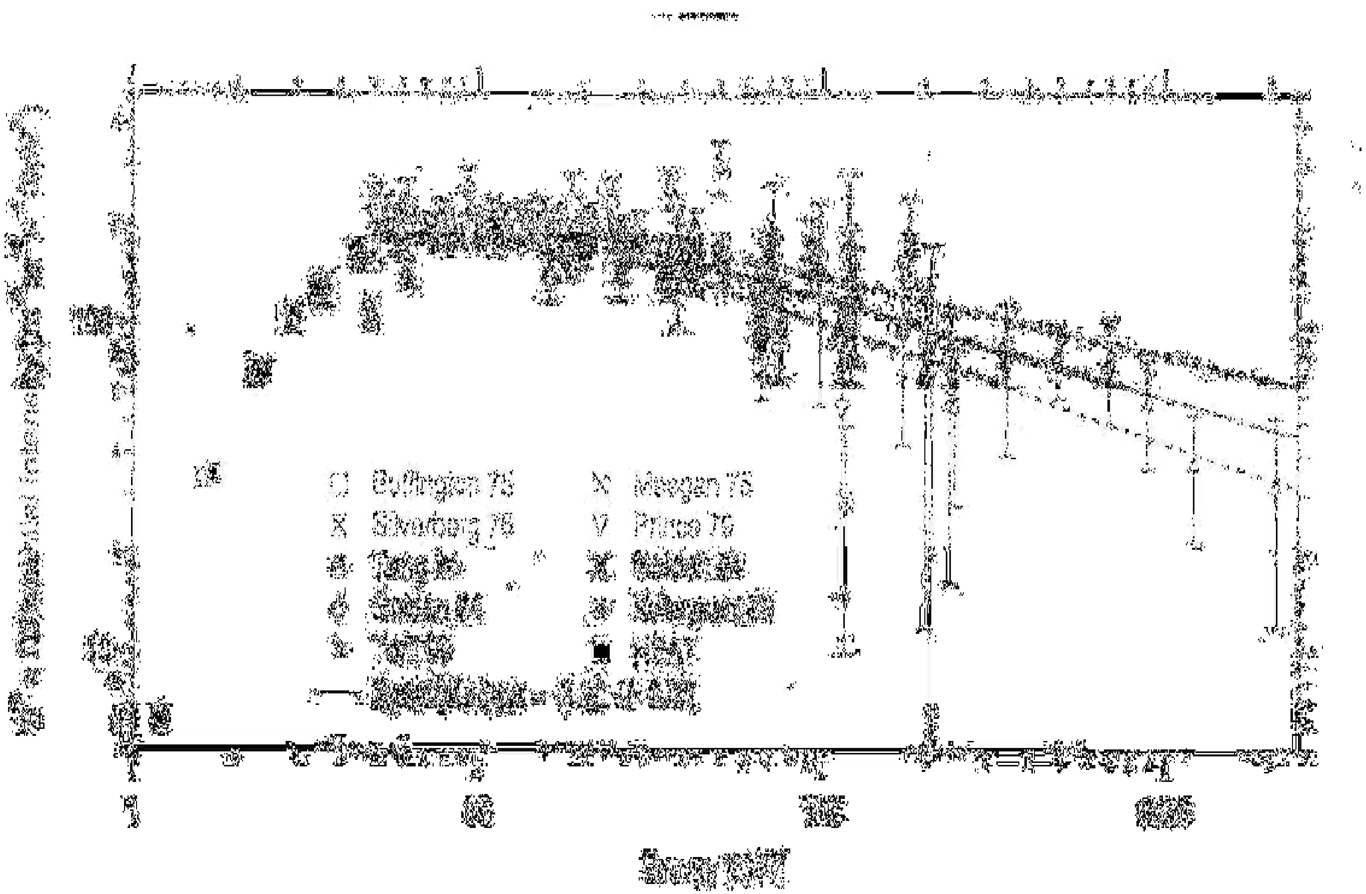


Yanasak et al. 2001

Cosmic Electrons



Mueller 2001



Mueller 2001

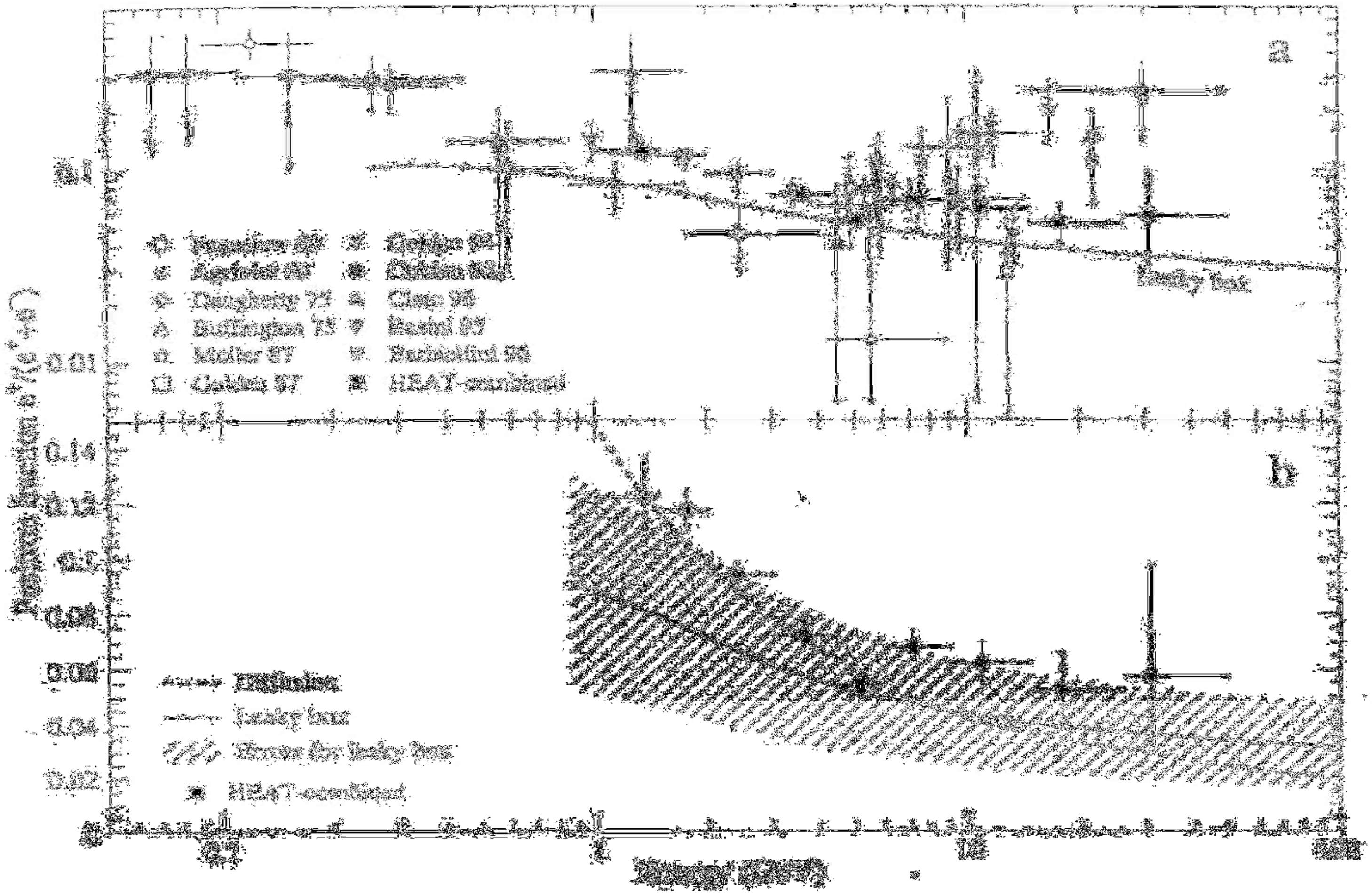
$$p + p \rightarrow \pi^{\pm} + \text{Anything}$$

$$\pi^{\pm} \rightarrow \mu + \nu_{\mu}$$

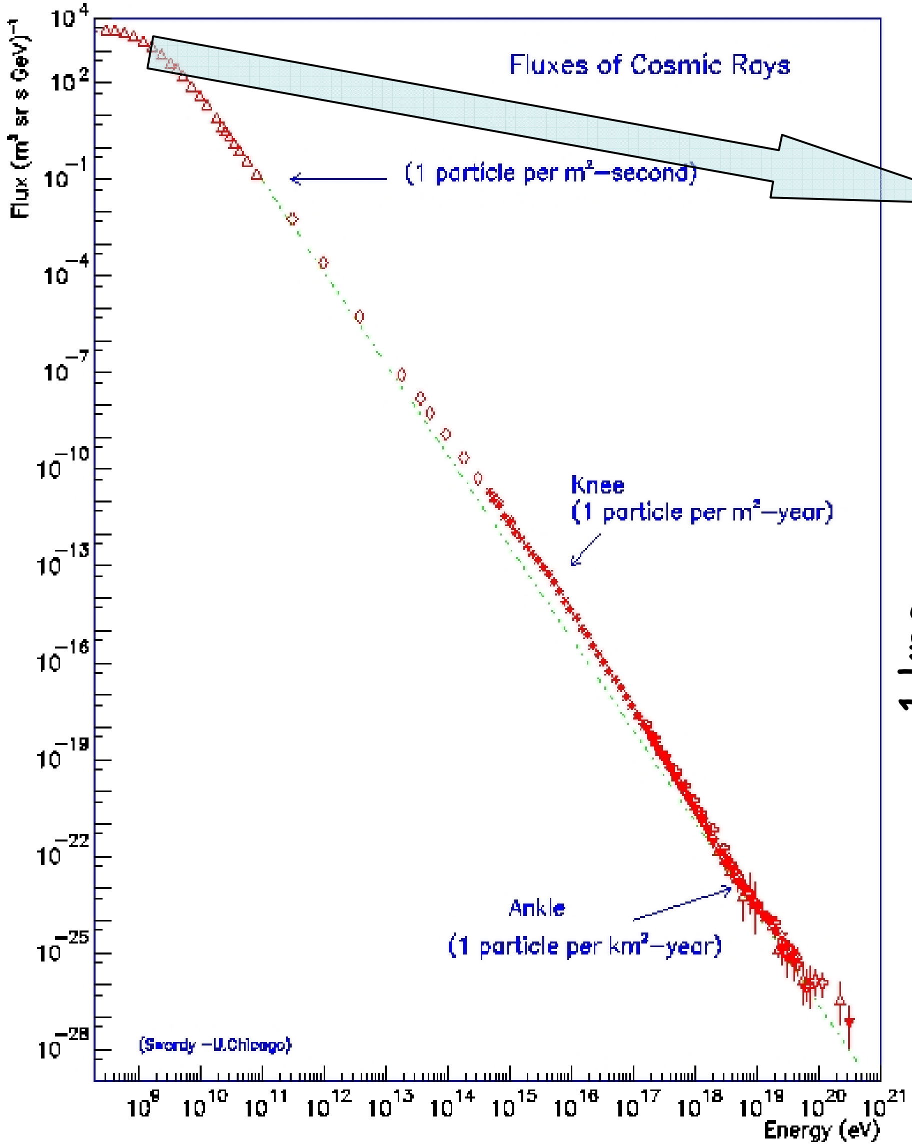
$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e} + \nu_{\mu}$$

Positrons

Mueller 2001

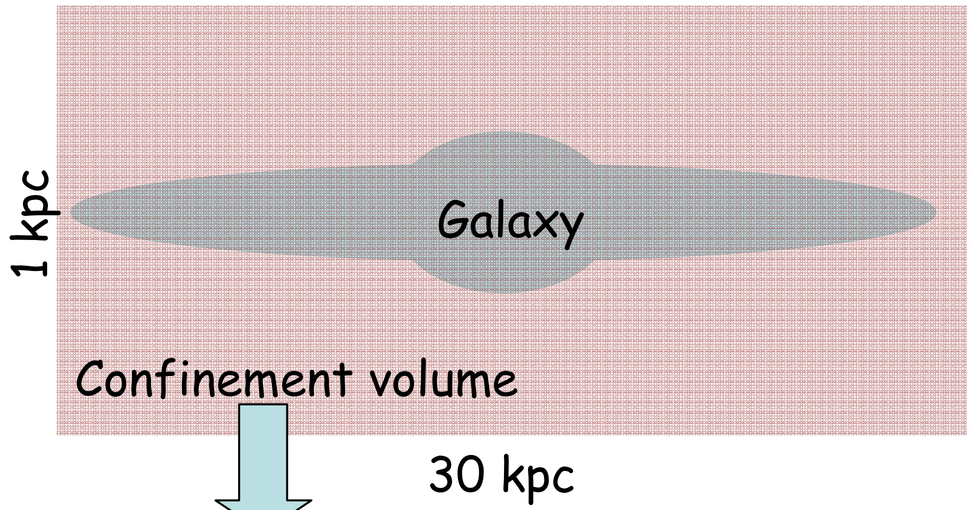


Sources of Cosmic Rays



Flux @ 1 GeV ~ 10^4 m^{-2} sr^{-1} s^{-1} GeV^{-1}

$$\omega_{CR} = 0.5 eV cm^{-3}$$



$$V_{conf} = \pi R^2 h = 2 \times 10^{67}\ cm^3$$

Sources of Cosmic Rays

The total energy in the form of CR in the Galaxy is then

$$\mathbf{W_{CR}} = \omega_{\mathbf{CR}}\ \mathbf{V_{conf}} \approx \mathbf{2 \times 10^{55}\ erg}$$

But we said that the permanence time of CR in the Galaxy as obtained from The abundance of light elements and from the decay of unstable elements is About 10 million years. Therefore the CR luminosity of the Galaxy is

$$\mathbf{L_{CR}} \approx \frac{\mathbf{W_{CR}}}{\tau_{\mathbf{conf}}} \approx \mathbf{5 \times 10^{40}\ erg\,s^{-1}}$$

The role of supernovae

In the Galaxy the rate of supernovae is of about one every 100 years. The total energy released by a SN (included the one in the form of neutrinos) is

$$\mathrm{E_{SN}} = \frac{\mathrm{GM}^2}{\mathrm{R}} \approx 10^{53}\ \mathrm{erg}$$

for a star of one solar mass.

Tipically 1% of this energy is converted in the form of kinetic energy of Ejected material: $\mathbf{E_{kin} \sim 10^{51}}$ **erg**.

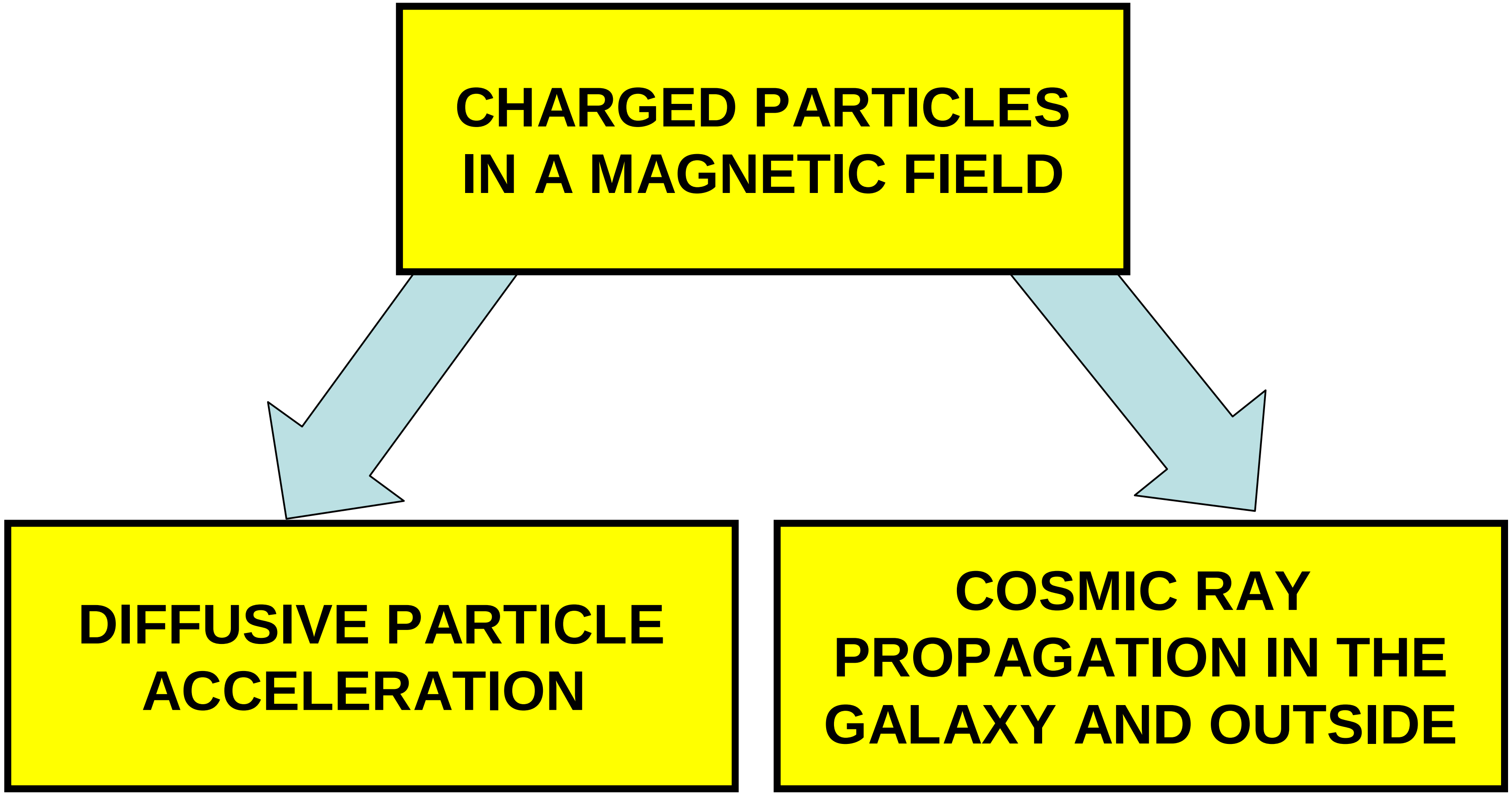
This corresponds to:

$$\mathrm{L_{SN}} = \mathrm{R_{SN}}\, E_{kin} \approx 3\times 10^{41}\ \mathrm{erg\,s^{-1}}$$

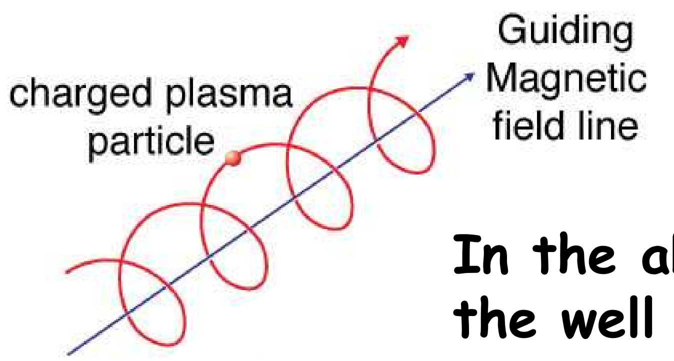
Efficiency of conversion to CR ~ 10-20 %

BUT HOW DOES THIS CONVERSION OCCUR?

COSMIC RAY TRANSPORT



Charged Particles in a regular B-field



$$\frac{d\vec{p}}{dt} = q\left[\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right]$$

In the absence of an electric field one obtains the well known solution:

$$p_z = \text{Constant}$$

$$v_x = V_0 \cos[\Omega\, t]$$

$$v_y = V_0 \sin[\Omega\, t]$$

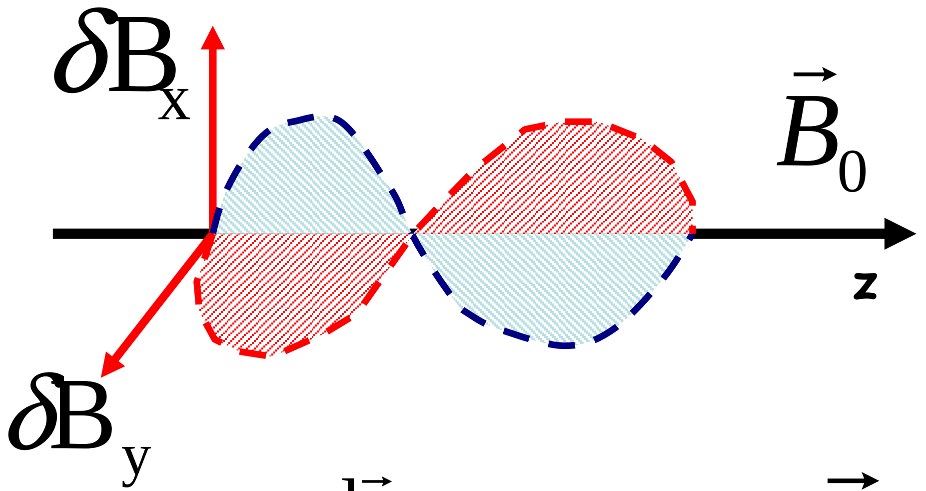
LARMOR FREQUENCY

$$\Omega = \frac{q\, B_0}{m\, c\, \gamma}$$

A FEW NOTES...

- THE MAGNETIC FIELD DOES NOT CHANGE PARTICLE ENERGY -> NO ACCELERATION BY B FIELDS
- A RELATIVISTIC PARTICLE MOVES IN THE Z DIRECTION ON AVERAGE AT C/3

Motion of a charged particle in a random magnetic field



$$\delta B << B_0$$

$$\delta \vec{B} \perp \vec{B}_0$$

$$\frac{d\vec{p}}{dt} = q\frac{\vec{v}}{c} \times (\vec{B}_0 + \delta\vec{B})$$

THIS CHANGES ONLY THE X AND Y COMPONENTS OF THE MOMENTUM

THIS TERM CHANGES ONLY THE DIRECTION OF $P_z = P\mu$

SITTING IN THE REFERENCE FRAME OF THE THE WAVE, THERE IS NO ELECTRIC FIELD…AND IF THE WAVE IS SLOW COMPARED WITH THE PARTICLE (THIS IS GENERALLY THE CASE) THEN THE WAVE IS STATIONARY AND Z:

$$\frac{d\mu}{dt} = \frac{q(1-\mu^2)^{1/2}}{m\gamma c}\left[\cos(\Omega t)\, B_y - \sin(\Omega t)\, B_x\right]$$

$$\frac{d\mu}{dt} = \frac{q(1-\mu^2)^{1/2} B_k}{m\gamma c}\left[\cos(\Omega t)\cos(kz+\psi) + \sin(\Omega t)\sin(kz+\psi)\right]$$

$$\boxed{\frac{d\mu}{dt} = \frac{q(1-\mu^2)^{1/2} B_k}{m\gamma c}\cos\left[(\Omega - kv\mu)t + \psi\right]}$$

RATE OF CHANGE OF THE PITCH ANGLE IN TIME

Diffusive motion

$$\boxed{\frac{d\mu}{dt} = \frac{q(1-\mu^2)^{1/2}B_k}{m\gamma c}\cos\left[(\Omega - kv\mu)t + \psi\right]}$$

ONE CAN TRIVIALLY SHOW THAT $\left\langle \frac{d\mu}{dt} \right\rangle = 0$

BUT:

$$\Delta\mu\Delta\mu = \frac{q^2(1-\mu^2)B_k^2}{m^2\gamma^2c^2}\int dt \int dt' \cos\left[(\Omega - kv\mu)t + \psi\right]\cos\left[(\Omega - kv\mu)t' + \psi\right]$$

$$\boxed{< \frac{\Delta\mu\Delta\mu}{\Delta t} >_\psi = \frac{q^2(1-\mu^2)\pi B_k^2}{m^2\gamma^2c^2}\frac{1}{v\mu}\delta(k - \frac{\Omega}{v\mu})}$$

Many waves

IN GENERAL ONE DOES NOT HAVE A SINGLE WAVE BUT RATHER A POWER SPECTRUM:

$$P(k) = B_k^2/4\pi$$

THEREFORE INTEGRATING OVER ALL OF THEM:

$$< \frac{\Delta\mu\Delta\mu}{\Delta t} >= \frac{q^2(1-\mu^2)\pi}{m^2\gamma^2c^2}\frac{1}{v\mu}4\pi\int dk\frac{B_k^2}{4\pi}\delta(k-\frac{\Omega}{v\mu})$$

OR IN A MORE IMMEDIATE FORMALISM:

$$\boxed{\left\langle\frac{\Delta\mu\Delta\mu}{\Delta t}\right\rangle = \frac{\pi}{2}\Omega(1-\mu^2)k_{res}F(k_{res})}$$

$$\boxed{k_{res} = \frac{\Omega}{v\mu}}$$

RESONANCE!!!

DIFFUSION COEFFICIENT

THE RANDOM CHANGE OF THE PITCH ANGLE IS DESCRIBED BY A DIFFUSION COEFFICIENT

$$D_{\mu\mu} = \left\langle \frac{\Delta\theta\Delta\theta}{\Delta t} \right\rangle = \frac{\pi}{4}\Omega k_{res} F(k_{res})$$

FRACTIONAL POWER $(\delta B/B_0)^2$ $=G(k_{res})$

THE DEFLECTION ANGLE CHANGES BY ORDER UNITY IN A TIME:

PATHLENGTH FOR DIFFUSION ~ $v\tau$

$$\tau \approx \frac{1}{\Omega\, G(k_{res})} \Rightarrow \left\langle \frac{\Delta z\Delta z}{\Delta t} \right\rangle \approx v^2\,\tau = \frac{v^2}{\Omega\, G(k_{res})}$$

SPATIAL DIFFUSION COEFF.

PARTICLE SCATTERING

- EACH TIME THAT A RESONANCE OCCURS THE PARTICLE CHANGES PITCH ANGLE BY $\Delta\theta \sim \delta B/B$ WITH A RANDOM SIGN

- THE RESONANCE OCCURS ONLY FOR RIGHT HAND POLARIZED WAVES IF THE PARTICLES MOVES TO THE RIGHT (AND VICEVERSA)

- THE RESONANCE CONDITION TELLS US THAT 1) IF $k \ll 1/r_L$ PARTICLES SURF ADIABATICALLY AND 2) IF $k \gg 1/r_L$ PARTICLES HARDLY FEEL THE WAVES

WAVES? Who asked them?

WAVES MAY BE GENERATED BY DIFFERENT SOURCES (SN EXPLOSIONS FOR INSTANCE) BUT THERE IS A MORE INTERESTING POSSIBILITY:

ASSUME PARTICLES ARE DRIFTING WITH VELOCITY $V_D > V_A$

THE EFFECT OF SCATTERING IS TO ISOTROPIZE CR:

$$N_{CR} m v_D \longrightarrow N_{CR} m v_A$$

Initial momentum — final momentum

$$\frac{dP_{CR}}{dt} = \frac{n_{CR}\, m\, \Gamma_{CR}\, (v_D - v_A)}{\tau}$$

$$\frac{dP_W}{dt} = \gamma_W \frac{\delta B^2}{8\pi} \frac{1}{v_A}$$

$$\longrightarrow \boxed{\gamma_W = \frac{n_{CR}}{n_{gas}} \Omega_{cyc} \left(\frac{v_D - v_A}{v_A} \right)}$$

LATER A MORE RIGOROUS AND GENERAL TREATMENT

Some Galactic Numbers

FOR $N_{CR}=10^{-10}$ CM^{-3}, $N_{gas}=10^{-1}$ cm^{-3} AND $B_0=1\mu G$, AND ASSUMING $V_D=2V_A$, ONE FINDS:

$V_A = 7\ 10^5$ cm/s

$\Omega_{cyc} = 10^{-2}\ s^{-1}$

$$\boxed{\gamma_W = \frac{n_{CR}}{n_{gas}} \Omega_{cyc} \left(\frac{v_D - v_A}{v_A} \right) = 10^{-3}\ \mathrm{yr}^{-1}}$$

WAVES MAY **GROW VERY FAST**, ON TIME SCALES MUCH SHORTER THAN THE MEASURED DIFFUSION TIME SCALES...

THE GROWTH ENDS WHEN $V_D = V_A$