COSMIC RAYS

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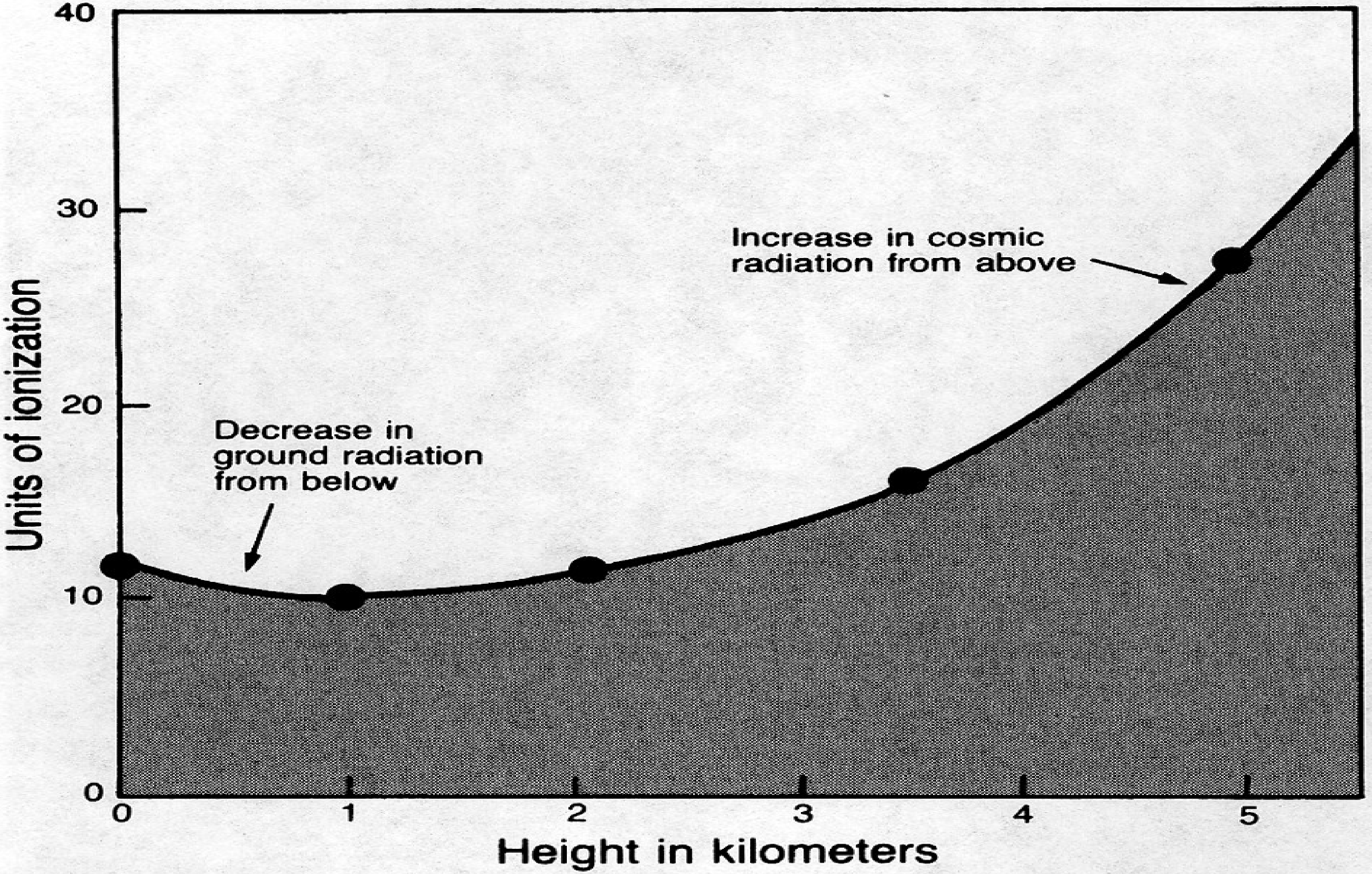
COSMIC Rays


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

Millikan Theory

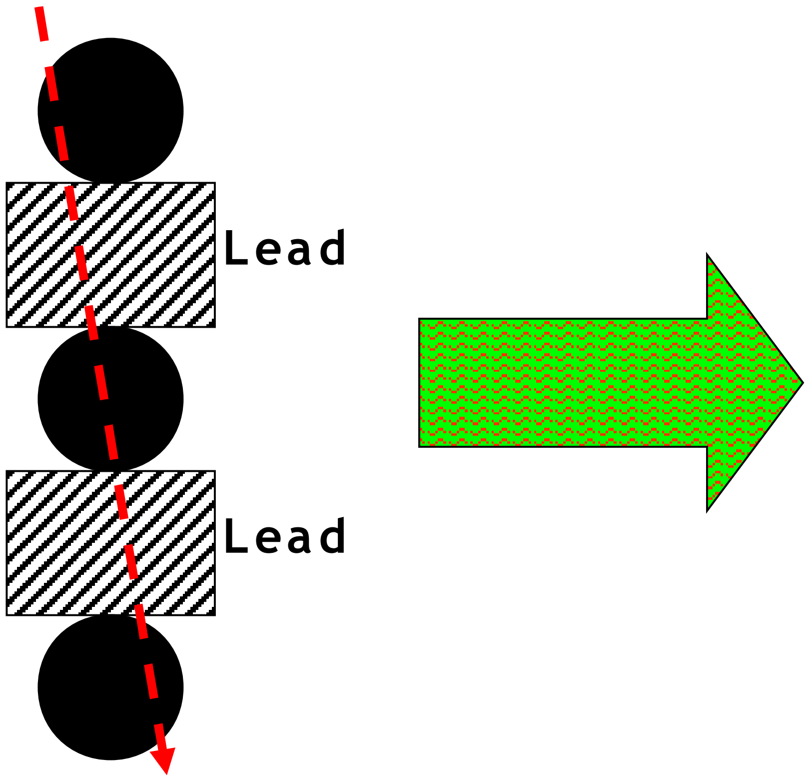
Cosmic Rays (as Millikan called them) are gamma rays as the birth cry of elements heavier than hydrogen

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

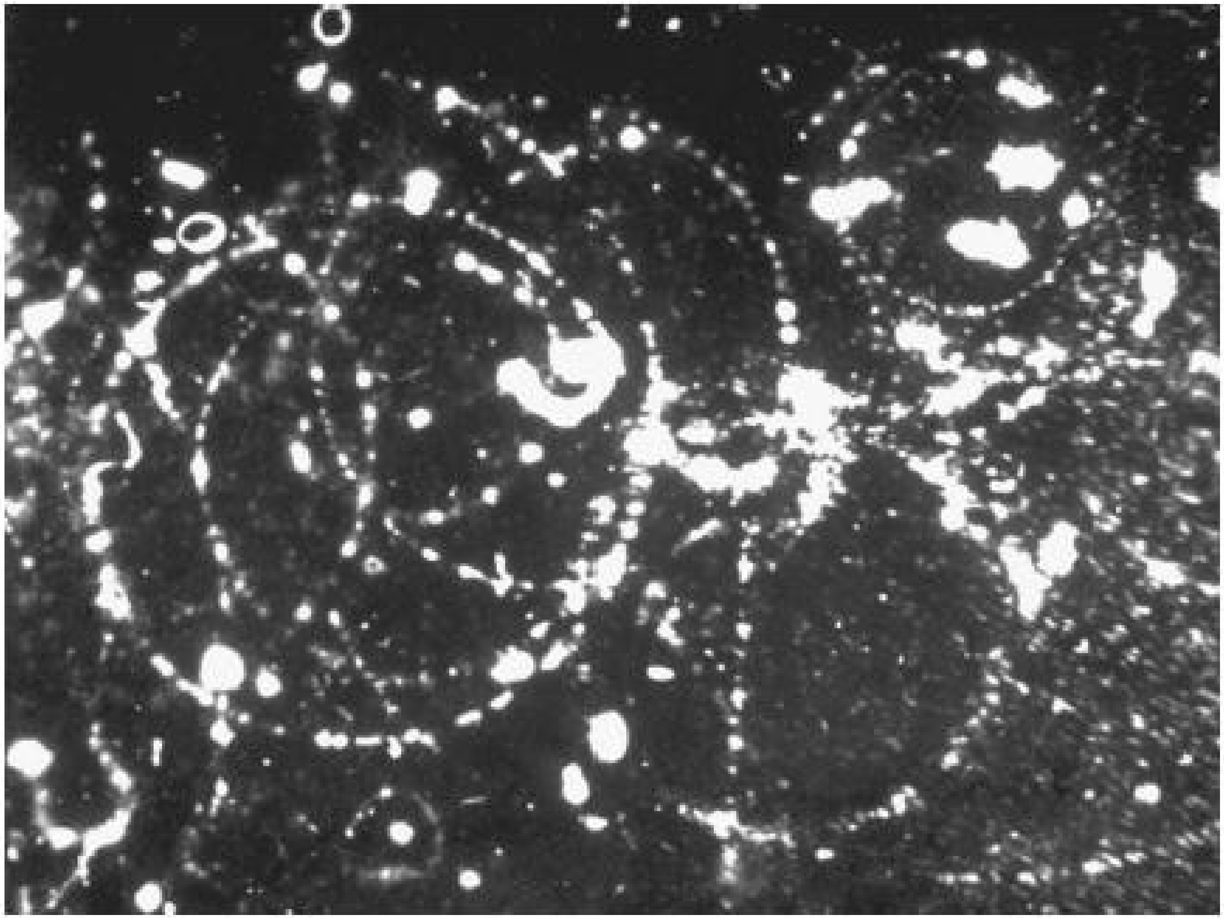
But birth cries do not go through lead!

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!

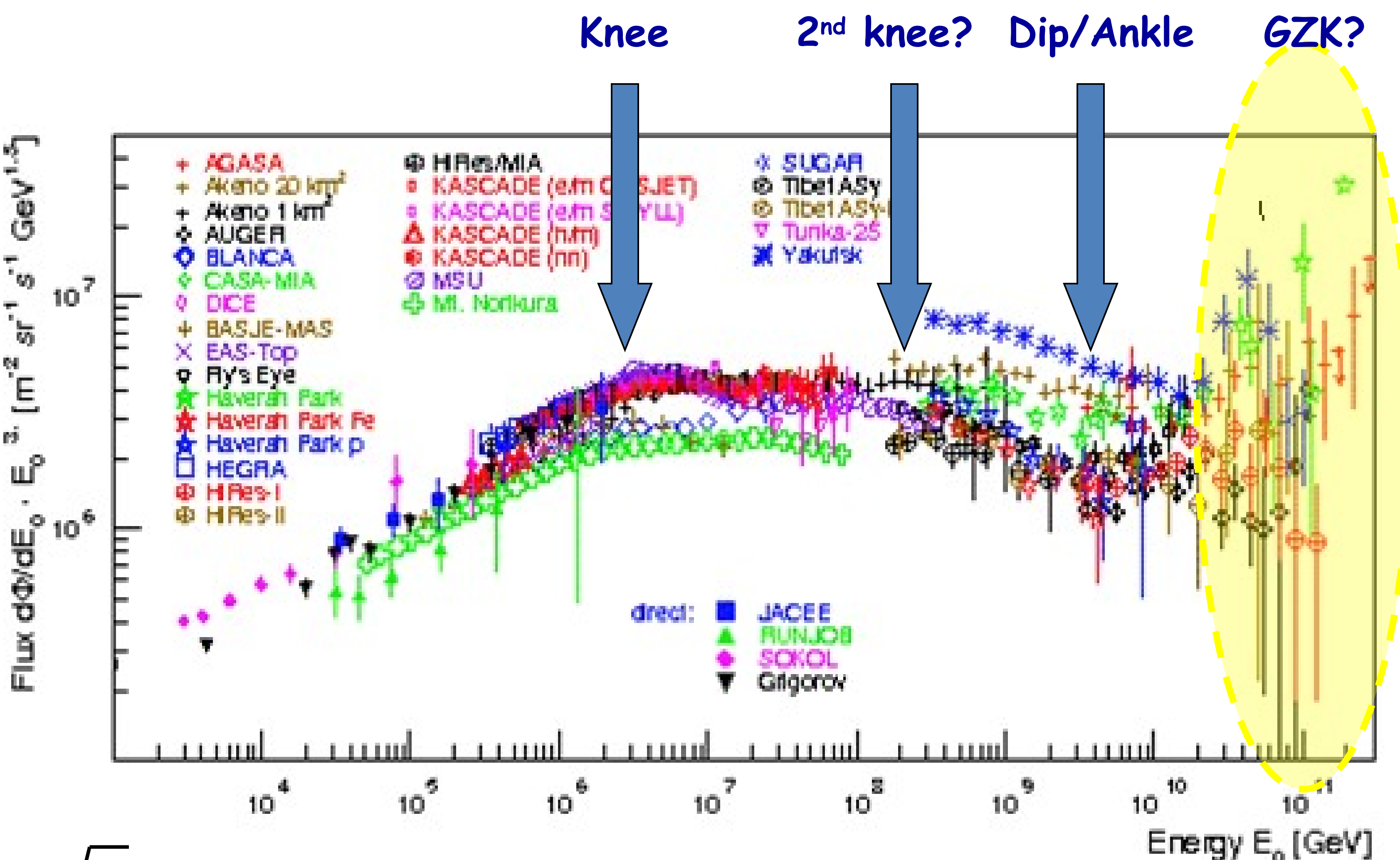
- 1937: Seth Neddermeyer and Carl Anderson discover the muon

- 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

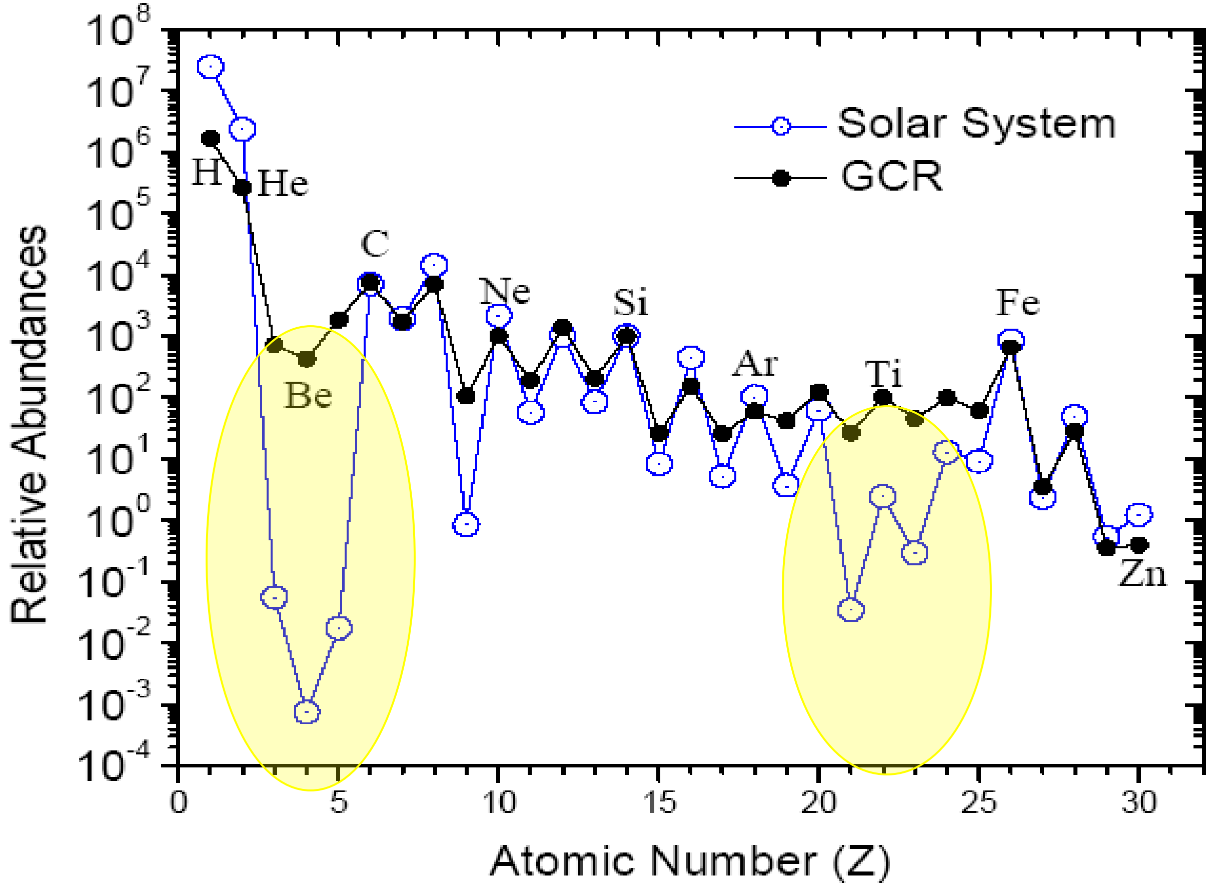
- 1962: UHECRs by Linsley & Scarsi

The Spectrum of Cosmic Rays



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

The Chemical Composition of Cosmic Rays



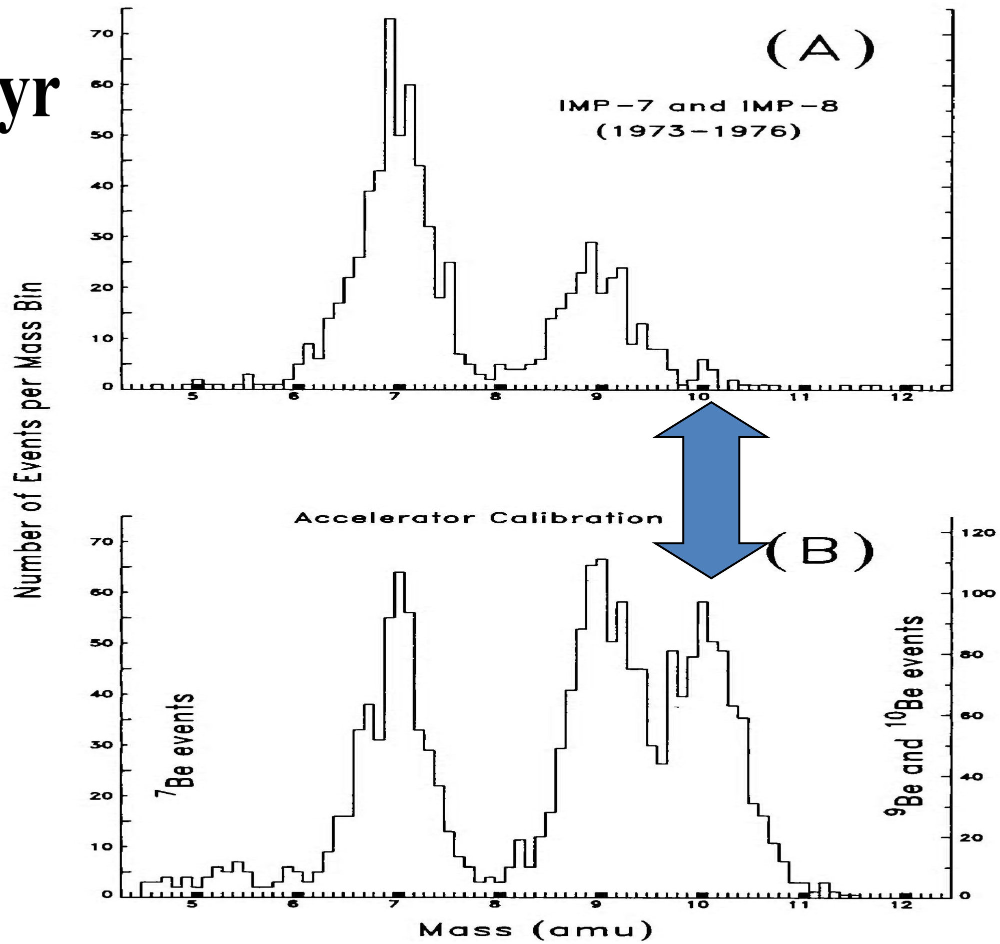
$$\tau_{int} \approx \frac{1}{n_{gas} c \, \sigma_{spall}} \approx \text{few Myr}$$

Unstable Elements

Simpson and Garcia-Munoz 1988

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

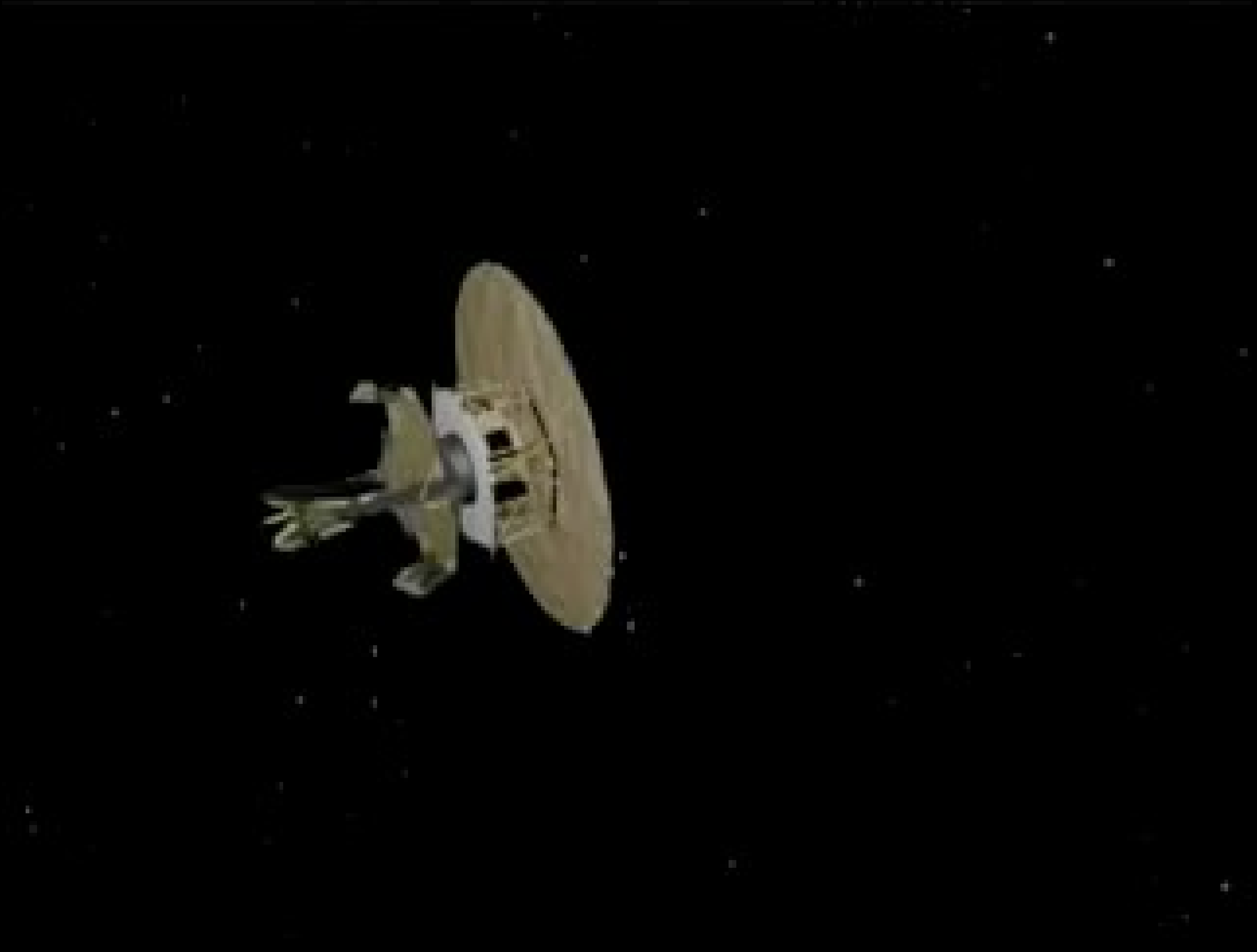
Age of Cosmic Rays about 10-15 million years

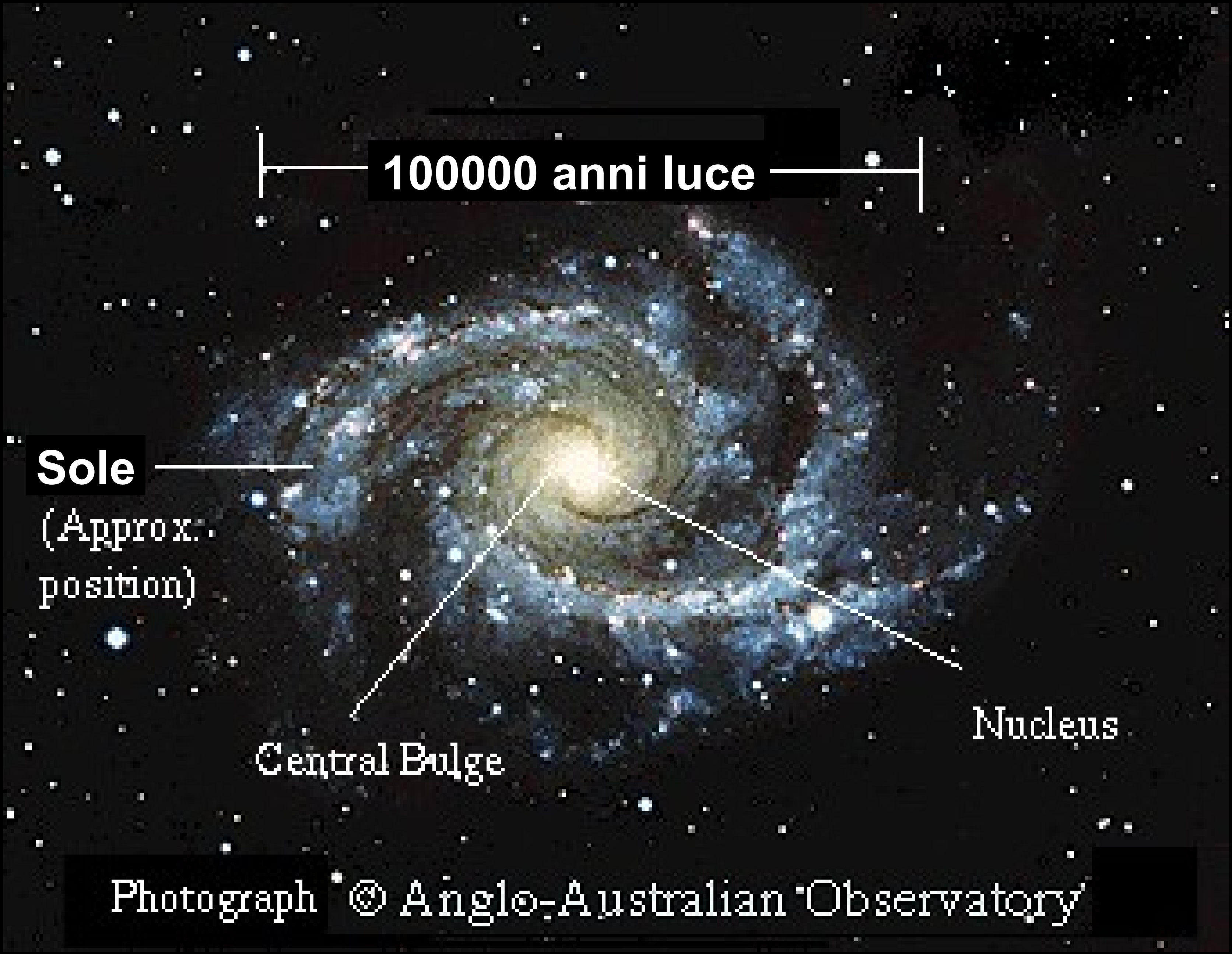


Balloon flights For Cosmic Rays

Laboratory Experiment

Il Nostro Posto Nell'Universo




100000 anni luce
Sole
(Approx.
position)
Central Bulge
Nucleus
Photograph © Anglo-Australian Observatory

PROPAGATION OF COSMIC RAYS

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

PROPAGATION TIME IN THE DISC

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

PROPAGATION TIME ALONG THE ARMS OF THE GALAXY

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

PROPAGATION TIME IN THE HALO

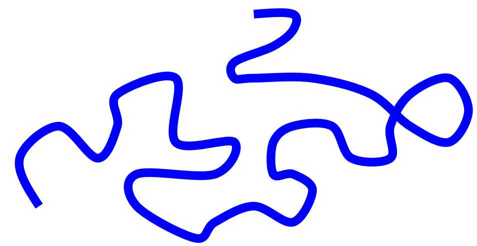
ALL THESE TIME SCALES ARE EXCEEDINGLY SHORT TO BE MADE COMPATIBLE WITH THE ABUNDANCE OF LIGHT ELEMENTS

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

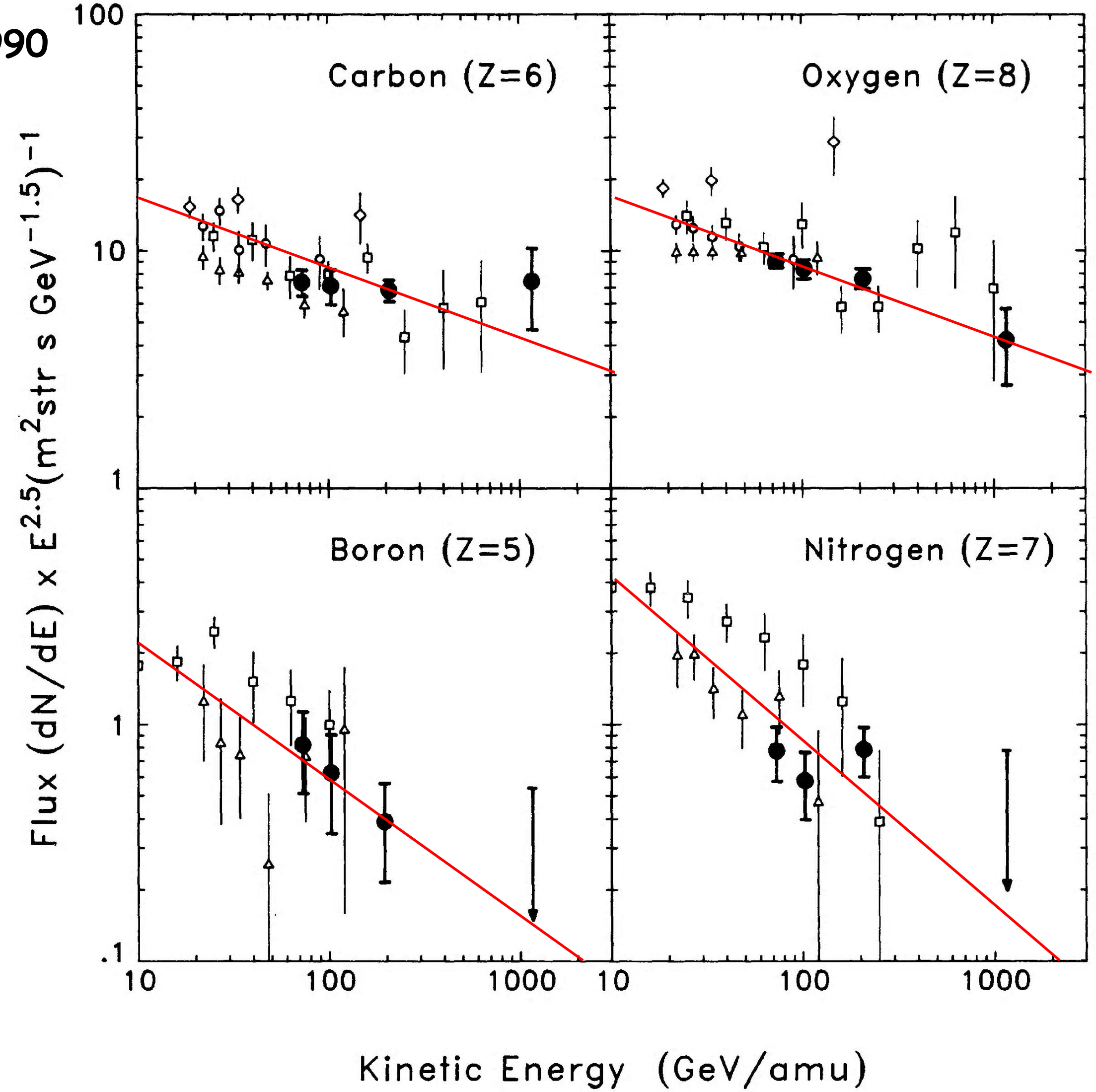
From the measured abundance of light elements and from the decay time of Unstable elements we know that the diffusion time on scales of about 1 kpc Must be about 5 million years. It immediately follows that

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

Diffusion Coefficient

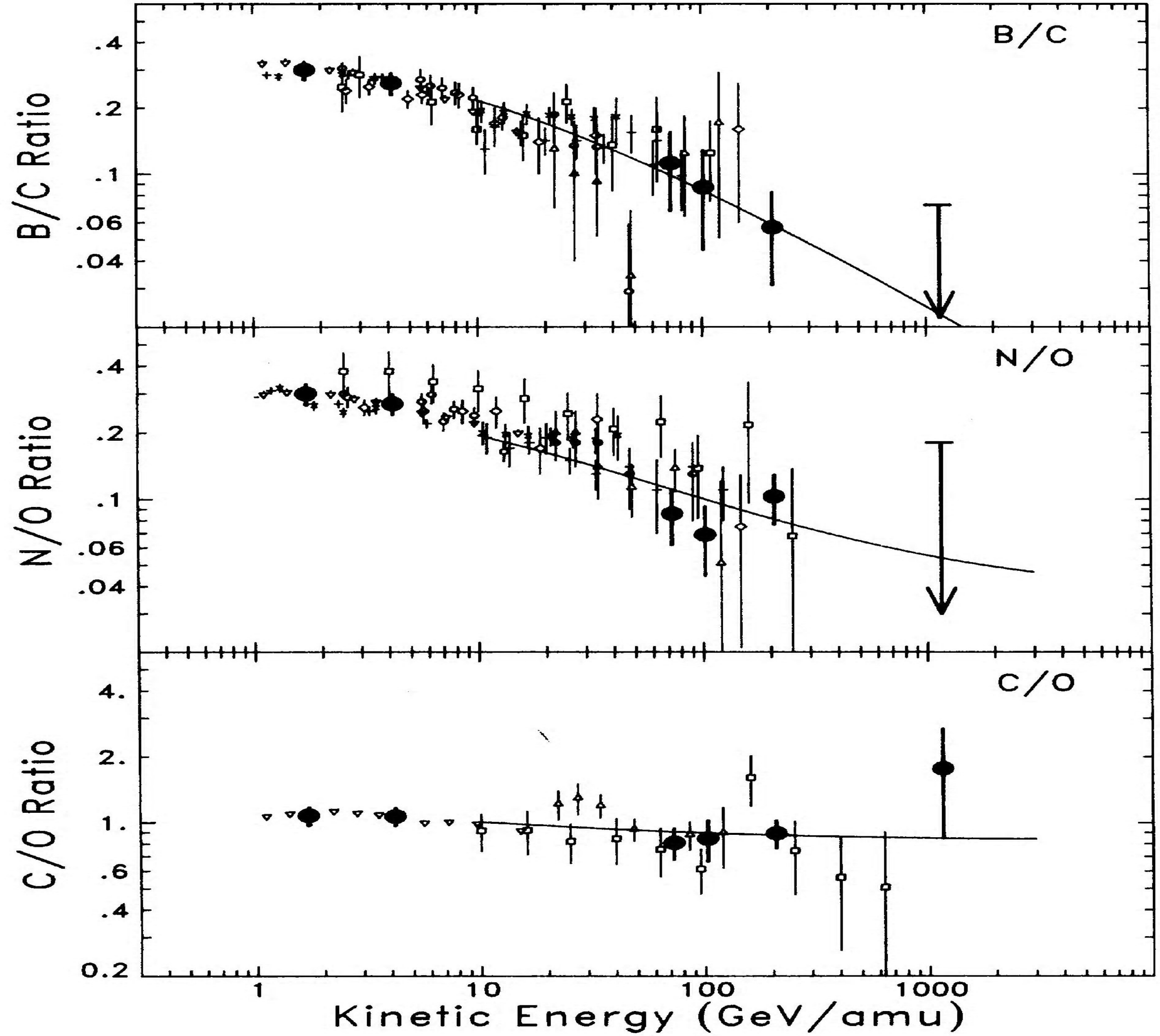
More detailed measurements

Swordy et al. 1990

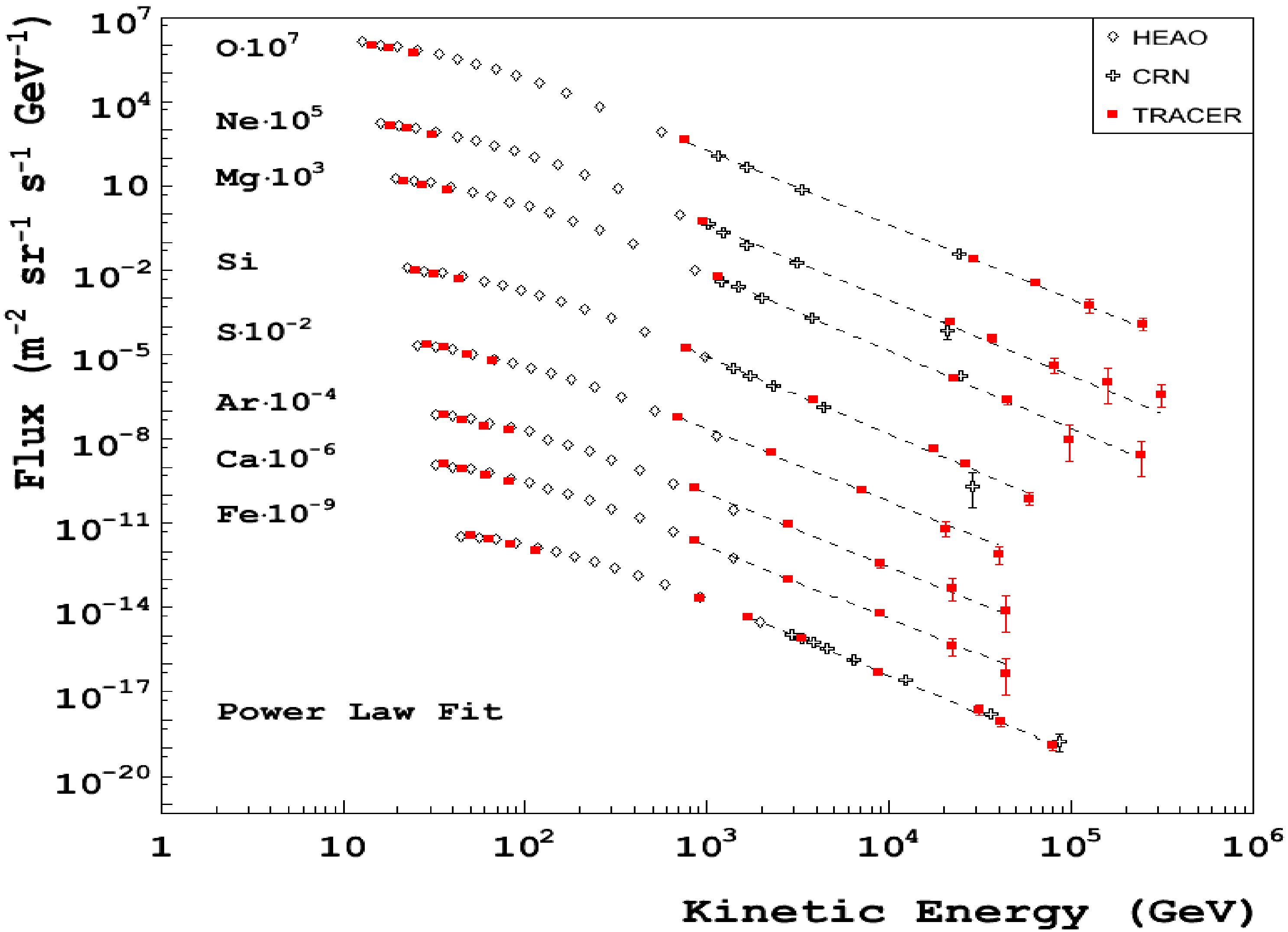


Swordy et al. 1990

RATIO SECONDARY/PRIMARY AND PRIMARY/PRIMARY

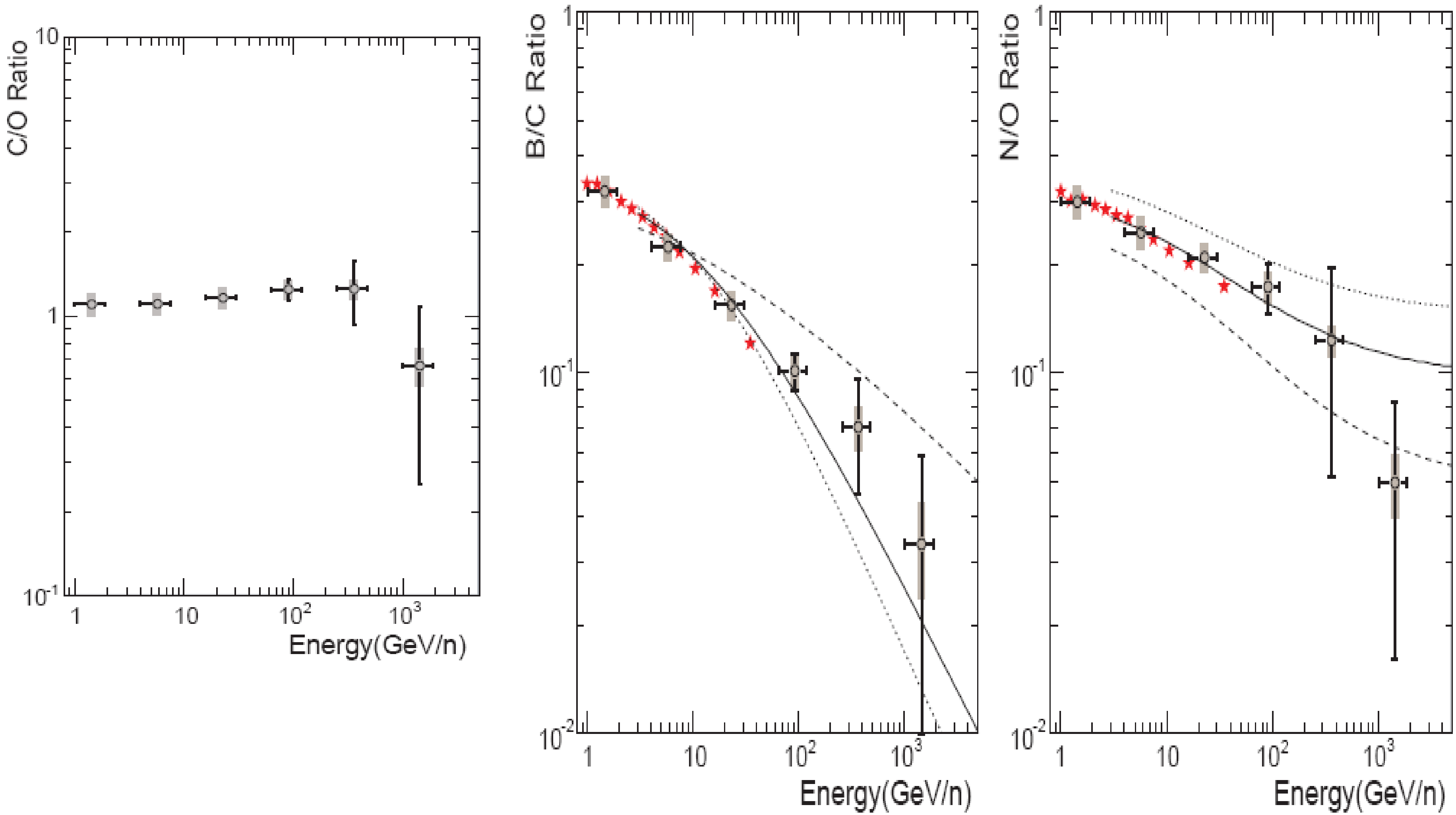


RECENT DATA



HEAO
CRN
TRACER
$O \cdot 10^7$
$Ne \cdot 10^5$
$Mg \cdot 10^3$
Si
$S \cdot 10^{-2}$
$Ar \cdot 10^{-4}$
$Ca \cdot 10^{-6}$
$Fe \cdot 10^{-9}$
Power Law Fit
Flux (m^{-2} sr^{-1} s^{-1} GeV^{-1})
Kinetic Energy (GeV)
10^7
10^4
10
10^{-2}
10^{-5}
10^{-8}
10^{-11}
10^{-14}
10^{-17}
10^{-20}
1
10
10^2
10^3
10^4
10^5
10^6

CREAM data (2008)



Dependence of the Diffusion Coefficient on energy

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

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

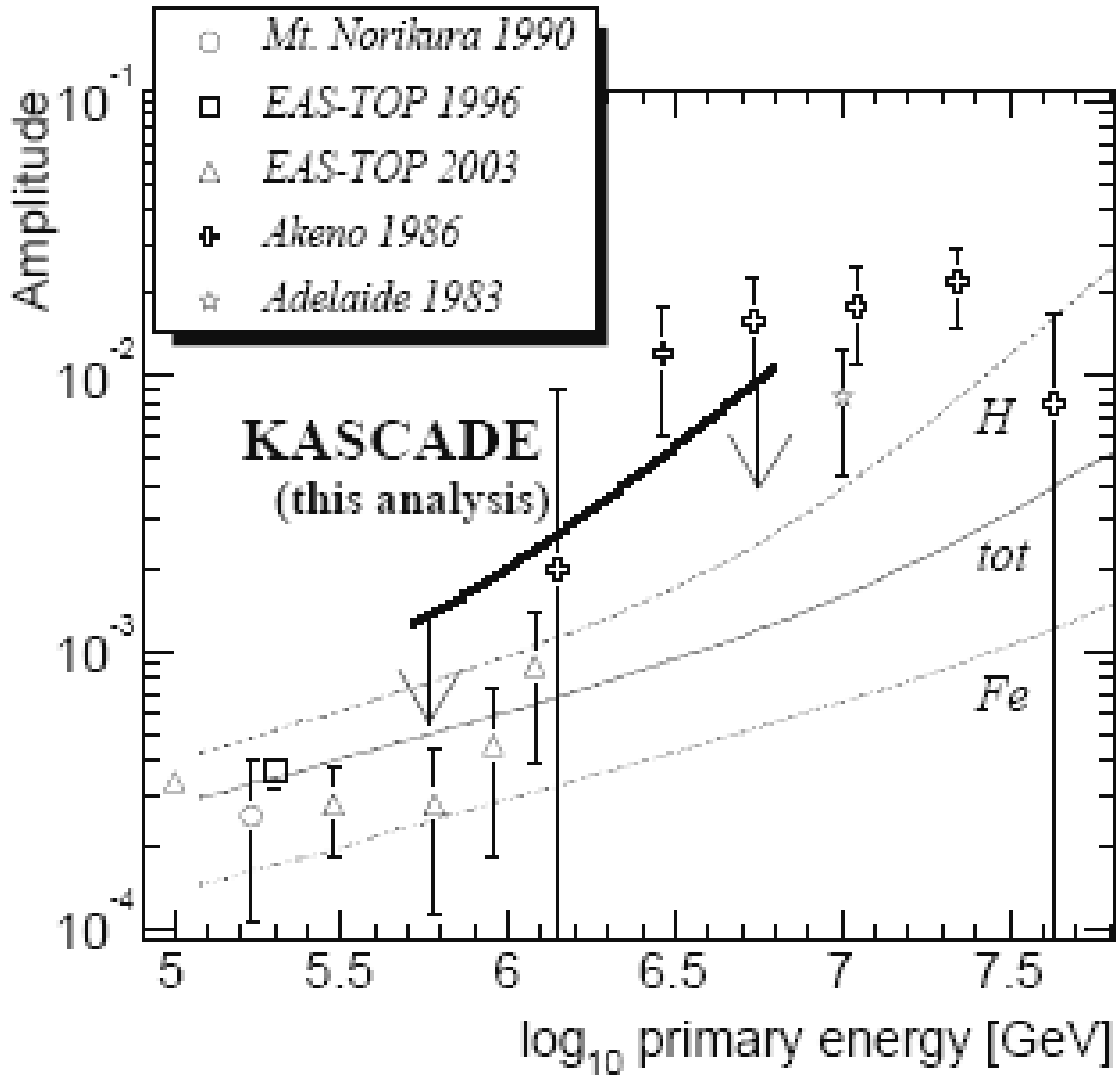
$$\frac{\text{Secondary}}{\text{Primary}} = \sigma\ Y\, n_{gas}\, c\,\tau_{conf}(E) \approx \frac{x(E)}{x_{nucl}} \qquad x_{nucl} \approx 50\ \mathrm{g\ cm^{-2}}$$

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

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

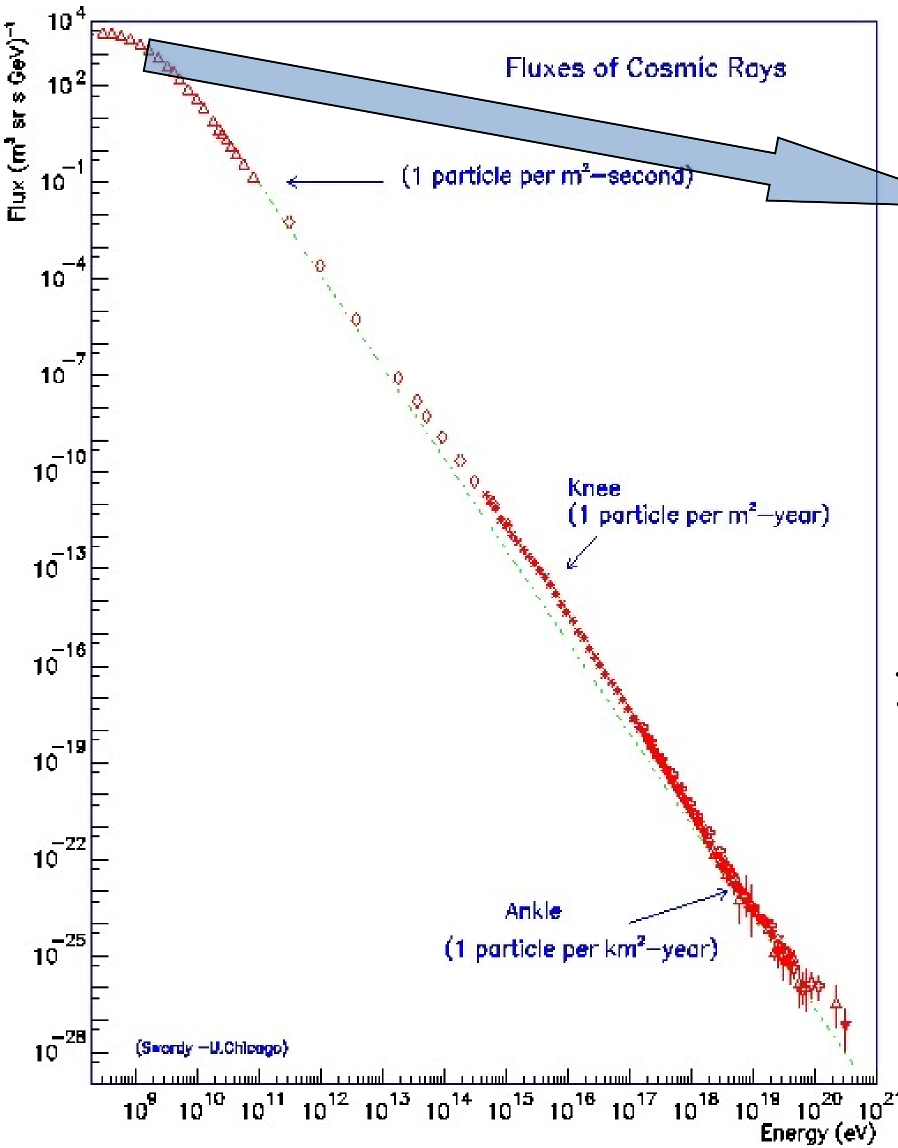
As a function of energy: $D(E) \propto (1/X(E)) \propto E^{\delta} \qquad \delta \sim 0.5$

ANISOTROPY



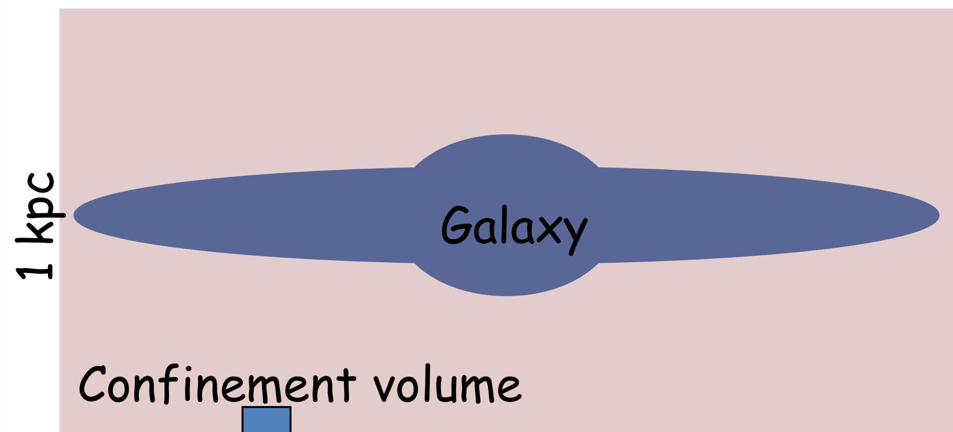
Mt. Norikura 1990
EAS-TOP 1996
EAS-TOP 2003
Akeno 1986
Adelaide 1983
KASCADE
(this analysis)
H
tot
Fe
Amplitude
10^{-1}
10^{-2}
10^{-3}
10^{-4}
5
5.5
6
6.5
7
7.5
$\log_{10}$ primary energy [GeV]

Sources of Cosmic Rays



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

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



30 kpc

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

Sources of Cosmic Rays

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

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

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

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

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

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

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**.

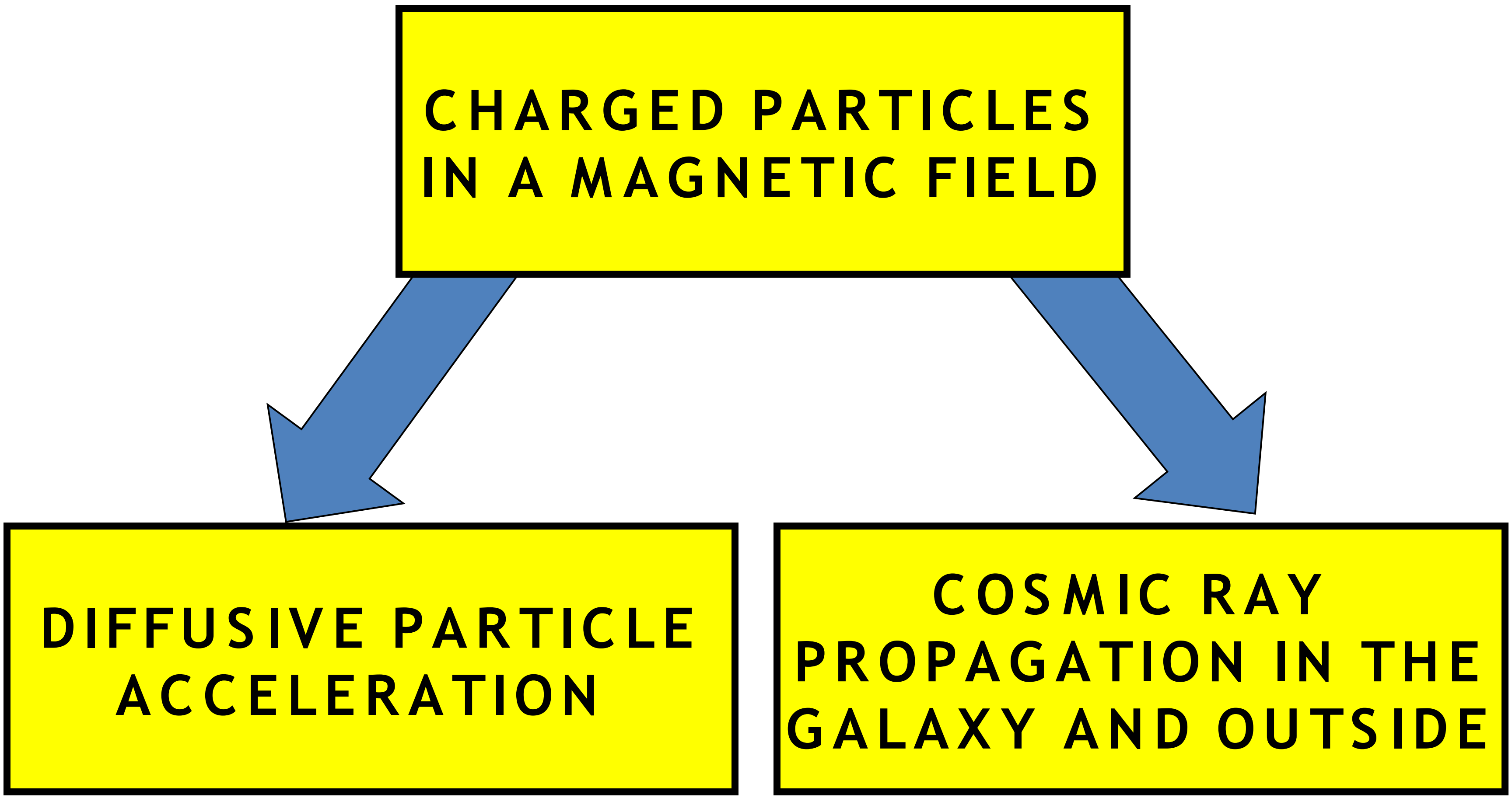
This corresponds to:

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

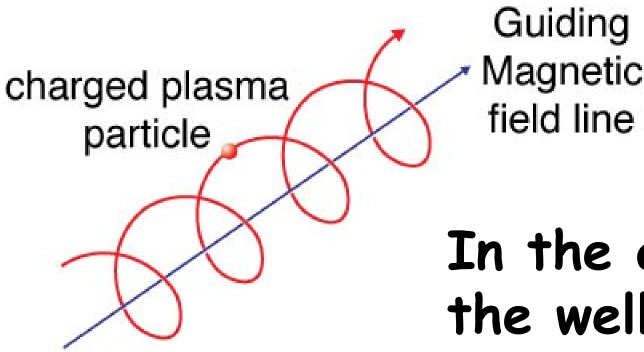
Efficiency of conversion to CR ~ 10-20 %

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:

$$p_z = \text{Constant}$$

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

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

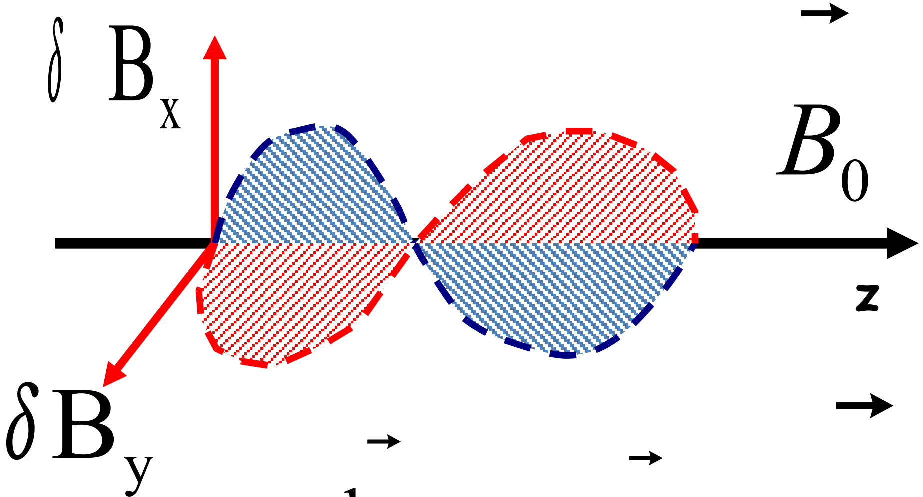
LARMOR FREQUENCY

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

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



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

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

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

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=

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

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

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

RATE OF CHANGE OF THE PITCH ANGLE IN TIME

Diffusive motion

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

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

BUT:

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

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

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:

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

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 ~ $v\tau$

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

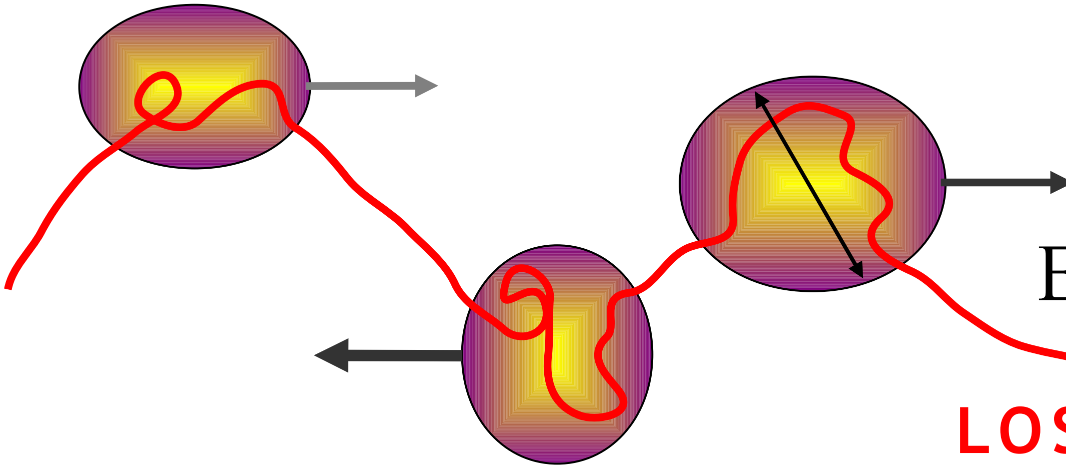
SPATIAL DIFFUSION COEFF.

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

PARTICLE ACCELERATION

A quick look at 2nd order Fermi Acceleration (Fermi, 1949)



$$E' = \gamma E_i (1 - \beta\mu)$$

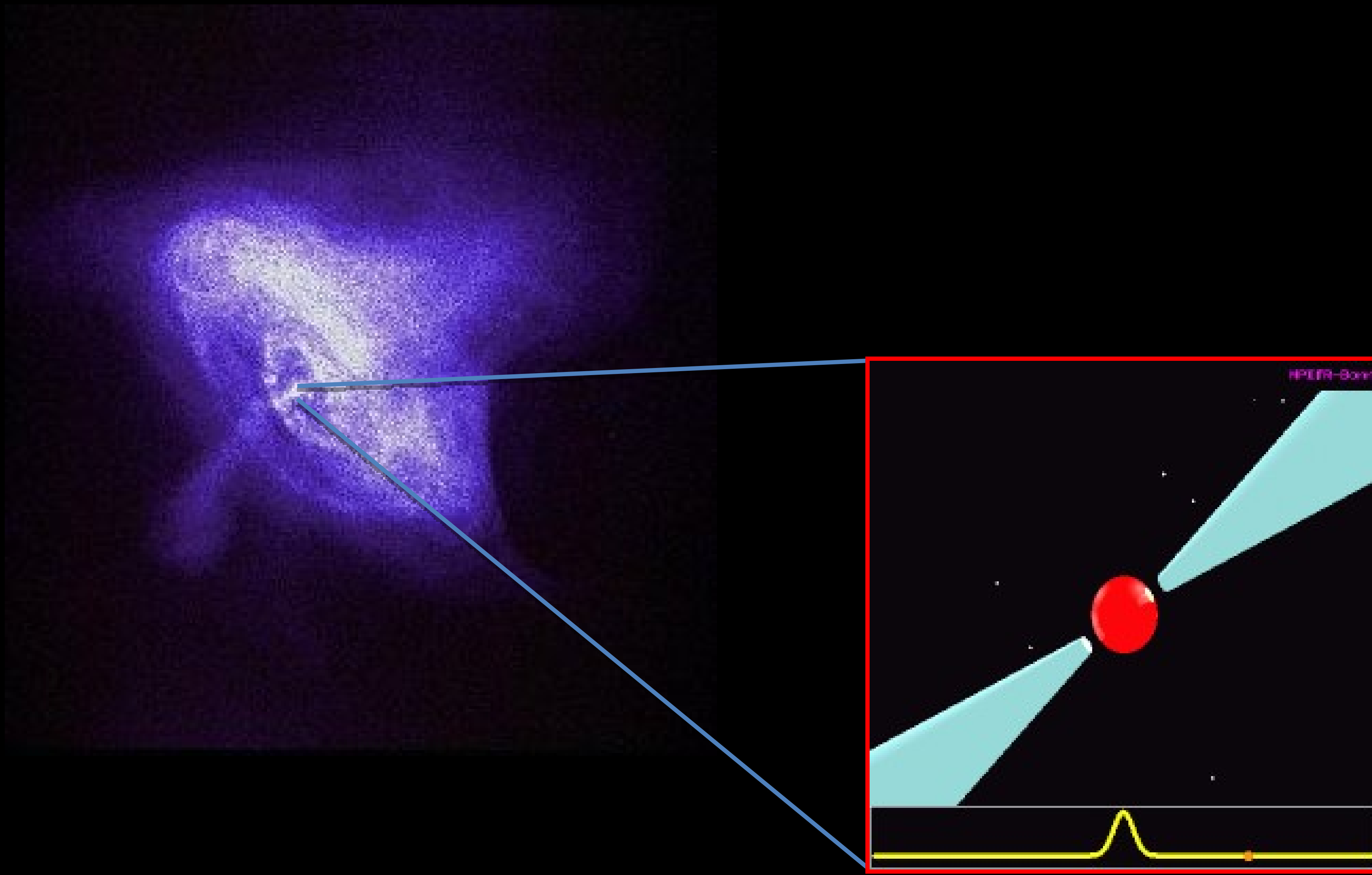
$$E_f = \gamma^2 E_i (1 - \beta\mu)(1 + \beta\mu')$$

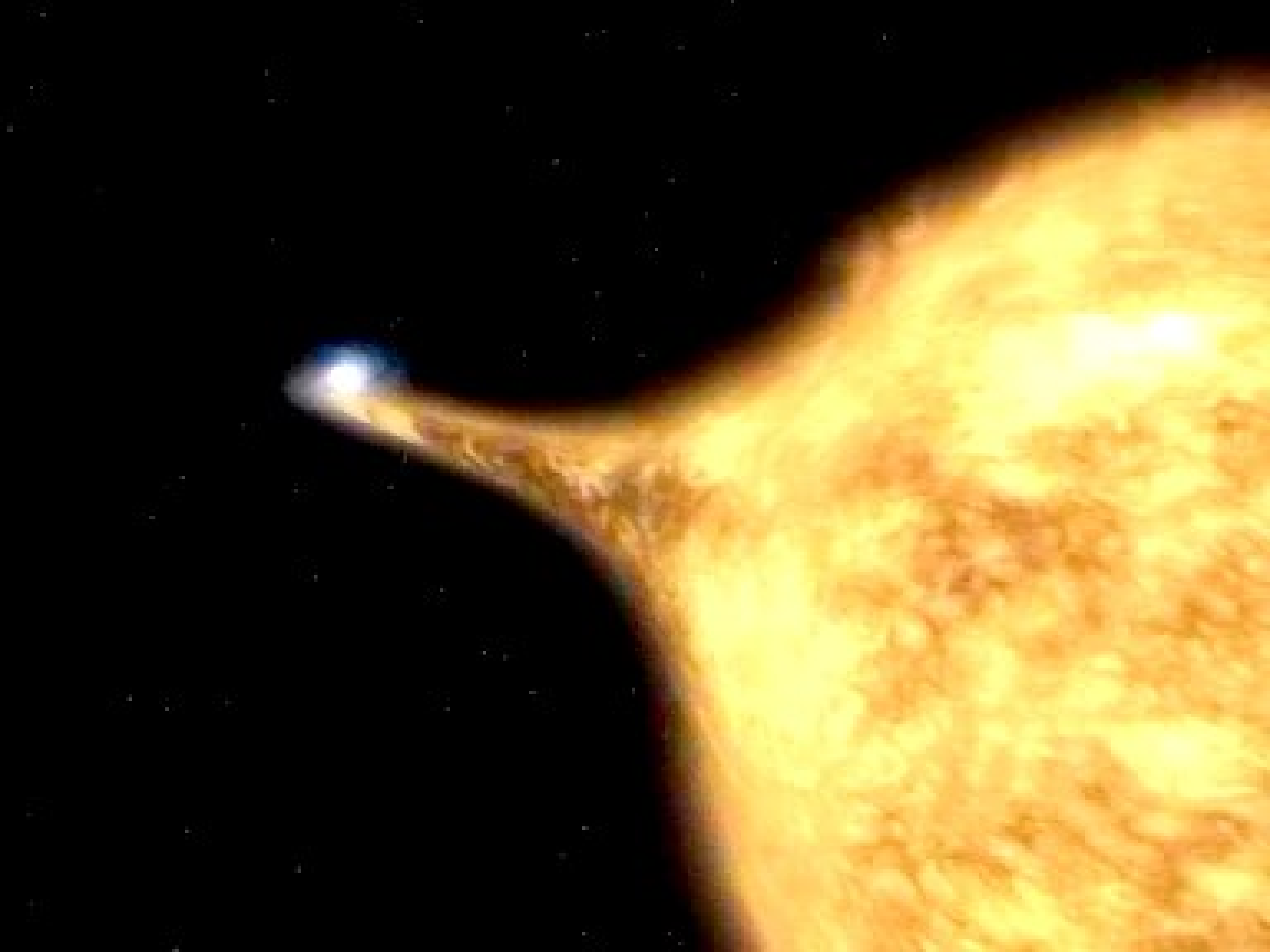
LOSSES AND GAINS ARE PRESENT BUT DO NOT COMPENSATE EXACTLY

$$\left\langle \frac{\Delta E}{E} \right\rangle_{\mu'} = 2[\gamma^2 (1 - \beta\mu) - 1]$$

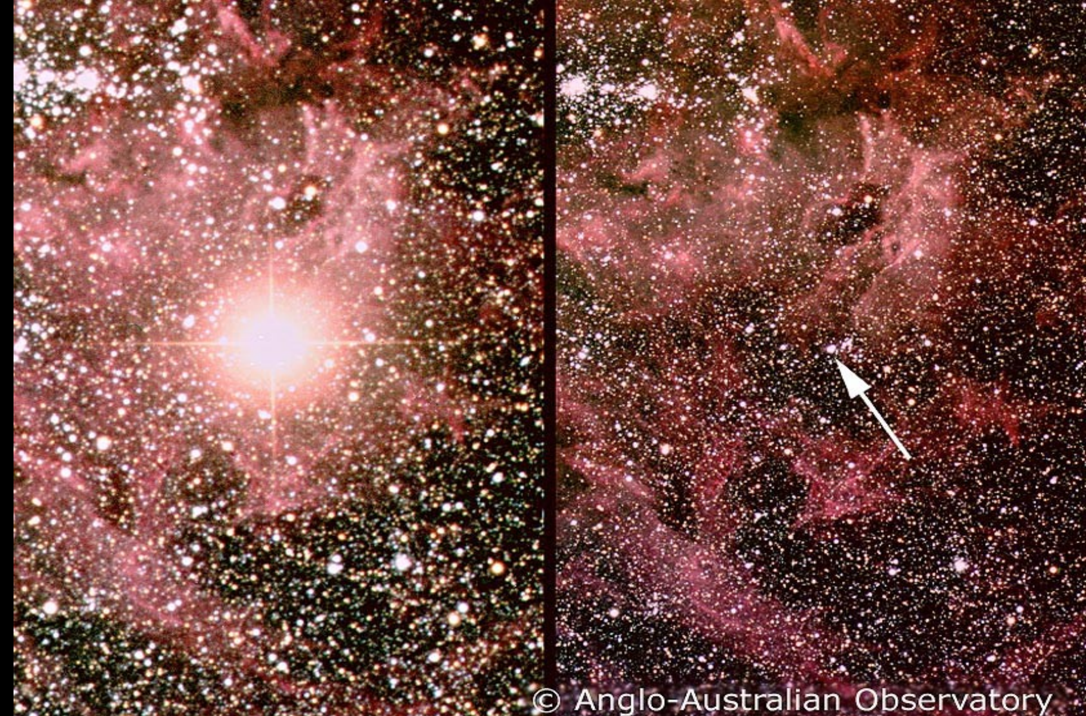
$$\left\langle \frac{\Delta E}{E} \right\rangle_{\mu} = \int_{-1}^{1} d\mu \, \frac{1}{2} (1 - \beta\mu) \, 2 \left(\gamma^2 (1 - \beta\mu) - 1 \right) \propto \beta^2$$

PROBABILITY OF ENCOUNTER


MPIfR-Bonn




supernova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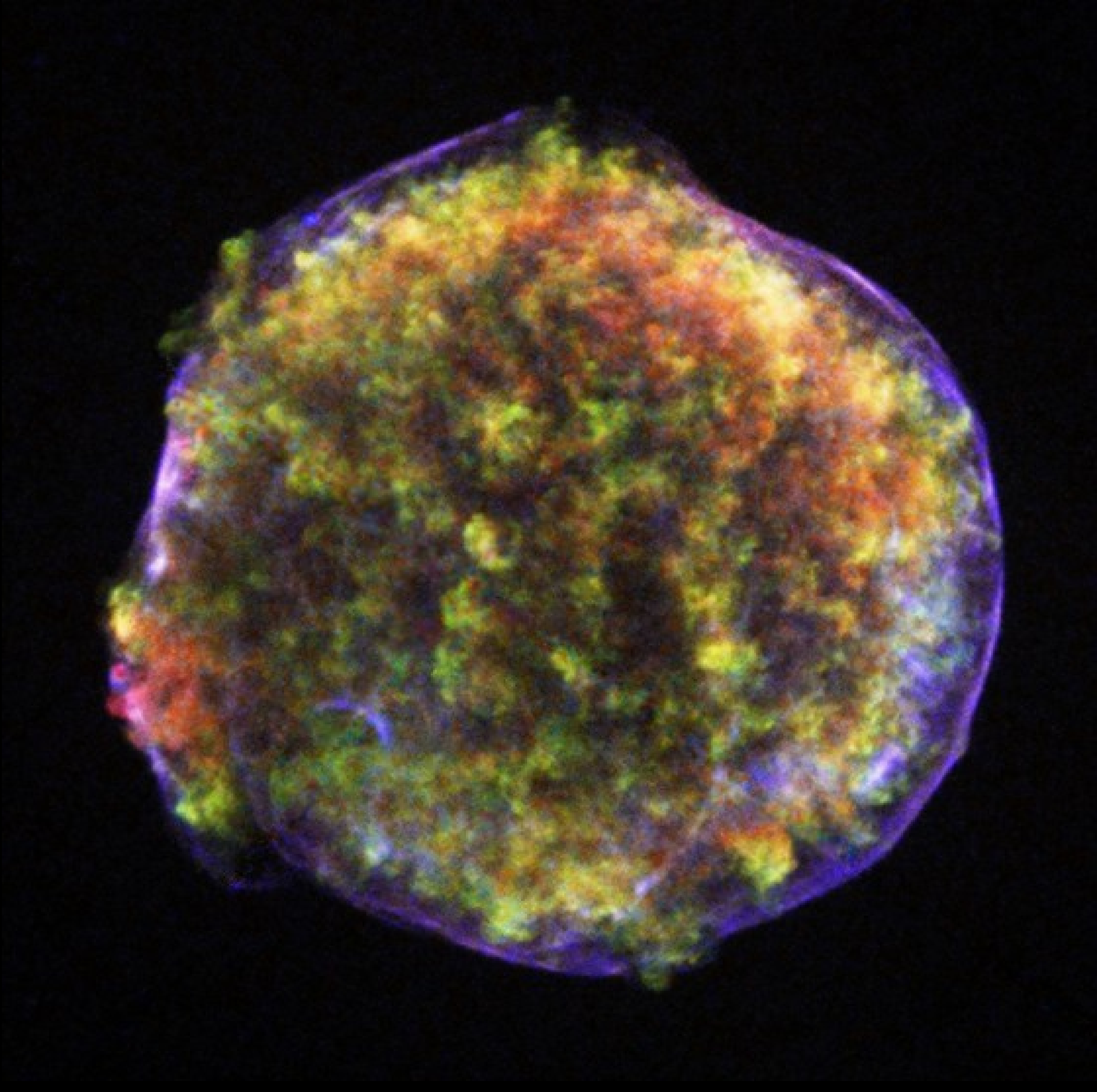
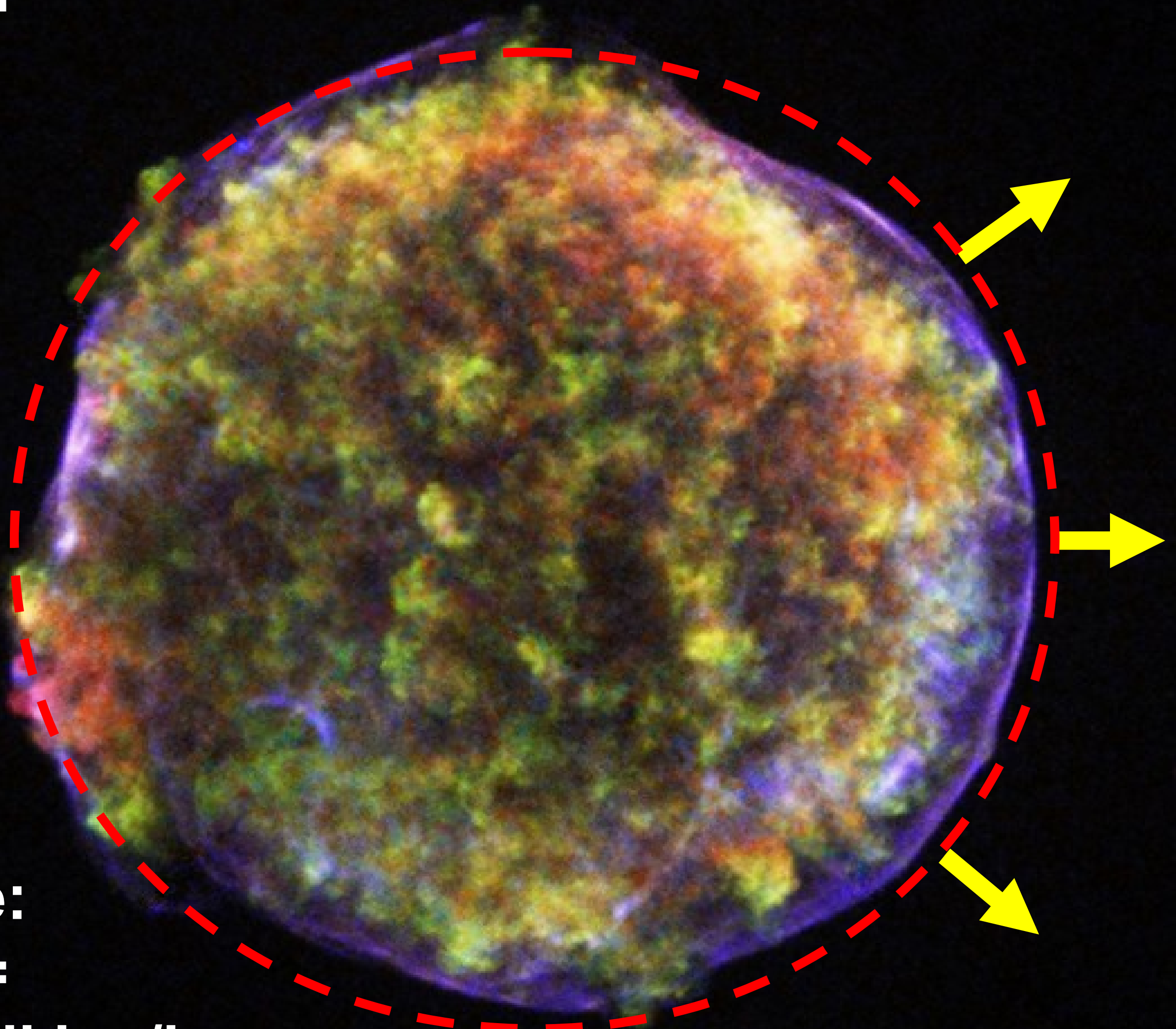



VELOCITA' DEL SUONO IN ARIA
311 metri al secondo =
1100 km/h

VELOCITA' DEL SUONO NEL MEZZO INTERSTELLARE
36000 km/h

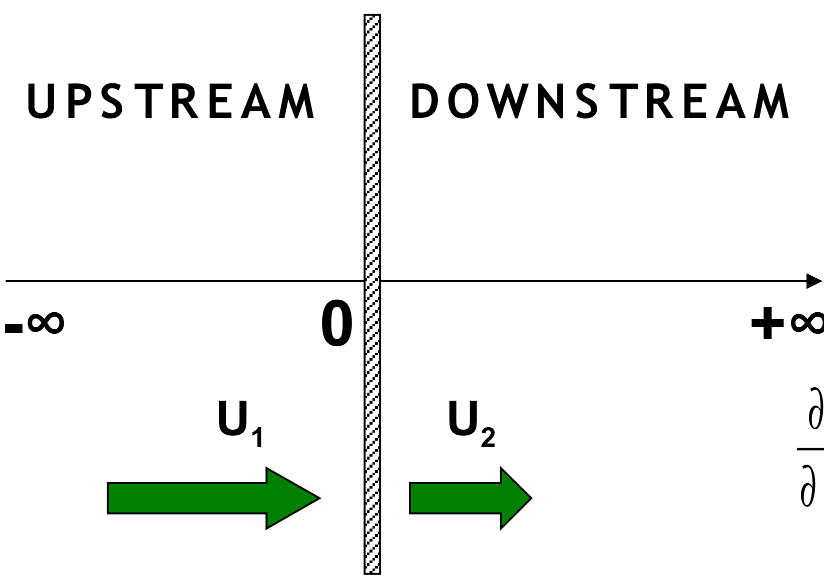


Esplosione:
5000 km/s=
18 milioni di km/h

A PRIMER ON SHOCK WAVES

For $\sigma \sim 10^{-25}$ cm^2 and density n~1 cm^{-3} the typical interaction length is ~3 Mpc >> than the typical size of astrophysical objects and even Larger than the Galaxy!!!

COLLISIONLESS SHOCKS



$$\frac{\partial \rho}{\partial t} = -\frac{\partial}{\partial x}[\rho u]$$

$$\frac{\partial}{\partial t}(\rho u) = -\frac{\partial}{\partial x}\left[\rho u^2 + P_{gas}\right]$$

$$\frac{\partial}{\partial t}\left[\frac{1}{2}\rho u^2 + \frac{P_{gas}}{\gamma - 1}\right] = -\frac{\partial}{\partial x}\left[\frac{1}{2}\rho u^3 + \frac{\gamma P_{gas} u}{\gamma - 1}\right]$$

STATIONARY SHOCKS

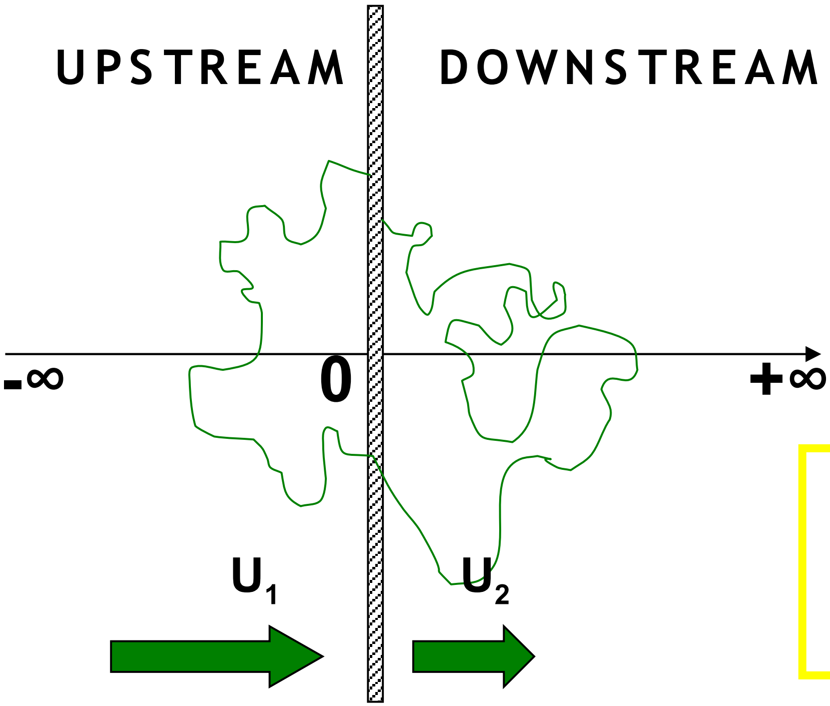
$$\frac{\rho_2}{\rho_1} = \frac{4M^2}{M^2 + 3} \xrightarrow[M \to \infty]{} 4$$

$$\frac{p_2}{p_1} = \frac{5}{4}M^2 - \frac{1}{4} \xrightarrow[M \to \infty]{} p_2 = \frac{6\rho_1 u_1^2}{8}$$

$$\frac{T_2}{T_1} = \frac{\left(\frac{10}{3}M^2 - \frac{2}{3}\right)\left(\frac{2}{3}M^2 + 2\right)}{\left(\frac{8}{3}M\right)^2} \xrightarrow[M \to \infty]{} T_2 = \frac{3}{16}mu_1^2$$

SHOCK WAVES ARE MAINLY HEATING MACHINES!

BOUNCING BETWEEN APPROACHING MIRRORS



$V = U_1 - U_2 > 0$ **Relative velocity**

INITIAL ENERGY DOWNS: E

$$E_d = E(1 - V\mu) \qquad -1 < \mu < 0$$

$$E_u = E(1 - V\mu)(1 + V\mu') \qquad 0 < \mu' < 1$$

TOTAL FLUX

$$J = \int_0^1 d\Omega \frac{N}{4\pi} v\mu = \frac{Nv}{4} \quad \Rightarrow \quad P(\mu)d\mu = \frac{ANv\mu}{\frac{Nv}{4}} d\mu = 2\mu d\mu$$

$$\left\langle \frac{\Delta E}{E} \right\rangle = \int_0^1 d\mu\, 2\mu \int_{-1}^0 d\mu'\, 2\mu' \left[(1 - V\mu)(1 + V\mu') - 1 \right] = \boxed{\frac{4}{3}(U_1 - U_2)}$$

FIRST ORDER

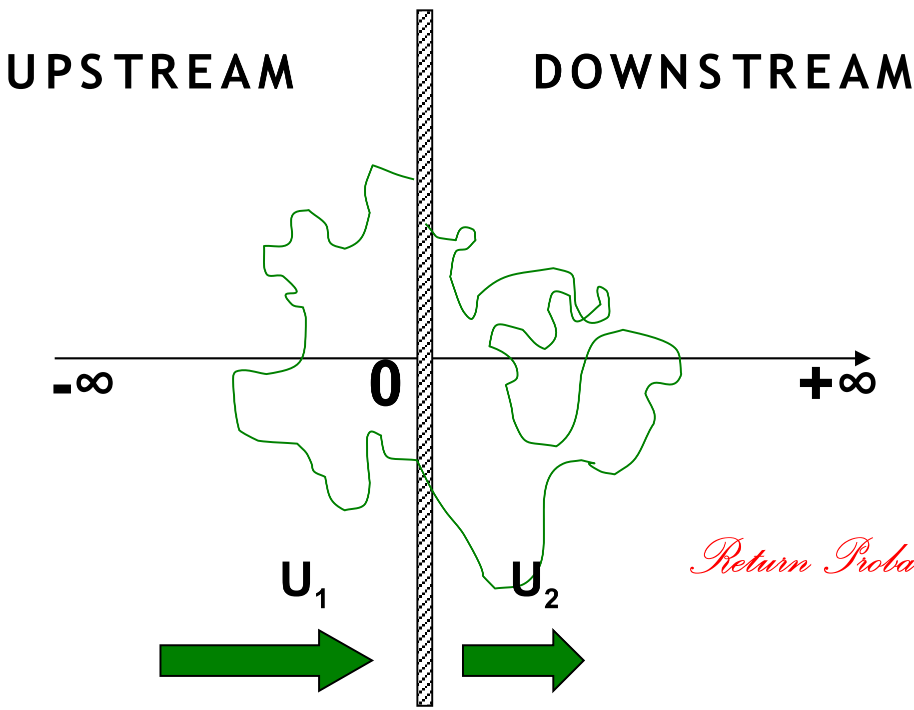
A FEW IMPORTANT POINTS:

There are no configurations that lead to losses

. The mean energy gain is now first order in V

I. The energy gain is basically independent of any detai on how particles scatter back and forth!

RETURN PROBABILITIES AND SPECTRUM OF ACCELERATED PARTICLES



$$\varphi_{in} = \int_{-u_2}^{1} d\mu\, f_0(u_2+\mu) = \frac{1}{2}(1+u_2)^2$$

$$\varphi_{out} = \int_{-1}^{-u_2} d\mu\, f_0(u_2+\mu) = \frac{1}{2}(1-u_2)^2$$

Return Probability from Downstream

$$P_d = \frac{\varphi_{out}}{\varphi_{in}} = \frac{(1-u_2)^2}{(1+u_2)^2} \approx 1-4u_2$$

HIGH PROBABILITY OF RETURN FROM DOWNSTREAM BUT TENDS TO ZERO FOR HIGH U_2

ENERGY GAIN: $E_{k+1} = \left(1 + \frac{4}{3}V\right)E_k$

$$E_0 \rightarrow E_1 \rightarrow E_2 \rightarrow \text{---} \rightarrow E_K = [1+(4/3)V]^K \, E0$$

$$\ln\left(\frac{E_K}{E_0}\right) = K \ln\left(1 + \frac{4}{3}\left(U_1 - U_2\right)\right)$$

$$N_0 \rightarrow N_1 = N_0 * P_{ret} \rightarrow \text{---} \rightarrow N_K = N_0 * P_{ret}^{\,K}$$

$$\ln\left(\frac{N_K}{N_0}\right) = K \ln\left(1 - 4U_2\right)$$

Putting these two expressions together we get:

$$K = \frac{\ln\left[\dfrac{N_K}{N_0}\right]}{\ln[1 - 4U_2]} = \frac{\ln\left[\dfrac{E_K}{E_0}\right]}{\ln\left[1 + \dfrac{4}{3}(U_1 - U_2)\right]}$$

Therefore:

$$N(> E_K) = N_0\left(\frac{E_K}{E_0}\right)^{-\gamma} \qquad \gamma = \frac{3}{r-1} \qquad r = \frac{U_1}{U_2}$$

THE SLOPE OF THE DIFFERENTIAL SPECTRUM WILL BE **$\gamma+1=(r+2)/(r-1)$** → **2** FOR $r \to 4$ (STRONG SHOCK)

PROPAGATION OF EXTRAGALACTIC COSMIC RAYS

MOLOGICAL TIME SCALES THERE ARE THREE PROCESSES THAT ARE RE
OPAGATION

ADIABATIC LOSSES DUE TO THE EXPANSION OF THE UNIVERSE

$$p + \gamma_{CMB} \rightarrow p + e^{+} + e^{-}$$

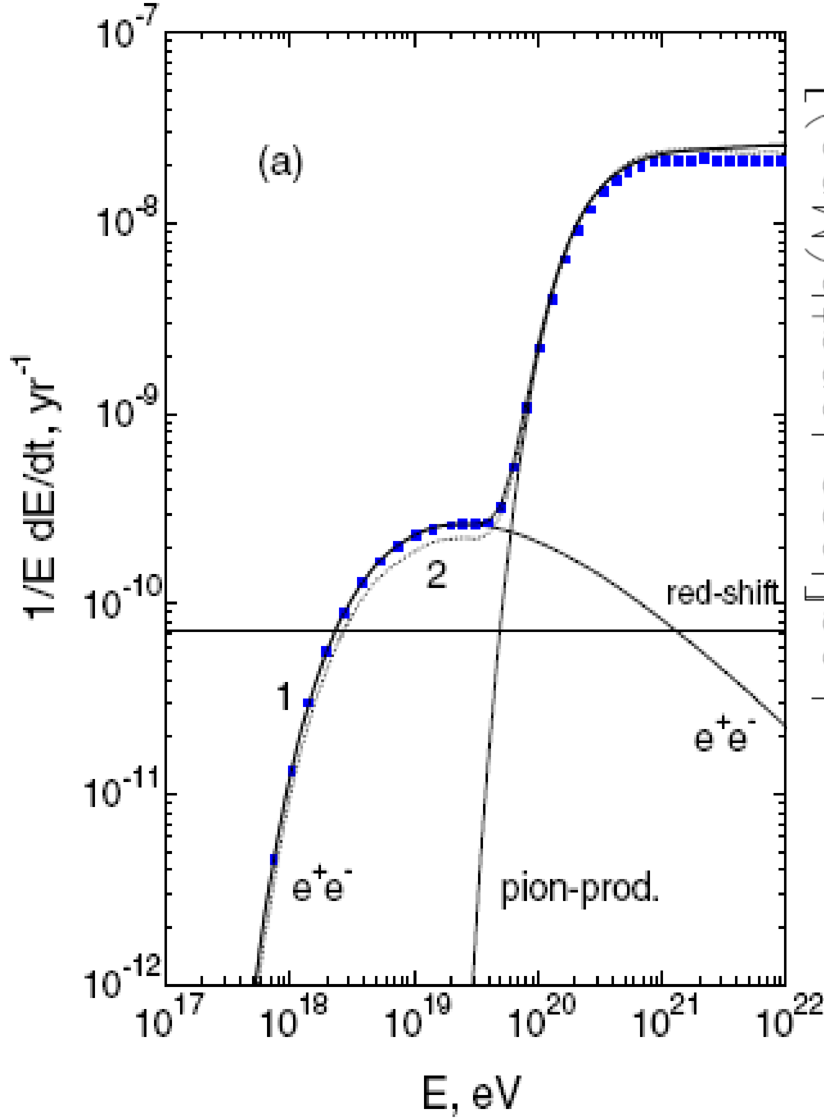
BETHE-HEITLER PAIR PRODUCTION

$$p + \gamma_{CMB} \rightarrow n + \pi^{+}$$

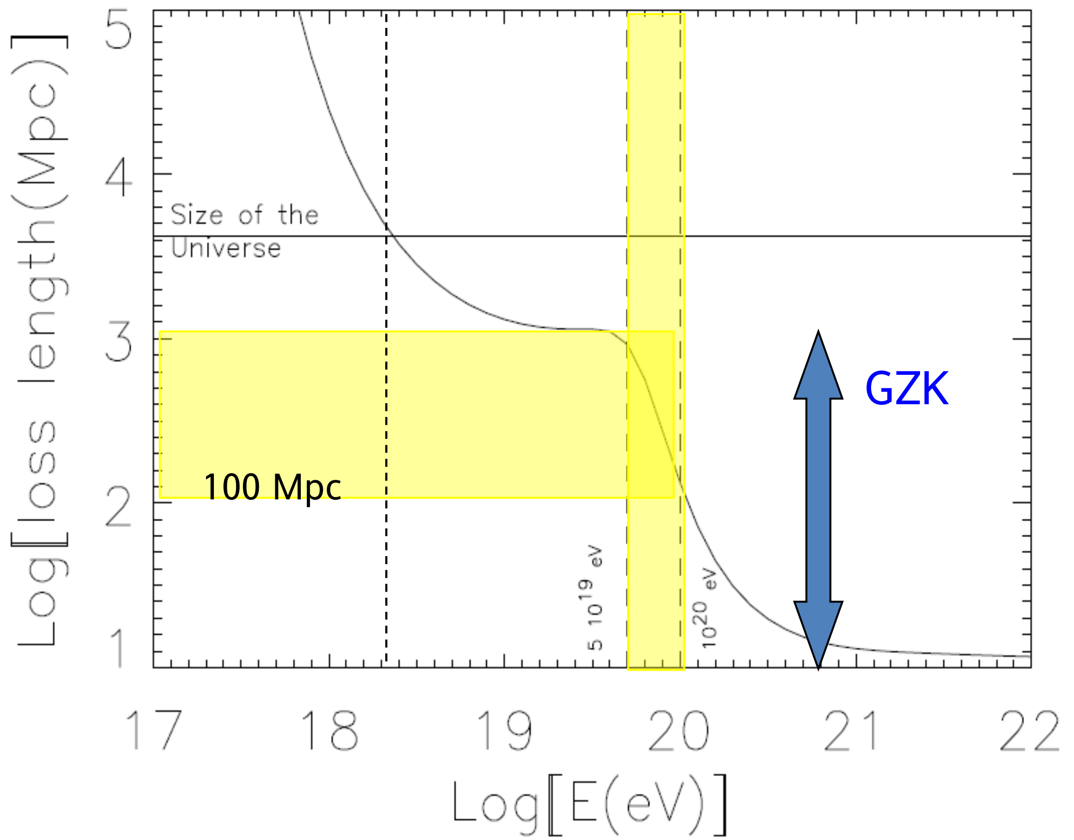
PHOTOPION PRODUCTION

$$p + \gamma_{CMB} \rightarrow p + \pi^{0}$$

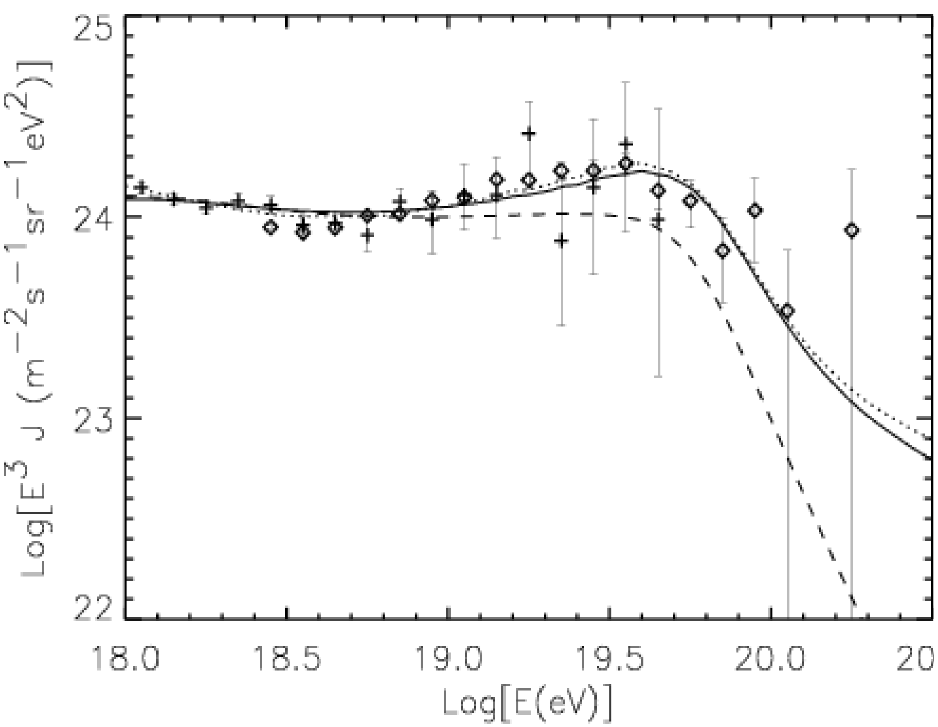
LOSS TIME



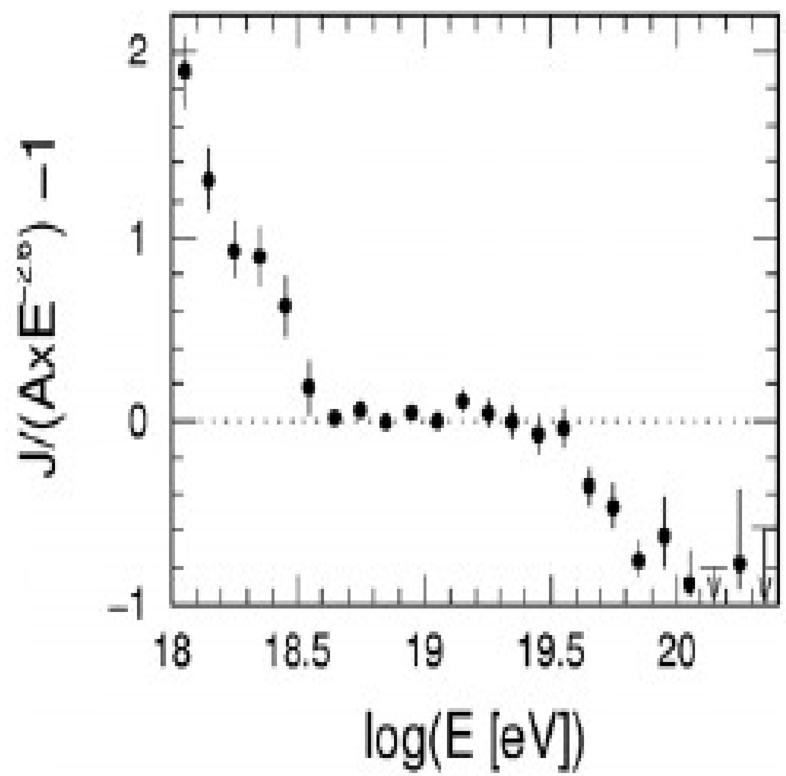
LOSS LENGTH



Spectrum of UHECRs: case of protons



$Q(E,z) \sim E^{-\gamma} (1+z)^m \exp(-E/E_{max})$



Solid: γ=2.6 m=0 Emax=10^{21}eV

Dashed: γ=2.6 m=0 Emax=10^{20}eV

Dotted: γ=2.4 m=4 Emax=10^{21}eV