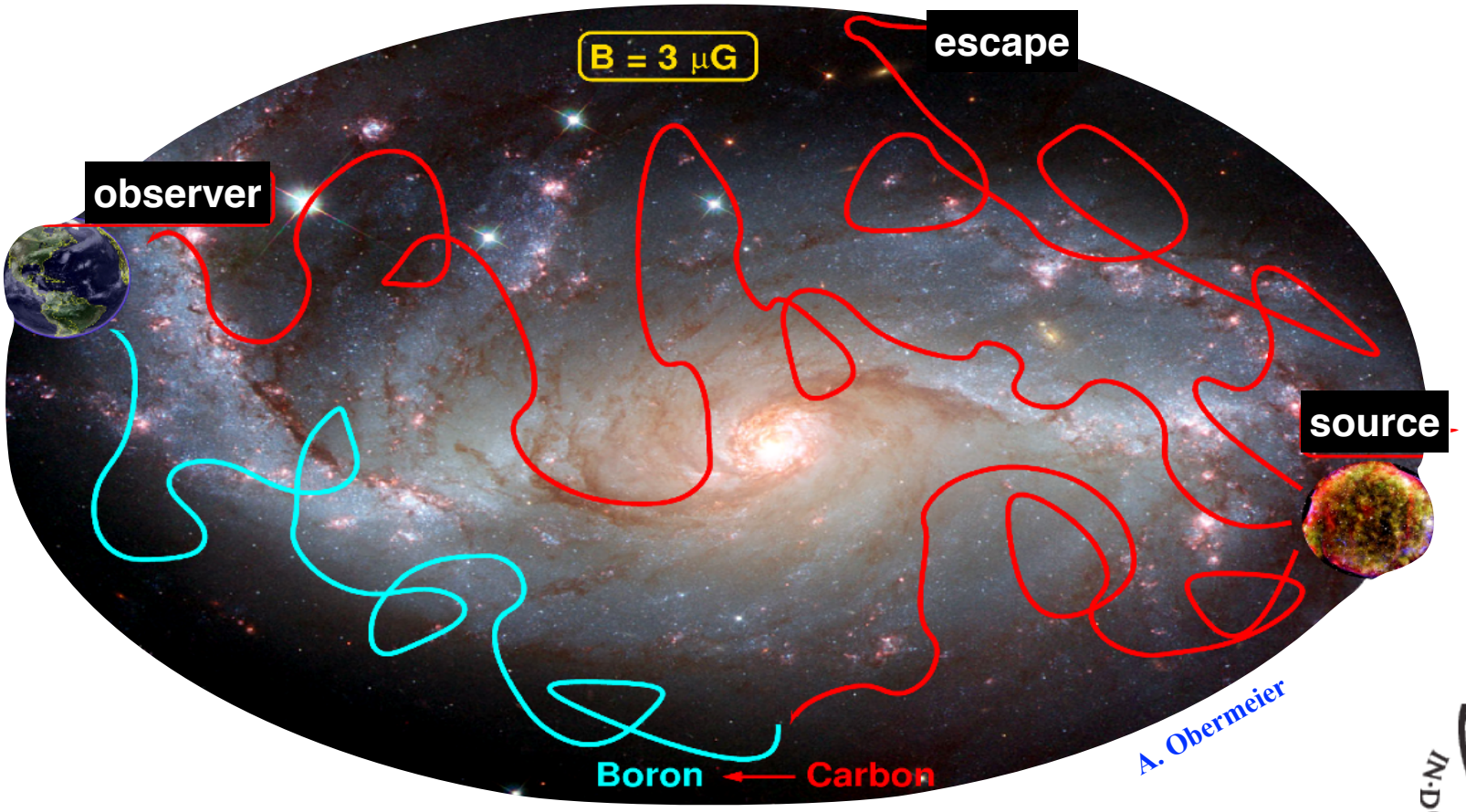
Transport of Cosmic Rays

Propagation of cosmic rays in our Galaxy



Jörg R. Hörandel
Radboud University Nijmegen & Nikhef

http://particle.astro.ru.nl

Transport equation for cosmic rays in the Galaxy

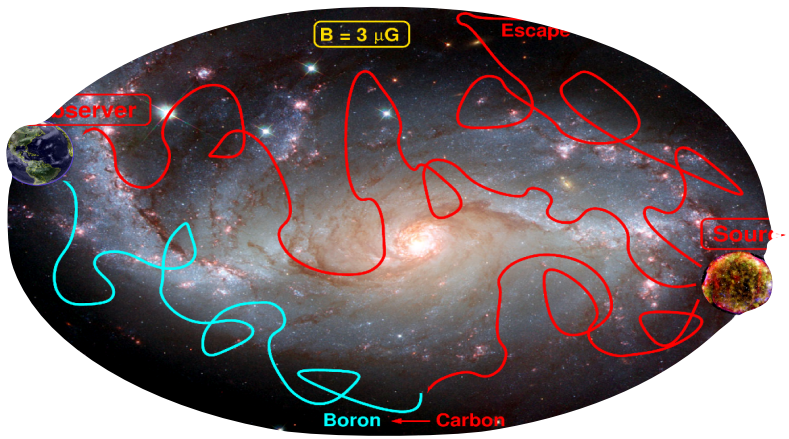
diffusion

energy loss (Bethe Bloch)

loss through interactions with ISM (spallation)

loss through radioactive decay

$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E}(b_i N_i) - n\nu\sigma_i N_i - \frac{N_i}{\gamma\tau_i} + Q_i + \sum_{j>i} n\nu\sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j \tau_{ij}}$$



source term

production through spallation of heavy neulcei

production through decay of heavy nuclei

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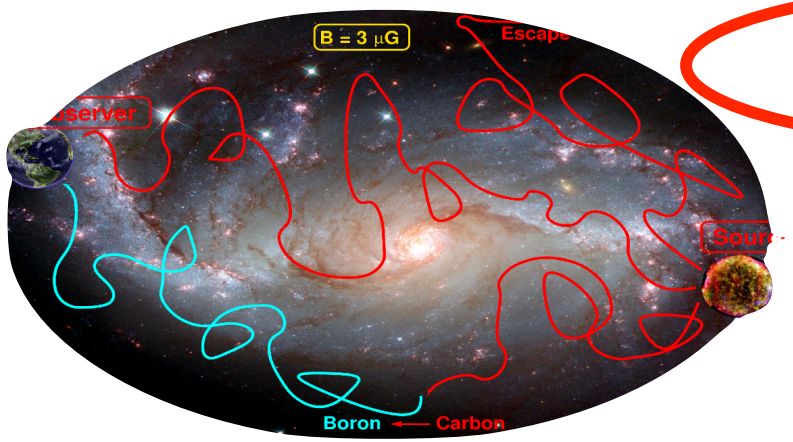
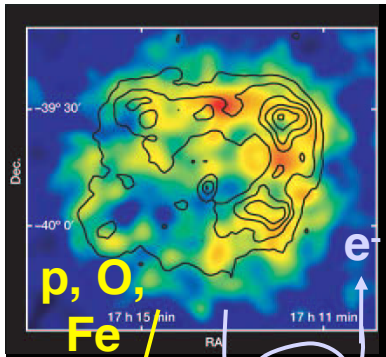


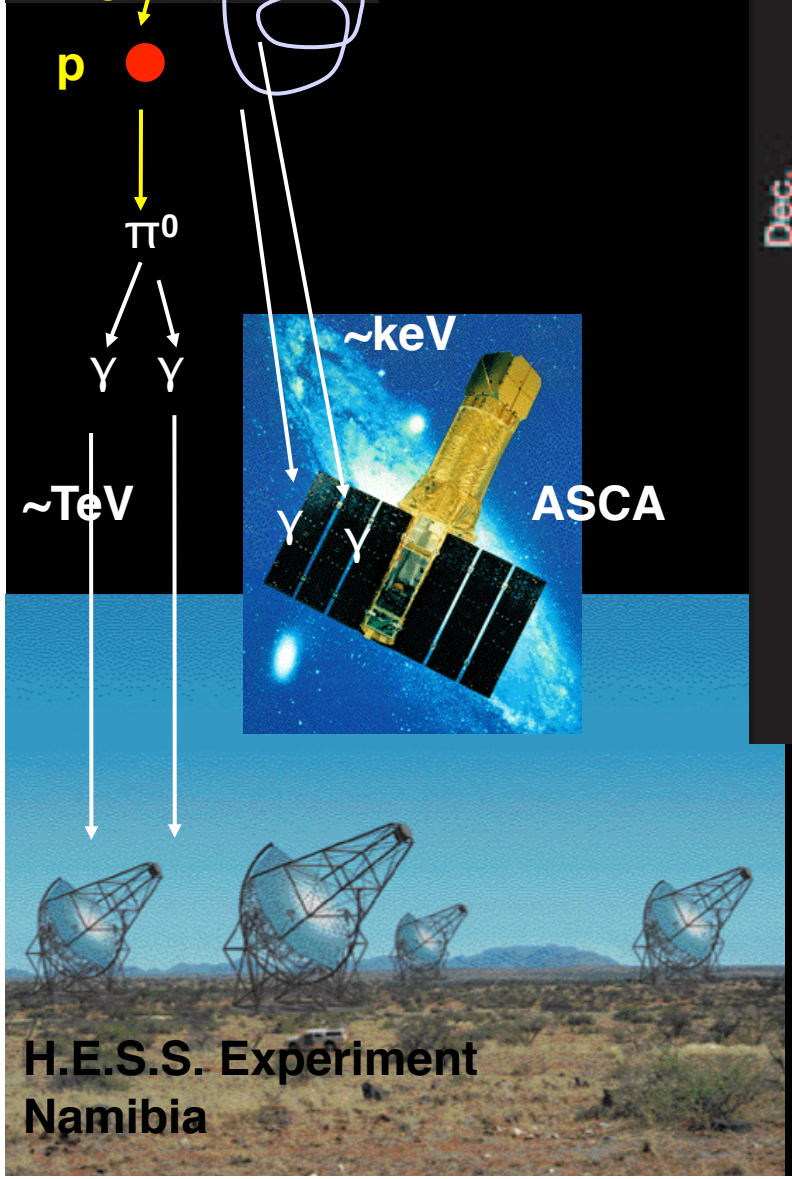
source term

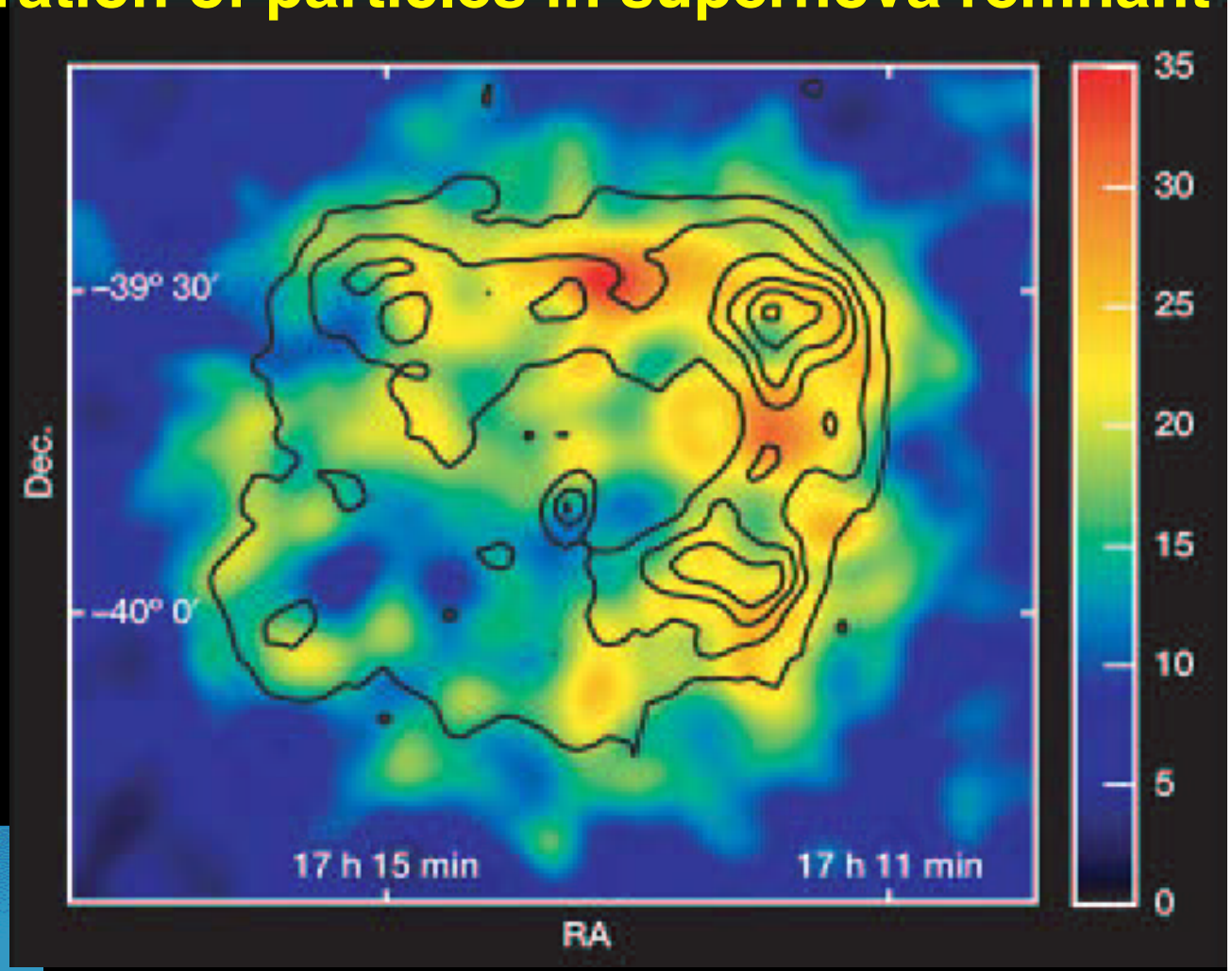
production through spallation of heavy neulcei

production through decay of heavy nuclei

Acceleration of particles in supernova remnant



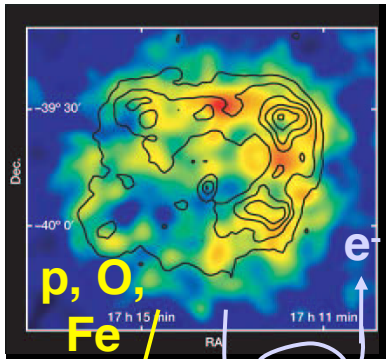


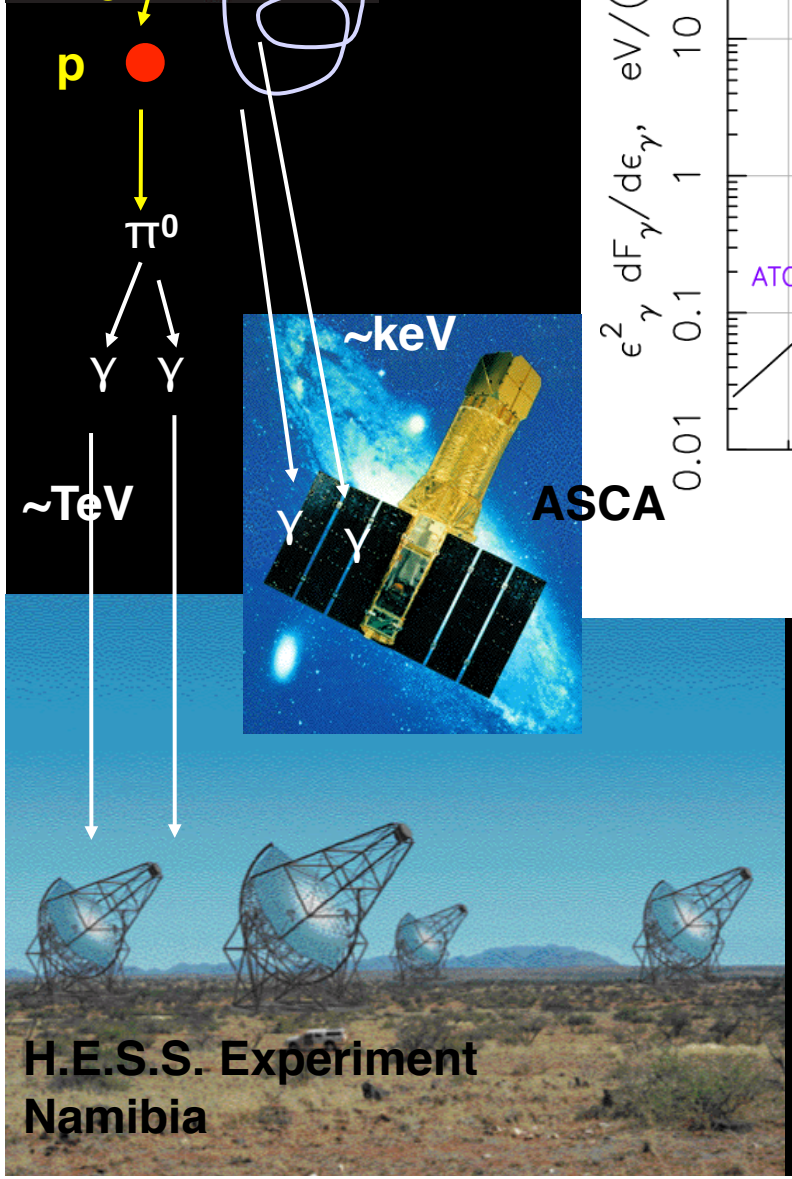


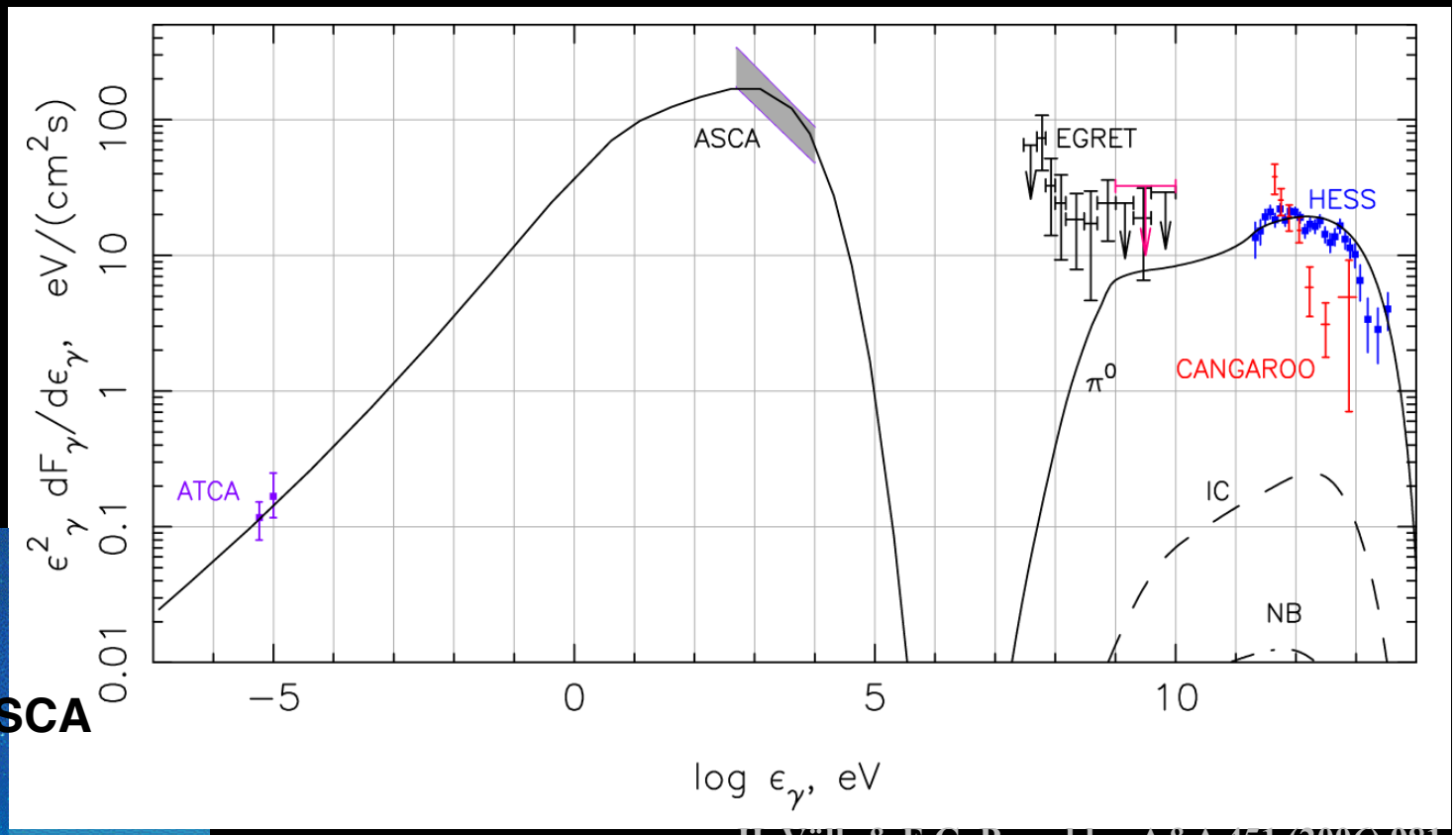
SN R RX J1713.7-3946
H.E.S.S.: TeV-Gamma rays
ASCA: X-rays (keV)

F.A. Aharonian, Nature 432 (2004) 75

Acceleration of particles in supernova remnant







H. Völk & E.G. Berezhko, A&A 451 (2006) 981

1st order Fermi acceleration

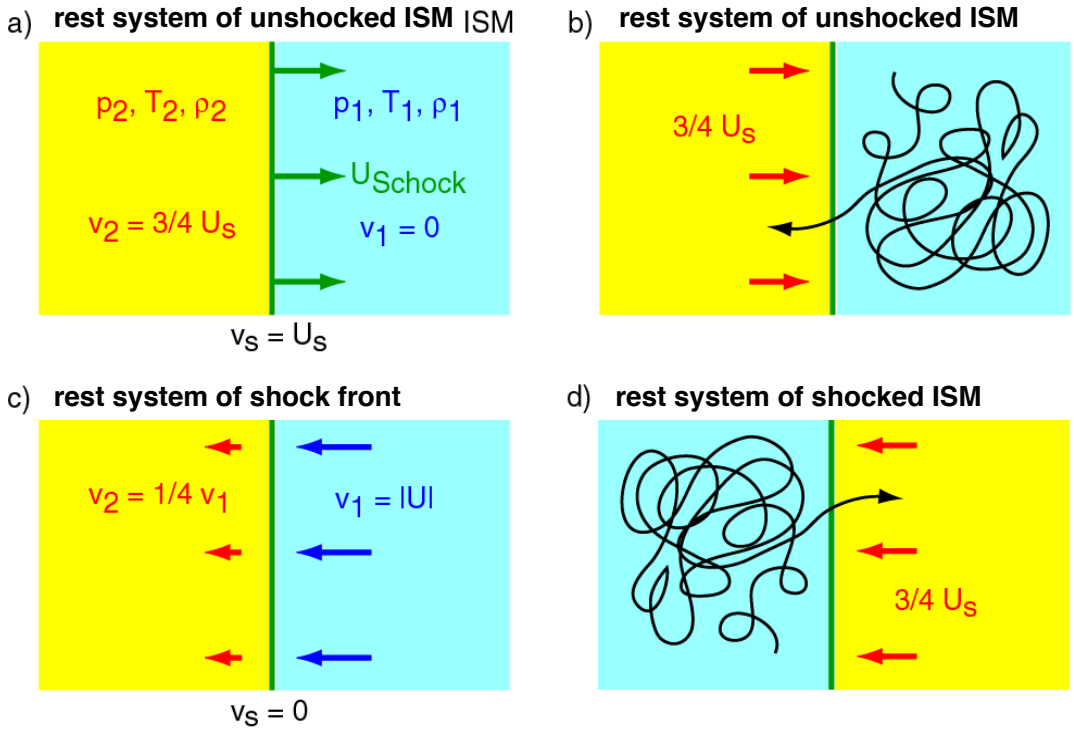
maximum energy

$$E_{max} \approx Ze\,\beta_S\,B\,T\,V_S \qquad \beta_S = \frac{V_S}{c}$$ velocity of shock

$$E_{max} \approx Z \cdot 100\ \mathrm{TeV} \ldots Z \cdot 5\ \mathrm{PeV}$$

Lagage & Cesarsky, A&A 118 (1983) 223

1st order Fermi acceleration at strong shock

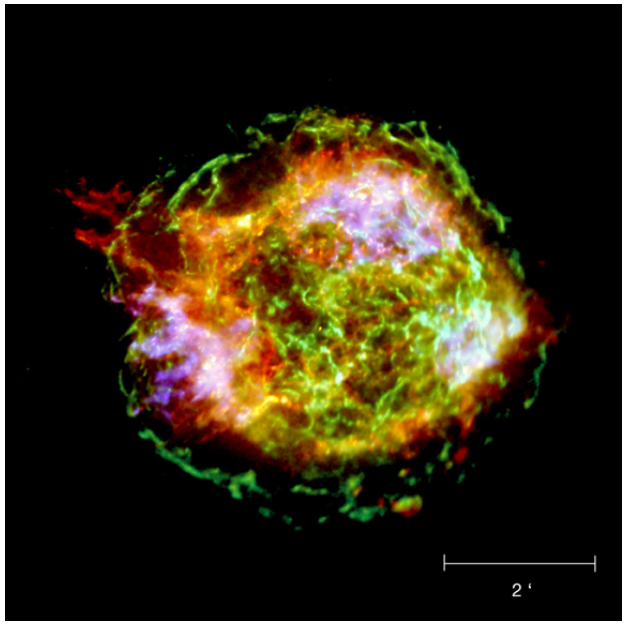


Bell, Blanford,Ostriker (1978)

energy gain $$\frac{\Delta E}{E} \propto \frac{U_s}{c}$$

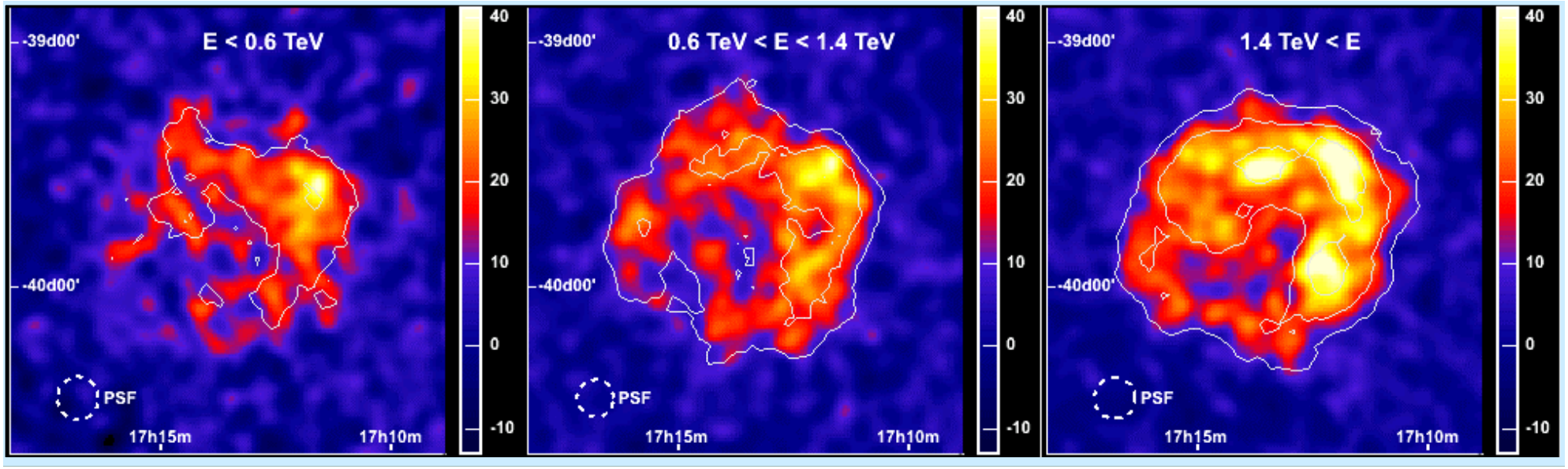
$$N(E)\,dE \propto E^{-2}\,dE$$

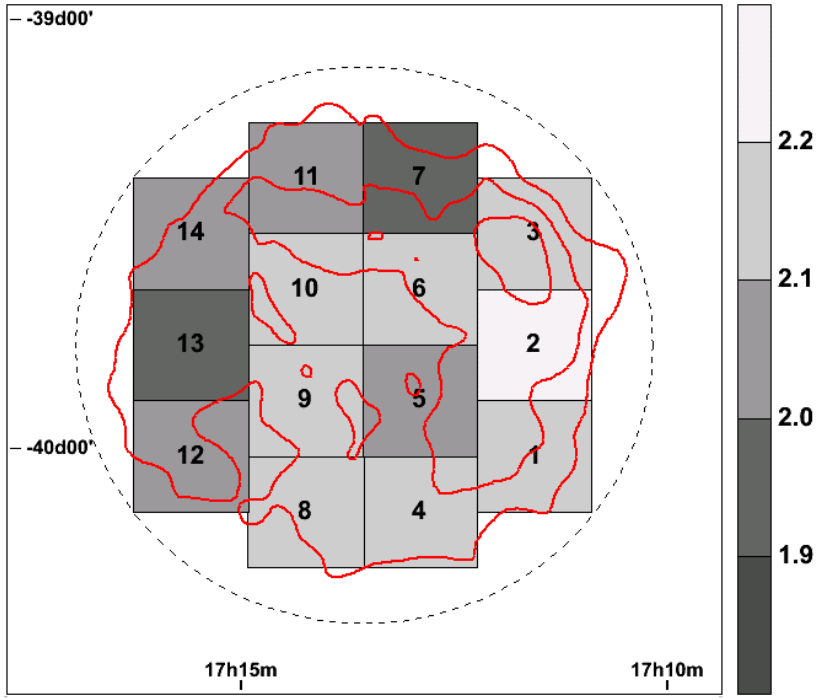
power law with spectral index -2.0 ... -2.1

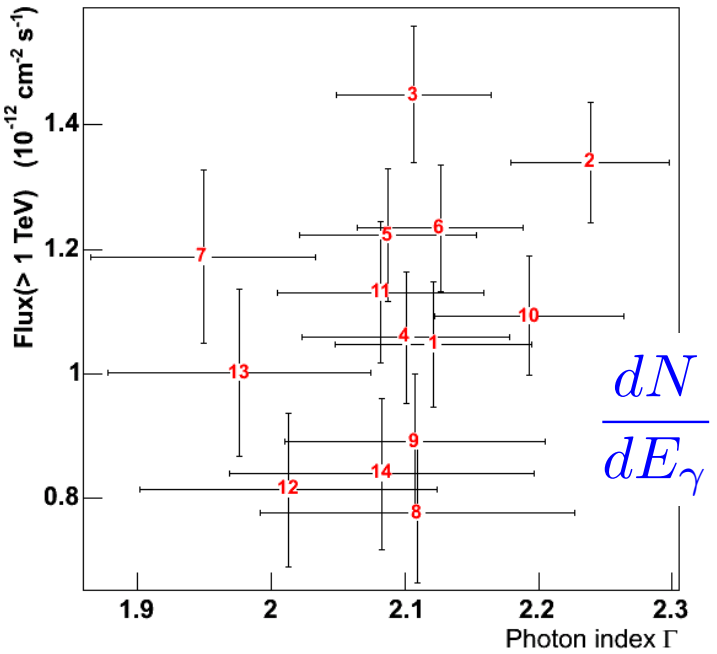


Supernova remnant (SNR) Cassiopeia A

H.E.S.S. supernova remnant RXJ 1713







$$\frac{dN}{dE_\gamma} \propto E_\gamma^{-\Gamma}$$

Transport equation for cosmic rays in the Galaxy

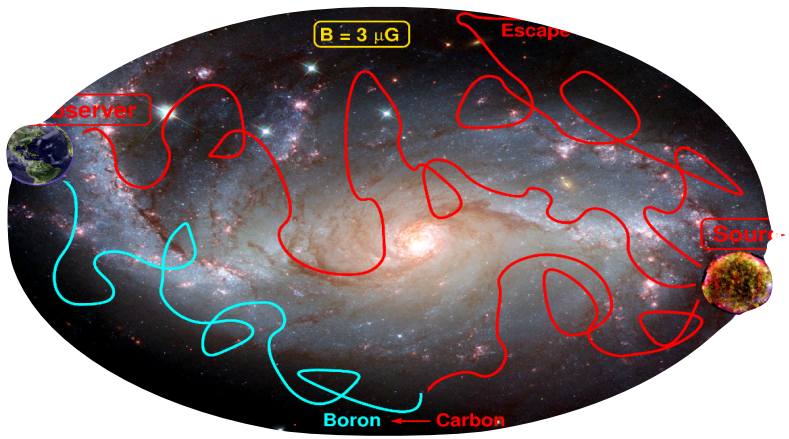
diffusion

energy loss (Bethe Bloch)

loss through interactions with ISM (spallation)

loss through radioactive decay

$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E}(b_i N_i) - n\nu\sigma_i N_i - \frac{N_i}{\gamma\tau_i} + Q_i + \sum_{j>i} n\nu\sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j \tau_{ij}}$$

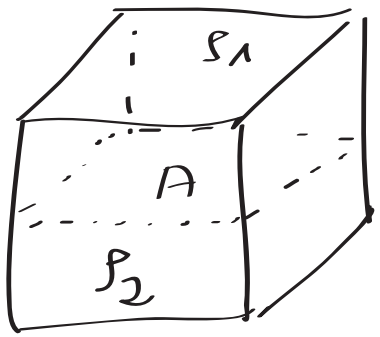


source term

production through spallation of heavy neulcei

production through decay of heavy nuclei

diffusion of gases



remove wall → diffusion

$$\frac{\Delta m}{\Delta t} = -D \cdot A \cdot \frac{d\rho}{dx}$$

mass flow per unit time

area

density gradient

diffusion coefficient $\left[\frac{cm^2}{s}\right]$

current density $j = \frac{\Delta m}{A \cdot \Delta t} \cdot \frac{N_A}{M}$

particle number density $n = \frac{\rho \cdot N_A}{M}$

$$\Rightarrow \quad j = -D \frac{dn}{dx}$$

① $\vec{j} = -D \operatorname{grad} n$ 1st law of Fick

② $\frac{\partial n}{\partial t} + \operatorname{div} \vec{j} = 0$ conservation of the number of particles

① + ② $\Rightarrow \frac{\partial n_i}{\partial t} = -\operatorname{div}(-D \nabla n_i)$ $\operatorname{div} \vec{A} = \nabla \vec{A}$

$= \nabla (D \nabla n_i)$ 2nd law of Fick

Transport equation for cosmic rays in the Galaxy

diffusion

energy loss (Bethe Bloch)

loss through interactions with ISM (spallation)

loss through radioactive decay

$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E}(b_i N_i) - n\nu\sigma_i N_i - \frac{N_i}{\gamma\tau_i} + Q_i + \sum_{j>i} n\nu\sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j \tau_{ij}}$$

source term

production through spallation of heavy neulcei

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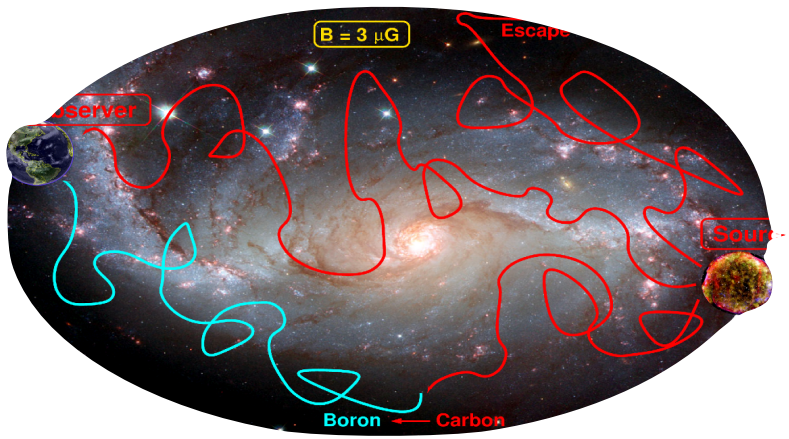


specific energy loss
Bethe Bloch formula

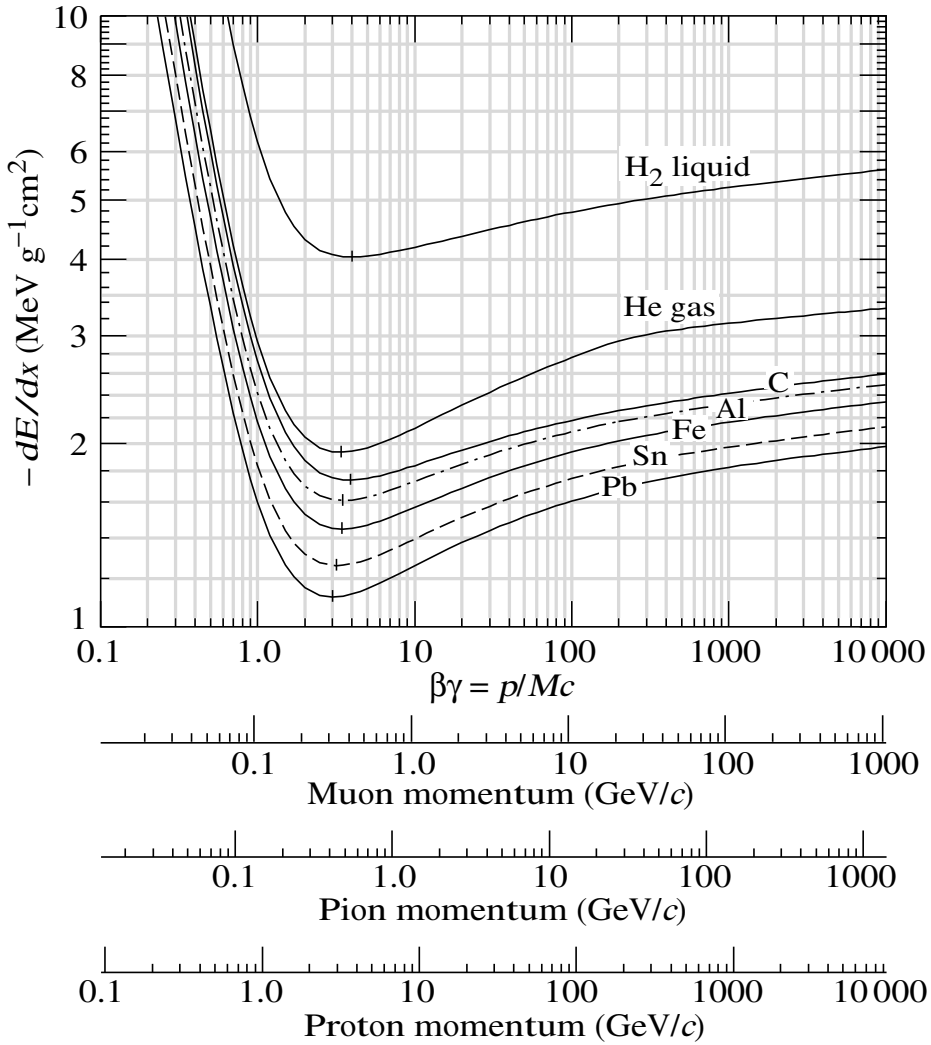


Figure 27.2: Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, iron, tin, and lead. Radiative effects, relevant for muons and pions, are not included. These become significant for muons in iron for $\beta\gamma \gtrsim 1000$, and at lower momenta for muons in higher-Z absorbers. See Fig. 27.21.

Leaky Box Model

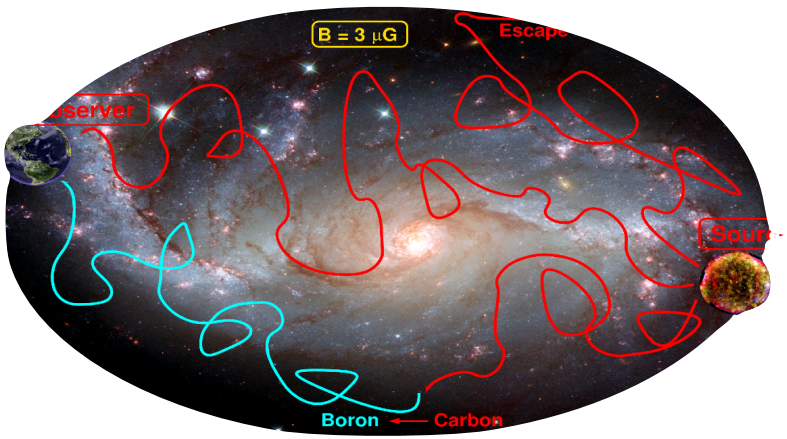
simple approach, replace diffusion term

τ_e **residence time of cosmic rays in Galaxy**

consider equilibrium $\dfrac{\partial N_i}{\partial t} = 0$

$$-\frac{N_i}{\tau_e(i)} \qquad -\frac{N_i}{\tau_{spal}(i)} \qquad -\frac{N_i}{\tau_r(i)} \qquad C_i = \sum_{j>i} \frac{p_{ij}}{\tau_j} N_j$$

$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E}(b_i N_i) - n\nu\sigma_i N_i - \frac{N_i}{\gamma\tau_i} + Q_i + \sum_{j>i} n\nu\sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j \tau_{ij}}$$



assume all Be isotopes are produced through spallation

Leaky Box Model

for stable isotopes:

$$-\frac{N_i}{\tau_e(i)} + C_i - \frac{N_i}{\tau_{spal}(i)} = 0$$

for radioactive isotopes:

$$-\frac{N_j}{\tau_e(j)} + C_j - \frac{N_j}{\tau_{spal}(j)} - \frac{N_j}{\tau_r(j)} = 0.$$

we assume

$$\tau_{spal} >> \tau_e \qquad \tau_{spal} >> \tau_r$$

Leaky Box Model

„age“ of cosmic rays

the ratio of the two beryllium isotopes ^{9}Be (stable) and ^{10}Be (radioactive) in cosmic rays is given as

$$\frac{N(^{10}\mathrm{Be})}{N(^{9}\mathrm{Be})} = \frac{\frac{1}{\tau_e(^{9}\mathrm{Be})}}{\frac{1}{\tau_e(^{10}\mathrm{Be})} + \frac{1}{\tau_r(^{10}\mathrm{Be})}} \frac{C(^{10}\mathrm{Be})}{C(^{9}\mathrm{Be})}$$

Chart of nuclides

16										S 26 0.012s	S 27 0.021s	S 28 0.125s	S 29 0.187s	S 30 1.178s
15										P 25 0.0368s	P 26 0.0437s	P 27 0.26s	P 28 0.2703s	P 29 4.142s
14								Si 22 0.029s	Si 23 0.0423s	Si 24 0.14s	Si 25 0.22s	Si 26 2.234s	Si 27 4.16s	Si 28 92.2297
13								Al 21 0.0428s	Al 22 0.0911s	Al 23 0.446s	Al 24 2.053s	Al 25 7.183s	Al 26 7.17e+05y	Al 27 100
12							Mg 19 4e-12s	Mg 20 0.0908s	Mg 21 0.122s	Mg 22 3.875s	Mg 23 11.32s	Mg 24 78.99	Mg 25 10	Mg 26 11.01
11							Na 18 0.0347s	Na 19 0.435s	Na 20 0.4479s	Na 21 22.49s	Na 22 2.603y	Na 23 100	Na 24 15h	Na 25 59.1s
10						Ne 16	Ne 17 0.1092s	Ne 18 1.666s	Ne 19 17.22s	Ne 20 90.48	Ne 21 0.27	Ne 22 9.25	Ne 23 37.24s	Ne 24 3.38m
9						F 15 0.14s	F 16 1e-19s	F 17 1.075m	F 18 1.83h	F 19 100	F 20 11.16s	F 21 4.158s	F 22 4.23s	F 23 2.23s
8				O 12	O 13 0.00858s	O 14 1.177m	O 15 2.037m	O 16 99.757	O 17 0.038	O 18 0.205	O 19 26.88s	O 20 13.51s	O 21 3.42s	O 22 2.25s
7				N 11 0.09s	N 12 0.011s	N 13 9.965m	N 14 99.632	N 15 0.368	N 16 7.13s	N 17 4.173s	N 18 0.619s	N 19 0.271s	N 20 0.13s	N 21 0.095s
6			C 8	C 9 0.1265s	C 10 19.31s	C 11 20.39m	C 12 98.93	C 13 1.07	C 14 5700y	C 15 2.449s	C 16 0.747s	C 17 0.193s	C 18 0.092s	C 19 0.049s	C 20 0.014s
5				B 8 0.77s	B 9 8.5e-19s	B 10 19.9	B 11 80.1	B 12 0.0202s	B 13 0.01736s	B 14 0.0125s	B 15 0.0105s		B 17 0.00508s		B 19 0.00292s
4				Be 7 53.22d	Be 8 6.7e-17s	Be 9 100	Be 10 1.51e+06y	Be 11 13.81s	Be 12 0.0213s		Be 14 0.00484s				
3				Li 6 7.59	Li 7 92.41	Li 8 0.8399s	Li 9 0.1783s		Li 11 0.0087s						
2		He 3 0.000137	He 4 99.9999		He 6 0.8067s		He 8 0.1191s								
1	H 1 99.9885	H 2 0.0115	H 3 12.32y												
0		n 1 10.23m													

„Age“ of galactic cosmic rays

THE AGE OF THE GALACTIC COSMIC RAYS DERIVED FROM THE ABUNDANCE OF ^{10}Be*

M. GARCIA-MUNOZ, G. M. MASON, AND J. A. SIMPSON†
Enrico Fermi Institute, University of Chicago
Received 1977 March 14; accepted 1977 April 21

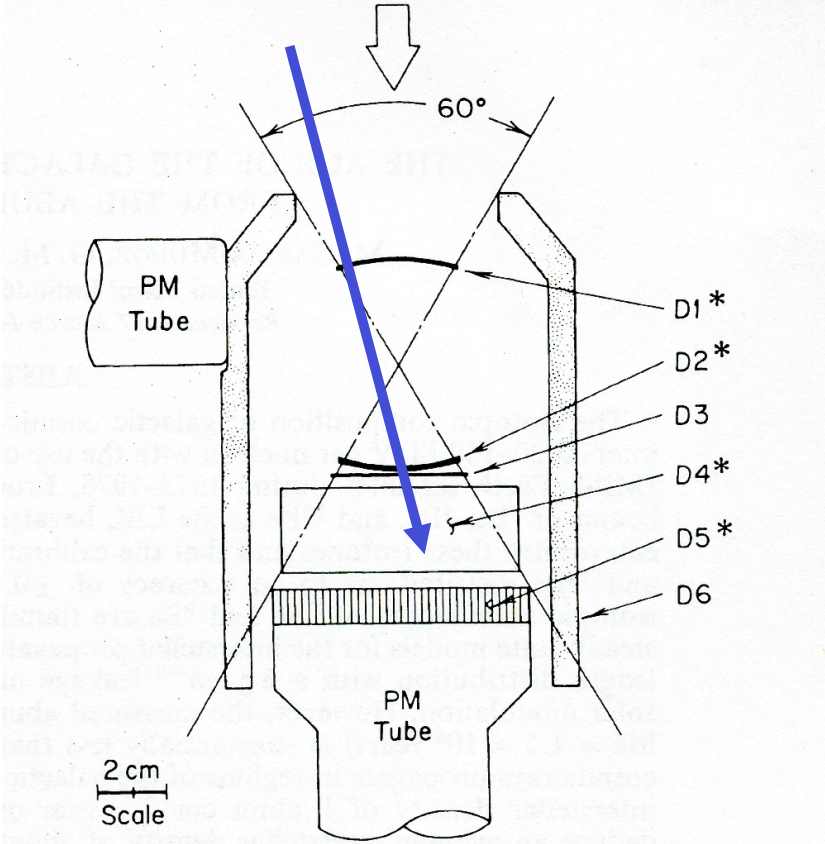
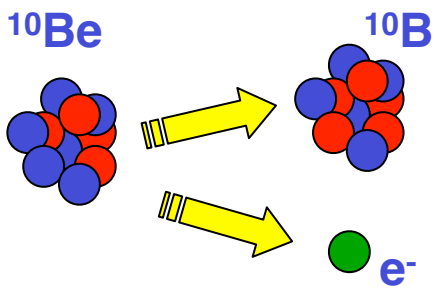


FIG. 1.—Cross section of the IMP-7 and IMP-8 telescopes. D1, D2, and D3 are lithium-drifted silicon detectors of thickness 750, 1450, and 800 μm, respectively. D4 is an 11.5 g cm^{-2} thick CsI (Tl) scintillator viewed by four photodiodes. D5 is a sapphire scintillator/Cerenkov radiator of thickness 3.98 g cm^{-2}, and D6 is a plastic scintillation guard counter viewed by a photomultiplier tube. Asterisks denote detectors whose output is pulse-height analyzed.

Residence time in Galaxy

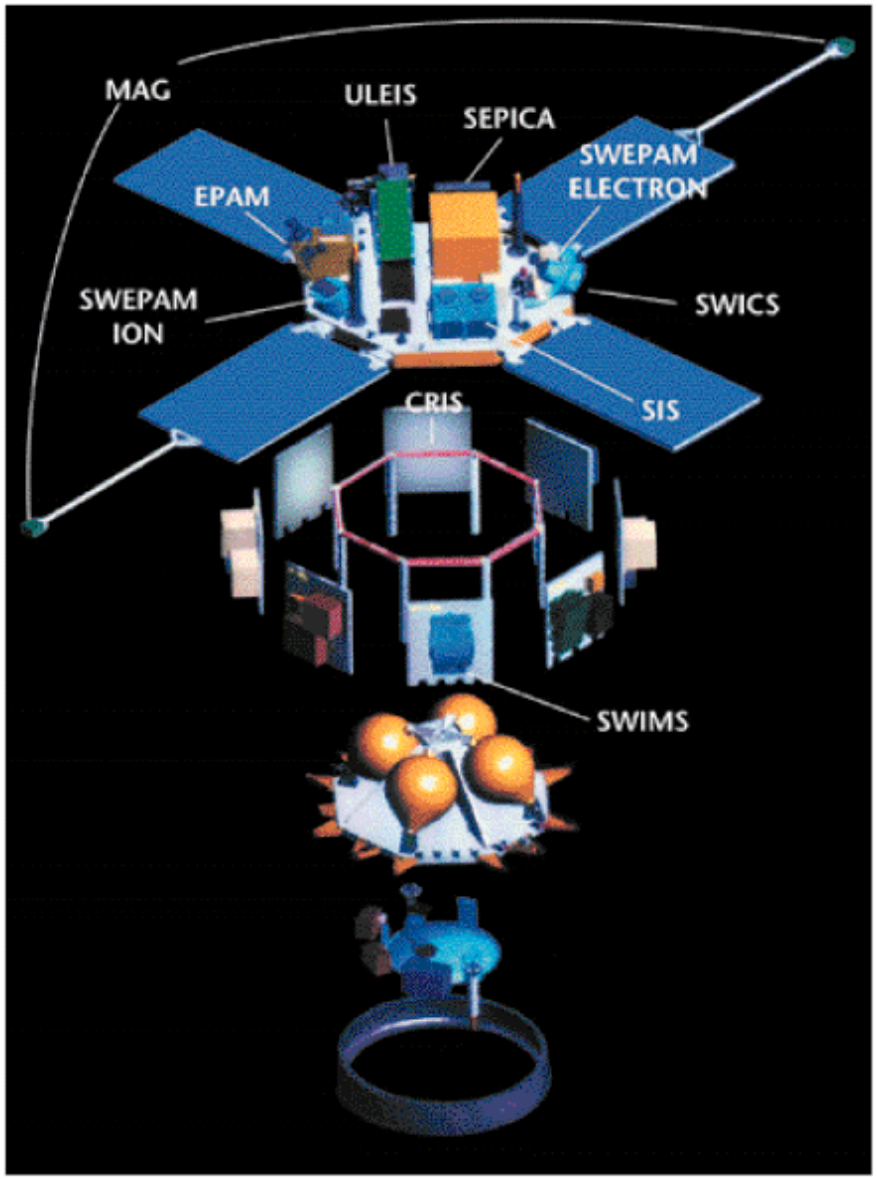
$^{10}Be \rightarrow {}^{10}B + e^-$ (τ=2.4 10^6 a)



$\tau = 15*10^6$ a

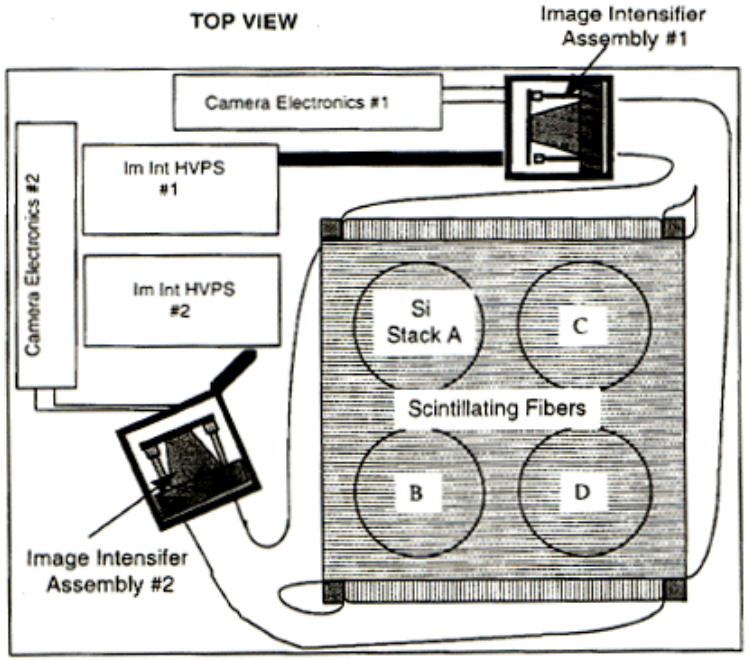
THE ASTROPHYSICAL JOURNAL, 217:859–877, 1977 November 1

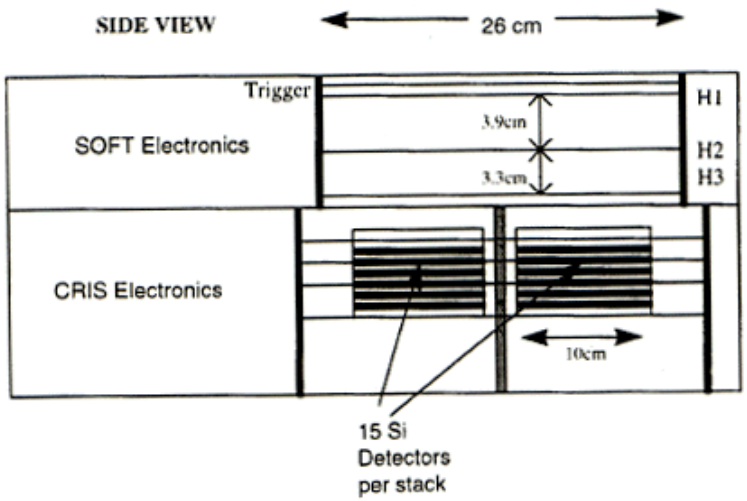
Advanced Composition Explorer (ACE)



NASA / Goddard Space Flight Center; Start: 25.8.97,
9 wissensch. Instrumente (156 kg) ; 90% duty cycle
$1 \leq Z \leq 28$; 1 keV $\leq E \leq 600$ A·MeV

CRIS: The Cosmic Ray Isotope Spectrometer





THE ASTROPHYSICAL JOURNAL, 563:768–792, 2001 December 20

MEASUREMENT OF THE SECONDARY RADIONUCLIDES ^{10}Be, ^{26}Al, ^{36}Cl, ^{54}Mn, AND ^{14}C AND IMPLICATIONS FOR THE GALACTIC COSMIC-RAY AGE

N. E. YANASAK[1] AND M. E. WIEDENBECK

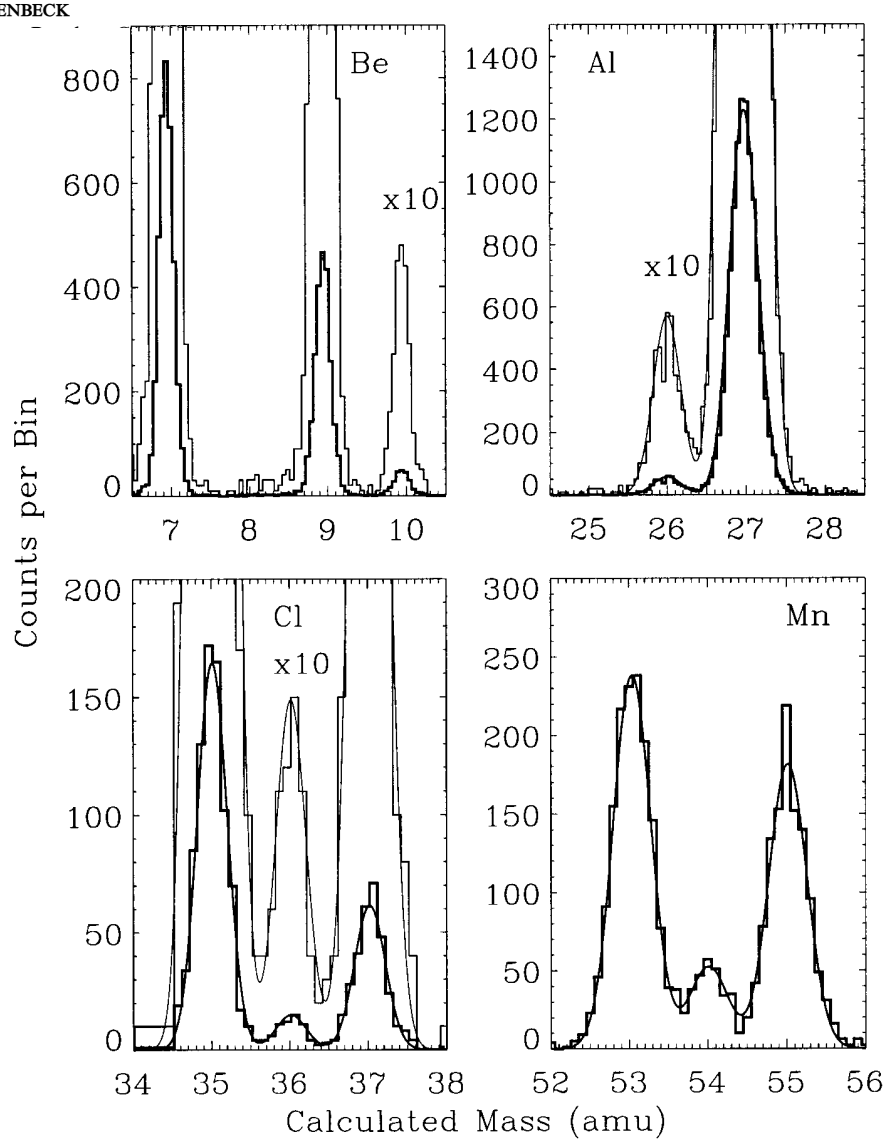


FIG. 2.—Mass histograms for Be ($\langle E \rangle$ = 107 MeV nucleon^{-1}), Al ($\langle E \rangle$ = 212 MeV nucleon^{-1}), Cl ($\langle E \rangle$ = 250 MeV nucleon^{-1}), and Mn ($\langle E \rangle$ = 289 MeV nucleon^{-1}). The maximum allowed zenith angles for these data are $\theta_{max} < 40°$ for Be and Al and $\theta_{max} < 30°$ for Cl and Mn. The overlying curves for Al, Cl, and Mn were obtained using maximum-likelihood fits, as discussed in the text. A 10× magnification of the Be, Al, and Cl counts scale is shown as a light histogram and fitted curve. The total number of events in the histograms are 6552 for Be, 10967 for Al, 1196 for Cl, and 2954 for Mn.

THE ASTROPHYSICAL JOURNAL, 563:768–792, 2001 December 20

MEASUREMENT OF THE SECONDARY RADIONUCLIDES ^{10}Be, ^{26}Al, ^{36}Cl, ^{54}Mn, AND ^{14}C AND IMPLICATIONS FOR THE GALACTIC COSMIC-RAY AGE

N. E. YANASAK[1] AND M. E. WIEDENBECK

τ = 15*10⁶ a

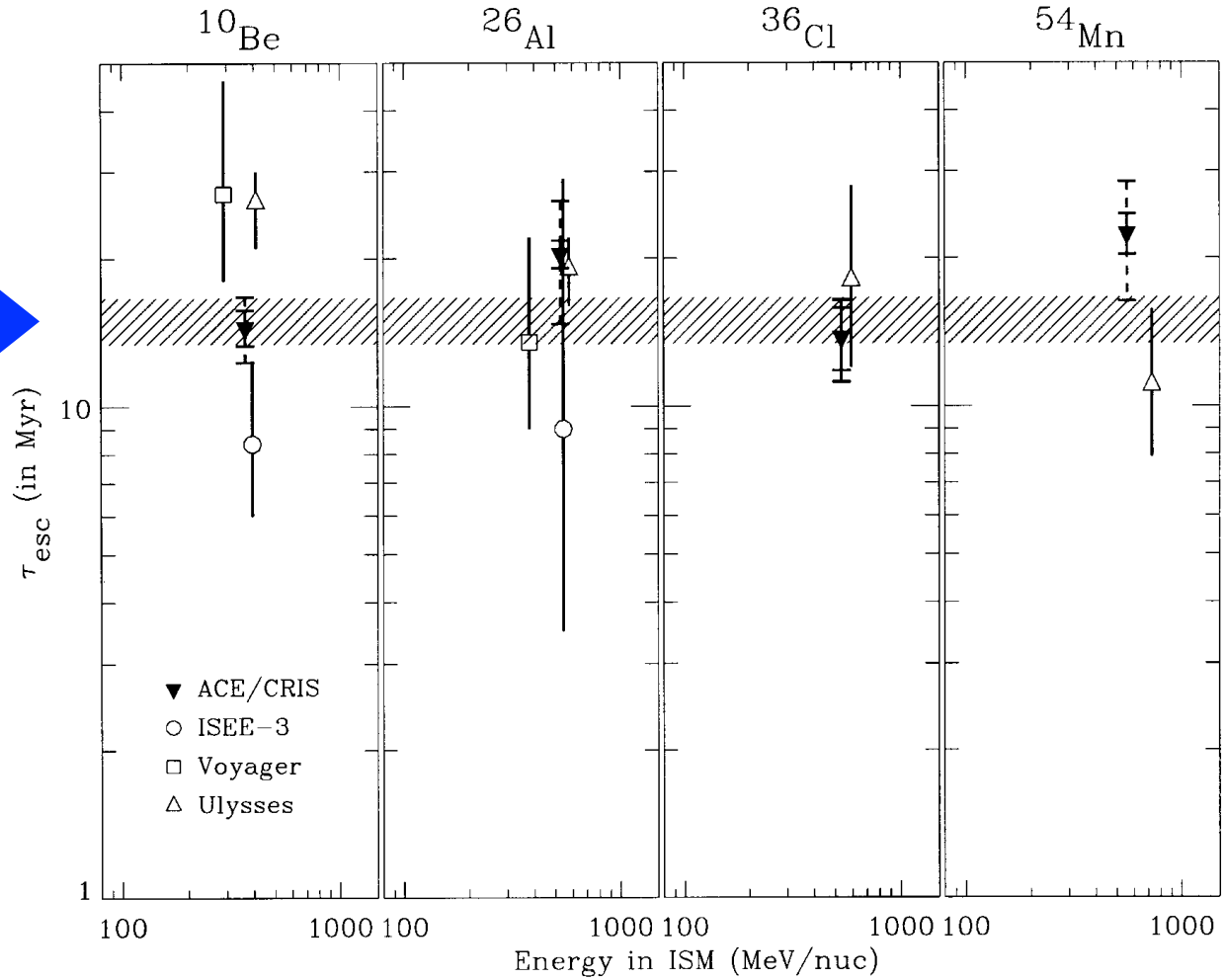


FIG. 8.—Confinement times obtained by CRIS and previous experiments. Data shown are from the references listed in the caption of Fig. 7. Uncertainties shown with solid error bars are 1 standard deviation statistical. The average value of the confinement time, $\tau_{esc} = 15.0 \pm 1.6$ Myr, indicated by the CRIS data for these four clock isotopes is shown as a hatched band. The dashed lines running through the CRIS data represent the uncertainty introduced from the combined systematic uncertainties shown in Table 5. The data point plotted for the *Ulysses* ^{54}Mn confinement time is based on the recalculation by Connell et al. (1998) using the ^{54}Mn decay half-life of $T_{1/2}(^{54}\mathrm{Mn}) = 0.63$ Myr from Wuosmaa et al. (1998). Using the half-life of $T_{1/2}(^{54}\mathrm{Mn}) = 0.68$ Myr assumed in this study raises the confinement time from *Ulysses* by ~ 1.5 Myr.

Leaky Box Model

pathlength in Galaxy

τ_e **residence time of cosmic rays in Galaxy**

consider equilibrium $\dfrac{\partial N_i}{\partial t} = 0$

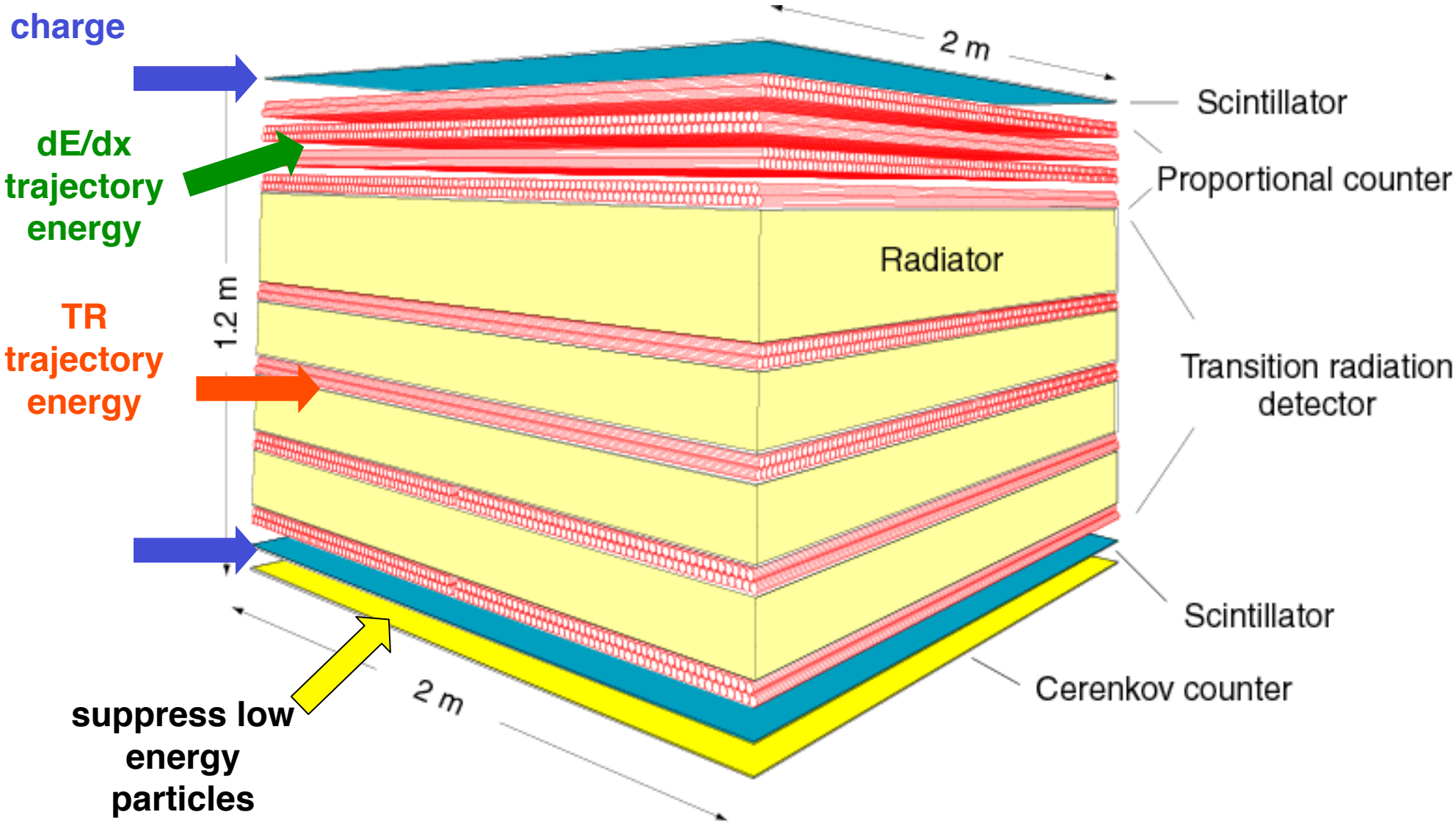
$$-\frac{N_i}{\tau_e(i)} \qquad -\frac{N_i}{\tau_{spal}(i)} \qquad C_i = \sum_{j>i} \frac{p_{ij}}{\tau_j} N_j$$

$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \cancel{\frac{\partial}{\partial E}(b_i N_i)} - n\nu\sigma_i N_i - \cancel{\frac{N_i}{\gamma\tau_i}} + Q_i + \sum_{j>i} n\nu\sigma_{ij} N_j + \cancel{\sum_{j>i} \frac{N_j}{\gamma_j \tau_{ij}}}$$

consider stable nuclei only (no decay)

$$\frac{N_i}{\tau_e(i)} = \sum_{j>i} \frac{p_{ij}}{\tau_j} N_j - \frac{N_i}{\tau_{spal}(i)} + Q_i$$

Transition Radiation Array for Cosmic Energetic Rays



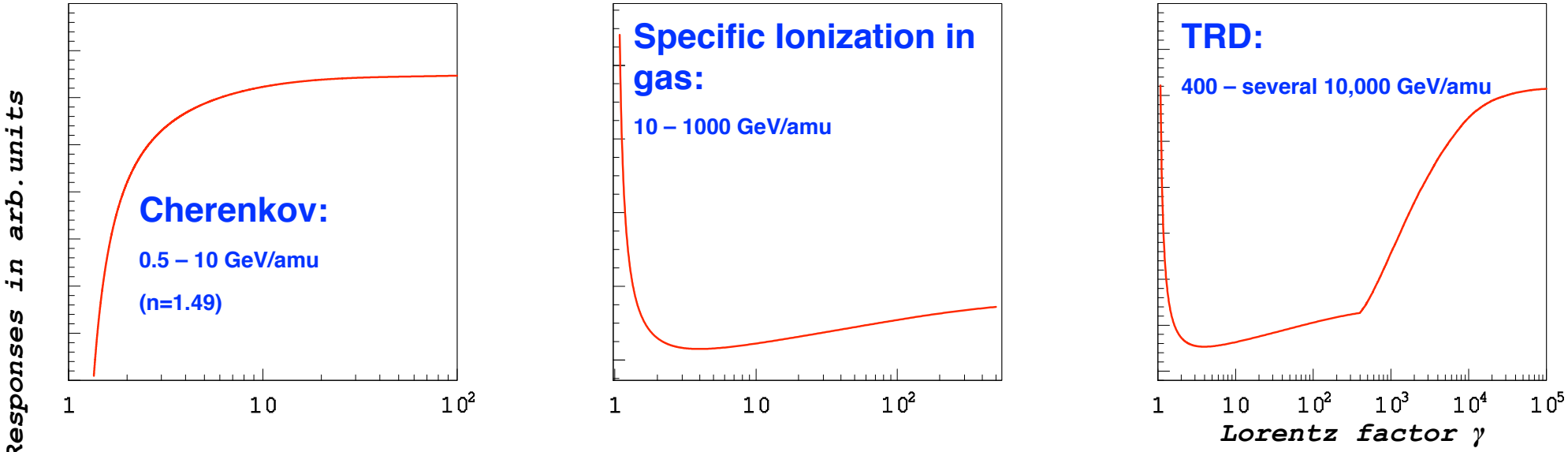
Geometric factor: 5 m² sr

1600 proportional tubes total

Transition Radiation Array for Cosmic Energetic Radiation

Direct measurement of the composition of cosmic rays from 0.5 to 10,000 GeV/amu with single elemental resolution

Combined responses for energy measurements over 4 decades:

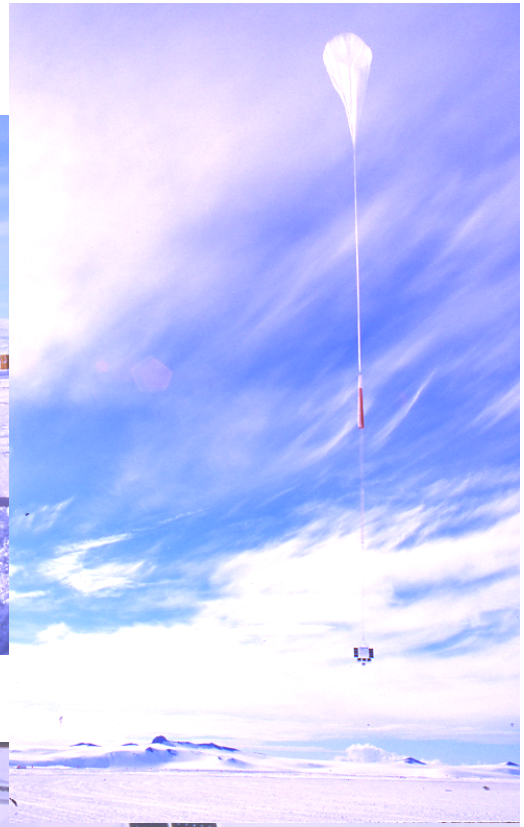


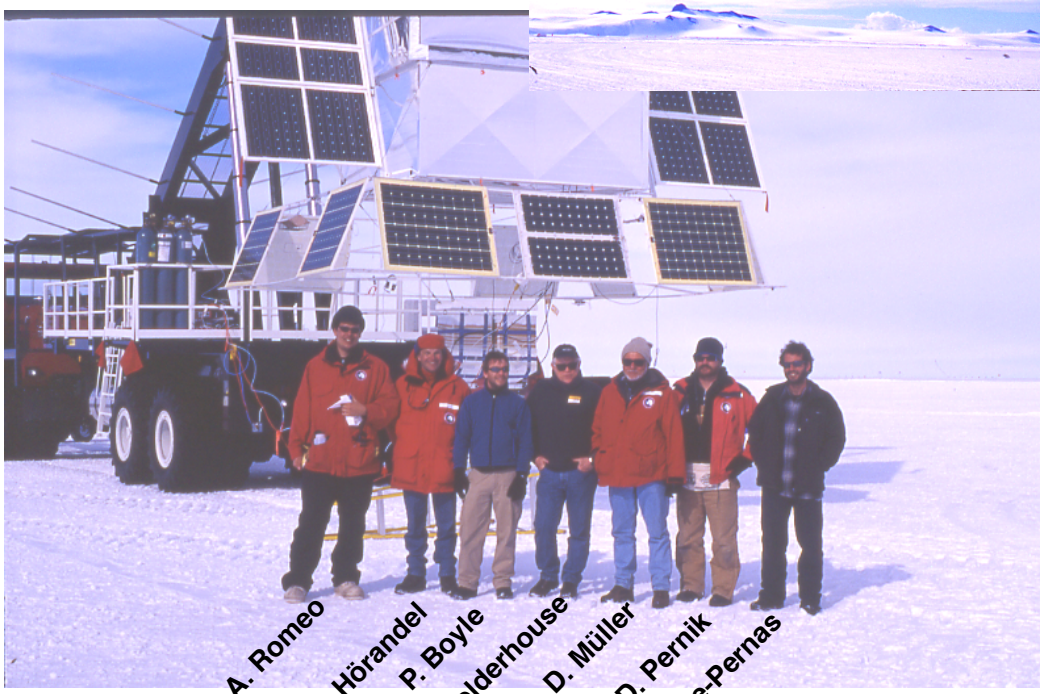
$L \sim (1 - 1/n^2\beta^2)$ $\qquad$ $dE/dx \sim 1/\beta^2 \ln(E)$ $\qquad$ $TR = dE/dx + \text{x-rays}$

all signals scale with Z^2

$5m^2$ sr - currently the largest cosmic-ray detector on balloons

TRACER Experiment





TRACER Experiment - Mc Murdo, Antarctica
flight: 12. – 26. December 2003 ~ 40 km (3-5 g/cm²)

TRACER: propagation of cosmic rays

Leaky-Box Propagation Parameters

- Continuity equation:

$$N_i(E) = \frac{1}{\Lambda_{esc}(E)^{-1} + \Lambda_i^{-1}} \times \left(\frac{Q_i(E)}{\beta c \rho} + \sum_{k>i} \frac{N_k}{\lambda_{k \to i}} \right)$$

- Source Spectrum:

$$Q_i(E) = n_i \cdot E^{-\alpha}$$

- Escape Path Length:

$$\Lambda_{esc}(E) = CE^{-\delta} + \Lambda_0$$

- Spallation Path Length:

$$\Lambda_i = \frac{m}{\sigma(A)}$$

Boron to Carbon ratio

$$\frac{N_B}{N_C} = \frac{\lambda_{\to B}^{-1}}{\Lambda_{esc}(E)^{-1} + \Lambda_B^{-1}}$$

A. Obermeier et al., ICRC 2011

spallation cross sections measured at accelerators

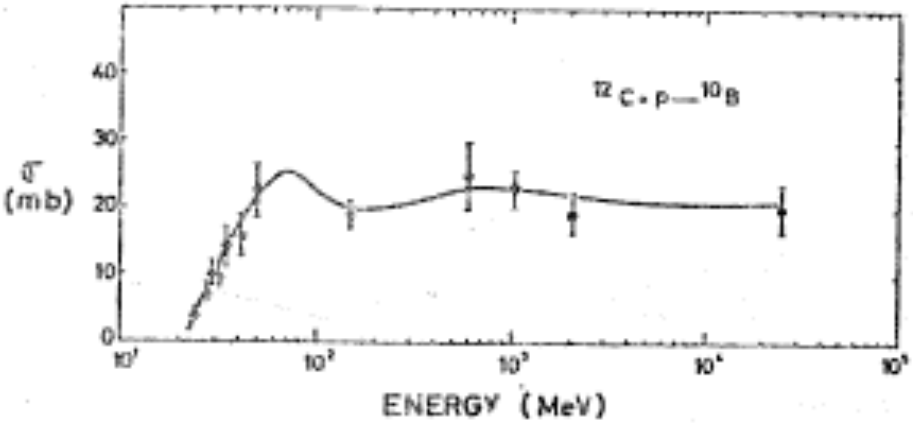


Figure 2 – ^{10}B production cross-section in carbon spallation by protons.
Solid circles are from this work. Triangles are from Davids et al. (1970) (mass 10 measurements below the threshold for ^{10}Be production) and squares from Lindstrom et al. (1975).

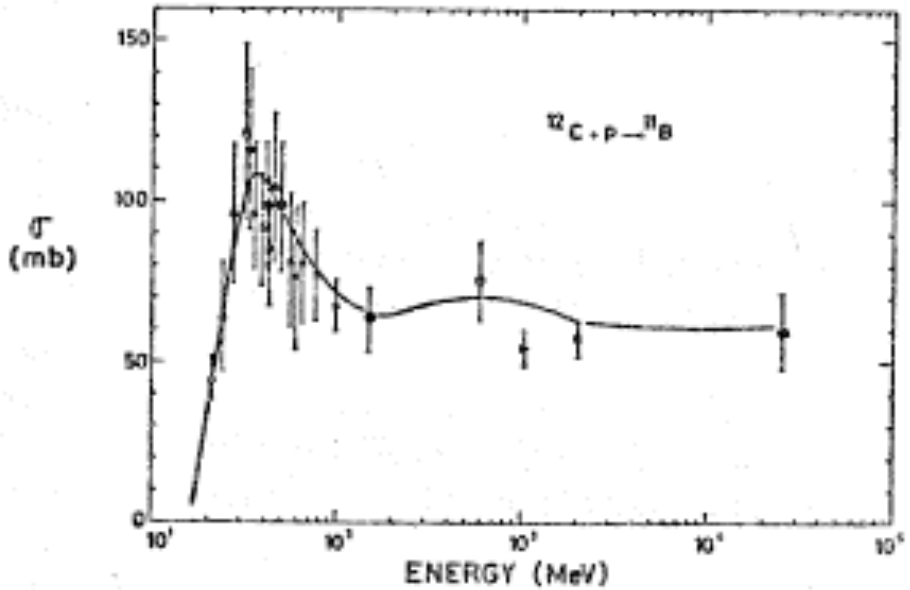
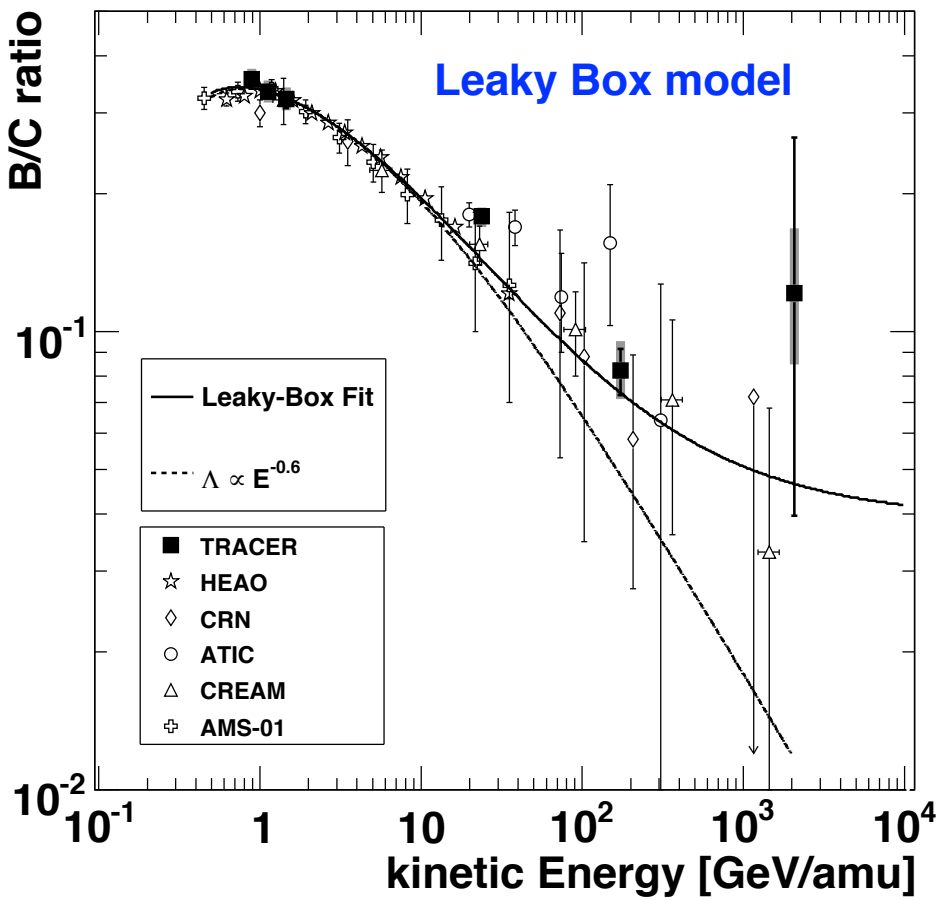
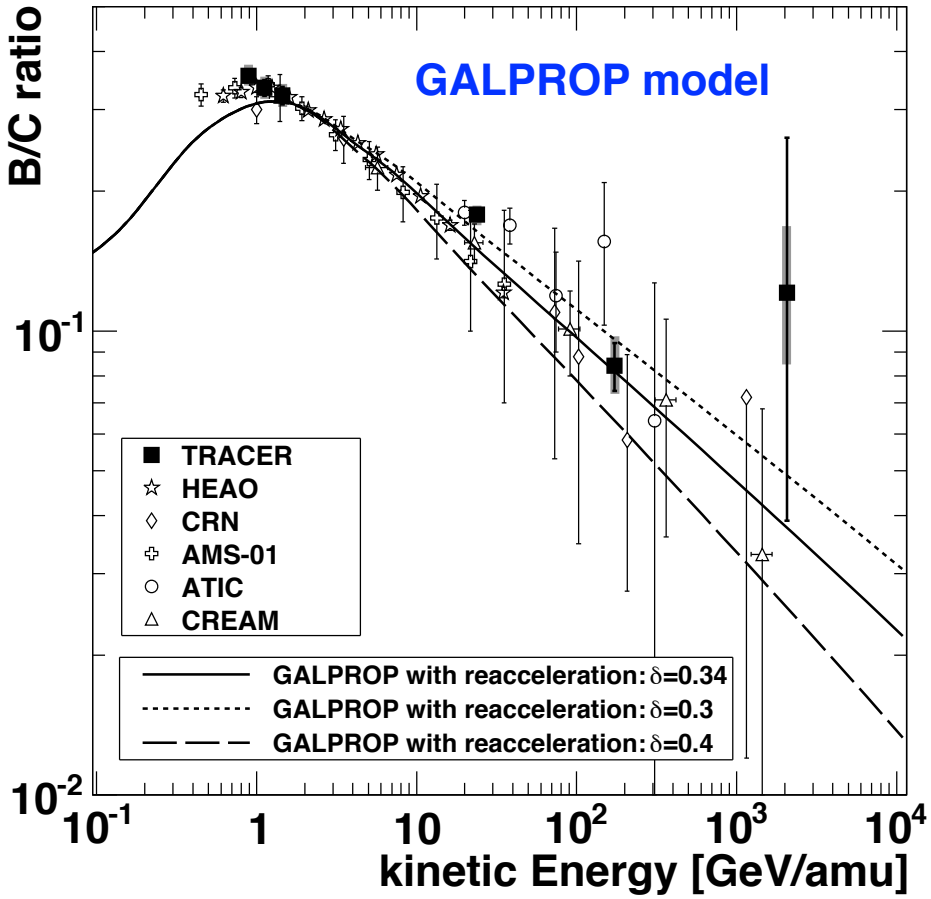


Figure 3 – ^{11}B production cross-section in carbon spallation by protons.
Solid circles are from this work. Triangles are from Davids et al. (1970), Crosses from Roche et al. (1976), and squares from Lindstrom et al. (1975).

TRACER: propagation of cosmic rays





Escape Path Length:

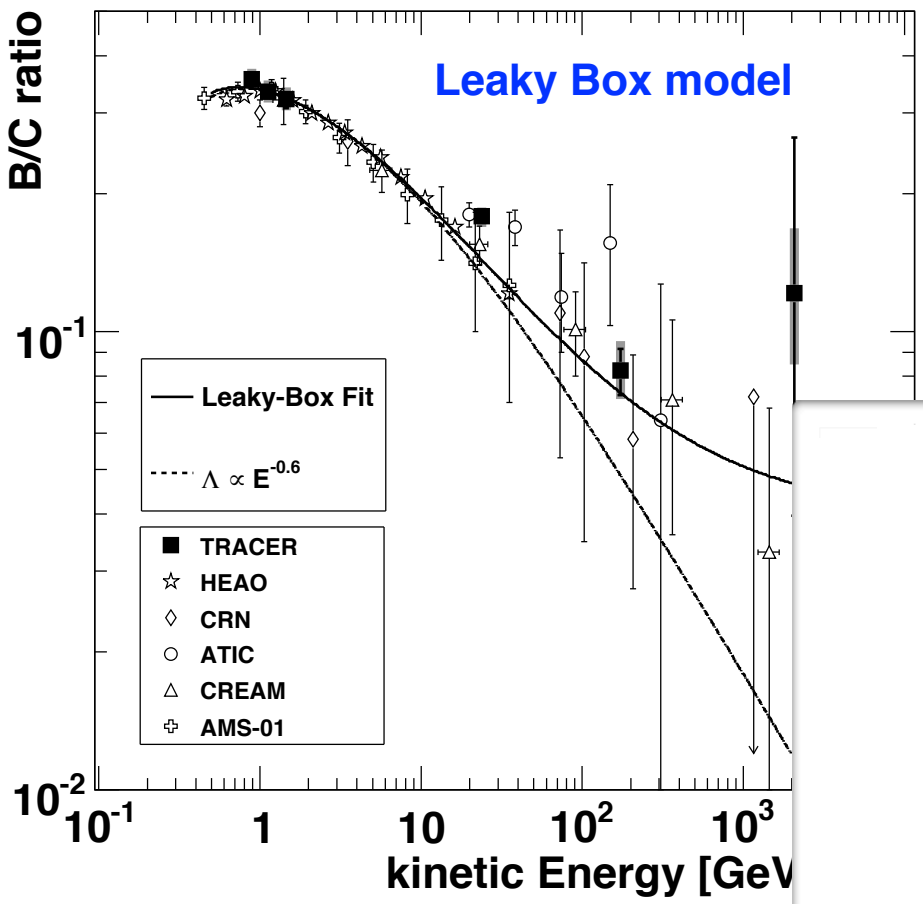
$$\Lambda_{esc}(E) = CE^{-\delta} + \Lambda_0$$

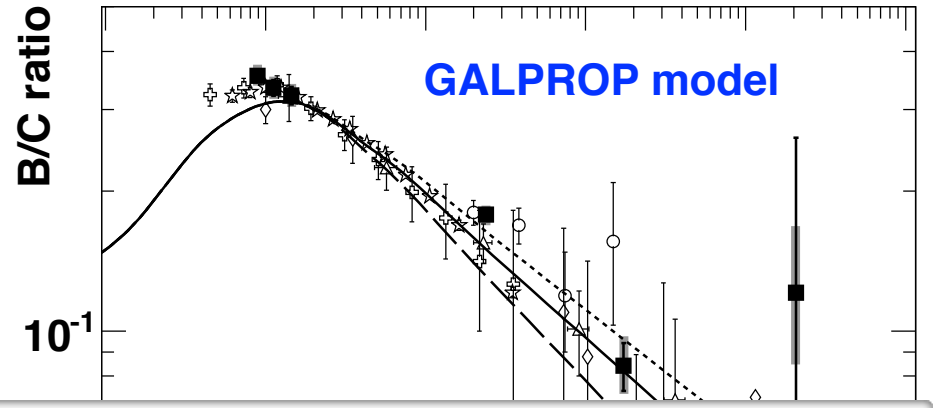
- Propagation index: $\delta = 0.64 \pm 0.02$.
- Residual path length: $\Lambda_0 = 0.7 \pm 0.2$ g/cm^2.

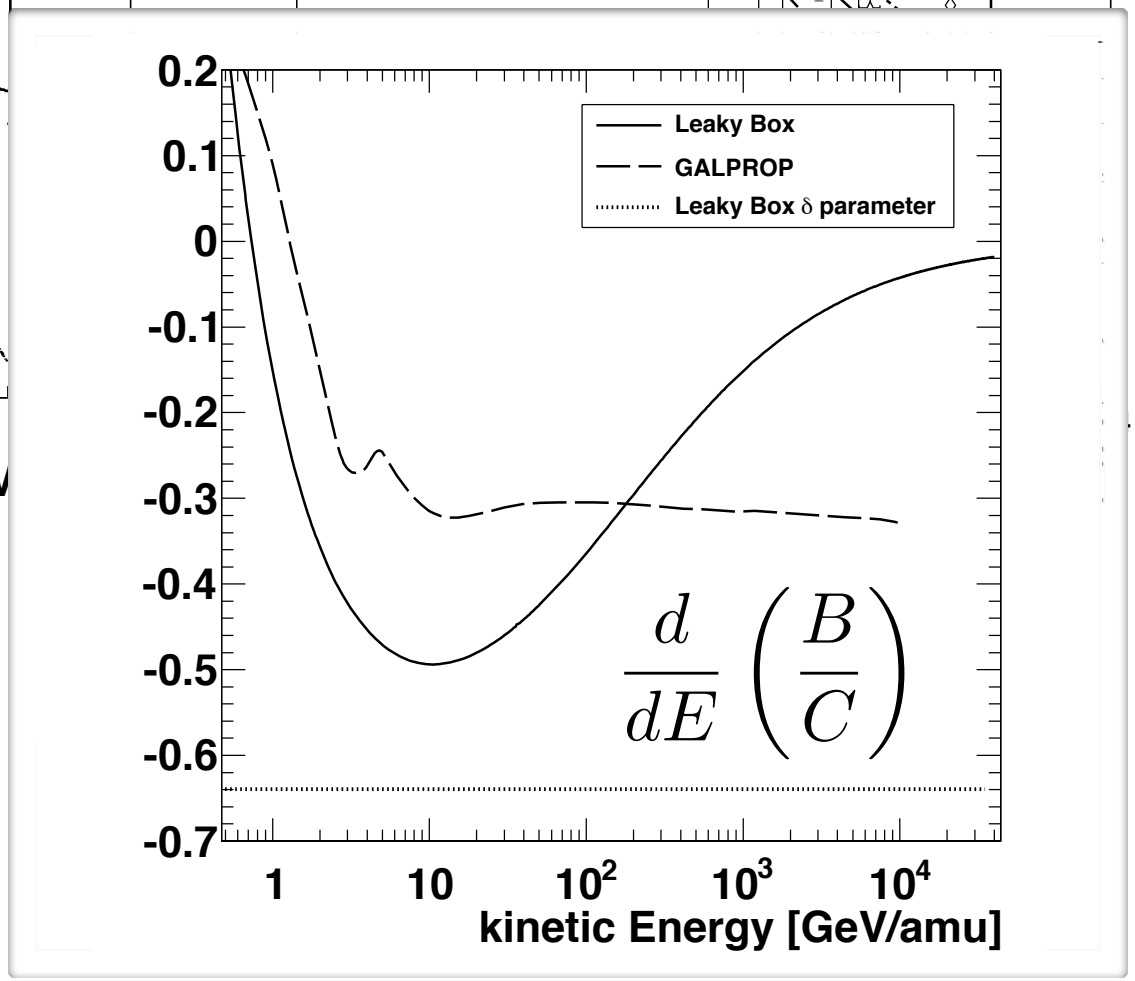
- Diffusion Index: $\delta = 0.34$.
- **Source index:** $\alpha = 2.34$.

A. Obermeier et al., ApJ 752 (2012) 69

TRACER: propagation of cosmic rays



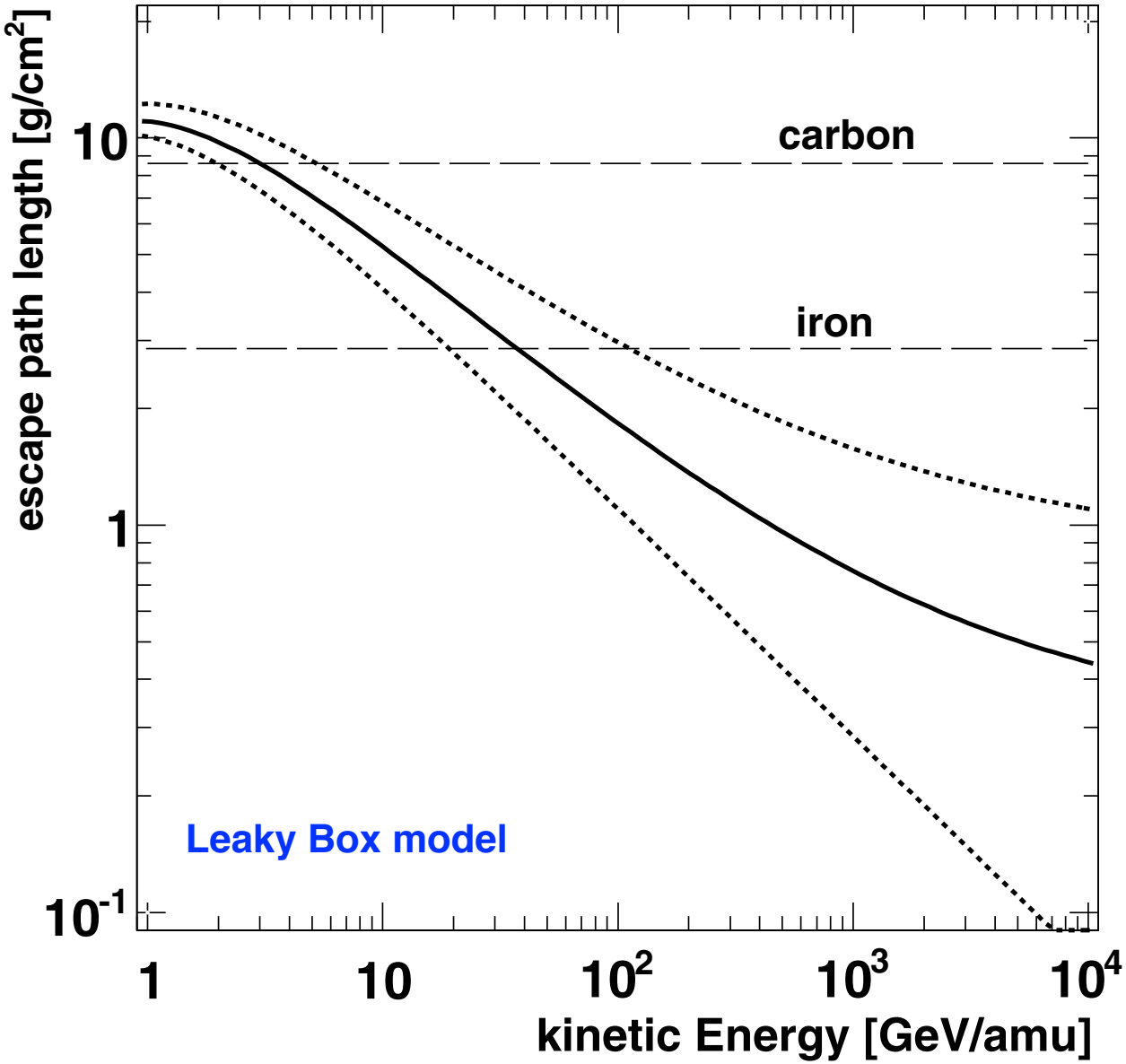




$$\Lambda(R) = \frac{26.7\beta}{(\beta R)^{\delta} + (0.714 \cdot \beta R)^{-1.4}} + \Lambda_0 \text{ g/cm}^2,$$

TRACER: propagation of cosmic rays

path length of cosmic rays in Galaxy



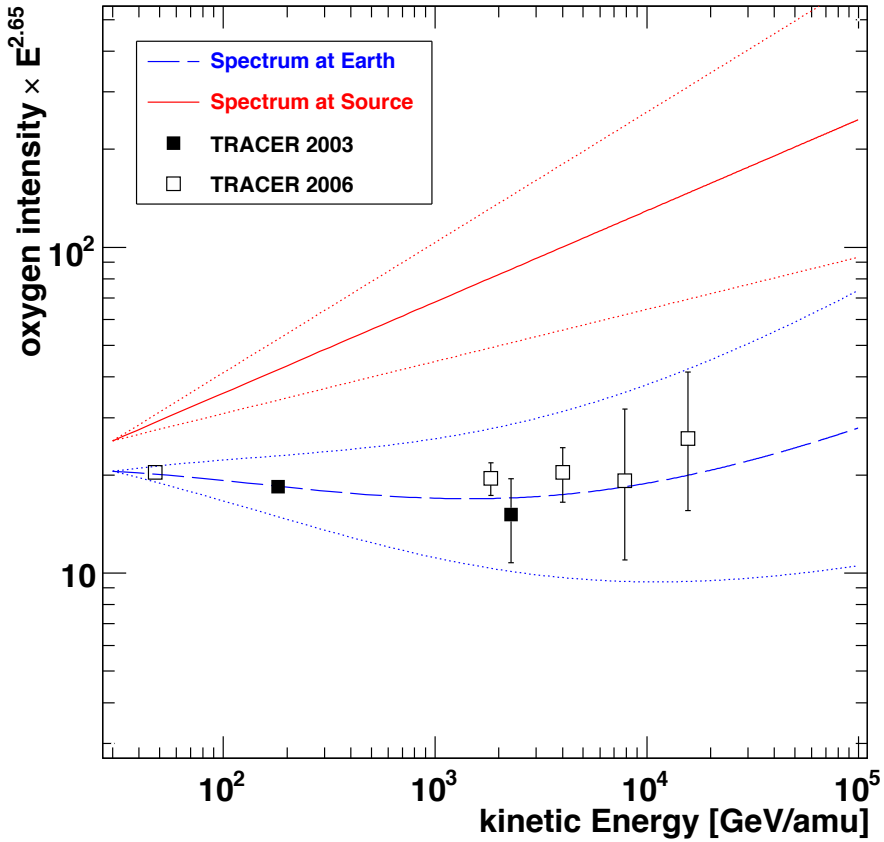
$$\Lambda(R) = \frac{26.7\beta}{(\beta R)^{\delta} + (0.714 \cdot \beta R)^{-1.4}} + \Lambda_0 \text{ g/cm}^2,$$

A. Obermeier et al., ApJ 752 (2012) 69

TRACER: propagation of cosmic rays

The Source Spectrum

- Fit to TRACER oxygen data.
- $\delta = 0.64$, $\Lambda_0 = 0.7$ g/cm^2



- Free parameter: α.
- Source spectrum: power law.

Result

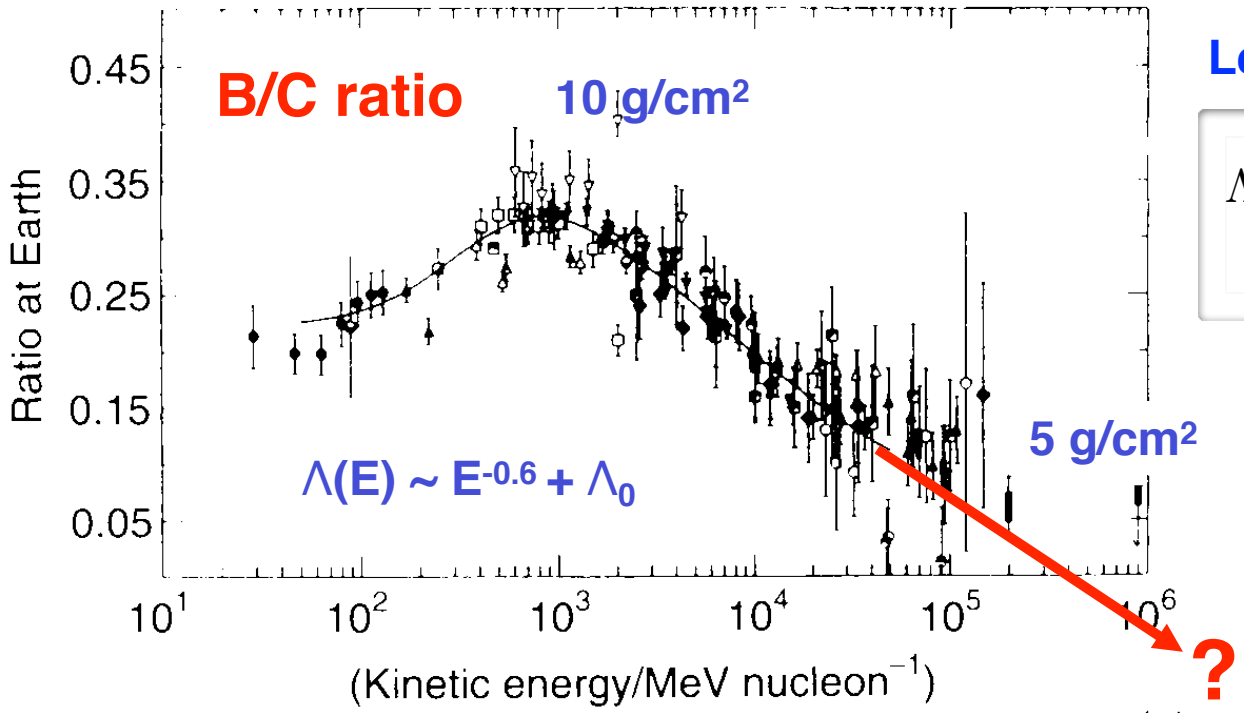
- Source index: $\alpha = 2.37 \pm 0.12$.

- Agrees with previous results.
- Model predicts spectrum at Earth may not be a power law (Λ_0).

GALPROP: $\alpha = 2.34$

A. Obermeier et al., ApJ 752 (2012) 69

Cosmic-ray propagation



Leaky box model

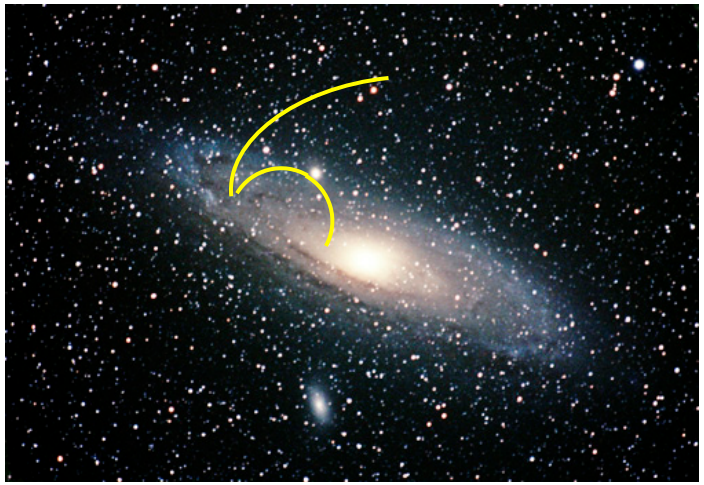
$$\Lambda = \frac{26.7\beta}{(\beta R)^{0.58} + \left(\frac{\beta R}{1.4}\right)^{-1.4}} + \Lambda_0$$

N. Yanasak et al., ApJ 563 (2001) 768

Radius of particle in magnetic field

$$r = \frac{p}{ZeB}$$

r[pc]=1.08*E[PeV]/B[μG]



Pathlength vs. interaction length

pathlength in Galaxy $\lambda_{esc} = 5 - 10 \text{ g/cm}^2$

interaction length

nuclear radius $r = r_0 A^{1/3}$ $r_0 = 1.3 \cdot 10^{-13} \text{ cm}$

cross section $\sigma_{p-A} = \pi(r_p + r_0 A^{1/3})^2$

ISM: protons $n = 1/\text{cm}^3$ $\rho = 1.67 \cdot 10^{-24} \text{ g/cm}^3$

interaction length $\lambda_{p-A} = \dfrac{\rho}{\sigma_{p-A} \cdot n}$

$$\lambda_{p-p} = 21 \text{ g/cm}^2$$

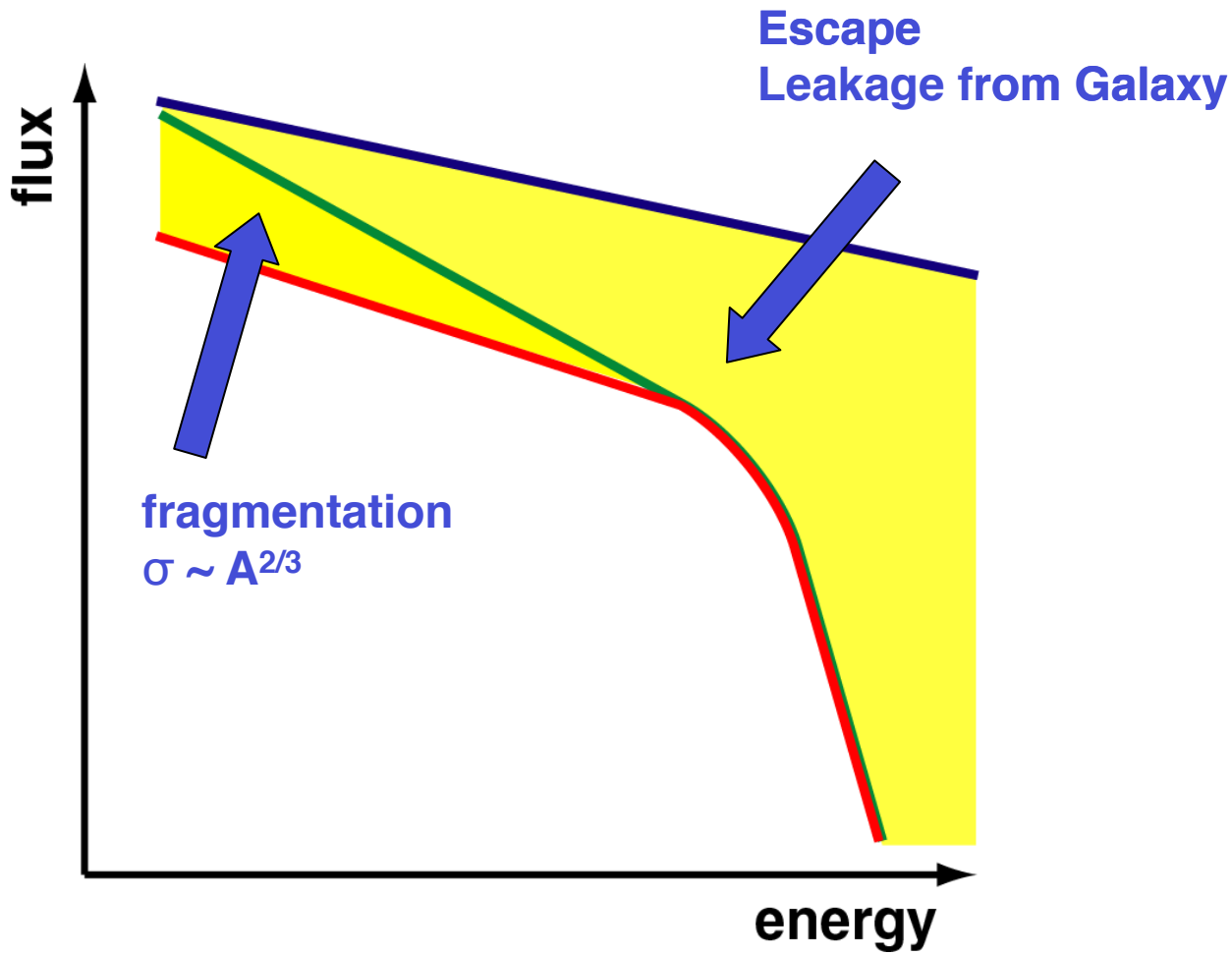
$$\lambda_{p-Fe} = 1.6 \text{ g/cm}^2$$

Shape of energy spectrum

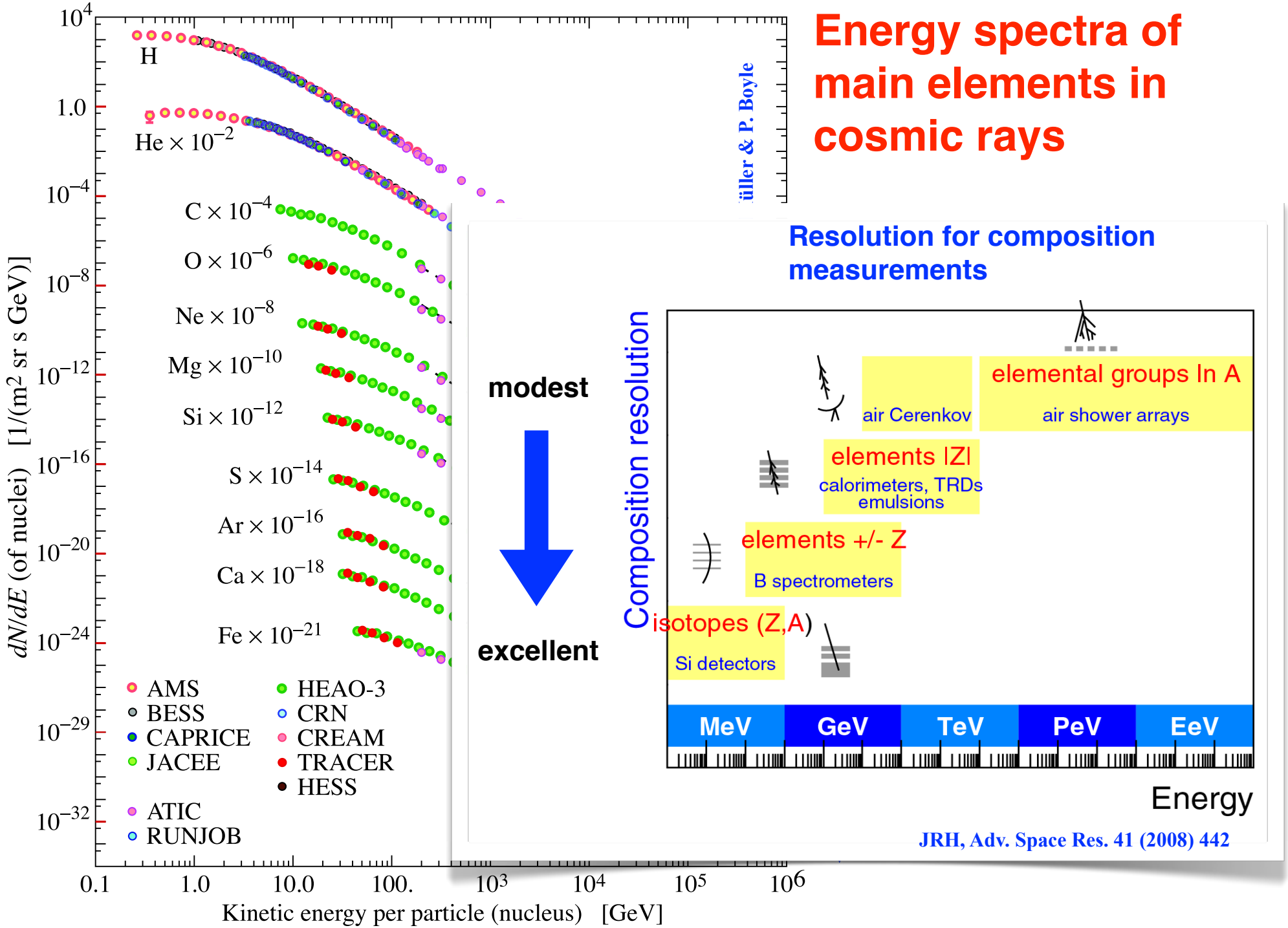
$$\frac{dN}{dE} \propto E_0^{\gamma}$$

at source γ ~ -2.1

at Earth γ ~ -2.6 to -2.7



Energy spectra of main elements in cosmic rays



Particle Data Book

Extensive air showers – Mass

Simple Heitler model of (hadronic) showers

Primary mass:

- **Average depth of shower maximum X_{max}**

$$X^{A}_{max} \sim \ln \frac{E_0}{A}$$

$$X^{A}_{max} = X^{p}_{max} - X_0 \ln A$$

$$X^{Fe}_{max} = X^{p}_{max} - 150\,\mathrm{g/cm^2}$$

- **N_e-N_μ ratio**

$$\frac{N_e}{N_\mu} \approx 35.1 \left(\frac{E_0}{A\ \mathrm{PeV}} \right)^{0.15}$$

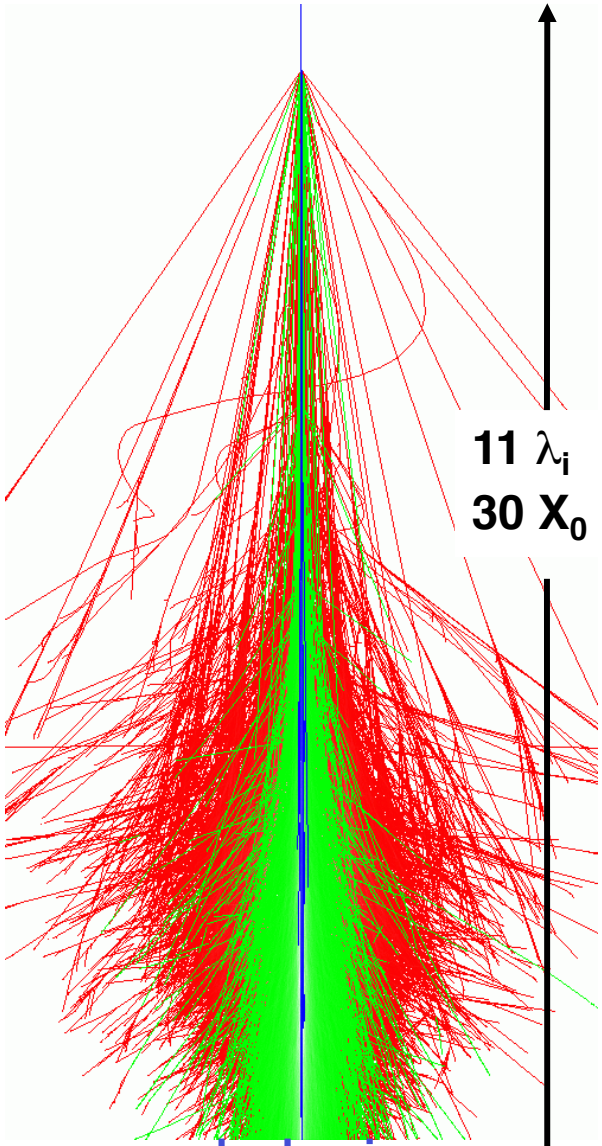
or

$$\lg \left(\frac{N_e}{N_\mu} \right) = C - 0.065 \ln A$$

$\Delta \ln A \sim 1$
$\rightarrow \Delta X_{max} \sim 36$ g/cm²
$\rightarrow \Delta (N_e/N_\mu) \sim 16\%$

$$\Delta \ln A \approx 0.8$$

in „best“ experiments

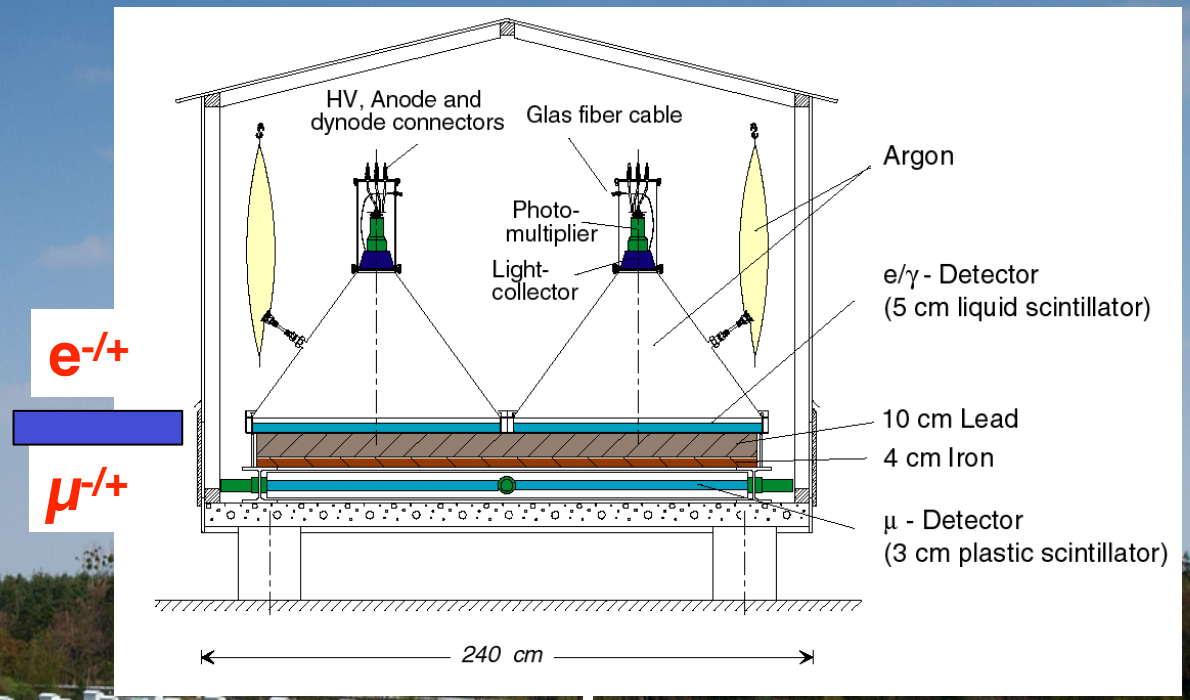


shower components

JRH, Mod. Phys. Lett. A 22 (2007) 1533
JRH, Nucl. Instr. and Meth. A 588 (2008) 181
J. Matthews, Astropart. Phys. 22 (2005) 387

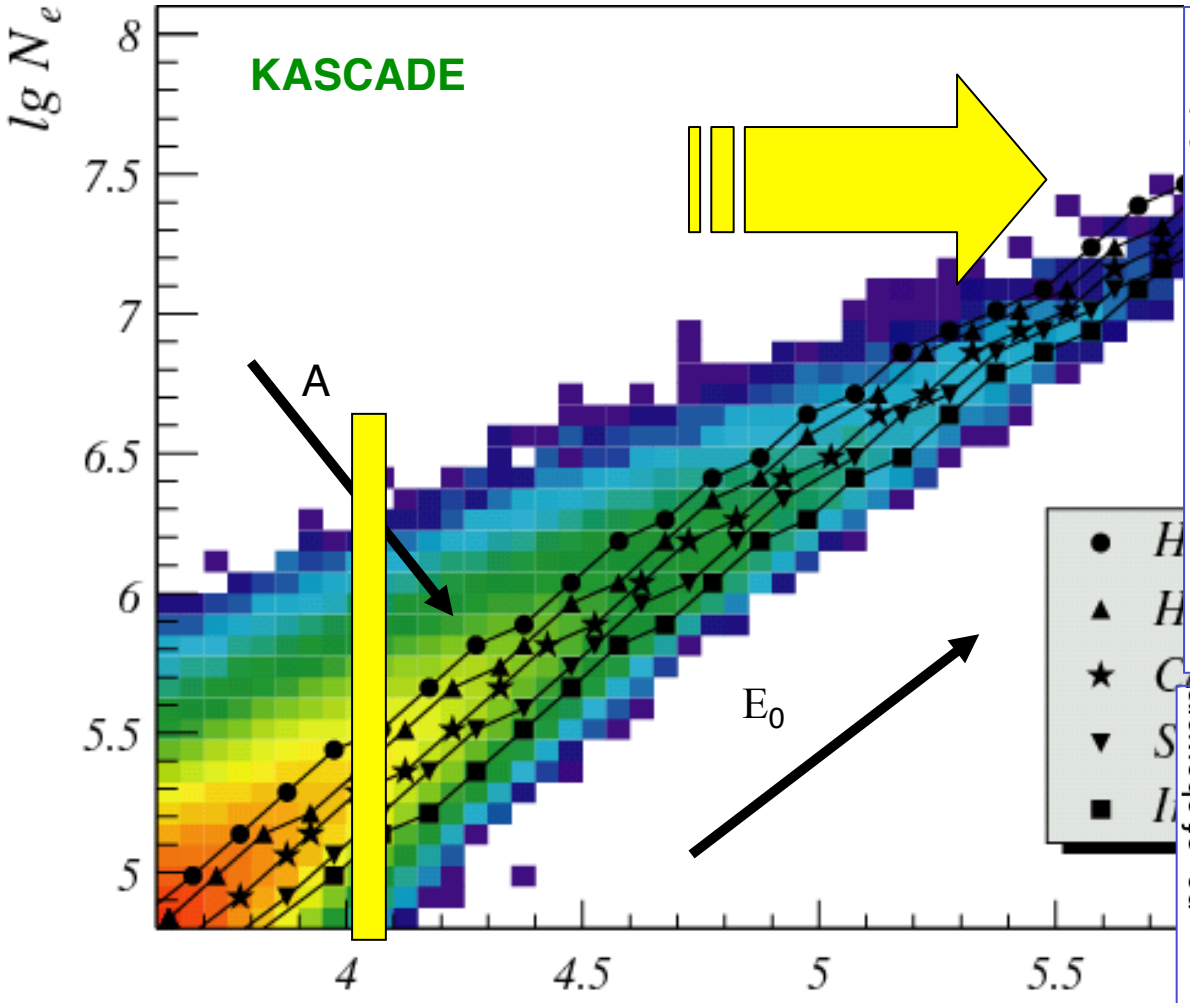
KArlsruhe Shower Core and Array DEtector

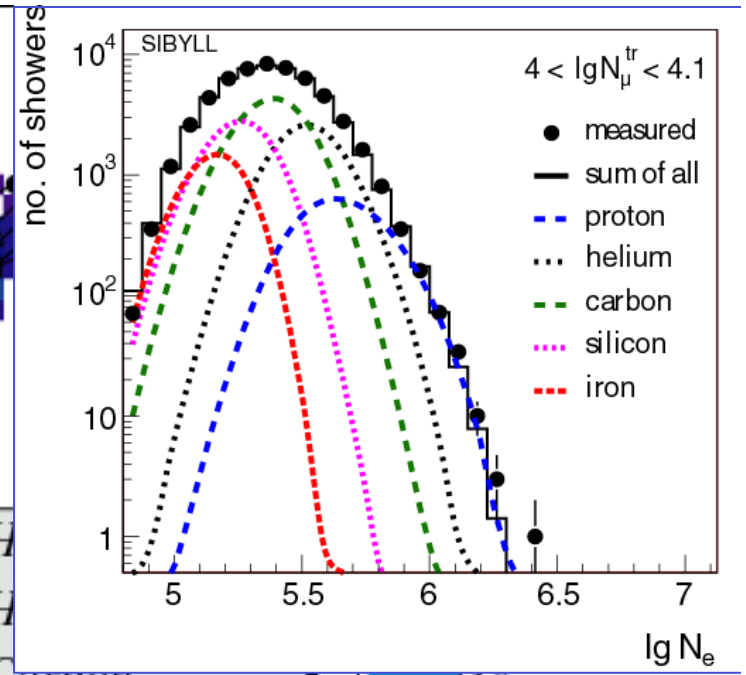
Simultaneous measurement of
electromagnetic,
muonic,
hadronic
shower components

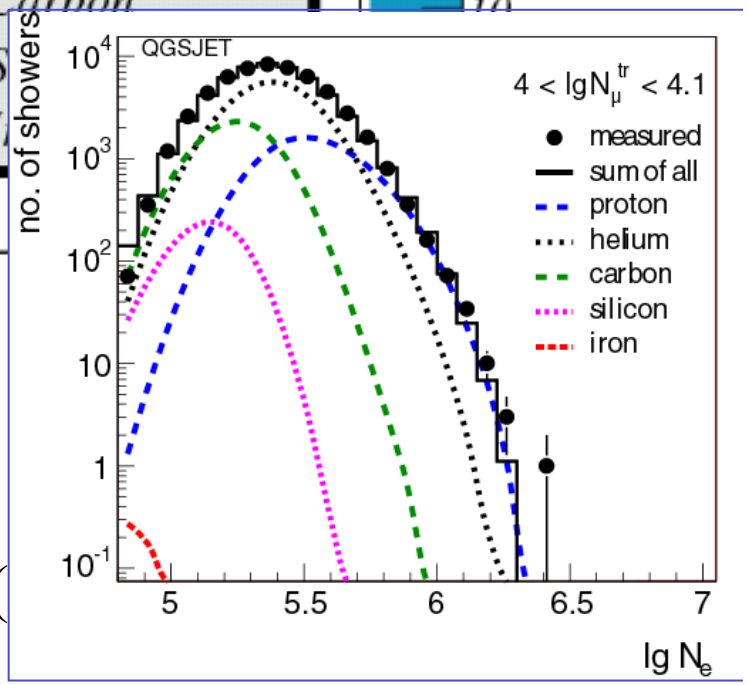


T. Antoni et al, Nucl. Instr. & Meth. A 513 (2004) 490

Two dimensional shower size spectrum lg N_e vs. lg N_μ





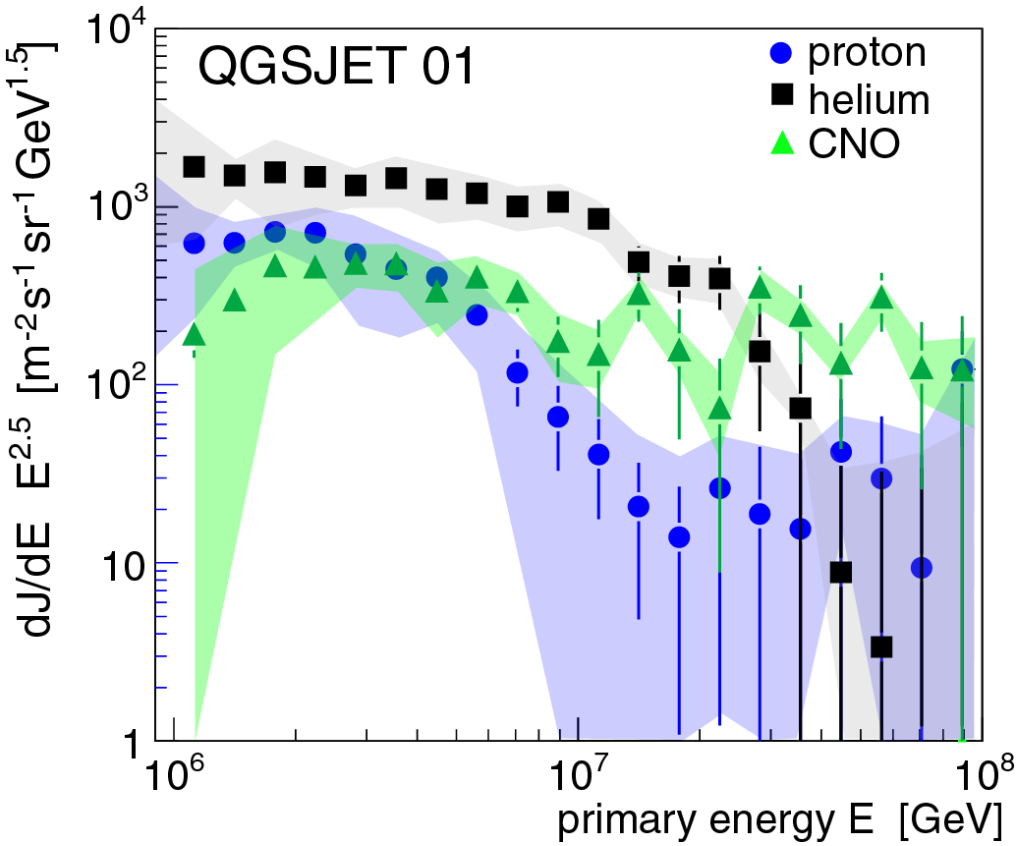


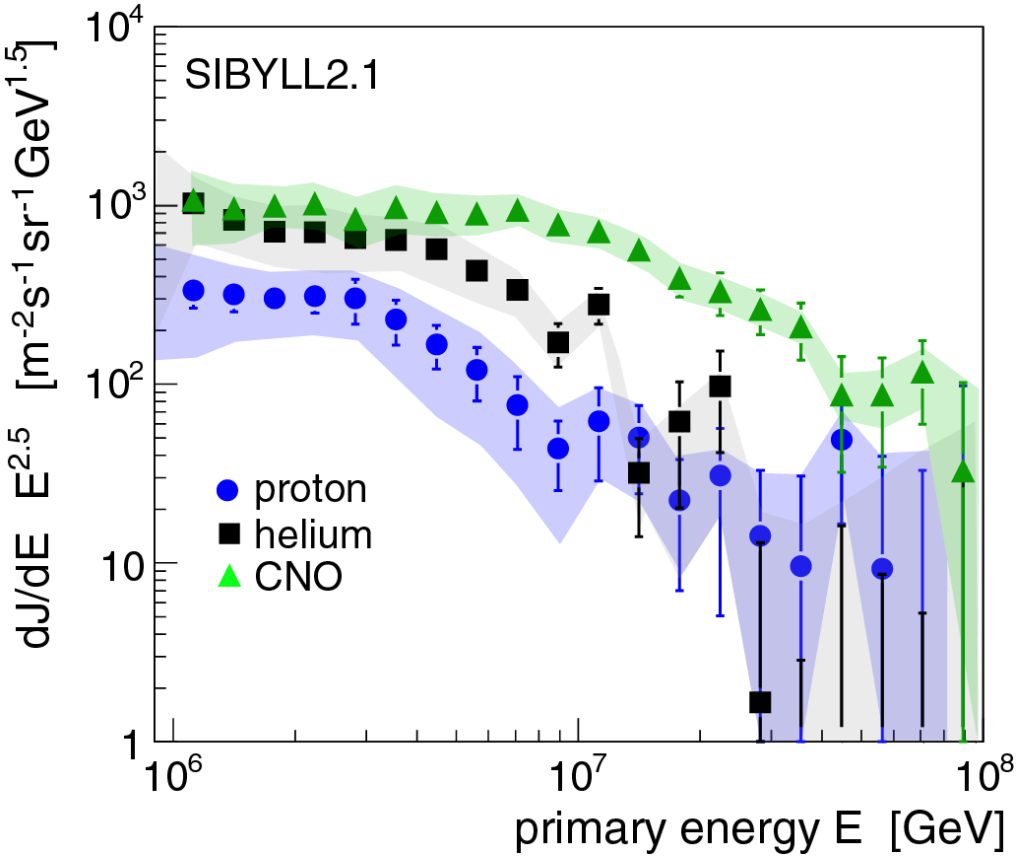
- derive E_0 and A from N_e and N_μ data
- Fredholm integral equations of 1st kind:

$$g_i(\lg N_e, \lg N_\mu) = \int_0^\infty t_i(\lg N_e, \lg N_\mu \mid E)\, p_i($$

T. Antoni et al., Astropart. Phys. 24 (2005) 1

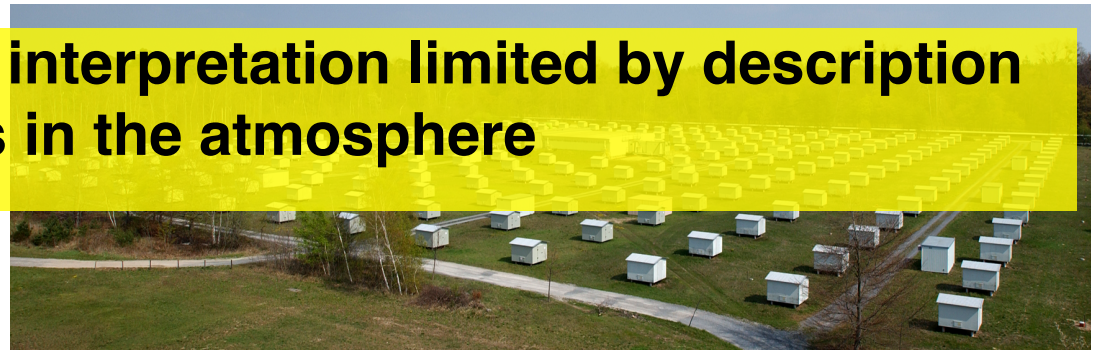
KASCADE: Energy spectra for elemental groups





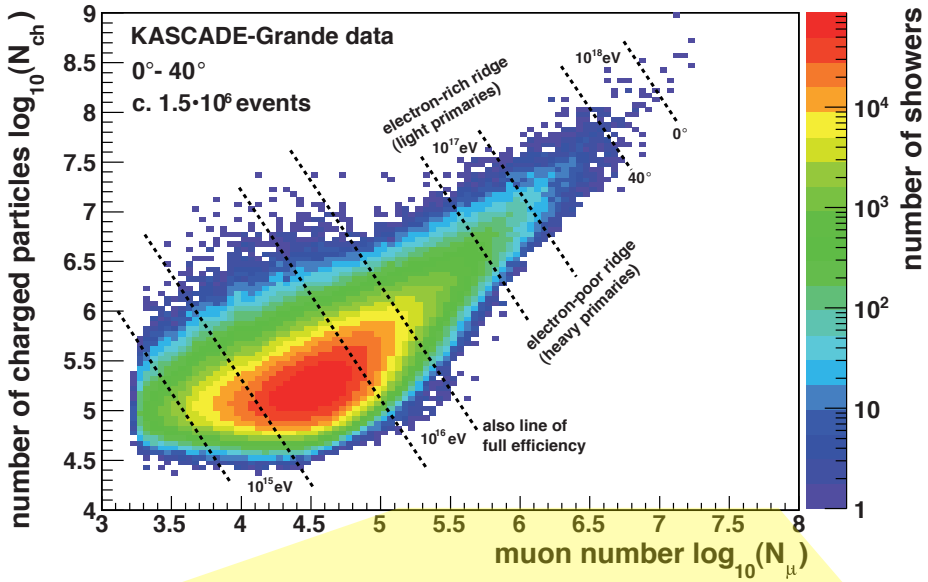
Knee caused by cut-off for light elements

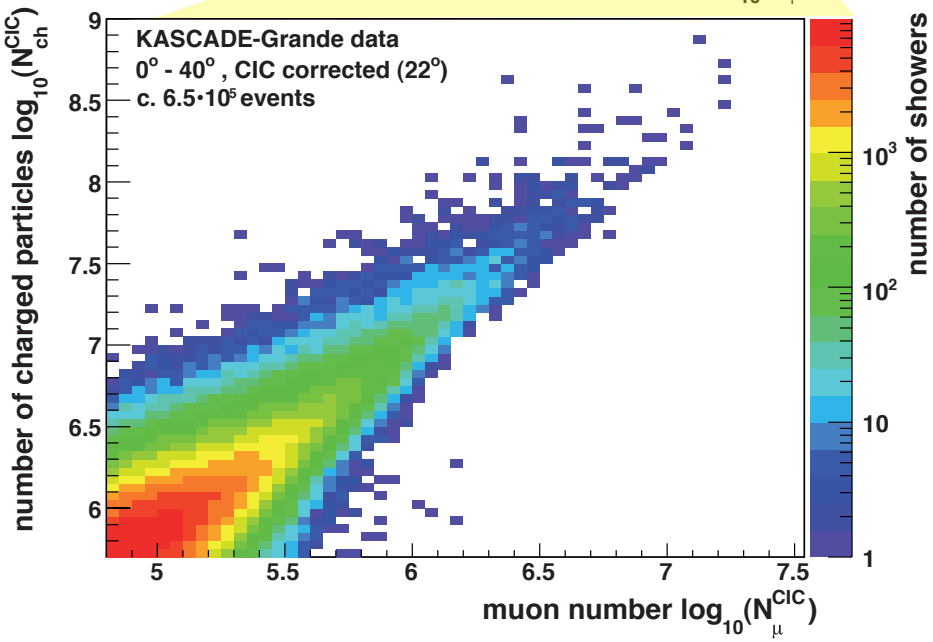
Astrophysical interpretation limited by description of interactions in the atmosphere

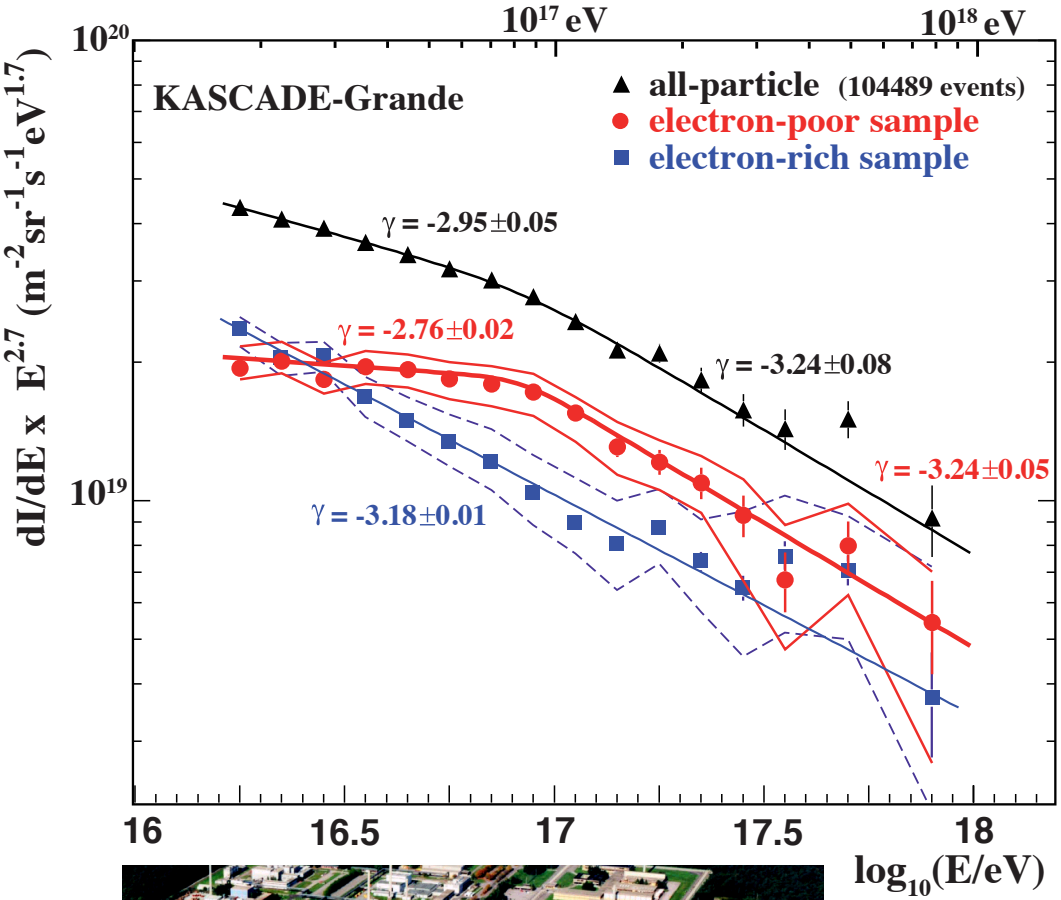


T. Antoni et al., Astropart. Phys. 24 (2005) 1

A knee-like structure in the spectrum of the heavy component of cosmic rays

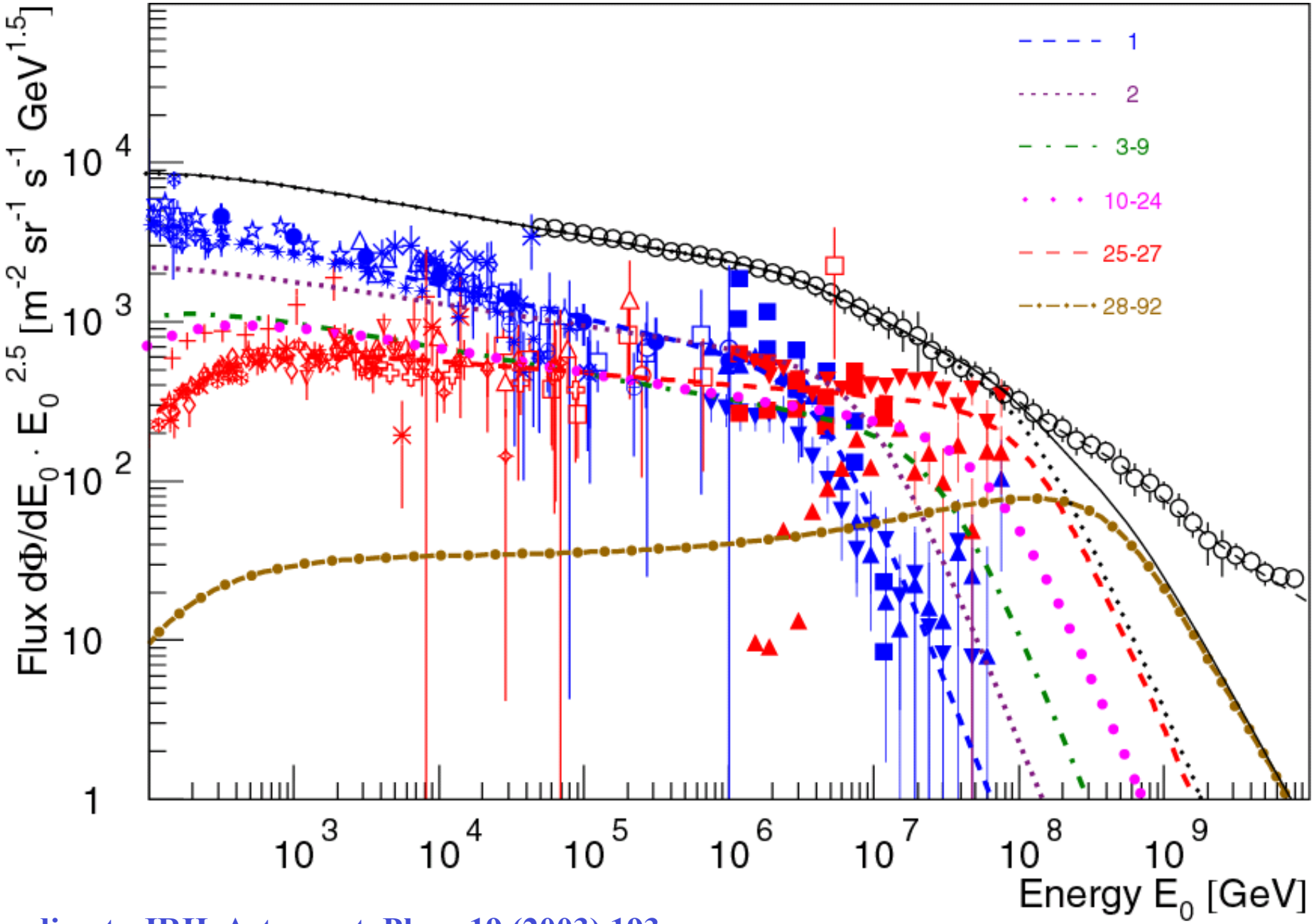




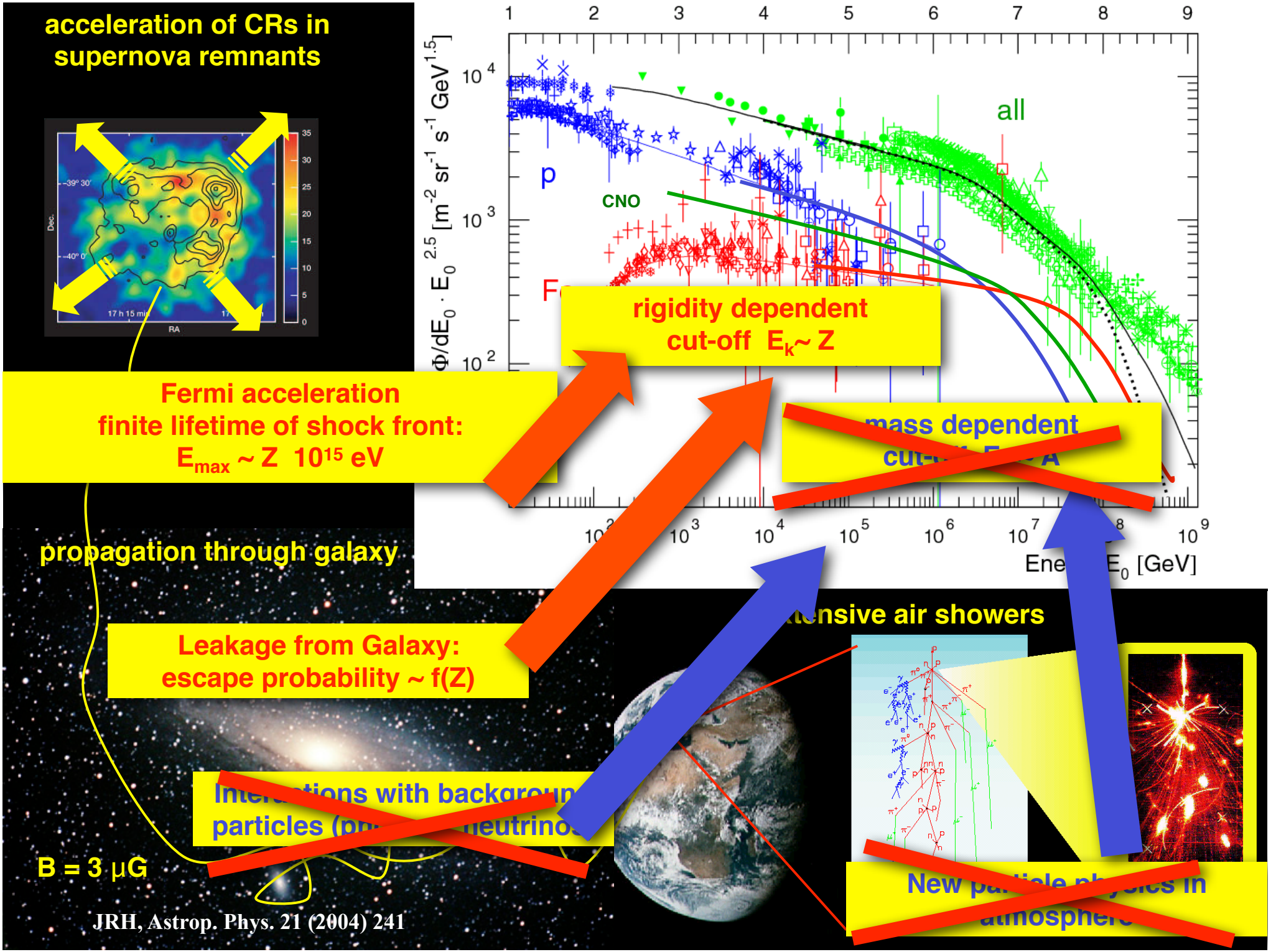


W.D. Apel et al, PRL 107 (2011) 171104

Cosmic-ray energy spectrum



according to JRH, Astropart. Phys. 19 (2003) 193

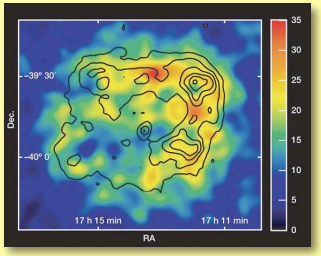

acceleration of CRs in supernova remnants
Fermi acceleration
finite lifetime of shock front:
$E_{max} \sim Z\ 10^{15}$ eV
rigidity dependent
cut-off $E_k \sim Z$
mass dependent
propagation through galaxy
Leakage from Galaxy:
escape probability ~ f(Z)
B = 3 μG
JRH, Astrop. Phys. 21 (2004) 241
all
p
CNO
Dec.
RA

Origin of the knee?

JRH, Astropart. Phys. 21 (2004) 241 (updated)

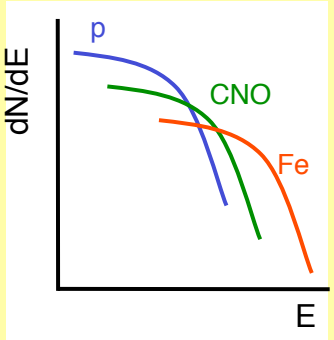
Acceleration (SNR)

.. in SNR	Berezhko & Ksenofontov
.. in SNR + radio galaxies	Stanev ..
.. in oblique shocks	Kobayakawa ..
.. in variety of SNR	Sveshnikova
Single source model	Erlykin & Wolfendale
Reacceleration in galactic wind	Völk & Zirakashvili



Leakage from Galaxy

Minimum pathlength model	Swordy
Anomalous diffusion model	Lagutin ..
Hall diffusion model	Ptuskin .., Kalmykov ..
Diffusion in turbulent magnetic fields	Ogio & Kakimoto
Diffusion and drift	Roulet ..



γ-ray bursts

Cannonball model	Plaga
Acceleration in GRB + diffusion	Wick ..
Acceleration in GRB E_{max} ~A	Dar ..

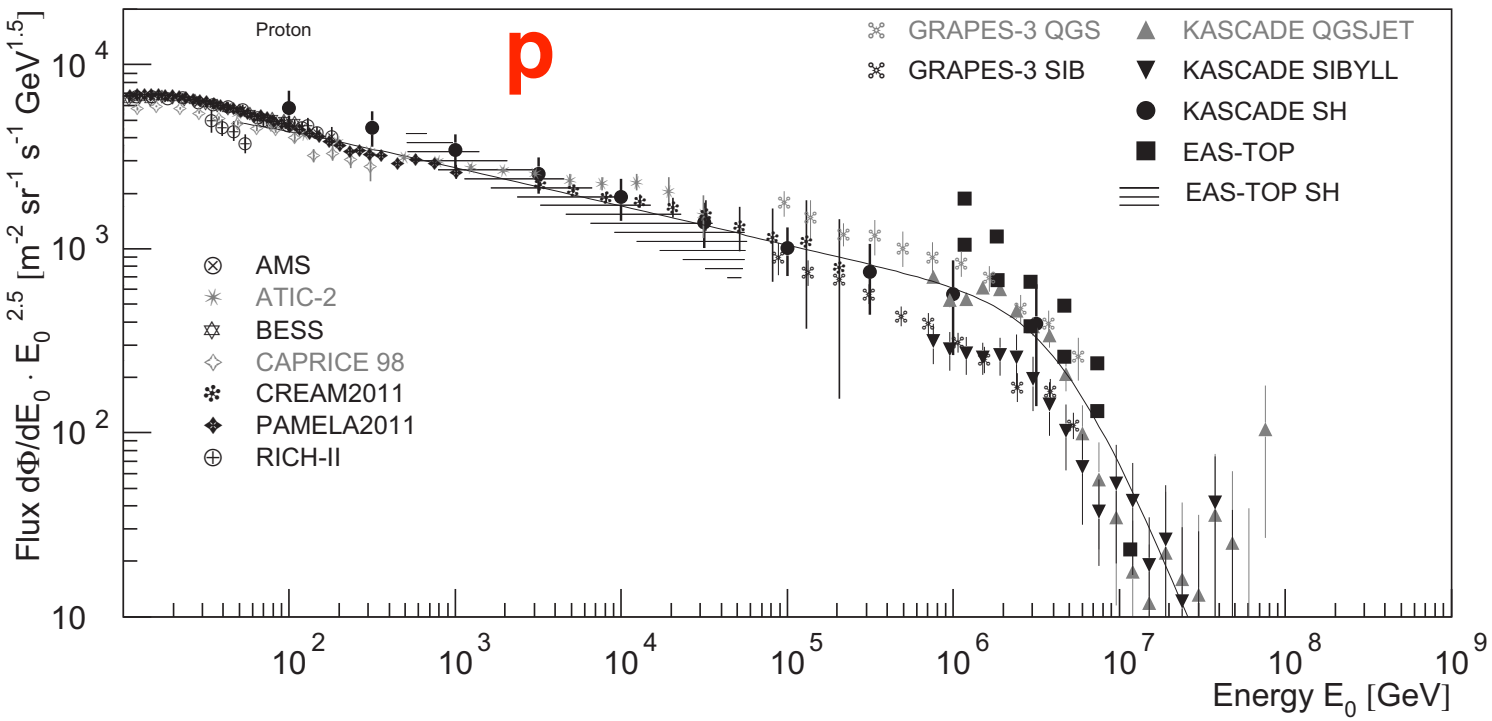
Interaction with background particles

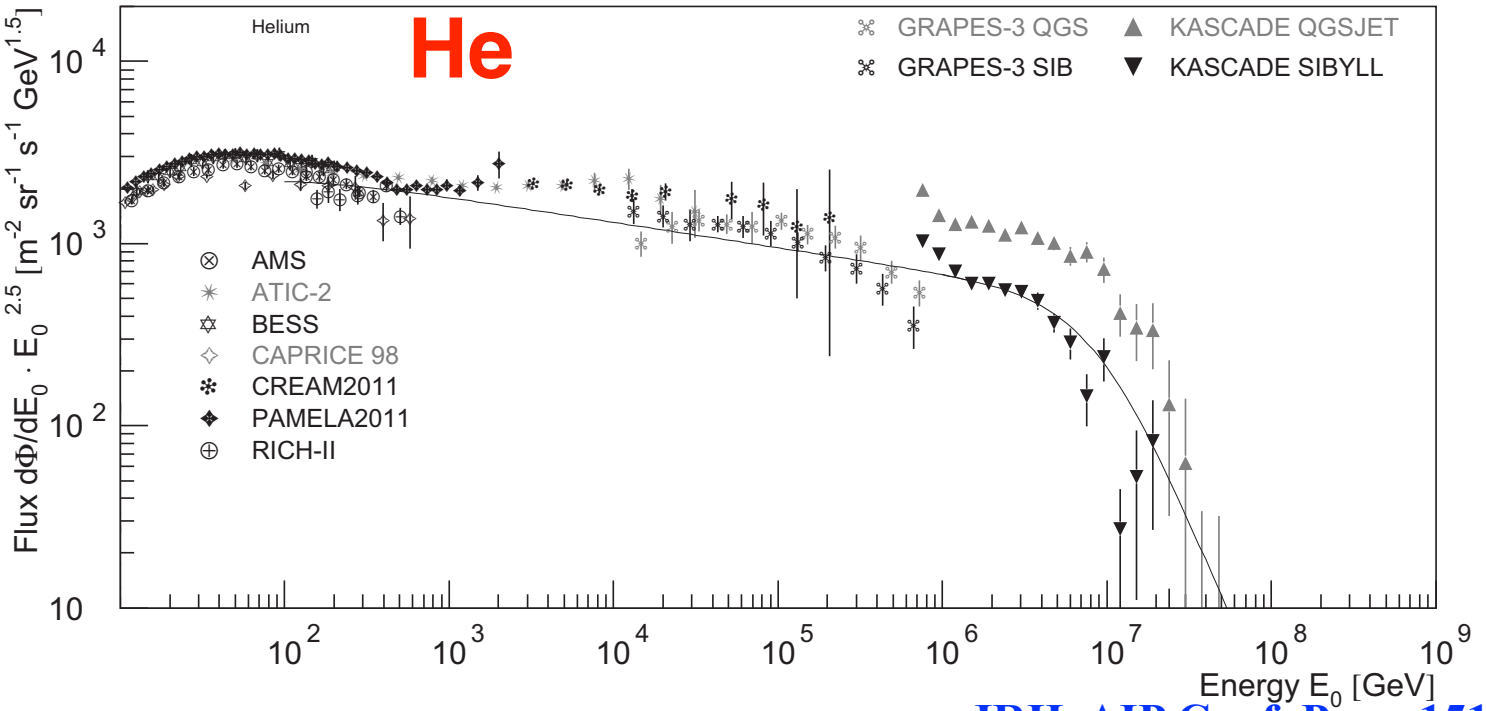
Diffusion model + photo-disintegration	Tkaczyk
Interaction with neutrinos in galactic halo	Dova ..
Photo-disintegration (optical and UV photons)	Candia ..

~ A

Particle physics in atmosphere

Gravitons, SUSY	Kazanas & Nicolaidis

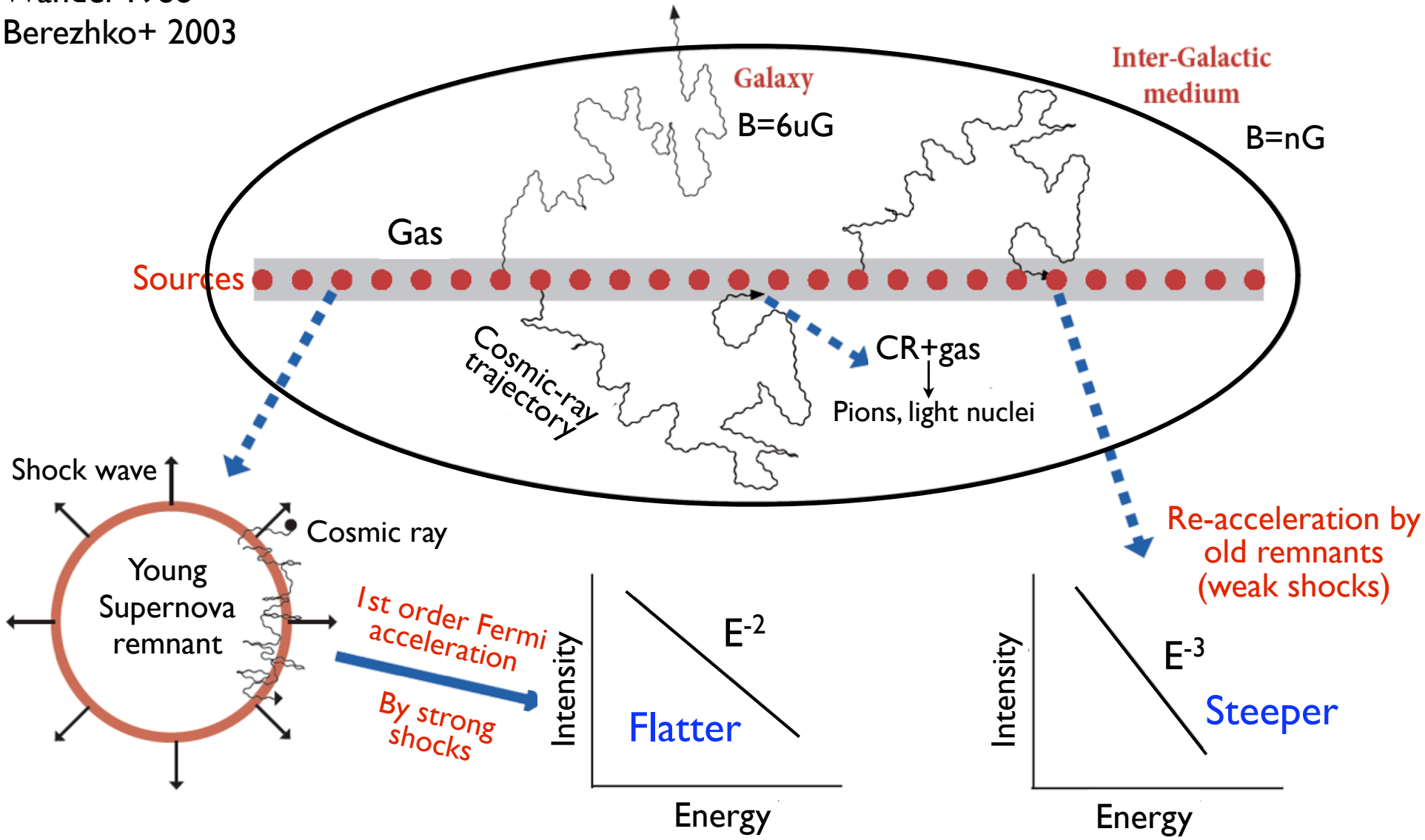




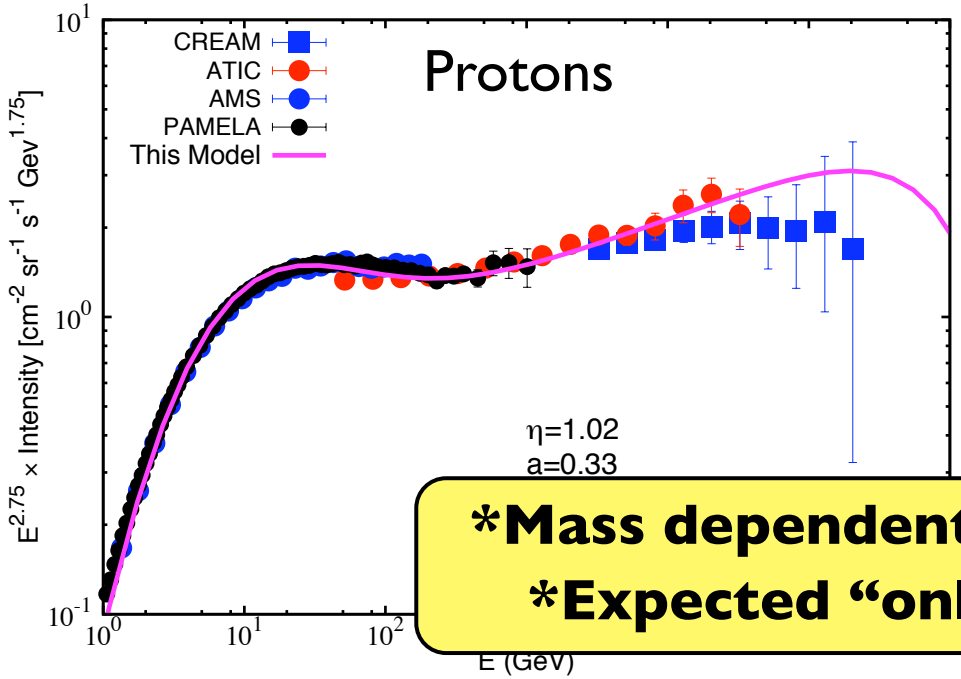
JRH, AIP Conf. Proc. 1516 (2013) 185

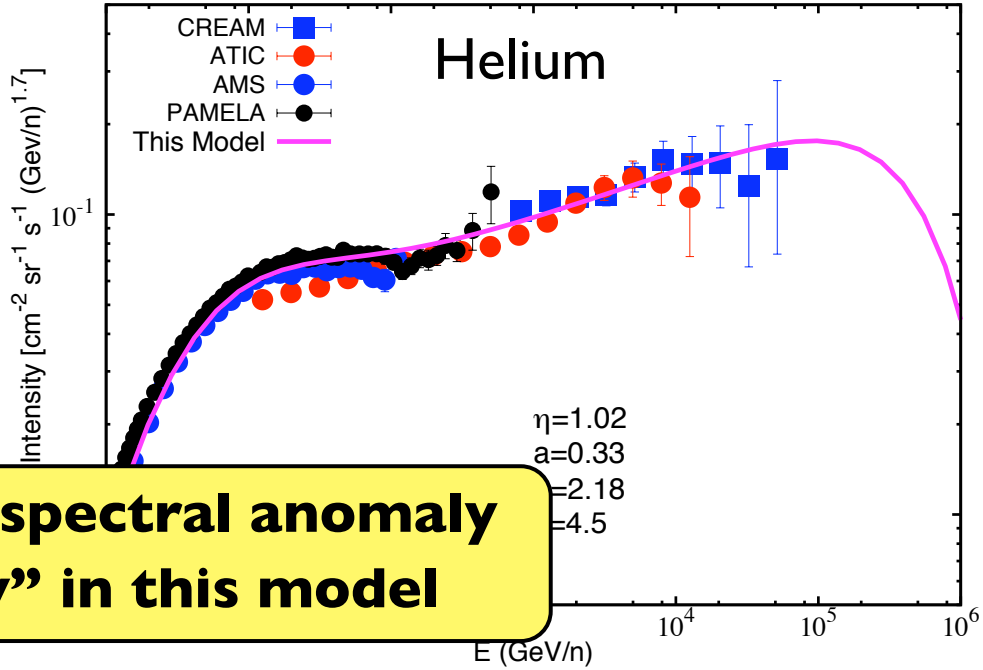
The re-acceleration model

Wandel 1988
Berezhko+ 2003



Results: Protons, Helium & Iron spectra



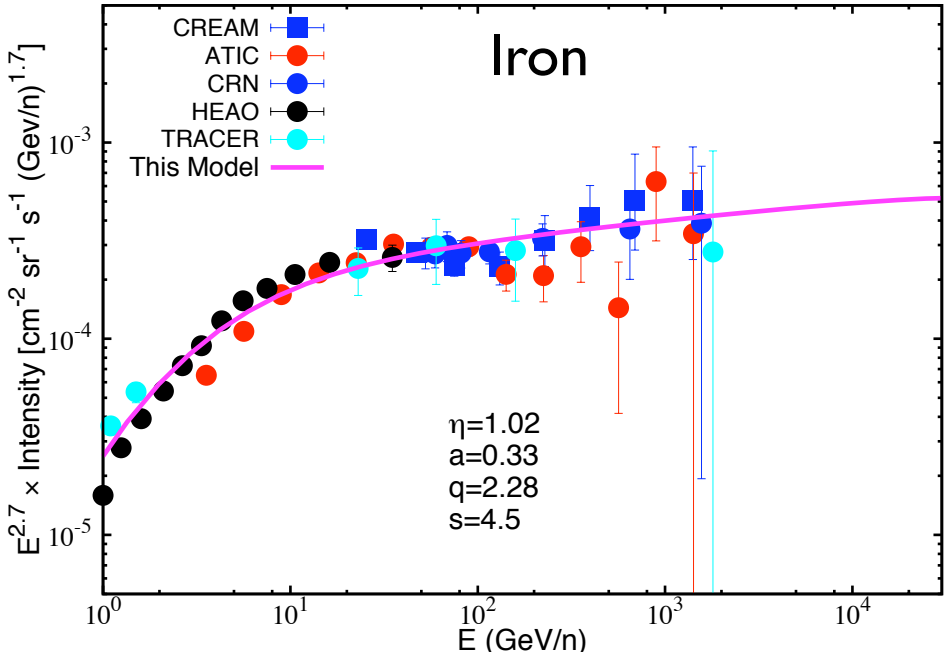


***Mass dependent spectral anomaly**
***Expected "only" in this model**

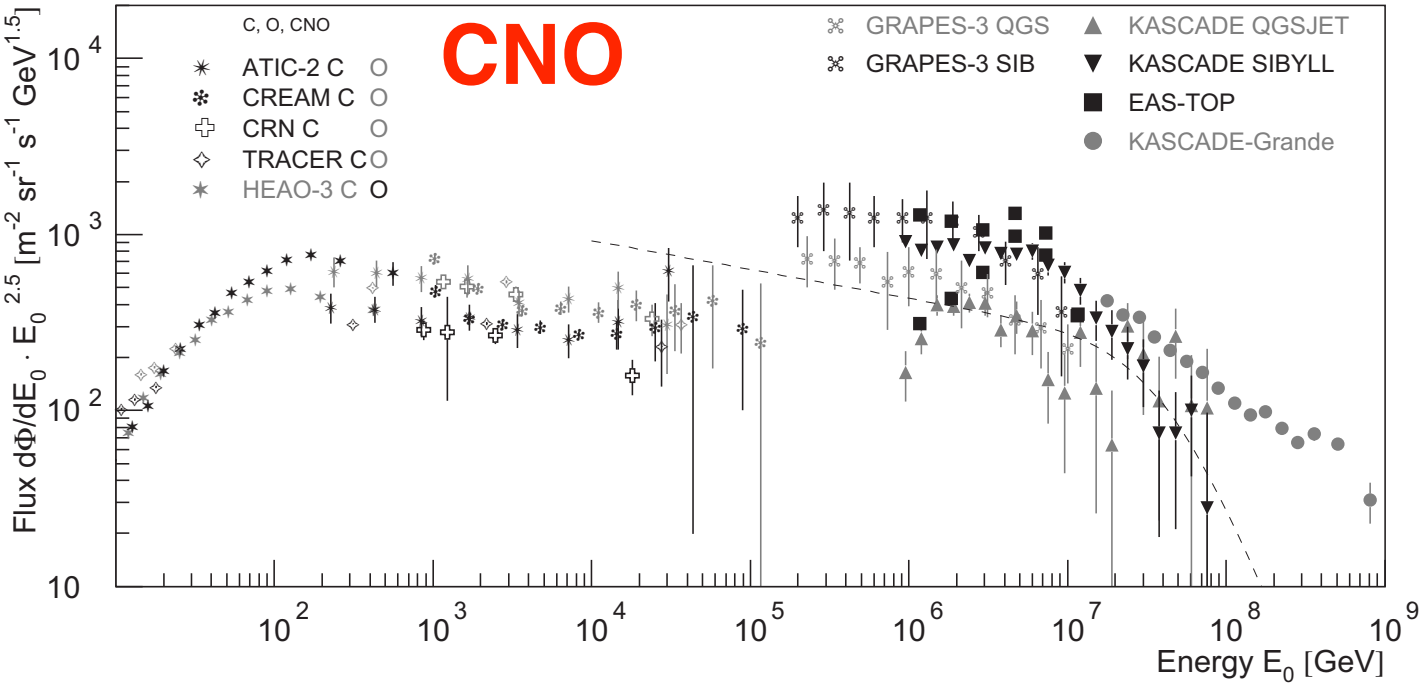
q_P=2.21, f_P=6.95%

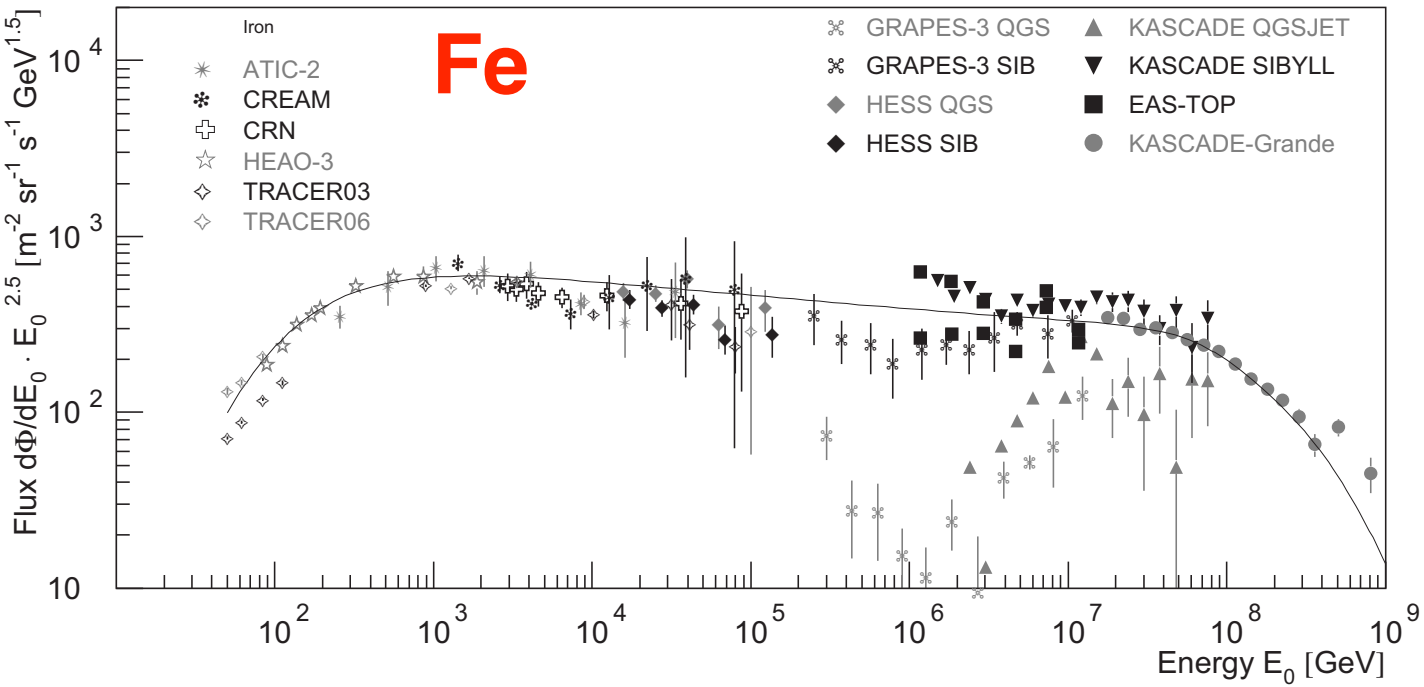
q_{He}=2.18, f_{He}=0.79%

q_{Fe}=2.28, f_{Fe}=4.9×10^{-3}%



S.Thoudam, ECRS 2014, Kiel





JRH, AIP Conf. Proc. 1516 (2013) 185

Fe

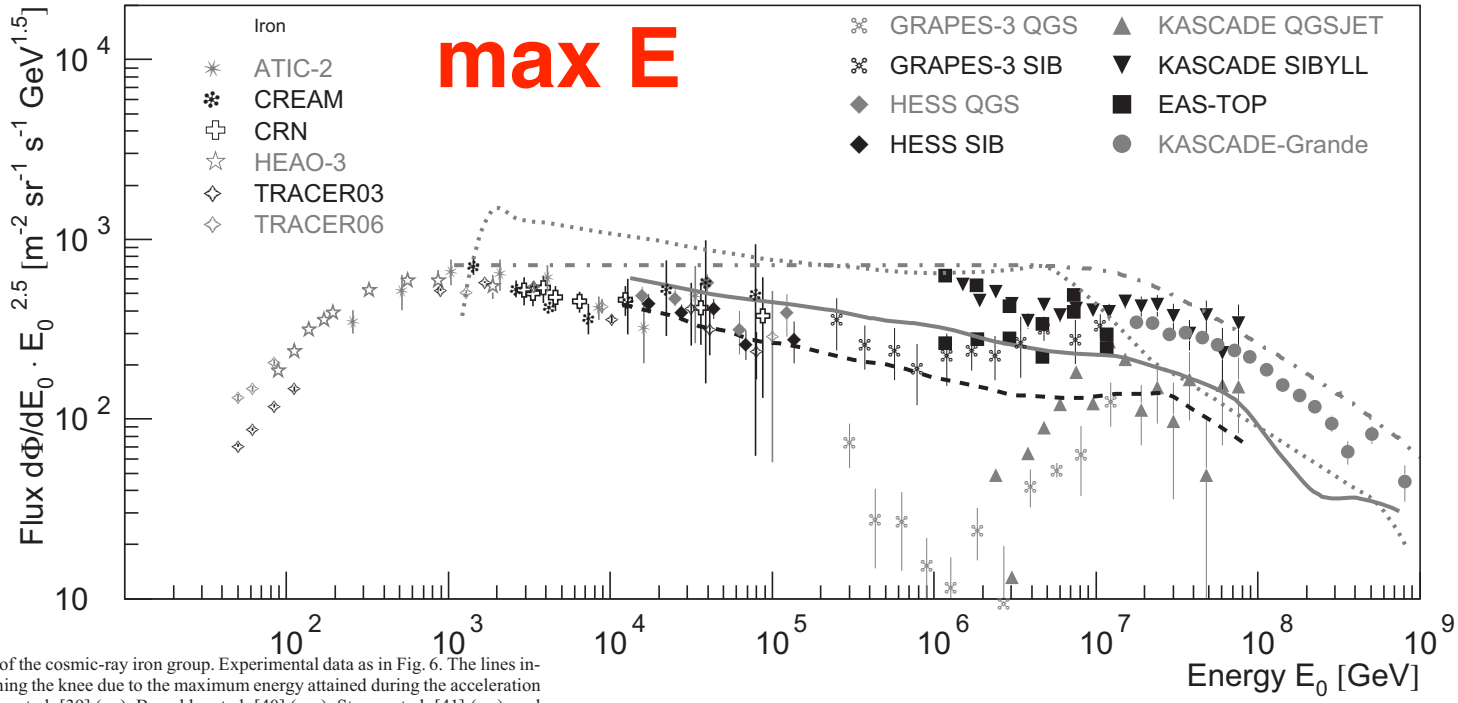


FIGURE 8. Energy spectrum of the cosmic-ray iron group. Experimental data as in Fig. 6. The lines indicate spectra for models explaining the knee due to the maximum energy attained during the acceleration process according to Sveshnikova et al. [39] (—), Berezhko et al. [40] (- - -), Stanev et al. [41] (· · ·), and Kobayakawa et al. [42] (-·-·).

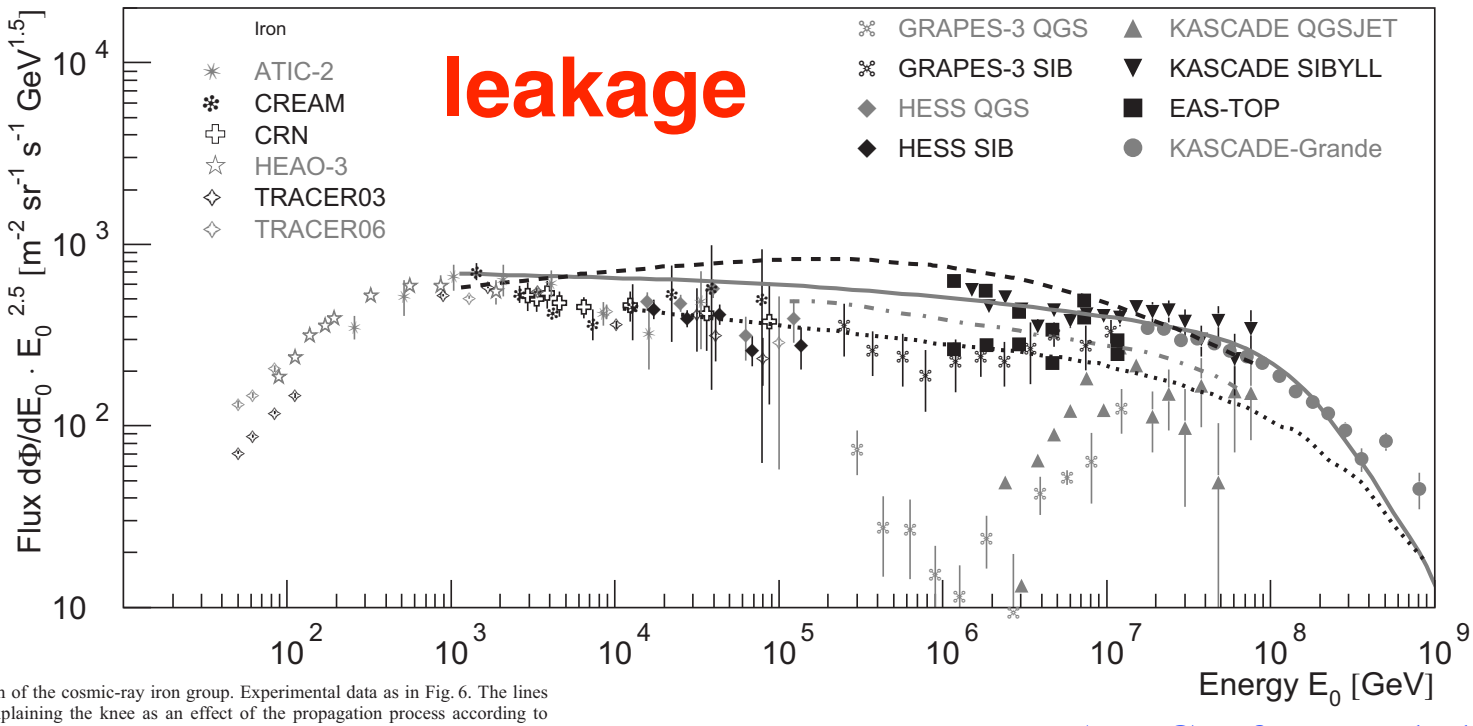


FIGURE 9. Energy spectrum of the cosmic-ray iron group. Experimental data as in Fig. 6. The lines indicate spectra for models explaining the knee as an effect of the propagation process according to Hörandel & Kalmykov et al. [43] (—), Ogio et al. [44] (- - -), Roulet et al. [45] (· · ·), as well as Völk et al. [46] (-·-·).

JRH, AIP Conf. Proc. 1516 (2013) 185

Transport of Cosmic Rays

Propagation of cosmic rays in our Galaxy

thank you!

questions?

Jörg R. Hörandel
Radboud University Nijmegen & Nikhef

http://particle.astro.ru.nl