Cosmic Rays
1. Introduction

Lecture 1: Introduction to cosmic rays

Lecture 2: Atmospheric μ and ν and ν telescopes

Lecture 3: Giant air shower experiments

Exercise: Expectations for γ-ray & ν-astronomy

Highlights of history of cosmic rays

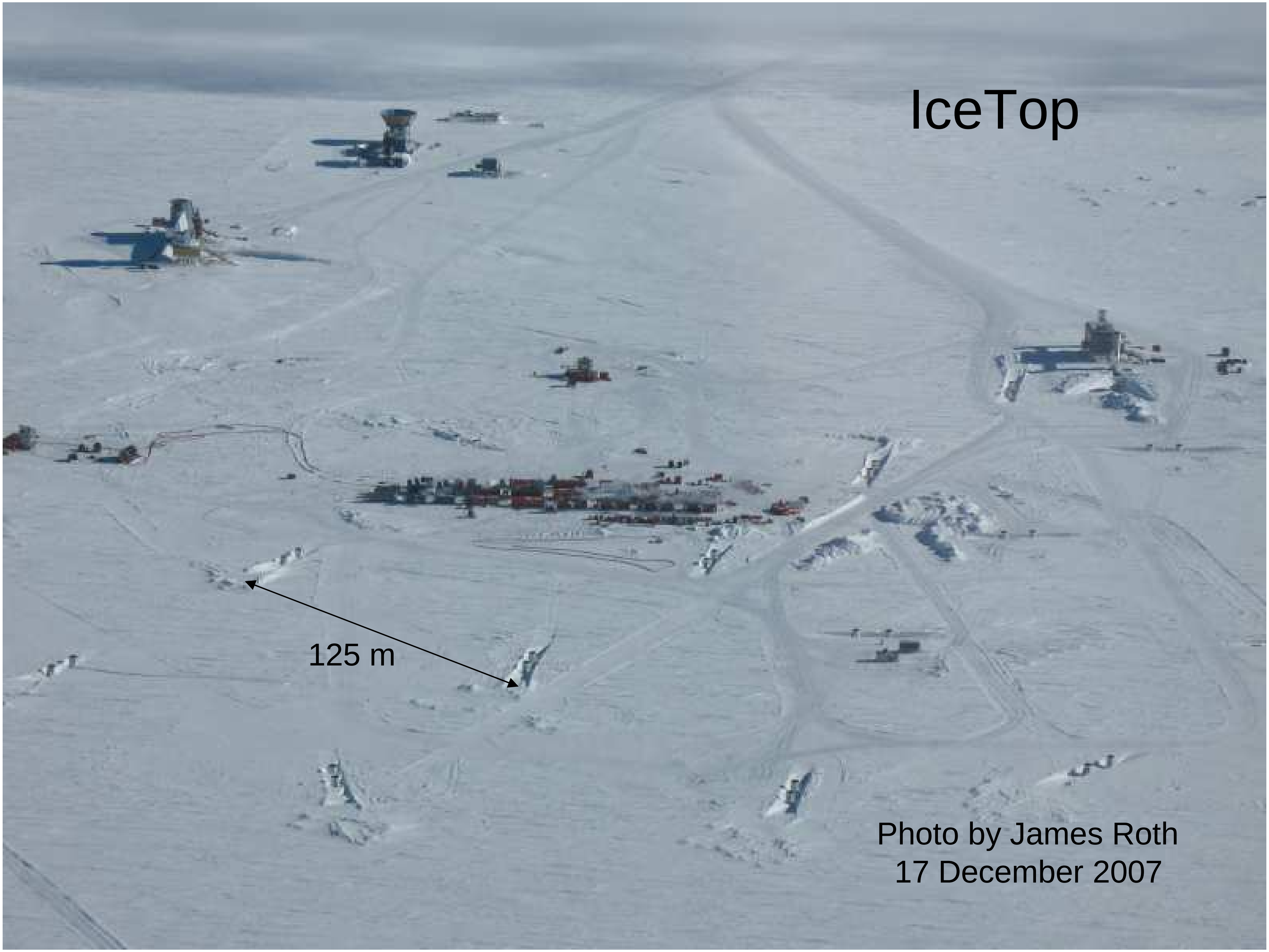
- 1912: Victor Hess, Nobel prize 1936
  - Ascended to 5300 m in an open balloon
  - Showed ionization of the air increased
- ~1920: Millikan (Caltech)
  - coined “cosmic rays”
  - thought they were photons
  - Compton (at Chicago) argued they were positive particles
- 1930’s: latitude surveys, Geiger counters
  - E-W effect proves primary cosmic rays are +charged
  - Atmospheric secondaries are muons, photons and $e^{\pm}$
- 1940’s: (post-war) photographic emulsions
  - 1947 Powell et al., discovery of the pion
  - 1948 discovery of nuclei in primary cosmic radiation
  - 1949 Fermi (Chicago) paper on cosmic-ray acceleration

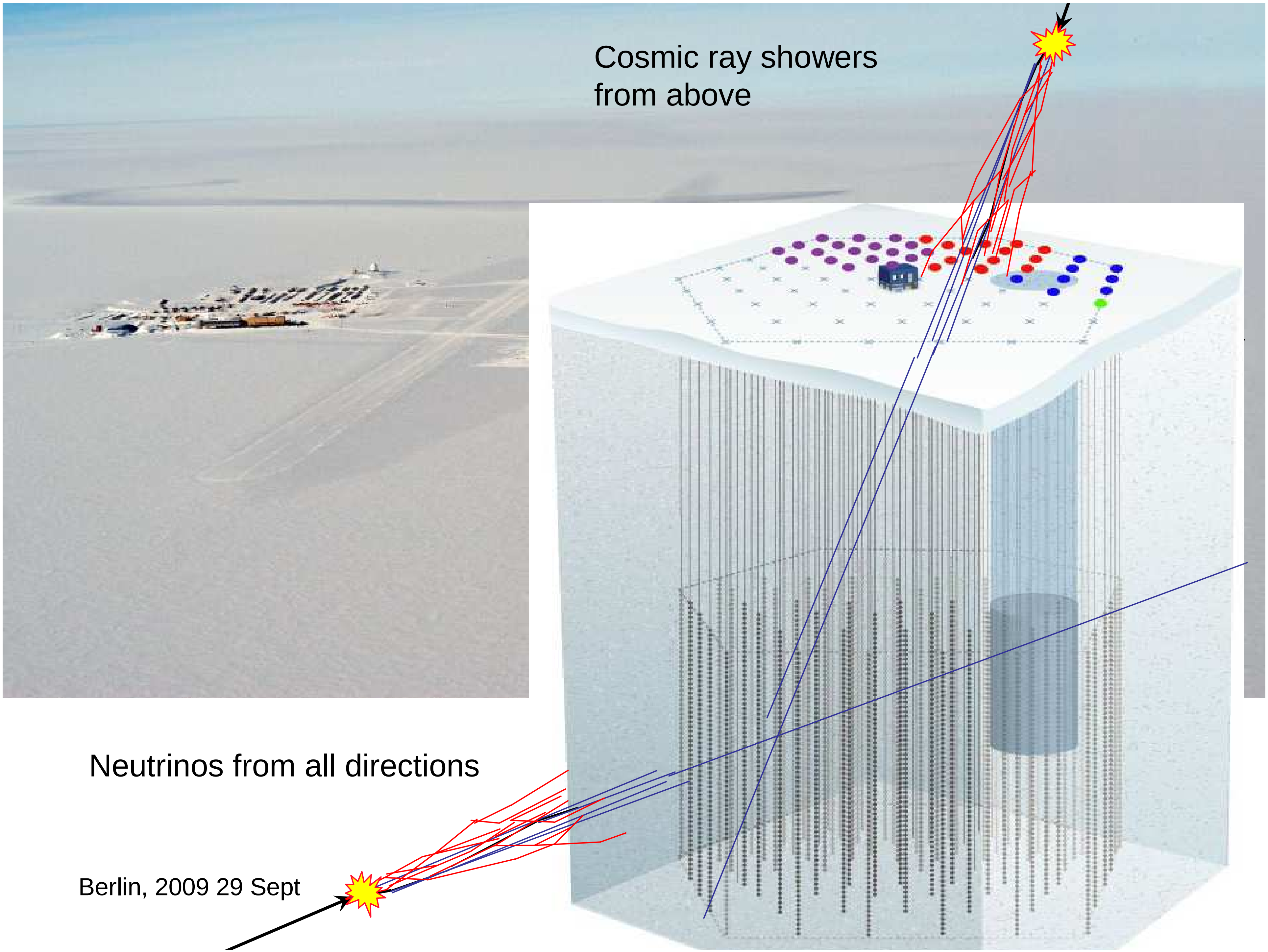
Air shower history

- 1937: Pierre Auger discovery
  - Observed earlier by Rossi
- 1940's: Rossi (M.I.T.)
  - Air shower studies with arrays of scintillators
- 1960's: discovery of the "knee"
  - Bernard Peters points out need for a new population
  - 1962: John Linsley (Volcano Ranch)
    - "Evidence for a Primary Cosmic-Ray Particle with Energy 10^{20} eV". *Physical Review Letters* **10**: 146, 1963
- AGASA, Fly's Eye, HiRes, Auger, TA …

Tibet hybrid air shower array

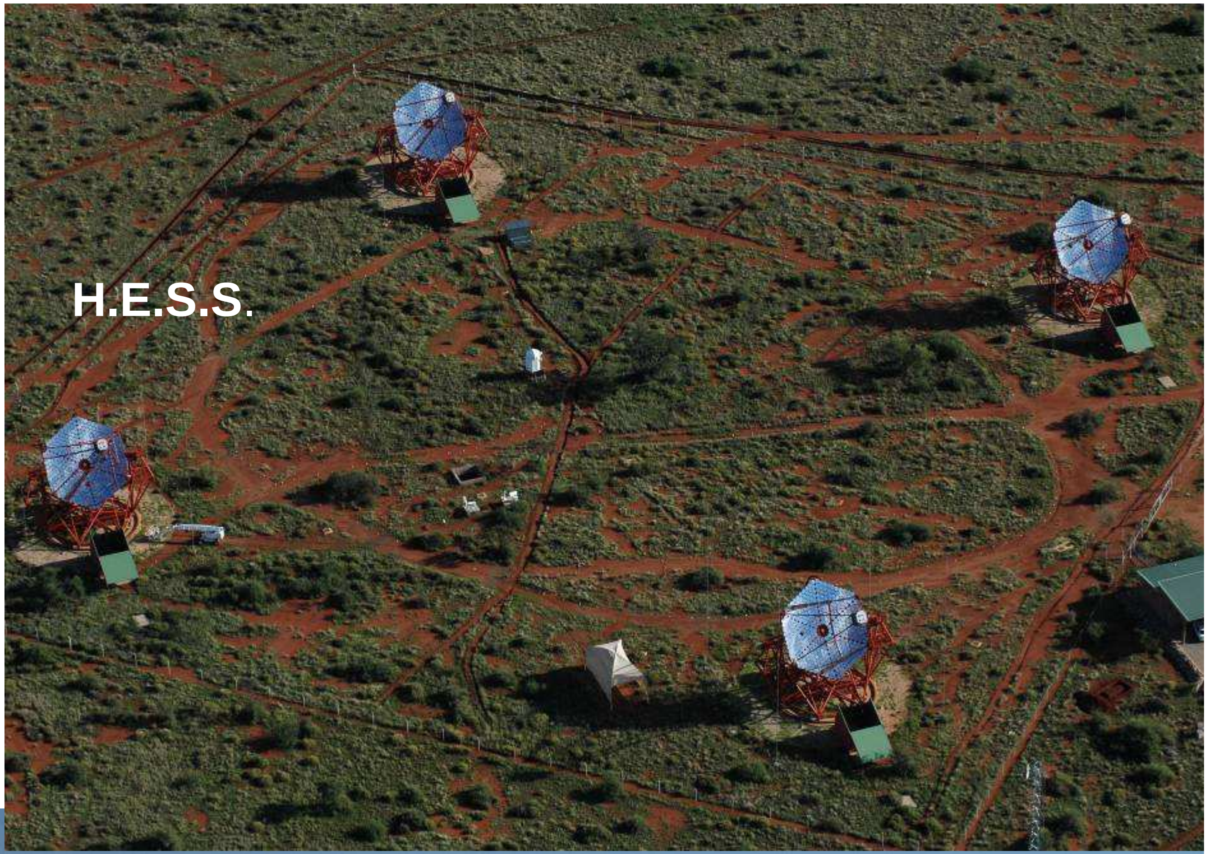
4300 m ~600 g/cm^2


IceTop
125 m
Photo by James Roth
17 December 2007



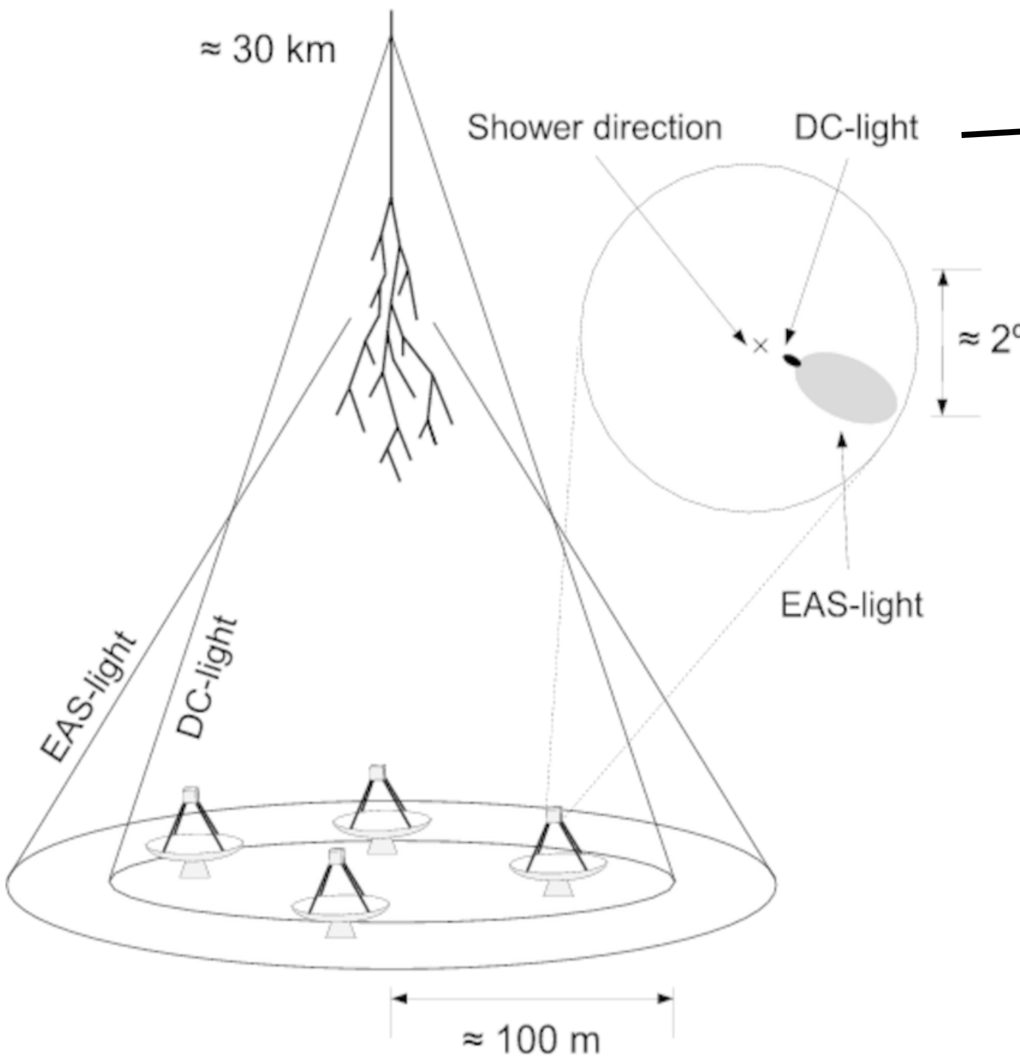
Berlin, 2009 29 Sept

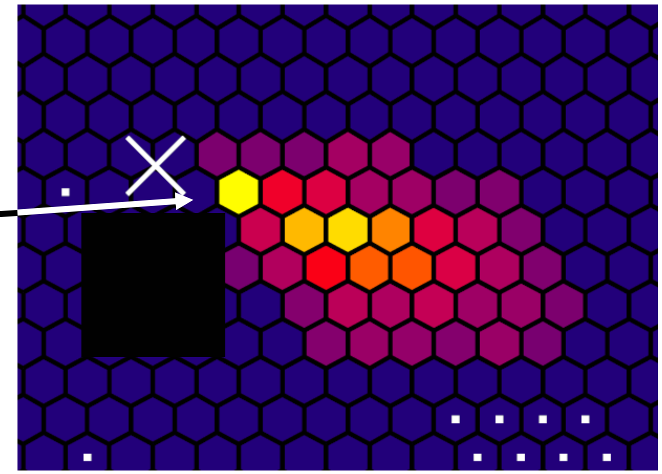
γ-ray telescopes

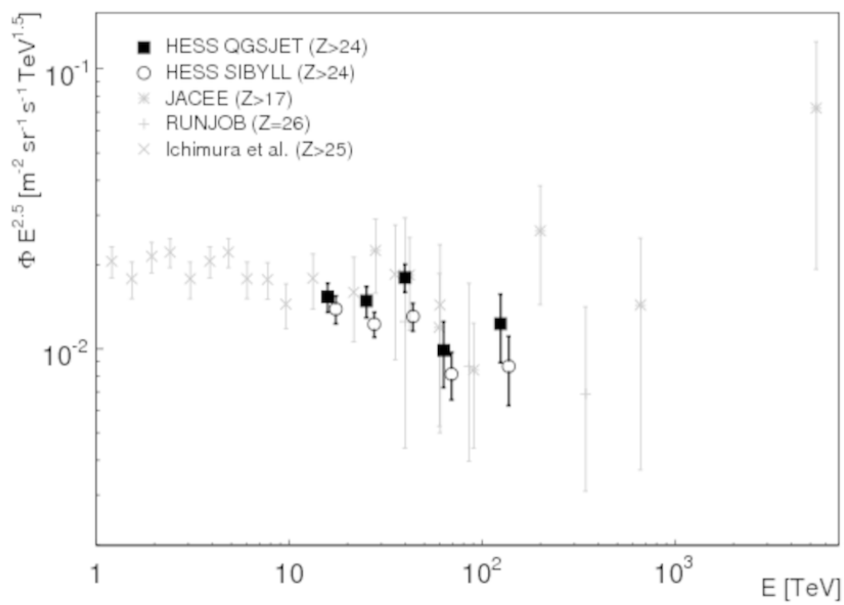


CR Iron spectrum from Direct Cherenkov

HESS collaboration, Phys Rev D 27, 2007



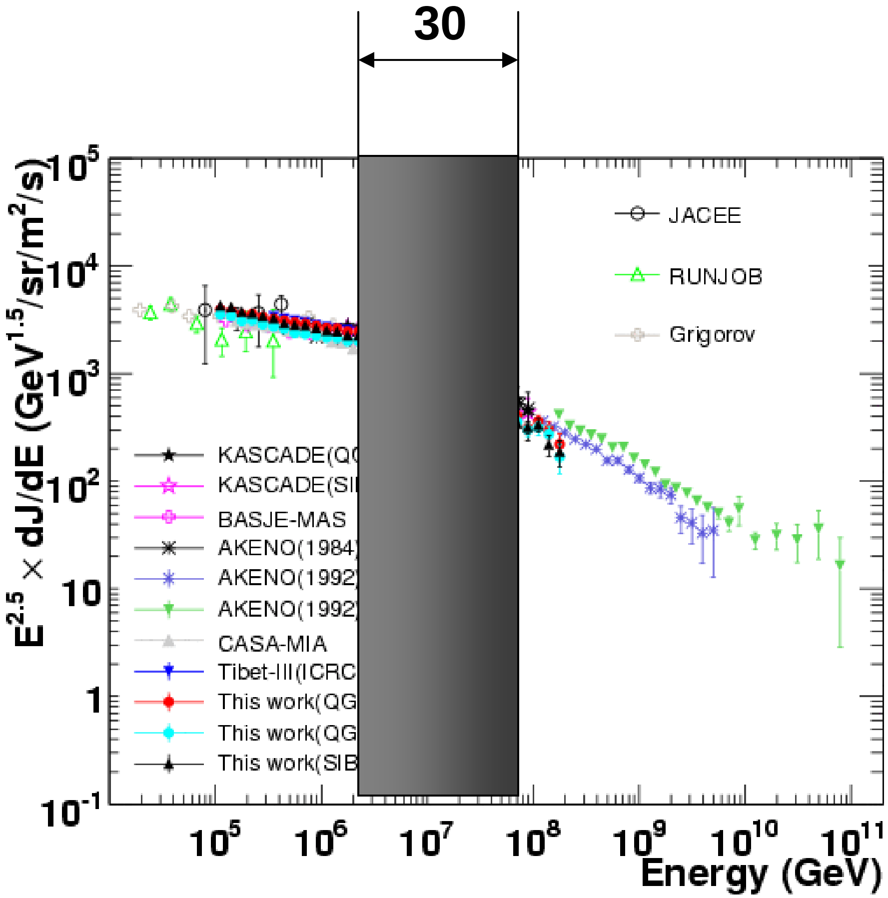




Method proposed by Kieda et al, 2001

Rigidity-dependence

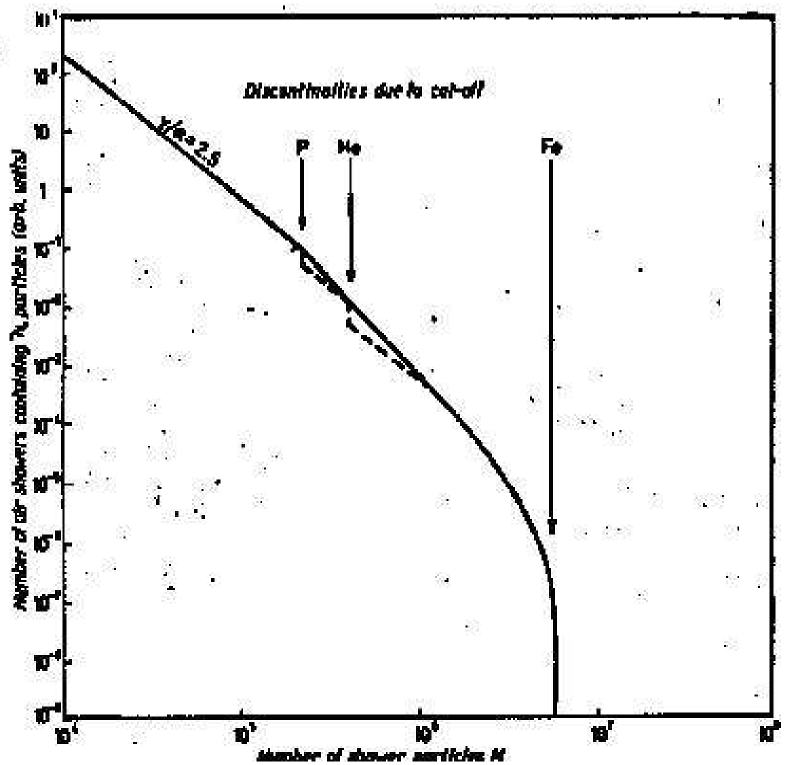
- Acceleration, propagation
  - depend on B: $r_{gyro} = R/B$
  - Rigidity, R = E/Ze
  - $E_c(Z) \sim Z\, R_c$
- $r_{SNR} \sim$ parsec
  - → $E_{max} \sim Z * 10^{15}$ eV
  - $1 \leq Z \leq 30$ (p to Fe)
- Slope change should occur within factor of 30 in energy
- With characteristic pattern of increasing A
- Problem: continuation of smooth spectrum to EeV
- More on this later…

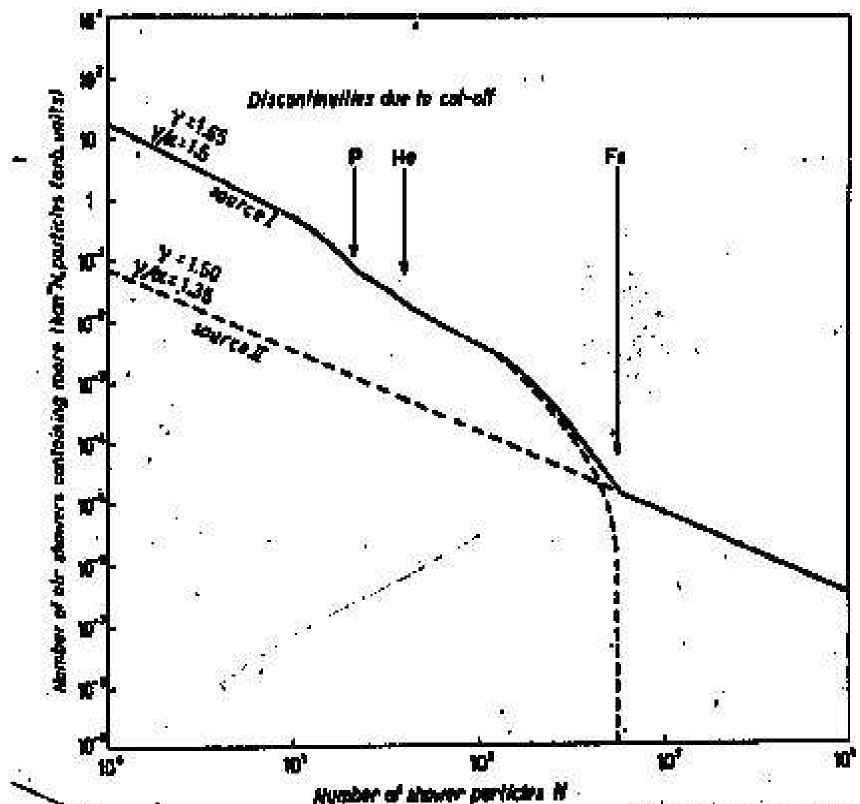


B. Peters: if E_{max} depends on B then p disappear first, then He, C, O, etc.

Peters cycle: systematic increase of < A > approaching E_{max}

<A> should begin to decrease again for $E > 30 \times E_{knee}$





gyro-radius = Pc / ZeB ≡ R (rigidity) / B

→ E_{total} (knee) ~ Z x R(knee)

B. Peters, Nuovo Cimento 22 (1961) 800

Primary spectrum

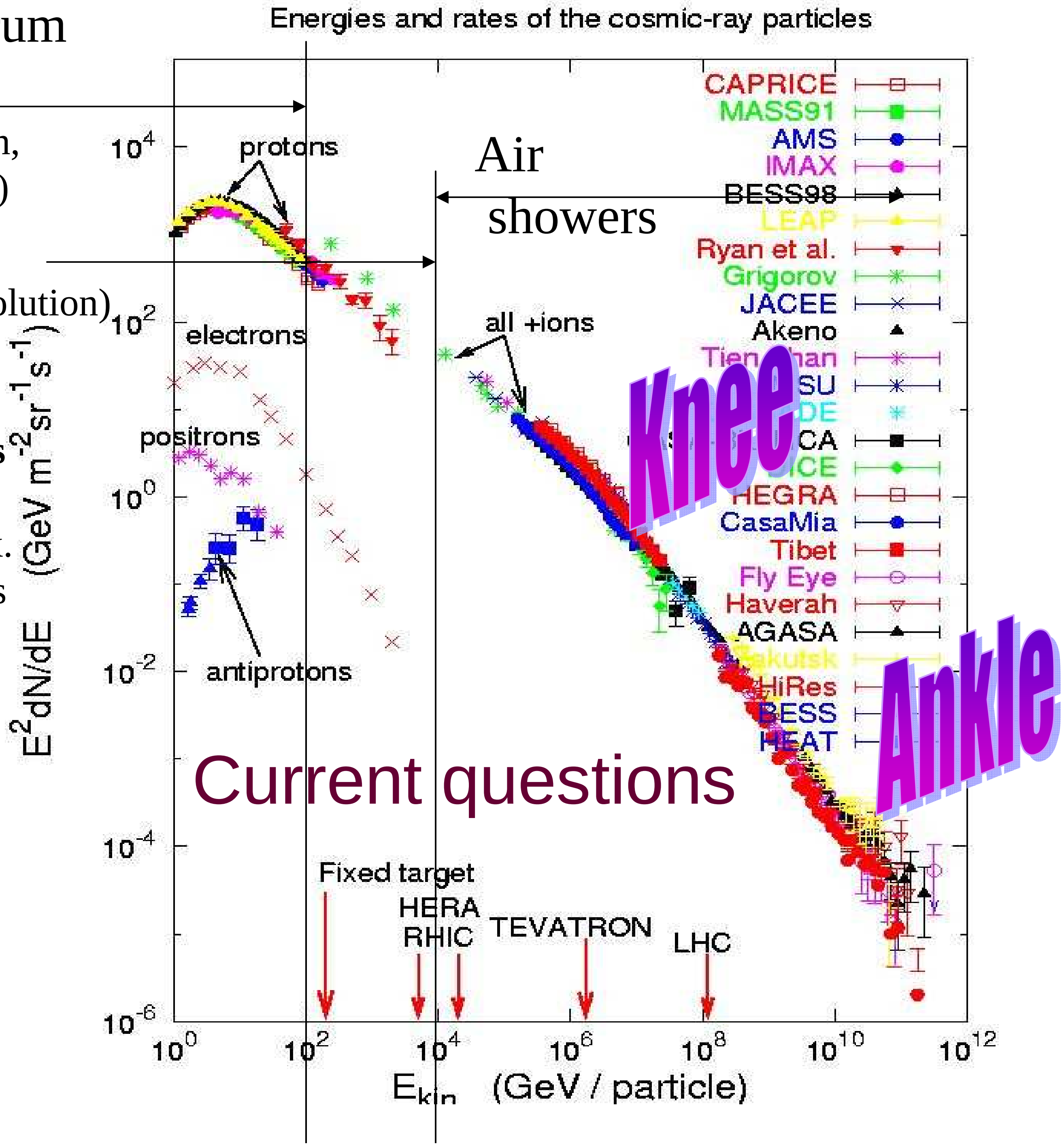
Spectrometers

($\Delta A = 1$ resolution, good E resolution)

Calorimeters

(less good resolution)

Air-shower arrays on the ground to overcome low flux. Don't see primaries directly.



31st Int. Cosmic Ray Conf.
July 7-15, 2009, Łódź, Poland

Scientific program

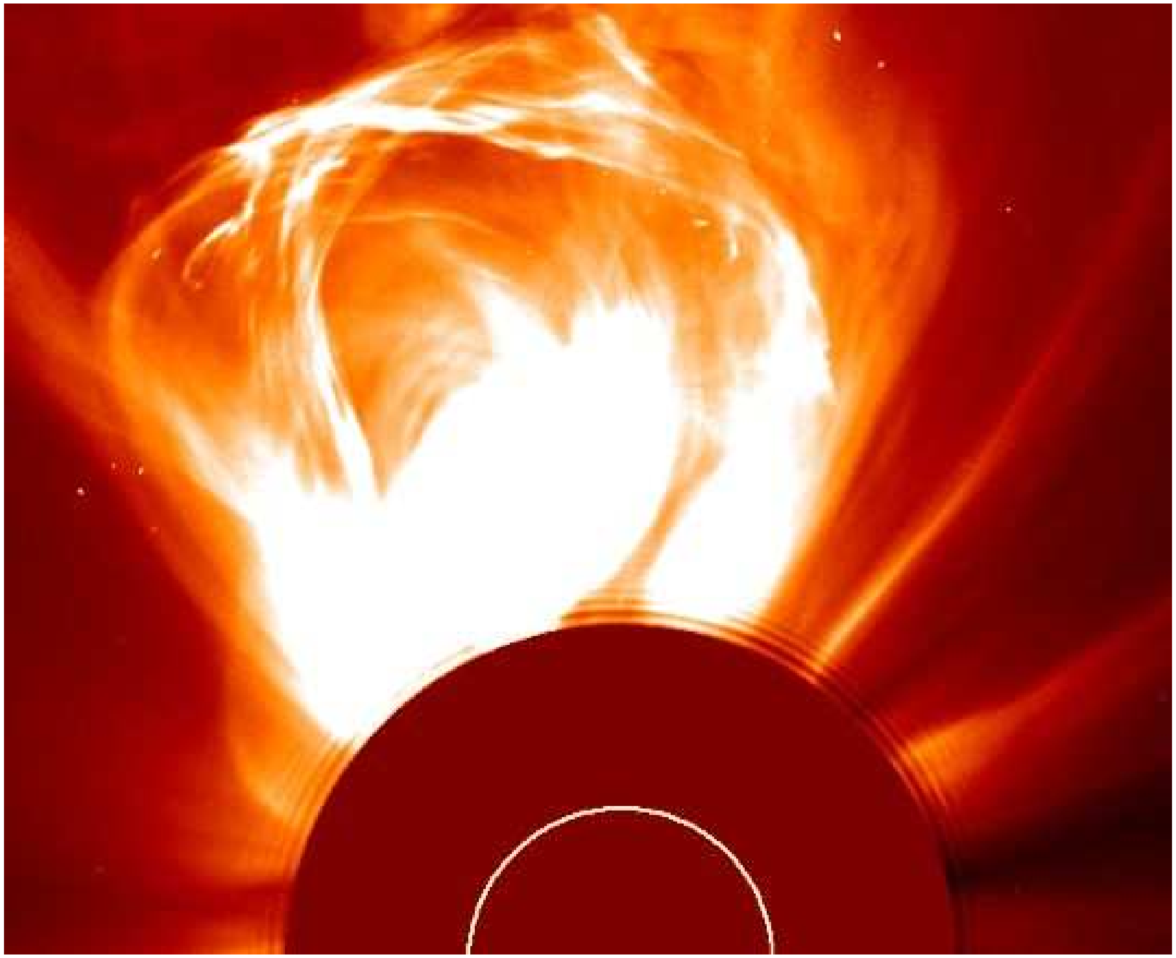
Solar and Heliospheric
SH.1: SOLAR EMISSIONS
SH.2: ACCELERATION AND PROPAGATION IN THE HELIOSPHERE
SH.3: GALACTIC COSMIC RAYS IN THE HELIOSPHERE

Origin and Galactic
OG.1: LOW ENERGY COSMIC RAYS
OG.2: X-RAY, GAMMA-RAY AND NEUTRINO ASTRONOMY AND ASTROPHYSICS

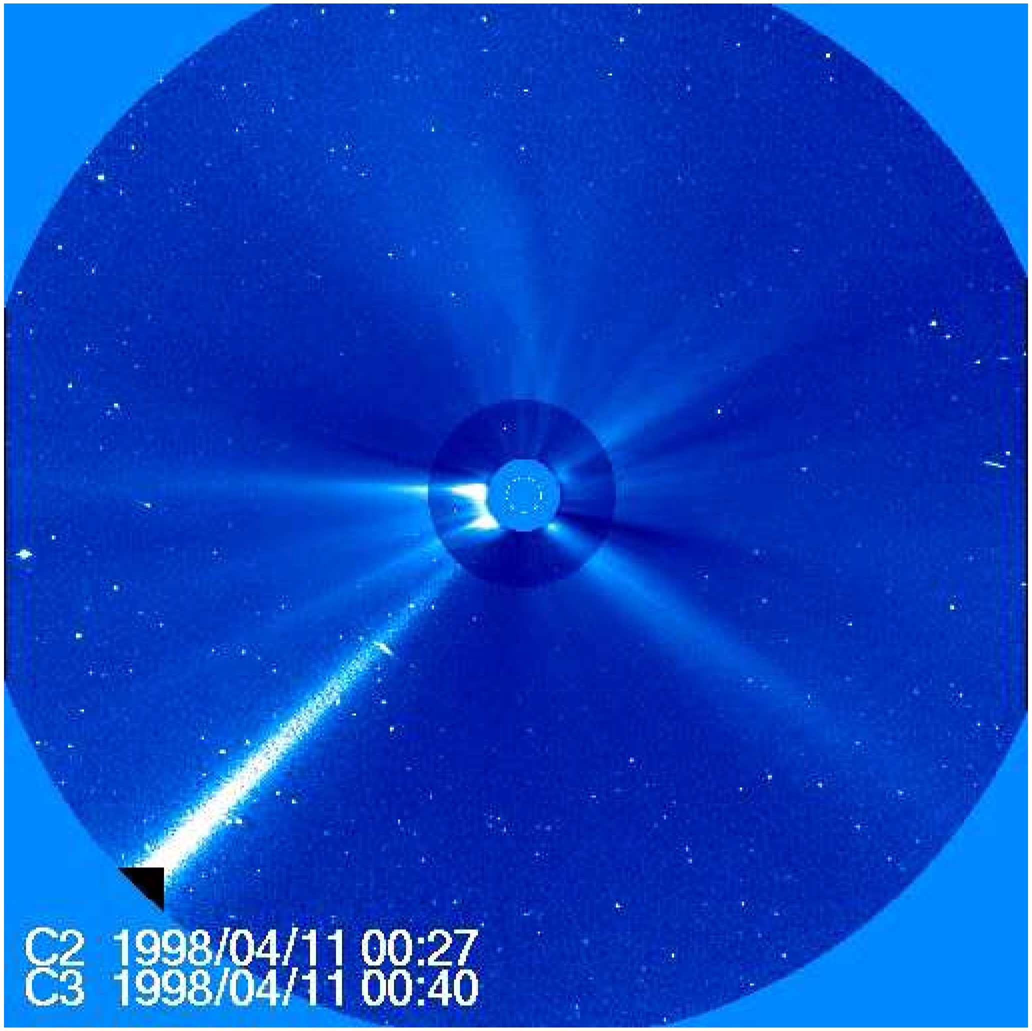
High Energy
HE.1: HIGH ENERGY COSMIC RAYS – EAS
HE.2: PARTICLE PHYSICS, ASTRO-PARTICLE PHYSICS AND COSMOLOGY

Solar flare shock acceleration

Coronal mass ejection
09 Mar 2000



Movie: LASCO on SOHO

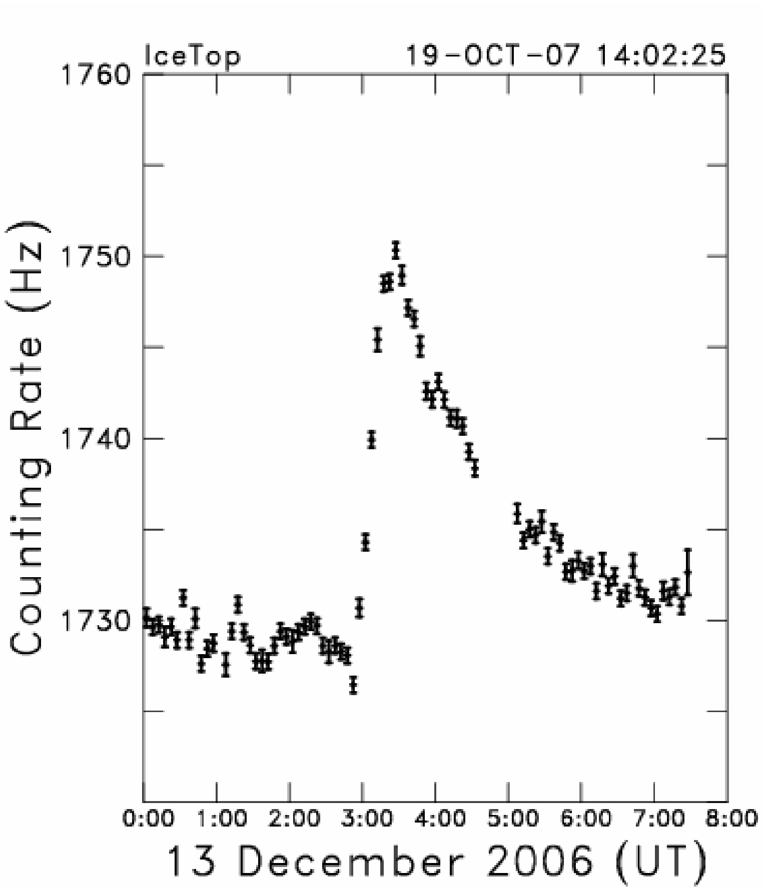


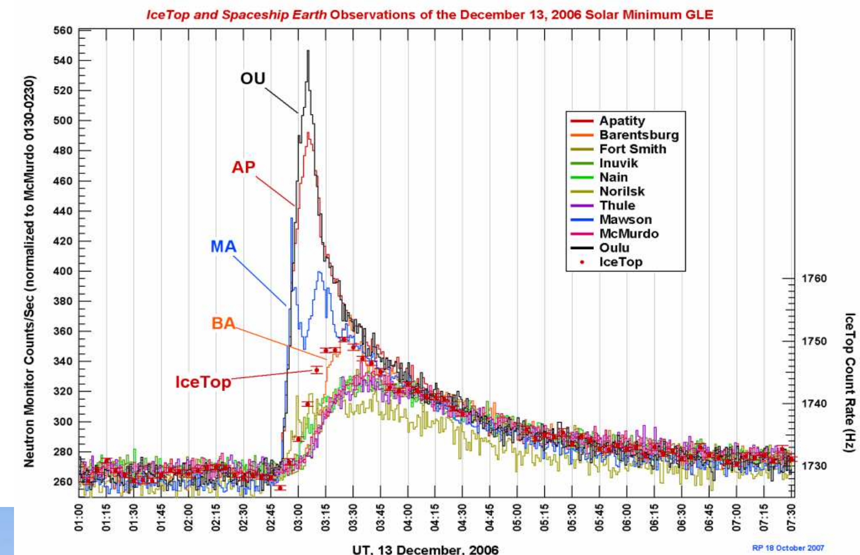
Movie from LASCO instrument on SOHO

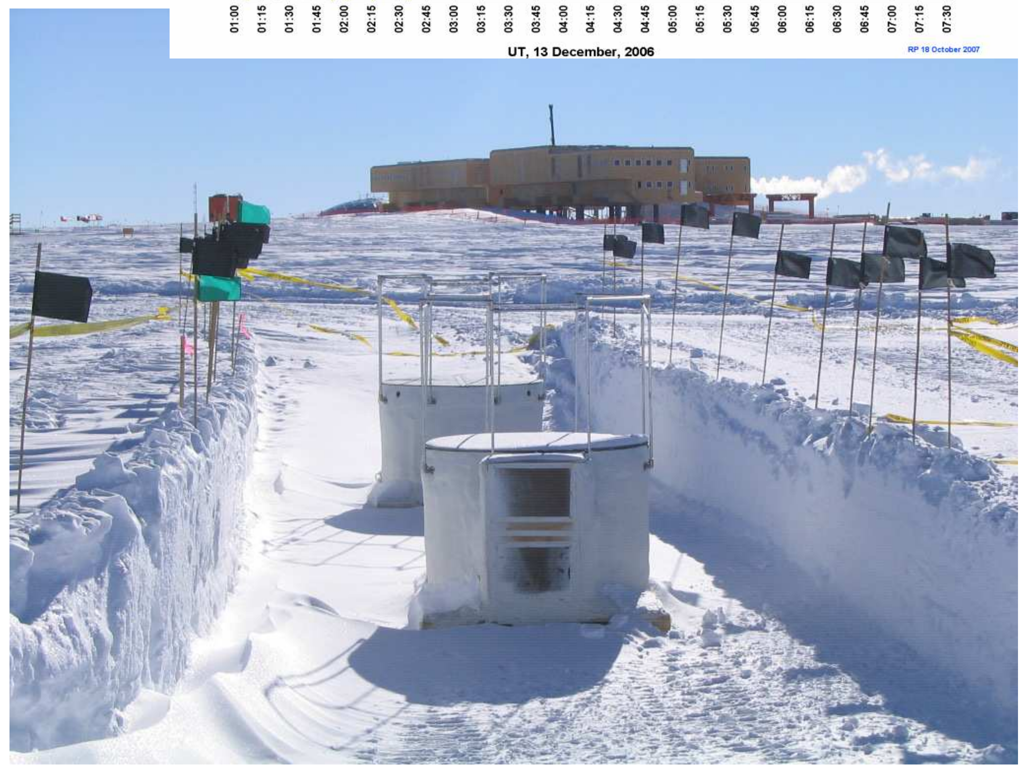
1998 April 11 - 20: An interesting period:
Between April 10 and April 13, a comet enters the field of view from the left (East) and passes around the Sun.
On April 10-11, a smaller sun-grazing comet approaches the Sun from the south, just to the right of the occulter pylon.
The period culminates in a fast CME associated with a high energy particle storm at SOHO

13 Dec 2006 solar flare: GLE in IceTop

With 32 tanks in 2006

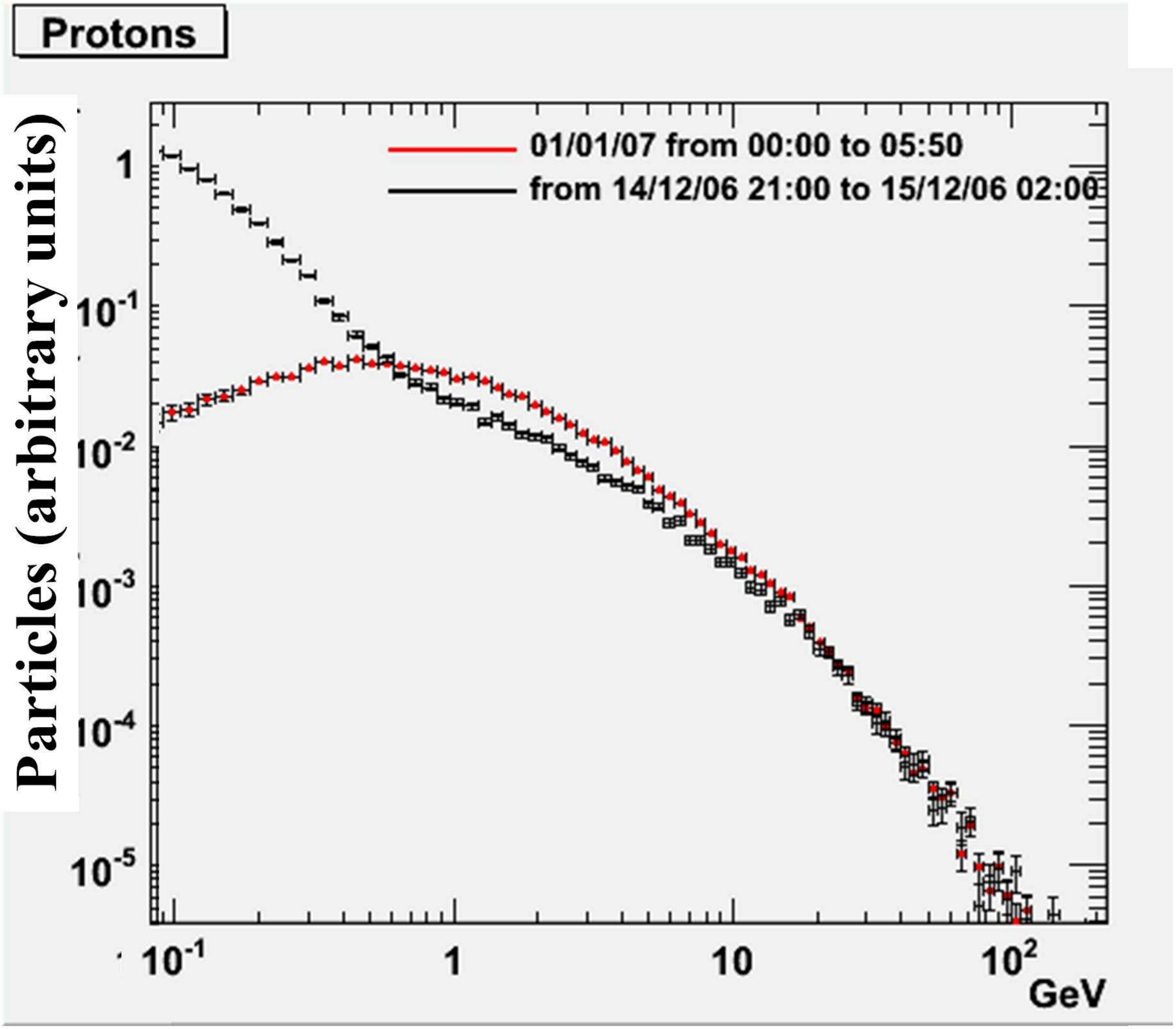






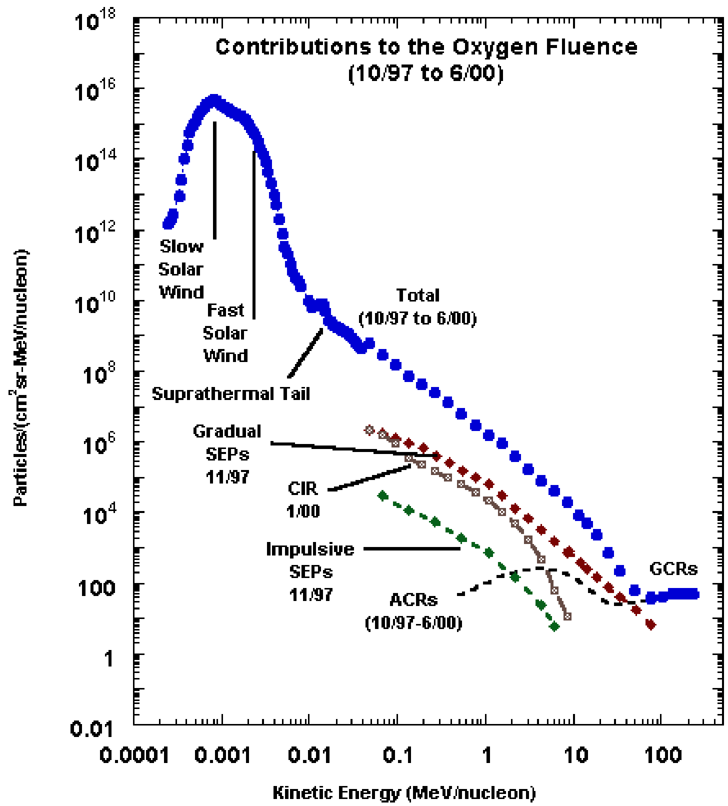
Ap. J. (Letters) 689 (2008) L65-L68

Solar flare


Protons
Particles (arbitrary units)
01/01/07 from 00:00 to 05:50
from 14/12/06 21:00 to 15/12/06 02:00
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-1}
1
10
10^{2}
GeV

Lessons from the heliosphere

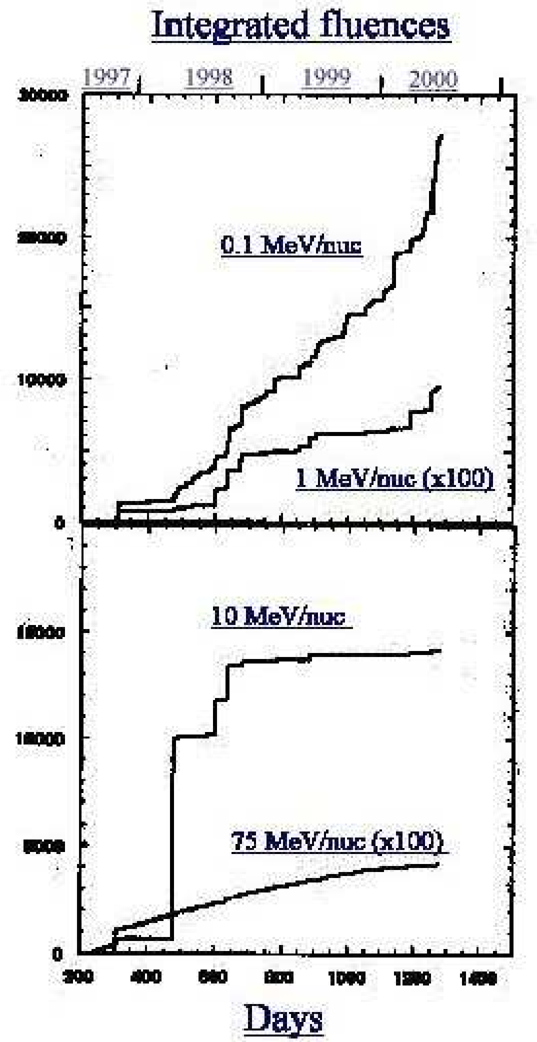
- ACE energetic particle fluences:
- Smooth spectrum
  – composed of several distinct components:
    - Most shock accelerated
    - Many events with different shapes contribute at low energy (< 1 MeV)
    - Few events produce ~10 MeV
  – Knee ~ Emax of a few events
  – Ankle at transition from heliospheric to galactic cosmic rays



R.A. Mewaldt *et al.*, A.I.P. Conf. Proc. 598 (2001) 165

Heliospheric cosmic rays

- ACE--Integrated fluences:
  - Many events contribute to low-energy heliospheric cosmic rays;
  - fewer as energy increases.
  - Highest energy (75 MeV/nuc) is dominated by low-energy *galactic* cosmic rays, and this component is again *smooth*



R.A. Mewaldt *et al.*, A.I.P. Conf. Proc. 598 (2001) 165

Galactic cosmic rays

Measurements from **TRACER**, BESS and others

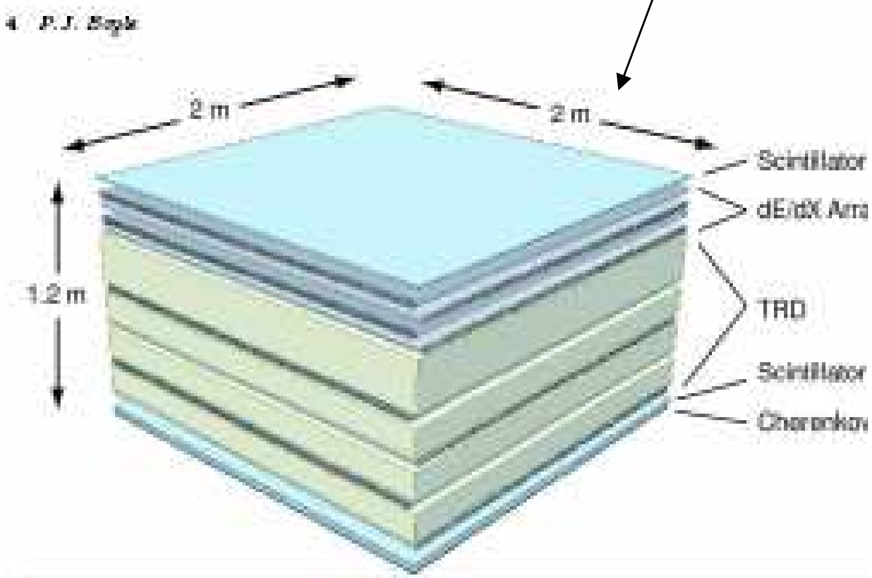


Fig. 2. Schematic diagram of the TRACER detector as flown during the Antarctic balloon campaign in 2003. [From Ave et al.]

The Elemental Composition of High-Energy Cosmic Rays: Measurements with TRACER 5

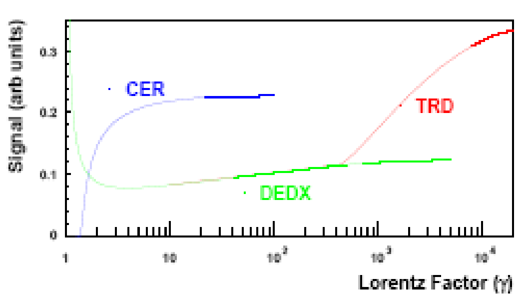


Fig. 3. Energy scale of TRACER. TRACER combines three energy measurements to cover more than 4 decades in energy. The relative amplitude of the response curves is representative of the signal/Z^2 in each detector [From Ave et al.]

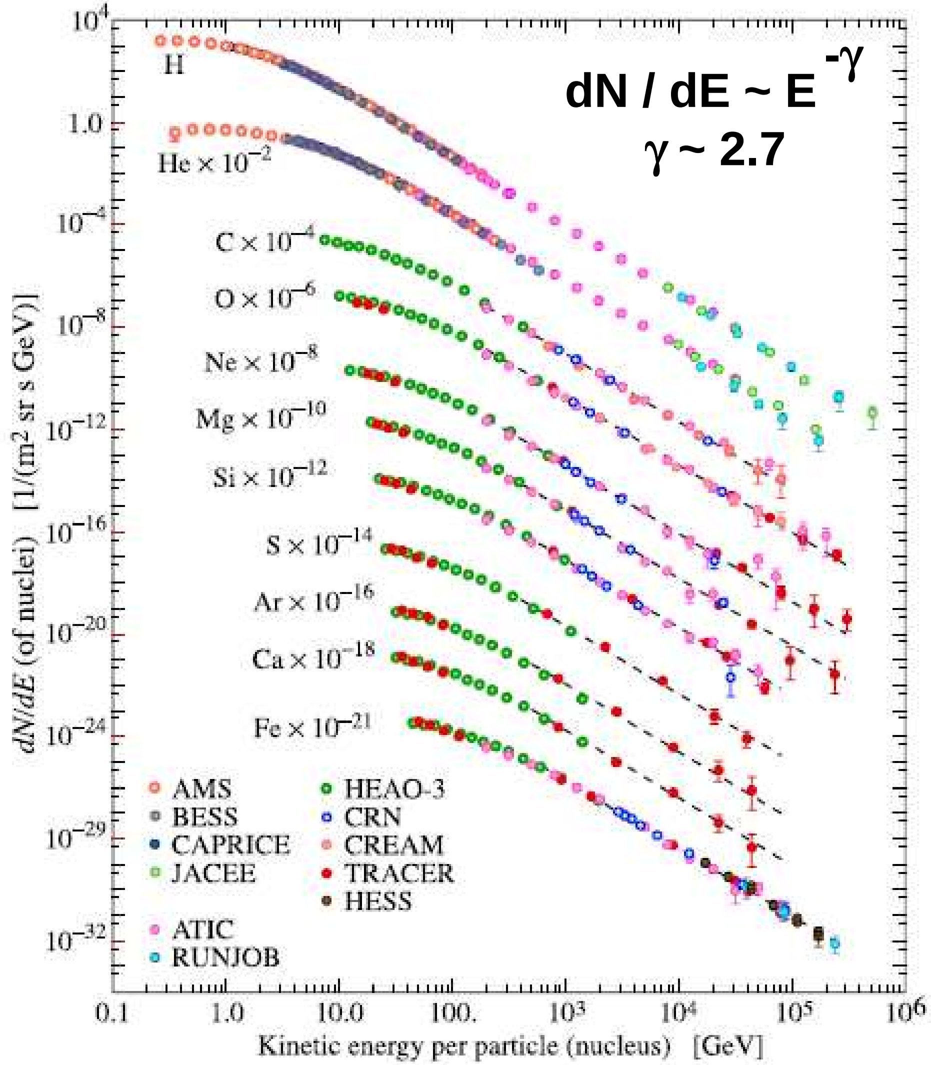
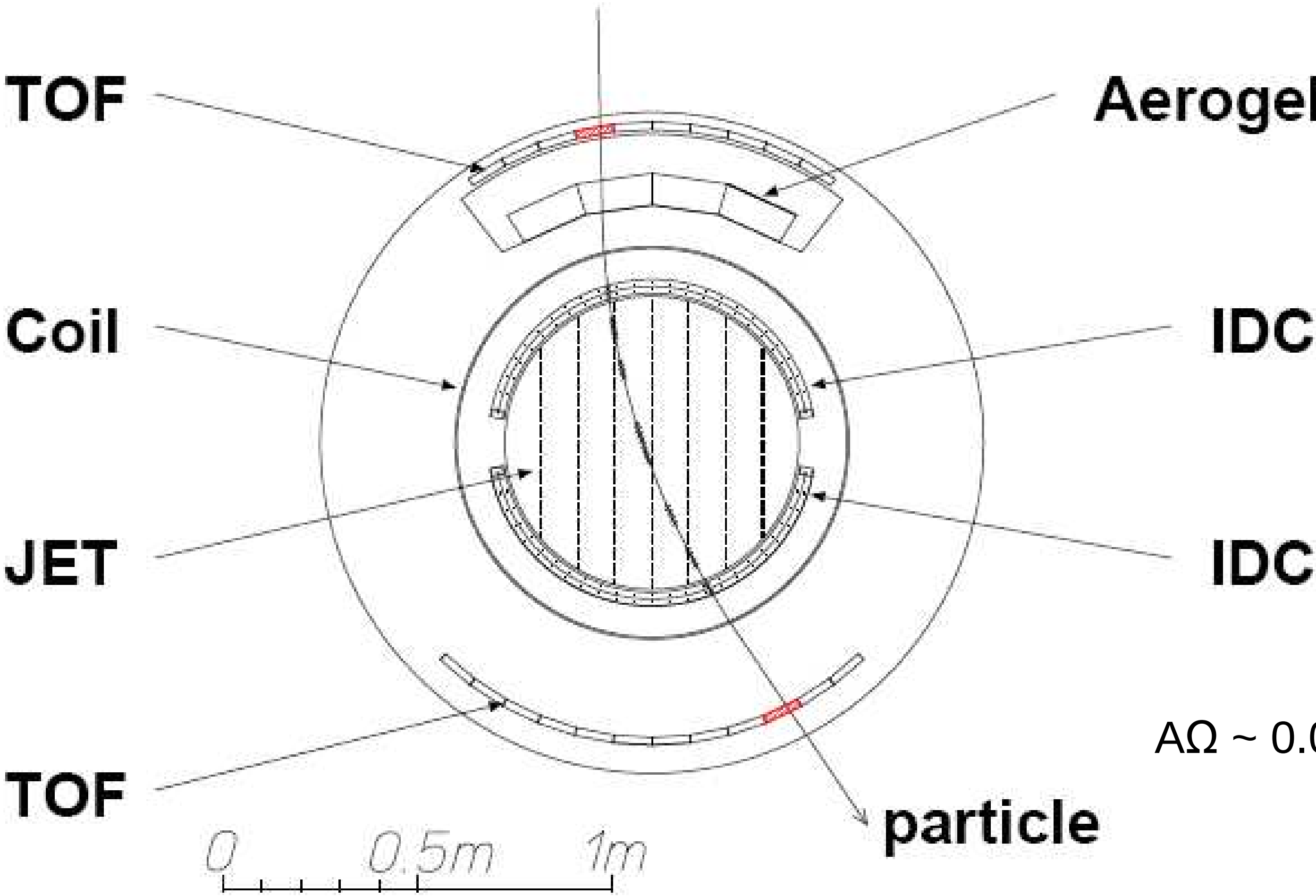


Figure by P. Boyle & D. Müller in RPP

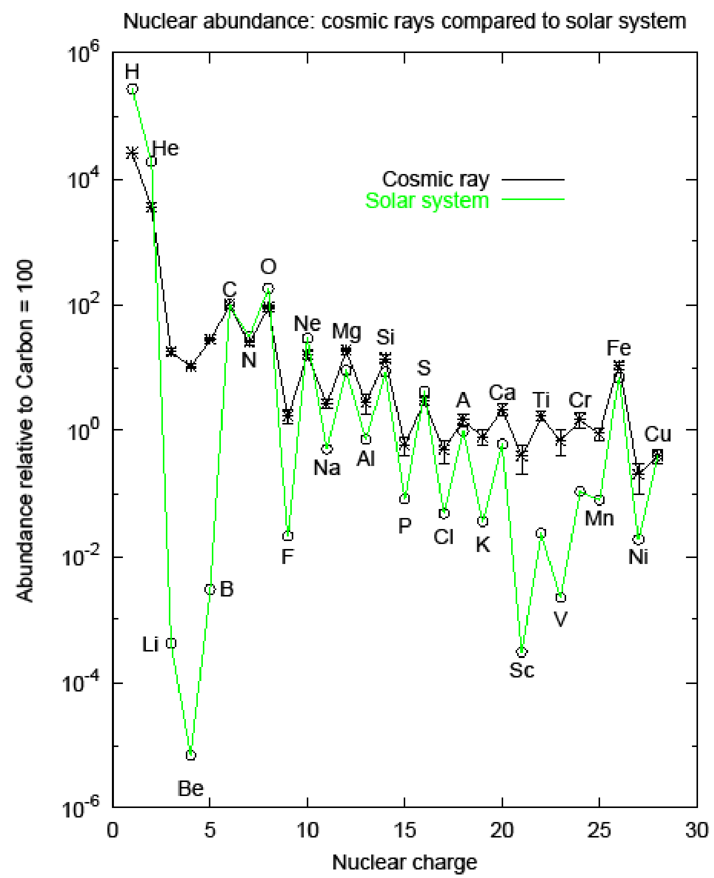
BESS spectrometer



AΩ ~ 0.085 m^2 sr

A fundamental result

- Excess of Li, Be, B from fragmentation of C, O
- Spallation σ plus ρ_{ISM} give dwell time of nuclei
  - Find $\tau \sim 3 \times 10^6$ yrs
  - $c\tau \sim$ Mpc >> size of galactic disk (kpc)
  - Suggests diffusion in turbulent ISM plasma
  - Predictions for γ-rays, positrons and antiprotons follow



Energy-dependence of secondary/primary cosmic-ray nuclei

- B/C ~ $E^{-0.6}$
- Observed spectrum:
  - $\phi(E) = dN/dE \sim K\, E^{-2.7}$
- Interpretation:
  - Propagation depends on E
  - $\tau(E) \sim E^{-0.6}$
  - $\phi(E) \sim Q(E) \times \tau(E) \times (c/4\pi)$
- Implication:
  - Source spectrum:

$$Q(E) \sim E^{-2.1}$$

No. 1, 1987 COSMIC-RAY PROPAGATION

B / C

sub-Fe / Fe

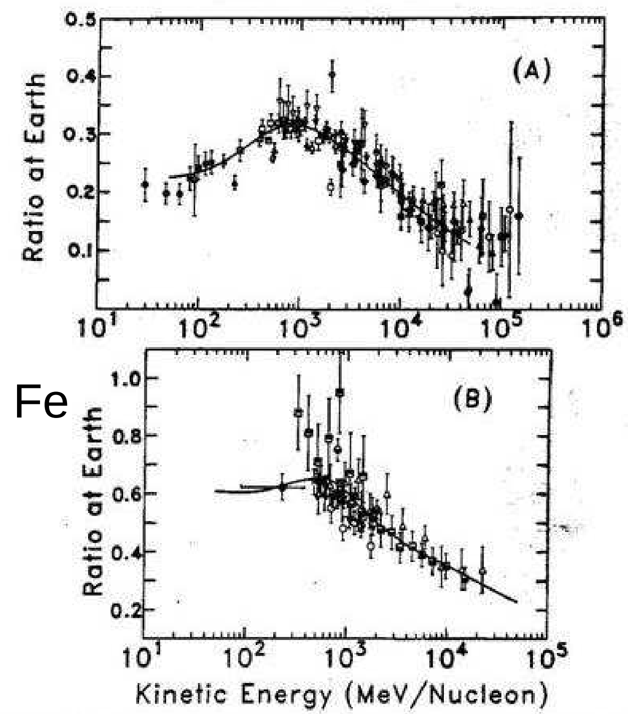


FIG. 10.—The ratios (a) B/C and (b) sub-Fe/Fe of Fig. 2 compared with the results of a propagation calculation using a path-length includes an energy-dependent deficiency of short path lengths as well as an energy-dependent mean for the exponential part of the distrit for details.)

Garcia-Munoz, Simpson, Guzik, Wefel & Margolis, Ap. J. 64 (1987) 269

Secondary / primary ratios from CREAM

arXiv: 0808.1718

- B is entirely secondary
- Source is production in ISM
- Spectral index at production is same as observed (propagated) primary nuclei
- Therefore observed spectral of B is 2.7 + δ = 2.1 + 2δ ~3.3

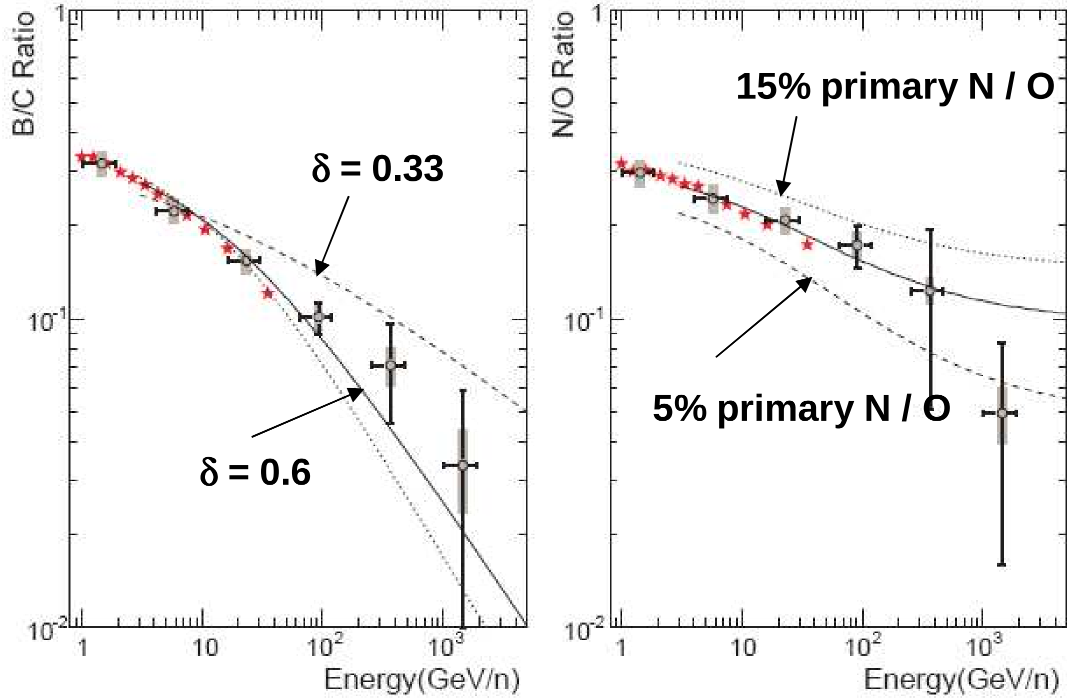
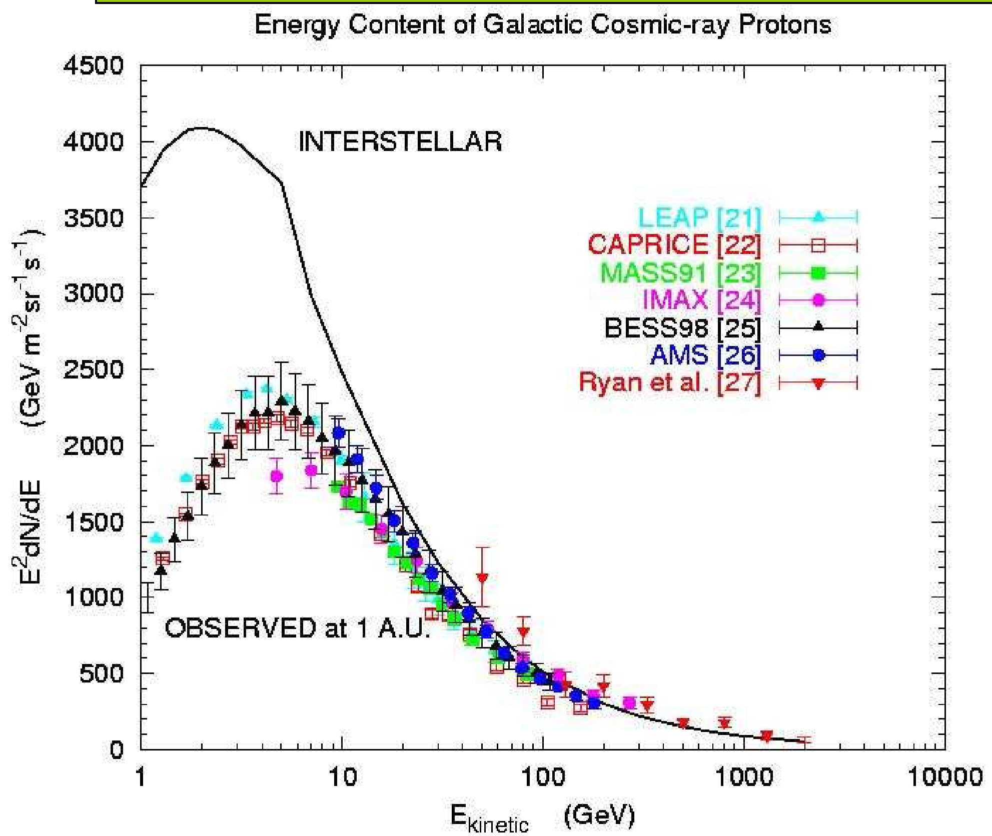


Fig. 7. Measurements of the ratios of nuclei as a function of energy. Left: Filled circles show the ratio of boron to carbon vs. energy after corrections. The horizontal errors are an estimate of the systematic error in the overall energy scale. The thin vertical lines correspond to the statistical error of the ratio and the grey bars show the systematic uncertainty in the ratio. See text for details. The lines represent model calculations for various values of the magnetic-rigidity dependence parameter, δ, in escape from the Galaxy - as discussed in the text. These are; solid line δ=0.6, long-dashed line δ=0.333, short-dashed line δ=0.7. The stars are data from the space experiment, HEAO-3-C2[5]. Right: Filled circles show the ratio of nitrogen to oxygen vs. energy after corrections. The error bars and data points are as in the left panel. The lines represent model calculations of this ratio with the escape parameter δ=0.6 (solid line in the top left-hand panel). The different curves correspond to different assumptions on the amount of nitrogen in the source material. These are; solid line source N/O = 10%, long-dashed line source N/O = 5%, short-dashed line N/O = 15%.

Energetics of cosmic rays

- Total local energy density:
  - $(4\pi/c) \int E\phi(E)\, dE$
    $\sim 10^{-12}$ erg/cm^3 $\sim B^2 / 8\pi$
- Power needed:
  $(4\pi/c) \int E\phi(E) / \tau_{esc}(E)\, dE$
  galactic $\tau_{esc} \sim 10^7\, E^{-0.6}$ yrs
  Power $\sim 10^{-26}$ erg/cm^{3}s
- Supernova power:
  10^{51} erg per SN
  ~3 SN per century in disk
  $\sim 10^{-25}$ erg/cm^{3}s
- SN model of galactic CR
  Power spectrum from shock acceleration, propagation

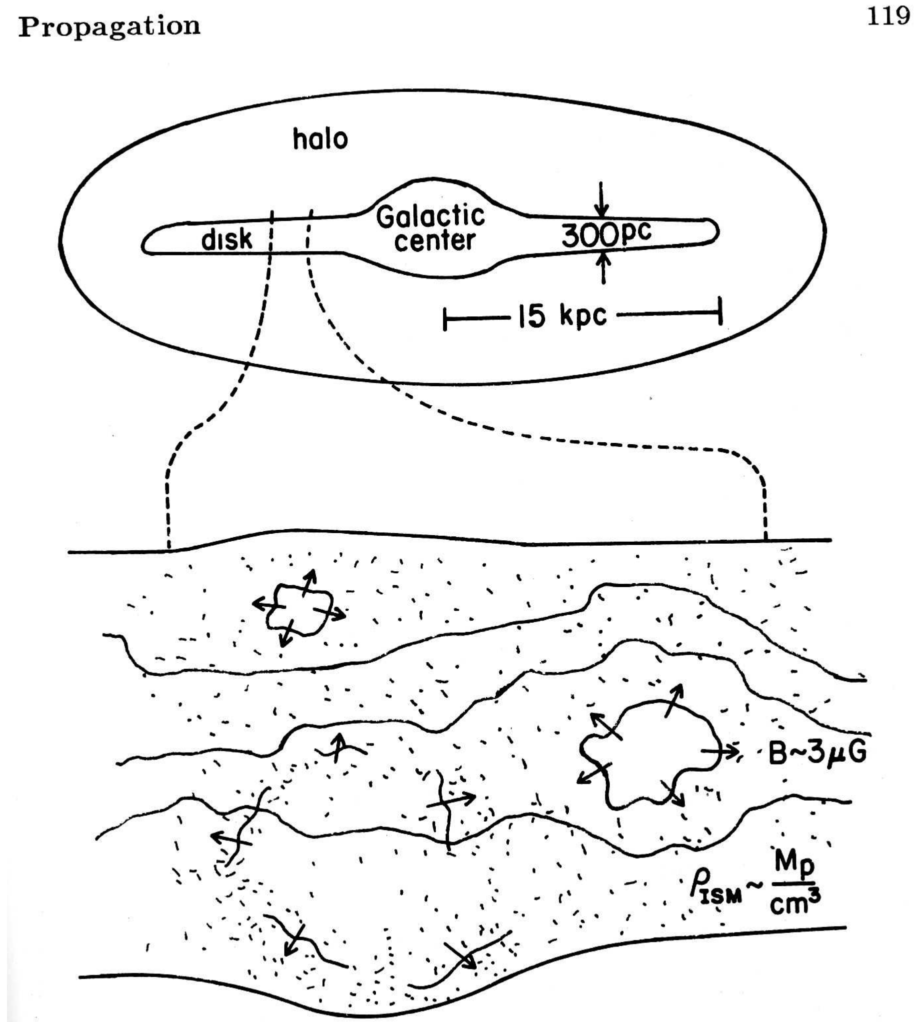
Spectral Energy Distribution
(linear plot shows most E < 100 GeV)
$(4\pi/c)\, E\phi(E)$ = local differential CR energy density



Cosmic rays in the Galaxy

- Supernova explosions energize the ISM
  - ~1% Kinetic energy;

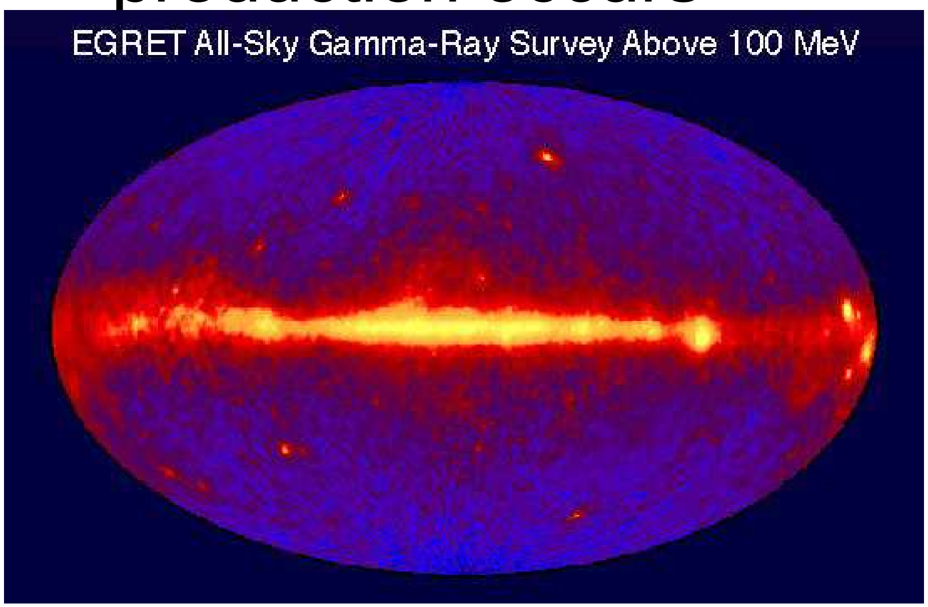
    neutrinos ~ 99%
  - >10% of kinetic energy → CR acceleration
  - Energy density in CR ~ $B^2/8\pi$
  - SN & CR activity drives Galactic wind into halo (Parker)
  - CR diffuse in larger volume
  - Eventually escape Galaxy



Diffuse galactic secondaries

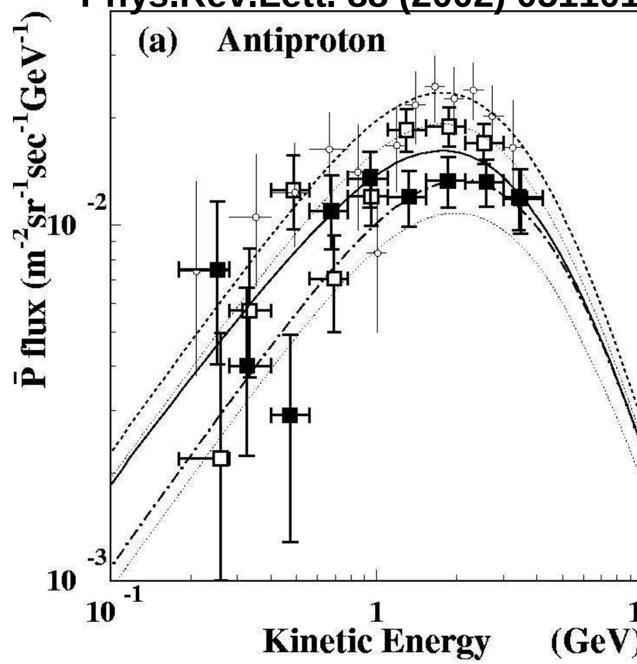
p + gas → π^0, $\pi^{+/-}$, antiprotons

- $\pi^0 \rightarrow \gamma\,\gamma$ [$\pi^{+/-} \rightarrow \nu, \mu \rightarrow e^{+/-}$]
- γ-spectrum depends on where production occurs



Before Fermi & PAMELA

Phys.Rev.Lett. 88 (2002) 051101

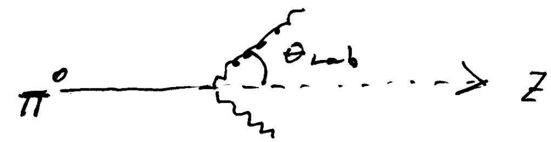


BESS antiprotons, 1997, ’99, ’00.
- Fully consistent with secondary production by collisions in ISM followed by solar modulation varying with solar cycle

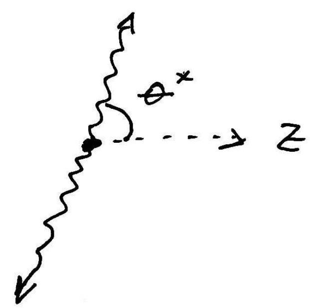
Kinematics of π^0 decay

$\pi^0 \rightarrow \gamma\gamma$ decay in flight, direction = z axis

$$\frac{dN_\gamma}{d\Omega} = \frac{1}{2\pi}\frac{dN_\gamma}{d\cos\theta^*} = \text{constant}$$



In rest frame of π^0



$$E_{Lab} = \gamma E^* + \beta\gamma p^* \cos\theta^*$$

$$p^* = E^* = \frac{m_{\pi^0}}{2} = 70 \text{ MeV}$$

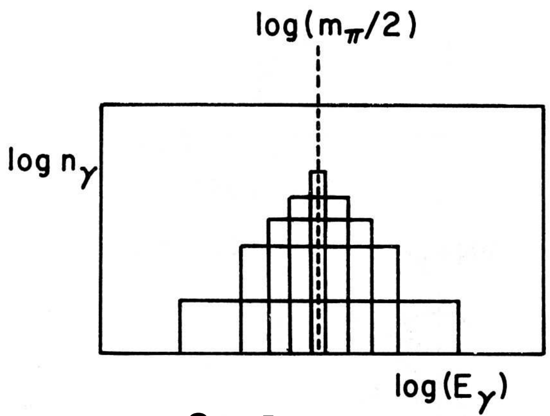
$$(1-\beta)\gamma\frac{m_\pi}{2} \le E_{Lab} \le (1+\beta)\gamma\frac{m_\pi}{2} \Rightarrow \frac{m_\pi}{2}\sqrt{\frac{1-\beta}{1+\beta}} \le E_\gamma \le \frac{m_\pi}{2}\sqrt{\frac{1+\beta}{1-\beta}}$$

Thus $\ln\frac{m_\pi}{2} - \frac{1}{2}\ln\frac{1+\beta}{1-\beta} \le \ln E_\gamma \le \ln\frac{m_\pi}{2} + \frac{1}{2}\ln\frac{1+\beta}{1-\beta}$

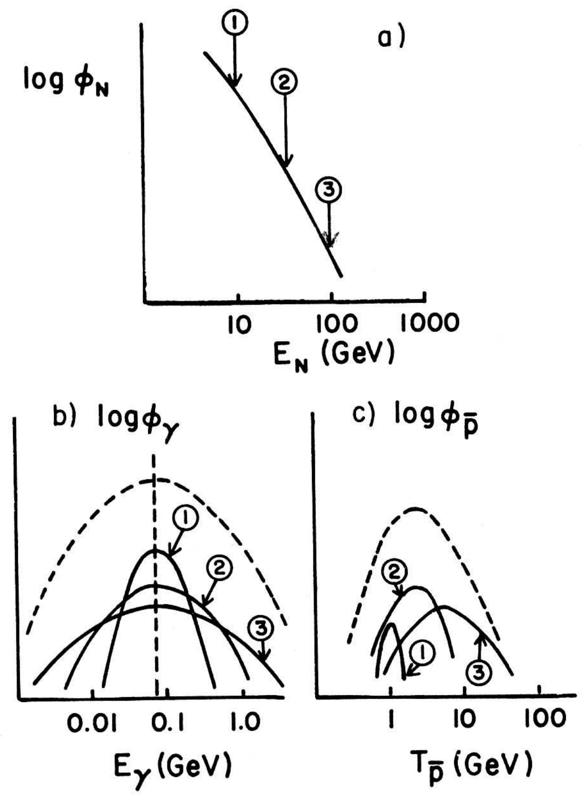
E

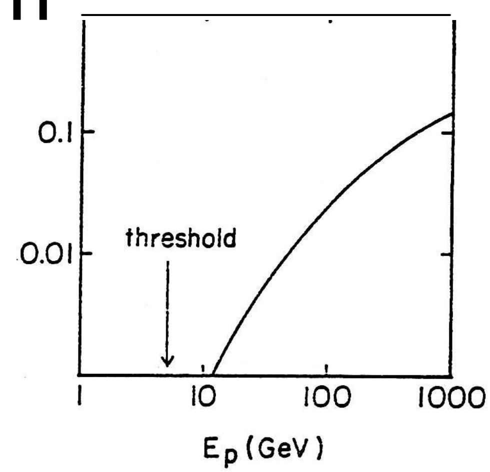
Flat distribution for fixed E_π with $\langle \ln E_\gamma \rangle = \frac{m_\pi}{2}$

Constructing secondary spectrum from primary spectrum



$\pi^0 \rightarrow \gamma\,\gamma$





$\bar{p}$ per proton interaction

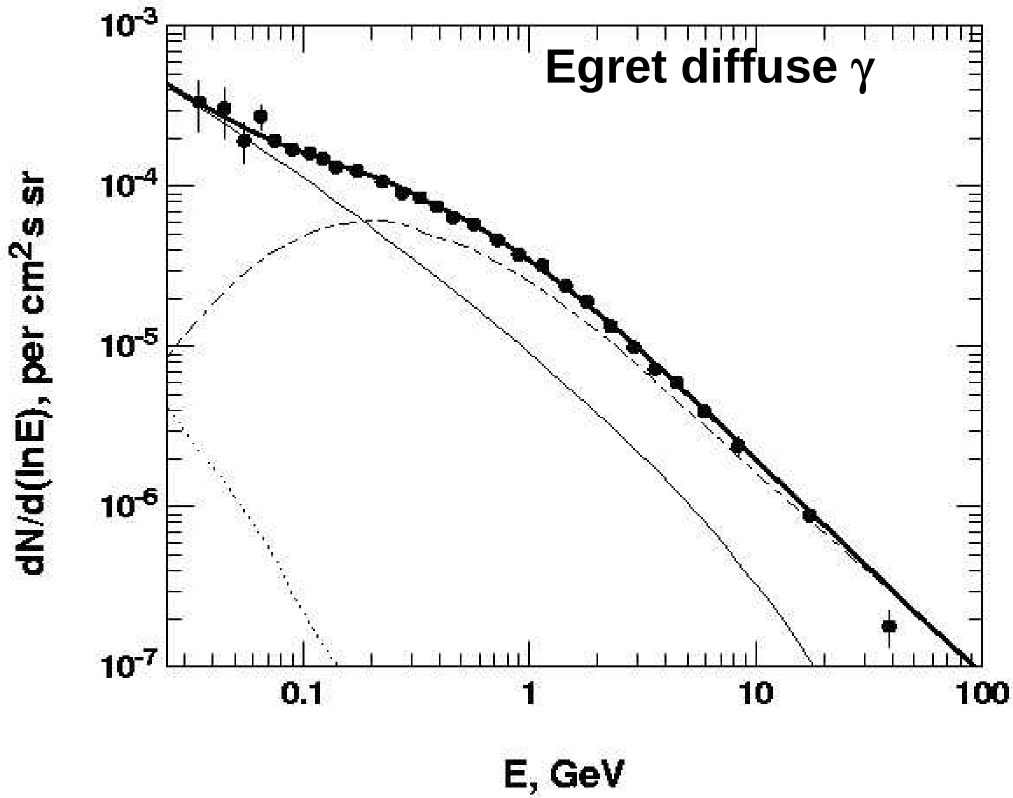
p p $\rightarrow$ π^0 + anything

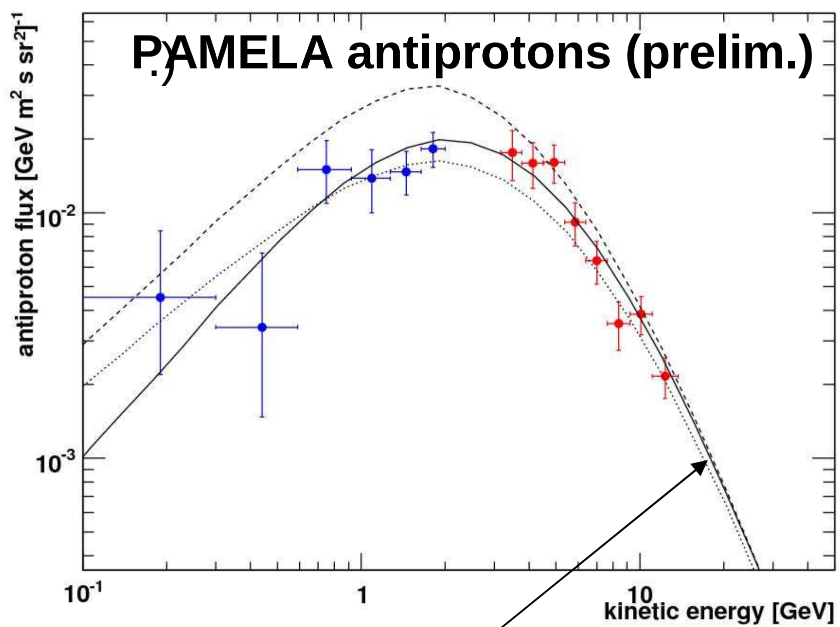
$\gamma\,\gamma$

p p $\rightarrow$ $\bar{p}$ + anything

Are all photons and $\bar{p}$ produced in ISM?

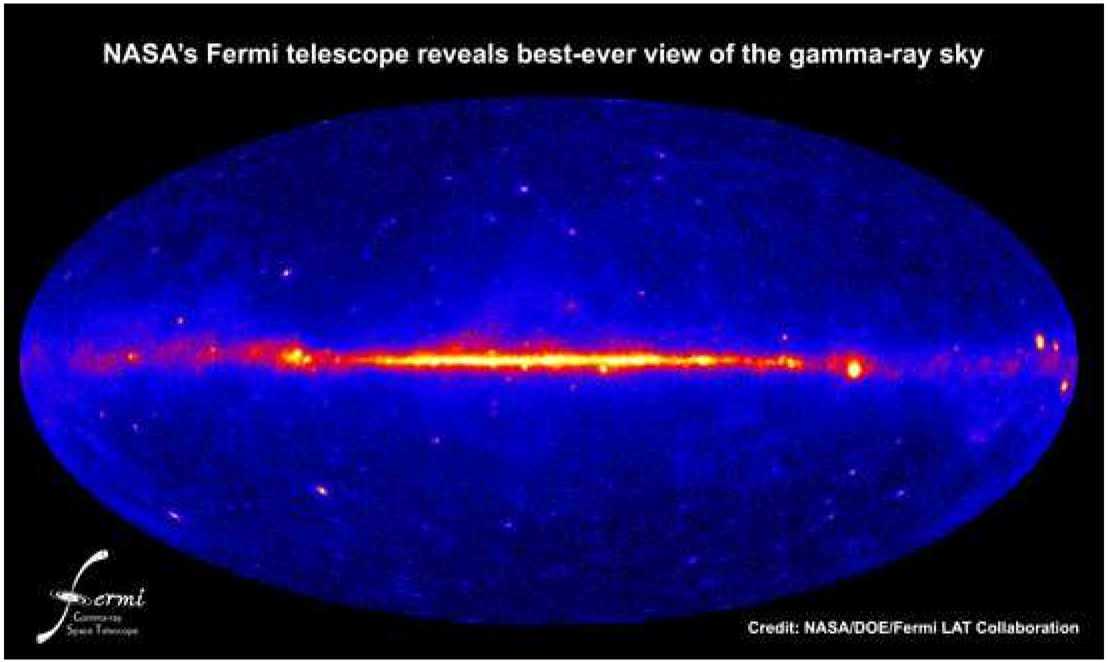
A fraction may be produced in the sources

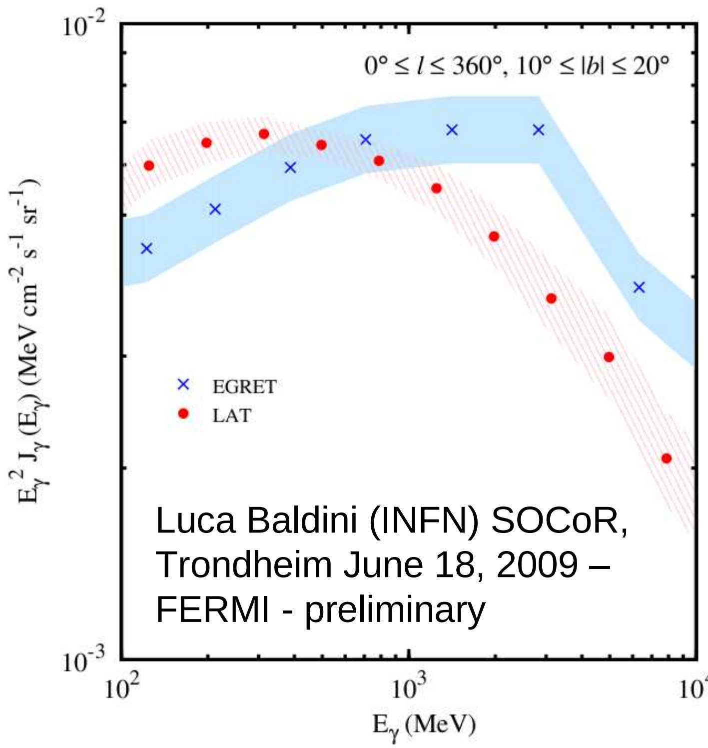




<u>Secondary production:</u>
V. S. Ptuskin et al, ApJ 642 (2006) 902

Diffiuse gamma-rays from FERMI

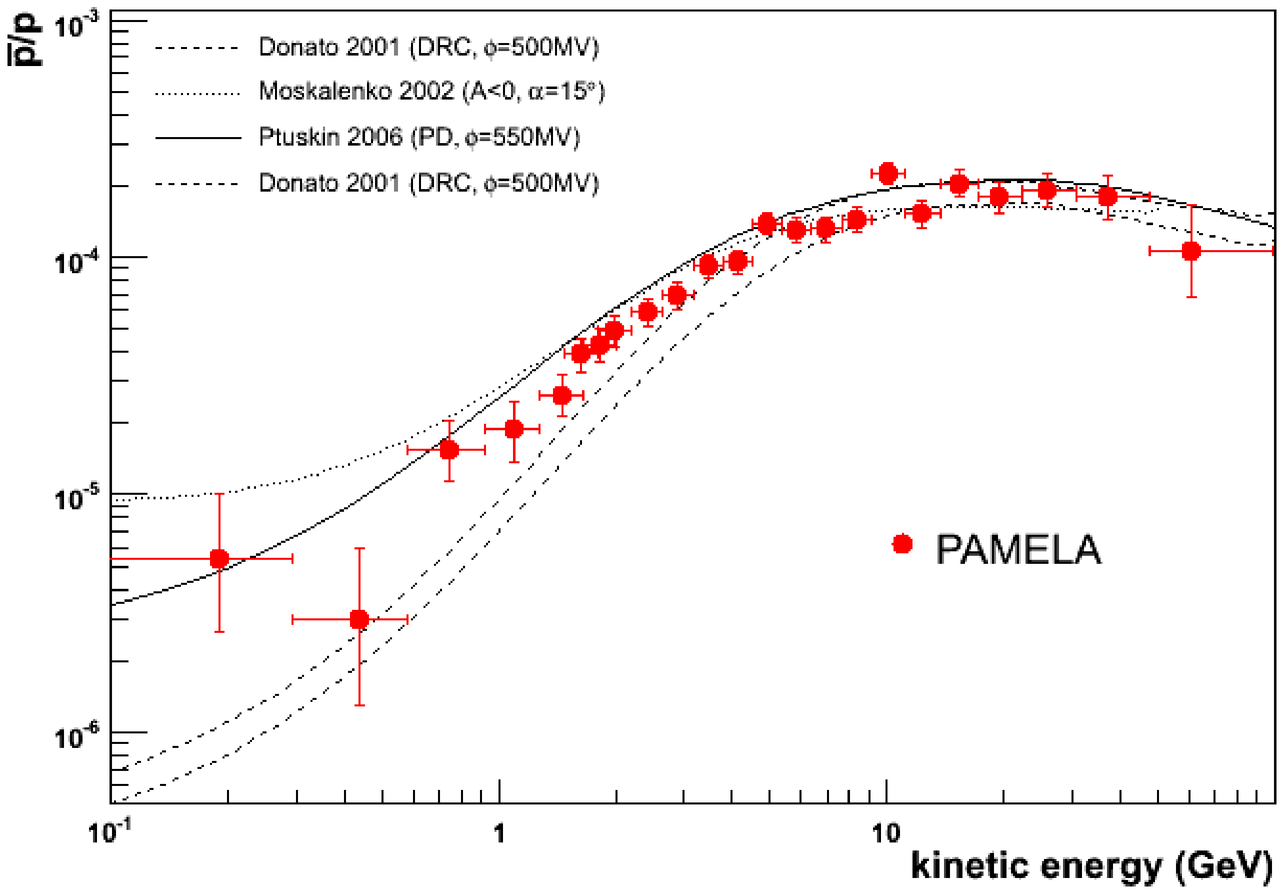




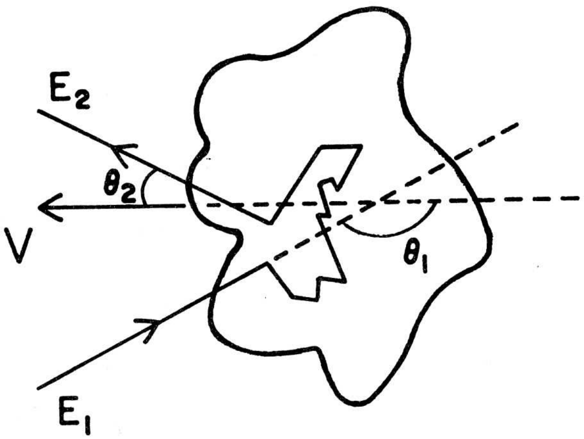
Antiproton to proton ratio

PRL 102, 051101 (2009)

Seconday Production Models



Acceleration



Fermi acceleration mechanism:

Transfer macroscopic energy of turbulent magnetized plasma to individual charged particles

Essential assumption: $\Delta E = \xi E$

energy gain per encounter $\propto$ Energy of particle.

After n encounters $E_n = E_0 (1+\xi)^n$

P_{esc} = probability per cycle of particle being lost from acceleration region.

$n = \ln \frac{E}{E_0} / \ln(1+\xi)$ needed to reach E

Probability of surviving n cycles $= (1 - P_{esc})^n$

$$N(\geq E) = \sum_{m=n}^{\infty} (1 - P_{esc})^m = \frac{(1 - P_{esc})^n}{P_{esc}}$$

where $n = \ln \frac{E}{E_0} \Big/ \ln(1+\xi)$

$$N(\geq E) = \frac{1}{P_{esc}} \exp\left\{ \ln \frac{E}{E_0} \times \frac{\ln(1 - P_{esc})}{\ln(1+\xi)} \right\}$$

$$= \frac{1}{P_{esc}} \left(\frac{E}{E_0} \right)^{-\gamma}, \quad \gamma = \frac{\ln \frac{1}{1-P_{esc}}}{\ln(1+\xi)} \sim \frac{P_{esc}}{\xi}$$

→ γ = integral spectral index of power-law spectrum

$P_{esc} \sim \frac{T_{cycle}}{T_{esc}}$ (from escape acceleration region)

After a time t, $n_{max} = t/T_{cycle}$

→ so $E \leq E_0 (1+\xi)^{t/T_{cycle}}$

"Scattering" = multiple bending in moving turbulent magnetic fields

= "collisionless" scattering

one "encounter" occurs when particle loses all memory of the direction with which it entered the scattering region

one cycle occurs when particle leaves the scattering region but is still available for another cycle of acceleration.

$$E_1' = \gamma E_1 (1 - \beta \cos\theta_1)$$ after randomization inside scattering region

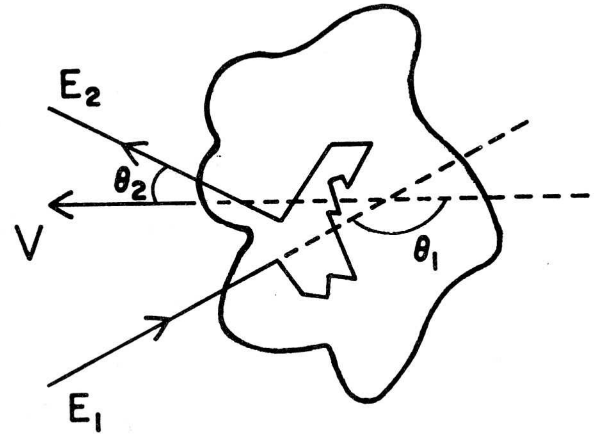
$$E_2' = E_1'$$ because motion in magnetic field does not change energy

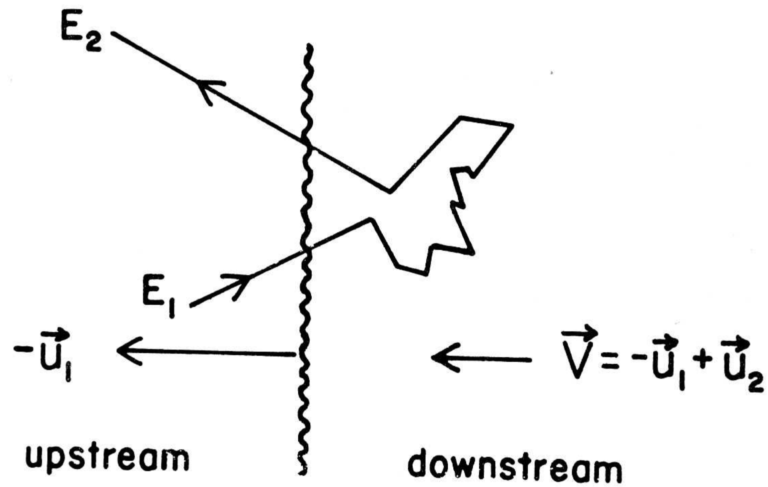
$$E_2 = \gamma E_2' (1 + \beta \cos\theta_2)$$

$$\frac{E_2 - E_1}{E_1} = \frac{\Delta E}{E} = \frac{1 - \beta\cos\theta_1 + \beta\cos\theta_2 - \beta^2\cos\theta_1\cos\theta_2}{1-\beta^2} - 1$$

Note: ΔE for a single encounter may be + or − depending on $\cos\theta_1$ or $\cos\theta_2$

Next step is to average over $\cos\theta_2$ and $\cos\theta_1$





Distribution of exit angles ($\cos\theta_2$)

$$\text{(a)} \quad \frac{\mathrm{d}n}{\mathrm{d}\cos\theta_2'} = \text{constant}, \quad -1 \le \cos\theta_2' \le 1,$$

$\cos\theta_2$ averages to 0 so

$$\text{(a)} \quad \frac{\langle\Delta E\rangle_2}{E_1} = \frac{1 - \beta\cos\theta_1}{1 - \beta^2} - 1$$

Distribution of entrance angles ($\cos\theta_1$):

$$\frac{\mathrm{d}n}{\mathrm{d}\cos\theta_1} = \frac{c - V\cos\theta_1}{2c}, \quad -1 \le \cos\theta_1 \le 1,$$

$\cos\theta_1$ averages to -V / 3c so

$$\text{(a)} \quad \xi = \frac{1 + \frac{1}{3}\beta^2}{1 - \beta^2} - 1 \sim \frac{4}{3}\beta^2$$

$$\text{(b)} \quad \frac{\mathrm{d}n}{\mathrm{d}\cos\theta_2'} = 2\cos\theta_2', \quad 0 \le \cos\theta_2' \le 1.$$

$\cos\theta_2$ averages to 2/3 so that

$$\text{(b)} \quad \frac{\langle\Delta E\rangle_2}{E_1} = \frac{1 - \beta\cos\theta_1 + \frac{2}{3}\beta - \frac{2}{3}\beta^2\cos\theta_1}{1 - \beta^2} - 1.$$

$$-1 \le \cos\theta_1 \le 0, \quad \text{so that } \langle\cos\theta_1\rangle_{\mathbf{b}} = -2/3$$

then

$$\text{(b)} \quad \xi = \frac{1 + \frac{4}{3}\beta + \frac{4}{9}\beta^2}{1 - \beta^2} - 1 \sim \frac{4}{3}\beta = \frac{4}{3}\frac{u_1 - u_2}{c}.$$

Recall γ spectral index $= P_{esc}/\xi = \frac{1}{\xi}\frac{T_{cycle}}{T_{esc}}$

For clouds (2nd order Fermi) $T_{cycle} = \frac{1}{c\,\rho_c\,\sigma_c}$

ρ_c = density of clouds

σ_c = area of clouds

c = velocity of cosmic ray

$T_{esc} \sim 7 \times 10^6$ yrs.

$\gamma = \frac{1}{\xi\, c\, \rho_c\, \sigma_c\, T_{esc}}$ is model dependent

For 1st order Fermi (large shock)

#1 rate of encounters $= \int_0^1 d\cos\theta \cos\theta \int_0^{2\pi} d\phi \frac{c\,\rho_{CR}}{4\pi} = \frac{c\,\rho_{CR}}{4}$

#2 rate of convection down stream $= \rho_{CR}\, u_2$

$$P_{esc} = \frac{\#2}{\#1} = \frac{\rho_{CR}\, u_2}{c\,\rho_{CR}/4} = 4\frac{u_2}{c}$$

$$\gamma = \frac{P_{esc}}{\xi} = \frac{4 u_2}{c} \times \frac{3}{4}\frac{c}{u_1 - u_2} = \frac{3}{u_1/u_2 - 1}$$

From kinetic theory of gas $\frac{u_1}{u_2} = \frac{\rho_2}{\rho_1} = \frac{(5/3+1)M^2}{(5/3-1)M^2+2}$

M = Mach number, $\frac{5}{3} = \frac{c_p}{c_v}$

$\frac{u_1}{u_2} \to 4$ for strong shocks and $\gamma \to 1$

$$\frac{dE}{dt} = \frac{\xi E}{T_{cycle}} = \text{acceleration rate}$$

Diffusion coefficient $D = \frac{1}{3} \lambda c$

$$T_{cycle} \sim \frac{\lambda}{u_1} \gtrsim \frac{r_L}{u_1} = \frac{E}{u_1 ZeB}$$

$$\frac{dE}{dt} \sim \xi u_1 ZeB = \frac{4}{3} \frac{u_1 - u_2}{c} u_1 ZeB$$

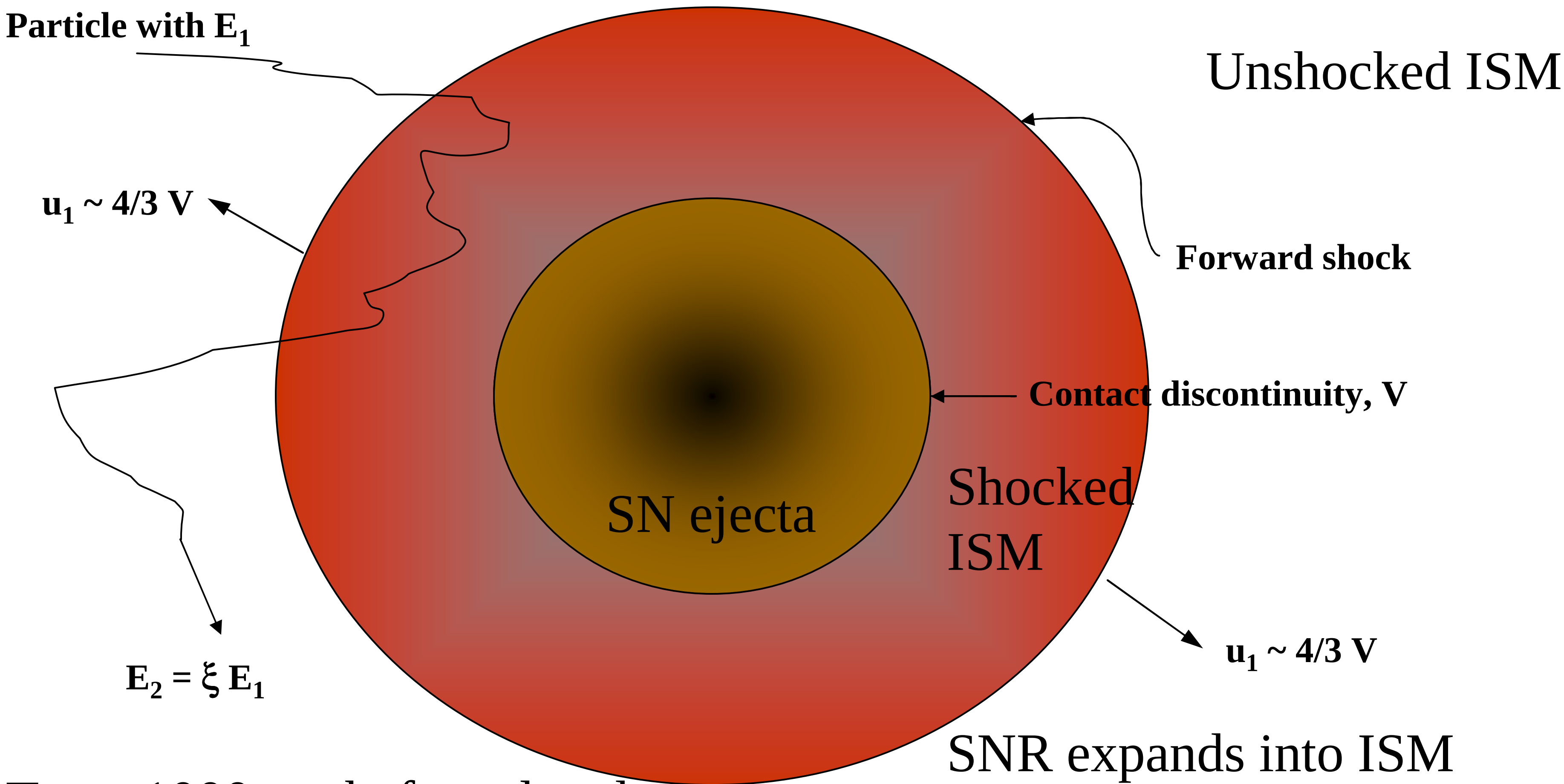
in time T

$$E_{max}(T) \sim \frac{4}{3} \frac{3}{4} \frac{u_1^2}{c} ZeBT$$

$$\frac{4}{3} \pi (u_1 T)^3 \rho_{ISM} = M_{ejecta} \sim \underbrace{2 \times 10^{34}}_{10 M_\odot} g \Rightarrow T \sim 1500 \text{ yrs}$$

$$E_{max} \sim 100 \text{ TeV}$$

Supernova blast wave acceleration



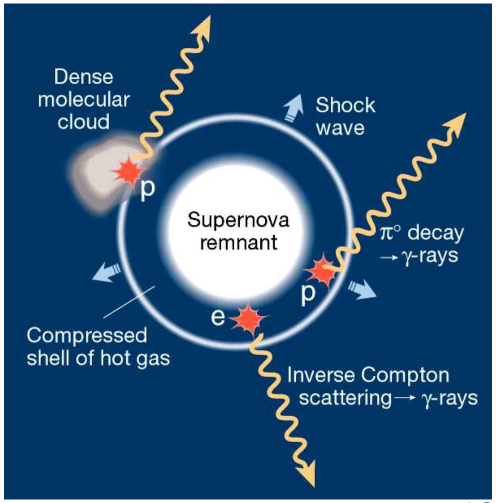
SNR expands into ISM with velocity V~ 10^4 km/s. Drives forward shock at 4/3 V

$T_{SN} \sim 1000$ yrs before slowdown
$E_{max} \sim Z \times 100$ TeV

Problems of simplest SNR shock model

- Expected shape of spectrum:
  - Differential index $\alpha \sim 2.1$ for diffusive shock acceleration
    - $\alpha_{observed} \sim 2.7$; $\alpha_{source} \sim 2.1$; $\Delta\alpha \sim 0.6 \rightarrow \tau_{esc}(E) \sim E^{-0.6}$
    - $c\,\tau_{esc} \rightarrow T_{disk} \sim 100$ TeV
    - → Isotropy problem
- $E_{max} \sim \beta_{shock}$ Ze x B x R_{shock}
  - → $E_{max} \sim$ Z x 100 TeV with exponential cutoff of each component
  - But spectrum continues to higher energy**:**
    - → E_{max} problem

- Expect p + gas → γ (TeV) for certain SNR
  - Need nearby target as shown in picture from *Nature (F. Aharonian,* April 02)
  - Some likely candidates (e.g. HESS J1745-290) but still no certain example
  - → Problem of elusive π^0 γ-rays



Solutions to problems ?

- Isotropy problem
  - $\gamma_{source} \sim 2.3$ and $\tau_{esc} \sim E^{-0.33}$??
  - $\tau_{esc} \sim E^{-0.33}$ is theoretically preferred, but $\gamma = 2.3$?
- Evidence for acceleration of protons at SNR
  - Look for TeV γ-rays mapping gas clouds at SNR
  - Possible example SNR IC443 (VERITAS, arXiv:0810.0799)
- Acceleration to higher energy
  - Magnetic field amplification in non-linear shock acceleration

Non-linear shock acceleration

- Discussion of acceleration so far
  - "Test particle" approximation
  - Neglects effects of particles being accelerated on the accelerator
- Non-linear theory
  - Accounts for magneto-hydrodynamic turbulence generated by cosmic-rays upstream of the shock.
  - Cosmic-rays scatter on MHD turbulence with wavelength matched to particle's gyro-radius
- Two important effects
  - Spectrum is distorted
  - Magnetic field in acceleration region is amplified

Non-linear shock acceleration - 2

- Cosmic-ray pressure in upstream region generates precursor
- Higher energy particles get further upstream
- Experience larger discontinuity r = $u_1(x) / u_2$

$$\frac{dN}{d\ln E} \sim E^{-\gamma}, \qquad \gamma = \frac{3}{r-1} \quad \text{where } r = \frac{u_1}{u_2}$$

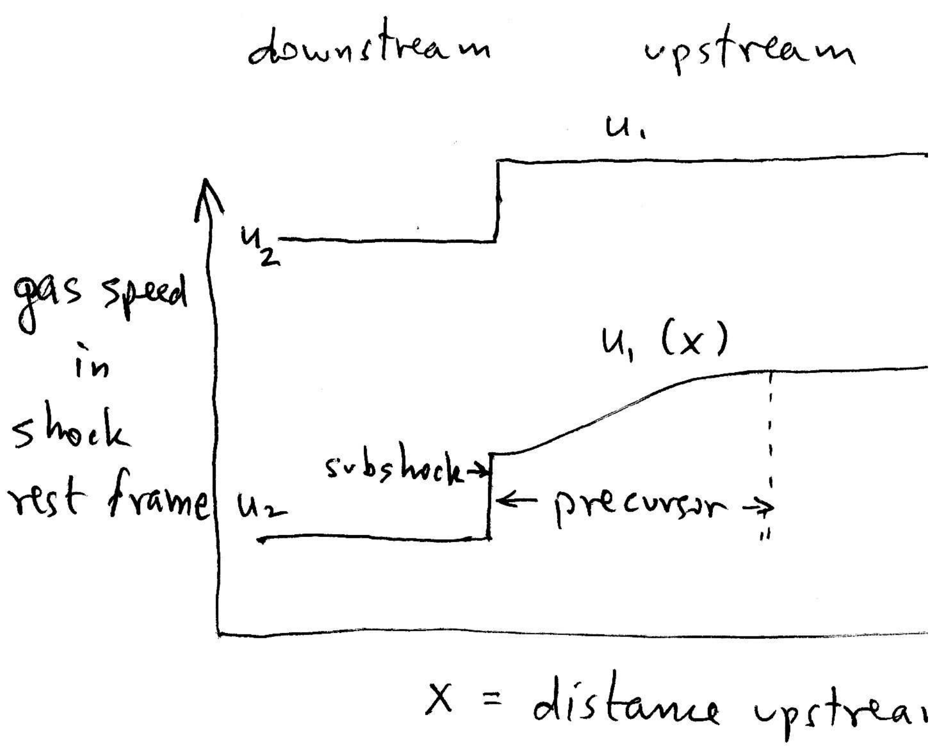
$$r = 4 - \frac{12}{(\text{Mach})^2} \quad \text{at subshock}$$

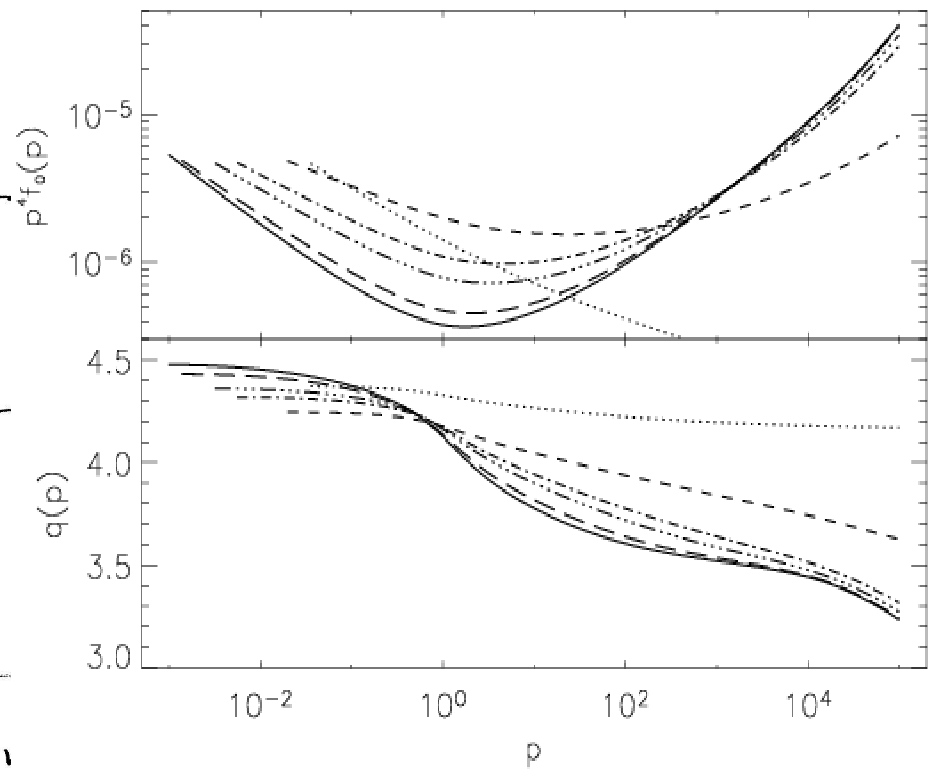
$$\Rightarrow \gamma = 1 + \epsilon \quad \text{at subshock}$$

$r > 4$ upstream of CRMS

Example: $r = 7 \Rightarrow \gamma = \frac{1}{2}$

Non-linear shock acceleration - 3





Note: CR acceleration theory calculates distribution in p-space:
$f(p) \equiv dn_{cr} / dp^3 \sim (1/p^2)\, dn/dE$
So here $q = \gamma + 3$

- Spectrum at shock concave,
- $\gamma < 1$ at high energy,
- energy concentrated at Emax

Plot from P. Blasi

Non-linear shock acceleration - 4

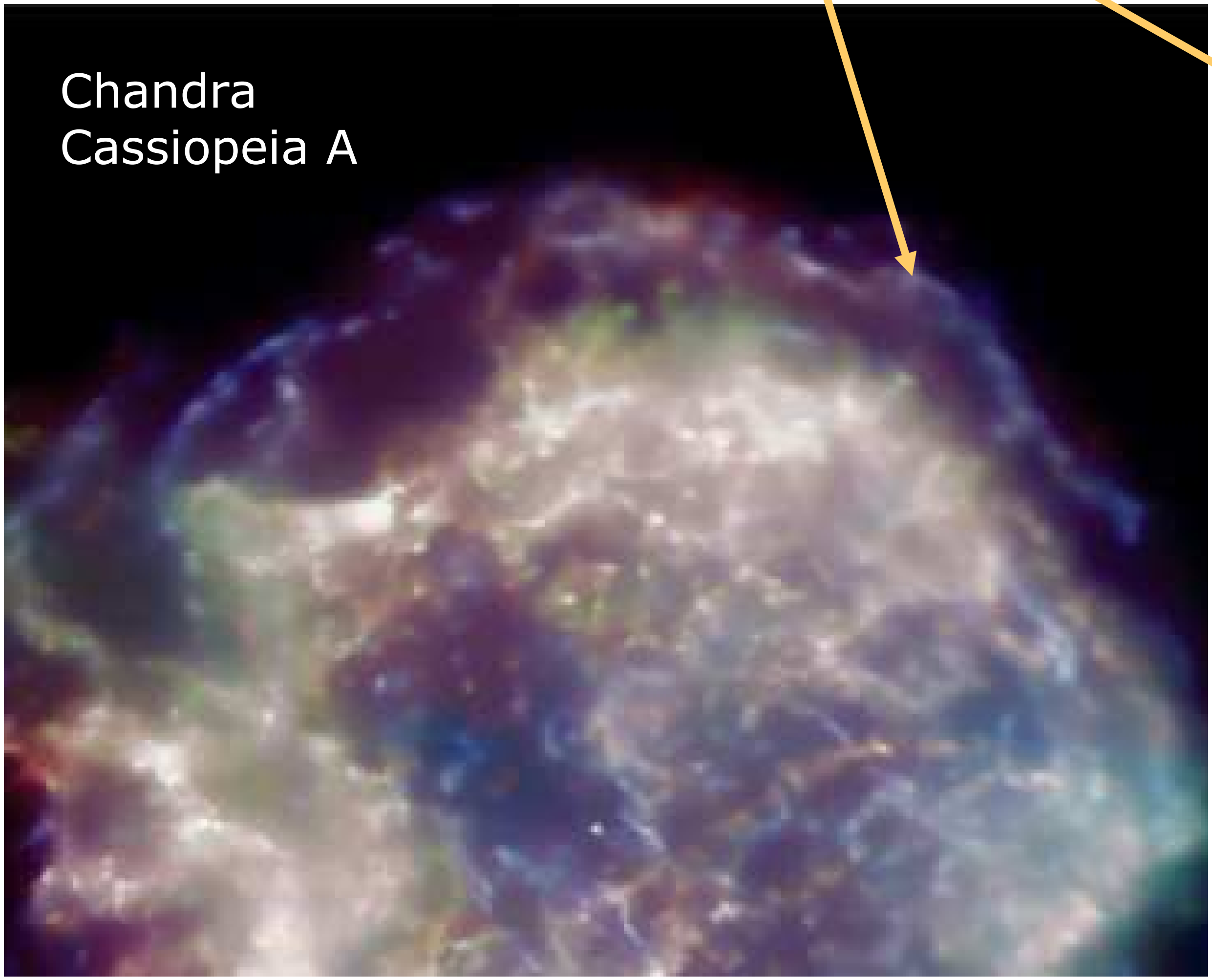
- Cosmic-ray pressure also amplifies magnetic field
  (Bell, MNRAS 353, 550, 2004)
- E_{max} increases to 10^{16} or 10^{17} eV in early,
  free-expansion phase of SNR expansion
- applies to small fraction of accelerated particles

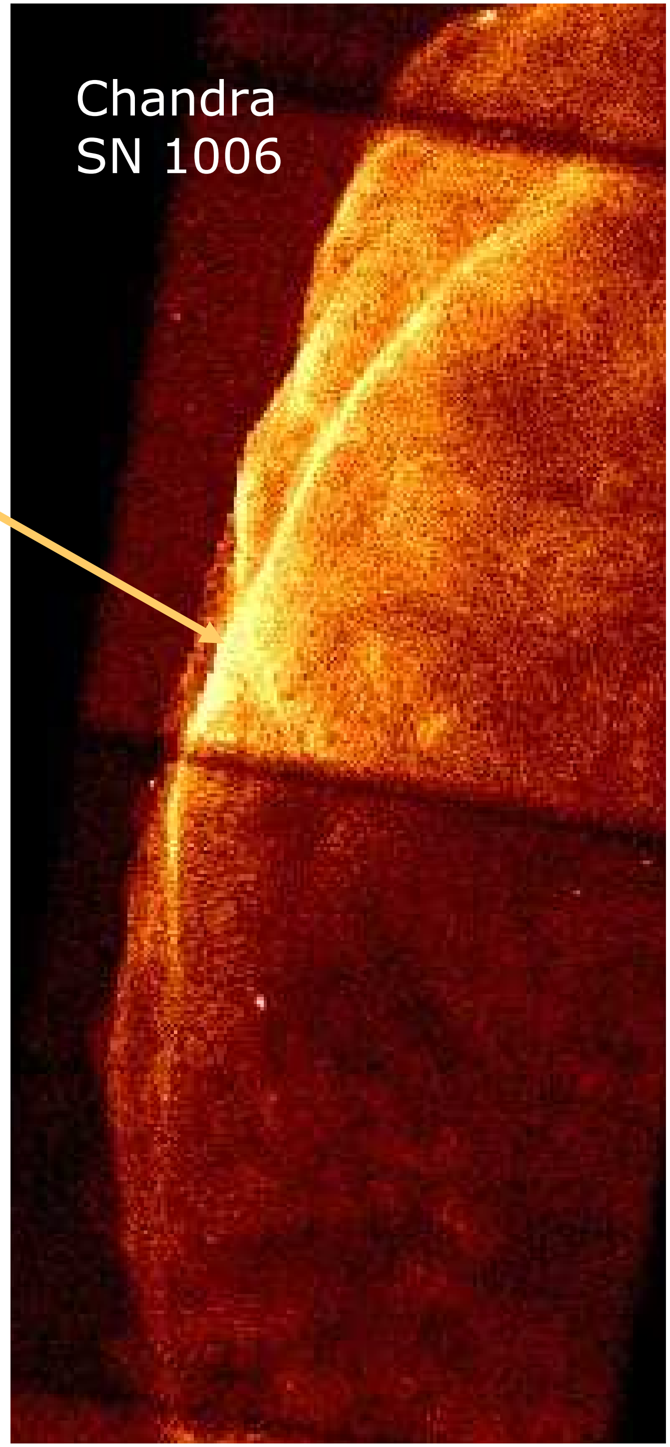
ALSO (Ptuskin & Zirakashvili, A&A 429, 755, 2005)

- In later phases of SNR expansion:
  - upstream scattering becomes inefficient
    as expansion slows down
  - $E_{max} \rightarrow E_{max}$ (t) decreases with time
  - Accelerated particles with $E > E_{max}(t)$
    escape upstream
  - observed spectrum is integral of SNR history

Filamentary structure of X-ray emission of young SNRs: Evidence for amplification, B ~ 100 μG

Berezhko&Volk, OG111

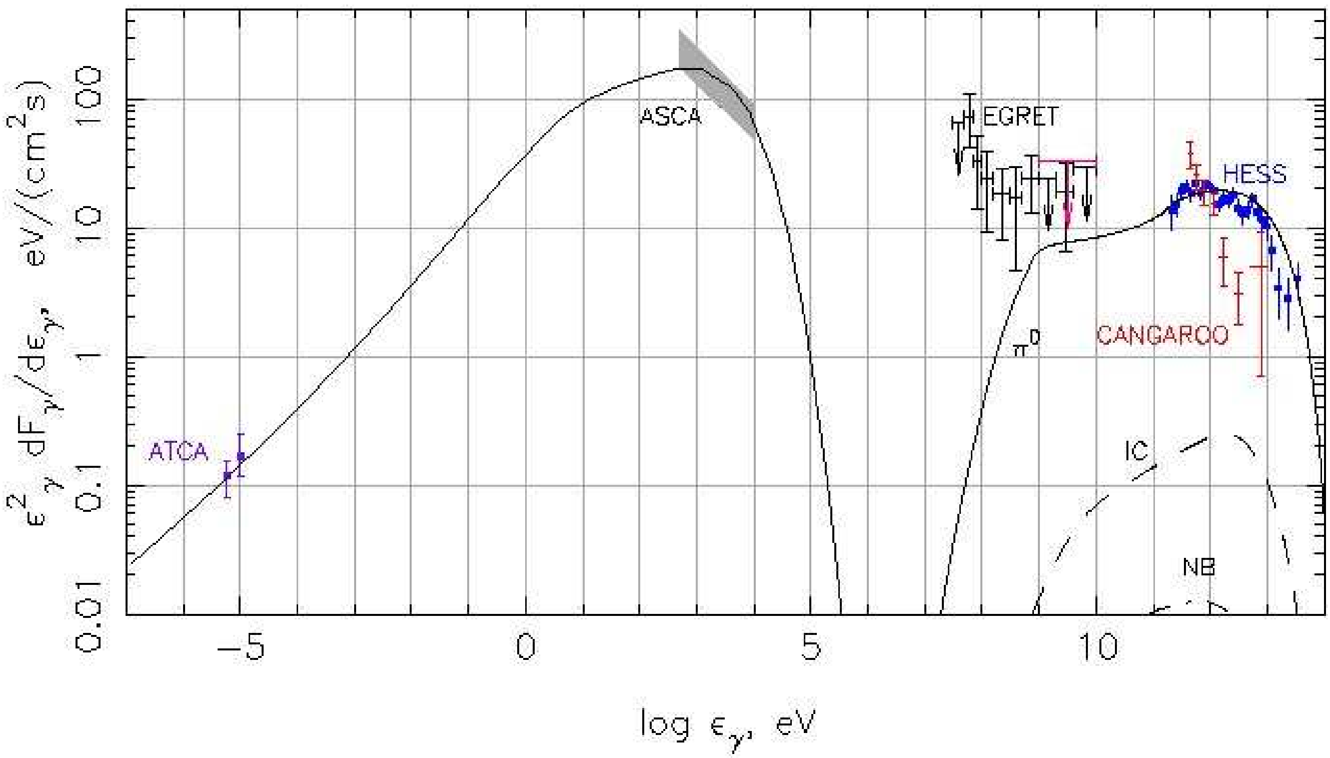




RX J1713.7-3946

Berezhko & Völk, arXiv:0707.4647

Contributions from electrons (IC, NB) suppressed by ~100 μG fields



Examples of power-law distributions

(M.E.J. Newman, cond-mat/0412004)

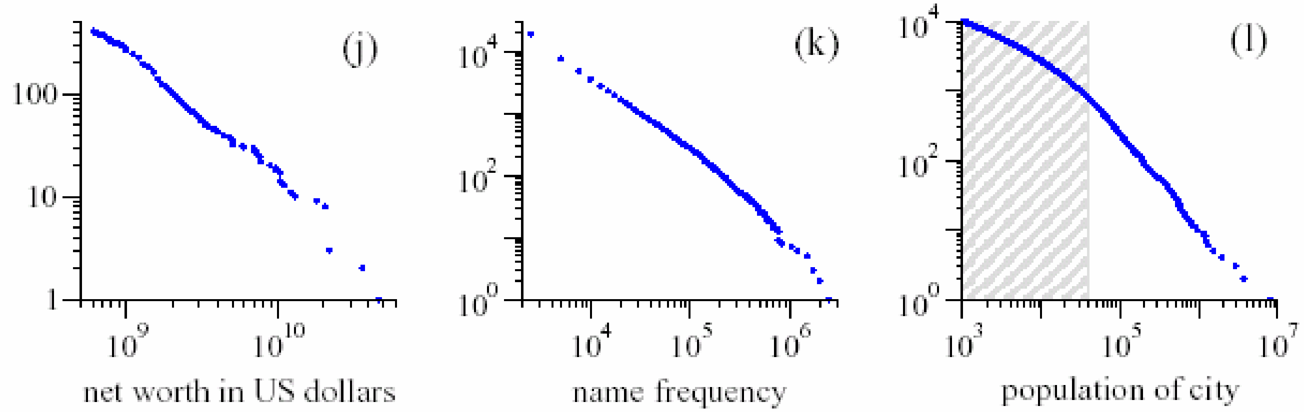
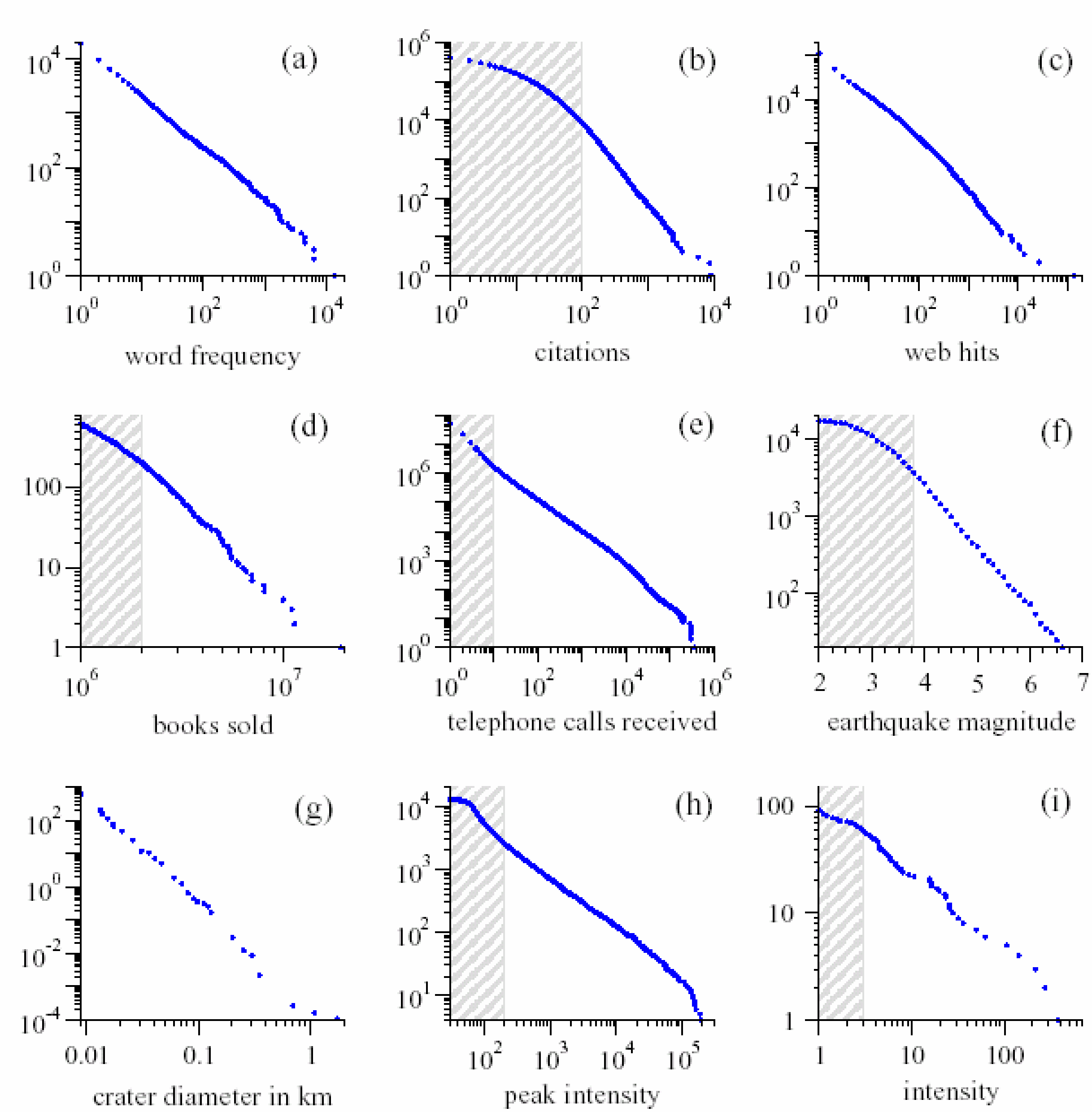


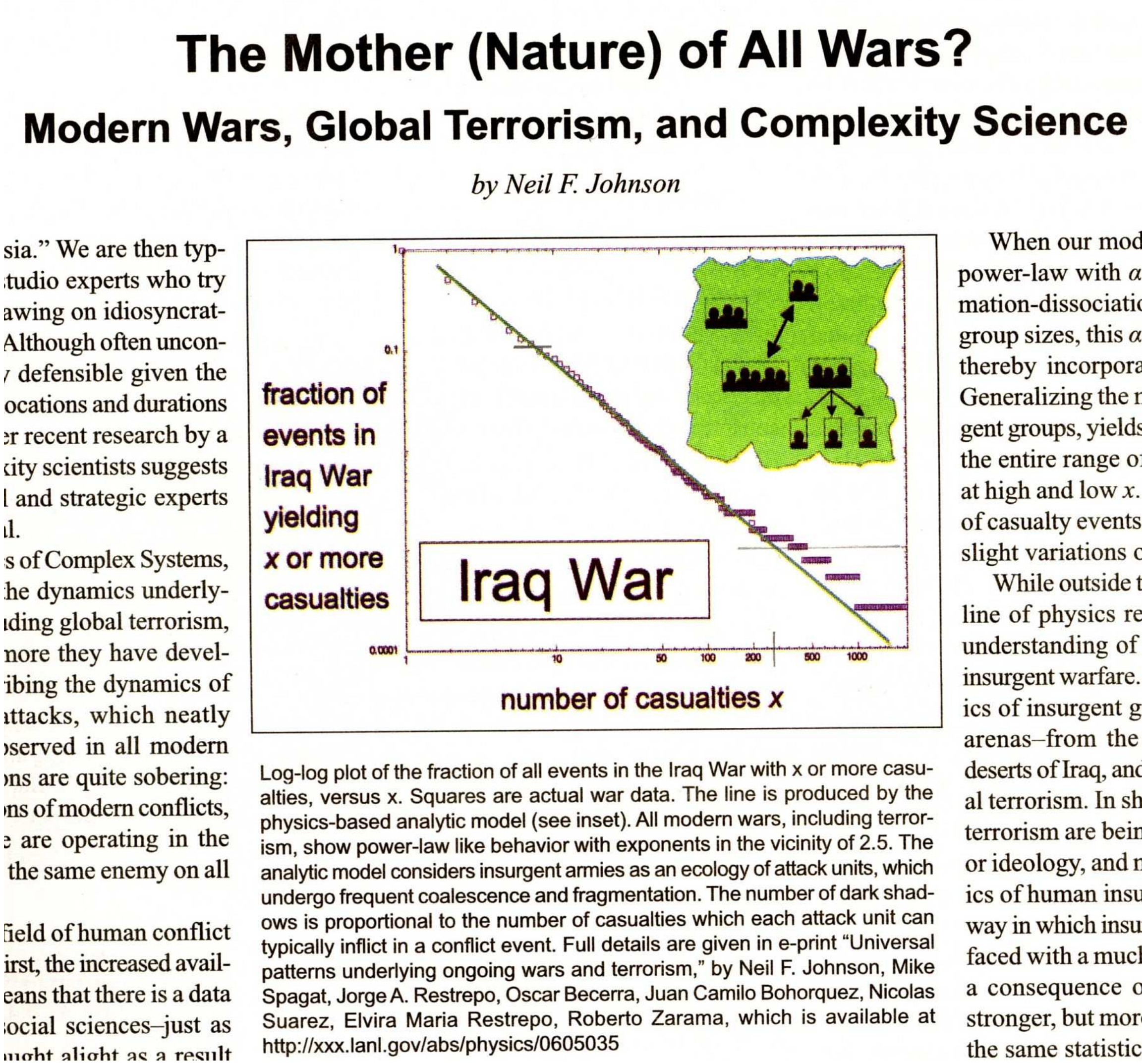
FIG. 4 Cumulative distributions or "rank/frequency plots" of twelve quantities reputed to follow power laws. The distributions were computed as described in Appendix A. Data in the shaded regions were excluded from the calculations of the exponents in Table I. Source references for the data are given in the text. (a) Numbers of occurrences of words in the novel *Moby Dick* by Hermann Melville. (b) Numbers of citations to scientific papers published in 1981, from time of publication until June 1997. (c) Numbers of hits on web sites by 60 000 users of the America Online Internet service for the day of 1 December 1997. (d) Numbers of copies of bestselling books sold in the US between 1895 and 1965. (e) Number of calls received by AT&T telephone customers in the US for a single day. (f) Magnitude of earthquakes in California between January 1910 and May 1992. Magnitude is proportional to the logarithm of the maximum amplitude of the earthquake, and hence the distribution obeys a power law even though the horizontal axis is linear. (g) Diameter of craters on the moon. Vertical axis is measured per square kilometre. (h) Peak gamma-ray intensity of solar flares in counts per second, measured from Earth orbit between February 1980 and November 1989. (i) Intensity of wars from 1816 to 1980, measured as battle deaths per 10 000 of the population of the participating countries. (j) Aggregate net worth in dollars of the richest individuals in the US in October 2003. (k) Frequency of occurrence of family names in the US in the year 1990. (l) Populations of US cities in the year 2000.

More examples from M.E.J. Newman, cond-mat/0412004



Casualties per attack in Iraq

(Neil F. Johnson, et al., from *APS News*, 8 Nov 2006)



The Mother (Nature) of All Wars?

Modern Wars, Global Terrorism, and Complexity Science

by Neil F. Johnson

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Log-log plot of the fraction of all events in the Iraq War with x or more casualties, versus x. Squares are actual war data. The line is produced by the physics-based analytic model (see inset). All modern wars, including terrorism, show power-law like behavior with exponents in the vicinity of 2.5. The analytic model considers insurgent armies as an ecology of attack units, which undergo frequent coalescence and fragmentation. The number of dark shadows is proportional to the number of casualties which each attack unit can typically inflict in a conflict event. Full details are given in e-print "Universal patterns underlying ongoing wars and terrorism," by Neil F. Johnson, Mike Spagat, Jorge A. Restrepo, Oscar Becerra, Juan Camilo Bohorquez, Nicolas Suarez, Elvira Maria Restrepo, Roberto Zarama, which is available at http://xxx.lanl.gov/abs/physics/0605035

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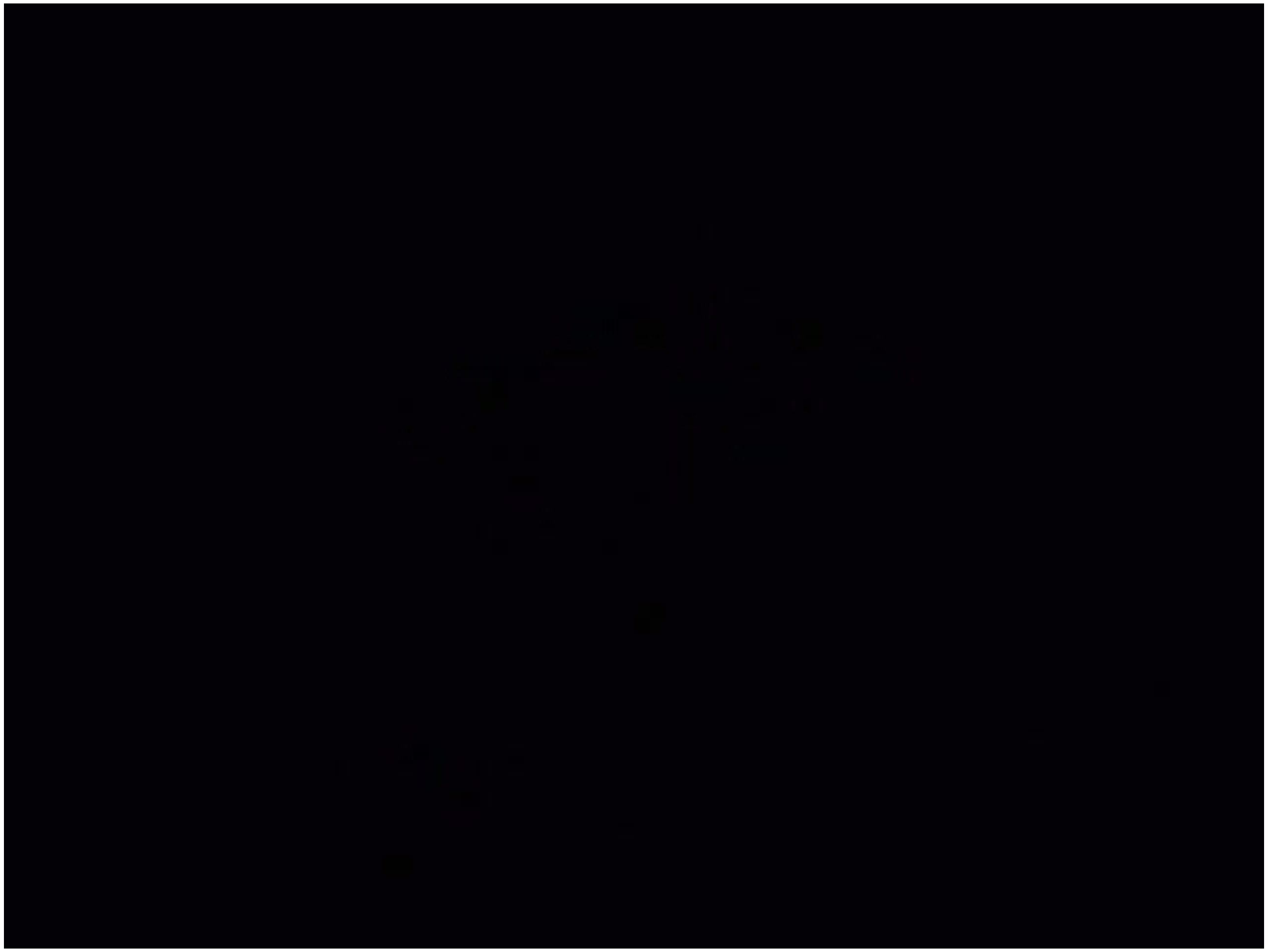

Frank Capra, 1957