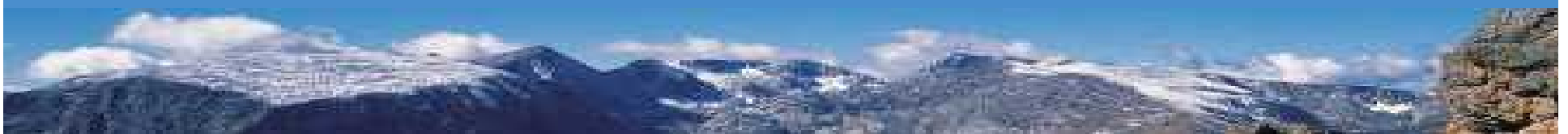




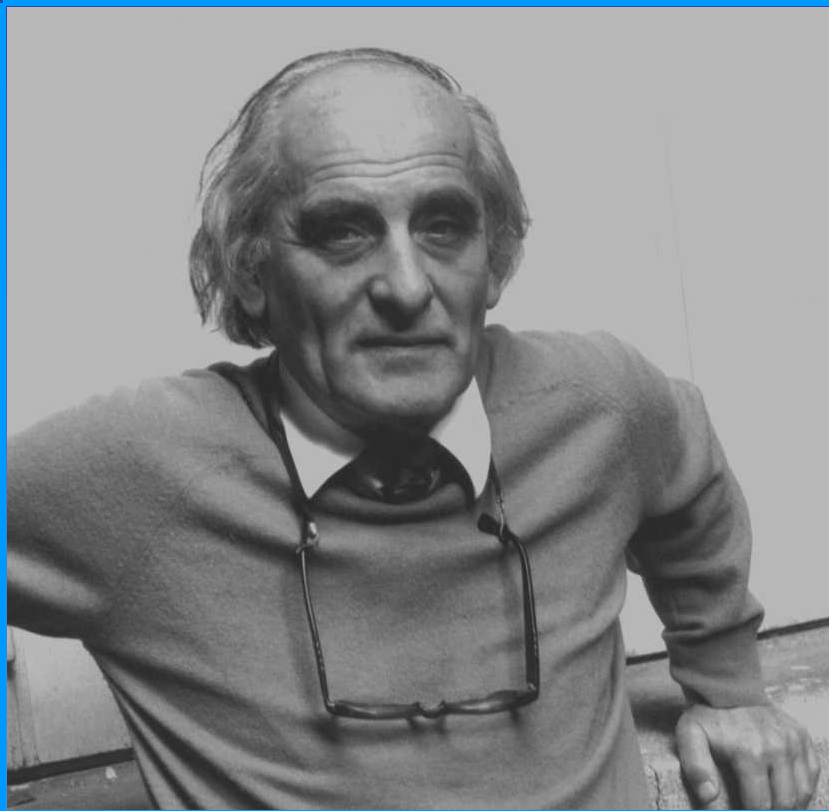
# Cosmic Rays, Gamma-Rays and the Universal Background Radiation

Malcolm Longair

Cavendish Laboratory, Cambridge



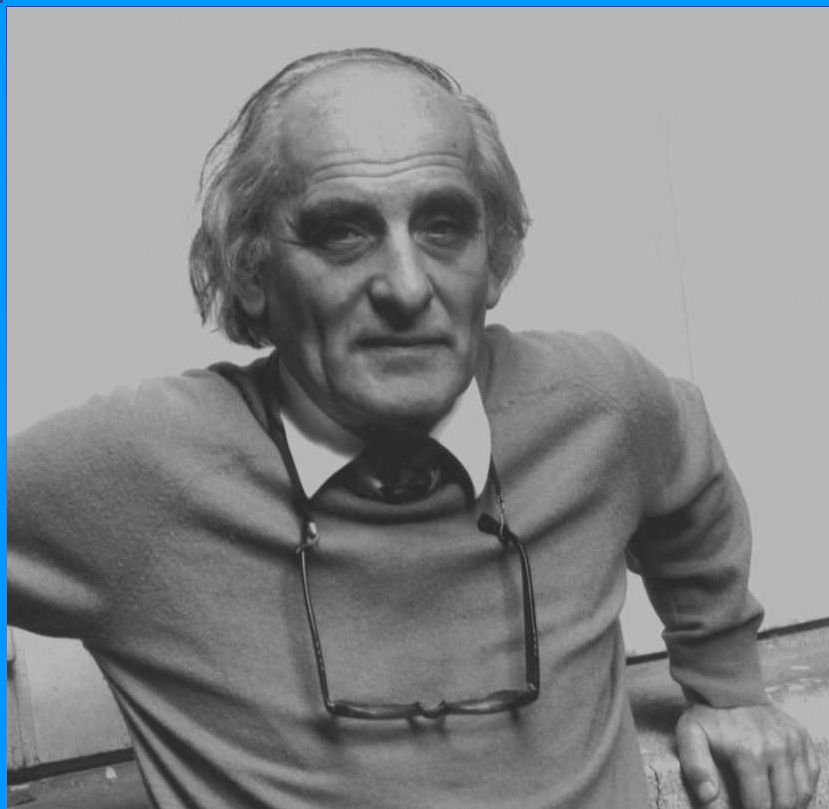
# Celebrating Occhialini



I met Occhialini only a few times, in connection with ESA projects and  $\gamma$ -ray astronomy.

The other connection is that, as a former director of the Cavendish Laboratory, his work with Blackett in the 1930s is one of the highlights of its scientific history.

# Celebrating Occhialini



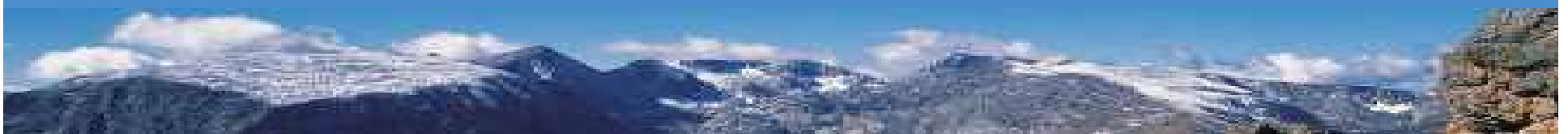
My charge is to describe the current state of two areas to which he made enormous contributions and which intersect with my interests in High Energy Astrophysics and Cosmology.

- Cosmic ray astrophysics
- High energy  $\gamma$ -rays.



# Programme

- Brief Historical Notes
- Cosmic ray physics
- High energy  $\gamma$ -rays
- Cosmology



# 1. Brief Historical Notes



# The Wilson Cloud Chamber

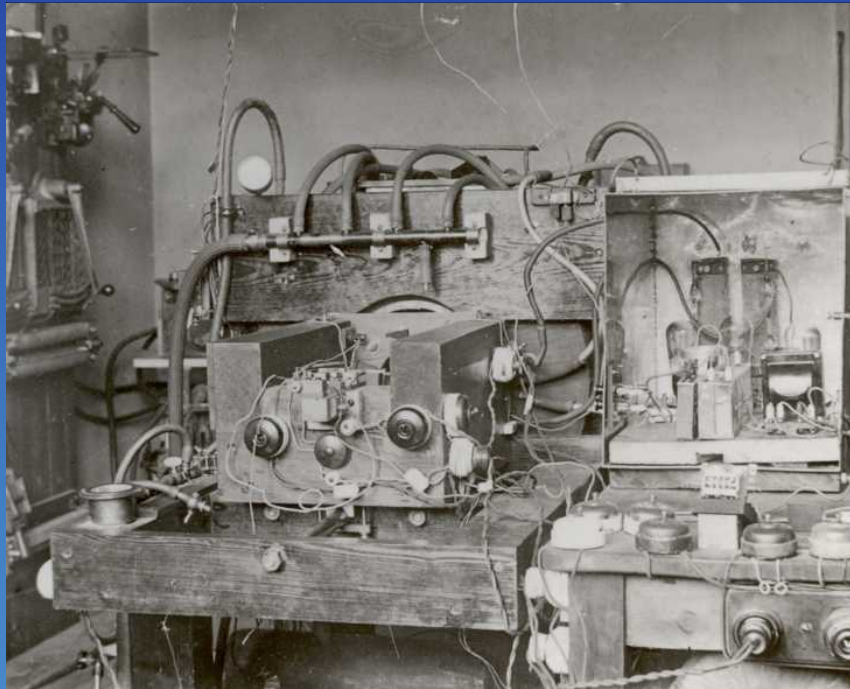
The first outstanding research involving Occhialini at the Cavendish Laboratory concerned development of the automatic Cloud Chamber. Patrick Blackett had already perfected the techniques of exploiting its capabilities.



Wilson's perfected Cloud Chamber



# Blackett's Automatic Cloud Chamber of 1928



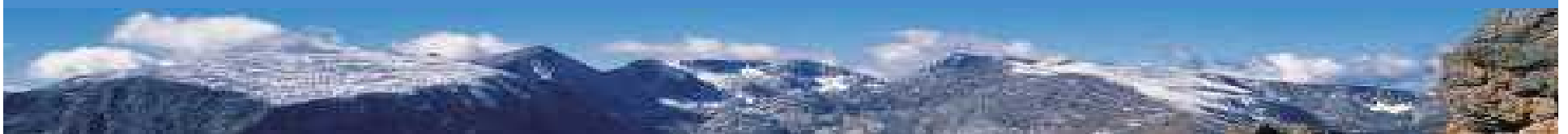
In 1924, Blackett succeeded in taking 23,000 automatic cloud chamber photographs which contained about 270,000 tracks of  $\alpha$ -particles. Among these were 8 tracks showing the ejection an energetic proton in the disintegration of a nitrogen nucleus.



# Blackett's Letter to Occhialini's Father

*For it was certainly his (Occhialini's) arrival in Cambridge which stimulated my embarking on the field of cosmic rays which I have never left. And our work together in 1932-33 was a real collaboration of the happiest kind.*

P.M.S. Blackett Letter (1948)



# Blackett's Nobel Prize Lecture

*Occhialini and I set about, therefore, the devising of a method of making cosmic rays take their own photographs, using the recently developed "Geiger-Müller counters" as detectors of the rays.*

P.M.S. Blackett Nobel Prize Speech (1948)

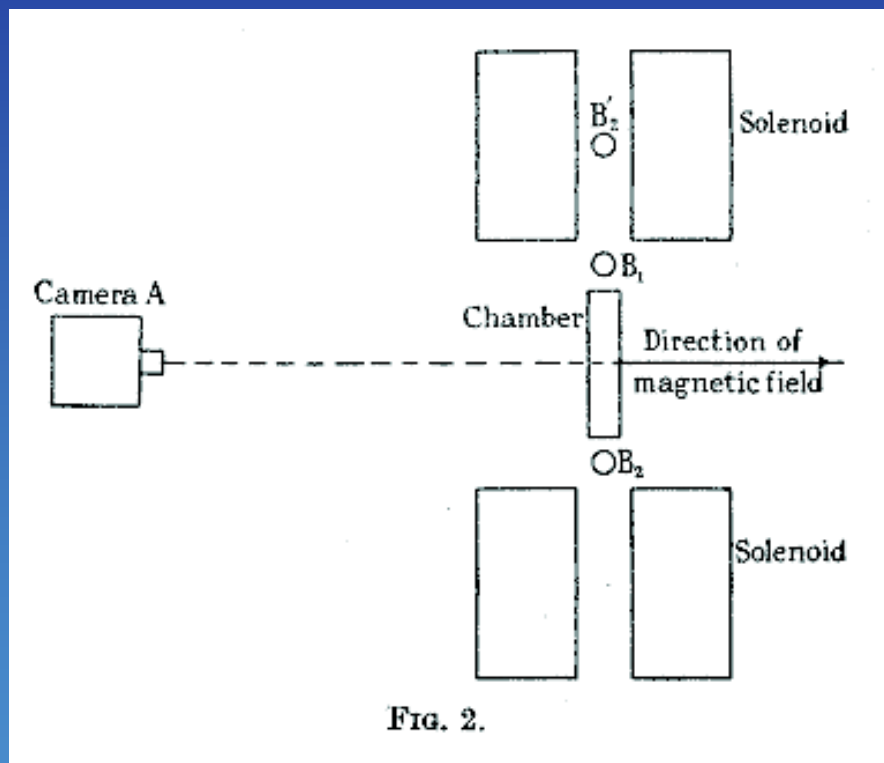


# The Discovery of the Positron

Occhialini had been working with Rossi using coincidence methods for detecting the arrival of cosmic rays. He arrived in Cambridge 'for three weeks; he stayed for three years'. They combined the **coincidence technique** with the **cloud chamber** so that, whenever a high energy particle passed through the chamber, its track was photographed.

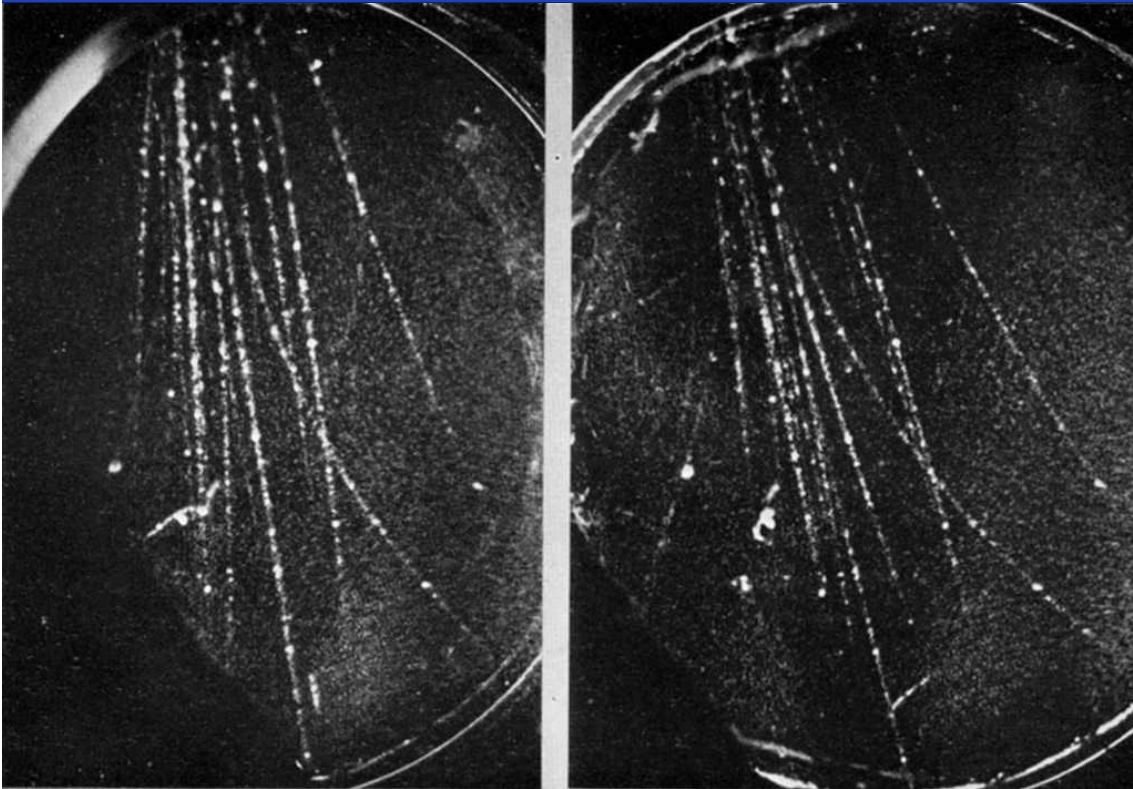


# Blackett and Occhialini, 1933



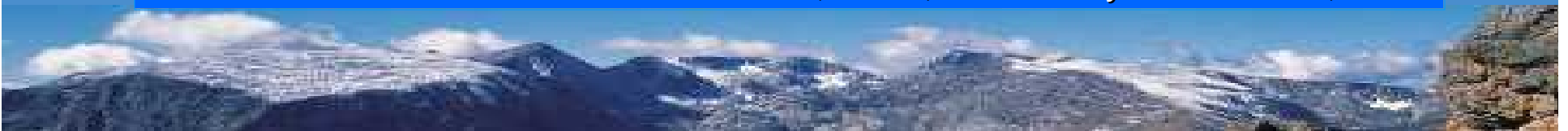
In the key experiment, the cloud chamber was placed on its side and solenoids placed above and below it. The upper solenoid acted as a converter for the cosmic rays.

# Blackett and Occhialini, 1933

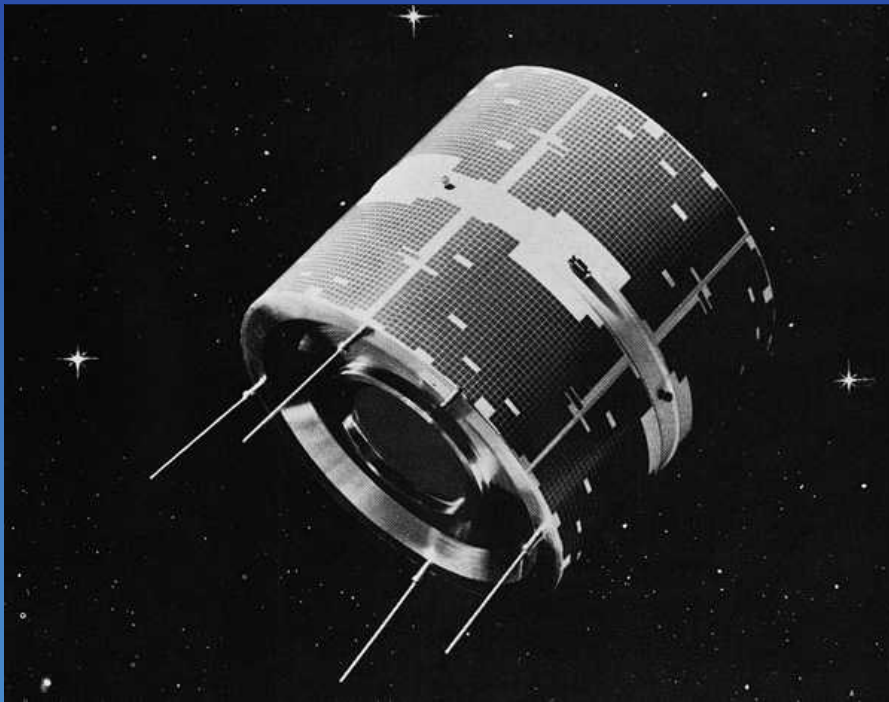


They discovered showers of high energy electrons, accompanied by positively charged particles which were deflected by the same amount in the opposite direction. This was the discovery of the positron, the first antiparticle to be discovered.

P.M S. Blackett and G.P.S. Occhialini, 1933,. Proc. Roy. Soc. A139, 699



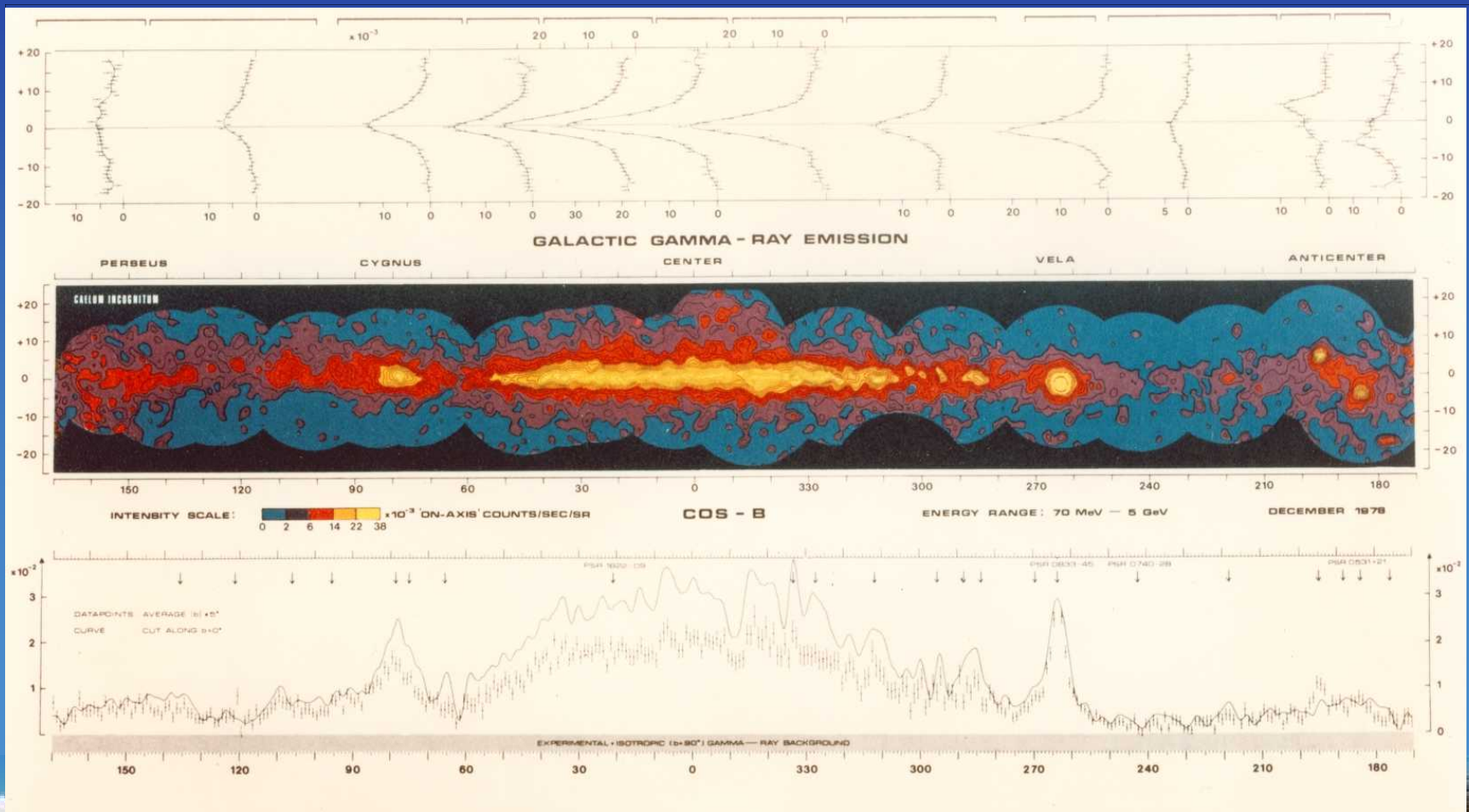
# COS-B $\gamma$ -ray Satellite



As soon as space astronomy became feasible, Occhialini became a leader of European efforts, particularly in  $\gamma$ -ray astronomy. Perhaps his greatest achievement was the success of COS-B.



# COS-B Map of the Galaxy in $\gamma$ -rays



# The Compton $\gamma$ -ray Observatory (CGRO)



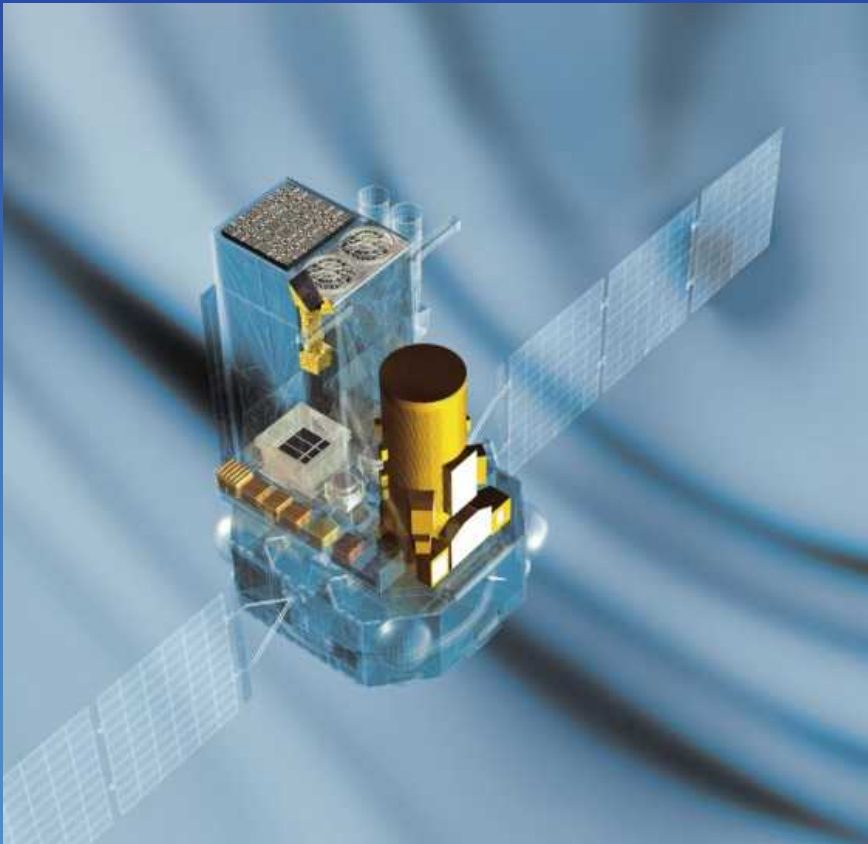
# Beppo-SAX Satellite



The Beppo-SAX satellite was a remarkable success – we will discuss some of the results later.



# The INTEGRAL Space Observatory



INTEGRAL is the  $\gamma$ -ray observatory mission of ESA launched on October 17 2002 on a Proton rocket. It is an ESA-led mission in collaboration with Russia and the USA.

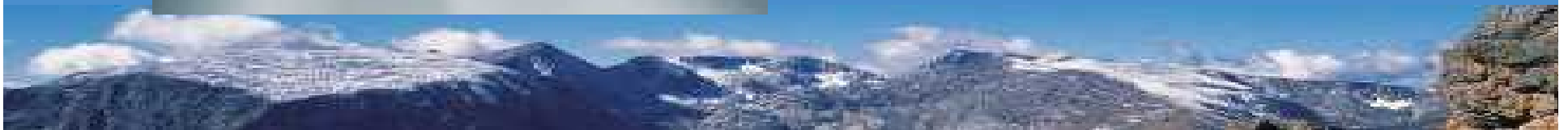


# SWIFT



NASA project to understand the physics of  $\gamma$ -ray bursts.

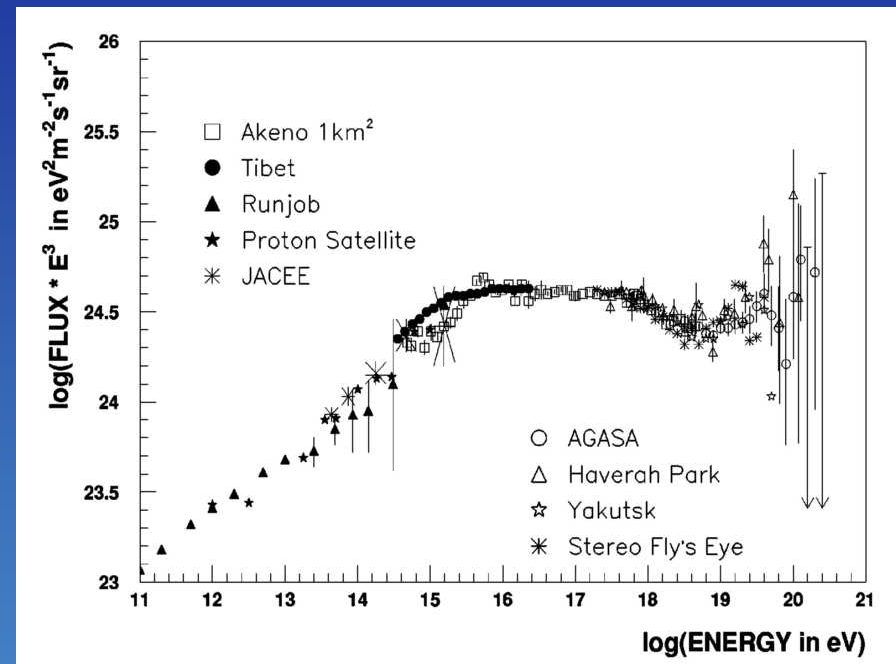
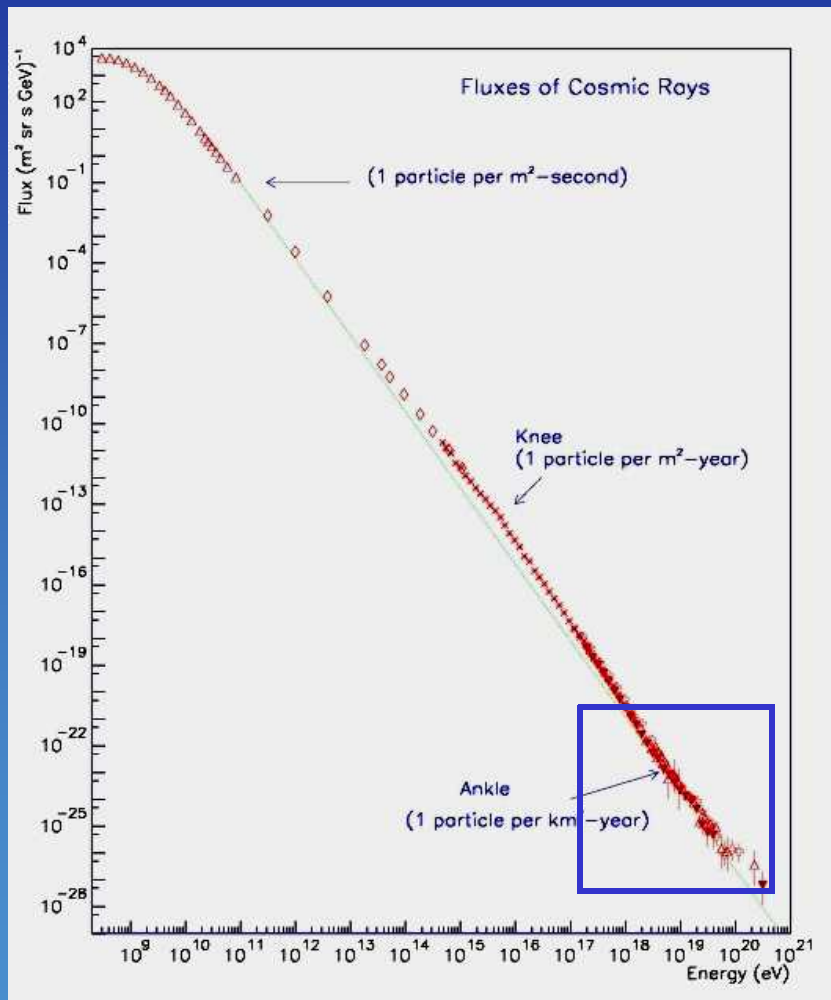
Launched  
November 20 2004



## 2. Cosmic Rays



# The Cosmic Ray Spectrum



There is encouraging agreement about the observed spectrum except at the very highest energies.

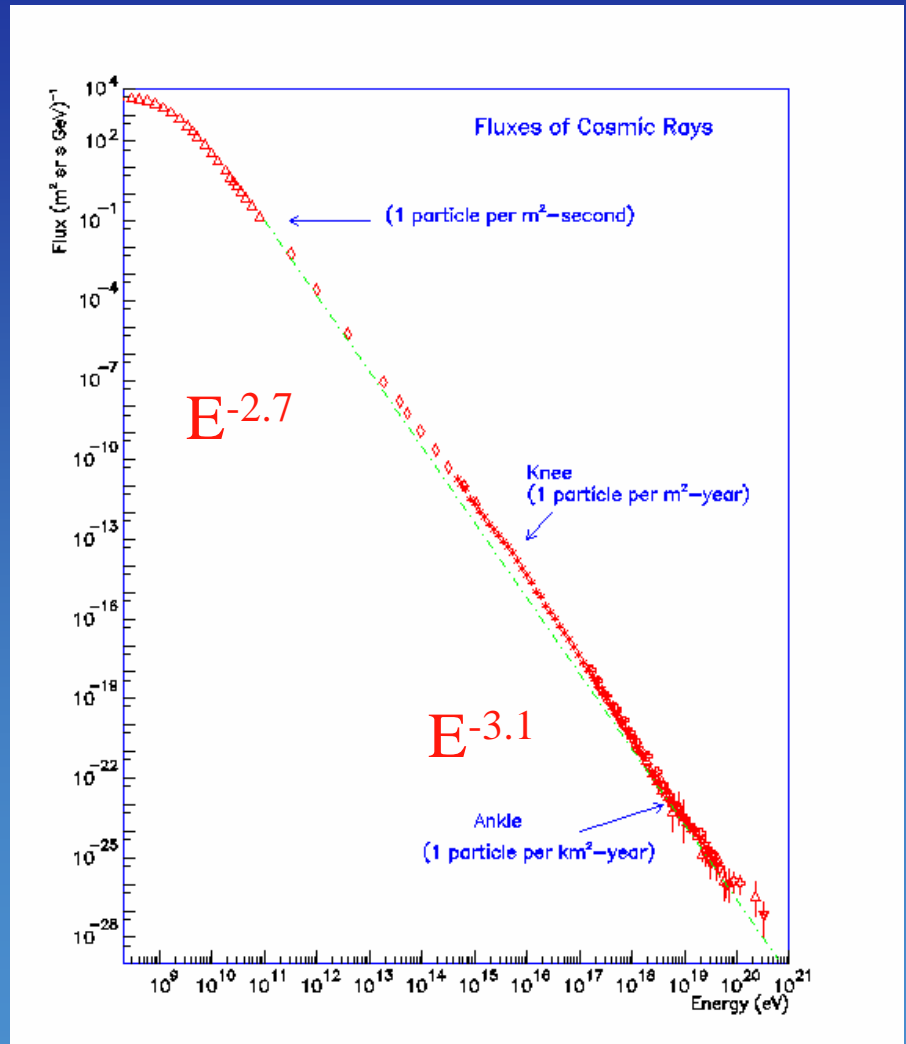
# The Universal Mechanism

Power-law energy spectra are found commonly in high energy astrophysical systems.

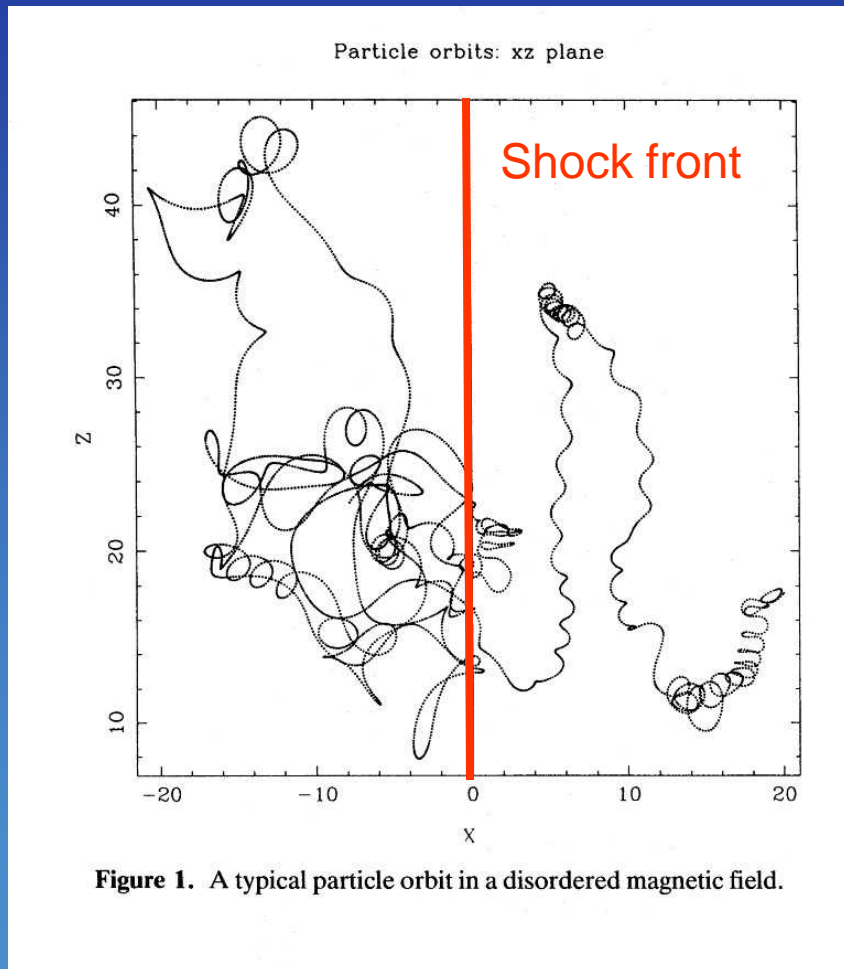
Radio, optical, X-ray and  $\gamma$ -ray spectra of quasars and active galaxies and  $\gamma$ -ray bursts require

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

$$x \sim 2.5 - 3$$

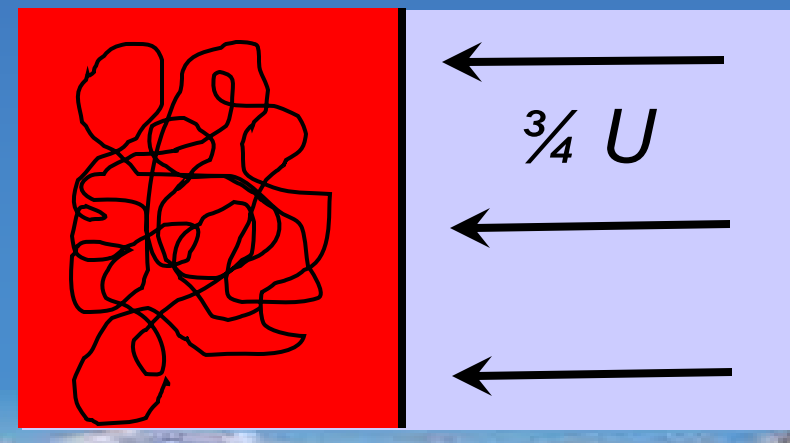
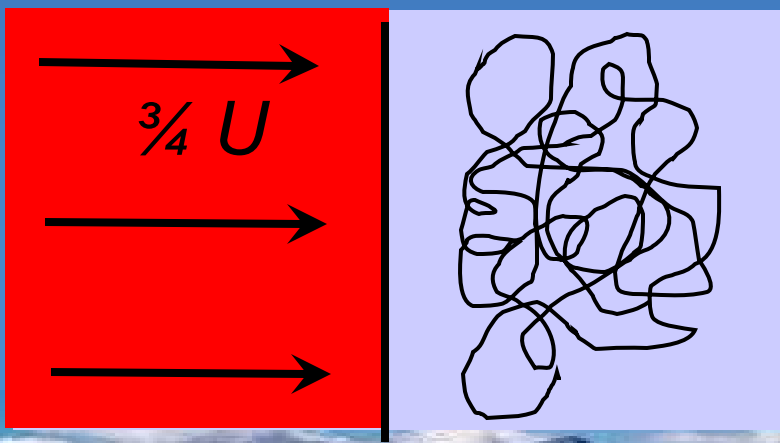
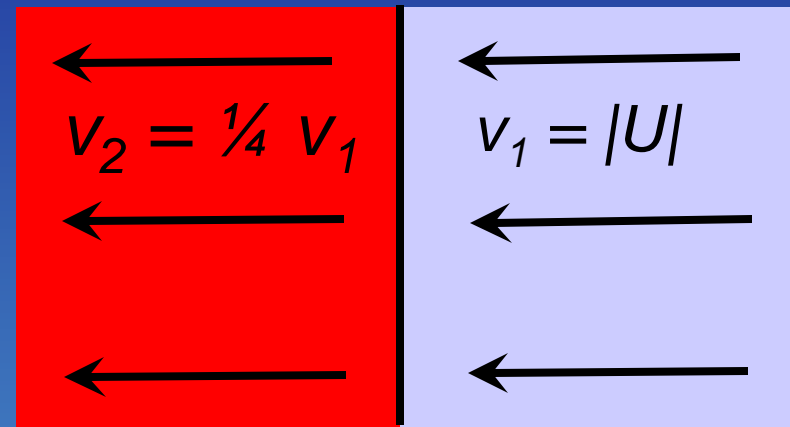
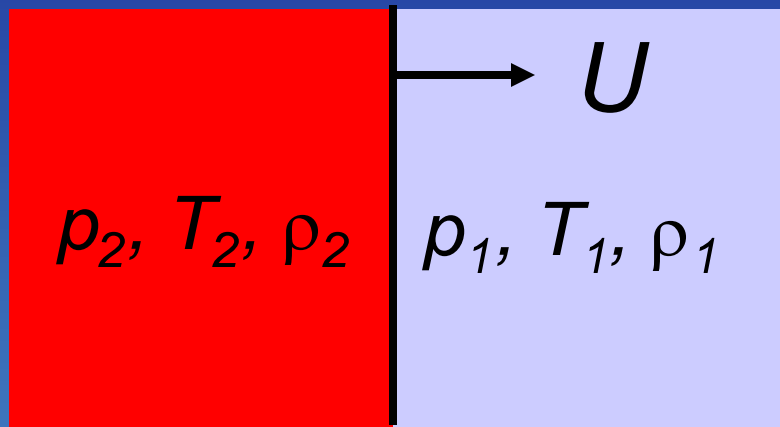


# First-order Fermi Acceleration



The great merit of the first order shock acceleration mechanism that it is not sensitive to the precise strength of the shock, so long as it is reasonably strong.

# First-order Fermi Acceleration in Strong Shocks, $U \gg v_s$



# First-order Fermi Acceleration

In the simplest calculation for non-relativistic shocks, a power-law spectrum is found which only depends upon the shock being strong.

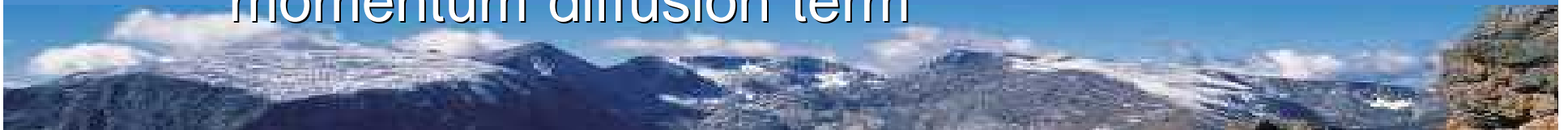
Momentum distribution	$f(p) \propto p^{-q}$ ,
Energy distribution	$N(E) \propto E^{-q+2}$ ,
Momentum spectral index	$q = \frac{3r}{r-1}$ ,
Compression	$r = \frac{\rho_2}{\rho_1} = \frac{u_1}{u_2}$ .

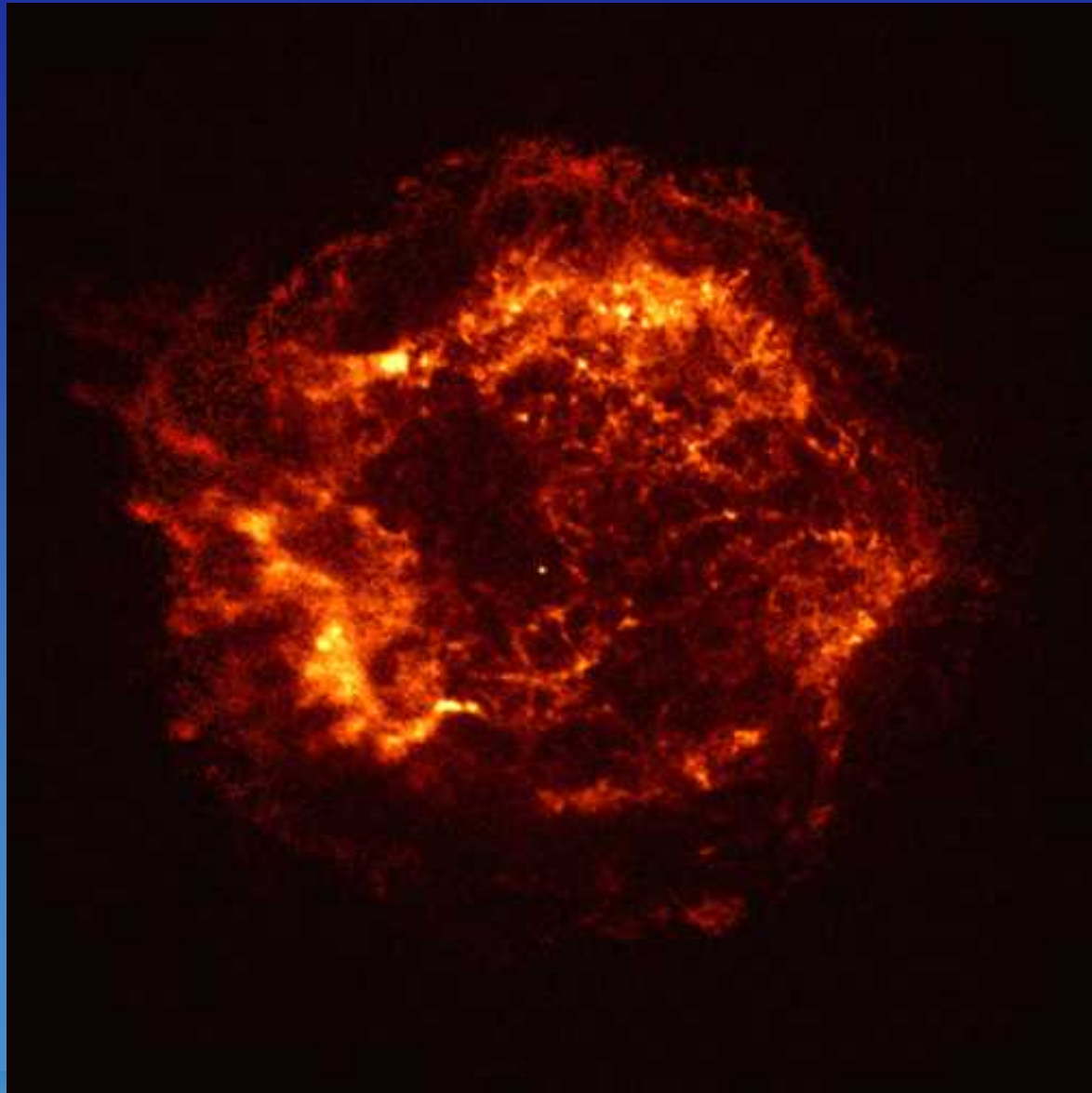
For strong shocks,  $r = 4$  and so  $N(E) \propto E^{-2}$

# The Acceleration of Charged Particles

Three Shock Acceleration mechanisms work together.

- First-order Fermi mechanism: scattering across the shock dominant at quasi-parallel shocks ( $\theta_{Bn} < 45^\circ$ )
- Shock Drift Acceleration: drift along the shock surface dominant at quasi-perpendicular shocks ( $\theta_{Bn} > 45^\circ$ )
- Second-order Fermi mechanism: Stochastic process, turbulent acceleration  $\rightarrow$  add momentum diffusion term





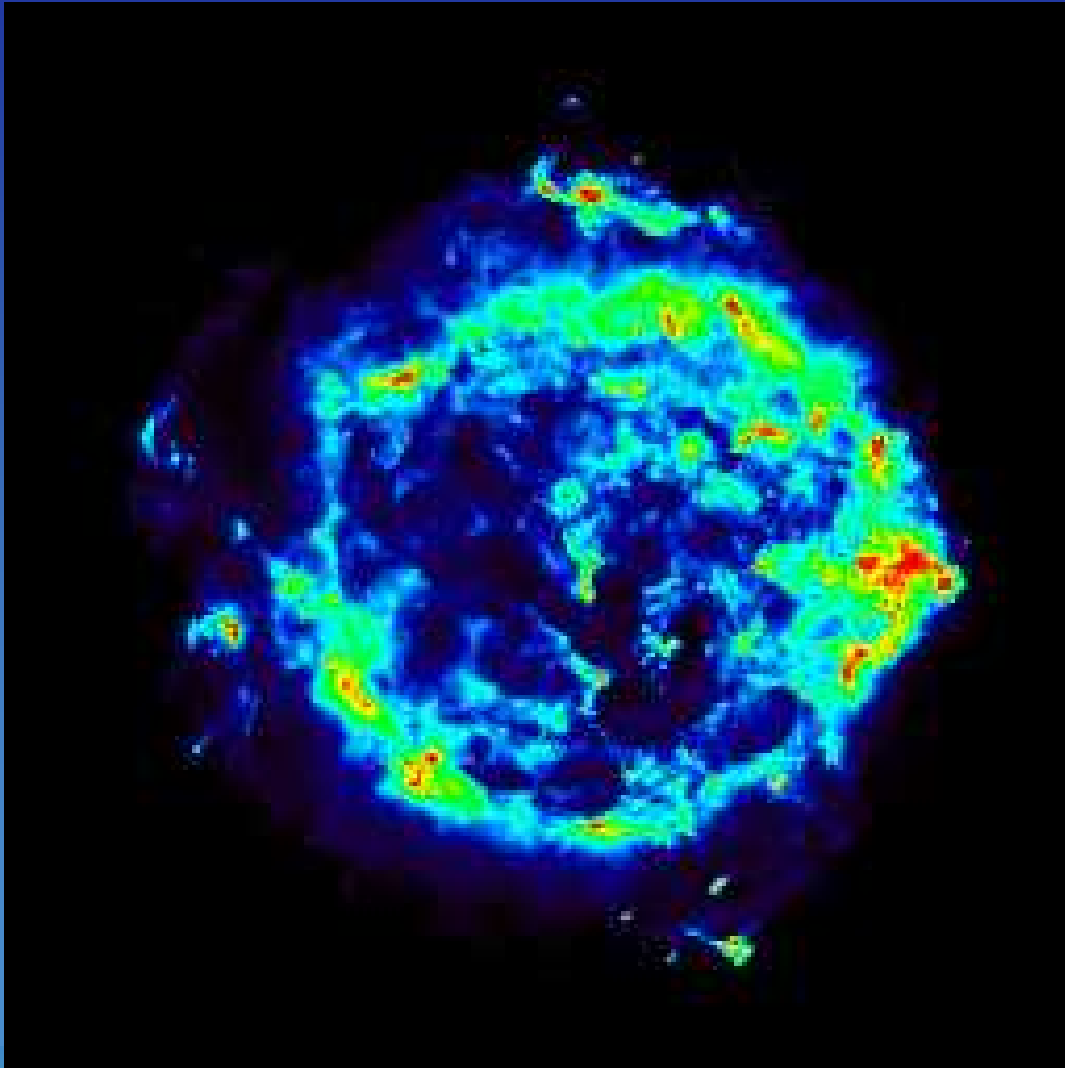
## Cassiopeia A

A supernova which exploded about 250 years ago. This **X-ray image** shows the faint stellar remnant for the first time. The shell of the remnant was heated by the explosion of the star. The shock is highly supersonic.

Chandra X-ray Observatory of NASA

## Cassiopeia A

A supernova which exploded about 250 years ago. This **radio image** shows the distribution of relativistic electrons and magnetic field in the remnant. These were accelerated in the shock.



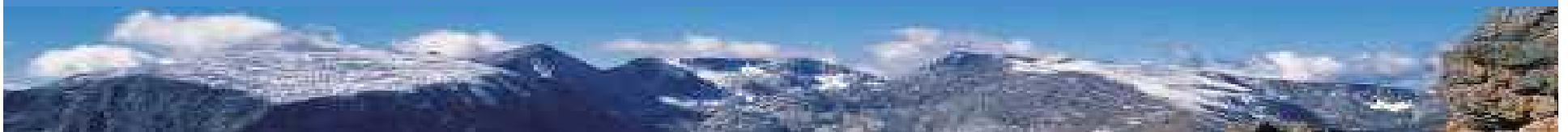
NRAO Very Large Array

# Detecting Ultra High Energy $\gamma$ -rays

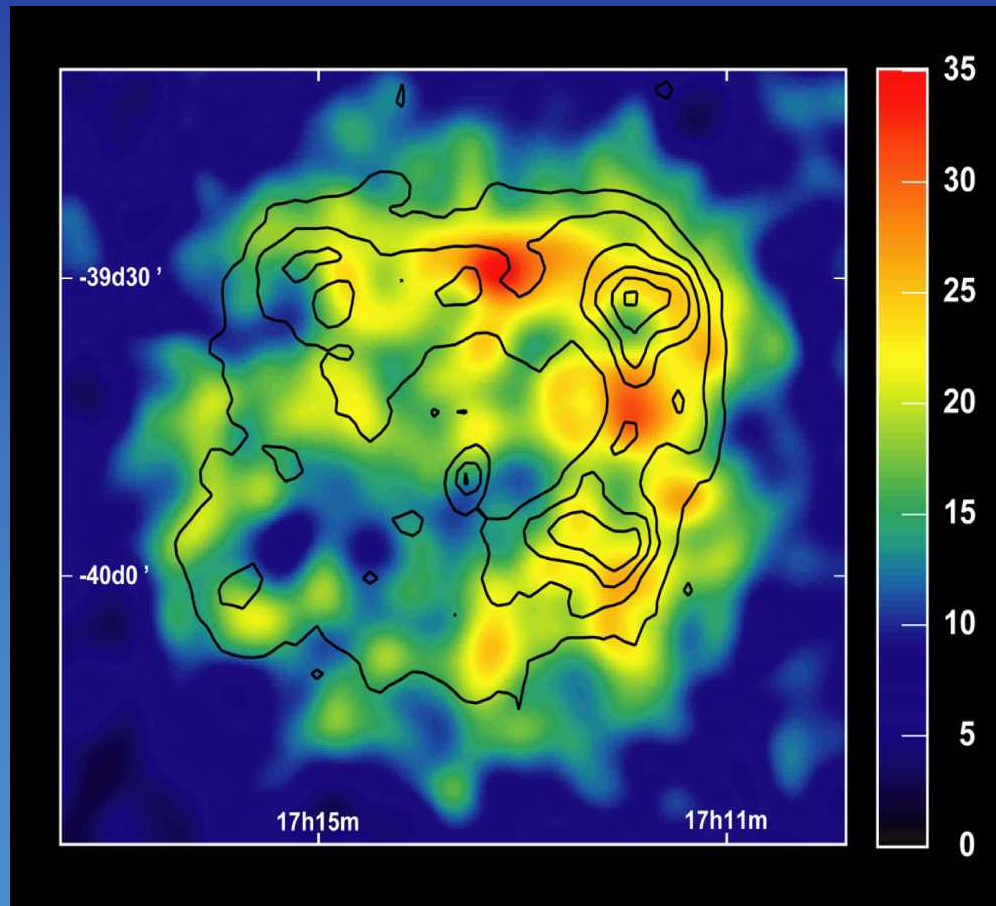


**High Energy Stereoscopic System (HESS) in Namibia.**

The HESS telescope system and similar telescopes detect the atmospheric Cerenkov radiation resulting from electron-photon cascades induced by the incoming very high energy  $\gamma$ -rays.



# A Supernova Remnant Detected in Ultra High Energy $\gamma$ -rays



The colour map shows the ultra high-energy  $\gamma$ -rays. The contours show the image obtained by the Japanese ASCA X-ray Observatory. The HESS  $\gamma$ -ray observations are interpreted as evidence for the acceleration of cosmic ray protons in the supernova remnant.

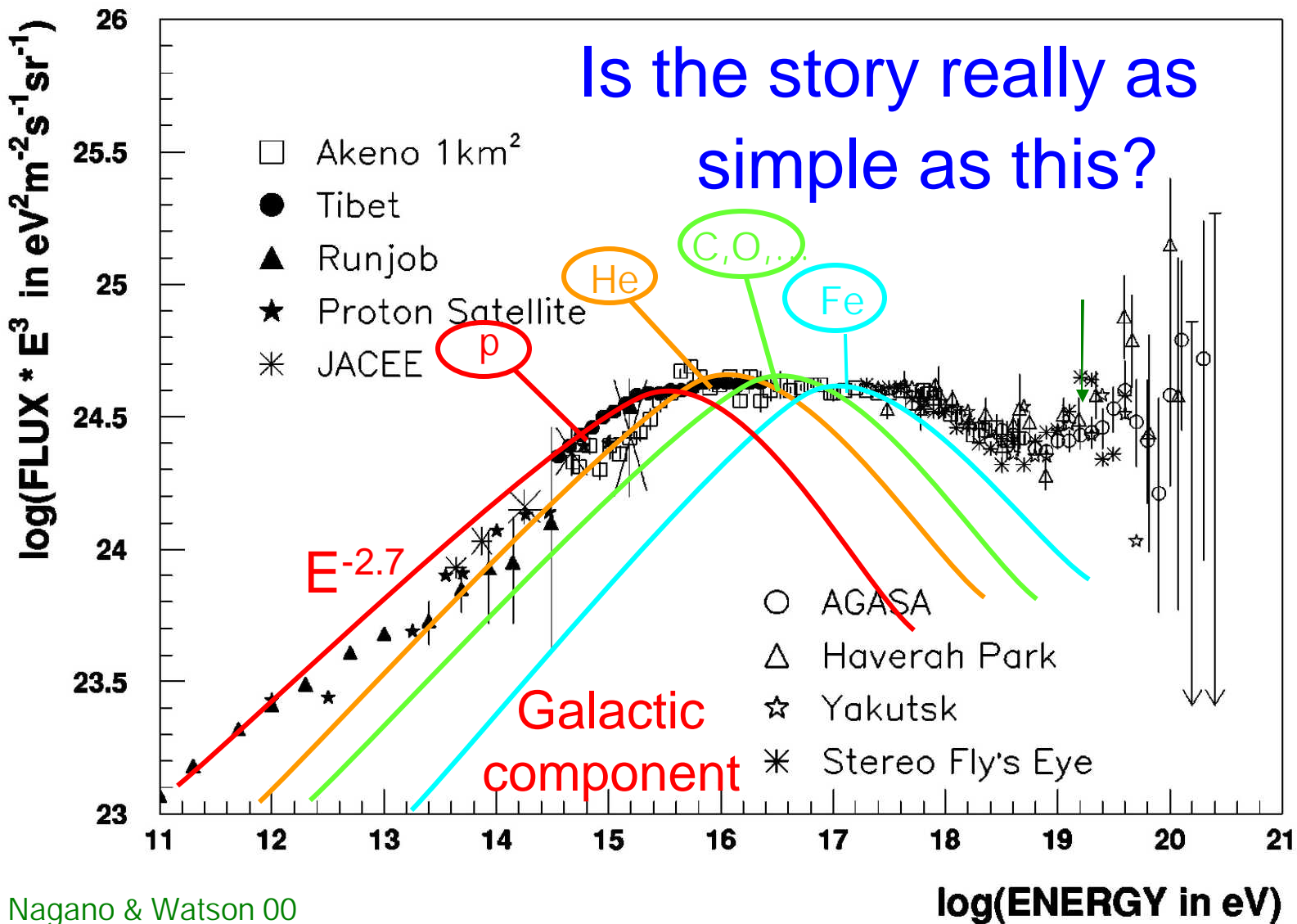


# Notes

- About 50 % of shock kinetic  $E$  can be transferred to cosmic rays for strong shocks with  $M_s > 30$ .
- Supernova acceleration works well. A cut-off at  $10^{15} - 10^{16}$  eV is expected when the gyroradii are equal to the scale of the remnant.
- If the overall spectrum consists of the superposition of the spectra of protons, helium nuclei, heavy elements, this could explain the spectrum above the knee, since the gyroradii of the particles scale with atomic number.



# Decomposing the Spectrum



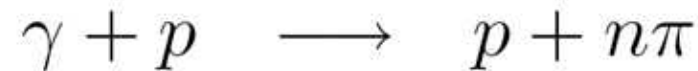
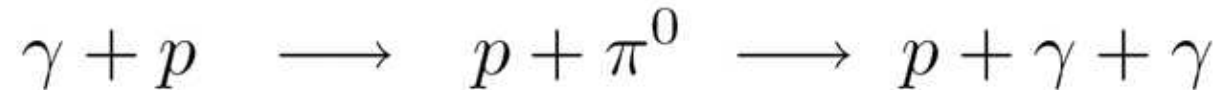
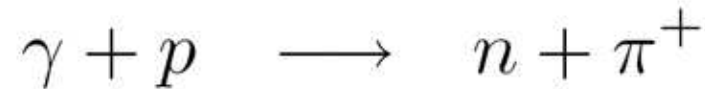
# The Ultrahigh Energy Cosmic Rays



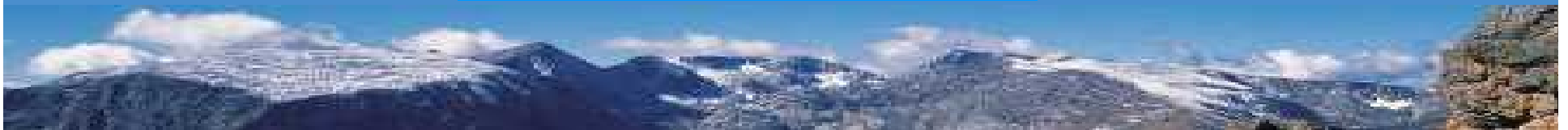
# The Greisen, Kuzmin, Zatsepin (GKZ) Cut-off

In the centre of momentum frame of reference, the ultrarelativistic protons are degraded by photo-pion and electron-positron pair production

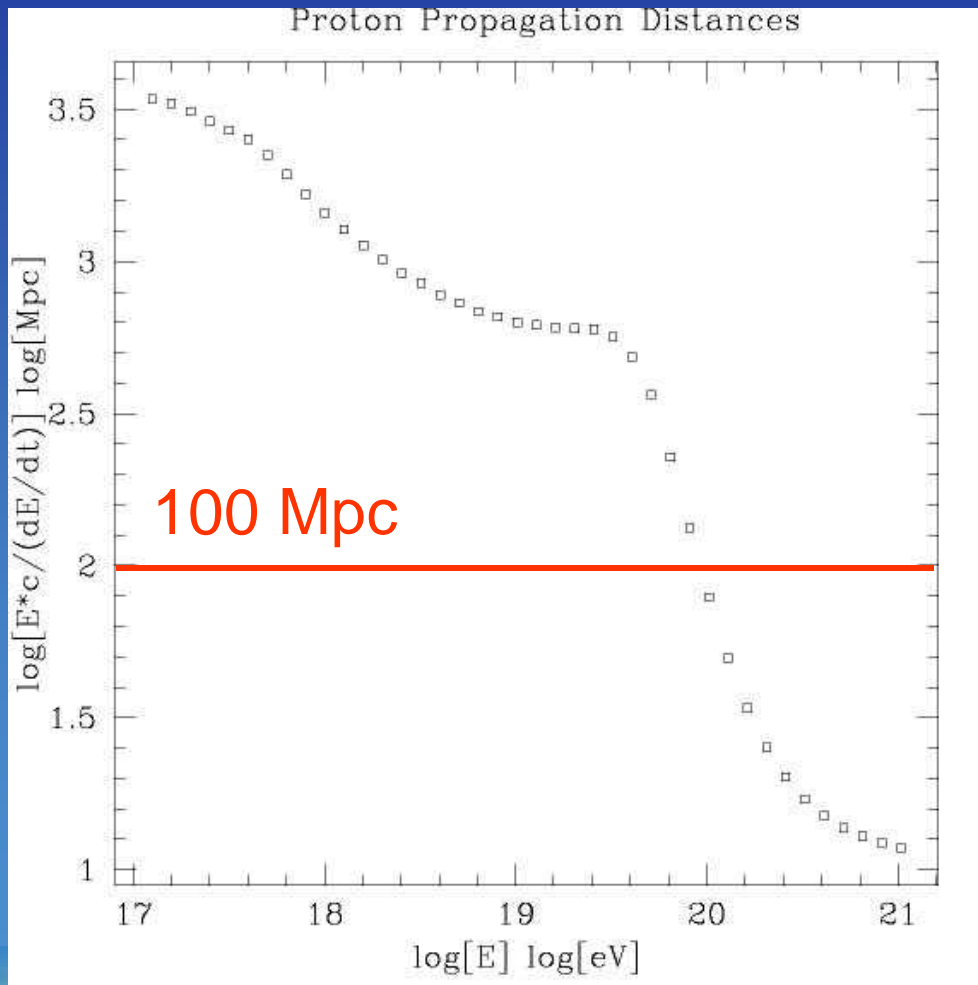
Photo-pion  
production



Electron-positron  
pair production

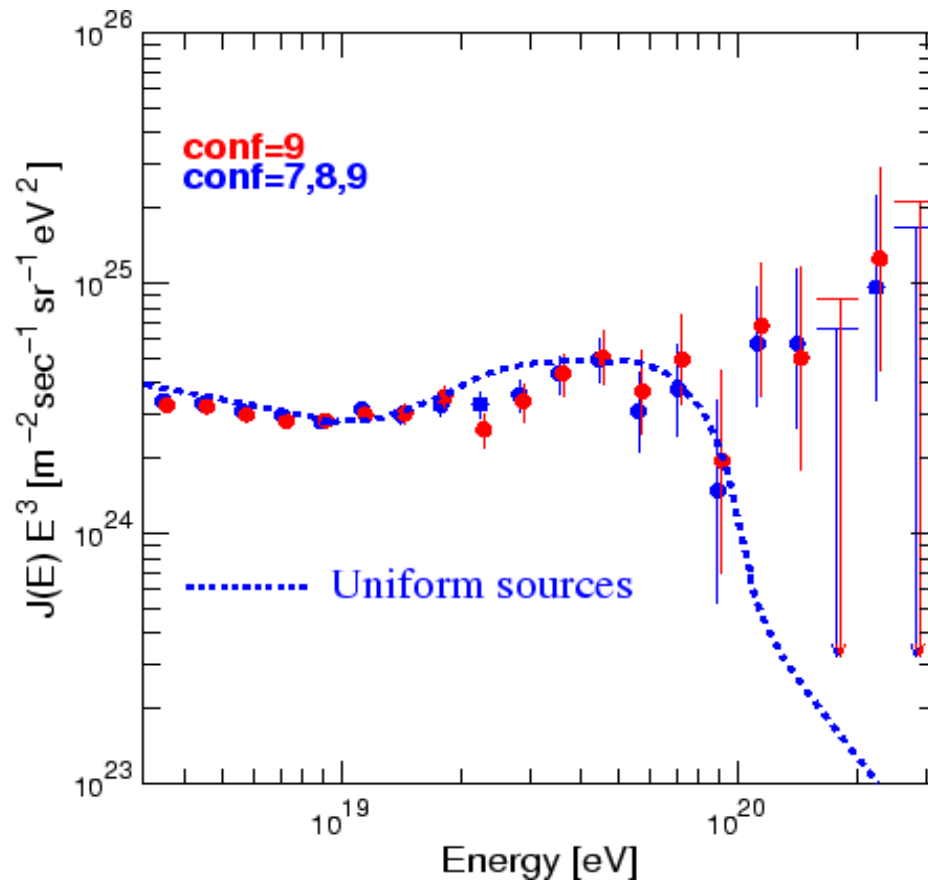


# The GZK Cut-off



As shown by Berezhinsky, when the cross-sections for these processes are worked out, there is a very strong dependence of the maximum distance of propagation. This is reflected in the predicted GZK cut-off.

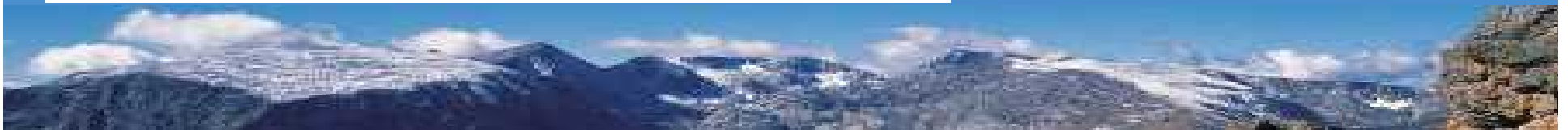
# Revised Agasa Results



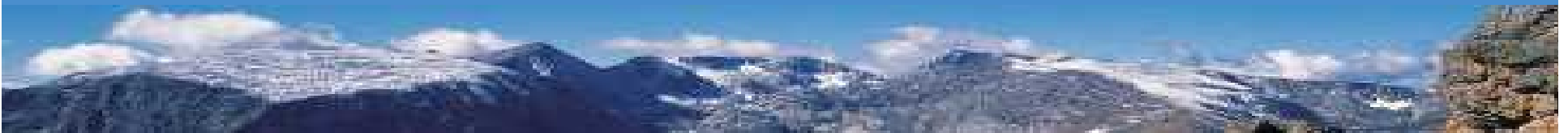
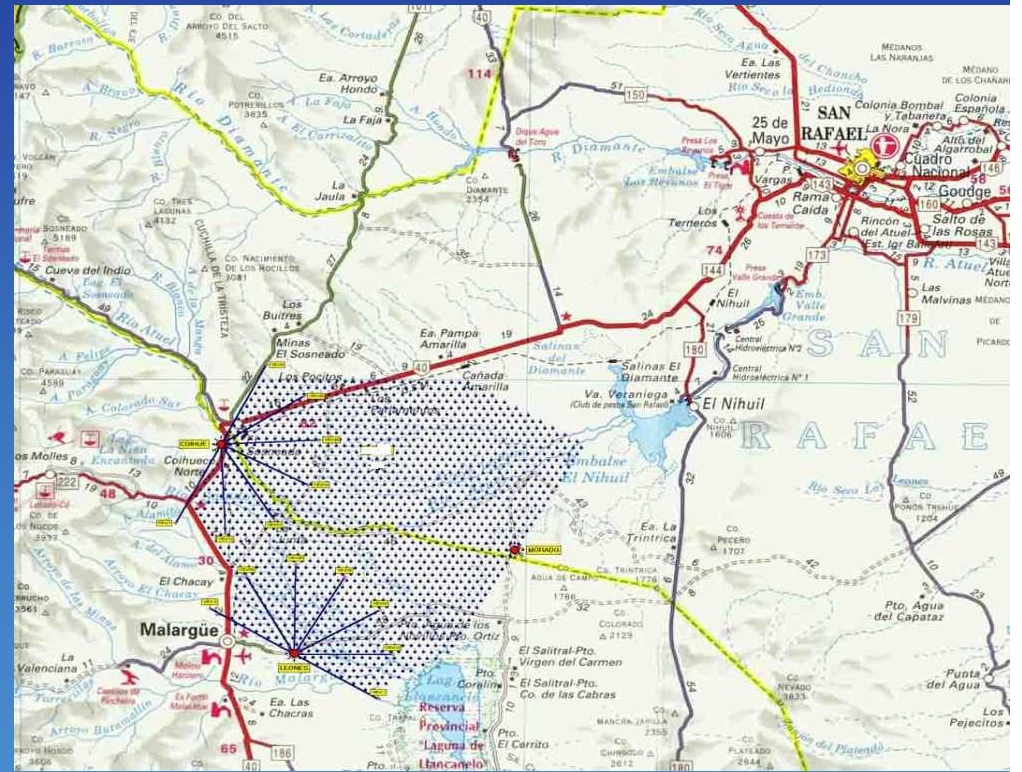
Energy shift  
~10% at  $10^{19}$  eV  
~15% at  $10^{20}$  eV  
to lower energies.

Above  $10^{20}$  eV  
11 events  $\rightarrow$  5~6  
events

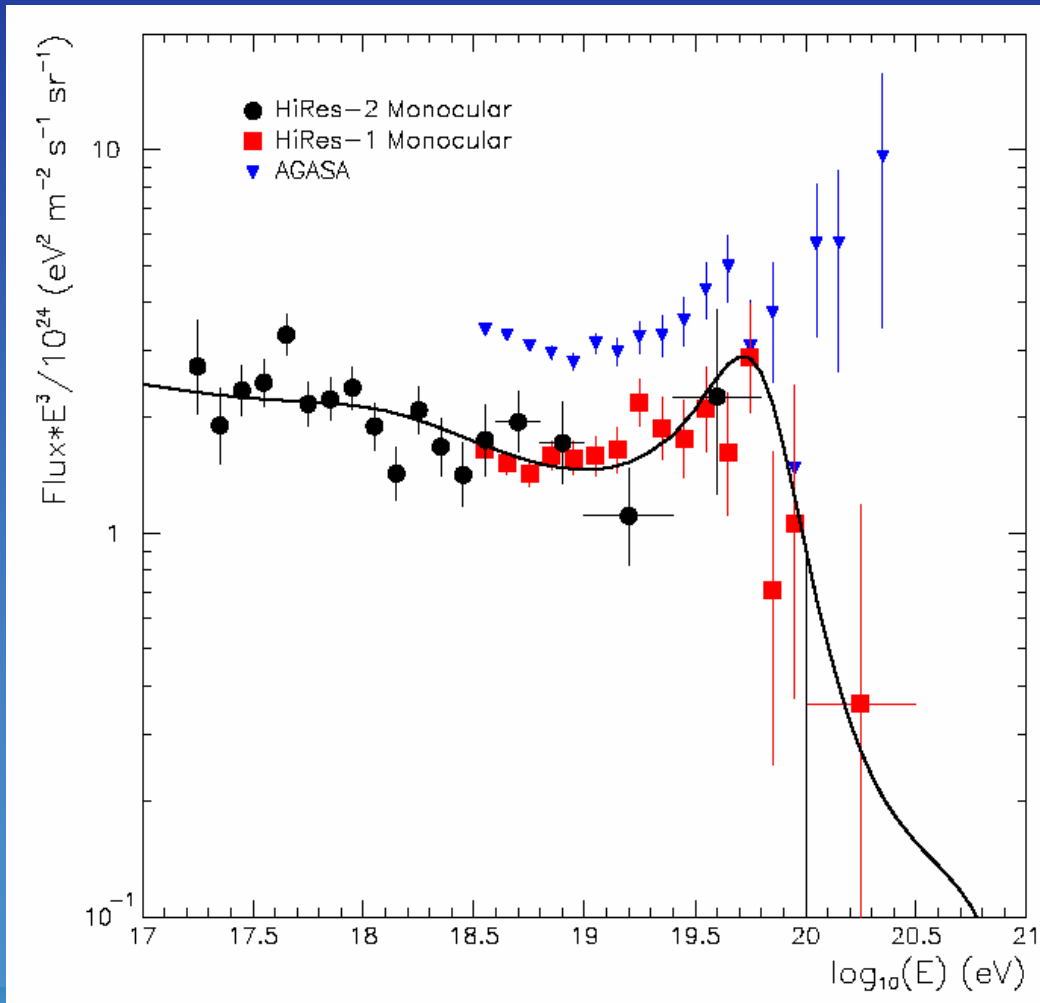
Teshima



# Auger Project



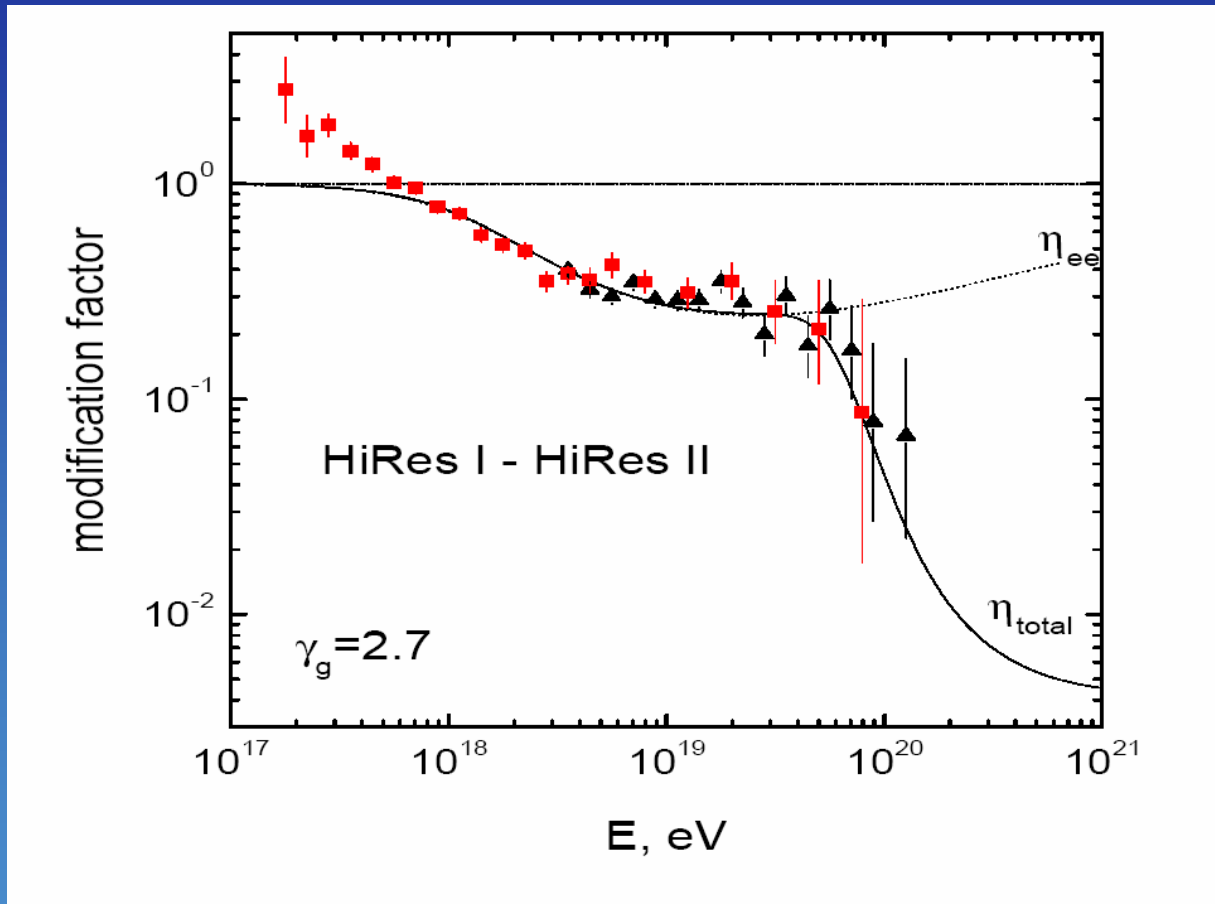
# HiRes1 and 2



Martens has reported that the HiRes data are consistent with the existence of the GZK cut-off.

Key importance of the Auger observations.

# The Berezinsky Fitting Formula

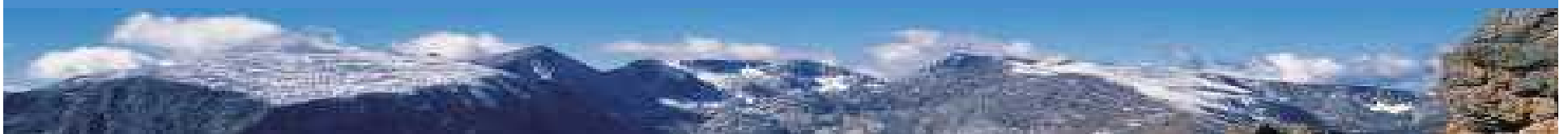


Looks very convincing, but need to get the calibration of the experiments right independent of knowing the answer.

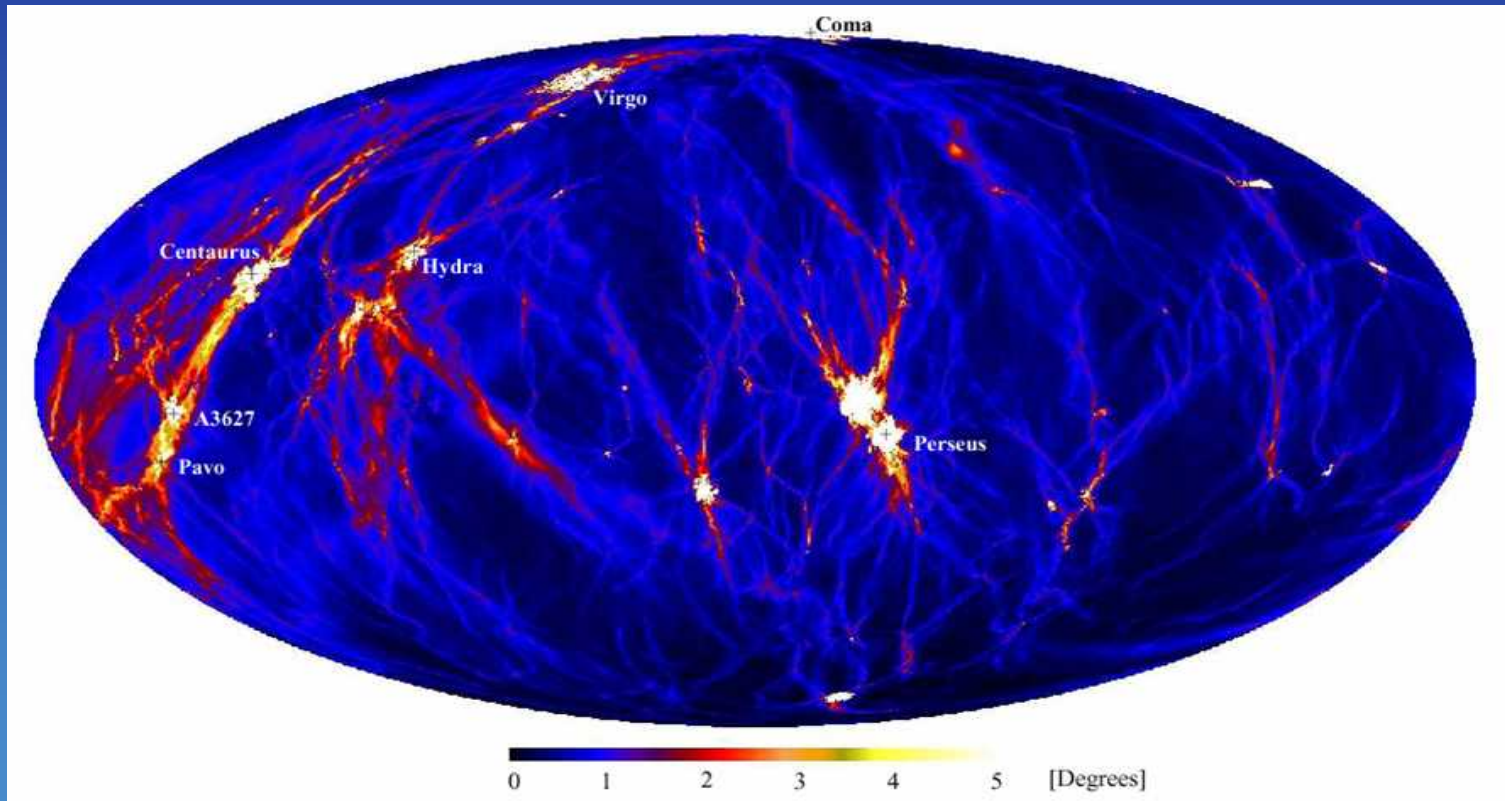
# Tracking the Sources of the UHECRs

There seems to be agreement that at the very highest energies,  $E > 3 \times 10^{19}$  eV, the deflections due to intergalactic magnetic fields are expected to be quite small.

Typical estimates of what the sky should look like at very high energies have been carried made by Dogel and others.

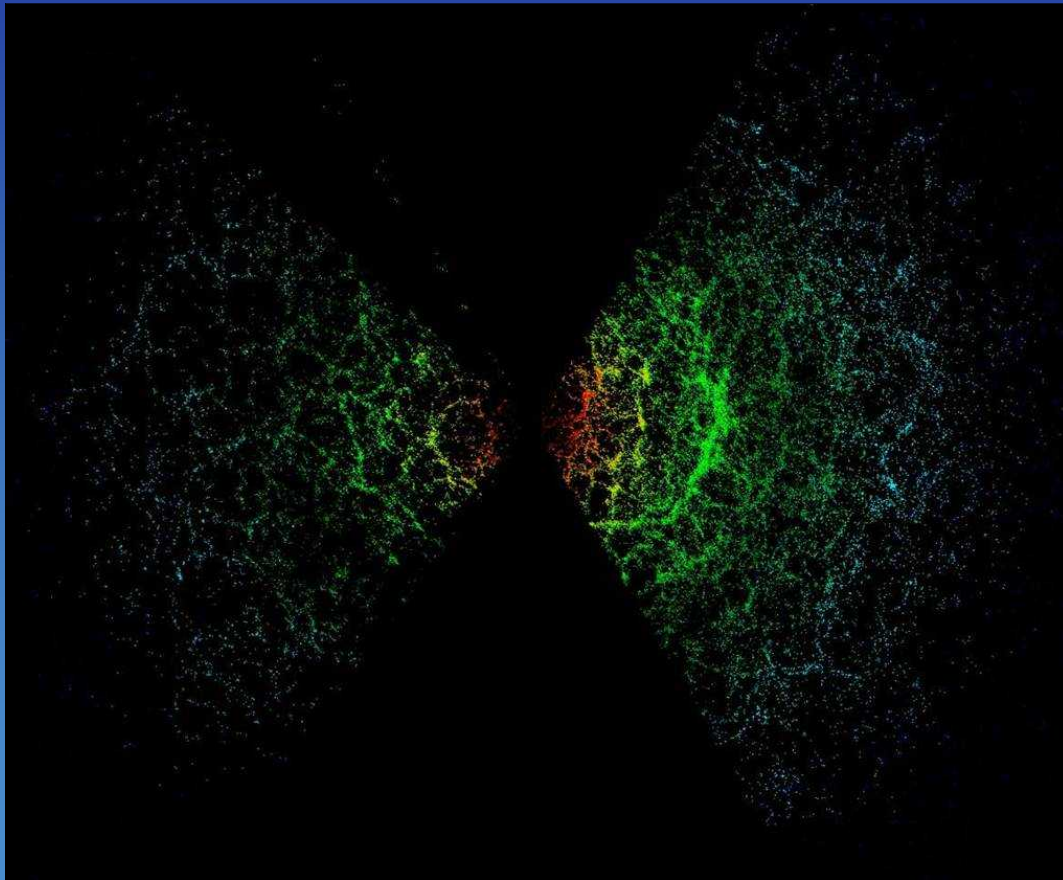


# Deflection of protons with energies $E > 4 \times 10^{19}$ eV



Trajectories of particles from within 100 Mpc.

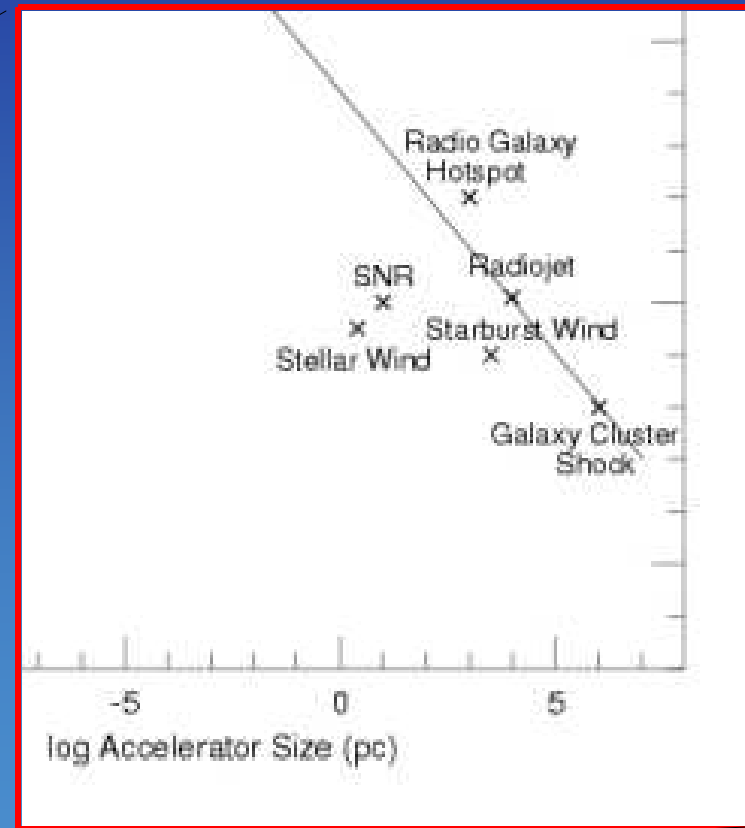
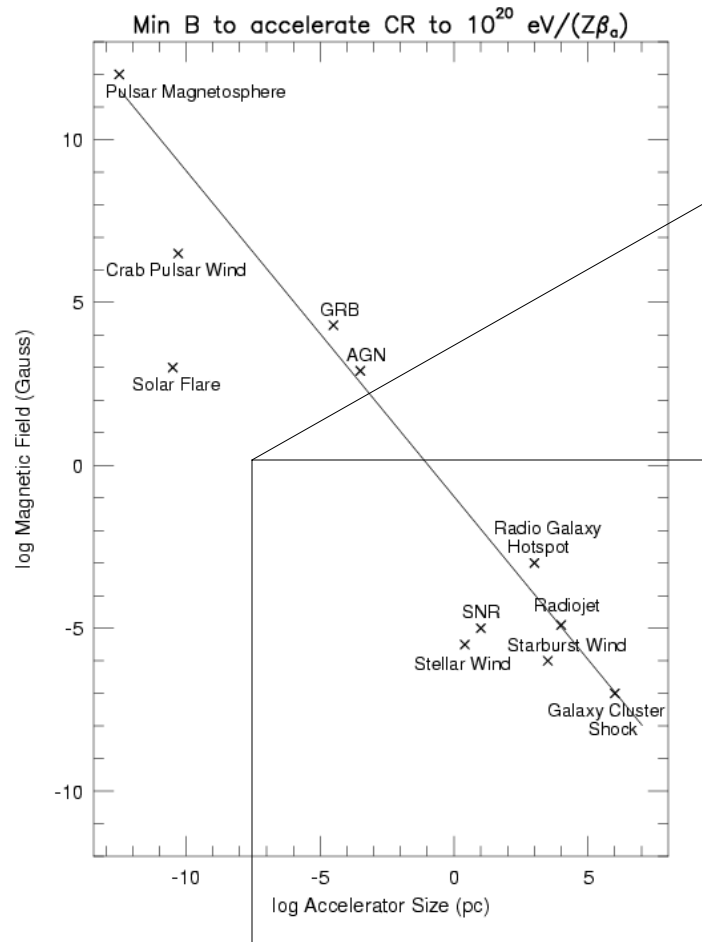
# The Importance of the Sloan Digital Sky Survey



One of the great puzzles is that, if this story is true, we should be able to find out directly what the associated astronomical objects are from the Sloan Digital Sky Survey – more than 250,000 galaxies to  $z \sim 0.4$ .

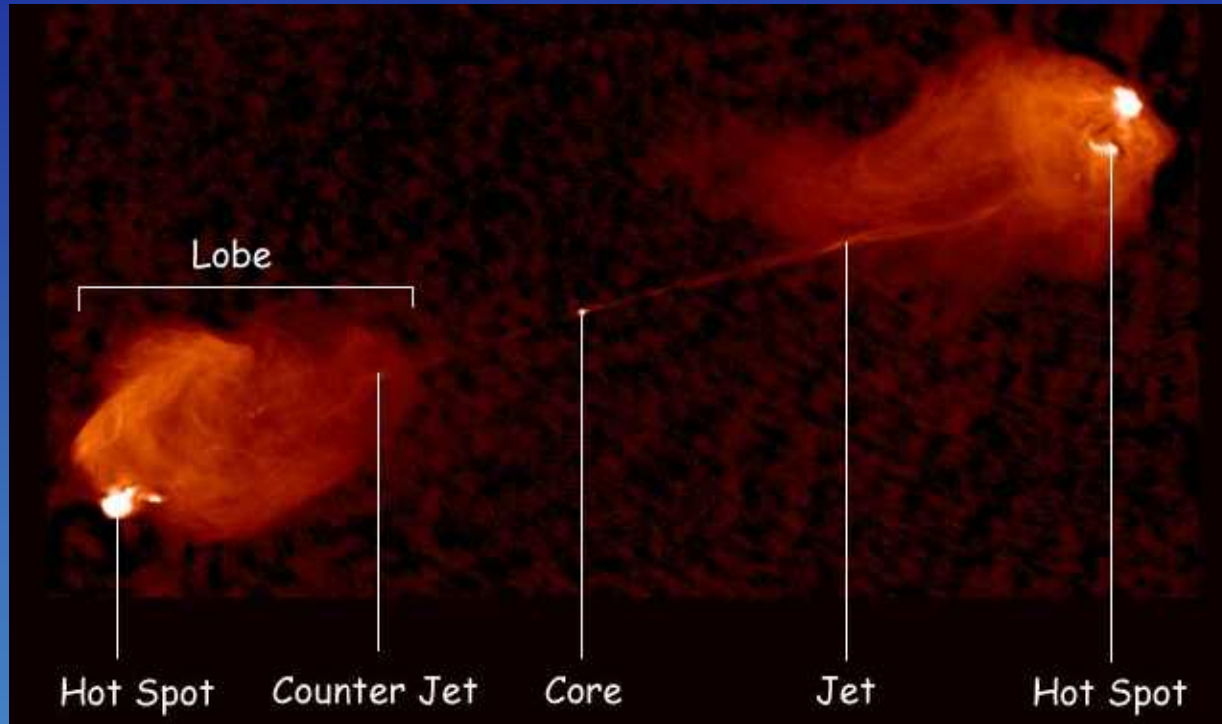


# The Hillas Acceleration Diagram



The size of the accelerating region

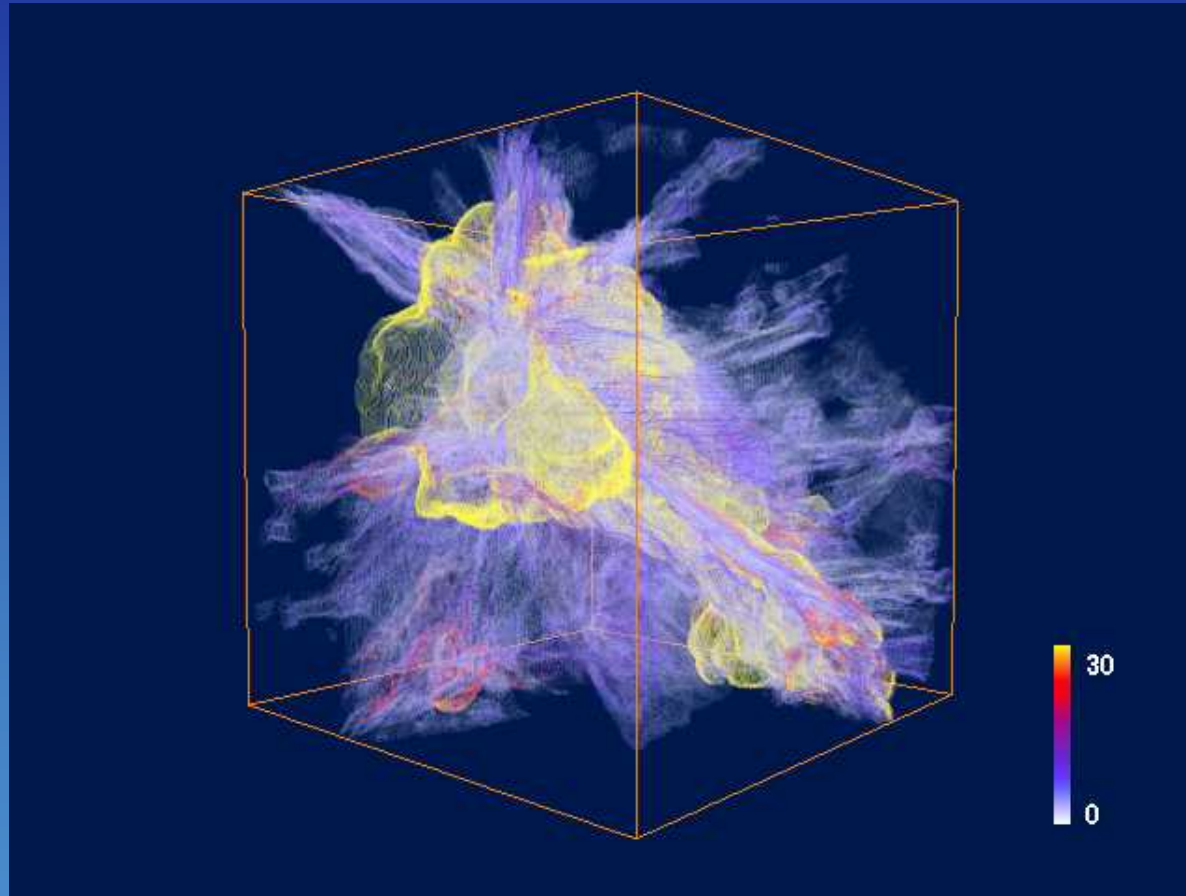
# Radio Galaxies



The radio emission is synchrotron radiation, the emission of extremely high energy electrons gyrating in a magnetic field.

The electrons are produced by jets of relativistic material ejected from the active galactic nucleus. Scales up to 1 Mpc, magnetic fields  $\sim 10^{-8}$  T.

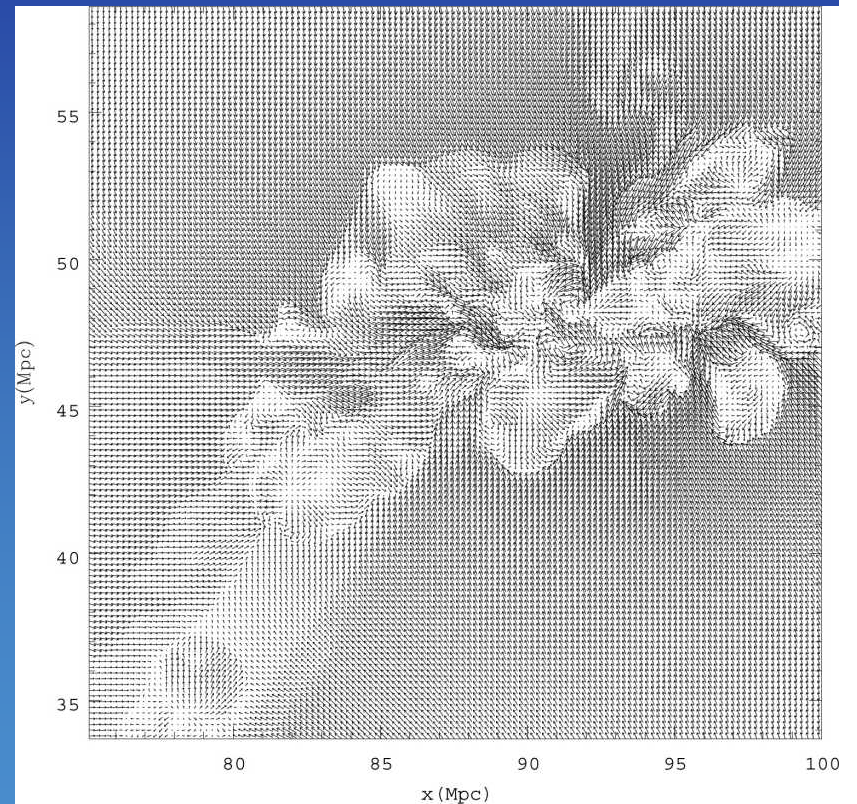
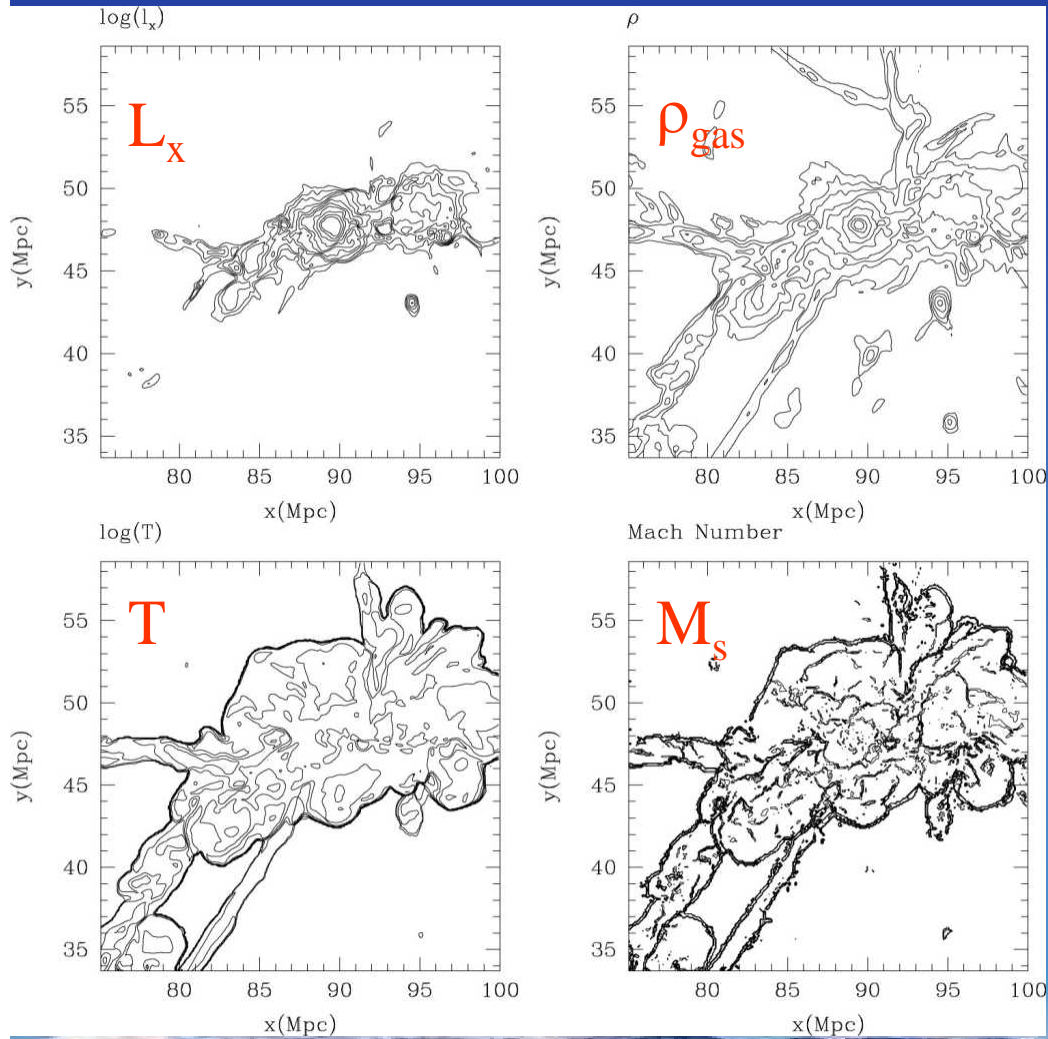
# Distribution of Shock Mach Numbers in Cluster of Galaxies



The Invisible Universe of Shocks

Ryu and Kang

# Velocity Field and Shocks in a Cluster Complex - simulations



Ryu and Kang

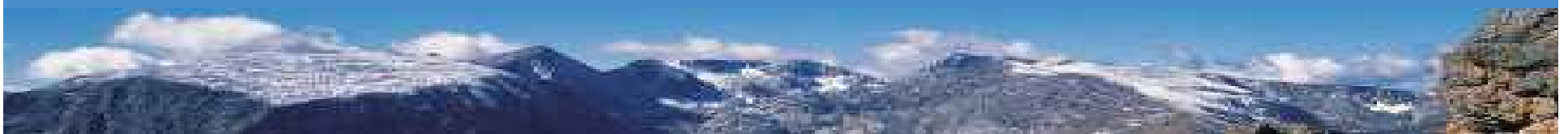
# Bottom-up versus Top-down

My instinct is that we can explain the highest energy particles by an acceleration mechanism.

**But**

What happens if future experiments do detect significant fluxes of  $E > 10^{20}$  eV particles and we cannot identify their sources?

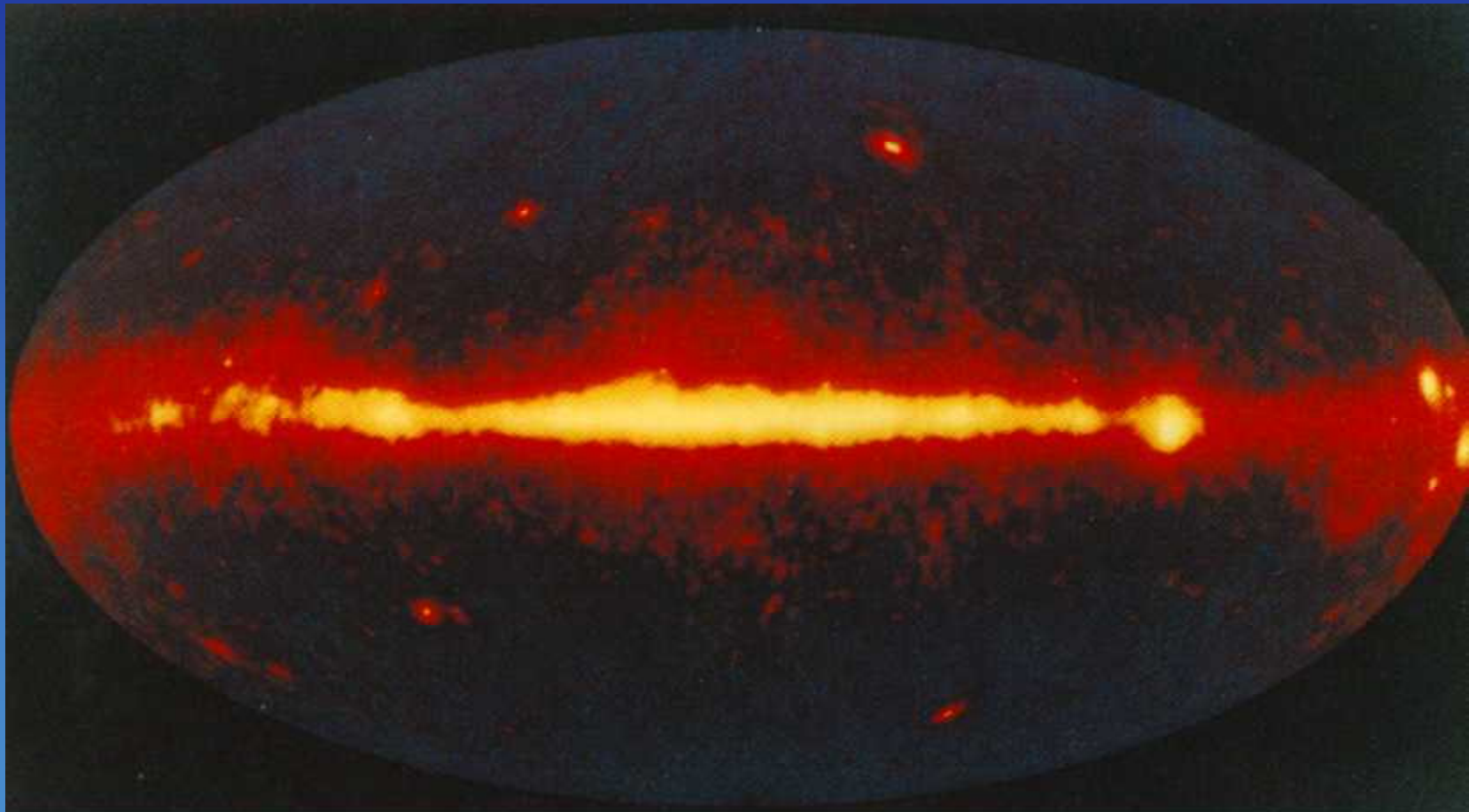
I believe this is the real reason these experiments are really important.



# 3. $\gamma$ -rays

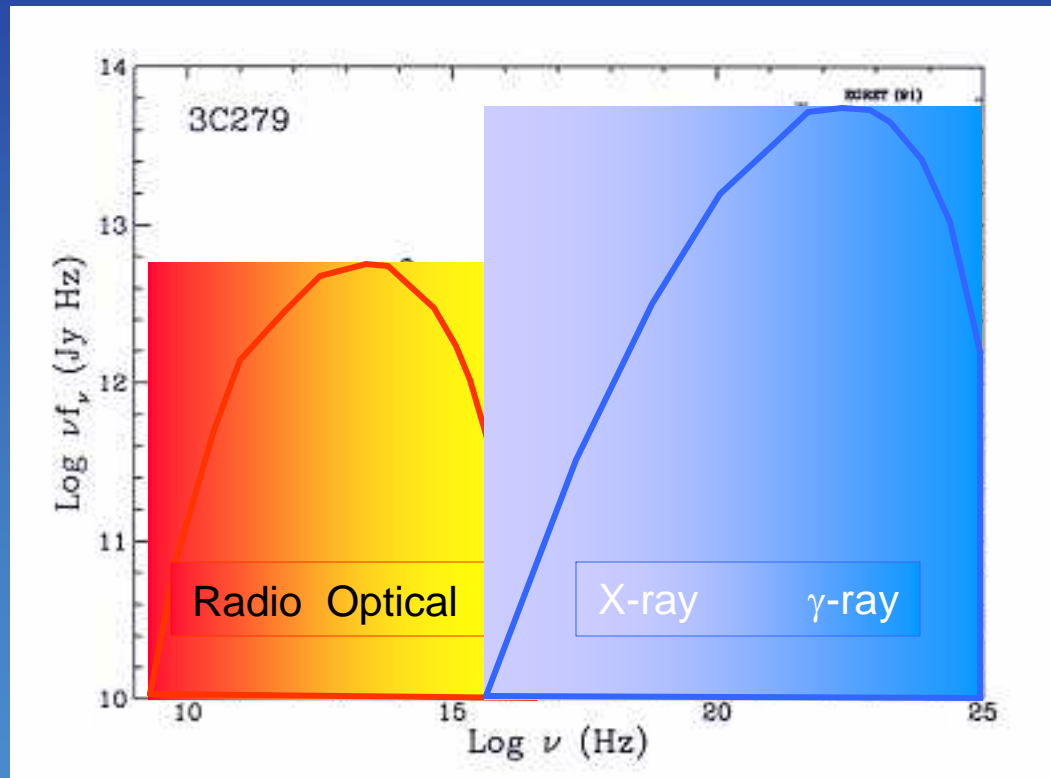


# The Sky at $\gamma$ -ray Wavelengths



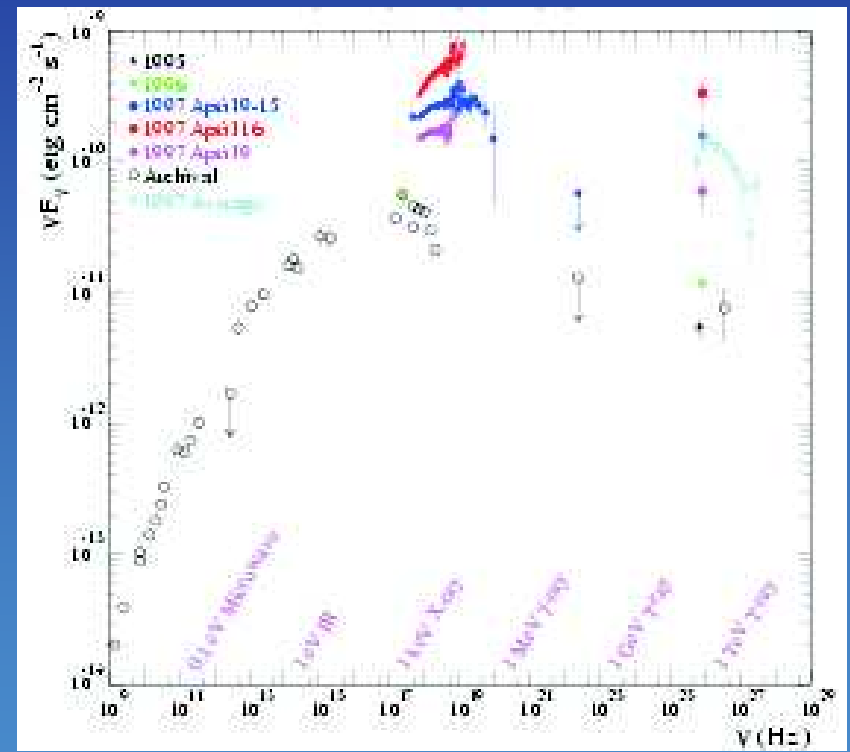
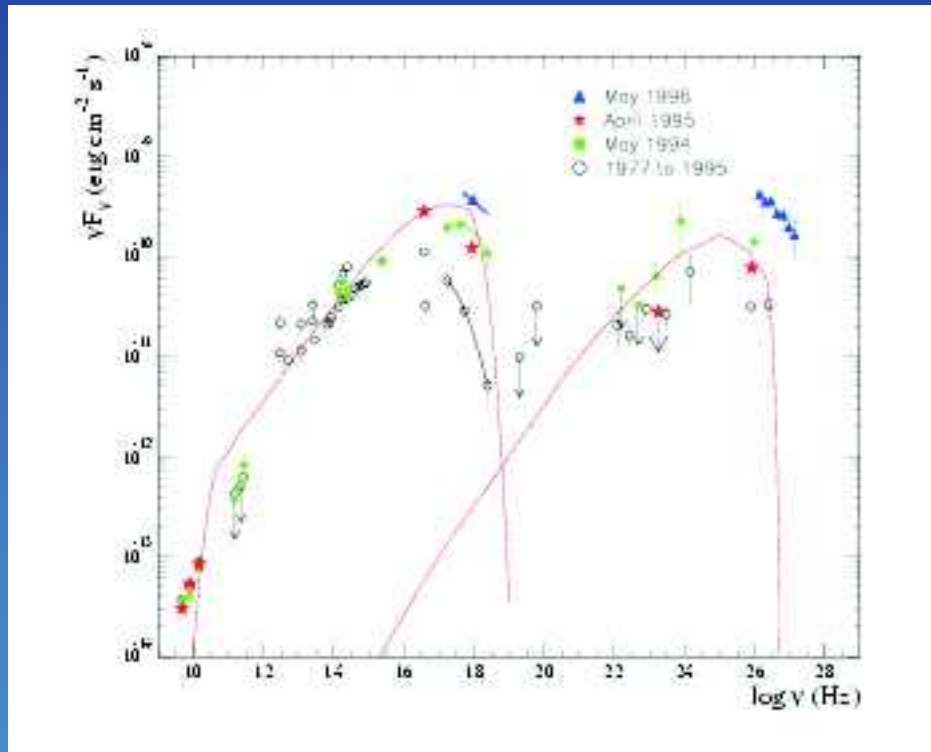
$\gamma$ -ray sources are extremely hot objects - extremely active galaxies and emission of high energy particles

# The Extreme $\gamma$ -ray source 3C279



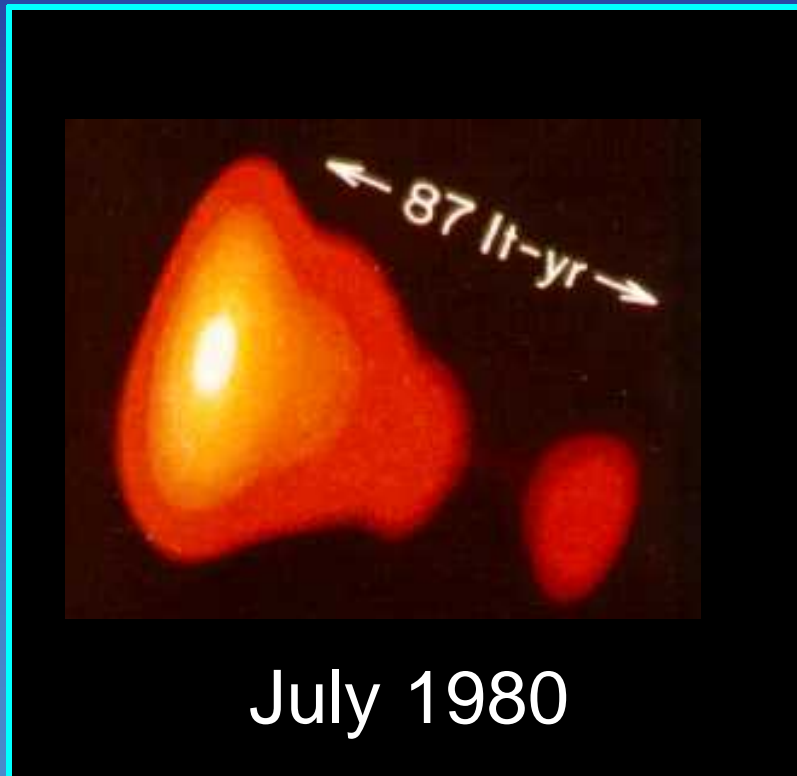
The Compton  $\gamma$ -ray Observatory discovered that the superluminal radio sources are extremely luminous  $\gamma$ -ray sources. The emission must also be relativistically beamed because of the same  $\gamma\gamma \rightarrow e^+e^-$  catastrophe described by Celotti.

# The Extreme $\gamma$ -ray Sources Markarian 421 and 501



These sources involve a huge range of high energy astrophysical processes, including relativistic beaming of the high energy  $\gamma$ -ray emission.

# Superluminal motions in 3C273



The structure of the radio quasar 3C273 was observed by Very Long Baseline Interferometry (VLBI) for 3 years.



# Superluminal motions in 3C120



The structure of the radio quasar 3C120 was observed by the Very Long Baseline Array (VLBI) for 6 years.

# Superluminal Velocities

The conventional picture is that these are associated with an **optical illusion** due to the fact that the jets are travelling at a speed  $v \sim c$  at an angle close to the line of sight.

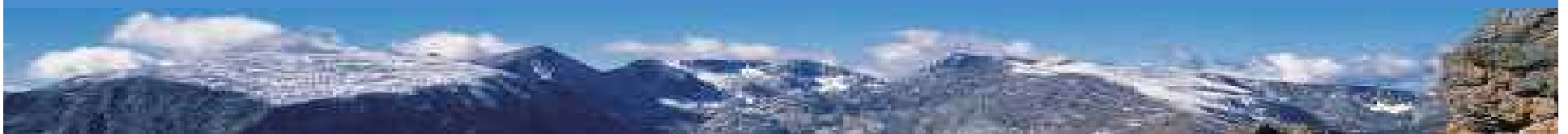


# Relativistic Beaming

The result is enormous enhancements of the luminosities, typically,

$$L \propto \kappa^4$$

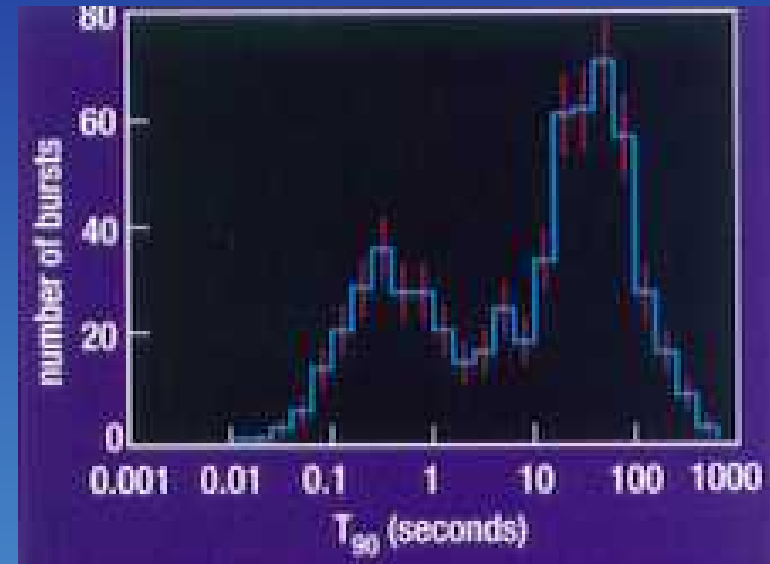
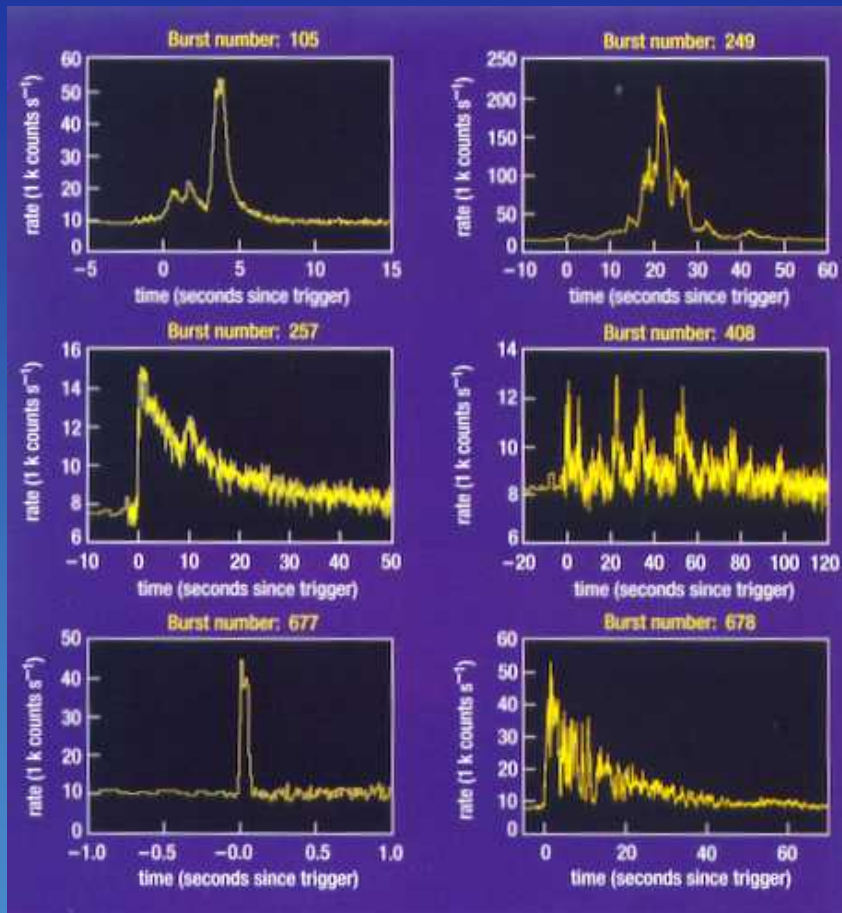
where  $\kappa = \gamma[1+(v/c) \cos \theta]$ . This is primarily due to relativistic aberration effects.



# 4. Cosmology

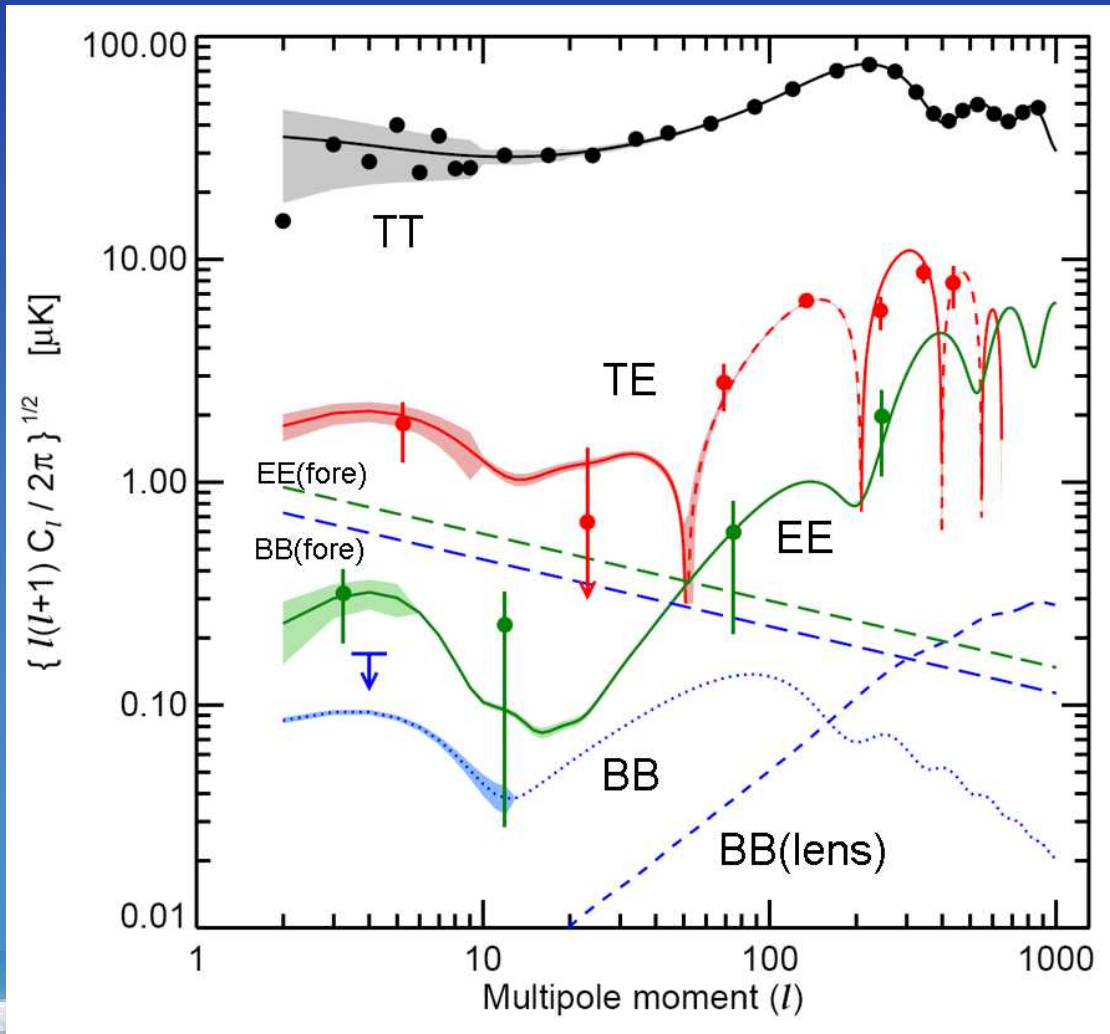


# $\gamma$ -ray Bursts



These were beautifully described by Celotti this morning and so I only mention them in their cosmological context.

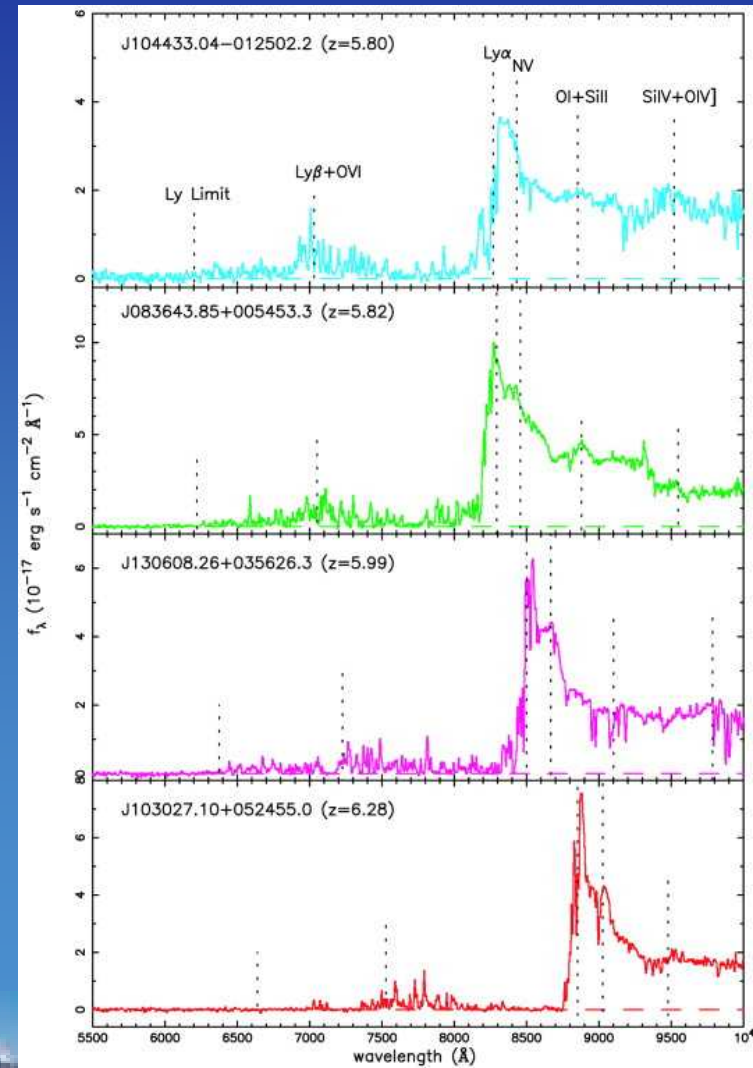
# The 3-year WMAP Power-spectra



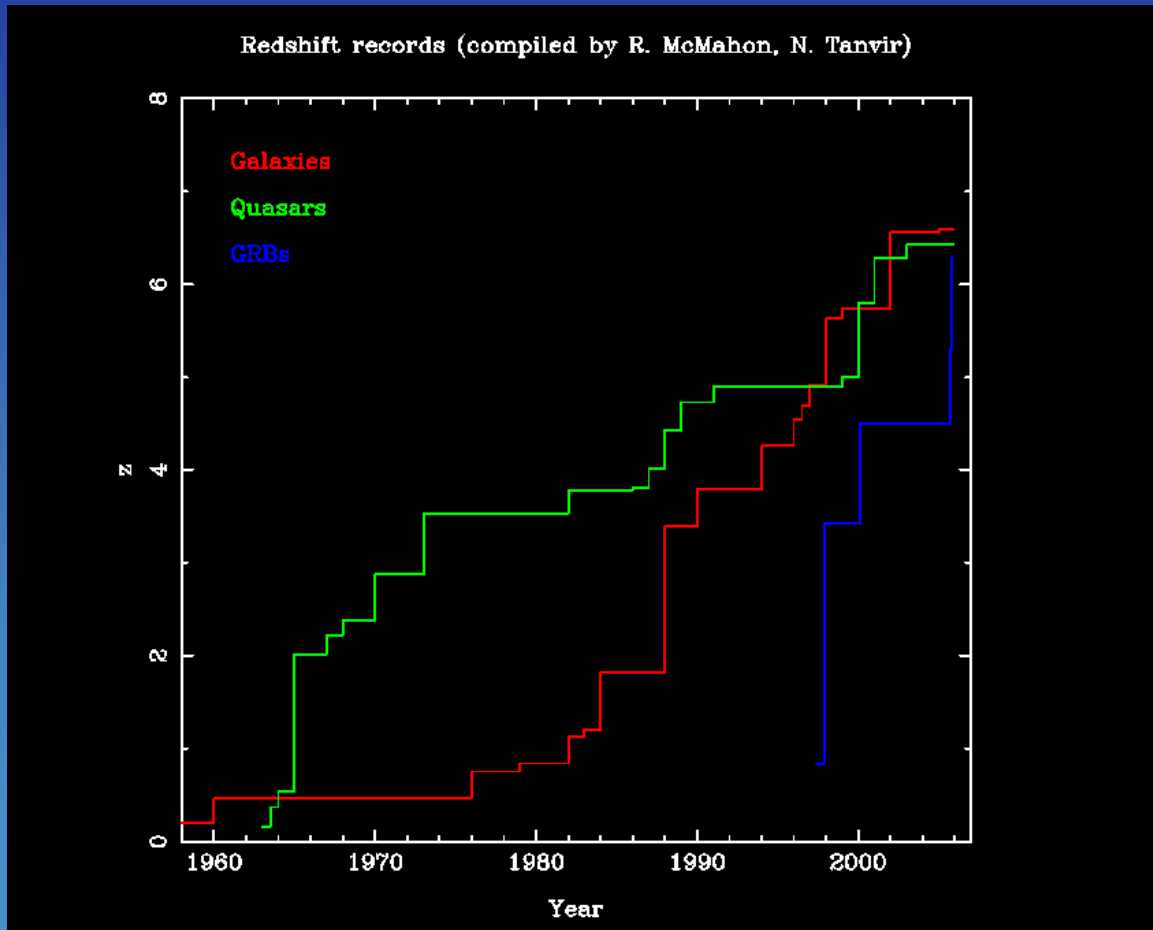
These observations provide strong constraints on the epoch of reionisation. It must have occurred in the redshift interval  $7 < z < 15$ .

# The High-Redshift IGM

- Period between recombination and reionization is crucial to understanding galaxy formation.
- Do the observed Gunn-Peterson troughs imply reionization?
- What is the re-ionisation history?



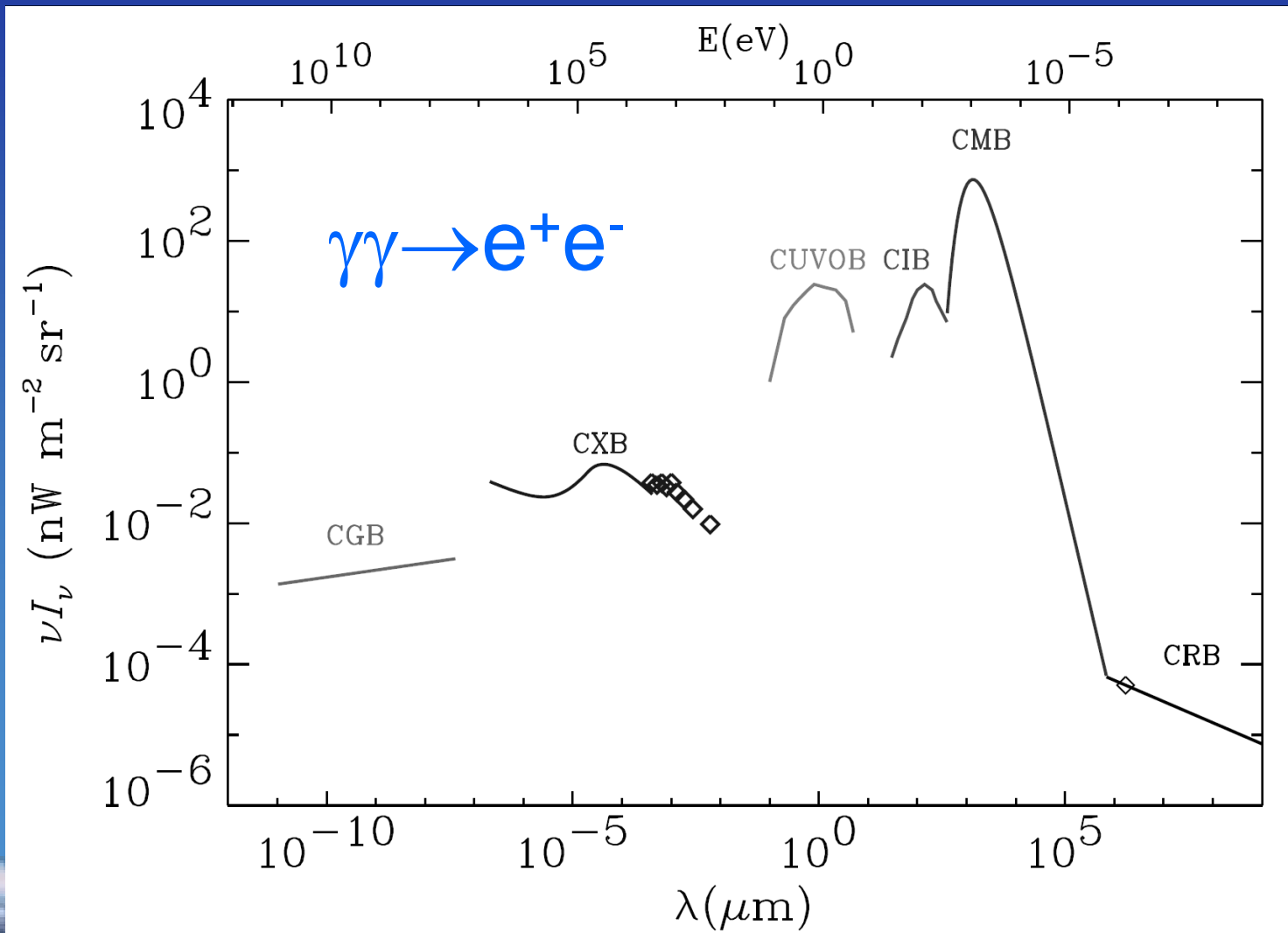
# The Distances of $\gamma$ -ray Bursts



$\gamma$ -ray bursts have turned out to be one of the most effective ways of finding very distant objects for cosmological studies. In particular, this is a way of getting beyond  $z = 6$ .

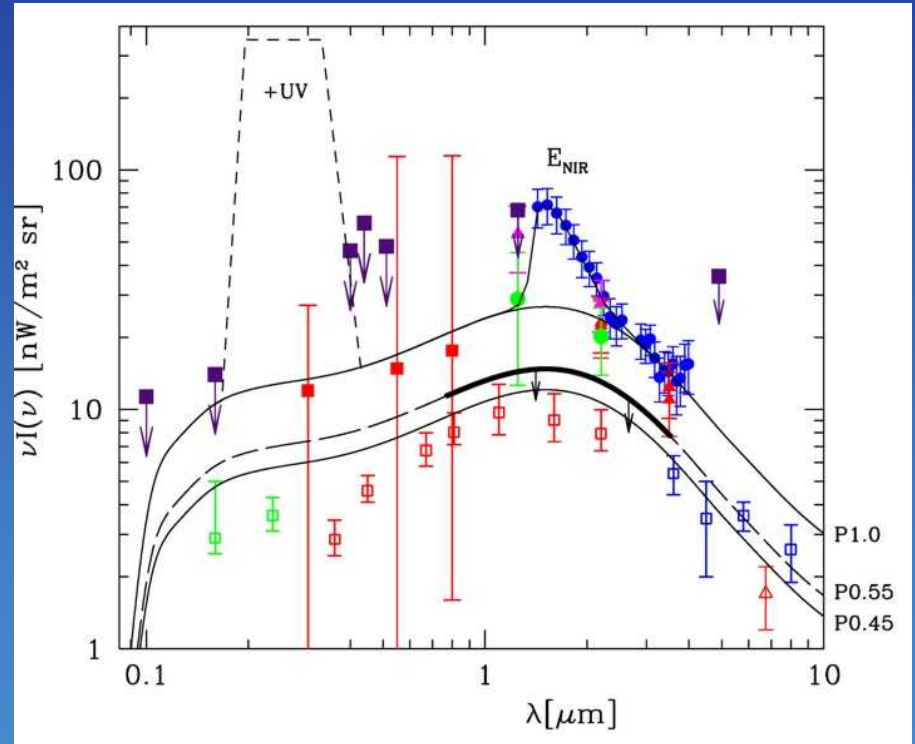
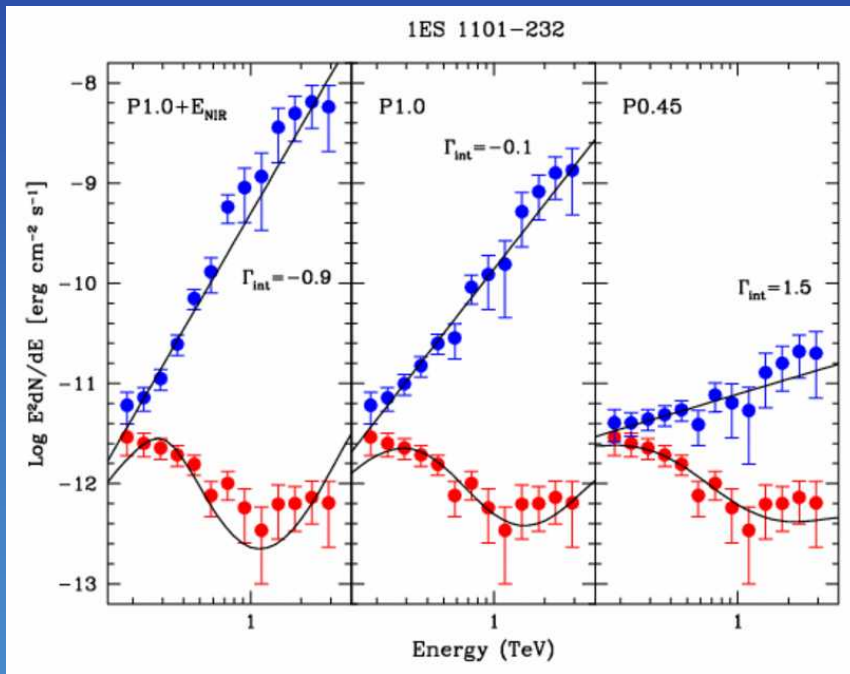


# Background Radiation



# Limiting the Extragalactic Background Radiation from $\gamma$ - $\gamma$ Interactions in Intergalactic Space

Redshift = 0.186



The  $\gamma$ - $\gamma$  interactions result in limits to the intergalactic fluxes of UV, optical and infrared photons. The total light cannot be much greater than that already detected in deep surveys of galaxies.

## Concluding Remark

Occhialini's legacy is much more than just a sequence of outstanding experiments and discoveries, but the inspiration of his colleagues and the next generation of physicists and astrophysicists. They have built on his achievements and played a key role of astrophysical research in Italy.

