

CATCHING THE UNIVERSE'S MOST  
ENERGETIC PARTICLES



# ULTRA-HIGH ENERGY COSMIC RAYS

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THE AUGER OBSERVATORY

LA-CONGA PHYSICS - COURSES 21B  
ASTROPARTÍCULAS Y COSMOLOGÍA  
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# OUTLINE

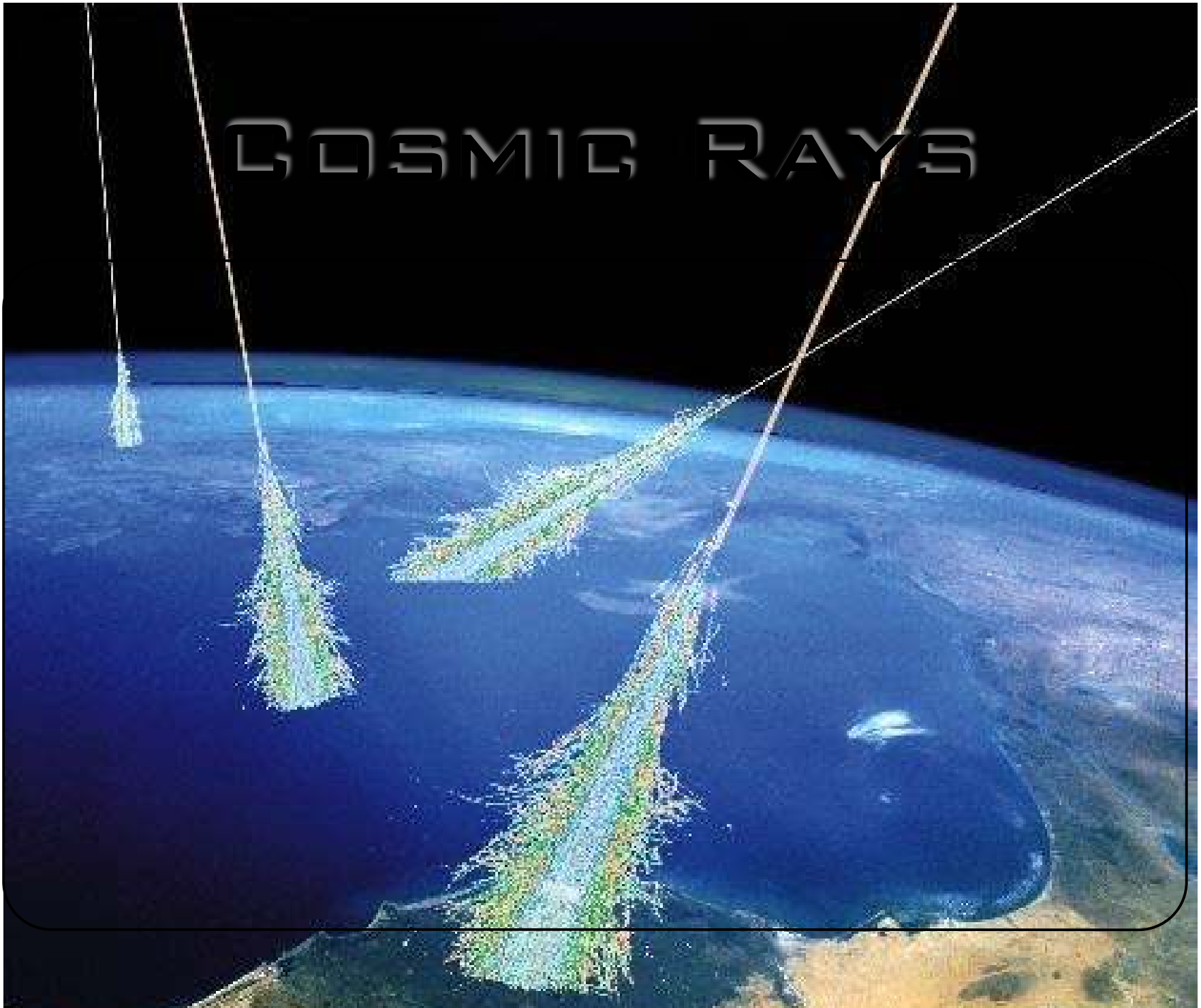
- ▶ **PART I: ASTROPHYSICS OF ULTRA-HIGH ENERGY COSMIC RAYS**
  - ▶ INTRODUCTION, HISTORY, & MOTIVATION
- ▶ **PART II: EXPERIMENTAL TECHNIQUES**
  - ▶ DETECTION TECHNIQUES & THE AUGER OBSERVATORY
- ▶ **PART III: EXPERIMENTAL RESULTS & IMPLICATIONS**
  - ▶ PHYSICS ANALYSES & PUBLISHED RESULTS
- ▶ **PART IV: CONCLUSIONS & FUTURE PROSPECTS**
  - ▶ NEW ANALYSES & FUTURE DETECTORS

# INTRODUCTION

▶ **WHAT ARE COSMIC RAYS?**

▶ **THE TERM "COSMIC RAYS" REFERS TO ELEMENTARY PARTICLES, NUCLEI, AND ELECTRO-MAGNETIC RADIATION OF EXTRA-TERRESTRIAL ORIGIN. THESE MAY INCLUDE EXOTIC, SHORT-LIVED PARTICLES SUCH AS MUONS, PI-MESONS OR LAMBDA BARYONS.**

# COSMIC RAYS



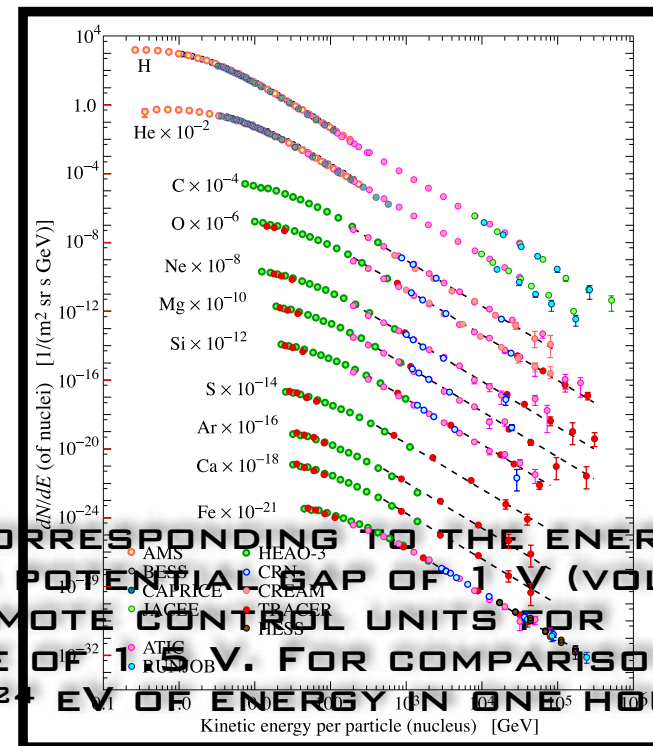
# WHAT ARE COSMIC RAYS?

J. Beringer et al. (Particle Data Group)  
Phys. Rev. **D86**, 010001 (2012)

▶ IN THE ENERGY RANGE OF  $10^{12}$ - $10^{15}$  EV (ELECTRON-VOLTS\*), COSMIC RAYS ARRIVING AT THE EDGE OF THE EARTH'S ATMOSPHERE HAVE BEEN MEASURED TO CONSIST OF:

- ▶ ~ 50% PROTONS
- ▶ ~ 25% ALPHA PARTICLES
- ▶ ~ 13% C/N/O NUCLEI
- ▶ < 1% ELECTRONS
- ▶ < 0.1% GAMMAS

AN ELECTRON-VOLT IS A MICROSCOPIC UNIT CORRESPONDING TO THE ENERGY GAINED/LOST BY AN ELECTRON IN CROSSING A POTENTIAL GAP OF 1 V (VOLT). A TYPICAL BATTERY (E.G. A AA-CELL USED IN REMOTE CONTROL UNITS FOR TELEVISION SETS) HAS A VOLTAGE DIFFERENCE OF 1.5 V. FOR COMPARISON: A 40 W (WATT) READING-LIGHT USES ABOUT  $10^{24}$  EV OF ENERGY IN ONE HOUR.



# ROUTE TO DISCOVERY

- ▶ AT THE START OF THE 1900's, FRENCH PHYSICIST HENRI BECQUEREL DISCOVERED THAT CERTAIN ELEMENTS ARE UNSTABLE, AND WOULD TRANSMUTE INTO OTHER ELEMENTS, AND IN THE PROCESS, EMIT WHAT APPEARED TO BE PARTICLES. THESE "PARTICLES" WERE GIVEN THE NAME "RADIATION", AND THE PROCESS ITSELF REFERRED TO AS "RADIOACTIVE DECAY".

# ROUTE TO DISCOVERY

- ▶ IT WAS NOTICED THAT AN INSTRUMENT CALLED AN "ELECTROSCOPE" WOULD SPONTANEOUSLY DISCHARGE IN THE PRESENCE OF RADIOACTIVE MATERIALS. THE RATE OF DISCHARGE OF AN ELECTROSCOPE IS THEN USED AS A MEASURE OF THE LEVEL OF RADIATION. THE ELECTROSCOPE THUS BECAME A STANDARD INSTRUMENT FOR STUDYING RADIATION AND RADIOACTIVE MATERIALS IN THE FIRST DECADES OF THE TWENTIETH CENTURY.

# ROUTE TO DISCOVERY

- ▶ **HOWEVER, PHYSICISTS NOTICED THAT ELECTROSCOPES WERE FOUND TO DISCHARGE SLOWLY EVEN IN THE ABSENCE OF RADIOACTIVE MATTER!**
- ▶ **THIS RESIDUAL DISCHARGE COULD NOT BE ATTRIBUTED TO LEAKAGE. THERE APPEARS TO BE A BACKGROUND RADIATION.**

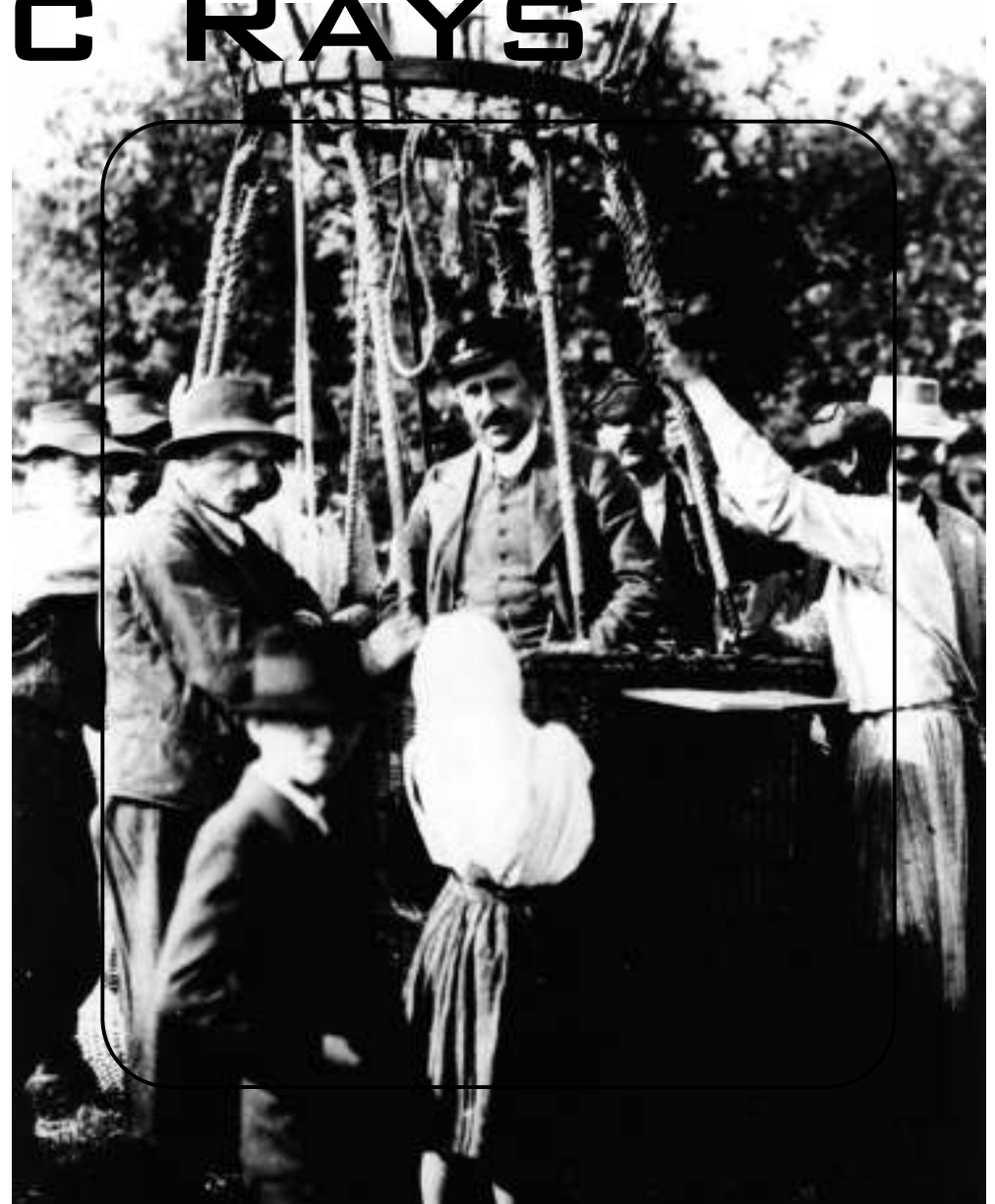
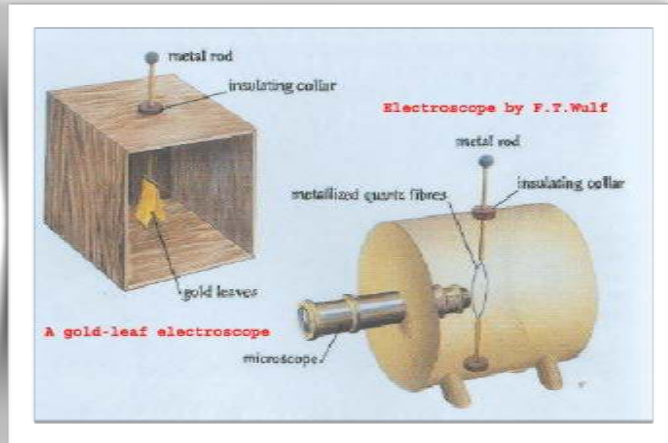


**A GOLD-LEAF BENNET-TYPE ELECTROSCOPE (CA. 1880s) MANUFACTURED BY DUCRETET.**



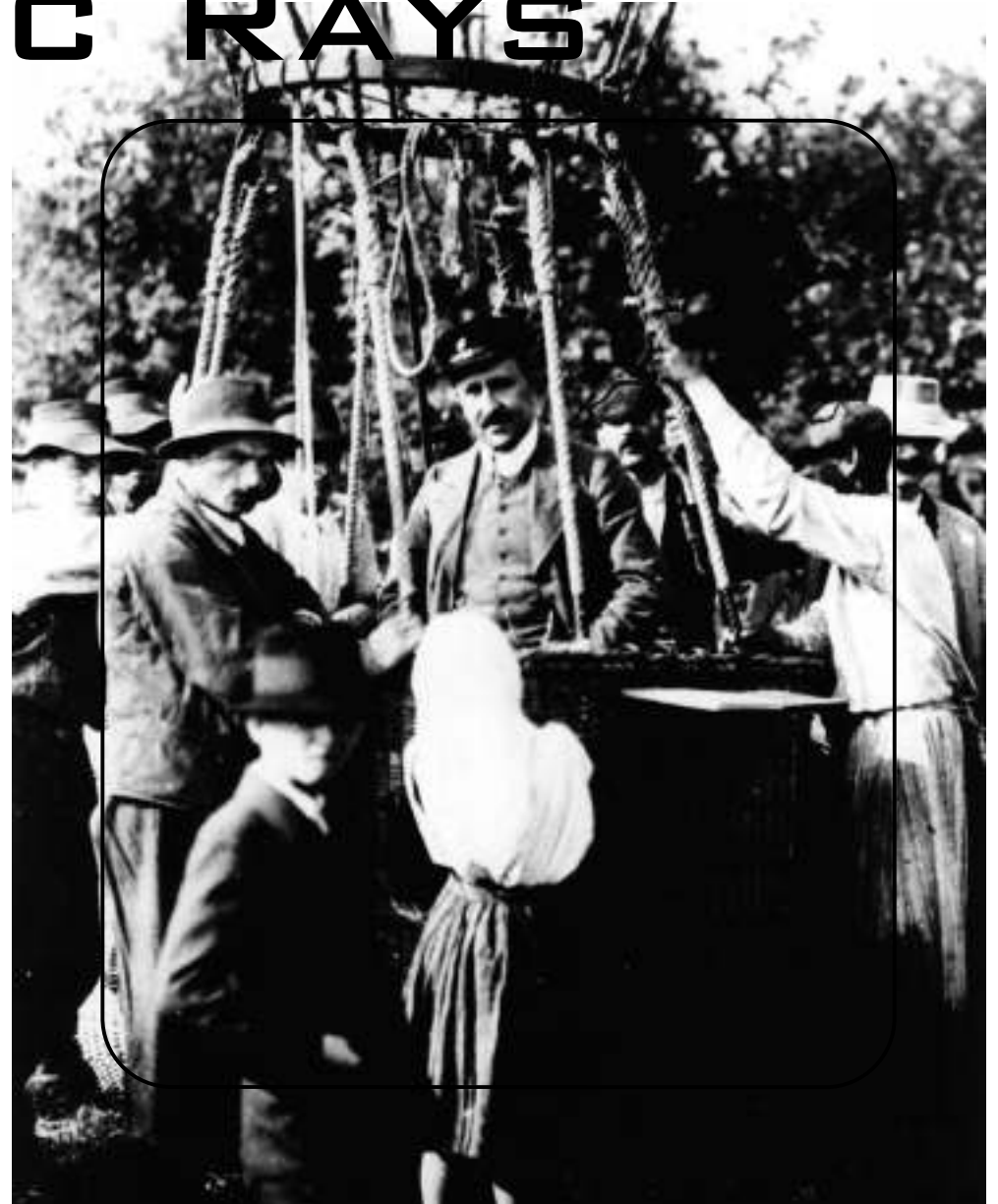
# DISCOVERY OF COSMIC RAYS

▶ TO STUDY THE SOURCE OF THIS BACKGROUND, AUSTRIAN PHYSICIST VICTOR. F. HESS MADE MEASUREMENTS OF RADIATION LEVELS AT DIFFERENT ALTITUDES WITH ELECTROSCOPES ABOARD A BALLOON.



# DISCOVERY OF COSMIC RAYS

▶ THE MOTIVATION FOR THIS STUDY WAS TO DISTANCE THE ELECTROSCOPES FROM RADIATION SOURCES IN THE EARTH.

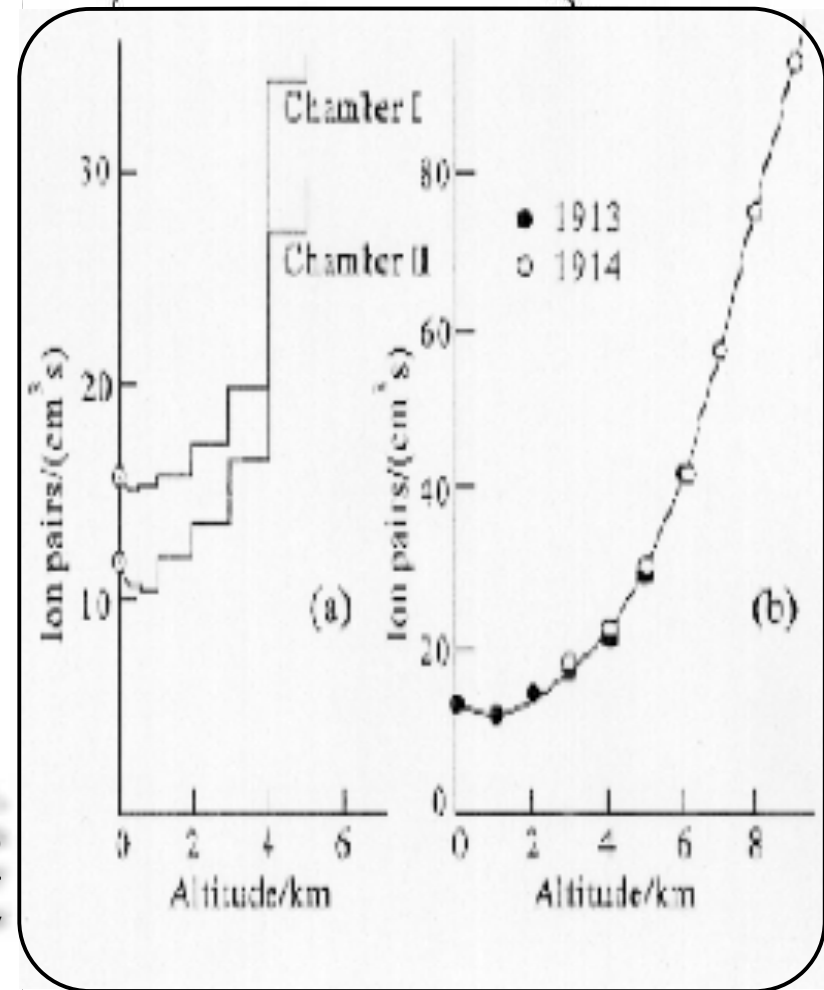


# DISCOVERY OF COSMIC RAYS

▶ HESS WENT AS HIGH AS 17,500 FEET (OVER 5 KM!) IN HIS BALLOON WITHOUT OXYGEN TANKS.

▶ SURPRISINGLY, HE FOUND THAT THE RADIATION LEVELS INCREASED WITH ALTITUDE!

THE FLIGHT OF HESS & CREW ON AUGUST 7, 1912, STARTED IN AUSSIG AT 06:12 AND REACHED THE MAXIMUM HEIGHT OF 5350 M AT 10:45. THE LANDING TOOK PLACE NEAR PIESKOW IN BRANDENBURG AT 12:15.



VARIATION OF IONIZATION WITH ALTITUDE ACCORDING TO (A) HESS (1912) AND (B) KOLHÖRSTER (1913, 1914).

# DISCOVERY OF COSMIC RAYS

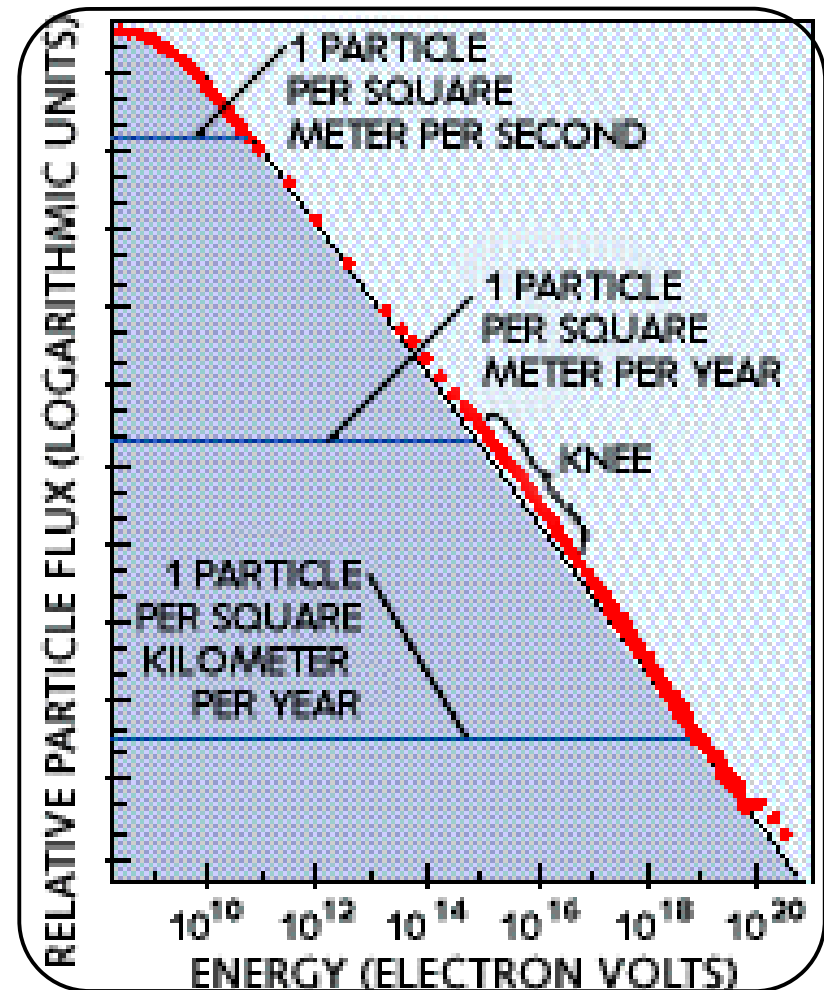
- ▶ HESS INTERPRETED THIS RESULT TO MEAN THAT RADIATION IS ENTERING THE ATMOSPHERE FROM OUTER SPACE.
- ▶ HE GAVE THIS PHENOMENON THE NAME "COSMIC RADIATION", WHICH LATER EVOLVED TO "COSMIC RAYS".
- ▶ HESS WAS AWARDED THE NOBEL PRIZE IN 1936 FOR HIS DISCOVERY OF COSMIC RAYS.

# COSMIC RAYS ENERGY

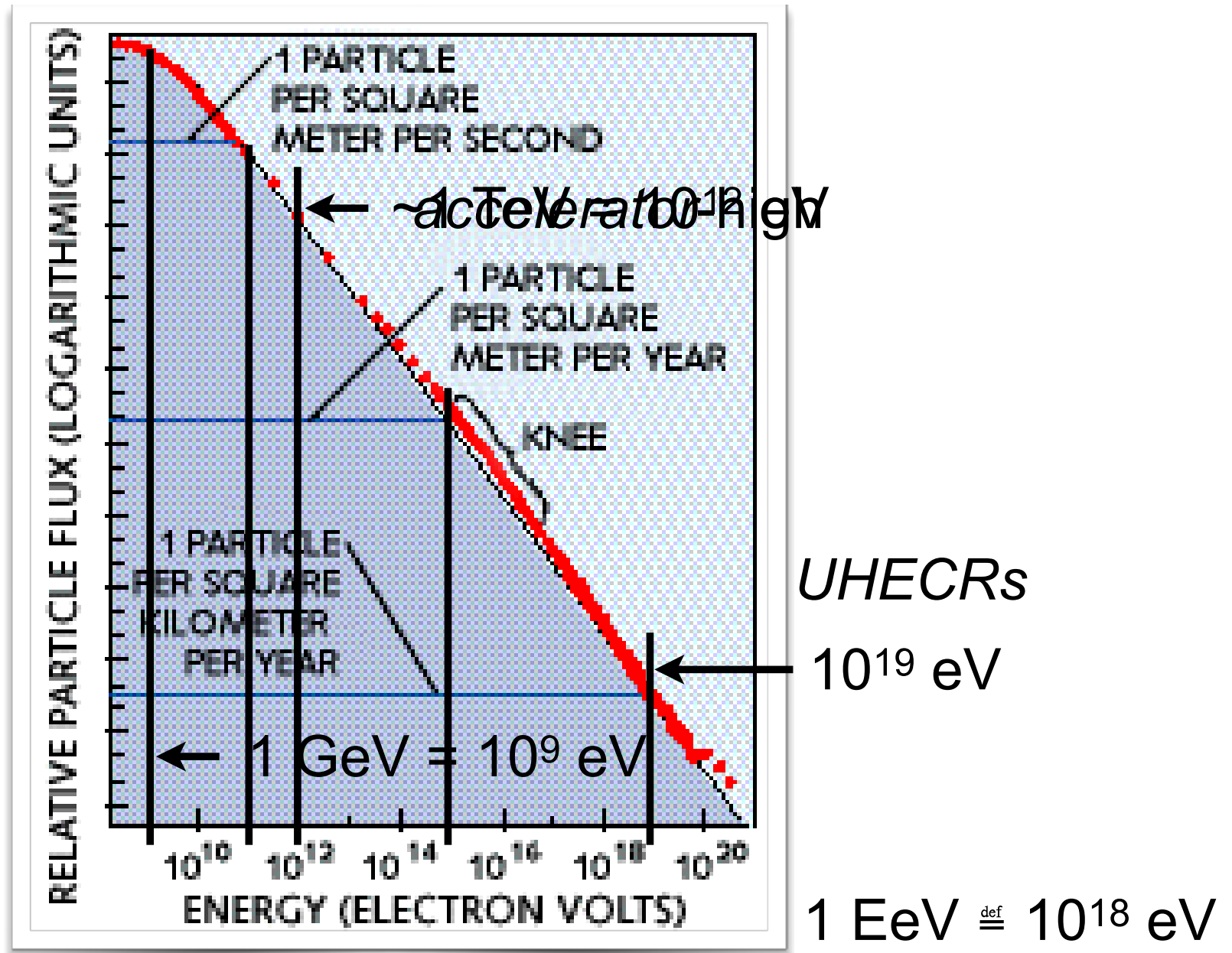
- ▶ COSMIC RAYS HAVE BEEN OBSERVED WITH ENERGIES FROM  $10^9$  EV TO OVER  $10^{20}$  EV.
- ▶ THE "FLUX" OF COSMIC RAYS APPEARS TO FOLLOW A SINGLE POWER LAW  $\sim E^{-3}$ .
- ▶ THE VARIATION OF THE FLUX WITH ENERGY IS REFERRED TO AS THE "ENERGY SPECTRUM".

# ENERGY SPECTRUM

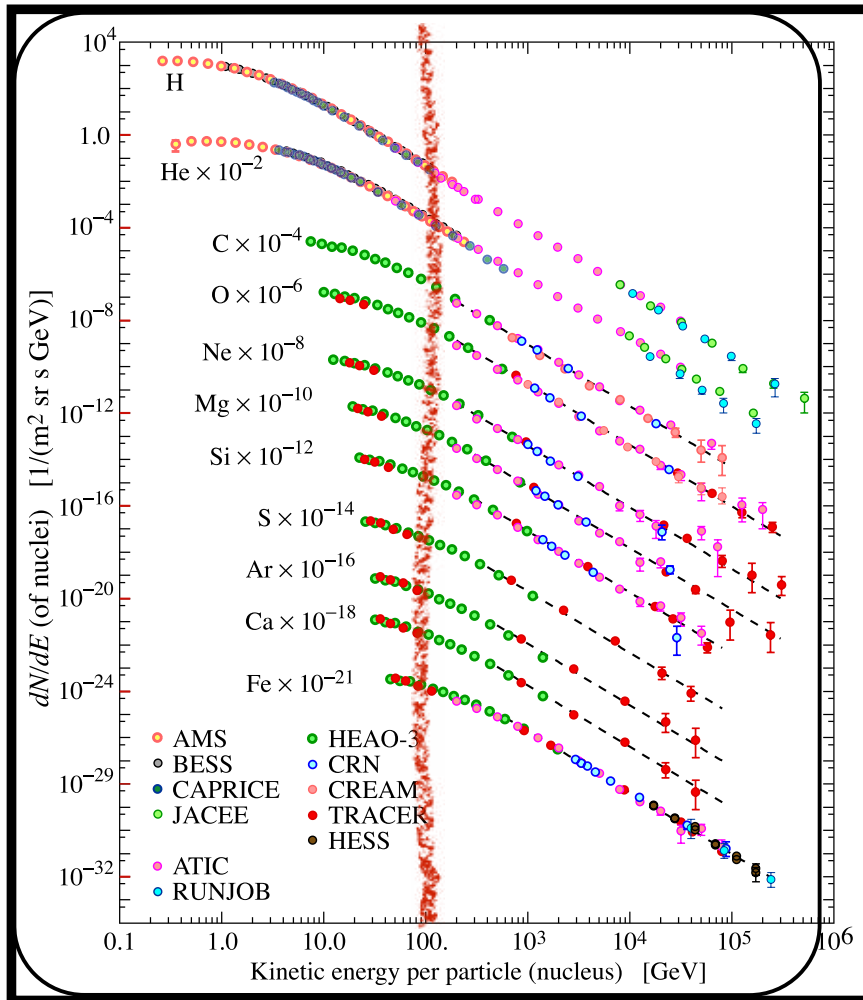
- ▶ IT APPEARS TO BE A SMOOTH CURVE OVER 10 DECADES OF ENERGY.
- ▶ THE SMALL CHANGES IN THE SPECTRAL INDEX ARE AT  $\sim 10^{15}$  EV AND  $\sim 10^{18}$  EV.
- ▶ THEY APPEAR AS SMALL "KINKS" IN THE LINE.
- ▶ IN THE FIELD, THESE FEATURES ARE USUALLY REFERRED TO AS THE "KNEE" AND THE "ANKLE".



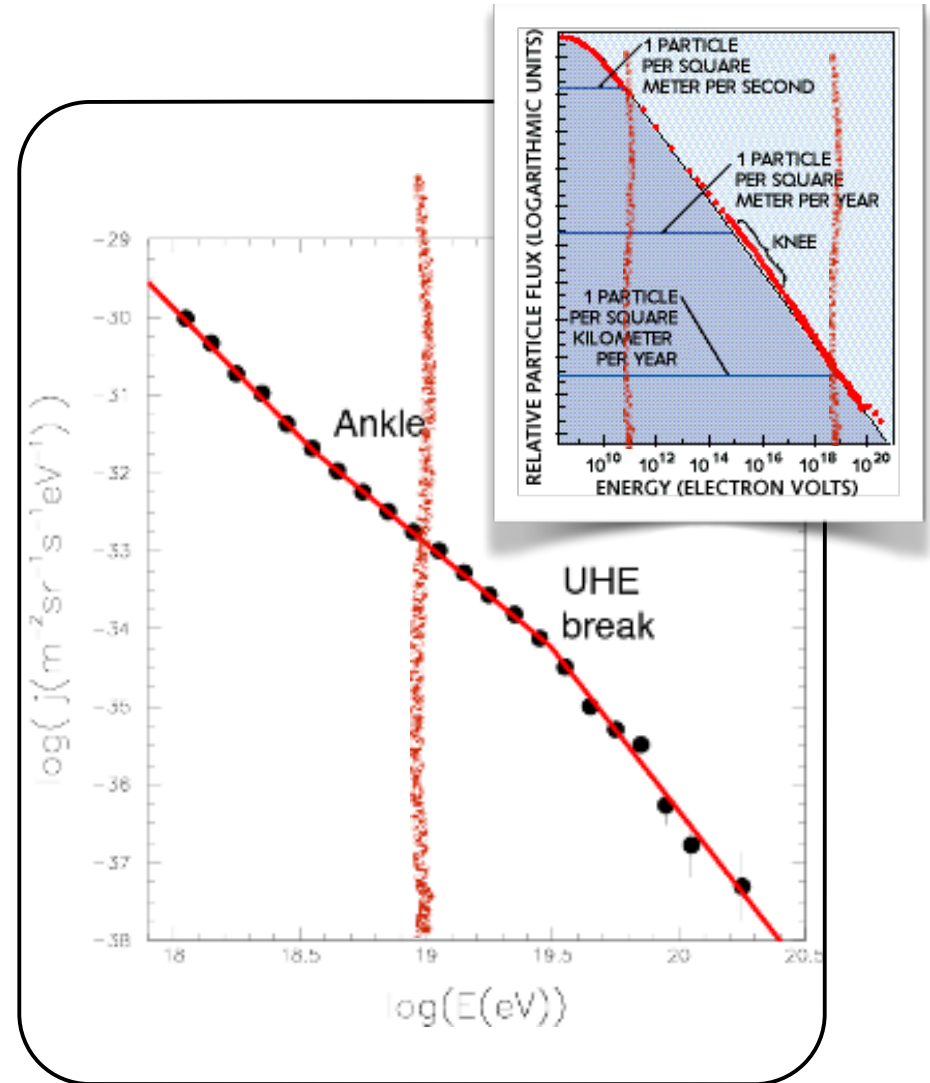
# ENERGY SPECTRUM



# ENERGY SPECTRUM



J. Beringer et al. (Particle Data Group)  
Phys. Rev. **D86**, 010001 (2012)





# THE MYSTERY OF UHECRS

- ▶ COSMIC RAYS WITH ENERGIES ABOVE  $10^{18}$  EV ARE REFERRED TO AS "ULTRA-HIGH ENERGY COSMIC RAYS" (UHECR).
- ▶ THESE ARE MICROSCOPIC PARTICLES WITH A MACROSCOPIC AMOUNT OF ENERGY - ABOUT A JOULE OR MORE.  
(FOR COMPARISON:  $1 \text{ J} = 6.25 \times 10^{18} \text{ EV.}$ )
- ▶ THE EXISTENCE OF SUCH ENERGETIC PARTICLES REMAINS A MYSTERY!

# MOTIVATION

- ▶ THE THREE MAIN QUESTIONS CONCERNING UHECR'S ARE:
  - ▶ HOW ARE THESE PARTICLES ACCELERATED TO SUCH EXTREME ENERGIES?
  - ▶ WHERE DO UHECRS COME FROM?
  - ▶ WHAT IS THE COMPOSITION OF THE UHECRs?

# MOTIVATION

- ▶ **TO STUDY THE ACCELERATION MECHANISM, ONE MUST MEASURE THE ENERGY SPECTRUM TO COMPARE WITH THE PREDICTIONS FROM DIFFERENT ACCELERATION MODELS.**
- ▶ **TO UNDERSTAND WHERE THEY COME FROM, ONE NEEDS TO SURVEY THE ARRIVAL DIRECTIONS, AND SEARCH FOR BOTH SMALL- AND LARGE-SCALE ANISOTROPIES IN THEIR DISTRIBUTION.**
- ▶ **COMPOSITION IS ONE OF THE MOST DIFFICULT MEASUREMENTS BECAUSE UHECRs CANNOT BE DETECTED DIRECTLY USING CONVENTIONAL PARTICLE DETECTORS. (MORE LATER.)**

# ACCELERATION MECHANISMS

- ▶ ONE OF THE EARLIEST THEORIES ON THE ACCELERATION OF COSMIC RAYS WAS PROPOSED BY ENRICO FERMI IN 1949 [1].
- ▶ IT BECAME KNOWN AS THE "SECOND ORDER FERMI MECHANISM".

**Fermi Acceleration Mechanism**

Stochastic energy gain in collisions with plasma clouds

2nd order :  
randomly distributed magnetic mirrors

$\frac{\Delta E}{E} \sim \beta^2 \quad \beta = \frac{V}{c} \lesssim 10^{-4}$

[Slow and inefficient]

1st order :  
acceleration in strong shock waves (supernova ejecta, RG hot spots...)

$\frac{\Delta E}{E} \sim \beta \quad \beta = \frac{V}{c} \lesssim 10^{-1}$

[1] FERMI, E. PHYS. REV., 75, 1169 (1949).

# FERMI'S 2<sup>ND</sup> ORDER MECHANISM

- ▶ IN THIS MODEL, PARTICLES COLLIDE STOCHASTICALLY WITH MAGNETIC CLOUDS IN THE INTERSTELLAR MEDIUM.
- ▶ THOSE PARTICLES INVOLVED IN HEAD-ON COLLISIONS WILL GAIN ENERGY (SIMILAR TO A SLING-SHOT PROCESS USED TO ACCELERATE SPACECRAFTS AROUND PLANETS), AND THOSE INVOLVED IN TAIL-END COLLISIONS WILL LOSE ENERGY.
- ▶ ON AVERAGE, HOWEVER, HEAD-ON COLLISIONS ARE MORE PROBABLE. IN THIS WAY, PARTICLES GAIN ENERGY OVER MANY COLLISIONS.

# FERMI'S 2<sup>ND</sup> ORDER MECHANISM

- ▶ THIS MECHANISM NATURALLY PREDICT A POWER LAW ENERGY SPECTRUM, BUT THE POWER INDEX DEPENDS ON THE LOCAL DETAILS OF THE MODEL AND WOULD NOT GIVE RISE TO A UNIVERSAL POWER LAW FOR COSMIC RAYS ARRIVING FROM ALL DIRECTIONS.
- ▶ THIS MECHANISM IS ALSO TOO SLOW AND TOO INEFFICIENT TO ACCOUNT FOR THE OBSERVED UHECRs.

# ACCELERATION MECHANISMS

- ▶ A MORE EFFICIENT VERSION OF FERMI ACCELERATION WAS PROPOSED BY A NUMBER OF WORKERS IN THE LATE 70'S [2].
- ▶ THIS MODEL IS REFERRED TO AS THE "FIRST ORDER FERMI MECHANISM".

**Fermi Acceleration Mechanism**

Stochastic energy gain in collisions with plasma clouds

2nd order :  
randomly distributed magnetic mirrors

$\frac{\Delta E}{E} \sim \beta^2$        $\beta = \frac{V}{c} \lesssim 10^{-4}$

[Slow and inefficient]

1st order :  
acceleration in strong shock waves (supernova ejecta, RG hot spots...)

[2] BLANDFORD, R.D. AND OSTRICKER, J. P.  $\frac{\Delta E}{E} \sim \beta$   $\beta = \frac{V}{c} \lesssim 10^{-1}$   
ASTROPHYS. J., 221, L29 (1978)

# FERMI'S 1<sup>ST</sup> ORDER MECHANISM

- ▶ IN THIS MODEL, PARTICLES ARE ACCELERATED BY A STRONG SHOCK PROPAGATING THROUGH INTERSTELLAR SPACE; E.G. [3]
- ▶ SHOCK WAVES TYPICALLY HAVE MOVING MAGNETIC INHOMOGENEITIES BOTH PRECEDING AND FOLLOWING THEM.
- ▶ A CHARGED PARTICLE TRAVELING THROUGH THE SHOCK WAVE CAN GREATLY INCREASE ITS ENERGY THROUGH MULTIPLE REFLECTIONS.
- ▶ THE RESULTING ENERGY SPECTRUM OF MANY PARTICLES UNDERGOING THIS PROCESS TURN OUT TO BE A POWER LAW!

[3] LONGAIR, M. S., CHAPTER 21 OF HIGH ENERGY ASTROPHYSICS VOL. 2, 2ND ED. CAMBRIDGE UNIVERSITY PRESS (1994).



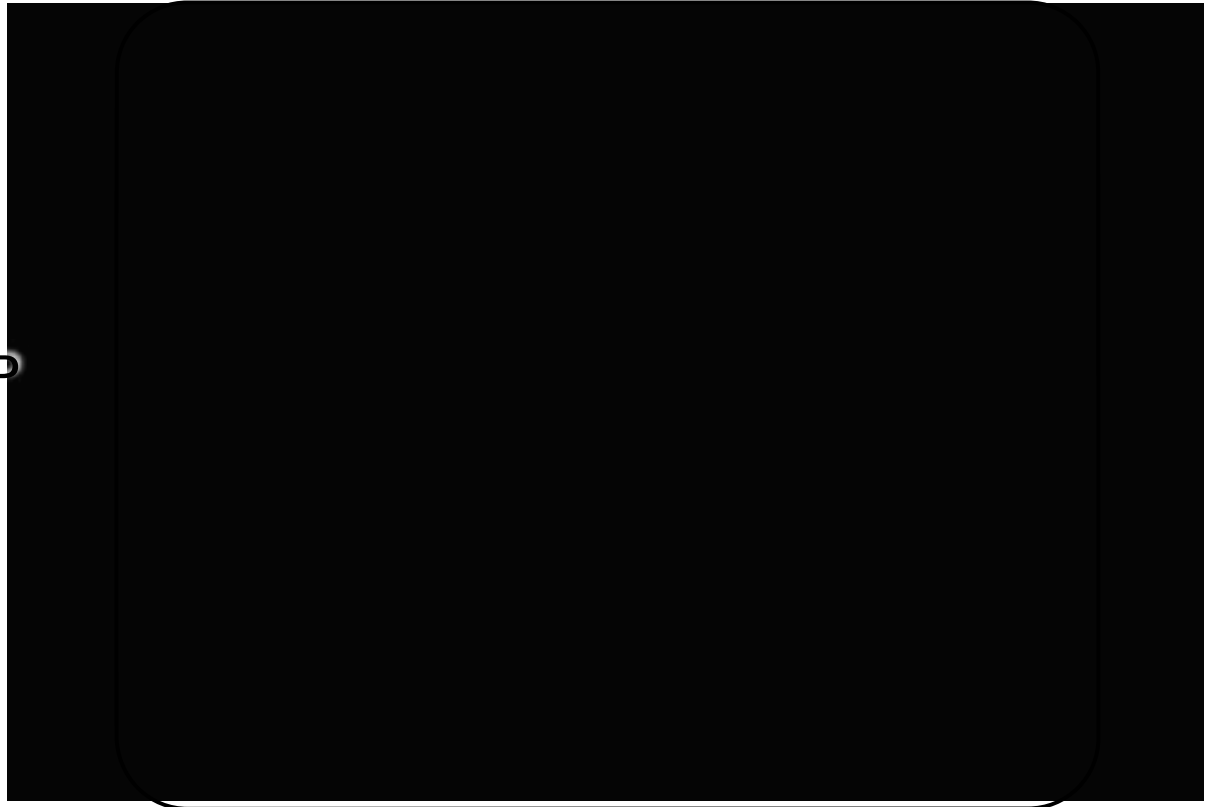
# MINI-BREAK

▶ **SO FAR:**

▶ **INTRODUCTION,  
SOME HISTORY, AND  
ACCELERATION  
MECHANISMS**

▶ **COMING SOON:**

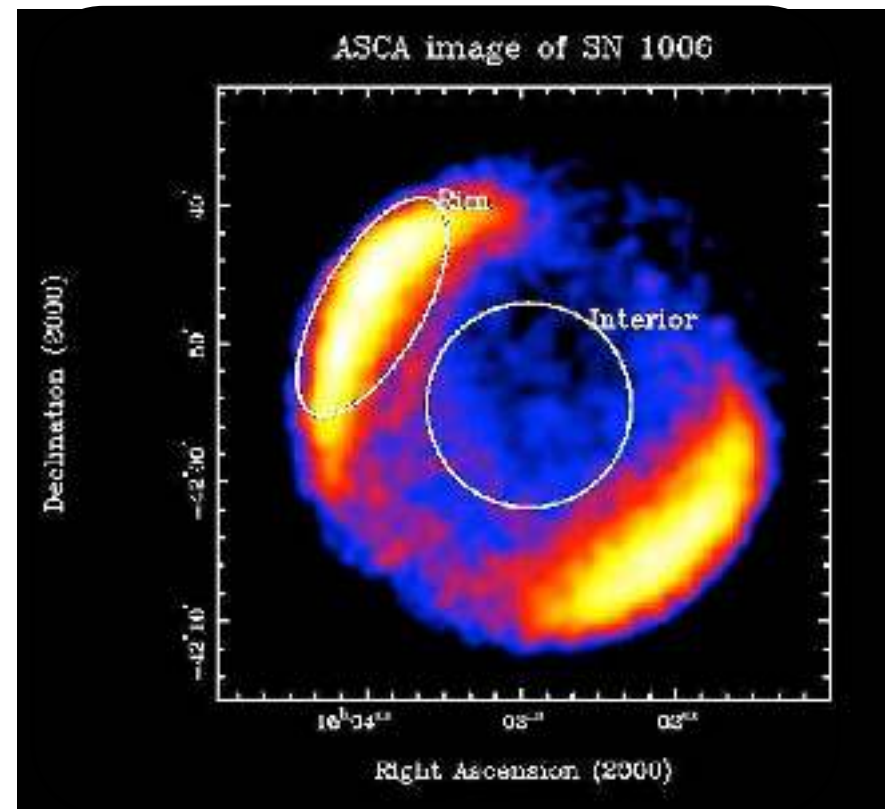
▶ **POSSIBLE  
SOURCES,  
LIMITATIONS, AND  
OTHER IDEAS**



# POSSIBLE SOURCES

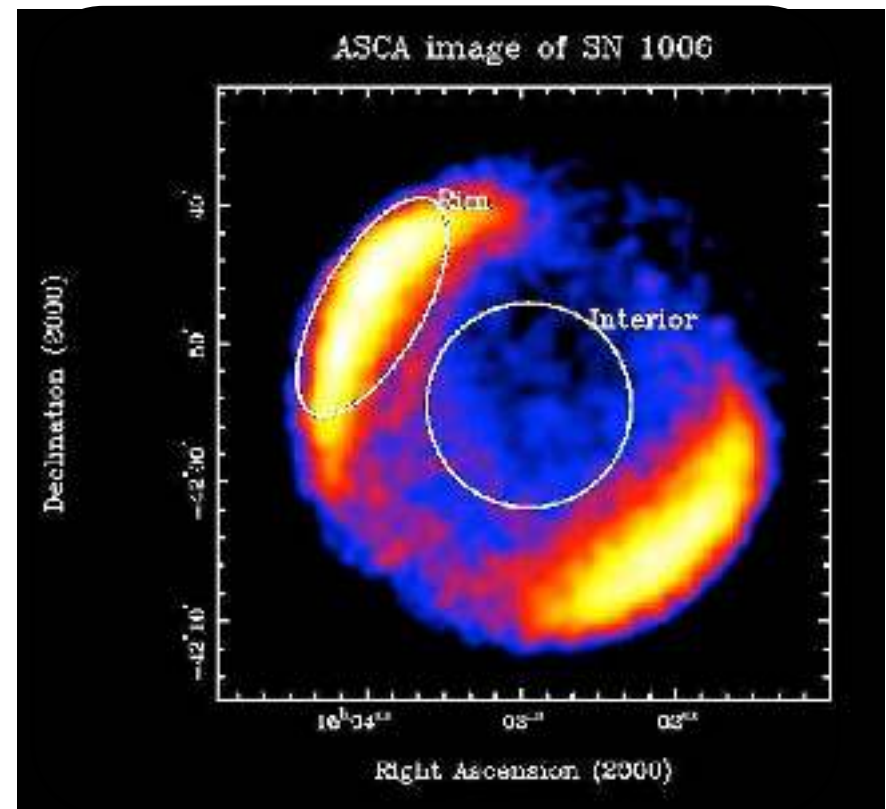
SOURCE CANDIDATES USUALLY INCLUDE LARGE, ENERGETIC STRUCTURES WHERE STRONG SHOCKS ARE EXPECTED TO BE FOUND.

- ▶ SUPERNOVA REMNANTS
- ▶ IN 1995, JAPAN'S ASCA X-RAY SATELLITE, REPORTED POSITIVE OBSERVATION NON-THERMAL X-RAY EMISSIONS FROM THE SUPERNOVA REMNANT SN1006.



# POSSIBLE SOURCES

- ▶ SUPERNOVA REMNANTS
- ▶ THE OBSERVED EMISSION SPECTRUM IS CONSISTENT WITH SYNCHROTRON EMISSION BY ACCELERATED CHARGED PARTICLES.
- ▶ THIS CONFIRMED SUPERNOVA REMNANTS AS A POSSIBLE SOURCE OF COSMIC RAYS.



# POSSIBLE SOURCES

- ▶ THE OBSERVED EMISSION FROM SN 1006, WITH SOME FINE TUNING OF THE EMISSION MODELS, CAN EXPLAIN THE EXISTENCE OF COSMIC RAYS UP TO  $\sim 10^{15}$  EV.
- ▶ HOWEVER, IT IS DIFFICULT TO EXPLAIN THE EXISTENCE OF COSMIC RAYS ABOVE  $10^{18}$  EV, BECAUSE SUPERNOVAE ARE SIMPLY NOT LARGE ENOUGH TO MAINTAIN ACCELERATION TO THE UHE RANGE.
- ▶ FURTHERMORE, NO POSITIVE CORRELATION HAS BEEN OBSERVED BETWEEN THE ARRIVAL DIRECTIONS OF UHECRs AND SUPERNOVA REMNANTS.

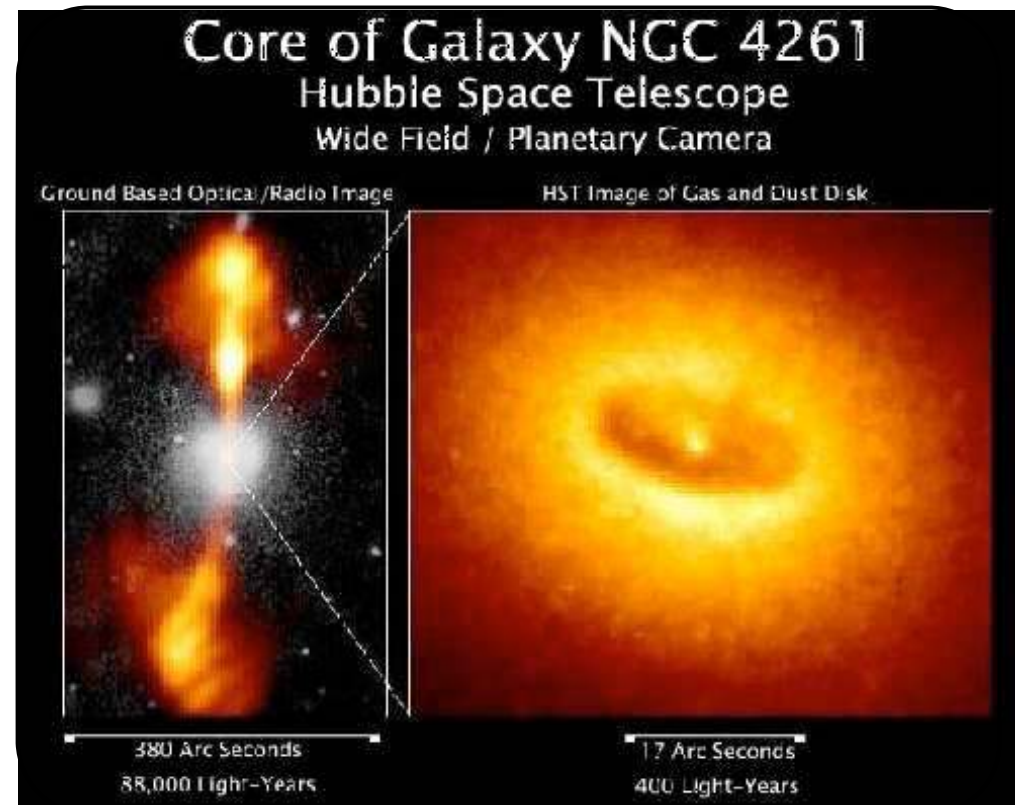
# POSSIBLE SOURCES

- ▶ **STRONG SHOCKS ARE POSSIBLE AROUND COLLIDING GALAXIES SUCH AS NGC 4038/9.**
- ▶ **HOWEVER, THERE IS NO EVIDENCE TO INDICATE THESE OBJECTS ARE SOURCES OF UHECRs.**



# POSSIBLE SOURCES

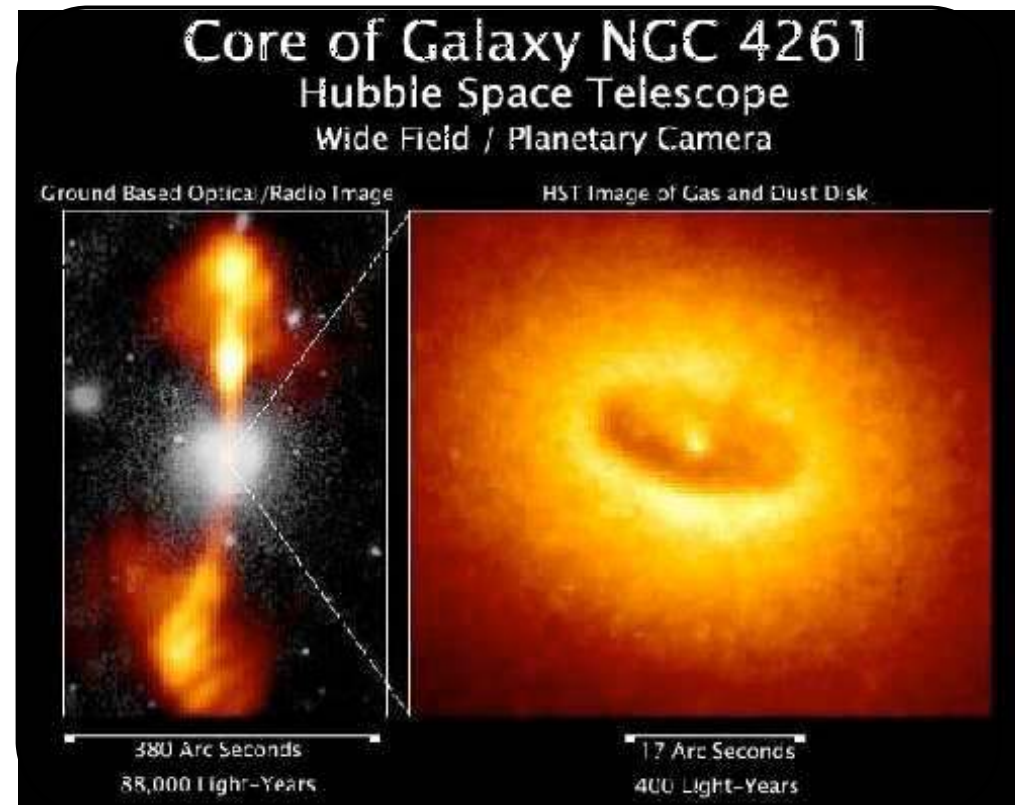
- ▶ ANOTHER CANDIDATES ARE ACTIVE GALACTIC NUCLEI (AGN).
- ▶ AGN IS THE GENERIC NAME GIVEN TO A CLASS OF GALAXIES SUSPECTED TO HAVE AT THEIR CENTER A SUPER MASSIVE BLACK-HOLE.



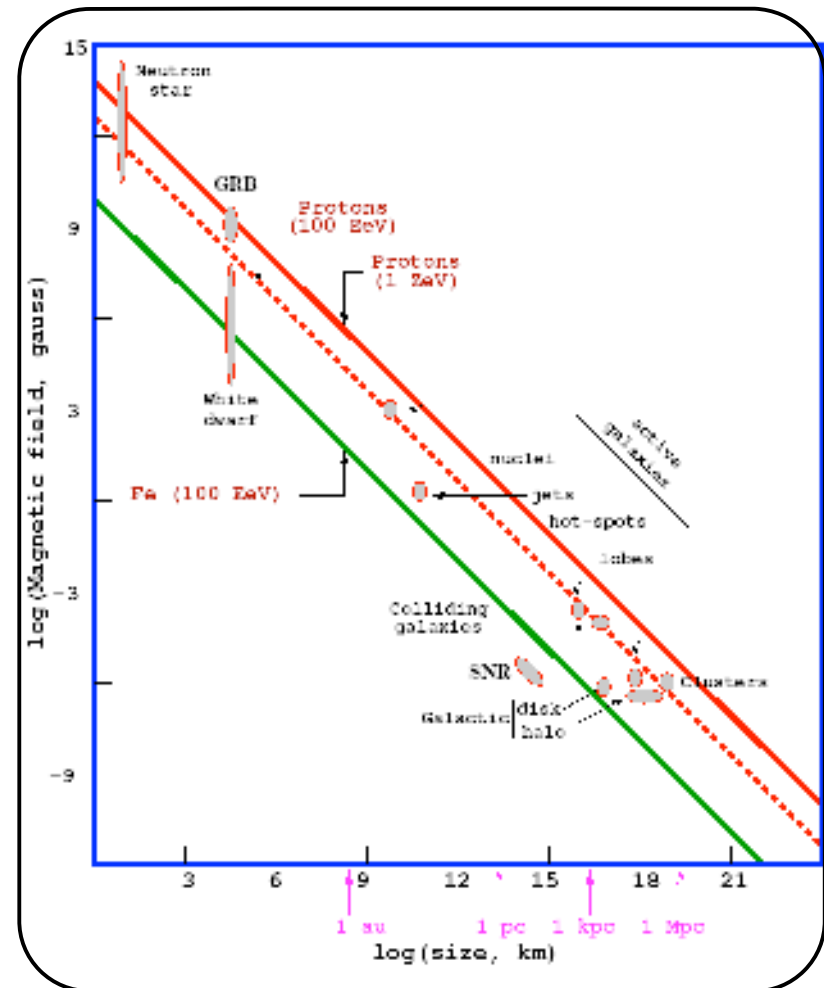
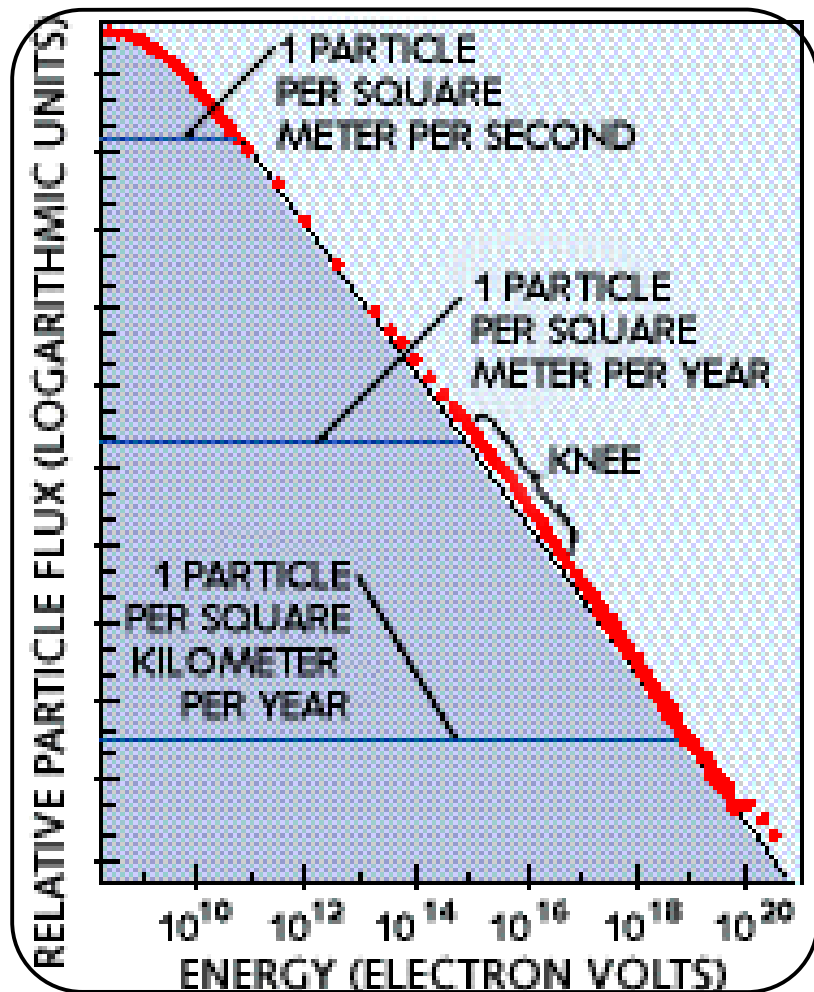
# POSSIBLE SOURCES

- ▶ **AGN ARE TYPICALLY ACCOMPANIED BY JETS WHICH CAN EXTEND 50 - 100 THOUSAND LIGHT-YEARS.**
- ▶ **ROUGHLY ONE OF EVERY TEN KNOWN GALAXIES IS AN AGN.**

**IT IS POSSIBLE TO FIND AN AGN WITHIN ERROR OF THE ARRIVAL DIRECTION OF A UHECR.  
(MORE ON THIS LATER!)**



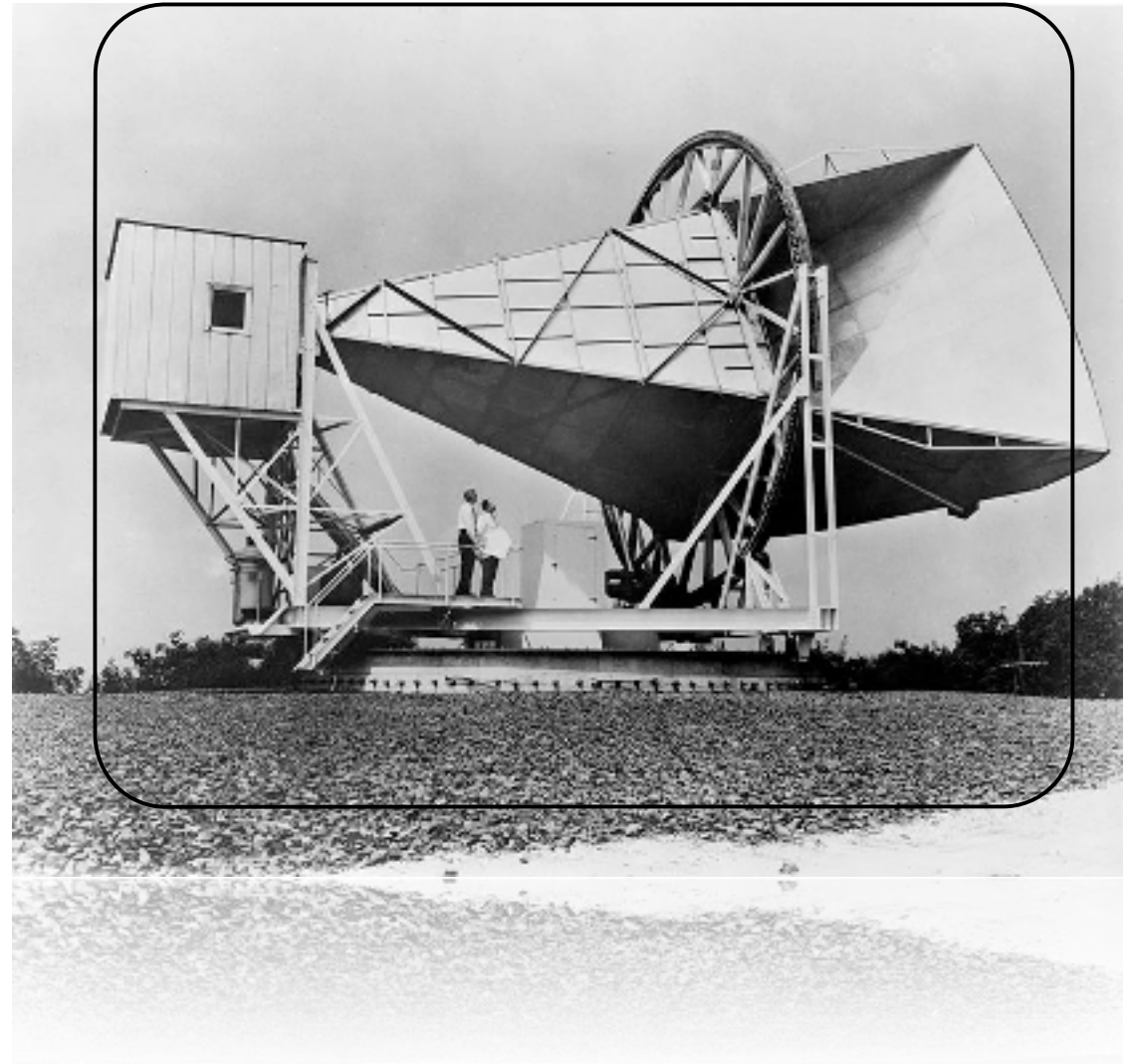
# CONVENTIONAL EXPLANATION



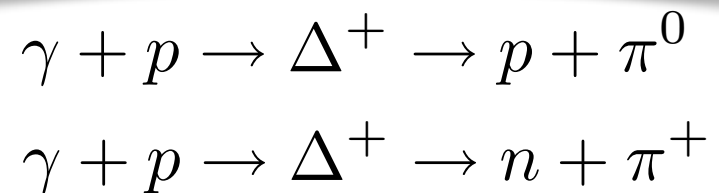
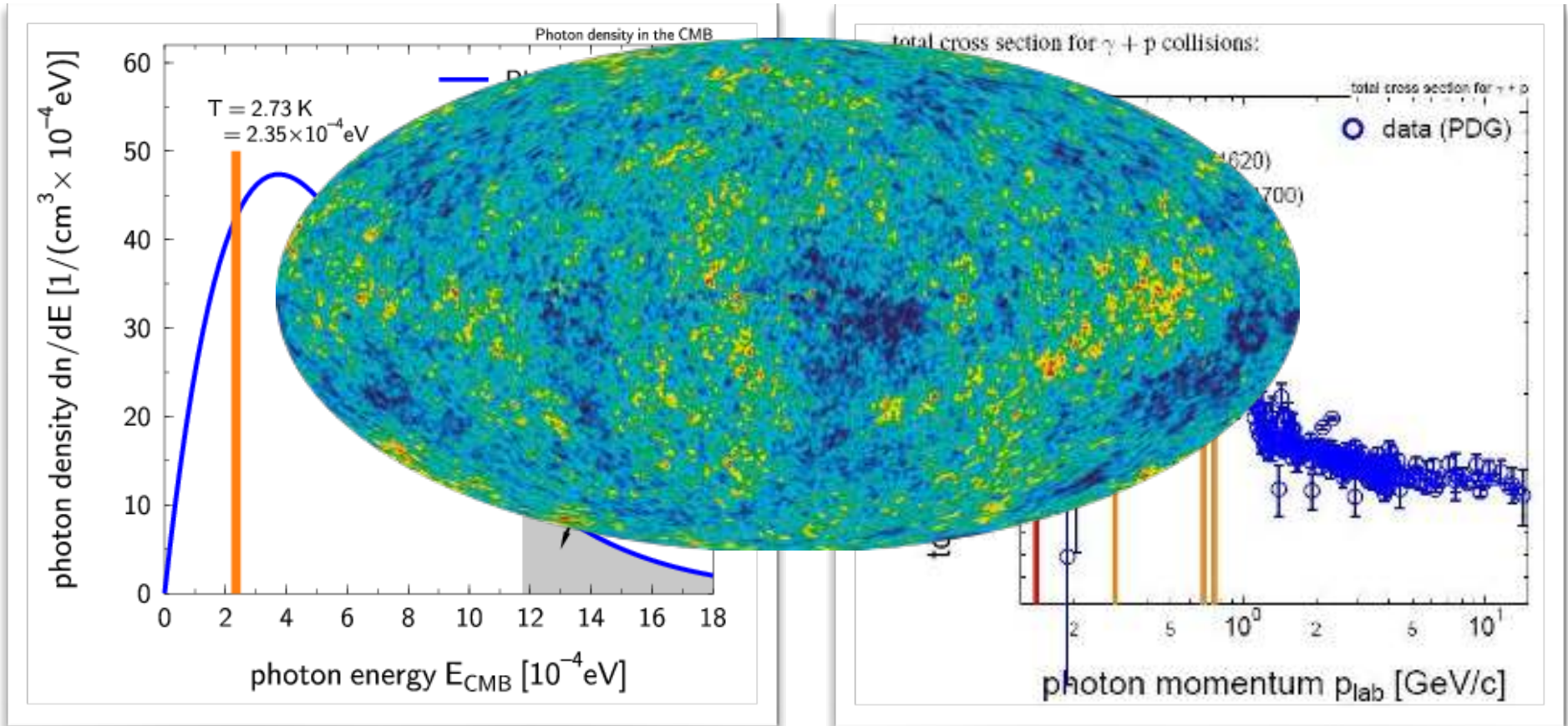


# DISCOVERY OF CMB

▶ ARNO PENZIAS  
AND ROBERT  
WILSON  
DISCOVER THE  
COSMIC  
MICROWAVE  
BACKGROUND  
(CMB) IN 1964.



# CMB



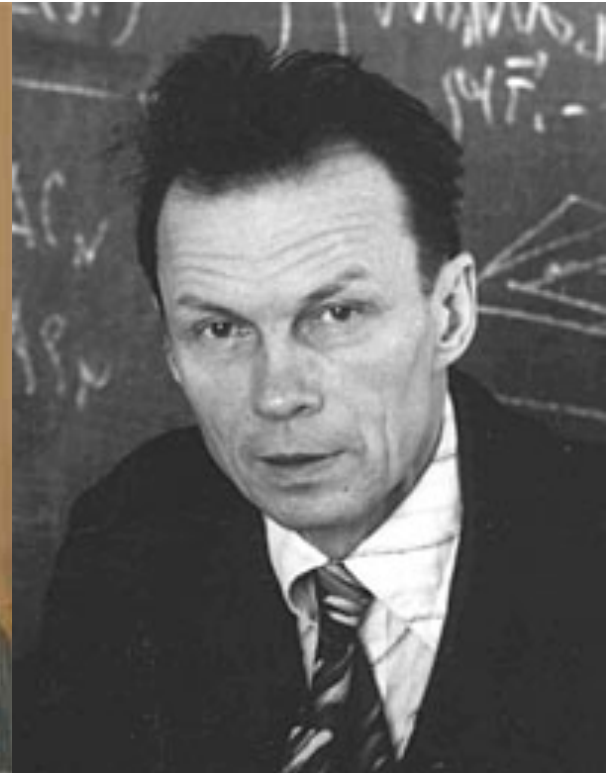
# GZK EFFECT



**KENNETH  
GREISEN**



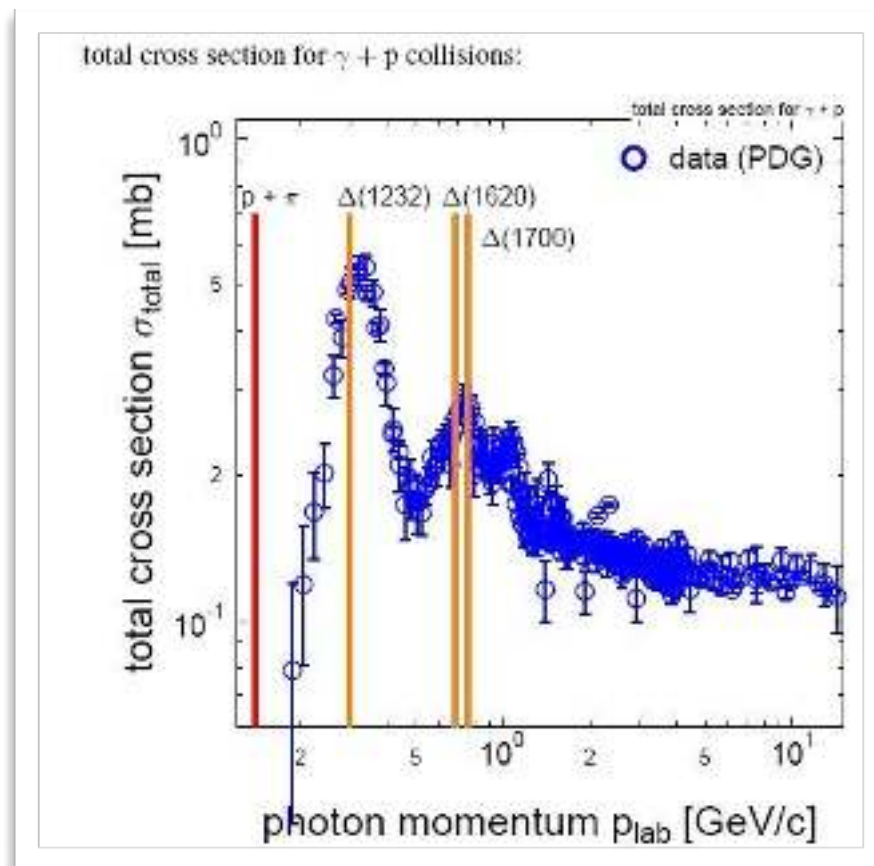
**GEORGIY  
ZATSEPIN**



**VADIM  
KUZMIN**

# GZK EFFECT

*They should not be there!*



# GZK EFFECT

...but they are!

## EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY $10^{20}$ eV†

John Linsley

Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts  
(Received 16 January 1963)

mic-ray air shower recorded  
Ranch station in February  
the total number of particles  
No. 2-4834) was  $5 \times 10^{19}$ .  
the primary particle which  
was  $1.0 \times 10^{20}$  eV. The show-  
size of the largest we had  
No. 1-15832, recorded in

point marked "A," assuming only (1) that shower  
particles are distributed symmetrically about an  
axis (the "core"), and (2) that the density of par-  
ticles decreases monotonically with increasing  
distance from the axis. The observed densities

Even before  
CMB was  
discovered!

mic-ray particles having  
importance to astrophys-  
is (believed to be atomic  
magnetic rigidity. It is  
which such a particle  
ough and possess a  
ic field so that  $RH \gg (1/300)$   
is the radius of the region (cm).  
is the intensity of the magnetic field (gauss).  
 $E$  is the total energy of the particle (eV) and  $Z$  is  
its charge. Recent evidence favors the choice  
 $Z=1$  (proton primaries) for the region of highest  
cosmic-ray energies.<sup>2</sup> For the present event one  
obtains the condition  $RH \gg 3 \times 10^{17}$ . This condition  
is not satisfied by our galaxy (for which  $RH \approx 5$   
 $\times 10^{13}$ , halo included) or known objects within it,  
such as supernovae.

The technique we use has been described else-  
where.<sup>2</sup> An array of scintillation detectors is  
used to find the direction (from pulse times) and  
size (from pulse amplitudes) of shower events  
which satisfy a triggering requirement. In the  
present case, the direction of the shower was  
nearly vertical (zenith angle  $10 \pm 5^\circ$ ). The values

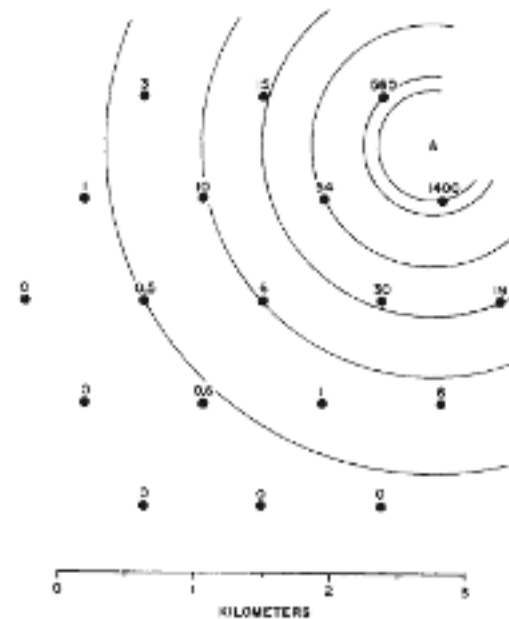


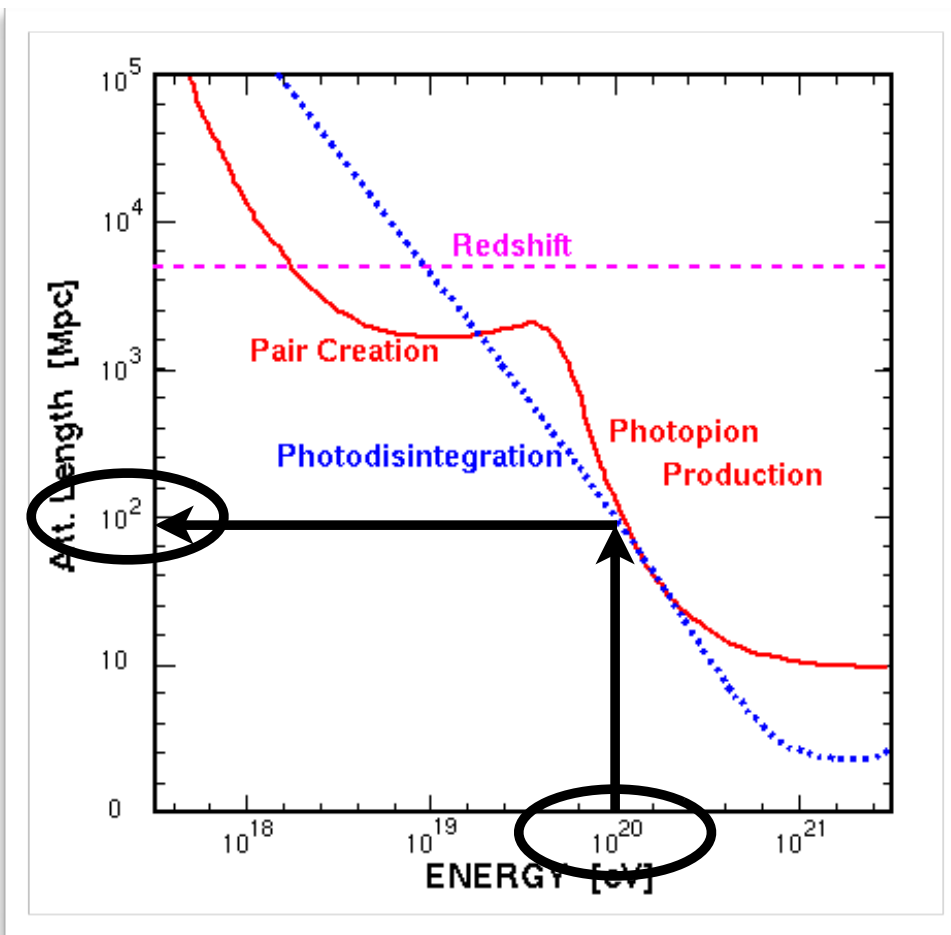
FIG. 1. Plan of the Volcano Ranch array in February 1962. The circles represent  $3.3\text{-m}^2$  scintillation detectors. The numbers near the circles are the shower

# GZK FLUX SUPPRESSION

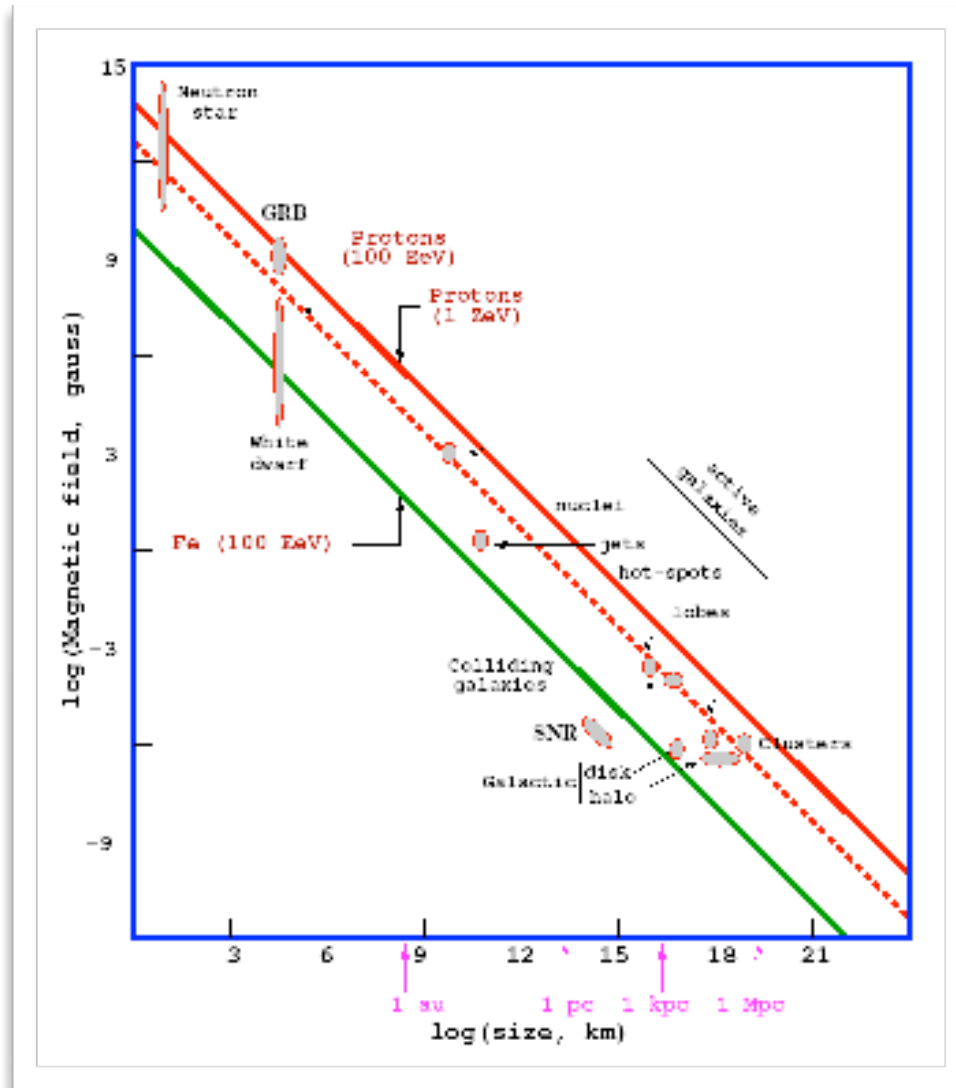


1 pc = 3.26 ly

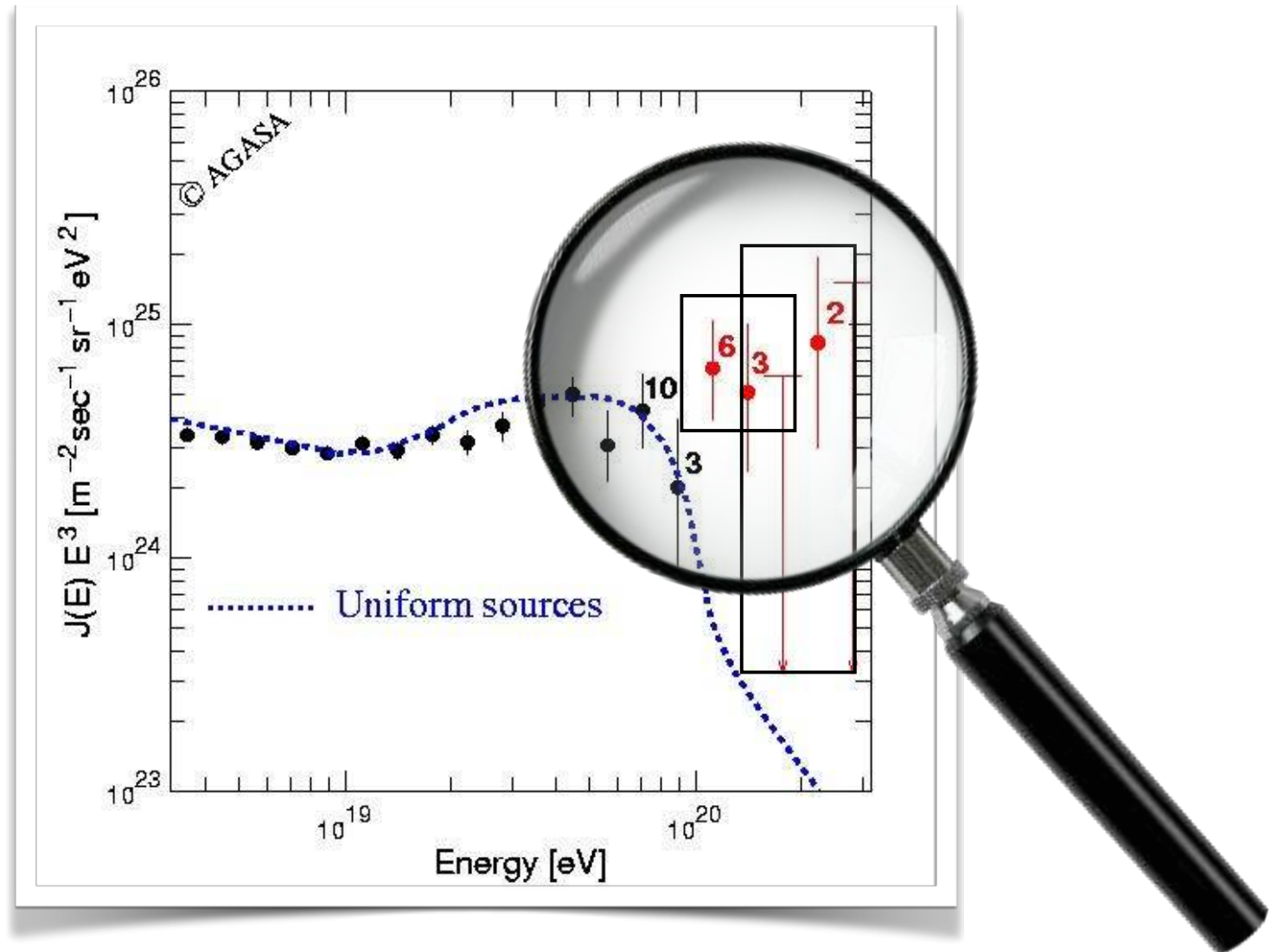
326 Mly ≡



# STILL CONVENTIONAL...



# NO MORE CONVENTIONAL?





# EXOTIC MECHANISMS

**OTHER IDEAS FOR EXPLAINING THE EXISTENCE OF UHECRS INCLUDE:**

**▶TOP-DOWN MODELS:**

**▶DECAY OR ANNIHILATION OF SOME SUPER-HEAVY PARTICLES OR COSMOLOGICAL RELICS (E.G. TOPOLOGICAL DEFECTS, RELIC MAGNETIC MONOPOLES.)**

**▶ACCELERATION IN CATASTROPHIC EVENTS**

**▶GRB's**

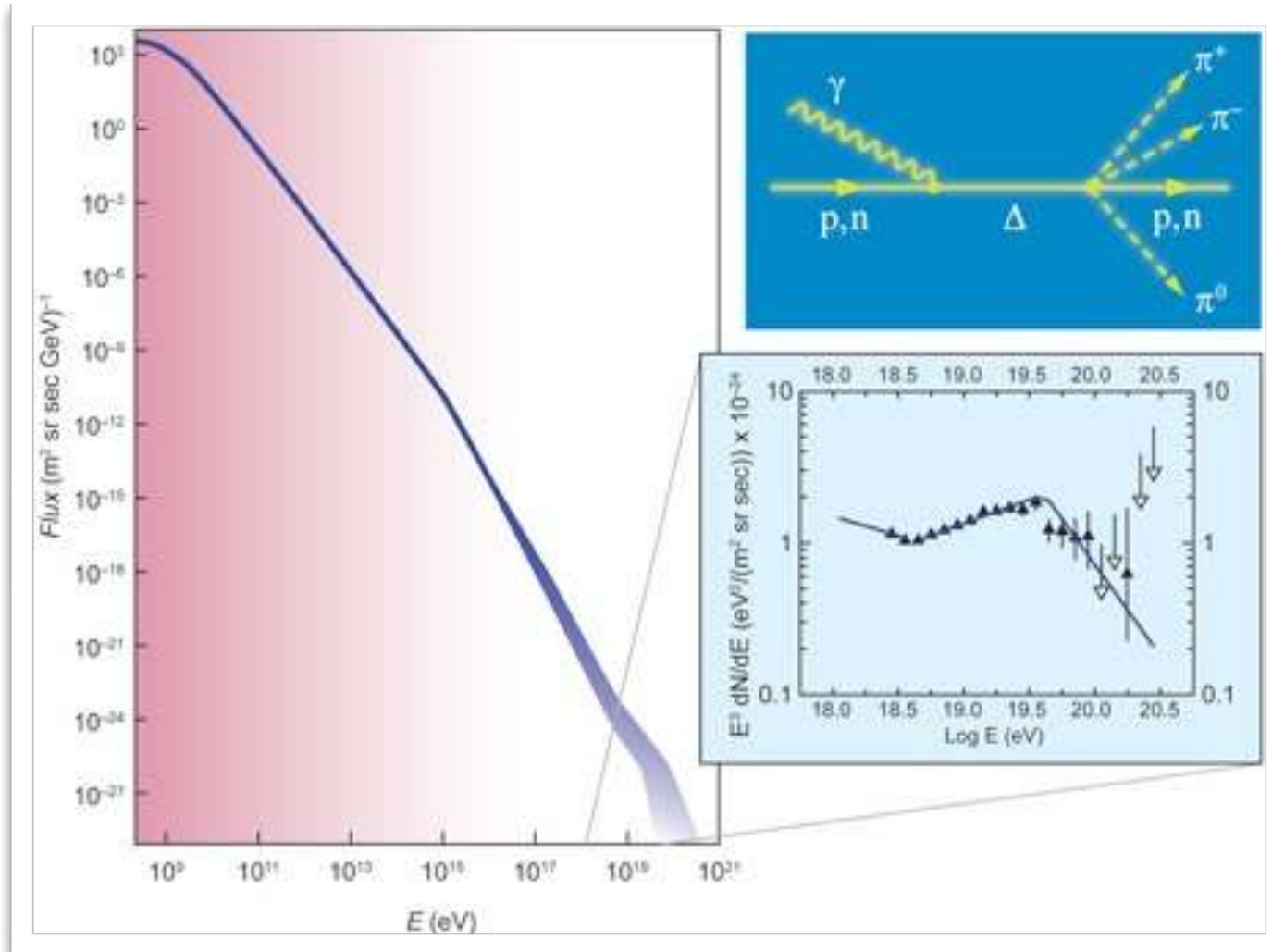
**▶NEW PHYSICS**

# SCIENTIFIC MOTIVATION

- ▶ ORIGIN OF COSMIC RAYS
- ▶ ACCELERATION MECHANISM (OR DECAY?)
- ▶ DISTRIBUTION OF SOURCES, LOCAL OR COSMOLOGICAL?

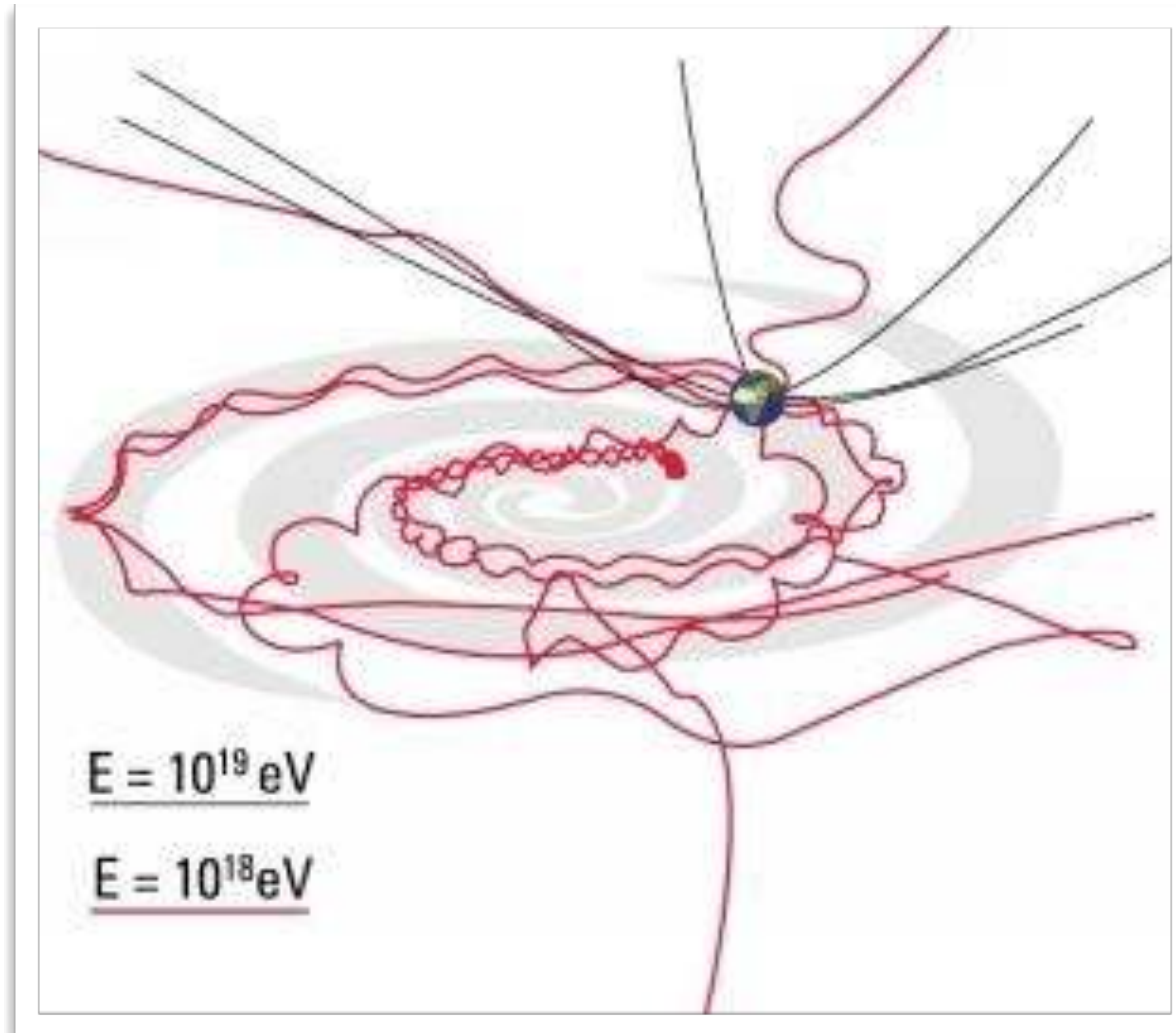
# THE CHALLENGE

▶ VERY VERY LOW FLUX...



# THE REWARD

►...BUT THEY MIGHT POINT BACK!



# MOTIVATION

## WE MUST ADDRESS:

- ▶ ENERGY DISTRIBUTION

  - ▶ GZK SUPPRESSION

  - ▶ NEED FOR NEW PHYSICS?

- ▶ DIRECTIONALITY

  - ▶ KNOWN ASTROPHYSICS?

  - ▶ NEW PHYSICS?

- ▶ PRIMARY COMPOSITION

  - ▶  $p, \gamma, Fe, n, \nu, \dots?$

# SUMMARY

- ▶ INTRODUCTION TO COSMIC RAYS
- ▶ HISTORY
- ▶ SCIENTIFIC MOTIVATION

# NEXT CLASS

- ▶ EXTENSIVE AIR SHOWERS
- ▶ DETECTION TECHNIQUES
- ▶ THE PIERRE AUGER  
OBSERVATORY

**THANK YOU!**