



# COSMIC RAYS

ELENA AMATO

INAF-OSSERVATORIO ASTROFISICO DI ARCETRI

# OUTLINE

- INTRODUCING ACCELERATED PARTICLES
- DETECTION
- THE SUPERNOVA REMNANT PARADIGM
- RECENT PUZZLES
- COURSE OUTLINE

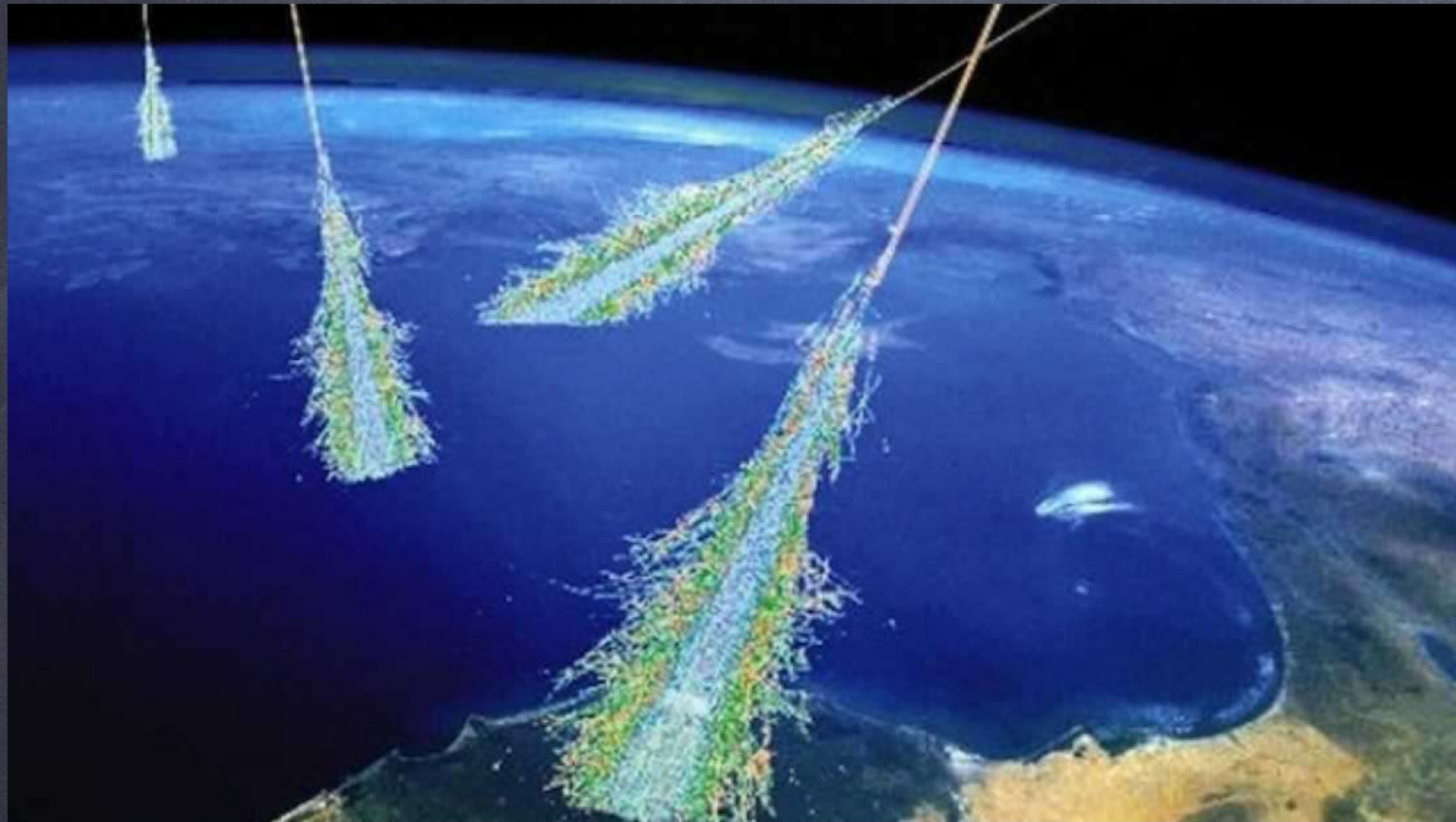
# EVIDENCE FOR ENERGETIC PARTICLES AND EXTREME ACCELERATORS

-DETECTION OF COSMIC RAYS AT EARTH

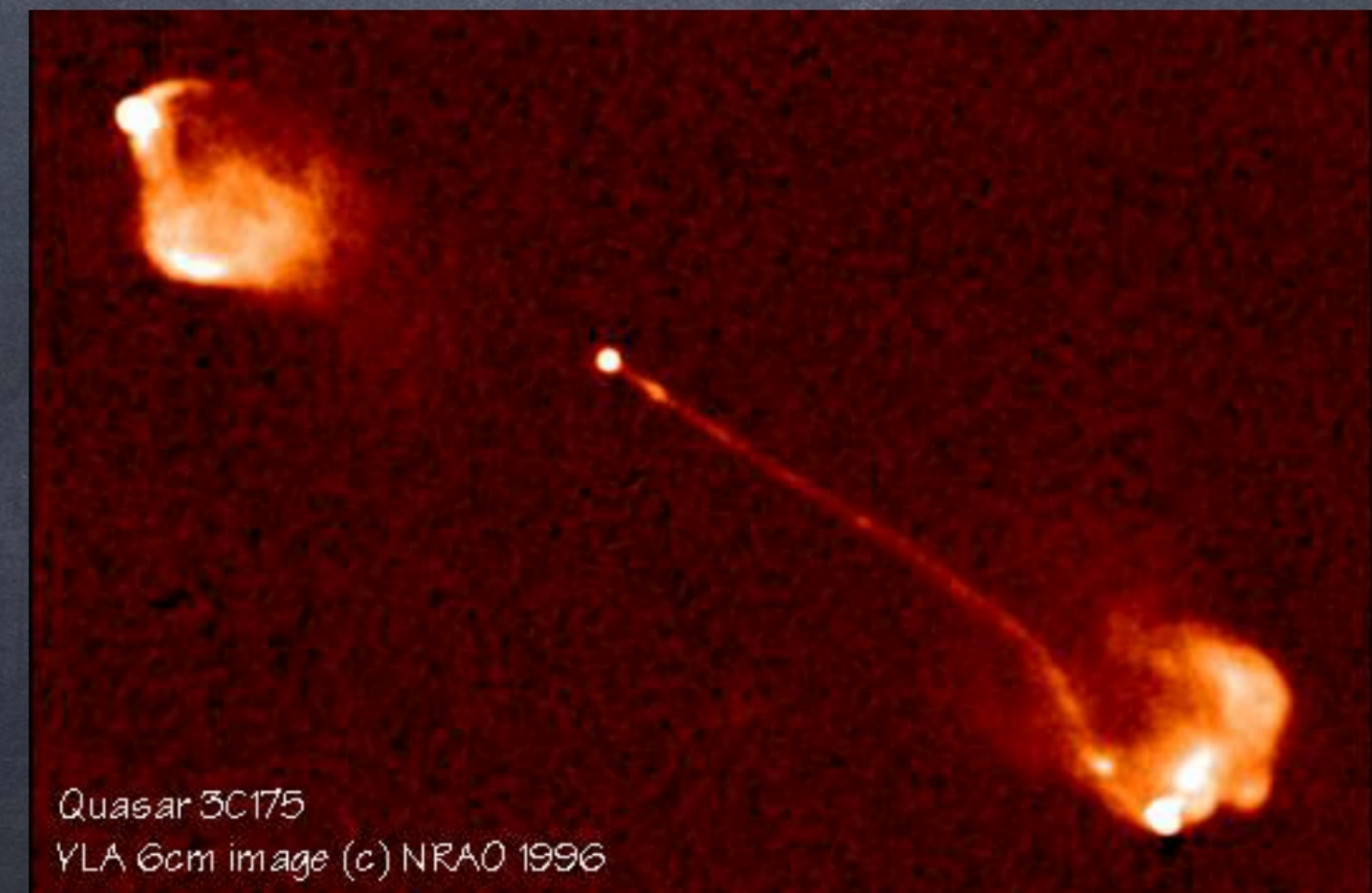
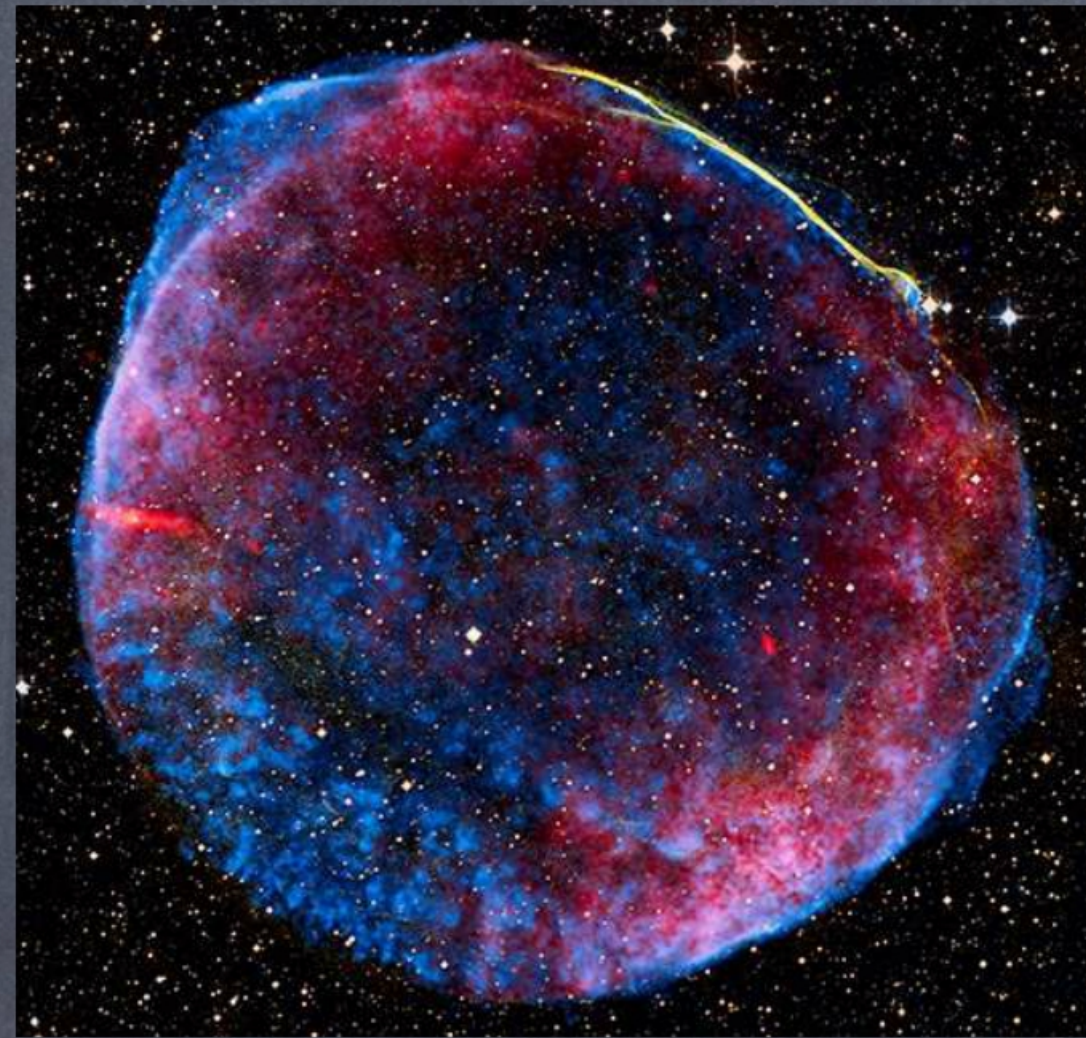
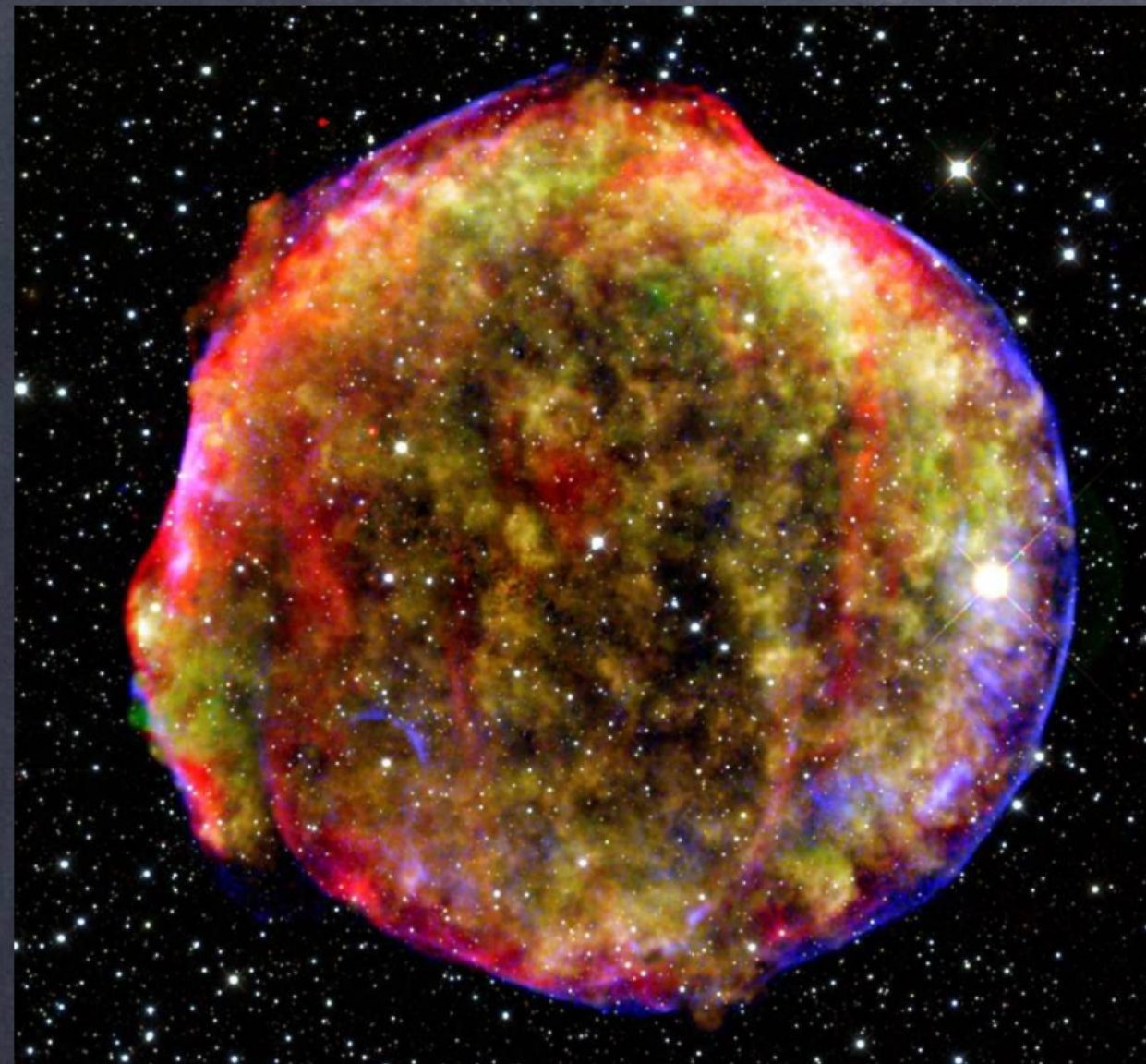
-DETECTION OF NON-THERMAL RADIATION IN ASTROPHYSICAL SOURCES

-DIFFUSE NON THERMAL EMISSION

# DETECTION OF COSMIC RAYS AT EARTH

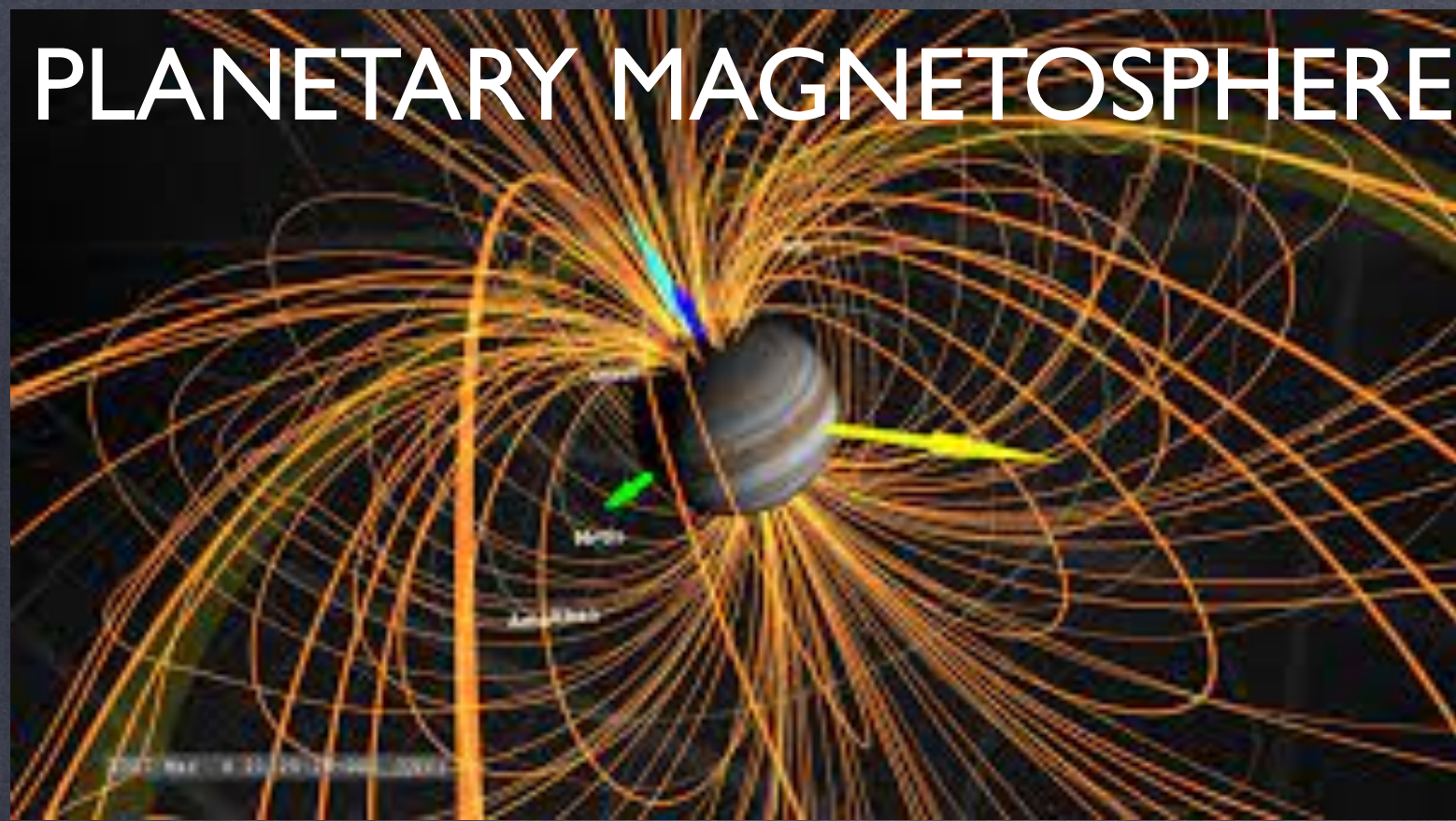


# DETECTION OF NON-THERMAL EMISSION FROM ASTROPHYSICAL SOURCES

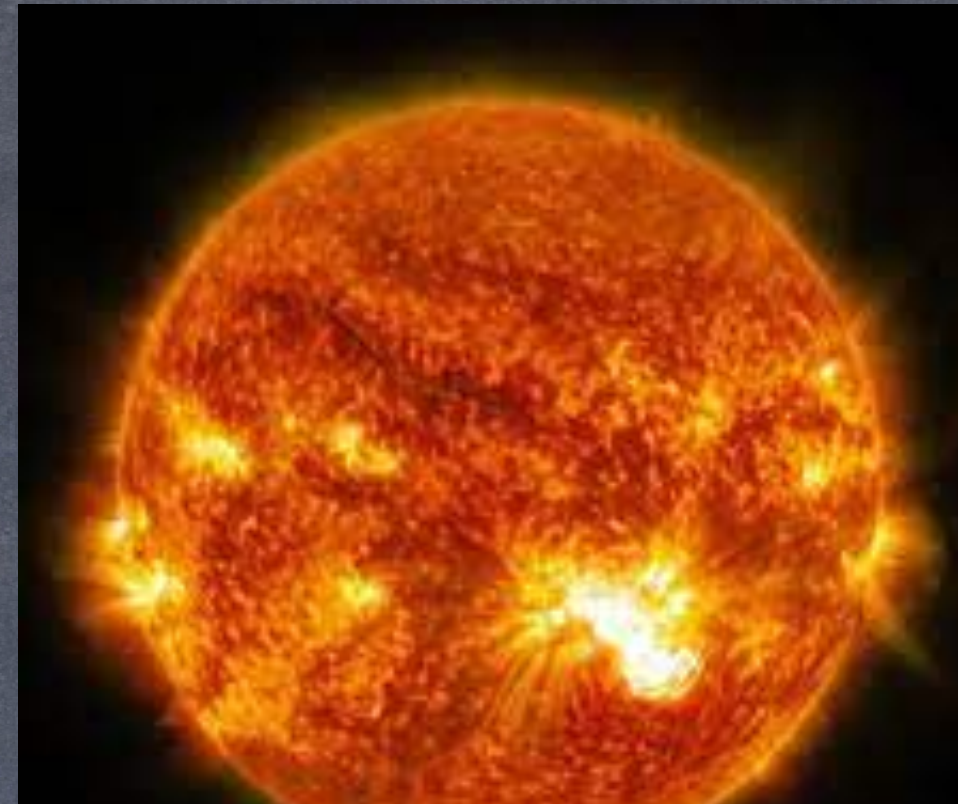


# A LARGE AND INCREASING VARIETY

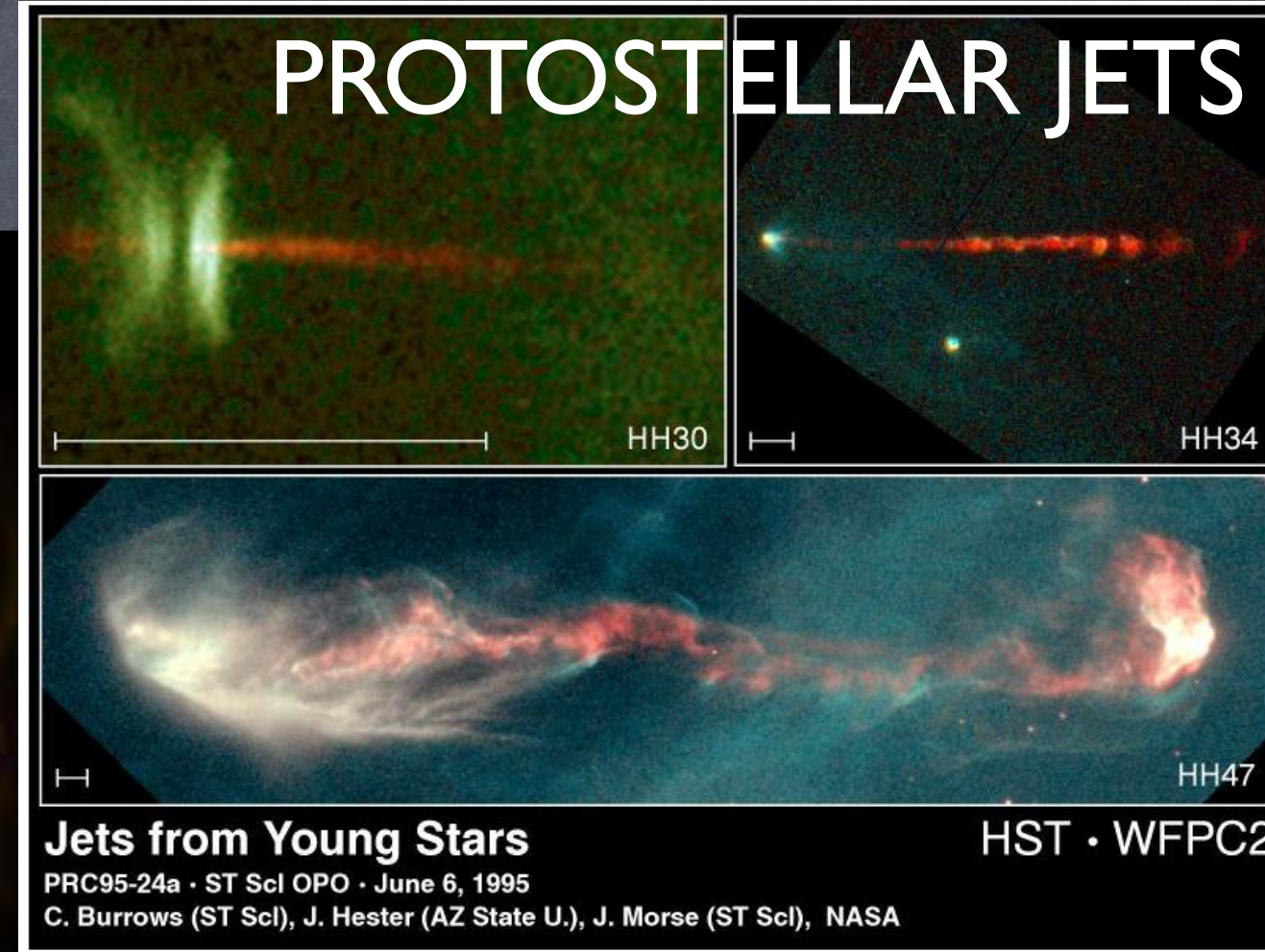
PLANETARY MAGNETOSPHERES



SUN AND STARS



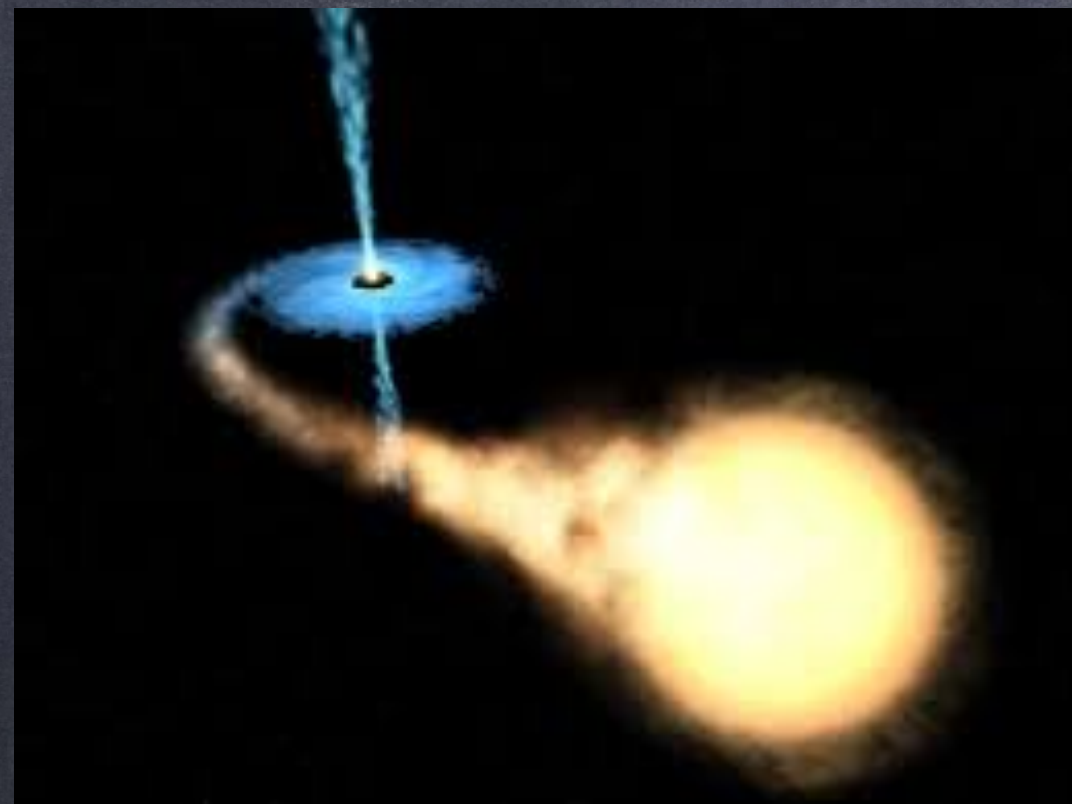
PROTOSTELLAR JETS



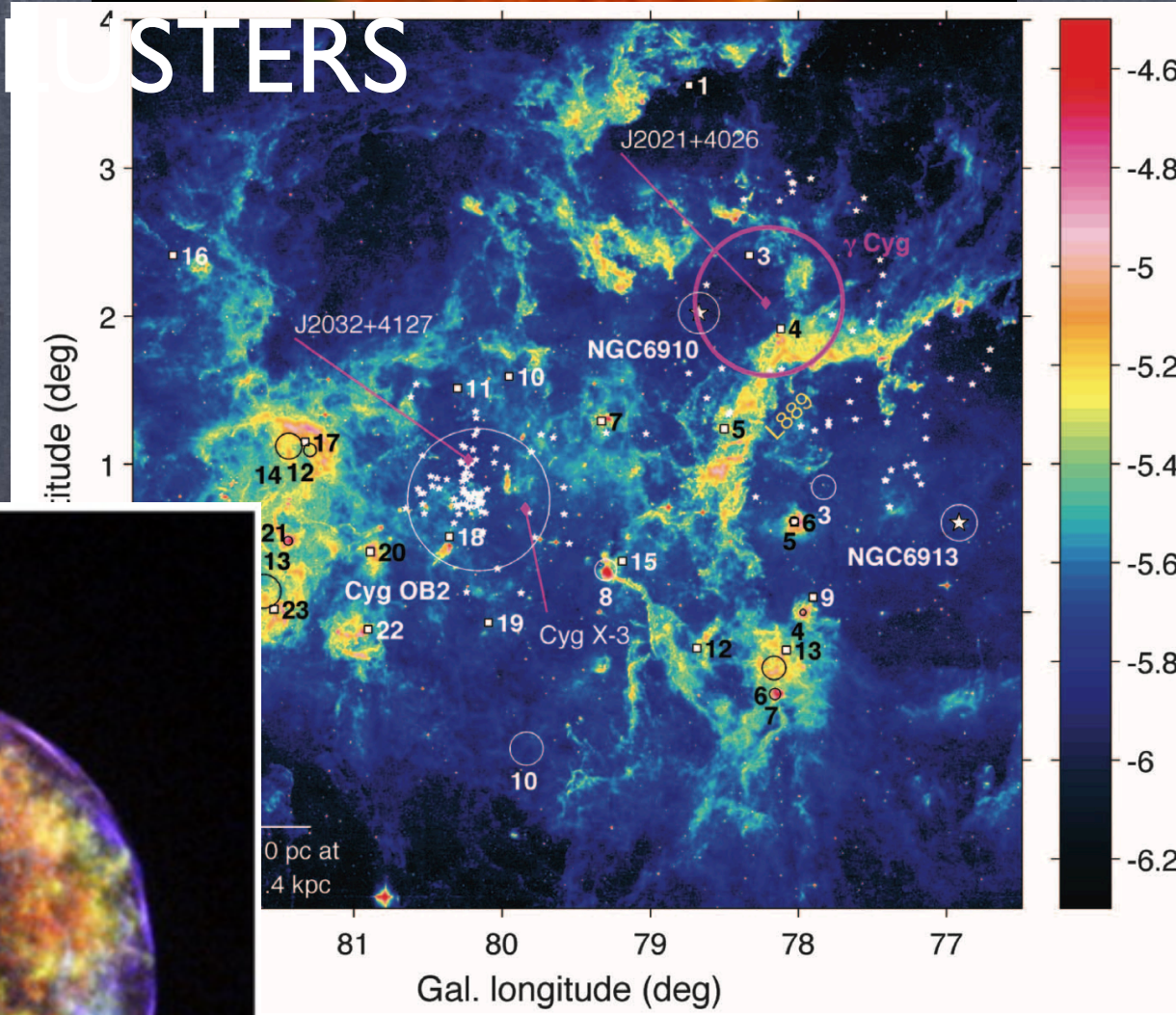
NOVAE



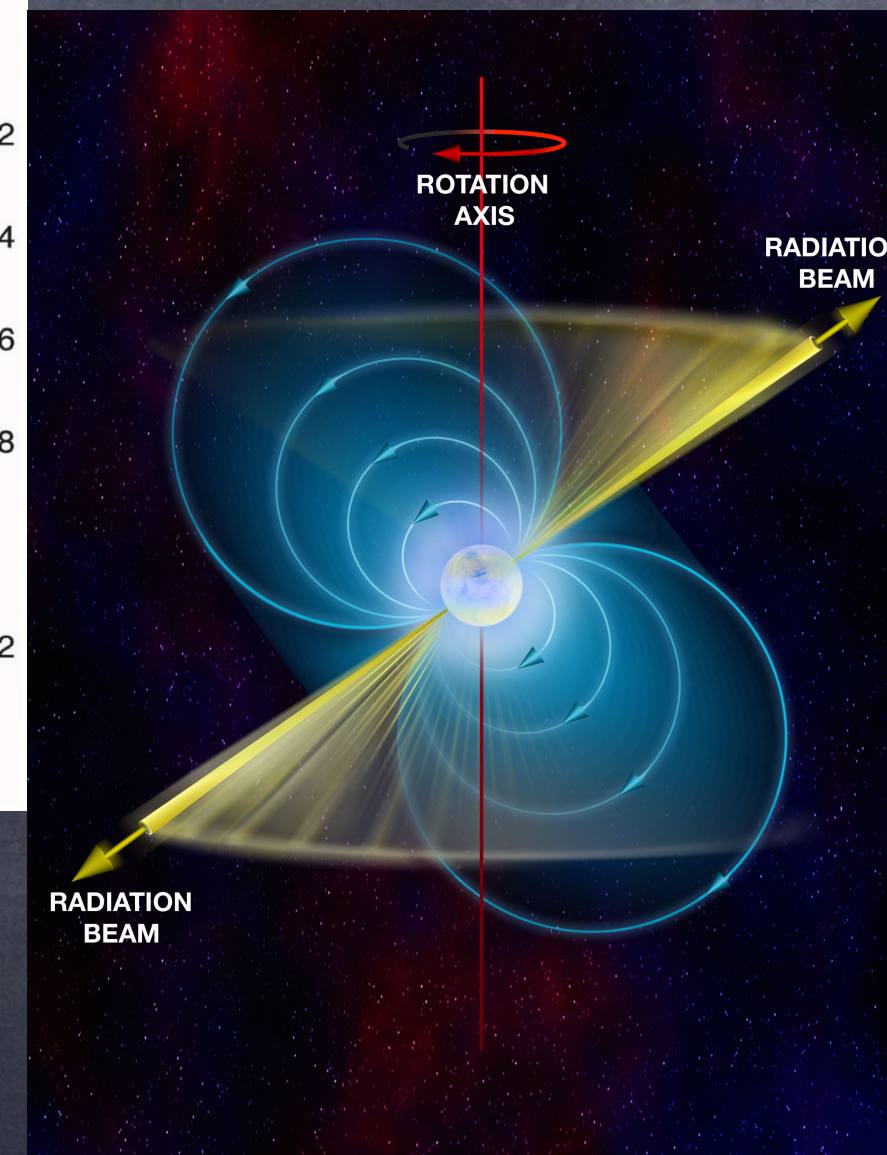
MICROQUASARS



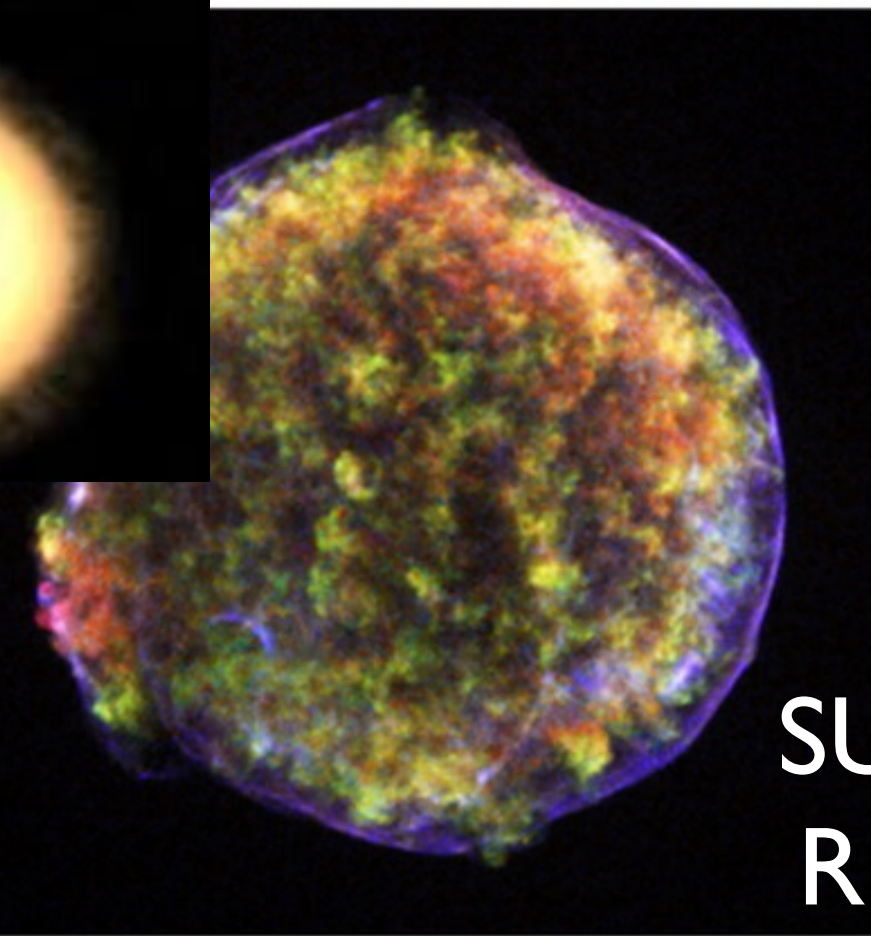
STAR CLUSTERS



PULSARS

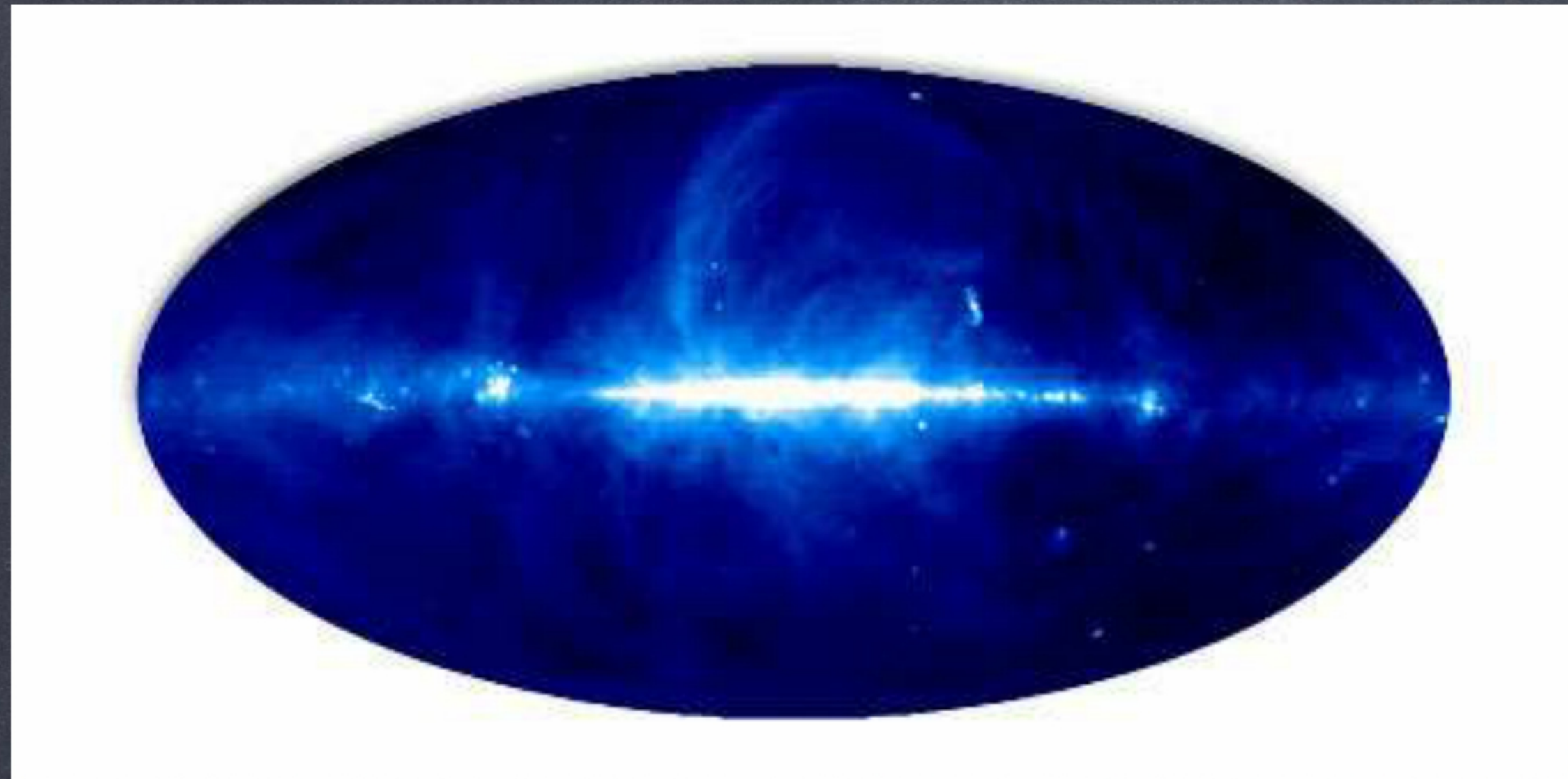


PSR WIND NEBULAE



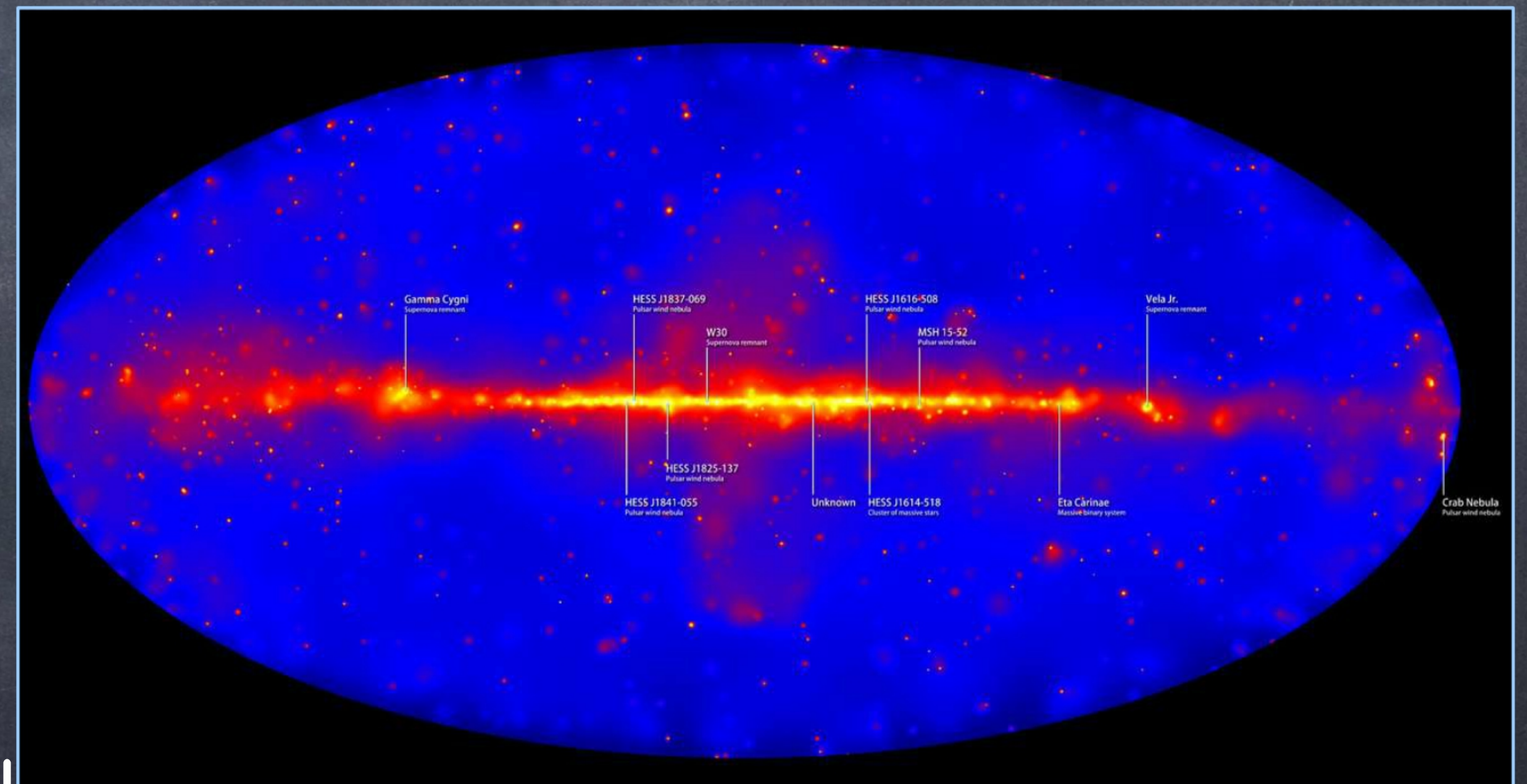
SUPERNOVA REMNANTS

# DIFFUSE NON-THERMAL EMISSION



RADIO EMISSION  
(SYNCHROTRON)

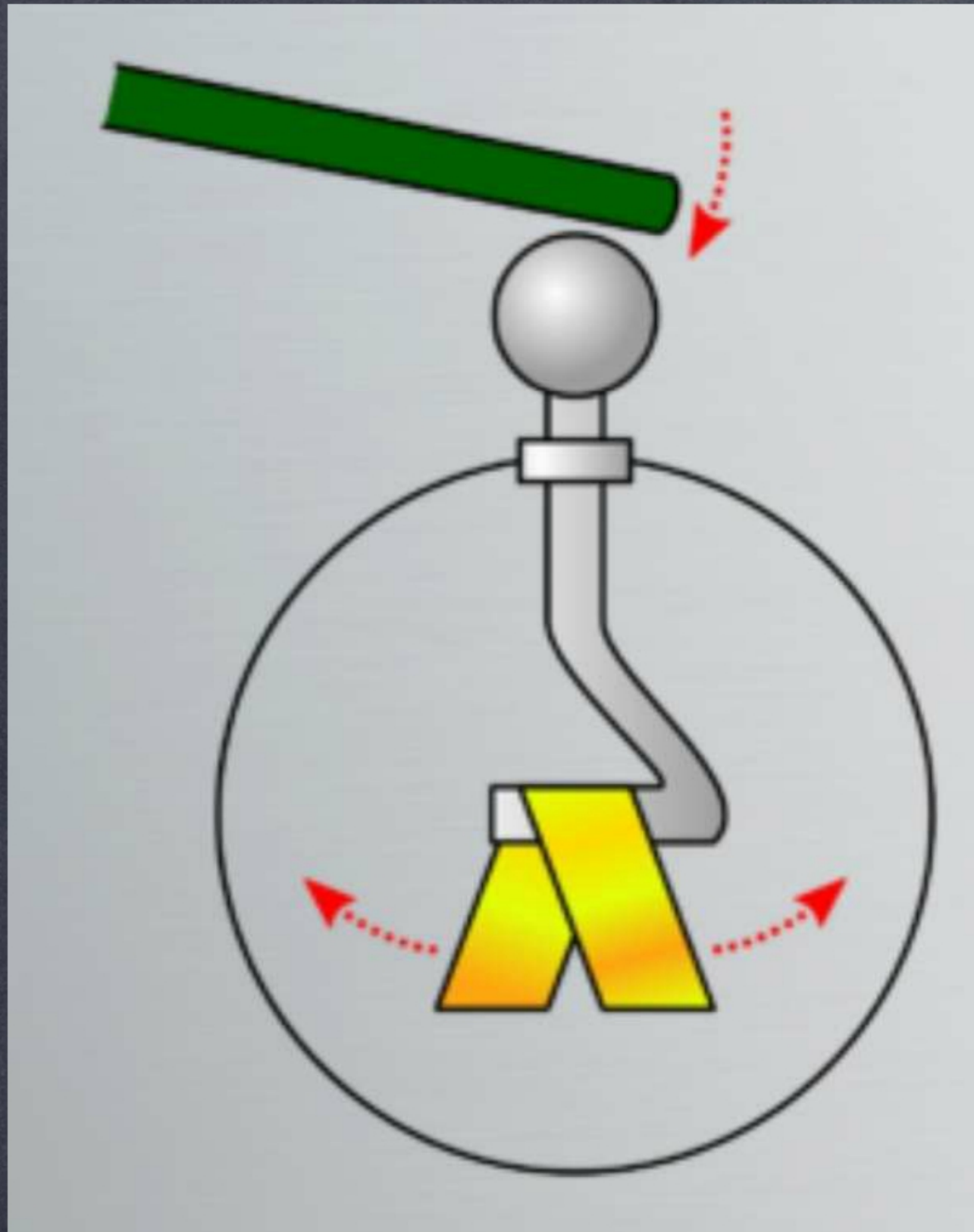
GAMMA-RAY EMISSION  
(INVERSE COMPTON  
AND  
NEUTRAL PION DECAY)



NOW DETECTED UP TO PeV ENERGIES!

# HISTORICAL NOTES

# PLAYING WITH ELECTROSCOPES



ELECTROSCOPES DISCHARGE  
HOW?



RESIDUAL IONIZATION IN AIR  
FROM WHERE?

?-RAYS?

1895: X-RAYS ARE DISCOVERED (Rontgen)

1896: RADIOACTIVITY IS DISCOVERED (Becquerel)

BUT IONIZATION EVEN IN  
THICK LEAD OR WATER FILLED CAVITY

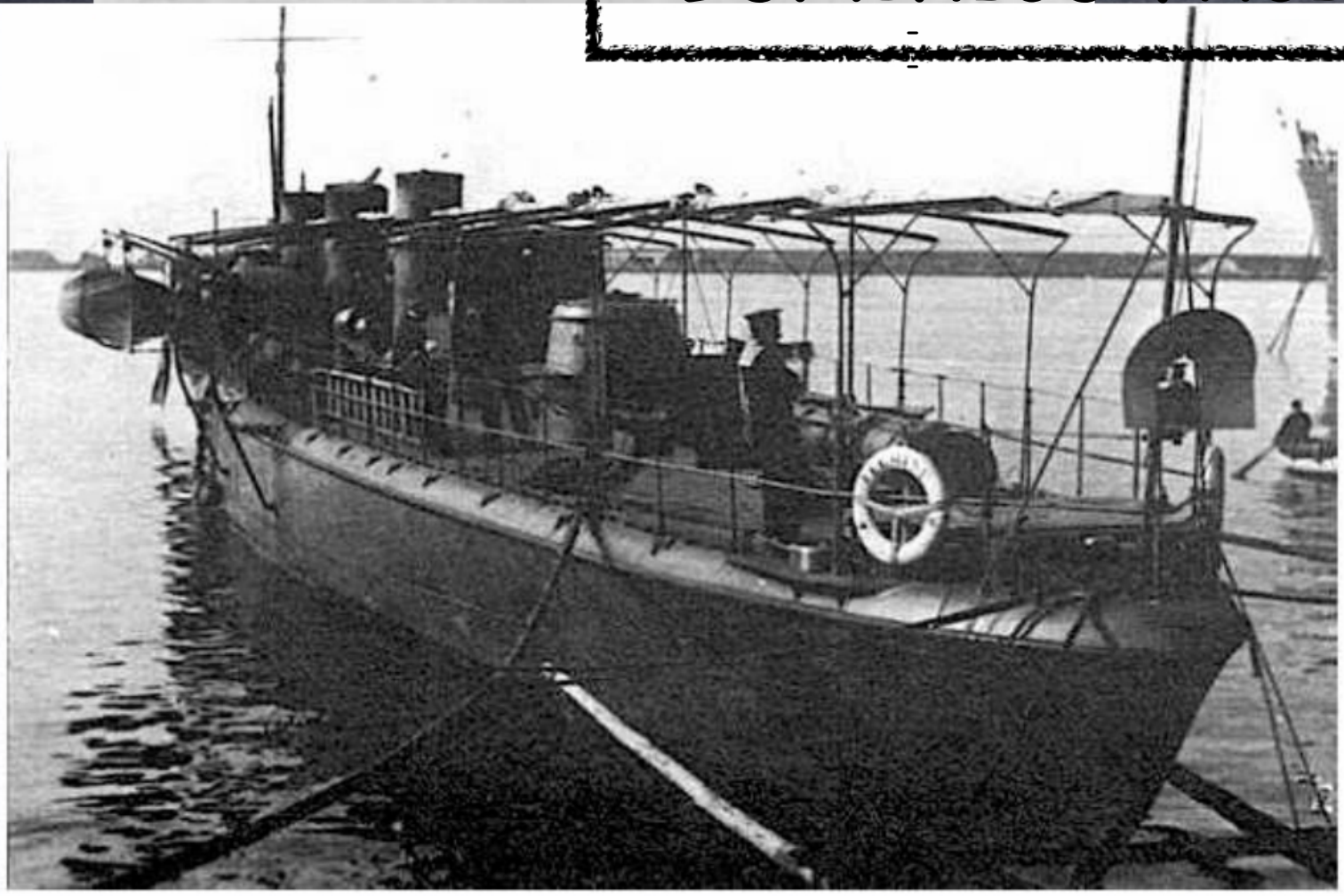


HIGHLY PENETRATING RADIATION

# DROWNING AND FLYING ELECTROSCOPES

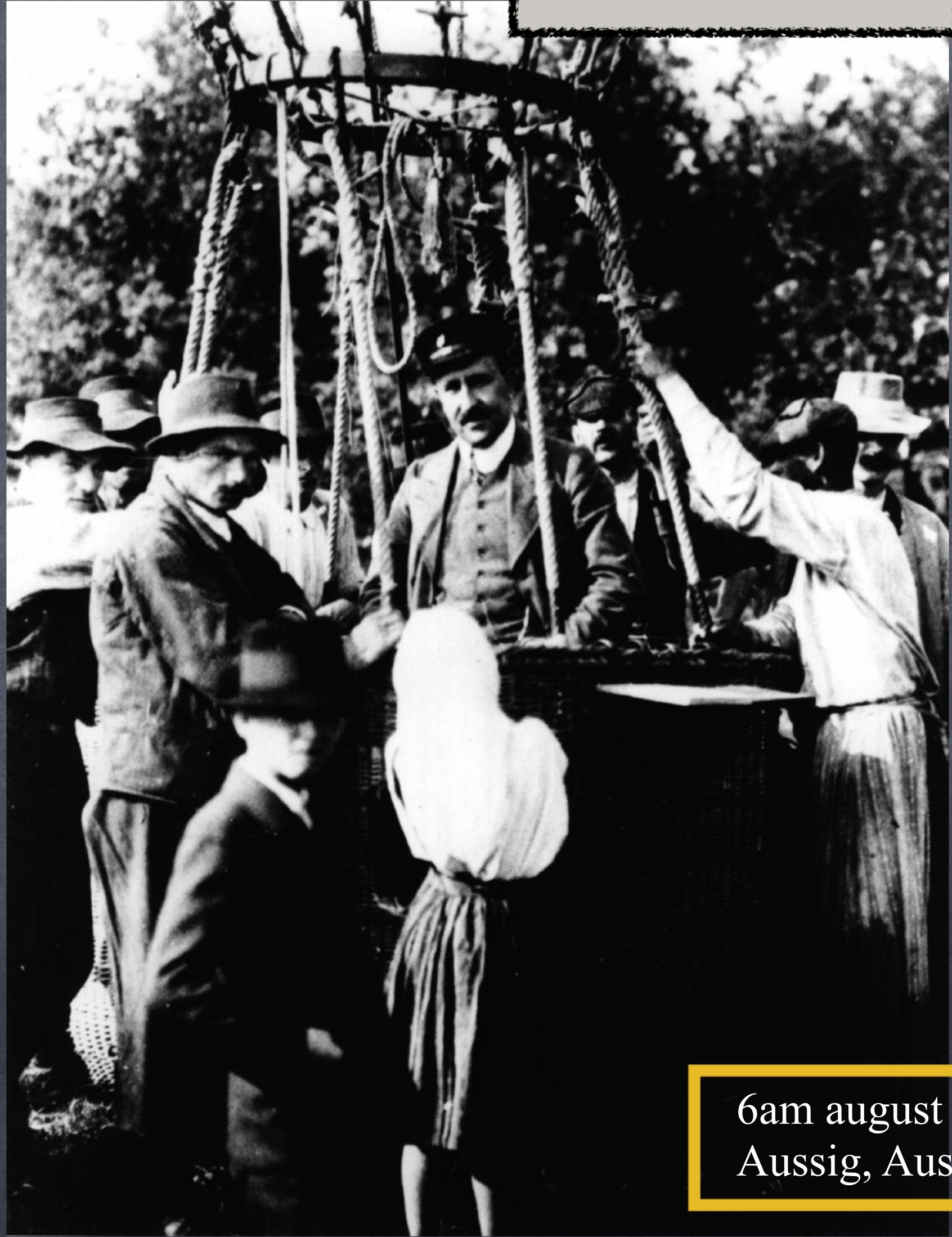


DOMENICO PACINI



NEARLY FORGOTTEN...

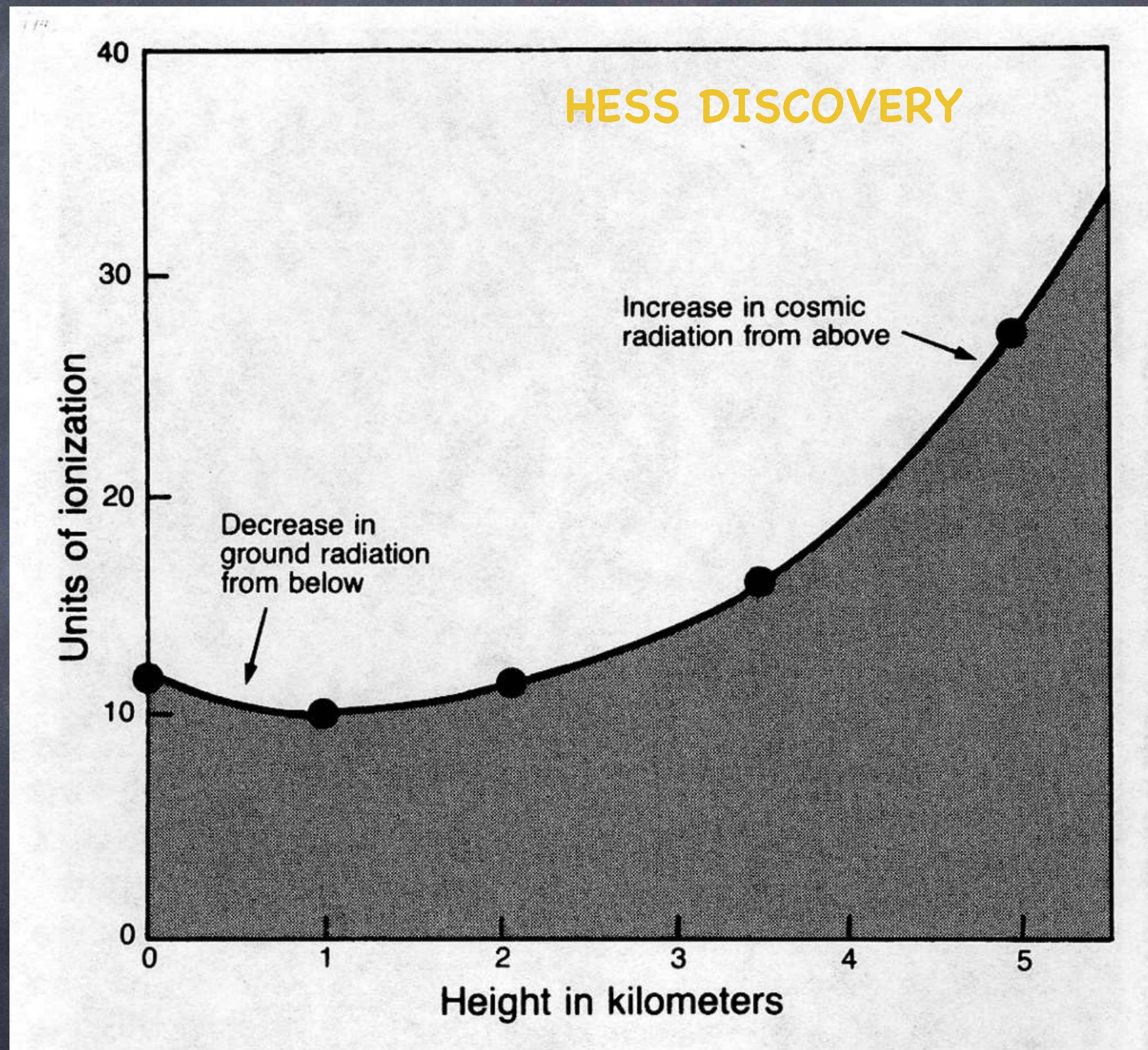
VICTOR F. HESS



6am august 7, 1912  
Aussig, Austria

PHYSICS NOBEL PRIZE 1936

# COSMIC RAYS



# FINE FOR COSMIC BUT RAYS?

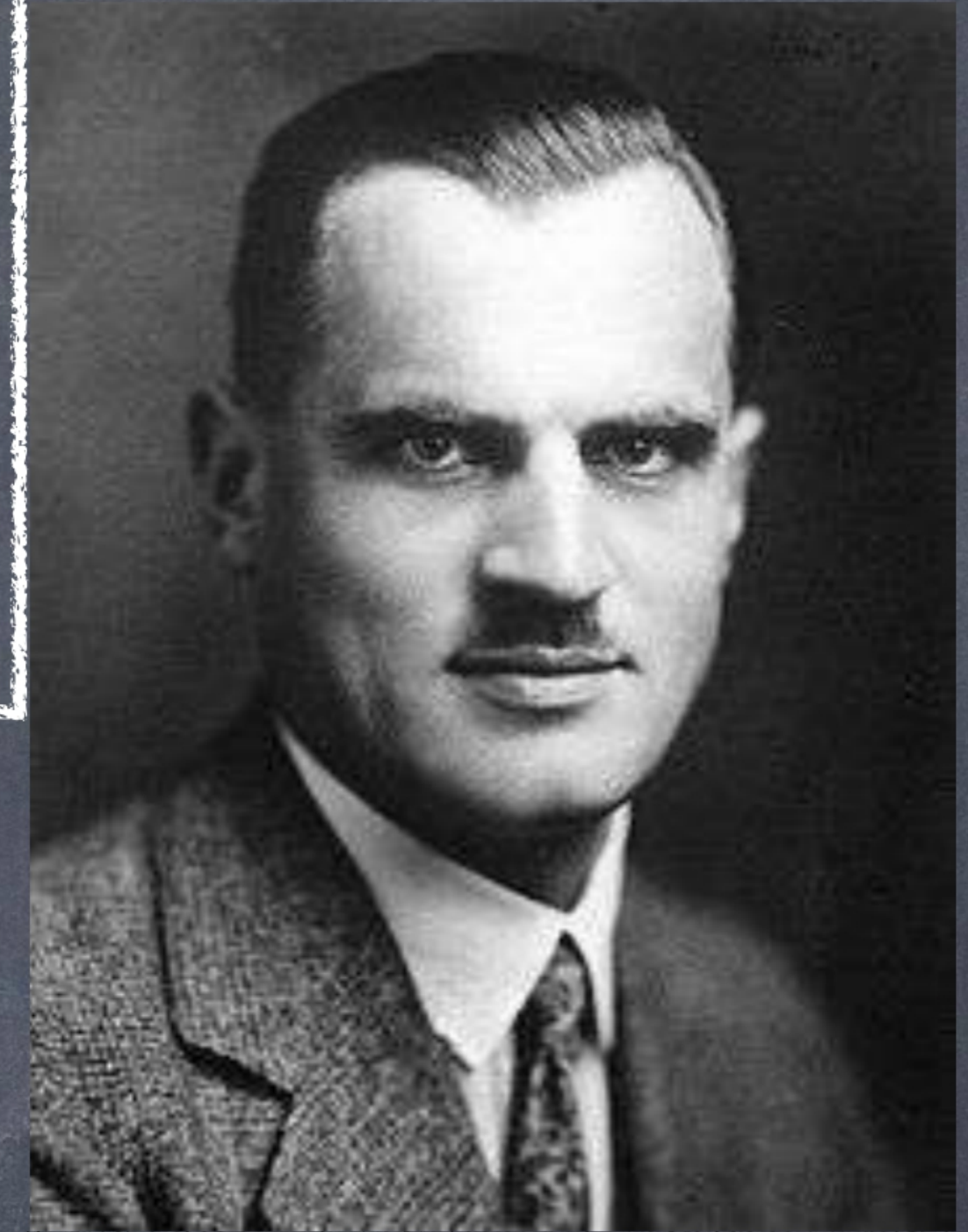
1930's: THE MILLIKAN-COMPTON CONTROVERSY

MeV ENERGIES COULD BE EXPLAINED AS  
BIRTH CRIES OF ELEMENTS HEAVIER THAN H:

- EVIDENCE FOR GeV ENERGIES
- EAST-WEST EFFECT
- LATITUDE DEPENDENCE



ROBERT MILLIKAN

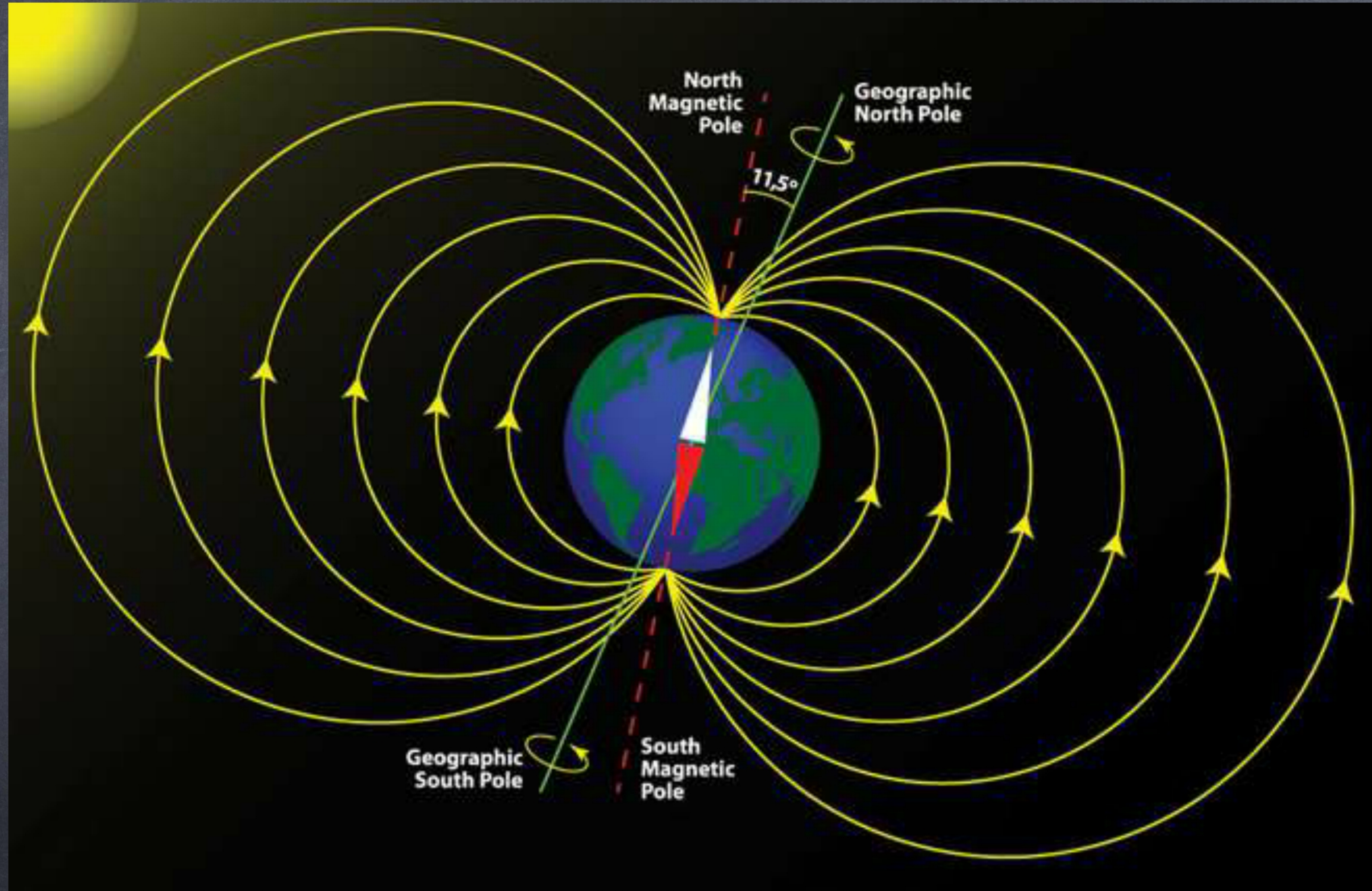


ARTHUR COMPTON

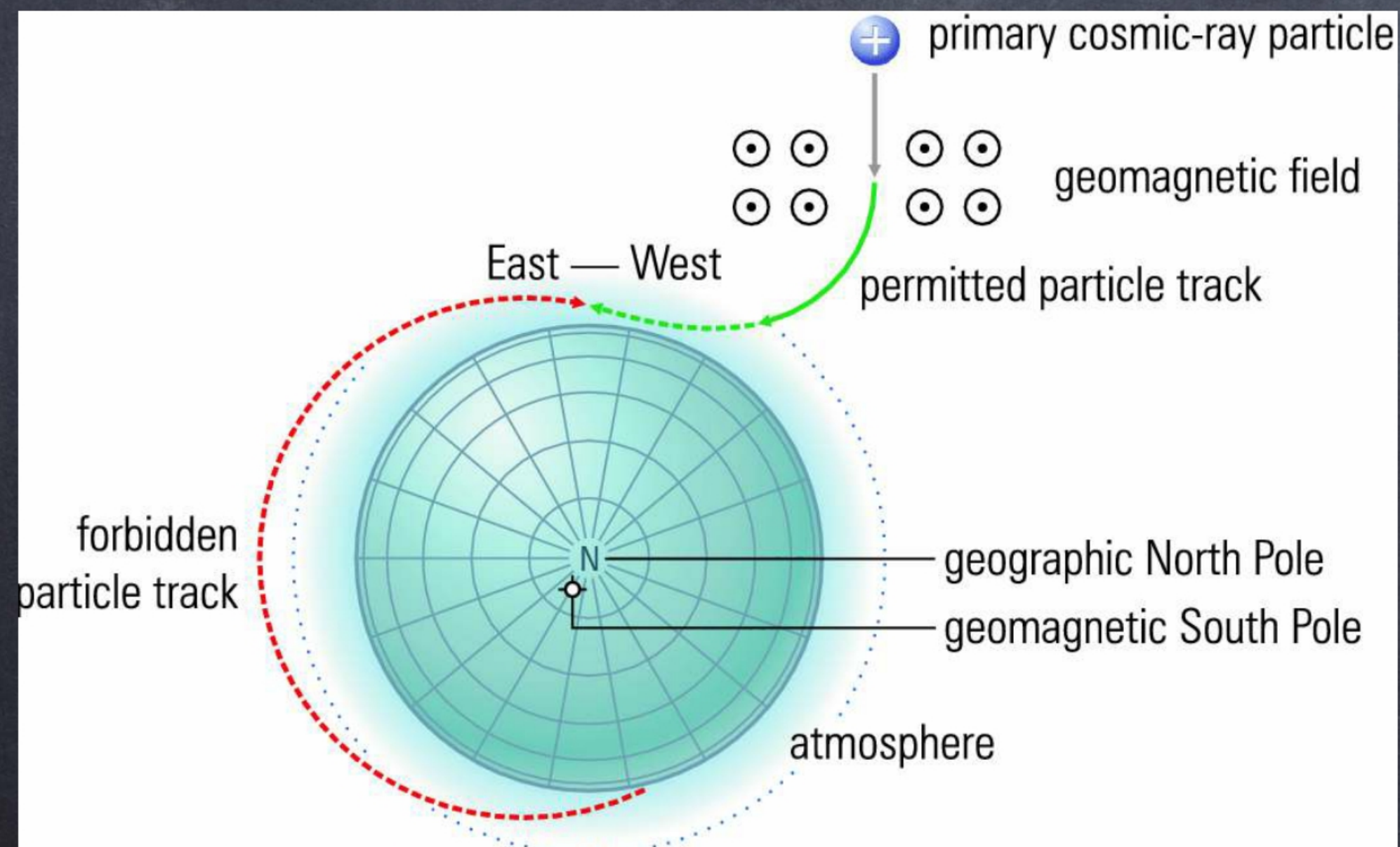
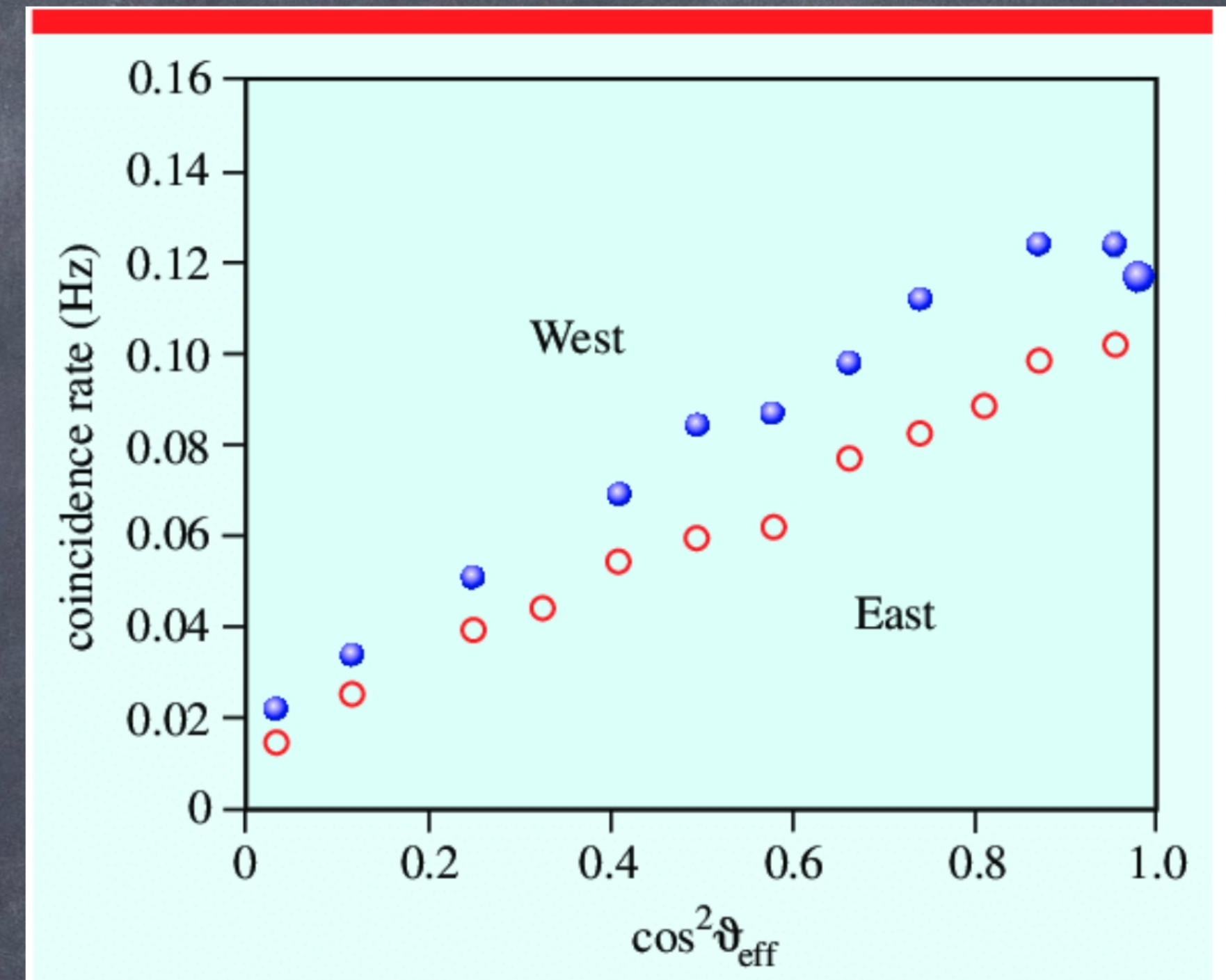
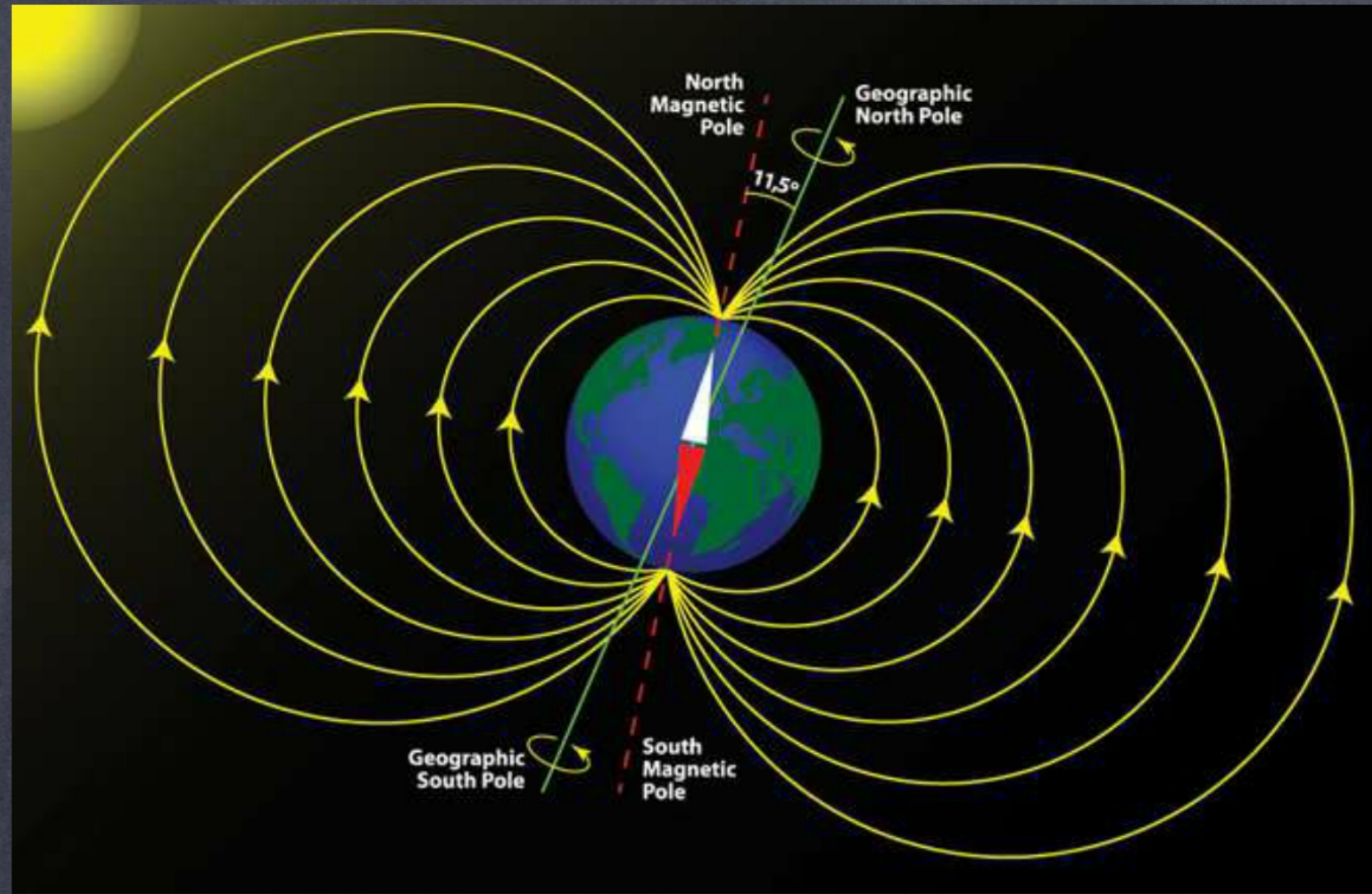


BRUNO ROSSI

# A NATURAL MAGNET

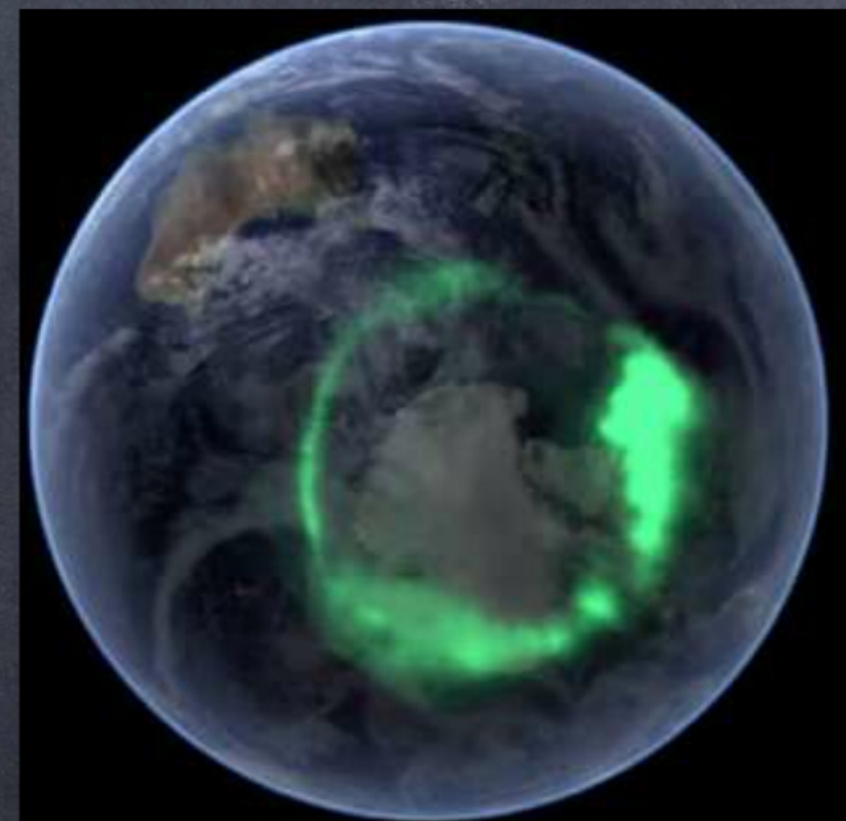
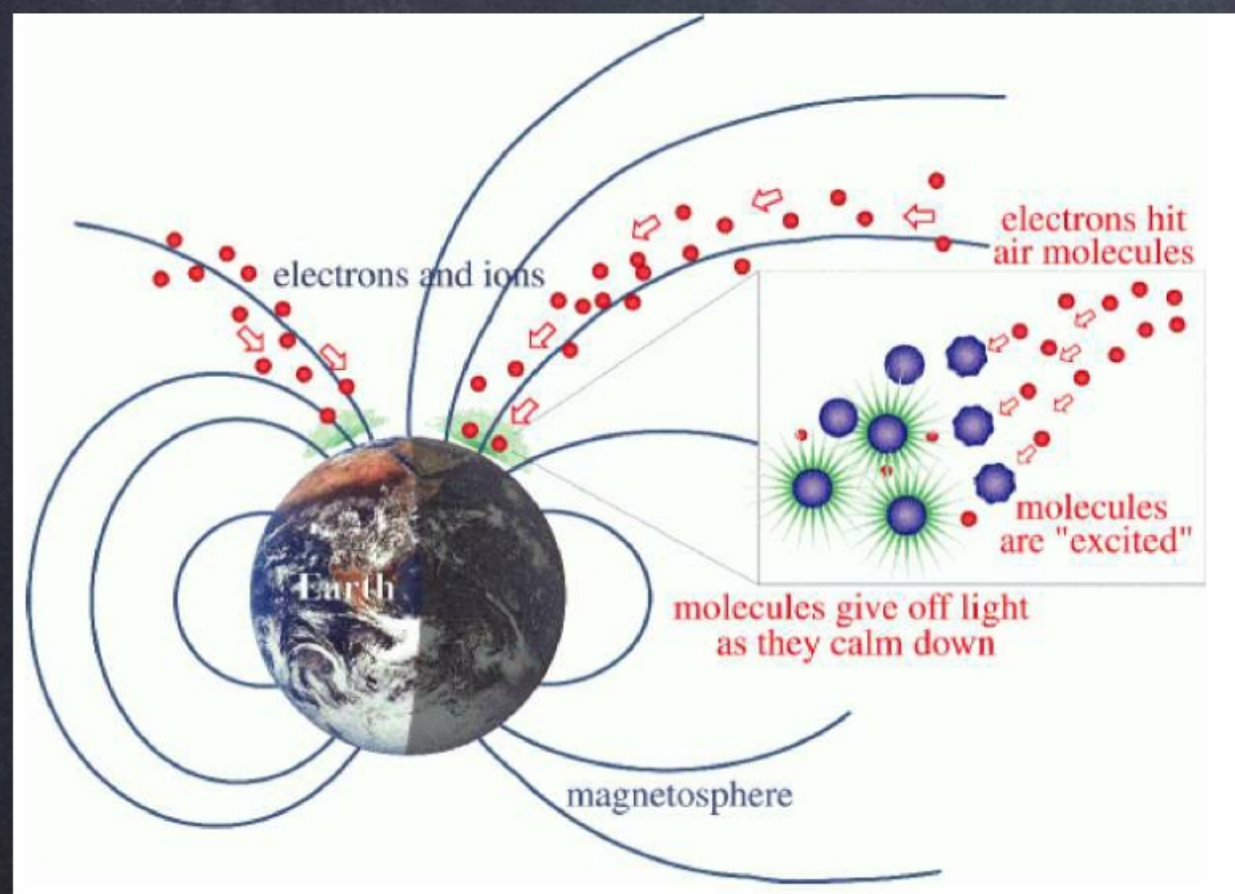
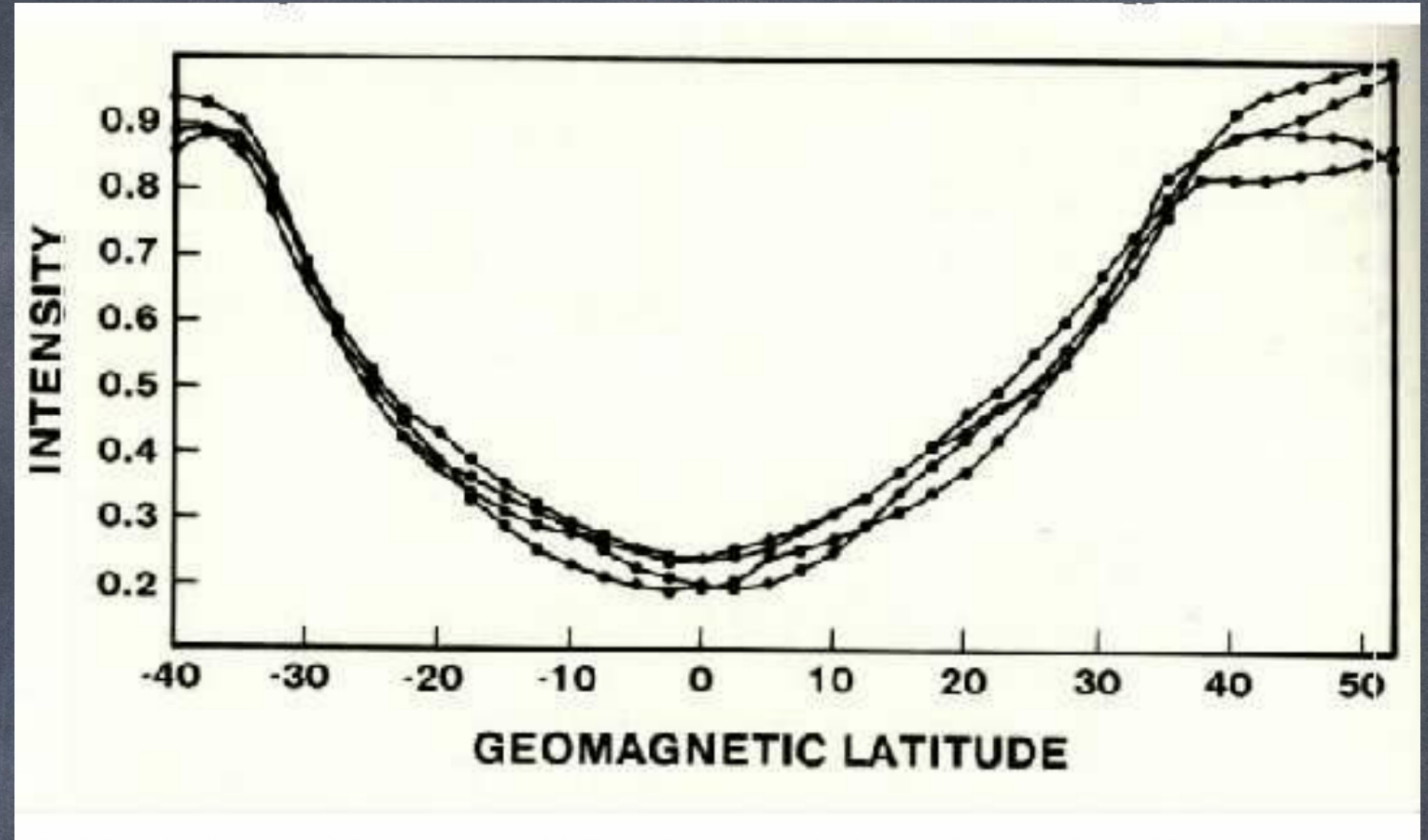
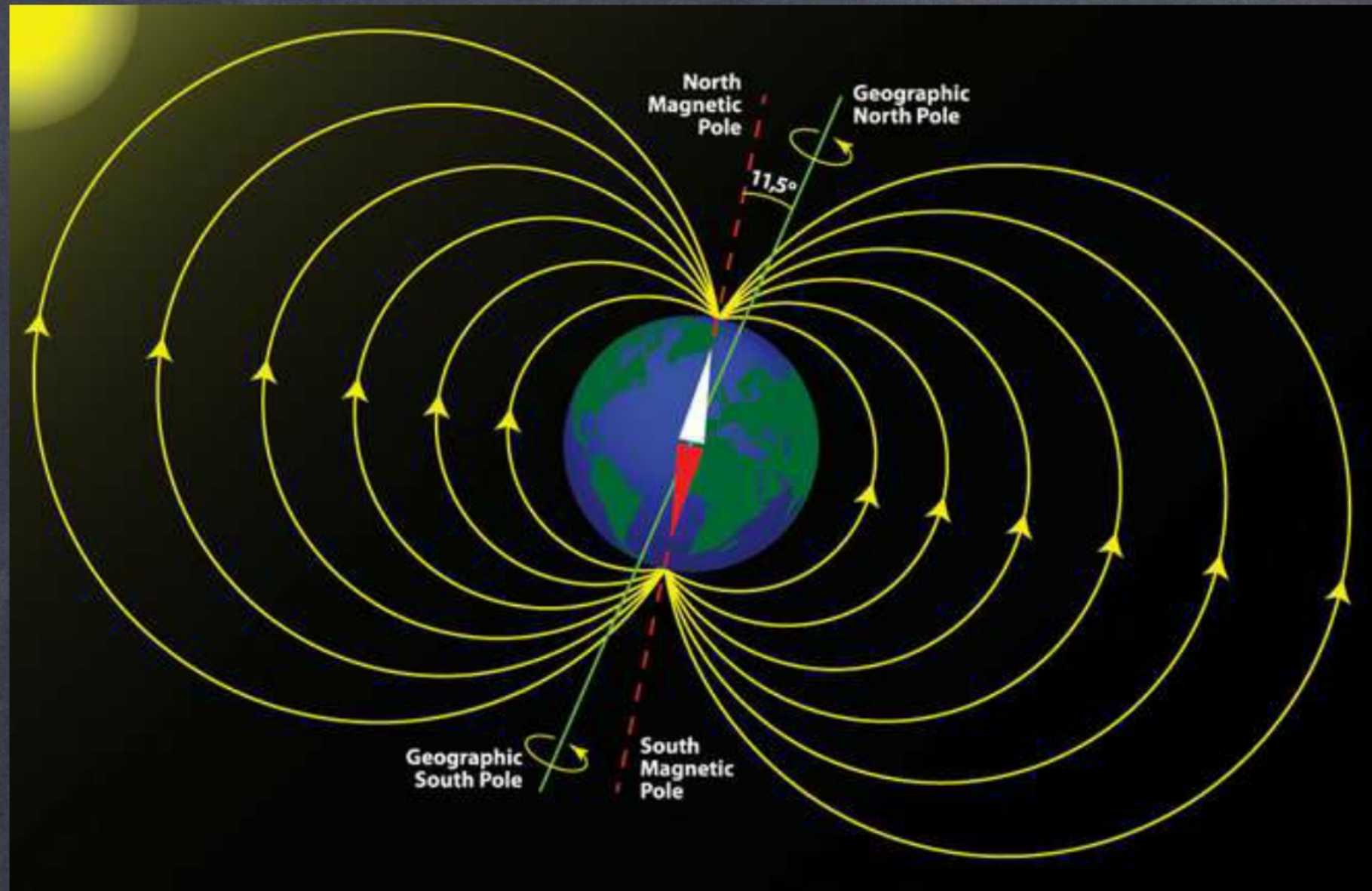


# EAST-WEST EFFECT



**MOST COSMIC RAYS  
ARE POSITIVELY CHARGED PARTICLES!**

# LATITUDE DEPENDENCE

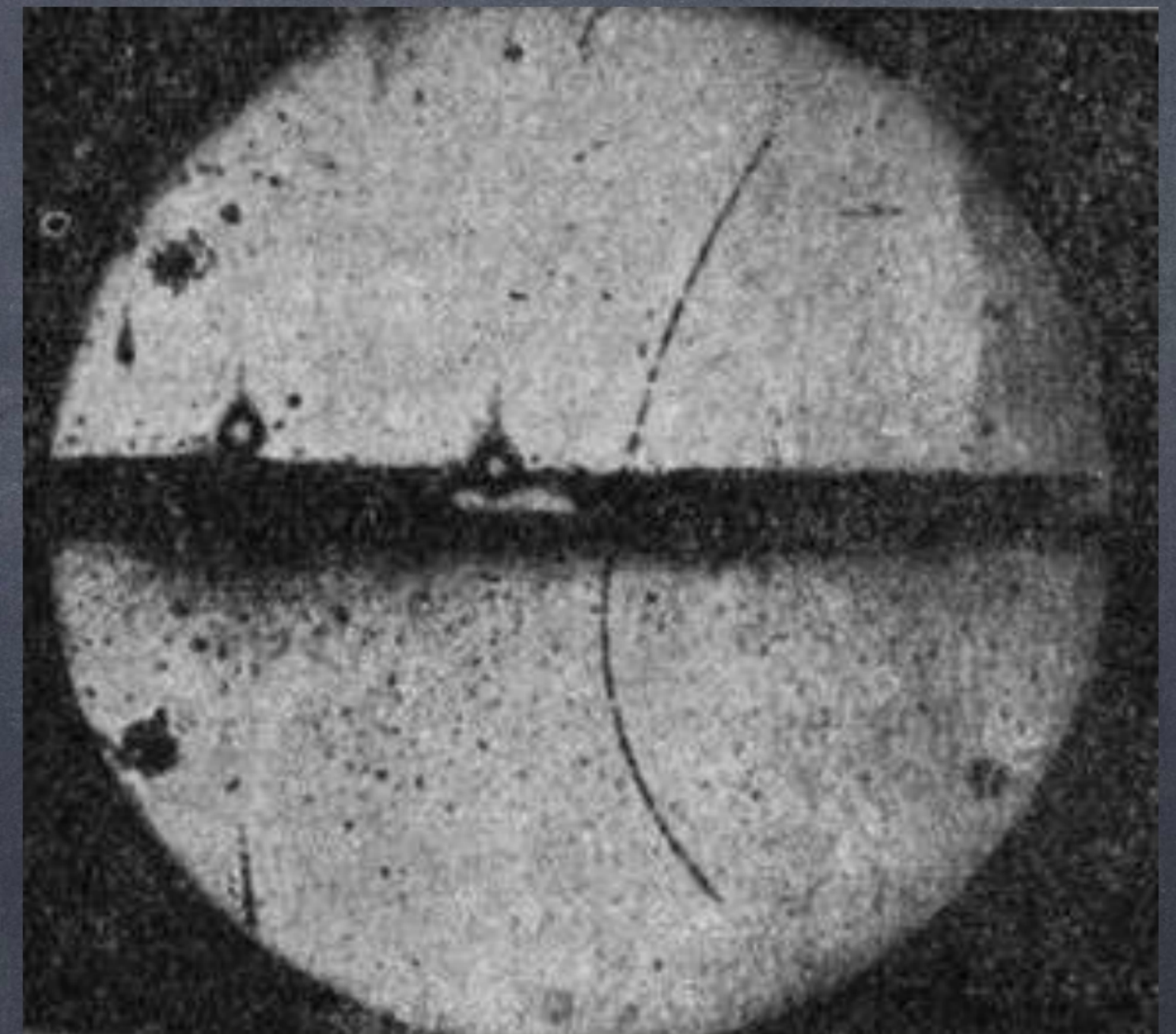


# NEW PARTICLES AND INCREASINGLY HIGHER ENERGIES

1932 (1929): **ANDERSON DISCOVERS THE POSITRON** (ANTIMATTER)

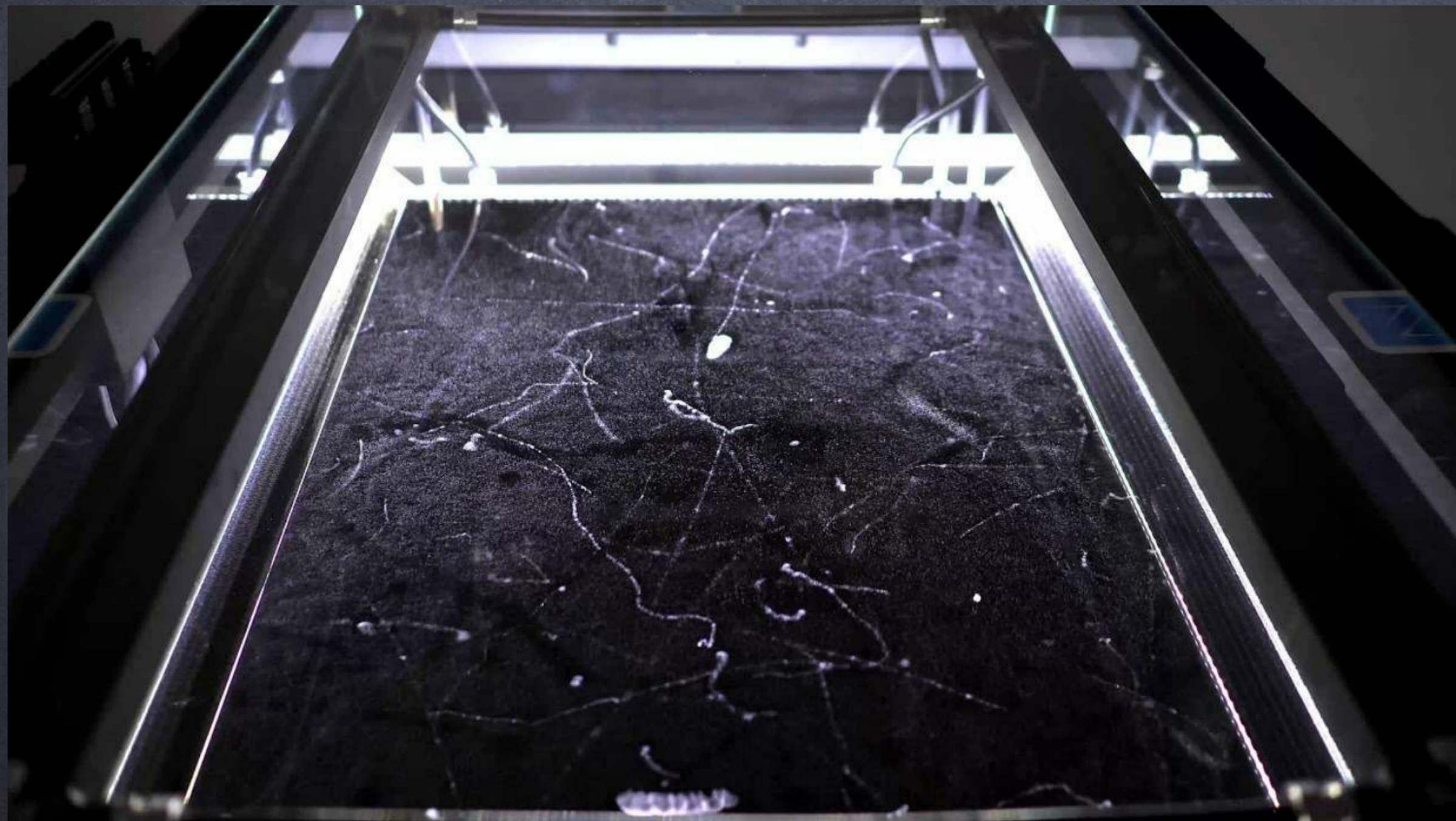


CARL ANDERSON  
NOBEL PRIZE 1936



# NEW PARTICLES AND INCREASINGLY HIGHER ENERGIES

## CLOUD CHAMBERS

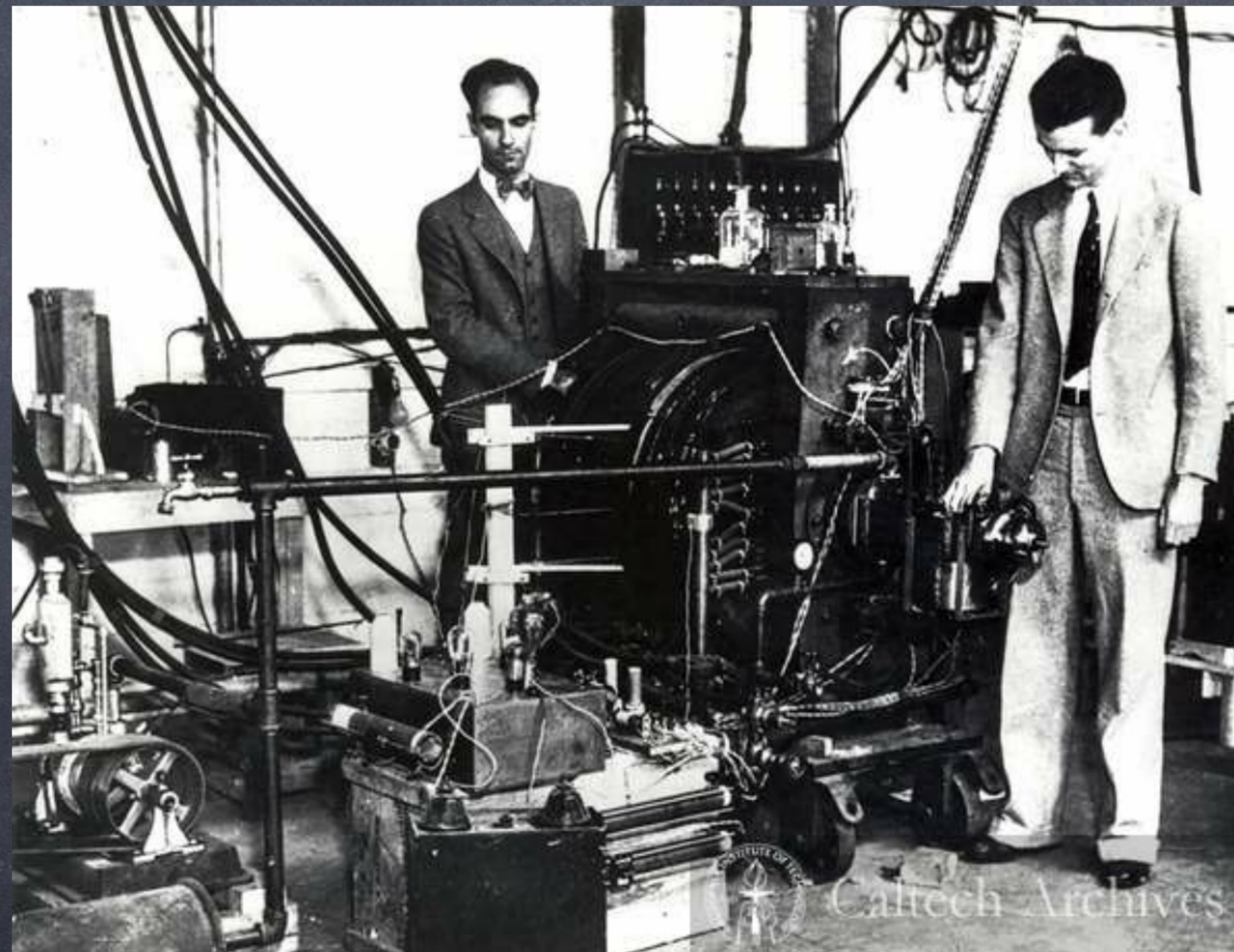
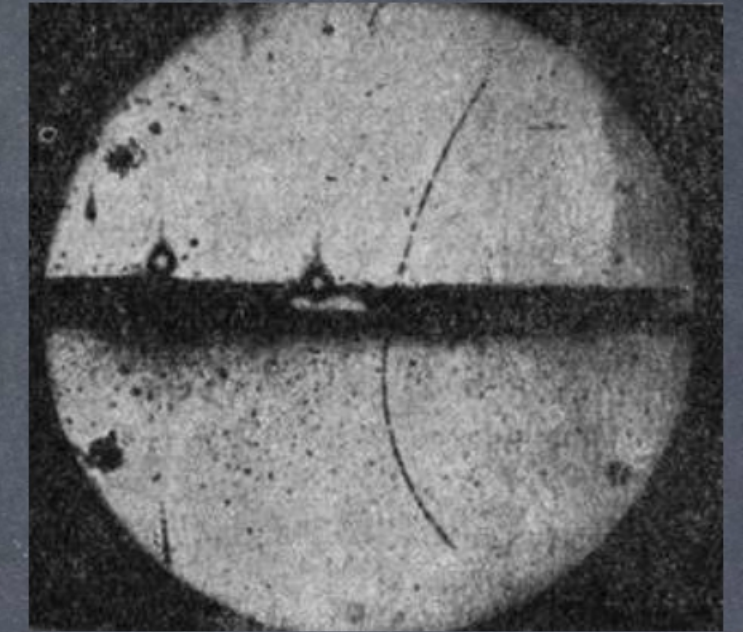


# NEW PARTICLES AND INCREASINGLY HIGHER ENERGIES

1932 (1929): **ANDERSON DISCOVERS THE POSITRON** (ANTIMATTER)

1934: BRUNO ROSSI, WITH A COINCIDENCE SYSTEM, DETECTS EVIDENCE FOR EXTENSIVE SHOWERS  $E > 1\text{GeV}$

1937: **ANDERSON AND NEDDERMEYER DISCOVER THE MUON**



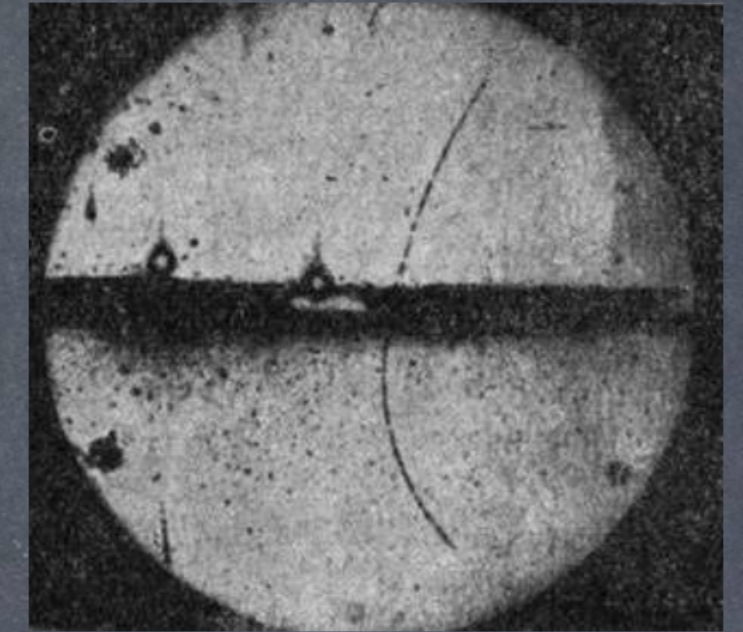
# NEW PARTICLES AND INCREASINGLY HIGHER ENERGIES

1932 (1929): **ANDERSON DISCOVERS THE POSITRON** (ANTIMATTER)

1934: BRUNO ROSSI, WITH A COINCIDENCE SYSTEM, DETECTS EVIDENCE FOR EXTENSIVE SHOWERS  $E > 1\text{GeV}$

1937: **ANDERSON AND NEDDERMEYER DISCOVER THE MUON**

1938–1939: AUGER DETECTS FIRST EXTENSIVE AIR SHOWER WITH  $E > 10^{13-14} \text{eV}$  (THIS IS TODAY LHC CENTER OF MASS ENERGY!)



# NEW PARTICLES AND INCREASINGLY HIGHER ENERGIES

1932 (1929): **ANDERSON DISCOVERS THE POSITRON** (ANTIMATTER)

1934: BRUNO ROSSI, WITH A COINCIDENCE SYSTEM, DETECTS EVIDENCE FOR EXTENSIVE SHOWERS  $E > 1\text{GeV}$

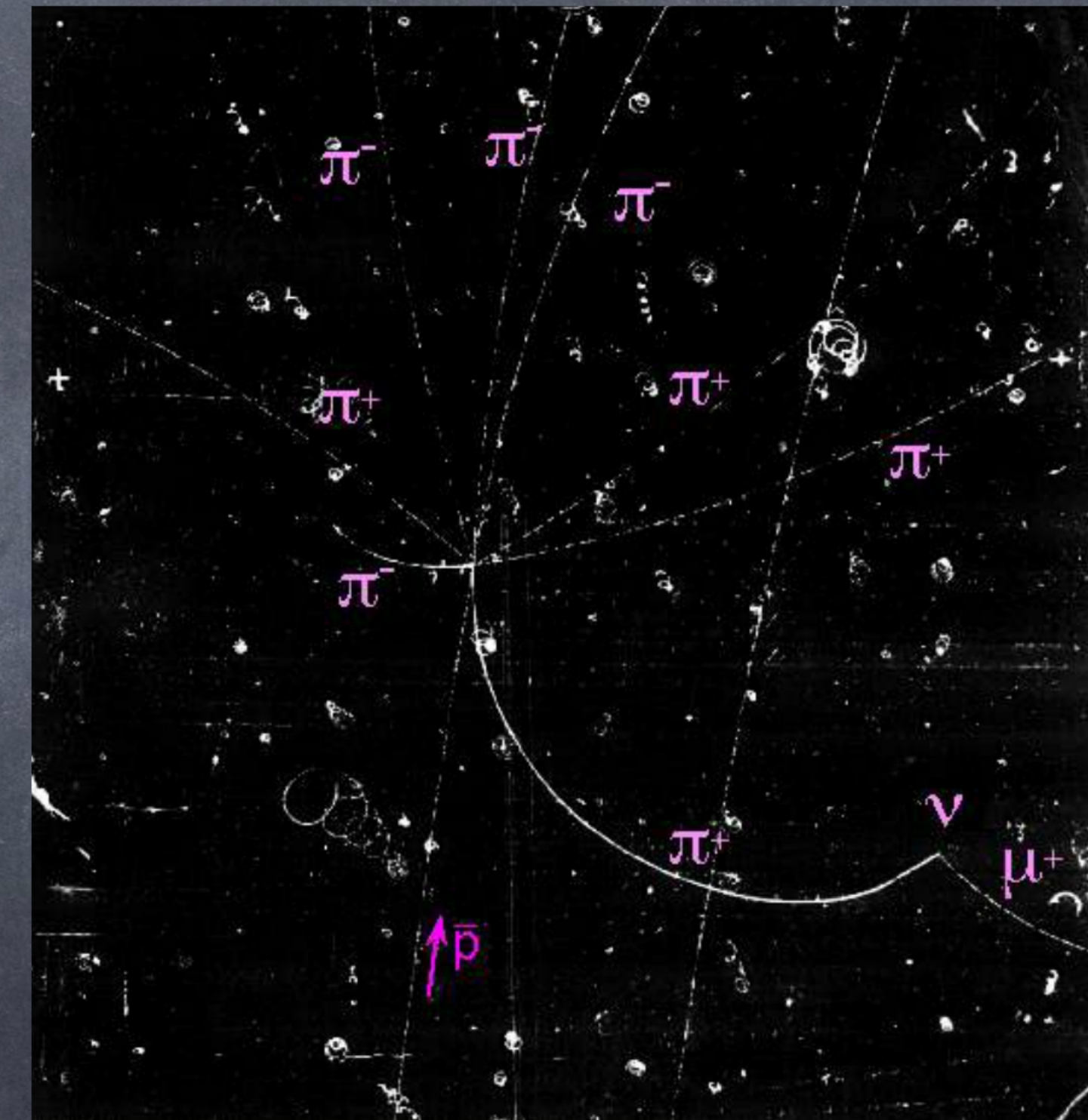
1937: **ANDERSON AND NEDDERMEYER DISCOVER THE MUON**

1938–1939: AUGER DETECTS FIRST EXTENSIVE AIR SHOWER WITH  $E > 10^{13-14} \text{ eV}$  (THIS IS TODAY LHC CENTER OF MASS ENERGY!)

1947: **DISCOVERY OF PION BY POWELL, LATTES, OCCHIALINI**



CECIL POWELL  
NOBEL PRIZE 1950



DOUBLE MESON?

$$\pi \rightarrow \mu + \nu$$

# NEW PARTICLES AND INCREASINGLY HIGHER ENERGIES

1932 (1929): **ANDERSON DISCOVERS THE POSITRON** (ANTIMATTER)

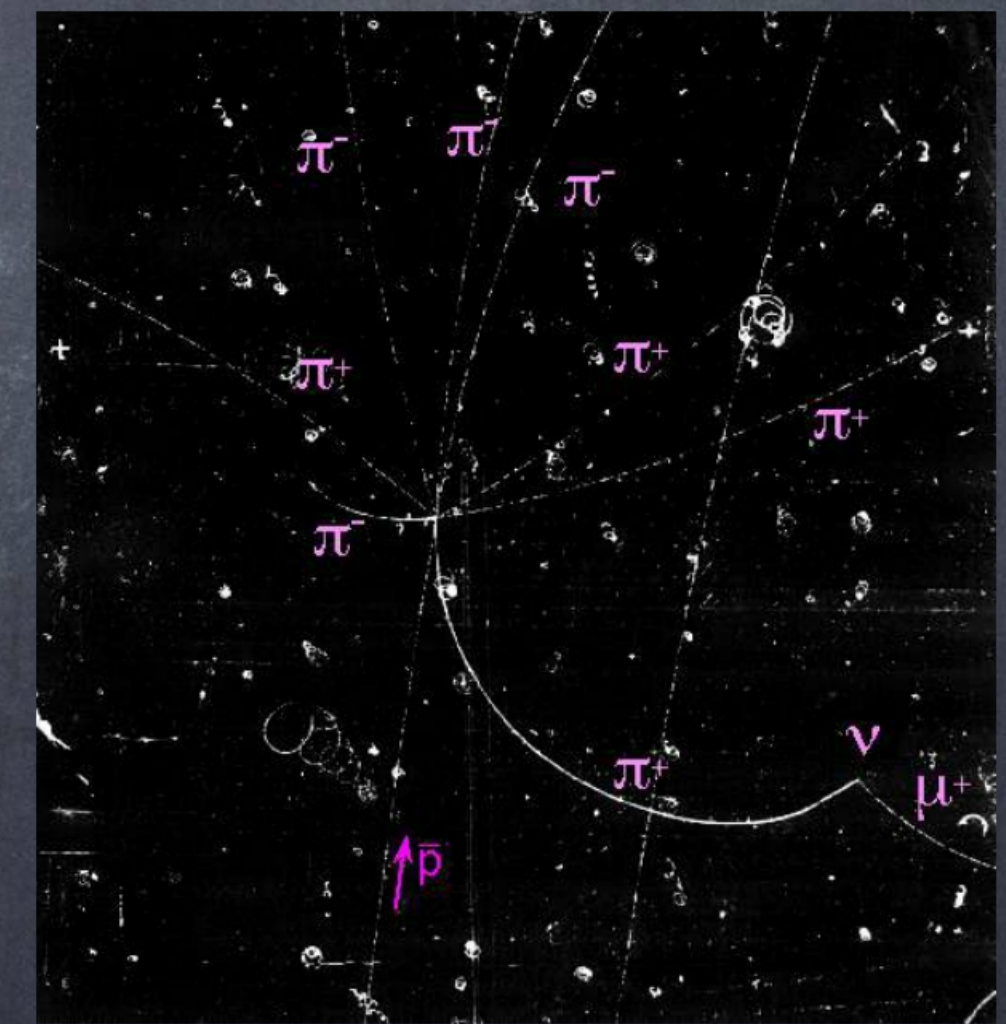
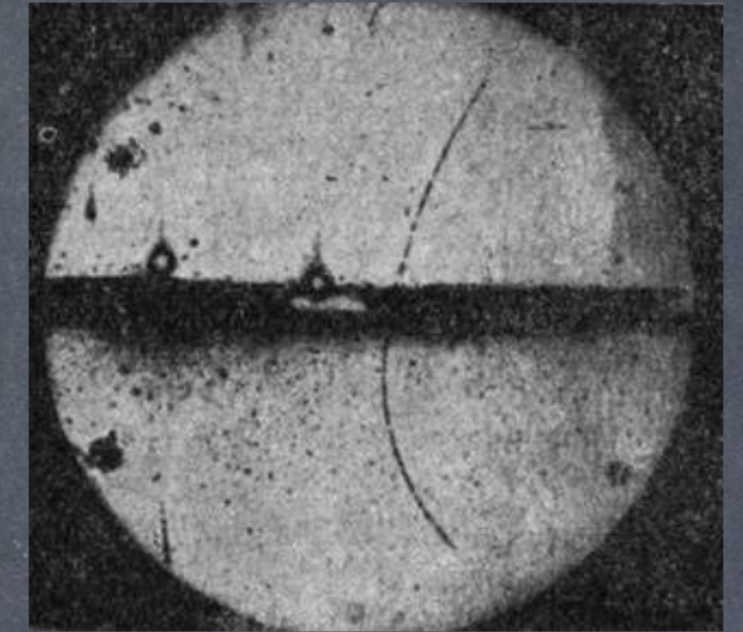
1934: BRUNO ROSSI, WITH A COINCIDENCE SYSTEM, DETECTS EVIDENCE FOR EXTENSIVE SHOWERS  $E > 1\text{GeV}$

1937: **ANDERSON AND NEDDERMEYER DISCOVER THE MUON**

1938–1939: AUGER DETECTS FIRST EXTENSIVE AIR SHOWER WITH  $E > 10^{13-14}\text{ eV}$  (THIS IS TODAY LHC CENTER OF MASS ENERGY!)

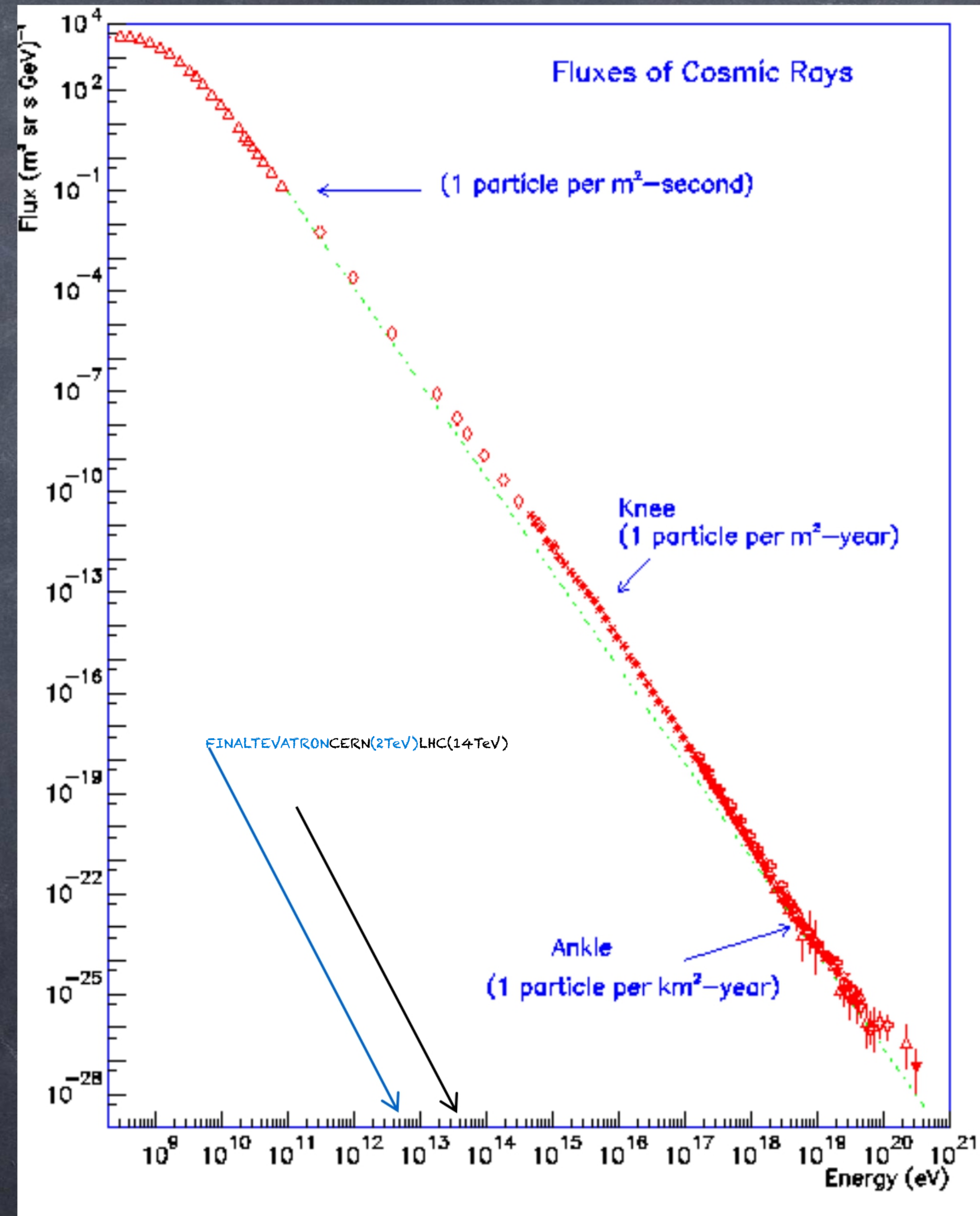
1947: **DISCOVERY OF PION**

1960: DETECTION OF PARTICLES WITH  $E \sim 10^{20}\text{ eV}$  (SUBATOMIC PARTICLES WITH MACROSCOPIC ENERGY: 1 kg falling from a 1 m height)

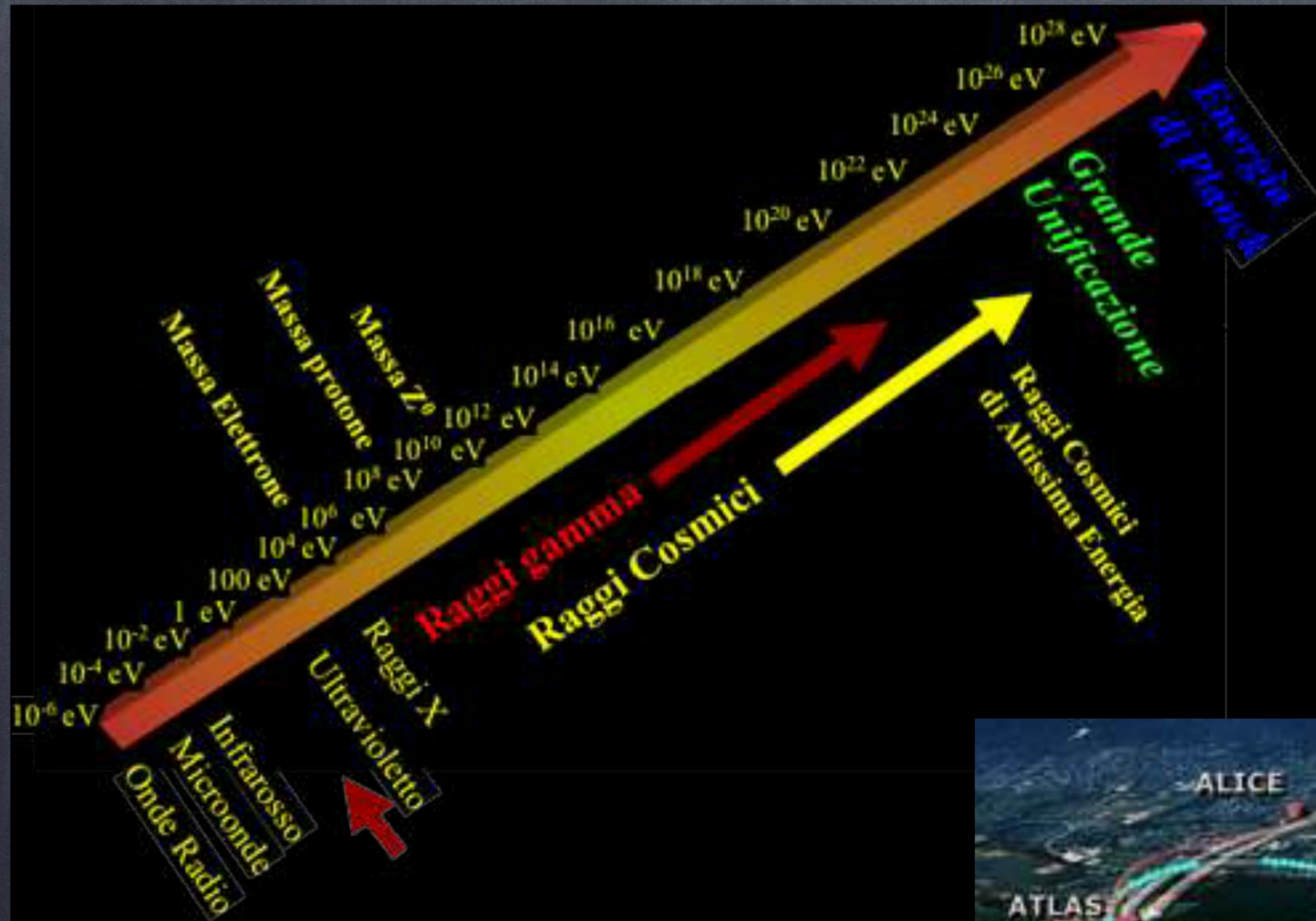


# RELEVANCE FOR PHYSICS AND ASTROPHYSICS

# THE HIGHEST ENERGIES PROBED



# COSMIC RAYS AS MESSENGERS



# THE "WEIGHT" OF CRs

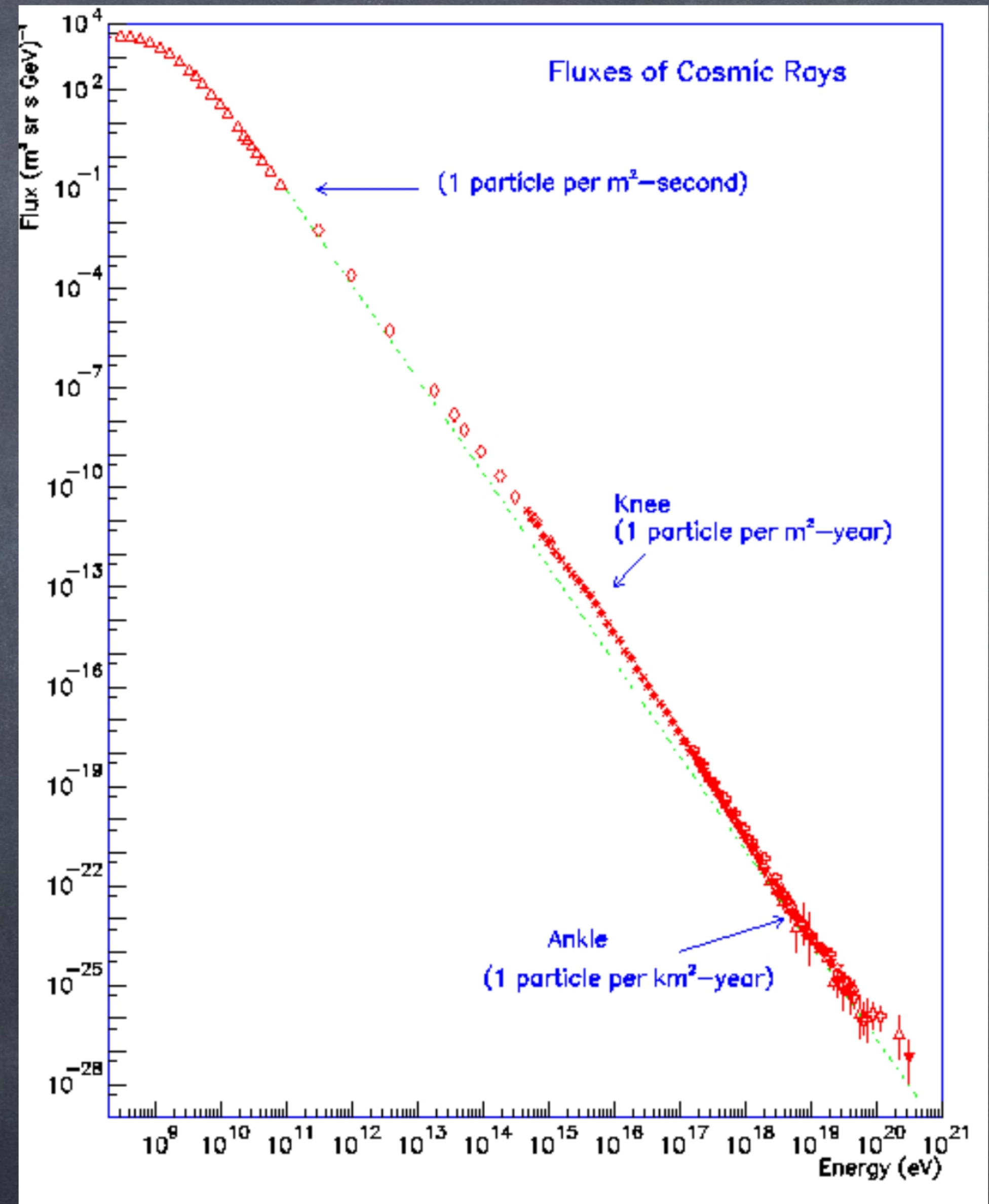
$$J = \frac{dN}{dE dt dS d\Omega}$$

$$J(1\text{GeV}) \approx 1 \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} \text{ GeV}^{-1}$$



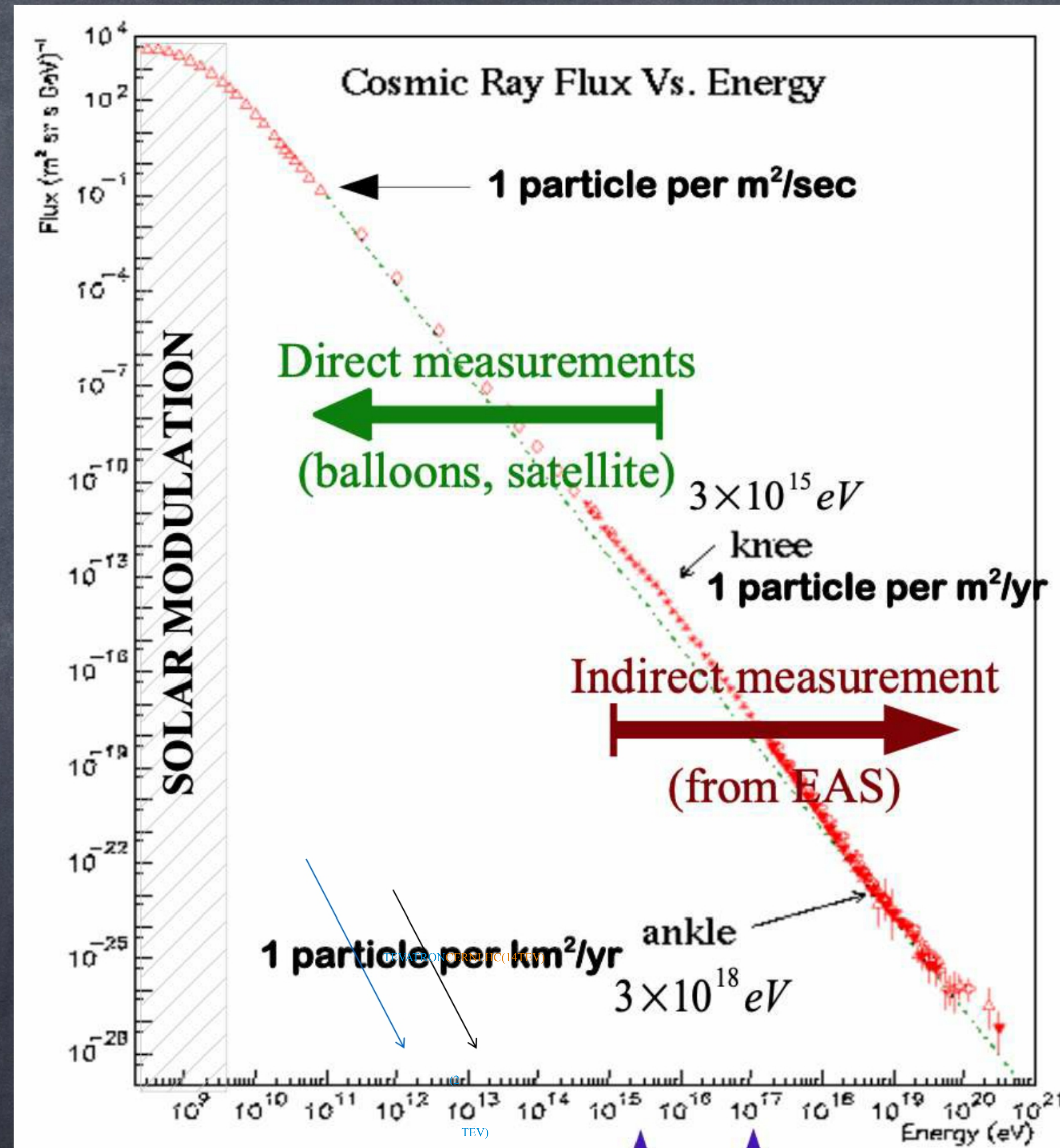
$$w_{CR} \approx 0.5 \text{ eV cm}^{-3}$$

$$w_{CR} \approx w_{th} \approx w_{CMB} \approx w_B$$



# HOW TO MEASURE CRs

EXTREME ENERGY  
EXTENSION: >12  
DECADES



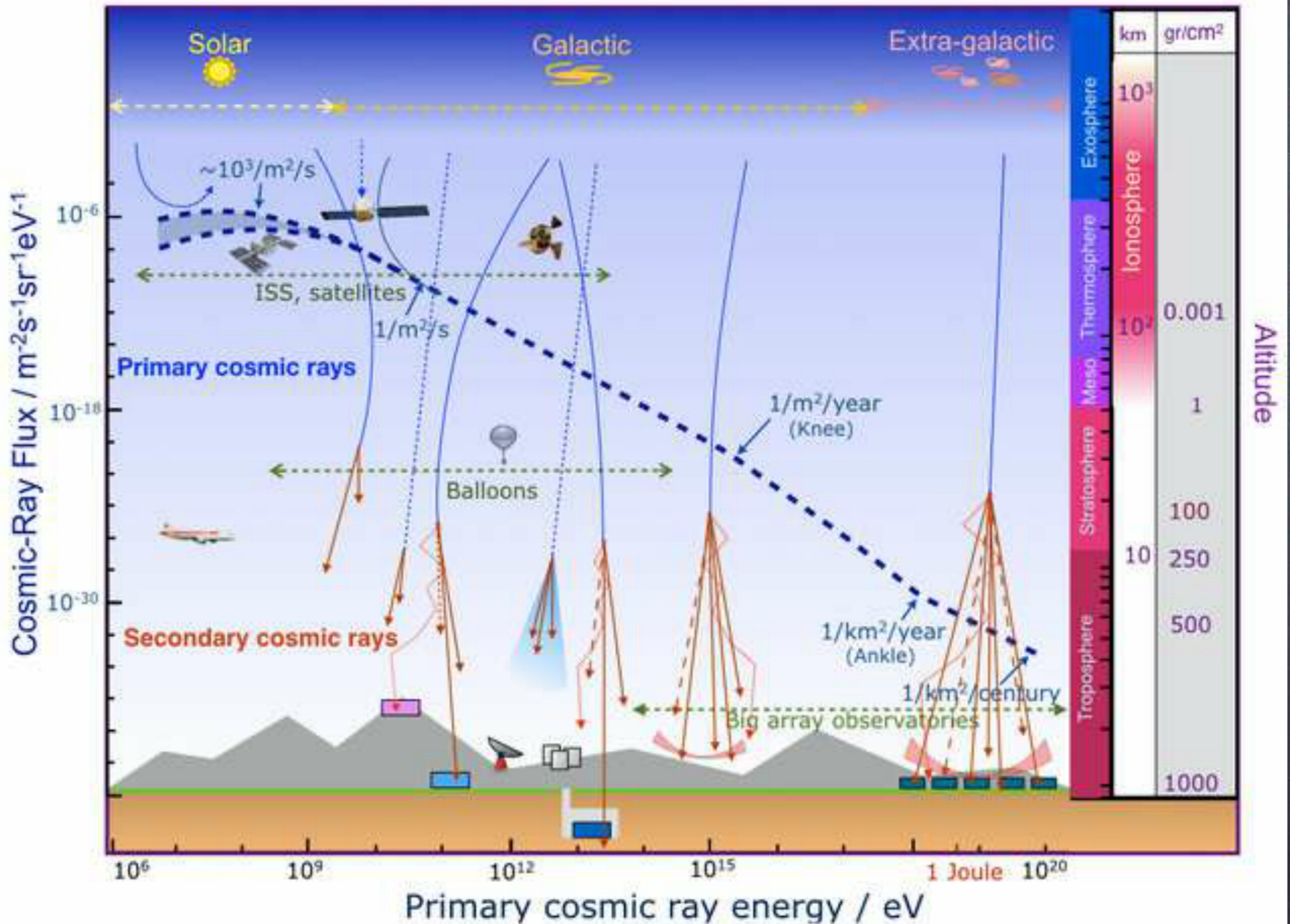
EXTREME FLUX  
VARIATION: 24  
DECADES

sub-GeV

ZeV

# CR DETECTION

# HOW WE MEASURE CRs



EARTH  
ATMOSPHERE  
AS A SCREEN AND  
AS PART OF THE  
DETECTOR.....

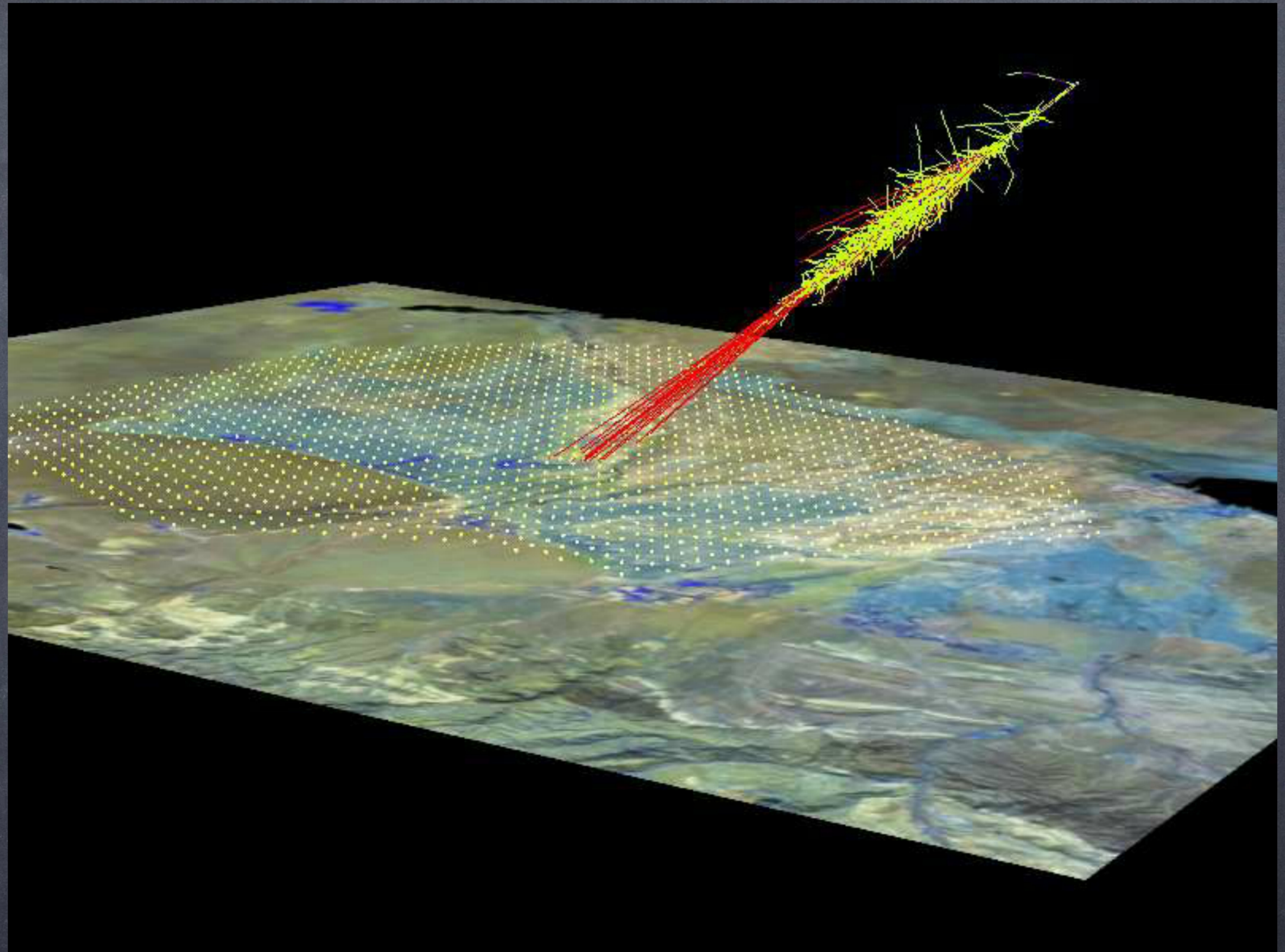
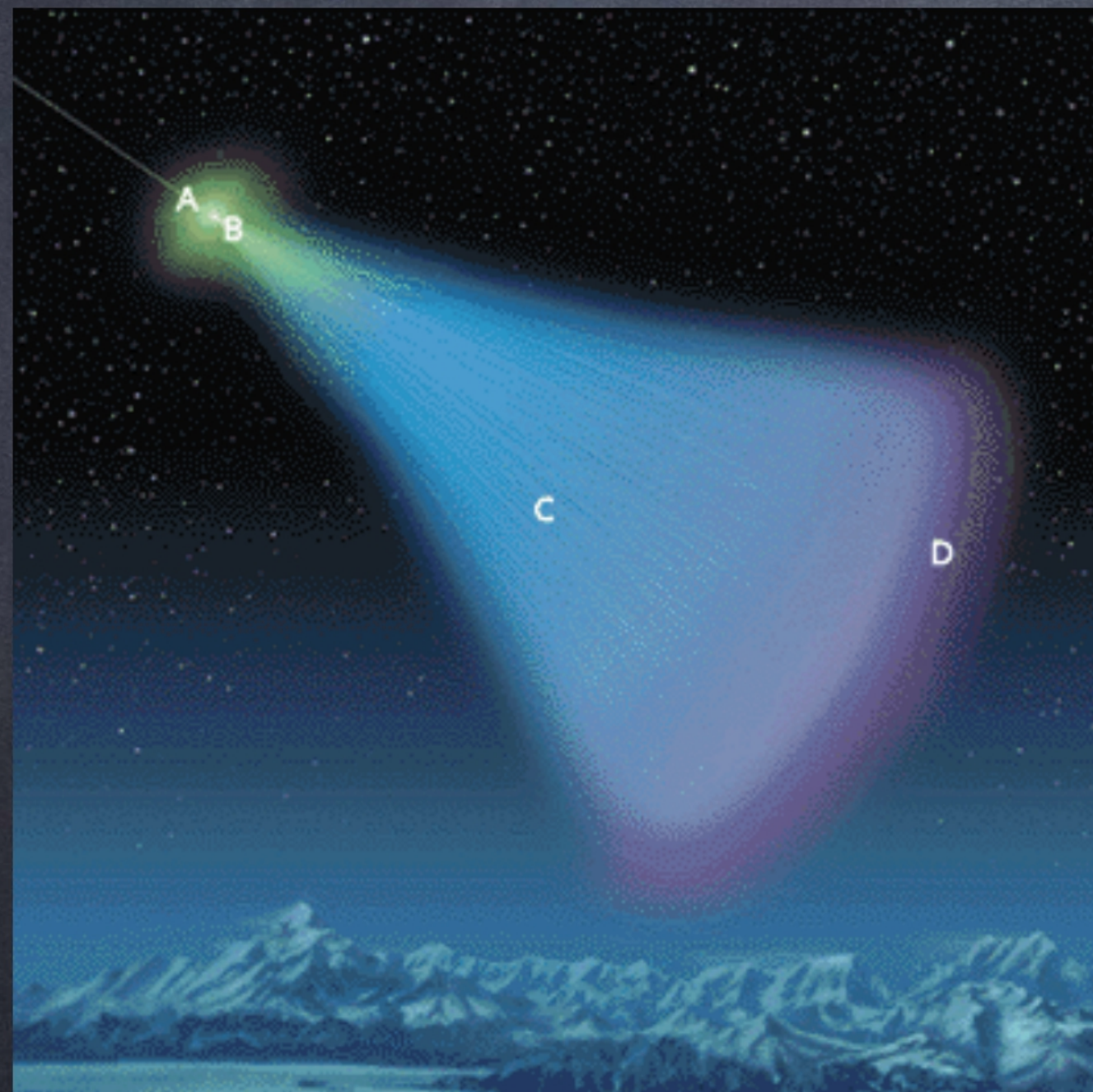
# CR DETECTORS AS PARTICLE DETECTORS

- CHARGED HIGH ENERGY PARTICLE IONIZES THE MEDIUM IN WHICH IT PROPAGATES
- HOW IT DOES THIS PROVIDES INDICATIONS ON ITS MASS
- THROUGH MAGNETIC DEFLECTION ONE CAN ALSO OBTAIN INFORMATION ON CHARGE
- THROUGH CHERENKOV RADIATION ONE CAN OBTAIN INFORMATION ON THE PARTICLE VELOCITY: THRESHOLD DETECTORS
- CALORIMETERS MEASURE TOTAL PARTICLE ENERGY



# AT THE HIGHEST (ULTRA-HIGH) ENERGIES...

FLUXES ARE TOO LOW  
FOR SPACE BORNE  
FACILITIES...



# AIR SHOWERS

$$p + N \rightarrow \pi_s + N_s$$

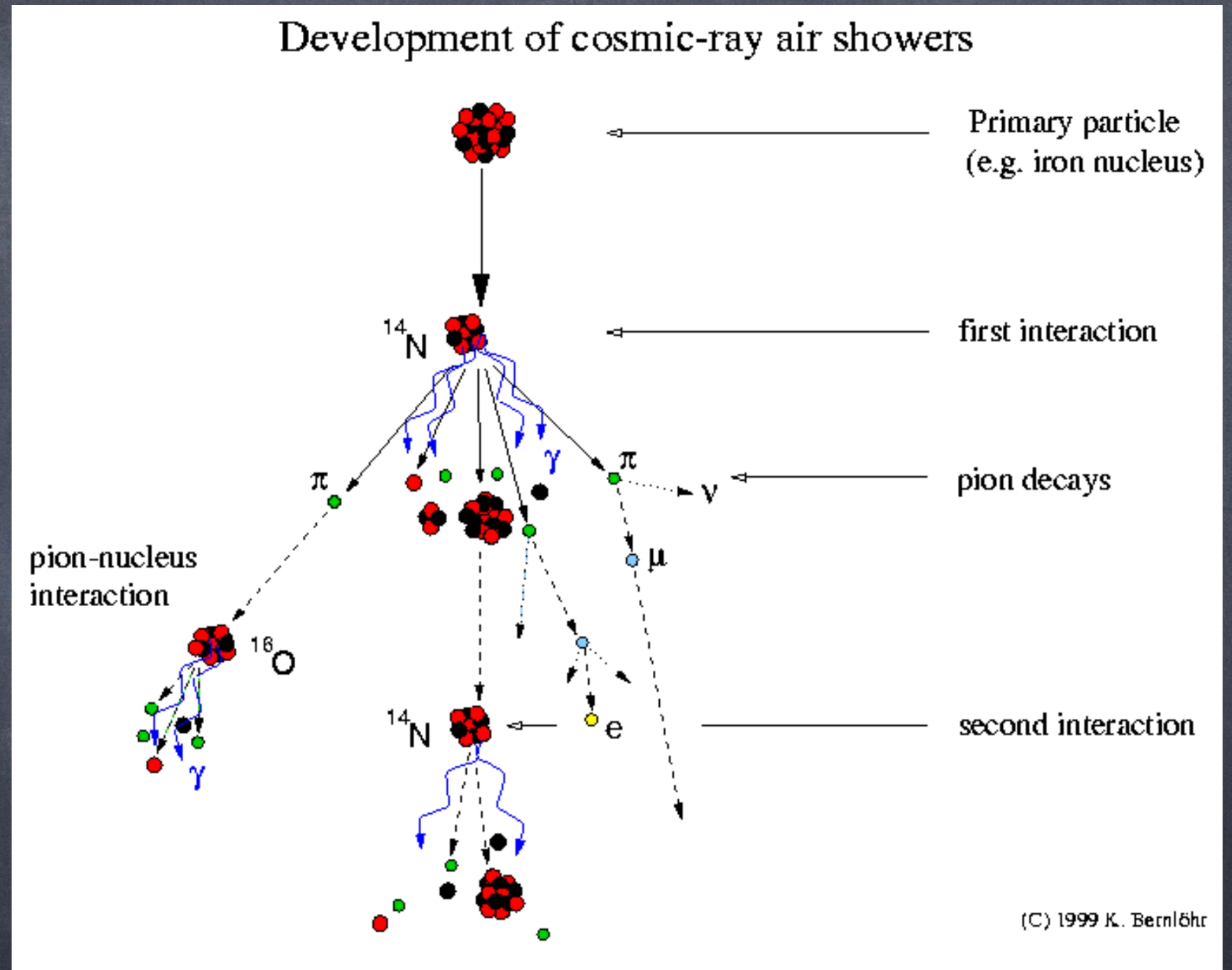
$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

-SECONDARY GAMMA-RAYS AND  
NUCLEI FORM SUB-SHOWERS

-MUONS ARE VERY PENETRATING AND  
REACH EARTH

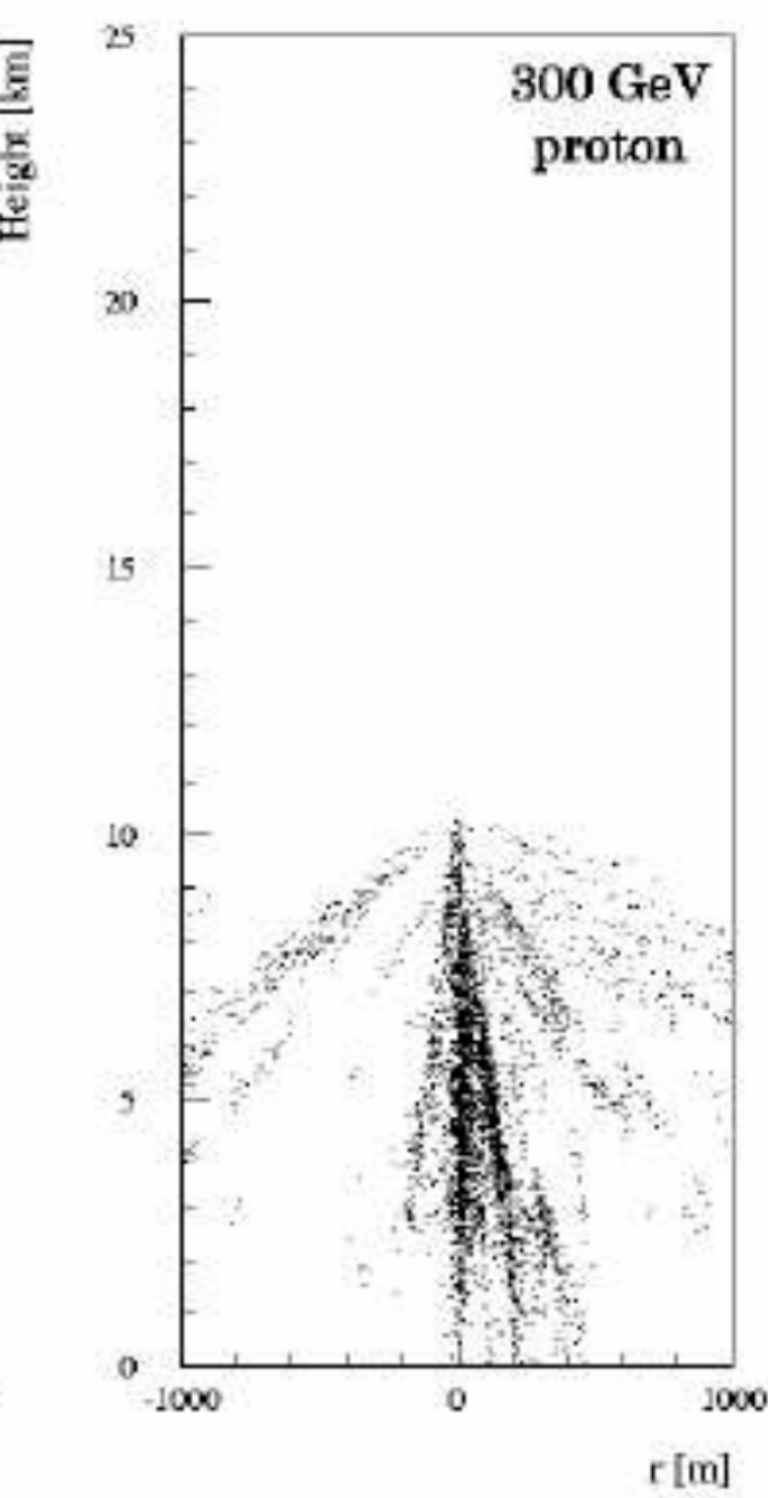
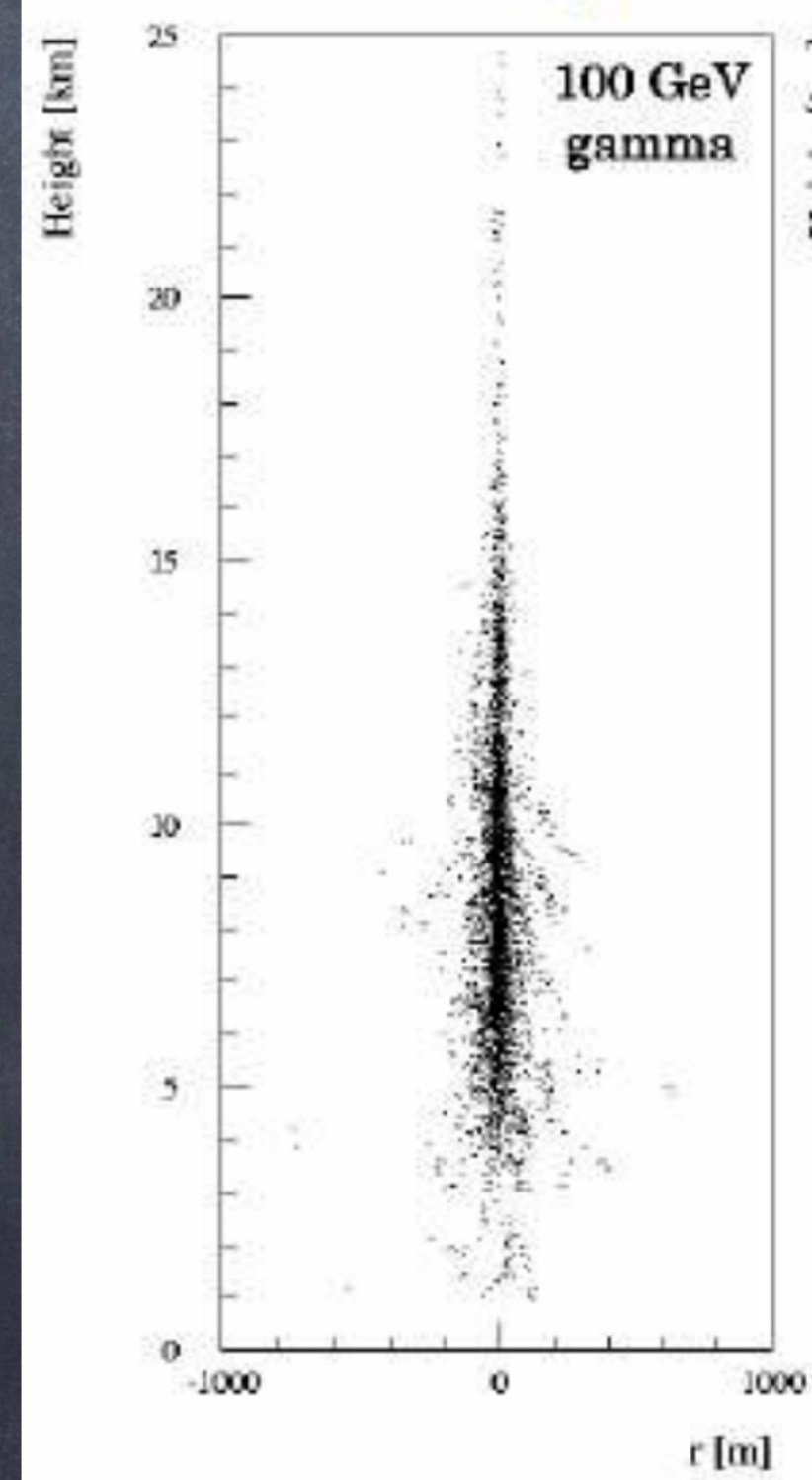
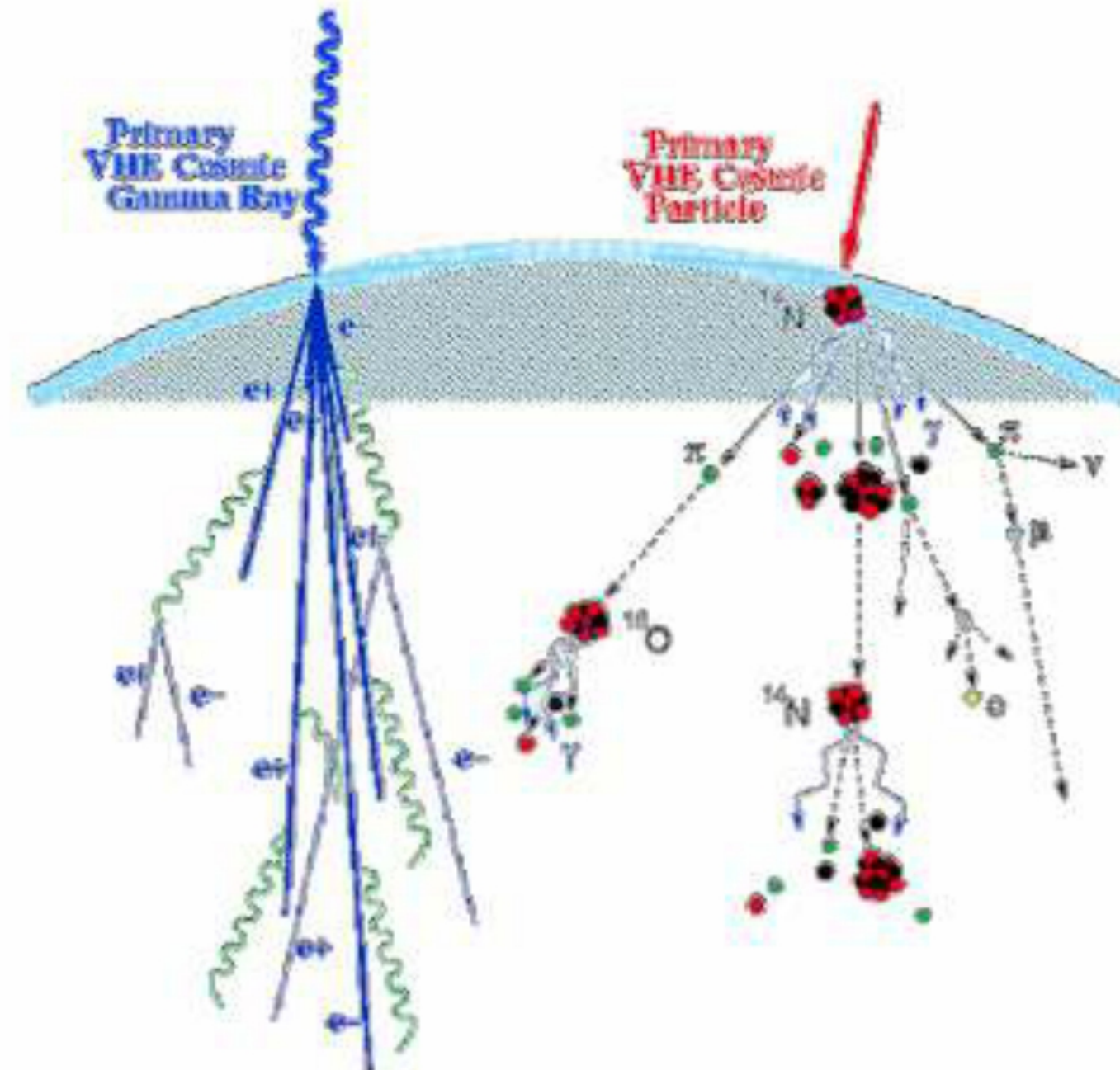


MORPHOLOGY UNVEILS PARENT PARTICLE

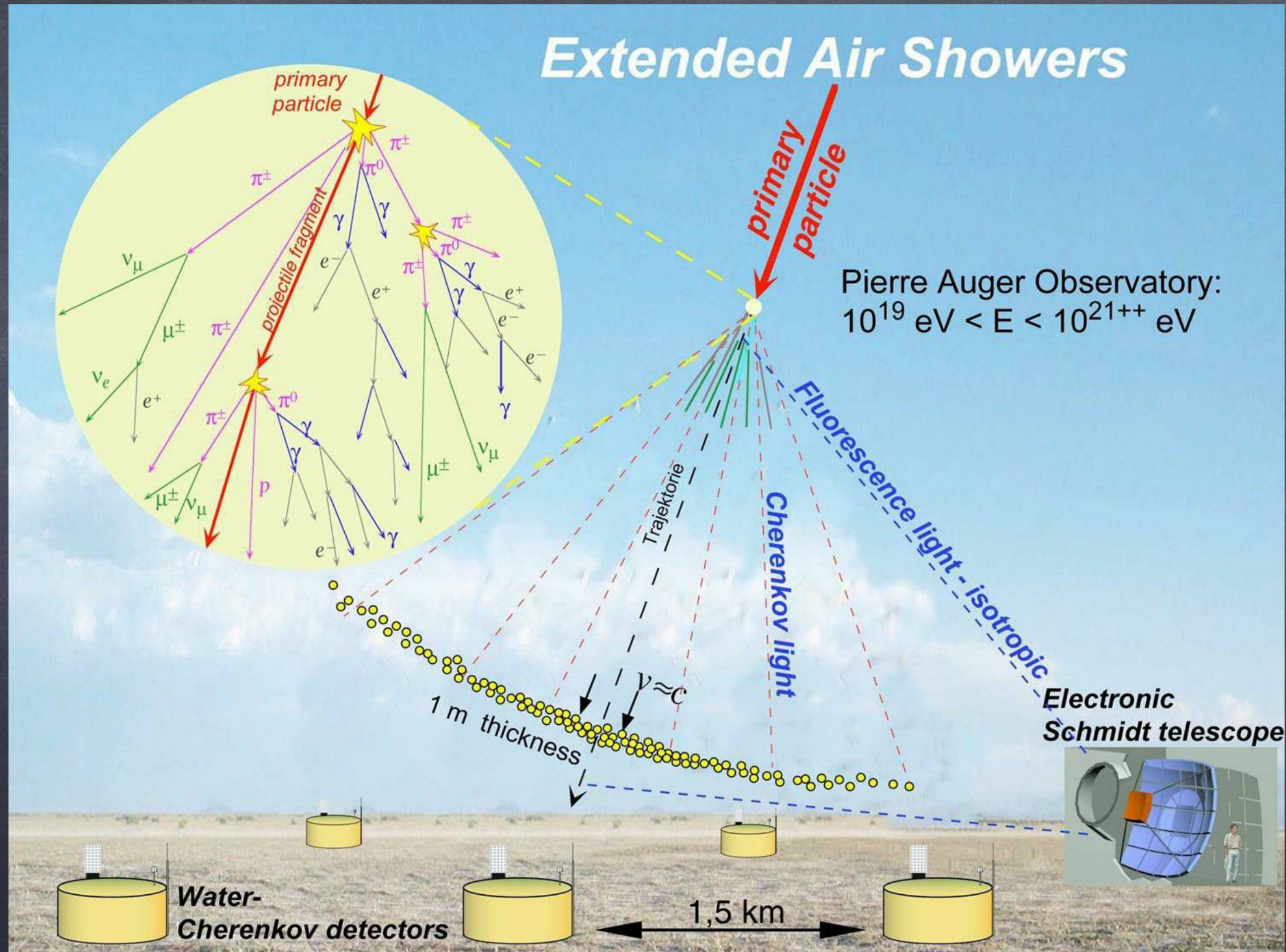
# PARENT PARTICLE IDENTIFICATION

-SHOWER MORPHOLOGY

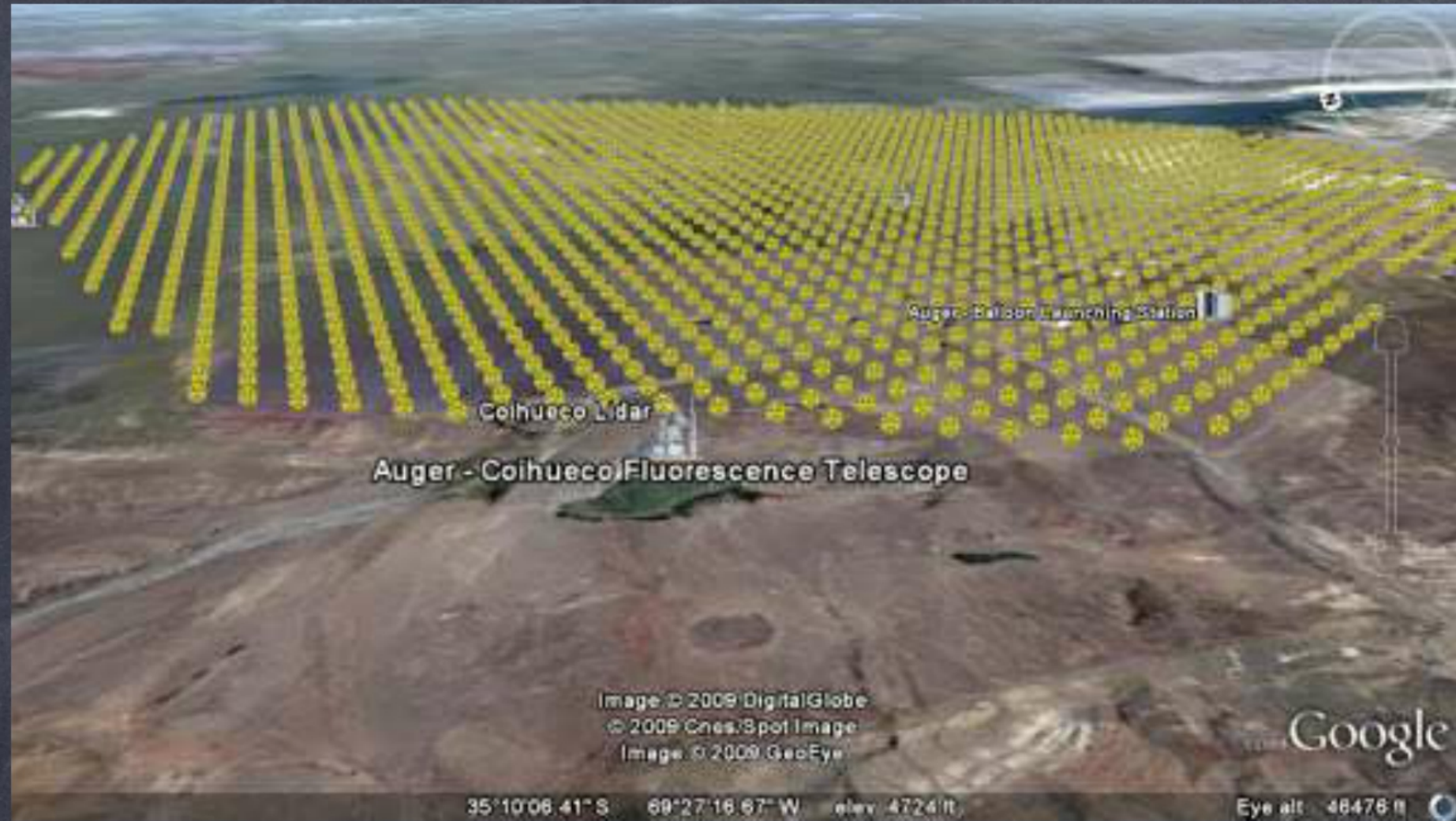
-MUON CONTENT



# CHERENKOV AND FLUORESCENCE LIGHT

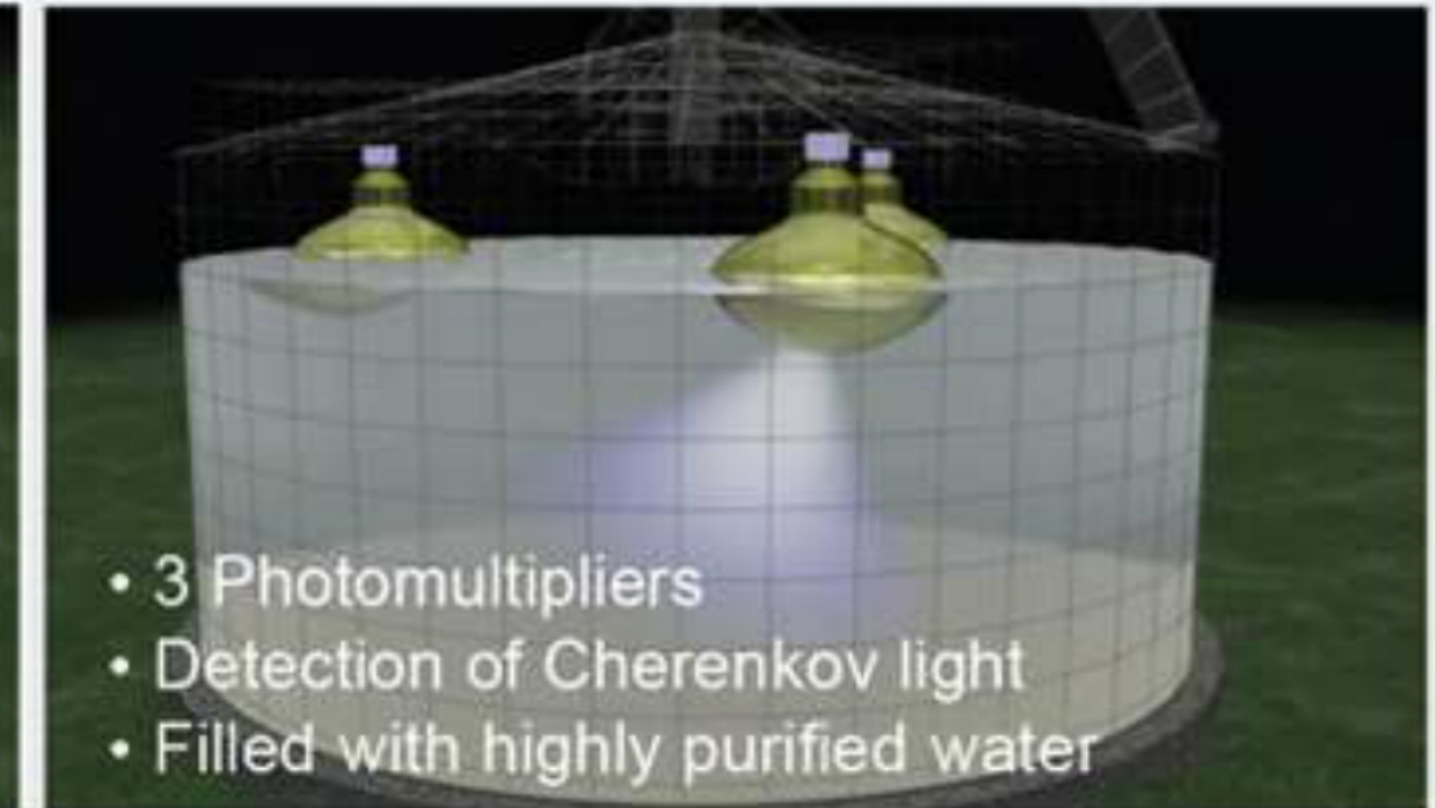
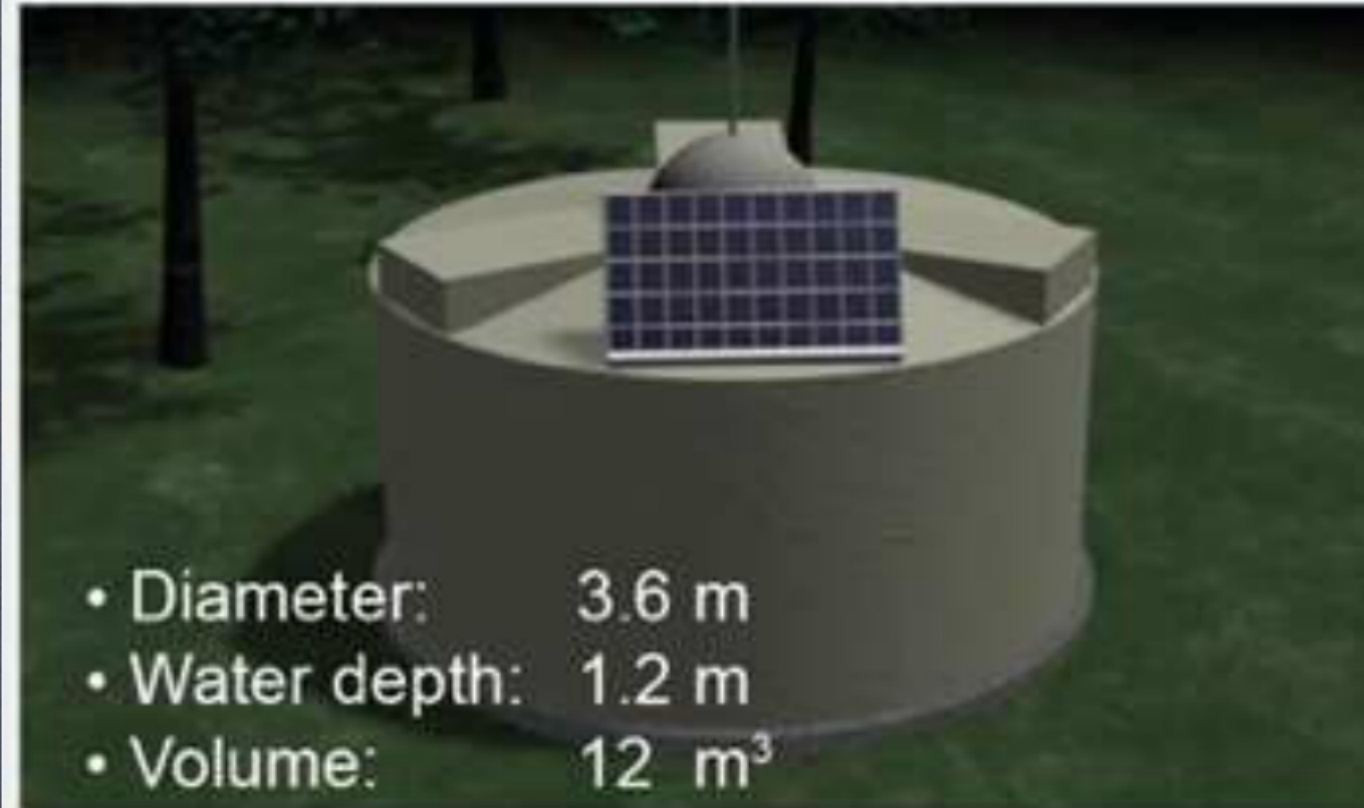


# THE PIERRE AUGER OBSERVATORY



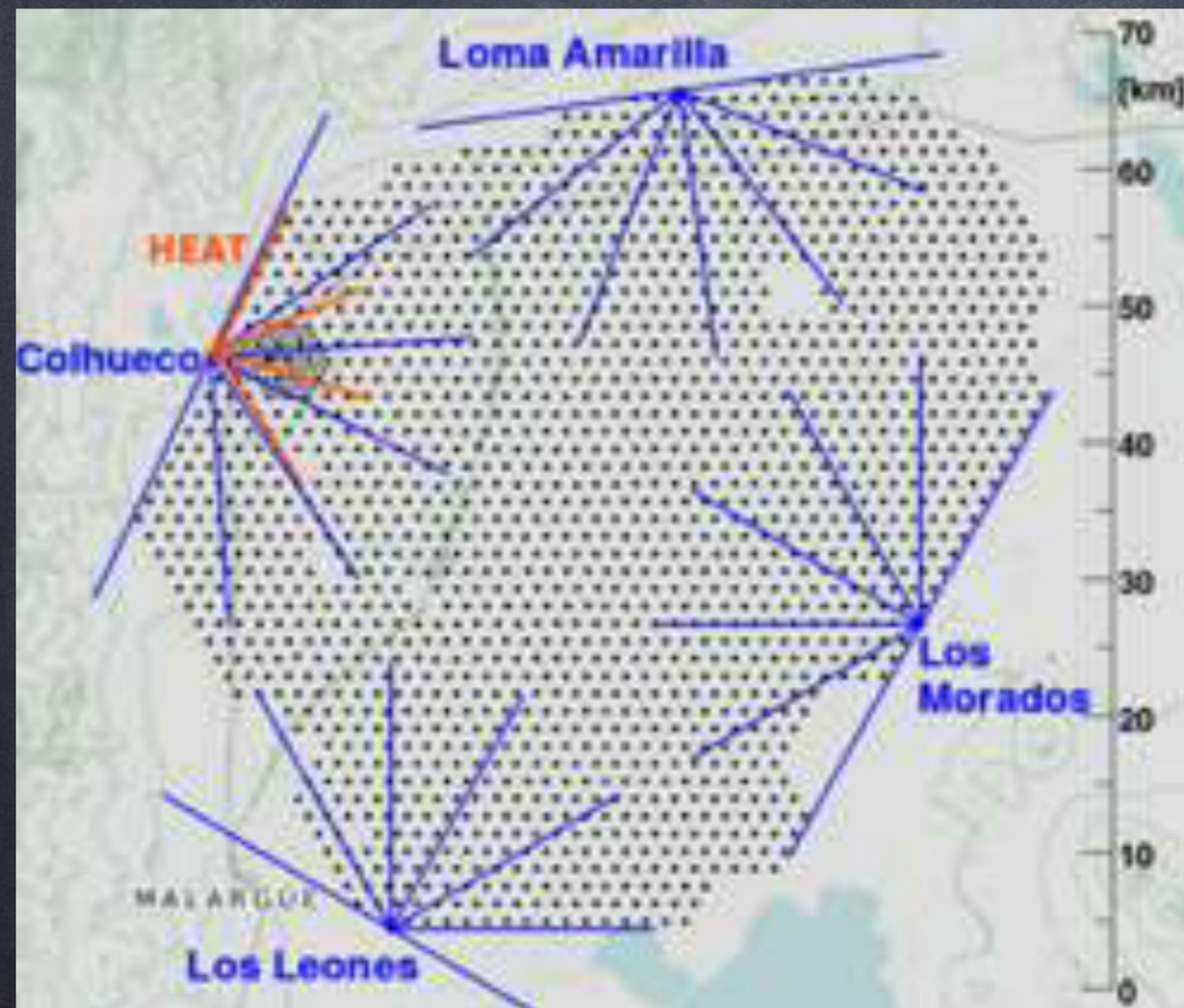
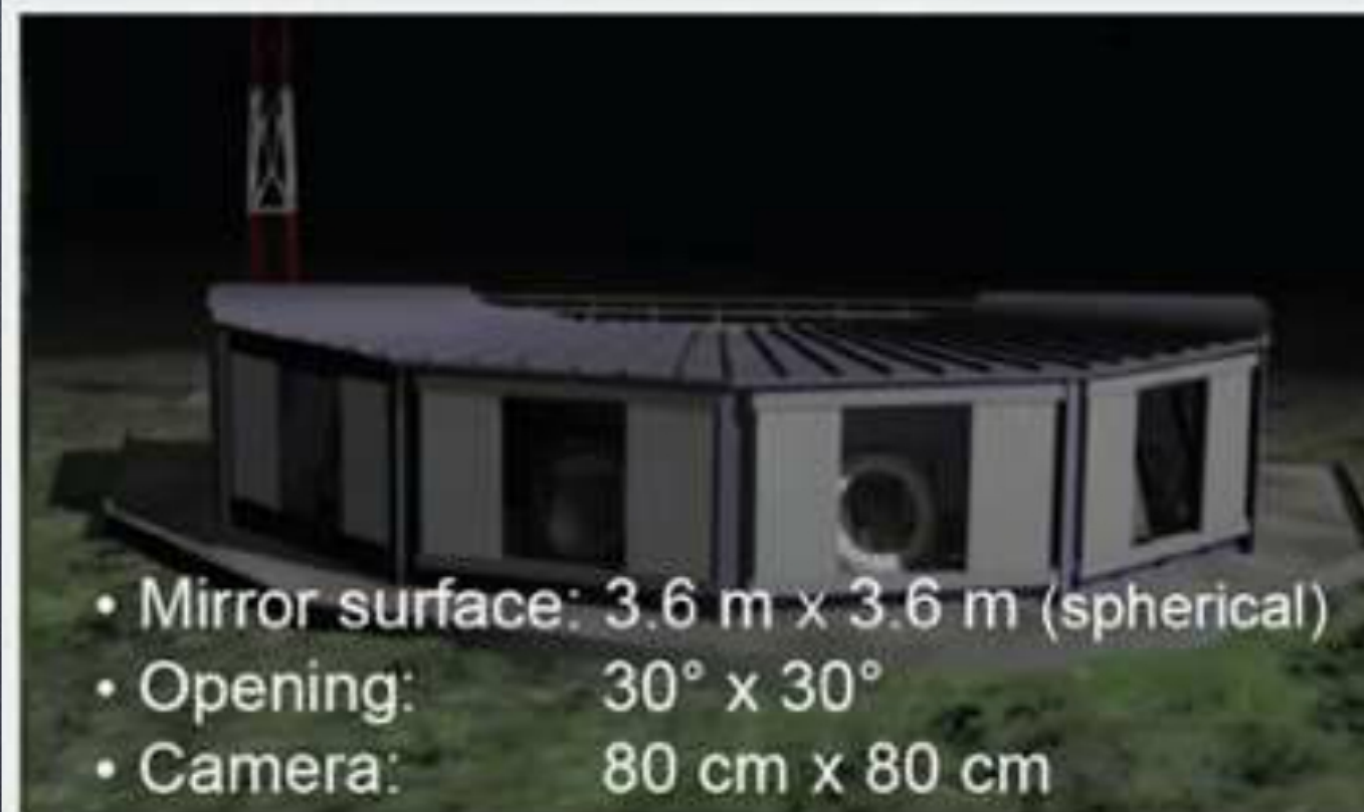
## Surface Detector

1,660 surface detector stations  
(1,500 m apart from each other)



## Fluorescence Detector

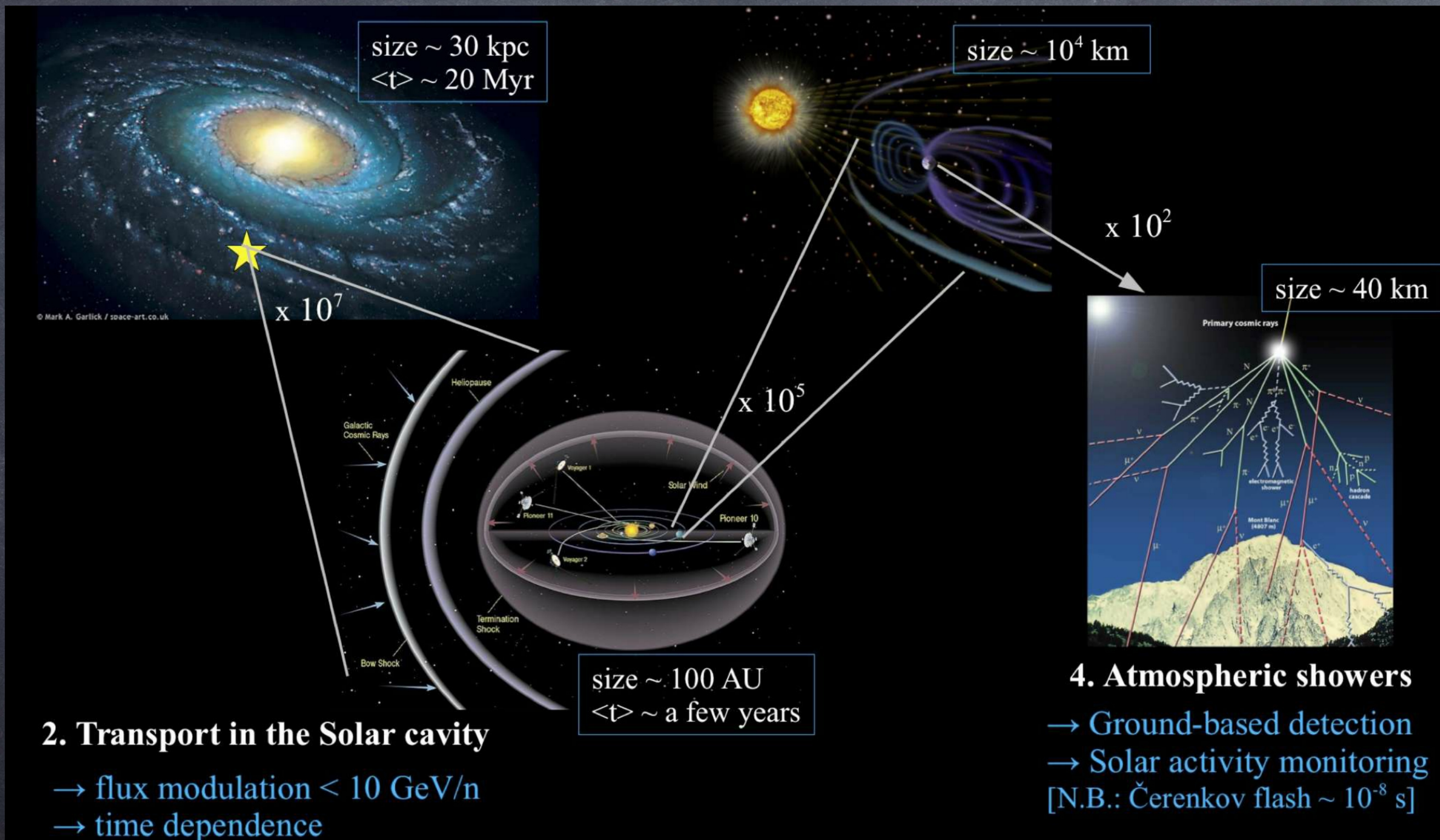
27 fluorescence telescopes  
(in 4 different places)



COMPLEX DECONVOLUTION!!!!

# WHAT AFFECTS CR MEASUREMENTS

# THE COMPLEX JOURNEY OF CRs



## 2. Transport in the Solar cavity

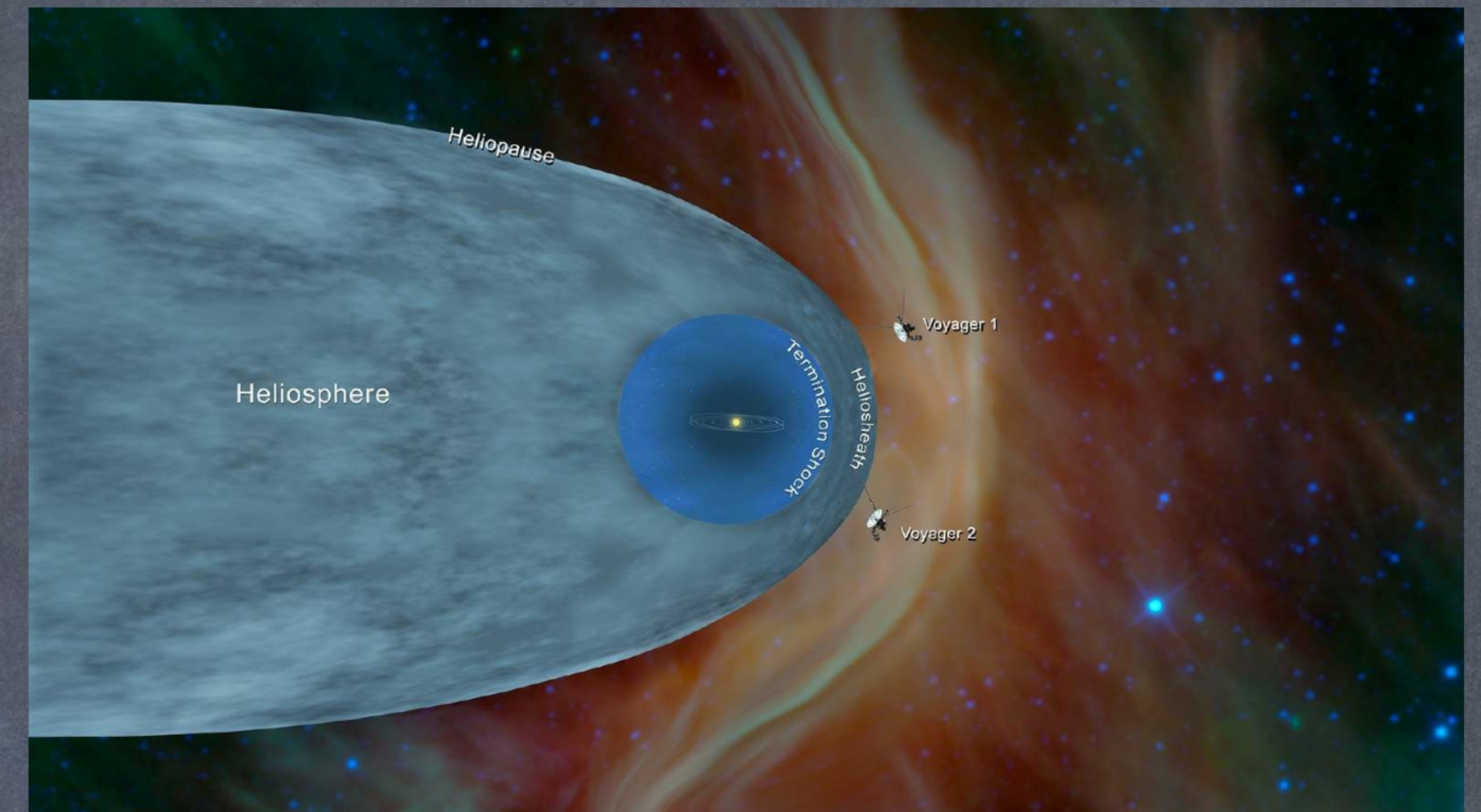
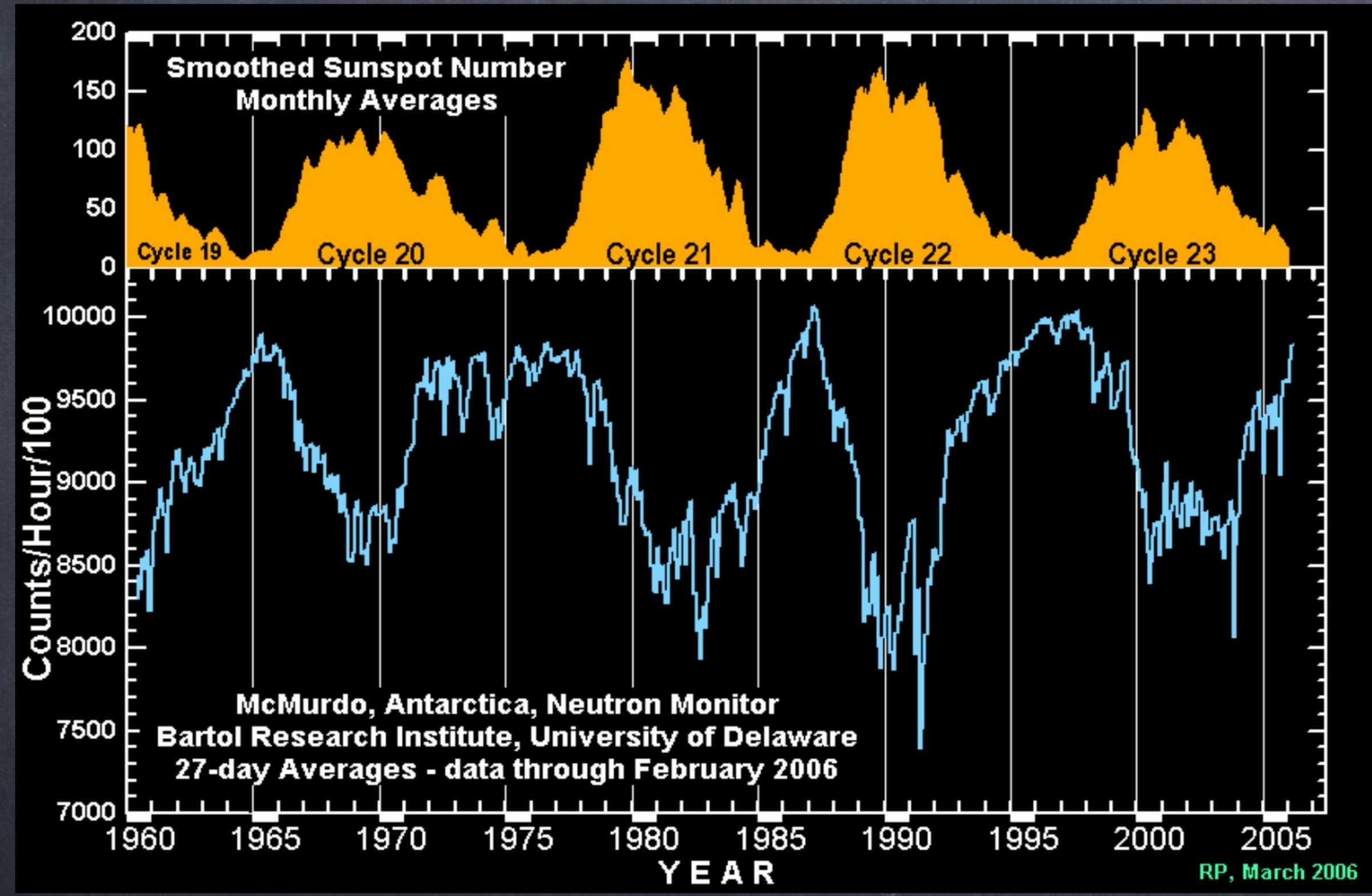
- flux modulation  $< 10 \text{ GeV/n}$
- time dependence

## 4. Atmospheric showers

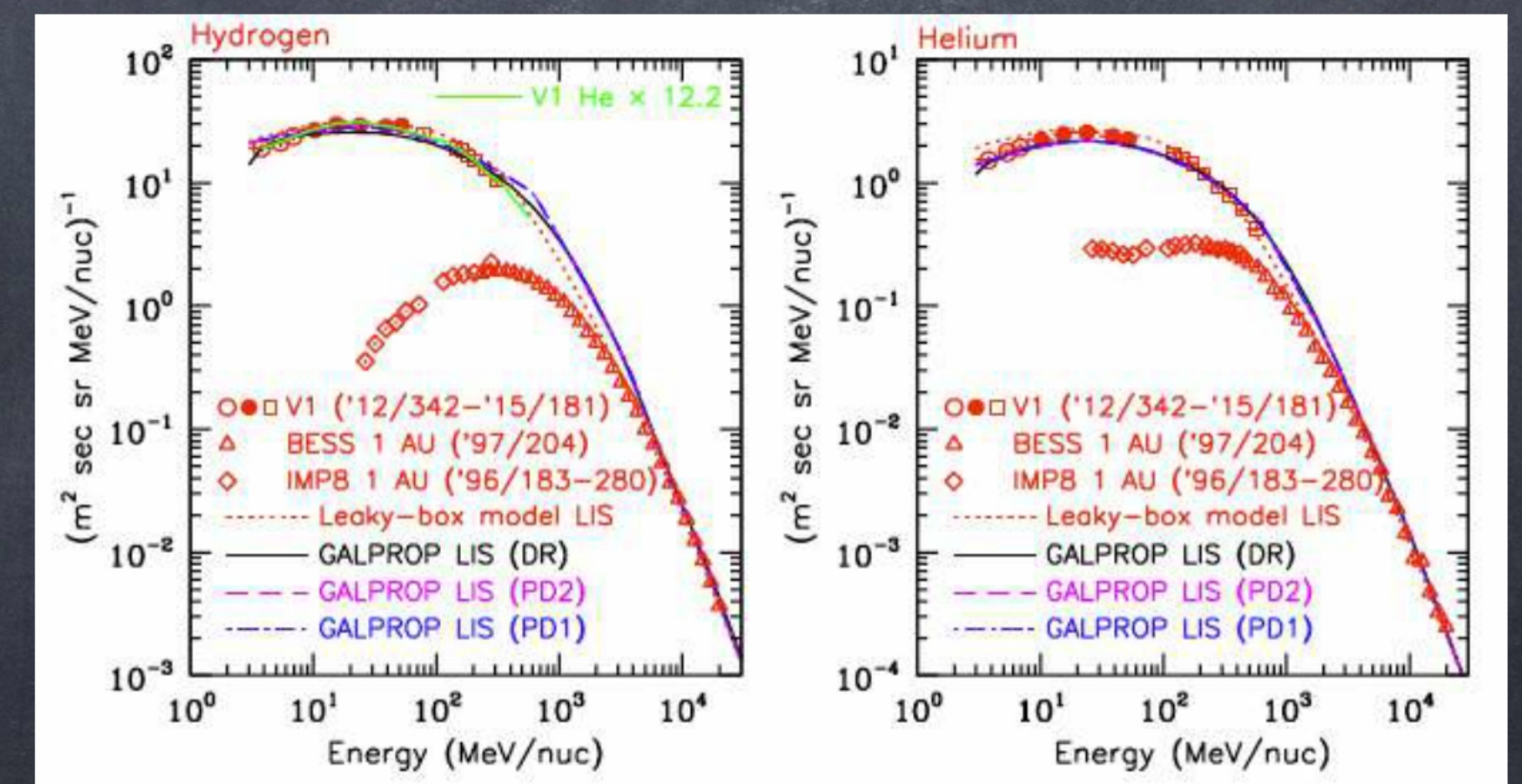
- Ground-based detection
- Solar activity monitoring [N.B.: Čerenkov flash  $\sim 10^{-8} \text{ s}$ ]

# SOLAR MODULATION

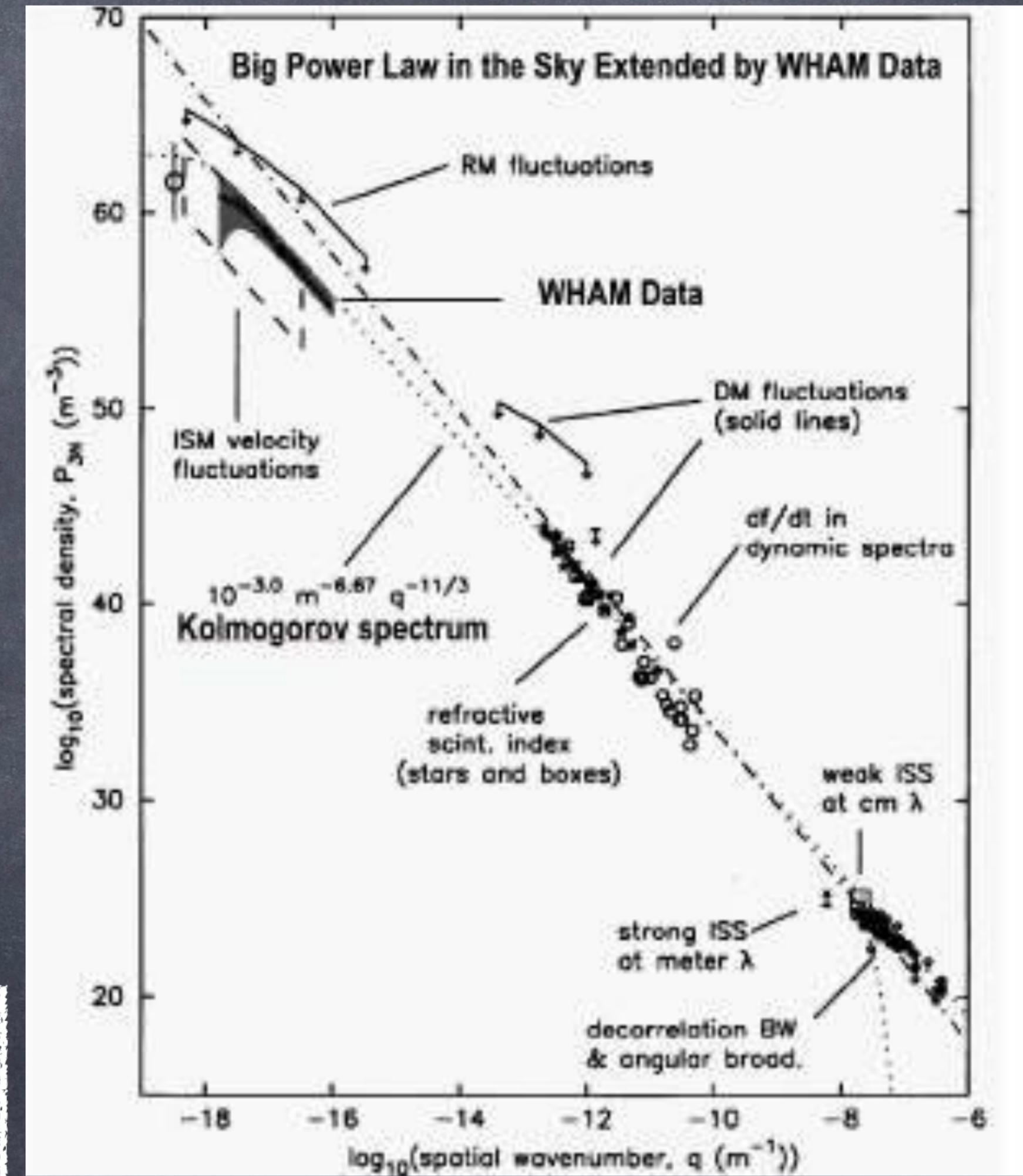
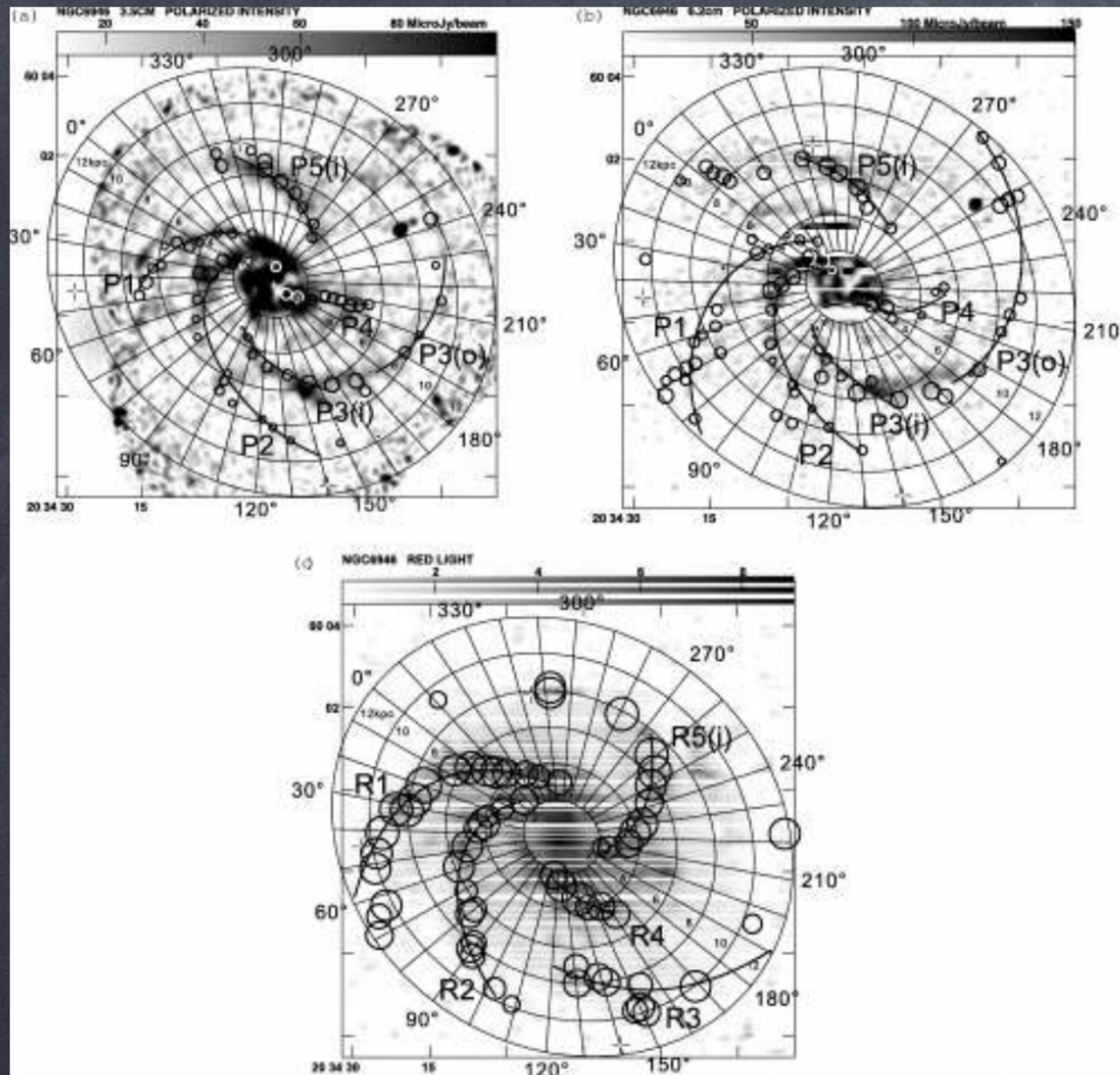
## NEUTRON MONITOR DATA



## VOYAGER MEASUREMENTS: THE LIS FINALLY!



# GALACTIC MAGNETIC FIELDS



LARGE SCALE FIELD MOSTLY ALIGNED WITH SPIRAL ARMS

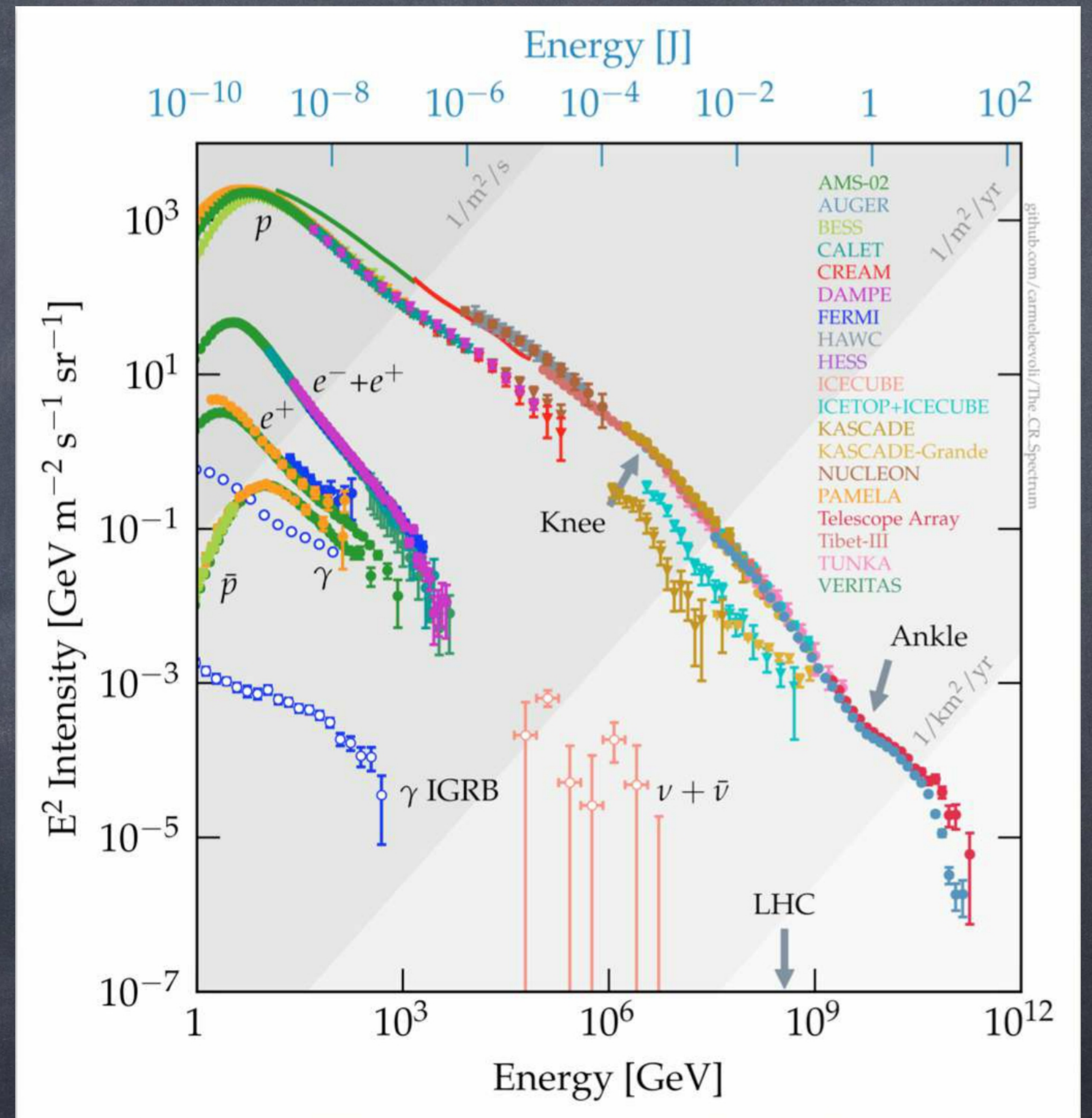
TURBULENT COMPONENT WITH  $\delta B/B \sim 1$  ON 10-100 kpc SCALE

AND LIKELY KOLMOGOROV SPECTRUM  $\delta B(k)^2 \propto k^{-5/3}$

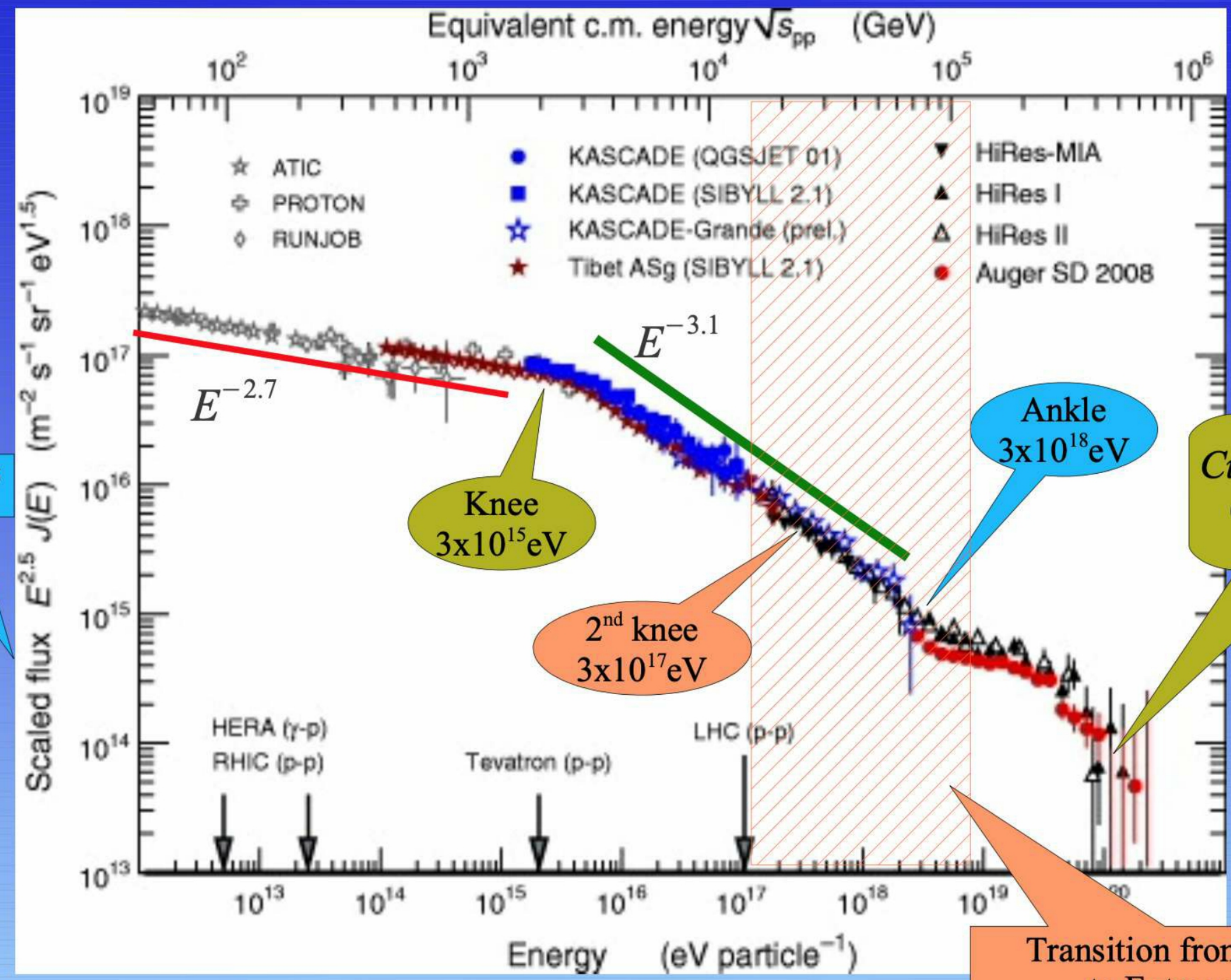
WHAT WE HAVE LEARNT  
ABOUT CRs

# ENERGY BUDGET

ENERGY DENSITY IN THE GALAXY	$\text{eV}/\text{cm}^3$
Magnetic field ( $B^2/8\pi$ )	$\sim 0.5$
Gas motion ( $Mv^2/2$ )	$\sim 0.5$
Starlight	$\sim 0.5$
CMB (2.7 K)	$\sim 0.5$
<b>CRs</b>	<b><math>\sim 0.5</math></b>



# MAIN SPECTRAL FEATURES



CR flux  $\times E^{2.5}$

Knee  
 $3 \times 10^{15}$  eV

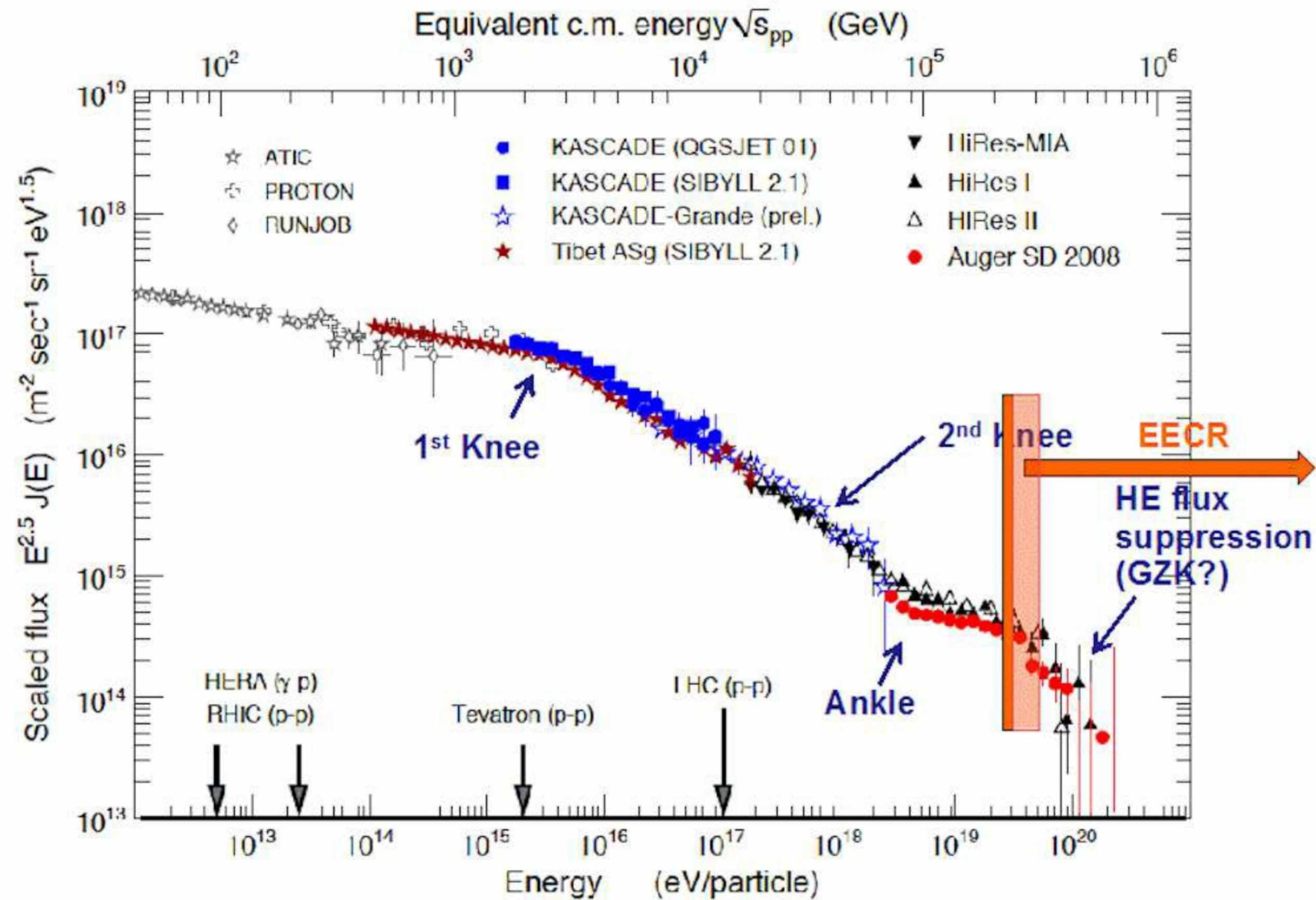
2<sup>nd</sup> knee  
 $3 \times 10^{17}$  eV

Ankle  
 $3 \times 10^{18}$  eV

Cutoff  $\sim 3 \times 10^{20}$  eV  
GZK or  $E_{max}$ ?

Transition from Galactic  
to Extragalactic  
 $10^8$  GeV- $10^{10}$  GeV

# SPECTRAL FEATURES: INTERPRETATION



KNEE:  $3 \times 10^{15}$  eV  
 END OF PROTONS

TRANSITION: *few*  $\times 10^{18}$  eV

CUT-OFF:  $3 \times 10^{20}$  eV  
 GZK or MAX ENERGY?

SECOND KNEE:  $3 \times 10^{17}$  eV  
 END OF GAL FE OR DIP?

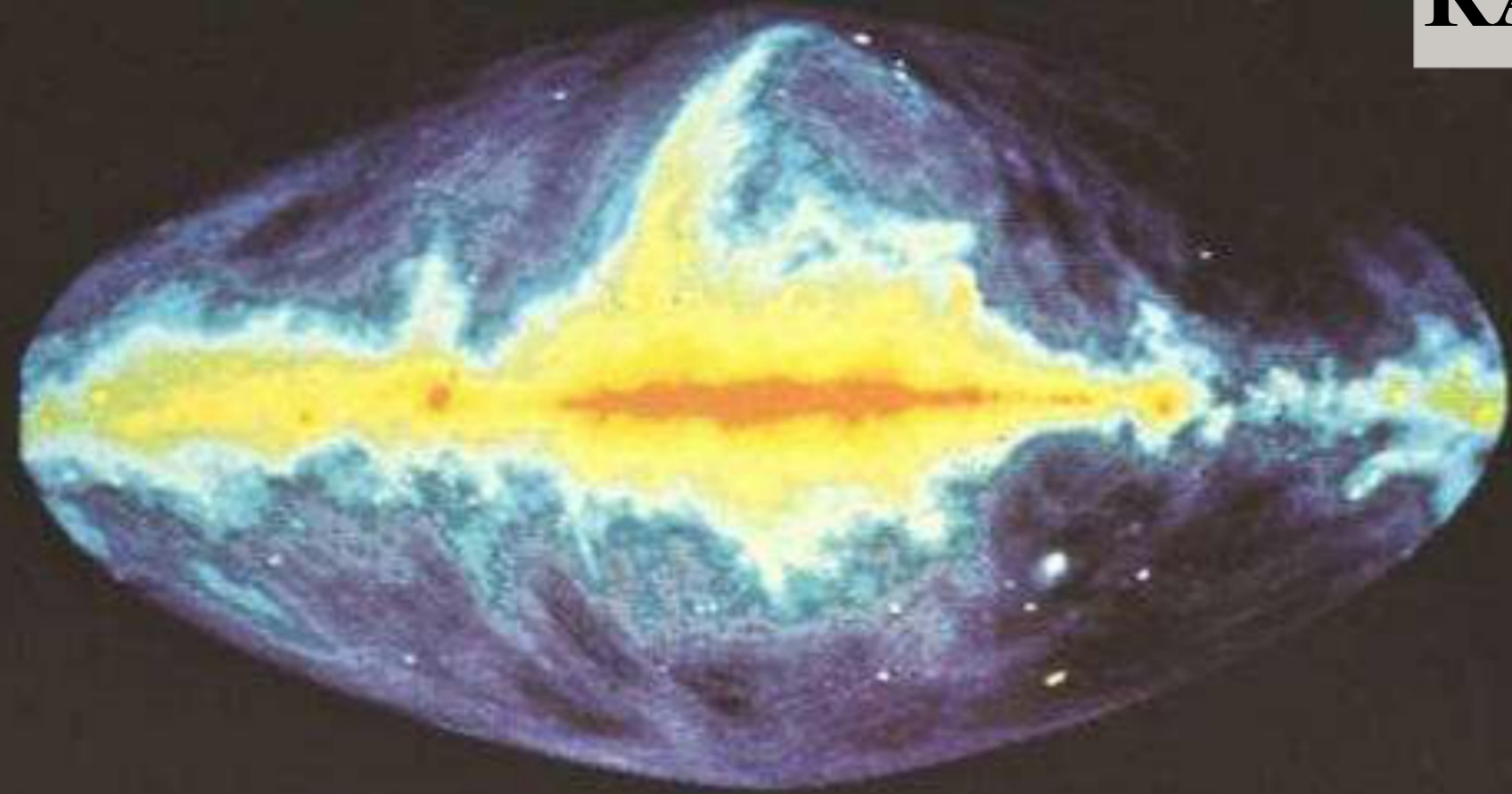
ANKLE:  $3 \times 10^{18}$  eV  
 FLATTER COMPONENT APPEARS?

NOTE: QUESTION MARKS DUE TO UNKNOWN COMPOSITION

MORE BREAKS LATER...

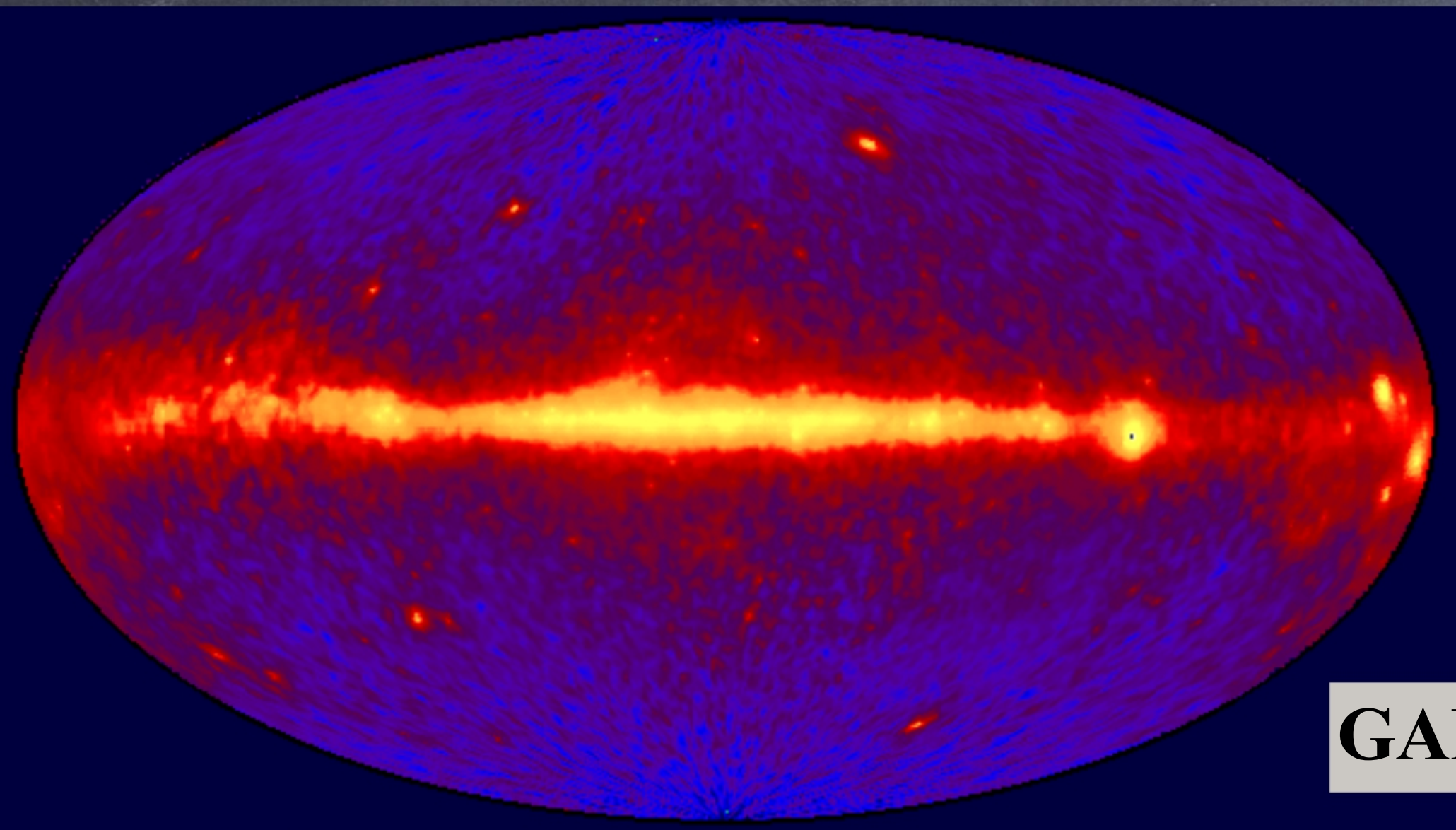
# THE GALAXY IN COSMIC RAYS

## RADIO EMISSION



COSMIC RAYS FILL A VOLUME  
LARGER THAN  
THAT OF THE GALACTIC DISK:

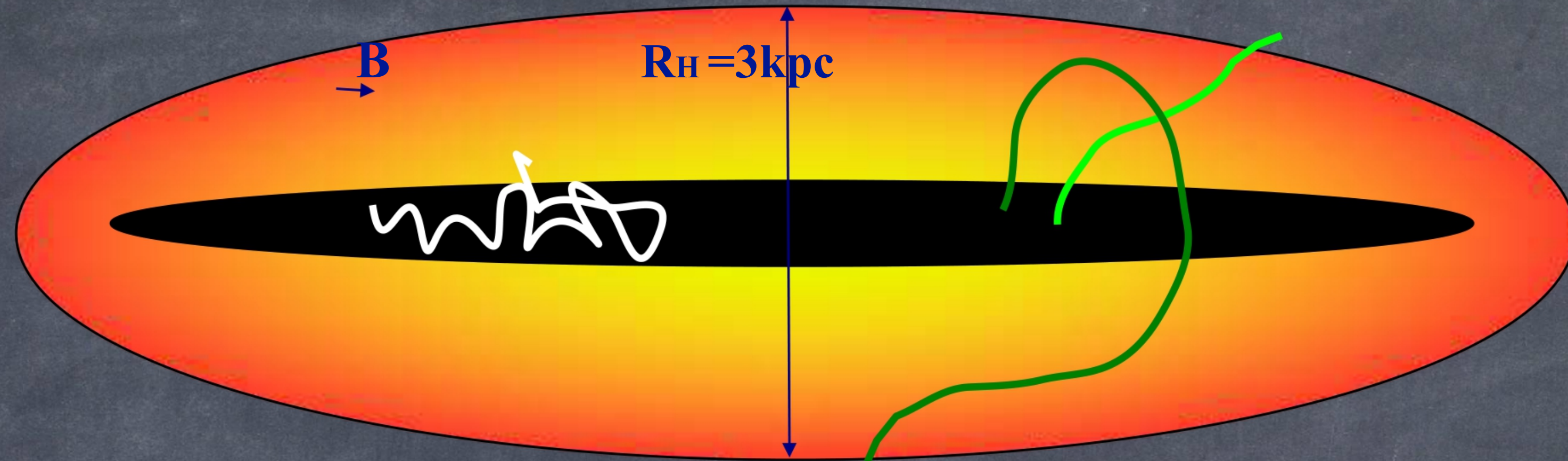
**CR HALO**



## GAMMA-RAY EMISSION



# GALACTIC CONFINEMENT



$$R_L(E) \approx R_H$$

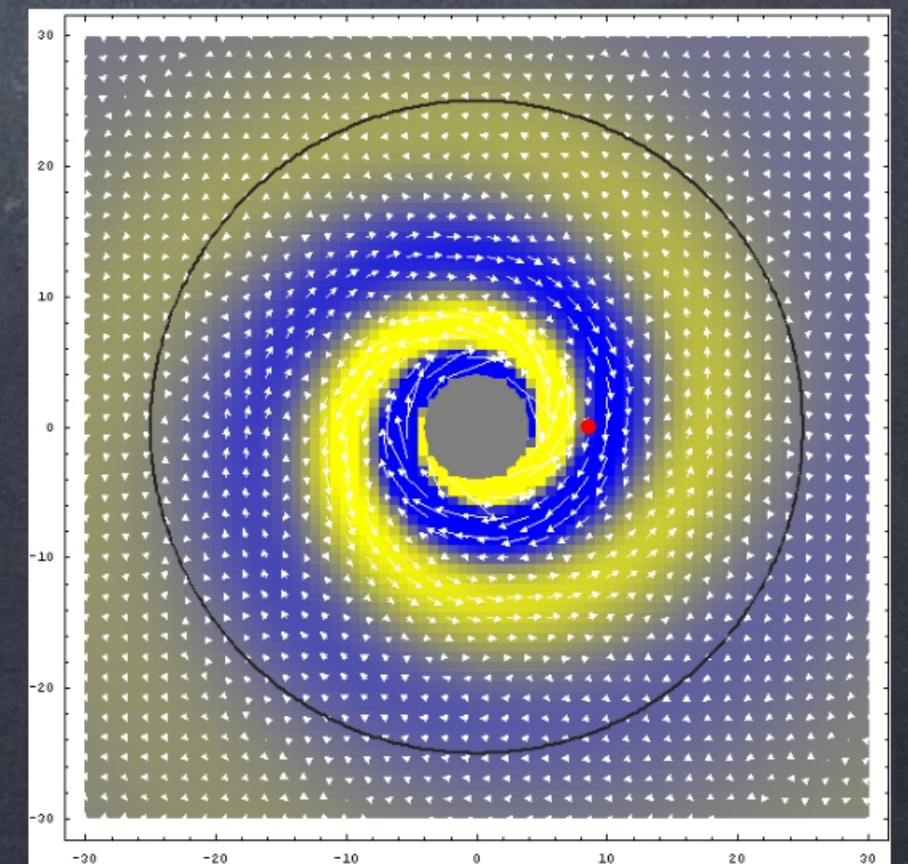


$$E [ eV ] \approx 300 B [ G ] R_H [ cm ]$$

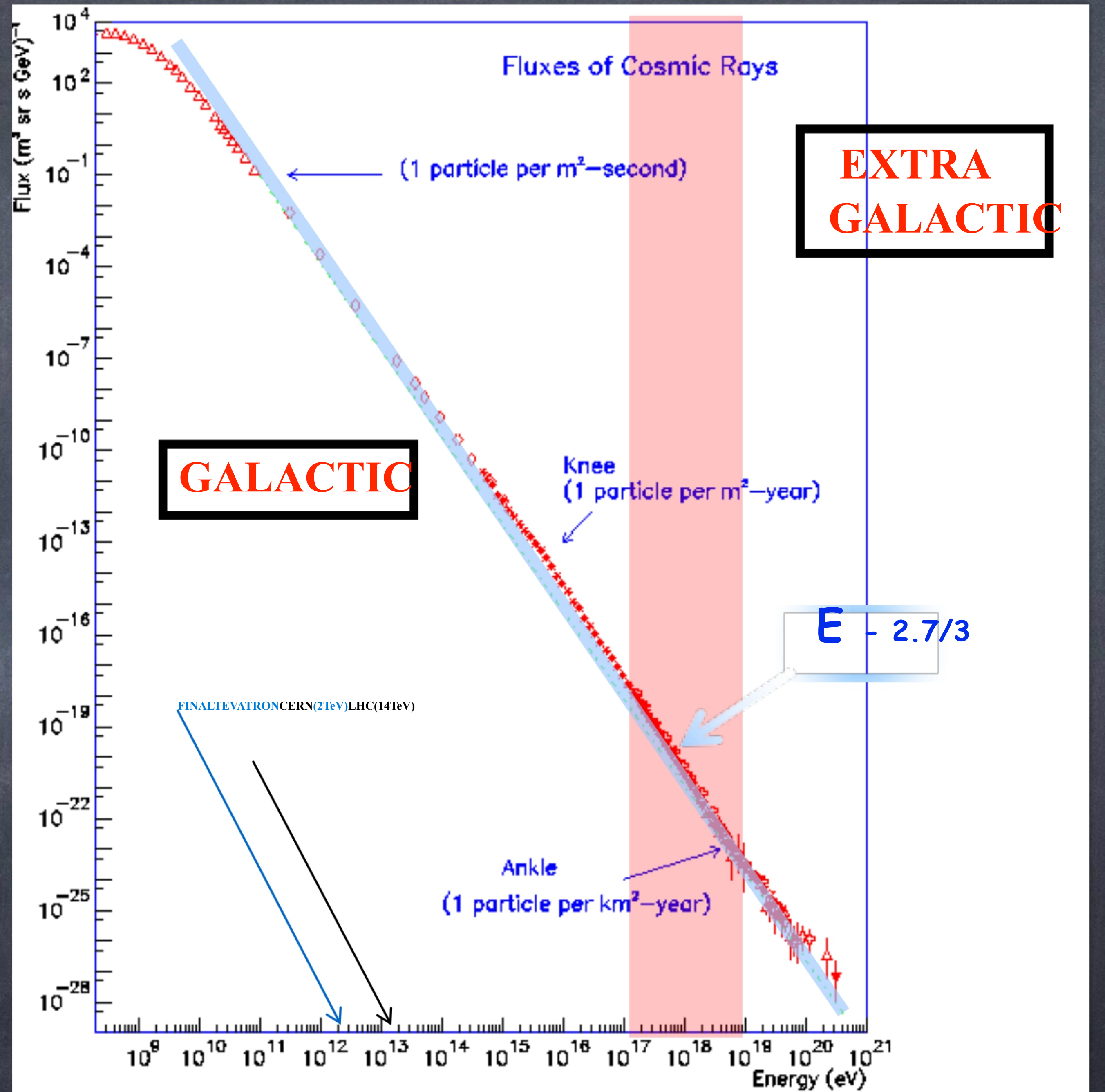
$$E_{\text{trans}} \approx 5 \times 10^{18} \text{ eV}$$

AT HIGH ENOUGH ENERGIES CRs ARE NO LONGER CONFINED WITHIN THE GALAXY.

CONTRIBUTION FROM OUTER GALAXIES BOUND TO BECOME IMPORTANT AND PROGRESSIVELY DOMINANT

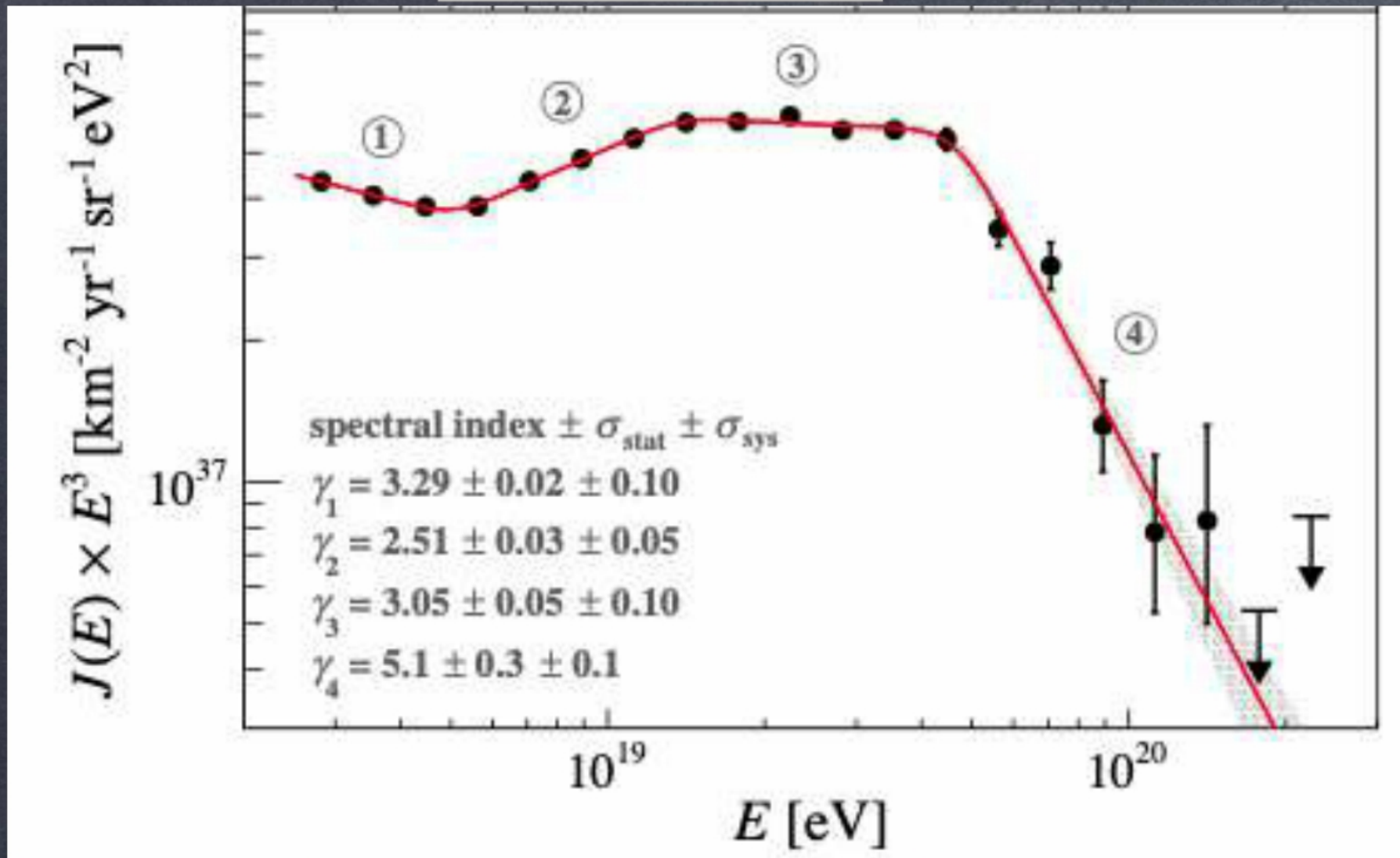


# GALACTIC AND EXTRAGALACTIC CRS

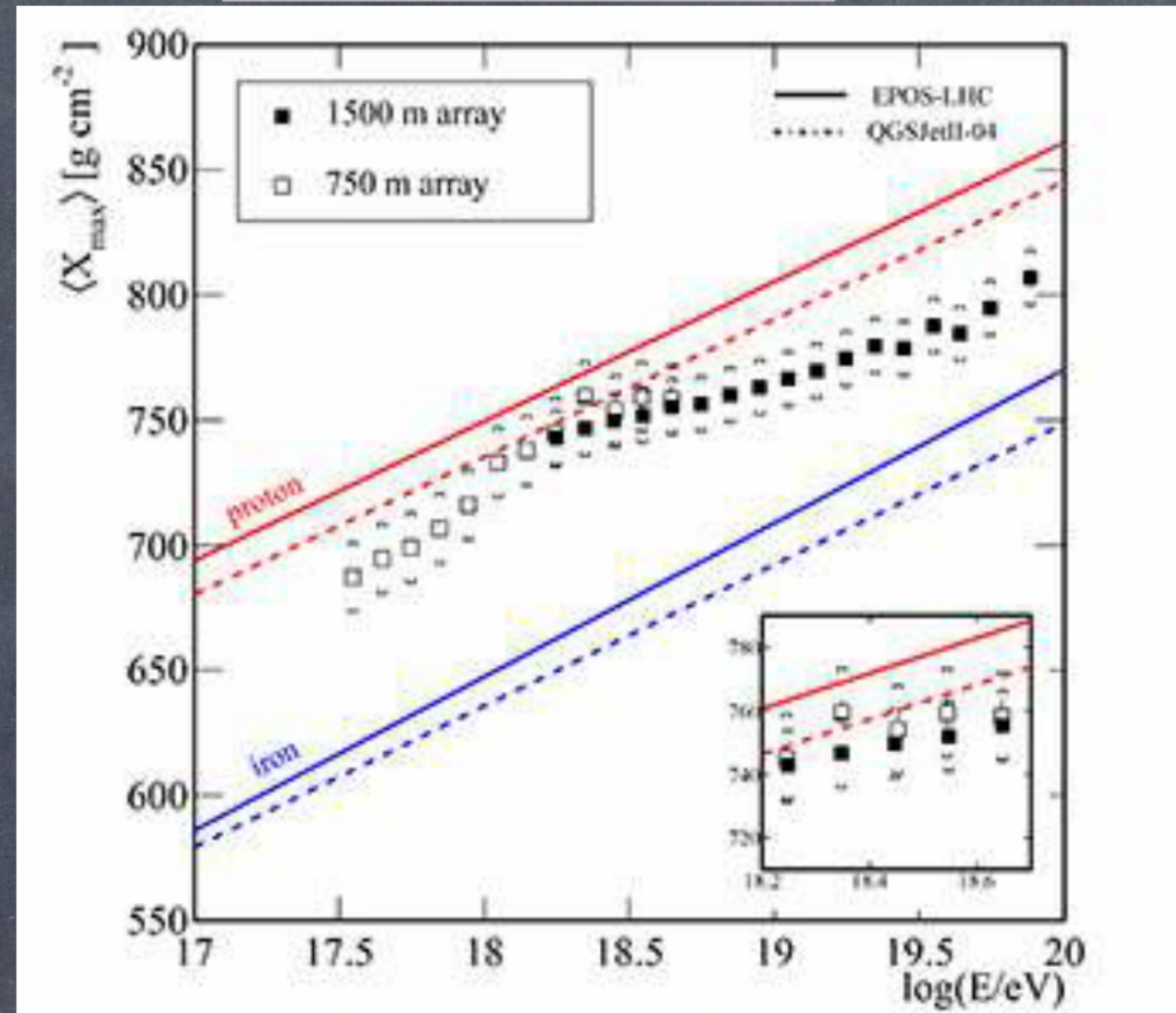


# LATEST RESULTS FROM AUGER

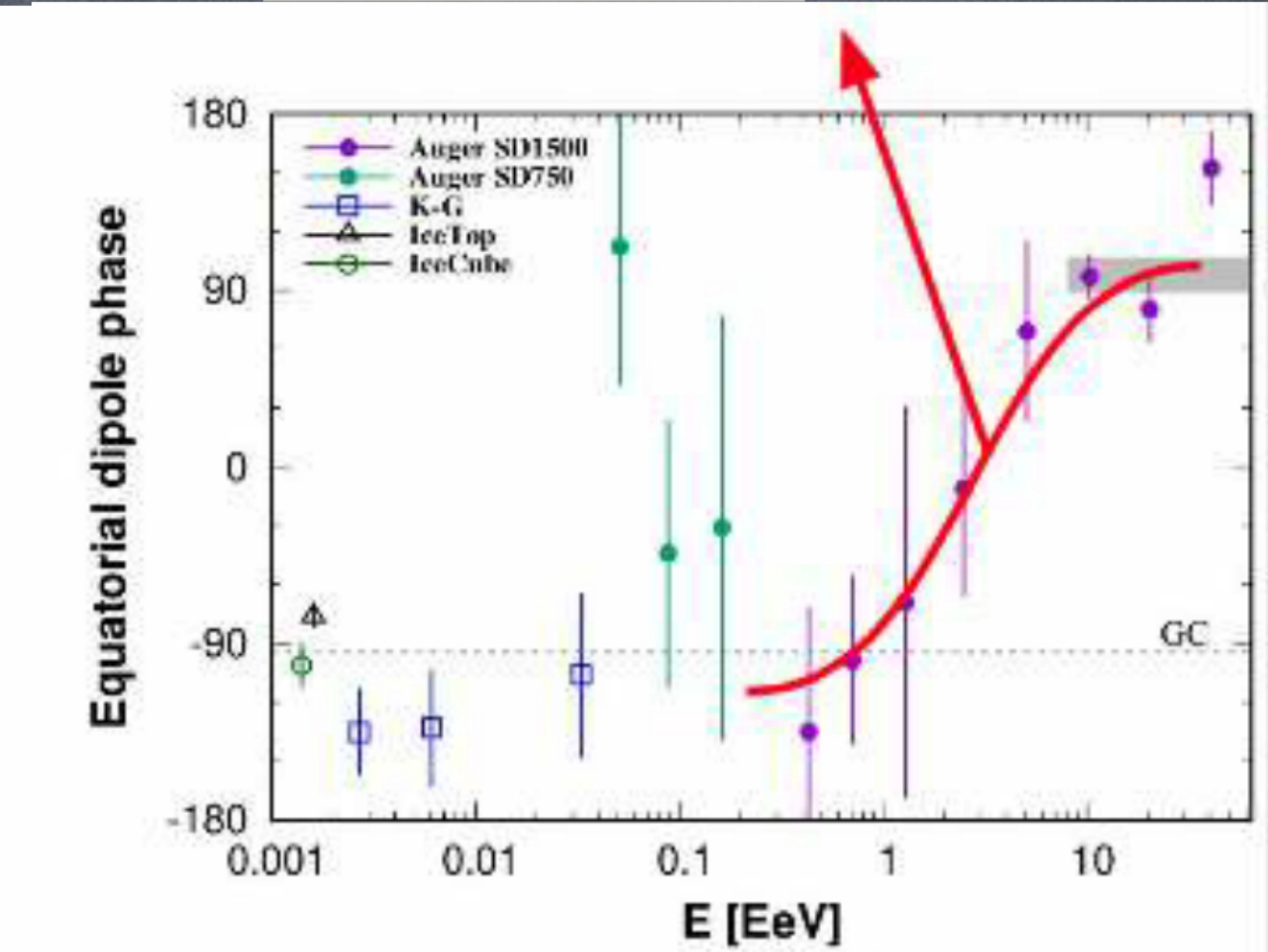
## SPECTRUM



## COMPOSITION



## ANISOTROPY



EGAL DOMINANCE ABOVE FEW  $\times 10^{18}$  eV

Auger 20

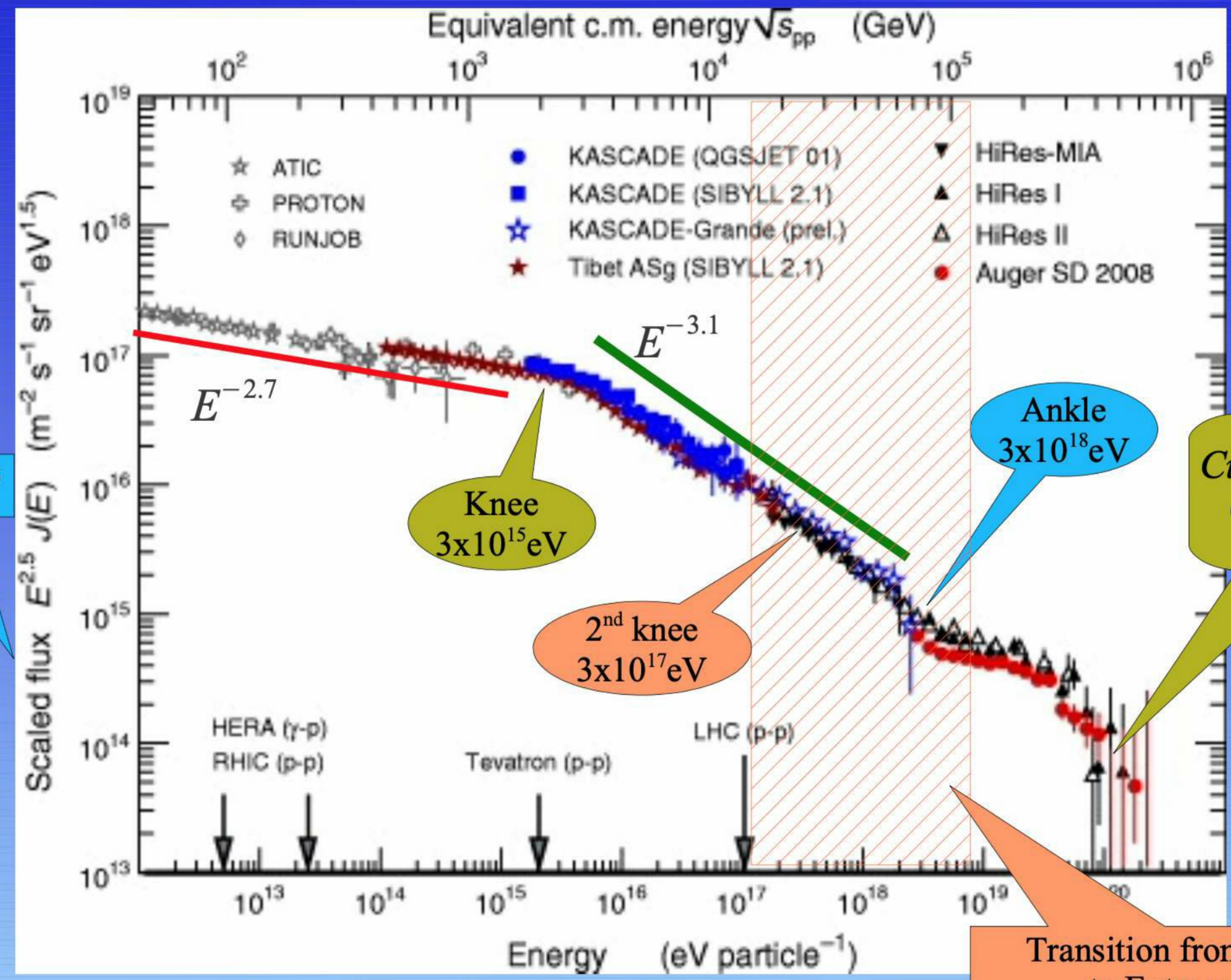
MASS COMPOSITION: BECOMES HEAVIER ABOVE FEW  $\times 10^{18}$  eV BUT NOT UP TO Fe

CORRELATIONS: AGN:  $2.7\sigma$  ; AGN+SBG:  $3.7\sigma$  ; SBG:  $4\sigma$

BUT ALSO OTHER POTENTIAL SOURCES....

QUICK LOOK AT UHECRs

# MAIN SPECTRAL FEATURES



CR flux  $\times E^{2.5}$

Knee  
 $3 \times 10^{15}$  eV

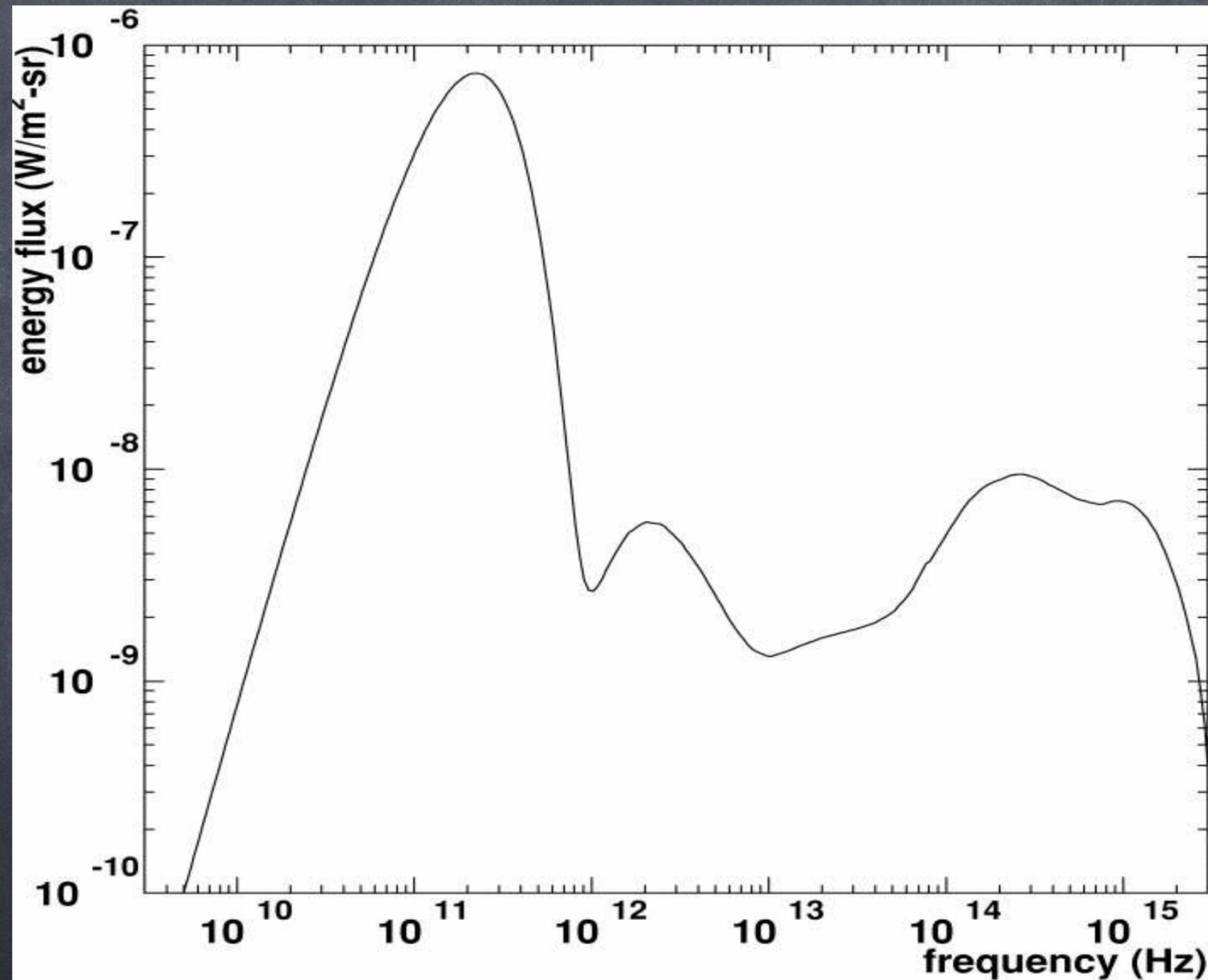
2<sup>nd</sup> knee  
 $3 \times 10^{17}$  eV

Ankle  
 $3 \times 10^{18}$  eV

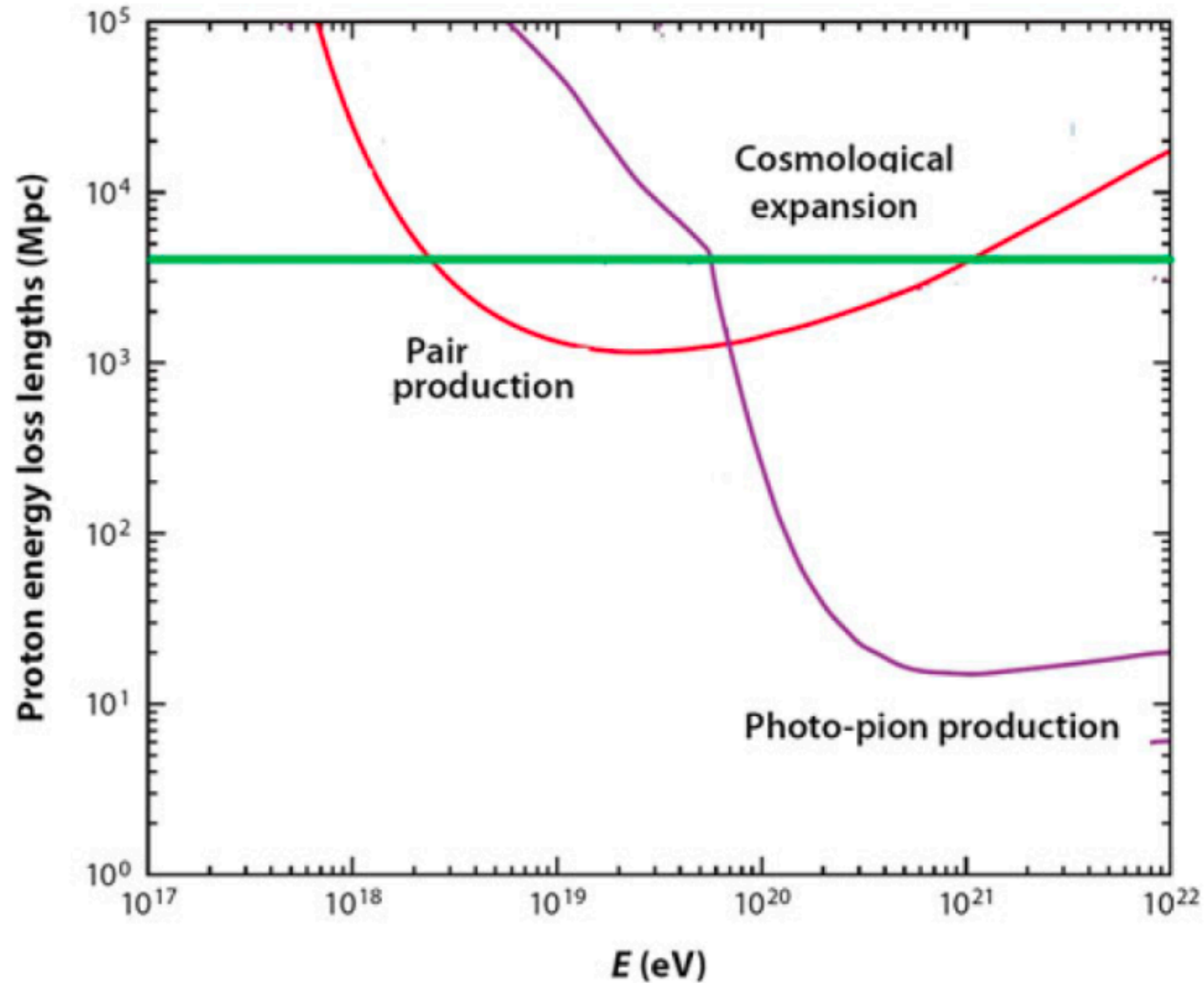
Cutoff  $\sim 3 \times 10^{20}$  eV  
GZK or  $E_{max}$ ?

Transition from Galactic  
to Extragalactic  
 $10^8$  GeV- $10^{10}$  GeV

# EXTRAGALACTIC BACKGROUND LIGHT

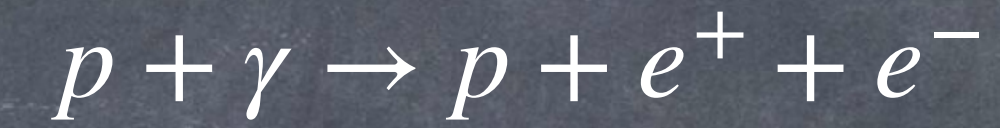


# SPECTRAL FEATURES: INTERPRETATION



$$\epsilon_{CMB} \approx 1.2 \times 10^{-3} \text{ eV}$$

$$n_\gamma \approx 400 \text{ cm}^{-3}$$



$$\gamma_{ppair}^{th} = \frac{2m_e c^2}{\epsilon_\gamma} \left( 1 + \frac{m_e}{m_p} \right) = 10^6 \left( \frac{\epsilon_\gamma}{\text{eV}} \right)^{-1}$$

$$\sigma_{p\gamma \rightarrow e^\pm} \approx 100 \mu\text{barn}$$

$$l_{p\gamma \rightarrow e^\pm} = \frac{m_p}{2m_e \sigma_{p\gamma \rightarrow e^\pm} n_\gamma} \approx 1 \text{ Gpc}$$

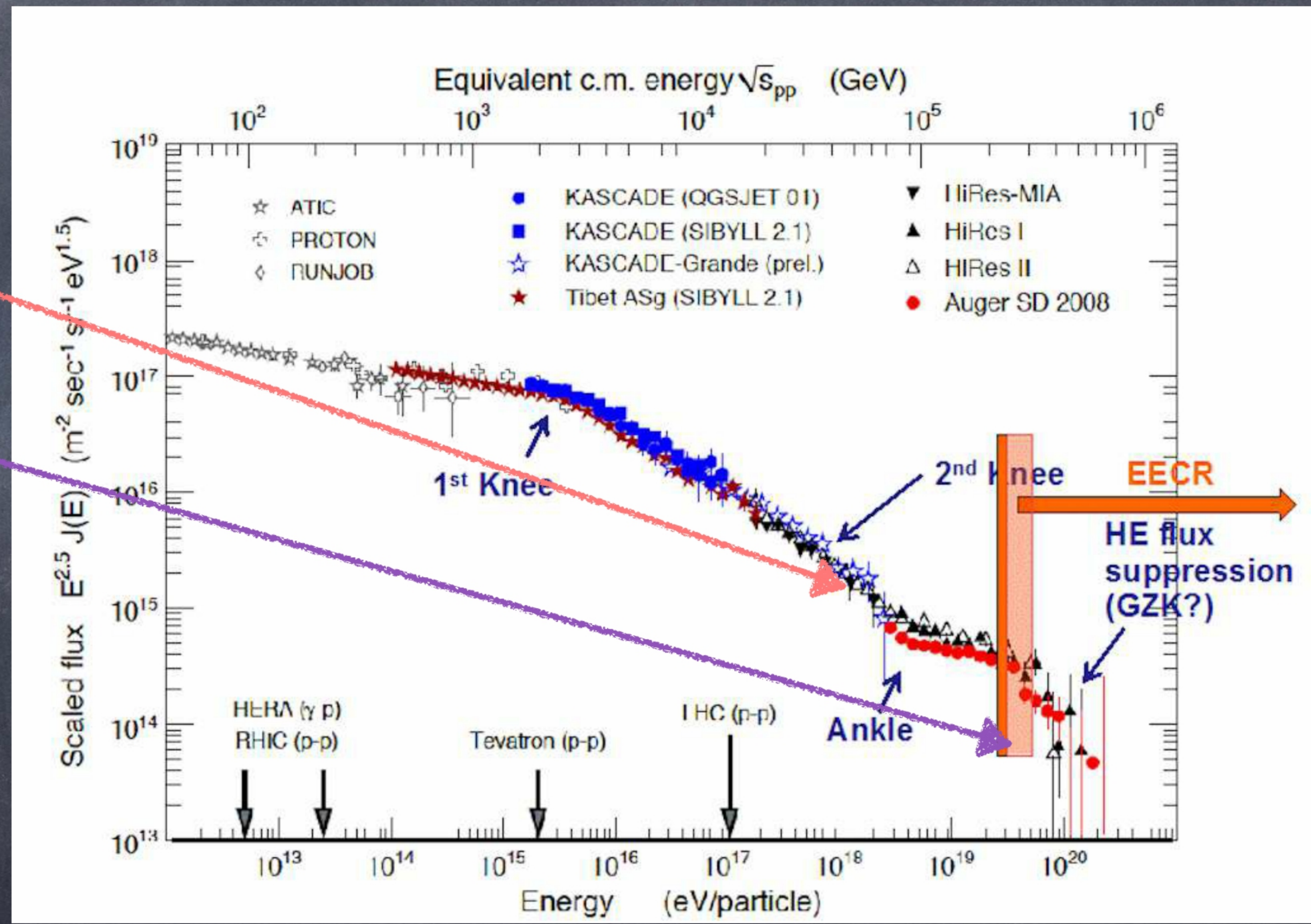
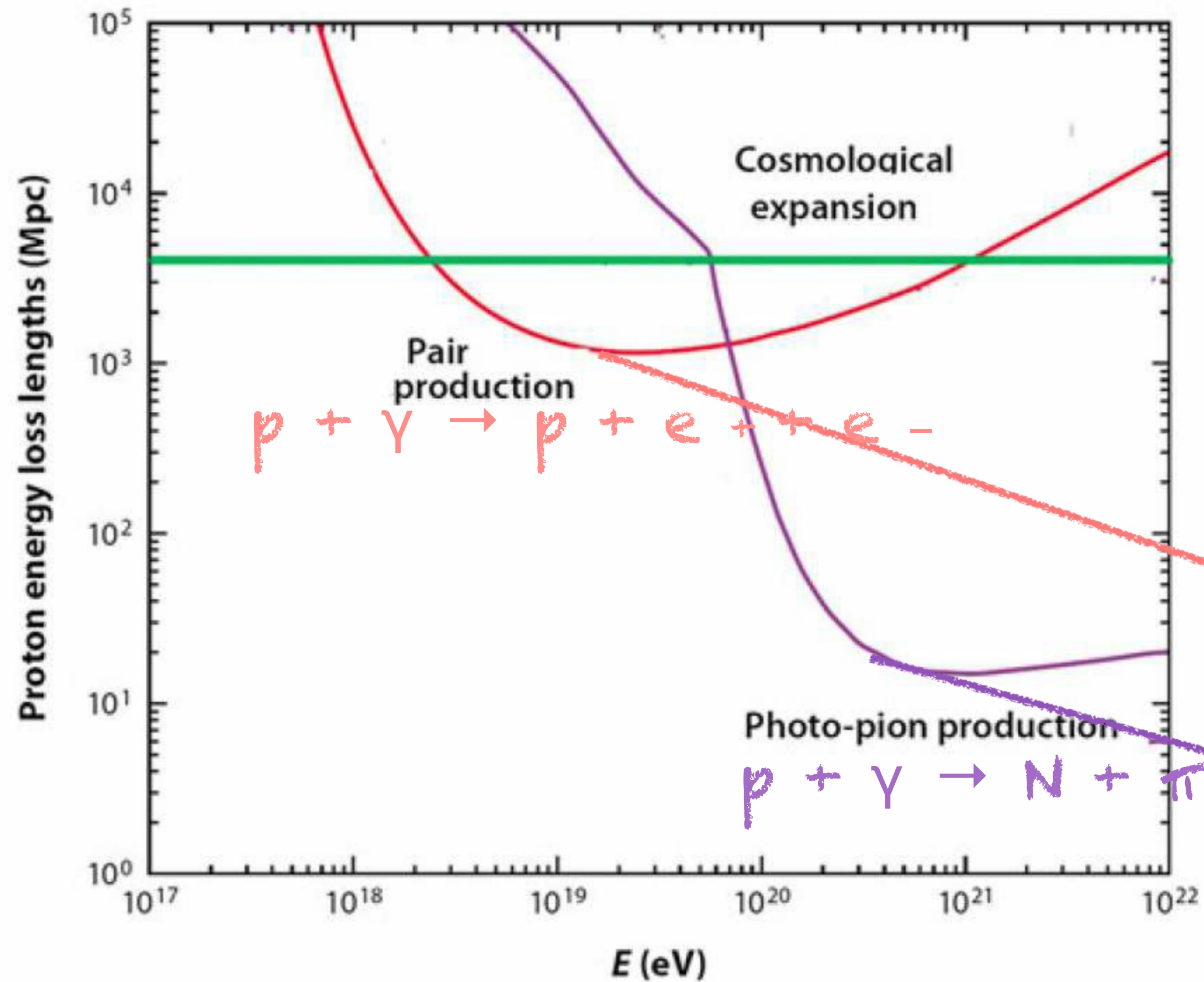


$$\gamma_{\gamma\pi}^{th} = \frac{m_\pi c^2}{\epsilon_\gamma} \left( 1 + \frac{m_\pi}{m_p} \right) = 1.5 \times 10^8 \left( \frac{\epsilon_\gamma}{\text{eV}} \right)^{-1}$$

$$\sigma_{p\gamma \rightarrow \pi} \approx 300 \mu\text{barn}$$

$$l_{p\gamma \rightarrow \pi} = \frac{m_p}{m_\pi \sigma_{p\gamma \rightarrow \pi} n_\gamma} \approx 30 \text{ Mpc}$$

# PROTON LOSS PROCESSES



**IF PROTONS :** DIP MODEL (Berezinski+06)  
 AND GZK

**IF Fe:** UHE COMPONENT WITH LOW ENERGY  
 CUT-OFF AND MAXIMUM ENERGY

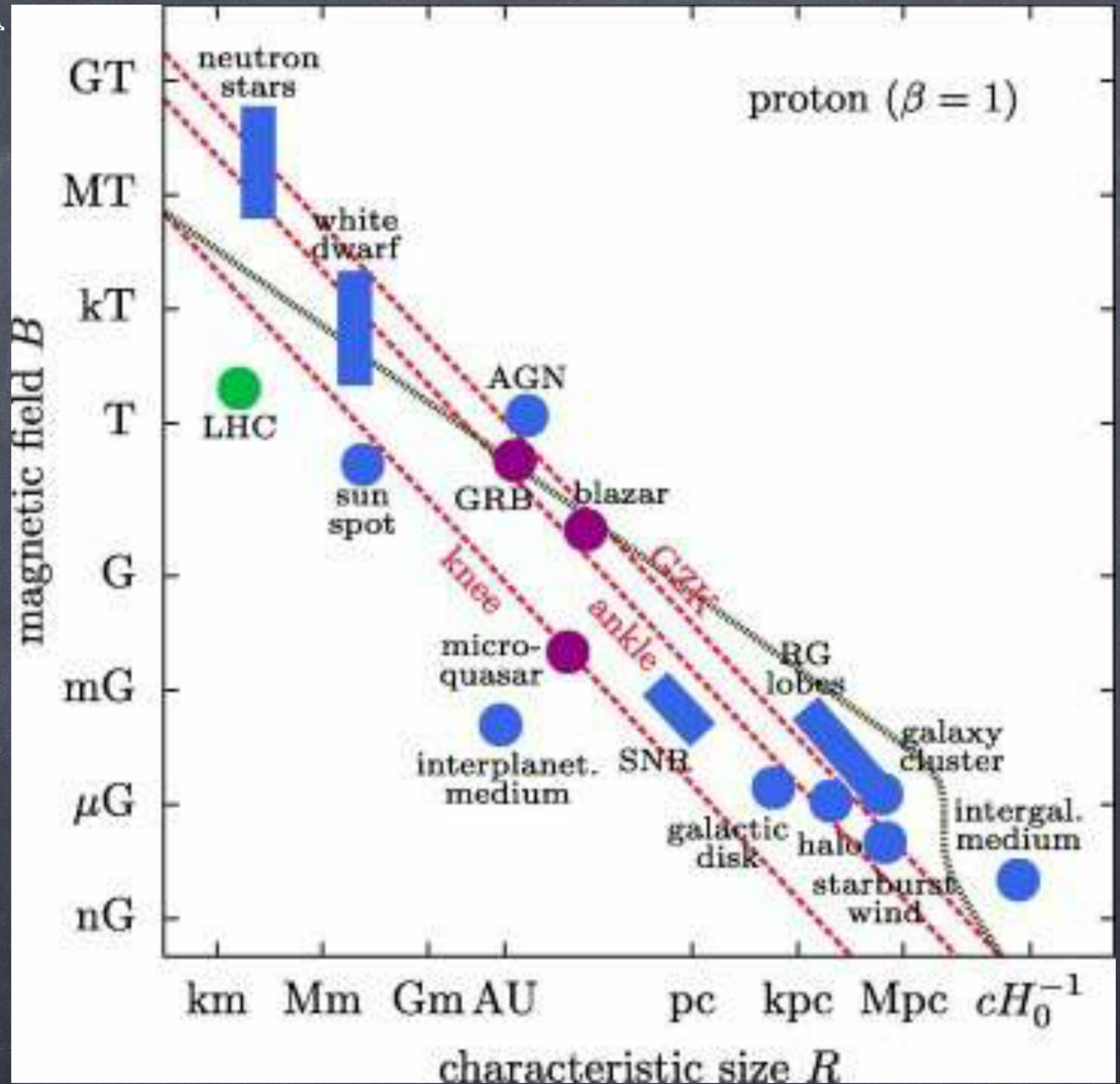
# HILLAS PLOT

## HILLAS CRITERION

$$r_L (E_{max}) < L$$

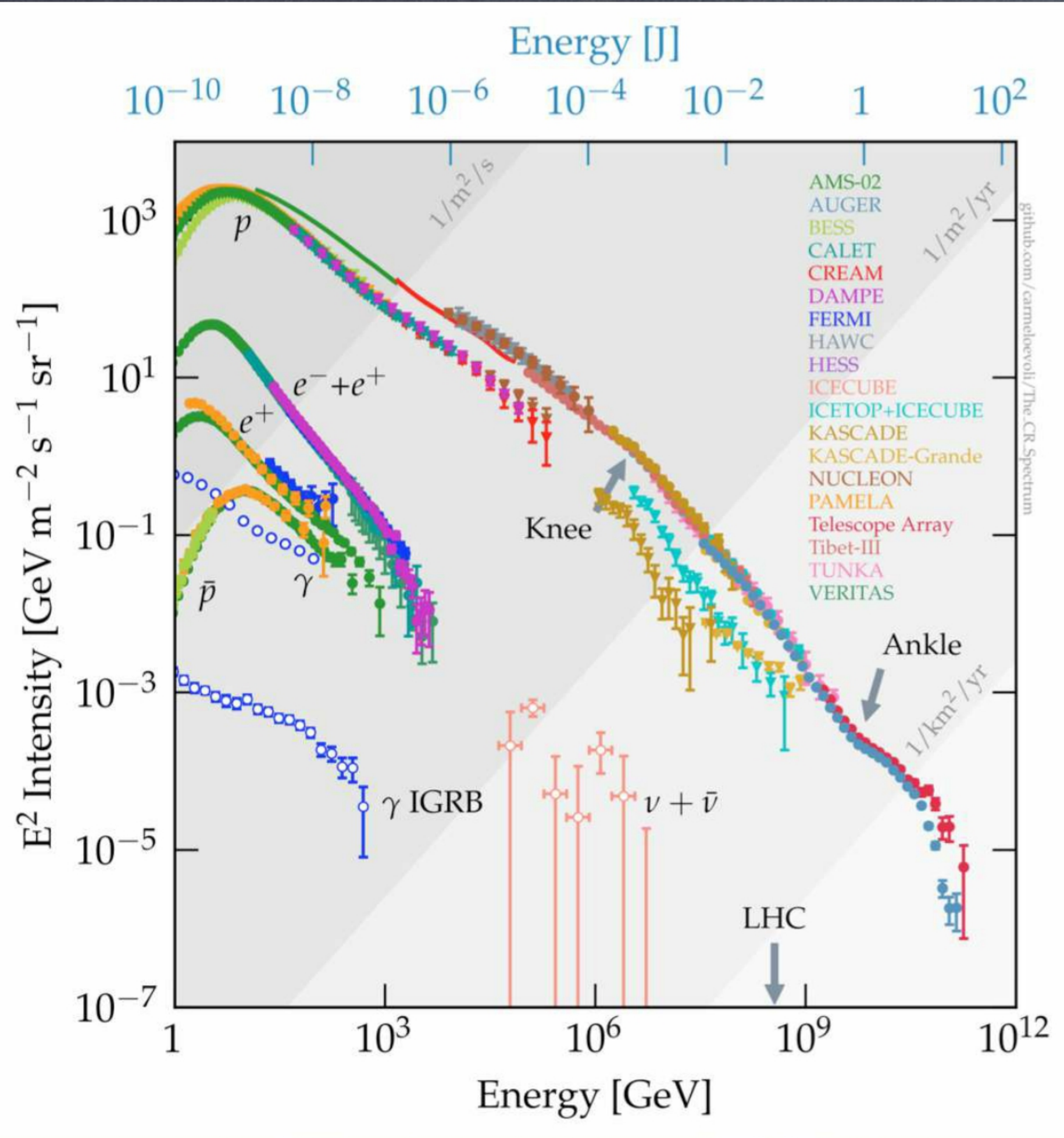


$$E_{max} < Z e B L$$



BACK TO THE GALAXY

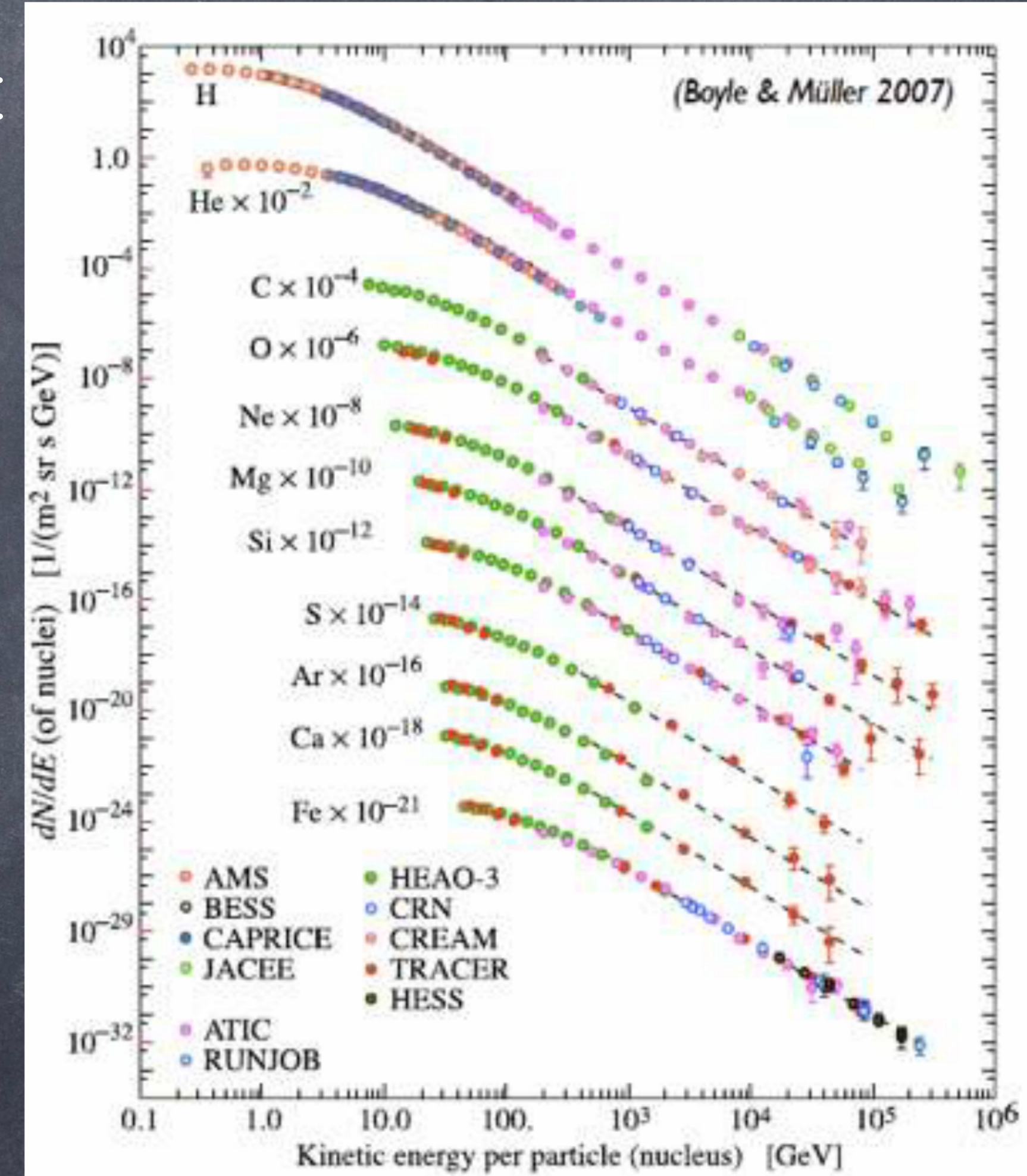
# COMPOSITION BELOW THE KNEE



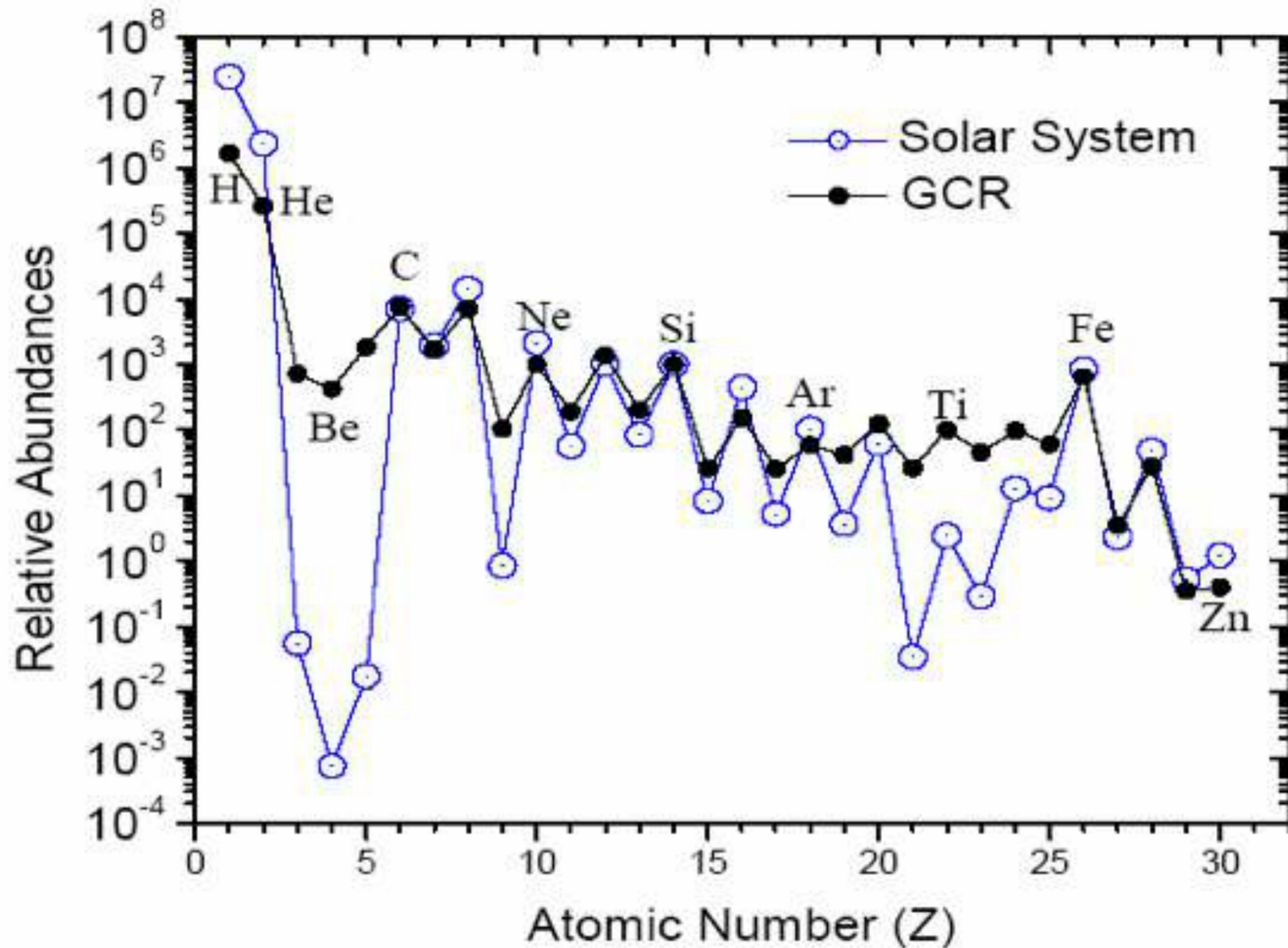
98% PROTONS AND NUCLEI  
 87% PROTONS  
 12% He  
 1% HEAVIER NUCLEI

2% ELECTRONS

0.1% ANTIMATTER  
 (POSITRONS AND ANTI-PROTONS)



# DETAILED COMPOSITION (<GeV ENERGIES)

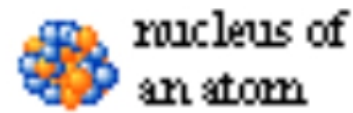


A simplified illustration of cosmic rays colliding with nuclei, and the subsequent reactions:

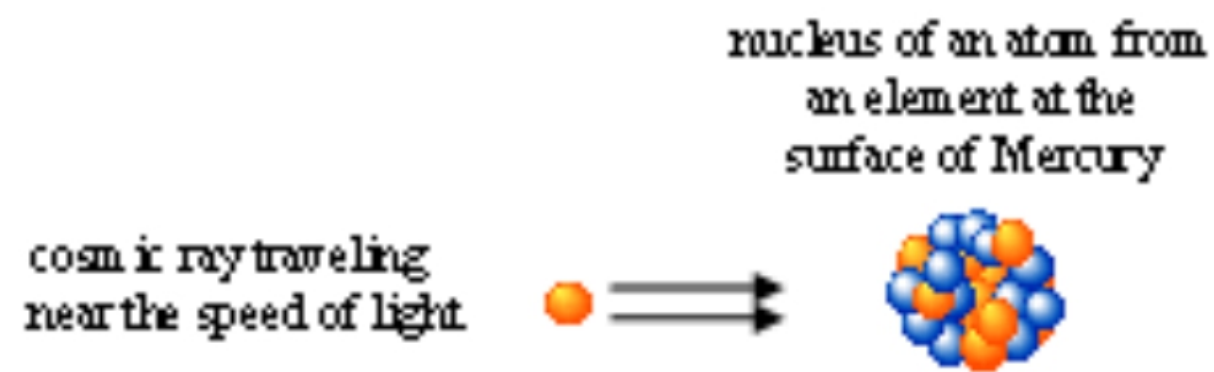
Legend:

● proton

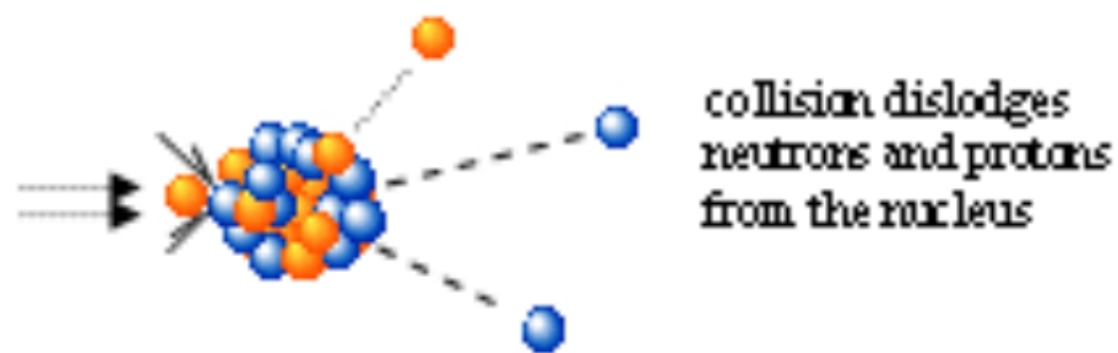
● neutron



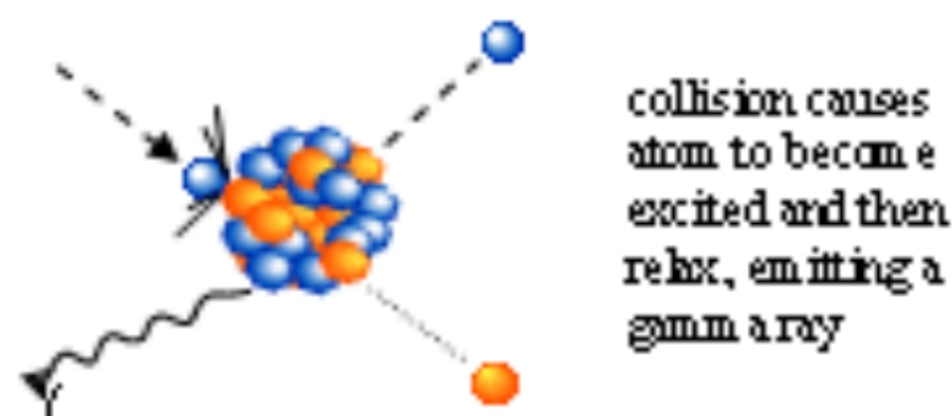
Frame 1: incoming cosmic ray (proton)



Frame 2: cosmic ray collides with a nucleus



Frame 3: a dislodged neutron collides with another nucleus



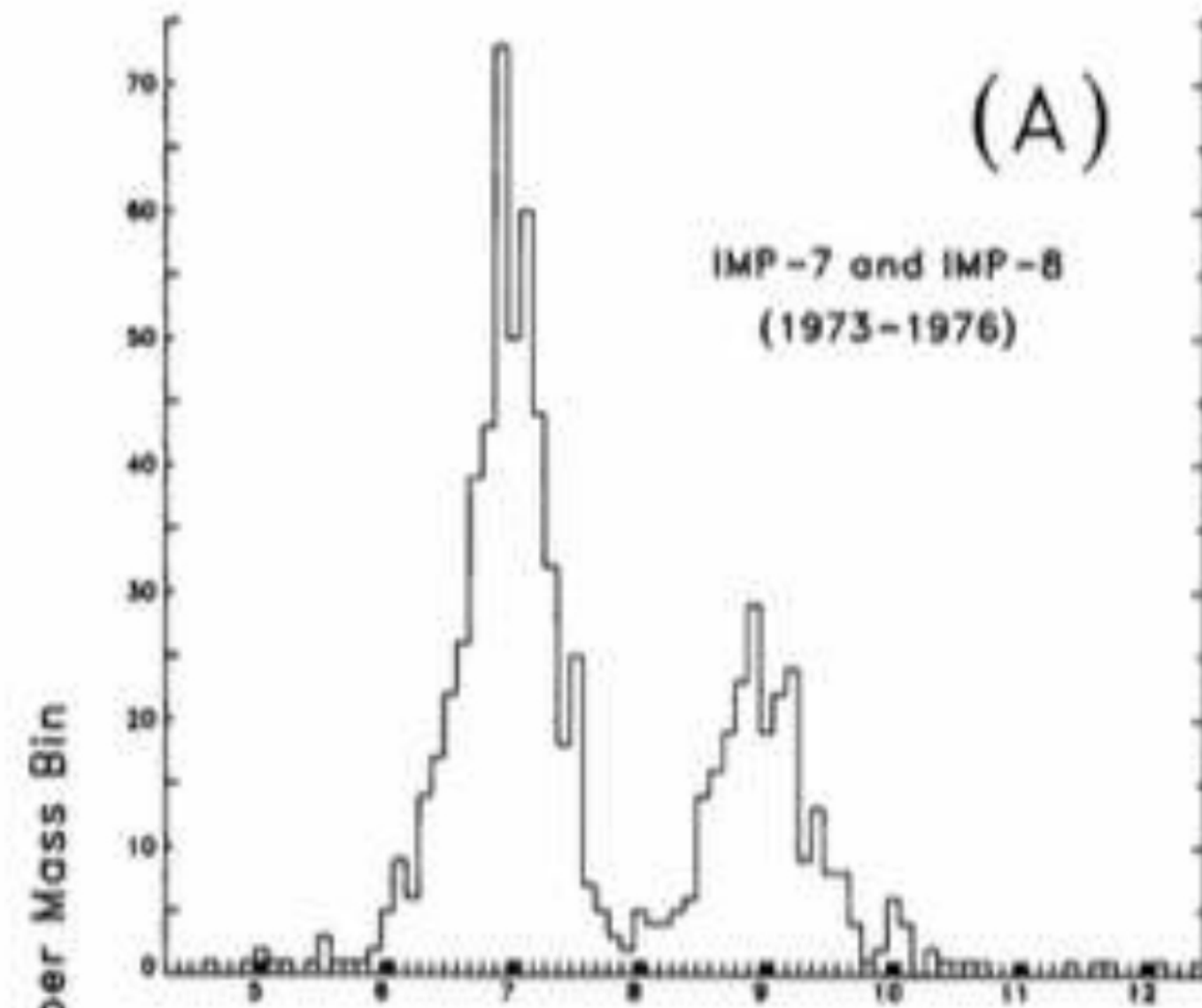
# SPALLATION PROCESSES AND SECONDARY ELEMENTS



ELEMENTS IN EXCESS OF SOLAR ARE OF SECONDARY ORIGIN

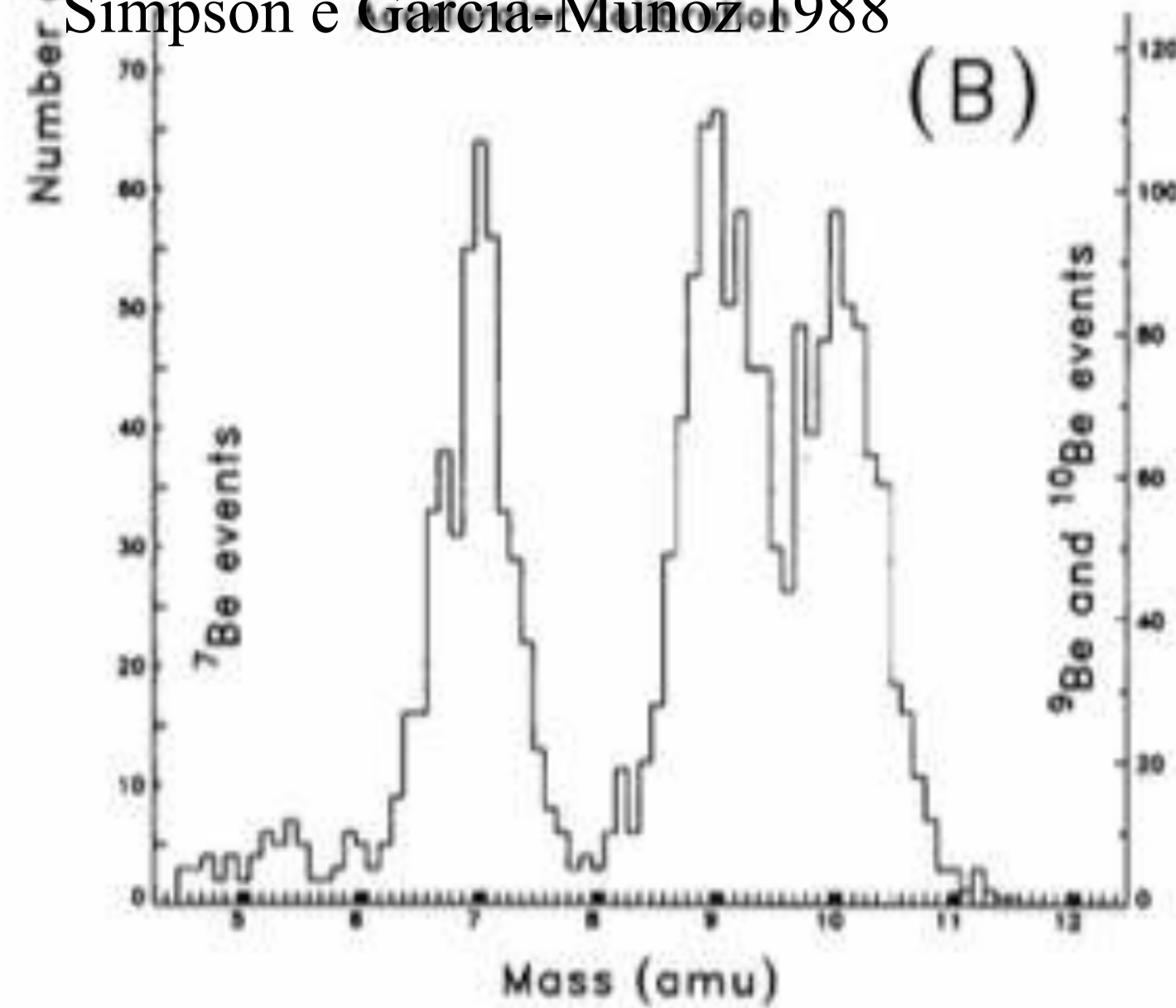
ABUNDANCE OF SECONDARIES====> GRAMMAGE  
====> CONFINEMENT TIME IN THE GALAXY

# UNSTABLE ELEMENTS

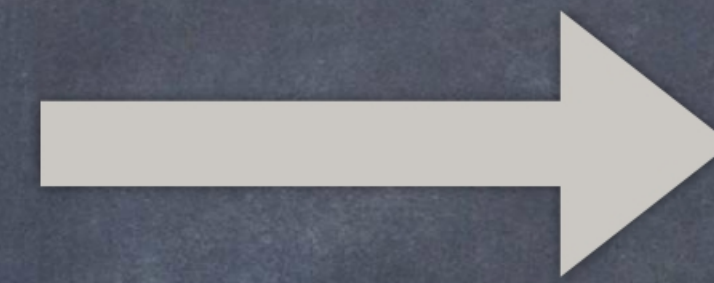


MEASURED  
IN CRS

Simpson e Garcia-Munoz 1988

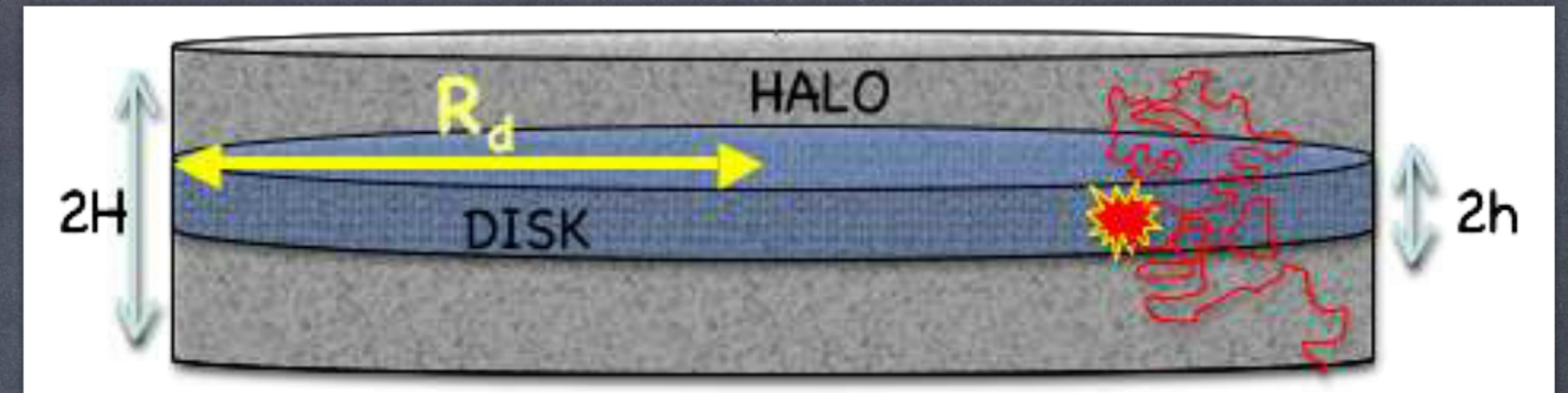
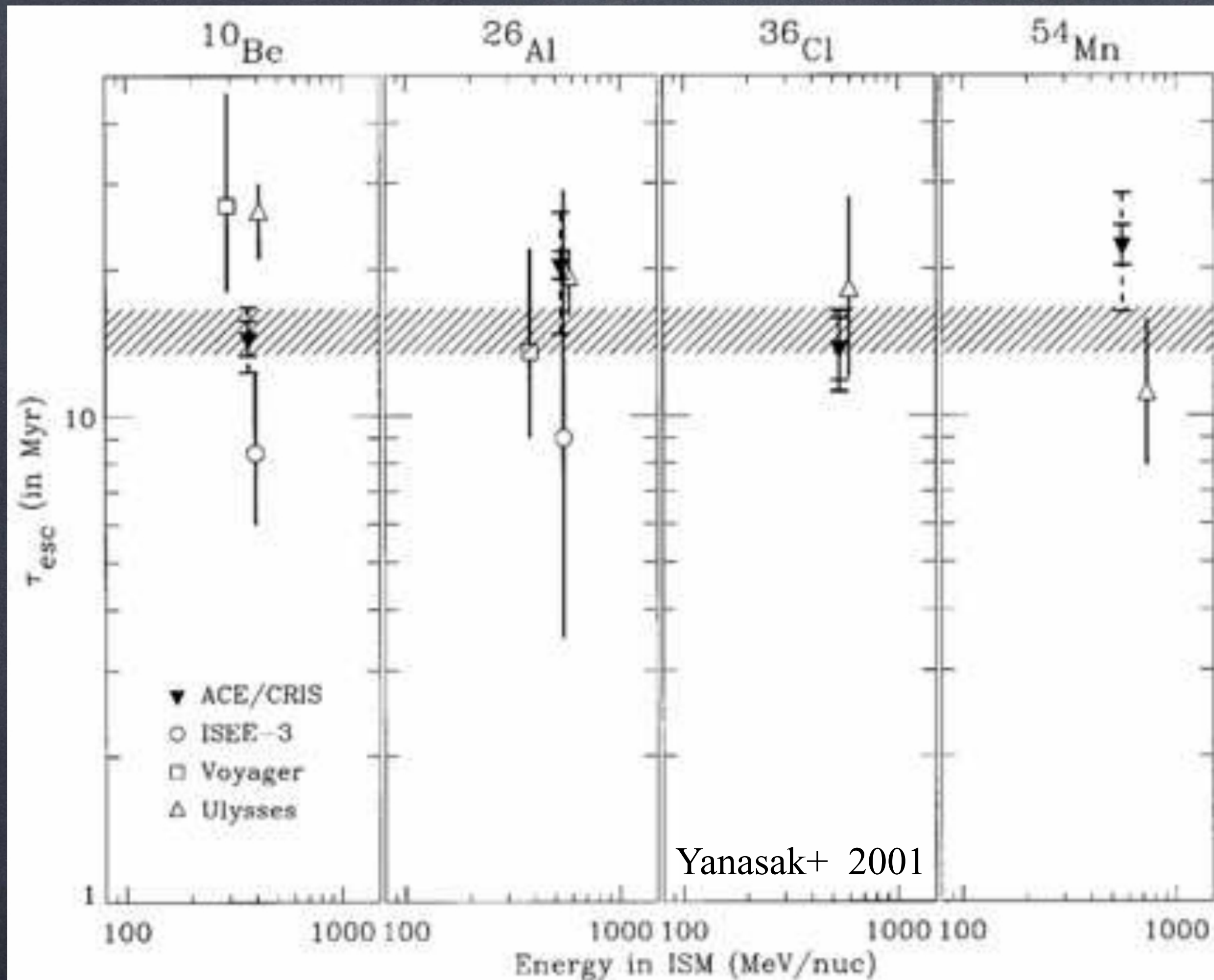


MEASURED IN  
THE LAB



CR AGE LARGER THAN  
 $\tau (^{10}\text{Be}) = 1.5 \times 10^6 \text{yr}$

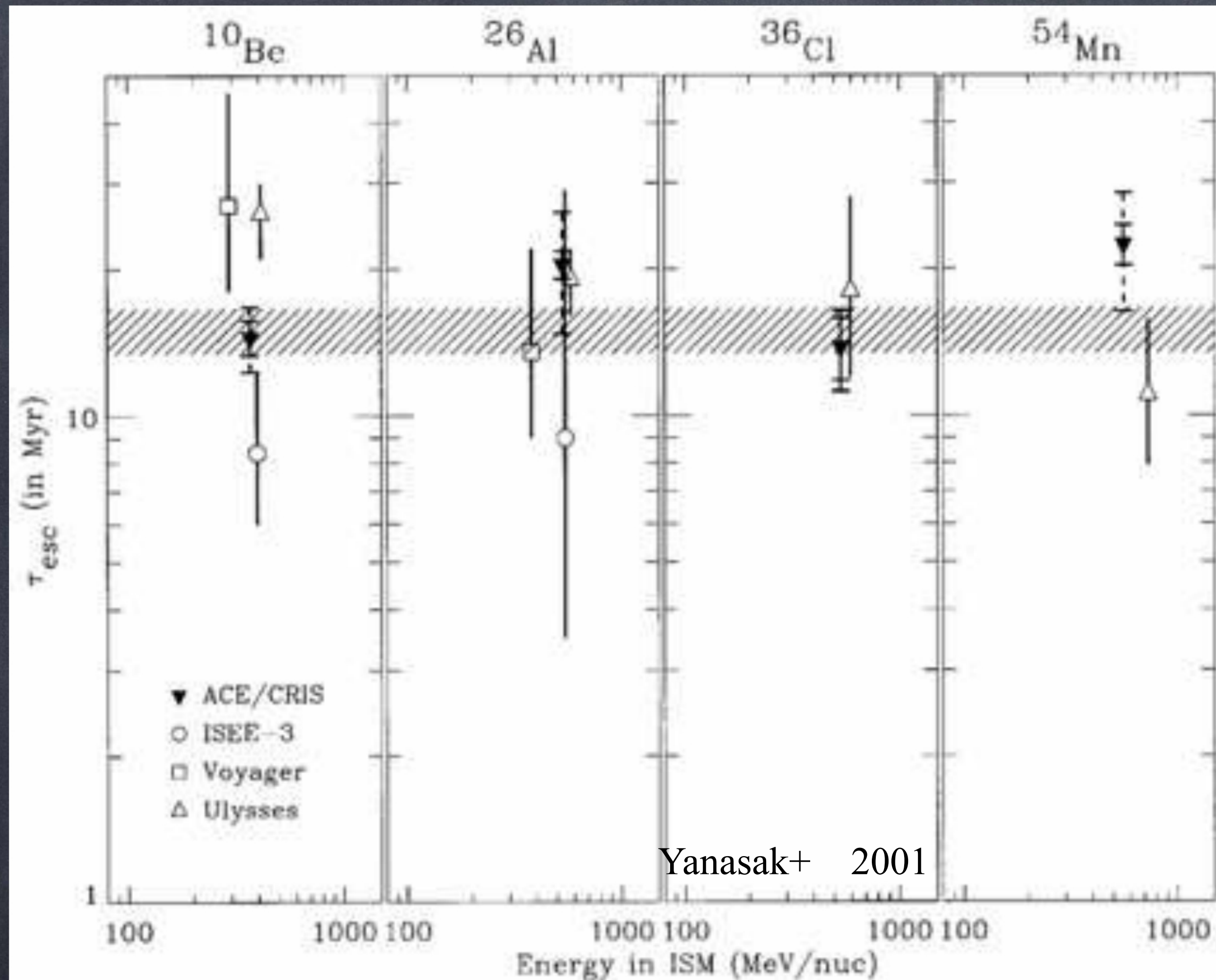
# RESIDENCE TIME IN THE GALAXY



RADIOACTIVE ELEMENTS POINT TO

$$\tau_{esc}(1\text{GeV}) \approx 15 \times 10^6 \text{ yr}$$

# RESIDENCE TIME IN THE GALAXY



$$\tau_d \approx \frac{300 \text{ pc}}{c} \approx 10^3 \text{ yr} \quad \text{DISK HEIGHT}$$

$$\tau_g \approx \frac{15 \text{ kpc}}{c} \approx 5 \times 10^4 \text{ yr} \quad \text{DISK RADIUS}$$

$$\tau_d \approx \frac{3 \text{ kpc}}{c} \approx 10^4 \text{ yr} \quad \text{DISK HALO}$$

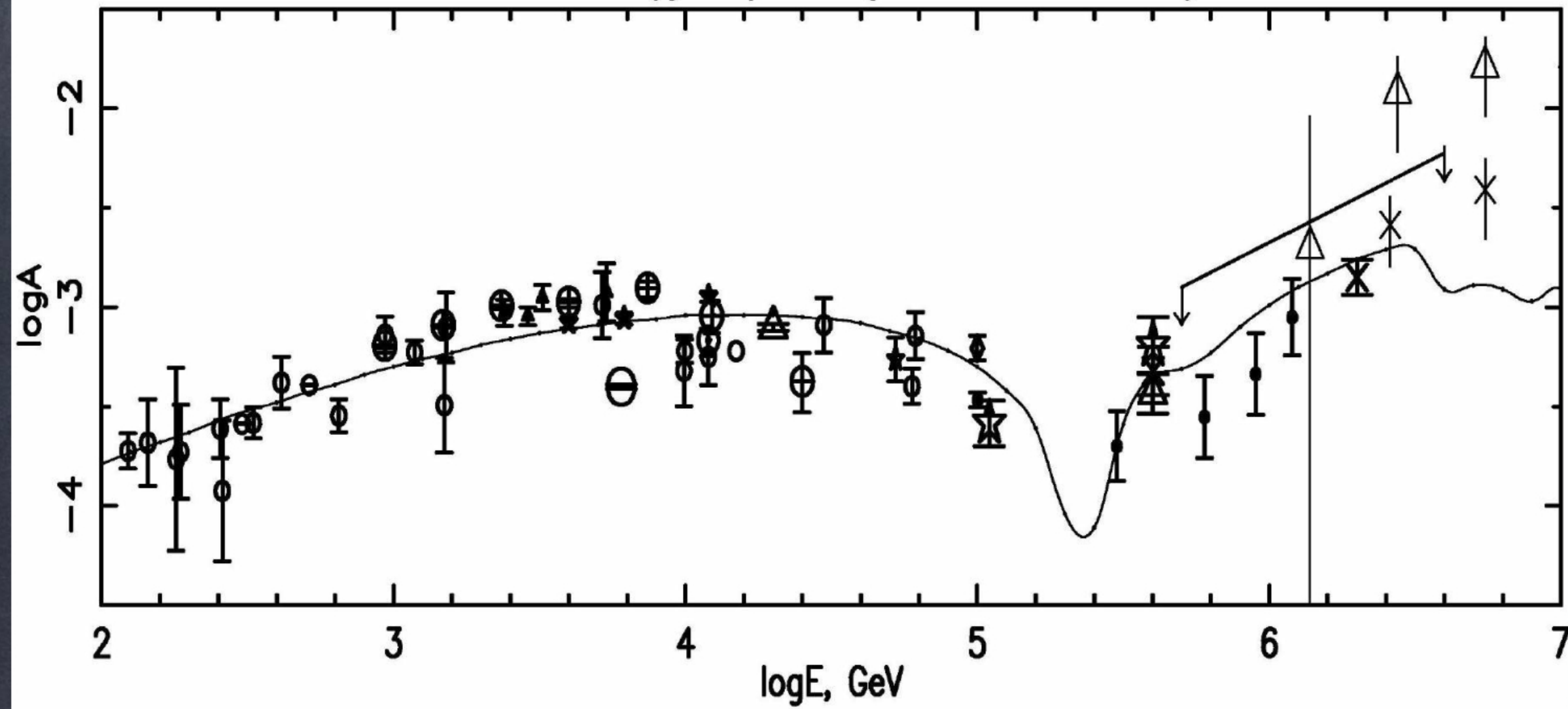
RADIOACTIVE ELEMENTS POINT TO

$$\tau_{\text{esc}}(1 \text{ GeV}) \approx 15 \times 10^6 \text{ yr}$$

PROPROPAGATION CANNOT BE BALLISTIC

# ANISOTROPY

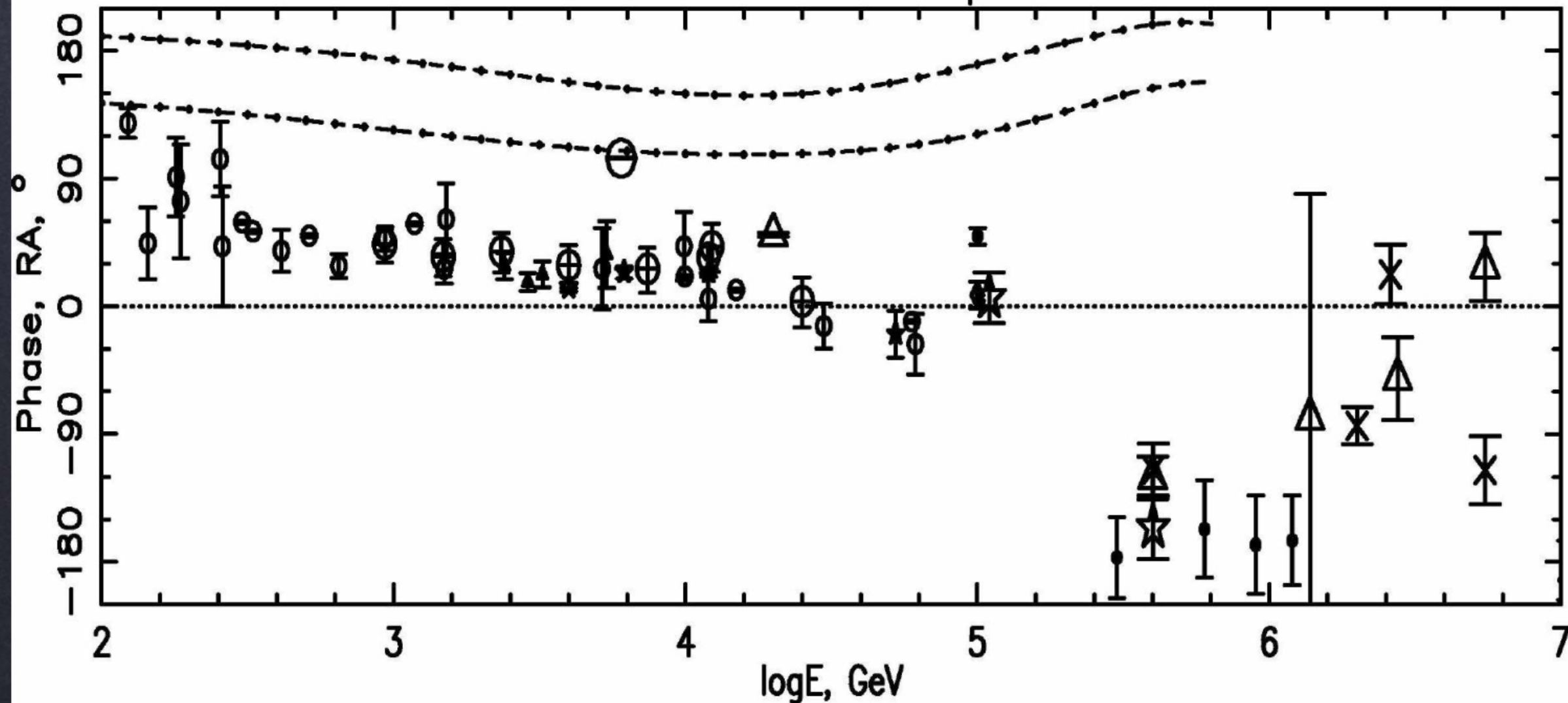
The Anisotropy Amplitude ( the first harmonic )



$$\delta \approx \frac{3J}{cn} \approx \frac{v_d}{c}$$

$$\delta \approx 10^{-4} \ll \frac{1}{\sqrt{N_{src}}}$$

The Phase of the Flux Maximum in Equatorial Coordinates



$$\delta \approx 10^{-4} \approx \frac{v_A}{c}$$

$$v_A = \frac{B_0}{\sqrt{4\pi\rho_{ISM}}} \approx 10 \text{ km/s}$$

# CR PROPAGATION

LONG CONFINEMENT TIME

+

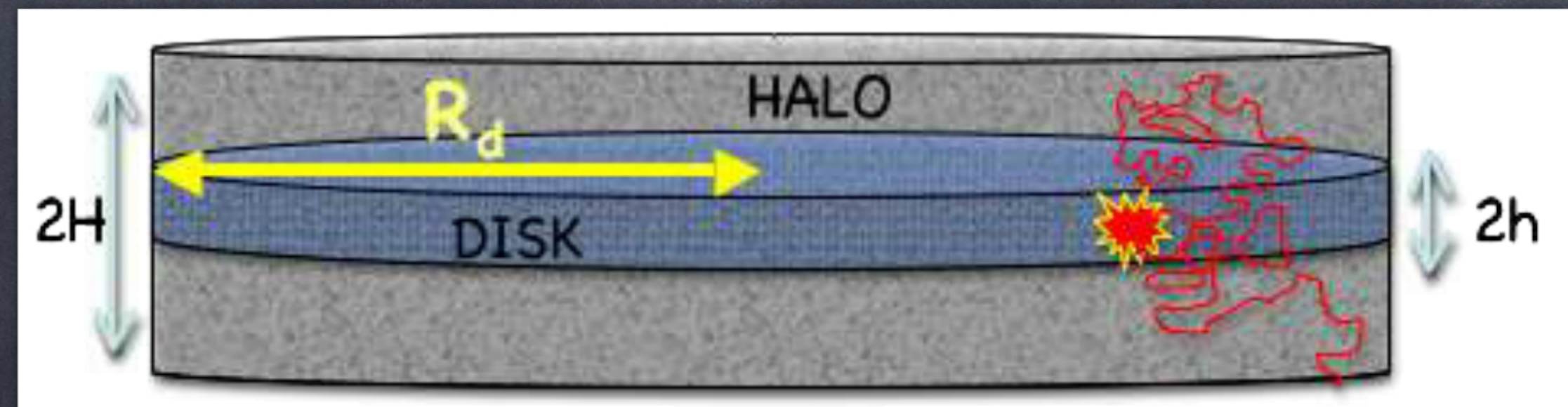
SMALL ANISOTROPY

(COMPATIBLE WITH DRIFT AT ALFVEN SPEED)



**PROPAGATION MUST BE DIFFUSIVE**  $l \propto \sqrt{D t}$

(SCATTERING ISOTROPIZES PARTICLES IN A SYSTEM COMOVING WITH ALFVEN WAVES)



**POSSIBILITY OF SOURCE LOCALIZATION LOST!**

THE SOURCES  
OF  
COSMIC RAYS

# ENERGETIC ARGUMENT

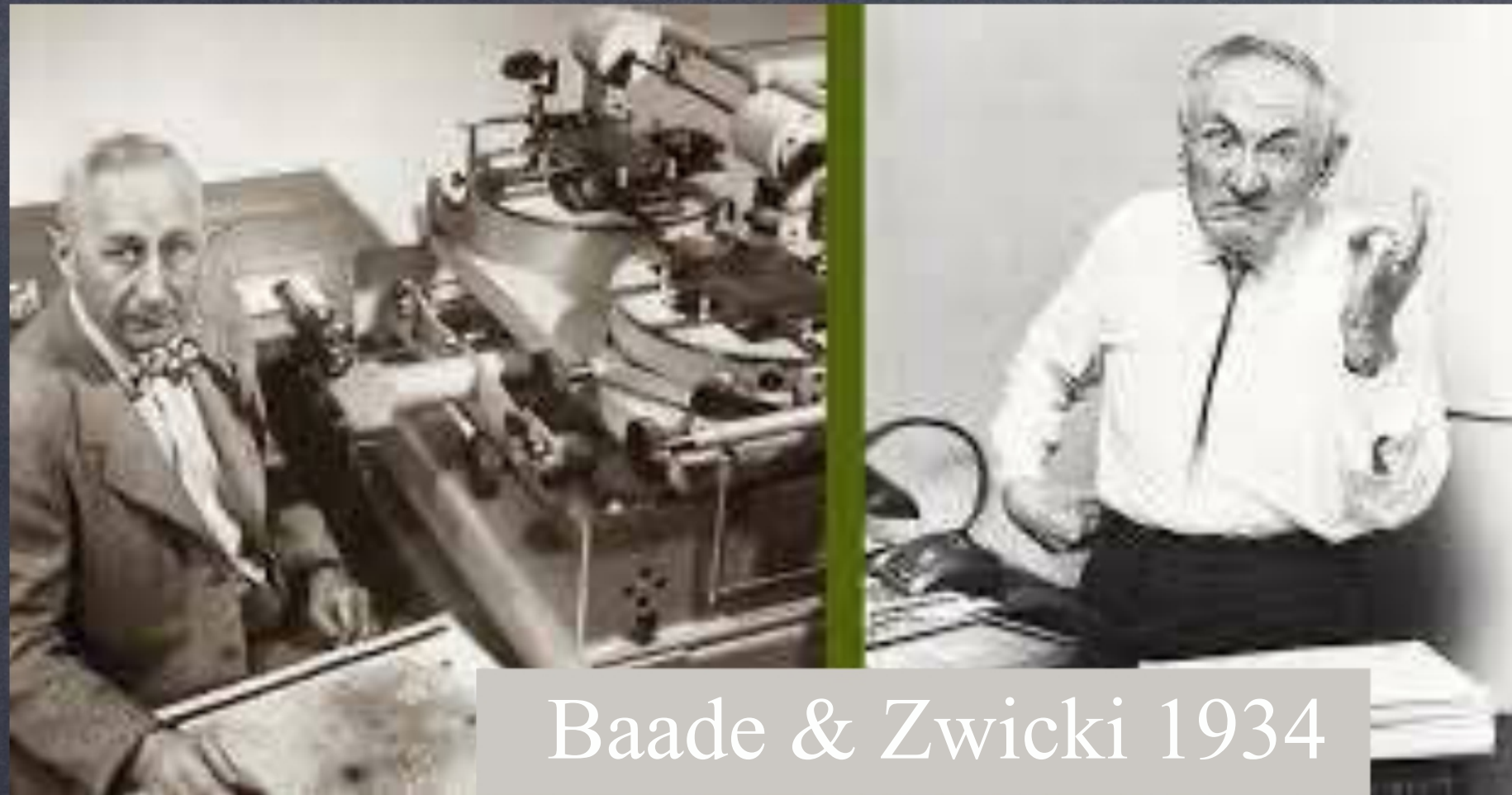
$$W_{\text{CR}} \approx 0.5 \text{ eV cm}^{-3}$$

$$V_{\text{CR}} = 2\pi R_d^2 R_H \approx 5 \times 10^{67} \text{ cm}^3$$

$$L_{\text{CR}} = \frac{w_{\text{CR}} \text{ Vol}}{\tau} \approx 10^{40} \text{ erg/s}$$

$$\tau_{\text{CR}}(1 \text{ GeV}) \approx 20 \times 10^6 \text{ yr}$$

# THE SNR/CR CONNECTION

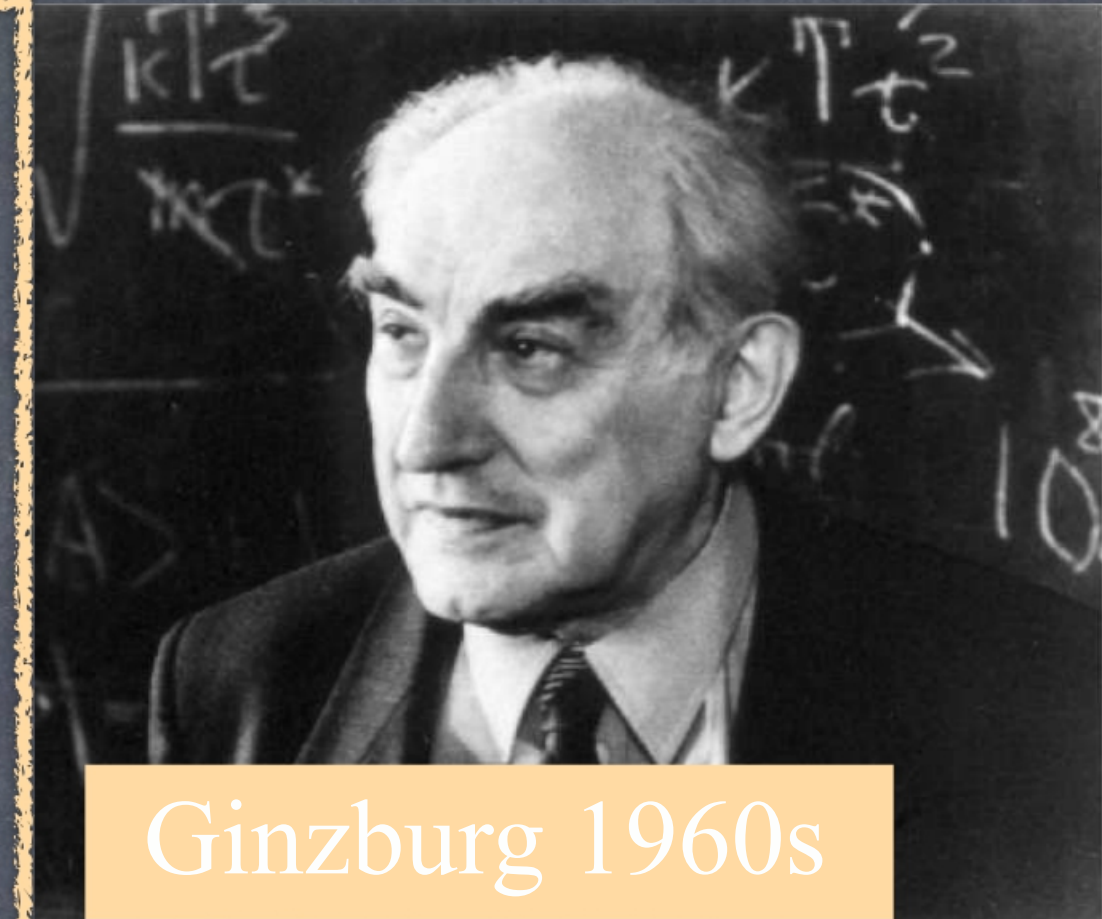


Baade & Zwicky 1934

$$L_{CR} = \frac{w_{CR} Vol}{\tau} \approx (3 - 10) \times 10^{40} \text{ erg/s}$$

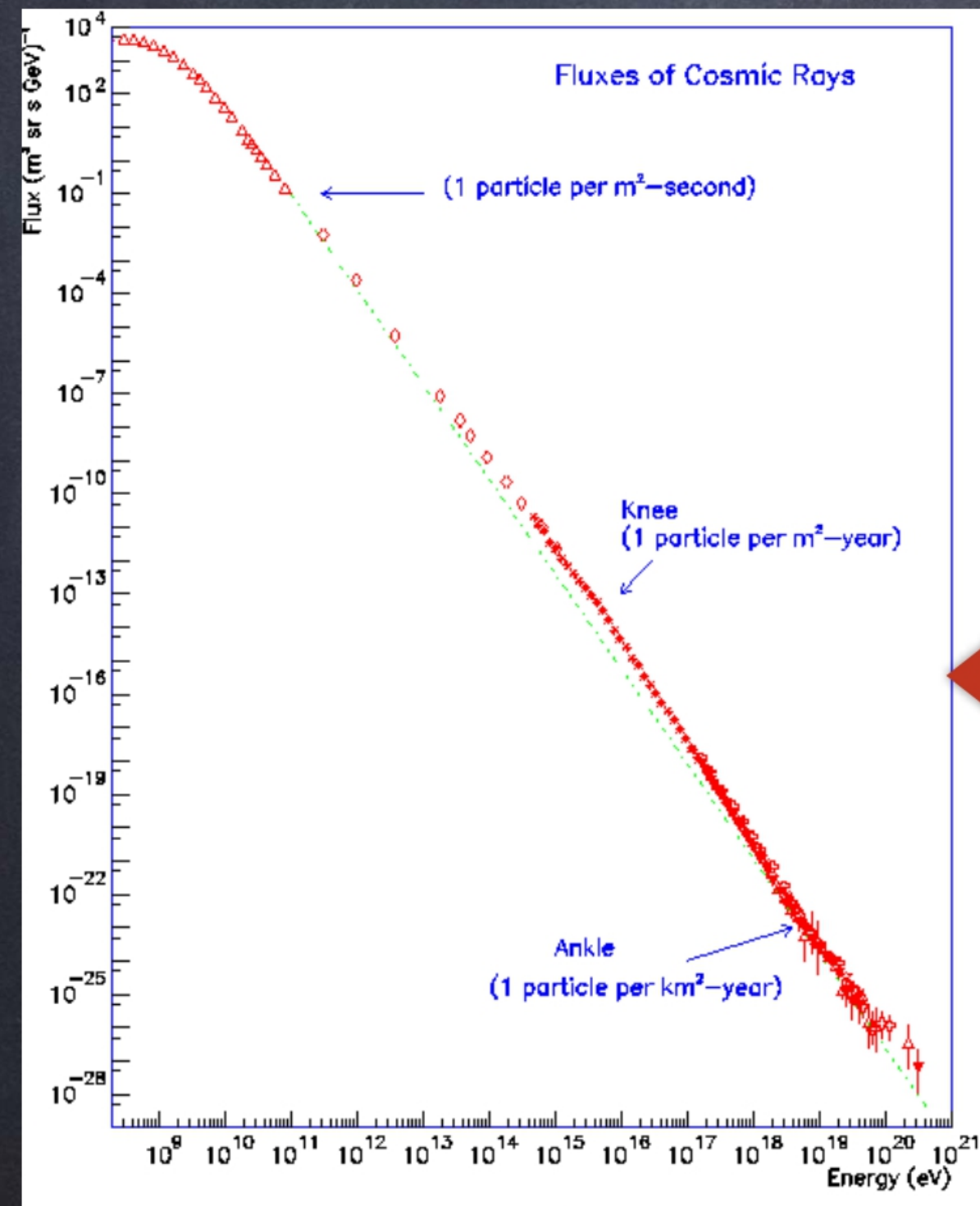
$$L_{SN} = \mathcal{R} E_{rmSN} \approx (3 - 10) \times 10^{40} \text{ erg/s}$$

$$\frac{L_{CR}}{L_{rmSN}} = 0.03 - 0.3$$

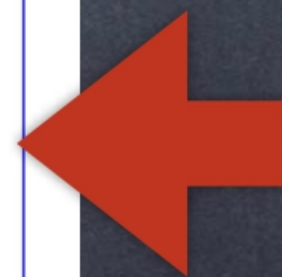


Ginzburg 1960s

QUANTITATIVE SUGGESTION



QUALITATIVE SUGGESTION IN BRILLIANT PAPER



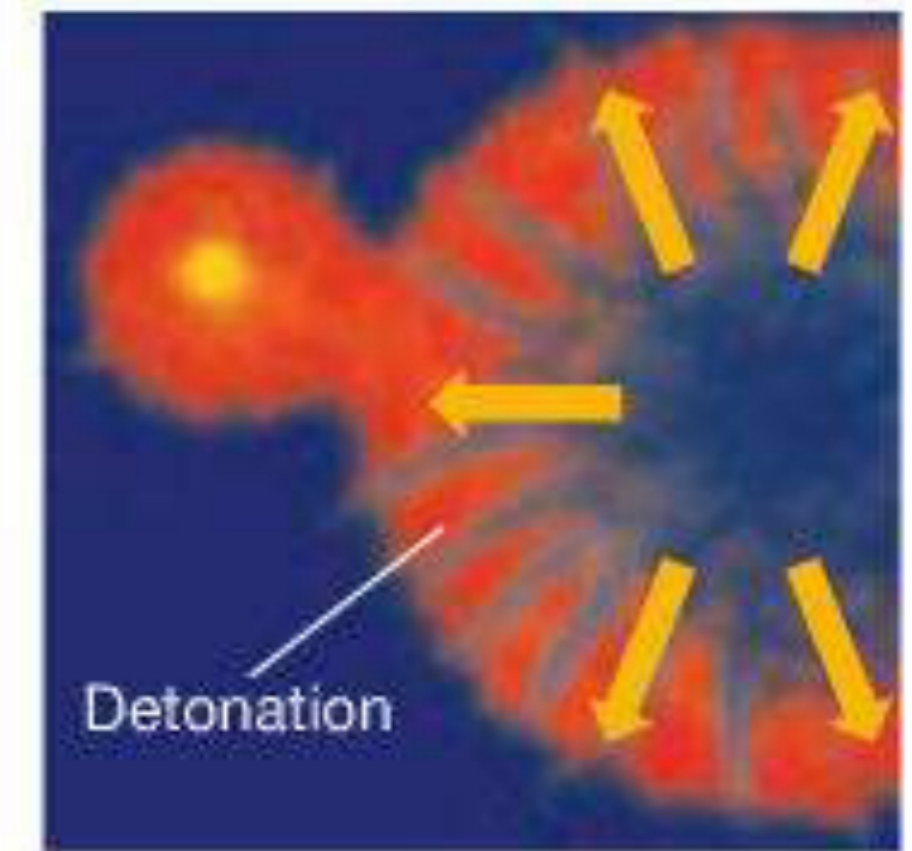
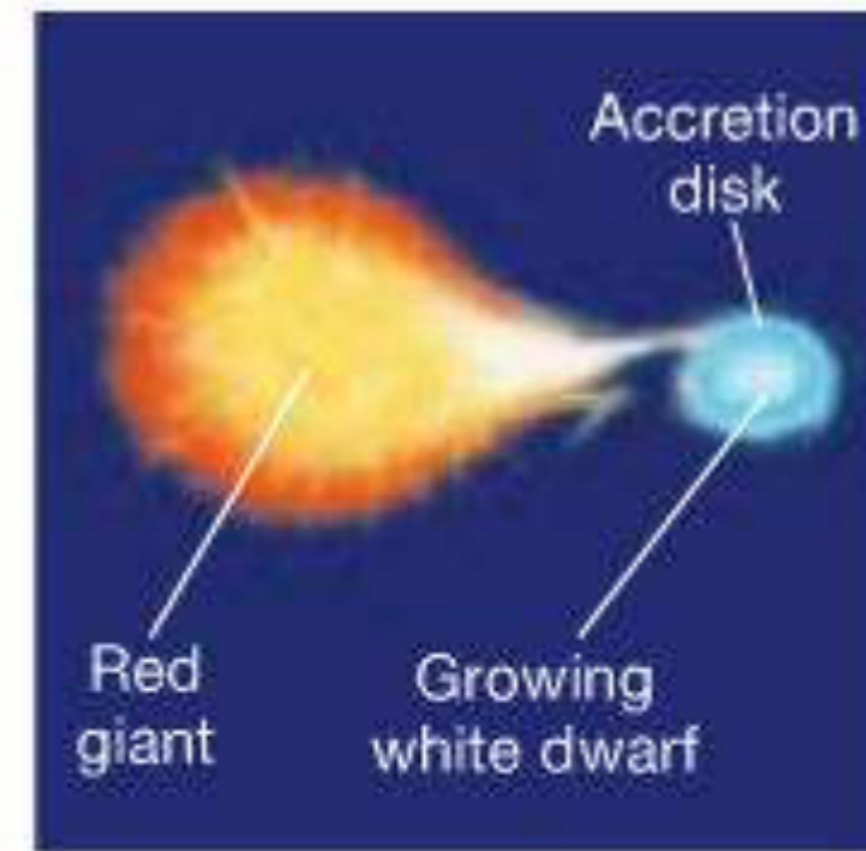
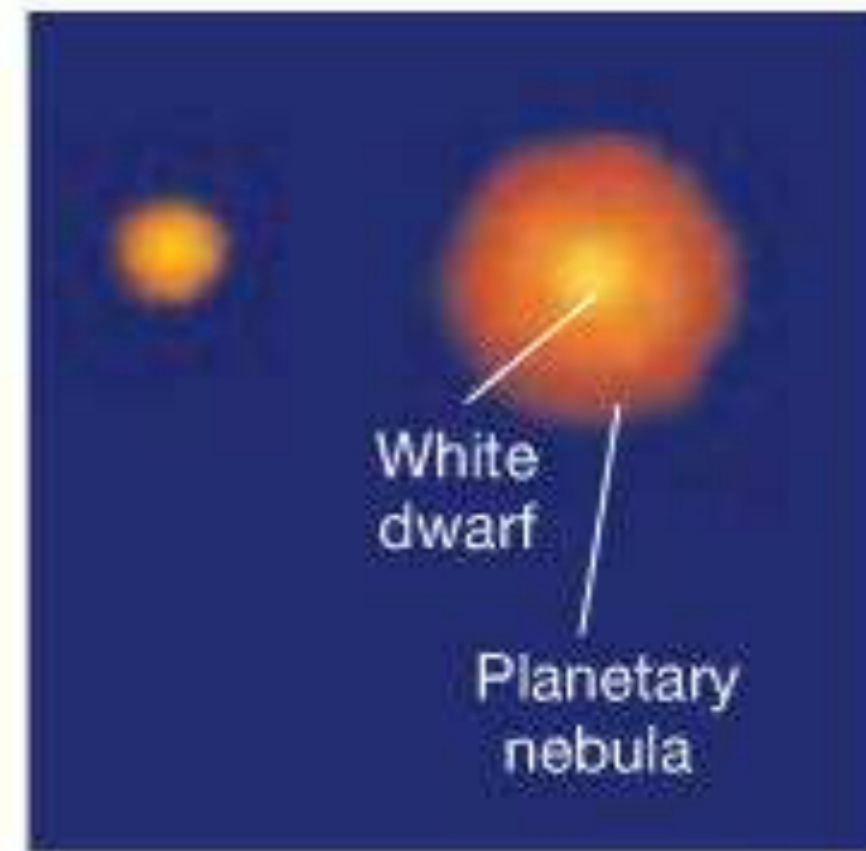
$$V_{CR} = 2\pi R_d^2 R_H \approx 2\pi (15 \text{ kpc})^2 (1 - 5) \text{ kpc}$$

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

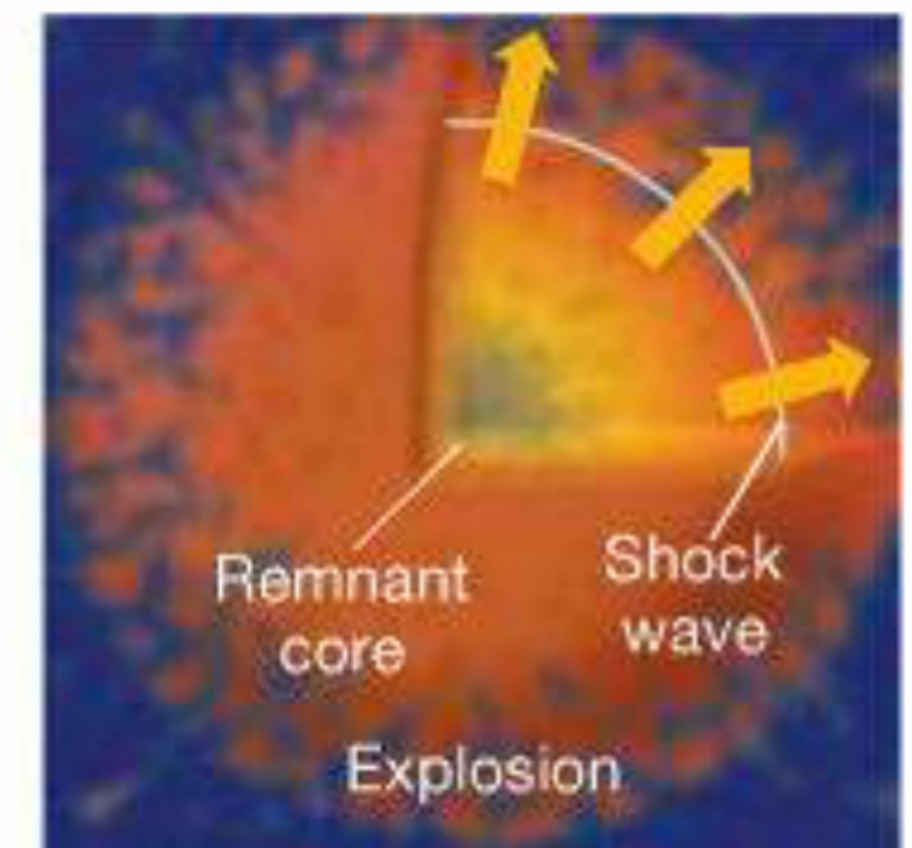
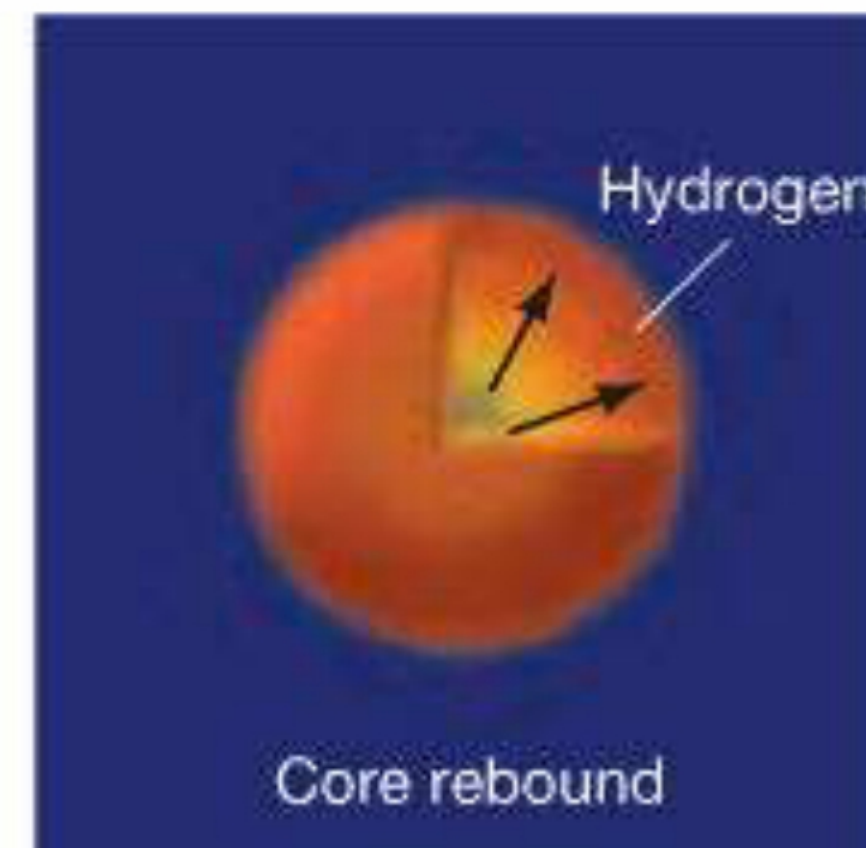
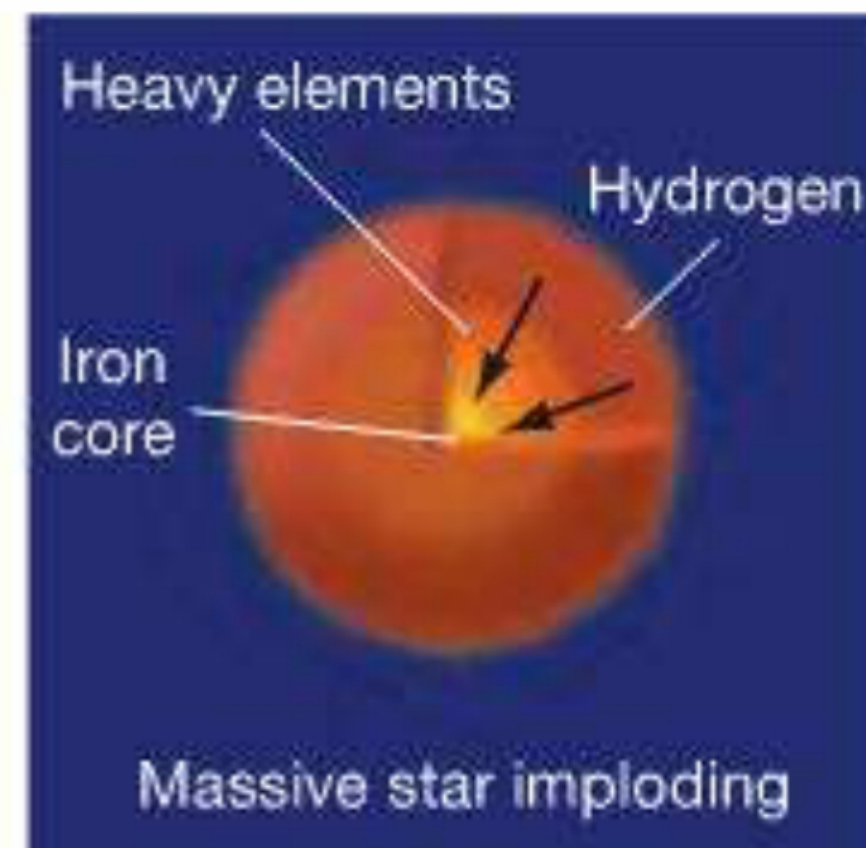
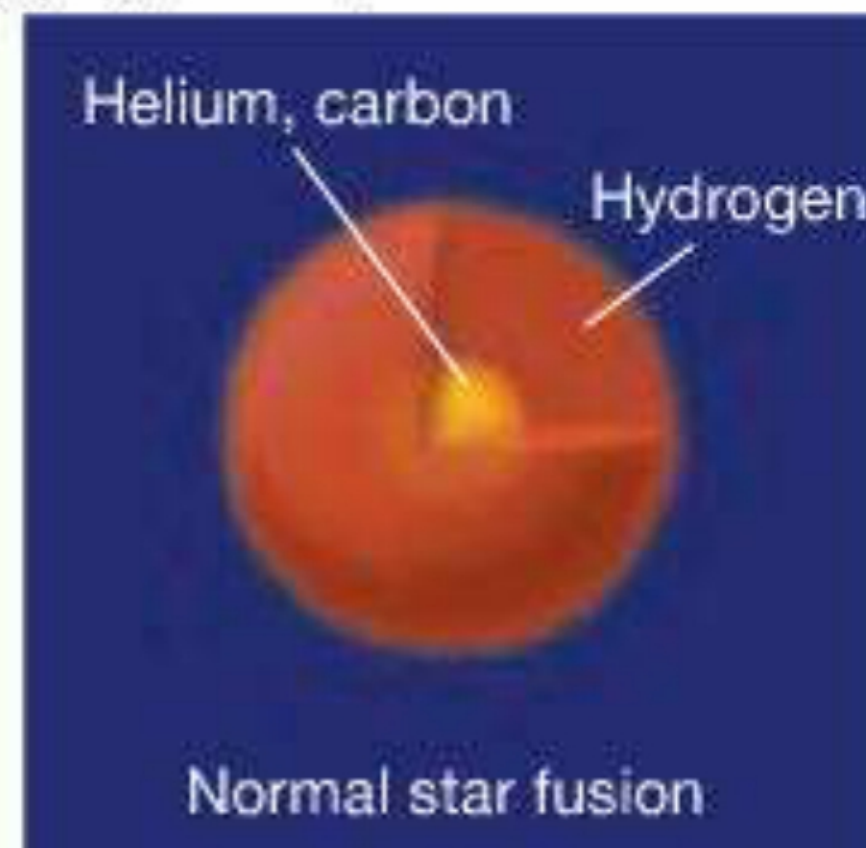
$$\mathcal{R} \approx \frac{1}{(30 - 100) \text{ yr}} \quad E_{SN} \approx 10^{51} \text{ erg}$$

# SUPERNOVAE

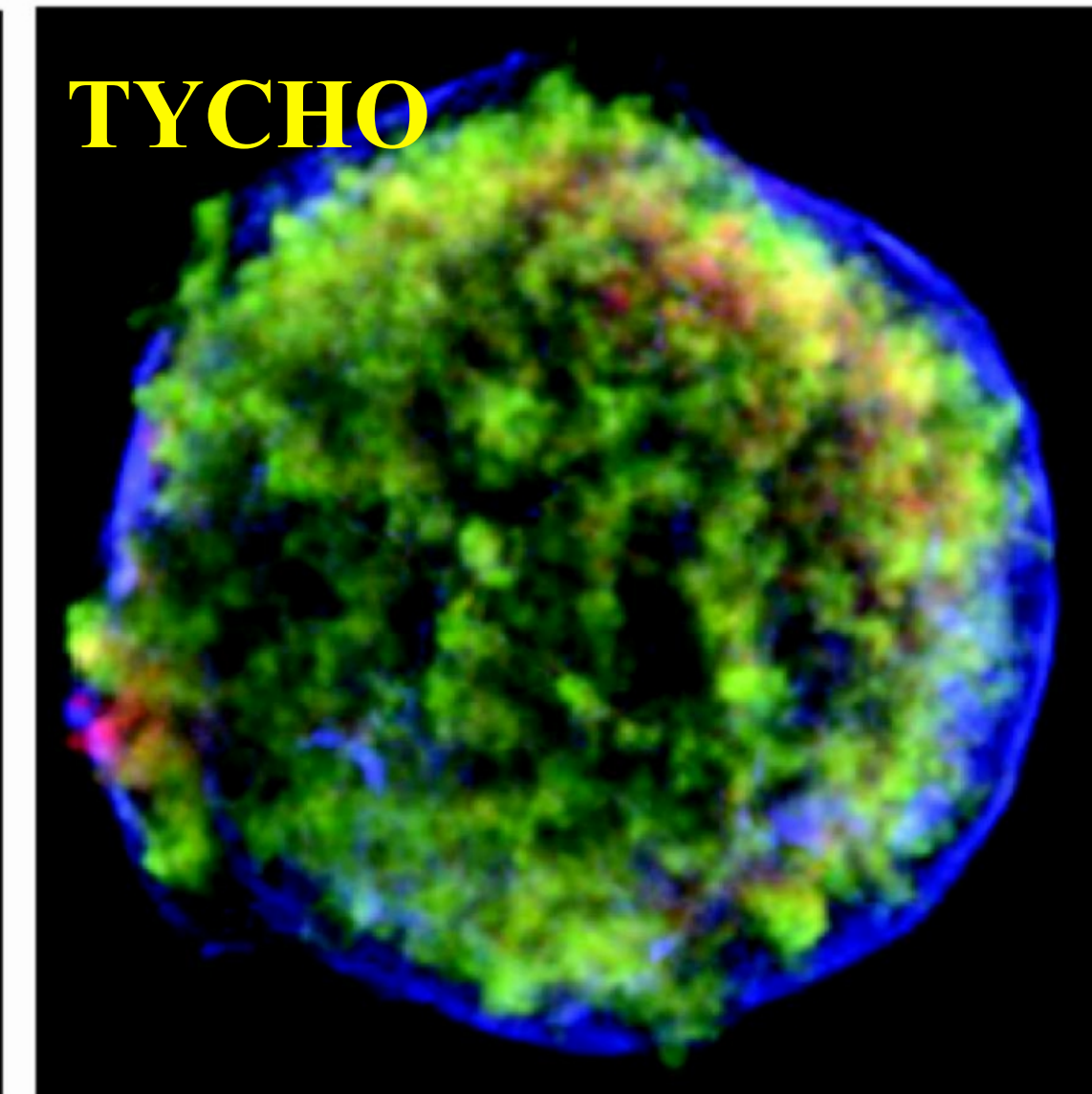
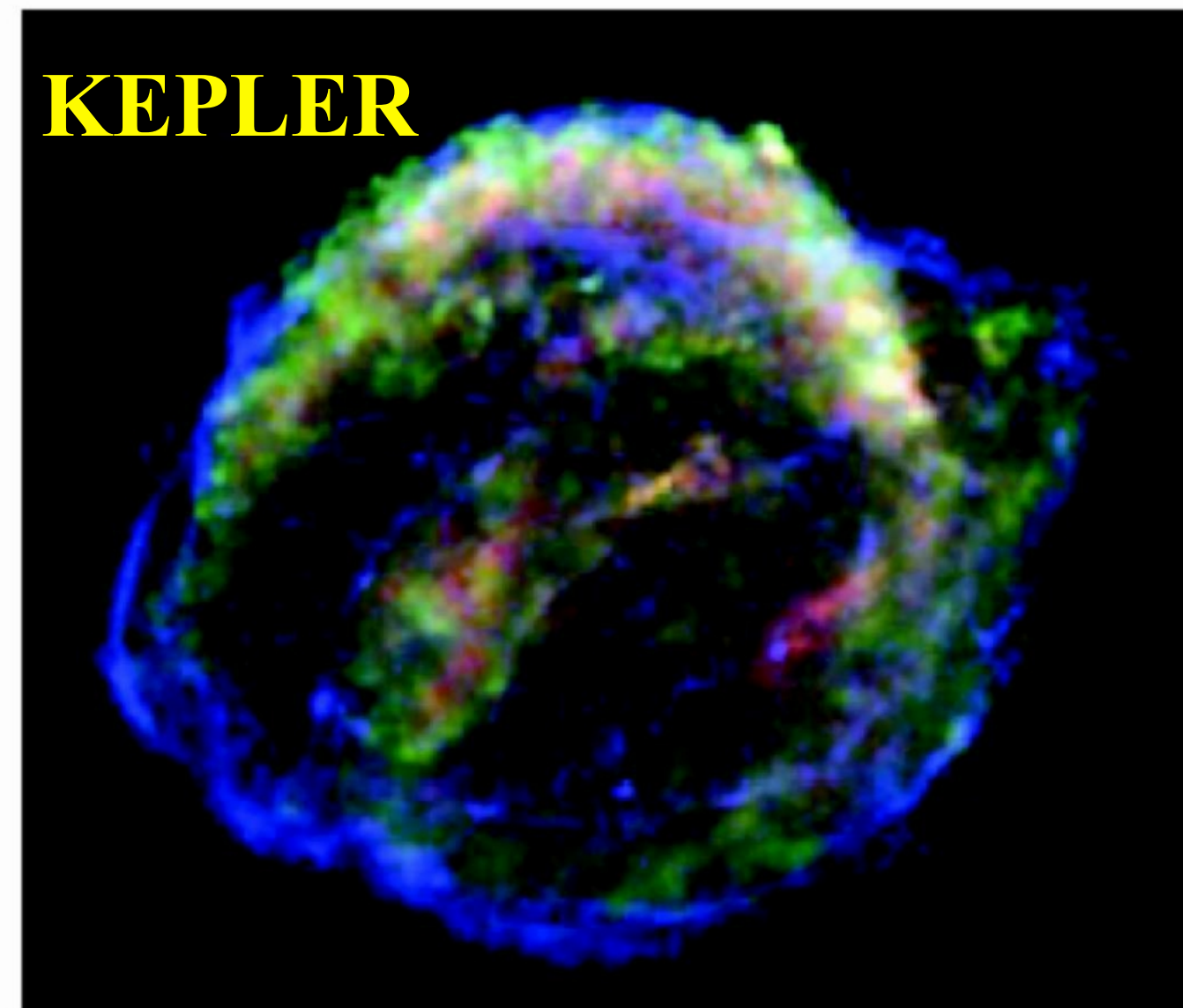
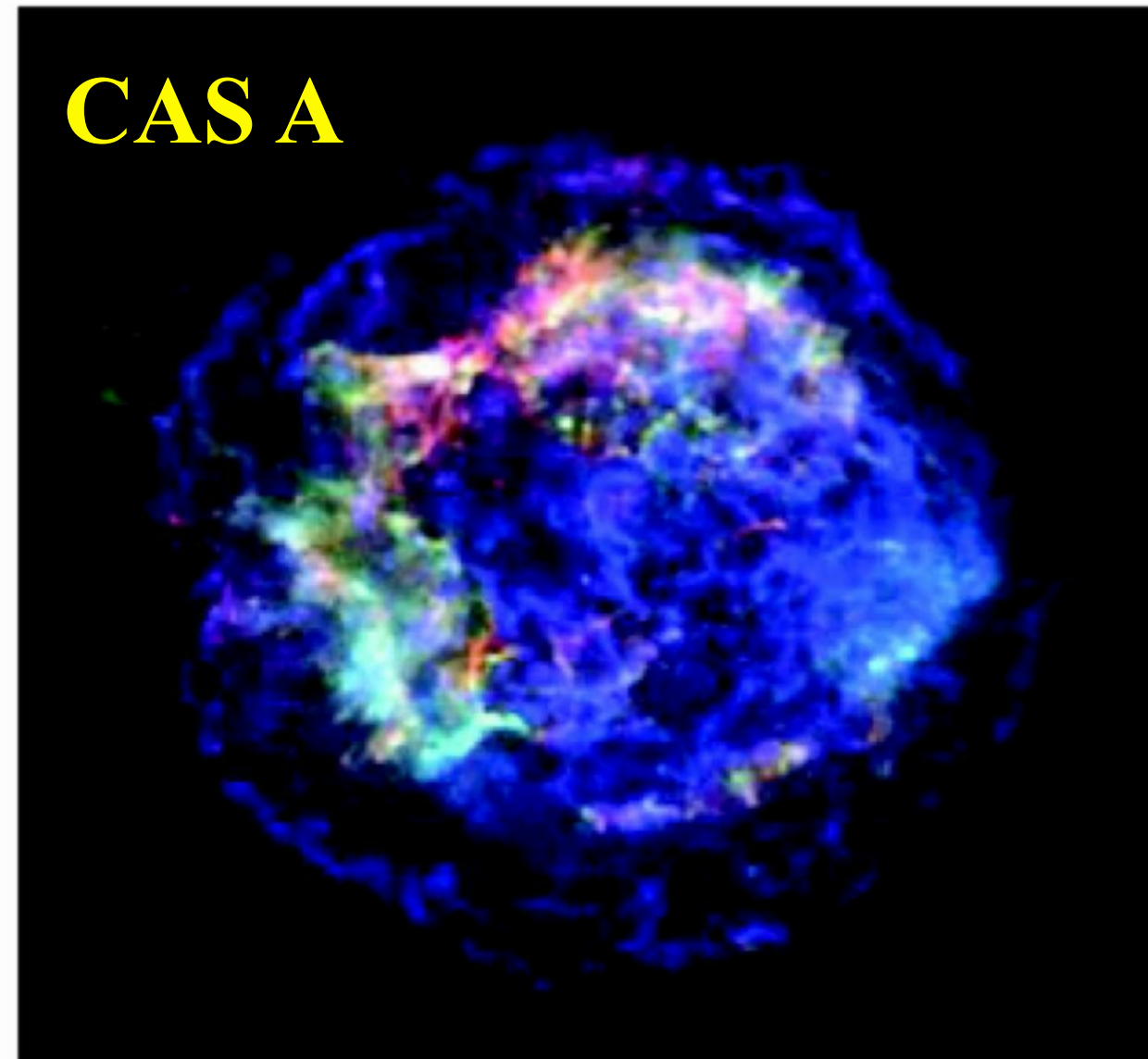
(a) Type I Supernova



(b) Type II Supernova



# SUPERNOVA REMNANT PARADIGM



- 10% EFFICIENCY OF CONVERSION OF SN EXPLOSION ENERGY IN ACCELERATED PARTICLES DOES NOT SEEM MUCH BUT WHAT IS THE MECHANISM?

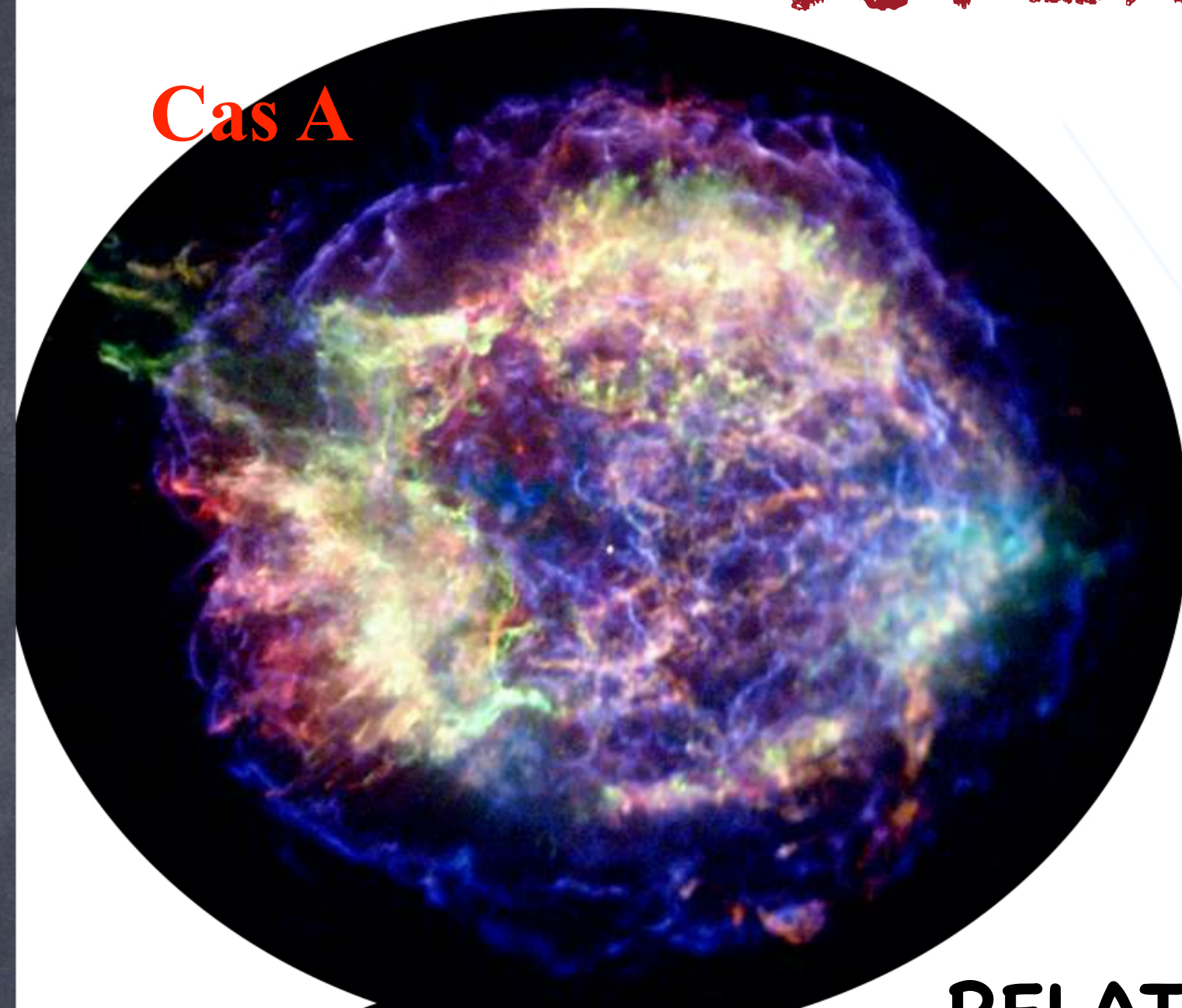
## FREE EXPANSION VELOCITY:

$$V_{ej} = \sqrt{\frac{2E_{SN}}{M_{ej}}} = 10^4 E_{51}^{1/2} M_{ej,\odot}^{-1/2} \text{ km/s}$$

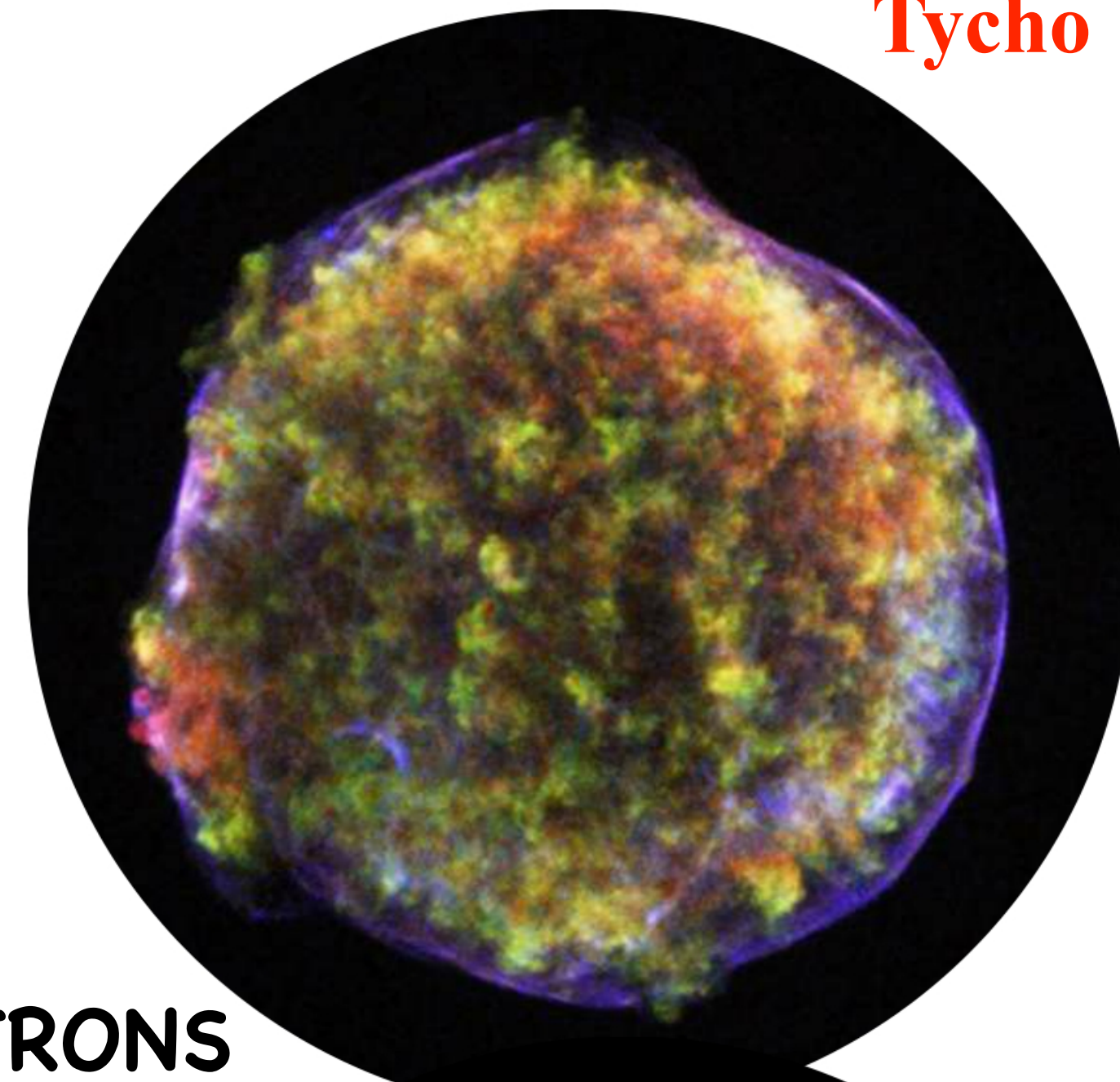
- EXPANSION VELOCITY HIGHLY SUPERSONIC:  
 $v_{ej}/c_s \approx 10^3$
- SUGGESTED MECHANISM: SHOCK ACCELERATION



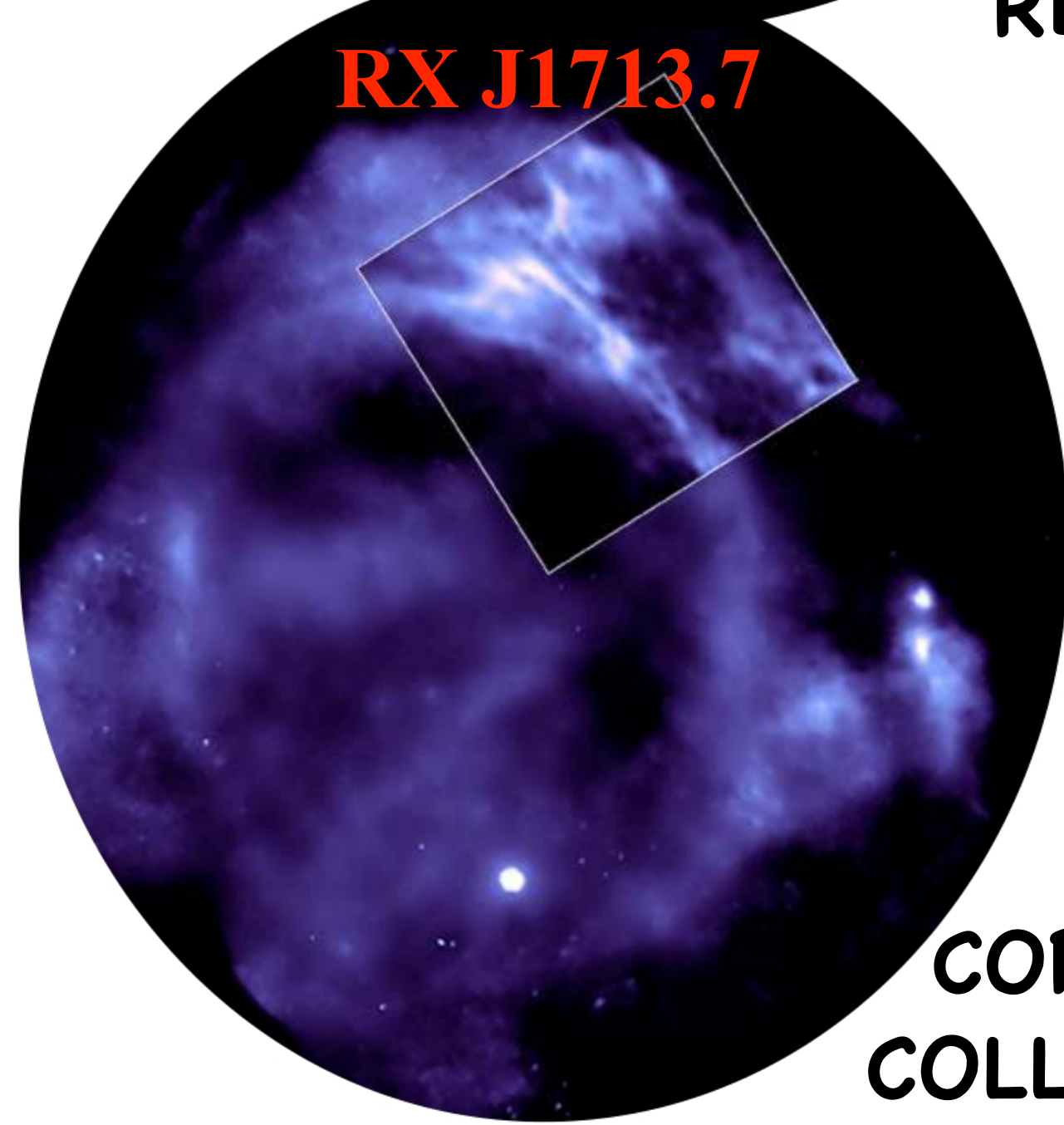
# SUPERNOVA REMNANTS



Cas A

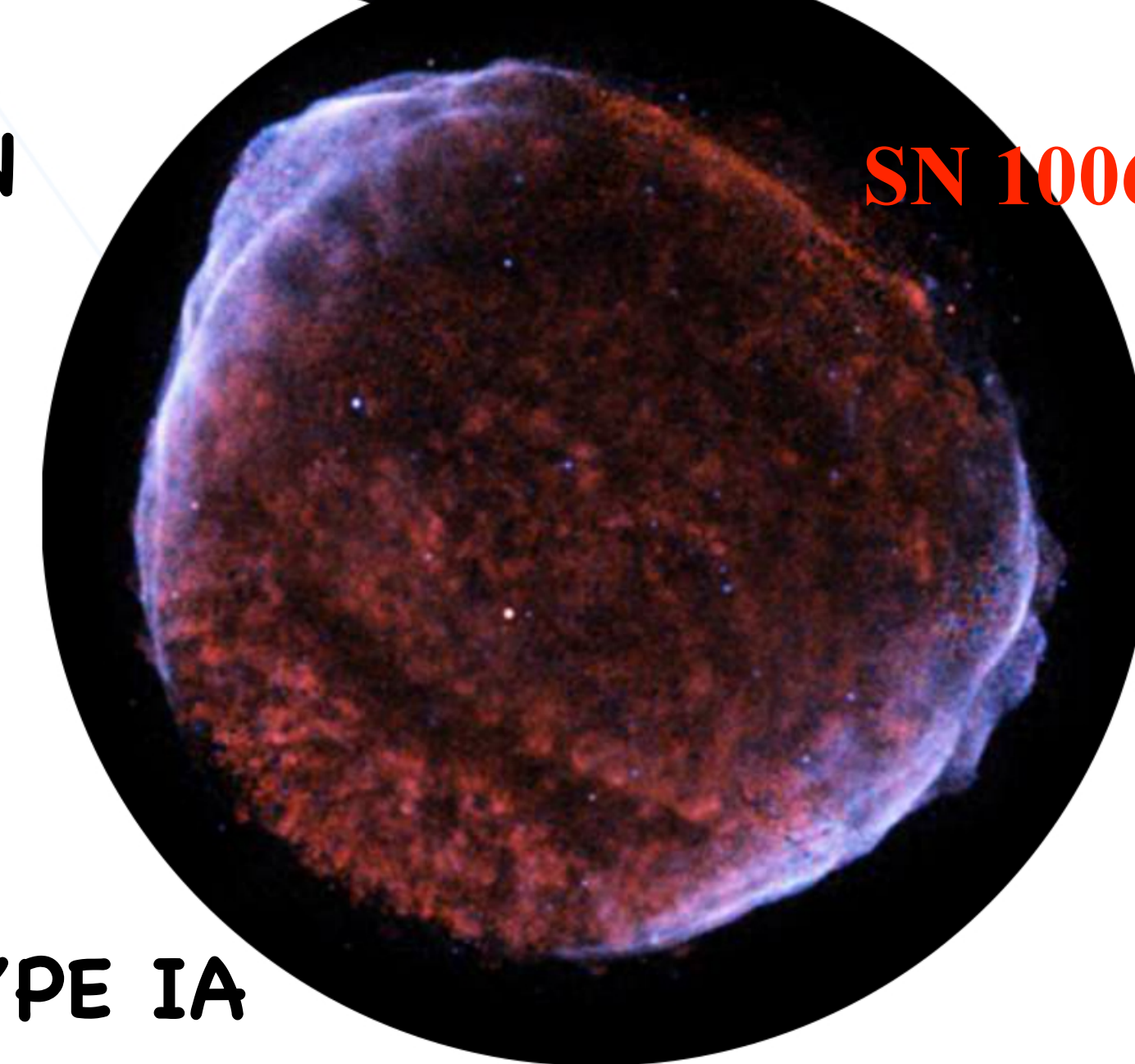


Tycho



RX J1713.7

RELATIVISTIC ELECTRONS  
SEEN THROUGH  
X- RAY EMISSION

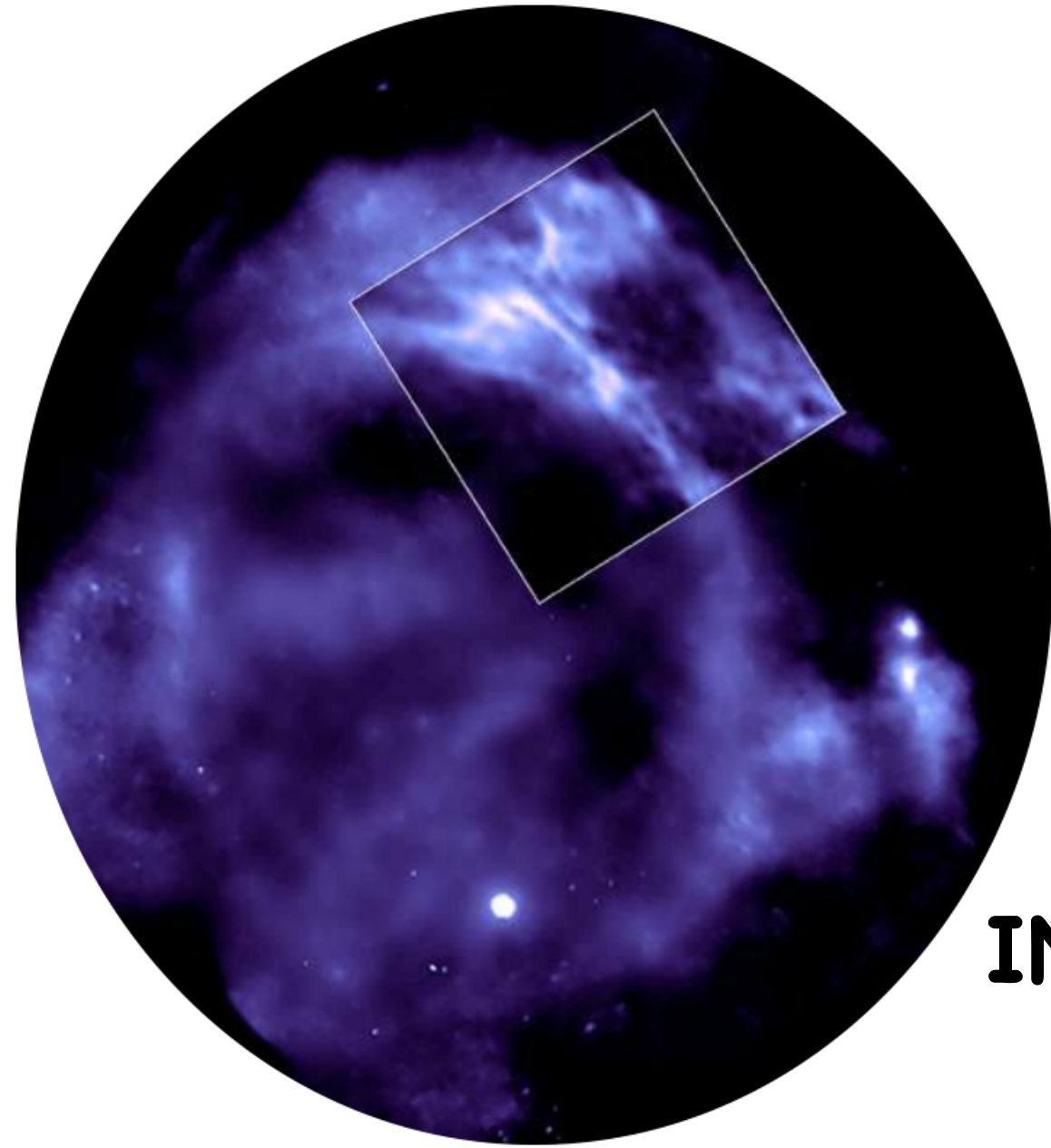


SN 1006

CORE  
COLLAPSE

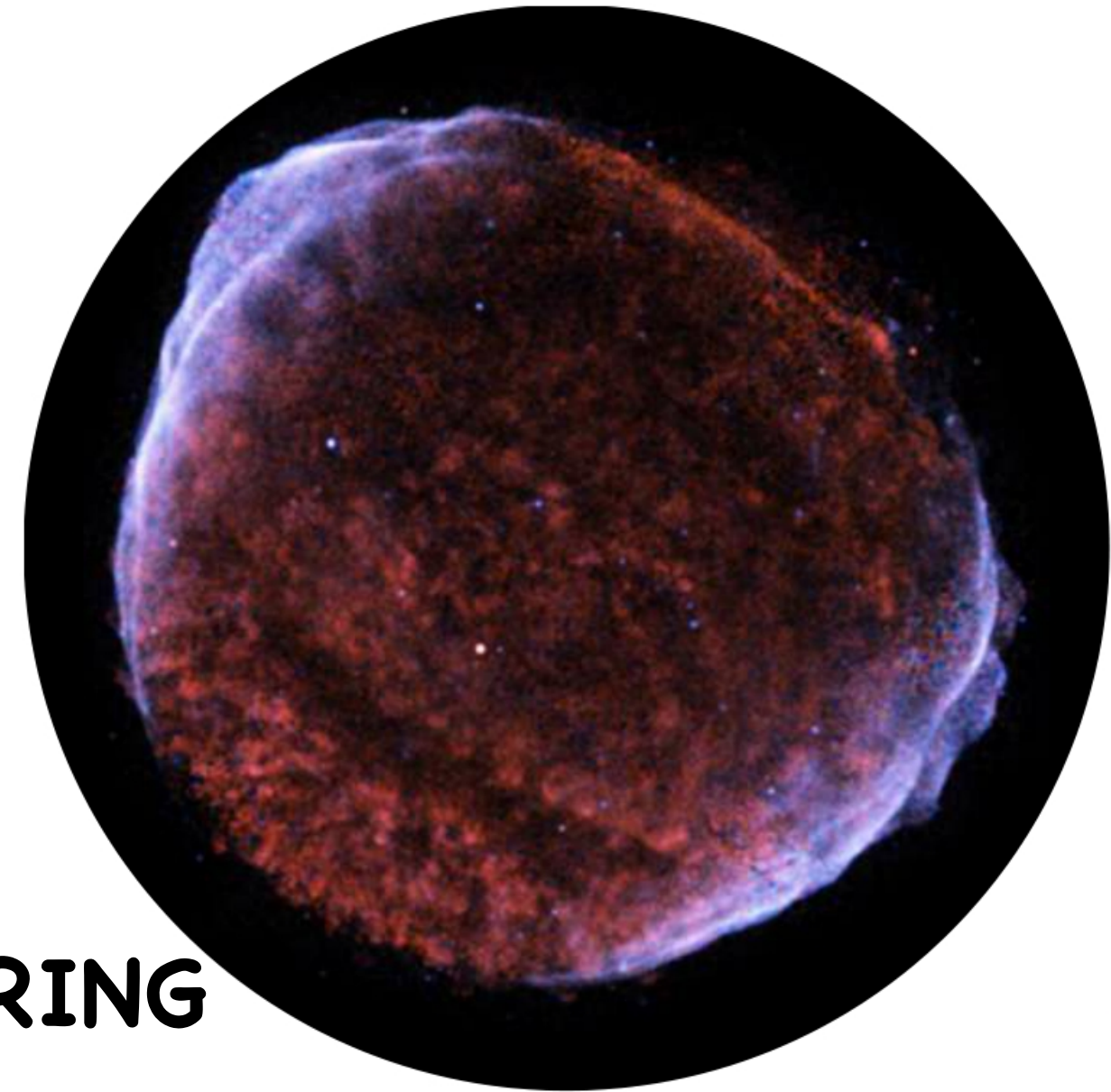
TYPE IA

# RELATIVISTIC PROTONS IN SNRS?



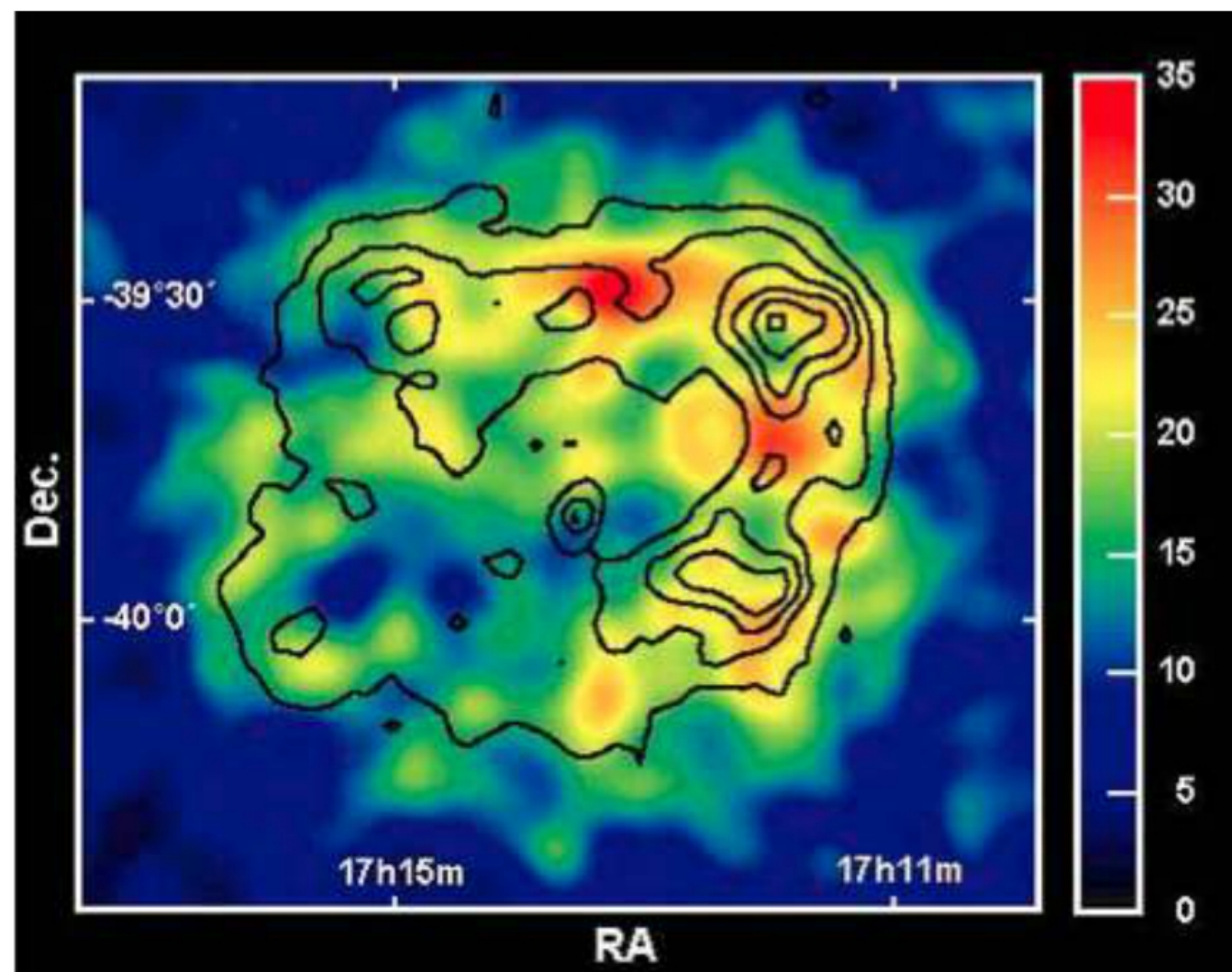
TeV EMISSION DETECTED!

NEUTRAL PION -DECAY  
OR  
INVERSE COMPTON SCATTERING  
OF ELECTRONS?



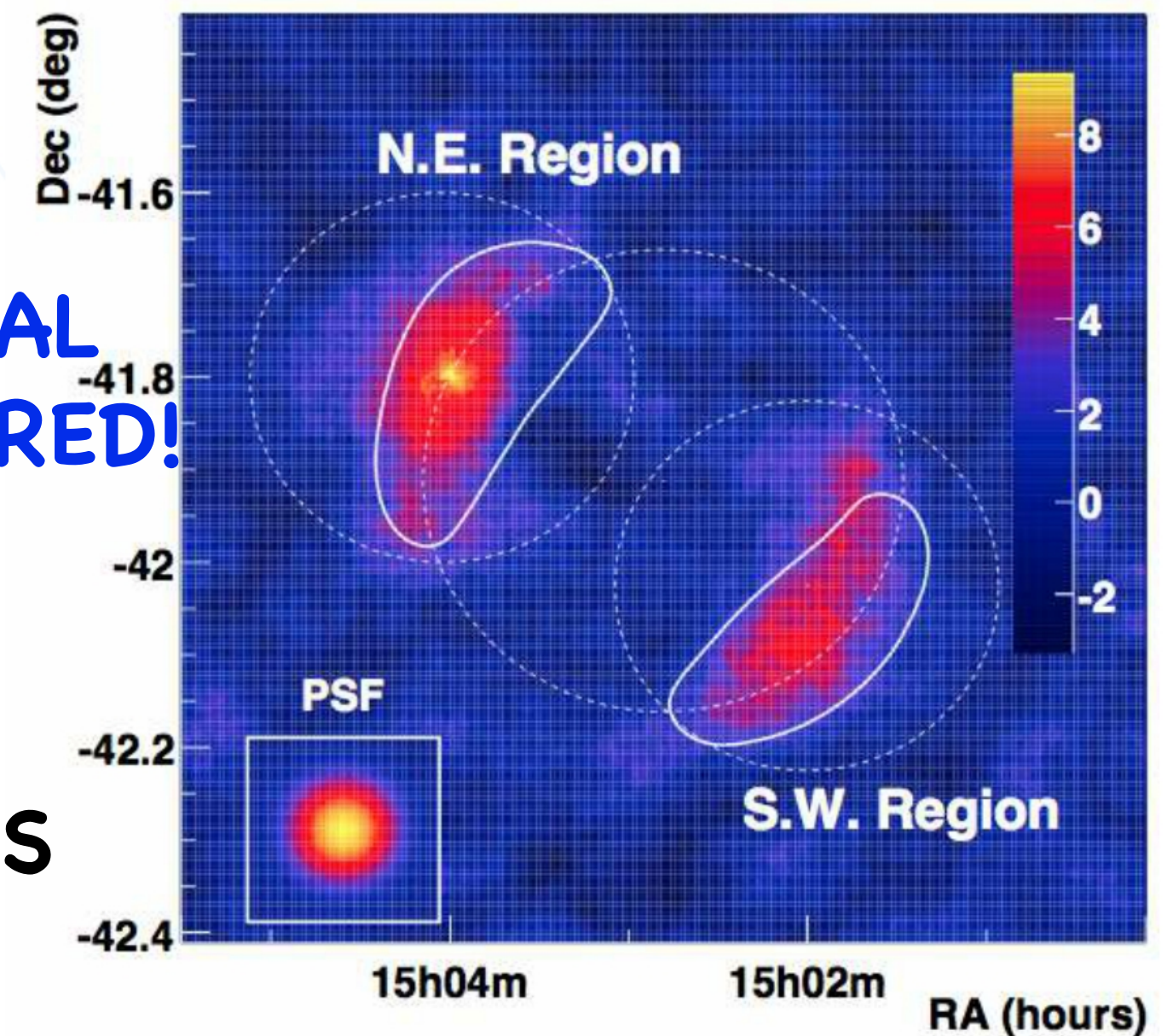
SN 1006

RX J1713.7



DETAILED SPECTRAL  
MODELING REQUIRED!

CONCLUSION  
UNCERTAIN  
IN MOST CASES  
BUT....



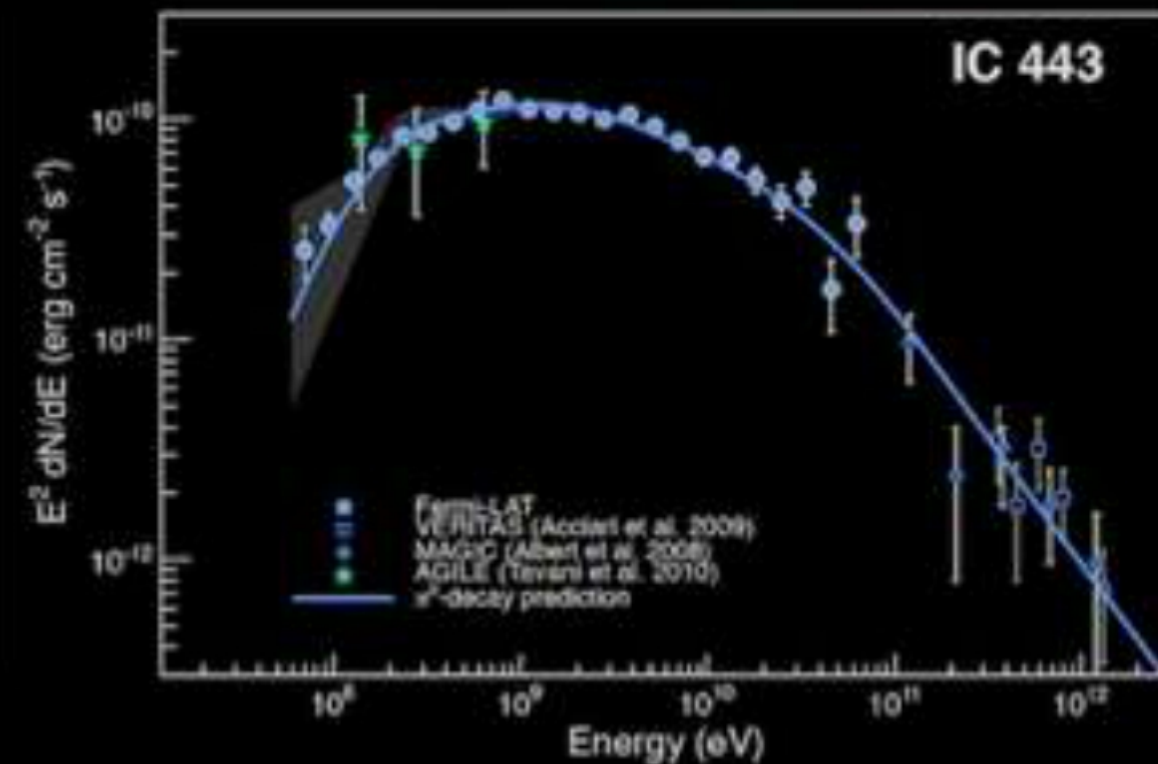
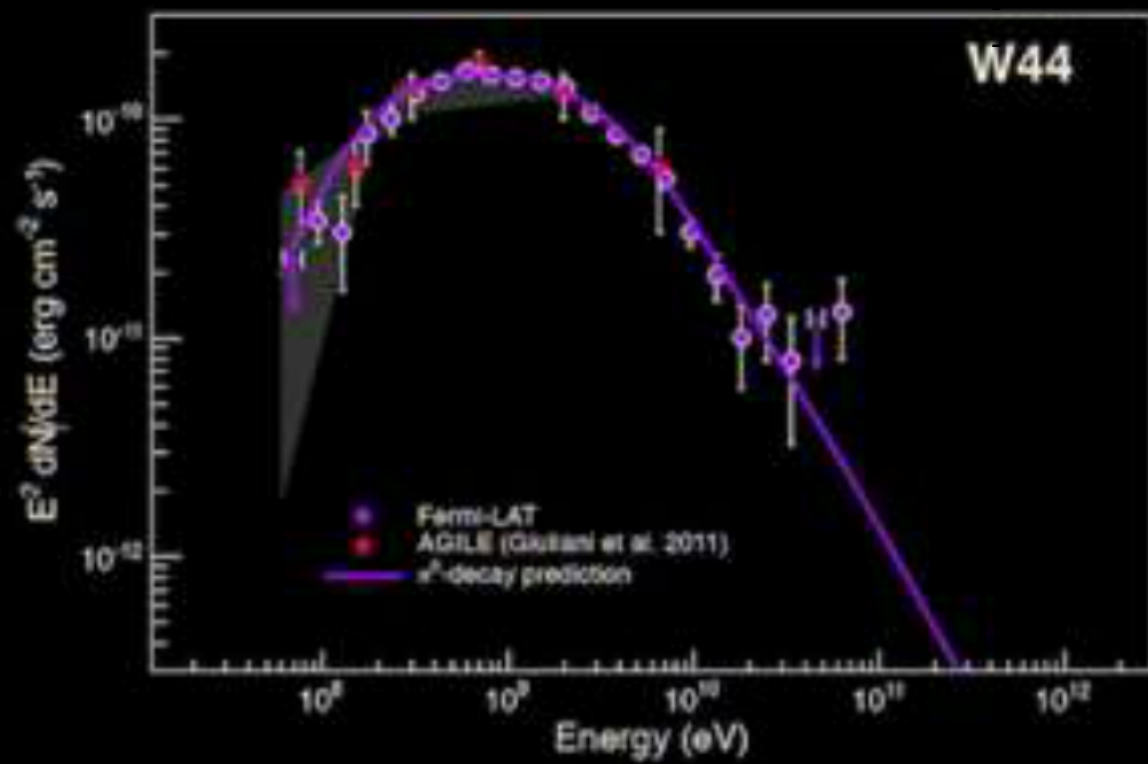
# GAMMA-RAY OBSERVATIONS

Supernova W44 & IC 443 Neutral Pion Decay Spectral Fit

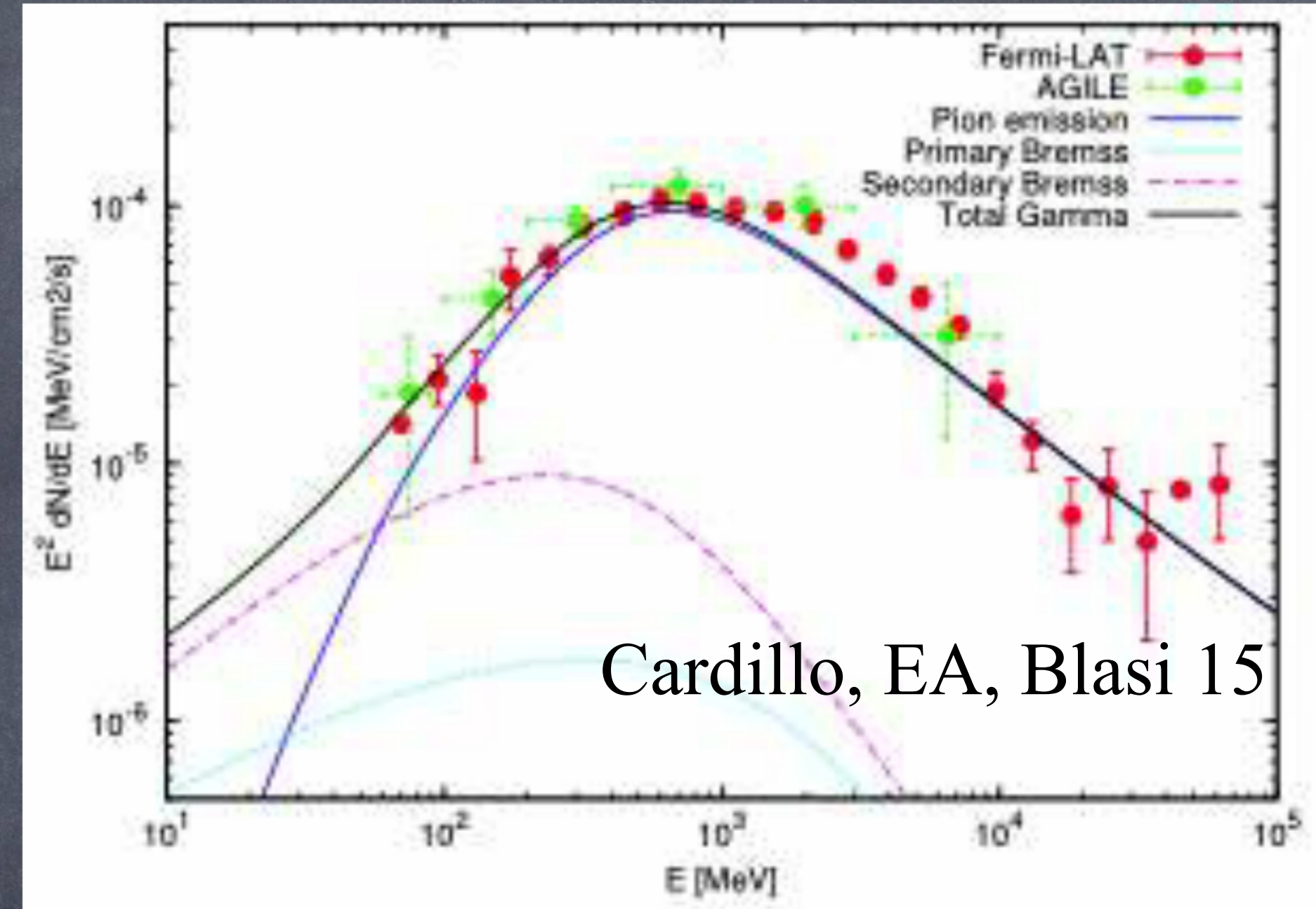
Image data from ESA Herschel and XMM-Newton



Image data Chandra X-ray, DSS Optical and VLA radio



Ackermann+13

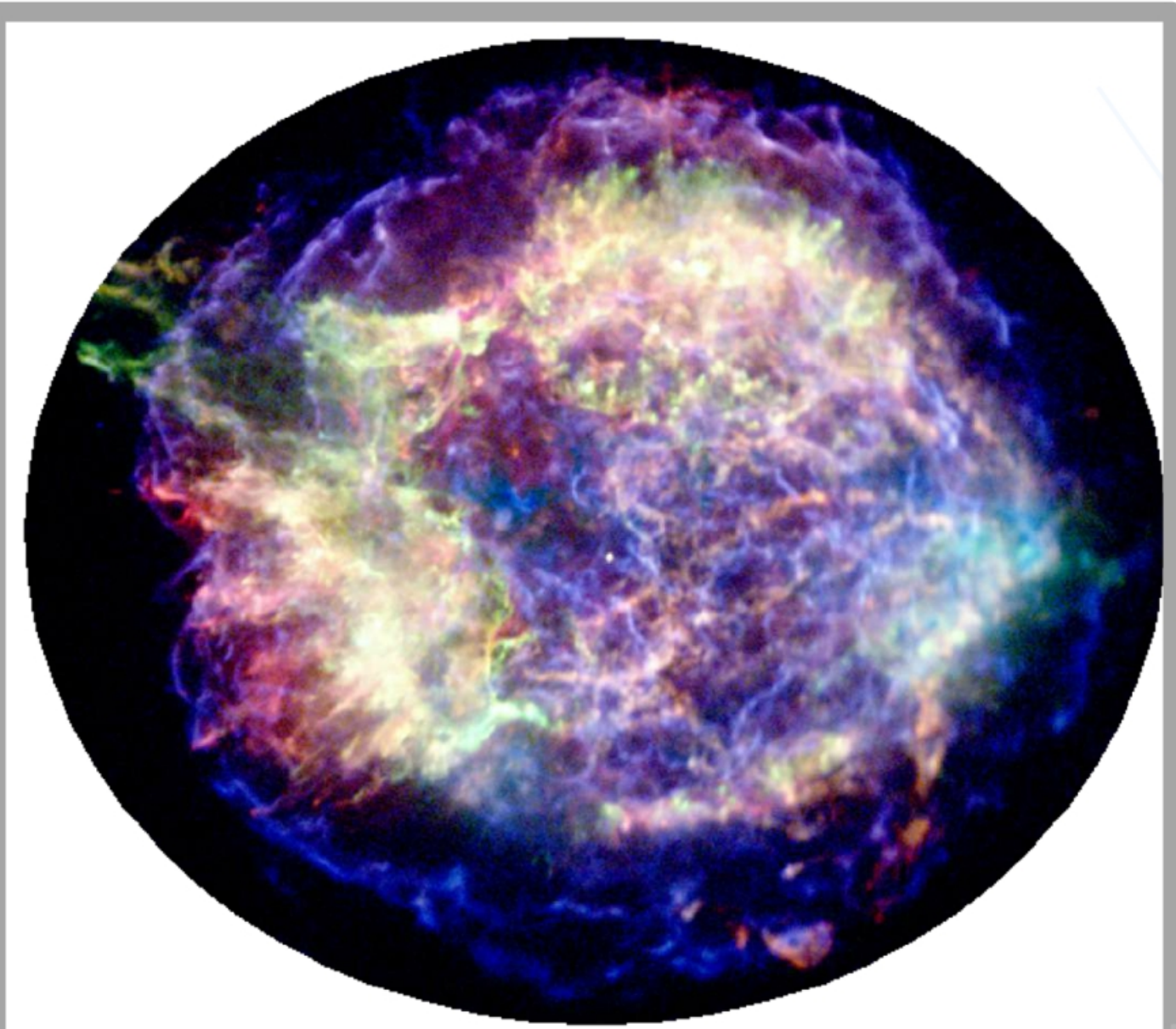


Cardillo, EA, Blasi 15

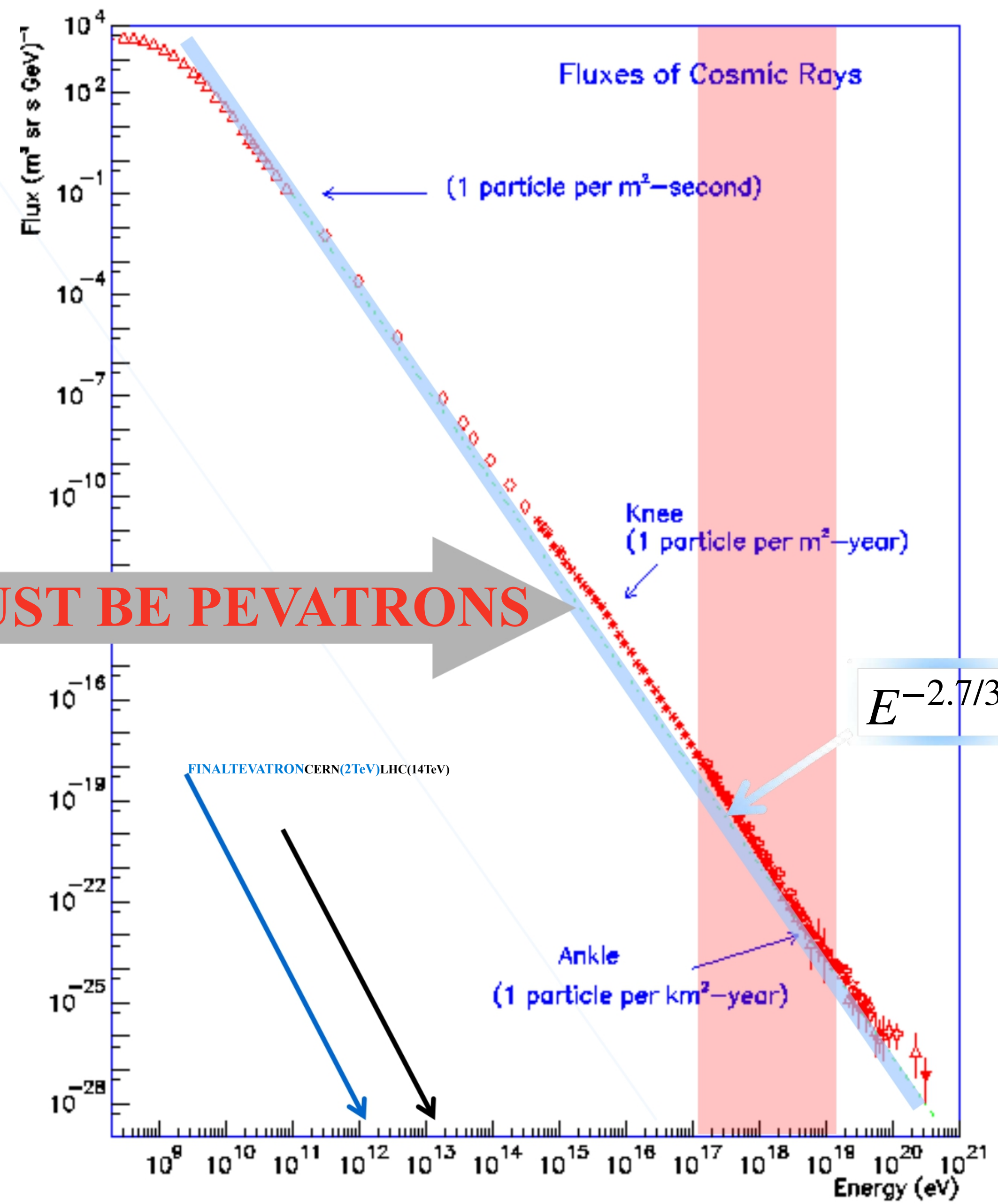
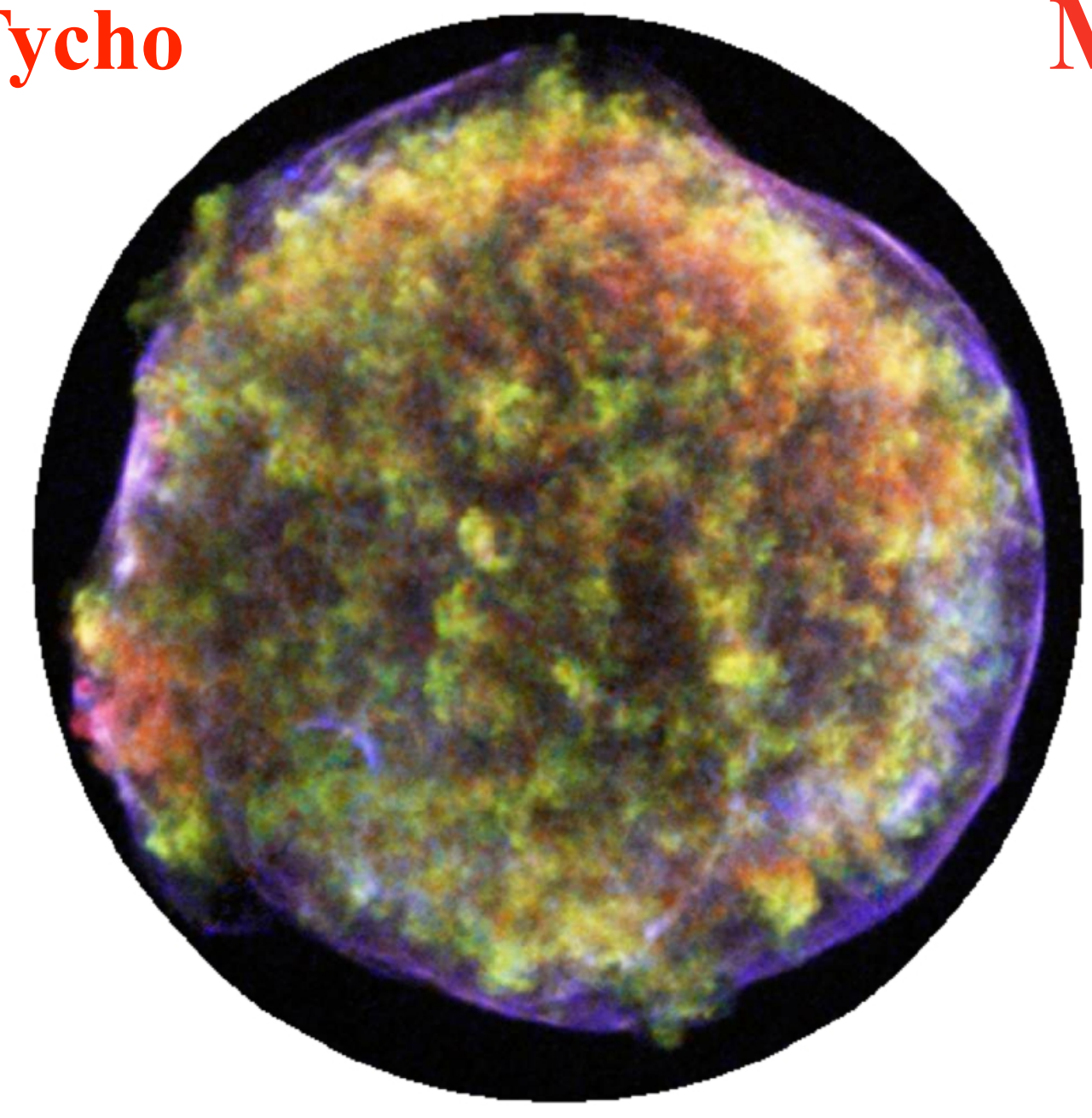
- PION BUMP IN MIDDLE AGED SNRS
- PROTON MAXIMUM ENERGY TENS OF TeV
- MOSTLY REACCELERATION OF AMBIENT CRs AT LEAST FOR W44 (Cardillo, EA, Blasi 16)

# SUPERNOVA REMNANT PARADIGM

Cas A



Tycho

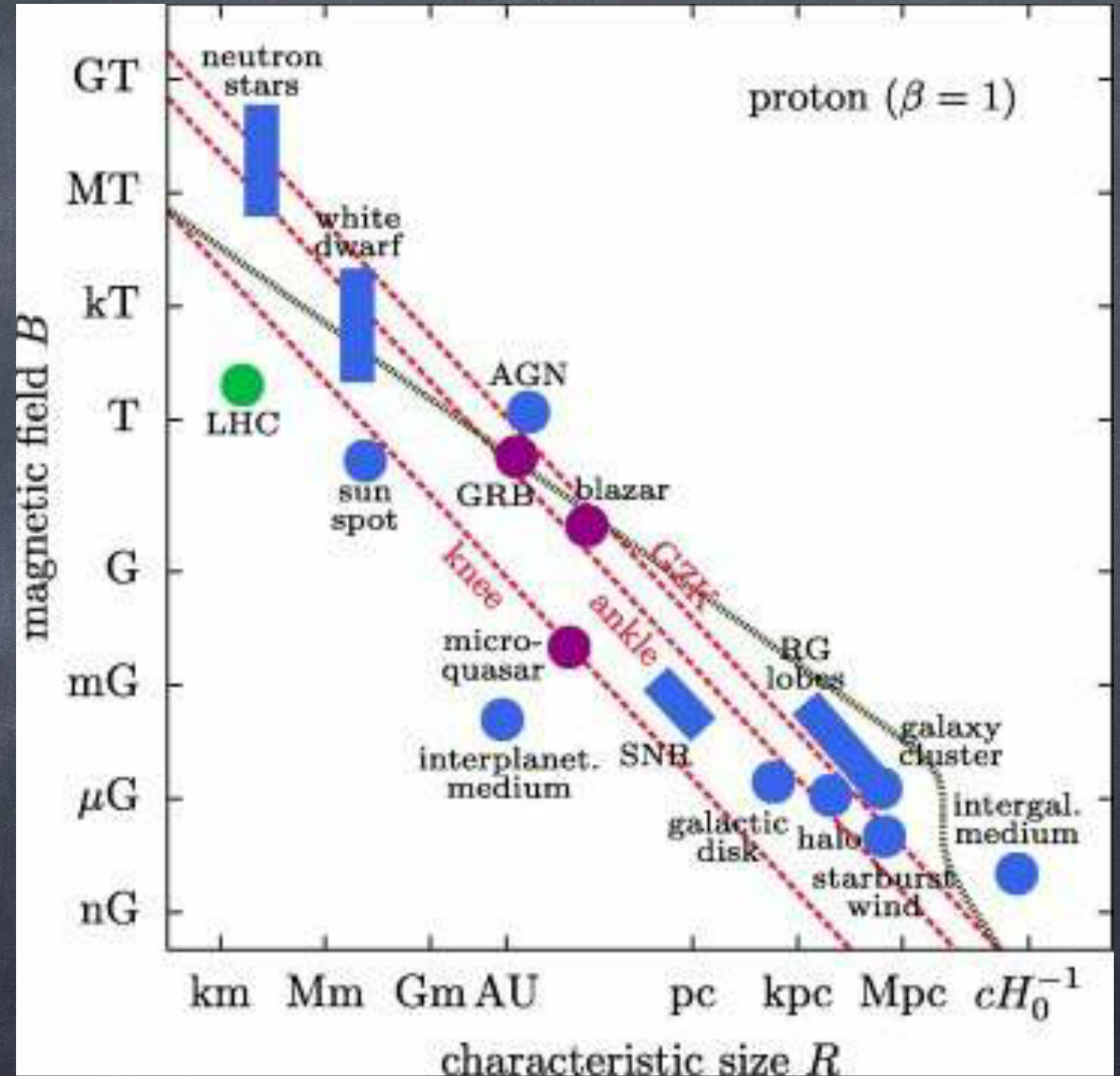


# REACHING THE KNEE

$$r_L < L$$

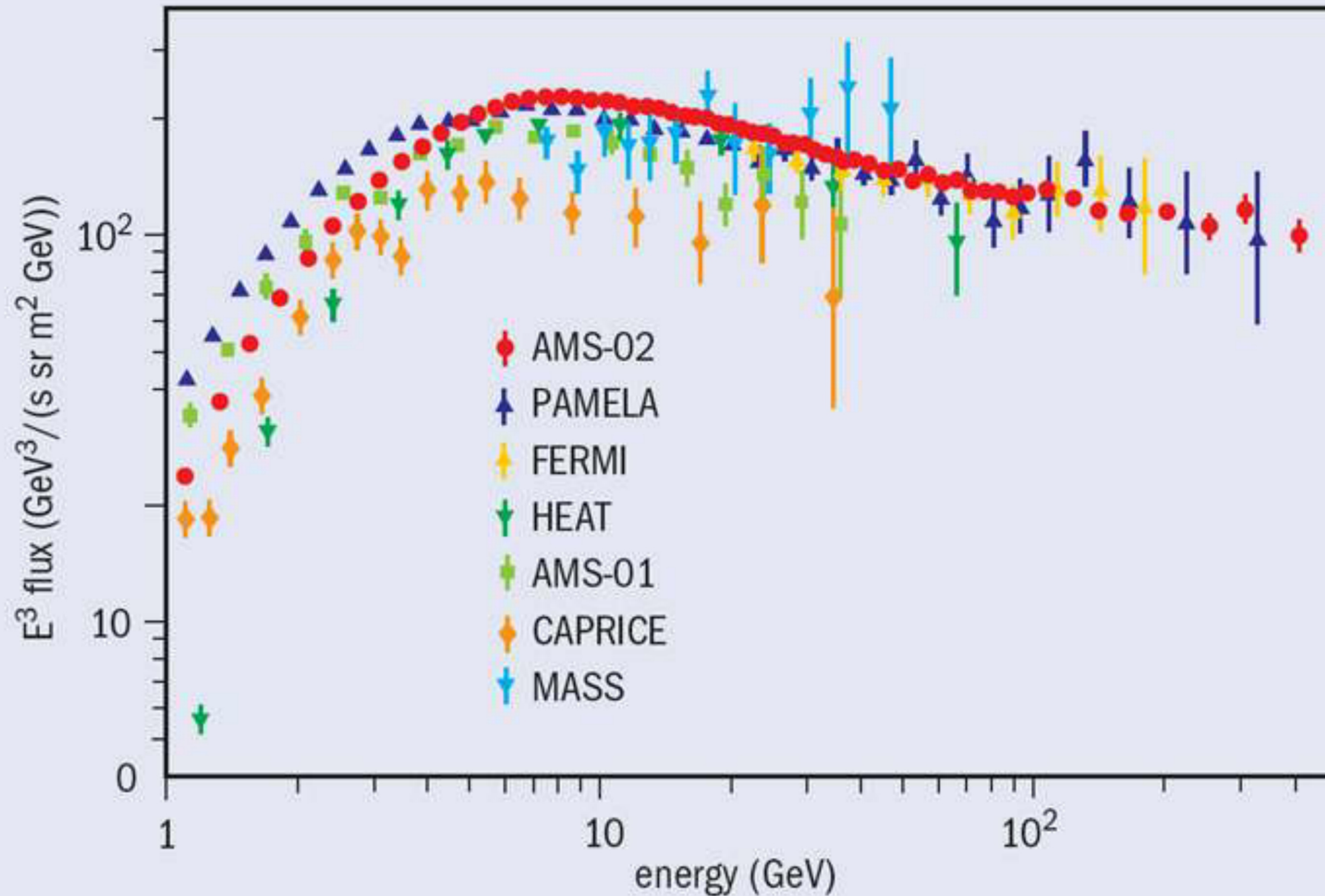


$$E < Z e B L$$



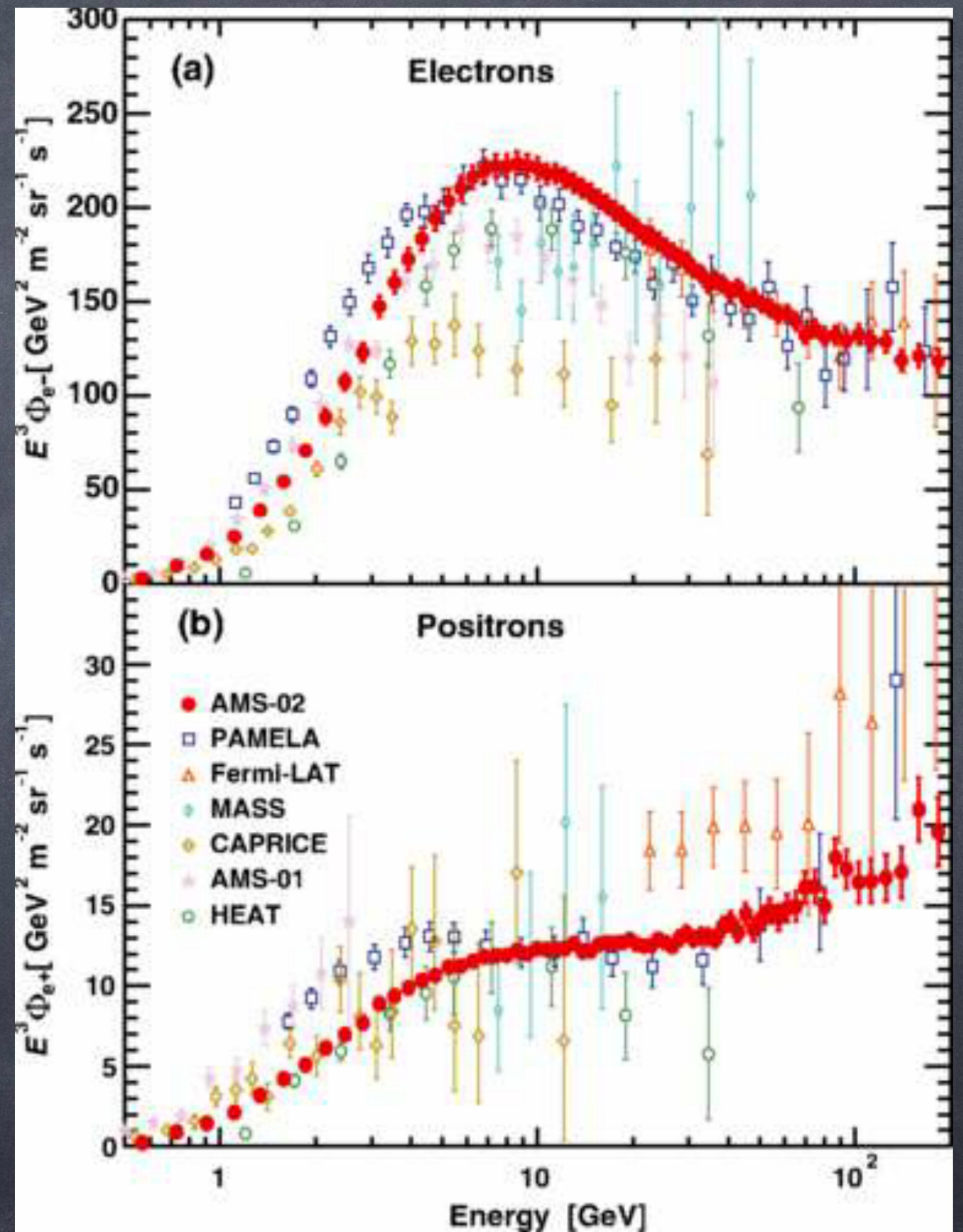
# RECENT MYSTERIES

# COSMIC RAY ELECTRONS

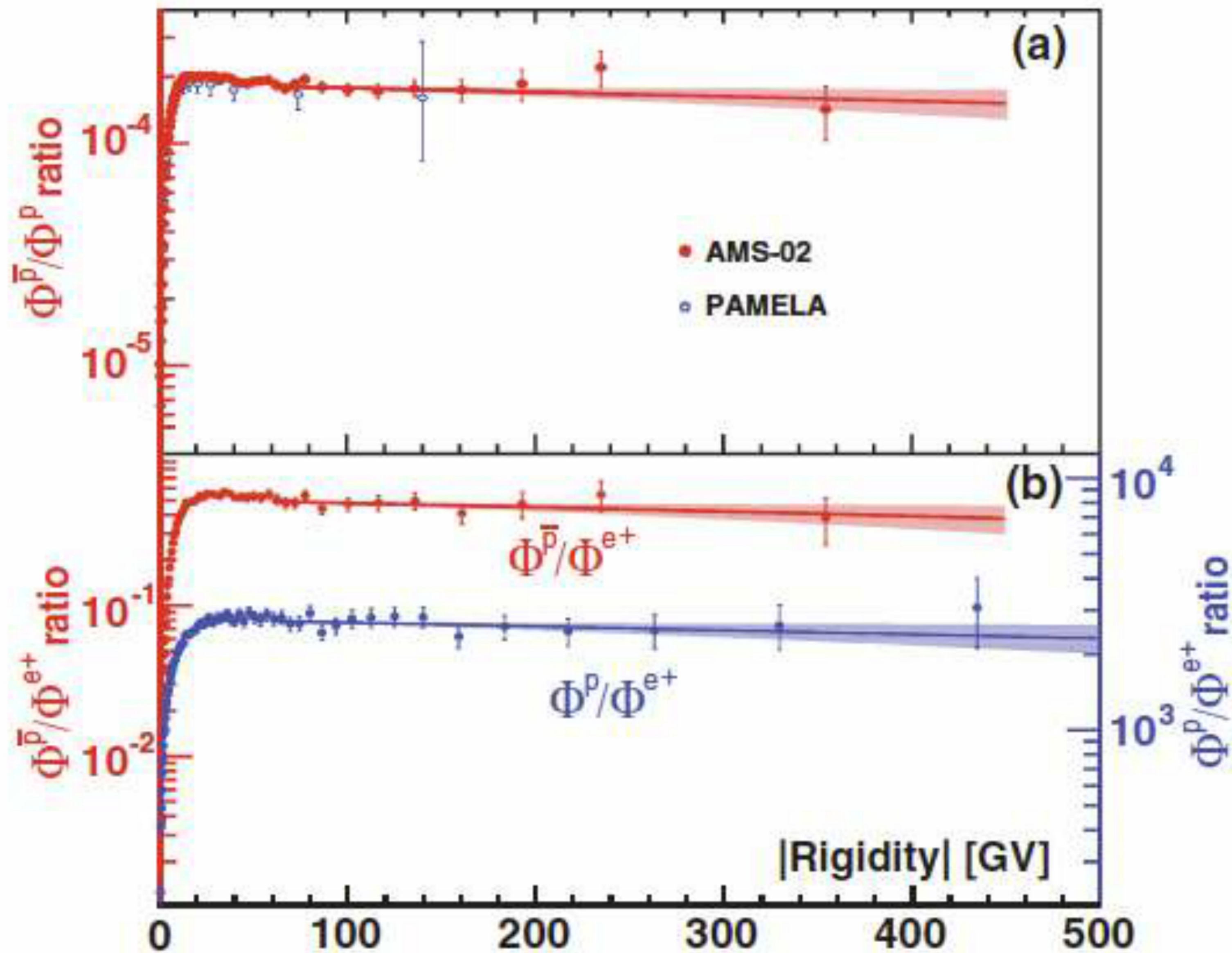


SPECTRUM STEEPENED  
BY LOSSES

# COSMIC RAY POSITRONS AND THEIR RISING FRACTION



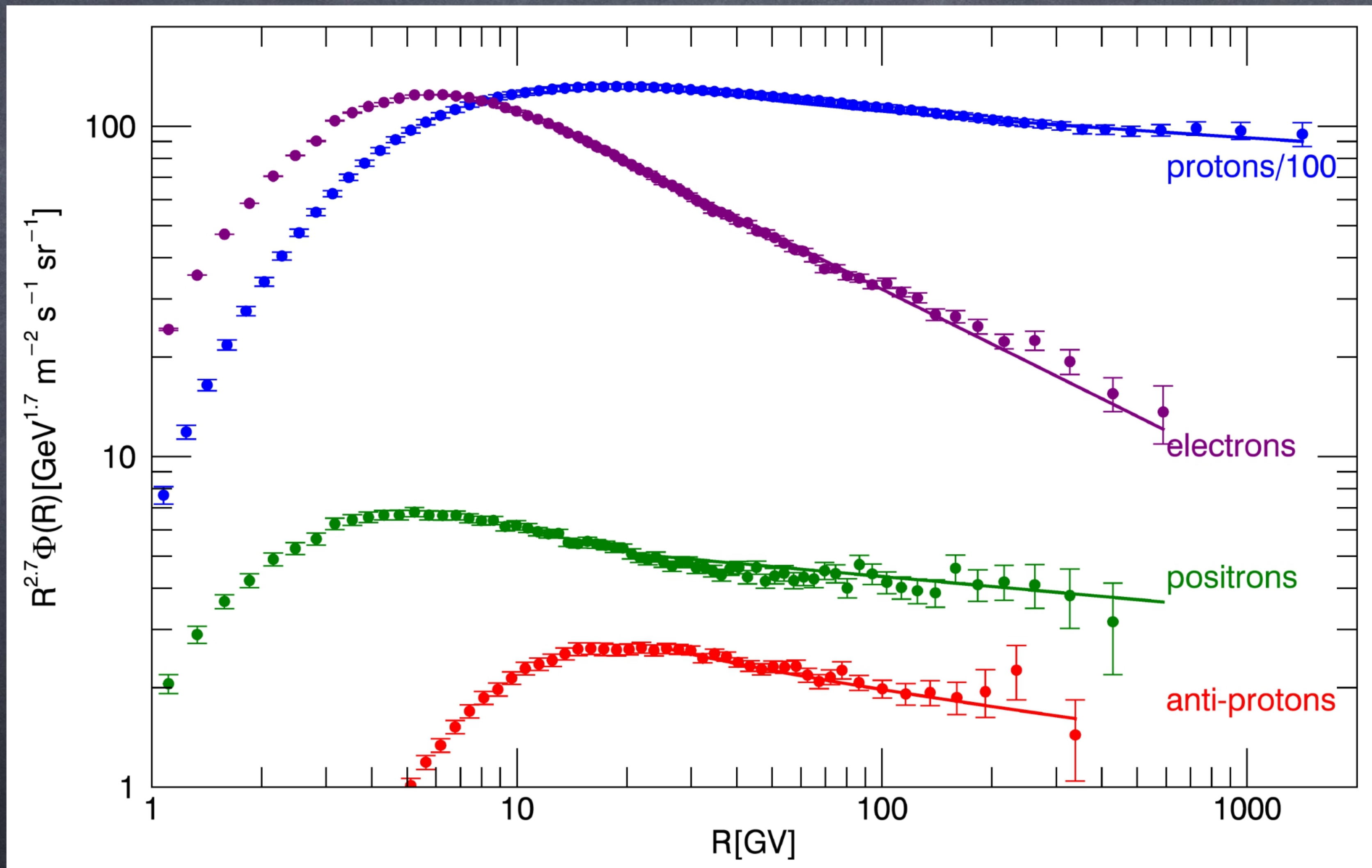
# ANTIPROTONS



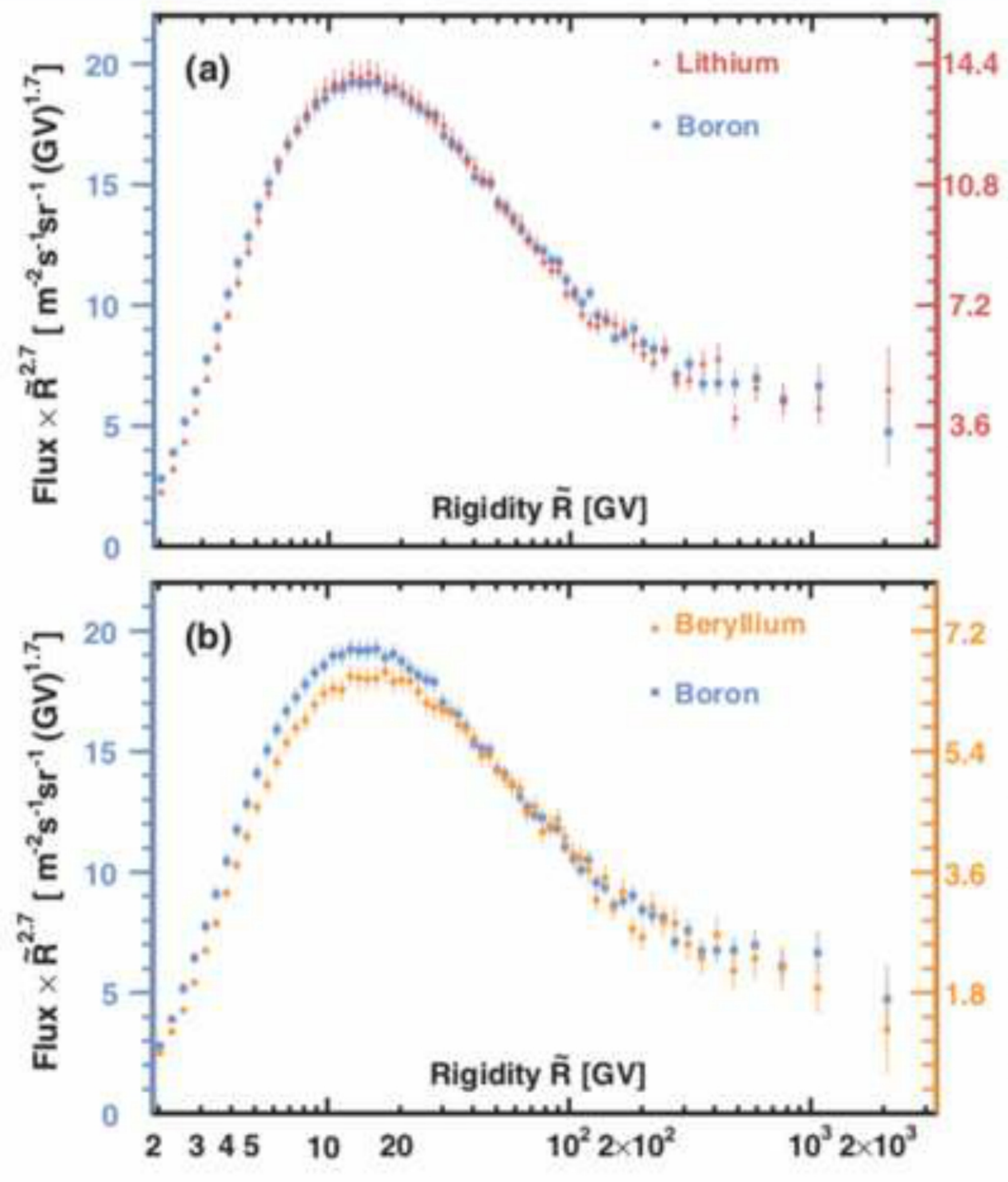
EXPECTED DIFFERENT FROM  
PROTONS  
BECAUSE SECONDARY

EXPECTED DIFFERENT FROM  
POSITRONS BECAUSE OF  
LOSSES

# PROTONS - ELECTRONS - POSITRONS - ANTIPROTONS



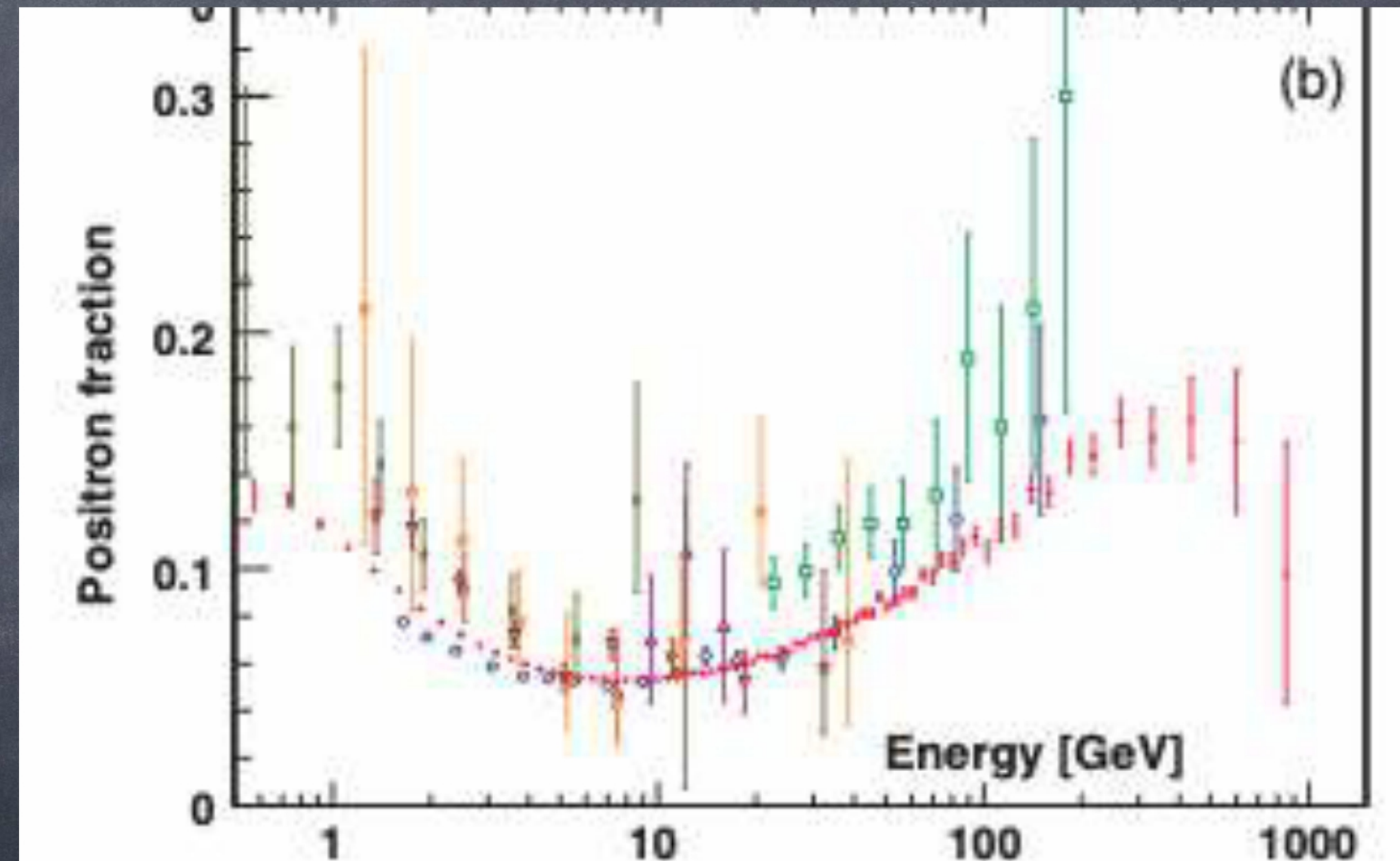
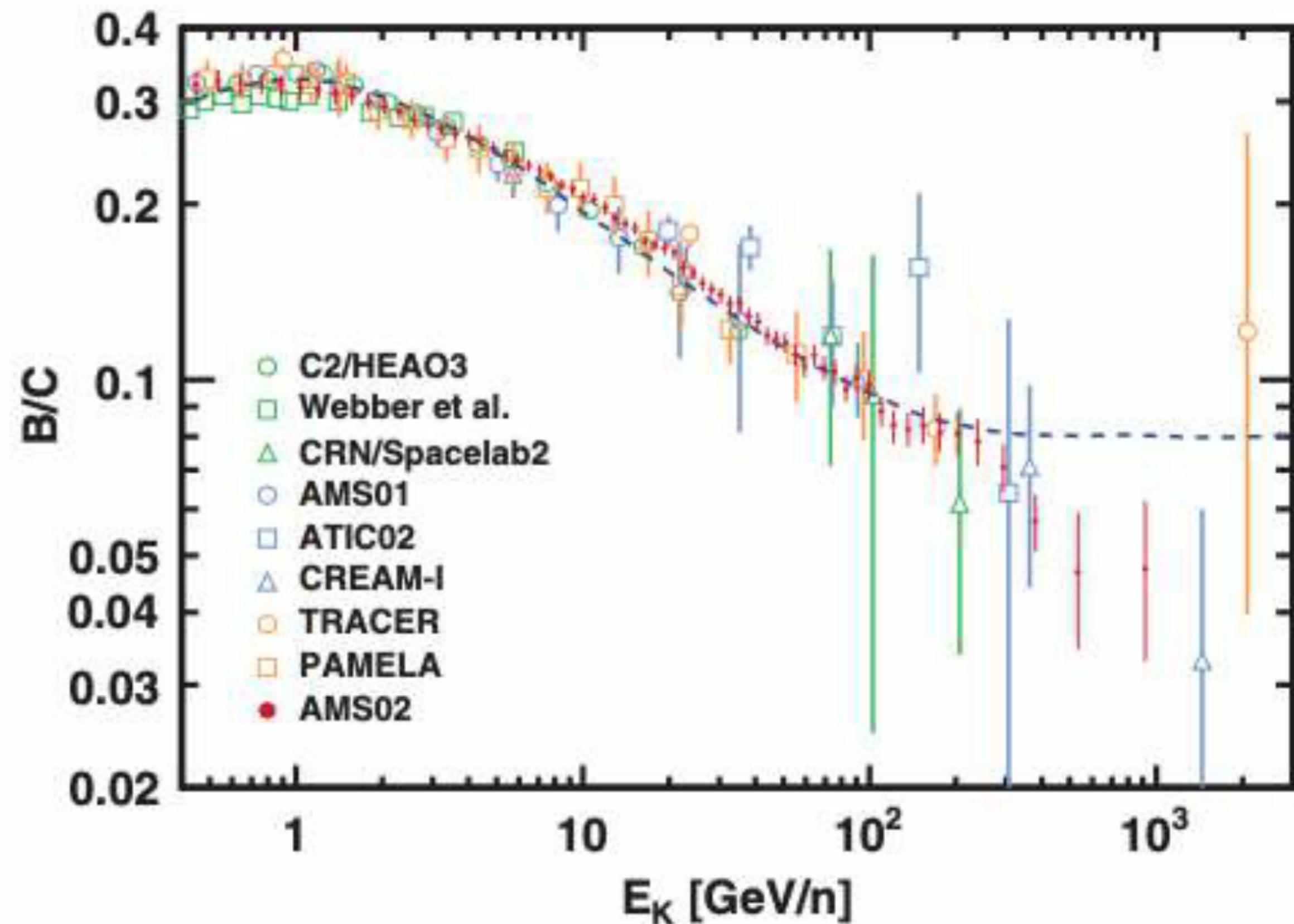
# SECONDARY NUCLEI



AMS02: Aguilar + 2018

IMPORTANT INFO ON PROPAGATION

# SECONDARY PARTICLES AND ANTIPARTICLES



# QUESTIONS

- q **ARE REALLY SNRs THE MAIN SOURCES OF CRs IN THE GALAXY?**
  - **DO THEY PROVIDE THE RIGHT SPECTRUM AND THE RIGHT MAXIMUM ENERGY?**
- q **WHAT MAKES THE HIGHEST ENERGY COSMIC RAYS?**
- q **HOW ARE ALL CRs ACCELERATED?**
- q **MORE FUNDAMENTAL YET: HOW DO CRs INTERACT WITH MATTER?**

# OUTLINE OF THE COURSE

- **PLASMA AND RADIATION PHYSICS TOOLS**
- **HOW CRS INTERACT WITH MATTER**
  - ALFVEN WAVES
  - WAVE-PARTICLE INTERACTION
  - DIFFUSION
- **PARTICLE TRANSPORT**
  - FROM KLIMONTOVICH TO FOKKER-PLANCK AND TRANSPORT EQUATION
- **PARTICLE ACCELERATION AT NEWTONIAN SHOCKS**
  - THE SIMPLE DESCRIPTION
  - MORE REFINED TREATMENT
  - MAXIMUM ENERGY
- **COSMIC RAY PROPAGATION THROUGH THE GALAXY**

END