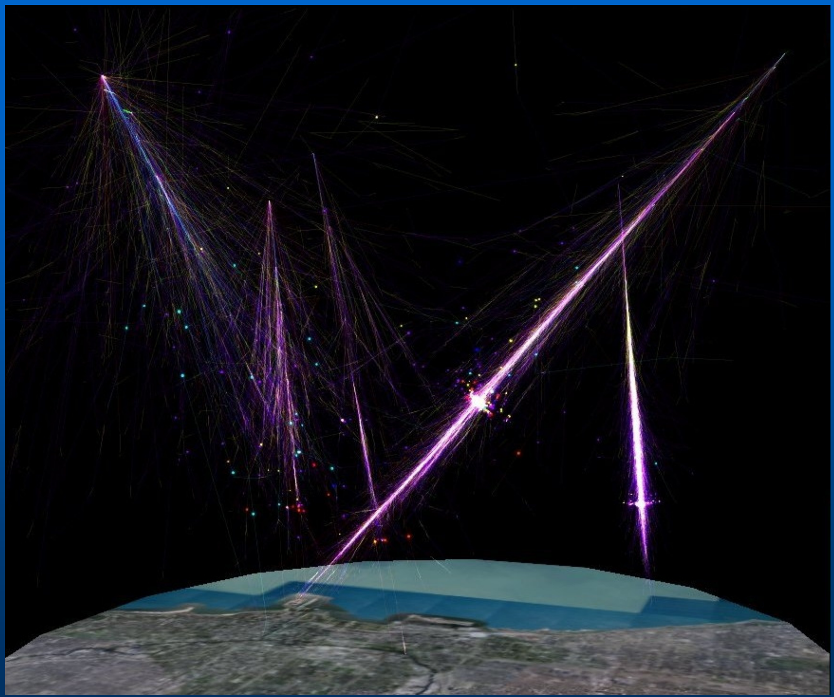
Oleh PETRUK
Institute for Applied Problems in Mechanics and Mathematics
(Lviv, Ukraine)

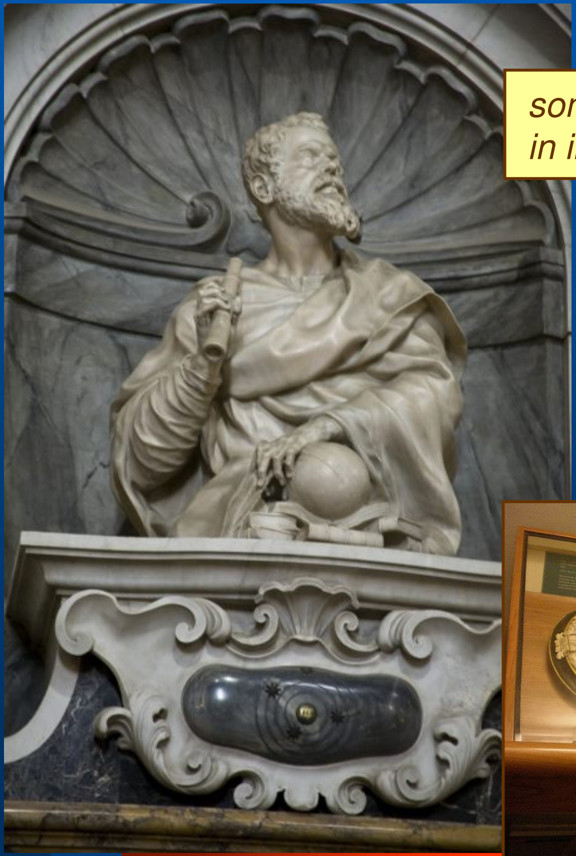
# Cosmic Rays

modern
experimental results
and challenges



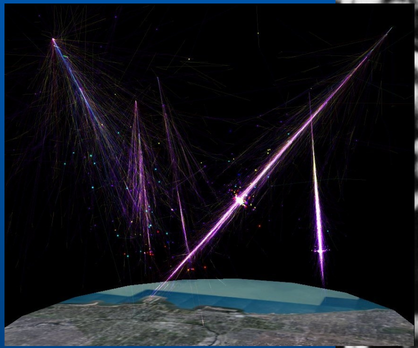
# The two anniversaries

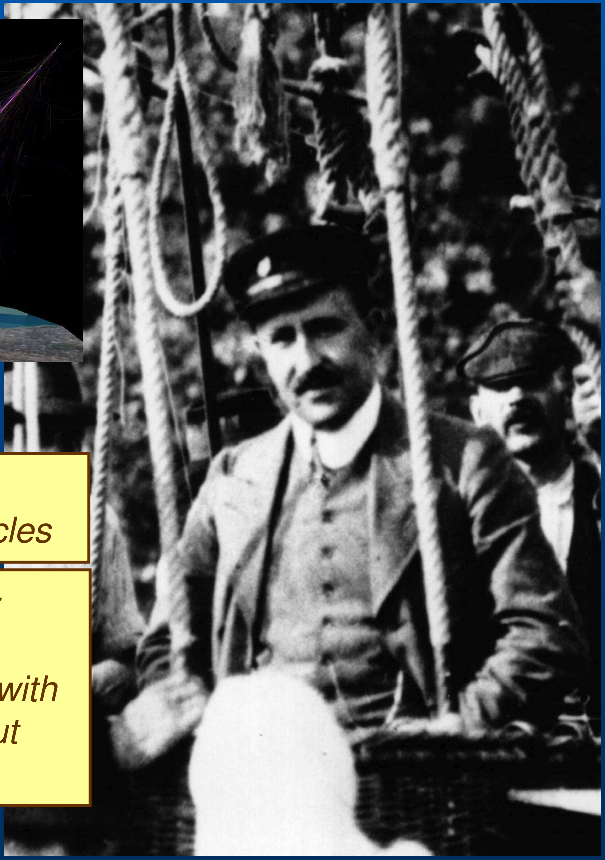
2009 – *400 years of the instrumental astronomy*



*some stuff may help us much in investigation of the Universe*

2012 – *100 years of the discovery of cosmic rays*





*Photon is just one of particles*

*something other than photons may provide us with information about the Universe*

# Astroparticle Physics as scintific field

Macro-world about micro-world

- *Astroparticle Physics studies the properties of particles from their manifestations in the Universe*
- *Until 1960-ths, it provided most of information for particle physics (e.g., discovery of muon, positron)*
- *Once the first accelerators were made, the main goals were shifted to astrophysical aspects (where, how particles are accelerated, what is their role in dynamics of Galaxy and the Universe etc.)*
- *Objects of studies: (charged) cosmic rays, neutrino, dark matter*

# Cosmic rays basics

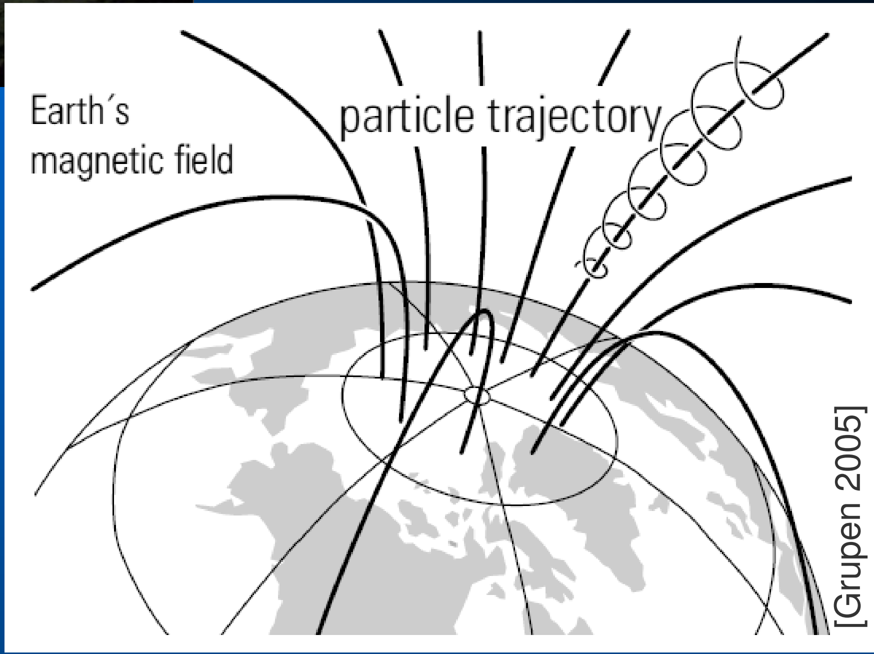
history of discovery

what are they?

where do they come from?

# Aurora

[Wiseman 2014]


[Grupen 2005]

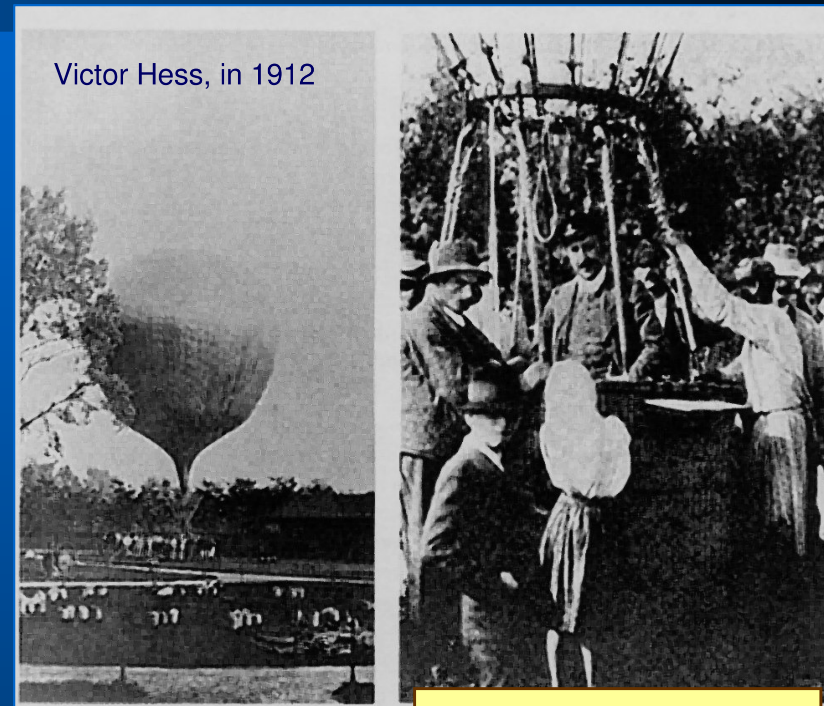
*Luminescent light caused by the particles from the solar wind*

Although the most famous and most common aurora is green, the colour changes depending on which elements are interacted with and where in the atmosphere the interaction occurs.

- Green (most common) - Oxygen, up to 240km
- Blue - Nitrogen, up to 100km
- Red - Oxygen, above 240km
- Purple/Violet - Nitrogen, above 100km

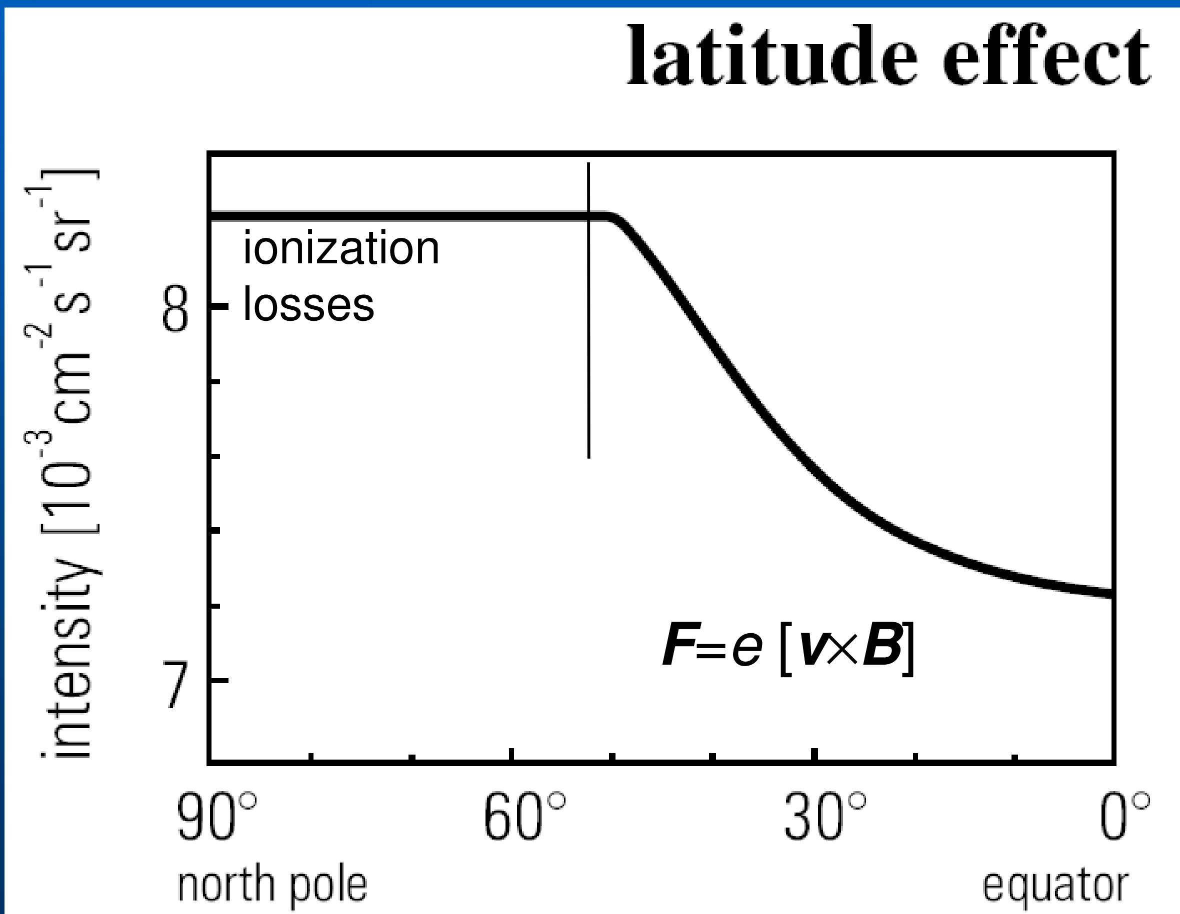
# *Cosmic rays: discovery and milestones*

| | |
|---|---|
| 1733 | 1733 idea: aurora is due to Sun |
| | 1895 discovery of X-rays |
| | 1896 discovery of radioactivity |
| | 1897 discovery of electron |
| 1900 | |
| 1912 | 1912 discovery of Cosmic Rays (Hess) |
| 1927 | 1927 latitute effect (Clay) – CRs are not γ-rays |
| 1934 | 1934 east-west effect – CRs are protons |
| 1938 | 1936 *Nobel prize* to Hess and Anderson ($e^+$) |
| | 1938 CRs hit separated detectors simultaneously (Auger, Maze) |
| 1950 | 1950-ths first detectors of WAS |
| 1963 | 1963 first Cherenkov telescope |
| 1990 | 1990-ths HiRes and AGASA experiments |
| 2000 | |
| 2008 | 2008 Experiment Auger confirmed cut off in the CR spectrum |

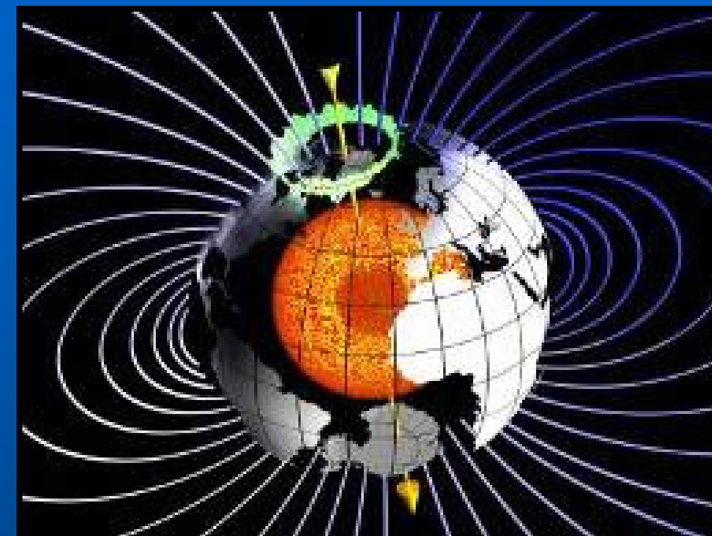


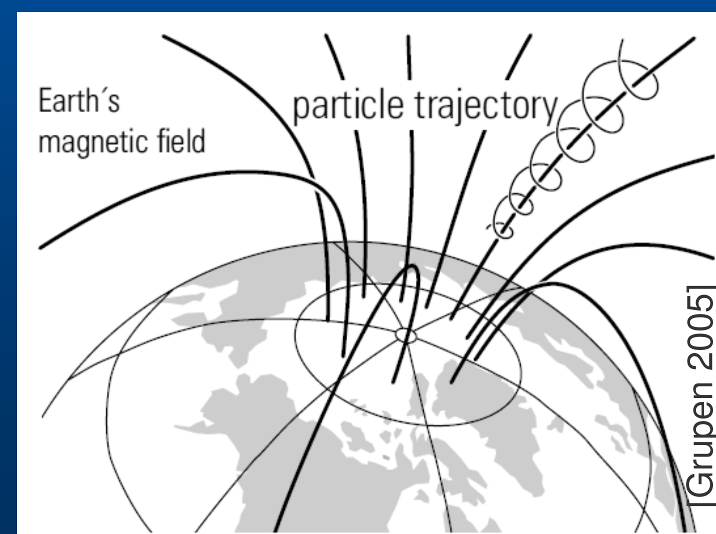

*<u>(7 August 1912)</u> ionization increased on altitude 5 km in 5 times comparing to the sea level*

# *Latitude effect: CRs are charged particles*

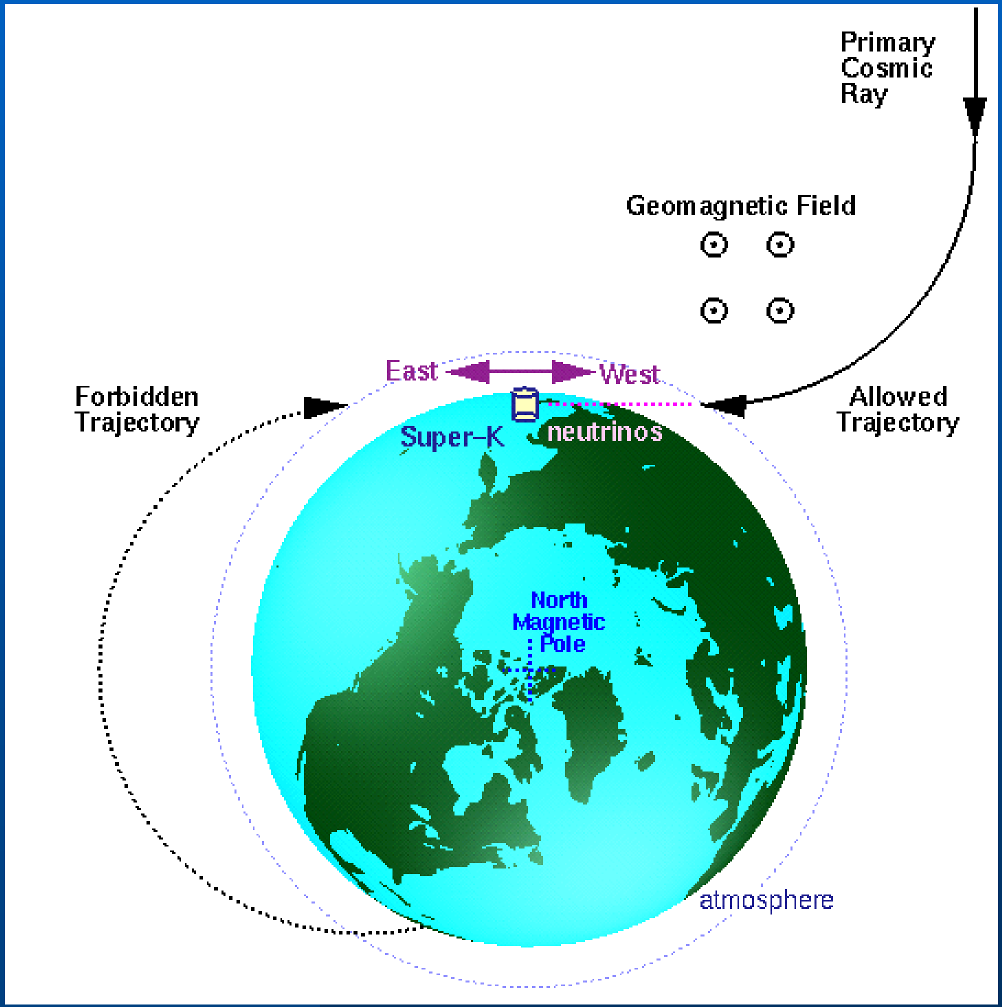



*(1927, J.Clay)*





# *"East-west effect": CRs are mainly protons*

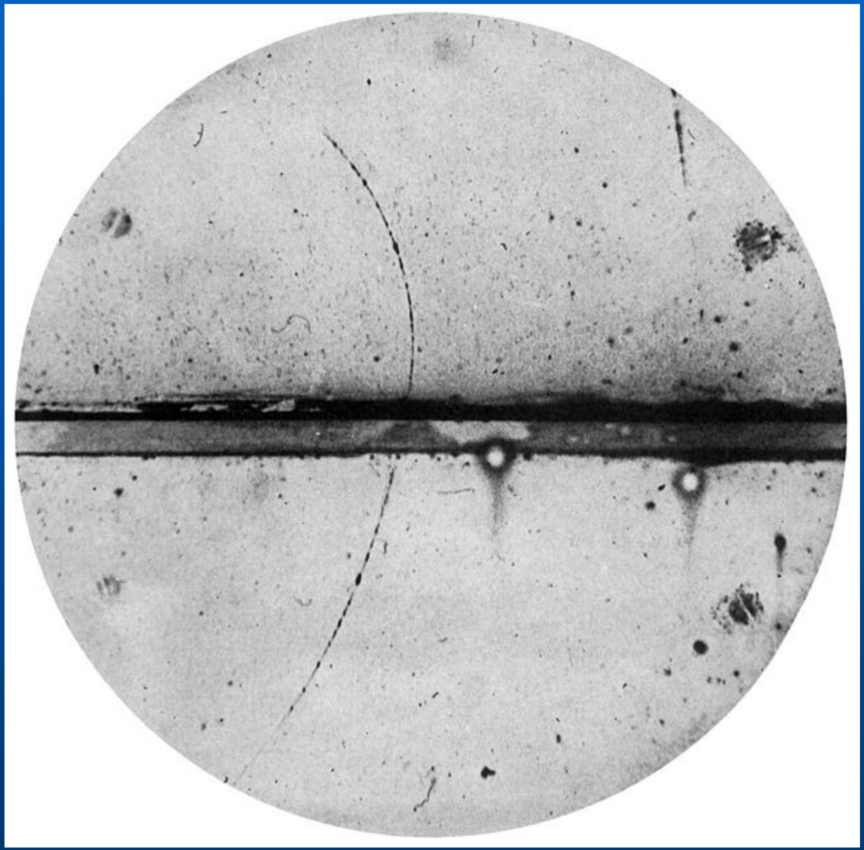



*Earth magnetic field causes dominant flux of CRs from west to east (Lorentz force; left hand)*

*(1934, B.Rossi)*

# Discovery of "positive electron"

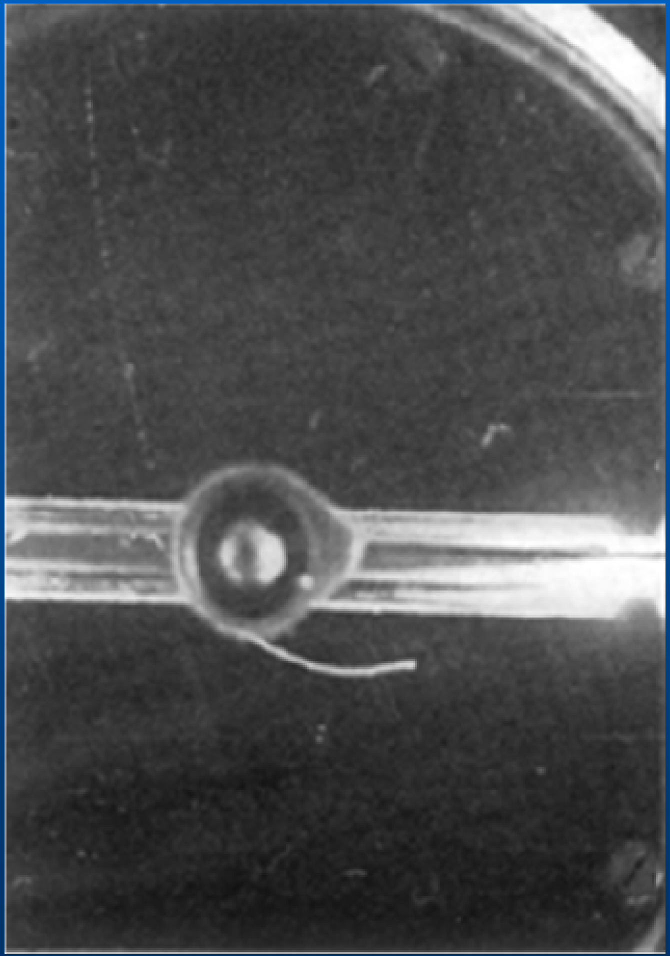
- P.Dirac 1928 – relativistic quantum equation for electron. It allows for the "positive-charged" electron. Unrealistic idea at that time.
- **Positrons were fixed in many photos done by Anderson with Wilson's chamber. However, the first prove of antiparticle was obtained in 1932, August 2.**



*(1932, C.Anderson; Nobel prize in 1936)*

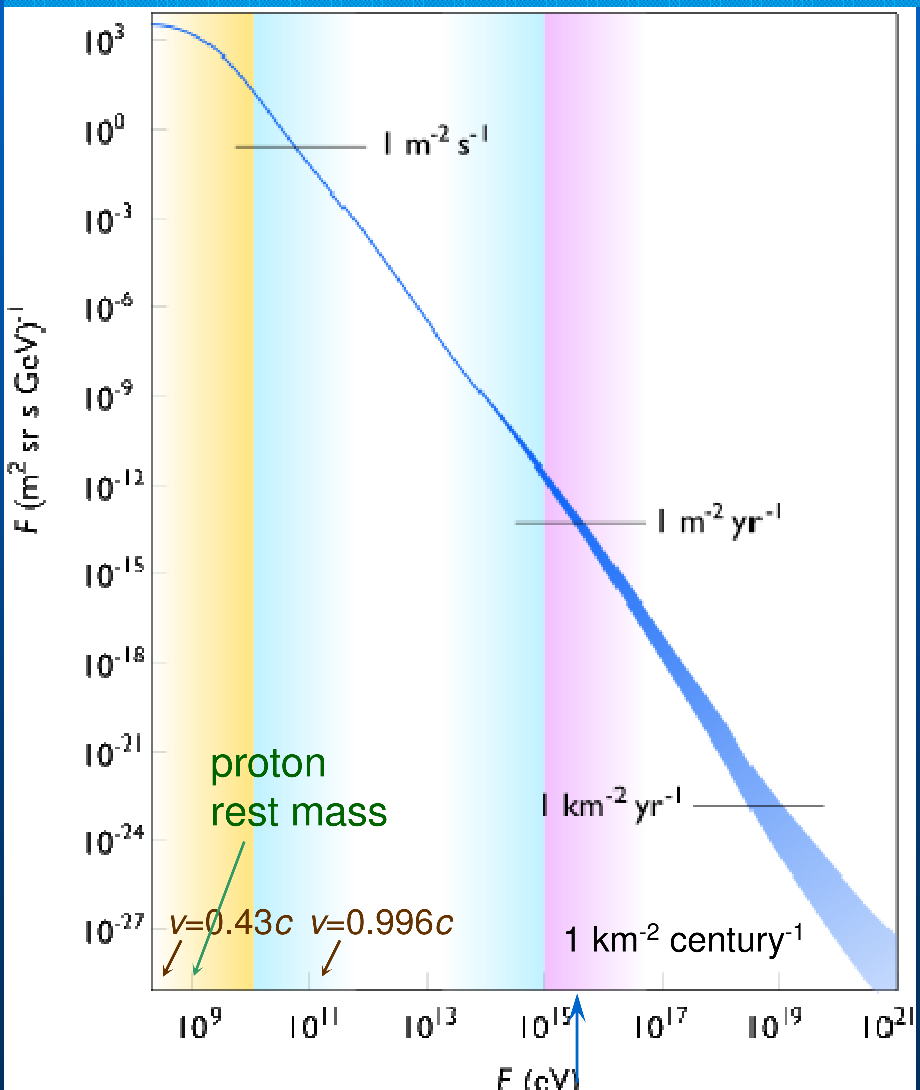
# Discovery of muon

- H.Yukawa theoretically predicted “meson” in 1934 as the carrier of the nuclear force that holds atomic nuclei together
- series of experiments in 1933-1937: there are particles wich charge of proton but with different degree of ionization along a trace and radius of curvature in magnetic field
- C.Anderson and S.Neddermeyer 1937-38 proved such new particle with mass between proton and positron ($207m_e$)



*(1938, S.Neddermeyer and C.Anderson)*

# Spectrum of Cosmic Rays: a remainder




LHC (4 TeV per beam in COM frame, 2012)

**Flux** – number of arriving particles per (unit area * unit time * unit energy interval)

**eV** – (very small) unit of energy

- energy of an electron passed through 1 volt
- 1 eV = 1.609 x $10^{-19}$ joules

**Rest mass of electron** – 0.511 $MeV/c^2$

**Rest mass of proton** – 938 $MeV/c^2$

**Large Hadron Collider**

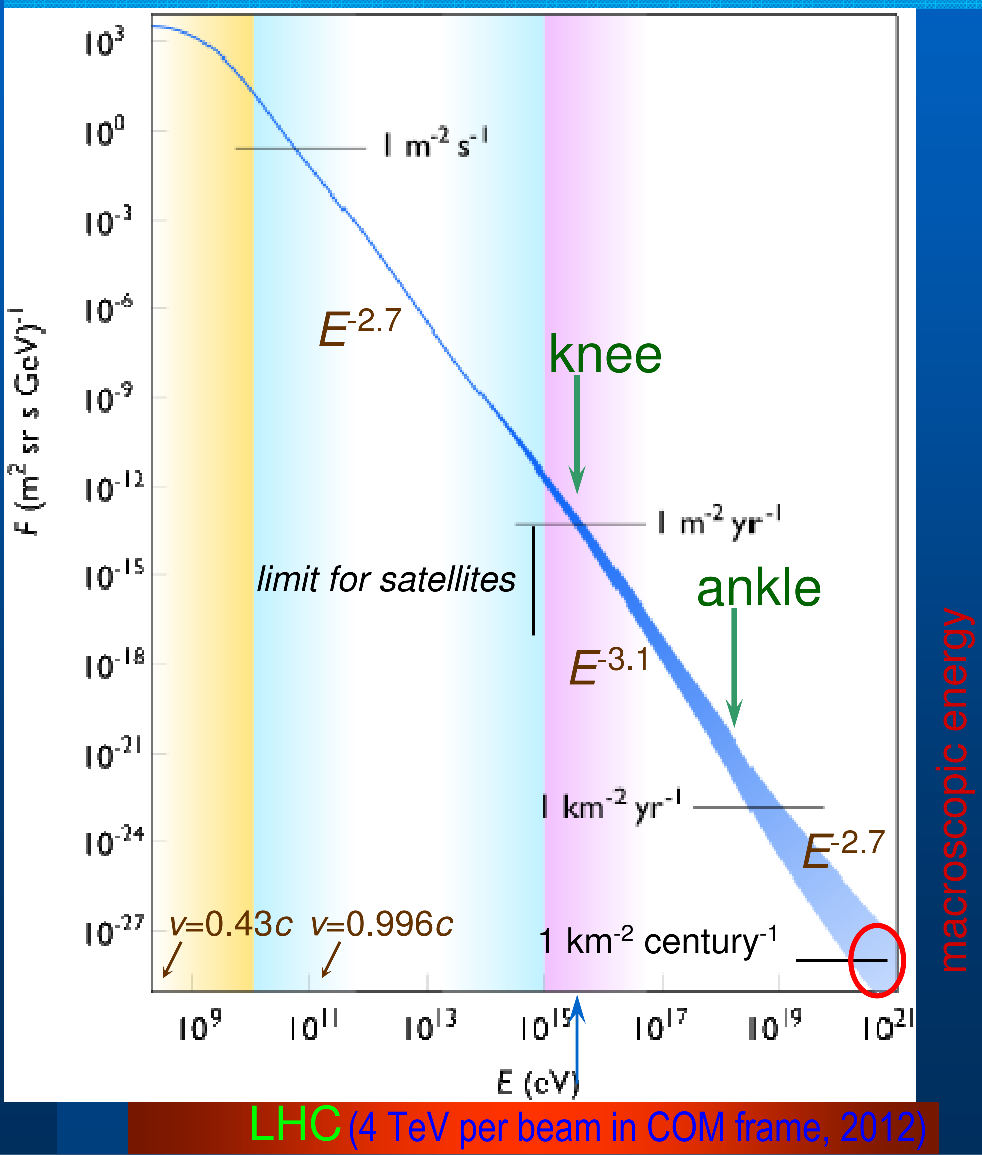
(2 beams) $E_{max}$ (2012) – 4 TeV per beam

$E_{max}$ (2015) – 14 TeV per beam

(8 TeV in COM frame – $4 \cdot 10^{15}$ eV in lab frame)

| | | |
|---|---|---|
| MeV=$10^6$ | GeV=$10^9$ | TeV=$10^{12}$ |
| PeV=$10^{15}$ (peta) | EeV=$10^{18}$ (exa) | ZeV=$10^{21}$ (zetta) |

# Spectrum of Cosmic Rays

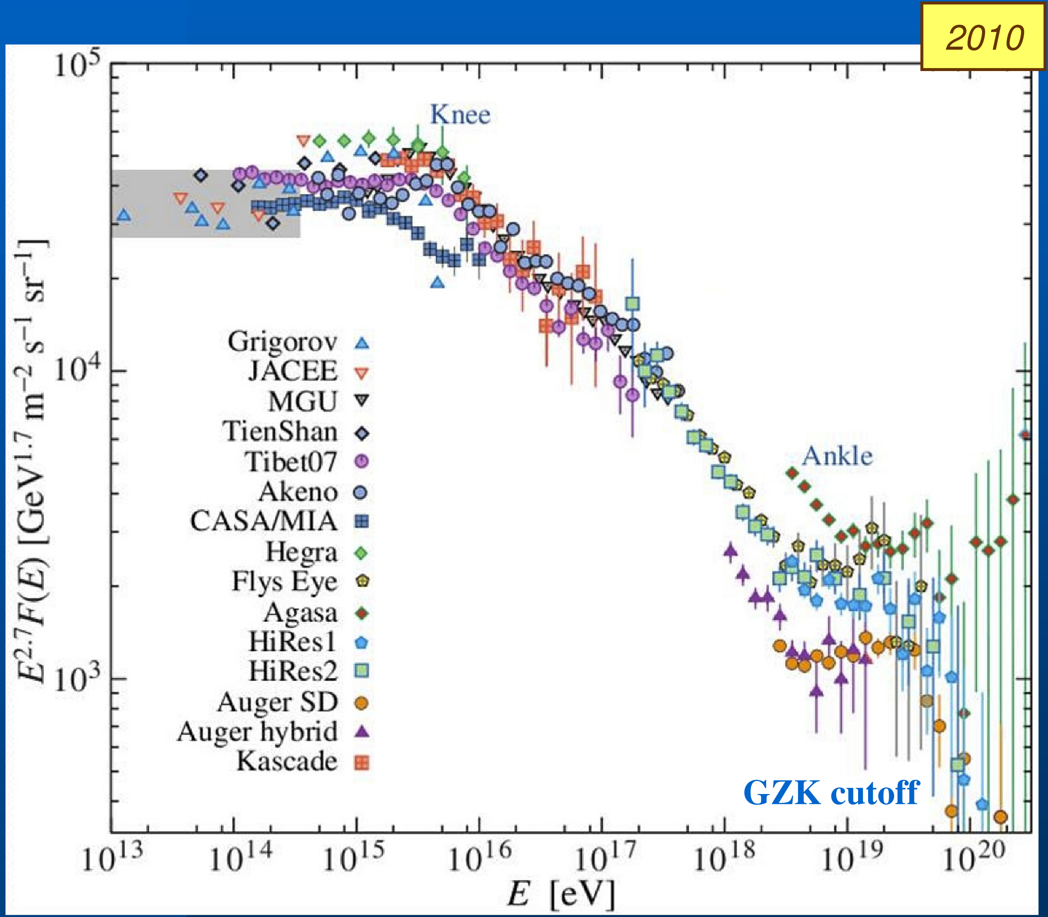



*Despite of the low density ($<10^{-4}$ $cm^{-3}$ while typical is 1 $cm^{-3}$), CRs play important role in energy balance of the Universe (energy density $w_{cr} \sim w_{gas} \sim w_B$)*

- Spectrum lasts over 12 orders in energy
- Spectrum has power-law character; there are changes in the slope around
  $3 \cdot 10^{15}$ eV ("knee") and
  $3 \cdot 10^{18}$ eV ("ankle").

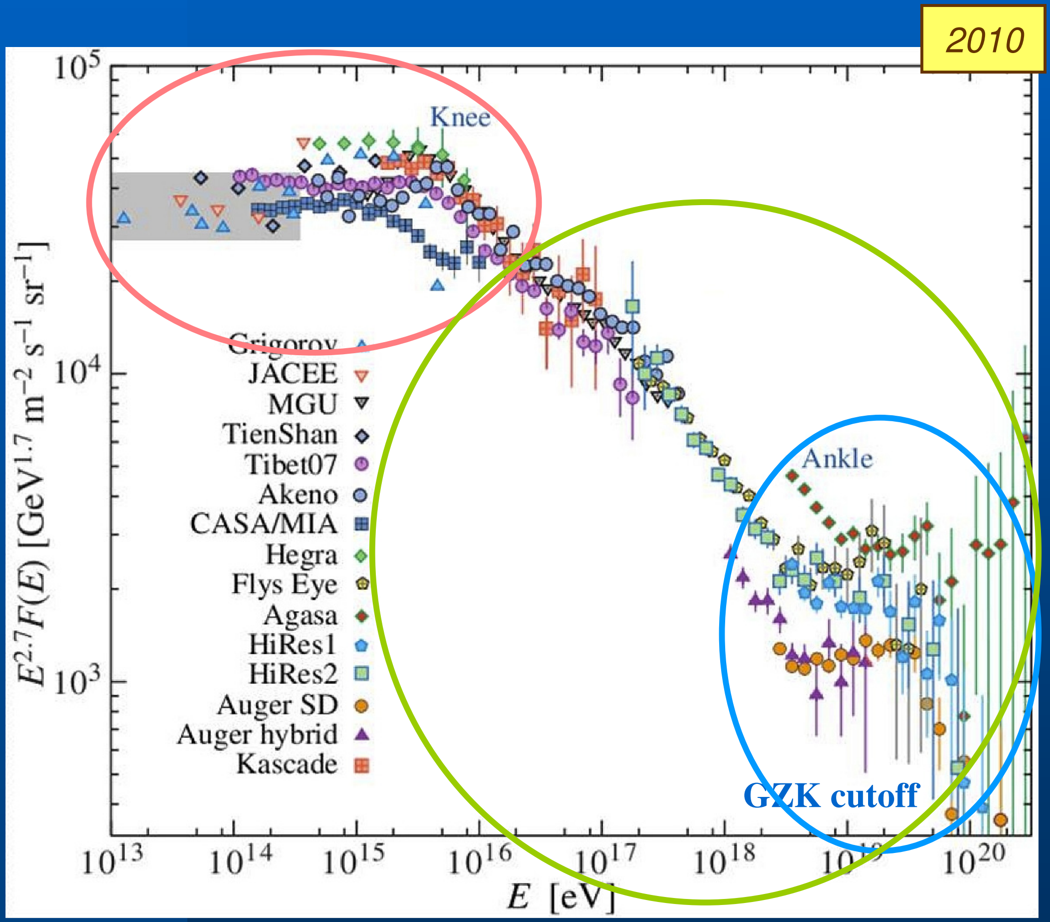
*Highest detected energy of CR is above $10^{20}$ eV (16 J), that is equivalent to kinetic energy of the tennis ball (100 g) moving with the speed > 70 km/h (1 eV=1.6 $10^{-19}$ J)*

# Structures in the CR spectrum




knee ankle

# Structures in the CR spectrum



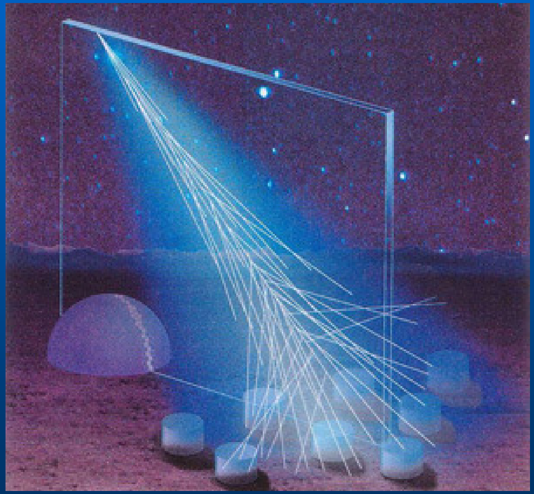

knee ankle

Galactic CRs extra-galactic CRs Ultra-high energy CRs

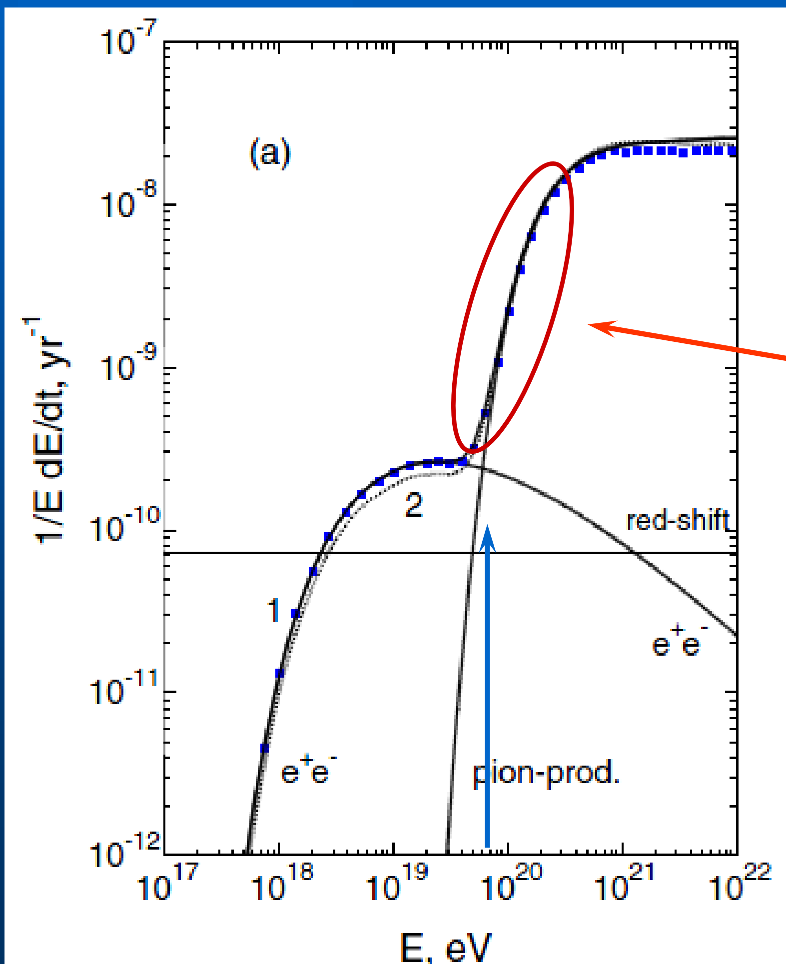
# Ultra high energy cosmic rays

## GZK cutoff

Greisen (1966)
Zatsepin, Kuzmin (1966)



# Energy losses of UHE proton




[Berezinsky et al. 2006]


Ultra-high energy proton produces a pion due to Interaction with CMBR.

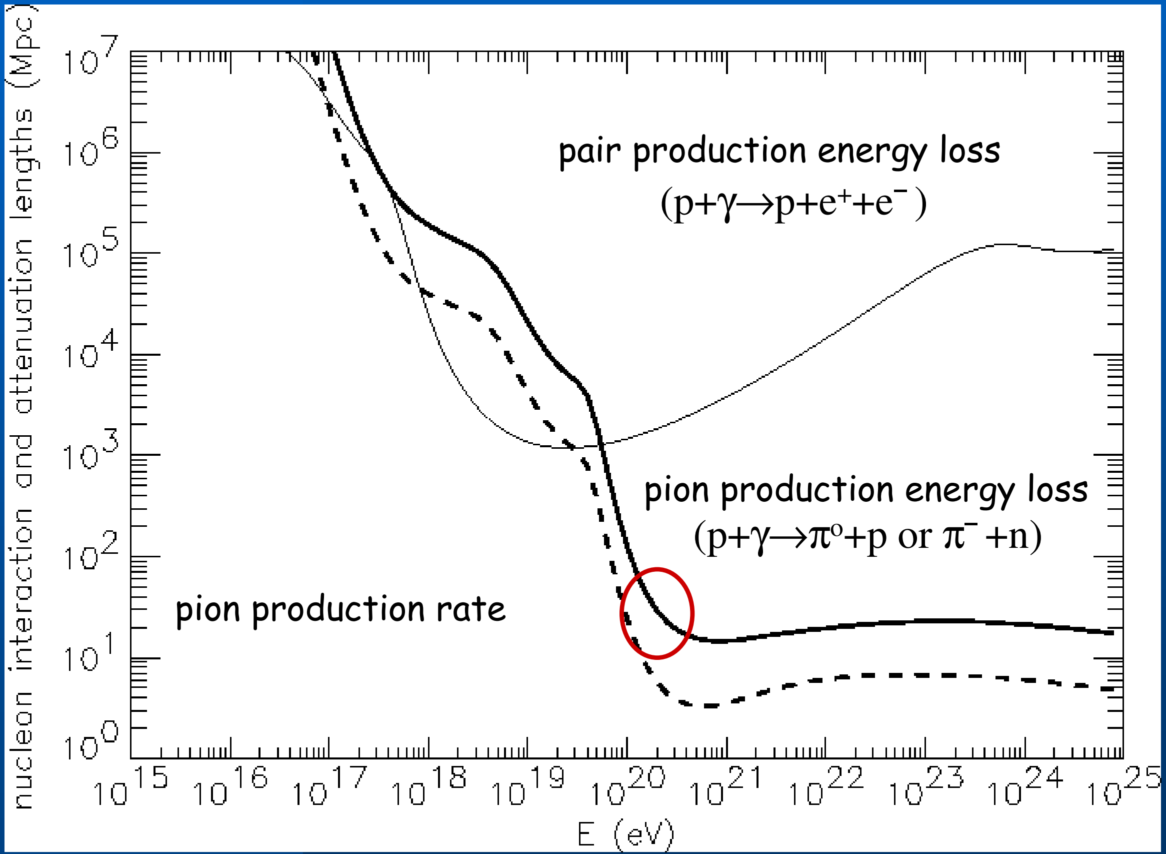
$p+\gamma \rightarrow \pi^{o}+p$ or $\pi^{-}+n$

This process continues until the cosmic ray energy falls below the pion production threshold.

Limiting energy is ~$6\times10^{19}$ eV

⇒ the end of the CR sprctrum should be observed above $10^{20}$ eV

# GZK horizon

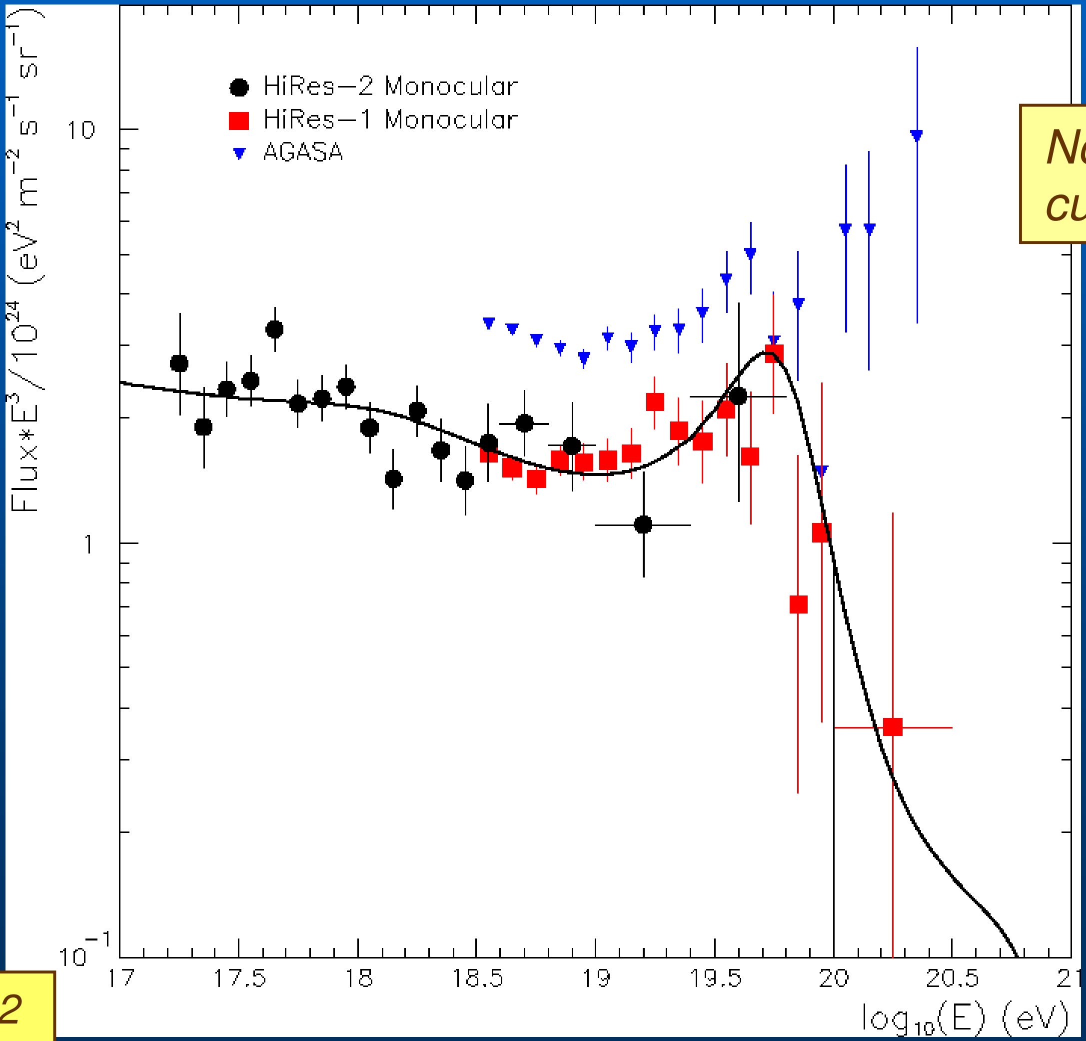



Due to the mean path associated with this interaction, extragalactic cosmic rays traveling over distances larger than 50 Mpc (163 Mly) and with energies greater than this threshold should never be observed on Earth.

particles around $10^{20}$ eV loose energy within about 50 Mpc

⇒ the source of UHECRs should be at a cosmological backyard

# Observations (1) HiRes+AGASA

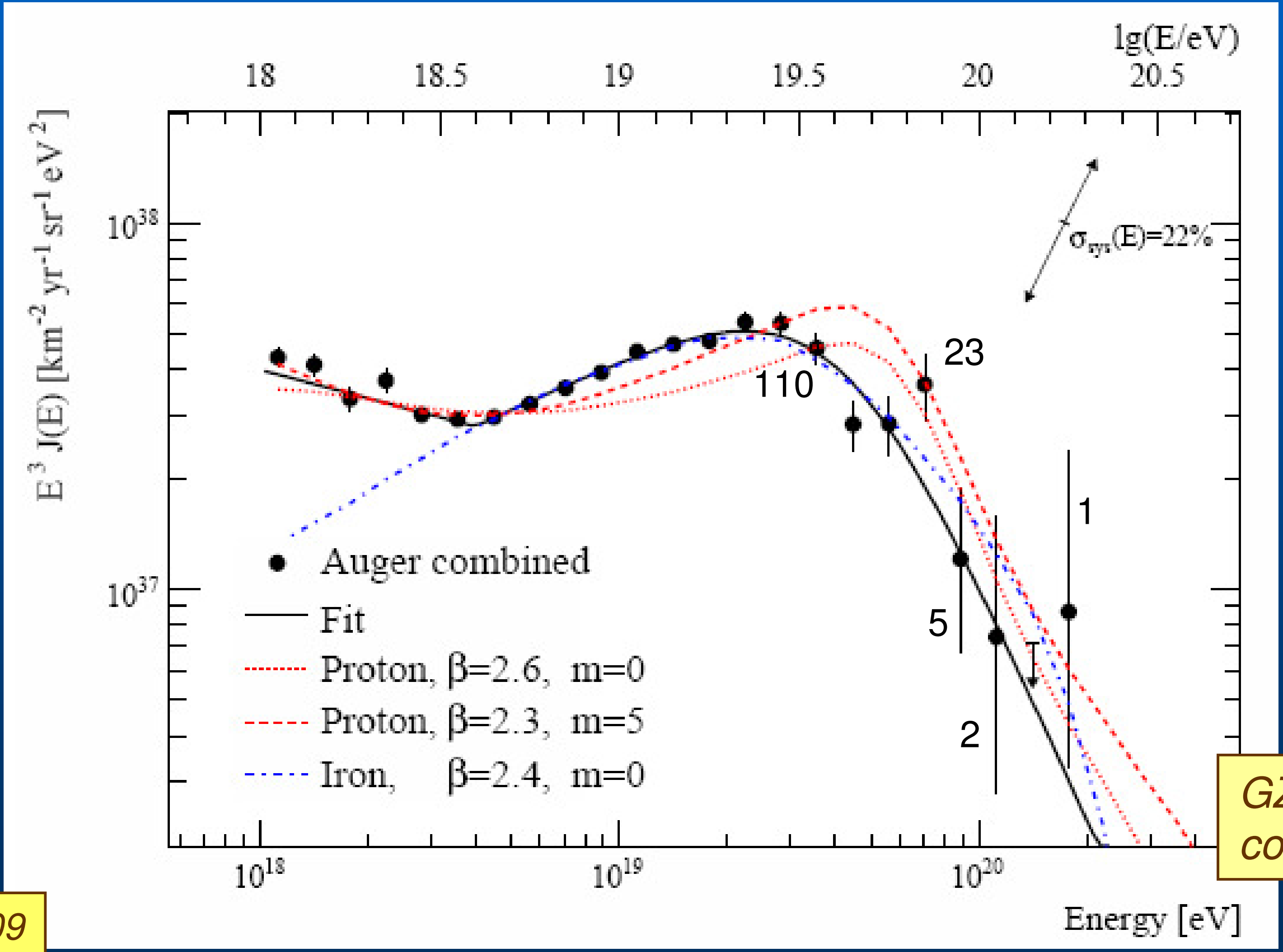



*No GZK cutoff?*

*HiRes, Utah*
*AGASA, Japan*
*(~100 km$^2$)*

*2002*

# Observations (2) Auger

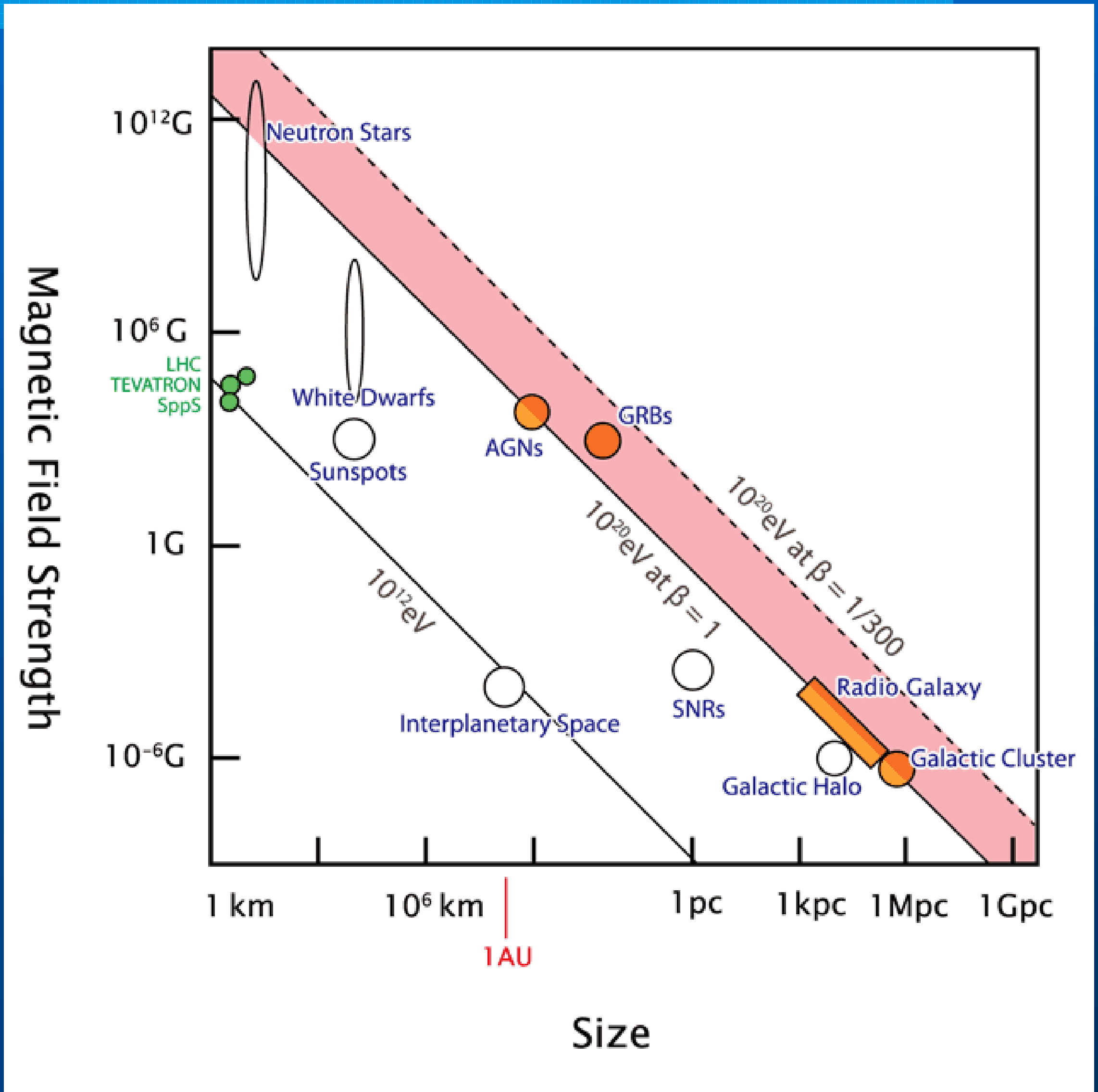



*Argentine (3000 $km^2$)*

*2009*

*GZK cutoff confirmed*

# Where do they come from?

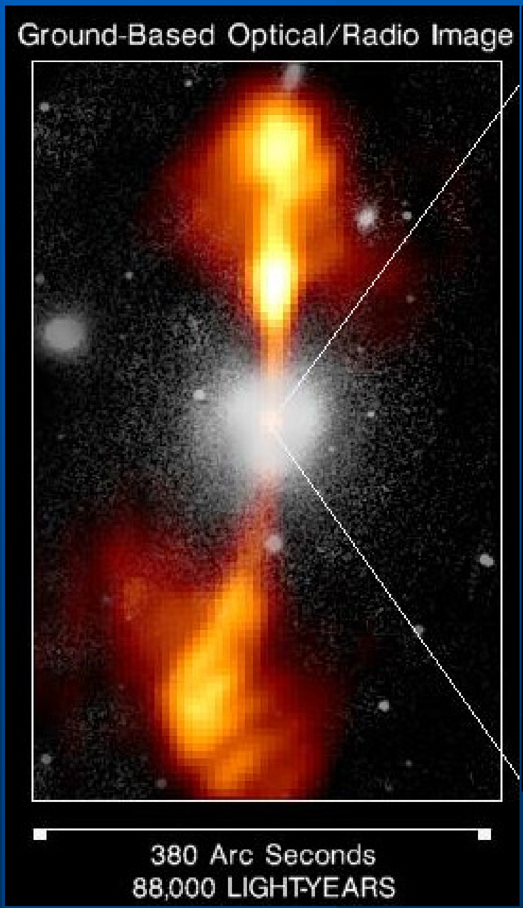



*Hillas Diagram:*
*Theoretical upper limits of the energy of the particle are determined by the size and MF strength of celestial objects.*

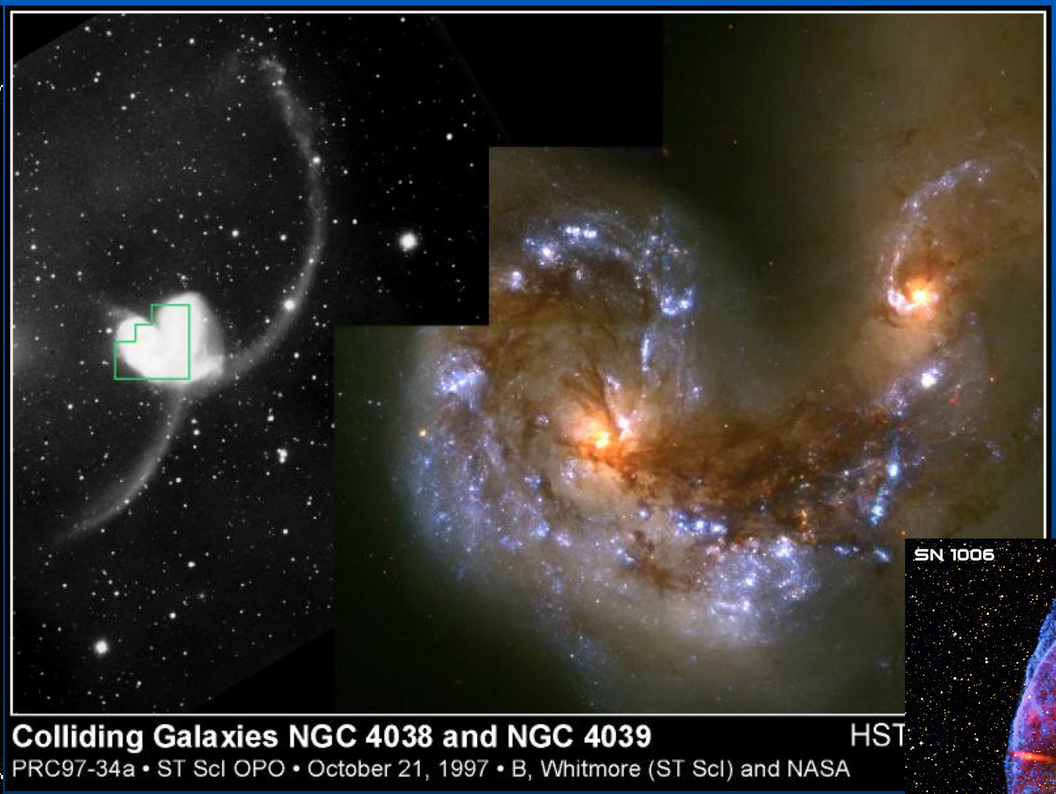
## *Possible sources of UHECRs*

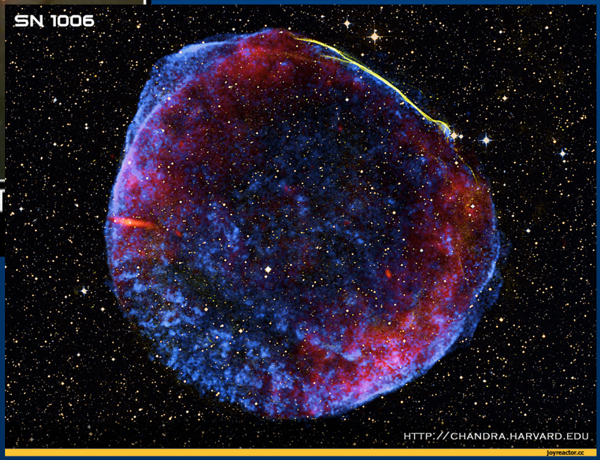
- Active Galactic Nuclei
- GRB (hypernova)
- colliding galaxies

# Possible sources of UHECRs

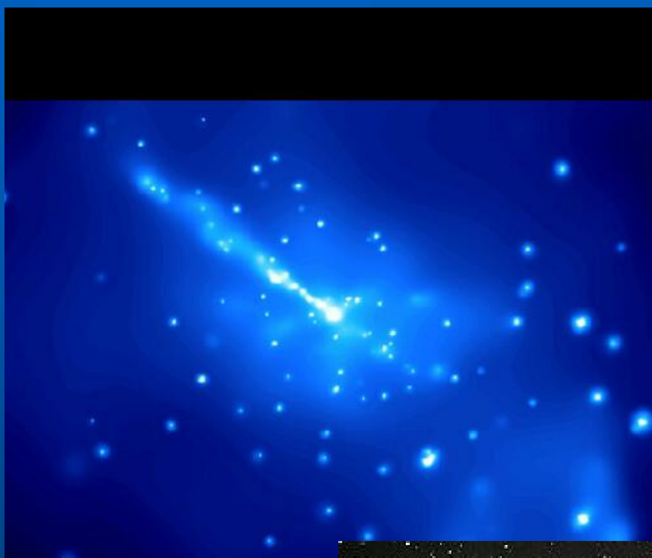



Galaxy NGC 4251

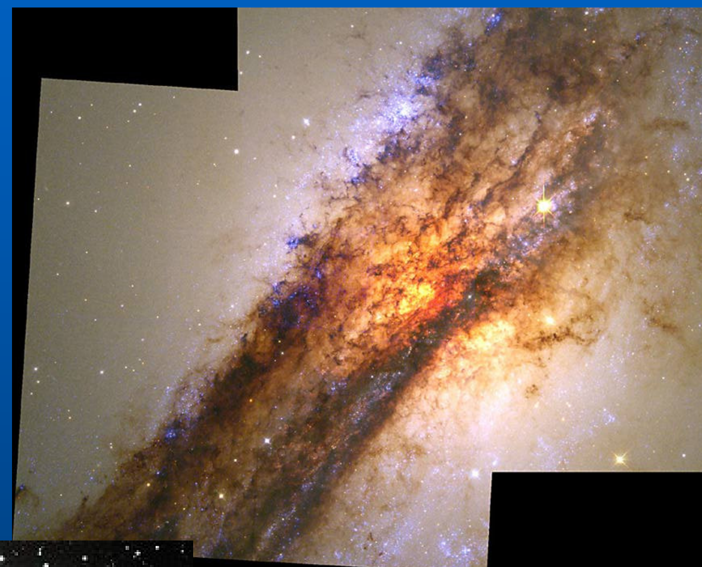


# Is *Centaurus A* a source of UHECRs?



X-ray observatory
Chandra



Habble
telescope

D=4-5 Mpc

Radio-
telescope
APEX

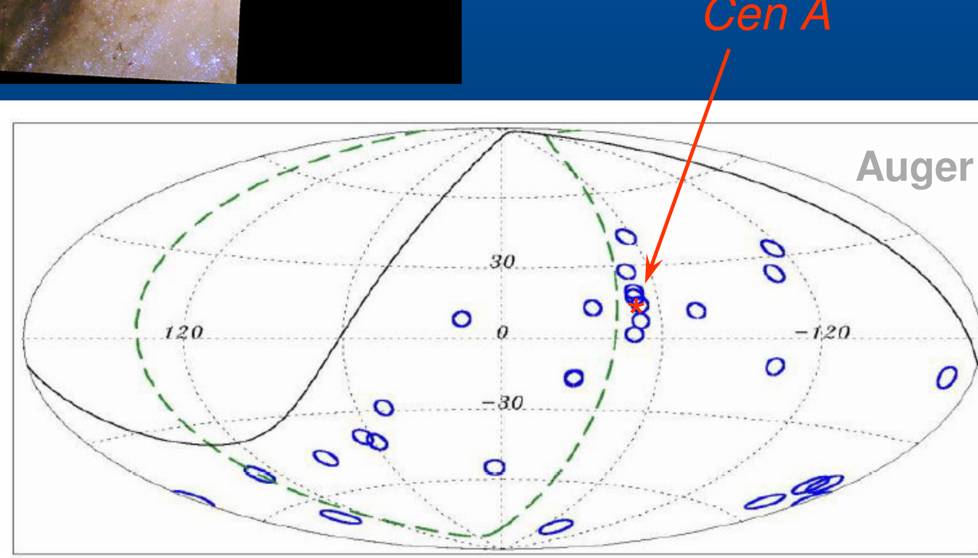
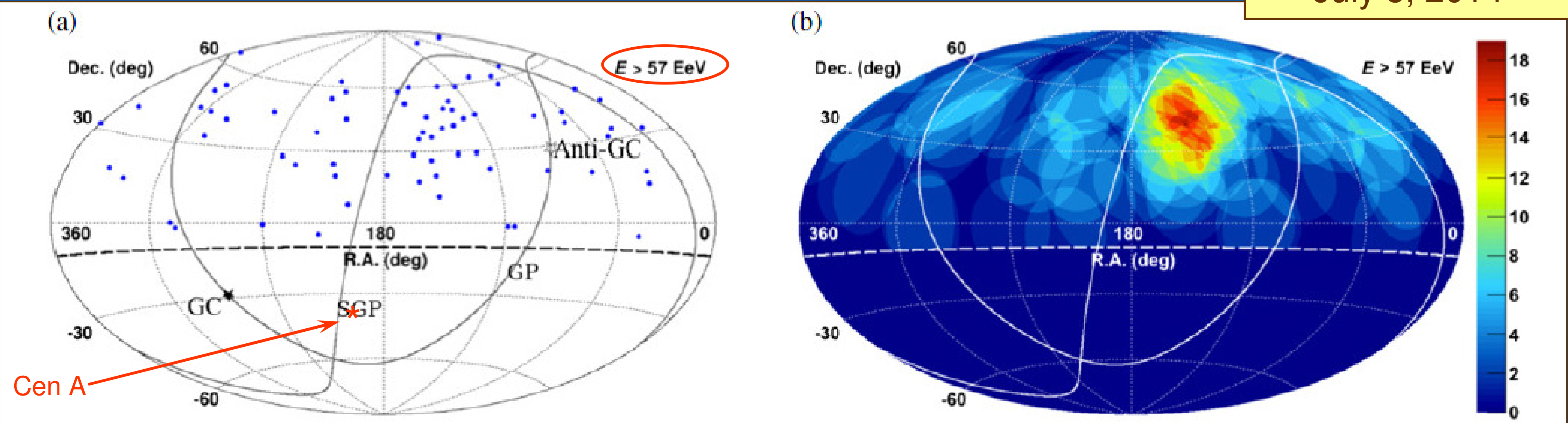



Figure 14. Plot in galactic coordinates showing the high-energy events as small blue circles. The supergalactic plane is indicated by the green dashed line.

# Nothern hot-spot (Telescope Array)

*** July 8, 2014 ***

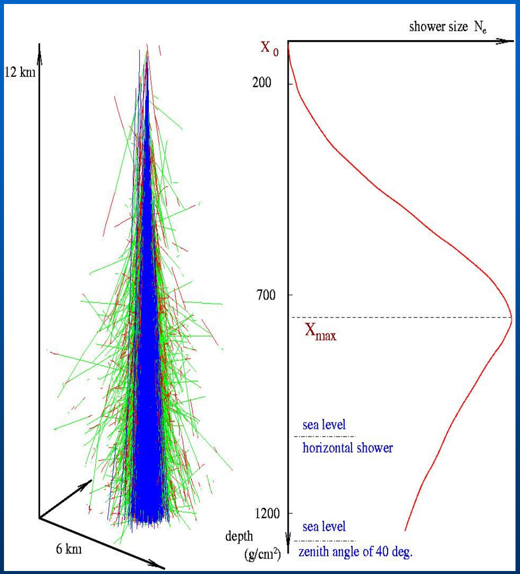



projection of the UHECR maps in equatorial coordinates. The solid curves indicate the galactic plane (GP) and supergalactic plane (SGP).

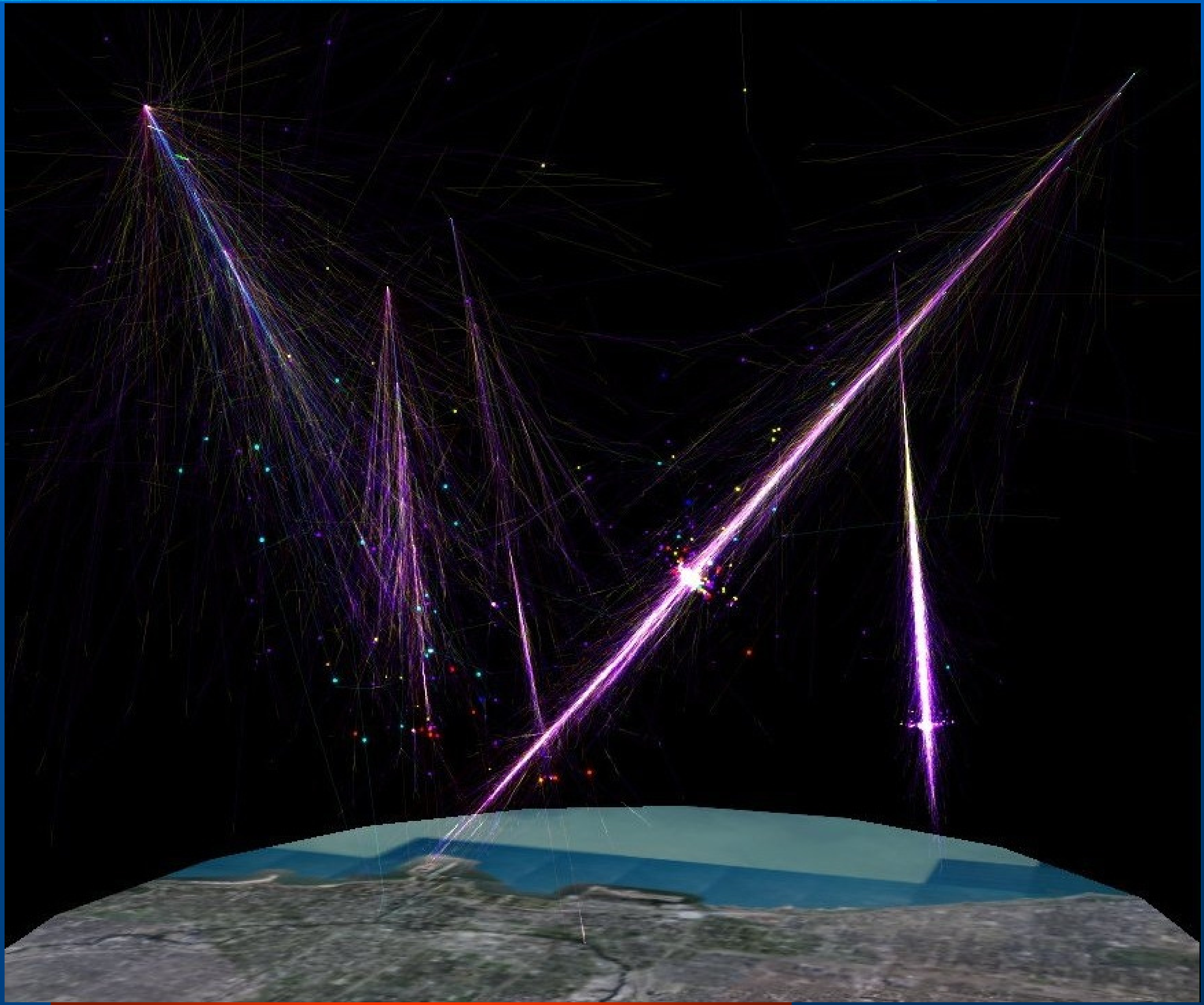
[Abbasi et al.2014]

This map of the northern sky shows cosmic ray concentrations, with a "hotspot" with a number of cosmic rays within 20$^o$.
Only events with E>57 EeV are choosen to avoid influence of MF (72 CRs in 2008-2013).
Probability to have such a distribution by chance is 1.4 in 10,000 (3.4σ).
The hotspot is a 40-degree-diameter circle representing 6 percent of the northern sky with a quarter of events in that circle instead of 6 percent.
*No known eventual source in that region of the sky.*

# Composition of UHECR



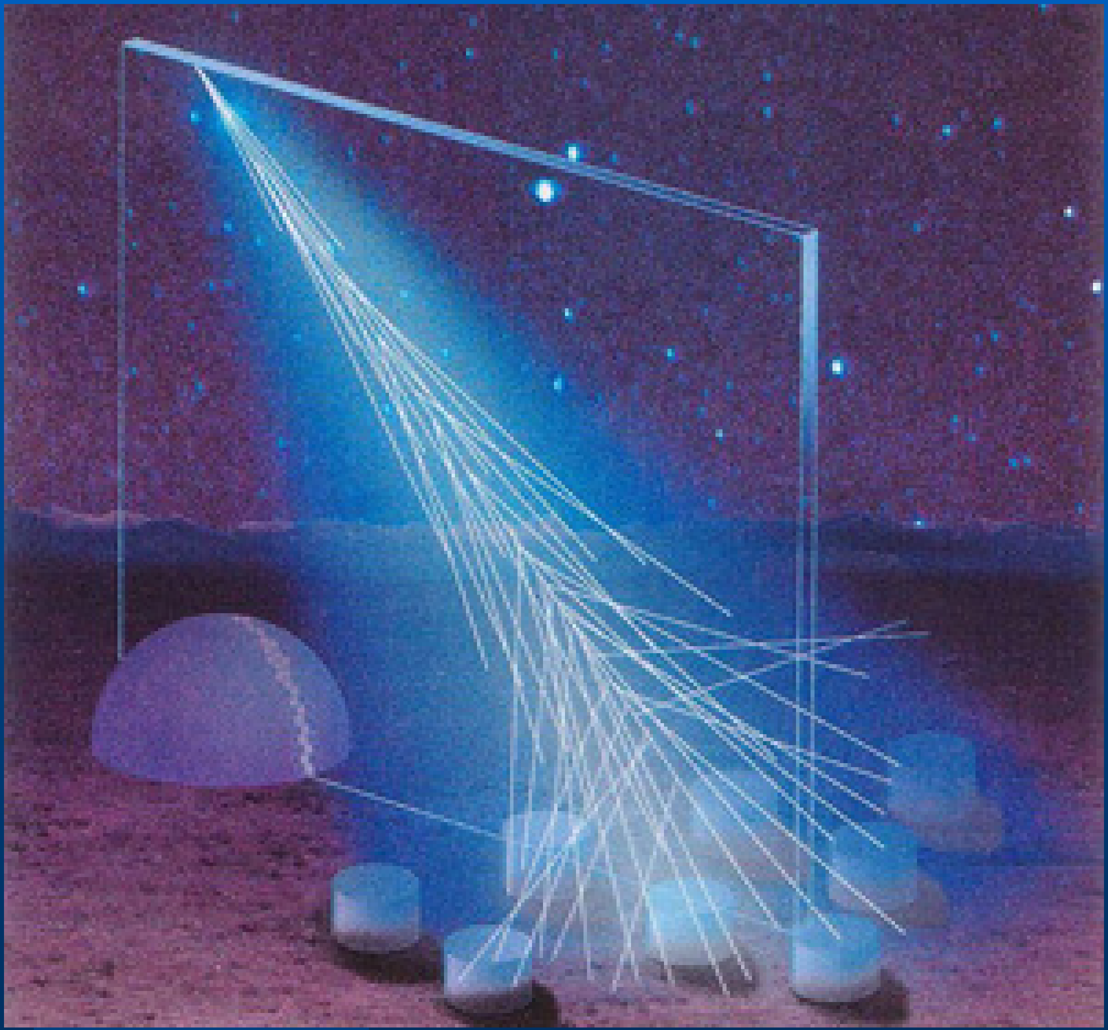
# Interactions of the primary CR



Primary cosmic ray interacts with elementary particles in the athmosphere and creates cascade of secondary ionized particles and electromagnetic radiation

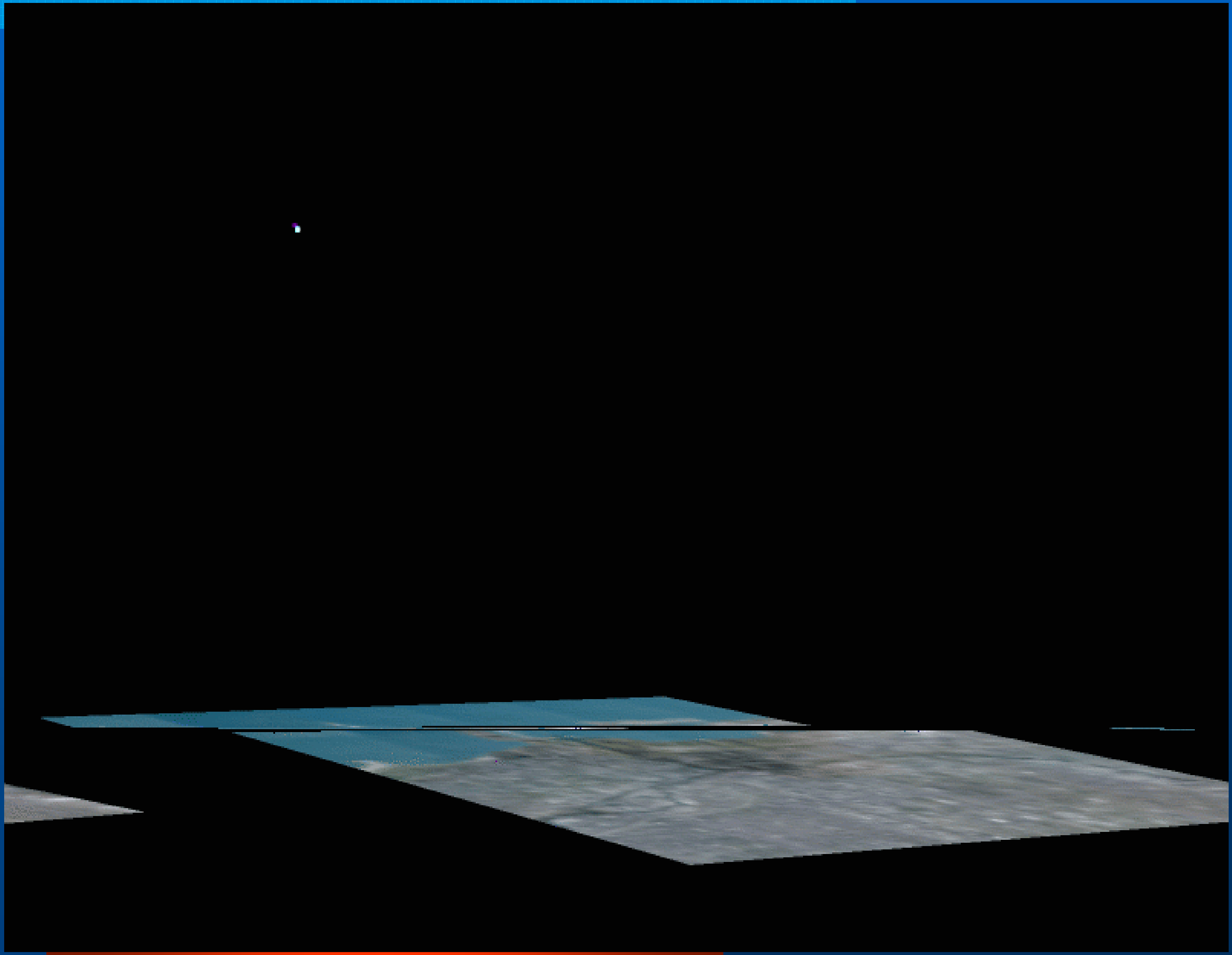
"wide athmospheric shower"

# Atmospheric shower



UHE Cosmic Rays are observed by detection of such atmospheric showers

# UHECR shower



- ground array samples the shower front only

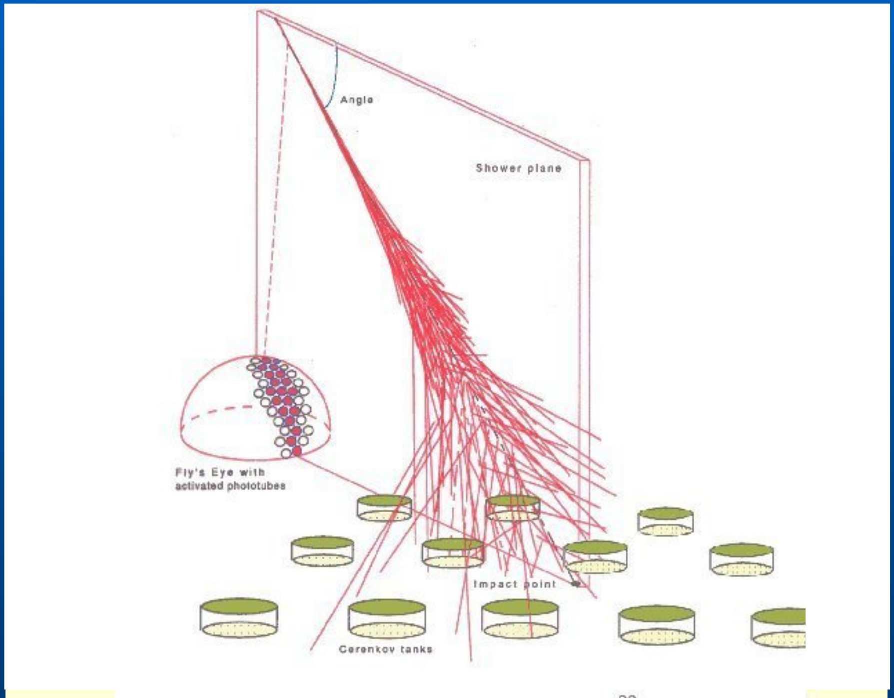
- fluorescent technics tracks the shower profile

- initial energy is devided between sub-showers

- $X_{max}$ inversely depends on mass A

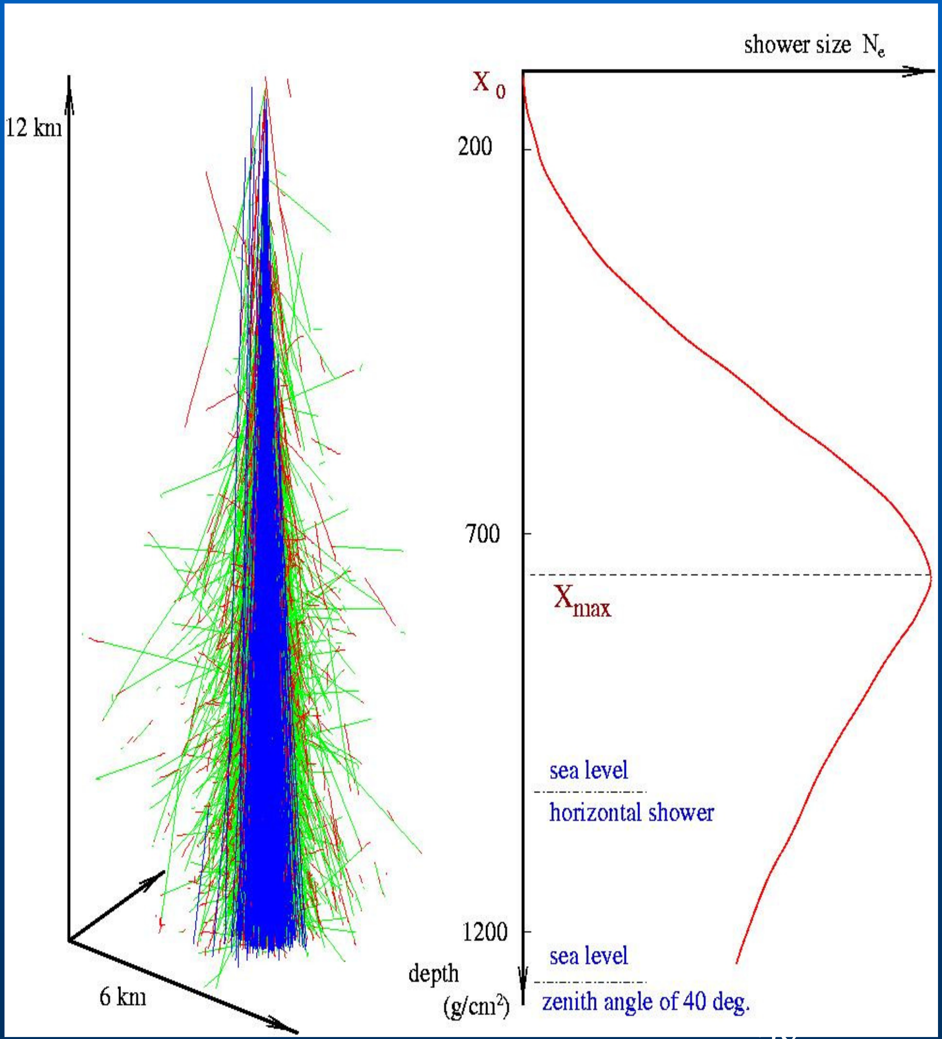
# Measuring the UHECR

*Schematic view of air shower detection: ground array and Fly's Eye*
idea is realised in Auger (+HiRes)

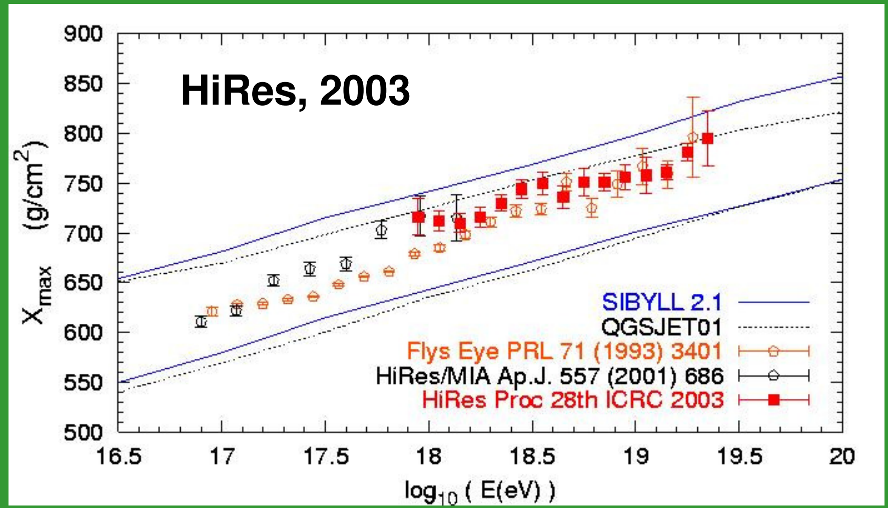



– $X_{max}$ sensitive to primary mass:
$X_{max} \sim \Lambda\, ln(E_0/A)$

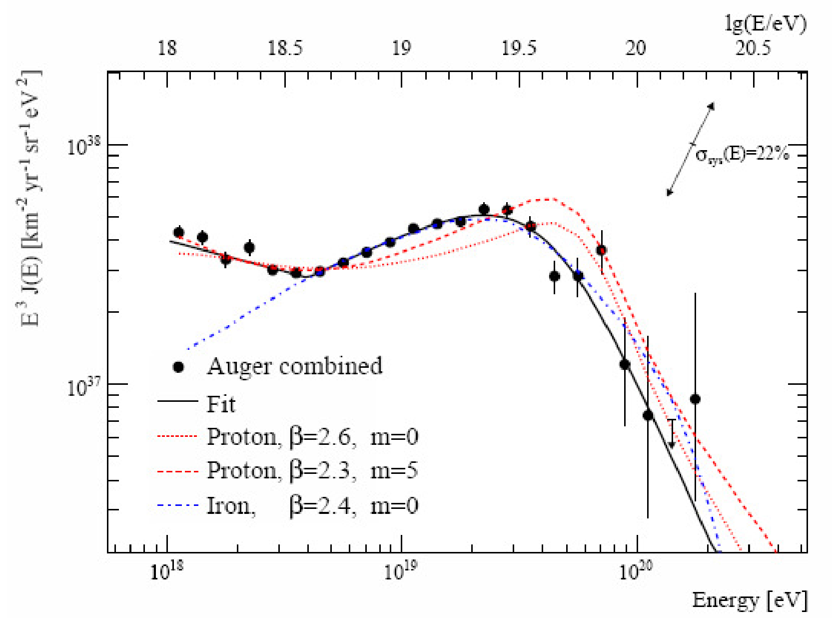
***protons penetrate more than heavier nuclei***

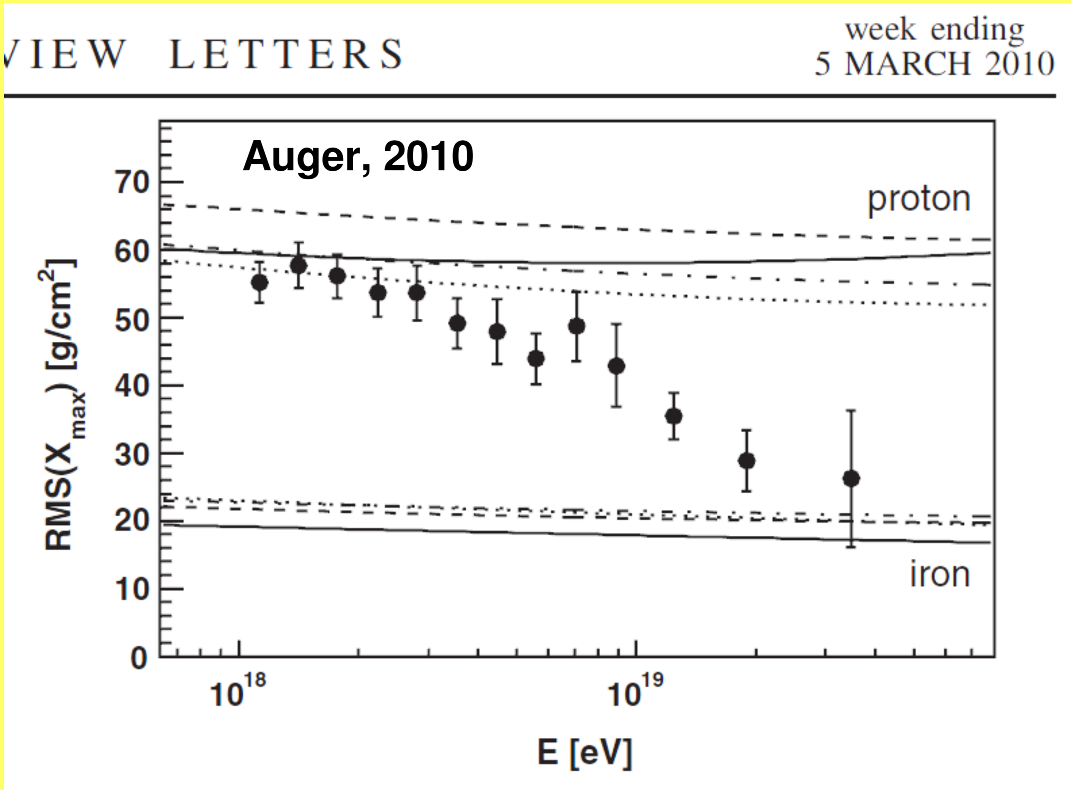


# Abundance of UHECRs

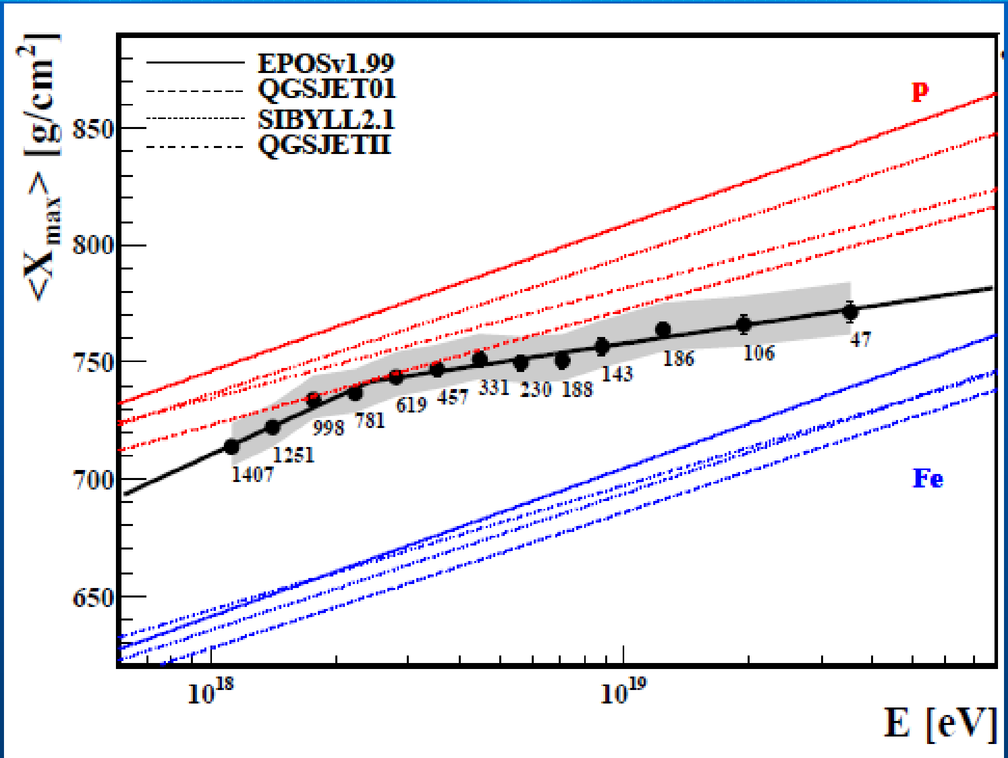


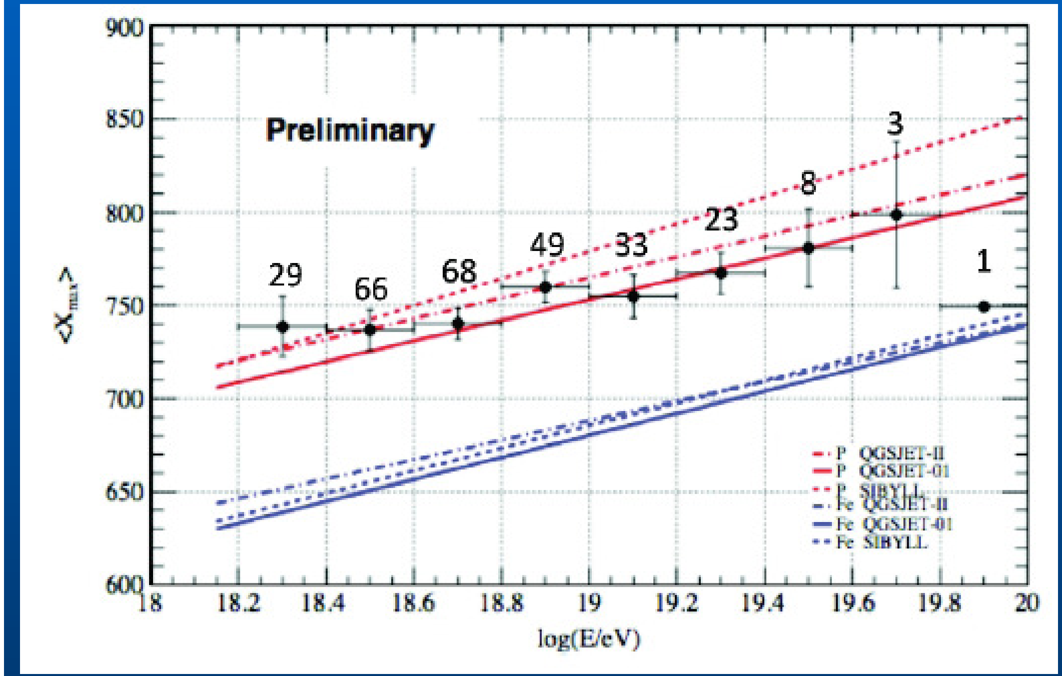

HiRes Collaboration disputes trend to heavy composition above $\approx 10^{19}$ eV



# Auger vs Telescope Array (2011): a new intrigue



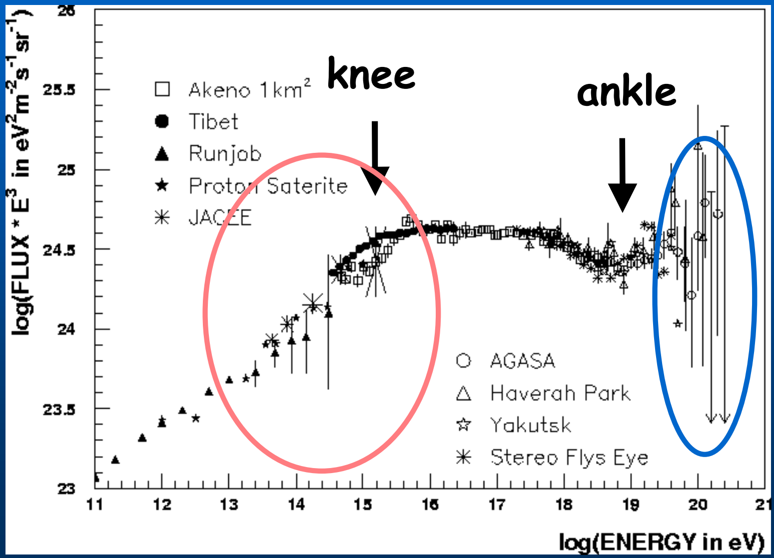




Auger
(Argentine)
3000 km$^2$

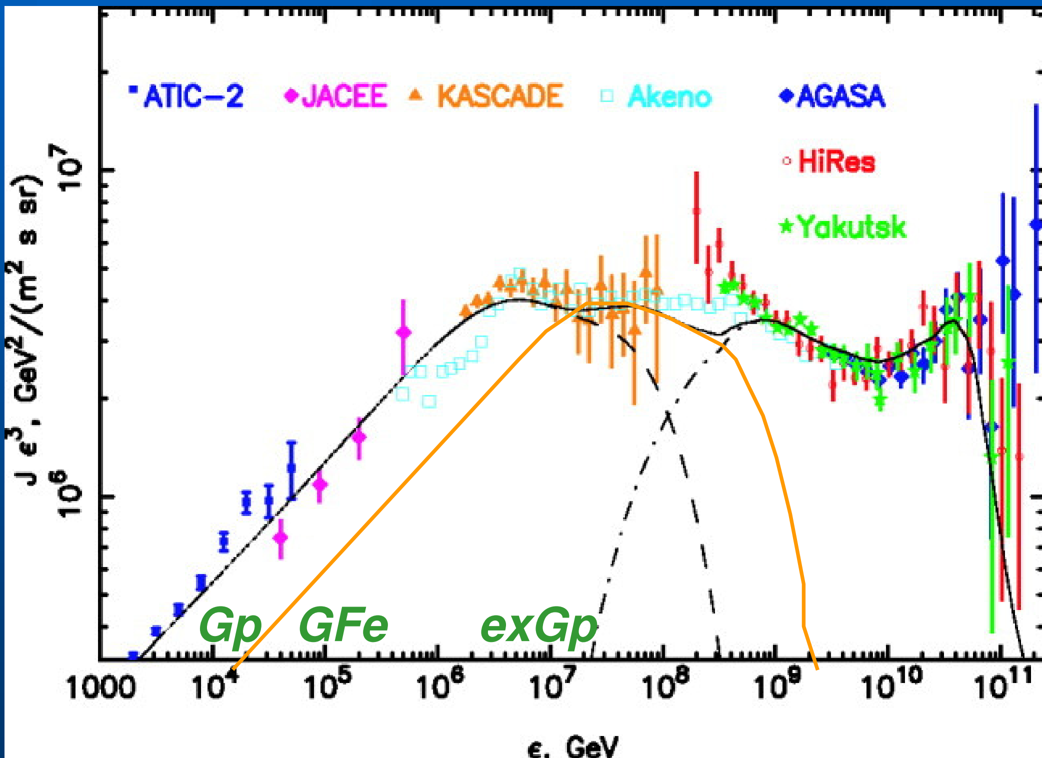
Telescope Array
(Utah, USA)
700 km$^2$

the trend in abundance of UHECRs may be similar

to that found in the galactic CRs (around a “knee”)

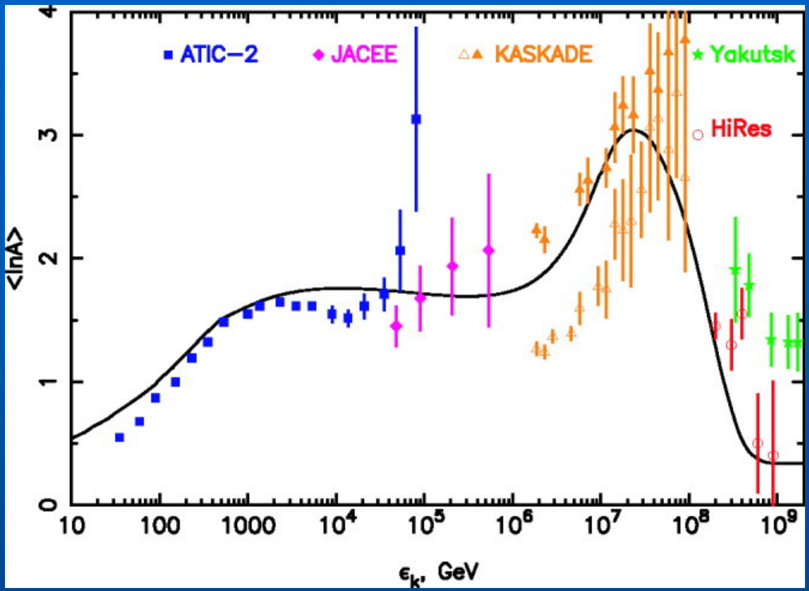


# Knee: *increasing fraction of heavy nuclei*

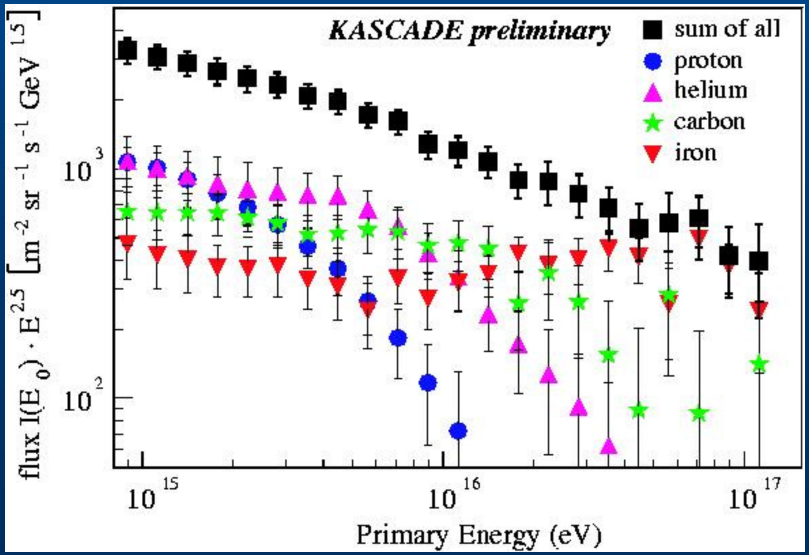



[Berezhko & Volk 2007]

***Knee** region is related to the transition from Gal to exGal cosmic rays*




[Berezhko & Volk 2007]

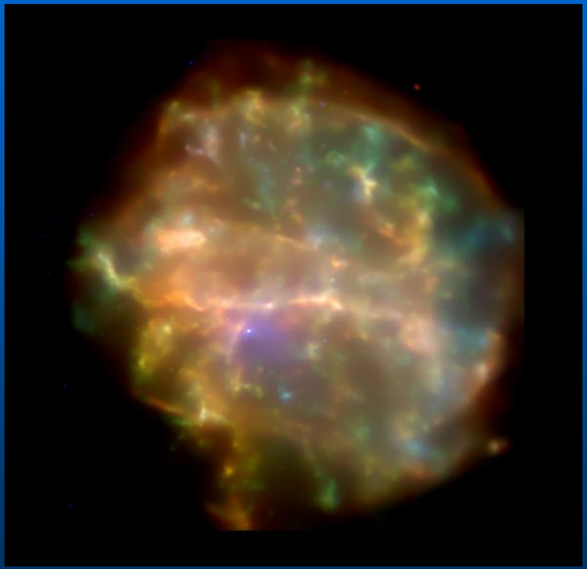



K-H Kampert et al. 2001

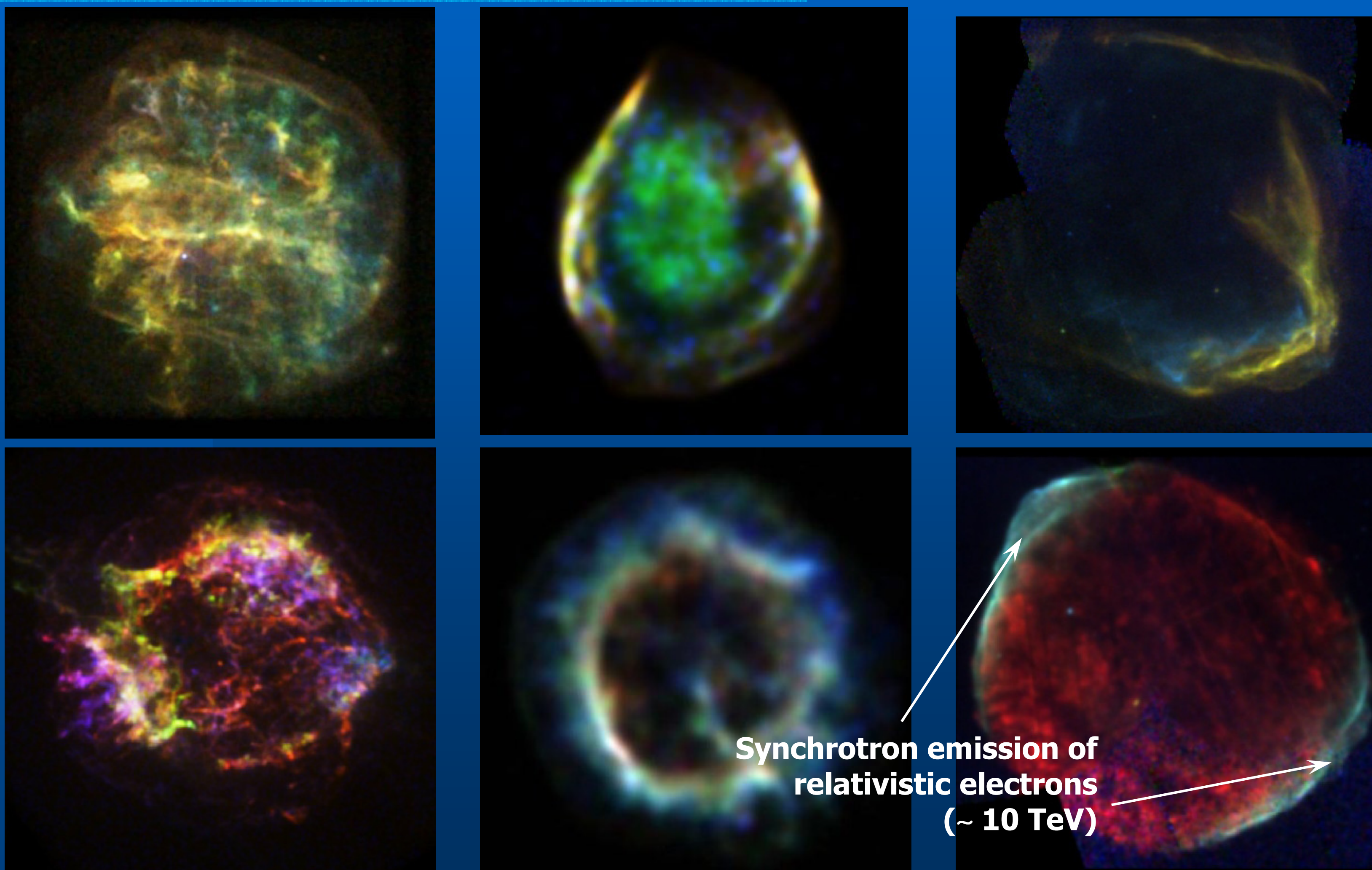
# Galactic Cosmic Rays

*Cosmic rays with energy up to $10^{15}$-$10^{17}$ eV are accelerated in Galaxy*

*Main sources of CRs in Galaxy are Supernova Remnants (SNRs)*



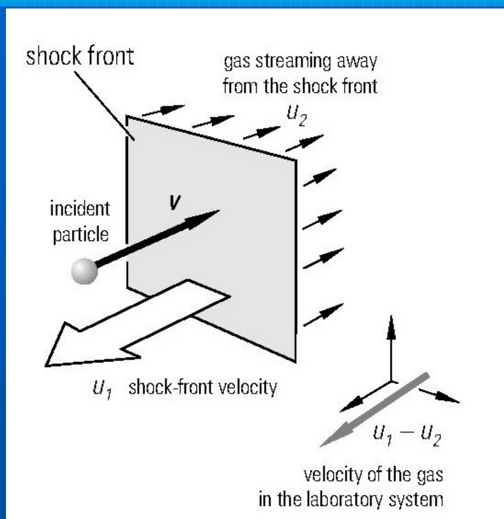
# *Supernova remnants*




Chandra Chandra XMM

Cas A (Mg XII, Si XIII), G292.2-1.8 (OVII/VIII, Ne, Si XIII), E0102-7219 (OVII, OVIII, Ne/Mg), Dem L71 (O,Fe L, Si), SN 1006 (O VII, 0.7-2 keV, 2-7 keV), RCW 86 (O VII, 0.7-2 keV, 2-7 keV) – (RGB channels)

# Acceleration of charged particles at shock




A particle of velocity $v$ colliding with the shock front and being reflected gains the energy

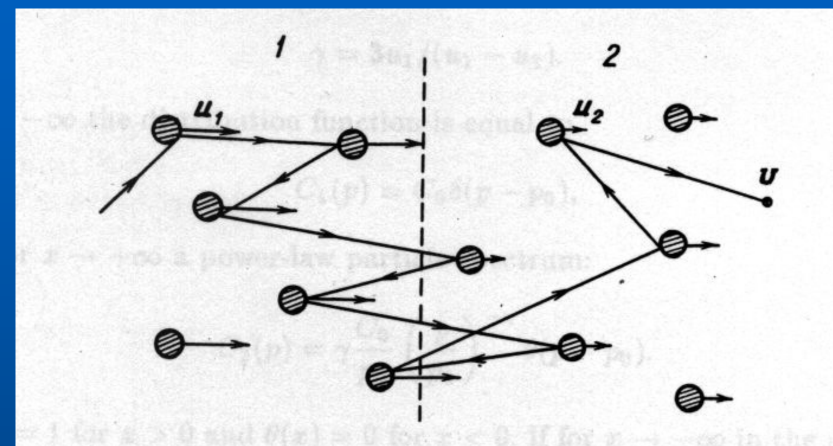
$$\Delta E = \frac{1}{2}m(v + (u_1 - u_2))^2 - \frac{1}{2}mv^2$$
$$= \frac{1}{2}m(2v(u_1 - u_2) + (u_1 - u_2)^2) \ .$$

Since the linear term dominates ($v \gg u_1, u_2, u_1 > u_2$), this simple model provides a relative energy gain of

$$\frac{\Delta E}{E} \approx \frac{2(u_1 - u_2)}{v} \ .$$

$u_2 = u_1/4 = V/4$, $\Delta E \sim V$, $V$ – *shock velocity*

shock



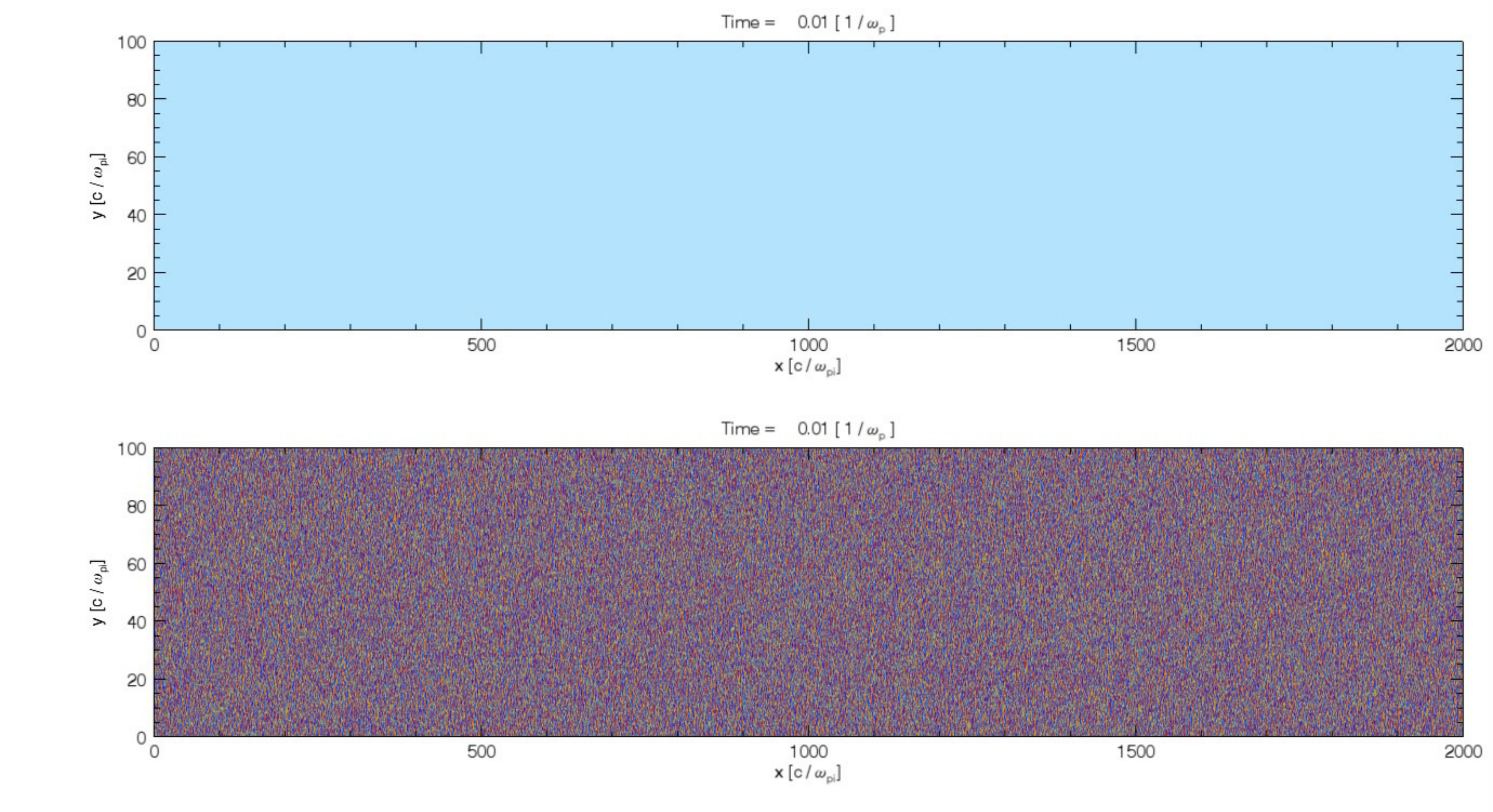

ambient medium

downstream

***Statistical nature of acceleration. The speed of scattering centers in front collisions is greater than in the chase collisions. Many crosses of the shock provide increasing of the particle energy.***

# *Numerical modeling*

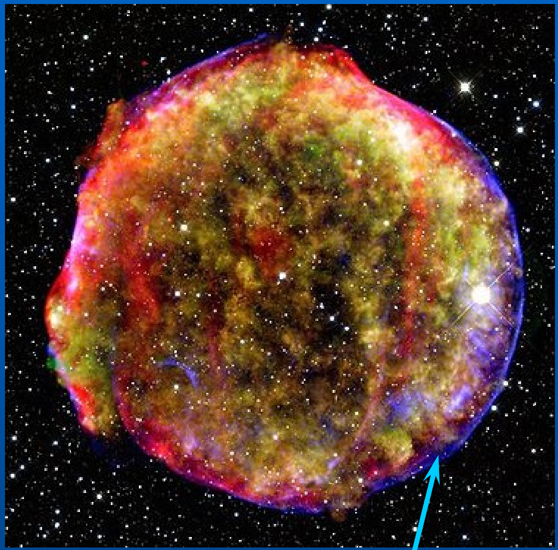
[Caprioli & Spatkovsky 2012]



# *Cosmic rays in SNRs are studied thanks to their (non-thermal) emission*

- **Cosmic rays are essentially deflected by the magnetic field of Galaxy from directions toward the sources.**

- **Therefore, we may analyse the only emission of CRs arising from their interactions with**
  - **magnetic field,**
  - **photons,**
  - **charged particles.**



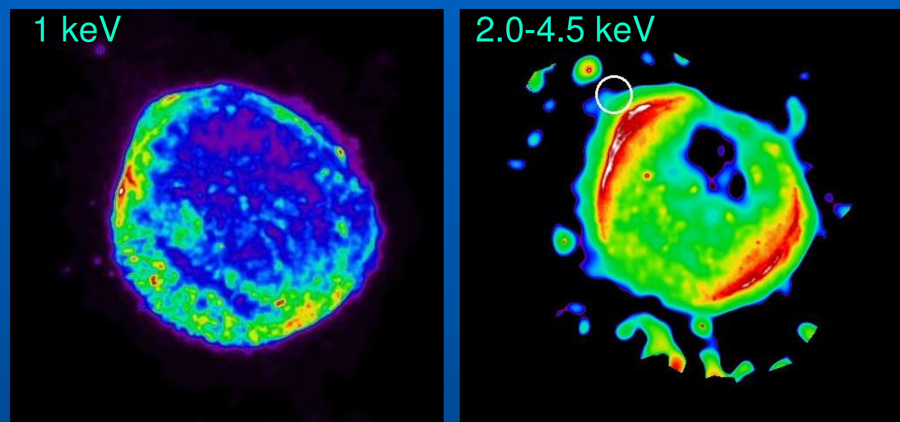
Tycho SNR (1572)

*blue –*
*emission of CRs*

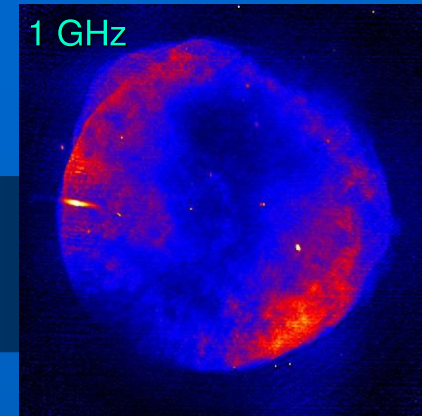
*Studies of CRs from their radiation –*
*close relation of*
***Cosmic Ray Astrophysics***
*to the*
***High-energy Astrophysics***

# *Observations of SNRs*

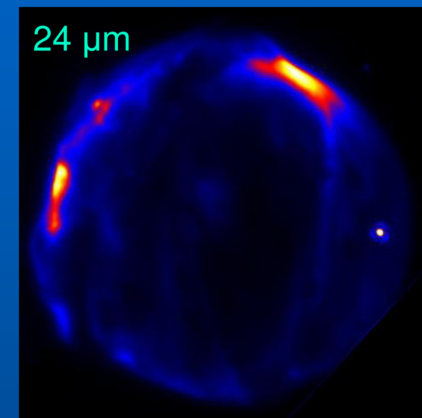
- radio
- IR
- Optical
- UV
- X-rays
- GeV γ-rays (since 2008)
- TeV γ-rays (since 2004)



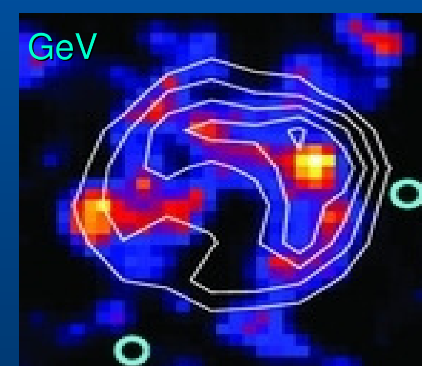

SN1006
[Miceli et al. 2010]



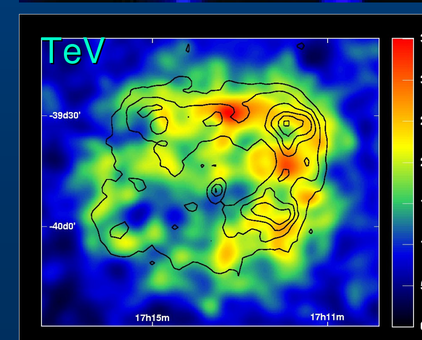

SN1006
[Petruk et al. 2009]




Tycho
[Ishihara et al. 2010]

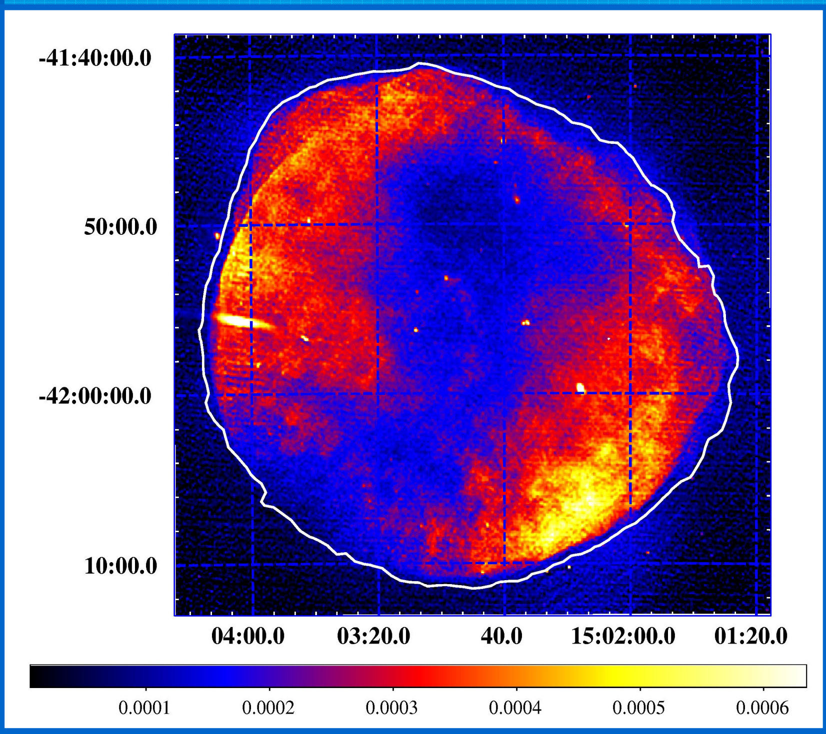


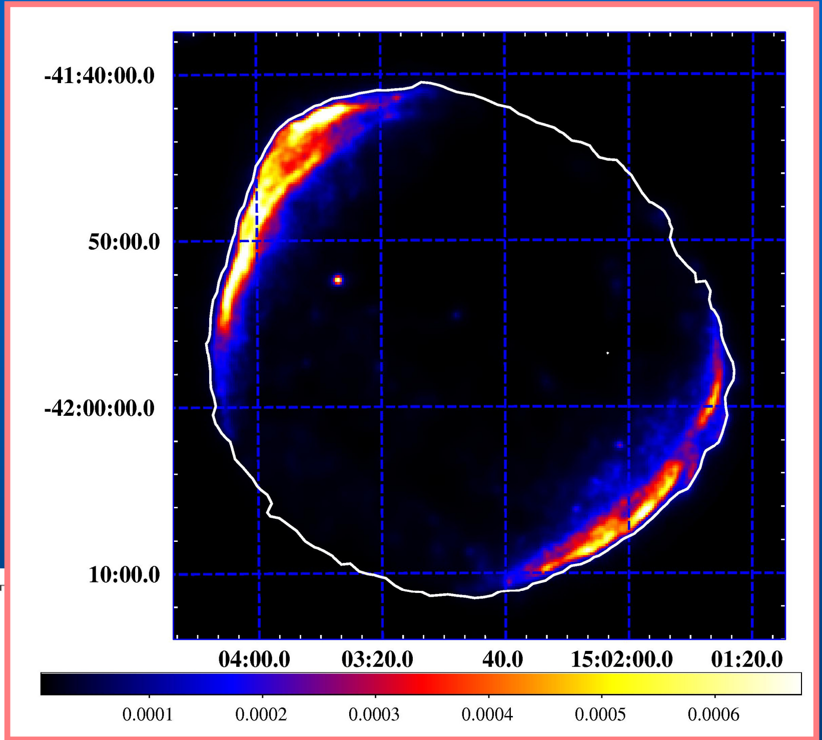

RX J1713.7−3946
[Abdo et al. 2011]




RX J1713.7−3946
[Aharonian et al. 2004]

# Synchrotron emission from radio to X-rays



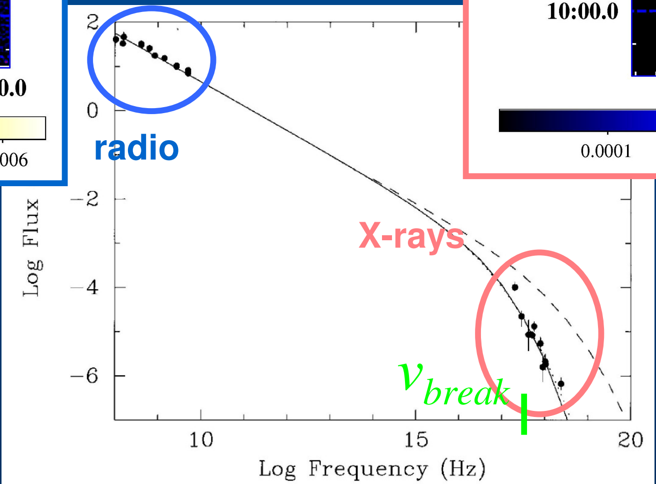
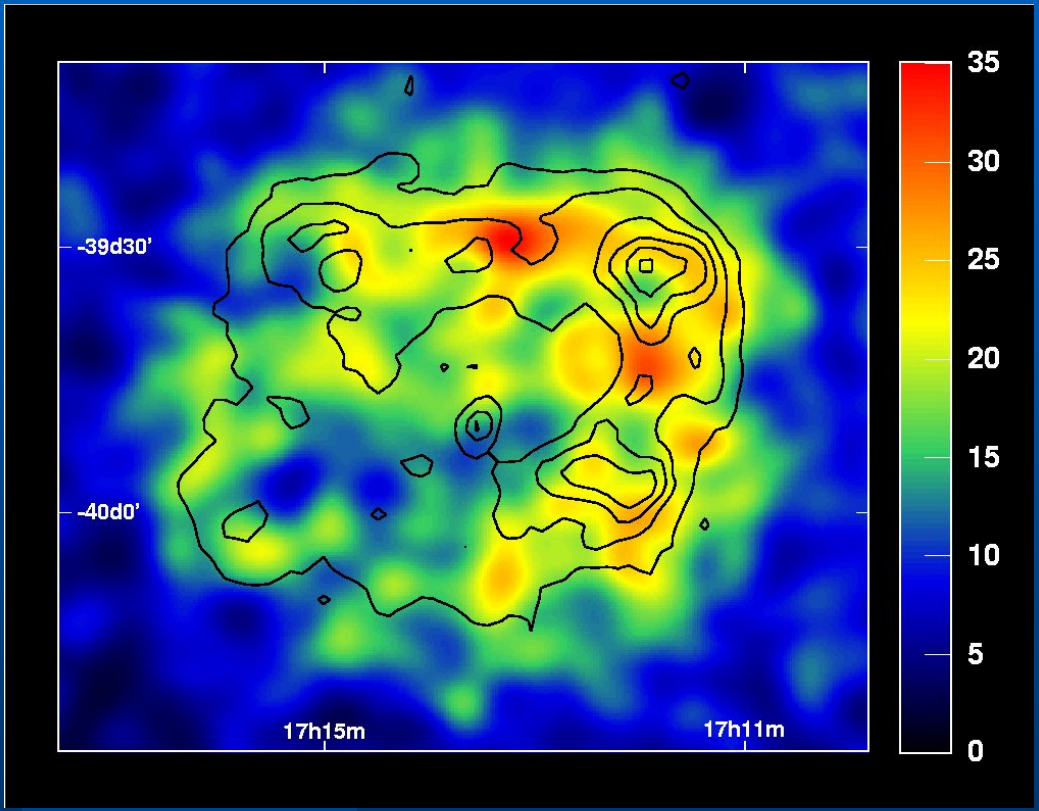




FIG. 1.—Model spectra from radio to X-ray frequencies. Radio data are collected in Ford & Reynolds (1995), and X-ray data are collected in Hamilton et al. (1986). The solid line shows the model with escape ($\lambda_{max} = 10^{17}$ cm) and with $B_1 = 3$ $\mu$G and $f = 10$. The dashed line has the same $B_1$ and $f$, but no escape. The dotted line invokes no escape, and has $B_1 = 0.6$ $\mu$G and $f = 1$.

# Discovery of TeV γ-rays from SNR



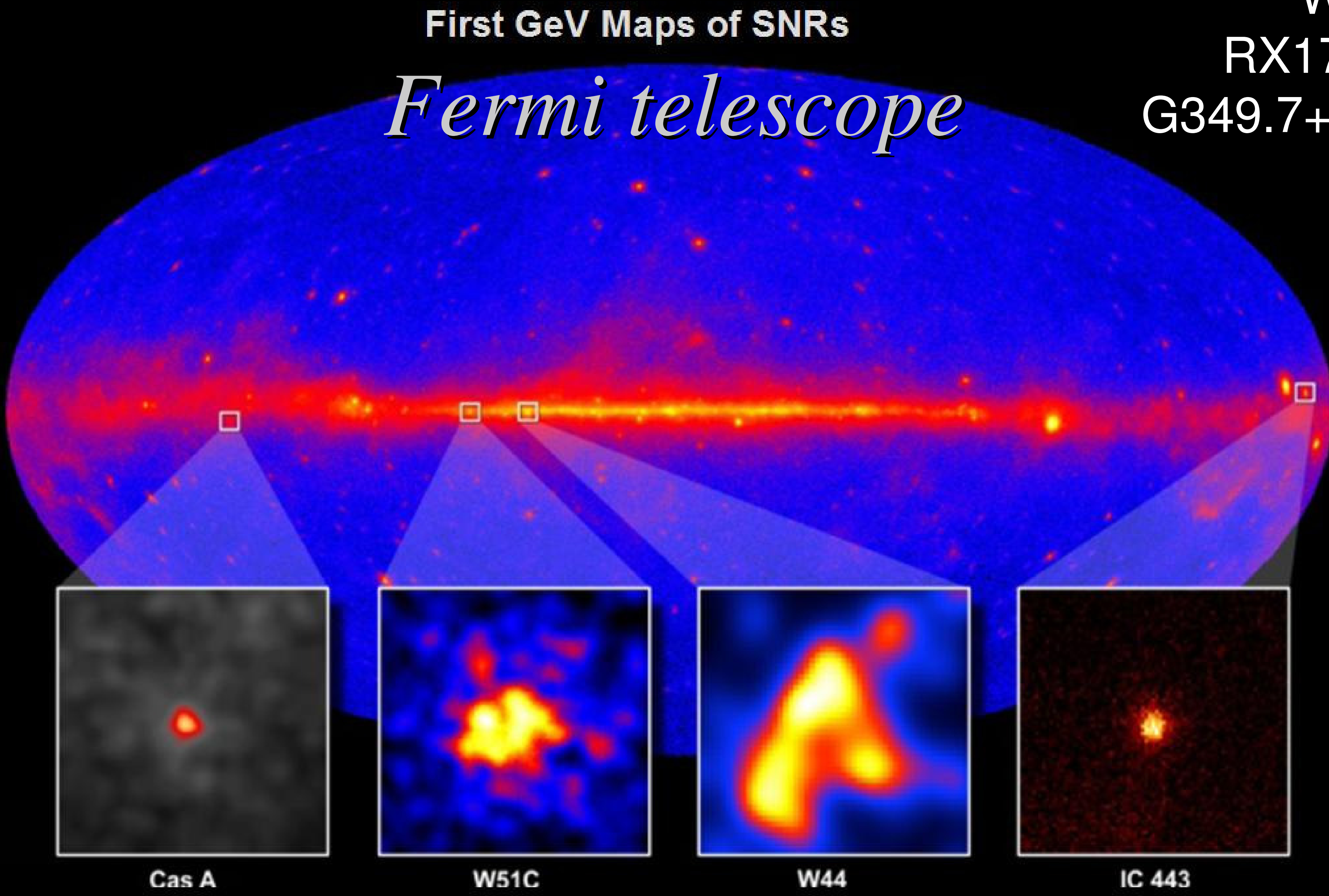

**RX J1713.7-3946**. Map of γ-rays (HESS) and X-ray contours (ASCA) [Aharonian et al., Nature 2004]

*2004*

The first map of an astronomical object (supernova remnant) in the hard γ-ray band was the next important step in studies of galactic CRs

# Fermi telescope

W28
RX1713
G349.7+0.2




2010

# *Nature of γ-rays from SNRs*

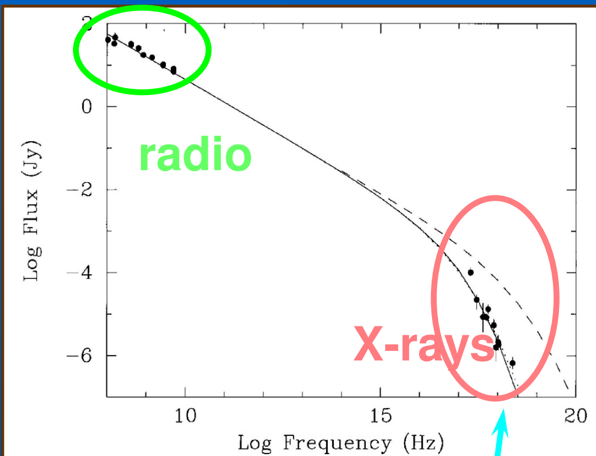
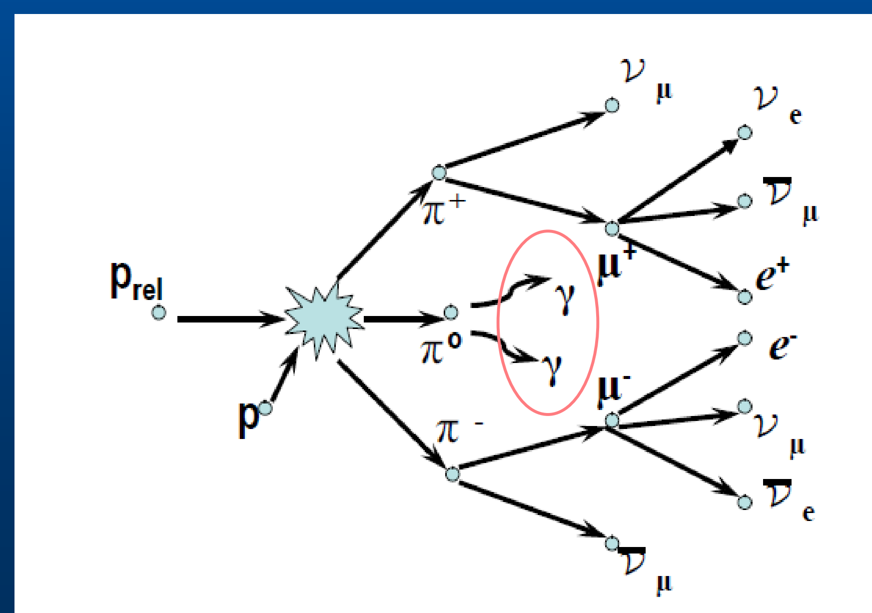



FIG. 1.—Model spectra from radio to X-ray frequencies. Radio data are collected in Ford & Reynolds (1995), and X-ray data are collected in Hamilton et al. (1986). The solid line shows the model with escape ($\lambda_{max} = 10^{17}$ cm) and with $B_1 = 3$ $\mu$G and $f = 10$. The dashed line has the same $B_1$ and $f$, but no escape. The dotted line invokes no escape, and has $B_1 = 0.6$ $\mu$G and $f = 1$.

<u>Leptonic</u> gamma-rays

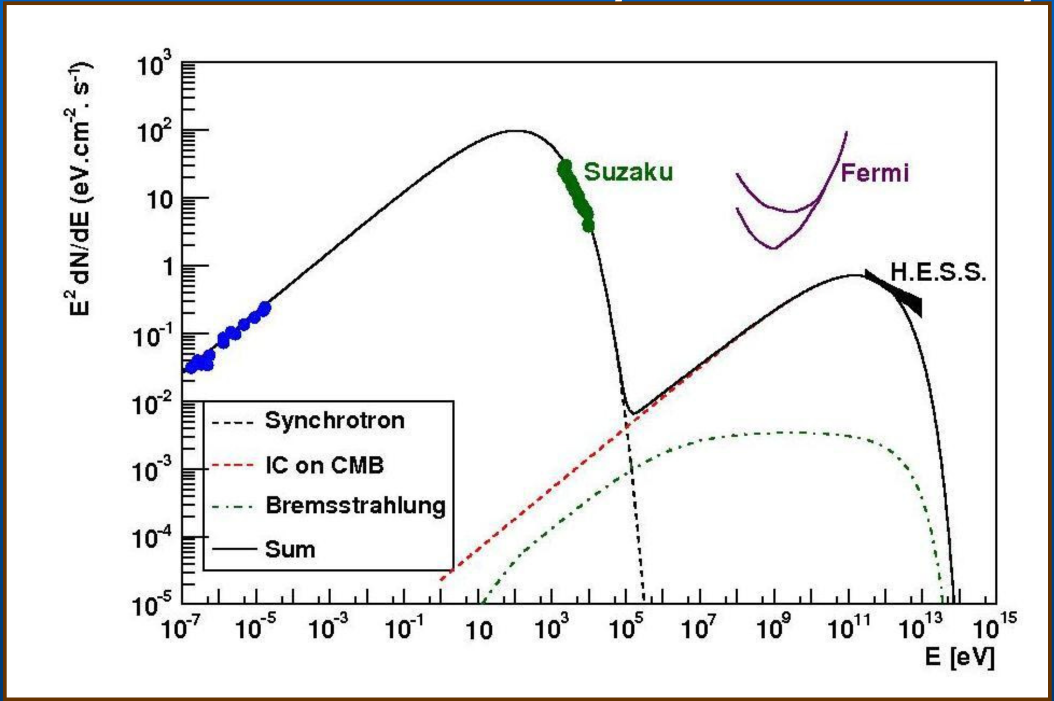
**The same electrons should emit also gamma-rays due to inverse Compton**

<u>Hadronic</u> gamma-rays

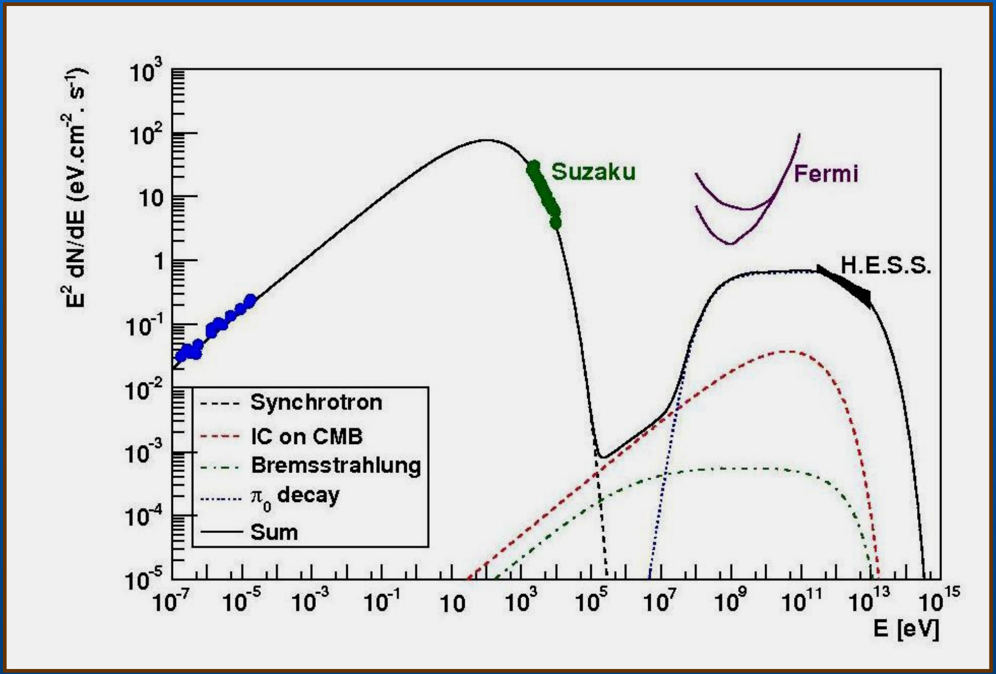


# Problem of the origin of γ-rays in SNRs

SN1006 [HESS Collaboration 2010]




Leptonic scenario

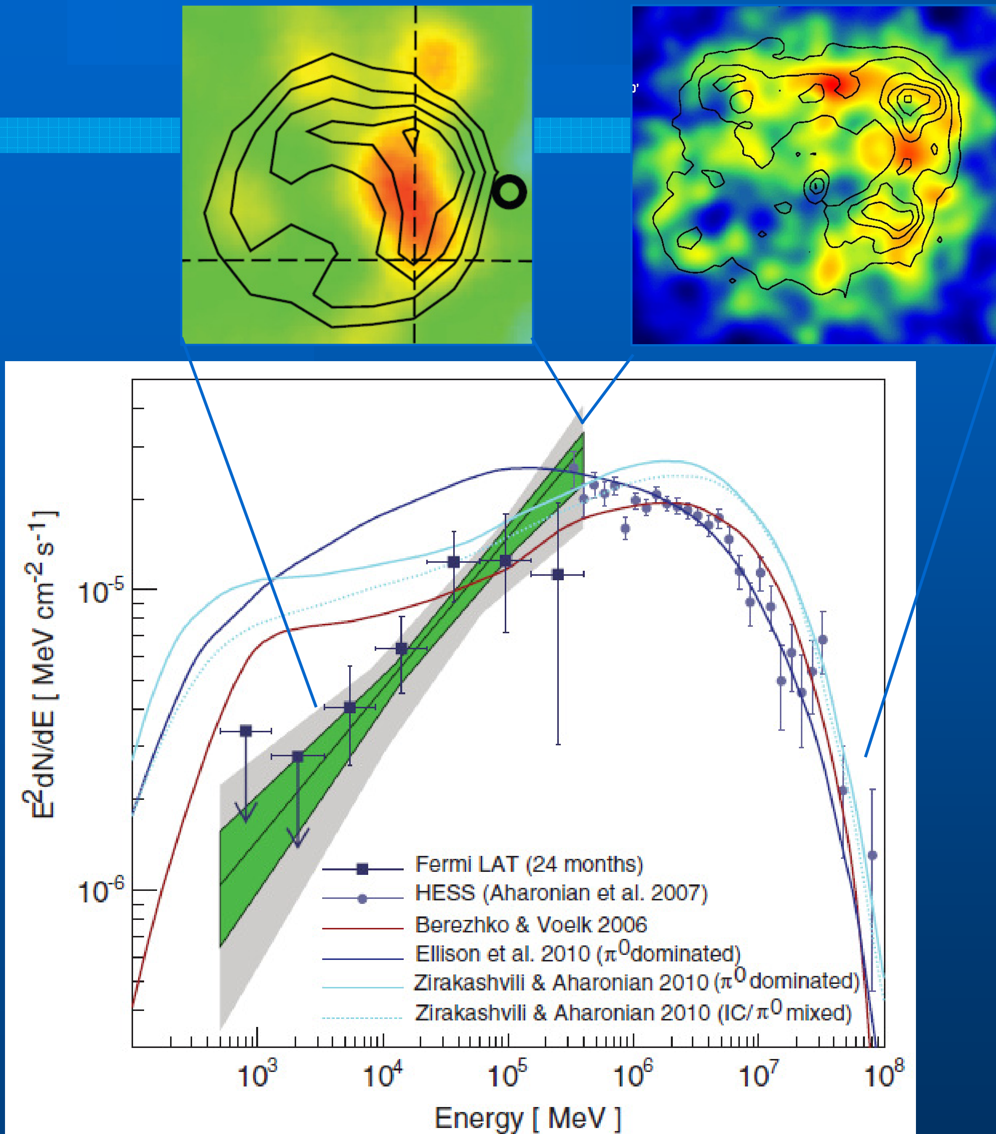



Hadronic scenario

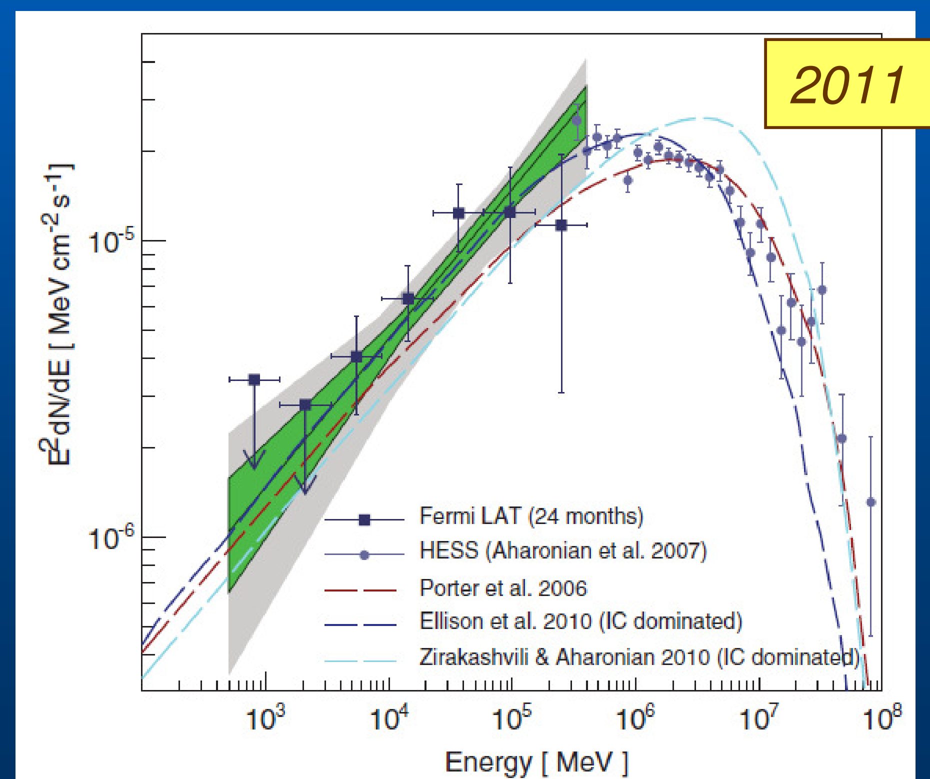
*What kind of particles emits gamma-rays: electrons or protons?*

# *FERMI observations – important step forward*

In 3 SNRs, FERMI allows us to distinguish between leptonic and hadronic scenario




*RX J1713.7–3946* [Abdo et al. 2011]

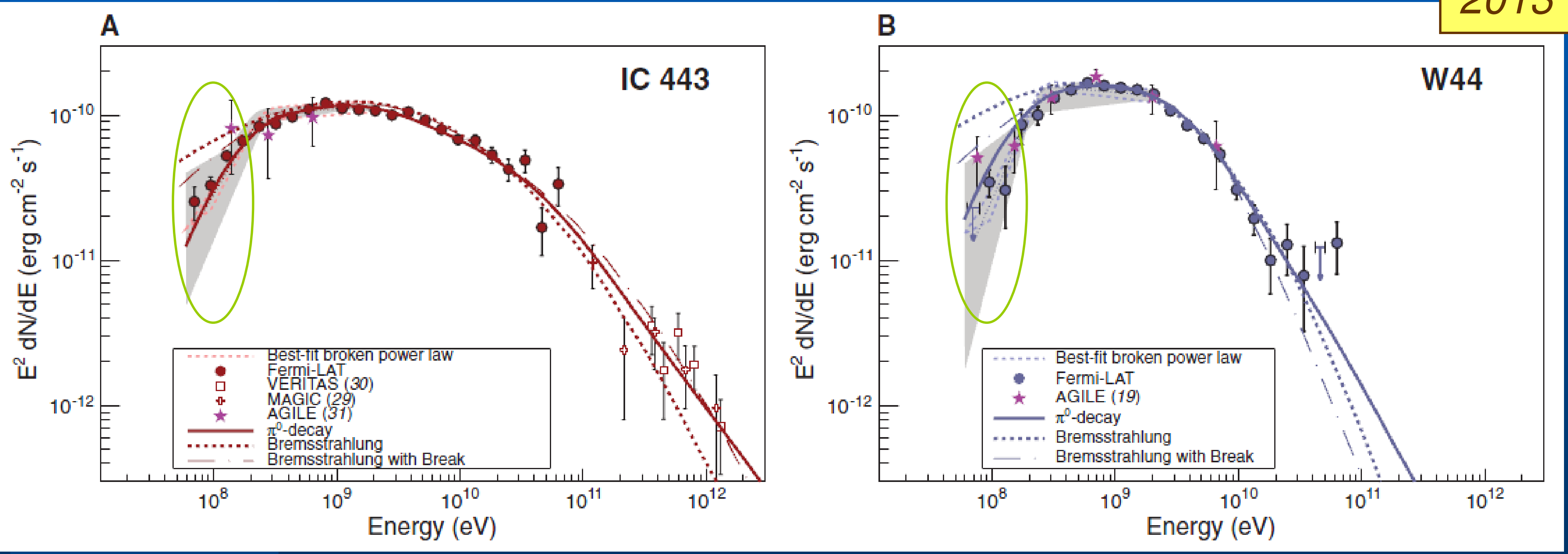



**Leptonic scenario**

# *FERMI observations – important step forward*

***No 5*** result in
***Science*'s Top 10**
**Breakthroughs of 2013**

*2013*

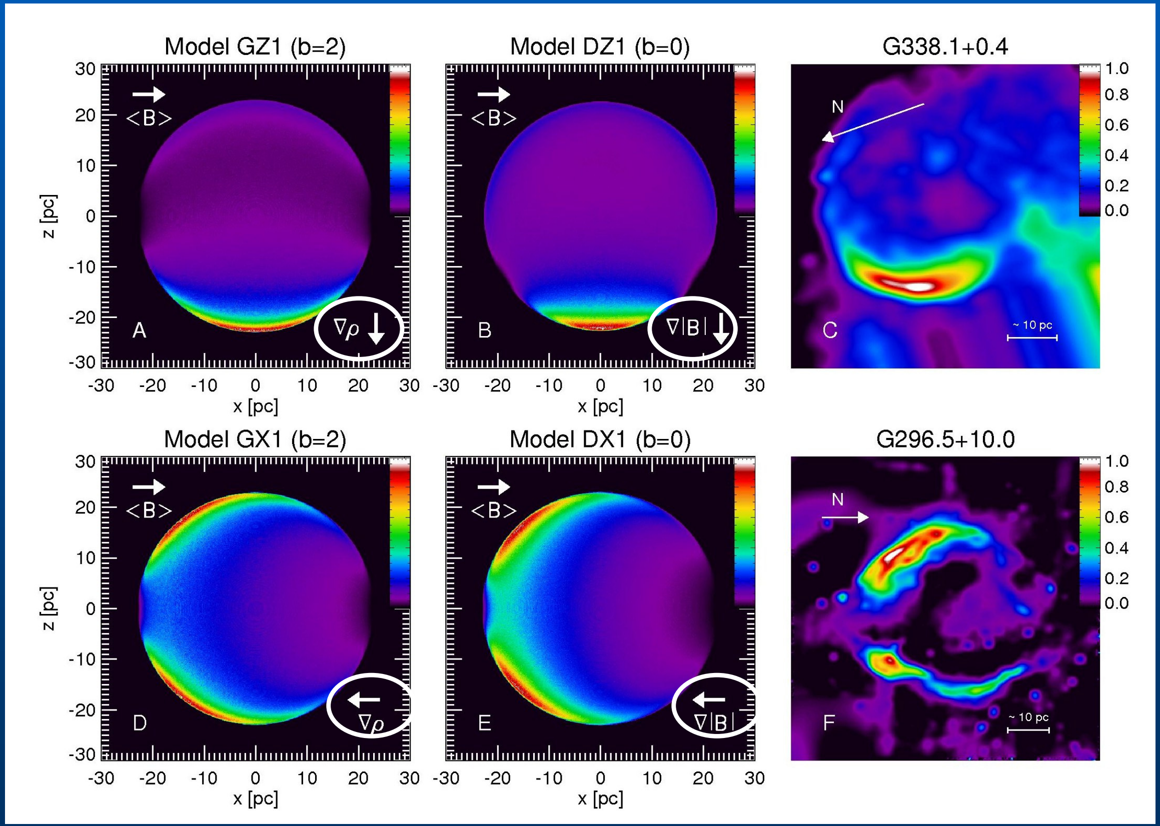



*IC 443 and W44 [Ackermann et al. 2013]*

**Hadronic scenario**

# *Surface brightness maps of SNRs*

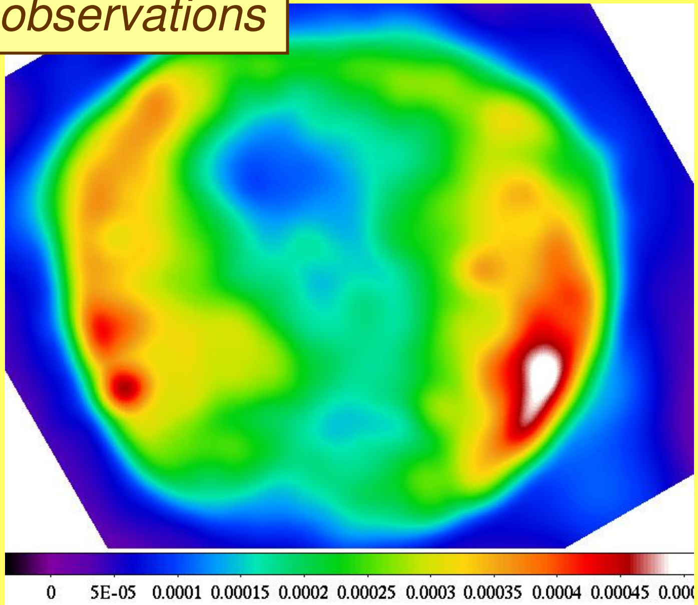
- **Important source of information about CR properties in accelerators**
- **A number of our works are devoted to maps of SNRs in different bands**



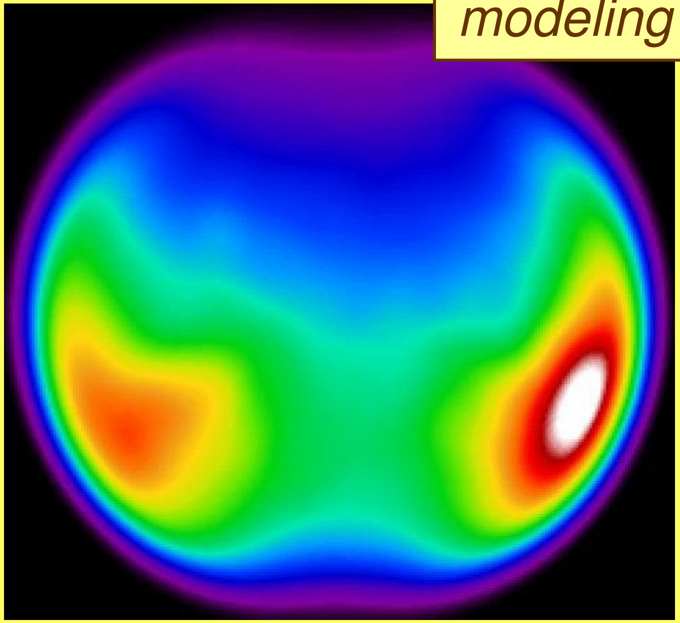
An example

# Radio morphology of SN1006

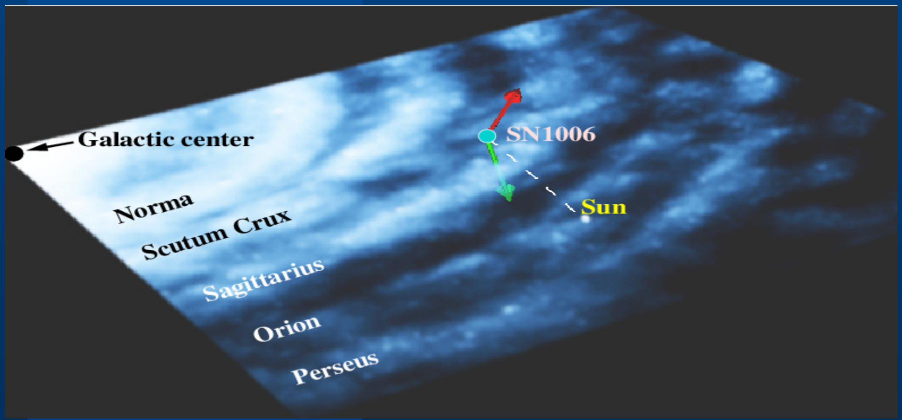
*observations*

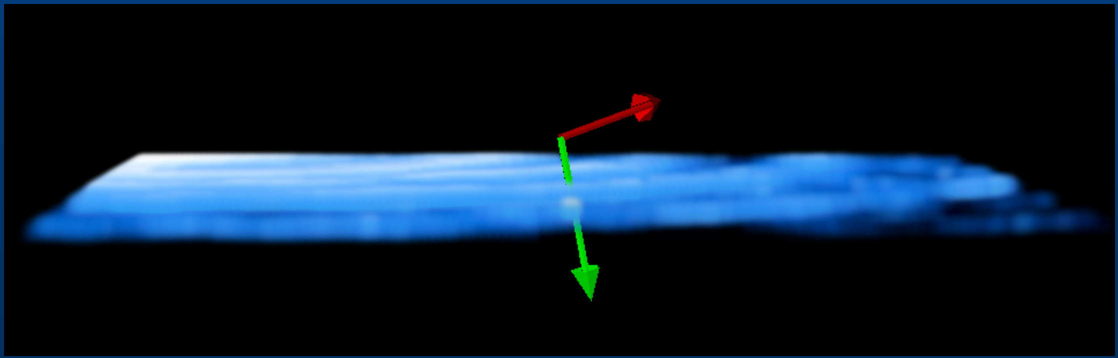



*modeling*



**3D structure of ISMF around SN1006**



# Main points

- **A scientific field:** *astroparticles and cosmic accelerators*
  - Cosmic Ray Astrophysics samples conditions which never be reached on Earth
  - It is closely related to High-energy Astrophysics (emission in radio, X-rays and $\gamma$-rays)

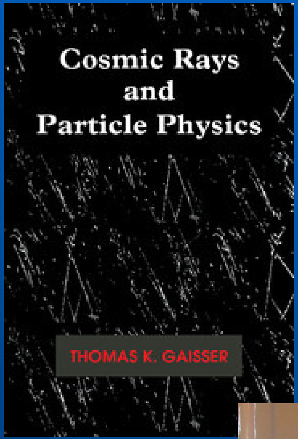
- **Cosmic rays basics:** *what are they, what they are, where do they come from?*

- **UHECRs:** *GZK cutoff, composition, sources*

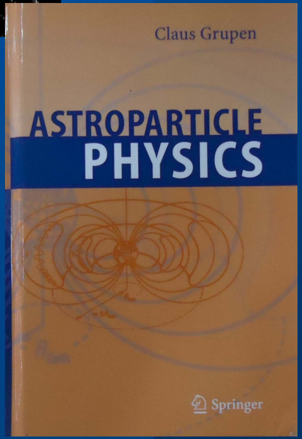
- **Galactic CRs:** *SNRs as sources, CRs are studied through their high-energy emission*

# Further reading

## Text-book

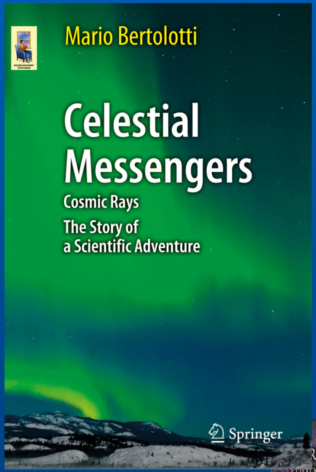



T.Gaisser
(1991)

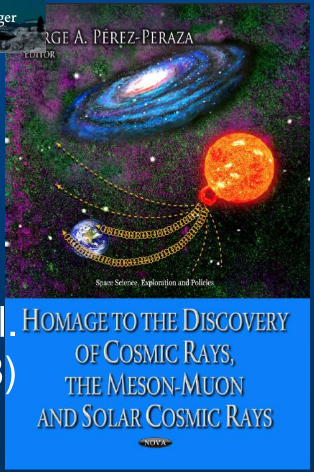



C.Grupen
(2005)

## History




M.Bertolotti
(2013)



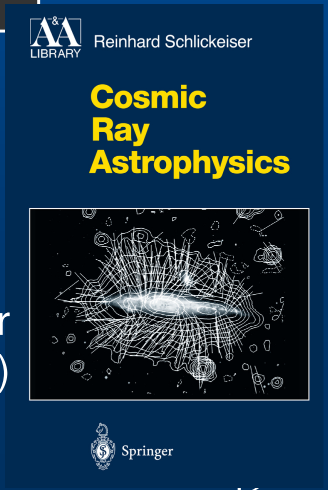

J. Perez-Peraza et al.
(2013)

## Review

***Astrophysics of Cosmic Rays***

Ed. Ginzburg

V.Ginzburg et al.
(1990)




R. Schlickeiser
(2002)