Cosmic Rays

History

1785 **Charles Coulomb, 1900 Elster and Geitel**

Charged body in air becomes discharged – there are ions in the atmosphere

1902 **Rutherford, McLennan, Burton:**

air is traversed by extremely penetrating radiation (γ rays excluded later)

1912 **Victor Hess**

Discovery of “Cosmic Radiation” in 5350m balloon flight, 1936 Nobel Prize

1933 **Anderson**

Discovery of the positron in CRs – shared 1936 Nobel Prize with Hess

1933 **Sir Arthur Compton**

Radiation intensity depends on magnetic latitude

1937 **Street and Stevenson**

Discovery of the muon in CRs (207 times heavier than electron)

1938 **Pierre Auger and Roland Maze**

Rays in detectors separated by 20 m (later 200m) arrive simultaneously

1985 **Sekido and Elliot**

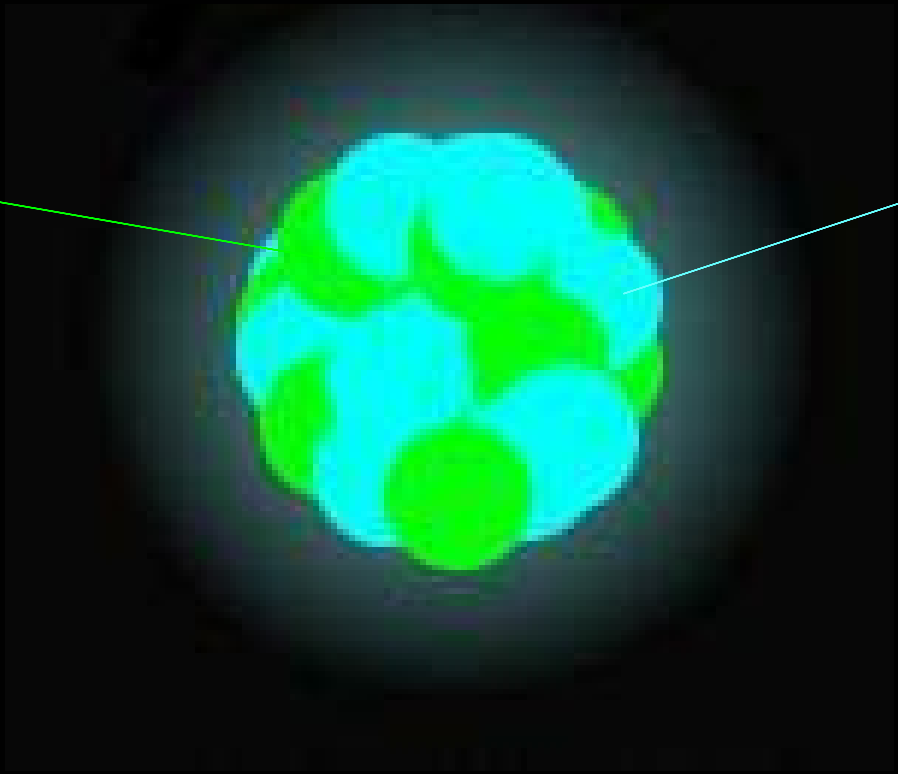
First correct explanation of what CR’s are …

Open question today: where do they come from ?

Discovery of Cosmic Rays

Victor Hess, return from his decisive flight 1912
(reached 5350 m !)
radiation increase > 2500m
Nobel Prize 1936

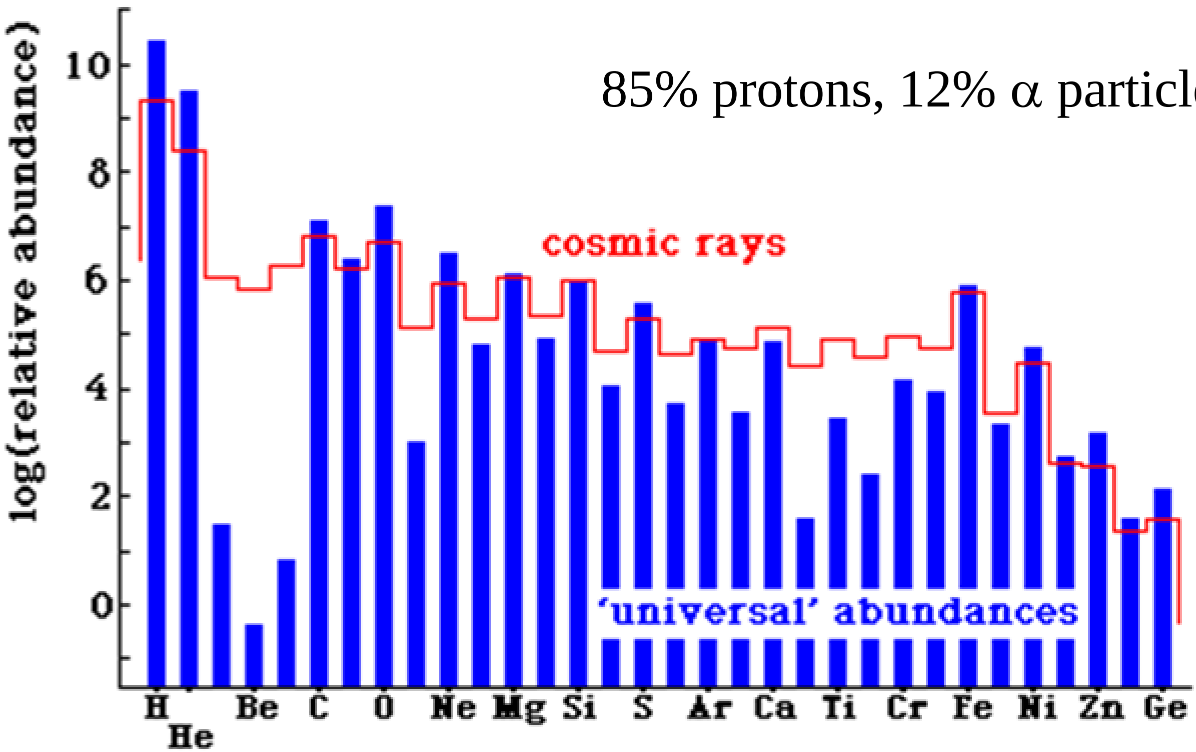
What are cosmic rays ?



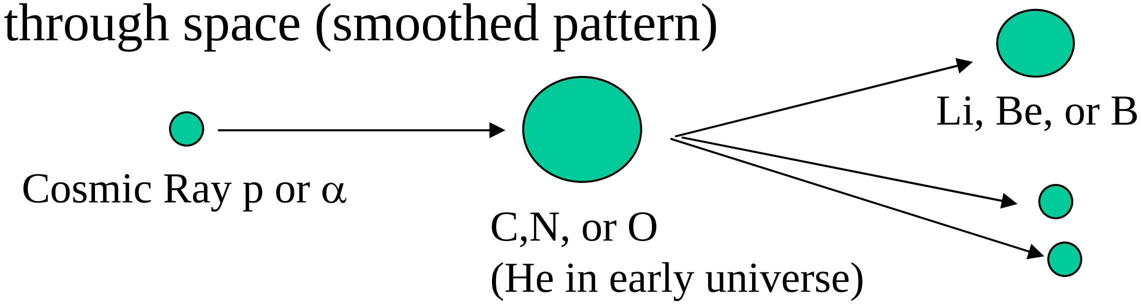
Ordinary nuclei (ions) flying through space
(single protons, helium nuclei, carbon, iron, …)

Satellite observations of **primaries** **(the particle that comes from outer space and hits the atmosphere)**

Primaries: energetic ions of all stable isotopes:

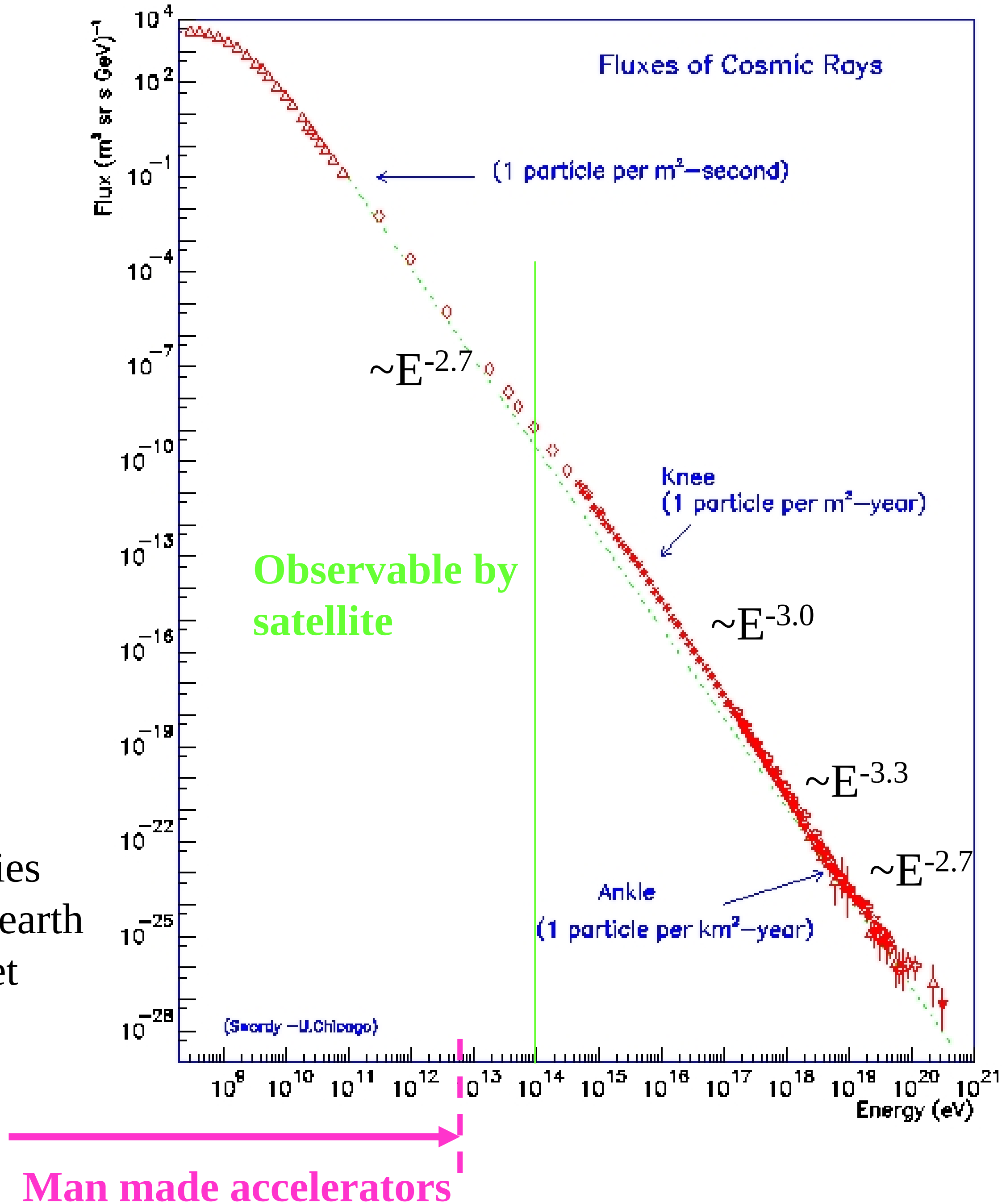


Similar to solar elemental abundance distribution but differences due to spallation during travel through space (smoothed pattern)



Major source of ^{6}Li, ^{9}Be, ^{10}B in the Universe (some ^{7}Li, ^{11}B)

Energies of primary cosmic rays



Lower energies do not reach earth (but might get collected)

UHECR's:

40 events > 4e19 eV
(more by Auger now …)
7 events > 1e20 eV
Record: October 15, 1991
Fly's Eye: 3e20 eV

What arrives on earth? Reminder: Physics Particle Zoo

Leptons:

	electron	muon	tauon
+1	e^+	μ^+	τ^+
-1	**e^-**	μ^-	τ^-

Quarks:

Q			
+2/3	**up**	charm	top
-1/3	**down**	strange	bottom

Baryons: 3 quarks

Meson: quark + antiquark

Force carriers (bosons) Strong: g (8), Weak : Z^0,W^+,W^-, Electromagnetic: γ

Ordinary matter

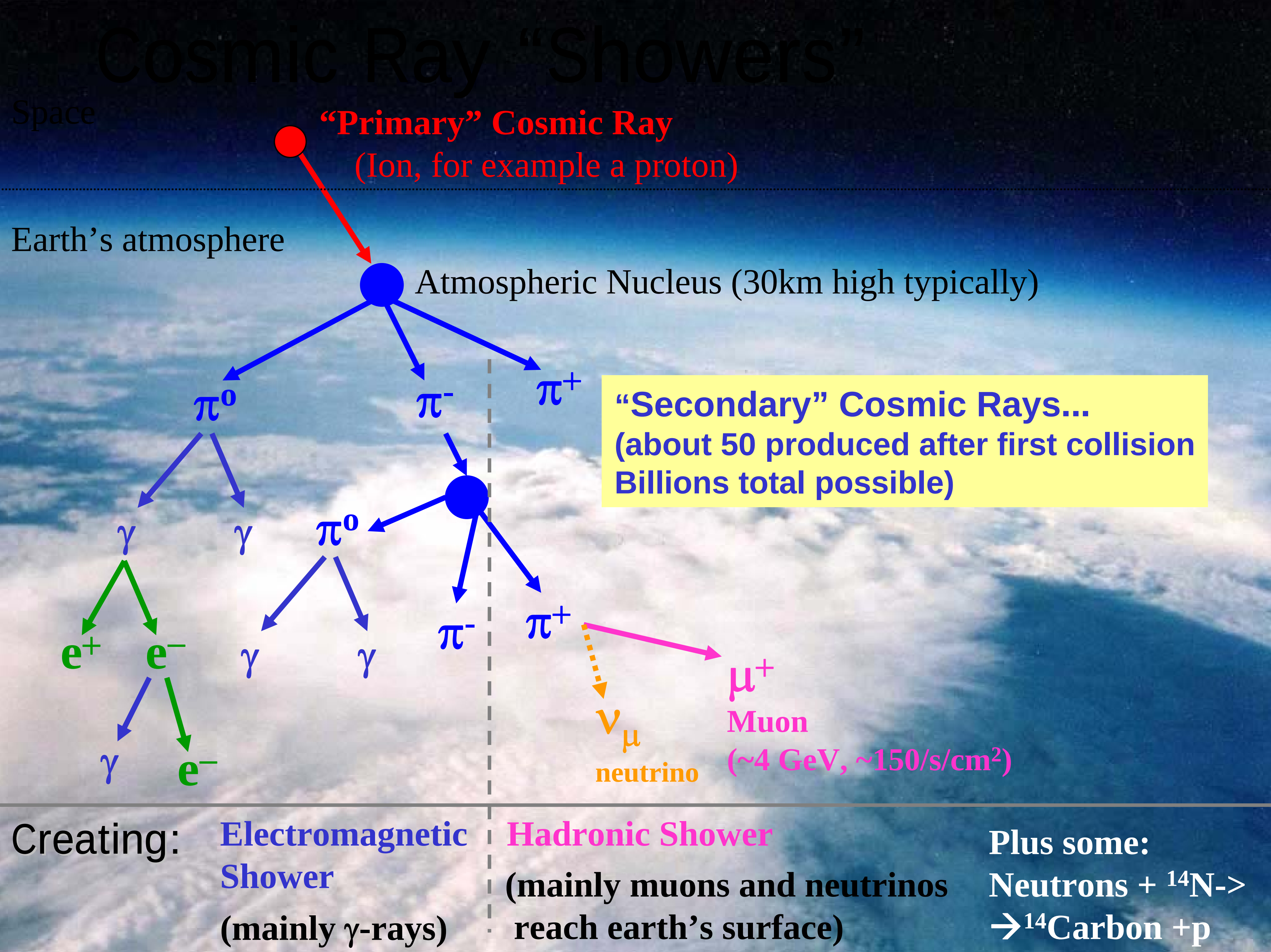
proton = uud
neutron = ddu

Nuclei = combinations of protons, neutrons, and electrons

Pions: $\pi^+ = u\bar{d}$ — 26 ns lifetime – decay into μ^+ and ν_μ

$\pi^- = d\bar{u}$ — 26 ns lifetime – decay into μ^- and ν_μ

$\pi^0 = u\bar{u} + d\bar{d}$ — 1e-17 s lifetime – decay into $\gamma\gamma$



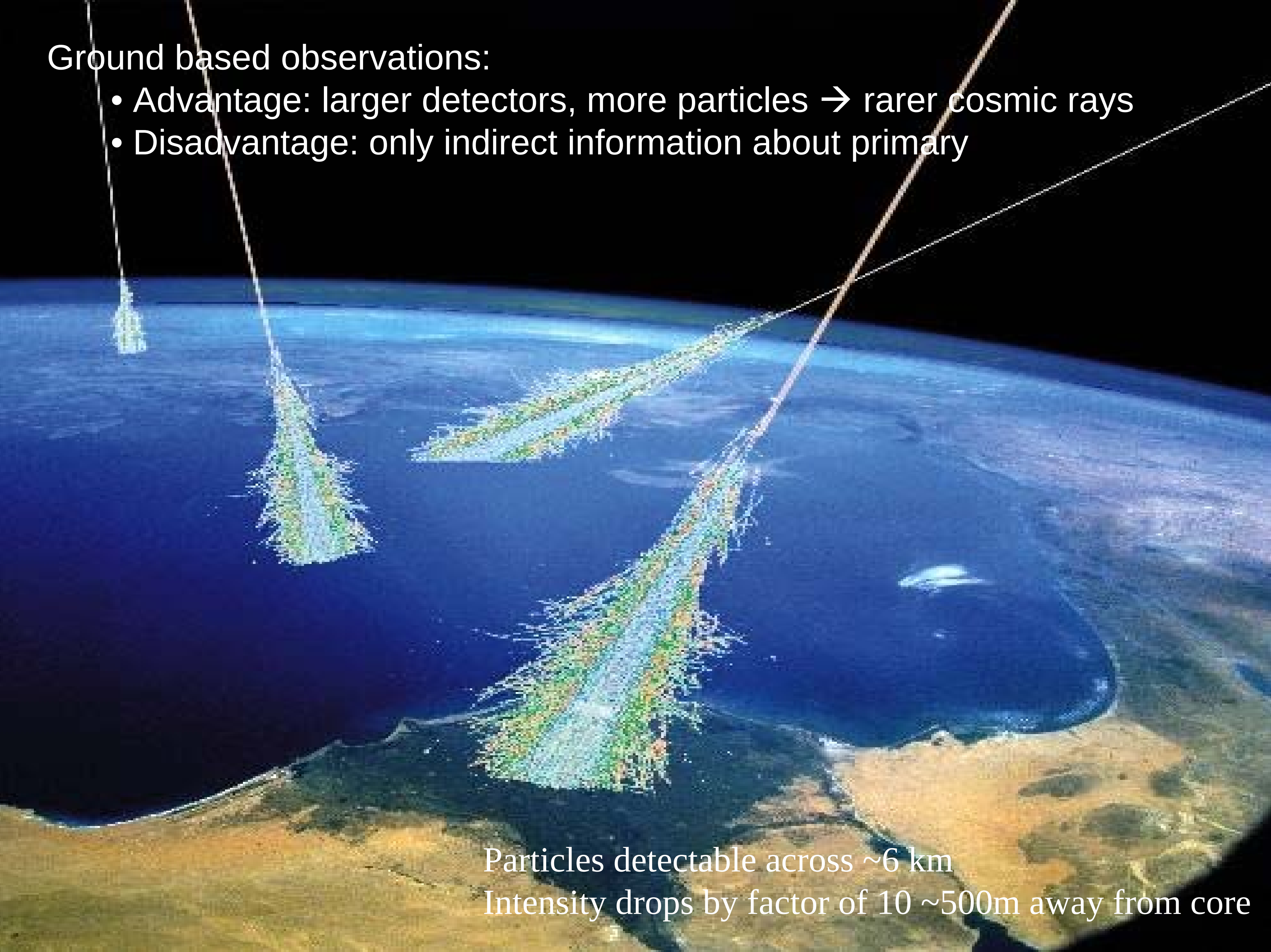
Cosmic Ray "Showers"
Space
"Primary" Cosmic Ray
(Ion, for example a proton)
Earth's atmosphere
Atmospheric Nucleus (30km high typically)
π^o
π^-
π^+
"Secondary" Cosmic Rays...
(about 50 produced after first collision
Billions total possible)
γ
γ
π^o
e^+
e^−
γ
γ
π^-
π^+
μ^+
Muon
(~4 GeV, ~150/s/cm^2)
ν_μ
neutrino
γ
e^−
Creating:
Electromagnetic Shower
(mainly γ-rays)
Hadronic Shower
(mainly muons and neutrinos reach earth's surface)
Plus some:
Neutrons + ^14N->
→^14Carbon +p

Cosmic ray muons on earth

- Lifetime: 2.2 μs – then decay into electron and neutrino
- Travel time from production in atmosphere (~15 km): ~50 μs
  why do we see them ?
- Average energy: ~4 GeV (remember: 1 eV = 1.6e-19 J)
- Typical intensity: 150 per square meter and second
- Modulation of intensity with sun activity and atmospheric
  pressure ~0.1%

Ground based observations:

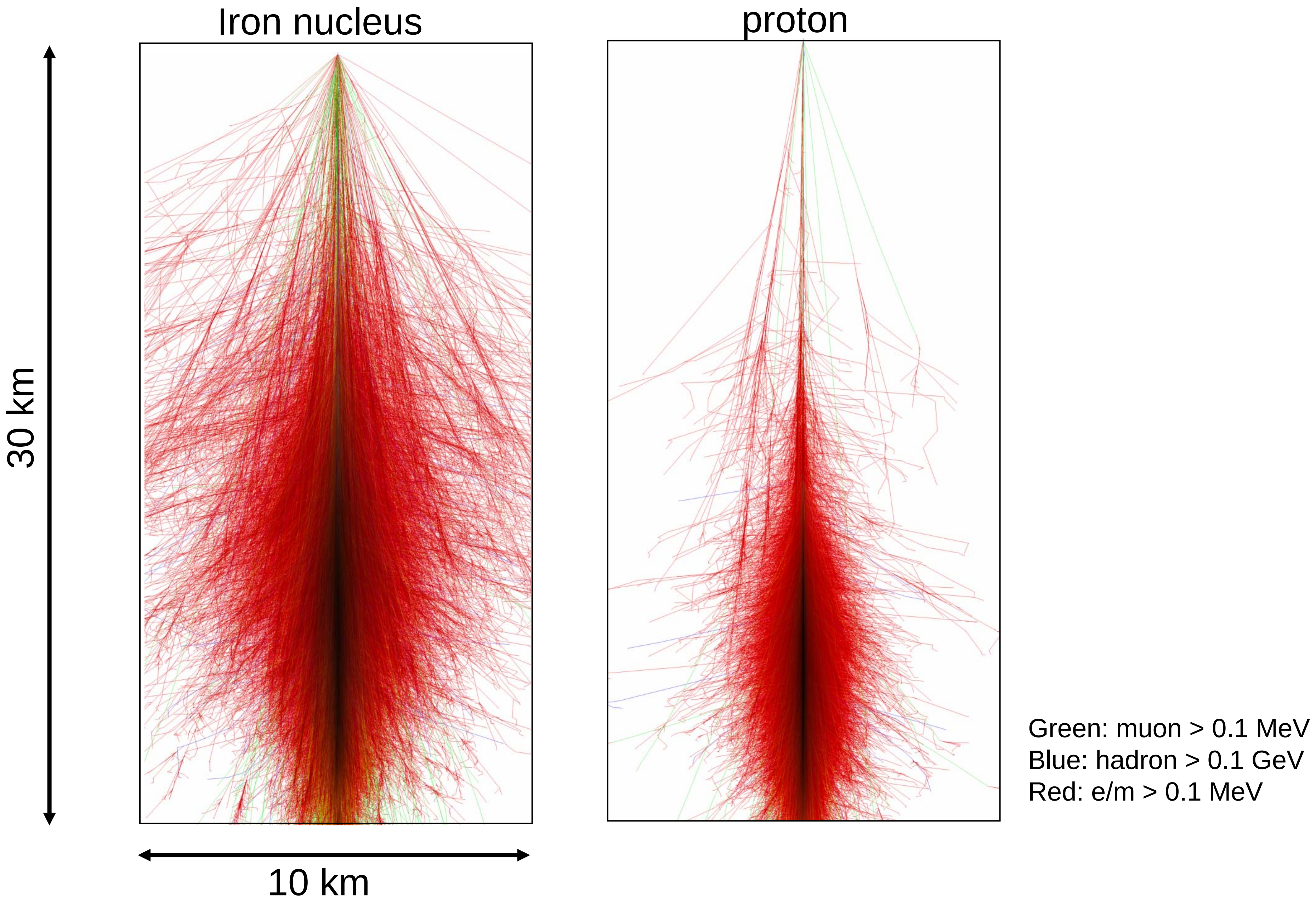
- Advantage: larger detectors, more particles → rarer cosmic rays
- Disadvantage: only indirect information about primary



Particles detectable across ~6 km
Intensity drops by factor of 10 ~500m away from core

A “real” simulation

F. Schmidt, "CORSIKA Shower Images", http://www.ast.leeds.ac.uk/~fs/showerimages.html

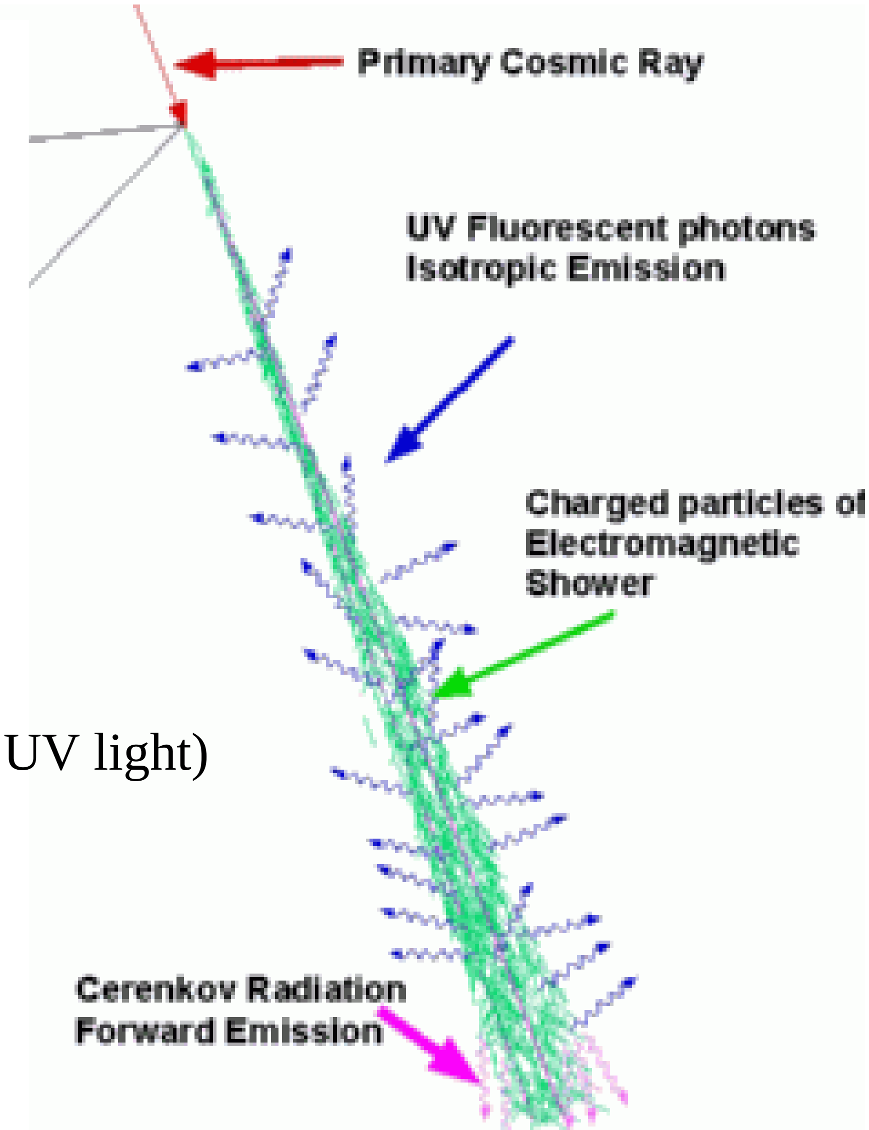


Method 1: Particle detector arrays

AGASA (Japan)	111 scintillation detectors over 100 km^2
Pierre Auger	1600 detectors, 3000 km^2 (still being constructed)

Other example: Casa Mia, Utah:

Method 2: Air flourescence



Use Air as detector (Nitrogen fluorescence → UV light)

Observe fluorescence with telescopes

Particles detectable across ~6 km

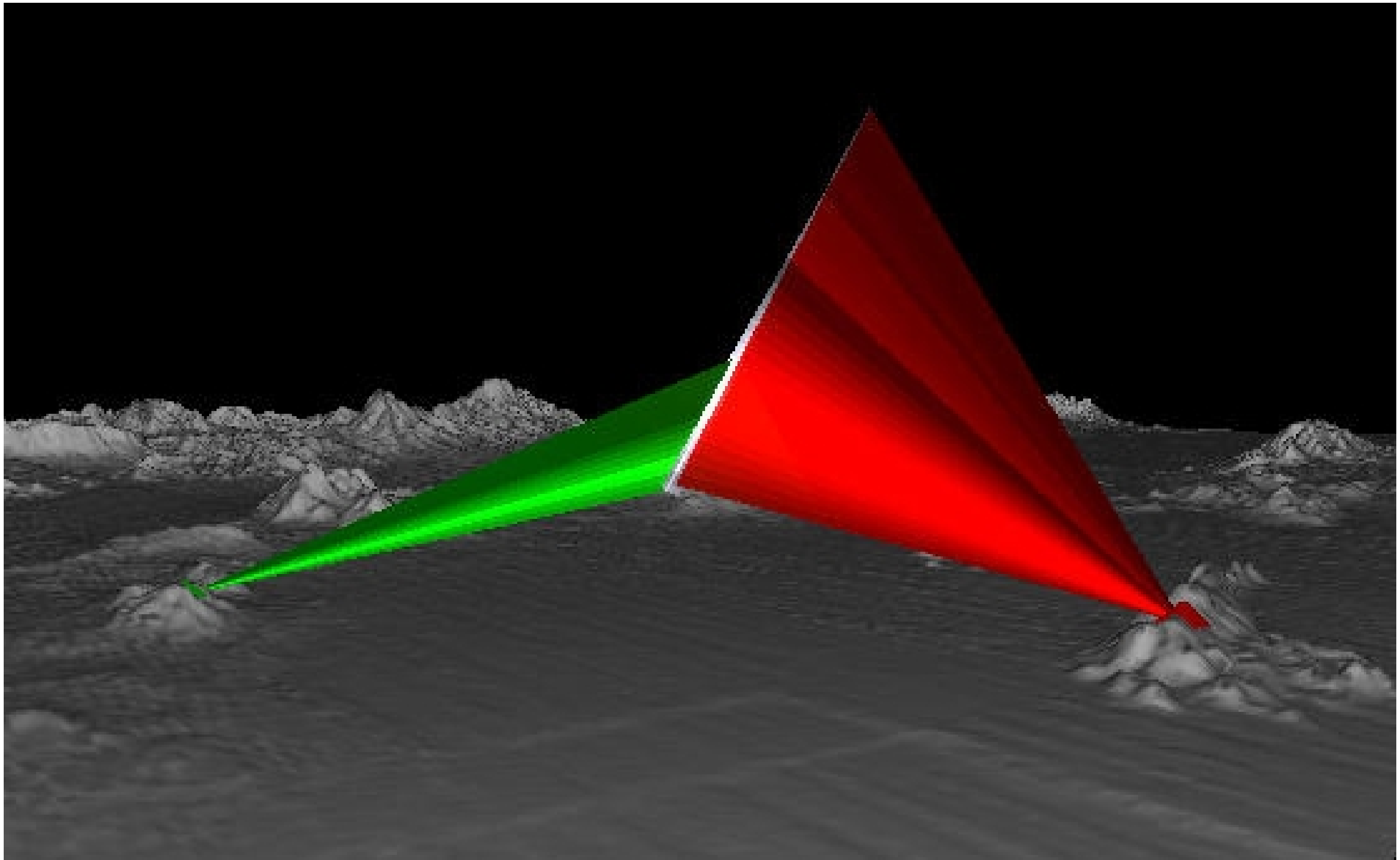
Intensity drops by factor of 10 ~500m away from core

Air Scintillation detector

1981 – 1992: Fly’s Eye, Utah

1999 - : HiRes, same site

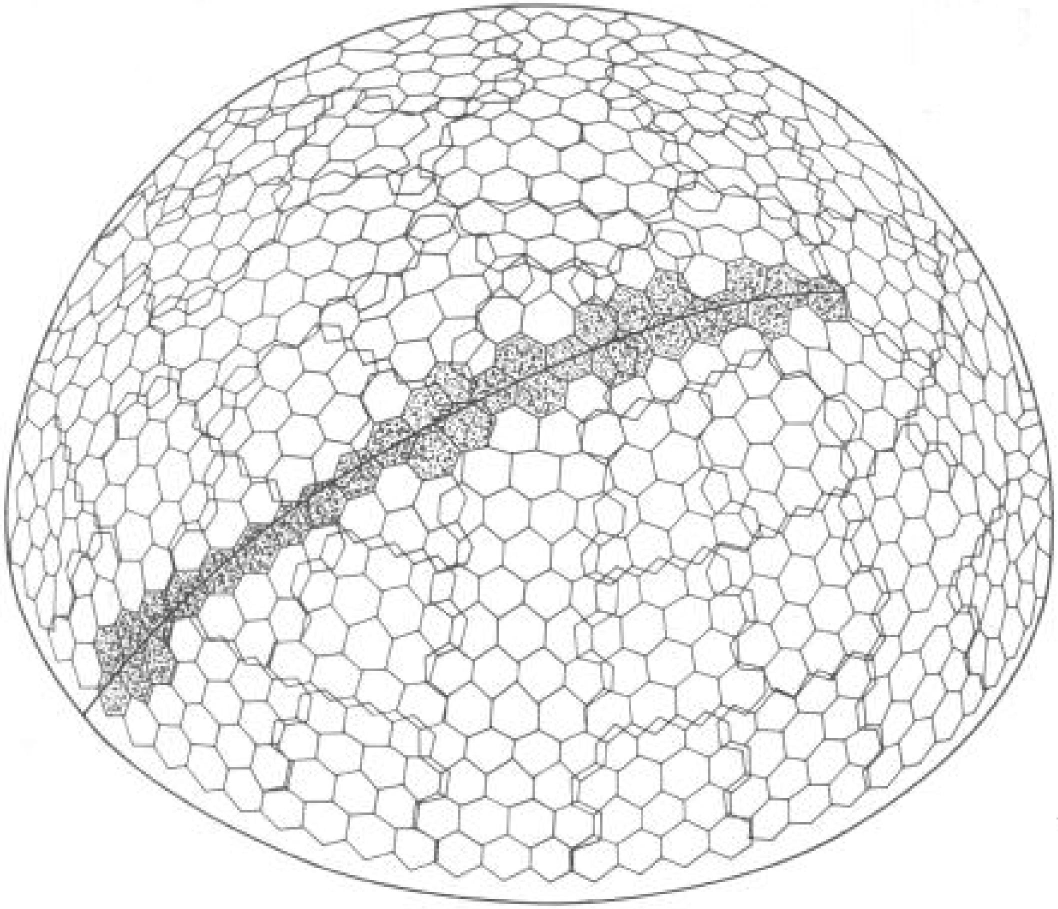
- 2 detector systems for stereo view
- 42 and 22 mirrors a 2m diameter
- each mirror reflects light into 256 photomultipliers
- see’s showers up to 20-30 km height



Fly’s eye

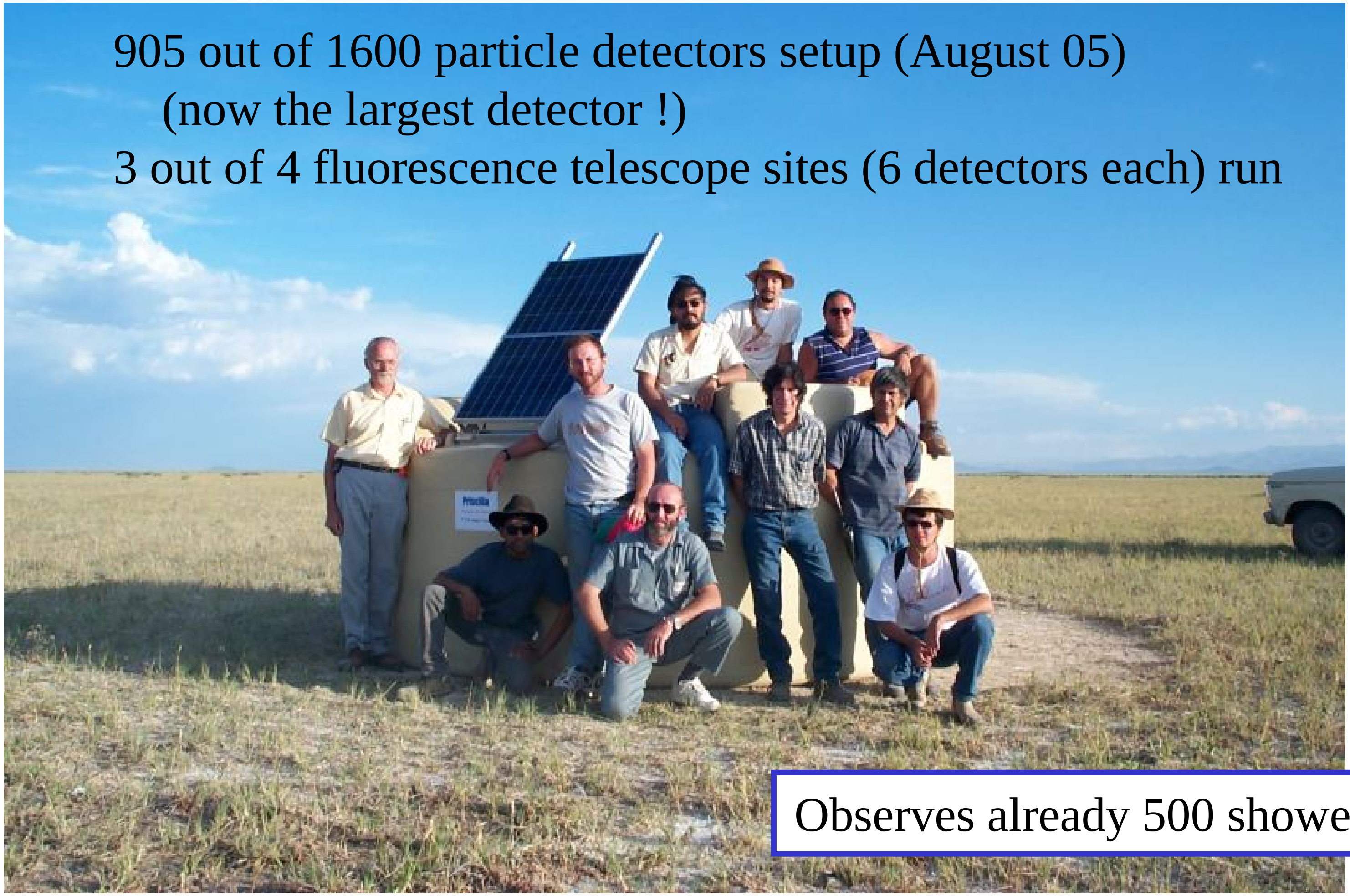
Fly’s Eye

Fly’s eye principle



Pierre Auger Project

Combination of both techniques (particles with water Cherenkov)
Site: Argentina + ?. Construction started, 18 nations involved
Largest detector ever: 3000 km^2, 1600 detectors



905 out of 1600 particle detectors setup (August 05)
(now the largest detector !)
3 out of 4 fluorescence telescope sites (6 detectors each) run

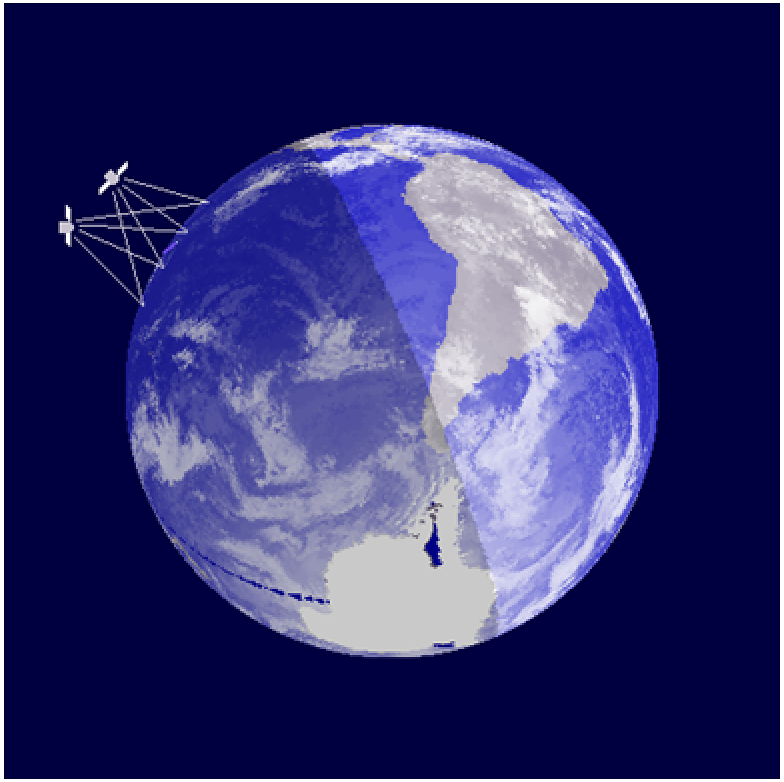
Observes already 500 showers/day

http://augersw1.physics.utah.edu/ED/

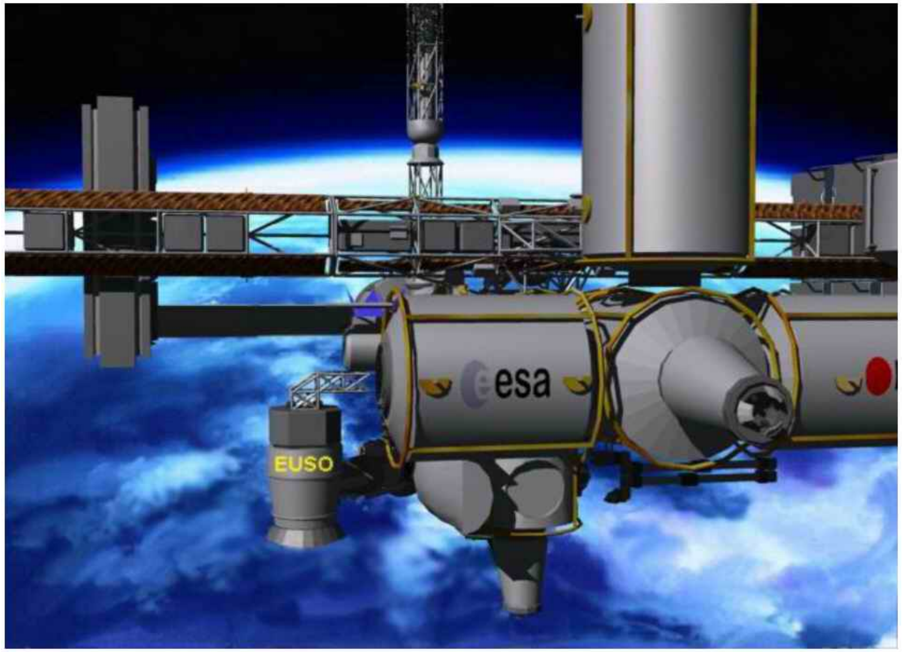
Other planned next generation observatories

Idea: observe fluorescence from space to use larger detector volume

OWL (NASA)
(Orbiting Wide Angle Light Collectors)



EUSO (ESA for ISS)
(Extreme Universe Space Observatory)



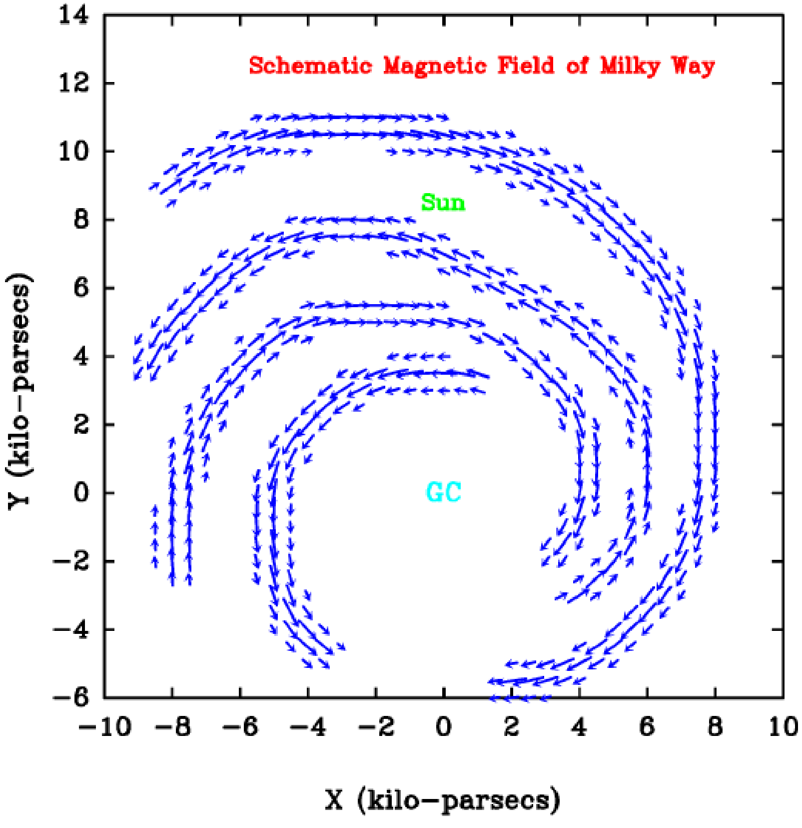
Where do cosmic rays come from?

Why not look at arrival direction?

Origin of cosmic rays with E < 10^{18} eV

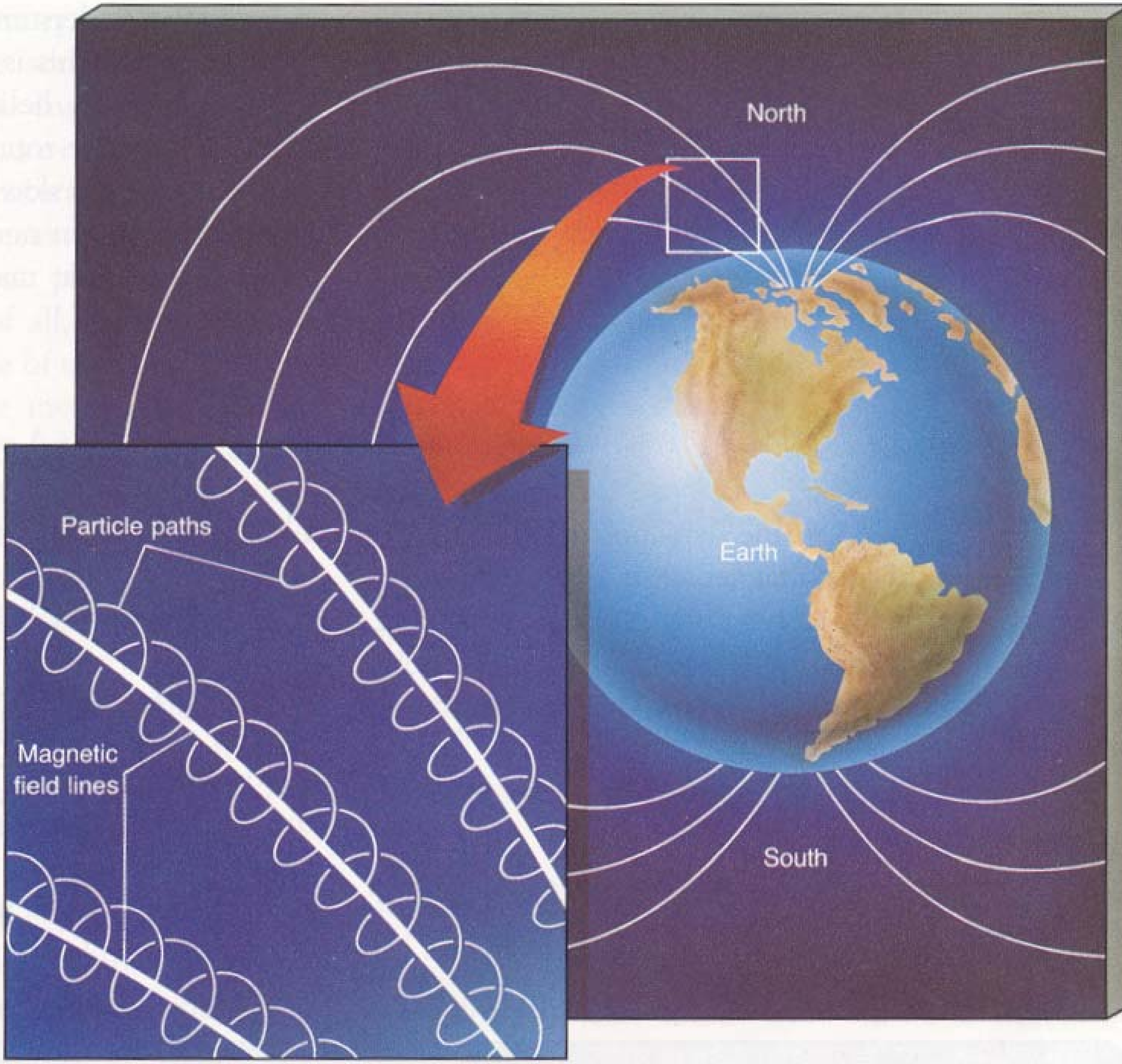
Direction cannot be determined because of deflection in galactic magnetic field

Galactic magnetic field



M83 spiral galaxy

Typical strength: 10s of micro Gauss (intergalactic 10 nano Gauss, earth 0.3-0.6)


North
Earth
South
Particle paths
Magnetic
field lines

X-ray image by Chandra of Supernova 1006

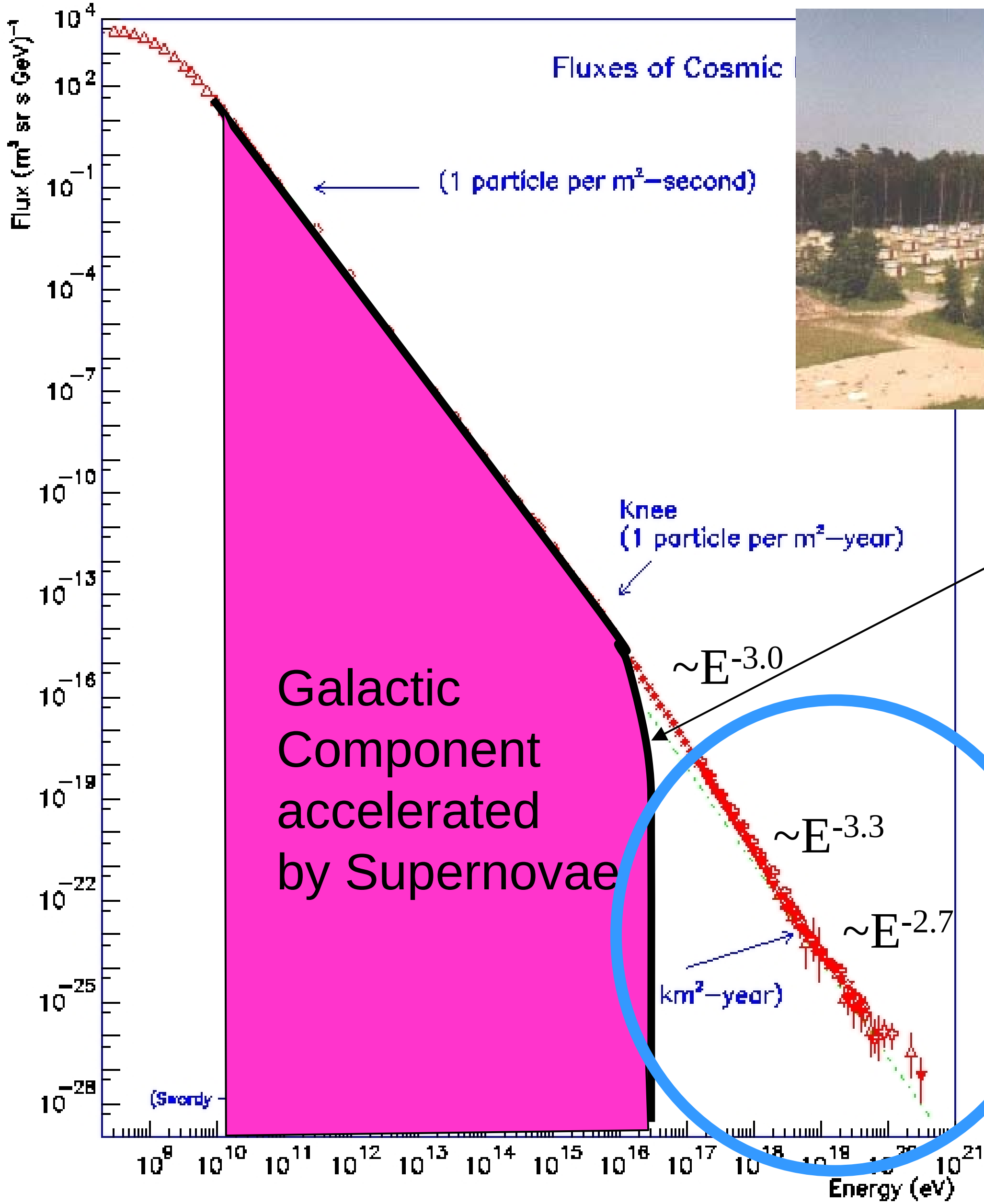
(7ly away, brightest SN on record, type Ia ?)

Blue: X-rays by high energy particles

Red: X-rays from heated gass (reverse shock)

Shock wave hits gas surrounding the explosion

Energies of primary cosmic rays



Gradual decline
p drop first
Fe somewhat higher
(shown by KASCADE)

So what are
these ????

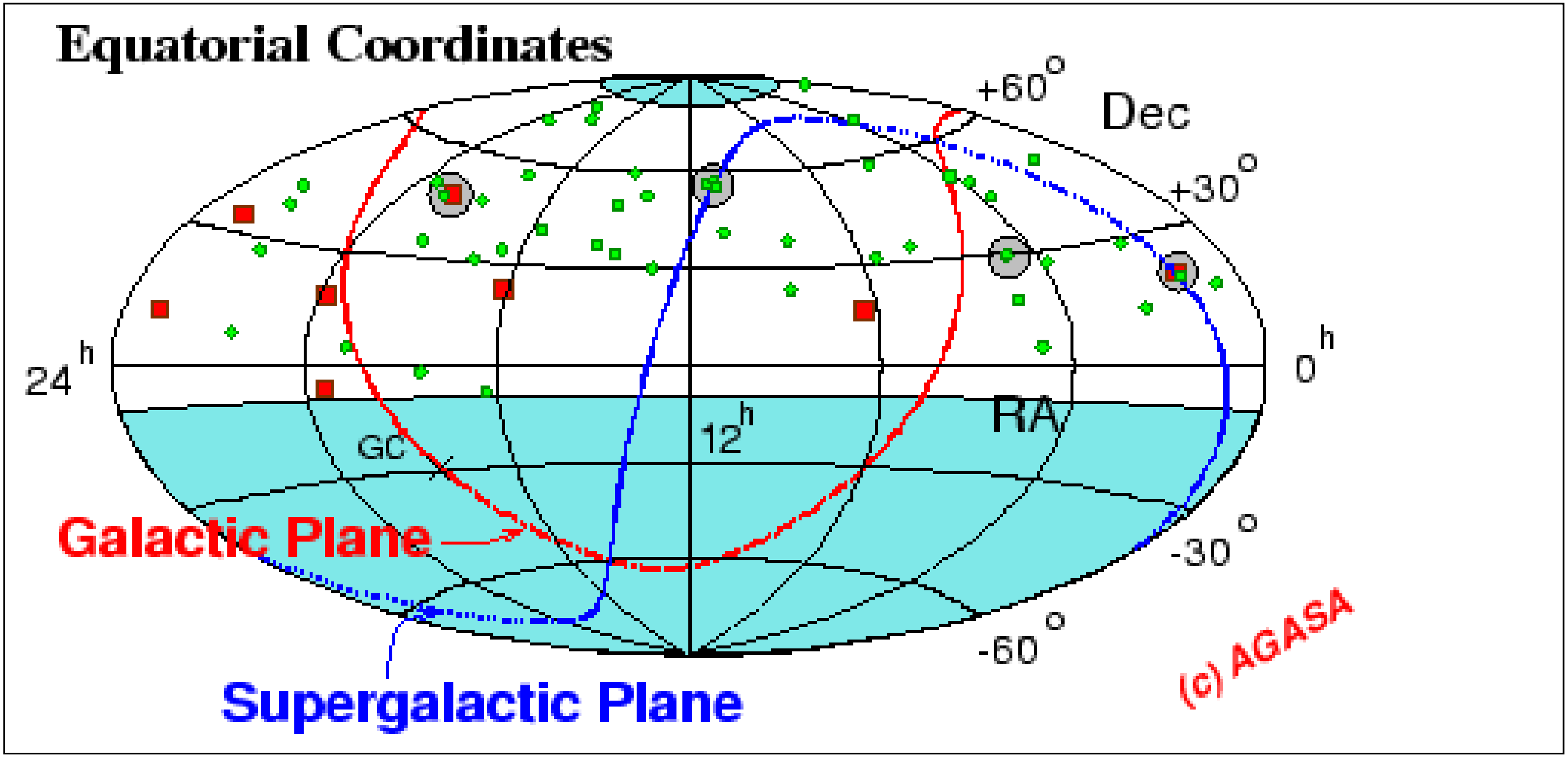
Good news:
high enough energy
to indicate arrival direction

Ultra high energy cosmic rays (UHECR) $E > 5 \times 10^{19}$ eV before Auger

Record event: 3×10^{20} eV 1991 with Fly's eye

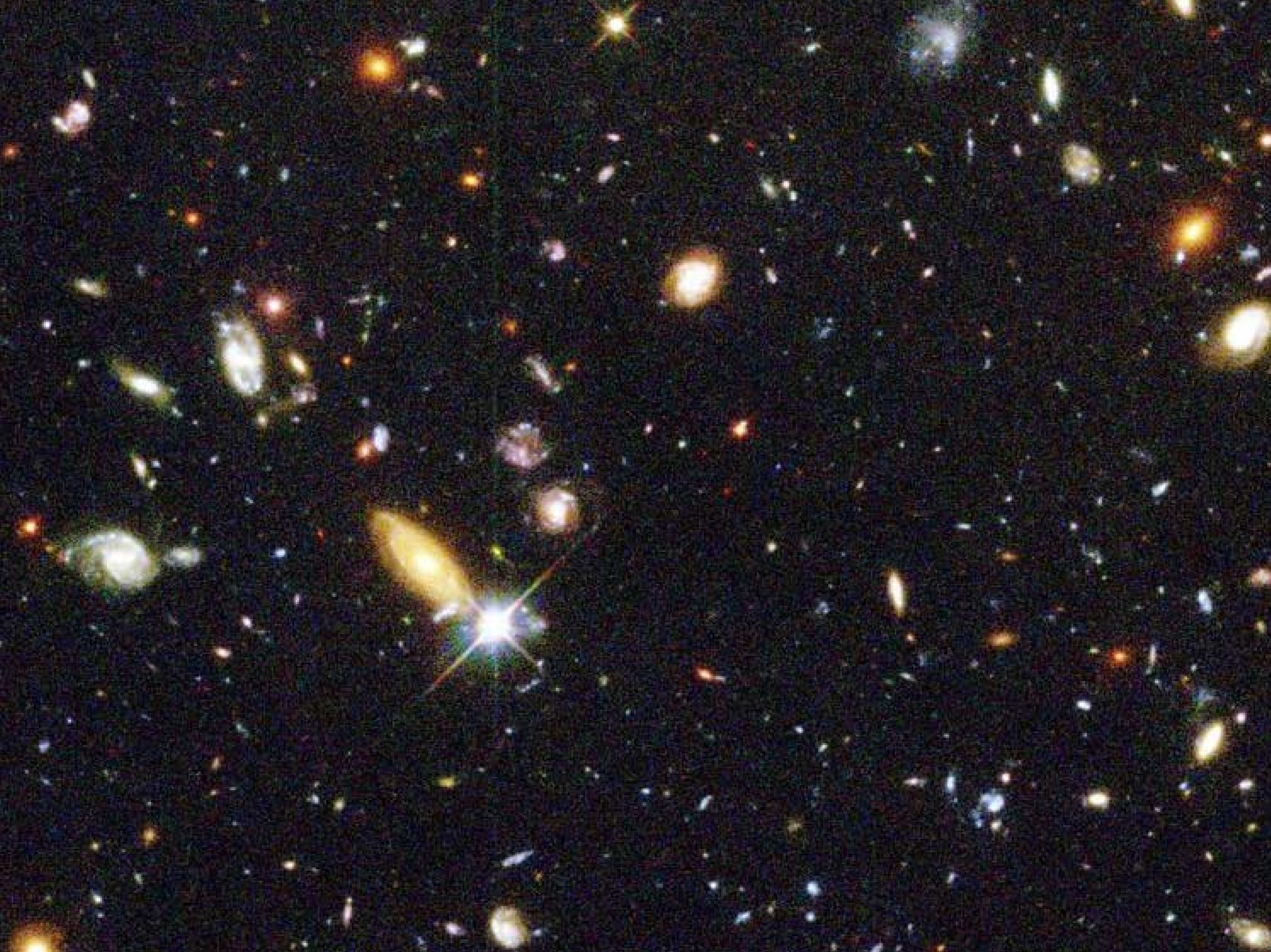
About 14 events with $E > 10^{20}$ known

Good news: sufficiently energetic so that source direction can be reconstructed (true ?)

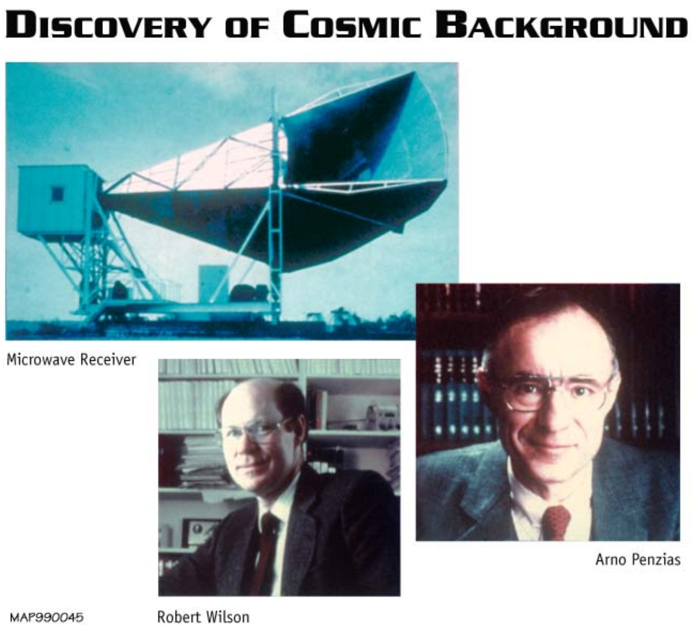


→ **Isotropic, not correlated with mass of galaxy or local super cluster**

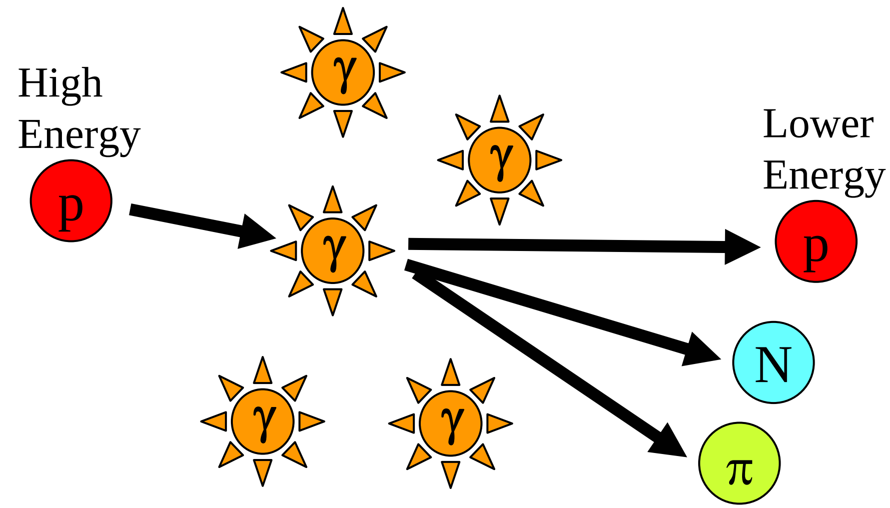

© Anglo-Australian Observatory



So UHECRs come from cosmological distances ?



2.7 K Cosmic microwave background

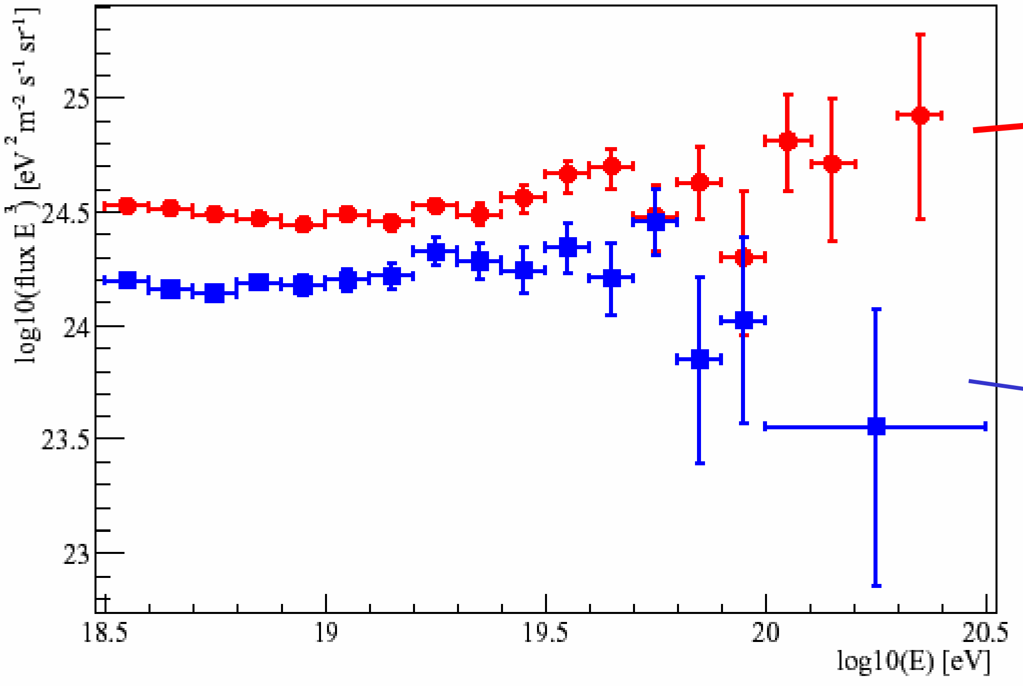


Threshold for photo pion production: 4×10^{19} eV

Higher energy protons would be slowed down by this effect by 1/e over 15 Mpc.

→If cosmic rays come from >> 15 Mpc distances, energy cutoff at $\sim 10^{20}$ eV (Greisen Zatsepin Kuz'min cutoff or GZK cutoff)

Observations of UHECRs ?

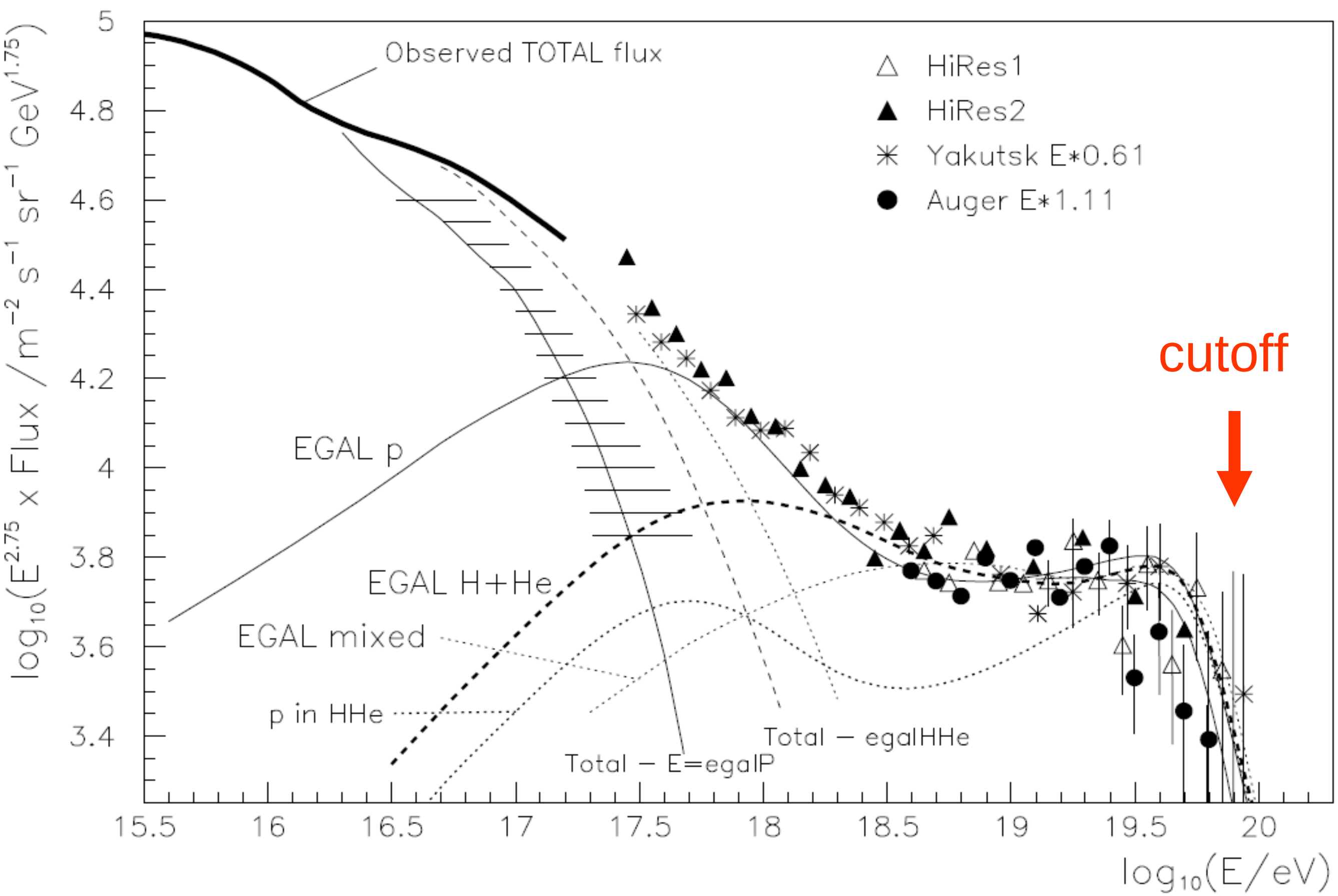


AGASA Data
→ no GZK cutoff

HIRES Data
→ See GZK cutoff

If AGASA is correct then there is a problem with isotropy of events

Major progress from recent Auger data



→ GZK cutoff and HiRes data confirmed

→ Can model UHECR with extragalactic proton component accelerated in AGNs?

→ Goal: detect few events above GZK cutoff WHY?

The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

ESO PR Photo 40f/99 (17 November 1999)

Supernovae

- Death of massive star
- Brighter than a galaxy
- About 1-2 per century and galaxy
- here: 1987A (LMC 170kly)

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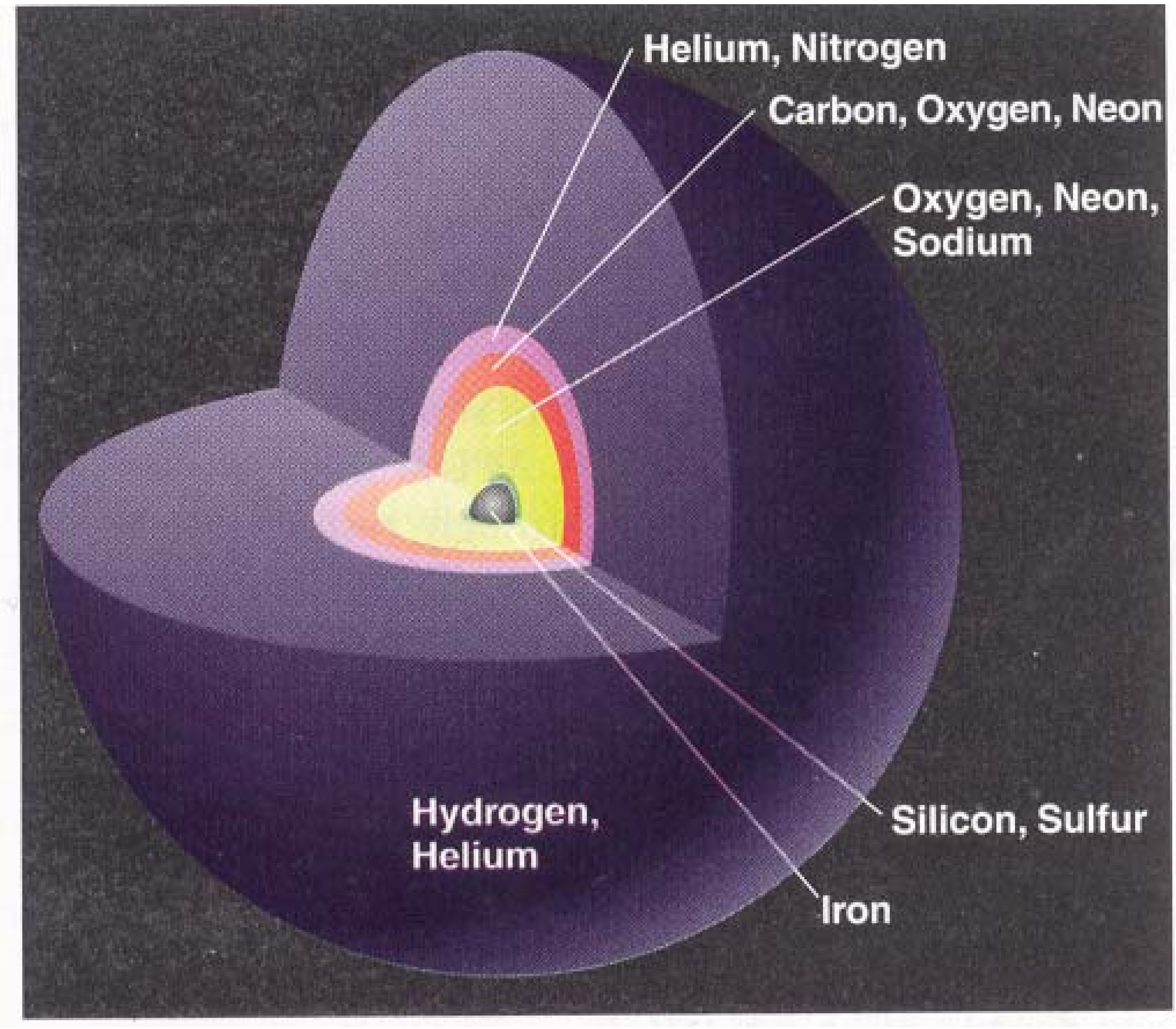
Precollapse structure of massive star



Iron core collapses and triggers supernova explosion → release of 10^{51} ergs (1 foe)

(ejecta speeds ~10000 km/s – 56Fe nucleus at that speed has only 30 MeV energy)

The Mystery

- Isotropy implies UHECR’s come from very far away

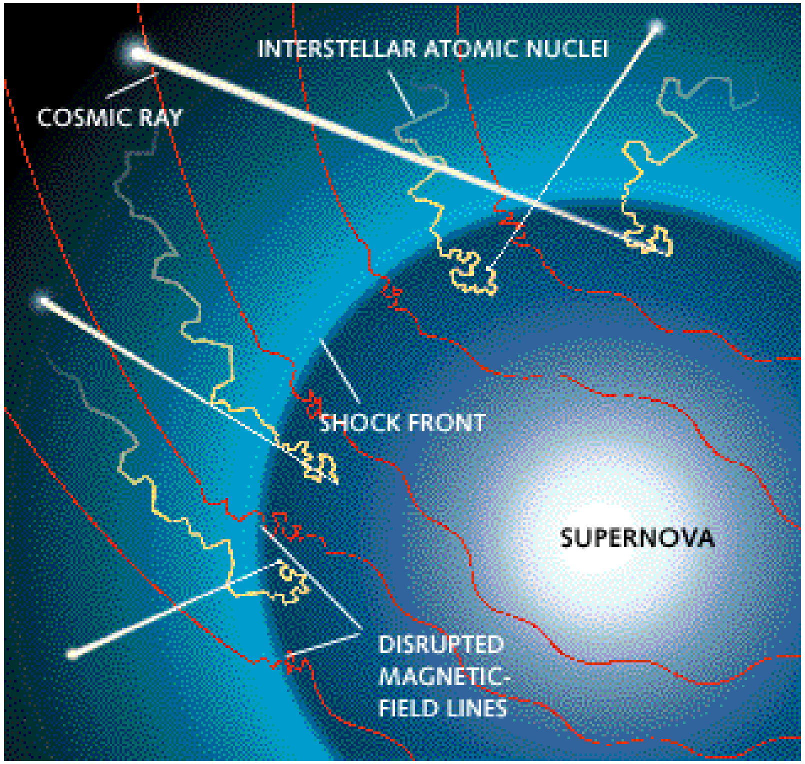
- But – UHECR’s cannot come from far away because collisions with the cosmic microwave background radiation would slow down or destroy them (most should come from closer than 20 MPc or so – otherwise cutoff at 10^{20} eV this is called the GZK cutoff (after Greisen-Zatsepin-Kuzmin)

- Other problem: we don’t know of any place in the cosmos that could accelerate particles to such energies (means: no working model)

<u>Speculations include:</u>

- Colliding Galaxies
- Rapidly spinning giant black holes (AGN’s)
- Highly magnetized, spinning neutron stars
- New, unknown particles that do not interact with cosmic microwave background
- Related to gamma ray bursts ?

Cosmic ray acceleration in supernova shockfronts



No direct evidence but model works up to 10^{18} eV:

- acceleration up to 10^{17} eV in one explosion
- explains correct spectral index and knee
  knee: heavier particles can be accelerated to higher energies
  protons accelerated up to knee (10^{15} eV), iron up to 10^{17} eV (at knee light particles disappear)– beyond extragalactic component or multiple accelerators) ?
- some evidence that acceleration takes place from radio and X-ray observations
- explains galactic origin that is observed (less cosmic rays in SMC)