The Many Mysteries of Cosmic Rays

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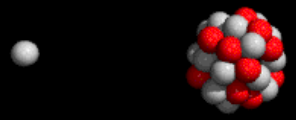
Questions…

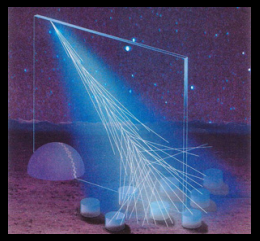
- What are cosmic rays?



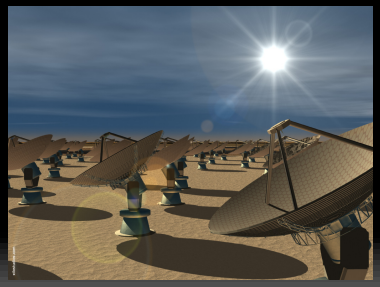
- Where do they come from?

[intermission?]

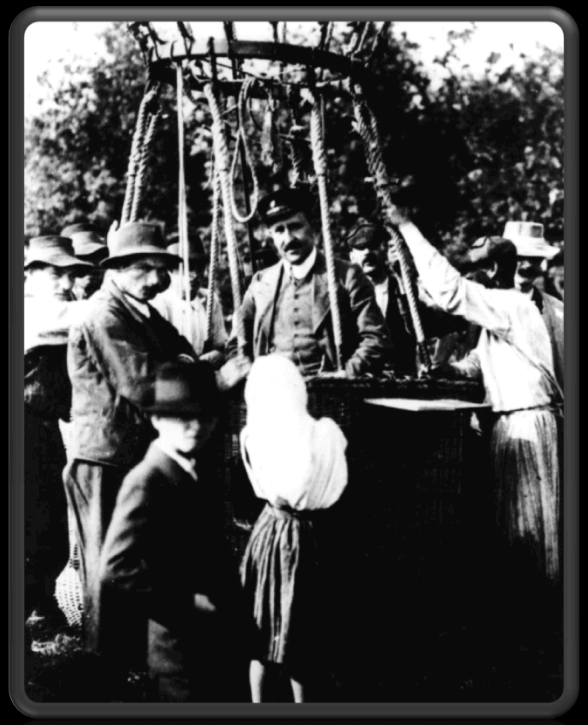
- How can we detect cosmic rays?



- Where do we go from here?



A bit of history



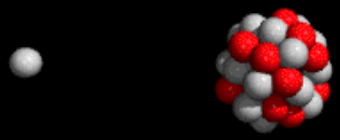
around 1900: scientists find mysterious background radiation (perhaps from the ground?)

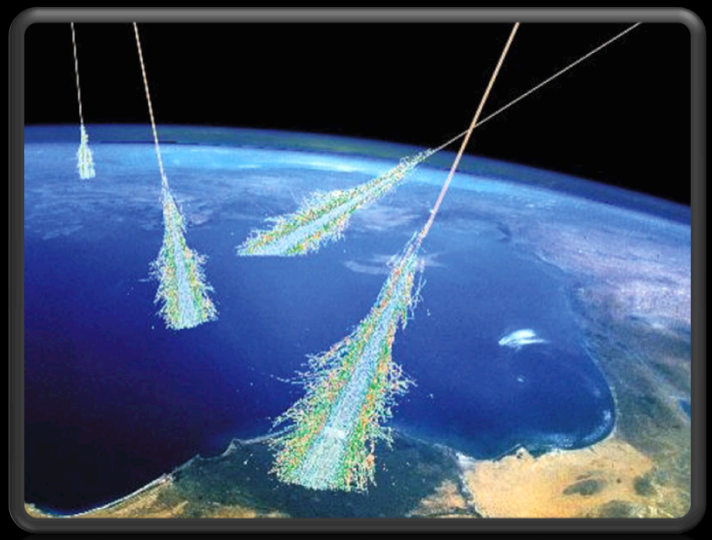
1912: Victor Hess launches balloon — amount of radiation increases with height

"… best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above"

What we know now…

- Cosmic "rays" are really charged particles from outer space
  - mostly protons, but also heavy nuclei…
- They hit the Earth from all directions in the sky, all the time
- Some are the highest energy particles known in the Universe





What we *don't* know…

- Cosmic "rays" are really charged particles from outer space
  - mostly protons, but also heavy nuclei…

ALL of them? What about at the highest energies?

- They hit the Earth from all directions in the sky, all the time

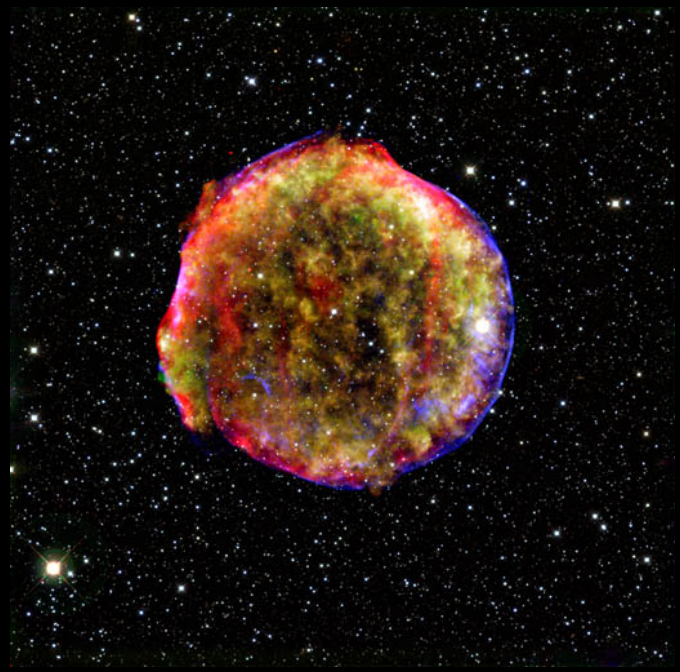
But where did they start?

- Some are the highest energy particles known in the Universe

How does Nature accelerate a particle to such high energies?

Why study them?

- Might come from violent, interesting objects!
- Particle physics
  - 1933: discovery of antimatter
  - 1937: discovery of the muon
  - …
  - 2008: hints of dark matter?
  - 2009+: testing Einstein's theory of relativity
- 2010+: Charged particle astronomy

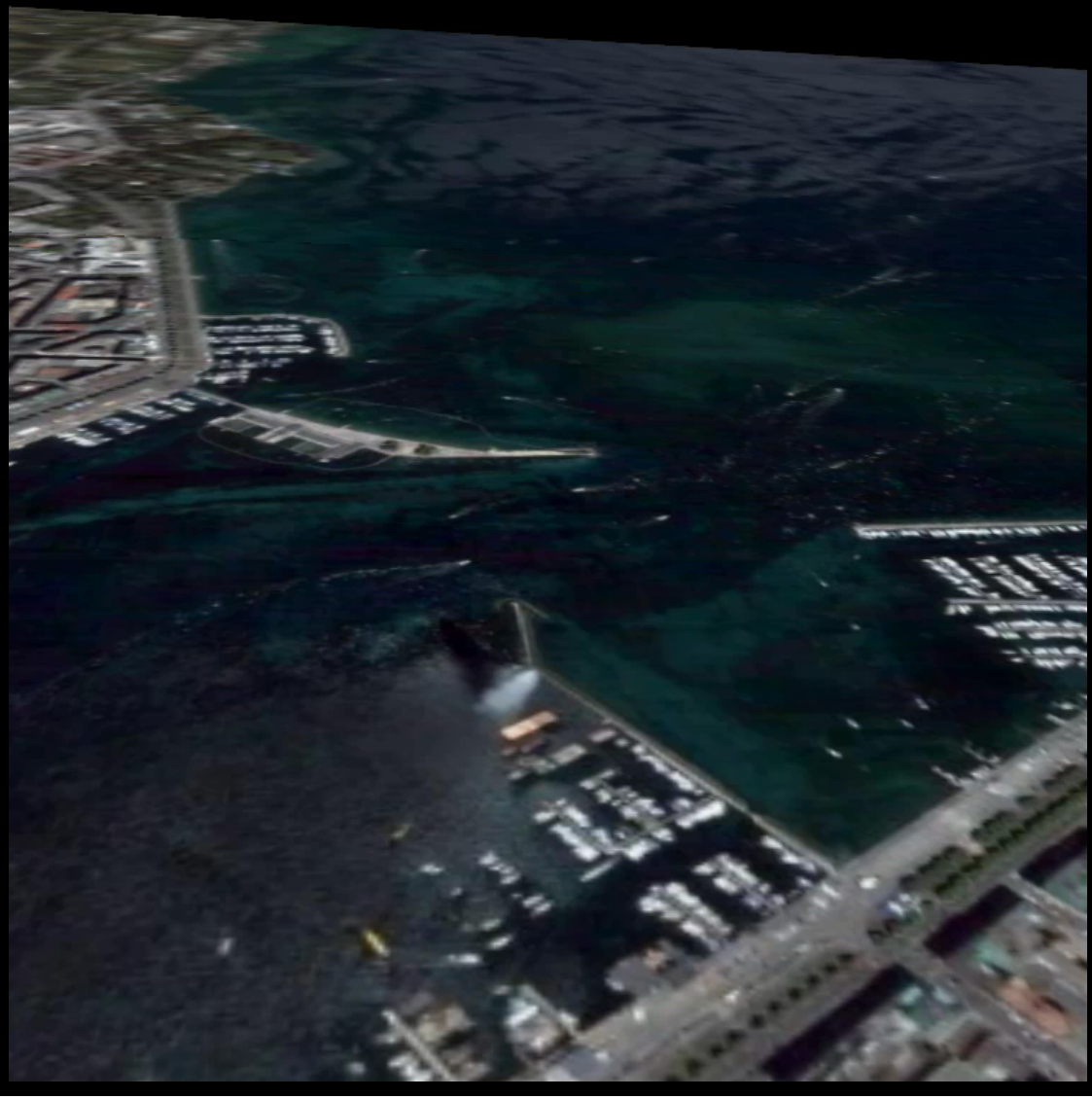


Tycho's supernova remnant
(from SN 1572, in Cassiopeia)

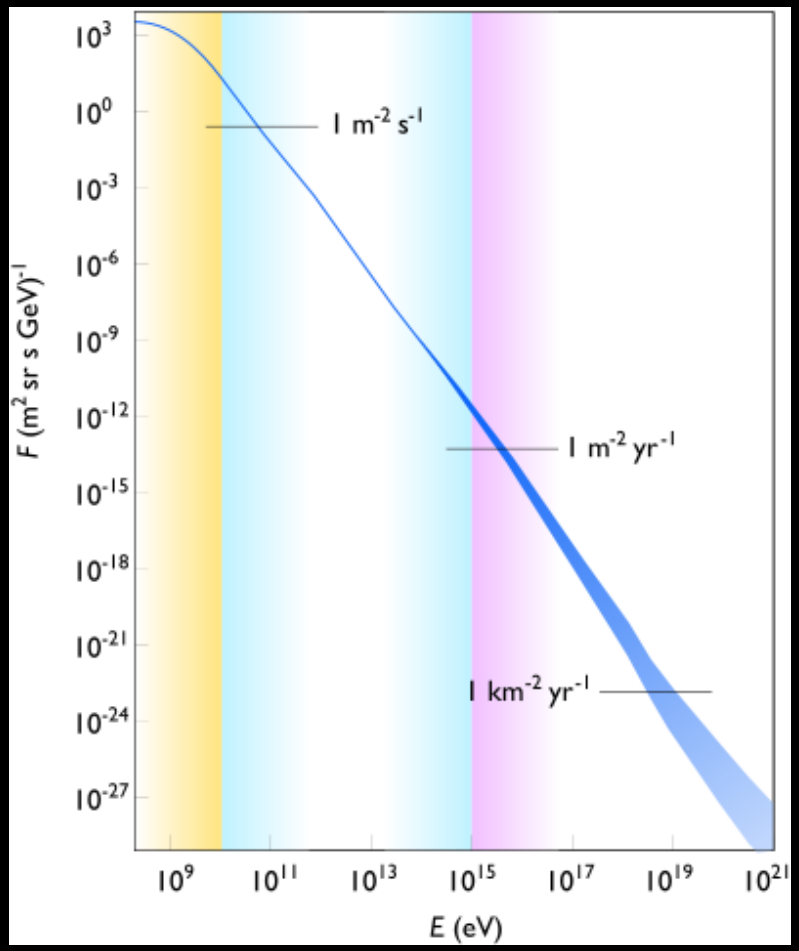
Cosmic Ray Air Showers

- Earth's atmosphere is our shield
- Chain reaction of particles
  - proton + air = pions (often)
  - "shower" of photons, electrons, positrons, muons, etc.
  - develops and hits ground in ~50 microseconds
- Detect particles that reach the ground
  - or look for flashes in the sky

Air Shower Computer Simulation



Energy Spectrum

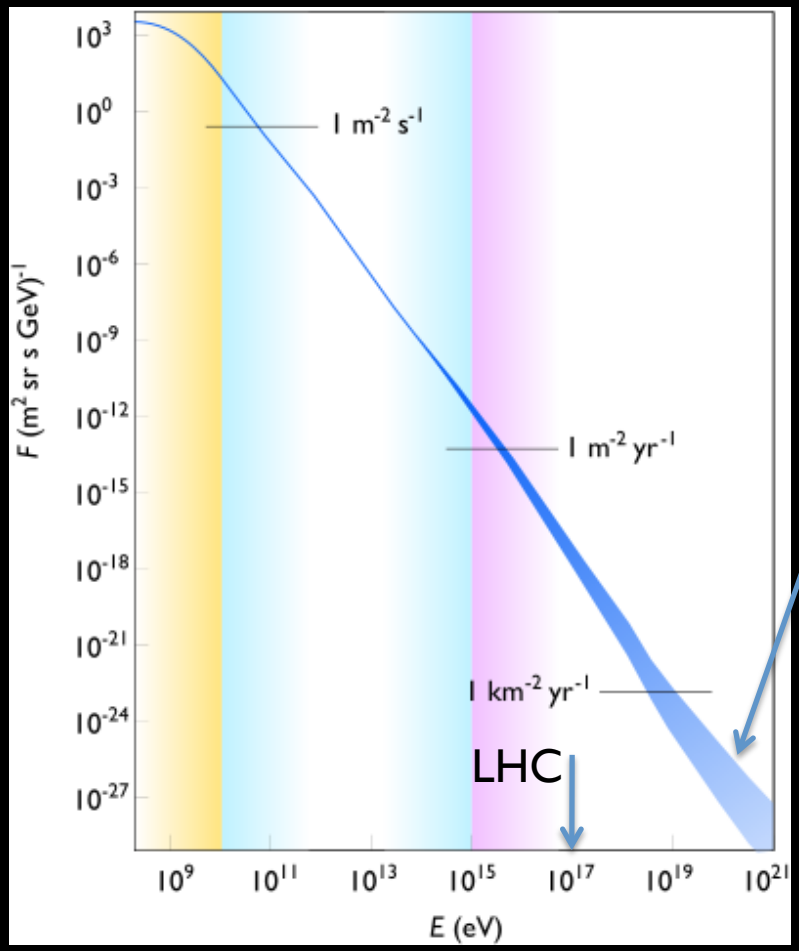


1 particle per m^2 per second

"Knee":
1 particle per m^2 per year

"Ankle":
1 particle per km^2 per year

Energy Spectrum

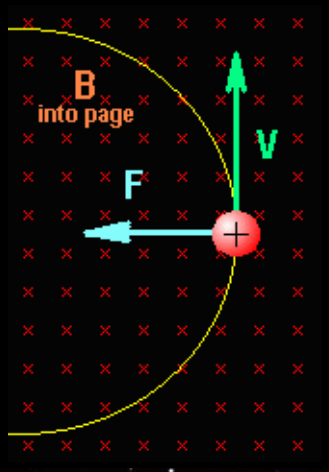


Ultra-high energy cosmic rays:

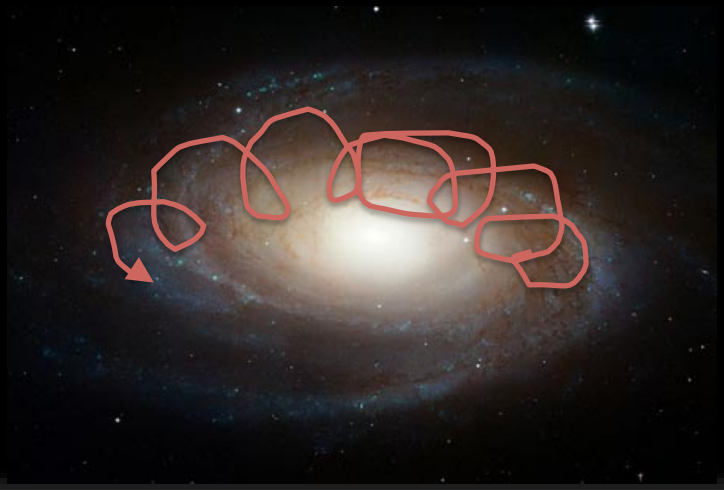
1000x LHC energy but very rare (new particle physics?)

(P. S. why man-made particle colliders won't destroy Earth)

Cosmic Ray Sources



- Main problem: magnetic fields scramble cosmic ray direction

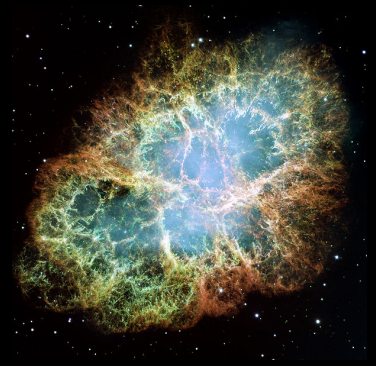


- May spiral around for a million years before hitting Earth

One Galactic Possibility

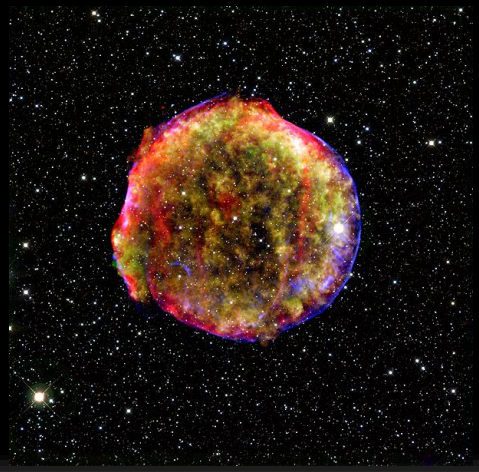
- Enough supernovae (1 per ~50 years) to balance the energy budget
- Acceleration in shock wave (SNRs), not original explosion

Some SNRs

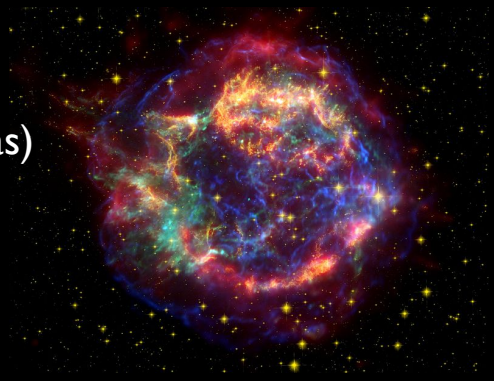


Crab nebula (M1)
Hubble, false color

Veil nebula
(NGC6992, etc.)
optical

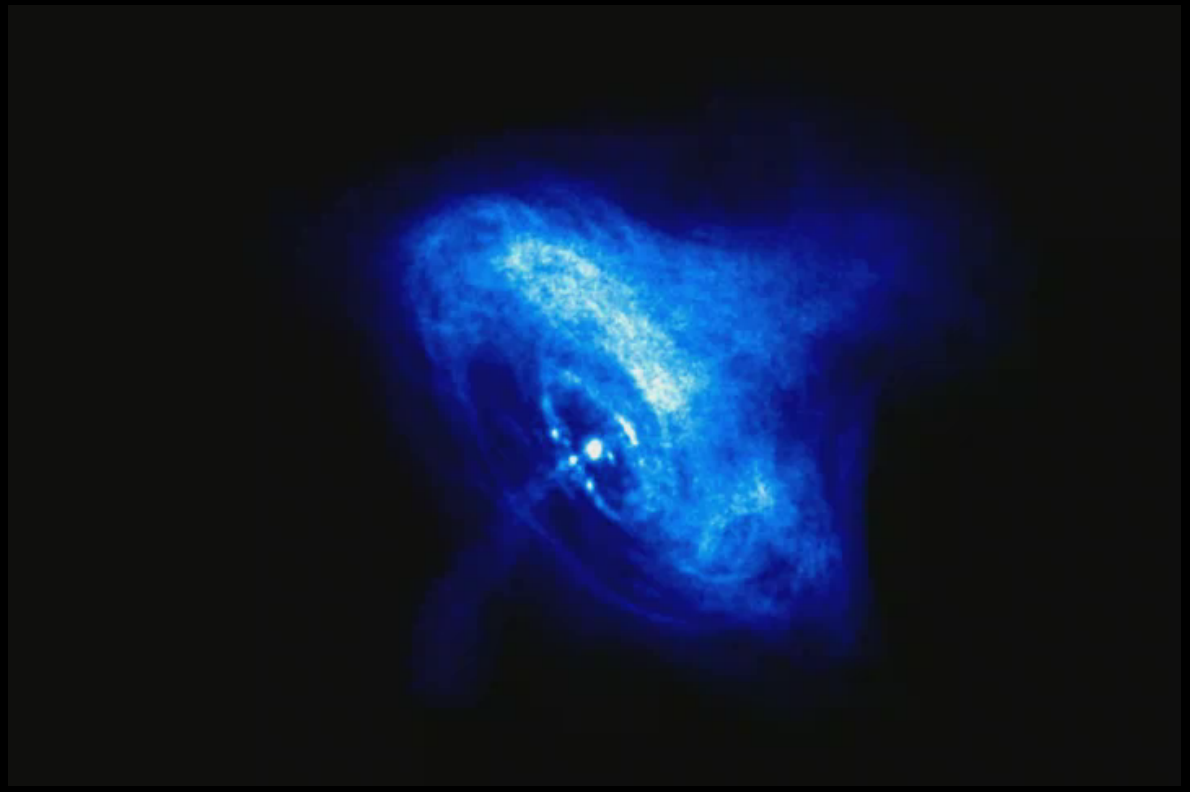


Tycho (SN1572 / B Cas)
X-ray / infrared



Cassiopeia A
X-ray / optical / infrared

Experimental Status

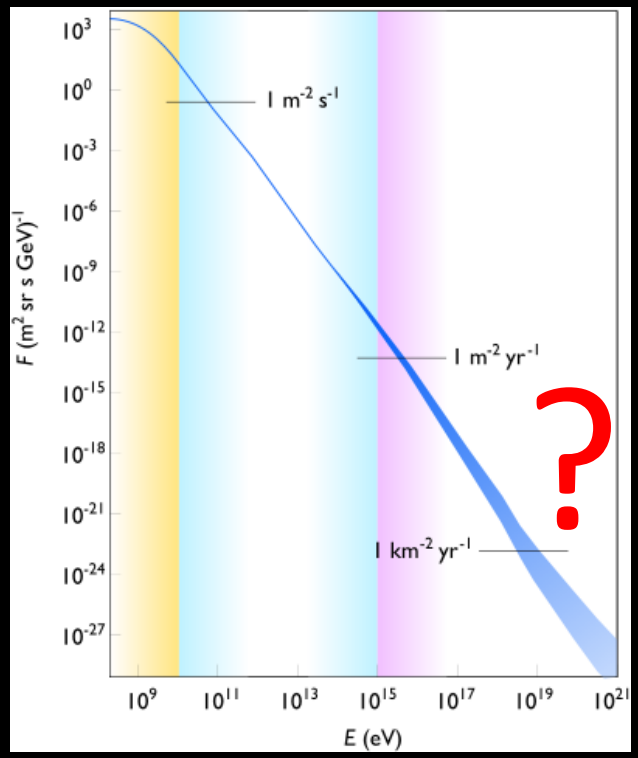


Chandra X-ray view of Crab core

- X-ray images show emission from high-energy particles in shocks
- Need independent confirmation by gamma ray and neutrino telescopes (no bending!)
- But only explains energies up to the "knee" (what about higher energies?)

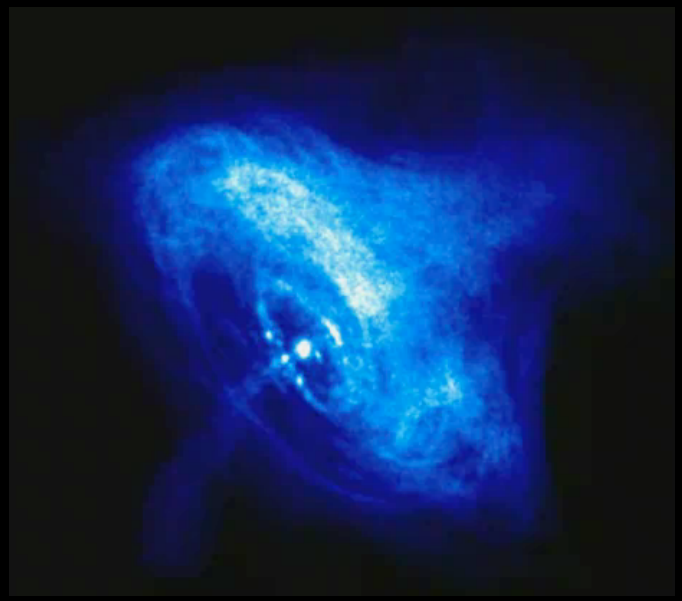
Ultra-high Energy Cosmic Rays

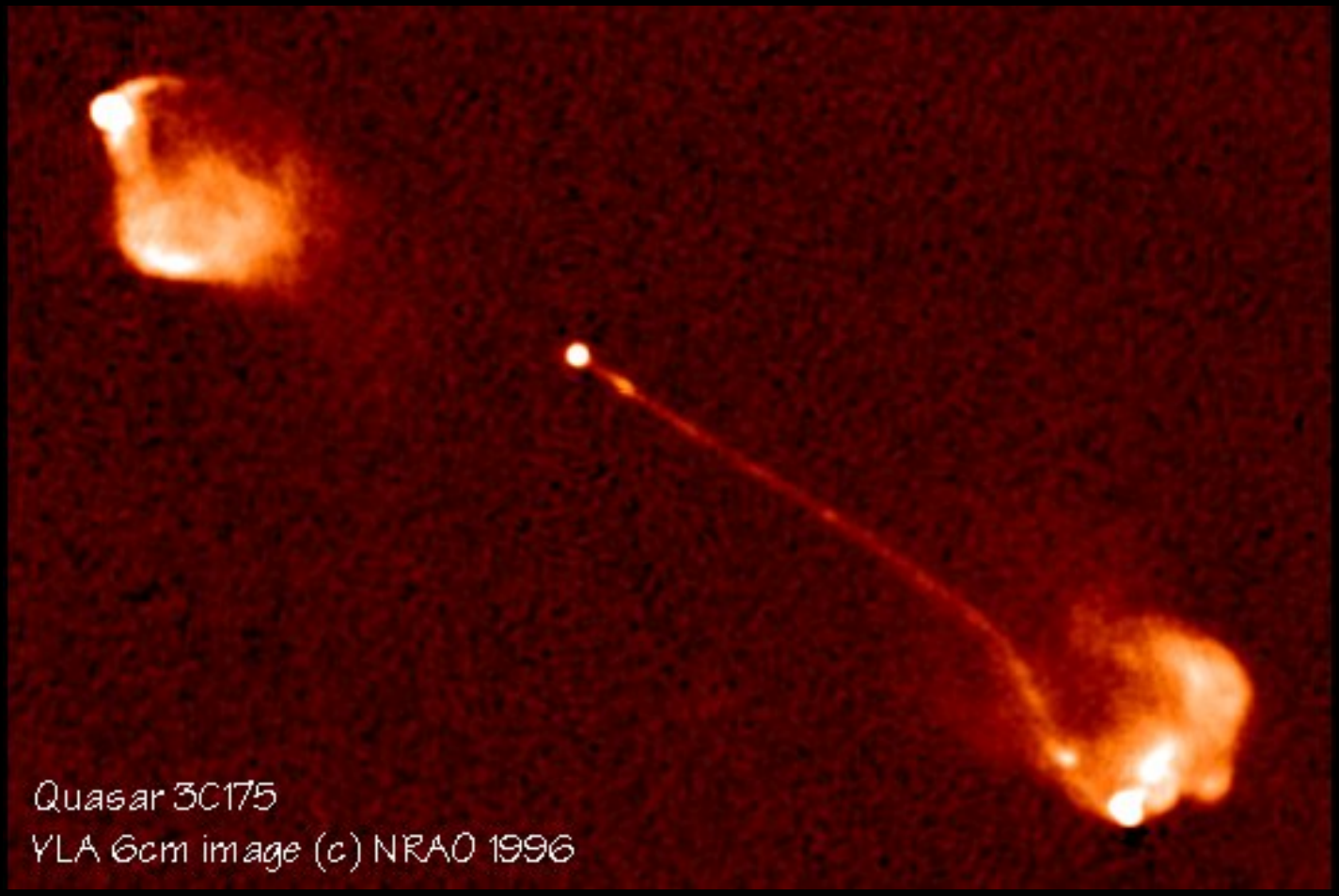
- Galactic magnetic fields too weak to hold them
- No known galactic sources can reach anywhere near 10^{20} eV
- Probably come from outside our Galaxy



Nature's Accelerators

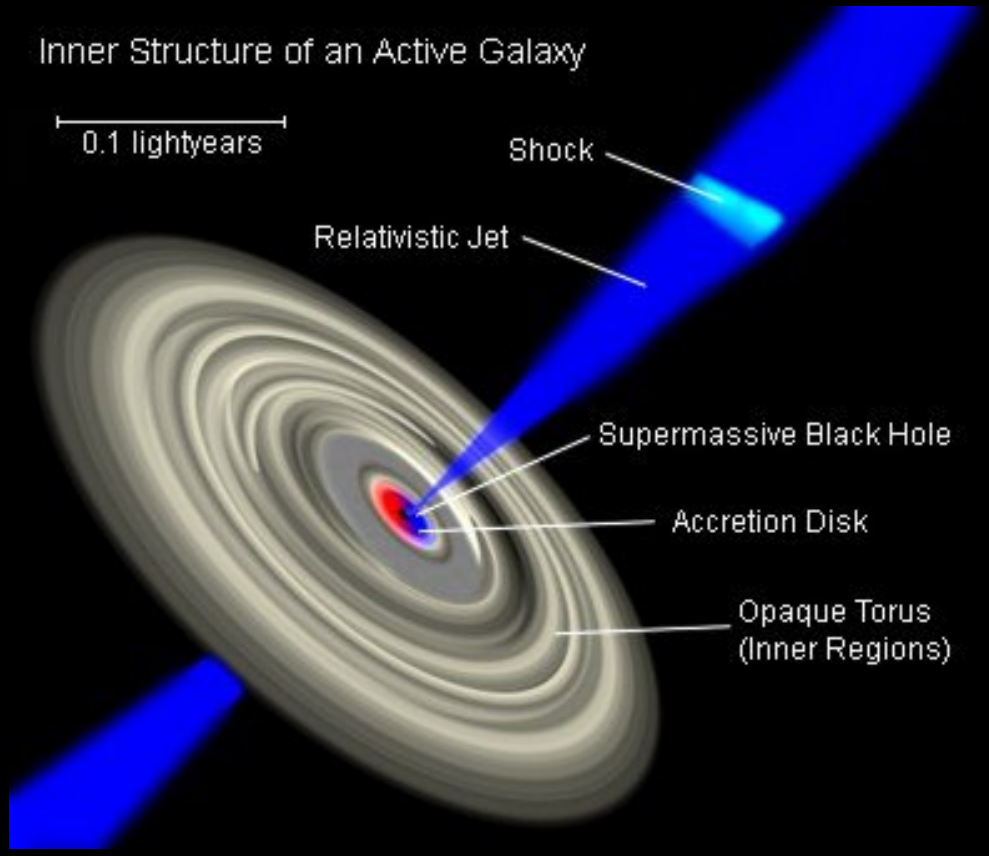
- Rotating compact object (neutron star or black hole)
- Powers jets along spin axis via complex magnetic field
- Is there a REALLY BIG version?




Quasar 3C175
VLA 6cm image (c) NRAO 1996

Active Galactic Nuclei (AGN)

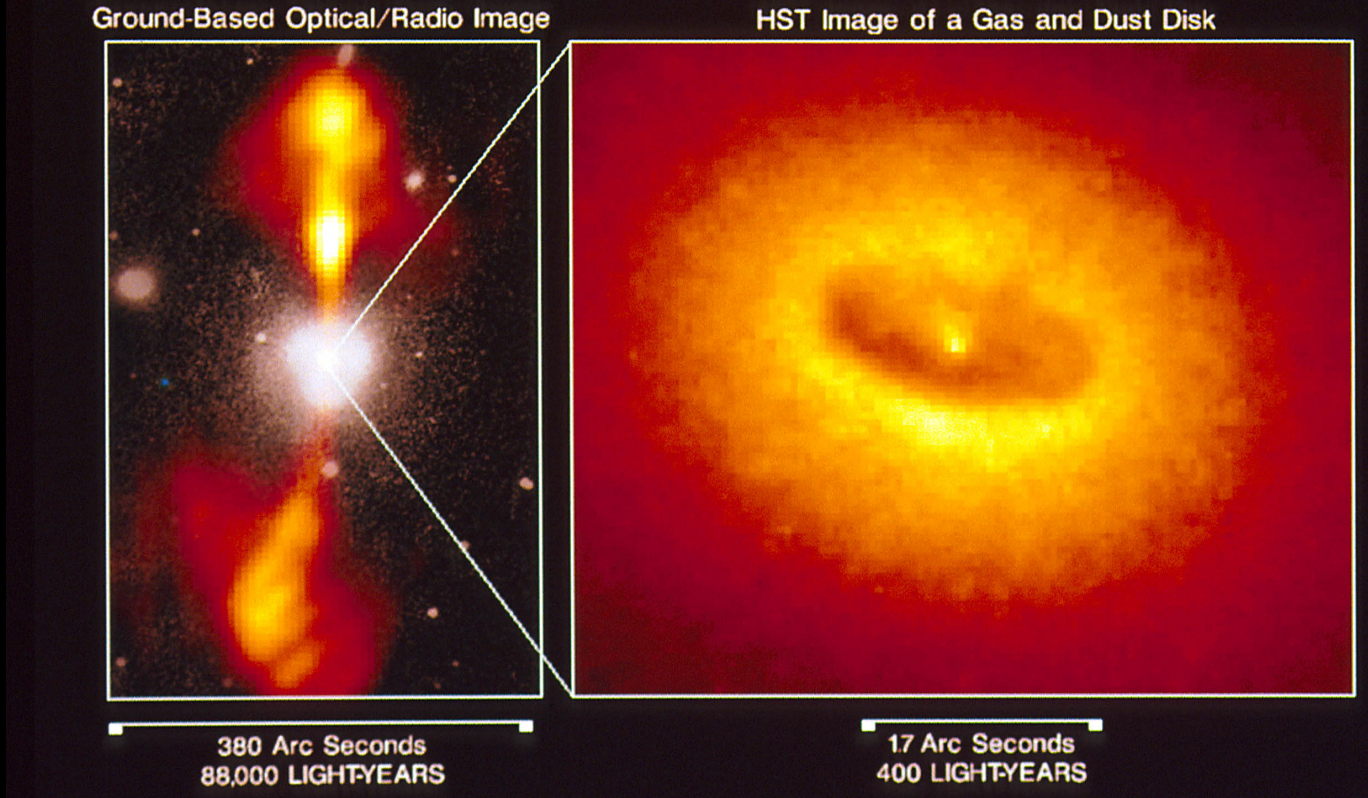
- Essentially all galaxies (including ours) house a supermassive black hole (10^6 to 10^{10} solar masses)
- Some are in an active phase (AGN)
- Shocks in jets: cosmic ray acceleration?



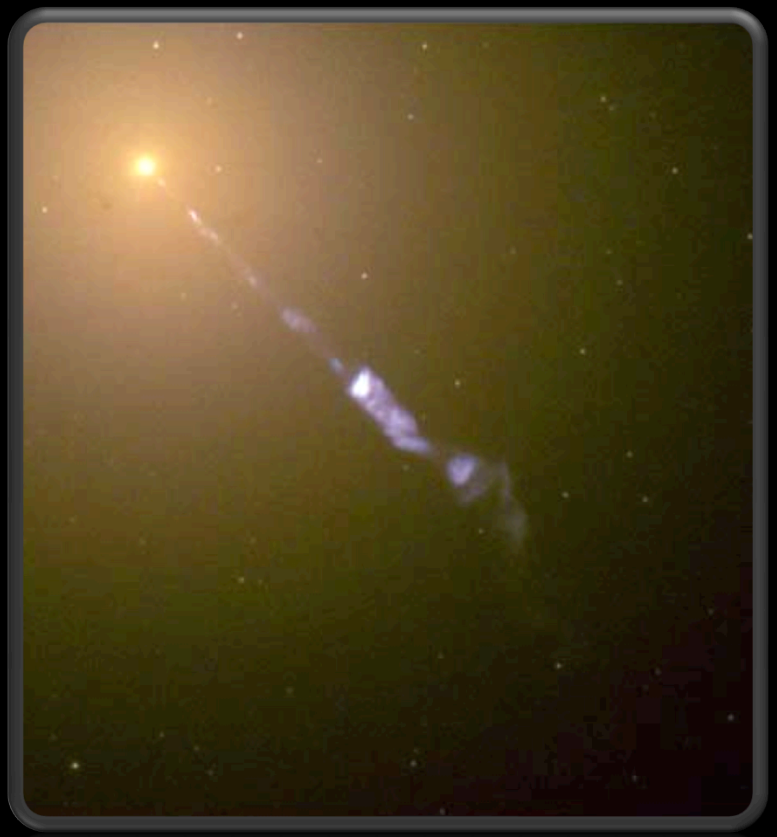
Core of Galaxy NGC 4261

Hubble Space Telescope

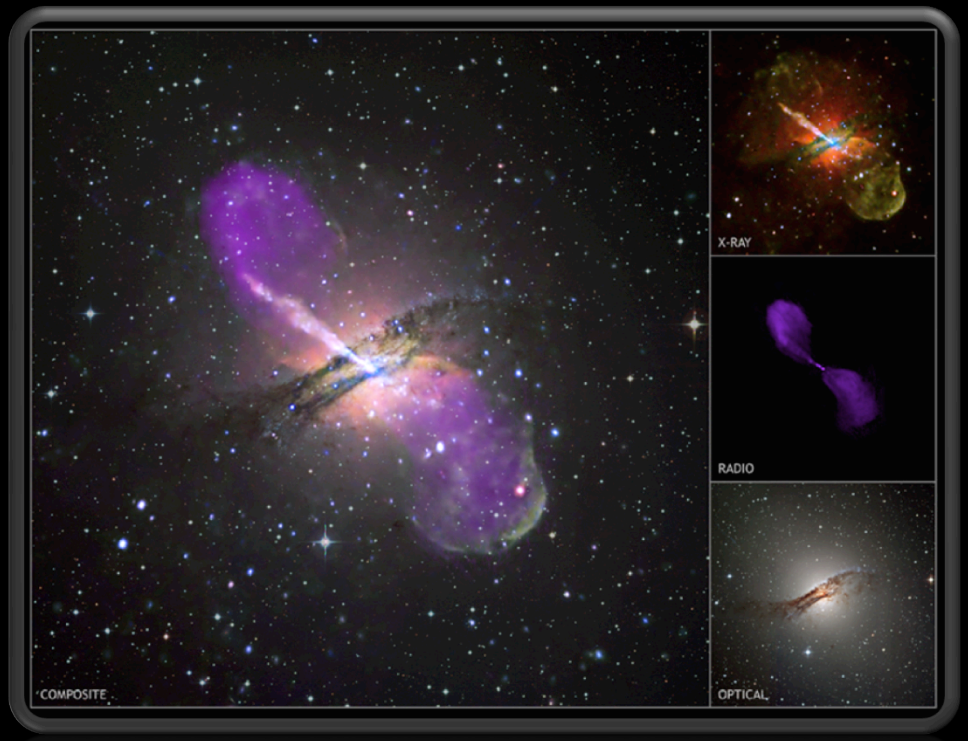
Wide Field / Planetary Camera



M87

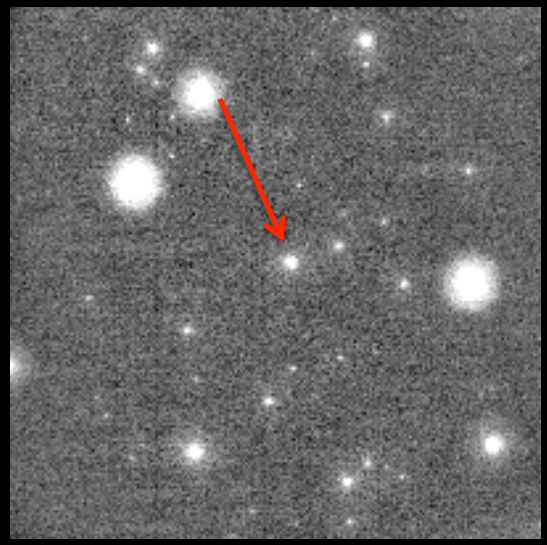


Centaurus A (NGC 5128)



March 19, 2008

- Light from an explosion nearly 8 billion years ago
- Visible with naked eye for 30 seconds in Boötes (most distant object ever)
- Spectacular example of a gamma ray burst (GRB 080319B)

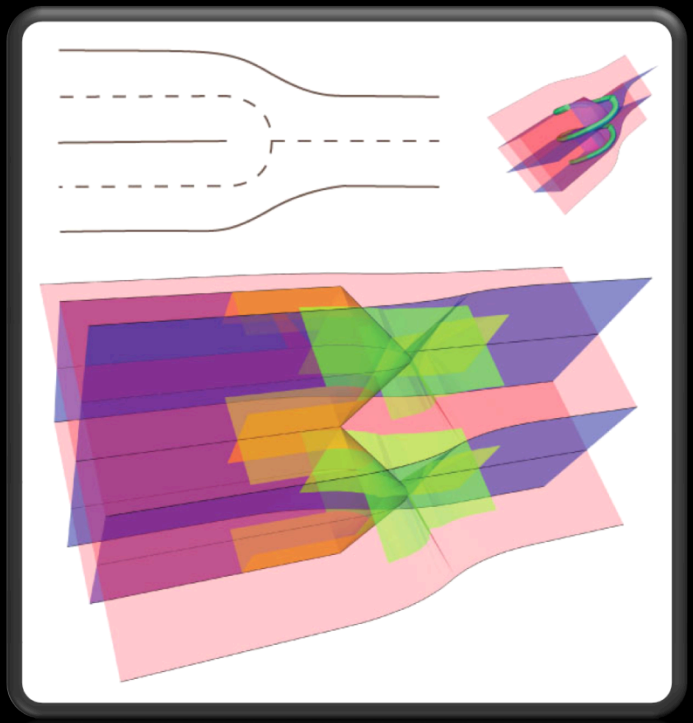


GRB Animation

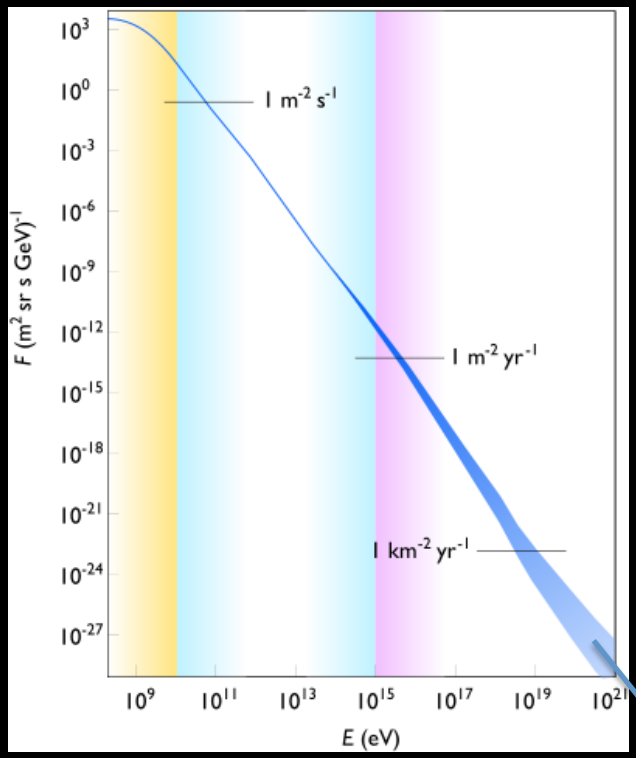
- Massive star (e.g. Wolf-Rayet) goes "hypernova"
- Inner core collapses to a black hole
- Jets bore through outer layers of star
- We see it if jet is pointed at us

Other UHECR Sources

- AGN and GRBs: only known objects producing remotely enough energy
- Exotic ideas: decay of topological defects left over from Big Bang
- Something we haven't thought of?



GZK Cutoff



???

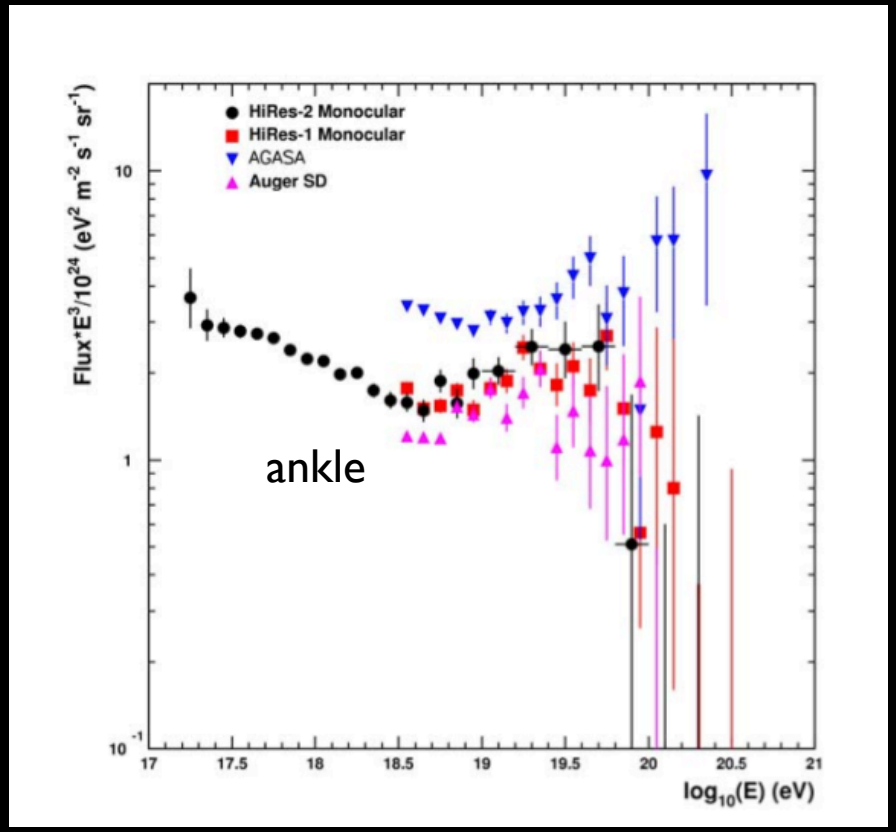
- Very high energy protons should react with glow from Big Bang (cosmic microwave background)

  $p + \gamma \rightarrow \Delta^+$ (then decay)

- Expect spectrum to "cut off" above a certain energy (Greisen-Zatsepin-Kuzmin)

- If no cutoff:
  - sources are really close?
  - cosmic rays are not protons?
  - Einstein's theory of special relativity is wrong (?!)

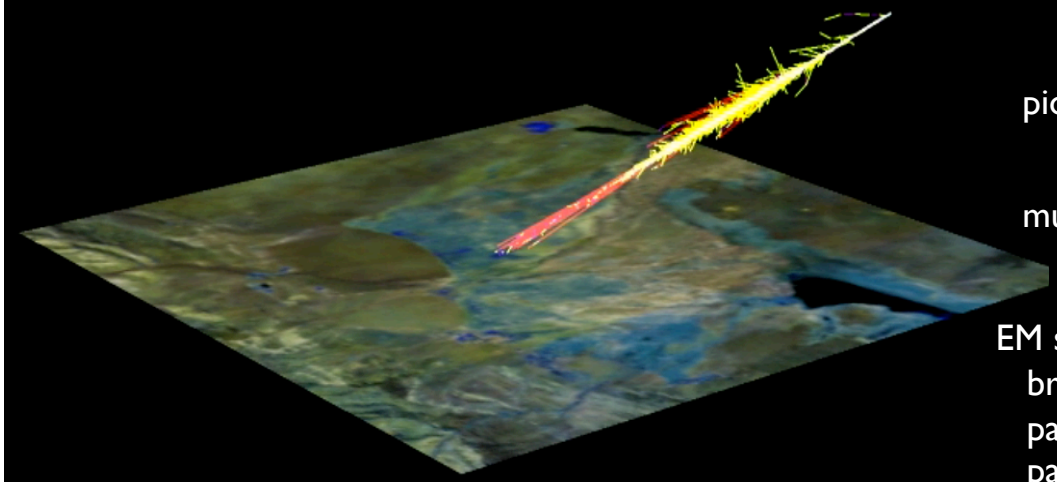
Situation in 2005



Cutoff? No cutoff?
What's going on?!

Let's talk about detectors…

A Bit of Particle Physics



One example

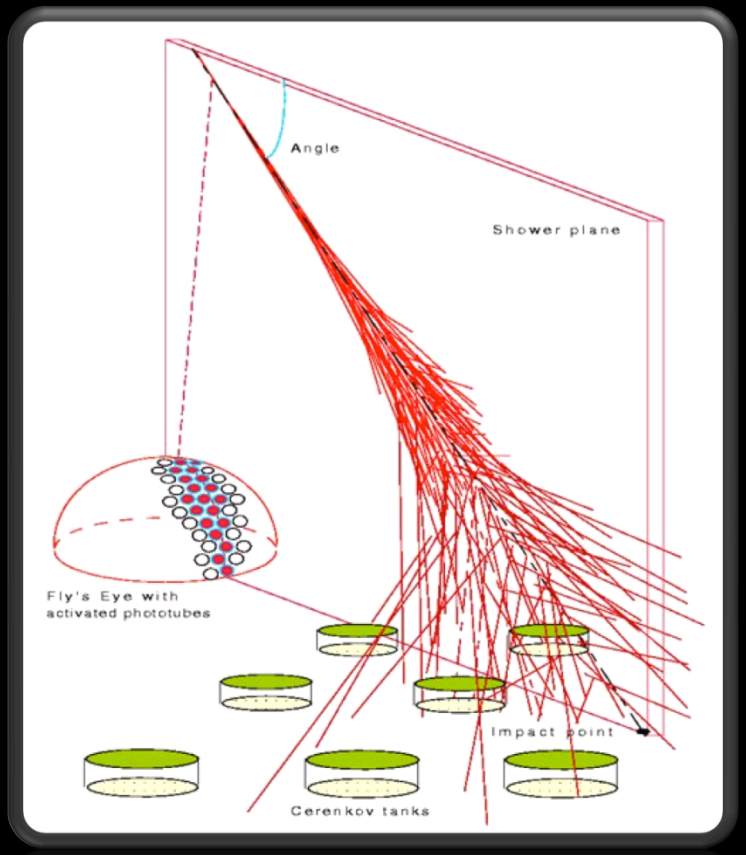
$p + N \rightarrow \pi^+ + \text{fragments}$

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

muon decay $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$

EM shower:
- bremstrahlung $e^\pm + \gamma \rightarrow e^\pm + \gamma$
- pair creation $\gamma + \gamma \rightarrow e^+ + e^-$
- pair annihilation $e^+ + e^- \rightarrow \gamma + \gamma$

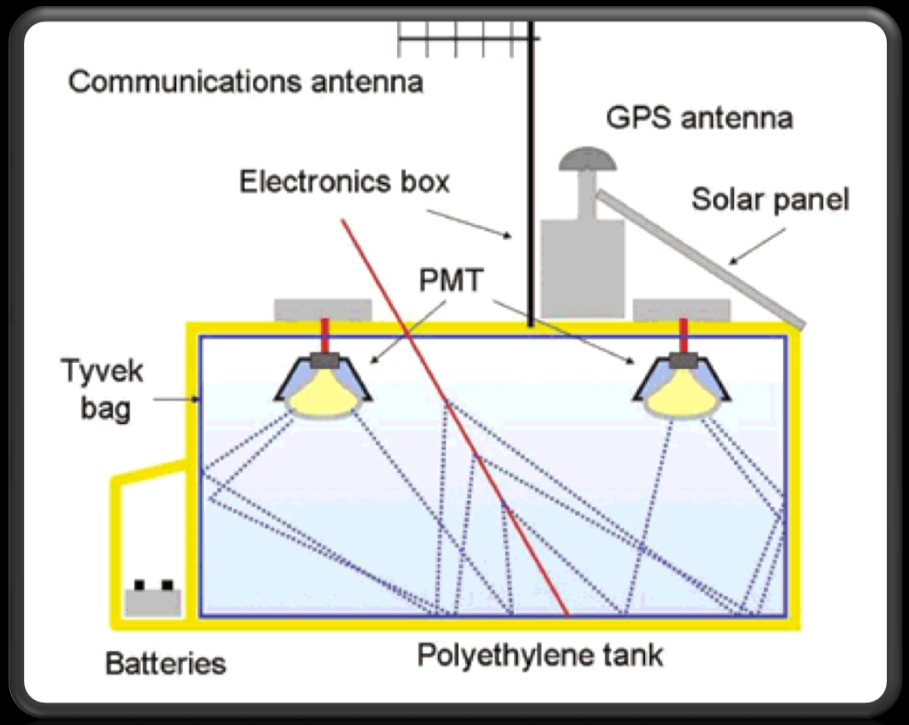
Hybrid Air Shower Detector



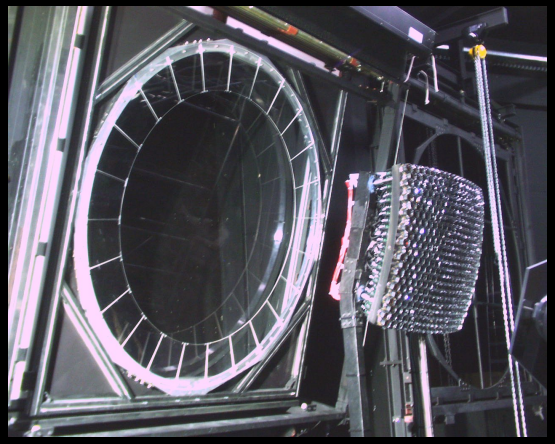
- Detect charged particles reaching ground with special water tanks
- See flash of light along track from fluorescence of air (if it's dark!)
- Each gives information about the cosmic ray (energy, particle type, etc.)
- Need huge area for highest-energy cosmic rays (or be really patient)

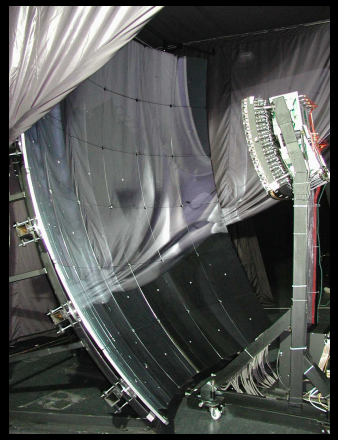
Water Cherenkov Tanks

- Charged particle moving faster than speed of light in water (or any transparent medium): Cherenkov light
- Detect light inside tank with photomultiplier tubes (PMTs)
- Tank records signals along with an accurate time (from GPS)



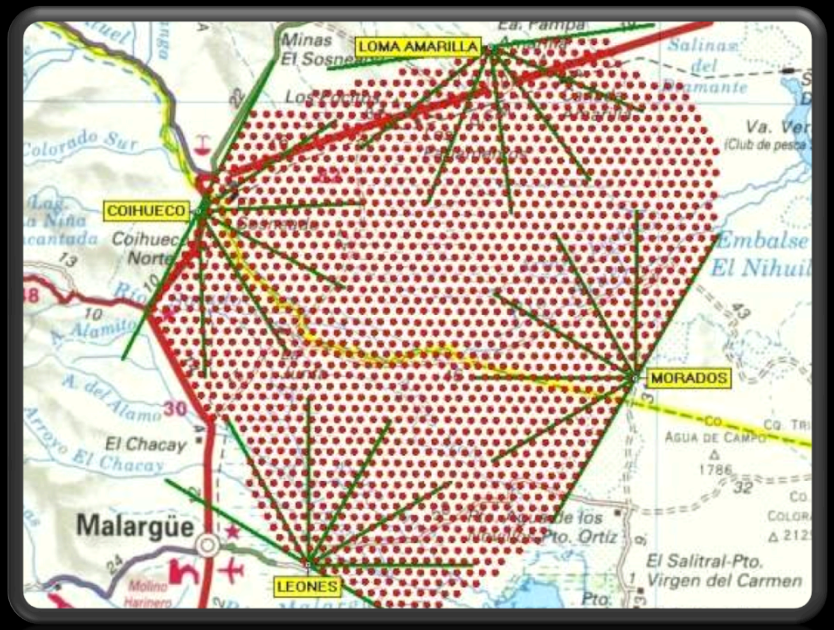
Fluorescence Telescopes



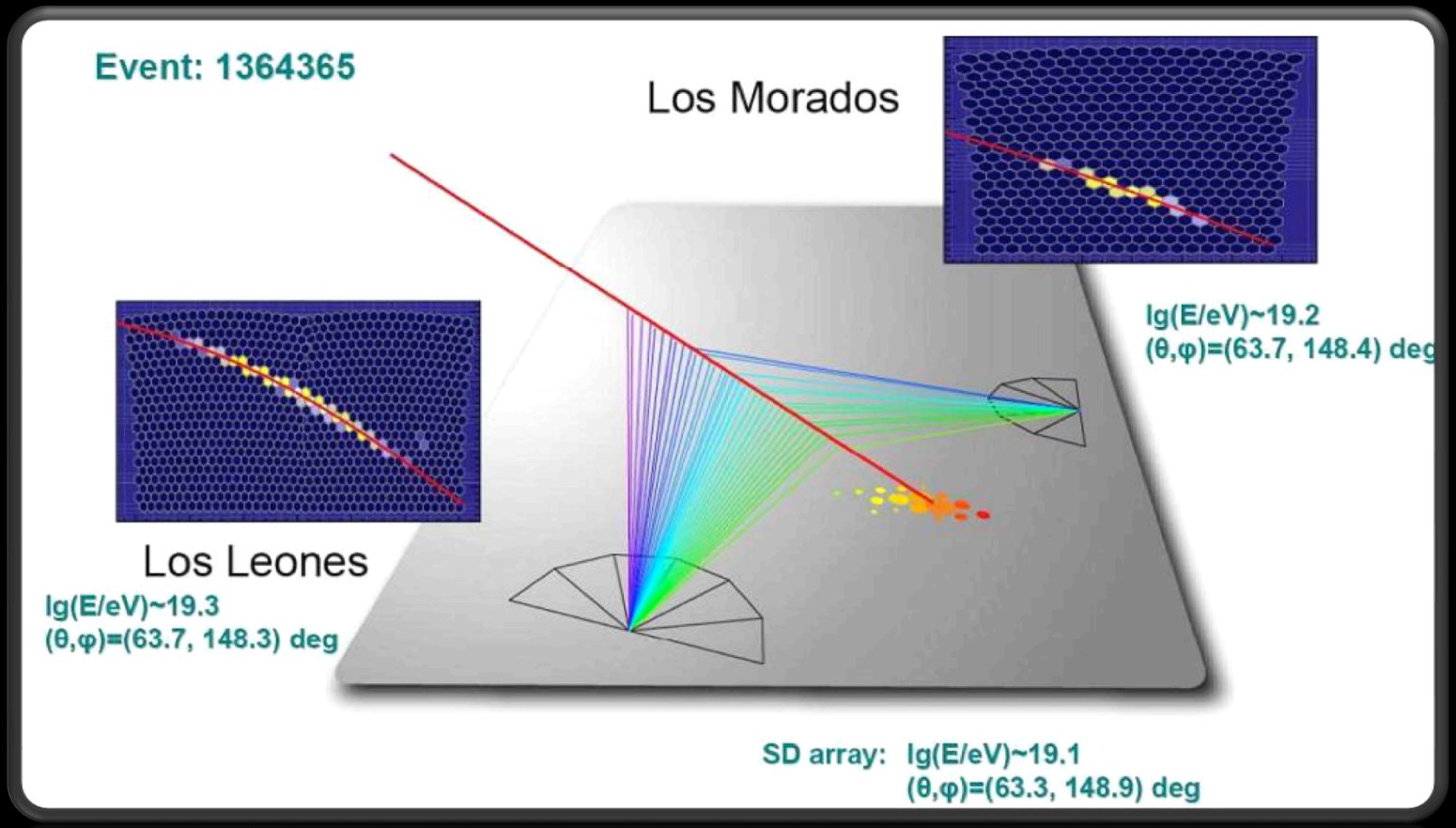


- Air shower energy excites air molecules: fluorescence light
- Detect flash / track with array of small PMTs
- Must be dark, clear

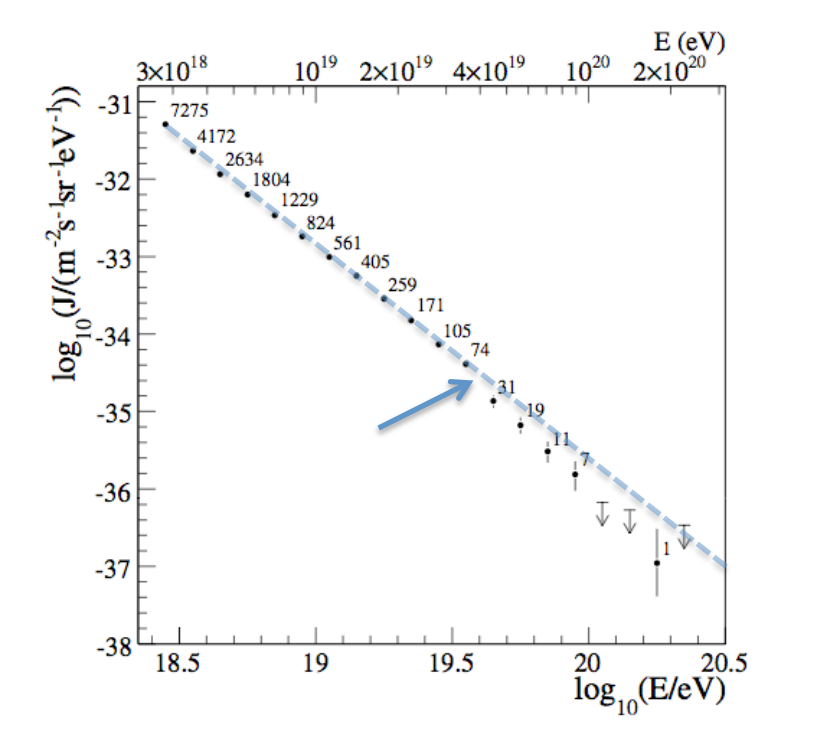
The Pierre Auger Detector



Example Cosmic Ray Event



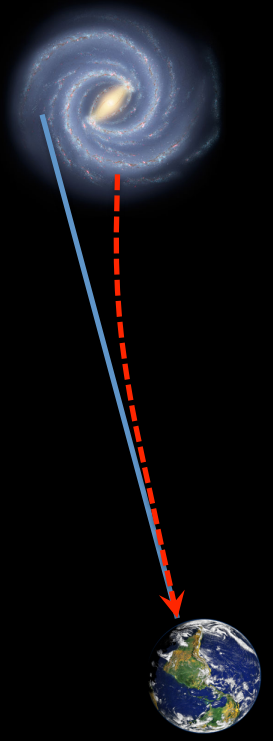
Auger Energy Spectrum (2009)



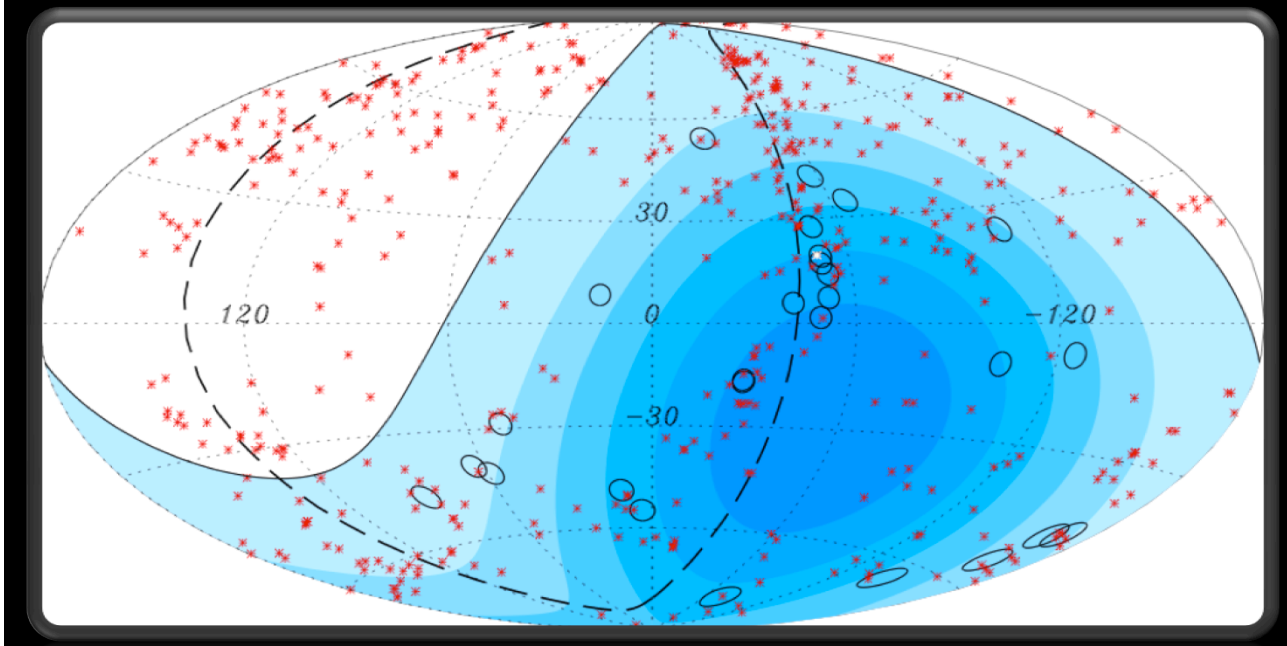
- "Break" in spectrum is where expected from GZK cutoff
- Statistics are not great (need more data)
- Future: shape of cutoff can tell us about distance of sources

Auger UHECR Directions

- At very high energies, magnetic fields only bend protons by a few degrees
- Can point back to source?
- Cosmic rays closer to one type of object than some other type (correlation)?



UHECR Skymap (2007)



- 38 highest-energy events (circles) seem to come from AGN (red dots)!
- Clump near Centaurus A (white dot)?
- BUT…
  - events since 2007 don't seem to correlate as well with AGN

    AND

  - events don't look like protons (curve more!)
- Need more data

Satellites (or Balloons)

- In space, can detect the primary cosmic ray (instead of air shower)

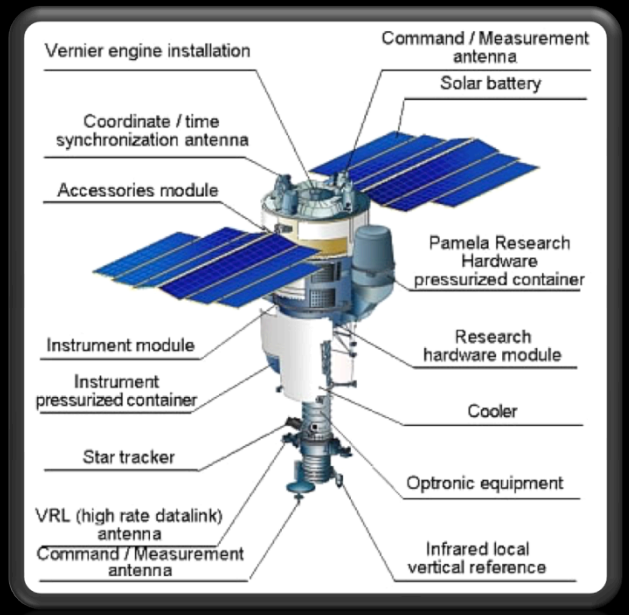
  BUT

- Spacecraft can only be around 1 m^2

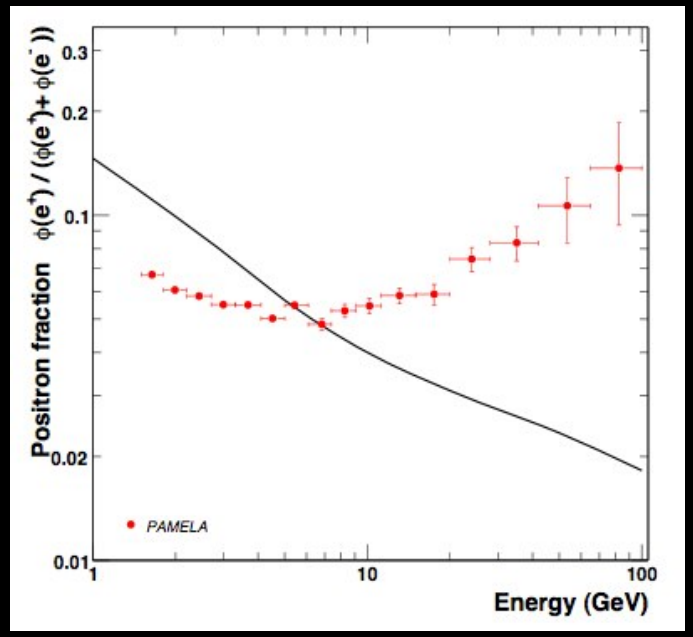
  AND

- Balloon flights are short

PAMELA Spacecraft



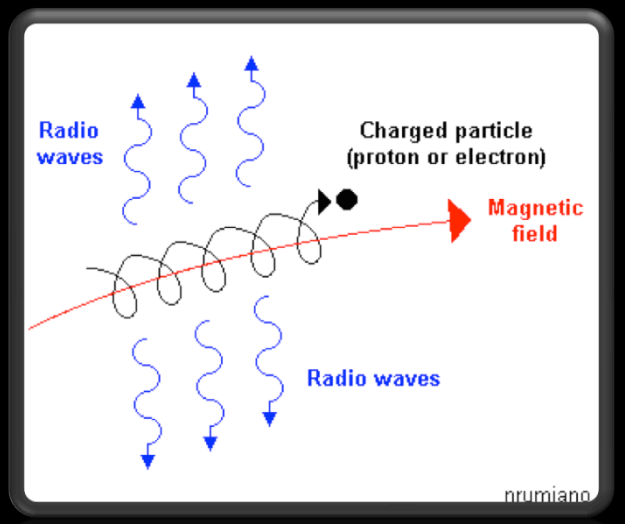
One mission: measure percentage of antimatter in the cosmic rays



2008: extra antimatter from dark matter annihilation?!?
Or just nearby pulsars? Stay tuned…

The Future: Radio Detection

- Electrons, positrons in air shower curve in Earth's magnetic field: emit radio pulse (geosynchrotron)
- Idea: detect cosmic ray air showers with radio antennas
- Complements other detection methods

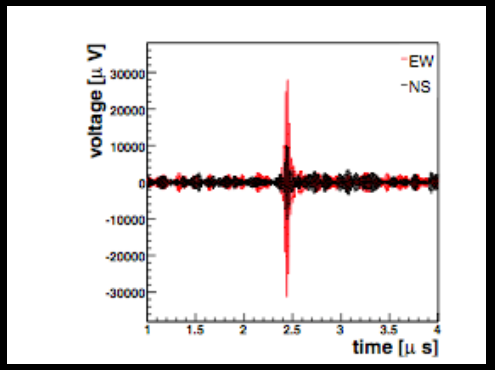


Prototype Station

antenna

electronics

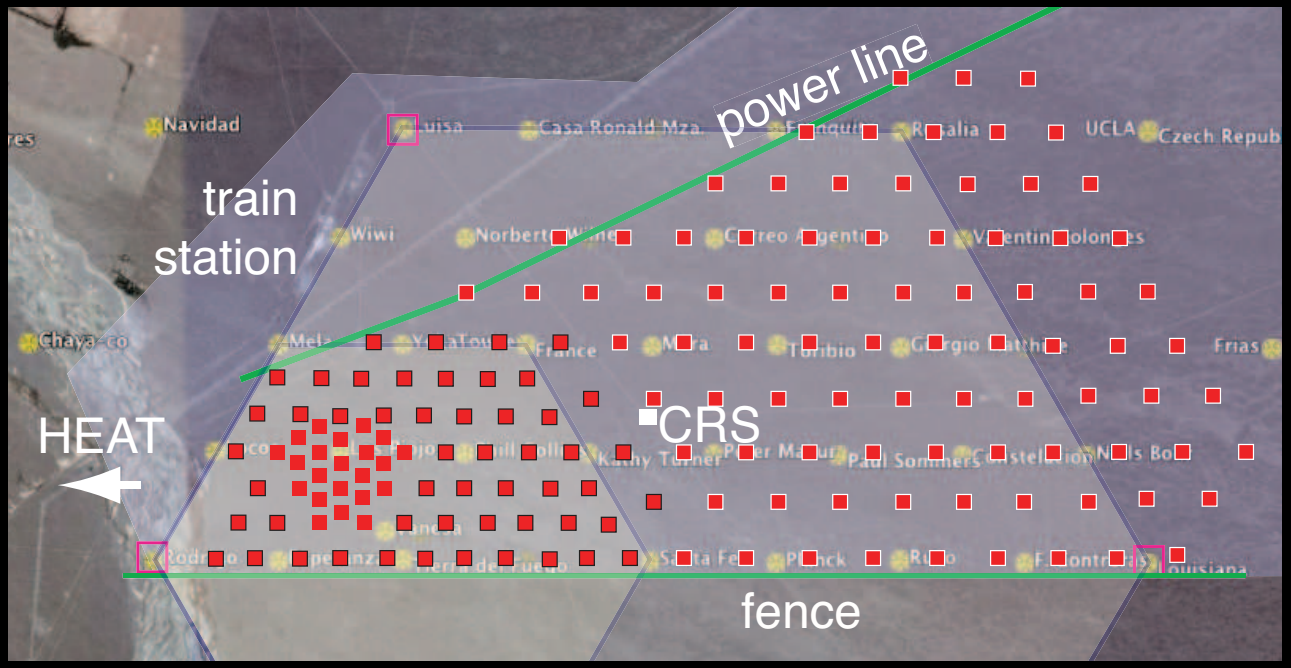
solar panels



An air shower pulse!

(also radio stations, TV stations, cars, power lines…)

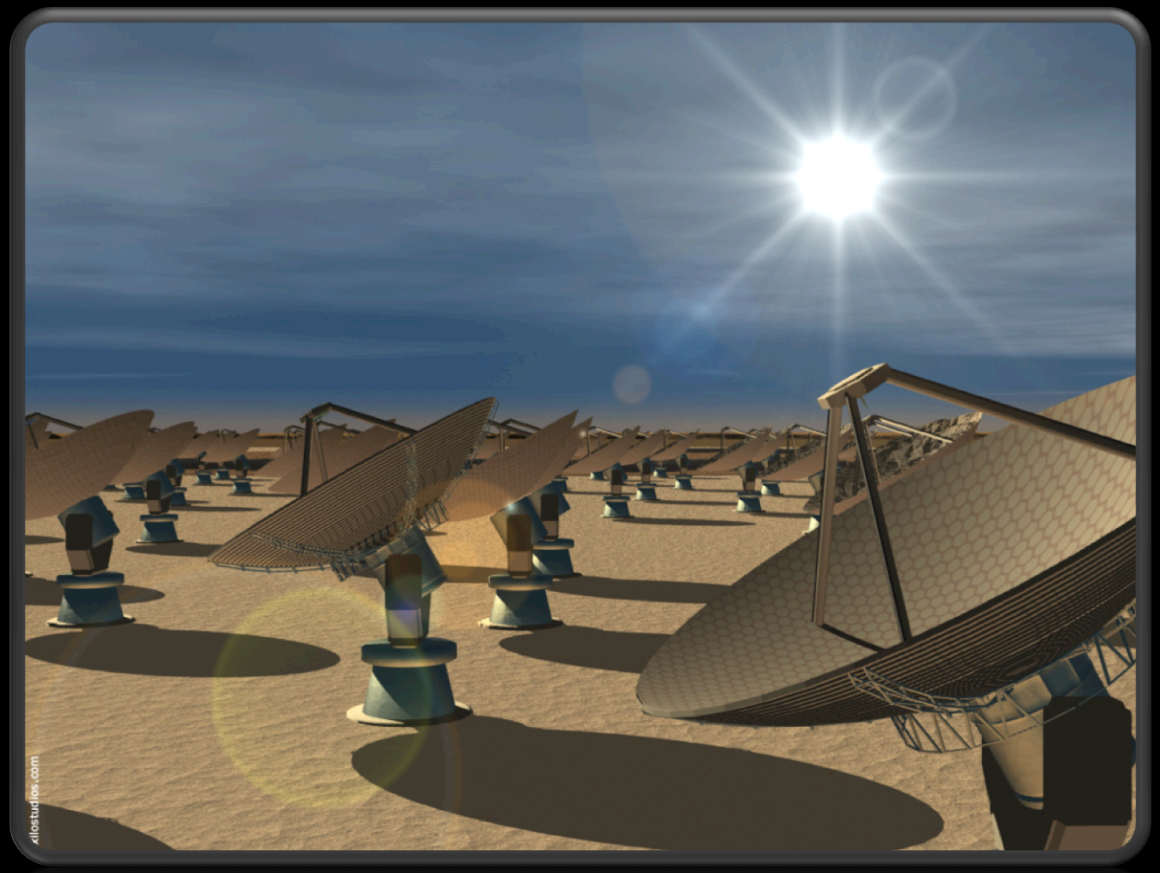
AERA



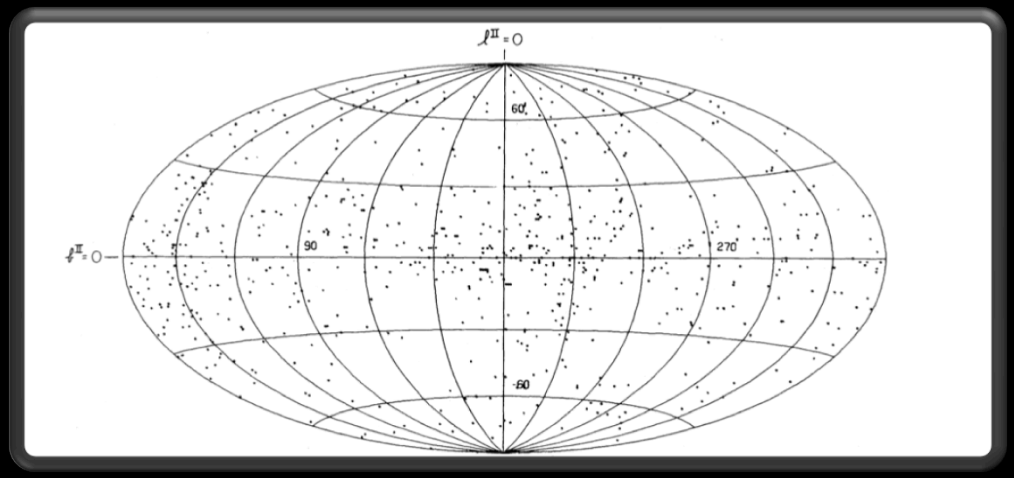
- Auger Engineering Radio Array
- ~40 scientists from Netherlands, Germany, and France
- Start construction in Argentina in early 2010

Next-generation Radio Telescopes

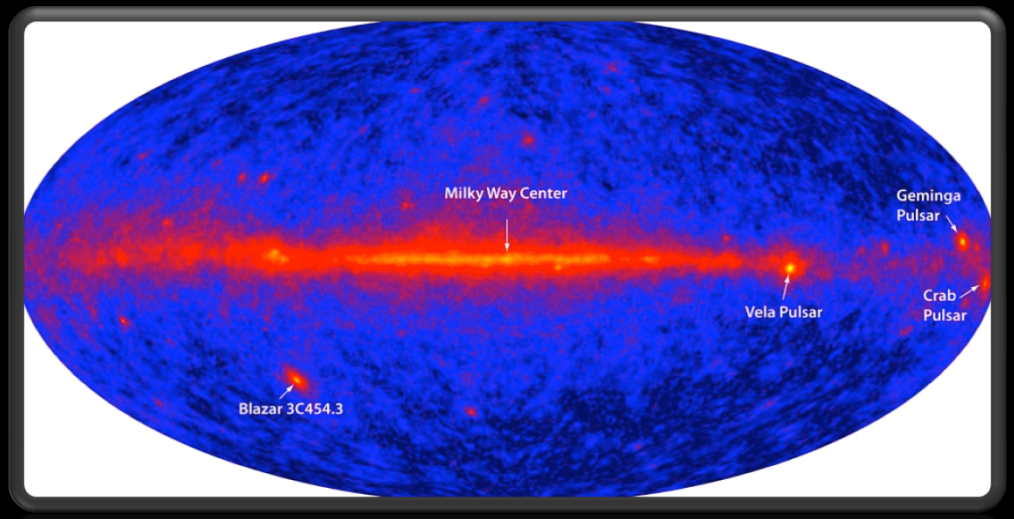
Square Kilometer Array



An Analogy with Gamma Ray Astronomy

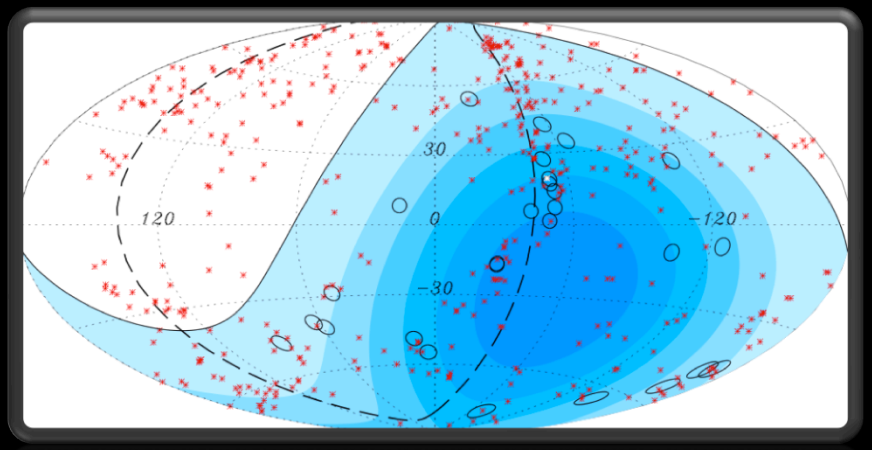


OSO-3 (1968)



Fermi (2008)

Charged Particle Astronomy



Auger (2007)

???

The future?

Summary

- Still many unanswered questions about cosmic rays
  - May come from SNRs and AGN… not sure
  - Many are protons, but at high energies…?
- Large air shower detectors like Auger continue taking data
  - We should know a lot more in a few years
- New experimental techniques like radio air shower detection in development
- The beginning of a new type of astronomy!

SN 1006 remnant (in Lupus)

Thank you!