

The Astroparticle Lens: Using Particles From Space To Understand Our World



**The highest energy neutrinos
to understand the most
extreme environments**

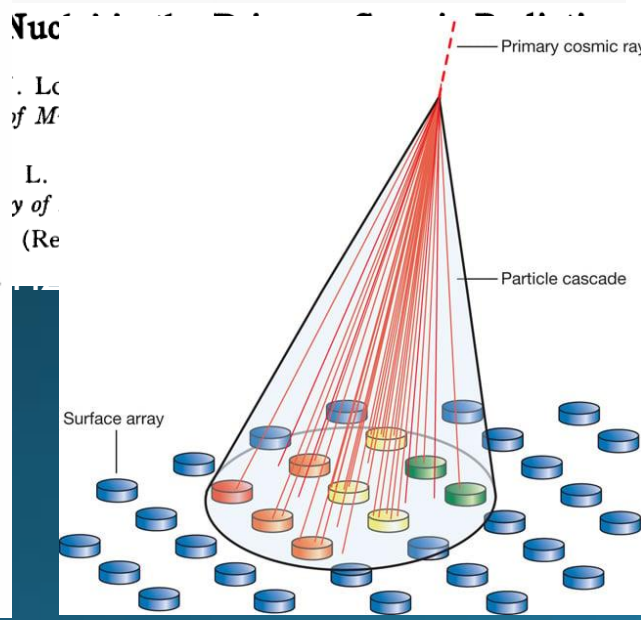
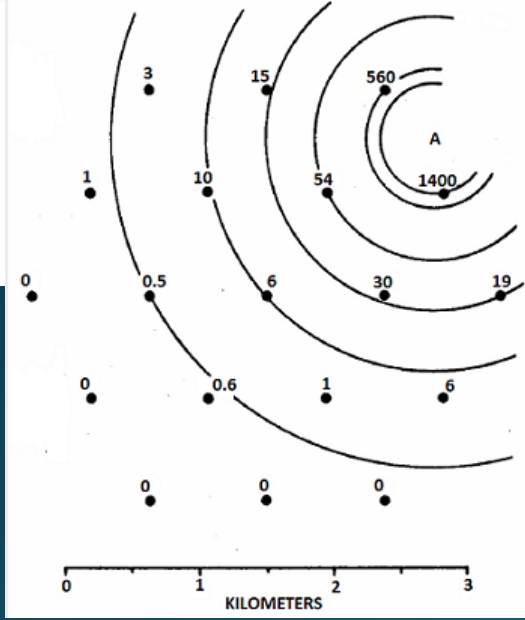
Keith McBride-Compton Lecture 8

Cosmic radiation

History of discoveries

Dr. Bruno Rossi, internationally-known M.I.T. authority on cosmic rays who is vacationing in Italy, cabled this statement: "The exceedingly large shower found by Linsley and Scarsi confirms the extragalactic acceleration mechanism for cosmic rays." In offering a new explanation, the opinion of the M.I.T. research group is based not only on the super shower but also on a series of recent observations of very high-energy showers.

1. (1912) This radiation is coming from space
2. (1948) This radiation is not just protons - nuclei of elements
3. (1960s) This radiation reaches extreme energies



LY 15, 1948

35
Cl
Chlorine
17

17 protons
20 neutrons
17 electrons

17 electrons

17 electrons

proton → photon

Darn, so close

Introducing some jargon

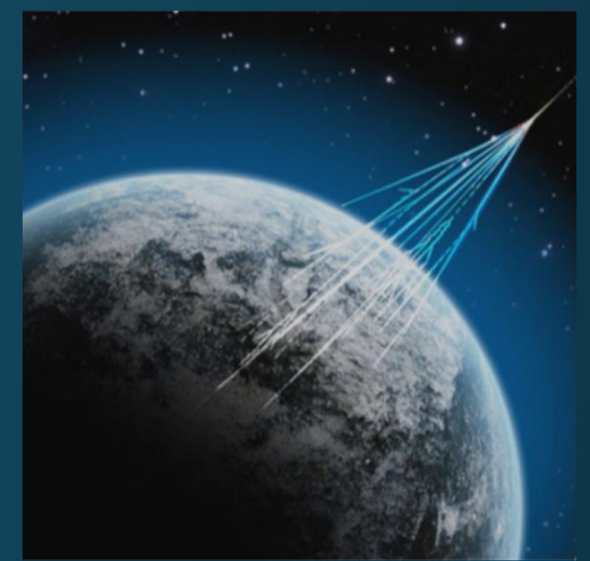
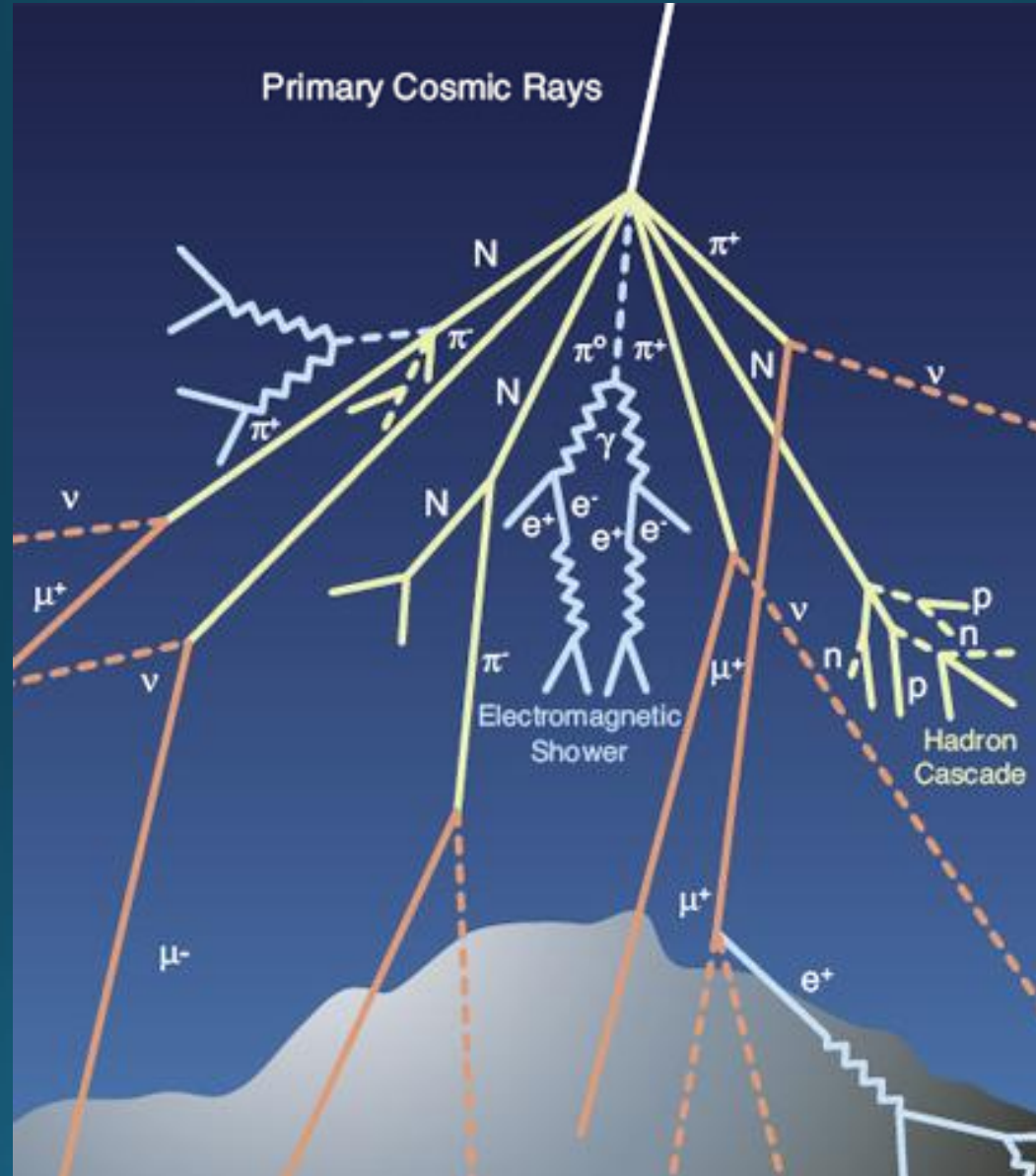
*Primary cosmic rays

More particles at higher energy

➤ Fewer “total number of particles”

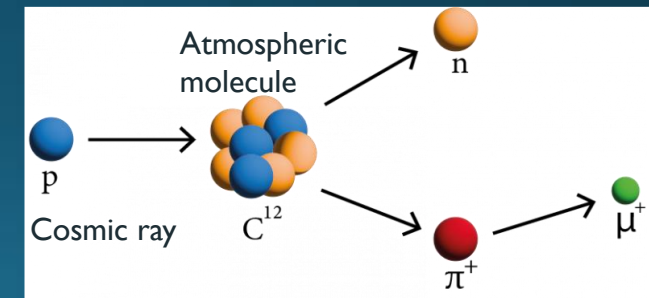
Less particles at higher energy

➤ lost energy through the atmosphere



Primary cosmic rays bombard the top of the atmosphere

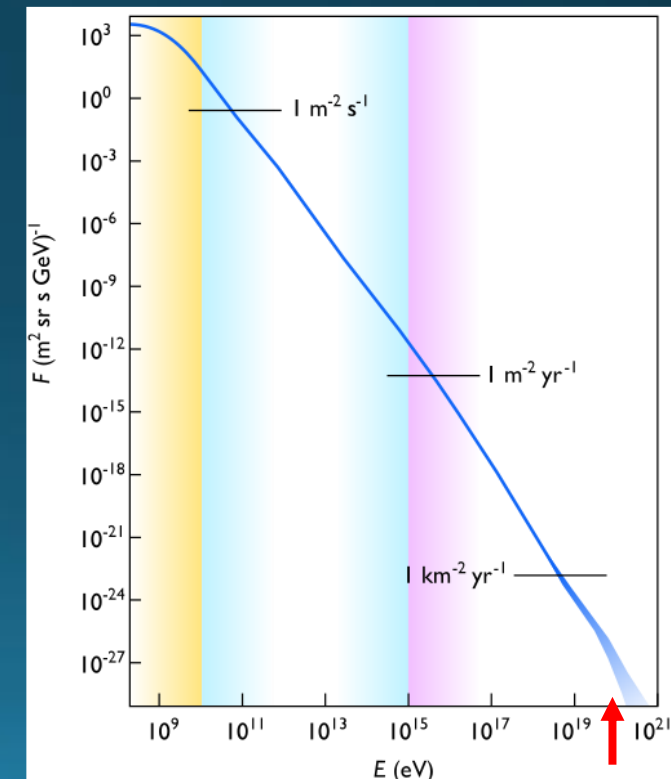
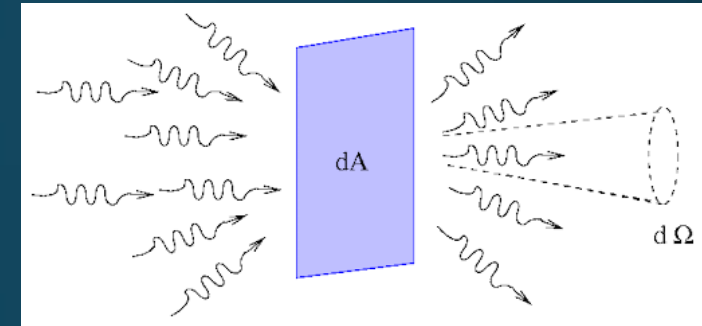
Cosmic rays interact with atmosphere



The flux of primary cosmic rays

- A spectrum of cosmic rays
- Cosmic rays at higher energies are rarer (i.e. less frequent)
 - Higher energies, flux falls off (i.e. power law)
- 1 EeV of energy (Exa electron Volts) is 1 billion times 1 GeV (Giga electron volts)
 - Hold out your hand (while in space) for 6 billion years to catch the 100 EeV cosmic ray
 - If you want 99% chance – then closer to 30 billion years

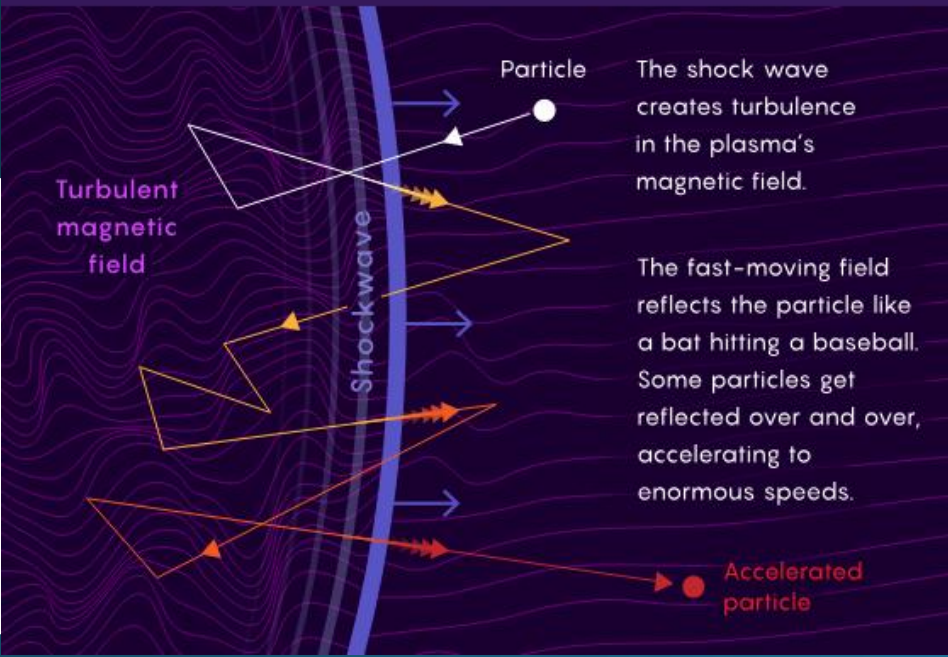
→Particles are accelerated somewhere in the universe to these extreme energies



How can cosmic rays be produced at these energies?

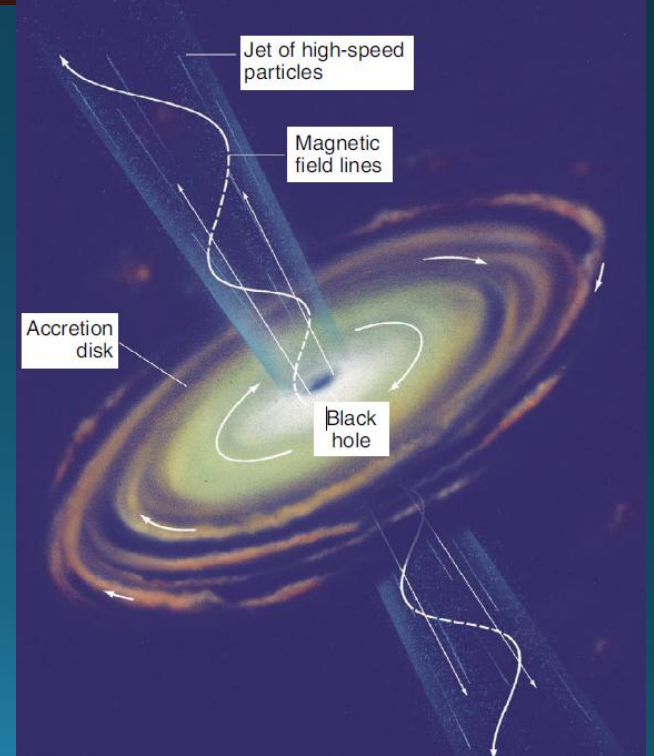
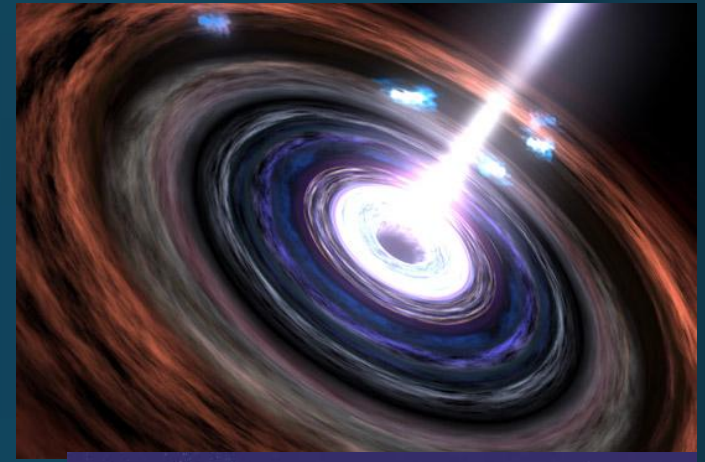
How to Accelerate Cosmic Rays

The most efficient known mechanism for accelerating particles involves shock waves moving through plasma. Charged particles ping-pong back and forth across the shock front, gaining speed each time.



by strong fields.

Ongoing research!
Many theories and models



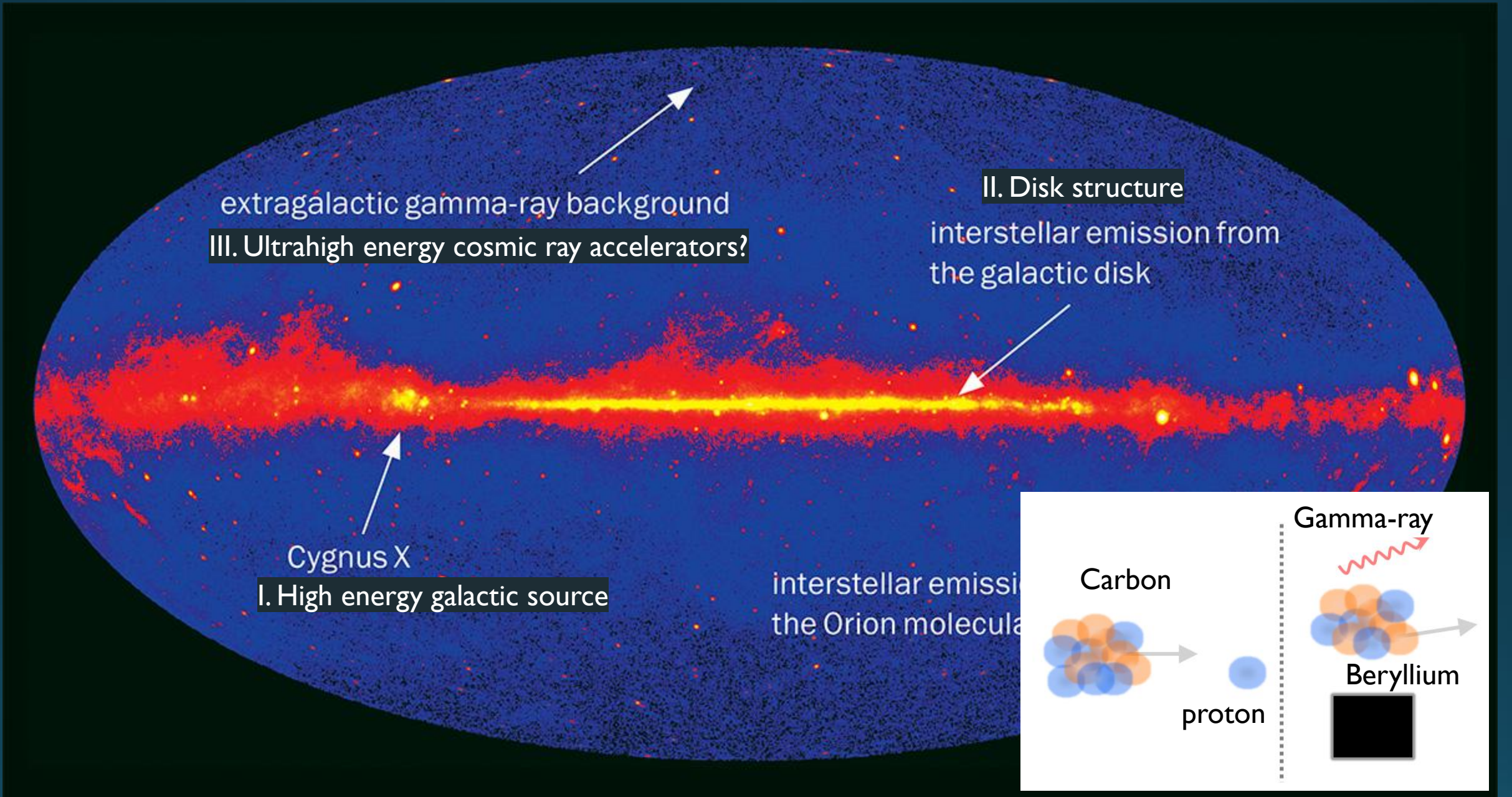
Candidate ultrahigh-energy accelerators

- Ultrahigh-energy ($E_{\text{eV}} = 10^{18}\text{eV}$ energy) cosmic rays
 - That's 1 billion times the Giga electron volts (GeV) cosmic rays
- Active Galactic Nuclei
 - Supermassive black holes at center of some galaxies
 - Blazars
- Gamma-Ray Bursts (GRBs)
 - Short-duration explosions emitting gamma rays
- Tidal Disruption Events
 - Star is torn apart by supermassive black hole

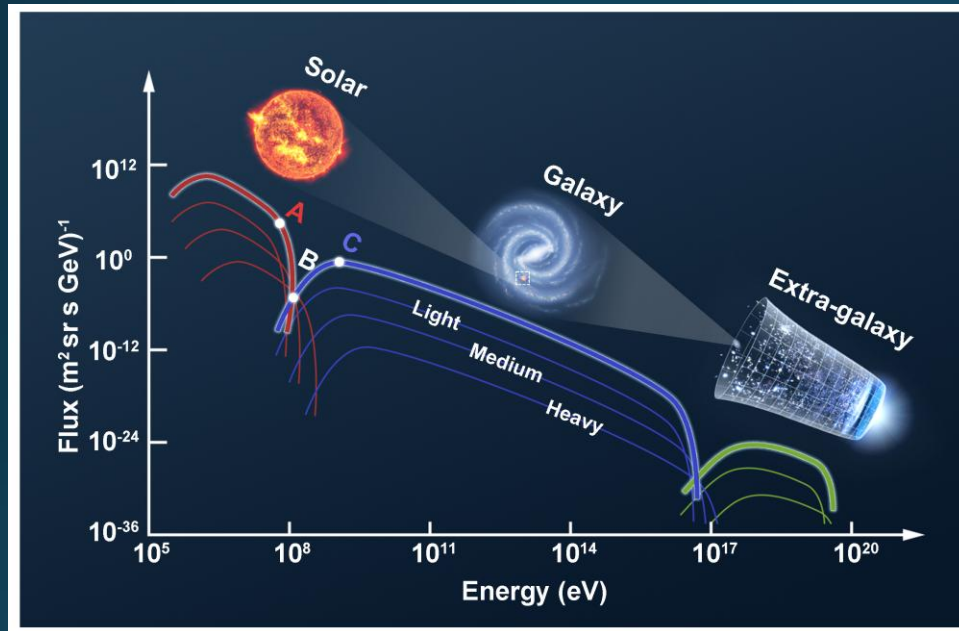


Similarities:

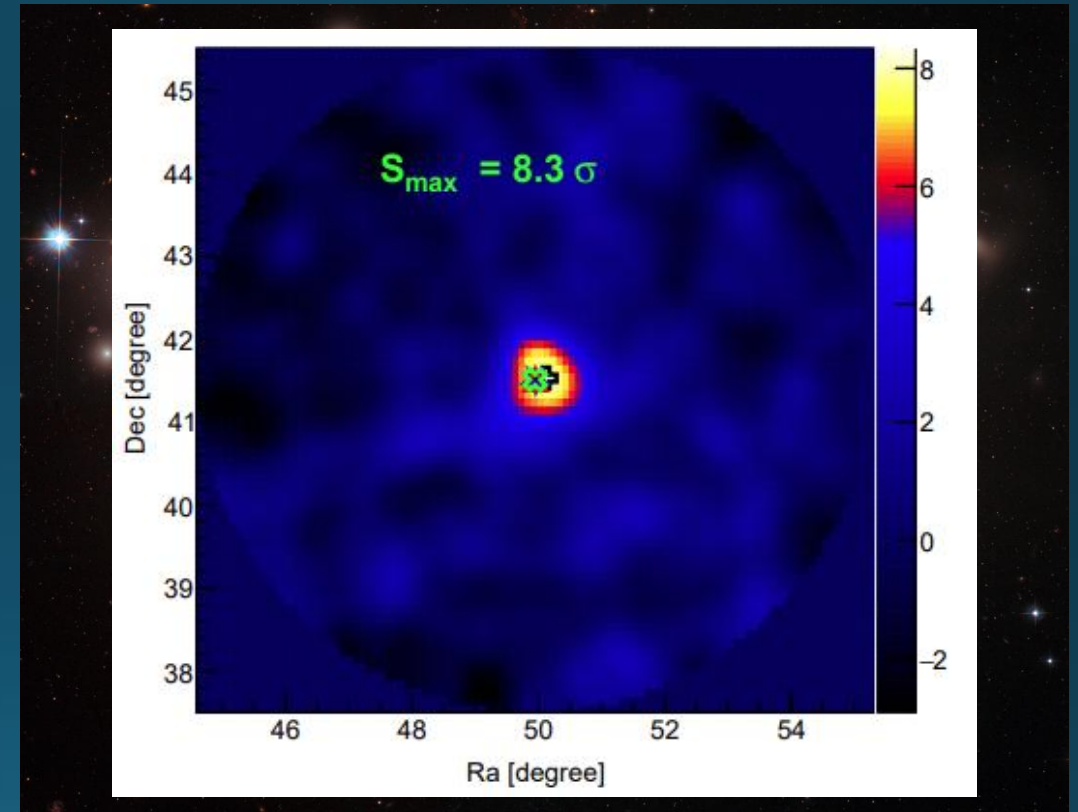
- Black holes and hot gas
- Emission of gamma-rays



Extragalactic radiation



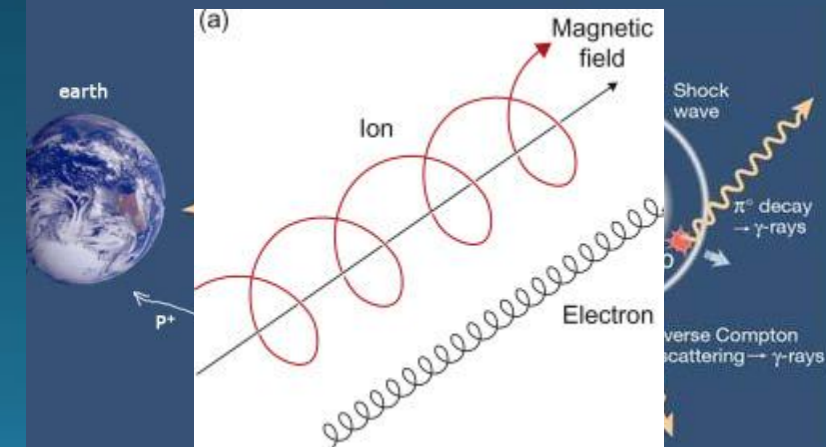
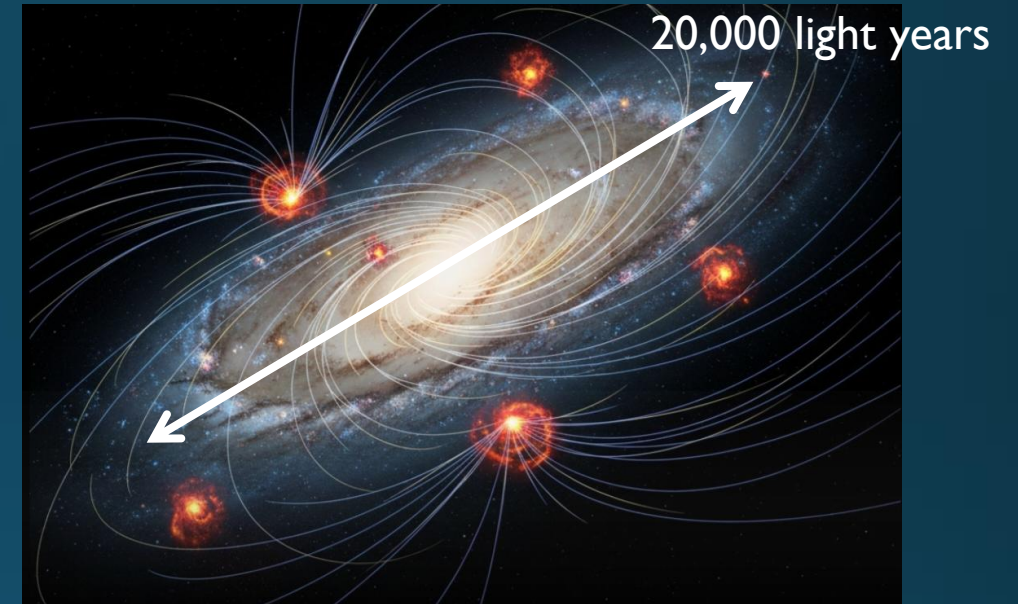
Infer an extragalactic flux of cosmic rays
“ultrahigh-energy” cosmic rays

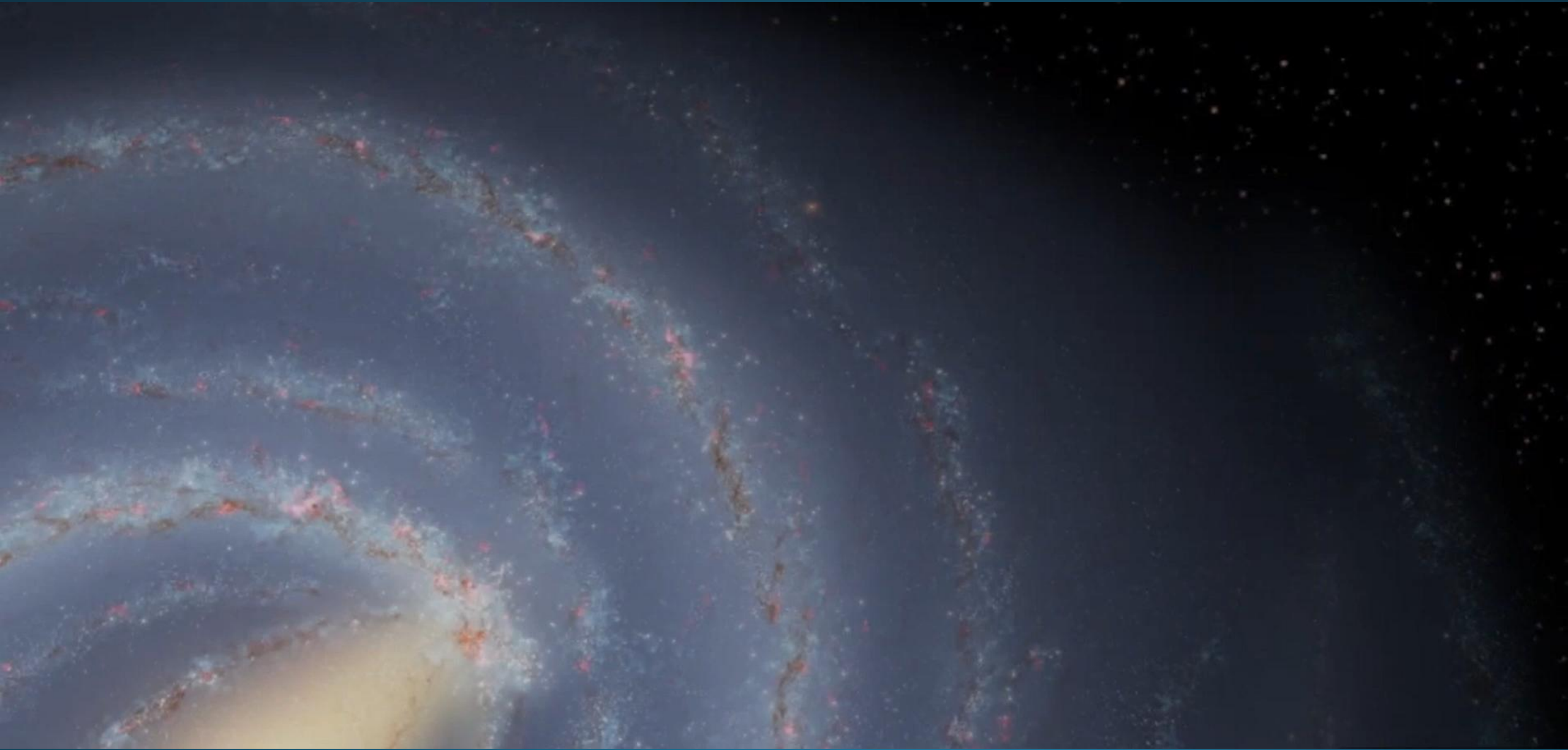


Well-known AGN NGC 1275
Gamma ray measurements from LHAASO
Large High Altitude Air Shower Observatory (LHAASO)

(Galactic) Cosmic rays are isotropic

- Primary cosmic rays arrive from all directions about equally
 - Shouldn't they point back to the Supernovae Remnants?
- Fermi had the solution
 - Galactic magnetic fields
 - 1950s and 60's – first measurements (1-3 millionths of a Gauss)
 - 100,000 times weaker than fridge magnet
- Cosmic rays are sort of confined within the Milky Way
 - Unless they have enough energy



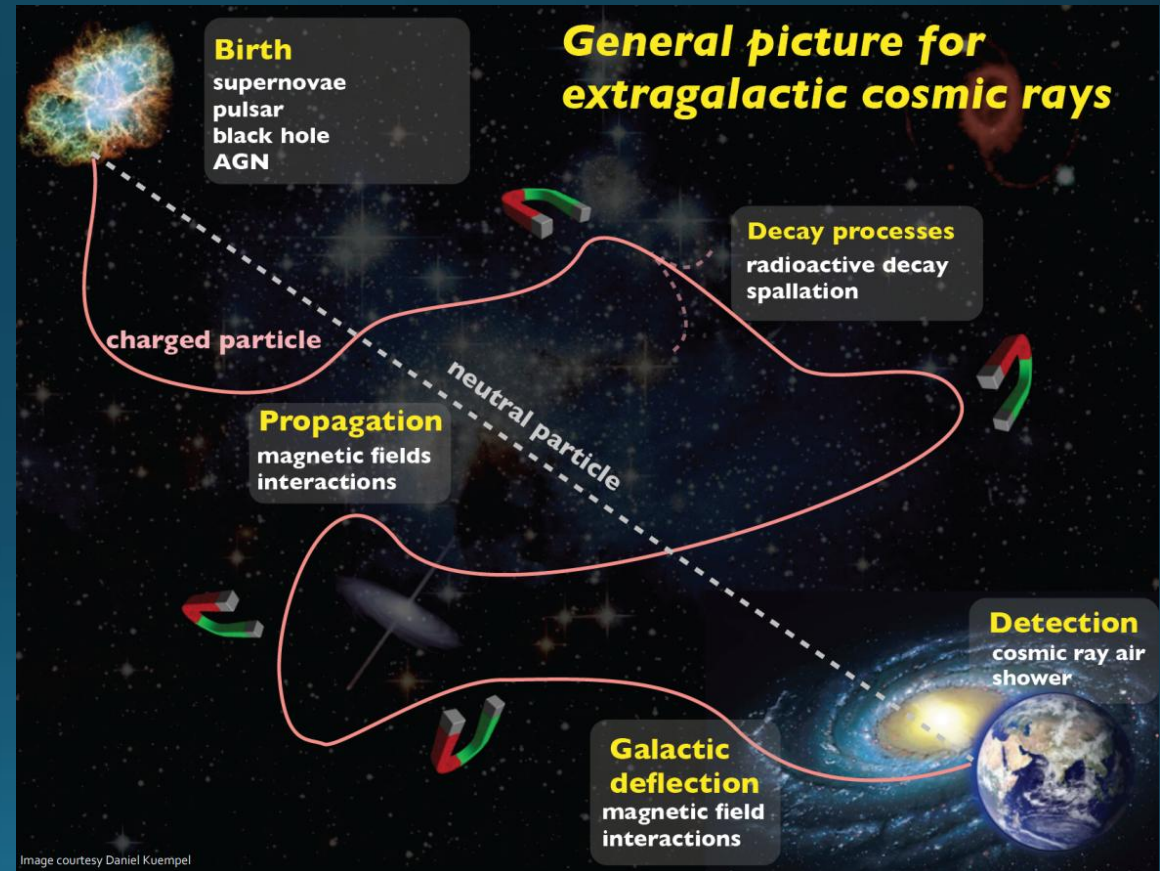


Intergalactic magnetic fields

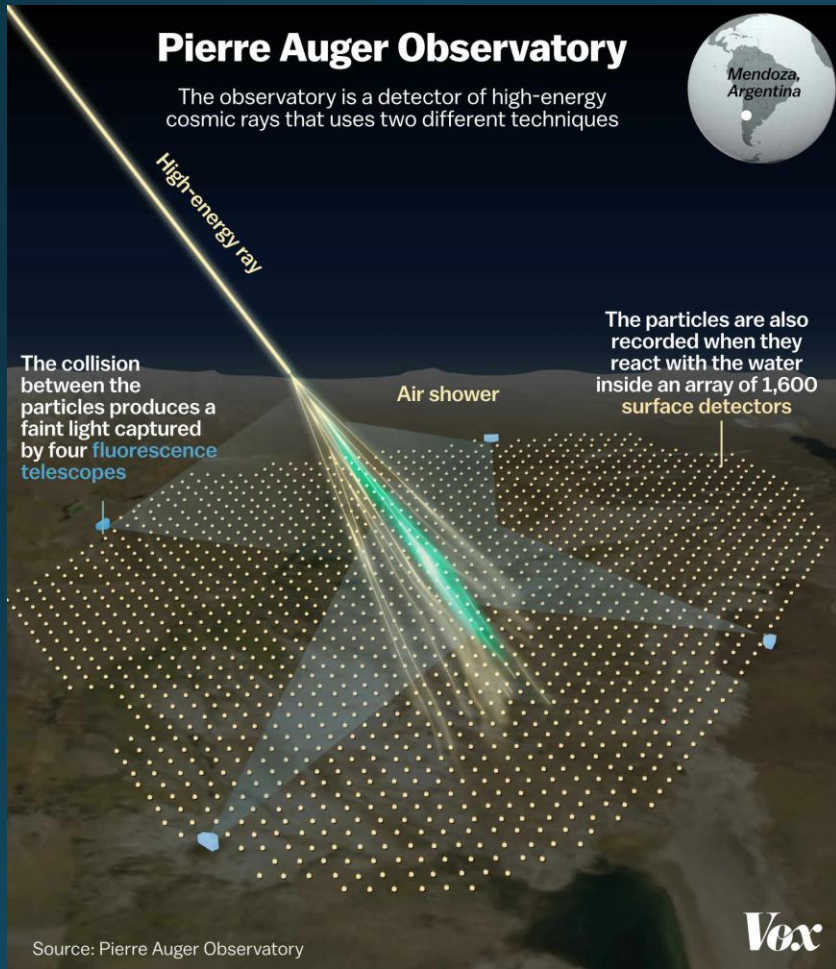
- Very small (but not zero) magnetic fields between galaxies
 - 100,000 times weaker than Milky Way's
- But ultrahigh-energy cosmic rays are moving so fast they might not deflect on magnetic fields so much
- Result → small deflections, smearing, random walk

Active area of research

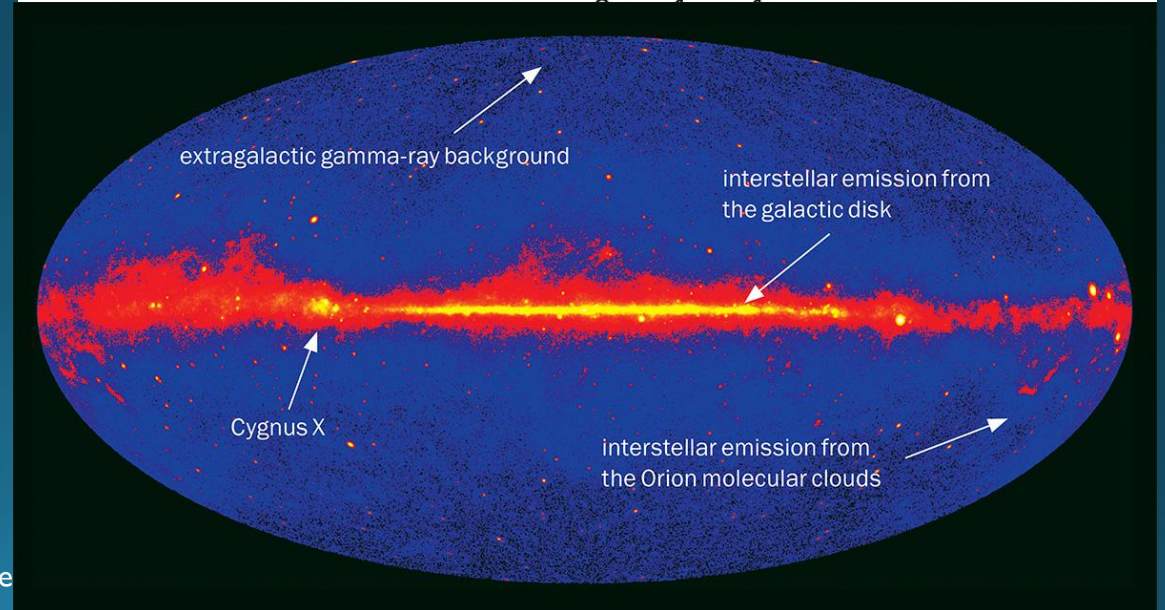
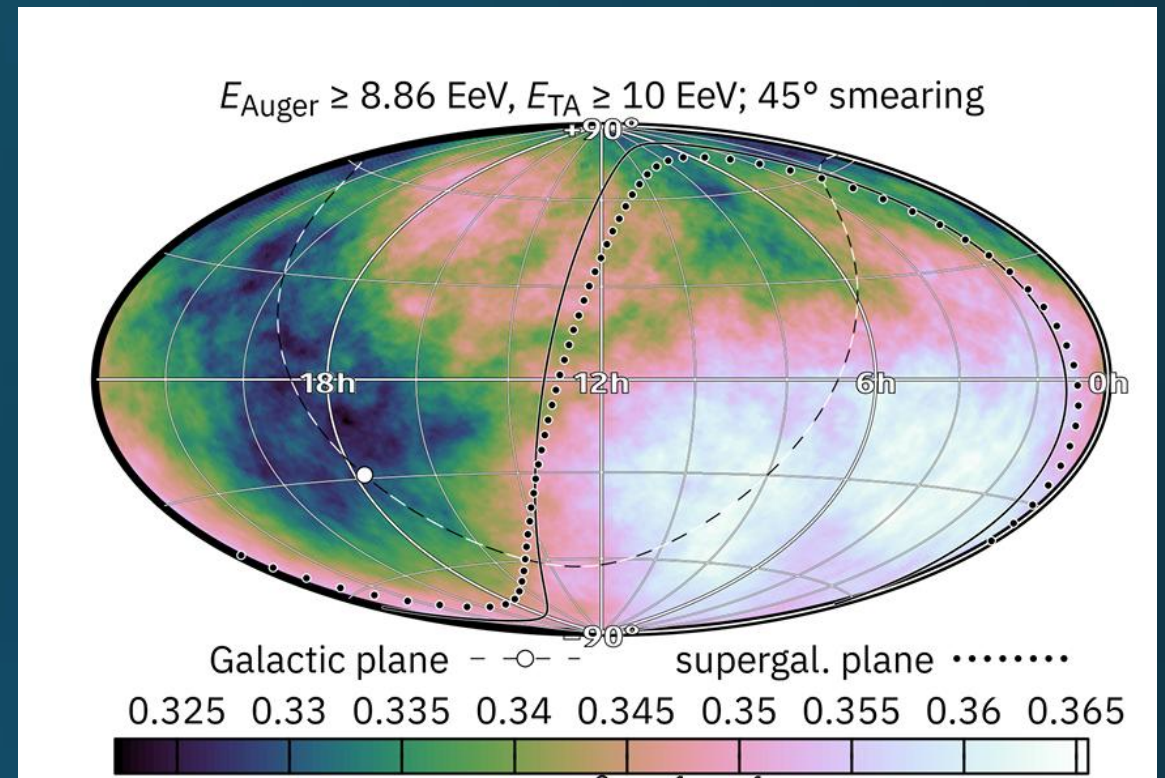
- Ongoing studies, not so well understood as galactic magnetic fields



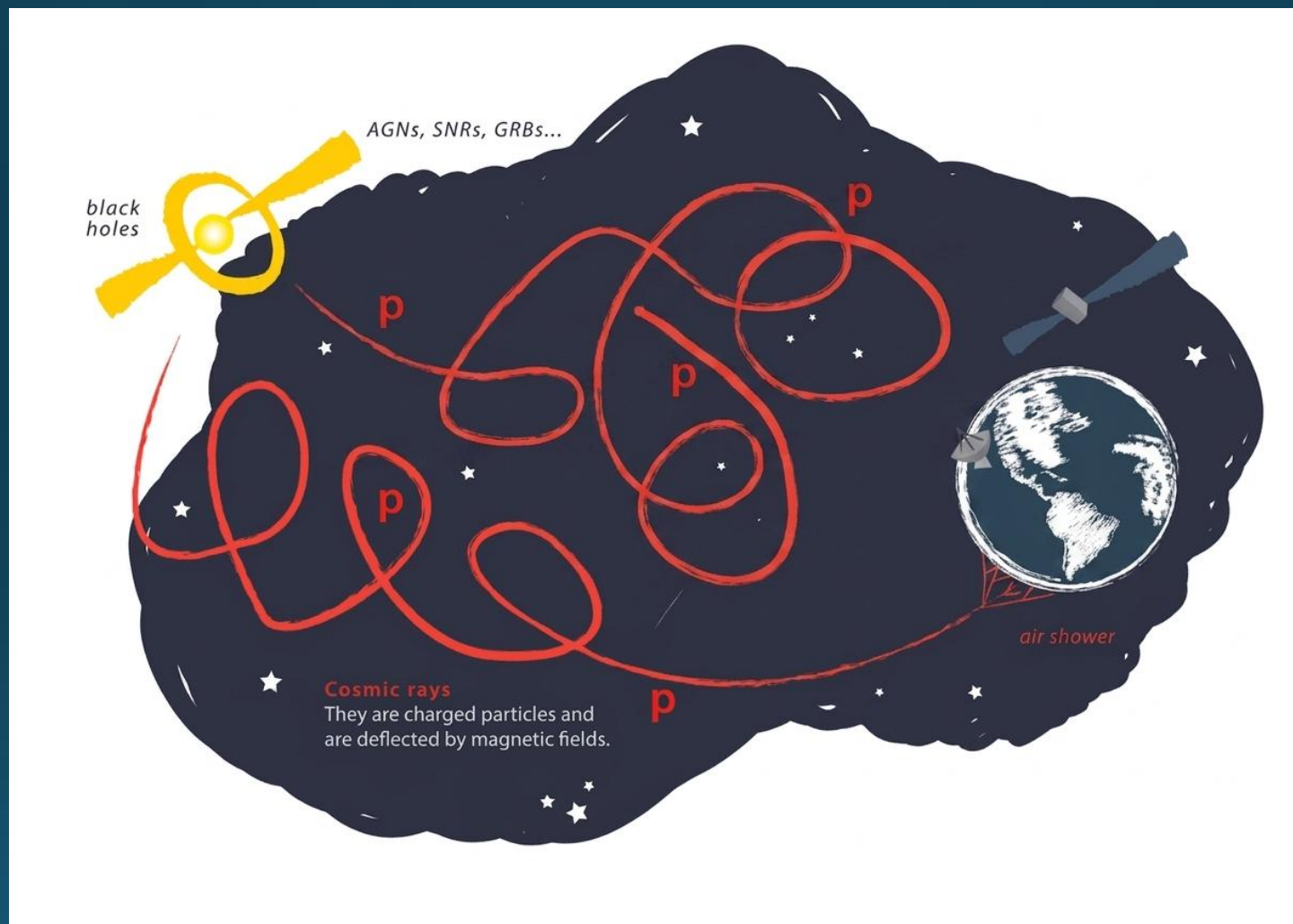
Extragalactic cosmic rays might not be isotropic



*Potentially a “hot spot” in the arrival direction of ultrahigh-energy cosmic rays



Finding the origin of ultrahigh-energy cosmic rays is challenging



Gamma-ray signatures

- Since cosmic rays don't point back to their sources
- What about gamma rays?
 - Neutral
- Cosmic rays measured at 10^{20} eV
 - Remember that's 100 Exa electron volts
- Gamma rays measured to ~ 1 PeV
 - PeVatrons in the Milky Way

Ultrahigh-energy gamma rays from extragalactic sources are attenuated.

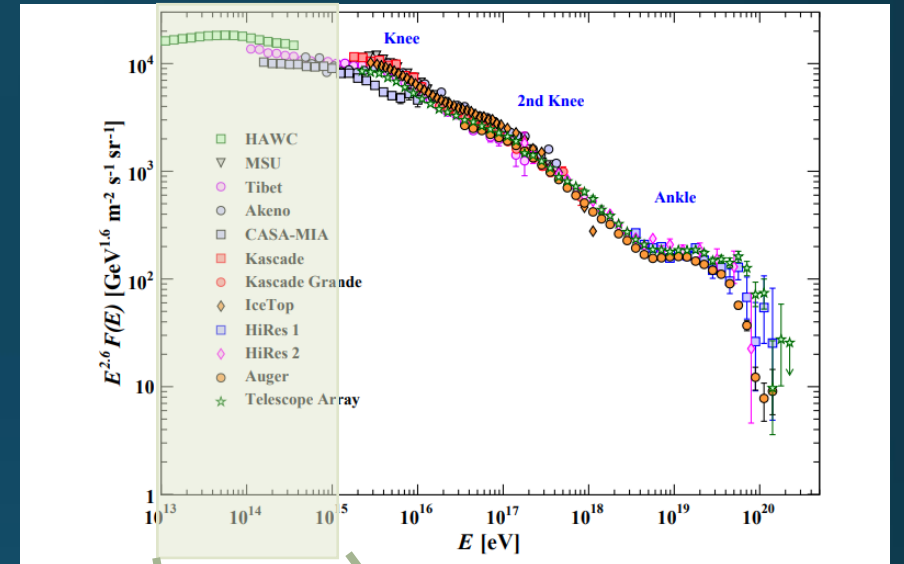
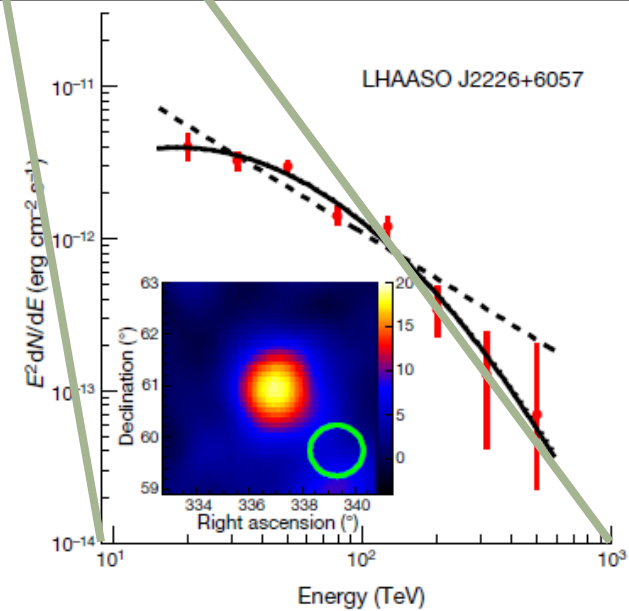


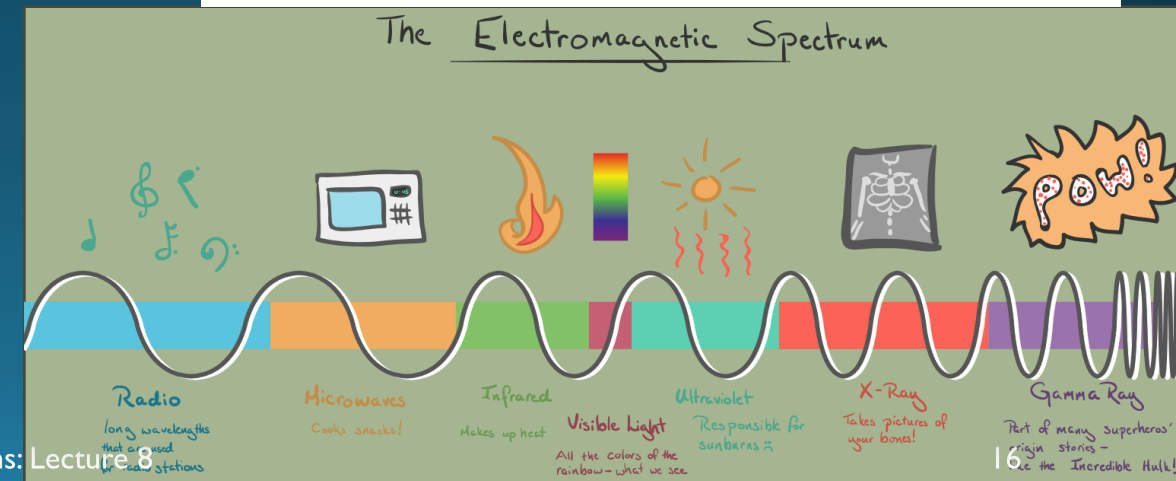
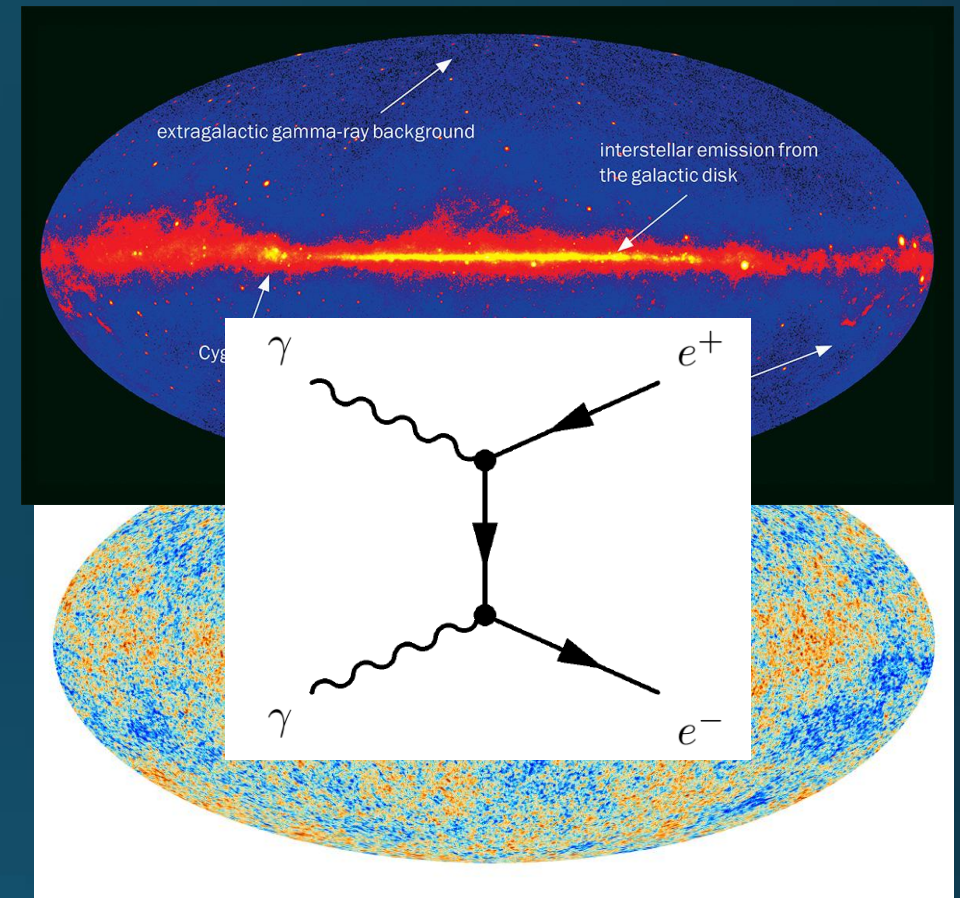
Figure 30.8
measureme

1 air shower

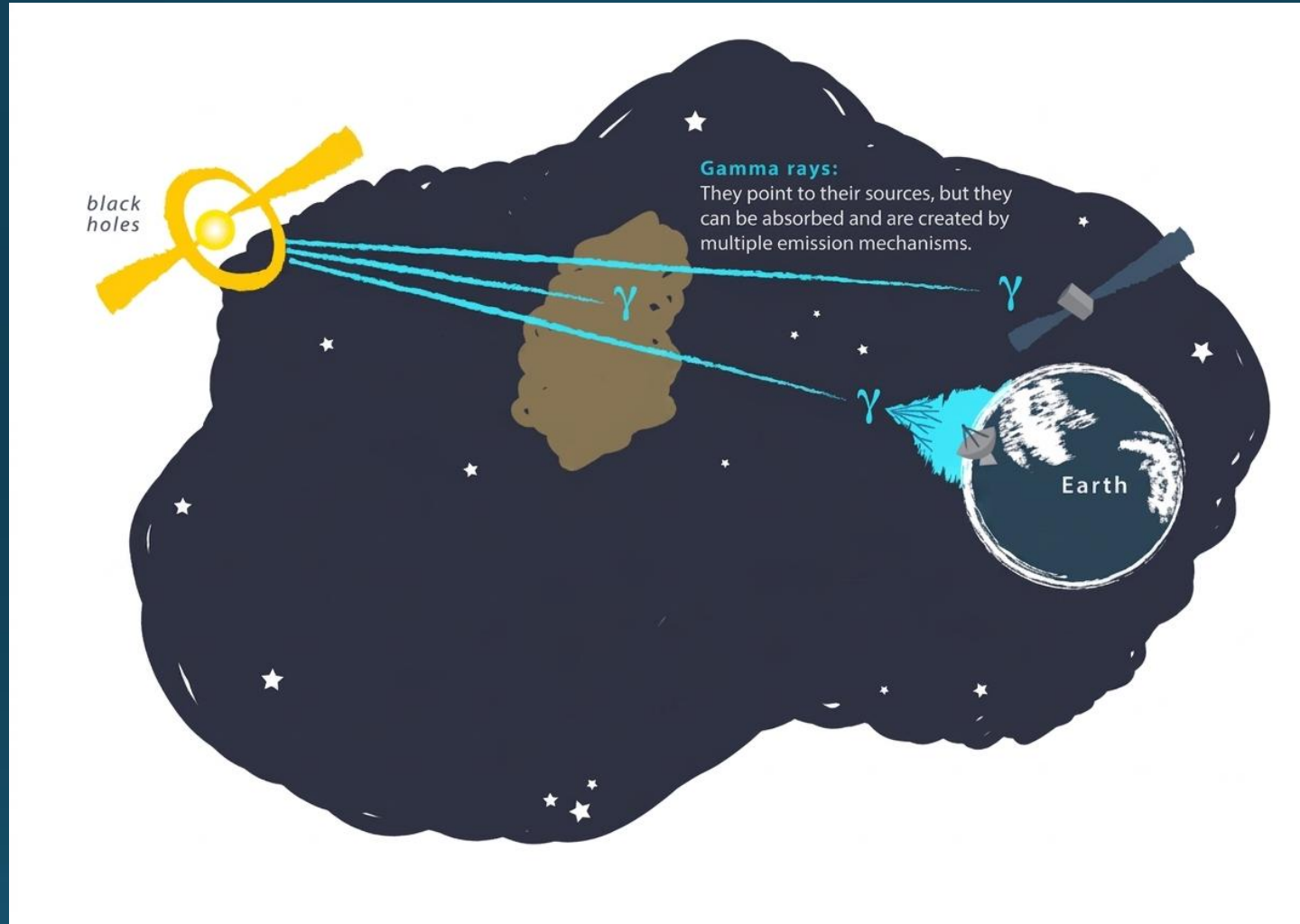


Gamma rays interact

- Cosmic Microwave Background
- Gamma rays and CMB light will interact
 - pair produce electron-positrons
 - The gamma rays above ~ 0.1 PeV (100,000 times 1 GeV) attenuated
- 1 PeV gamma rays are produced by local (galactic) sources



Finding the origin of ultrahigh-energy cosmic rays is challenging

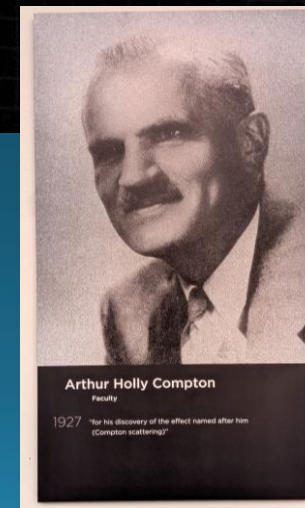
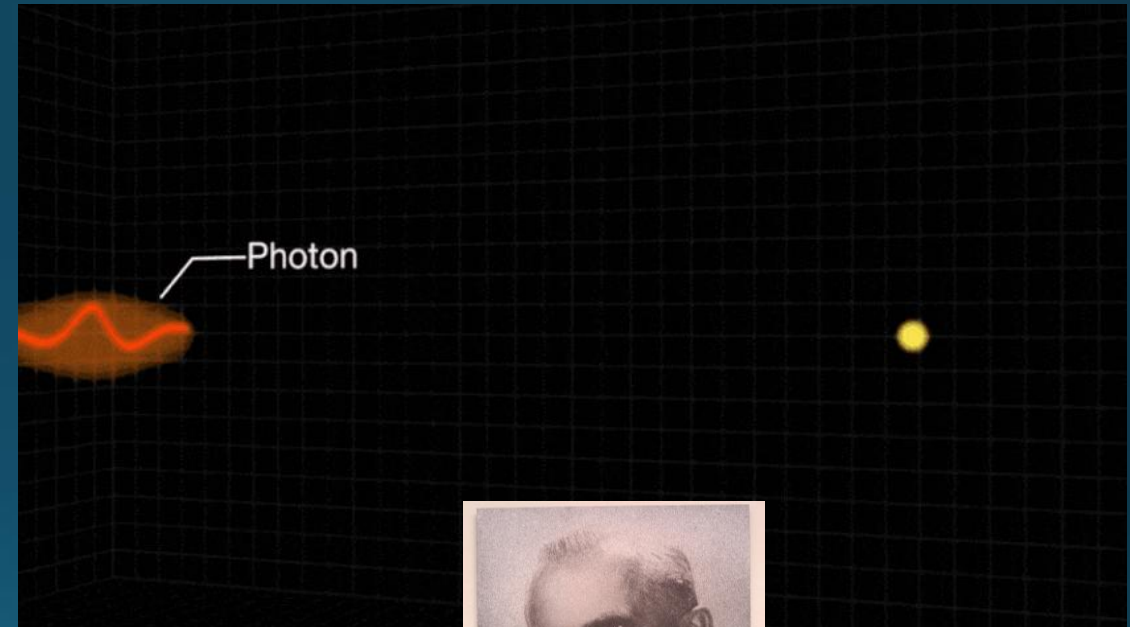


*Gamma rays can identify candidates?

Cosmic ray and gamma ray link?

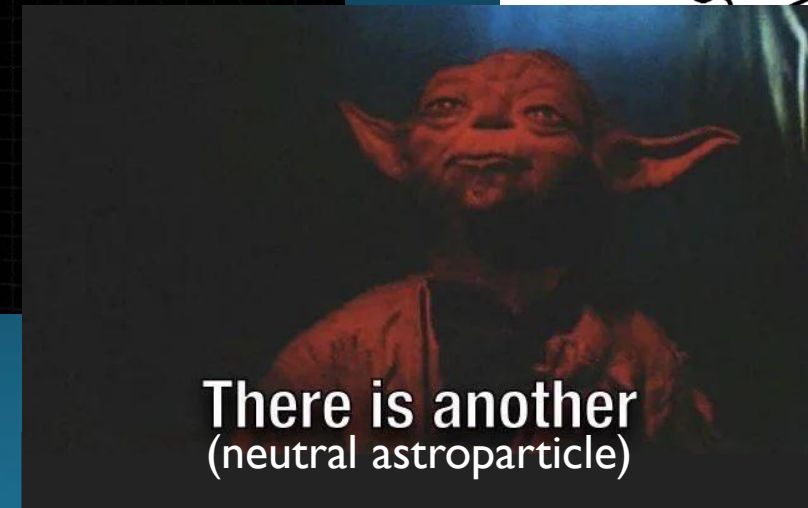
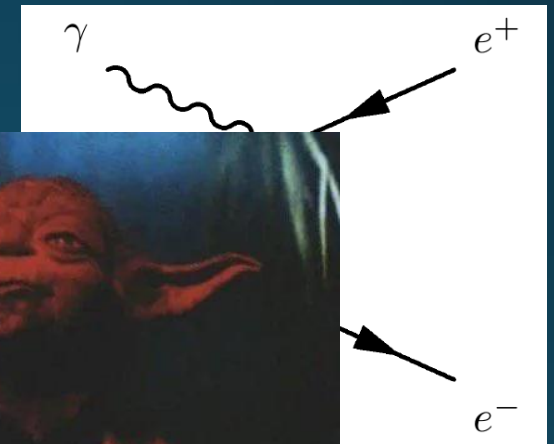
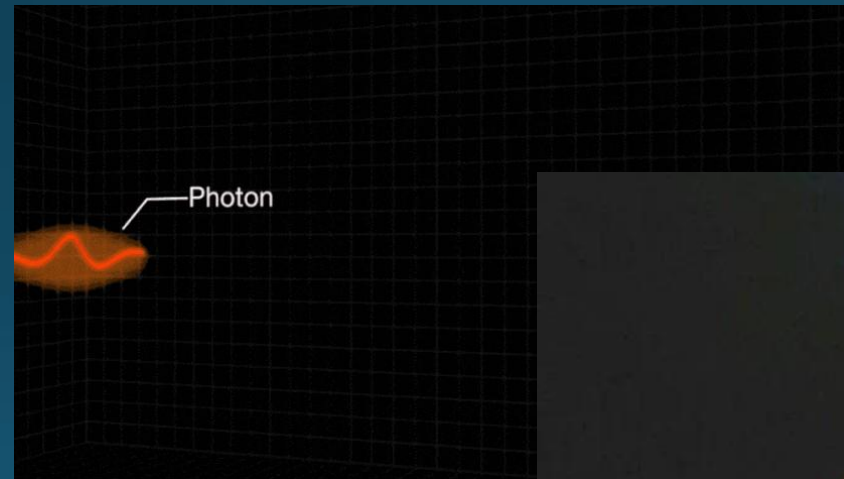
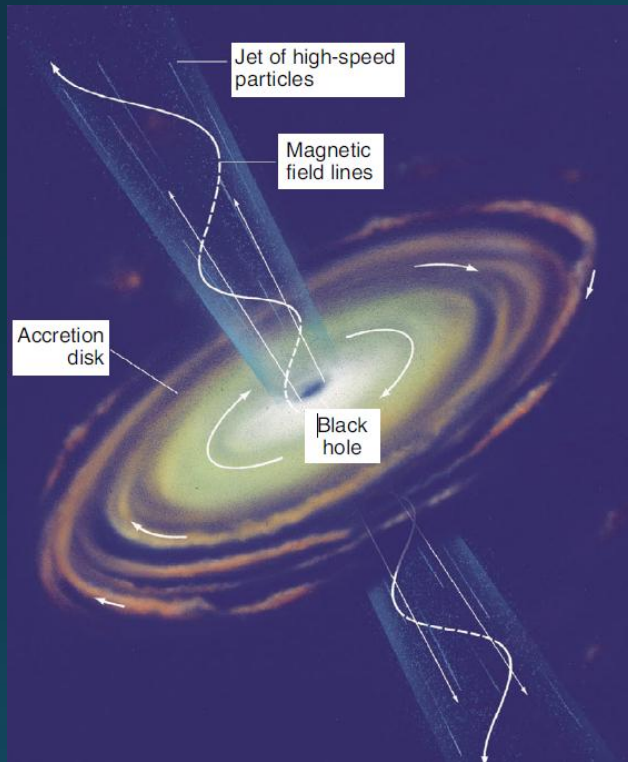
A conundrum

- Gamma rays can be produced at these cosmic ray candidate sites by processes without cosmic rays
- Electrons can up-scatter low-energy light into gamma rays
 - meaning “boost” low-energy light to higher energies
- This is the inverse of a famous process called ...
 - Inverse Compton Scattering



Maybe some kind of feedback loop produces the gamma rays we are observing!

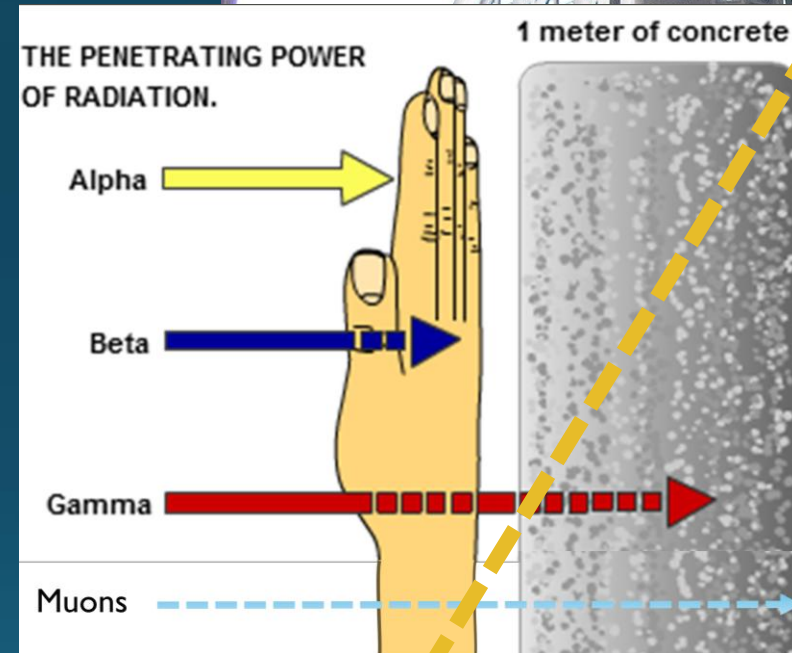
→ Not so certain that the gamma ray sources we observe are the same ultrahigh-energy cosmic ray sources



Electromagnetic force

- Get rid of the electromagnetic force from the muon
 - Just have the weak force left!
- It goes through all the lead!
 - Well not all, but most of it.
- This is why it's called the weak force

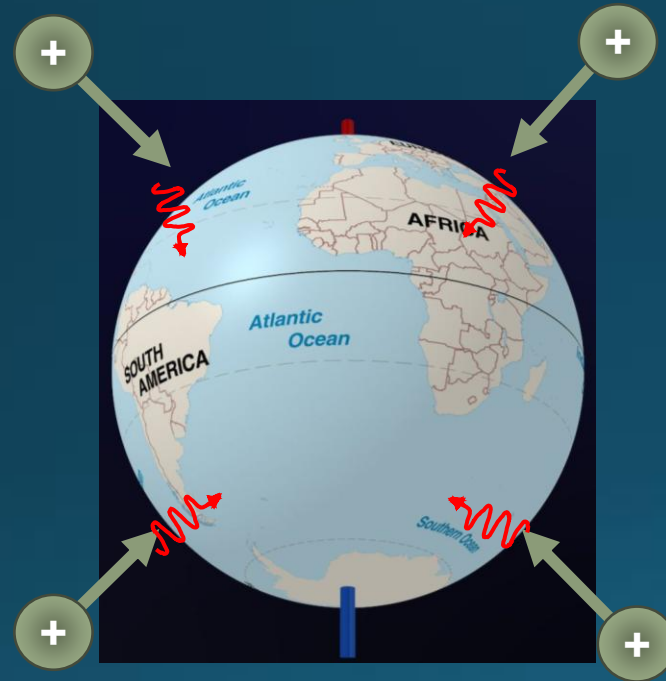
Monadnock Building, built in 1890's



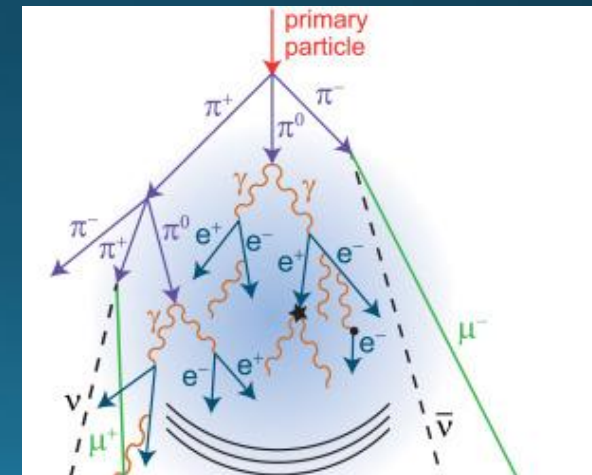
Neutrinos

Recall – neutrino tomography

Cosmic rays are constantly bombarding our atmosphere



And their interactions are producing neutrinos (and muons)

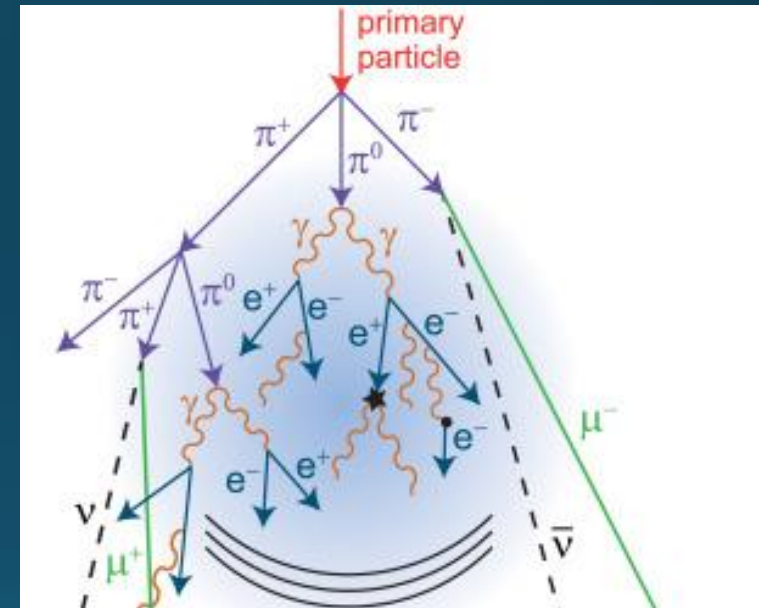


Do these sources produce neutrinos?

- Its possible they produce neutrinos
 - If they are accelerating/producing ultrahigh-energy cosmic rays

→ Interactions of cosmic rays (protons or nuclei) with gas near the acceleration site should produce neutrinos

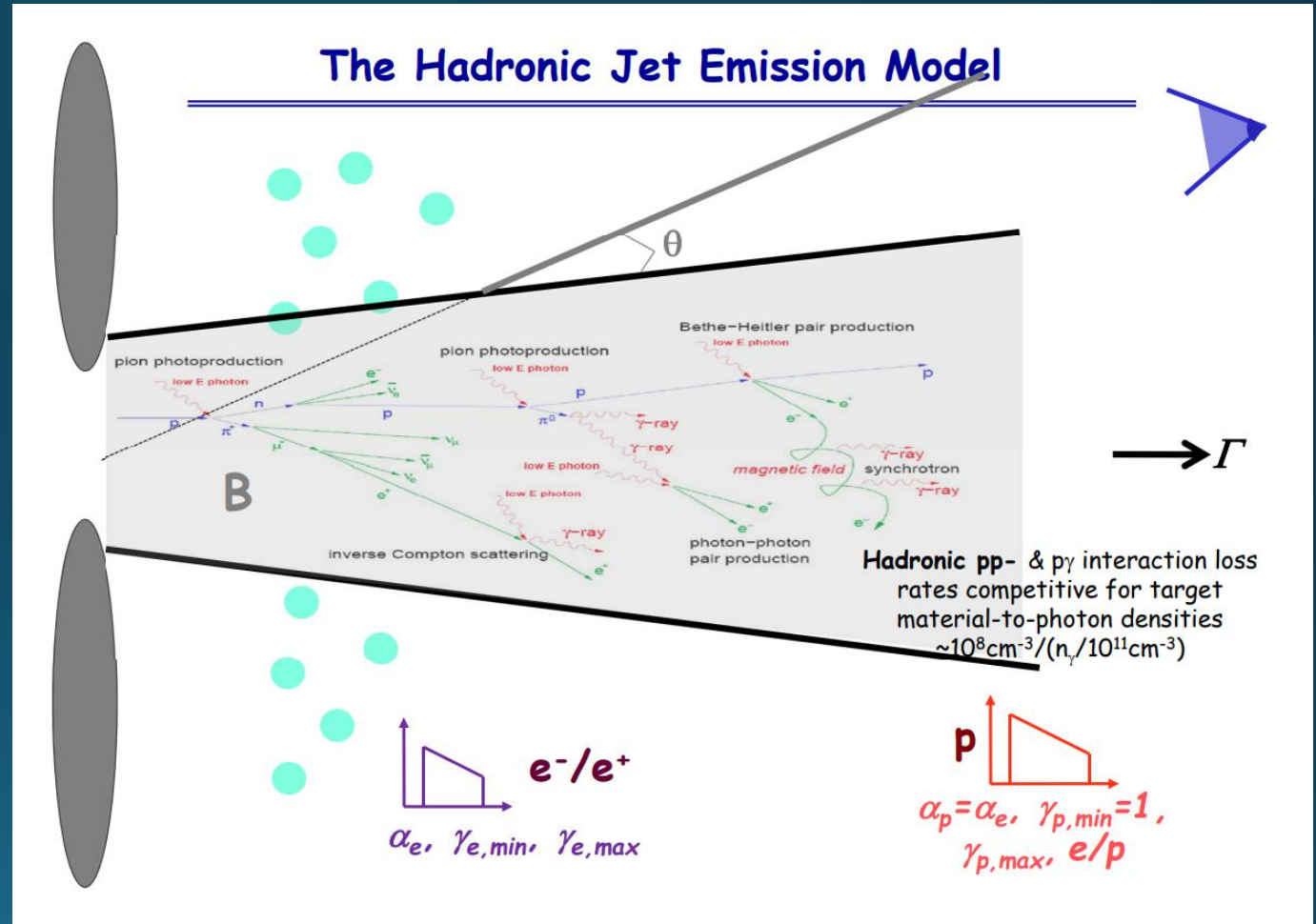
→ like our atmosphere



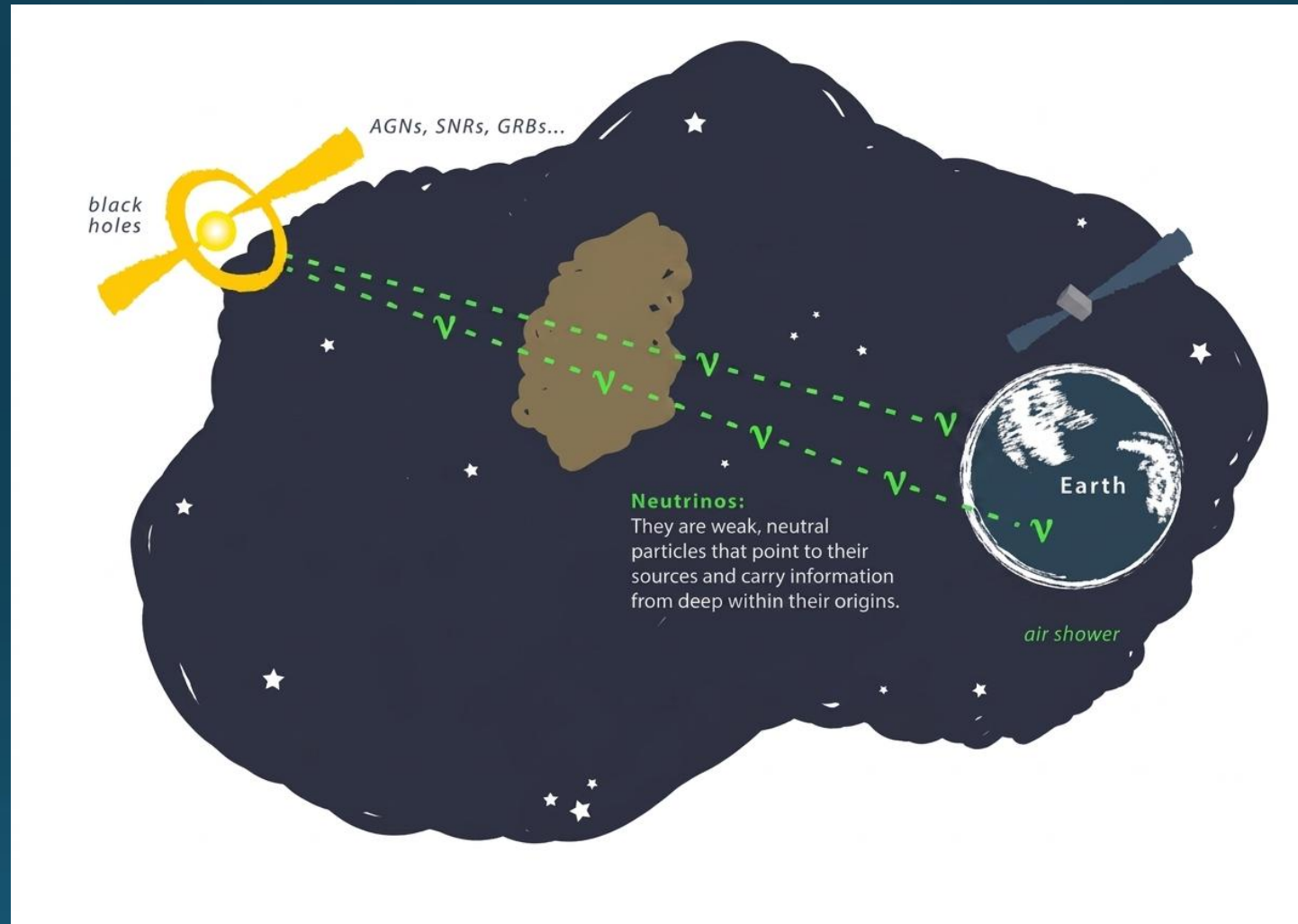
- Muons decay to neutrinos
- Pions decay to neutrinos
- Cosmic ray particles hit the atmosphere and produce pions and muons

(Some jargon) Leptonic vs Hadronic

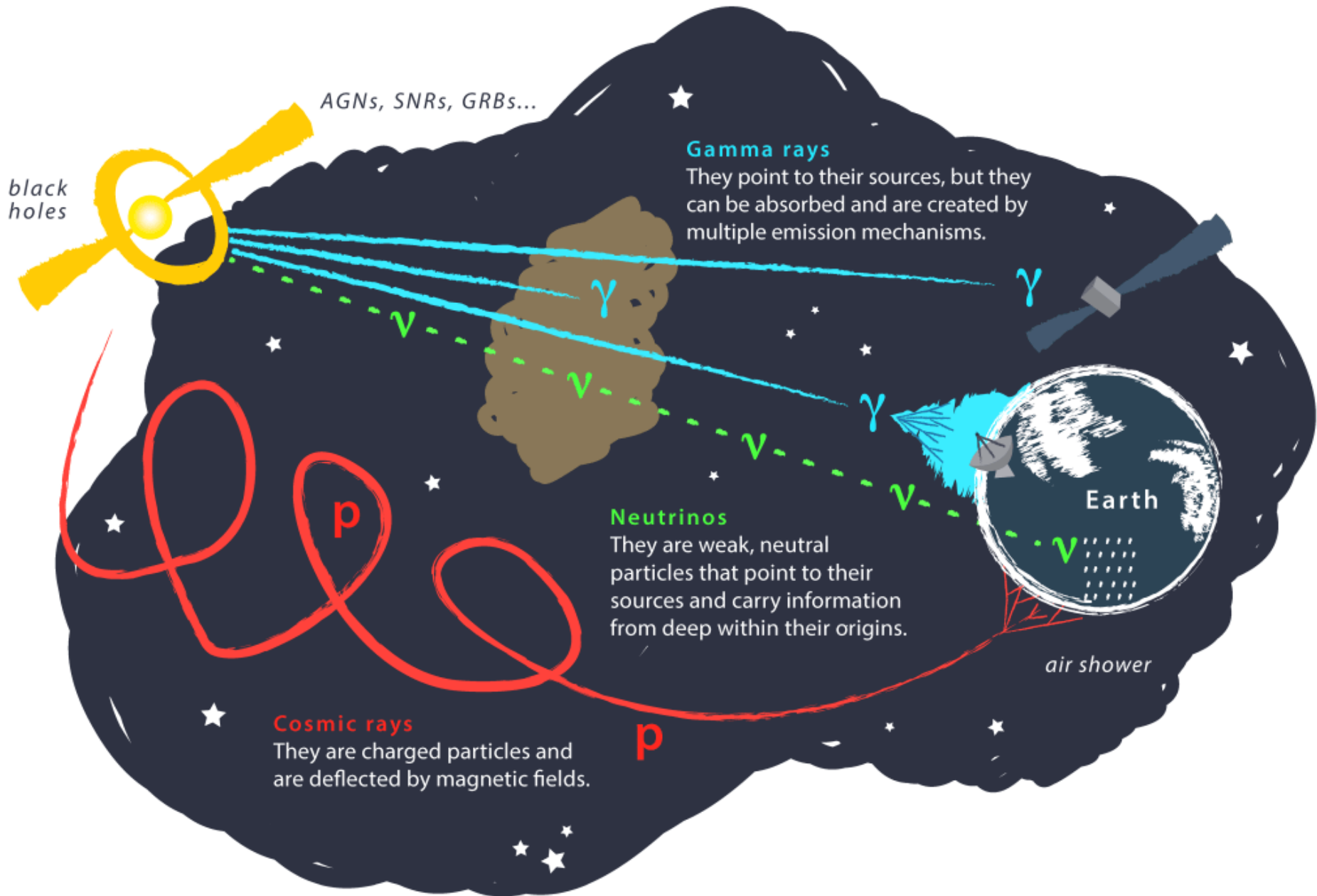
- Gamma rays could be emitted from electrons
 - Neutrinos are not produced
 - Leptonic (electrons are leptons)
 - Gamma rays could be emitted from cosmic ray interactions
 - Pions produced in interactions
 - Pions decay to neutrinos
 - Pions and protons are hadrons
- Detection of neutrinos points to hadronic accelerators



Finding the origin of ultrahigh-energy cosmic rays is challenging



*Neutrinos identify hadronic accelerators



AGNs, SNRs, GRBs...

black holes

Gamma rays
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.

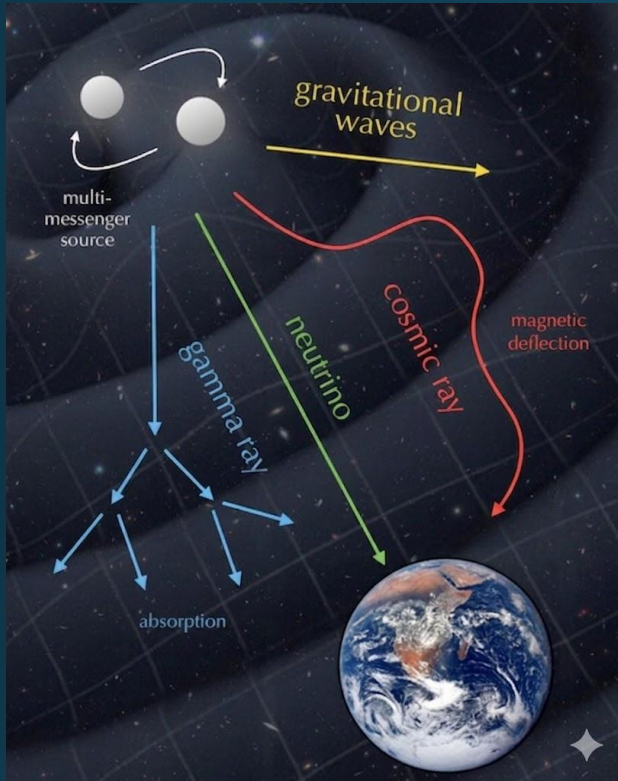
Neutrinos
They are weak, neutral particles that point to their sources and carry information from deep within their origins.

Cosmic rays
They are charged particles and are deflected by magnetic fields.

air shower

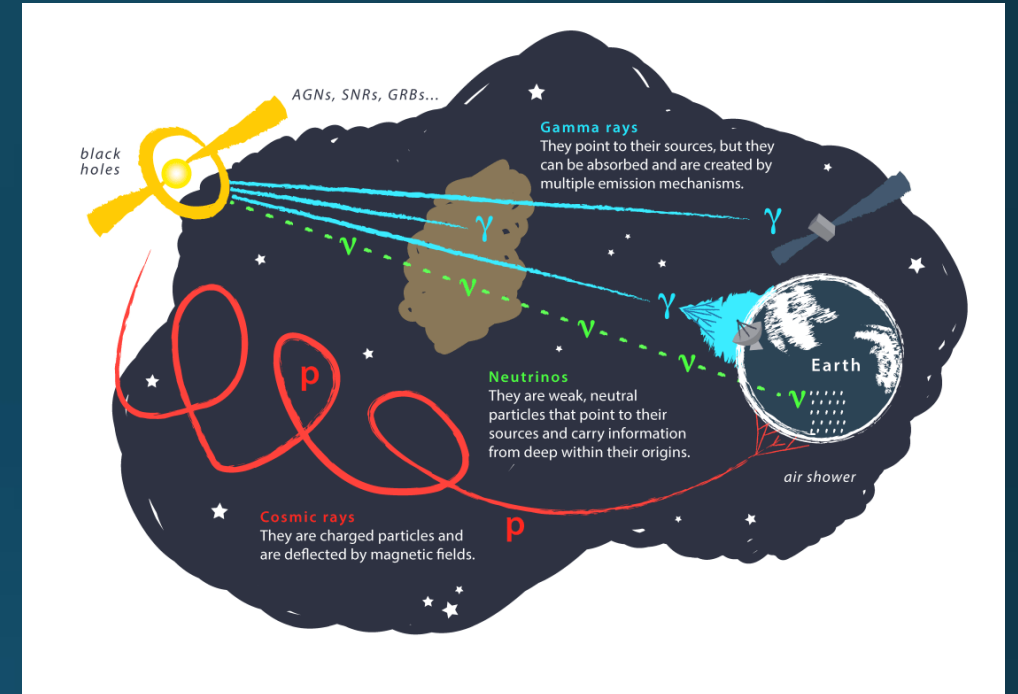
Earth

Multi-messenger Astrophysics



What is the origin of cosmic rays at ultrahigh energies?

Detection of all of these messengers is crucial to obtain the answer.



Cosmic rays

- Charged (deflected)
- Attenuated (somewhat)
- Hadronic

Gamma rays

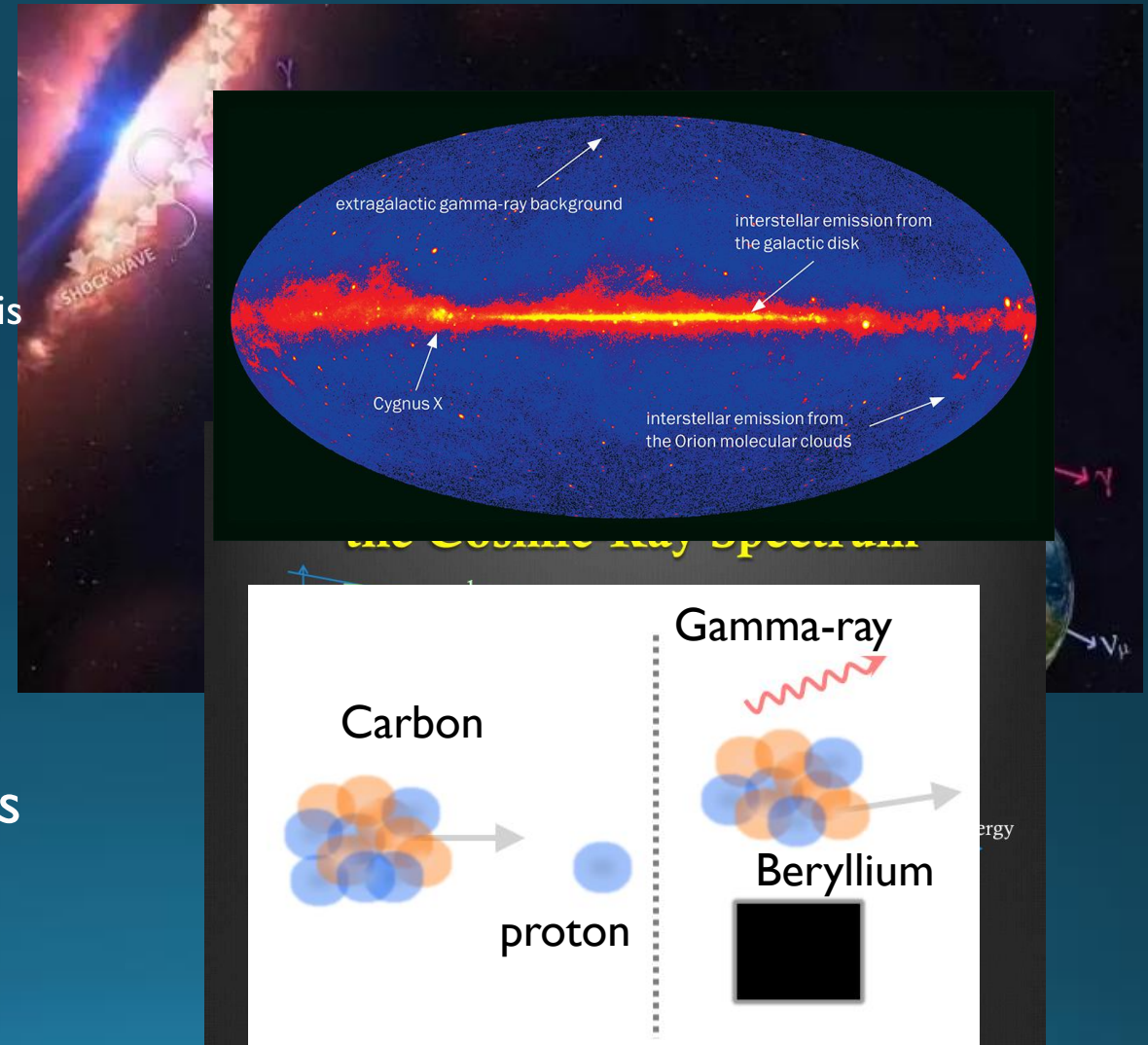
- Neutral
- Attenuated
- Leptonic or hadronic

Neutrinos

- Neutral
- Not attenuated (as far as we know)
- Hadronic

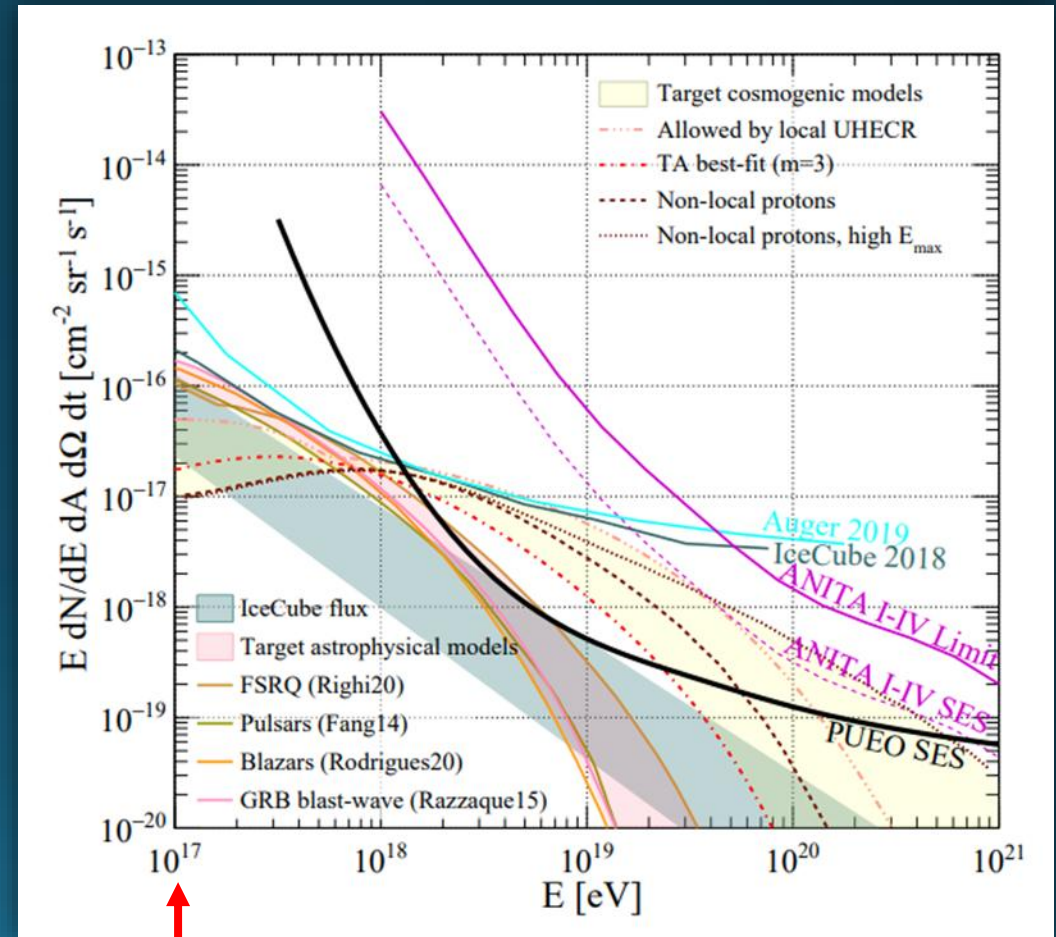
Ultrahigh-energy cosmic ray propagation

- Interactions of ultrahigh-energy cosmic rays propagating through the universe
 - Intergalactic medium – gas (yes, there is gas there)
 - In fact, very active area of research is to understand this IGM
 - CMB light
- At the ultrahigh energies, there may be a maximum energy reached
 - Even if a cosmic ray were accelerated to even higher energies than we have observed
 - That cosmic ray wouldn't make it to Earth
 - Greisen–Zatsepin–Kuzmin limit (1966)
- Similar to the Milky way glowing in gamma rays
 - From (Galactic) cosmic ray interactions with the Interstellar medium (spallation)



GZK-cosmic rays to BZ-neutrinos

- So those interactions should produce neutrinos
- Berezhinsky –Zatsepin (1969) predicted associated neutrino production
- Predictions
 - Emitted at cosmic ray acceleration sites (**astrophysical**)
 - Emitted from cosmic-ray interactions from propagation (**cosmogenic and diffuse**)
- and Limits



Highest energy neutrino detected

Neutrinos are challenging to detect

1. How do you detect these weakly interacting, neutral particles?

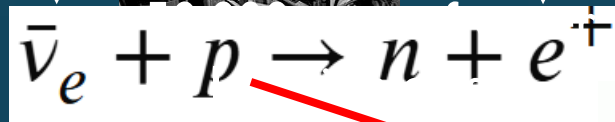
- You can't!
 - Well not directly

2. We have built very large detectors to detect neutrino interactions

- Cherenkov light measurements

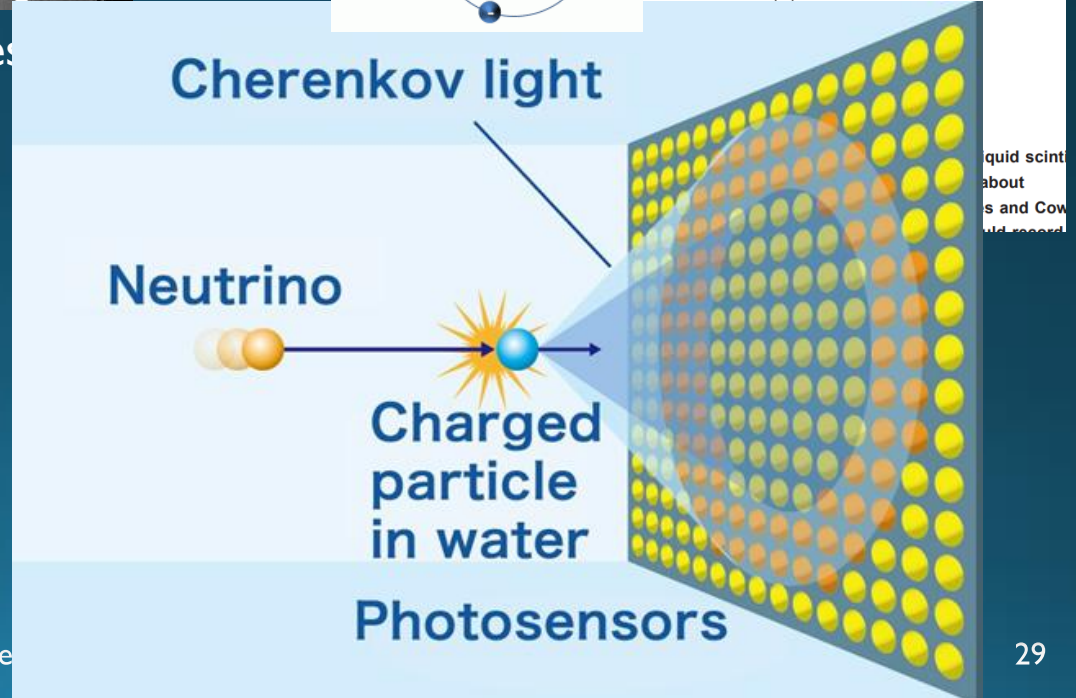
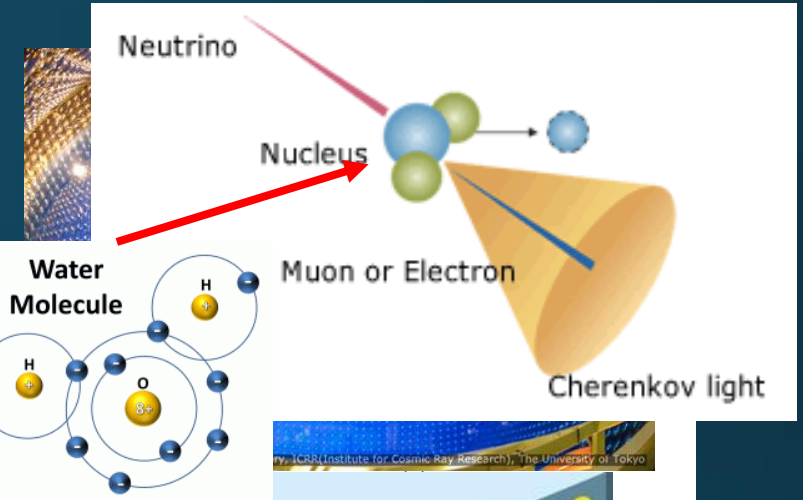
A lot of energy

A lot of energy



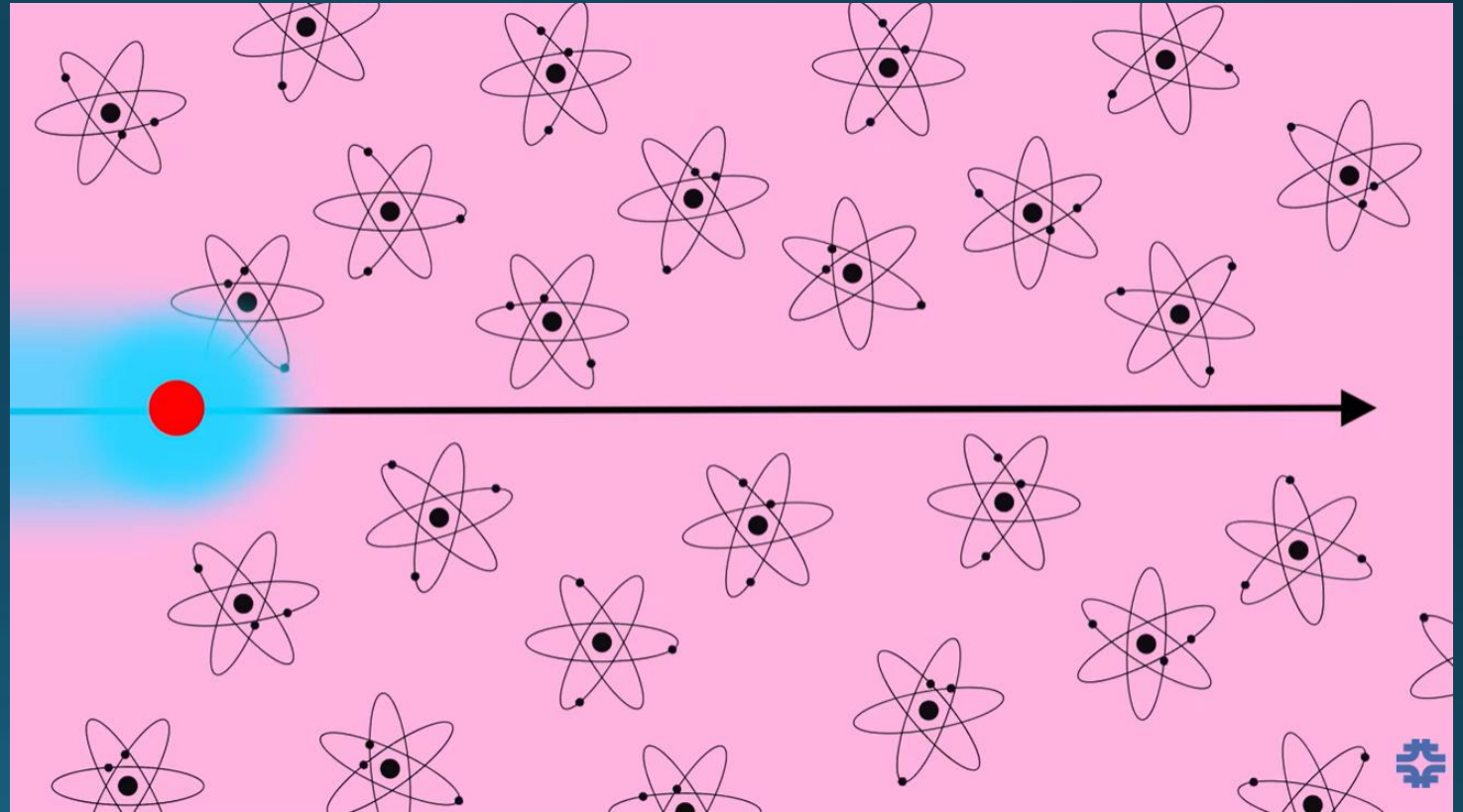
Super-Kamiokande
moving

Frederick Reines

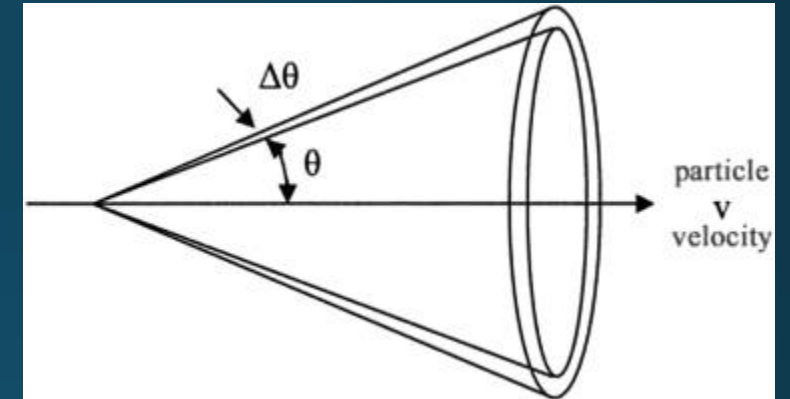
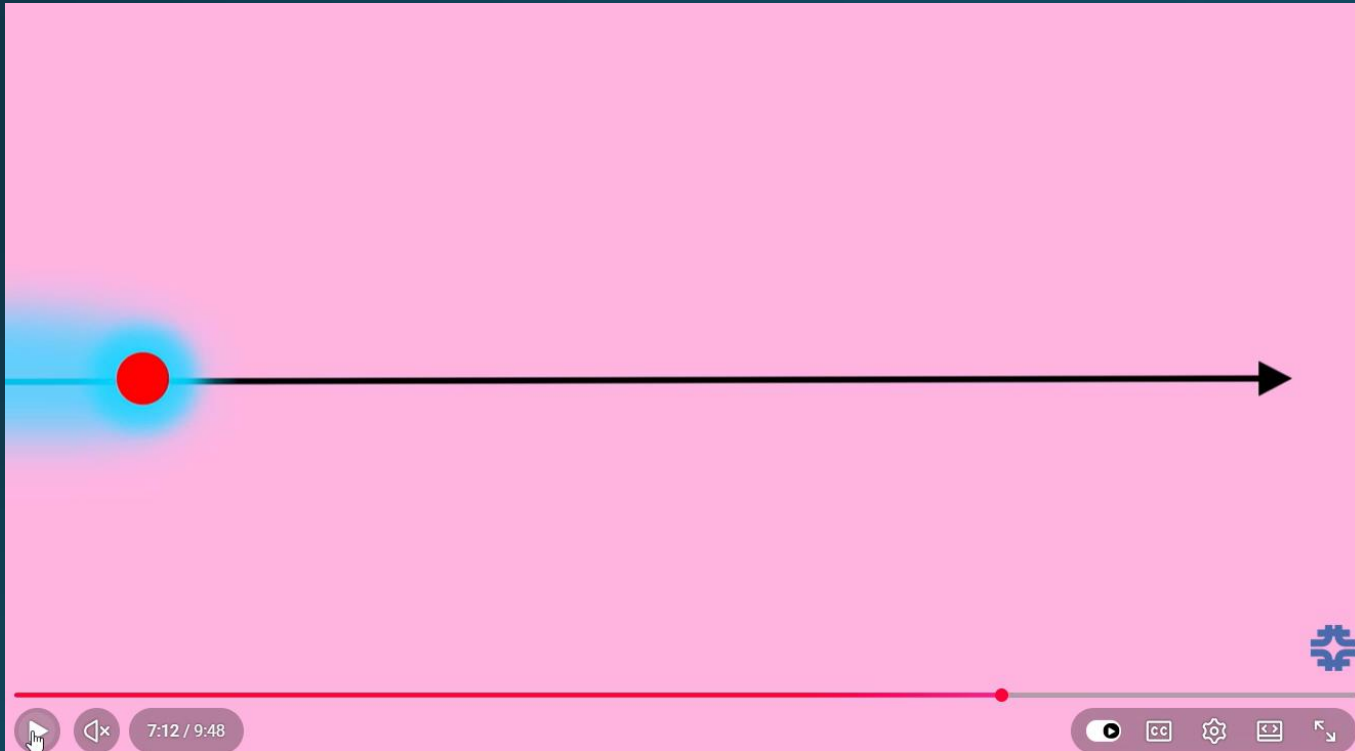


Cherenkov radiation 101

- Since light slows down in the medium, particles can travel “faster than light does in the medium”
- In the water, blue light emission
 - As was found in the discovery
 - *Only if the particle is charged



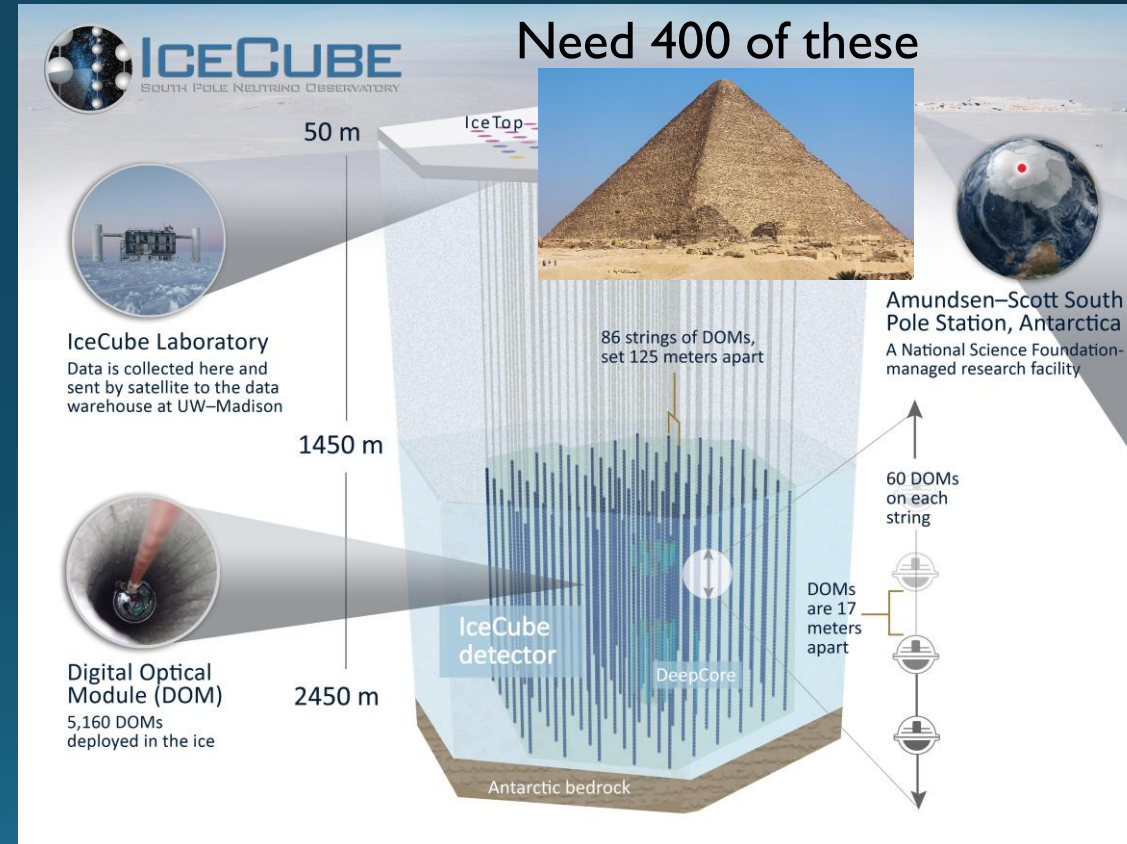
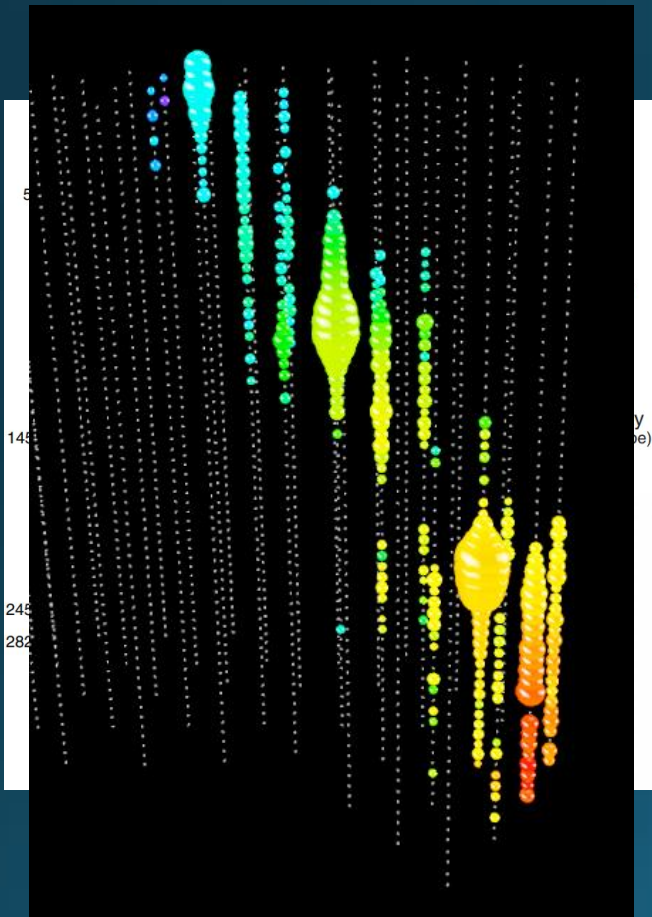
Cherenkov light tells you the direction of the fast, charged particle



1. Cherenkov light will be emitted at an angle
2. That angle is related to the speed of the particle and the speed of light in the medium

Neutrino interactions detected with Cherenkov light

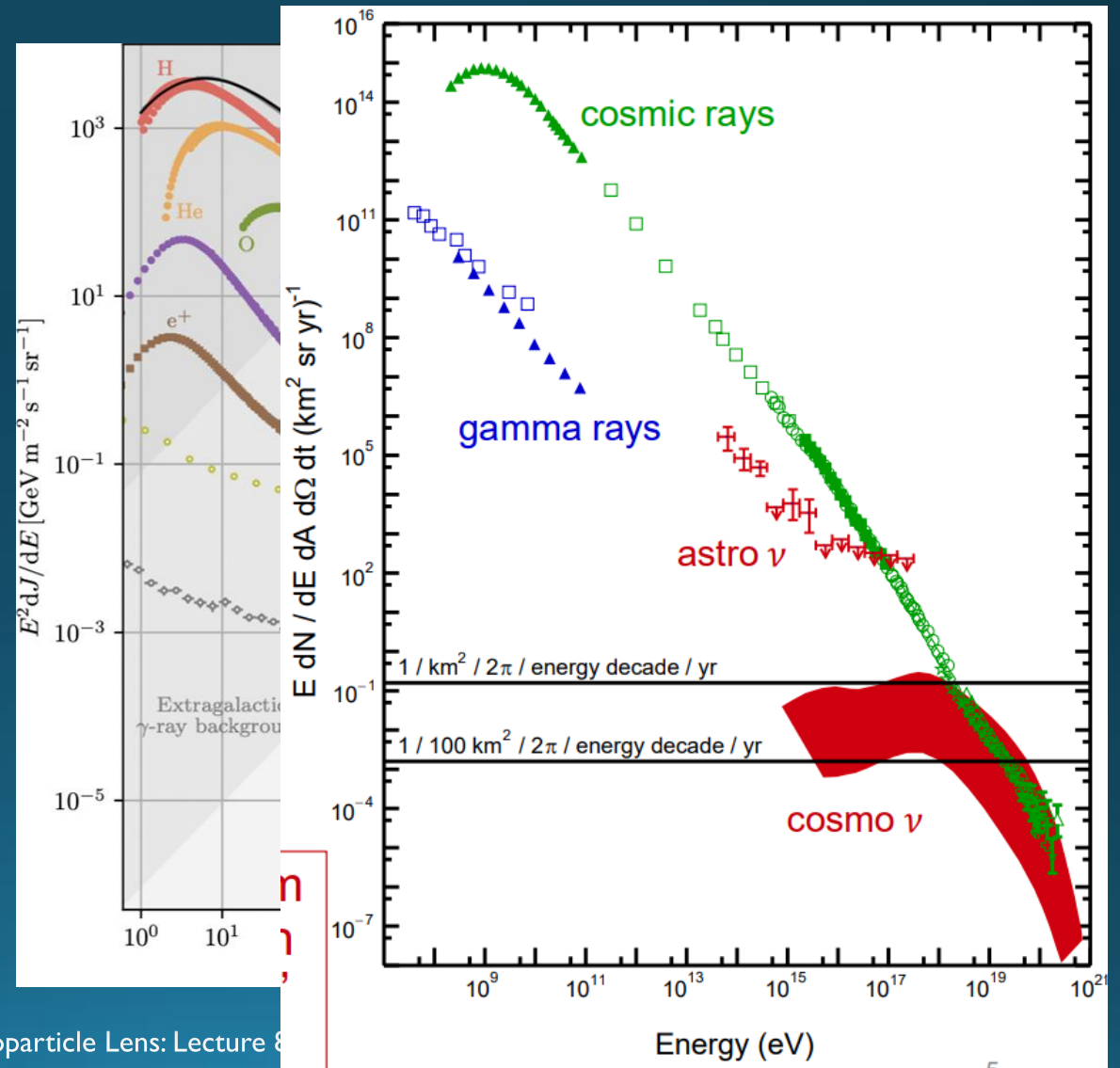
1 cubic kilometer!

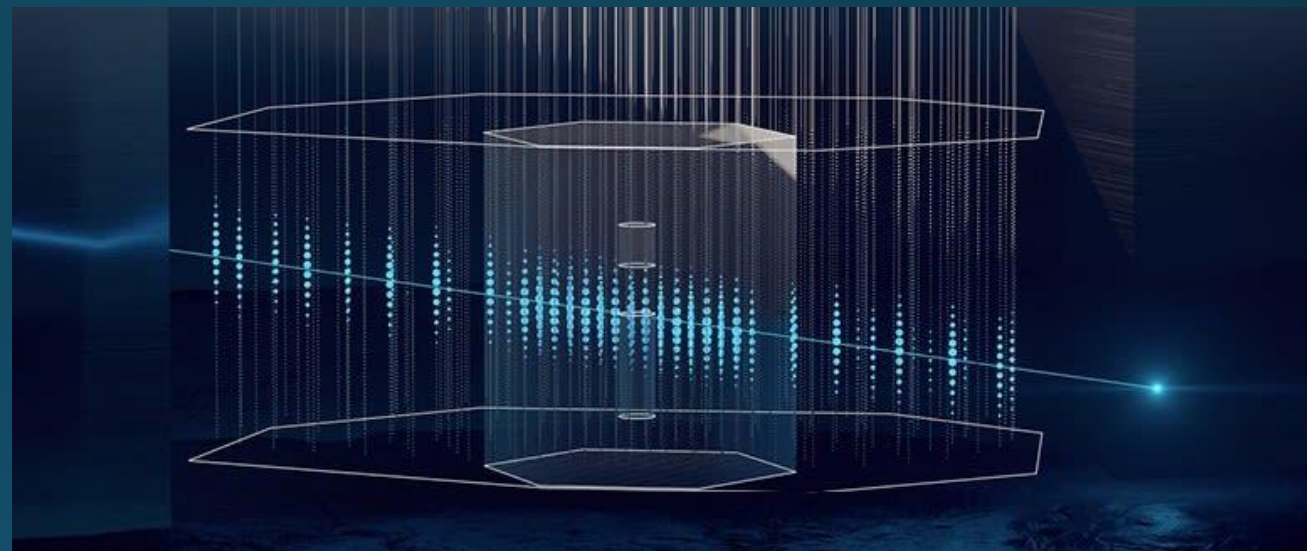
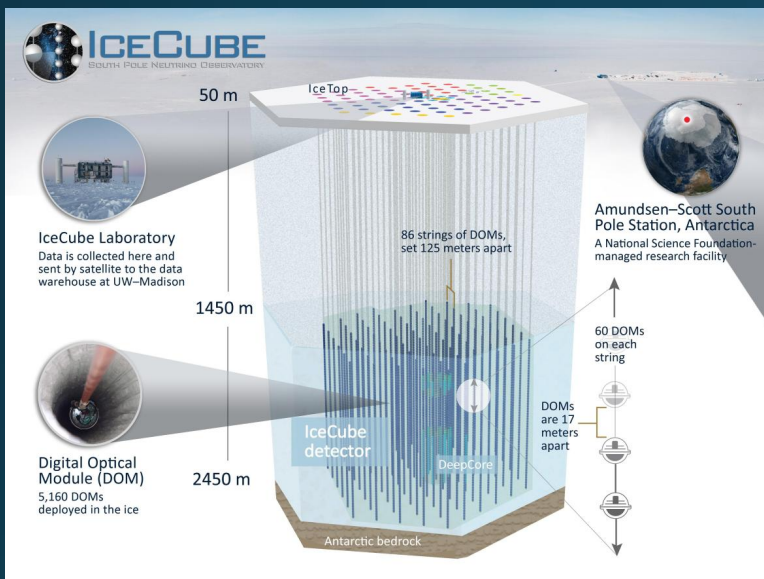


Detected \sim PeV energy neutrinos – ultrahigh energy cosmic rays are still 100,000 times more energetic

Weakly interacting and infrequent

- Flux of many different astroparticles
- Remember, hold your hand out for 6 billion years in space to get single 100 EeV cosmic ray
- Ultrahigh energy neutrinos are predicted to have a similar flux
 - But they are much harder to detect
 - IceCube would have to run for thousands of years to *maybe* detect a neutrino at these energies



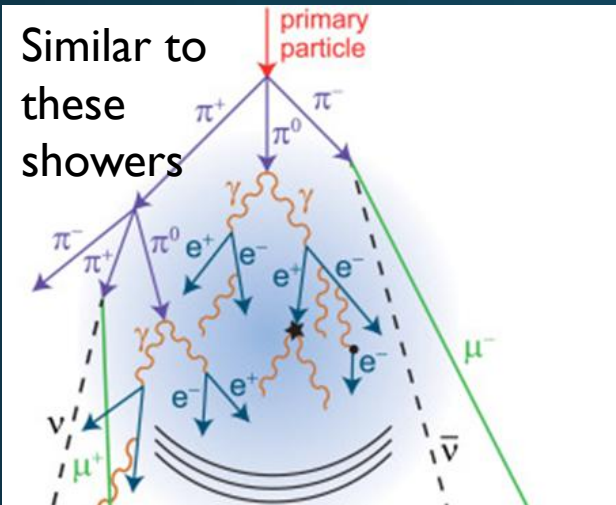


We don't want to wait for thousands of years

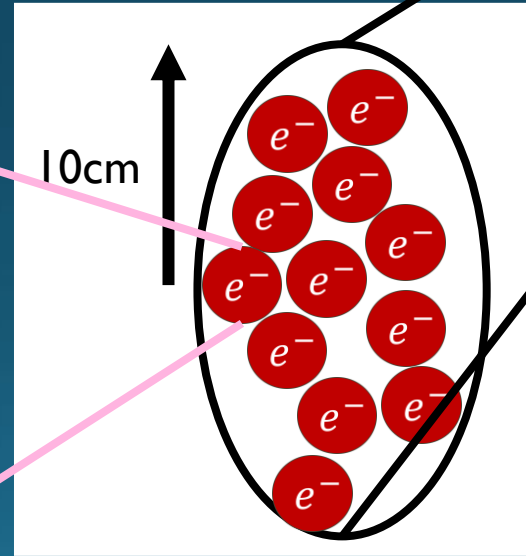
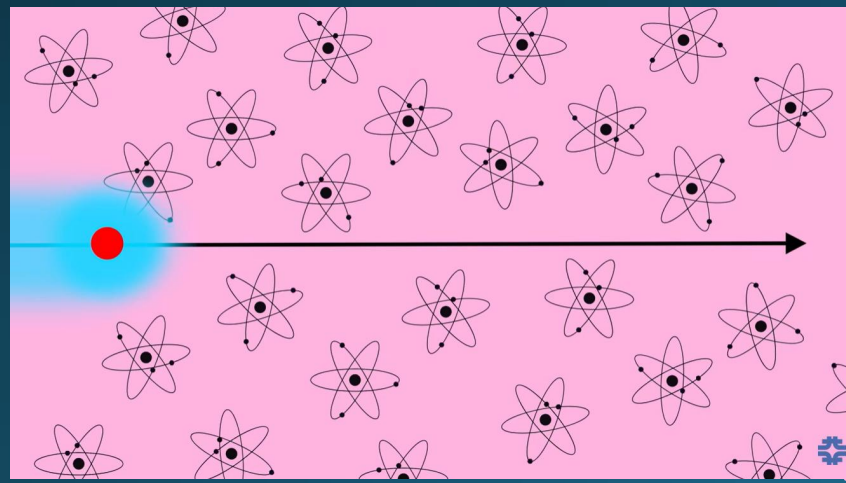
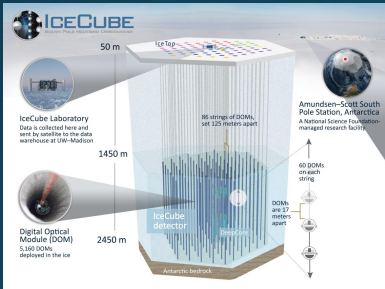
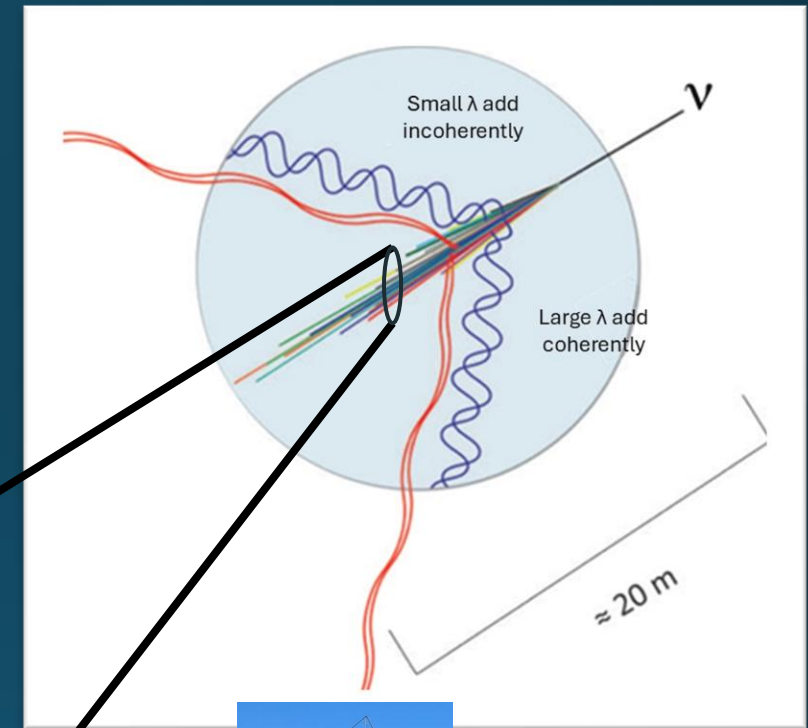
Build a bigger IceCube detector?
IceCube Gen 2

Leverages radio detection of neutrinos!

Similar to these showers

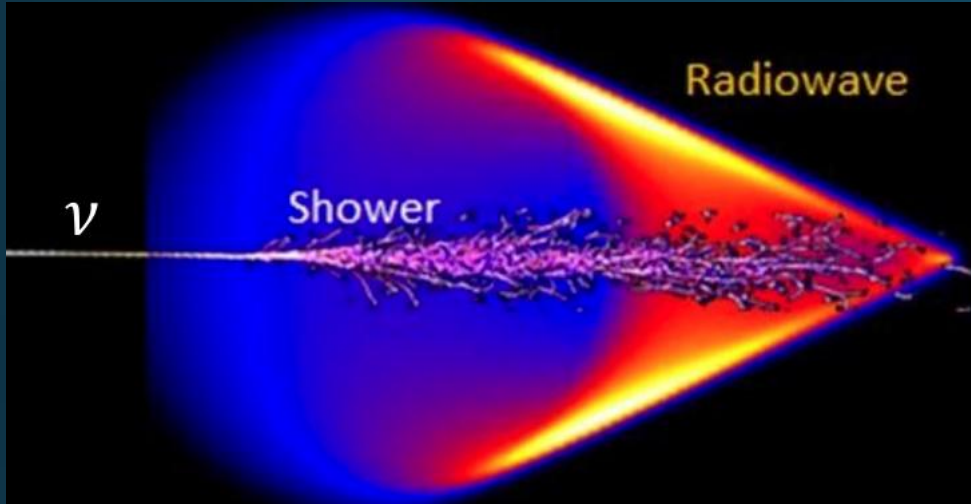


(1960s) Askaryan emission Radio Cherenkov

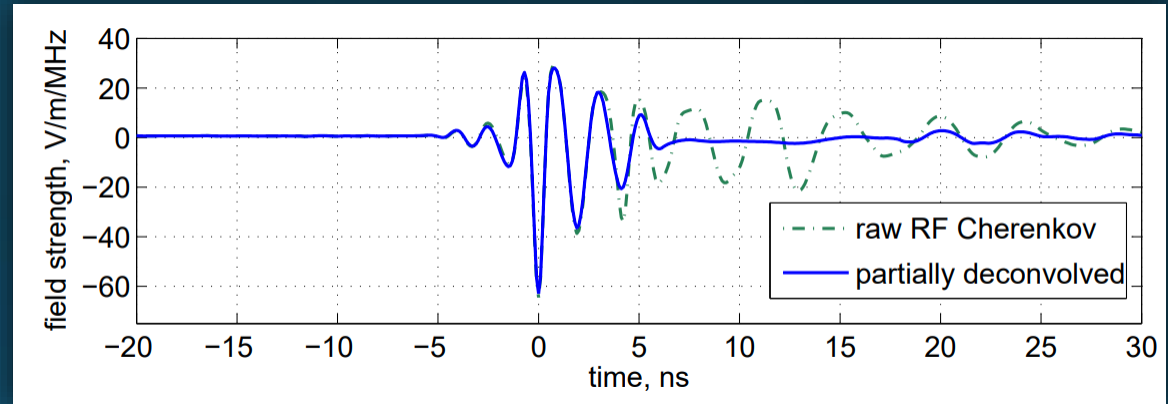


Neutrino detection with radio waves

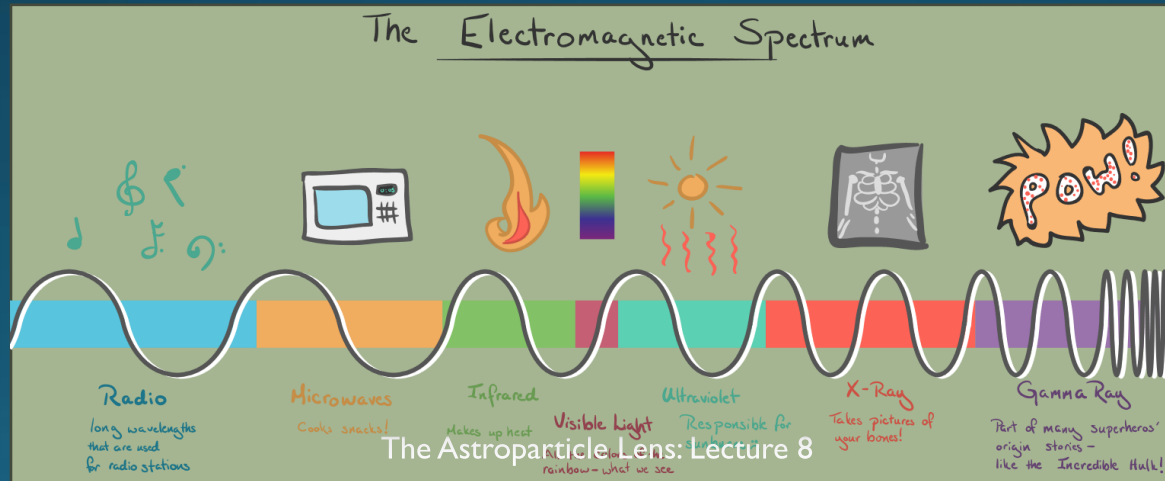
1. Neutrino interaction



2. The impulsive radio signal emitted



3. Array of antennas measure radio signal

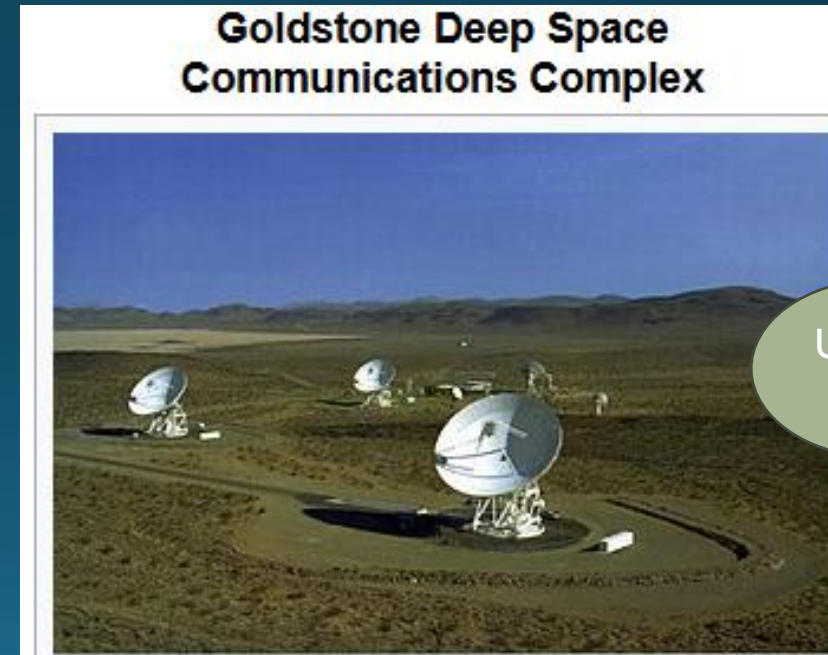
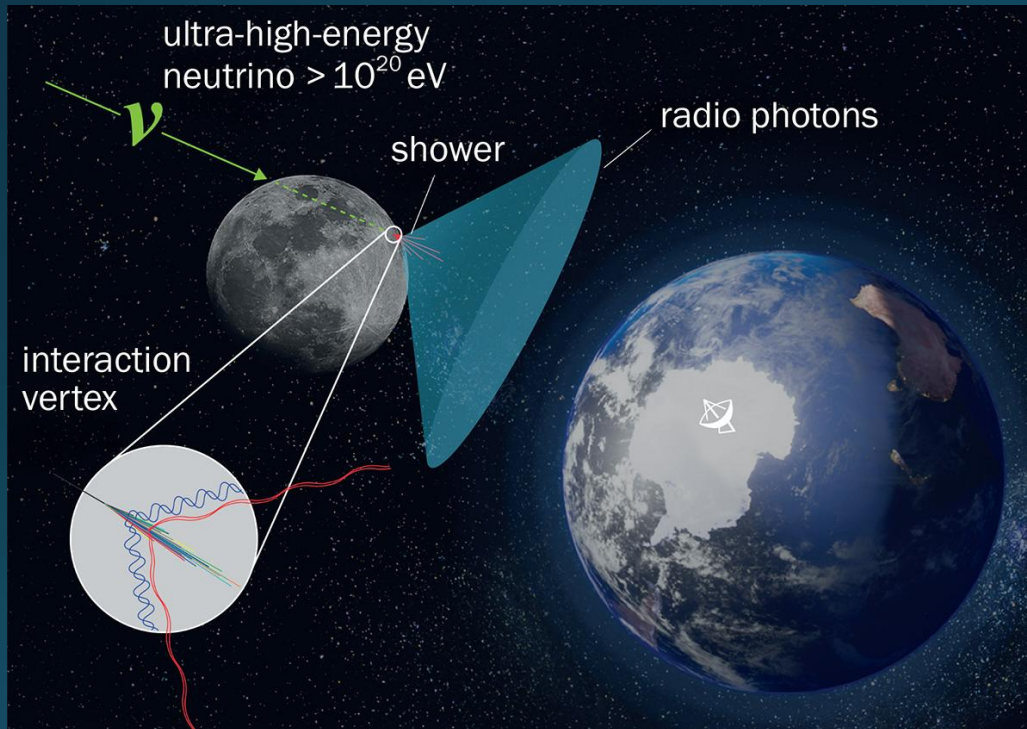


Radio detection of neutrinos in the early 2000s

Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE)

Neutrino detector equivalent size = 100,000 km³

That is 100,000 IceCube detectors

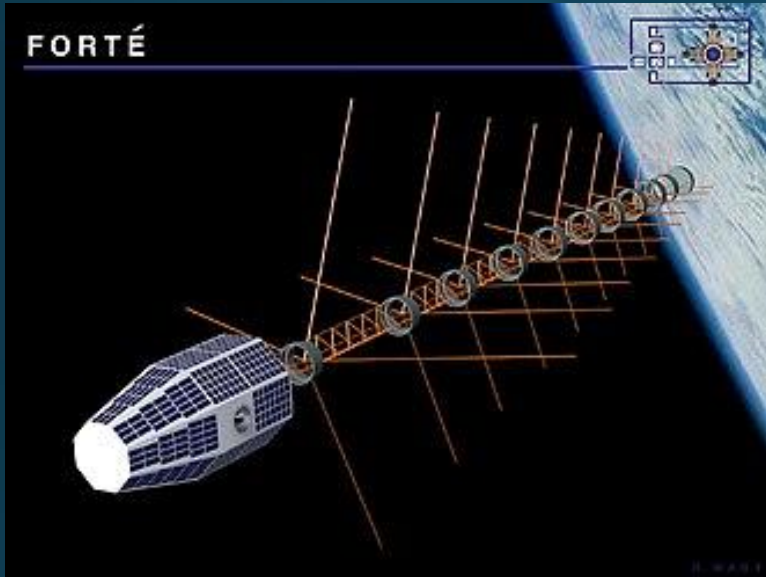


Use the moon

* In California, not Antarctica!

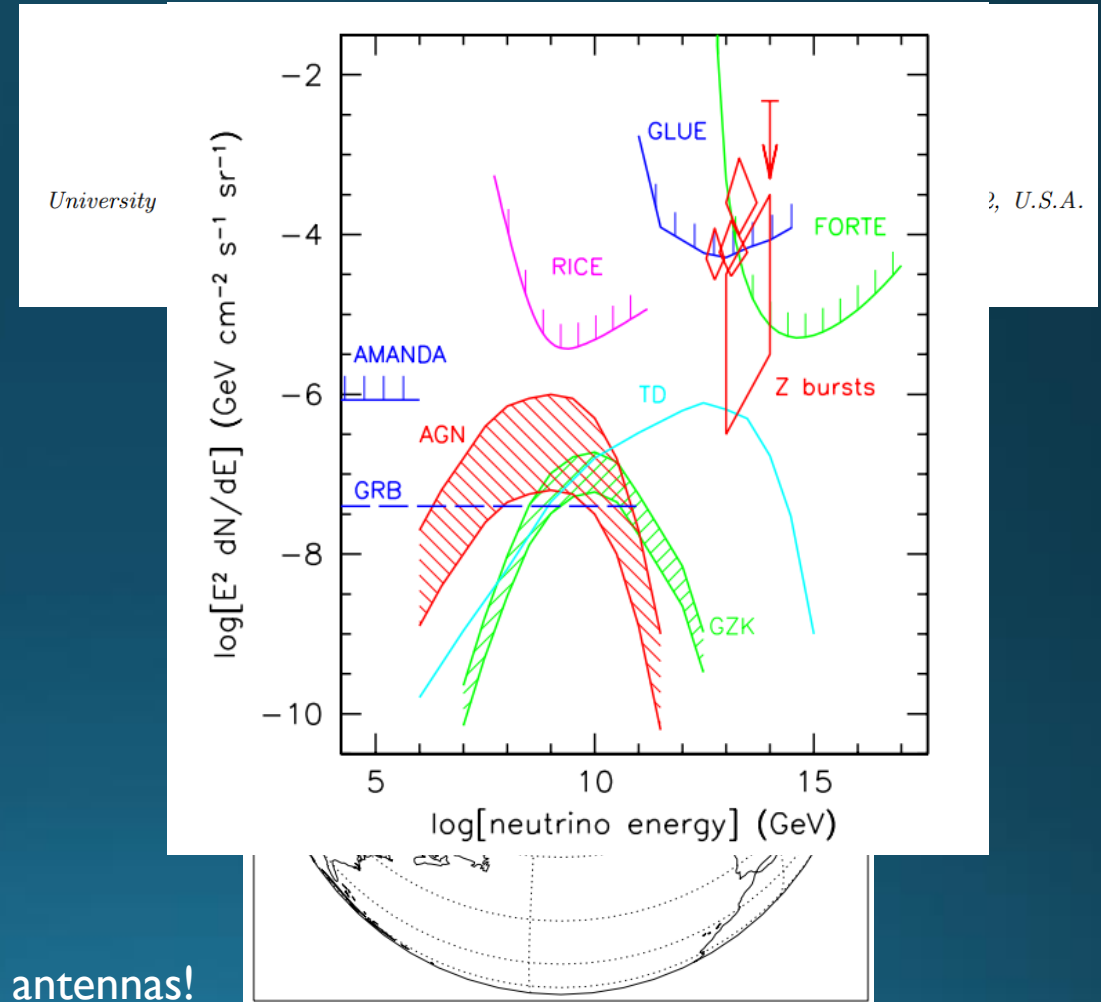


FORTE (Fast On-orbit Recording of Transient Events)



- Launched in 1997
- Test antennas and other technology in searching for radio pulses from secret nuclear testing sites
- Also, measure radio pulses from lightning

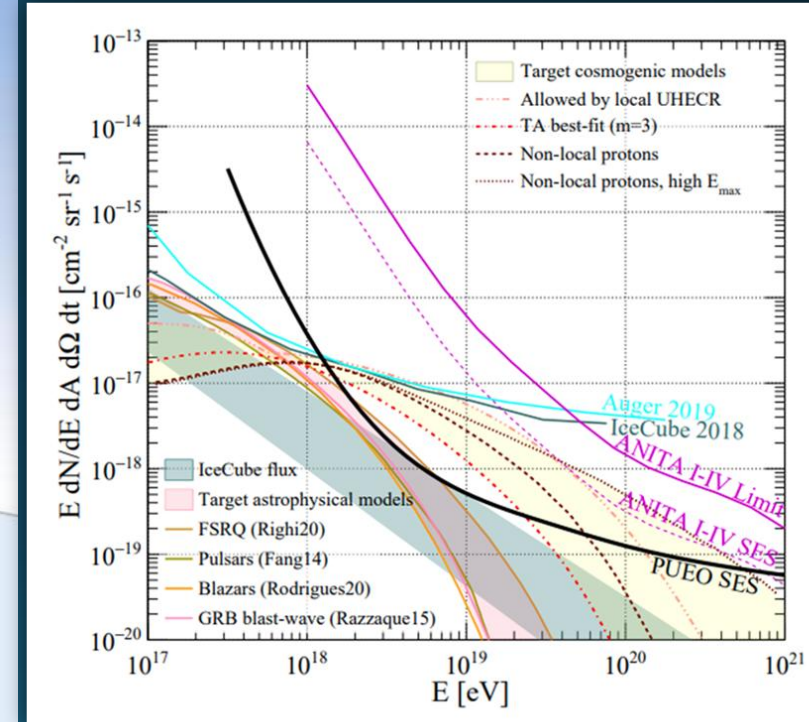
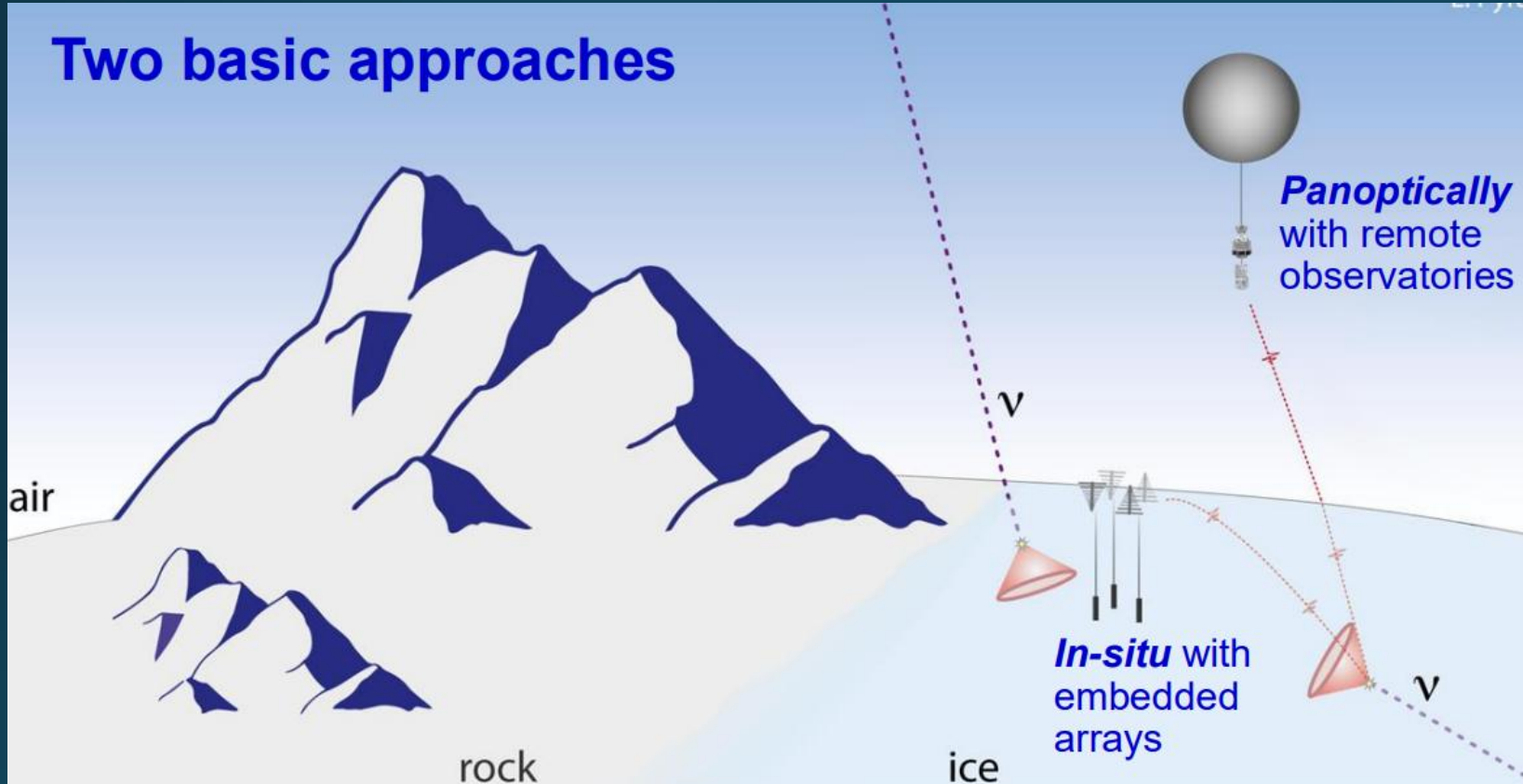
2003, Greenland ice sheets as neutrino detectors with FORTE antennas!
Close to 1 Million cubic kilometers!



University

, U.S.A.

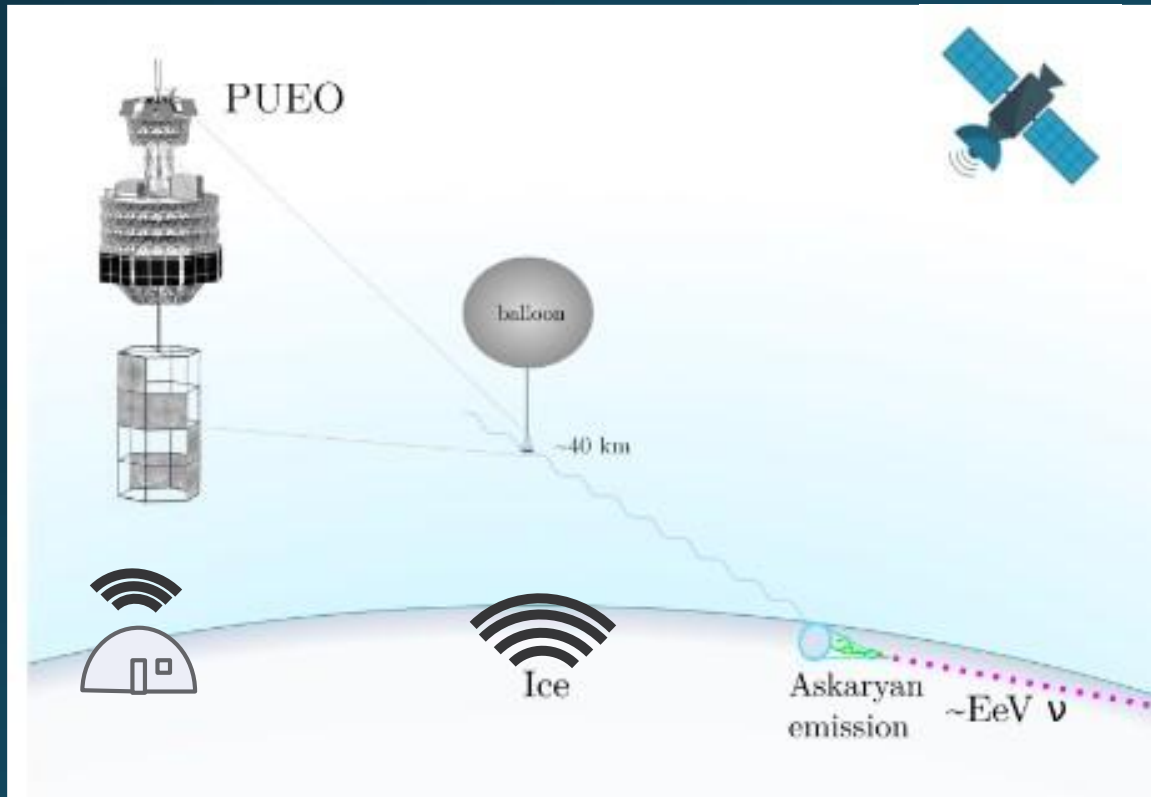
Nowadays



*Antarctic and Greenland ice



The Payload for Ultrahigh Energy Observations



*Antarctic Ice – close to 1 million cubic kilometers in view

PUEO is the successor to ANITA

ANtarctic Impulsive Transient Antenna (ANITA)

- 4 flights from 2006-2016 in Antarctica

Launched on Dec 20th, 2025

ANITA-III

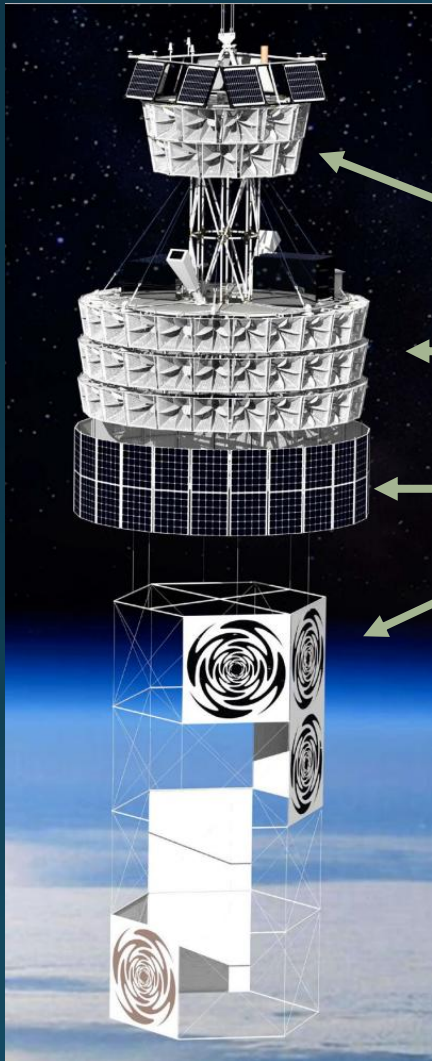


1. More antennas
2. Smaller antennas
3. Improved triggering firmware

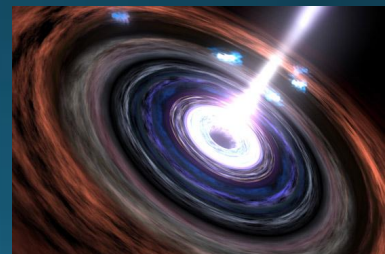
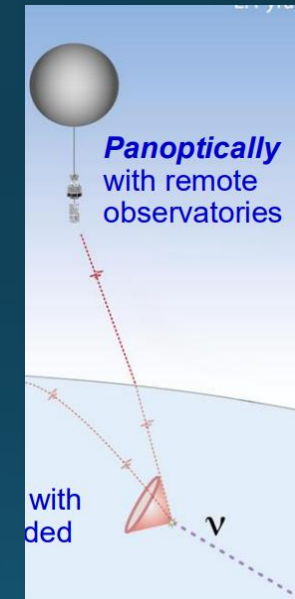
PUEO

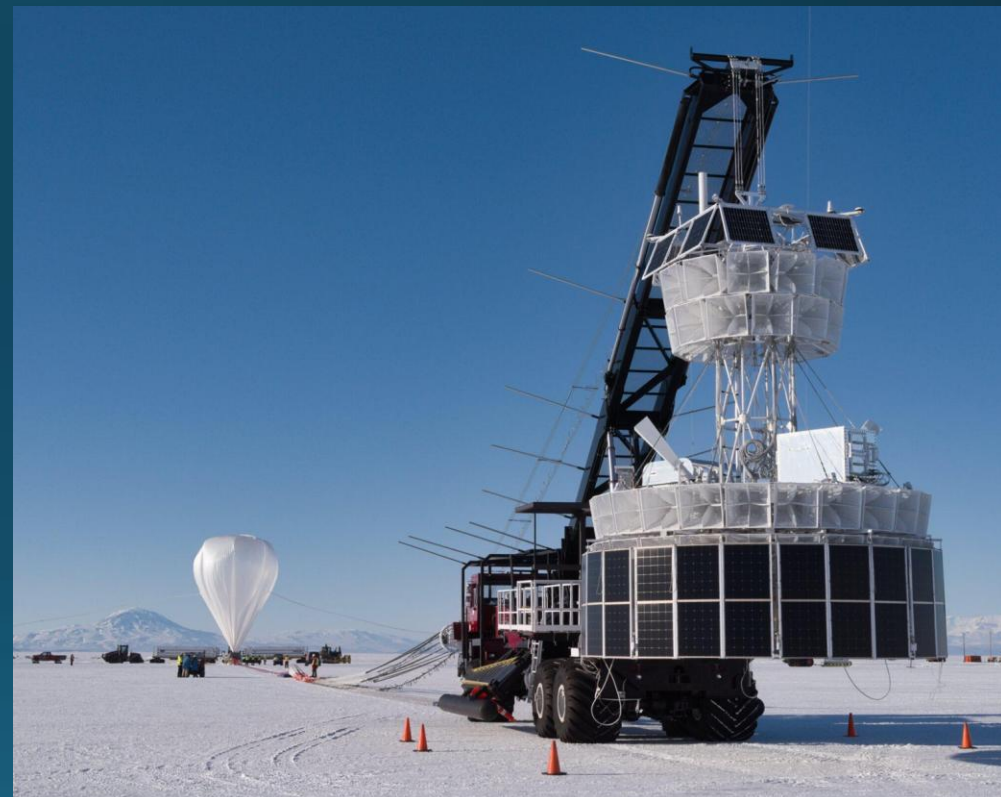


The PUEO instrument



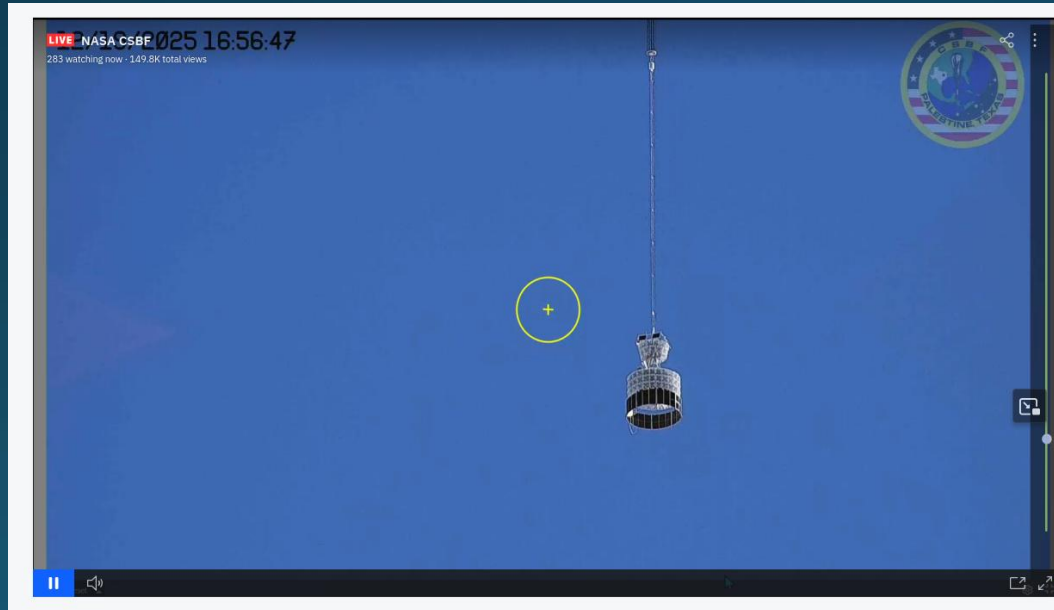
- 2 set of antennas to measure radio waves of neutrino interactions
 - 96 quad-ridged horn antennas
 - 8 (low-frequency) fabric sinuous antennas
- Solar panels to power instrument
- Telemetry antennas
- Navigation suite to localize neutrino direction back to sources





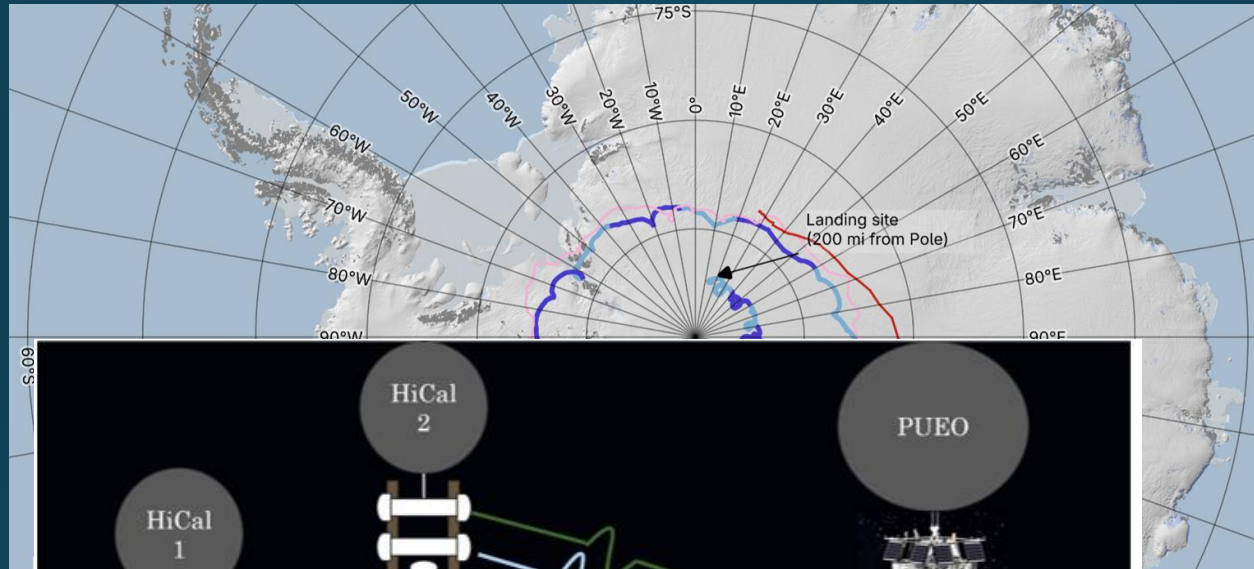
Deployables

PUEO is tall enough that the solar panels and sinuous antennas were deployed after launch

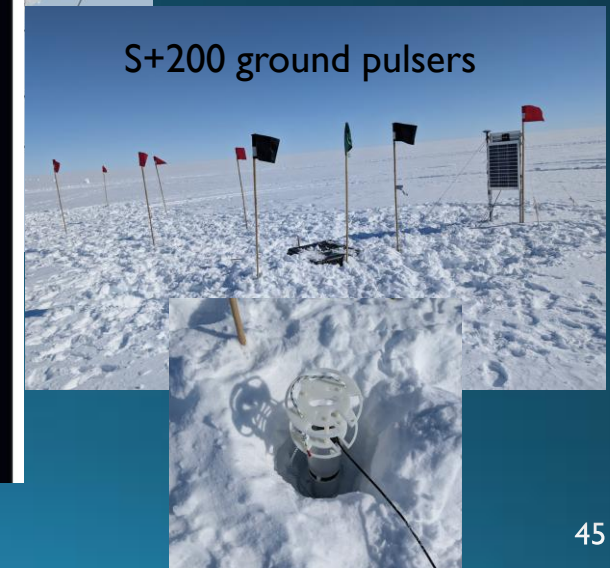
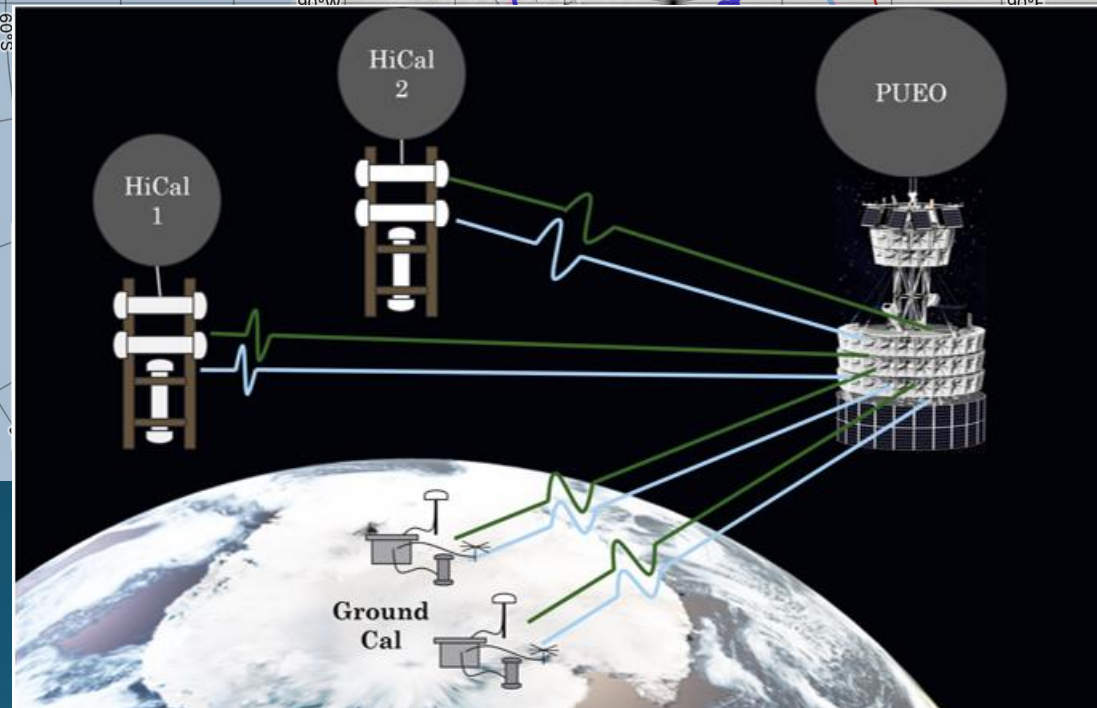


Flight path and ground calibration

- Launched Dec 20th, 2025
- Terminated January 12th, 2026
- 23 day flight



- Pulsed antennas to mimic neutrino signals
- Useful for calibration and triggering studies
- Both following, small balloon payloads and ground stations

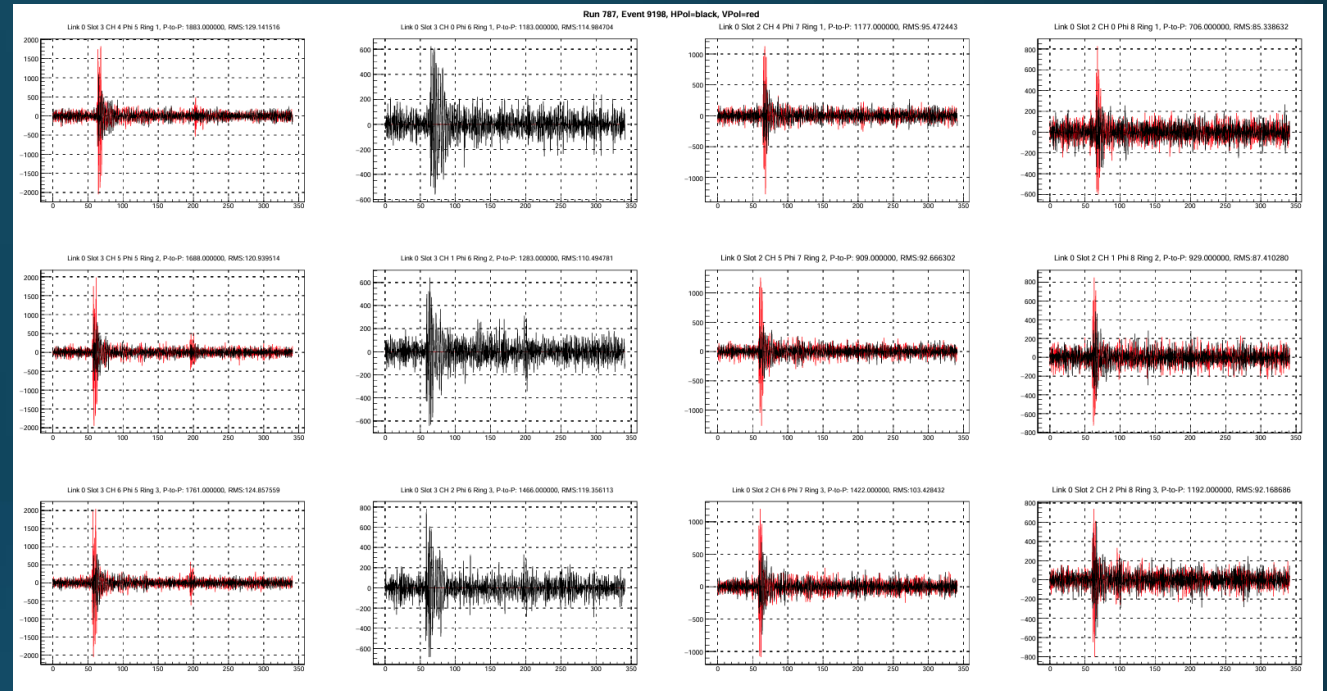


Status of PUEO

Over 55TB of data collected

- And data received here at U. Chicago

Find the right impulsive signals
“needle in a haystack”

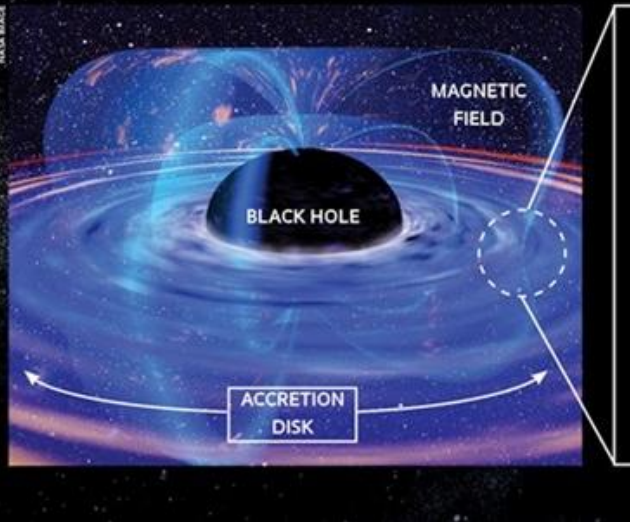


PUEO instrument recovered

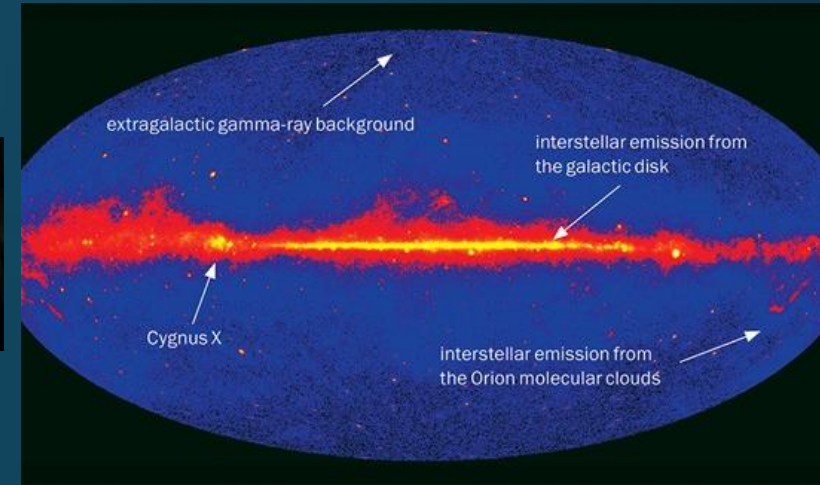
Stay tuned for the search for ultrahigh energy neutrinos



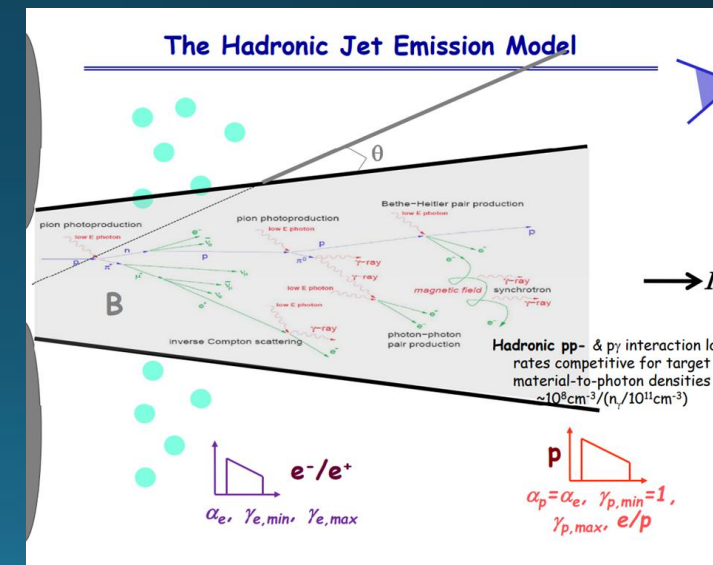
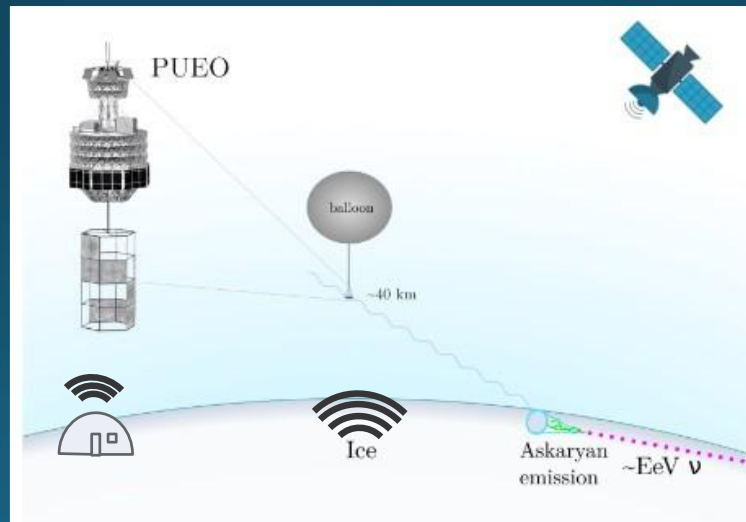
How a cosmic ray is formed.

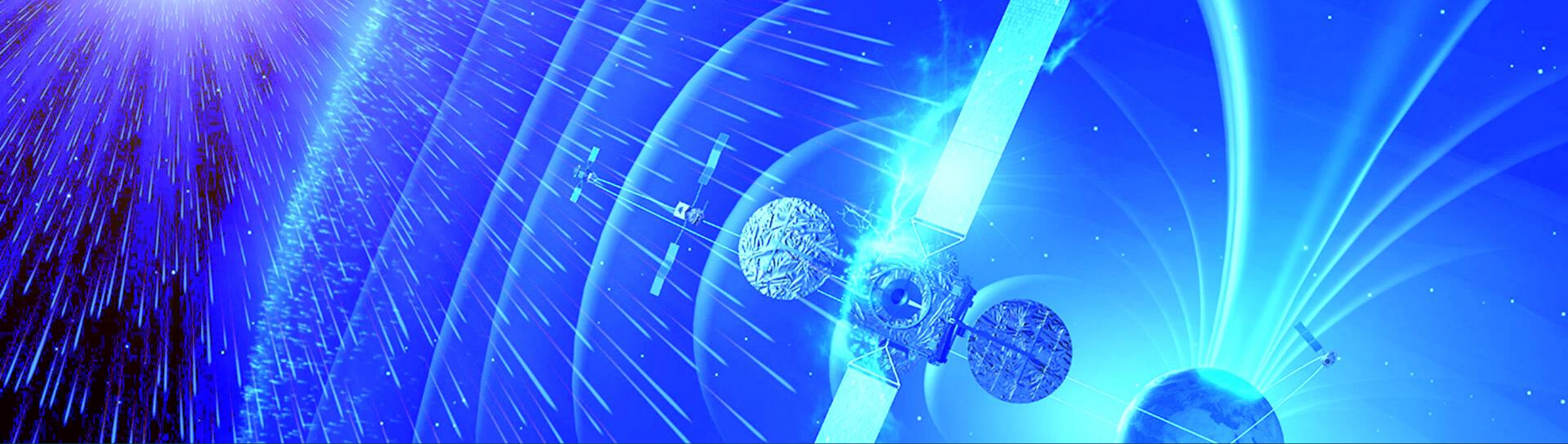


“Somewhere, something incredible is waiting to be known.”
 – Carl Sagan



We put on the astroparticle lens.
 We learn how the high-energy universe works.





Thanks to Prof. Ed Blucher for the opportunity!

Thanks to Mary for making it all run smoothly!

Thanks to the wonderful audience for being engaged and having excellent questions!

Thank you!