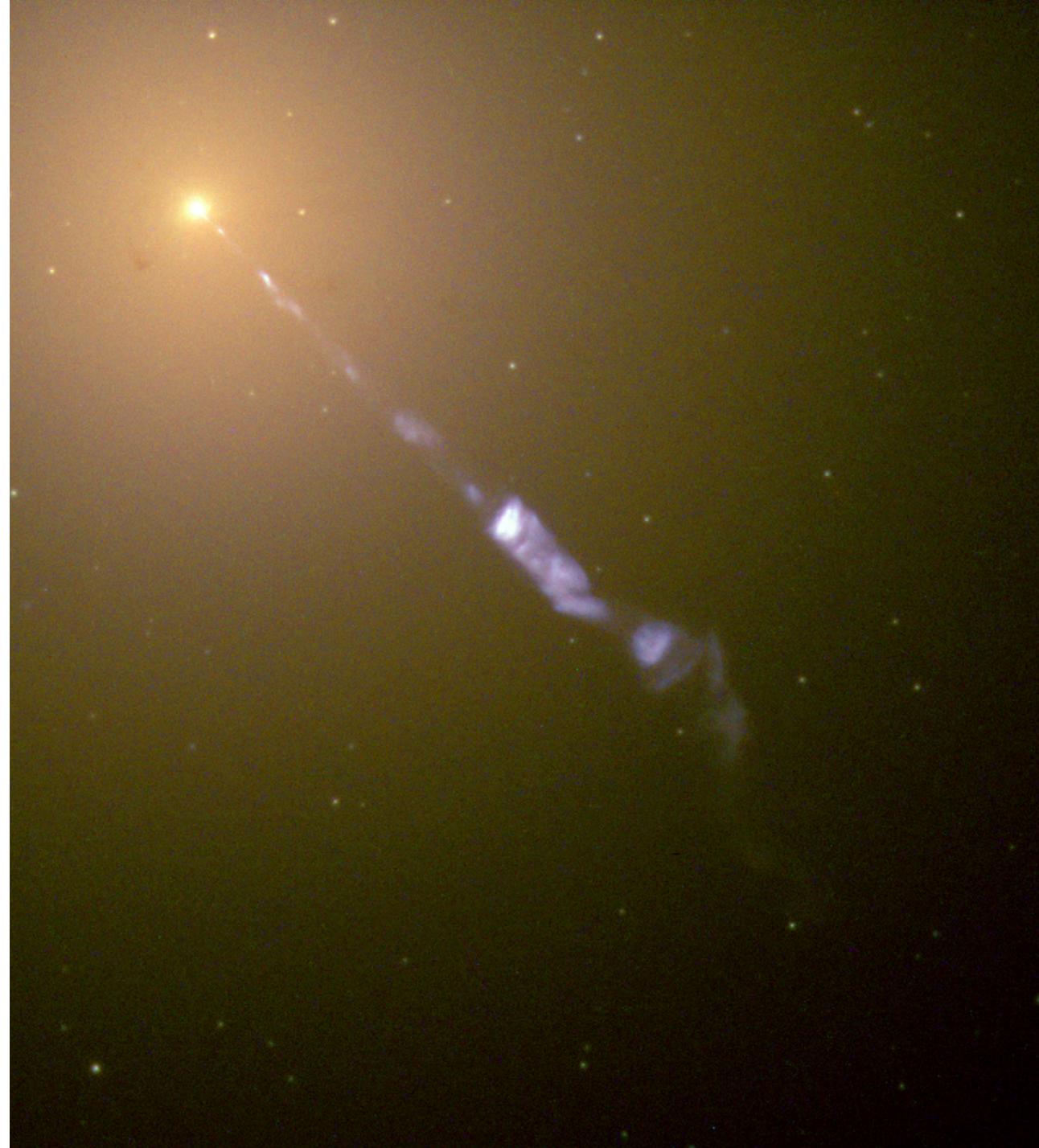
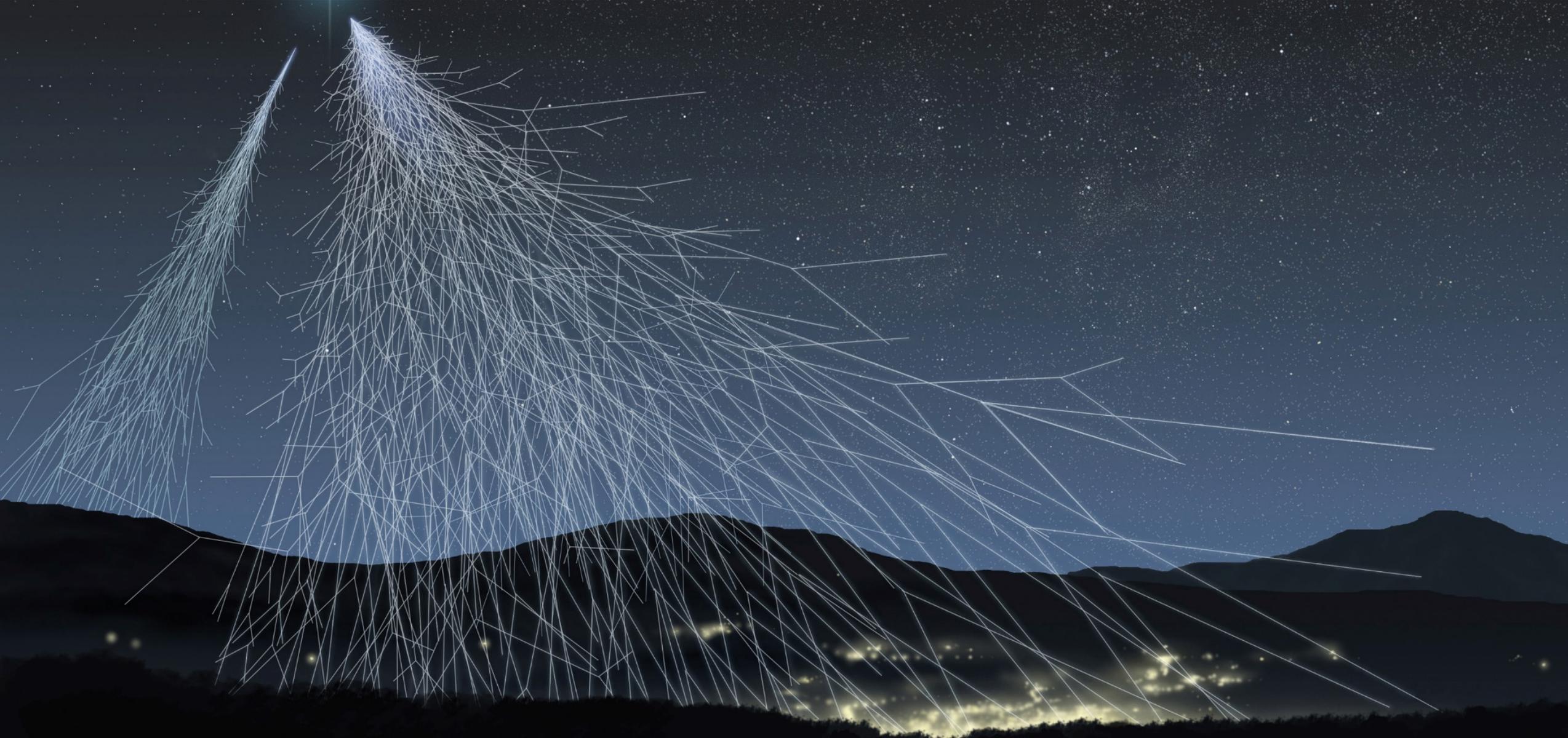


Lecture XIX.

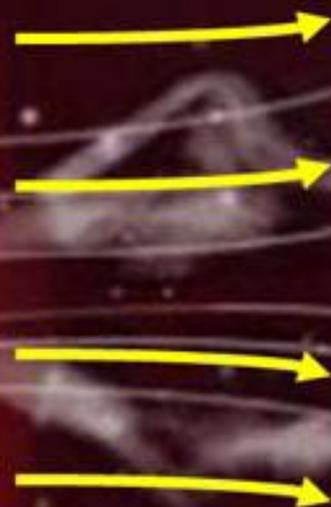
Astrophysical particle acceleration



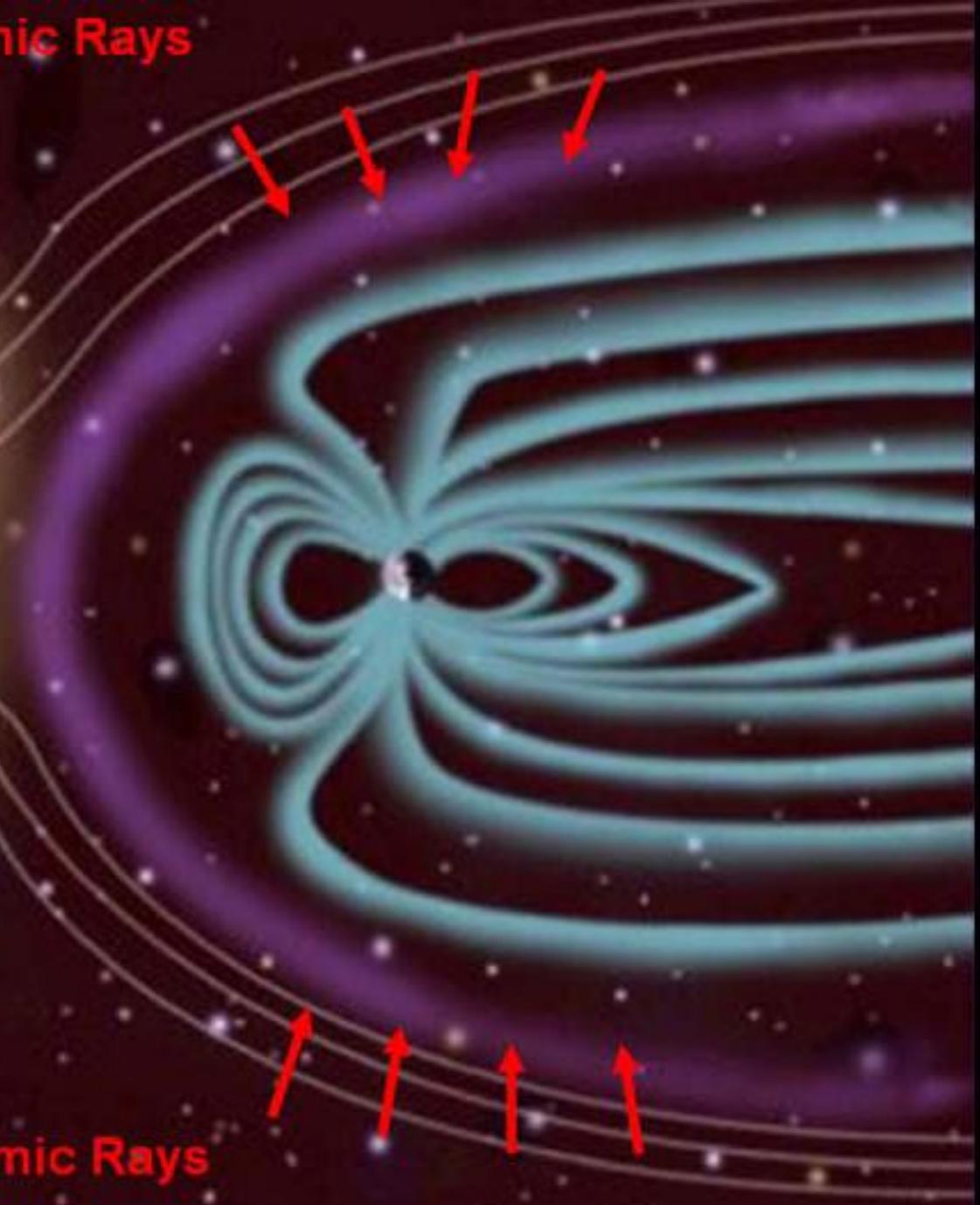
cosmic rays



Galactic Cosmic Rays

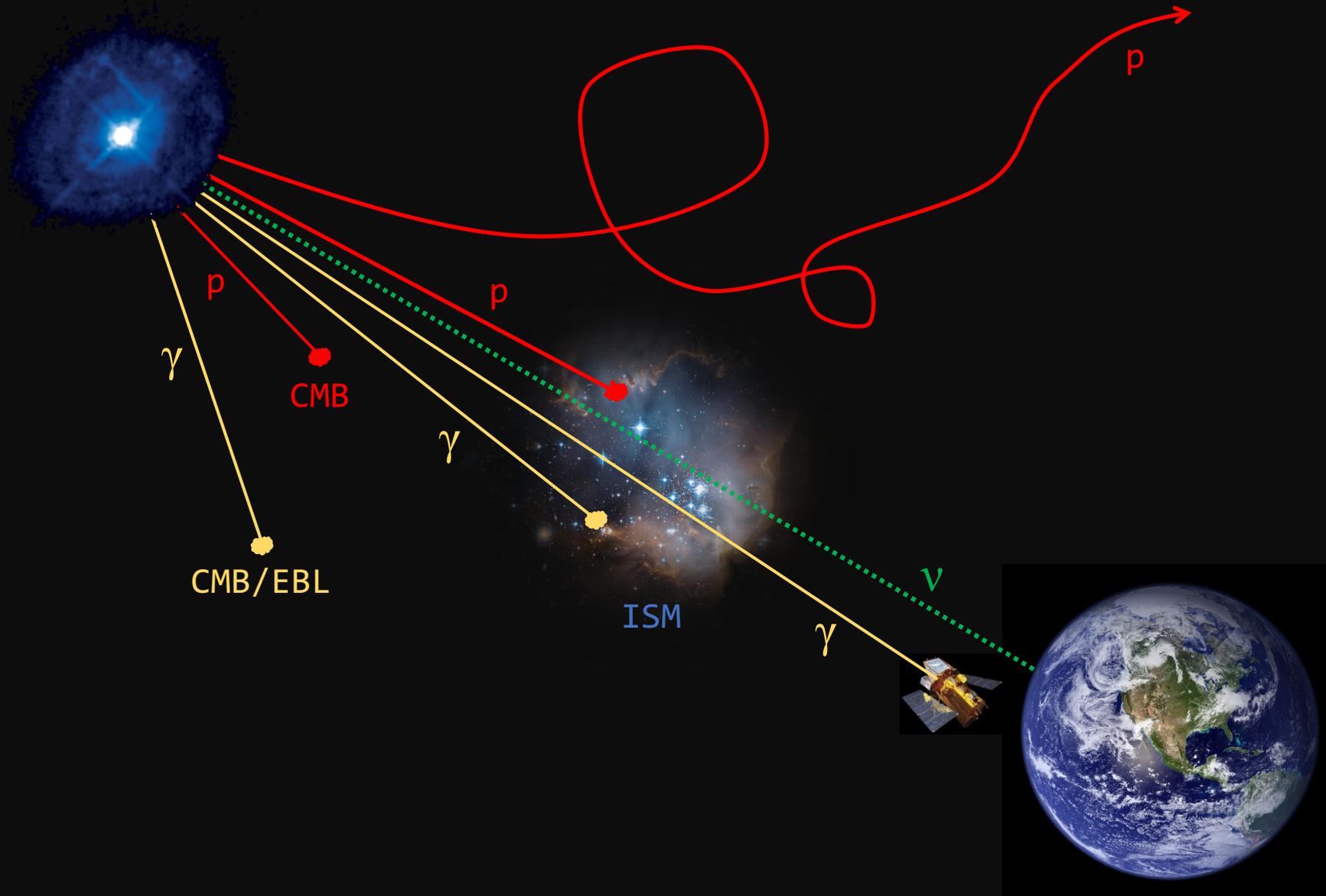


Solar Energetic Particles
(Solar Particle Events or
Coronal Mass Ejections)



Galactic Cosmic Rays

difficulty finding the origin



“Oh-My-God” particle

3×10^{20} eV cosmic ray --- highest-energy ever observed (1991)

Kinetic energy: ~ 50 Joules = baseball traveling at 60 mph.

Much more energetic than what we can produce in particle accelerators on Earth

(although accelerating both particles that collide in opposite directions dramatically reduces the effective difference)

Ultra-high energy: $> 10^{18}$ eV

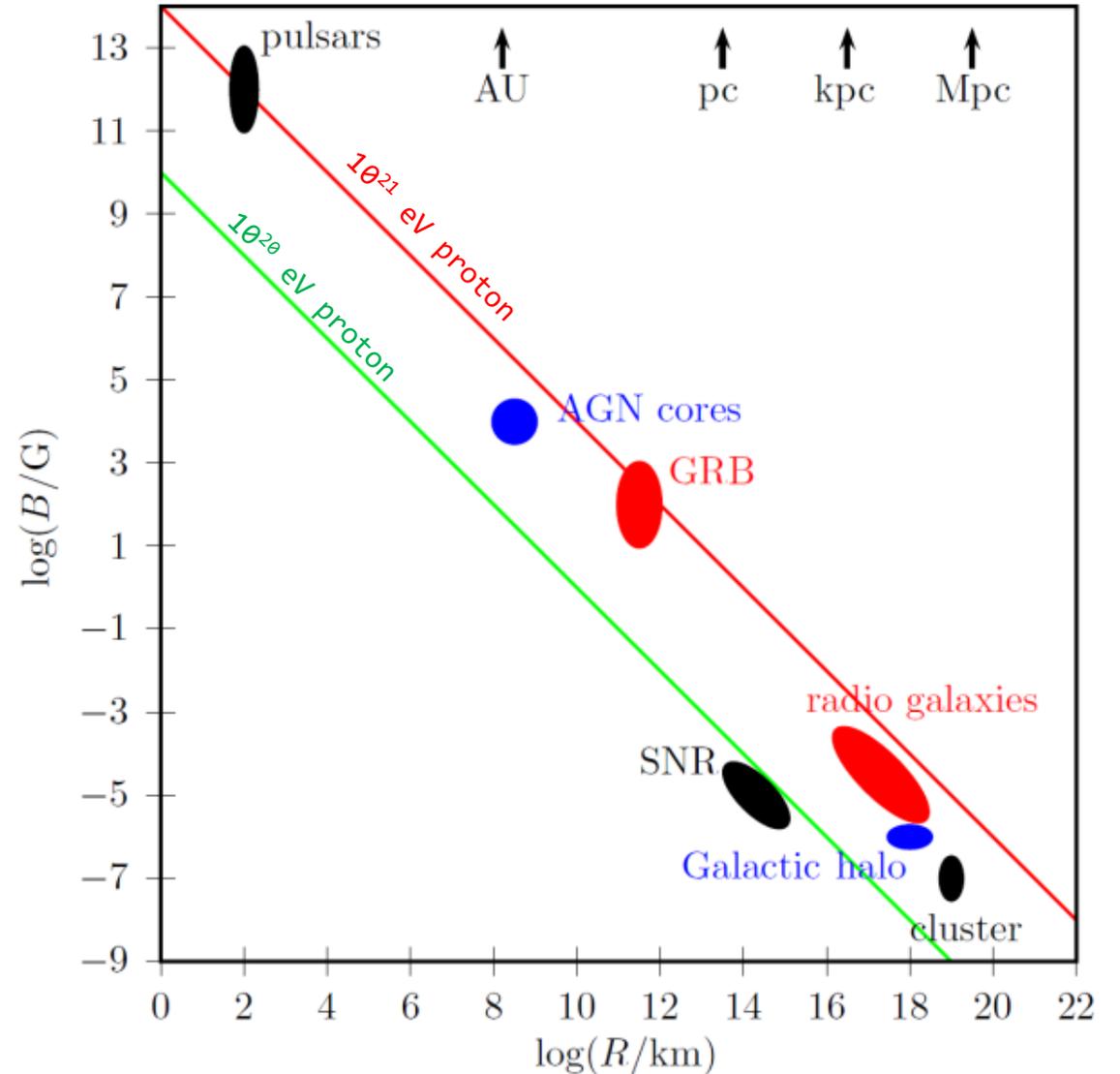
Hillas criterion

Max. energy of particle is such that it still needs to be contained by magnetic fields within source.

→ Larmor radius needs to be smaller than the size of the accelerator (Hillas 1984):

$$R_L = E_{\max} / (ZqB) \leq R_s$$

Very few astrophysical processes satisfy this for the highest-energy detected cosmic rays.



Greisen-Zatsepin-Kuzmin limit (GZK limit)

independently calculated in 1966

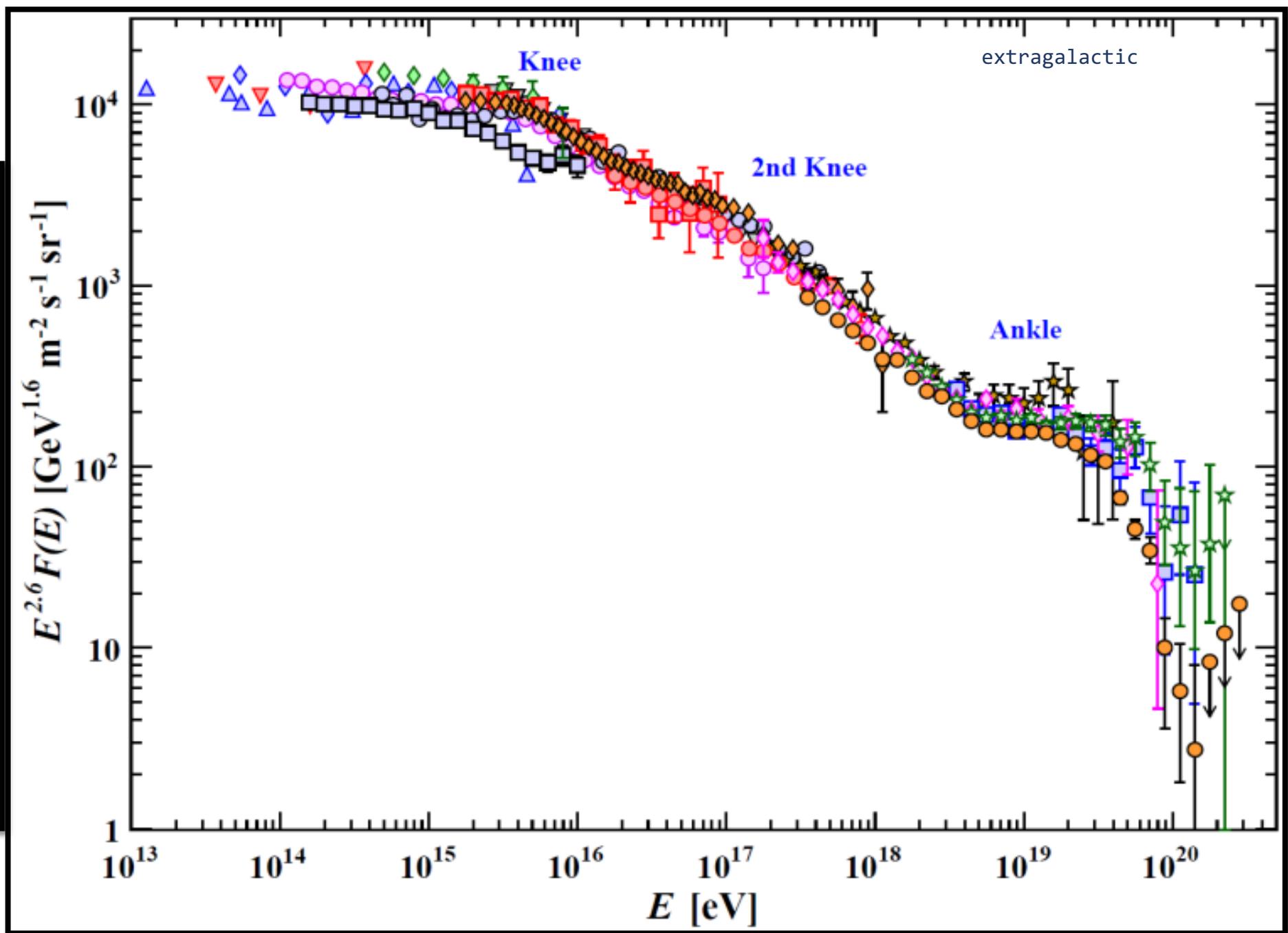
Cosmic rays with energies above the GZK limit will interact with the cosmic microwave background, are attenuated and will make it to Earth with reduced energies.



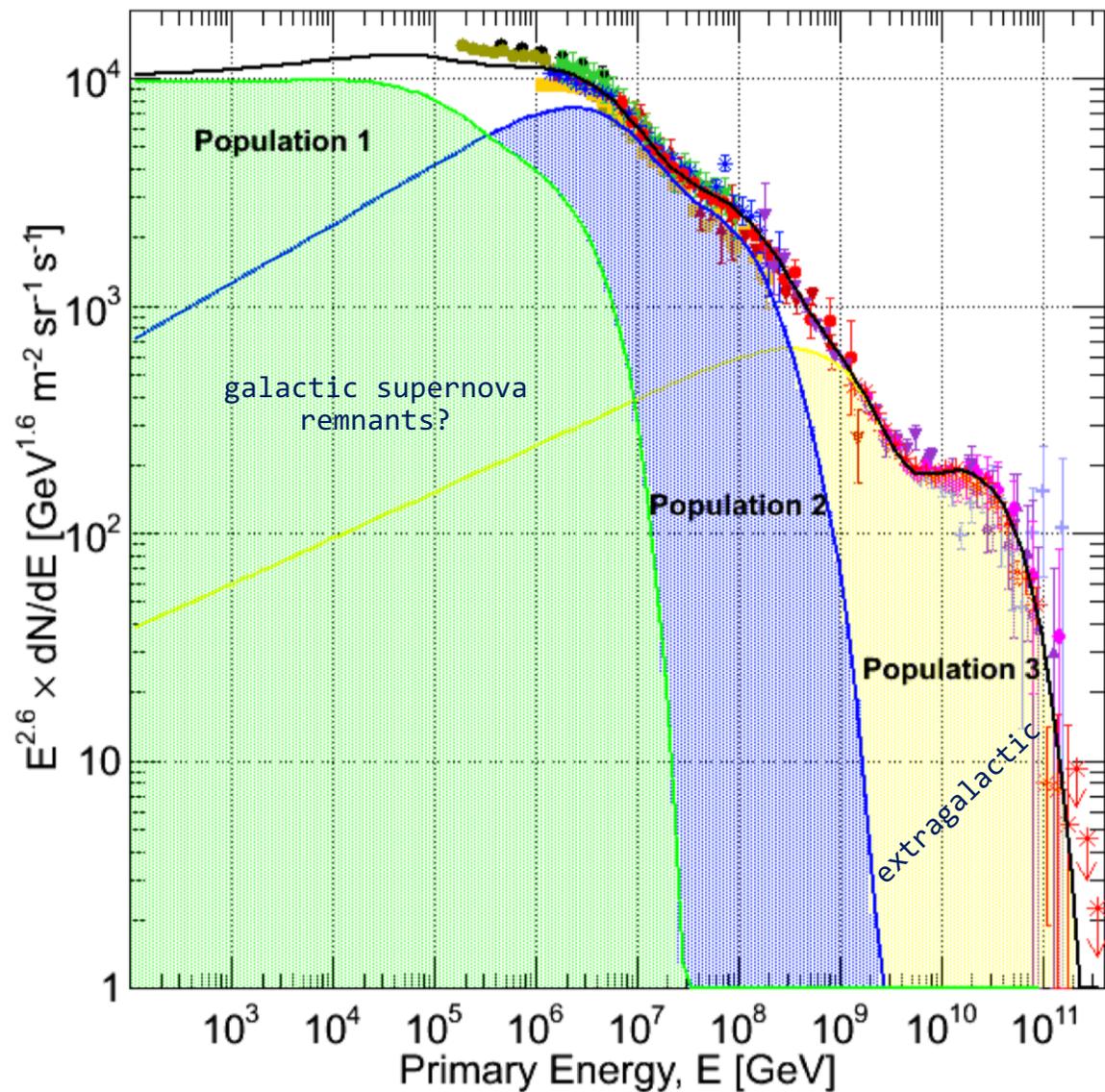
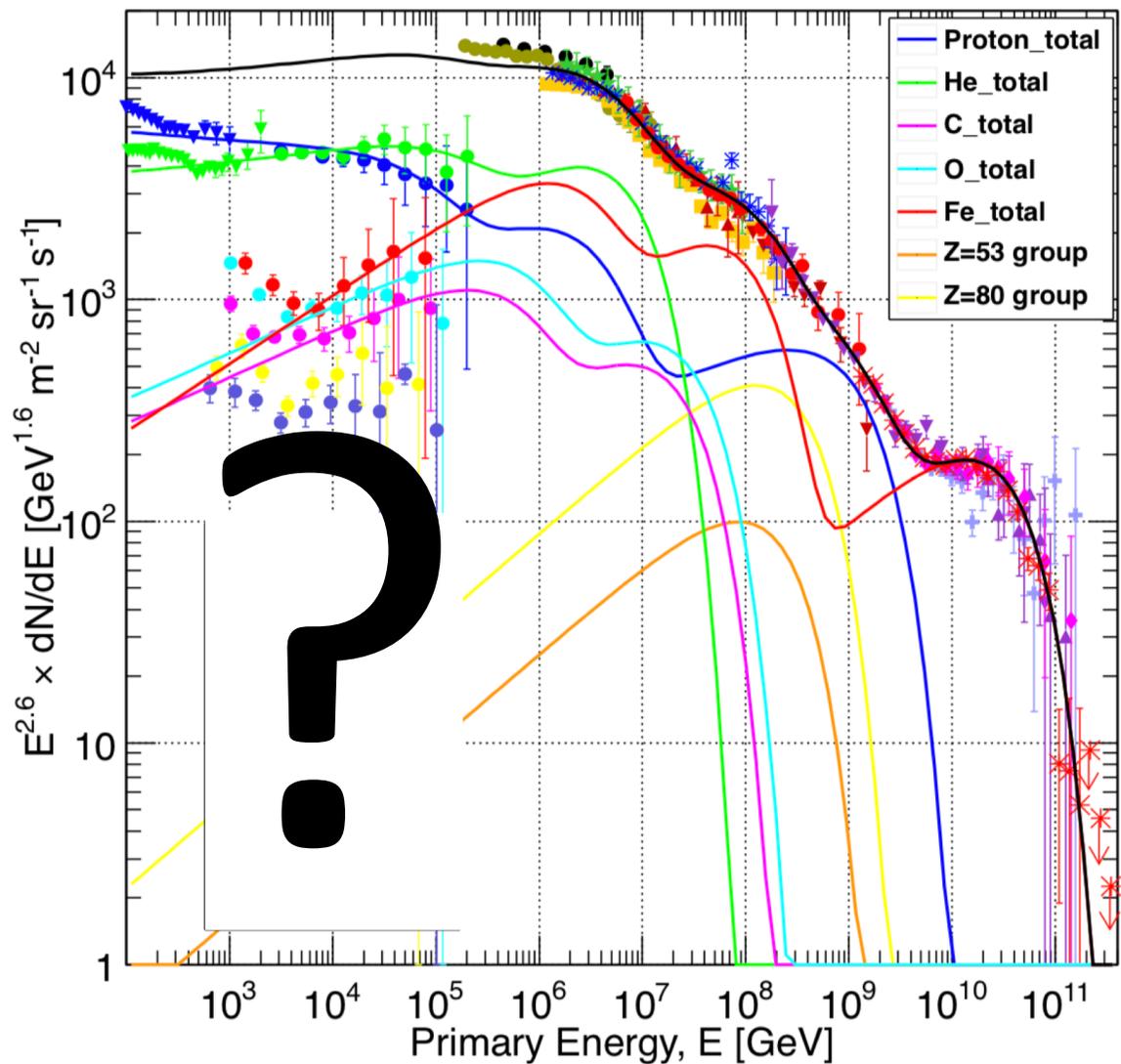
GZK limit for protons: 5×10^{19} eV (c.f. highest energy observed, 3×10^{20} eV)

→ Protons observed beyond the GZK limit cannot have originated from beyond ~50 Mpc

(limit is different for heavier elements)



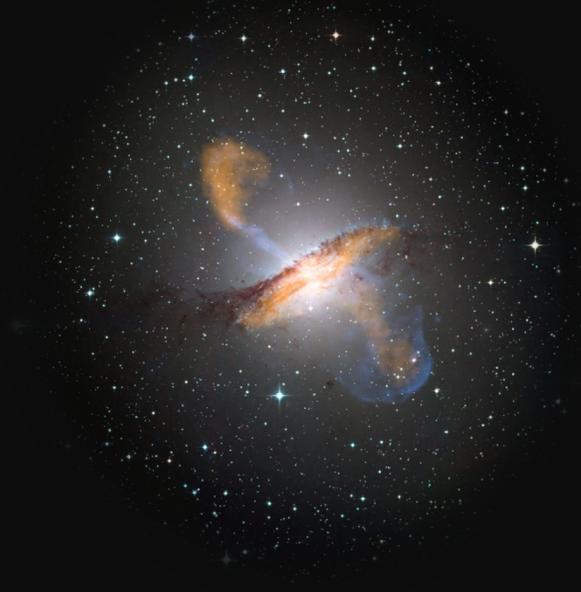
- △ Grigorov
- ▽ JACEE
- ▽ MGU
- ◇ Tien-Shan
- Tibet07
- Akeno
- CASA-MIA
- ◇ HEGRA
- ★ Fly's Eye
- Cascade
- Cascade Grande
- ◇ IceTop-73
- HiRes 1
- ◇ HiRes 2
- ★ Telescope Array
- Auger



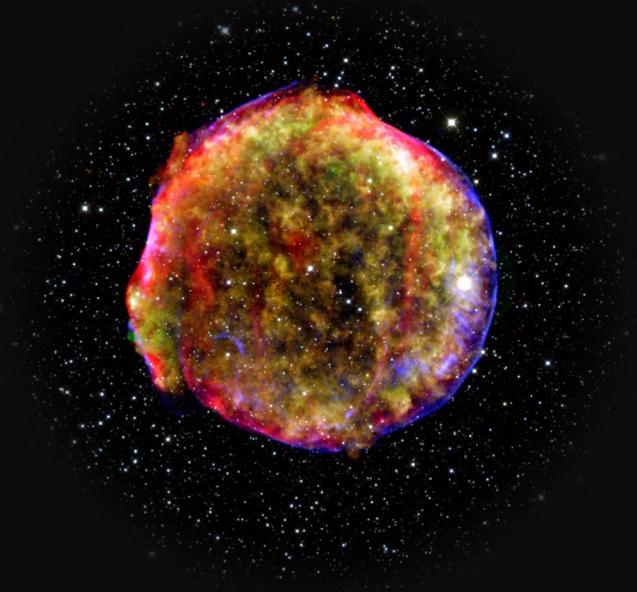
the high-energy (EM) universe



gamma-ray bursts

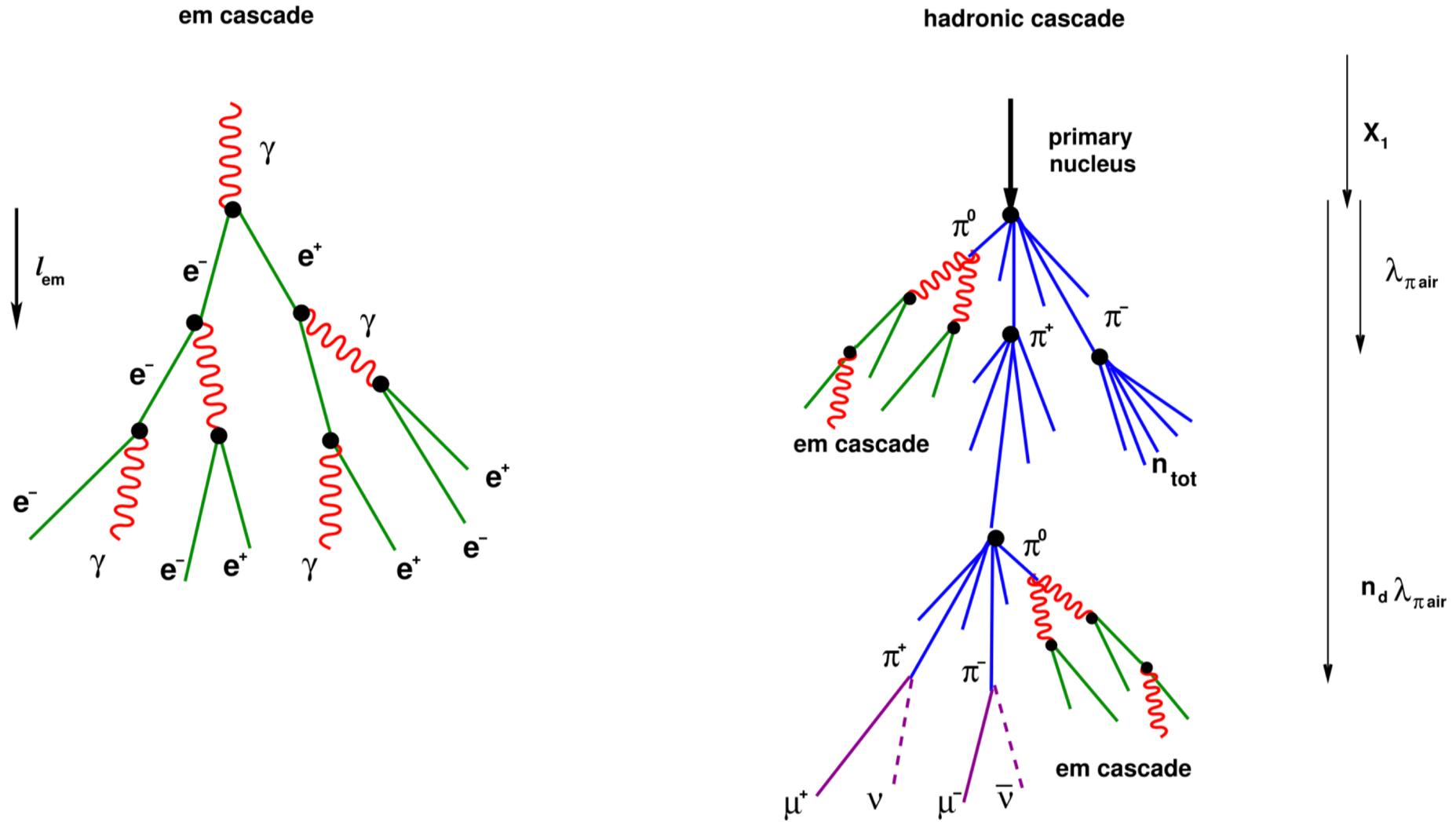


active galactic nuclei
(blazars)



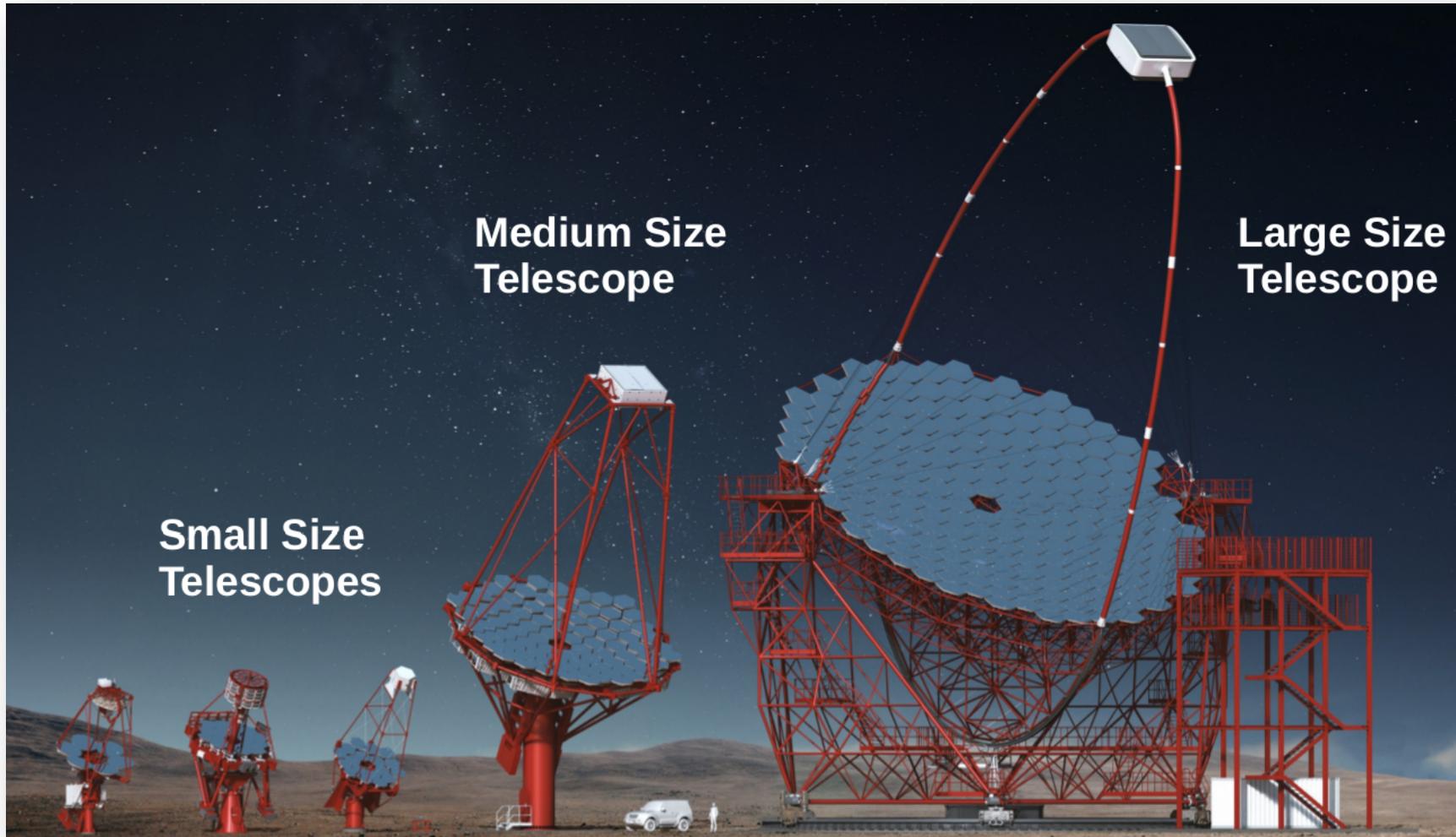
supernova remnants

Cosmic ray showers



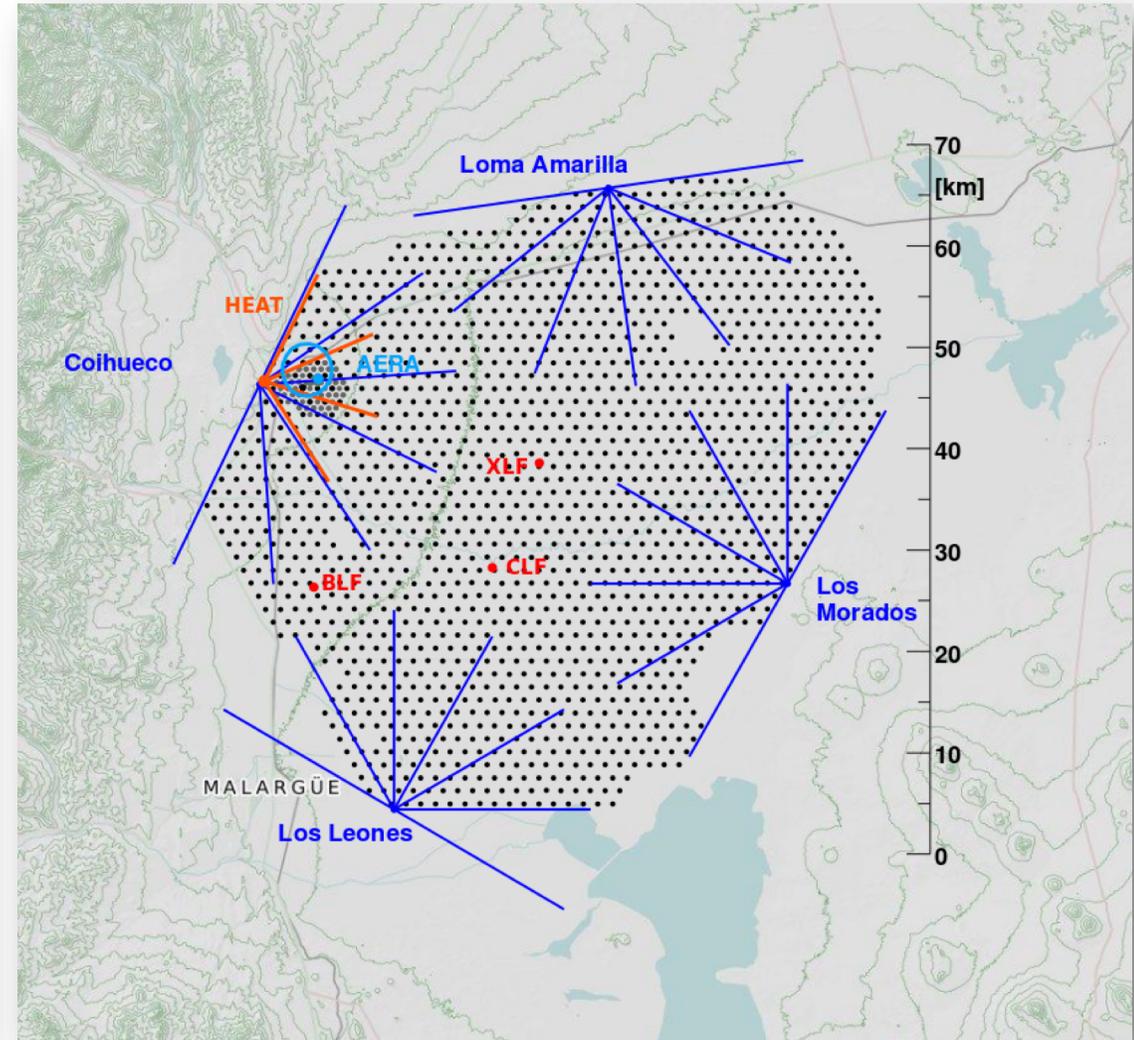
Cherenkov telescopes

- Cherenkov Telescope Array (completed soon soon)
- H.E.S.S.
- Magic
- Veritas



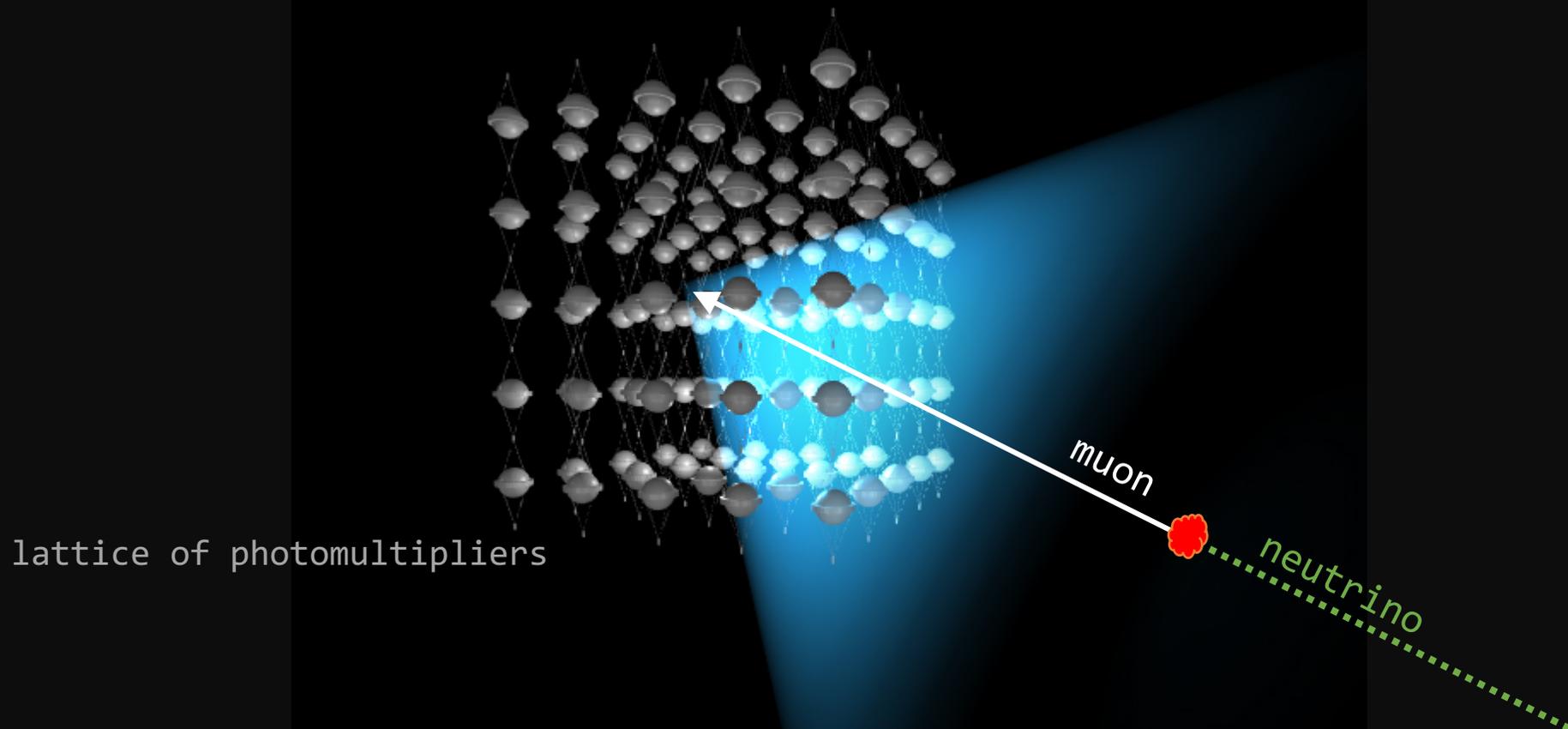
Cosmic ray observatories

- e.g. Pierre Auger Observatory



high-energy neutrino detection

Moisey Markov (1960): we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.



DUMAND (Deep Underwater Muon And Neutrino Detector)



1976-1995

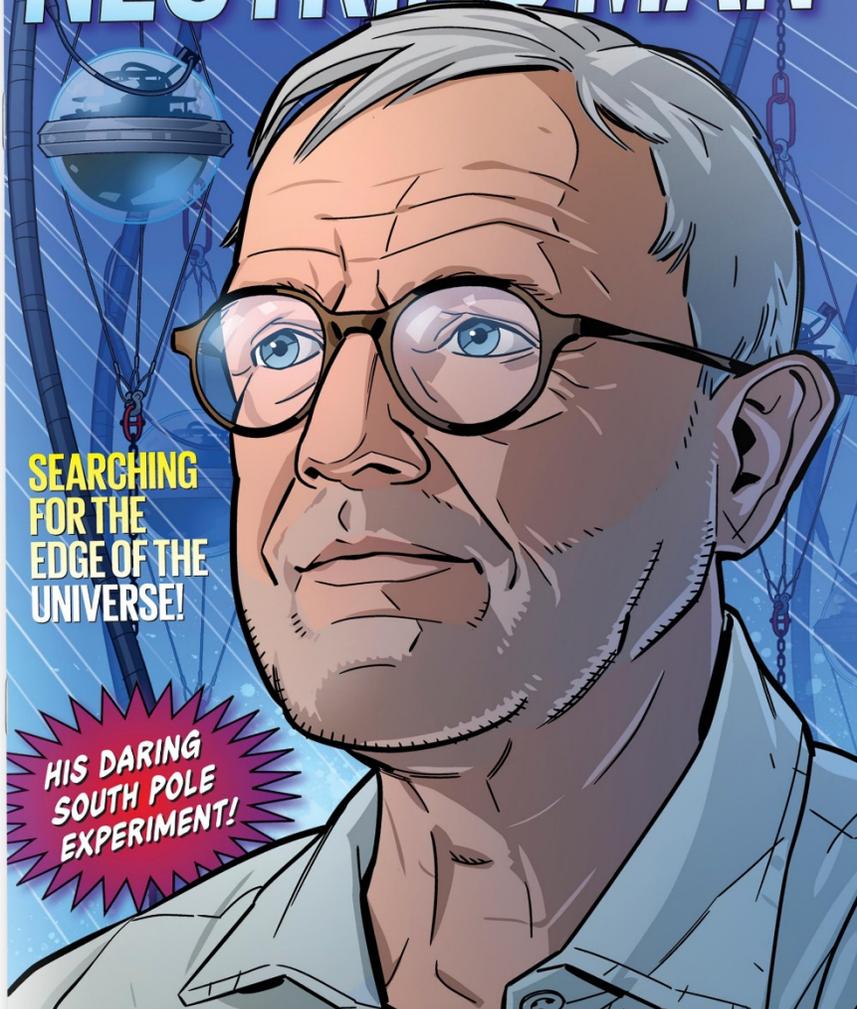
THE SUBATOMIC ADVENTURES OF

NEUTRINO MAN

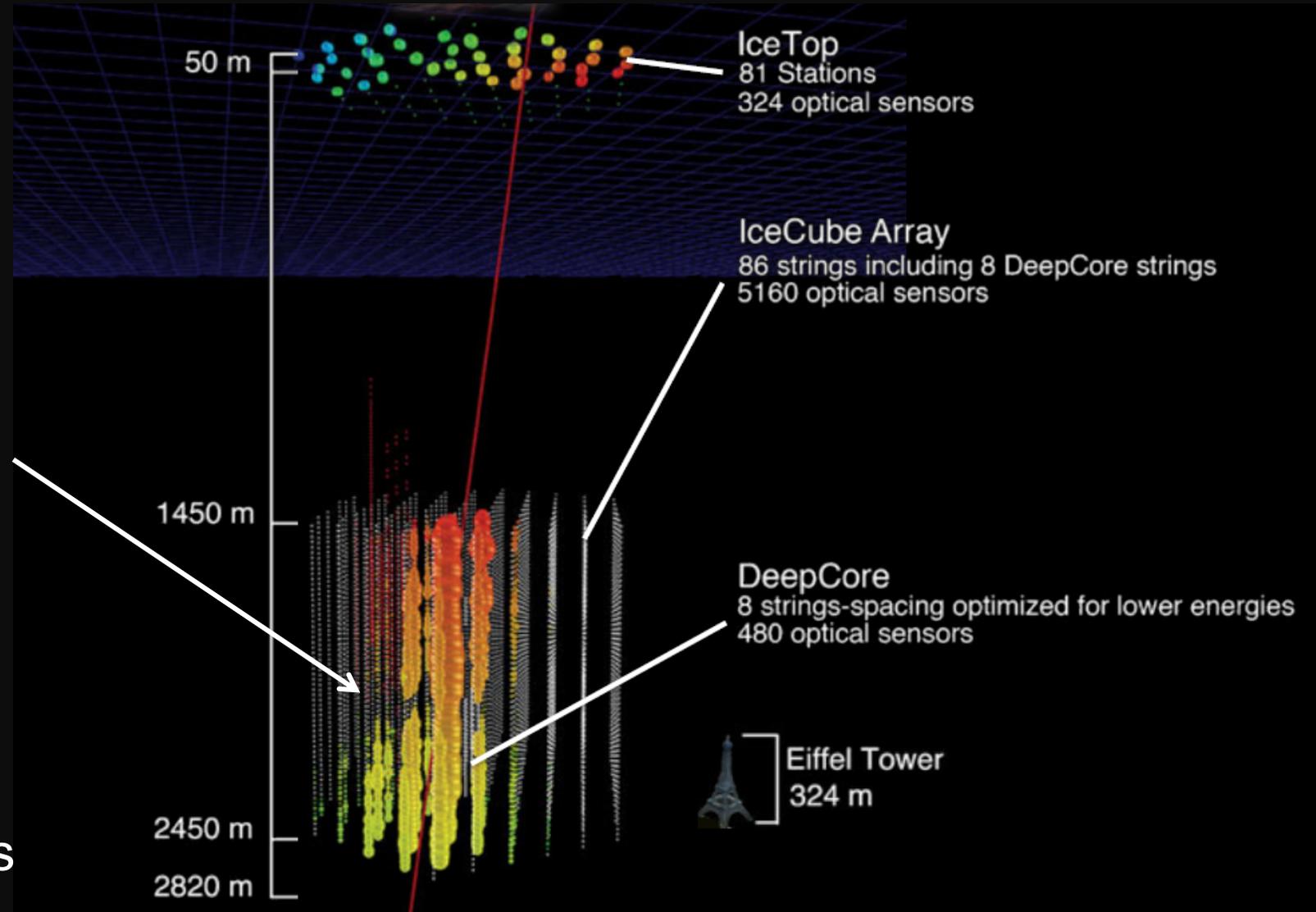
SEARCHING
FOR THE
EDGE OF THE
UNIVERSE!

HIS DARING
SOUTH POLE
EXPERIMENT!

DEFIES THE ODDS! CATCHES INVISIBLE PARTICLES FROM OUTER SPACE!



IceCube



5160 PMs
in 1 km³

Photomultiplier
tube - 10 inch

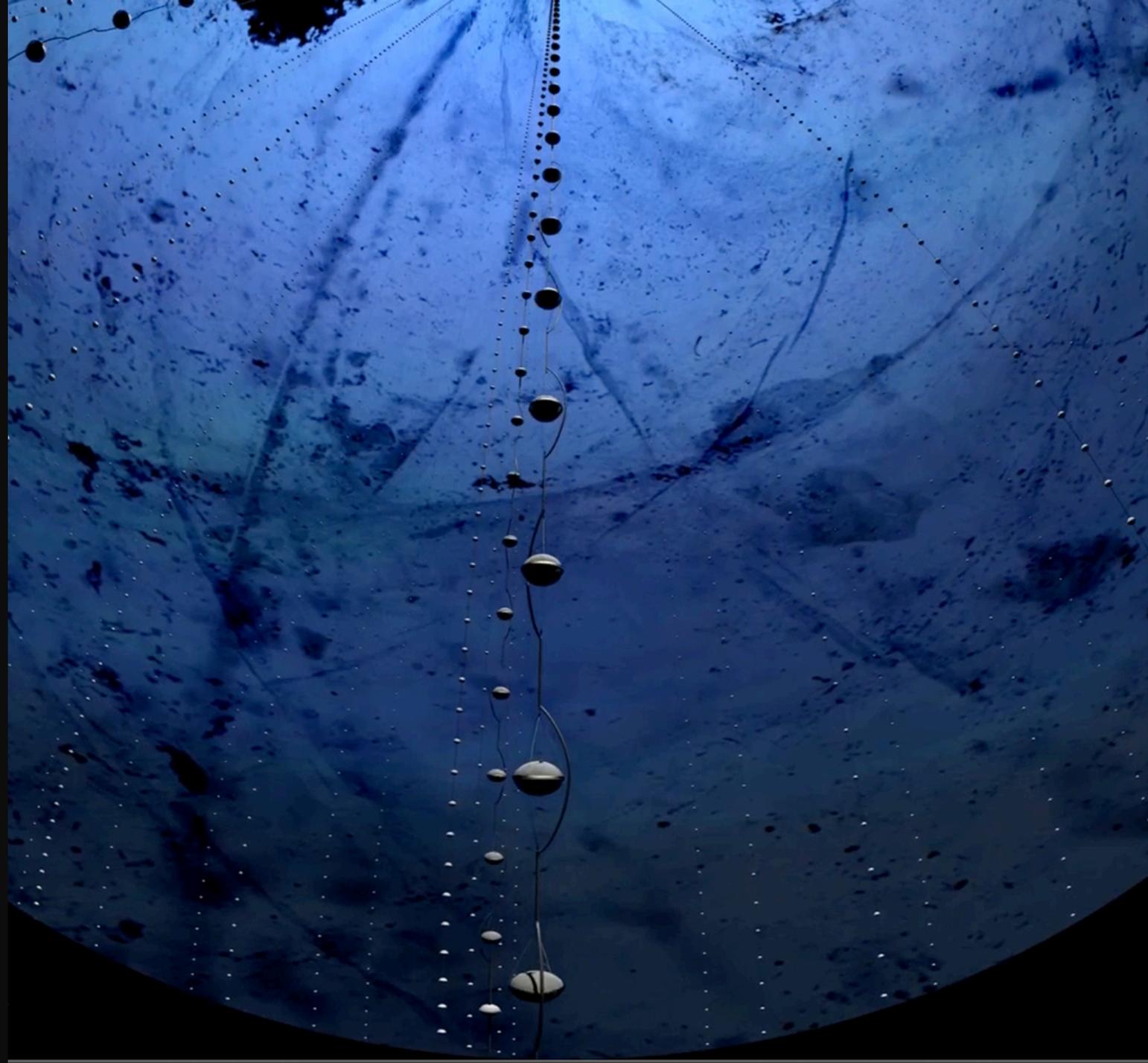


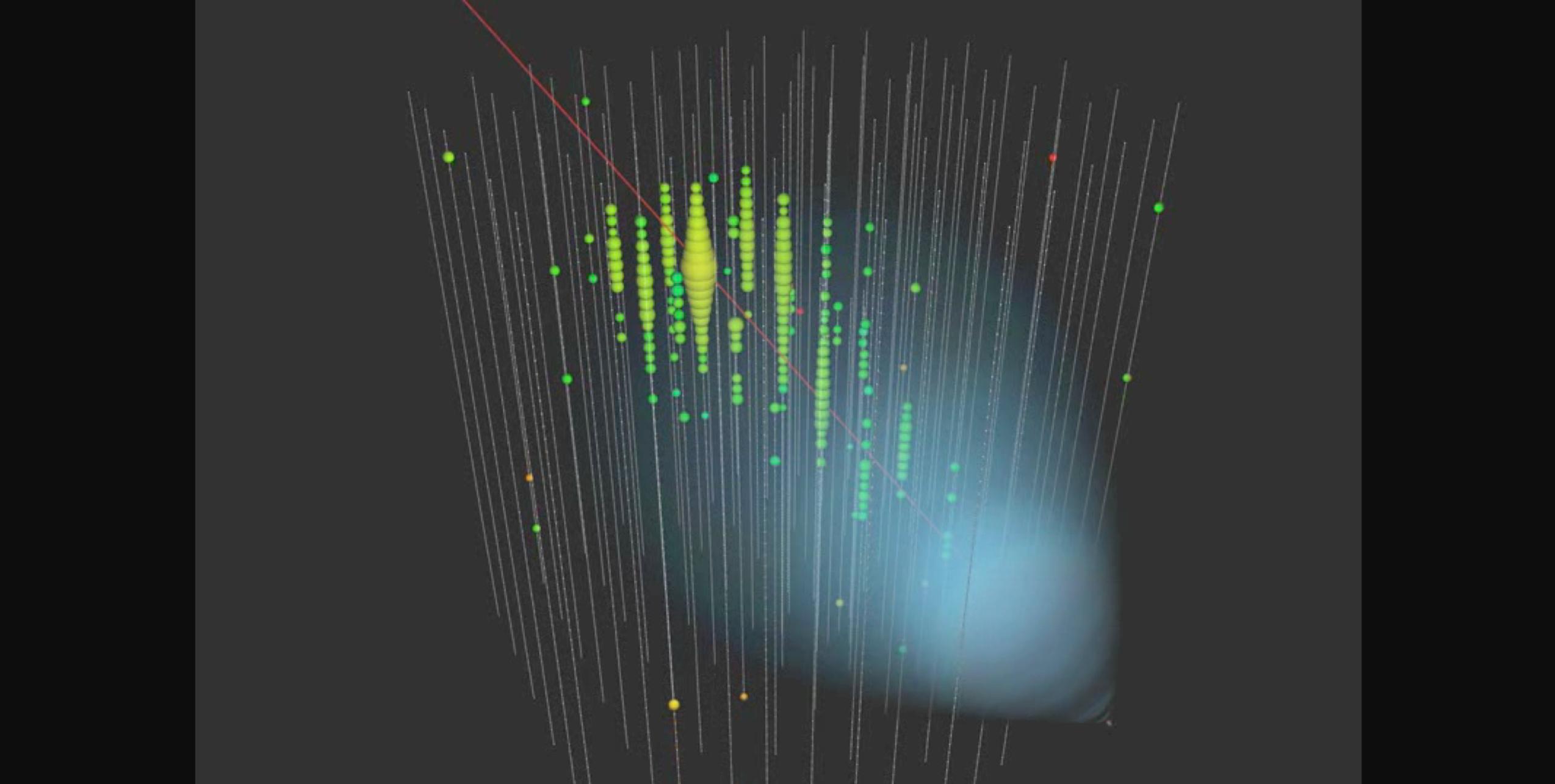


nozzle delivers:

- 200 gallons per minute
- 7 Mpa
- 90 degree C

4.8 megawatt
heating plant →





muon track: time is color; number of photons is energy