Cosmic Rays

Paolo Desiati
desiati@wipac.wisc.edu

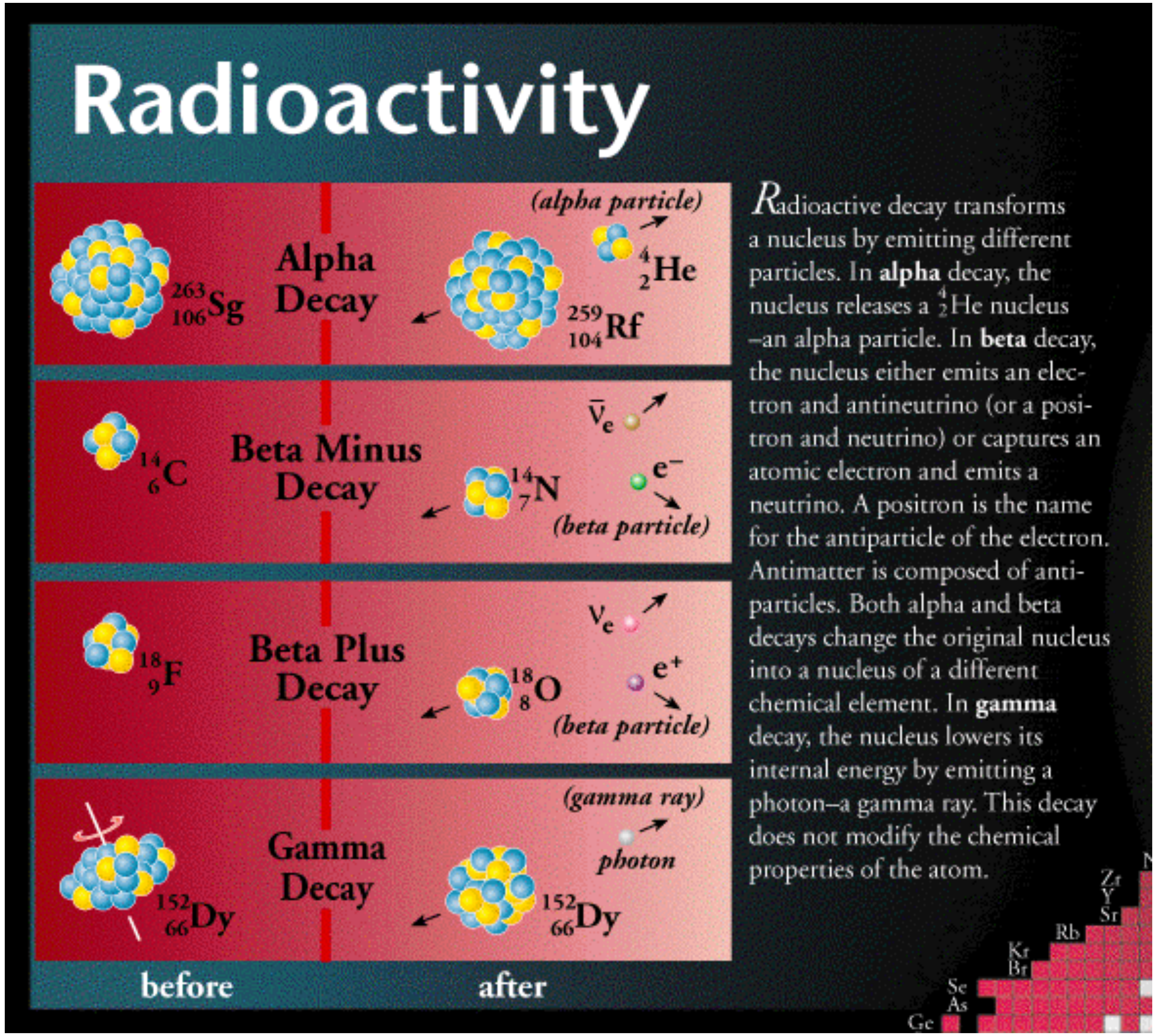
IceCube Bootcamp

Madison, WI - June 13-17, 2022

Photo by Bryce Richter

The discovery of the Cosmic Rays

...looking for something else



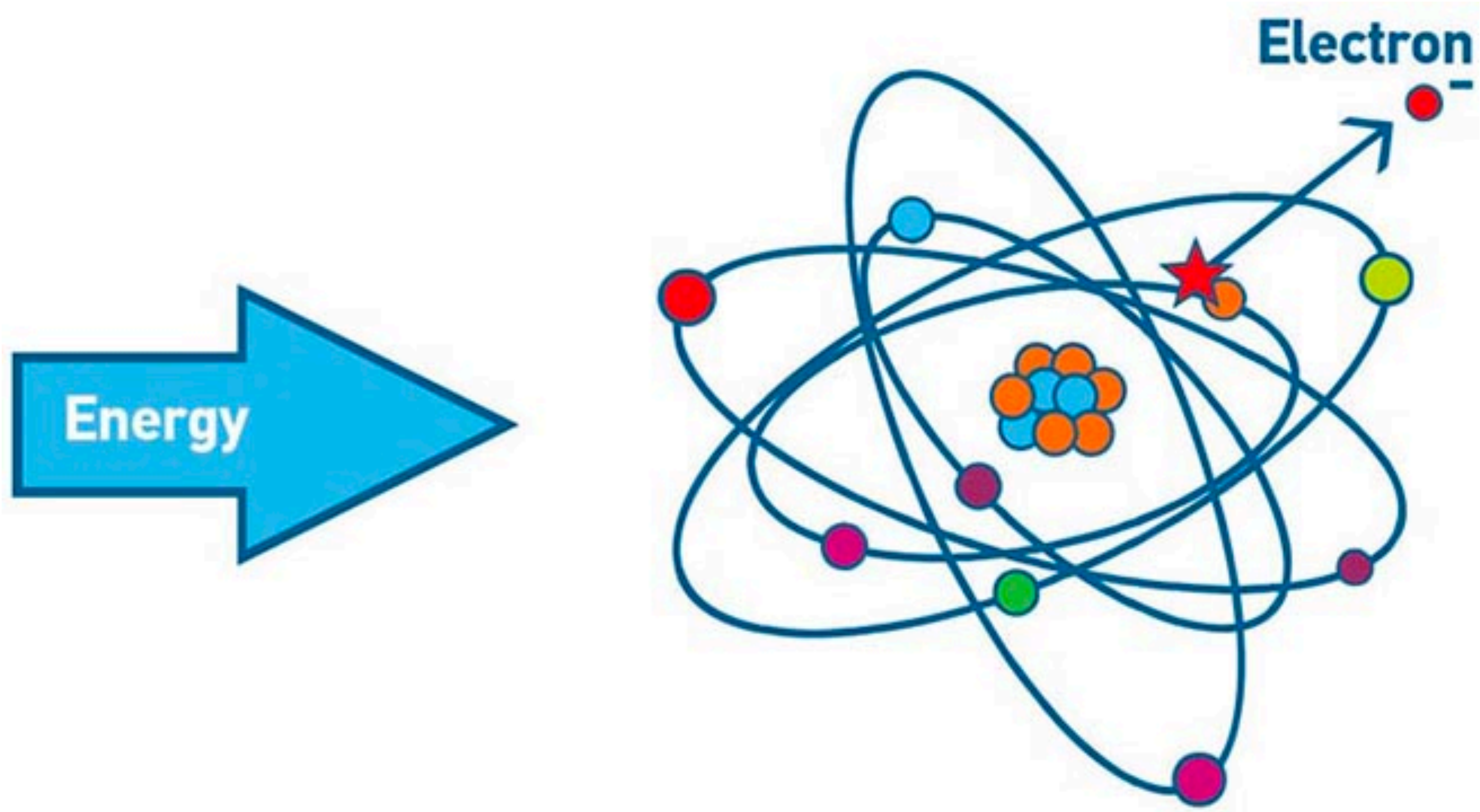
… after the accidental discovery of X-rays by Röntgen in 1896 and of Uranium particle emission by Henri Bequerel that same year

… radioactivity was intensively studied as a natural phenomenon occurring inside Earth's crust

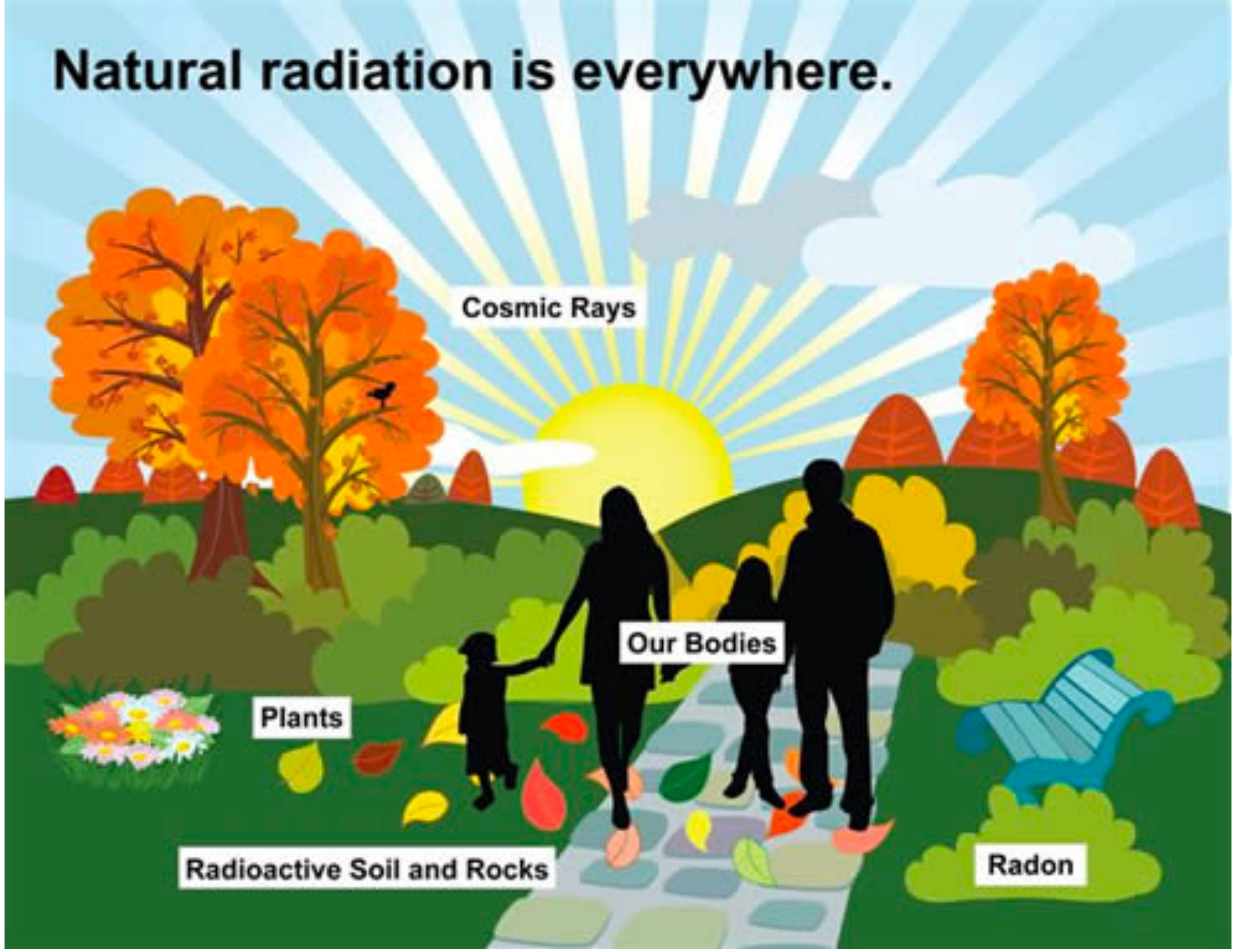
radiation - the emission of energy as electromagnetic waves or as moving subatomic particles, especially high-energy particles which cause ionization.

ionizing radiation

these invisible rays of energy
produce electric currents in the air



electrometer capable of measuring
weak electric currents (Pierre & Jacques Curie)

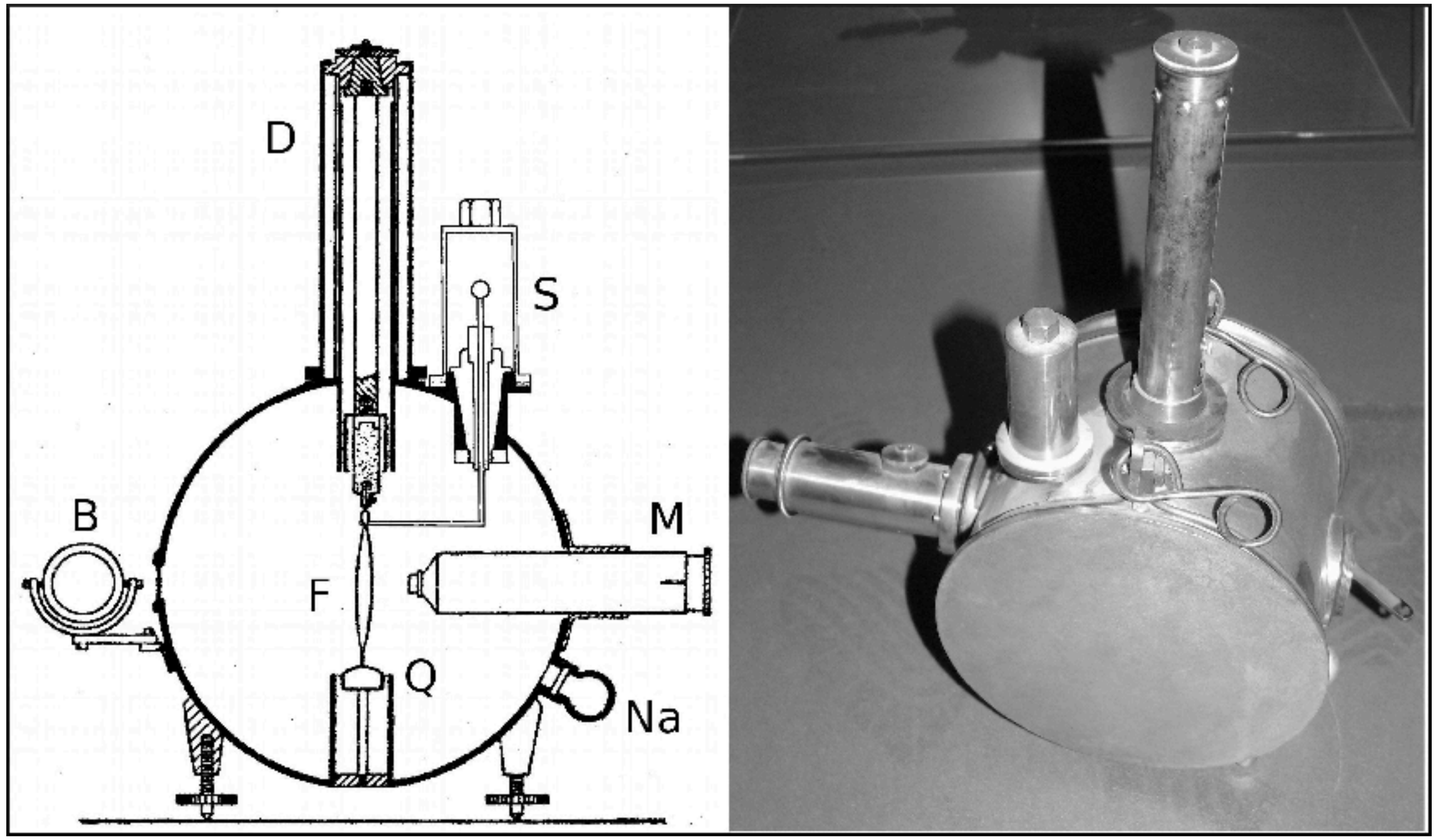


natural radioactivity from the ground

does it mean that it is expected to decrease the higher we go?

Theodor Wulf (1868-1946)

air ionization measurements on the ground and on top of **Eiffel Tower**



electrometer to measure ionization currents from gamma rays

@300m - **15.7** ions/cm³ sec

expected - **6** ions/cm³ sec

@ground - **17.5** ions/cm³ sec

Domenico Pacini (1878-1934)

LA RADIAZIONE PENETRANTE ALLA SUPERFICIE ED IN SENO ALLE ACQUE.

NOTA DI D. PACINI.

Le osservazioni eseguite sul mare nel 1910 [1]) mi conducevano a concludere che una parte non trascurabile della radiazione penetrante che si riscontra nell' aria, avesse origine indipendente dall' azione diretta delle sostanze attive contenute negli strati superiori della crosta terrestre.

Riferirò ora sopra ulteriori esperienze che confermano quella conclusione.

I risultati precedentemente ottenuti indicavano esistere, sulla superficie del mare, dove non è più sensibile l'azione del terreno, una causa ionizzante di tale intensità da non potersi spiegare esaurientemente considerando la nota distribuzione delle sostanze radioattive nell'acqua e nell' aria.

air ionization measurements on the ground, **on the sea and under the sea**

radiation strength decreases underwater. But isn't it closer to the ground below?

“Observations carried out on the sea during the year 1910 led me to conclude that a significant proportion of the pervasive radiation that is found in air had an origin that was independent of direct action of the active substances in the upper layers of the Earth’s surface.”

The discovery of the Cosmic Rays

…the breakthrough

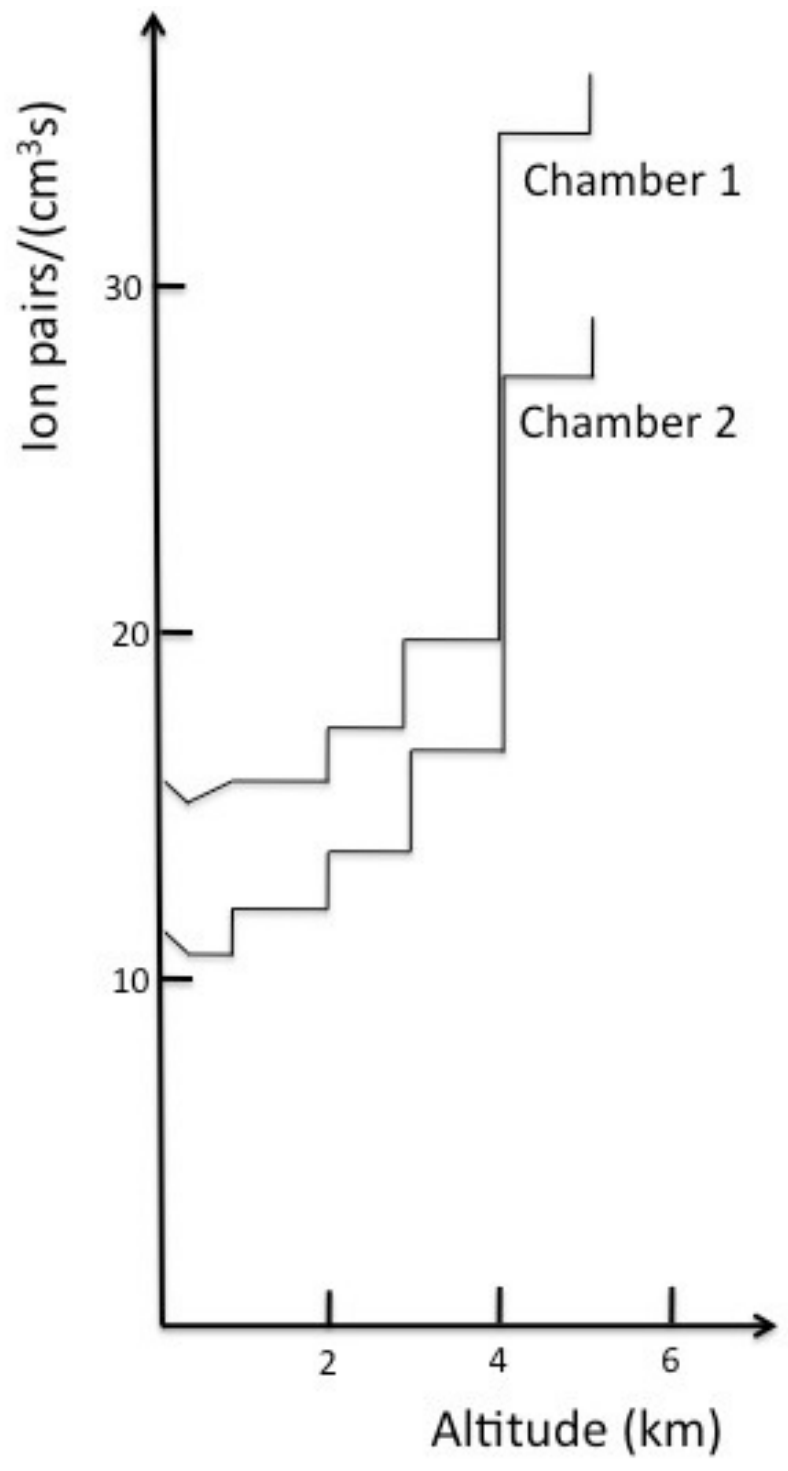
Victor Francis Hess (1883-1964)

air ionization measurements at high altitude, up to 5,000 meters (3 miles)

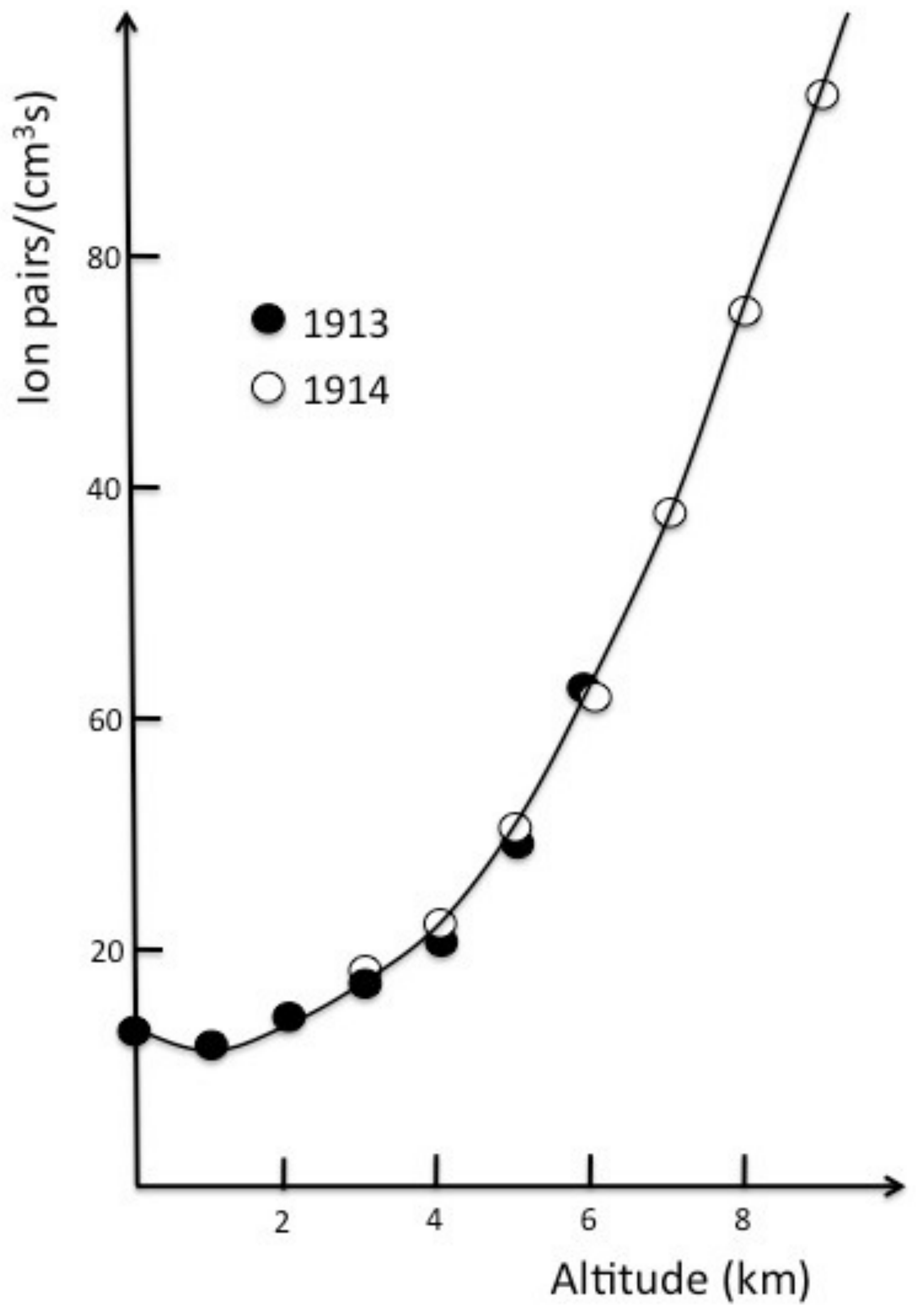
radiation strength increases with altitude

there must be a source of radiation from the sky…

… cosmic **rays?**



Hess (1912)



Kolhörster (1913-14)

rays of particles?

COSMIC RAY RIVALS TO MEET IN DEBATE

Clash of Millikan and Compton Theories to Form High Point at Scientific Convention.

4,500 TO ATTEND SESSIONS

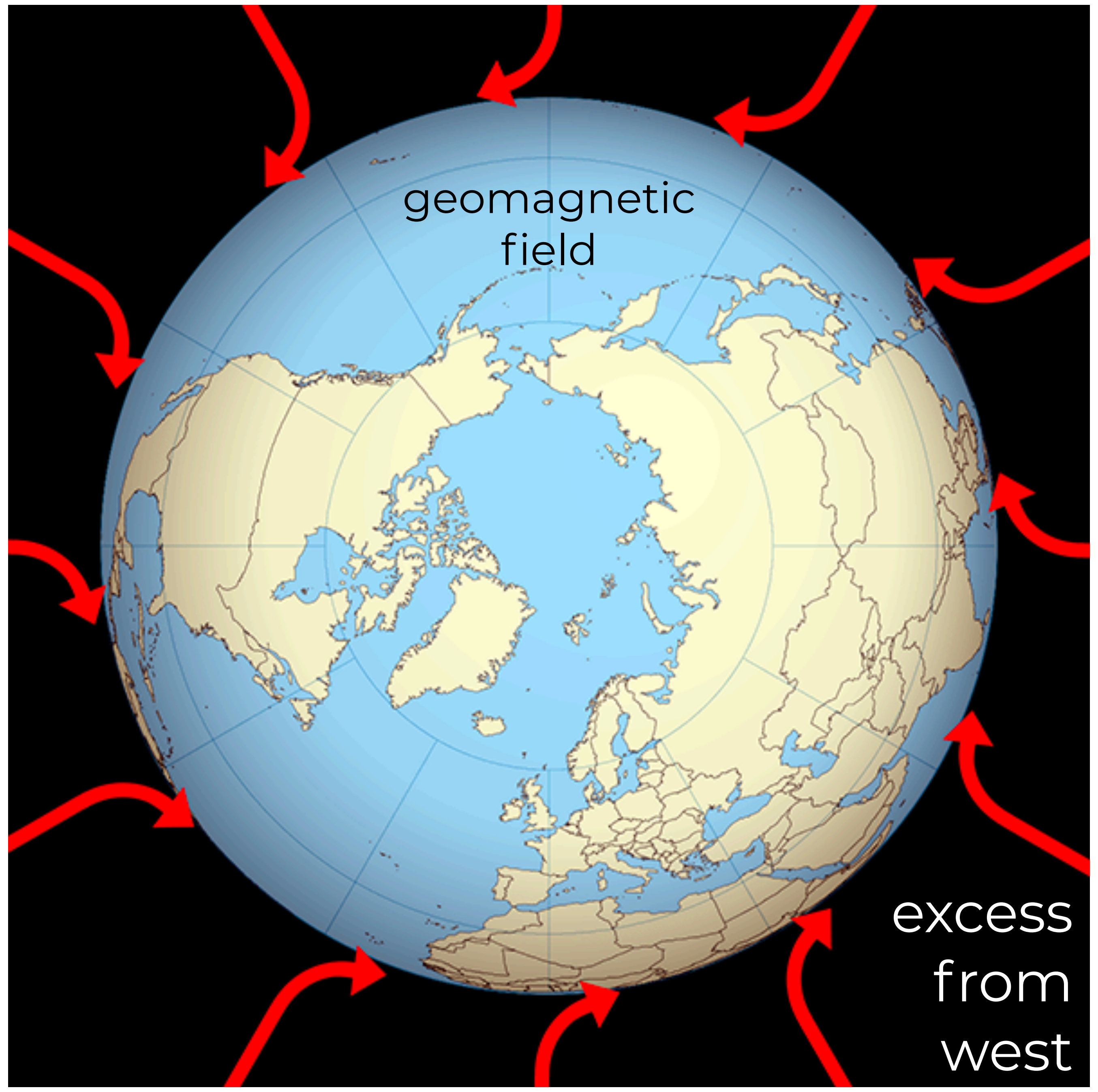
Atlantic City Meeting This Week to Hear 1,500 Papers—Gerard Swope to Speak on Unemployment.

Special to THE NEW YORK TIMES.

ATLANTIC CITY, Dec. 25.—The nature of cosmic rays, revolving around the specific question whether they enter the earth's atmosphere as electrically charged particles or as photons, will be the subject of debate between two of America's outstanding physicists at the annual meeting of the American Association for the Advancement of Science, which opens here Tuesday.

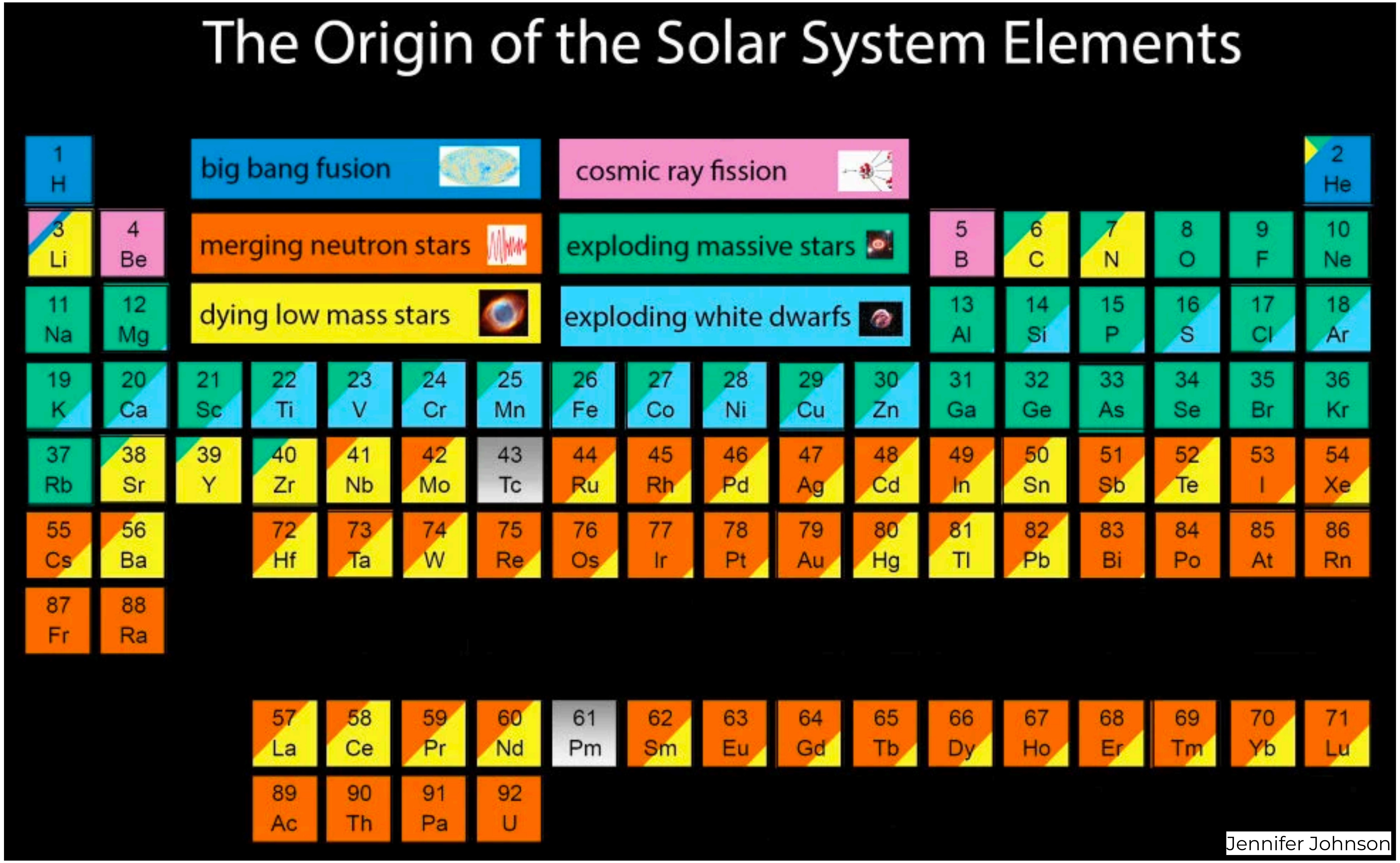
More than 4,500 scientists, laboratory workers and teachers of science

The New York Times
December 26, 1932

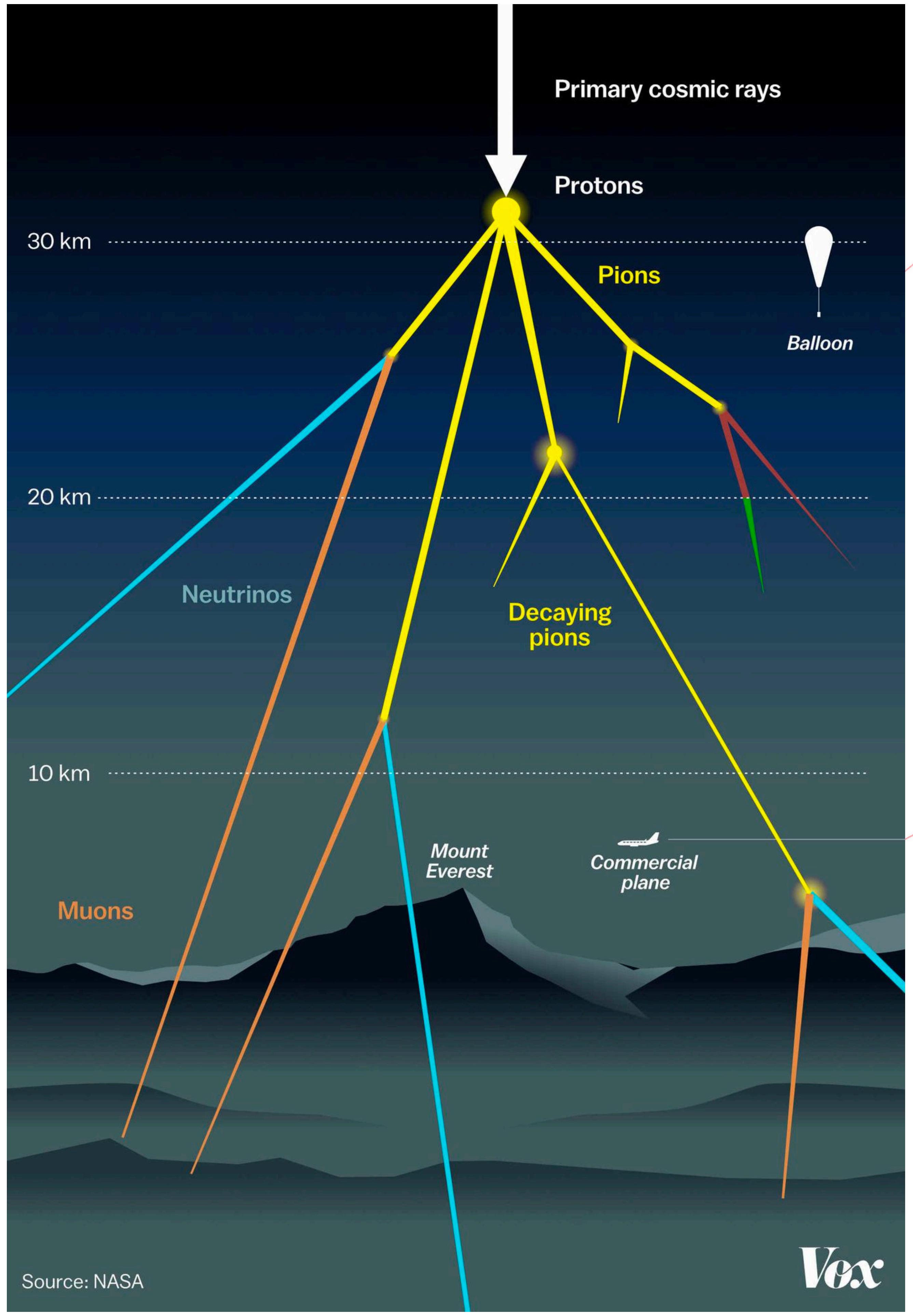


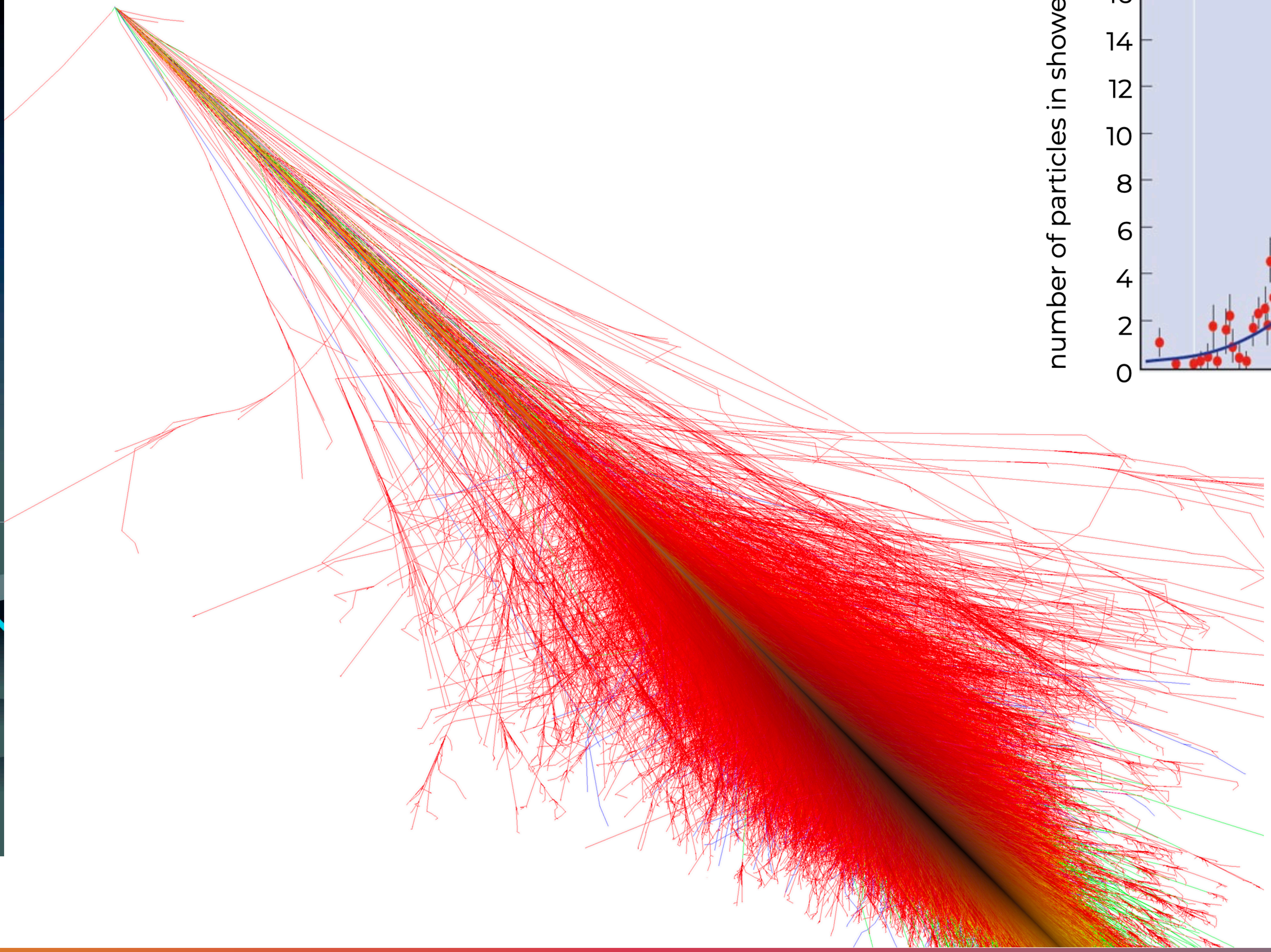
cosmic rays are not rays after all
but positively charged particles...

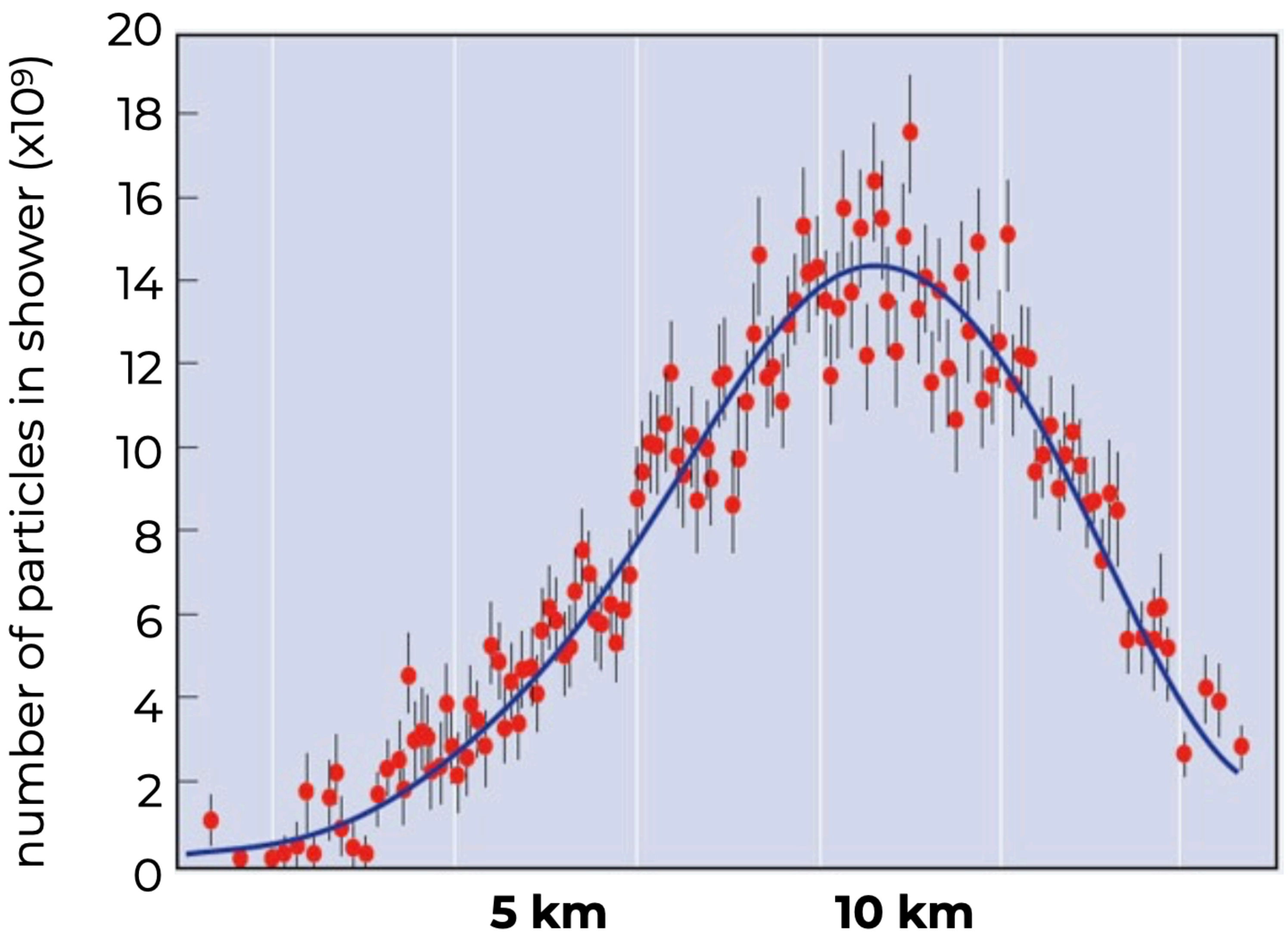
What are Cosmic Rays?



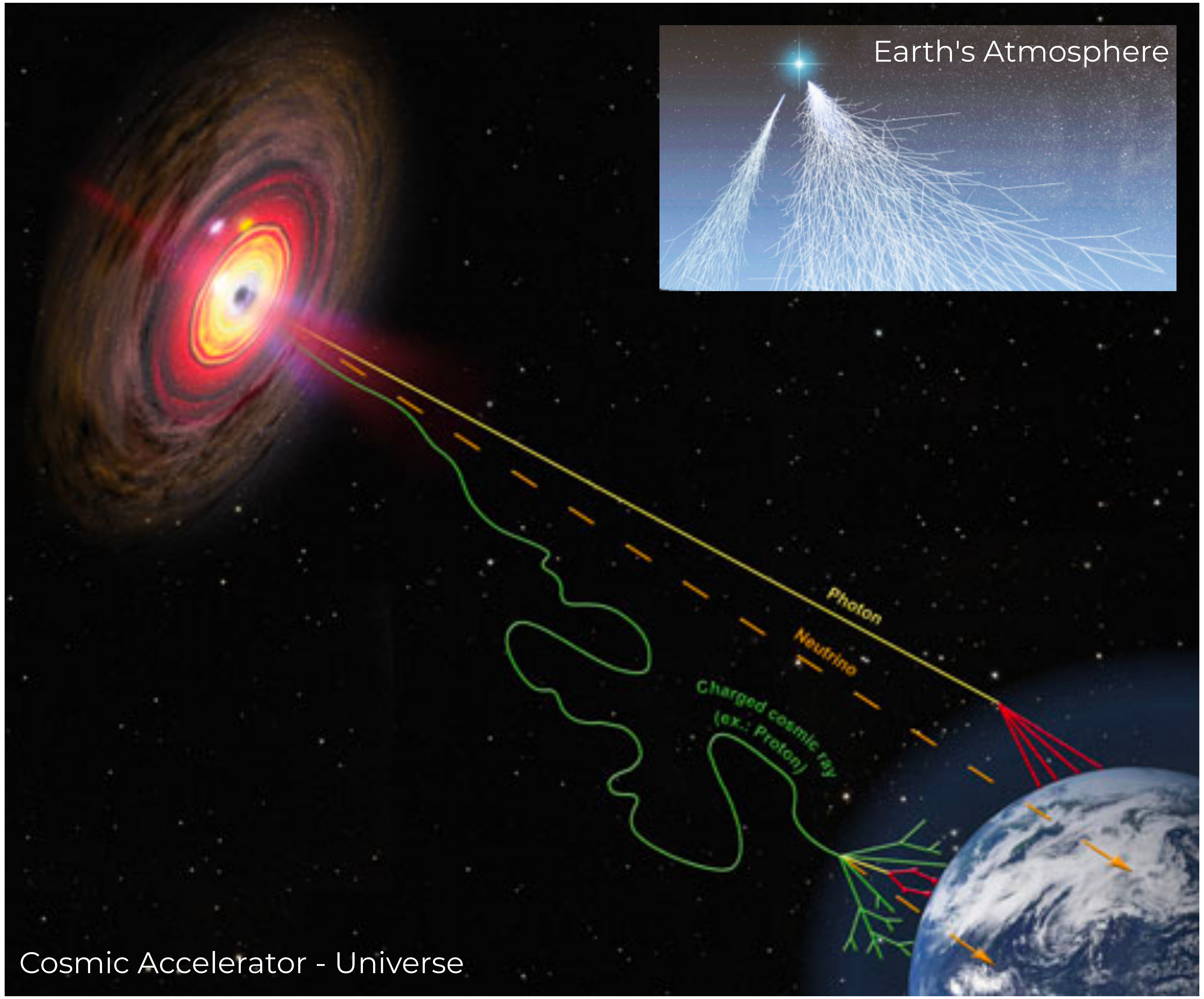
What are Cosmic Rays?
Extensive Air Showers







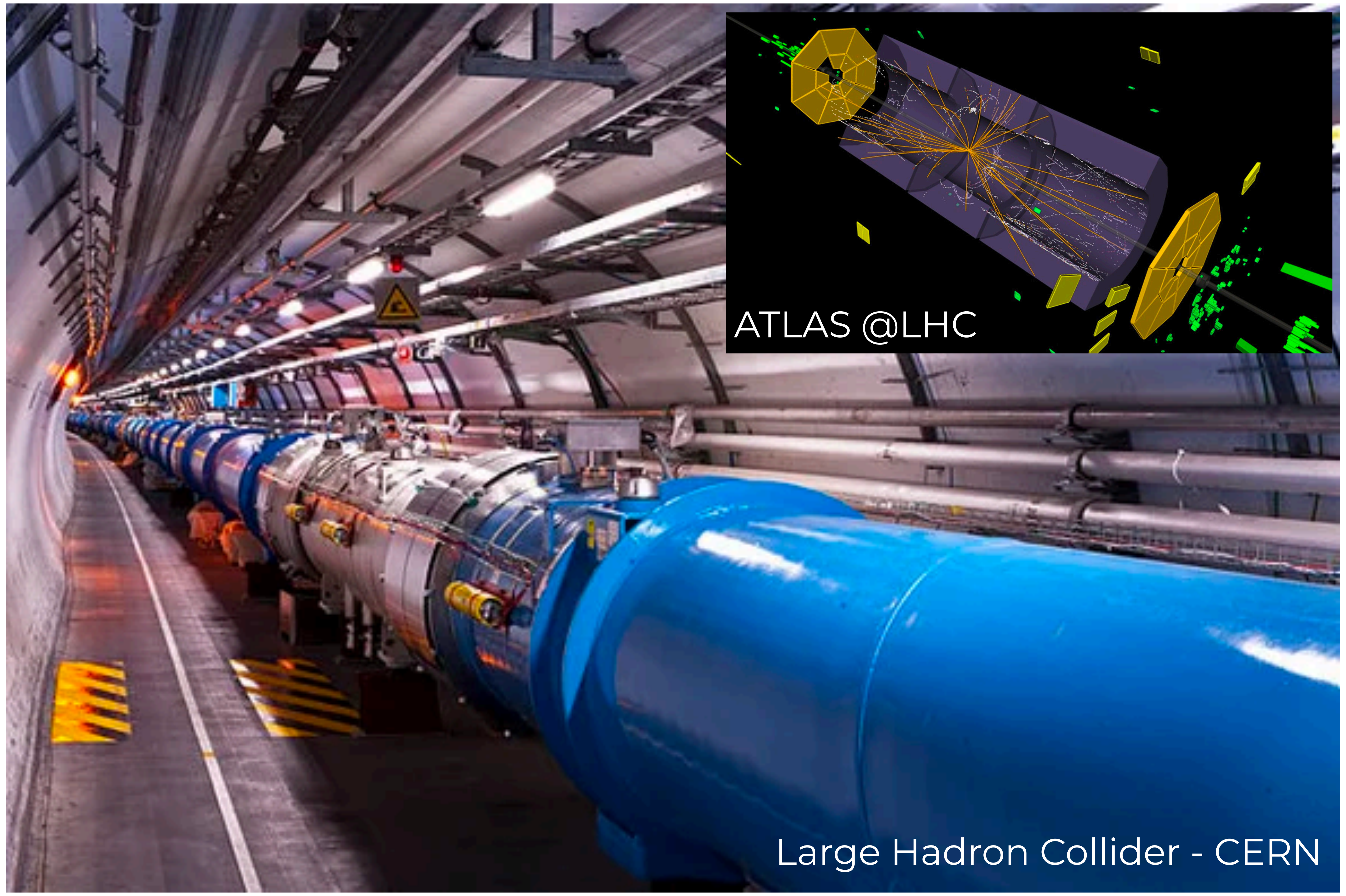
Where do Cosmic Rays come from?



Cosmic Accelerator - Universe

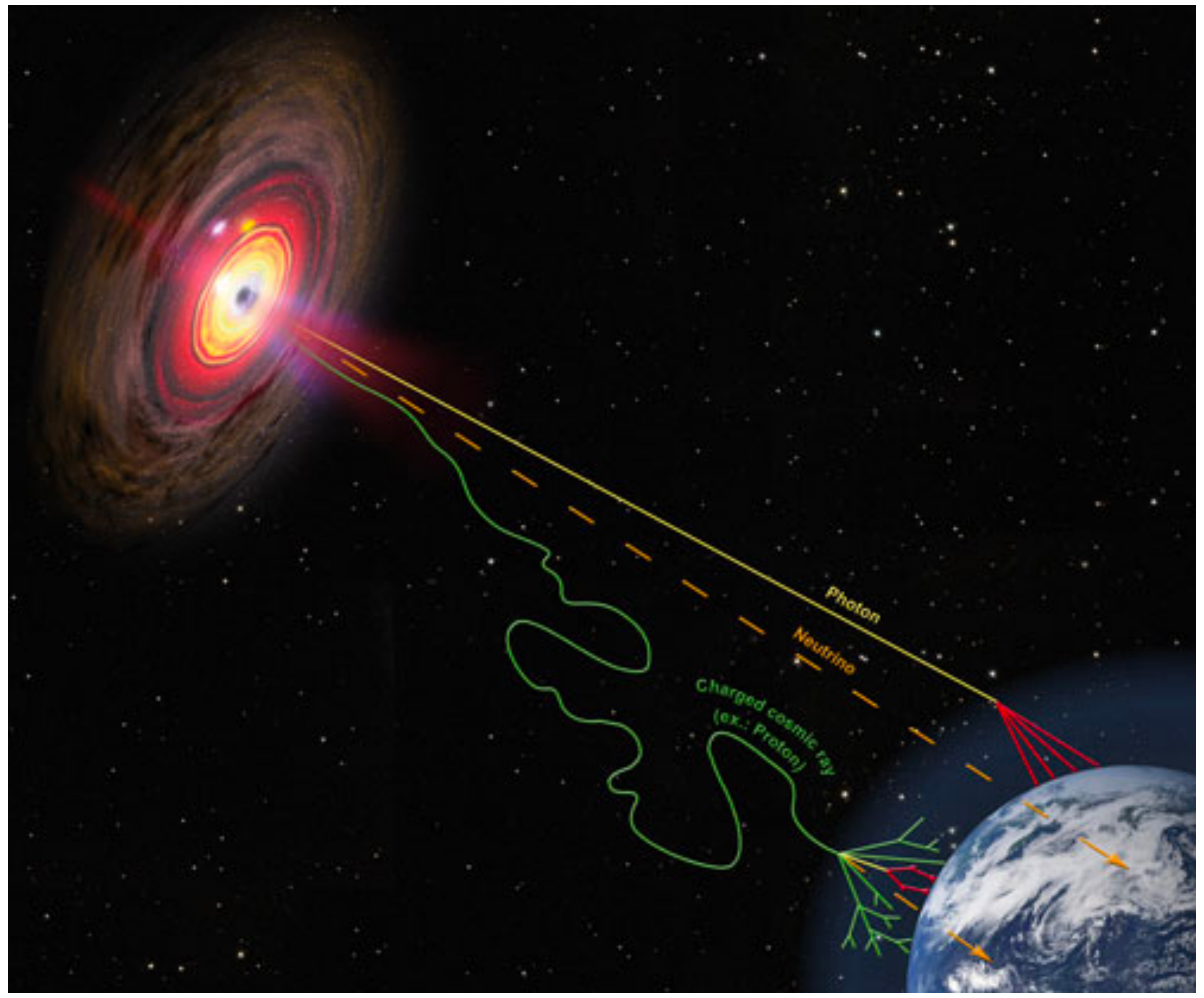
cosmic particle accelerator

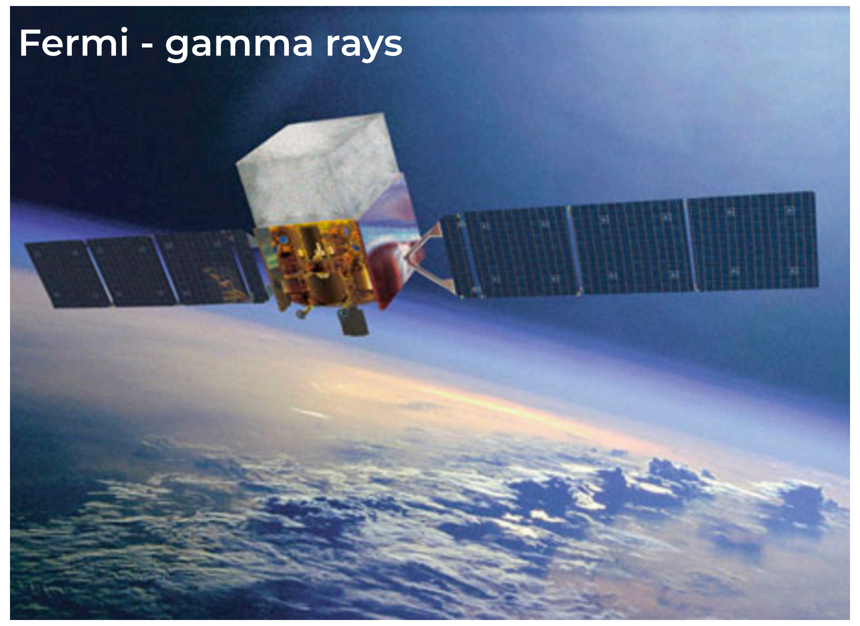
injecting high energy atomic nuclei into space (cosmic rays)

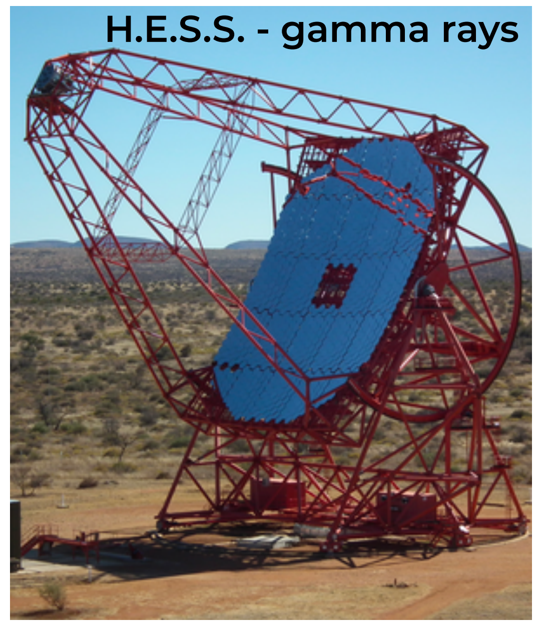


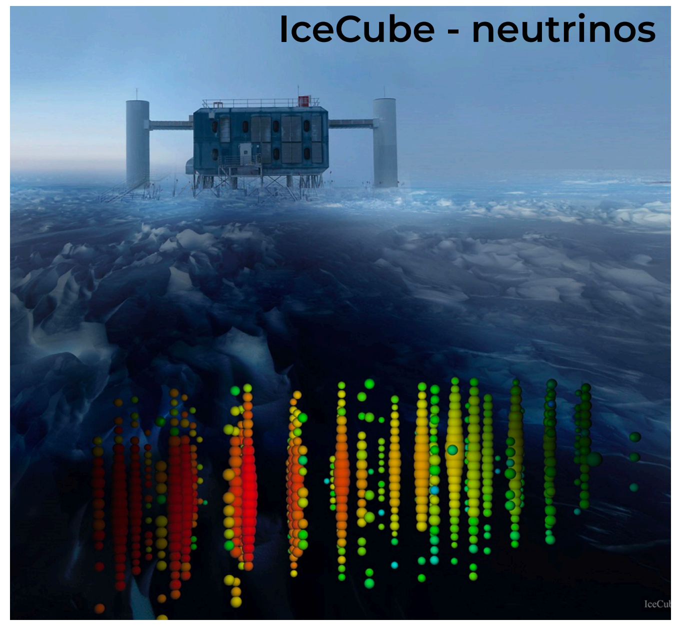
Large Hadron Collider - CERN

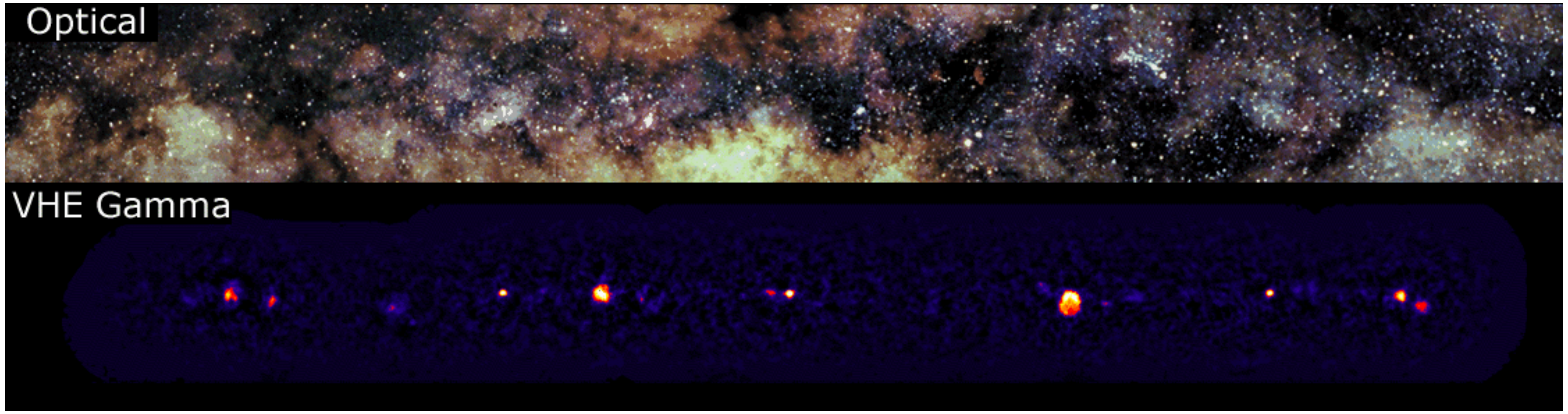
Where do Cosmic Rays come from?







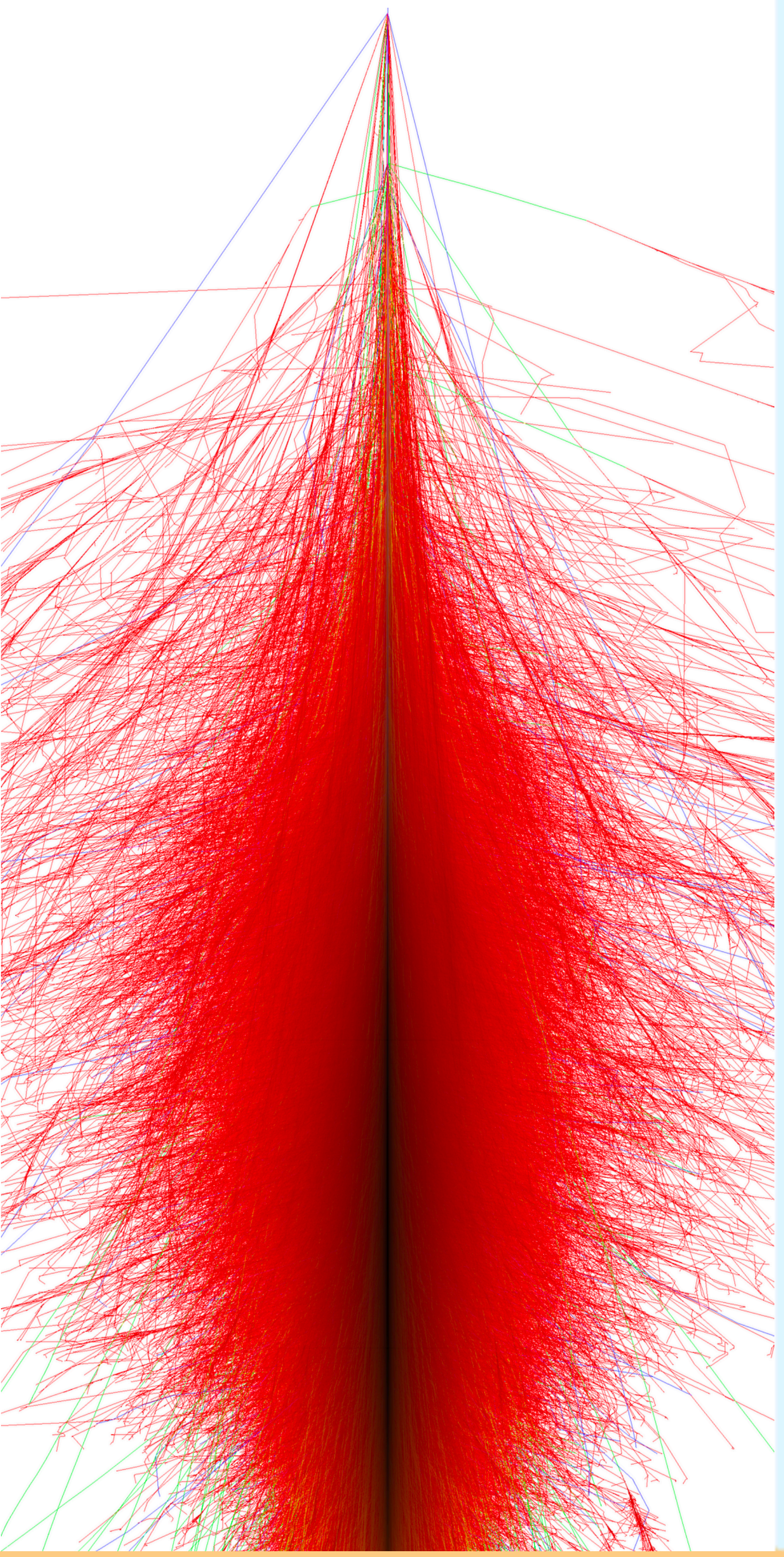


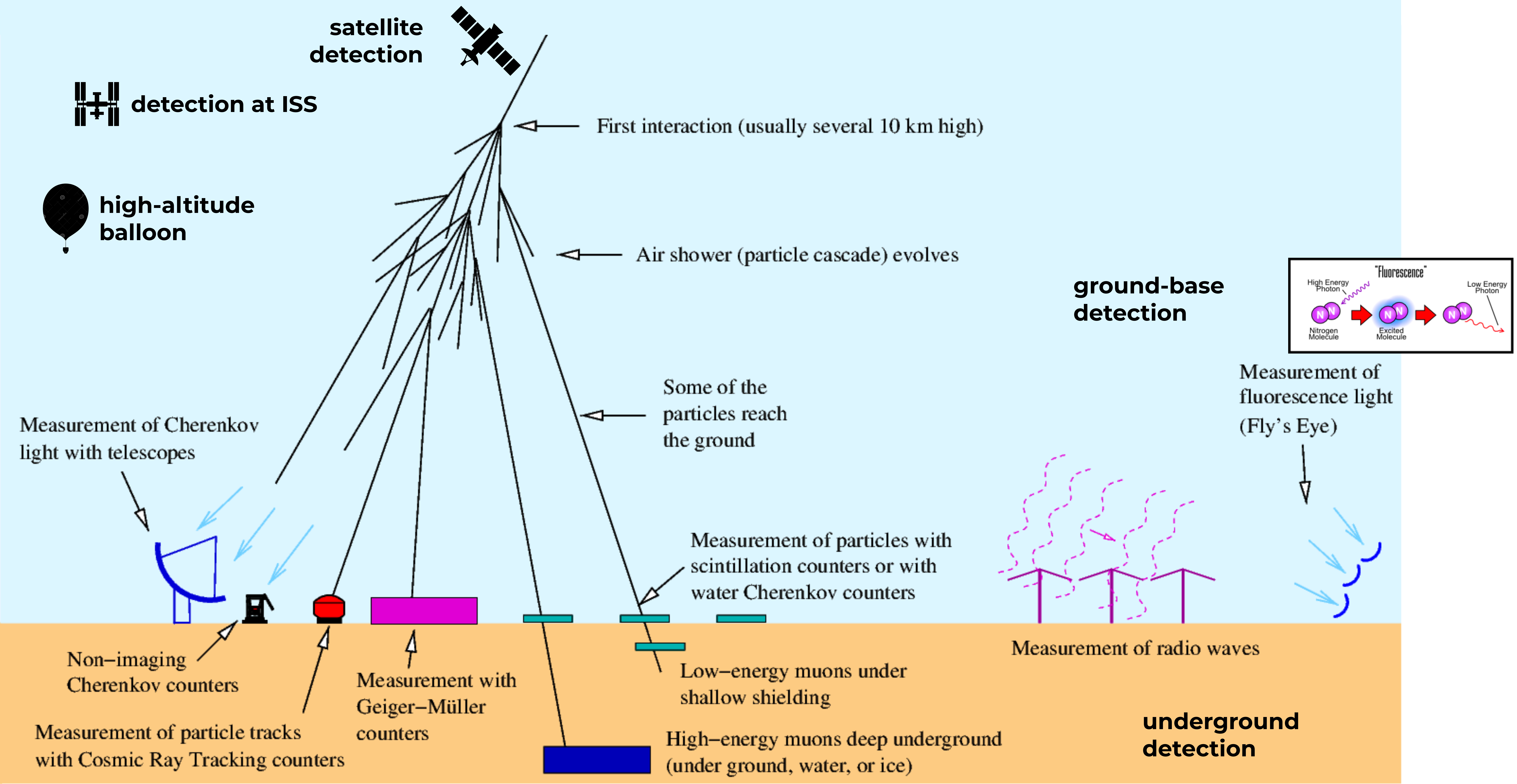


gamma ray sources to pinpoint where **cosmic rays** are accelerated
hadronic cosmic ray sources must emit **neutrinos** as well

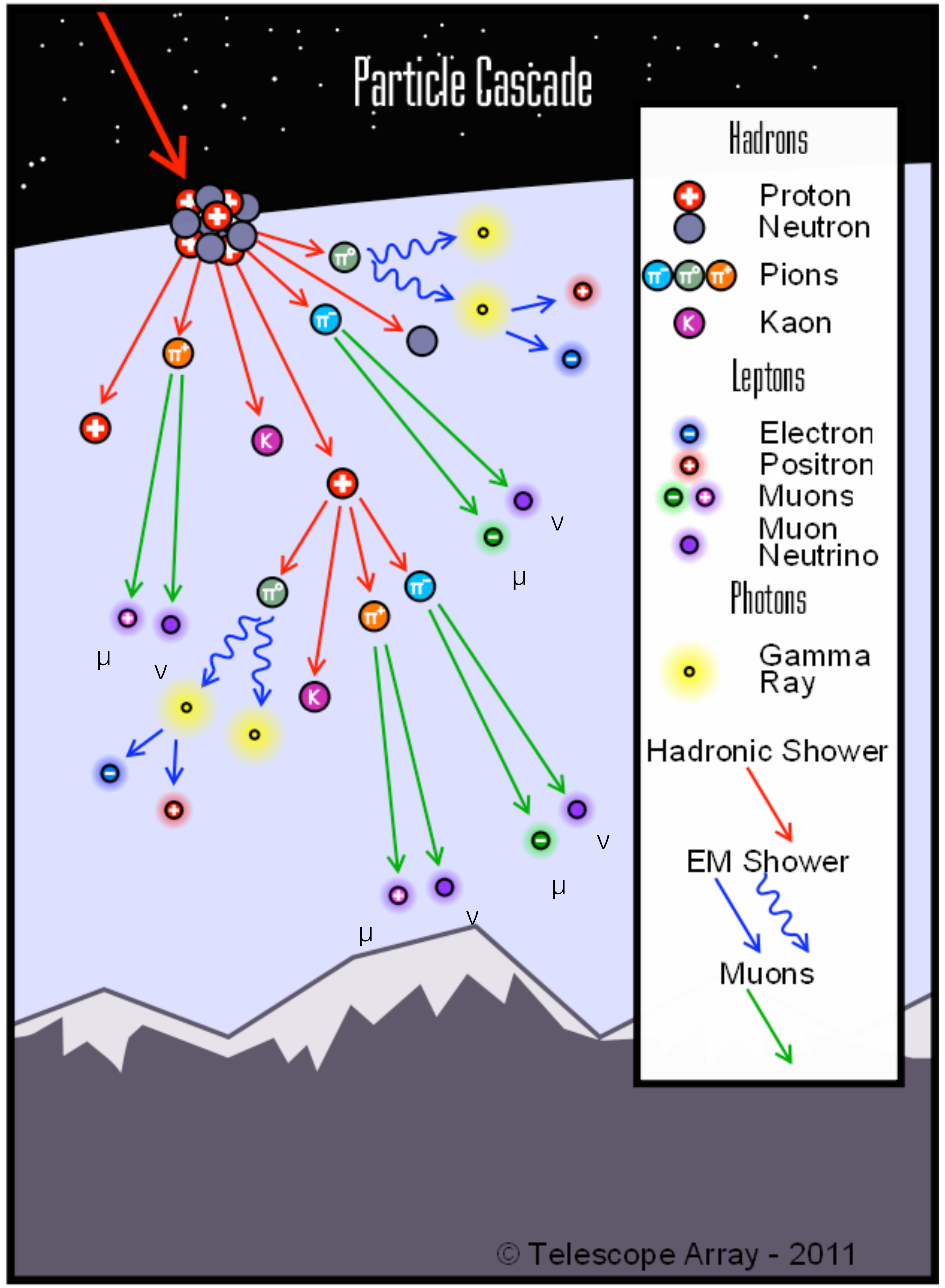
multi-messenger astronomy

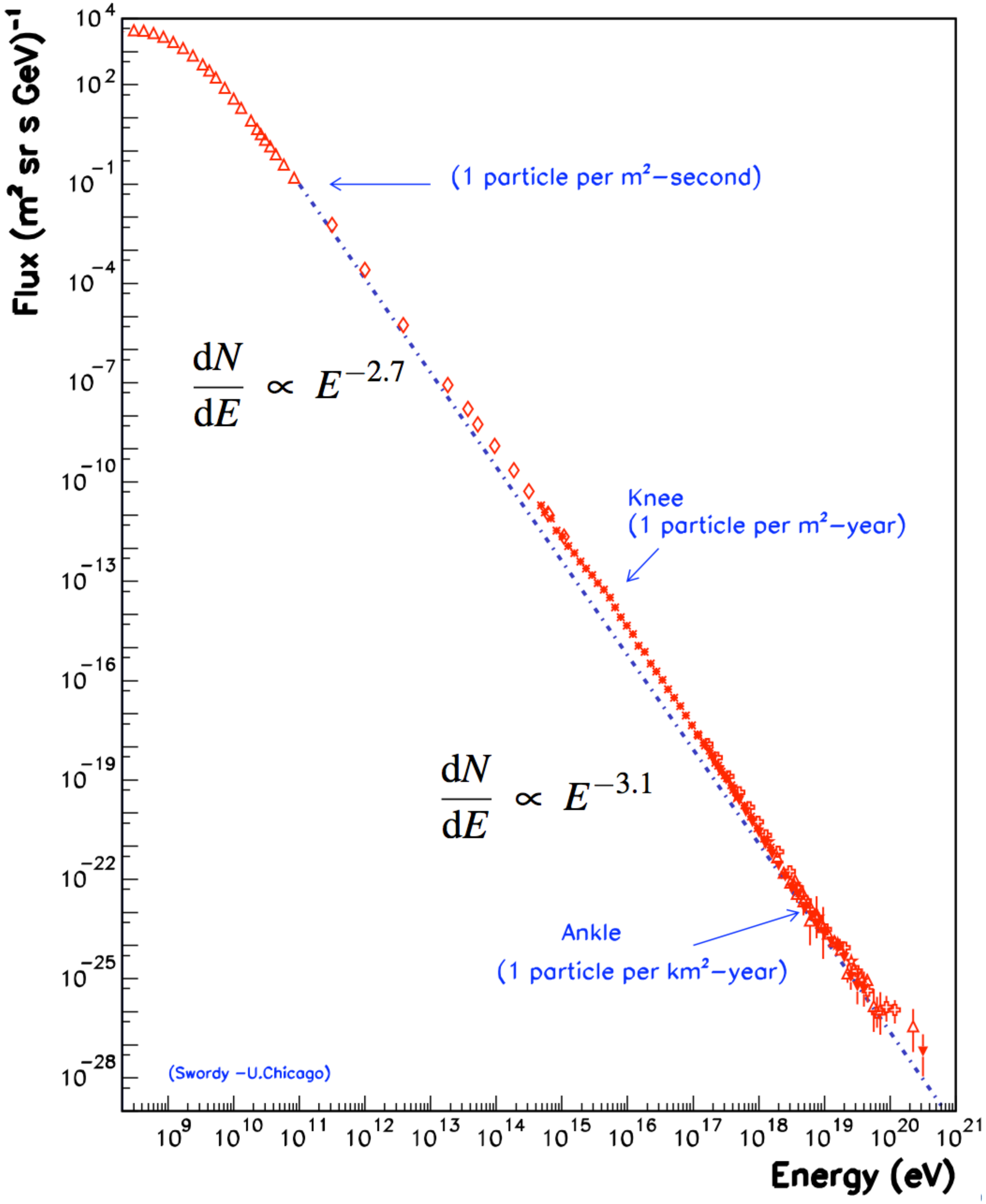
How do we detect Cosmic Rays?



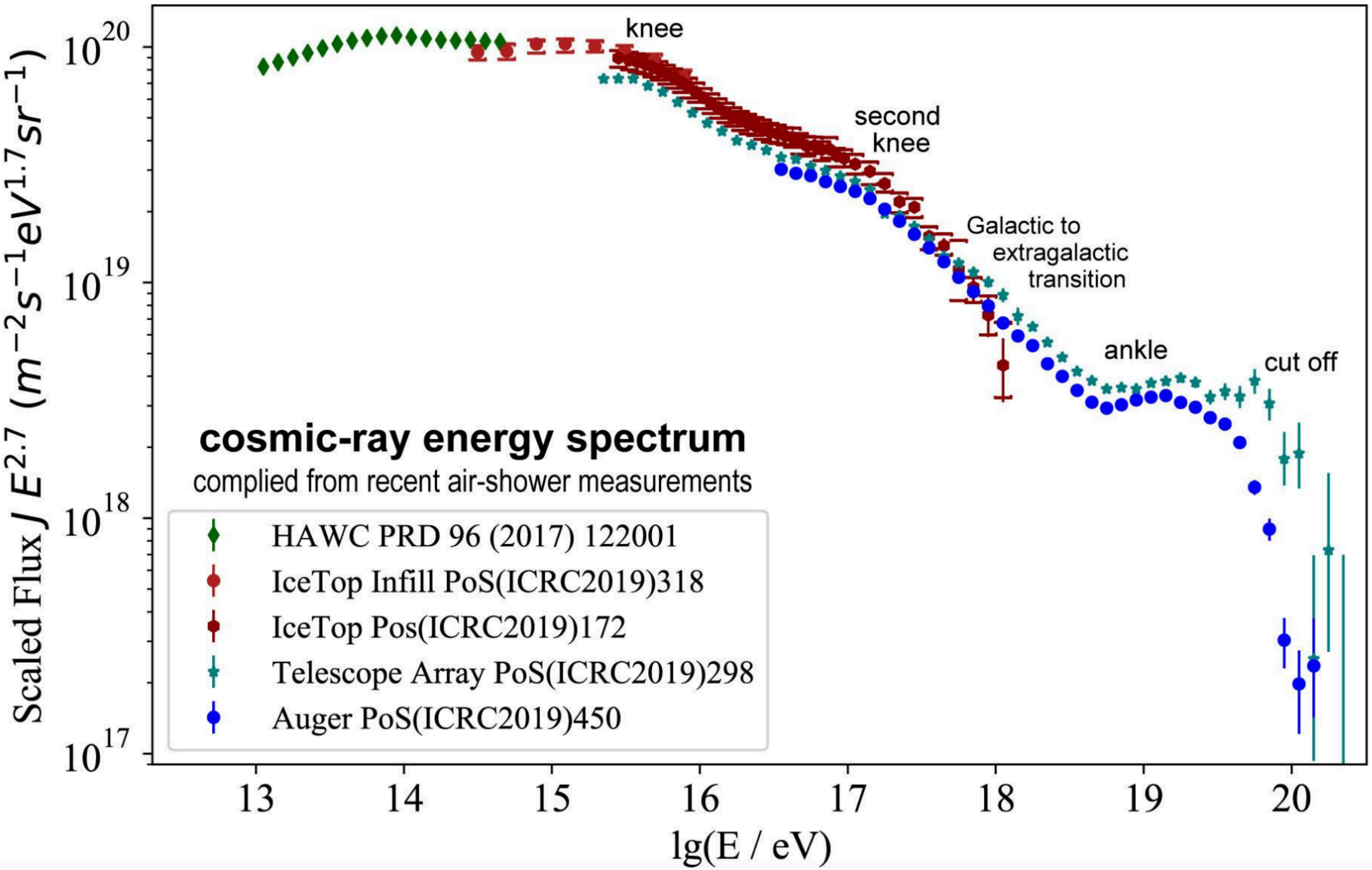


Cosmic Ray Energy Spectrum





Cosmic Ray Energy Spectrum



Frank Schröder

Cosmic Ray Energy Spectrum
direct vs indirect observations

direct detection of cosmic rays

small instrumentation at high-altitude or in orbit

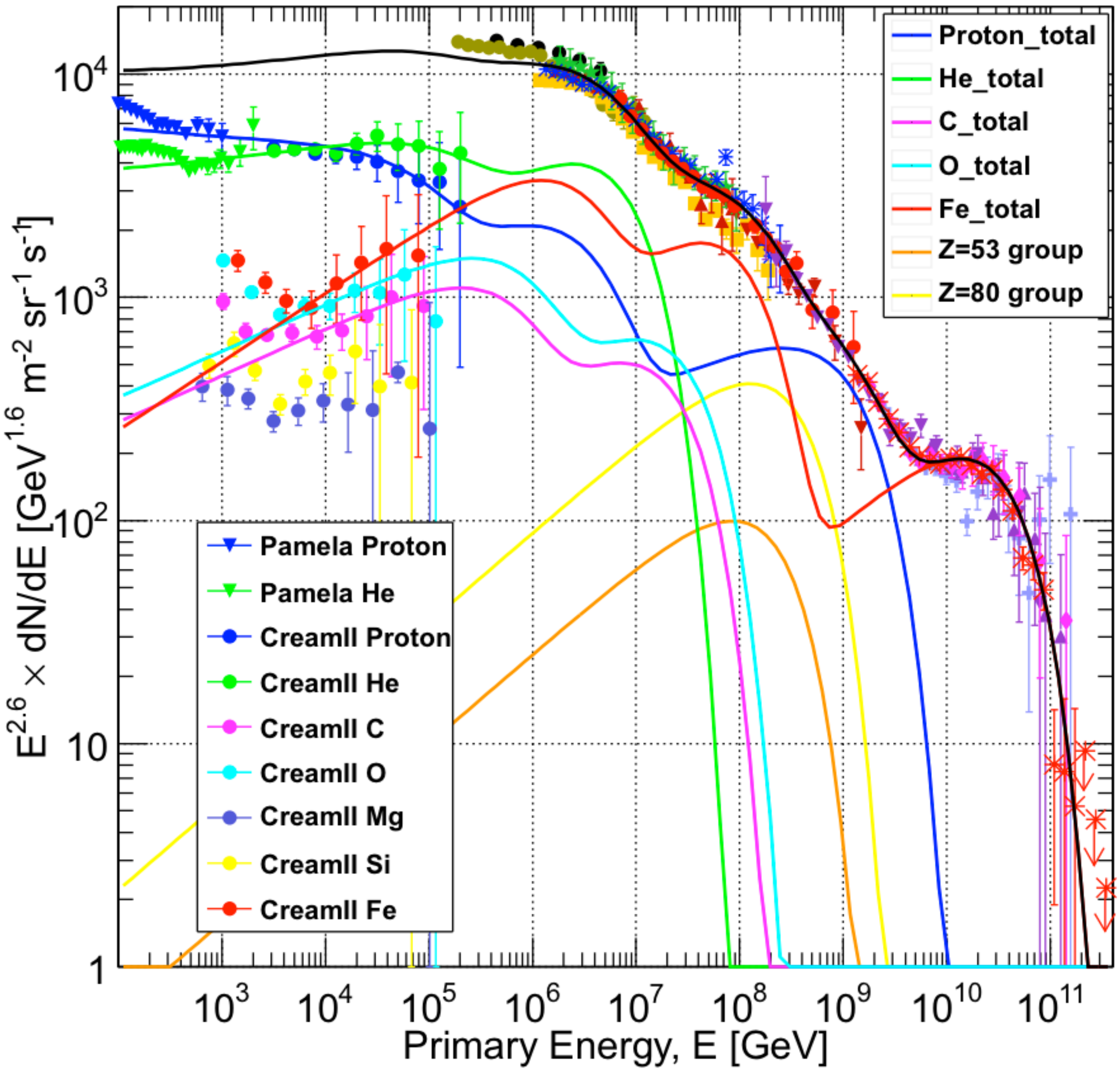
easy particle ID

indirect detection

large ground-based experiments

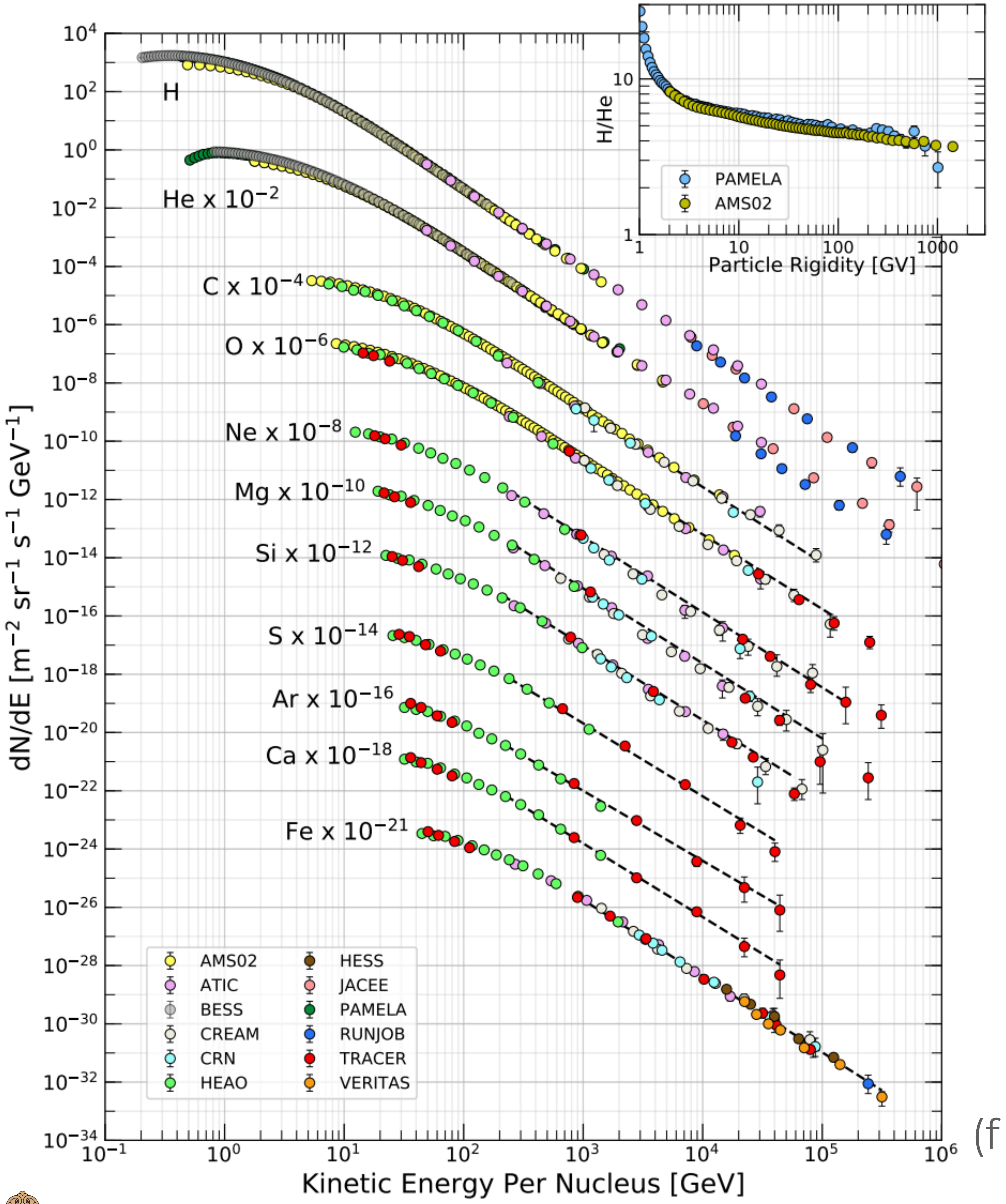
difficult particle ID (hadronic interactions)

Gaisser, Stanev, Tilav, 2013 - arXiv:1303.3565



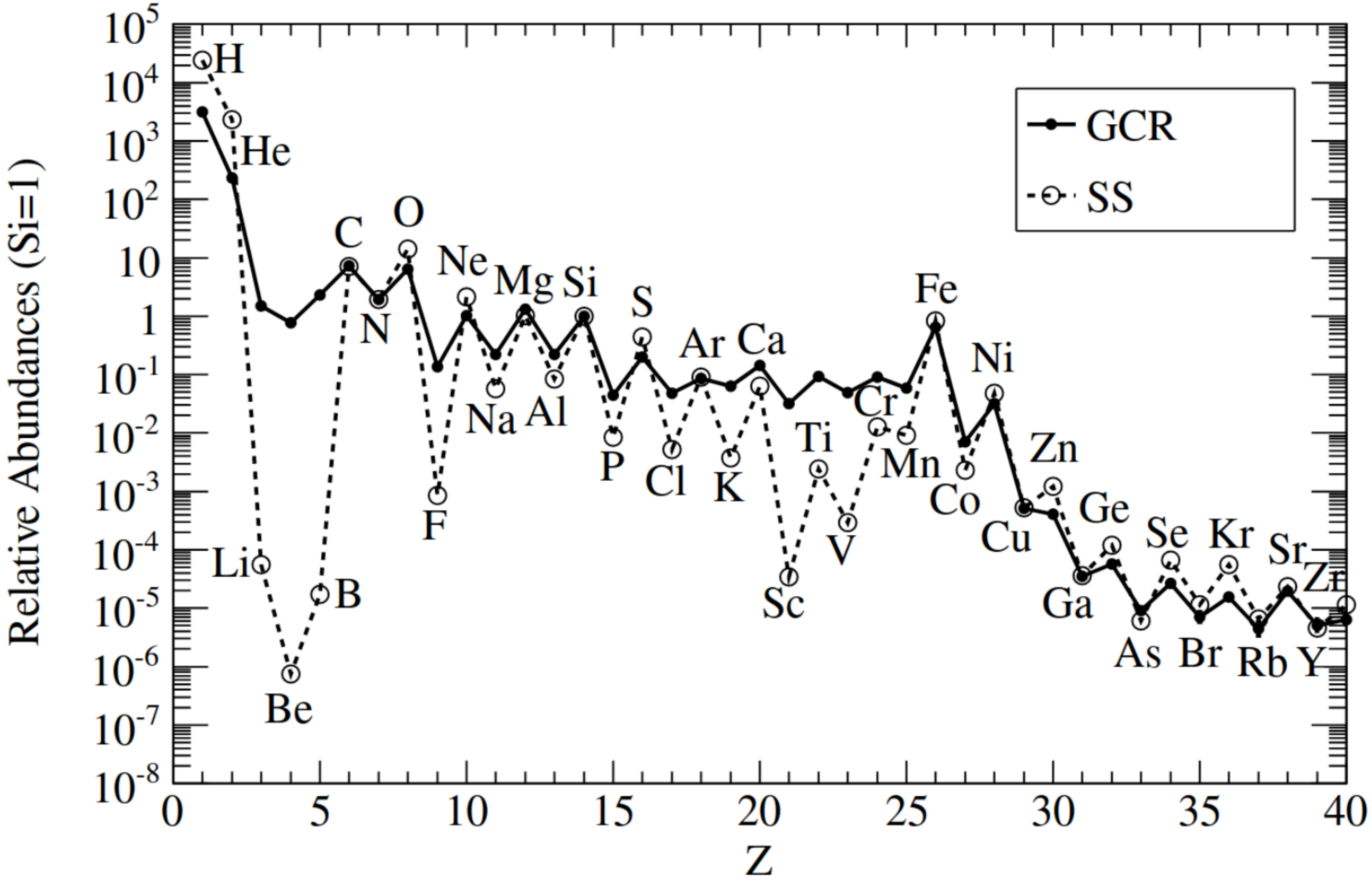
Cosmic Ray mass composition

direct observations

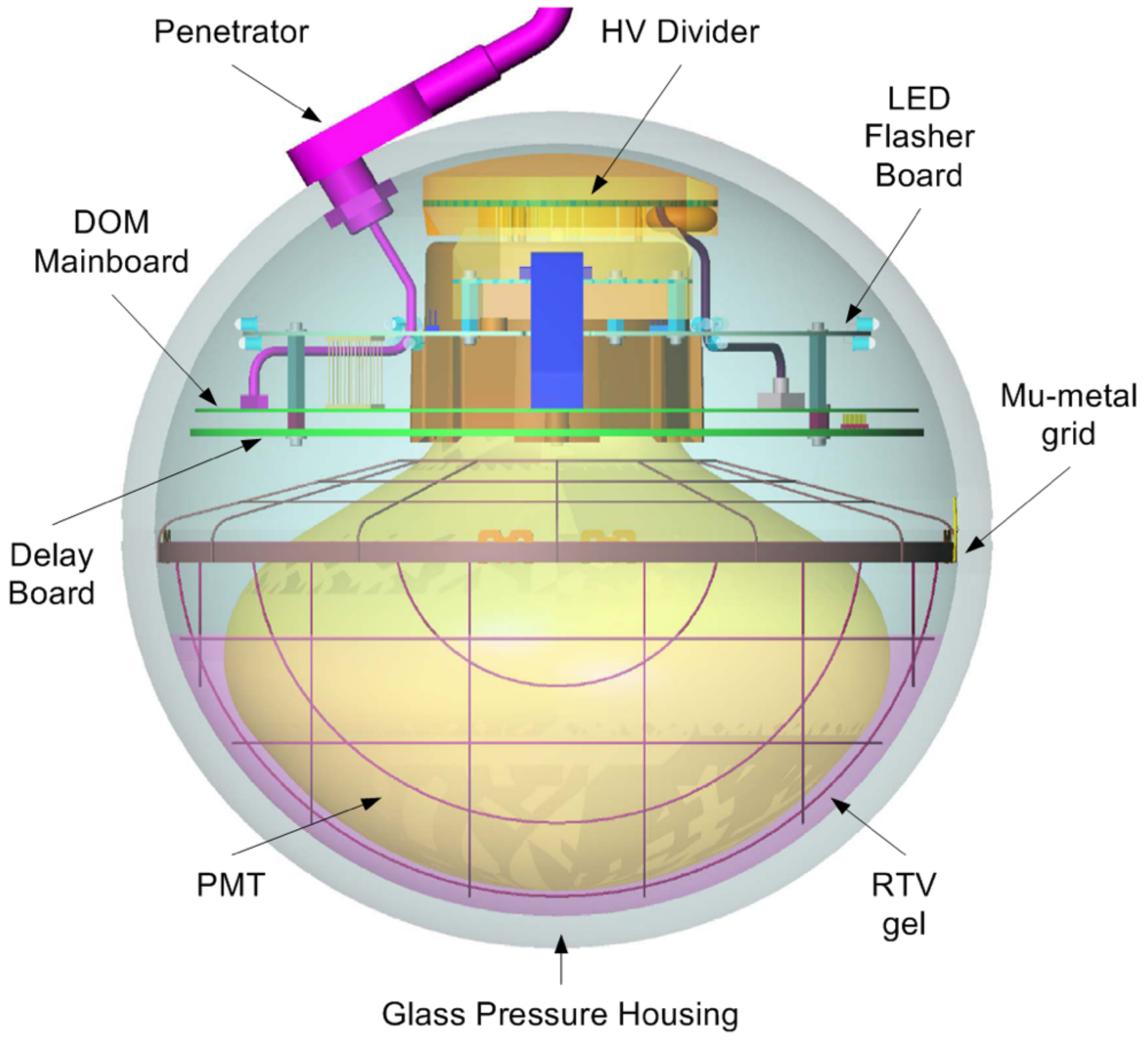


(from PDG)

PoS(ICRC2021)124

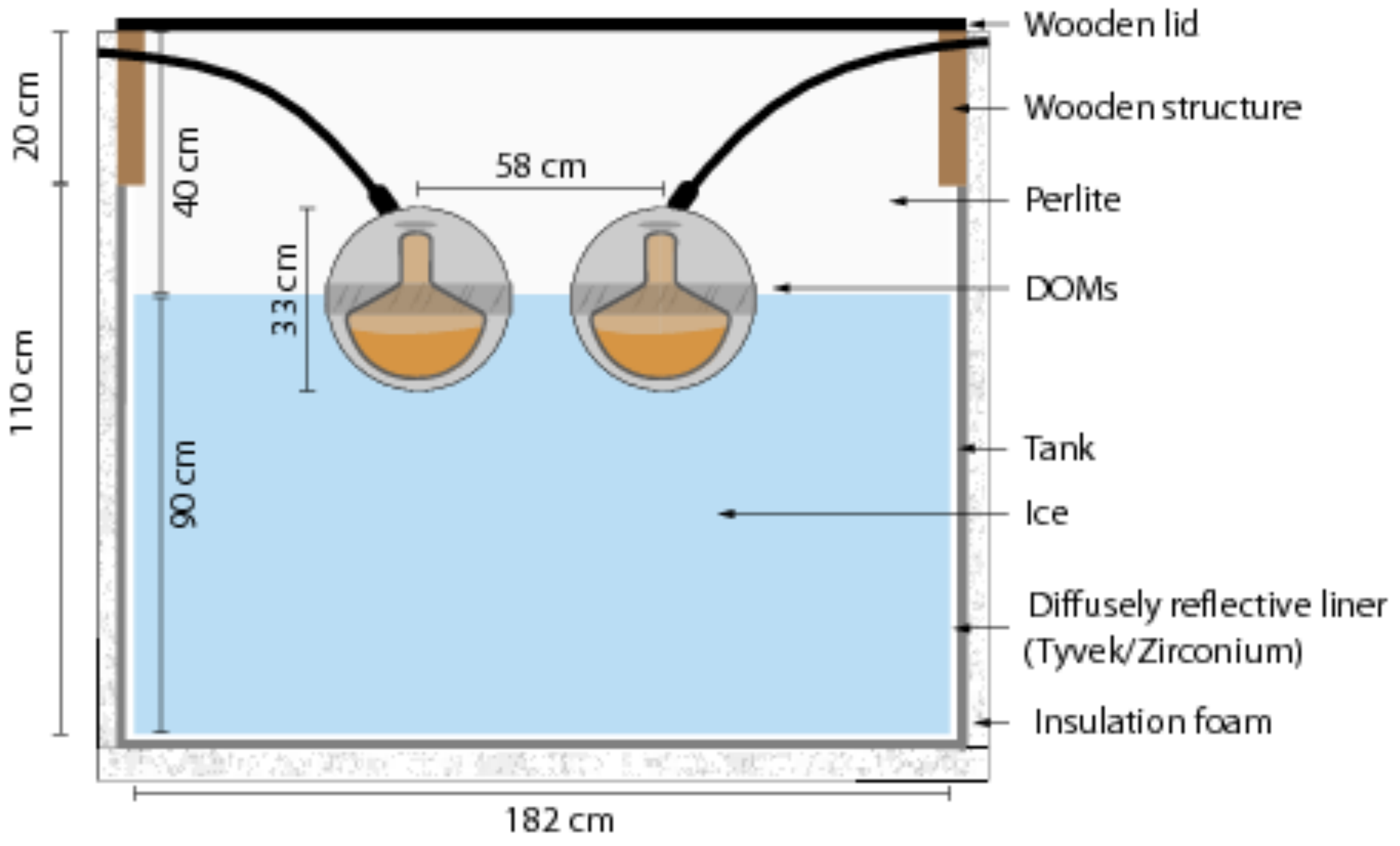


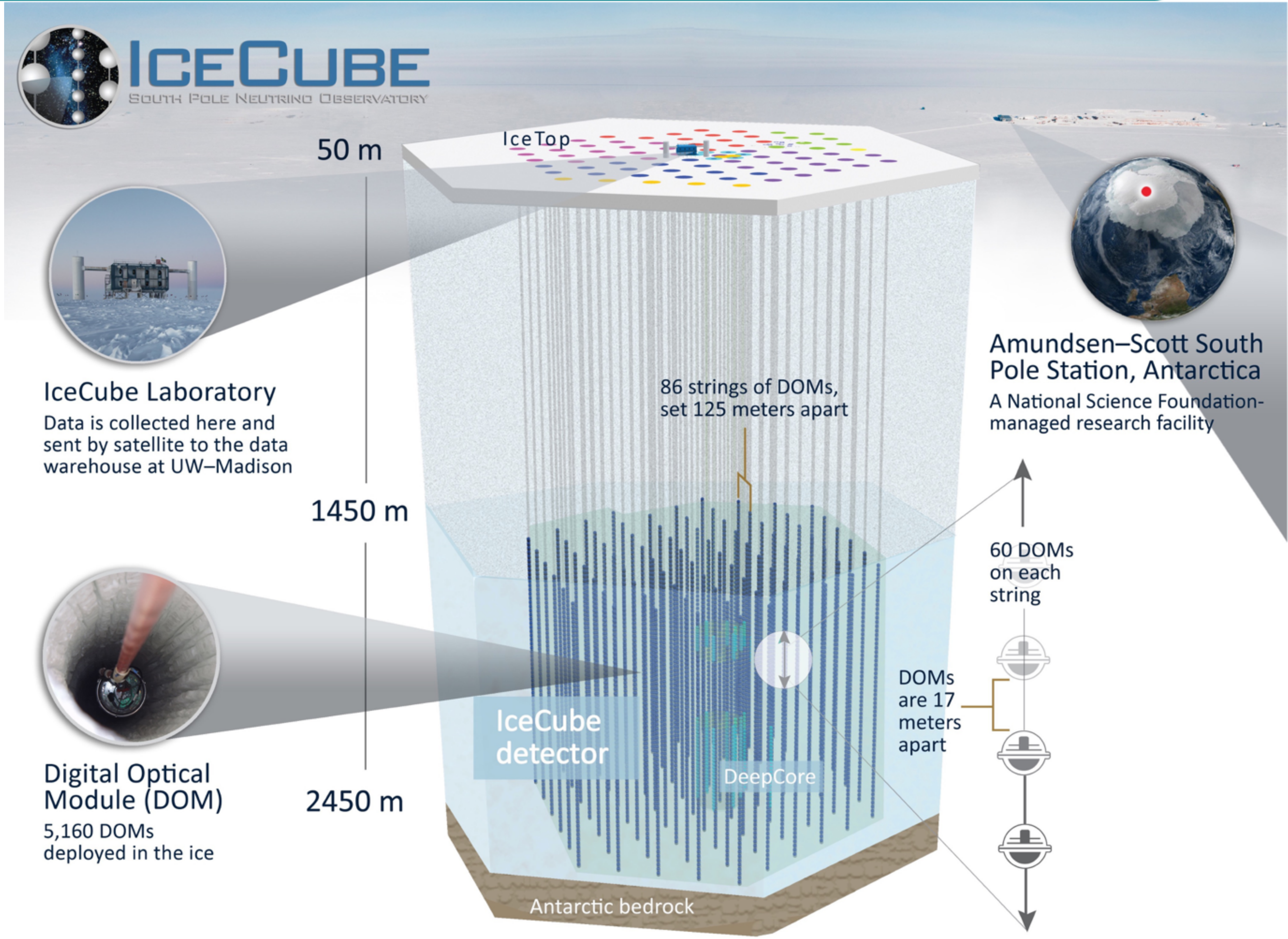
The IceCube Observatory
The Instrumentation



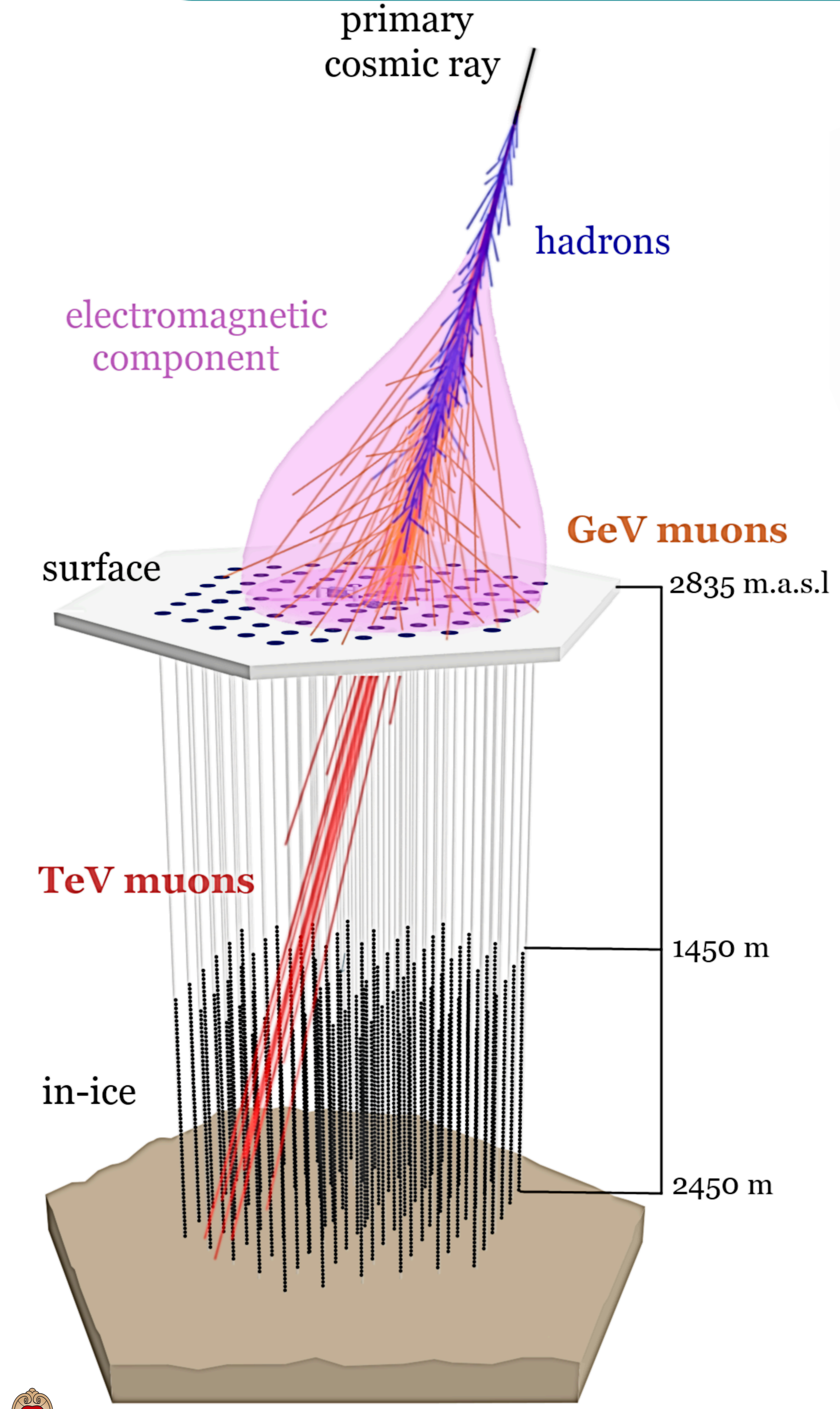
Digital Optical Module (DOM)

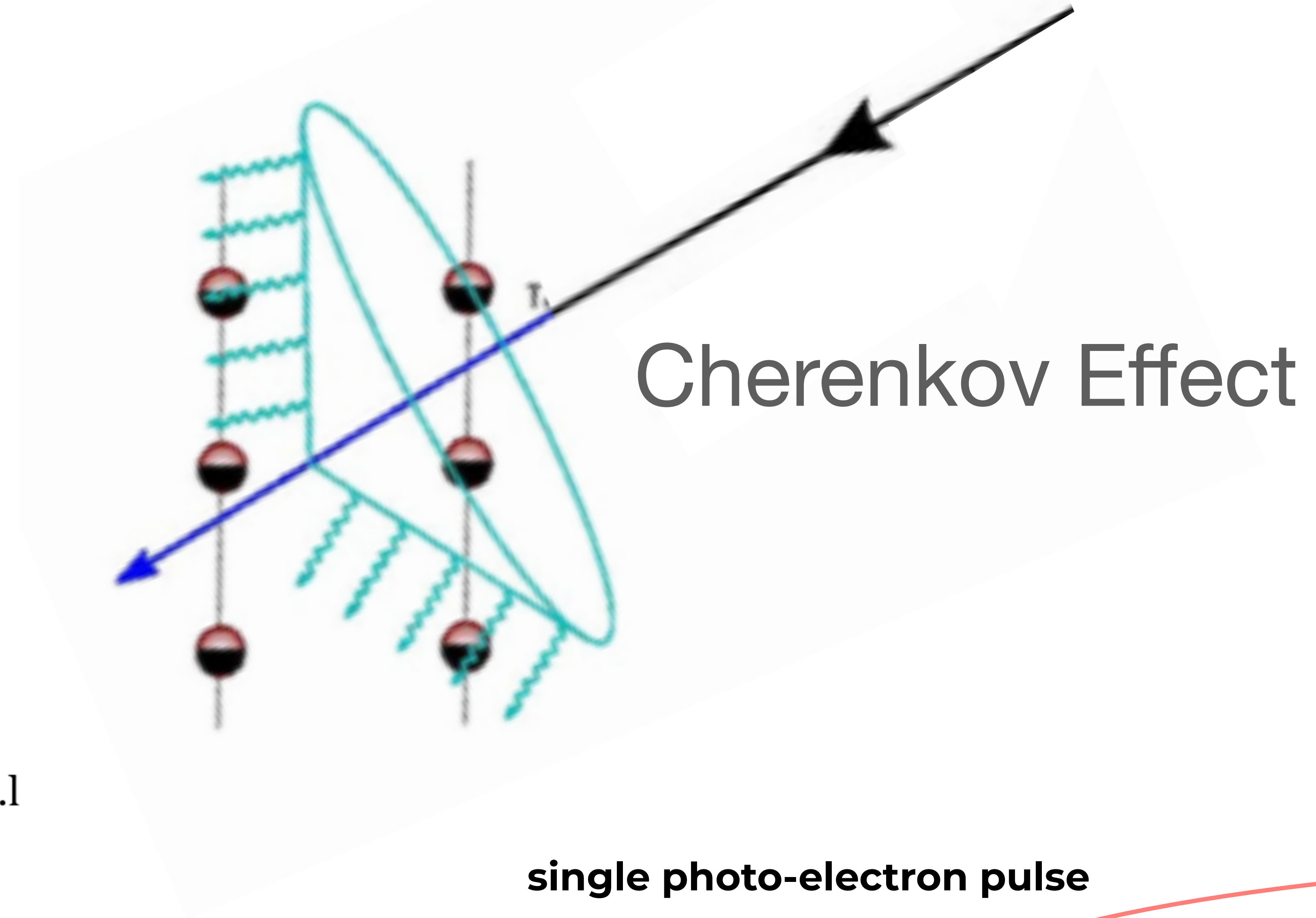
with 10” PMT
&
local DAQ electronics

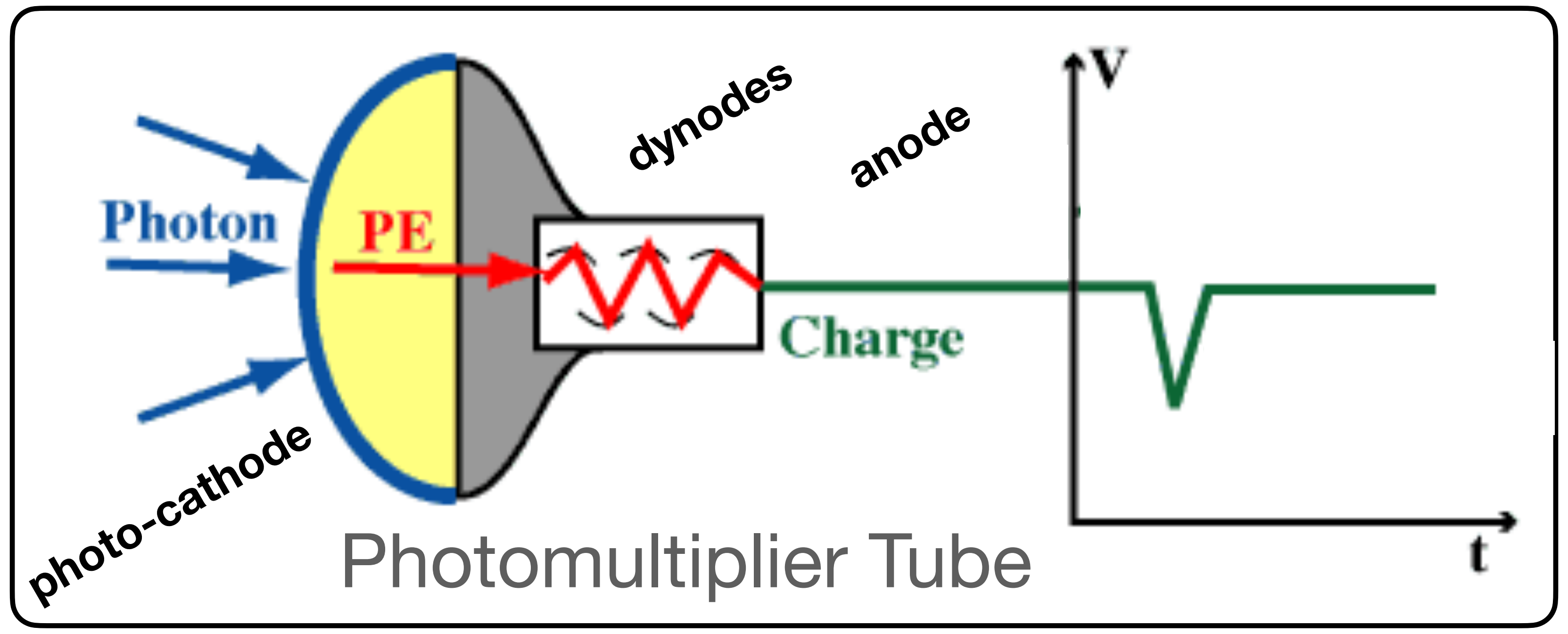


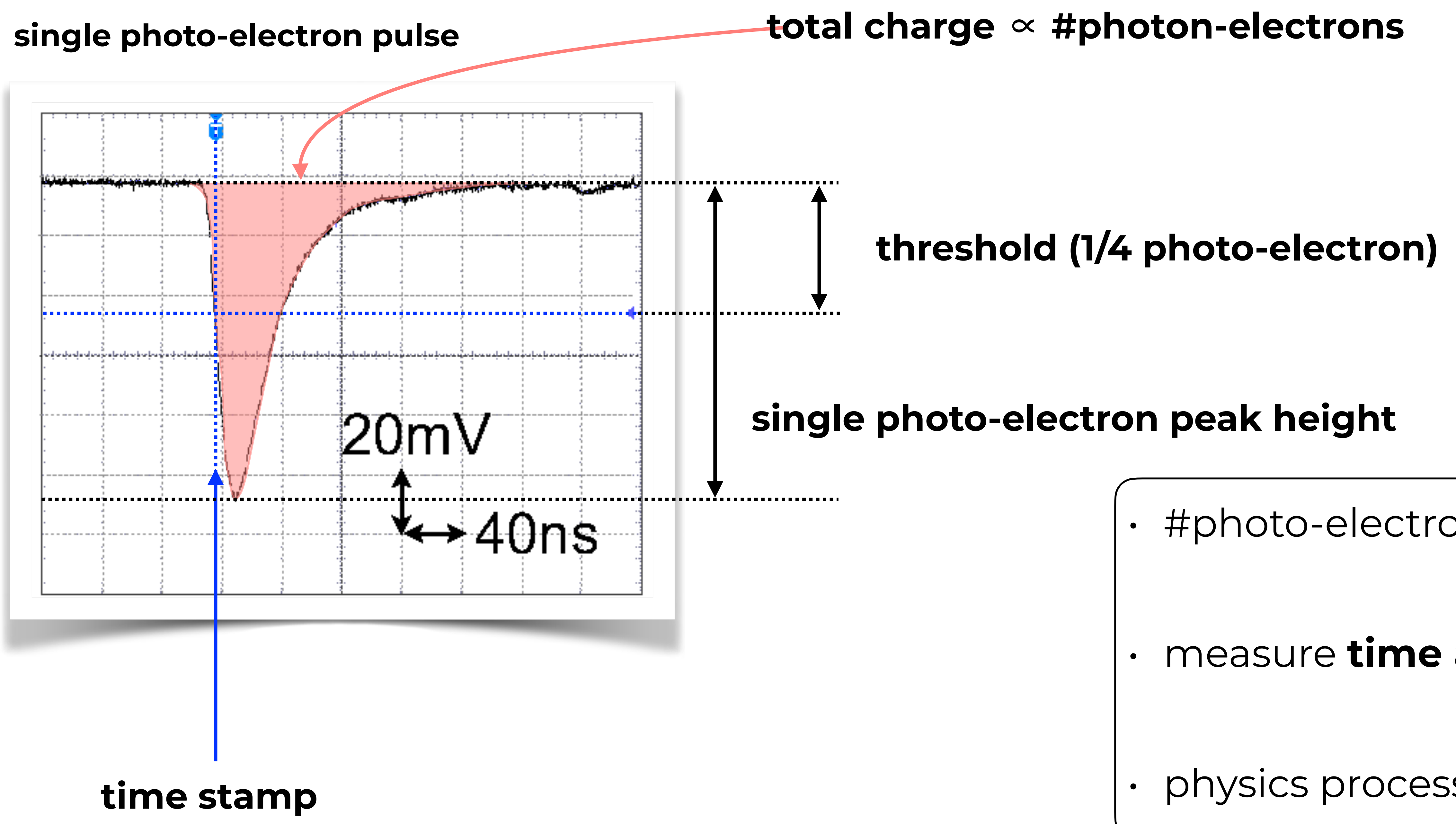


The IceCube Observatory
Detecting Cosmic Rays



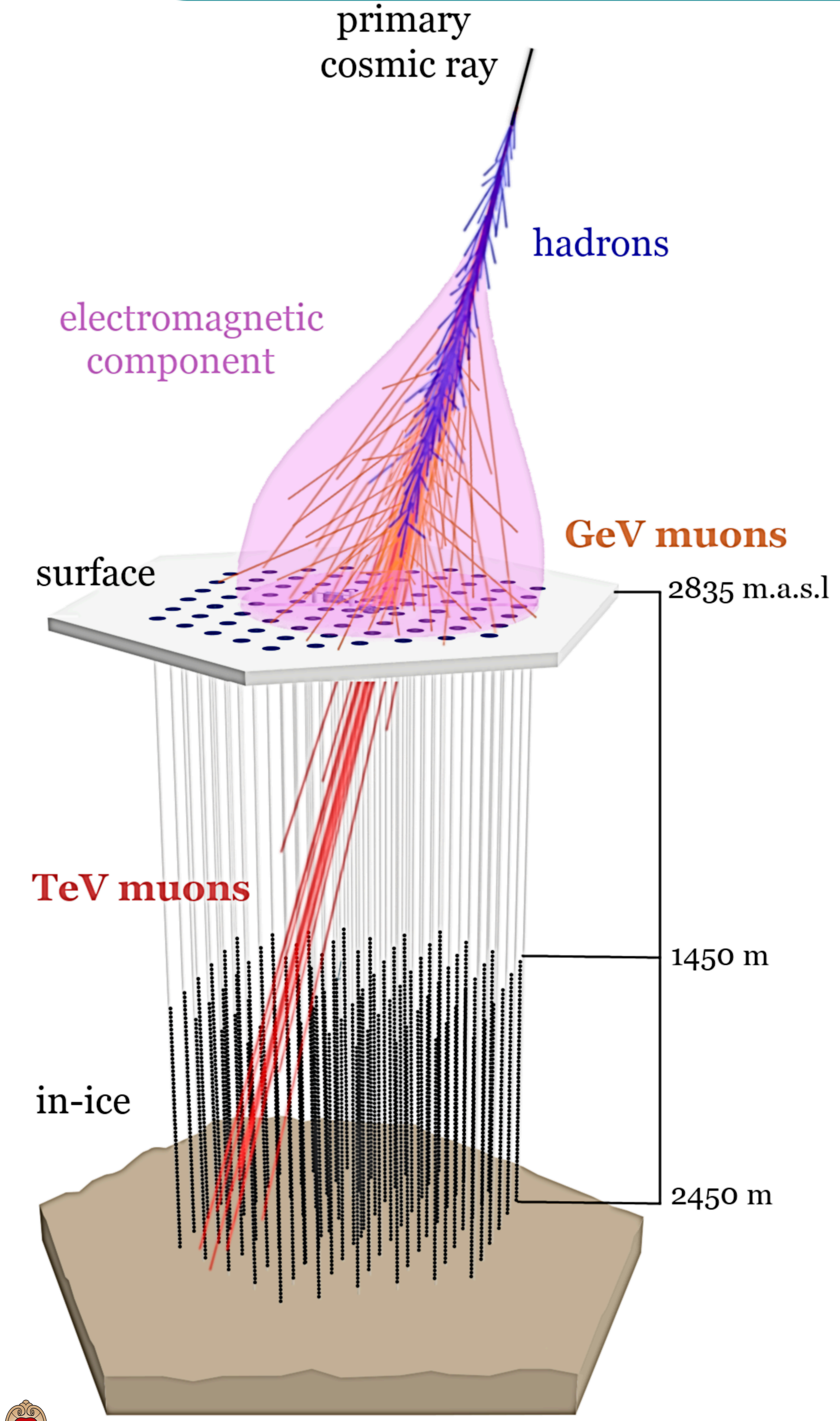


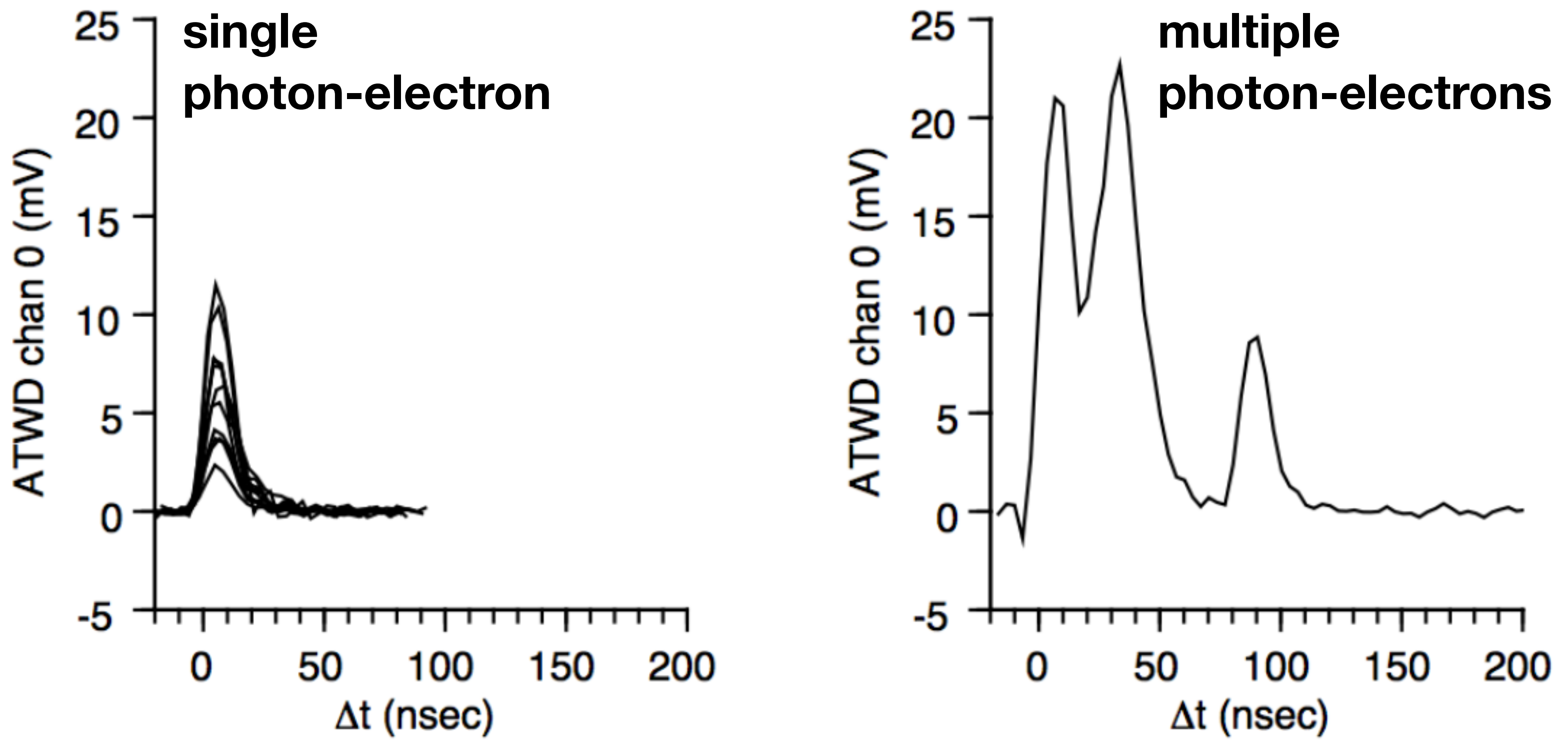




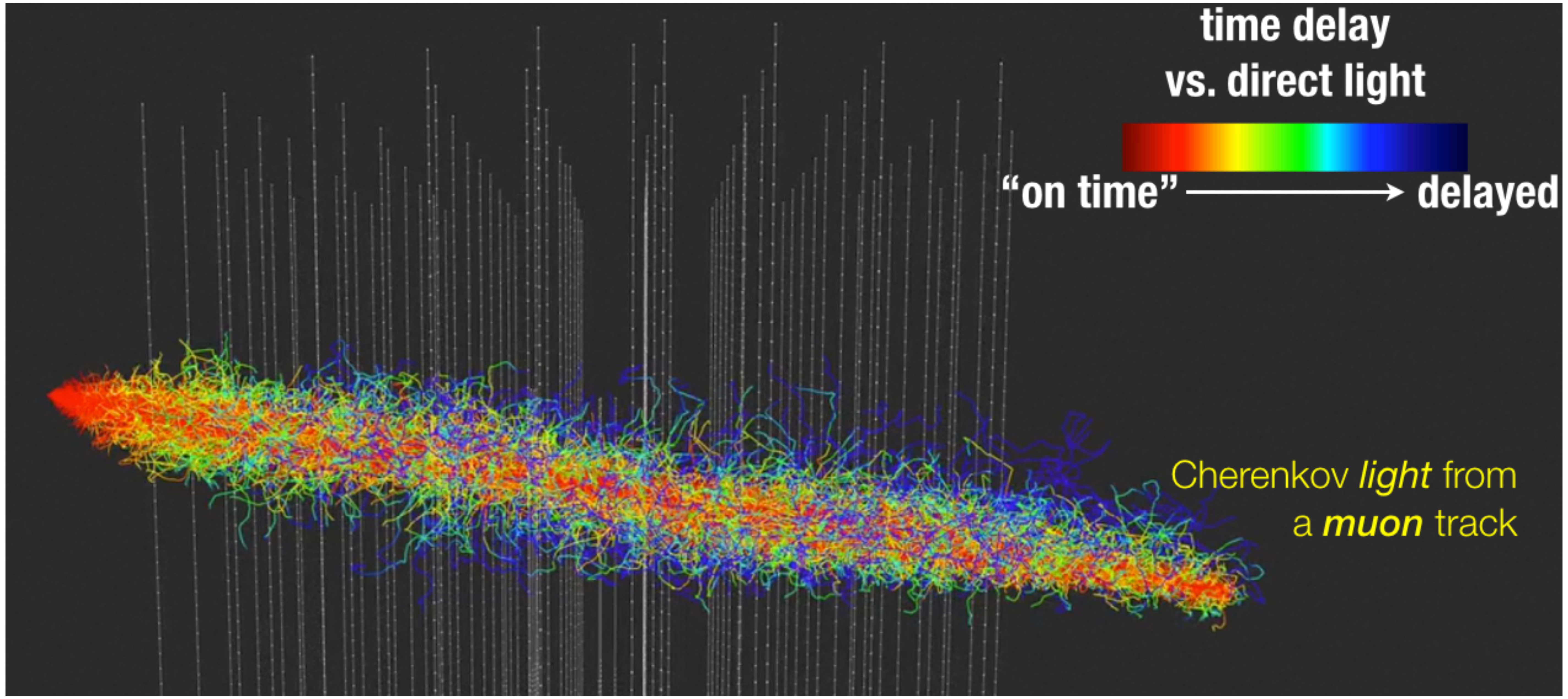
- #photo-electron = energy deposited × ε_{eff}
- measure **time** and **deposited energy**
- physics processes **shapes waveform**

The IceCube Observatory
Detecting Cosmic Rays

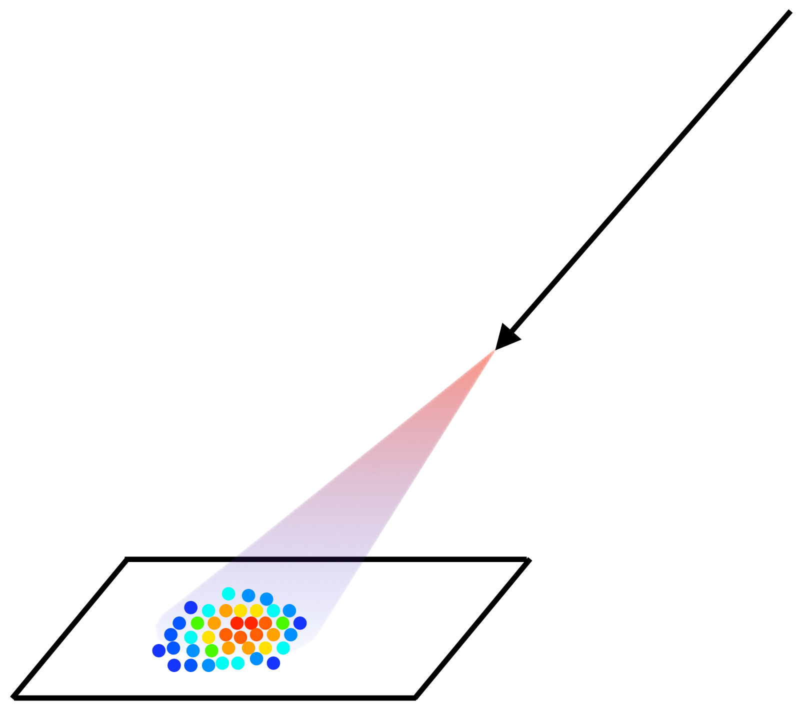


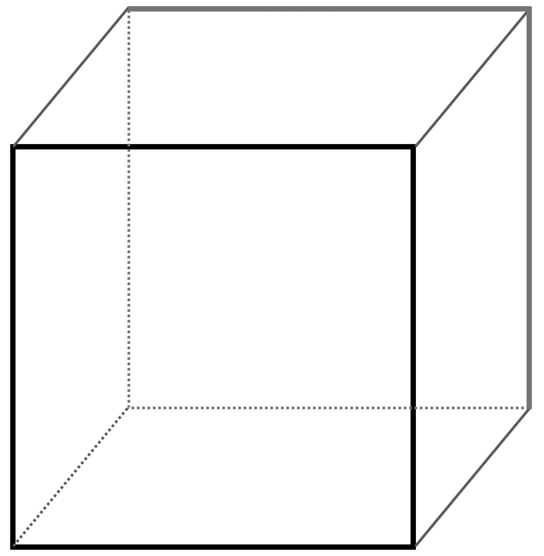


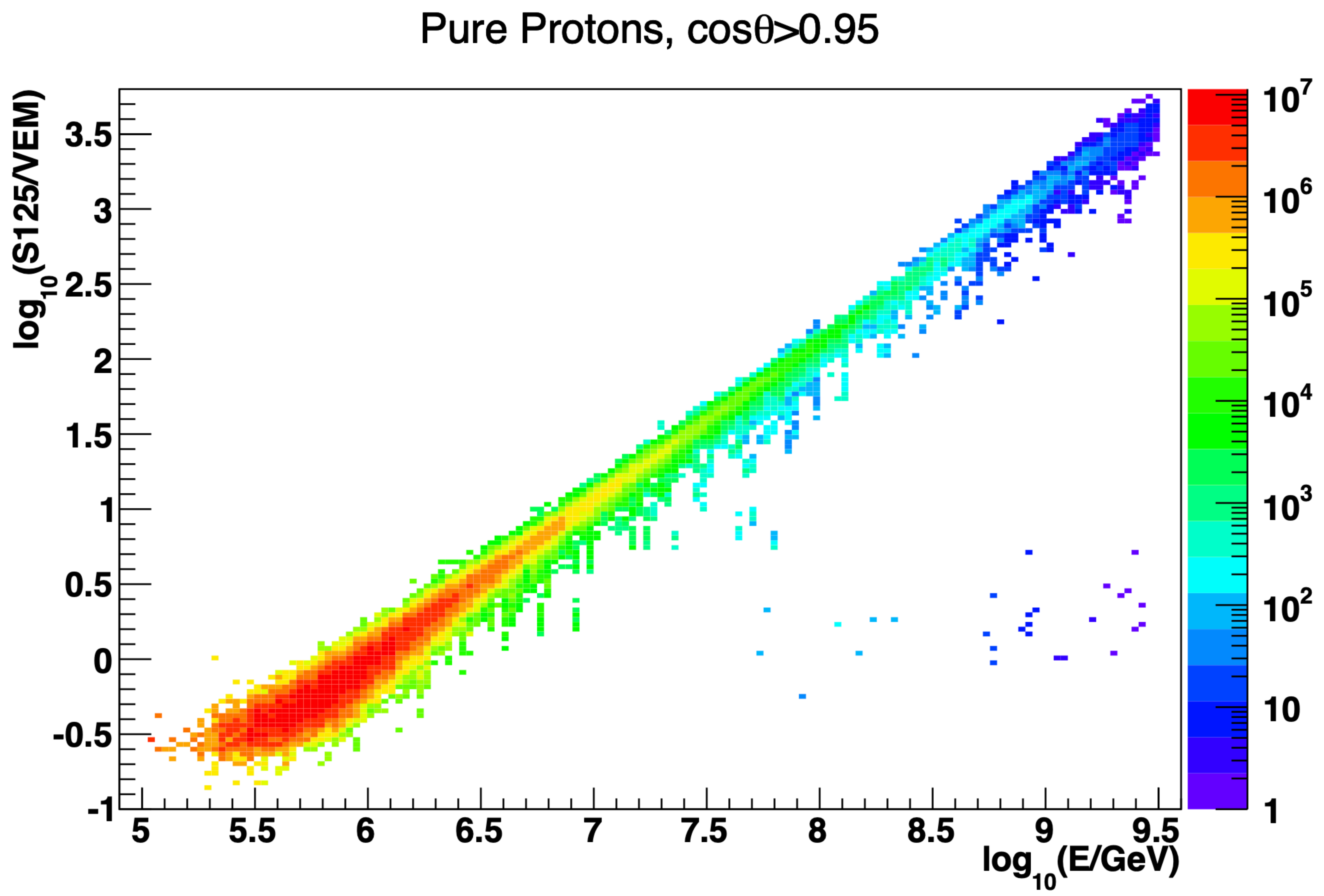
optical properties of glacial ice: **absorption** & **scattering**



Cosmic Rays with IceTop



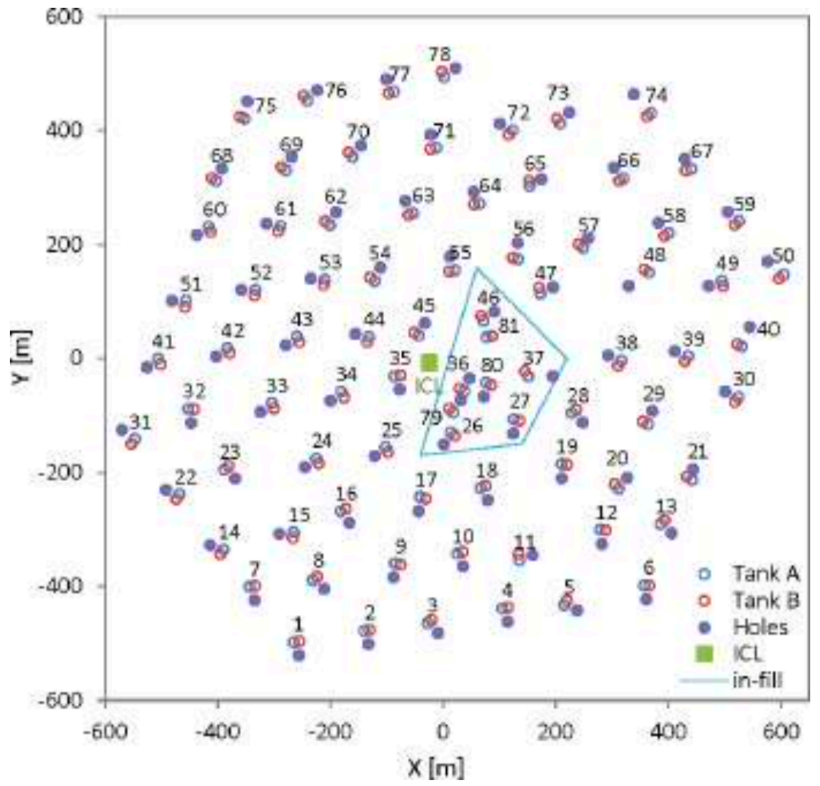


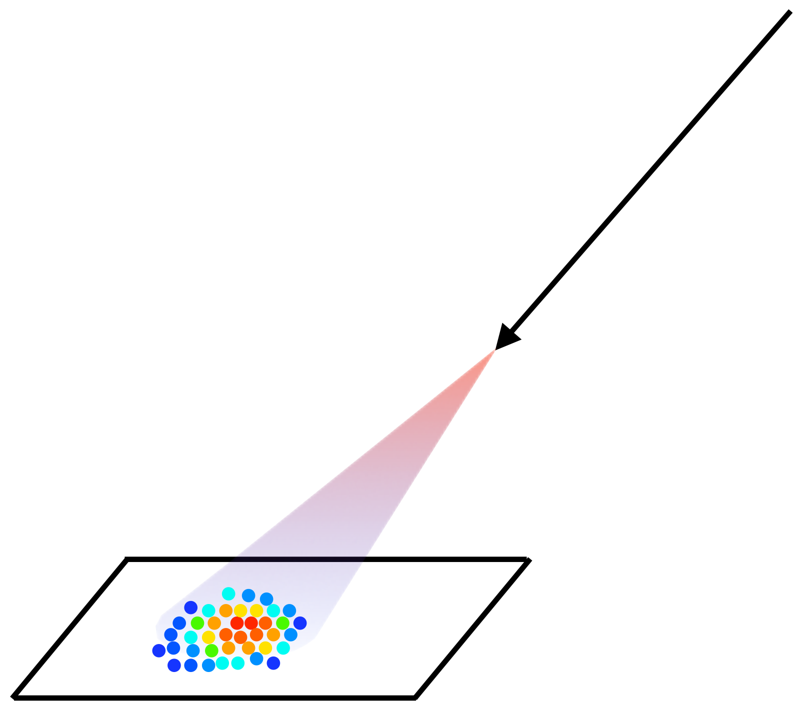


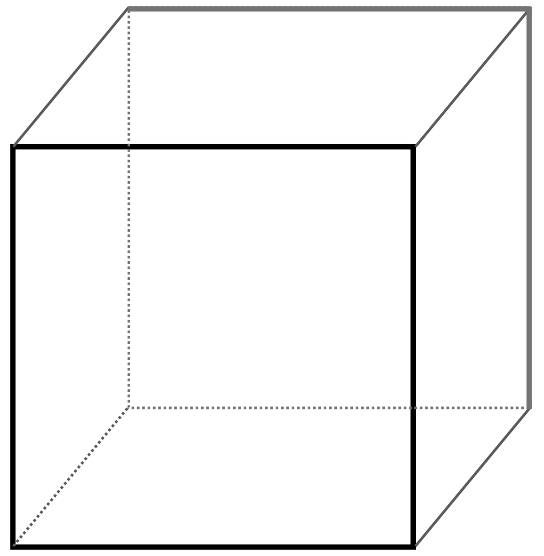
lateral distribution function

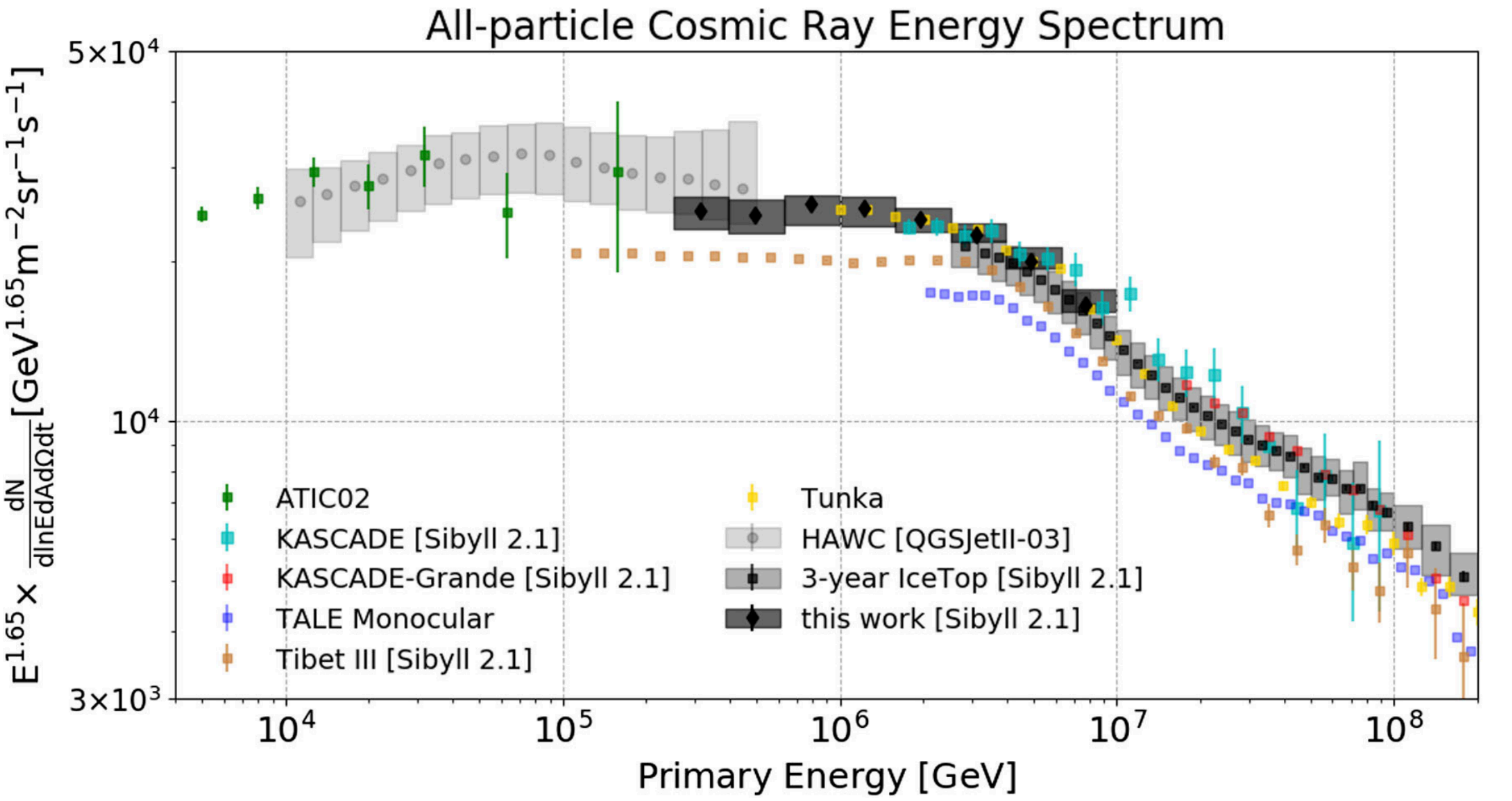
$$S(r)=S_{125}\cdot\left(\frac{r}{125\,\mathrm{m}}\right)^{-\beta-\kappa\cdot\log_{10}(r/125\,\mathrm{m})}$$

Cosmic Rays with IceTop
all-particle energy spectrum





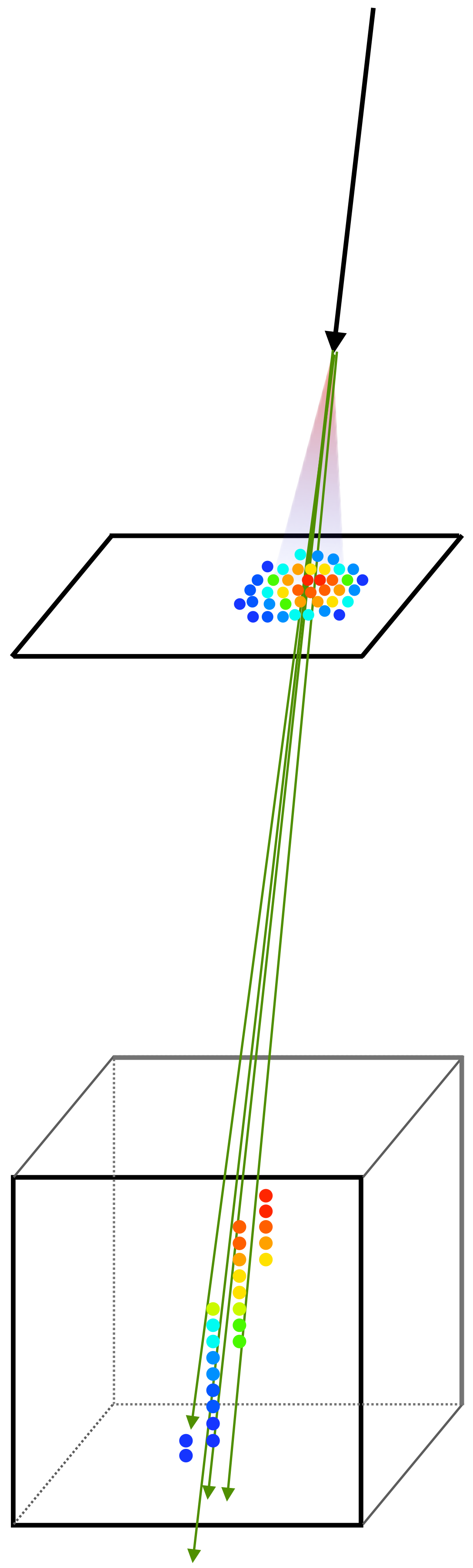


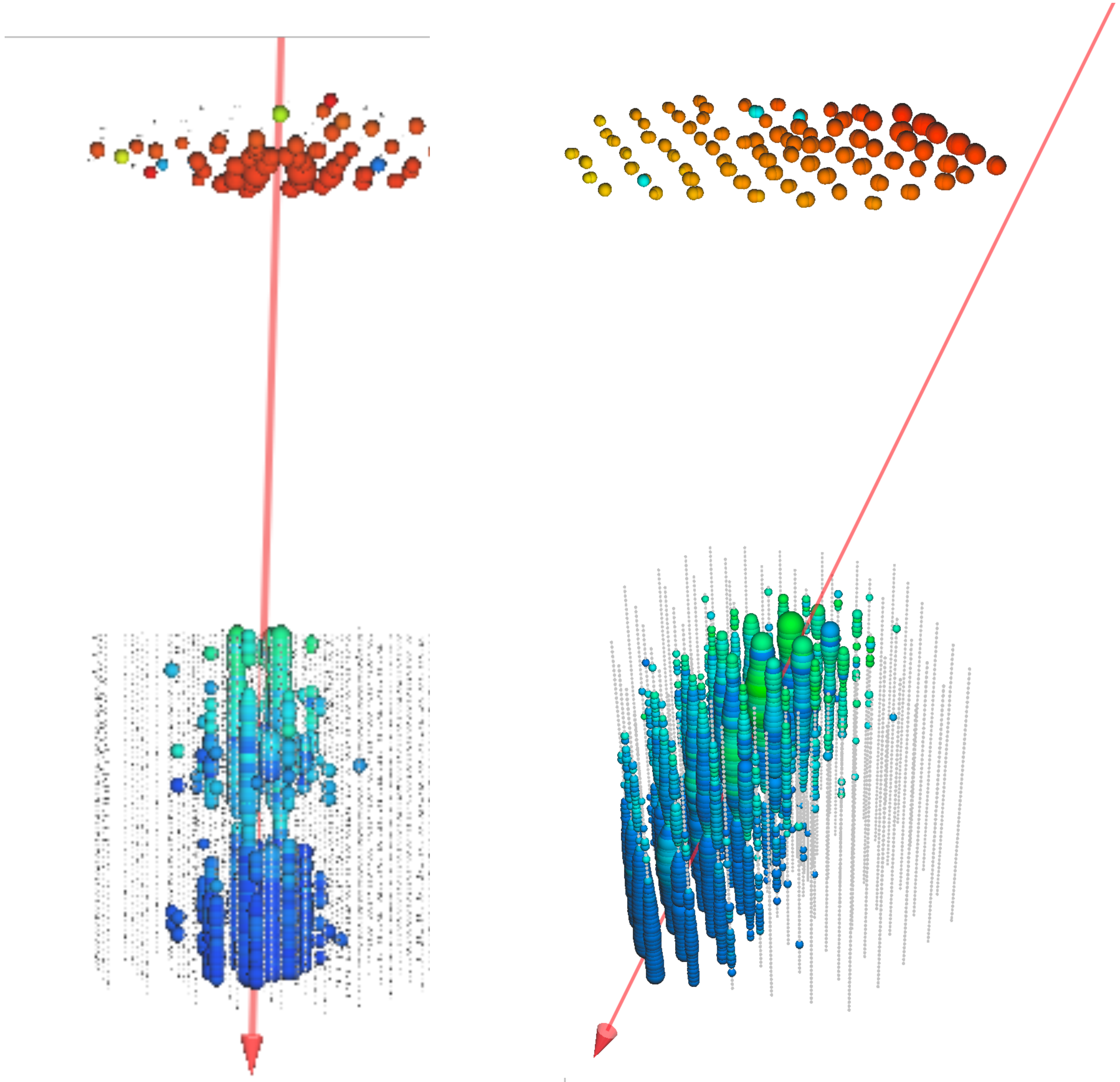


Cosmic Rays with IceTop & IceCube
elemental composition

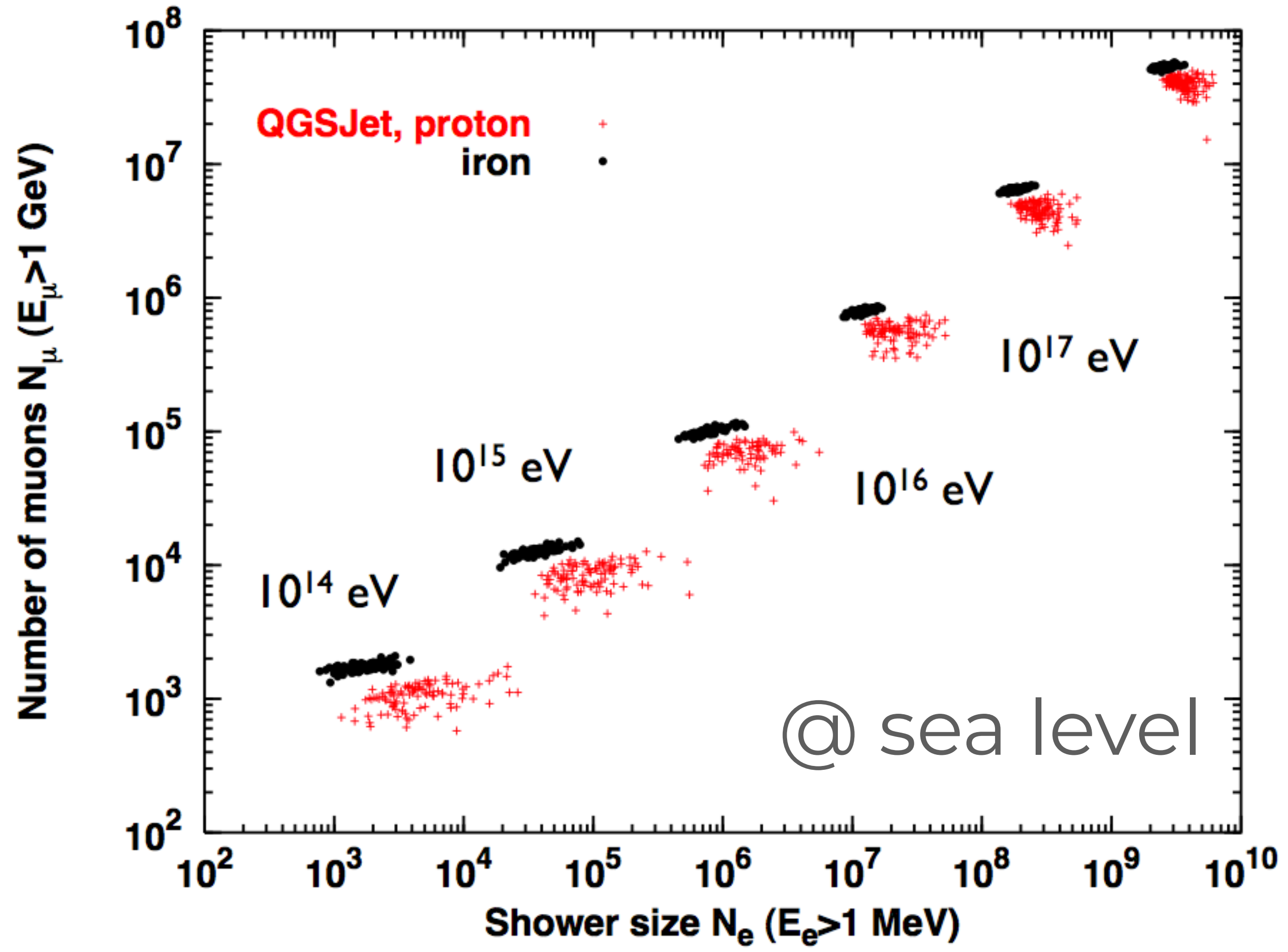
N_e

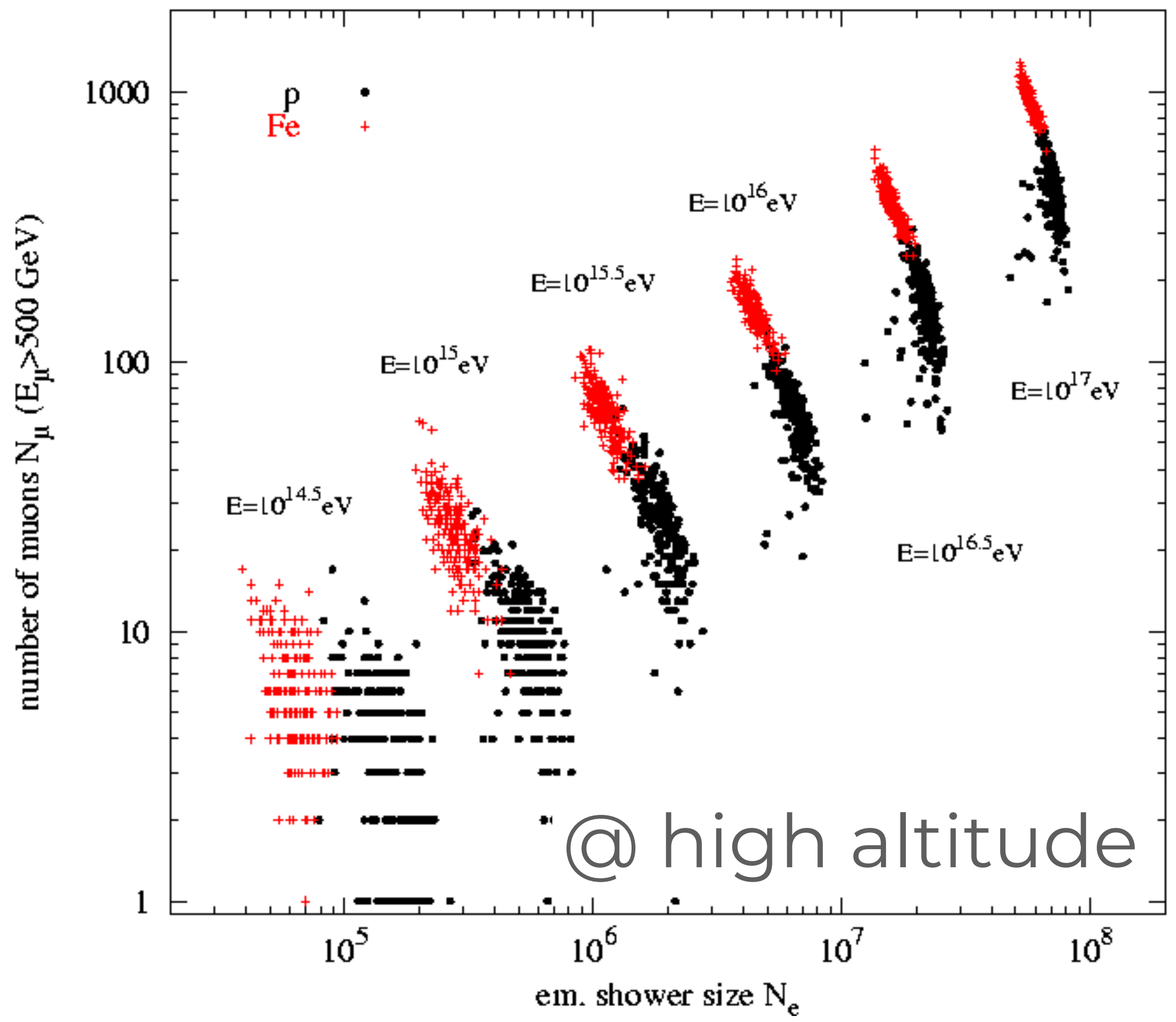
N_μ



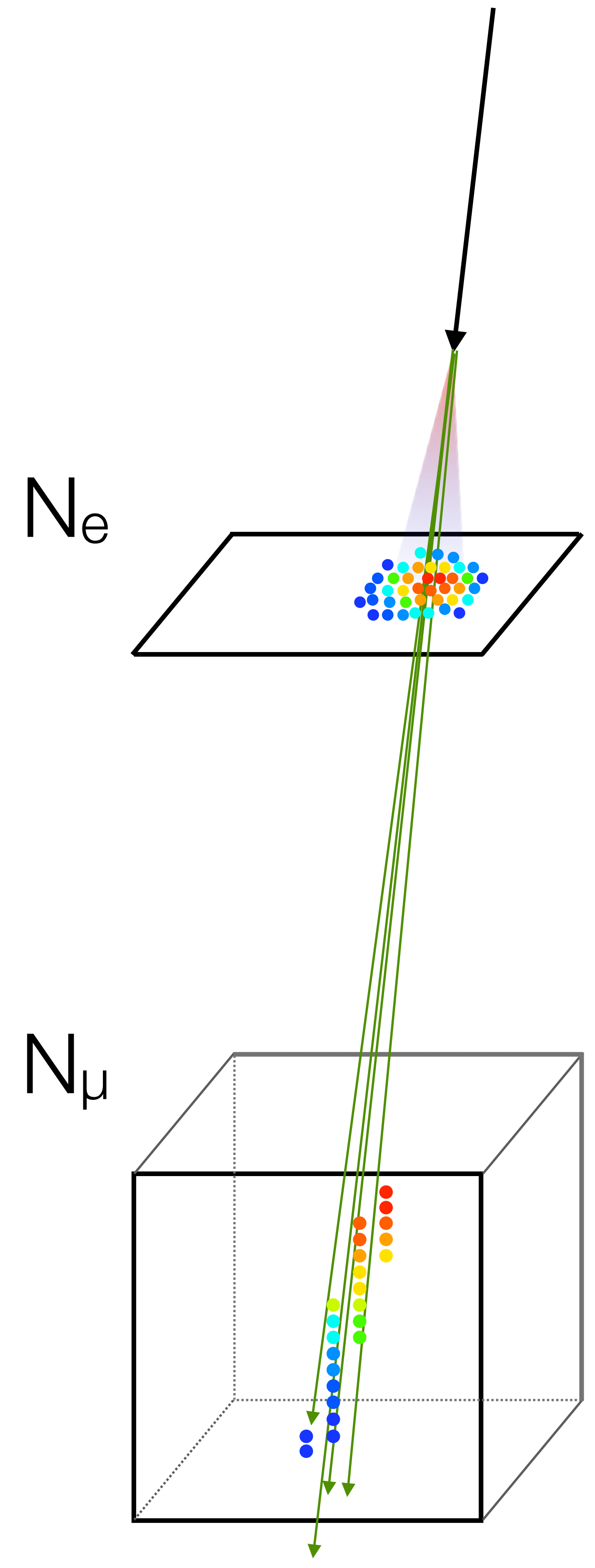


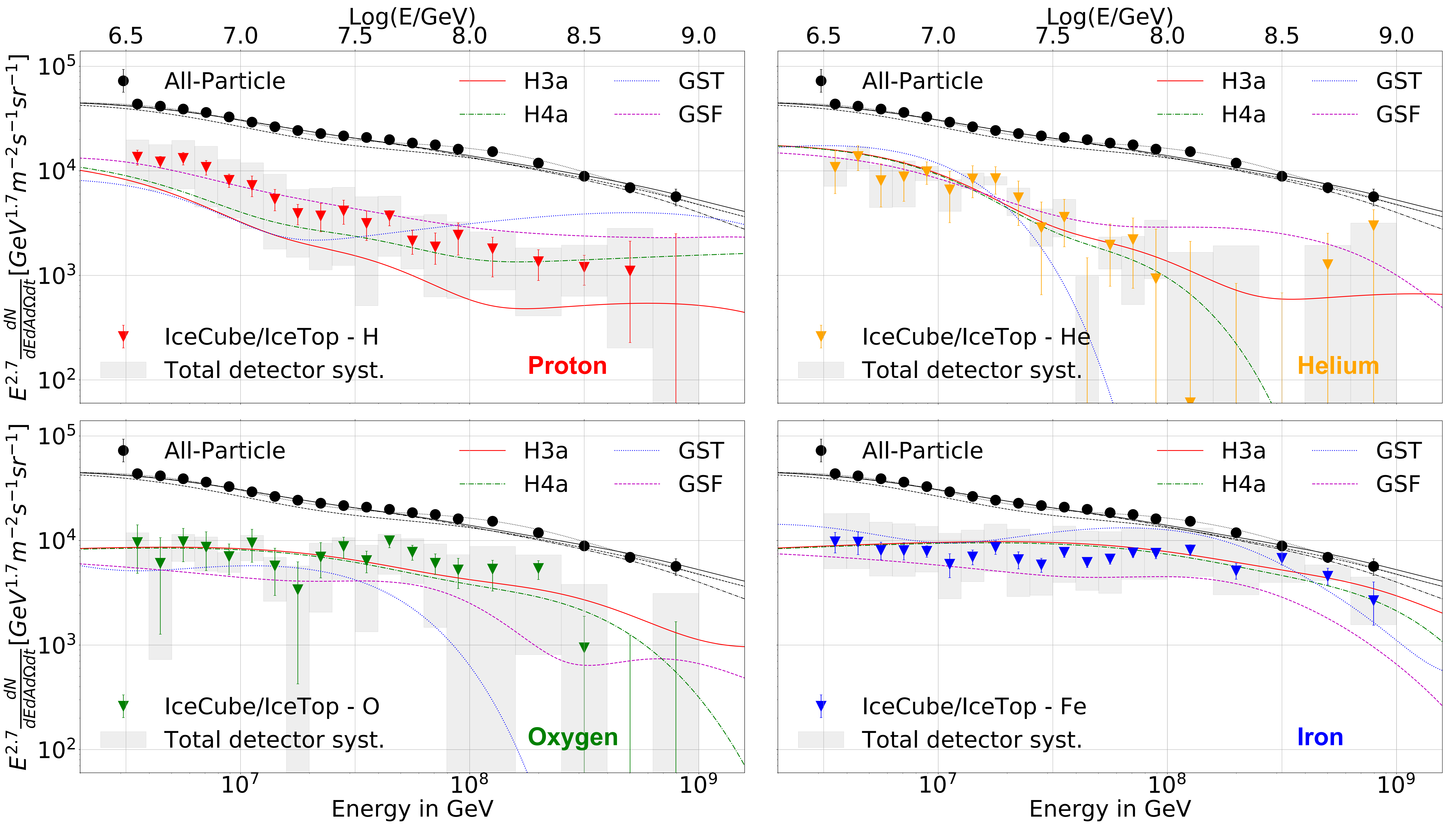
simulations - Ralph Engel



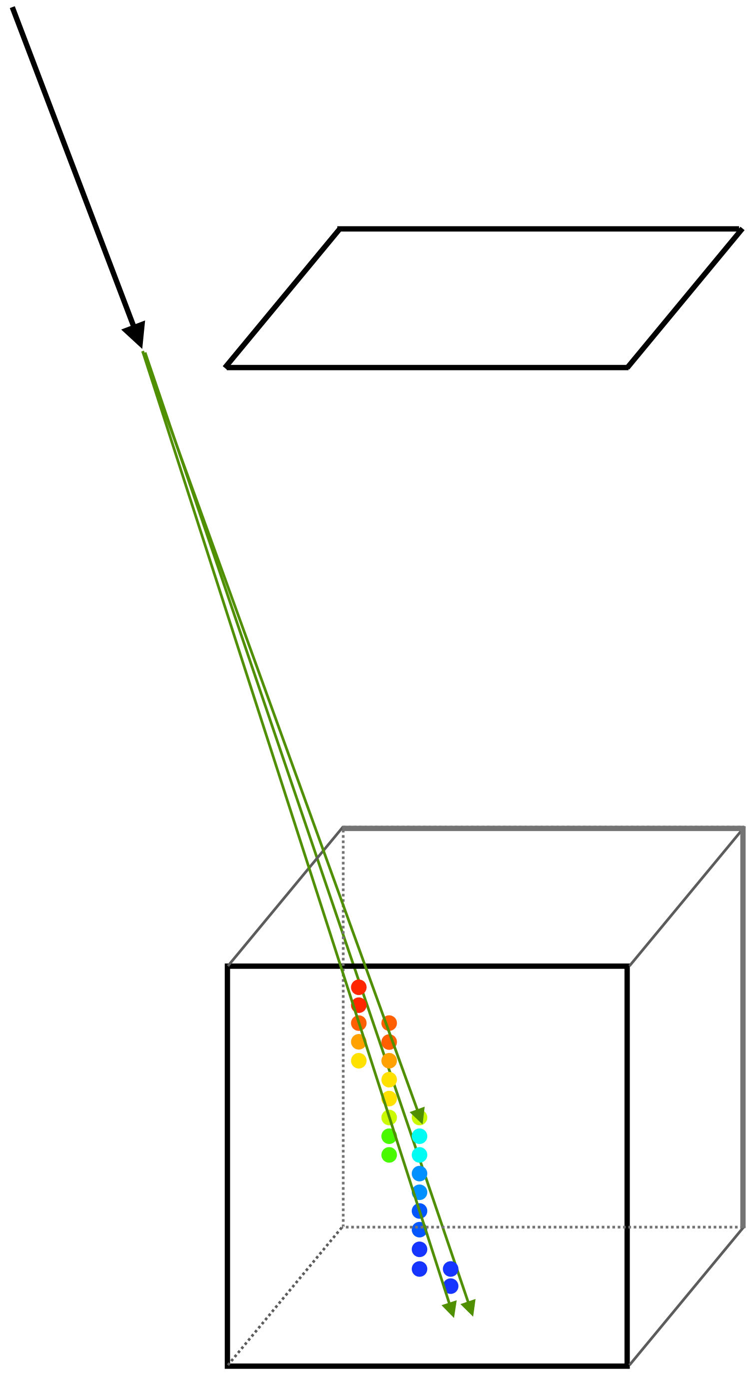


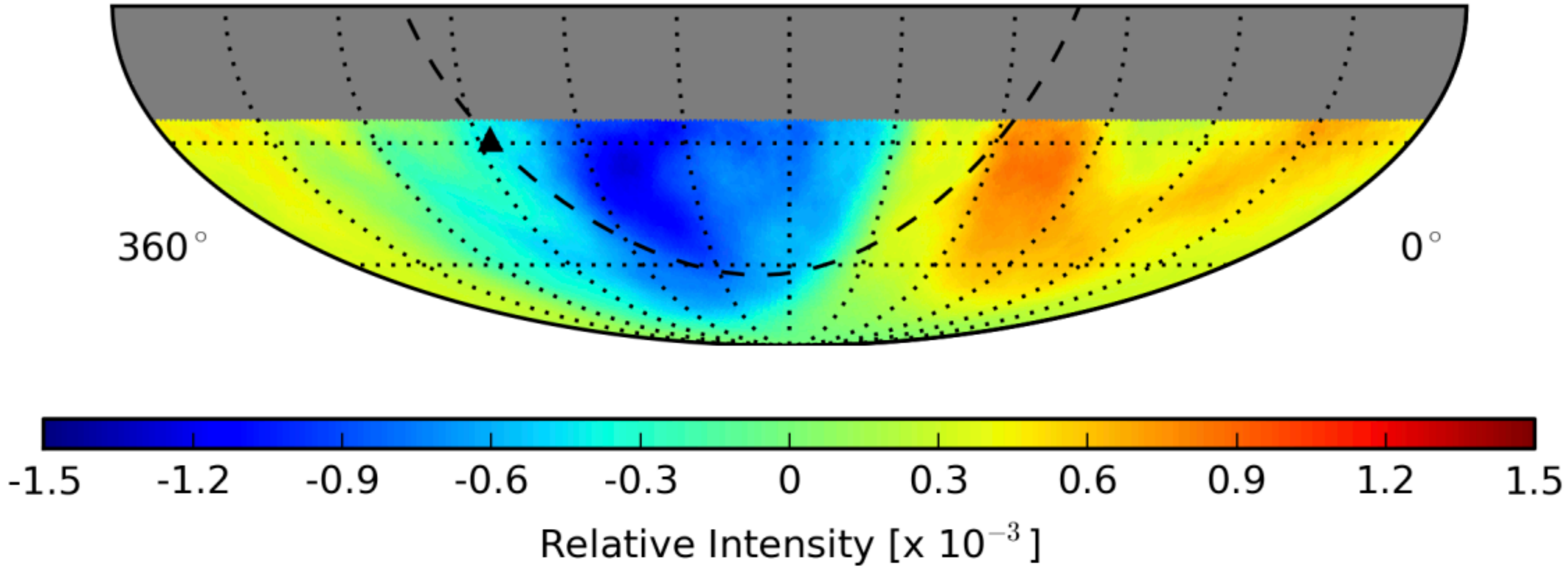
Cosmic Rays with IceTop
elemental composition





Cosmic Rays with IceCube
arrival direction distribution





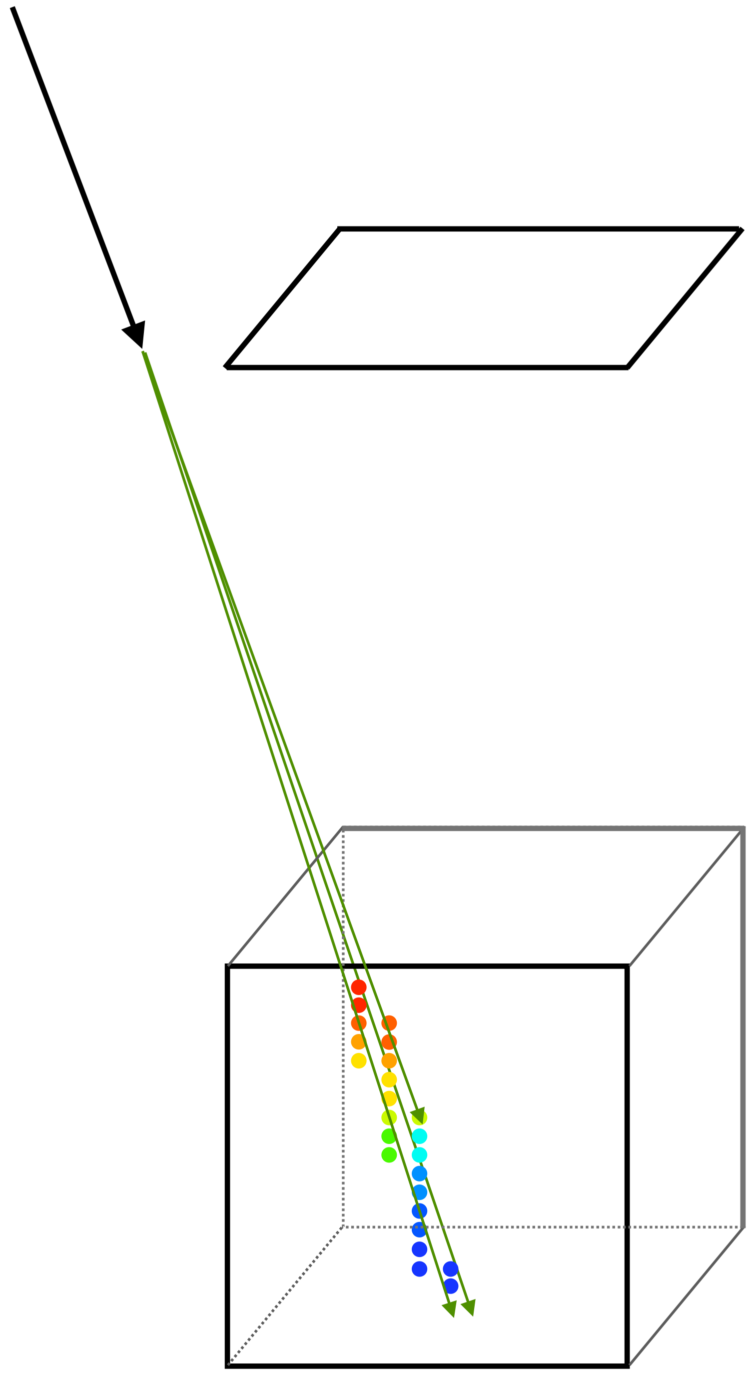
Relative Intensity

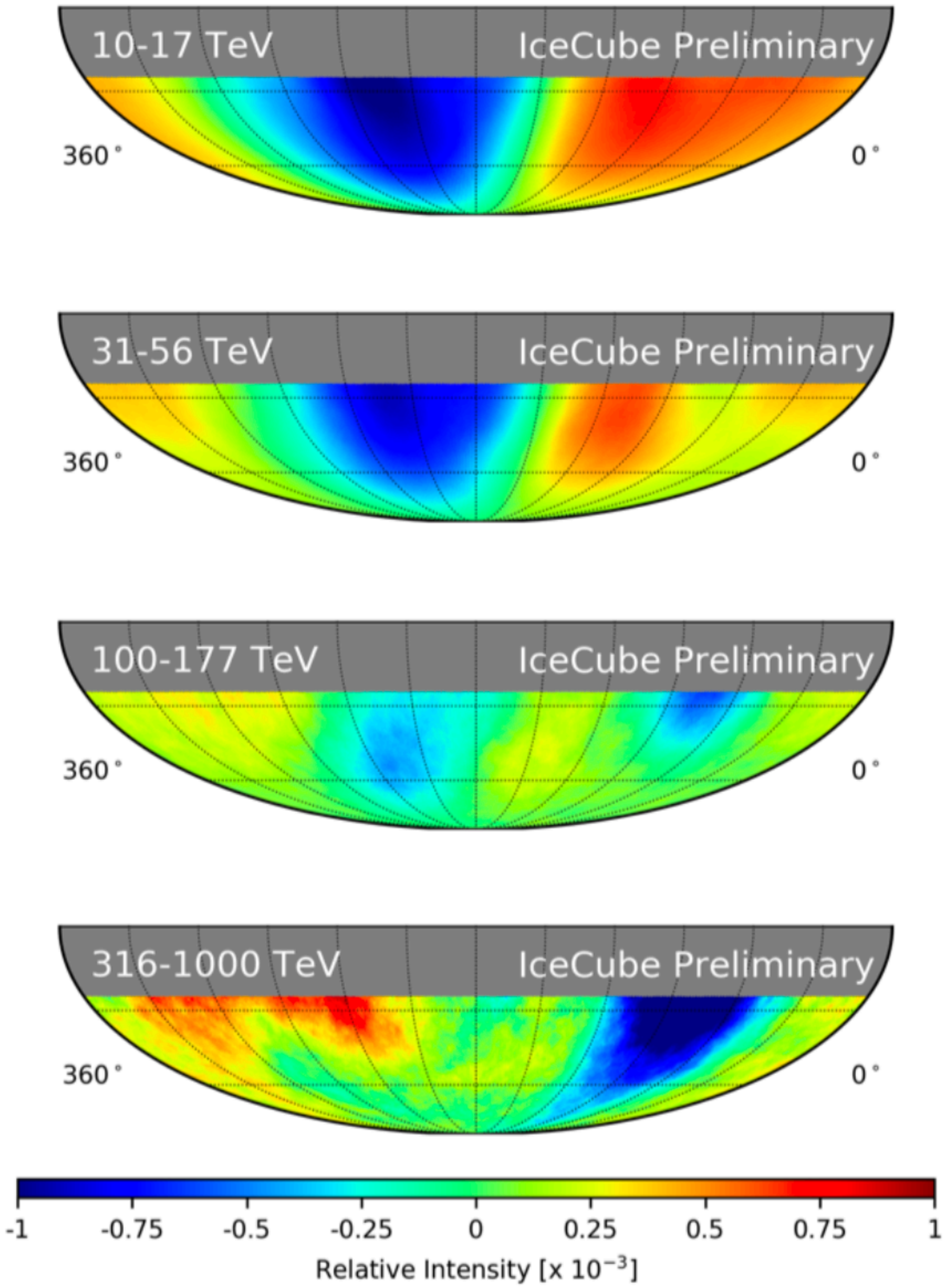
$$\boxed{\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}}$$

Median energy of cosmic ray particles ~ 20 TeV

Cosmic Rays with IceCube
arrival direction distribution

IceCube Collaboration - PoS(ICRC2021)320



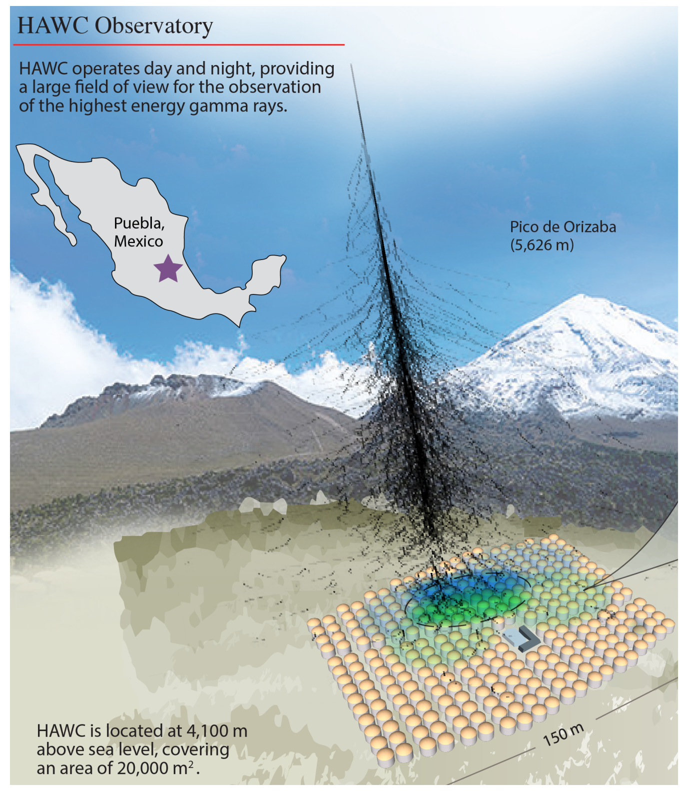


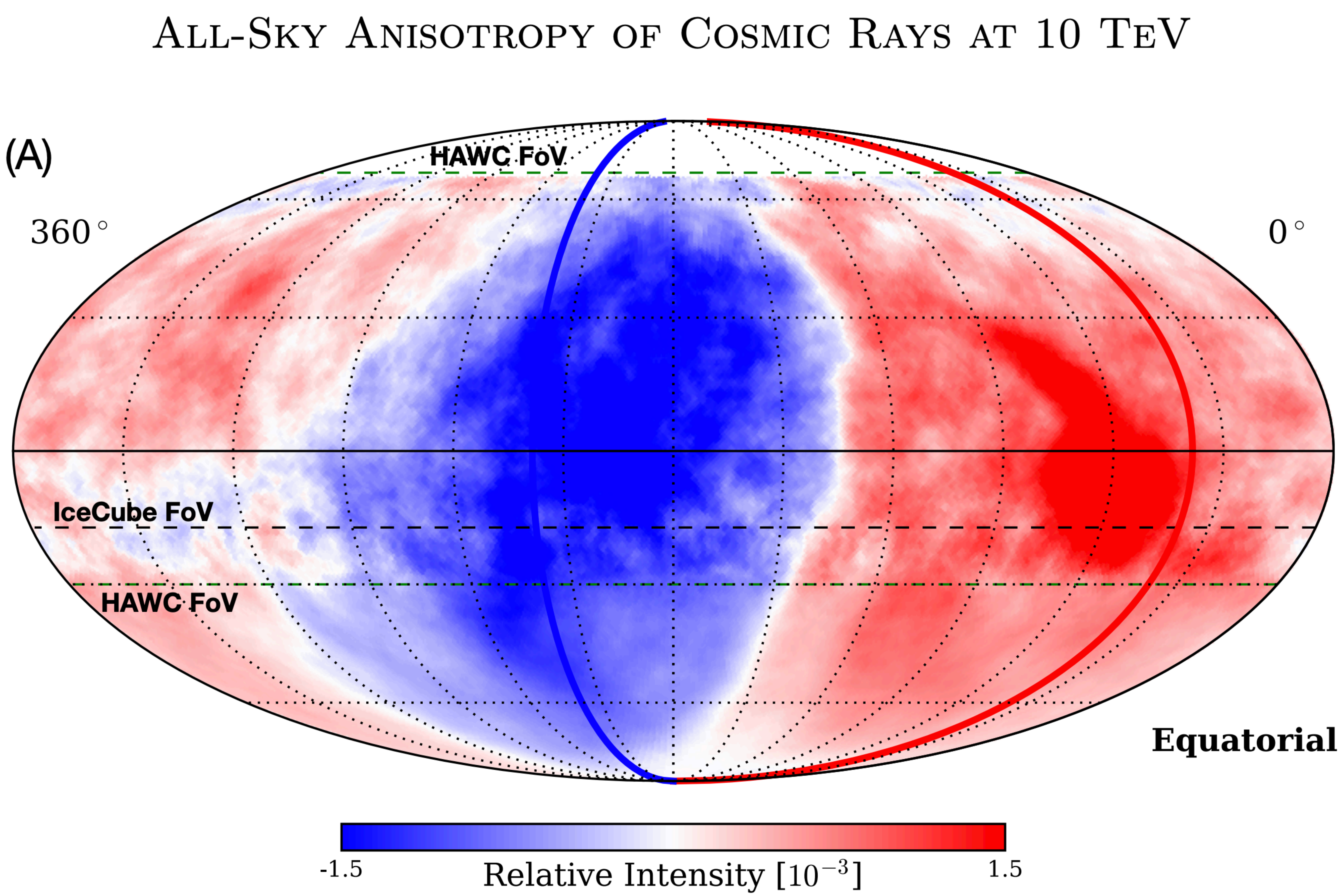
Relative Intensity

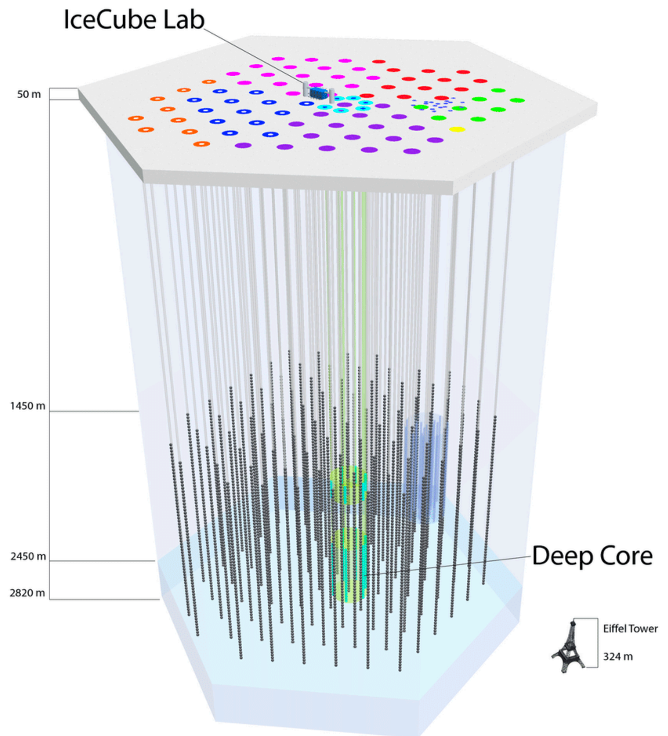
$$\boxed{\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}}$$

it changes as a function of energy

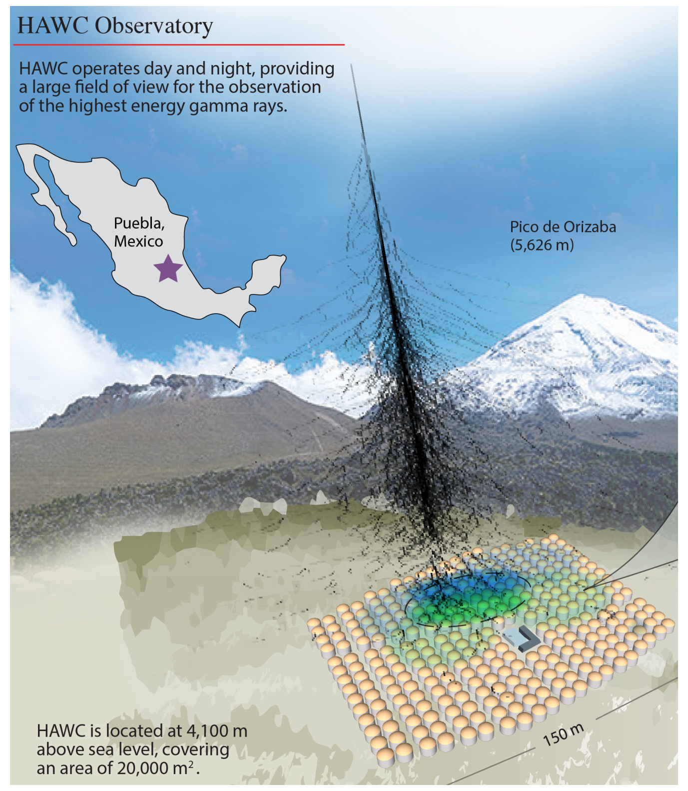
Cosmic Rays Anisotropy
with HAWC - IceCube

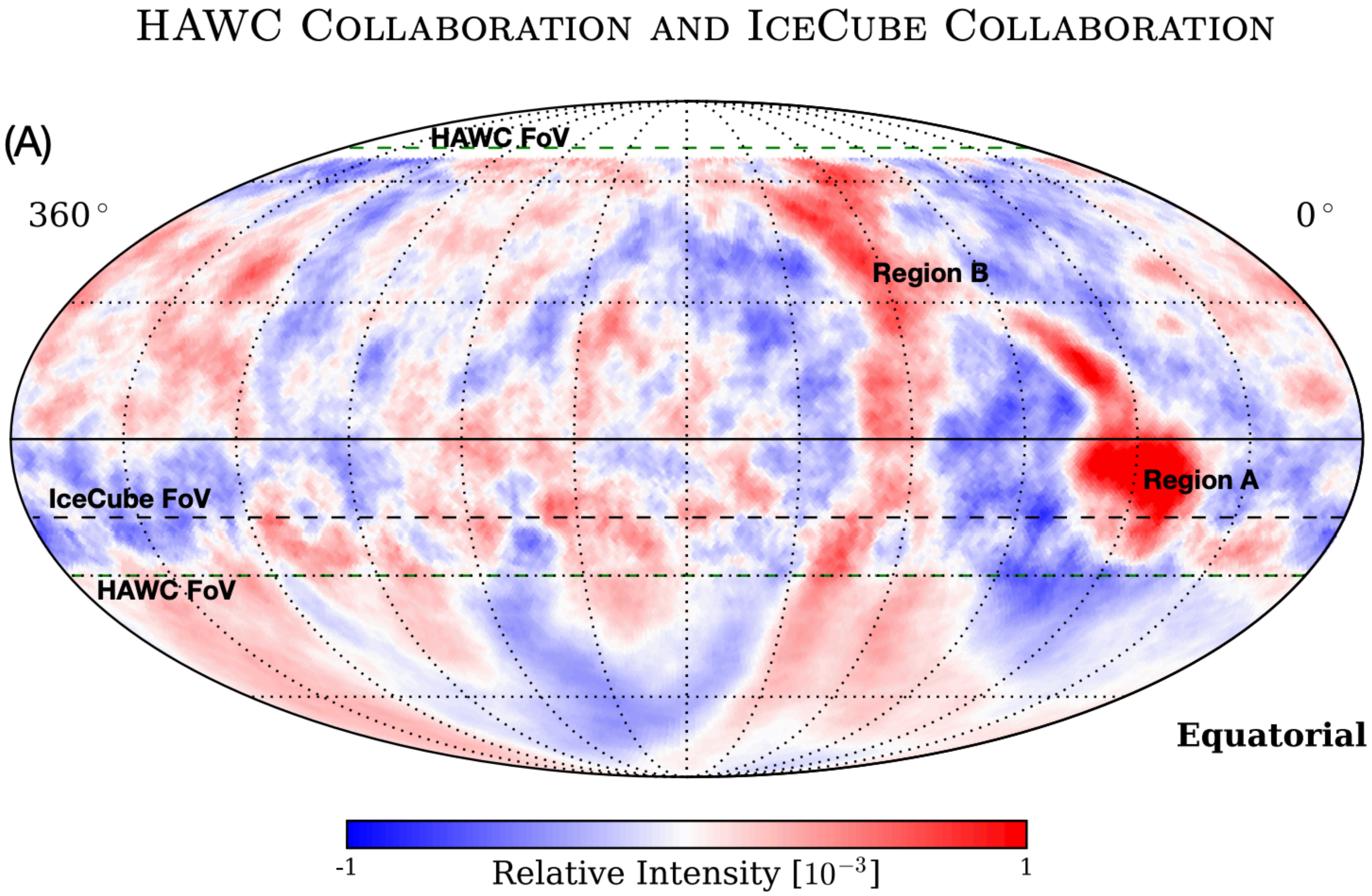


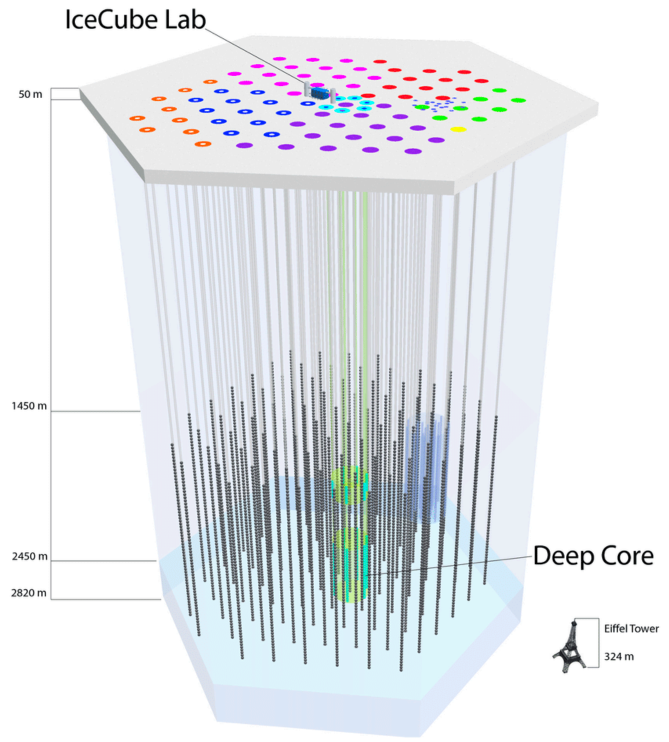




Cosmic Rays Anisotropy
with HAWC - IceCube







without dipole, quadrupole, and octupole components

Conclusions

Cosmic Rays are atomic nuclei sweeping across the Universe up to ultra-high energy

their origin is unknown and the subject of multi-messenger astrophysics

cosmic rays arriving on Earth bring information about the medium they crossed

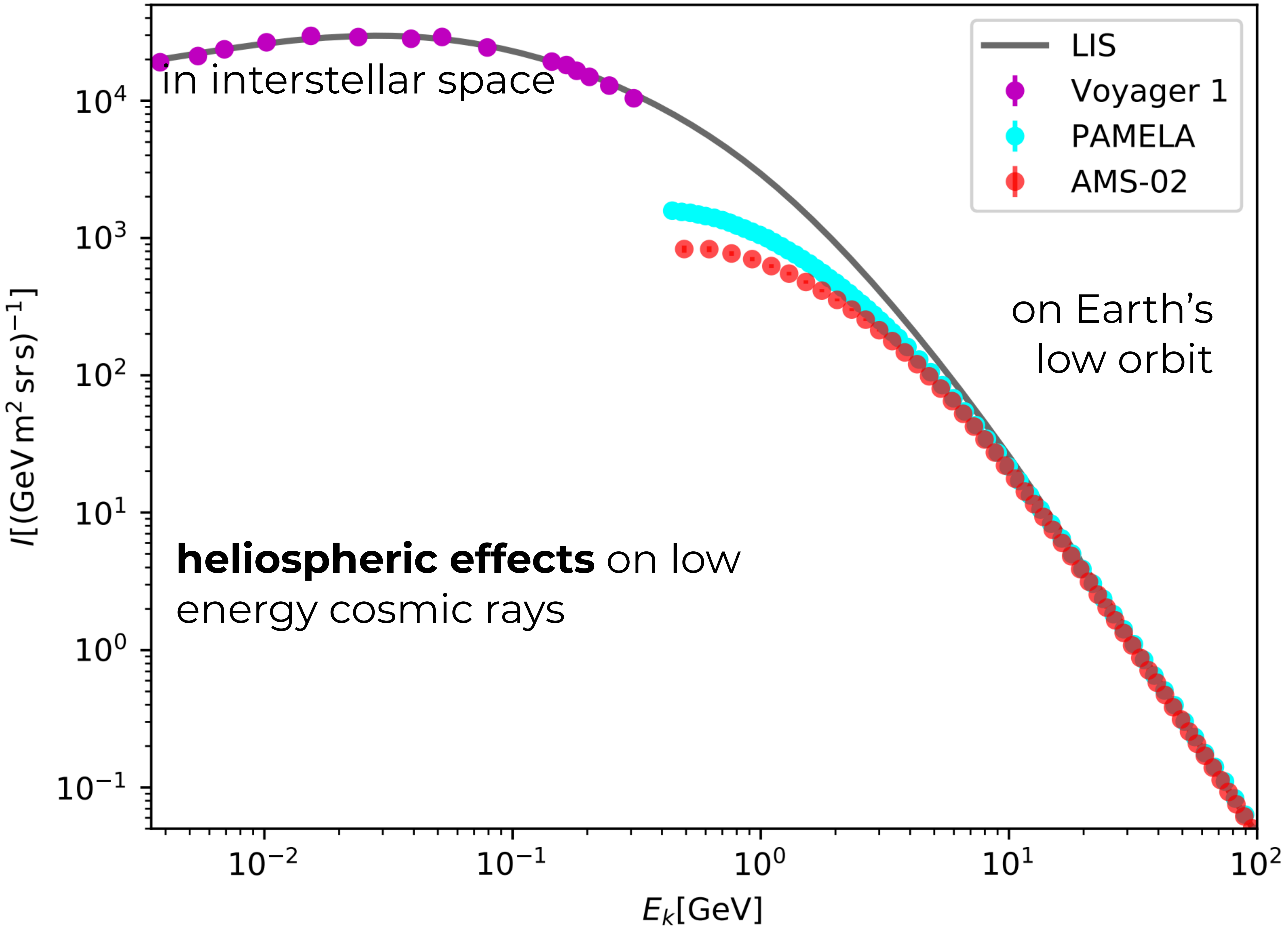
GeV-scale cosmic rays used to probe solar wind and interplanetary magnetic field

TeV-scale cosmic rays can be used to probe the heliosphere's boundary with the ISM

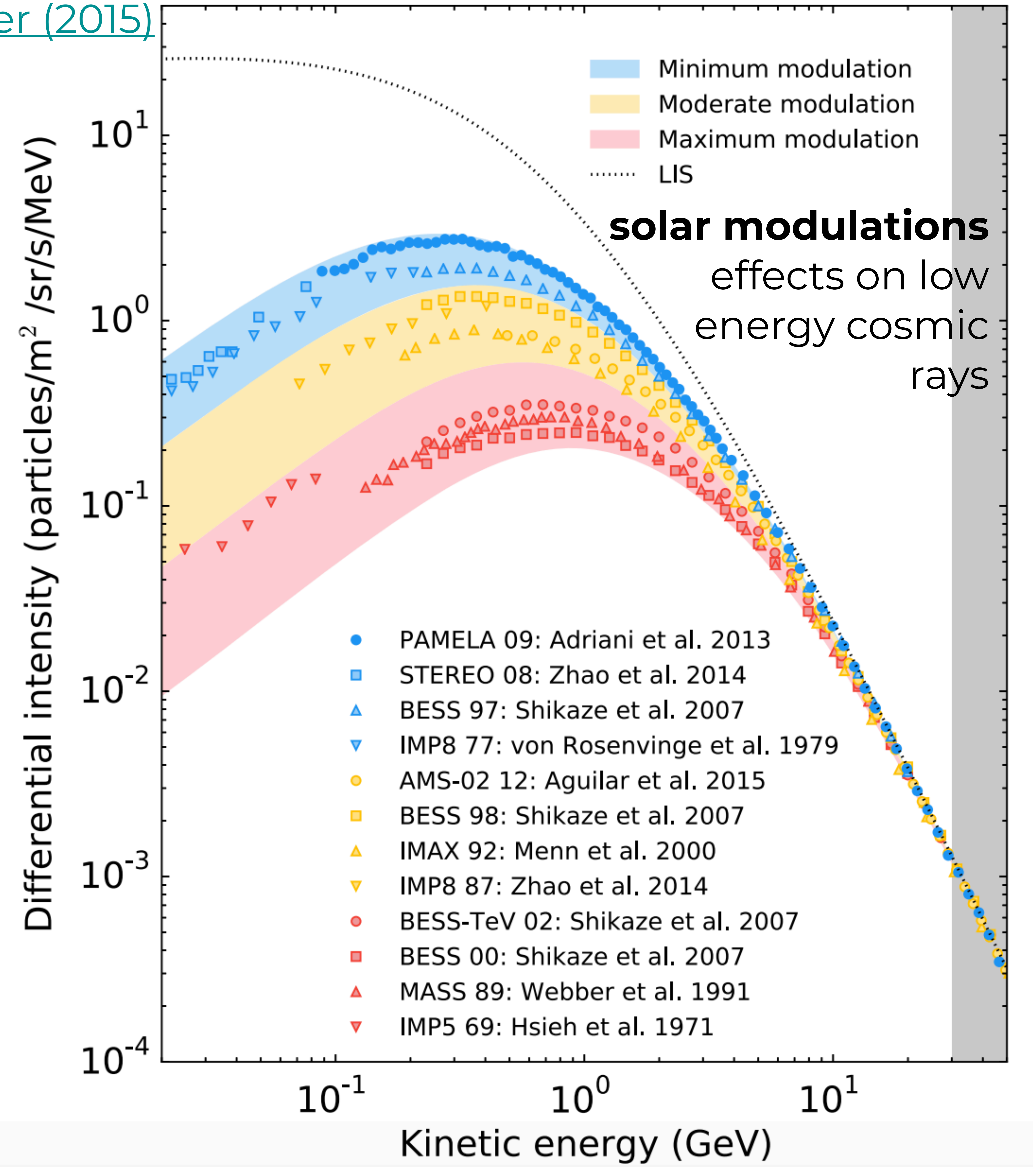
backup slides

proton flux

https://arxiv.org/abs/1904.03747

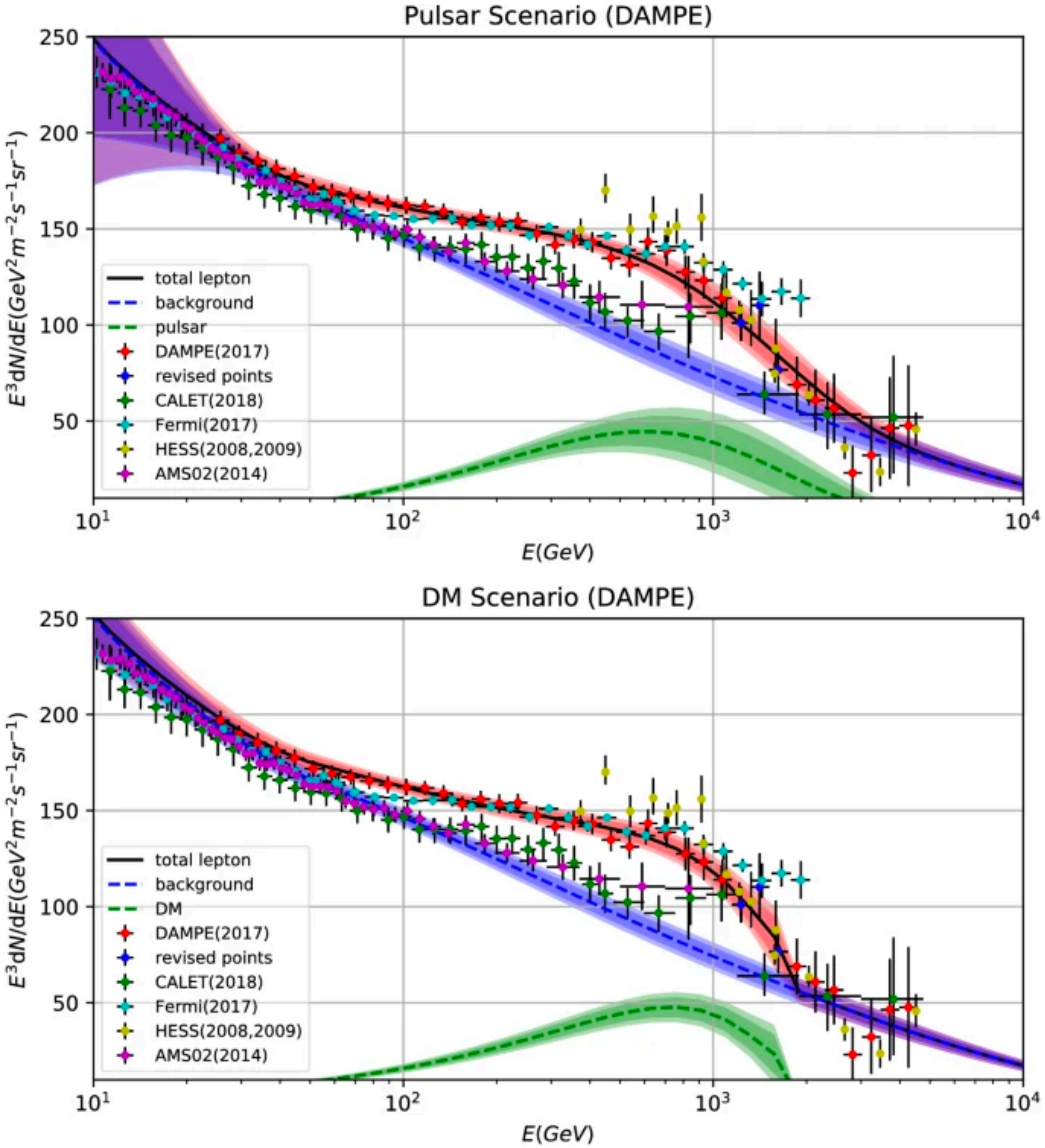


Vos & Potgieter (2015)



proton flux

Niu et al. (2019)



Lebedev et al. (2021)