

Cosmic Rays



Paolo Desiati IceCube Bootcamp

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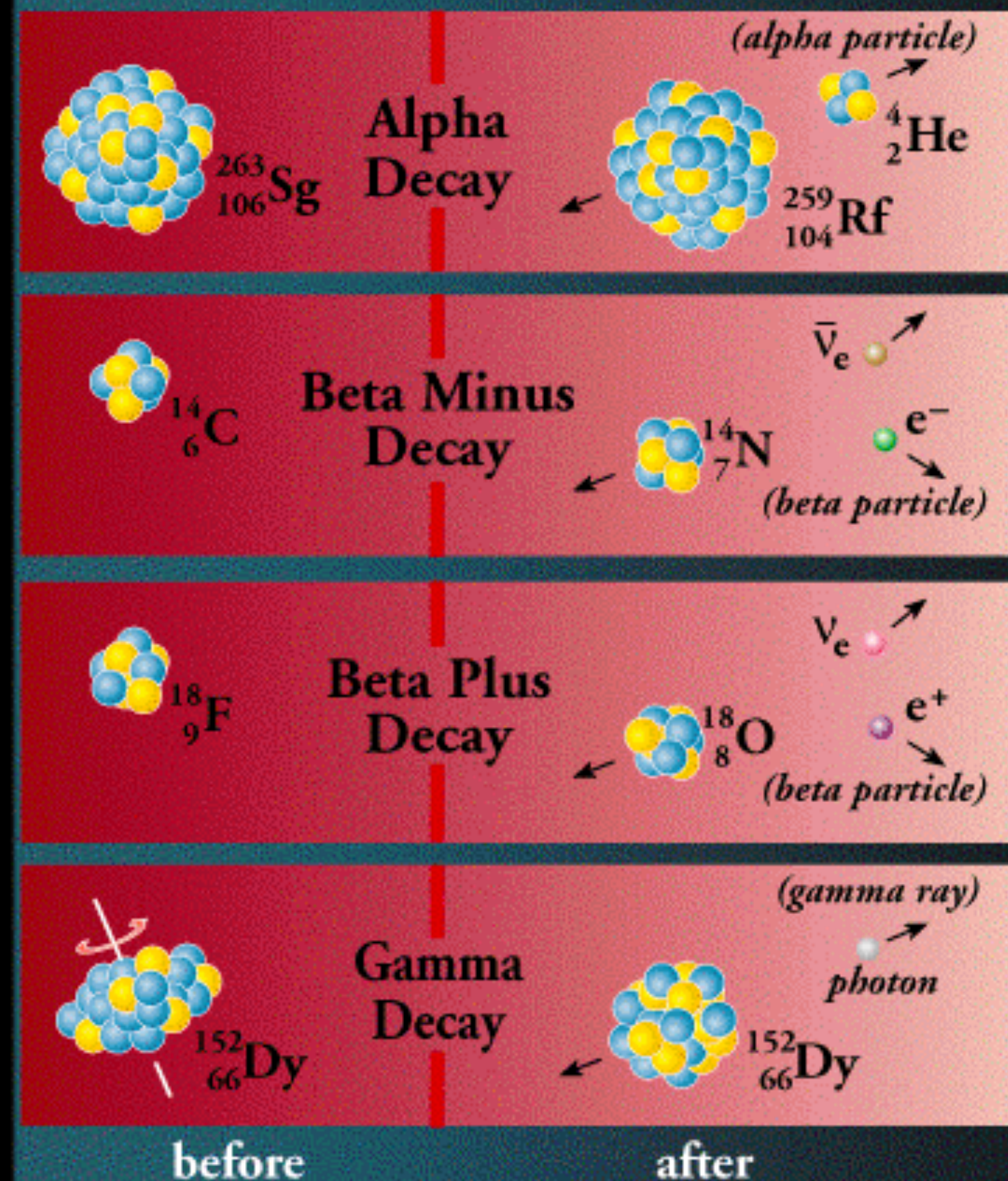
Madison, WI - June 13-17, 2022



The discovery of the Cosmic Rays

...looking for something else

Radioactivity



Radioactive decay transforms a nucleus by emitting different particles. In **alpha** decay, the nucleus releases a ^4_2He nucleus—an alpha particle. In **beta** decay, the nucleus either emits an electron and antineutrino (or a positron and neutrino) or captures an atomic electron and emits a neutrino. A positron is the name for the antiparticle of the electron. Antimatter is composed of anti-particles. Both alpha and beta decays change the original nucleus into a nucleus of a different chemical element. In **gamma** decay, the nucleus lowers its internal energy by emitting a photon—a gamma ray. This decay does not modify the chemical properties of the atom.

... 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

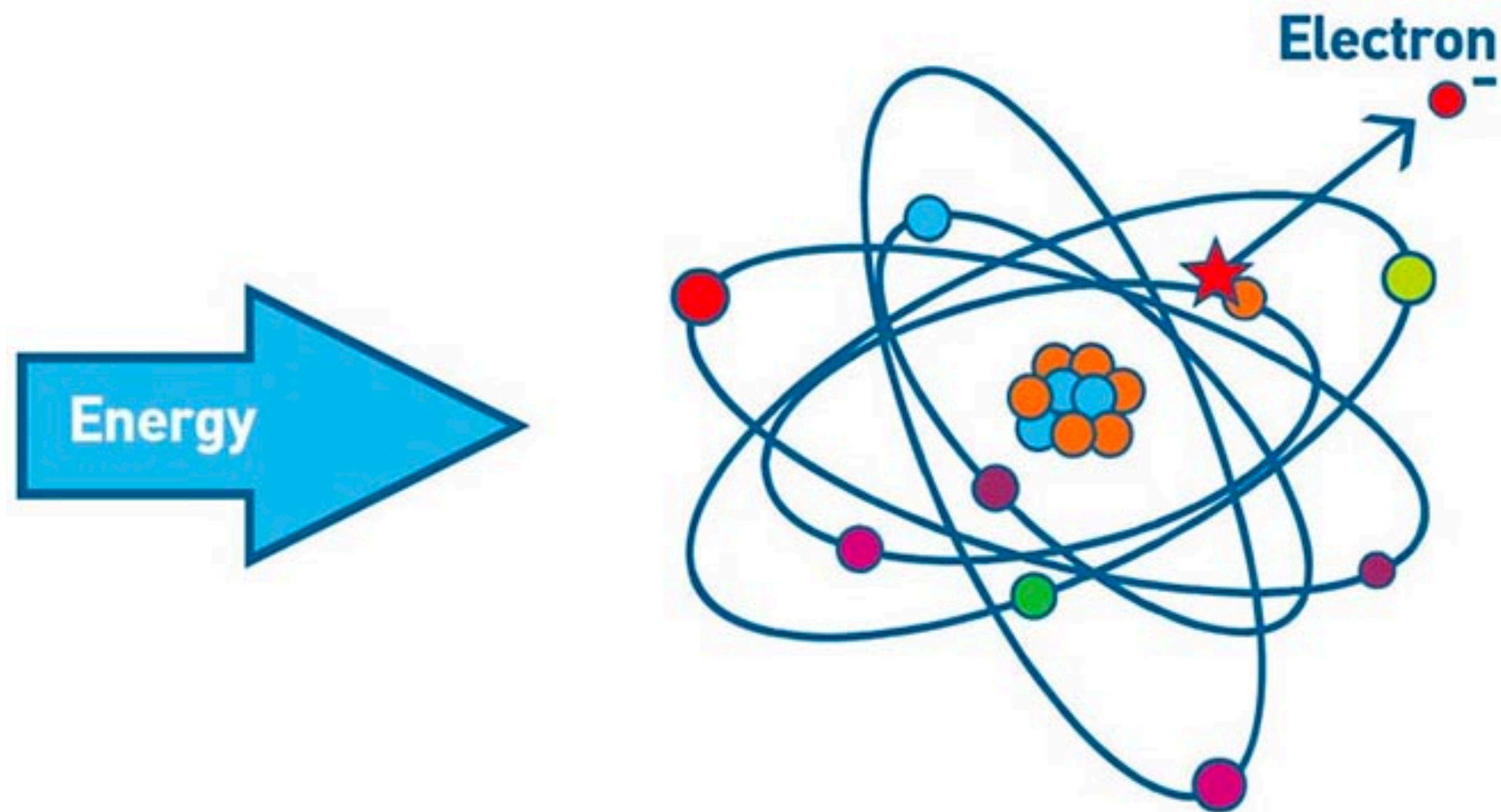
radiation - the emission of energy as electromagnetic waves or as moving subatomic particles, especially high-energy particles which cause ionization.

The discovery of the Cosmic Rays

...looking for something else

ionizing radiation

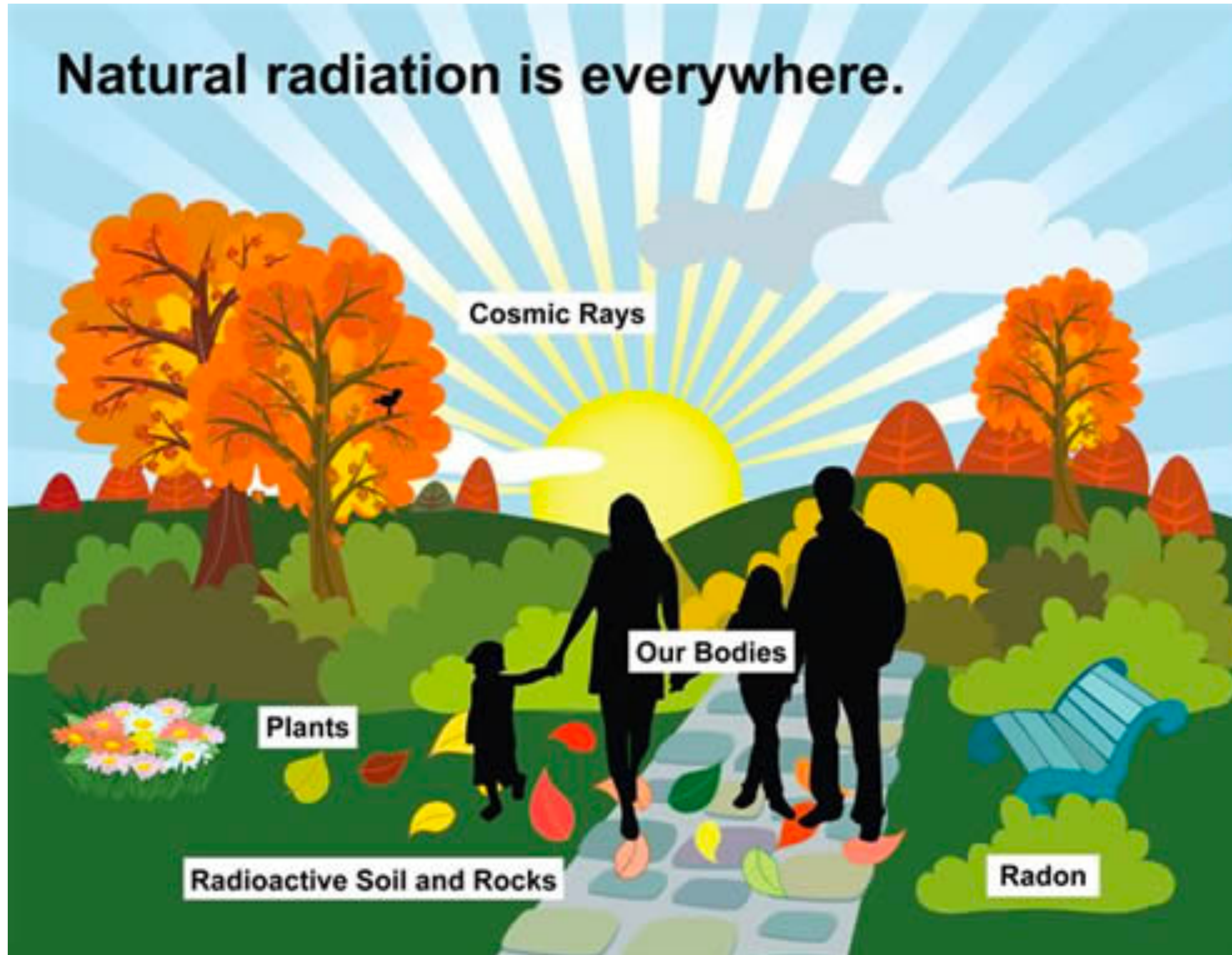
these invisible rays of energy
produce electric currents in the air



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

The discovery of the Cosmic Rays

...looking for something else



natural radioactivity from the ground

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

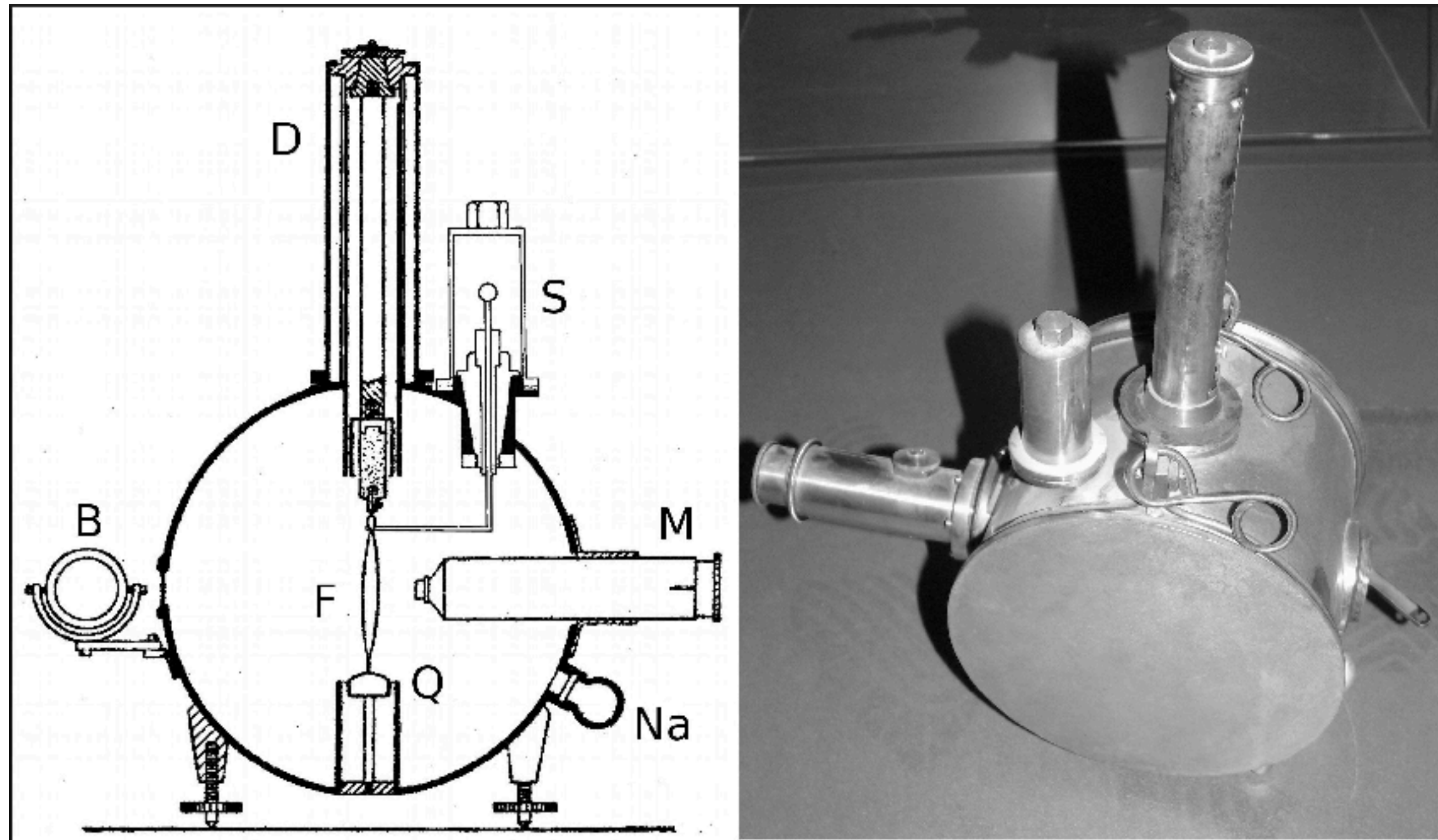
The discovery of the Cosmic Rays

...something is odd

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



The discovery of the Cosmic Rays

...something is odd

Domenico Pacini (1878-1934)



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

LA RADIAZIONE PENETRANTE ALLA SUPERFICIE
ED IN SENO ALLE ACQUE.

NOTA DI D. PACINI.

Le osservazioni eseguite sul mare nel 1910 ') 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.

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

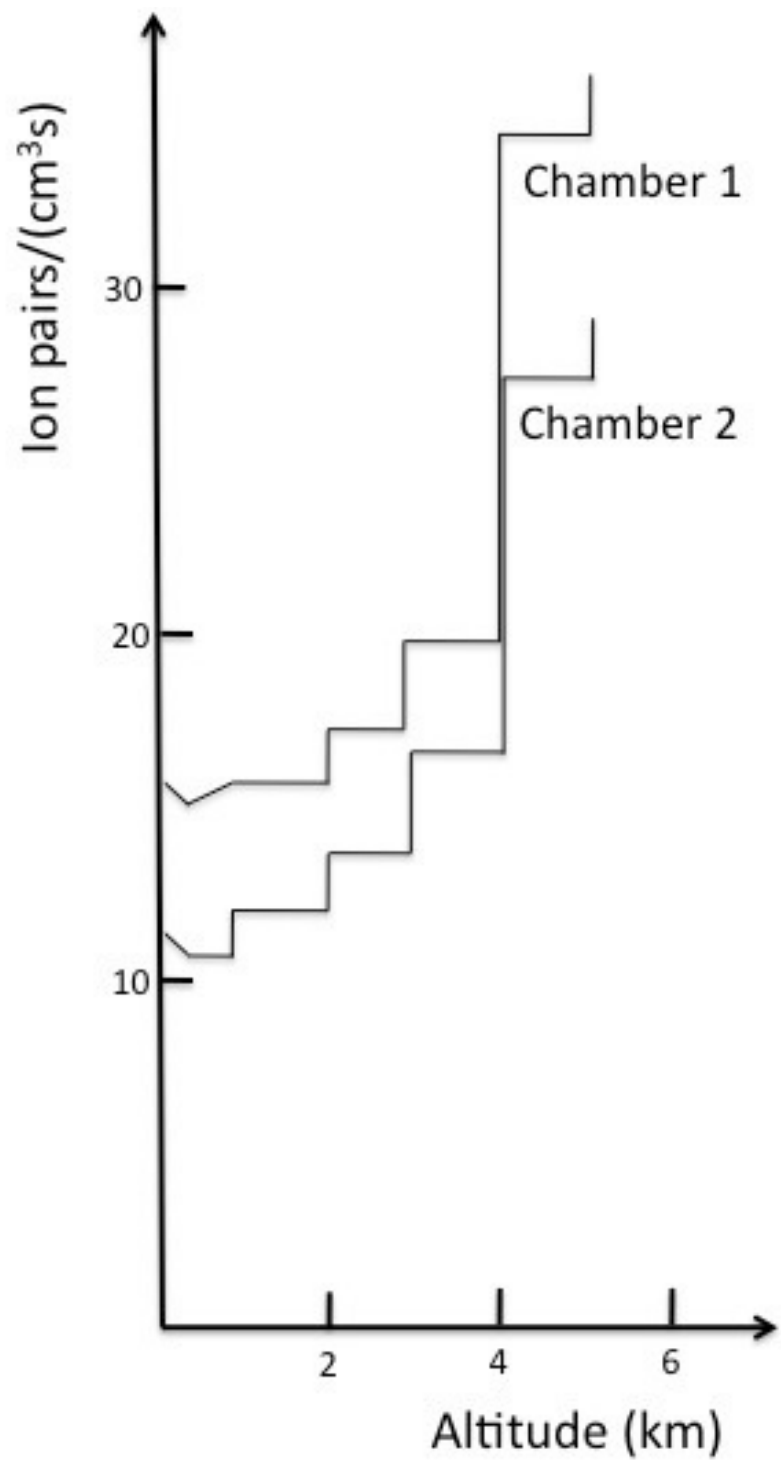
there must be a source of radiation from the sky...

... cosmic **rays?**

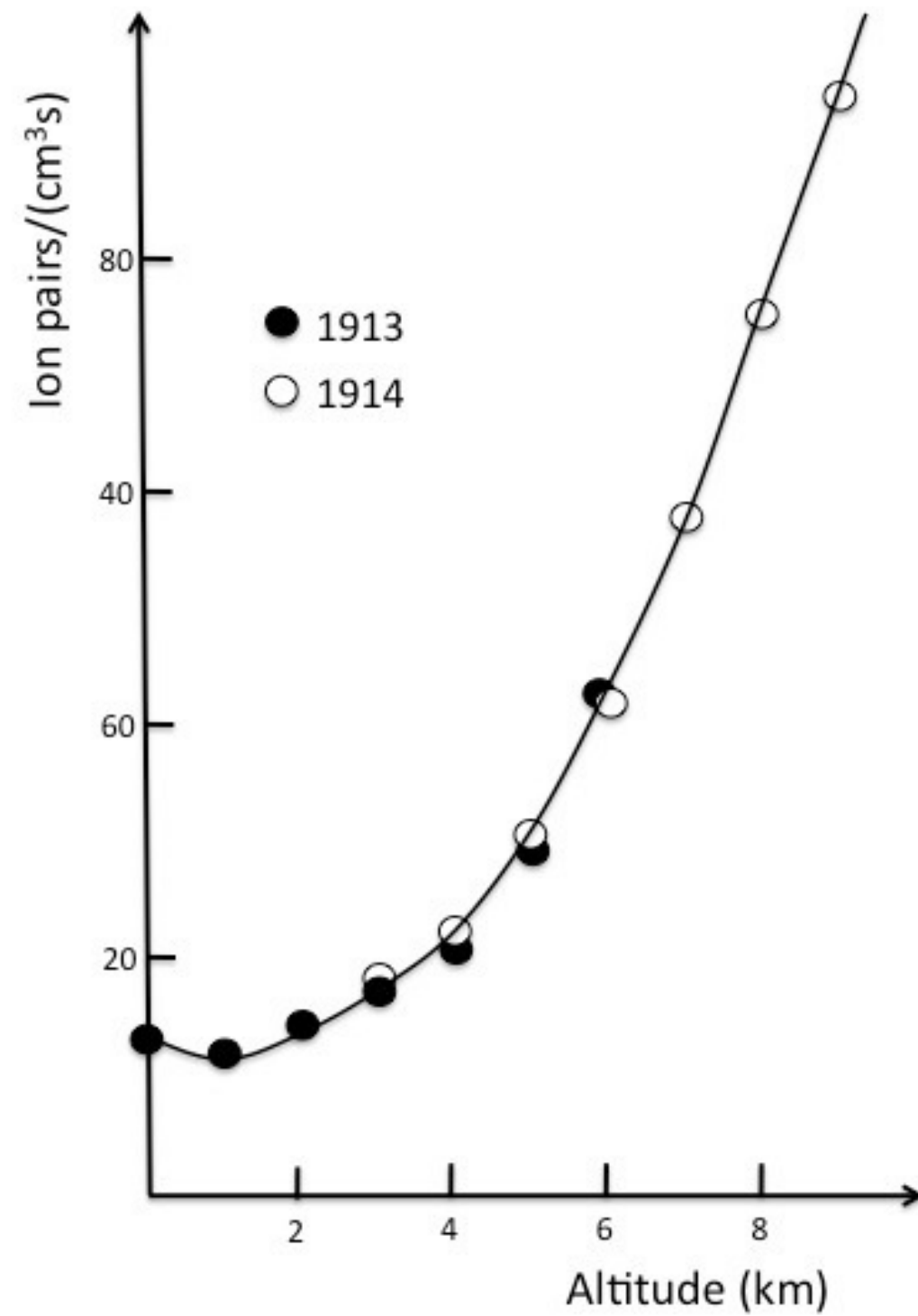


The discovery of the Cosmic Rays

...the clarification



Hess (1912)



Kolhörster (1913-14)

rays of particles?

COSMIC RAY RIVALS TO MEET IN DEBATE

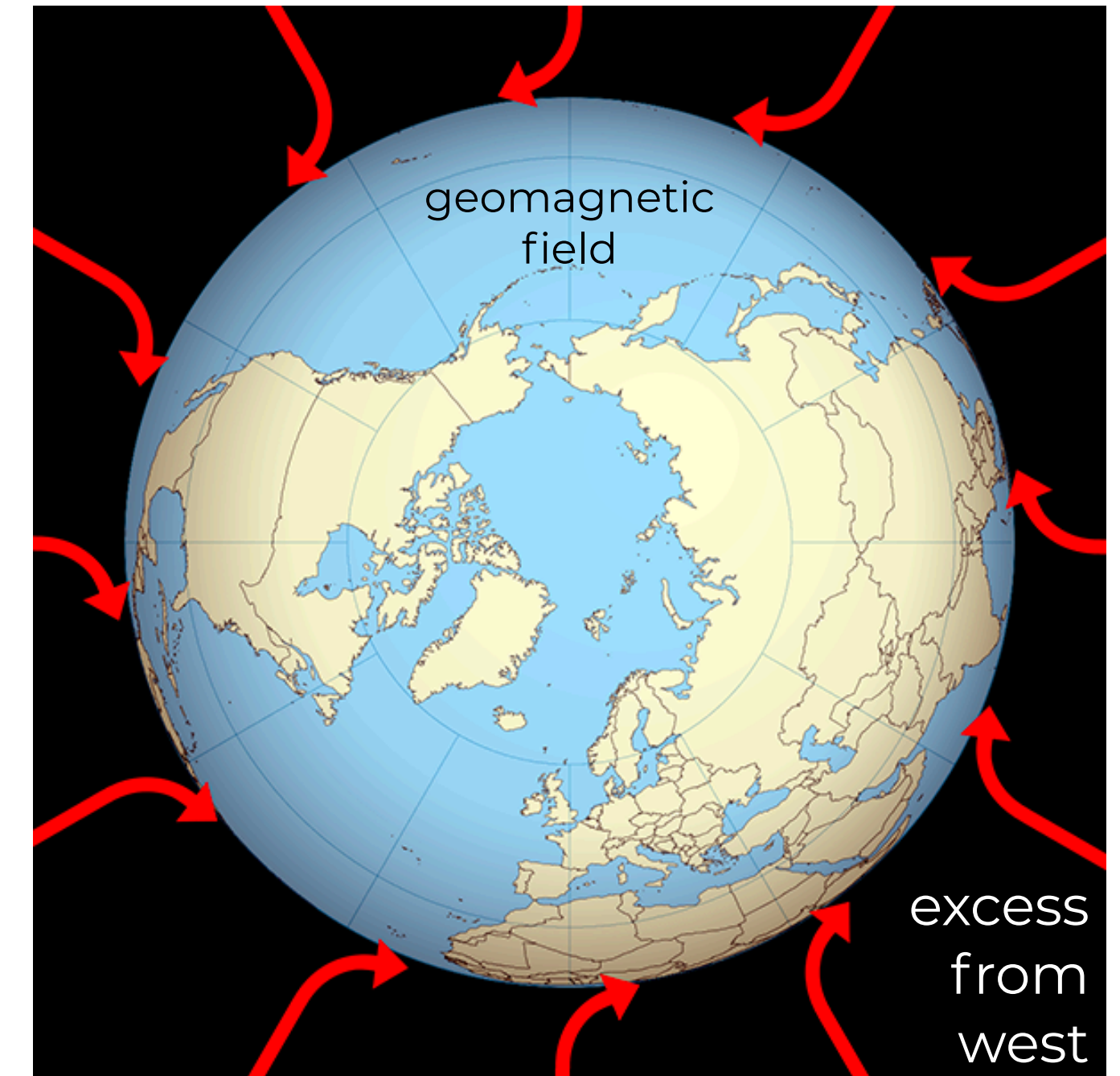
Clash of Millikan and Compton Theories to Form High Point at Scientific Convention.

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?

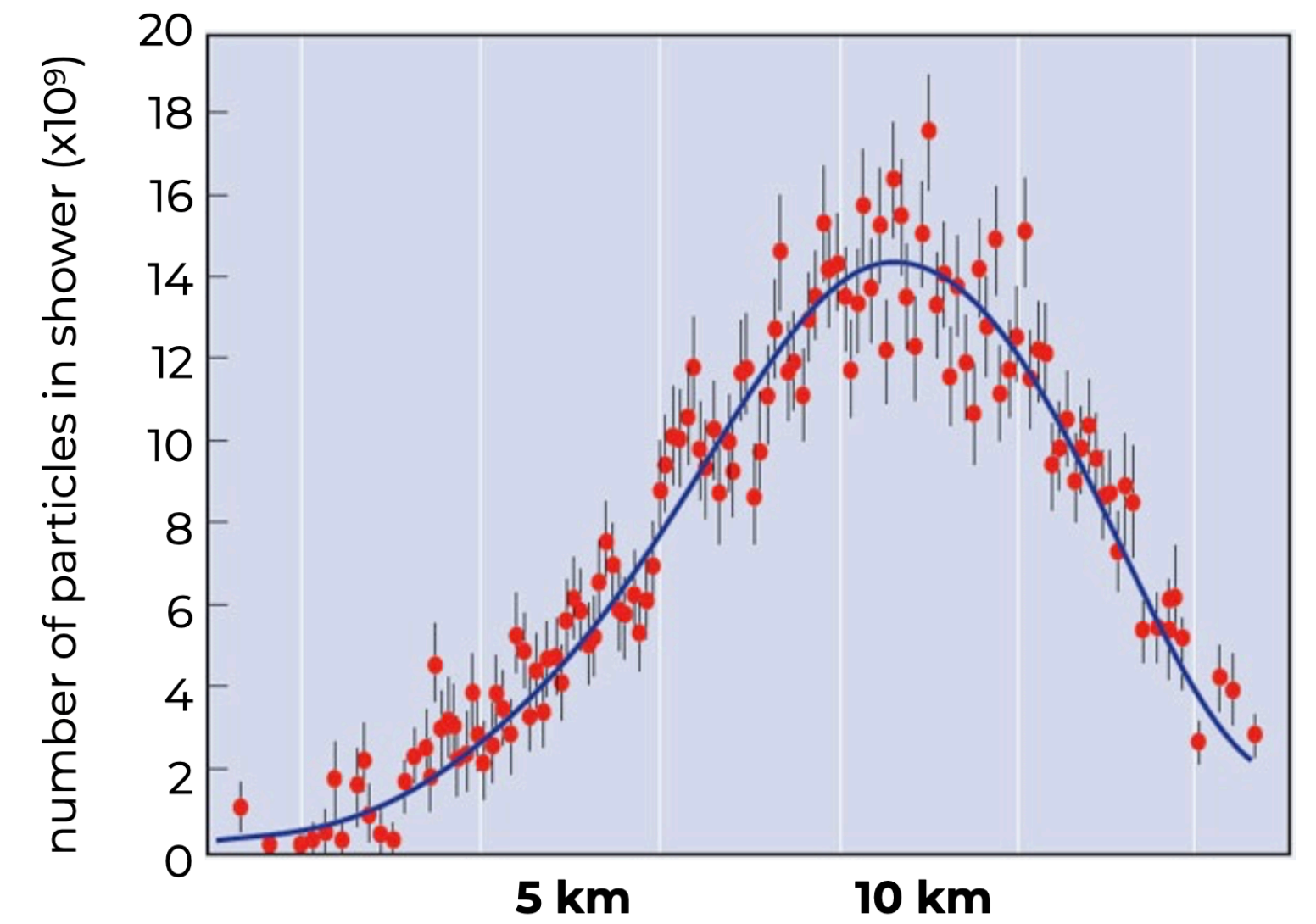
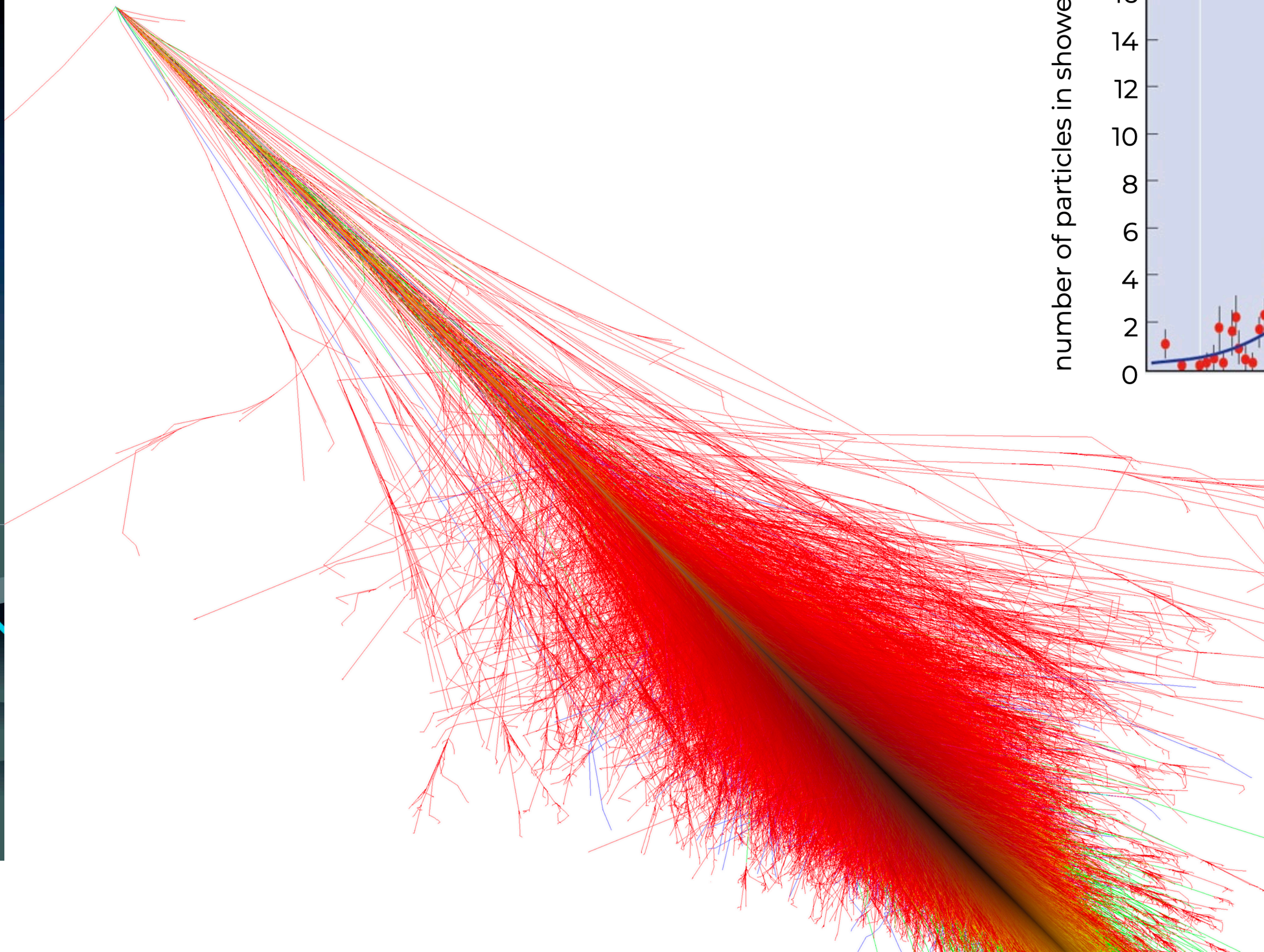
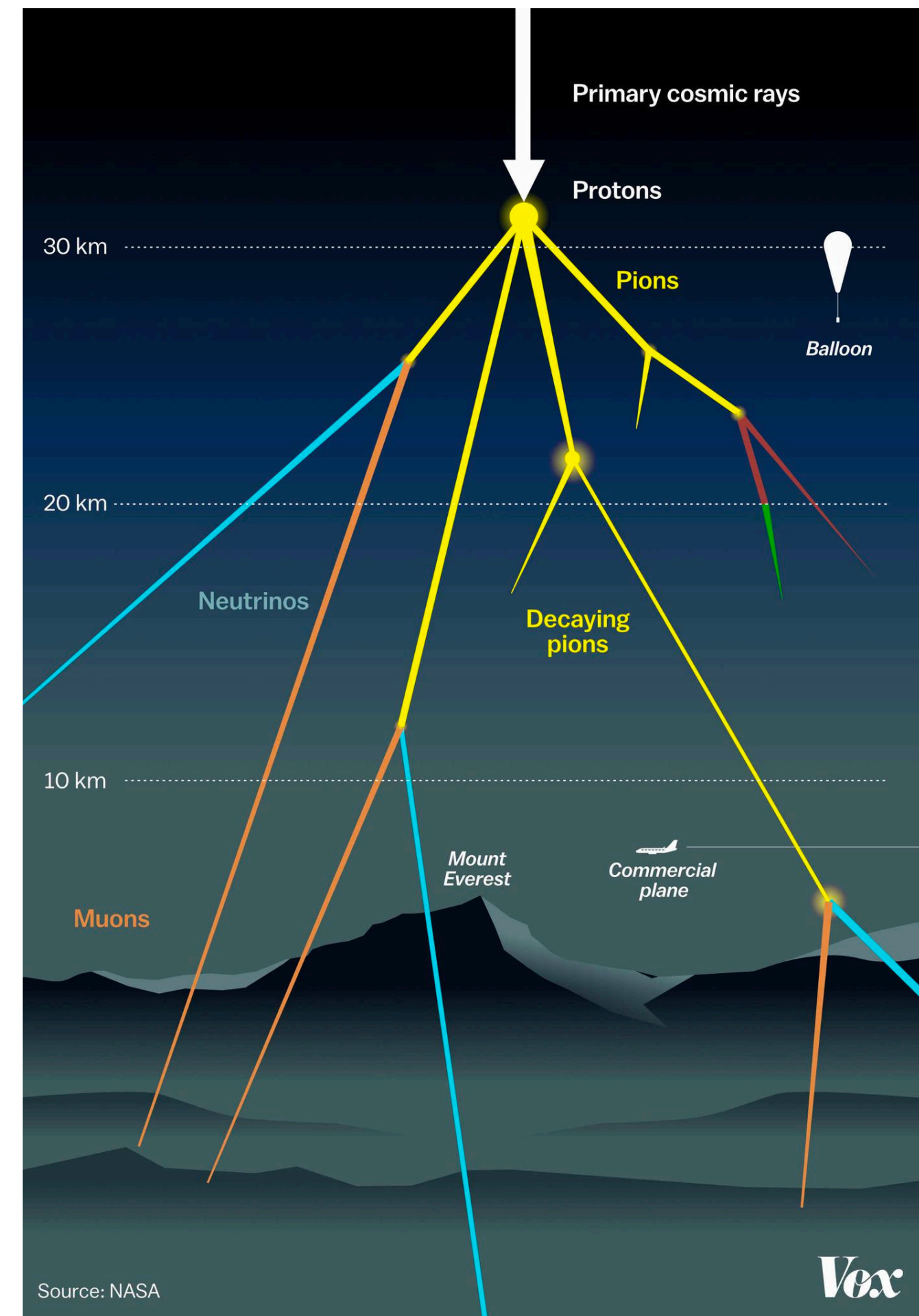
The Origin of the Solar System Elements

1 H	big bang fusion 										cosmic ray fission 					2 He	
3 Li	4 Be	merging neutron stars 					exploding massive stars 					5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	dying low mass stars 					exploding white dwarfs 					13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U											

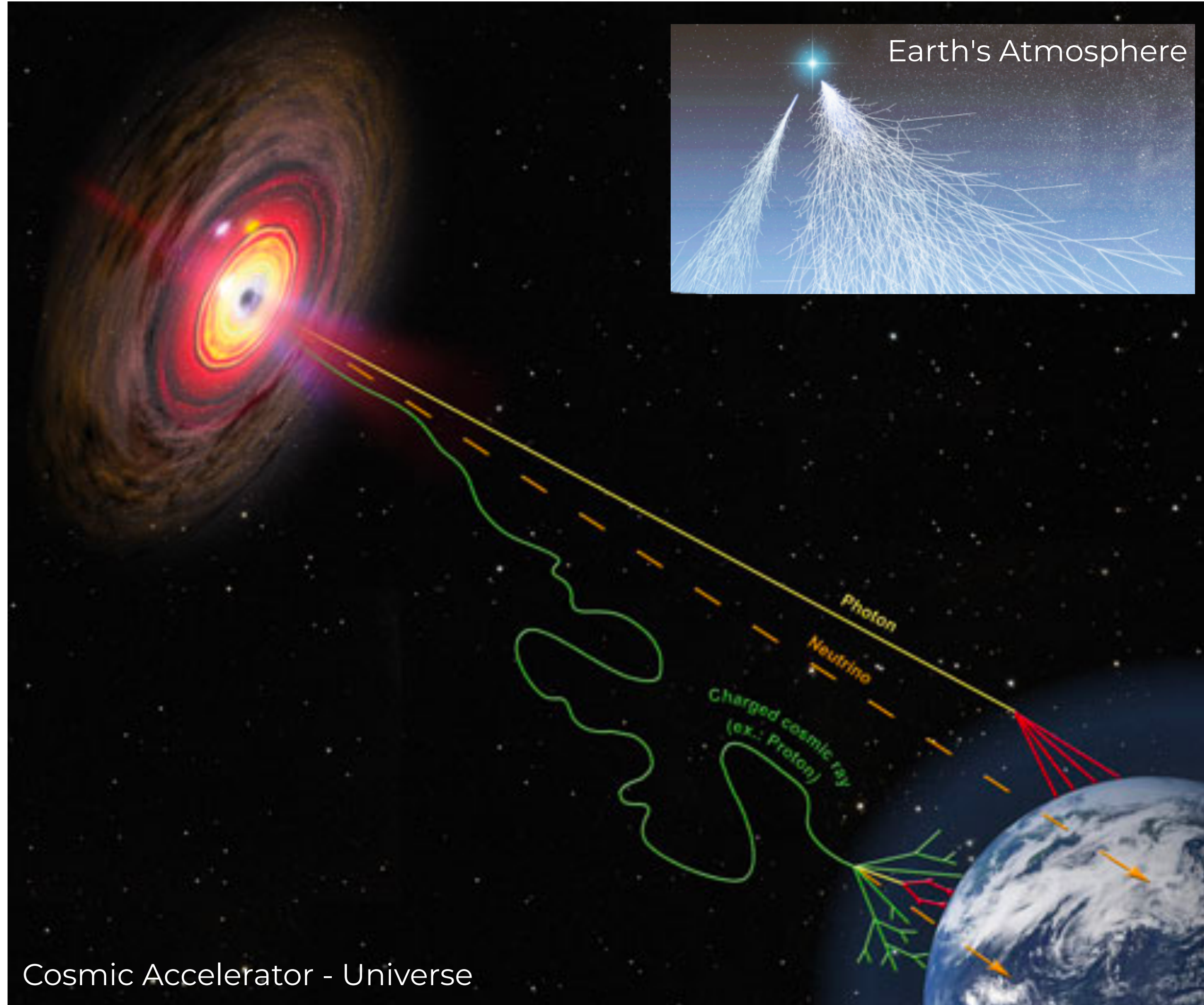
Jennifer Johnson

What are Cosmic Rays?

Extensive Air Showers



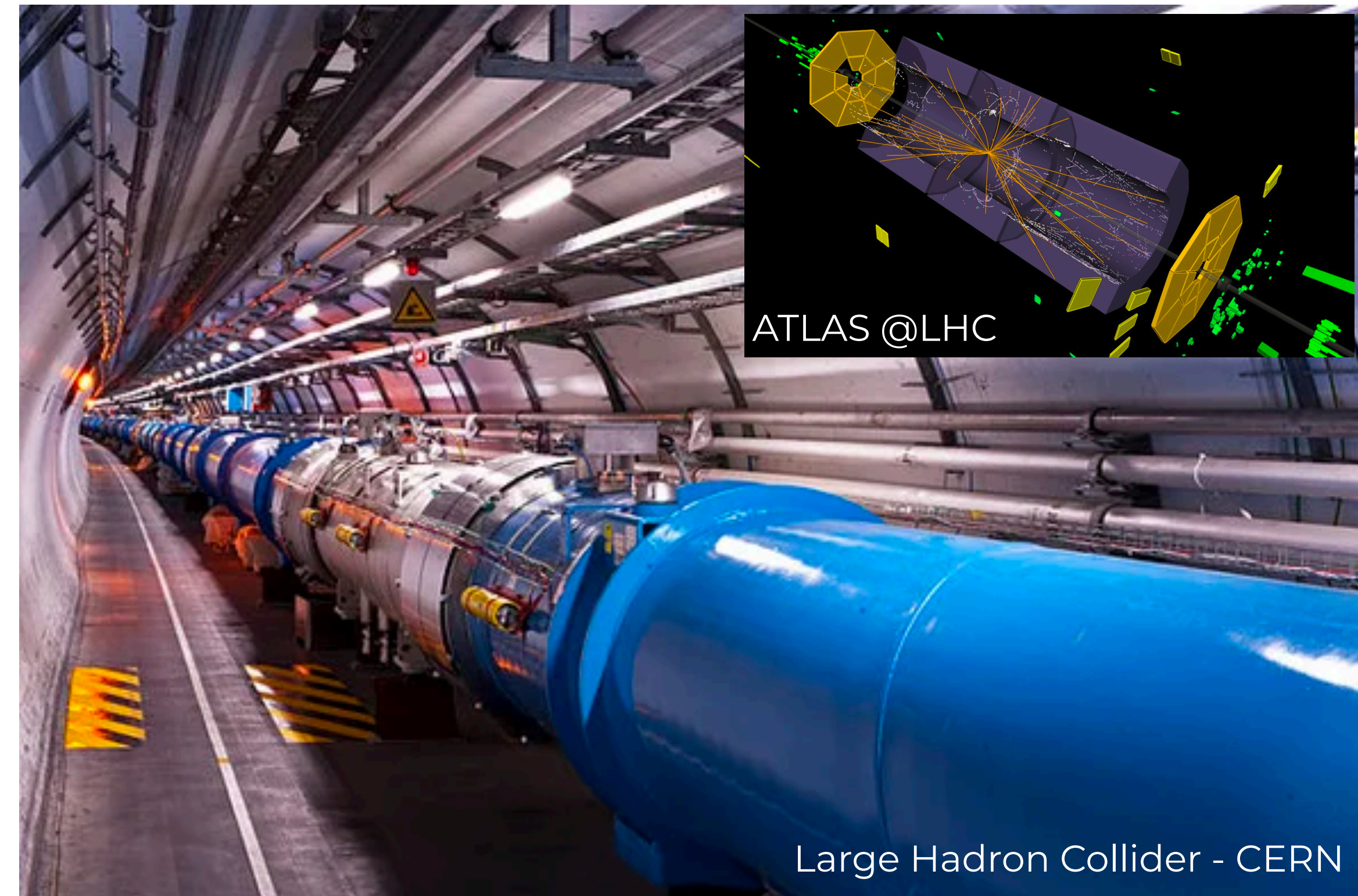
Where do Cosmic Rays come from?



Cosmic Accelerator - Universe

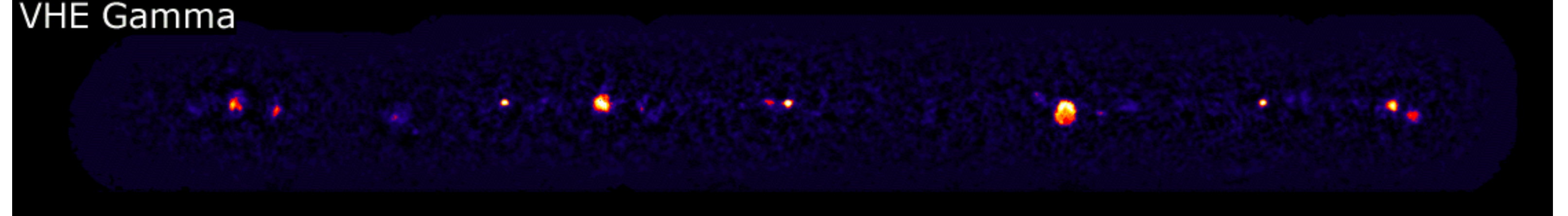
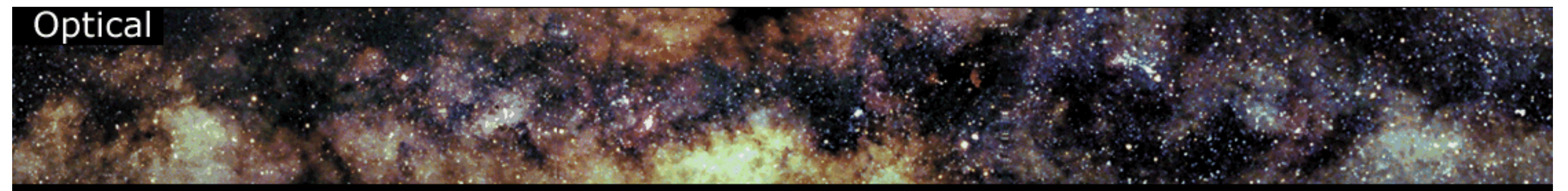
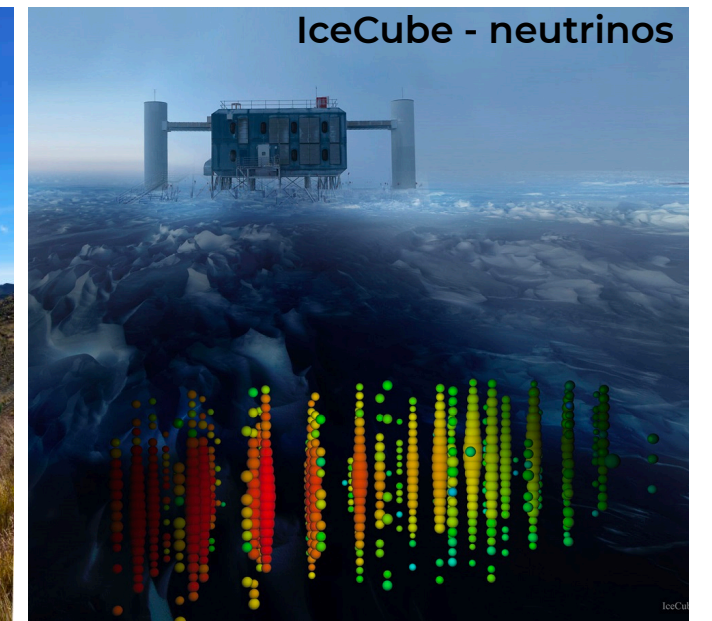
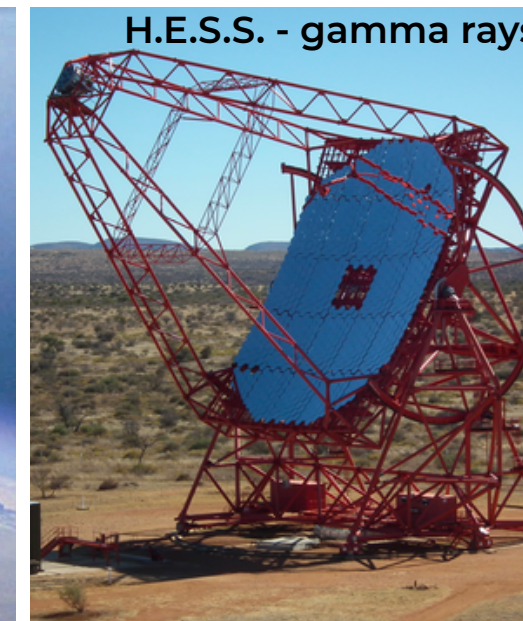
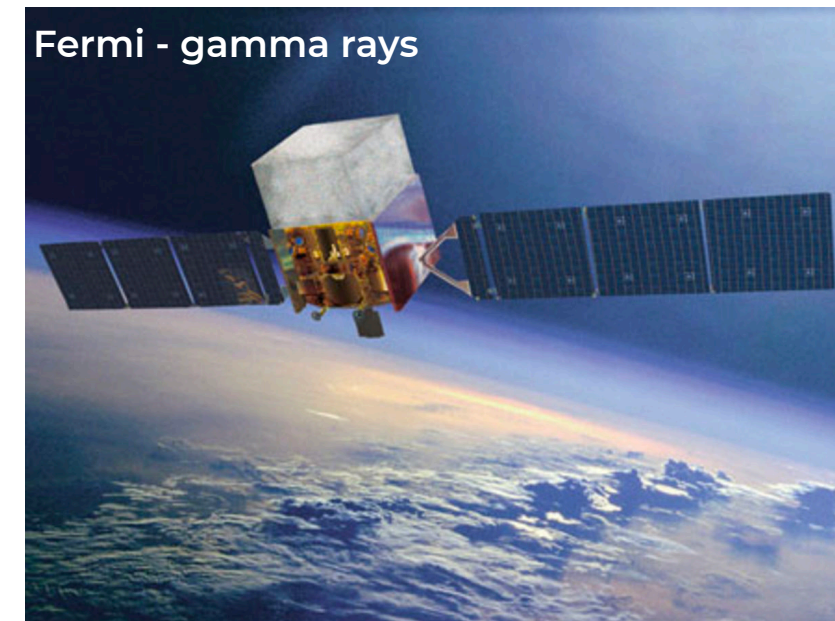
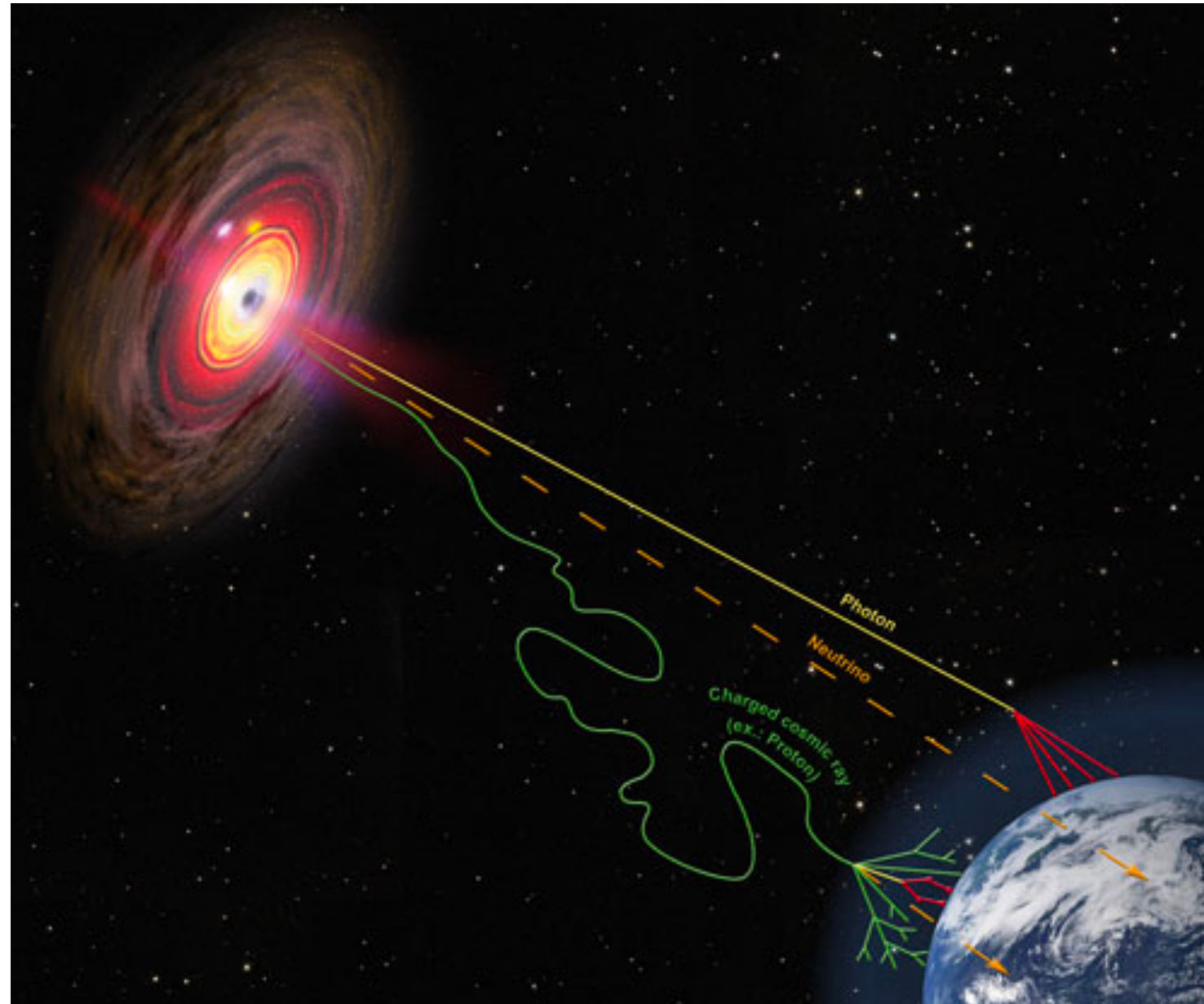
cosmic particle accelerator

injecting high energy atomic nuclei into space
(cosmic rays)



Large Hadron Collider - CERN

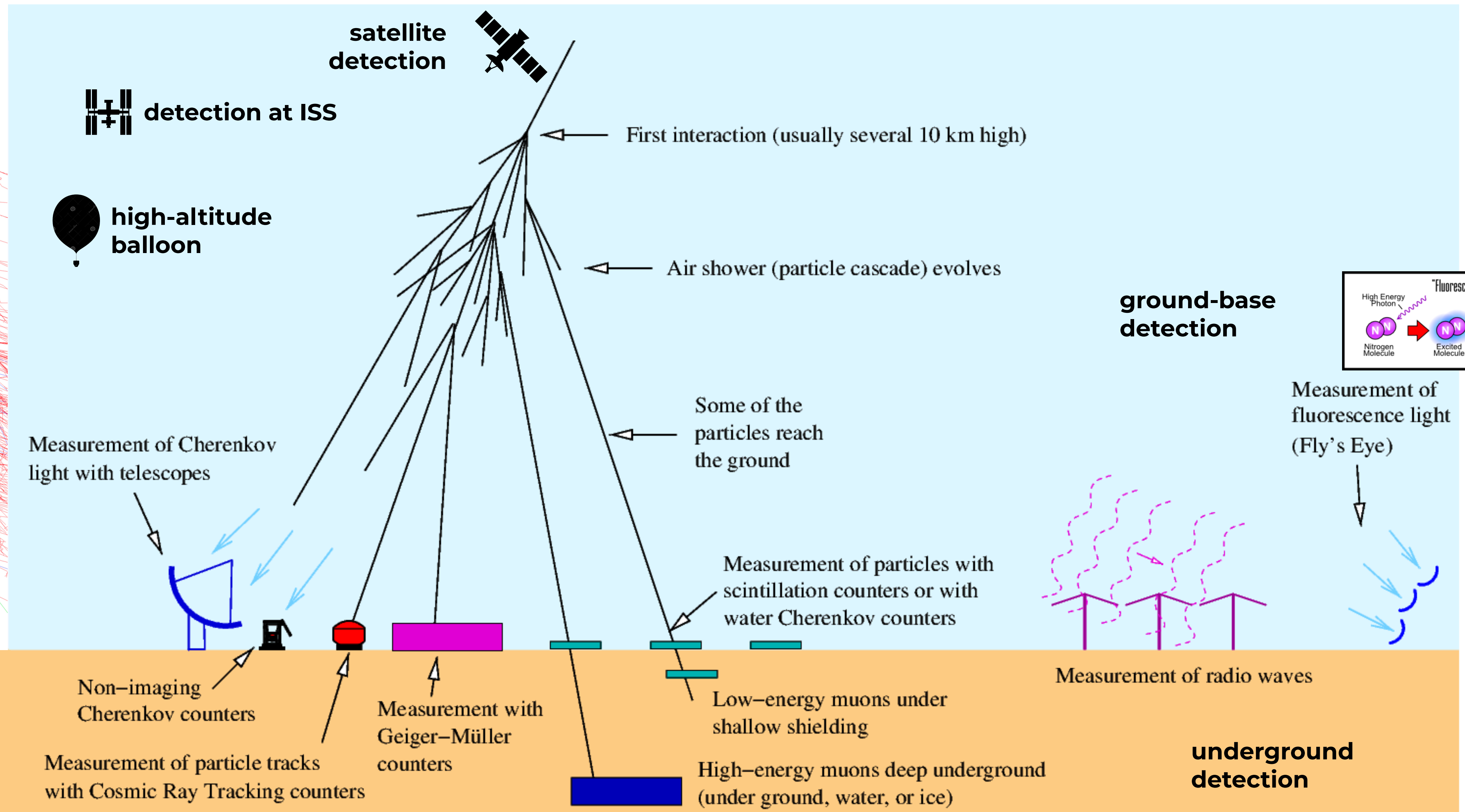
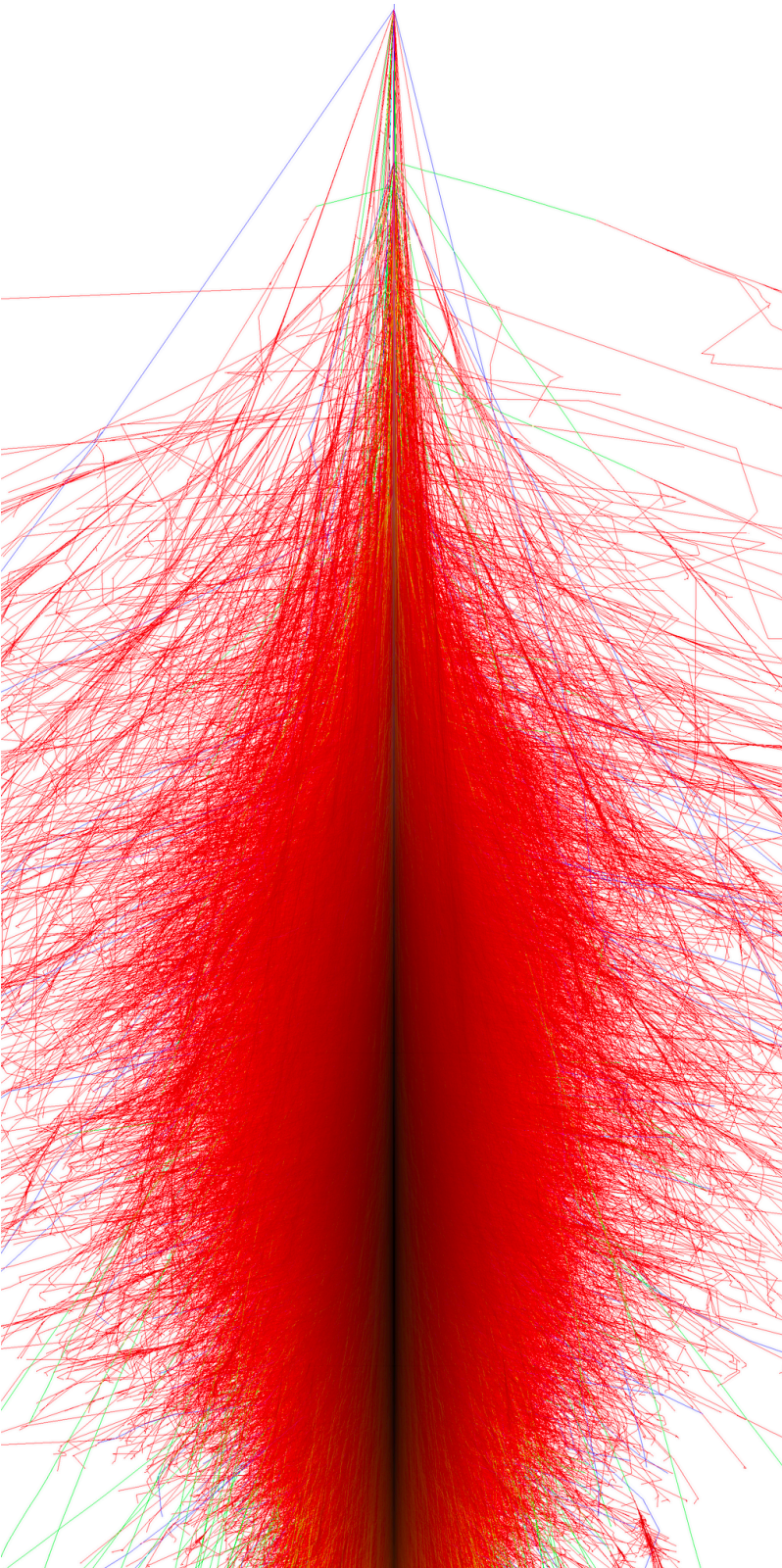
Where do Cosmic Rays come from?



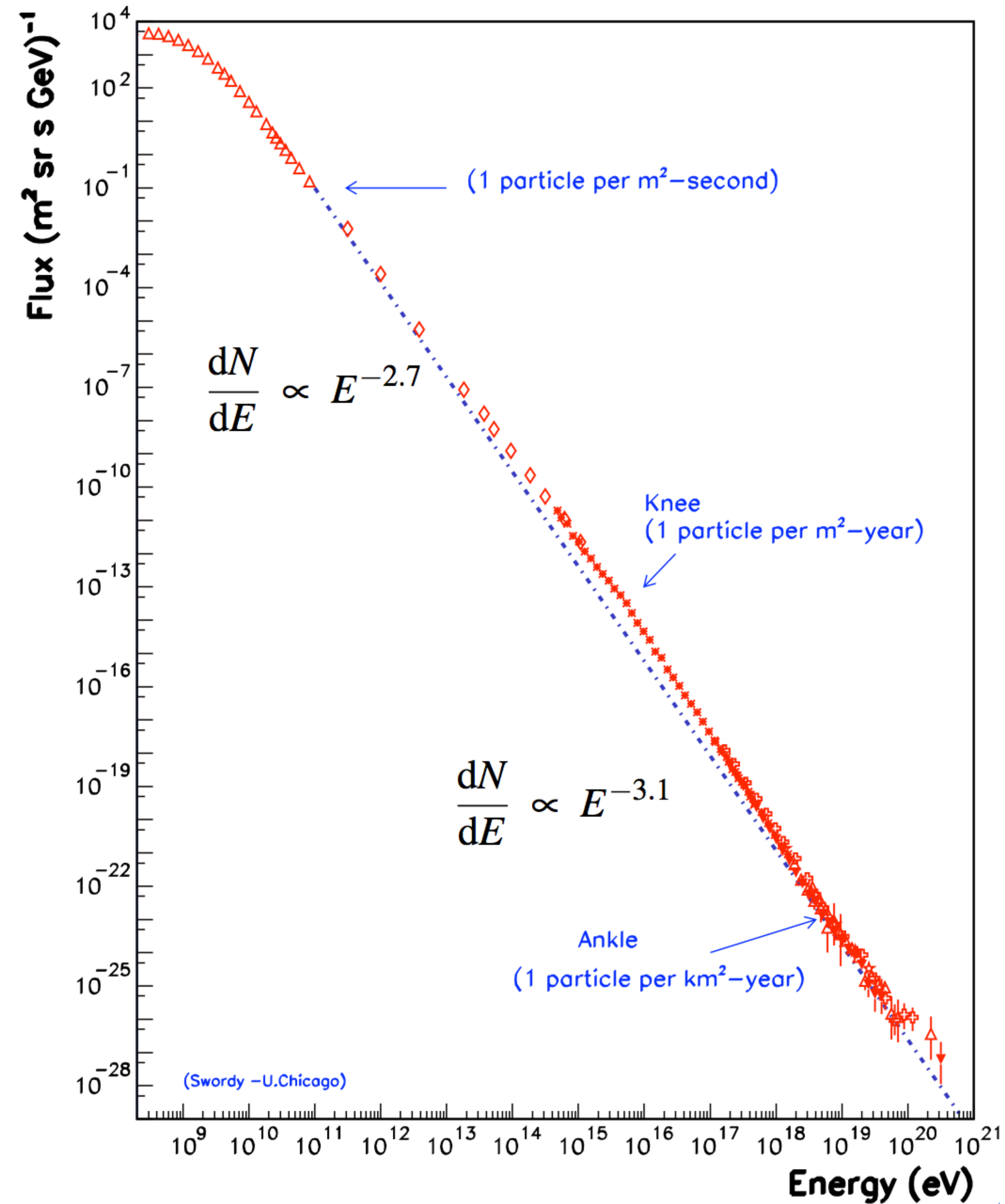
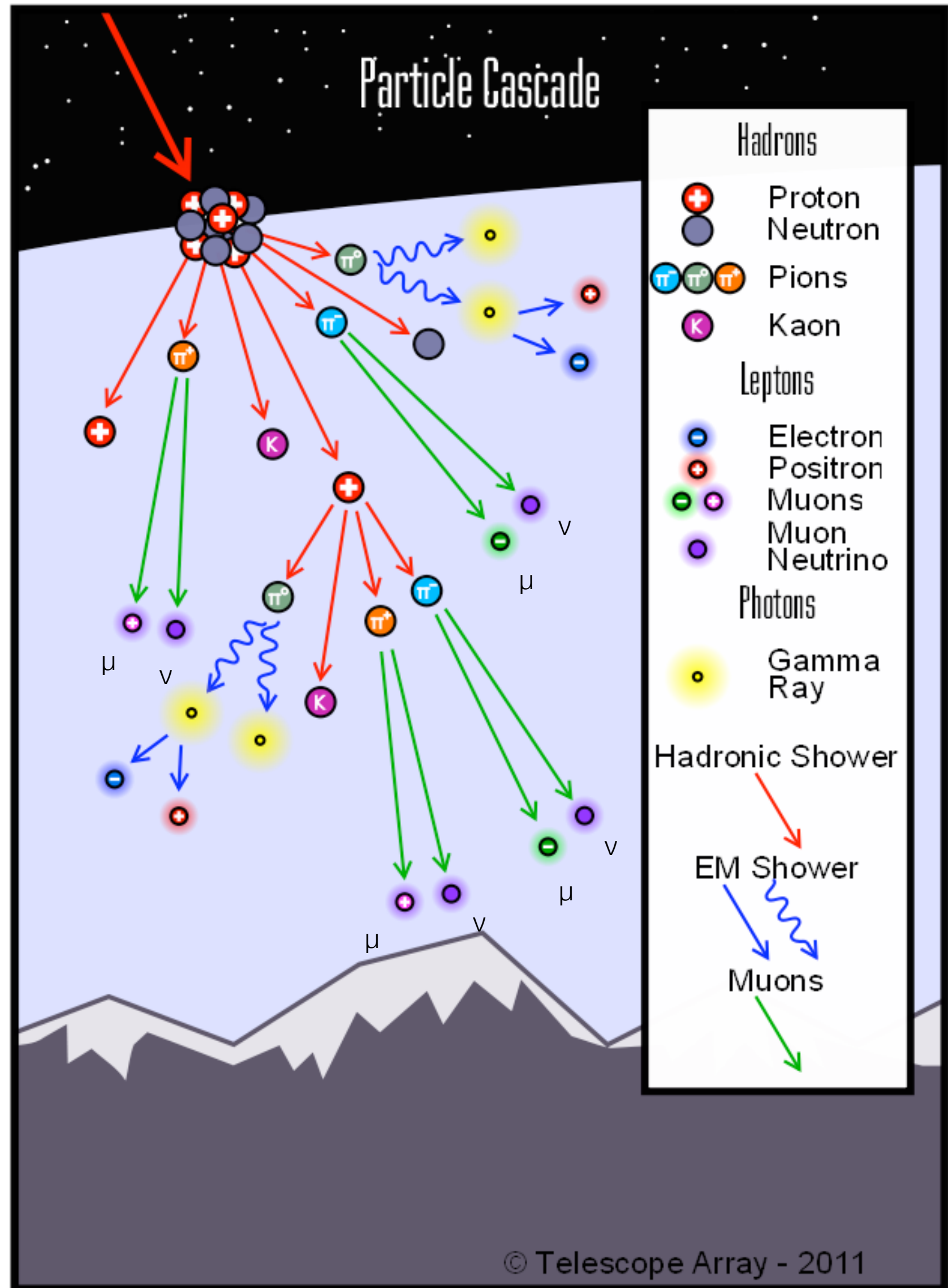
gamma ray sources to pinpoint where **cosmic rays** are accelerated
hadronic cosmic ray sources must emit **neutrinos** as well

multi-messenger astronomy

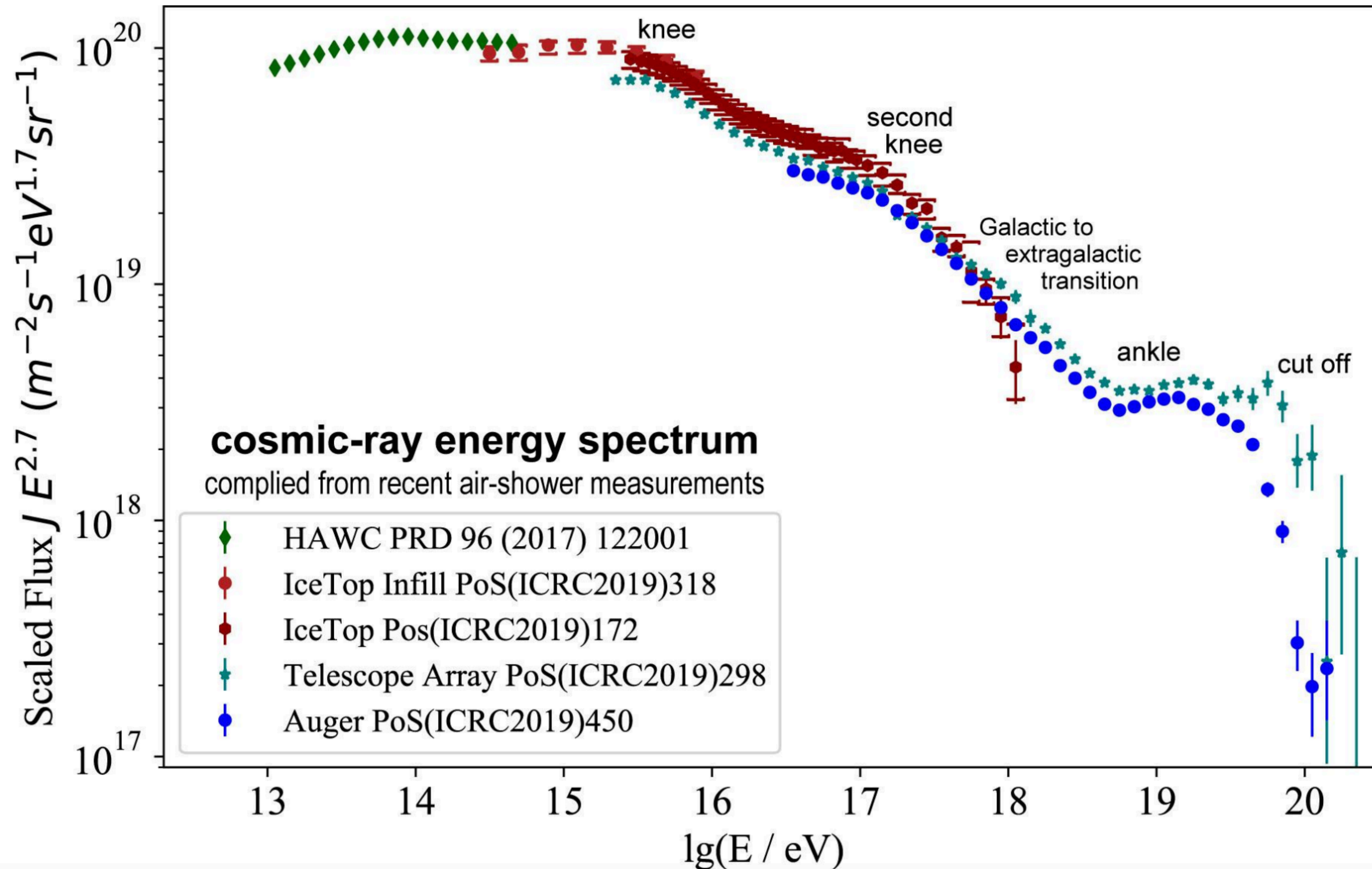
How do we detect Cosmic Rays?



Cosmic Ray Energy Spectrum



Cosmic Ray Energy Spectrum



Frank Schröder

Cosmic Ray Energy Spectrum

direct vs indirect observations

direct detection of cosmic rays

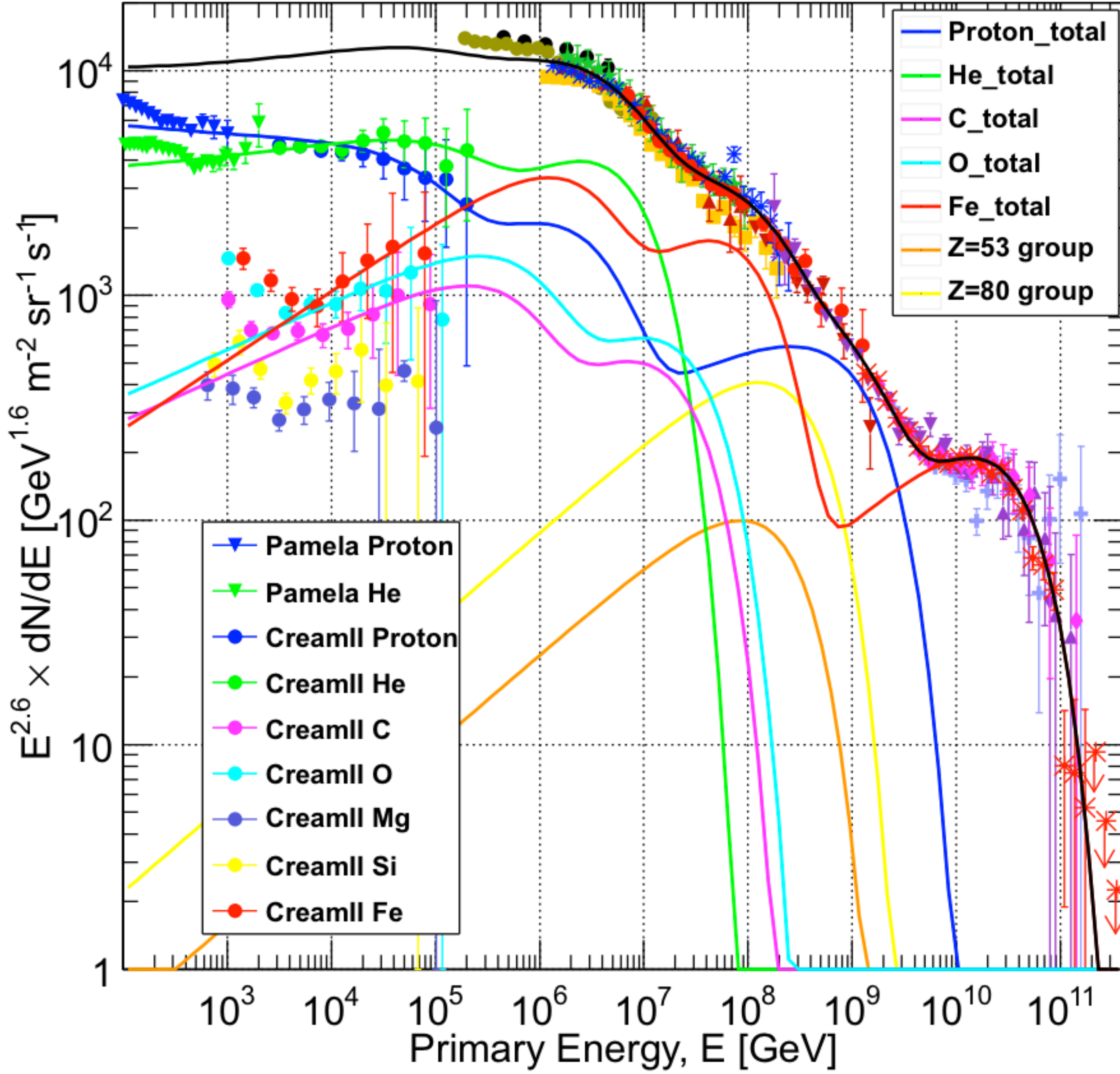
small instrumentation at high-altitude or in orbit

easy particle ID

indirect detection

large ground-based experiments

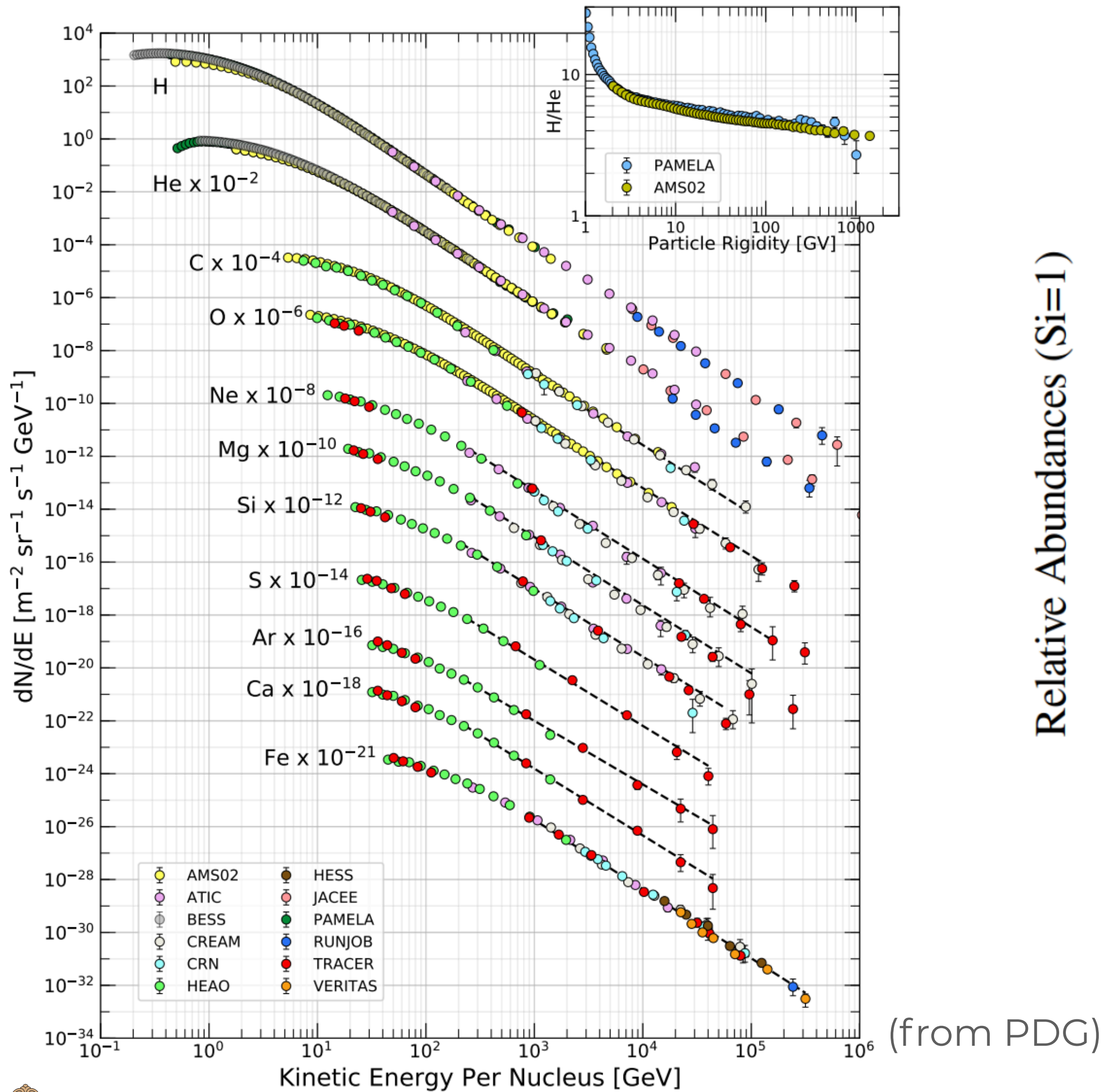
difficult particle ID (hadronic interactions)



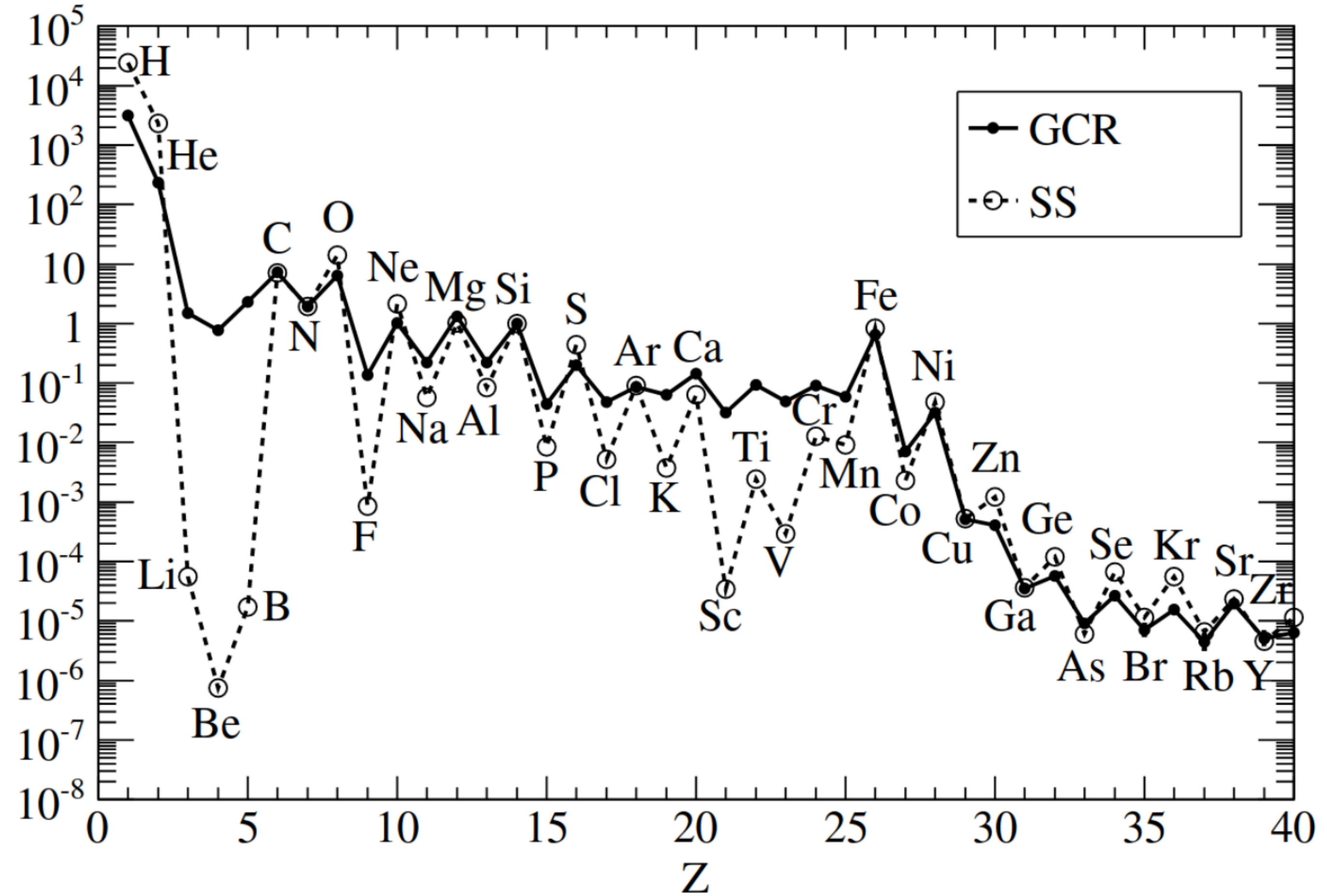
Cosmic Ray mass composition

direct observations

PoS(ICRC2021)124



Relative Abundances (Si=1)

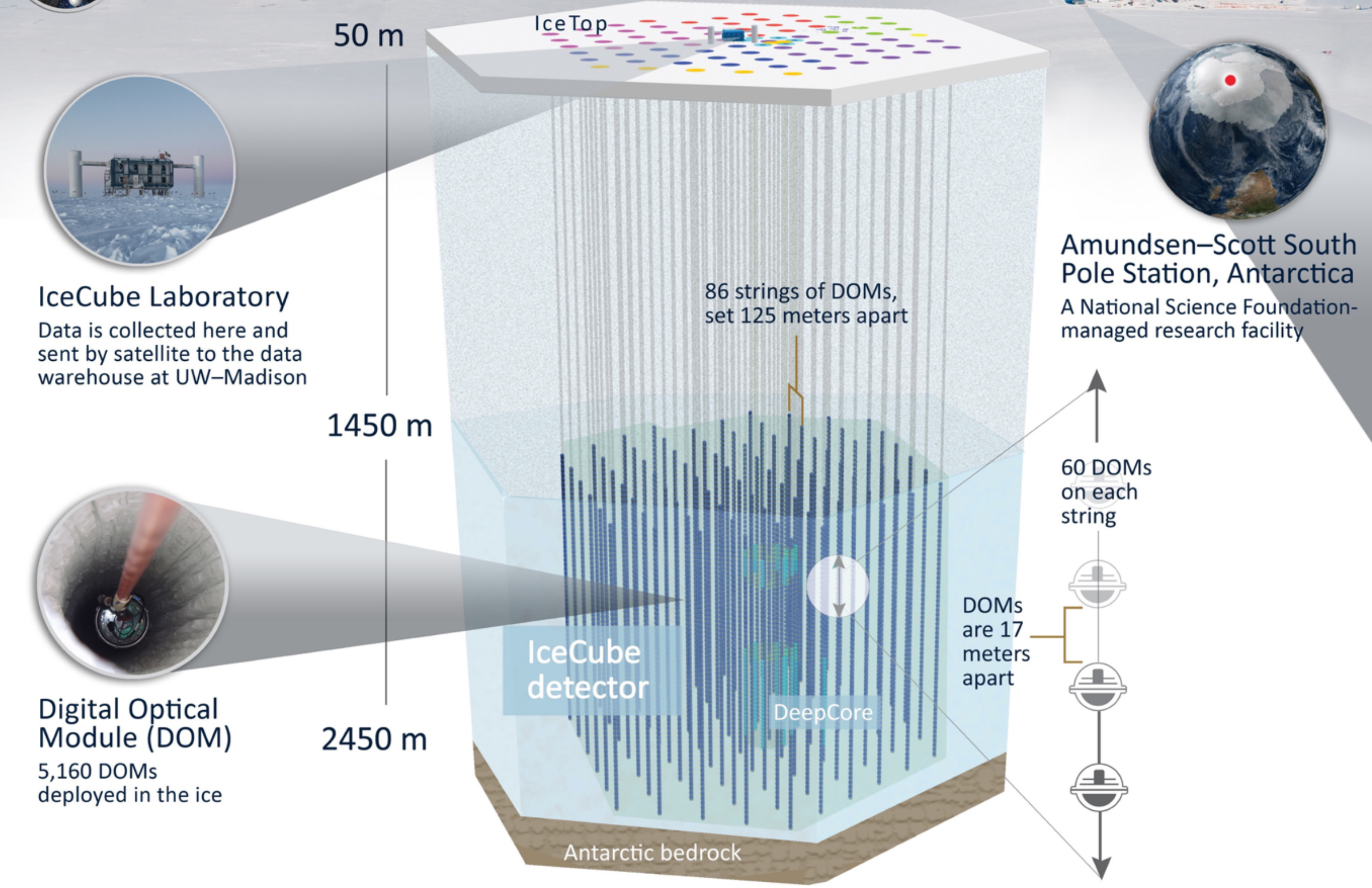


(from PDG)



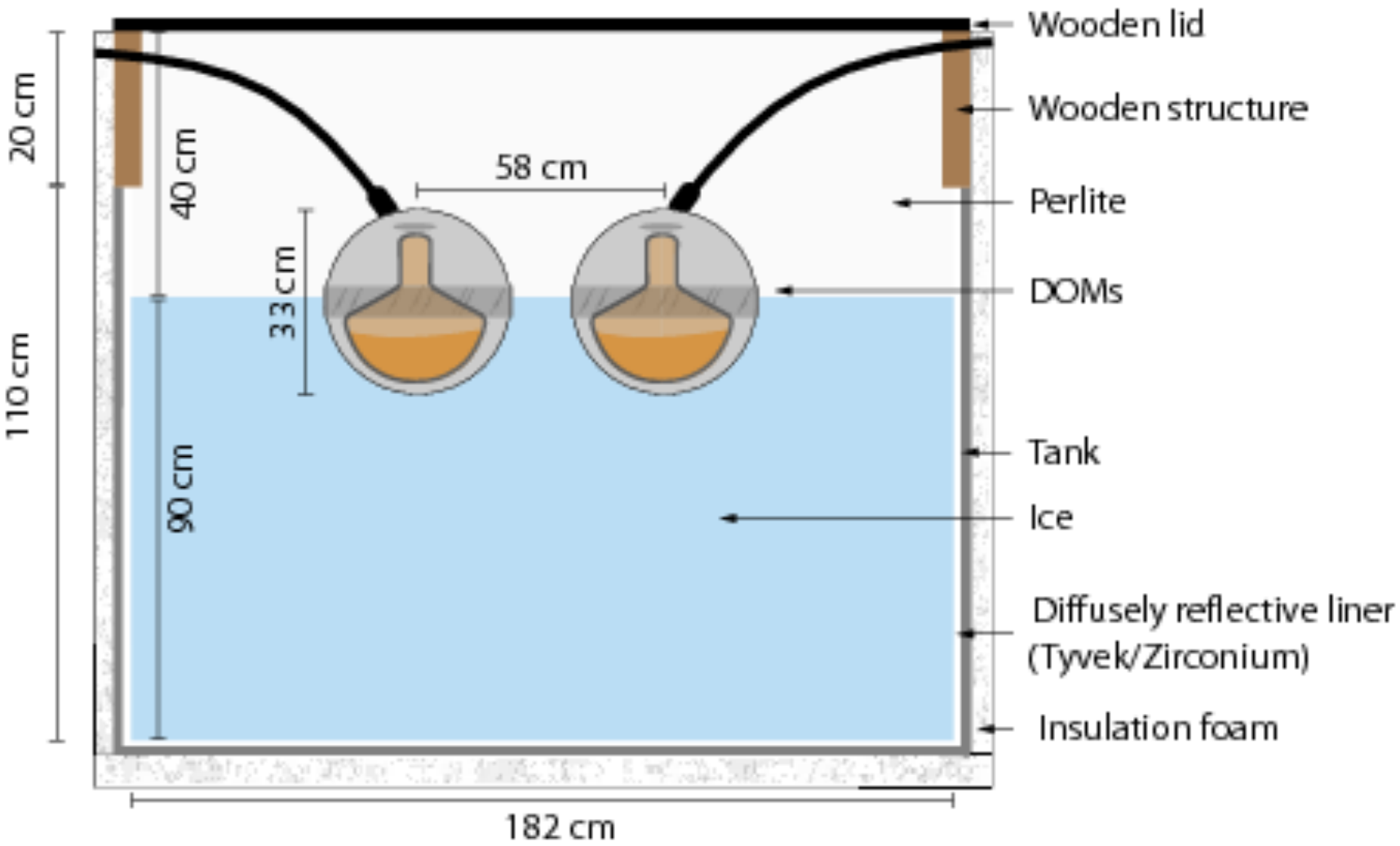
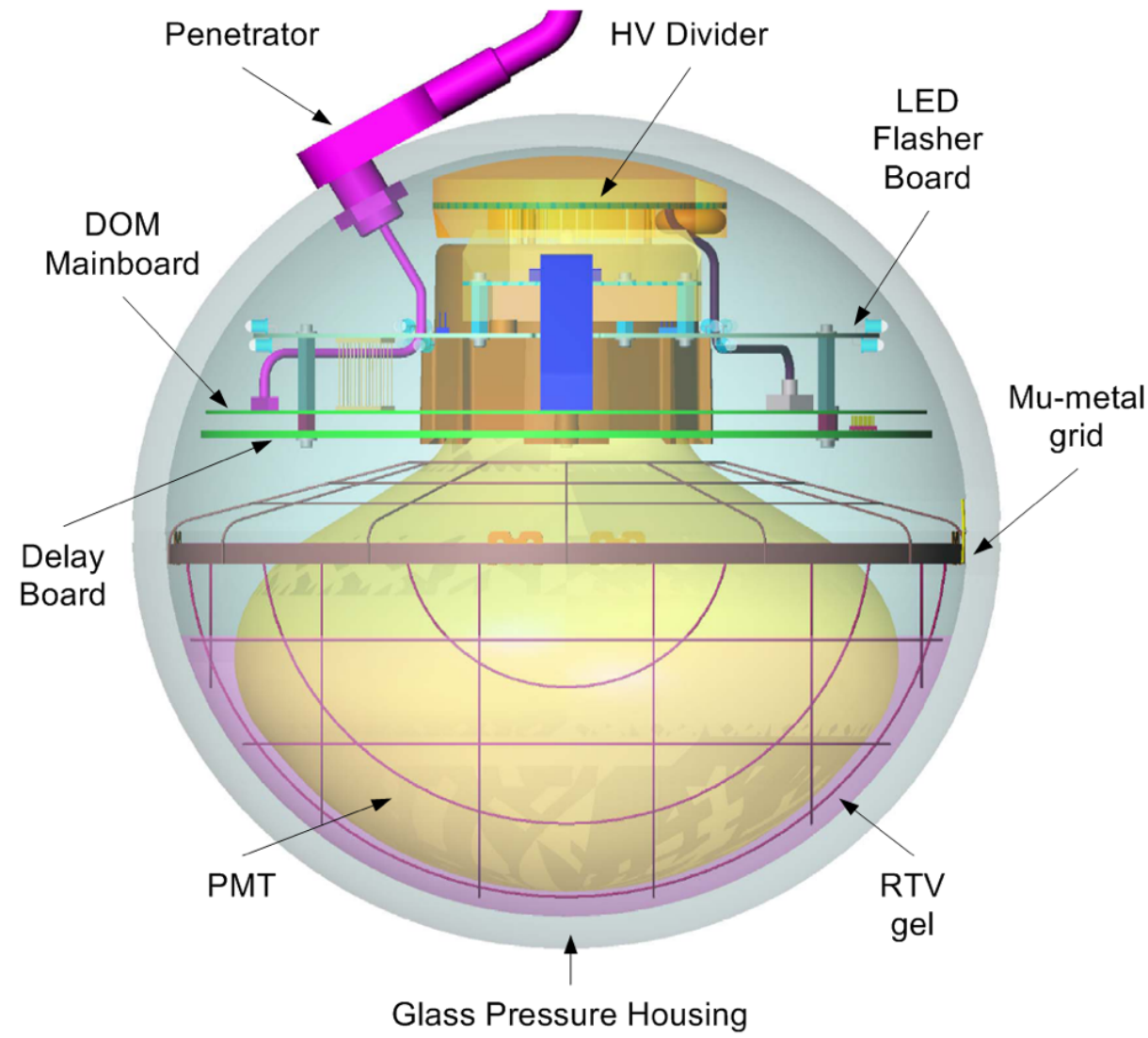
The IceCube Observatory

The Instrumentation



Digital Optical Module (DOM)

with 10" PMT & local DAQ electronics

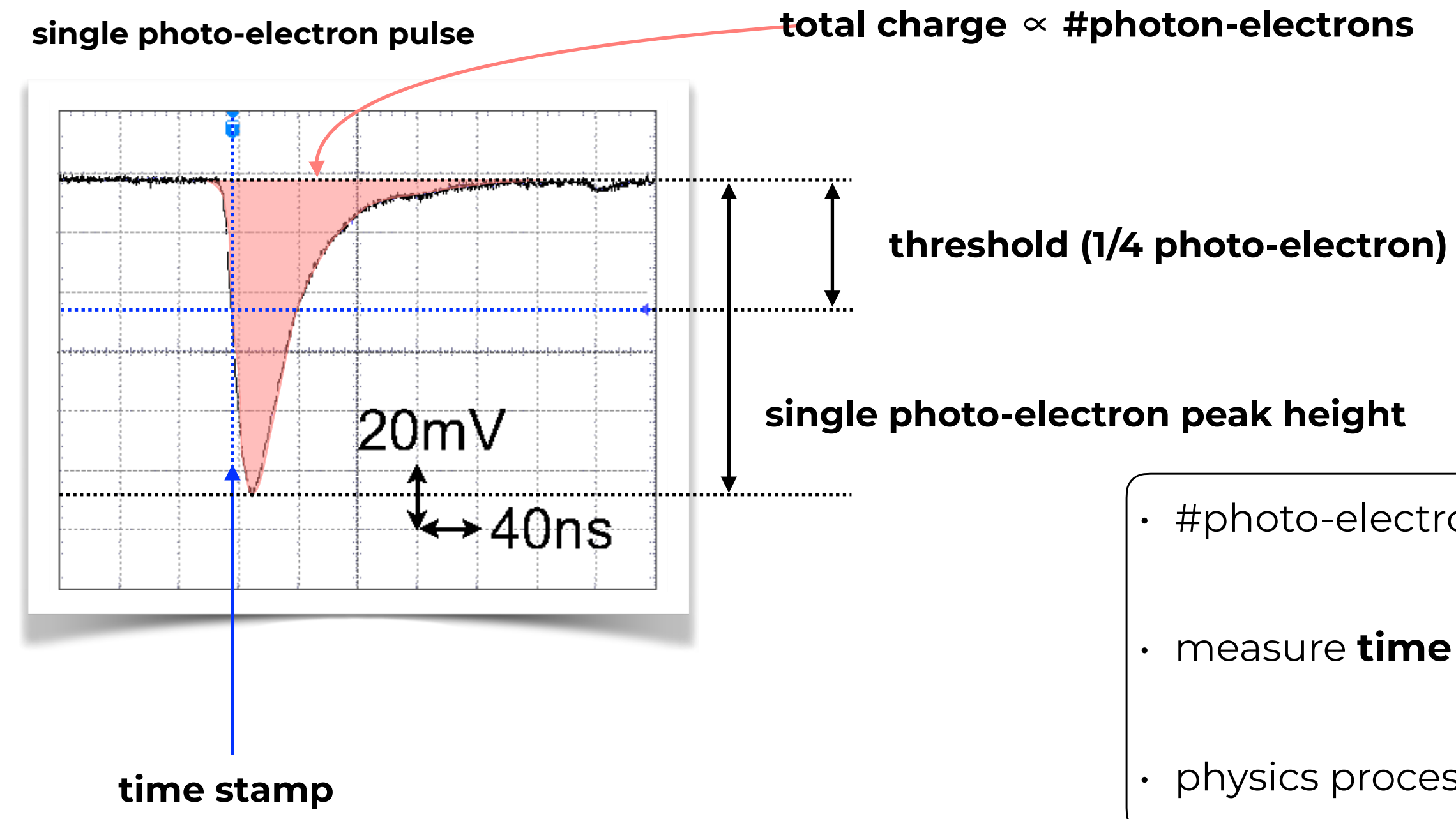
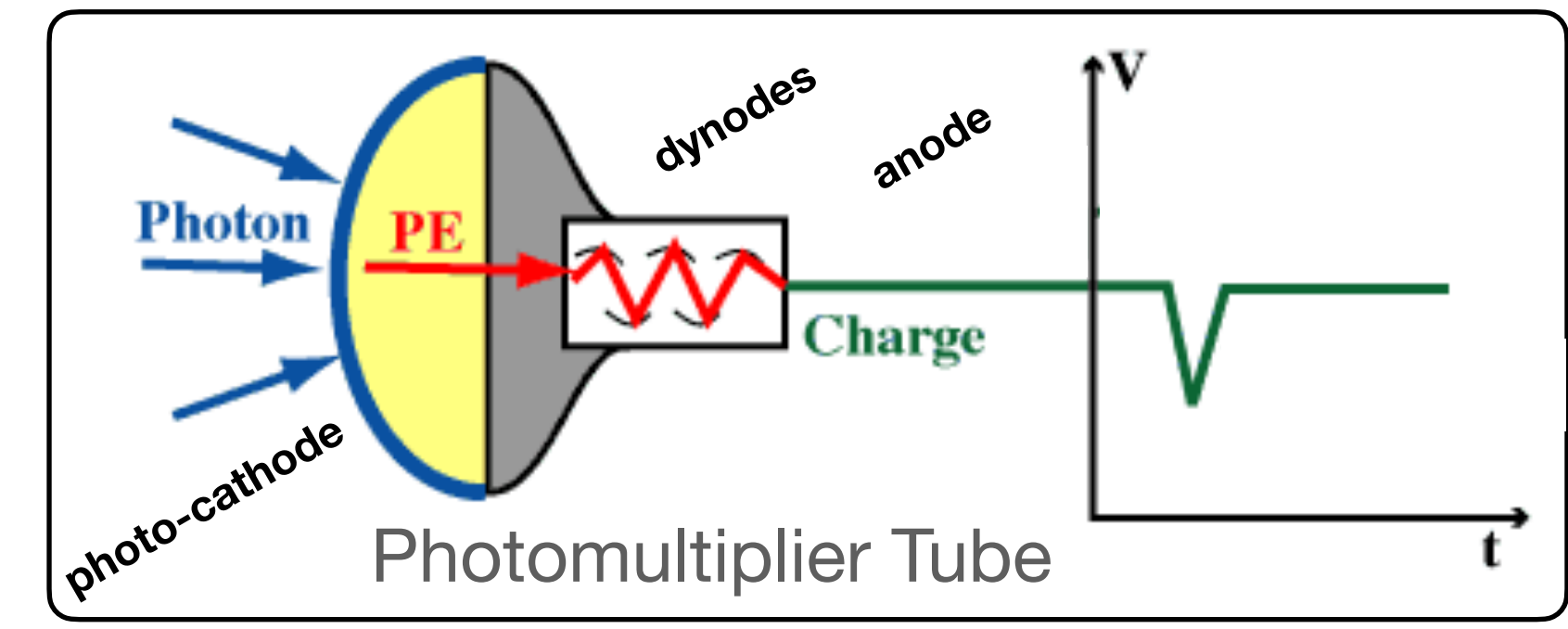
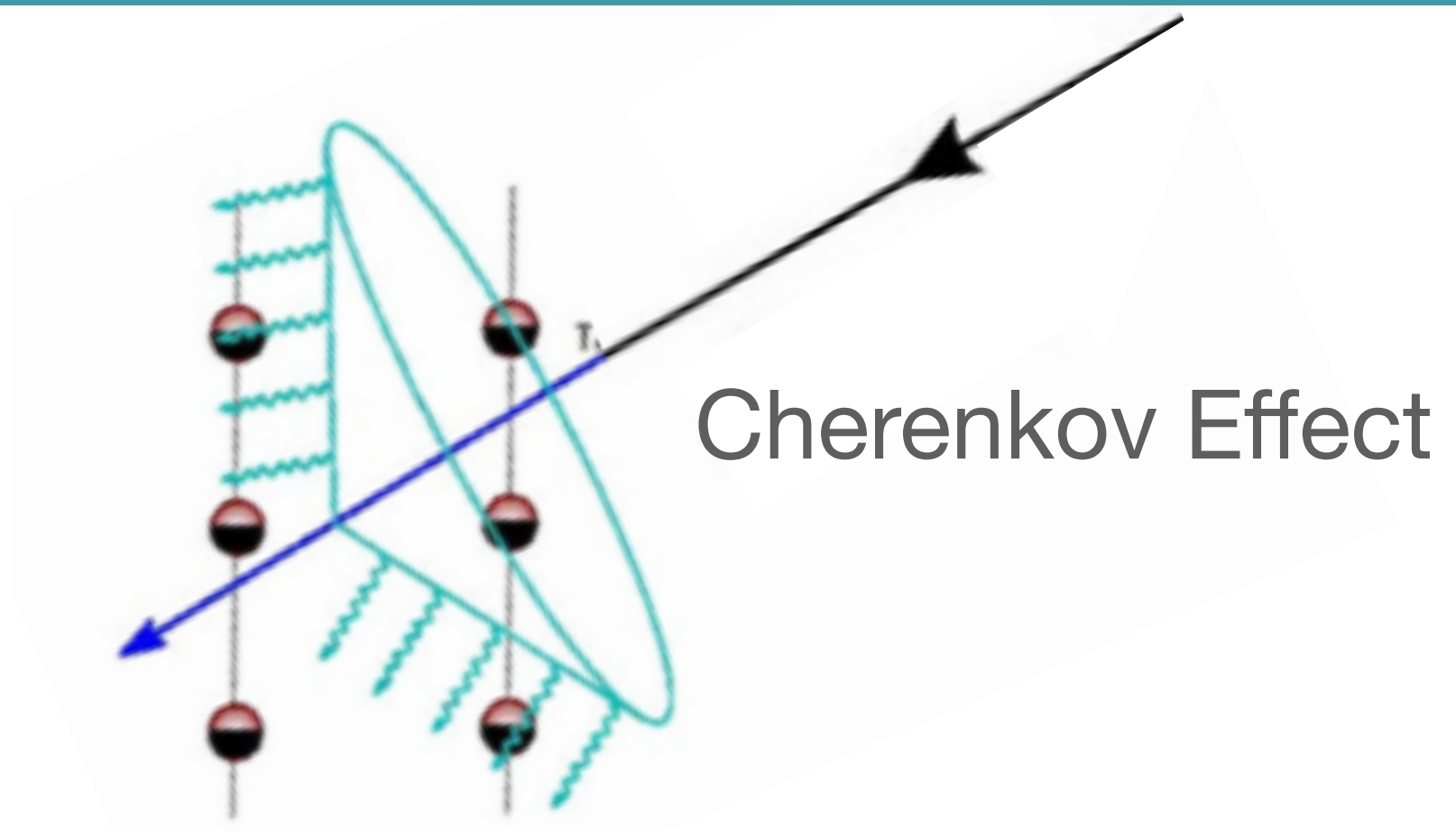
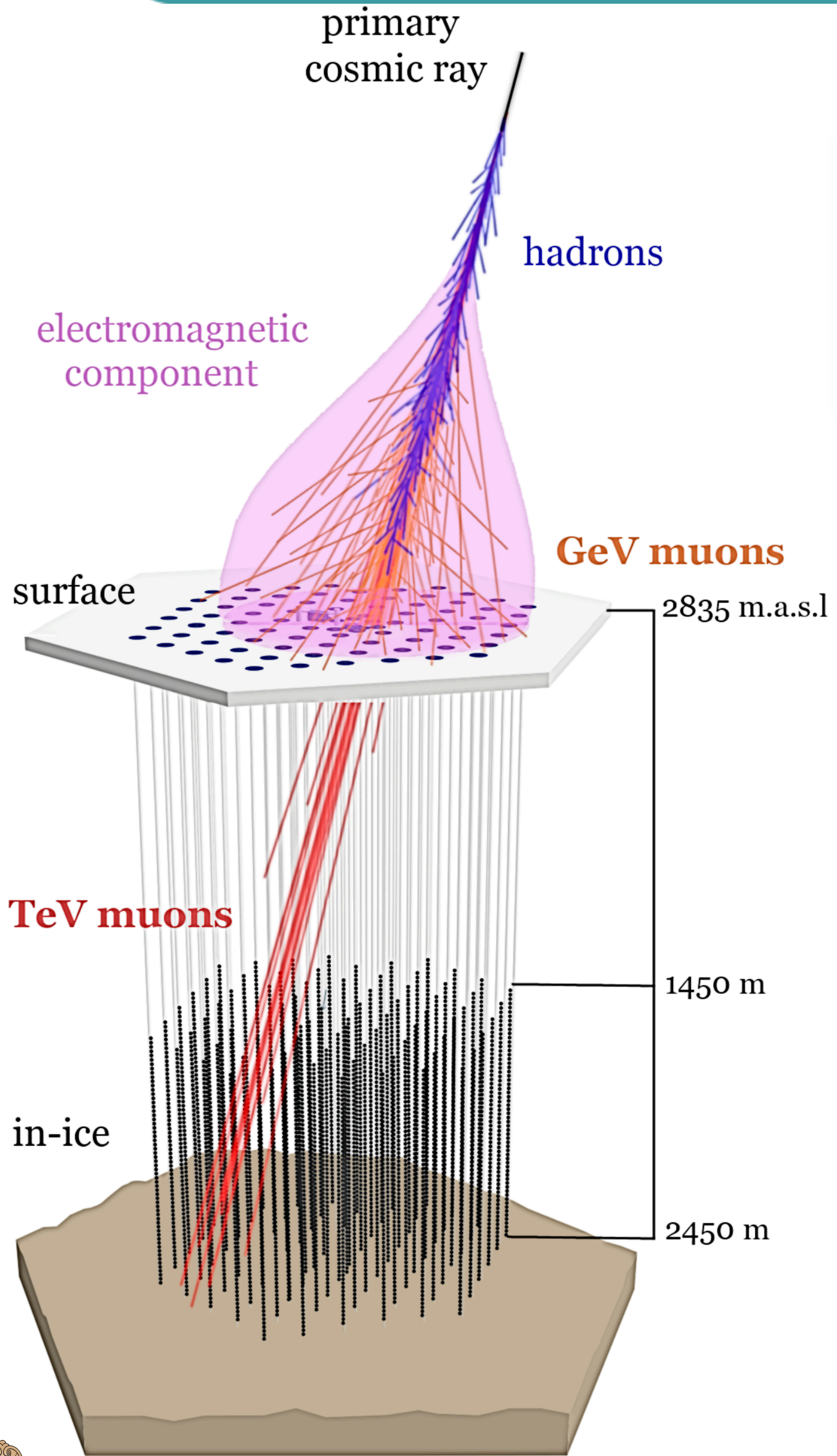


Digital Optical Module (DOM)
5,160 DOMs deployed in the ice



The IceCube Observatory

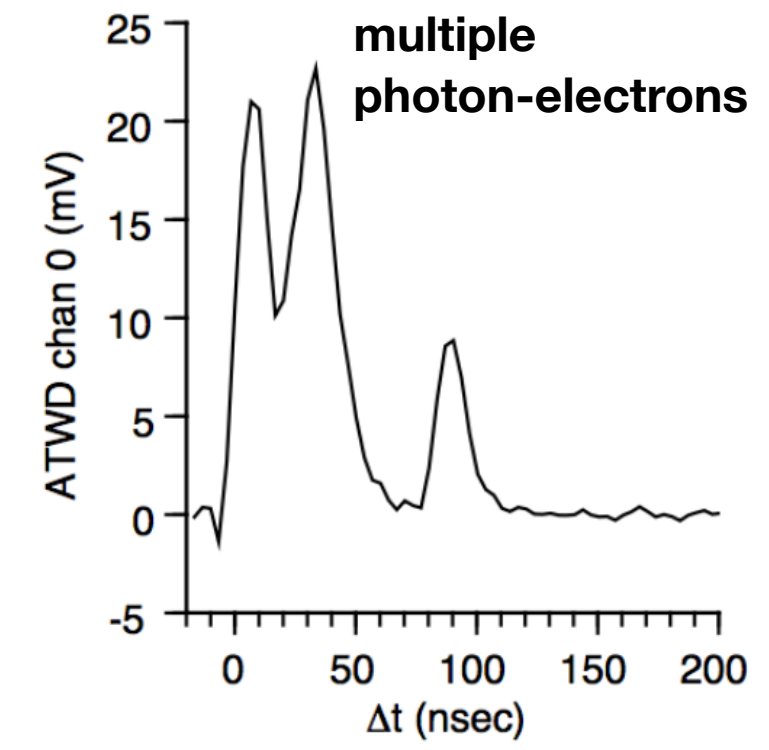
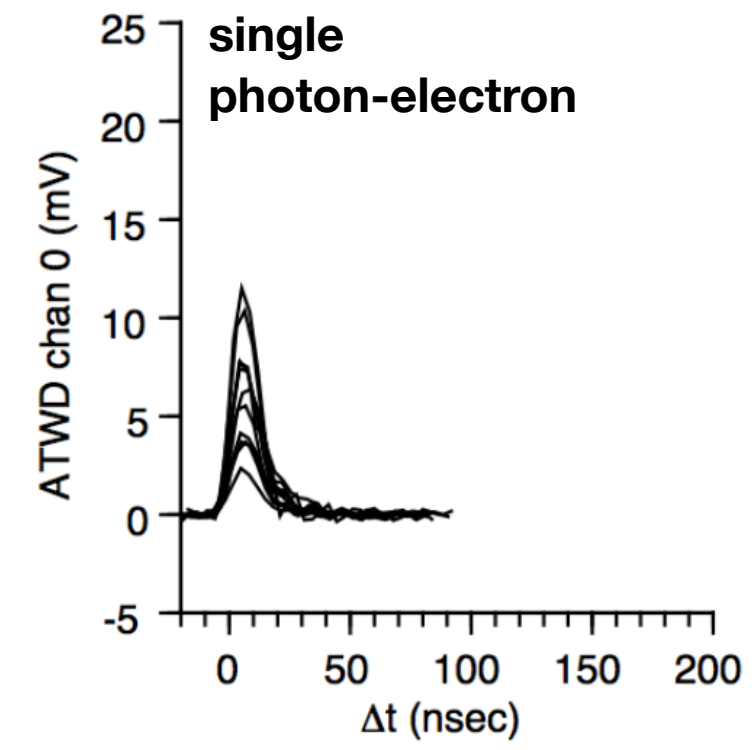
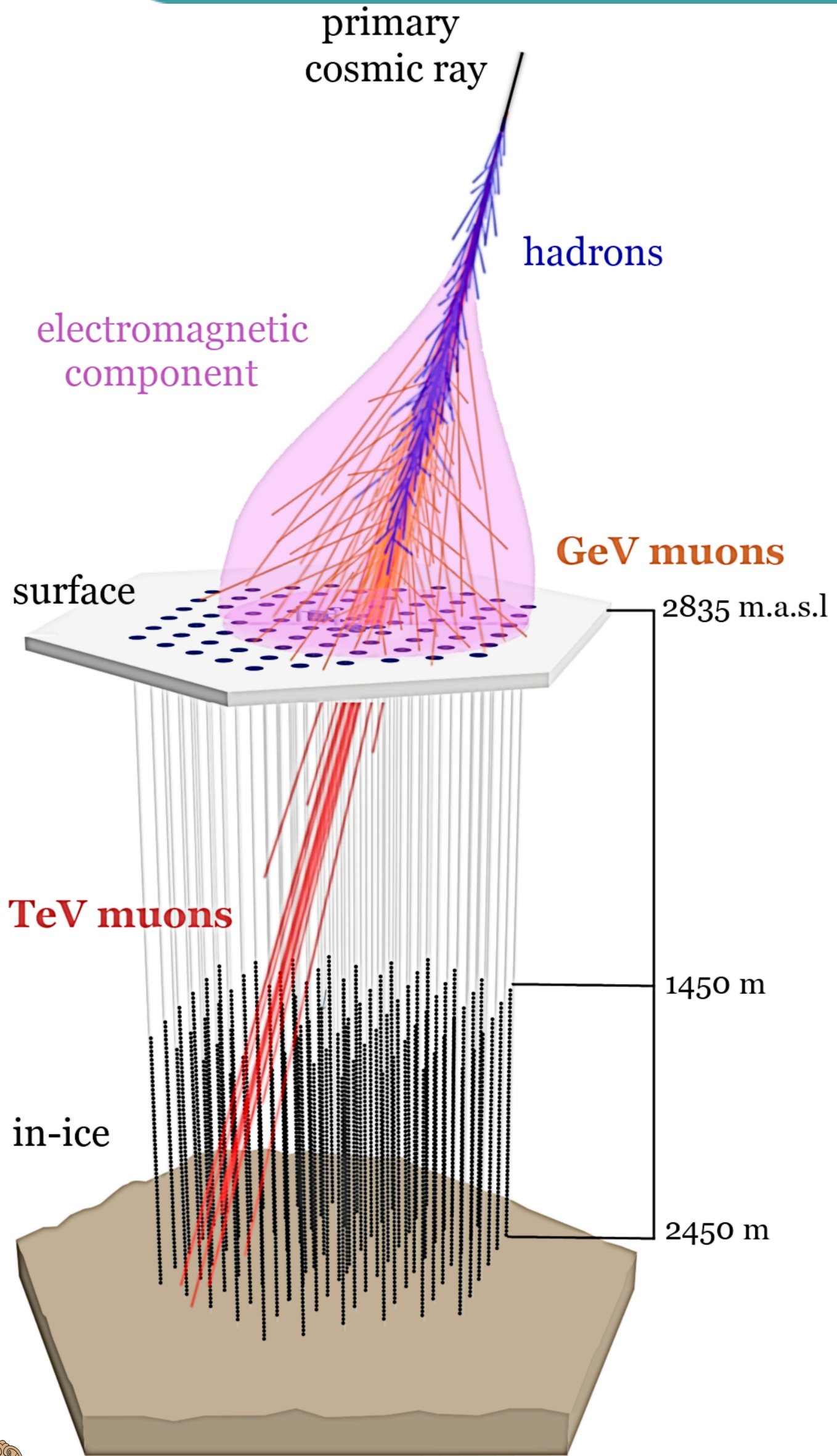
Detecting Cosmic Rays



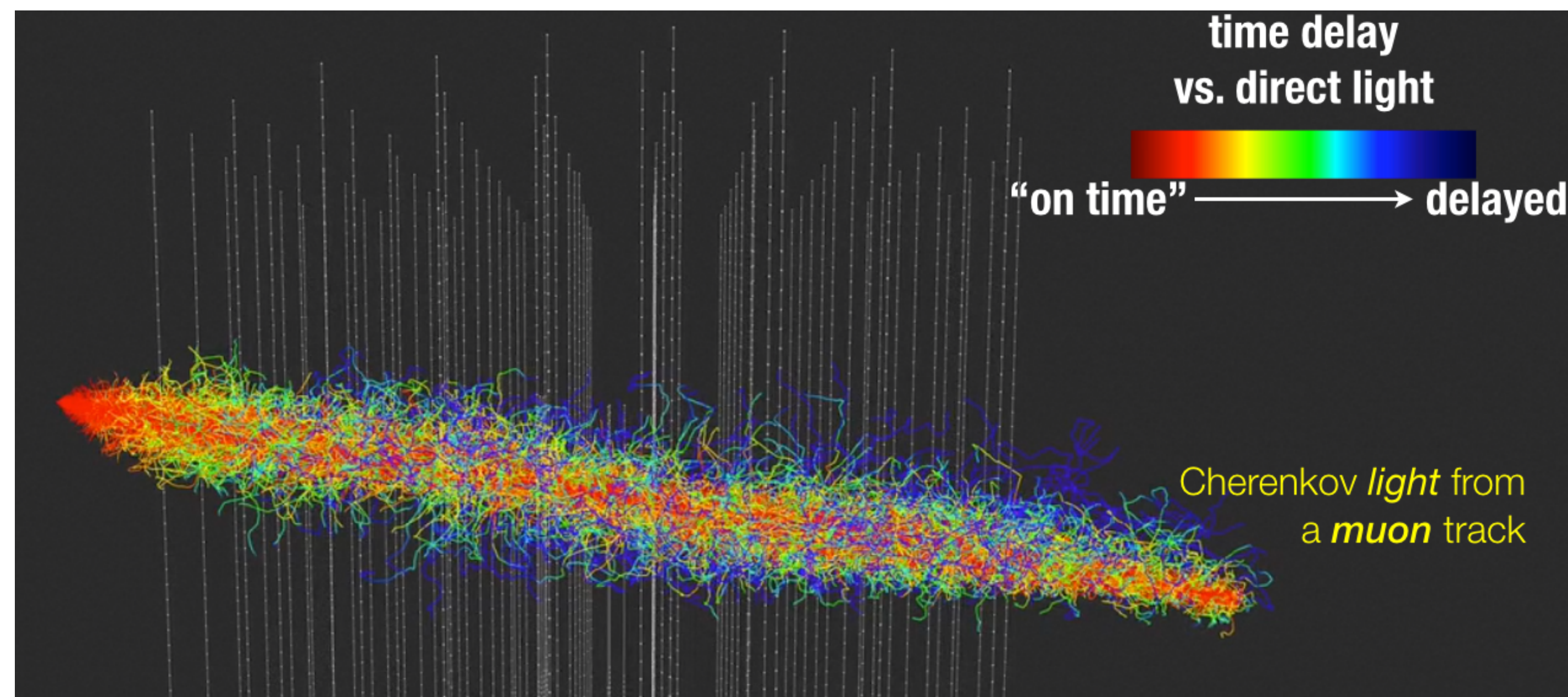
- #photo-electron = energy deposited $\times \epsilon_{\text{eff}}$
- measure **time** and **deposited energy**
- physics processes **shapes waveform**

The IceCube Observatory

Detecting Cosmic Rays

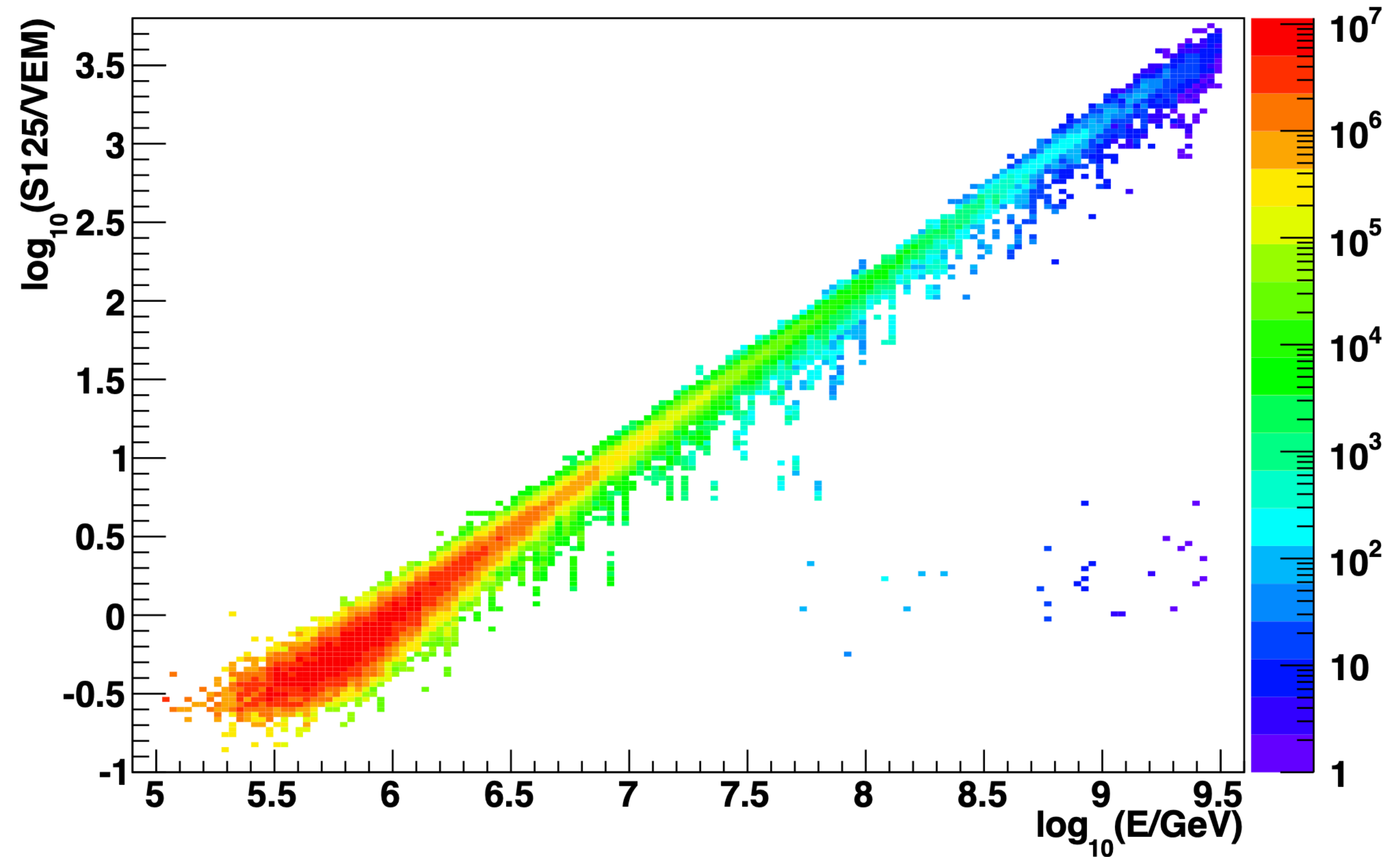


optical properties of glacial ice: **absorption & scattering**



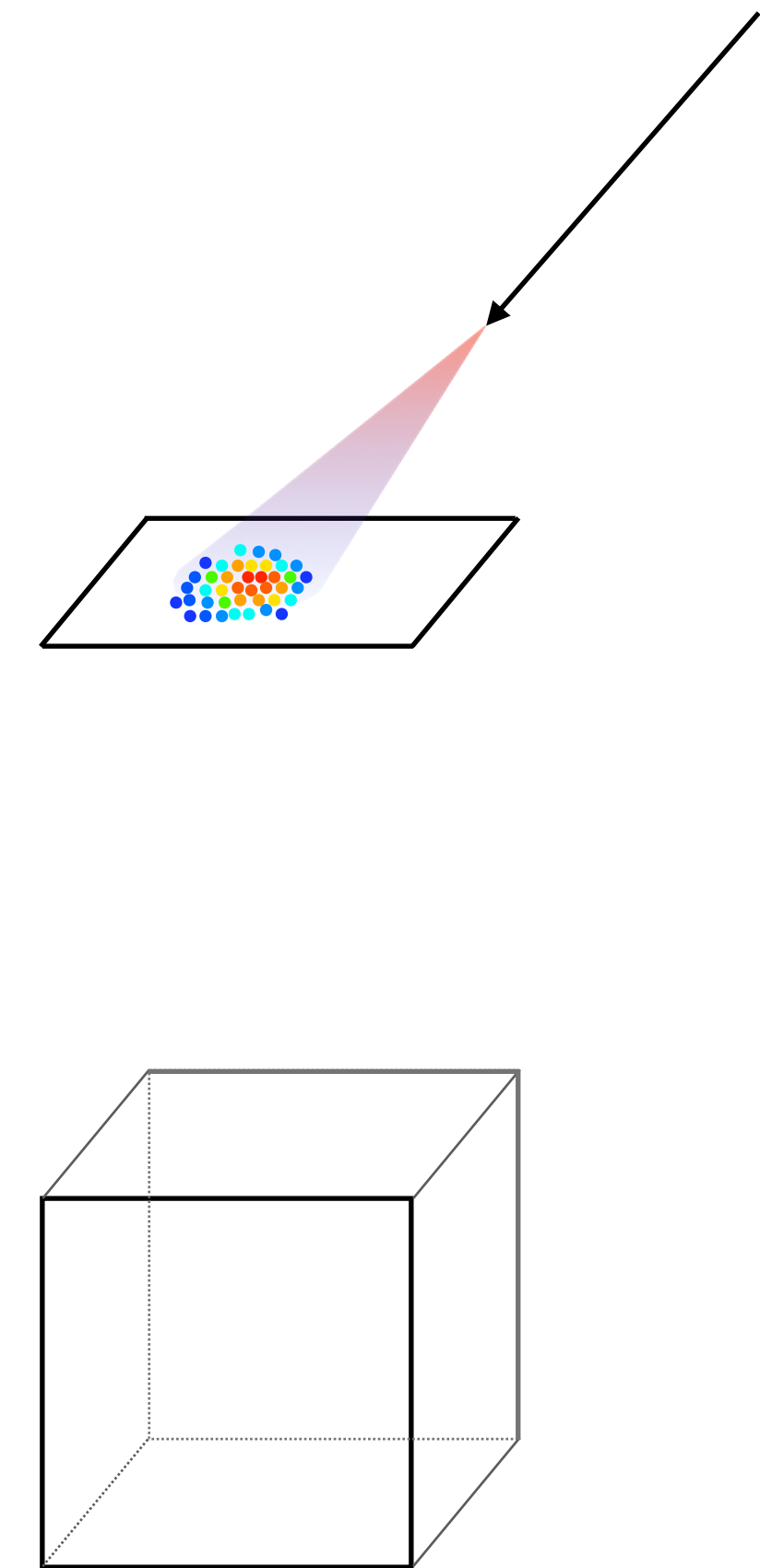
Cosmic Rays with IceTop

Pure Protons, $\cos\theta > 0.95$



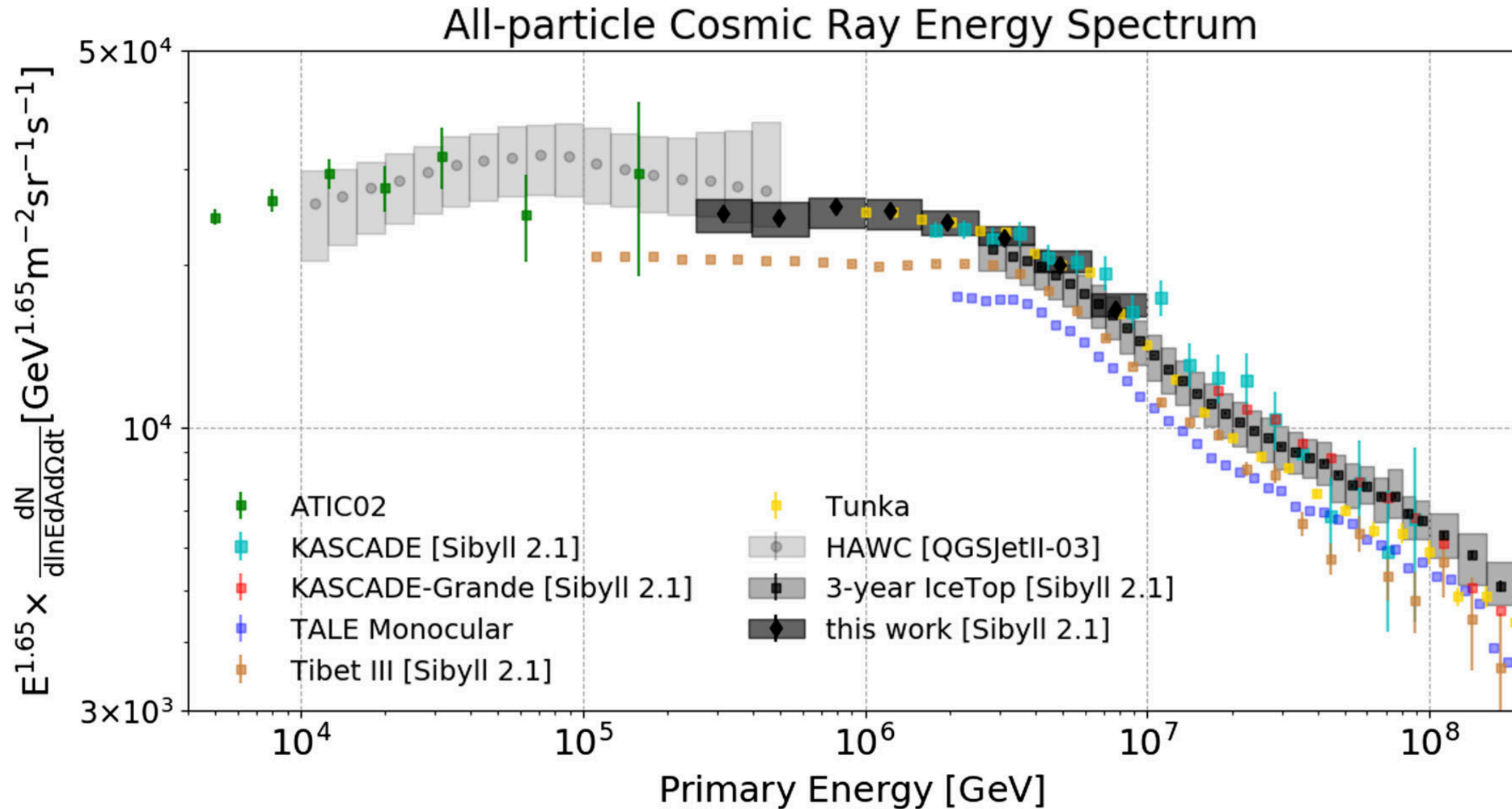
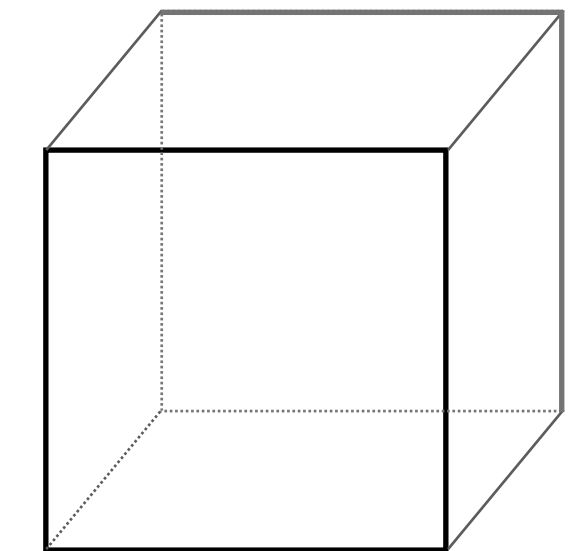
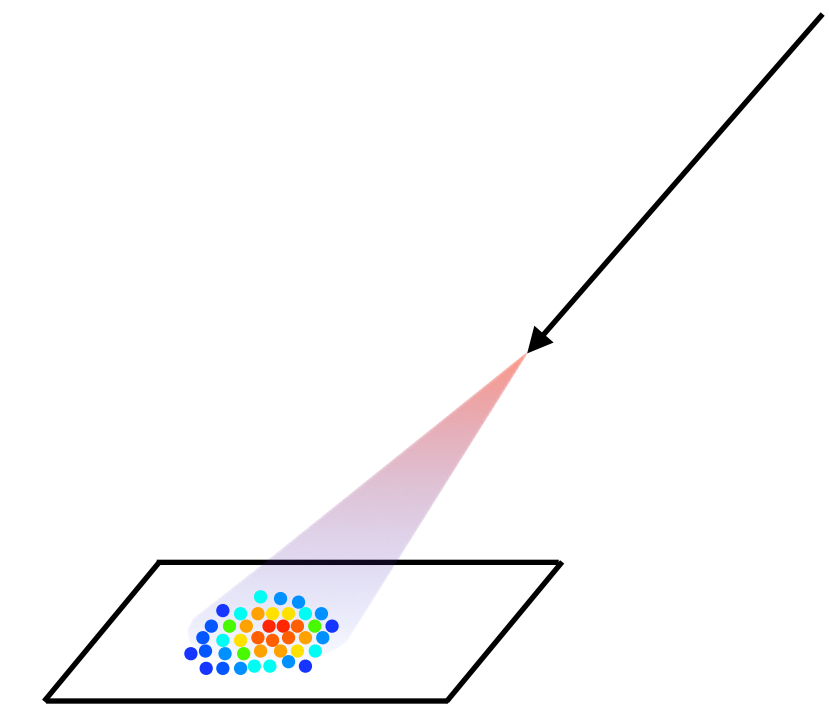
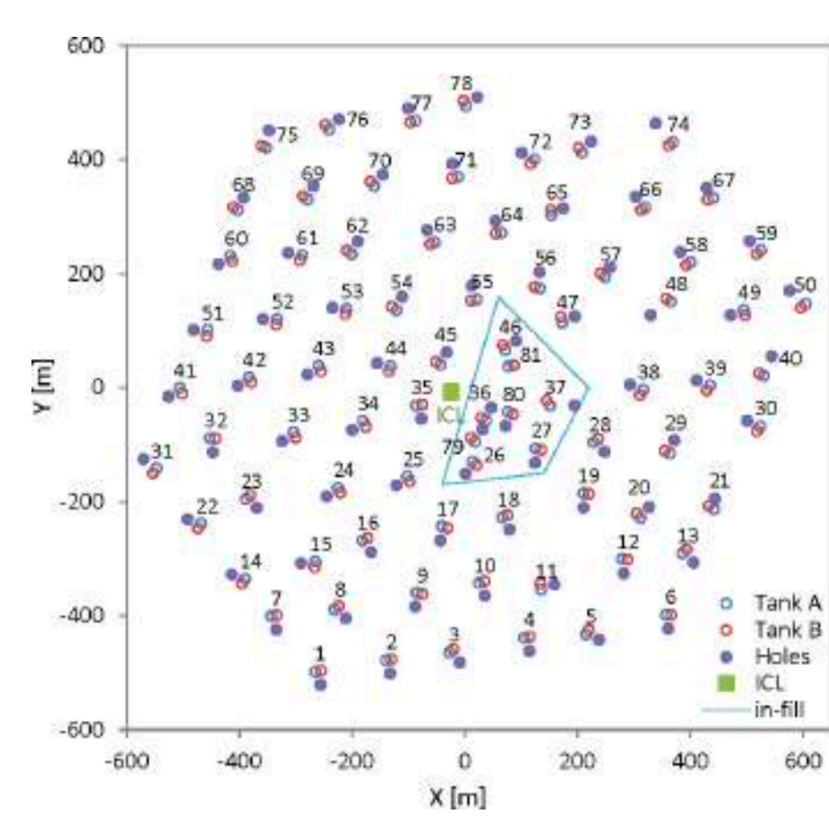
lateral distribution function

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

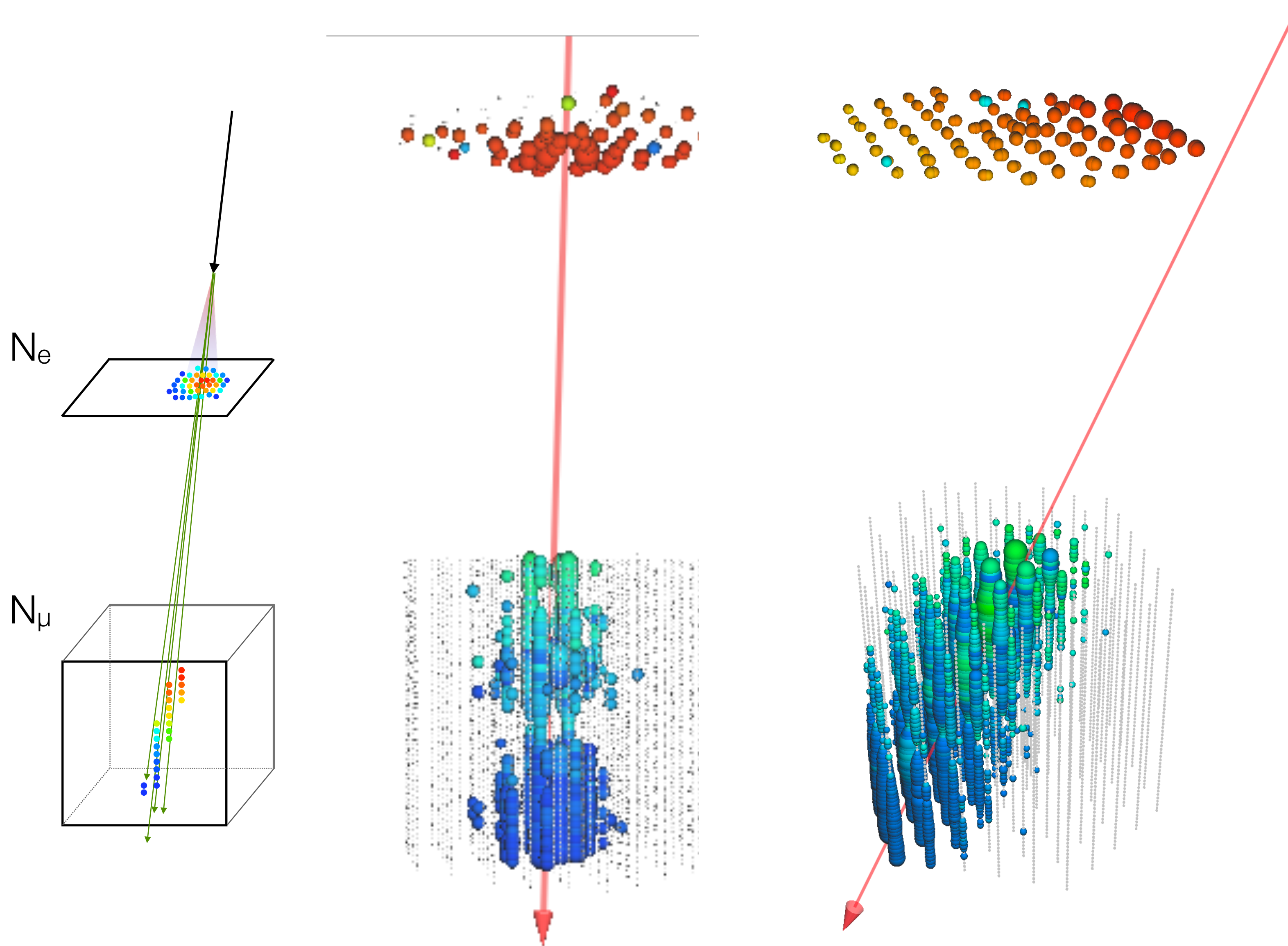


Cosmic Rays with IceTop

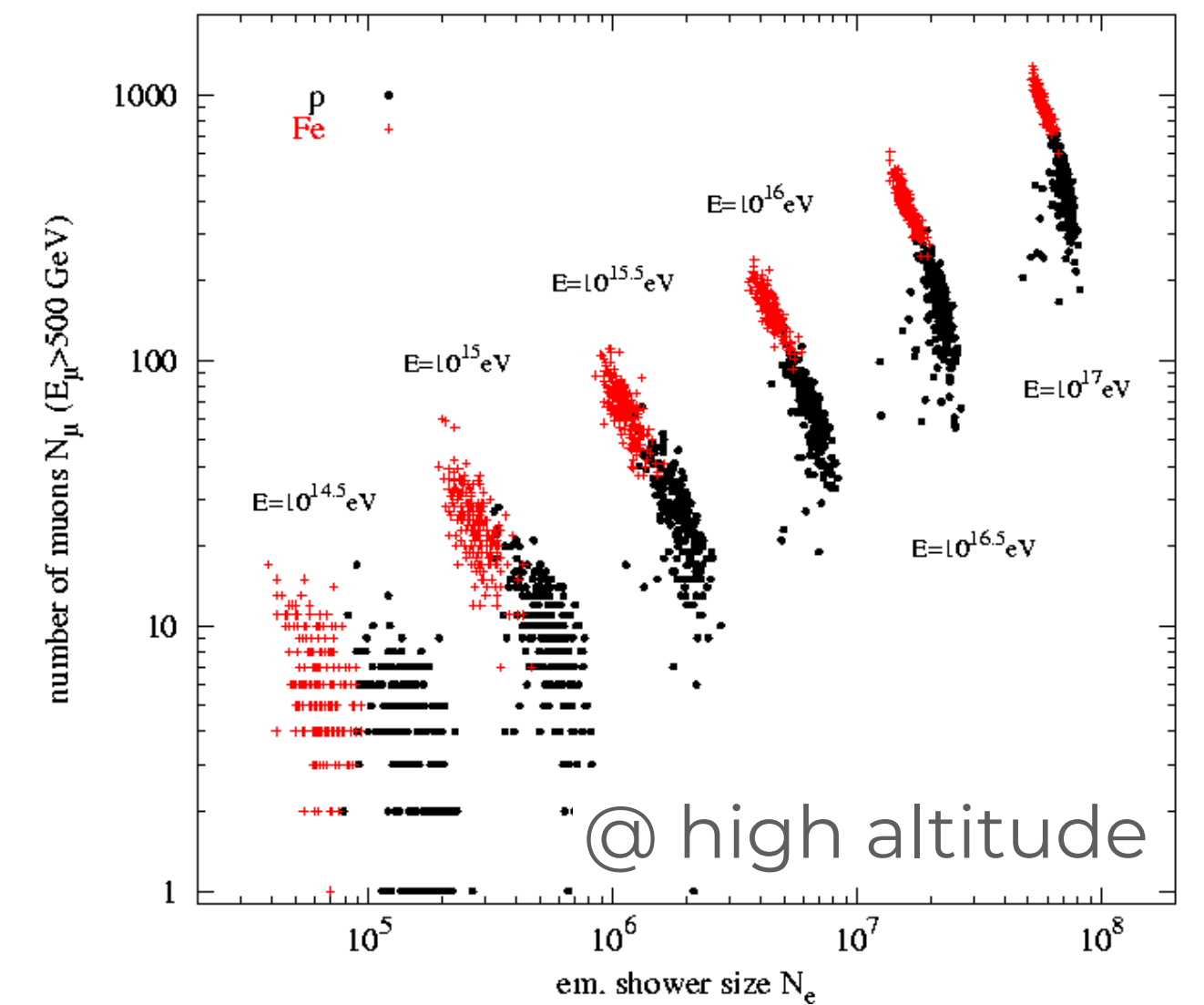
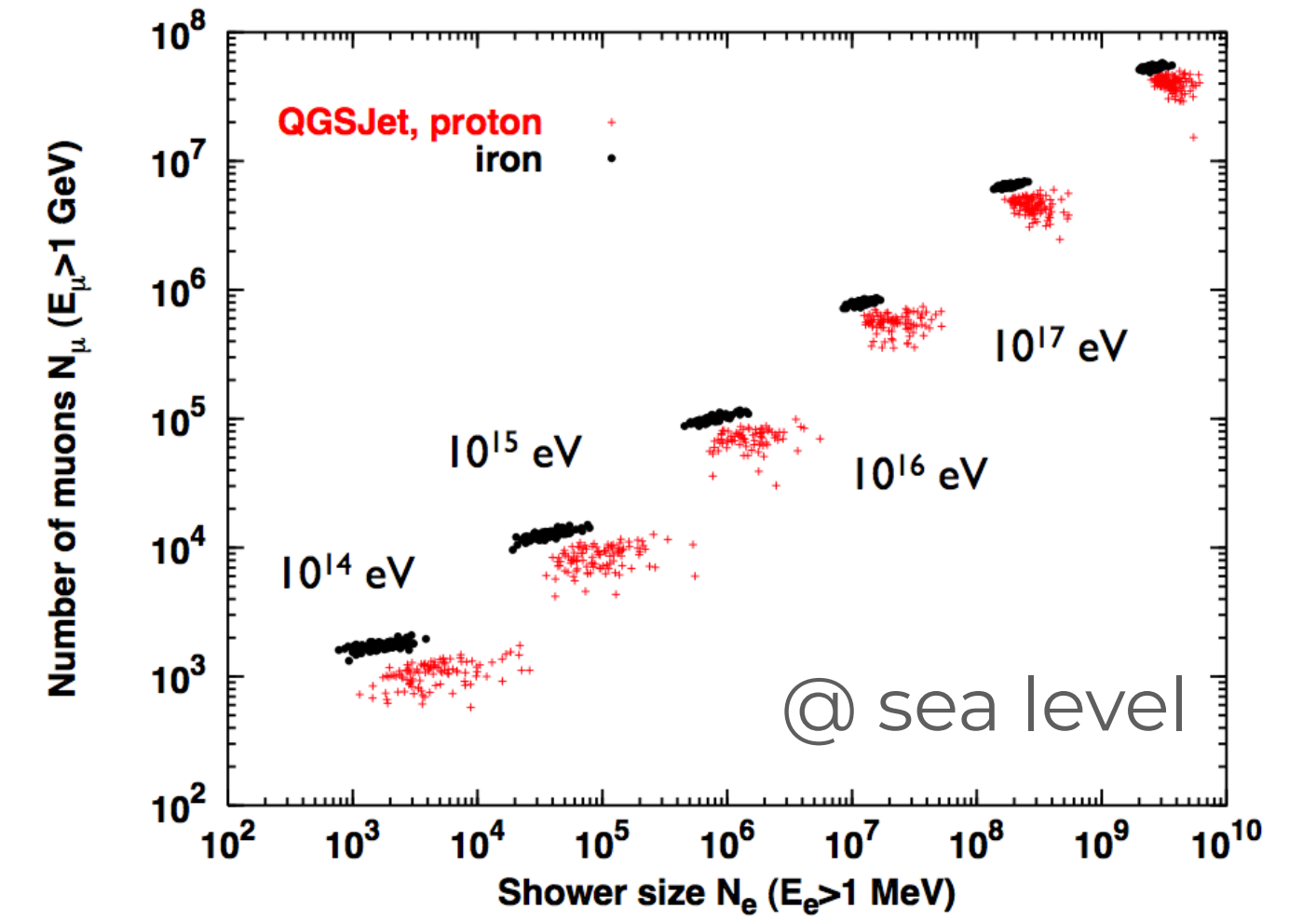
all-particle energy spectrum



Cosmic Rays with IceTop & IceCube elemental composition

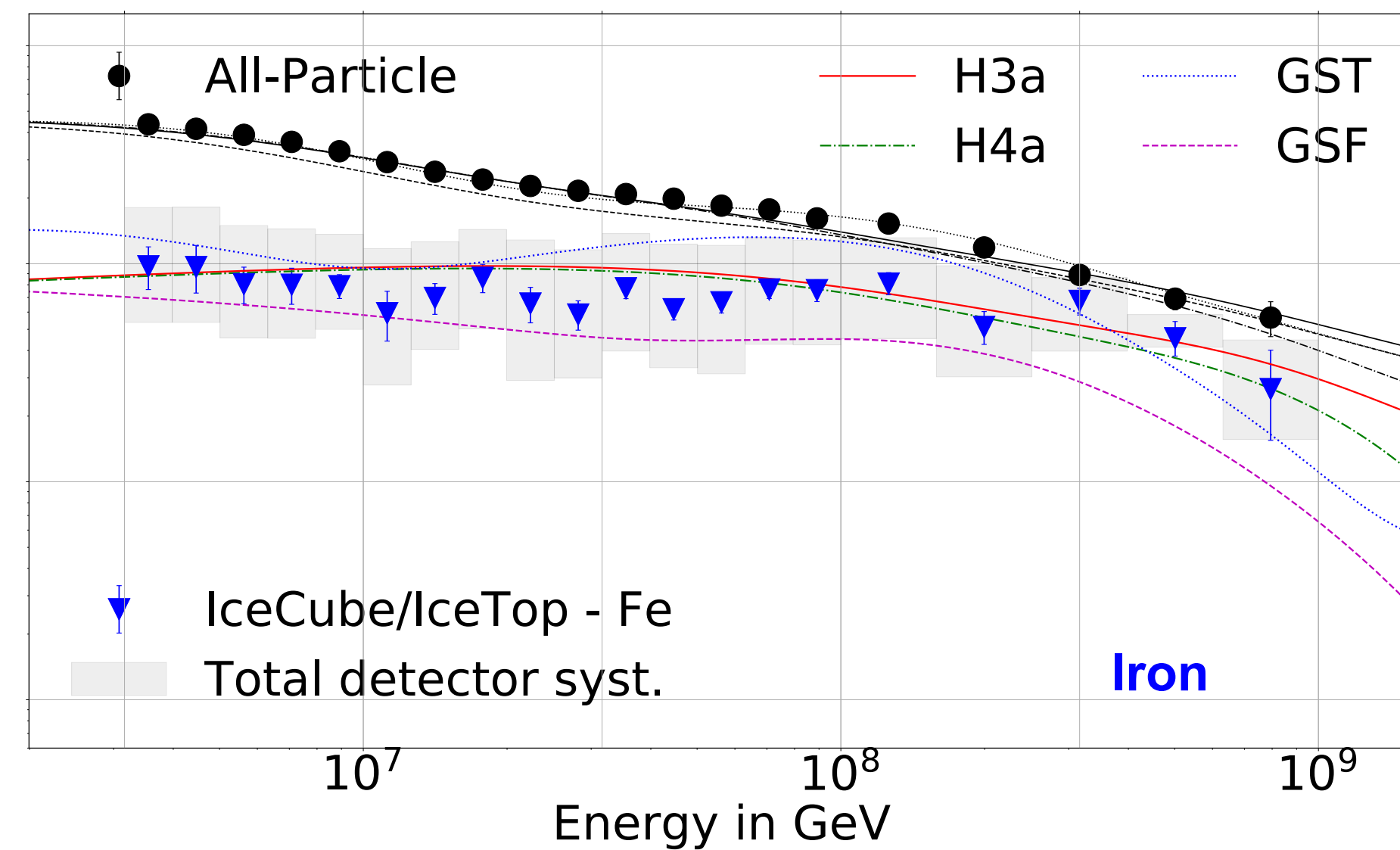
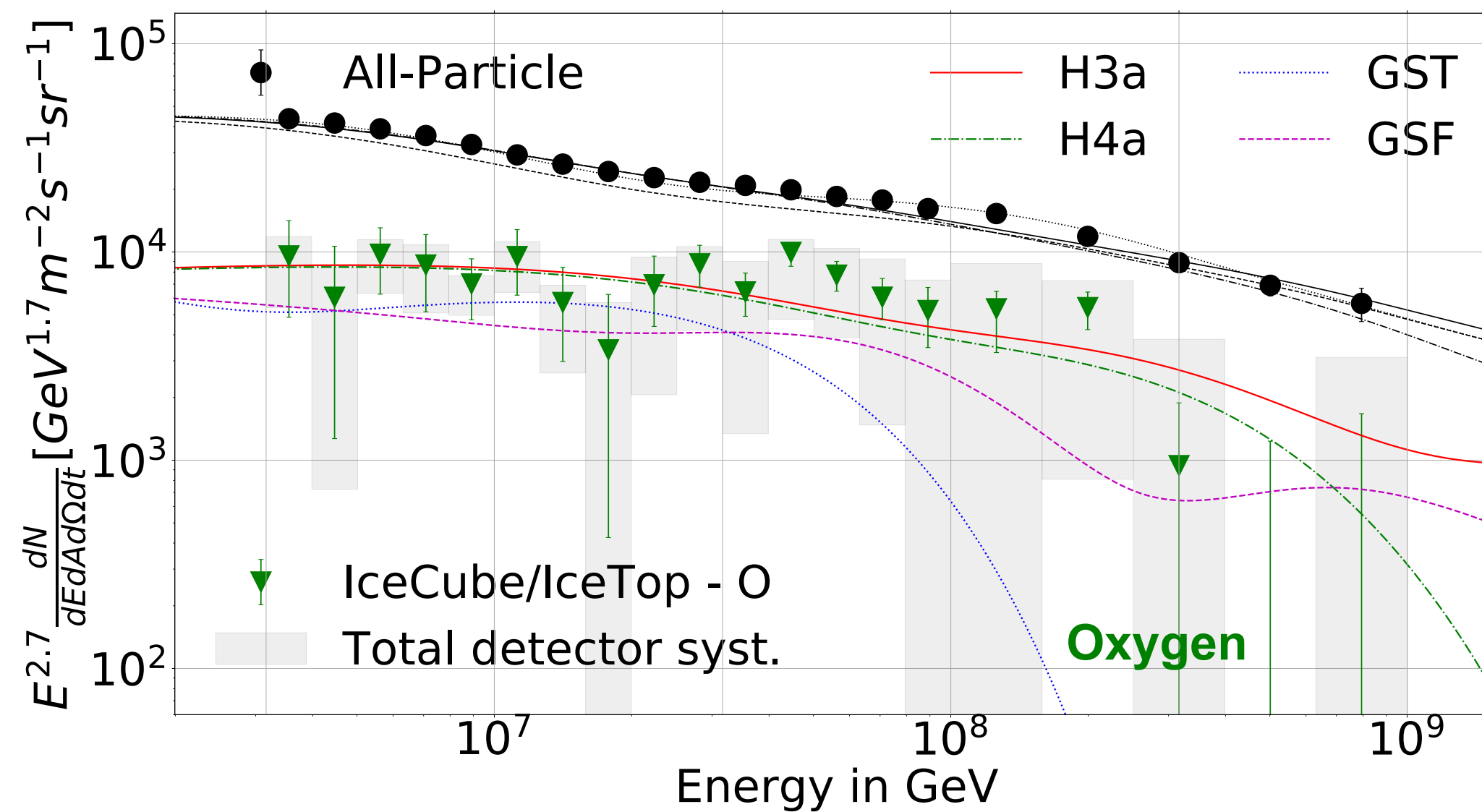
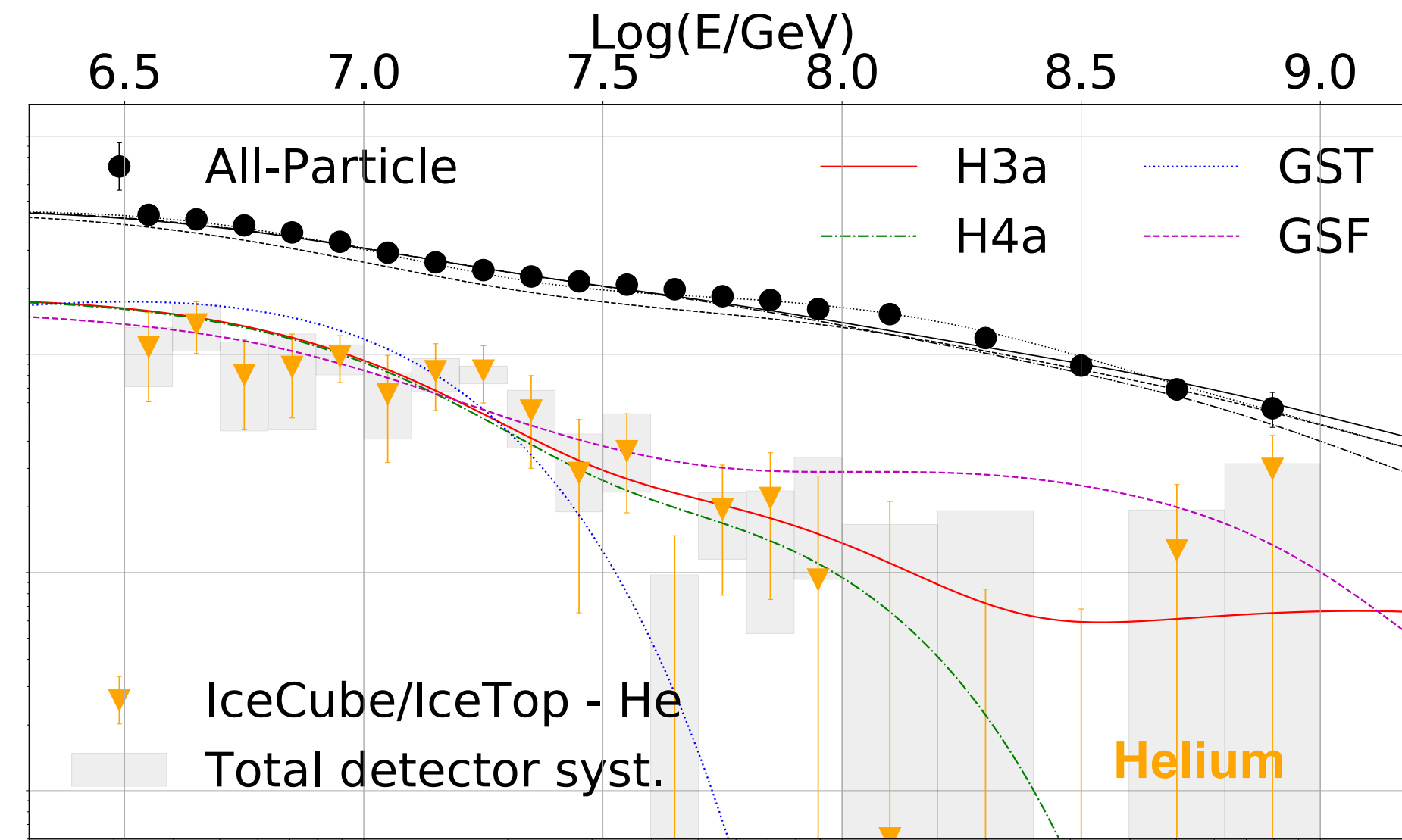
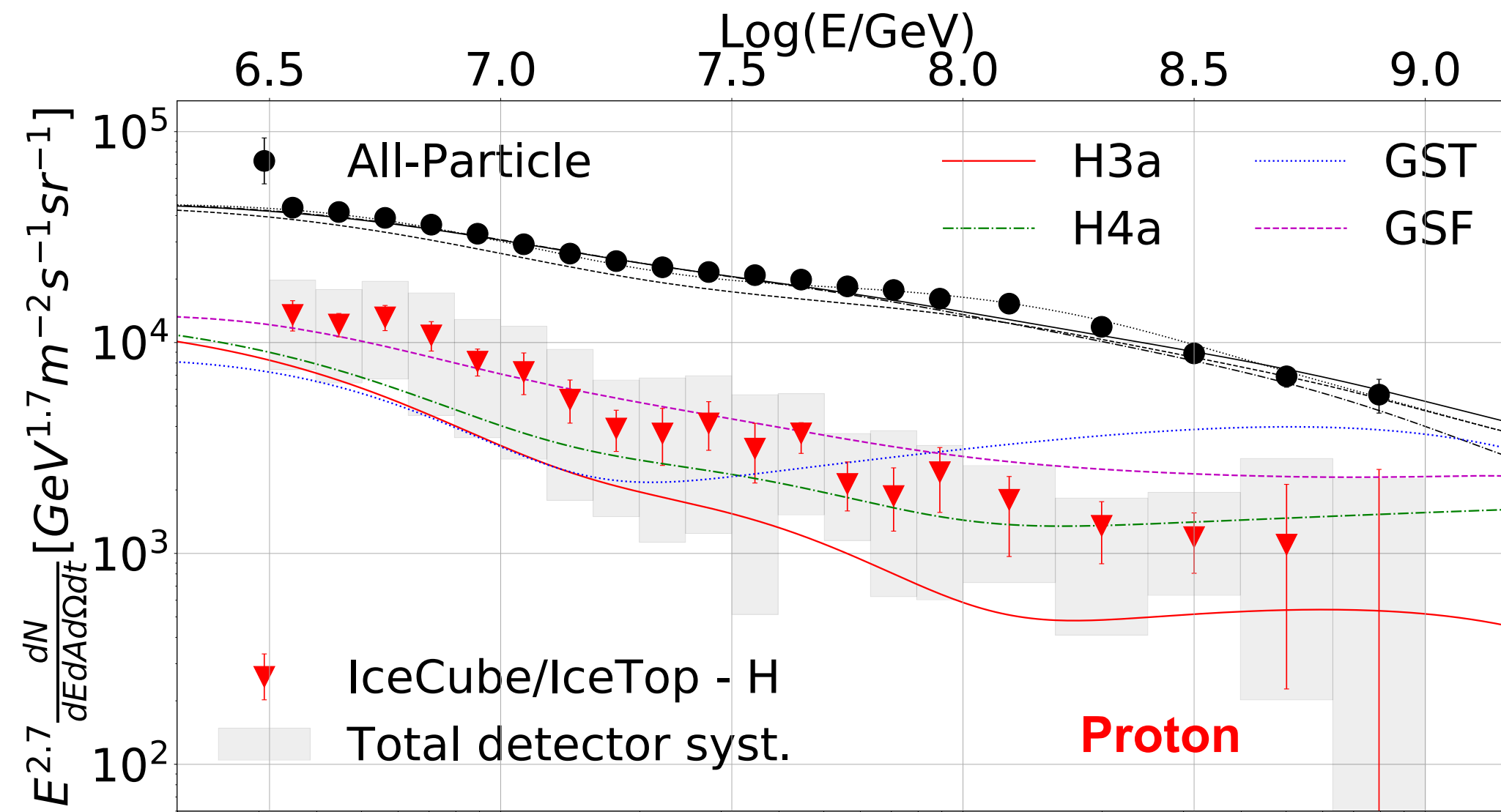
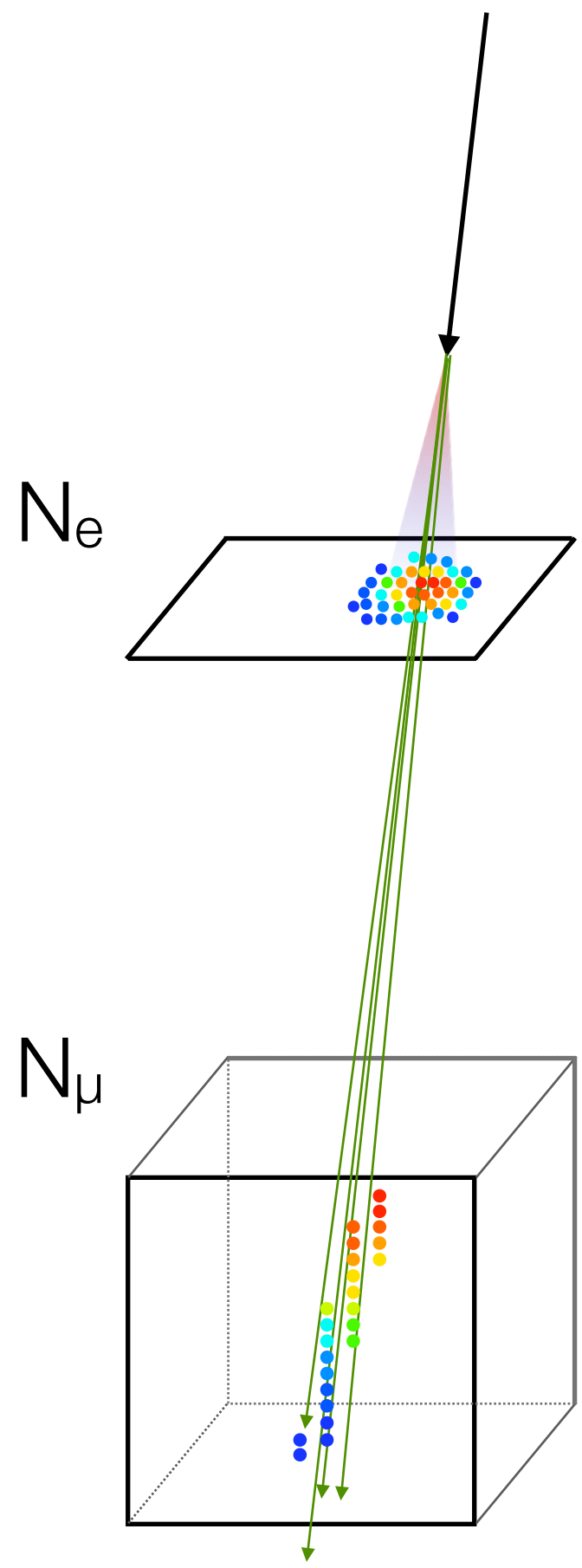


simulations - Ralph Engel

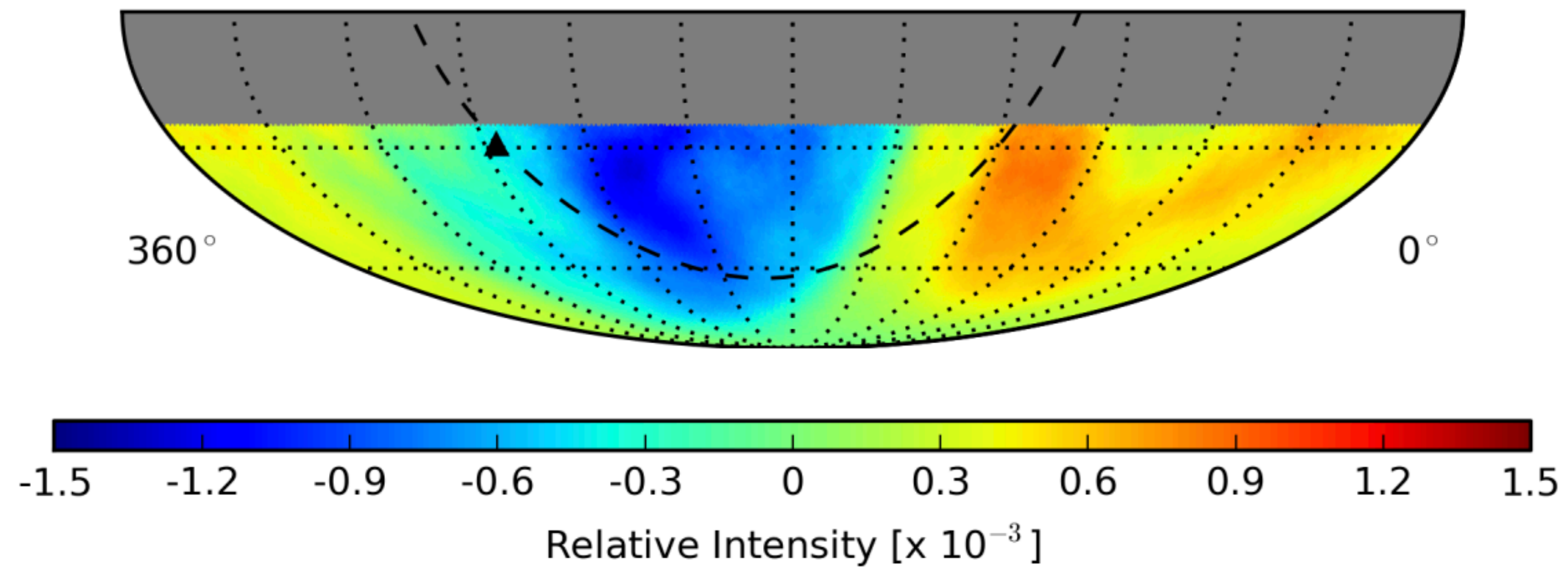
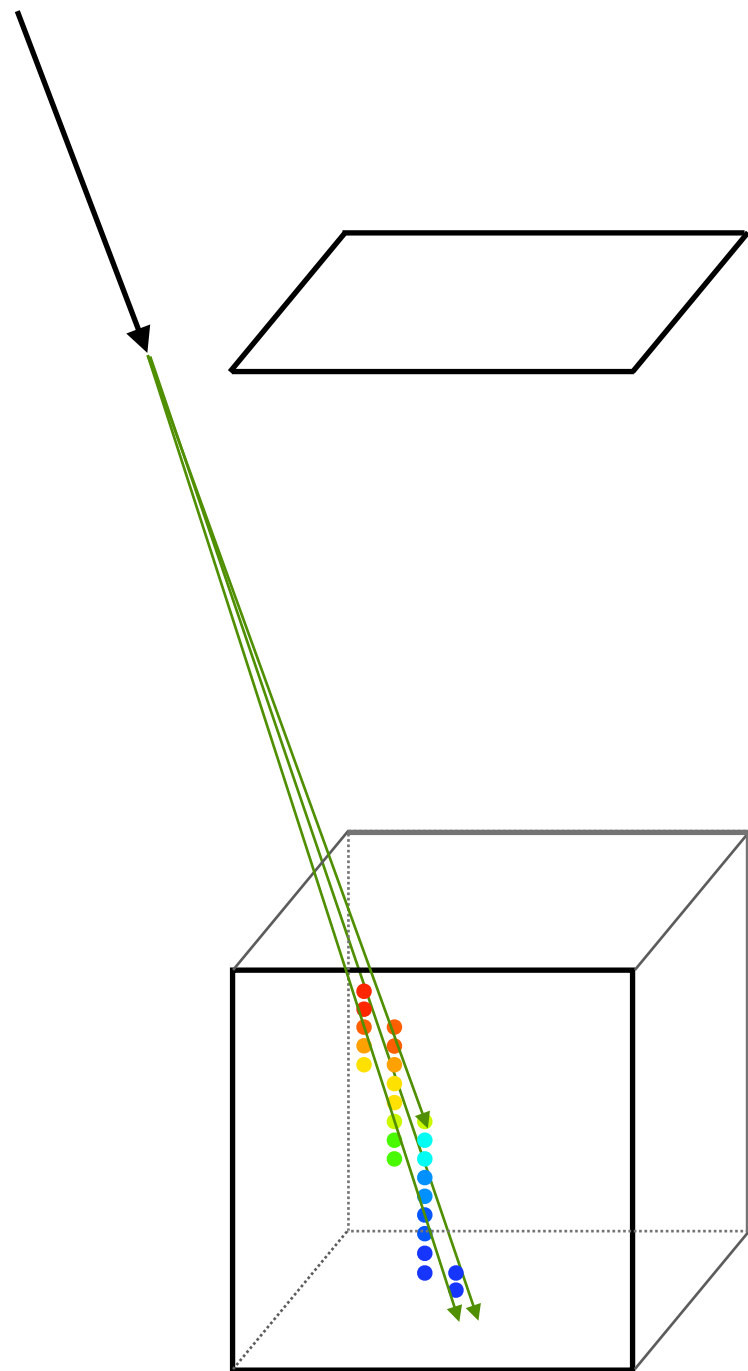


Cosmic Rays with IceTop

elemental composition



Cosmic Rays with IceCube arrival direction distribution



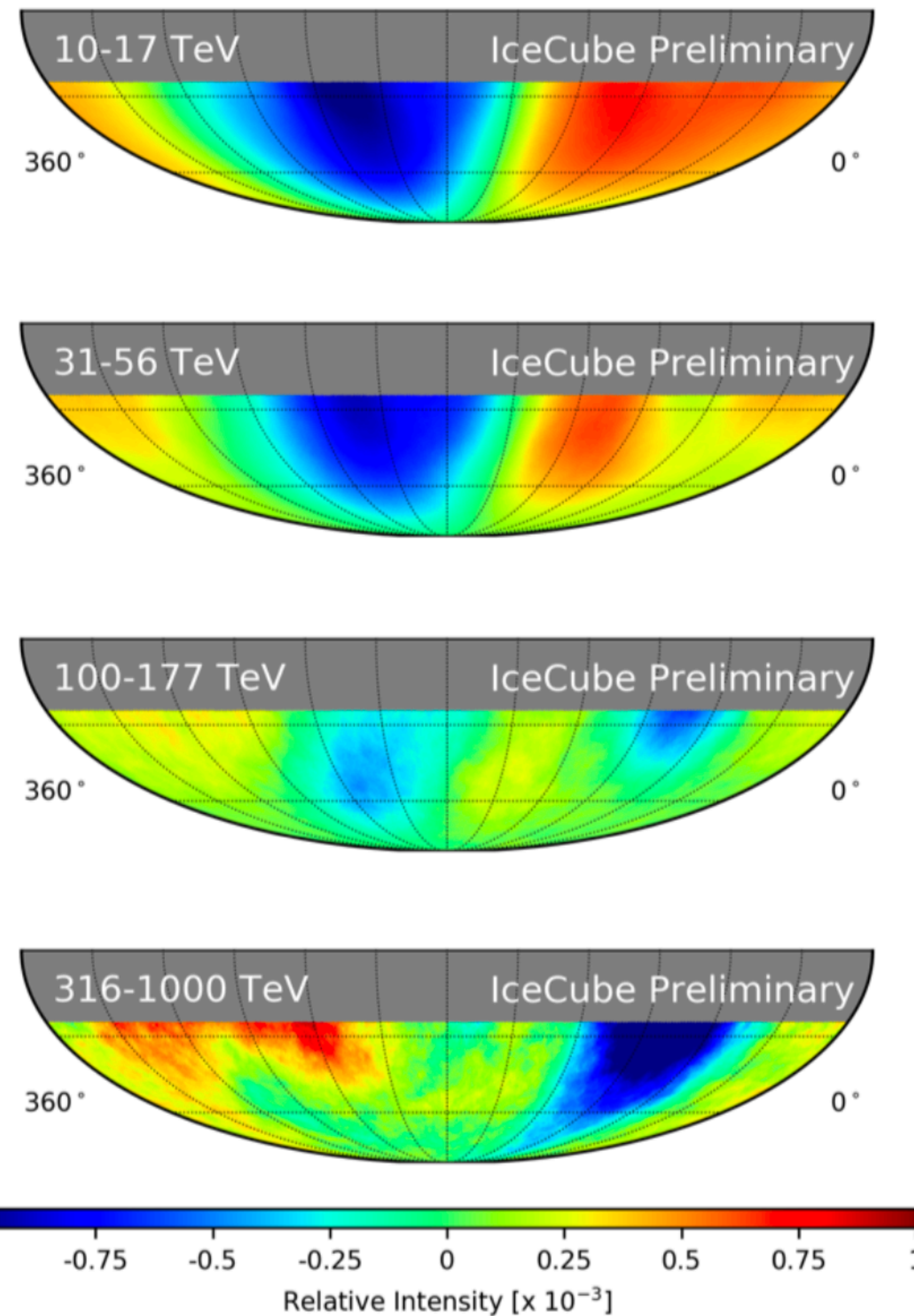
Relative Intensity

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

Median energy of cosmic ray particles ~ 20 TeV

Cosmic Rays with IceCube arrival direction distribution

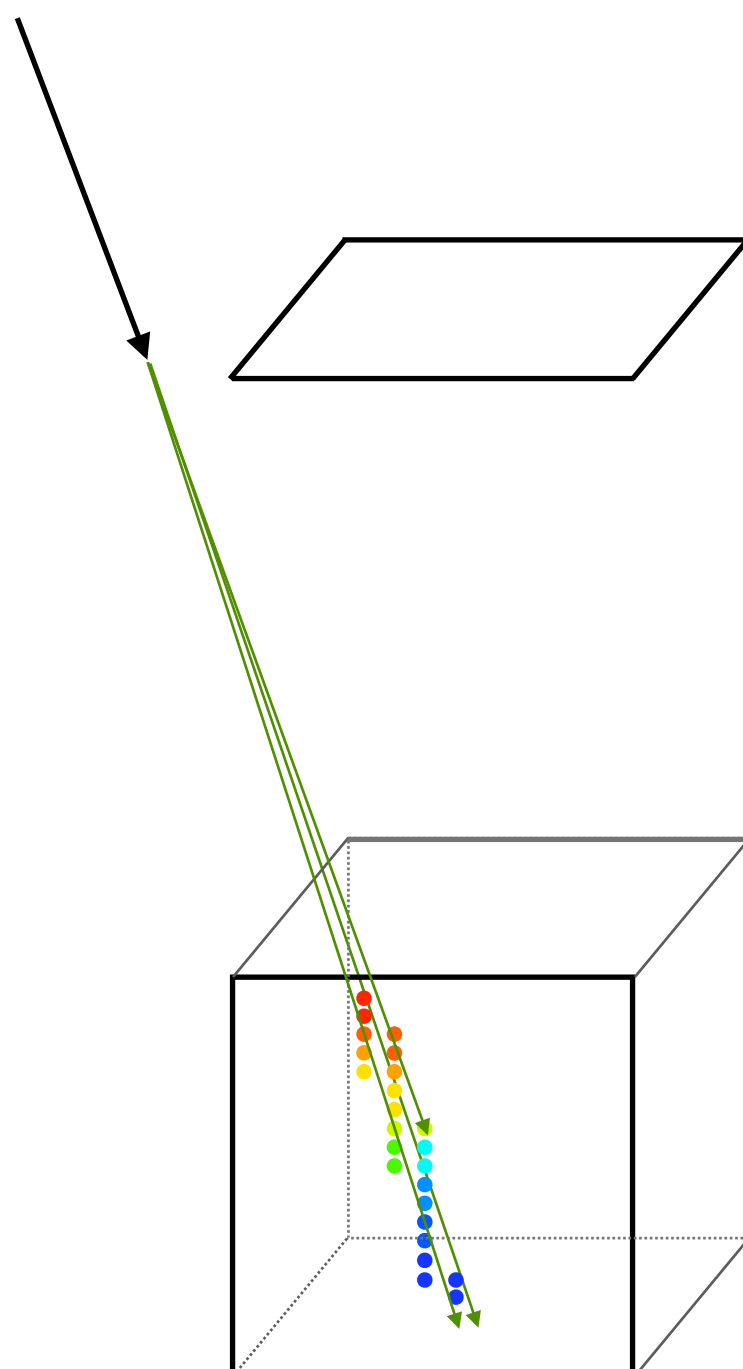
IceCube Collaboration - PoS(ICRC2021)320



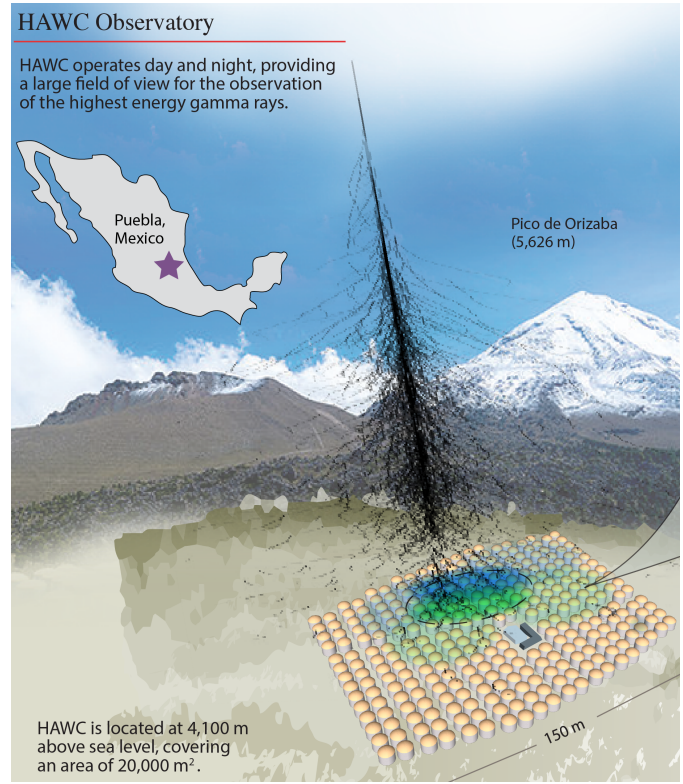
Relative Intensity

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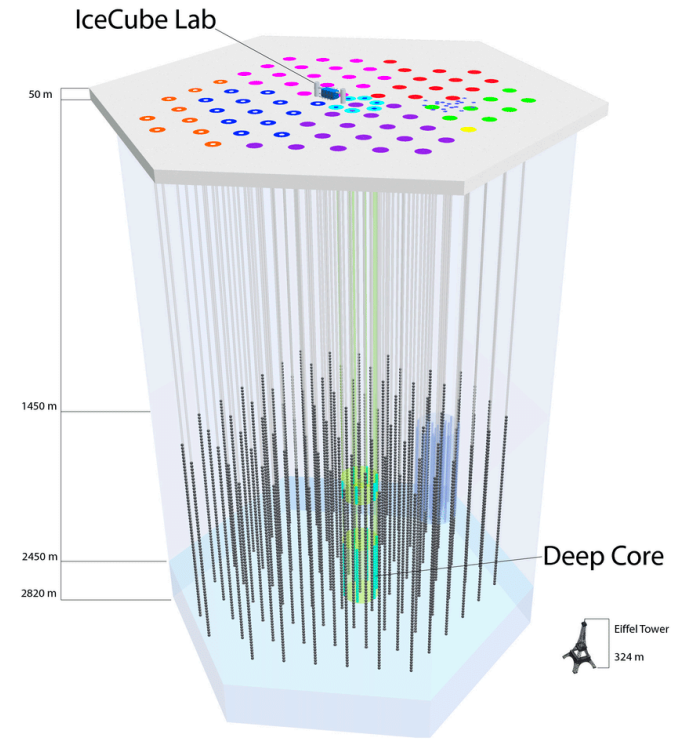
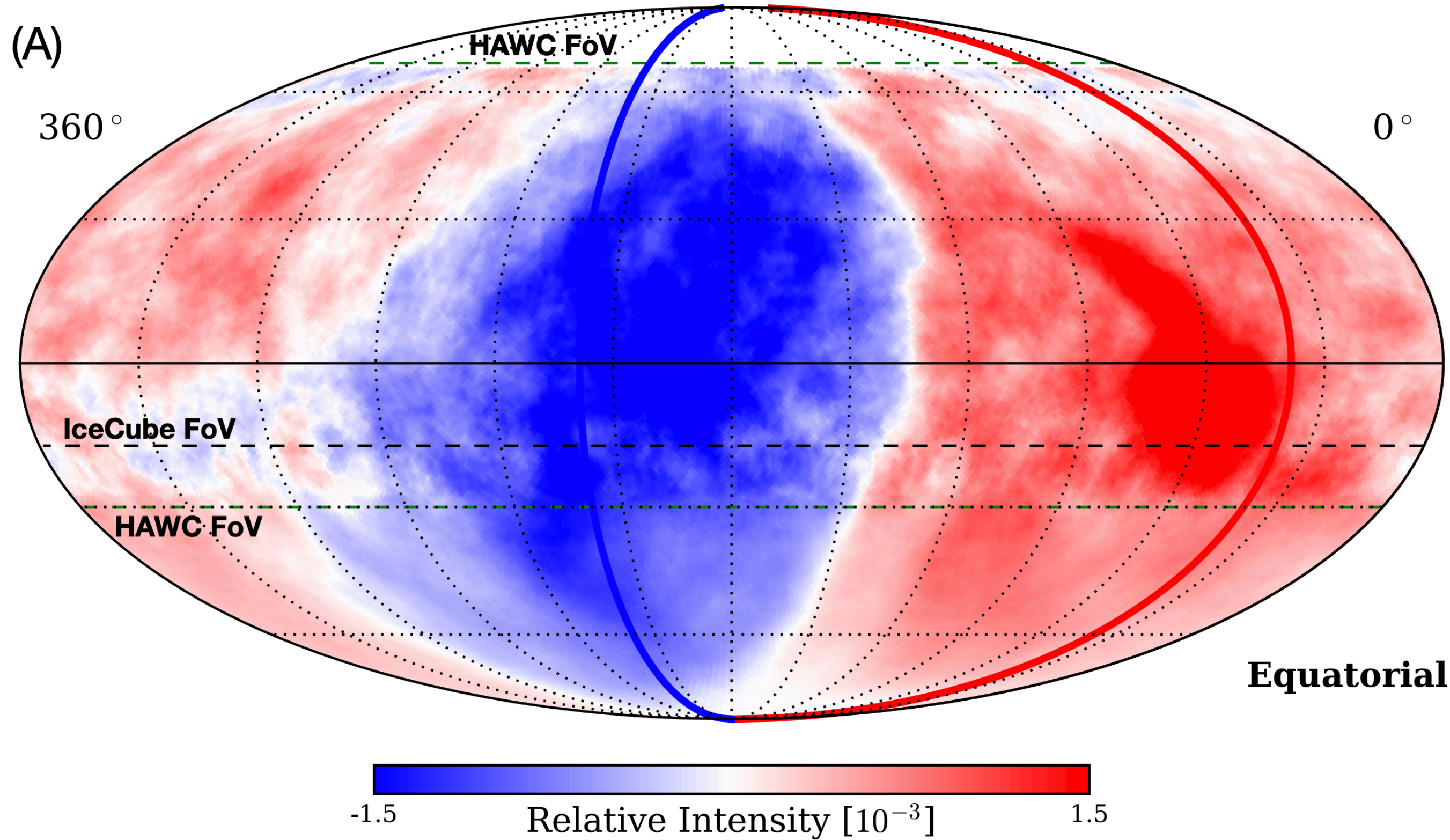
it changes as a function of energy



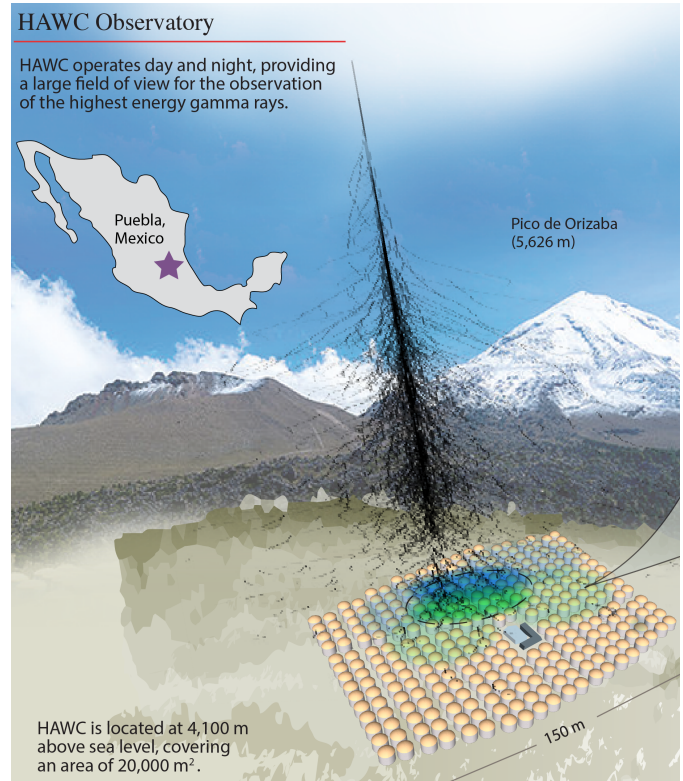
Cosmic Rays Anisotropy with HAWC - IceCube



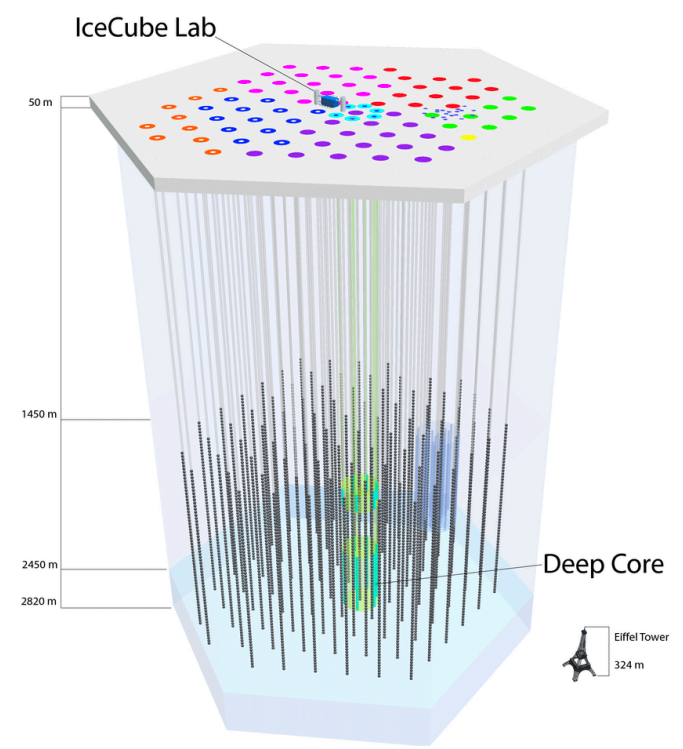
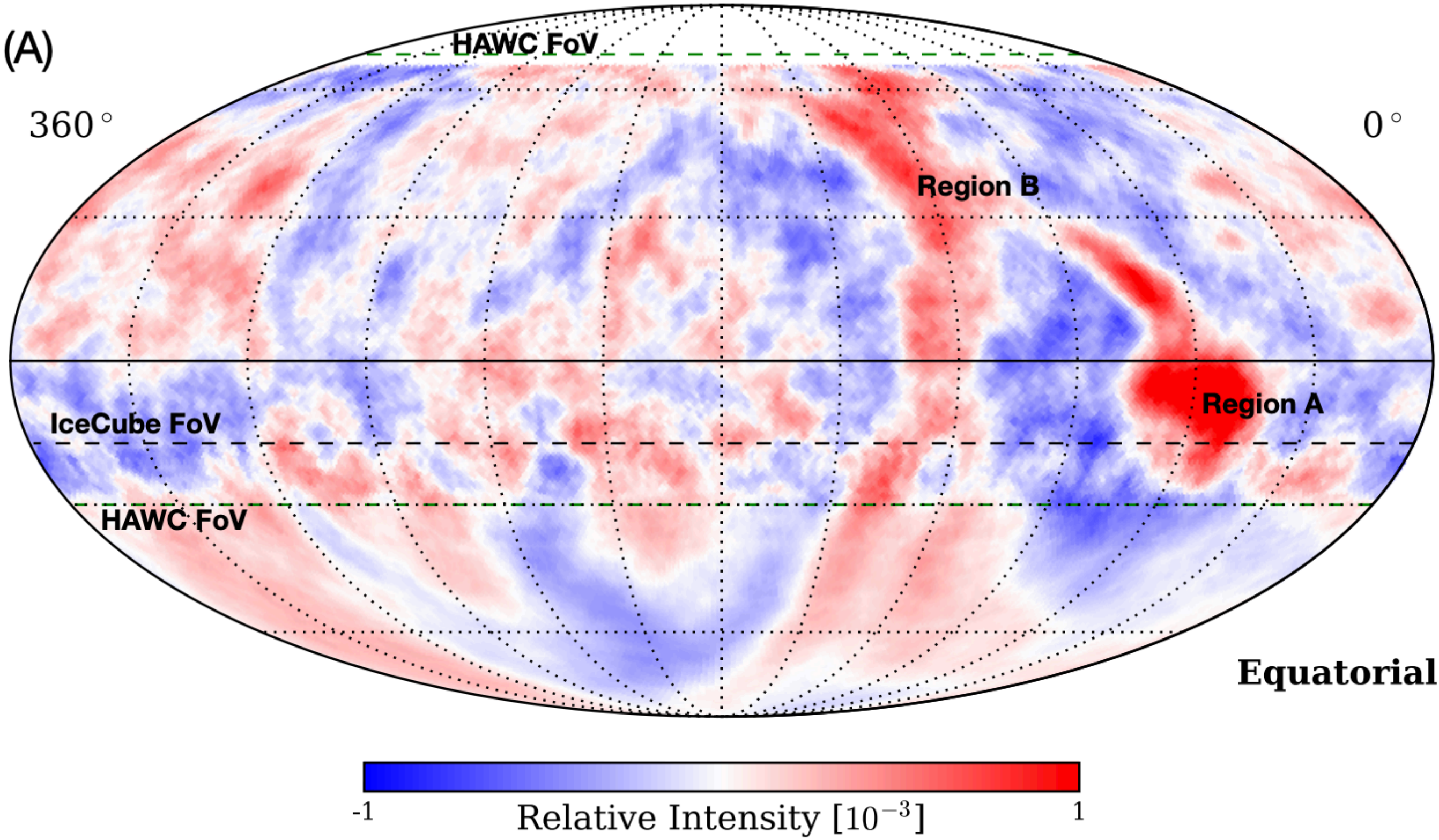
ALL-SKY ANISOTROPY OF COSMIC RAYS AT 10 TEV



Cosmic Rays Anisotropy with HAWC - IceCube



HAWC COLLABORATION AND ICECUBE COLLABORATION



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

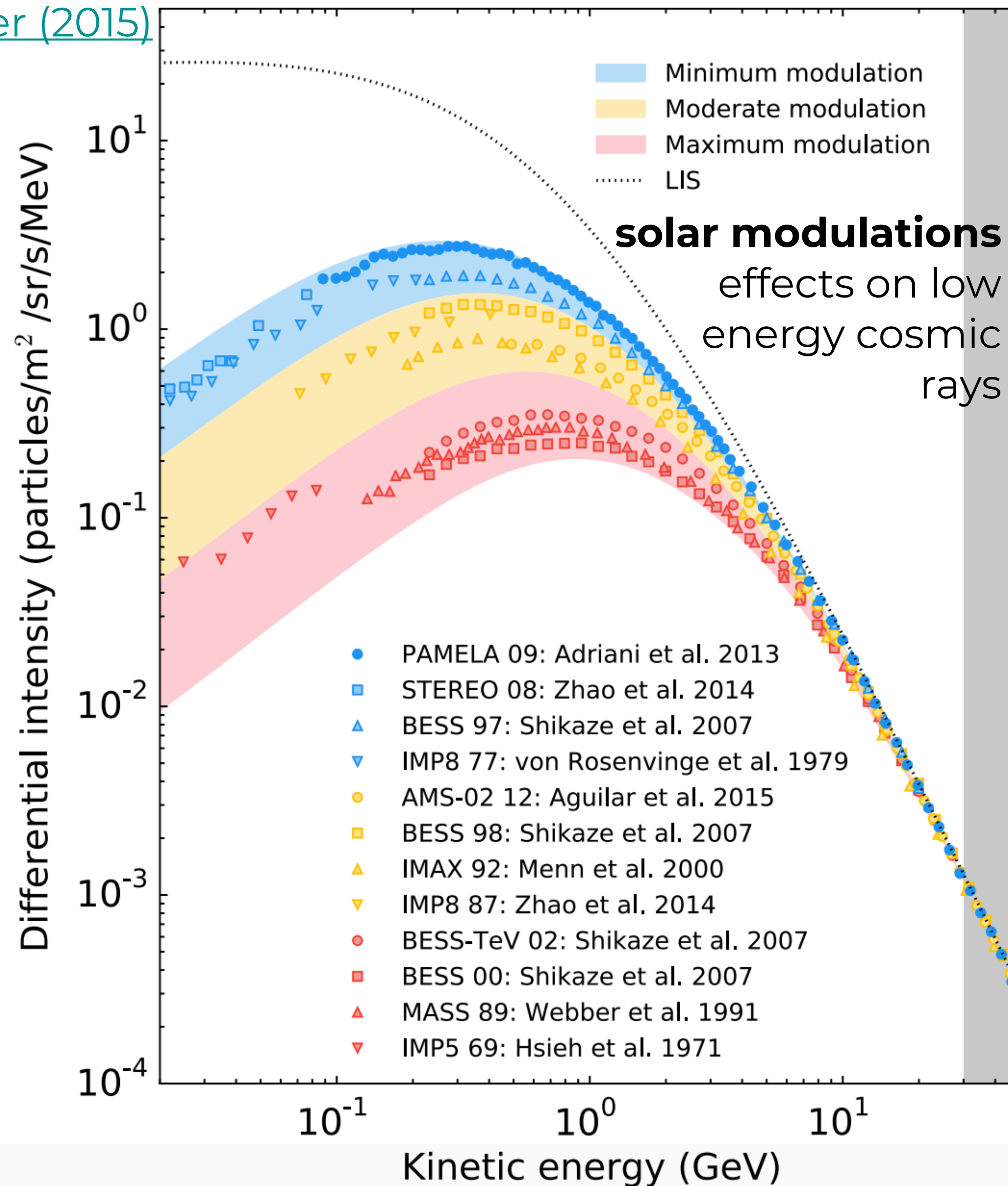
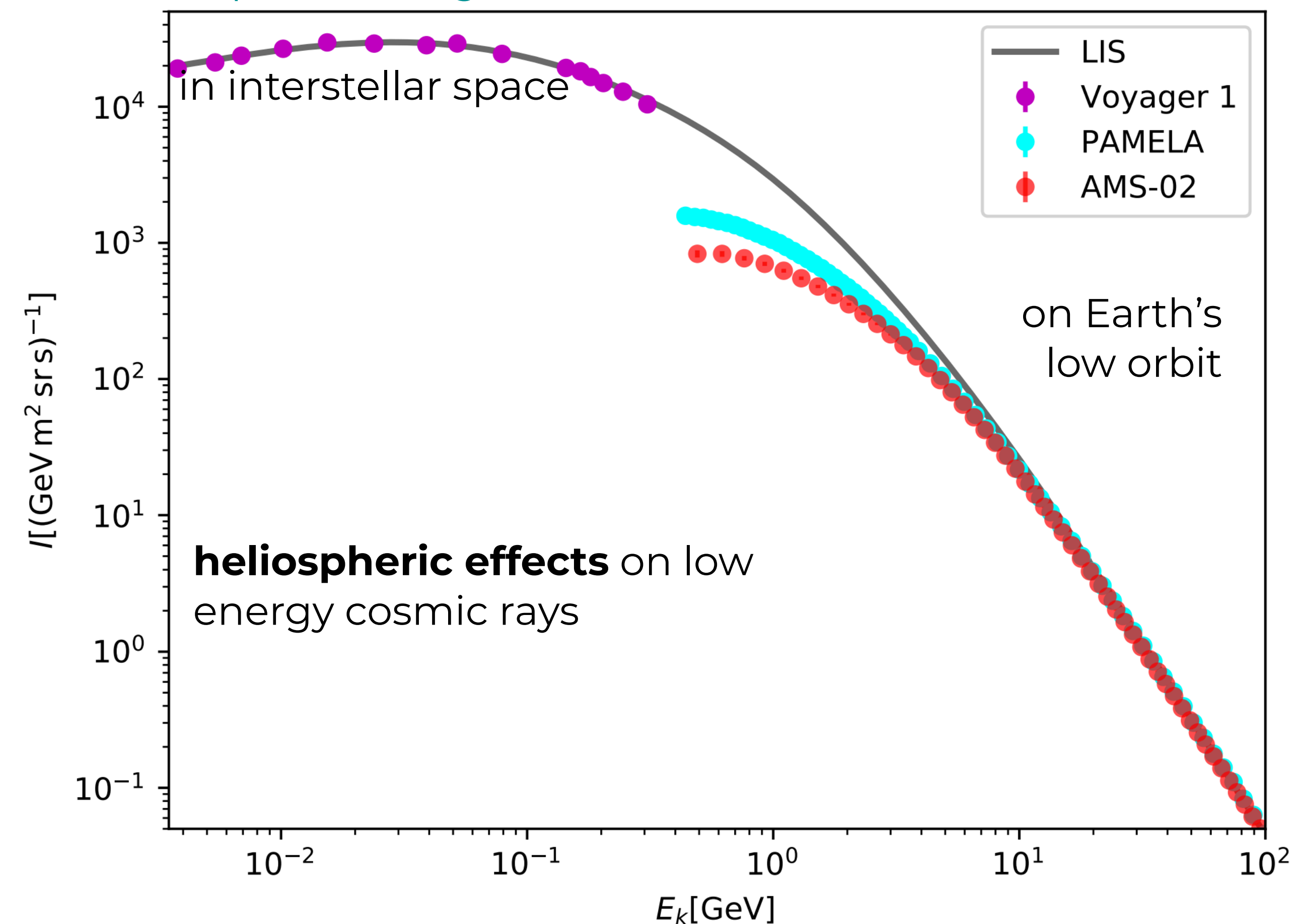
Cosmic Ray Energy Spectrum

Low Energy

Vos & Potgieter (2015)

proton flux

<https://arxiv.org/abs/1904.03747>



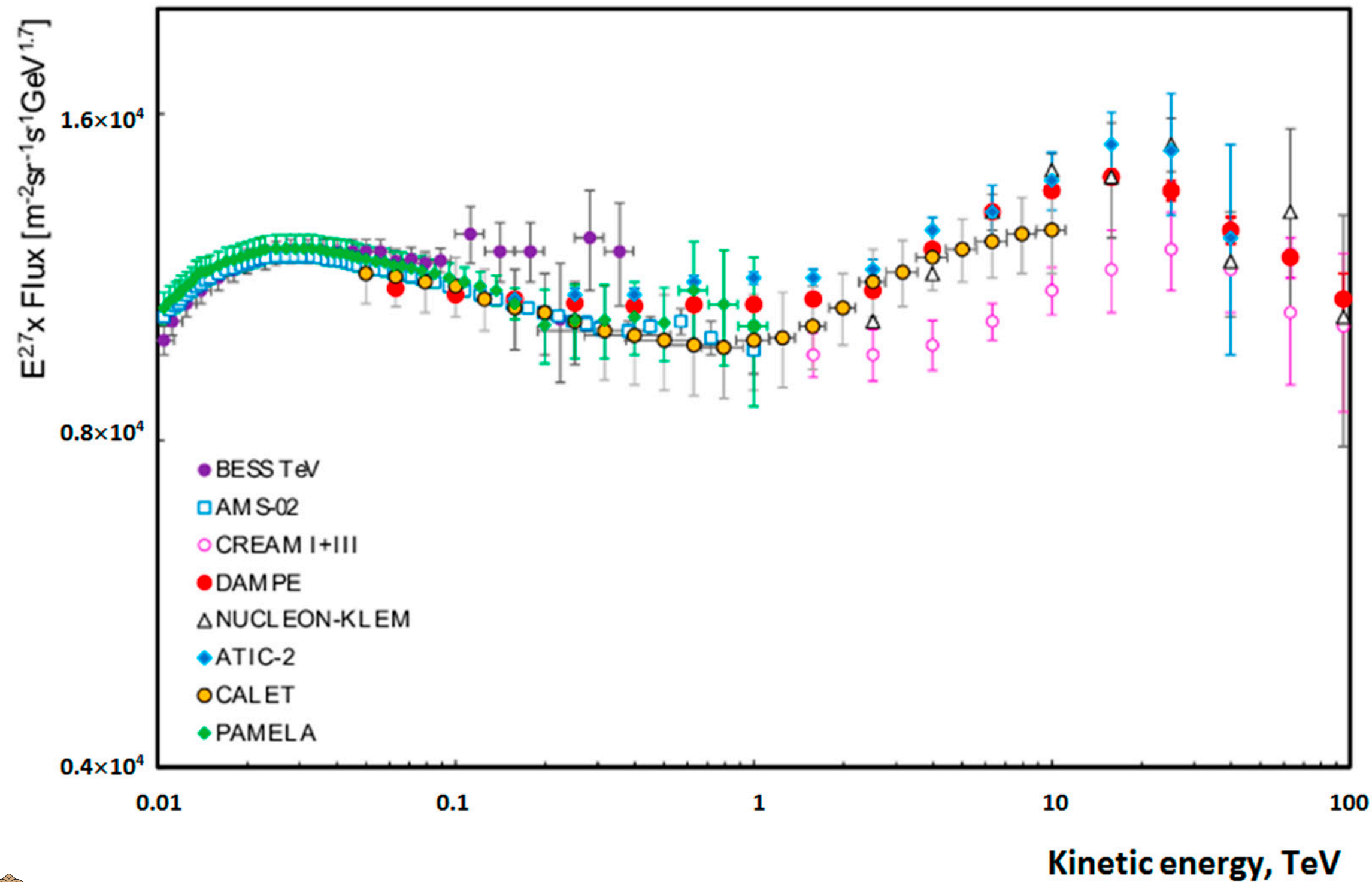
Cosmic Ray Energy Spectrum

Local Sources?

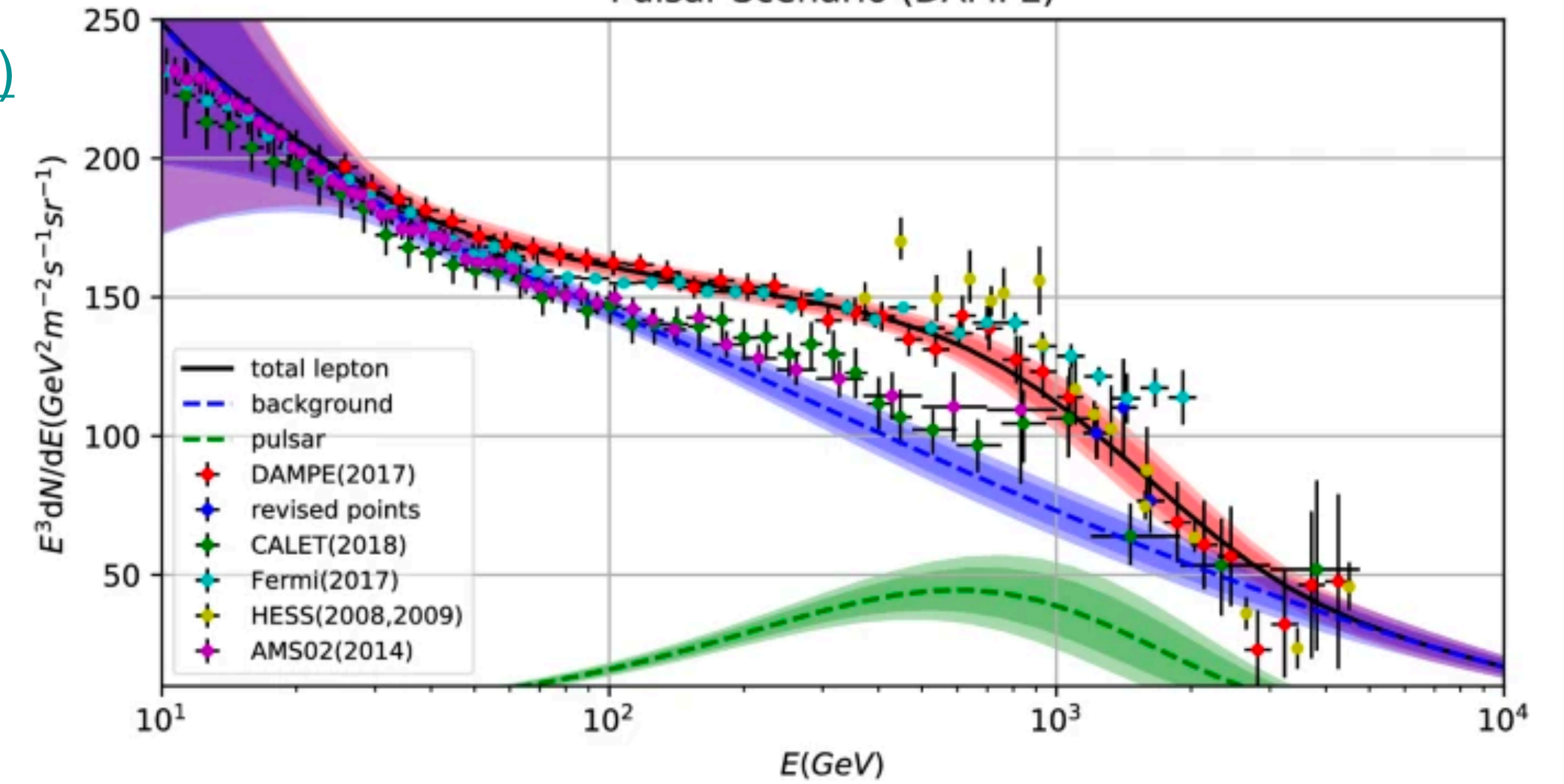
proton flux

[Niu et al. \(2019\)](#)

[Lebedev et al. \(2021\)](#)



Pulsar Scenario (DAMPE)



DM Scenario (DAMPE)

