Cosmic Ray Flux Measurements at Global Scale and the Associated Applications

Xiaochun He
Department of Physics & Astronomy
Georgia State University
Atlanta, Georgia, USA

Radiation and Life

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and
the Associated Applications

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Cosmic ray measurements at global scale & applications

Focus of this talk

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Finding GSU on the World Map

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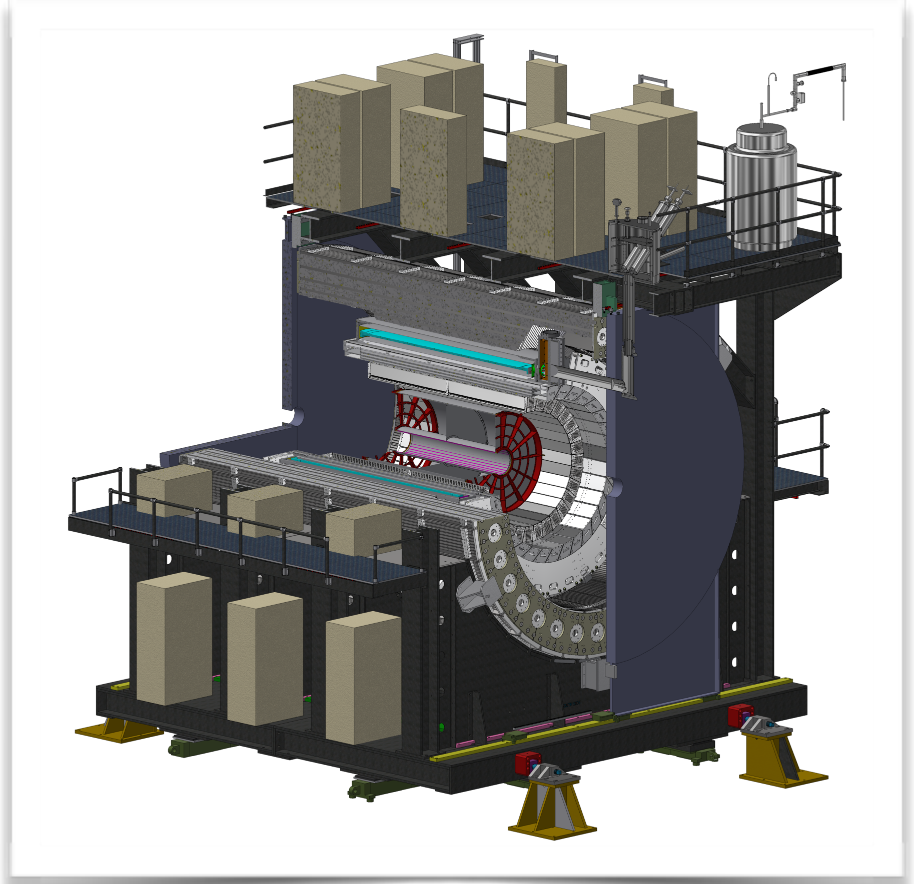
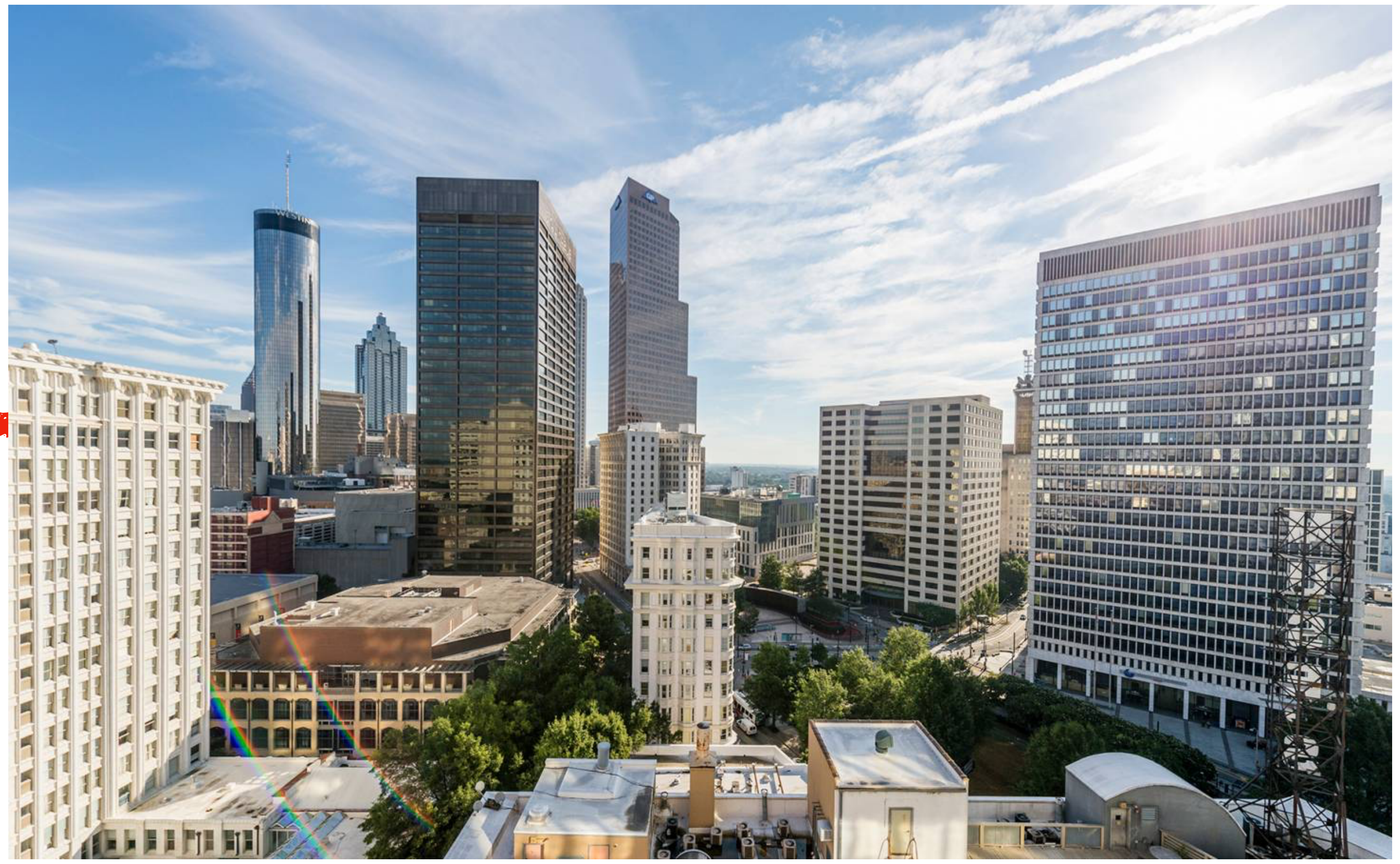
sPHENIX Experiments at the Relativistic Heavy Ion Collider at Brookhaven National Lab





Welcome to Join GSU Family as Your Next Journey for Higher Education

Research Topics in Nuclear Physics Group

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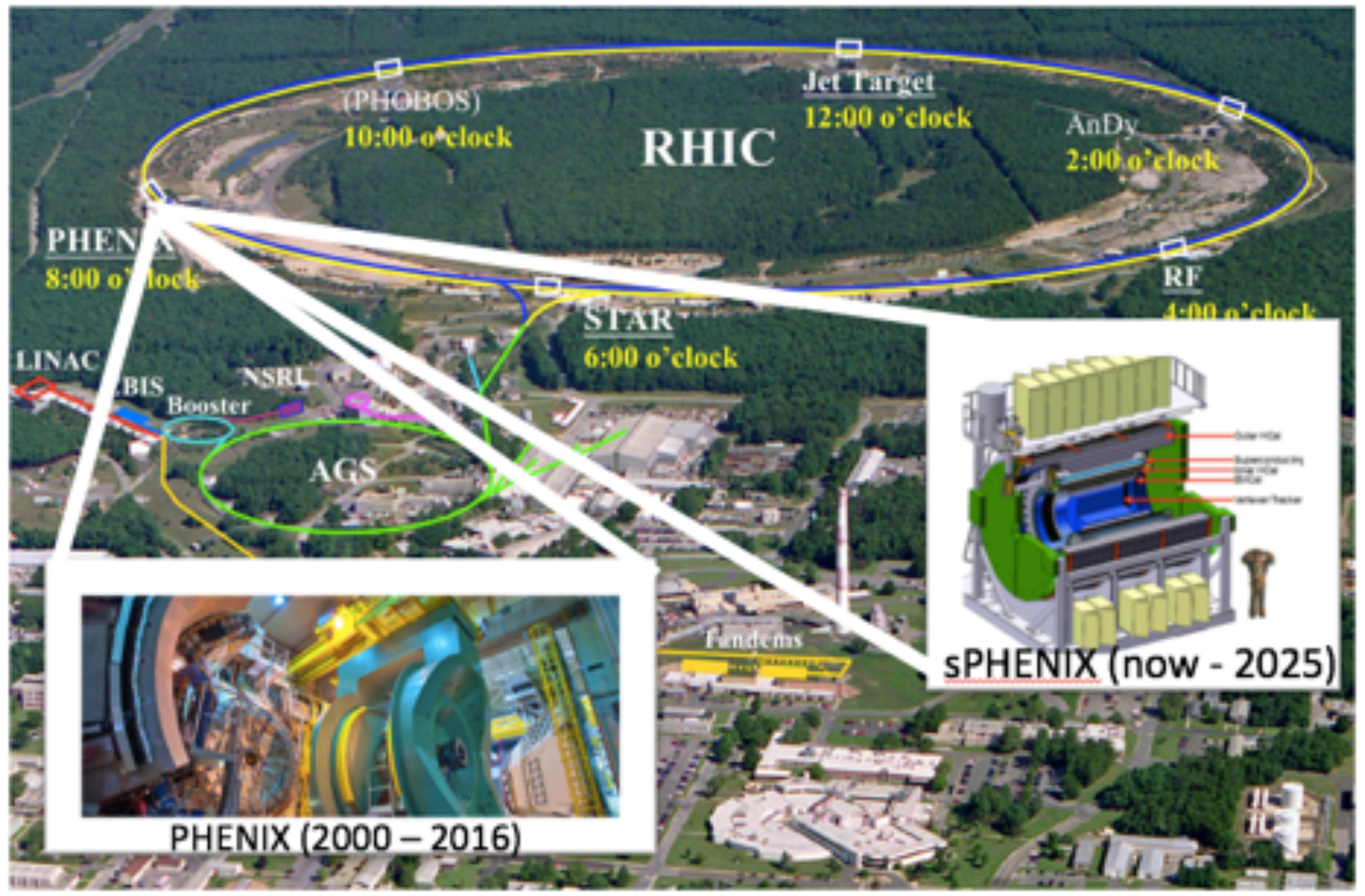
Study nuclear matter properties at extreme high temperature and density in a form of quark-gluon plasma by colliding heavy nuclei at the Relativistic Heavy Ion Collider at Brookhaven National Lab, New York, USA.



1990's to 2030

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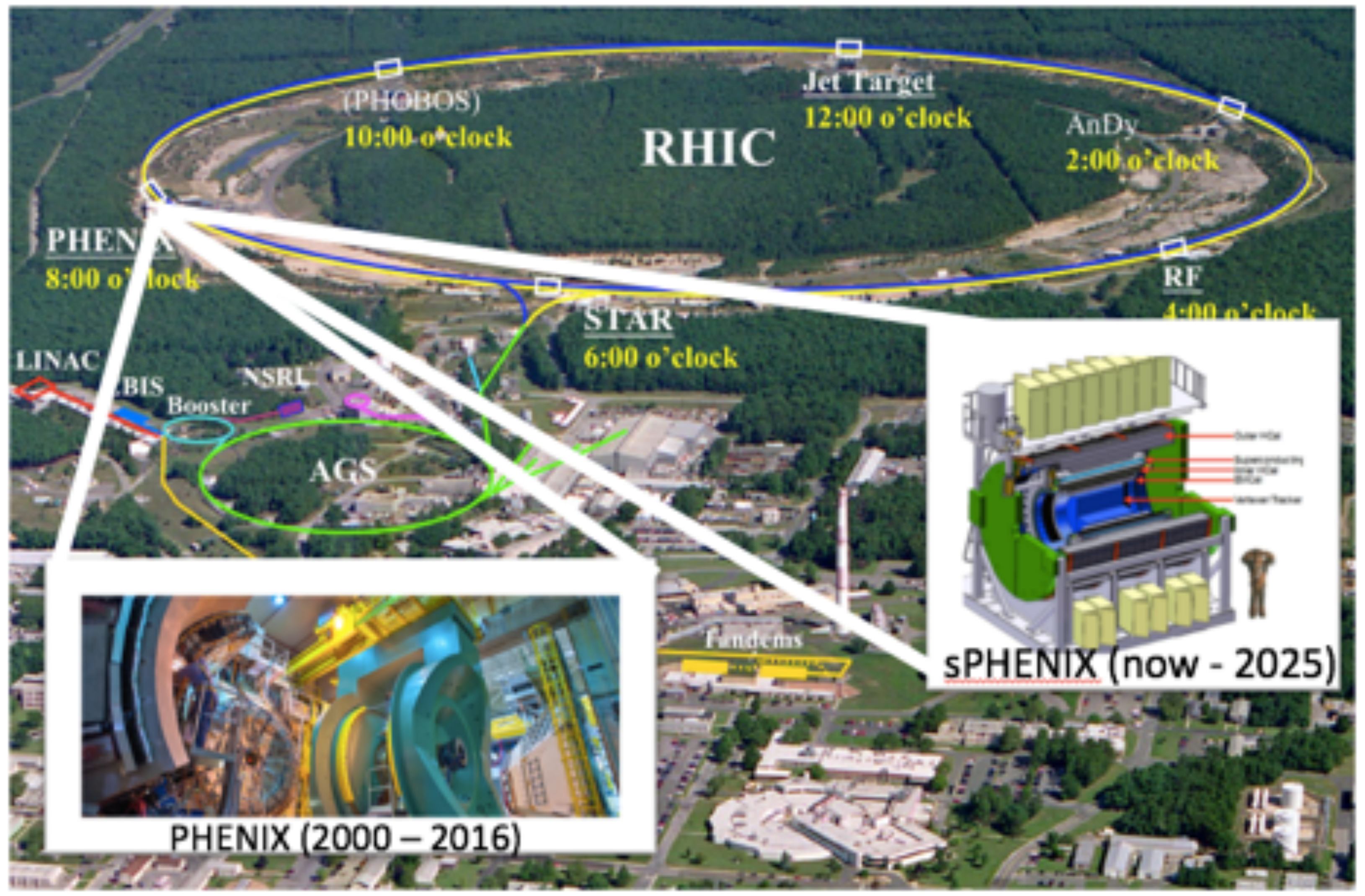
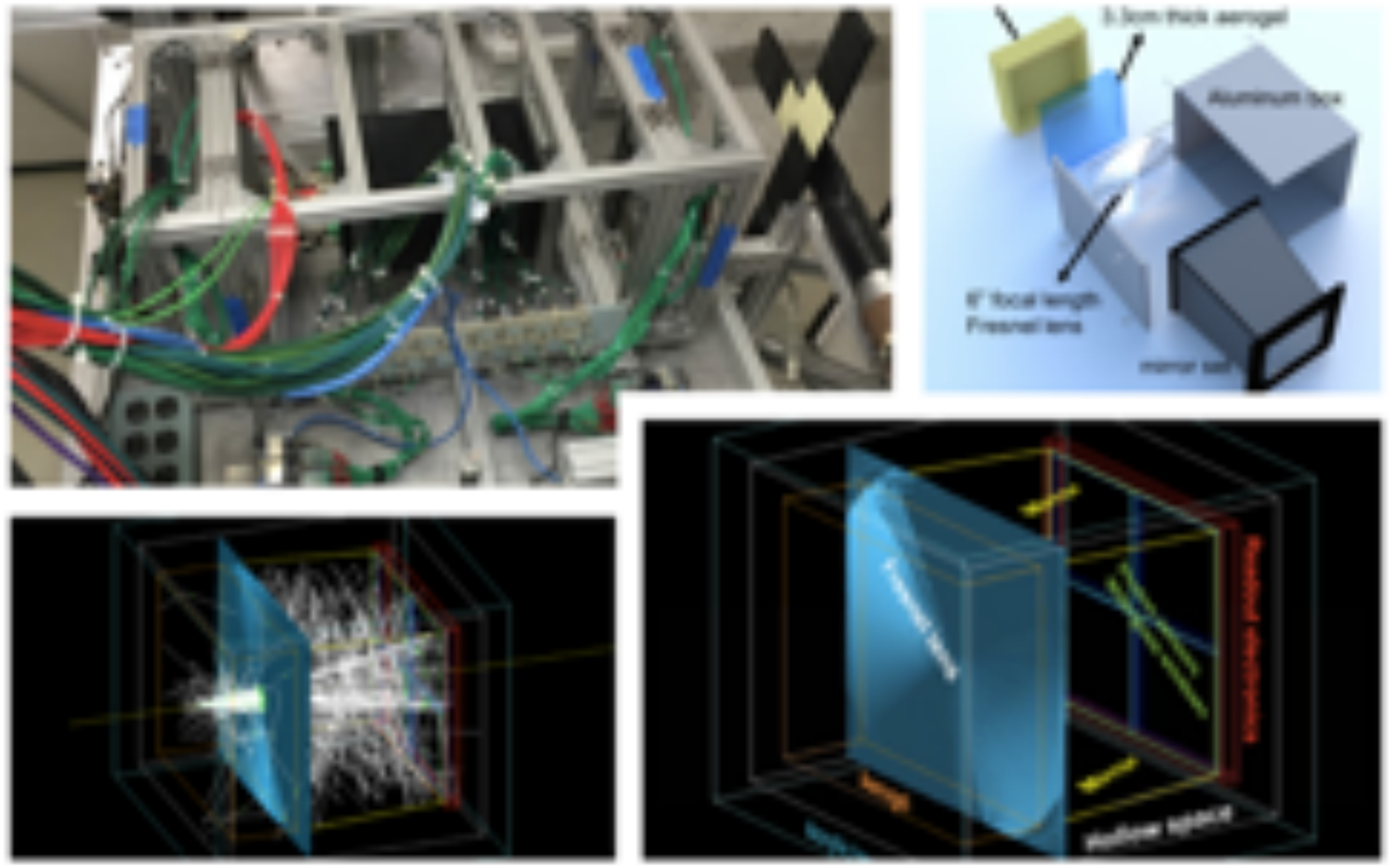
Explore the inner structures of nucleon and nuclei by colliding polarized electrons and protons (and nuclei) in the to-be-built Electron and Ion Collider. GSU group is developing a key detector technology for these experiments.



1990's to 2030



2013 to 2040

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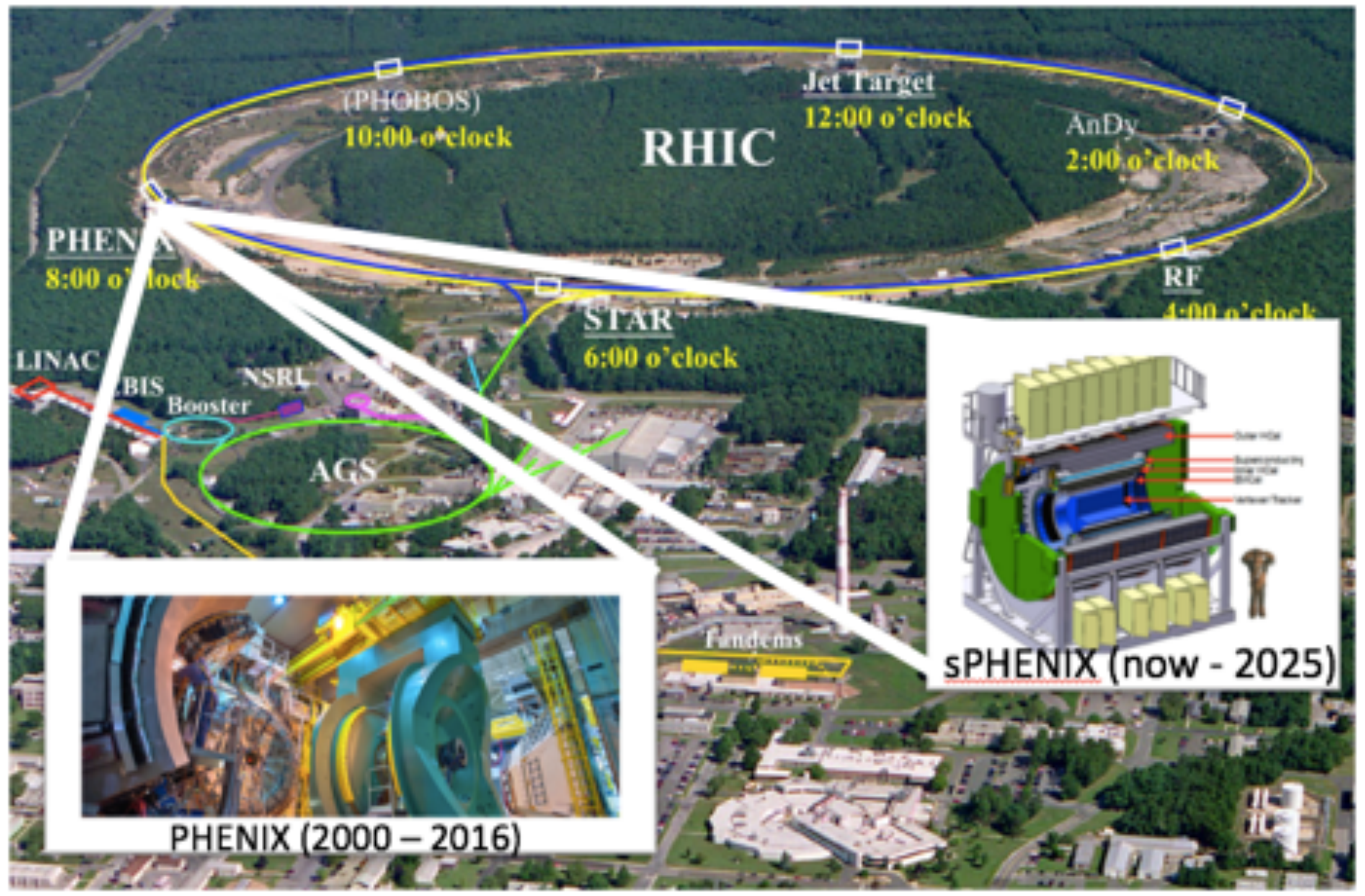

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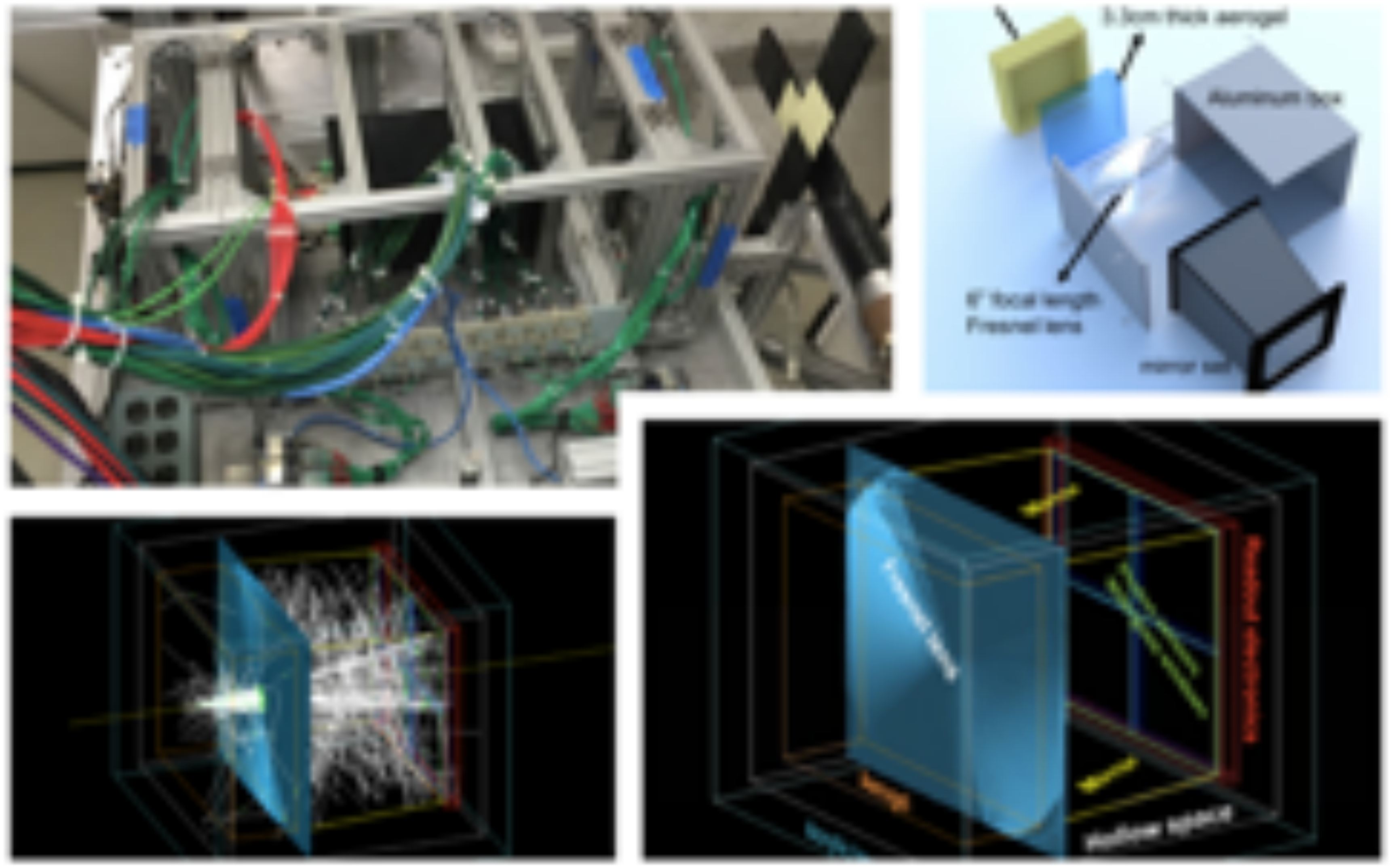
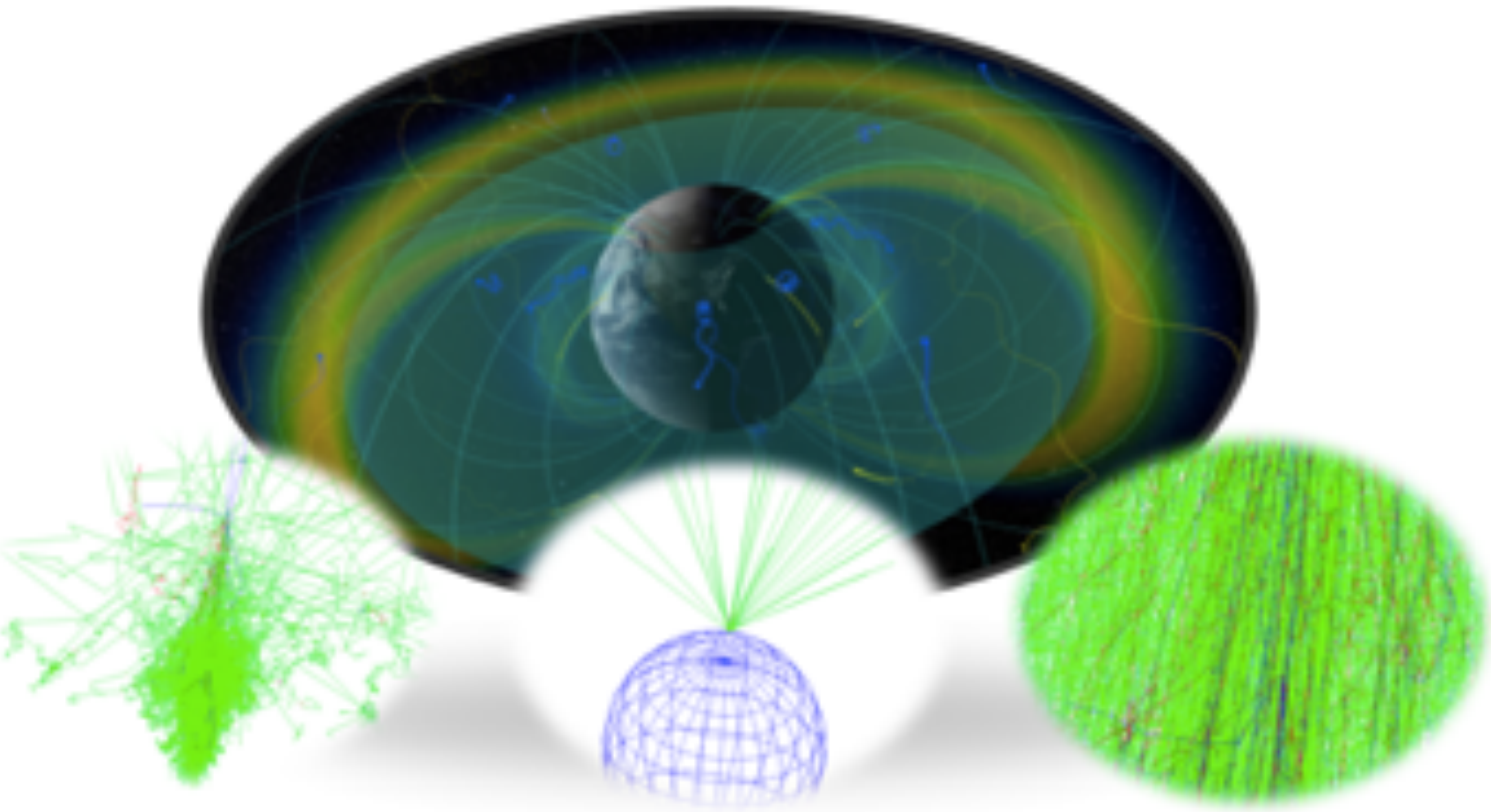


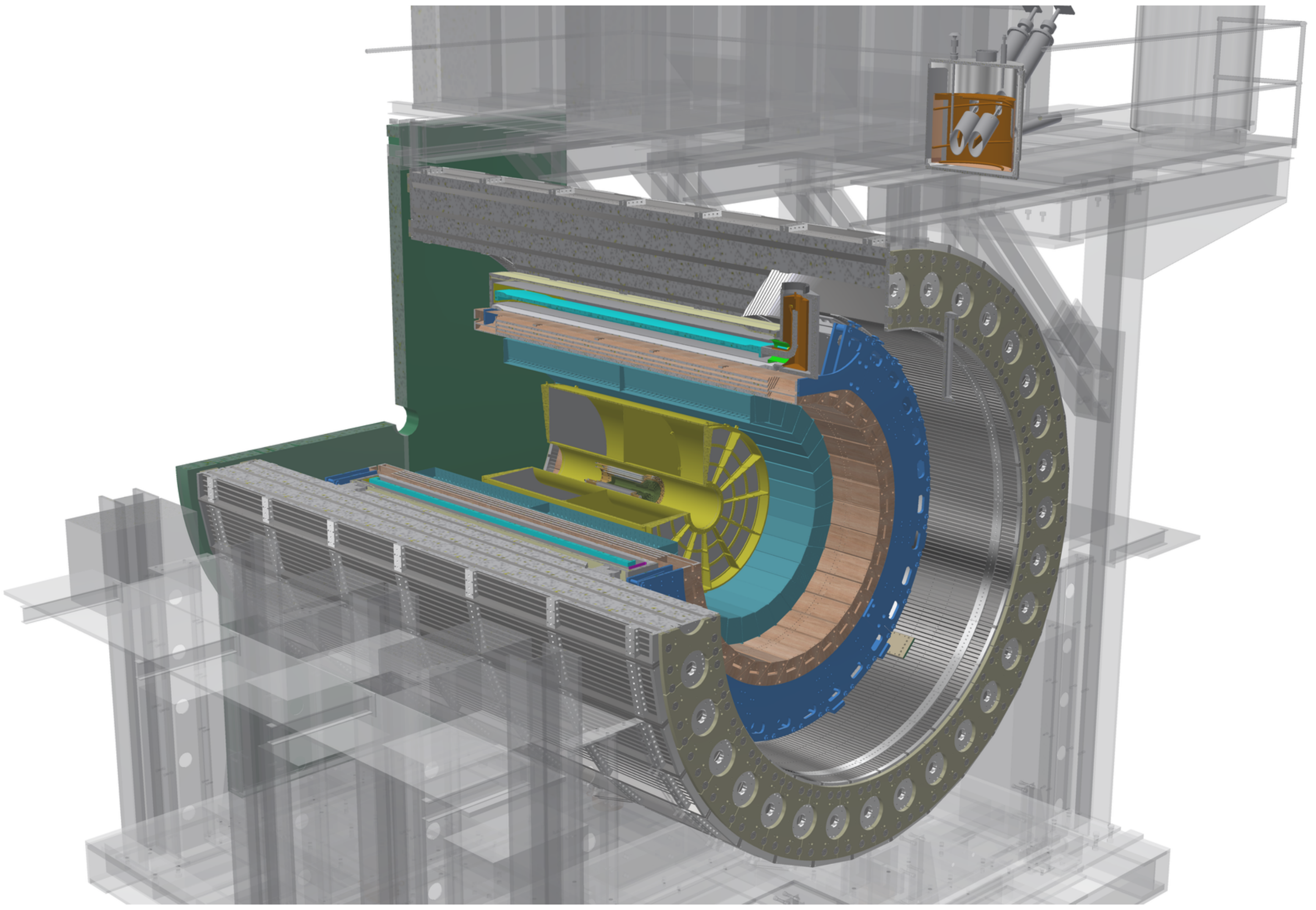
2013 to 2040

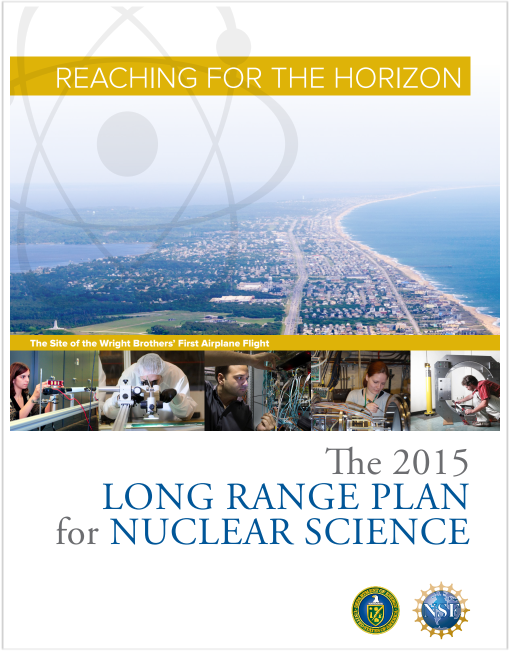
Understand the connection between radiation (cosmic rays) and life on earth in broad spectra. GSU group is developing novel, portable and low-cost cosmic ray detectors for simultaneous measurements of cosmic ray flux variations at global scale.



Cosmic ray flux measurement at global scale and the associated applications

Since 2003





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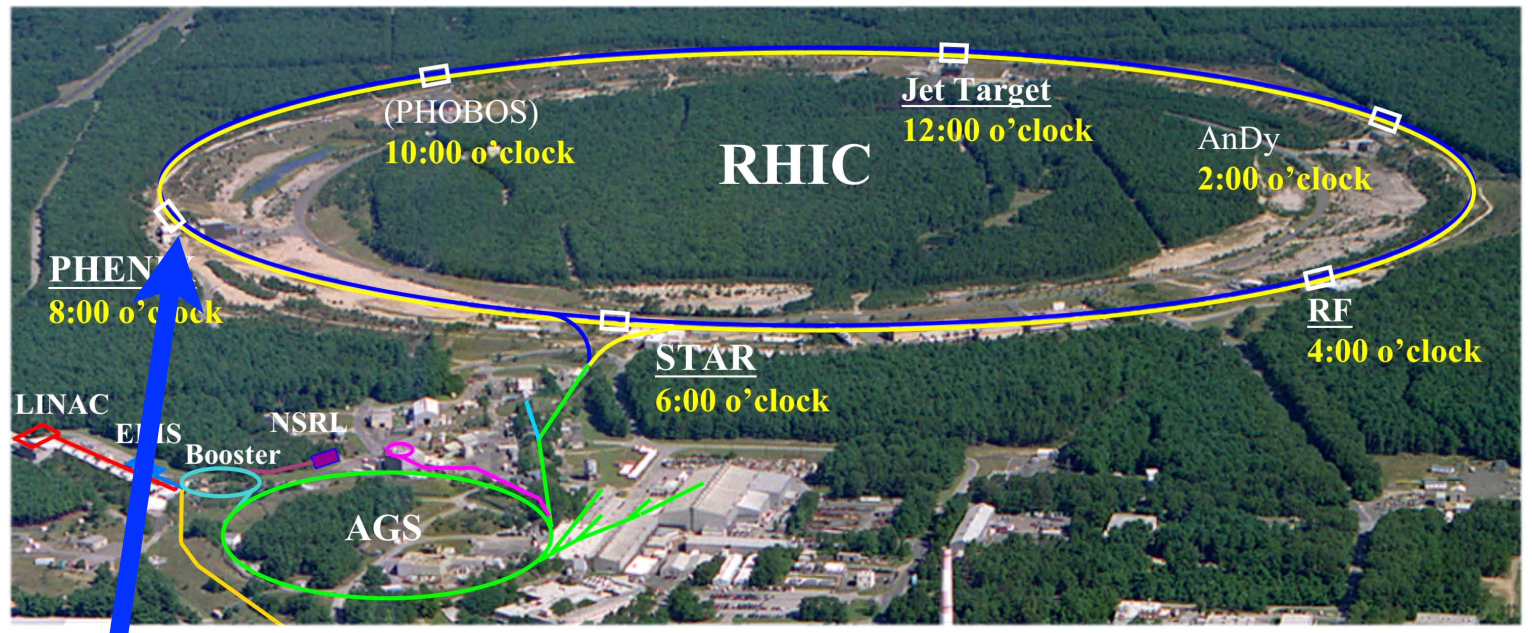

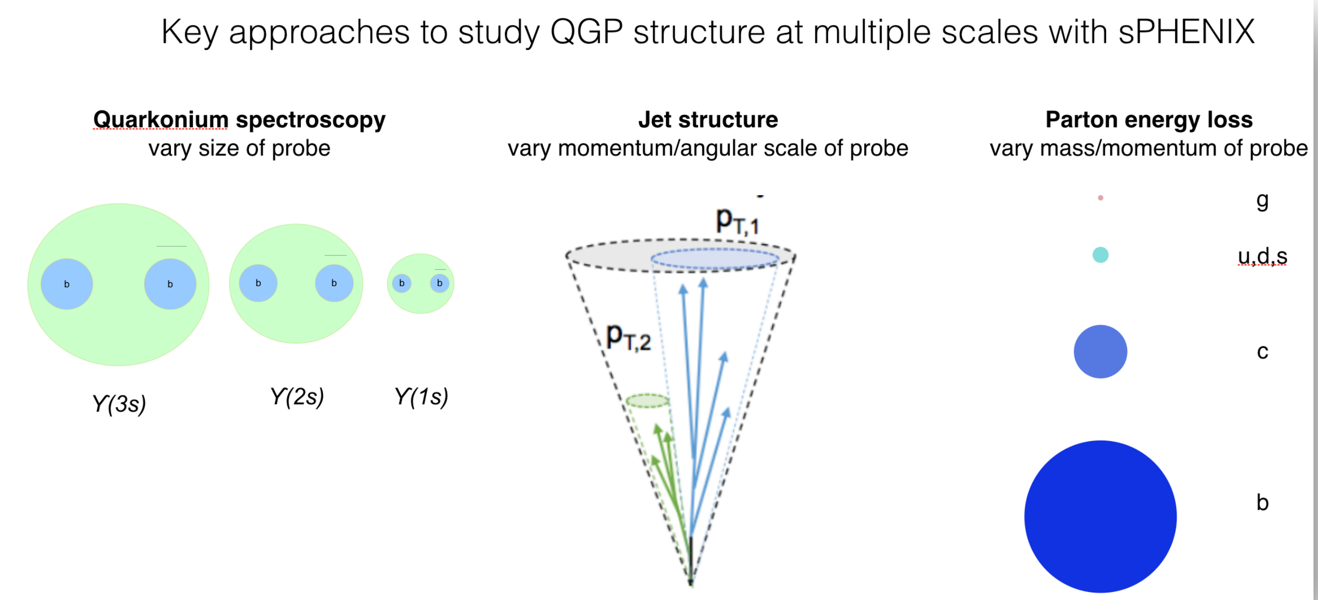

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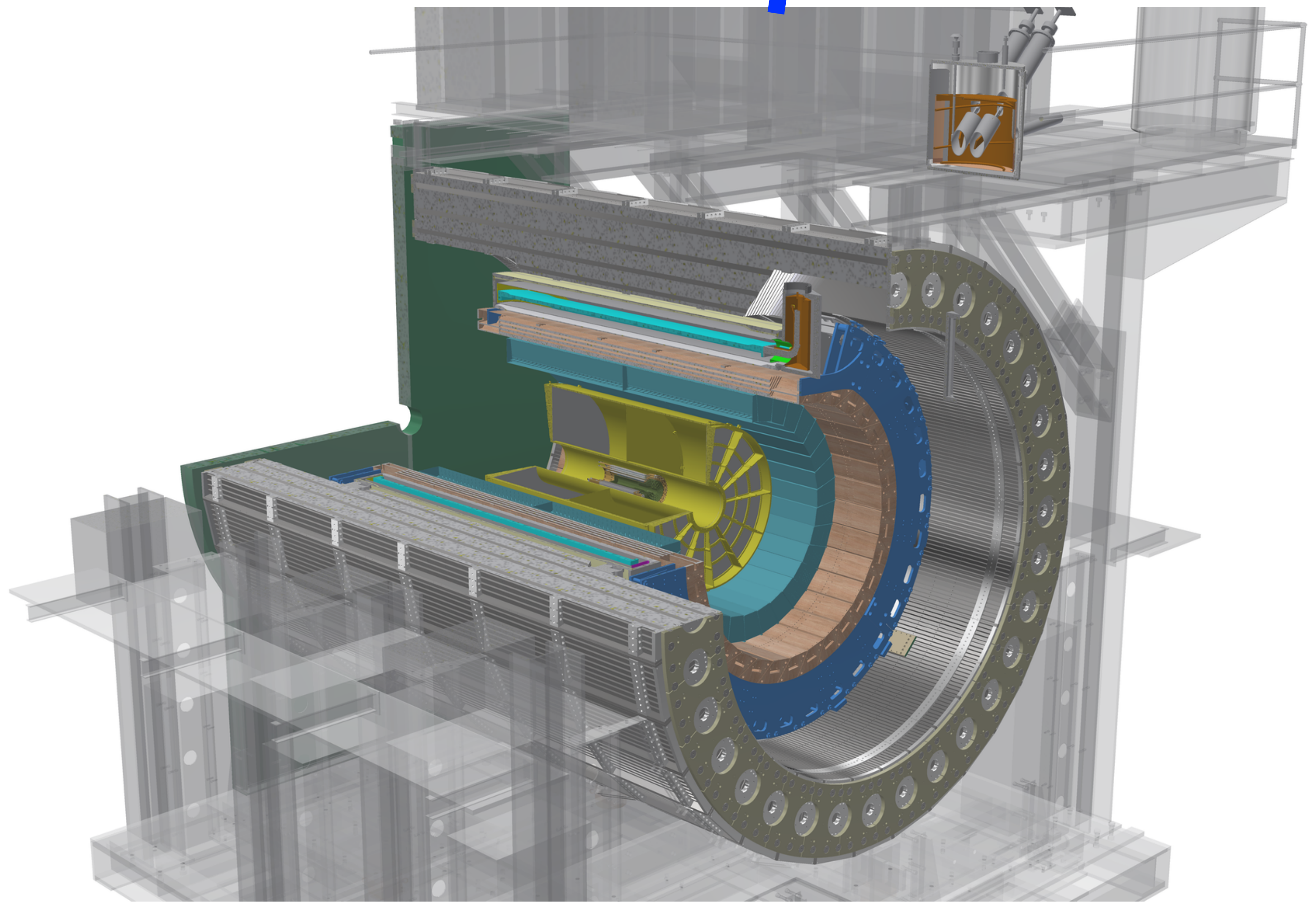

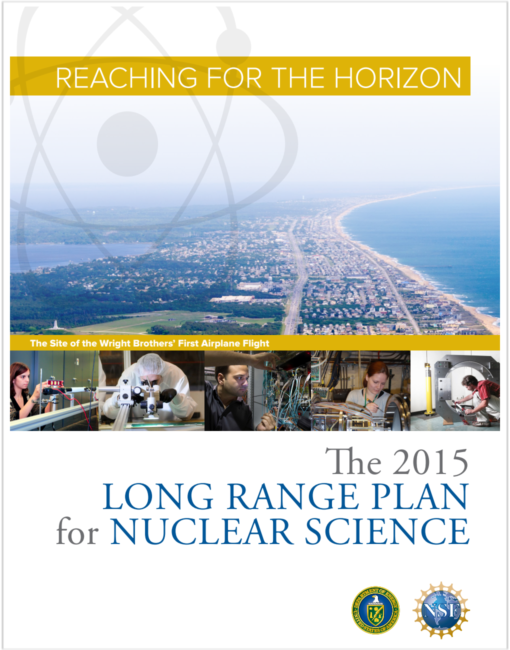

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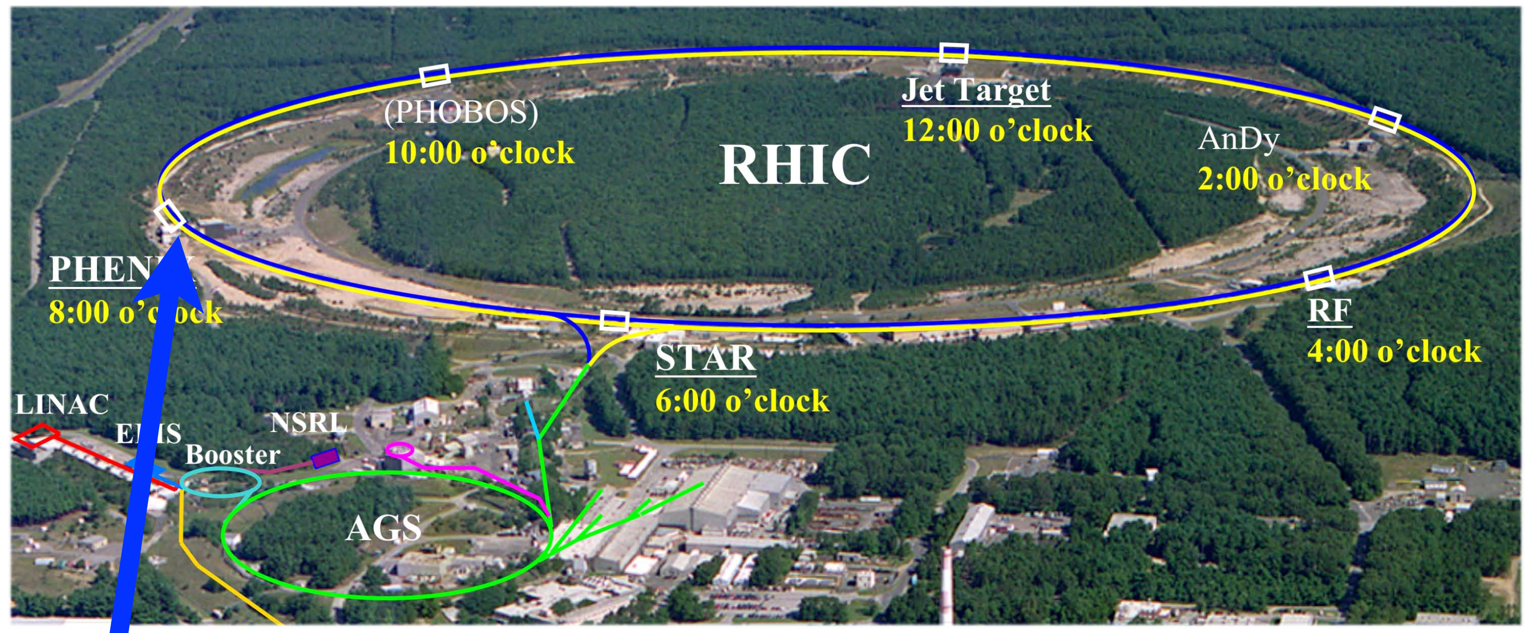

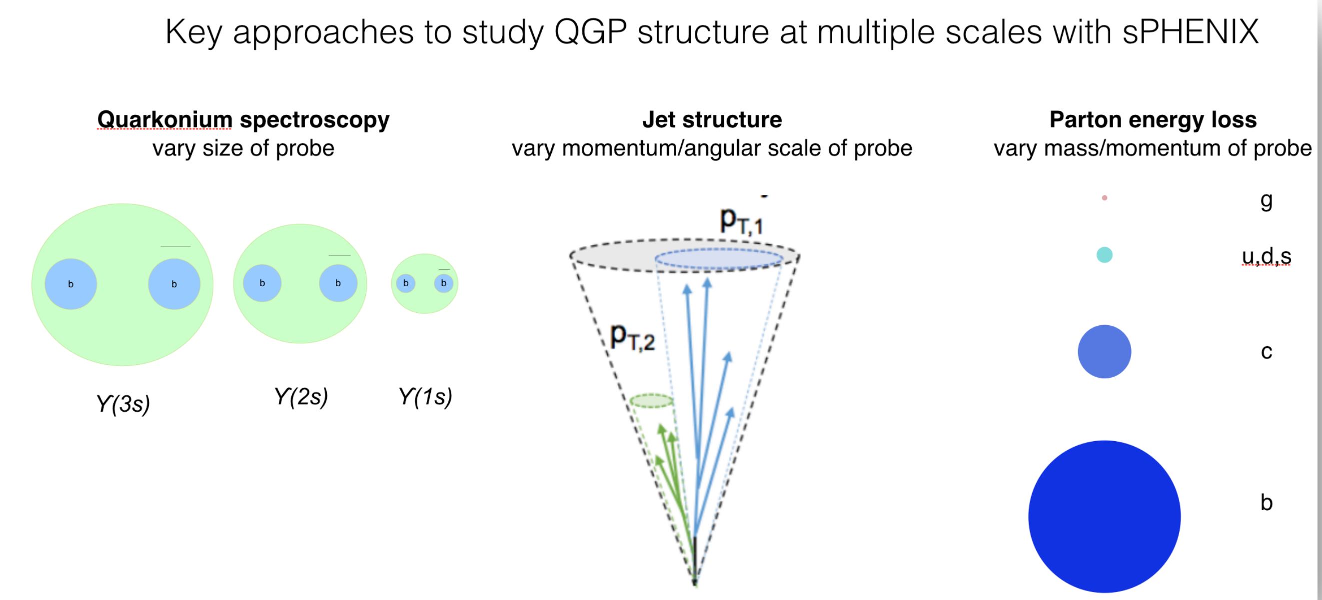

sPHENIX

Scope of Work

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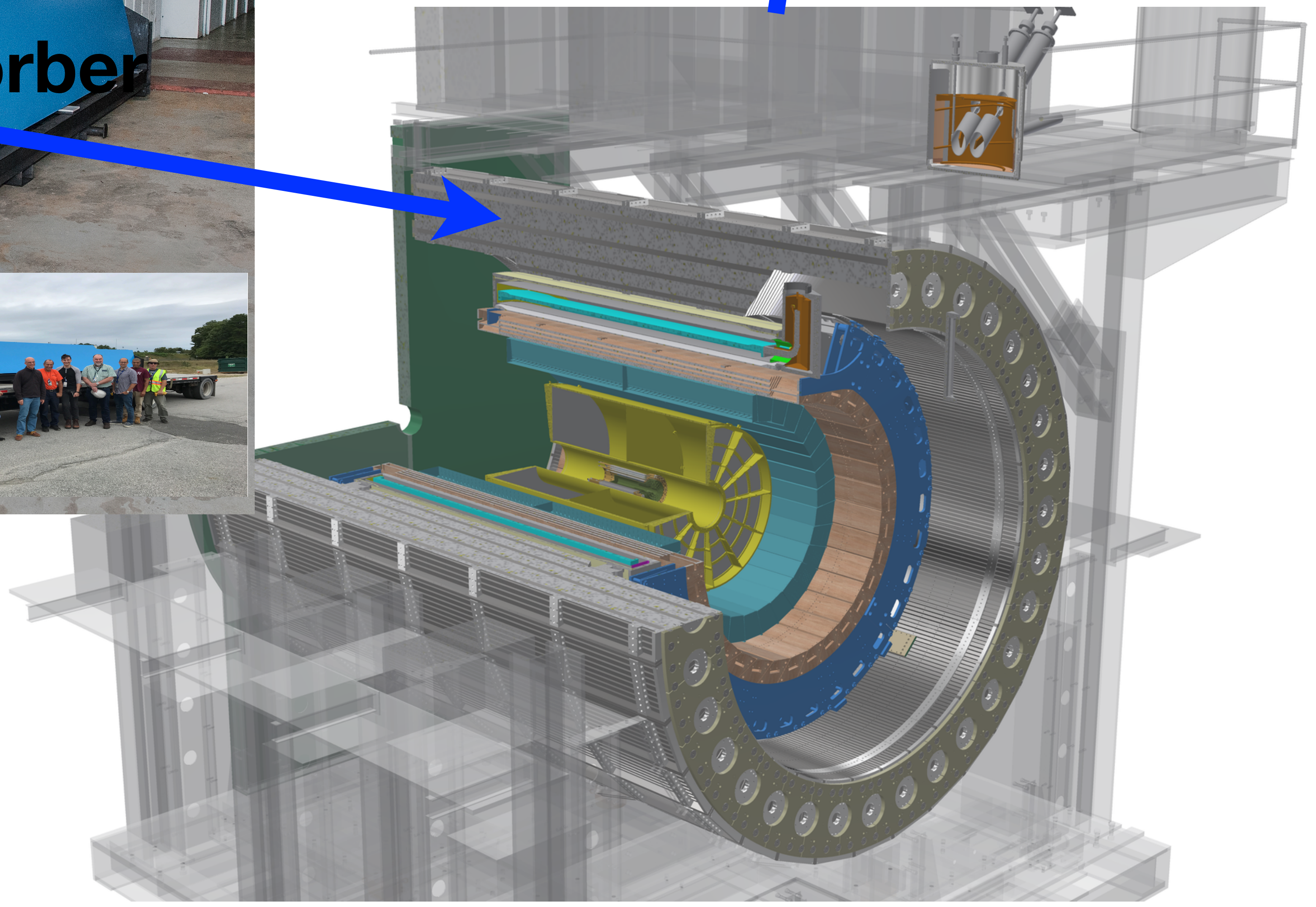
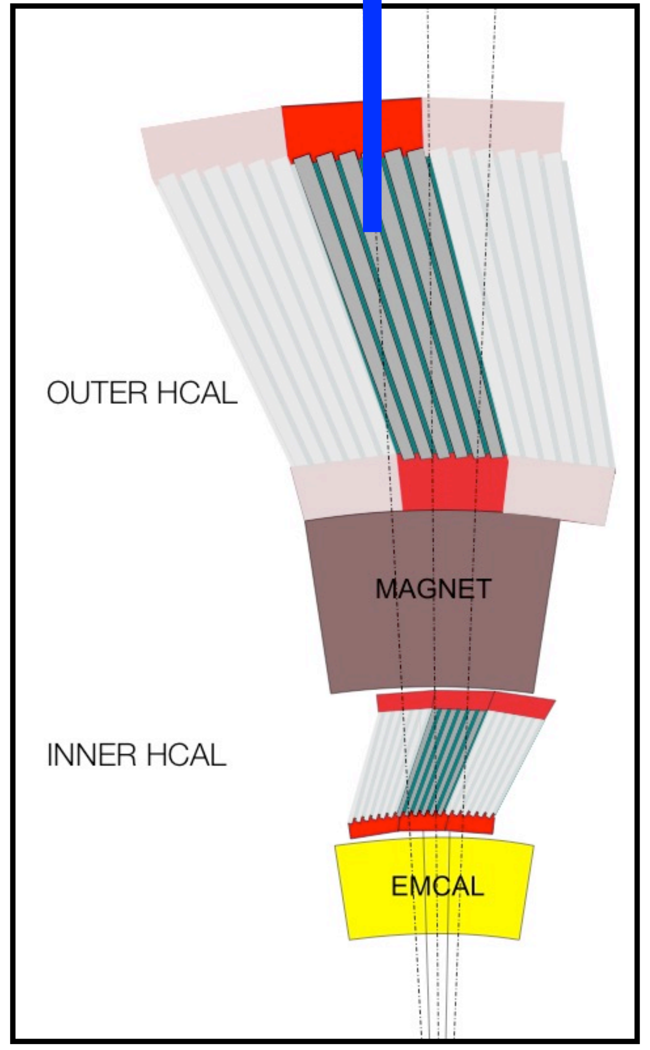
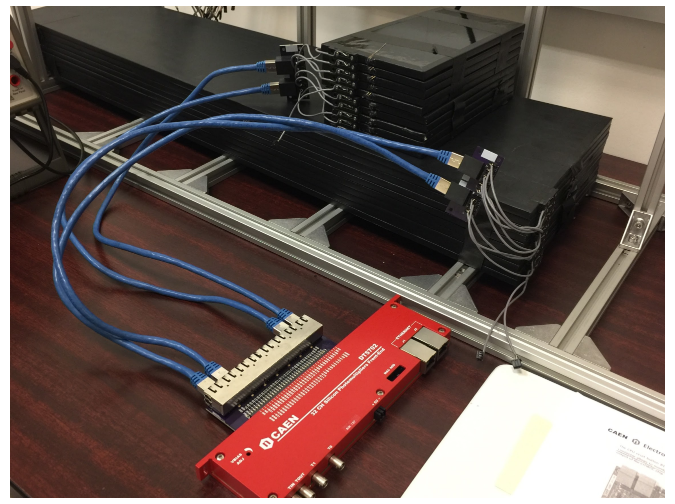
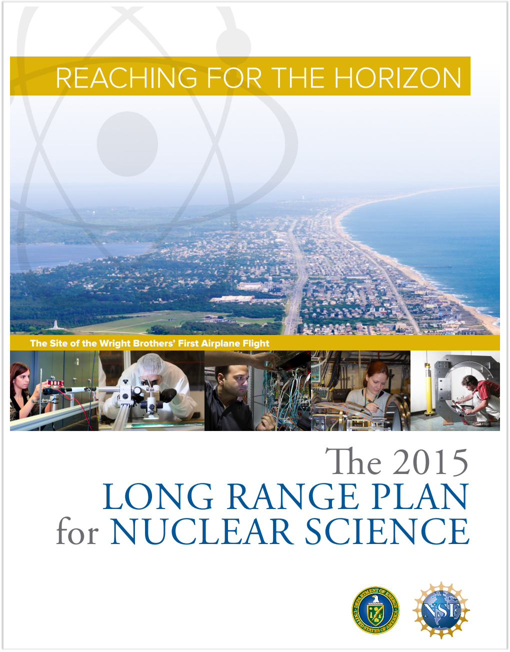






Scintillation tile test @ GSU



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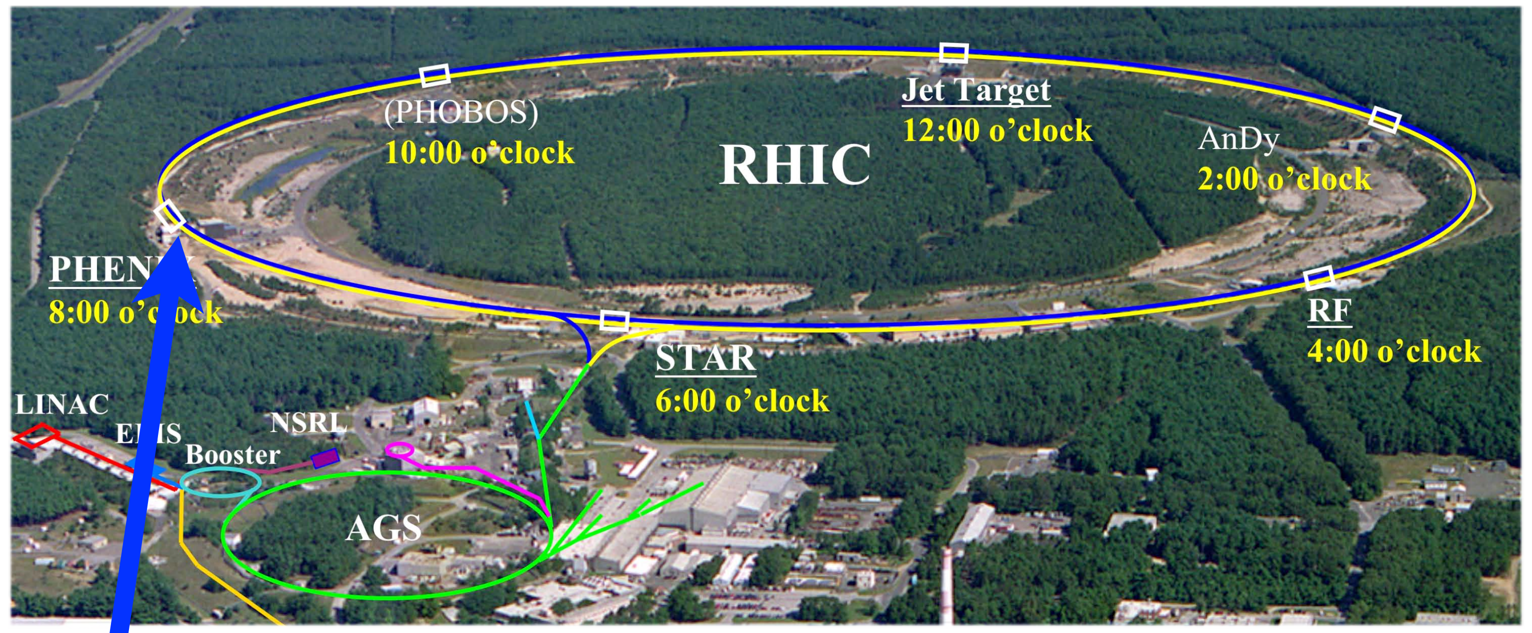

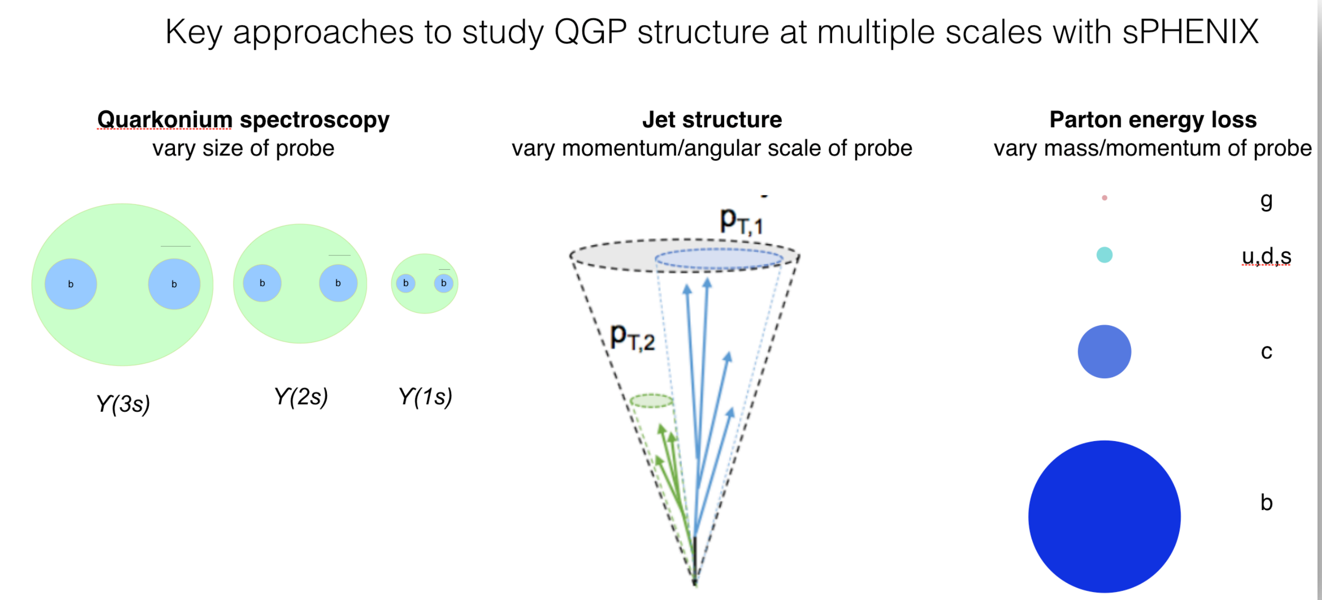

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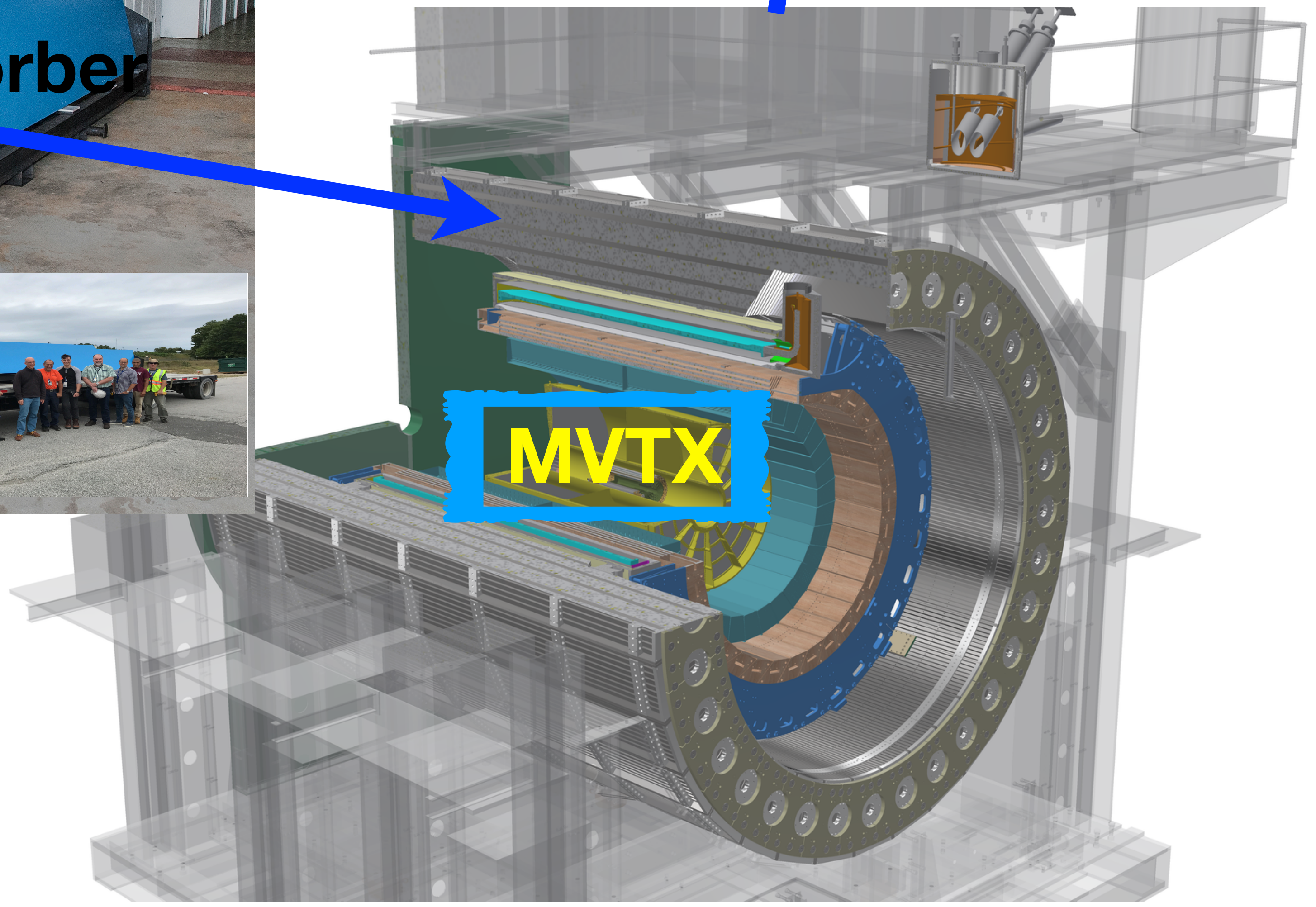

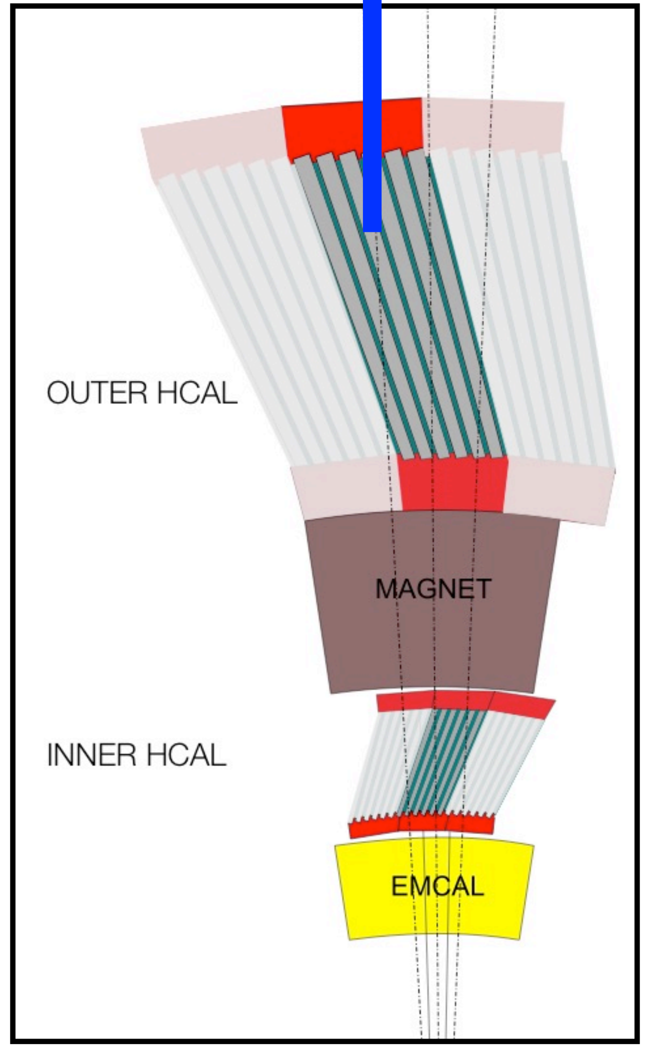

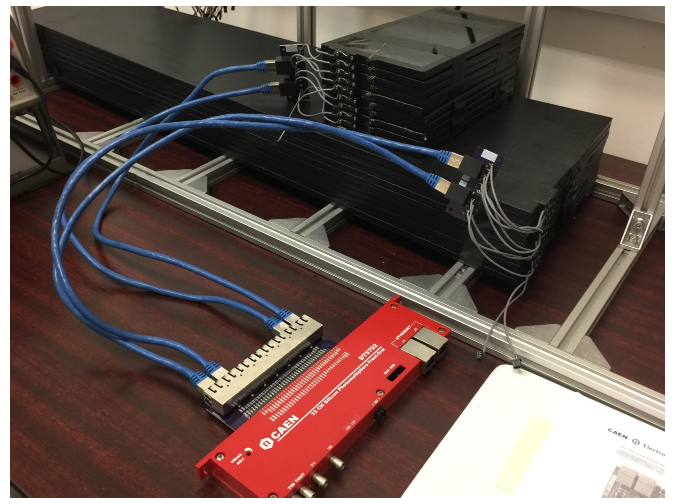

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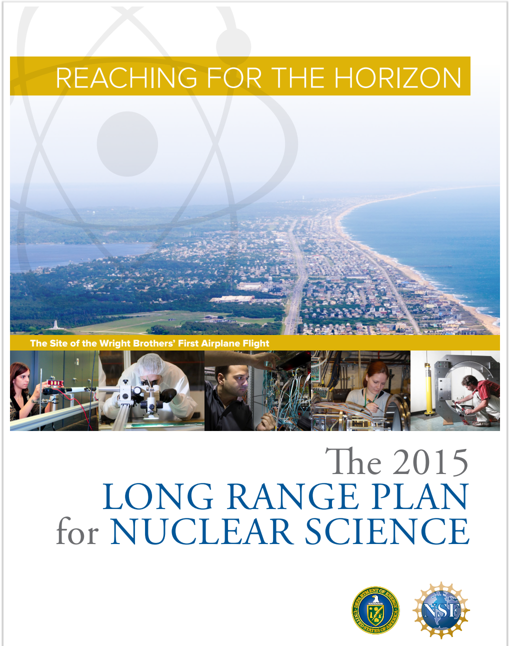

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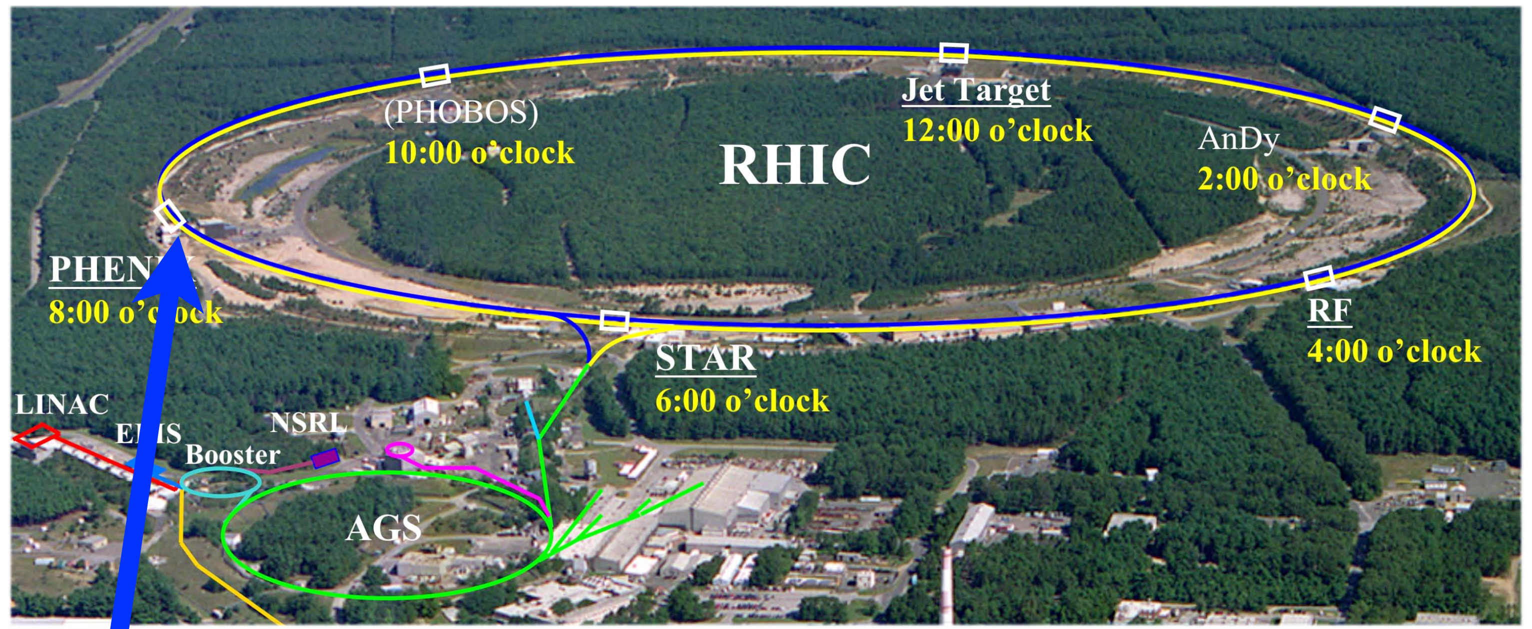

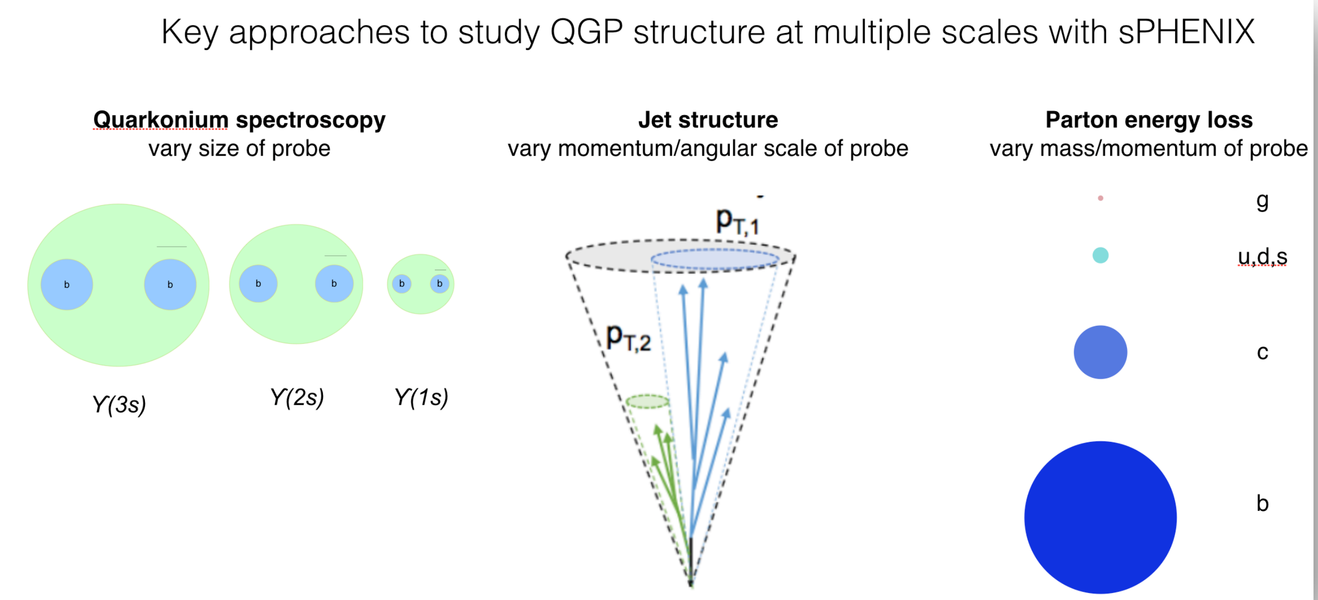

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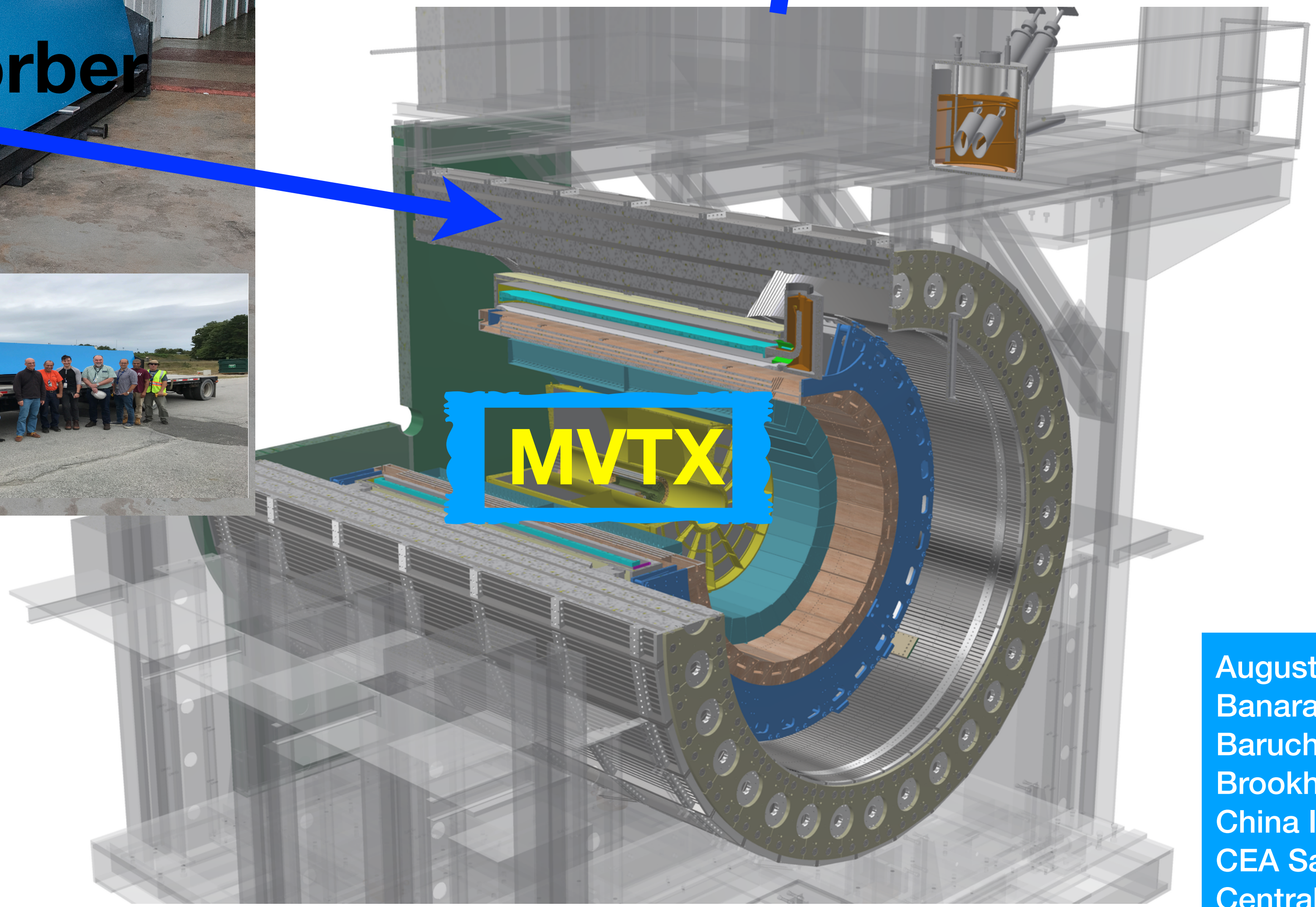
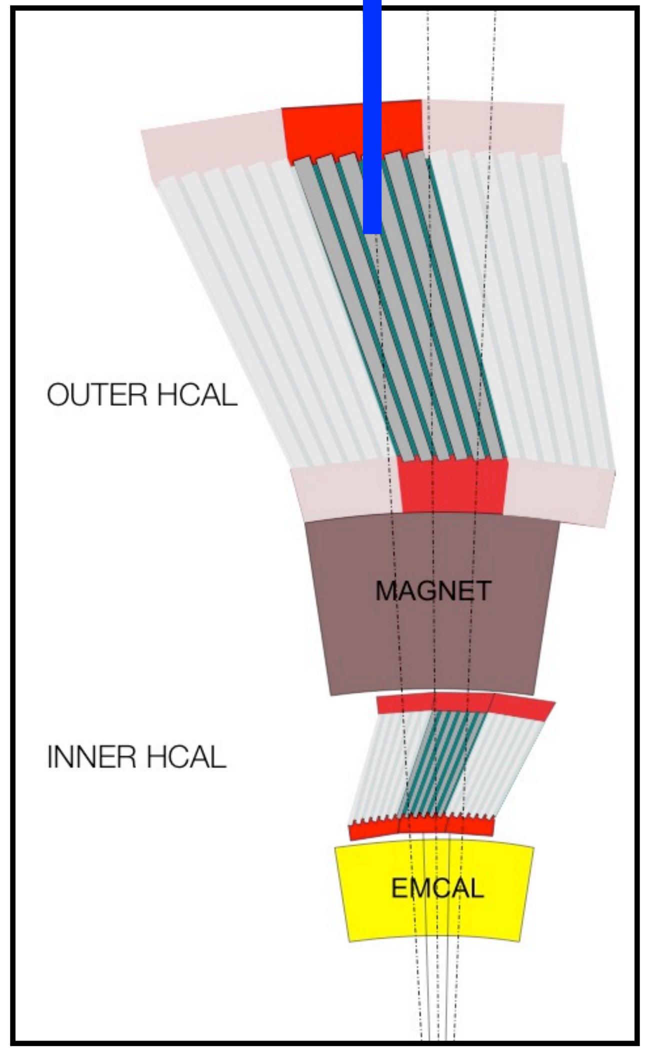
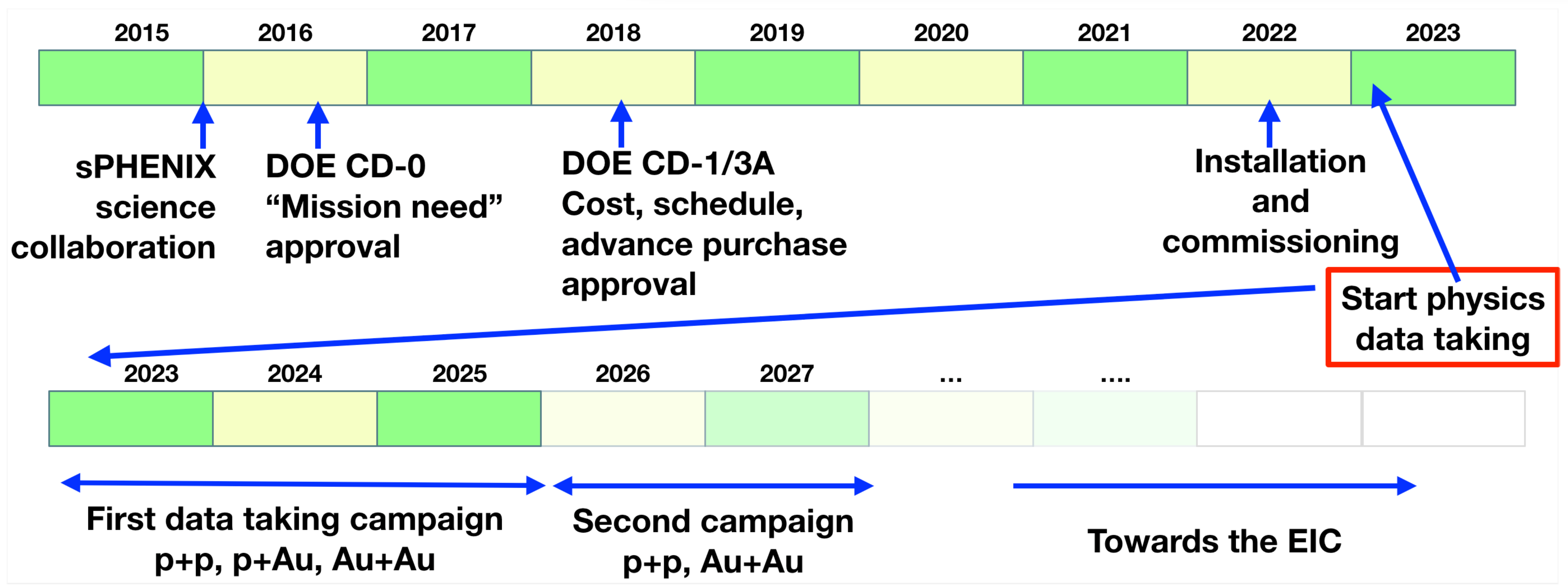
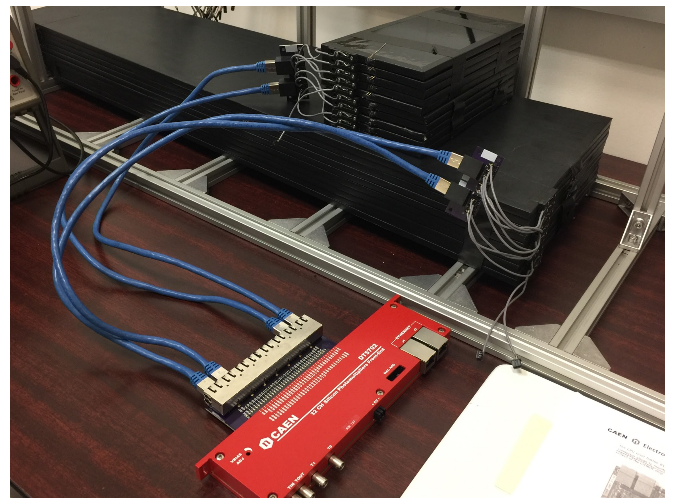






Collaboration Meeting at GSU, Dec '16



Scintillation tile test @ GSU

Georgia State University

Augustana University
Banaras Hindu University
Baruch College, CUNY
Brookhaven National Laboratory
China Institute for Atomic Energy
CEA Saclay
Central China Normal University
Chonbuk National University
Columbia University
Eötvös University
Florida State University
Fudan University
Georgia State University
Howard University
Hungarian sPHENIX Consortium
Institut de physique nucléaire d'Orsay
Institute for High Energy Physics, Protvino
Institute of Nuclear Research, Russian Academy of Sciences, Moscow
Institute of Physics, University of Tsukuba
Institute of Modern Physics, China
Iowa State University
Japan Atomic Energy Agency
Charles University (CUNI), Prague
Czech Technical University in Prague (CTU)
Korea University
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Lehigh University
Los Alamos National Laboratory
Massachusetts Institute of Technology
Muhlenberg College
Nara Women's University
National Research Centre "Kurchatov Institute"
National Research Nuclear University "MEPhI"
New Mexico State UniversityOak Ridge National Laboratory
Ohio University
Peking University
Petersburg Nuclear Physics Institute
Purdue University
Rice University
RIKEN
RIKEN BNL Research Center
Rikkyo University
Rutgers University
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Stony Brook University
Sun Yat Sen University
Temple University
Tokyo Institute of Technology
Tsinghua University
Universidad Técnica Federico Santa María
University of California, Berkeley
University of California, Los Angeles
University of California, Riverside
University of Colorado, Boulder
University of Debrecen
University of Houston
University of Illinois, Urbana-Champaign
University of Jammu
University of Maryland
University of Michigan
University of New Mexico
University of Tennessee, Knoxville
University of Texas, Austin
University of Tokyo
University of Science and Technology, China
Vanderbilt University
Wayne State University
Weizmann Institute
Yale University
Yonsei University

A Great International Collaboration

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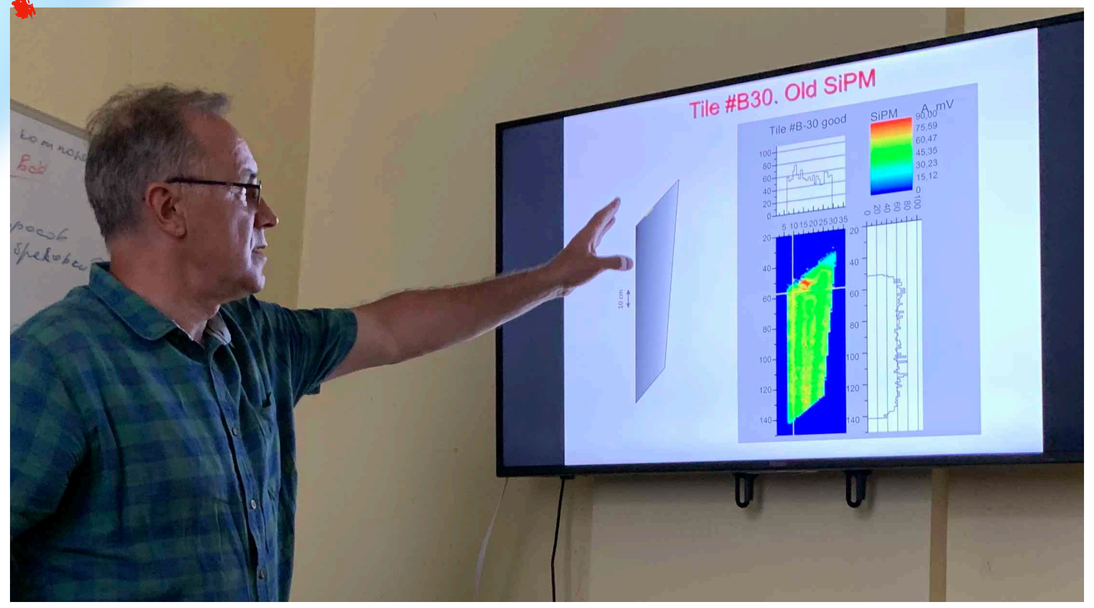
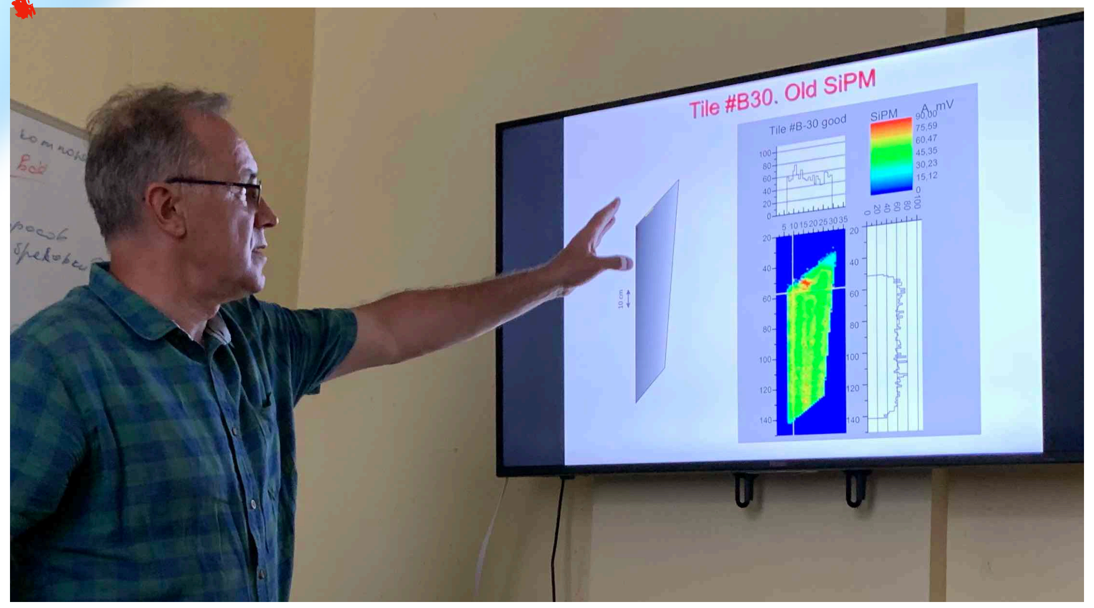


A Great International Collaboration



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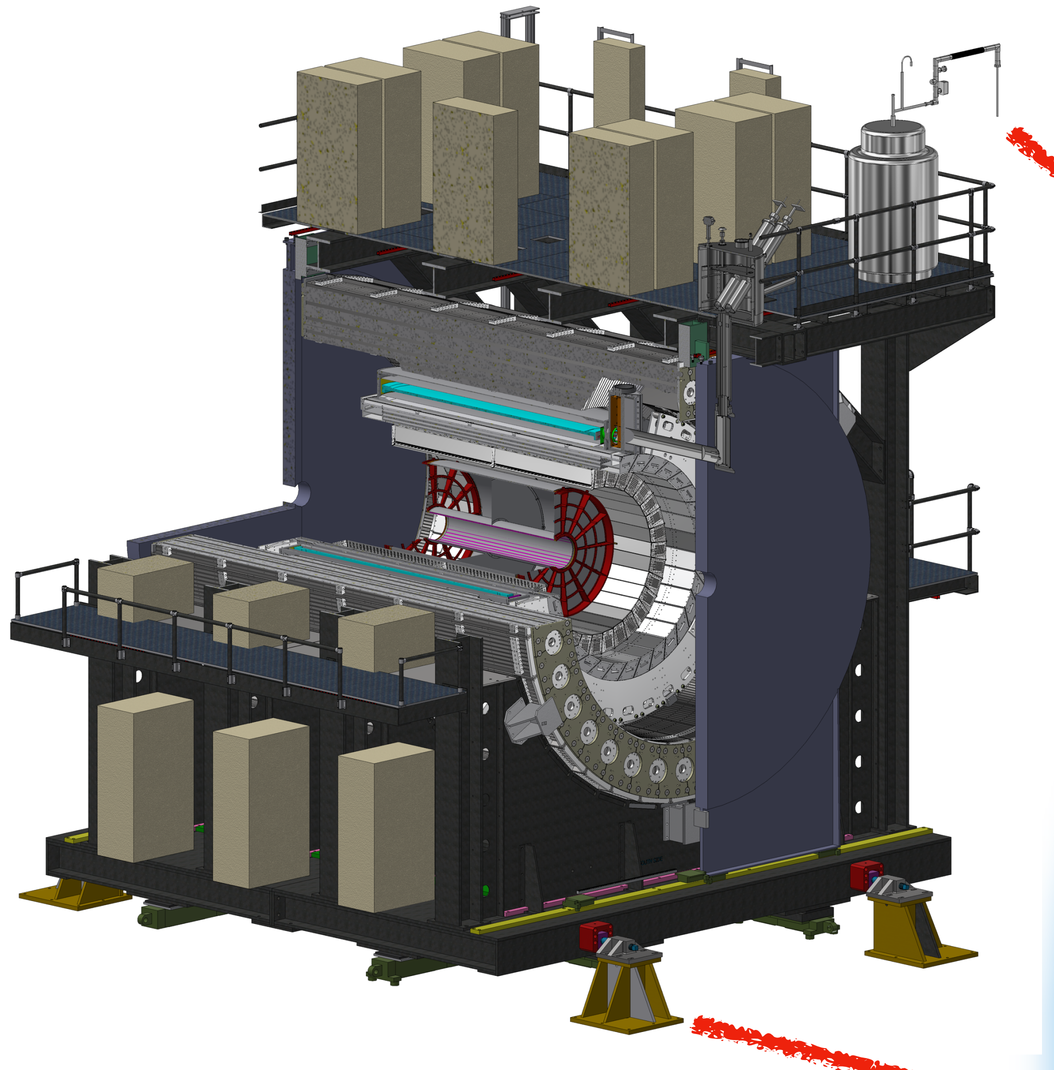
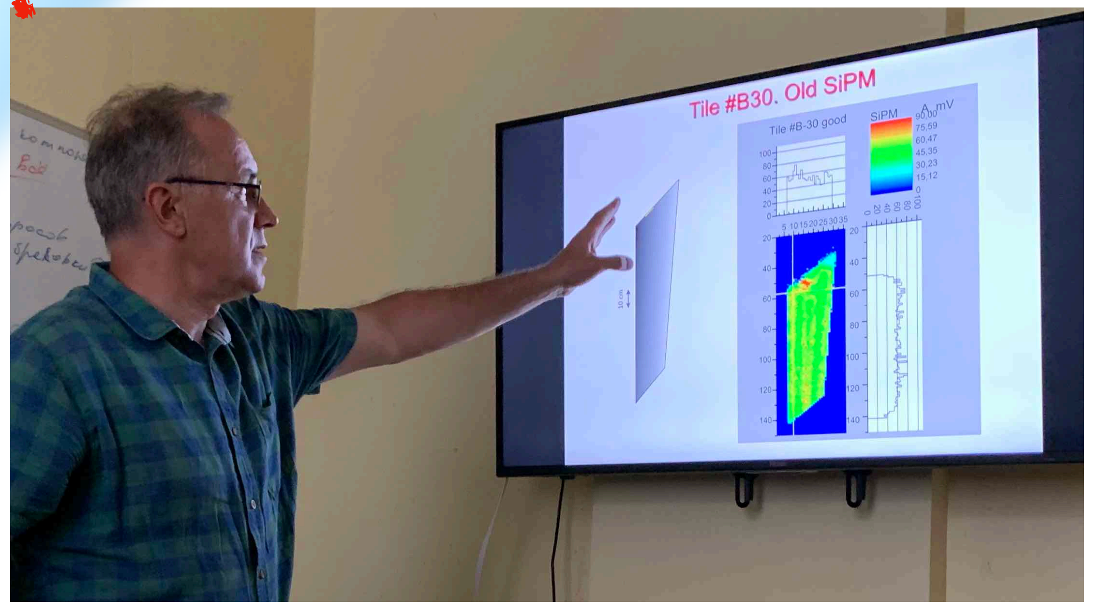
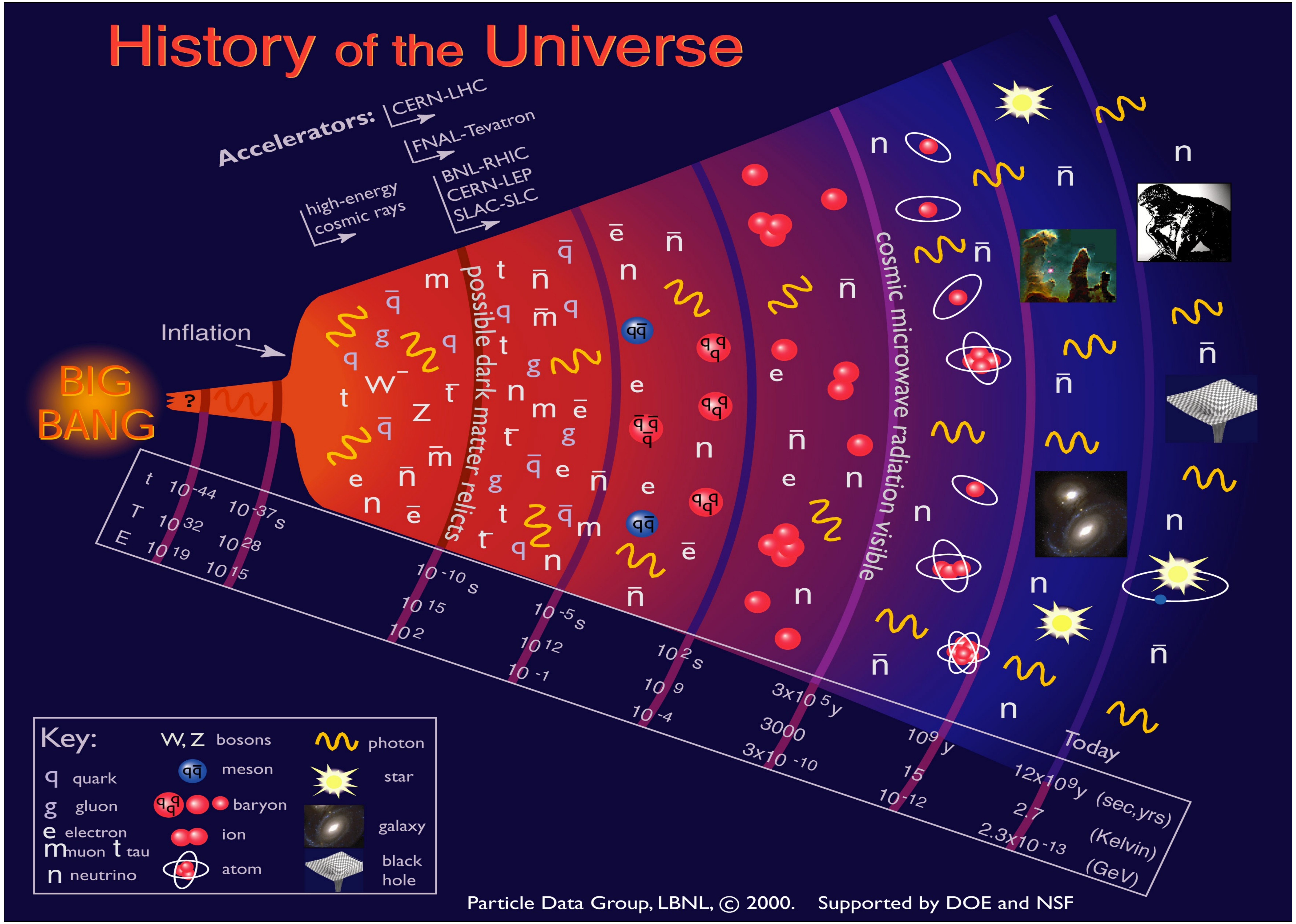
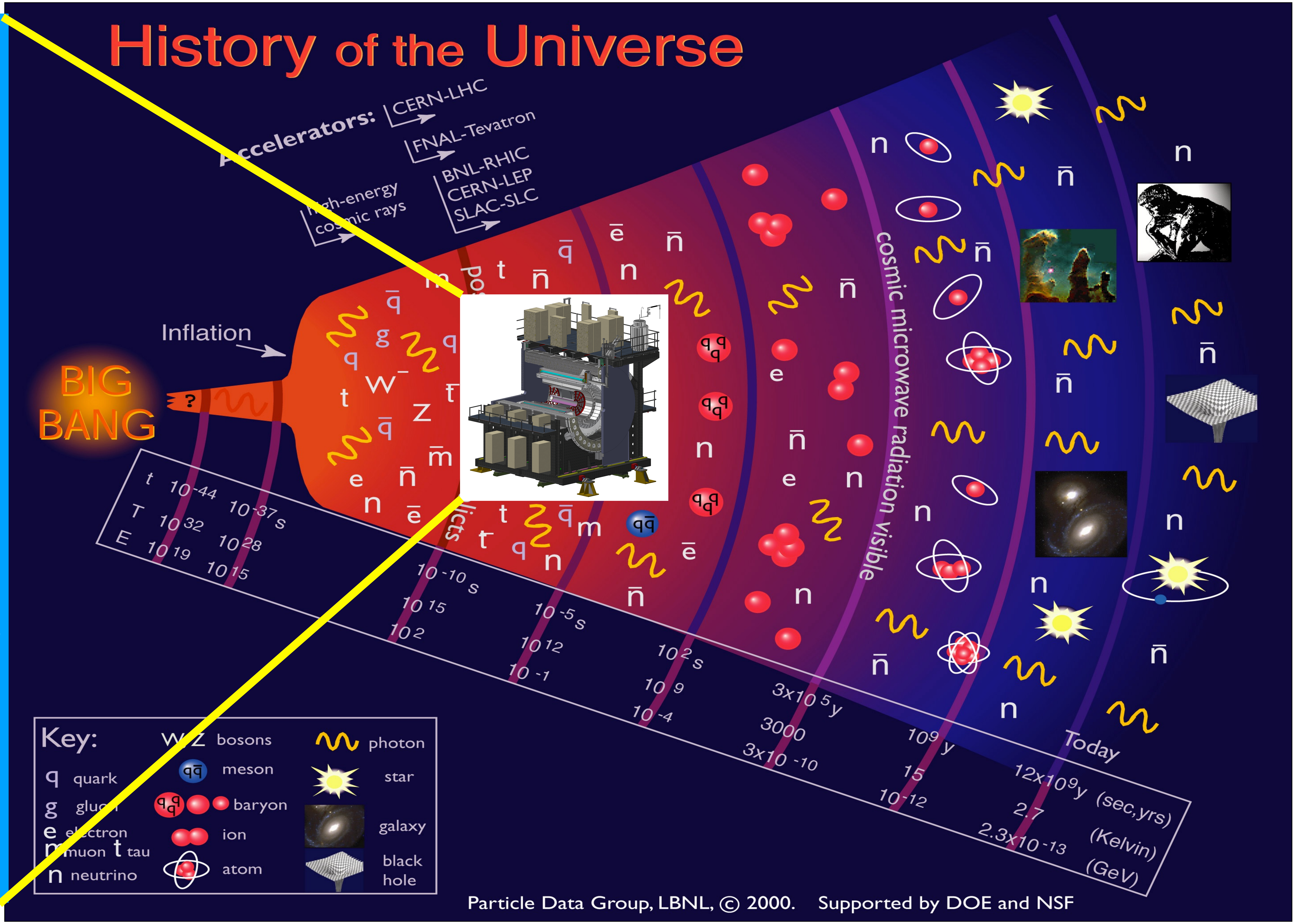






History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
Today
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
galaxy
e electron
ion
m muon t tau
n neutrino
atom
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

sPHENIX allows us to study and quantify the matter properties a few microseconds after the big-band through the collisions of relativistic heavy ion collisions.



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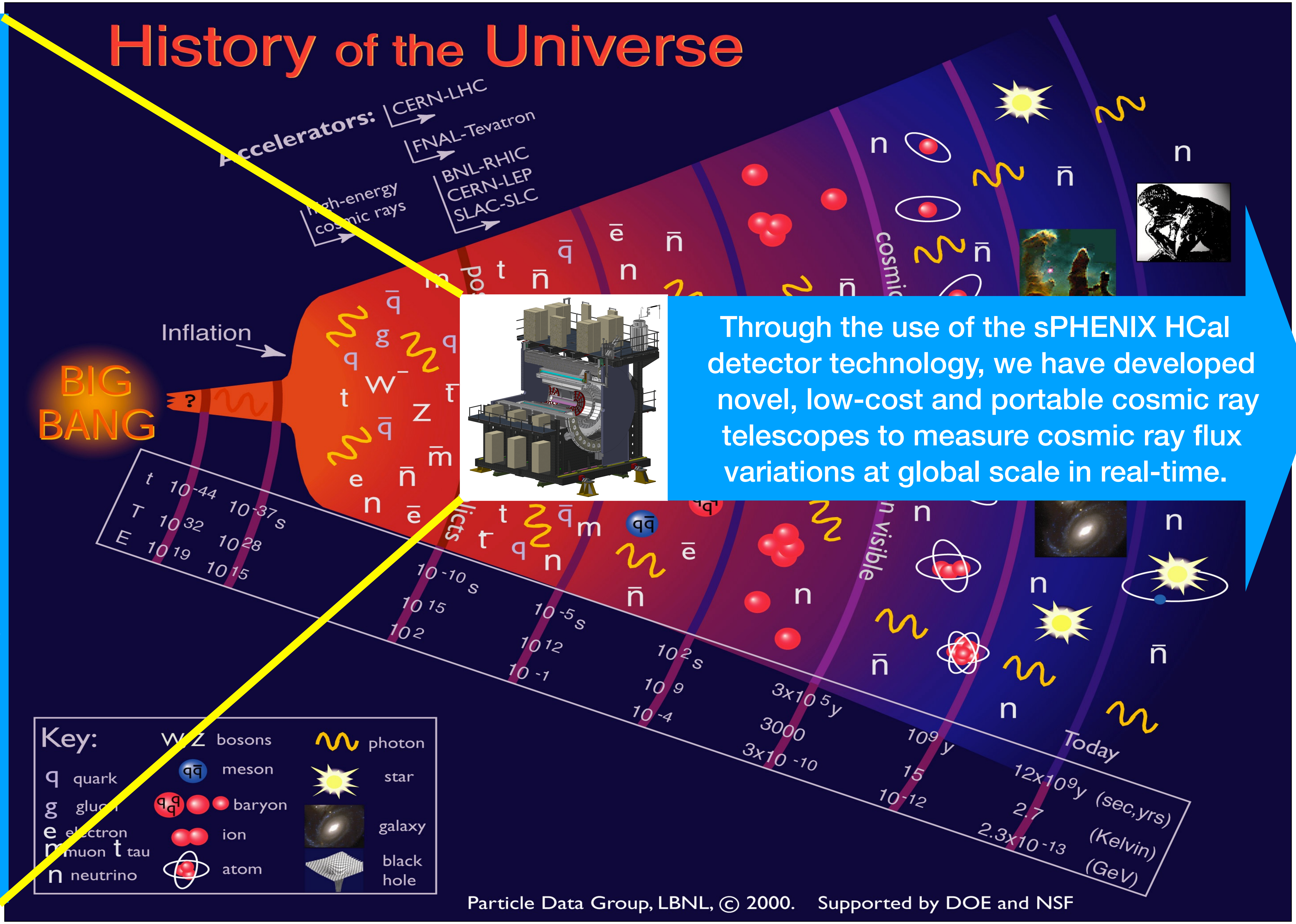
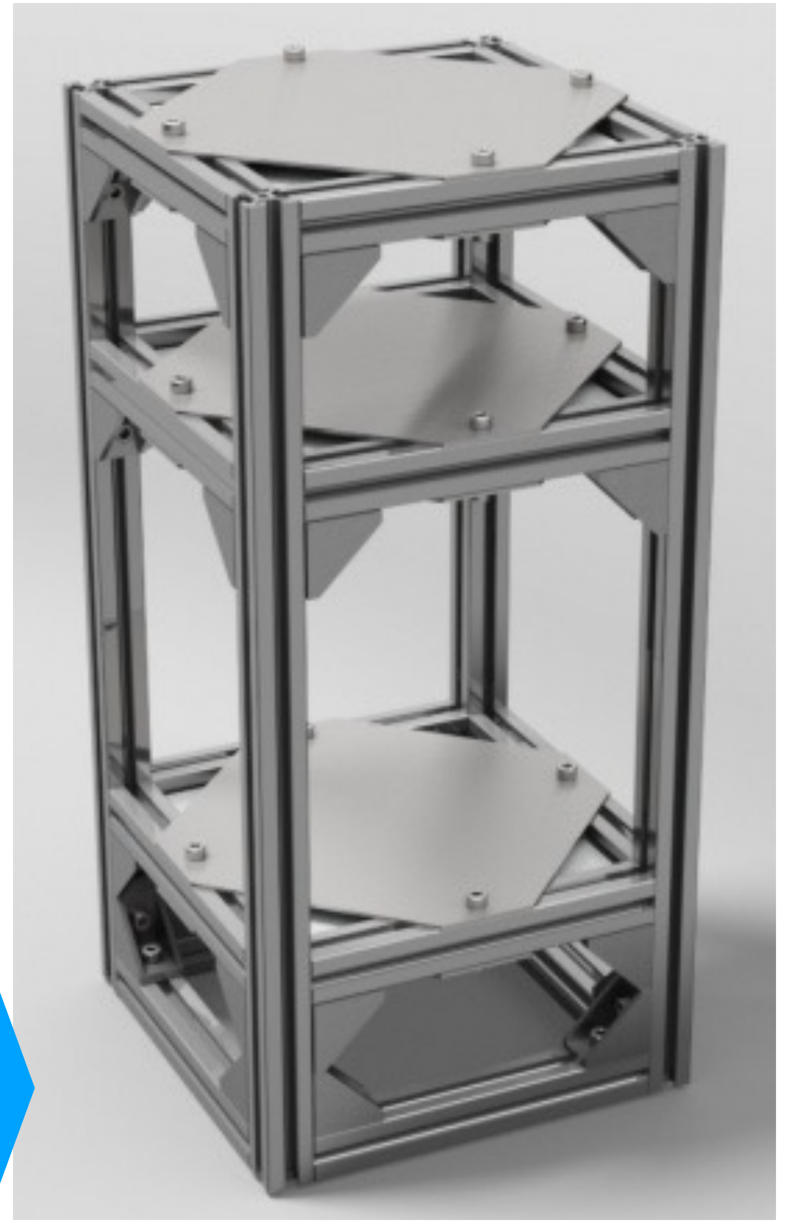
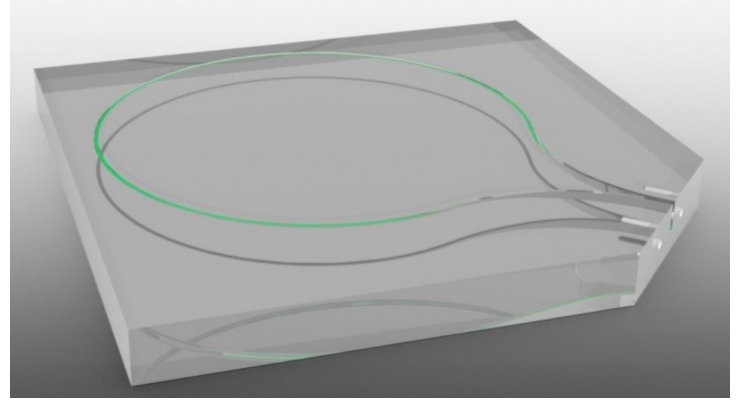
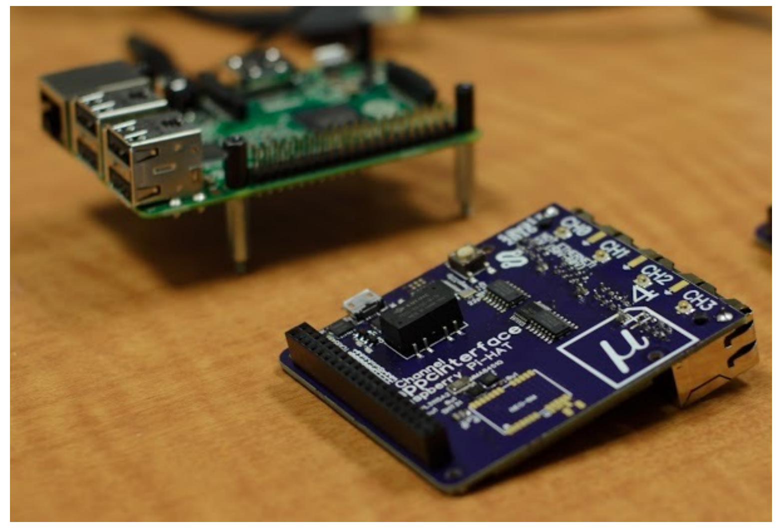


Through the use of the sPHENIX HCal detector technology, we have developed novel, low-cost and portable cosmic ray telescopes to measure cosmic ray flux variations at global scale in real-time.







A Few Interesting Studies Related to Cosmic Ray Applications

Earliest Study on Records

Cosmic Rays in the Earth's Atmosphere and Underground

By Lev I. Dorman

14.5. Possible influence of solar activity/cosmic ray intensity long term variations on wheat prices (through weather changes) in medieval England

As we mentioned in Section 14.1, Herschel (1801) was the first who paid attention to an evident correlation between the observed number of sunspots and the state of the wheat market, based on a series of wheat prices published by Smith (M1776). Herschel showed that five prolonged periods of few sunspots correlated with costly wheat. The next scientist in this field was the well known English economist and logician William Stanley Jevons (1875), one of the creators of Neoclassical Economic Theory. He directed his attention to the first part of the data, published later in the first volume of a series of monographs by Rogers (M1887). In this volume were presented wheat prices over 140 years, from 1259 up to 1400. Jevons (1875) discovered that the time intervals between high prices were close to 10–11 years. The coincidence of these intervals with

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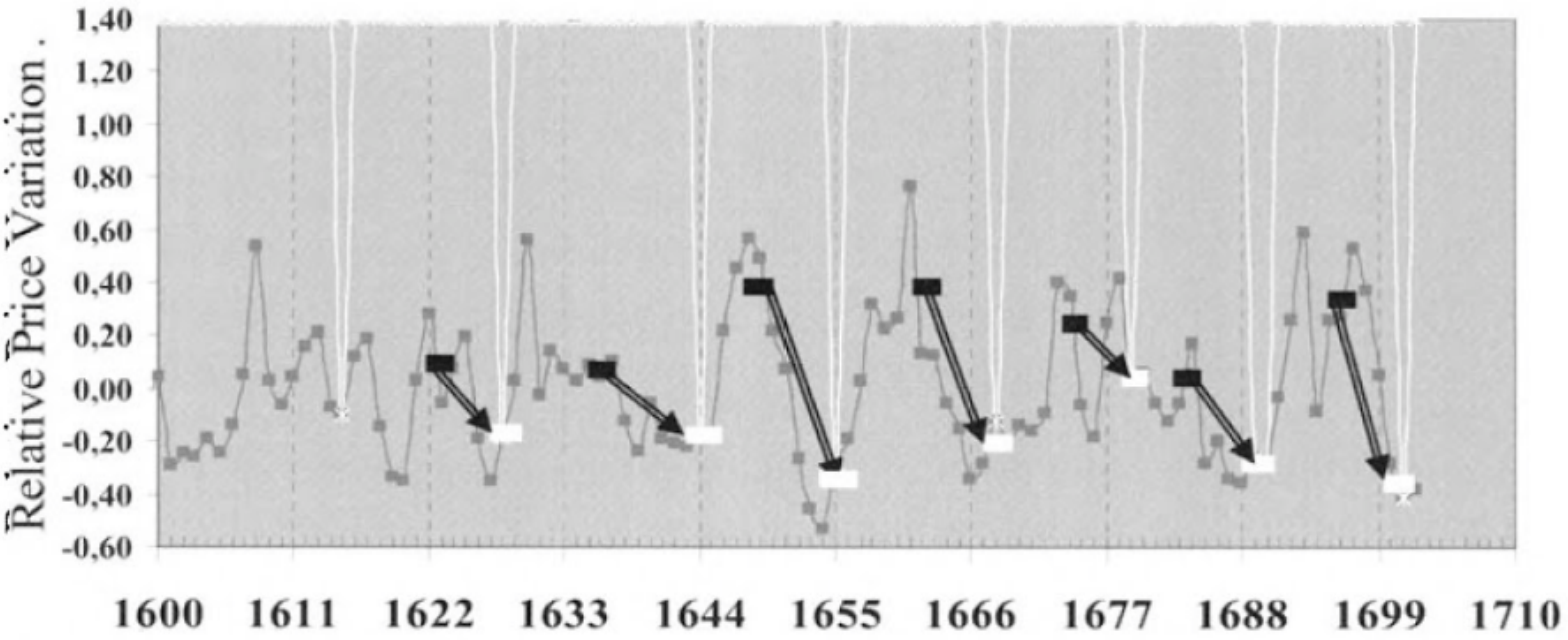
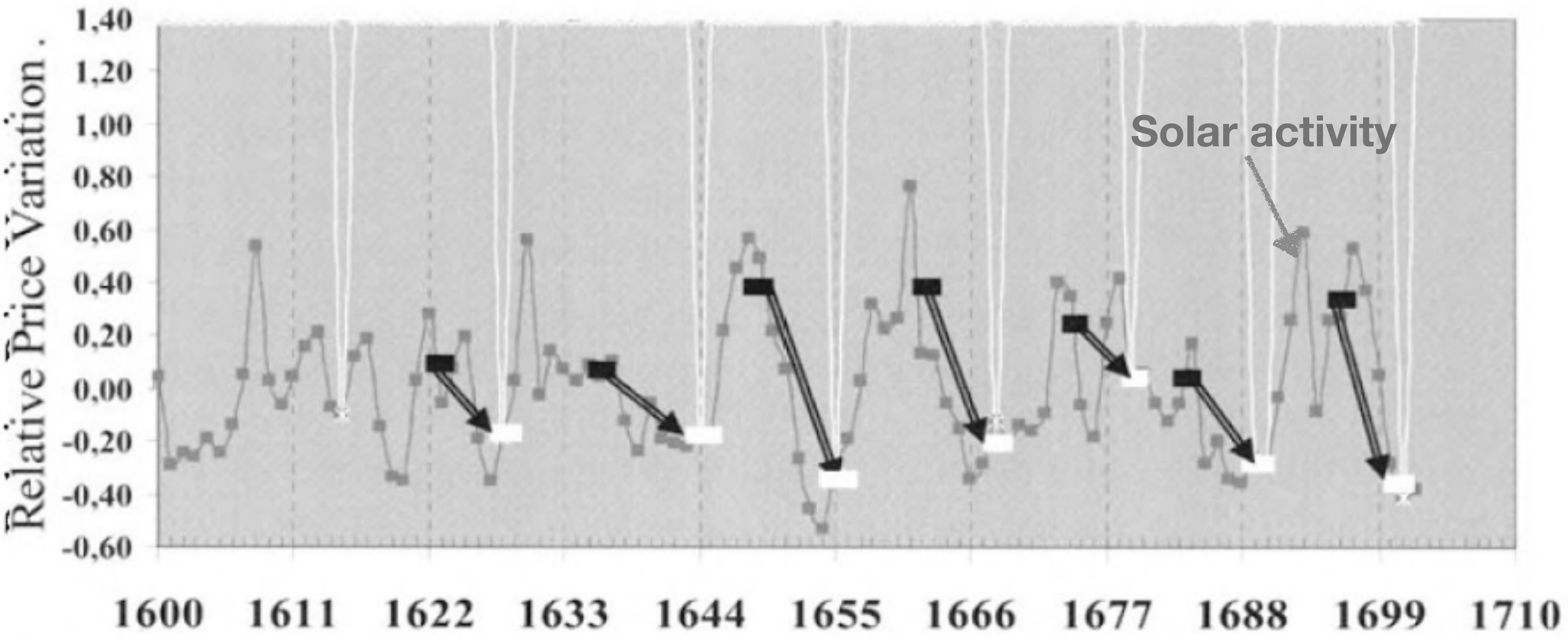


Fig. 14.5.3. Systematic differences in prices at moments of minimum and maximum CR intensity determined according [10]Be data (Beer et al., 1998). White rectangles show prices averaged for 3-year intervals centered on

Wheat Price Variation in Correlation with Solar Activity



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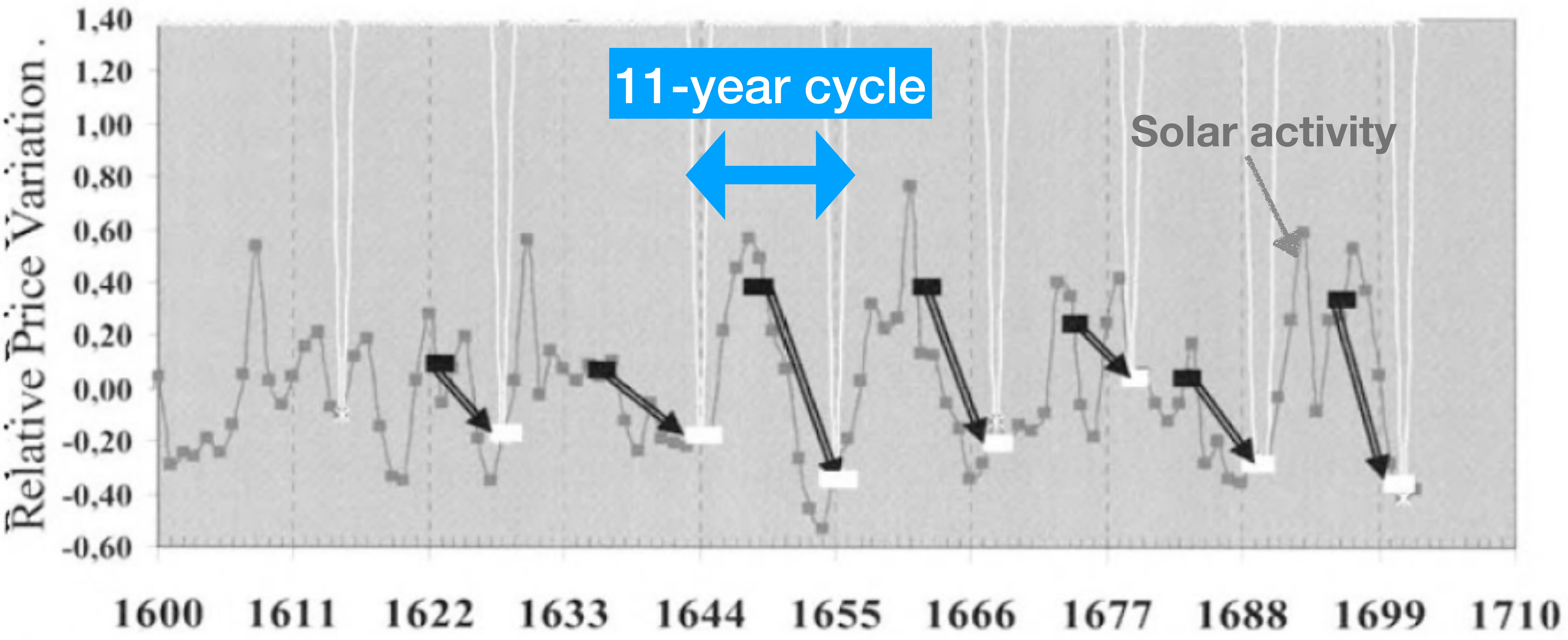

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1959

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Cloud formation may be linked to cosmic rays

Experiment probes connection between climate change and radiation bombarding the atmosphere.

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Maximilien Brice / CERN

The findings, published today in *Nature*[1], are preliminary, but they are stoking a long-running argument over the role of radiation from distant stars in altering the climate.

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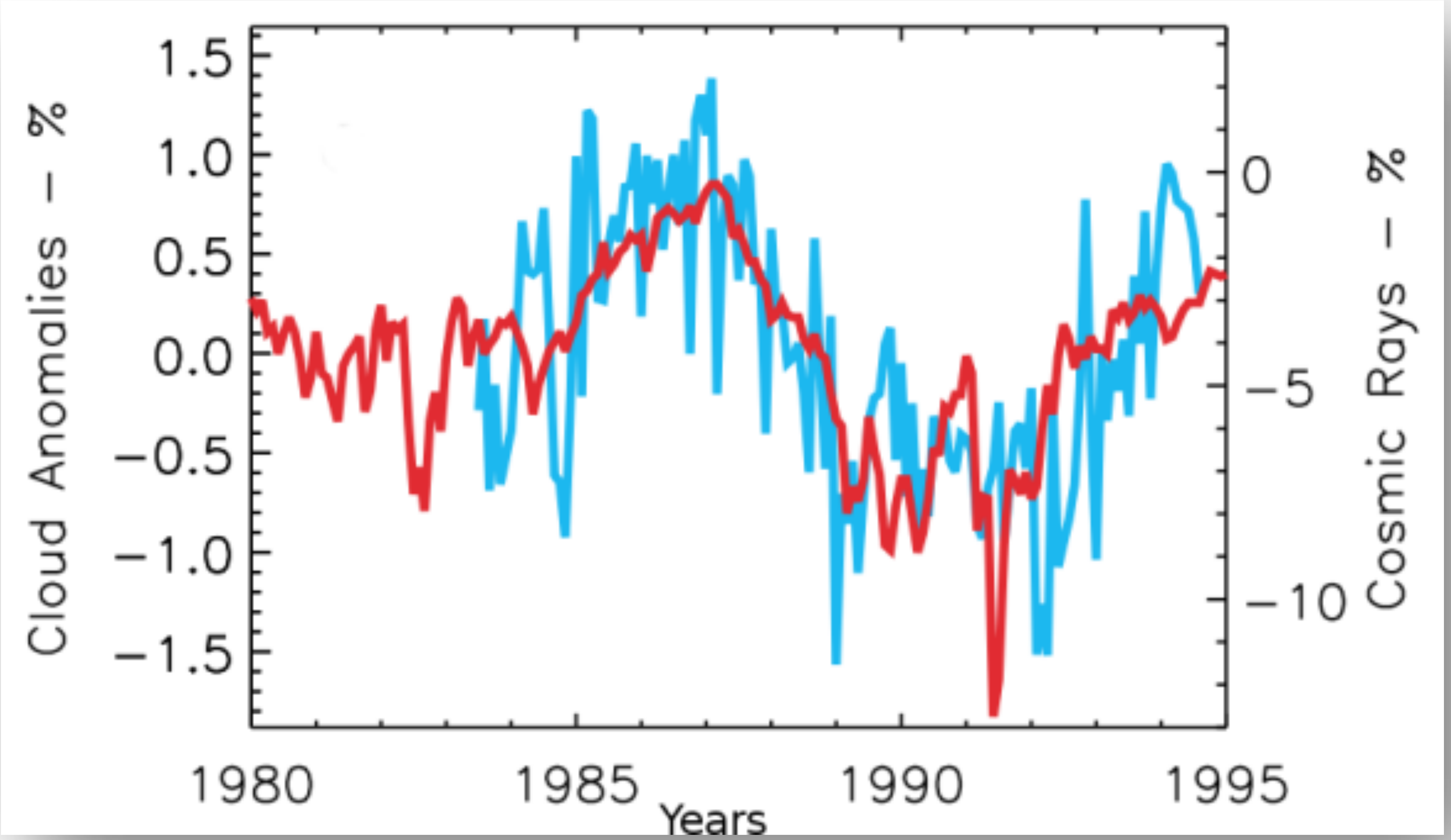
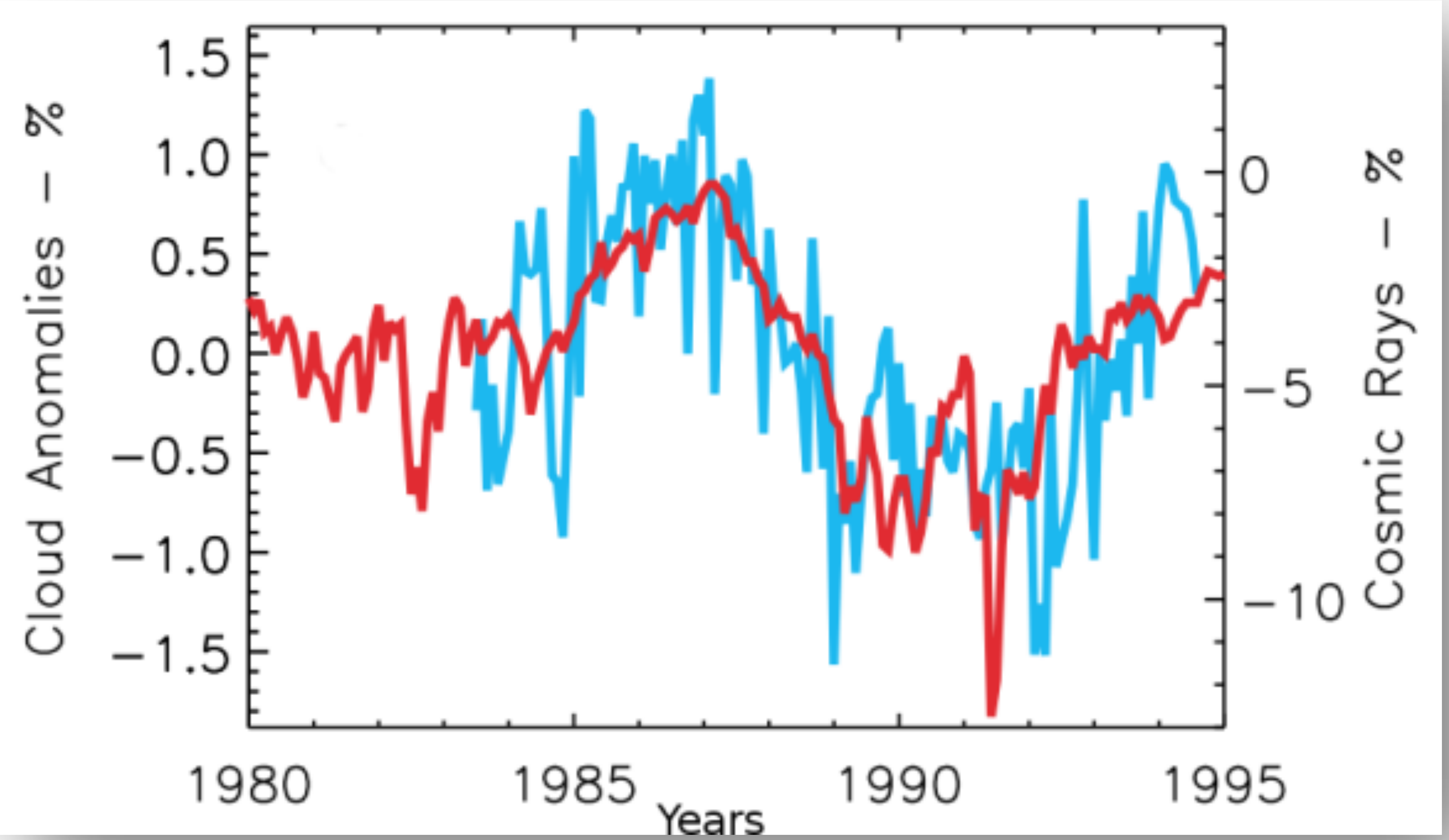
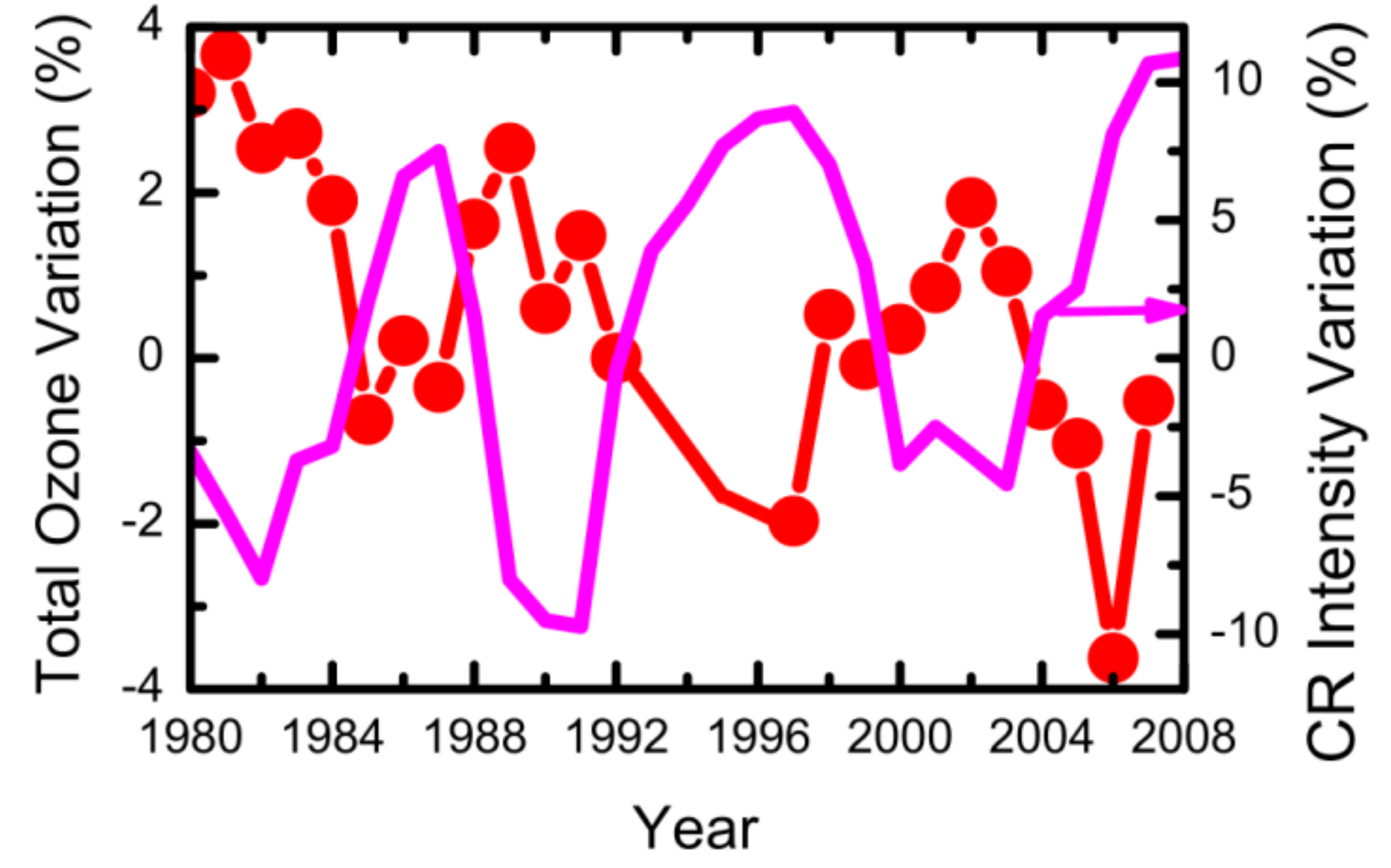


Svensmark showed a causal relationship between galactic cosmic rays and low cloud coverage (< 3.2km) .

N. D. Marsh and H. Svensmark, "Low cloud properties influenced by cosmic rays," **Phys. Rev. Lett., vol. 85, pp. 5004–5007, 2000"**





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Lu showed a correlation between cosmic rays and ozone depletion, especially in the polar region over Antarctica .

Q.-B. Lu, "Correlation between cosmic rays and ozone depletion," **Phys. Rev. Lett., vol. 102, pp. 118 501–1 – 118 501–4, 2009 "**

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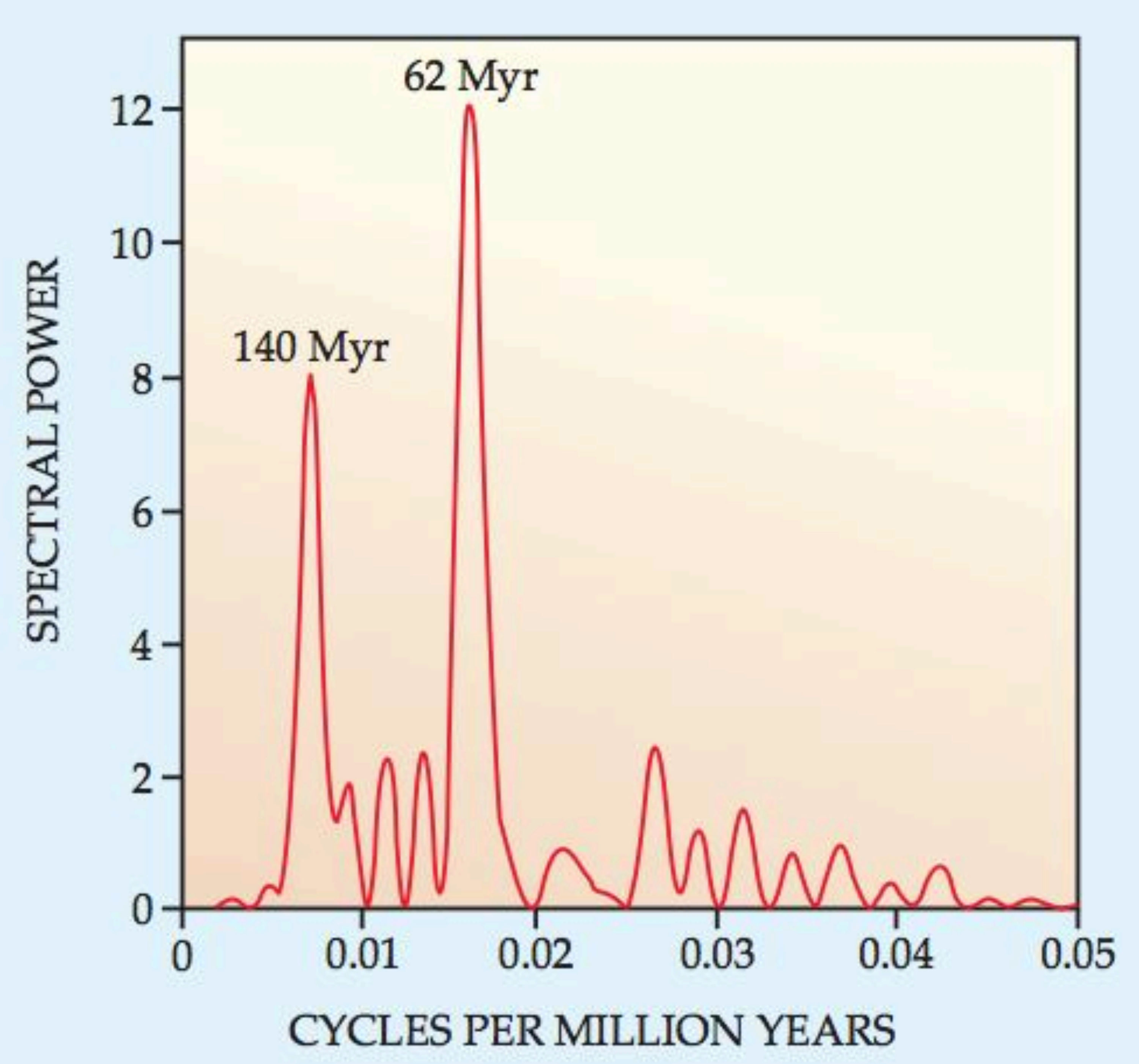

Figure 1. Fourier spectral analysis of the time variation of the total number of marine-animal genera living at any particular time during the past 542 million years. The prominent peak corresponding to a period of 140 Myr is confidently attributed to the recurring passage of the solar system through spiral arms of the Milky Way.[3] But the peak at 62 ± 3 Myr, discovered two years ago, has been a puzzle that is now addressed in reference 2. The peak is about 10 times higher than its estimated background. (Adapted from ref. 1.)

Physics Today (Oct 2007) by Bertran Schwarzschild.

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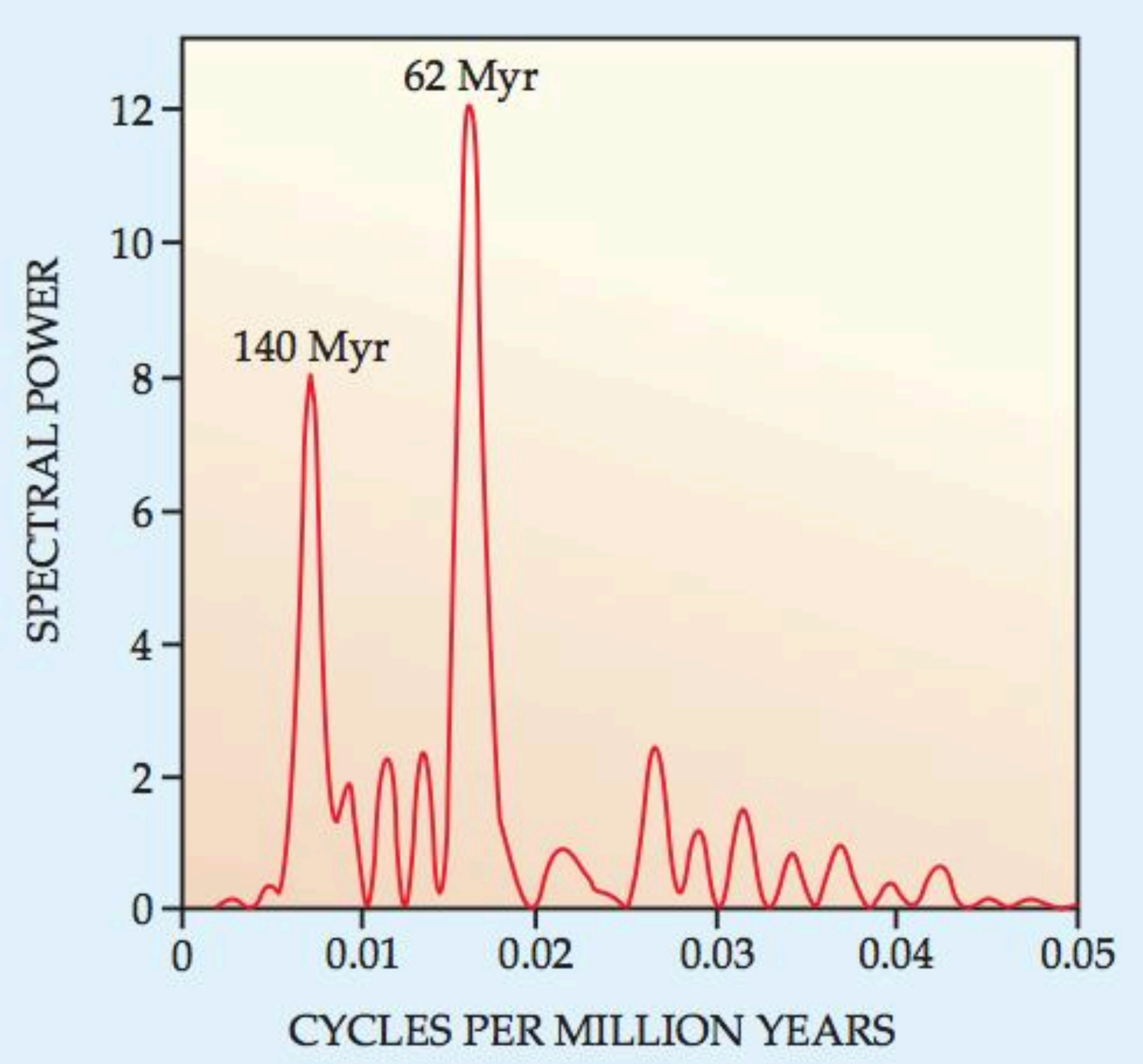

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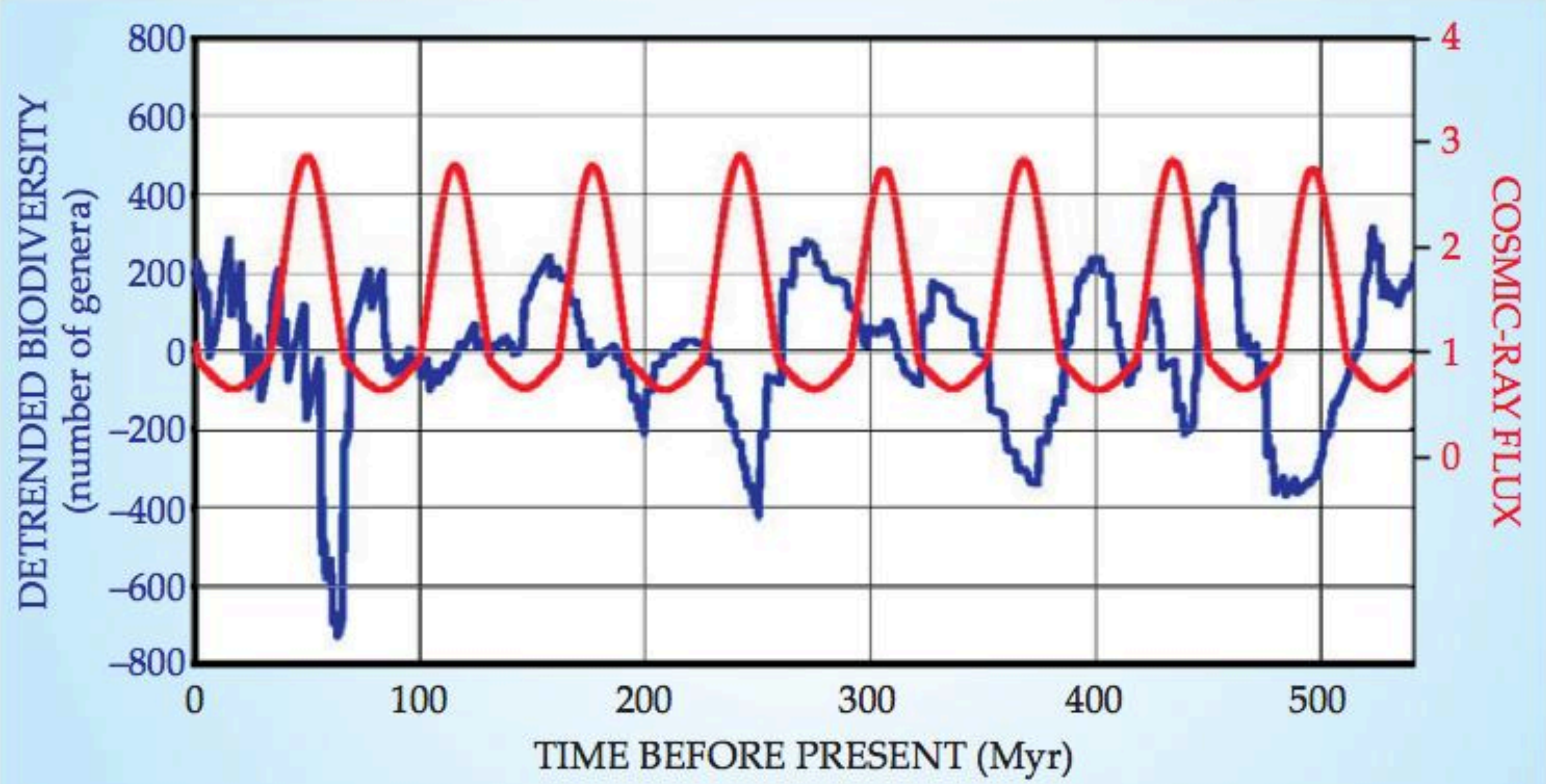

Figure 3. The cyclic variation of extragalactic cosmic-ray flux (red) at Earth, calculated from the model in reference 2, is compared with the variation (blue) in the number of extant marine-animal genera.[1] The cosmic-ray flux is normalized to a present value of 1. The biodiversity curve is detrended by subtracting from the total number of genera a cubic polynomial fit to the raw 542-Myr data. The biodiversity curve shows very deep minima at the well-known great extinctions 65 and 250 Myr ago, both attributed to causes other than cosmic rays. But the general trend appears to correlate biodiversity minima with cosmic-ray maxima. (Adapted from ref. 2.)

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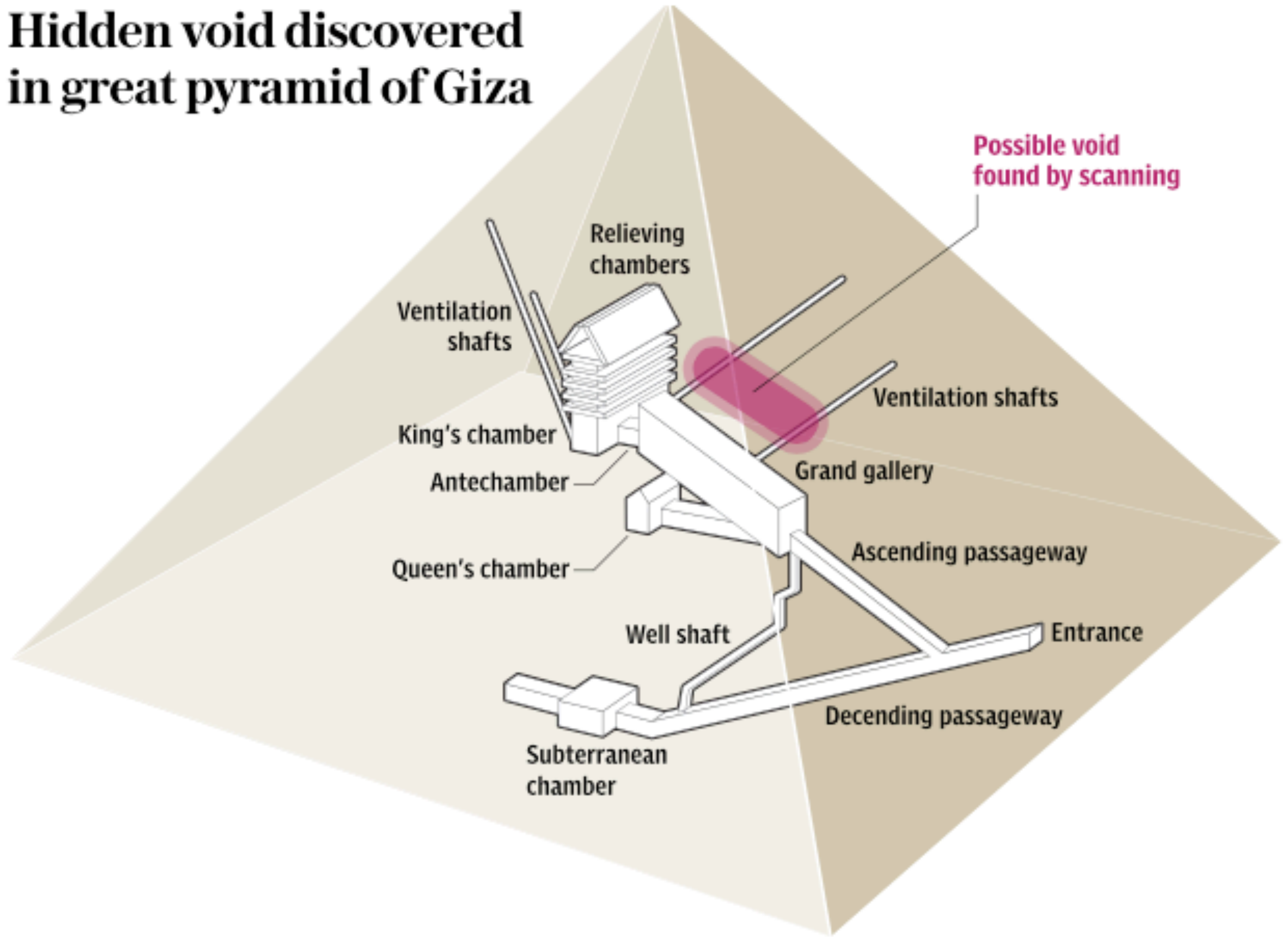

Cosmic Rays

Cosmic Rays

- Discovered by Victor Hess in 1912 during a balloon flight with friends.
- Vicrtor Hess received Nobel Prize in 1936 for this discovery.
- The study of cosmic ray particles in 1930's and 40's inspired and built the foundation of exploring the colorful subatomic world.
- Still today, possibly in many years to come, measurements of the most energetic cosmic ray showers are very active around the world, e.g., P. Auger LARSO, etc. for understanding the origin of these particles and their implications to the evolution of our universe.

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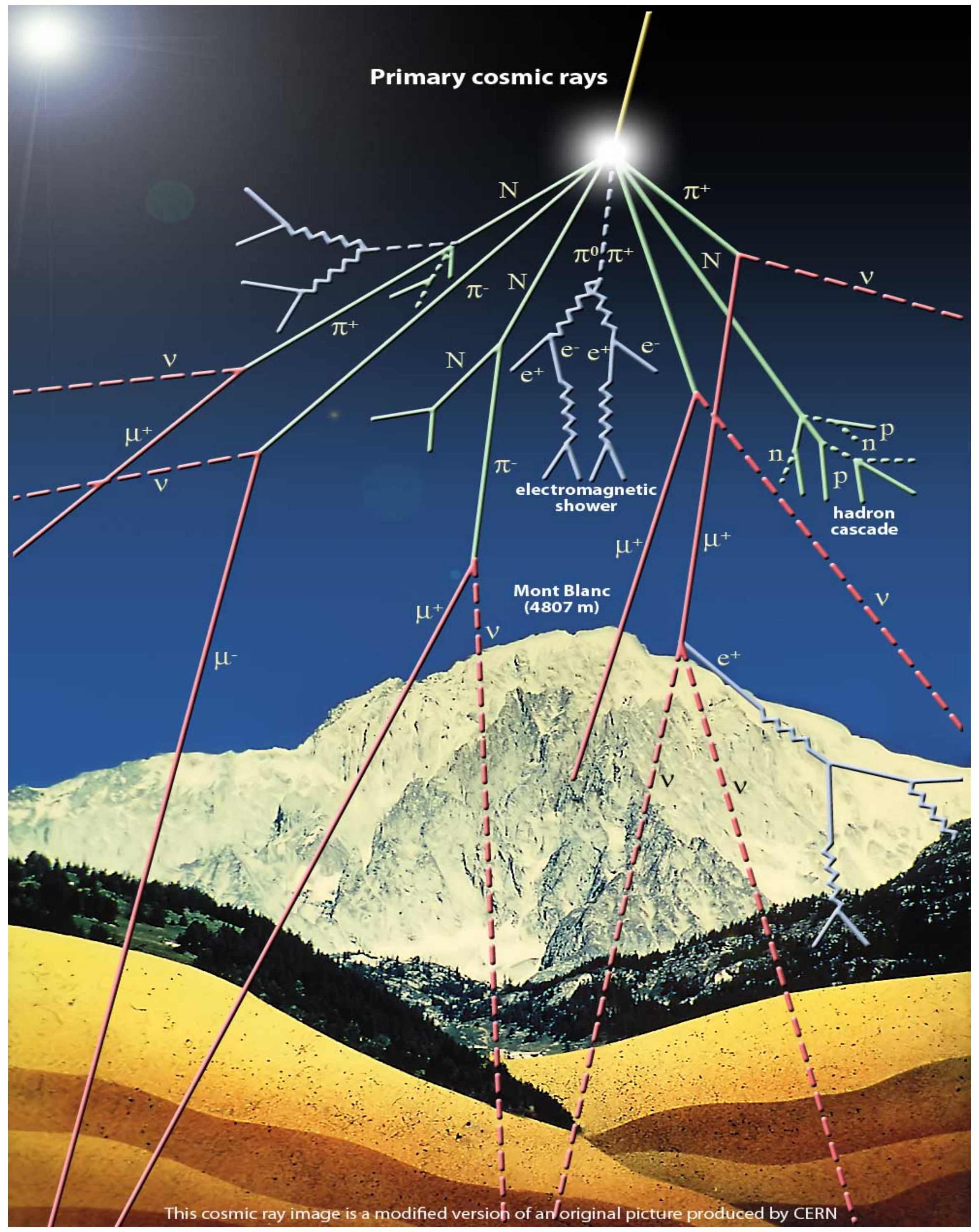

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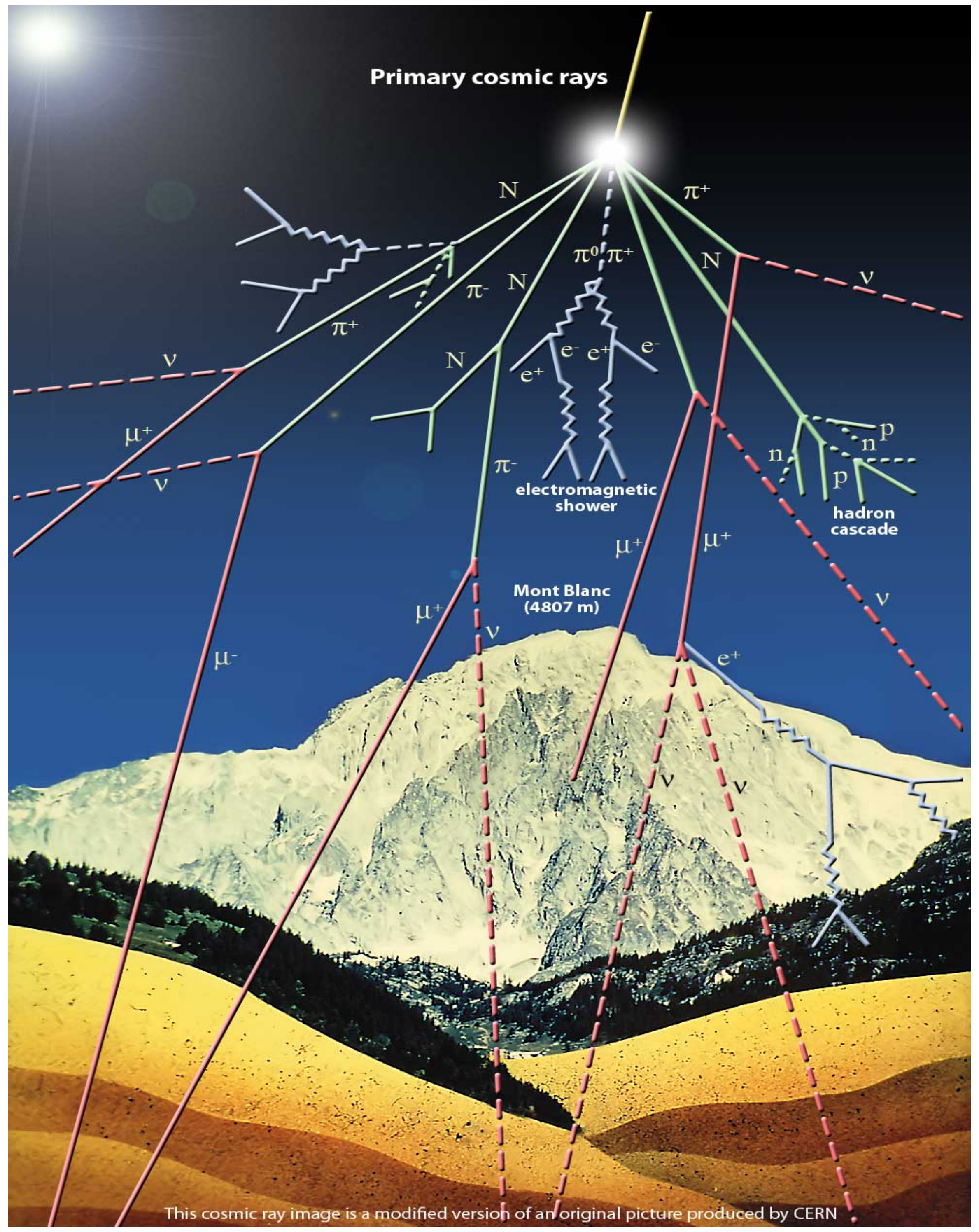

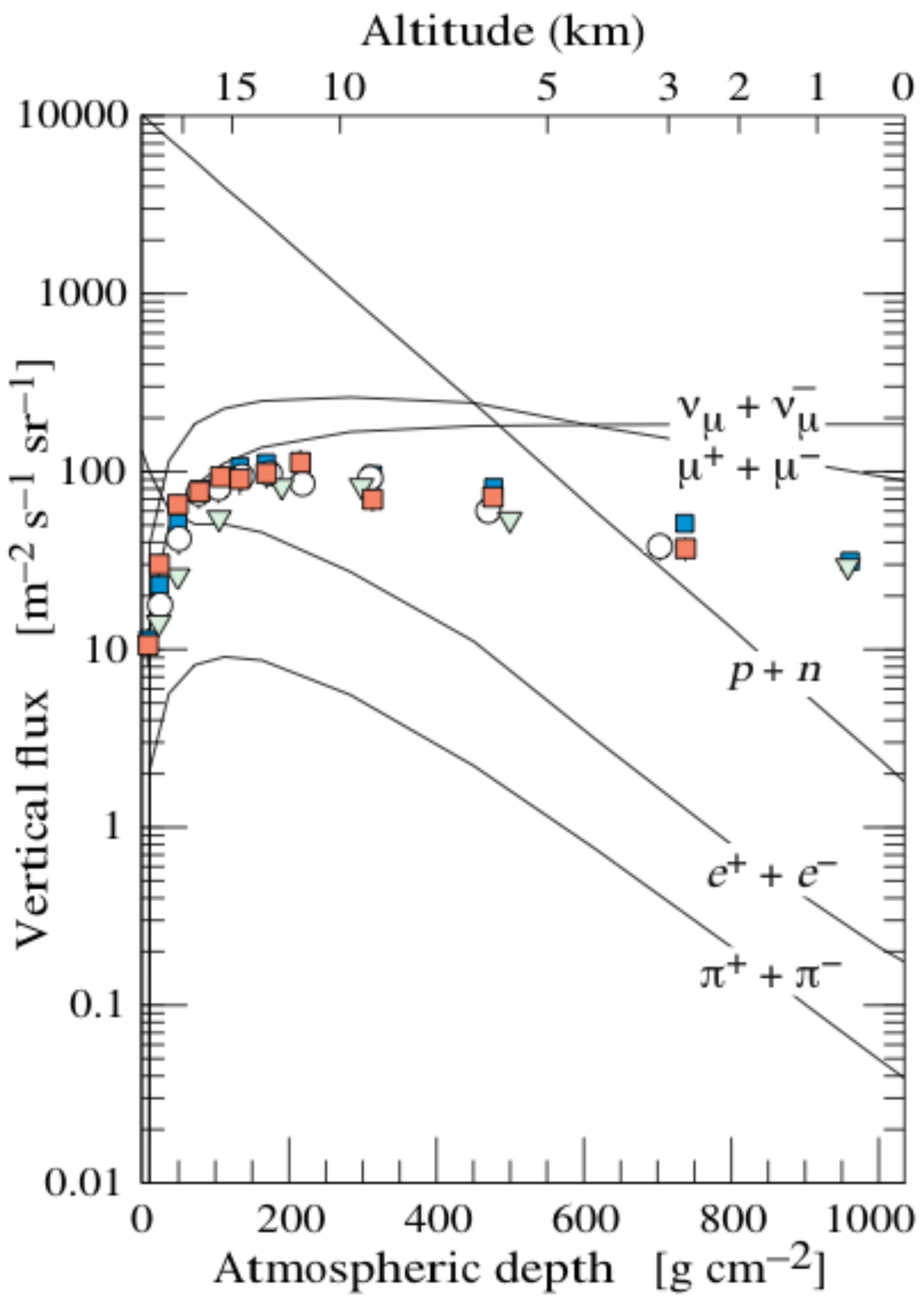

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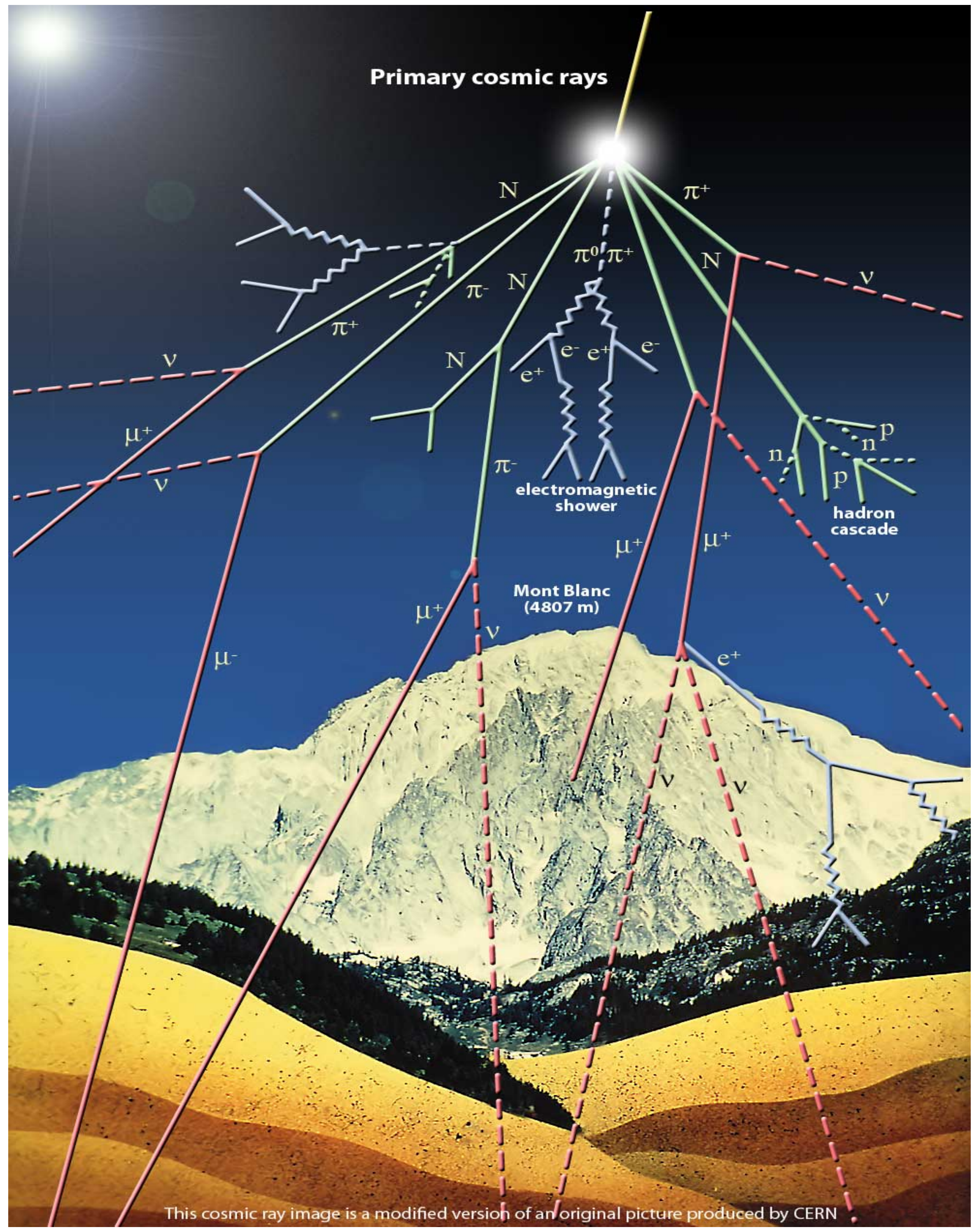

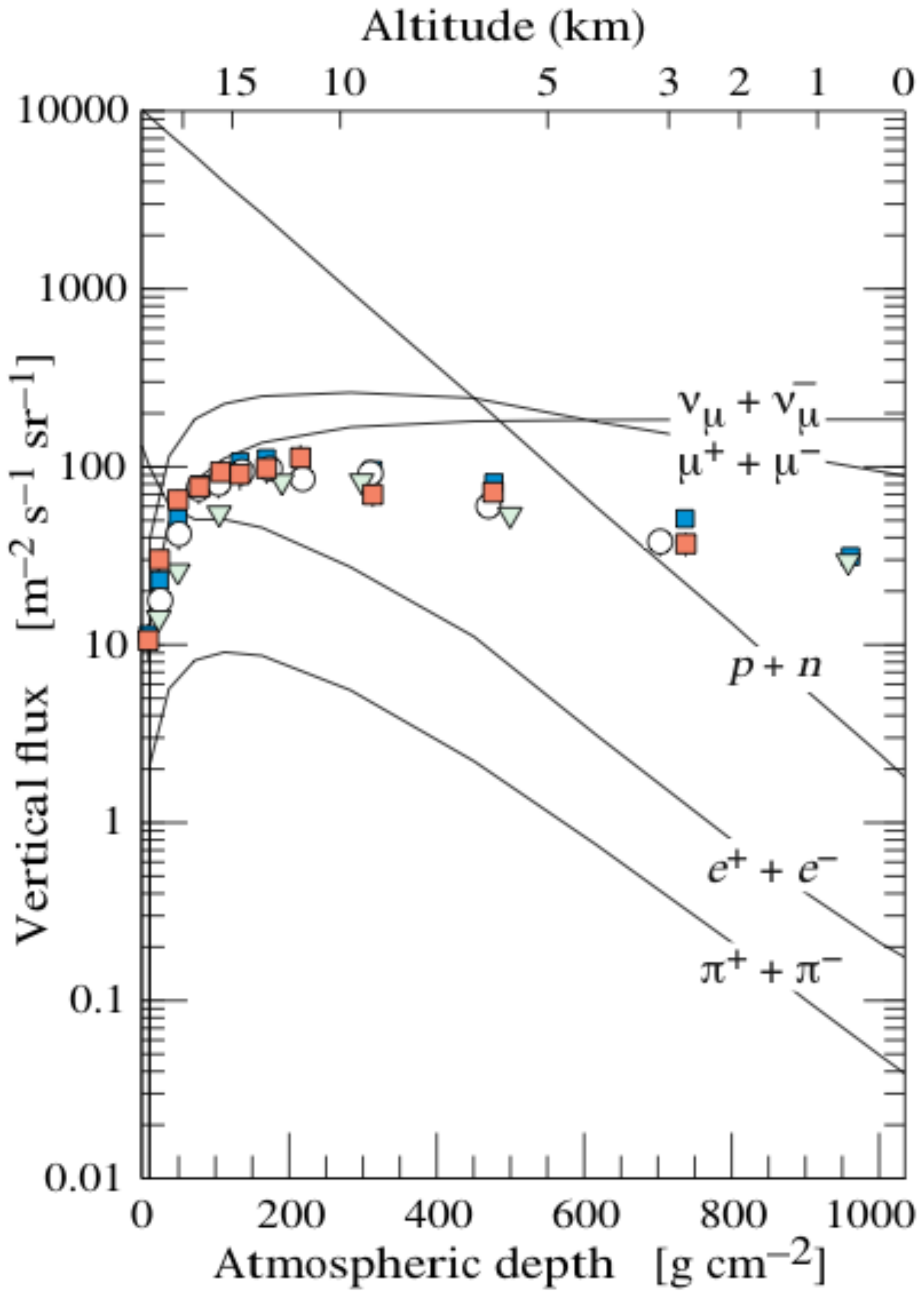

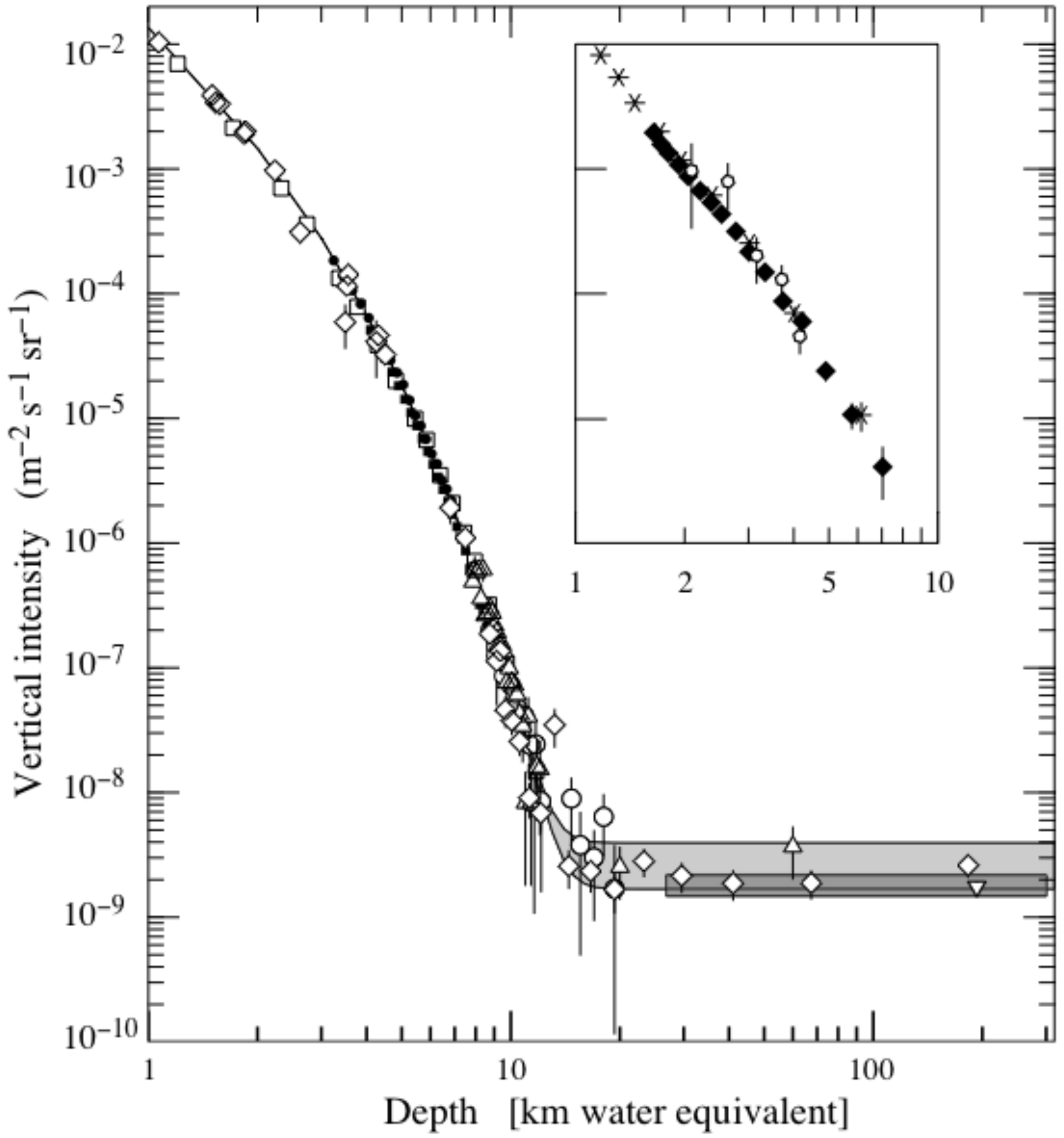

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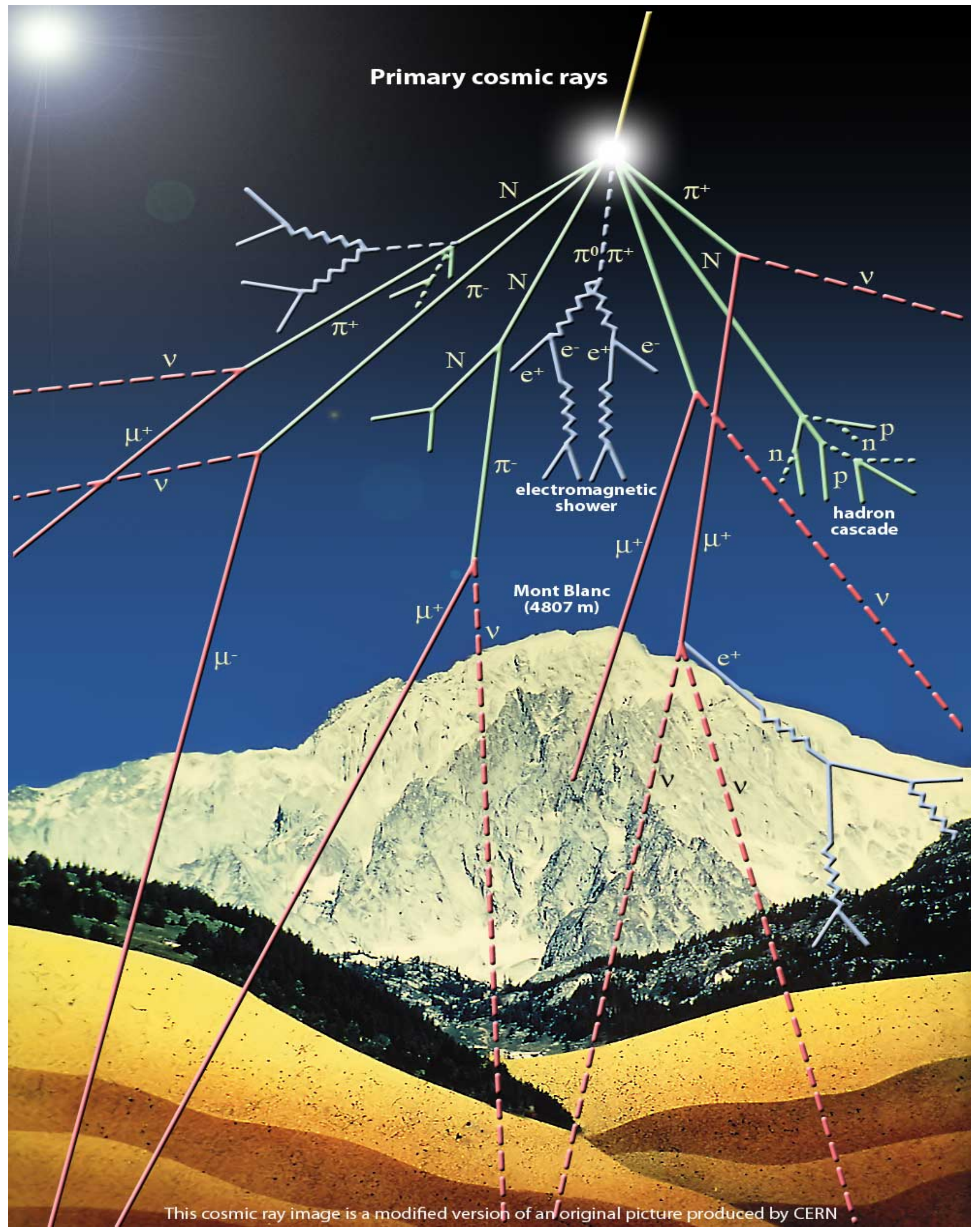

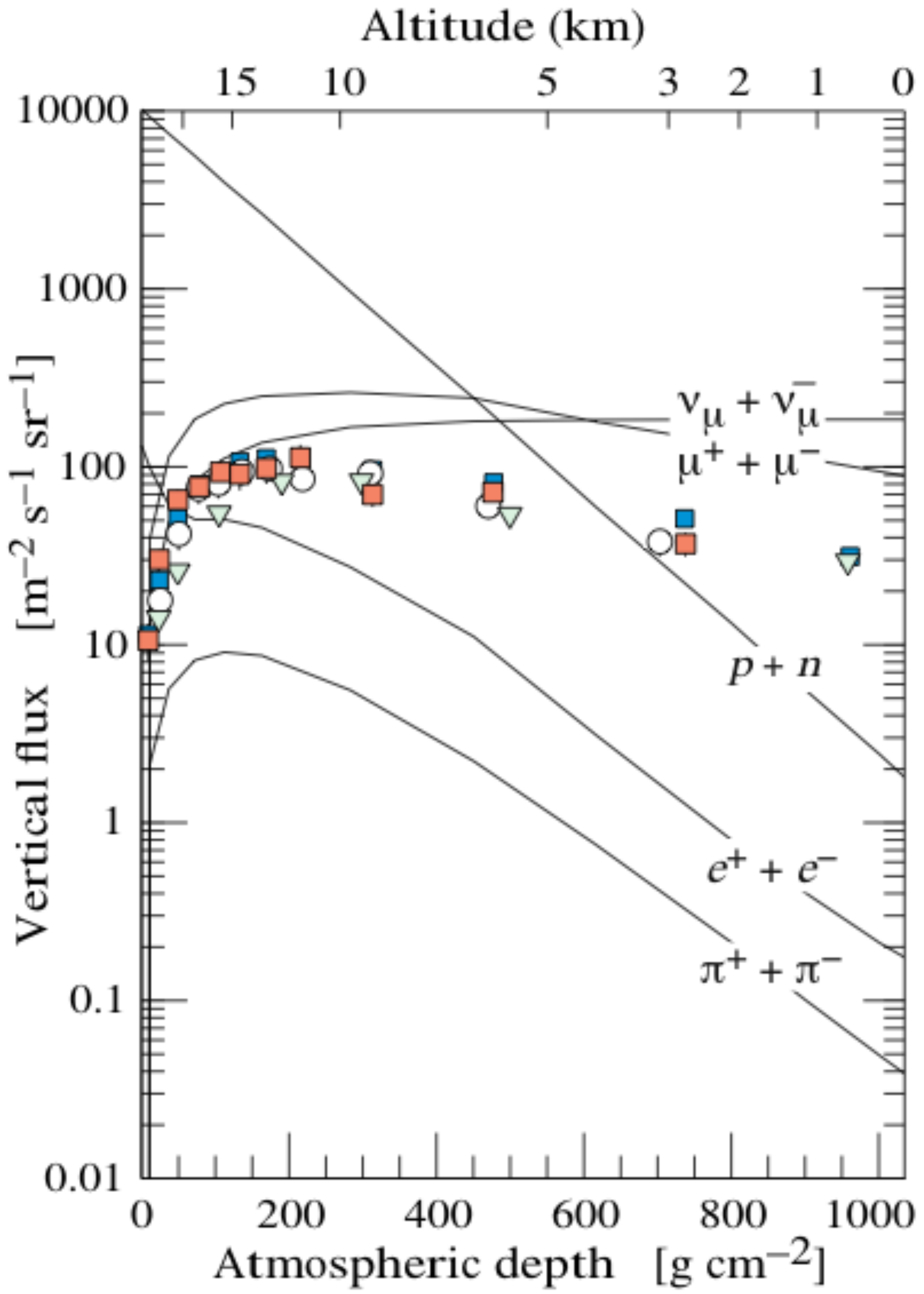

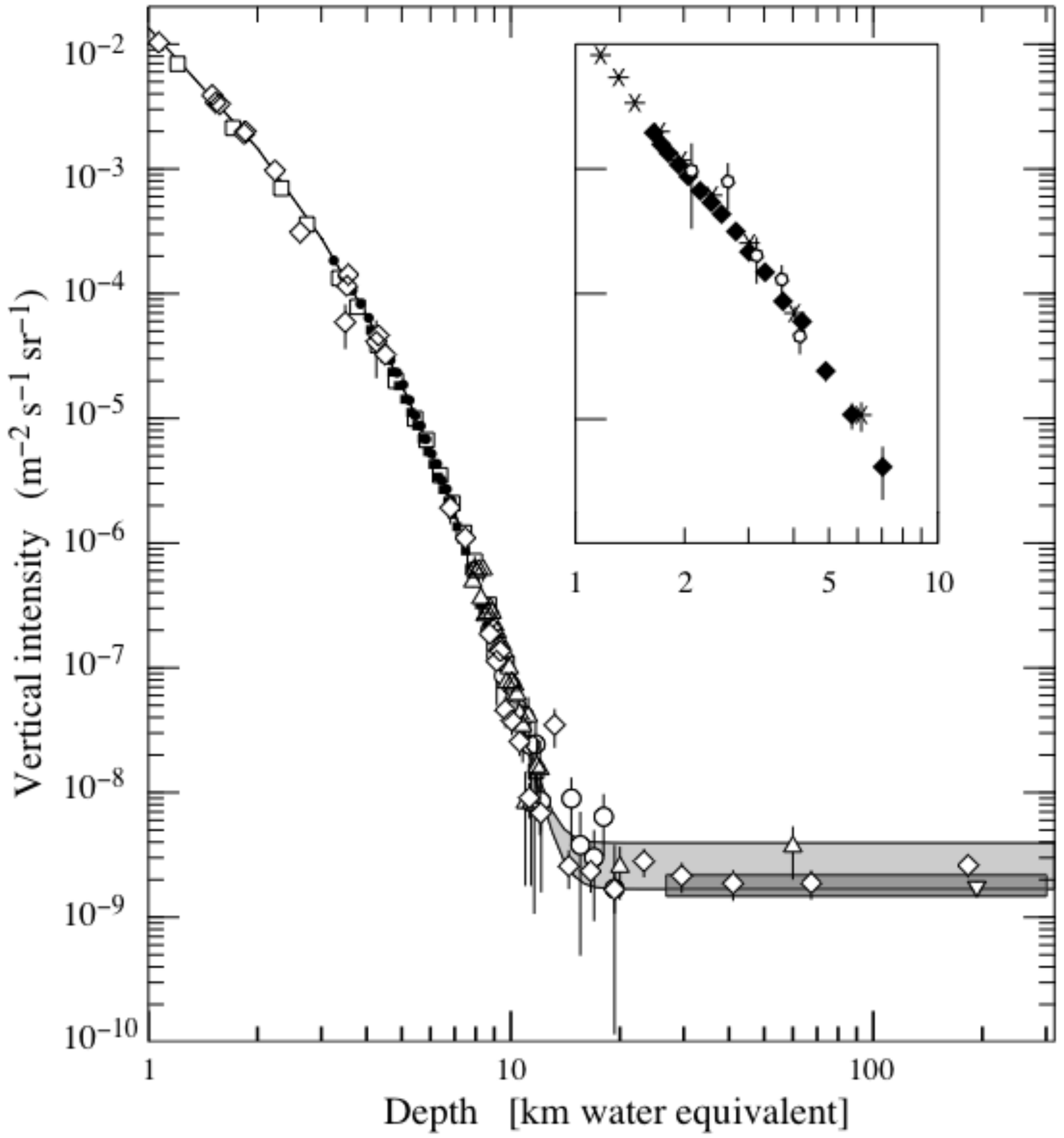

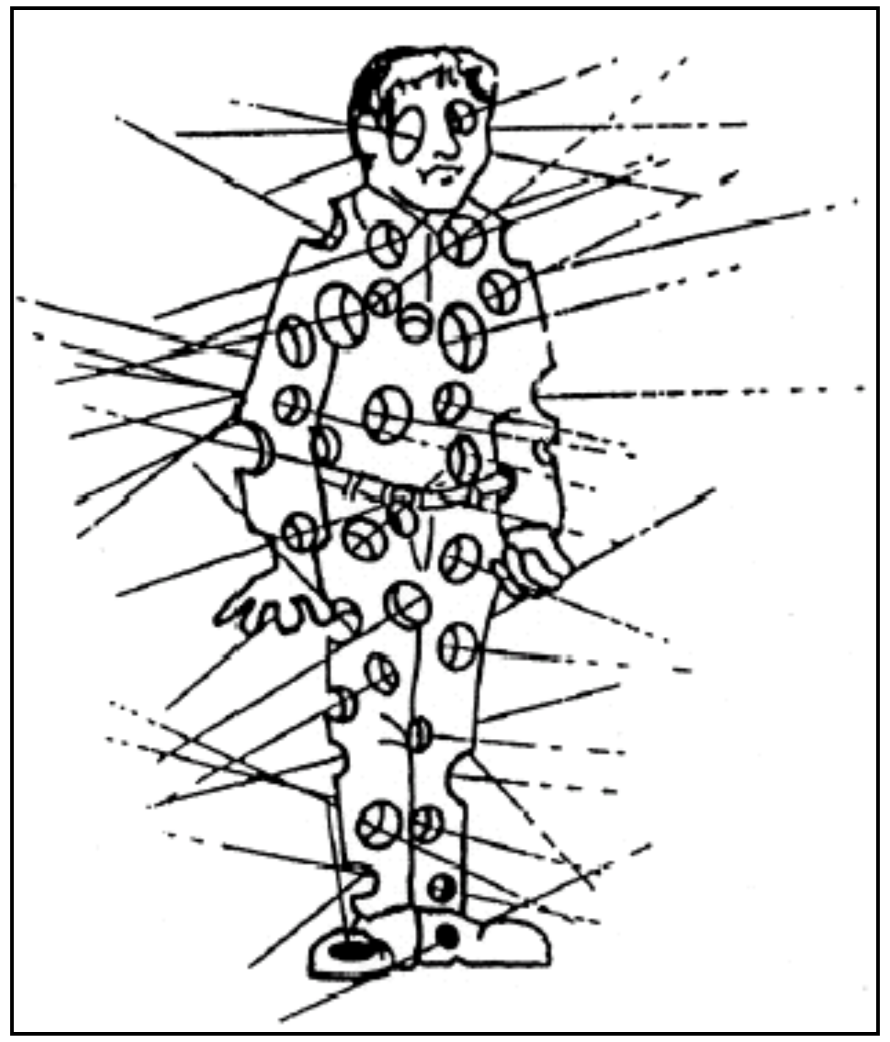

There are ~100k muons passing through our body every hour

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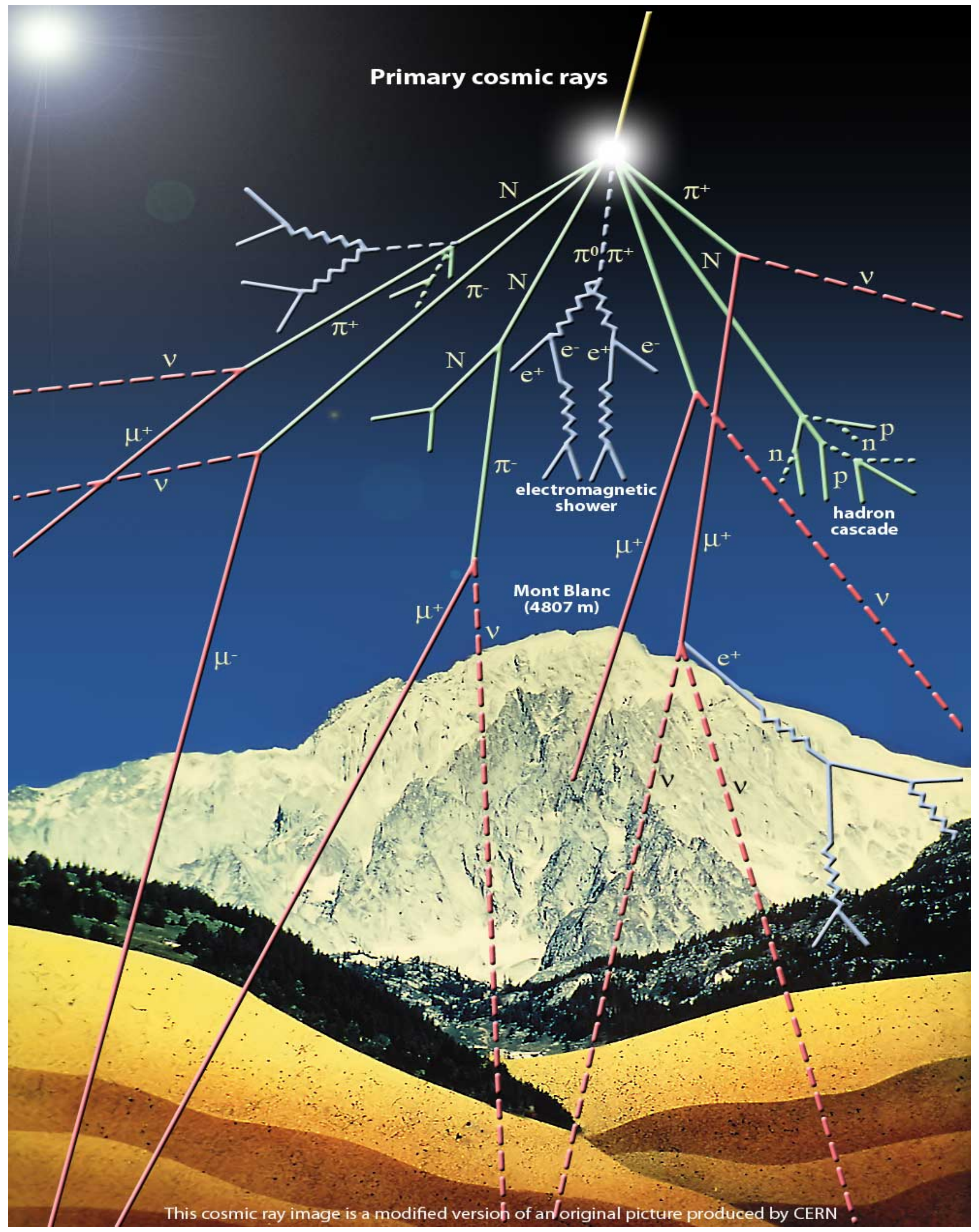

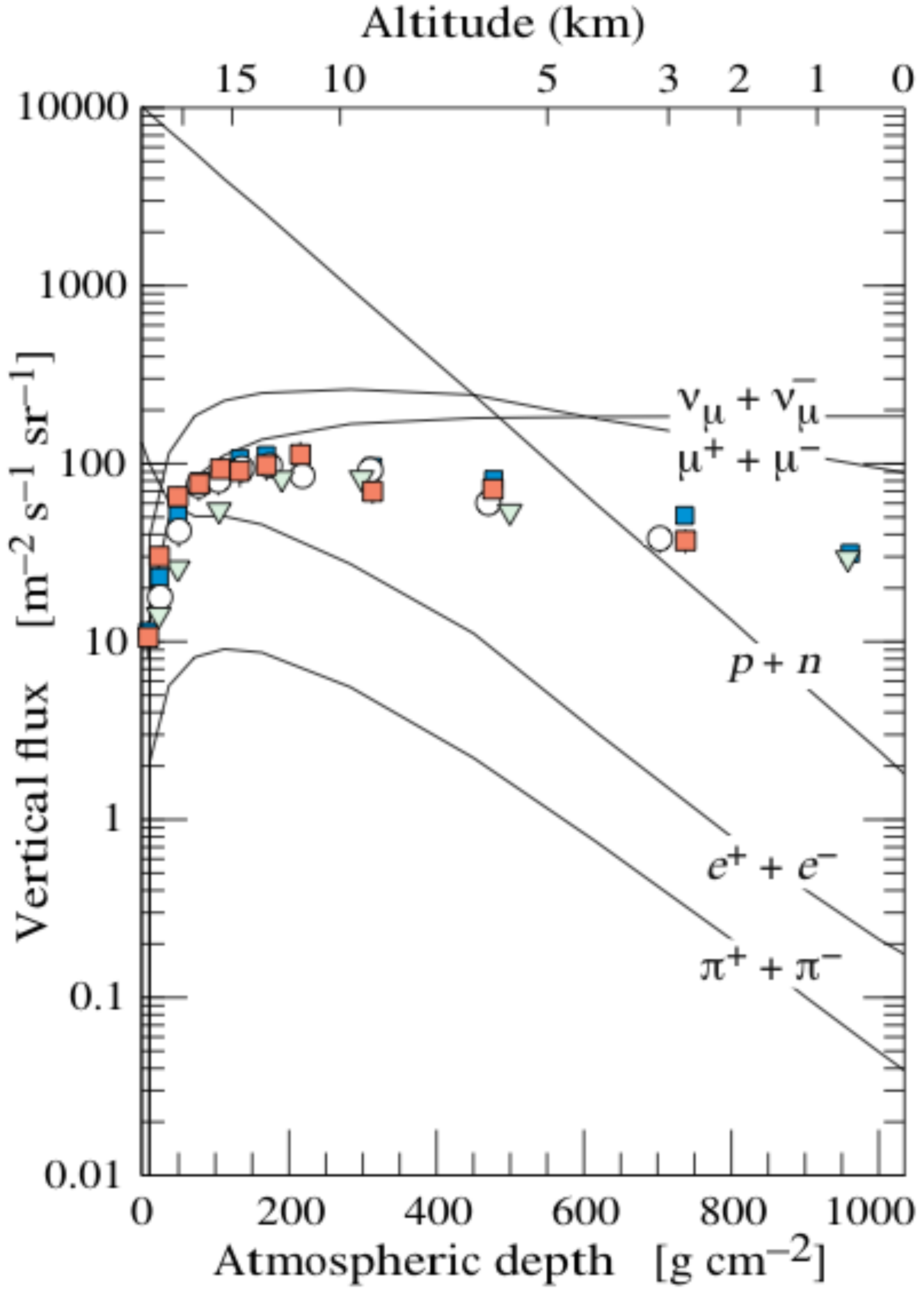

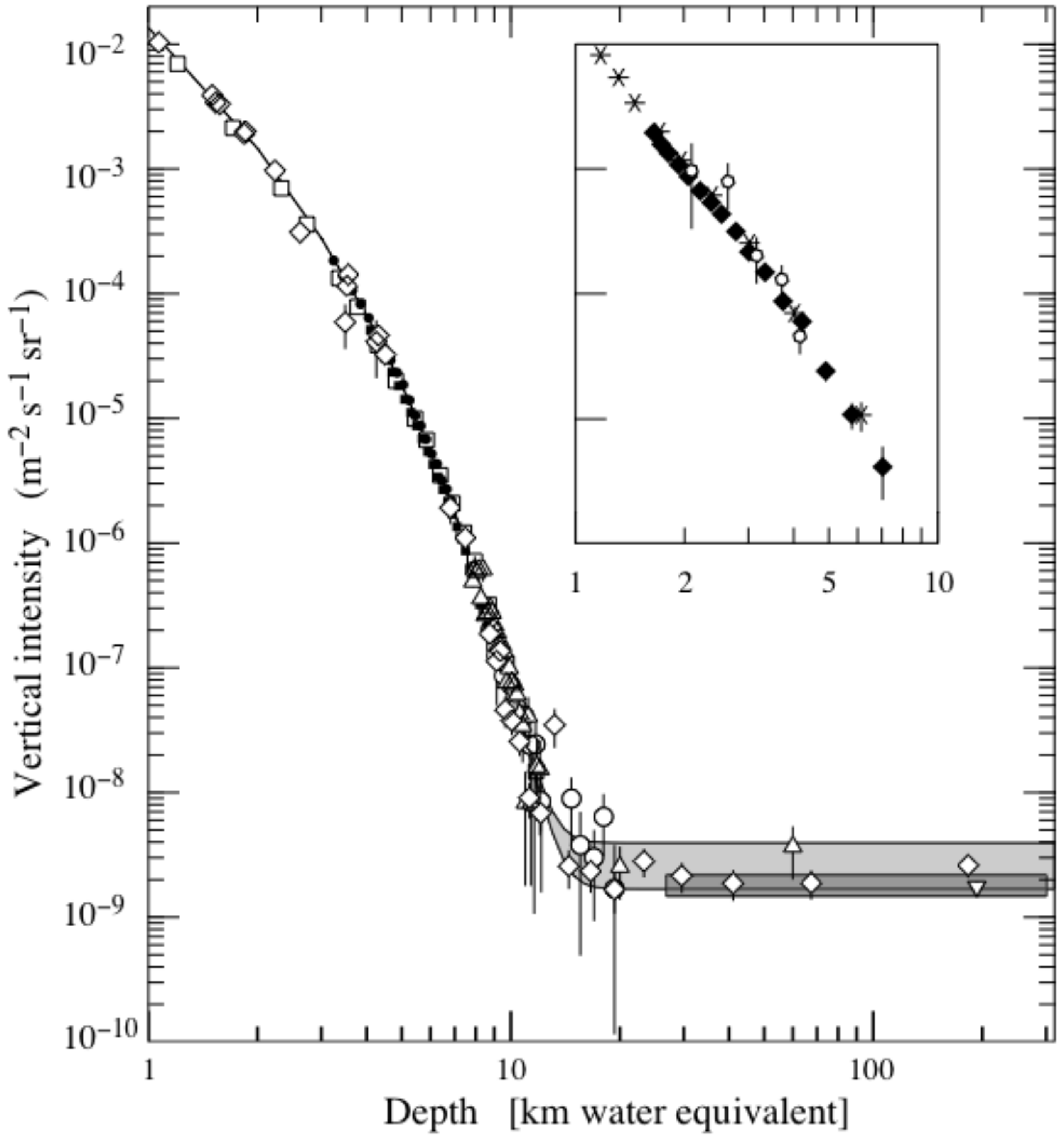

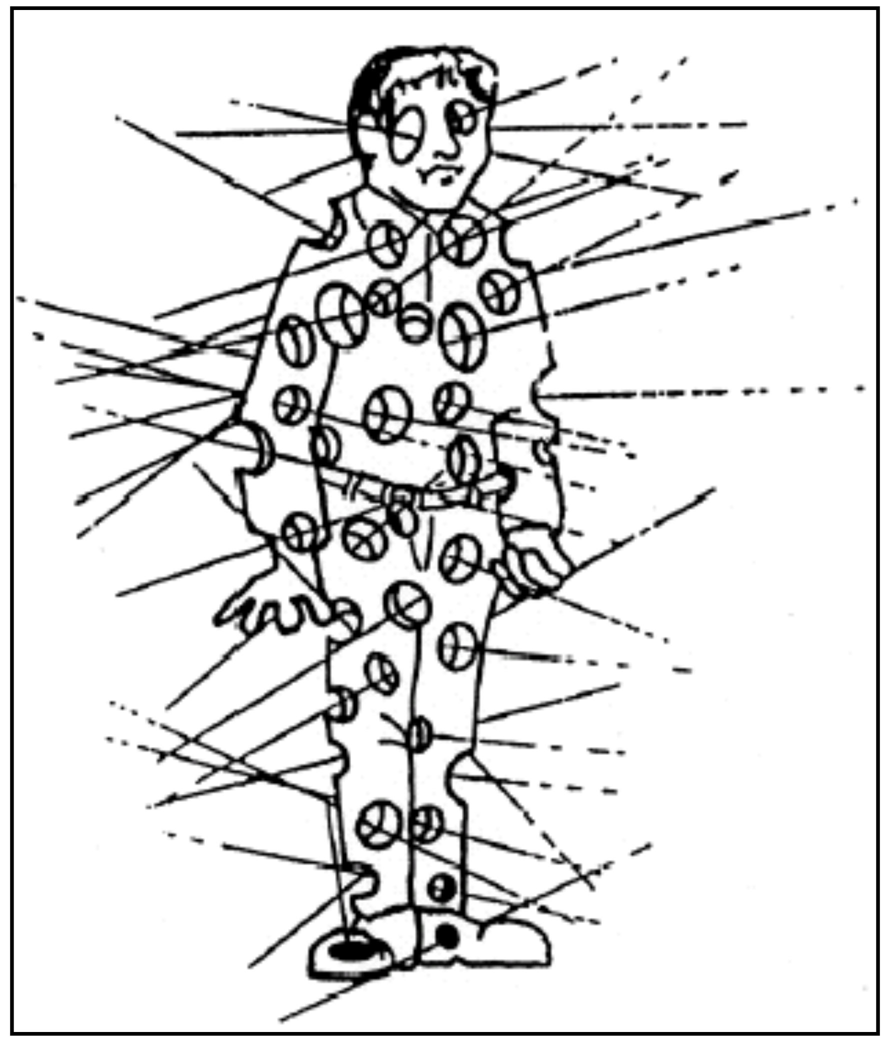

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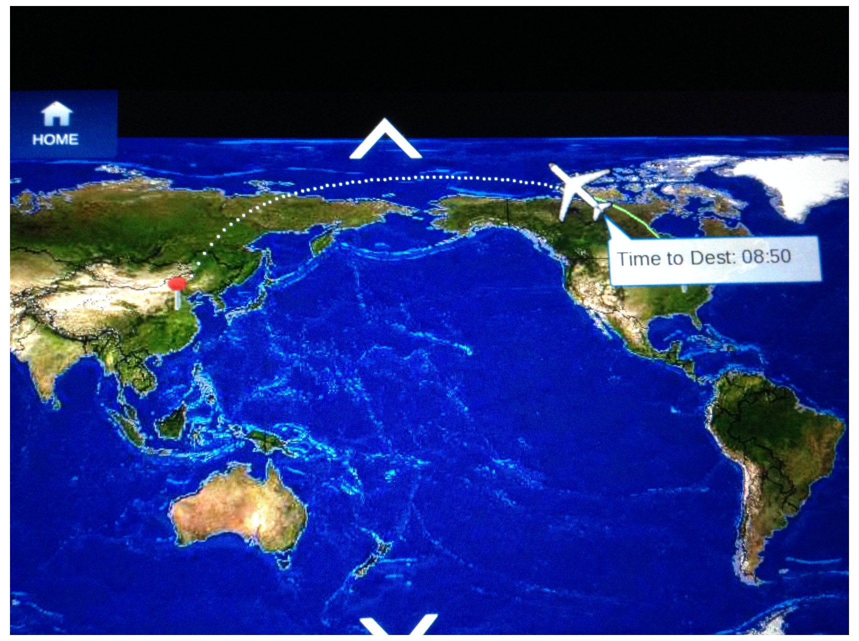
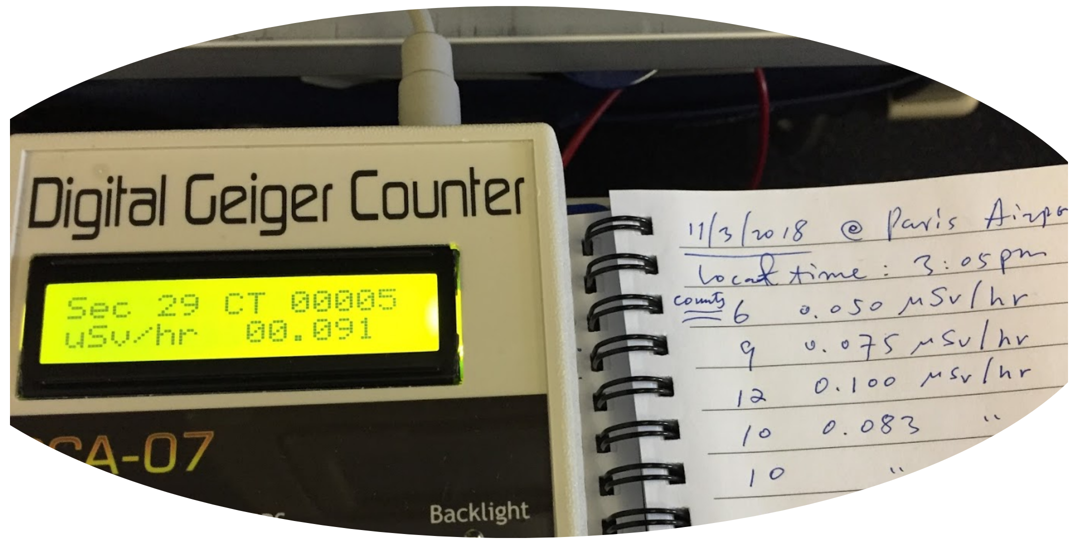
First Hand Measurement of Cosmic Ray Radiation Level at Flight Altitude Since 2015





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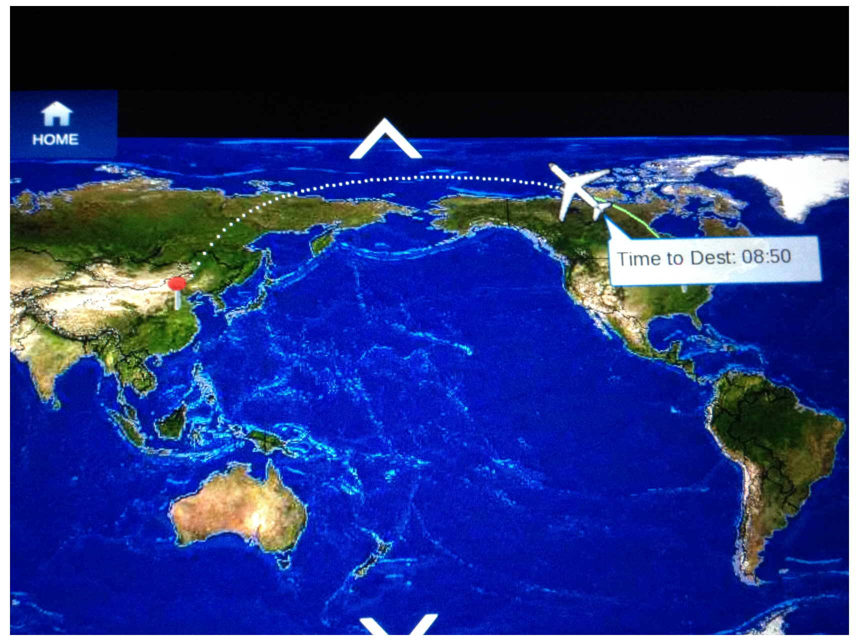
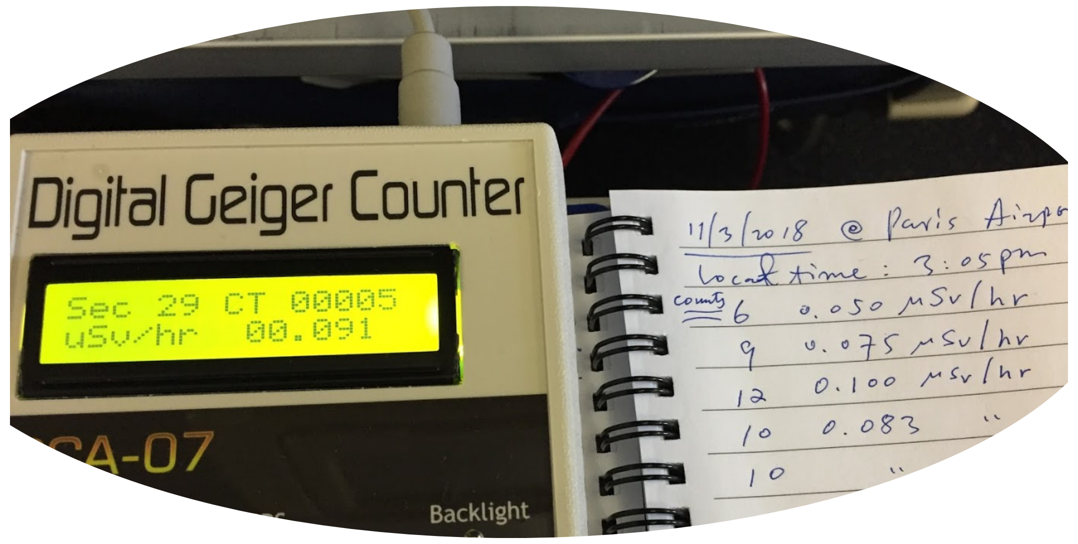
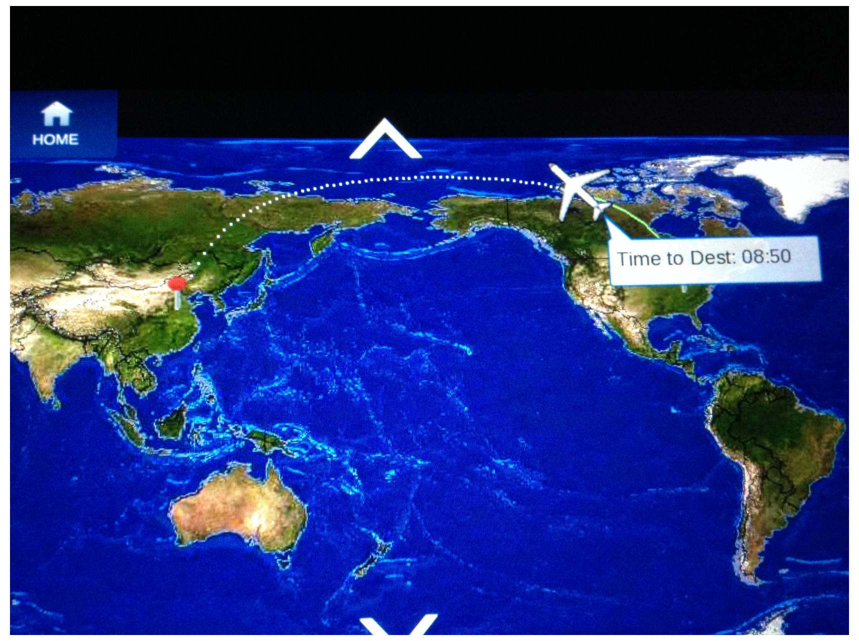
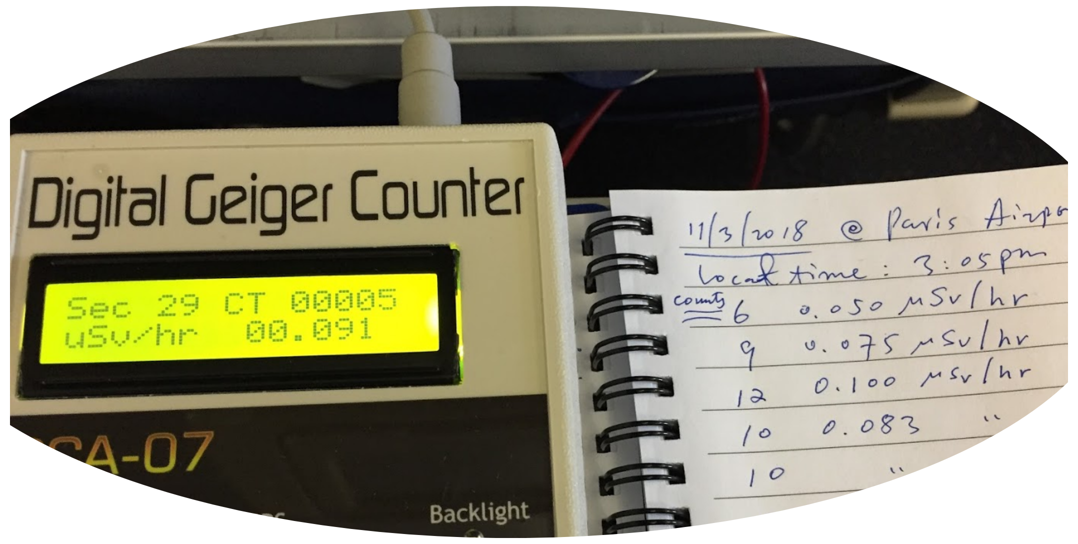




On average, one receives a factor of 20 more radiation dose from cosmic rays in flight in comparison to staying on surface!

First Hand Measurement of Cosmic Ray Radiation Level at Flight Altitude Since 2015





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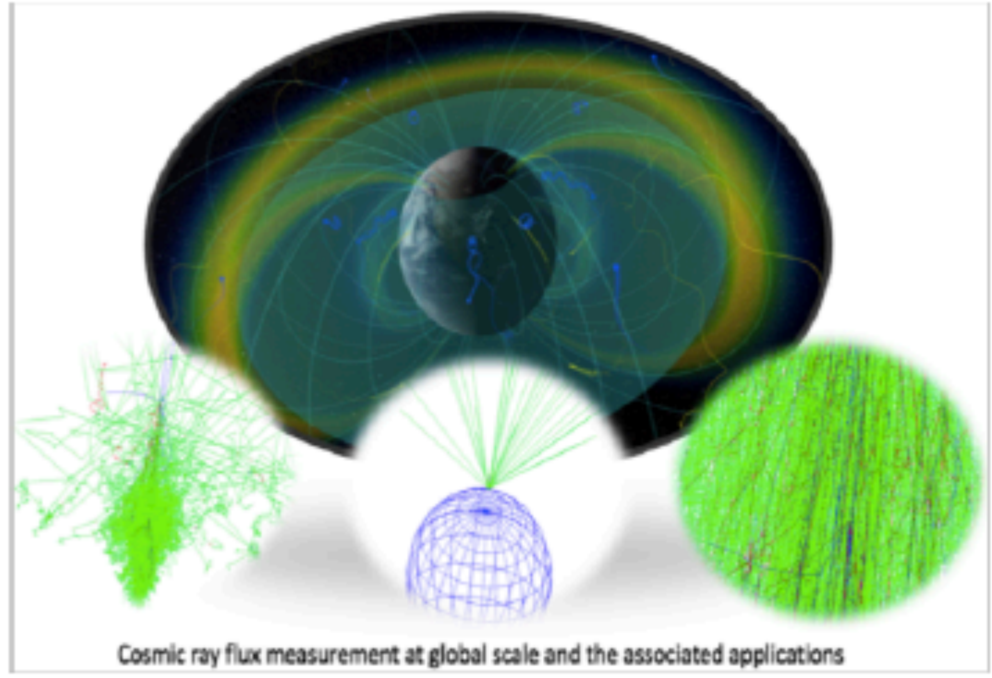
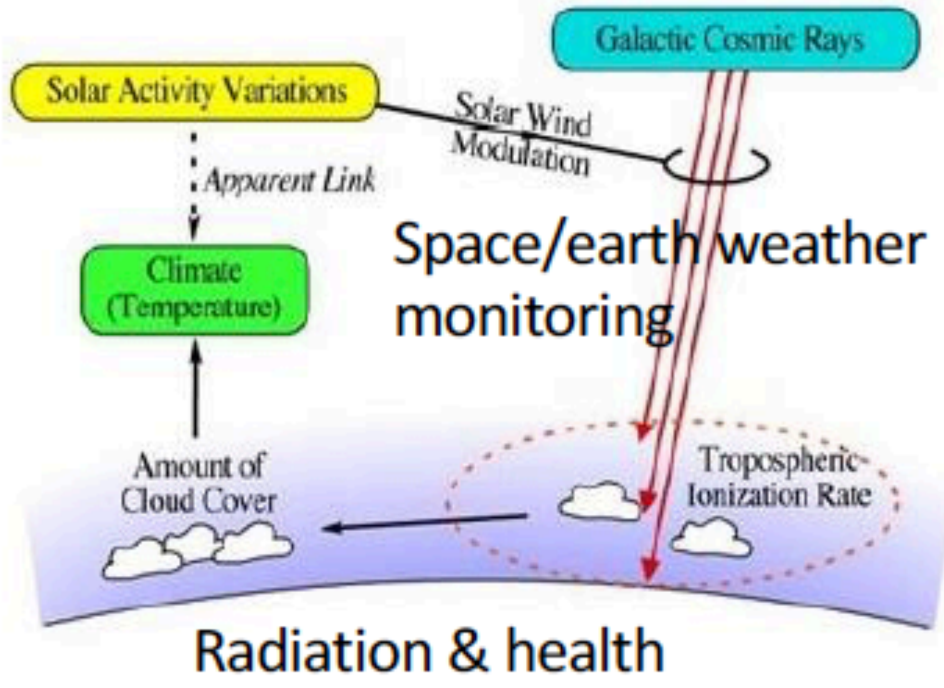
Verify Victor Hess's observation > 100 years ago

Outline

- Cosmic ray shower simulation
- Cosmic ray detector development
- Cosmic ray applications

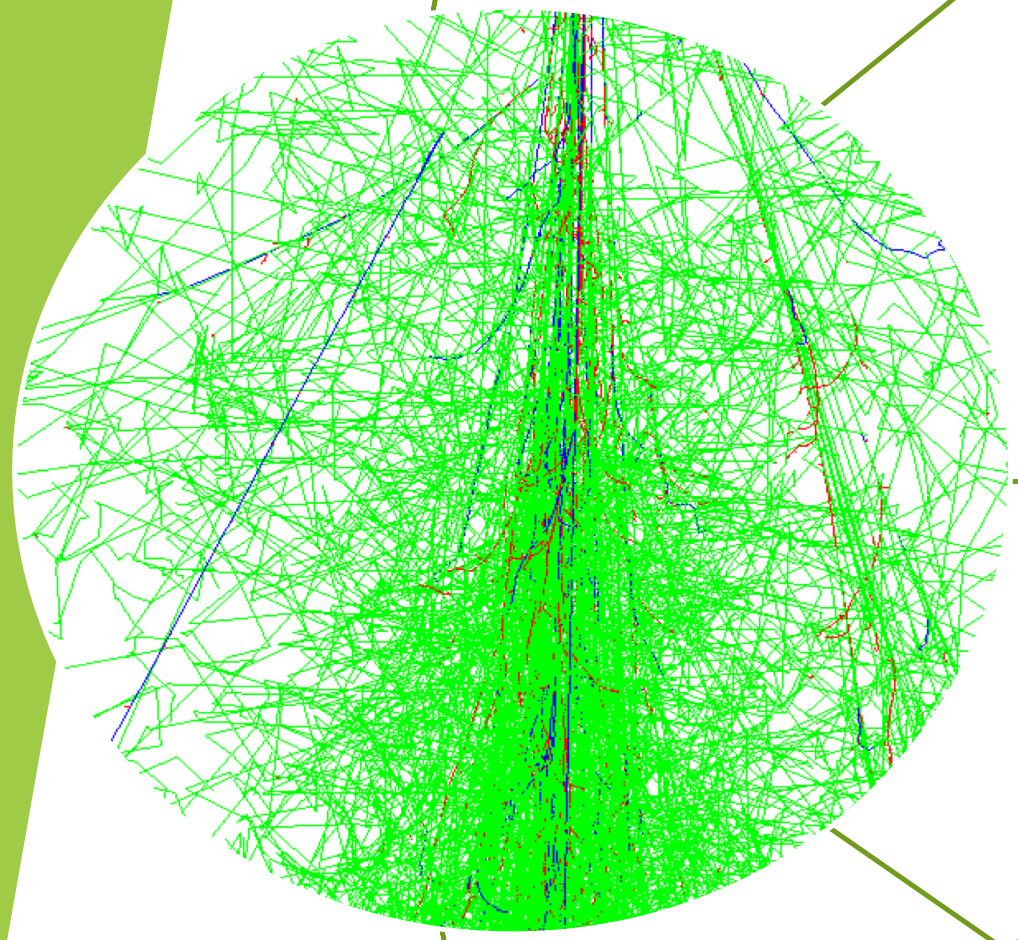
Cosmic Ray Project

Cosmic ray shower simulation	Cosmic ray detector development	Applications of cosmic ray flux measurements	Students training
			

Applications of Cosmic Ray Flux Measurements

Space weather monitoring

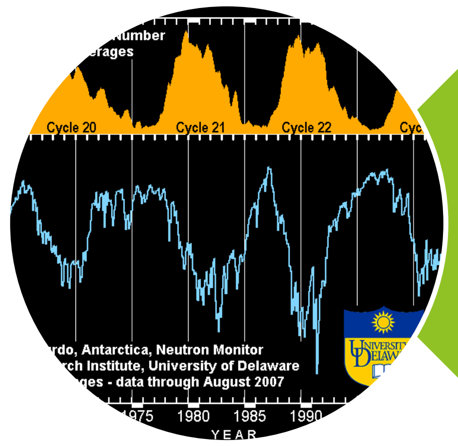
Dynamical monitoring of the upper atmosphere properties



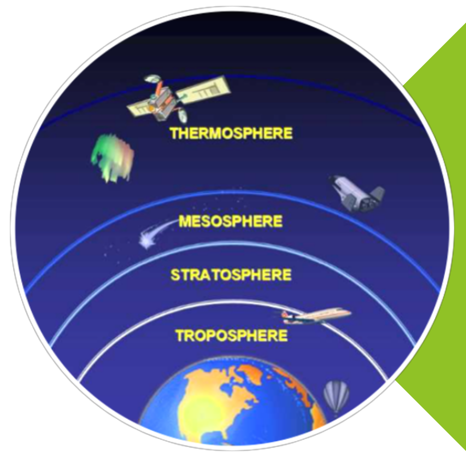
Ionization of atmospheric air molecules and health

Cosmic ray muon and neutron tomography

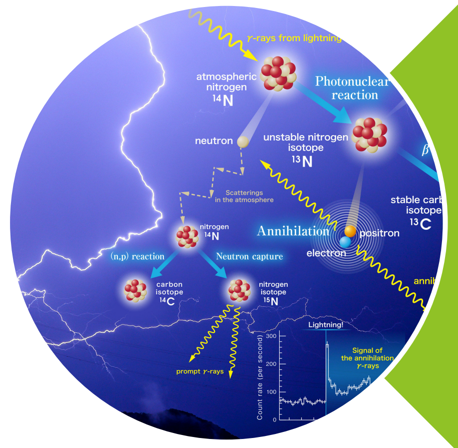
STEM training



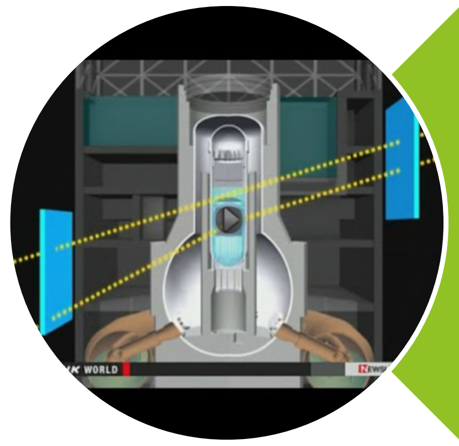
It has been well known for more than half a century that solar activity has a strong influence of cosmic ray flux reaching to the earch (anti-correlation), one could use cosmic ray flux measured at the surface of the earth to monitor the space weather and solar activity.



Since most of the cosmic ray showers are occurring between the upper troposphere and lower stratosphere, cosmic ray flux measurement at the earth surface around the world simultaneously could help to determine the dynamical changes of air density in this region at global scape in real-time.



Secondary cosmic ray shower particles (electrons, gamma rays, muons, neutrons) are ionizing the atmospheric air molecules. These ionizations triggers lightning and cloud formation. They also ionize pollutants in air which could be a serious public health problem. Since neutron loses large fraction of its energy by scattering with hydrogen nuclei (i.e. protons) , cosmic ray neutrons have been used for monitoring the near surface and soil moistures.

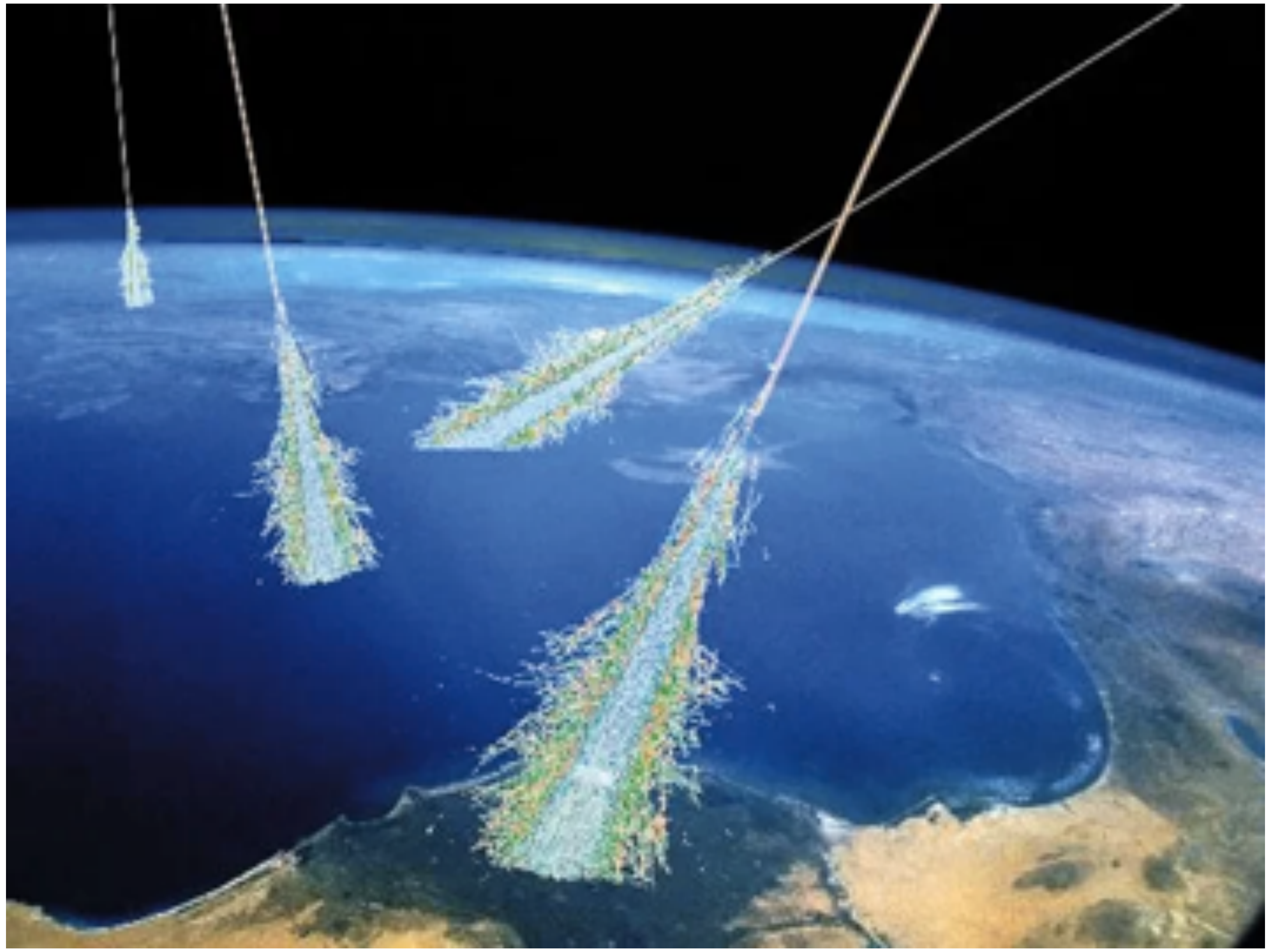


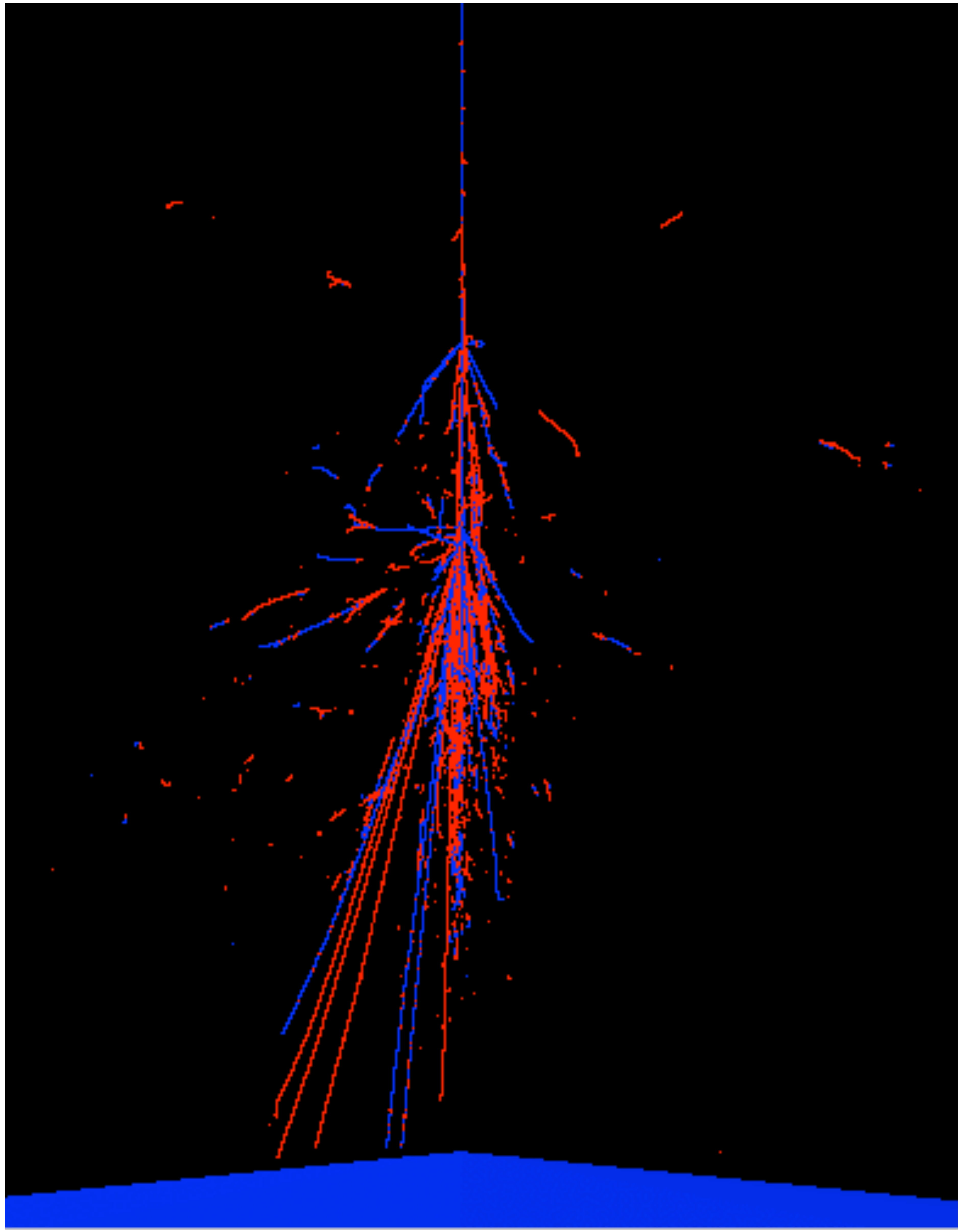
Near the earth surface, more than 80% of particles are muons which have been used for imaging hidden objects in non-destructive way similar to X-ray imaging. Since muon particles are very penetrating, this technique has been used for monitoring volcanic activity, nuclear reactors, cargo containers inspection, and in archaeology.

Created 2/2019

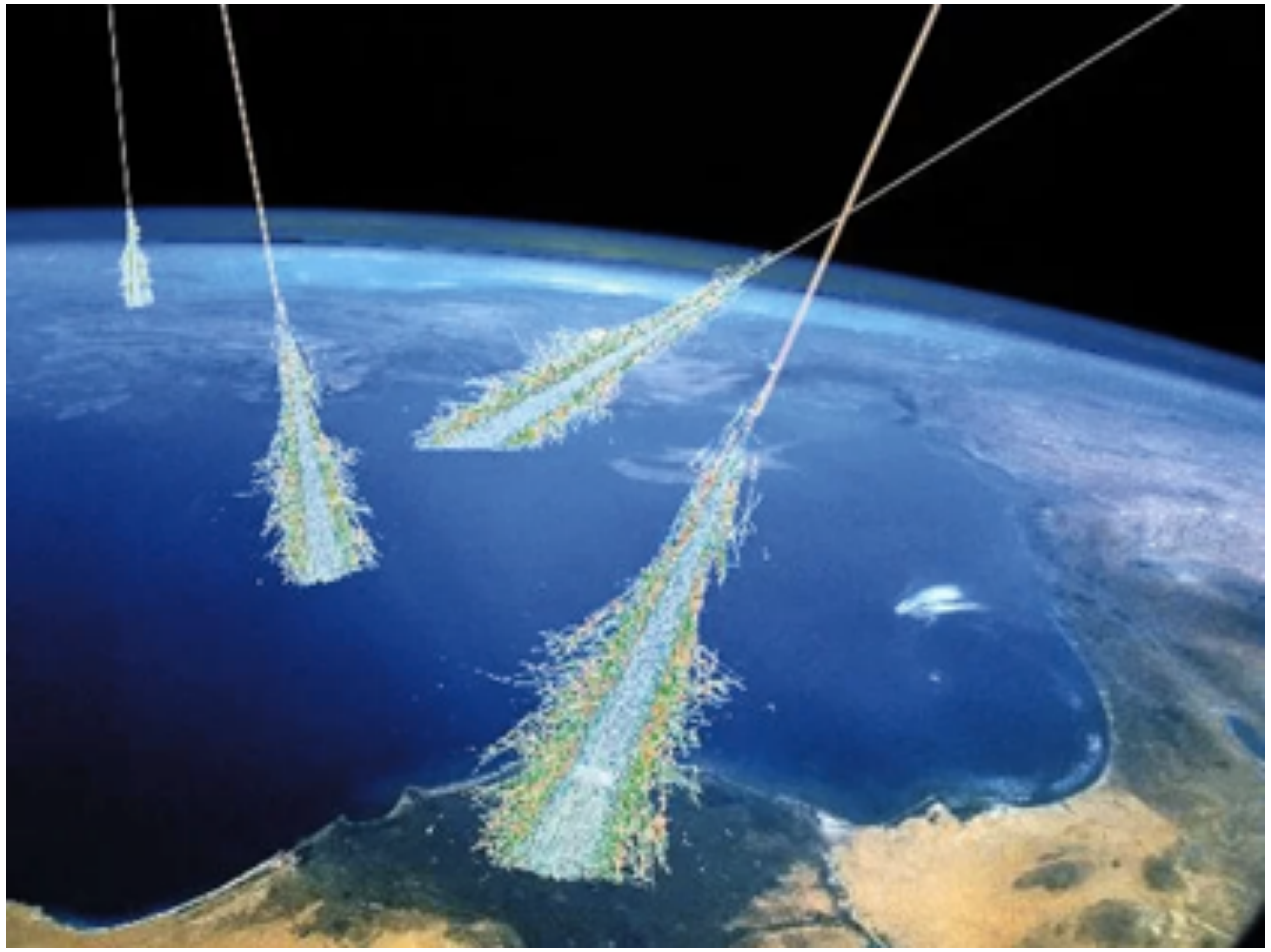
Xiaochun He GeorgiaStateUniversity

Cosmic Ray Simulation





Cosmic Ray Simulation



Computing Simulation Model

Computing Simulation Model

Geant4-based simulation program, called ECRS, has been developed to study cosmic ray particle showers in the full range of Earth's atmosphere

Computing Simulation Model

Geant4-based simulation program, called ECRS, has been developed to study cosmic ray particle showers in the full range of Earth's atmosphere

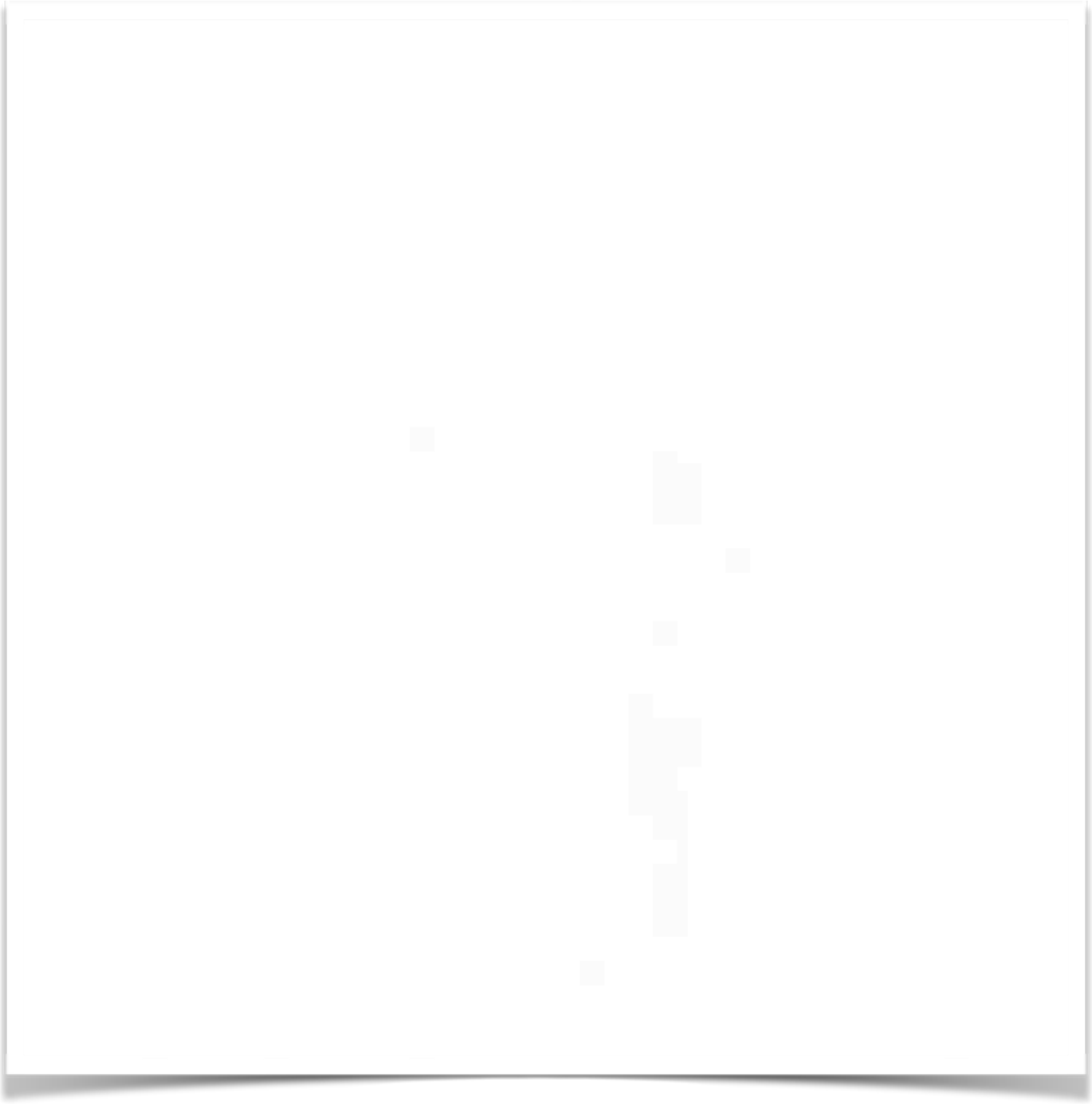
- The earth atmosphere is modeled by varying the density and chemical composition according to NASA’s atmospheric model (grc.nasa.gov)
- Geomagnetic field (internal and external field) is implemented according to NOAA’s IGRF model (ngdc.noaa.gov)

Simulated Event Display

100 GeV primary proton launched toward Atlanta, from 1.2 Re in altitude with full magnetic field configuration

Negatively charged particles are in red
Positively charged particles are in blue

Neutral particles are in green



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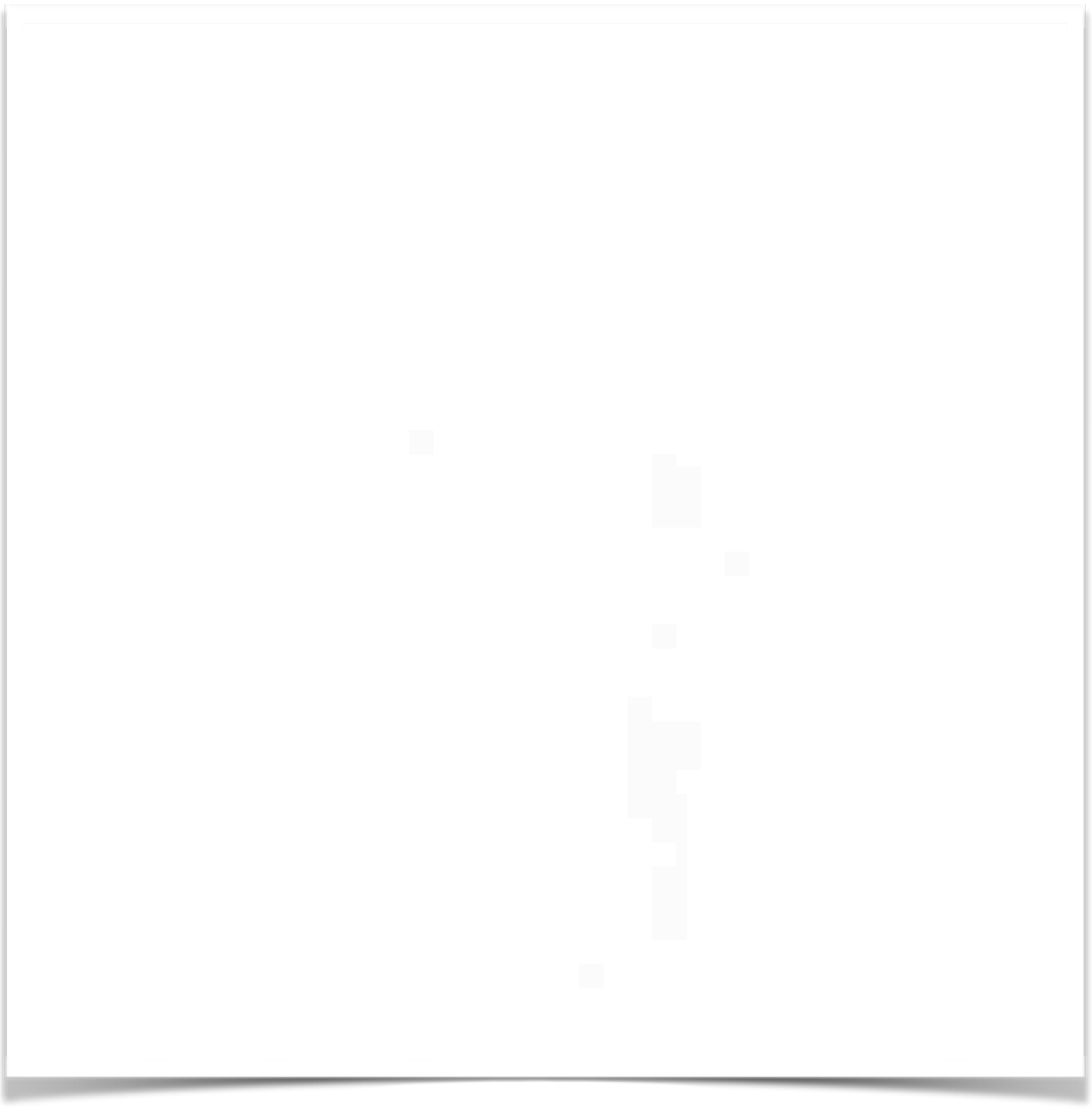
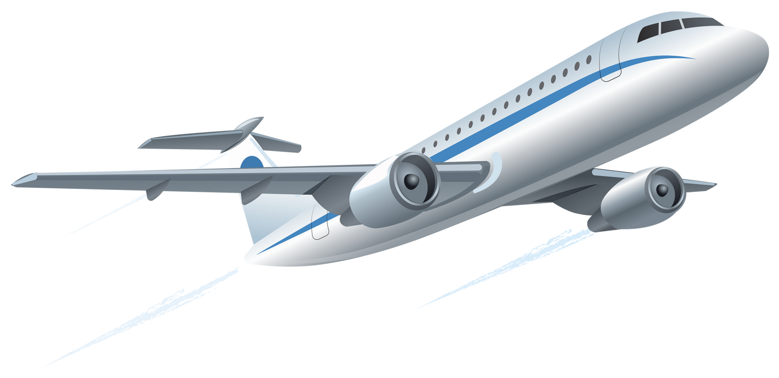


20 km

Stratosphere



10 km

Troposphere

Sea Level

Simulated Event Display

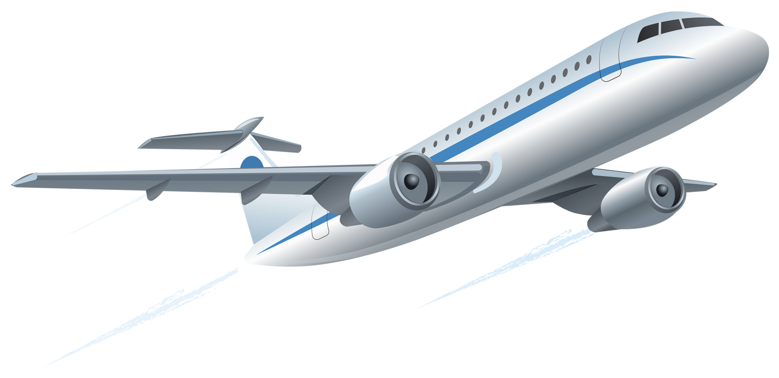
100 GeV primary proton launched toward Atlanta, from 1.2 Re in altitude with full magnetic field configuration

Negatively charged particles are in red
Positively charged particles are in blue

Neutral particles are in green

20 km

Stratosphere

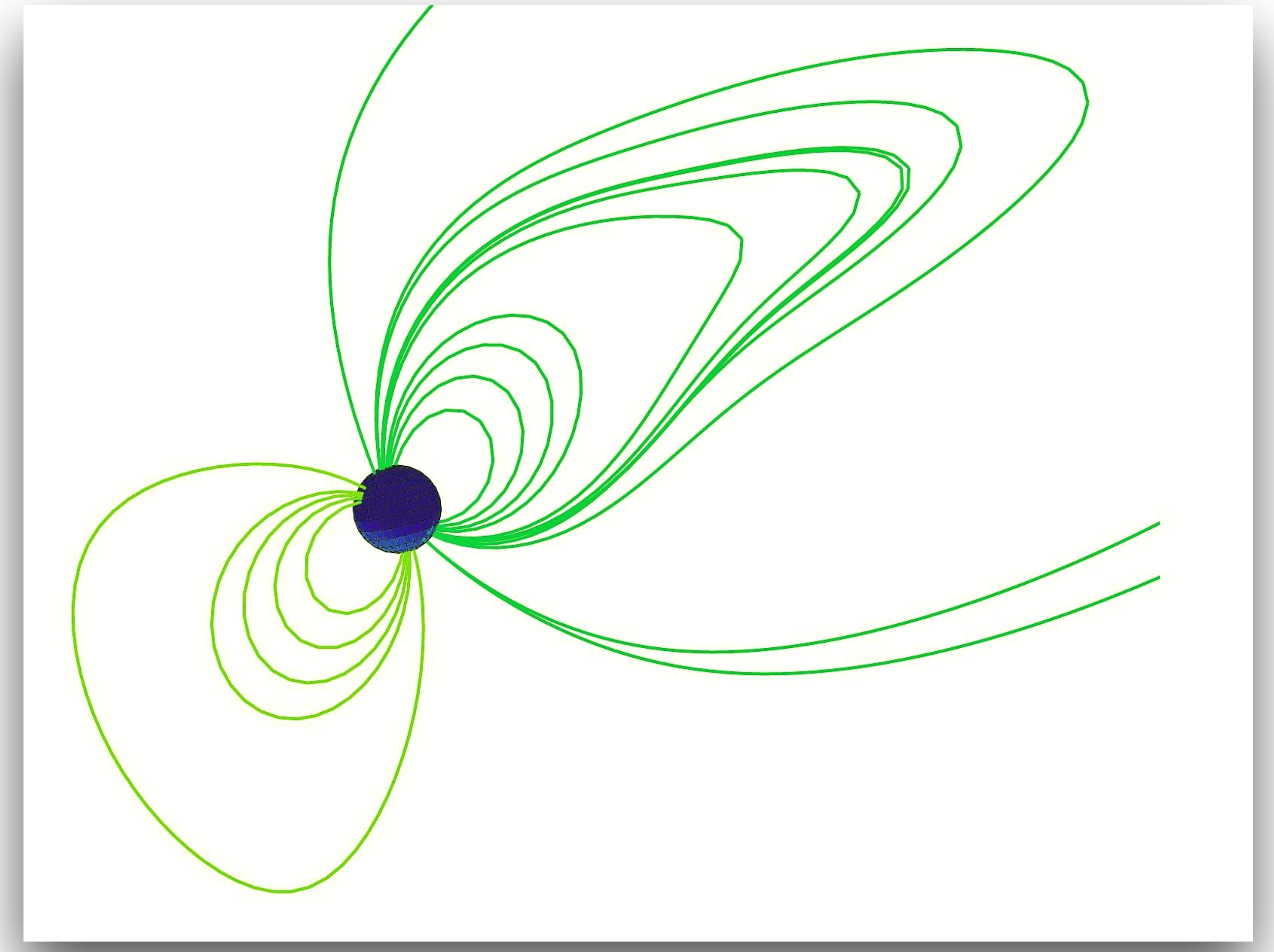


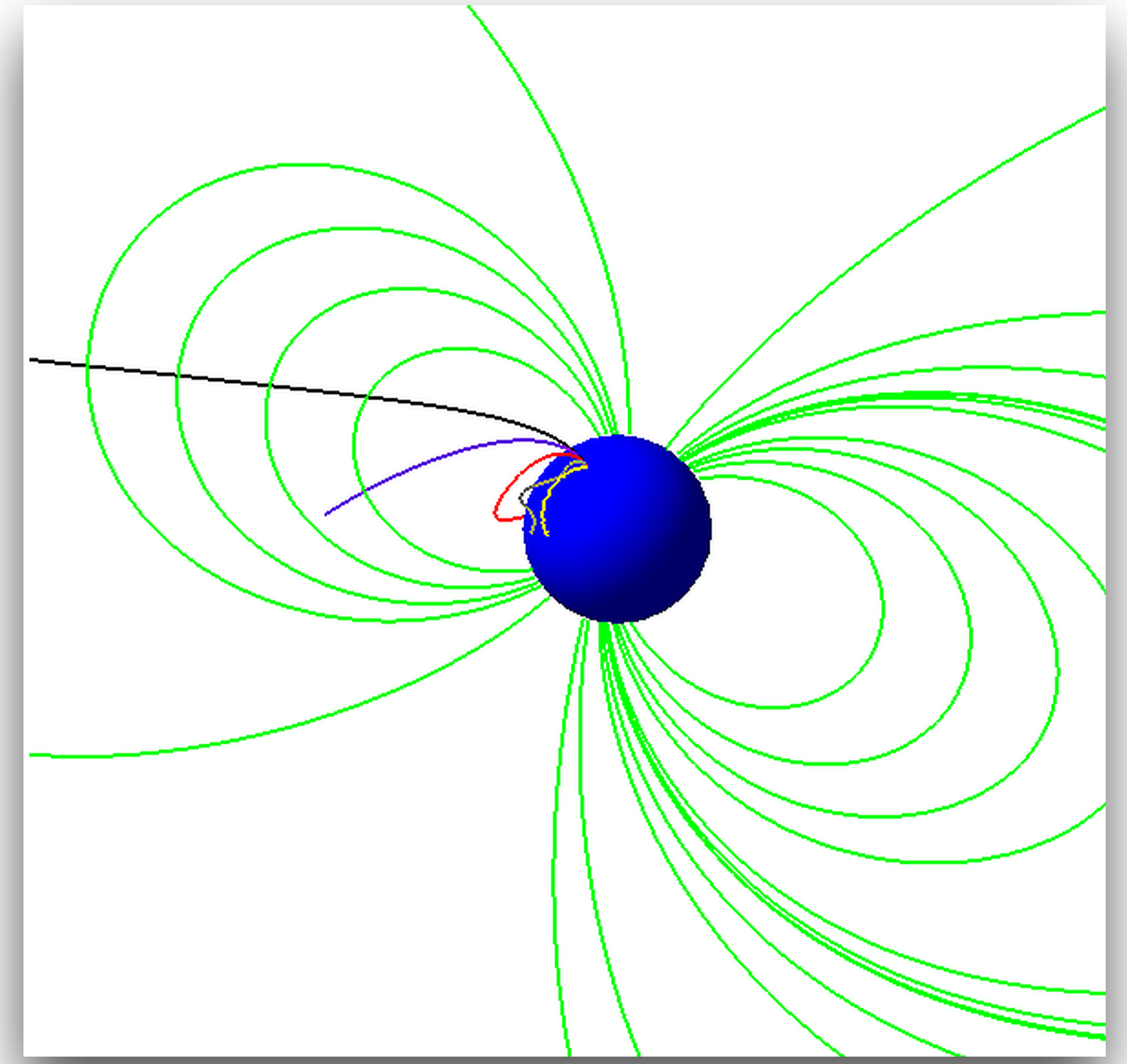
10 km

Troposphere

Sea Level

Implementation of Realistic Geomagnetic Field



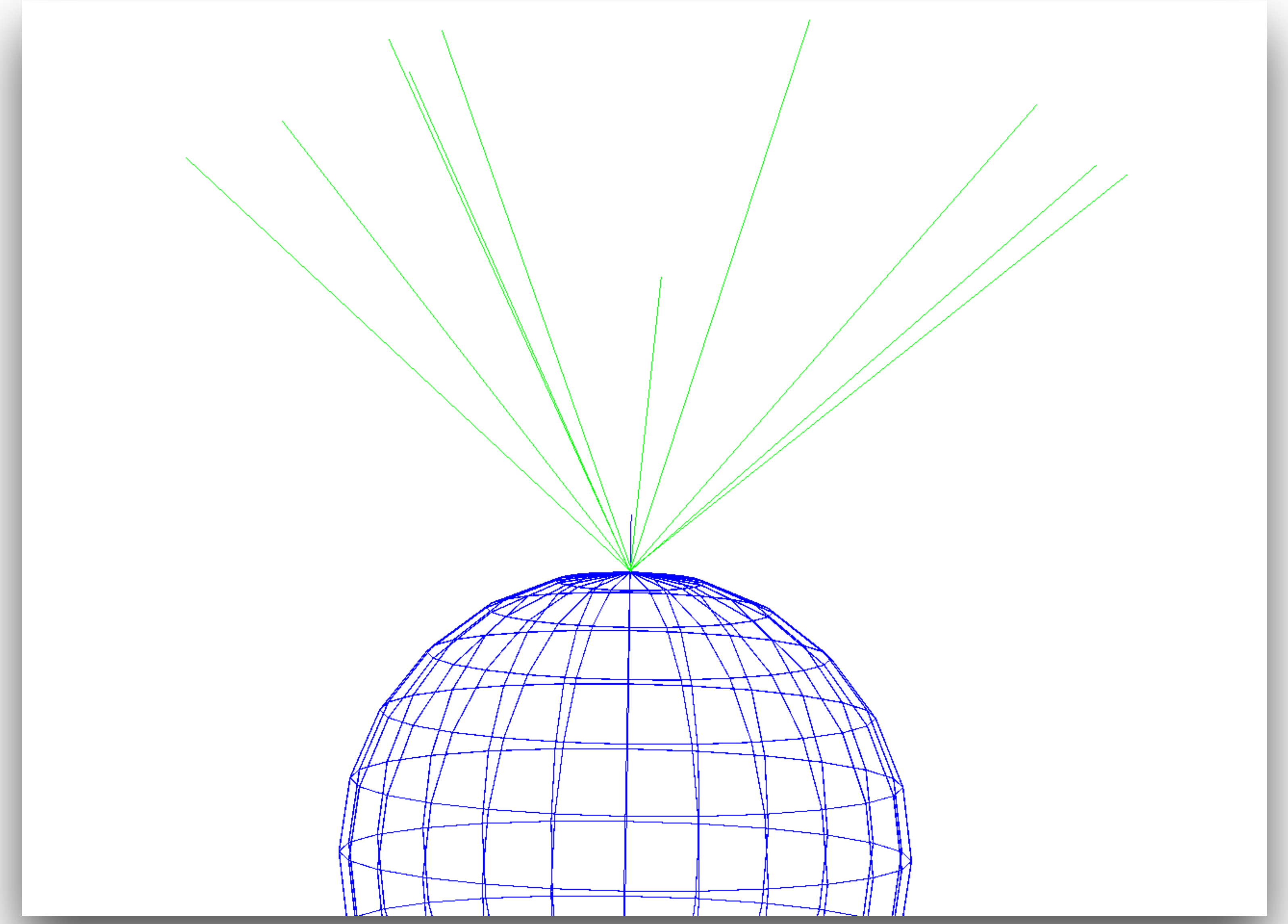


- External magnetic field
  - Based in Tsyganenko model
  - Very asymmetric because of solar wind

- Internal magnetic field
  - Based on the Internal Goemagnetic Reference Field (IGRF) model
  - Close to be symmetric

If There is No Magnetic Field

One of the design features of the ECRS simulation is the flexibility of switching on and off the geomagnetic field



If There is No Magnetic Field

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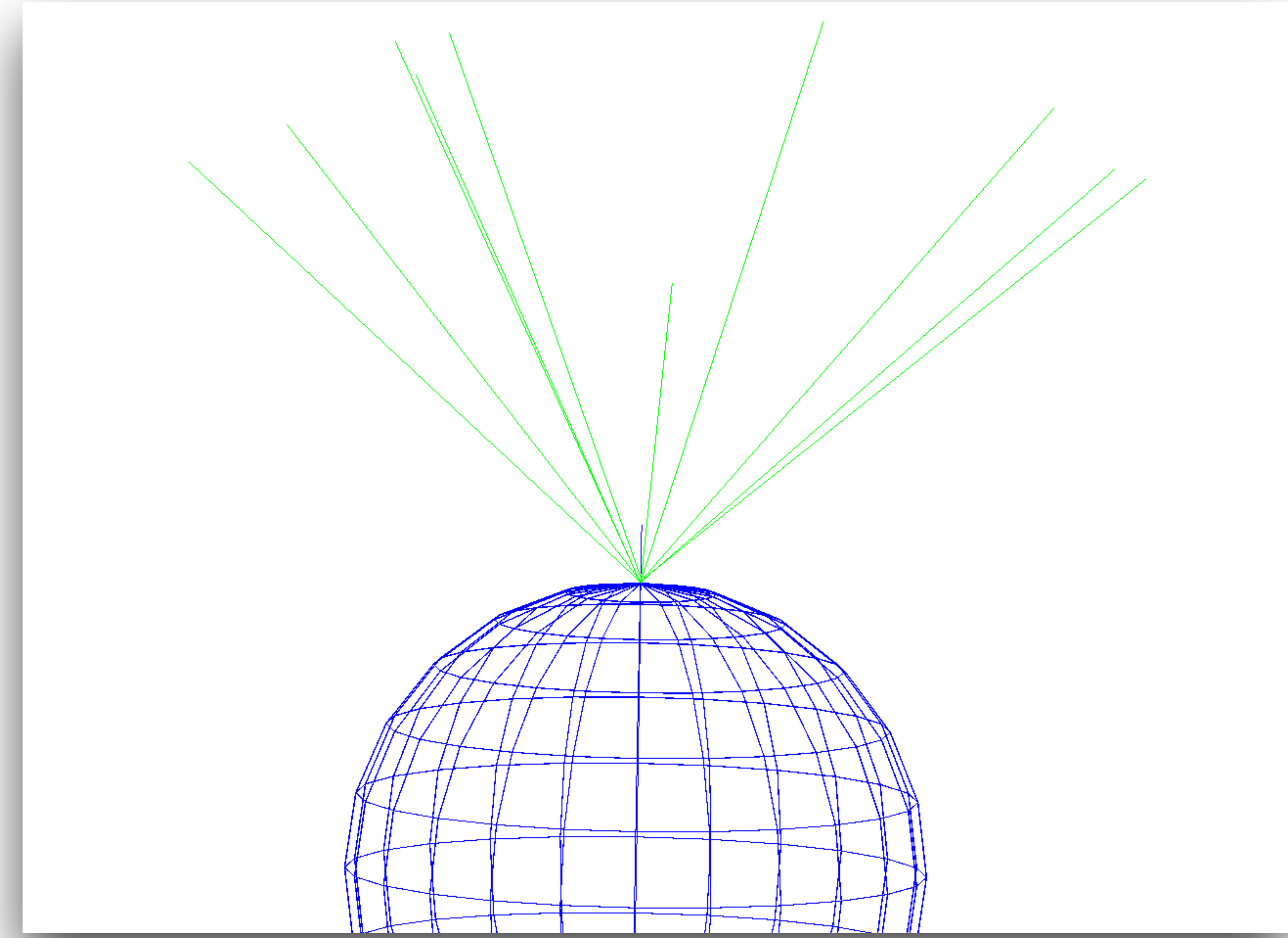

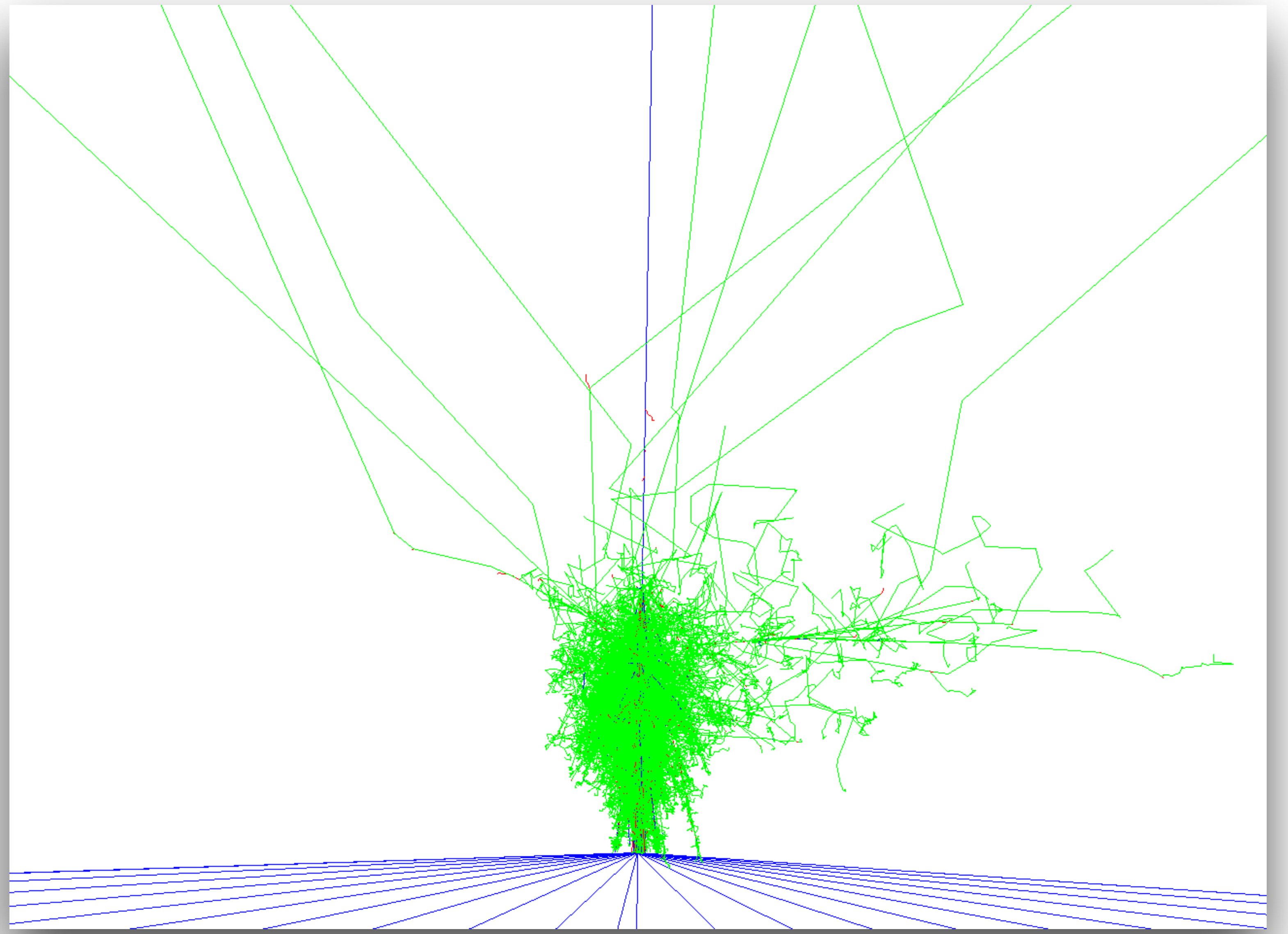

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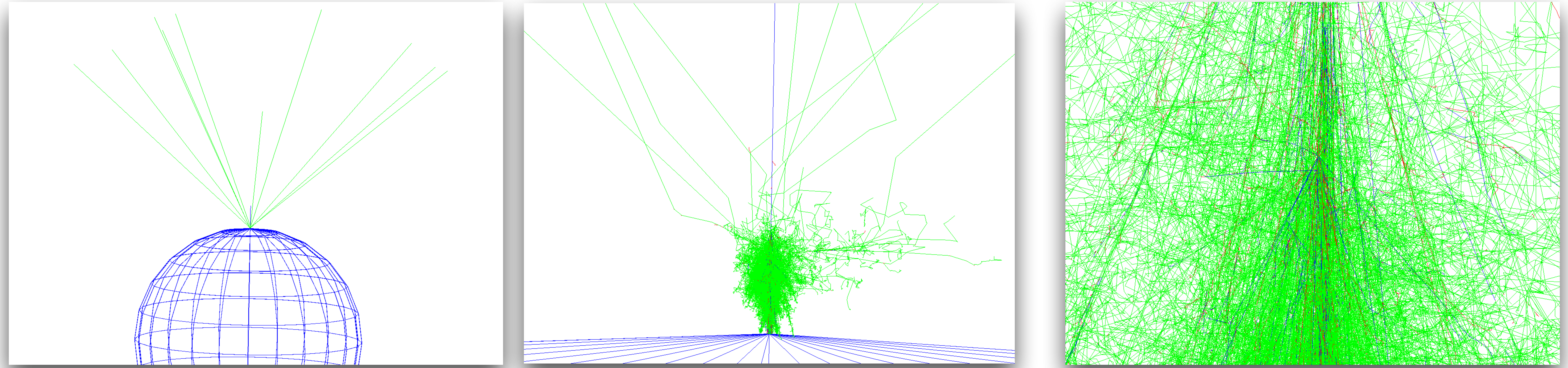

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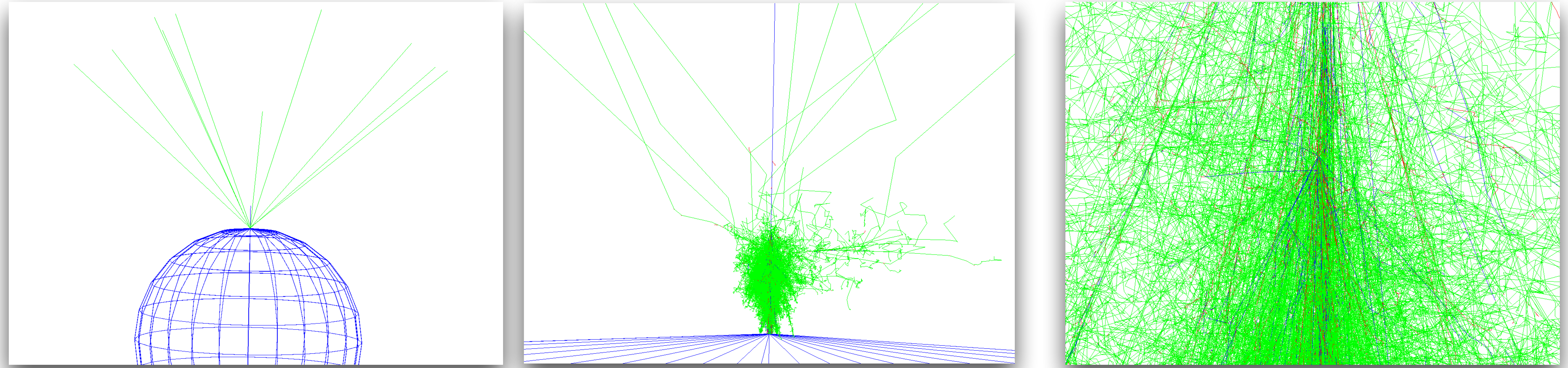
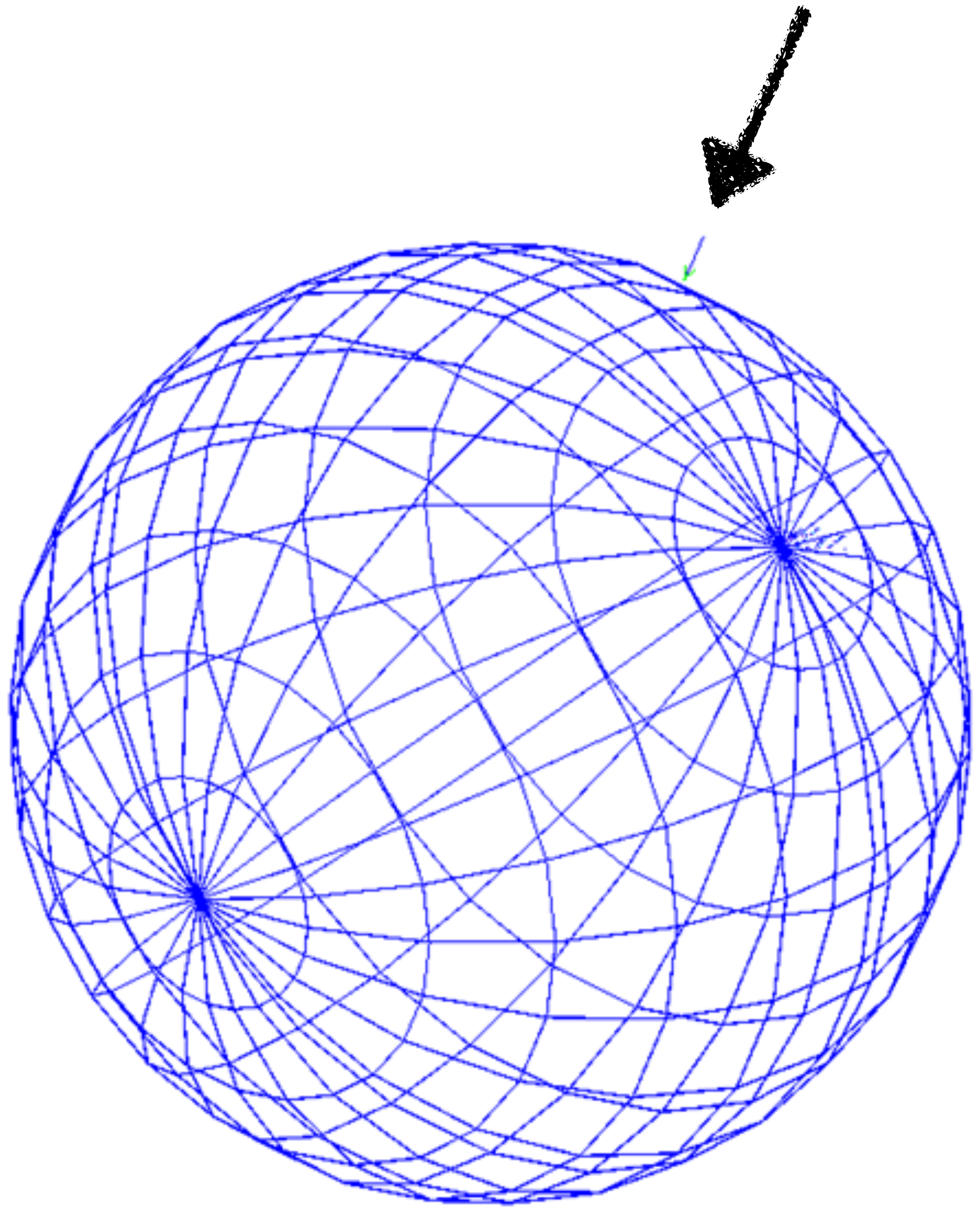


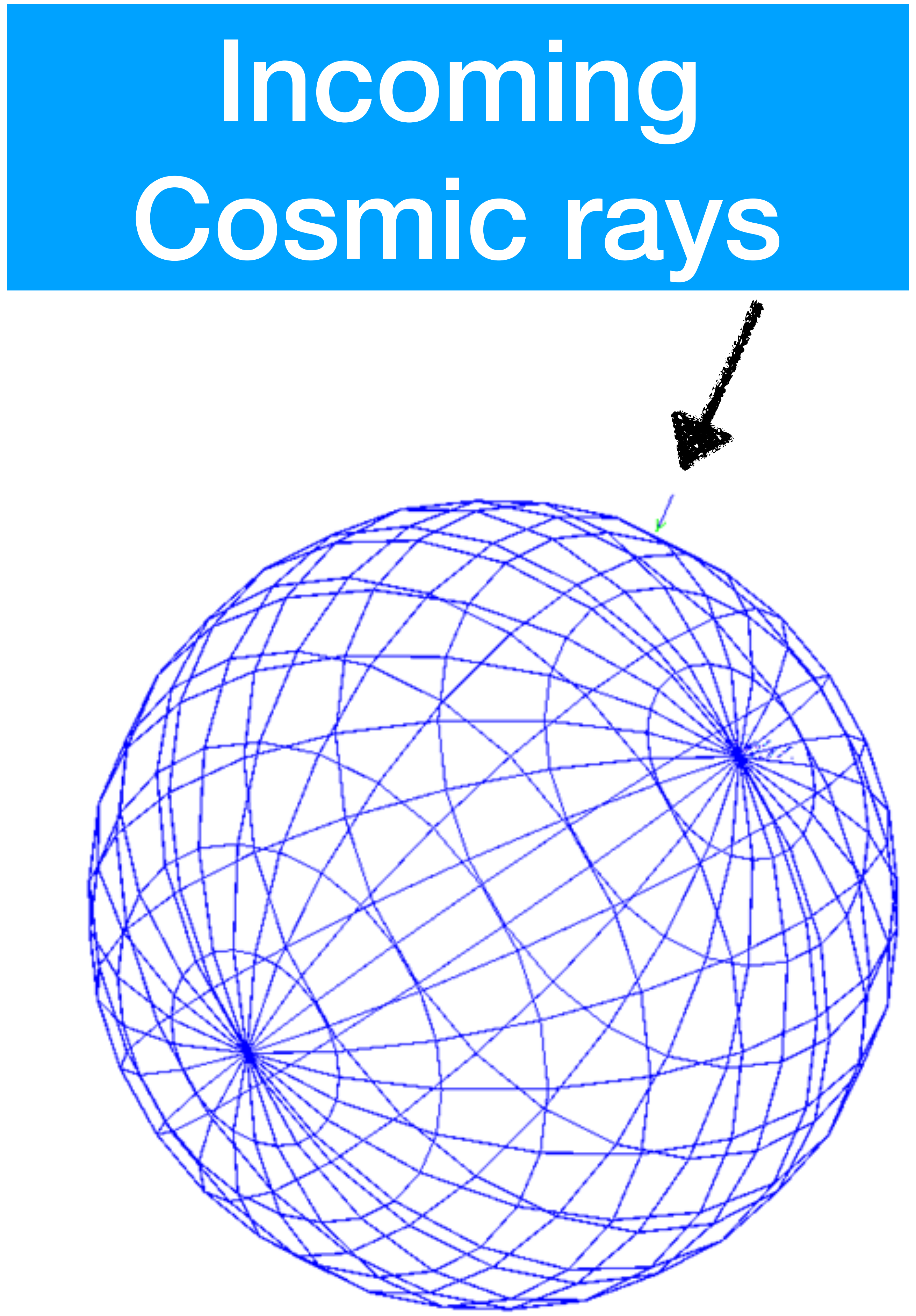
The simulation allows us to systematically explore the geomagnetic field effect on the cosmic ray shower development in the earth's atmosphere.

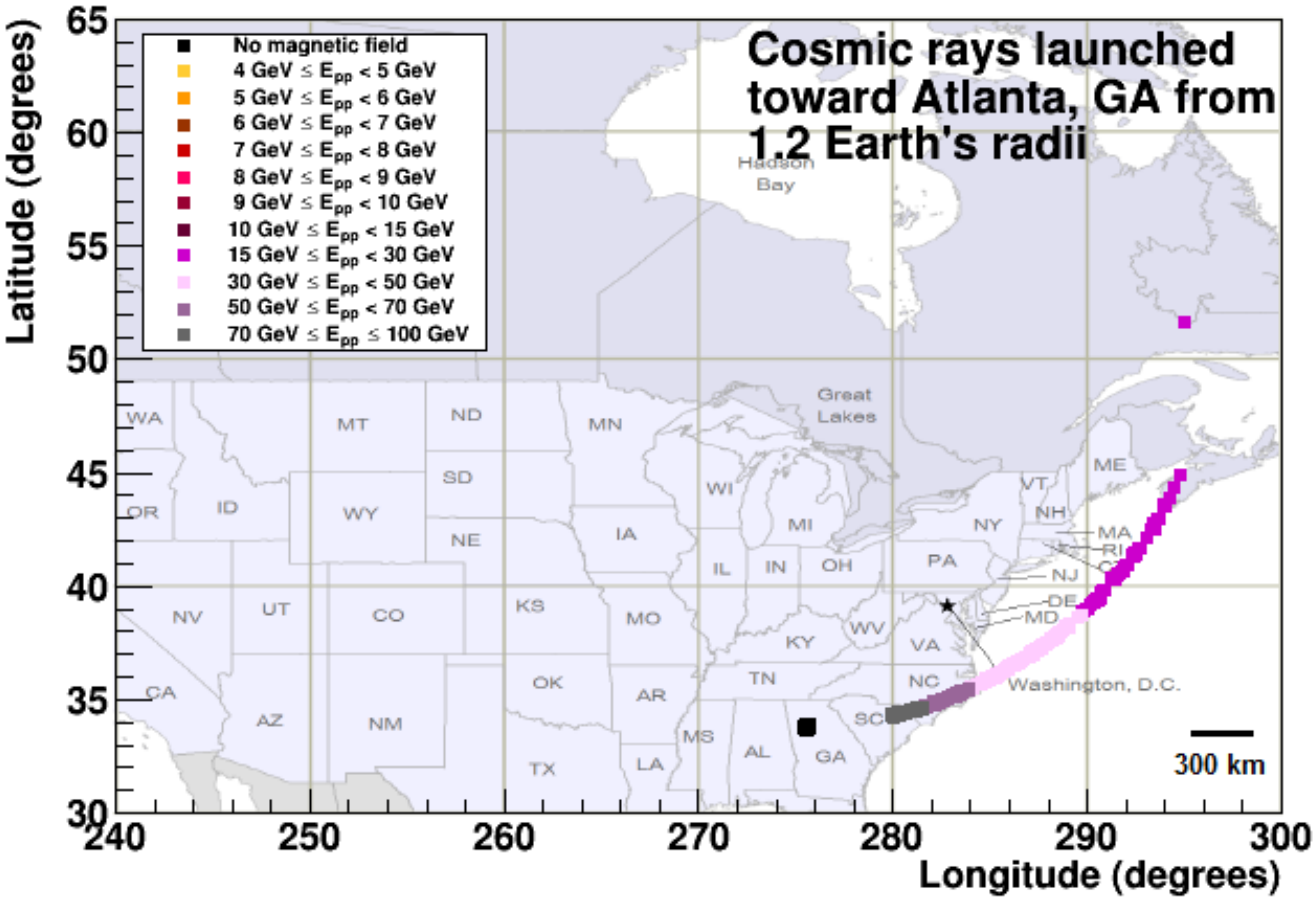
With Magnetic Field

Incoming
Cosmic rays



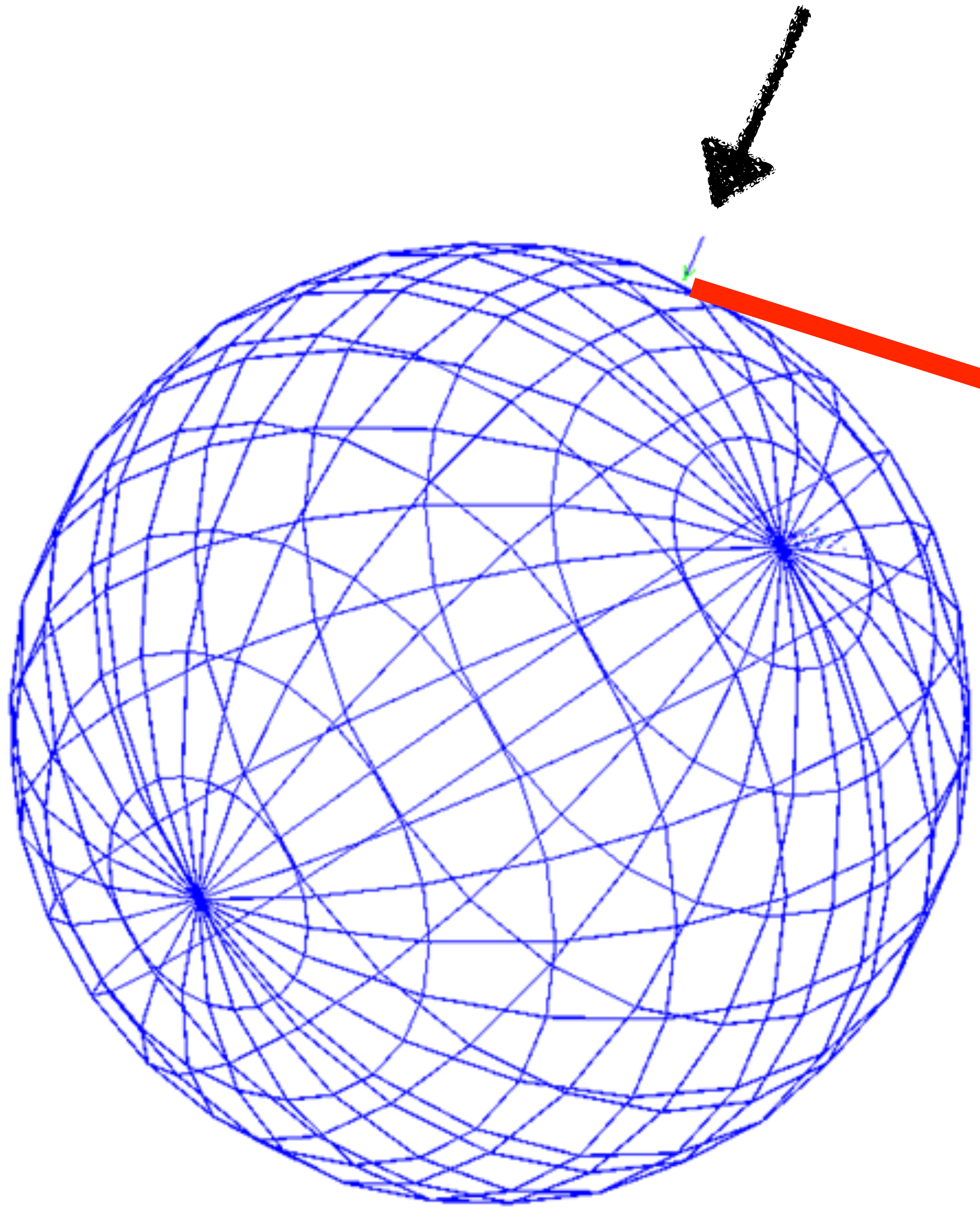
With Magnetic Field

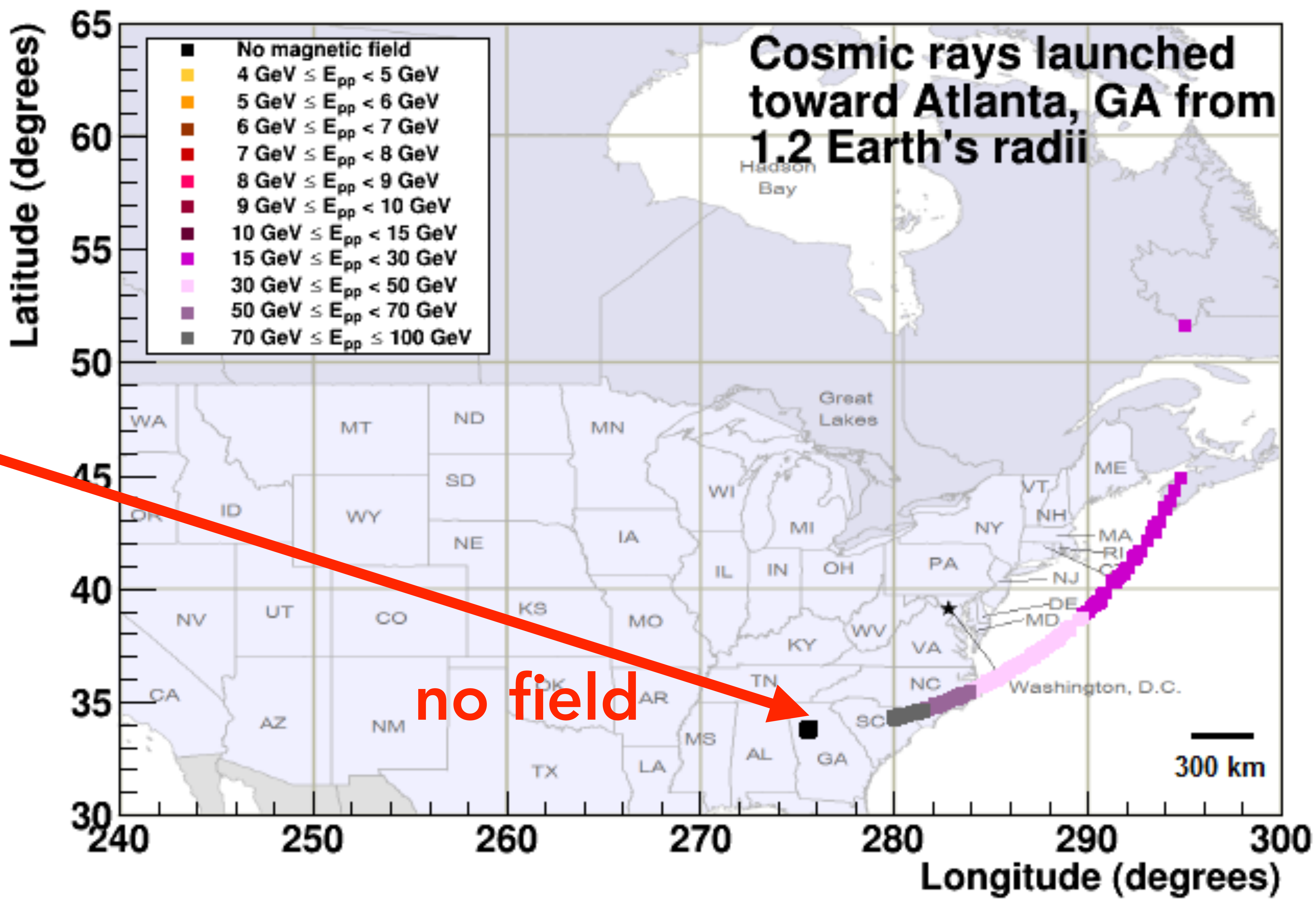




With Magnetic Field

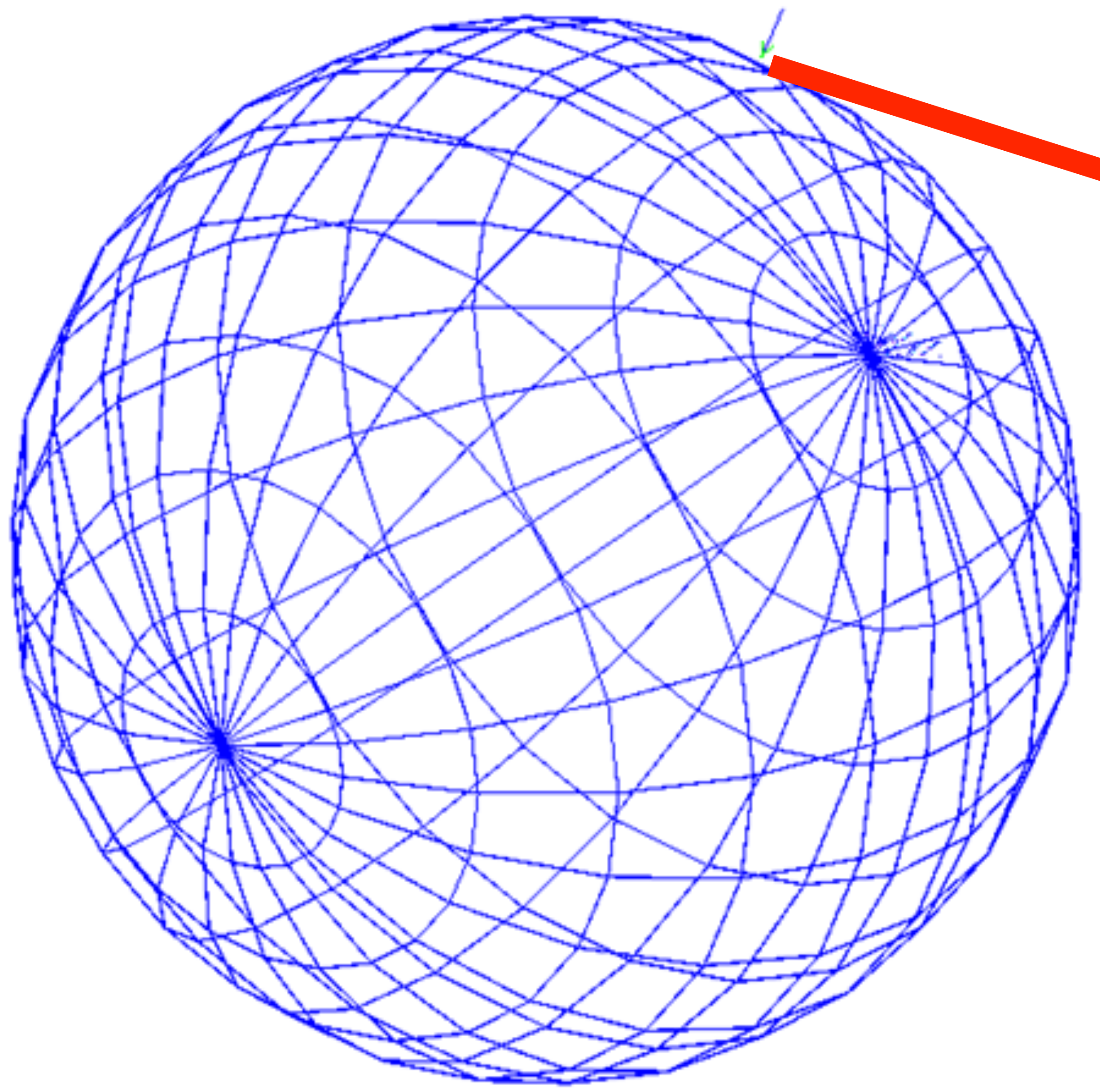
Incoming Cosmic rays

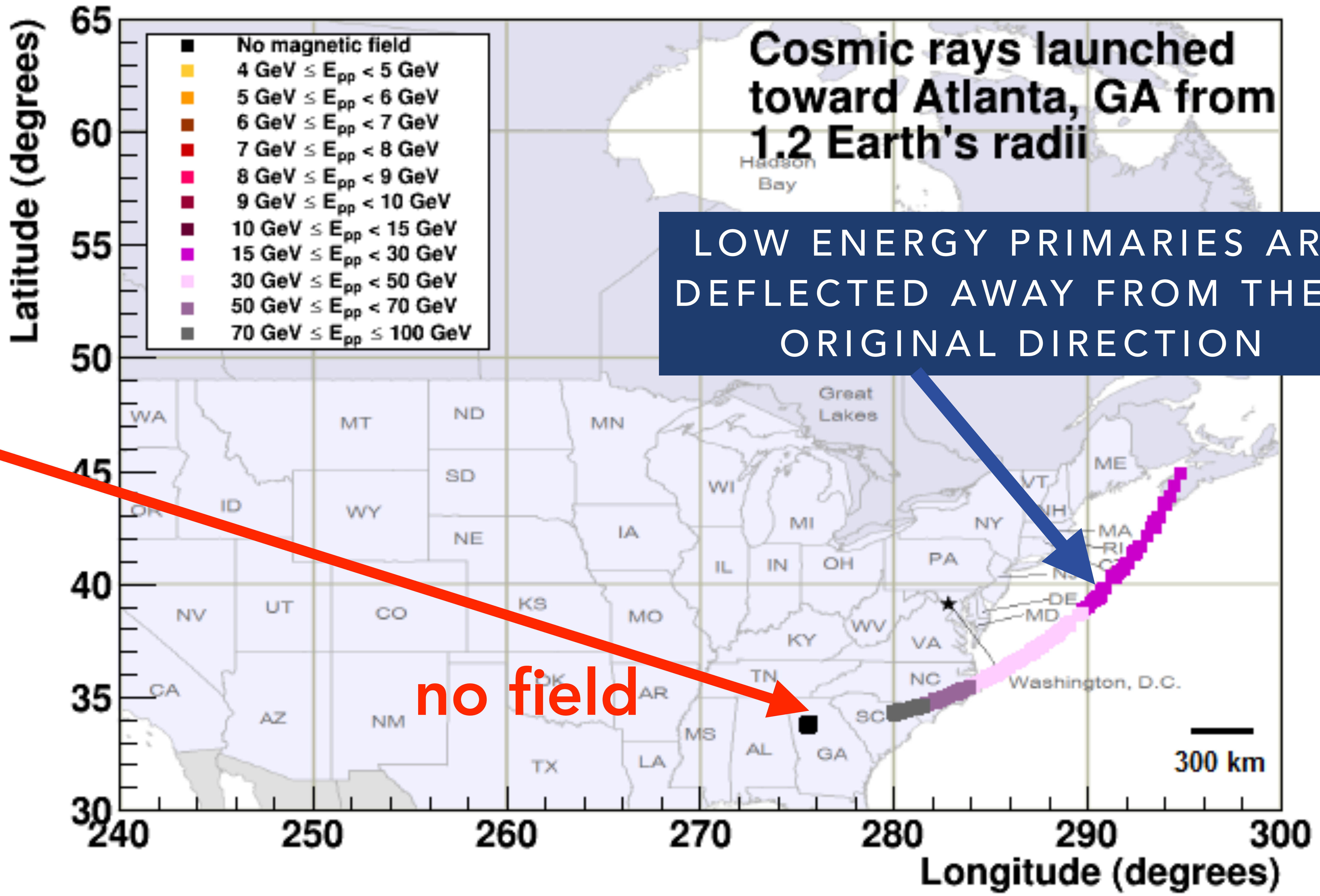




With Magnetic Field

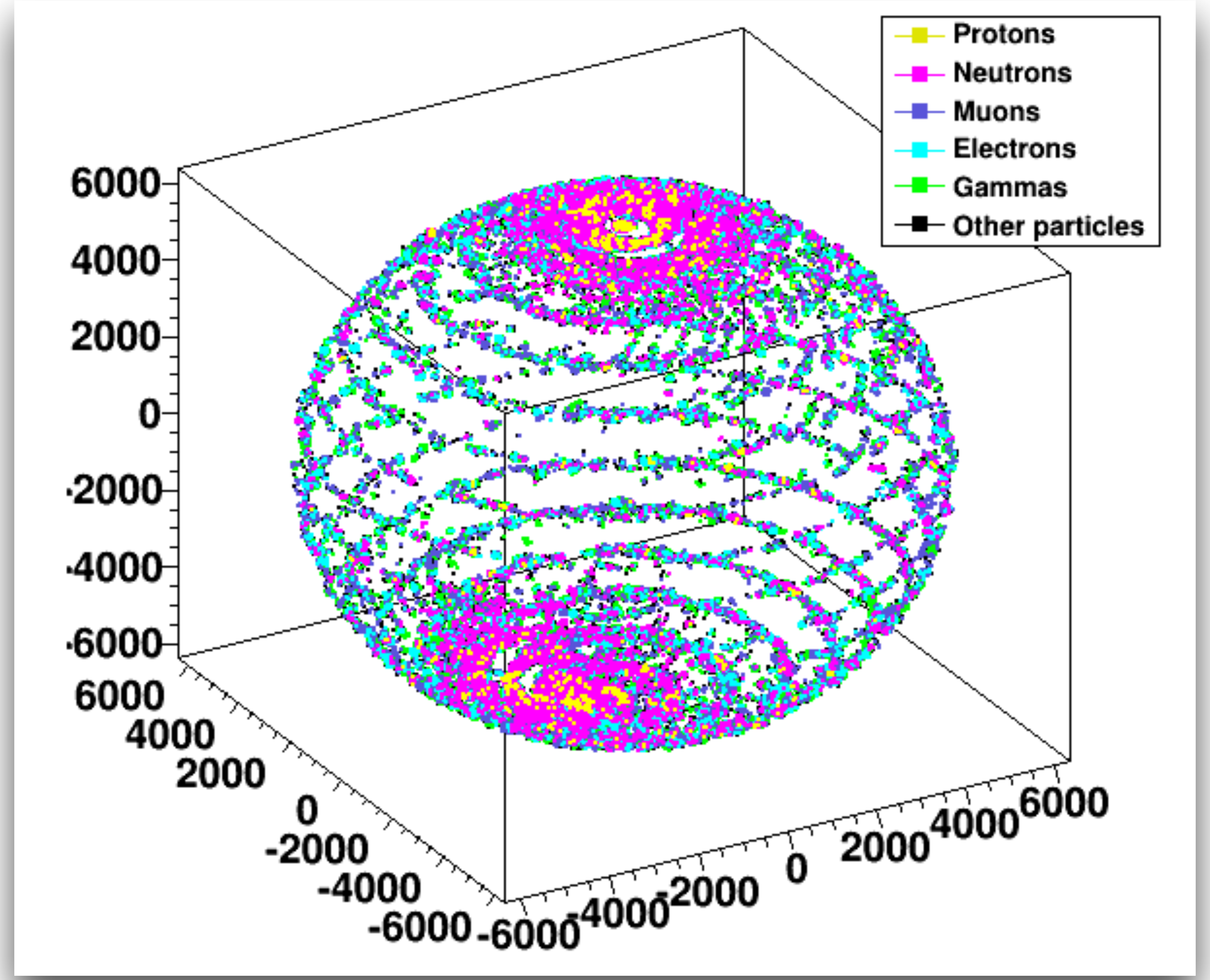
Incoming Cosmic rays



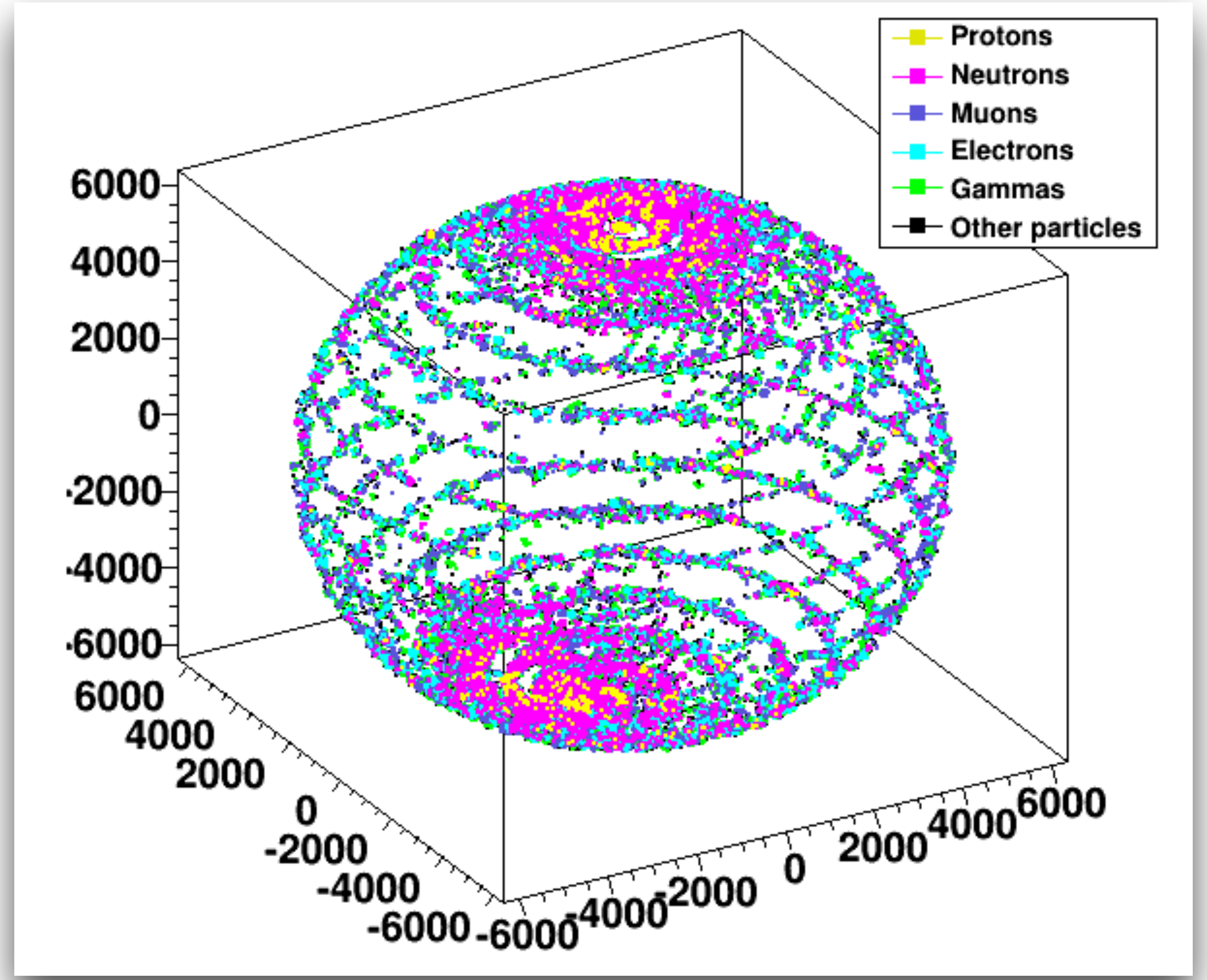


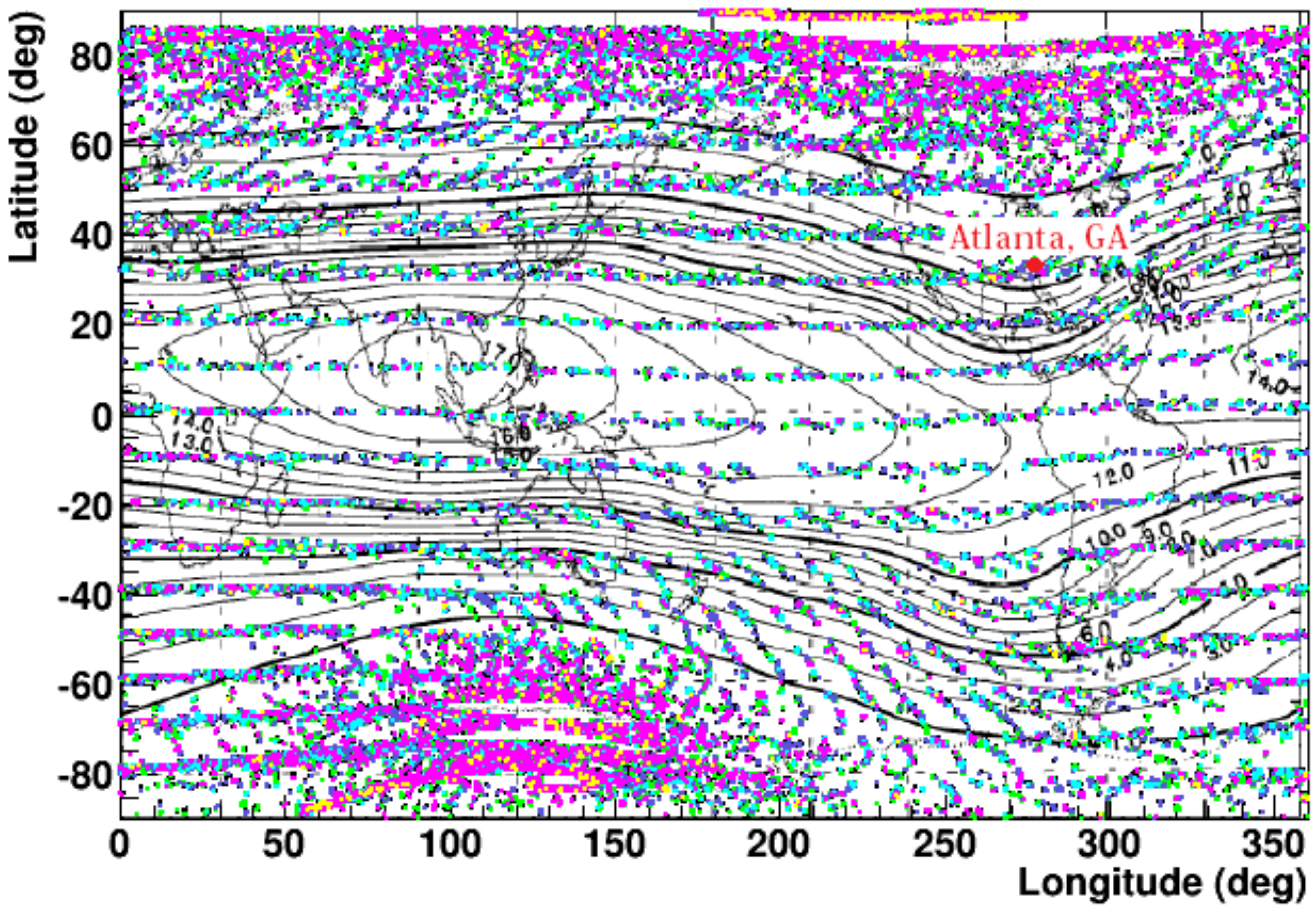
LOW ENERGY PRIMARIES ARE DEFLECTED AWAY FROM THEIR ORIGINAL DIRECTION

Cosmic Ray Flux Variation at Global Scale

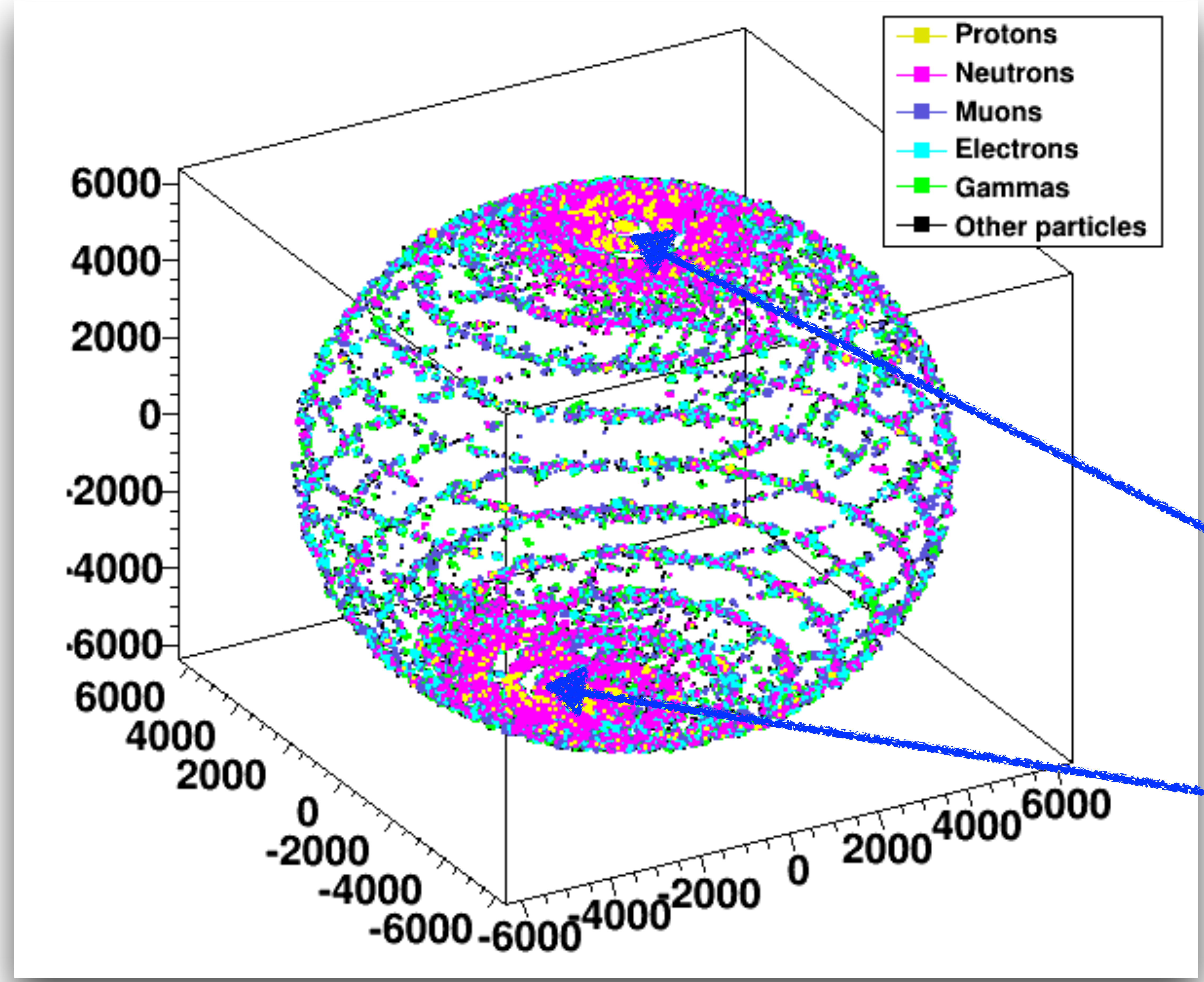


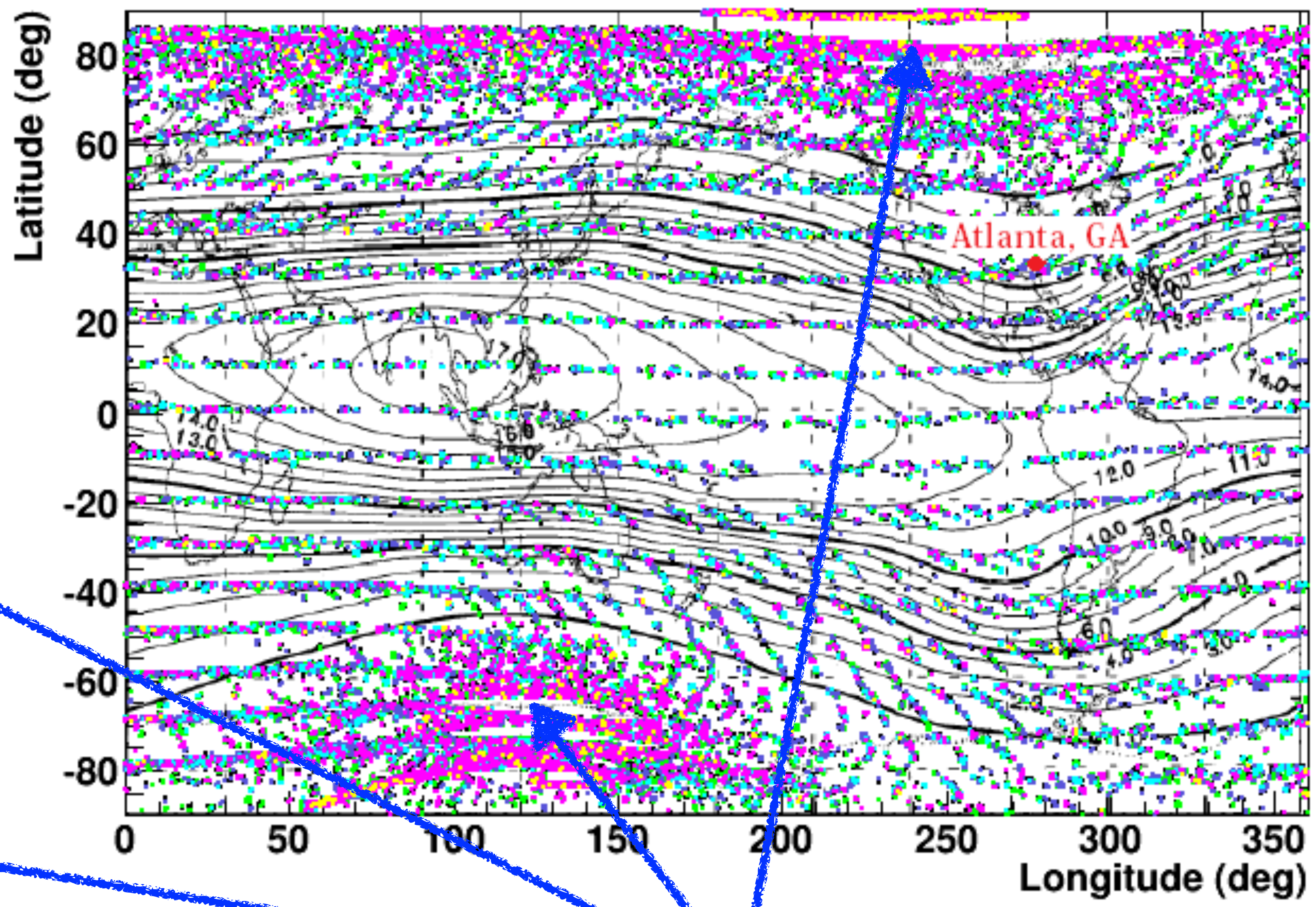
Cosmic Ray Flux Variation at Global Scale





Cosmic Ray Flux Variation at Global Scale





Higher radiation level close to pole regions!

Novel Cosmic Ray Detector Development

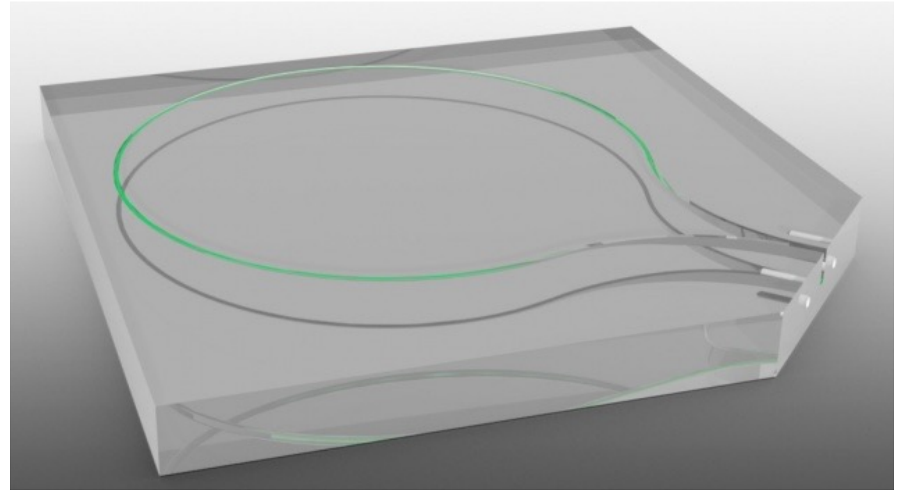
Portable, low-cost and reliable!

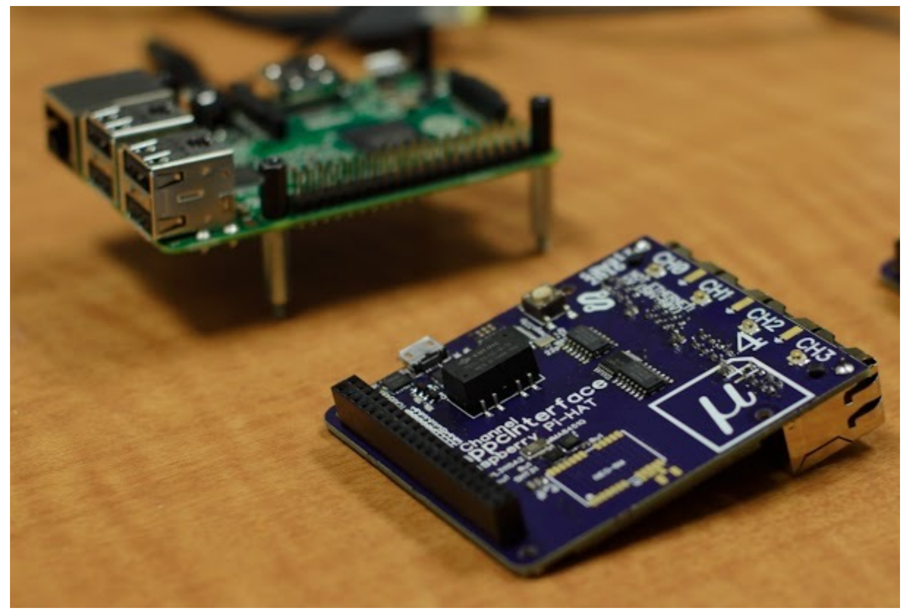
Novel Cosmic Ray Detector Development

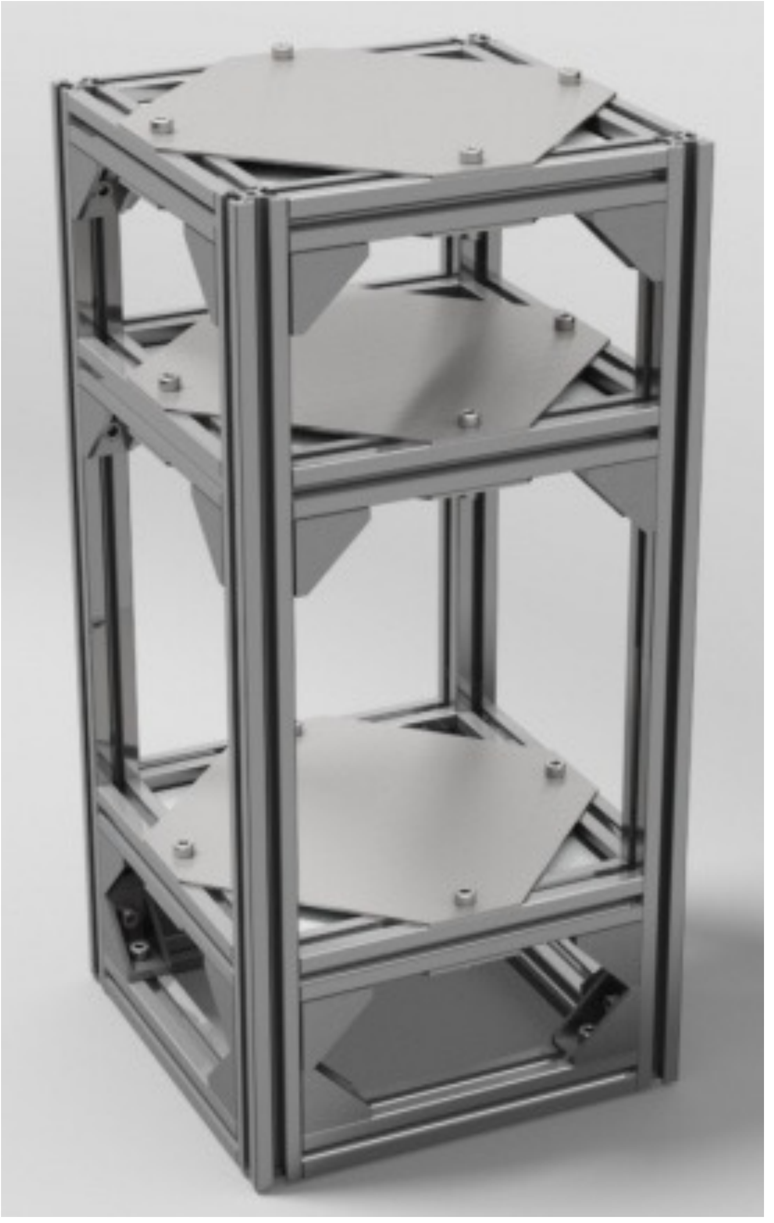
Portable, low-cost and reliable!

Novel Cosmic Ray Detector Development

GSU group is focusing on developing and building detectors and Prof. Wei's group is working on signal readout and power system.

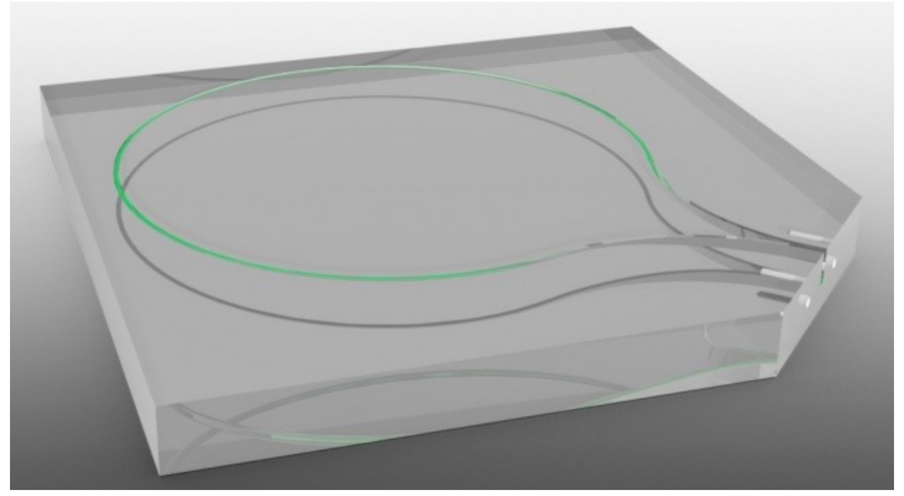


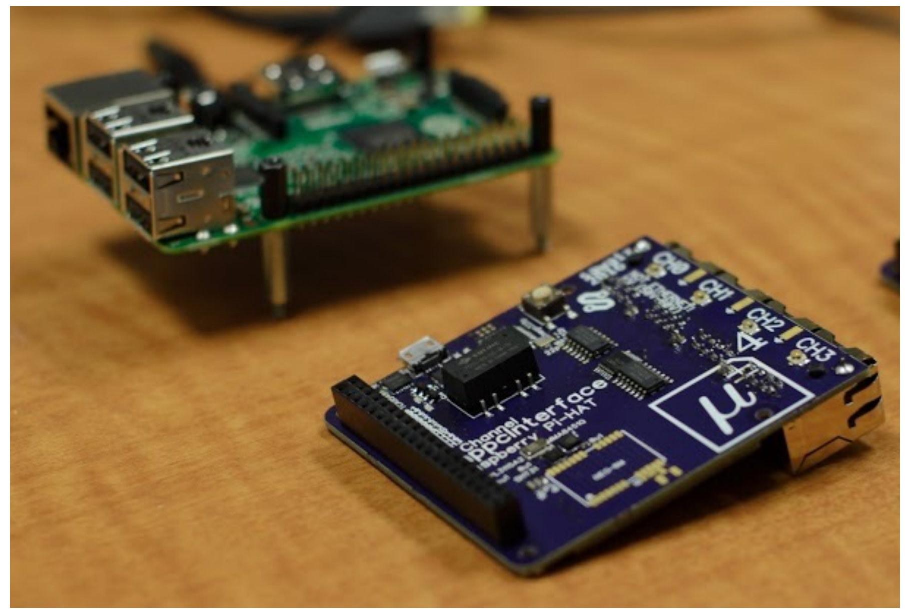


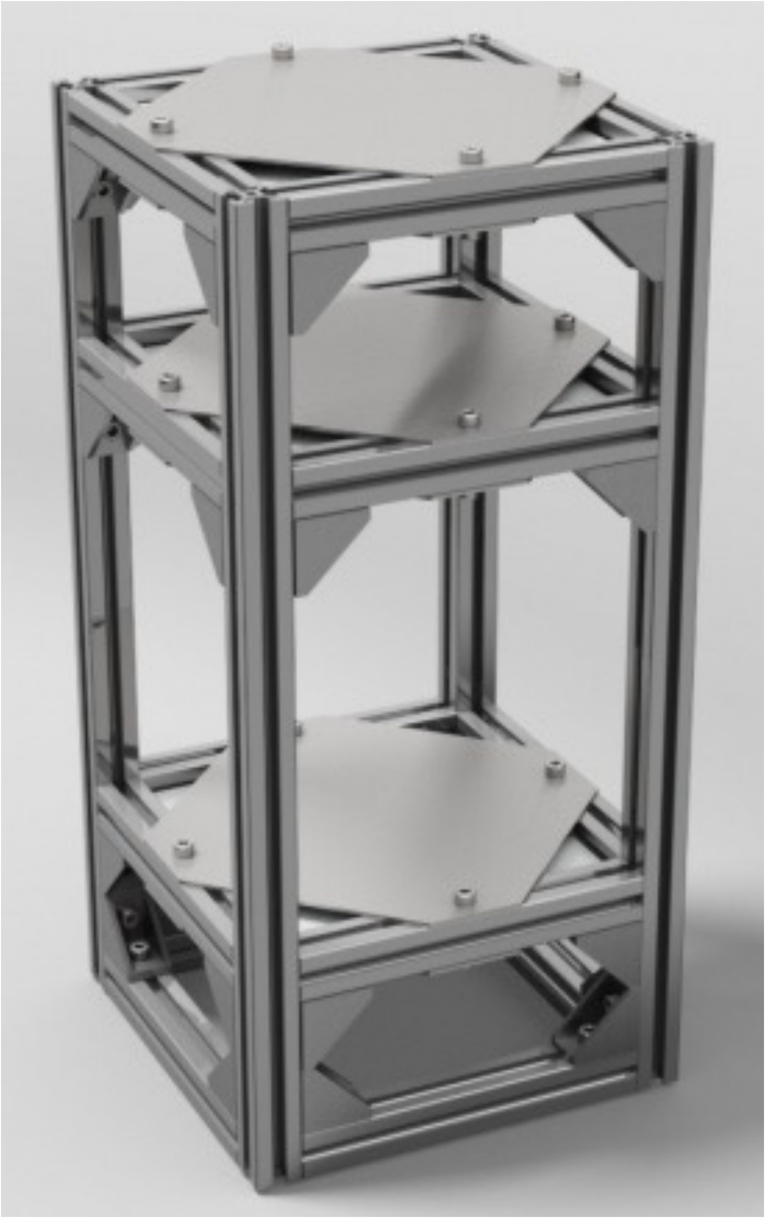


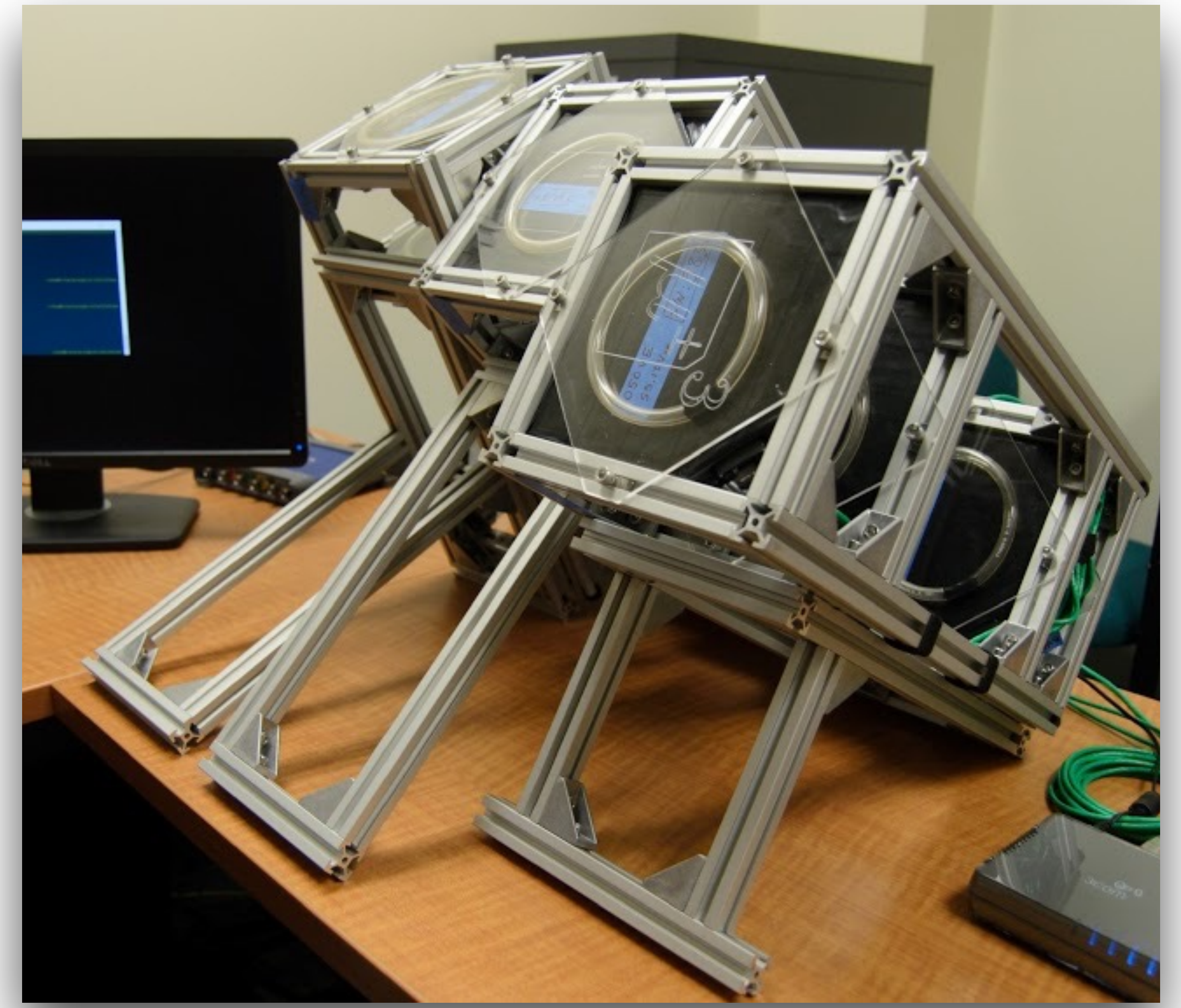
Cosmic Ray Muon Telescope Prototype

Cosmic Ray Muon Telescope Prototype

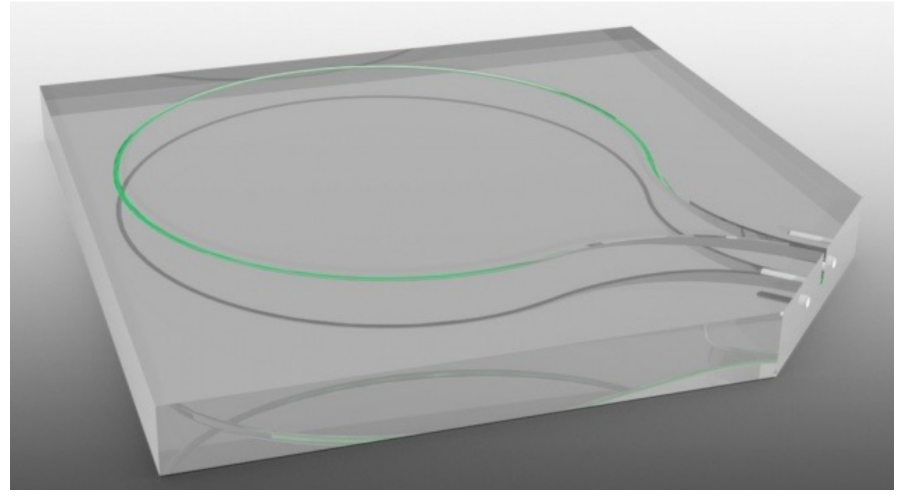


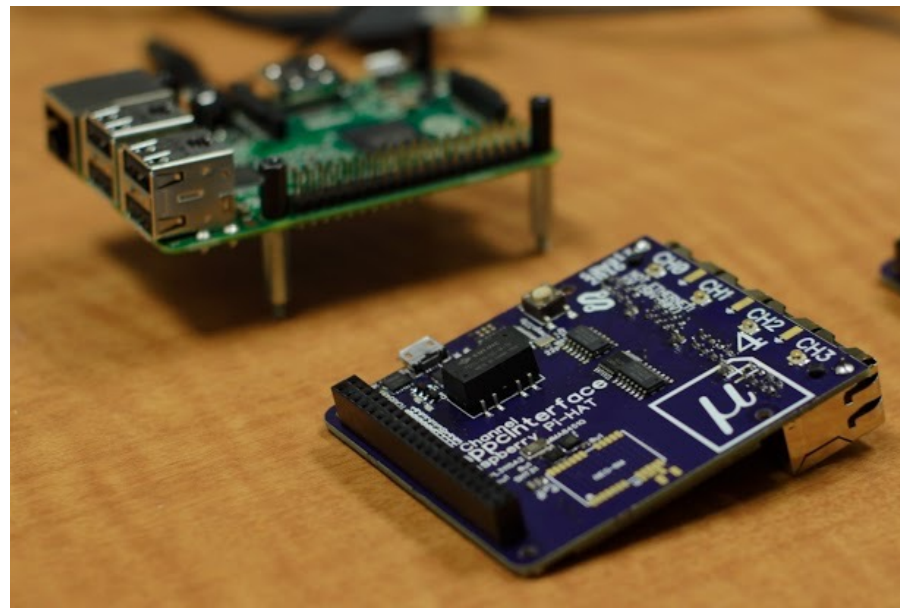


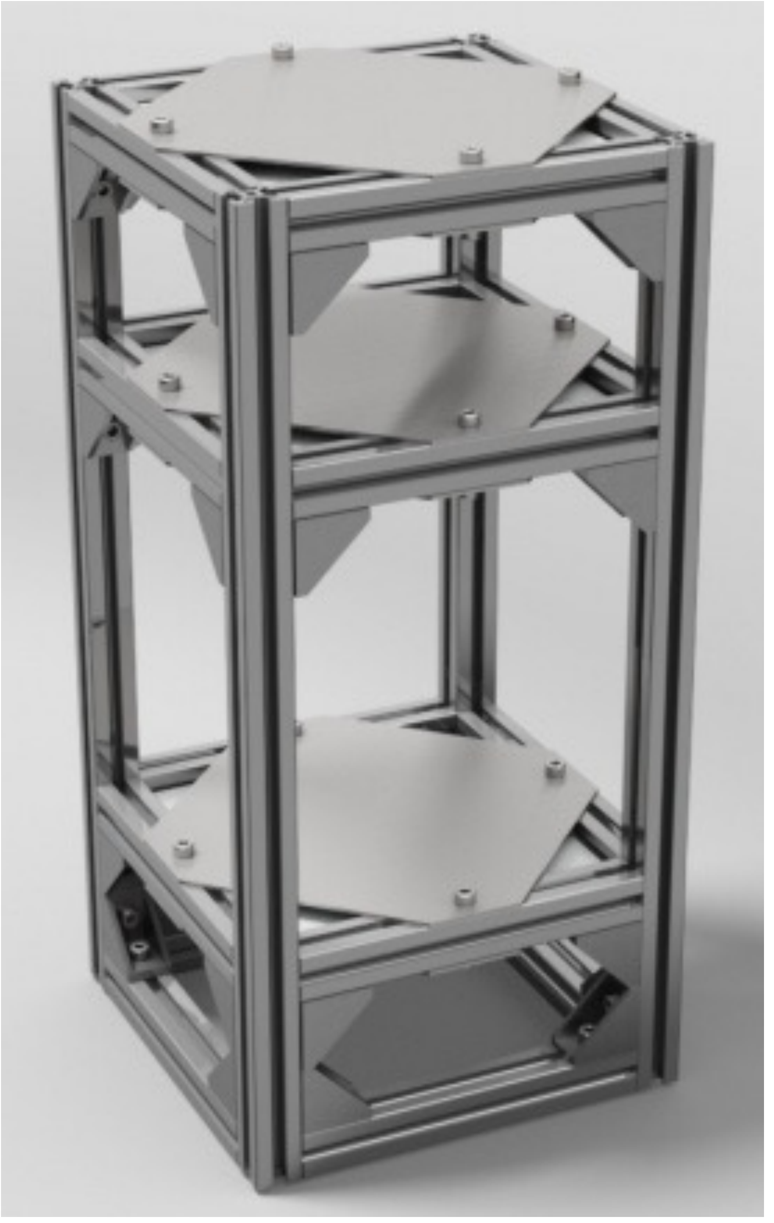


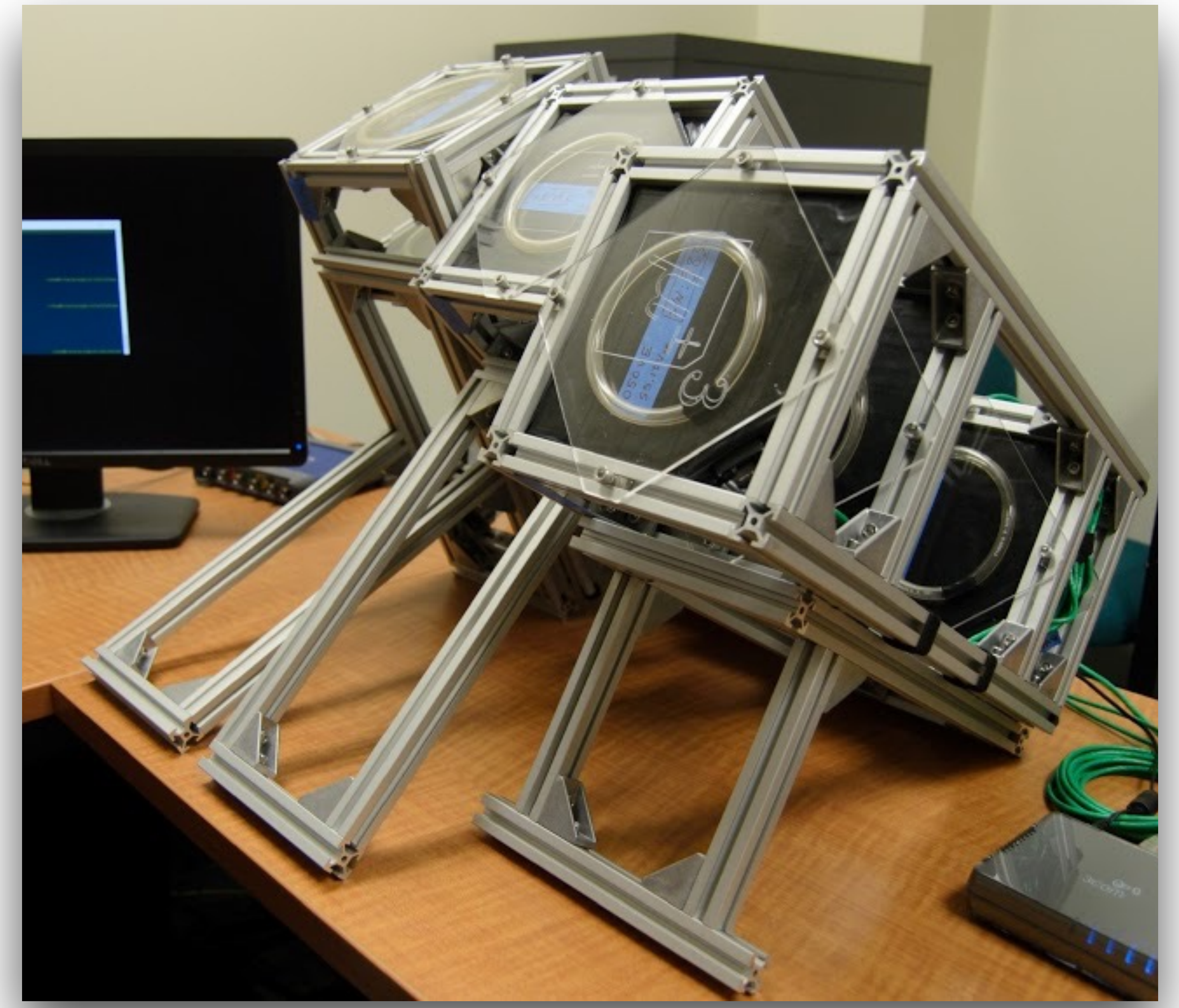


Cosmic Ray Muon Telescope Prototype





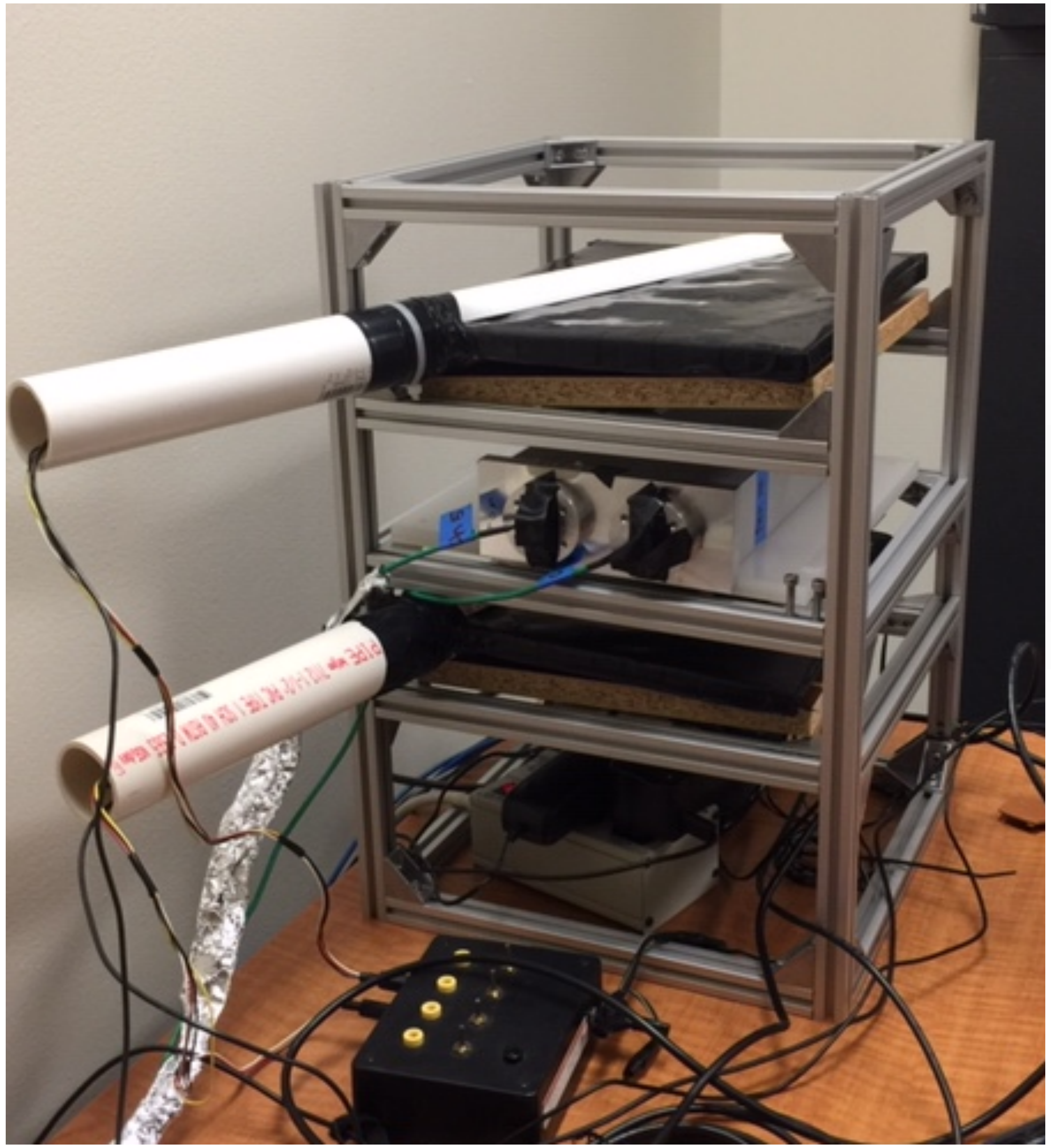




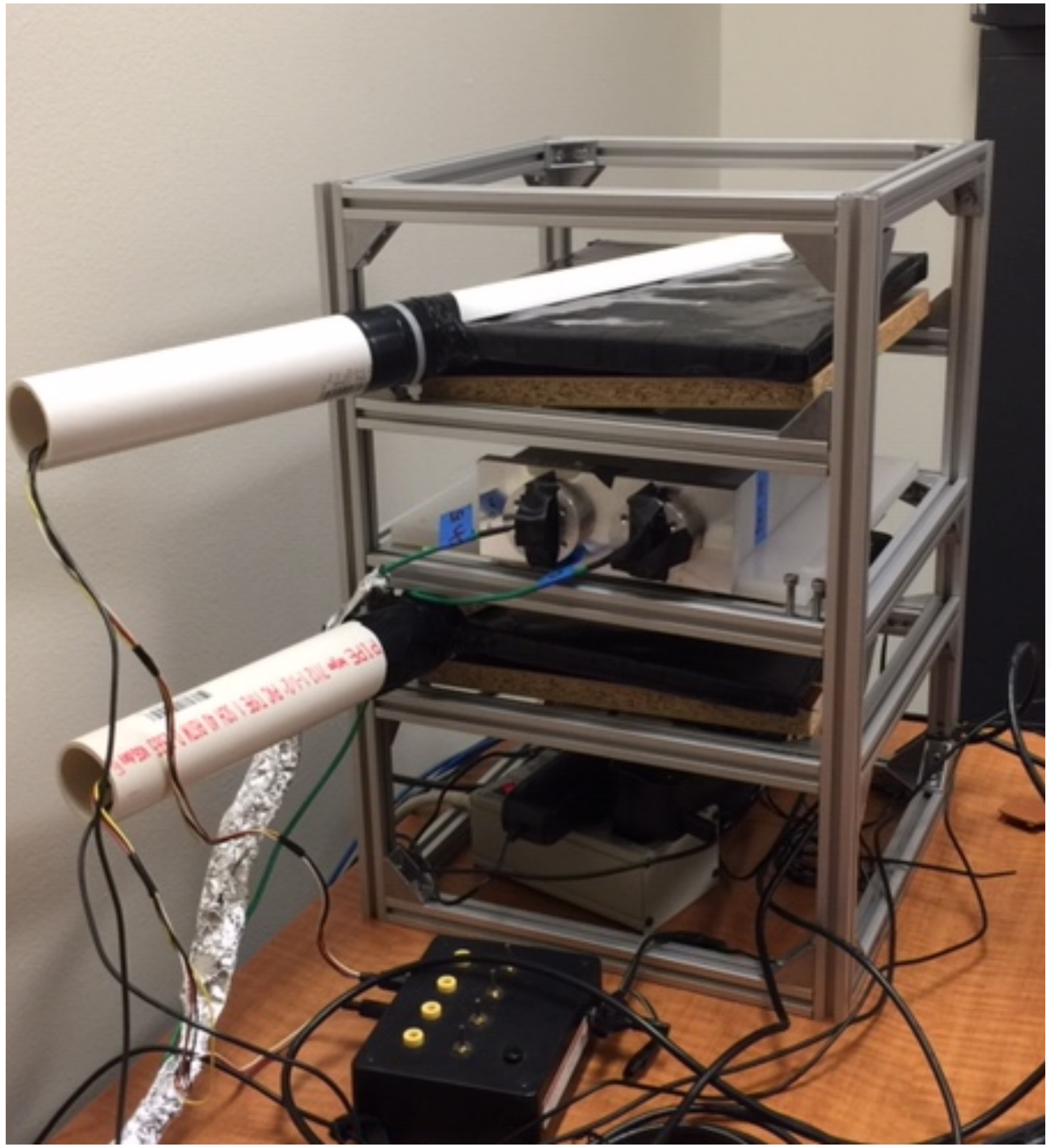
Neutron Bottle: Proof-of-Principle

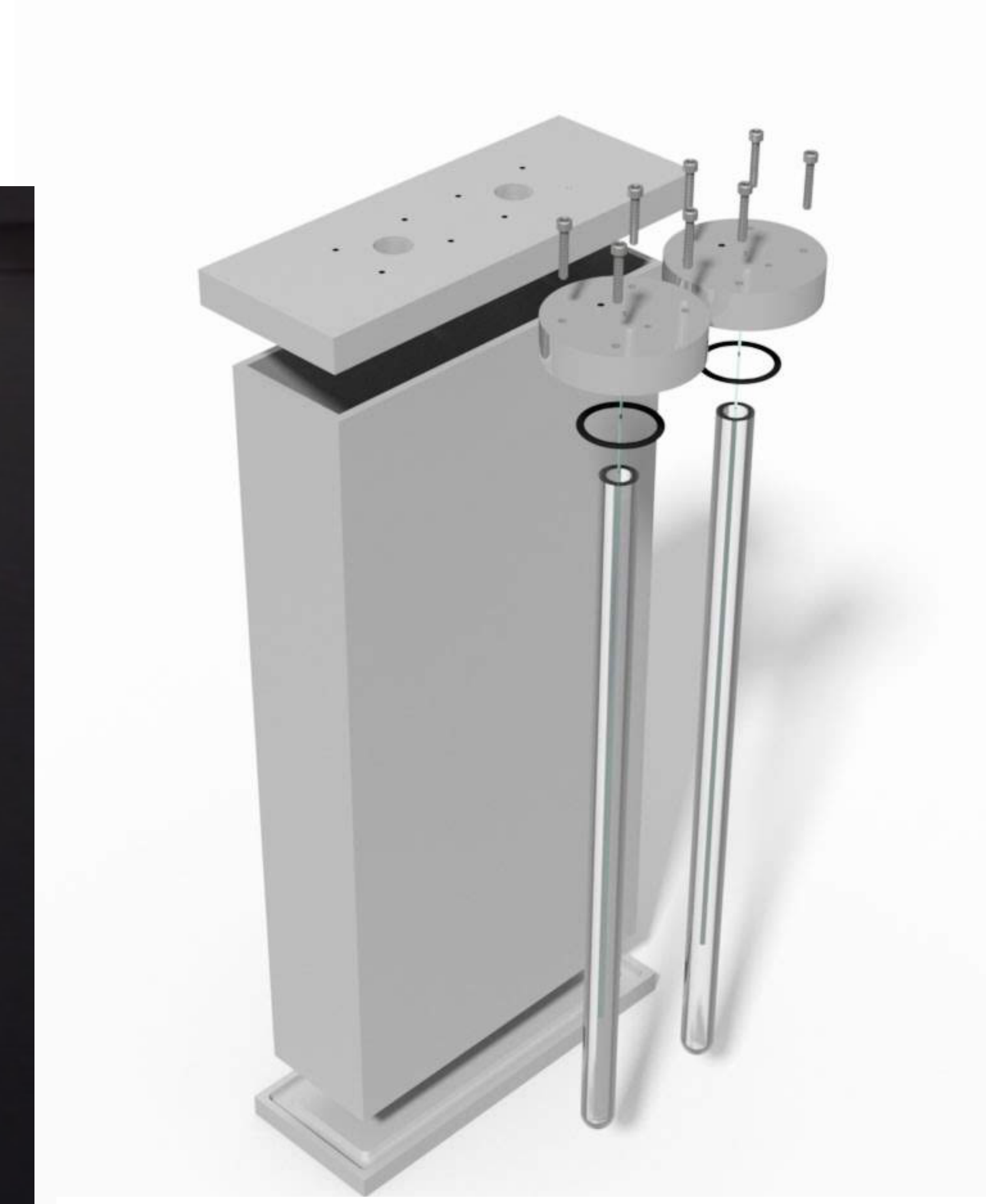
Key components: Liquid scintillator, wavelength shifting fiber, glass tube, SiPM

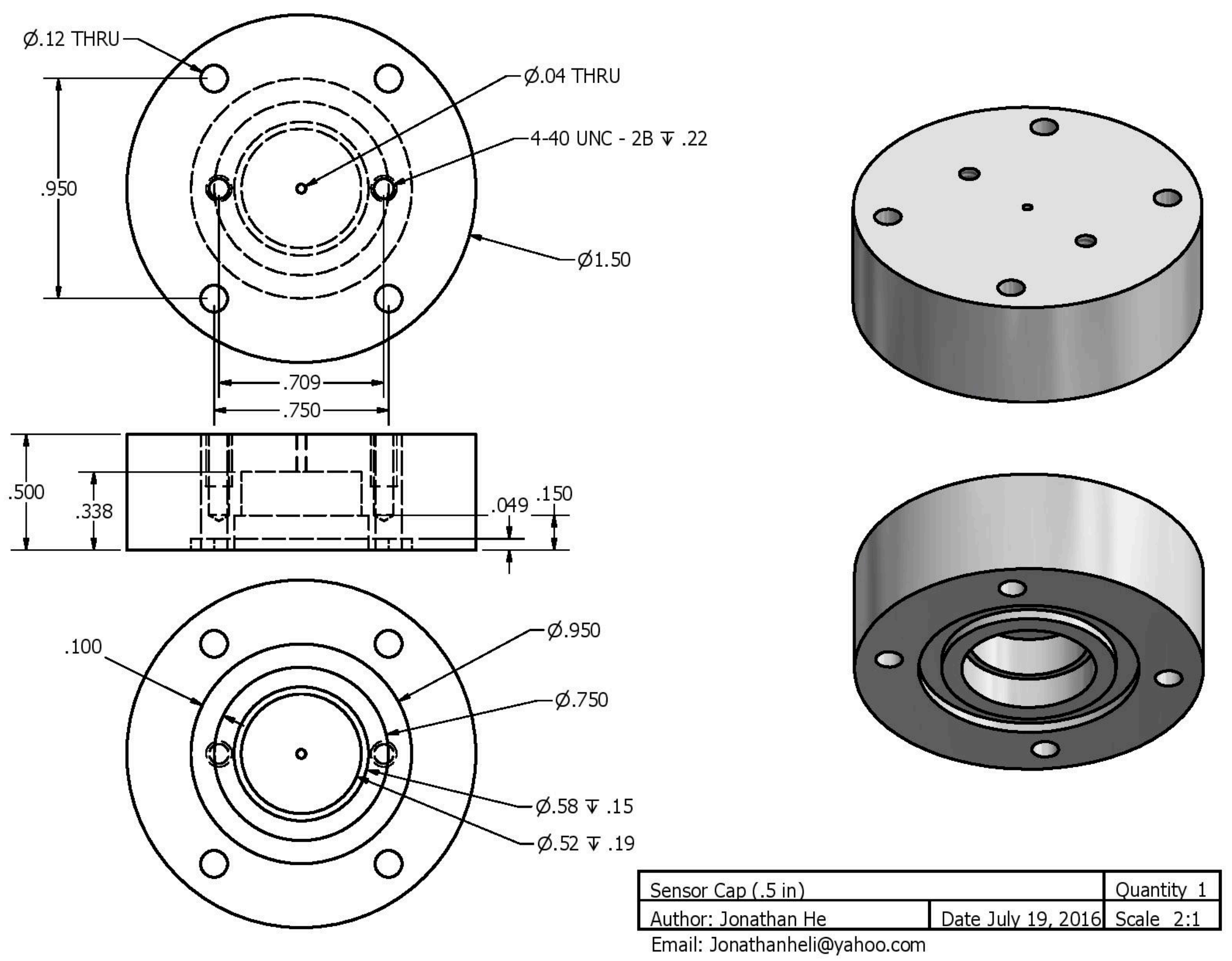
Neutron Detection with Better Design



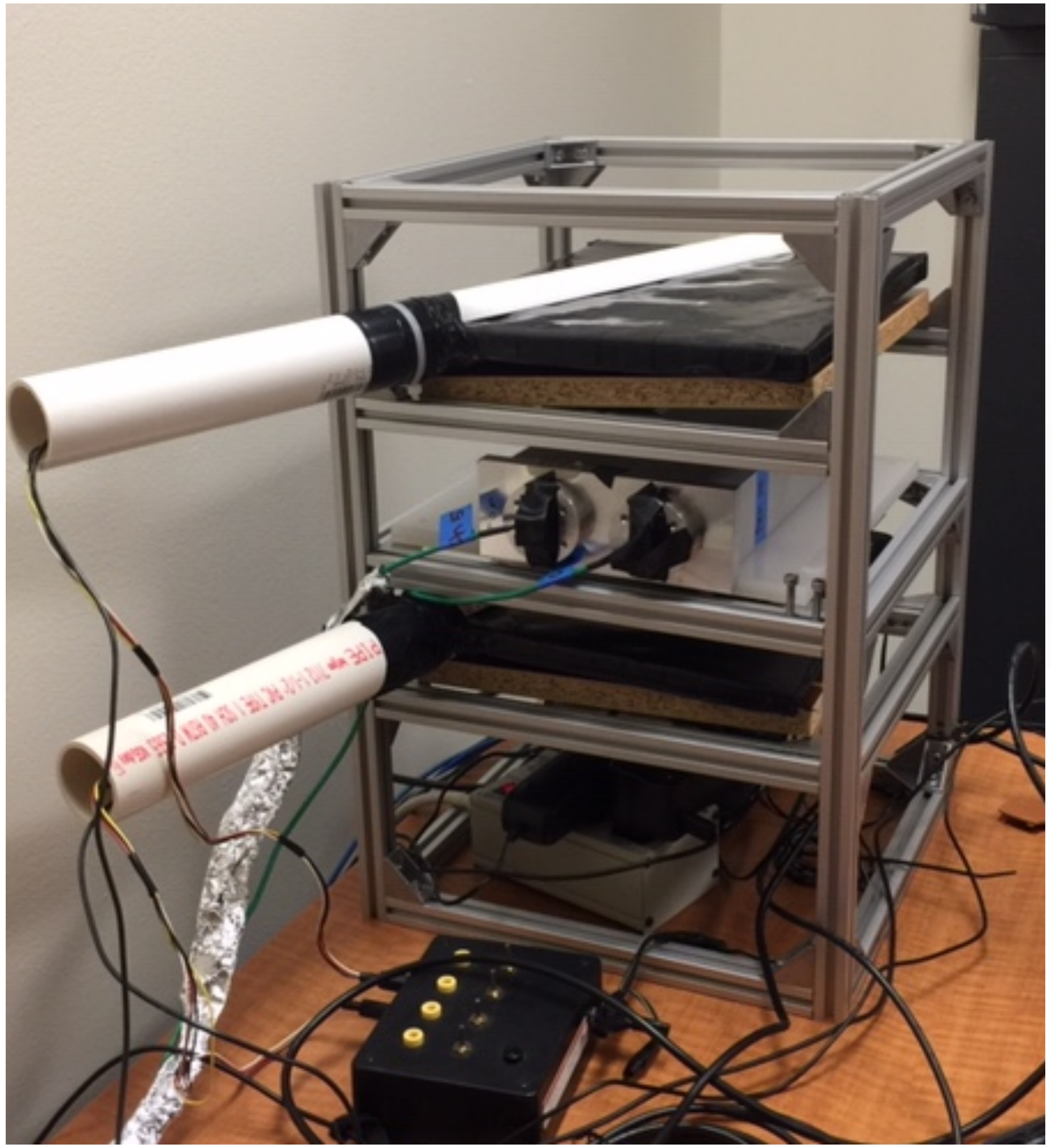
Neutron Detection with Better Design

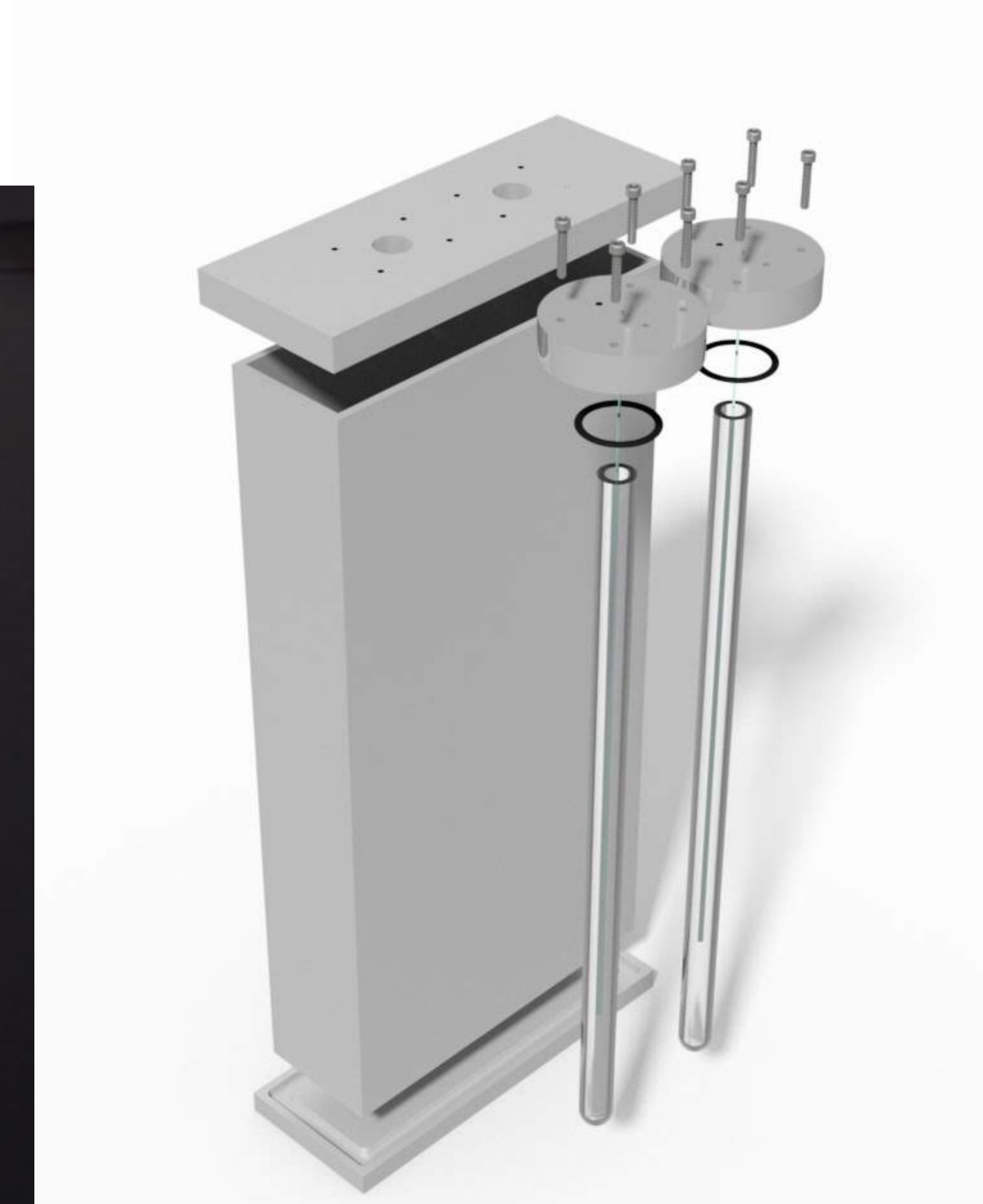


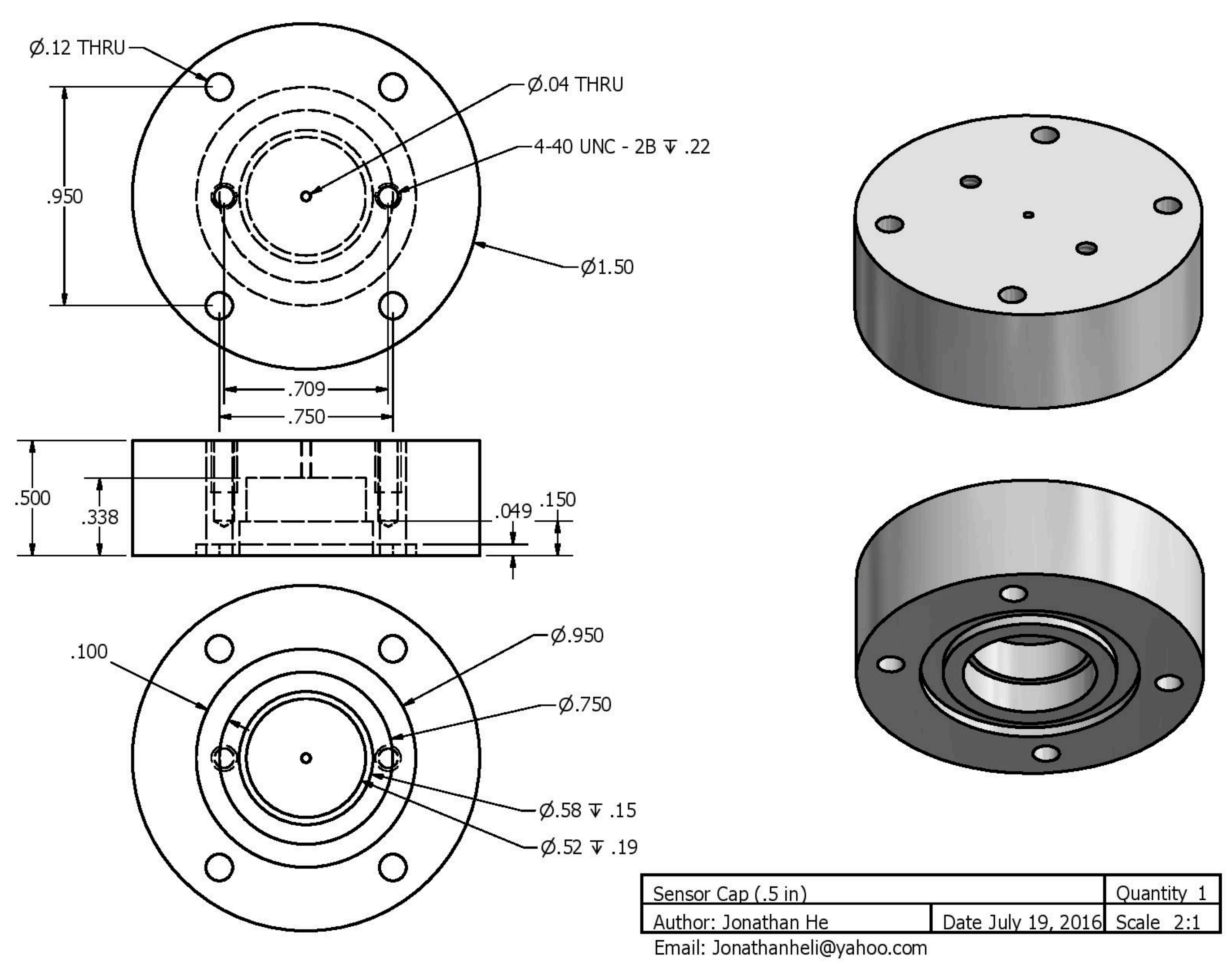


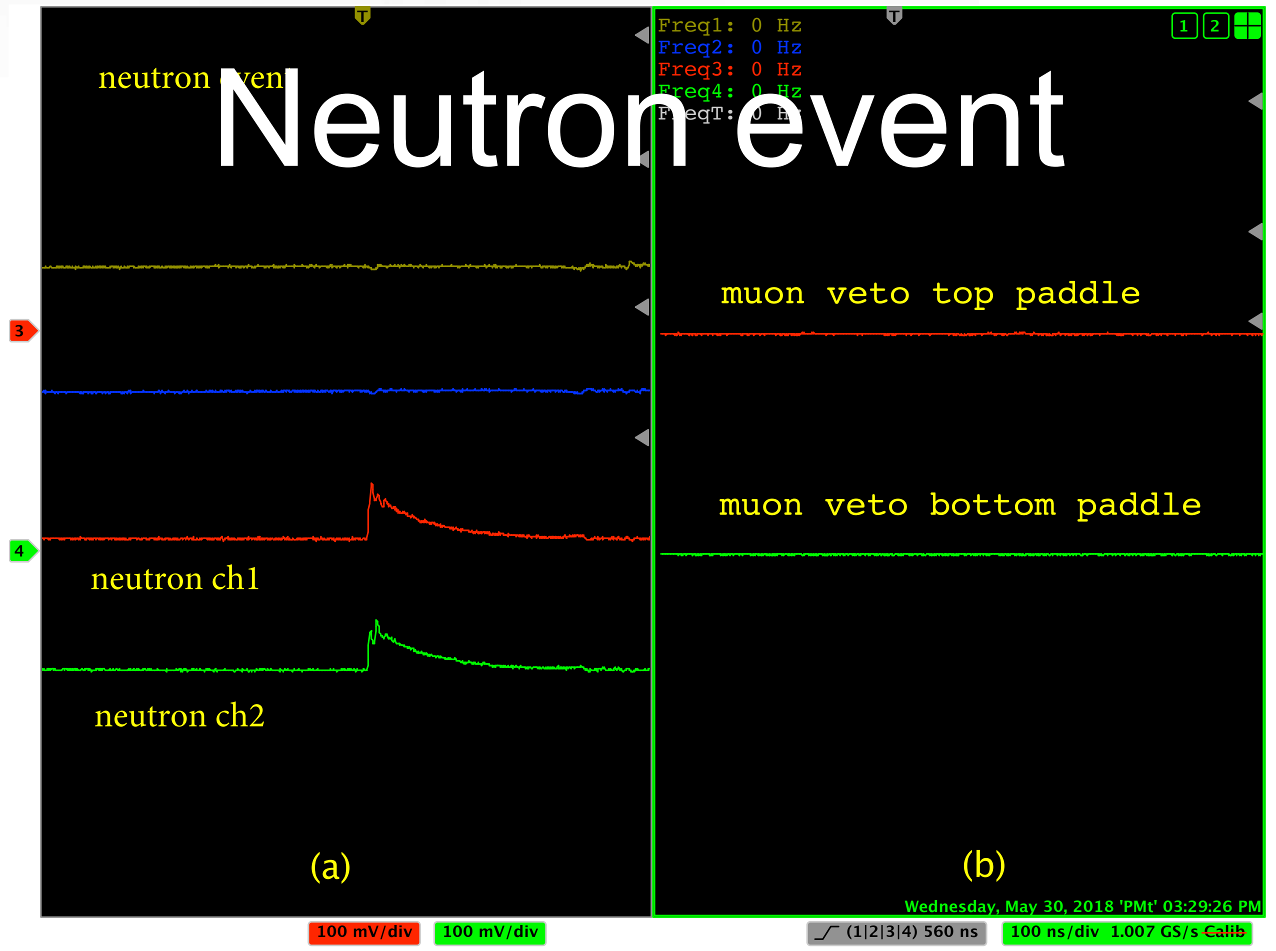


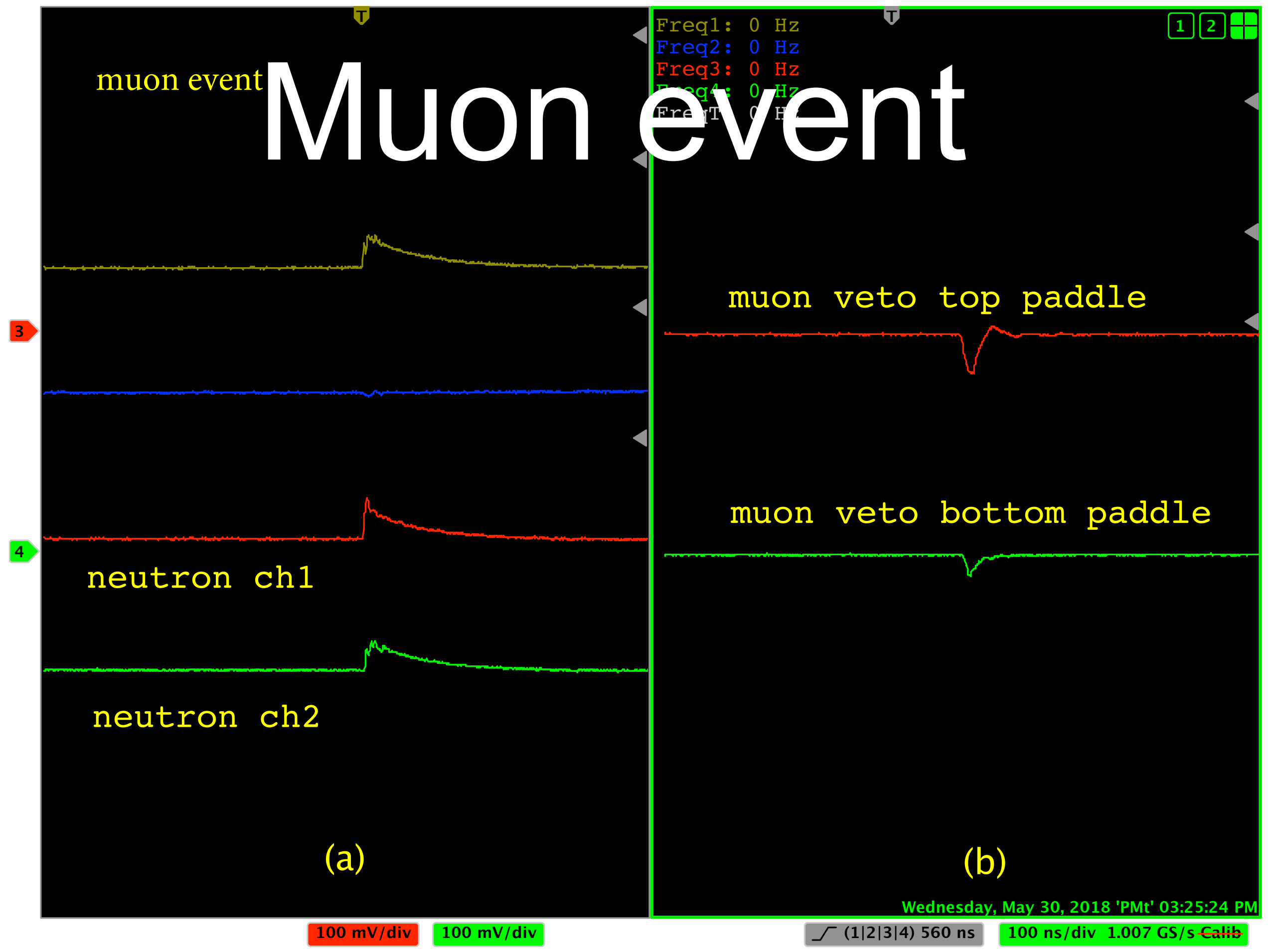
Neutron Detection with Better Design



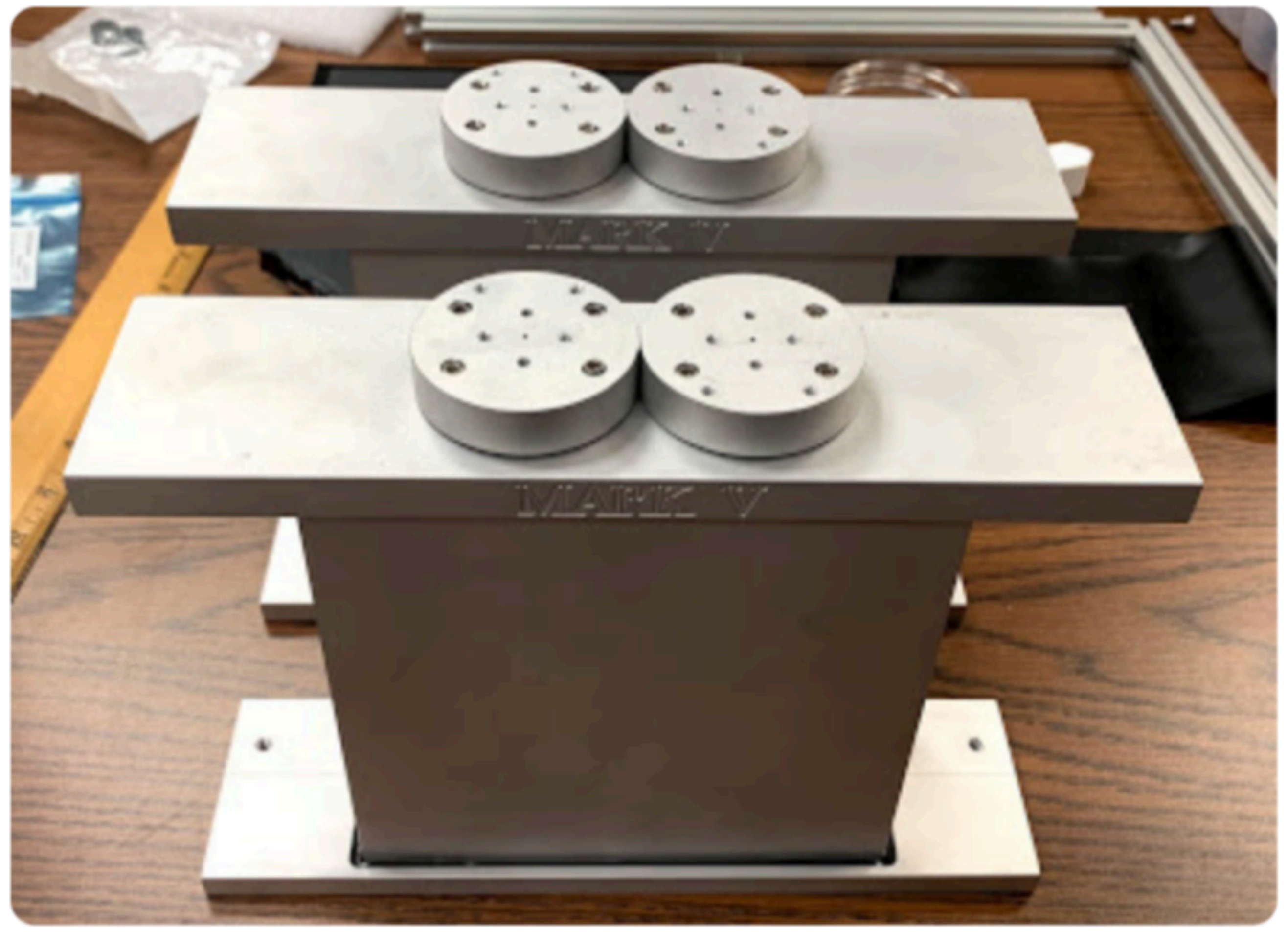


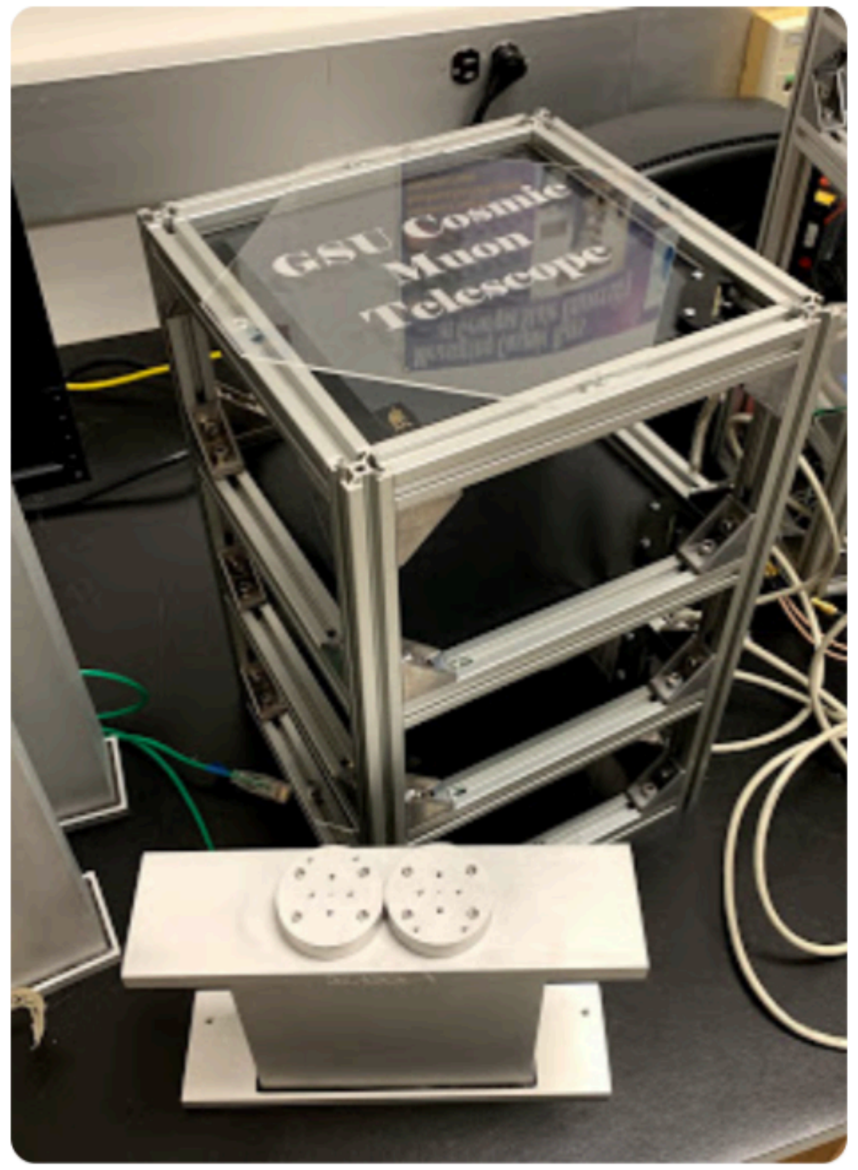


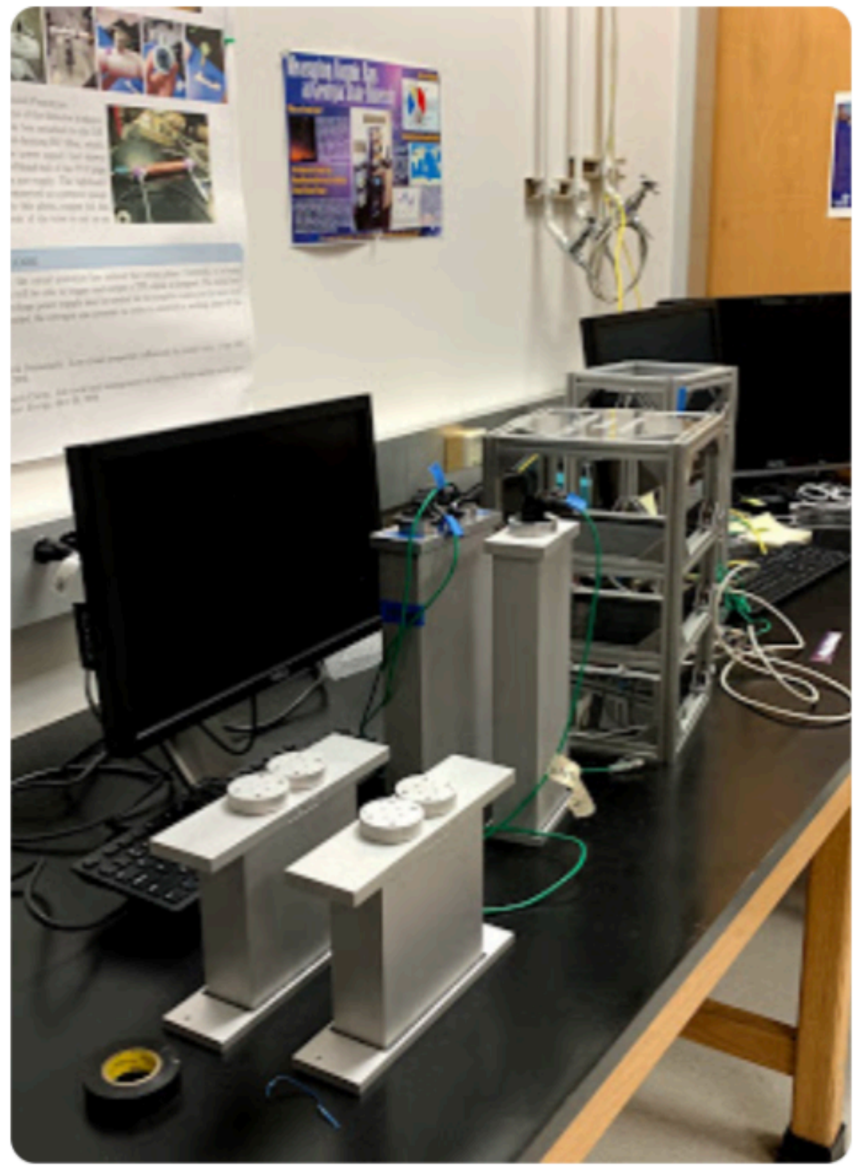




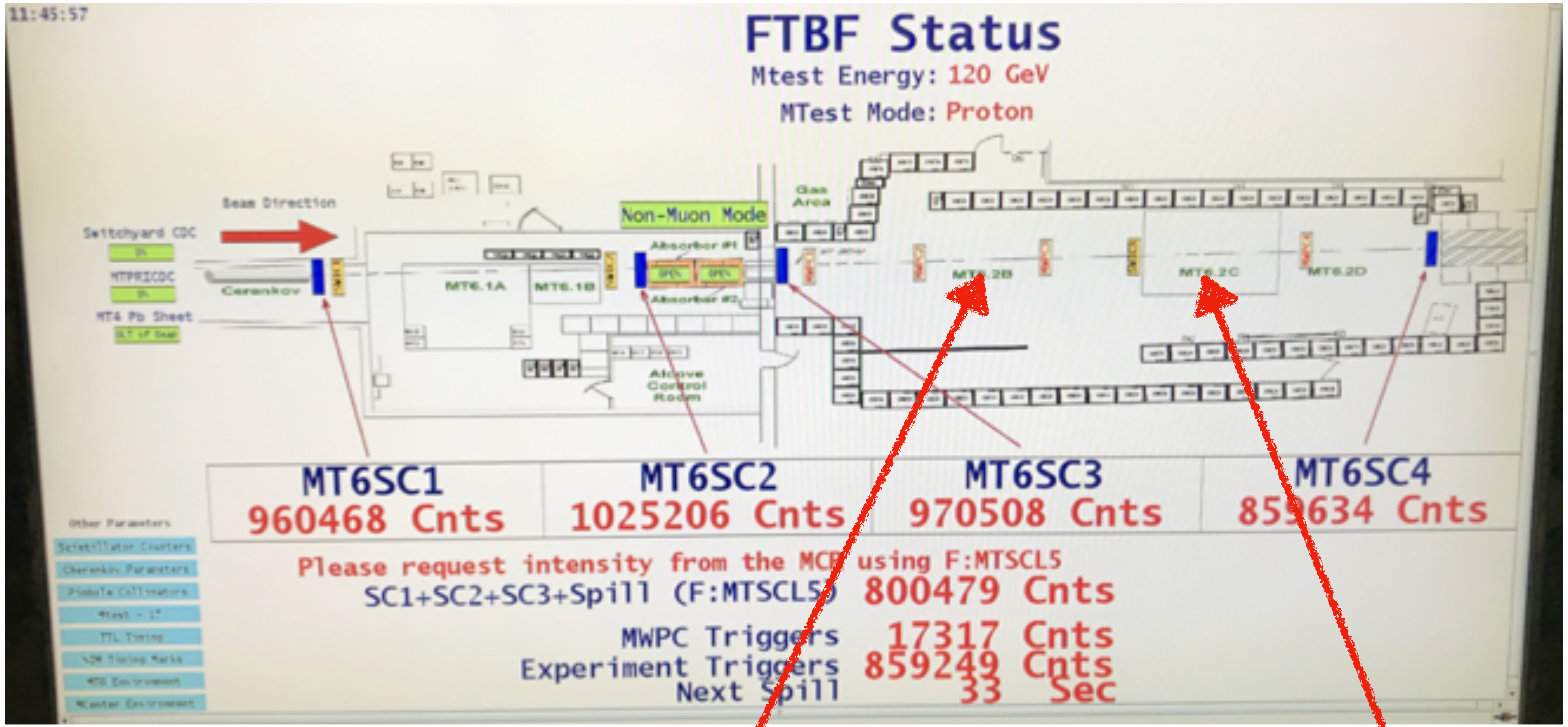
Cosmic Ray Muon/Neutron Telescope

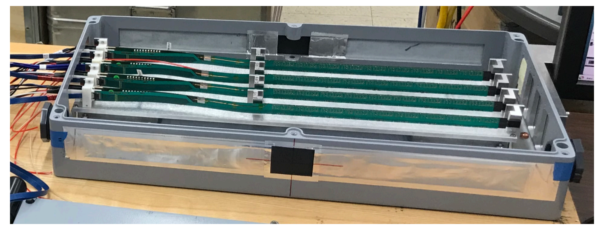



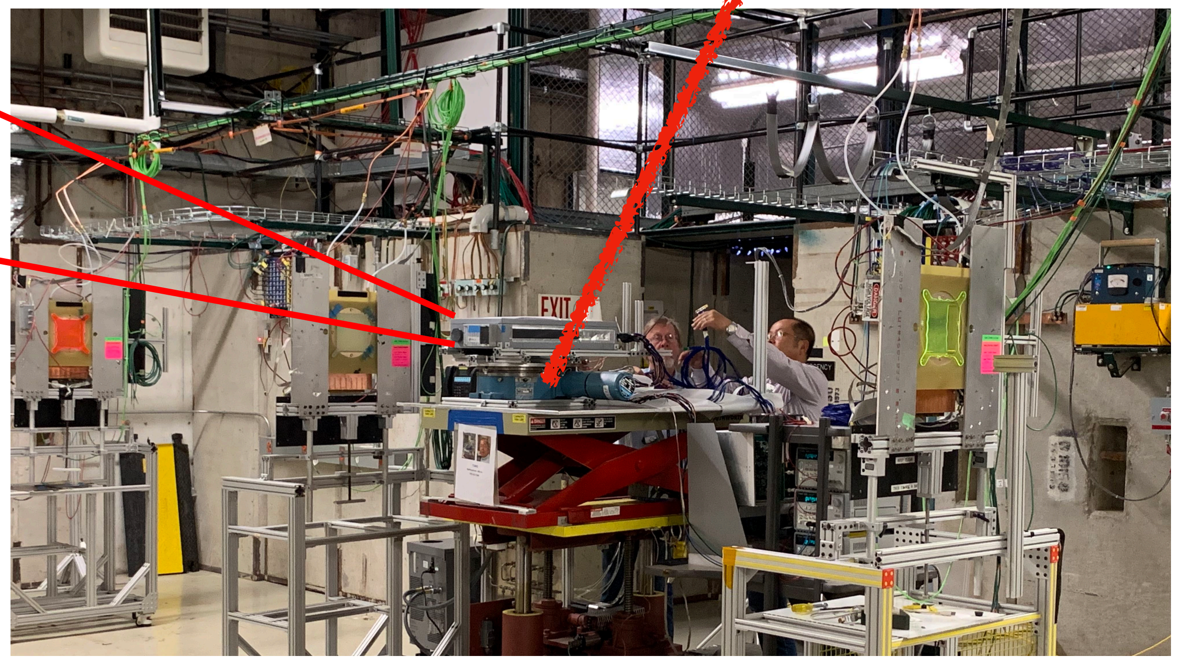





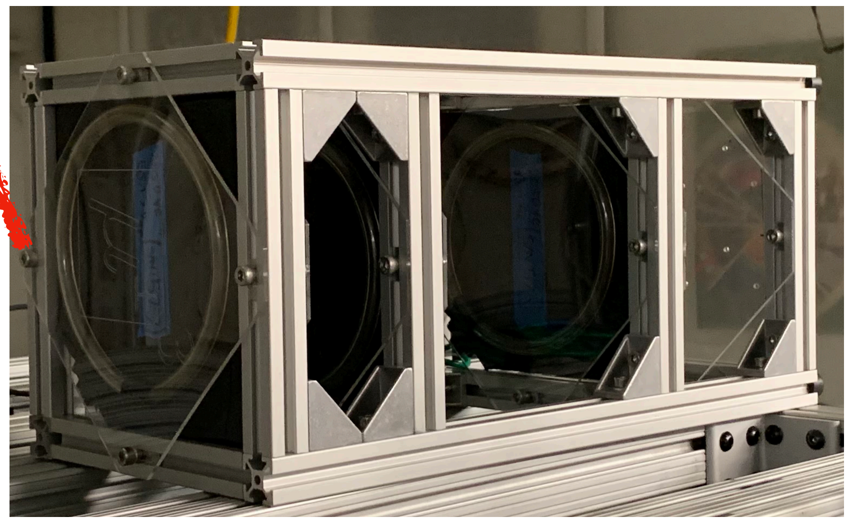

Recent Beam Test at Fermi National Accelerator Laboratory





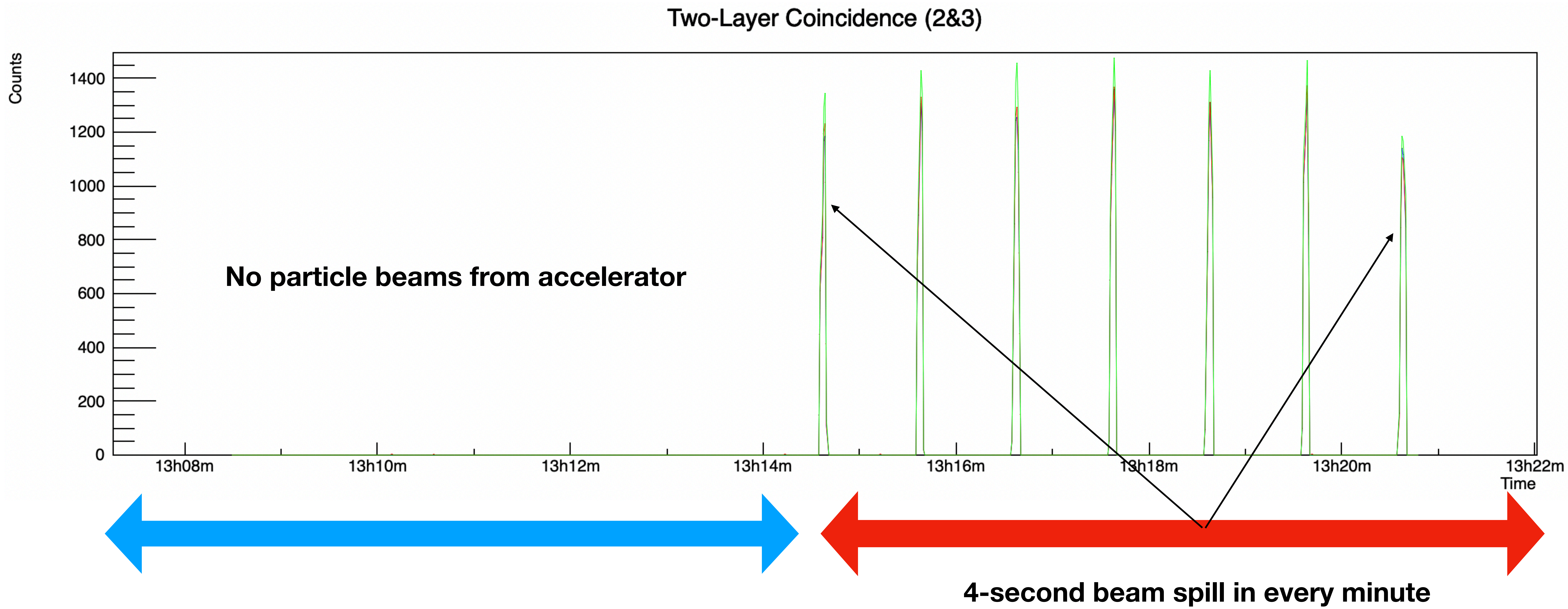


sPHENIX MVTX beam test

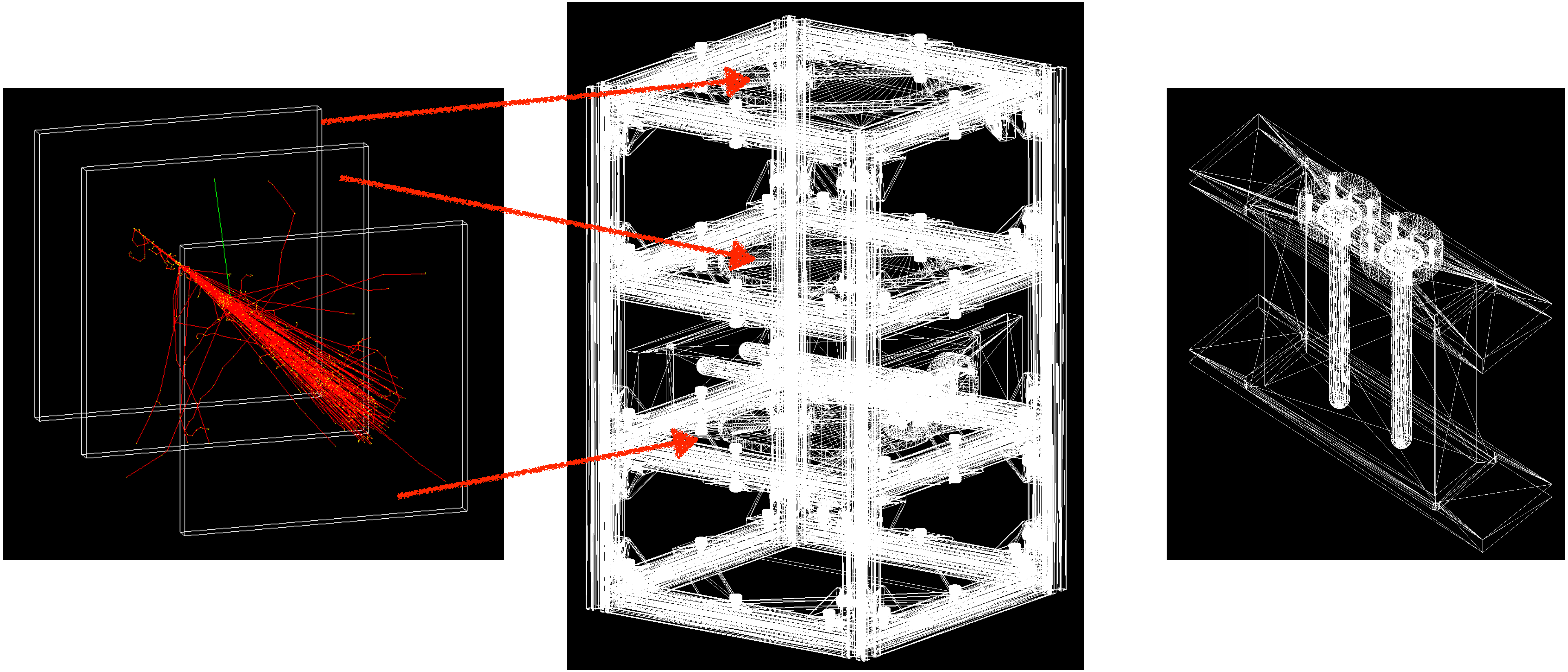


GSU muon telescope test

Muon Telescope Sees the Beam Structure



Detector Simulation Study Using GEANT4



BUILD A GLOBAL COSMIC RAY NETWORK FOR STUDYING THE CORRELATIONS BETWEEN THE COSMIC RAY FLUX VARIATIONS AND THE DYNAMICAL CHANGES OF THE EARTH AND SPACE WEATHER.

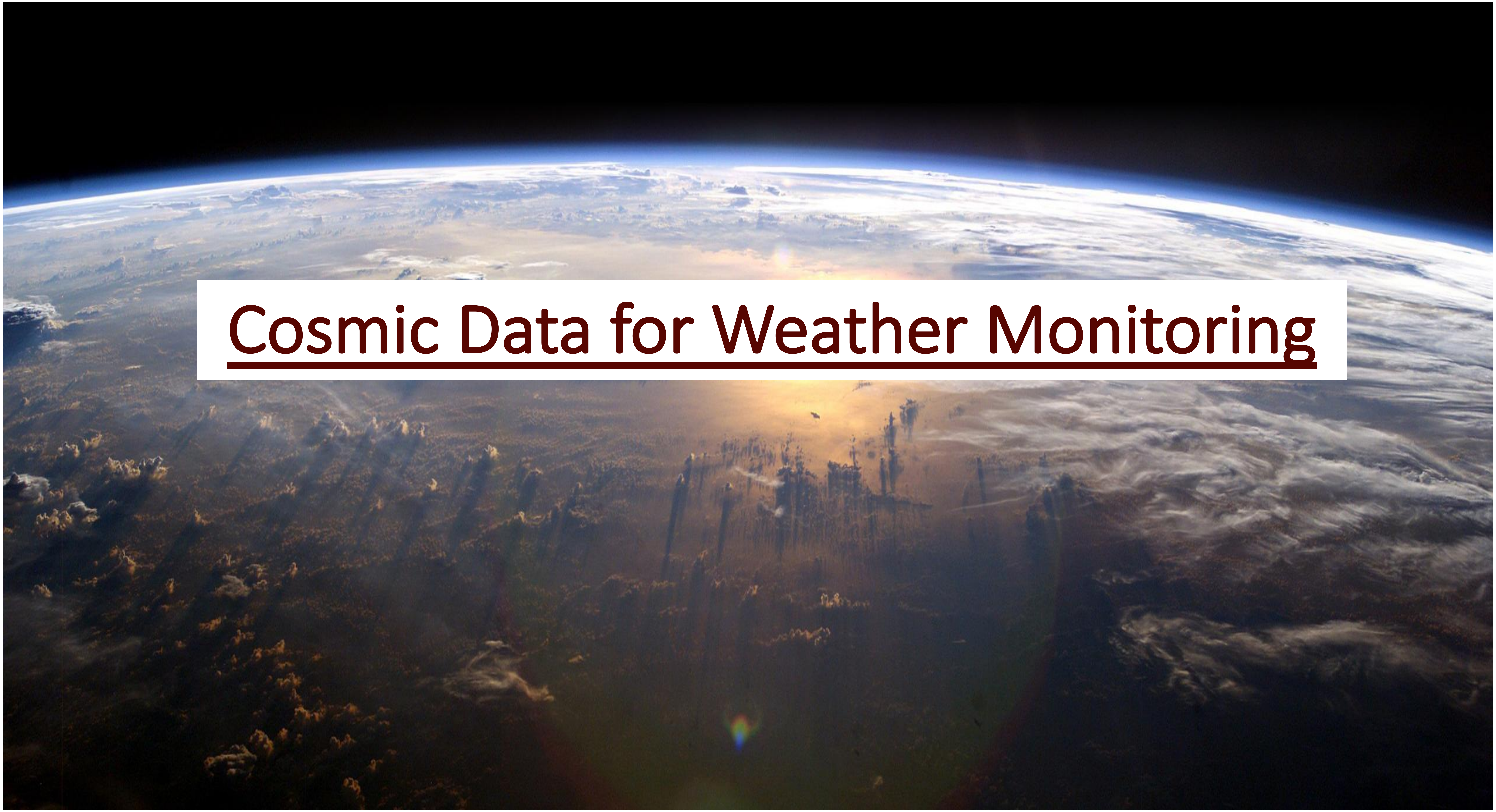
Understanding and Protecting the earth for a livable space for every walks of life

BUILD A GLOBAL COSMIC RAY NETWORK FOR STUDYING THE CORRELATIONS BETWEEN THE COSMIC RAY FLUX VARIATIONS AND THE DYNAMICAL CHANGES OF THE EARTH AND SPACE WEATHER.

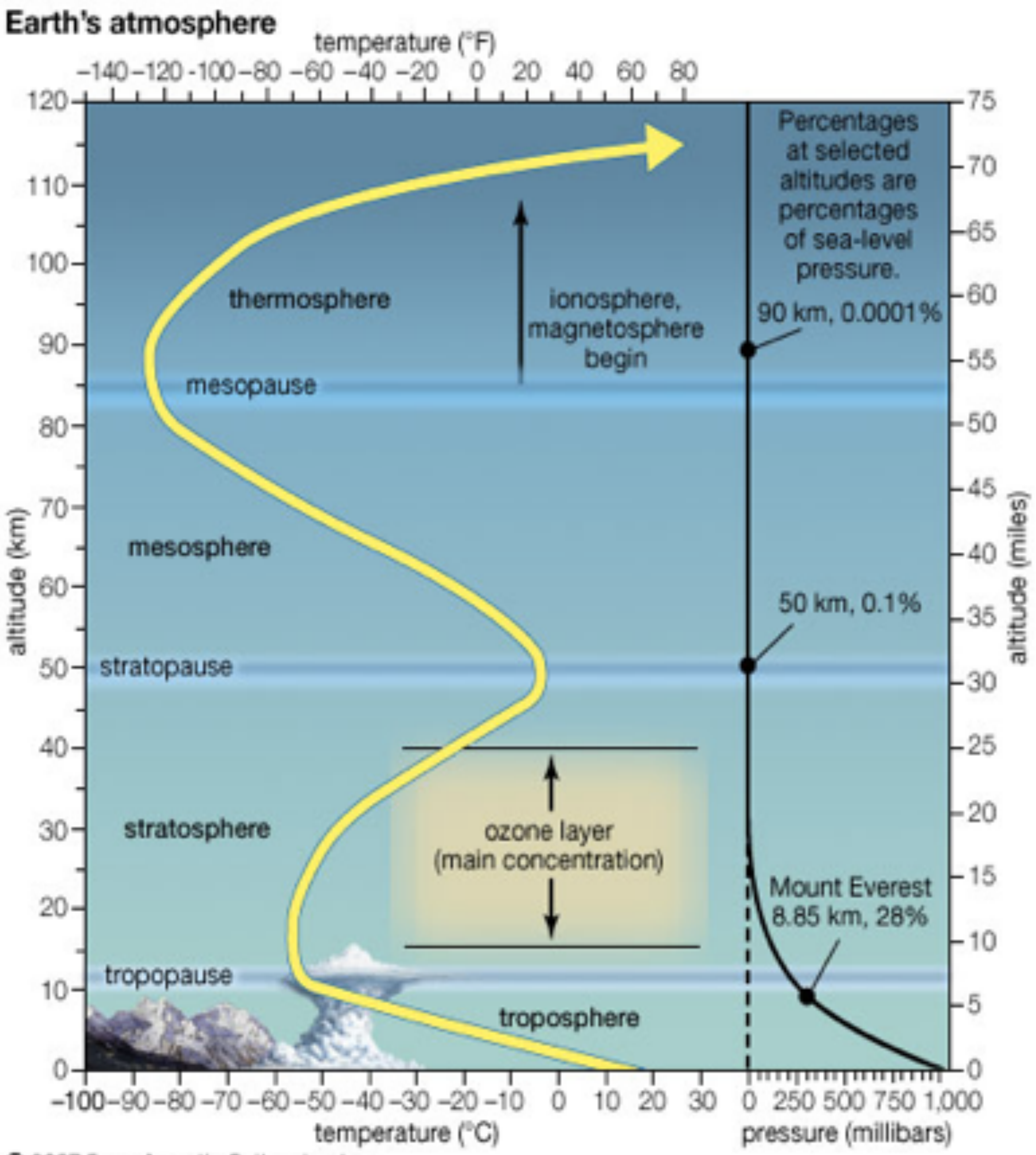
Understanding and Protecting the earth for a livable space for every walks of life

THANK YOU
And
Please Join the Projects

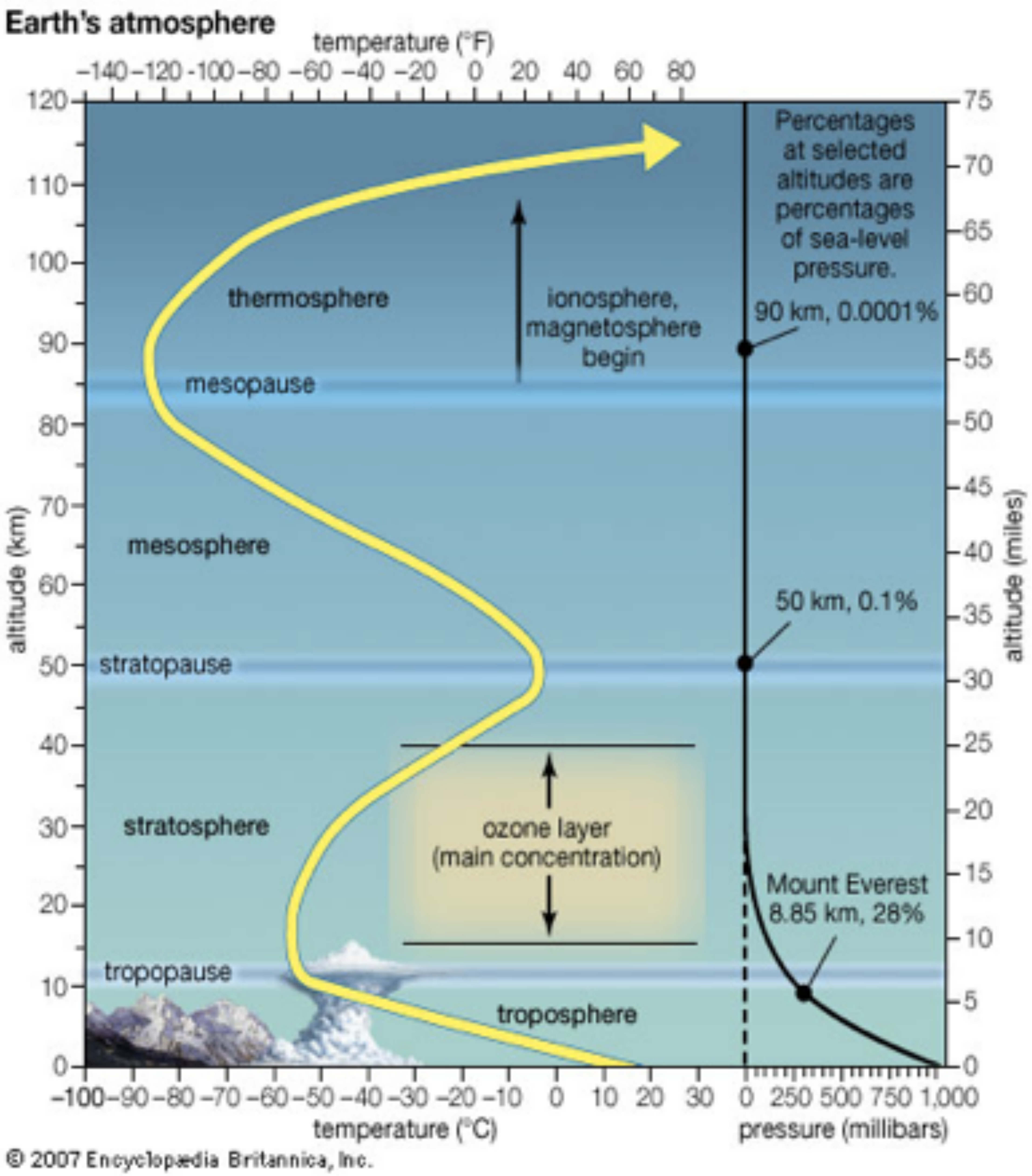
Cosmic Data for Weather Monitoring



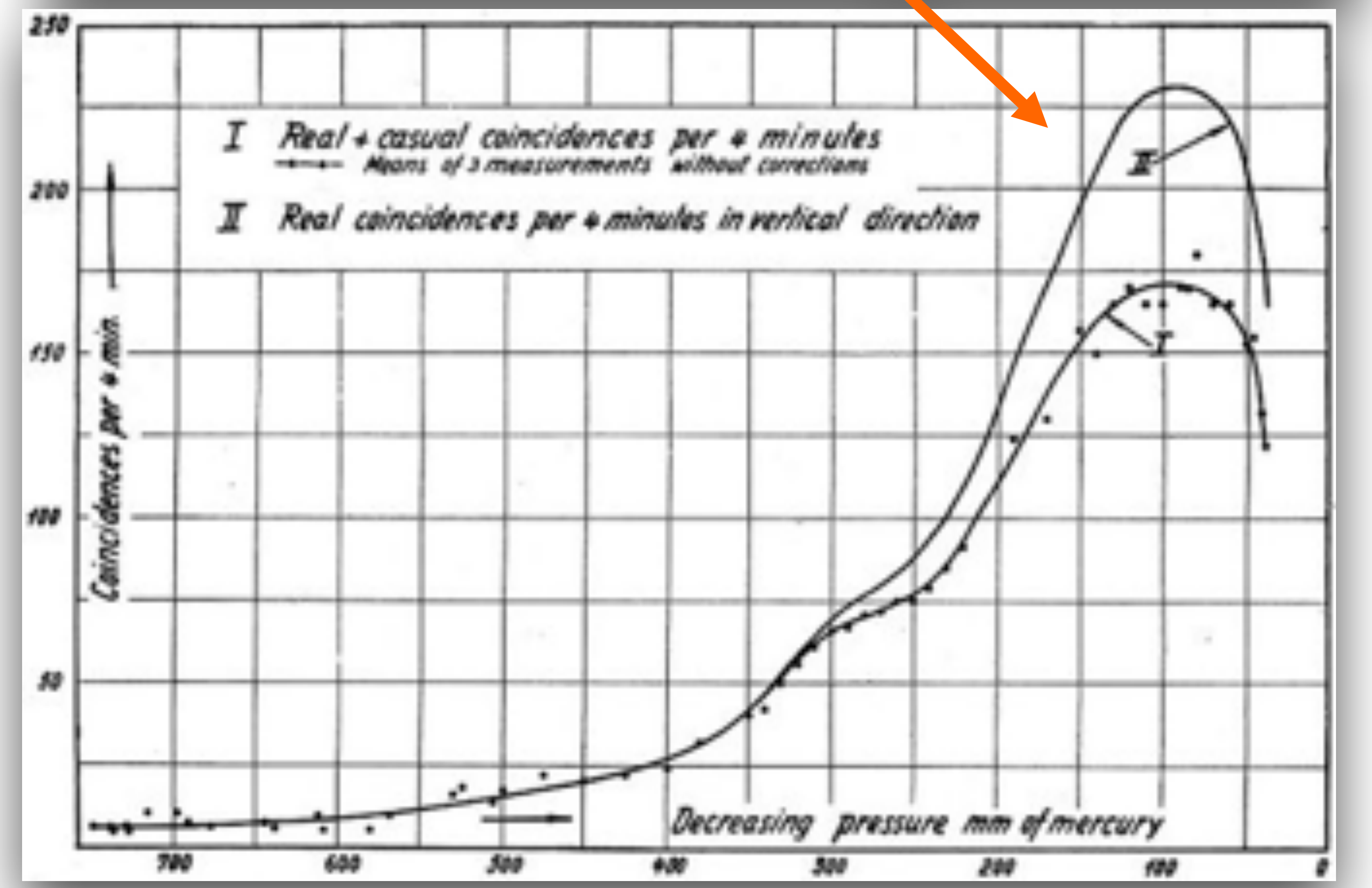
Working Principle



Working Principle

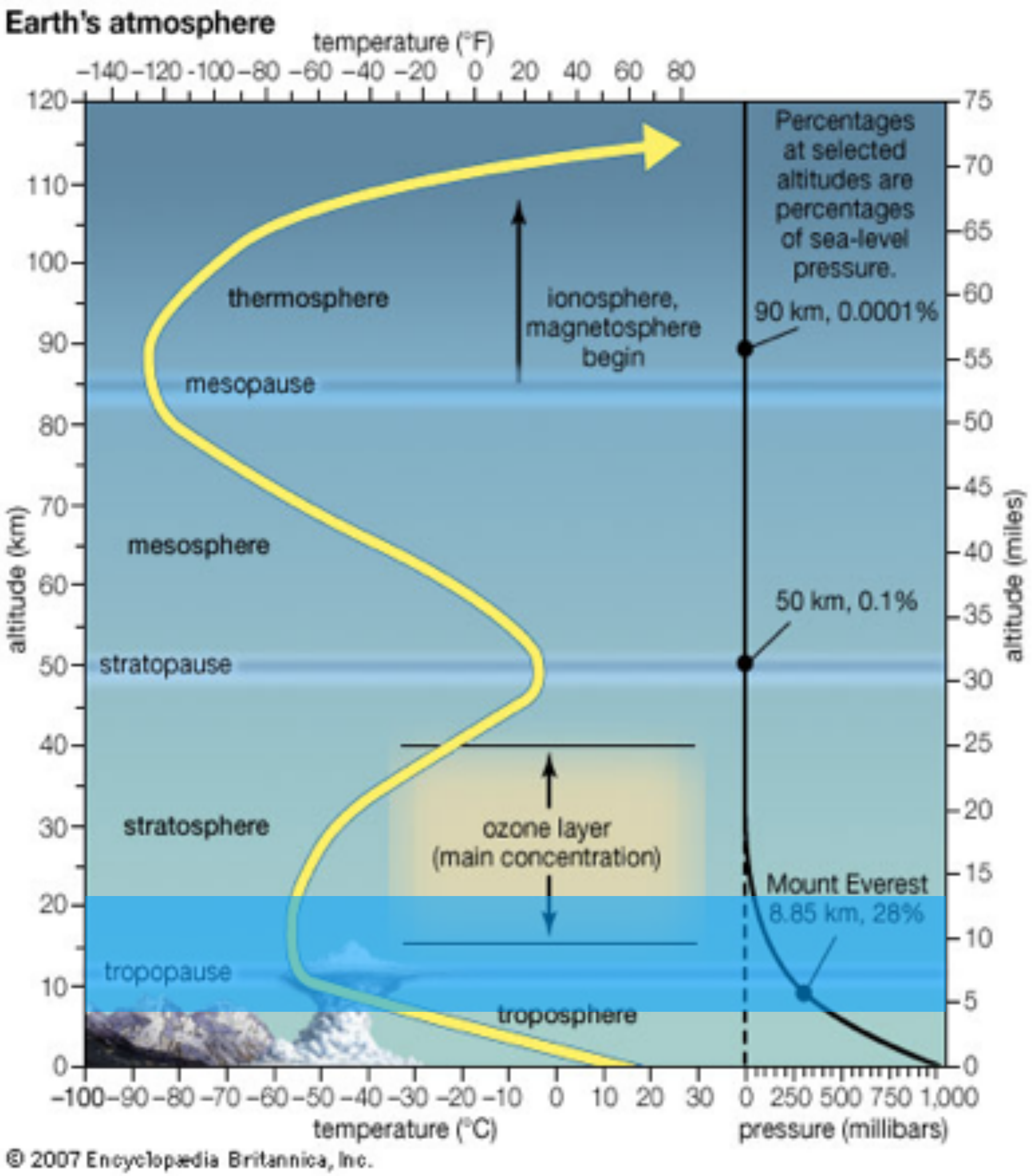


maximum between ~100 - 200 hPa

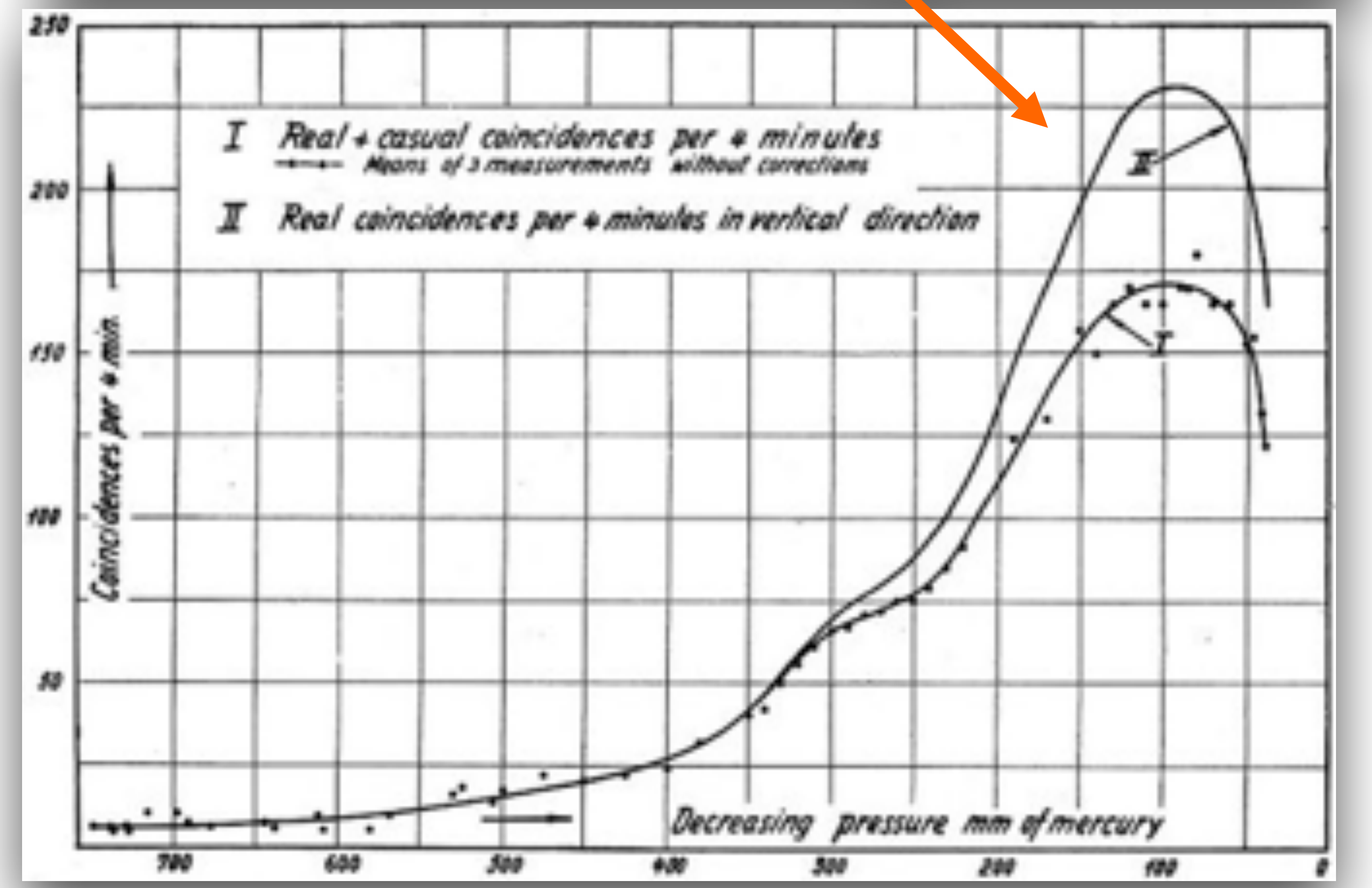


Pfotzer
1936

Working Principle

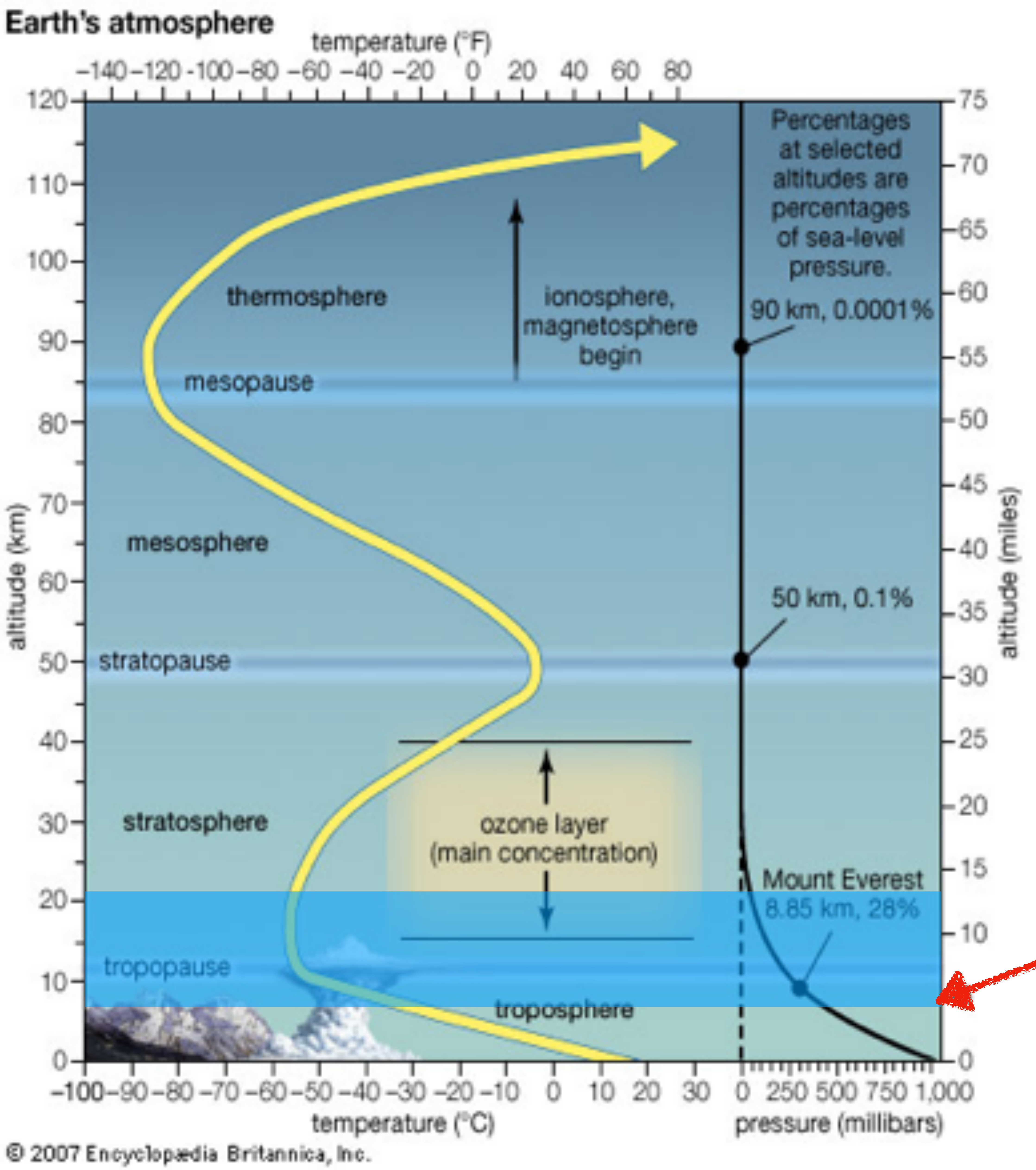


maximum between ~100 - 200 hPa

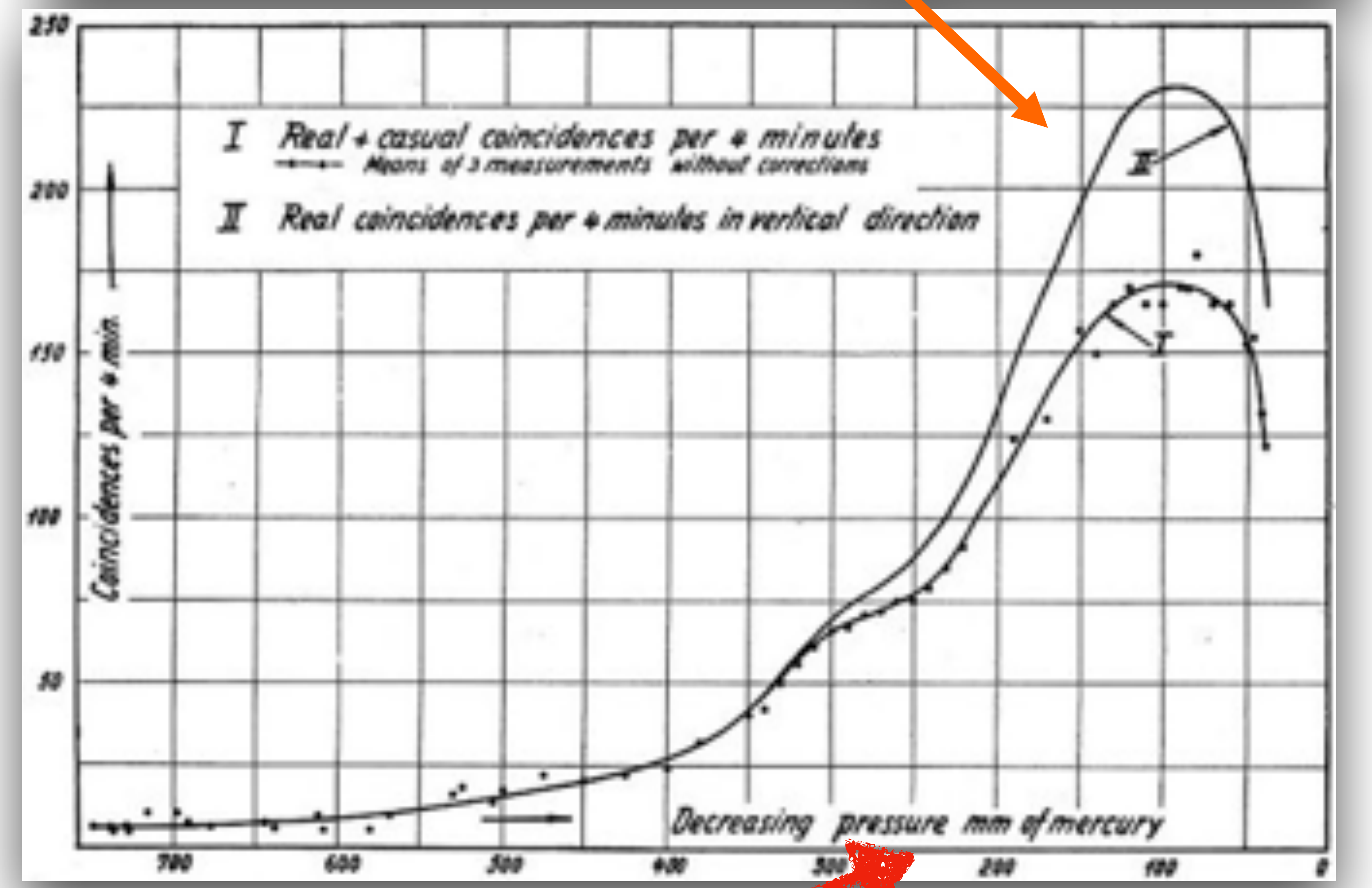


Pfotzer 1936

Working Principle

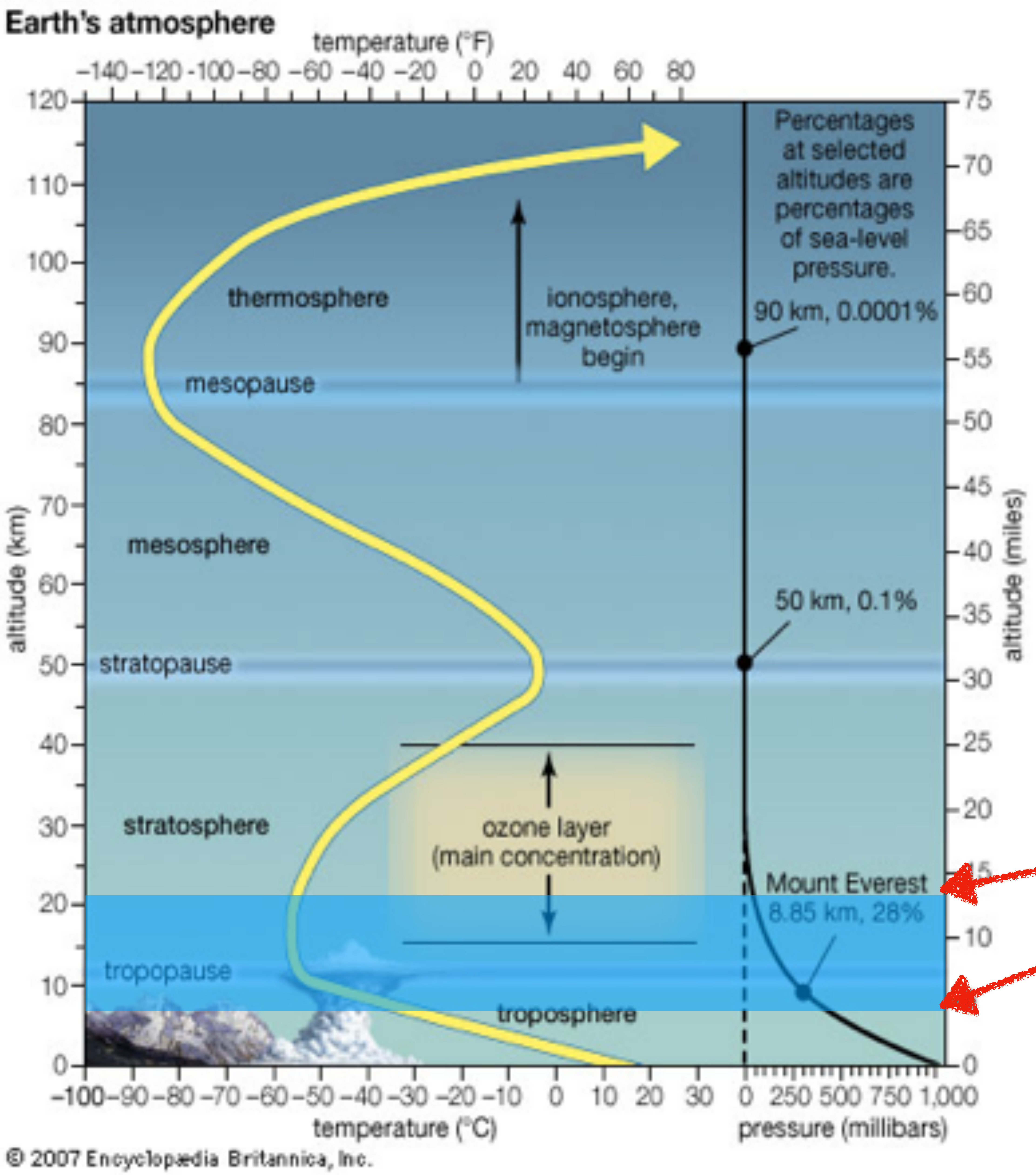


maximum between ~100 - 200 hPa



Pfotzer
1936

Working Principle



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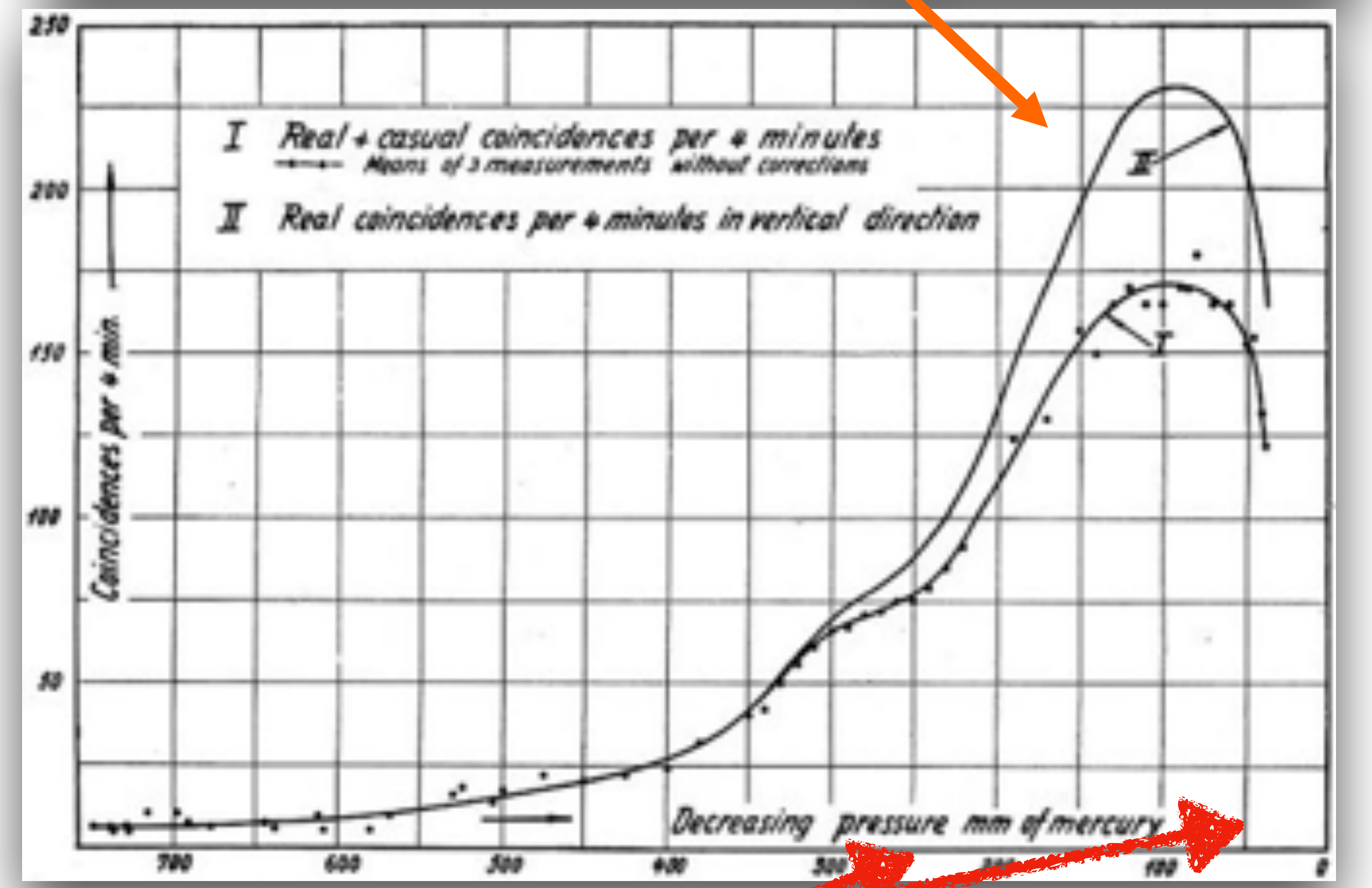
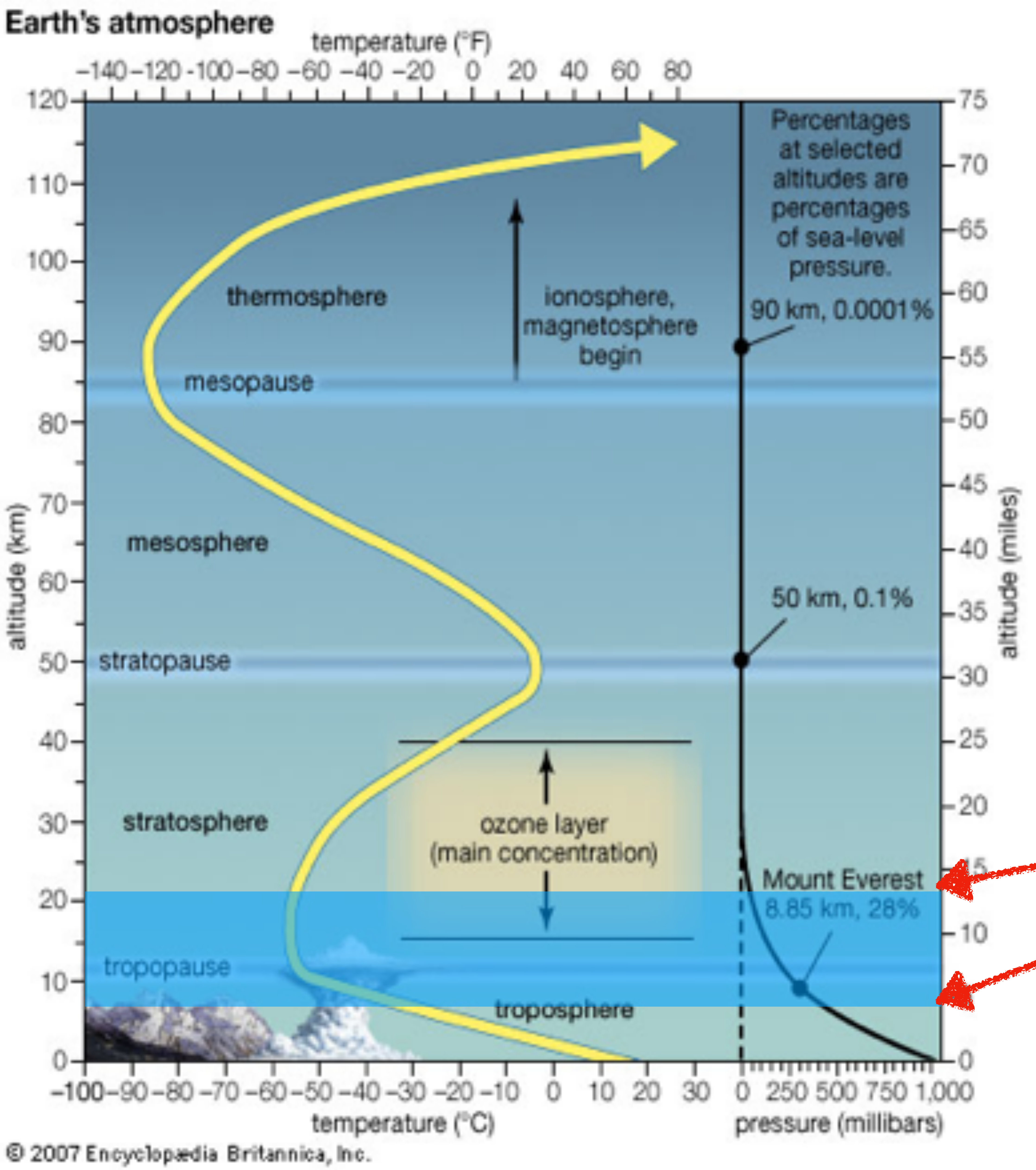


Pfotzer 1936

Working Principle



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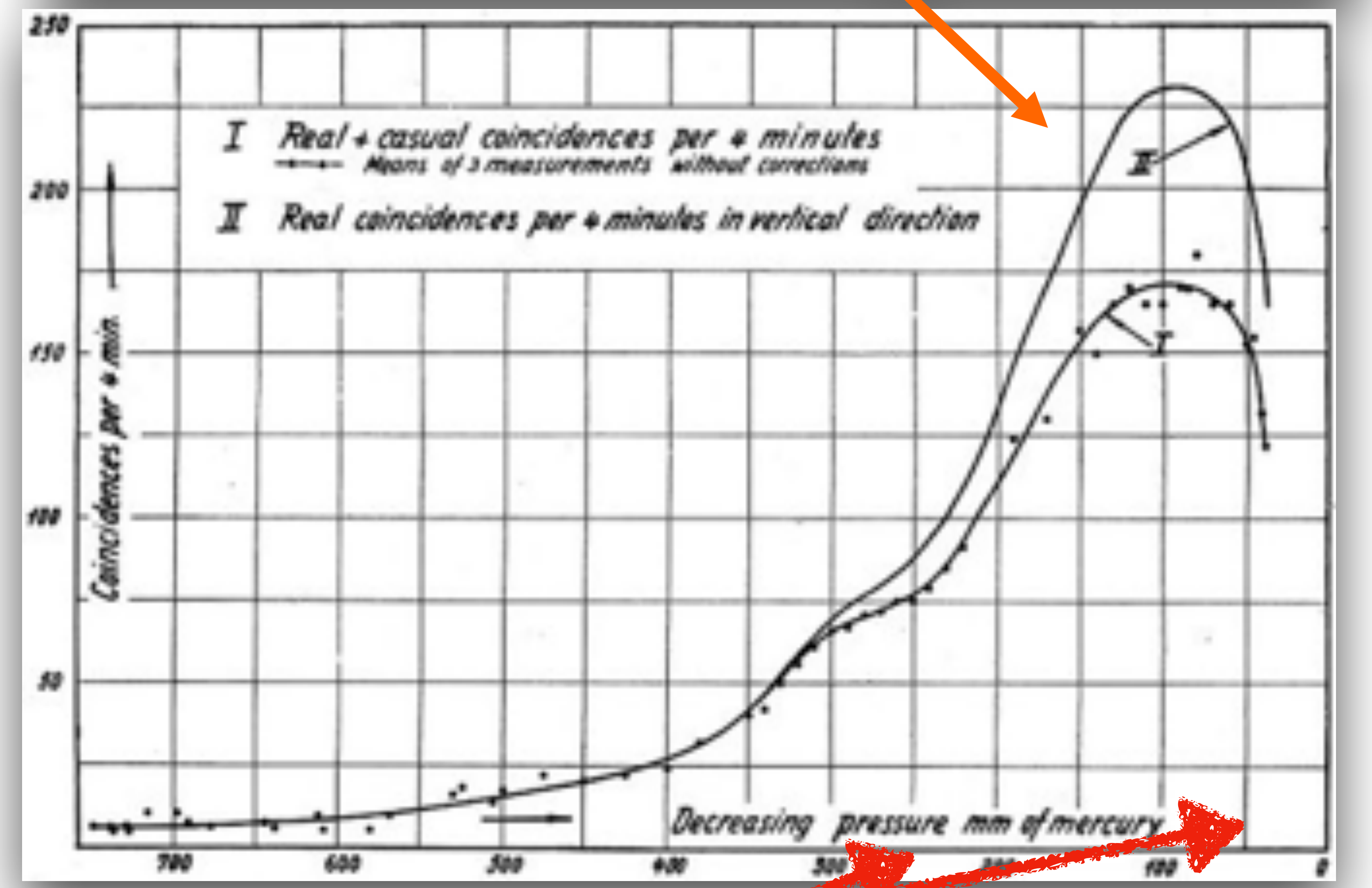
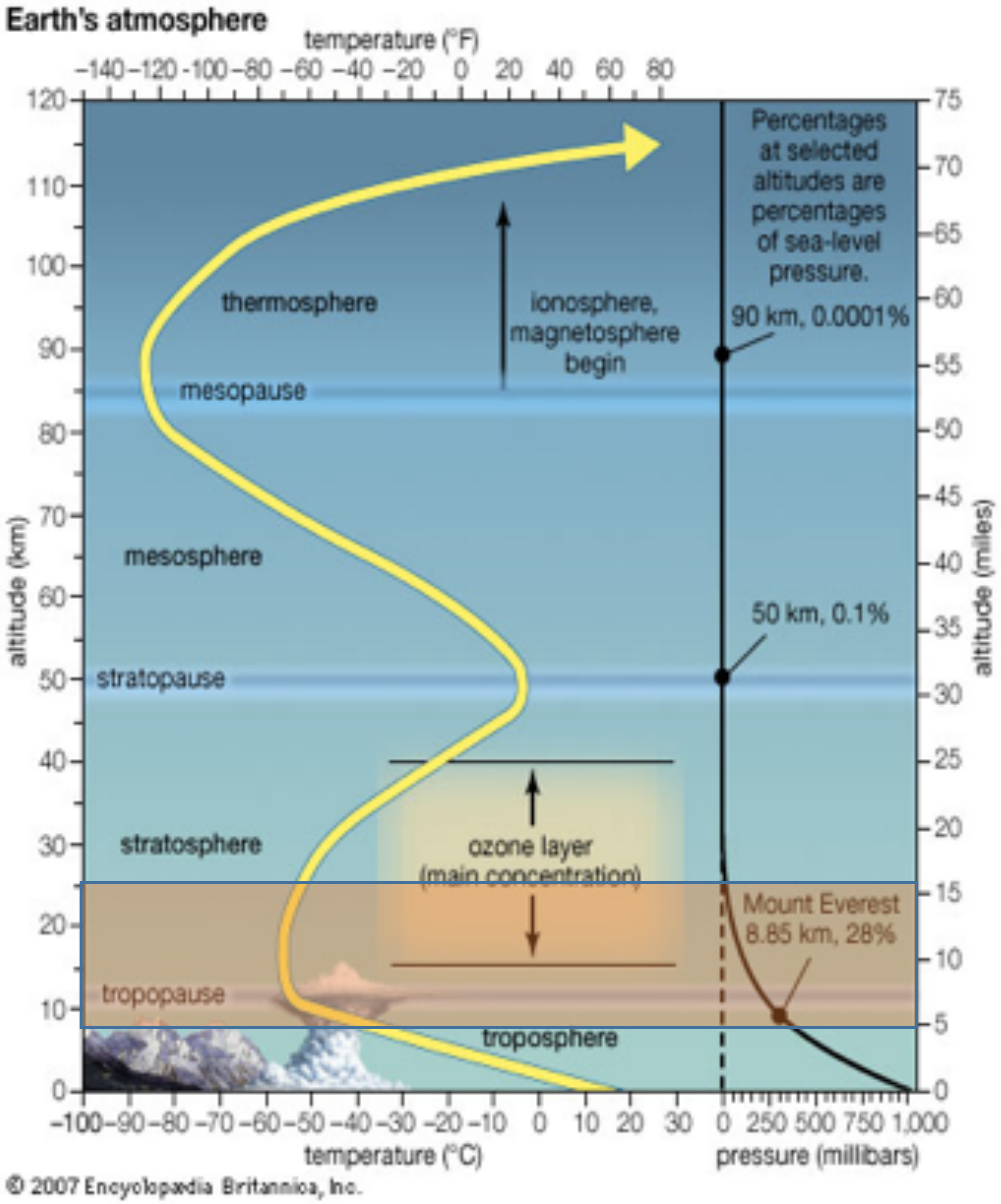


Pfotzer 1936

- Most of the muons are produced in upper troposphere - lower stratosphere region **[UT-LS]**
- **Change in temperature→ Change in air density →Muon flux variation**

Determining the Effective Temperature



$$T_{eff} = \frac{\int_{x=0}^{\infty} T(X)W(X)dX}{\int_{x=0}^{\infty} W(X)d(X)}$$

T(x): Temperature at atmospheric depth X

W(x): Weight of atmospheric depth X

depends on particle production at that depth

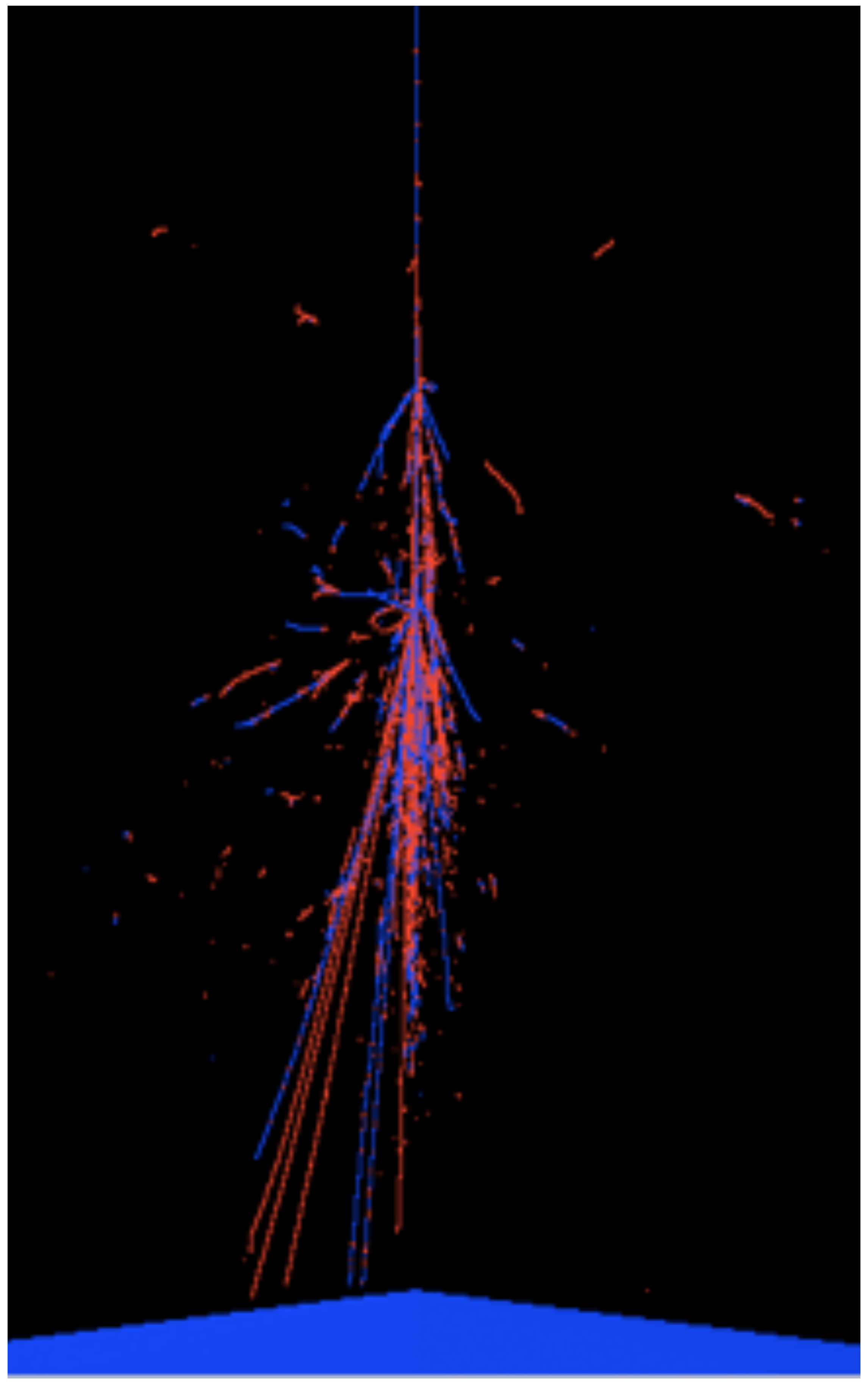
$$\frac{\delta I_\mu}{I_\mu^0} = \alpha_T \frac{\delta T_{eff}}{T_{eff}}$$

α_T =Temperature Coefficient:

20Km

15Km

0Km



Cosmic Rays as Temperature Gauge

Procedure:

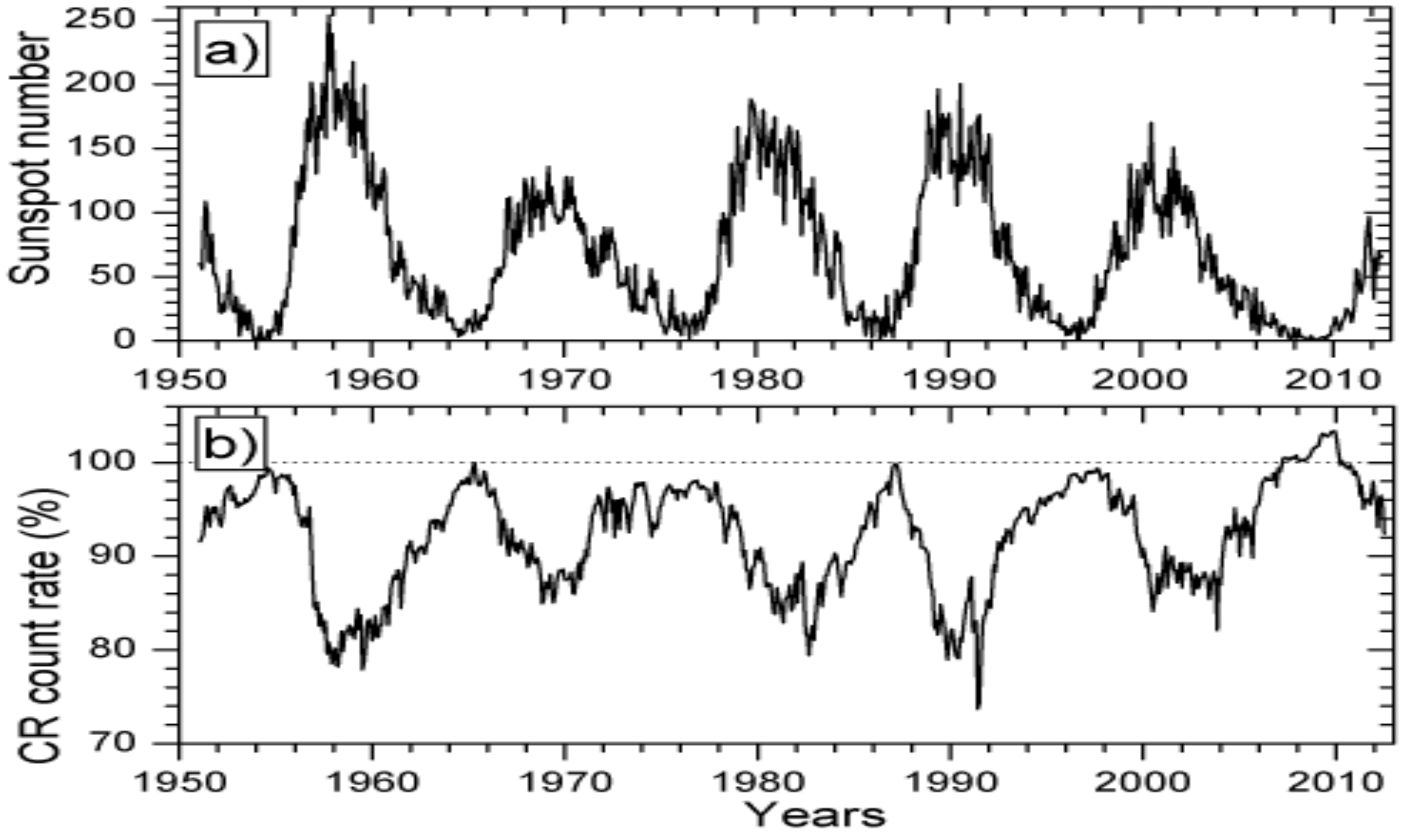
$$\delta I_\mu = f(\delta T_{eff}, \delta P, \delta I_N)$$

$$\delta T_{eff} = g(\delta I_\mu, \delta I_N, \delta P)$$

[Atmospheric effects]

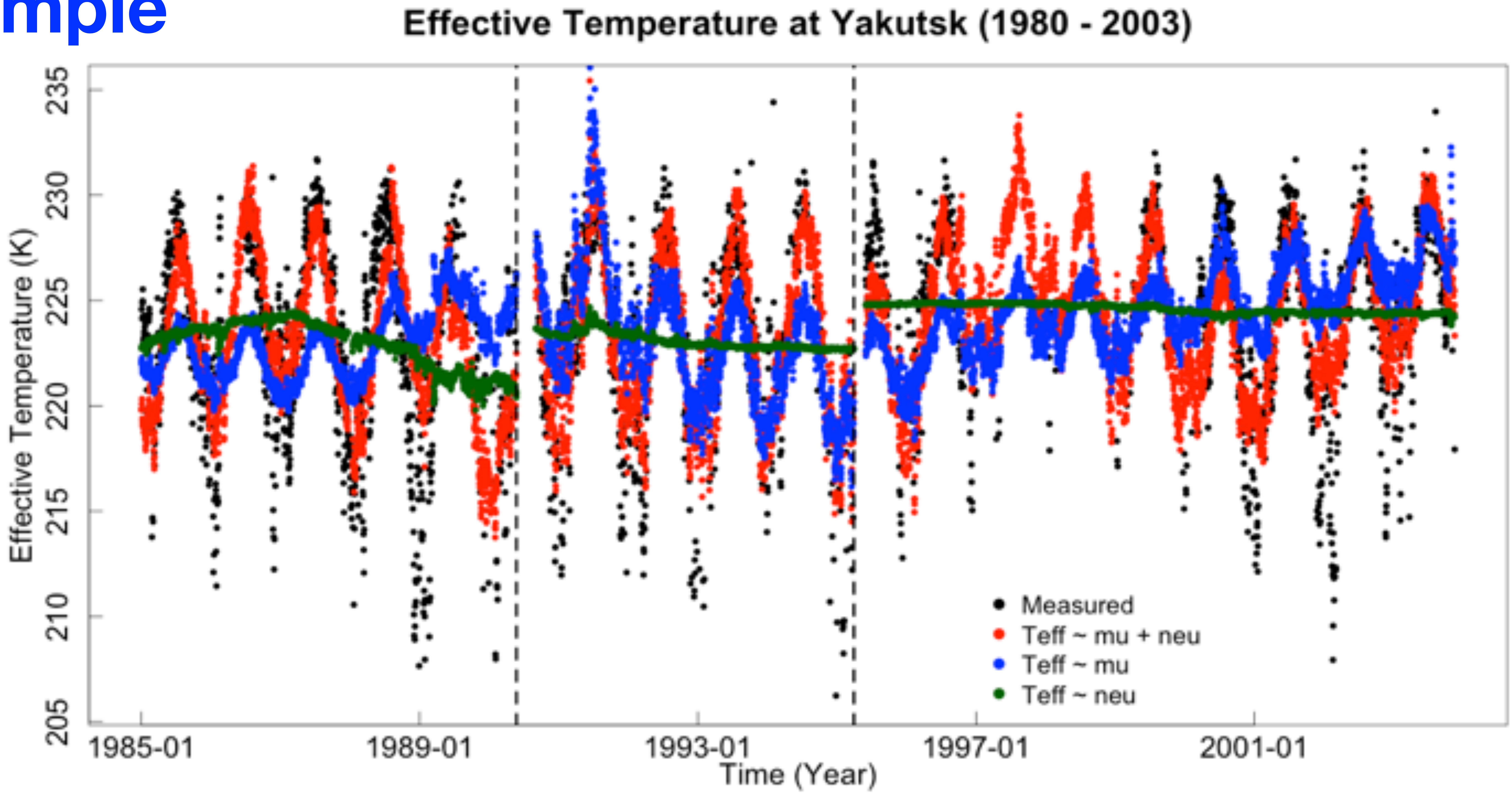
δP: Change in air pressure

δI_N: *Neuton Flux variation* (to correct the solar effects and primary particle fluctuation) [Extraterrestrial effects]



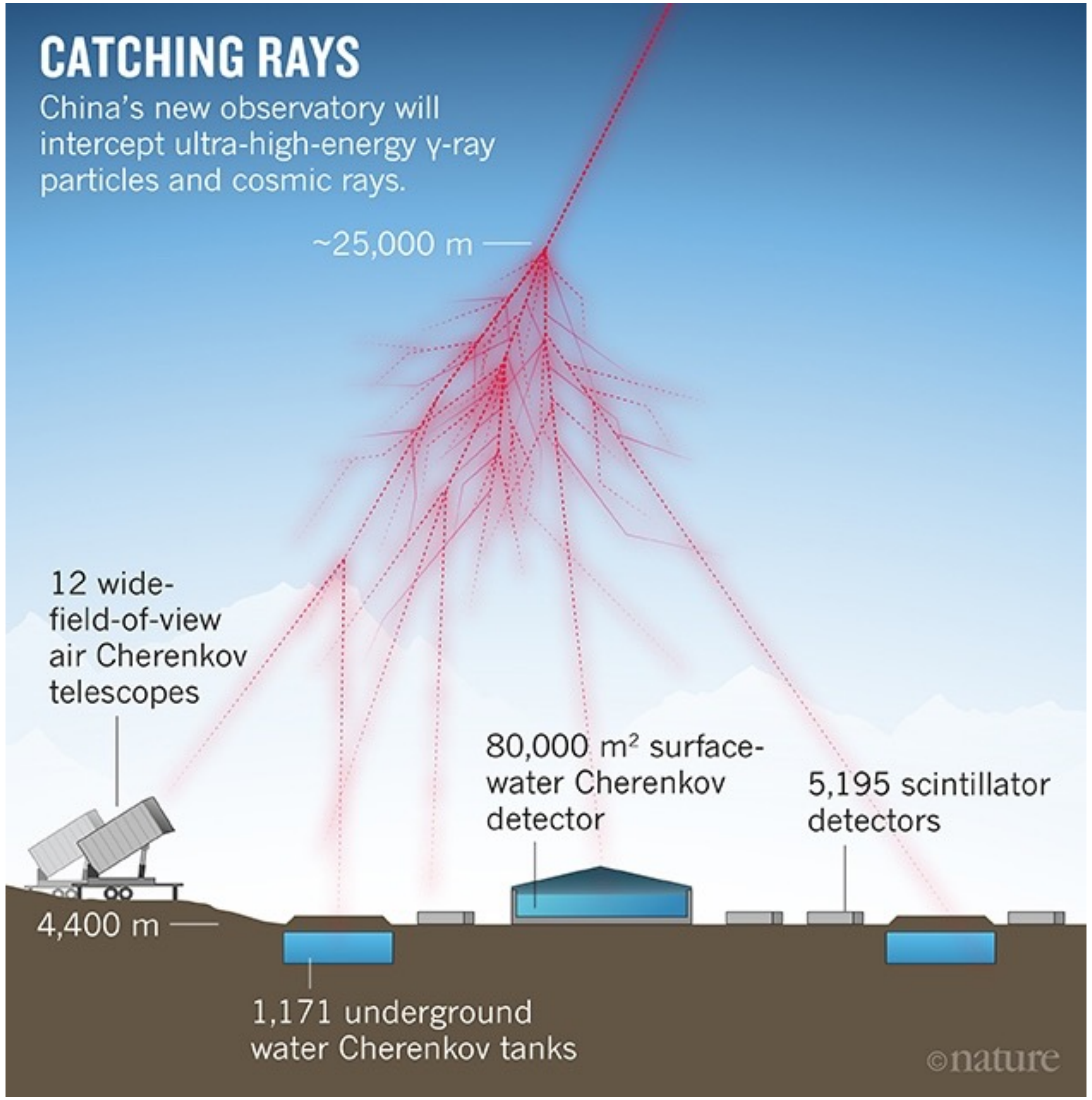
Ilya G. Usoskin, Living Rev. Solar Phys., 10 (2013)

Example

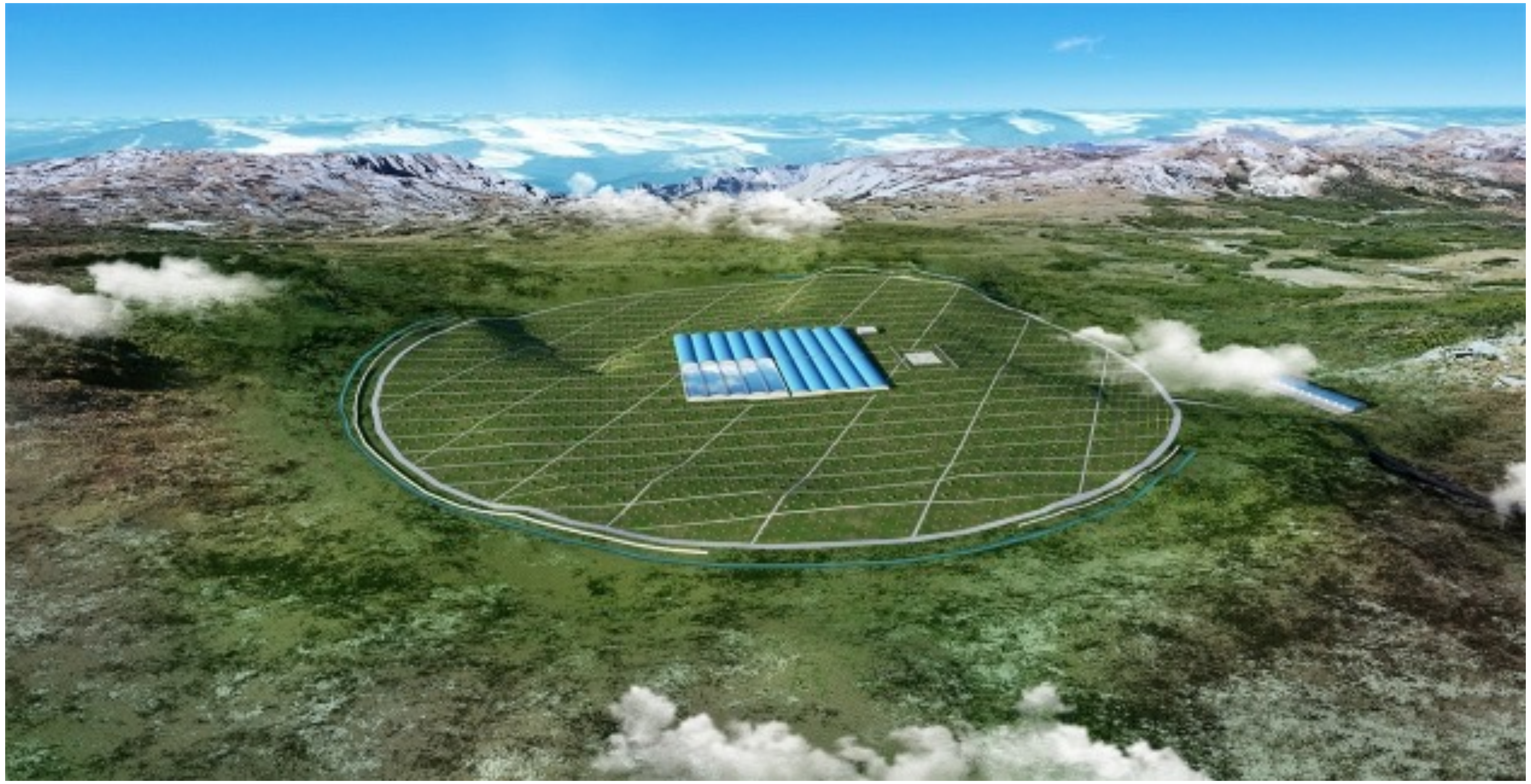


Regression was performed and T_{eff} was constructed separately on three different datasets corresponding to three time periods to compare the results and plotted together.

LHAASO Cosmic Ray Project in China



Nature **543**, 300–301 (16 March 2017) | doi:10.1038/543300a



Ultra High Energy Cosmic Ray Search

In 1939, Pierre Auger and his co-workers have estimated the energy of extensive cosmic ray shower to be above 10^{12} eV

Discovery of astronomical events that accelerate the primary cosmic ray particles at energies of 10^{20} eV was first detected in 1962 by John Linsley in the Volcano Ranch array in New Mexico, USA

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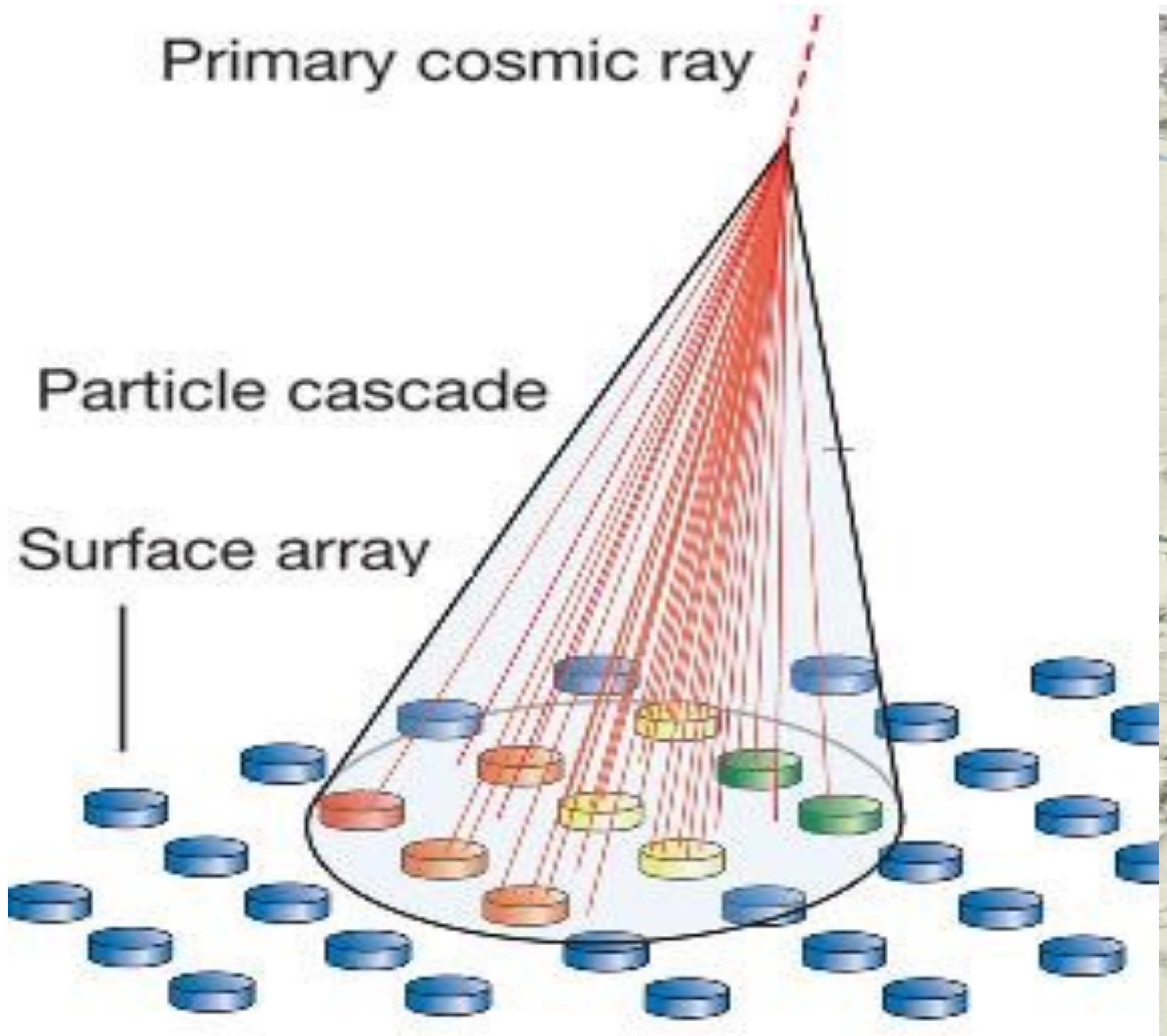
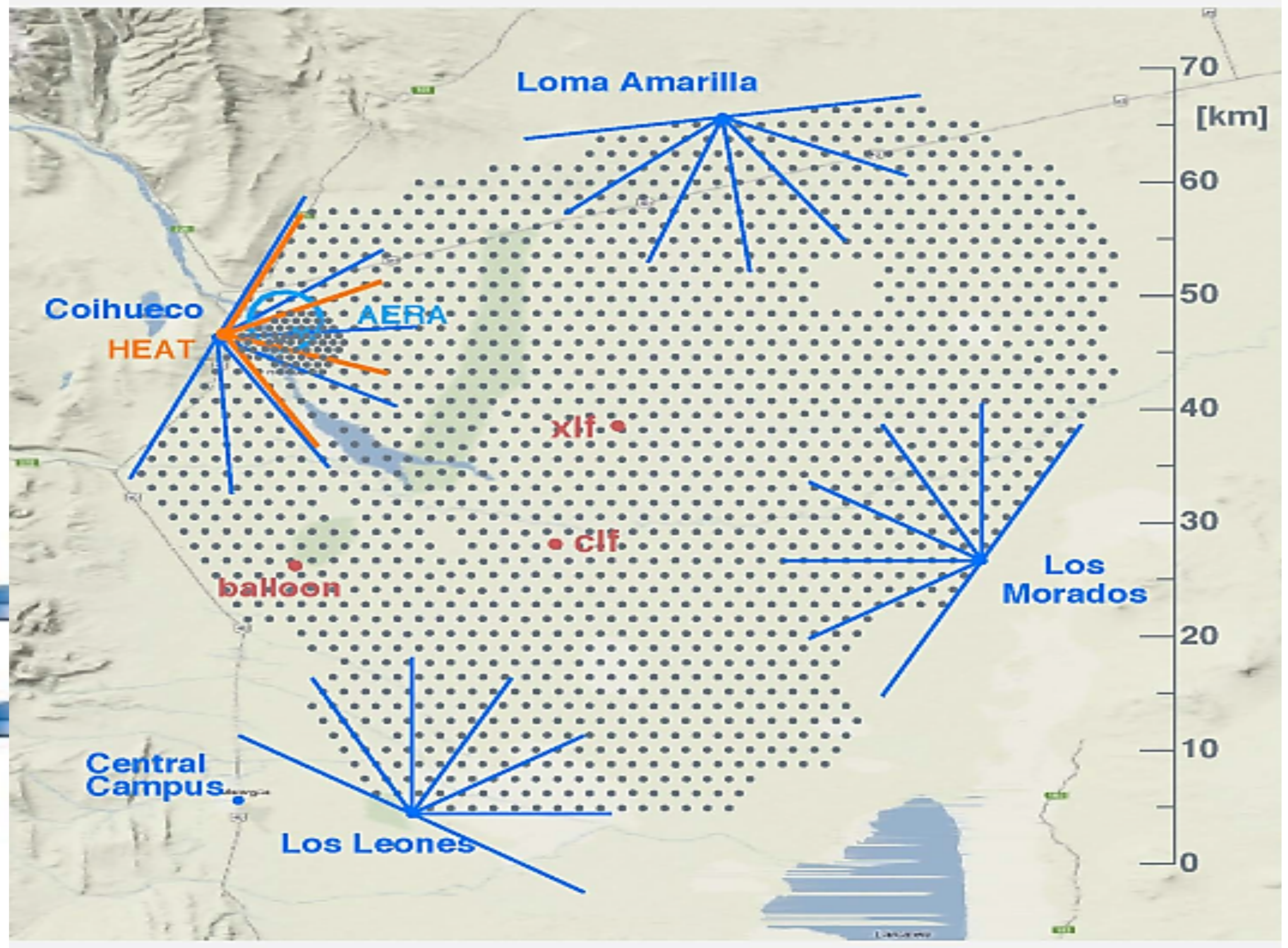
In 1995, Pierre Auger Project begun, named in honor of the discoverer of extensive air showers with a purpose of tracing high-energy cosmic rays to their unknown source that will advance the understanding of the origin and evolution of the universe.



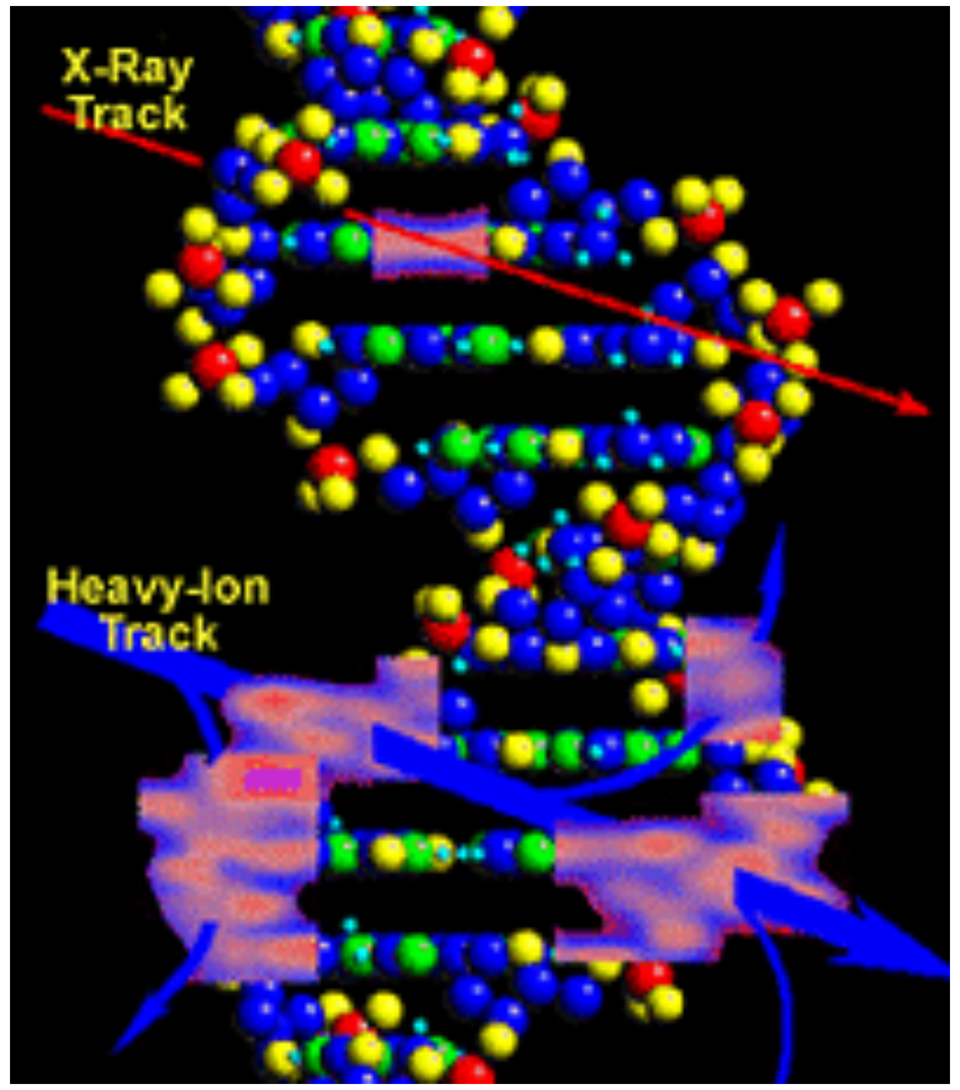


Cosmic Applications

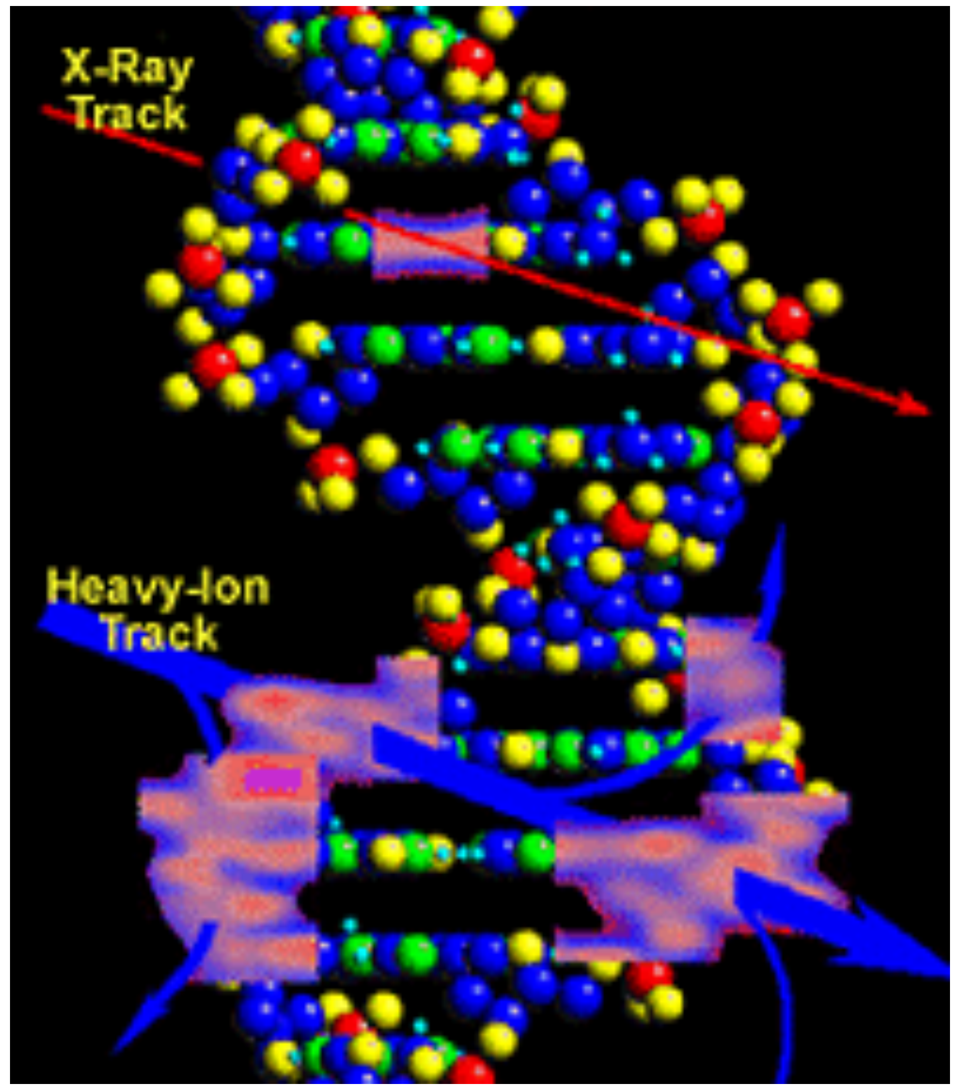


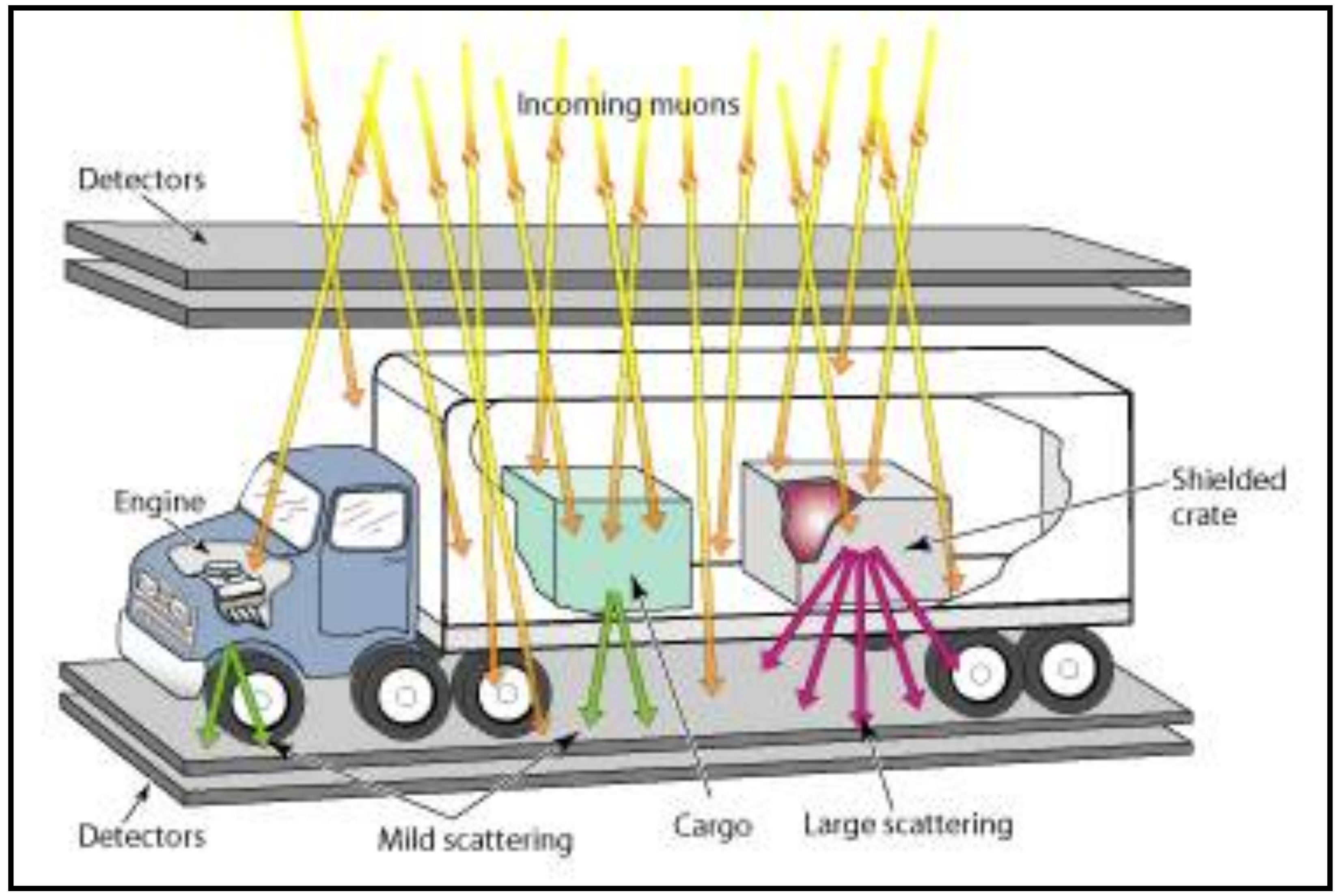
Cosmic Applications

Cosmic Applications



Cosmic Applications





Cosmic Applications