Particle Astrophysics with the HAWC Gamma-Ray Observatory

(High Altitude Water Cherenkov)

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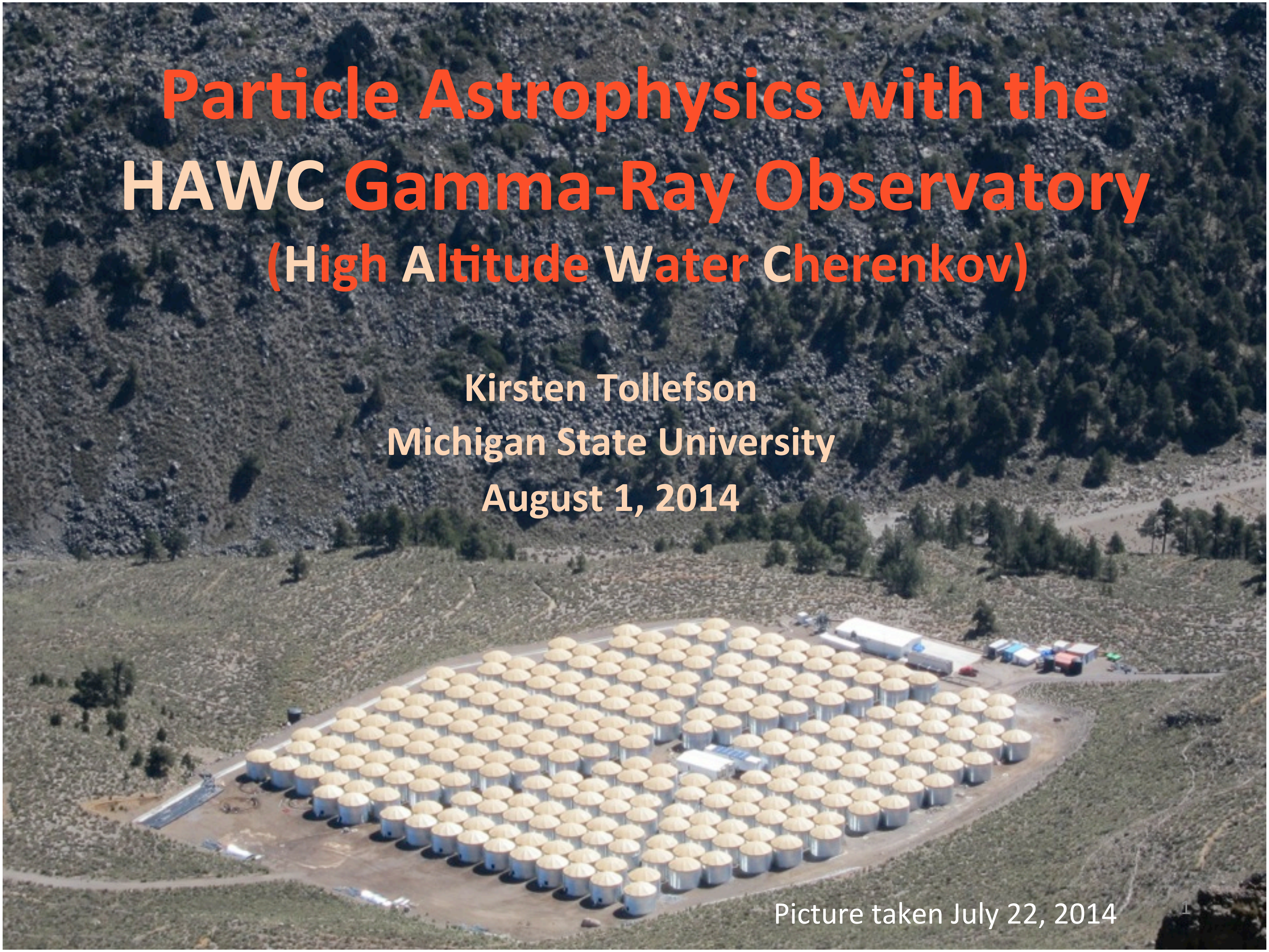
Michigan State University

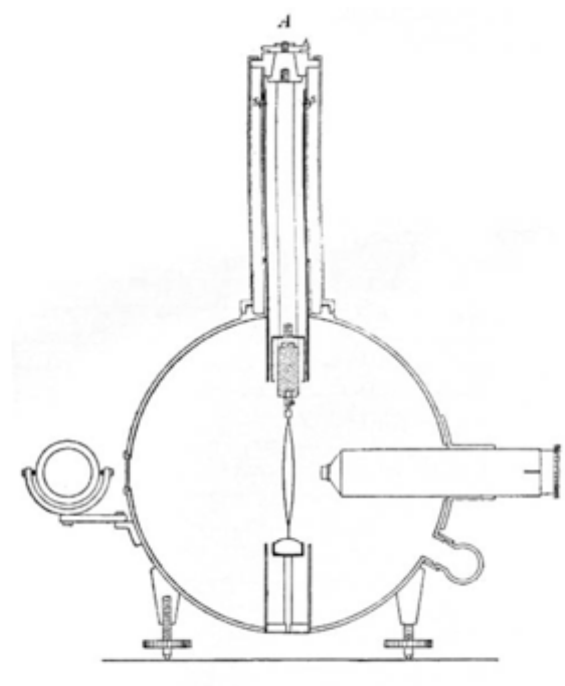
August 1, 2014



Picture taken July 22, 2014

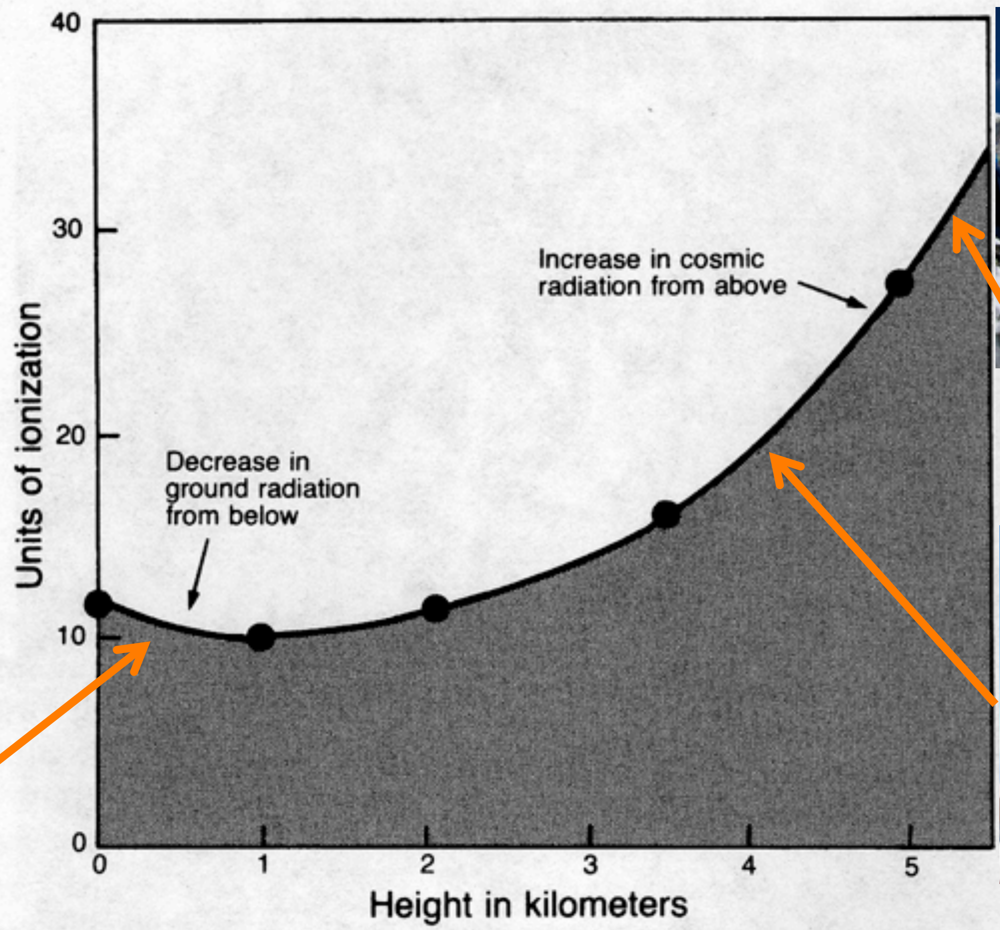
A Century Old Question:
Where do cosmic rays come from?

Electroscopes



A Century Old Question: Where do cosmic rays come from?

Eiffel Tower
0.3 km

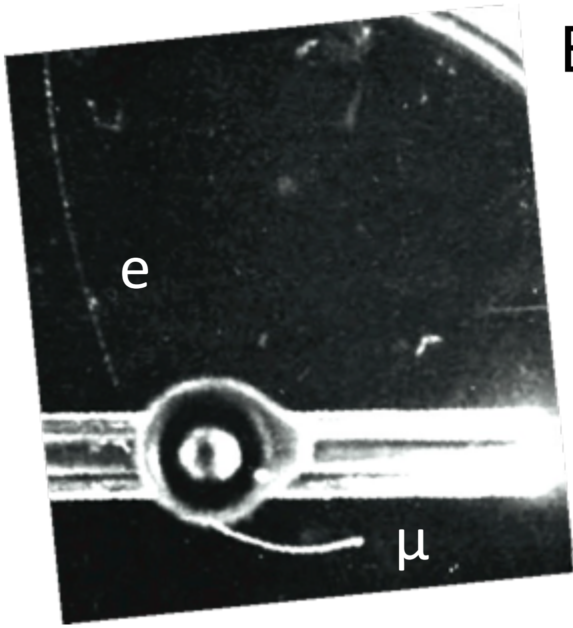


Readings on ionization chamber Victor Hess carried aloft in the Böhmen. Above four kilometers the ionization rose rapidly indicating "that rays of very great penetrating power are entering our atmosphere from above".

Mt. Everest Base Camp
5.3 km

Pikes Peak
4.3 km

Beginnings of Particle Physics



Before there were man-made particle accelerators there were **cosmic rays…**

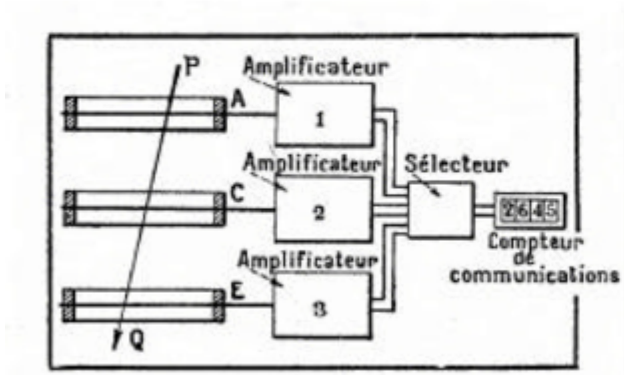
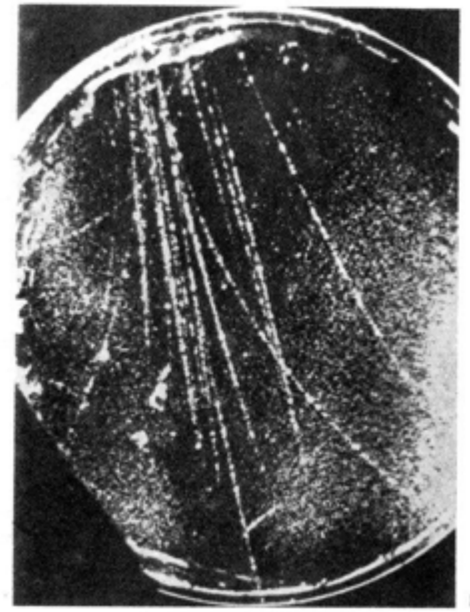
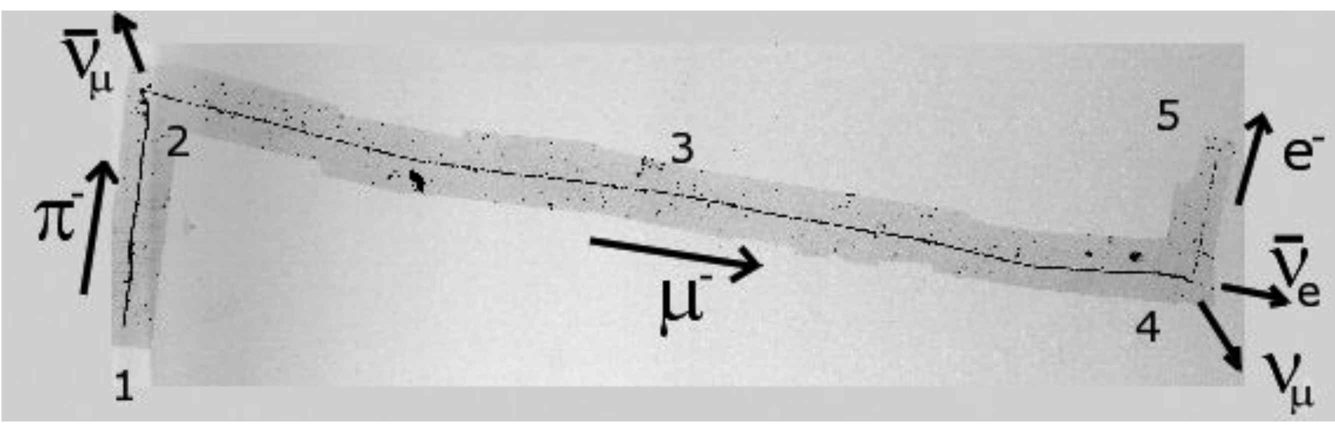
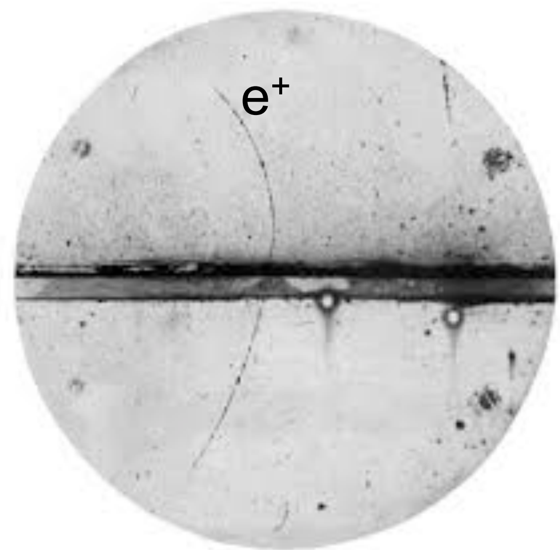


FIG. 5. — MÉTHODES DES COÏNCIDENCES

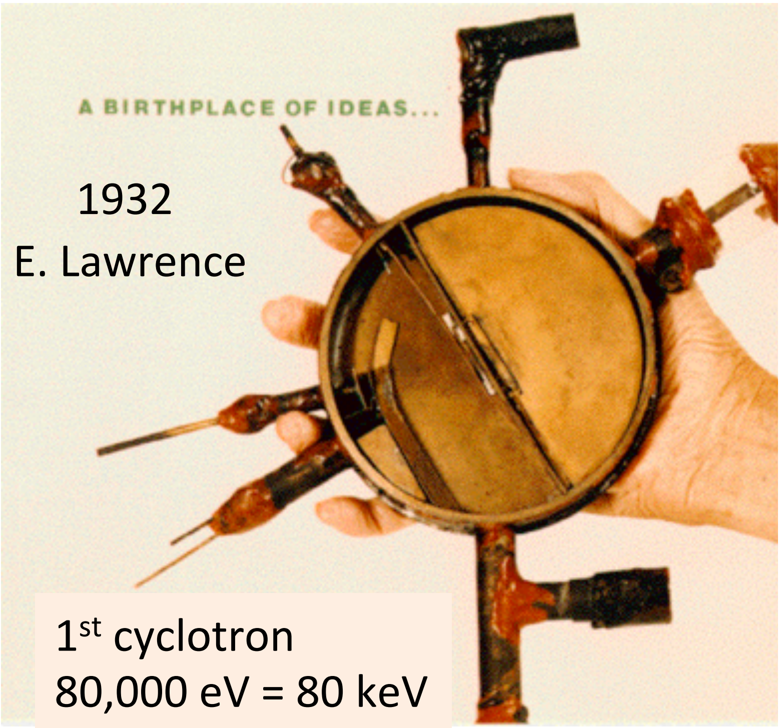






Studying cosmic rays led to the discovery of the positron (e^+), pion (π), muon (μ) plus others

Man-made Accelerators

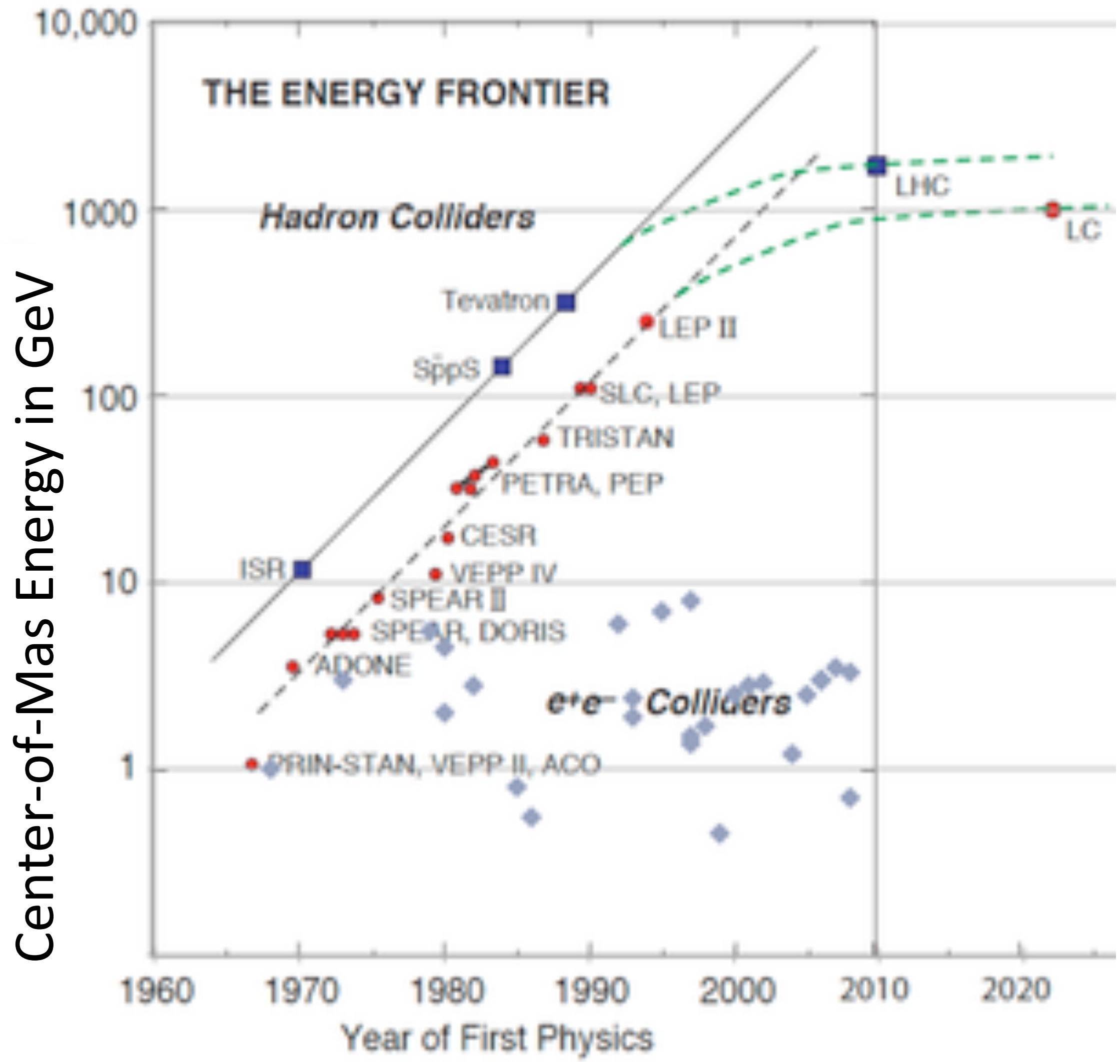


1932
E. Lawrence

1st cyclotron
80,000 eV = 80 keV

$$E = qV$$

1 eV = 1.6x10^{-19} J
1 GeV = 10^9 eV
1 TeV = 1000 GeV = 10^{12} eV

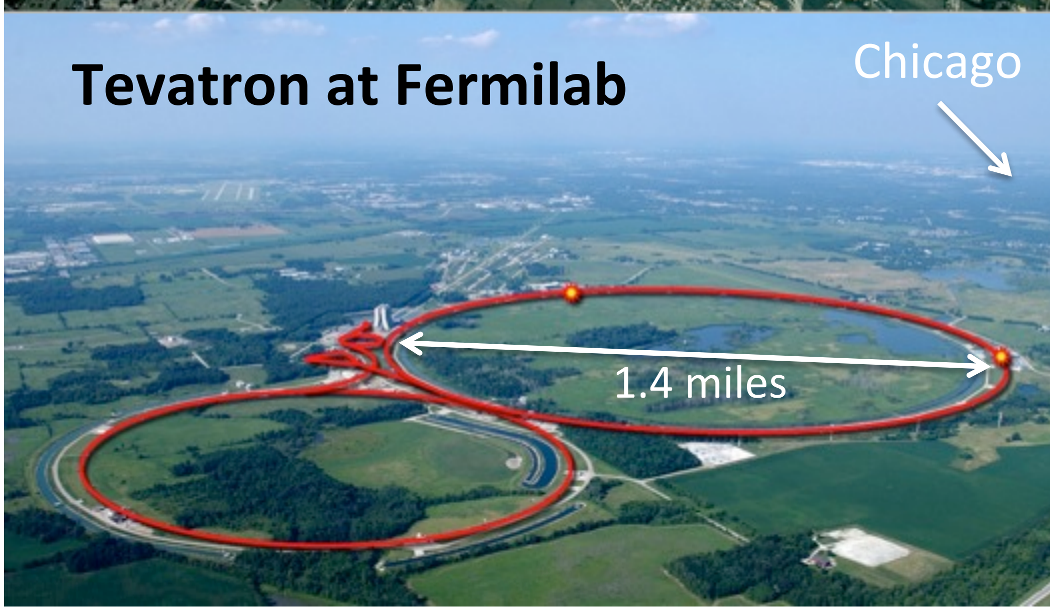


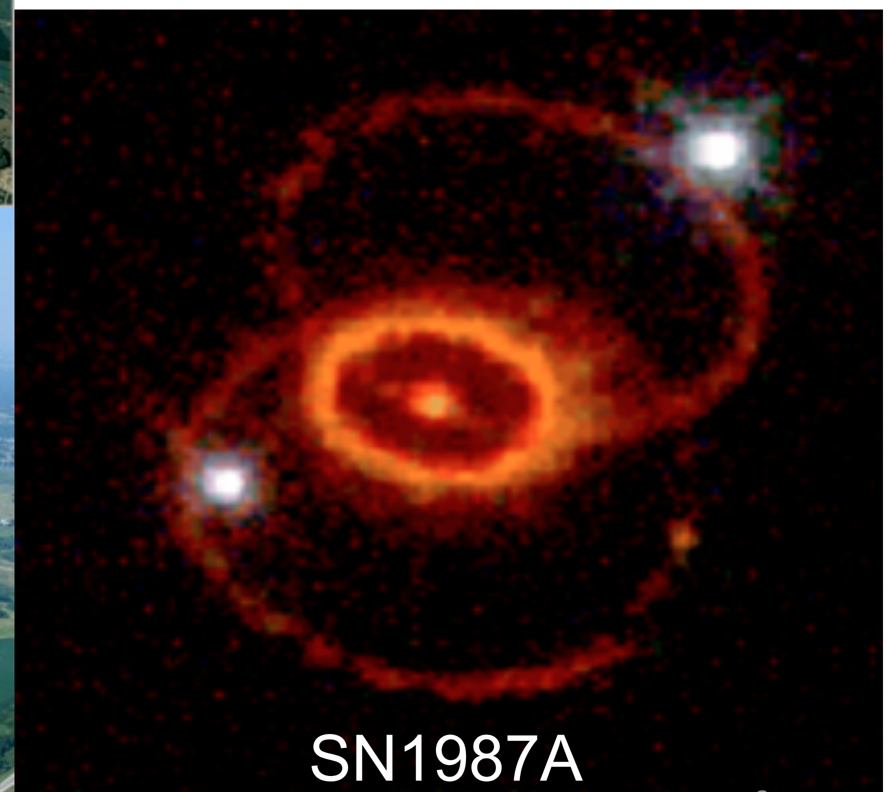
Particle Accelerators

Fermilab $\sqrt{s} \approx 2$ TeV = 2×10^{12} eV

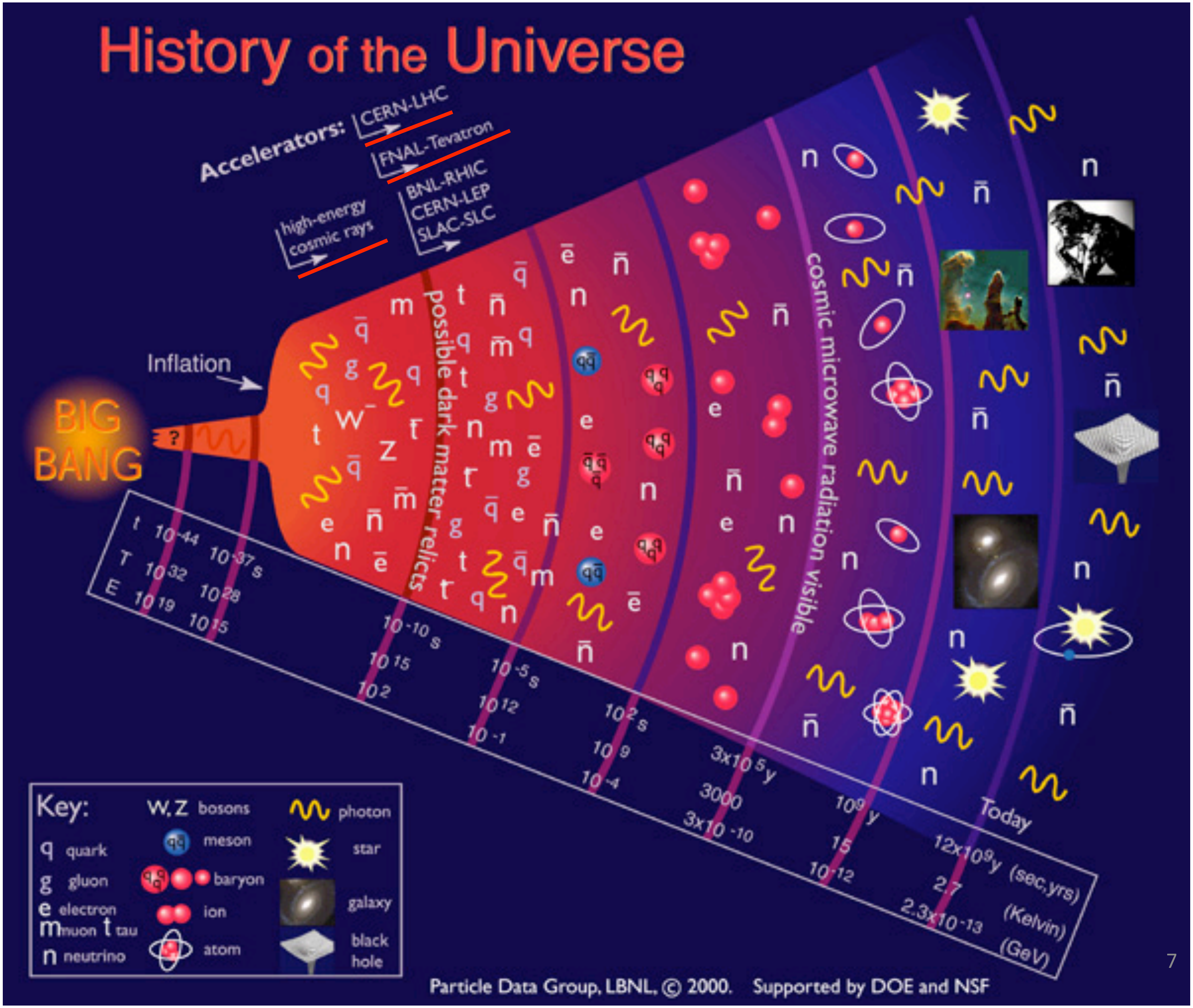
LHC $\sqrt{s} = 8$ TeV (soon 14 TeV)

Supernova ≈ 300,000,000 TeV

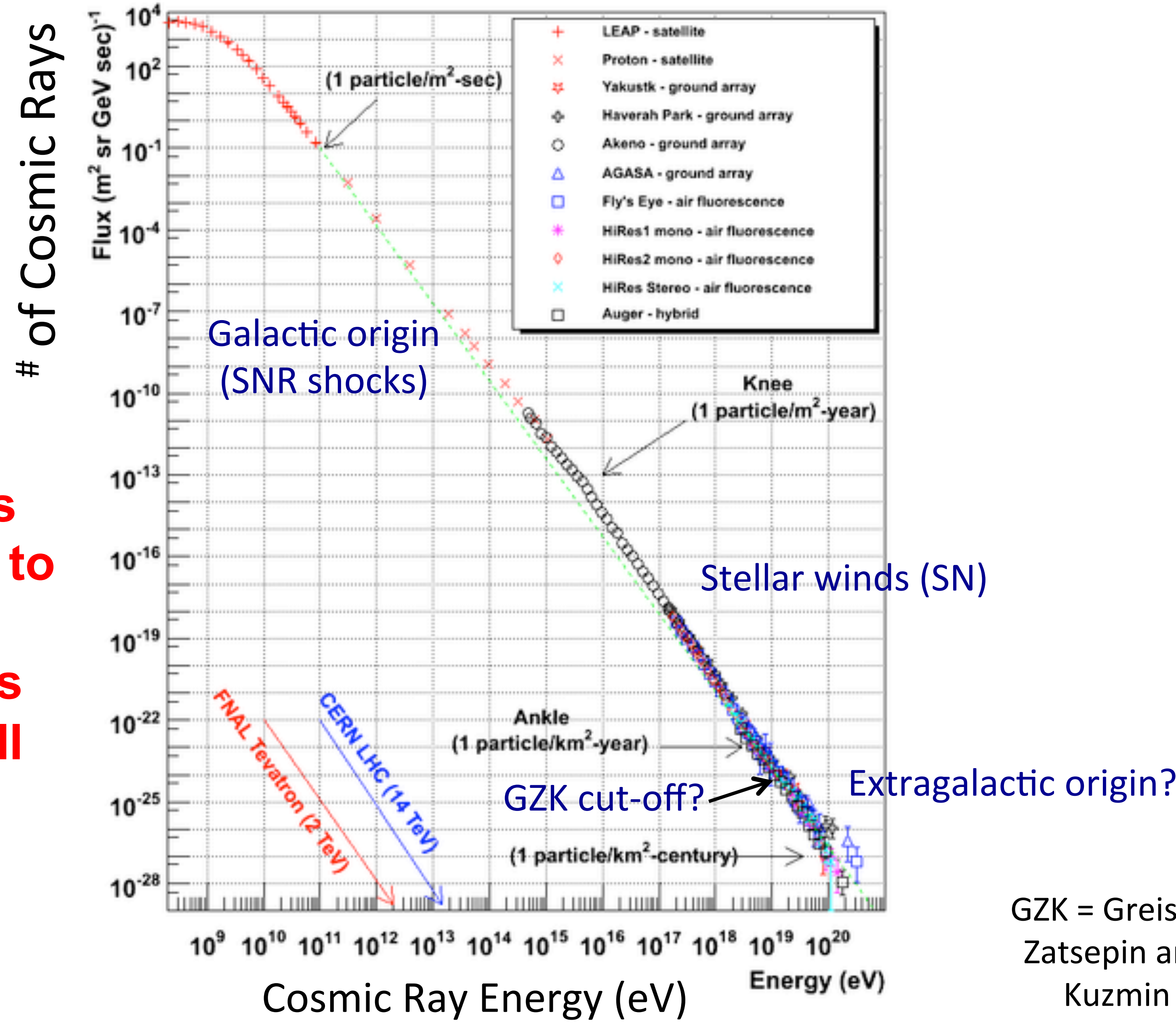




Not to scale


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
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

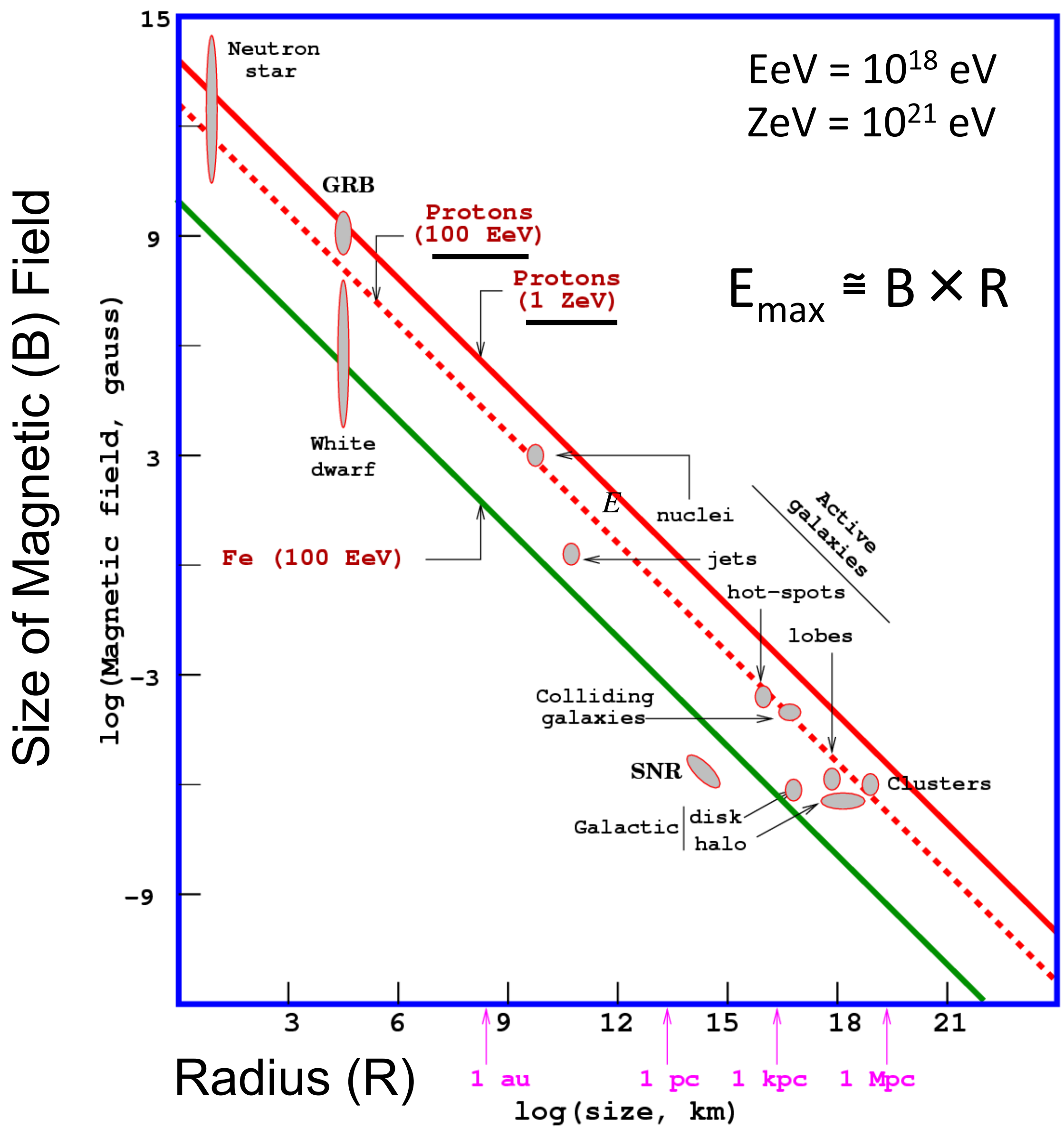
Cosmic Rays Detected up to 10^{20} eV



Nature accelerates cosmic rays to $3\text{x}10^{20}$ eV = 50 Joules = a baseball thrown at 58 mph

GZK = Greisen, Zatsepin and Kuzmin

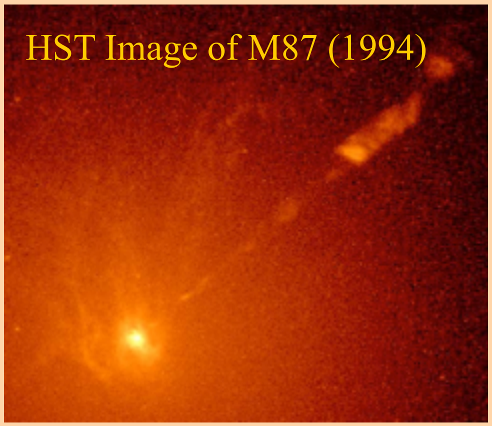
Sources of Cosmic Rays



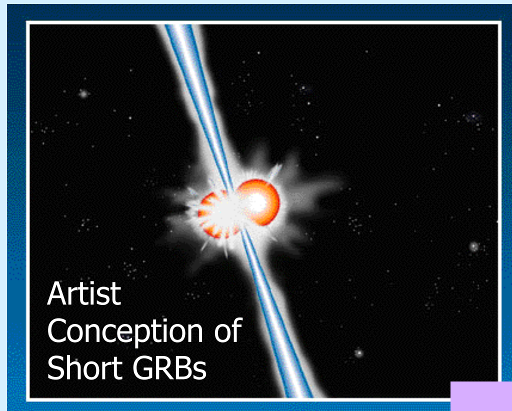
Cosmic rays are charged particles, mostly protons (90%) but also nuclei of elements such as helium (9%) and a few heavier elements (1%)

Astrophysical Particle Accelerators

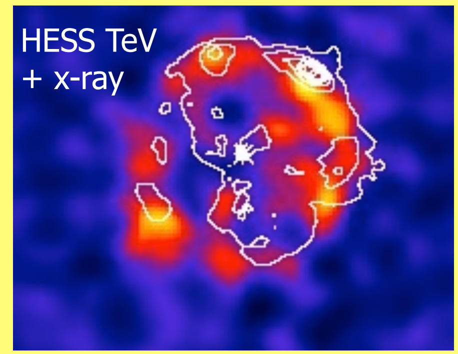
Black Hole producing relativistic jet of particles



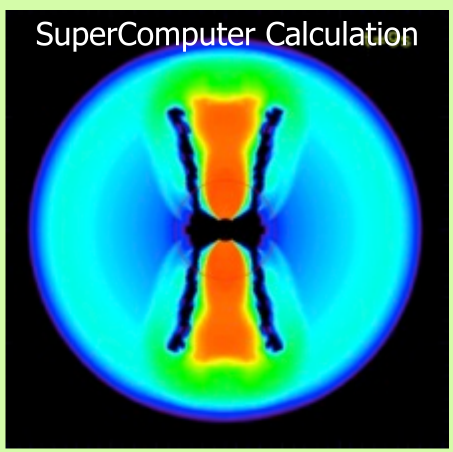
Binary Neutron Star Coalescing



TeV image of Vela Jr. Supernova Remnant

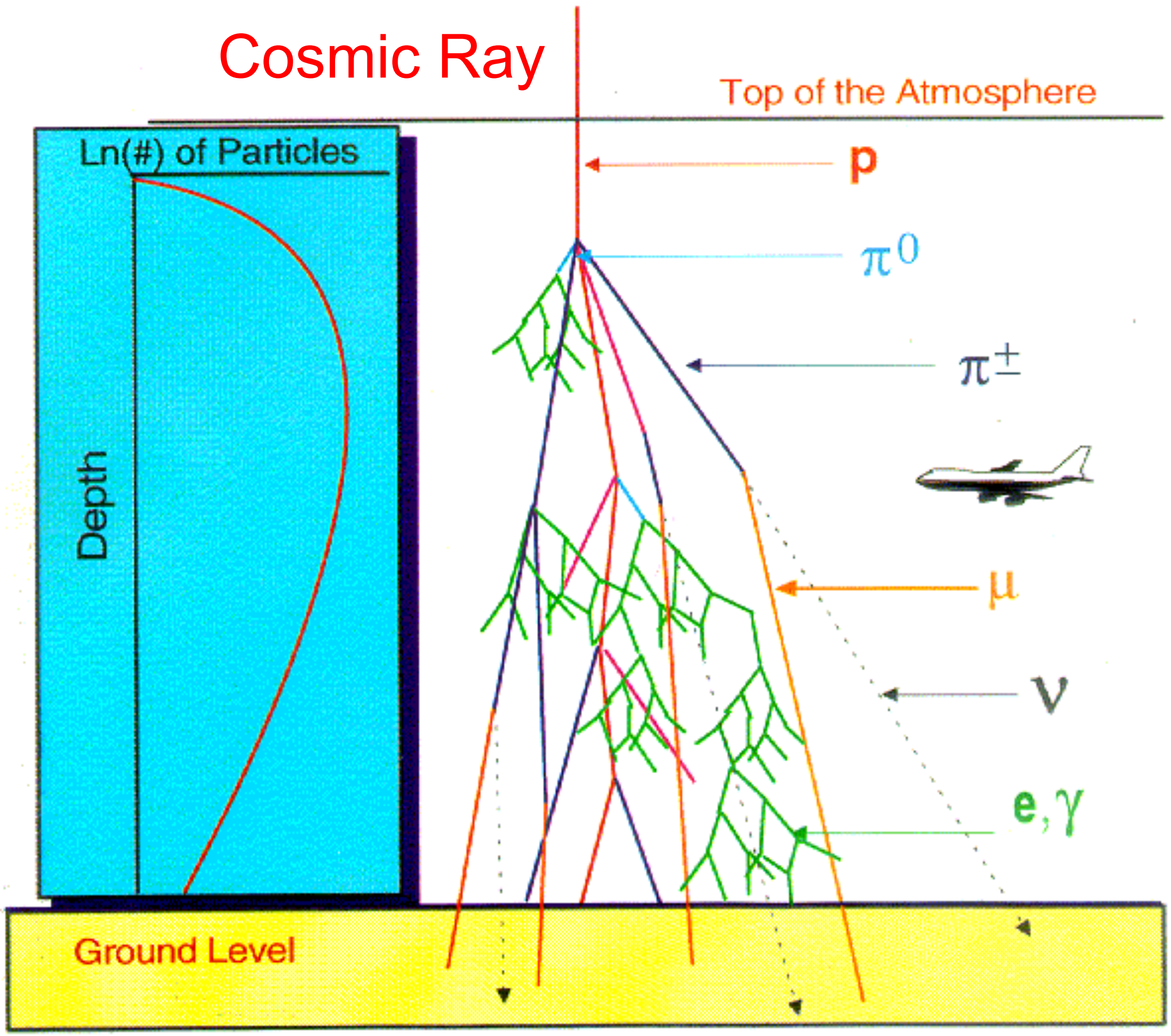


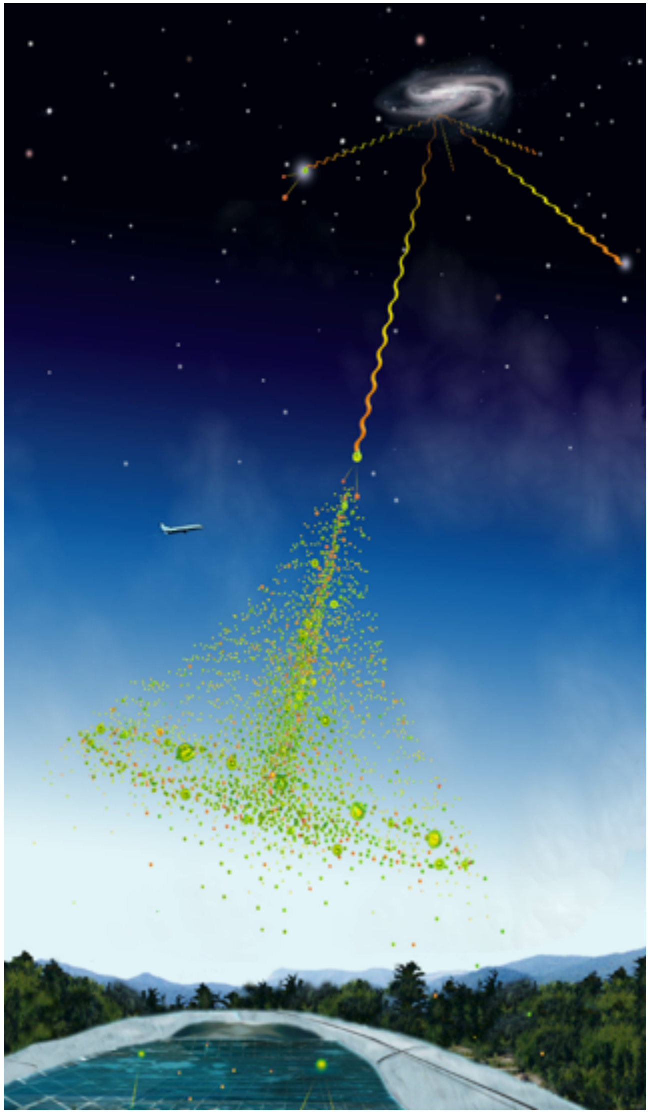
Massive Star Collapsing into a Black Hole



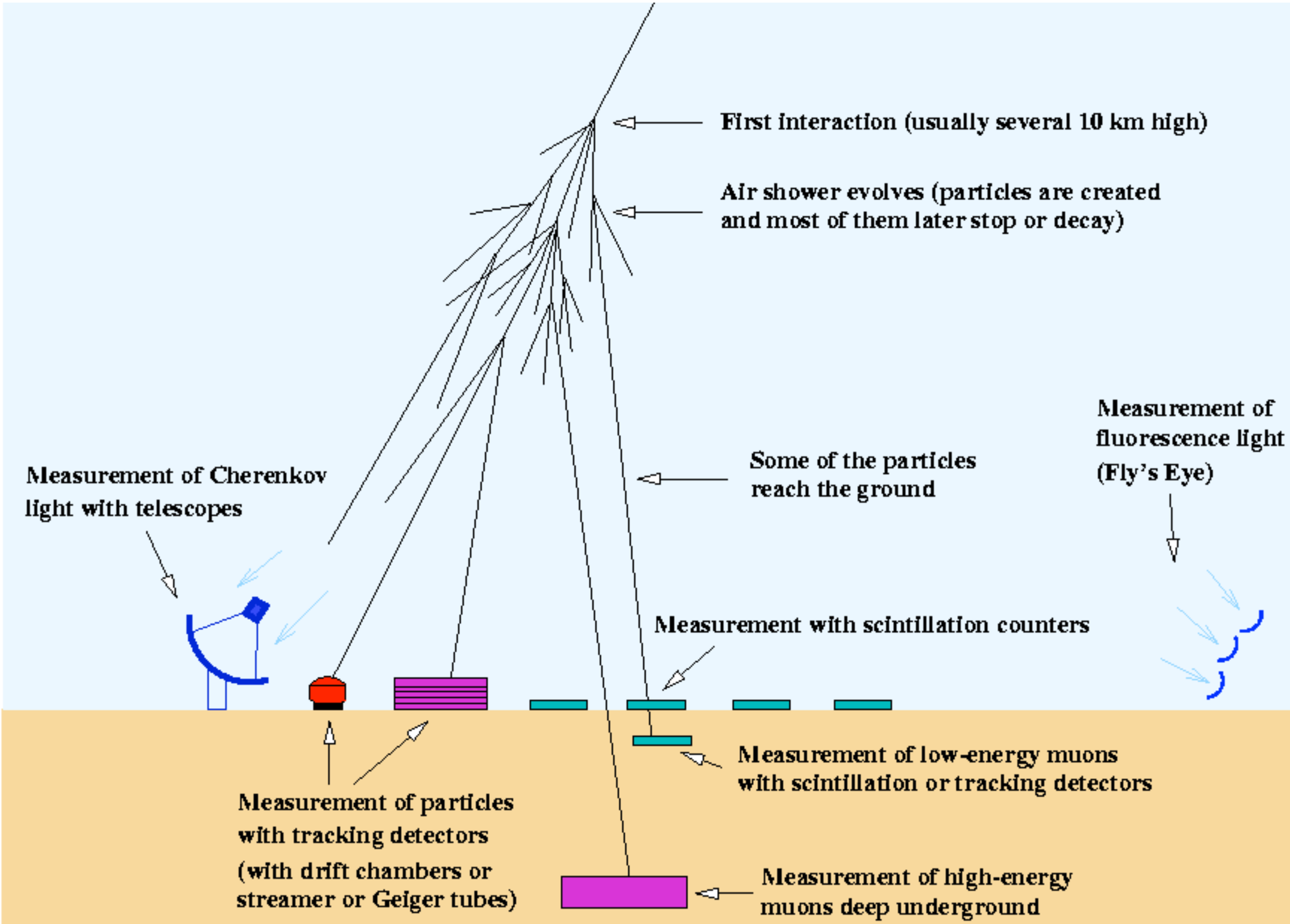
Spinning Neutron Star powering a relativistic wind

Extensive Air Showers (EAS)

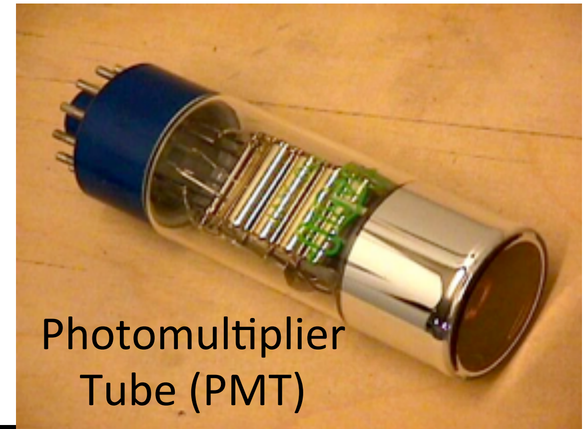


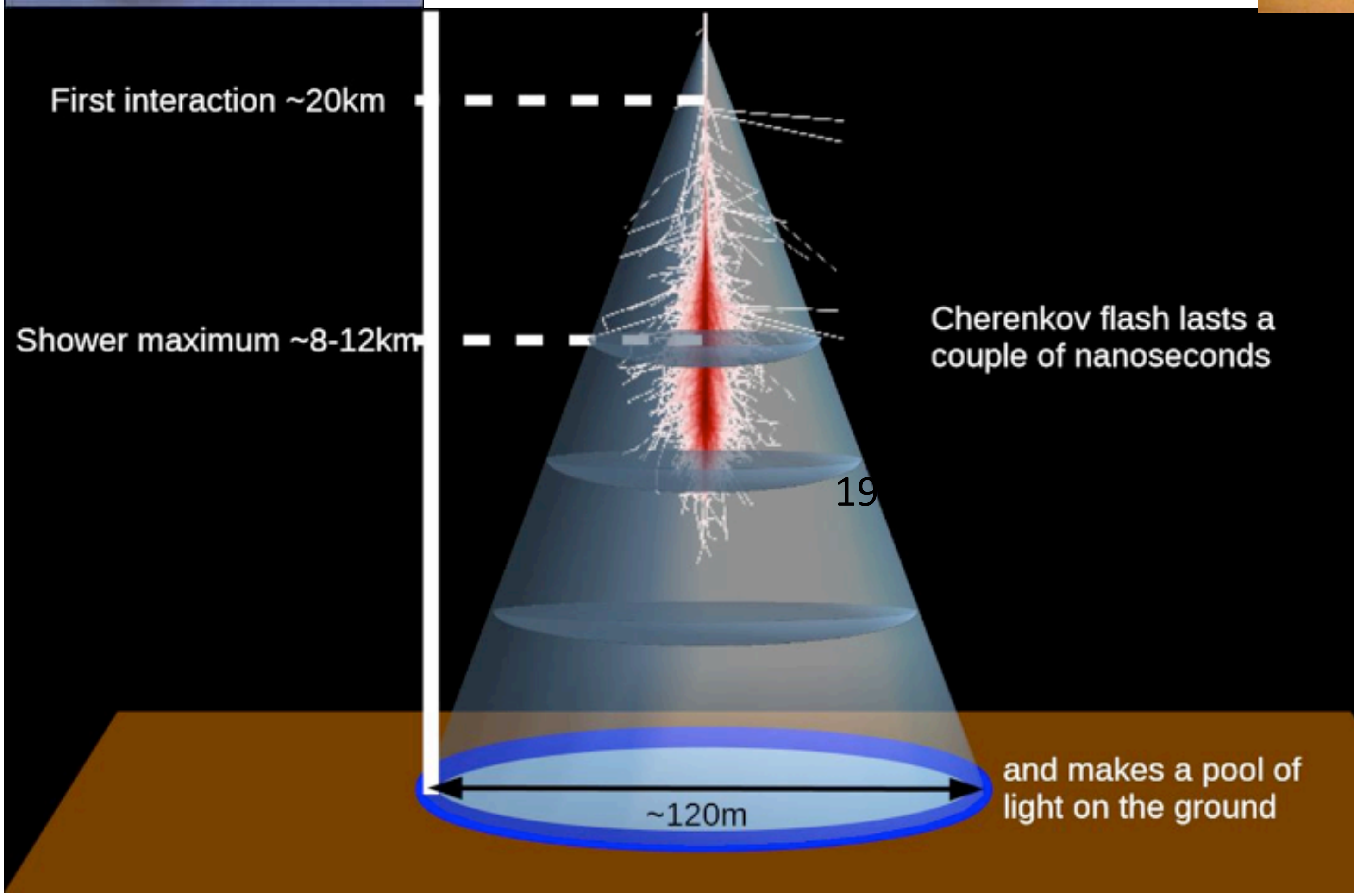


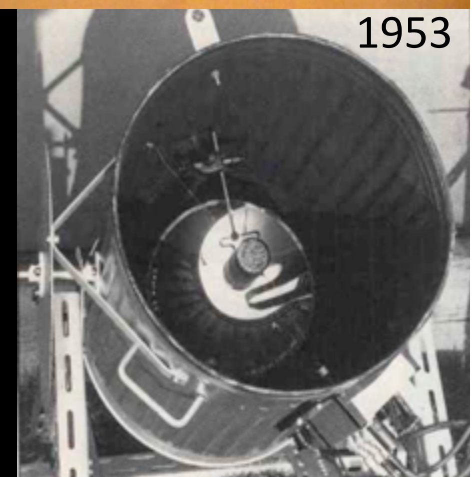
Detecting Extensive Air Showers (EAS)



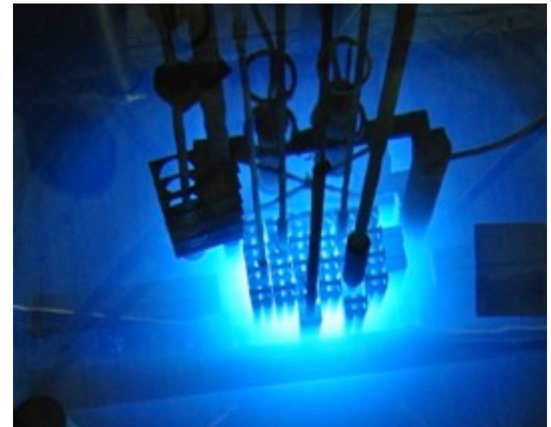
Cherenkov Light in Air

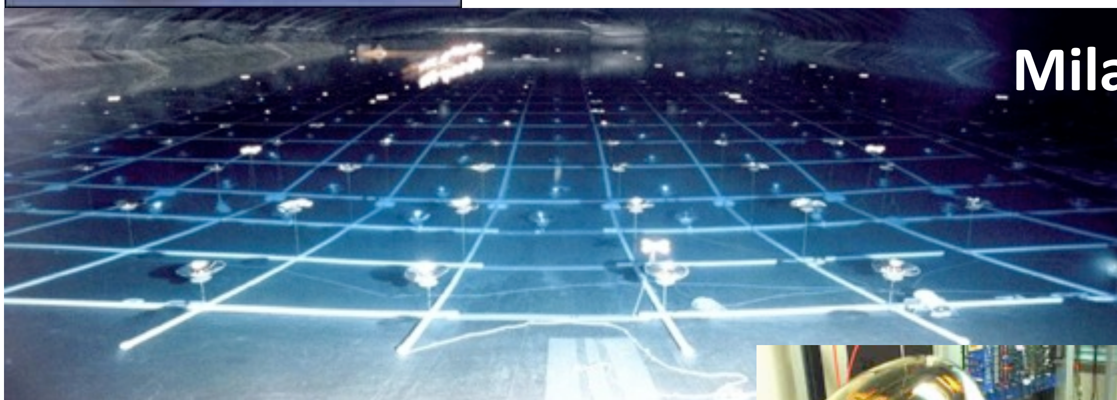


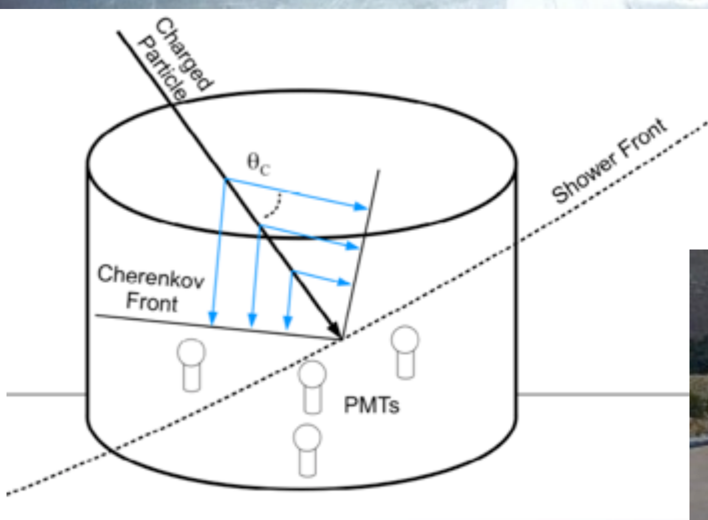




Cherenkov Light in Water

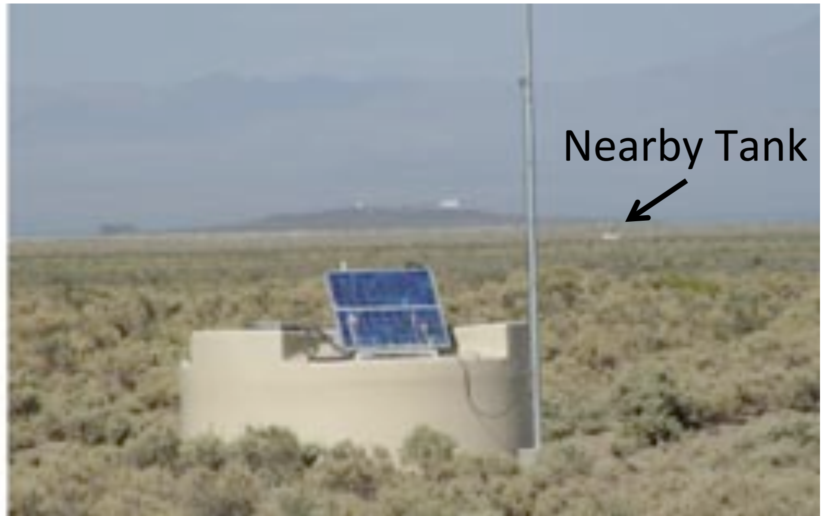






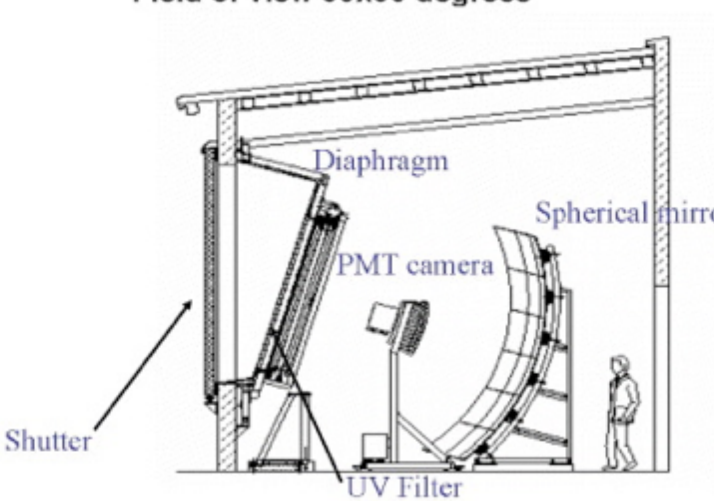
PIERRE AUGER OBSERVATORY

Pierre Auger Observatory

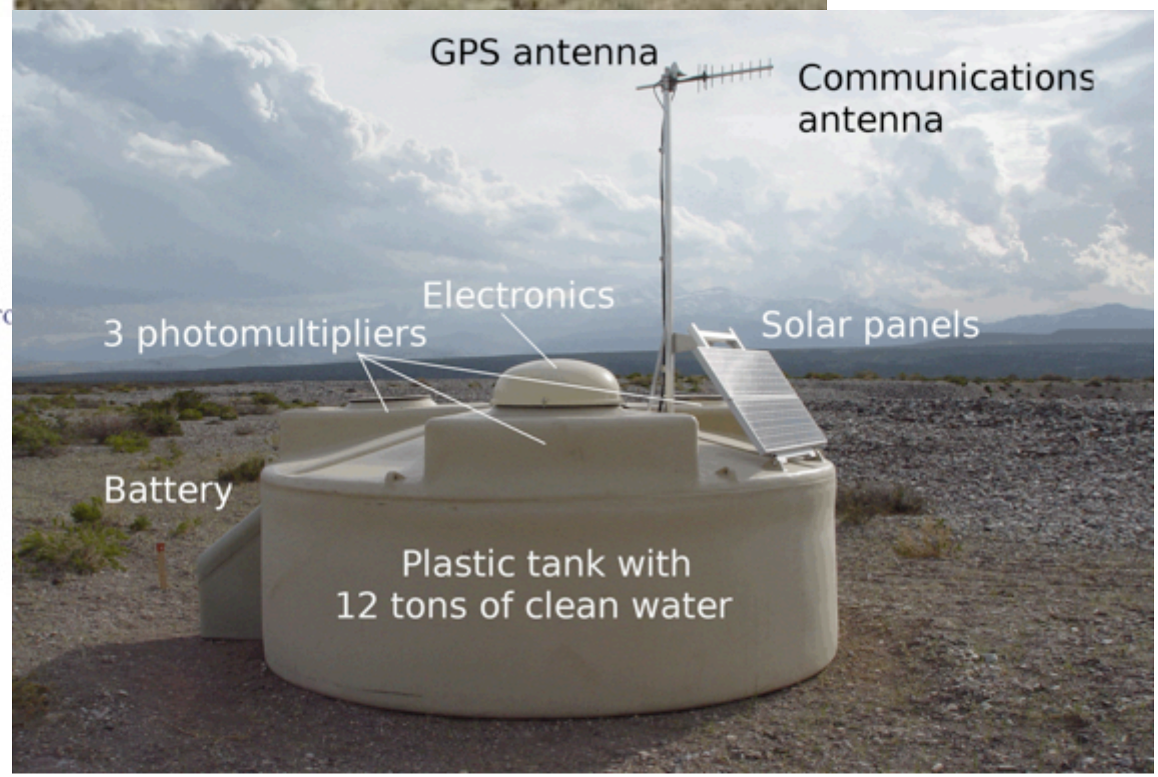


1600 tanks
1.5 km apart

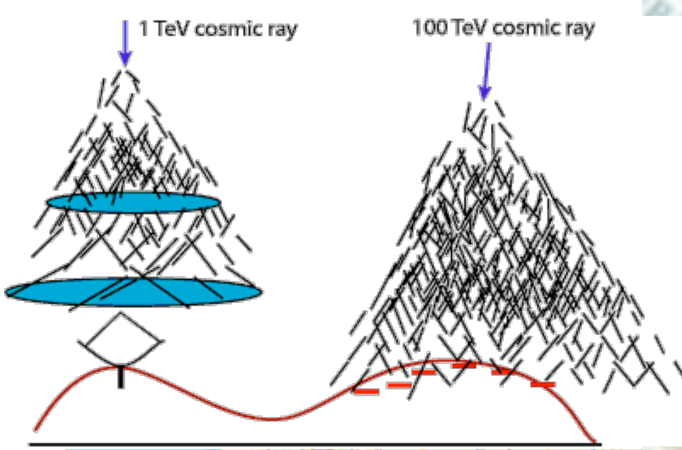
The FD telescope
Field of view 30x30 degrees

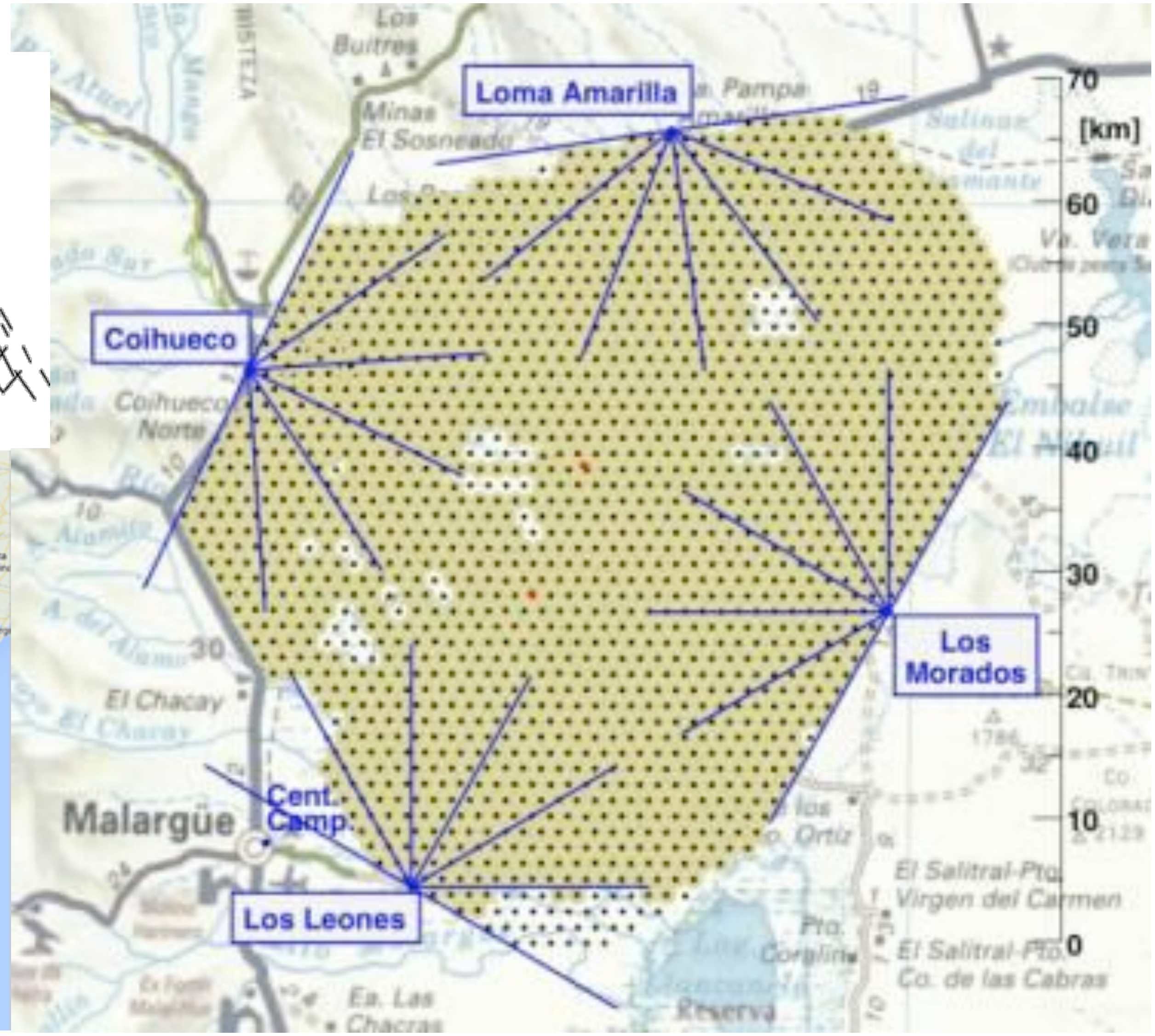


24 Fluorescence telescopes



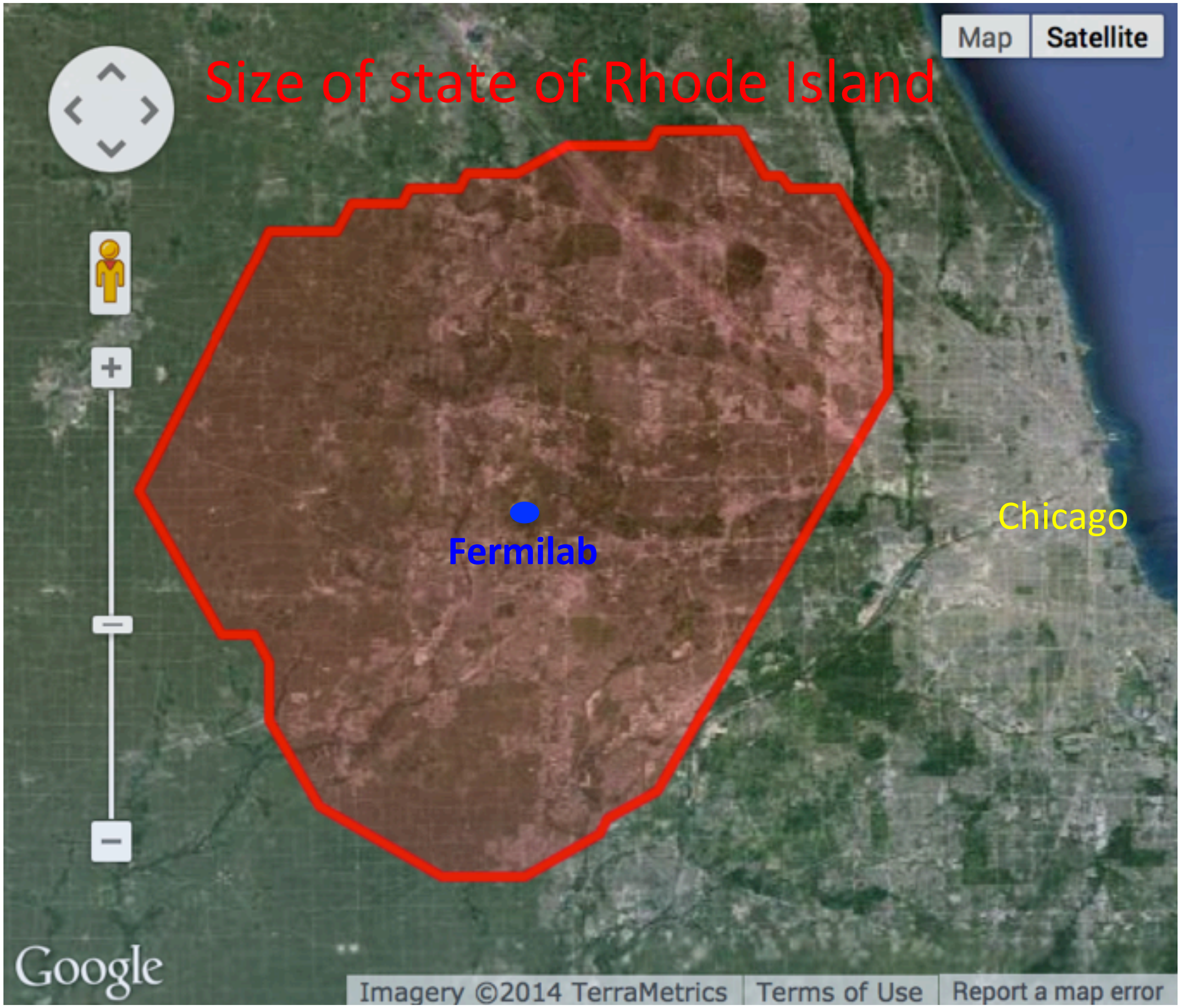
Pierre Auger Observatory



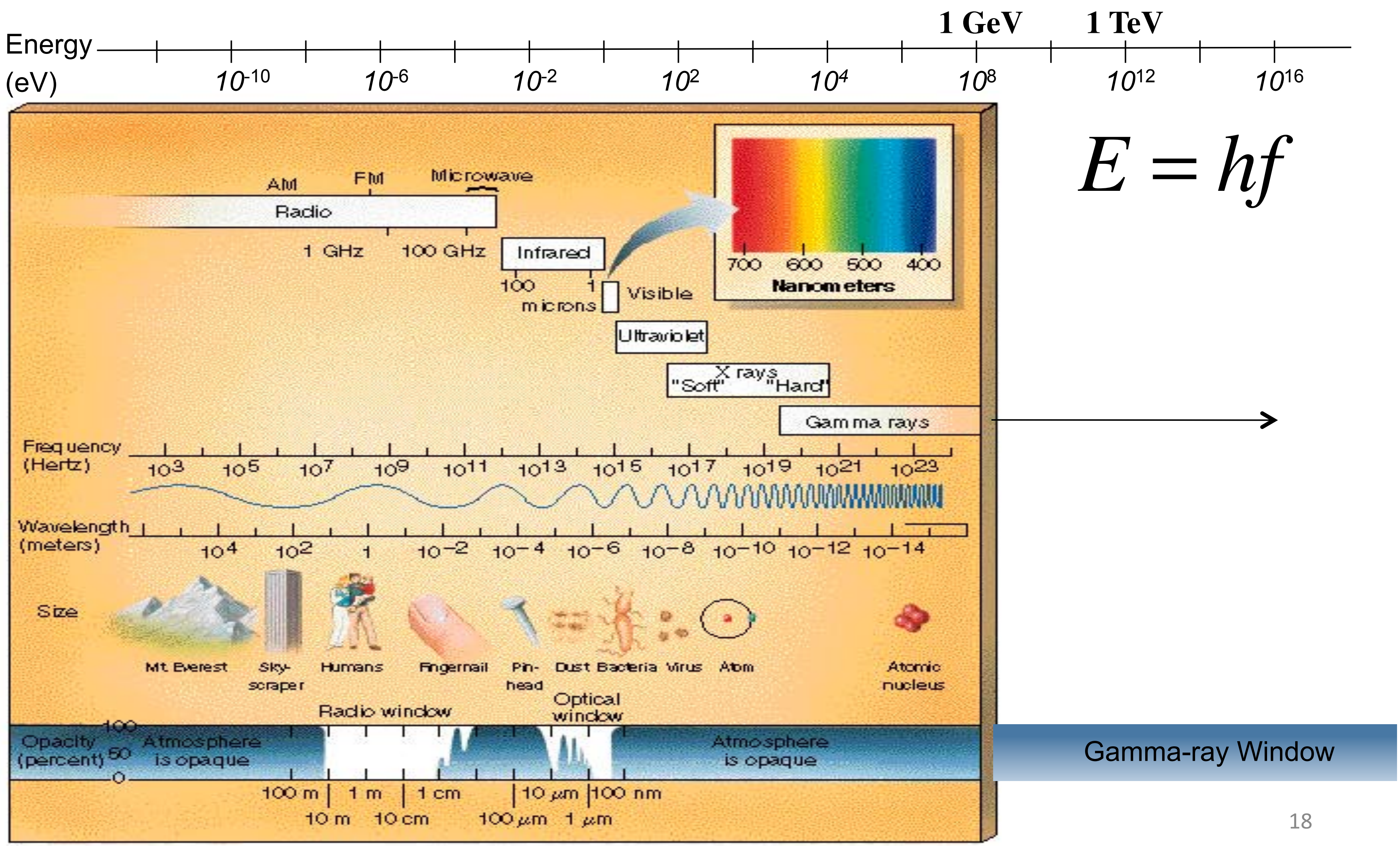


Mendoza province, Argentina

Size of Pierre Auger vs. Chicago

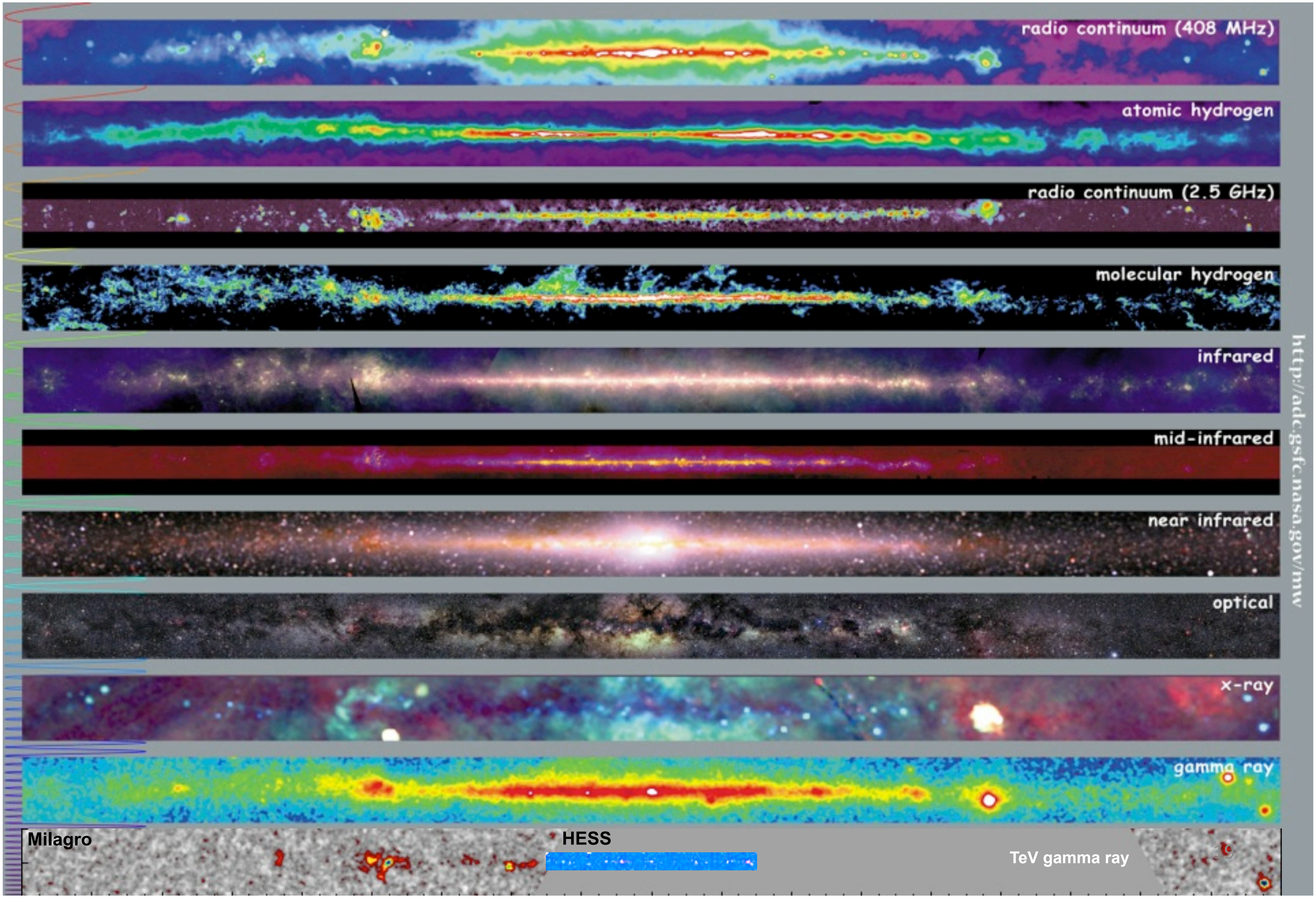


Gamma rays are the highest energy light (photons)

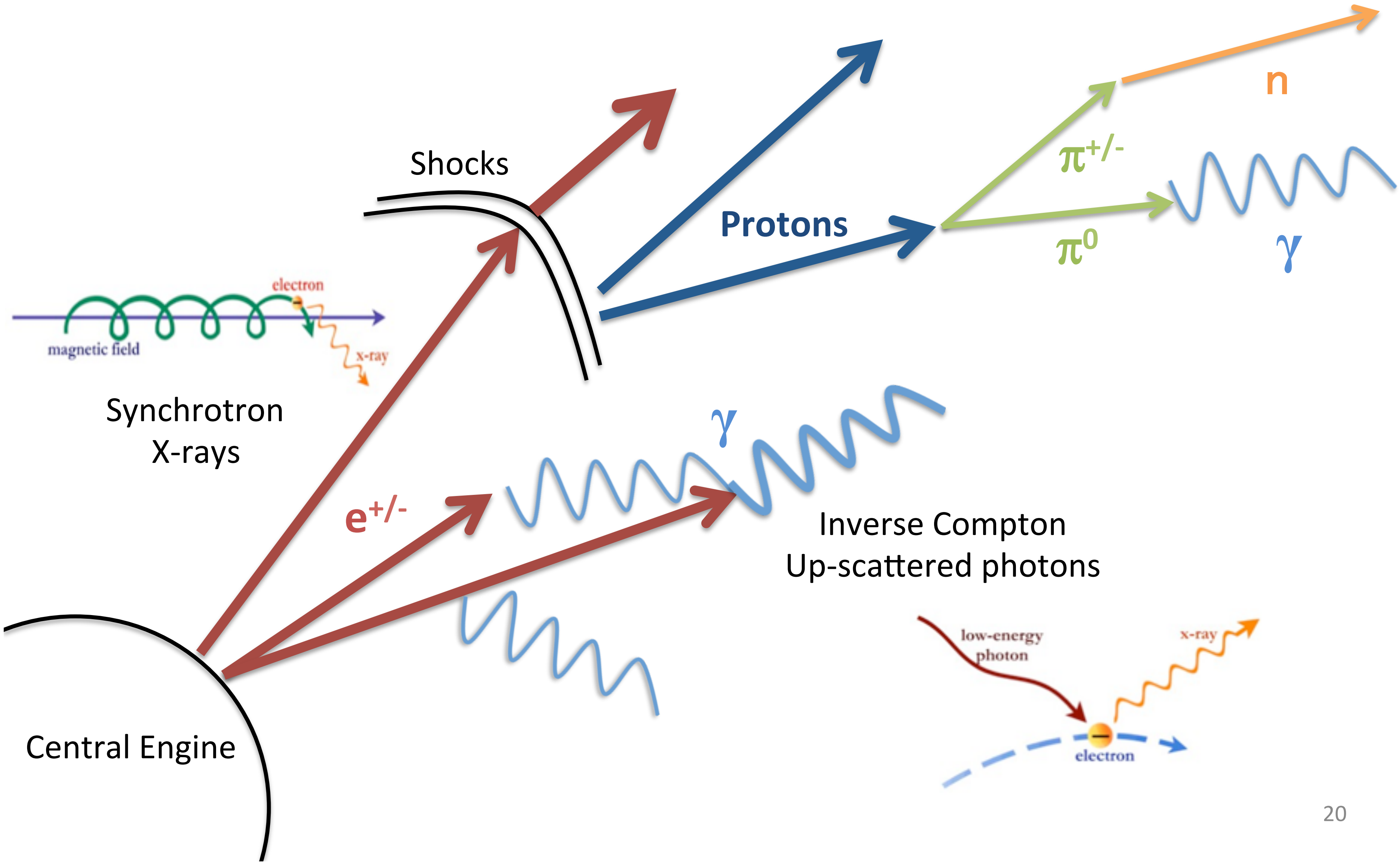


$$E = hf$$

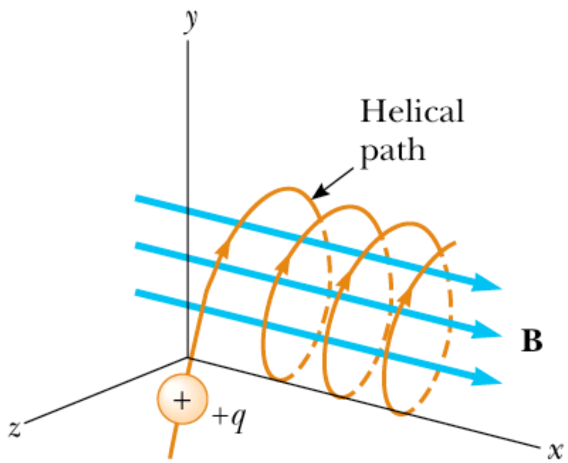
The Milky Way in Photons



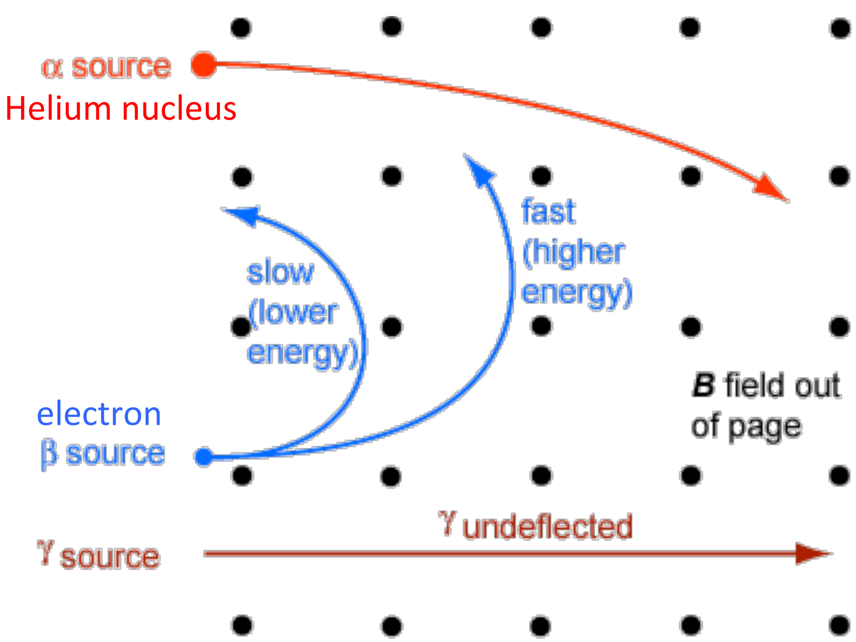
Acceleration / Emission Processes in Astrophysical Sources



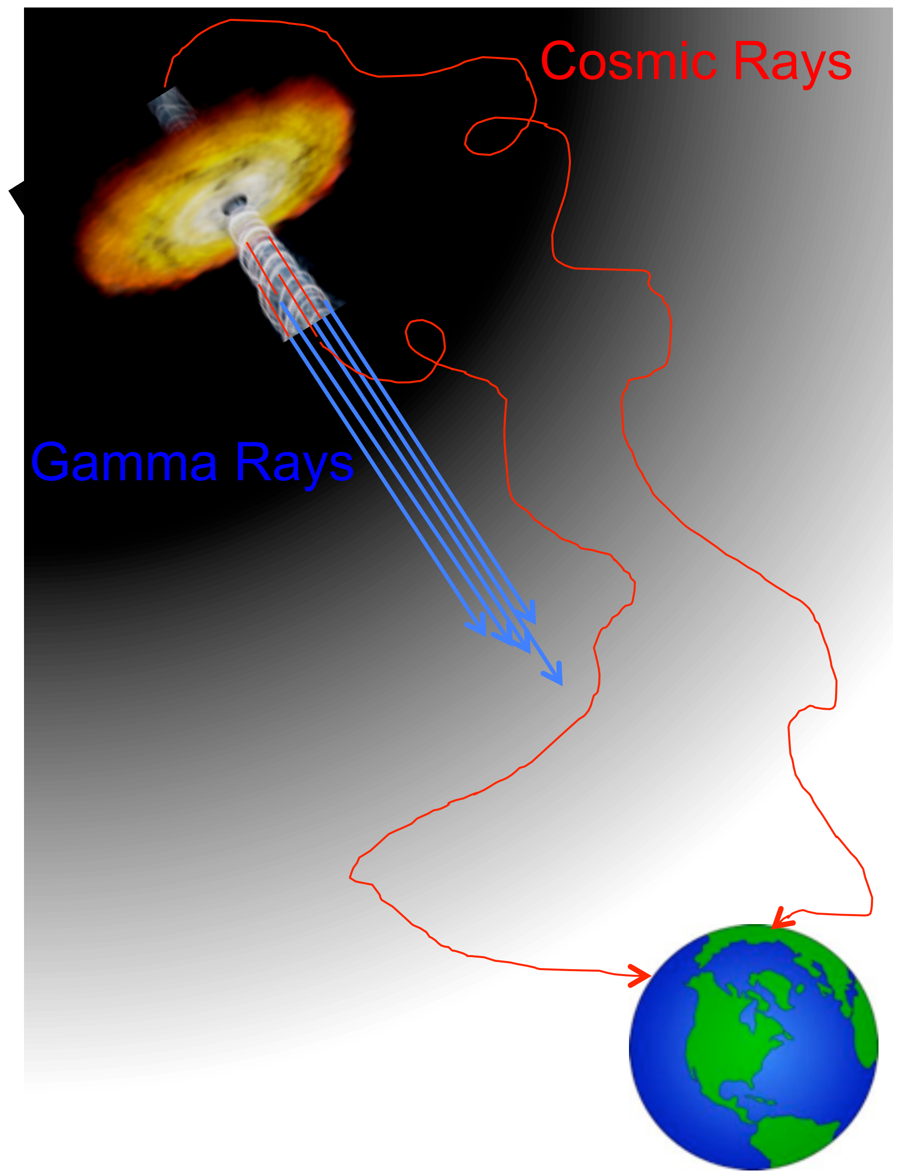
Gamma Rays Probe Cosmic Rays



$$r = \frac{mv}{qB}$$



Effect of a magnetic field on alpha, beta and gamma radiation



HAWC Science Objectives (High Altitude Water Cherenkov)

- Discover the origin of cosmic rays by measuring the gamma-ray spectra in the range of 100 GeV to 100 TeV from discrete sources and the Galactic plane.

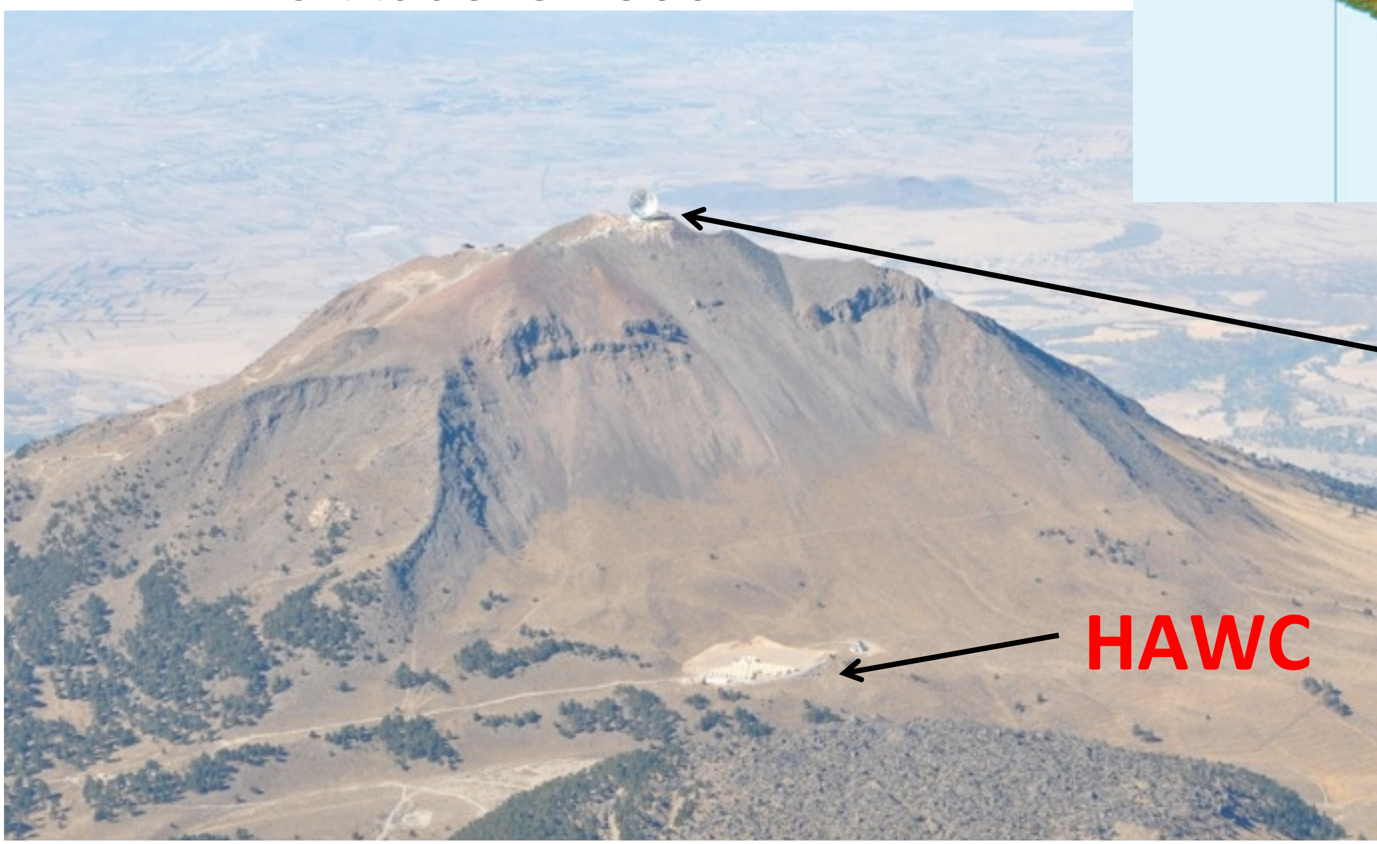
- Understand particle acceleration in extreme magnetic and gravitational fields via HAWC's observations of transient TeV sources, such as gamma ray bursts (GRBs) and super-massive black holes.

- Explore new physics (such as searching for dark matter) via HAWC's unbiased survey of ½ the sky.

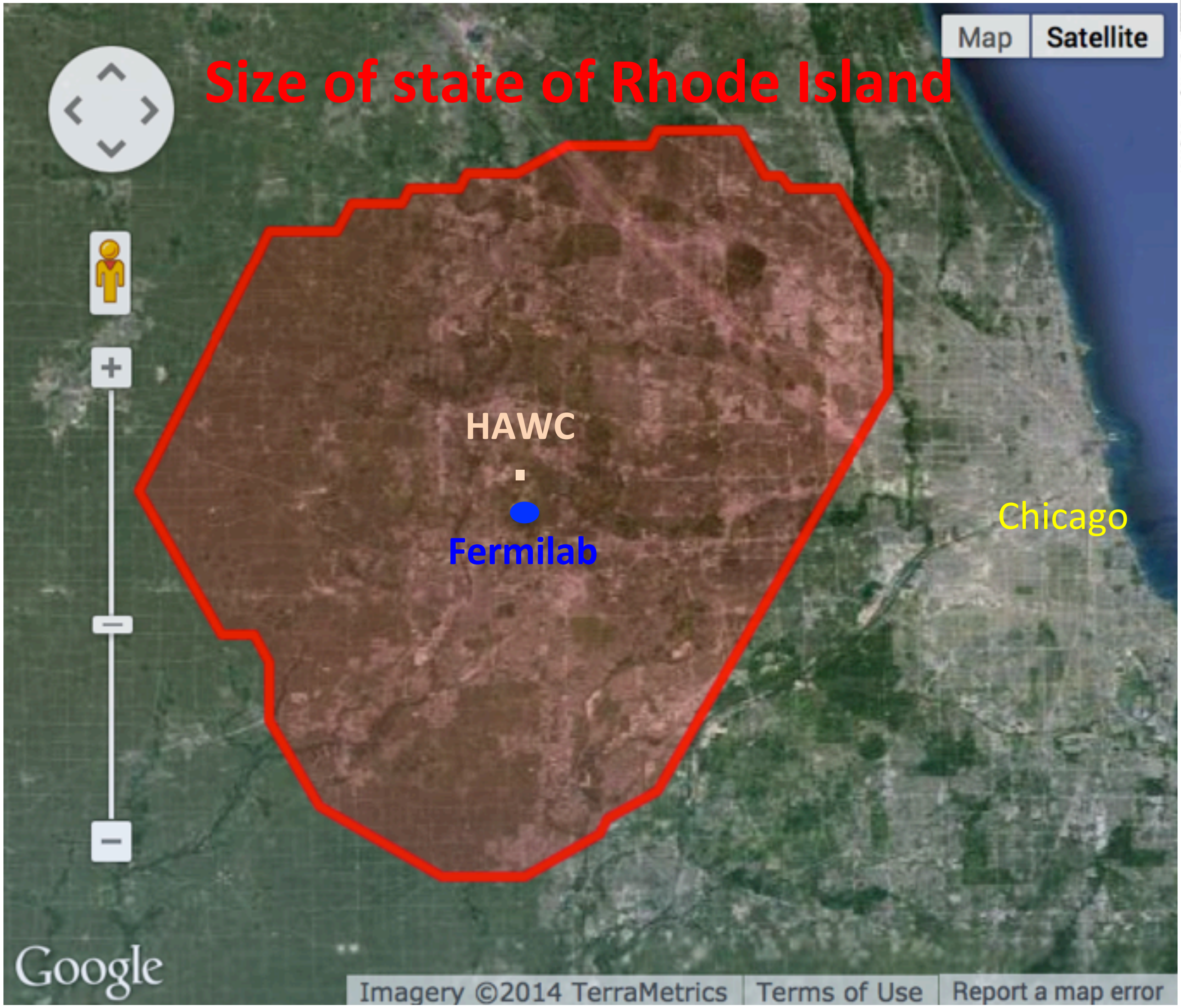
The HAWC Detector

Site Location

- Sierra Negra volcano near Puebla, Mexico
- HAWC altitude is 4100 m (2.55 miles)
- LMT altitude is 4500 m



HAWC vs. Pierre Auger



HAWC vs. **Pierre Auger**

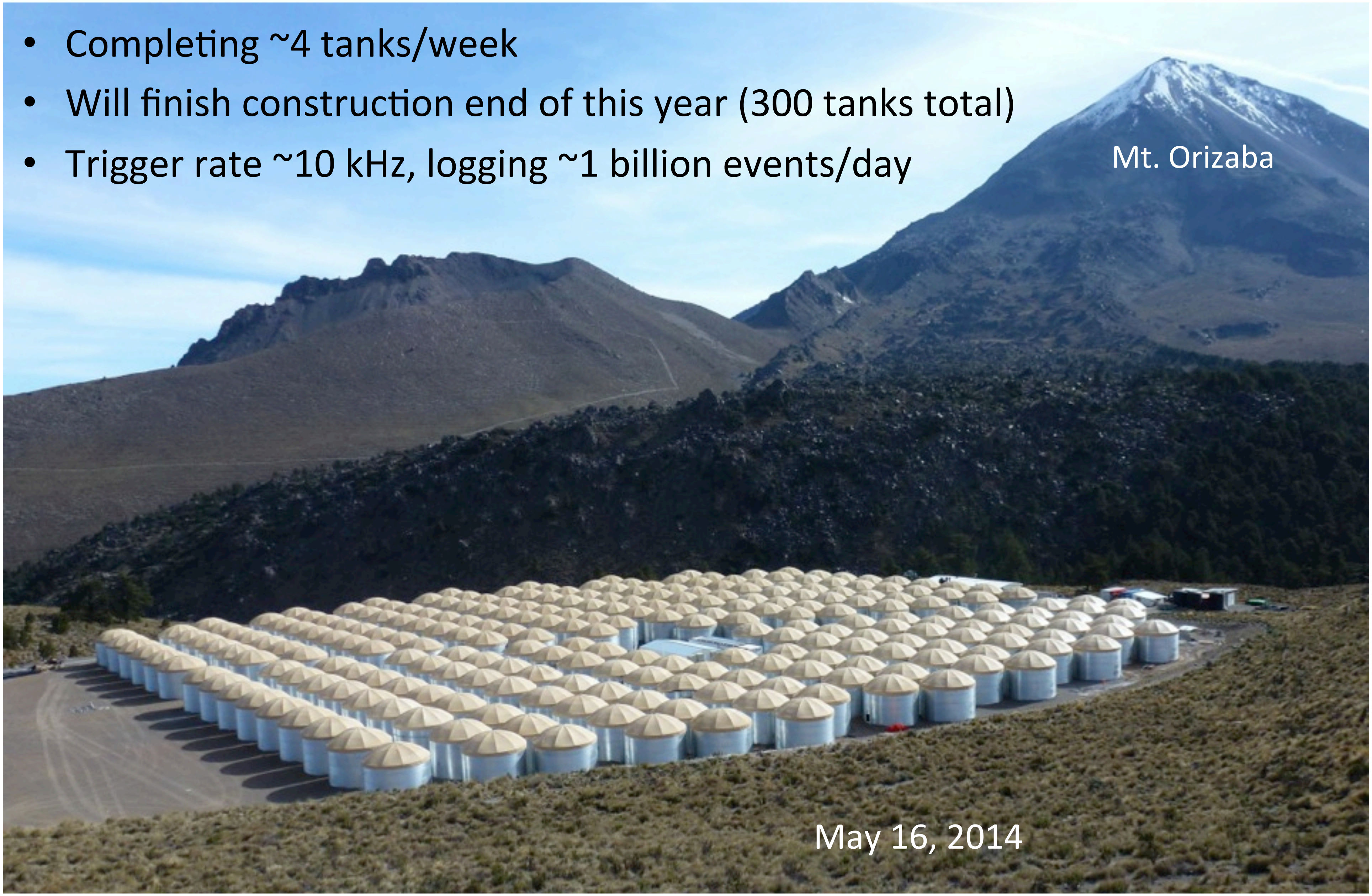
- **Studies gamma rays from 0.1 to 100 TeV**
- Looking for gamma rays coming from the cosmic rays
- Can point back to source directly without worrying about magnetic fields
- Smaller detector for lower energy particles and good shower reconstruction

- **Studies cosmic rays $>10^{18}$ eV = 10^{6} TeV**
- Looking for Ultra High Energy Cosmic Rays (UHECR) which are extremely rare
- UHECR showers cover a large area (several km^2)
- Need huge detector to see events which happen once per km^2 per year/decade

PIERRE AUGER OBSERVATORY

250 tanks on May 16, 2014

- Completing ~4 tanks/week
- Will finish construction end of this year (300 tanks total)
- Trigger rate ~10 kHz, logging ~1 billion events/day

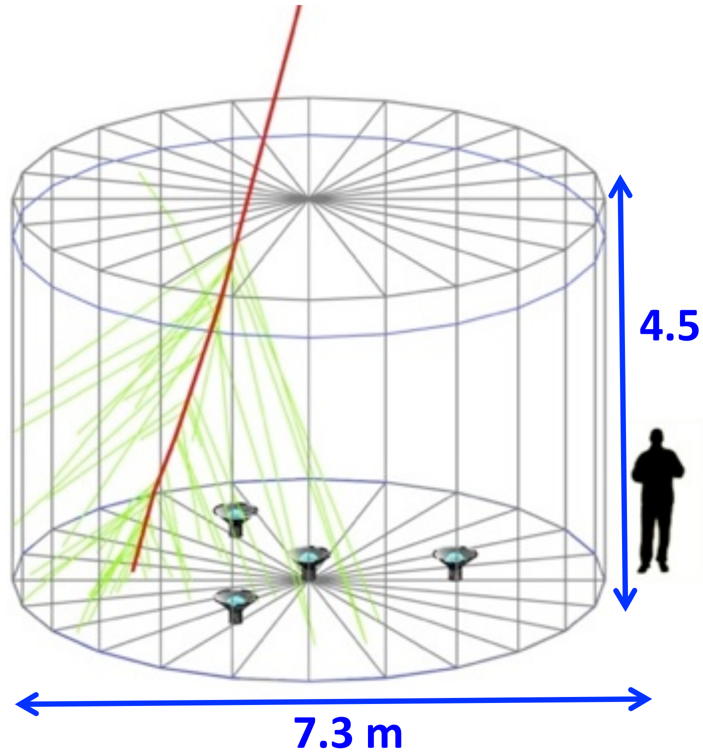


Tank construction

7.3 m dia x 4.5 m deep

Bladders and PMTs

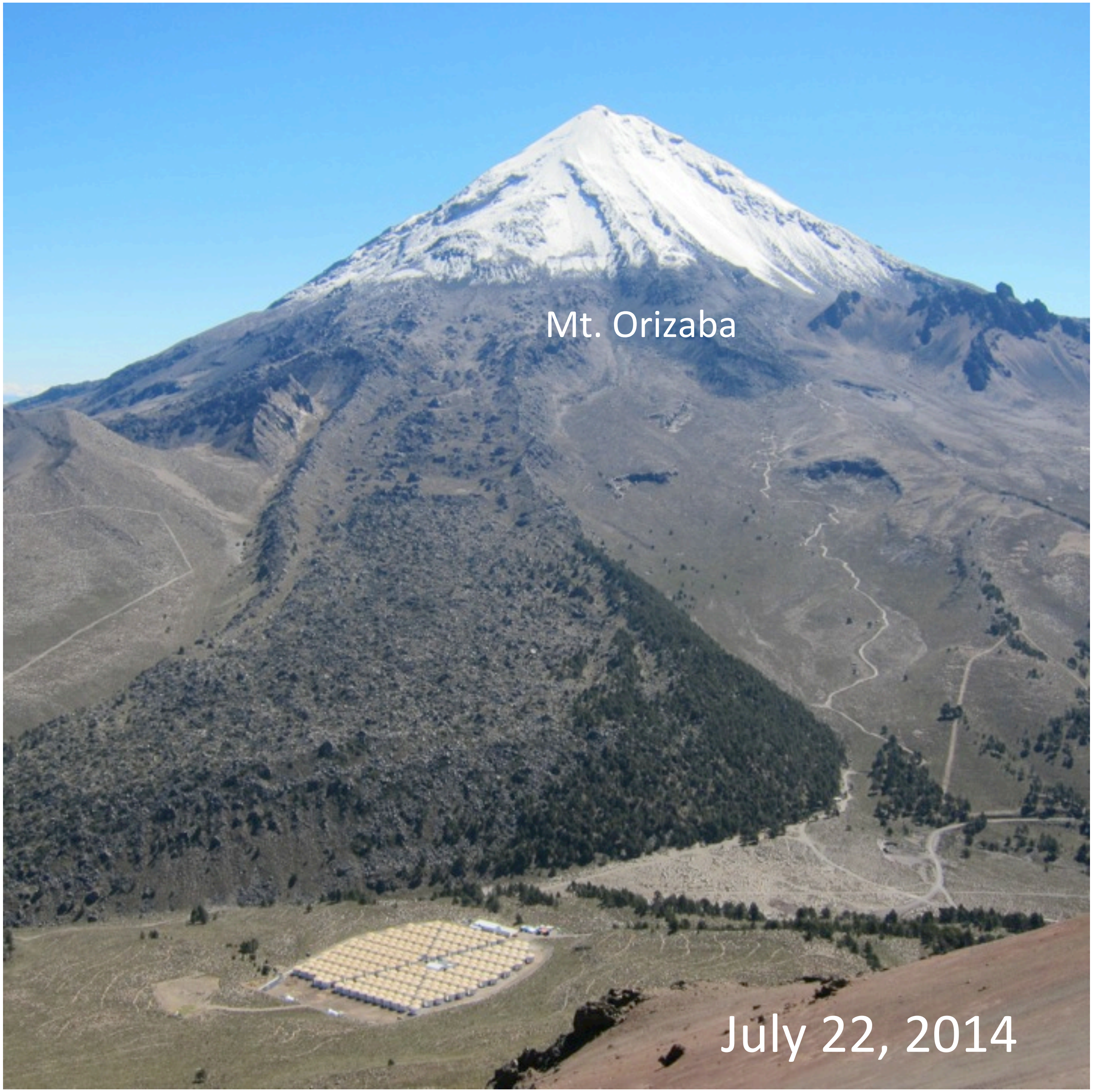
Depth and spacing of PMTs was optimized for γ-ray **sensitivity from 50 GeV to 100 TeV**.



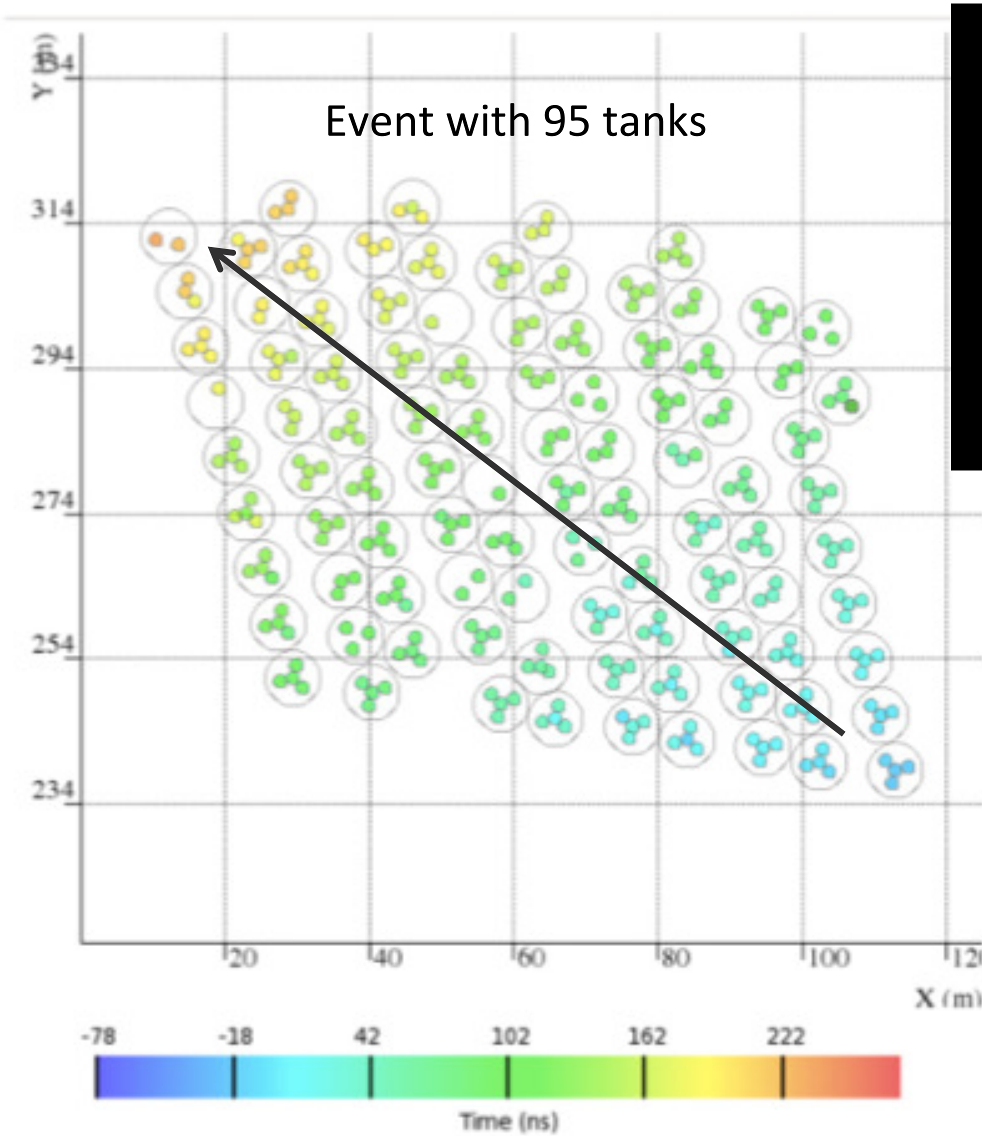
Funding from LANL to add 4th (higher QE) 10” PMT
effectively 2x 8” PMT

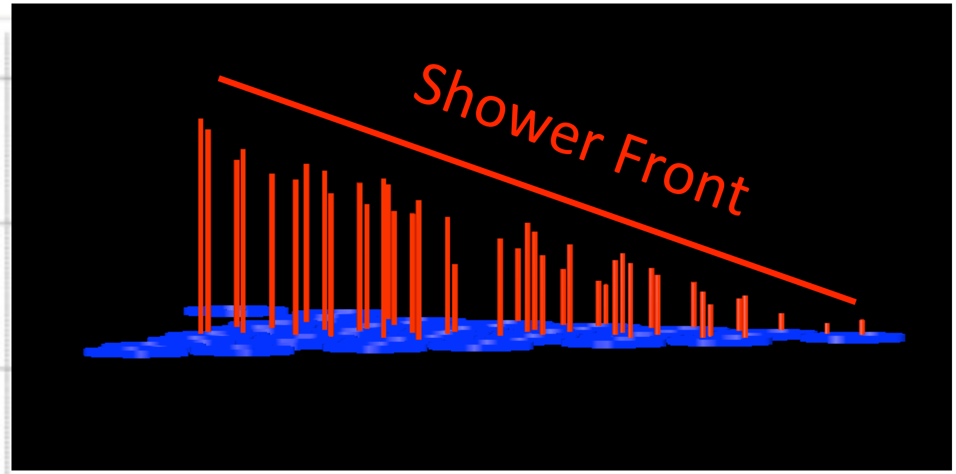
Filling the Tanks with Water

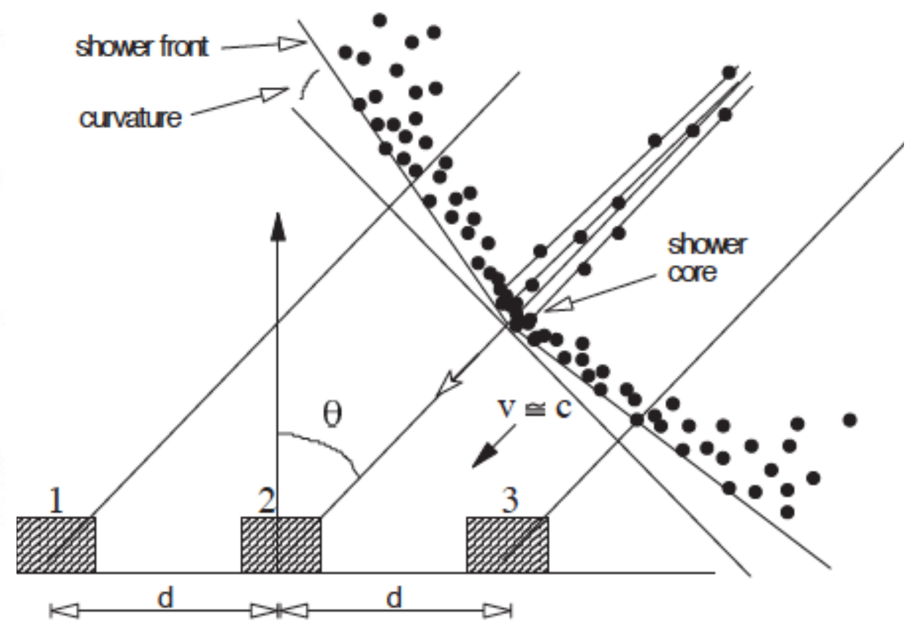
- One tank requires 14 truck loads of water (200,000 L)
- Filtration system takes 5 hours to fill one tank.
- PMTs are installed wet in batches later, independent of water filling.


Mt. Orizaba
July 22, 2014

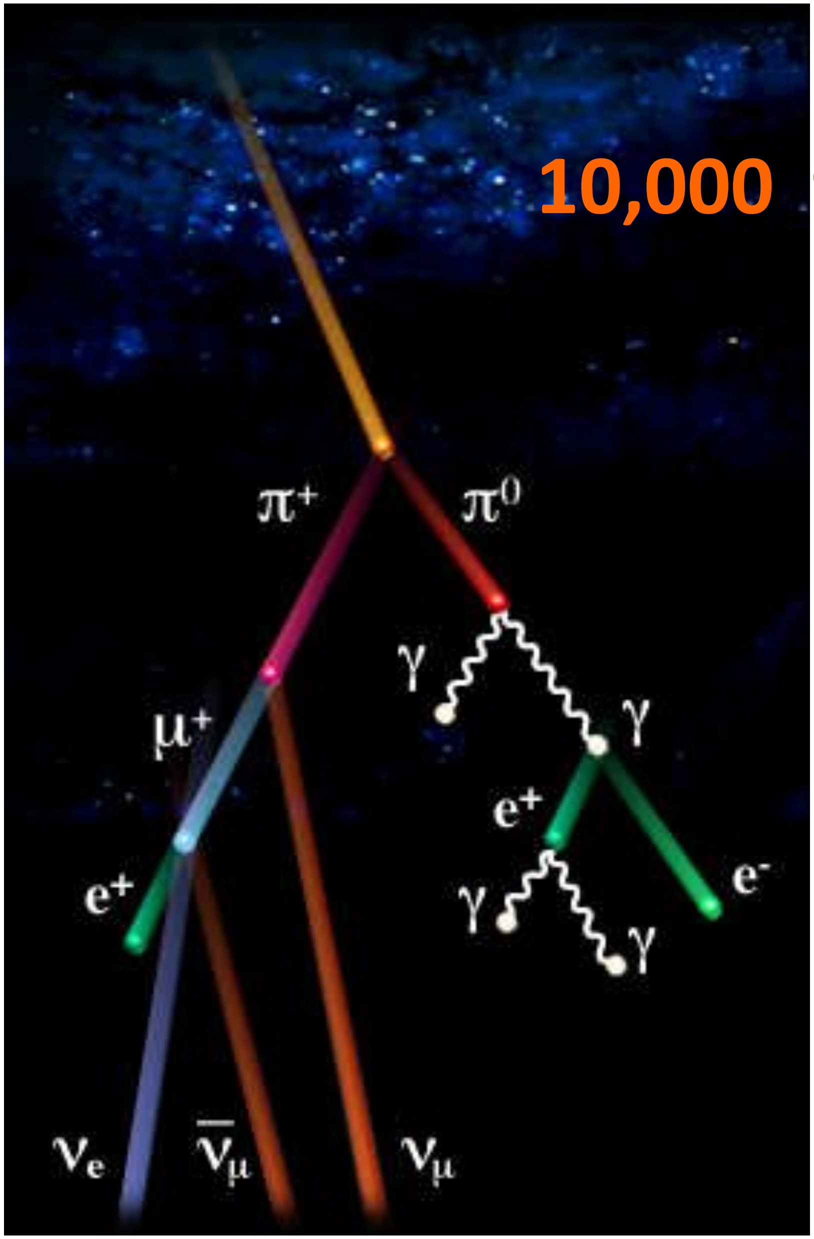
Pointing Back to a Source



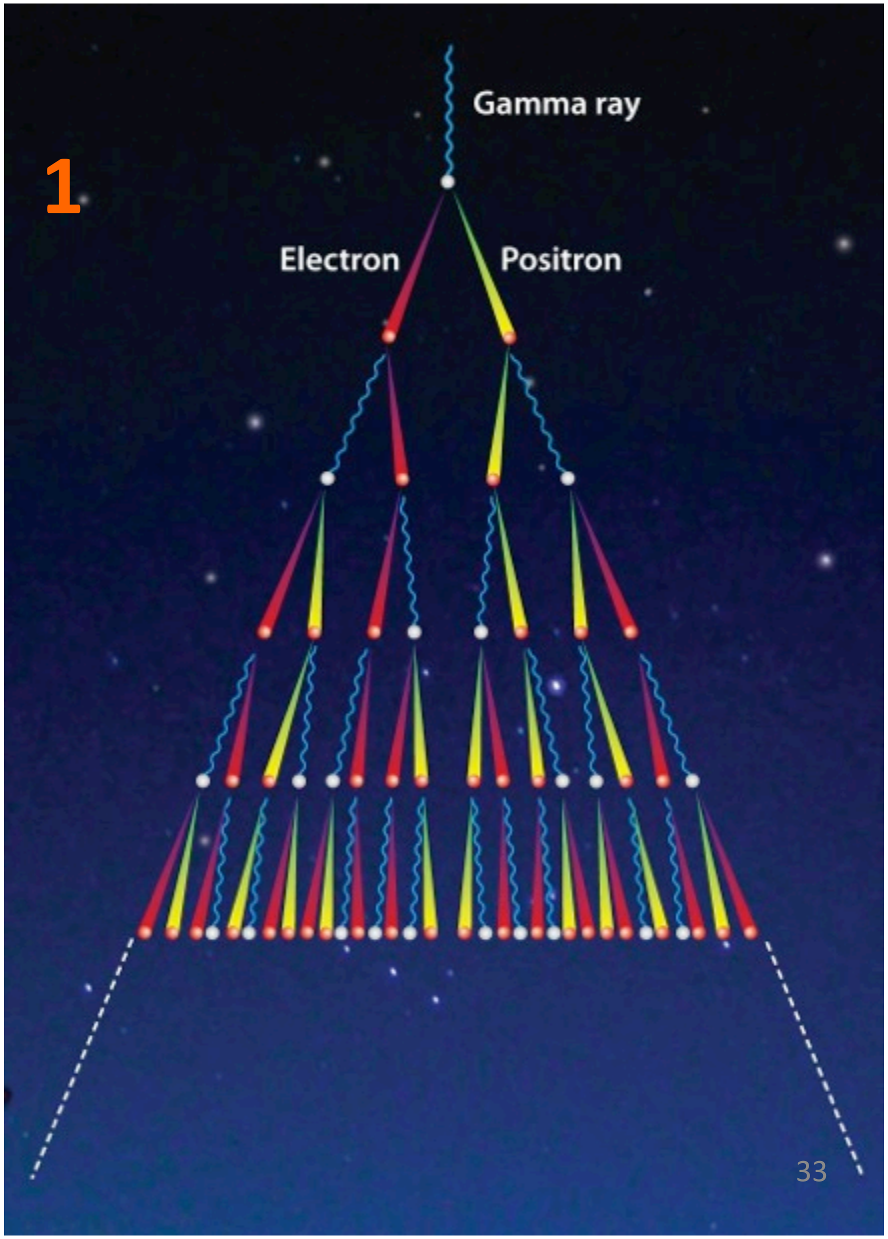




Cosmic Rays vs. Gamma Rays

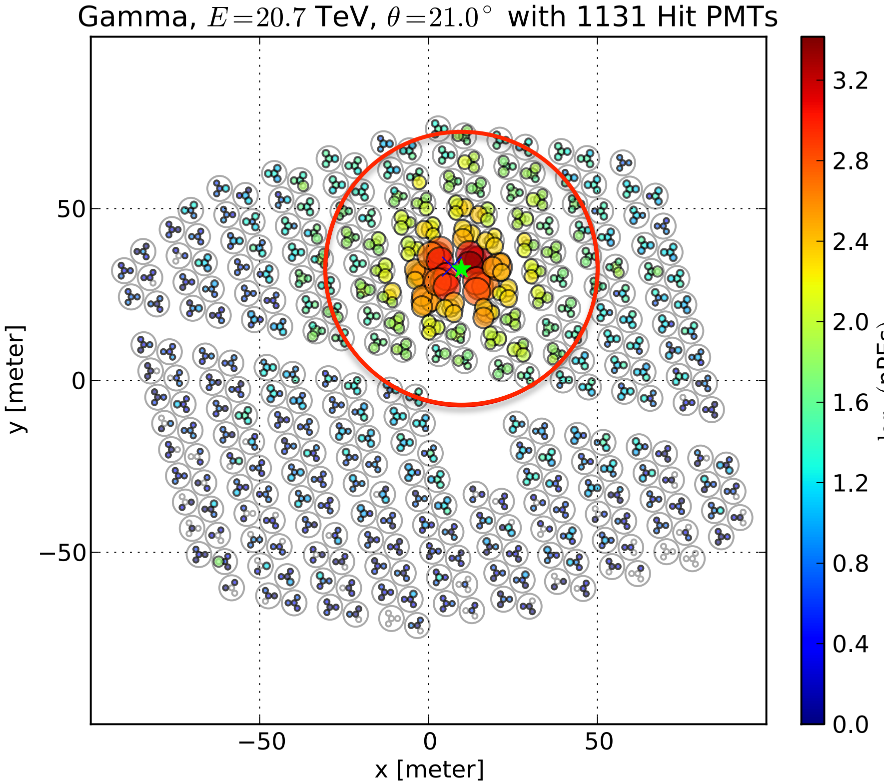


10,000 to 1

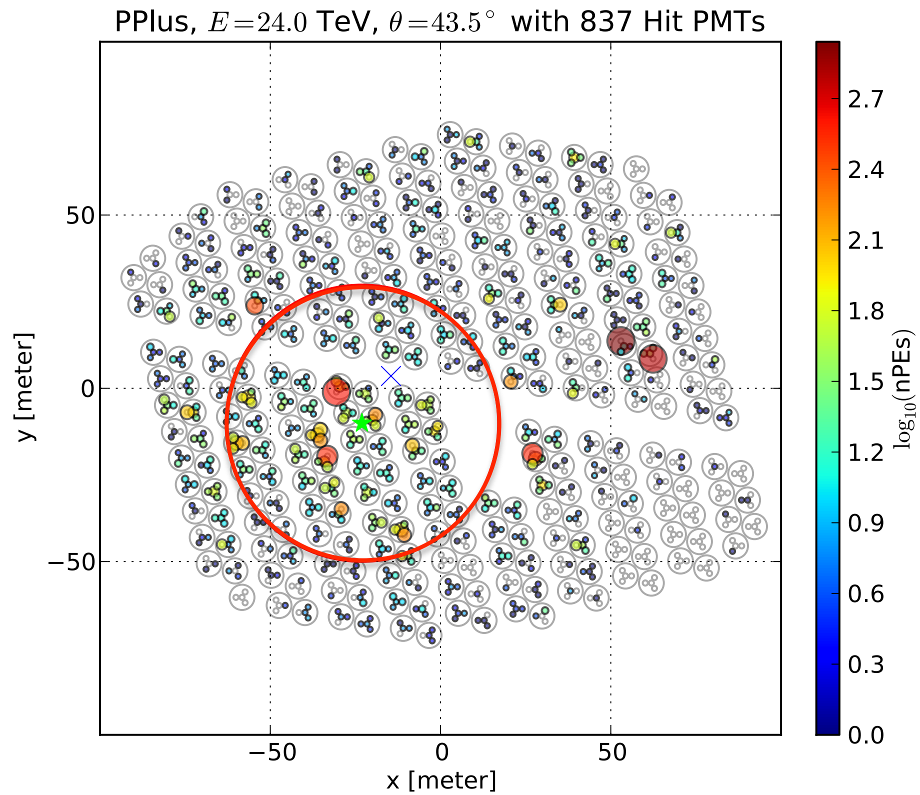


Photon / Hadron Discrimination

Gamma Ray

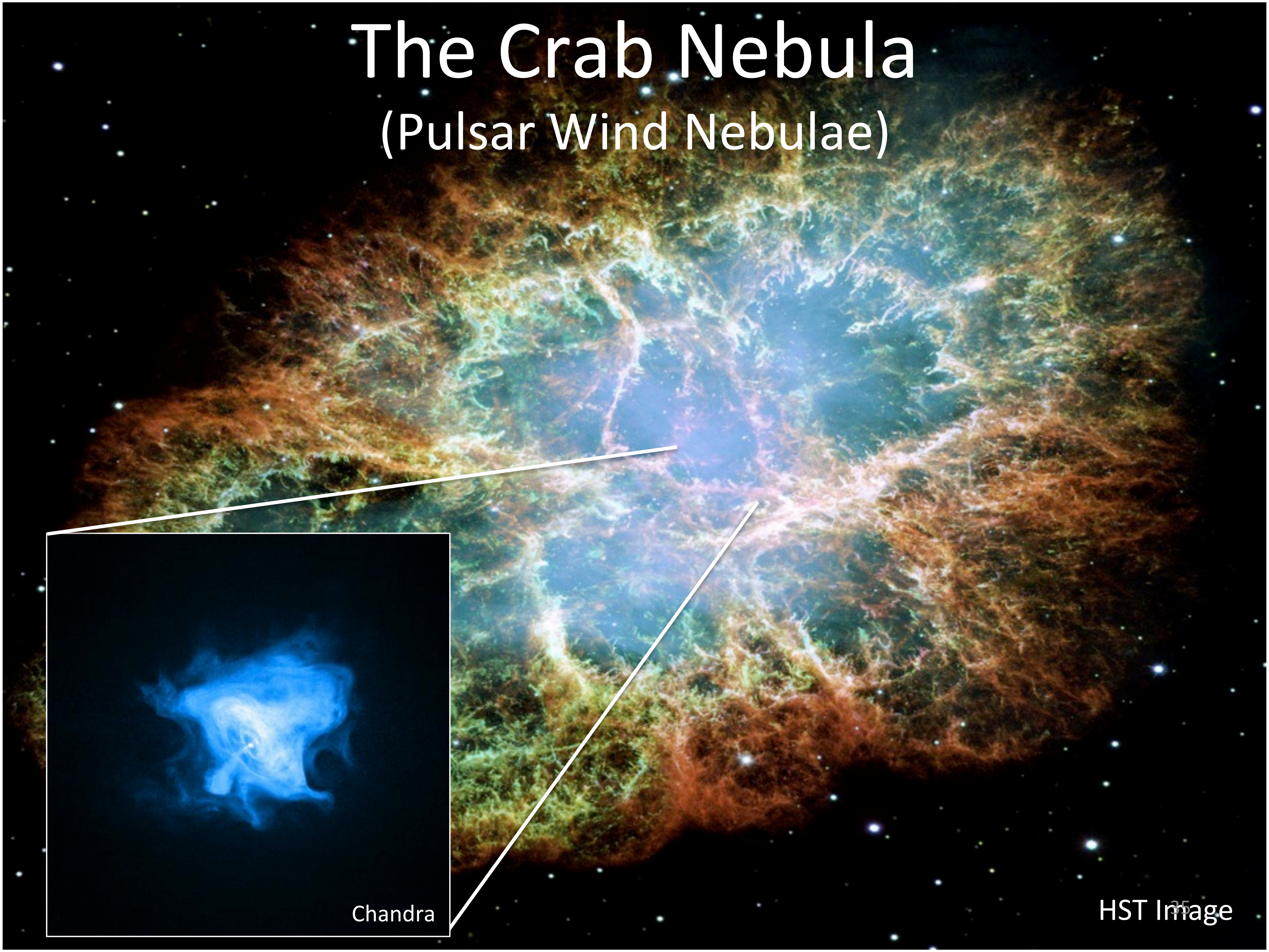


Proton



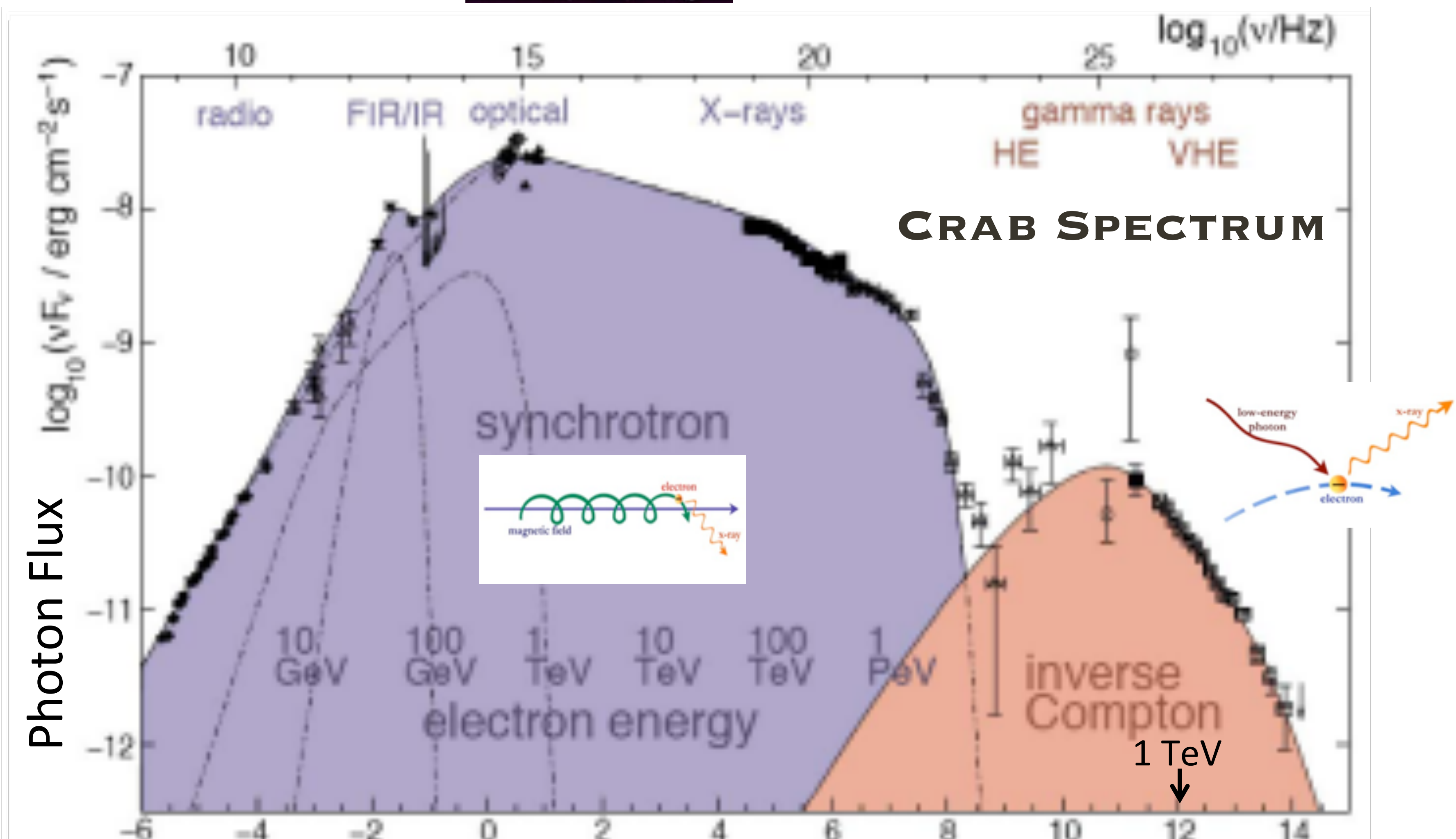
$$\text{Compactness} = \frac{\#\text{ of PMTs}}{\#\text{ of PEs outside } R > 40\text{ m}}$$

Play the game at http://www.hawc-observatory.org/observatory/ghsep.php


The Crab Nebula
(Pulsar Wind Nebulae)
Chandra
HST Image

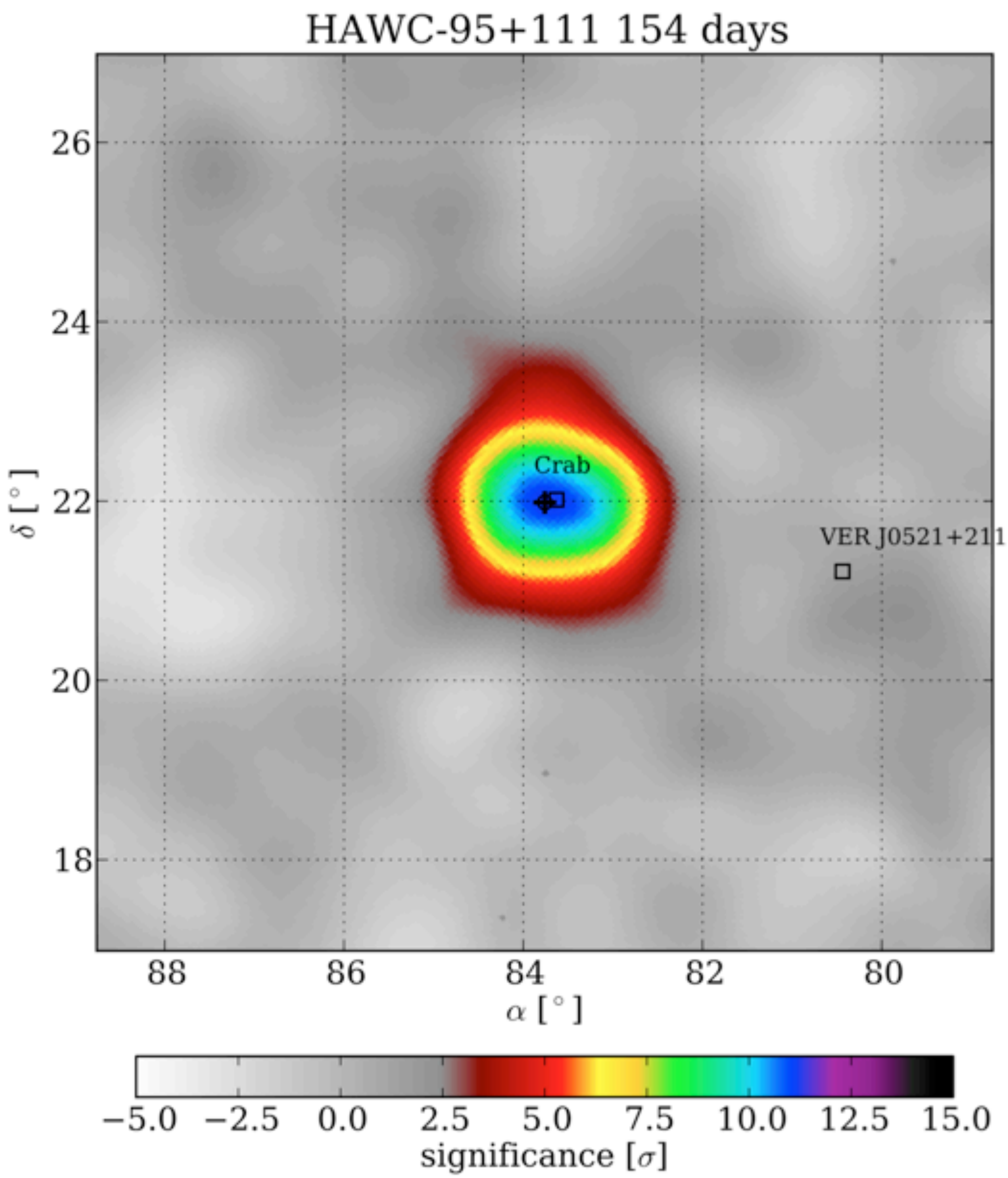
Crab Nebula

RADIO
INFRARED
OPTICAL
X-RAY



Photon Flux
log10(νFν / erg cm−2s−1)
log10(ν/Hz)
log10 (E/eV)
radio
FIR/IR
optical
X–rays
gamma rays
HE
VHE
Crab Spectrum
synchrotron
magnetic field
electron
x-ray
10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
1 PeV
electron energy
inverse Compton
1 TeV
low-energy photon
x-ray
electron

HAWC Sees the Crab



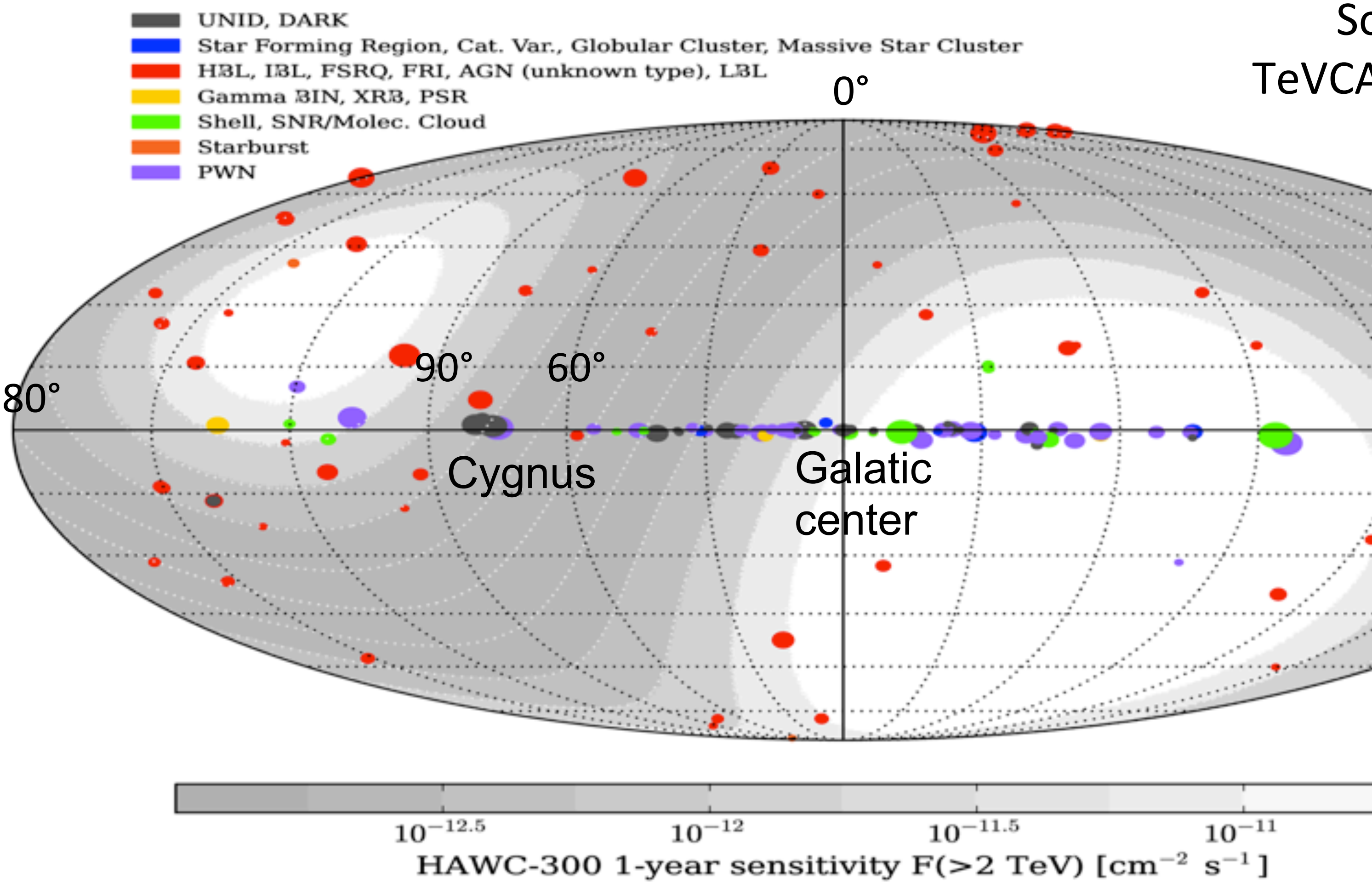
HAWC-300 will:

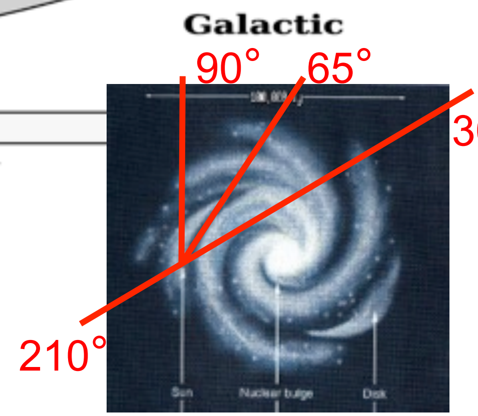
Detect the Crab at >5σ every day

5×10^{-13} γ/cm^{-2} s^{-1} sensitivity (> 2 TeV) across 5 sr (40%) of the sky in 1 year.

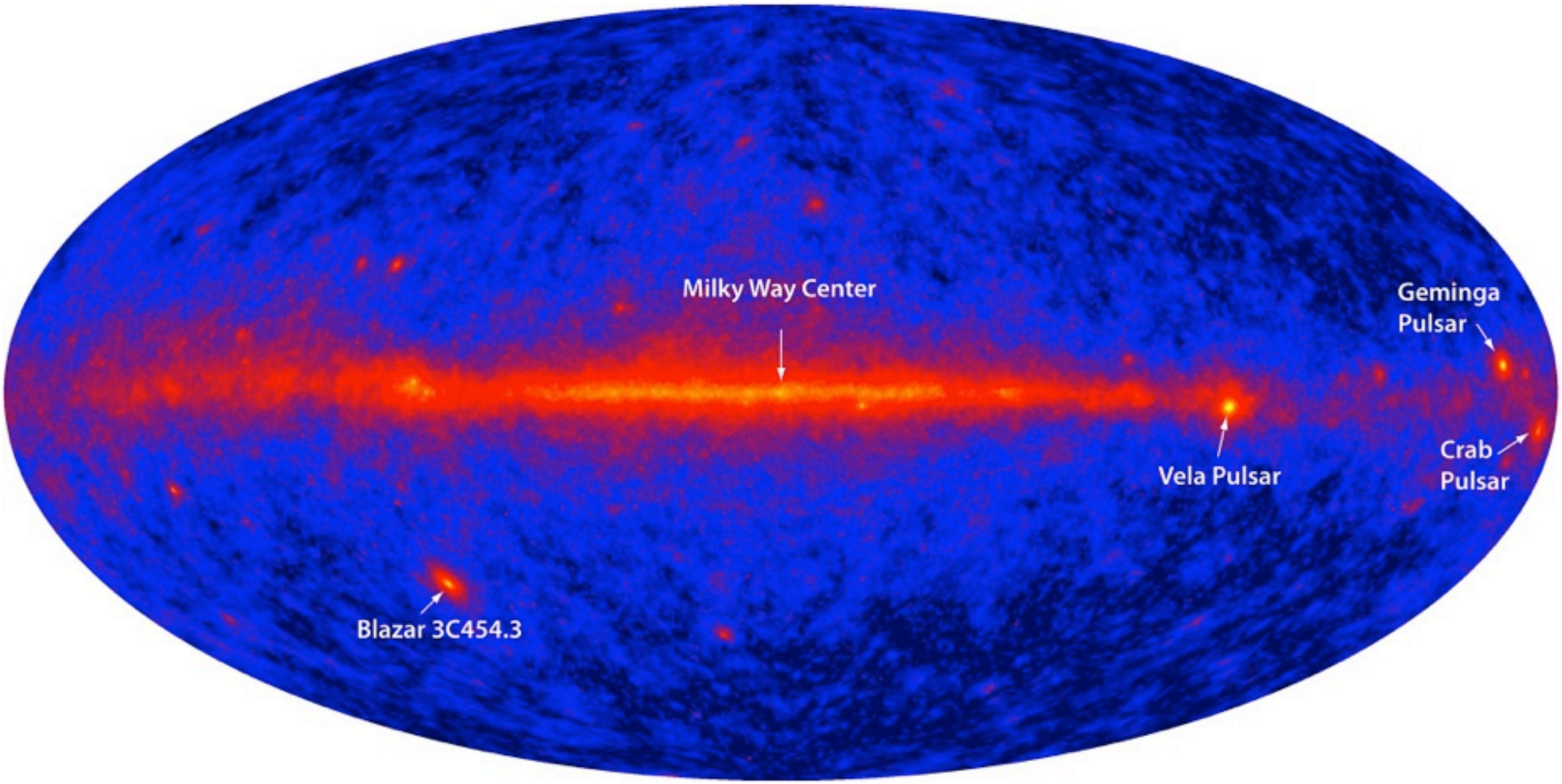
HAWC Field Of View

Sources from
TeVCAT.uchicago.edu



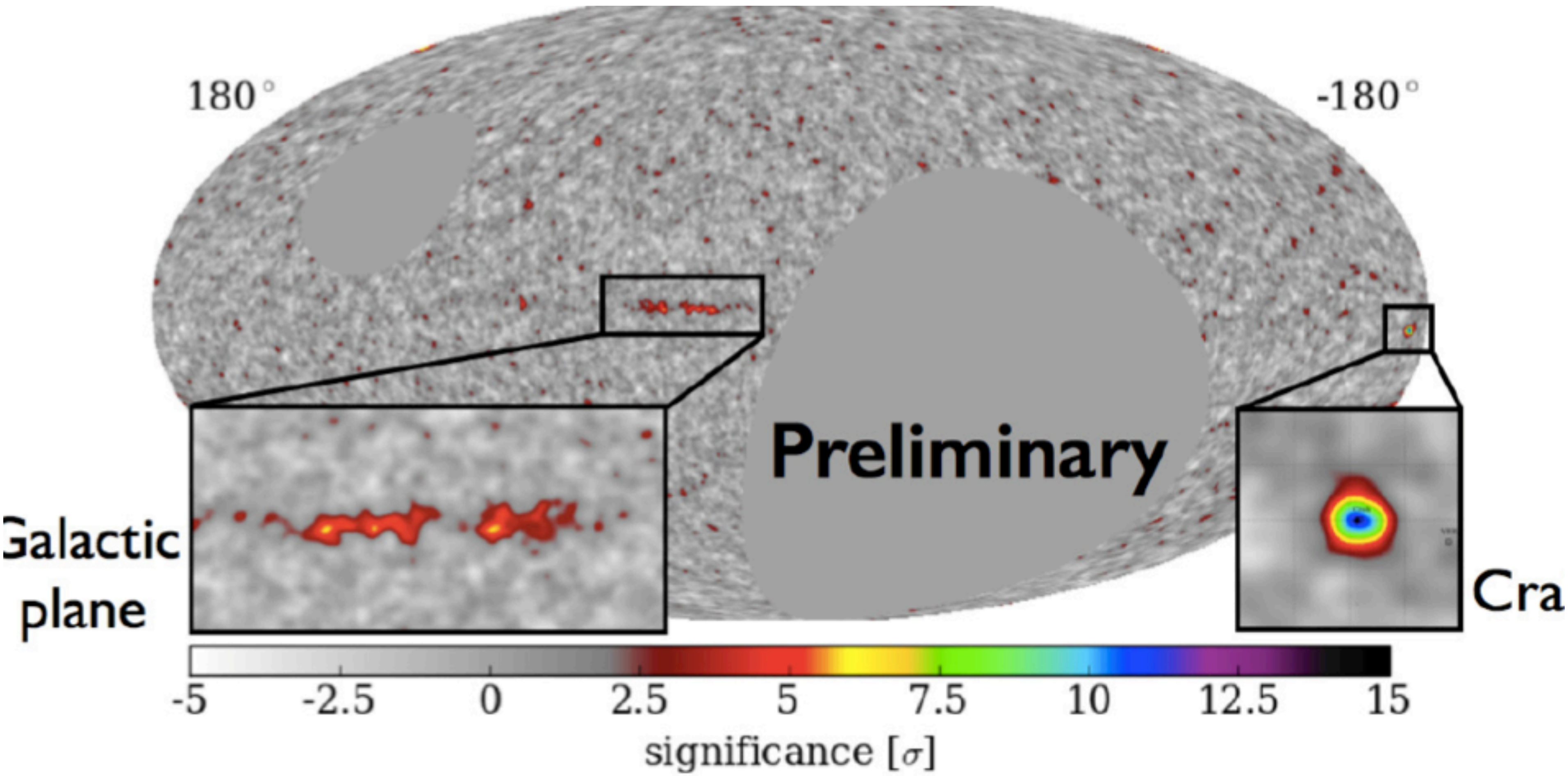


FermiLAT Satellite Sky Map



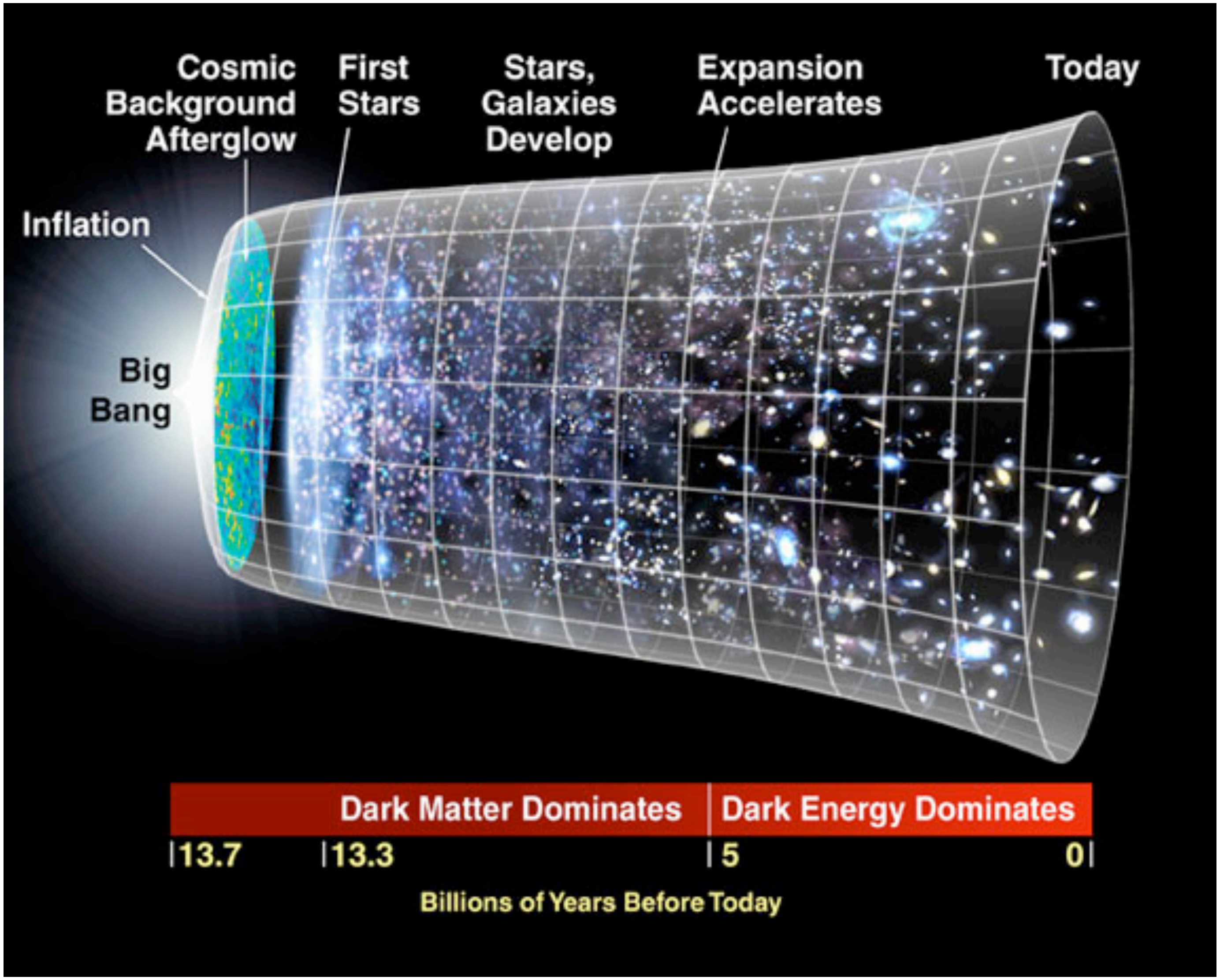
30 MeV to 300 GeV

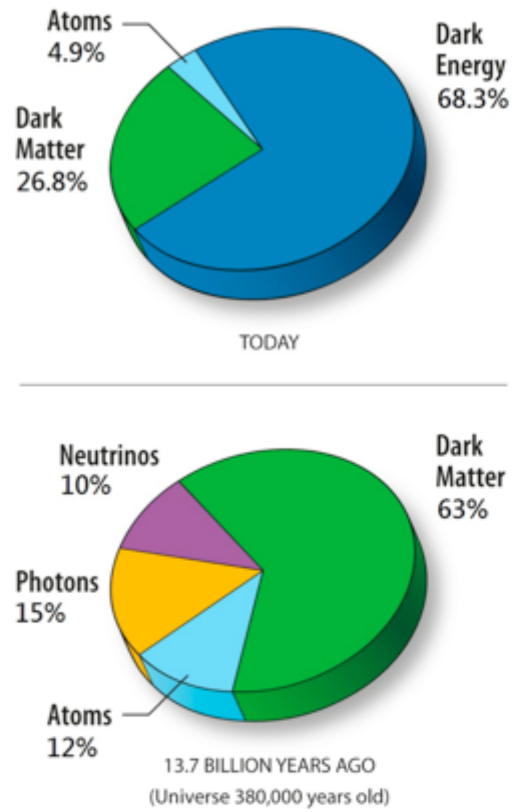
HAWC Sky Map



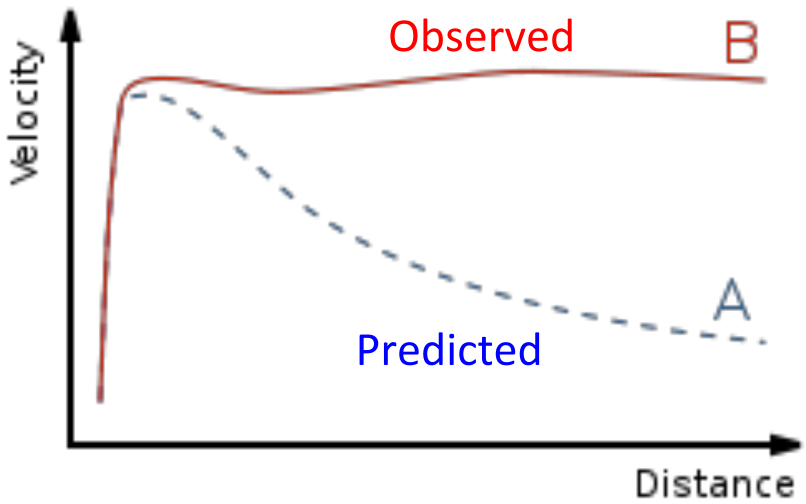
100 GeV to 100 TeV

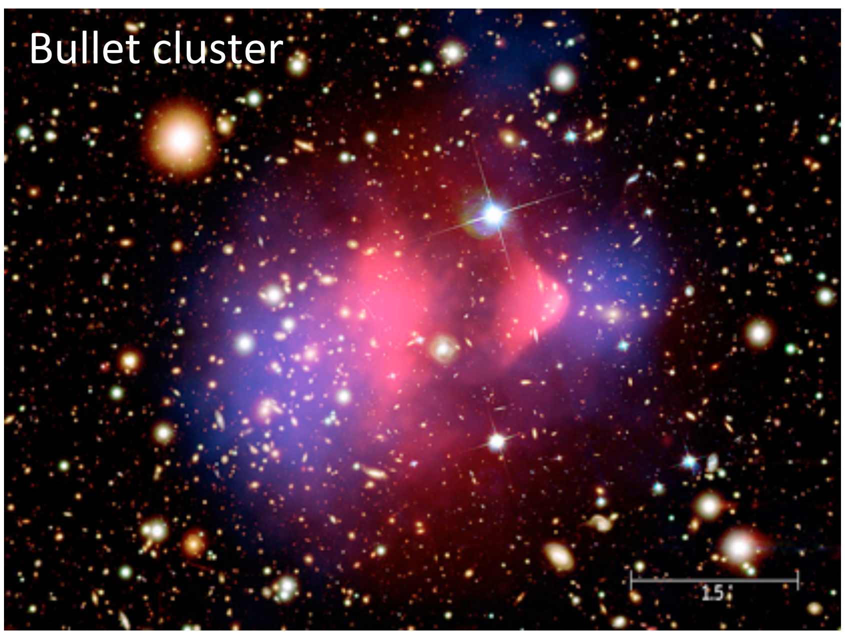
Evolution of the Universe

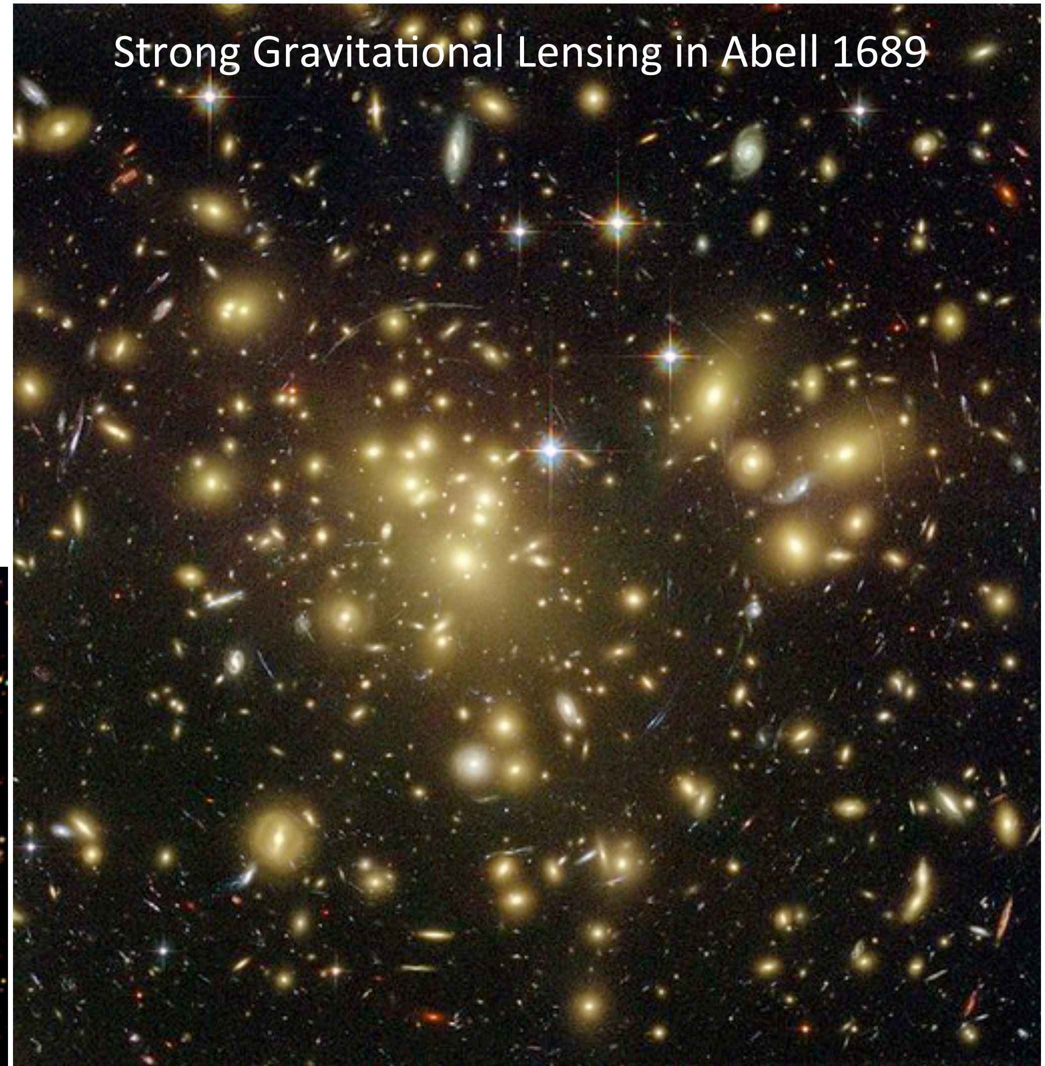




Dark Matter

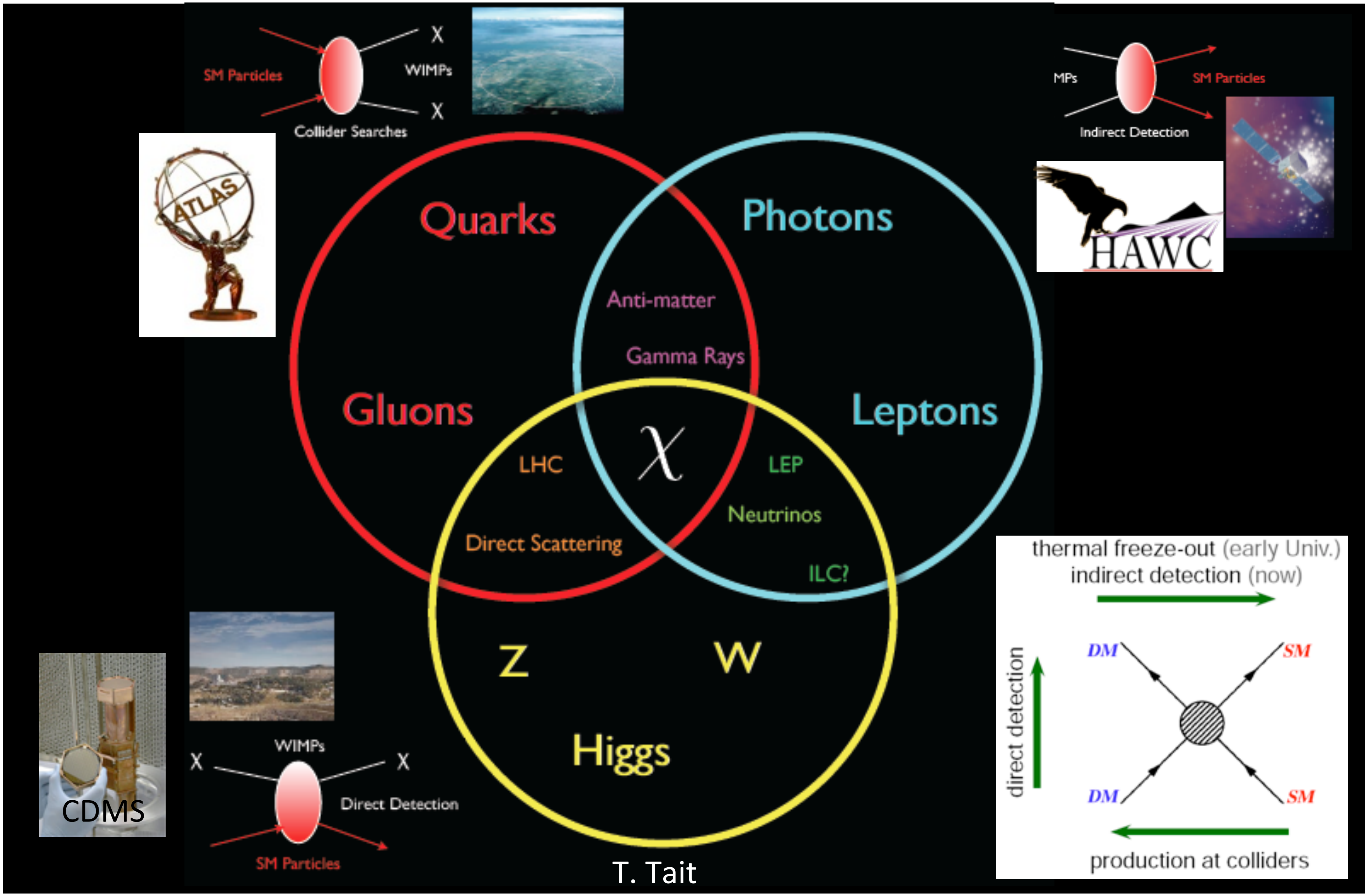


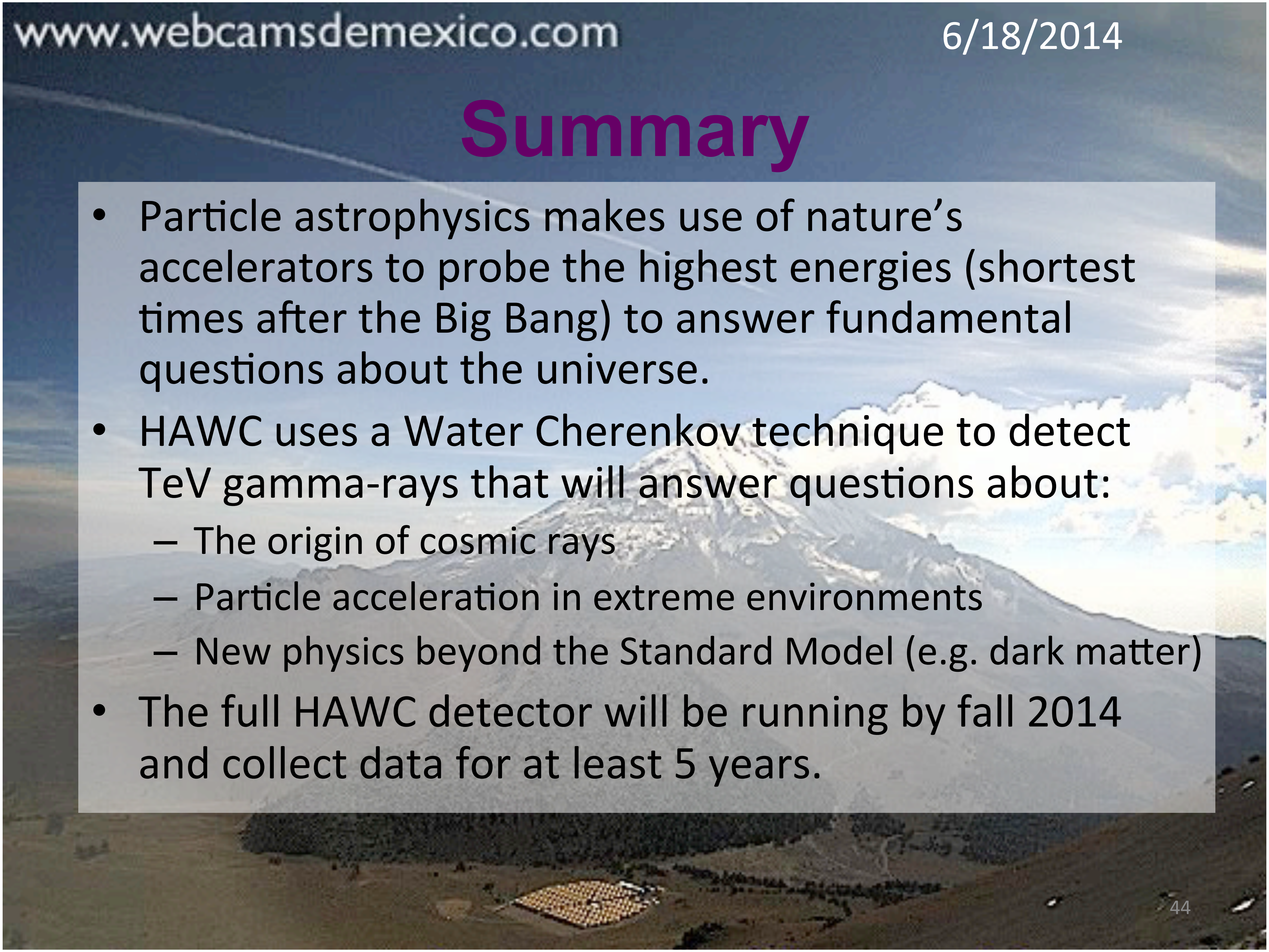




Red = x-ray emitting hot gas
Blue = Total projected mass from gravitation lensing

Looking for Dark Matter, χ





Summary

- Particle astrophysics makes use of nature's accelerators to probe the highest energies (shortest times after the Big Bang) to answer fundamental questions about the universe.
- HAWC uses a Water Cherenkov technique to detect TeV gamma-rays that will answer questions about:
  - The origin of cosmic rays
  - Particle acceleration in extreme environments
  - New physics beyond the Standard Model (e.g. dark matter)
- The full HAWC detector will be running by fall 2014 and collect data for at least 5 years.