HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

GAMMA RAY ASTROPHYSICS AND THE HAWC OBSERVATORY

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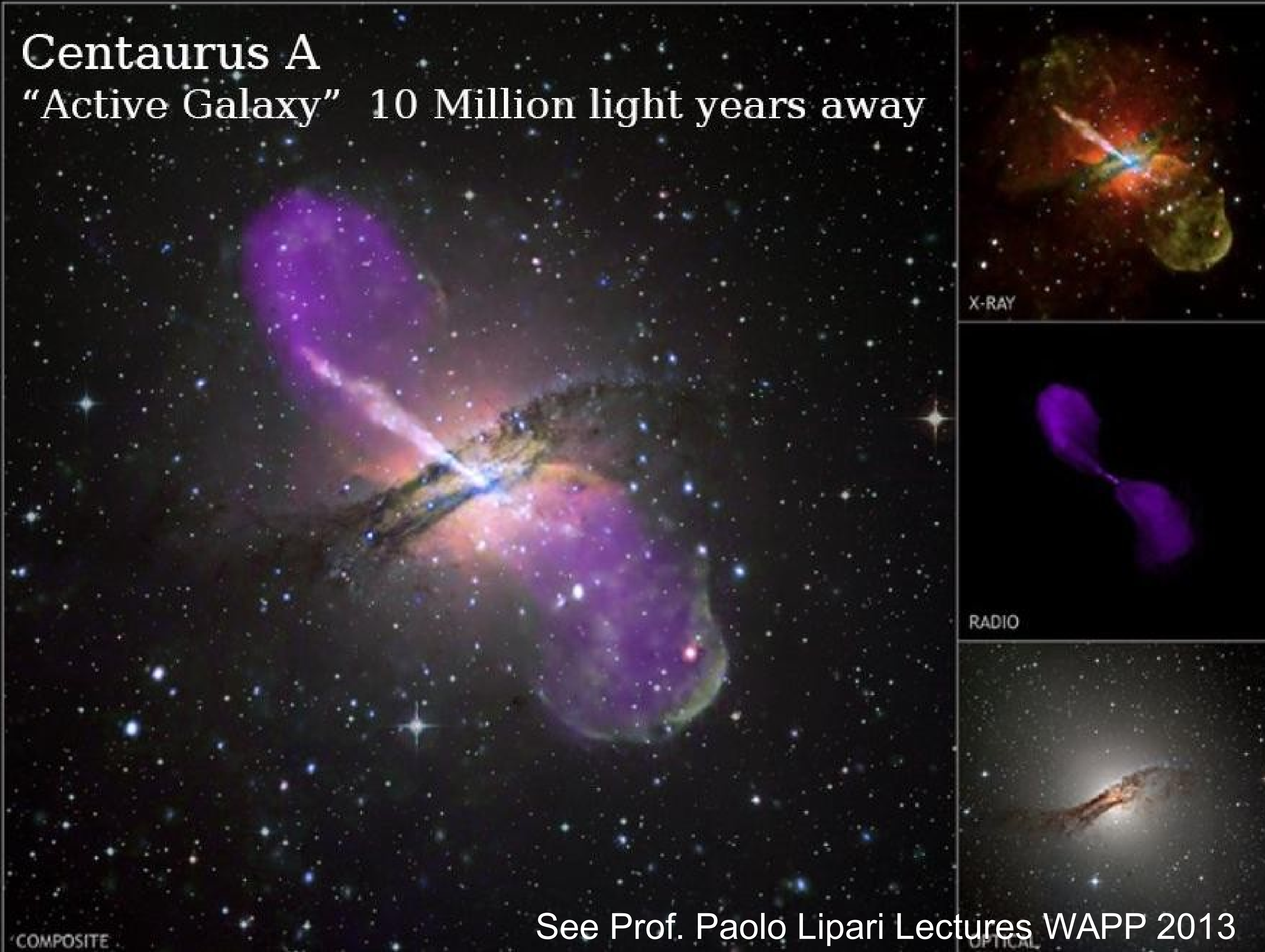
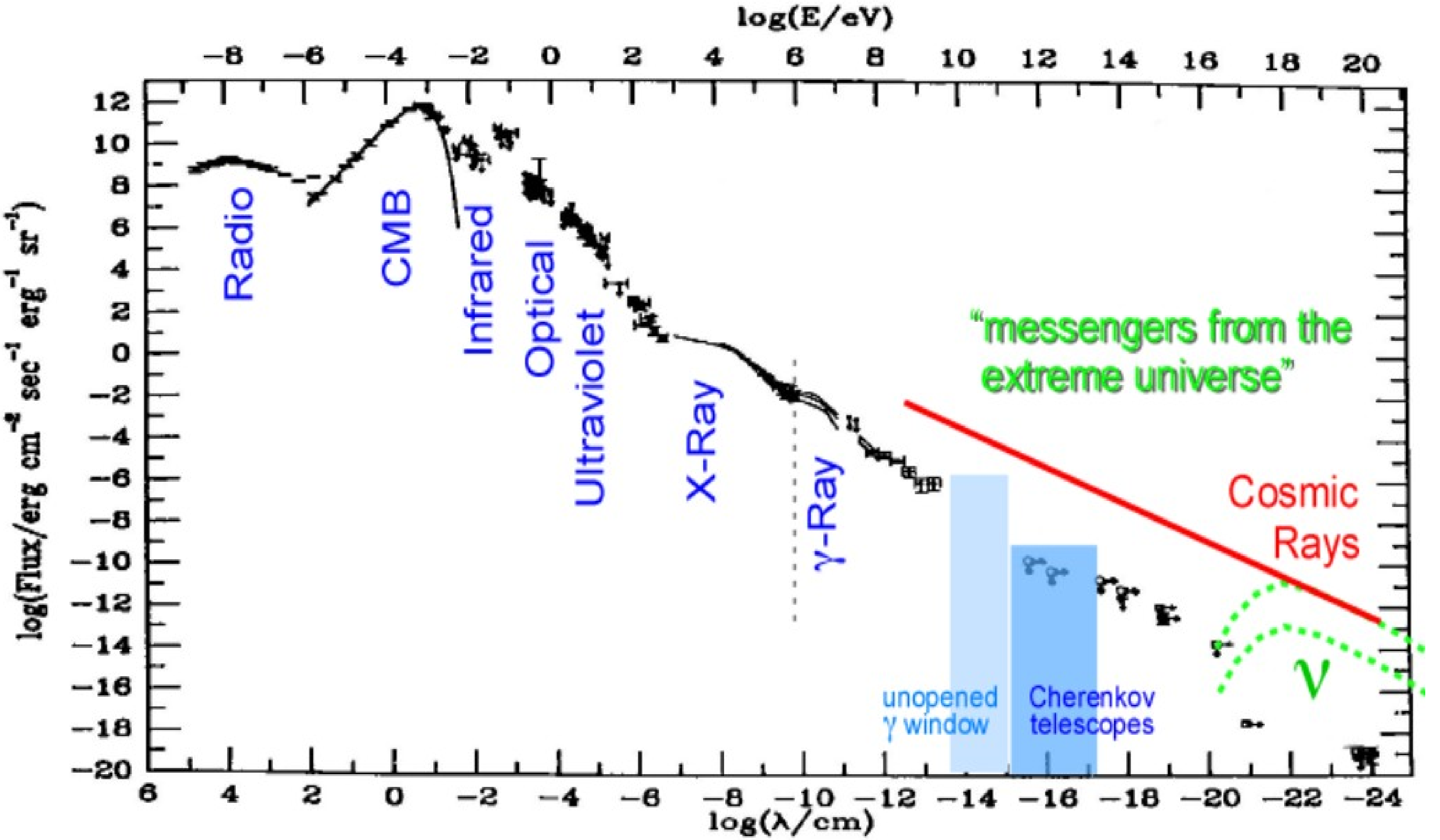
10th Winter School on Astroparticle Physics, 21-29 December, 2015, Bose Institute, Darjeeling, India


Centaurus A
“Active Galaxy” 10 Million light years away
X-RAY
RADIO
OPTICAL
COMPOSITE
See Prof. Paolo Lipari Lectures WAPP 2013

universal photon / particle spectrum



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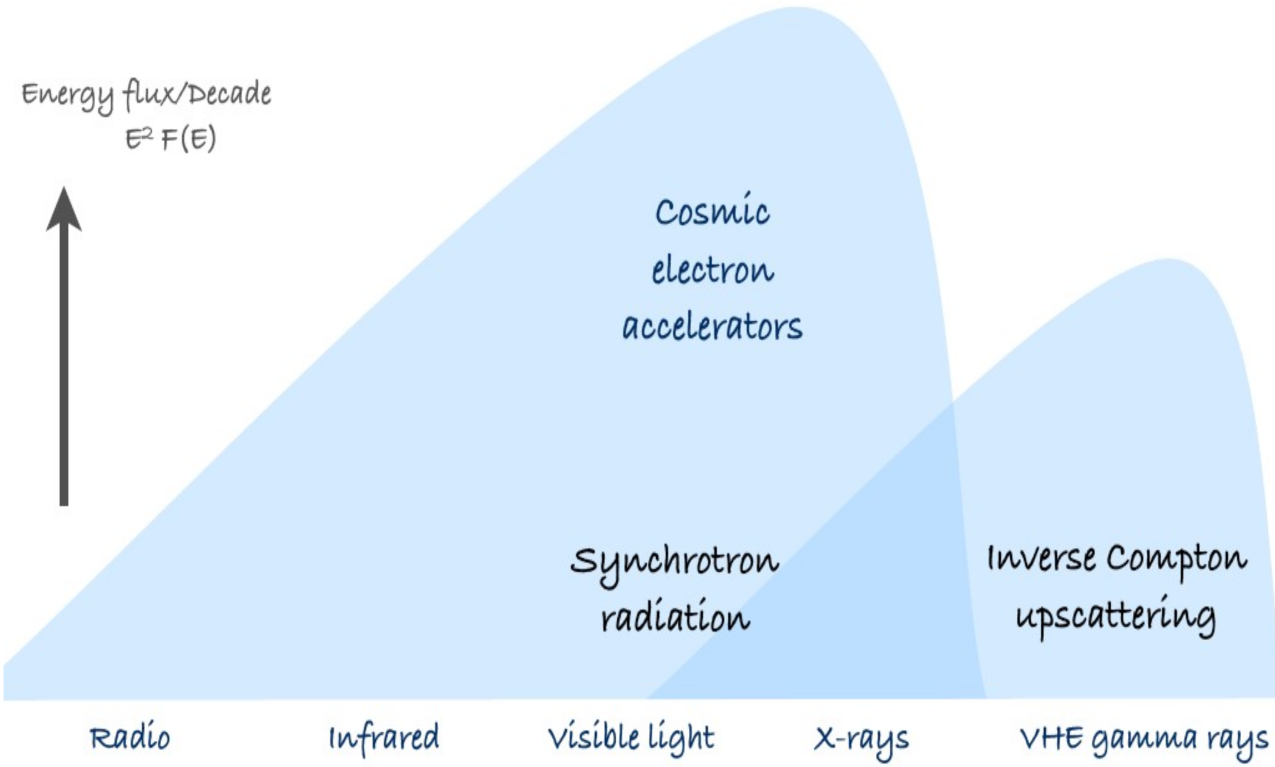
Spectral Energy Distribution (SED)



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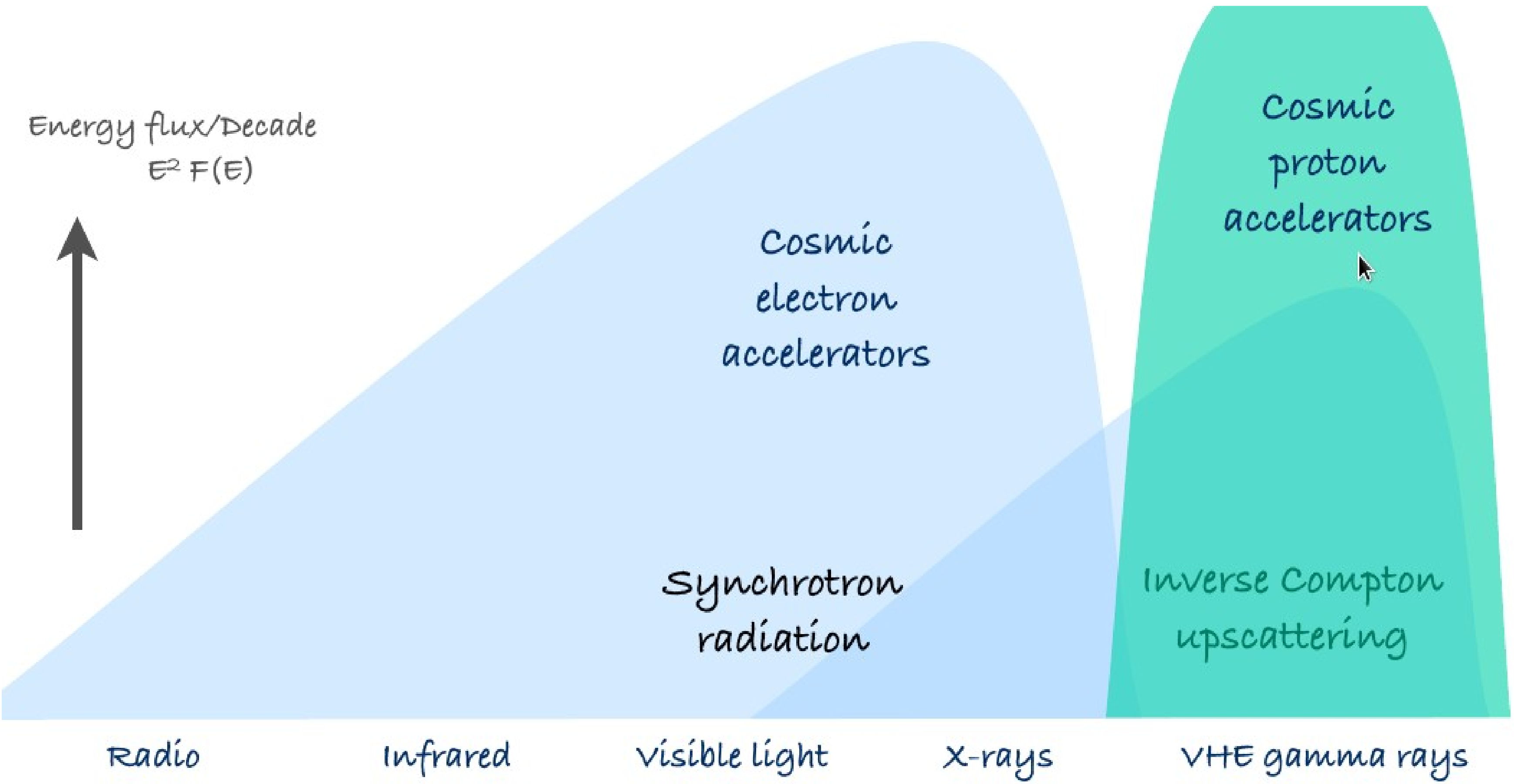
Spectral Energy Distribution (SED)



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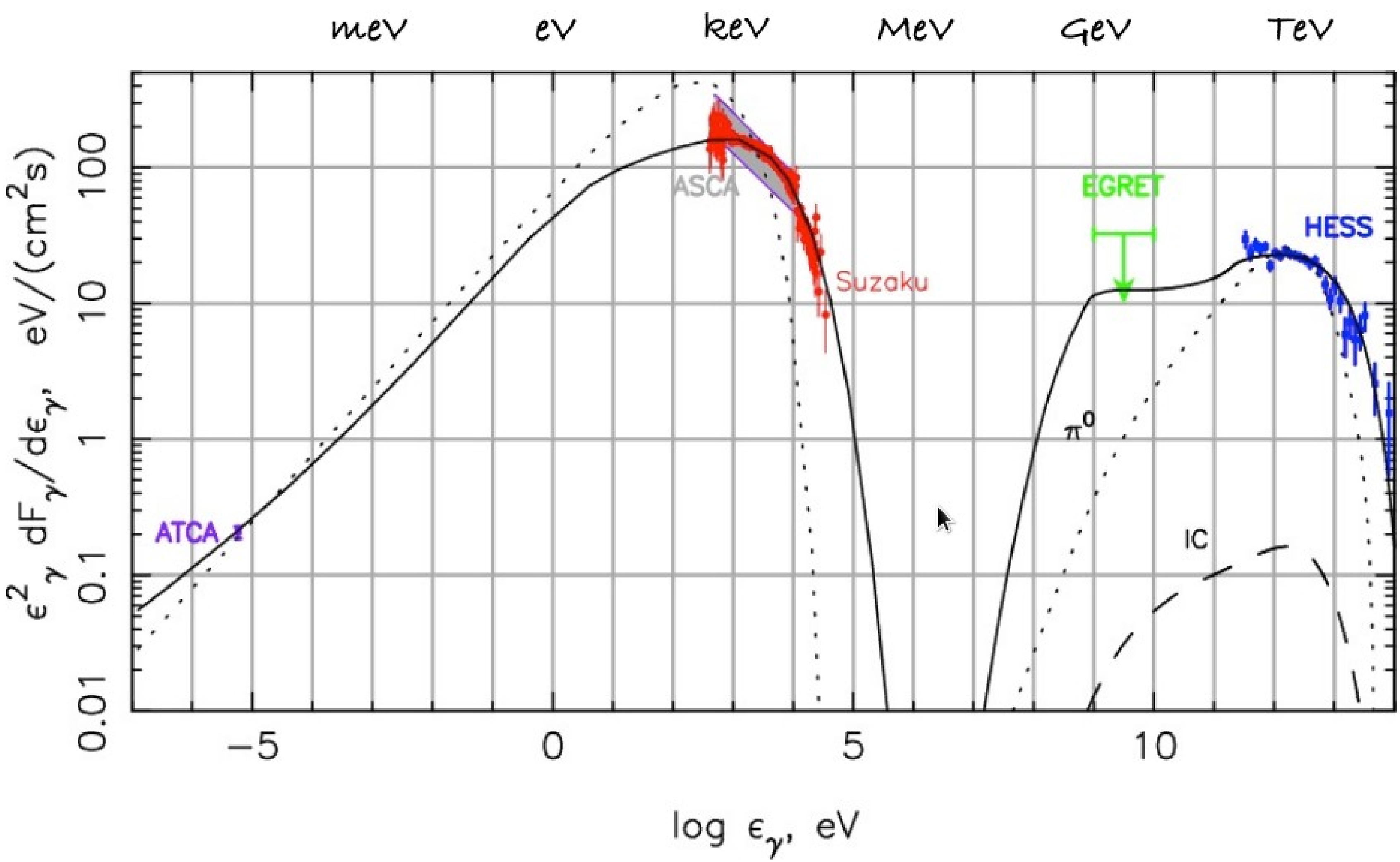
Supernova Remnant RX J1713.7-3946



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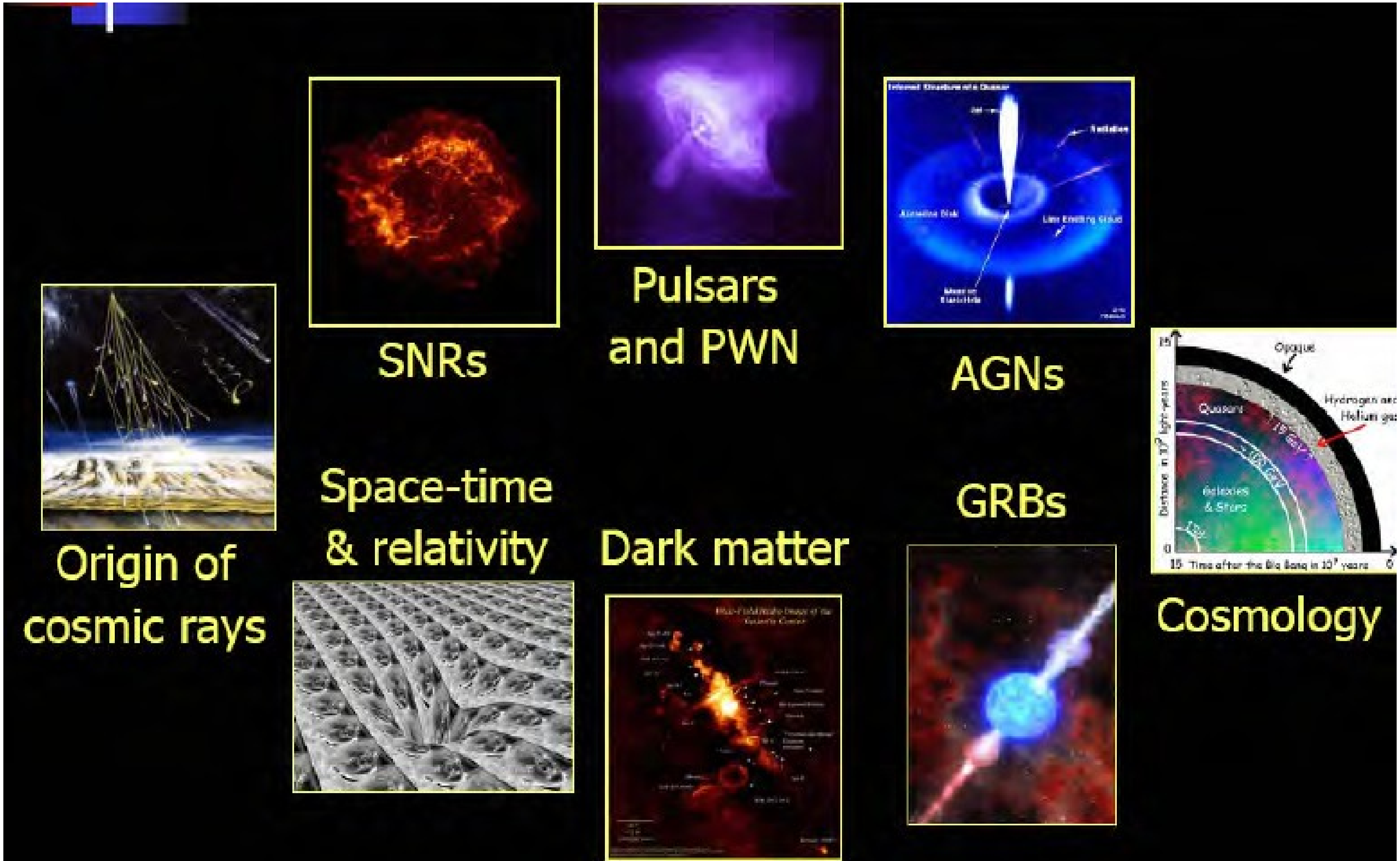
TeV γ-ray astronomy: science topics



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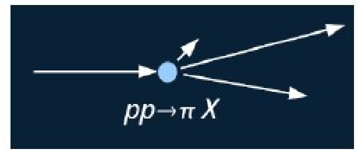
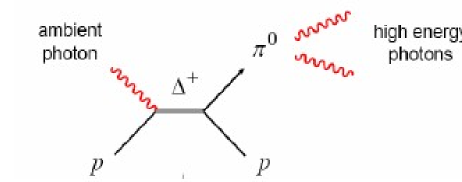
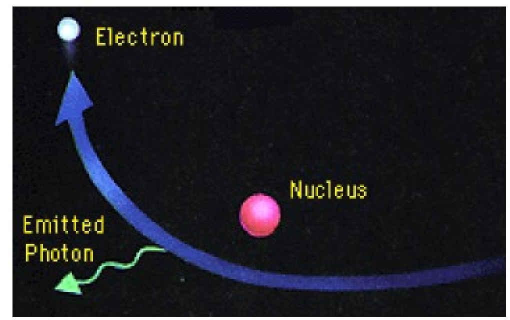
TeV γ-rays: production processes

By interaction with matter



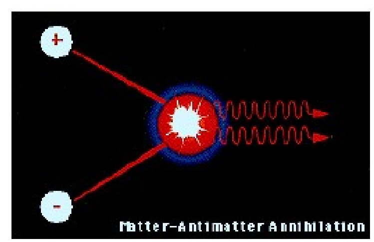


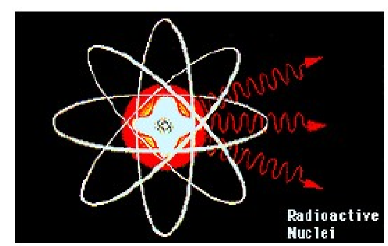
π^o – decay:
In hadronic interactions produced neutral pions decay Immediately: $\pi^0 \rightarrow \gamma + \gamma$ (τ = 8.4 · 10^{-17} s)



Electron - Bremsstrahlung:
Deflected electrons in the coulomb field of nuclei emit radiation with the probability
$\phi \propto z^2 Z^2 E_e / m^2$

Annilihation and radioactive decay:
In dense matter annihilate electron-positron (proton-antiproton) pairs
$e^+ + e^- \rightarrow \gamma + \gamma$ ($\rightarrow E_\gamma = 511$ keV)
$p + \bar{p} \rightarrow \pi^+ + \pi^- + \pi^0$





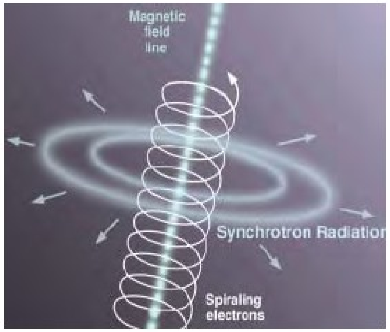
In elemental synthesis exist radioisotopes which have β – decay.

See Prof. Paolo Camarri Lectures WAPP 2012

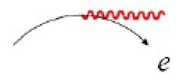
TeV γ-rays: production processes

By interaction with magnetic fields

Synchrotron radiation:
Radiation of accelarated charged particles (electrons) in magnetic fields.
Power of the radiation: $P \propto E_e^2 \cdot B^2$



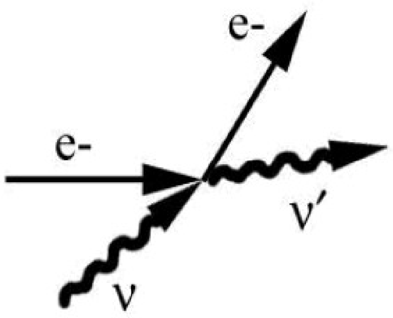
Synchrotron radiation



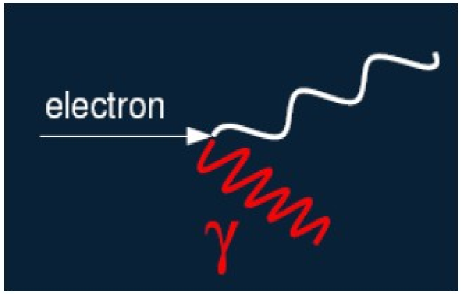
Inverse Compton scattering

By interaction with photon fields

Inverse compton scattering:
fast electrons transfer energy on low energy photons
➔ Blue shifted photons



$\nu' > \nu$
High energy e- initially
e- loses energy



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$$p + \text{target} \rightarrow \text{many particles}$$

$$\rightarrow p(n) + \pi^{+} + \pi^{-} + \pi^{\circ}$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$\pi^{\circ} \rightarrow \gamma + \gamma$$

$$\mu^{+} \rightarrow e^{+} + \nu_e + \overline{\nu}_{\mu}$$

"Hadronic Emission"

"Leptonic Emission"

$$e^{\mp} + B \rightarrow e^{\mp} + \gamma_{\text{synchrotron}}$$

$$e^{\mp} + \gamma_{\text{soft}} \rightarrow e^{\mp} + \gamma_{\text{Inverse Compton}}$$

See Prof. Paolo Lipari Lectures WAPP 2013

Electrons:

Synchrotron Emission

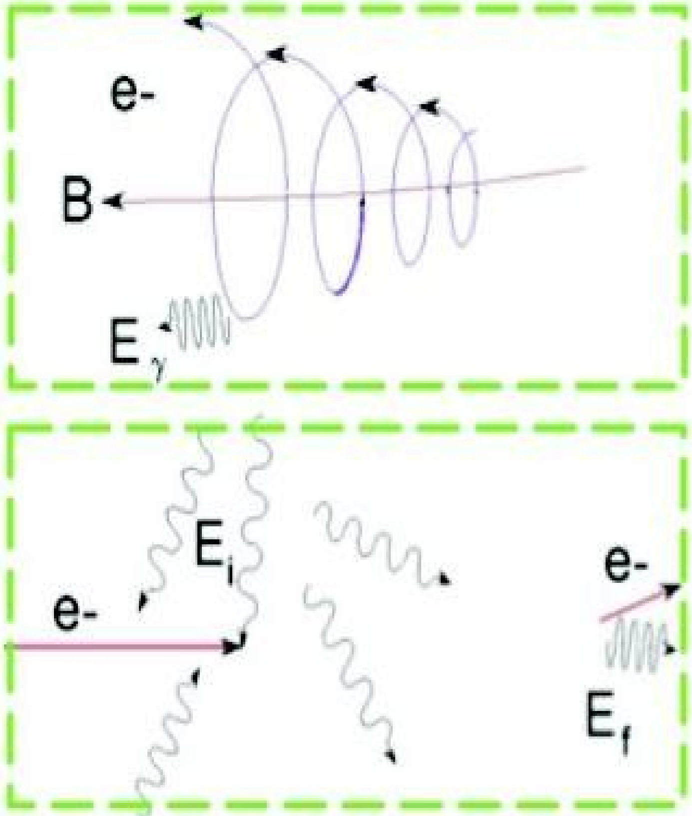
- Probes Magnetic Field, Electron Energy

Inverse Compton Scattering

- Probes Photon Field, Electron Energy

Synchrotron Self Compton

- If photon field is synchrotron, then Electron Energies & Magnetic Field are determined
- Quadratic relation between variability of TeV (IC) and X-rays (synch)



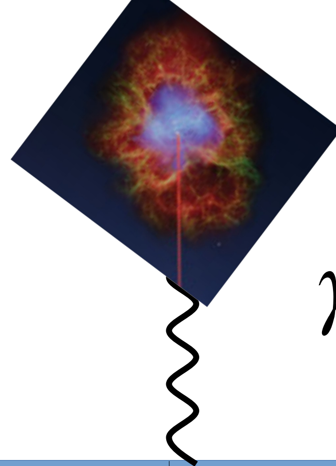
Hadrons:

$p + p \rightarrow \pi^{+} + \pi^{o} + \ldots \rightarrow e + \nu + \gamma + \ldots$

$p + \gamma \rightarrow \pi^{+} + \pi^{o} + \ldots \rightarrow e + \nu + \gamma + \ldots$

See Prof. Paolo Camarri Lectures WAPP 2012

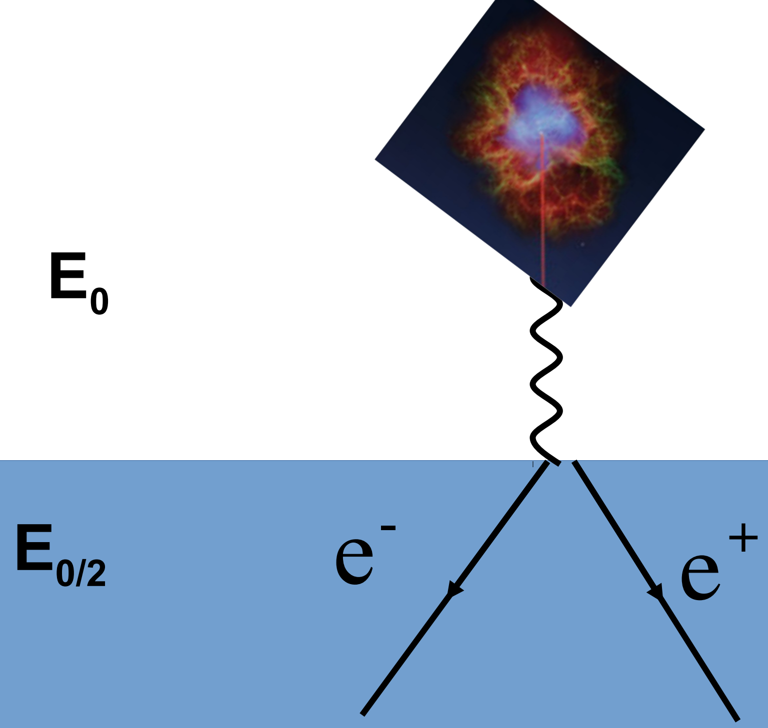
The Bhabha-Heitler Model



See prof. B.S.Acharya talk on WAPP 2012

W. Heitler, *The Quantum Theory of Radiation ,3rd Ed.*, (1954), p.386.

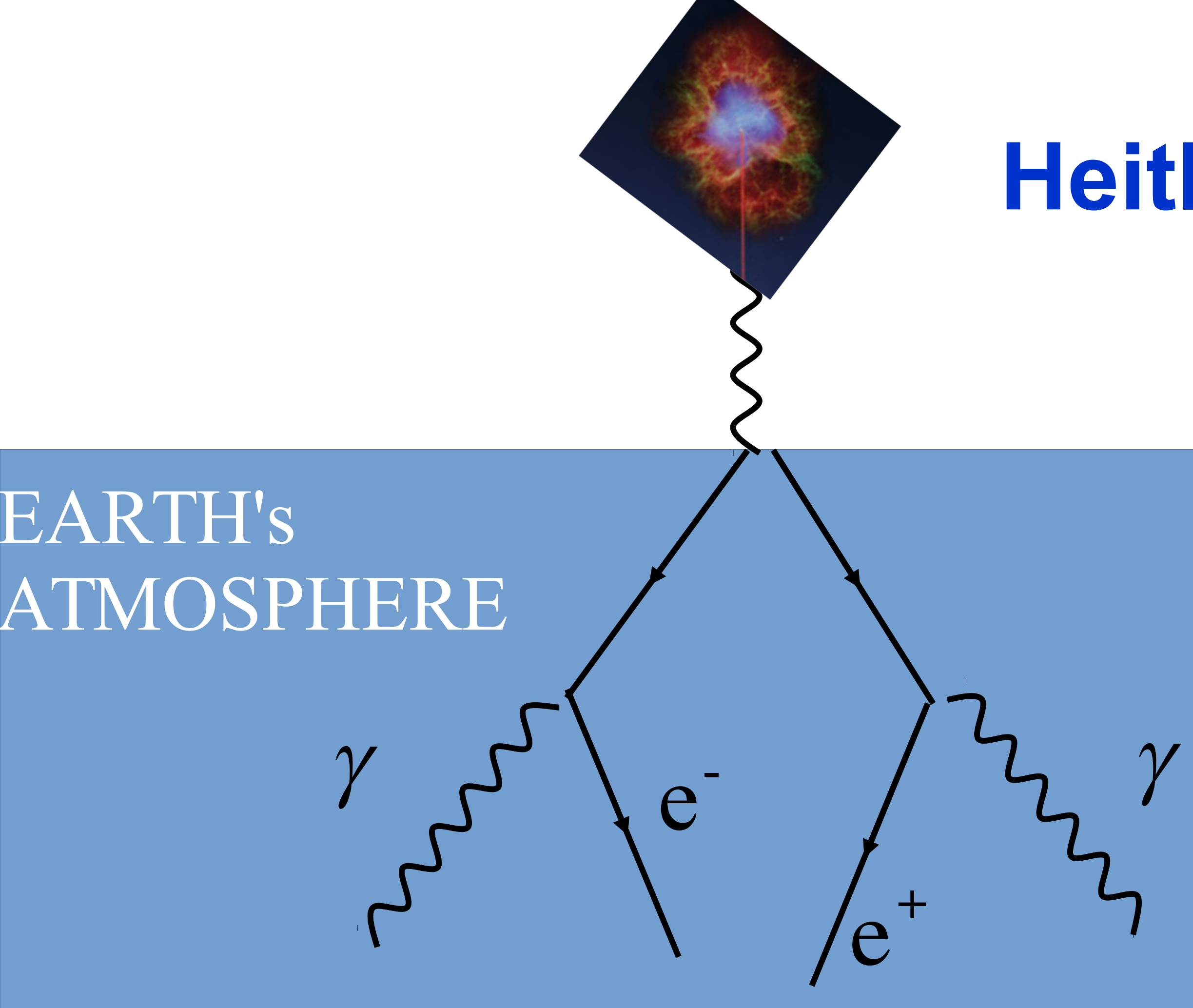
"Heitler's Model"



See prof. B.S.Acharya talk on WAPP 2012

W. Heitler, *The Quantum Theory of Radiation* ,3rd *Ed*., (1954), p.386.

Heitler Model



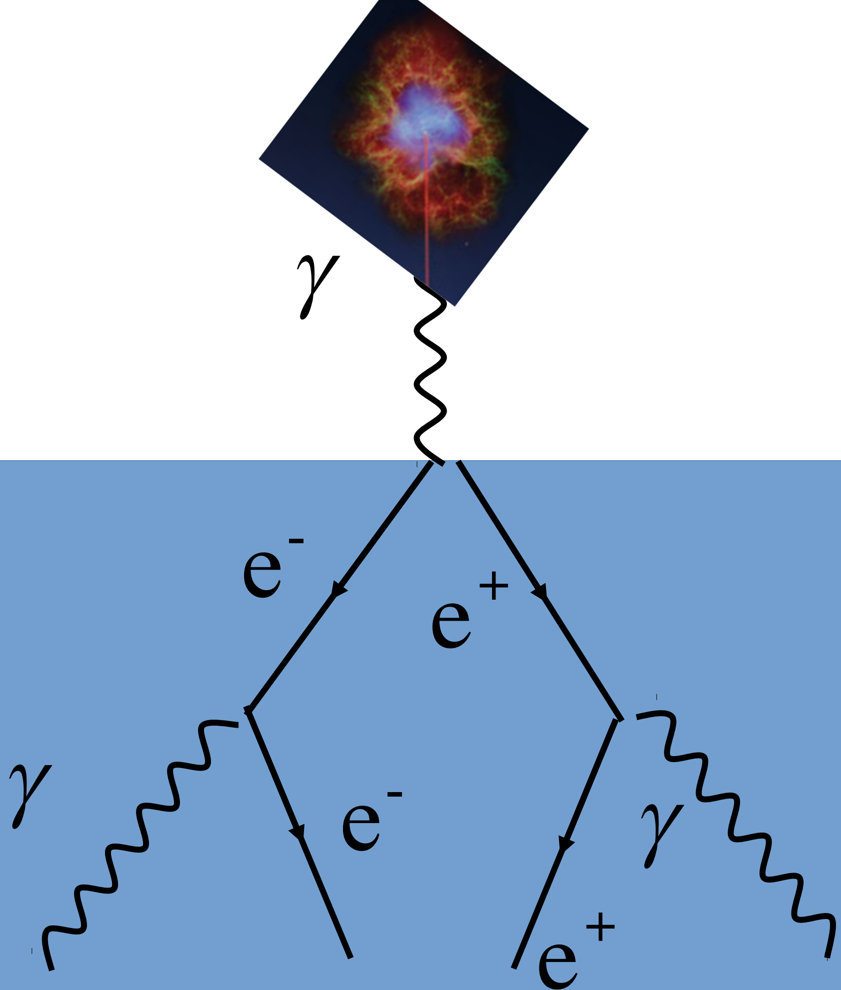
$E_{0/4}$

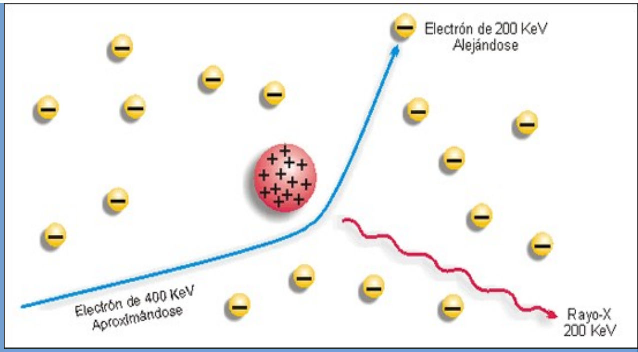
See prof. B.S.Acharya talk on WAPP 2012

W. Heitler, *The Quantum Theory of Radiation* ,3rd *Ed.*, (1954), p.386.

Heitler Model

- Energy is evenly split between two secondaries.
- Cascade **stops** after "n_c"





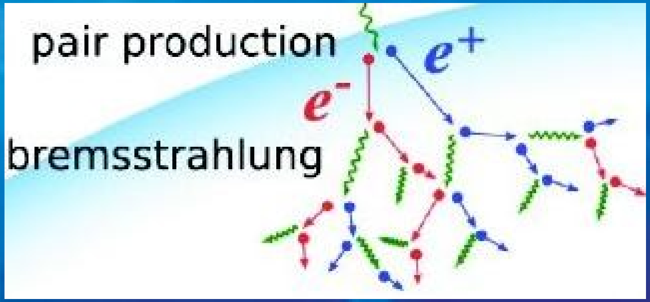
λ_r = 37 g cm^{-2} in air (radiation length)

After "n" splits, there are "N" particles (e^+, e-, and photons):

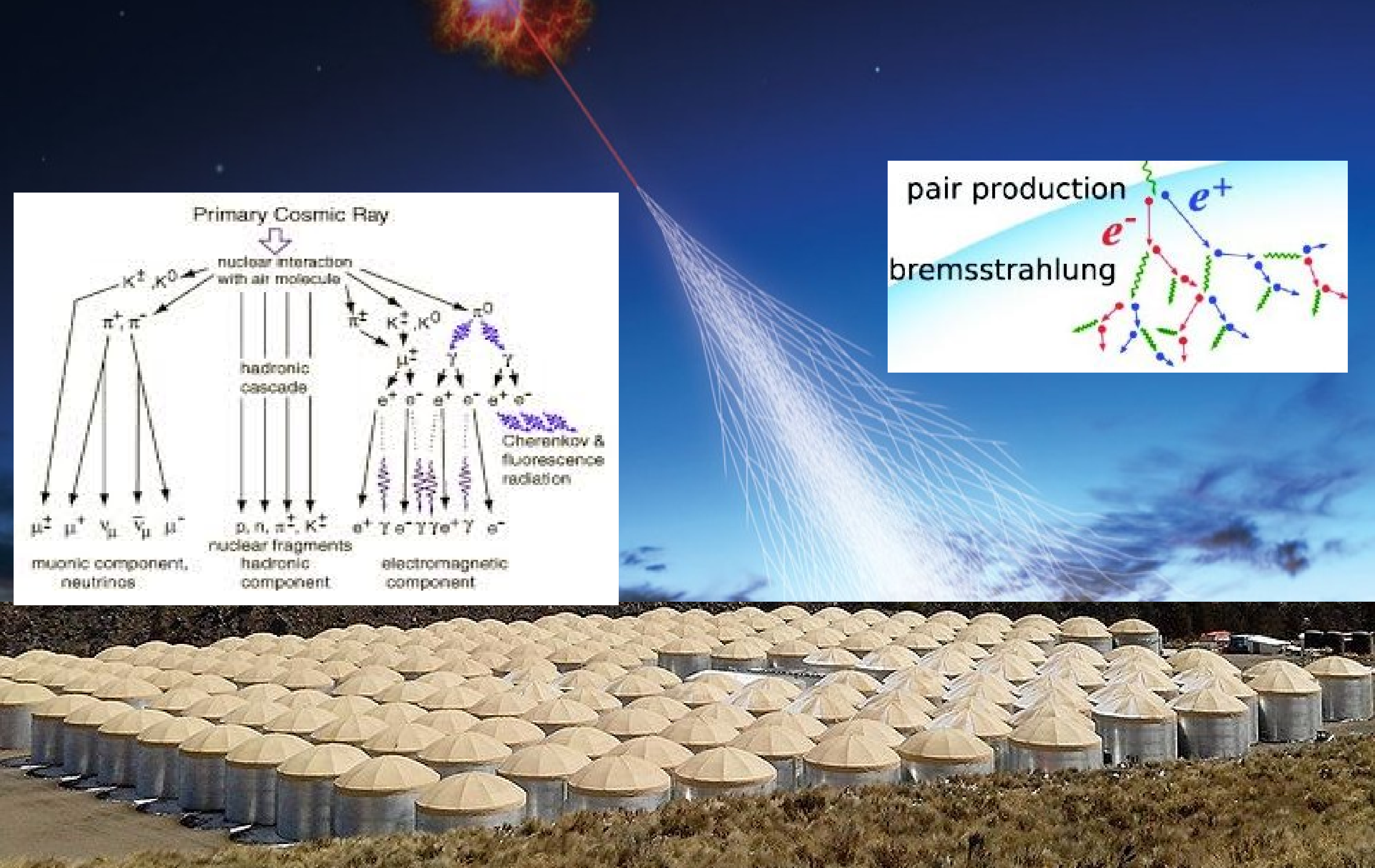
$$N = 2^n = e^{x/\lambda_r}$$

See prof. B.S.Acharya talk on WAPP 2012

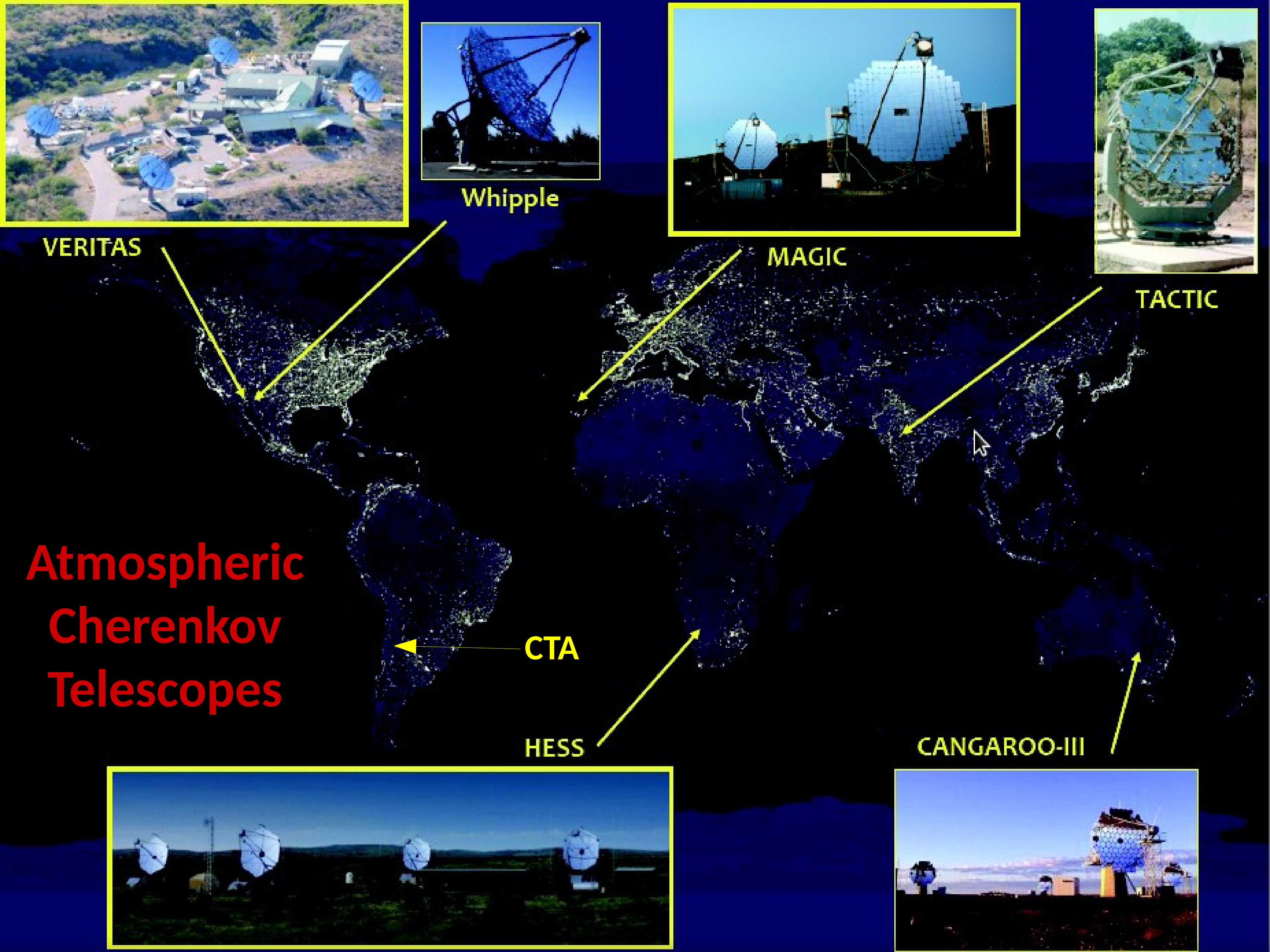
CHERENKOV RADIATION (WATER OR AIR) produced by the charged particles from the Extensive Air Shower that was created by the interaction of the incident Astroparticle with the Earth Atmosphere



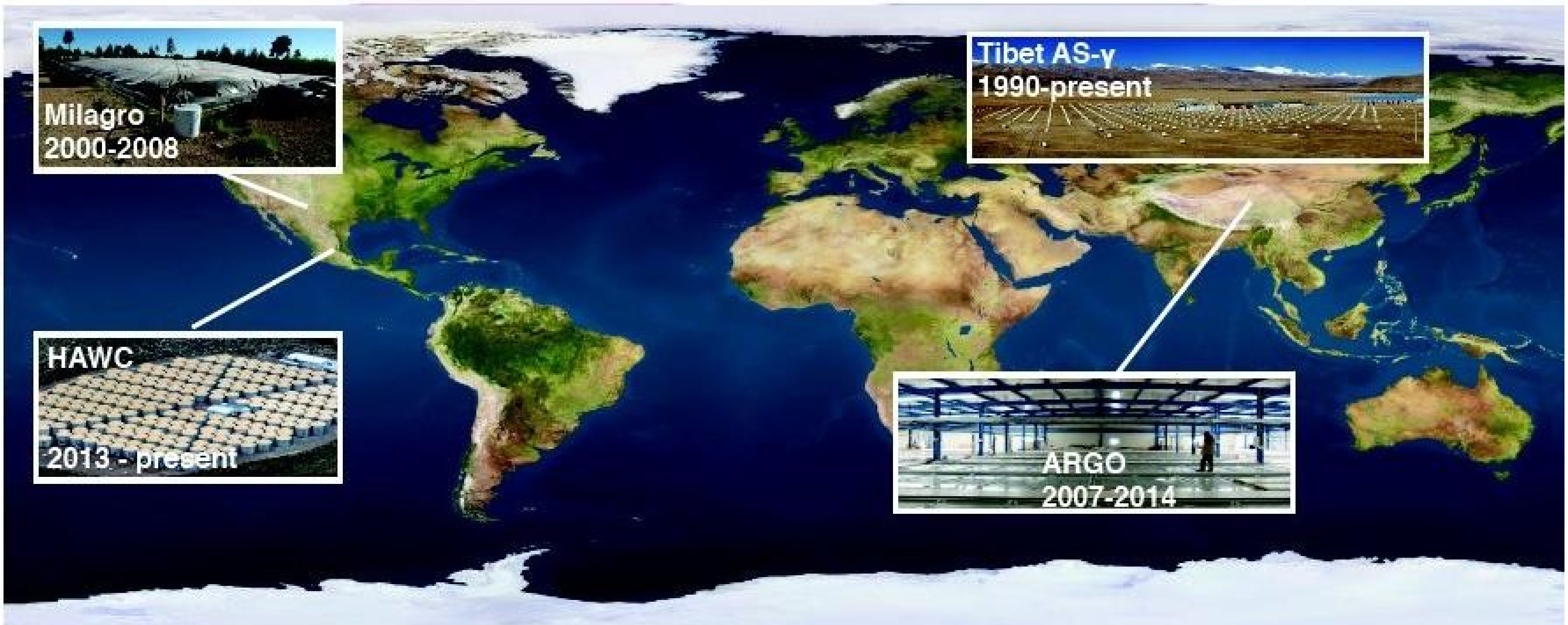
SUMMARY

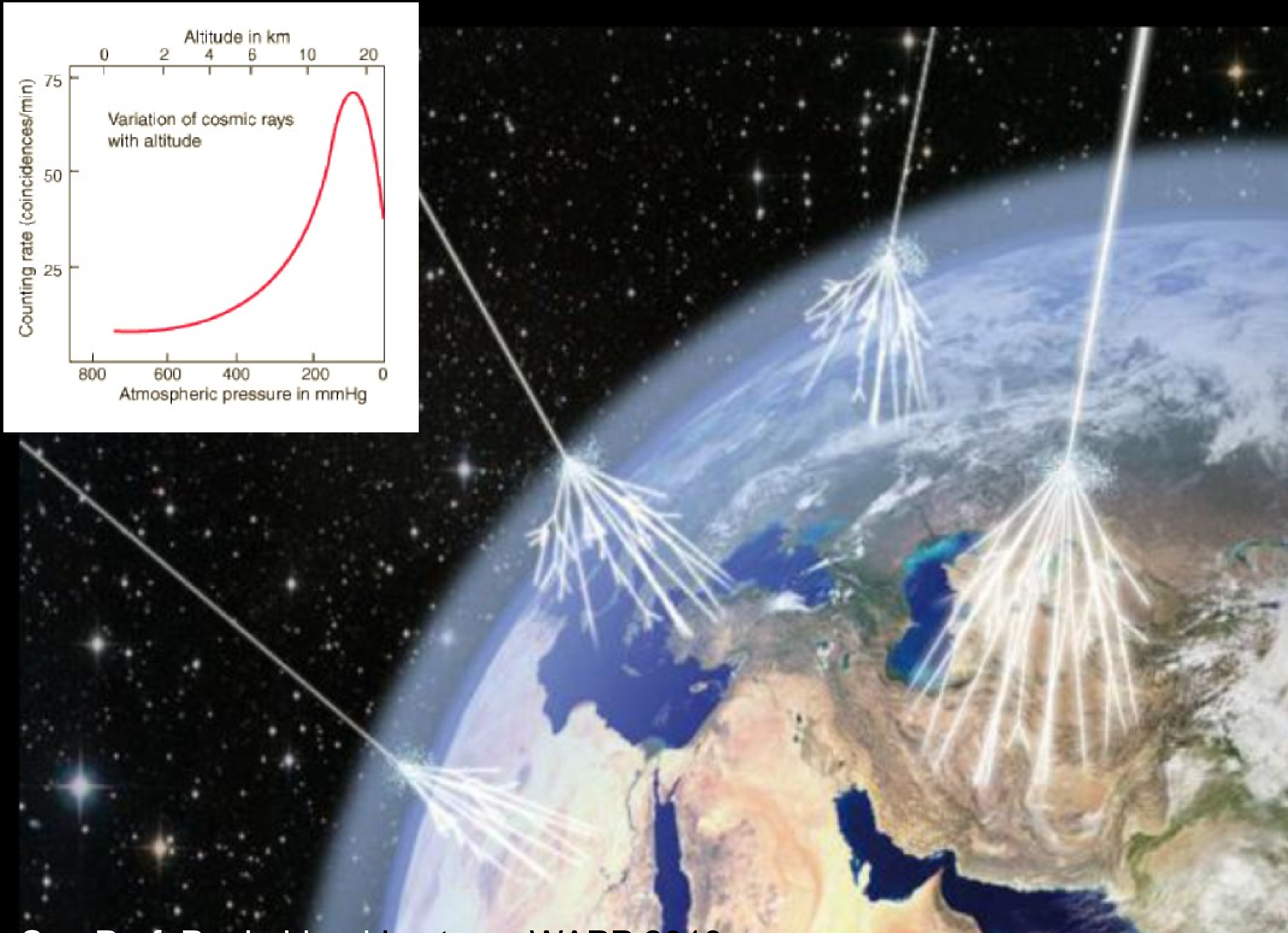


See Profs. Borisov and Maris Lectures WAPP 2015 for details on EAS


Whipple
VERITAS
MAGIC
TACTIC
Atmospheric
Cherenkov
Telescopes
CTA
HESS
CANGAROO-III

γ-ray observatories: air shower arrays





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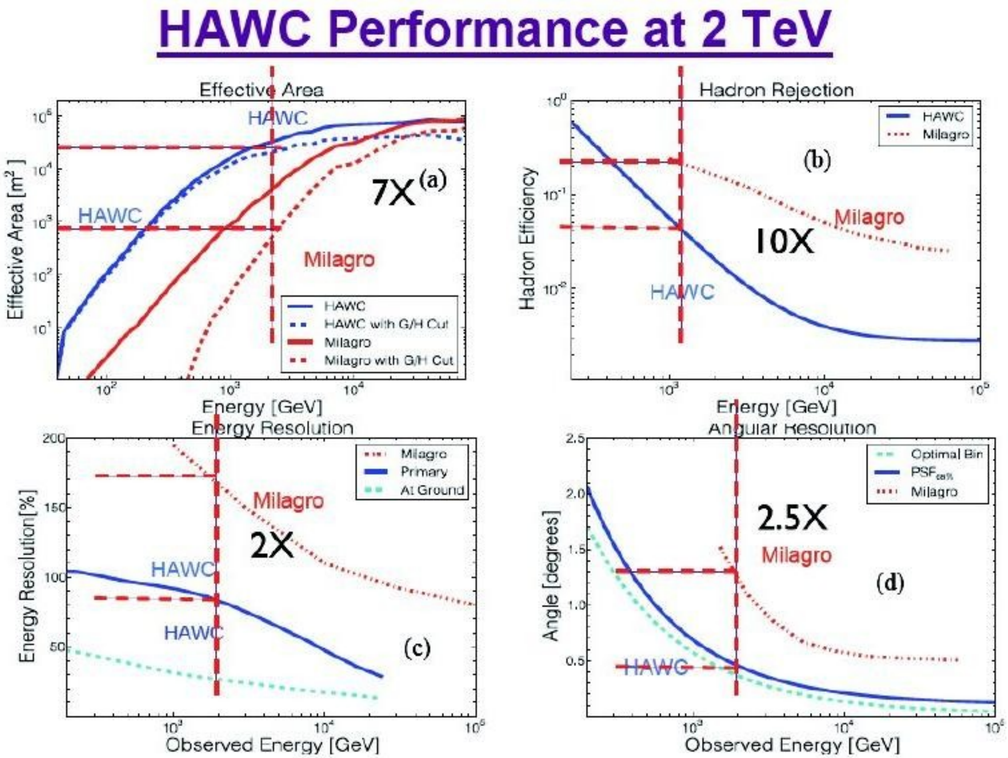
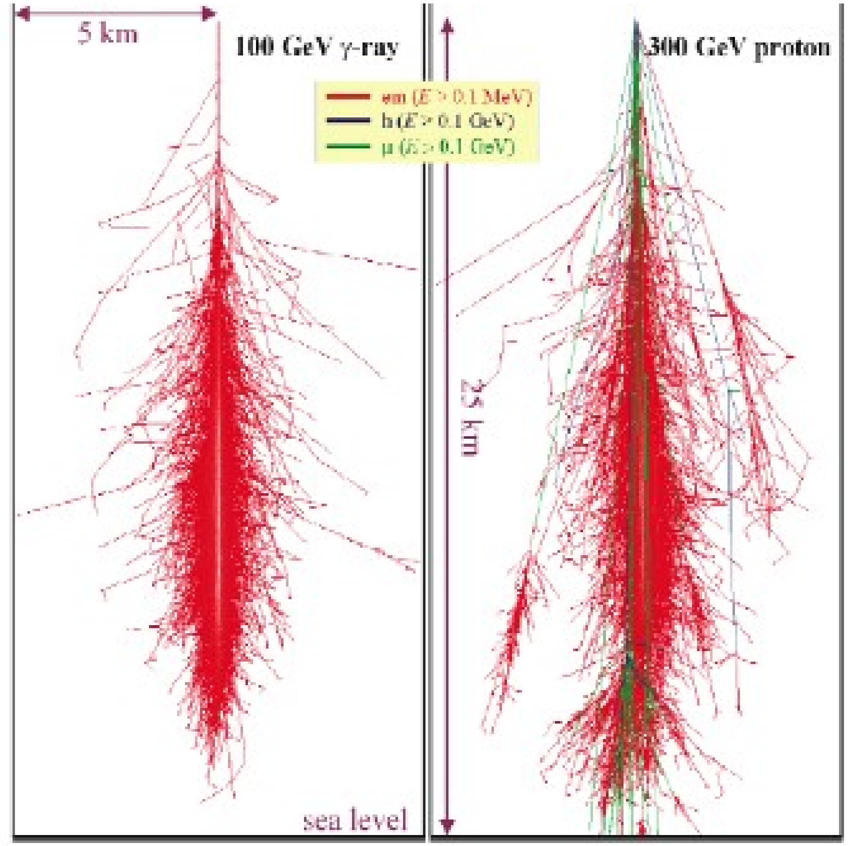
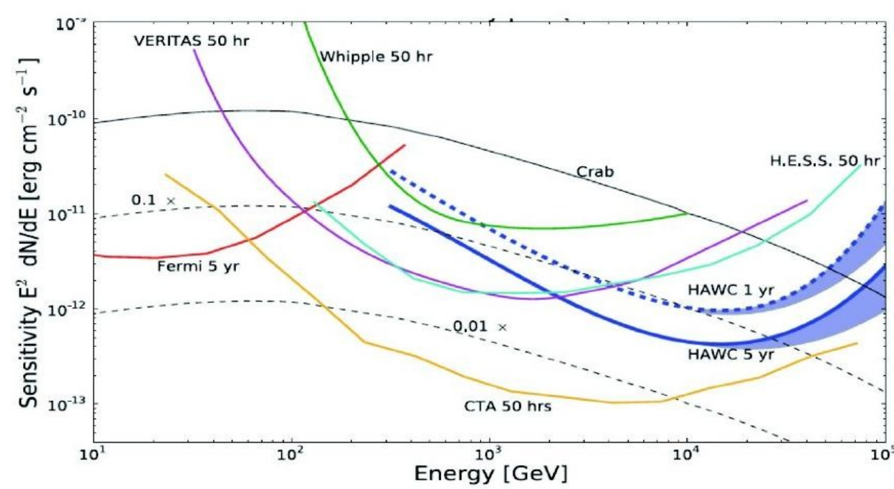
Do not forget the EM component for a CR







Moon Shadow

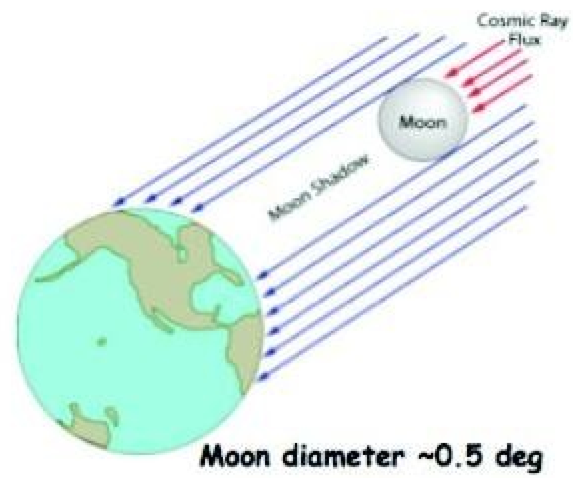
Cosmic rays are hampered by the Moon → **Deficit of cosmic rays in the direction of the Moon**

- Size of the deficit → **Angular Resolution**
- Position of the deficit → **Pointing Error**

Geomagnetic Field: positively charged particles deflected towards the West and negatively charged particles towards the East.

→ Ion spectrometer

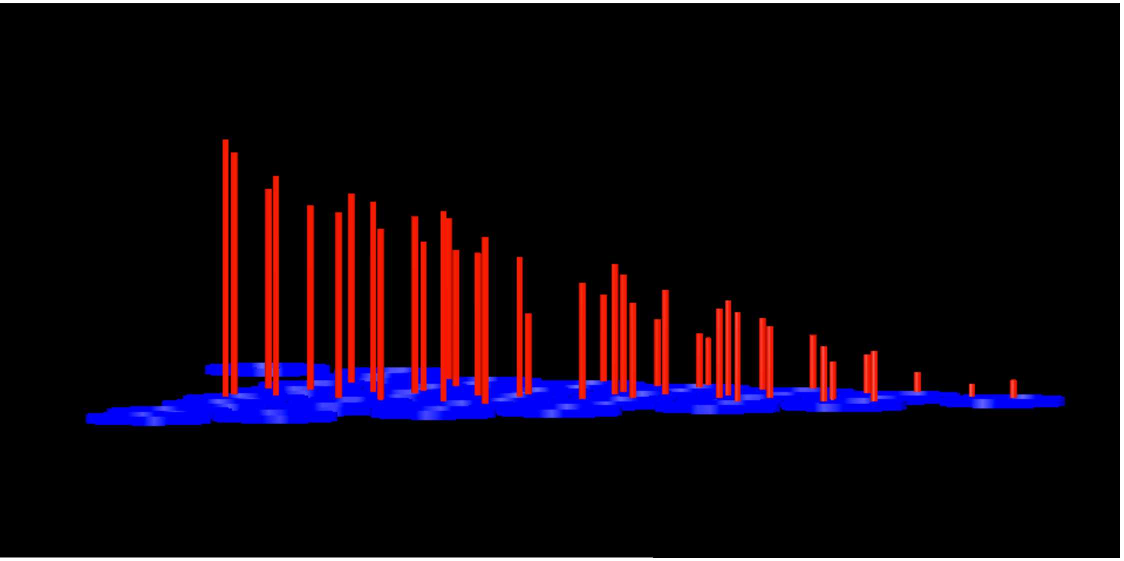
$$\Delta\vartheta \approx \frac{1.6^0}{E(TeV)}$$

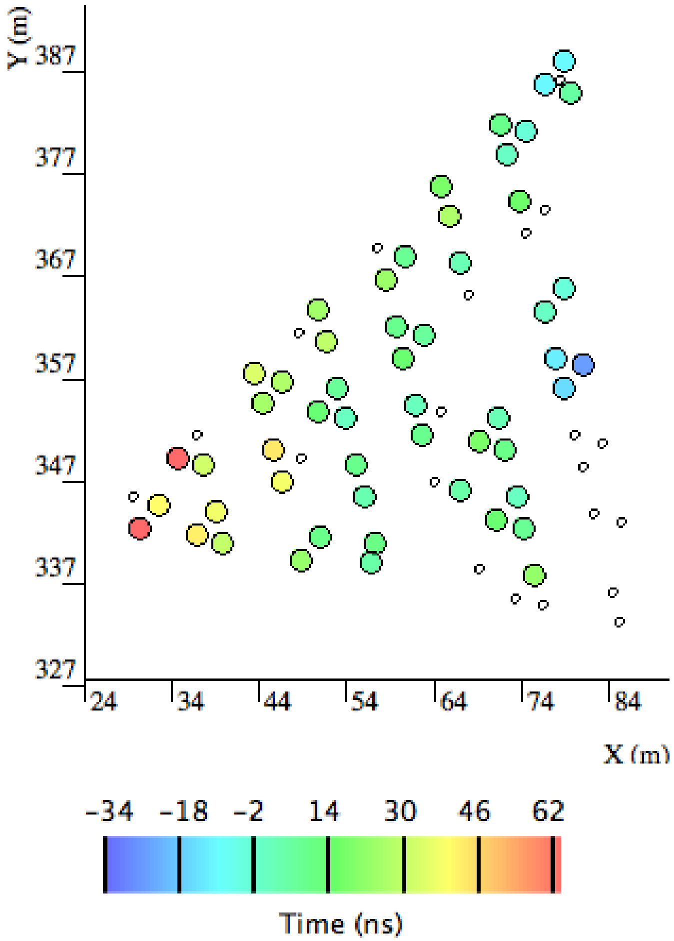


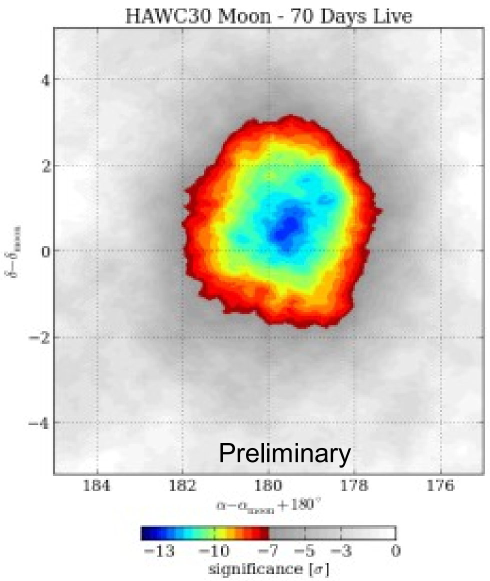
The observation of the Moon shadow can provide a direct check of the relation between size and primary energy: → Energy Calibration

See Prof. Paolo Camarri Lectures WAPP 2012

HAWC-30 Completed Sept 2012





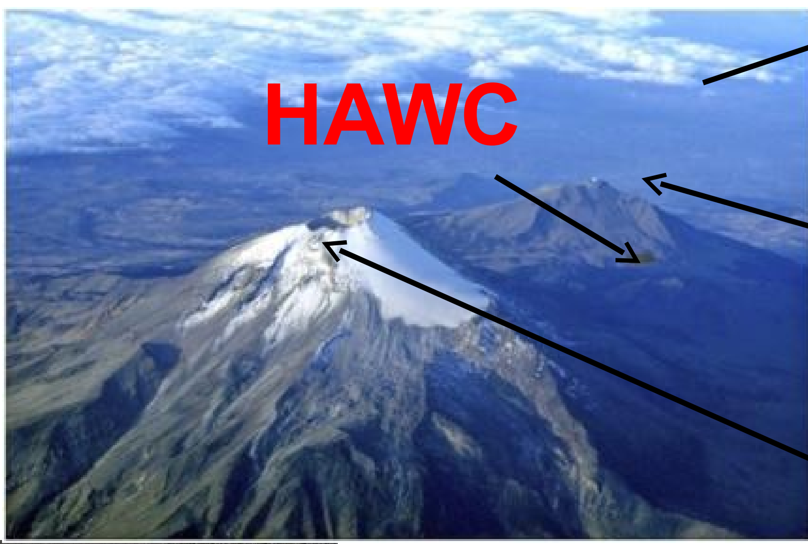


HAWC 30 Events and Observation of cosmic ray shadow of Moon with 70 days of data

Credit: HAWC collaboration Abeysekara et al.

HAWC Site Location in Mexico

- High Altitude Site of 4100 m with temperate climate and existing infrastructure
    - 17 R.L. of atmospheric overburden vs 27 R.L. at sea level
- Latitude of 19 deg N



Large Millimeter Telescope (50m dia. dish)

Pico de Orizaba 5600 m (18,500’)

The HAWC Collaboration

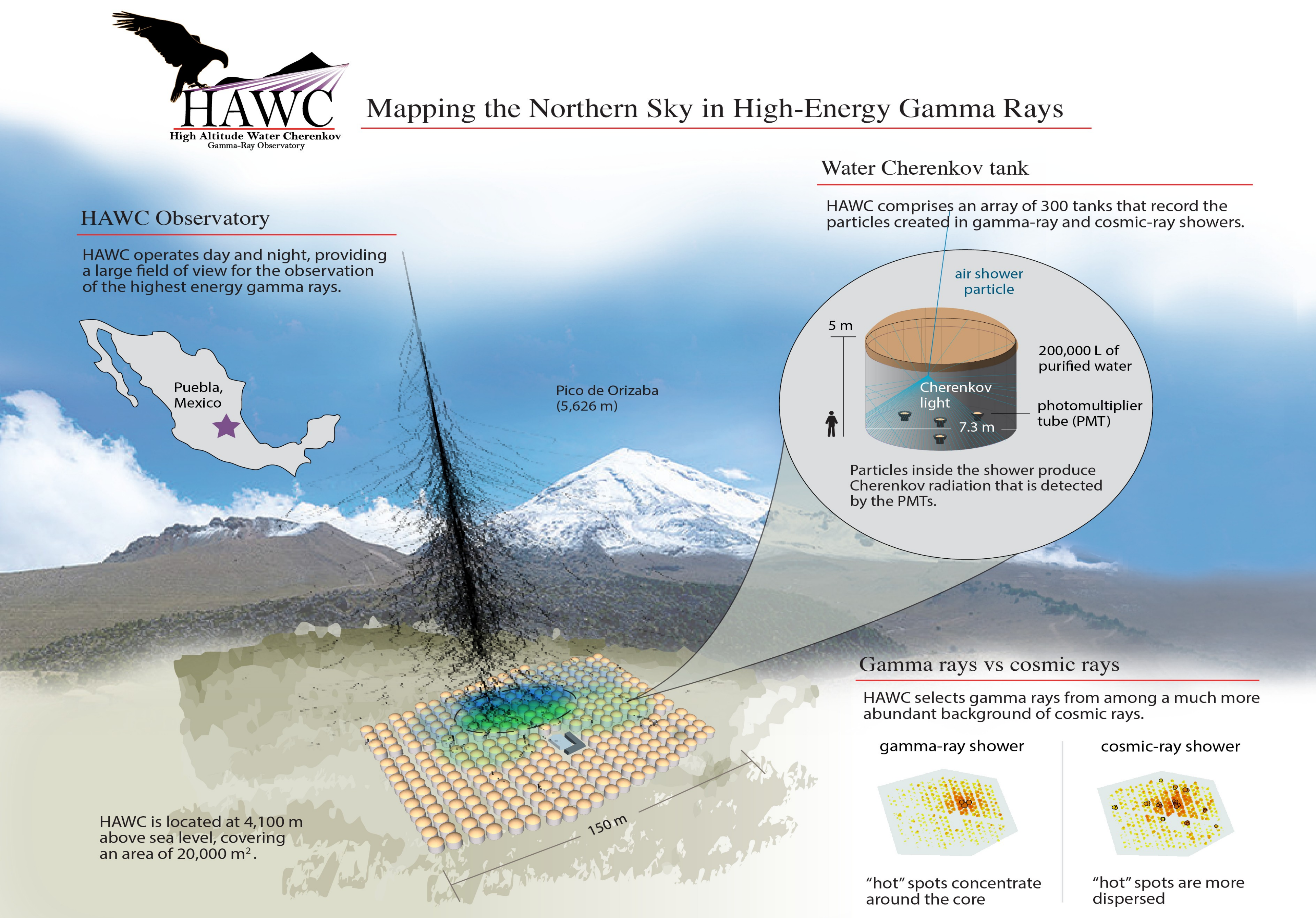
- Los Alamos National Laboratory
- Univ. of Maryland
- Michigan State Univ.
- University of Wisconsin
- Pennsylvania State Univ.
- Univ, of Utah
- Univ. California Irvine
- George Mason University
- University of New Hampshire
- University of New Mexico
- Michigan Technological University
- NASA/Goddard Space Flight Center
- Georgia Institute of Technology
- University of Alabama
- Colorado State Univ.
- Univ. California Santa Cruz

~100 Members

- Instituto Nacional de Astrofísica Óptica y Electrónica
- Universidad Nacional Autónoma de México
  - Instituto de Física
  - Instituto de Astronomía
  - Instituto de Geofisica
  - Instituto de Ciencias Nucleares
- Benemérita Universidad Autónoma de Peubla
- Universidad Autónoma de Chiapas
- Universidad Autónoma del Estado de Hidalgo
- Universidad de Guadalajara
- Universidad Michoacana de San Nicolás de Hidalgo
- Centro de Investigacion y de Estudios Avanzados

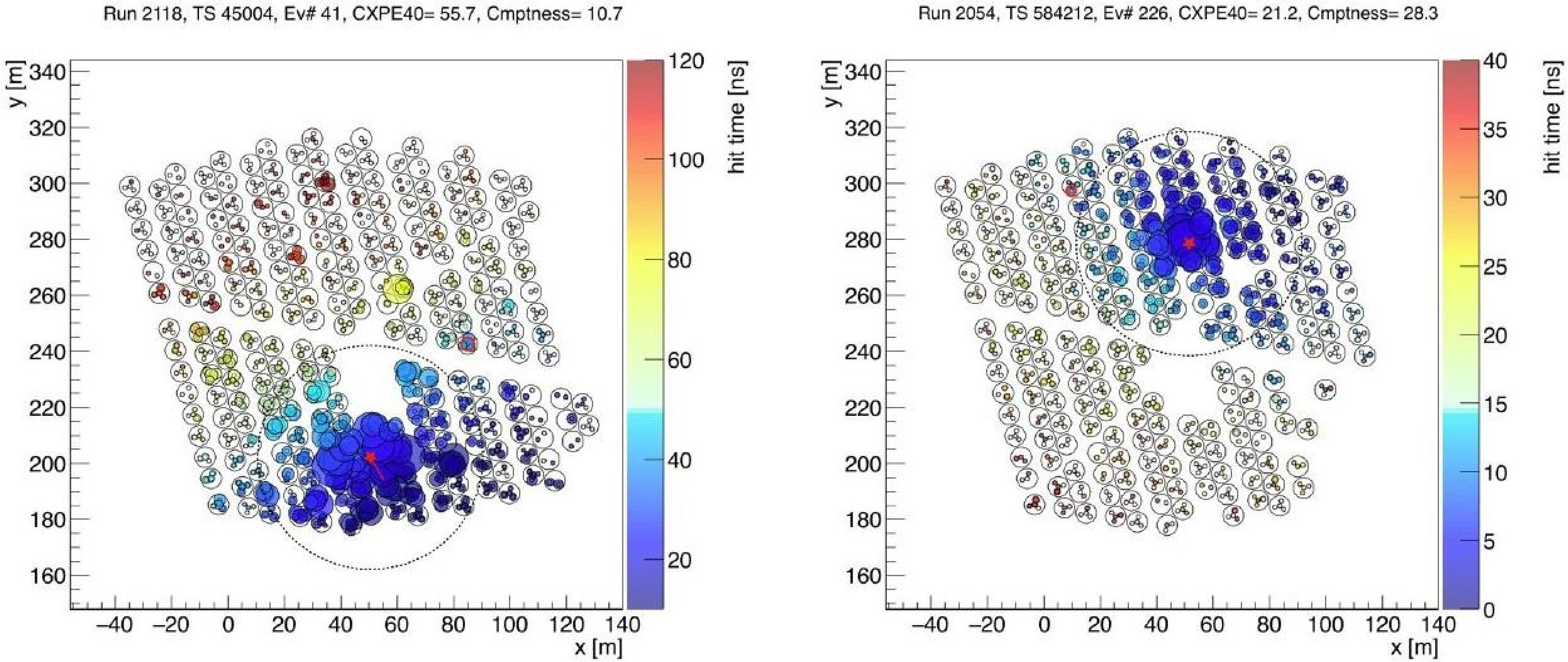
USA

Mexico



Credit: HAWC / WIPAC

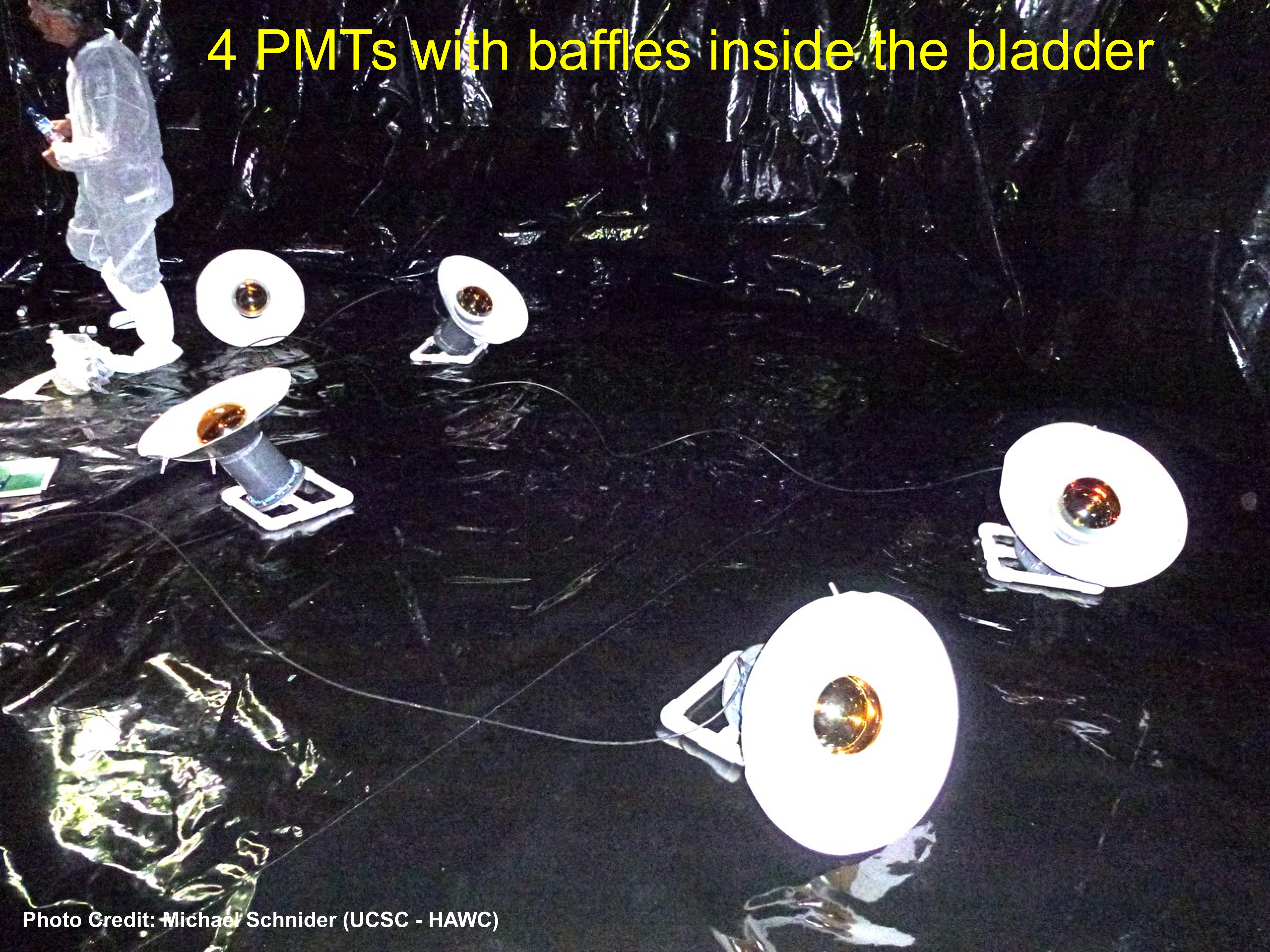
Gamma / Hadron Rejection



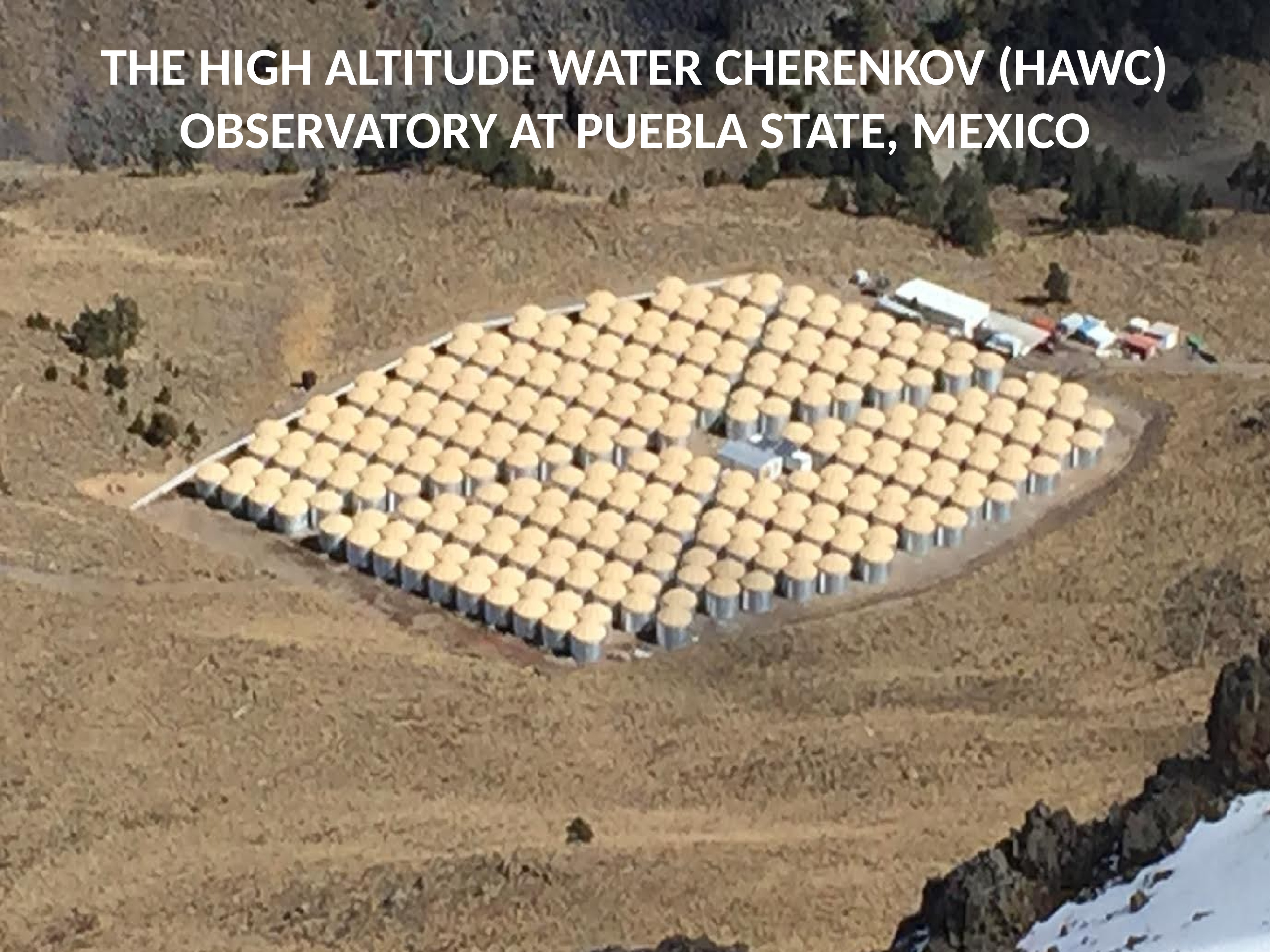
Corrugated Metal Tanks: Dimensions 7.3 x 4.5 meters
Geotextile cover inside the structure

Made on CSU

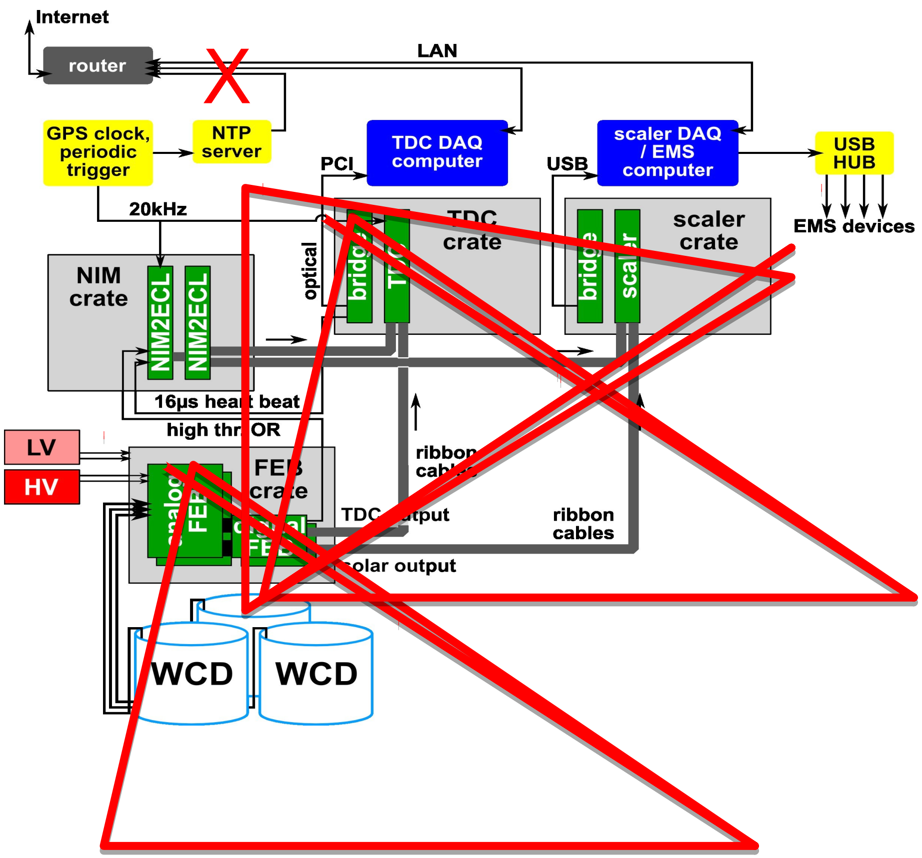
Each bladder weighs < 140 Kg and fits in a 75cmx2.7m tube.

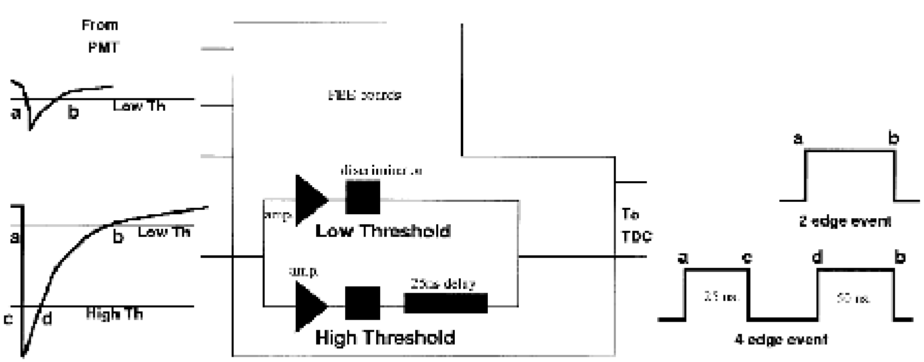

4 PMTs with baffles inside the bladder
Photo Credit: Michael Schnider (UCSC - HAWC)

THE HIGH ALTITUDE WATER CHERENKOV (HAWC) OBSERVATORY AT PUEBLA STATE, MEXICO



Front End Electronics and DAQ as in HAWC





EMS records pressure, temp, water level

Scalers take single rates and are readout every 10 ms

TDC record the ToT of every signal above ¼ and 5 single photo electron
~30 kHz/PMT
11 MB/s to disk

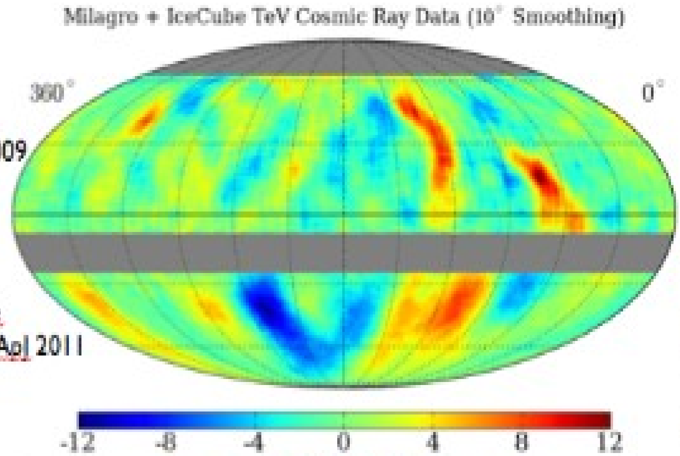
Data stored in 8 TB portable disk arrays
they are transported to UNAM read into the ICN cluster and mirrored to UMD
26 TB recorded during Octobe

HAWC

Unexpected Anisotropy of 10TeV Cosmic Rays; Gyroradius of 10TeV proton in 2μG field is 1000AU

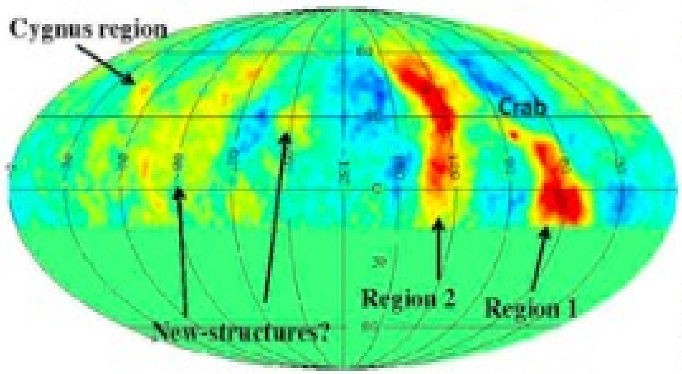
Milagro: Abdo, et al. PRL, 2009

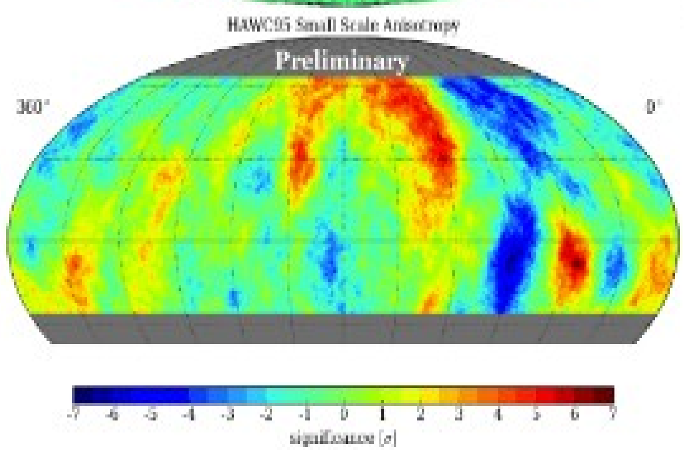
IceCube R. Abbasi, et al., ApJ 2011



ARGO-YBJ

S. Vernetto et al., Proc. 31st ICRC, 2009





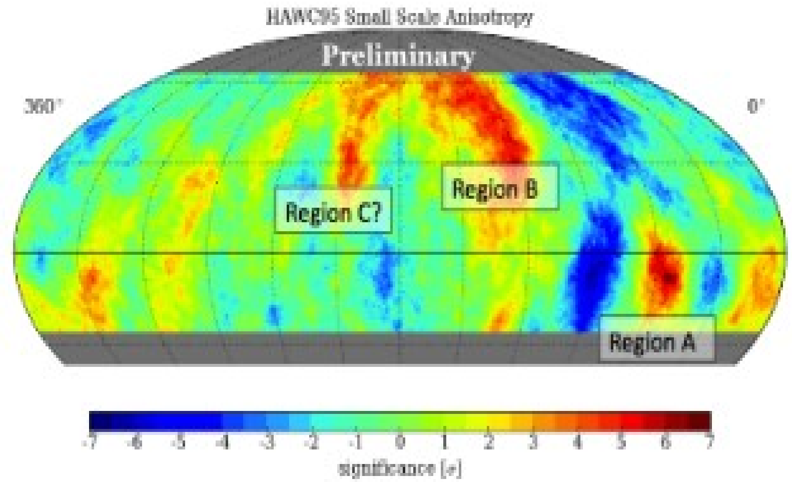
nCh ≥ 32

Direct integration

2hr ≥ dt ≥ 1hr

10° smoothing

Li/Ma signif.



Region A : 7.0 sigma
Region B: 5.5 sigma
Region C: 4.9 sigma

Pre-trial will be greater than 7 with another month of data.

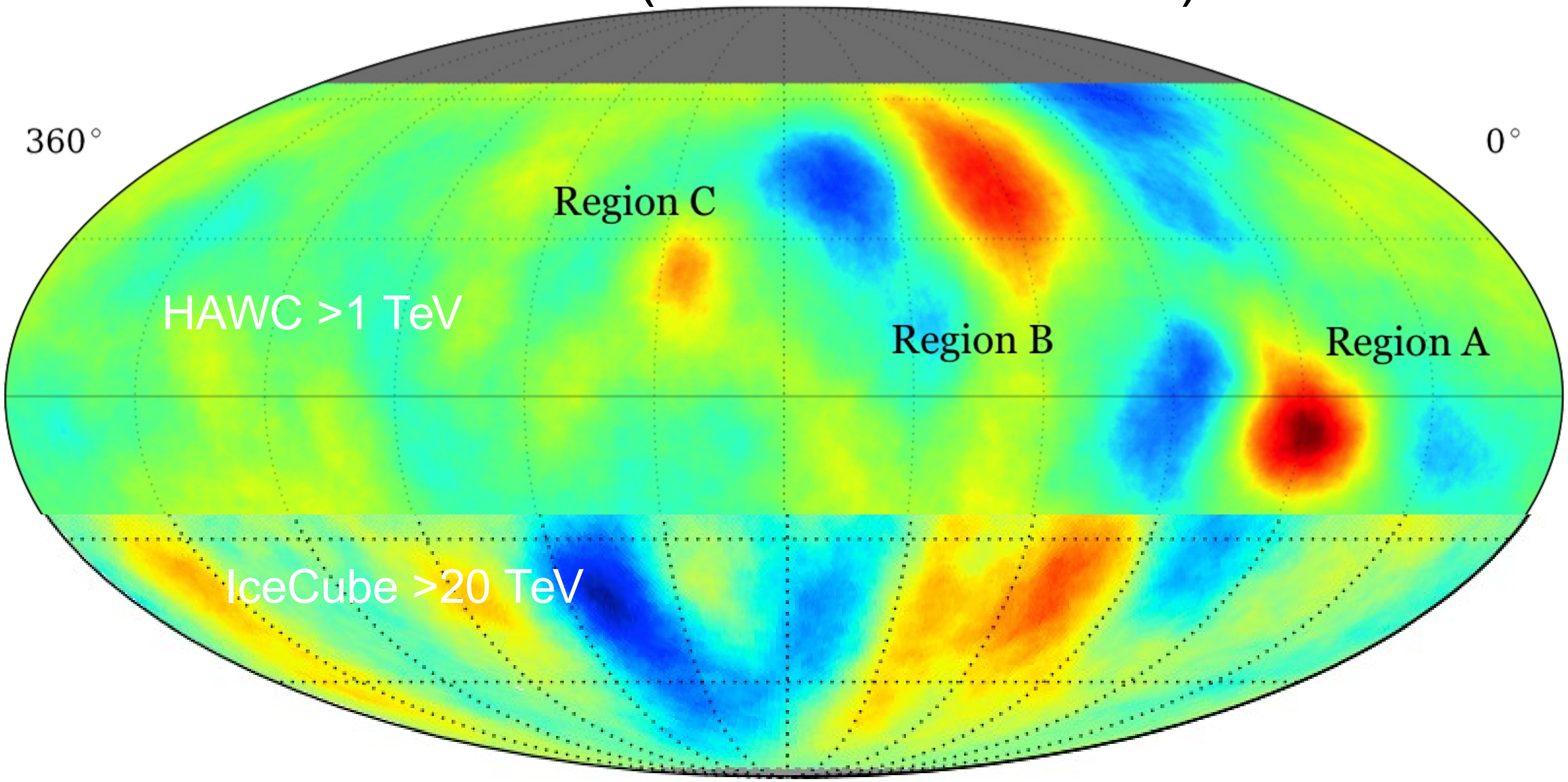
Find post-trial with random data sets.

See Abeysekara et al. Astroparticle Physics paper (2014) and

The HAWC Collaboration contributions on Proceedings (POS) of the ICRC 2015, la Hague

Cosmic Ray Anisotropy

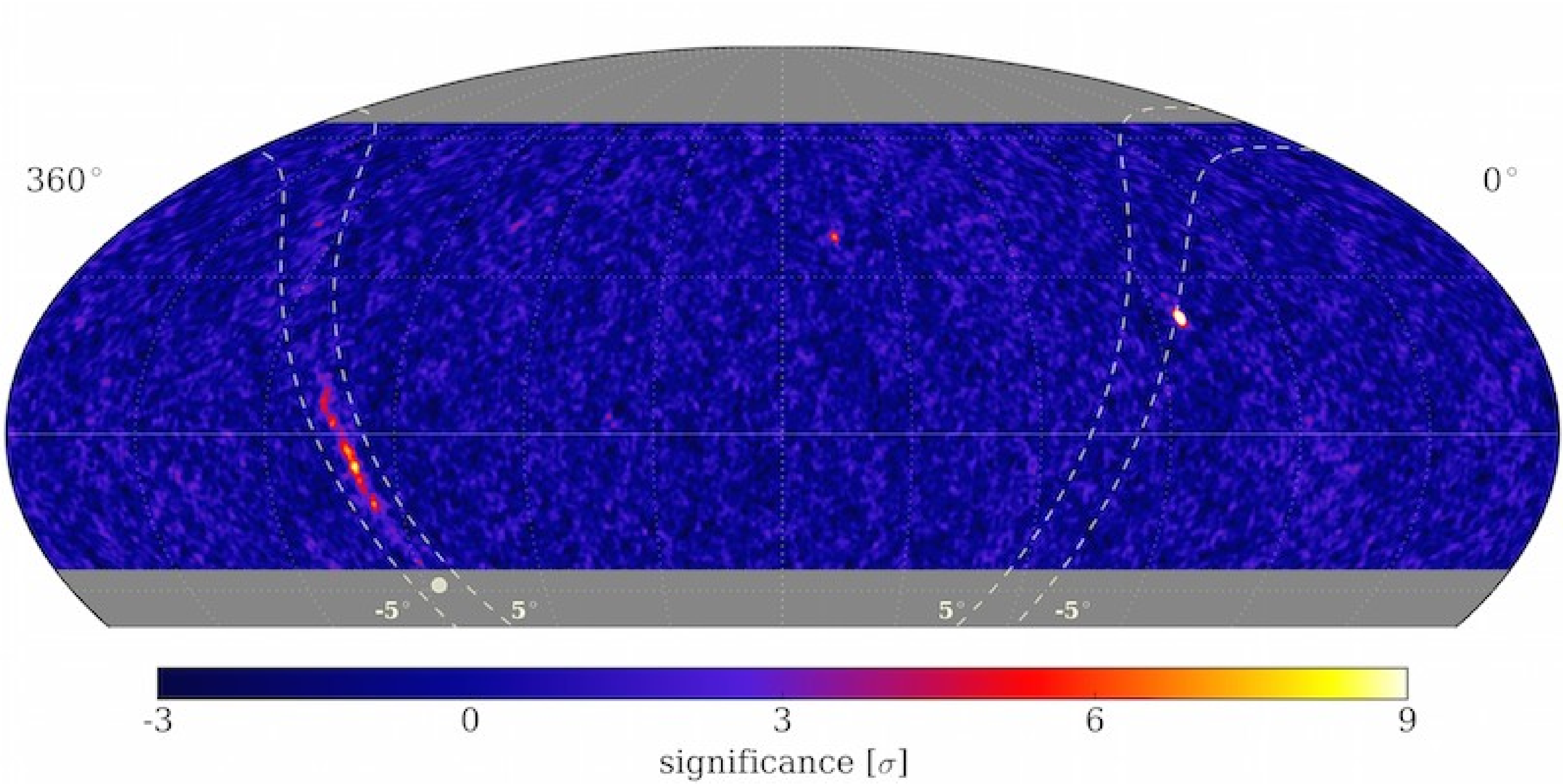
HAWC and IceCube (>1 TeV vs >20 TeV)



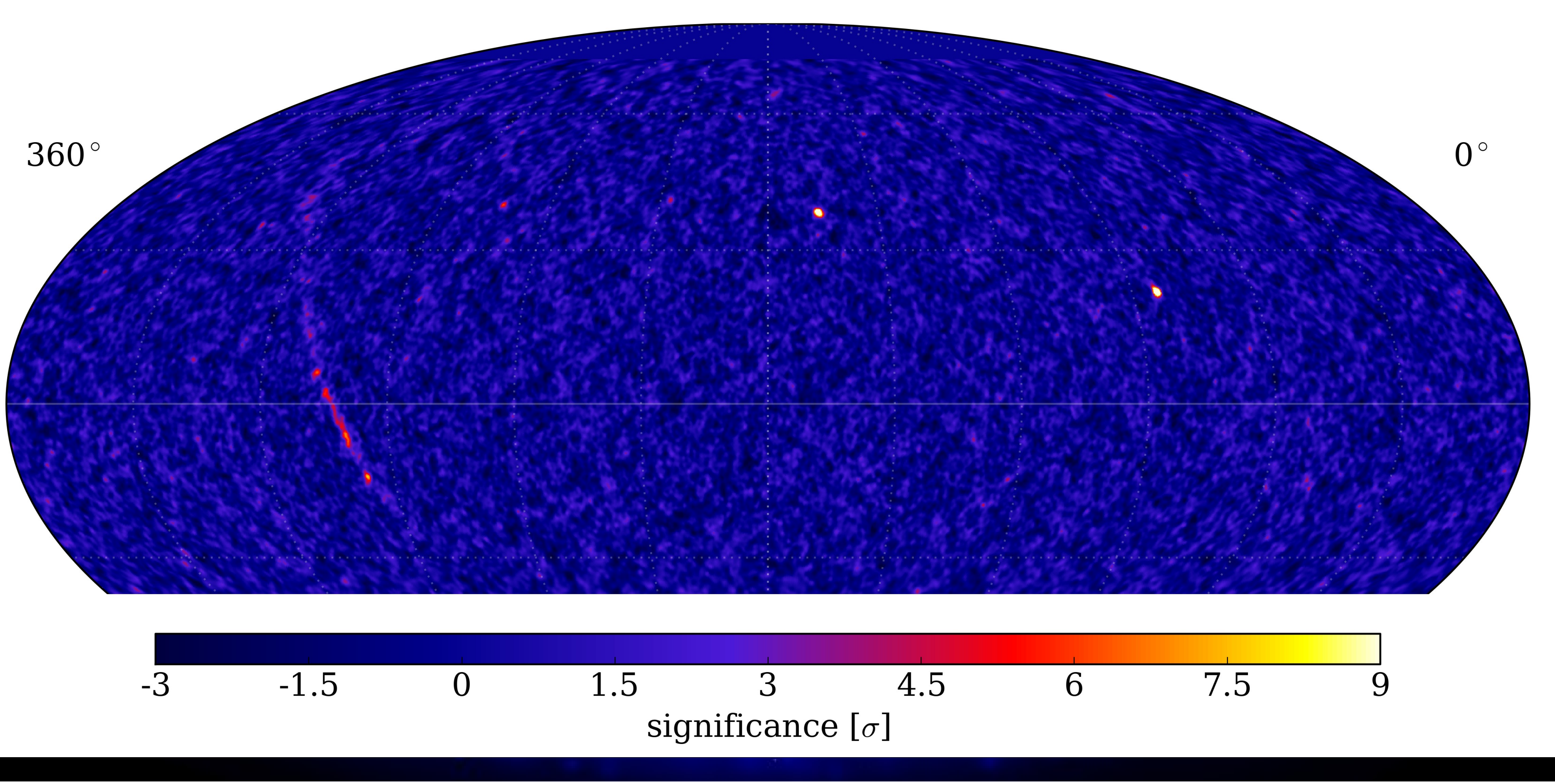
See Segev Y. BenZvi, Daniel W. Fiorino, and Stefan Westerhoff; 2015, Proceedings of the ICRC 2015 (POS): arxiv 1508-04781

Credit: HAWC/WIPAC

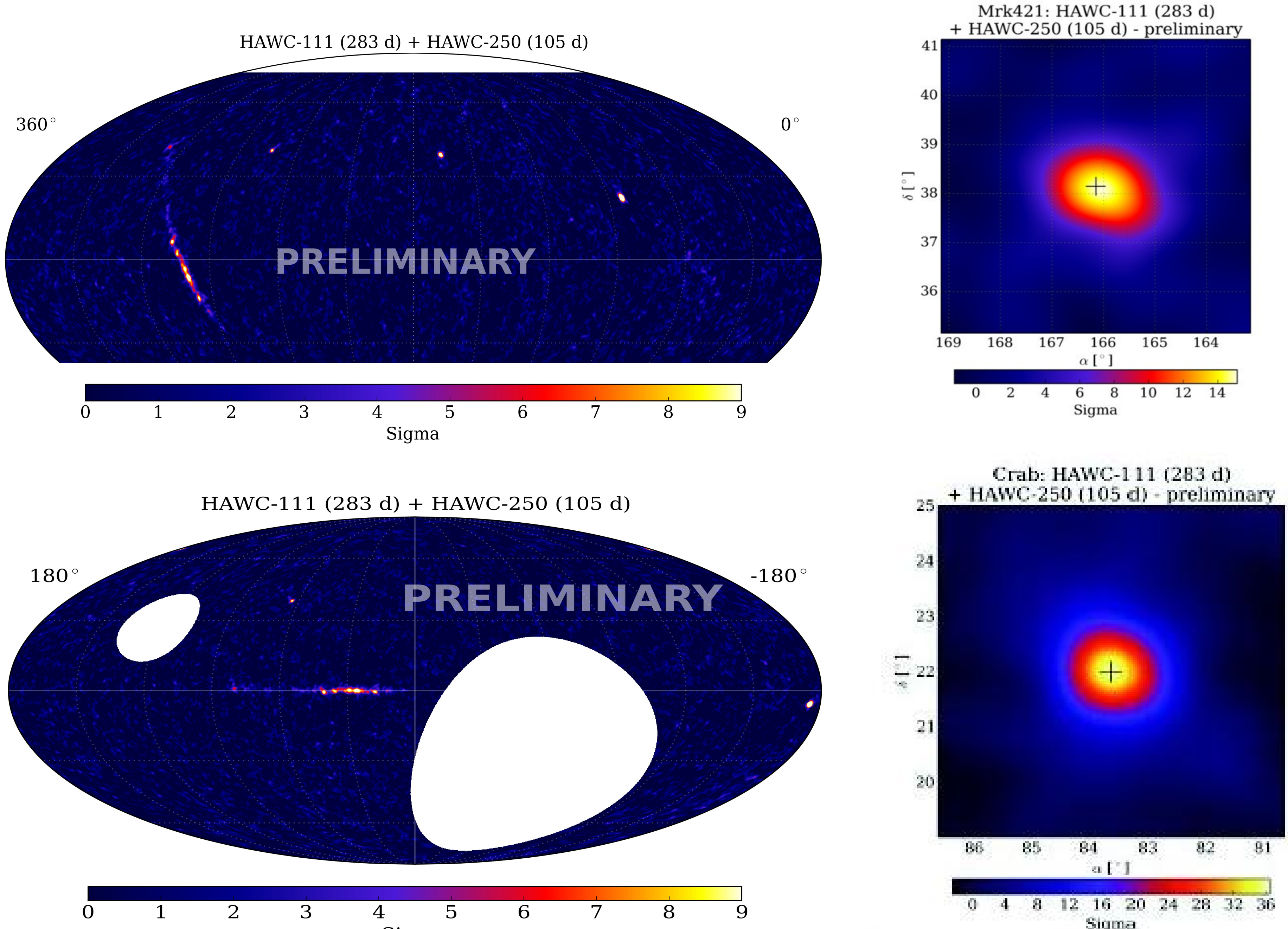
HAWC 250 Preliminary



HAWC - Fermi



Highest energy γ's from LAT (E>50 GeV) with a preliminary map from HAWC-250
(slide courtesy M. Ajello)



Maps Author: Colas Rivière (HAWC / UMD)

Credit: HAWC Collaboration

On WAPP 2013, Prof. Johanes Knapp gave a very good set of problems as homework. With these and the lectures, you have a very good background on Gamma Ray Astrophysics and related optics.

I strongly recommend, to do these problems.

Send it by June 2016 to my email. There is a special price.

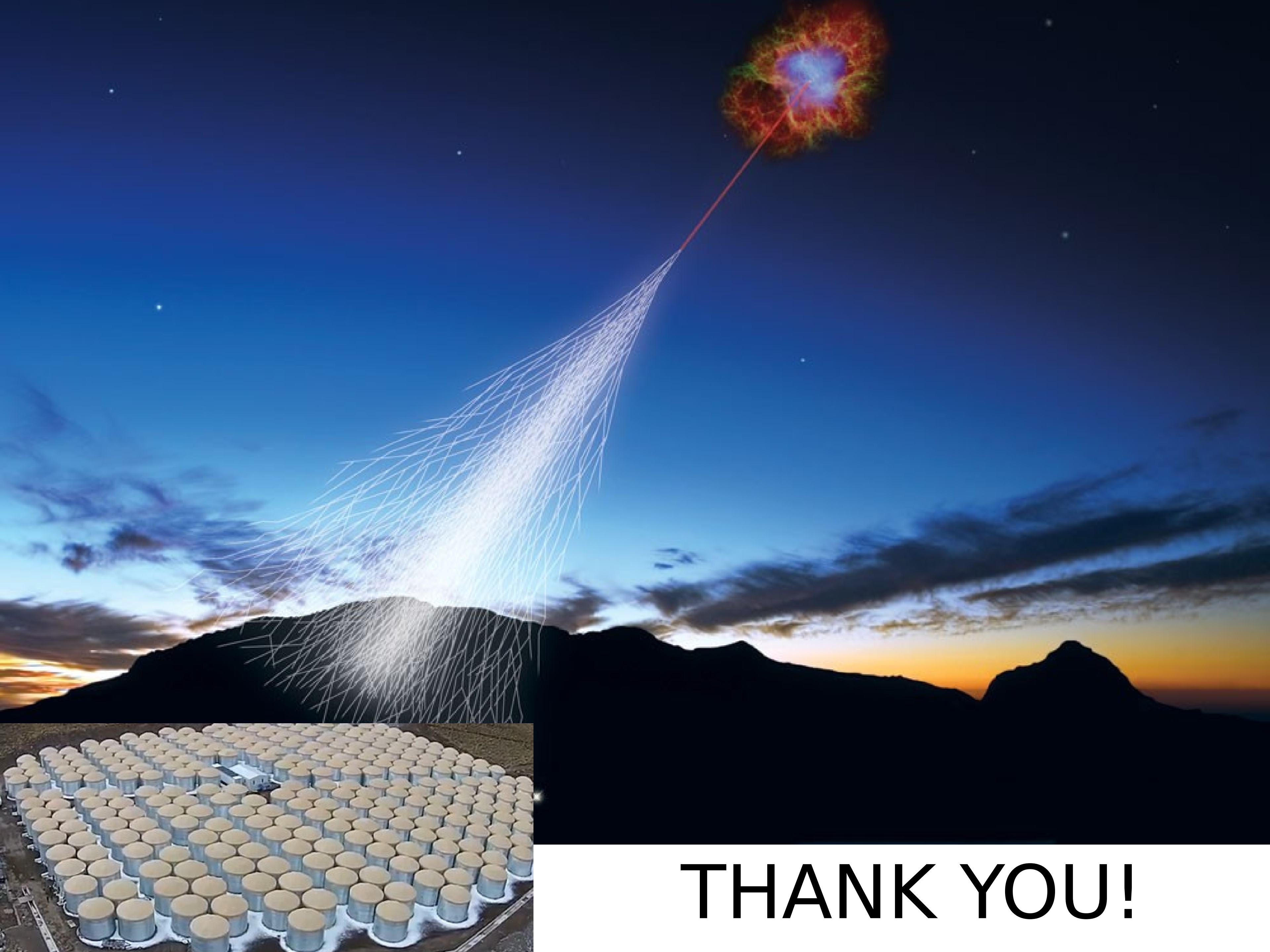
Homework:

Exercises in γ Ray Astronomy

Johannes Knapp[1], Astroparticle Physics, DESY Zeuthen

Some of these problems can be solved with basic university physics, others are a bit more demanding and require some web search or educated guesses.

1. What are the frequency and wavelength of a photon of 1 TeV?
   How does it (most likely) interact when impinging on matter?
2. A proton (rest mass $m_p = 938$ MeV/c^2) moves with a velocity $v = 0.7c$.
   Calculate its relativistic mass, momentum, kinetic and total energy. Show that for $v \ll c$ the relativistic momentum and kinetic energy approach the classical values.
3. In a satellite detector like Fermi photons are detected via the measurement of the e^+e^- pairs they produce. A pair is observed with the following direction unit vectors $\vec{d_i}$ and energies E_i. What are the energy and direction of the incident photon?
   $\vec{d_1}$(x,y,z) = (-0.65, 0.14, -0.75) E_1 = 2.93 GeV and
   $\vec{d_2}$(x,y,z) = (0.66, -0.04, -0.75) E_2 = 2.27 GeV.
4. What is the energy threshold for a high energy photon to produce an e^+e^- pair when colliding with an infrared photon of 1100 nm wavelength?
5. What is the average amount of air (in g/cm^2) traversed by a TeV photon to its first interaction in the atmosphere? What is the distribution of first interaction points? To what height (in km) does this roughly correspond for a vertical primary photon?
6. How can photons in satellite and ground-based Cherenkov experiments be separated from the overwhelming background of charged cosmic rays?
7. In 2007 the gamma-ray source PKS 2155-304 was observed to double its output within 5 min. Estimate the size of the emission region.
   What if the emission region is moving towards us with a Lorentz γ factor of 15?
8. The energy spectrum of the Crab nebula (the strongest steady TeV gamma ray source) is about $J = 3.2 \times 10^{-7}\,(E/\mathrm{TeV})^{-2.5}\ \frac{1}{m^2\ s\ TeV}$. Can you explain the units?
   Estimate roughly how many photons above 500 GeV a single Cherenkov telescope would detect per minute from the Crab. (assume the detection efficiency ε_γ is 100%.)
9. How does CTA achieve better performance than existing Cherenkov experiments?
   Where and why is it superior to the Fermi LAT observatory?
10. How are the fluxes of gamma rays and neutrinos from an astrophysical source linked?



THANK YOU!