HAWC

Ibrahim Torres

CUDI
Otoño 2015
PUEBLA, Pue.
22 y 23 de octubre

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

INAOE
Instituto Nacional de Astrofísica, Optica y Electrónica

Outline

Science

- TeV Gamma-Ray Astronomy
- Cosmic Rays and Their Sources

Detection techniques

- Air Showers
- The HAWC Observatory

Results

- First Look at HAWC Data

Particle Astrophysics

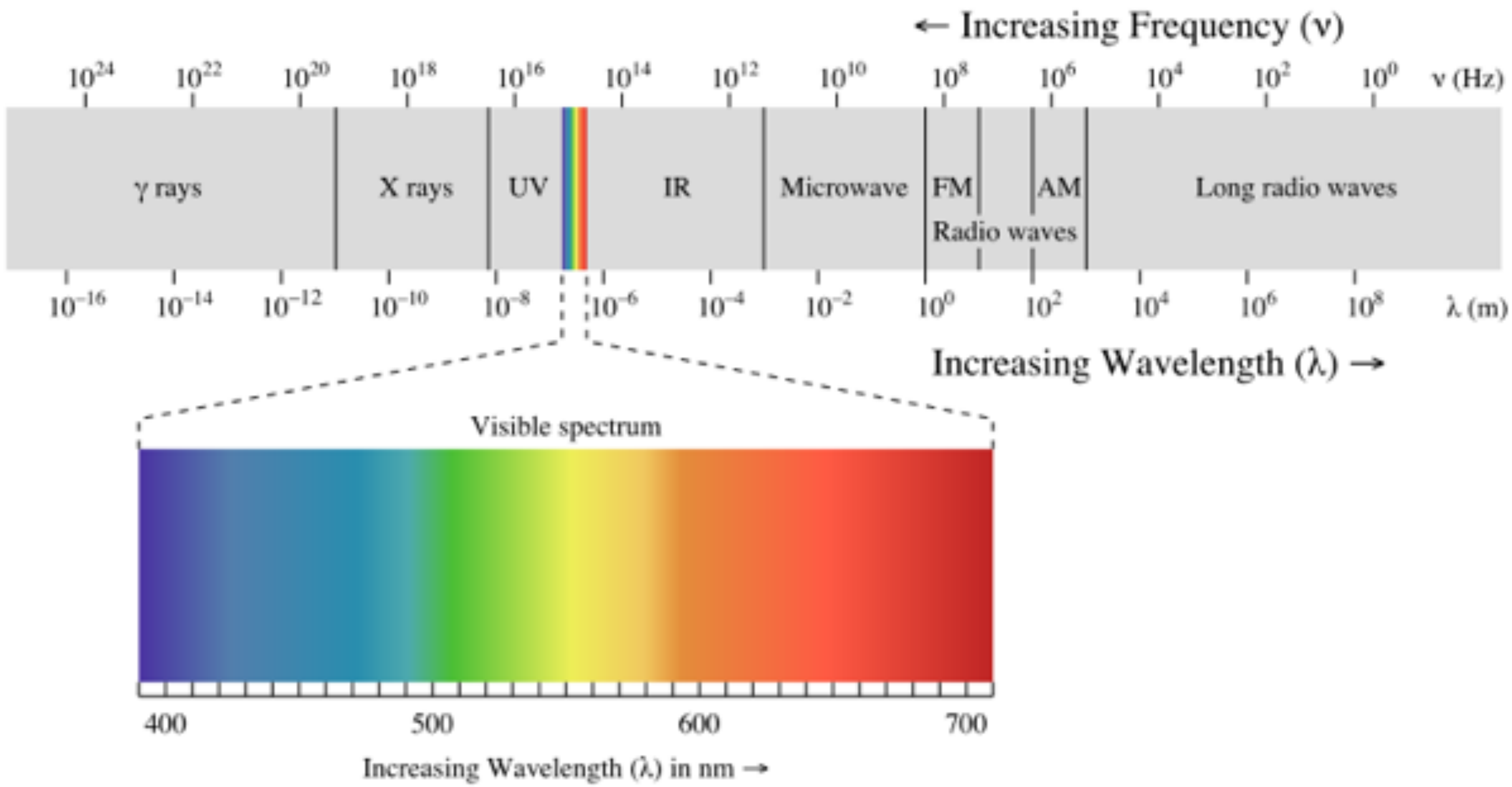
- "Classical" Astronomy – electromagnetic spectrum from radio to X-rays.
- Gamma-Ray Astronomy – photons (light particles) with energies 10^{10} larger than optical light.
- Cosmic Rays – protons and heavier nuclei with energies up to several Joule, the highest particle energies observed in the Universe.
- Neutrinos – tightly connected to cosmic rays and their sources, but neutral and not subject to deflection in magnetic fields (= easier for "astronomy").

energy

Electromagnetic Spectrum

TeV gamma-ray astronomy

Energy



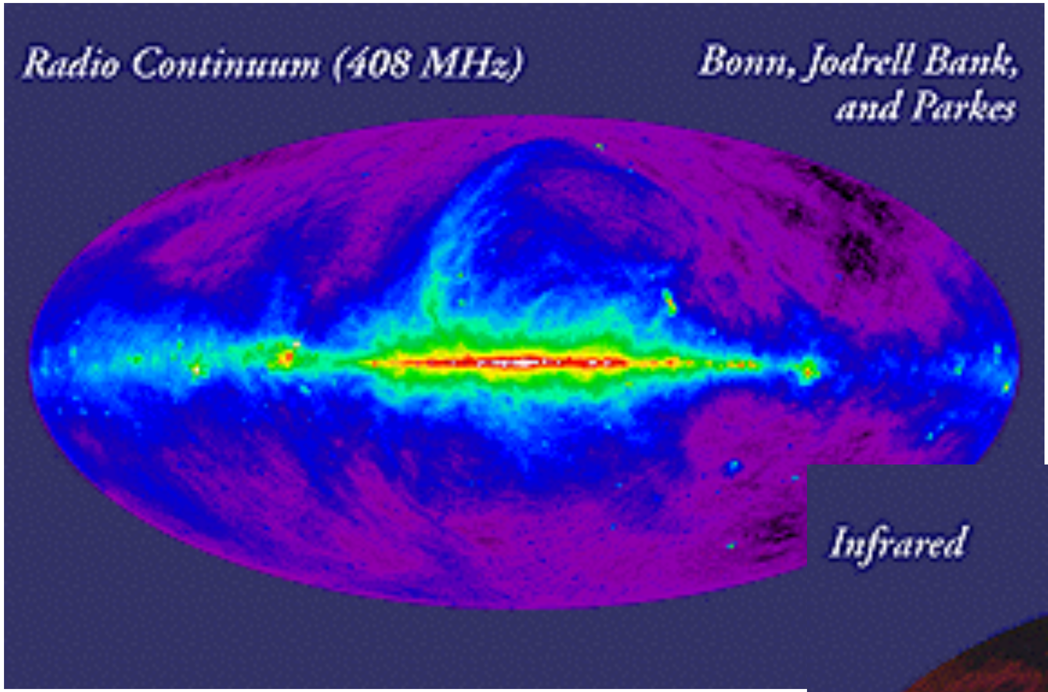
The Multiwavelength Sky

The most familiar wavelength: optical…

Stars, low density gas

~eV

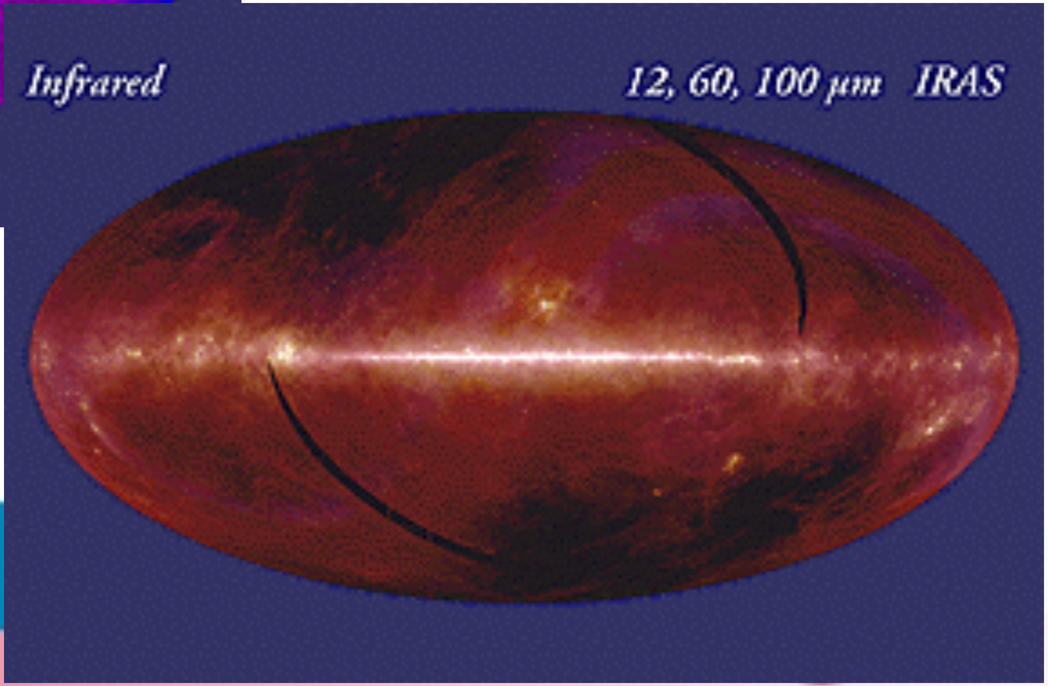
Going to *Lower* Energy…



radio

0.002 eV = 2 meV

Scattering of free electrons in ionized interstellar gas

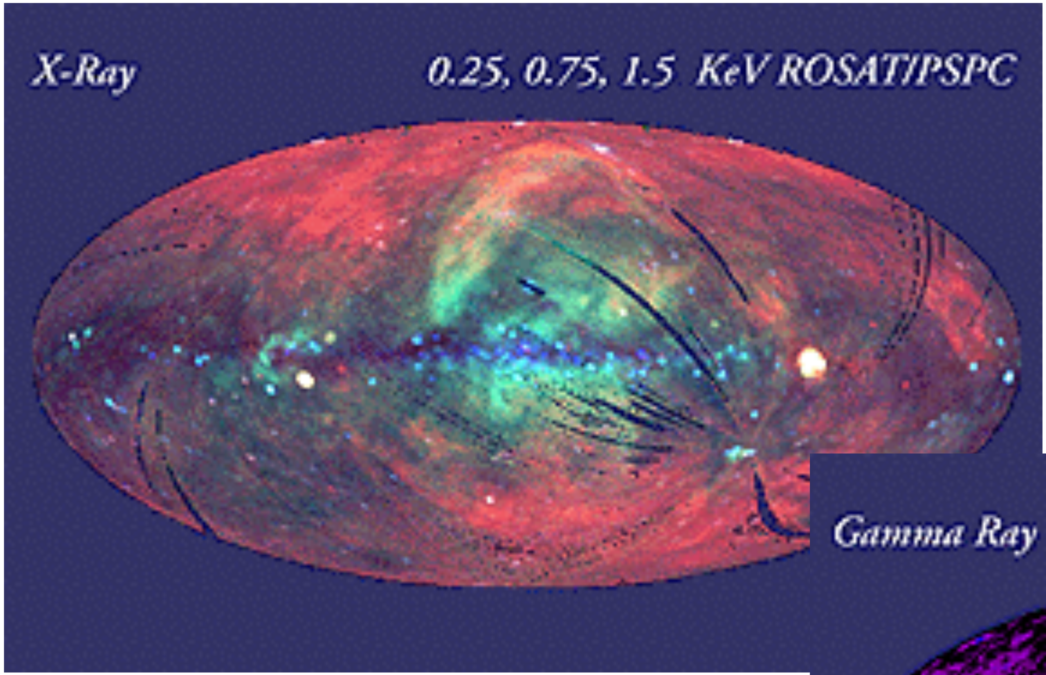


Interstellar dust warmed by absorbed starlight, starforming regions

infrared

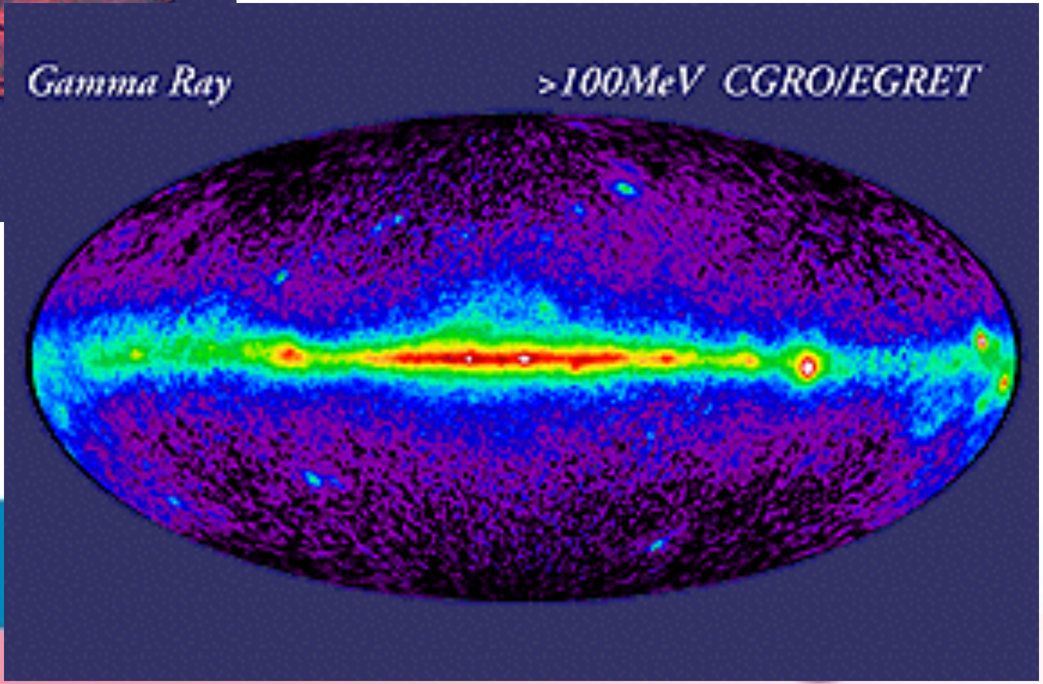
0.01 – 2 eV

Going to *Higher* Energy



X-ray
1000 eV = 1 keV

Hot gas

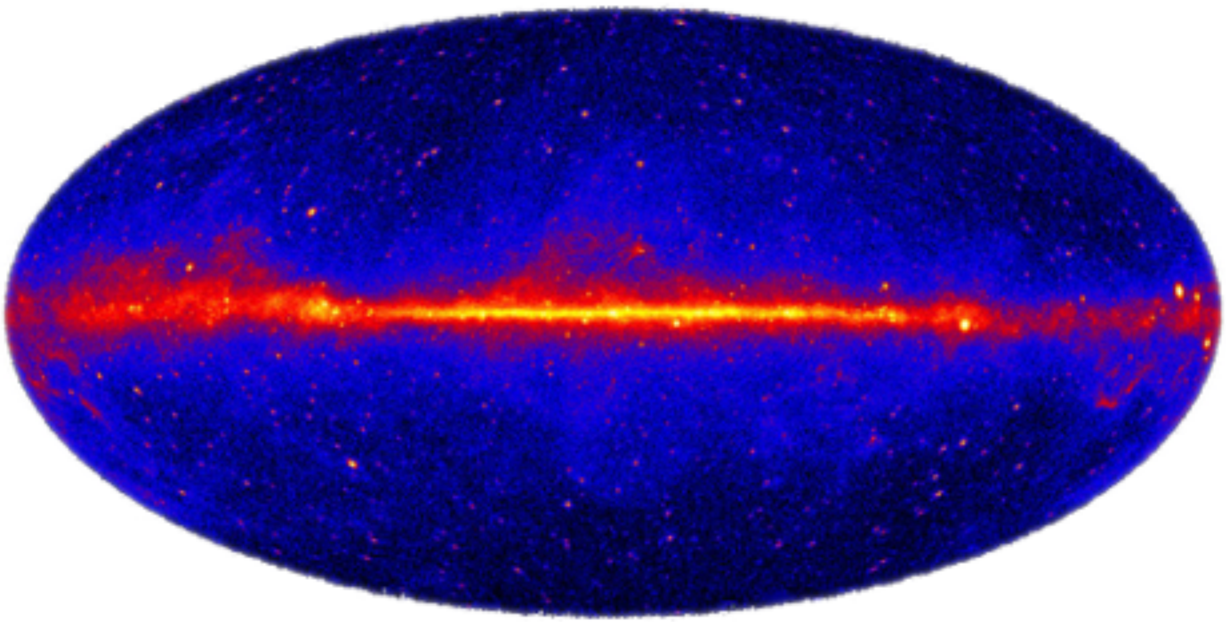


Collisions of cosmic rays with nuclei in interstellar clouds

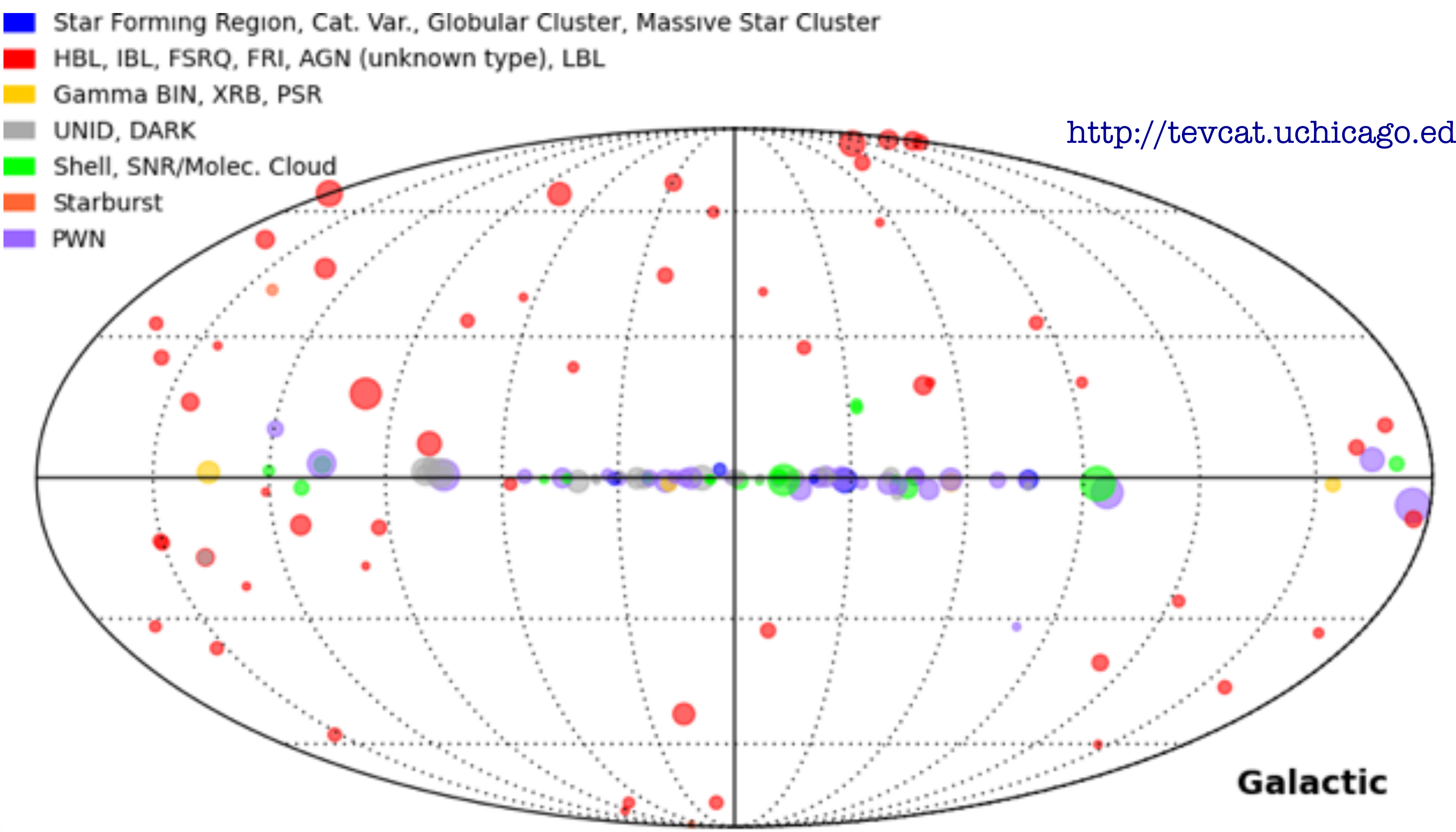
Gamma ray
>100 MeV

GeV Sky (10^9 eV) sources of Gamma Rays

- Most gamma rays with energy > 100 MeV originate in collisions of *cosmic rays* with nuclei in interstellar clouds (so the Milky Way is a diffuse source of gamma-ray light).
- Superimposed are several *gamma-ray pulsars*, e.g., the Crab, Geminga, and Vela pulsars along the Galactic plane.
- Away from the plane, many of the sources are known to be *active galactic nuclei.*

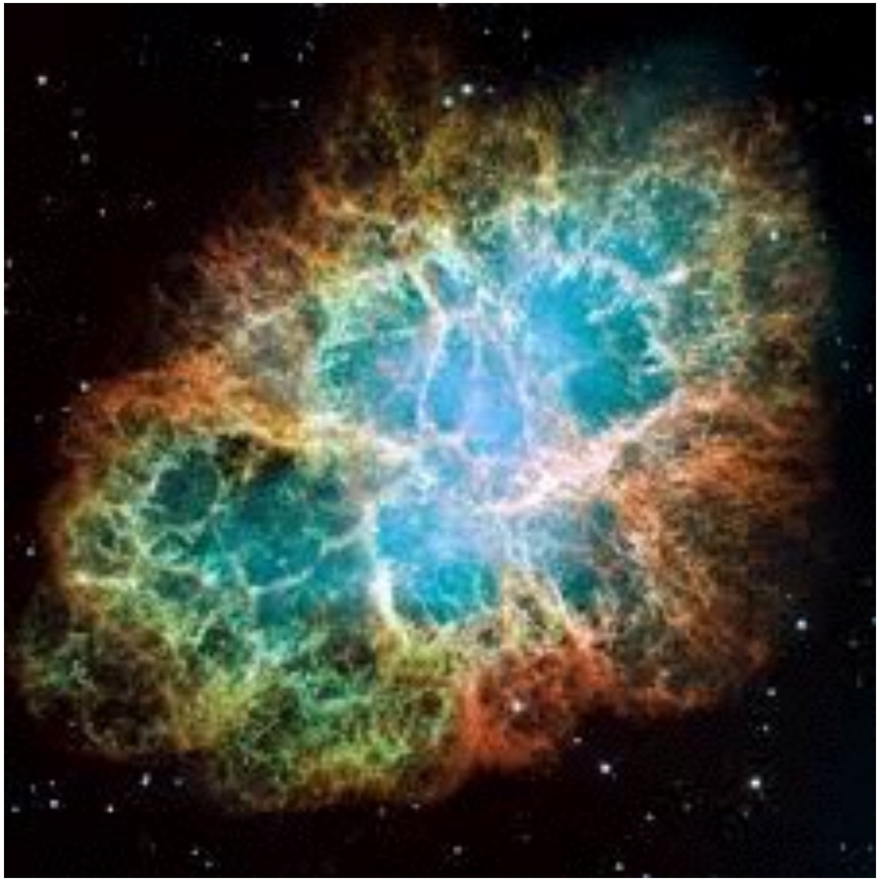


TeV Sky (10^{12} eV)

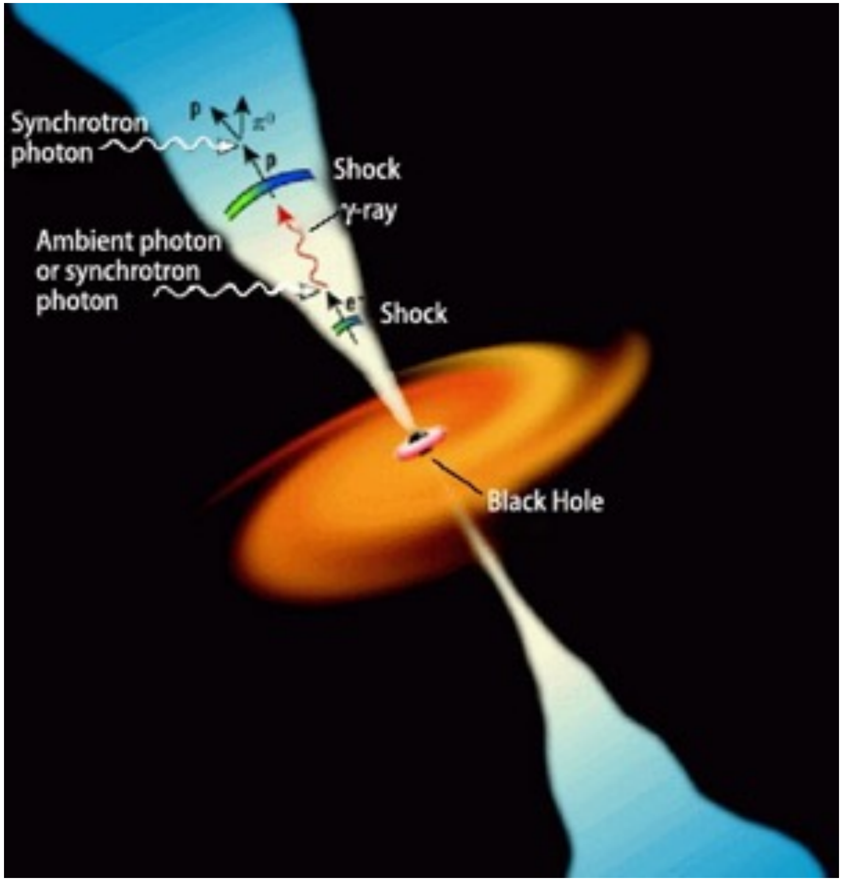


http://tevcat.uchicago.edu

TeV Sources

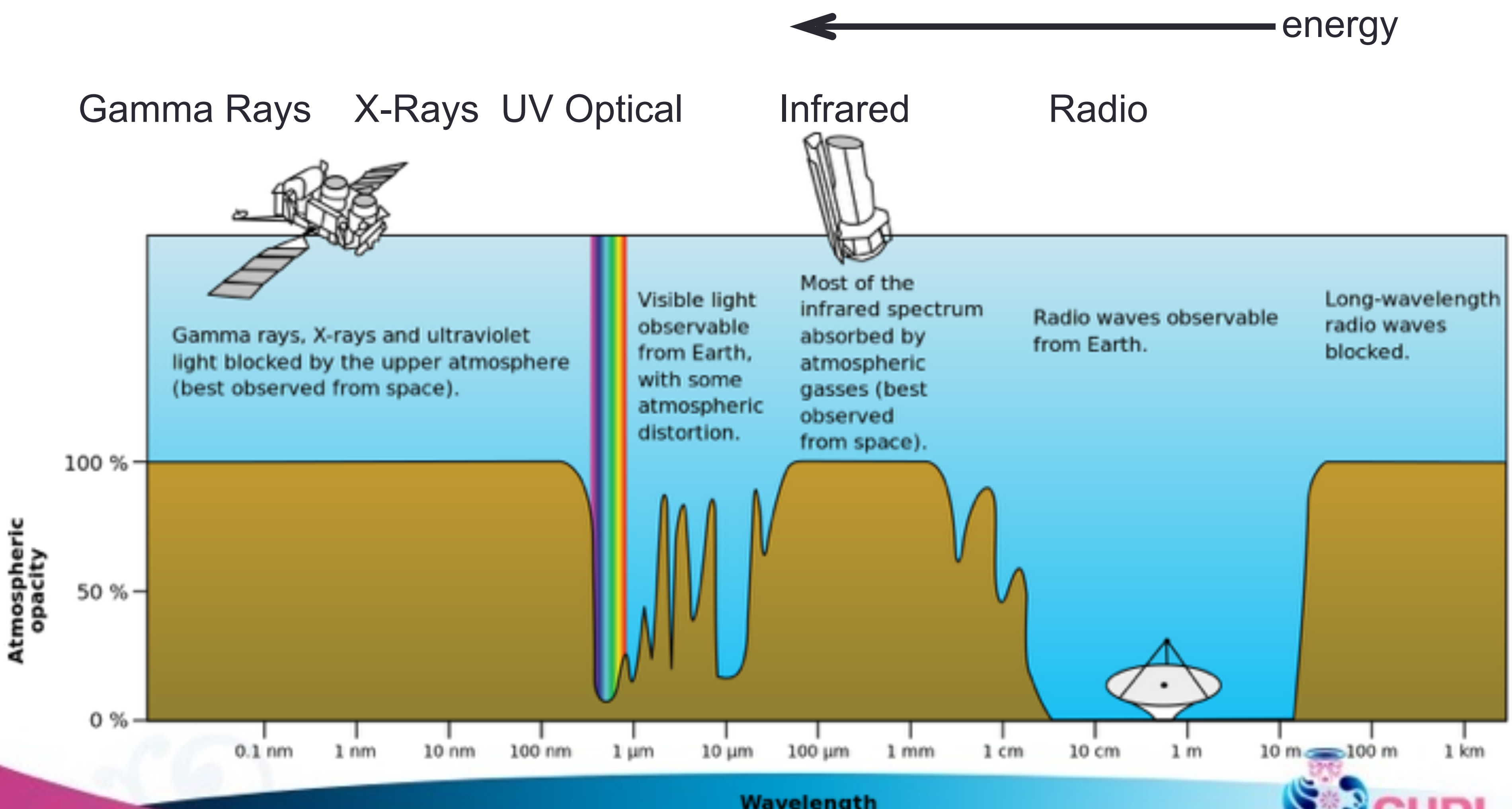


Galactic Sources:
Supernova Remnants, pulsars, …



Extragalactic Sources:
Active Galactic Nuclei,…

Observation Techniques



Why Study the TeV Band?

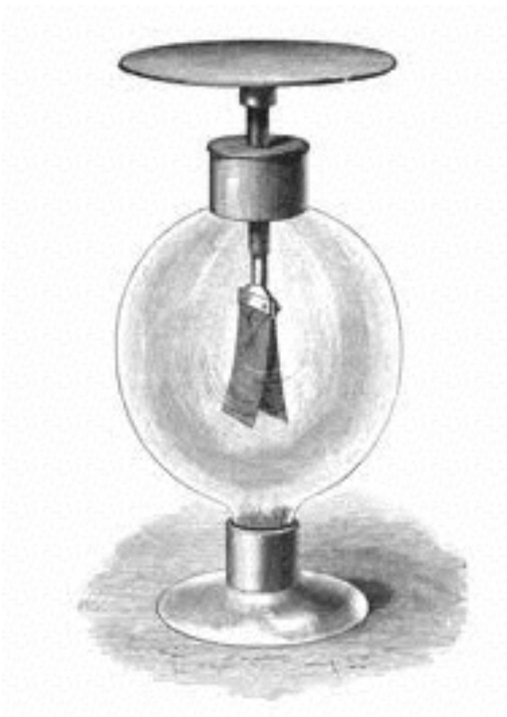
- TeV gamma rays are the highest energy gamma rays observed so far – this is the *energy frontier* of astronomy!

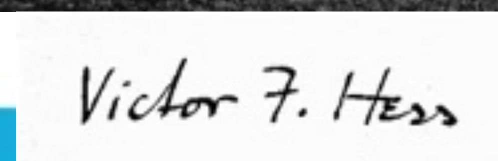
- TeV sources emit radiation over more than 15 orders of magnitude in energy, from radio to TeV!

- Historically, opening new windows in astronomy always results in major, *unforeseen discoveries.*

- Among the most tantalizing possibilities: the TeV window might help to identify the *sources of cosmic rays* and solve a hundred year old mystery…!

Victor Hess, 1912





- Electroscopes discharge slowly even if no radioactive material is around - does the Earth radiate?

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Discovery of “Cosmic Rays”

- Going up as high as 17,500 feet, Hess showed that the radiation level *increases* with altitude!

7. Fahrt (7. August 1912).

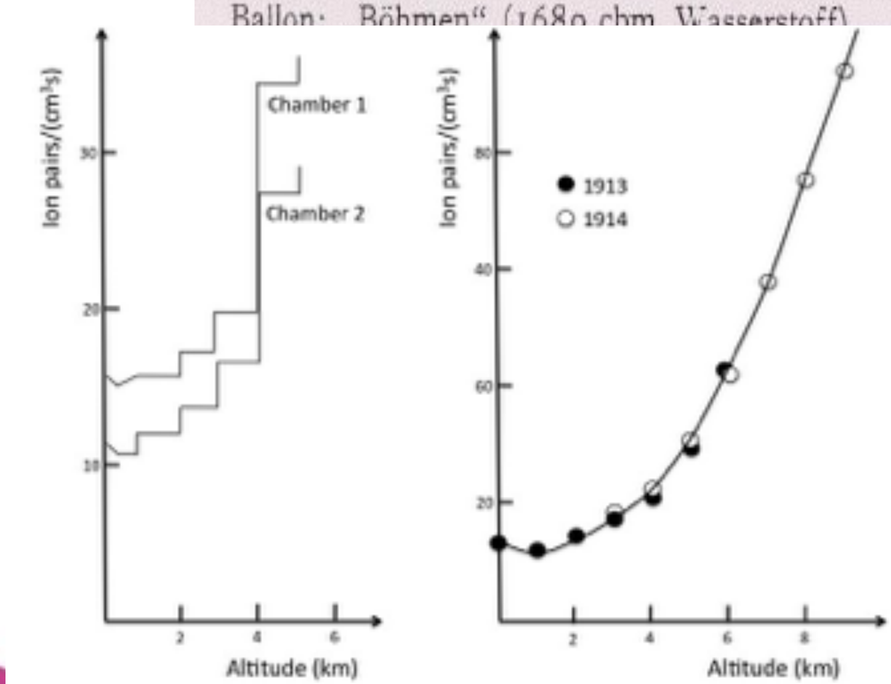
Ballon: „Böhmen“ (1680 cbm Wasserstoff)

Führer: Hauptmann W. Hoffory.
Luftelektr. Beobachter: V. F. Hess.

Beobachtete Strahlung

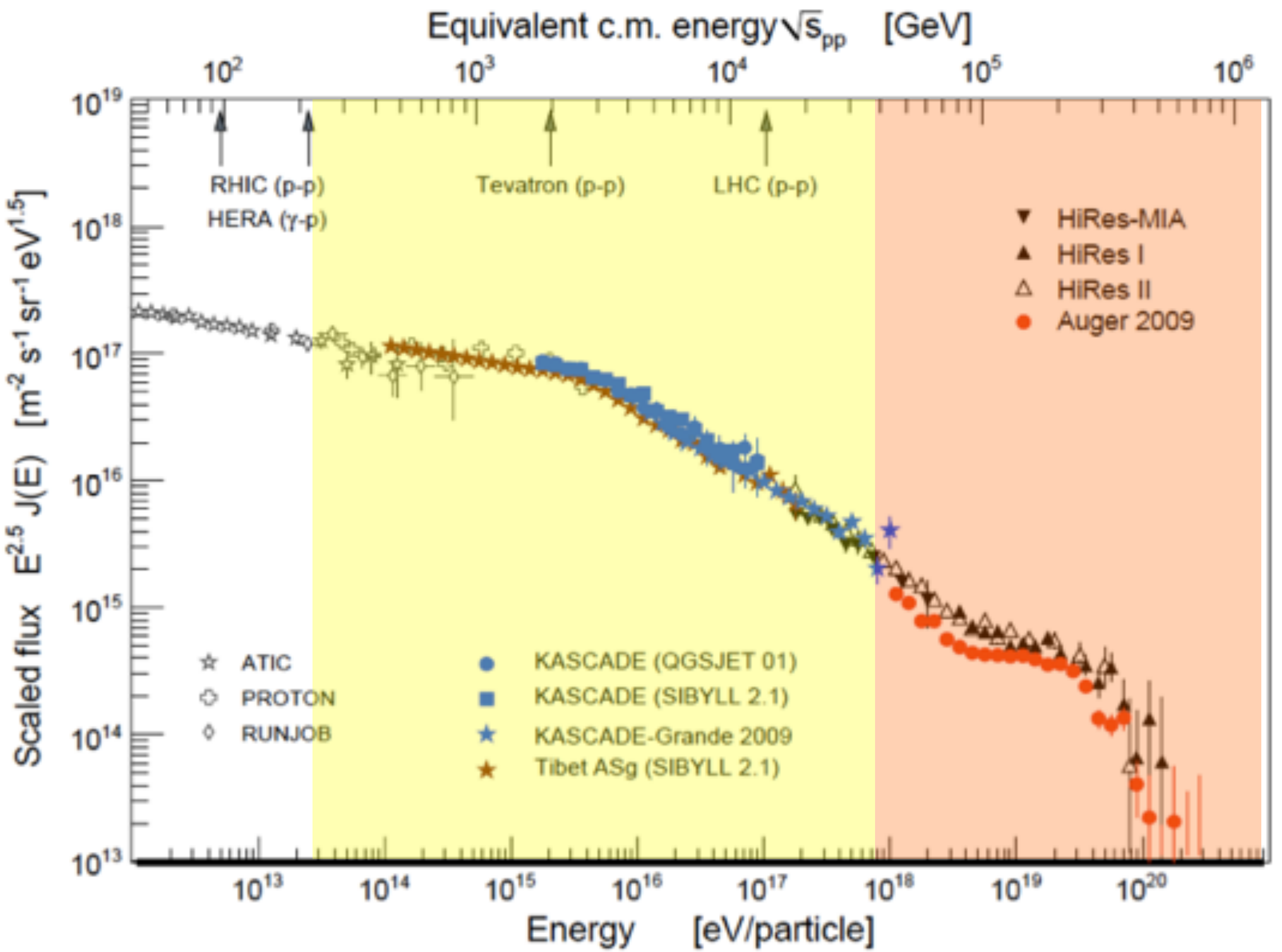
10	11h 45—12h 10	250	150	11,9
11	12h 25—13h 12	140	0	15,0

Pieskow, Brandenburg)



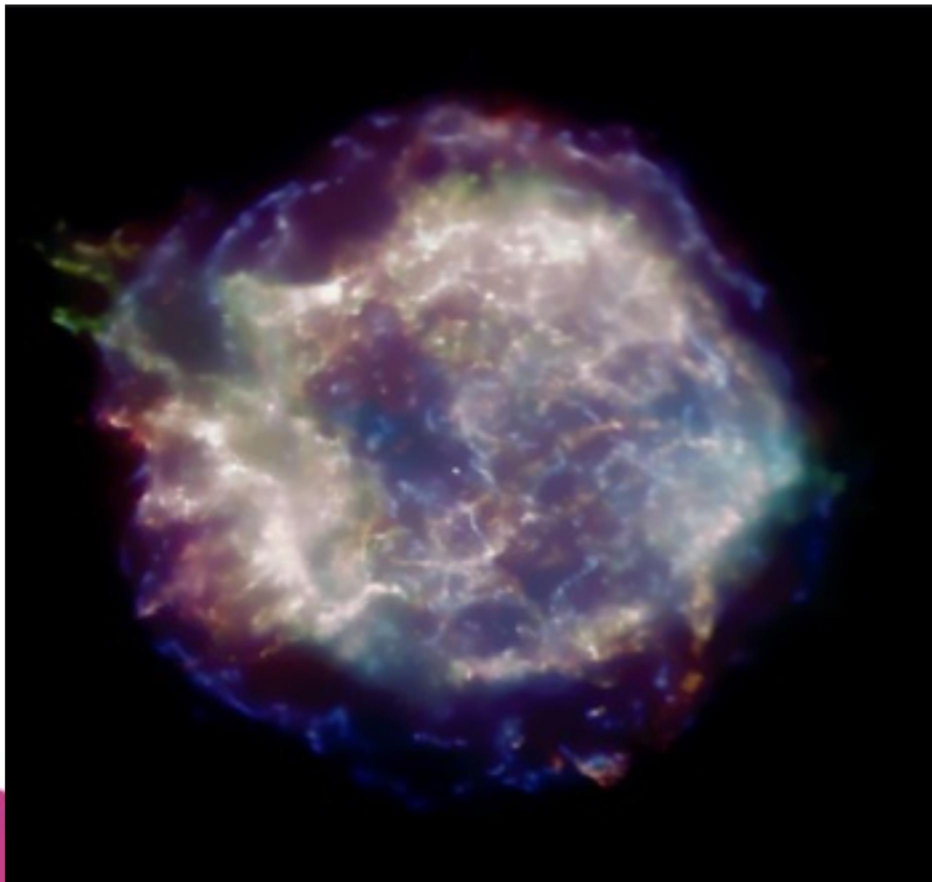
22 y 23 de octubre

Cosmic-Ray Energy Spectrum

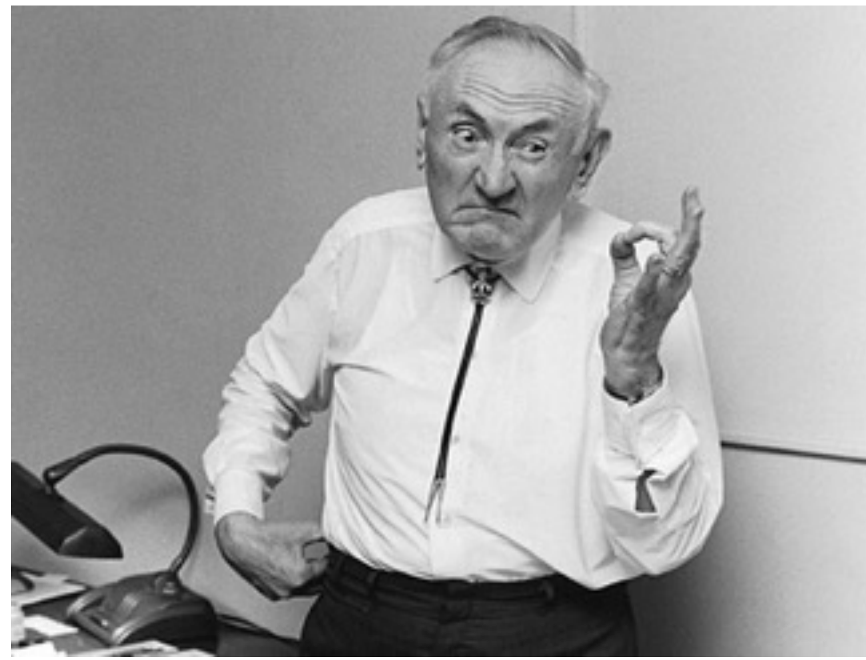


Galactic Cosmic Rays

- Baade and Zwicky suggested in 1934 that *supernova remnants* could be the sources of Galactic cosmic rays.



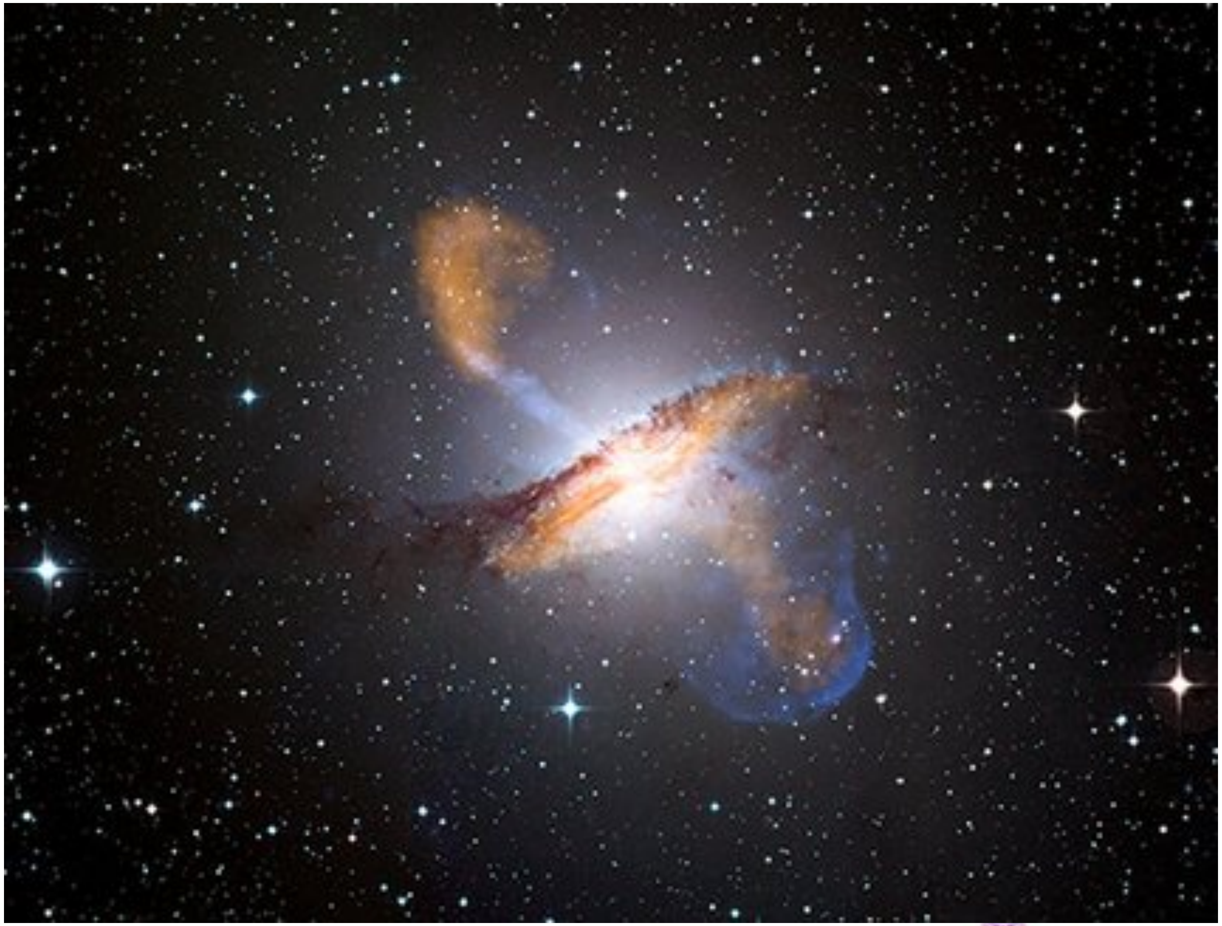
Cas A, Chandra (NASA)



Fritz Zwicky

Extragalactic Sources

- *Active Galactic Nuclei* (AGN) are possible sources for the highest energy cosmic rays.
- AGN consist of a supermassive black hole, an accretion disk, and two jets in which shocks move outward.



Centaurus A (ESO 2.2 m WFI + APEX + Chandra)

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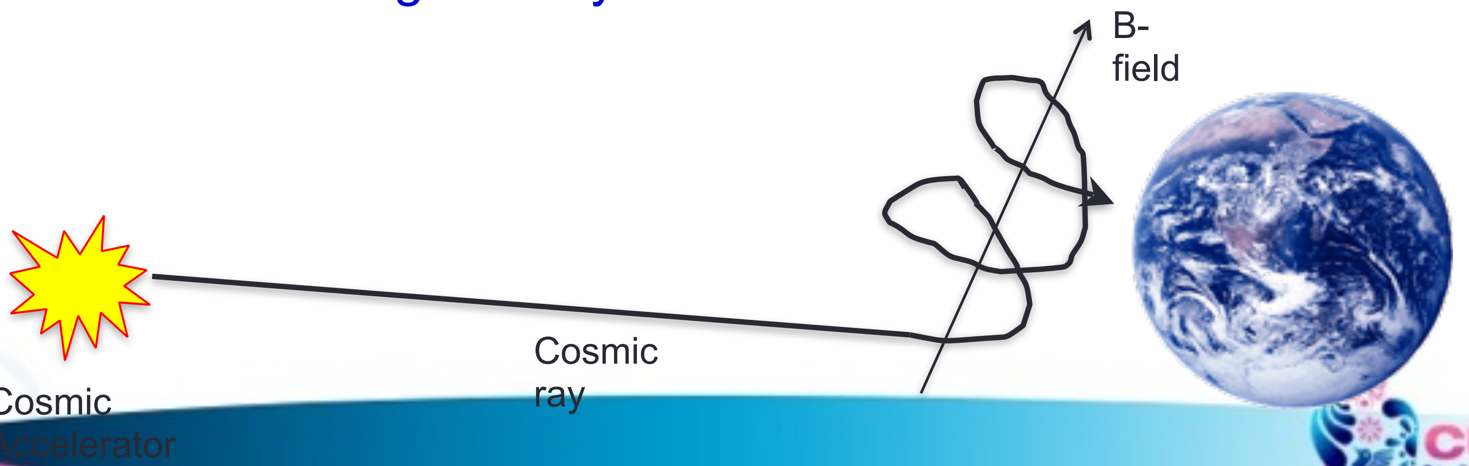
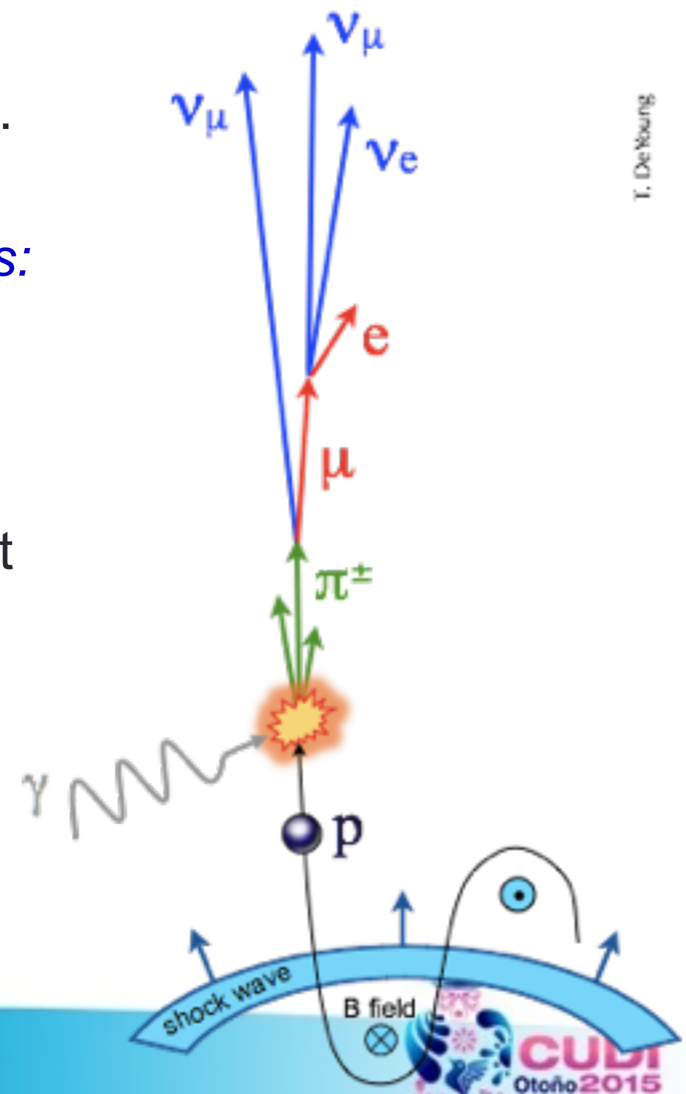
Cosmic-Ray Astronomy?

- No source of Galactic or extragalactic cosmic rays has been identified so far.
- The problem: cosmic rays are charged, and the universe is full of magnetic fields.
- Below 10^{19} eV (*at least*) we expect the arrival directions of cosmic rays at Earth to be magnetically scrambled.



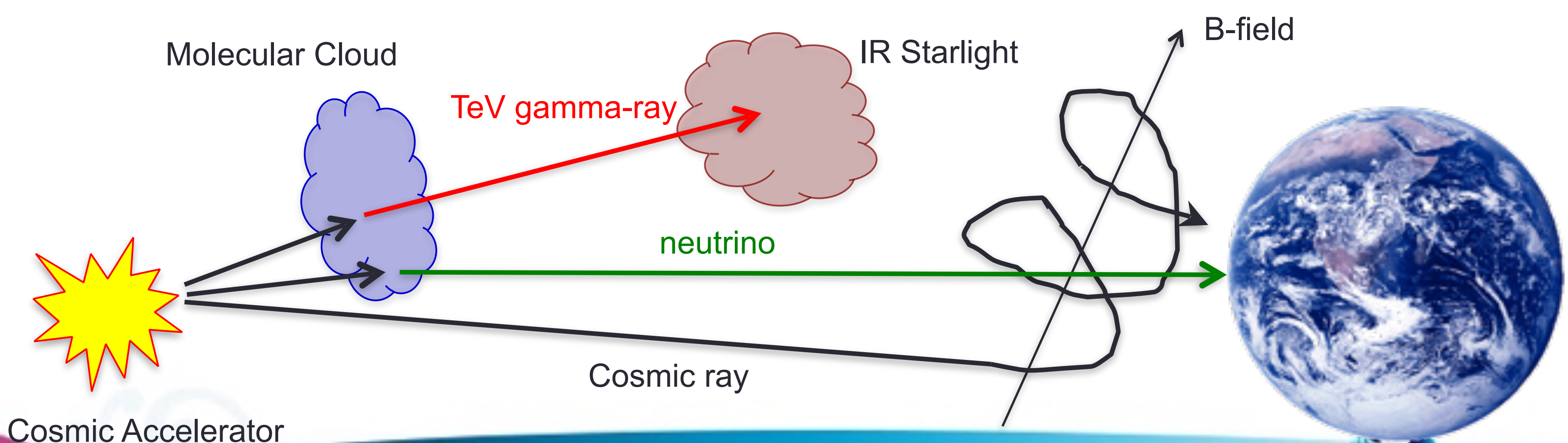
Gamma Rays

- Cosmic rays *interact* with their surroundings.
- The interactions will produce *decay products:*
  - Gamma rays
  - Neutrinos
- Both are neutral and come to us in a straight line!
- Energy escaping the source is distributed among *cosmic rays, gamma rays,* and *neutrinos.*



Multi-Messenger Astrophysics

- Each channel has relative strengths and weaknesses:
  - Cosmic rays: ✓ largest flux, ✗ deflected by magnetic fields
  - Gamma-rays: ✓ undeflected, ✗ attenuated
  - Neutrinos: ✓ undeflected, ✓ unattenuated, ✗ difficult to observe



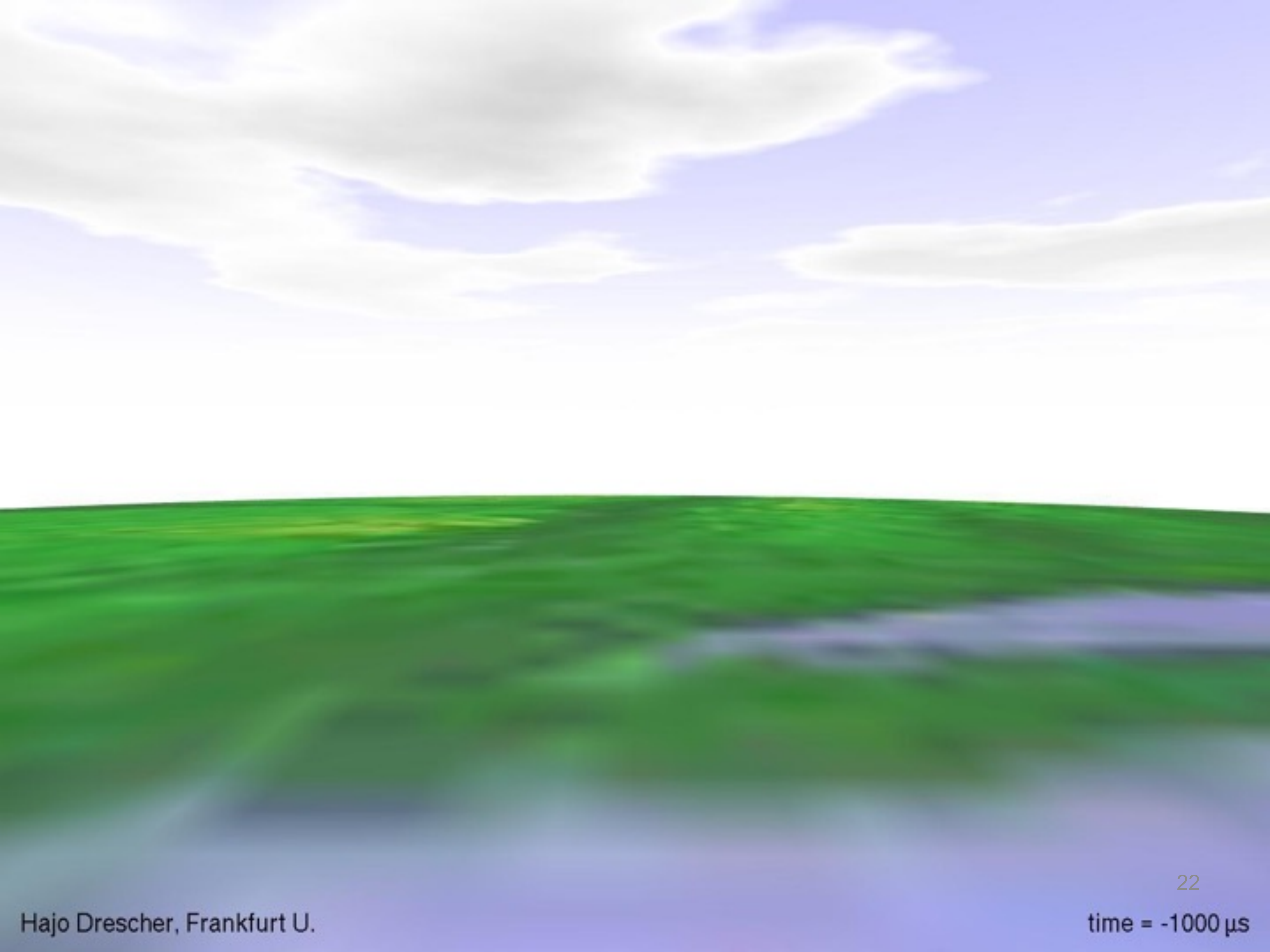
Detecting TeV Gamma Rays

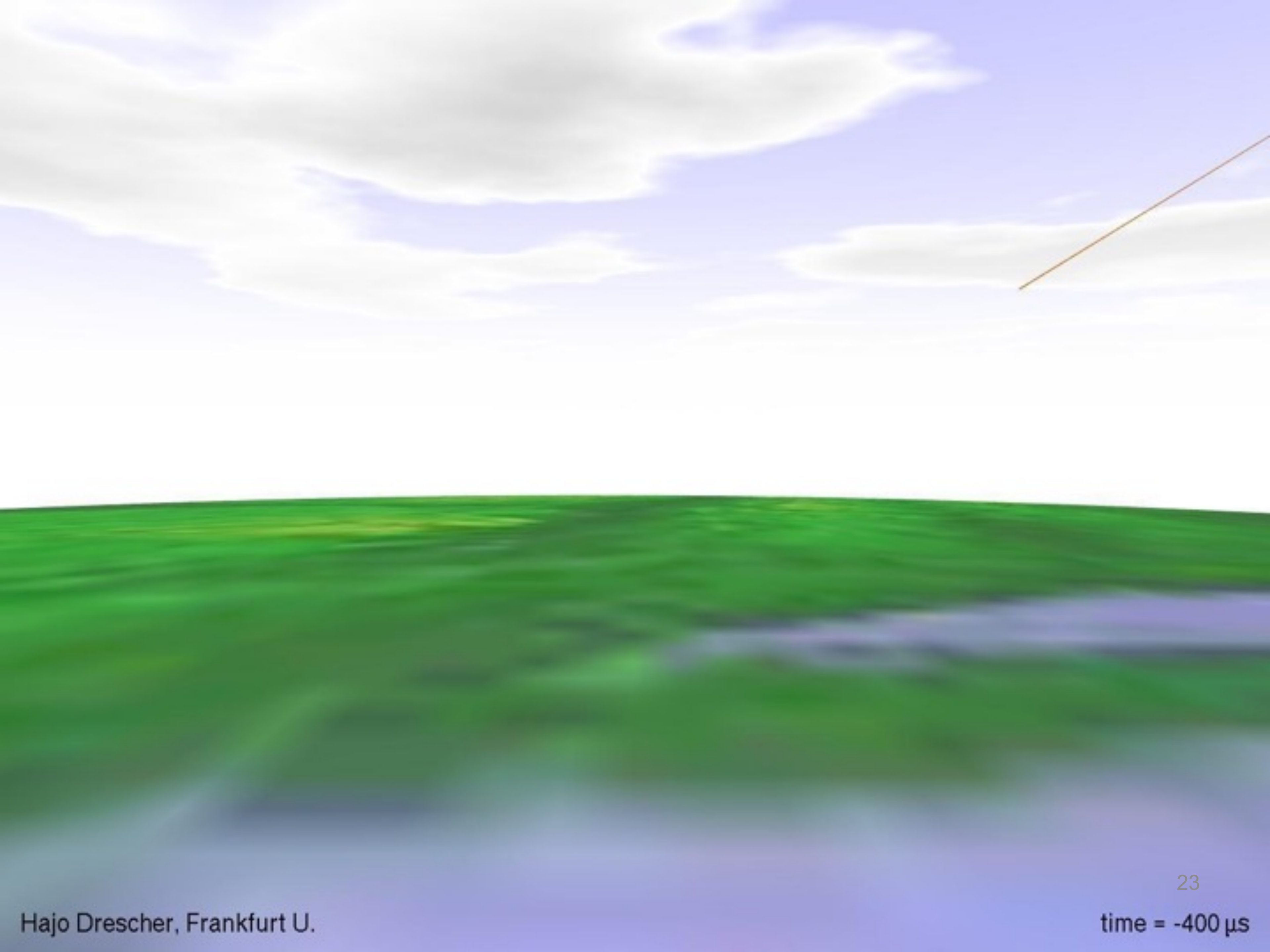
- The flux of TeV (= 10^{12} eV) gamma rays is more than 6 orders of magnitude smaller than at GeV(= 10^{9} eV) energies, where the Fermi satellite operates. To get sufficient flux, the experiment must cover a large area, at least soccer field size…

- … so the experiment must be Earth-bound.

- The Earth's atmosphere is 100% *opaque* to gamma rays at TeV energies.

- Gamma rays and cosmic rays interact with air molecules and develop cascades of secondary particles, so-called *air showers.* The atmosphere acts as a giant calorimeter. We can use this to our advantage!


Hajo Drescher, Frankfurt U.
time = -1000 μs


Hajo Drescher, Frankfurt U.
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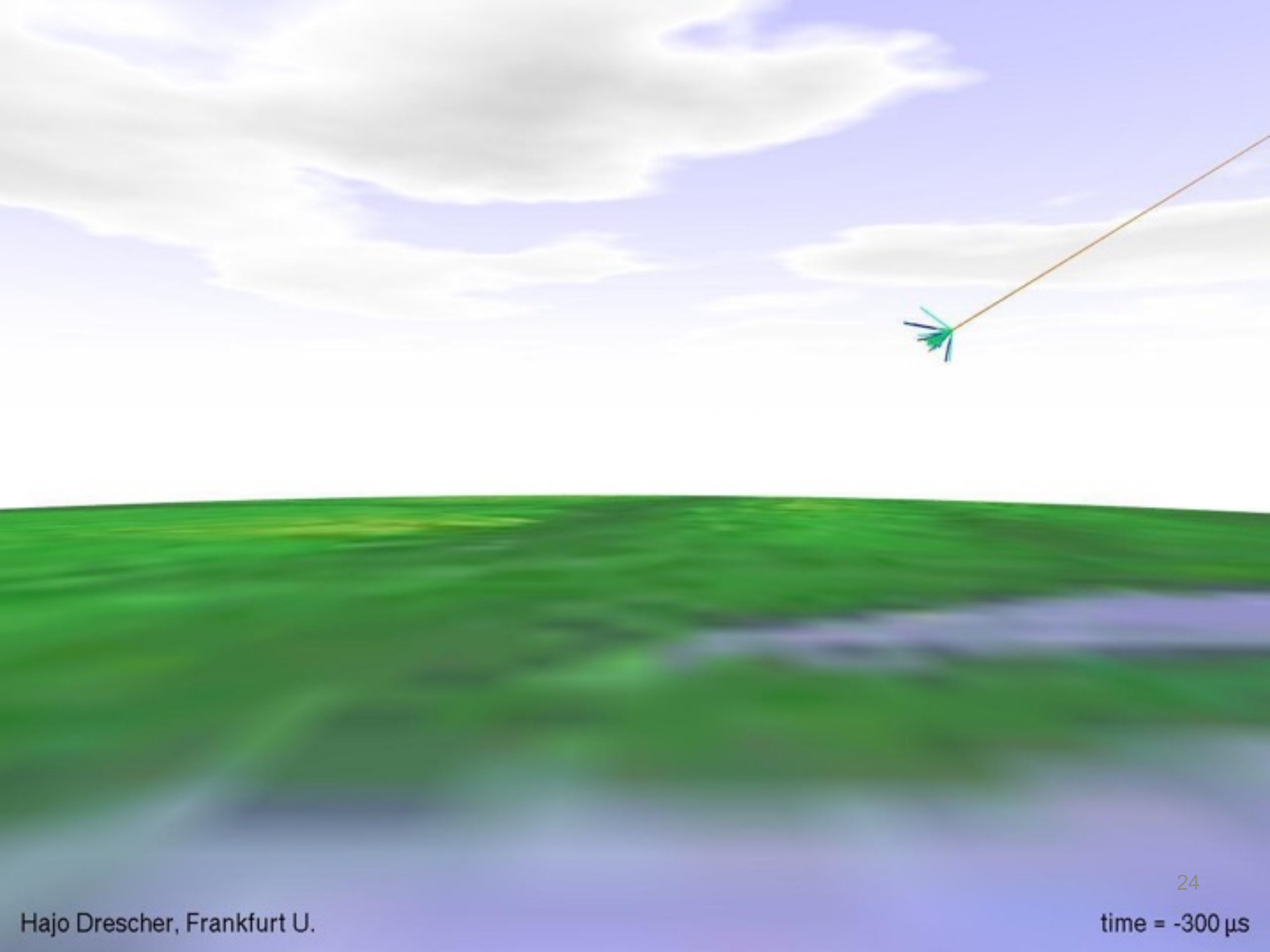
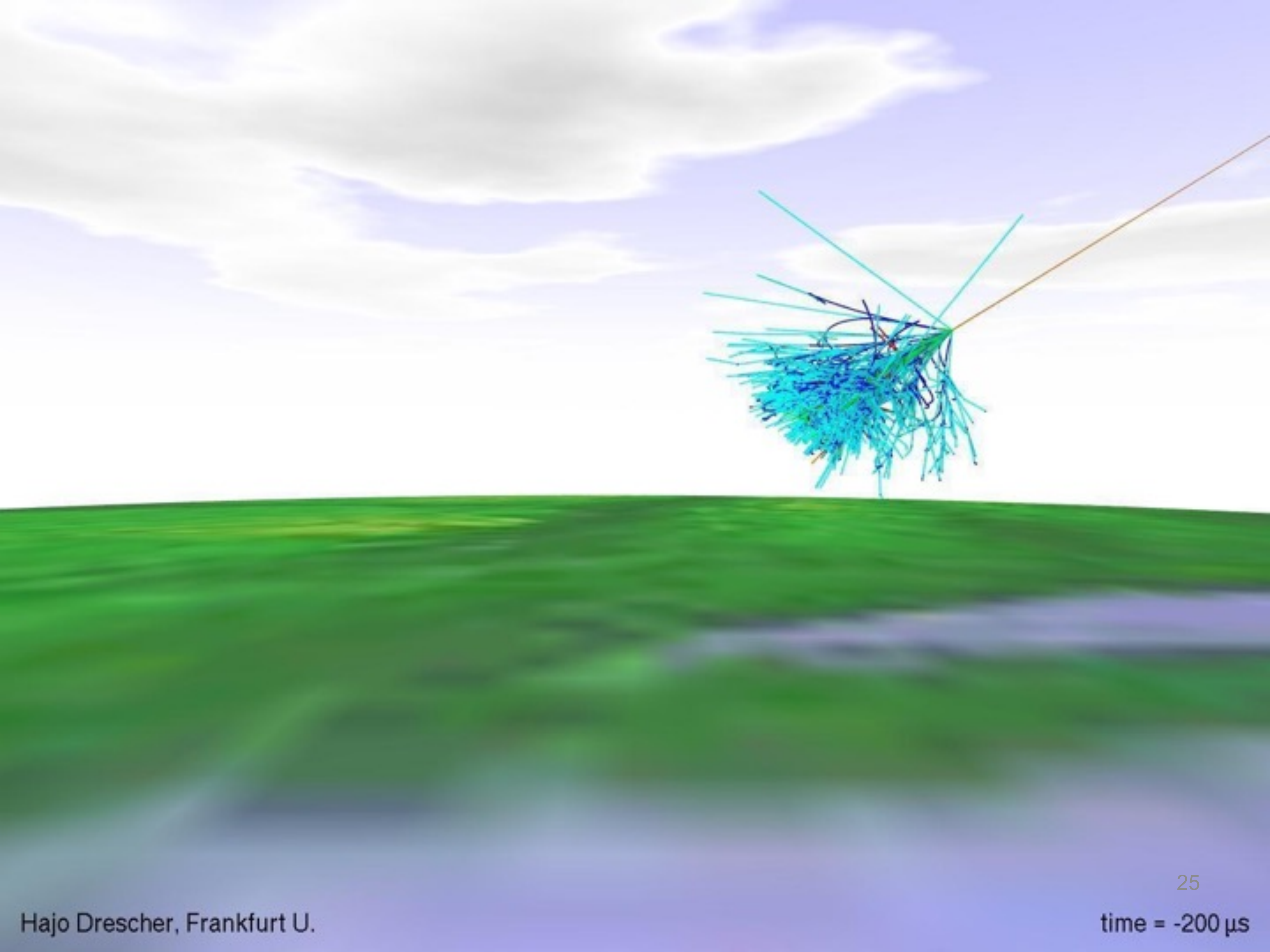

Hajo Drescher, Frankfurt U.
time = -300 µs


Hajo Drescher, Frankfurt U.
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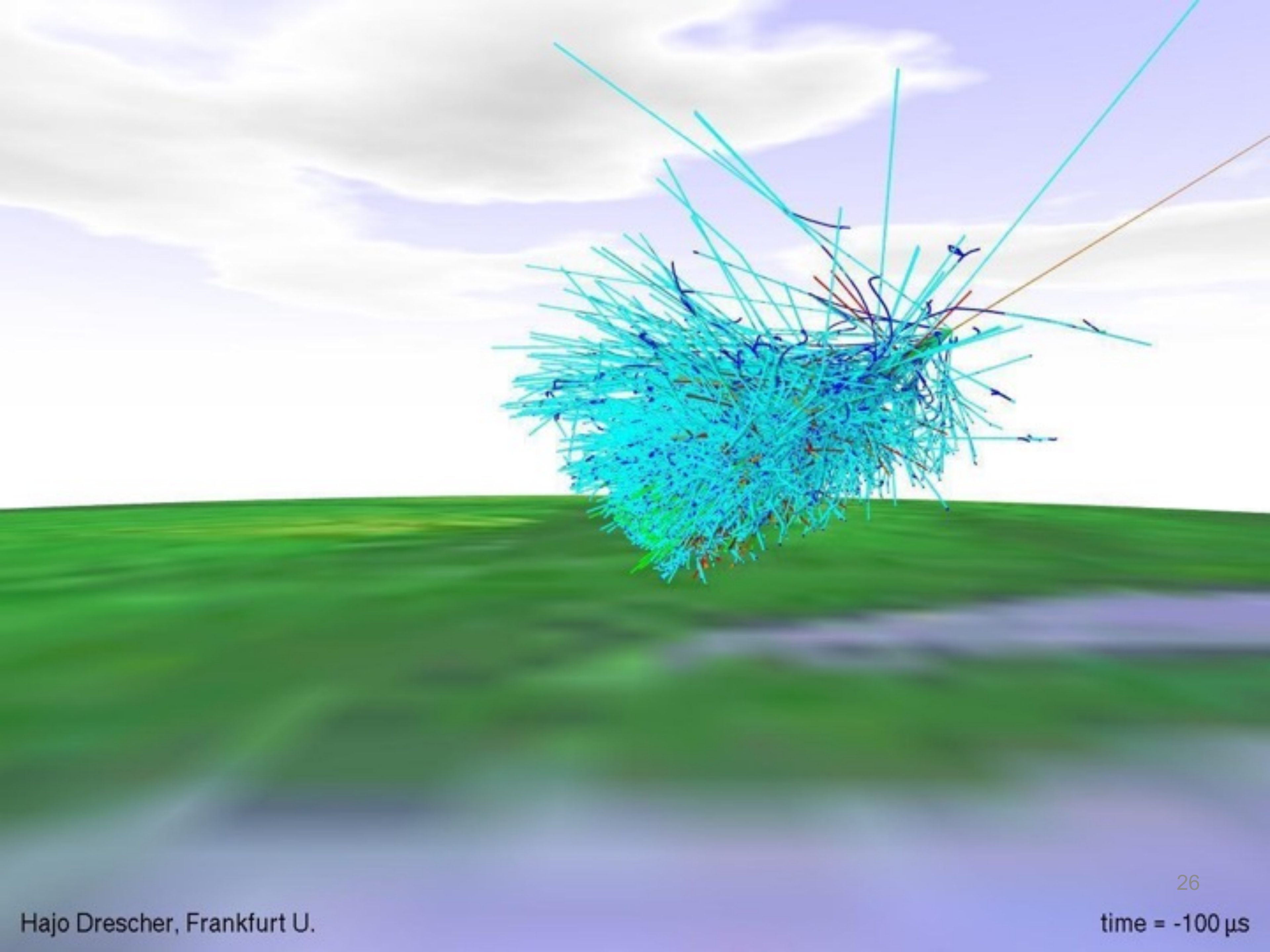
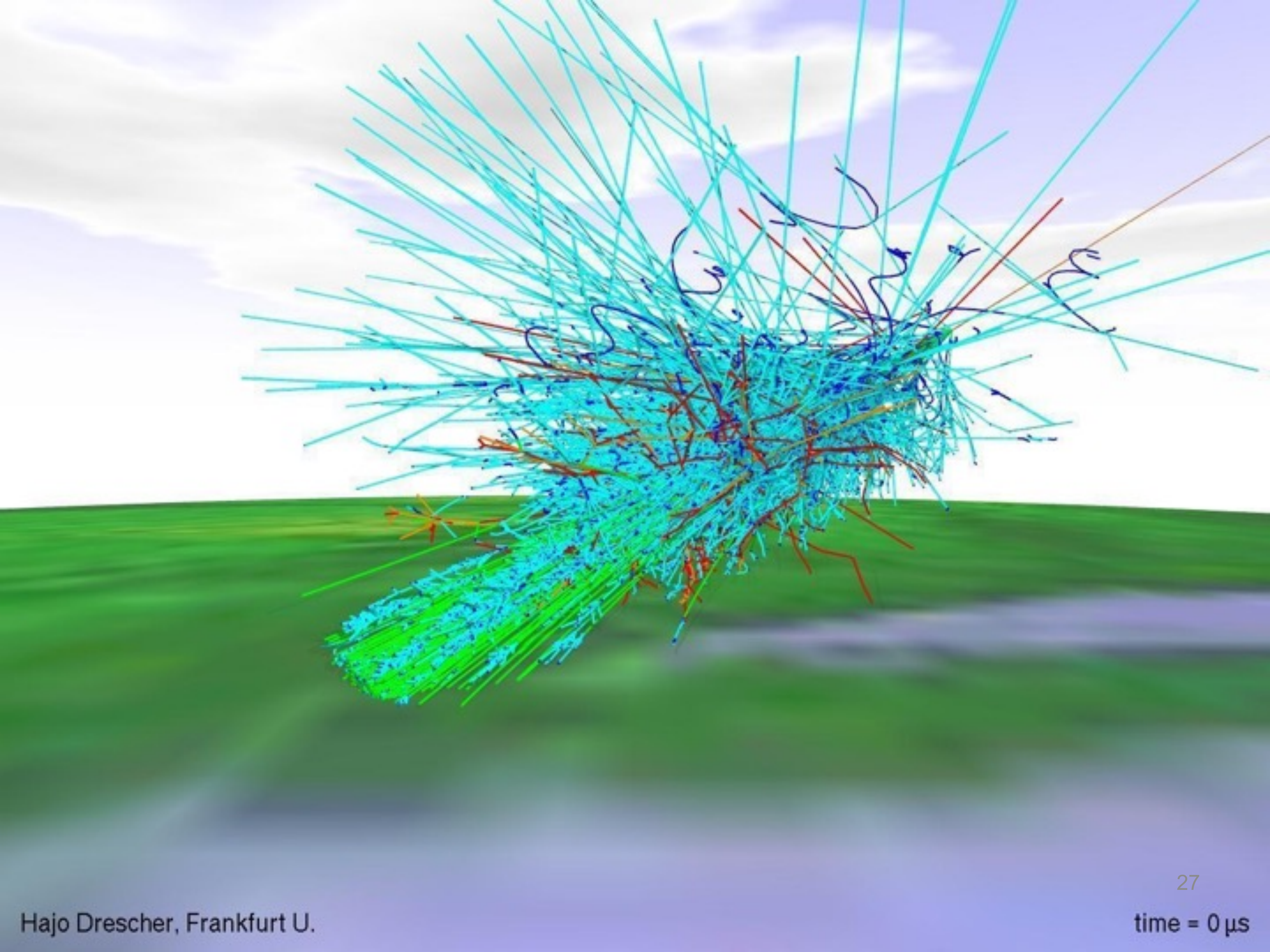
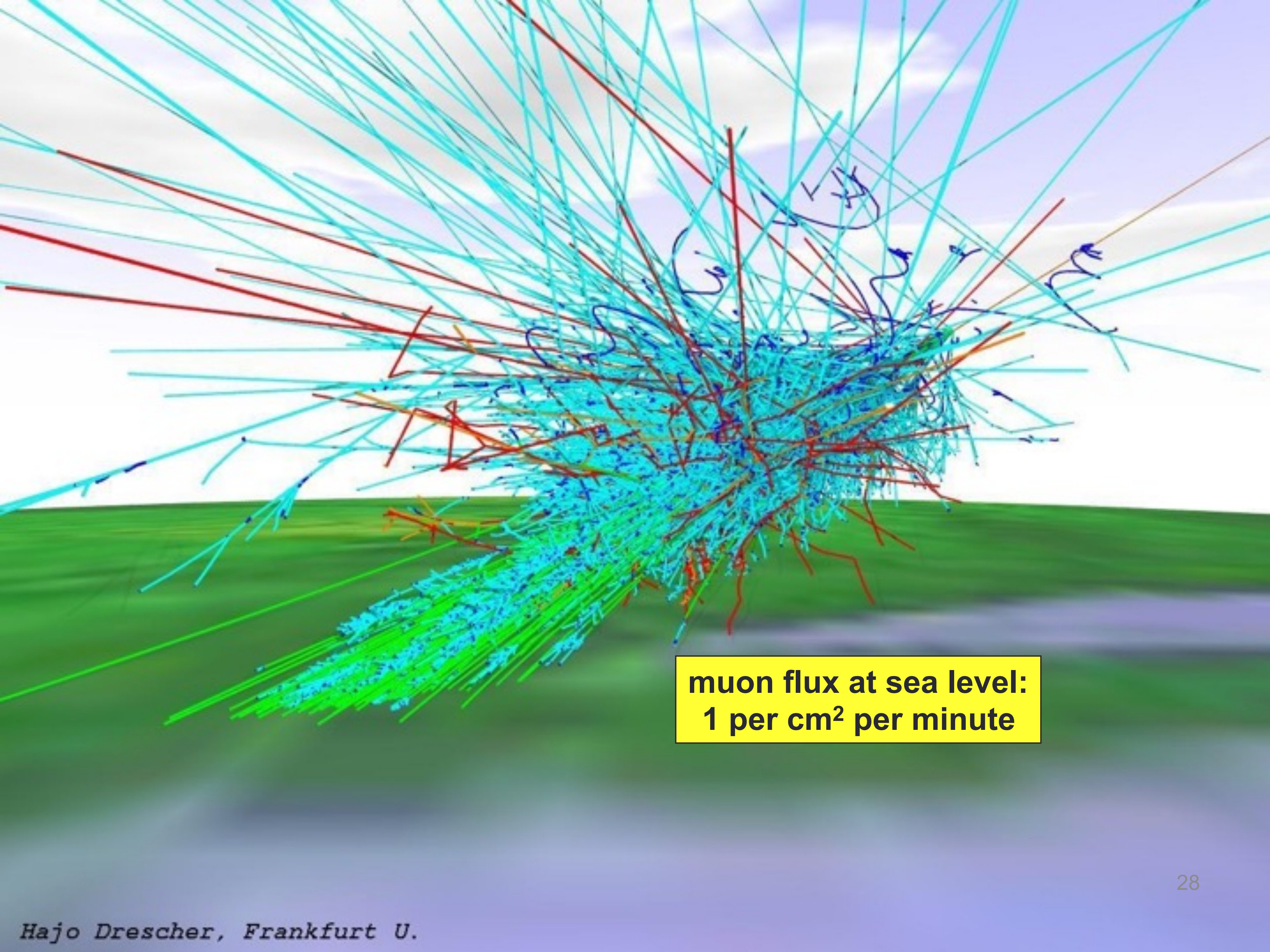
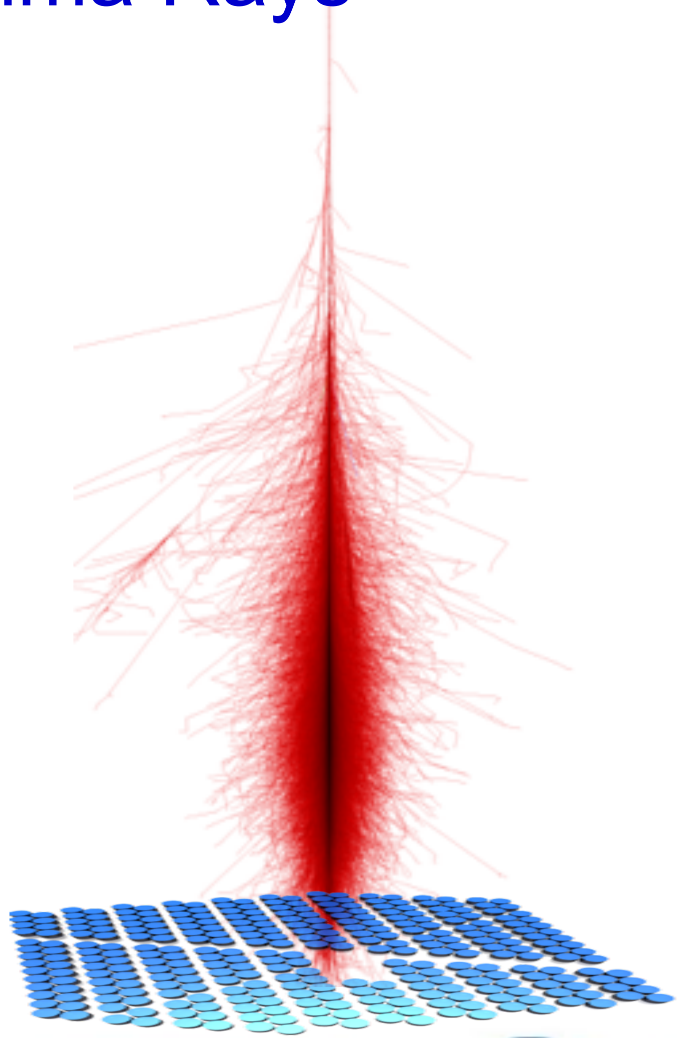

Hajo Drescher, Frankfurt U.
time = -100 µs


Hajo Drescher, Frankfurt U.
time = 0 µs


muon flux at sea level:
1 per cm^2 per minute
Hajo Drescher, Frankfurt U.

Detecting TeV Gamma Rays

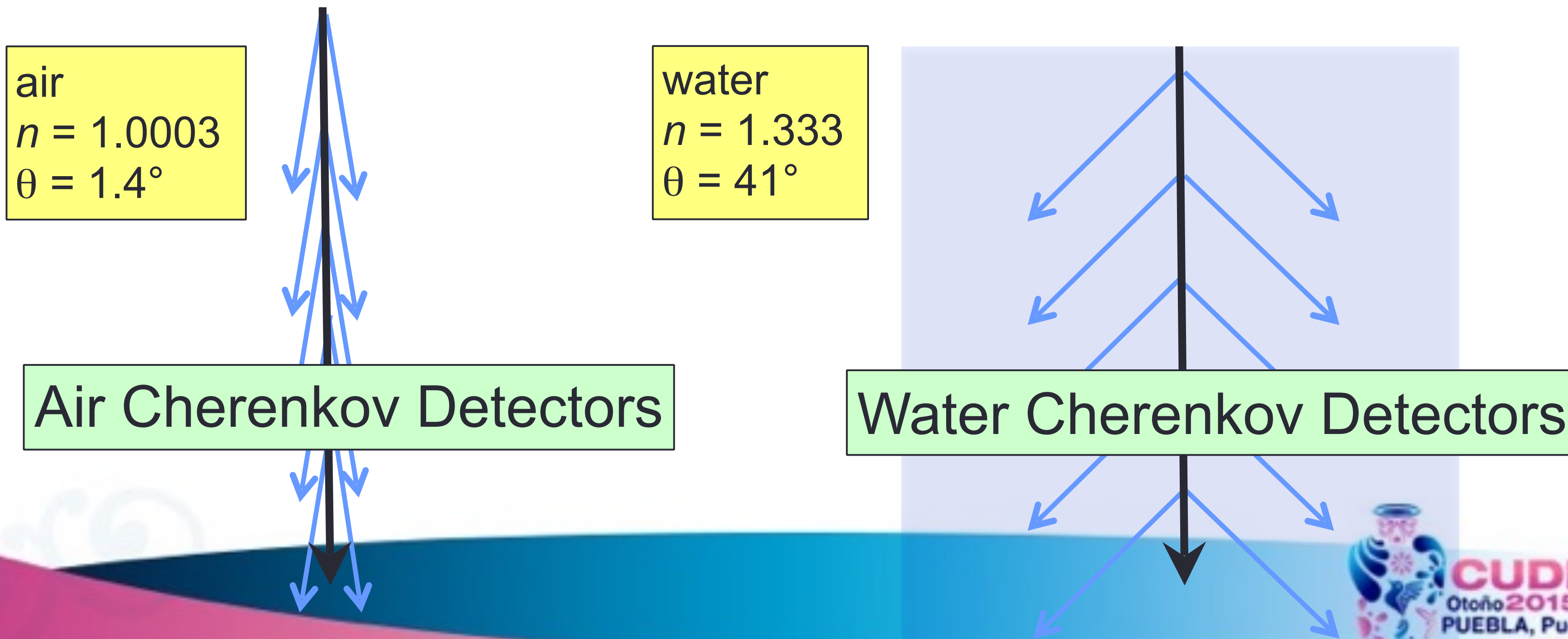
- (Two) methods for detecting air showers:
  - A fraction of the secondary particles hits the ground and can be detected by arrays of particle counters.
  - The air shower particles are relativistic and produce *Cherenkov light* which can be picked up by light detectors.
  - Both techniques use Cherenkov light and photomultiplier tubes…



Cherenkov Light

- Cherenkov light is produced when particles travel through a medium (air, water,…) at a speed *faster* than the speed of light *in the medium.*

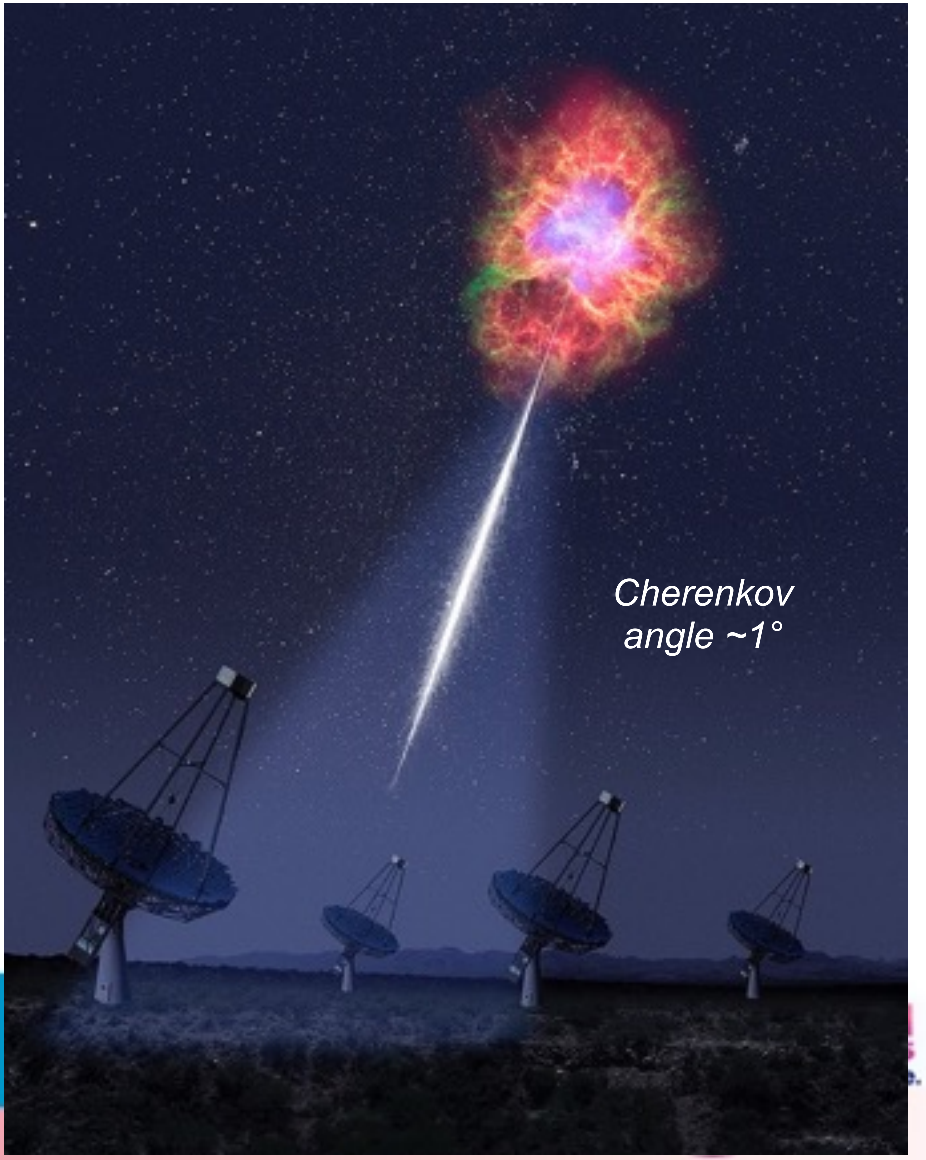
- Cherenkov light is emitted in the forward direction, and the emission angle depends on the index of refraction *n* of the medium.



Air Cherenkov Telescopes

- Air Cherenkov telescopes detect the *Cherenkov light cone* produced by the particle shower.

- They consist of systems of small mirrors that reflect the light into cameras made of arrays of photomultipliers.



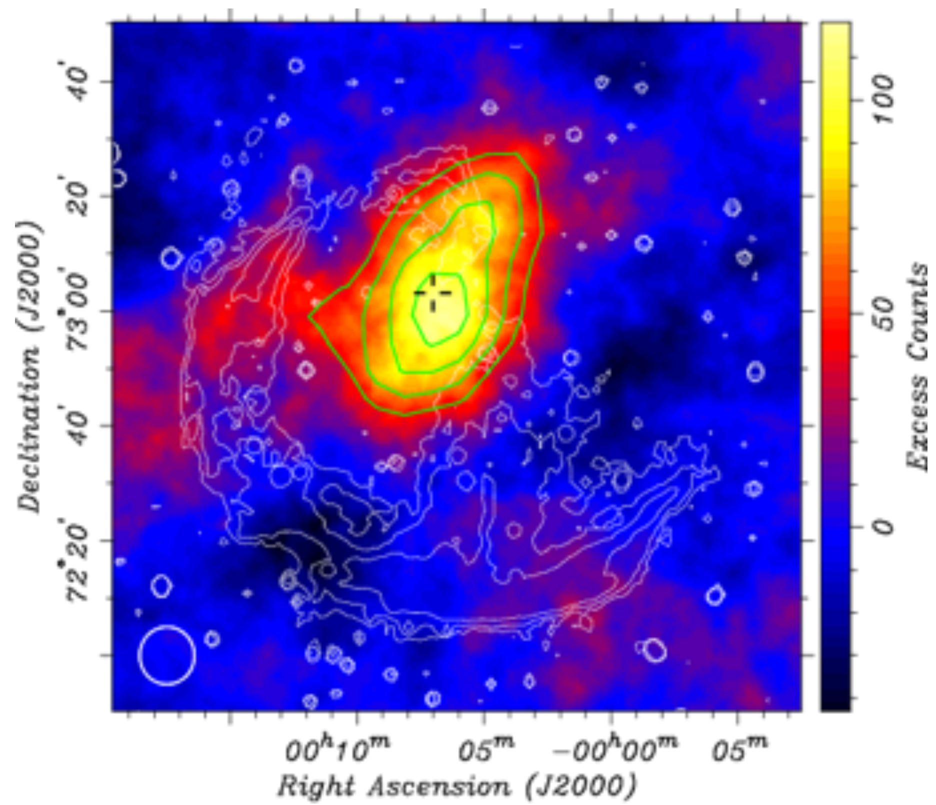
Air Cherenkov Telescopes

Pros:

- *Excellent sensitivity,* with a typical angular resolution of about 0.1°.
- They produce detailed pictures of individual sources.

Cons:

- They are *pointed* instruments that can only observe one object at a time.
- Only operate during dark nights and have a *limited duty cycle* (~1000 hours/year).

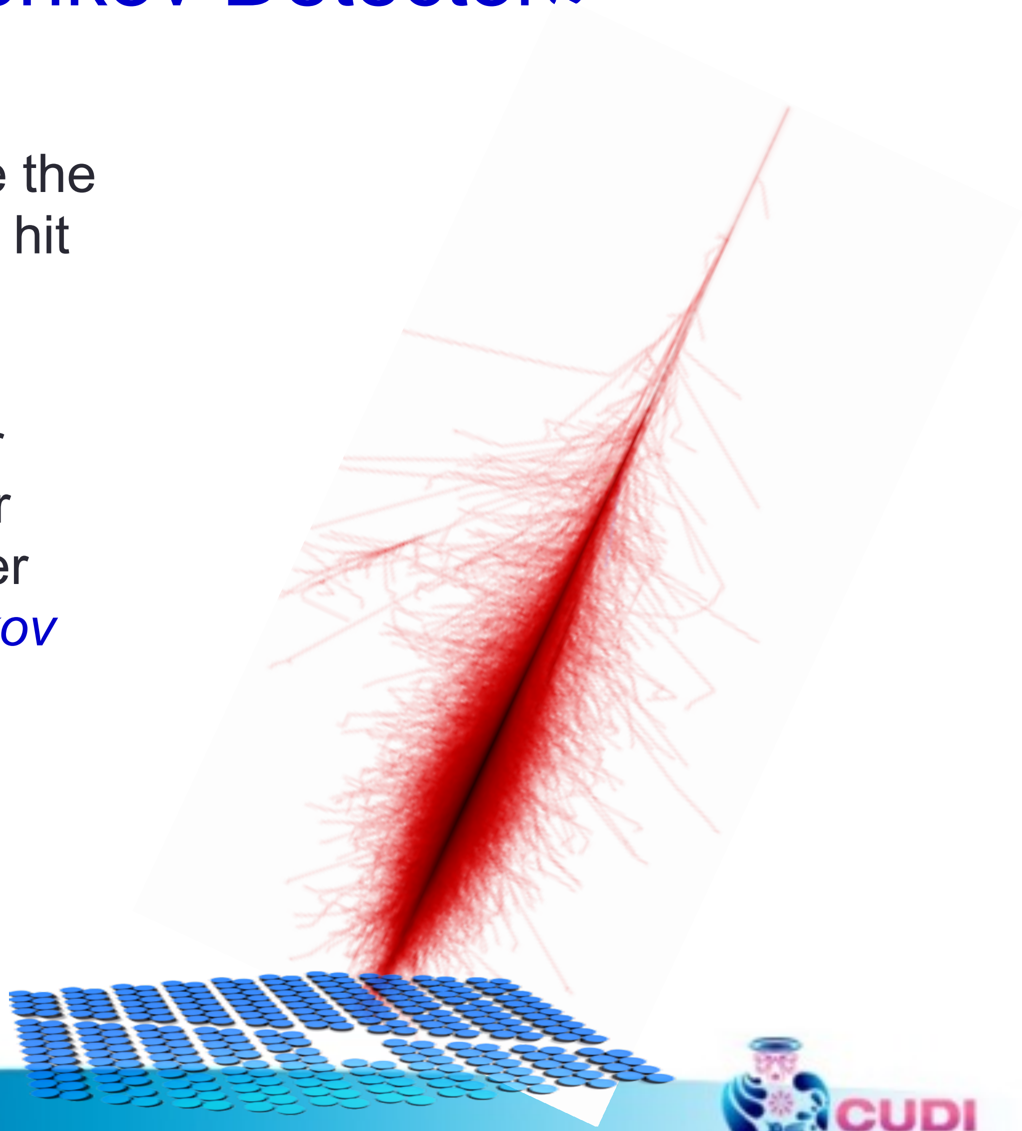


VERITAS image of the SNR CTA1

Water Cherenkov Detectors

- Alternative approach: measure the *air shower particles* when they hit the ground.

- *Water* is the cheapest detector material: the particles of the air shower move through the water volume and generate *Cherenkov light* that is captured by photomultipliers.



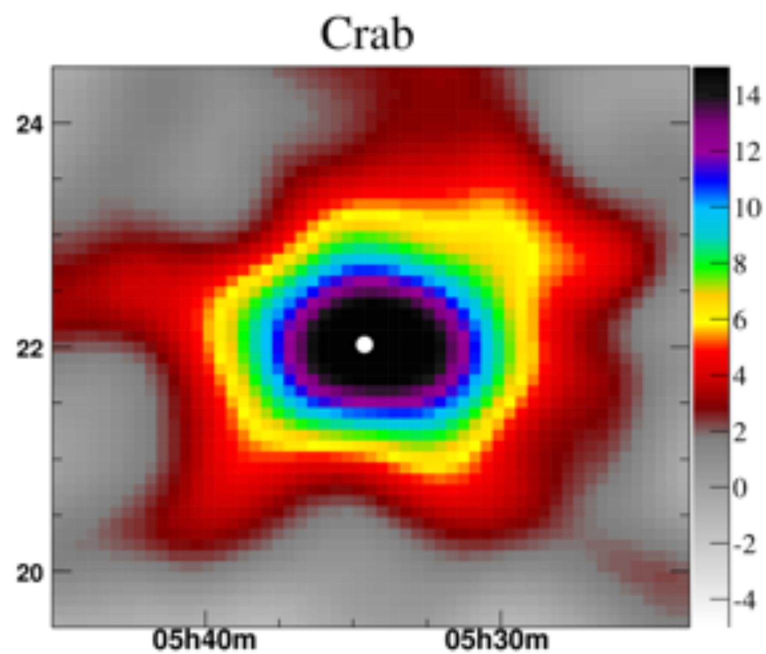
Water Cherenkov Technique

Pros:

- *Large duty cycle* (>95%), independent of weather and daylight.
- *Large field-of-view.*
- *Large effective area.*

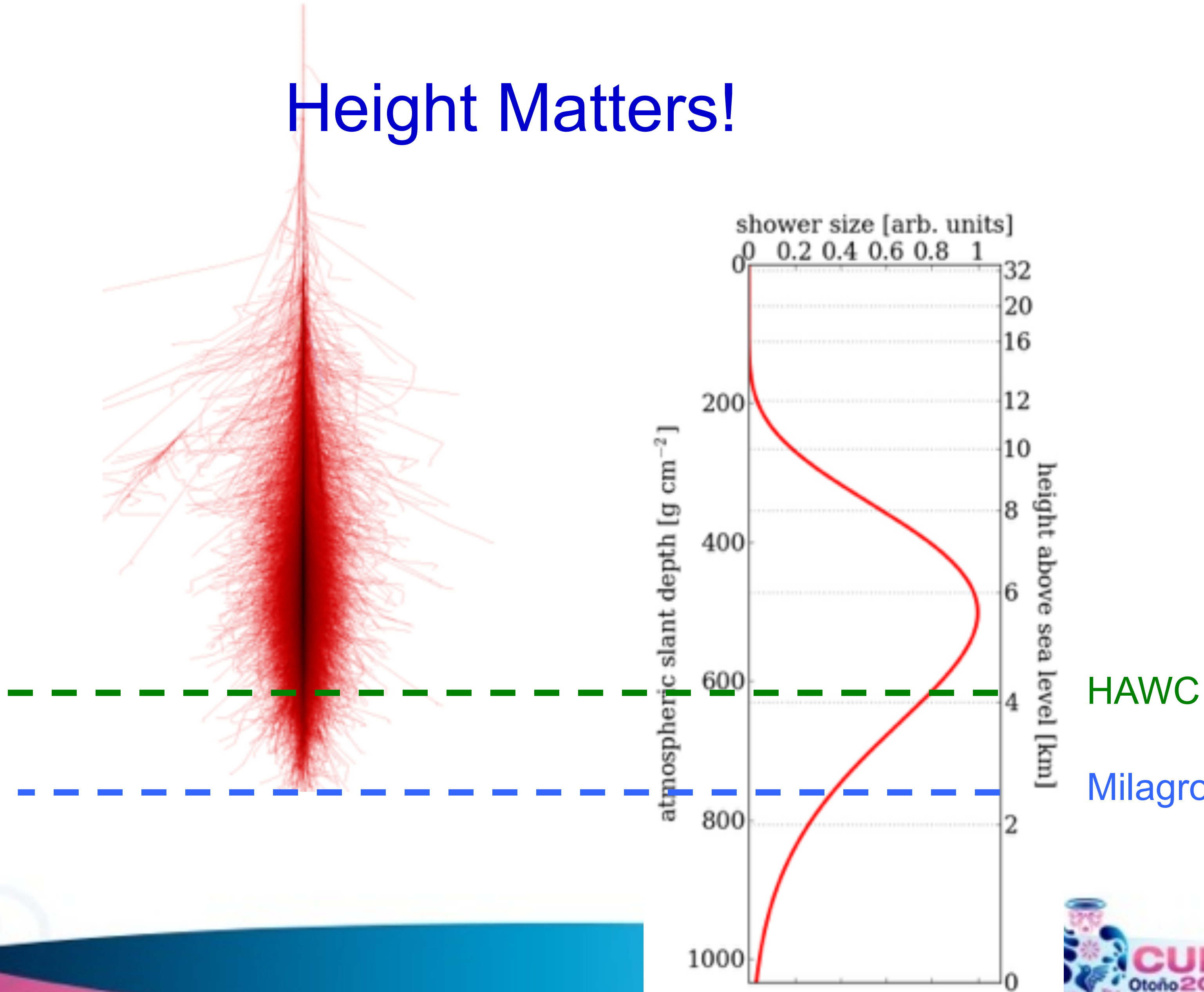
Cons:

- Much *lower sensitivity* for point sources.
- Angular resolution ~1°.
- High energy threshold (~10 TeV).

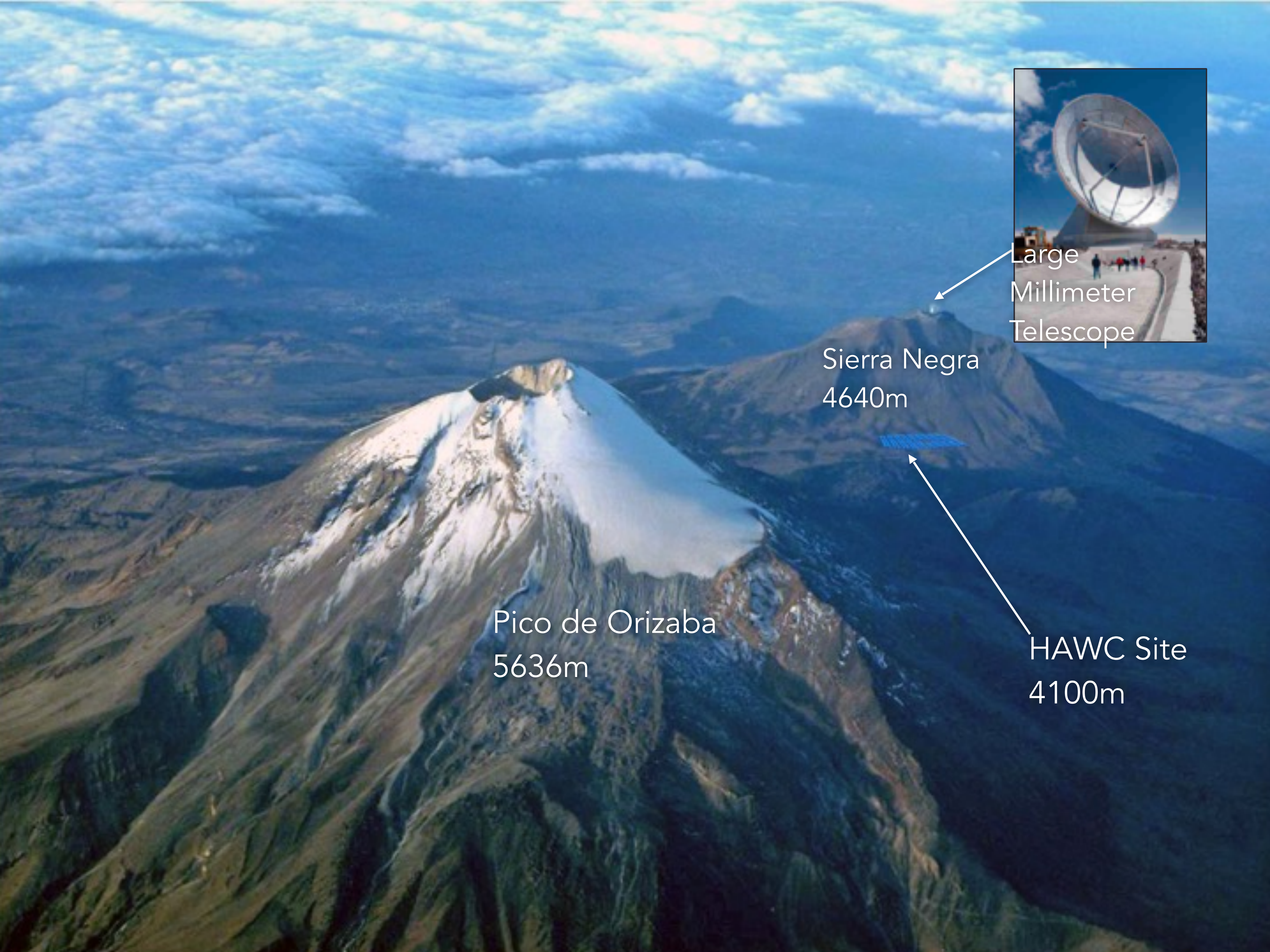


Significance of Milagro Crab signal in ~8 years of data

Height Matters!



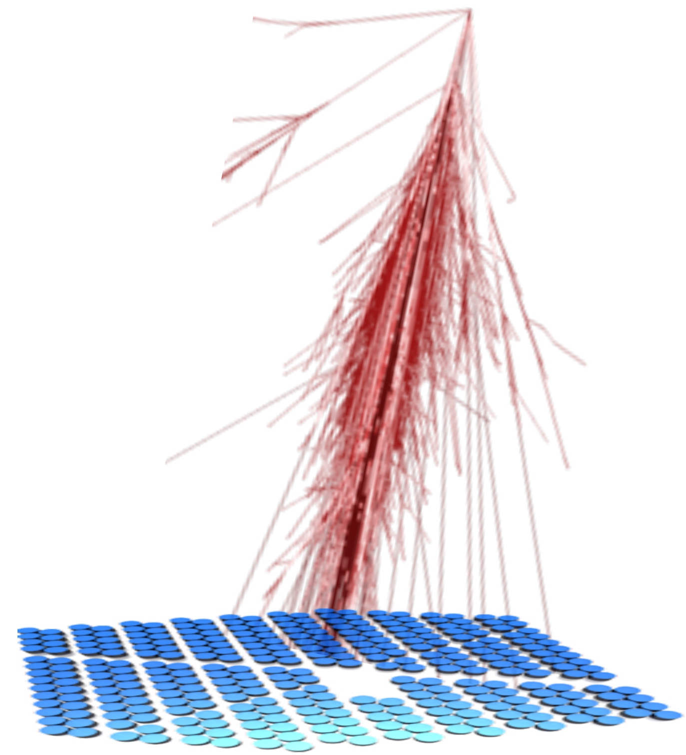
The HAWC Observatory

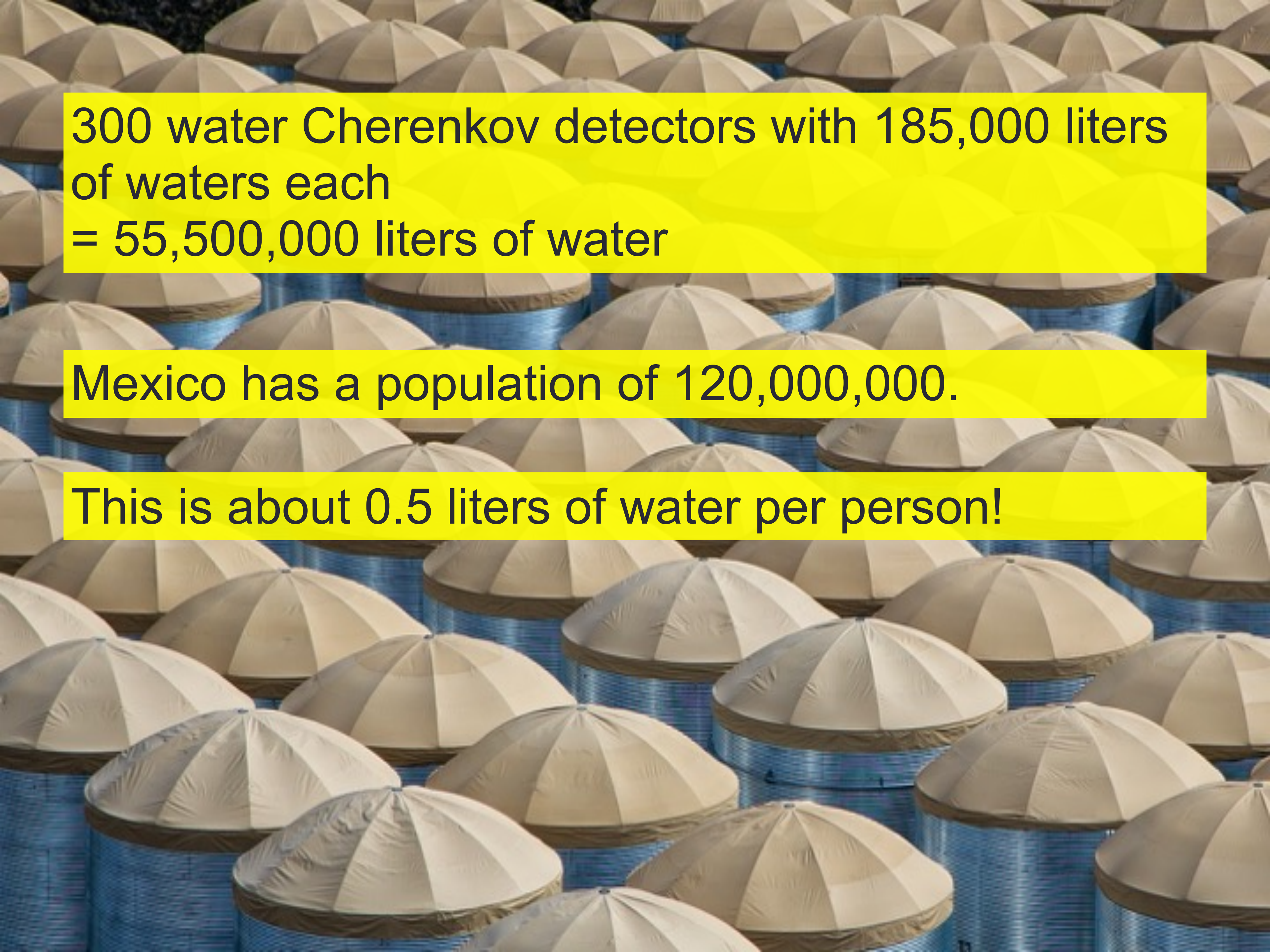

Large
Millimeter
Telescope
Sierra Negra
4640m
Pico de Orizaba
5636m
HAWC Site
4100m

The HAWC Detector

- 4,100 altitude meter site at *Sierra Negra, Mexico* (~19º N), near the Large Millimeter Telescope.

- 22,000 m^2 area (57% coverage).
- 300 water tanks:
  - 7.3 m diameter × 4.5 m depth.
  - 3 upward-facing 8'' PMTs and one upward-facing 10'' PMT (with high quantum efficiency) on the bottom of each tank.





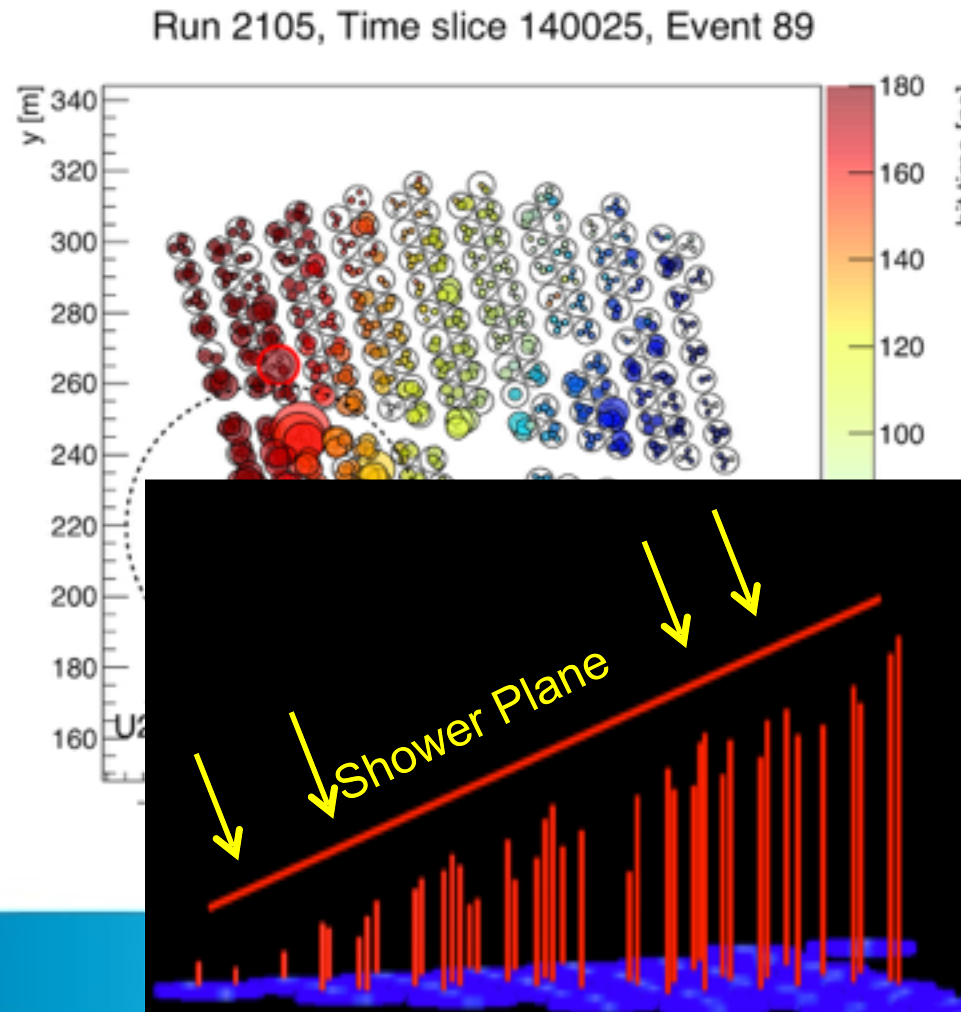
300 water Cherenkov detectors with 185,000 liters of waters each
= 55,500,000 liters of water

Mexico has a population of 120,000,000.

This is about 0.5 liters of water per person!

The HAWC Detector

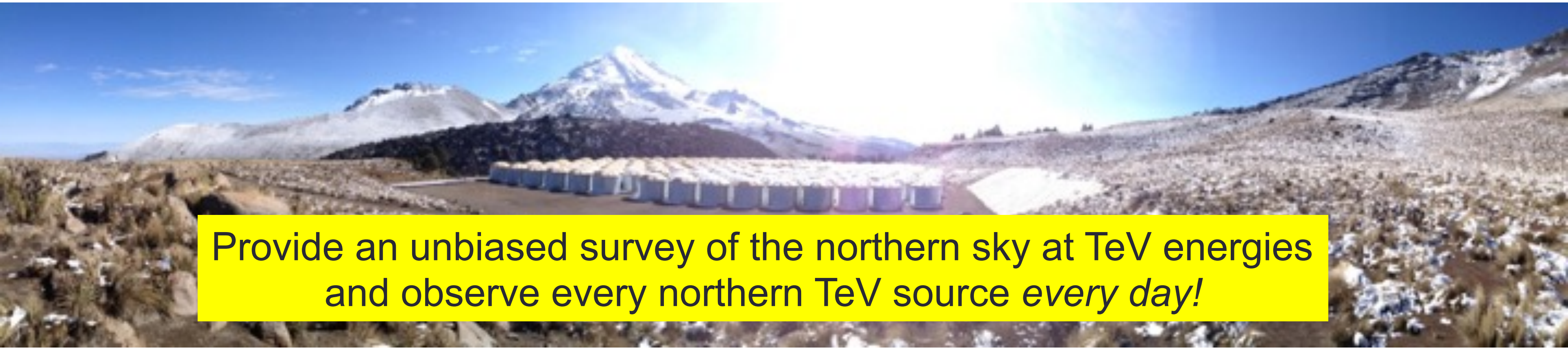
- Charged particles from air showers penetrate tanks.
- Particles produce *Cherenkov radiation* which is recorded in four PMTs.
- *Timing* and *charge* in each PMT used to reconstruct direction of primary particle.
- Angular resolution is better than 0.5° at TeV energies.



Data taking started

Inauguration Day
March 20, 2015

HAWC Science Goals



Provide an unbiased survey of the northern sky at TeV energies and observe every northern TeV source *every day!*

Galactic Sources of Gamma Rays

Supernovae remnants
- Crab Nebula (SN 1054)
  - Recent GeV flares

Extended objects (e.g. molecular clouds)

Galactic plane

Particle Physics

Indirect dark matter searches

Lorentz invariance violation

Theoretical particle searches (e.g Q-balls)

Extragalactic (z<0.1) Sources of Gamma Rays

Active galactic nuclei (AGN)
- Flaring
- Multiwavelength campaigns (Fermi-LAT)

Gamma-ray bursts (GRBs)
- Counterpart (Fermi-LAT/optical telescope alerts)

Constrain EBL and IGMF

Nearby galaxies
- Starburst galaxies (many SNRs)

Cosmic Rays

Cosmic-ray anisotropy

Electron/positron spectrum

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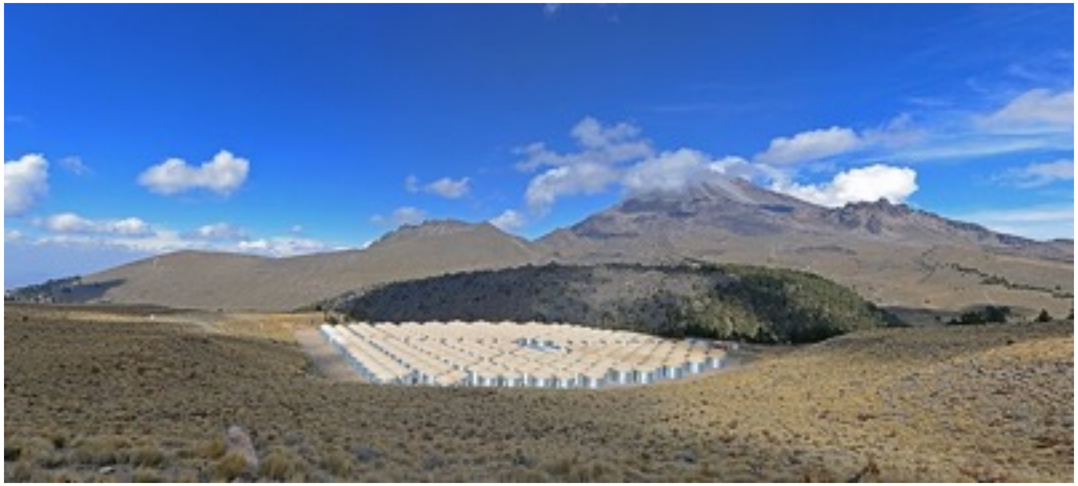


The Shadow of the Moon

First Look at the Gamma-Ray Sky

Large Scale Cosmic-Ray Anisotropy

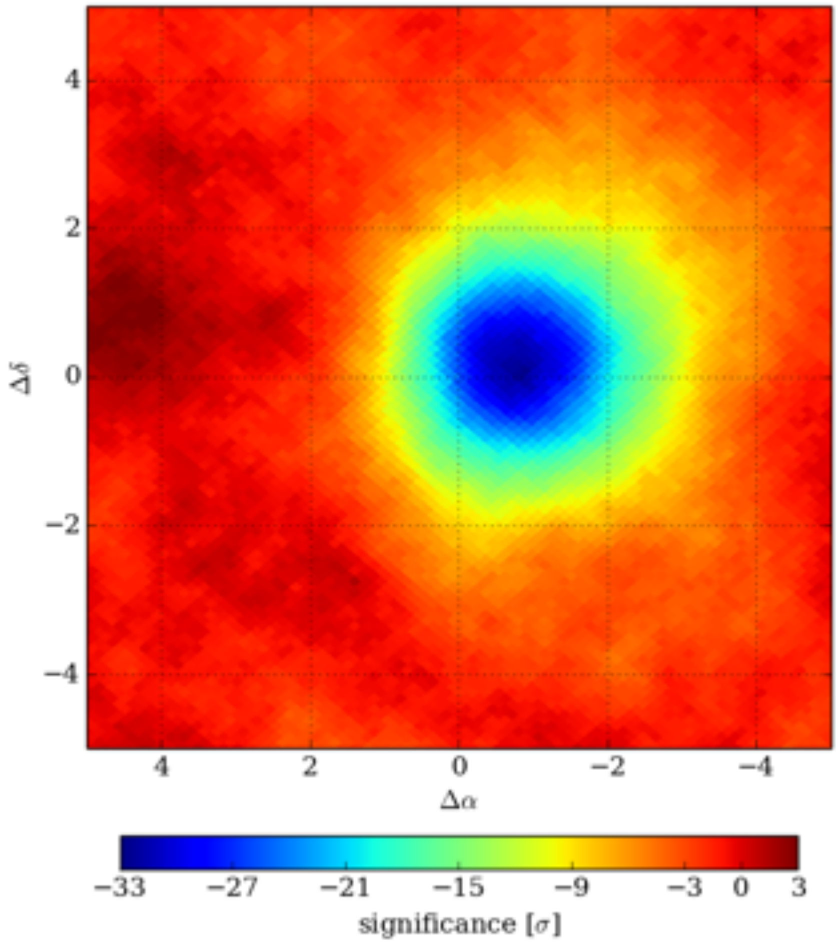
FIRST LIGHT

Shadow of the Moon

- The Moon *blocks* part of the nearly isotropic cosmic-ray causing a "cosmic-ray Moon shadow" on Earth.

- The Moon's apparent diame is about 0.5°.

- Observing the *width* of the Moon shadow is a good wa access the *angular resolutio* and *pointing accuracy* of the detector.



Moon Shadow

BBC NEWS

Home | US & Canada

15 April 2013 Last upd

Hawc gan first imag

By Jason Palmer
BBC News, Denver

Breakfast with Andrew Dunkley

6:00am - 6:40am
6:55am - 7:45am

HAWC discovers Moon

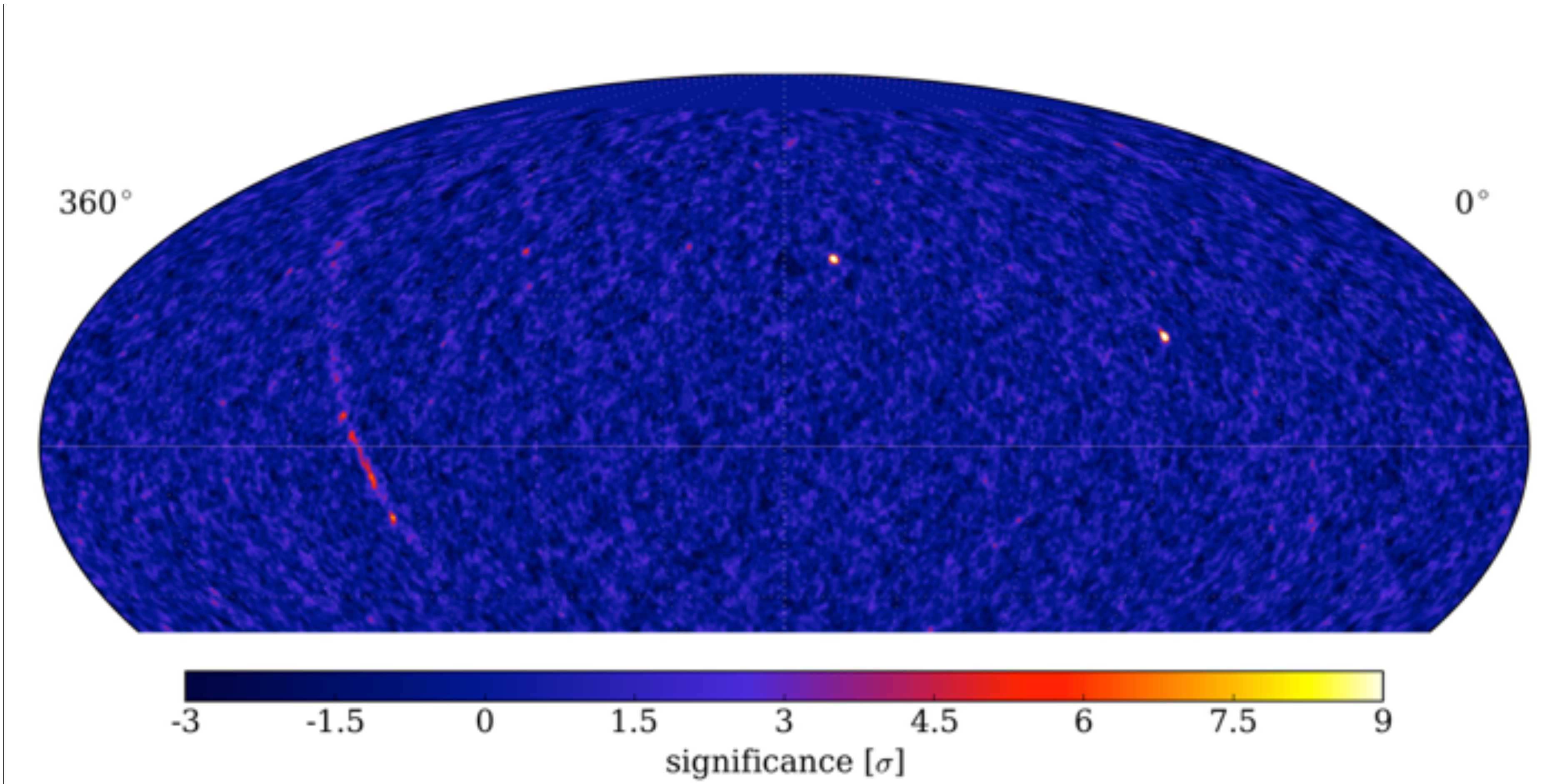
17/04/2013 , 8:44 AM by Andrew Dunkley

It's not what you think, we don't have a new Moon orbiting the planet.

This is about a new telescope in Mexico which has been built at an altitude of 4,400 metres and it's very different.

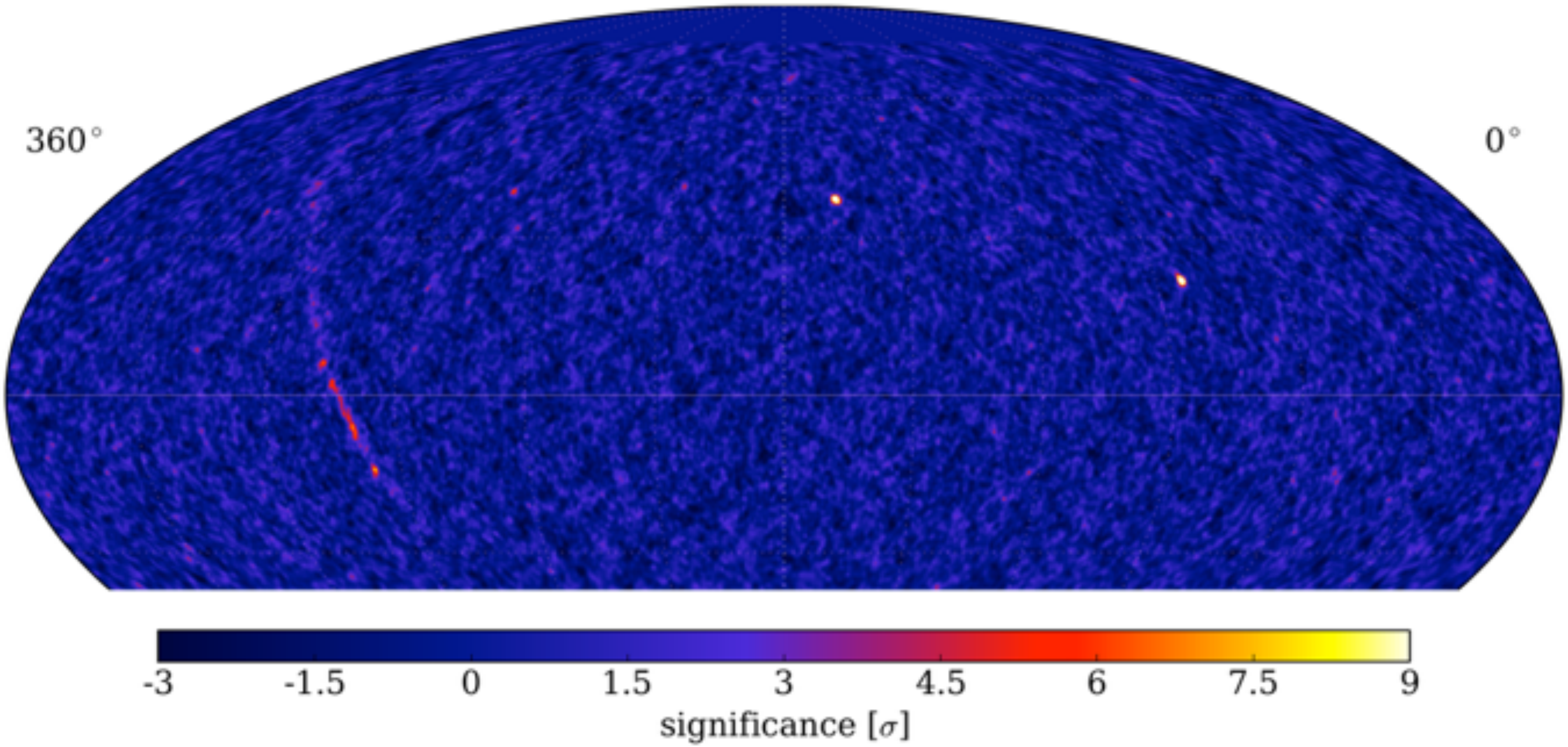
This one doesn't use light and mirrors to see what's going on in space it uses water which is held in a series of tanks designed to catch cosmic particles.

HAWC-250



equatorial coordinates

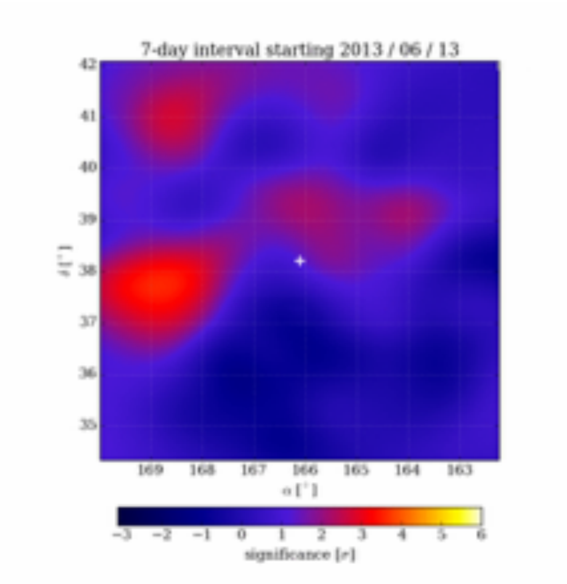
HAWC - Fermi

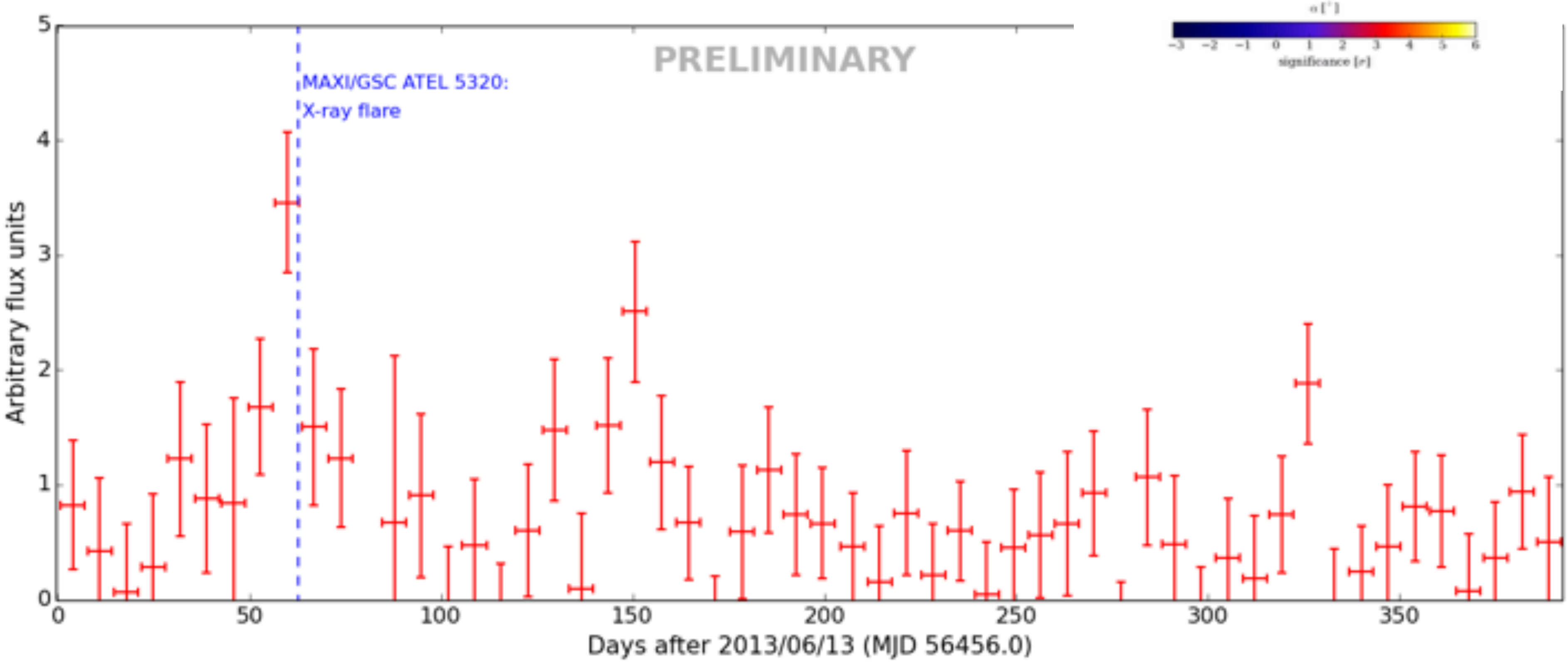


Highest energy γ's from LAT (E>50 GeV) with a preliminary map from HAWC-250 (slide courtesy M. Ajello)

Mrk 421
Time Dependence

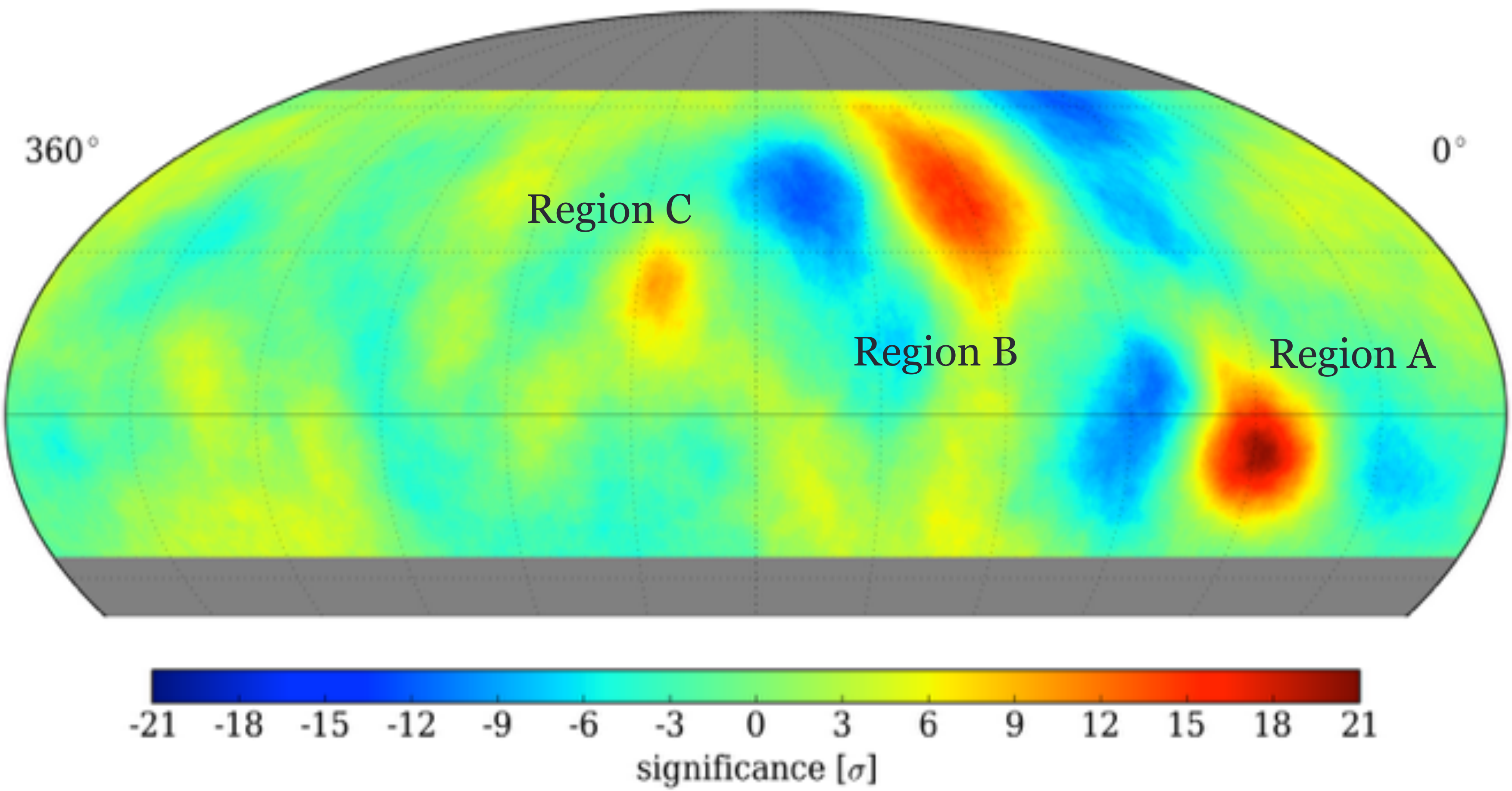
- AGN Mrk 421 in HAWC-111 data (7 day periods)



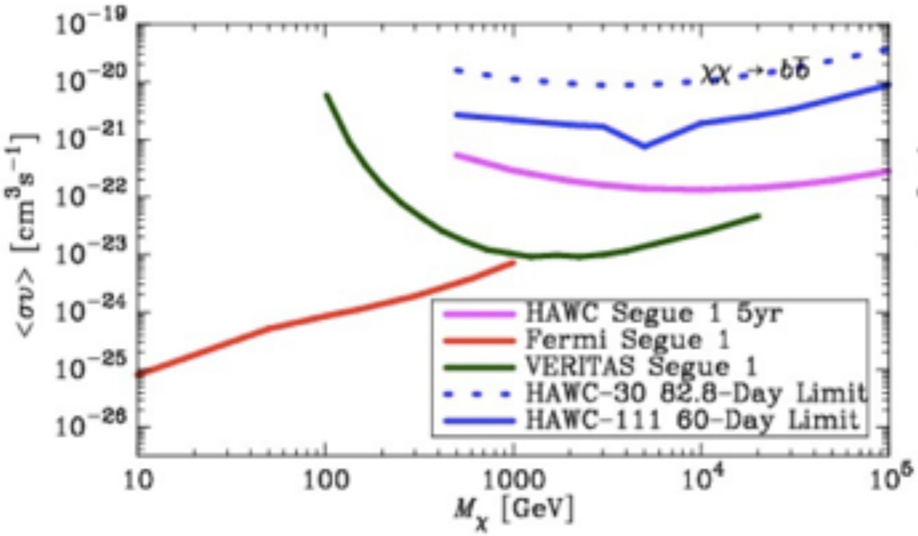


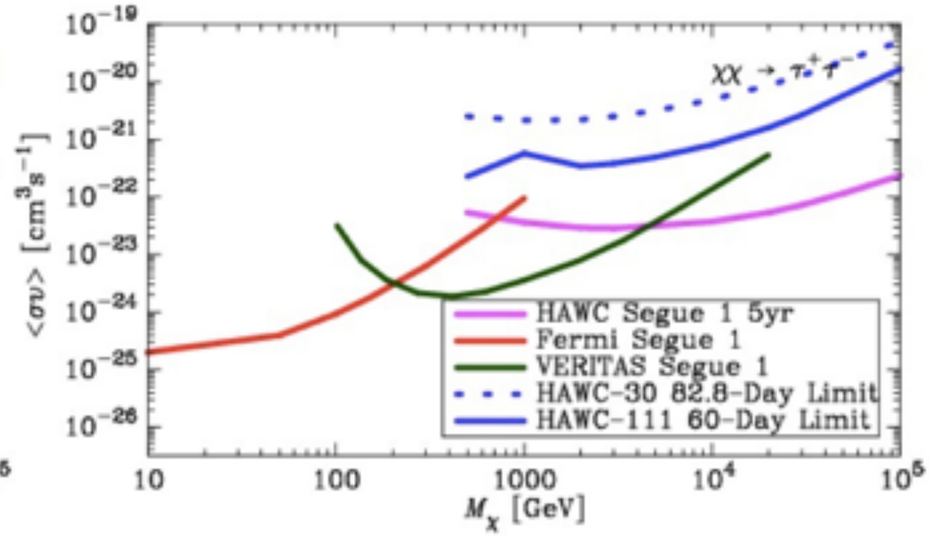
Cosmic-Ray Sky

The Astrophysical Journal 796:108, 2014



Dark Matter limits





Paper under internal review

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Summary

- TeV gamma-ray astronomy is the energy frontier of astronomy.
- HAWC is designed to perform a *wide field of view synoptic survey* of the TeV sky.
  - Large field of view: unbiased survey.
  - Large uptime: increased sensitivity to transients.
  - High-energy response: will help identify cosmic ray sources.
- It is an exciting time: *a new window on the Universe is opening!*


http://www.hawc-observatory.org