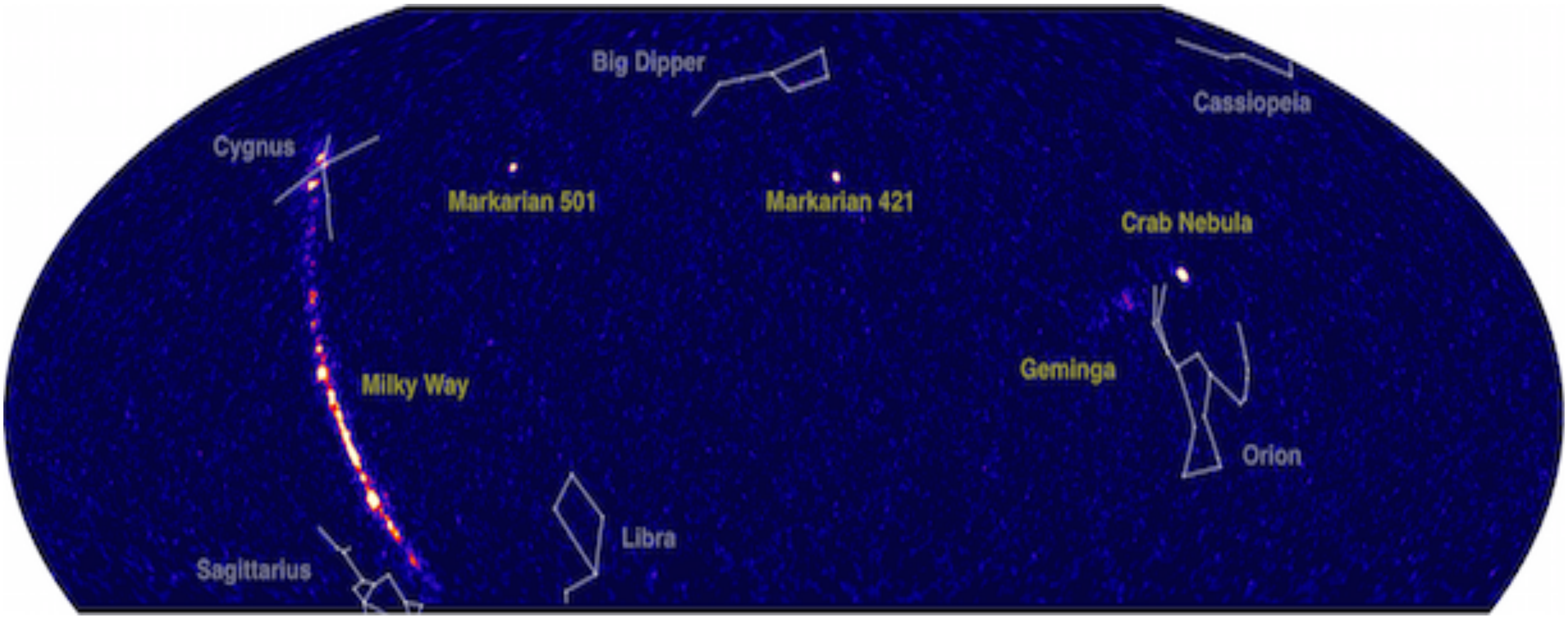
TeV Gamma-ray Astrophysics



John Matthews
P&A Colloquium, UNM, September 28, 2018

Figure shows the northern TeV sky as seen by HAWC

Abstract:

By observing the universe at different wavelengths (photon energies) we find new classes of sources and/or we better understand the physics of known sources, for example:

> optical wavelengths are well matched to thermal (Black Body = thermal) sources such as stars

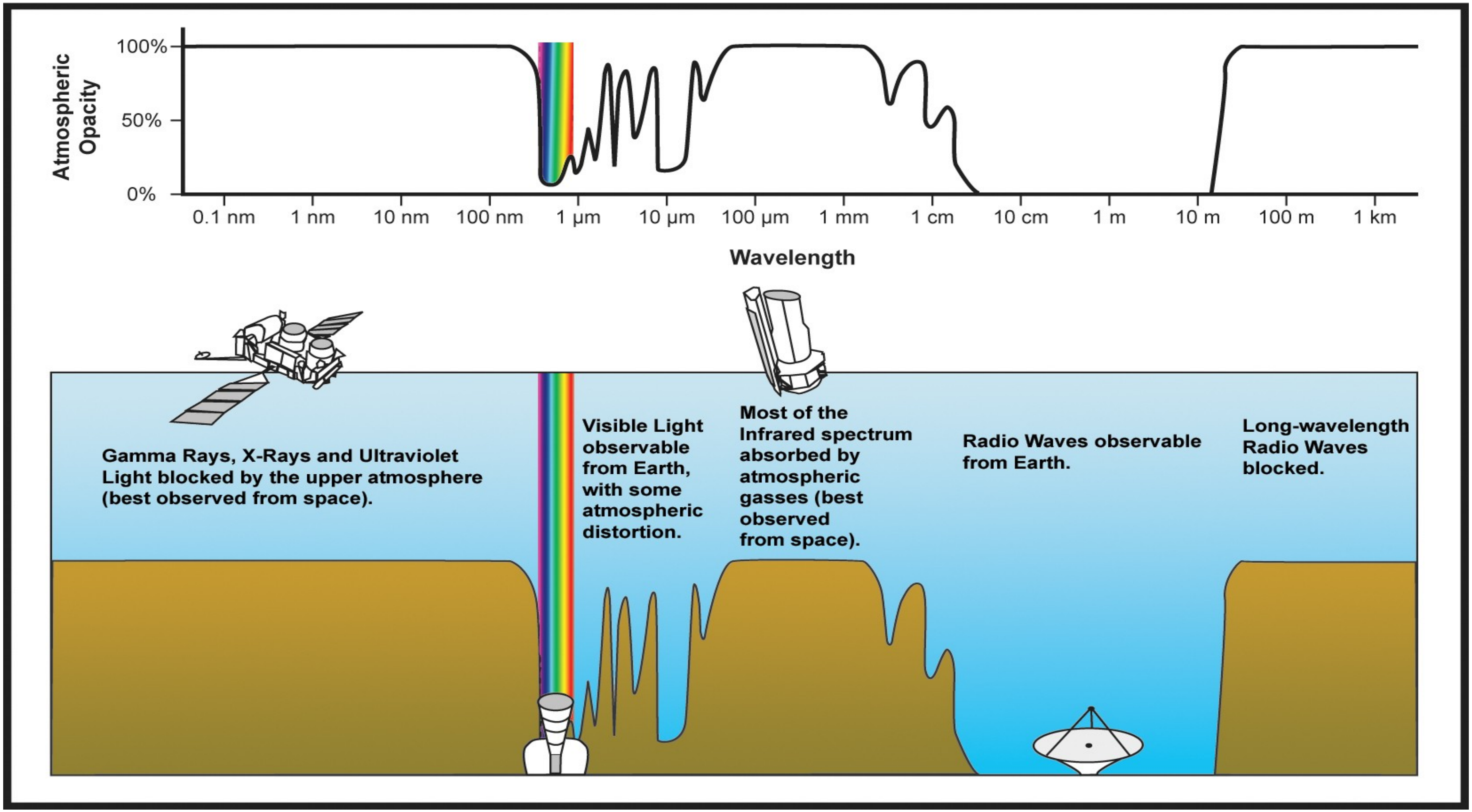
> radio wavelengths are sensitive to cold thermal sources (eg molecular clouds) and to non-thermal sources eg synchrotron radiation, with discovery of: radio galaxies and quasars, pulsars and binary pulsars, **...**

Detection of astrophysical sources at TeV energies took decades with the first observation in 1989 of the Crab nebula. In recent years so-called multi-wavelength and multi-messenger observations are critical to study the physics of these sources.

So: what does the Universe look like at TeV energies? What type of sources dominate the TeV sky? And what has been learned?

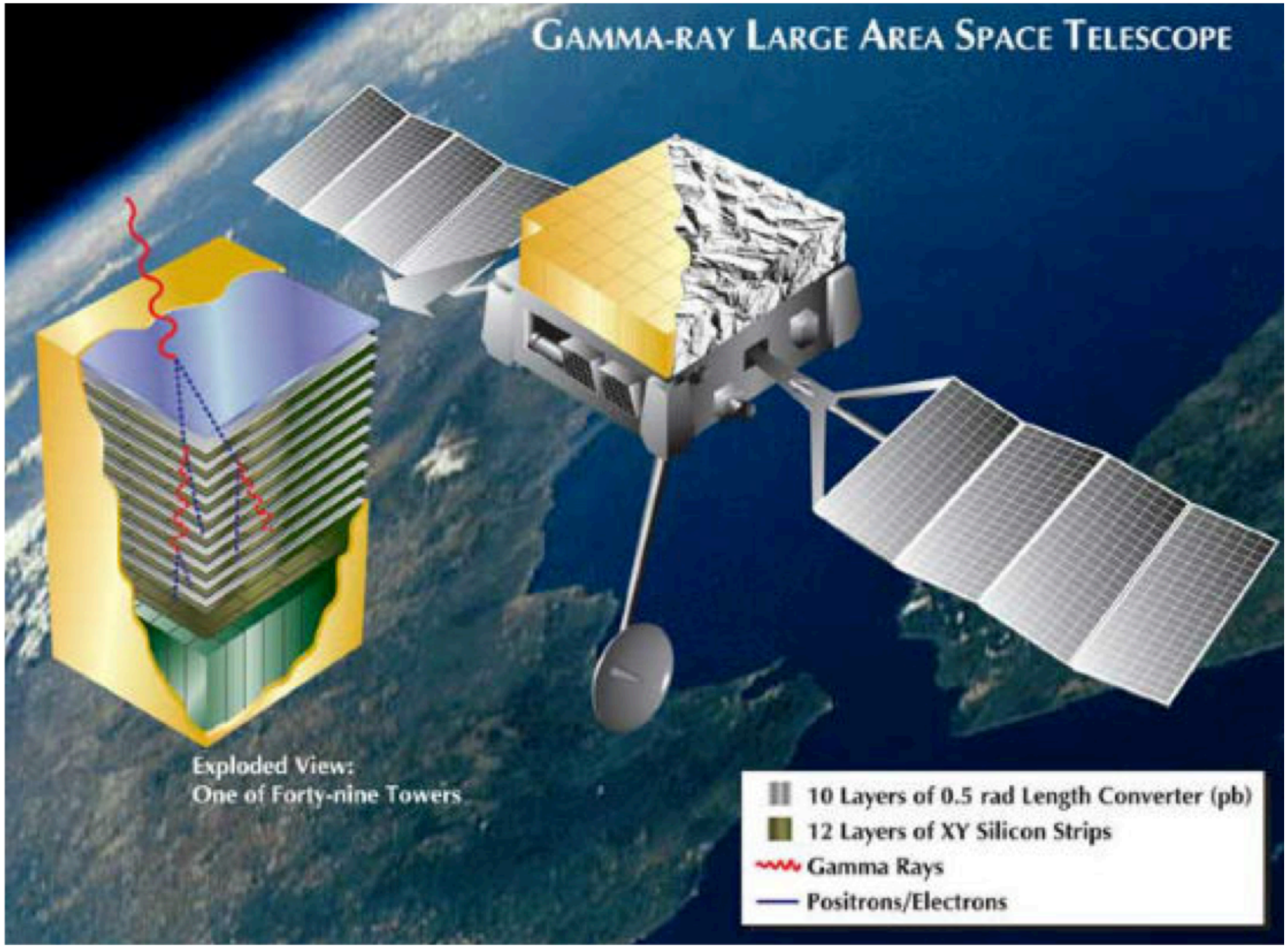
How do we Detect Sources at TeV Energies?

Curiously Earth's atmosphere is transparent in only a few regions of the electro-magnetic spectrum: visible, (near-IR) and radio.   At other wavelengths (energies) measurements are done in space.



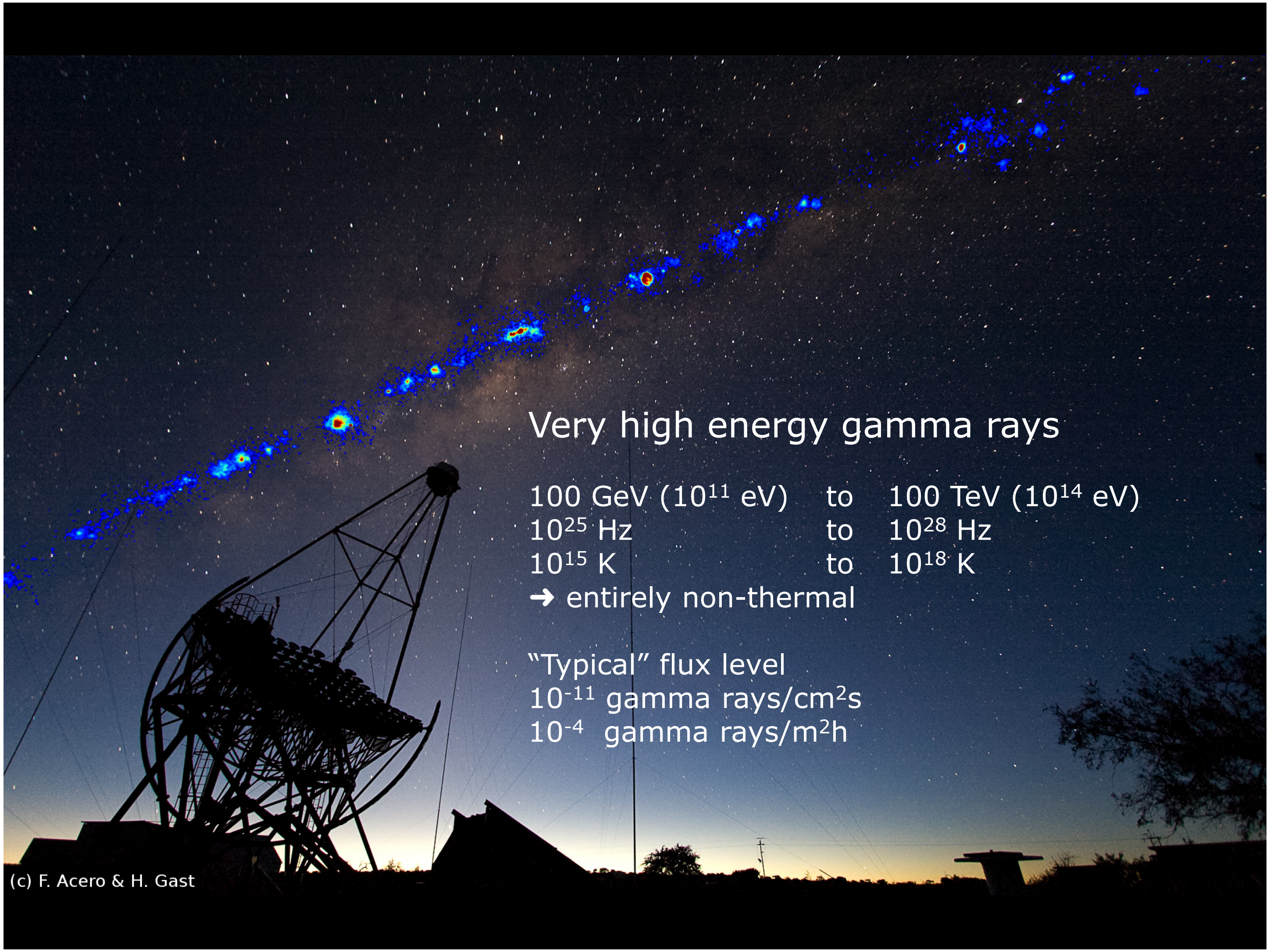
How do we Detect Sources at TeV Energies?

However by TeV energies the flux of photons is too low to be observed by *telescopes* in space which typically have at best a few square meters of effective area! EG the Fermi-LAT runs out of photon counts above a few 10s of GeV!



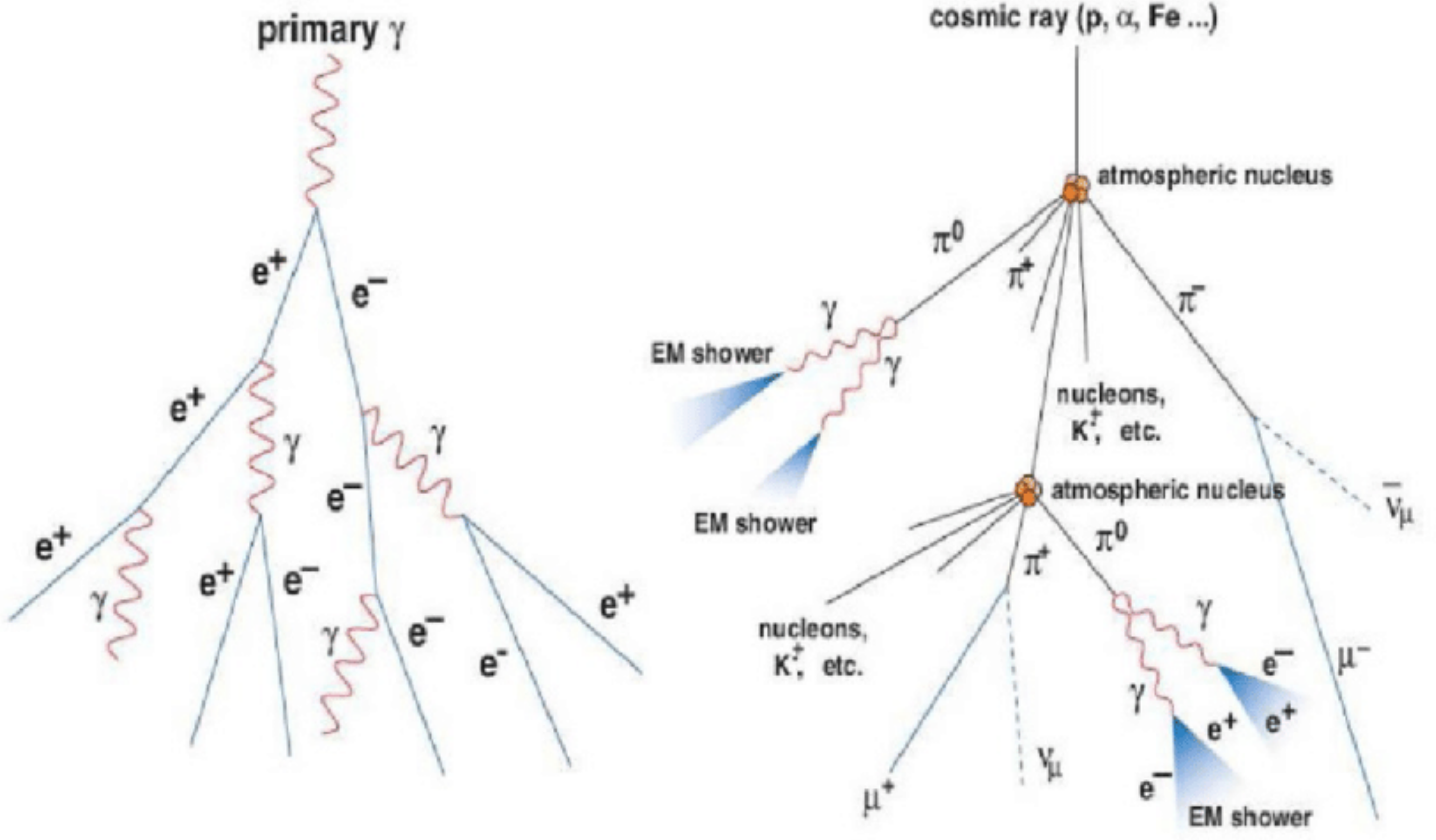
How do we Detect Sources at TeV Energies?

The good news is that by TeV energies *telescopes* using the atmosphere as part of the detector become practical.



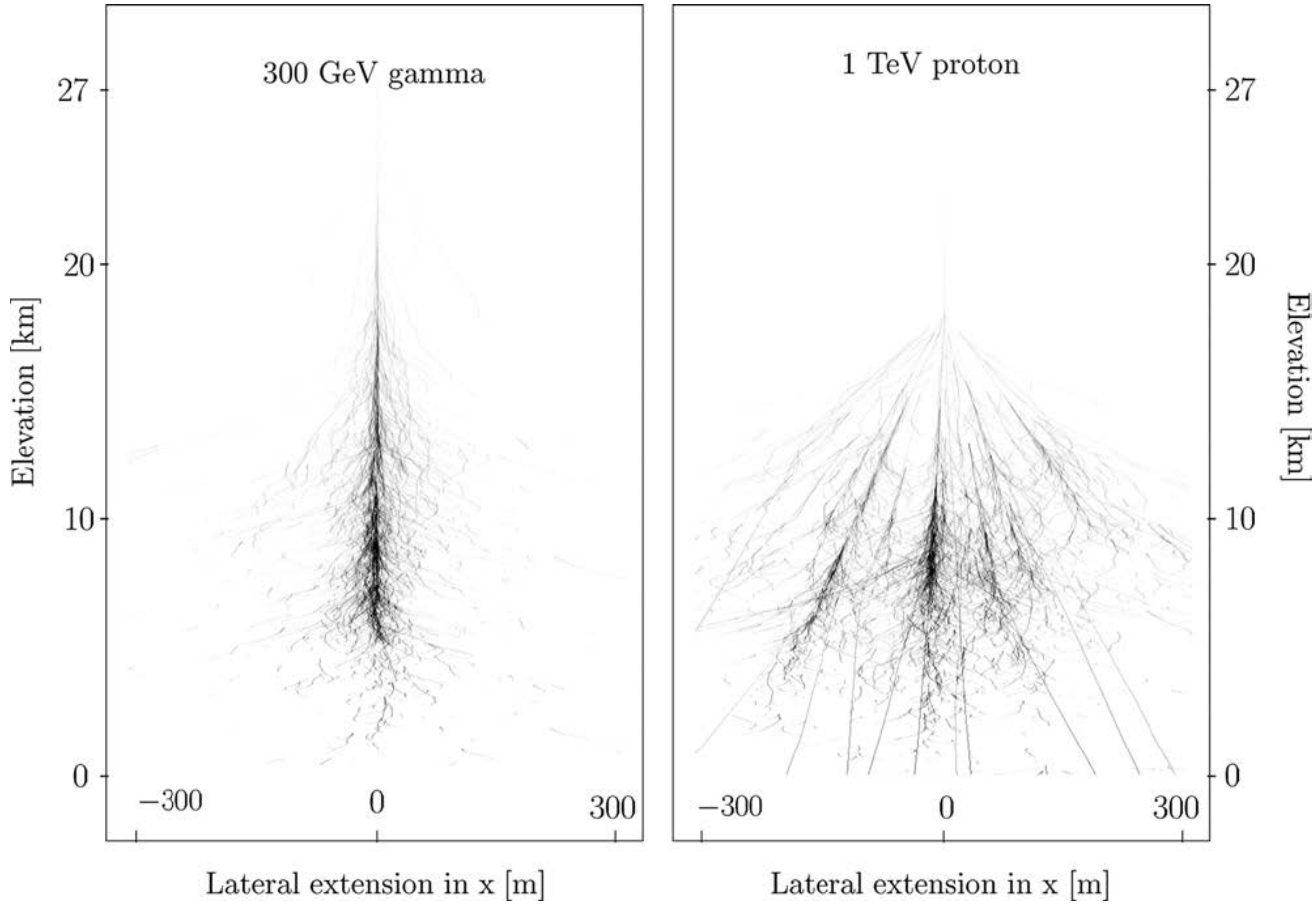
How do we Detect Sources at TeV Energies?

The high energy photons (**Left** sketch: via pair production and Bremsstrahlung) initiate an *extensive air shower* in the atmosphere that can then be observed with ground based **Particle Detectors** or **Cherenkov Telescopes***:*



How do we Detect Sources at TeV Energies?

High energy **photon** and high energy **Cosmic Ray (CR)** extensive air showers show significant differences.   These are used to separate the numerous **CRs** from the few **photons**!



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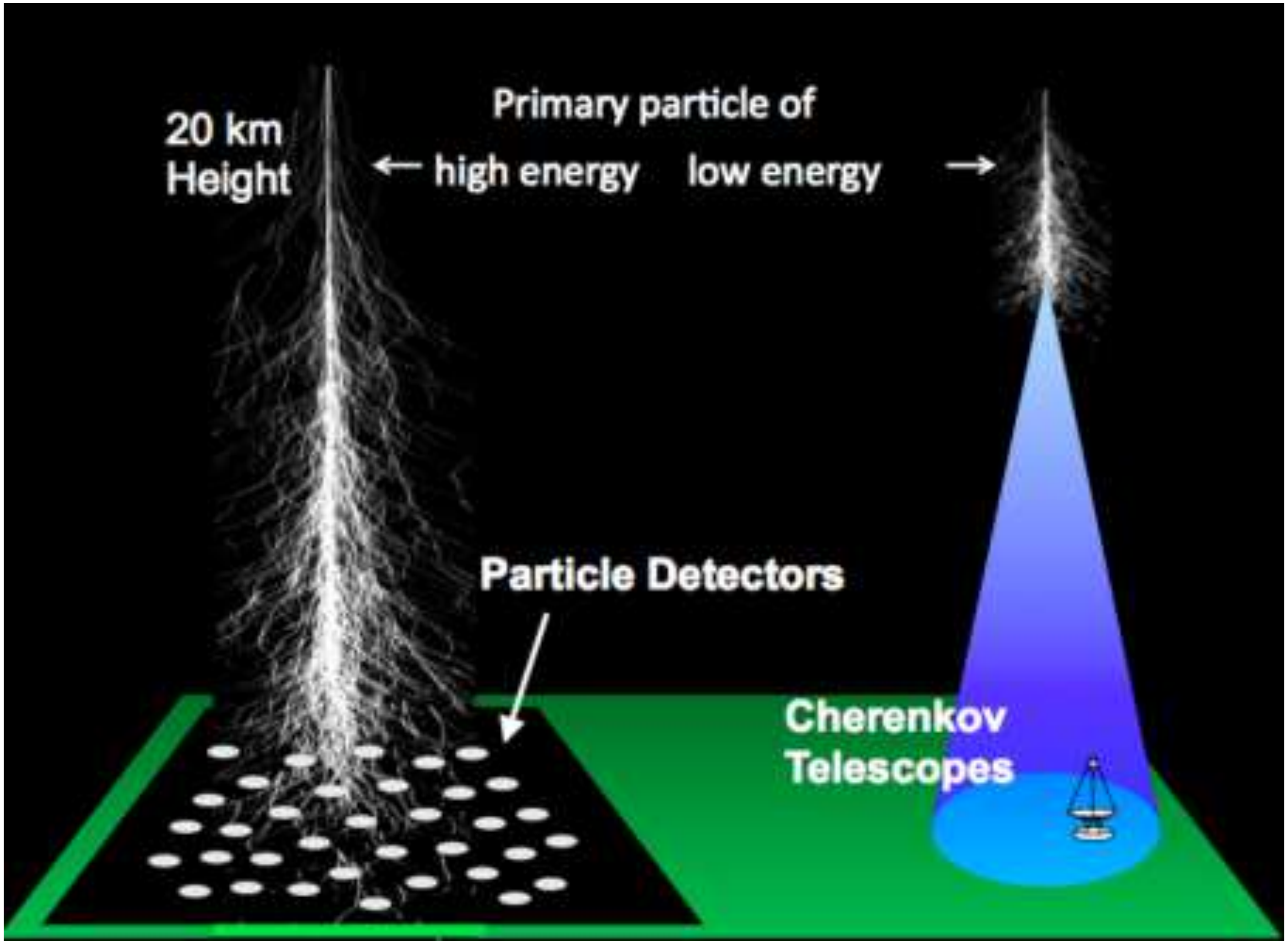
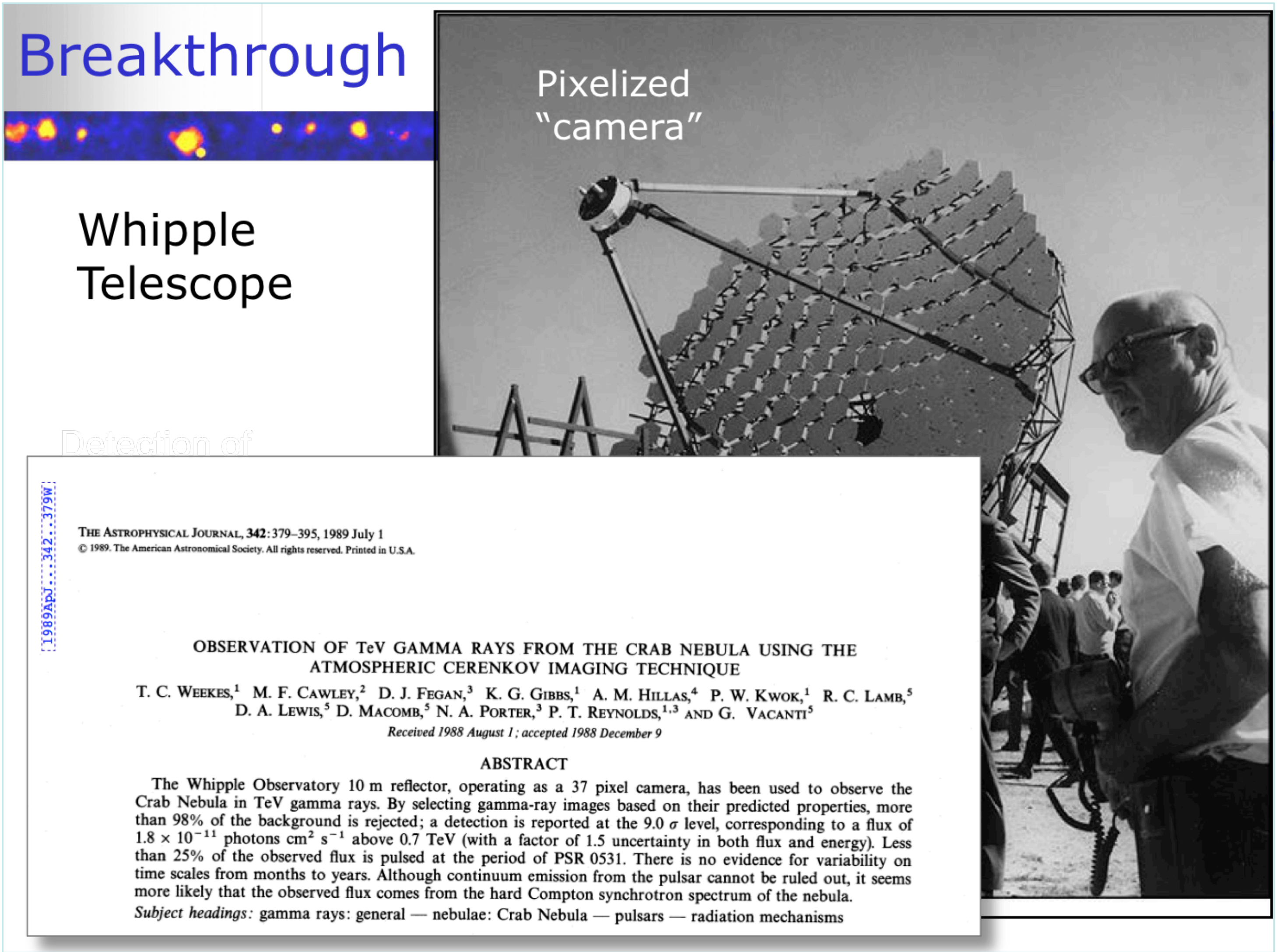


How do we Detect Sources at TeV Energies?

The breakthrough with **Cherenkov telescopes** was in late 1980s with *pixilated* Imaging Air Cherenkov Telescopes (**IACT**s):



1989ApJ...342..379W

THE ASTROPHYSICAL JOURNAL, **342**:379–395, 1989 July 1

OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

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Received 1988 August 1; accepted 1988 December 9

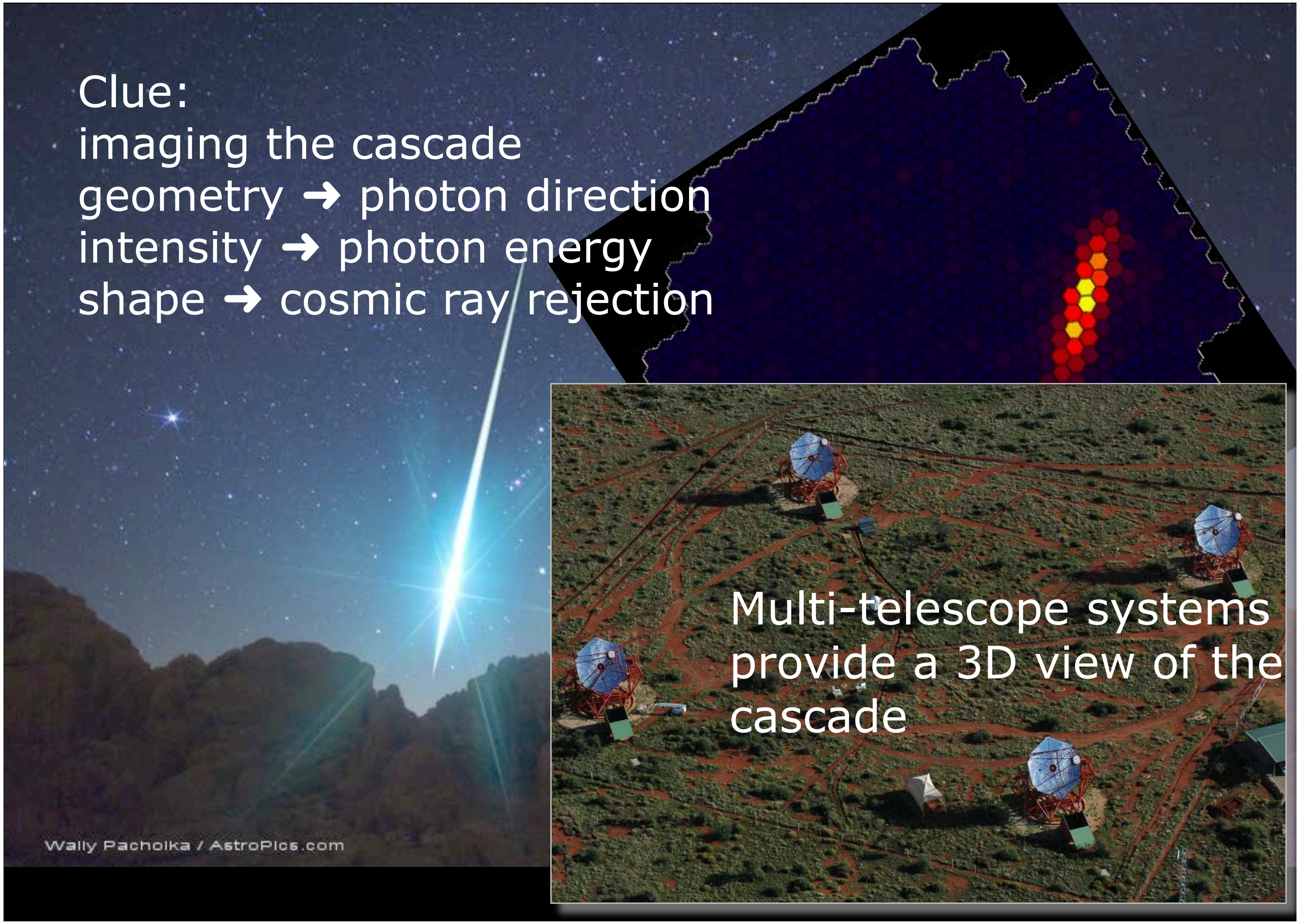
ABSTRACT

The Whipple Observatory 10 m reflector, operating as a 37 pixel camera, has been used to observe the Crab Nebula in TeV gamma rays. By selecting gamma-ray images based on their predicted properties, more than 98% of the background is rejected; a detection is reported at the 9.0 σ level, corresponding to a flux of 1.8×10^{-11} photons cm^2 s^{-1} above 0.7 TeV (with a factor of 1.5 uncertainty in both flux and energy). Less than 25% of the observed flux is pulsed at the period of PSR 0531. There is no evidence for variability on time scales from months to years. Although continuum emission from the pulsar cannot be ruled out, it seems more likely that the observed flux comes from the hard Compton synchrotron spectrum of the nebula.

Subject headings: gamma rays: general — nebulae: Crab Nebula — pulsars — radiation mechanisms

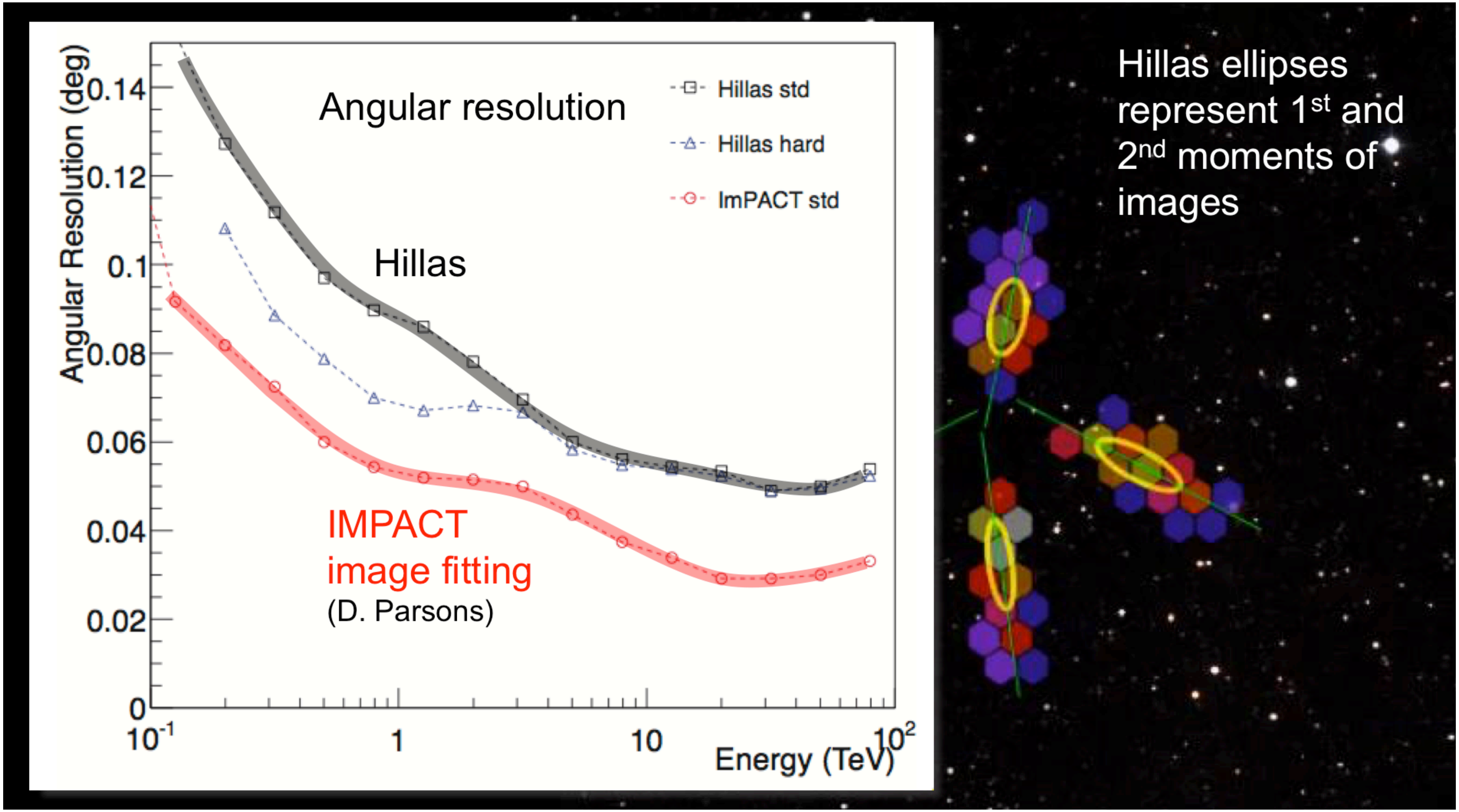
How do we Detect Sources at TeV Energies?

Modern IACTs: HESS (image below), MAGIC, VERITAS combine multiple telescopes in *stereo* for optimal photon energy and direction measurement:



How do we Detect Sources at TeV Energies?

Of the TeV gamma-ray detectors, the **IACTs** provide the best (sub-0.1 degree) angular resolution and are thus best for resolving spatial details in sources:

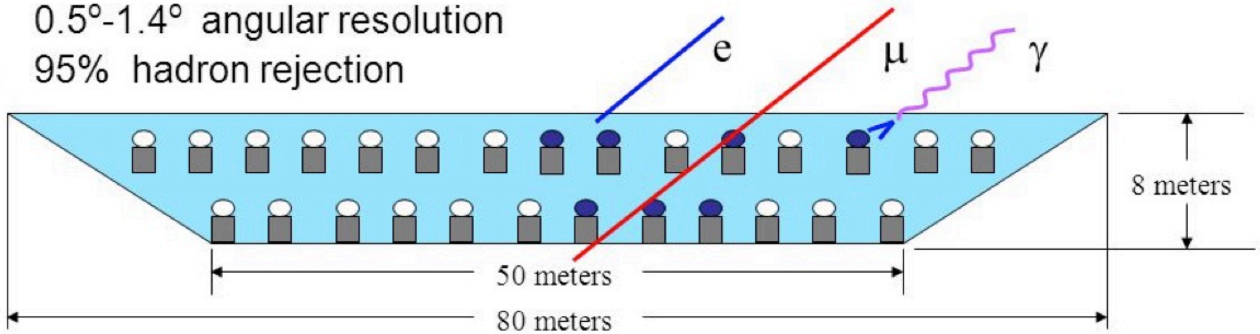


How do we Detect Sources at TeV Energies?

The breakthrough with photon **Particle Detectors** was in 2003: *Observation of TeV Gamma-rays from the Crab Nebula with Milagro using a New Background Rejection Technique*:

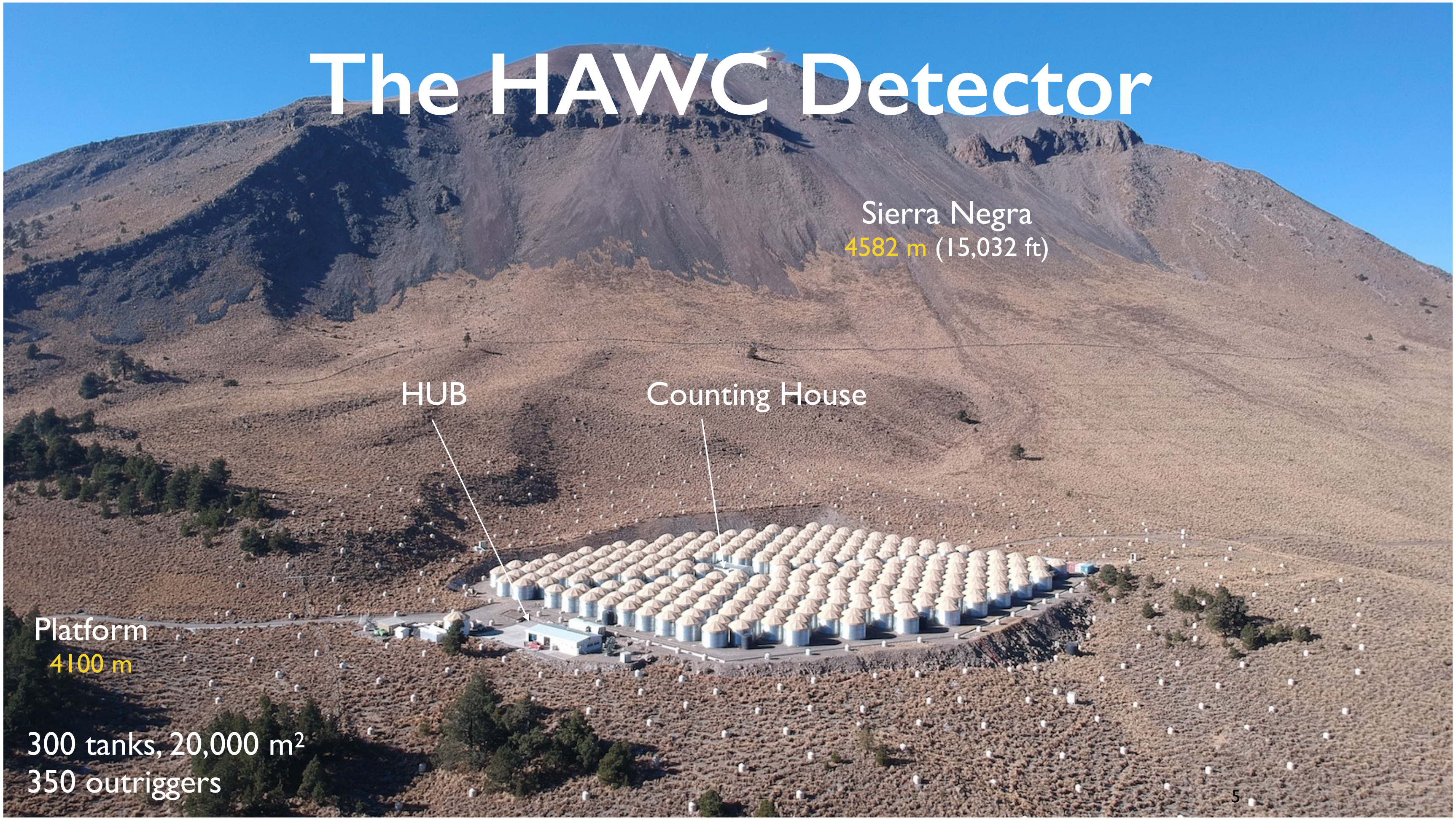
Milagro

- First water Cherenkov detector (gammas)
- Monitoring at TeV's
- 2600m masl
- 898 detectors
  - 450(t)/273(b) pool
  - 175 Water tanks (outriggers)
- 4000 m^2 / 4.0×10^4 m^2
- 2-12 TeV Energy
- 1700 Hz event rate
- 0.5°-1.4° angular resolution
- 95% hadron rejection



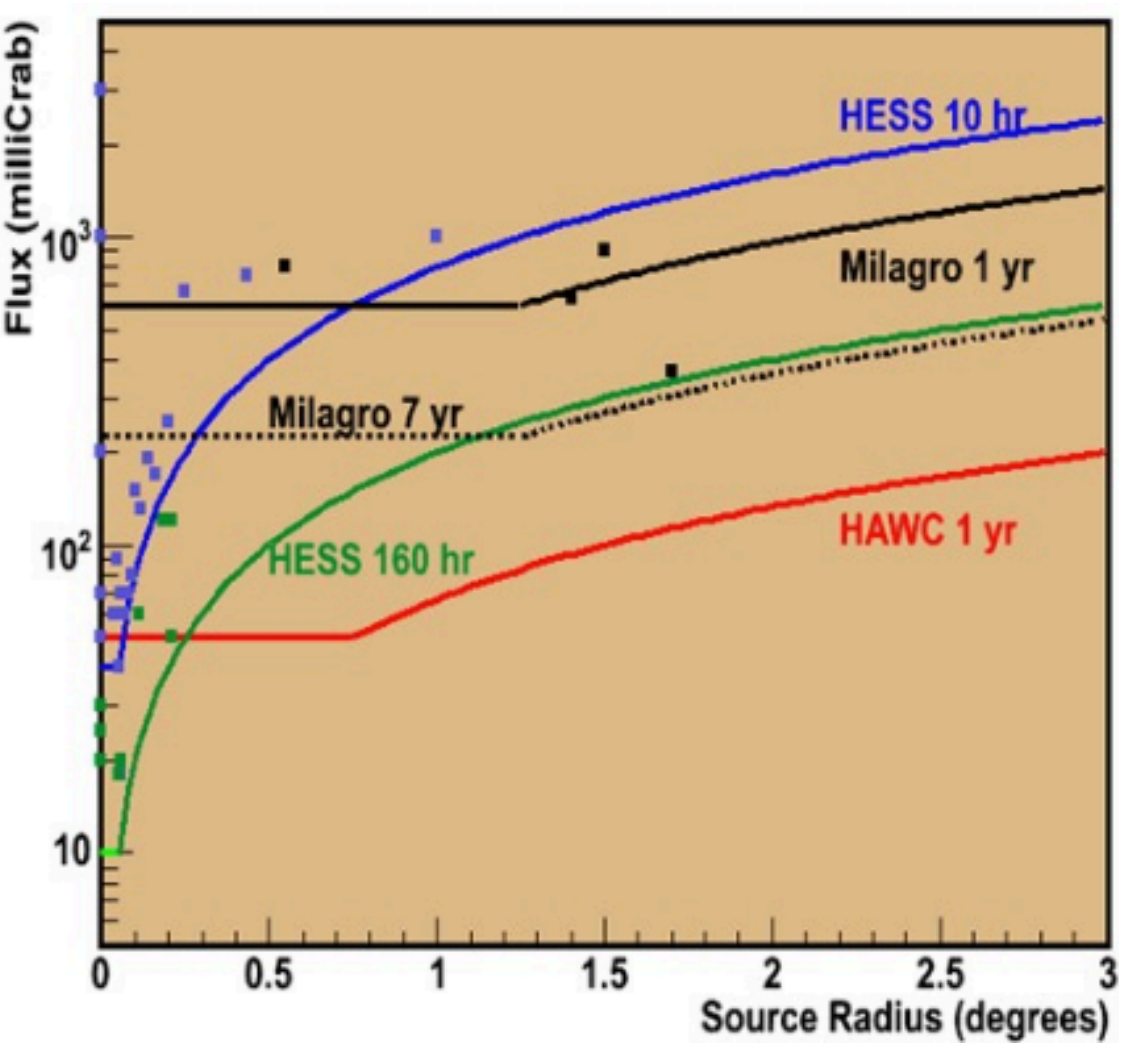
How do we Detect Sources at TeV Energies?

The currently most advanced photon **Particle Detector**: the High Altitude Water Cherenkov (HAWC) detector, profits from higher altitude and larger area (150m x 150m) of fully *pixilated* detectors (than Milagro):



How do we Detect Sources at TeV Energies?

Of the TeV gamma-ray detectors, the **Particle Detectors** provide the best sensitivity for *low-surface brightness* sources:



Large, low surface brightness sources require large fov and large observation time to detect.

EAS arrays obtain ~1500 hrs/yr observation for every source.

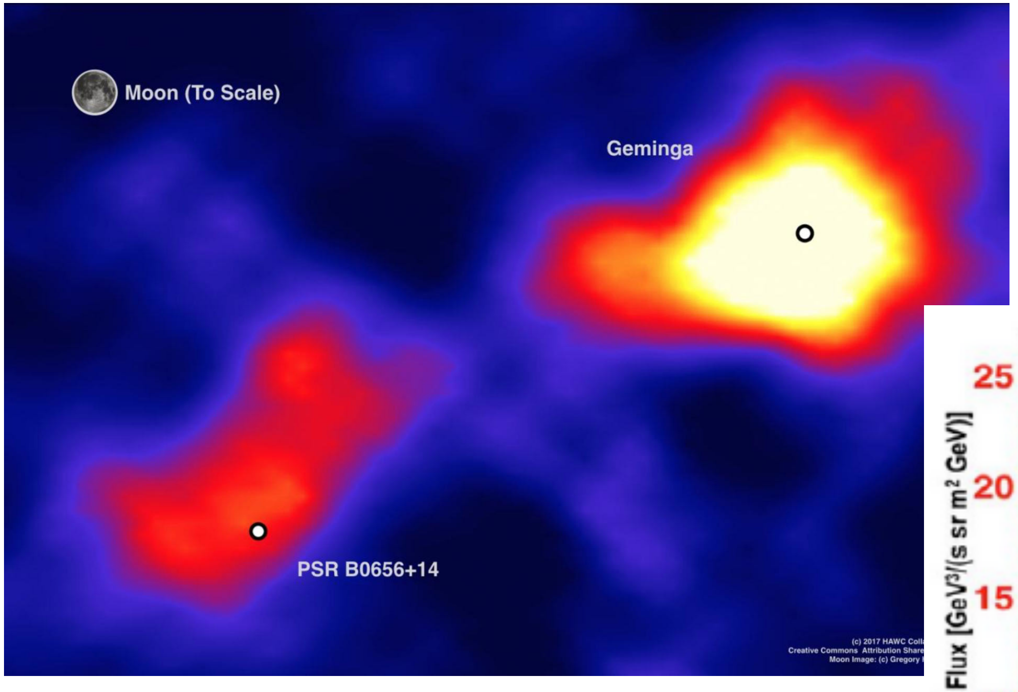
Large fov (2 sr):

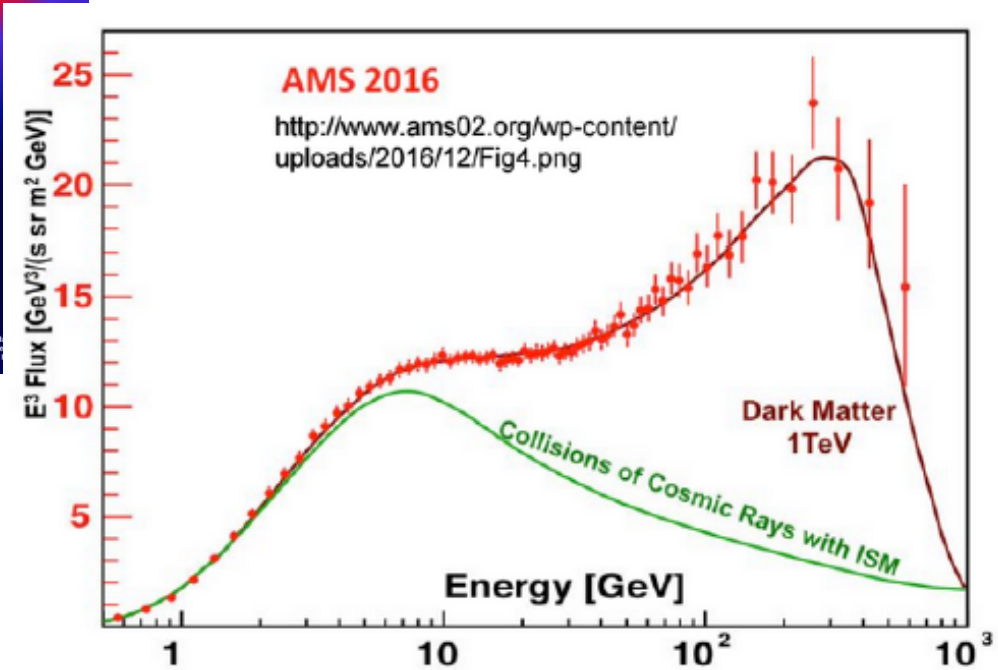
Entire source & background simultaneously observable

Background well characterized

How do we Detect Sources at TeV Energies?

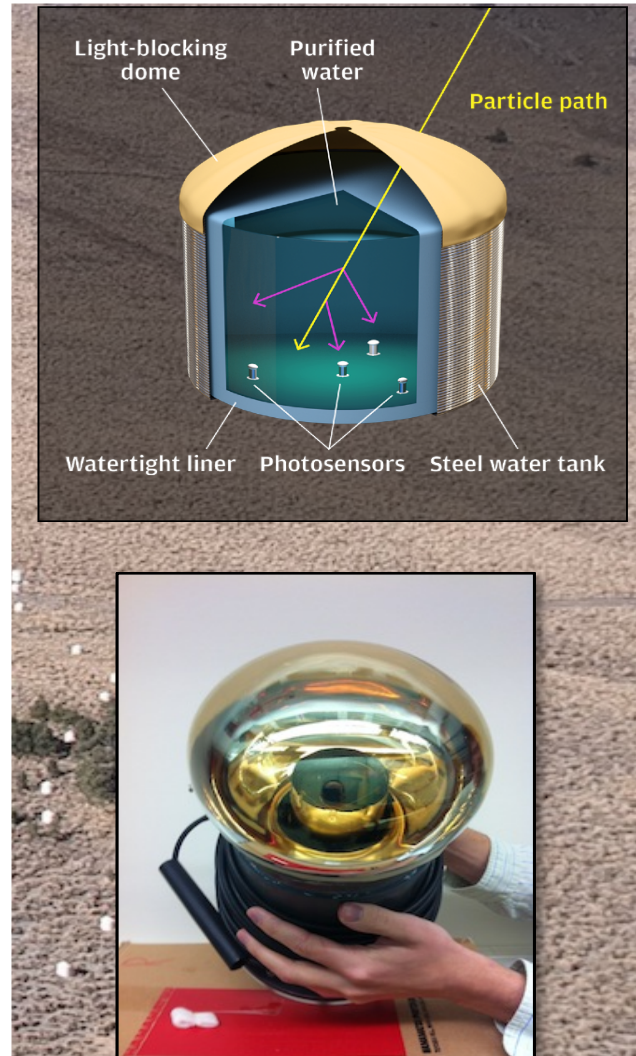
AND this is relevant to nearby TeV gamma-ray sources (eg middle-age pulsar sources Geminga and Monogem) that may contribute to the *local positron excess* observed by the AMS experiment:





HAWC: an array of large water tanks

HAWC’s individual water Cherenkov detector (WCD) *pixels* are 7.3m in diameter and ~4m tall! Each WCD is instrumented with 4 PMTs. At 4100m elevation it is sometimes winter even in the tropics (19-degrees N latitude)!

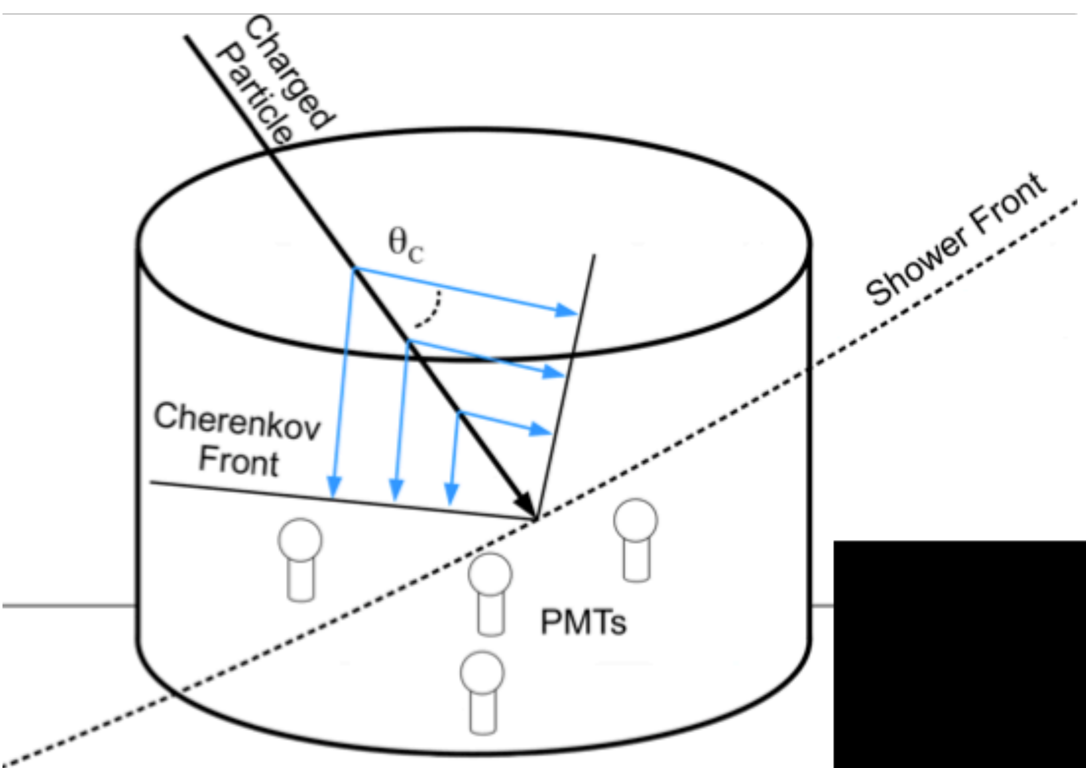


HAWC: an array of large water tanks

HAWC has a nice setting next to the 3rd highest peak in North America!

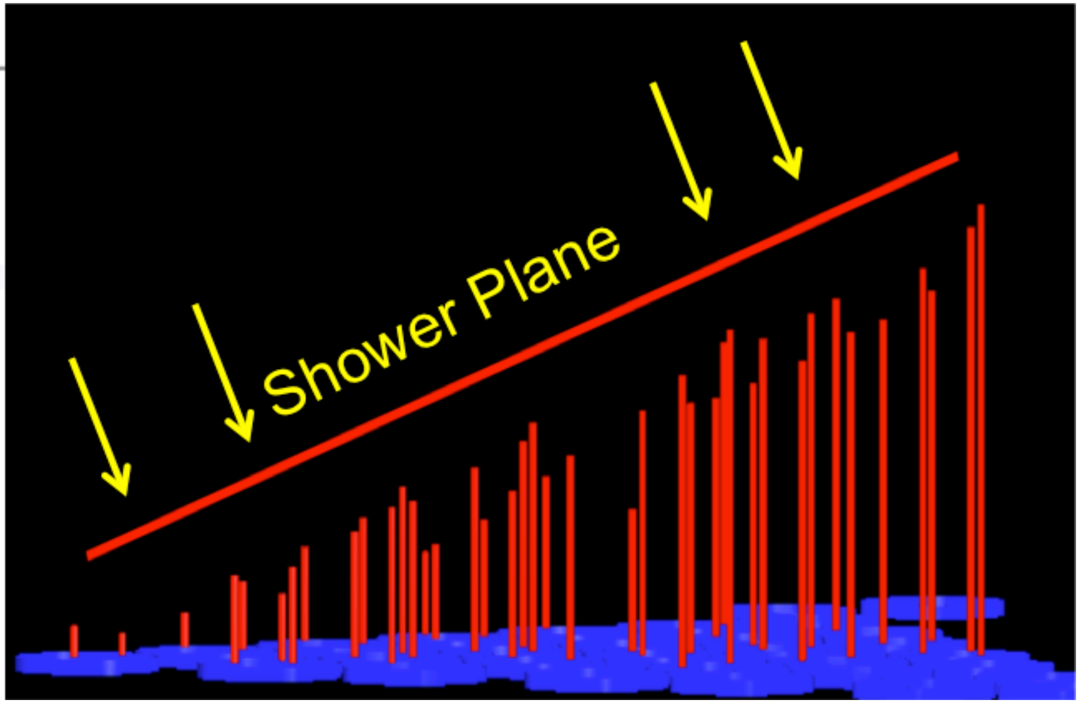
The (Left cartoon) shows a simulated gamma-ray shower onto the HAWC detector.

HAWC: times tell us the shower direction

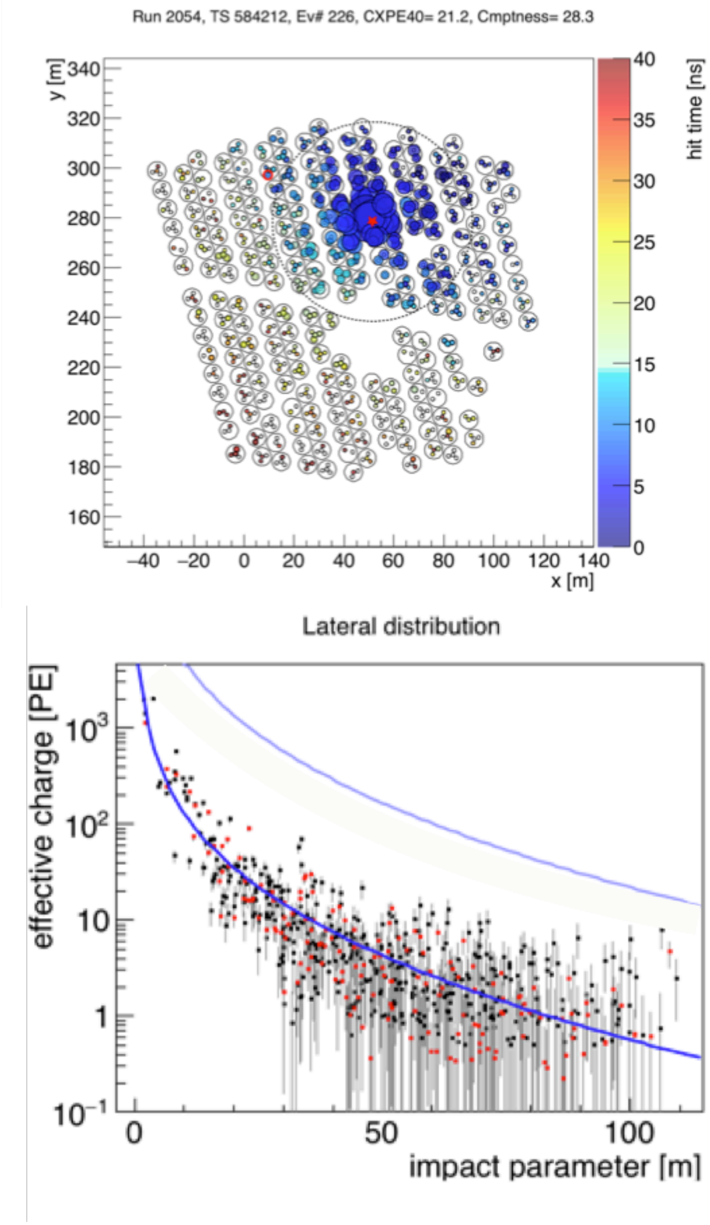


HAWC pointing accuracy varies from about 1-deg (near threshold) to about 0.1-deg for the highest energy gamma-rays.

For reference, angular size of the moon is 0.5-deg.

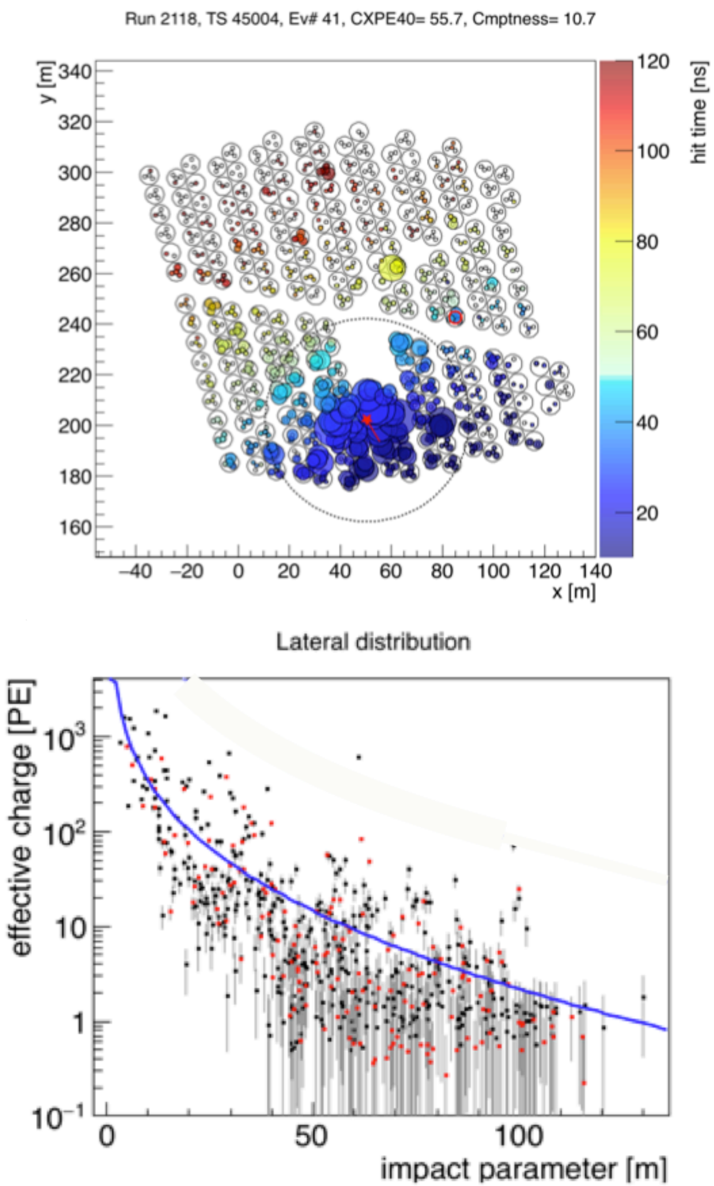


HAWC: what do events look like?



Gamma-ray events (left) are more *uniform* than cosmic ray (back ground) events (right).

To 0th order this is how we separate gammas from CRs.



HAWC: what do events look like?

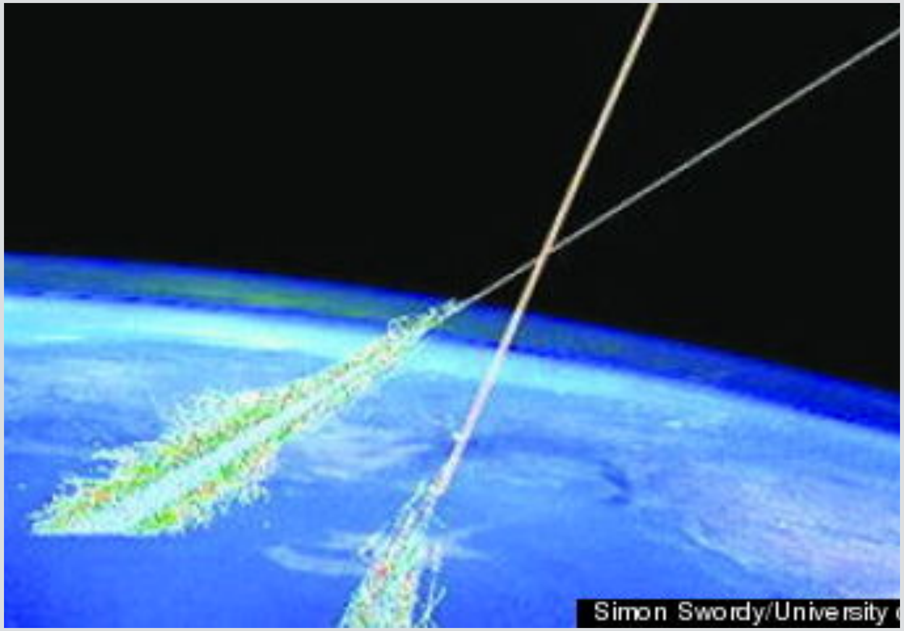
FYI: finding the gamma-ray needle in the cosmic ray haystack is an interesting challenge. Our UNM group of Zhixiang Ren and myself have enjoyed applying Human and Artificial Intelligence to this challenge ...

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

HAWC Data Rates

Collect 20,000 air showers /second
~3 TB /day

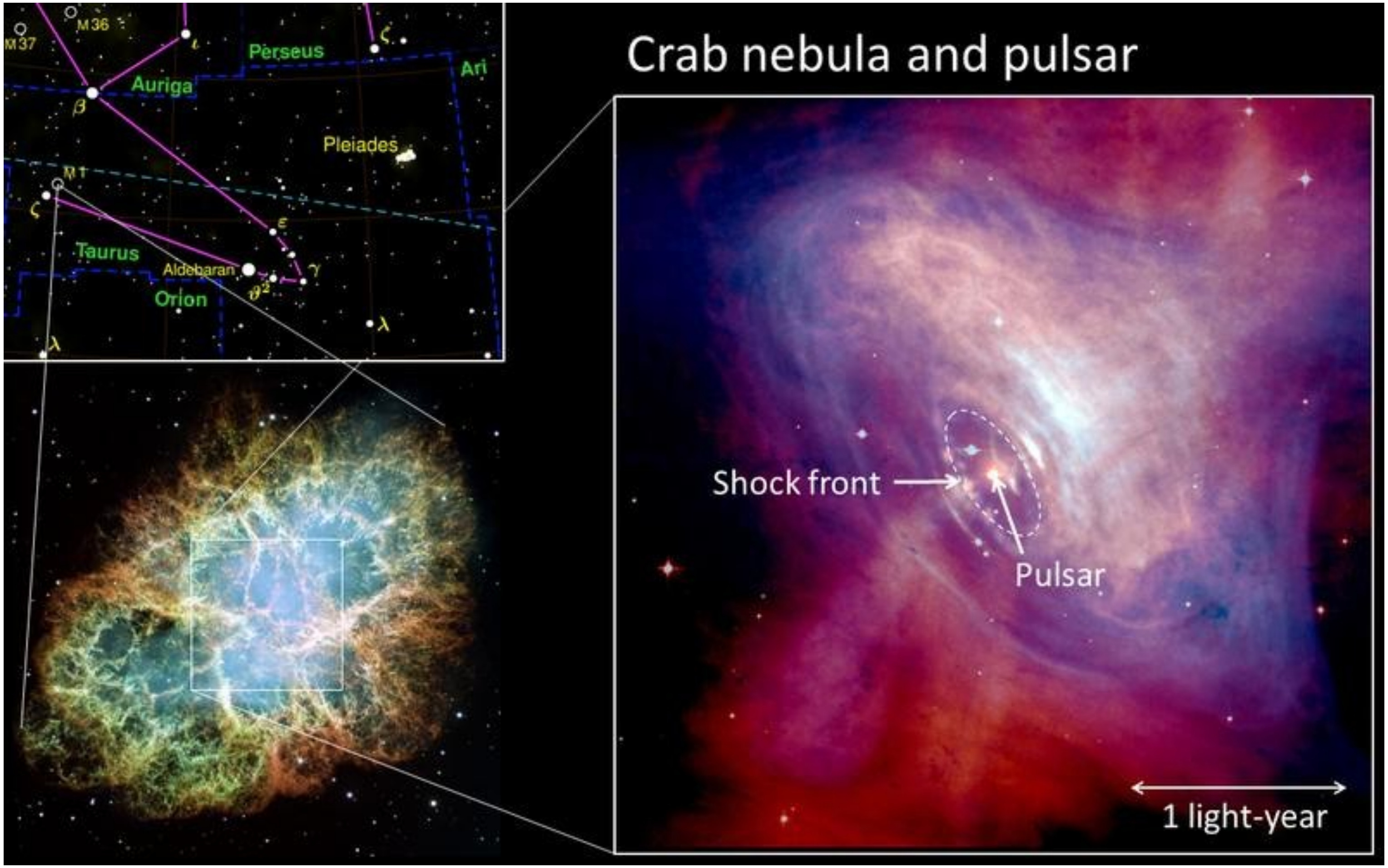
Rule of Thumb:
10^3-10^4 cosmic ray showers per gamma ray



Need to get Gamma/Hadron separation right!

The Crab was the 1st TeV gamma-ray source

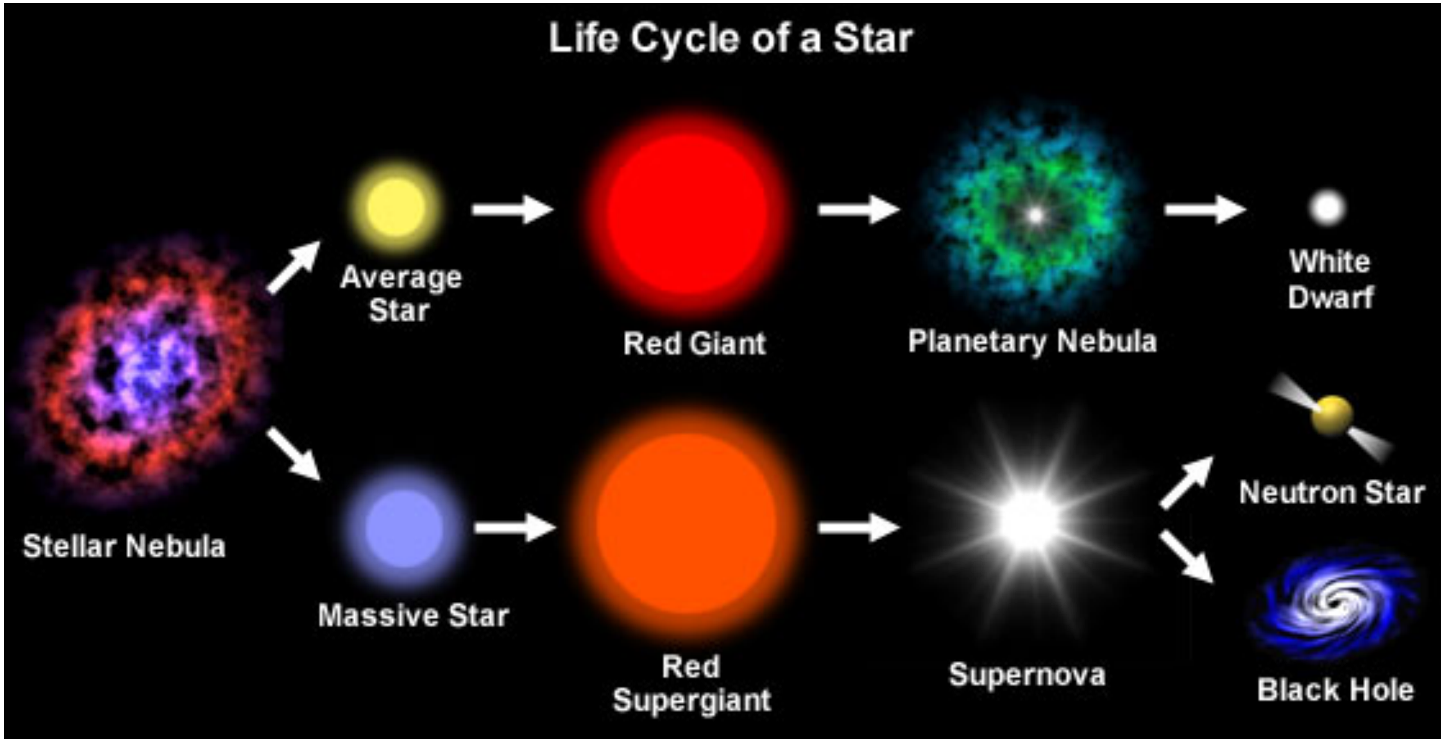
FYI, the Crab (seen by **Particle Detectors** or **Cherenkov Telescopes)** is the remnant of a Core Collapse supernova in 1054. Today we observe a **Super Nova Remnant** (SNR) **and** a **Pulsar**. What part of the Crab is bright at TeV energies?



Stars have lives too you know!

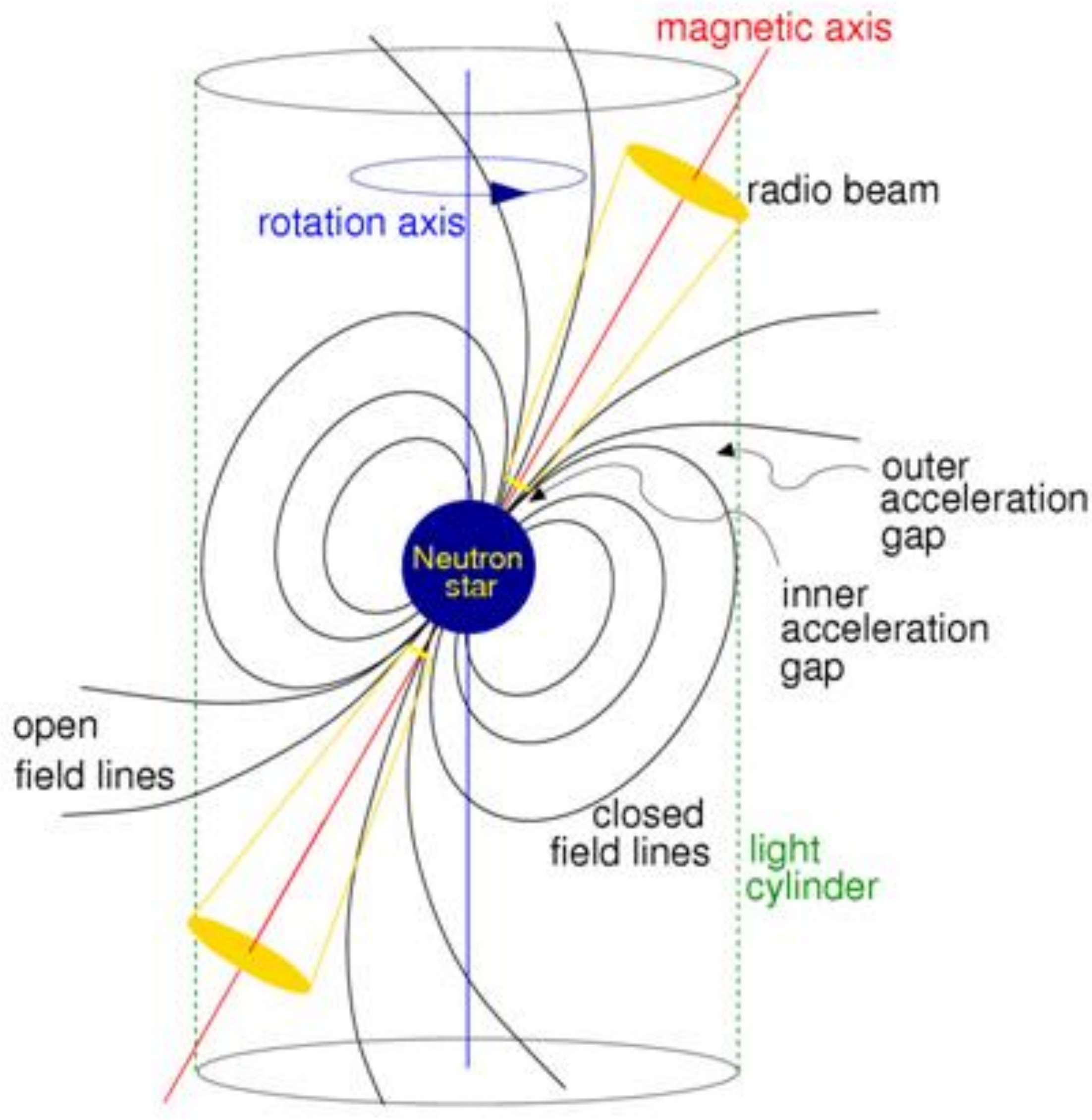
FYI, stars above ~0.08 solar-mass evolve along two paths: low-mass path to planetary nebula + white dwarf and higher-mass path to **Core Collapse** supernova. End products of **Core Collapse** supernovas are **neutron stars** (or **black holes**).

Curiously **neutron stars** were proposed as early as 1934 (Baade and Zwicky) but had to wait 34 years for evidence of their existence as **Pulsars**. They have masses of about 1 to 3 solar masses and radii of about 10km; the **black holes** are more massive.



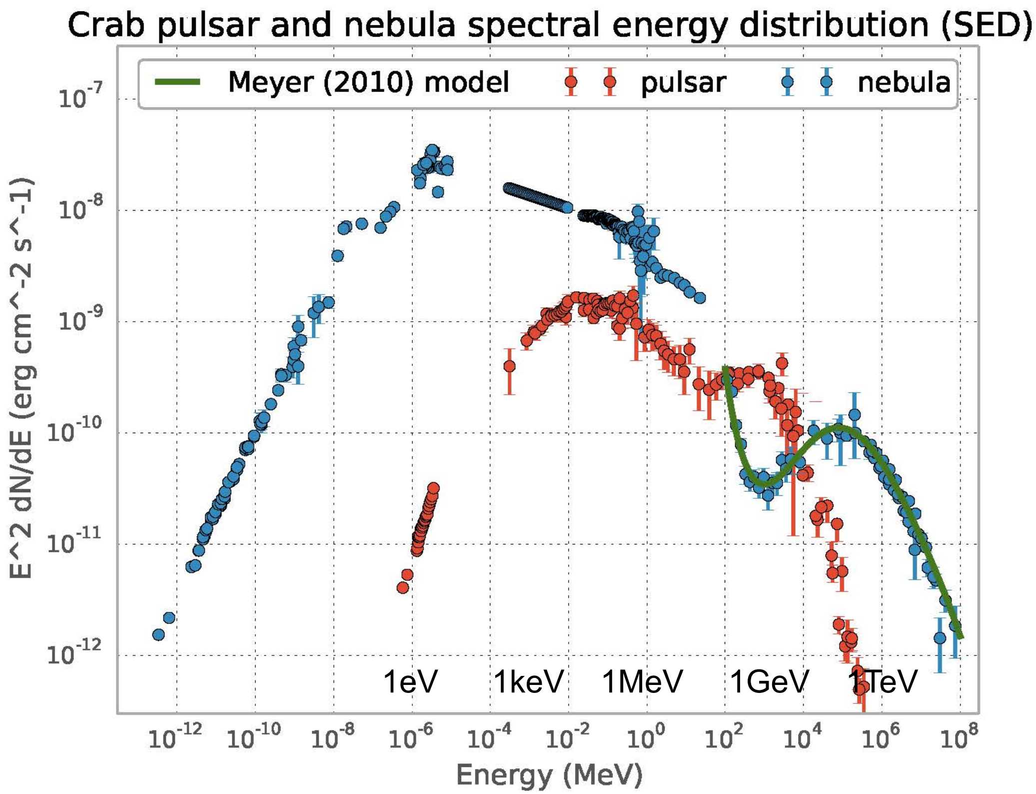
The Crab was the 1st TeV gamma-ray source

FYI, **neutron** stars are extreme astronomical objects of radius ~10km and masses ~1.5 solar mass. *Young* neutron stars have extreme magnetic fields and rotation periods <1 second. Part of the EM emission from the **neutron** star is beamed. If/when the beam is directed toward the Earth we observe the **neutron** star as a **pulsar**.



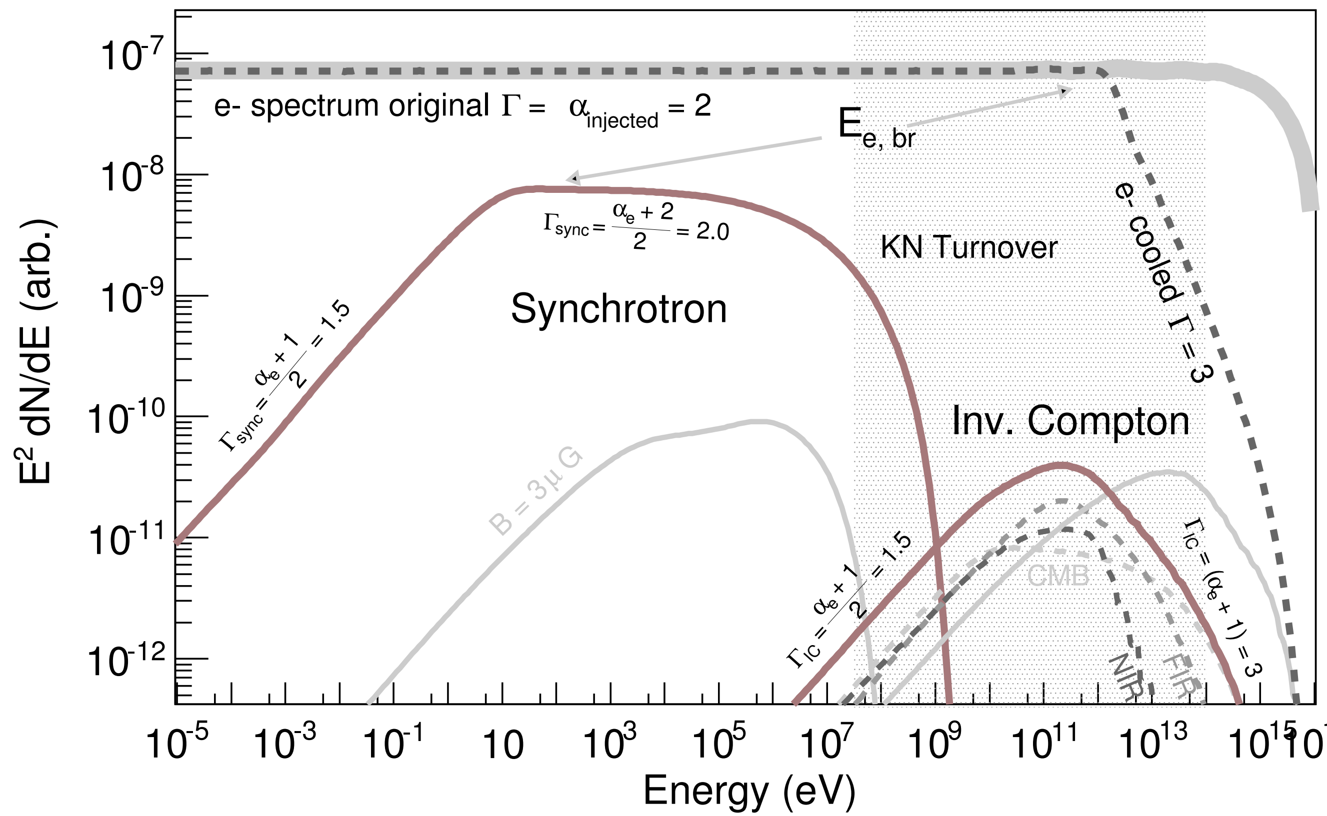
What are multi-wavelength studies?

Curiously one of the brightest TeV gamma-ray sources, the Crab (nebula + pulsar), radiates from radio to gamma-ray energies! To help understand the physics of this light source takes many individual telescopes: aka ***multi-wavelength*** astrophysics. Yes: the **nebula** and **pulsar** have different source Spectral Energy Distributions (SEDs); what are they telling us?



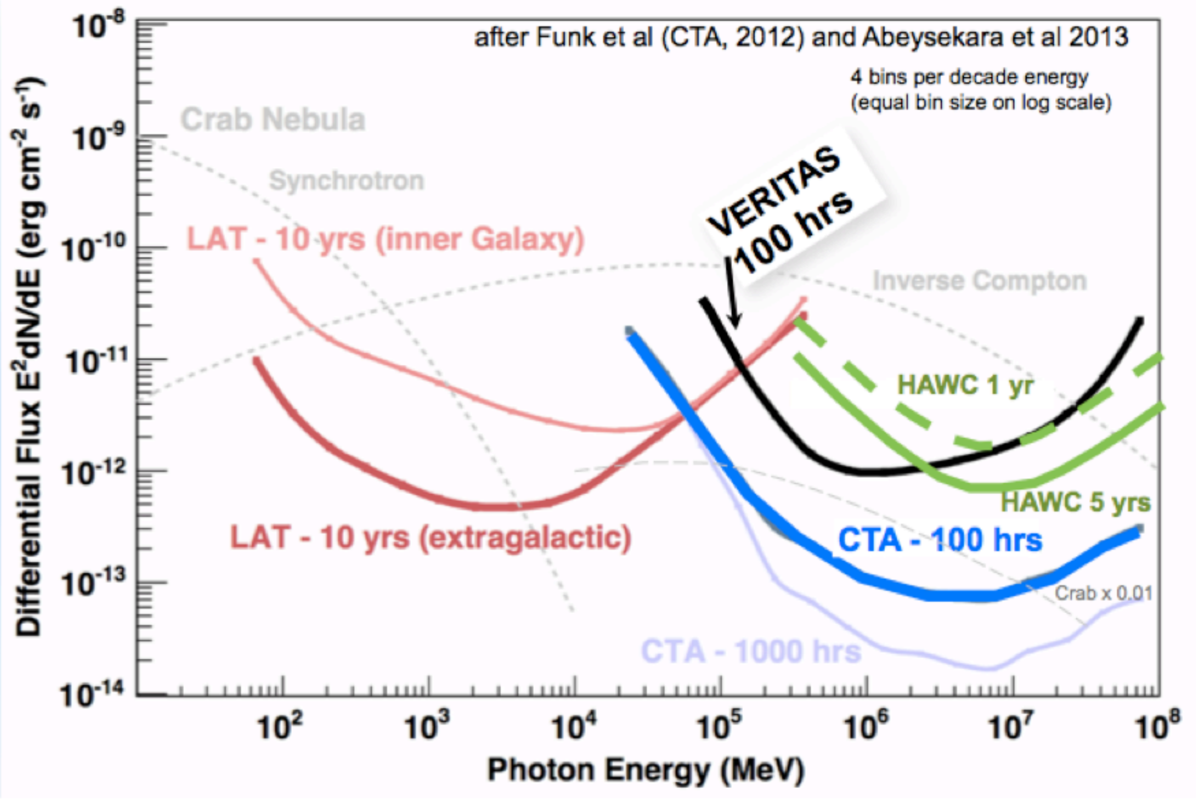
Aside: what are SEDs telling us?

What we observe are gamma rays. What the sources accelerate are electrons (and/or protons). For the **gamma-ray SED** one typically starts with an accelerated power-law spectrum of the eg **electrons** (potentially with a high-energy cutoff at Emax) and subsequently calculates the losses into photons from the different processes …

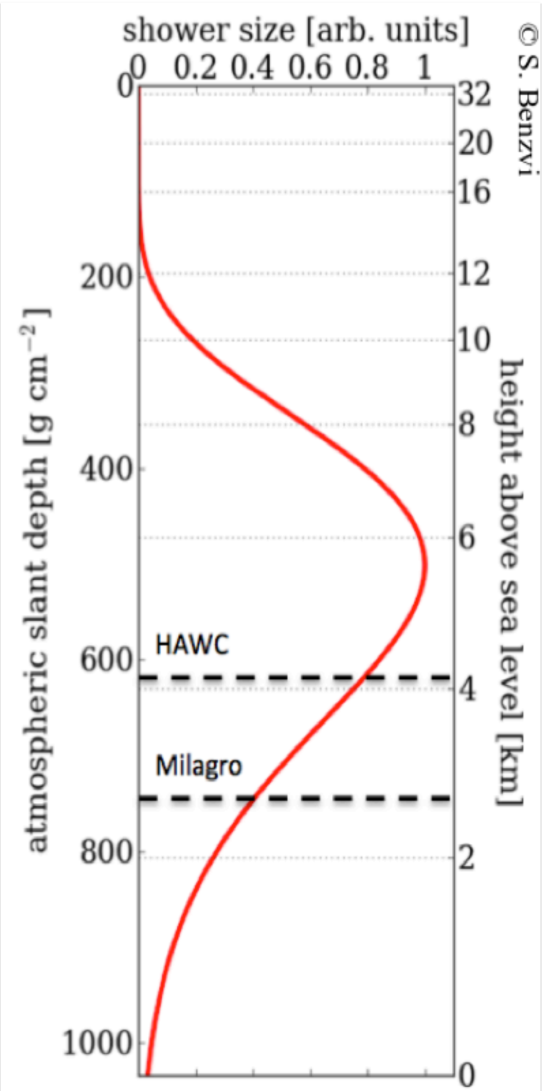


What are multi-wavelength studies?

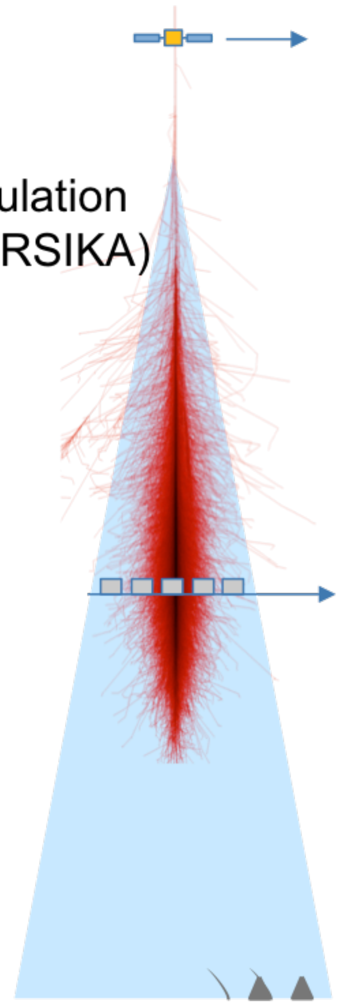
IACTs, HAWC and other gamma-ray (X-ray) experiments are sensitive in a large but limited energy range. To understand the source physics, eg Synchrotron emission VS Inverse-Compton emission VS …, many measurements must be combined. This is termed ***multi-wavelength*** astro-physics. Figure shows VHE gamma-rays (100MeV to 100TeV) require 2 to 3 instruments!



100MeV to 100TeV multi-wavelength studies



Simulation (CORSIKA)



Satellite Detector

Wide Field of View, Continuous Operations

Extensive Air Shower (EAS) Detector

TeV Sensitivity

Imaging Atmospheric Cherenkov Telescope (IACT)

What are multi-messenger studies?

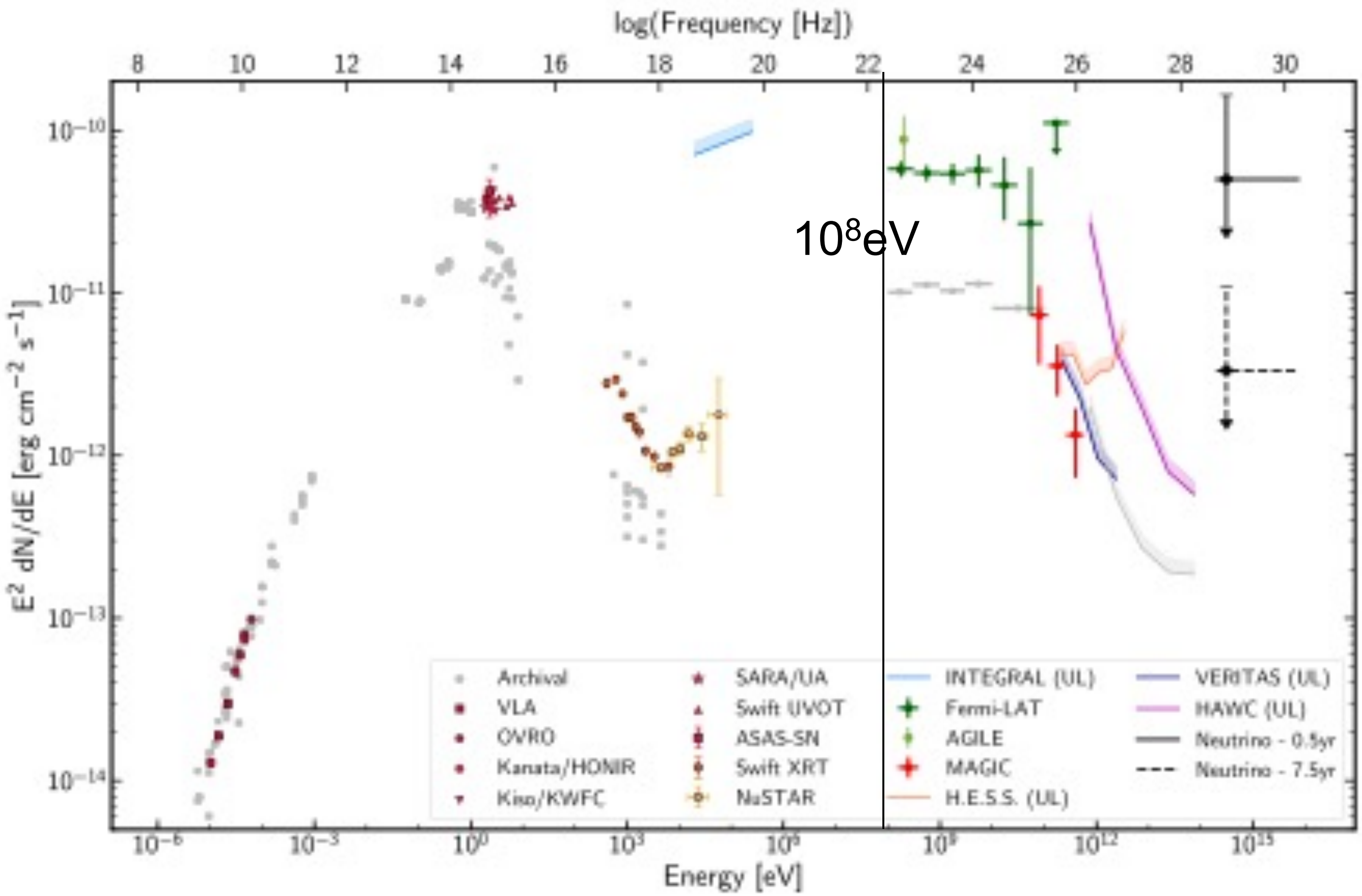
Multi-messenger astrophysics began with SN1987a observed at optical wavelengths and at 3 neutrino observatories.

On August 17, 2017, a new era of astronomy was inaugurated by a short gamma-ray burst (GRB) accompanying the gravitational wave GW170817 detected by LIGO-VIRGO from a **neutron star:neutron star** merger. The GRB was observed by FERMI and INTEGRAL satellites at photon energies <2 MeV.

On 22 September 2017 a high-energy neutrino, IceCube170922A, was detected with an energy of ~290 TeV. Its arrival direction was consistent with the location of a known gamma-ray blazar TXS 0506+056, observed to be in a *flaring* state.
… This observation of a neutrino in spatial (and temporal) coincidence with a gamma-ray emitting blazar, during an active phase, suggests that blazars (aka Super Massive Black Holes/ Active Galactic Nuclei) may be a source of high-energy neutrinos.

What are multi-messenger studies?

The Spectral Energy Distribution (SED) for the blazar, TXS 0506+056, is based on observations obtained within 14 days of the detection of the IceCube-170922A event. Historical (average values) are shown as grey points. Is the enhancement above 10^8eV (neutral pion → 2 gammas turn-on) significant?



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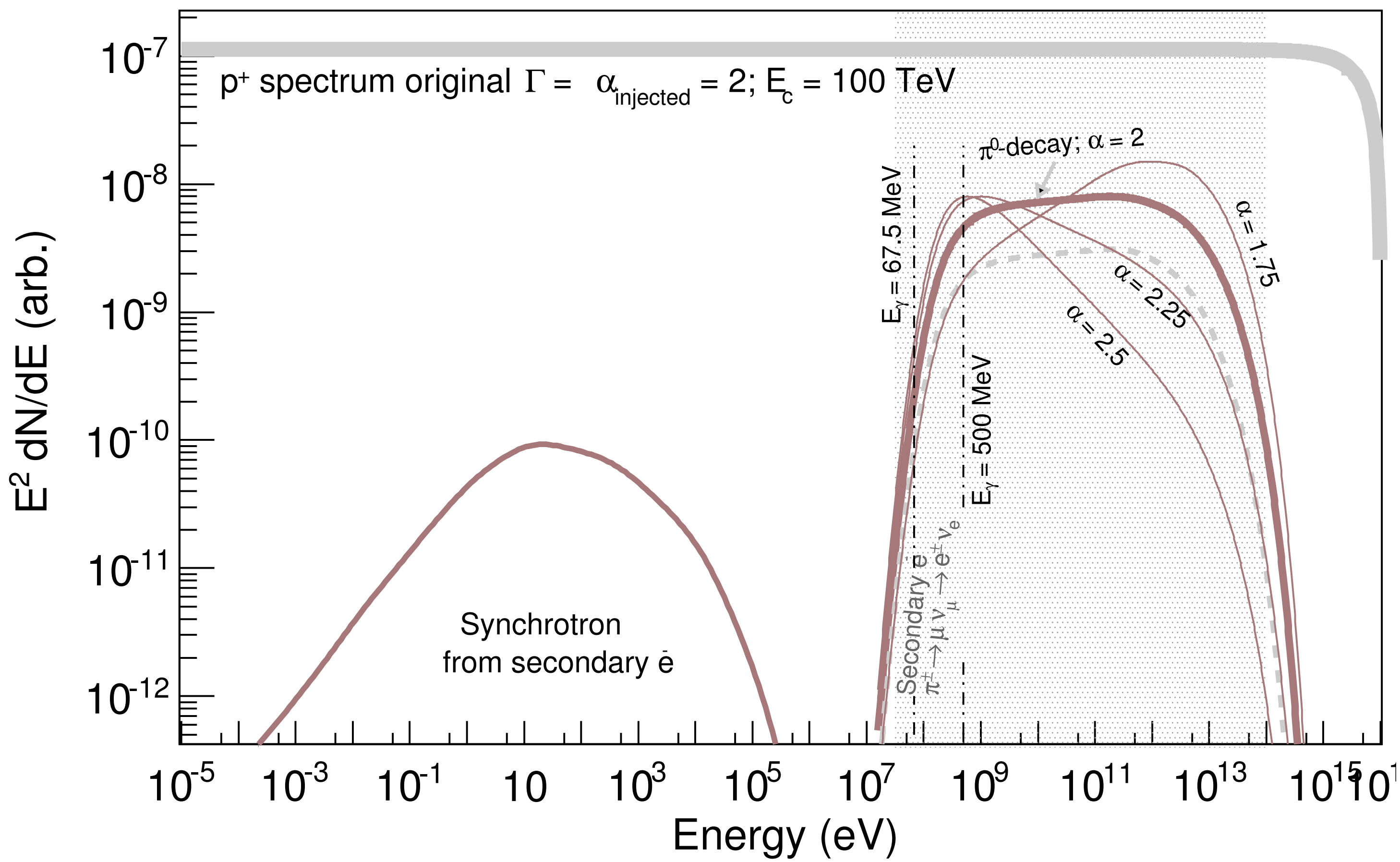
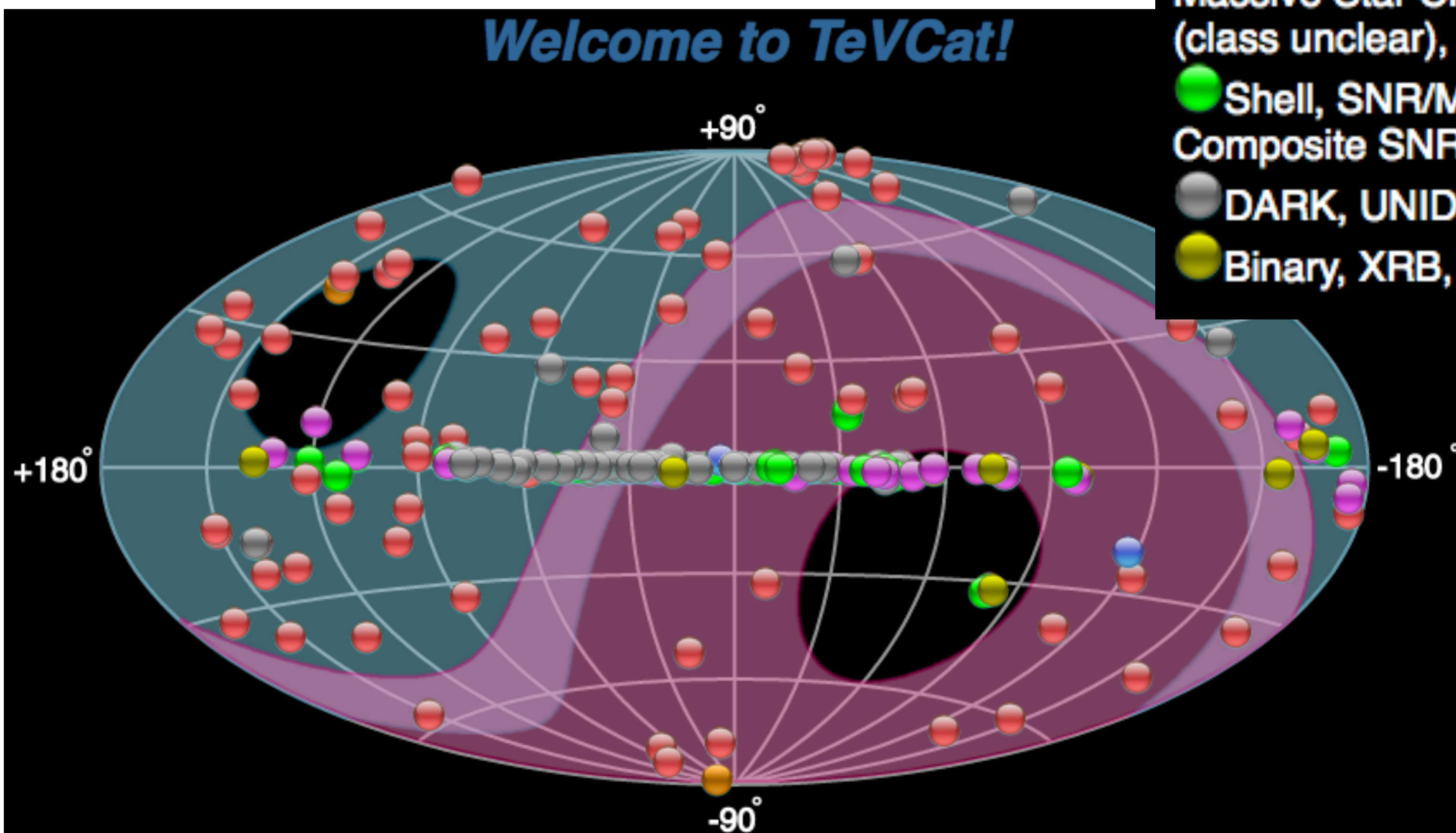


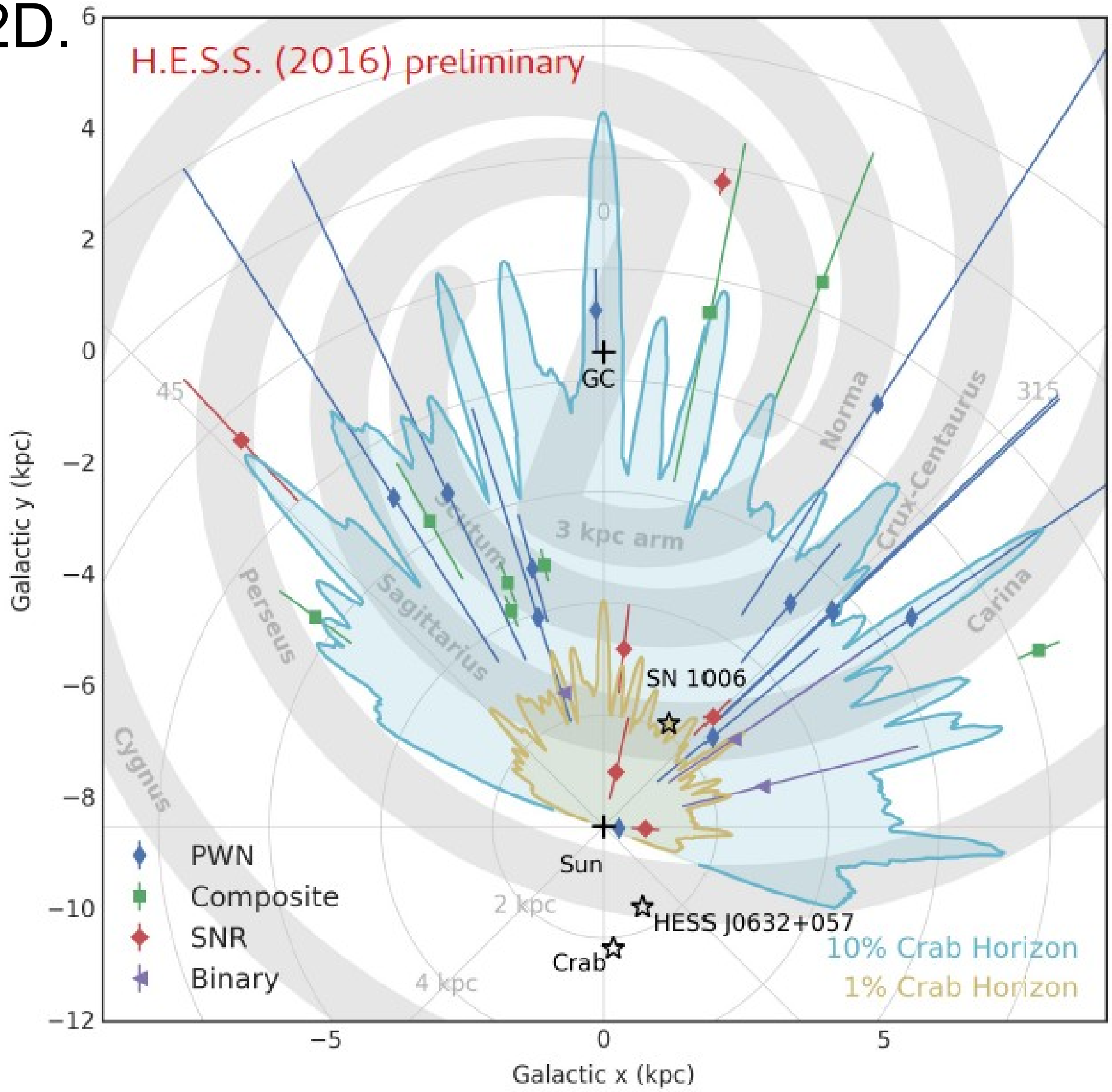
What does the Universe look like at TeV energies?

Before 1989 TeVCat had 0 sources …
The figure shows known sources *today* plotted in Galactic Coordinates. ~1/2 the sources are nearby (*Galactic)* sources, and ~1/3 of those are **UNID**entified.



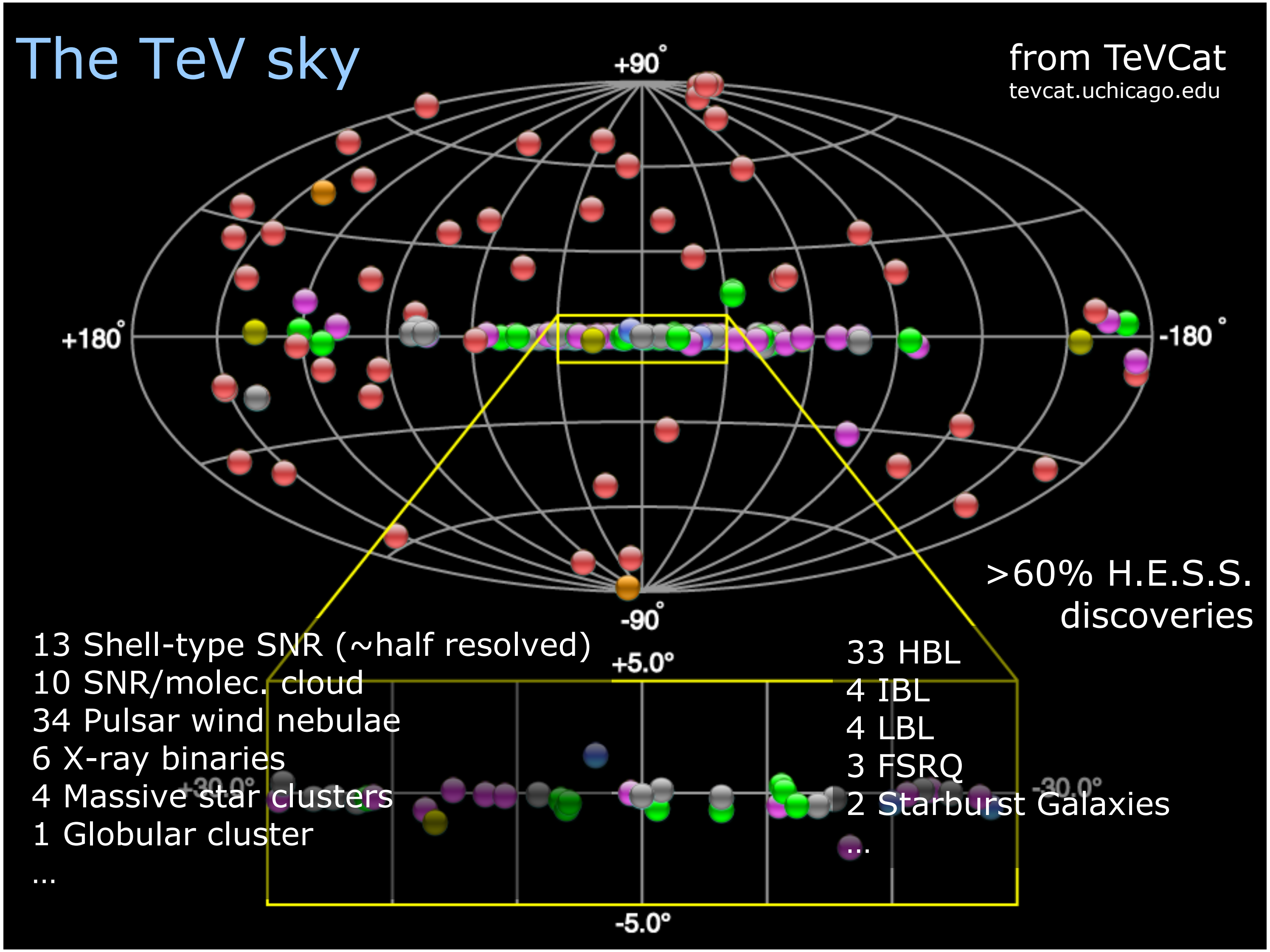
What does the Universe look like at TeV energies?

UNIDentified sources may be the result of source overlap **…**
Figure of HESS-sources shows how sources that are separated in 3D could overlap in 2D.



What does the Universe look like at TeV energies?

List of **ID**entified sources in 2013. The figure details Galactic sources (**Left** column) and Extra-galactic sources (**Right** column)



What does the Universe look like at TeV energies?

In broadest terms the TeV sky is dominated:

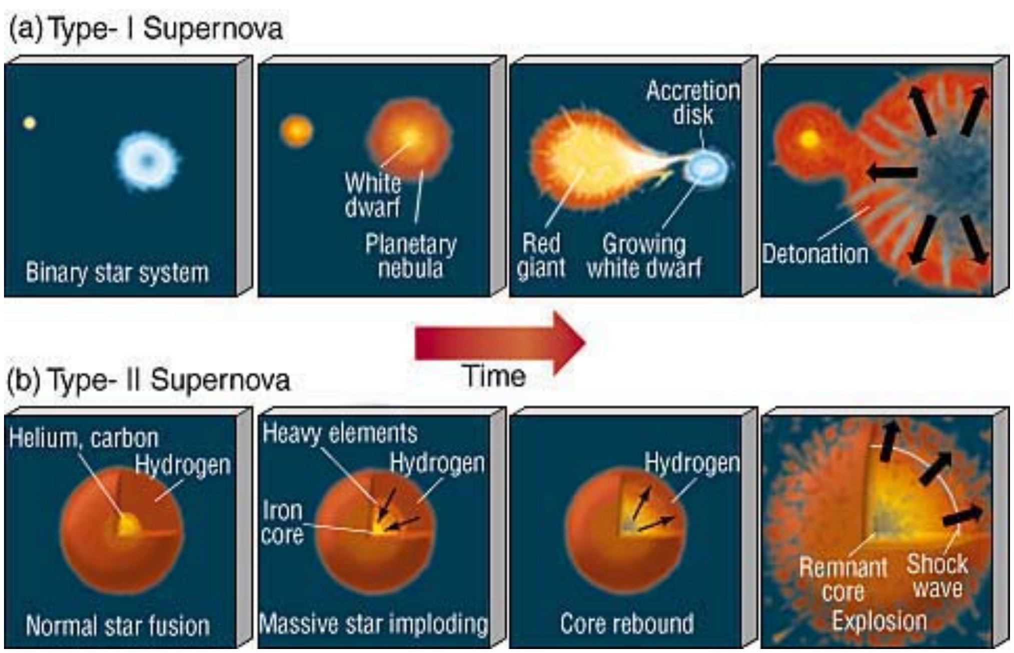
a) On Milky Way galaxy scales by **Supernova remnants** (**SNR**) including Pulsar Wind Nebulae (**PWN**), **Shell-type SNR**, and **mixed SNR/molecular clouds** (where the SNR particles are colliding with nearby giant molecular clouds) … plus probably combined SNR/PWN systems

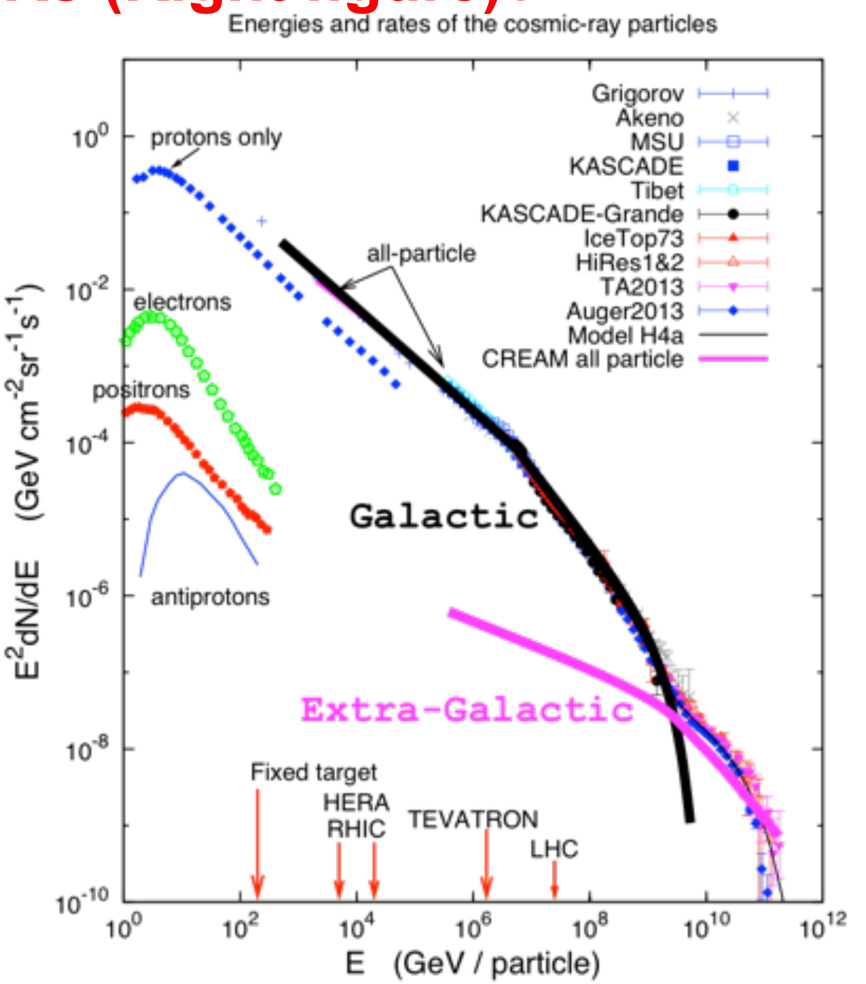
b) on Extra-galactic scales by the various manifestations of supermassive black holes in an active feeding phase called **Active Galactic Nuclei** (AGNs)

c) and on astronomical time scales these are all *young*: **SNRs** are luminous for possibly hundreds of thousands of years and **AGNs** are all in typically short-lived active feeding states.

What does the Universe look like at TeV energies?

Broadly there are two types of **Supernova**: Type I which is a ***Carbon* bomb** and Type II which has a remnant **neutron star** (or black hole). The Cosmic Ray community always asks: are **SNs** responsible for the **Galactic CRs (Right figure)**?

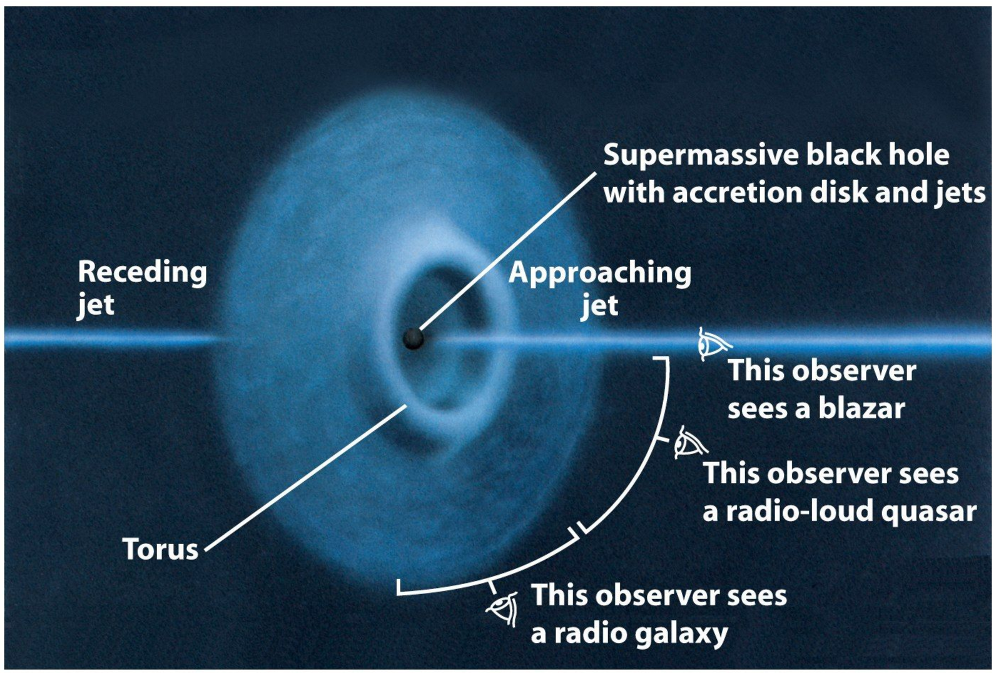


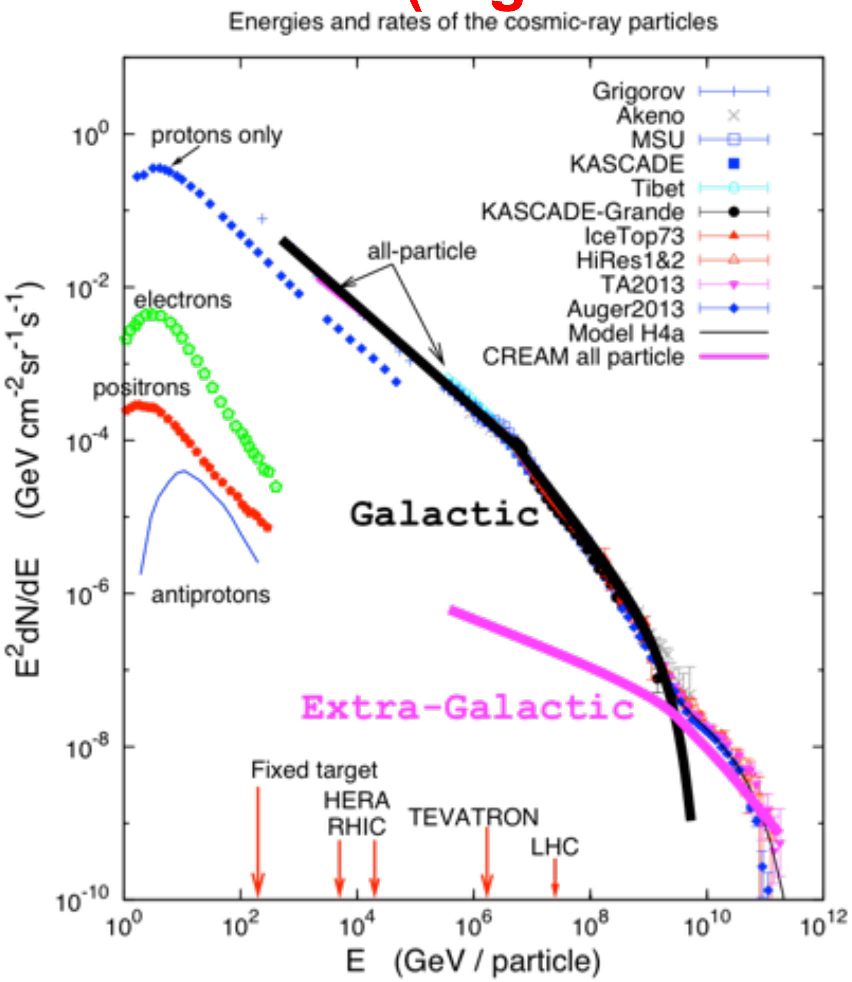


What does the Universe look like at TeV energies?

AGNs have many nick-names based on how we view them **…** and are observed in EM radiation from radio to gamma rays.

The Cosmic Ray community always asks: are **AGNs** responsible for (some of) the **Extra-Galactic CRs (Right figure)**?

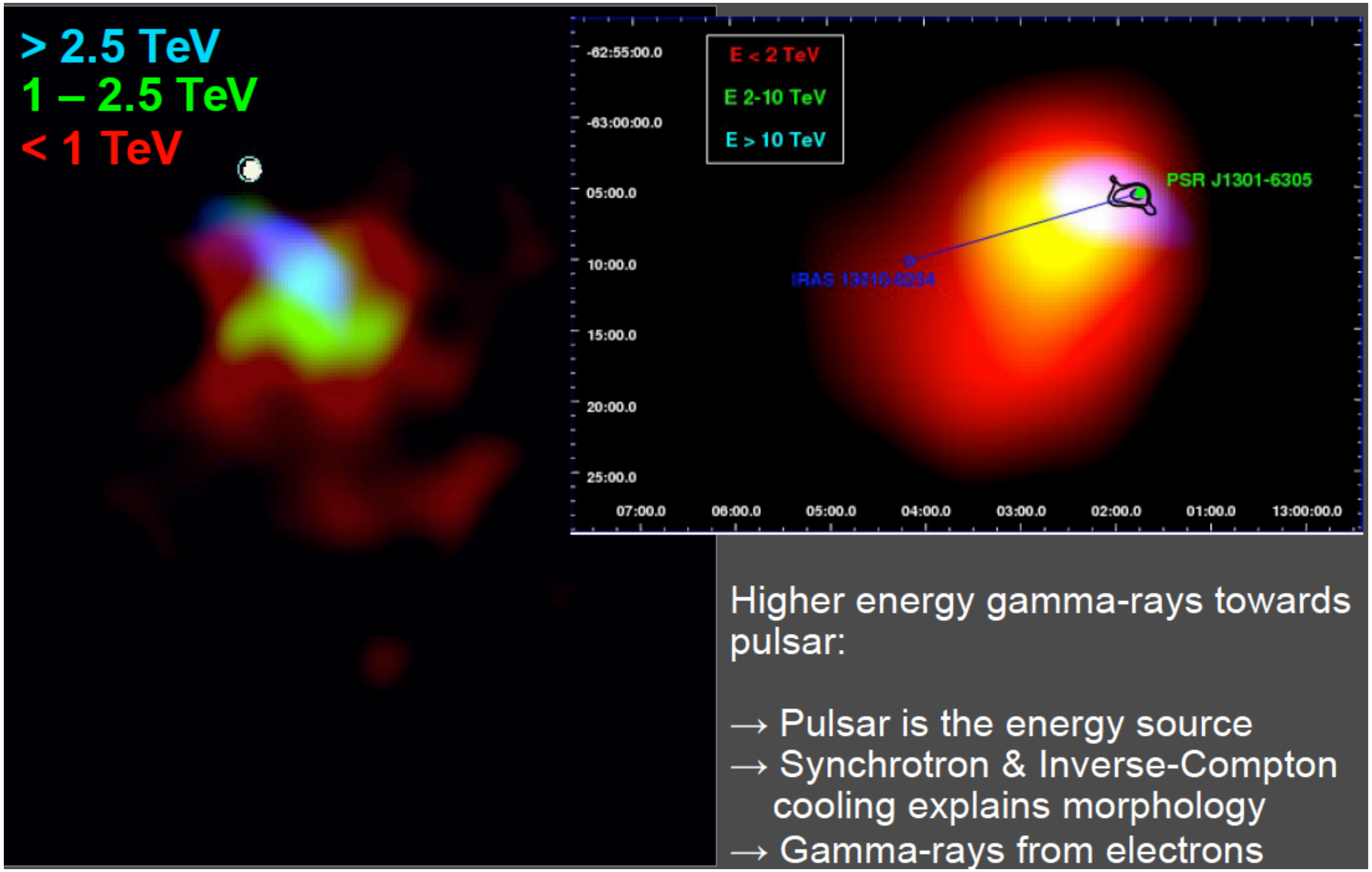




TeV sources: Pulsar Wind Nebulae

The most abundant (TeV) **Galactic sources** are pulsar-driven extended nebulae, so called **Pulsar Wind Nebulae** (**PWN**):

- are expected to change with time: (diffusion/cooling)
- some show energy-dependent morphology
- can be offset from pulsar (pulsar likely moving)



TeV sources: Pulsar Wind Nebulae

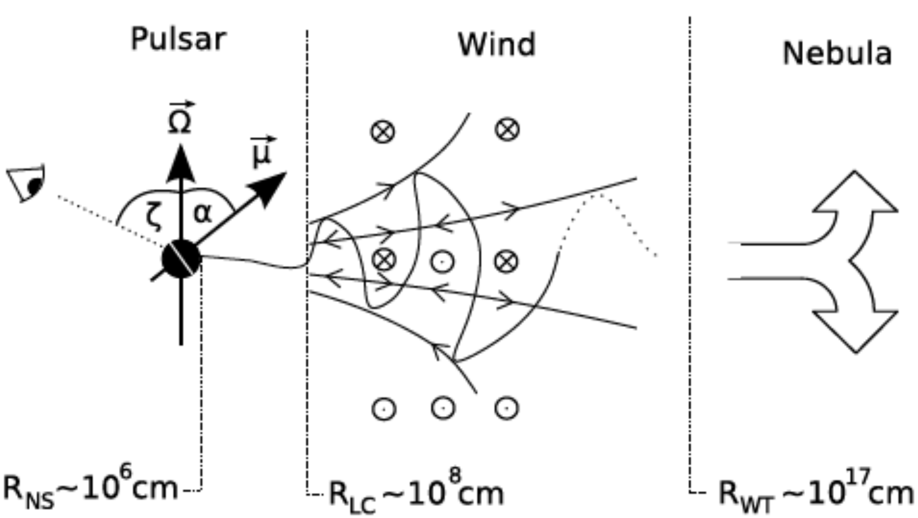
The most abundant (TeV) **Galactic sources** are pulsar-driven extended nebulae, so called **Pulsar Wind Nebulae** (**PWN**):

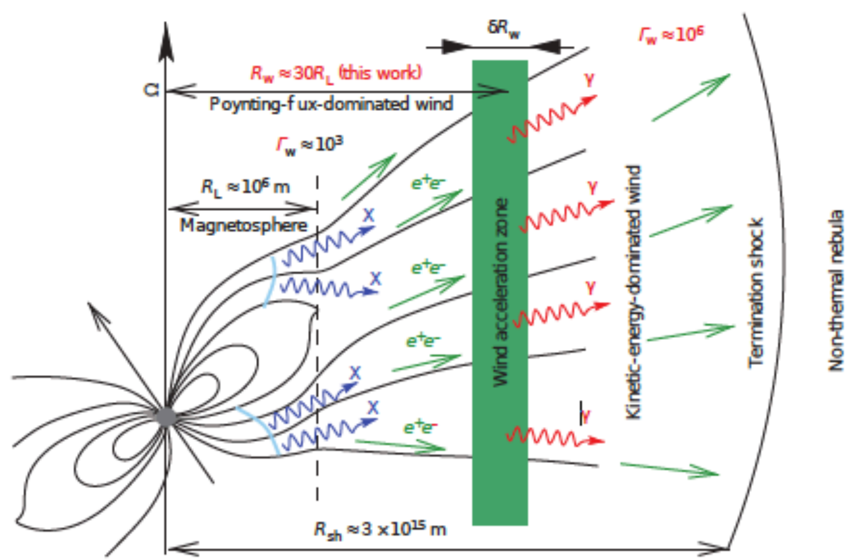
In this composite image of Kes 75, high-energy X-rays observed by Chandra are colored blue and highlight the pulsar wind nebula surrounding the pulsar, while lower-energy X-rays appear purple and show the debris from the explosion. (NASA: youngest known pulsar).

TeV sources: Pulsar Wind Nebulae

What are pulsar winds?

Pulsar winds are composed of charged particles (plasma) accelerated to relativistic speeds by the rapidly rotating, hugely powerful magnetic fields above 1 teragauss (100 million teslas) that are generated by the spinning pulsar. In the wind acceleration region (in green), the electromagnetic energy contained in the pulsar wind is converted into bulk kinetic energy of a relativistic e+/e- plasma:

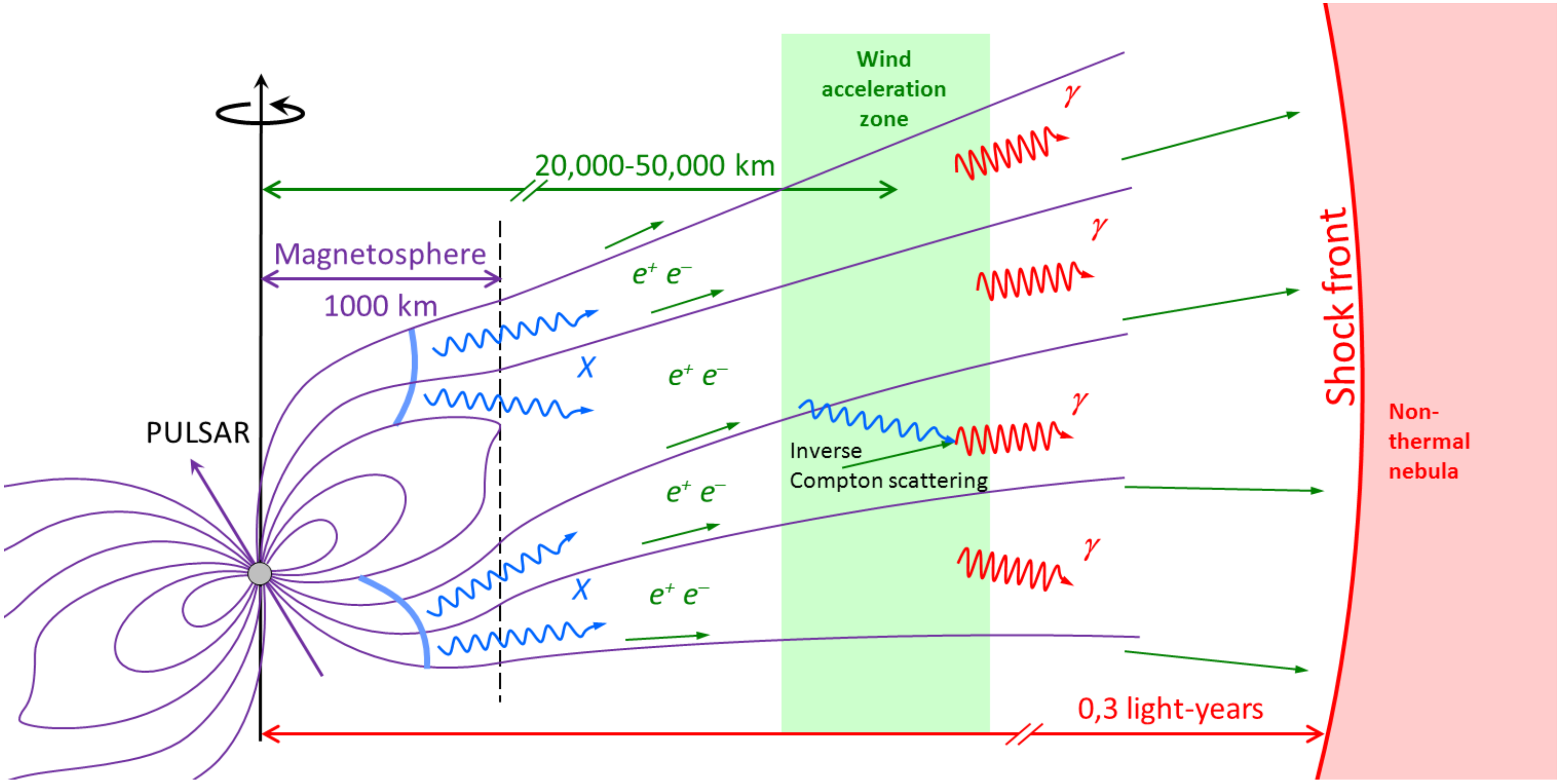




TeV sources: Pulsar Wind Nebulae

Why so many PWN?

The rotational energy of **pulsars** is an order of magnitude below the kinetic energy released in the **SNR** … but much of the energy goes into **electrons** which are much more efficient in producing gamma rays compared to protons … and **pulsars** accelerate particles over a much longer time scale than **SNR**:

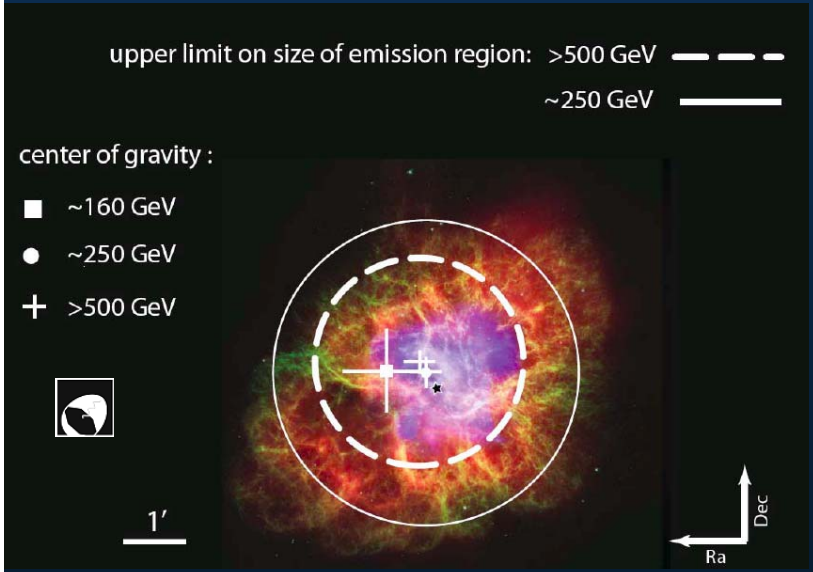


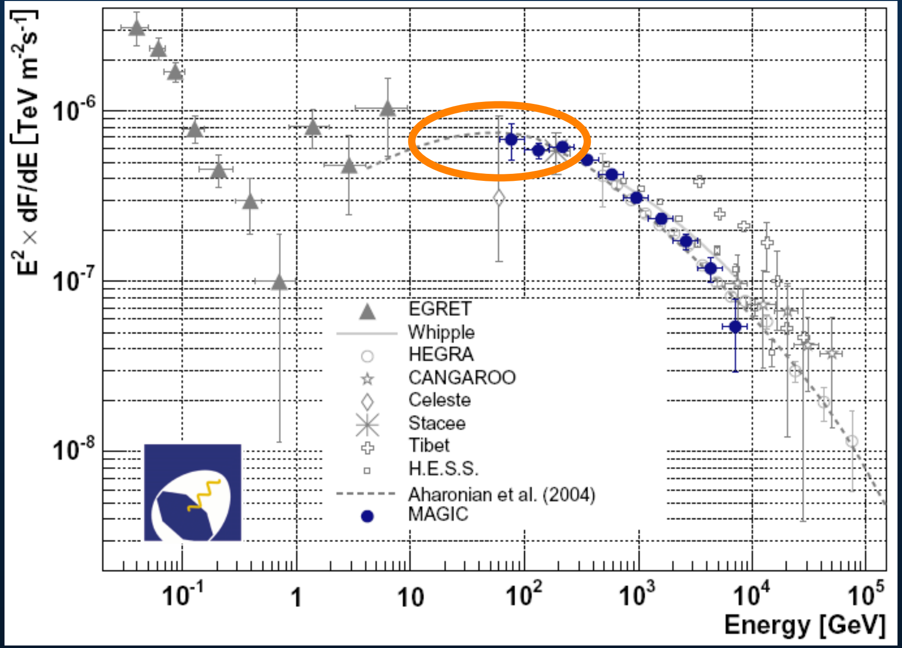
TeV sources: Pulsar Wind Nebulae

It is expected that the emission from **PWN** should be well described by **electron** processes: **synchrotron** emission below and **Inverse Compton** above **~1GeV …** as shown by **Crab data**

Steady emission from the PWN

MAGIC Collab., ApJ 674 (2008) 1037

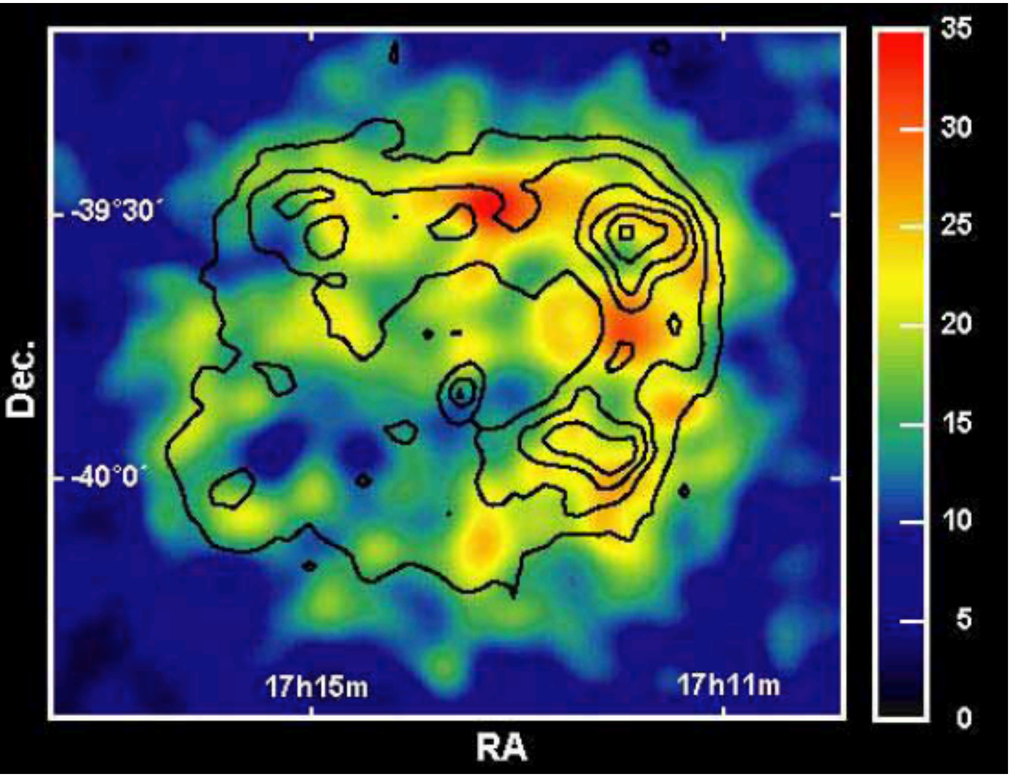


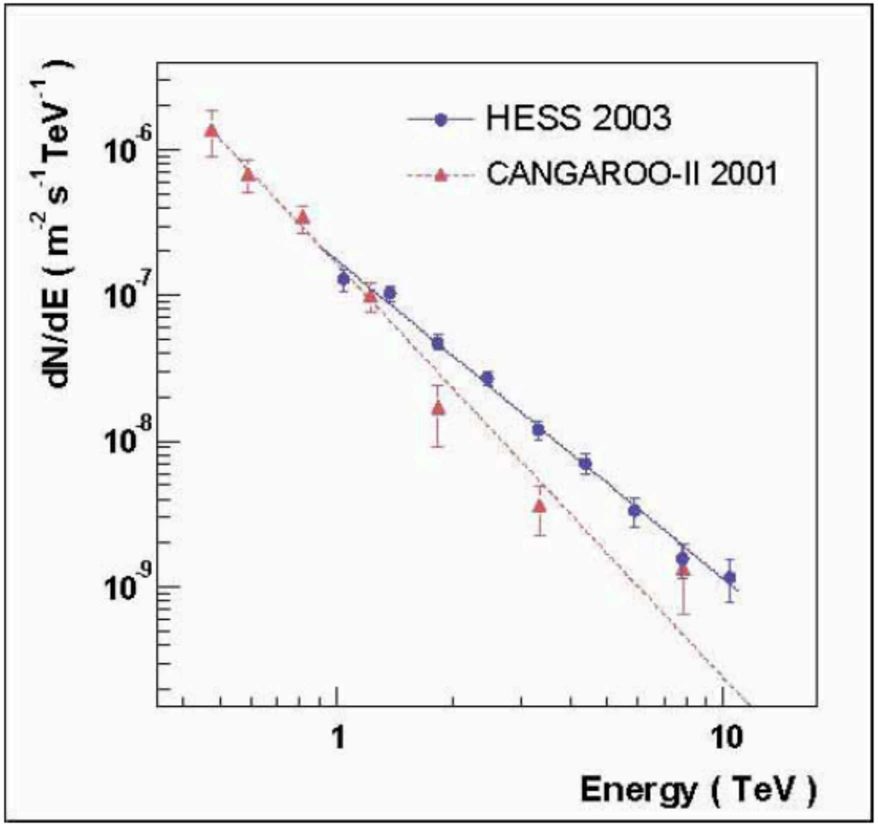


- MAGIC measured spectrum down to 60 GeV
- Energy spectrum well described by IC emission
- IC peak estimated at 77 GeV

TeV sources: Shell-type Super Nova Remnant

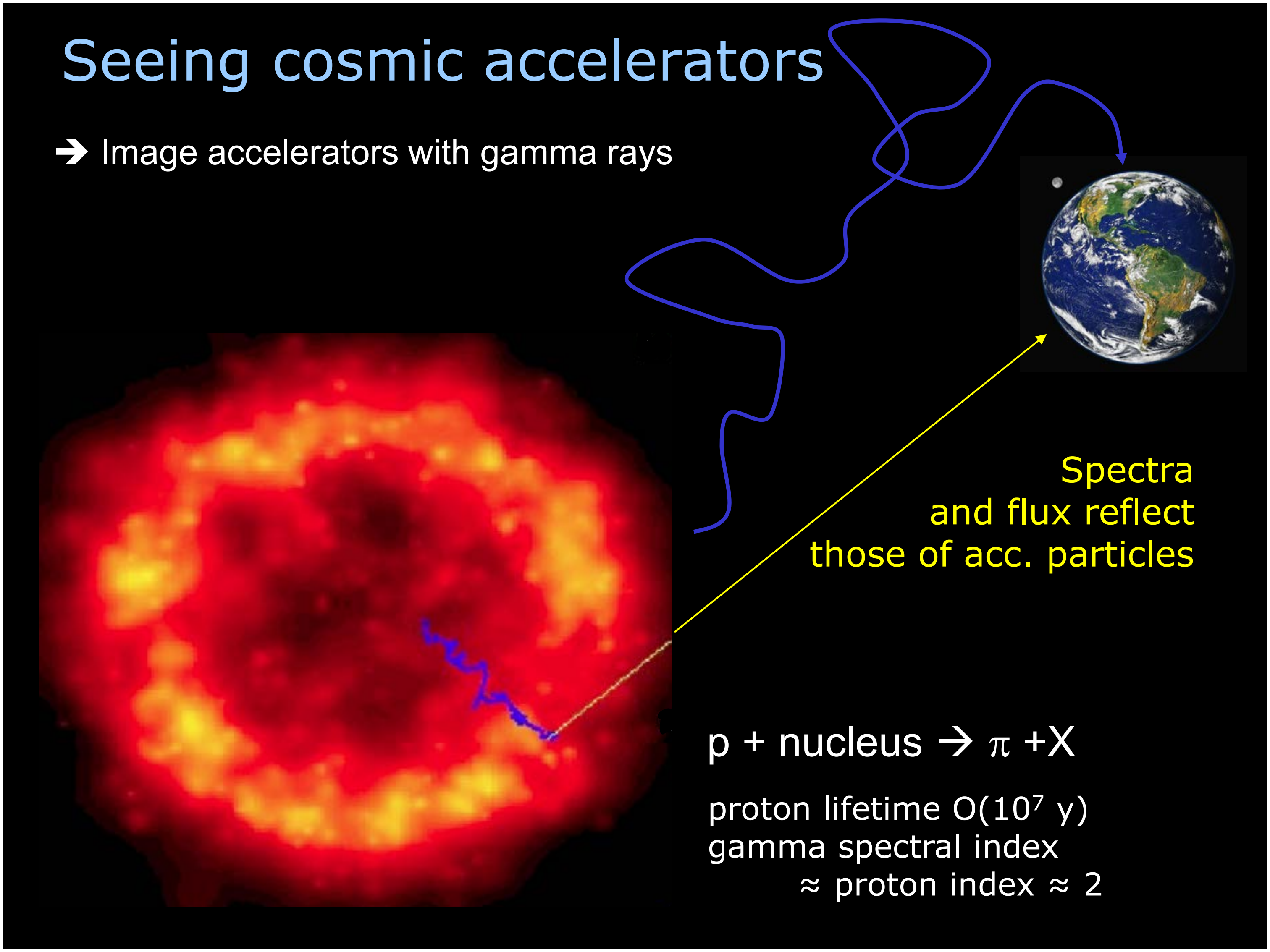
HESS Nature 2004: ``the spatially resolved remnant (RX J1713.7−3946) has a shell morphology similar to that seen in X-rays (*contours*), which demonstrates that very high-energy particles are accelerated there. The energy spectrum indicates efficient acceleration of charged particles to energies beyond 100 TeV consistent with current ideas of particle acceleration in young **SNR** shocks.''





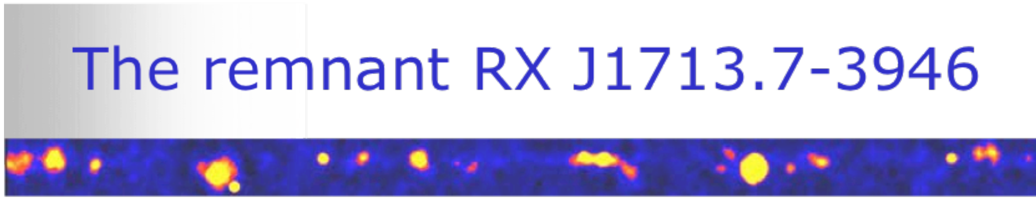
TeV sources: Shell-type Super Nova Remnant

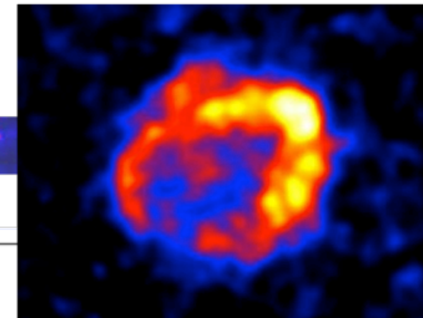
HESS Nature 2004: And can we distinguish **proton** (from electron) sources of the TeV emission?



TeV sources: Shell-type Super Nova Remnant

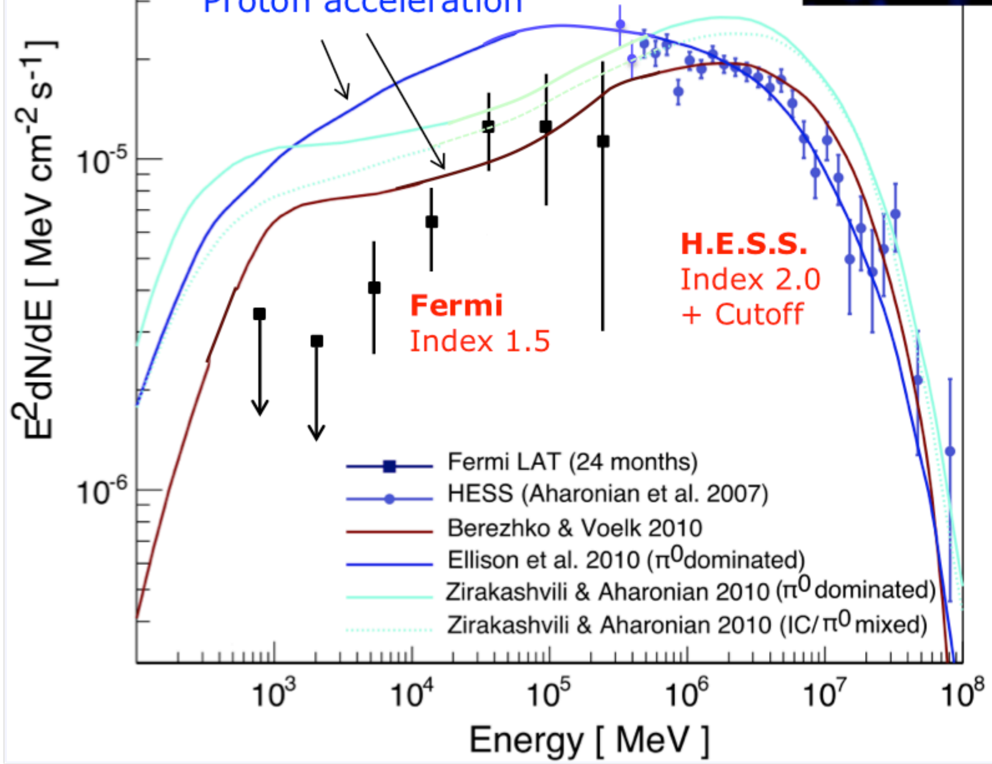
HESS Nature 2004: And can we distinguish **proton** (from electron) sources of the TeV emission? ... NO!





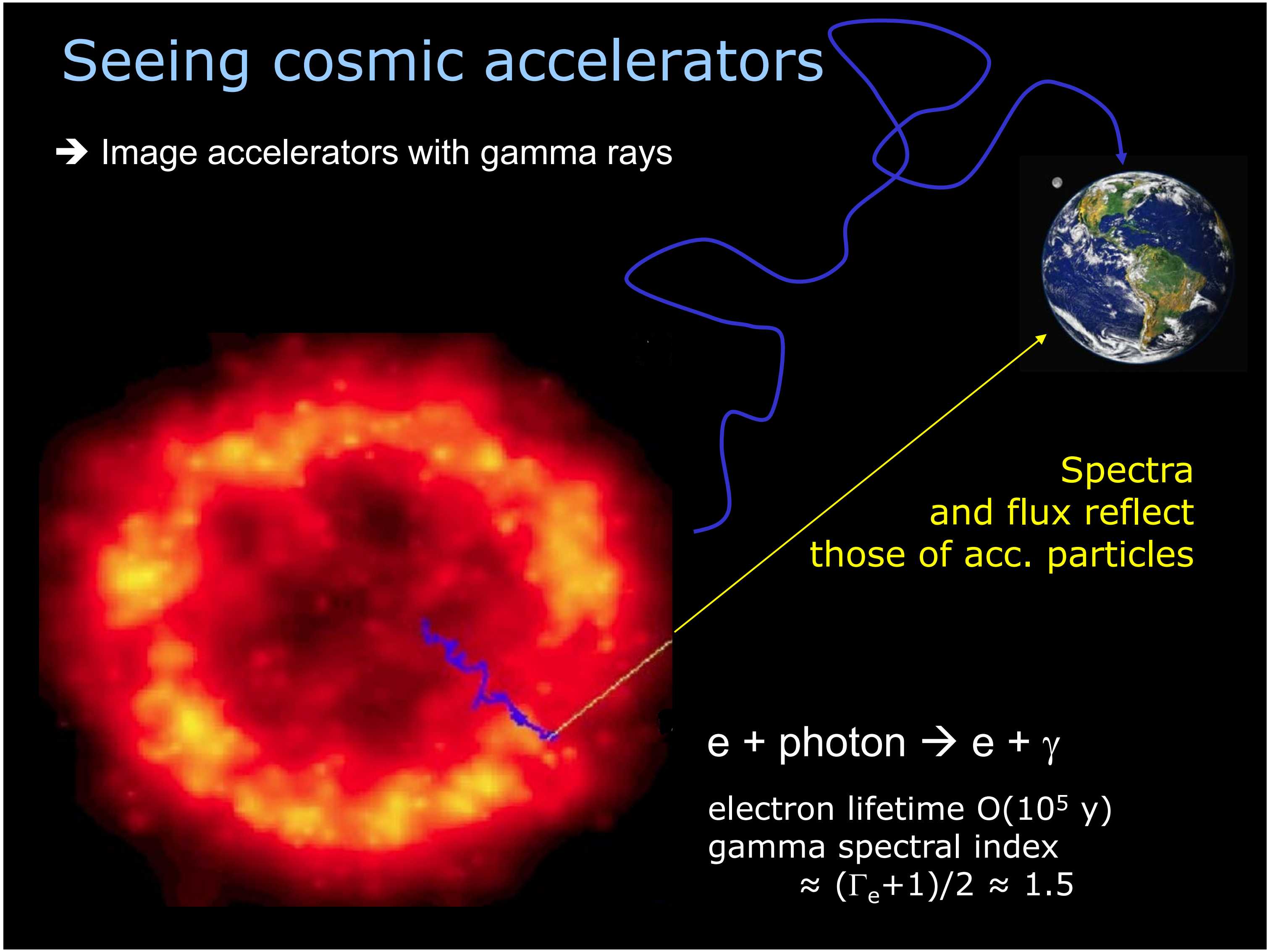
Fermi-LAT Collab.
arXiv:1103.5727

SED



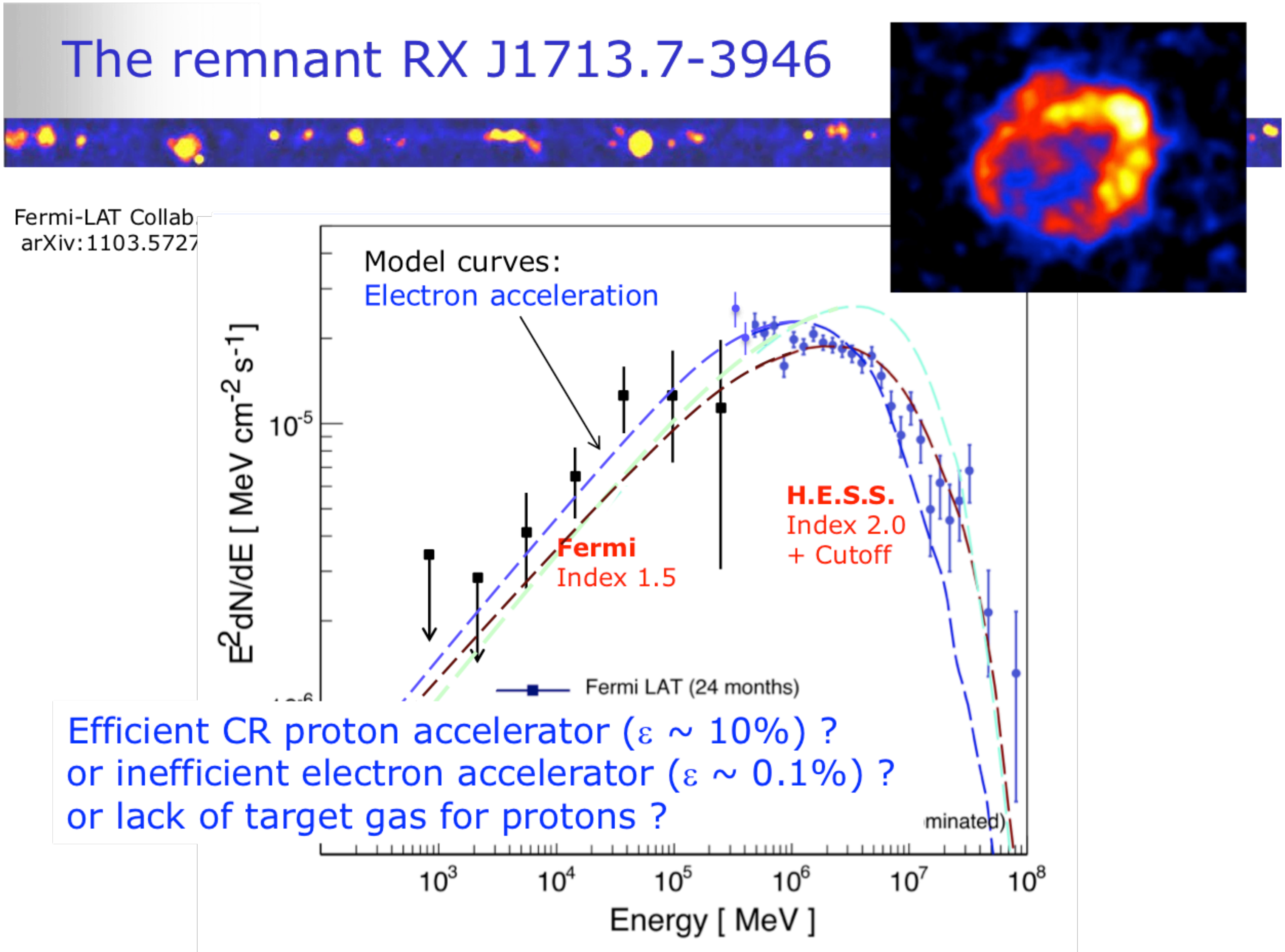
TeV sources: Shell-type Super Nova Remnant

HESS Nature 2004: And can we distinguish **electron** (from proton) sources of the TeV emission?



TeV sources: Shell-type Super Nova Remnant

HESS Nature 2004: And can we distinguish **electron** (from proton) sources of the TeV emission? ... NO!

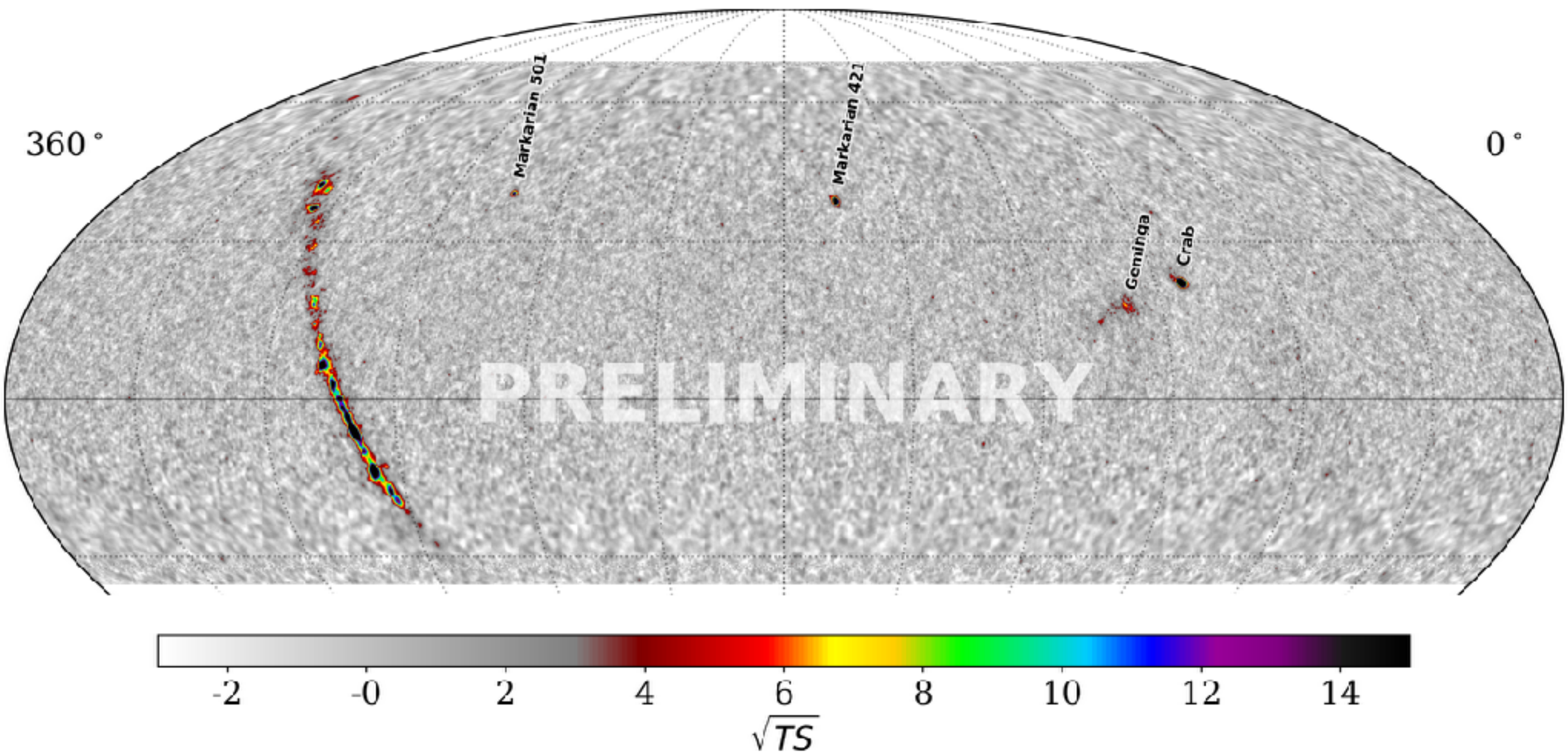


Efficient CR proton accelerator ($\varepsilon \sim 10\%$) ?
or inefficient electron accelerator ($\varepsilon \sim 0.1\%$) ?
or lack of target gas for protons ?

How does HAWC do TeV science?

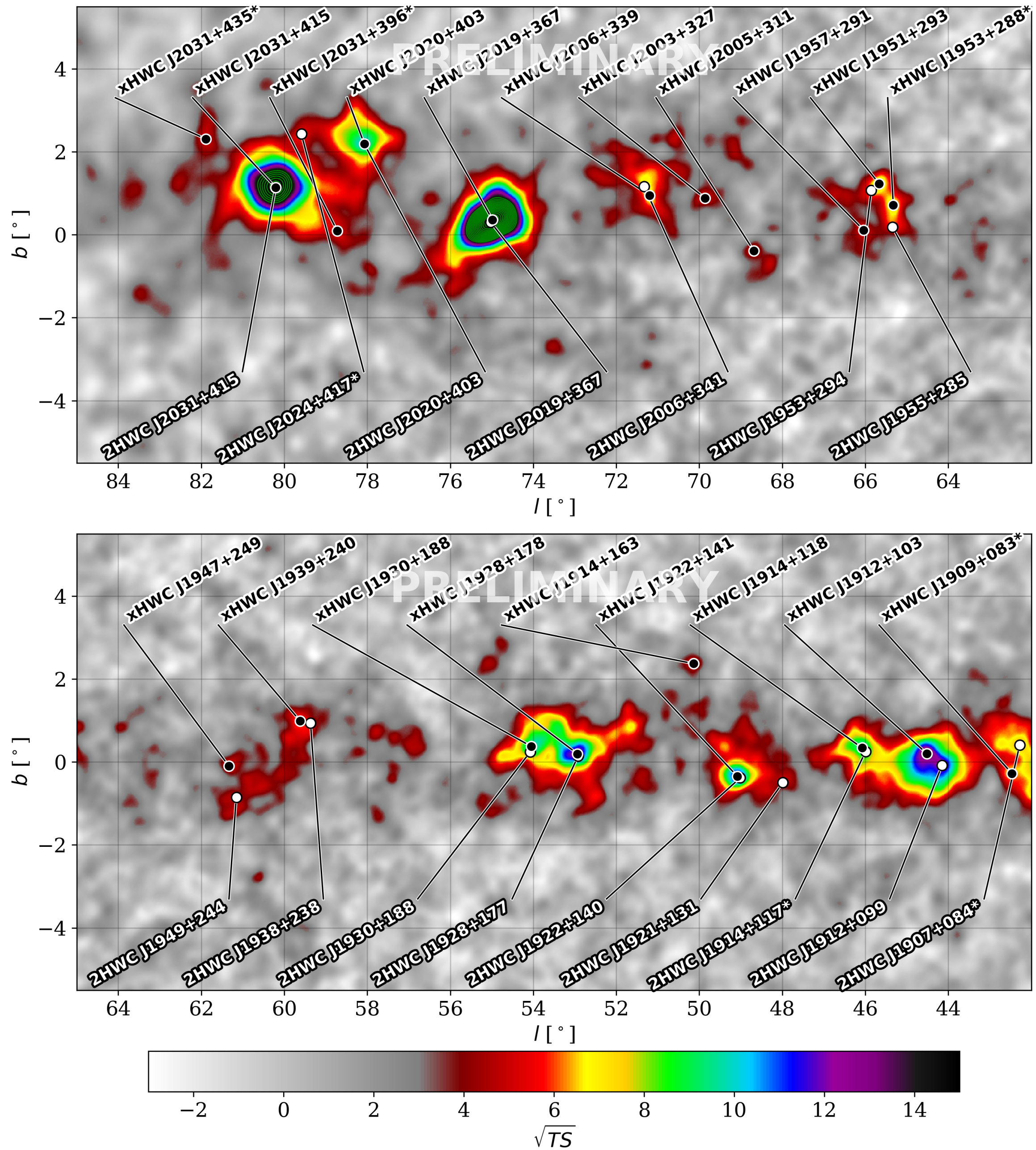
HAWC surveys ~2/3 of the sky detecting gamma-ray photons above a few hundred GeV. The photons are added “one by one” to make a *time exposure* image of the sky (and identifying ~50 TeV sources):

- 1128 days
- Point Source Hypothesis, with spectral index 2.7



How does HAWC do TeV science?

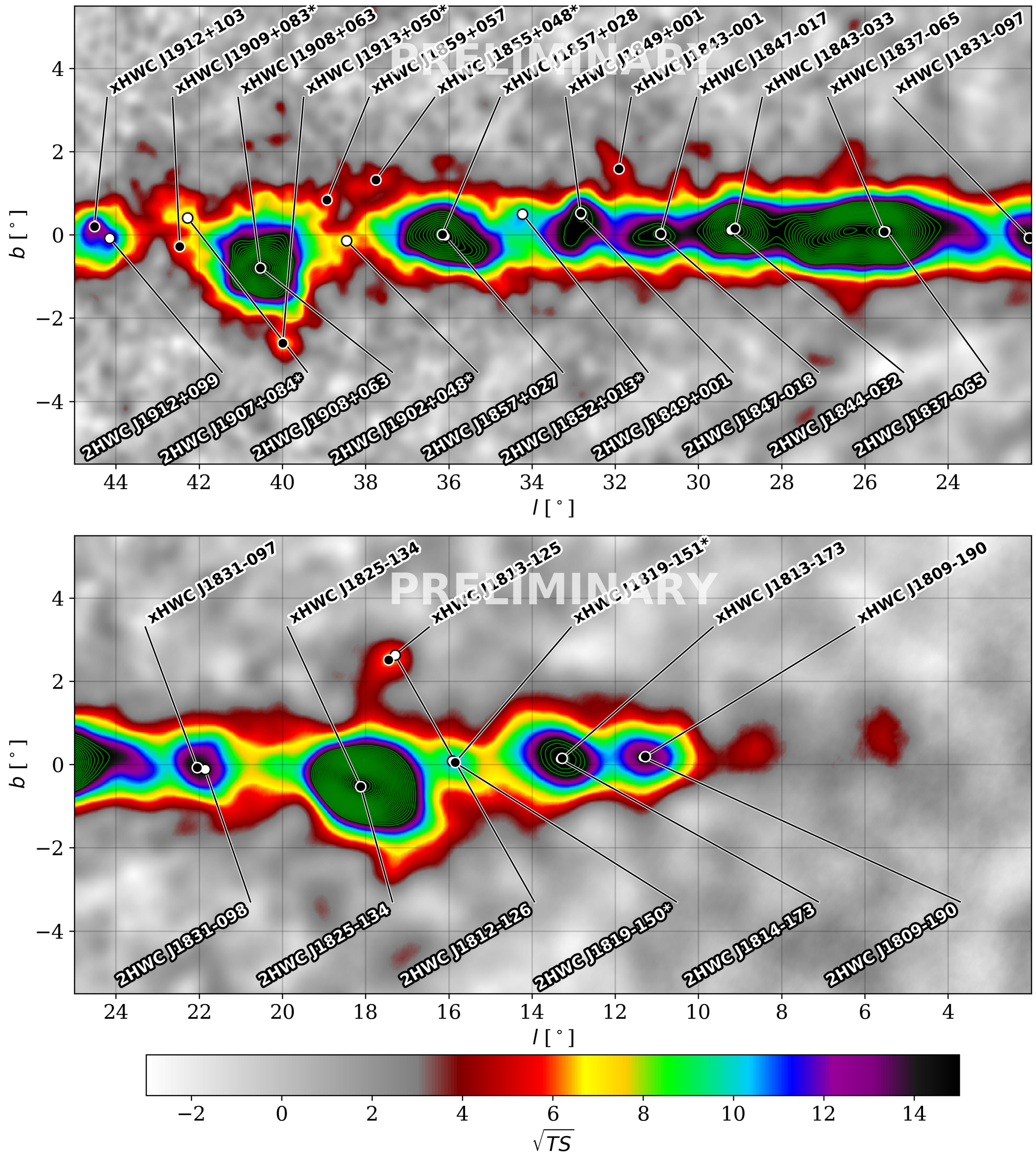
Zoomed-in images show the *inner* Galactic plane region plotted in Galactic Coordinates. Sources may be extended and often overlap. (Remember this is a 2D projection of sources at different distances).



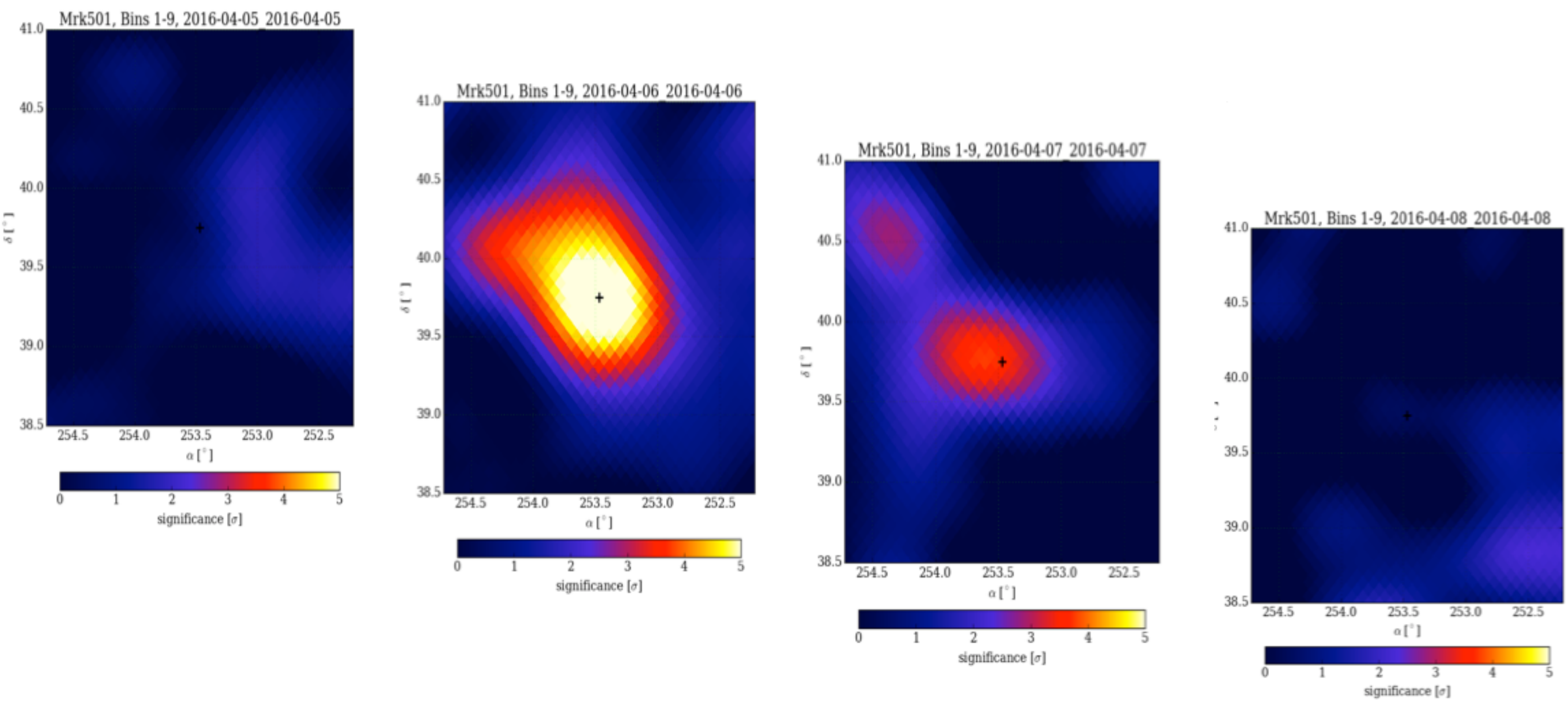
How does HAWC do TeV science?

Zoomed-in images show the *inner* Galactic plane region … a little further along from the previous figure.

50 sources in the most recent (1128 day) HAWC source catalog are denoted xHWC versus 40 sources in original (507 day) 2HWC catalog ...

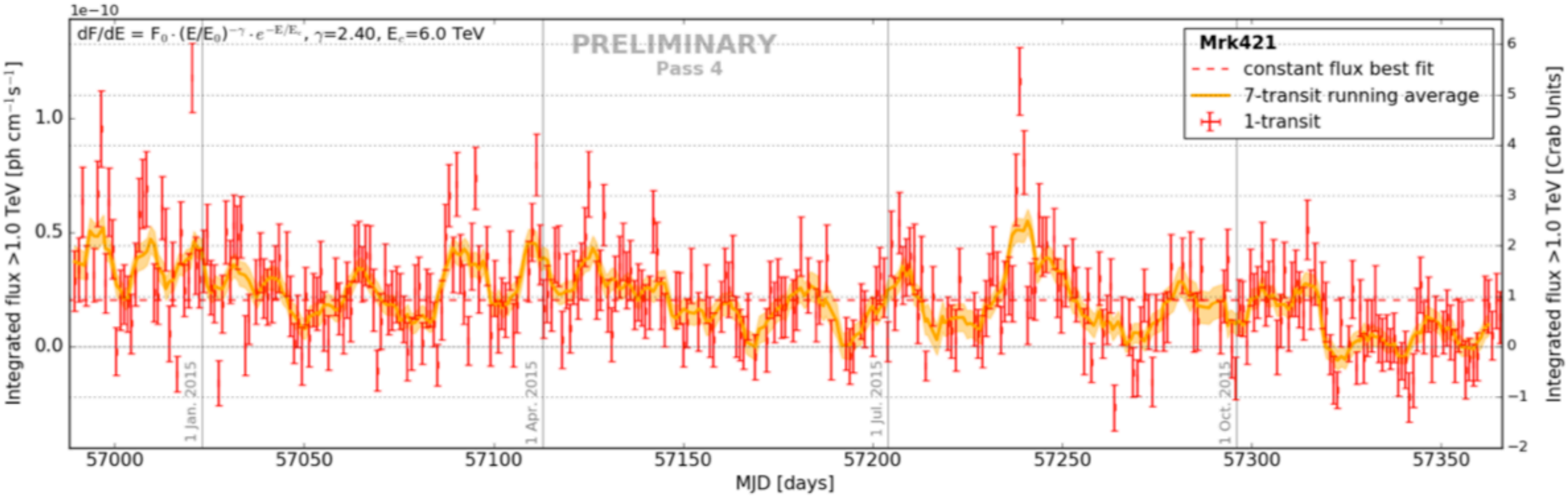


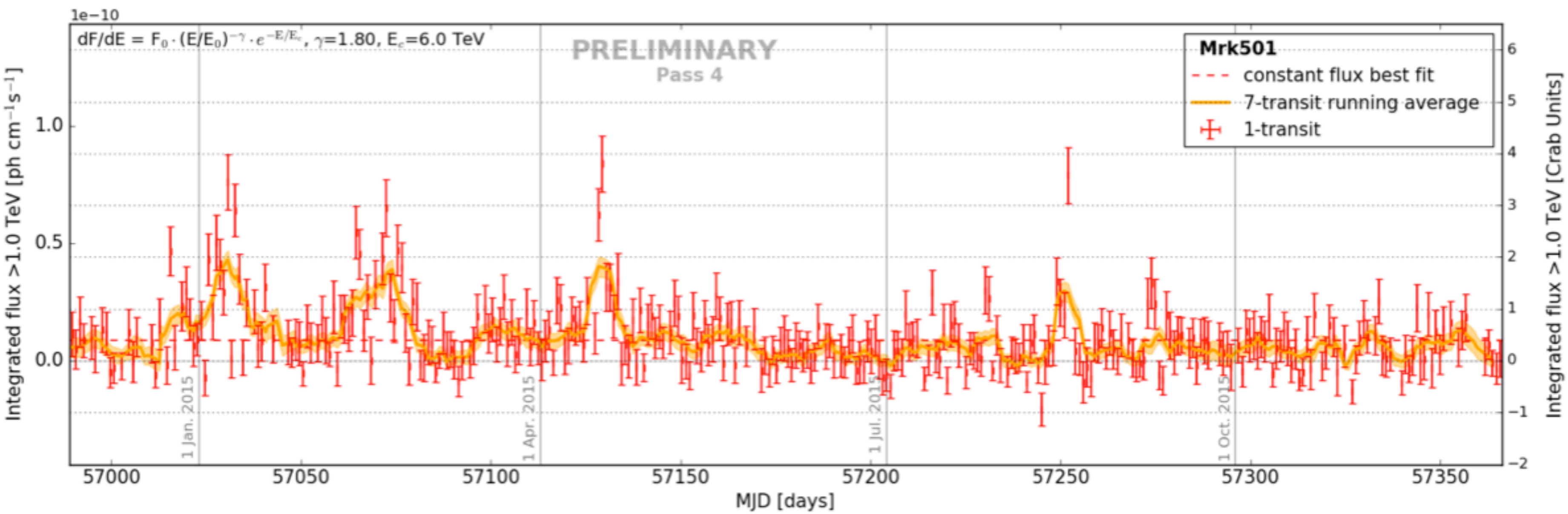
How does HAWC do TeV science?



Some sources show evidence for ***flaring* states** with large increases in brightness. These show the resulting *HAWC sky images* centered on Mrk 501 on April 5, 6, 7 and 8 of 2016. Note: each image is from a source *transit* of approximately 5 hour duration.

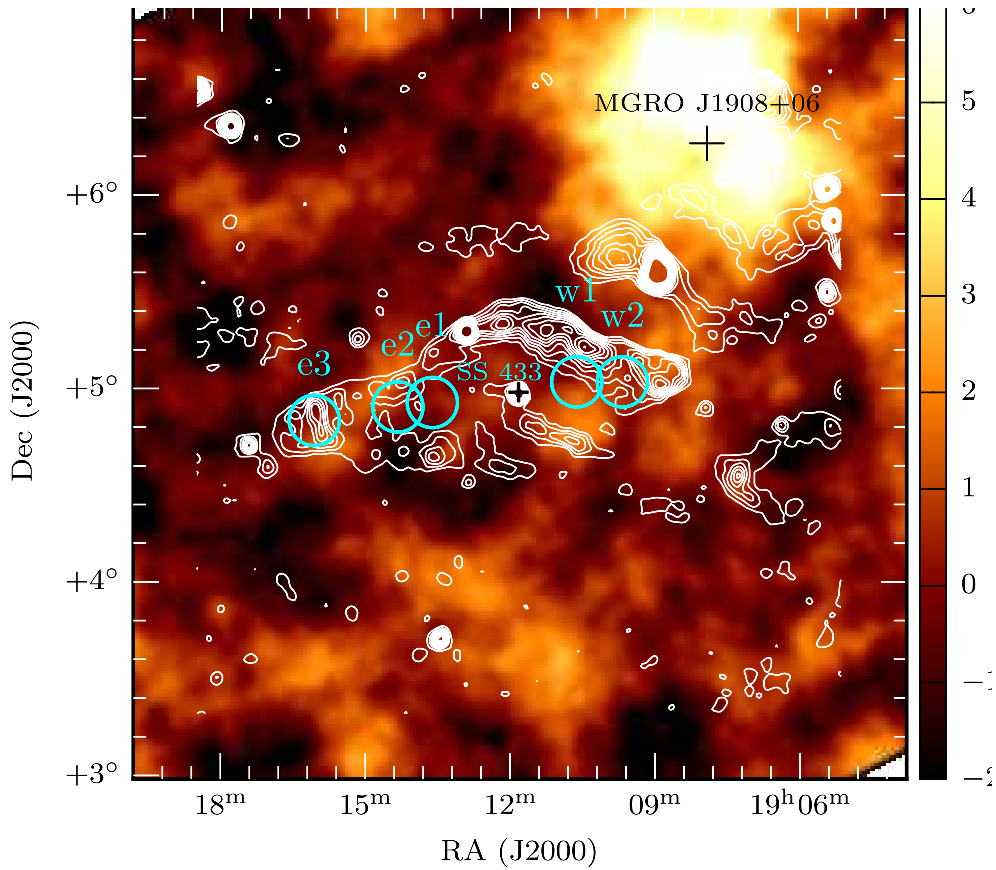
HAWC: monitors Mrk 421 and 501 every day!





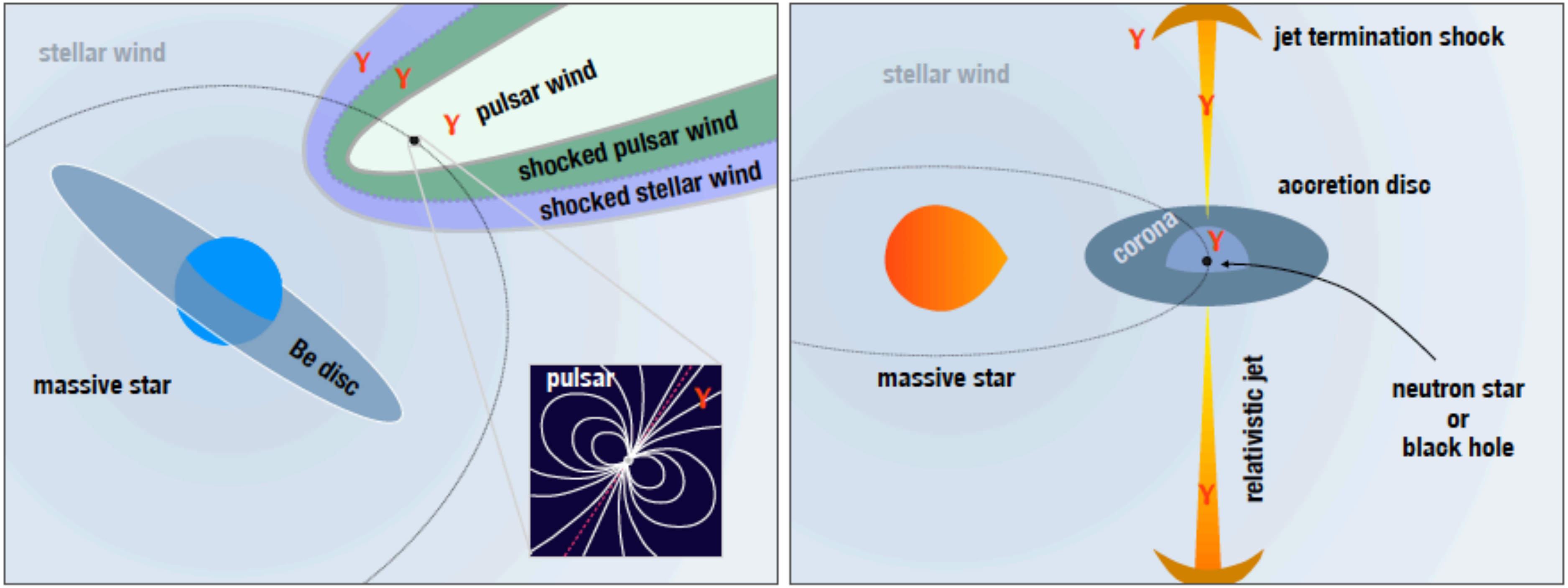
TeV sources: X-ray/gamma-ray binaries

HAWC also does **directed searches** based on sources seen at X-ray or lower gamma-ray energies. One example is the **SS 433/W50** X-ray binary system containing a black hole that is most likely 10~20 solar masses … **Previous measurements (2017 by IACTs) only set upper limits for TeV emissions.**



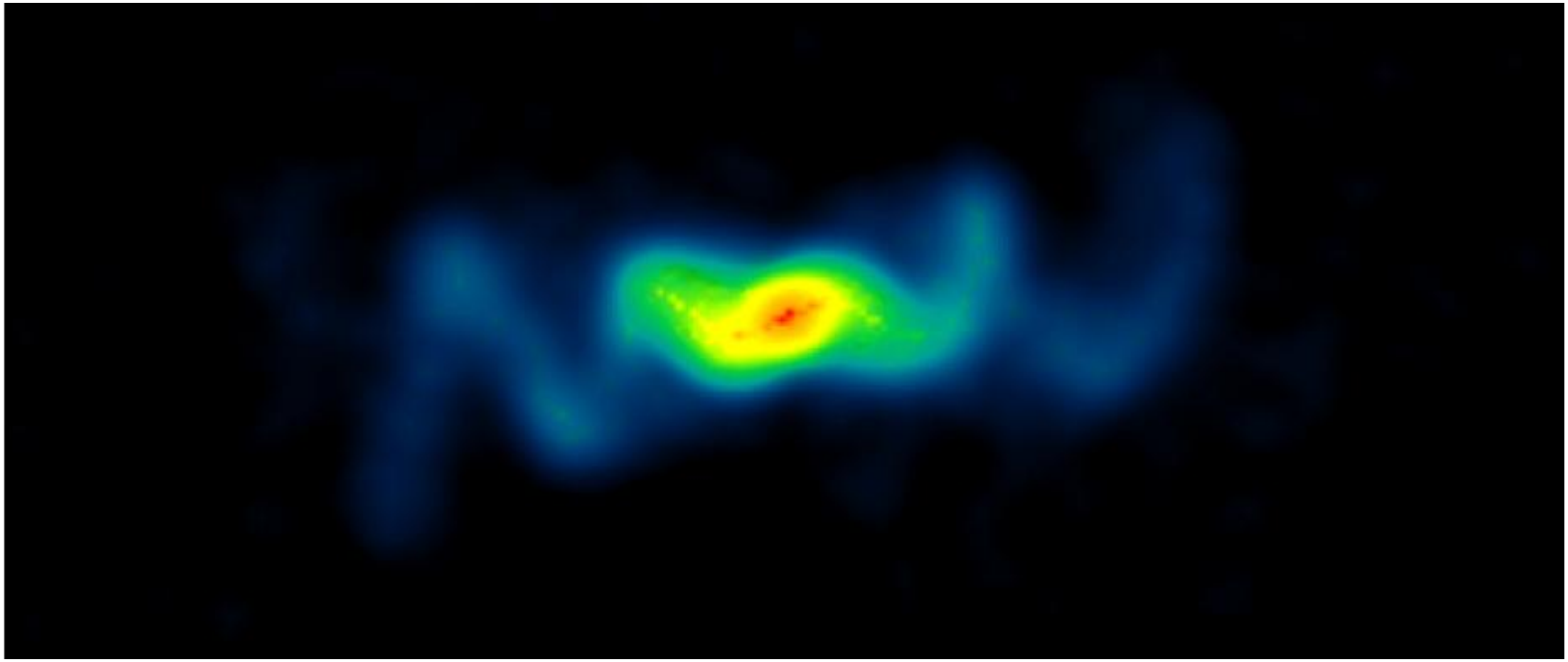
TeV sources: X-ray/gamma-ray binaries

The two main scenarios for gamma-ray emission from binaries.
Left: in the *pulsar wind* scenario, the variable emission arises from the interaction of the **pulsar wind** with the strong stellar wind of the companion star. **Right:** in the **micro-quasar** scenario, the emission is powered by the accretion of the companion star onto the compact object (black hole or neutron star) giving rise to relativistic jets. **SS 433 is likely of the latter type**.



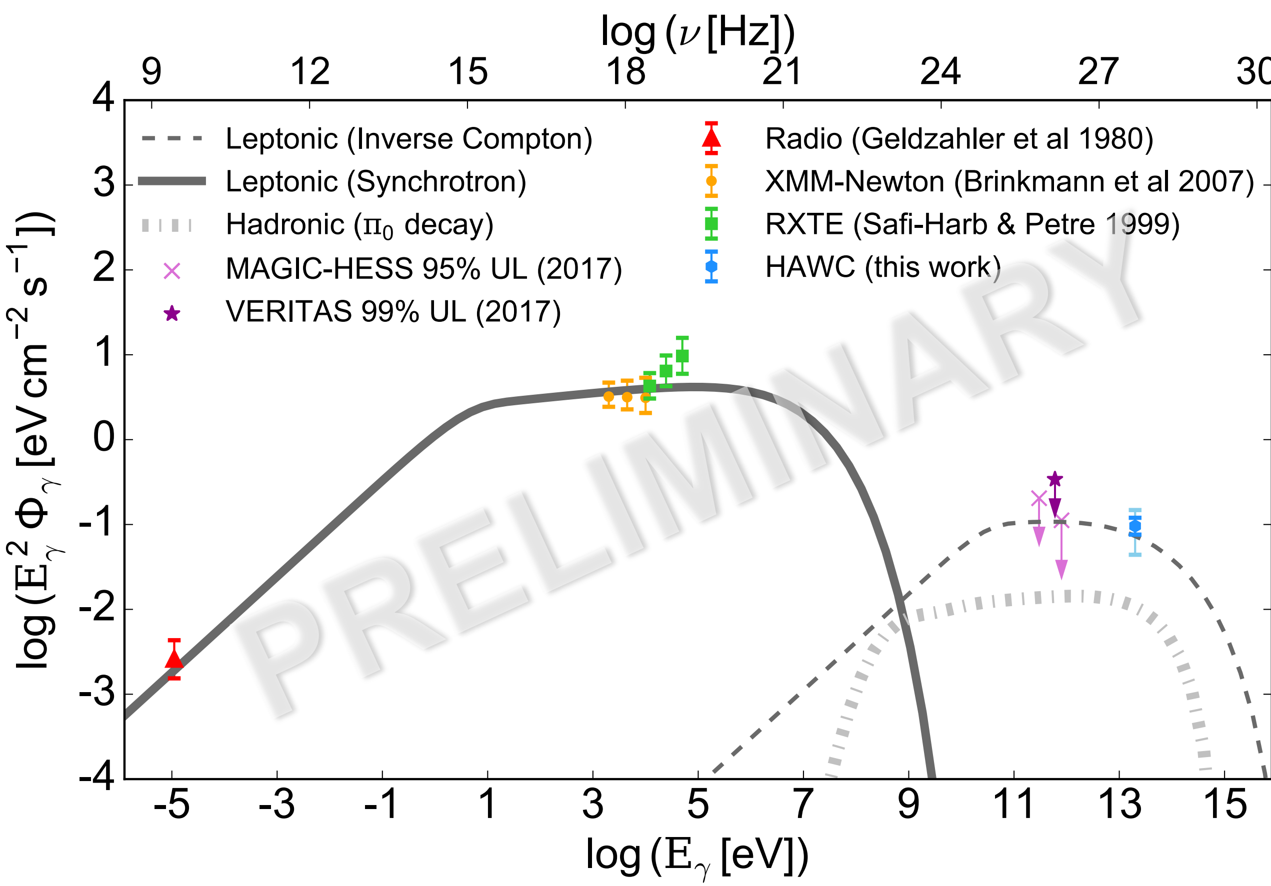
TeV sources: X-ray/gamma-ray binaries

Fortunately **SS 433** has been well studied at other energies.
The jets and disk precess around an axis inclined about 79° to a line between Earth and **SS 433**. The precessional period is around 162.5 days. The precession means that the jets corkscrew through space in an expanding helical spray.
The jets are *mapped* by the surrounding **W50** supernova remnant (NRAO image below):



TeV sources: X-ray/gamma-ray binaries

HAWC finds that the TeV emission is consistent with the likely jet termination lobes, about 40 pc from the central source. The lobes of **W50** are expected to accelerate charged particles. Then what dominates the photon emission: electrons or protons? Find some friends to plot the SED:



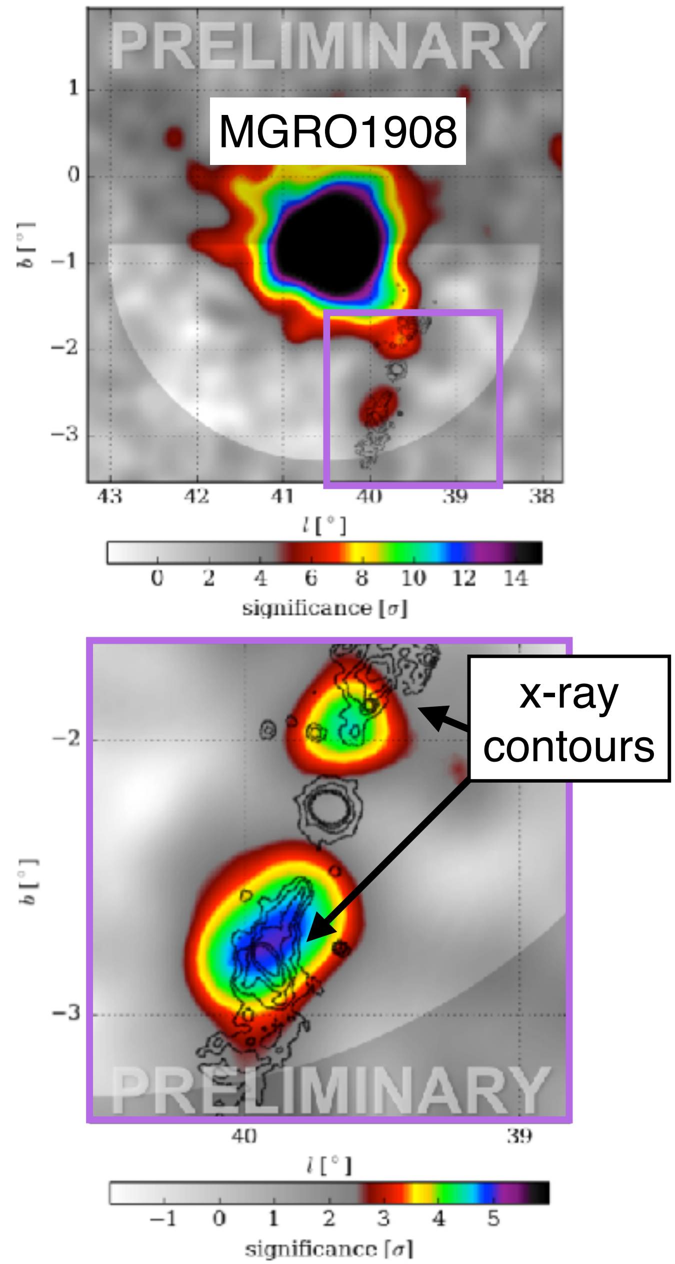
K. Fang

TeV sources: X-ray/gamma-ray binaries

In summary: HAWC finds that the TeV emission regions are well separated from the micro-quasar at the likely jet termination shock/lobes (and overlap the X-ray emission) (**Lower right**)

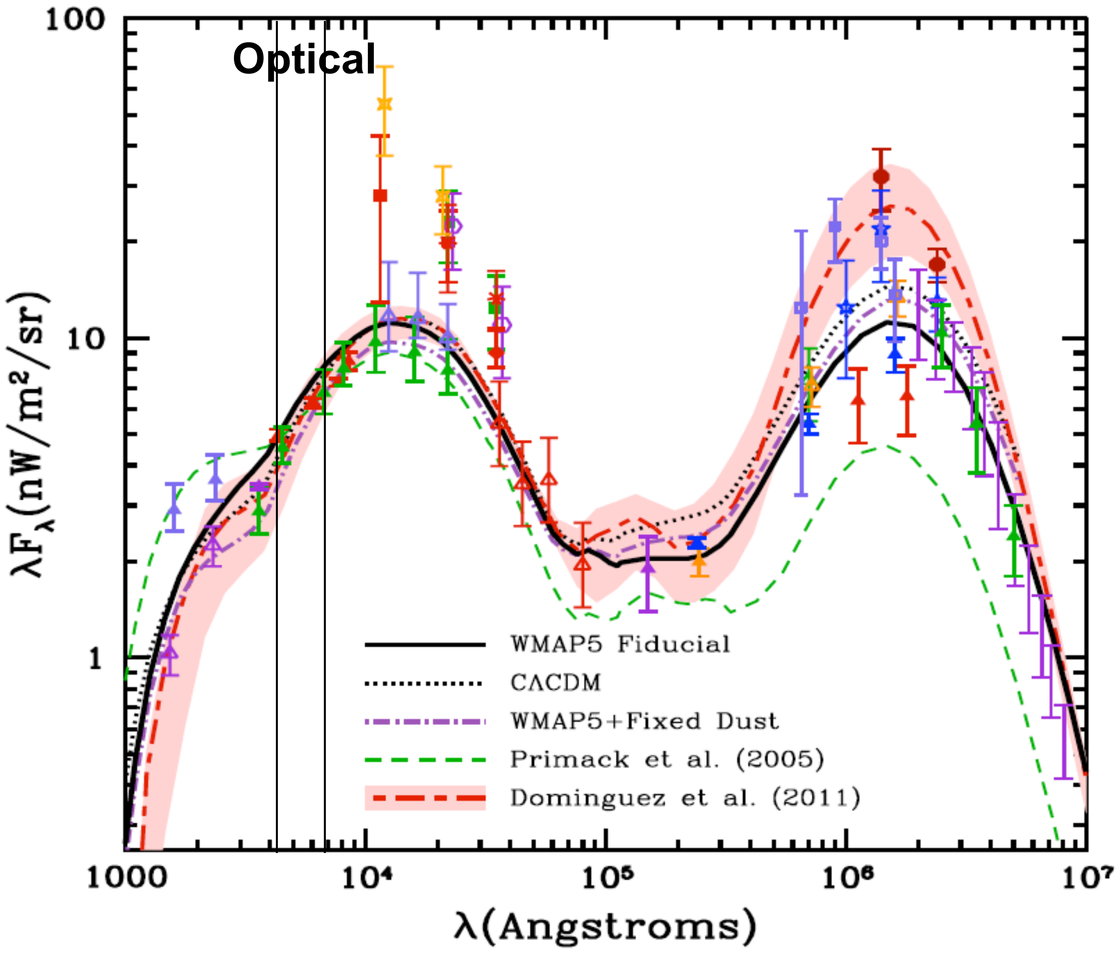
Key points:

- First time to resolve jet lobes at such high energies
- TeV emission is **not** from the center of the binary
- Leptonic scenario favored over pure hadronic scenario



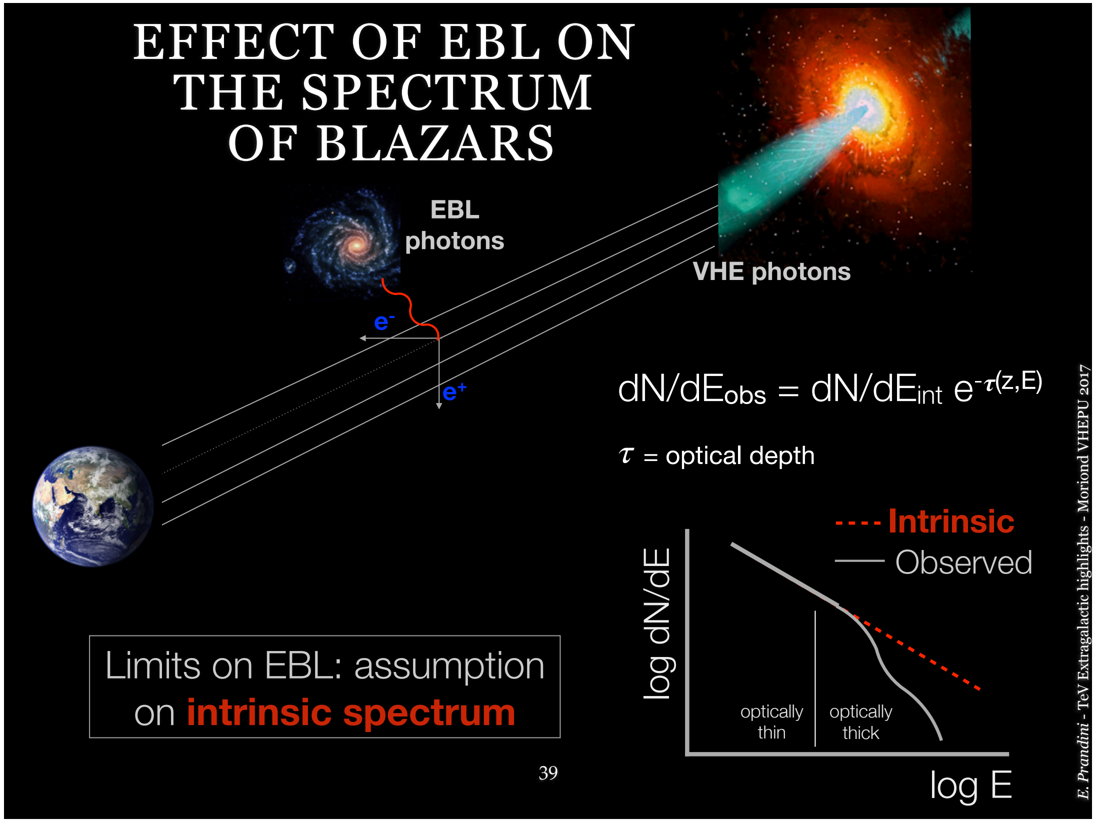
What does the Universe look like at TeV energies?

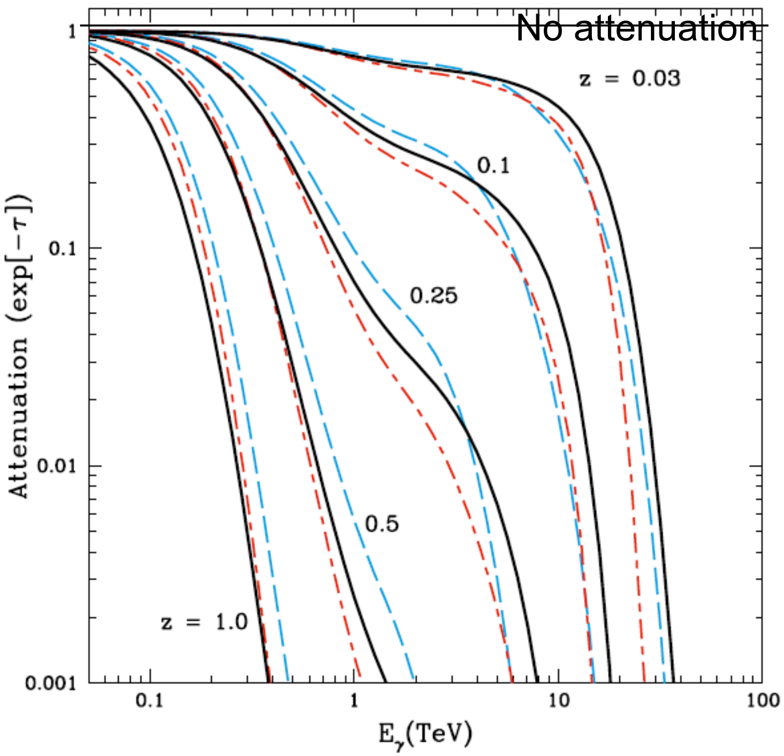
TeV gamma rays also allow a variety of *fundamental* science measurements. Most of these are non-discovery including: Dark Matter, Axion Like Particles, … As I prefer measurements: what do TeV gamma rays say about **Extra-galactic Background Light (EBL)**?



What does the Universe look like at TeV energies?

EBL is the accumulated radiation in the universe due to star formation processes, plus a contribution from active galactic nuclei (AGNs). The direct measurement of the **EBL** is a difficult task mainly due to the contribution of zodiacal light, but ...

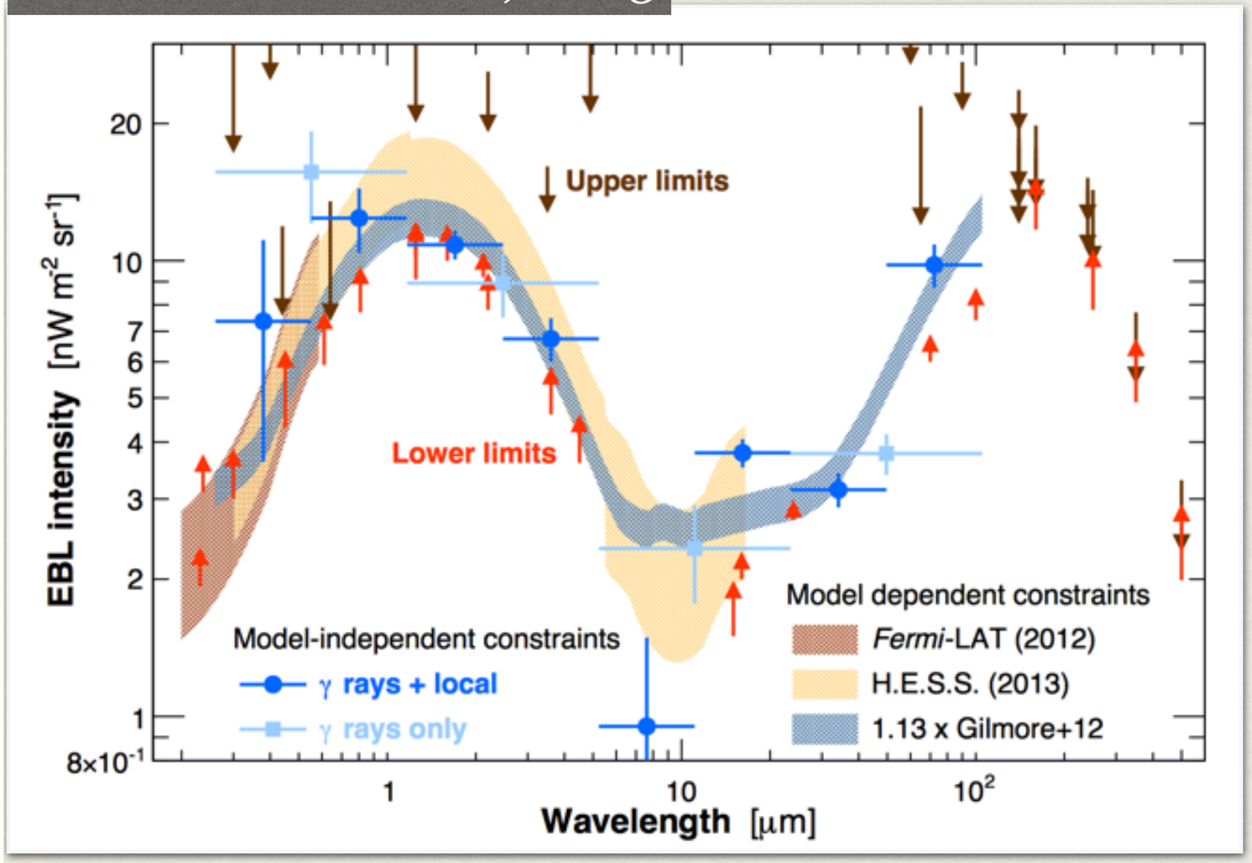




What does the Universe look like at TeV energies?

Observed SED attenuation in TeV gamma ray data are in good agreement with first principles **EBL** predictions.

Biteau & Williams, 2015



Set of 106 VHE spectra from 36 objects

- *The reconstructed EBL intensity is preferred at the 11 sigma level to the absence of gamma-ray absorption*
- *Eight-point EBL spectrum covering the wavelength range from mid-UV to far IR.*
- *The spectrum of the EBL based on gamma-ray observations is in good agreement with estimates based on galaxy counts*

What does the Universe look like at TeV energies?

In broad terms: what has been learned?

- TeV sources are dominated by: **supernova remnants**, **X-ray binary systems** (with one evolved star and one black hole or neutron star), and **A**ctive **G**alactic **N**uclei with a jet directed toward the Earth (aka **blazars**) … these are **nature's high energy accelerators!**
- While **Pulsar Wind Nebulae** are well described by models accelerating electrons (e^+/e^-) to ~100 TeV energies, the court is still out on the question: are **SNs** responsible for the **Galactic CRs?**
- Not presented: HESS (Nature 2016) reports "Acceleration of PeV protons in the Galactic Center" and (Science 2018) "Multi-messenger observation of a flaring blazar coincident with high energy neutrino IceCube-170922A" support **AGNs** as responsible for (at least some of) the **Extra-Galactic CRs.**

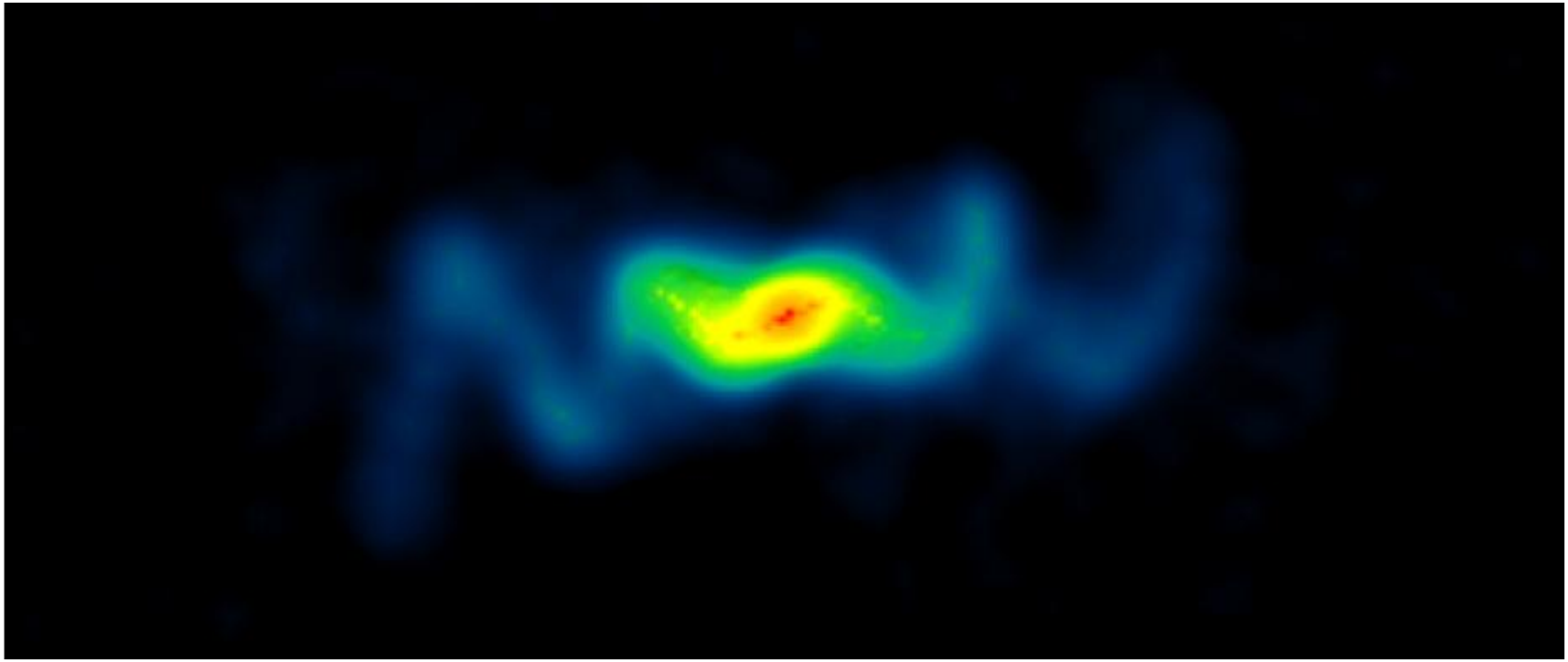
Backup slides

TeV sources: X-ray binaries

Fortunately SS 433 has been well studied at other energies.

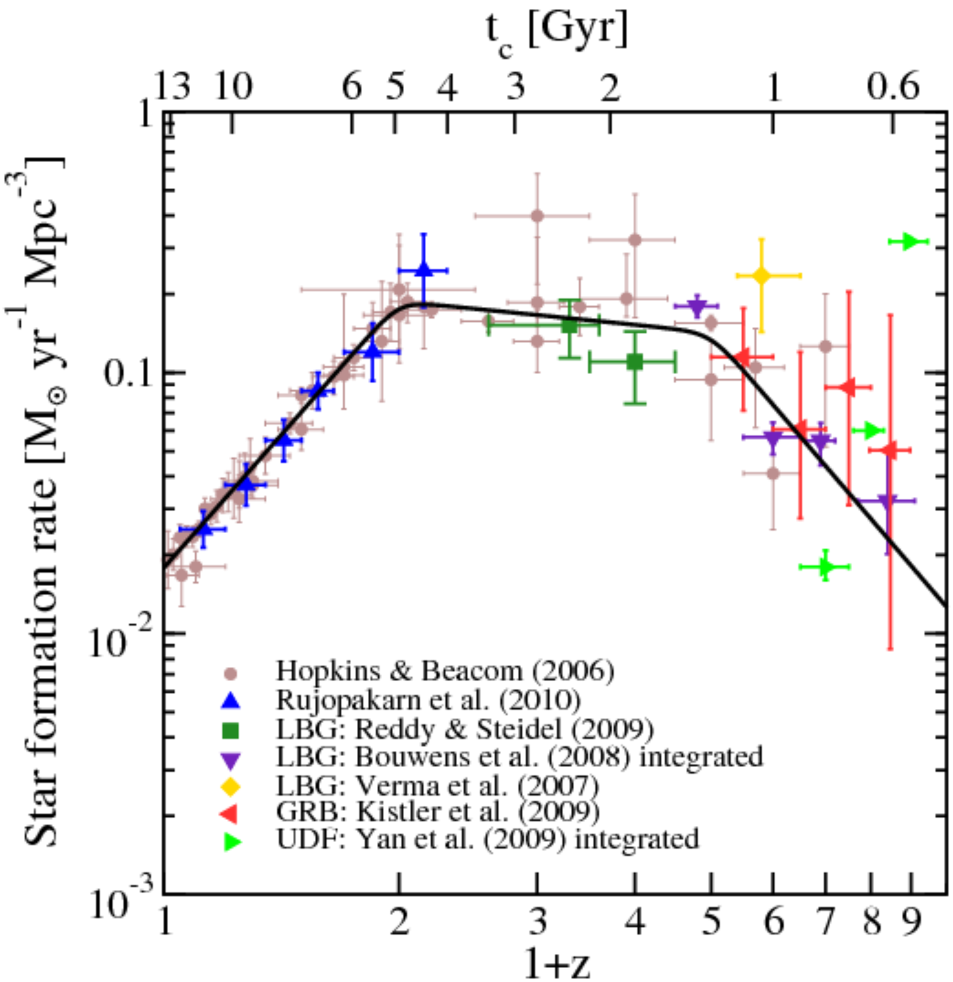
The jets from the primary are emitted perpendicular to its accretion disk. The jets and disk precess around an axis inclined about 79° to a line between Earth and SS 433. The angle between the jets and the axis is around 20°, and the precessional period is around 162.5 days. The precession means that the jets corkscrew through space in an expanding helical spray.

The jets are *mapped* by the surrounding W50 supernova remnant (NRAO image below):



What does the Universe look like at TeV energies?

What do TeV gamma rays say about **Extra-galactic Background Light (EBL)**? EBL depends on the history of star formation … Remember that we observed this starlight red shifted by the 1+z factor.



What does the Universe look like at TeV energies?

When asked: “why did you come to Albuquerque?” what comes to mind is the classic dialog from Casablanca …

Captain Renault: What in heaven's name brought you to Casablanca?
Rick: My health. I came to Casablanca for the waters.
Captain Renault: The waters? What waters? We're in the desert.
Rick: I was misinformed.

Seriously?   No … it was/is the sunshine and the unusually creative people in NM …