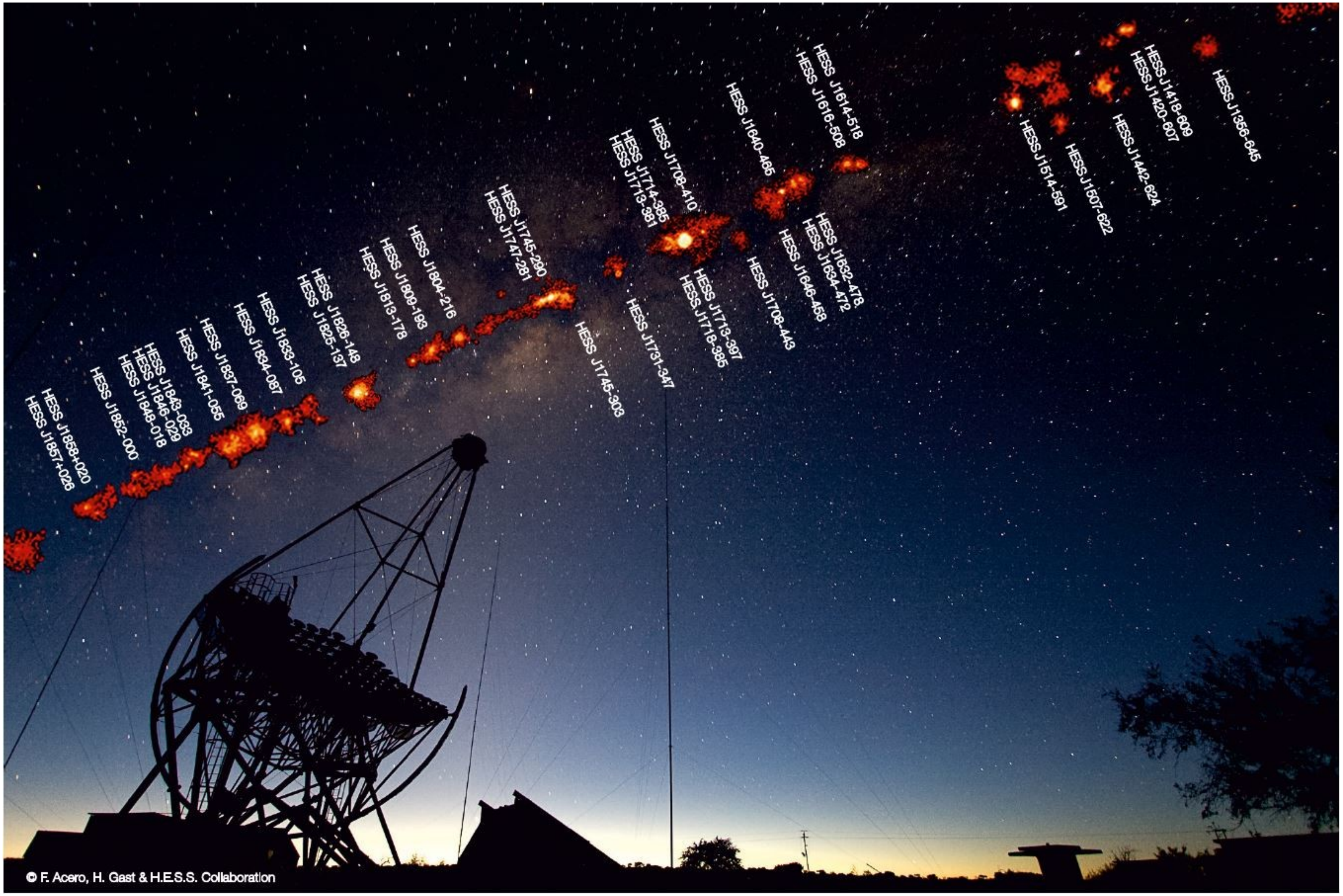


Gamma-ray Astronomy with H.E.S.S. and CTA

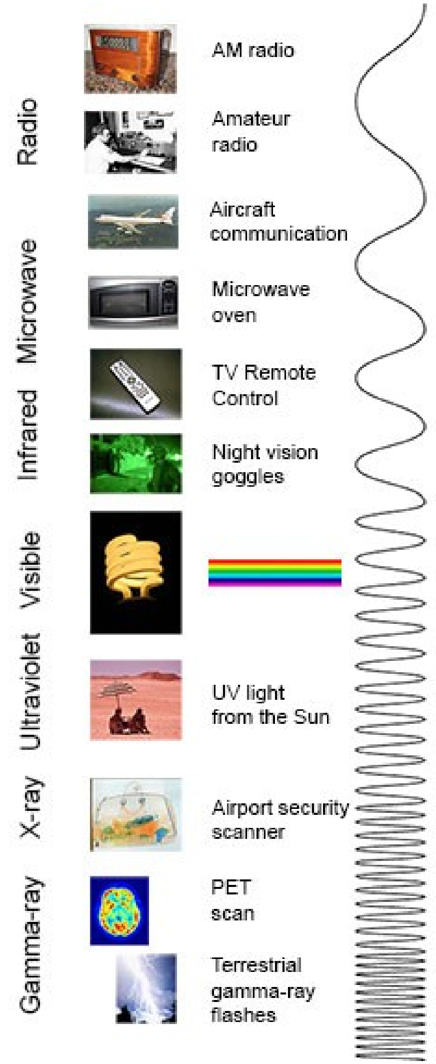
Ekrem Oğuzhan ANGÜNER
(C.P.P.M.)

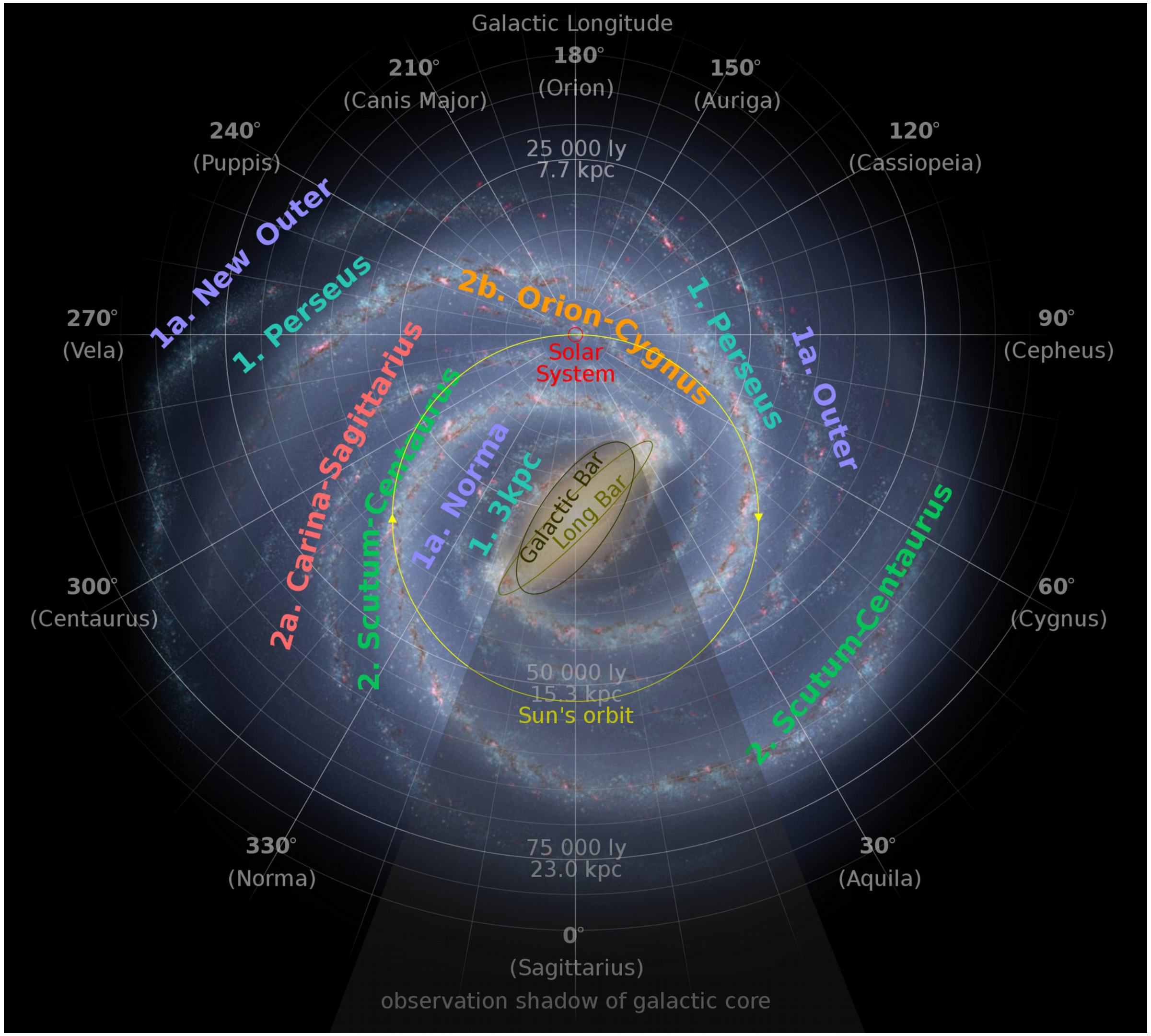
Outline

- Introduction
- VHE Gamma-ray Astronomy
- The Imaging Cherenkov Technique
- High Energy Stereoscopic System
- Cherenkov Telescope Array
- Outlook & Conclusions

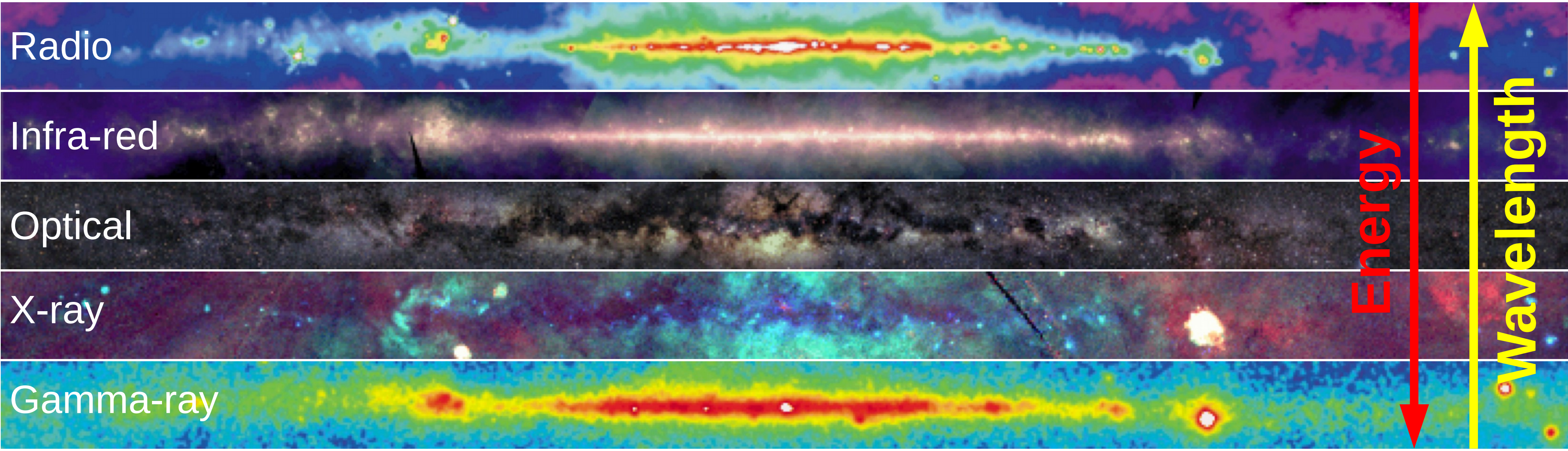
Introduction

- Astronomy is the oldest natural science. It had begun with the observations of the visible light from celestial objects by human eye.
- Currently, with the modern instrumentation, astronomers can conduct observations of the cosmos in a wide spectrum from radio to γ-ray frequencies.



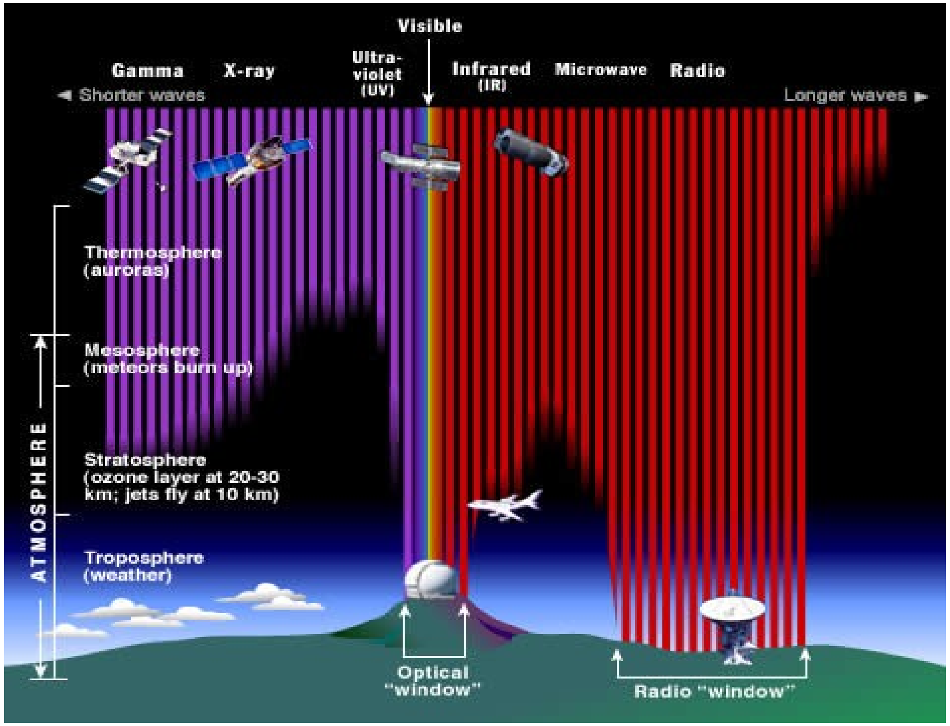


Introduction

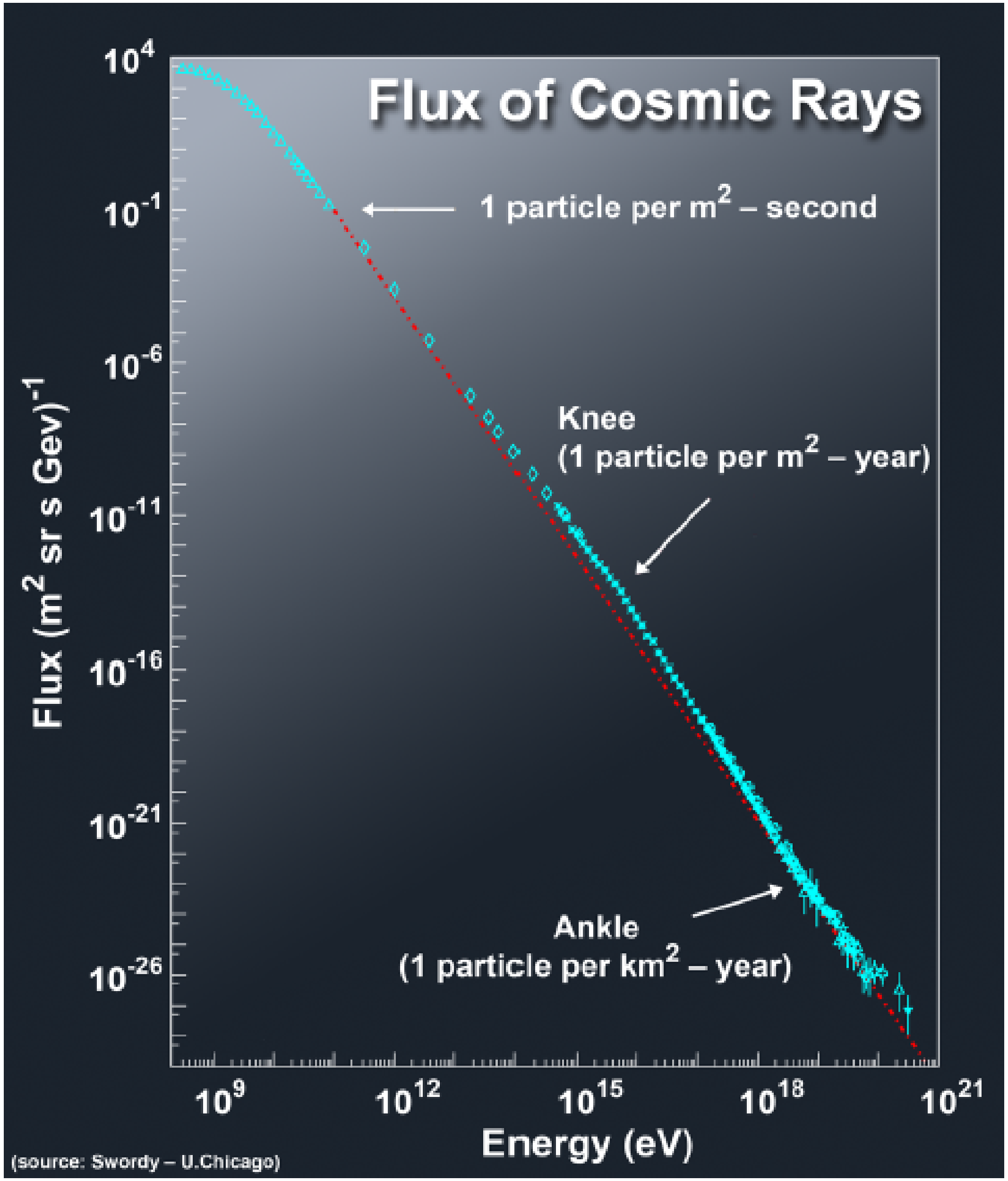


- Multi-wavelength view of the Milky Way Galaxy. The observed emission in different wavelengths give crucial information about the cosmos and its evolution.

- In the last two decades, very high energy (VHE) γ-ray astronomy has contributed substantially to our understanding of highly energetic processes of the non-thermal universe.



Cosmic-rays



The cosmic-ray spectrum measured from the Earth

$$J_{\odot}^{(\mathrm{p})} = 1.8 \times E_{\mathrm{GeV}}^{-2.7} \quad \mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{cm}^{-2}$$

- Cosmic-rays (CRs) are the particles coming from outer space and interacting with the Earth's atmosphere isotropically.

  (99% nuclei, 1% electrons).

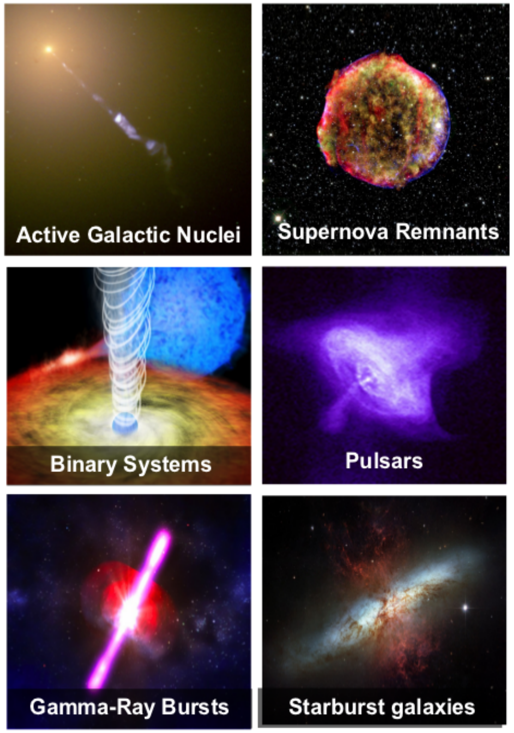
- The CR spectrum shows two distinct features "the knee" and "the ankle".

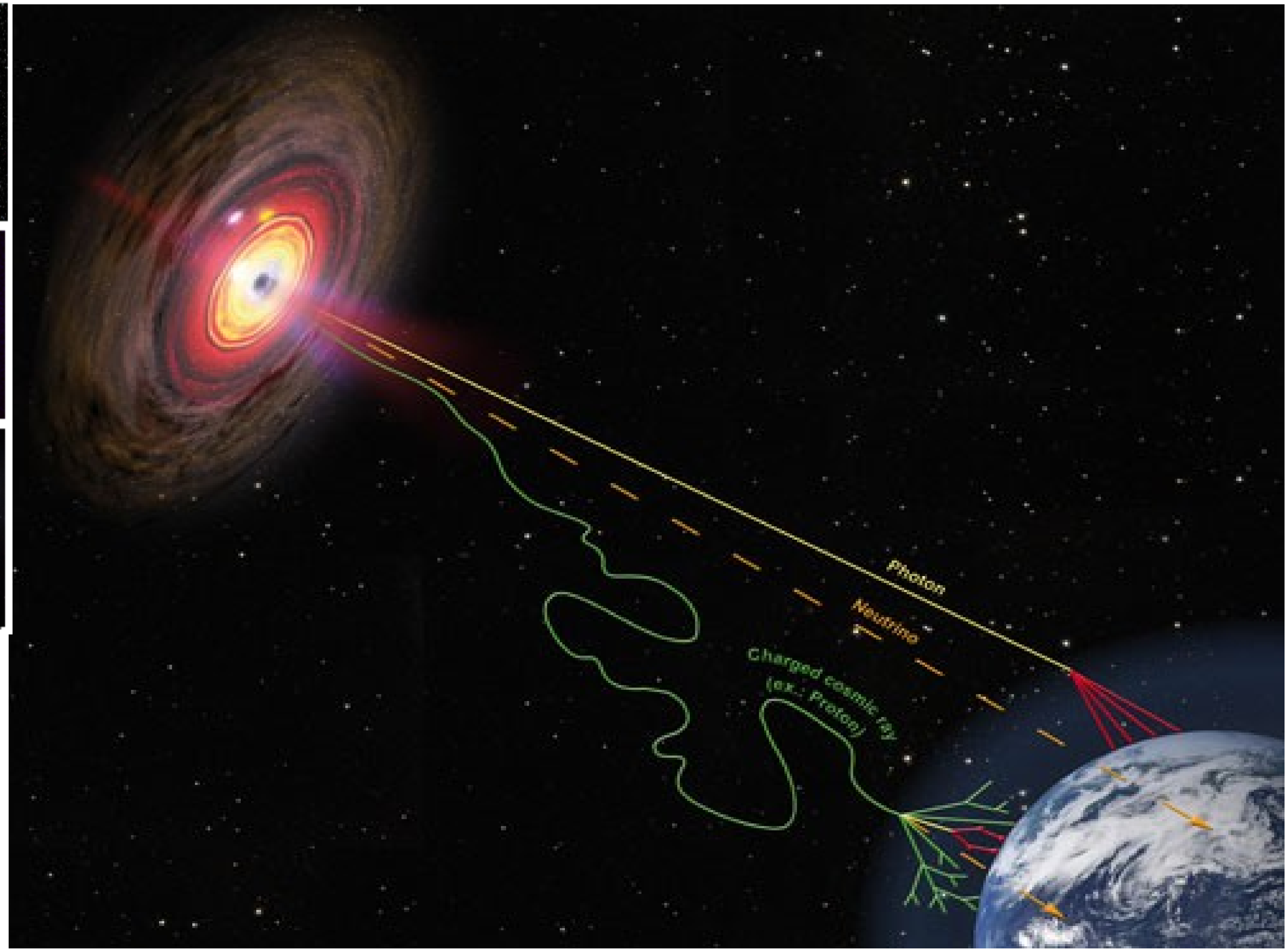
  - CRs up to the knee → Galactic (accelerated in galactic objects like SNRs, Fermi acceleration).

  - CRs beyond the ankle → Extra-Galatic.

- The origin of cosmic-rays :
  "It's a 100-year-old mystery". Neutral messengers can give hints about it.

Neutral Messengers





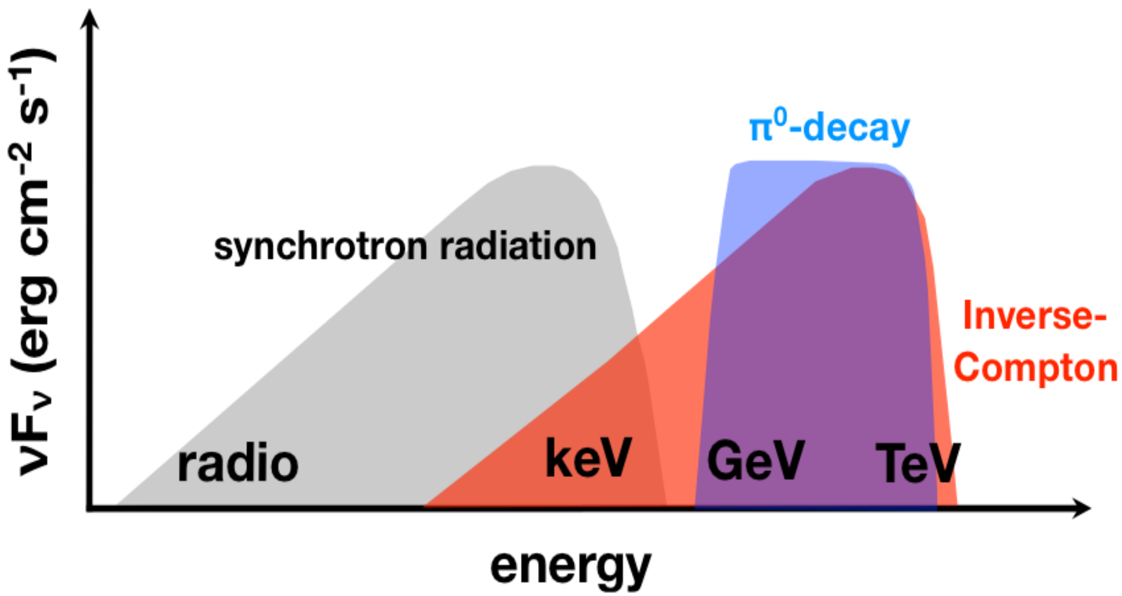
- Charged CRs are deflected by magnetic fields on their way → they lose their direction information.
- Photons and neutrinos (neutral messengers) can be used for tracing back to the origin of their astrophysical sources.

VHE Gamma-ray Astronomy

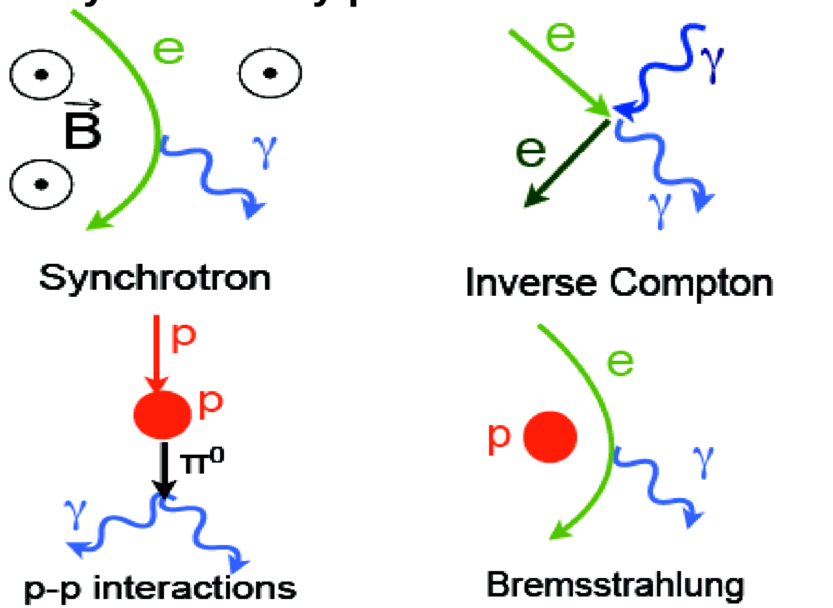
- The field of gamma-ray astronomy above several MeV can be considered as the study of non-thermal universe (1 MeV gamma-ray needs 10^9 K).

Nomenclature of cosmic-rays and γ-ray astronomy

Energy Range (MeV)	Classification	Detection Methods
$E < 10.0$	Low Energy (LE)	Balloons, Satellites
$10.0 < E < 30.0$	Medium Energy (ME)	Space Based Satellites
$30.0 < E < 30\times10^3$	High Energy (HE)	Space Based Satellites
$30\times10^3 < E < 30\times10^6$	Very High Energy (VHE)	Ground Based
$30\times10^6 < E < 30\times10^9$	Ultra High Energy (UHE)	Ground Based
$E > 30\times10^9$	Extremely High Energy (EHE)	Ground Based



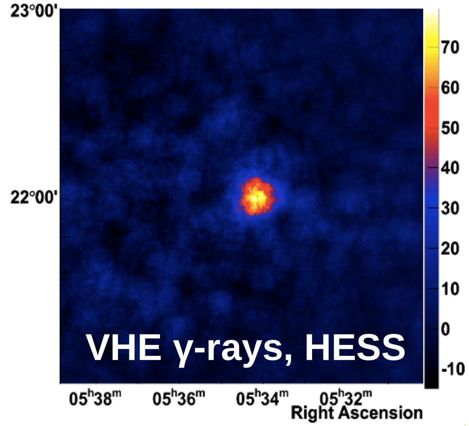
Gamma-ray astronomy production mechanisms

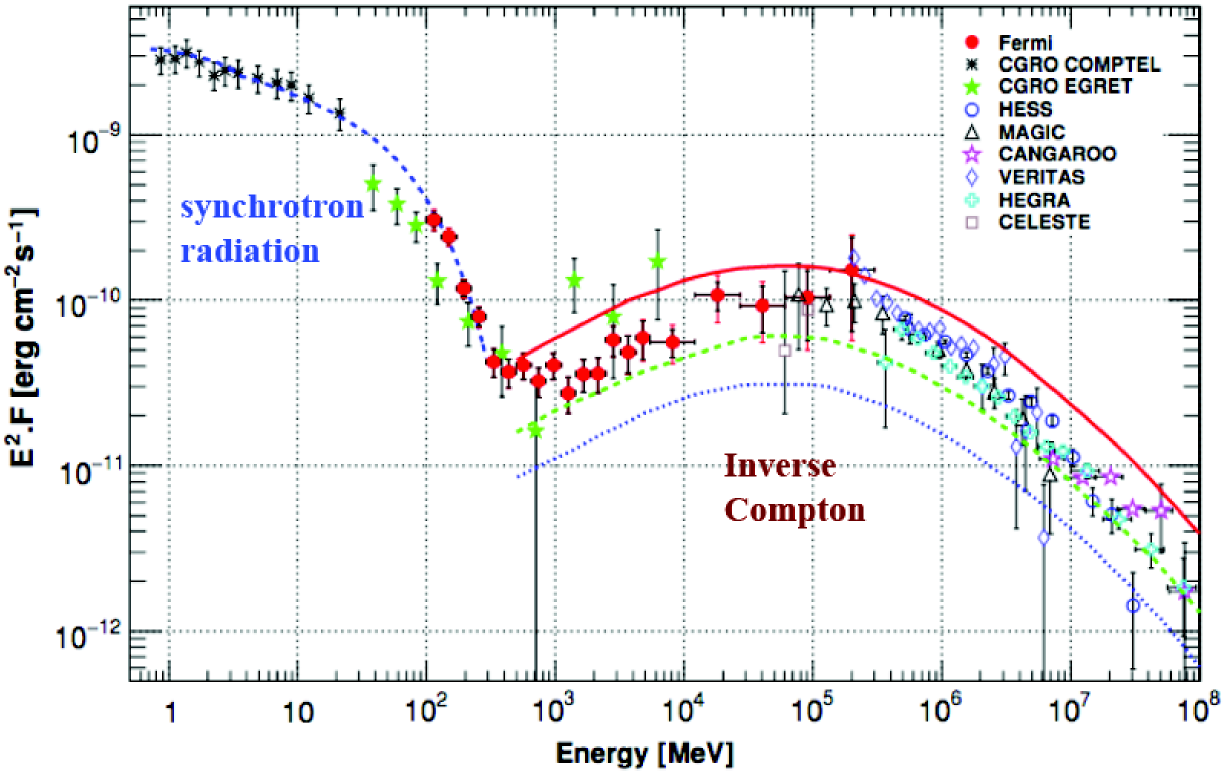


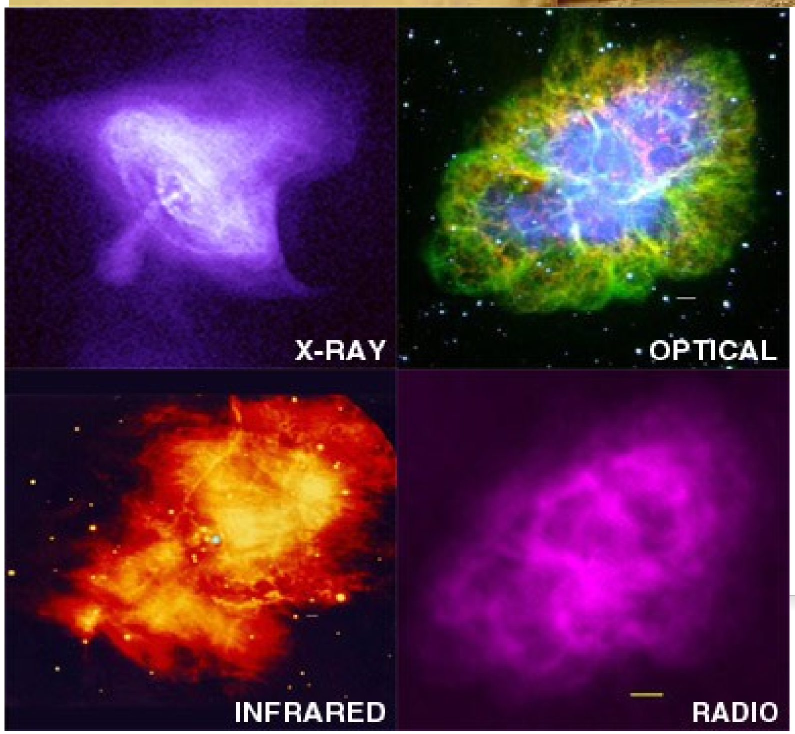
The Crab Nebula

- The Crab Nebula is the remnant of a supernova exploded in 1054. It was visible during the day for six weeks. F_{crab}(> 1 TeV) : ~13 ph . km^{-2} . min^{-1}

- In the center, there's a rotating neutron star (Crab Pulsar, ~30 Tour/s, 2kpc). Around the pulsar, there's a surrounding Pulsar Wind Nebula (PWN).

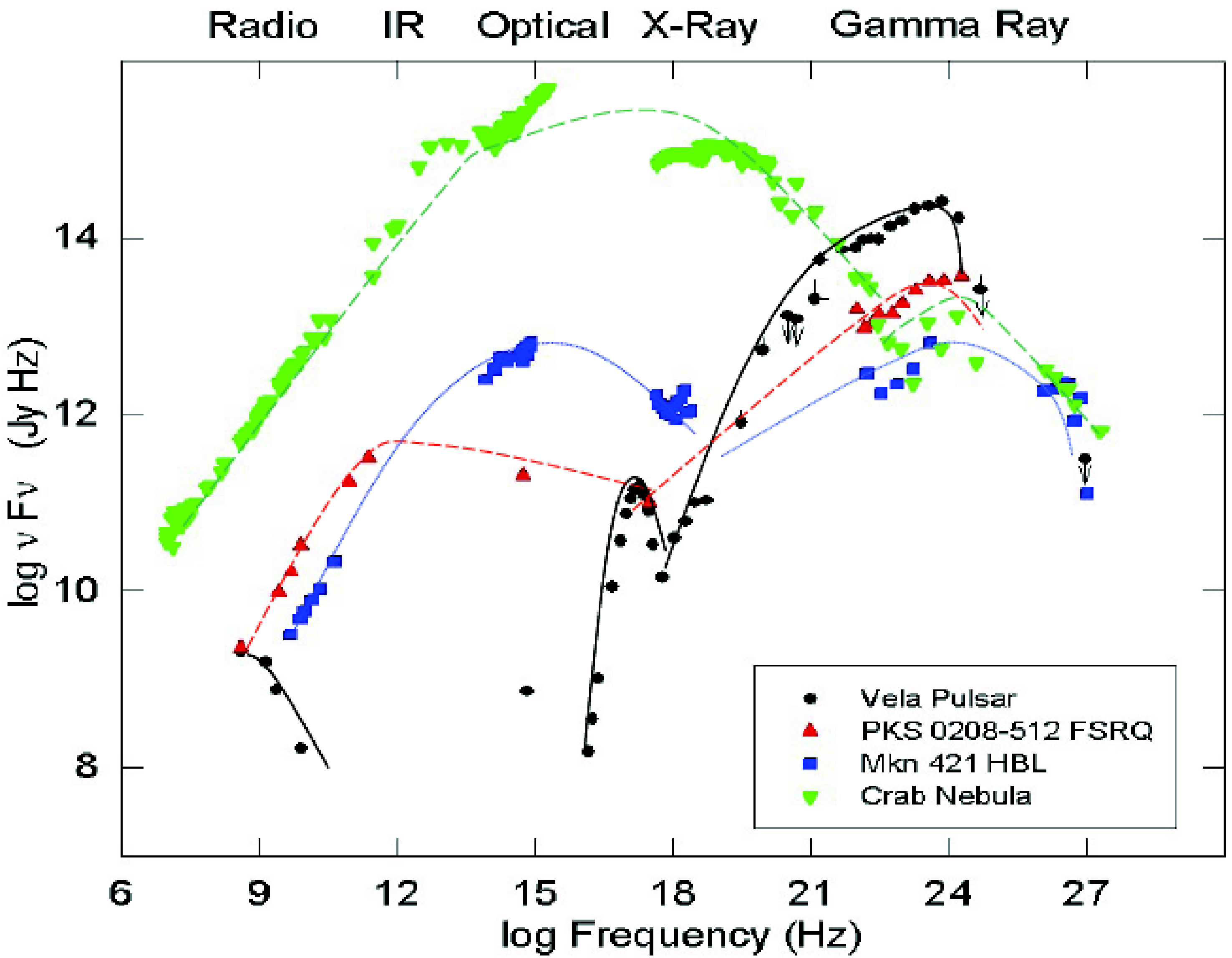




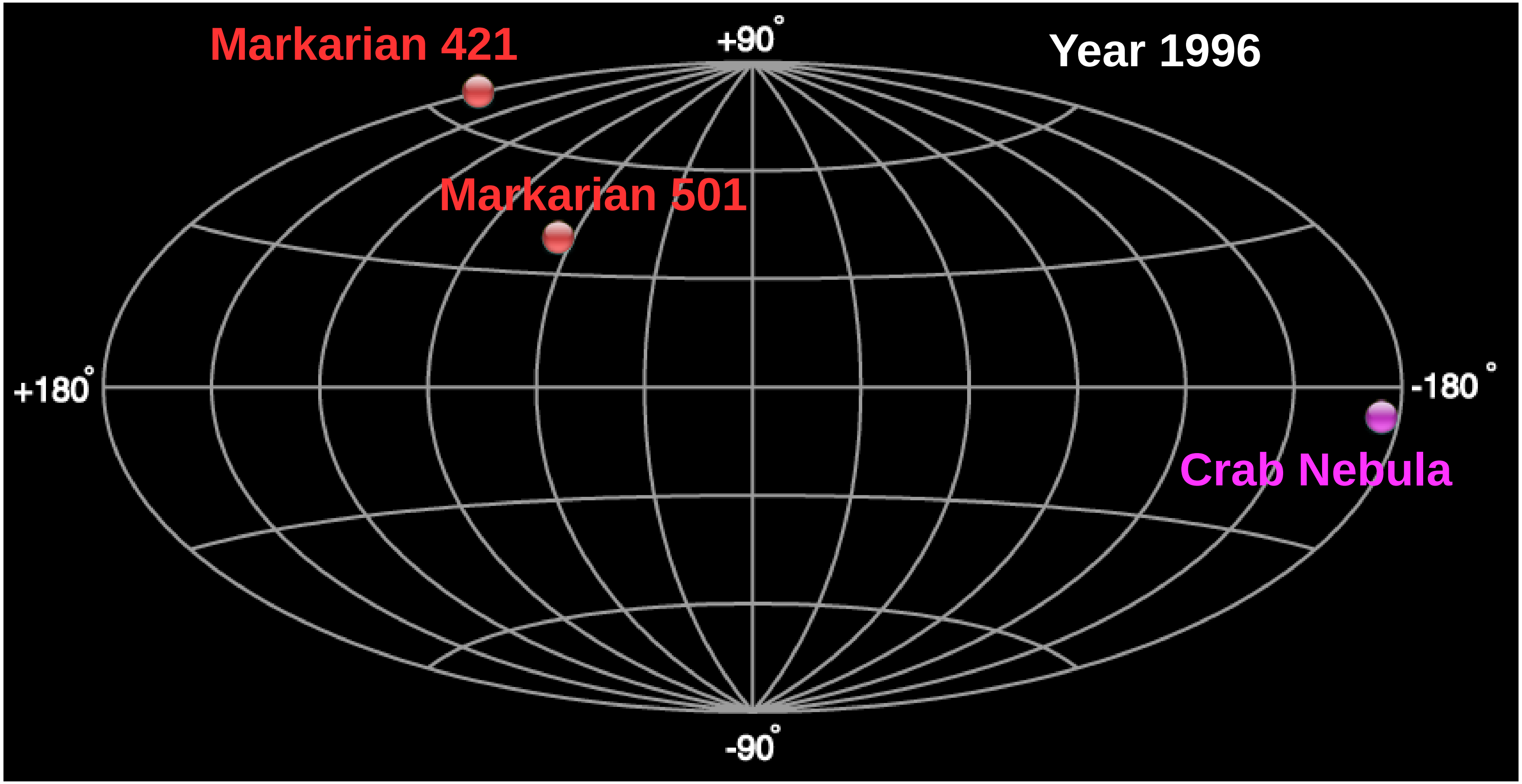


MWL view of VHE sources

- Some VHE gamma-ray sources emit in other wavelenghts, some does not. Observing the source in different wavelenghts (multi-wavelenghts observations) can provide important information about origin of sources.



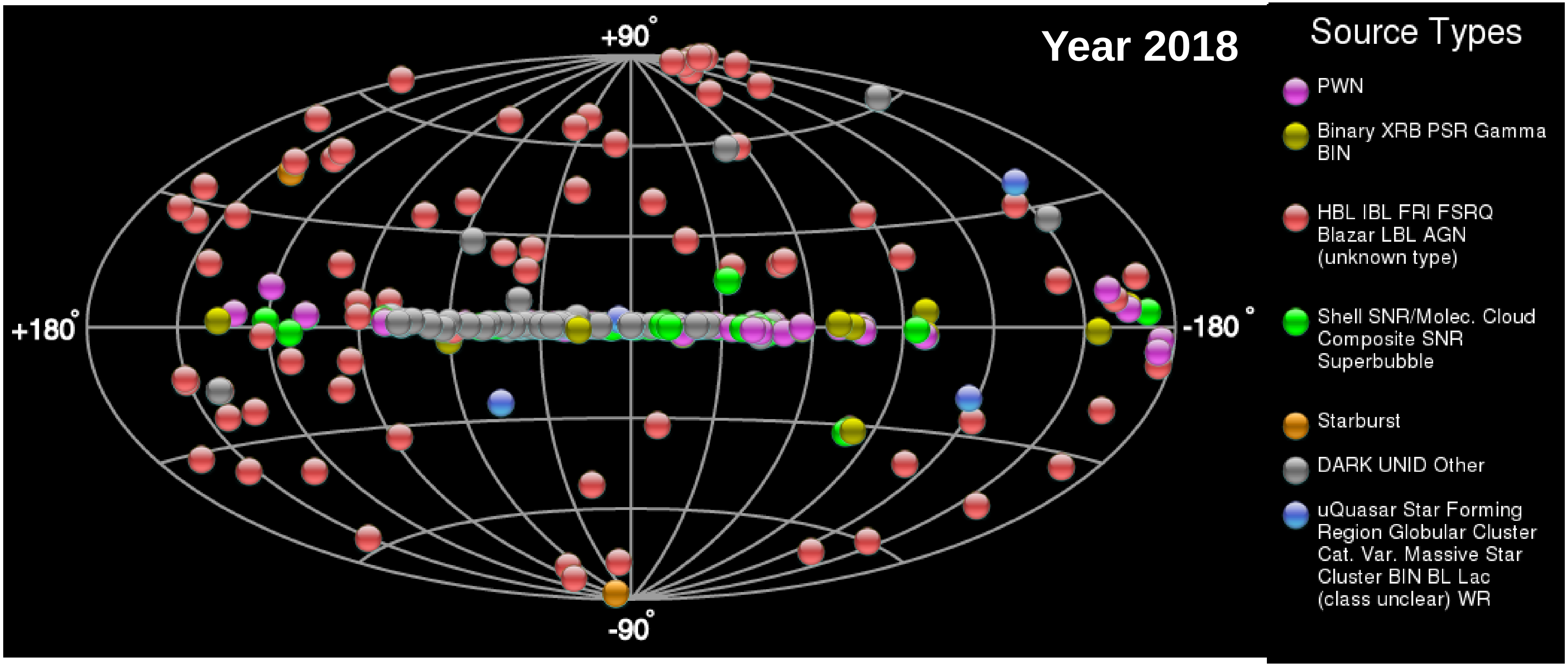
VHE Gamma-ray Astronomy



- In 1996, there were only three VHE gamma-ray sources known. Markarians are extra-galactic sources (other galaxies), while Crab Nebula is a Galactic source (located inside the Milky Way Galaxy).

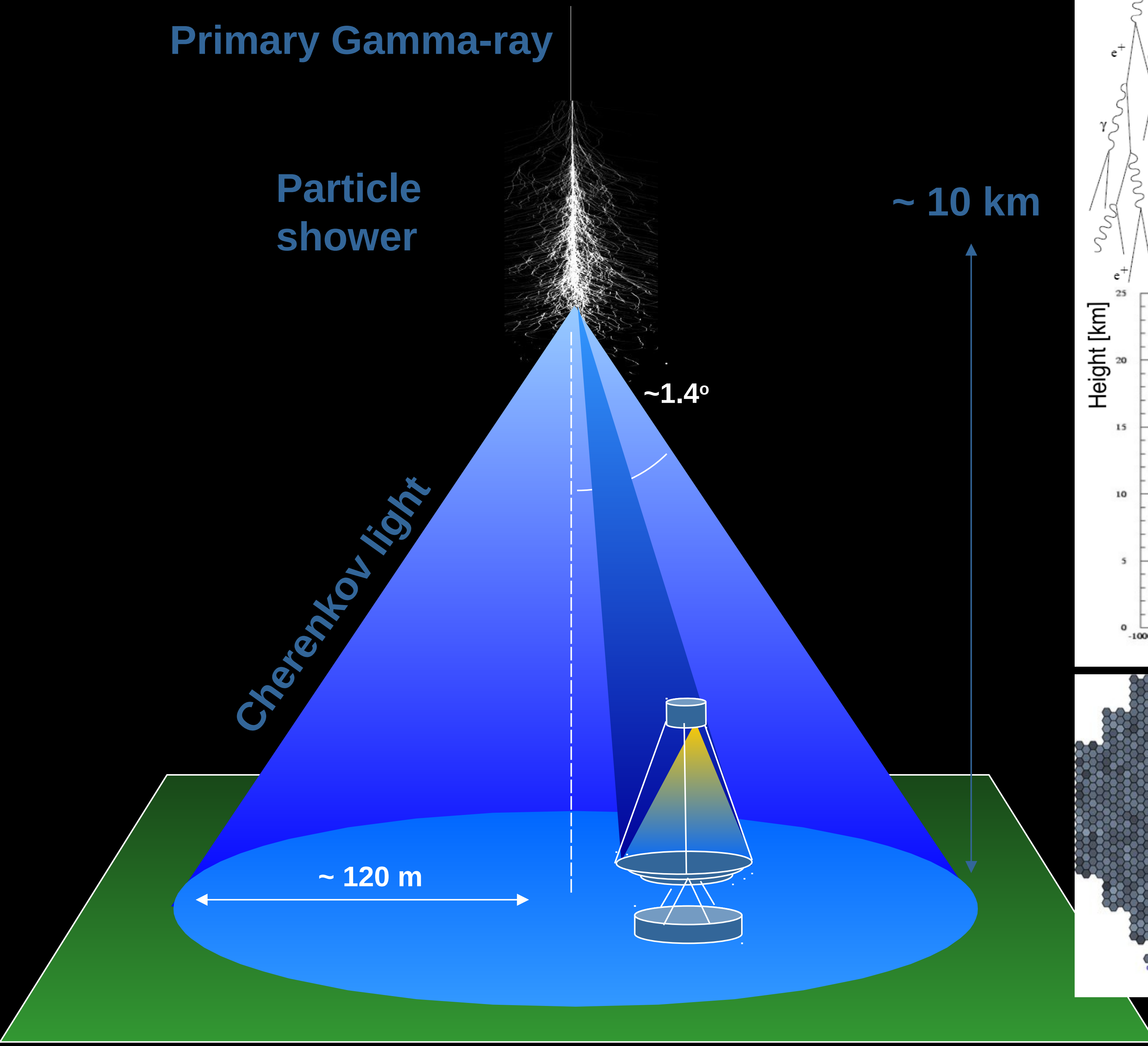
- A VHE source needs to be detected (over a background) first. Then its morphology and spectrum are studied. Afterwards, one can identify it (sometimes MWL study is needed).

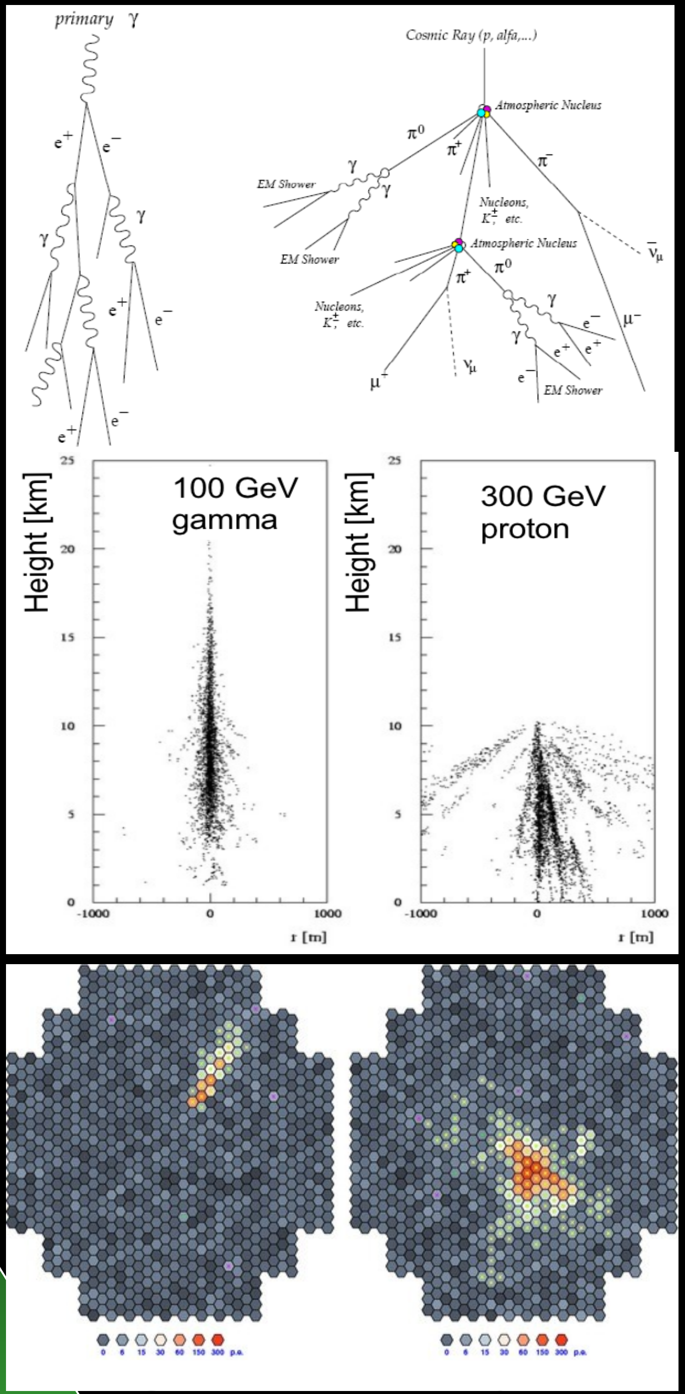
VHE Gamma-ray Astronomy



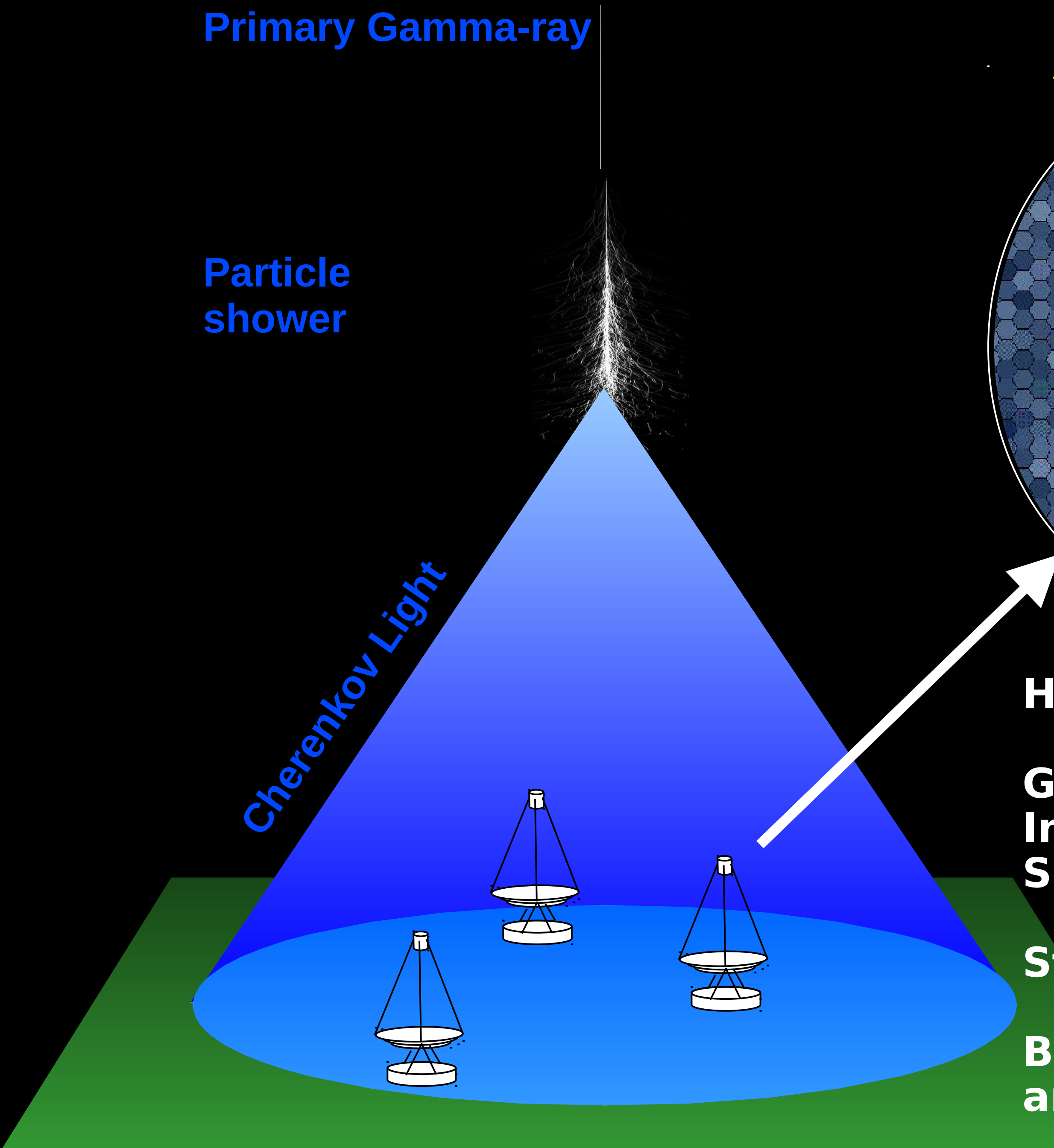
- Observations have revealed a large number (~210) of VHE sources. Most of these sources have been firmly identified.
- “Unidentified“ VHE gamma-ray sources → plausible multi-wavelength (MWL) counterparts but the associations have not yet been confidently established.
- “Dark sources“ → have no plausible counterparts at any wavelength.

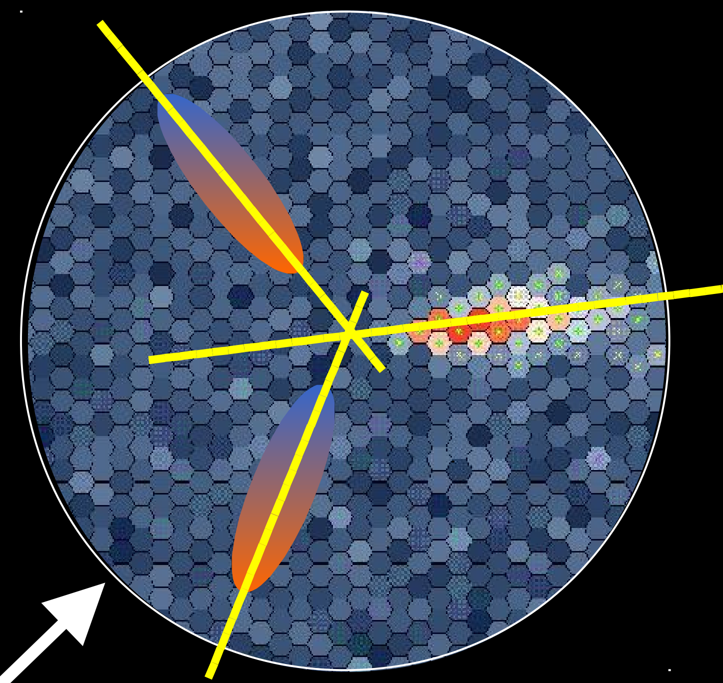
Imaging Cherenkov Technique





Imaging Cherenkov Technique





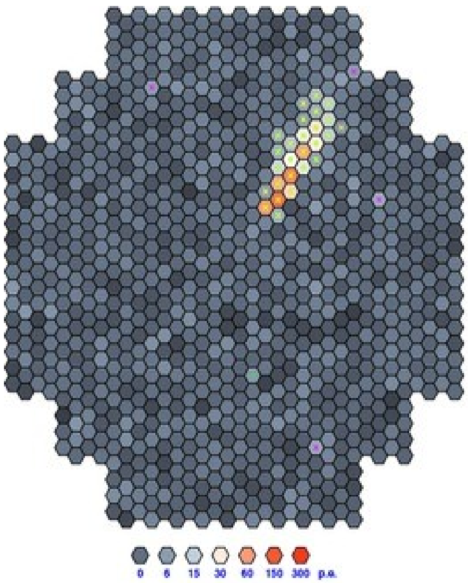
Hillas Ellipse:

Geometry → Photon Direction
Intensity → Photon Energy
Shape → CR rejection

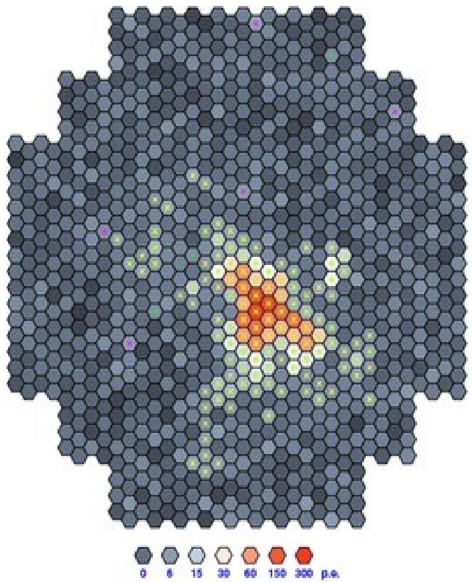
Stereoscopic system provides:

Better background reduction, angular and energy resolution.

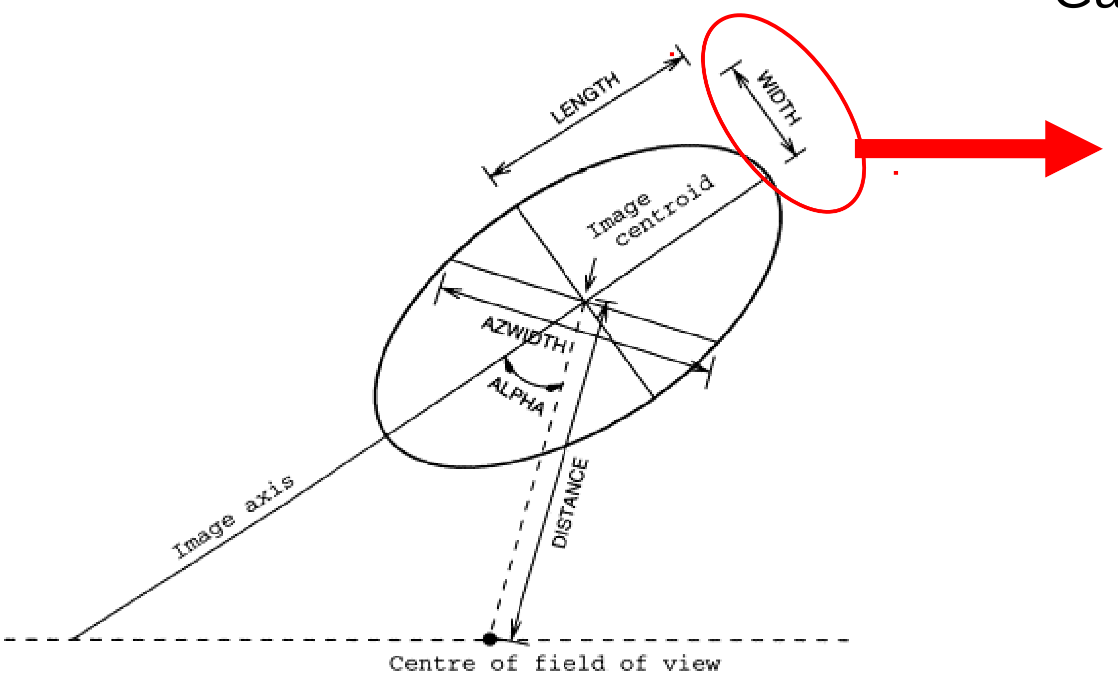
Gamma-ray / Hadron Seperation



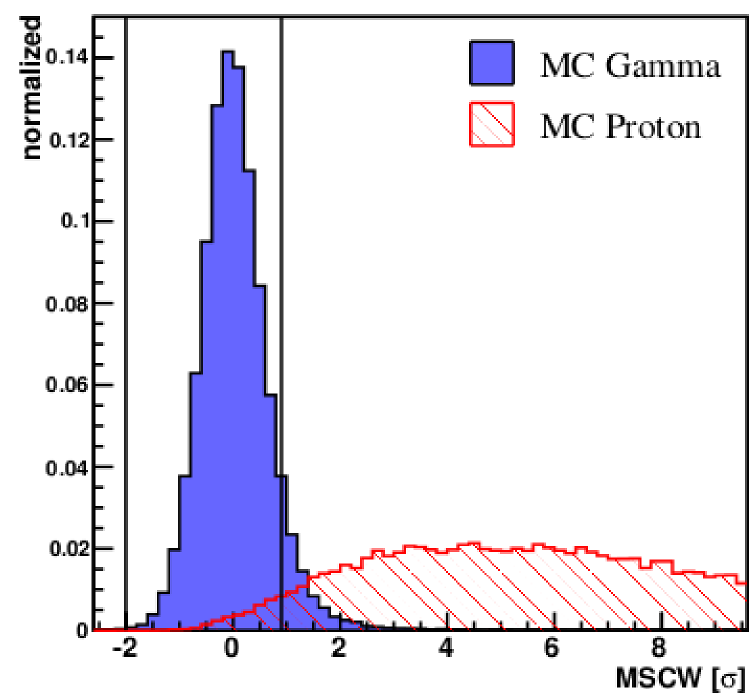
1.0 TeV gamma shower



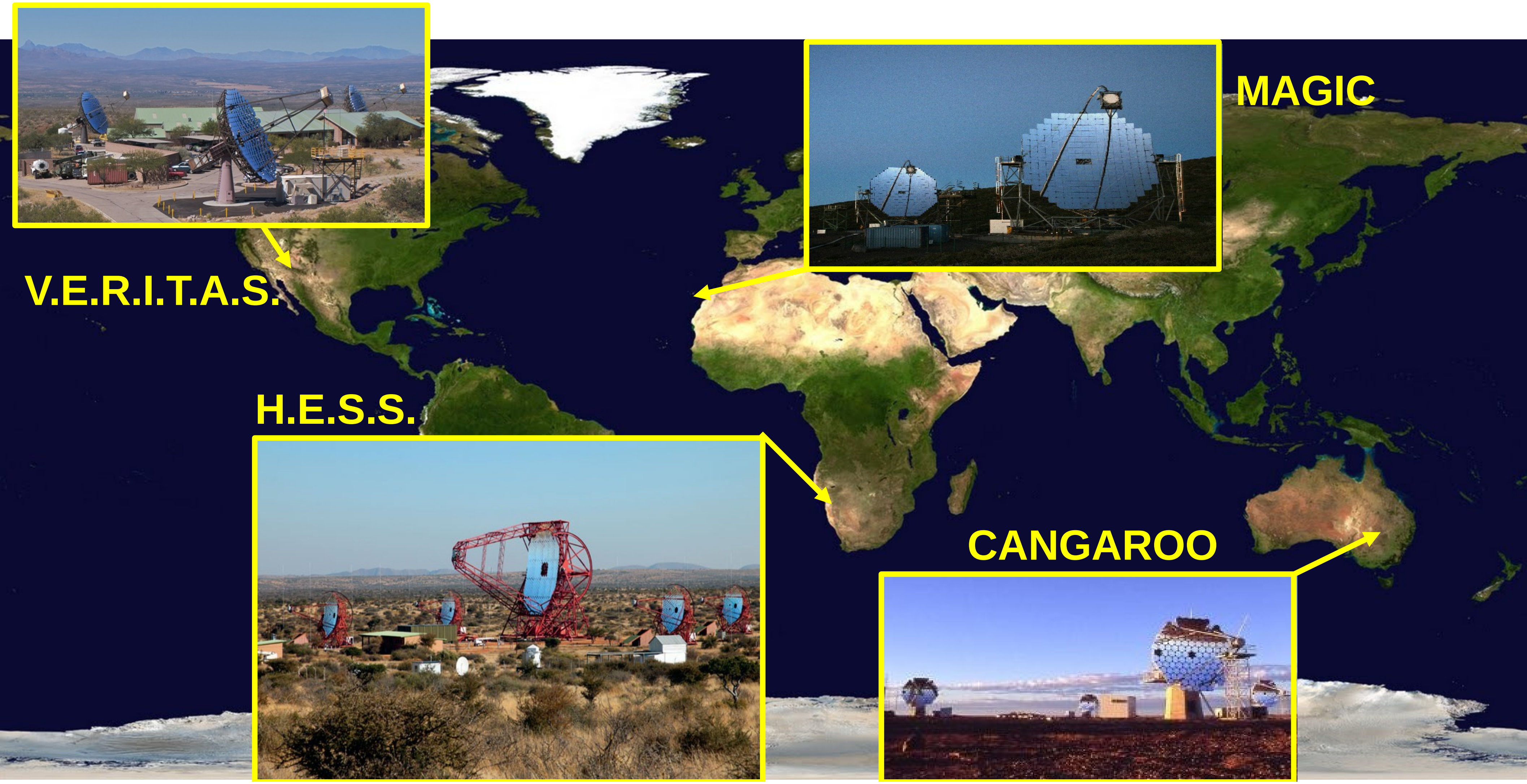
2.6 TeV proton shower



- We end up with ellipse like images (Hillas parametization) on the camera.
- Rate of gamma-rays are ~1000 times smaller than cosmic-rays.
- Hadronic showers show wider angular spread with respect to the showers generated by gamma-rays.
- Gamma / Hardon seperation.



Imaging Air Cherenkov Telescopes (IACTs)



Instrument	Lat (°)	Long (°)	Alt (m)	Telescopes #	Area (m^2)	Total (m^2)	Pixels	FoV (°)	Thresh (TeV)	Sensitivity (% Crab)
H.E.S.S.	-23	16	1800	4	107	428	960	5	0.1	0.7
H.E.S.S. II				1	614	614	2048	3.2	tbd	tbd
VERITAS	32	-111	1275	4	106	424	499	3.5	0.07	0.7
MAGIC I†+II	29	18	2225	2	234	468	576/1039	3.5	0.03	1.0
CANGAROO-III	-31	137	160	3	57.3	172	427	4	0.4	15

High Energy Stereoscopic System

- Good sky transparency, dry weather conditions
- Southern hemisphere, direct view on the Galactic Center

<u>H.E.S.S. Phase I (2002) :</u>

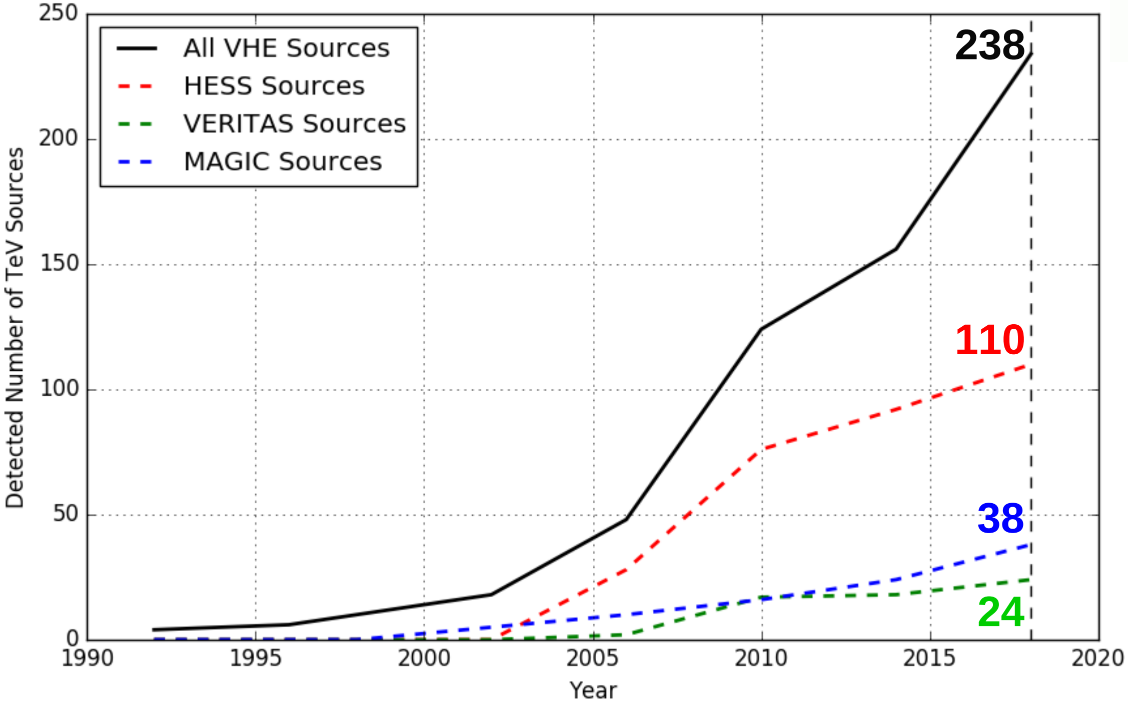
- 4 telescope system (12 m, 107 m^2)
- 960 PMTs / cam, FoV 5°
- Energy threshold ~100 GeV
- Angular resolution ~0.1°

<u>H.E.S.S. Phase II (2012) :</u>

- Single large telescope (CT5) (28 m, 600 m^2)
- 2048 PMTs, FoV 3.5° (CT5)
- Energy threshold O(30) GeV
- Angular resolution ~0.4°

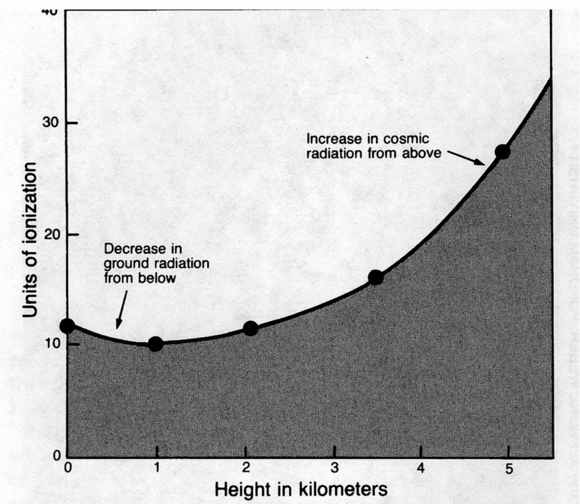
High Energy Stereoscopic System

- The name H.E.S.S. and is also intended to pay homage to Victor HESS, who received the Nobel Prize in Physics in 1936 for his discovery of cosmic radiation.
- H.E.S.S. is an international consortium from 14 countries, 40 institutions, > 250 physicists.



Victor Hess

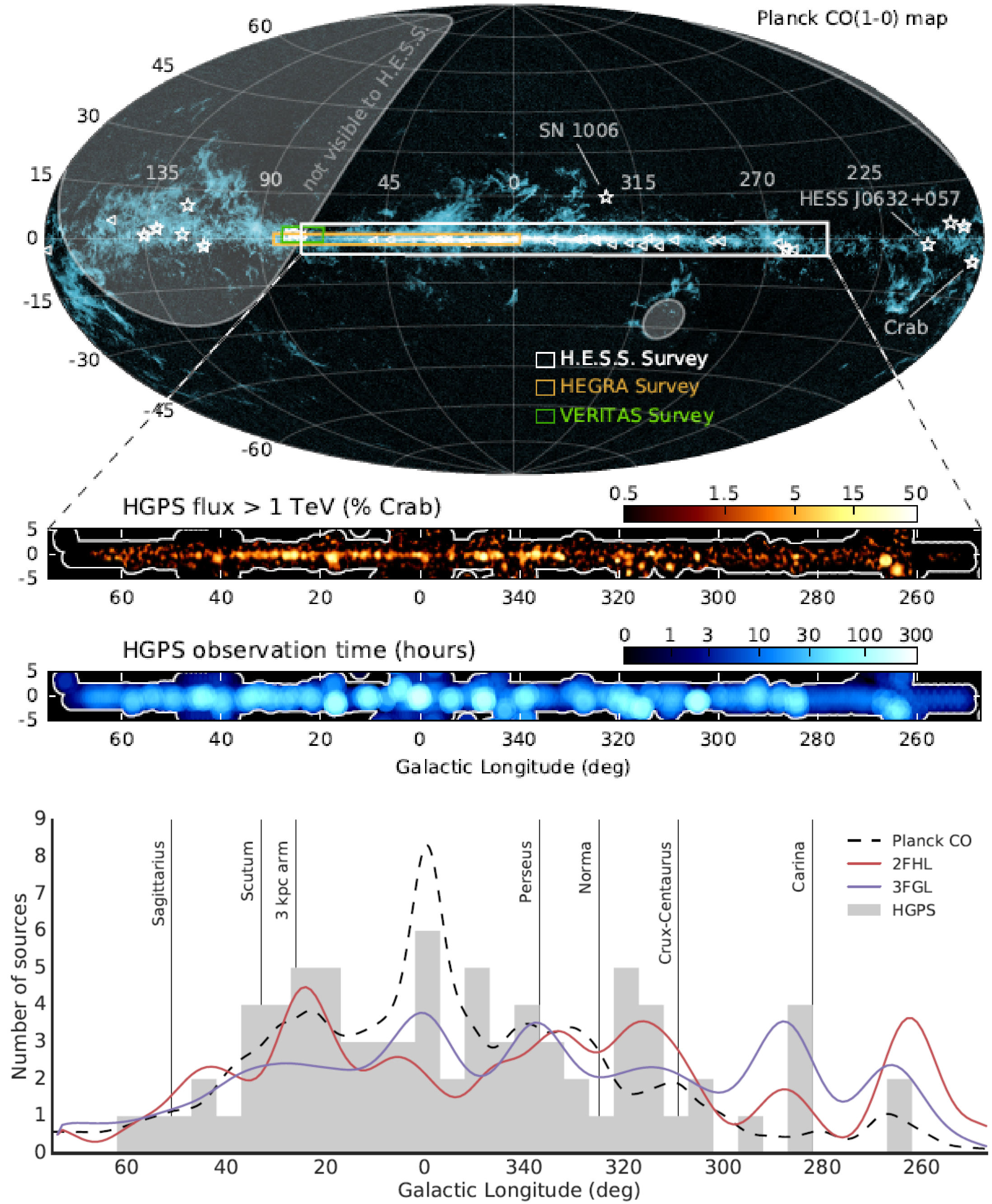
- In 1912, Austrian physicist victor Hess took an ionization chamber aloft in balloon and measured background radiation. He found that from 2000 meters to 5300 meters the amount of radiation increased, indicating the radiation came from space. He had discovered "Cosmic Rays."



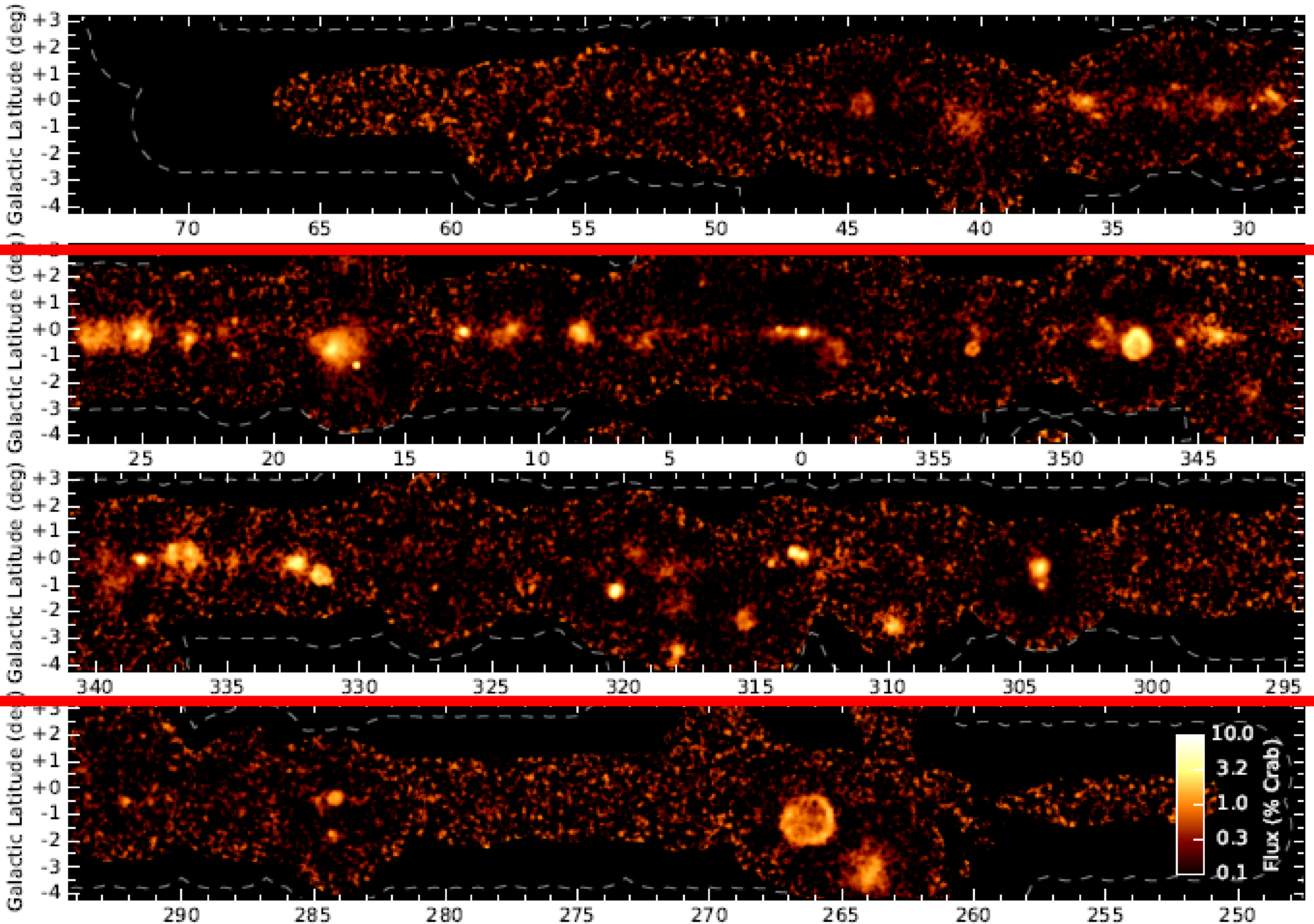
Readings on ionization chamber Victor Hess carried aloft in the Böhmen. Above four kilometers the ionization rose rapidly indicating "that rays of very great penetrating power are entering our atmosphere from above". These cosmic rays contain the only modern samples of matter from outside our solar system which can be investigated directly.

H.E.S.S. Galactic Plane Survey

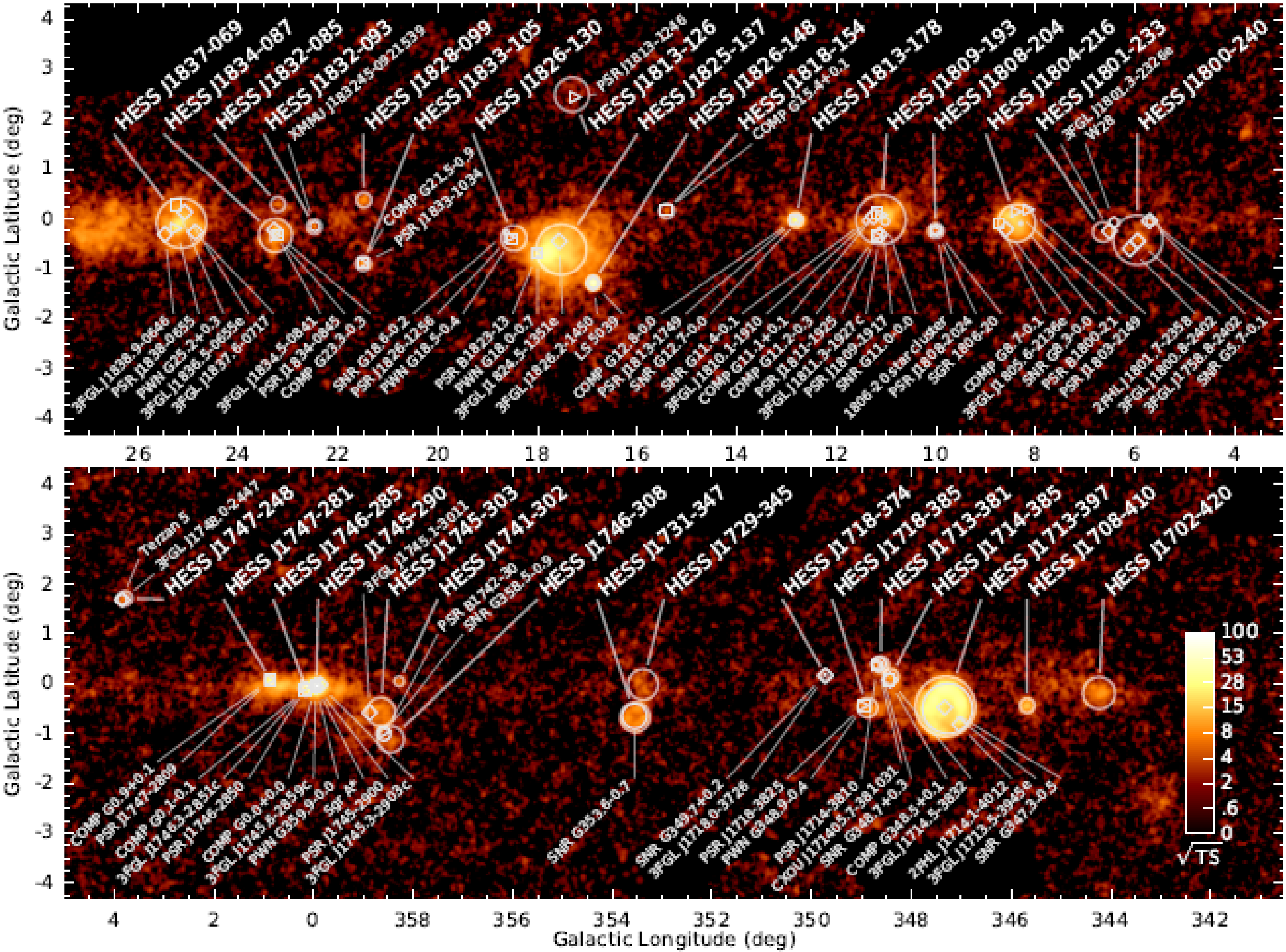
- Use data from H.E.S.S. I telescope system (CT1 – CT4).
- 2673 hours of (good quality) observations, years 2004 – 2013. Inhomogenous exposure.
- Sky Coverage:
  -110° < l < 65° (Galactic long.)
  -3.5° < b < 3.5° (Galactic lat.)
- Energy Range:
  (0.2 – 100.0) TeV
- $R_{68\%}$ ~ 0.07°
  (Angular resolution)



H.E.S.S. Galactic Plane Survey

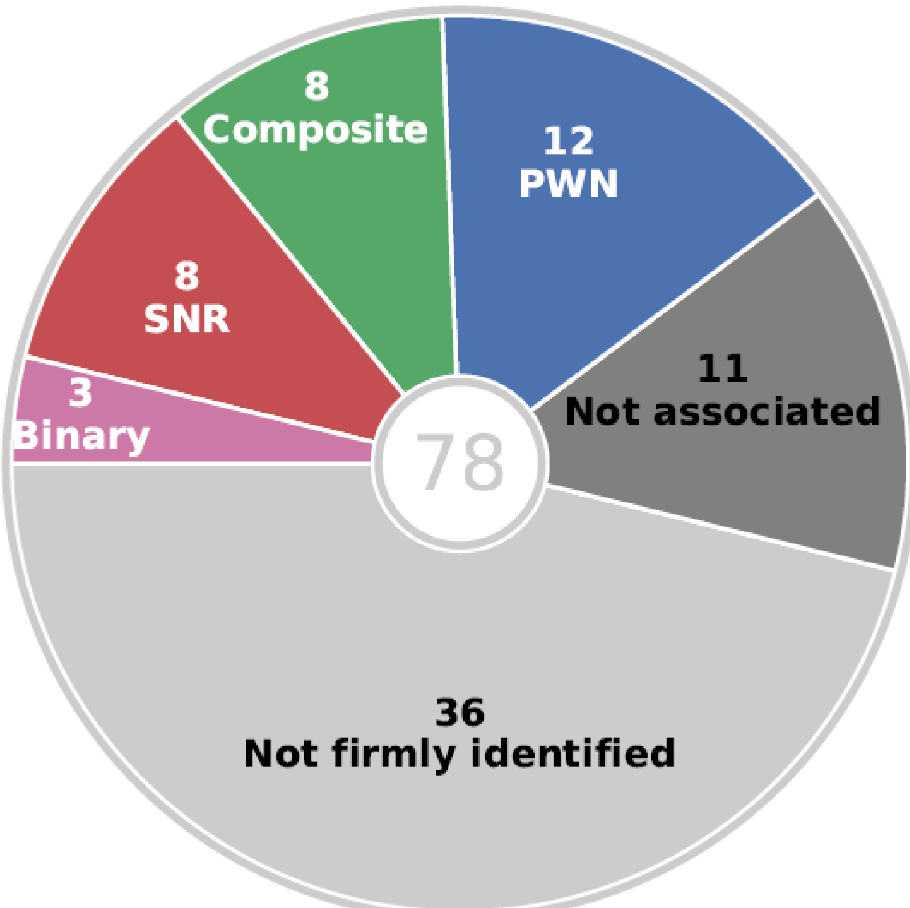


H.E.S.S. Galactic Plane Survey

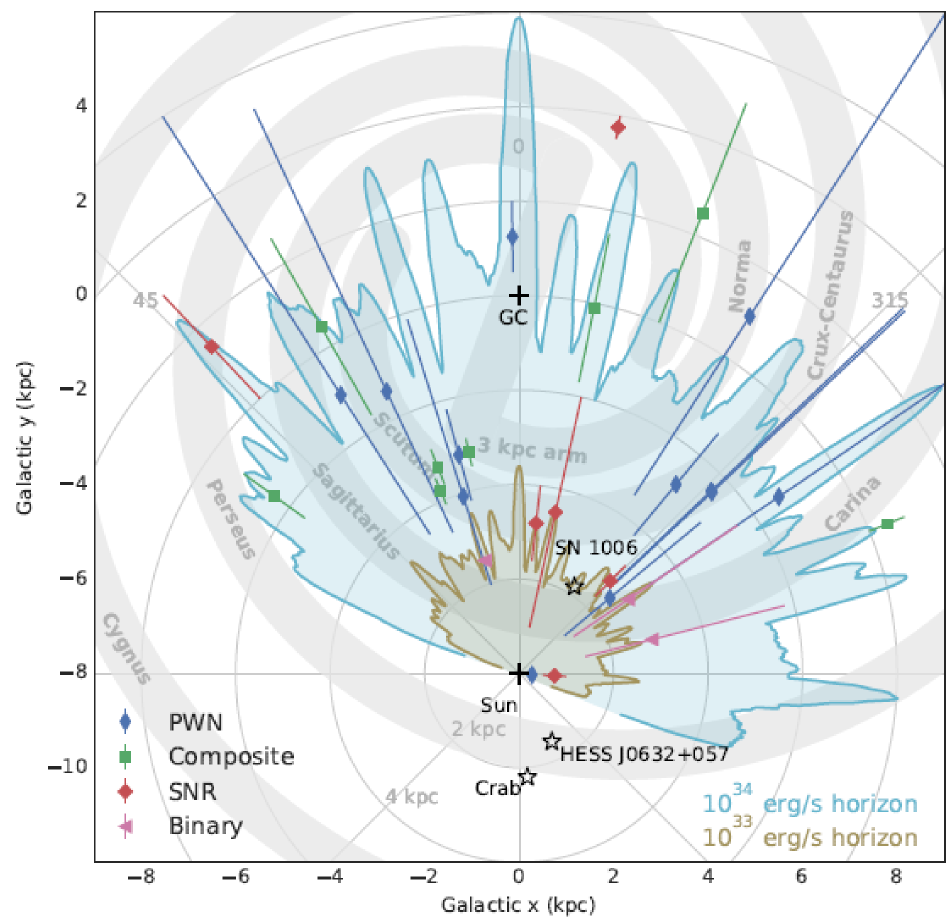


H.E.S.S. Galactic Plane Survey

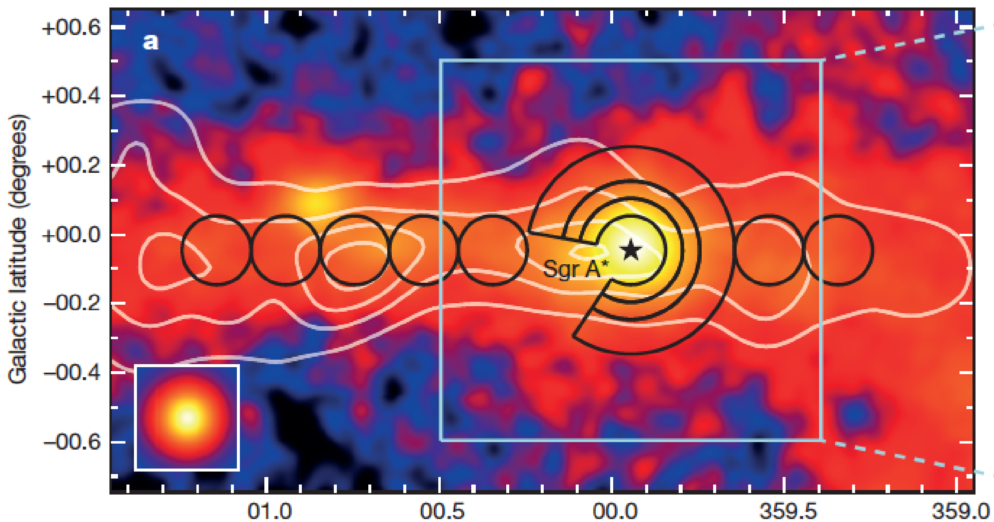
Source Identification and Association Chart

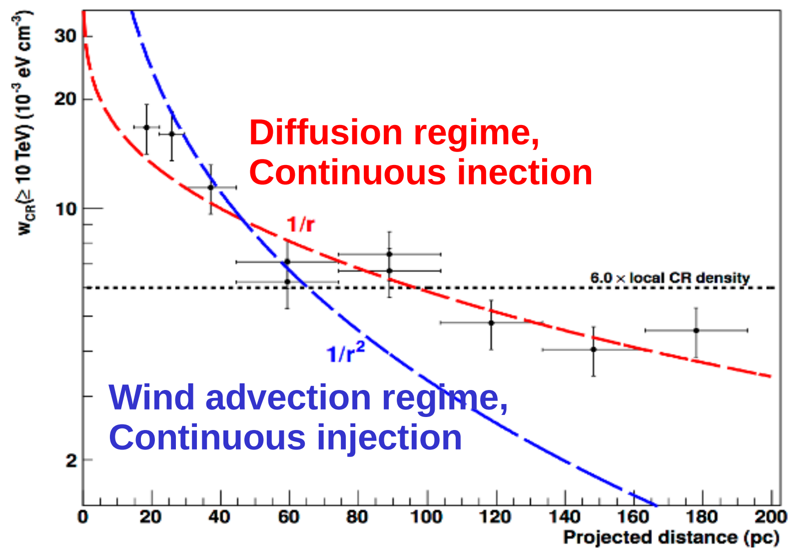


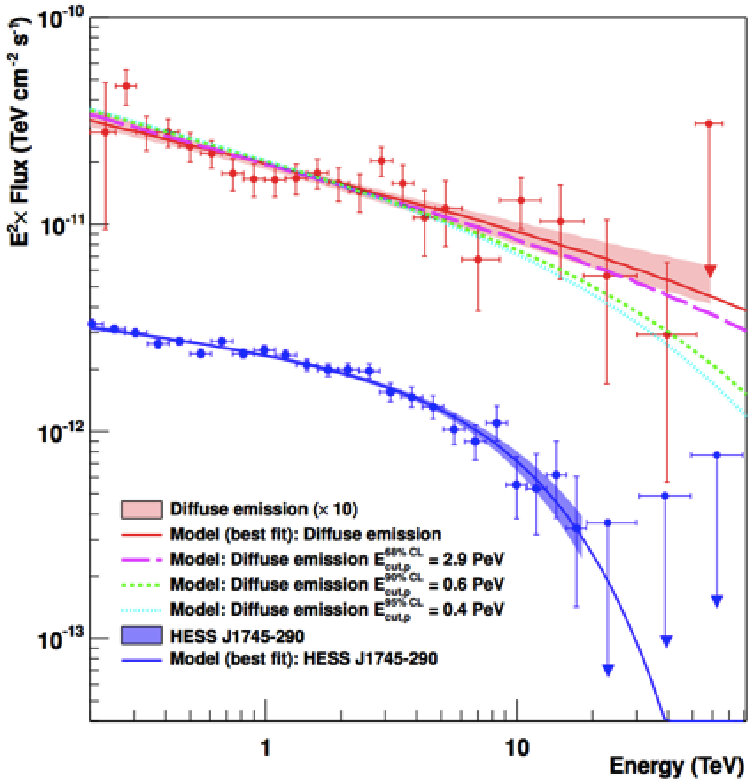
The location of identified H.E.S.S. sources in the Galaxy



H.E.S.S. Galactic Center PeVatron



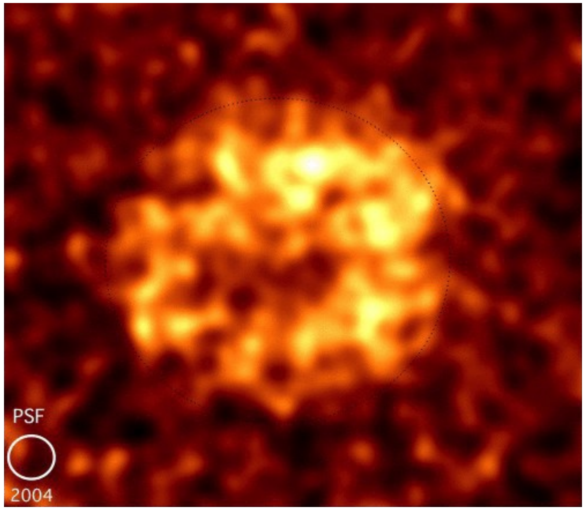




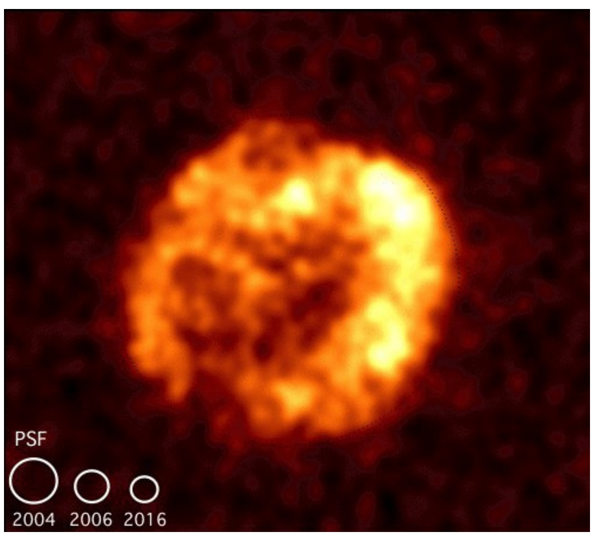
- Point-like, central source on top of extended (ridge) emission. Central source: cut-off @ 10 TeV
- Diffuse emission shows no cut-off well > 10 TeV
- Emission profile consistent with propagation of protons accelerated around central black hole (Sgr A*) and diffusing away (projected radial distribution matches)
- Parent proton population up to 1 PeV

  (2.9 PeV @ 68% CL)
- First robust detection of a Galactic PeVatron! Central accelerator located within 10 pc, but no clear association could be made.

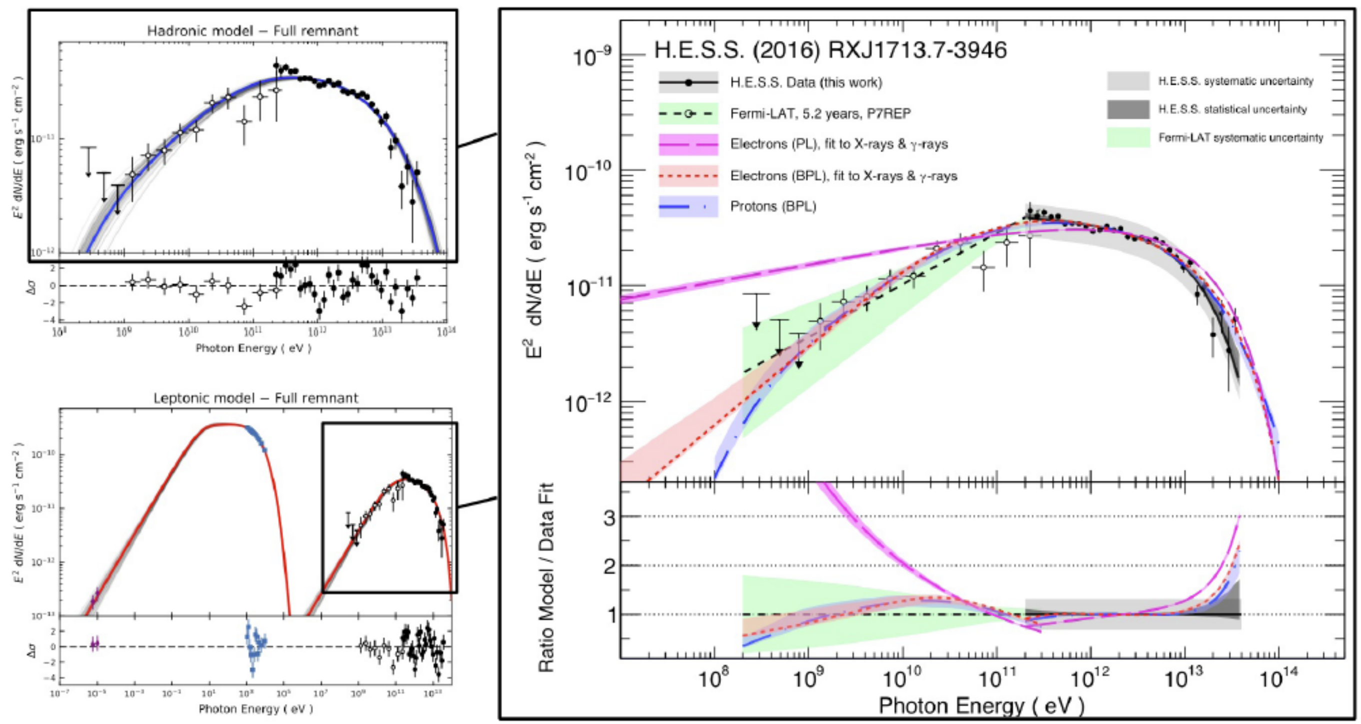
SNR RXJ1713.7 – 3946



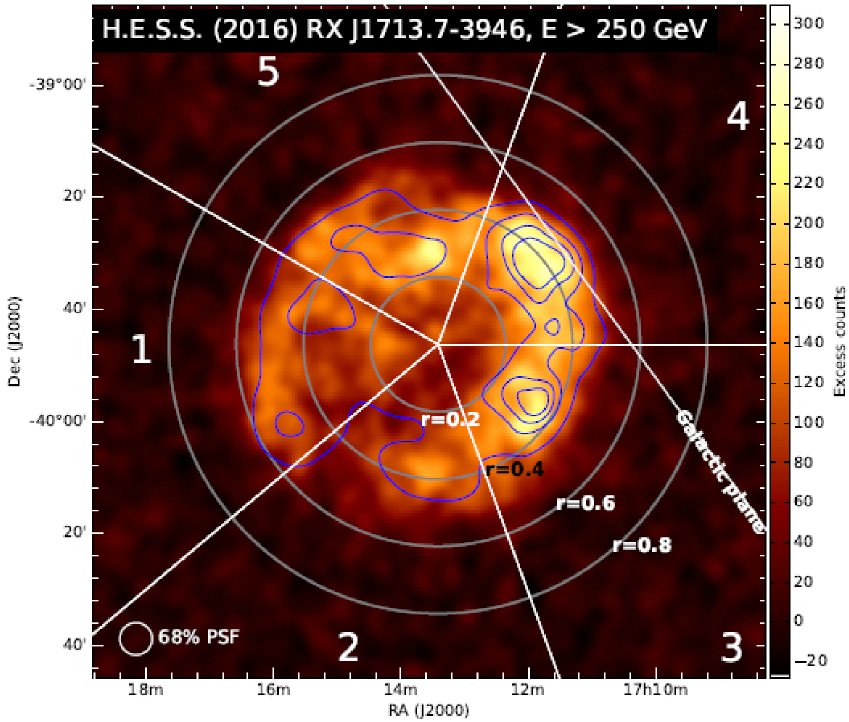
Improved Point Spread Function (PSF)

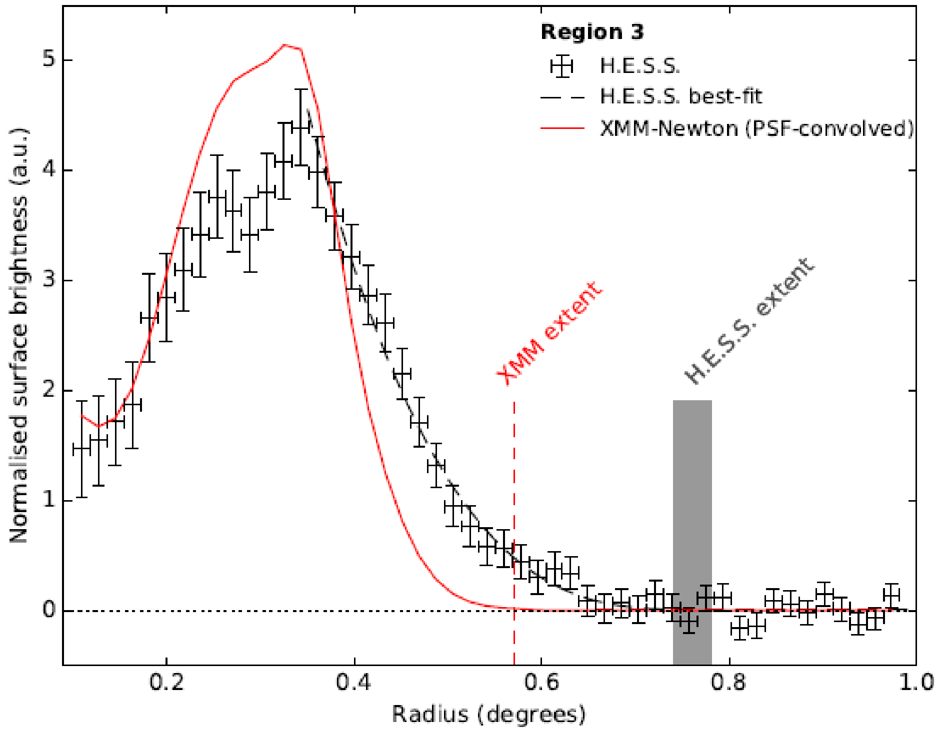


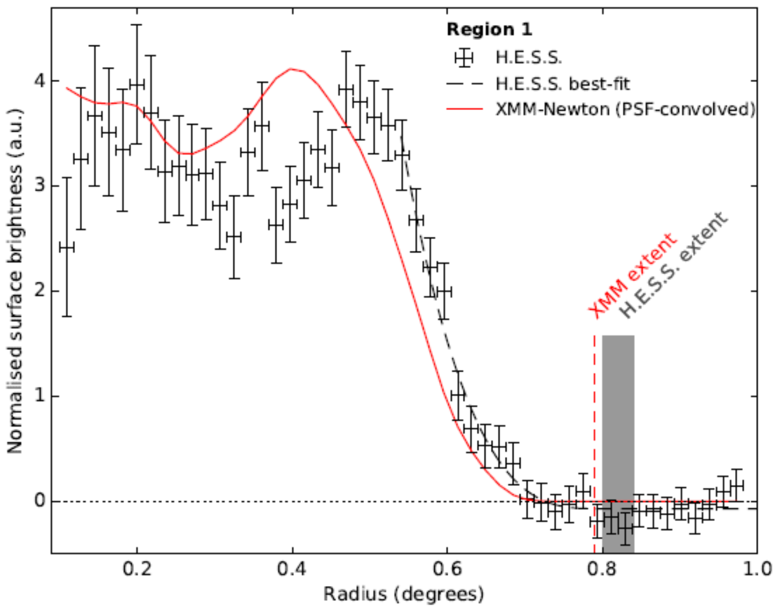
- Establishing the Galactic sources of charged CRs is one of the main science goals.
- The standard paradigm is that young supernova remnants (SNRs) are these accelerators of high energy Galactic CRs.
- RXJ1713 is a well studied young SNR (~1600 yrs) located at a distance of ~1 kpc.



SNR RXJ1713.7 – 3946



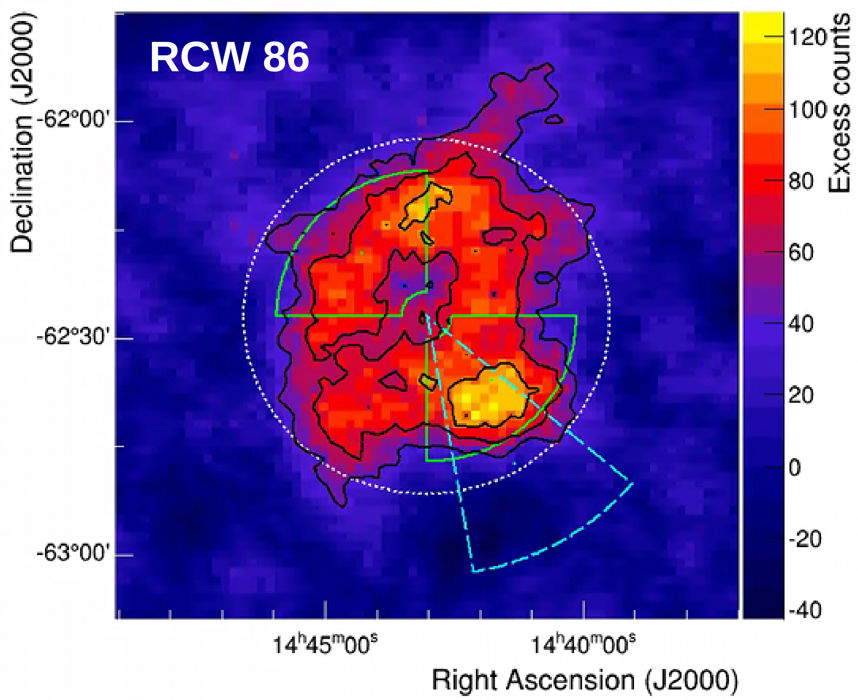


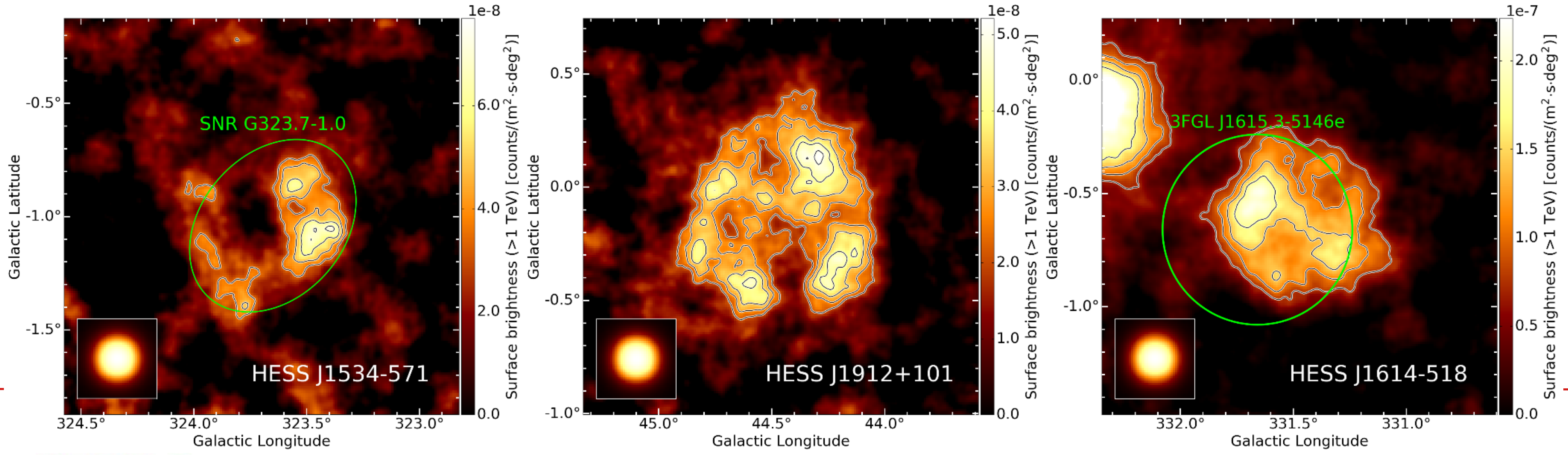


- Comparison of TeV and X-ray radial profiles. No good correlation.
- SNRs can be PeVatrons only during a short time when they are young.
- Evidence for run-away Cosmic-rays interacting with inter-stellar medium ?

New shell-type SNRs seen by HESS

- New shell-type SNRs resolved by H.E.S.S.
- RCW 86 from deep exposure
  - Good correlation between TeV and hard X-ray (IC vs synchrotron)
  - Likely leptonic dominated
  - Max energy ~ 3 TeV
- HESS J1534-471, HESS J1614-518 and HESS J1912+101 from HGPS
  - HESS J1912+101 only TeV SNR without any counterparts in other wavebands

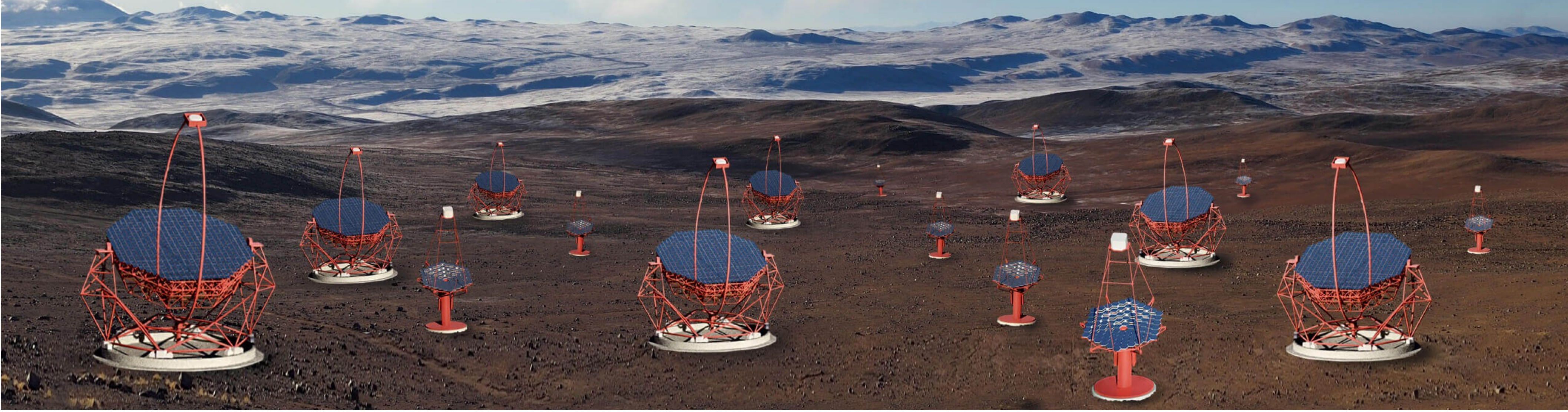




Cherenkov Telescope Array

- 10 times more sensitive than any existing experiment.
- Angular resolution <0.1° (for most of the energy range)
- Large field of view → (8° - 10°)
- Energy coverage → 20 GeV – 300 TeV (opening up a new window)
- Rapid slew (20 s) to catch flares
- Two sites for full sky coverage

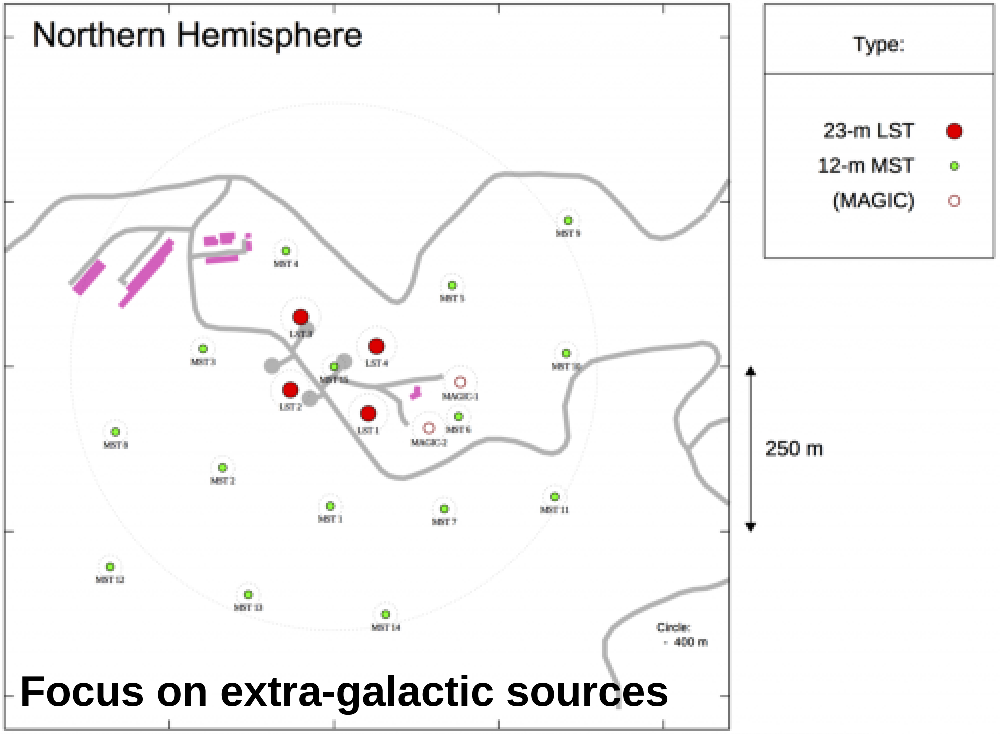
(Northern Site → La Palma , Southern Site → Chile)



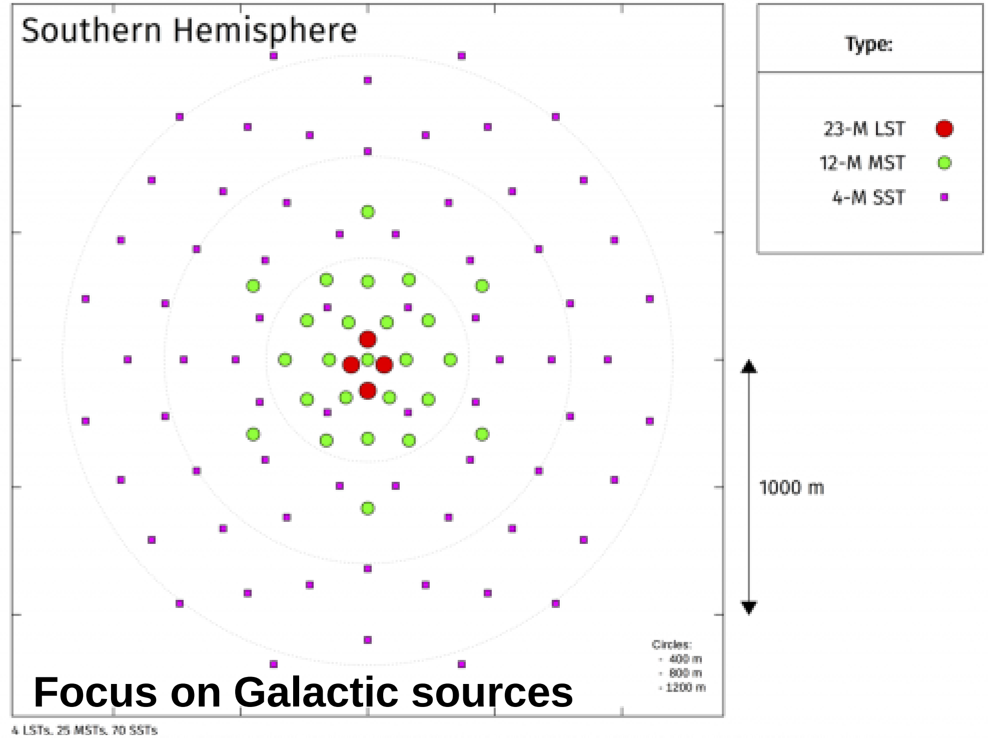
THINK BIGGER!!! ~100 Telescopes

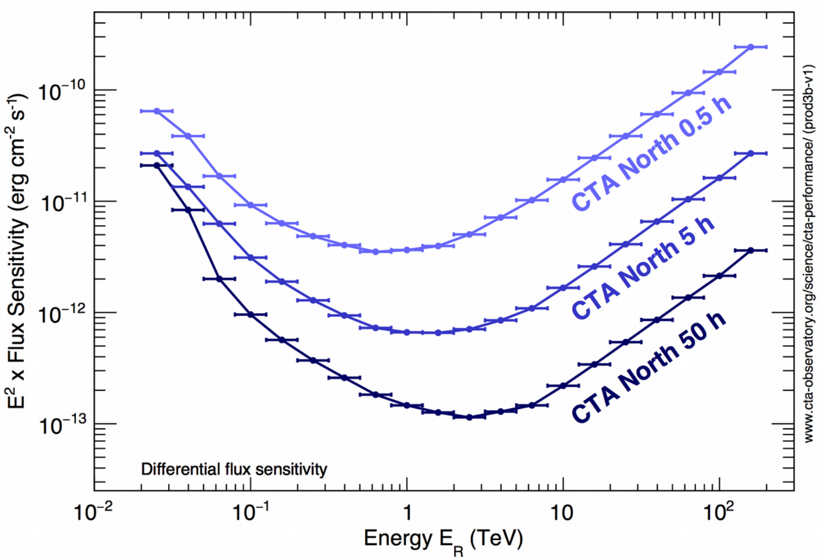
Cherenkov Telescope Array

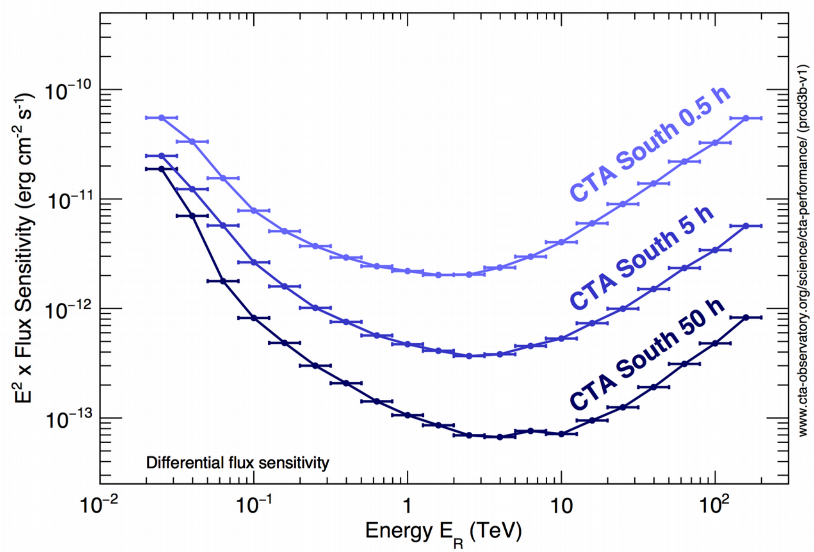
Roque de los Muchachos Observatory (Spain)



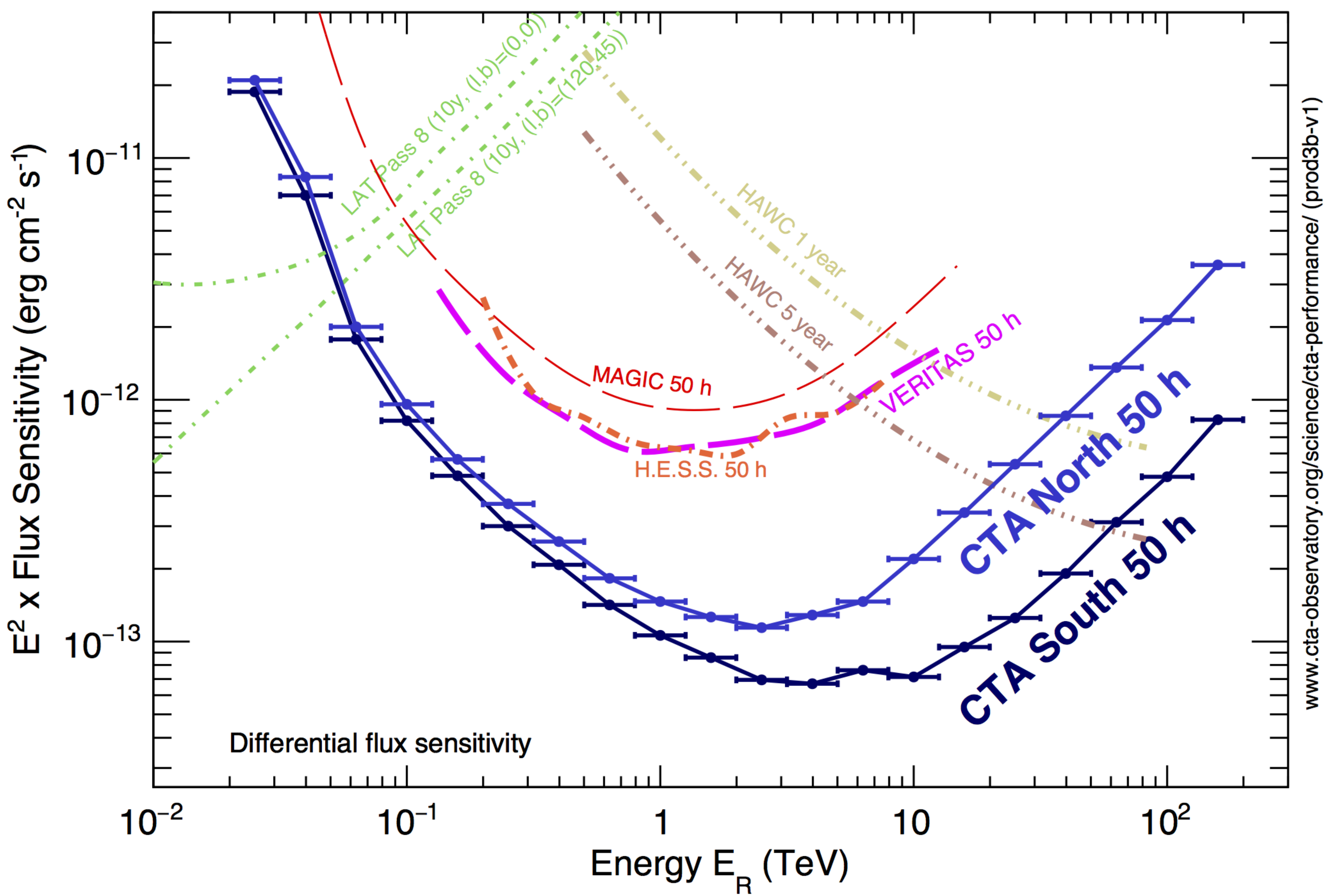
Paranal Observatory (Chile)



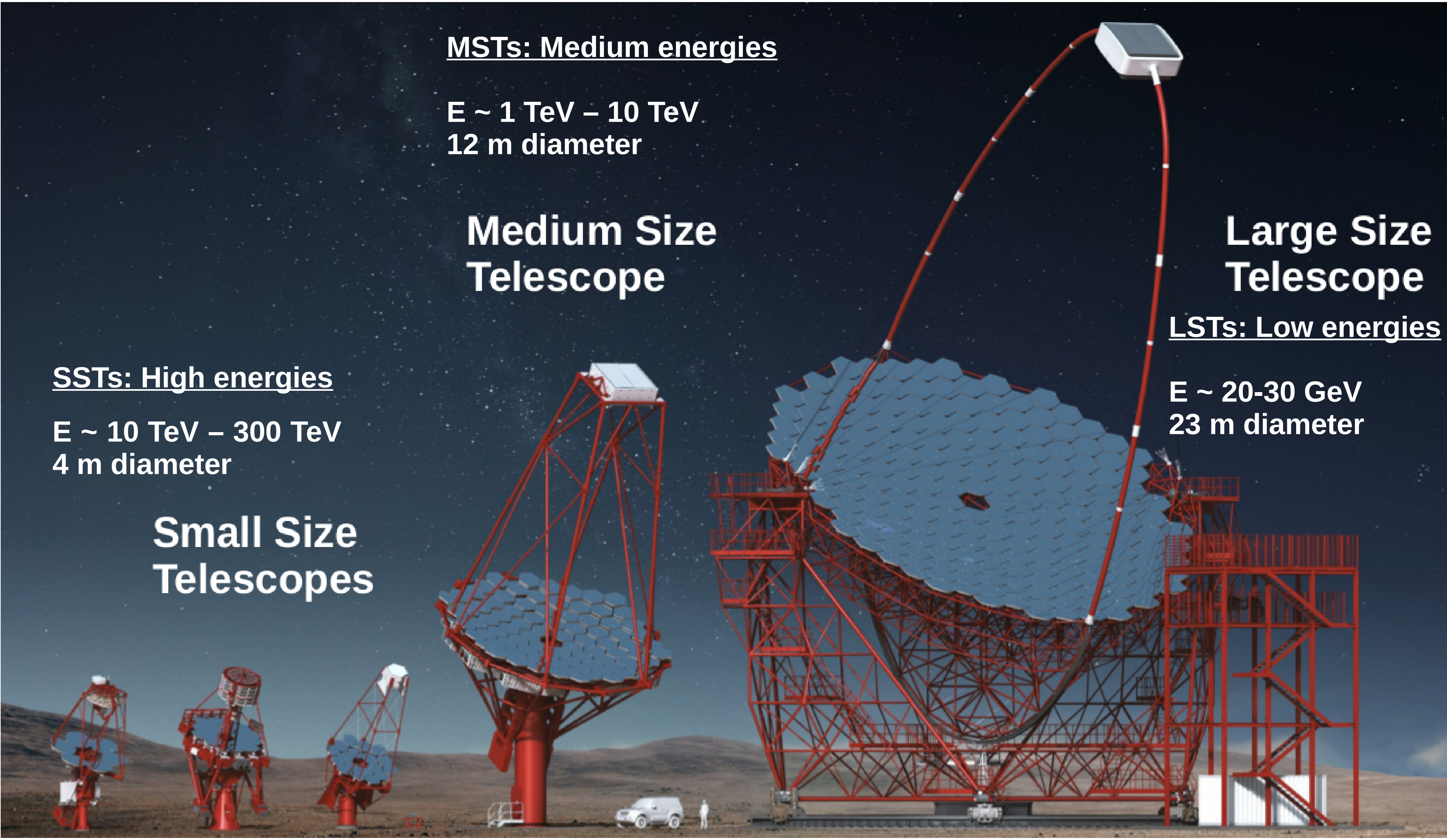




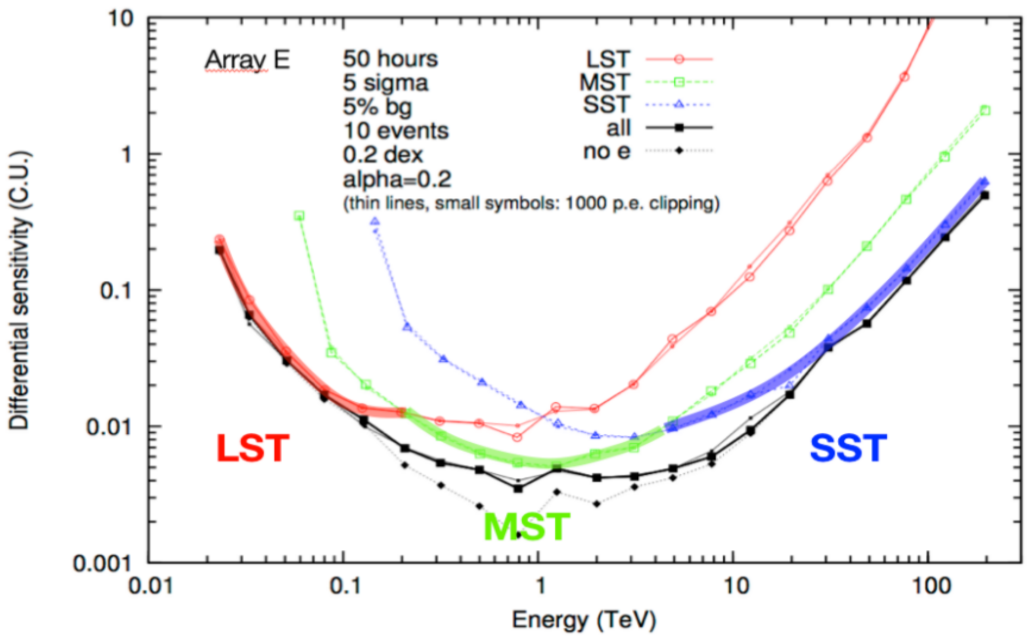
Cherenkov Telescope Array

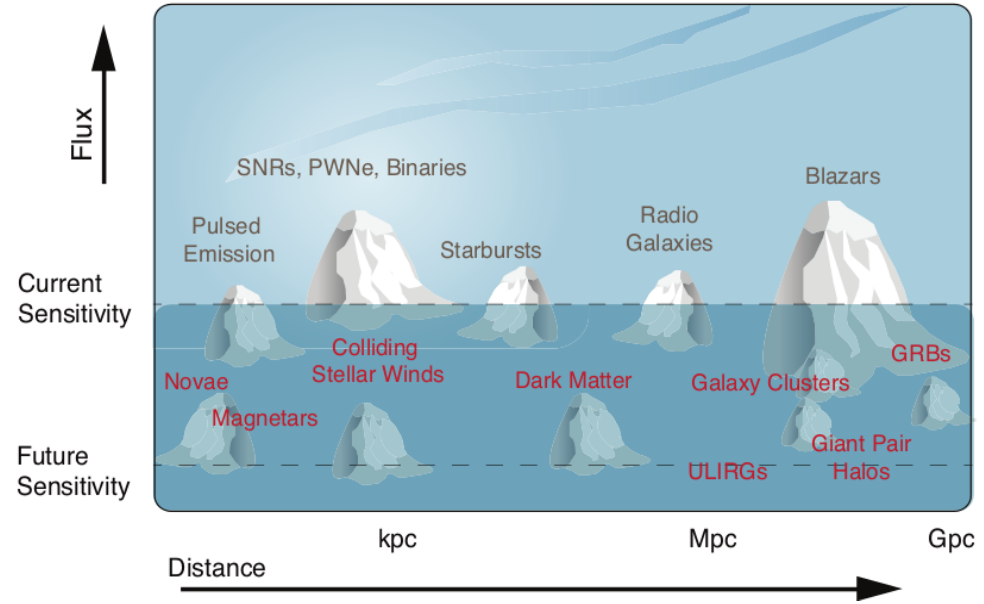


Cherenkov Telescope Array

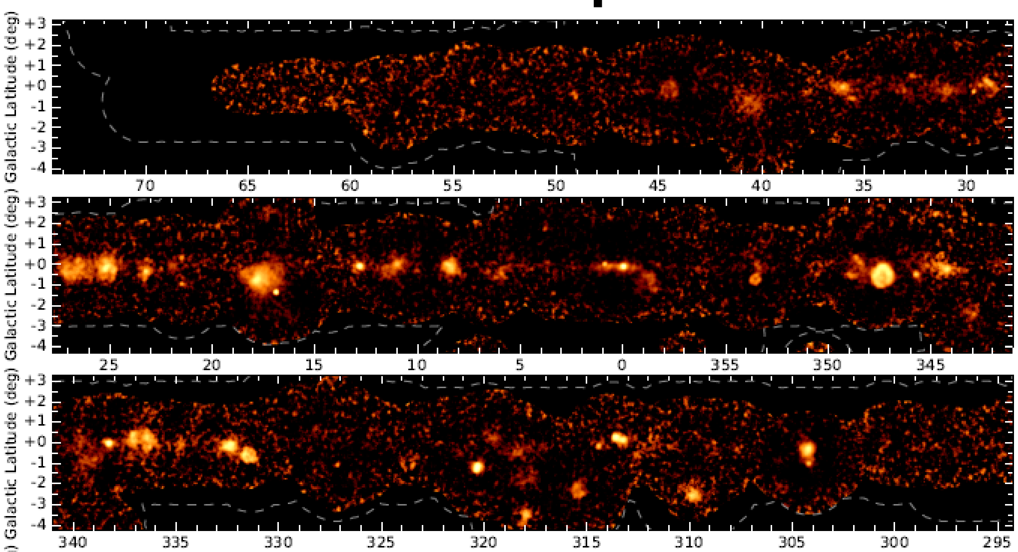


Cherenkov Telescope Array

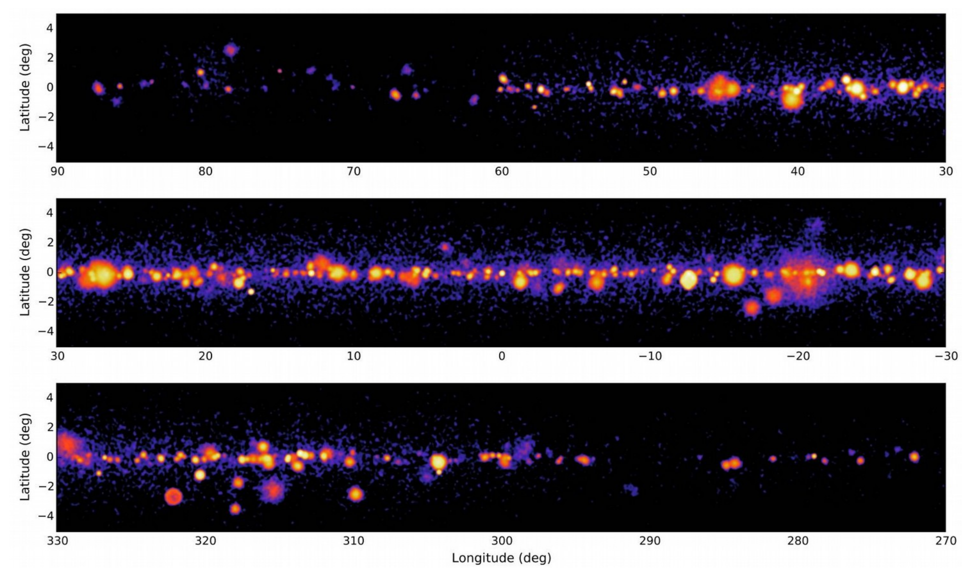




Real data (HESS GPS), 4 Telescopes



Simulated data (CTA South GPS), ~100 Telescopes



Activities at CPPM

- H.E.S.S. Side :

  - Data analysis of PeVatron candidate sources

  - Search of TeV gamma-rays from microquasars

  (Follow up observation alerts from X-ray and Radio data)

- CTA Side :

  - Search for PeVatron candidates in the future CTA Galactic Plane survey

  - MC simulations and performance evaluation of one of the SST prototypes (GCT)

  - Acquisition system of the Camera for the MST (NectarCam) and LST (LSTCam)

Outlook & Conclusions

• Thanks to many discoveries, VHE gamma-ray astronomy has become a major exciting field of research.

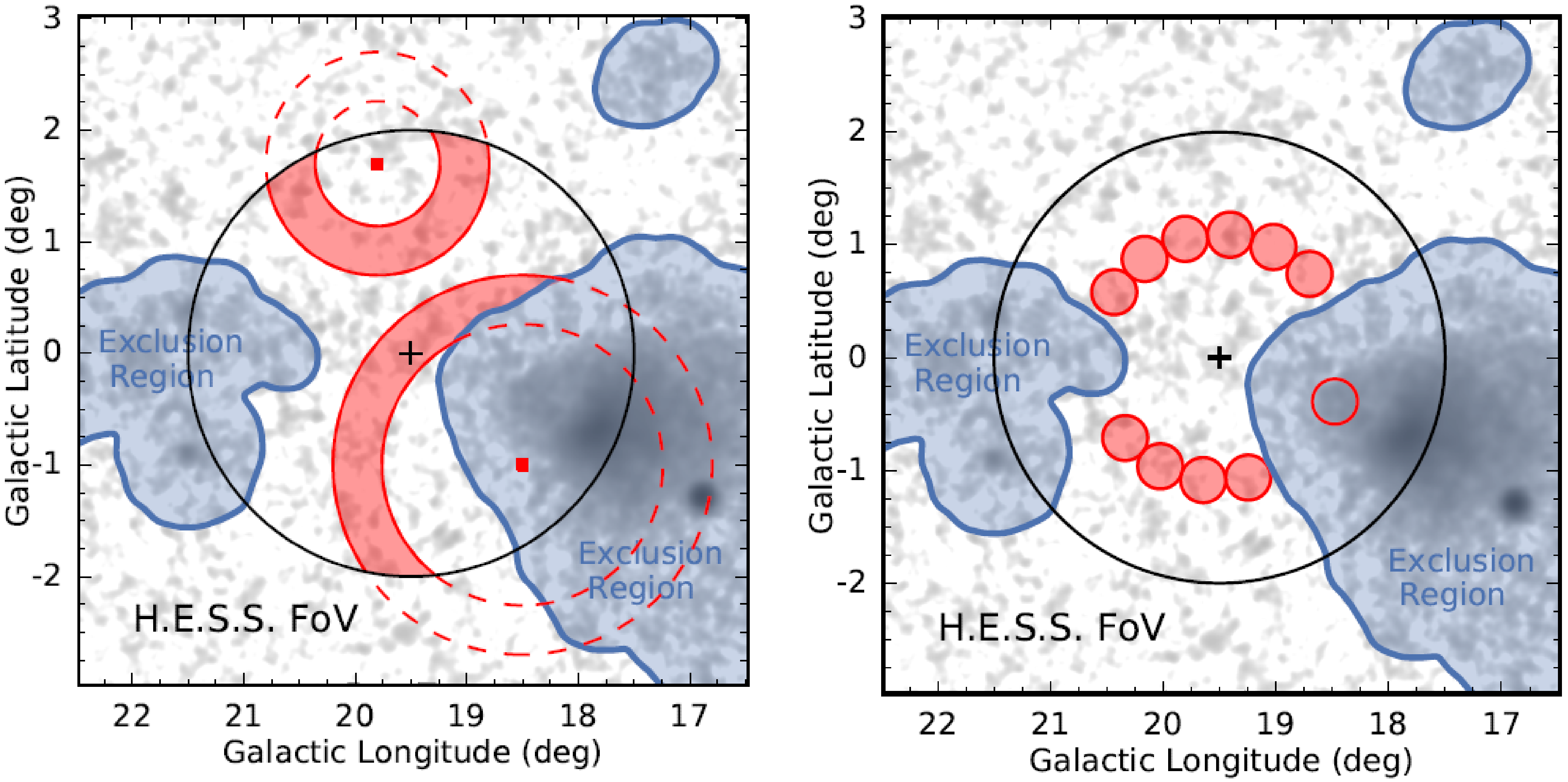
• Outstanding science potential and the power of Atmospheric Cherenkov technique has brought to CTA.

• CTA will open new windows on the Universe with a huge potential for new discoveries.

• Construction will start very soon! Join and contribute to the future astronomy, it‘s exciting :)

BACKUP SLIDES

H.E.S.S. Galactic Center PeVatron



VHE Gamma-ray Production Mechanisms

- Inverse Compton Scattering :

The up-scattering of low energy photons by relativistic e^- (or e^+) to higher energies is called inverse Compton (IC) scattering. It is a very efficient process to increase photon energies up to VHE.

$$E_{\text{boosted}} = \gamma^2 E_{\text{initial}} \quad \text{if} \quad \gamma E_{\text{initial}} \ll m_e c^2$$

Initial Waveband	Initial Frequency (Hz)	Scattered waveband and frequency (Hz)
Radio	10^9	Ultra-Violet, 10^{15}
Far-Infrared	3×10^{12}	X-Rays, 3×10^{16}
Optical	4×10^{14}	Gamma-Rays, 4×10^{20}

Table 2.2: Table of up-scattered photons of different wavebands from an electron population with Lorentz factor of $\gamma = 1000$.

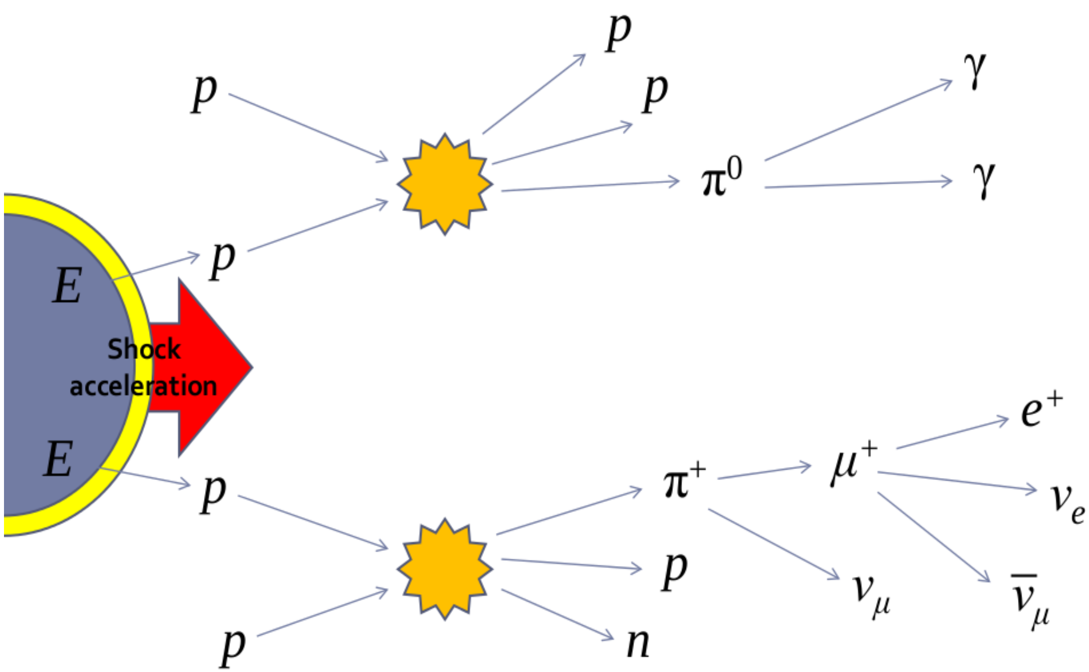
The Thomson regime can be used for 2.7 K CMB photons ($E = 6 \times 10^{-4}$ eV). In this regime, the up-scattered photons follow the spectral shape of the electrons, $\Gamma_\gamma = (\Gamma_e + 1)/2$.

Klein-Nishina regime → $\gamma x > 1$ where $x = h\nu/(m_e c^2)$

Electron spectrum in KN regime is harder than in Thomson regime $(\Gamma_{\text{e,KN}} < \Gamma_{\text{e,Thomson}})$

VHE Gamma-ray Production Mechanisms

- Proton-proton Interactions and π^0 Decay



$$\pi^0 \rightarrow \gamma_1 + \gamma_2,$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu,$$

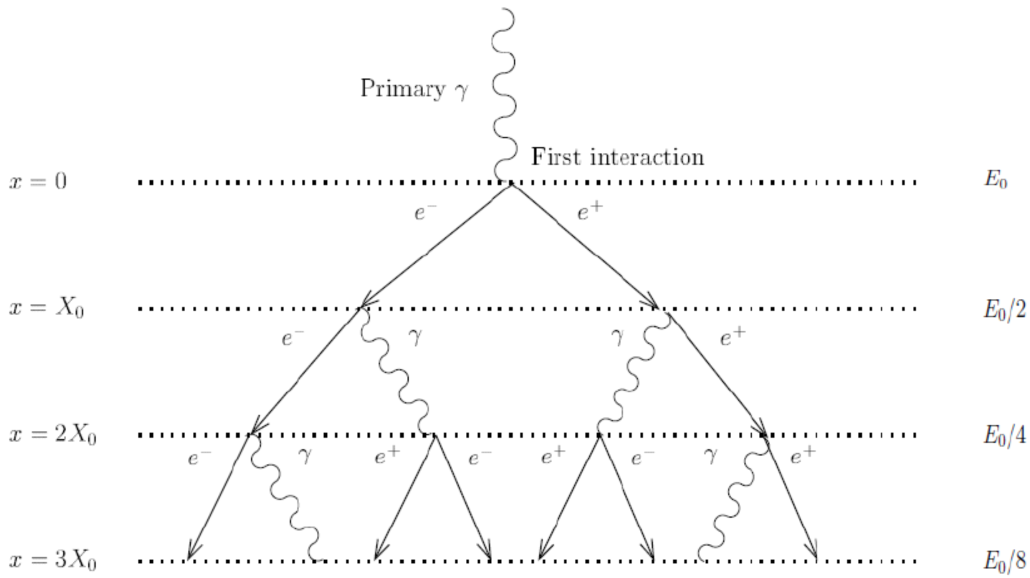
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu.$$

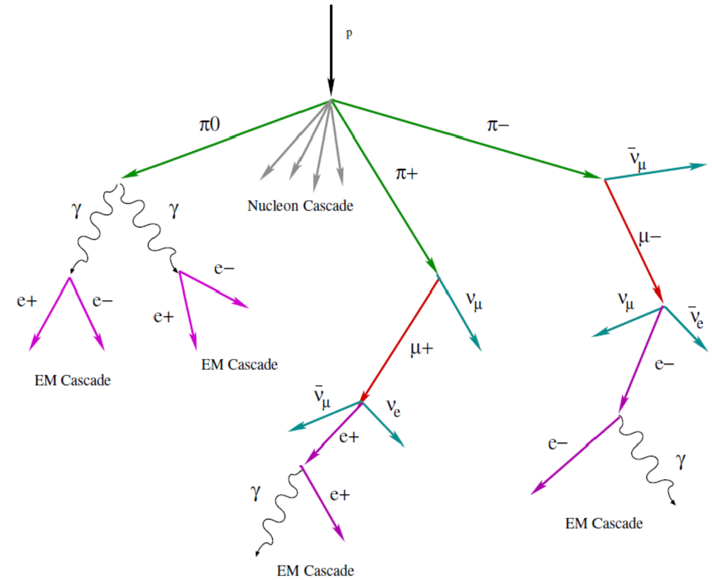
In hadronic interactions, π^0 decay is the most effective gamma-ray production channel.

The spectrum of gamma-rays from π^0 decays follows approximately the spectrum of the parent protons, $\Gamma_\gamma = 4/3(\Gamma_p - 1/2)$. So, gamma-rays carry direct information about the spectrum of progenitor particles (important for investigating the origin of Galactic cosmic-rays).

Expected neutrino flux will be relatively smaller when compared to observed gamma-ray flux.

Air Showers and Cherenkov Radiation





- Electromagnetic showers:

  VHE photon enters the atmosphere, it interacts with an atmospheric nucleus resulting in a pair production. e^{+}, and e^{-} are deflected by air molecules and emit bremsstrahlung radiation.

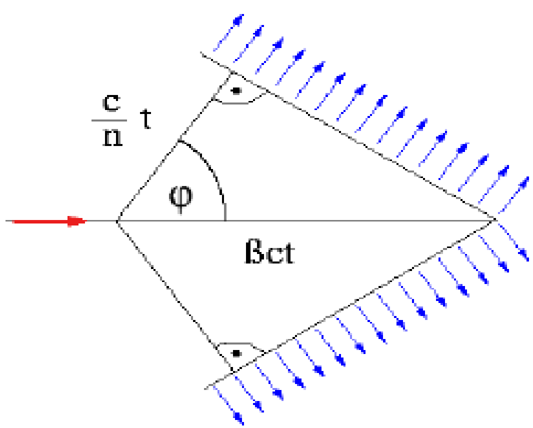
- Hadronic showers :

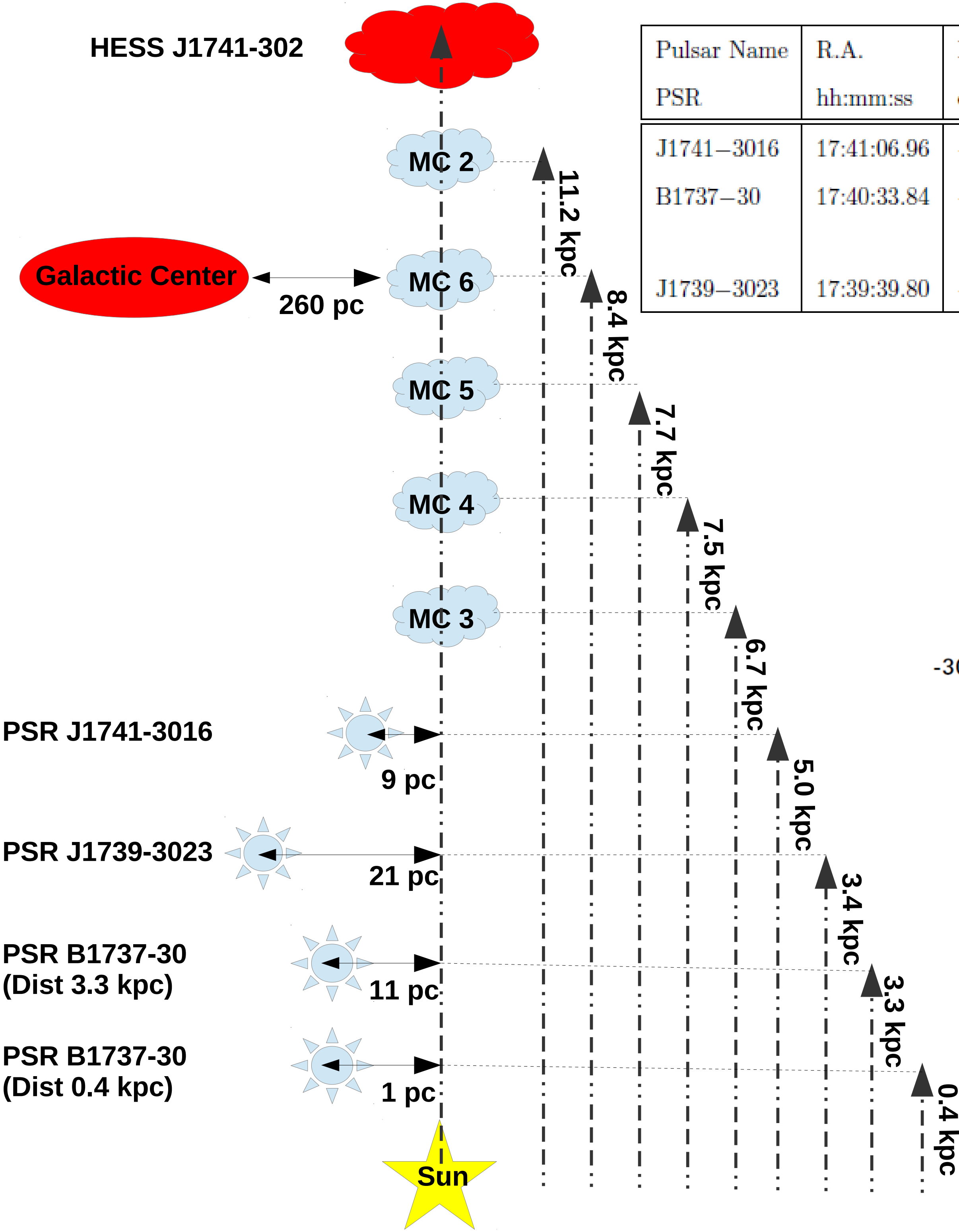
  Hadrons interact nearly only via strong interaction with the atmospheric nuclei. resulting in the production of secondaries, mainly mesons, but also nucleons (neutrons, protons)

- Cherenkov radiation is emitted when a charged particle passes through a dielectric medium at a speed faster than the speed of light in that medium.

$$\cos(\varphi) = \frac{1}{\beta n(\lambda)}$$

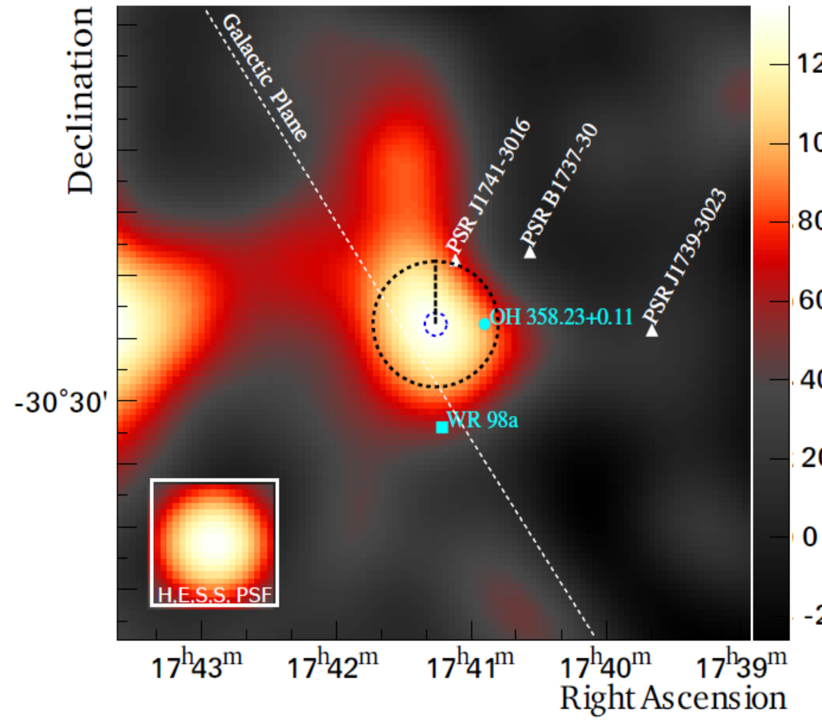
$$N(\nu)d\nu = 4\pi^2 \frac{(Zq)^2}{hc^2}\left(1 - \frac{1}{n^2\beta^2}\right)d\nu$$





Pulsar Properties

Pulsar Name PSR	R.A. hh:mm:ss	Dec. dd:mm:ss	τ_c kyr	$\dot{E}$ erg s^{-1}	Distance kpc	$\dot{E}/d^2$ erg s^{-1}kpc^2	Offset Degree
J1741−3016	17:41:06.96	−30:16:30.0	3340	5.2×10^{31}	5.02	2.06×10^{30}	0.1
B1737−30	17:40:33.84	−30:15:43.2	20.6	8.2×10^{34}	0.4	5.1×10^{35}	0.19
					3.28	7.6×10^{33}	
J1739−3023	17:39:39.80	−30:23:12.0	159	3.0×10^{35}	3.41	2.6×10^{34}	0.35

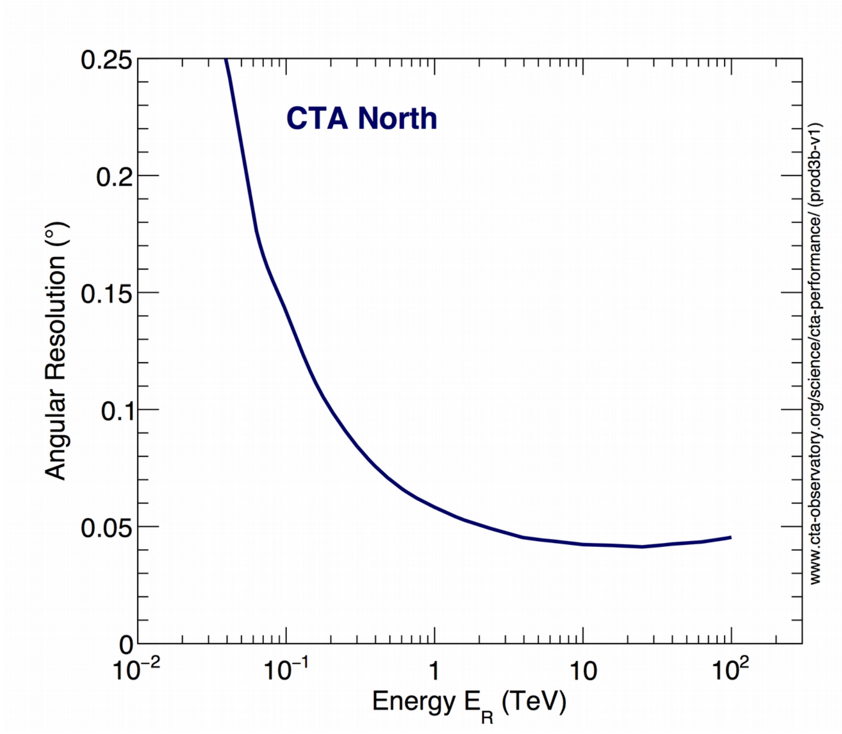


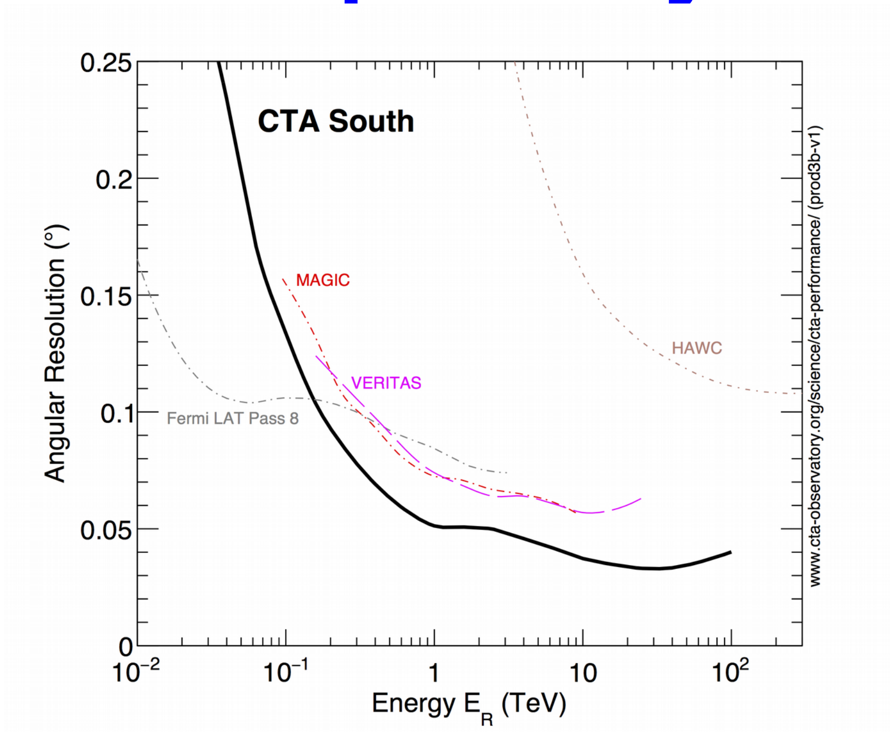
OH/IR star OH 358.23+0.11
(Distance = 0.4 – 4.0 kpc)

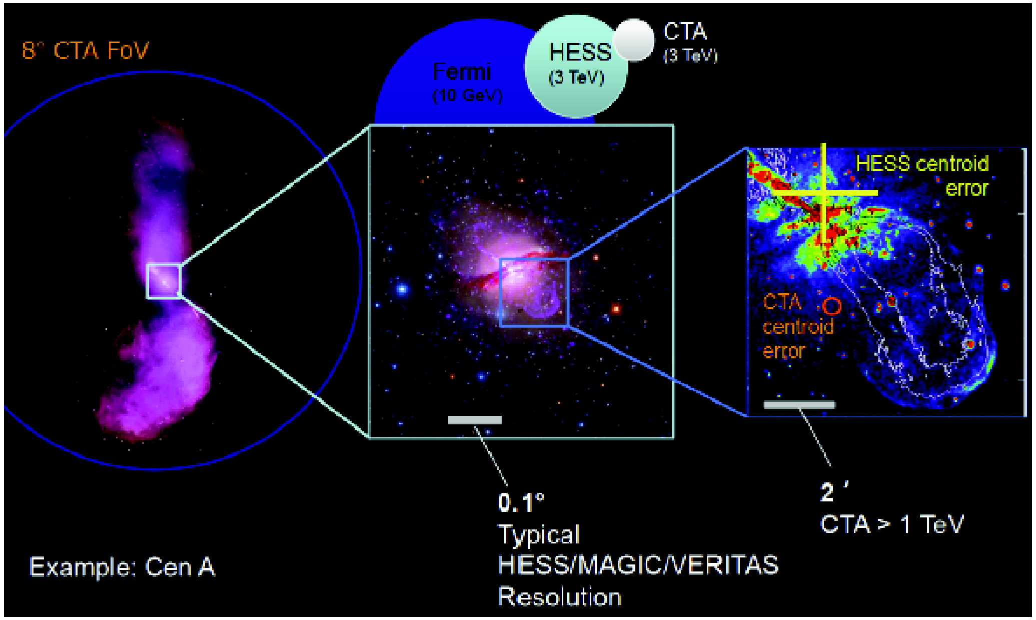
Wolf-Rayet (WR) binary WR 98a
(Distance 1.6 kpc)

No nearby or spatially coincident SNR

Cherenkov Telescope Array







- Better angular resolution allows better pin-pointing the observed VHE gamma-ray emission.
- CTA‘s improved angular resolution will allow much more detailed morphology studies of sources.

Centaurus A is the closest active radio galaxy, a giant elliptical galaxy about 11 million light years away.