Exploring the Extreme Universe: key results from the HAWC Observatory

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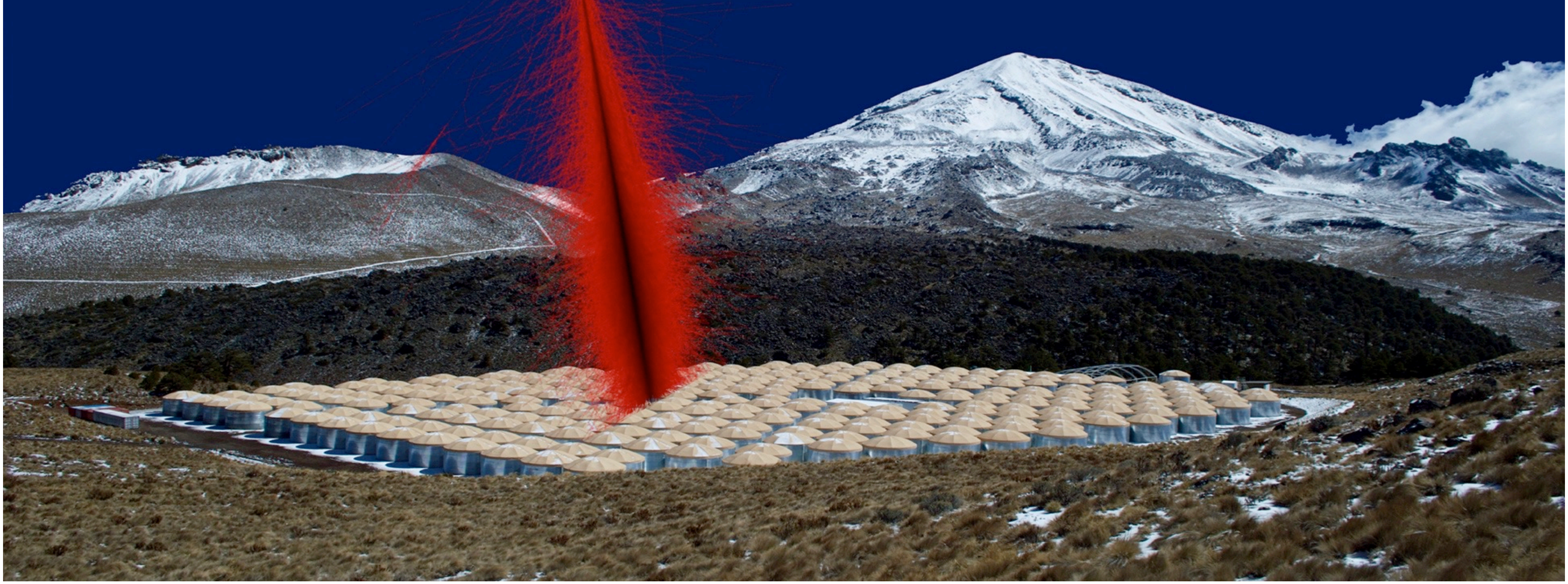

HAWC Collaboration

Mexico	United States of America	Europe	
Instituto Nacional de Astrofísica, Óptica y Electrónica	University of Maryland	Max Planck Institute für Kernphysik, Heidelberg	Alemania
Universidad Nacional Autónoma de México	Los Alamos National Laboratory	F. Alexander Universität, Erlangen	Alemania
Instituto de Astronomía UNAM	George Mason University	Institute of Nuclear Physics, Cracovia	Polonia
Instituto de Ciencias Nucleares UNAM	Georgia Institute of Technology	INFN & Universita di Padova	Italia
Instituto de Física UNAM	Michigan State University	IFIC - Universidad de Valencia	España
Instituto de Geofísica UNAM	Michigan Technological University		
Benemérita Universidad Autónoma de Puebla	Pennsylvania State University	**Asia**	
Centro de Investigación y Estudios Avanzados	NASA GSFC	University of Seoul	Corea del Sur
Instituto Politécnico Nacional	Stanford University	Shanghai Jiao Tong University	China
Centro de Investigación en Cómputo	University of California Santa Cruz	Chulalongkorn University	Tailandia
Instituto de Física	University of California Irvine		
Universidad Autónoma de Chiapas	University of New Hampshire	**Latin America**	
Universidad Autónoma del Estado de Hidalgo	University of New Mexico	Universidad de Costa Rica	Costa Rica
Universidad de Guadalajara	University of Rochester		
Universidad Michoacana de San Nicolás de Hidalgo	University of Utah		
Universidad Politécnica de Pachuca	University of Wisconsin		

United States of America
400 mi
400 km
San Diego
Phoenix
Tijuana
Mexicali
Tucson
El Paso
Dallas
Nogales
Ciudad Juarez
Rio Grande
San Antonio
Houston
New Orleans
Mobile
Hermosillo
Chihuahua
Galveston
Baja Peninsula
Guaymas
Sierra Madre Occidental
Conchos
Nuevo Laredo
Gulf of California
Gulf of Mexico
Pacific Ocean
Mexico
Brownsville
Monterrey
Matamoros
Central Plateau
Sierra Madre Oriental
Caribbean Sea
La Paz
TROPIC OF CANCER
Cabo San Lucas
Mazatlan
Durango
Playa del Carmen
Cancun
Tampico
Aguascalientes
Marias Islands
Merida
N
Leon
Bay of Campeche
Puerto Vallarta
Guadalajara
Mexico City
Yucatan Peninsula
Veracruz
Revillagigedo Islands
Manzanillo
Puebla
Volcan Orizaba
Sierra Madre del Sur
Cozumel
Balsas
Ixtapa/Zihuatanejo
Oaxaca
Usumacinta
Tuxtla
Acapulco
Santa Cruz
Gulf of Tehuantepec
Central America
MEXICO
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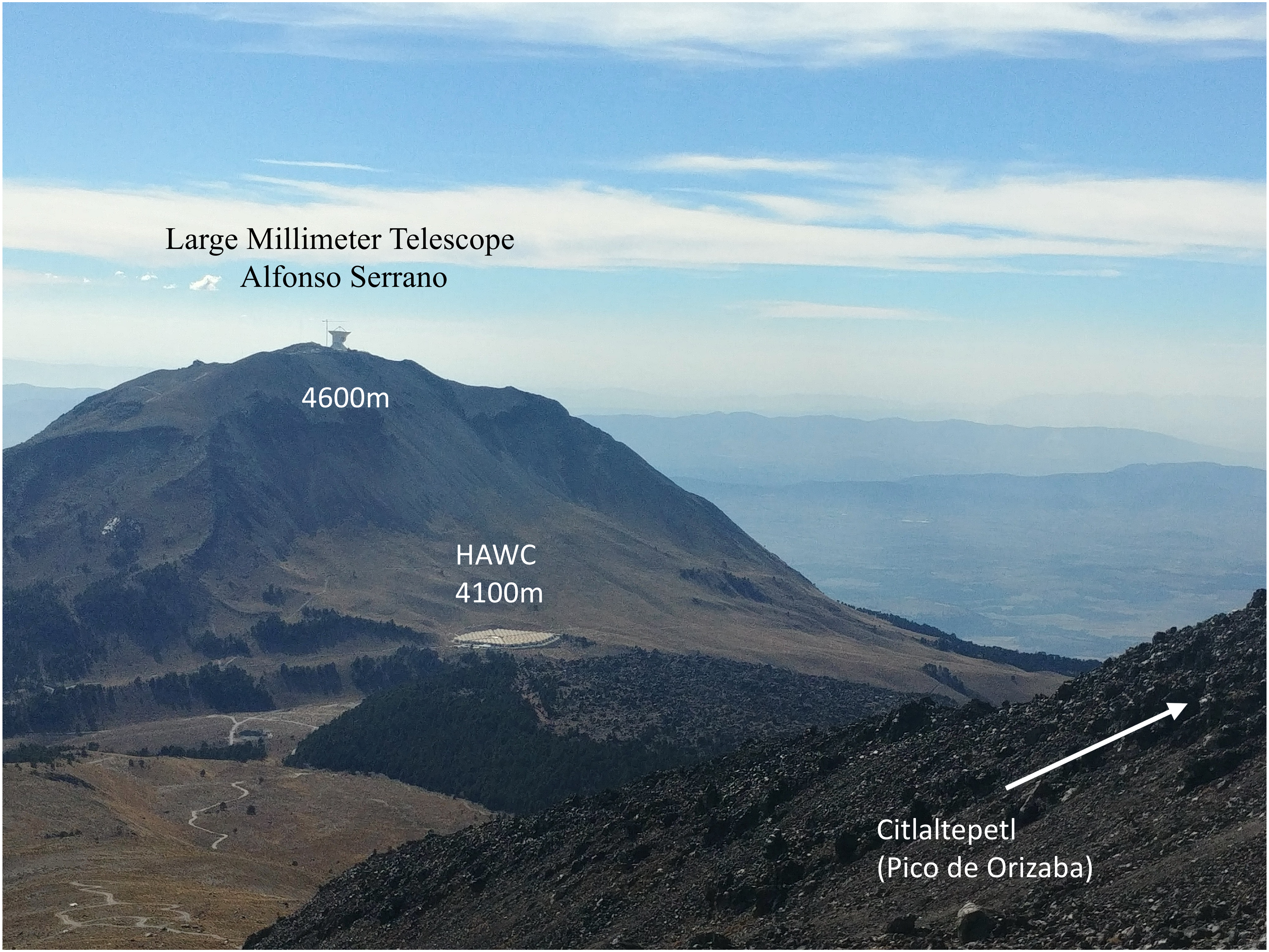
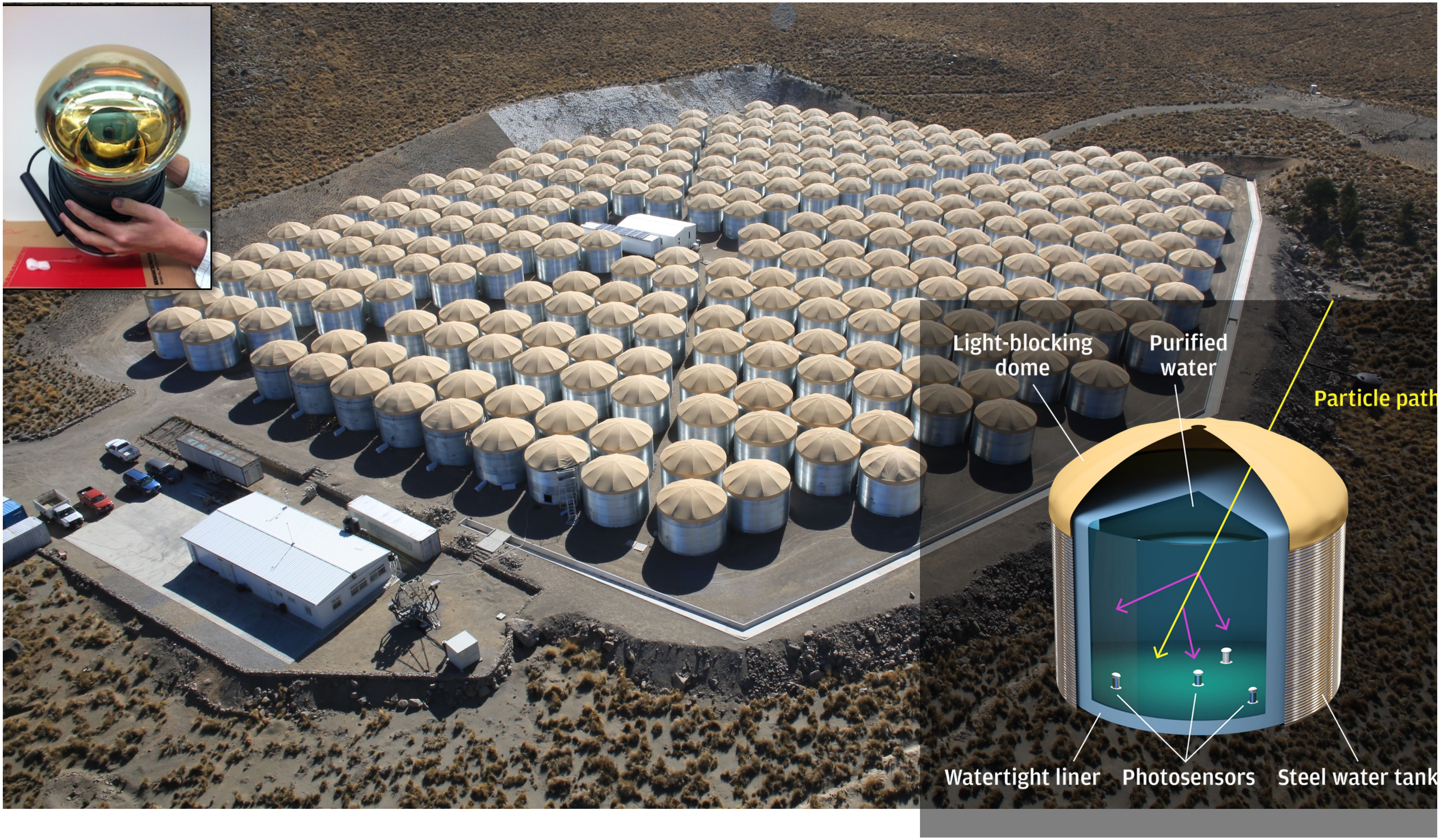
Pico de Orizaba
“Citlaltepetl”
5610m (18,400 ft)
HAWC
Sierra Negra
“Tliltepetl”
4582m (15,000 ft)

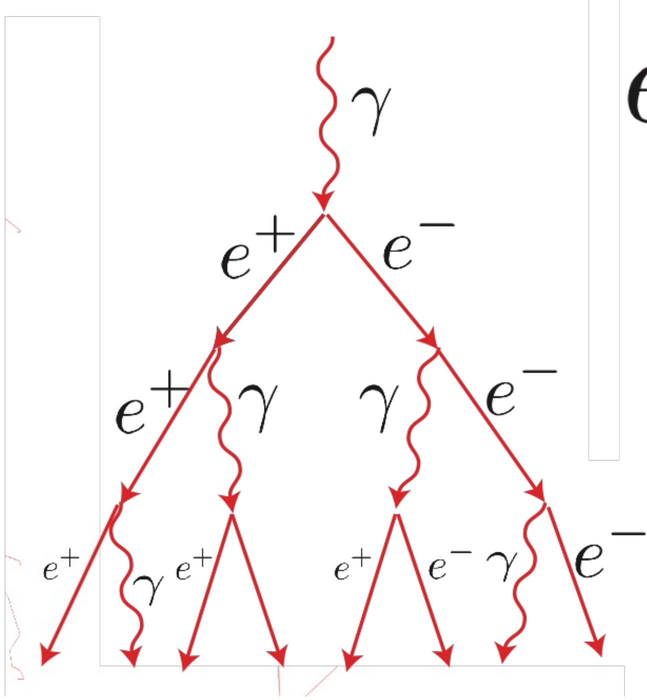

Large Millimeter Telescope
Alfonso Serrano
4600m
HAWC
4100m
Citlaltepetl
(Pico de Orizaba)

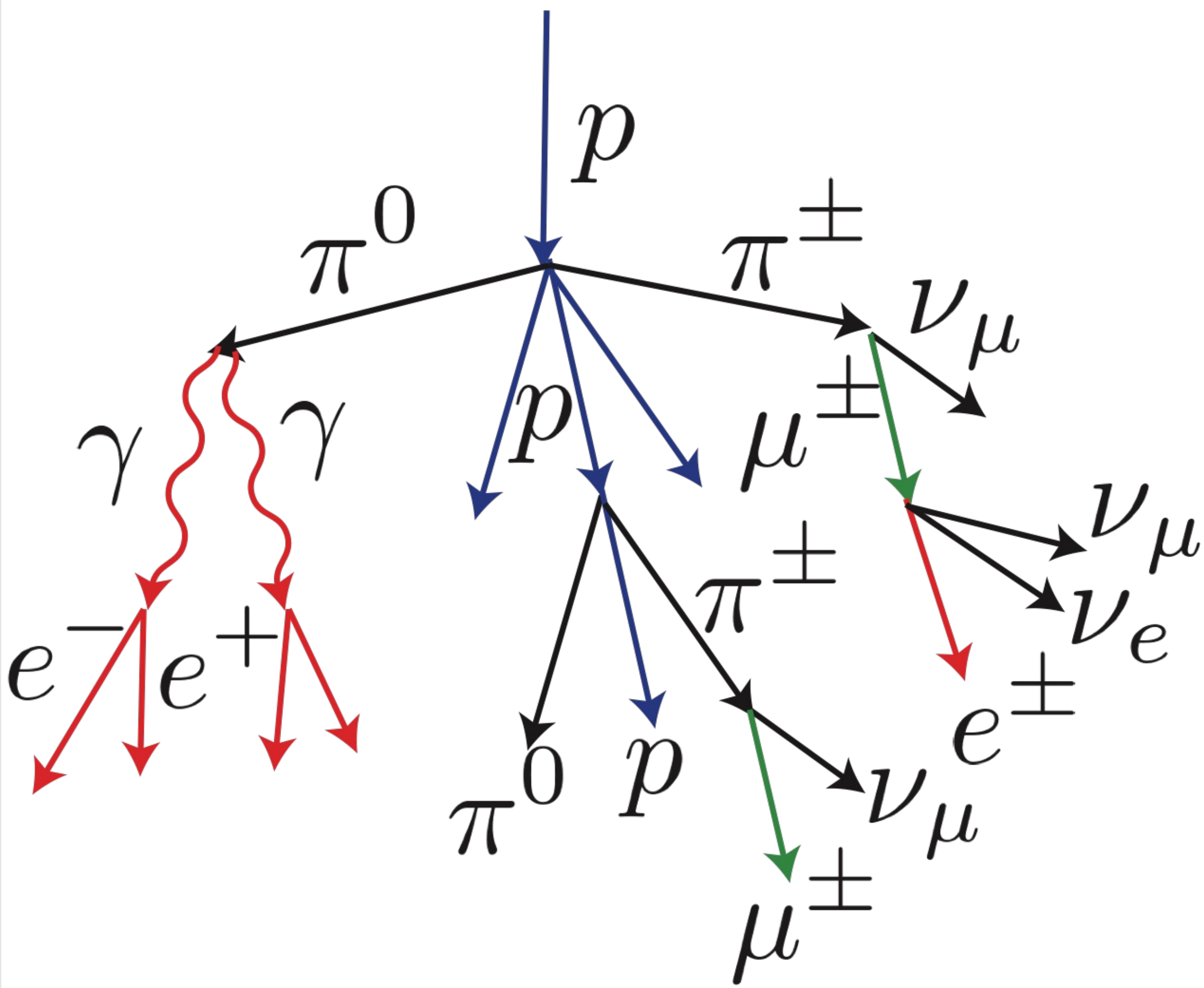


300 close-packed optically isolated water Cherenkov detectors
Funding from a combination of US and Mexican agencies
Takes data with >95 on time
~5 trillion triggers to date - 7PB of data

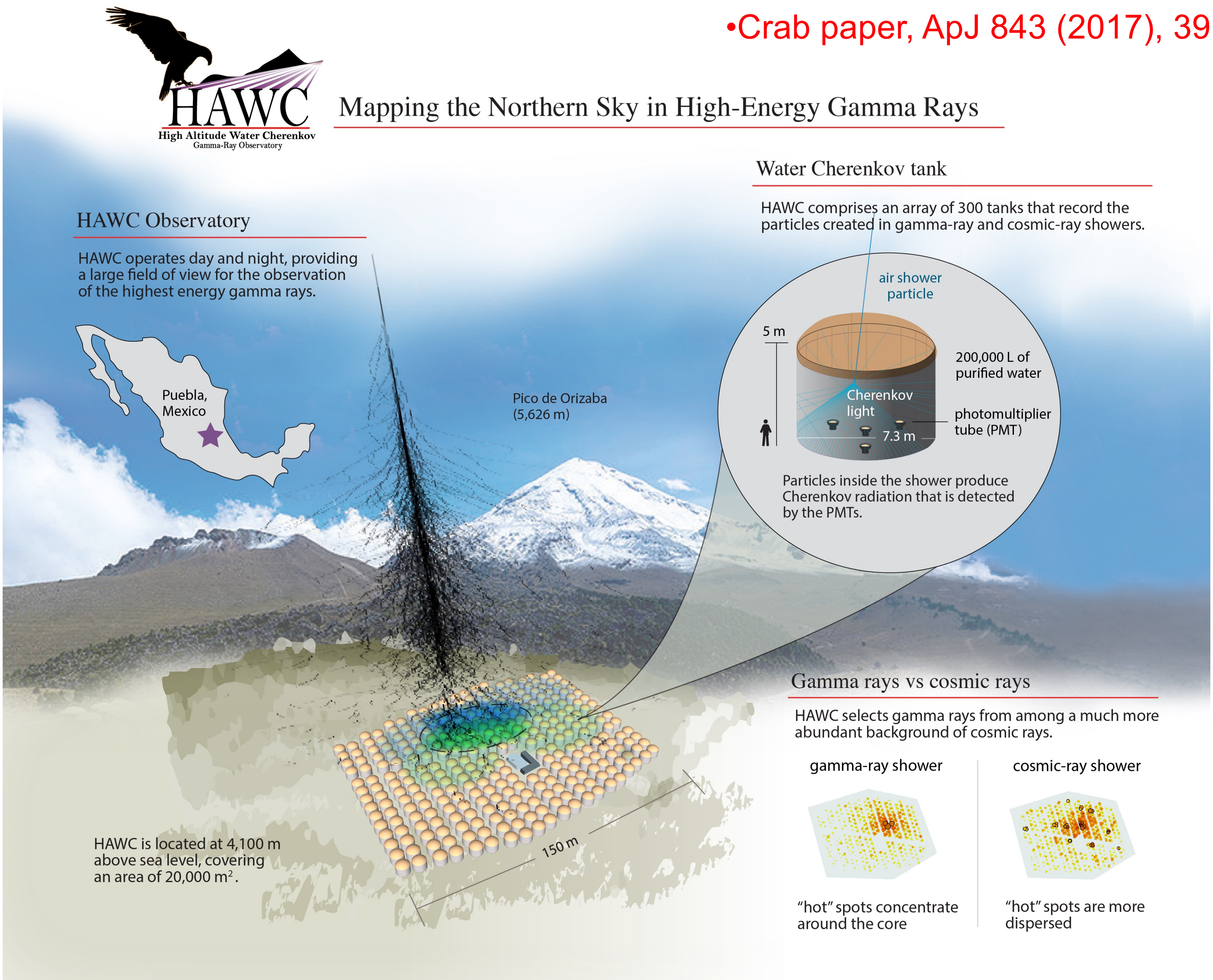
2015 – main array

High energy extension
2018 – outrigger array

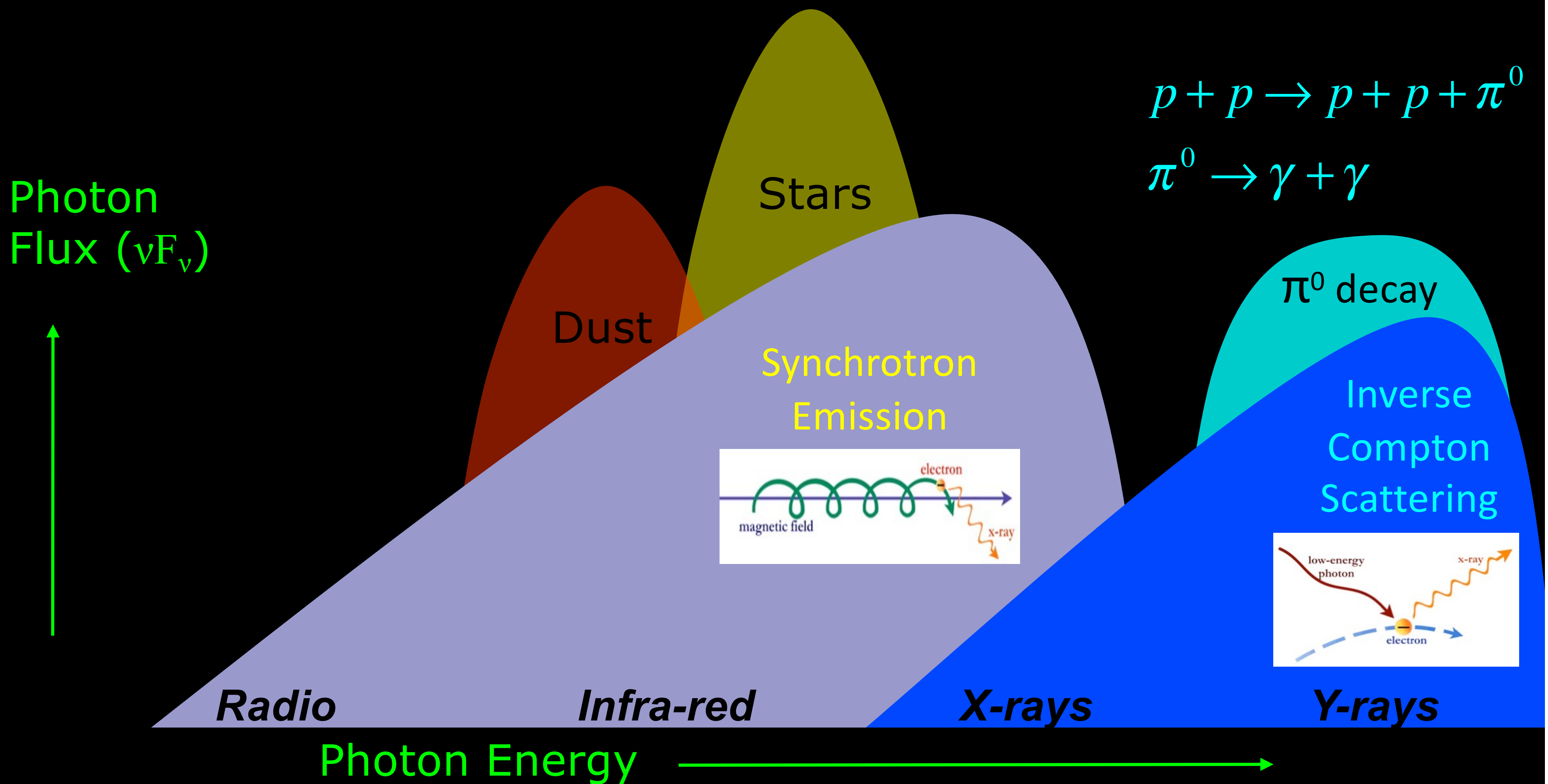

γ
e^+
e^-
e^+
γ
γ
e^-
e^+
γ
e^+
e^+
e^-
γ
e^-


p
π^0
$\pi^\pm$
ν_μ
γ
γ
p
$\mu^\pm$
ν_μ
$\pi^\pm$
ν_e
e^-
e^+
$e^\pm$
π^0
p
ν_μ
$\mu^\pm$

•Crab paper, ApJ 843 (2017), 39.



- **High energy** gamma rays are only produced by ***non-thermal*** processes.
  - Inverse Compton Scattering (for electrons) – Leptonic Model
  - Neutral pion decay (for protons) – Hadronic Model



PROS and CONS

Leptonic models

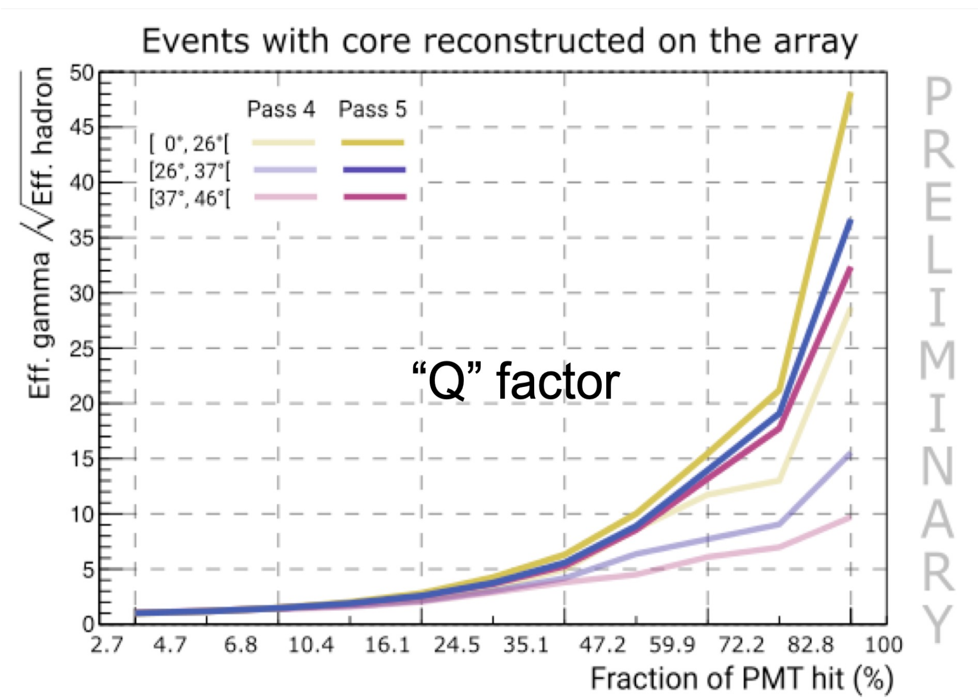
- Electrons are easy to accelerate but they are also Good radiators
- Produce X-ray or radio emission by synchrotron
- Klein-Nishina limit – cross section decreases dramatically
- They don’t travel far because of fast cooling

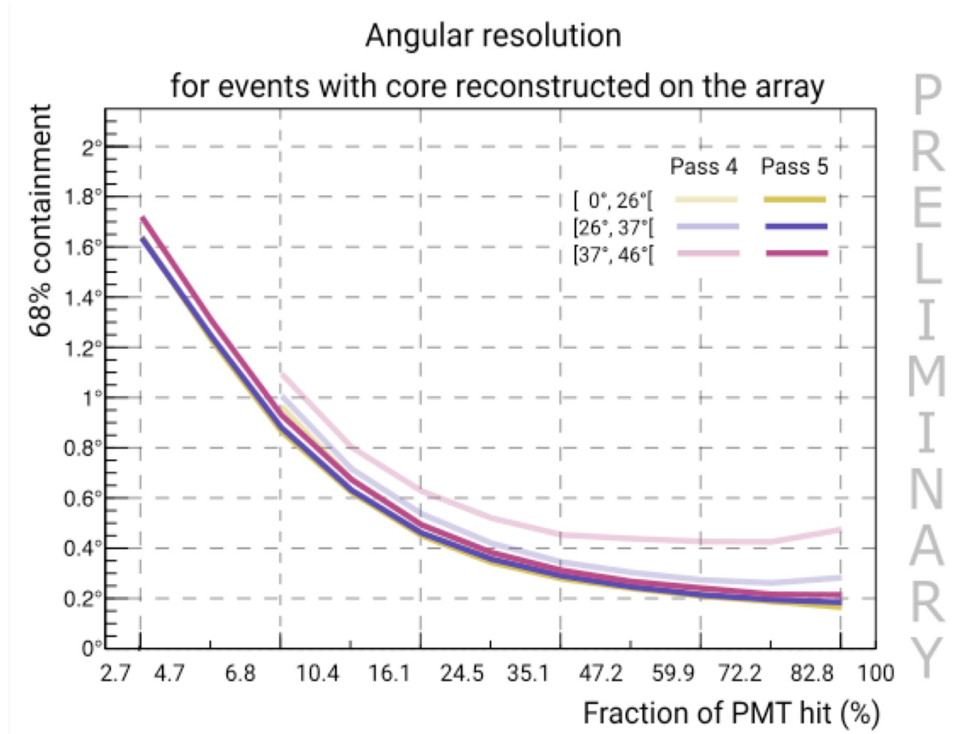
Hadronic models

- Need targets – other protons (molecular clouds) or low energy photons
- Difficult to accelerate – large amount of energy
- Accompanied by neutrinos
- Galactic PeVatrons

HAWC

- 300 GeV to >100 TeV sensitive energy range.
- Angular resolution of 0.15˚
- f. o. v. up to zenith of 55˚
- Continuous operation > 95% of the time



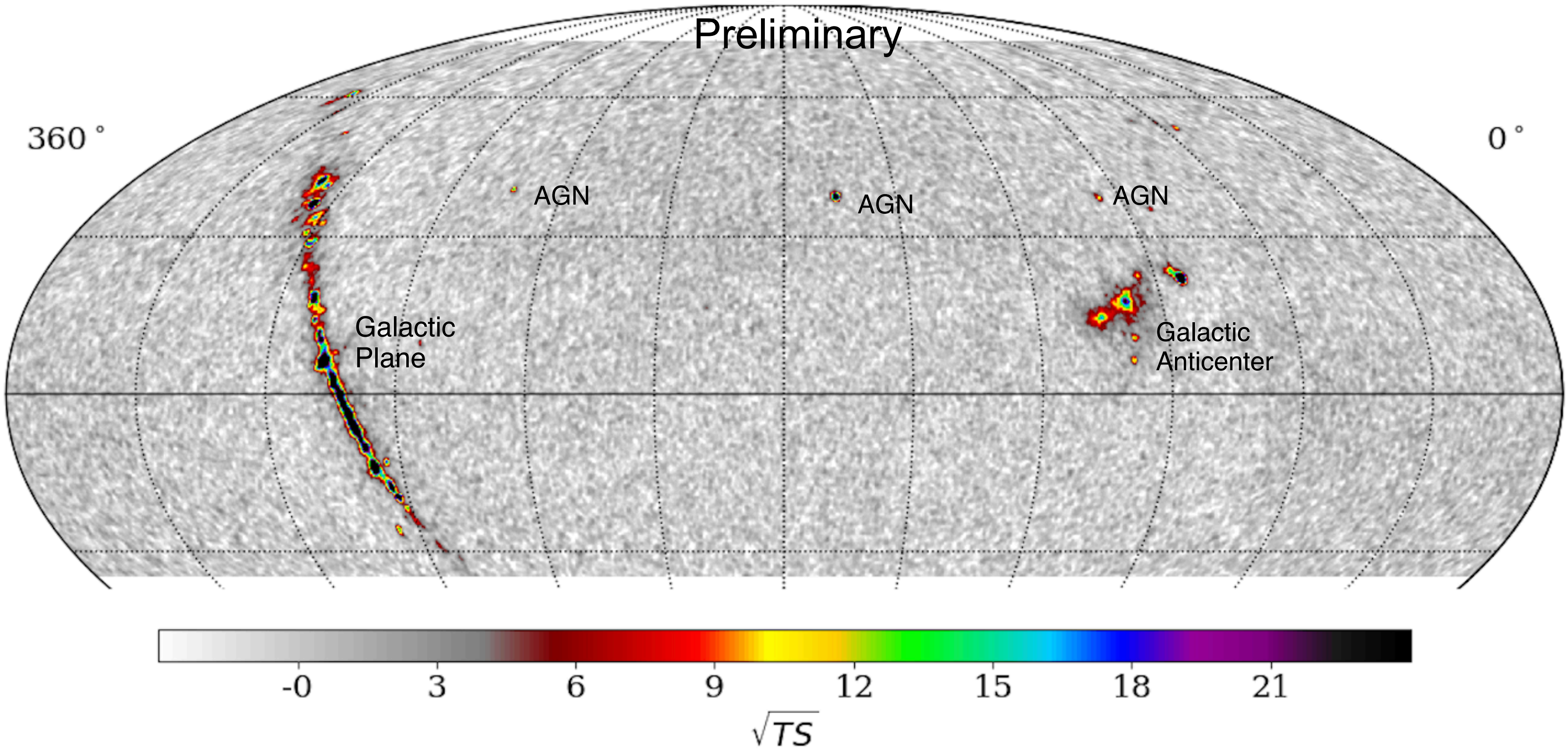


HAWC strengths for:

- Sky Survey
- Extended sources (>1-2˚)
- Sources of the highest energies (>10 TeV)
- Transient/variable sources

- HAWC operating since March 2015
- Standard analysis excludes the smallest showers (> 2.7% of detector) ➔ energy range (~0.3-100 TeV for ≥1 day integration time)

HAWC Sky Map 3040 Days of Data - Pass 5

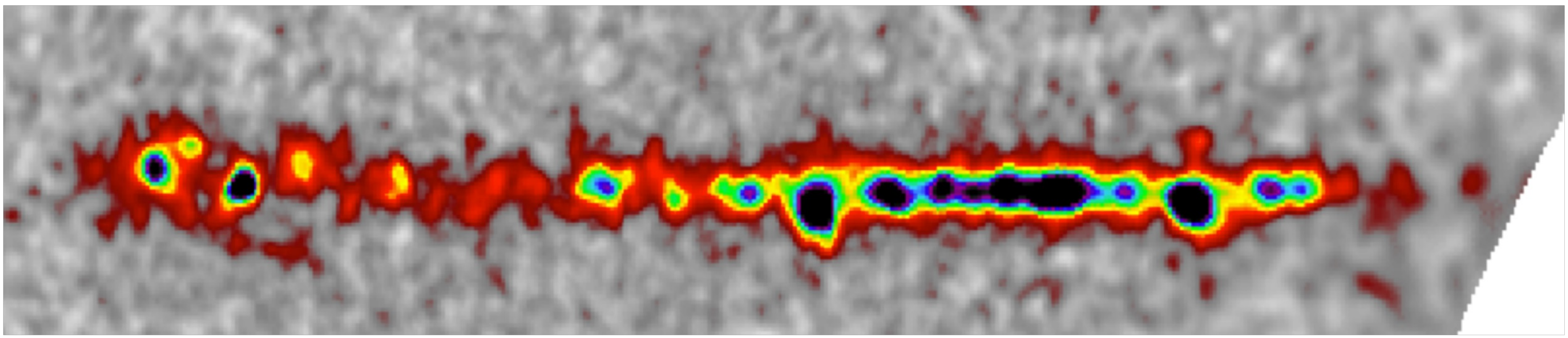


Spring 2024 - J Goodman

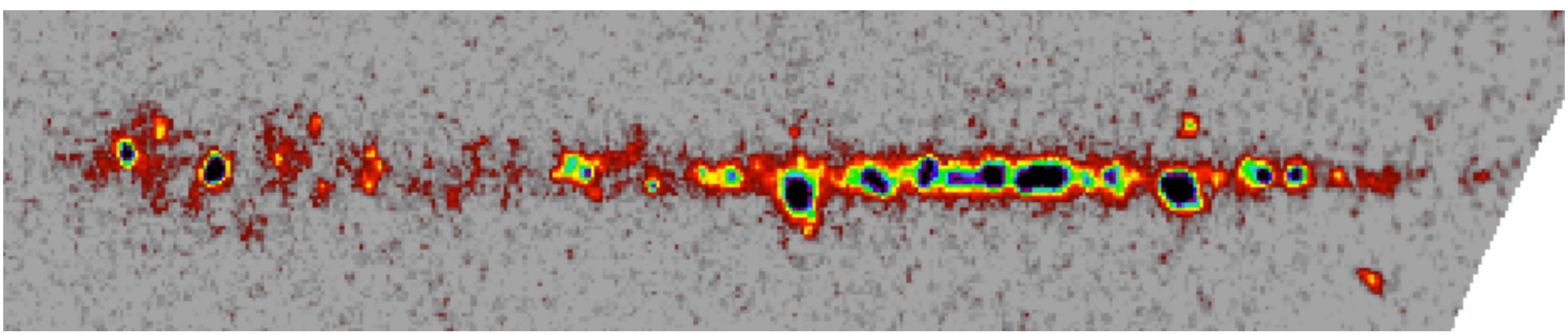
X

Pass 4 (1523d) vs Pass 5 (2090d)

Pass 4



Pass 5

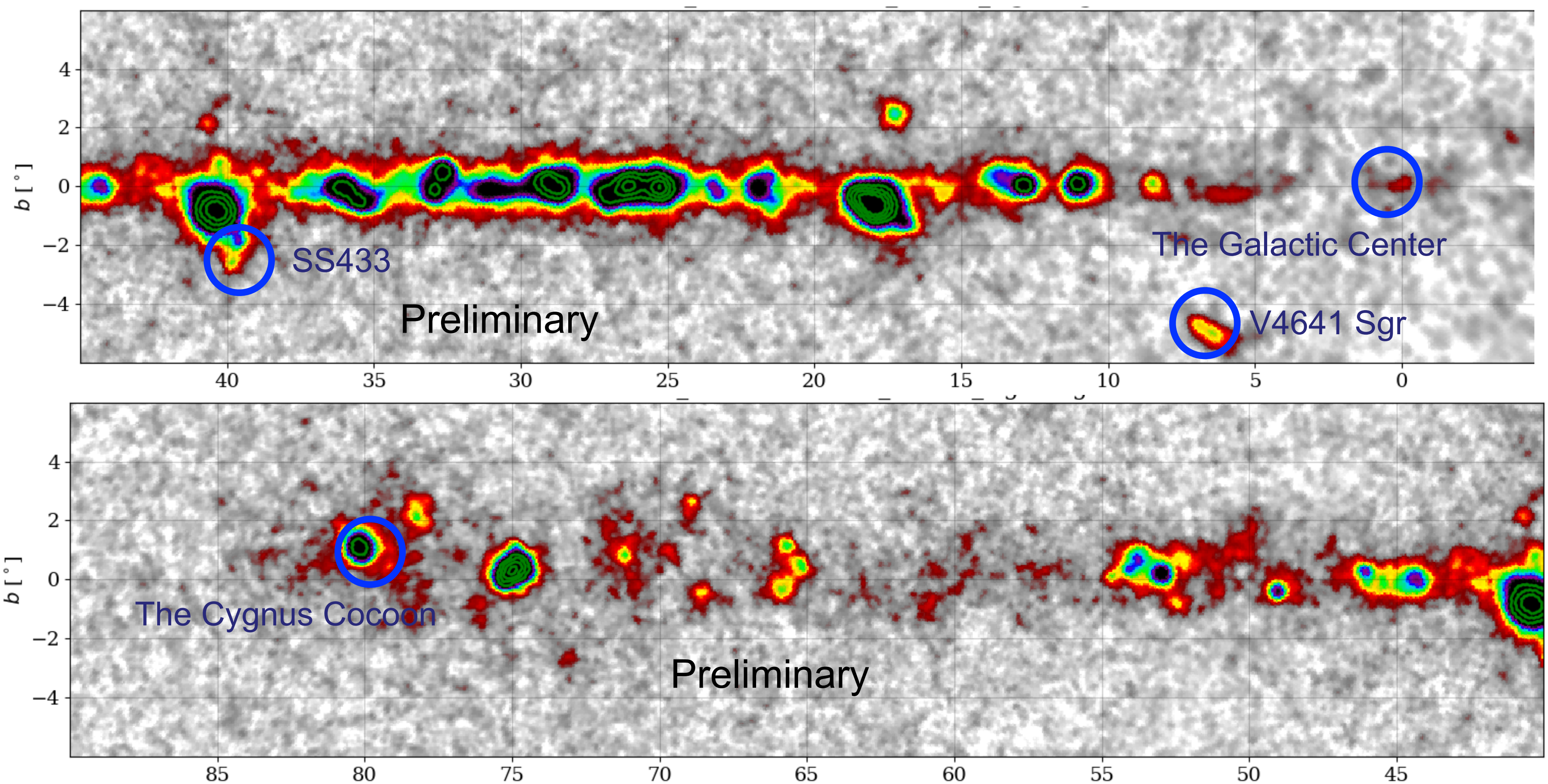



Pass 6 is coming

HAWC Recent Results

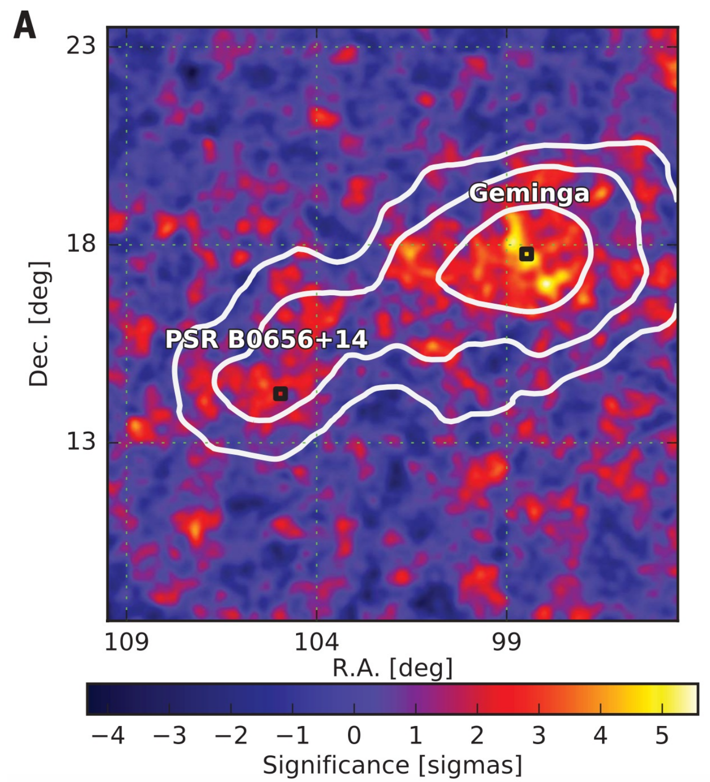
- Updated sky maps:
  - Improved resolution and gamma/hadron rejection
- Highest Energy Sky
- HAWC measurements of potential PeVatrons
- Binaries
  - LS 5039, SS 433
  - V4641 Sgr
- Galactic Center
- More AGNs detected
- Cygnus Cocoon
- TeV Halos (a new one)
- TeV Gamma rays from the Sun
- Cosmic Ray Spectra
- Dark Matter and LIV Limits
- Follow up of extragalactic transients: GRBs and GW

Pass 5 - 3040 Day Map



Nearby PWN are very extended

- Geminga and PSR J0659+1414 (associated with Monogem SNR) are seen in 2˚ radius (~ 10 pc) smoothed HAWC maps



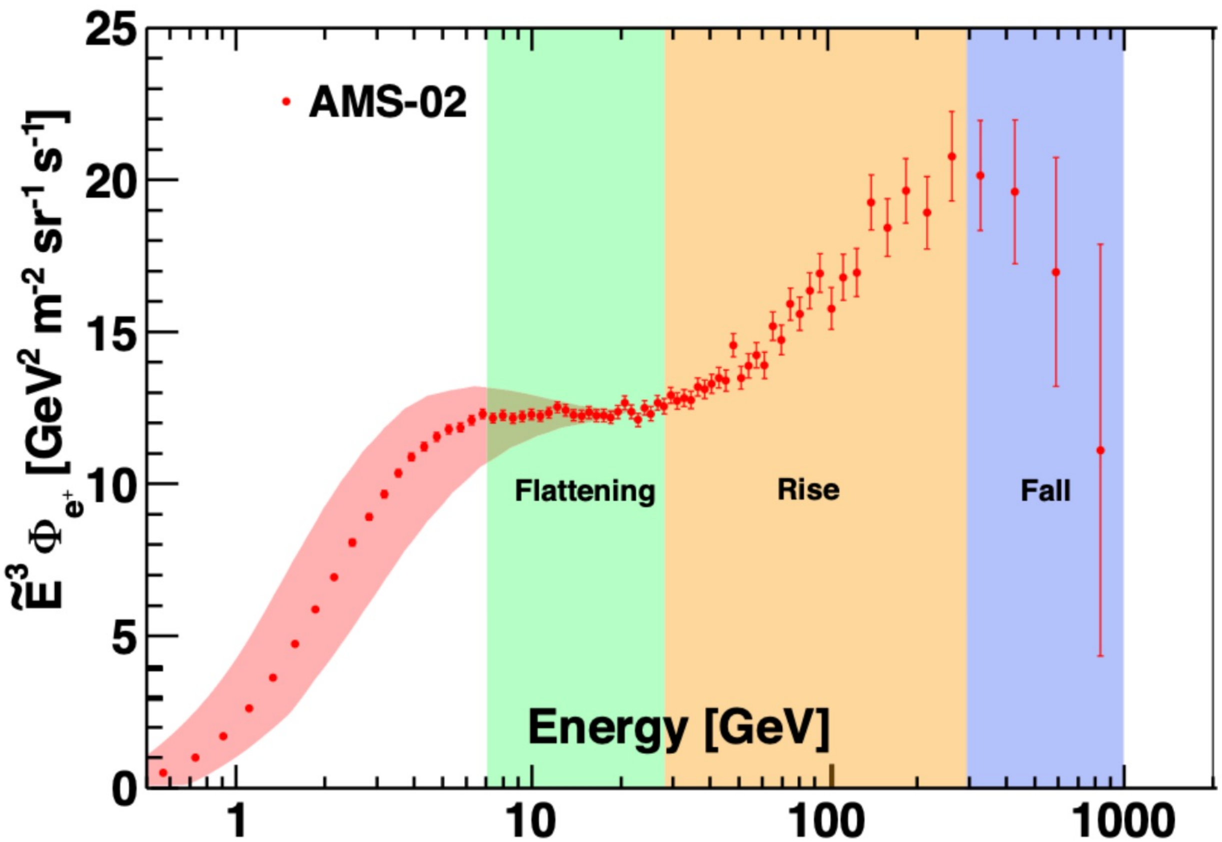
Abeysekara, et al, Science 358 (2017) iss. 6365.

Coincidentally similar pulsars:

	Geminga (J0633+1746)		B0656+14
$\dot{E}$	3.2x10^{34} erg/sec	$\dot{E}$	3.8x10^{34} erg/sec
τ	3.42x10^{5} yr	τ	1.1x10^{5} yr
d	250 pc	d	288 pc
Diameter:	5.5 deg	Diameter:	4.5 deg
Extent:	17 pc	Extent:	24 pc

(for 20 TeV γ-rays)

• Postulated as the best sources of the observed PAMELA and AMS positron excess.
- Close and old enough so highest-energy electron and positrons arrive to the Earth



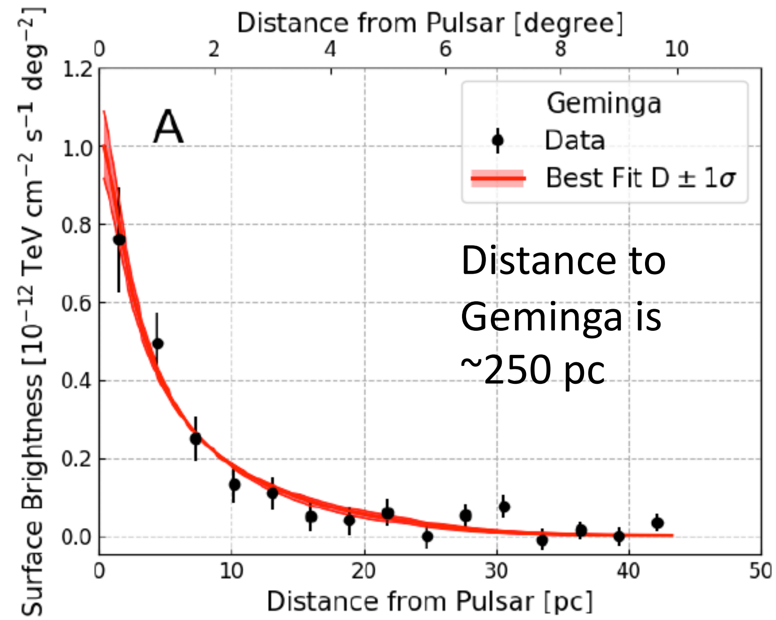
Possible sources:

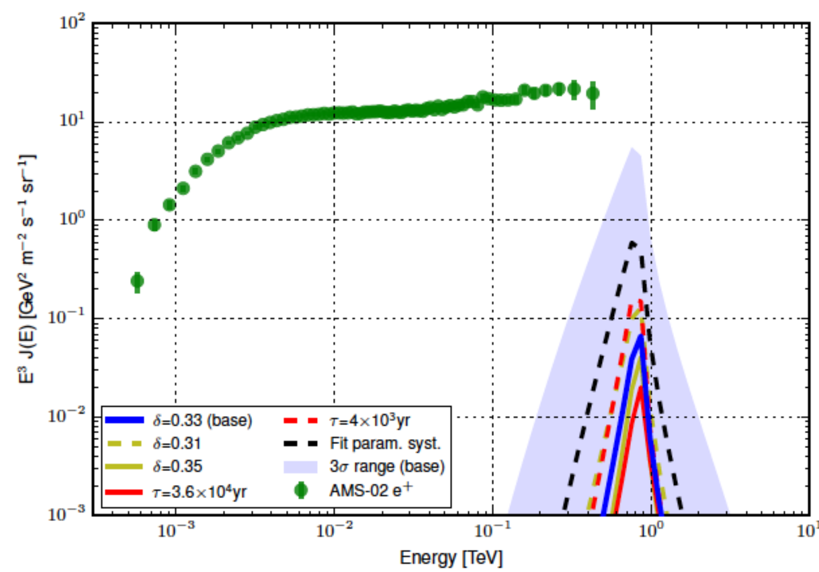
- Pulsars/PWN (Aharonian et al 1995, Yüksel et al, 2009, Linden & Profumo, 2013)
- Dark Matter (many)
- Microquasar jets (Gupta & Torres 2014)

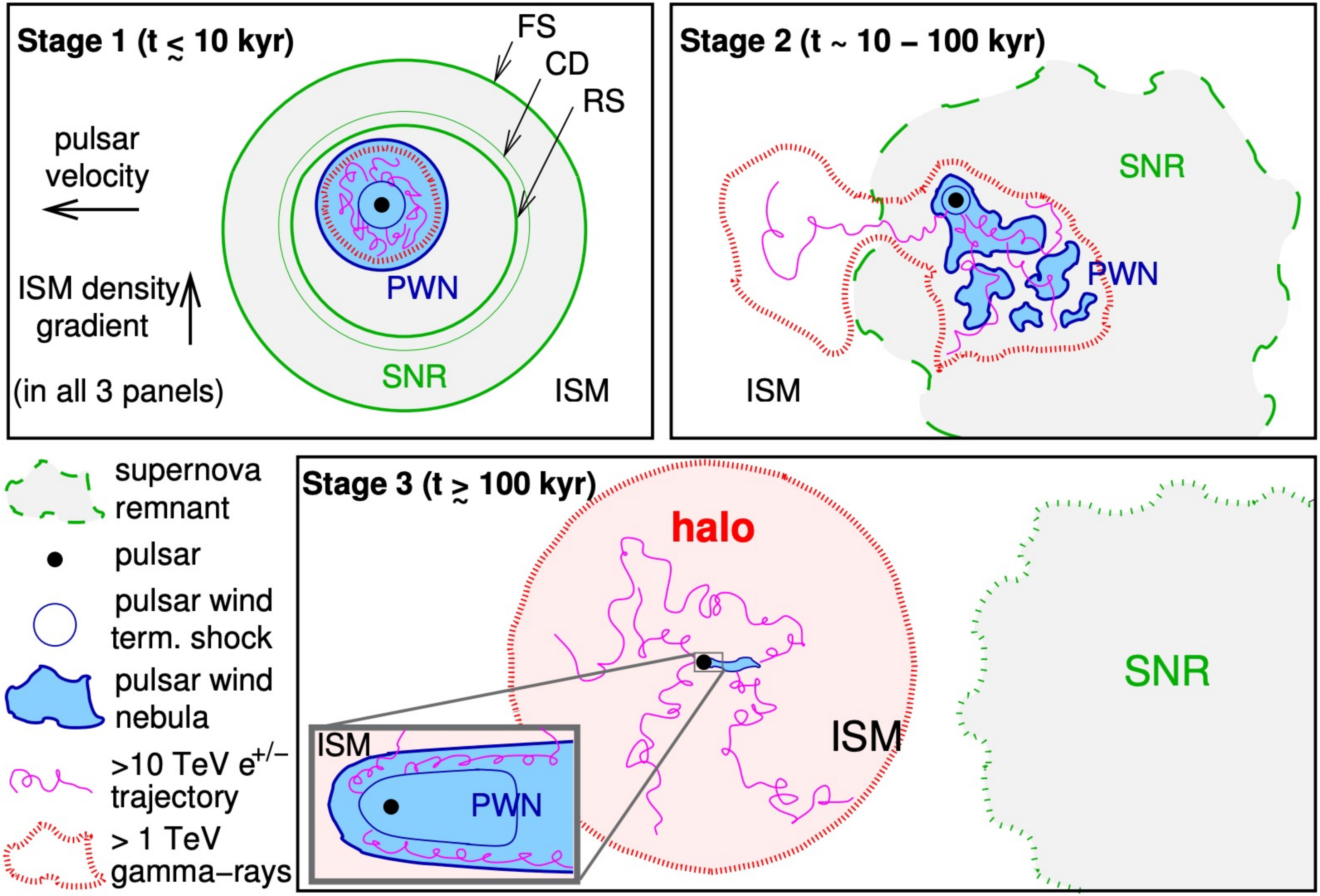
Science 17 November 2017

Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth

- indeed accelerating electrons and positrons to multi-TeV energies.
- measurement of the total energy released in electrons and positrons which is much of their measured spin down energy.
- HAWC observations of the angular extent of these TeV nebula measures the diffusion coefficient of their propagation in the interstellar medium.
- HAWC observations show that Geminga and Monogem do NOT contribute significantly to the AMS measured positron excess if that same diffusion continues to Earth
- Fermi detection of Geminga PWN confirmed this conclusion and measures consistent diffusion coefficient at lower energies
- Diffusion coefficient too small compared to the measured locally.

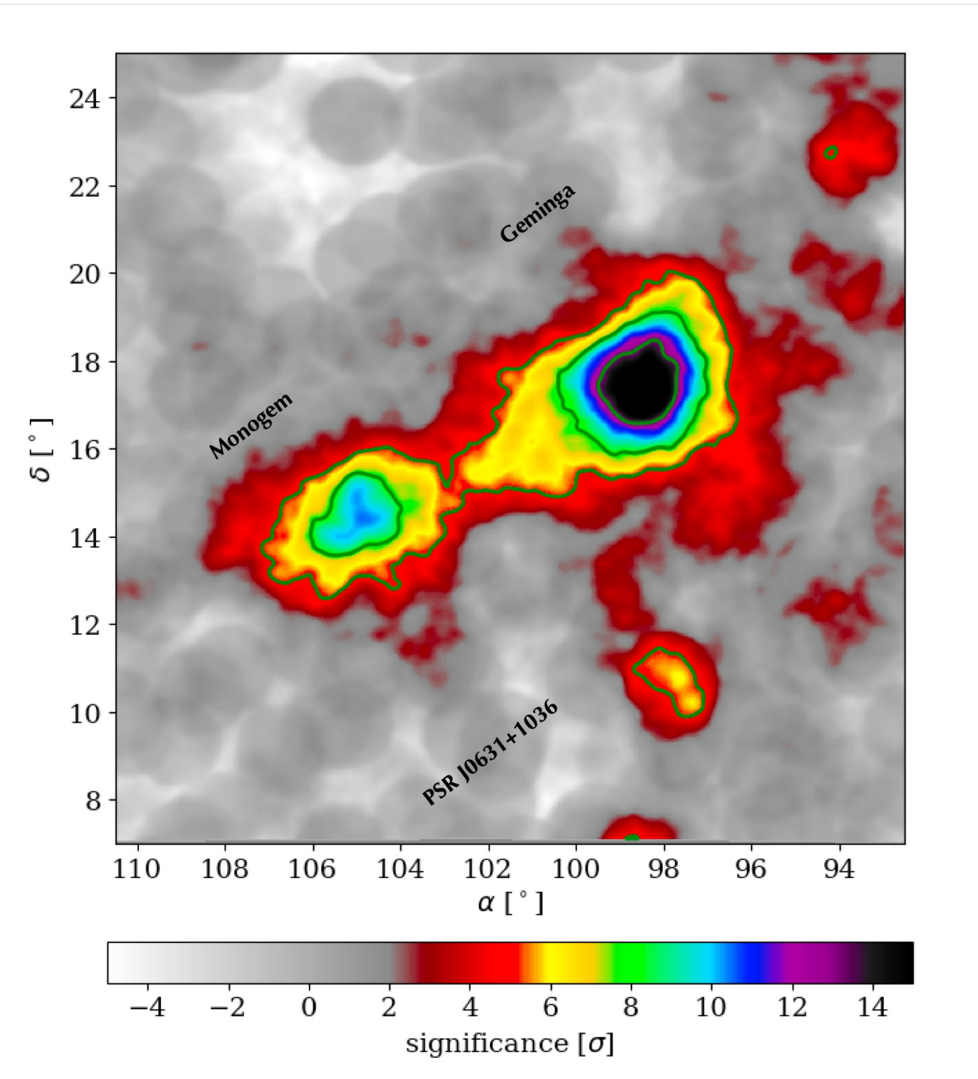


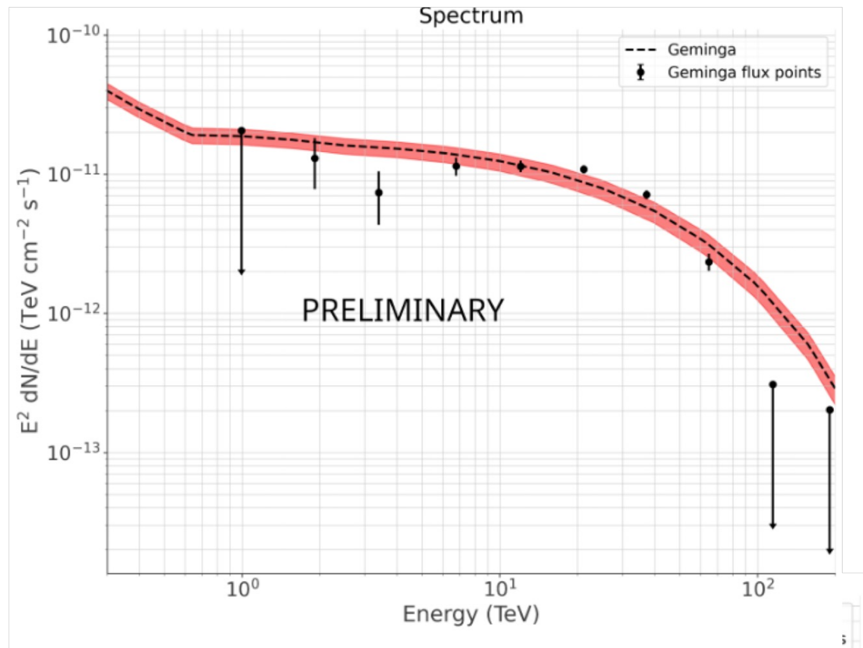


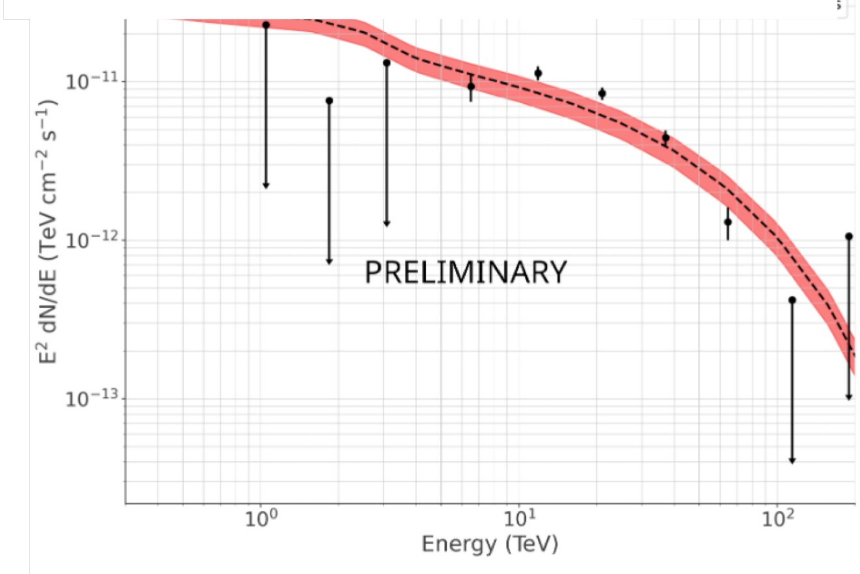


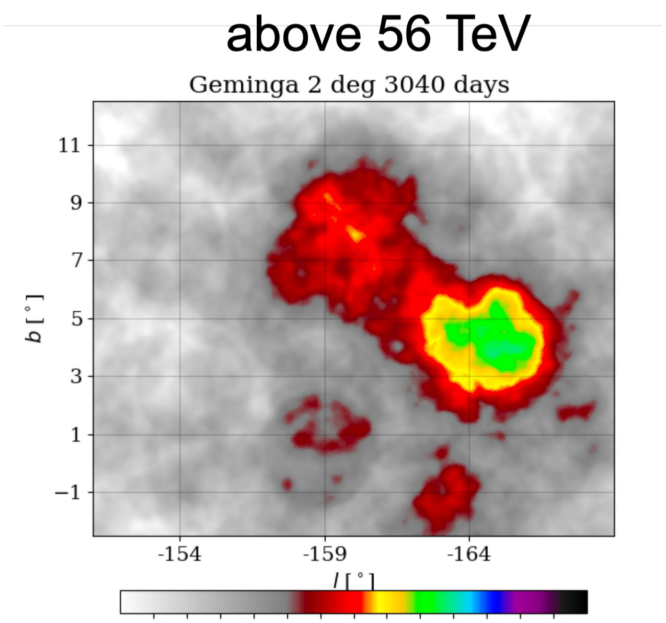
Stage 1 (t ≲ 10 kyr)
FS
CD
RS
pulsar velocity
ISM density gradient
(in all 3 panels)
PWN
SNR
ISM
Stage 2 (t ~ 10 – 100 kyr)
SNR
PWN
ISM
supernova remnant
pulsar
pulsar wind term. shock
pulsar wind nebula
>10 TeV e+/− trajectory
> 1 TeV gamma–rays
Stage 3 (t ≳ 100 kyr)
halo
ISM
PWN
ISM
SNR

New From Pass 5









Confirms the diffusive model with a diffusive coefficient three orders of magnitude lower than the measured locally

Emission beyond 56 TeV
Leptonic emission through IC with CMB

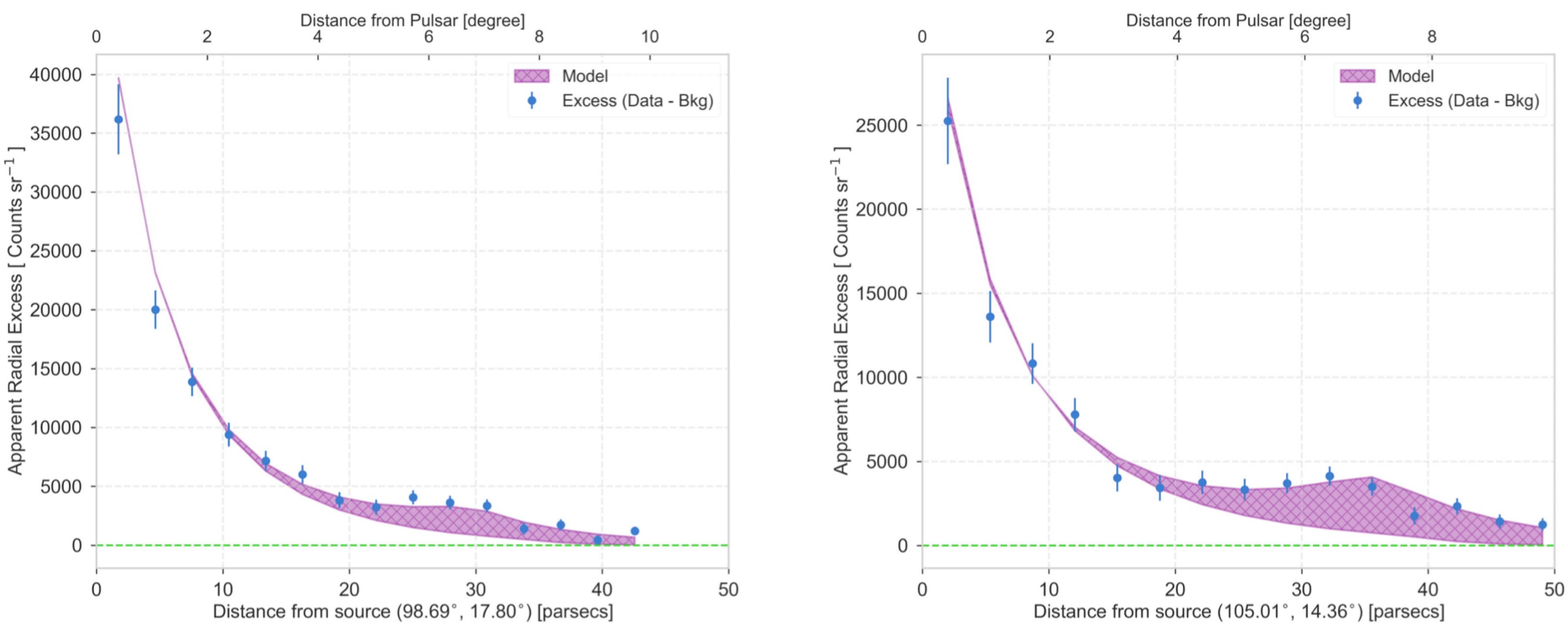


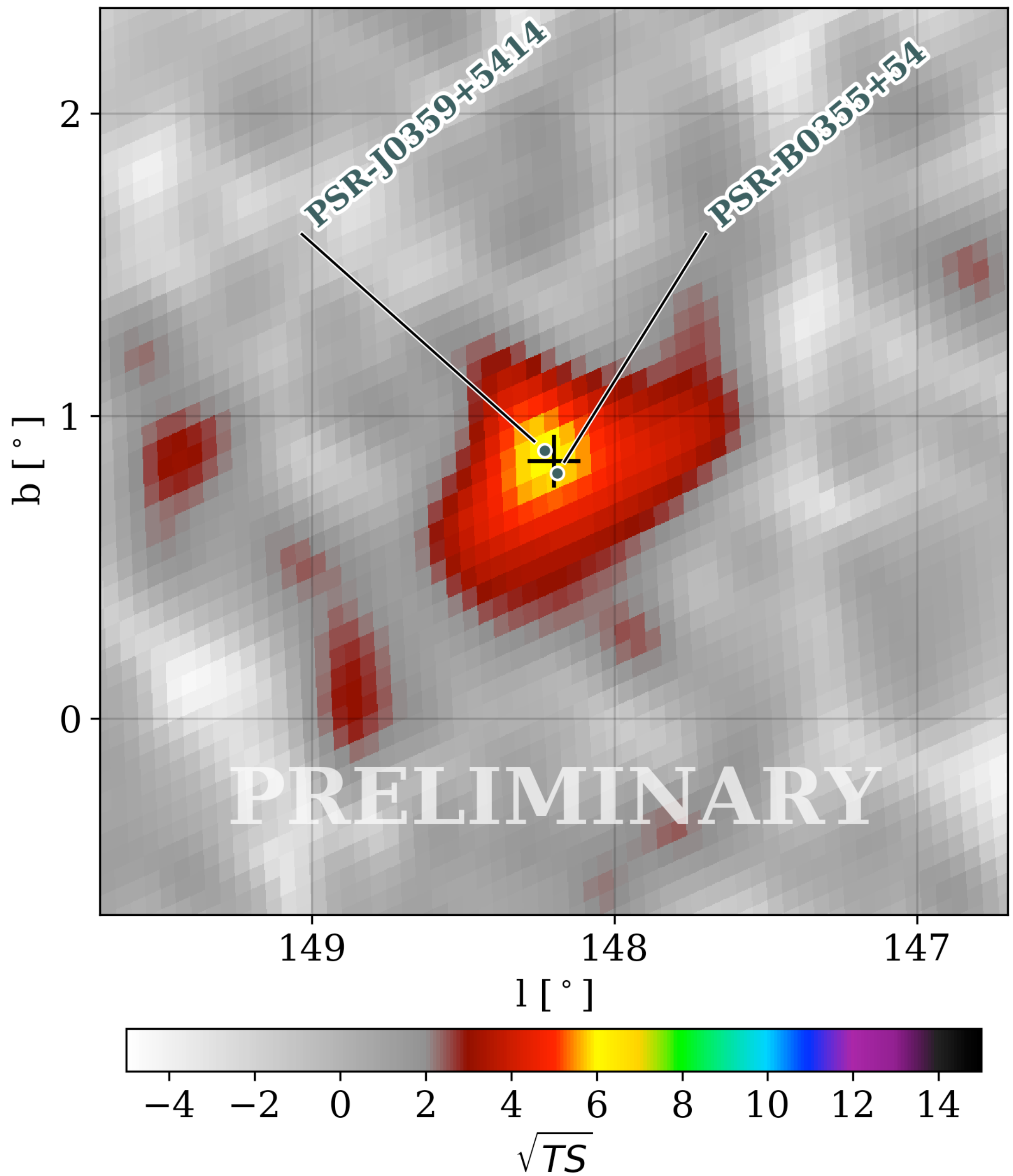
Figure: The purple band shows the contamination of neighboring pulsar.

•PSR J0359+5414 - Newly discovered TeV Halo

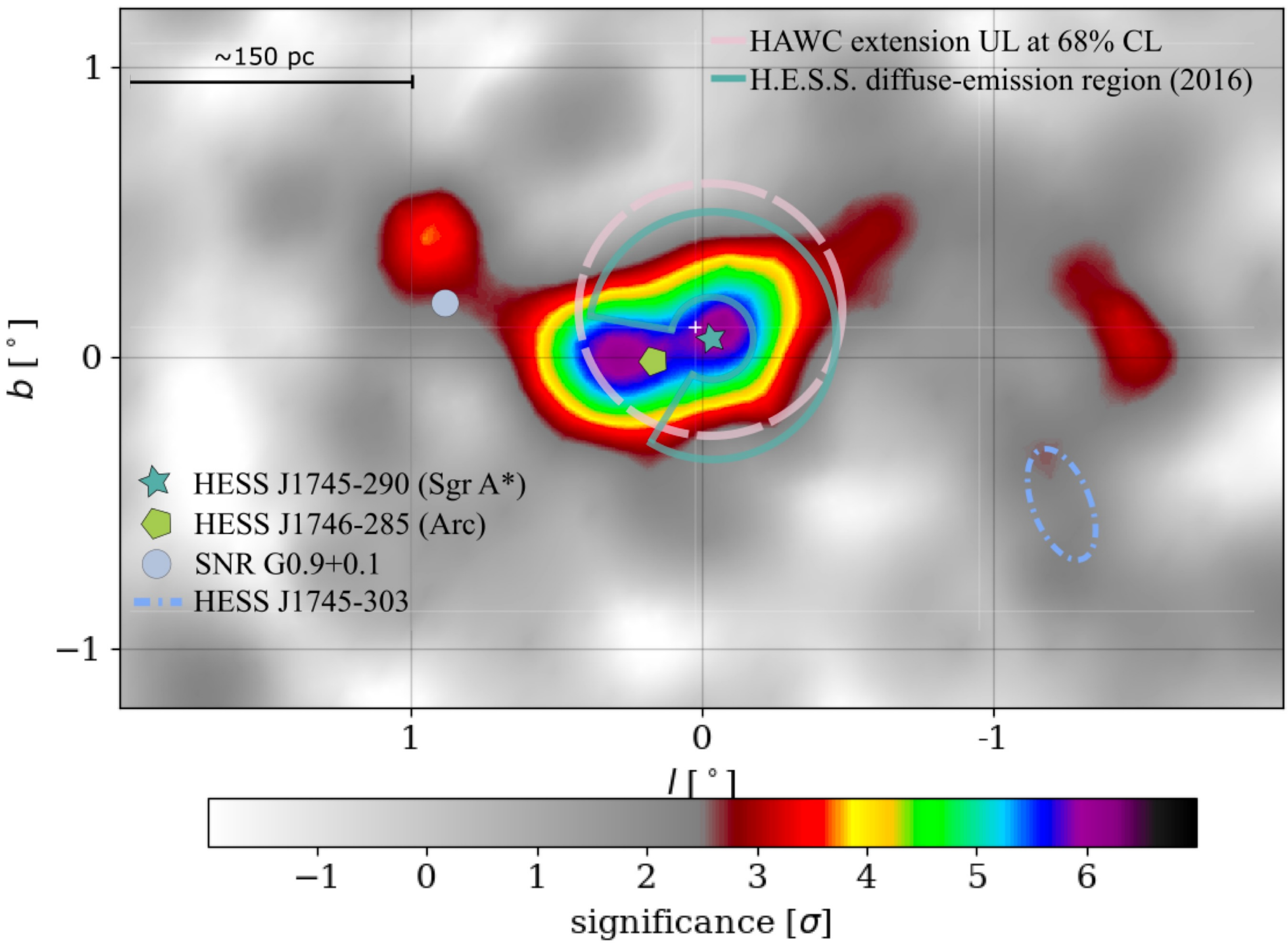
•Outer galaxy, isolated

•Age = 75kyr (younger)

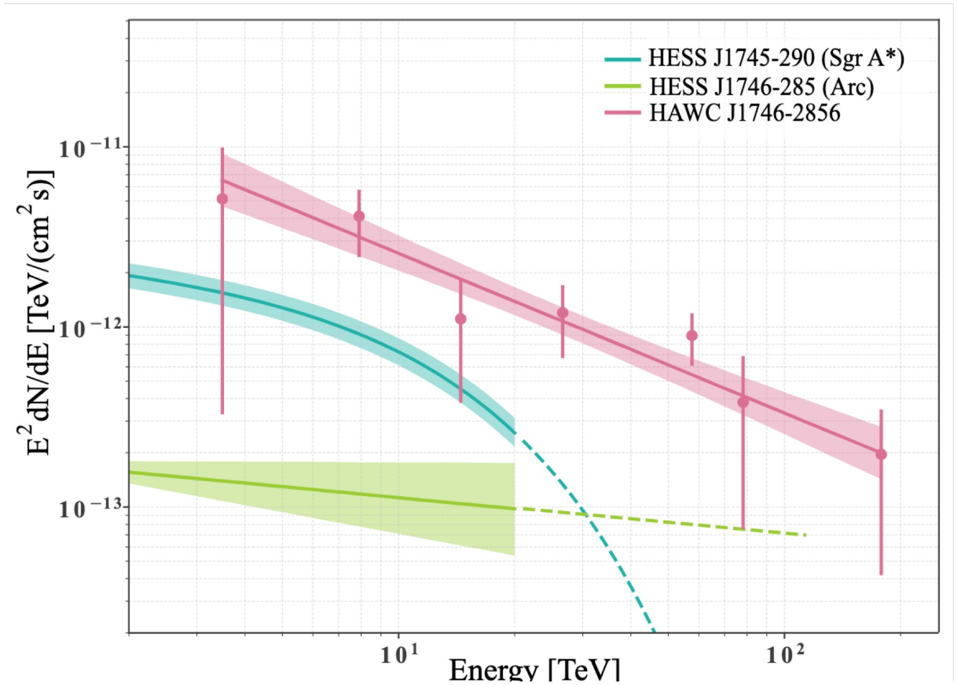
•High Spin-down power: 10^{36} ergs/s - much larger than Geminga & Monogem



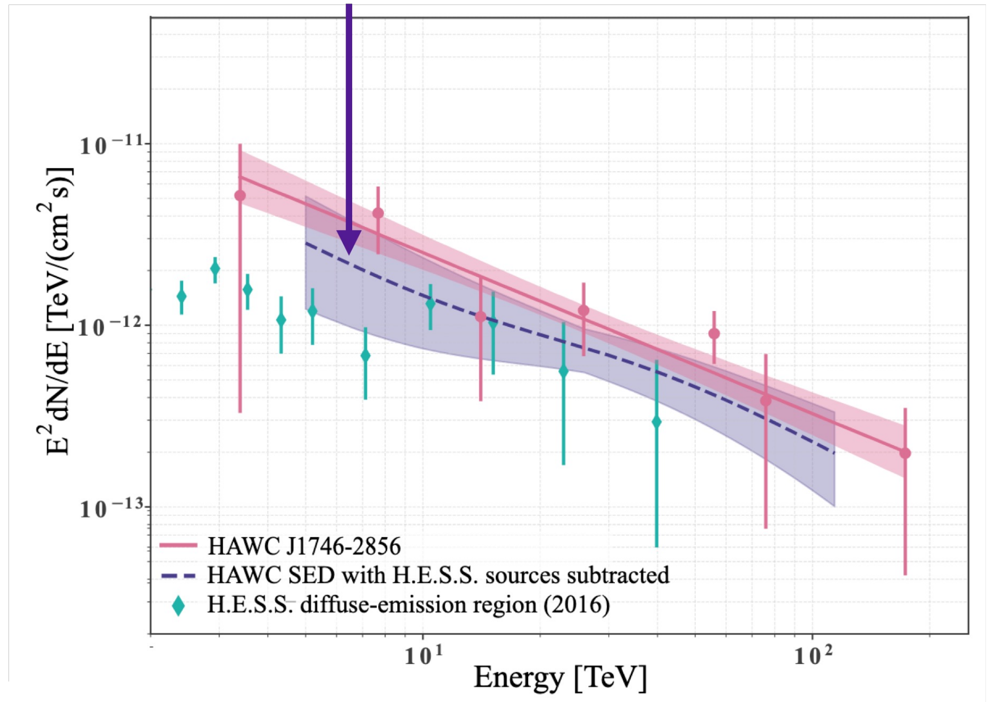
The Galactic Center

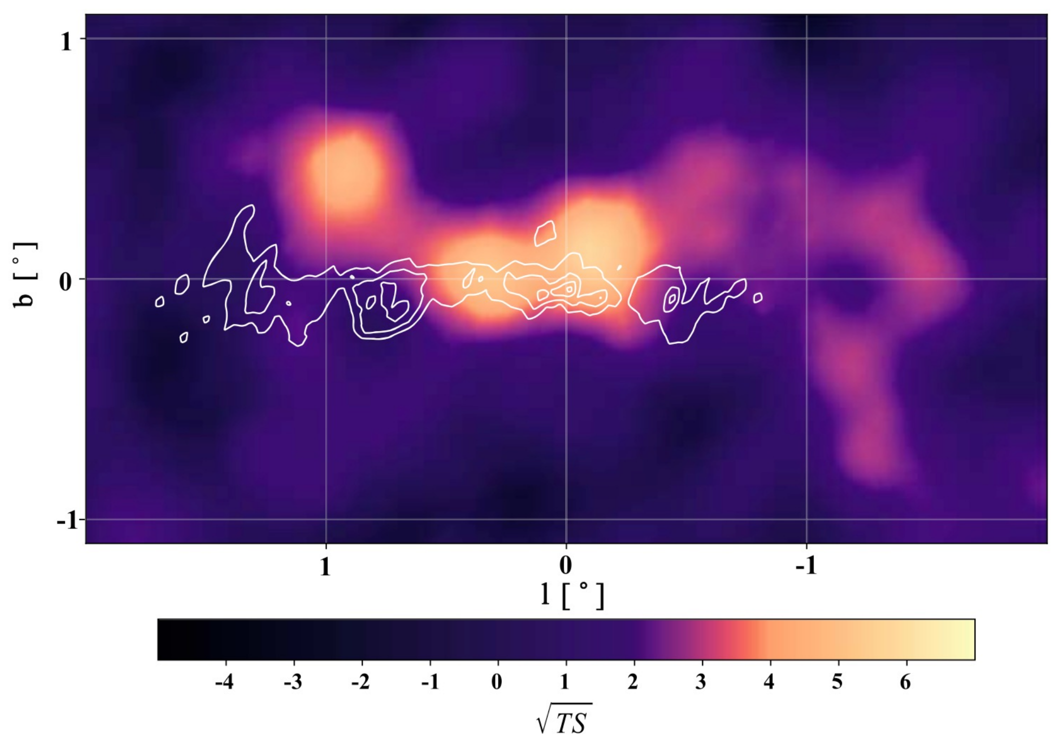


HAWC cannot resolve H.E.S.S. point sources



HAWC power law with H.E.S.S. sources subtracted.



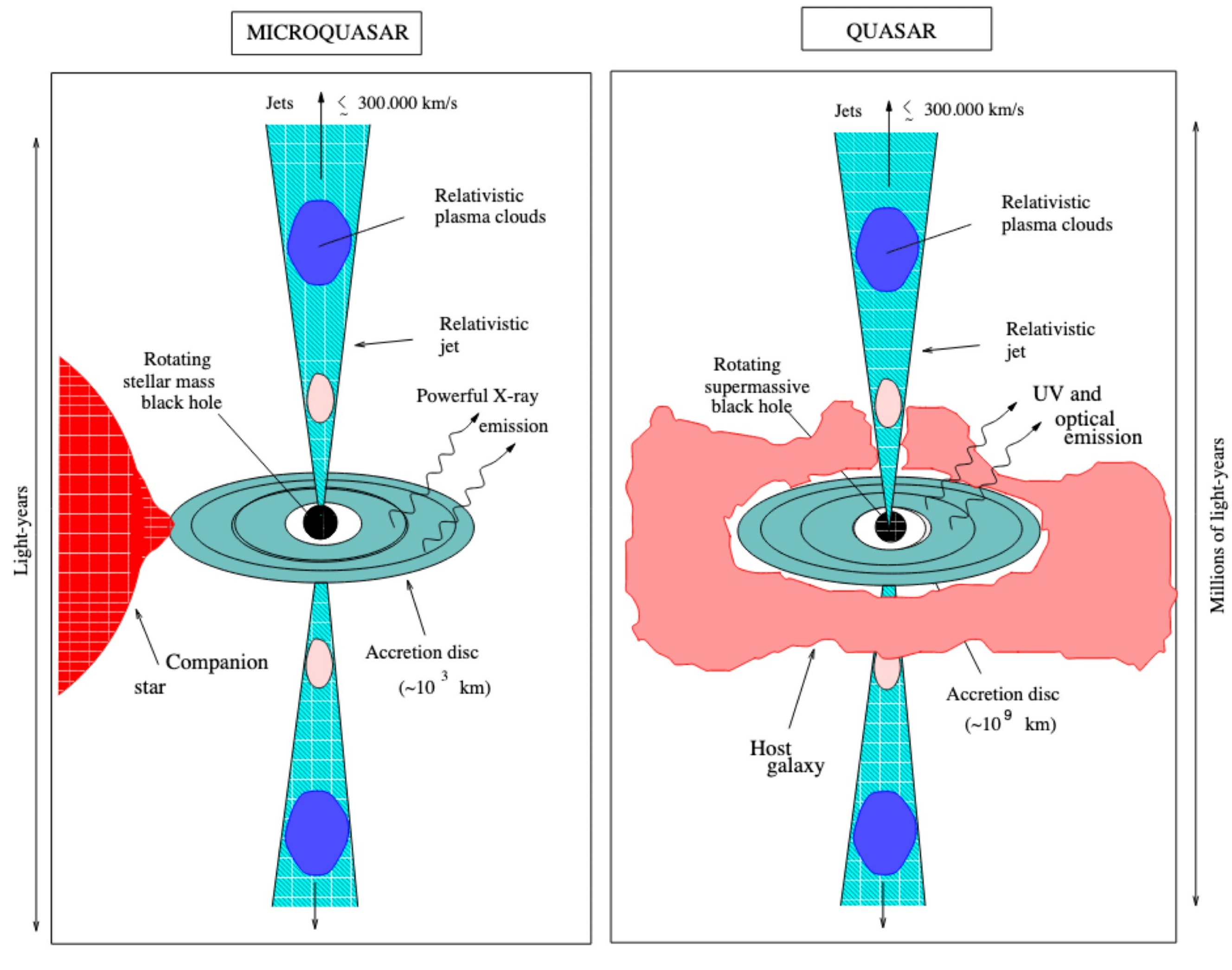


- Emission beyond 100 TeV
- Size of regiôn 150 pc
- p interacting with central molecular zone

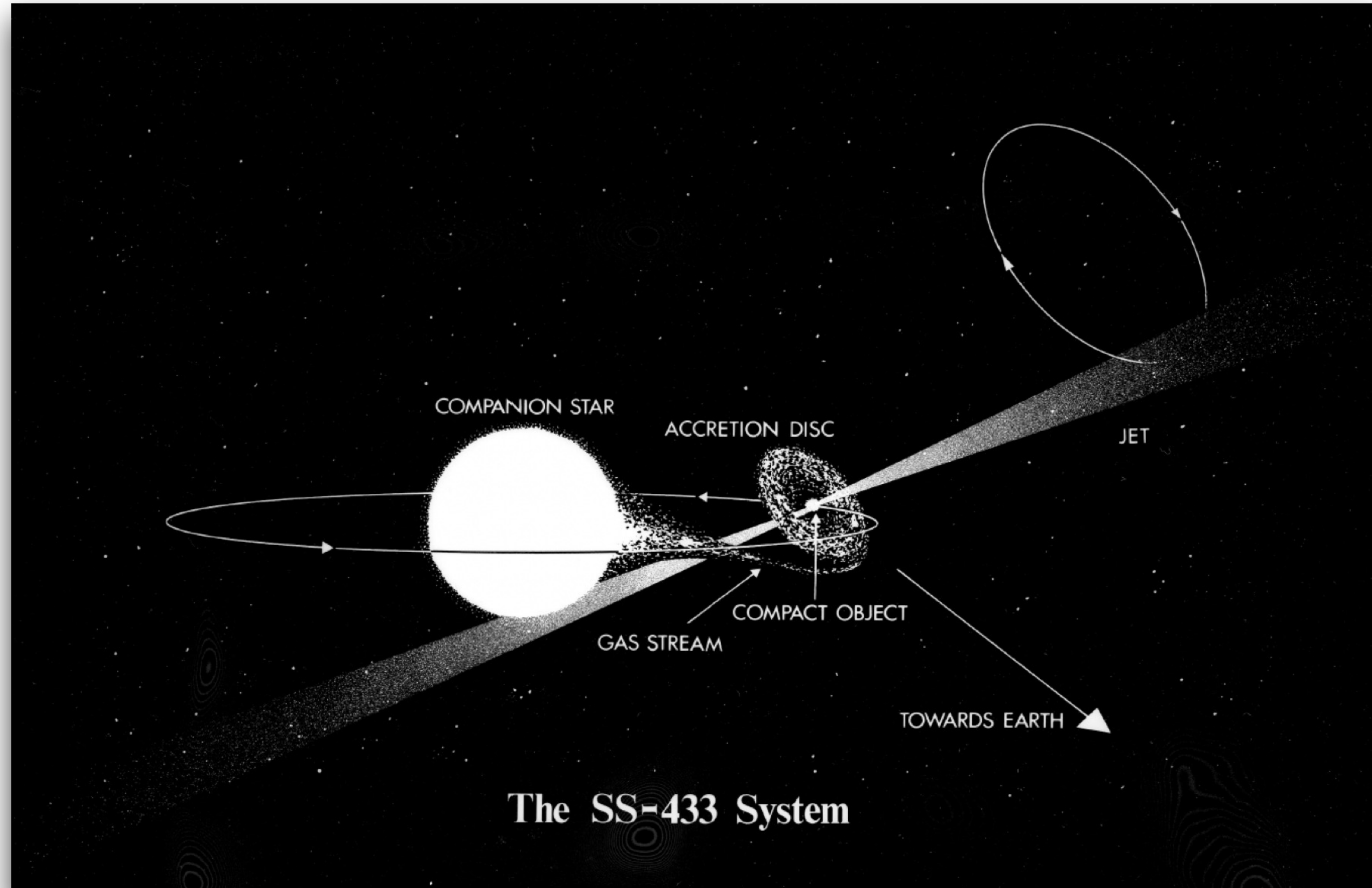
- e cool down very fast 4pc -> multiple sources !!
- p cool down slower but scape from region
  - source too young or
  - emitting constantly

Microquasar

- Binary system
  - Compact object
  - star
- Compact Object mass: 1-tens solar Mass
- Smaller scales tan quasar
- Relativistic jets
- Accretion of star mass into the compact object.
- Mostly galactic, more than 20 microquasars



- Only 3 microquasars with TeV emisión LS 5039, SS 433 and V4641 Sgr

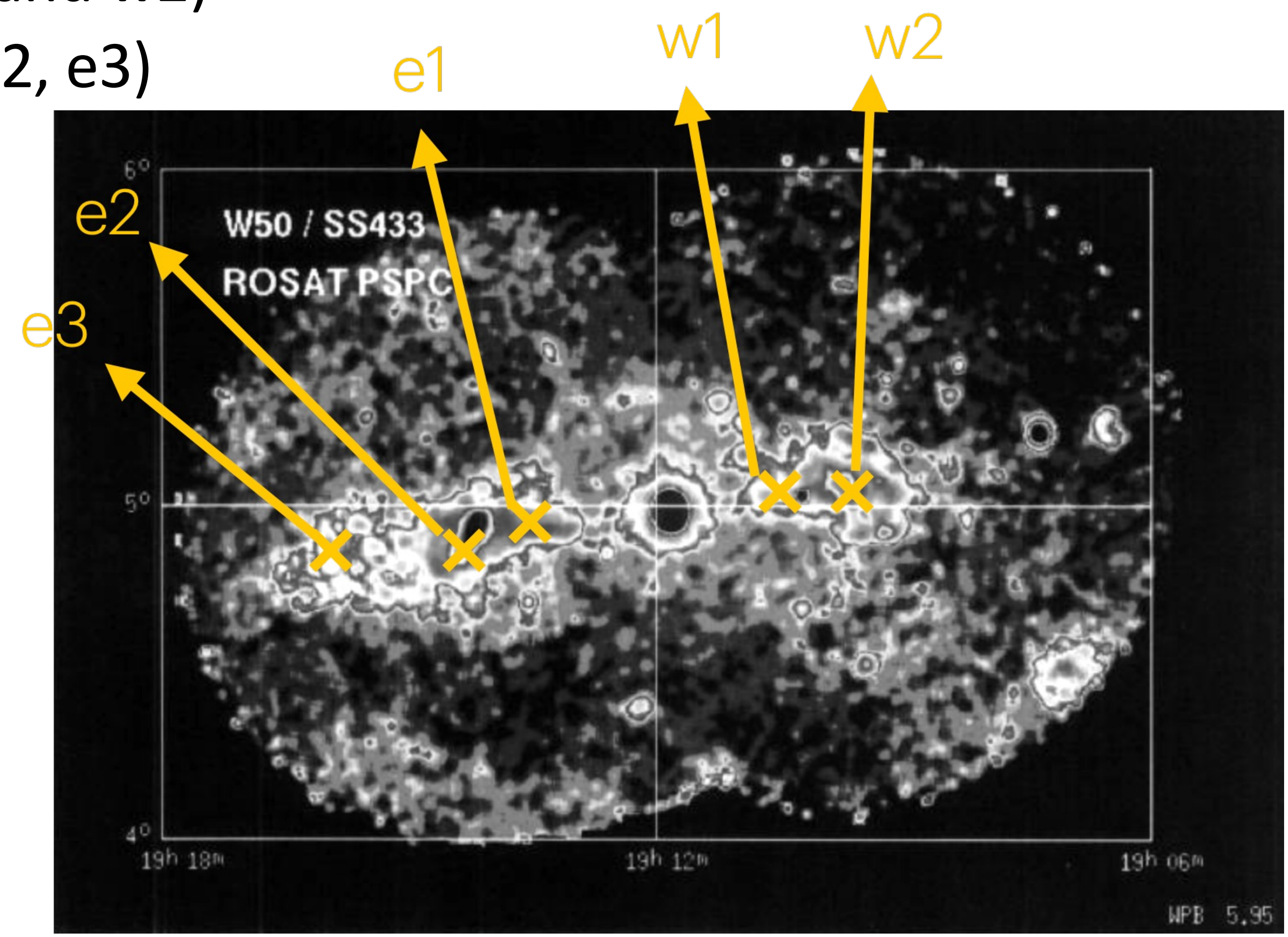


SS 443

- At a distance of 4.5-5.5 kpc
- Black hole (10-20 M_s) + supergigant star type A7
- Orbital period of 13 days
- Age: 10^4-10^5 years.
- Accretion disk fed by the star
  - $L_{bol} \sim 10^{40}$ erg s^{-1}
  - Accretion mass rate ($\sim 10^{-4} M_s$ yr^{-1})
- Jets ($\sim$0.26c, $\Gamma \sim 1.04$), terminate inside W50
  - Precess with an angle of 20^o
  - period of 162 days
  - Extension. Of 0.2pc

- X-ray jets reappear 25 pc from the central object and end after 100pc
- Many X-ray emission zones.
  - Central region
  - West region (w1 and w2)
  - East region (e1, e2, e3)

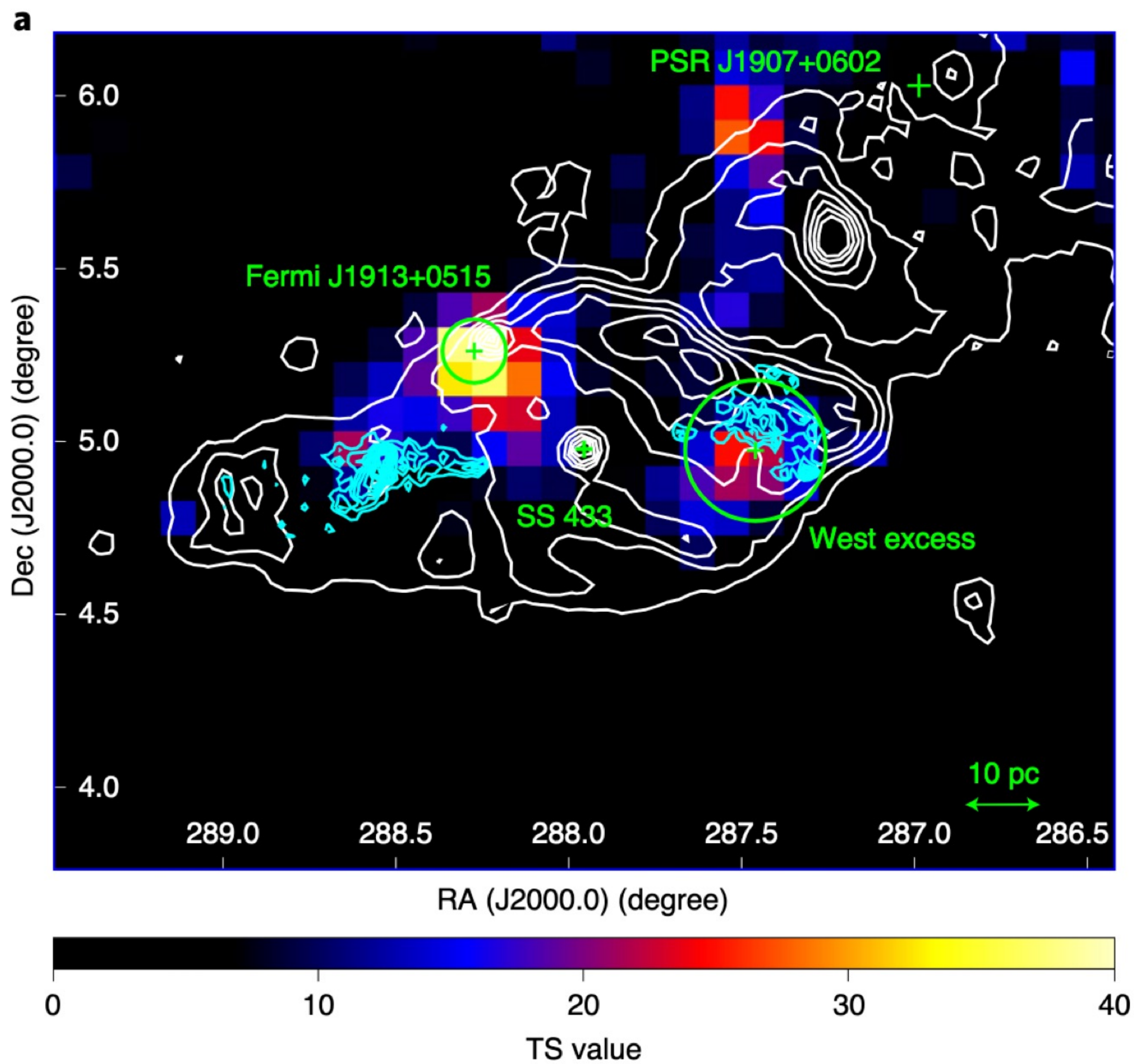
- Synchrotron emission
- Asymmetric jets because interaction with ISM

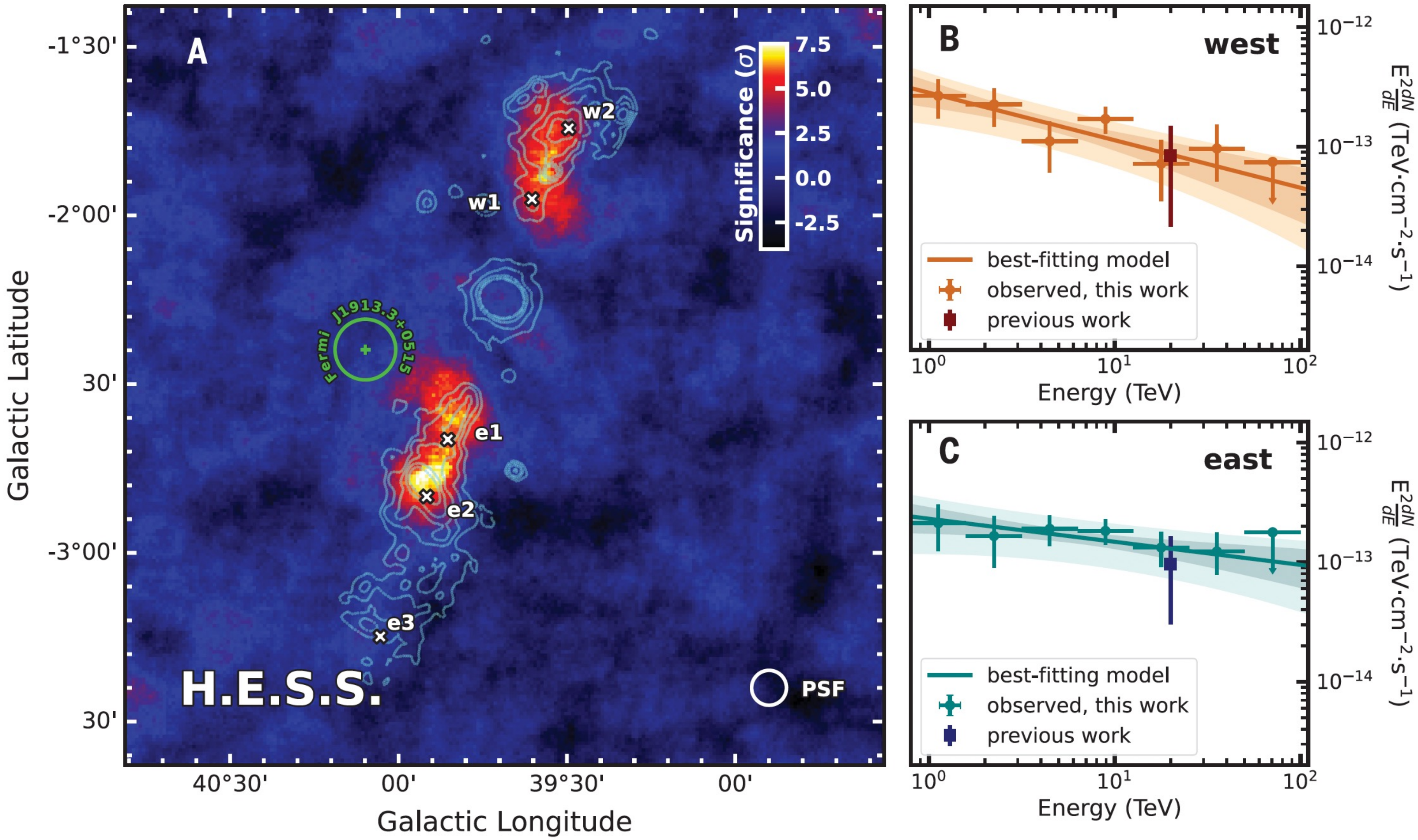


Créditos: Brinkmann, W (1996)

Fermi emission 100MeV – 300 GeV

- Two regions
    - Fermi J1913+0515
    - Near west lobe
    - Periodicity consistent with pressesion of jets for Fermi J1913+0515

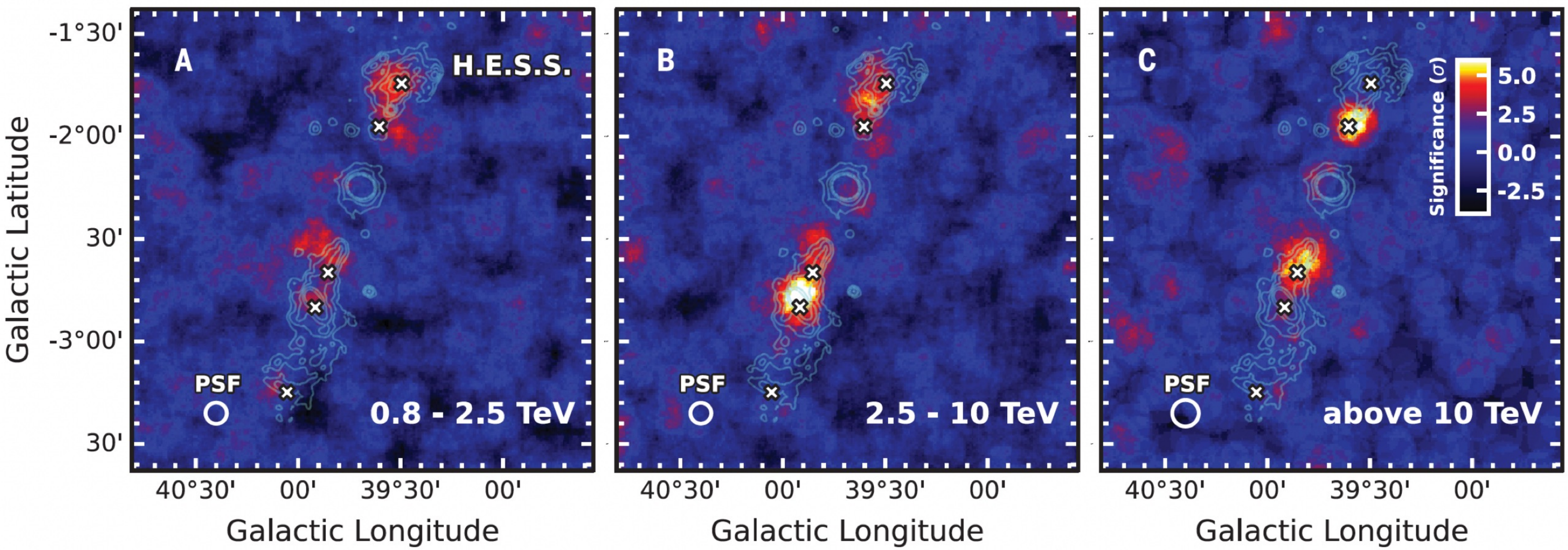




HAWC (E>0.8 TeV)

- No significant emission from the central object
- No significant emission in the east termination region
- Significant emission in two regions, east and west

- Emission less significant at lower energies
- Maximum superficial intensities in regions at further distances along the jets.
- Emission just in the base of external jets
- Gamma rays are not Doppler boosted, observed Edge-on



- Emission is leptonic

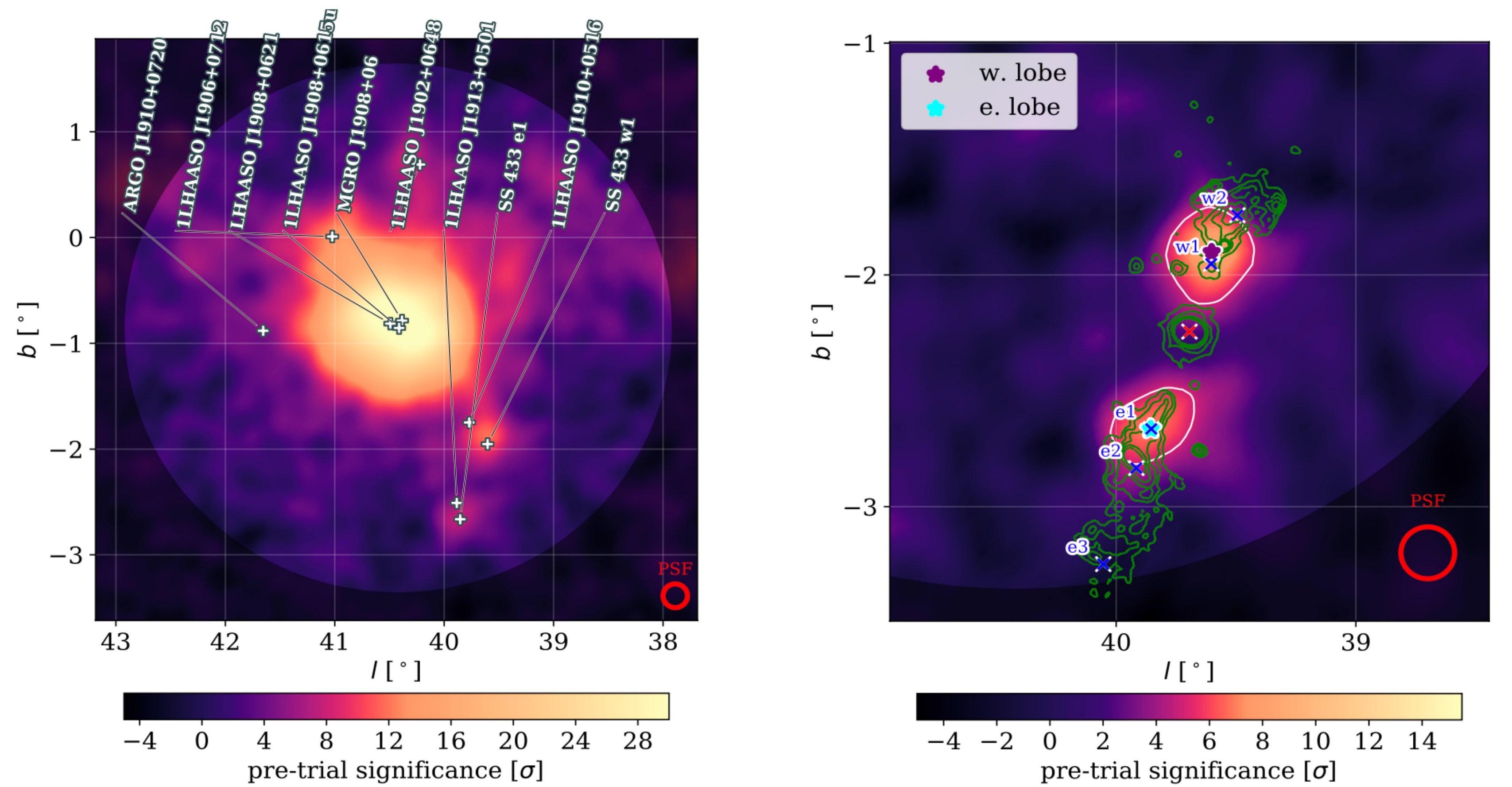
  - We have X-rays emission larger than gamma-ray emission. Protons would have less X-ray emission.
  - Electrons accelerated close to the emission zone, probably in the terminated shocks.
  - Electrons are not accelerated in the central region

Why not protons?

- There is not matter around jets, particle density between 0.05-0.1 cm^{-3}.
- Then we require many protons such that the carried energy is similar to the total energy in a lifetime of the jet except if diffusion is very slow.

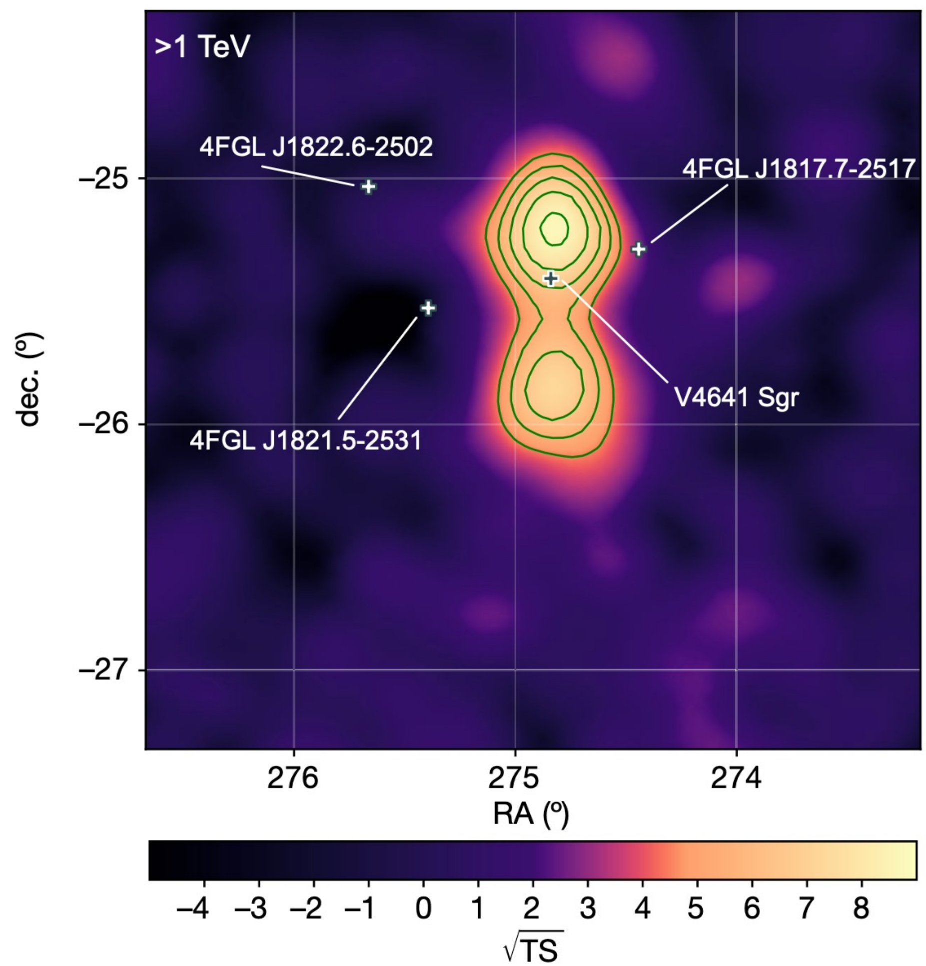
Update

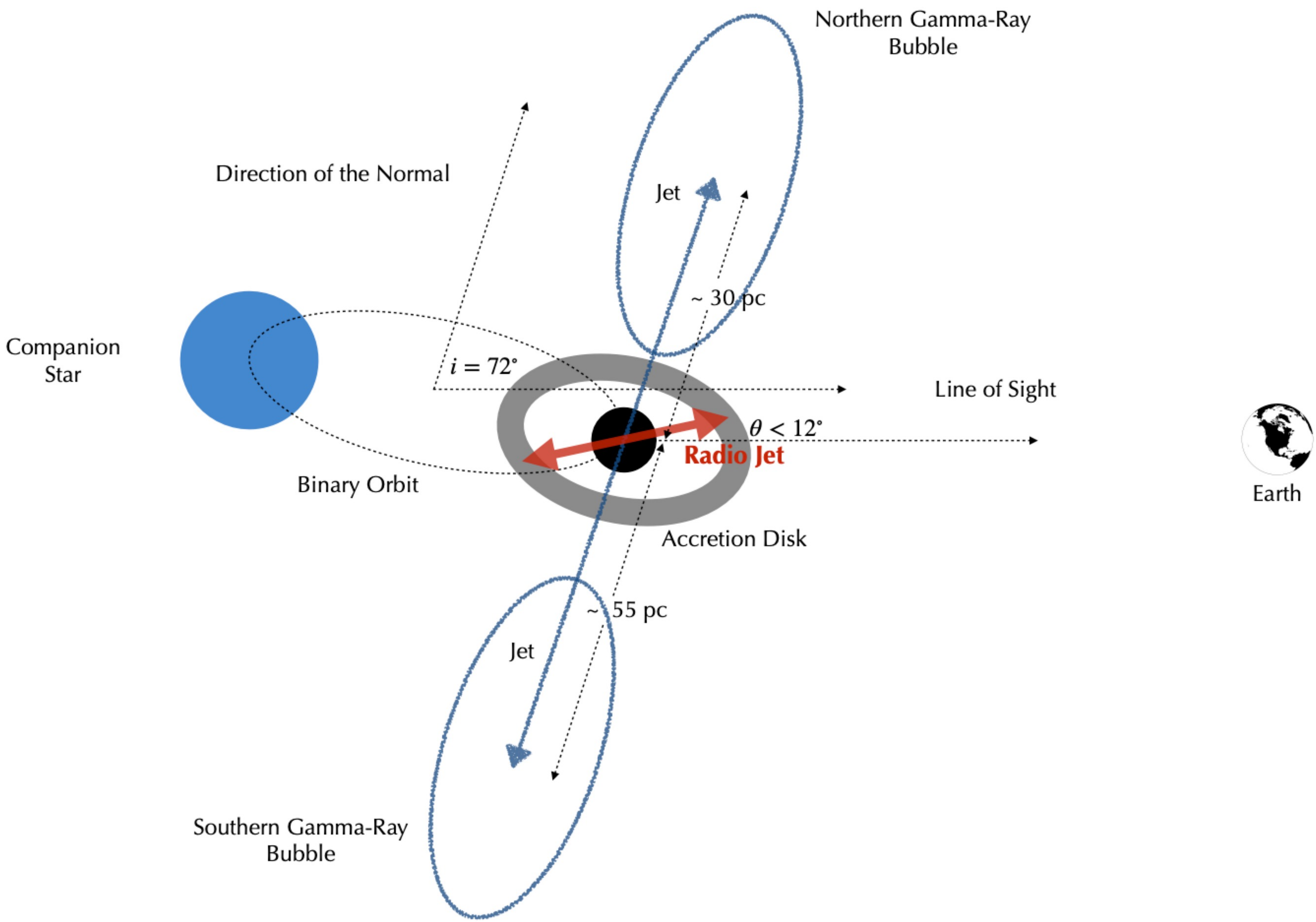
- Before emission up to 25 TeV, NOW emission beyond 100 TeV in the east lobe.
- First LHAASO catalogue indicates emission up to 50 TeV
- These energies are challenging for electron acceleration because KN.
- HESS also sees a morphology dependent on energy - electrons

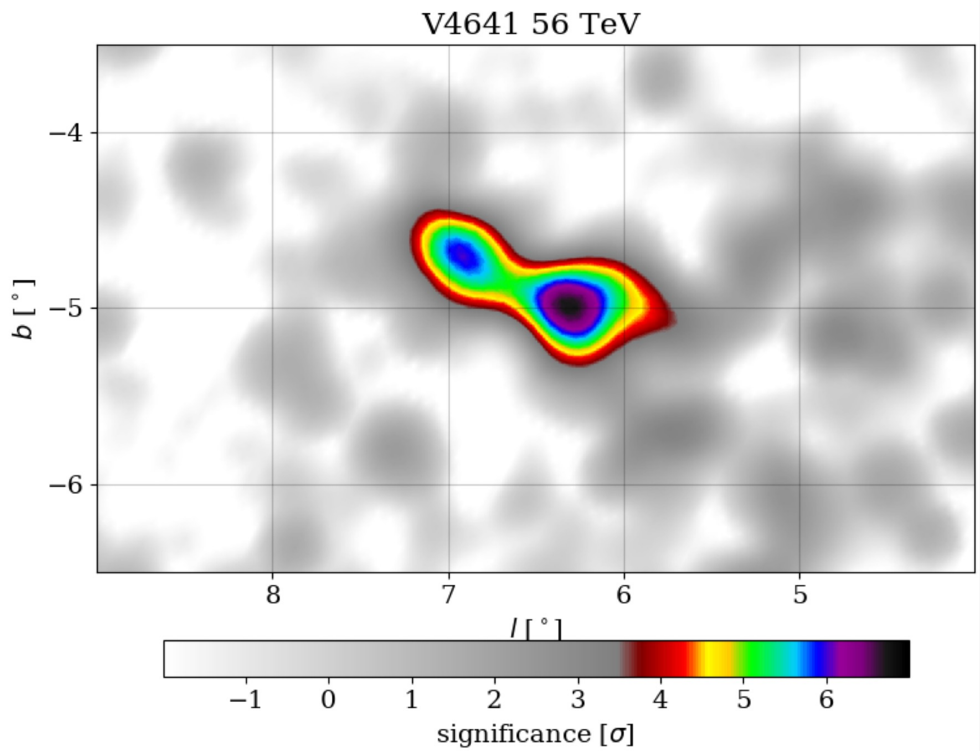


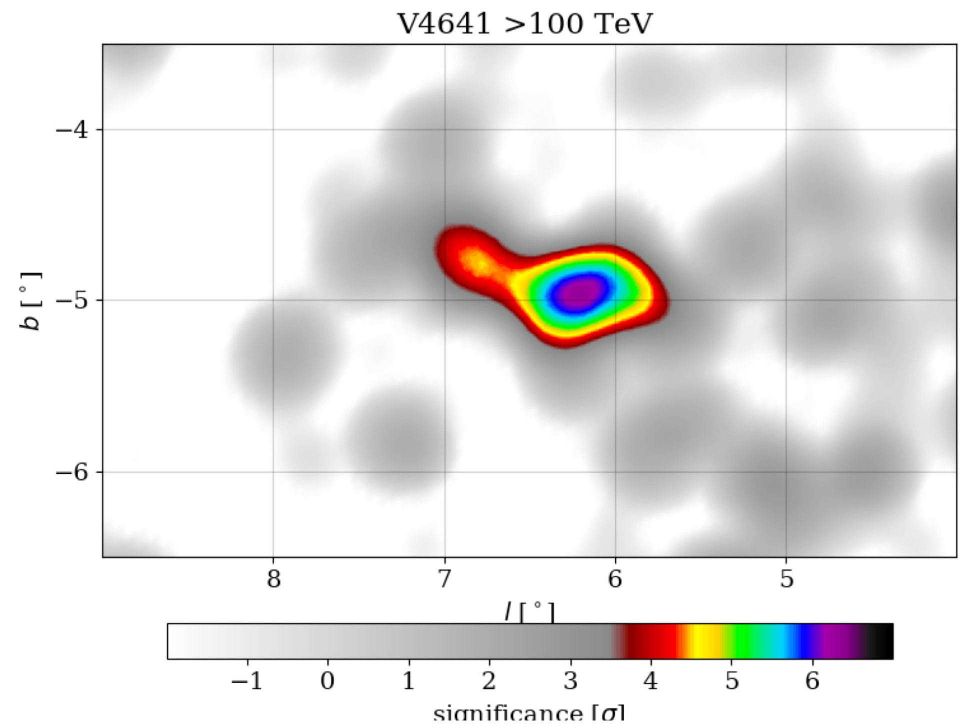
When we understand…

- V4641 Sgr microquasar is discovered in TeVs
  - Emission from 300 GeV – 200 TeV. No sign of cutoff
  - Surrounded by a bubble of very high energy emission of 100 pc, more extended than radio jets

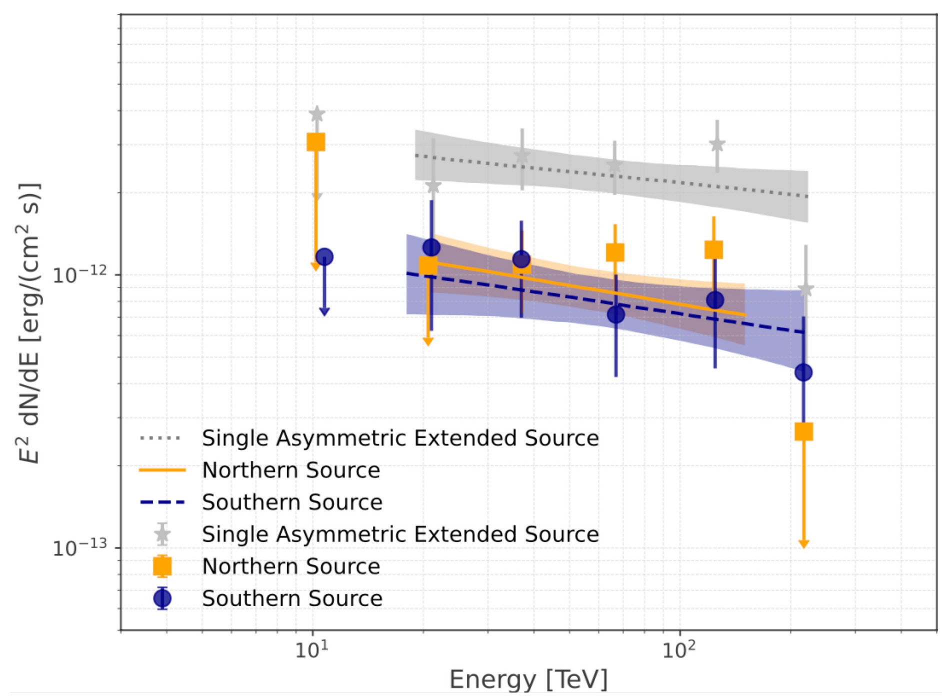



Northern Gamma-Ray
Bubble
Direction of the Normal
Jet
~ 30 pc
Companion
Star
$i = 72^{\circ}$
Line of Sight
$\theta < 12^{\circ}$
Radio Jet
Binary Orbit
Earth
Accretion Disk
~ 55 pc
Jet
Southern Gamma-Ray
Bubble





- Highest energy 217 TeV -> hadronic
- LHAASO paper consistent with HAWC but spectrum extends with some steepening to 800 TeV !!
- New microquasar LS 5039.



Cygnus Cocoon

•No evidence of particle acceleration in **SNRs** beyond 100s of TeV

•**Can SFRs provide this energy via e.g. collective star winds?**

•**Candidate: OB2 association in Cygnus Region**

- *Fermi detection at GeV* (Ackermann et al., ***Science*** 334, 2011, '*The Cocoon')*

•***Cygnus OB2 is an OB association that is home to some of the most massive and most luminous stars known***

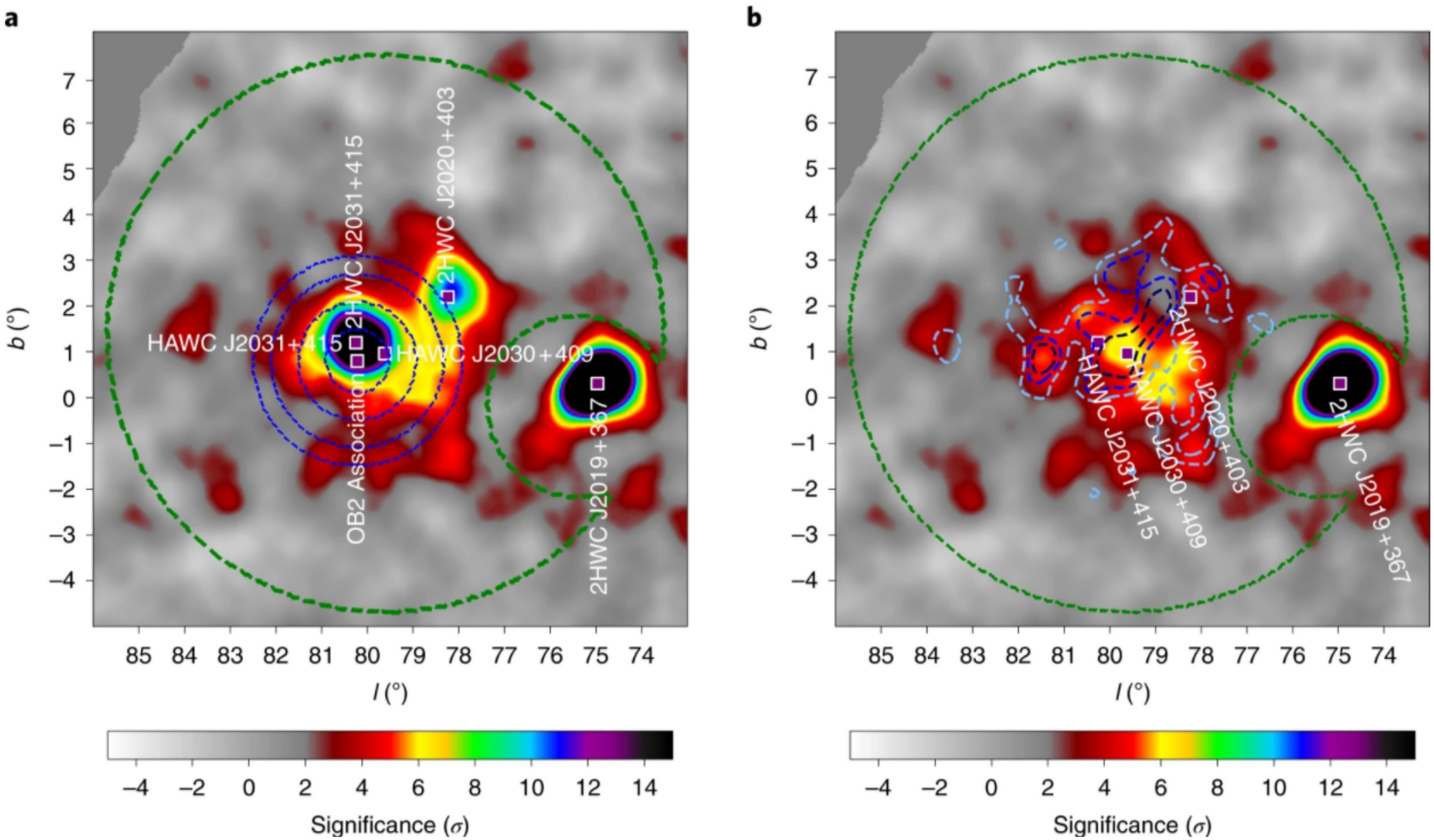
- ***It is hidden behind a massive dust cloud known as the Cygnus Rift, which obscures many of the stars in it. This means that despite its large size, it is hard to determine its actual properties.***

•***Including t*****wo Massive stars orbiting tightly**

- **Steller Winds collide producing x-rays**
- **These can influence star formation and possibly accelerate particles**

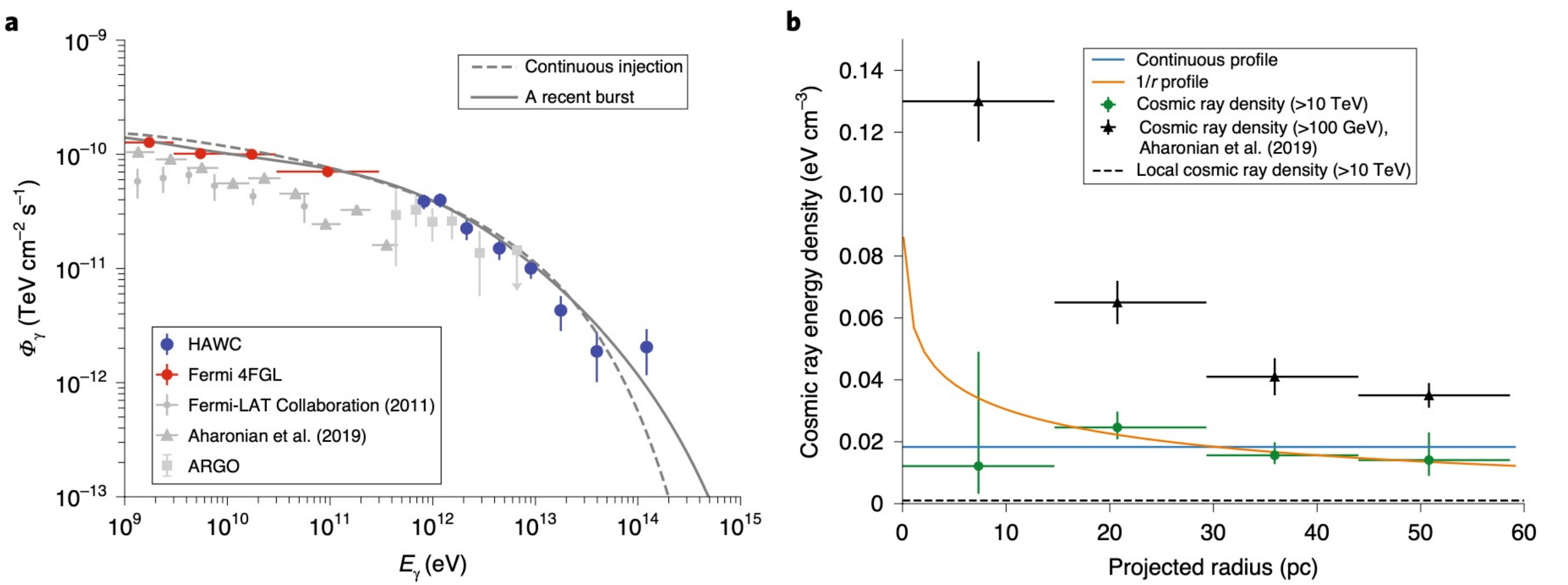
Fig. 1: Significance map of the Cocoon region before and after subtraction of the known sources at the region.

From: HAWC observations of the acceleration of very-high-energy cosmic rays in the Cygnus Cocoon



- Spectrum softens at higher energies
- Below 300 GeV leptonic origin
- In leptonic at TeV – superhigh X-ray emission from Bremsstrahlung below 1 GeV – not observed
- CR energy density as 1/r constantly injected particles
- CR energy density constant burst-like injection like supernova

- Particle constantly accelerated with a cutoff in the spectrum describes the spectrum



Conclusions

- HAWC results are like bread from the oven: hot and tasty
- I missed results on Cosmic Rays, Dark Matter searches, more MW followups of new HAWC sources but, time is over!
- Keep tuned for the results I was not able to talk about
- Coming results:
  - Spectra to > 100 TeV (outriggers)
  - UHE catalogue
  - Transients catalogue
  - MW observations with MoU partners
  - …..