

*CNOC (cnoc knocking' on Heaven's door) XII  
27-30 settembre 2022*



# Very High Energy Astrophysics and the search of the lost Pevatrons

*Martina Cardillo*

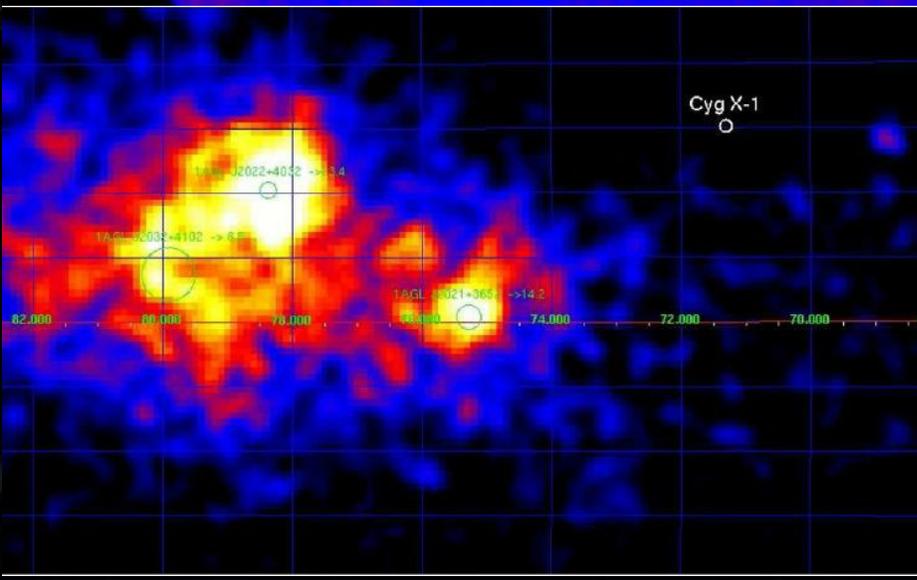
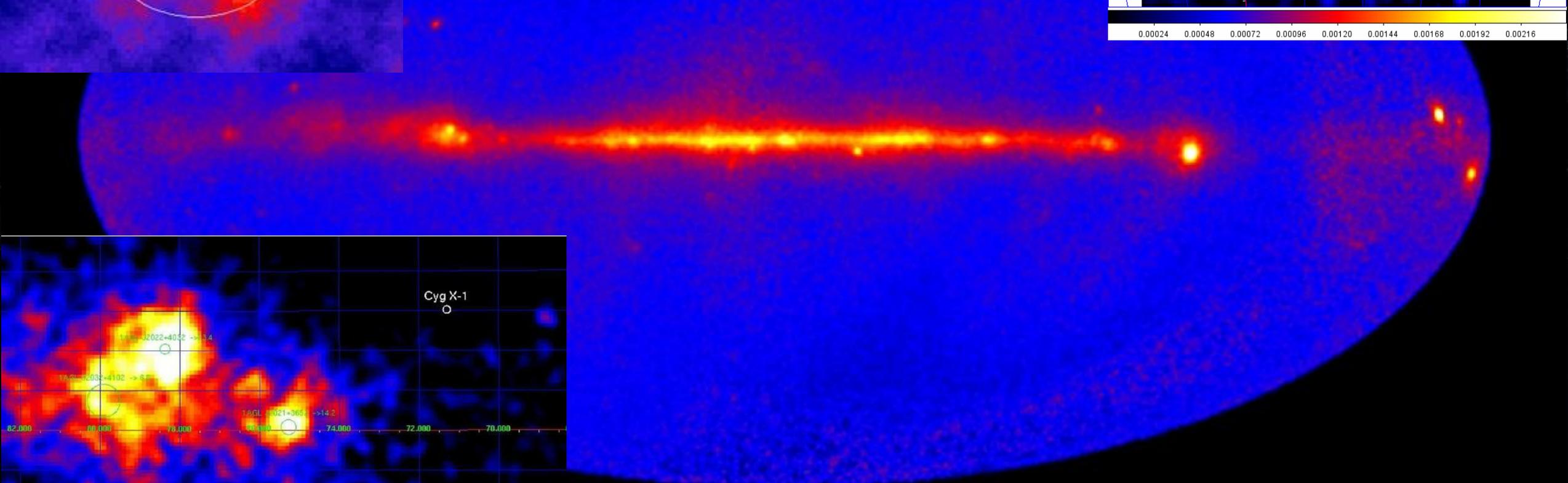
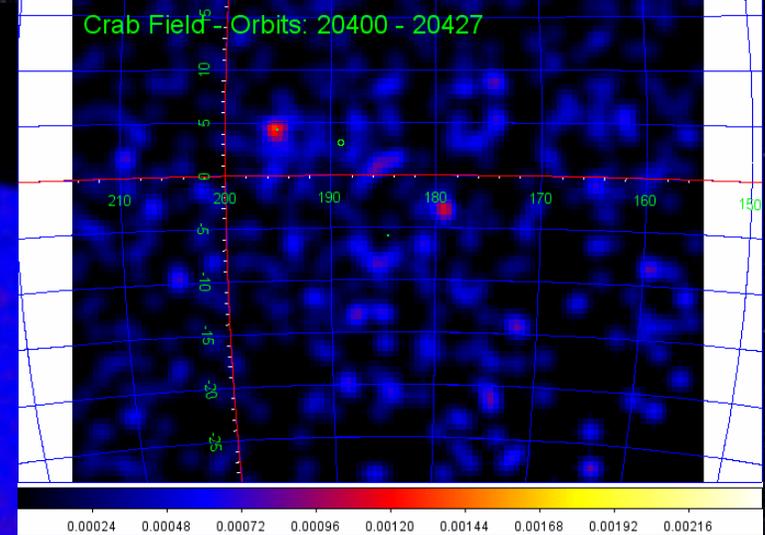
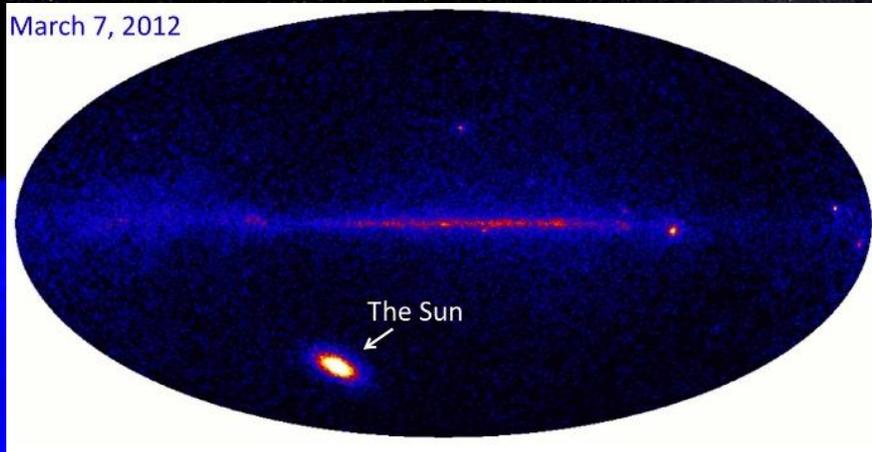
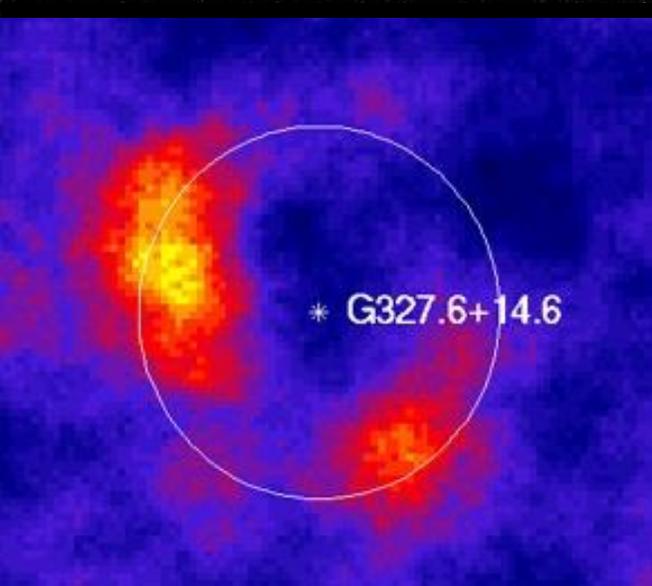
*INAF- IAPS*

*martina.cardillo@inaf.it*

*29 settembre 2022*

# AFTER THE TERRIFIC IMAGES OF JWT





WE, GAMMA-RAY SCIENTISTS, NEED A MOTIVATIONAL MOMENT

Gamma-ray is fundamental in the "hot topic" of the VHE astrophysics



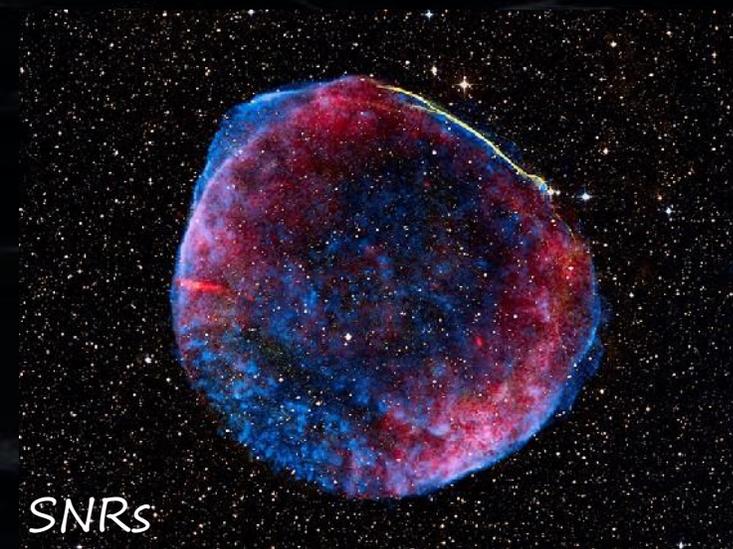
**PARTICLE  
ACCELERATION**



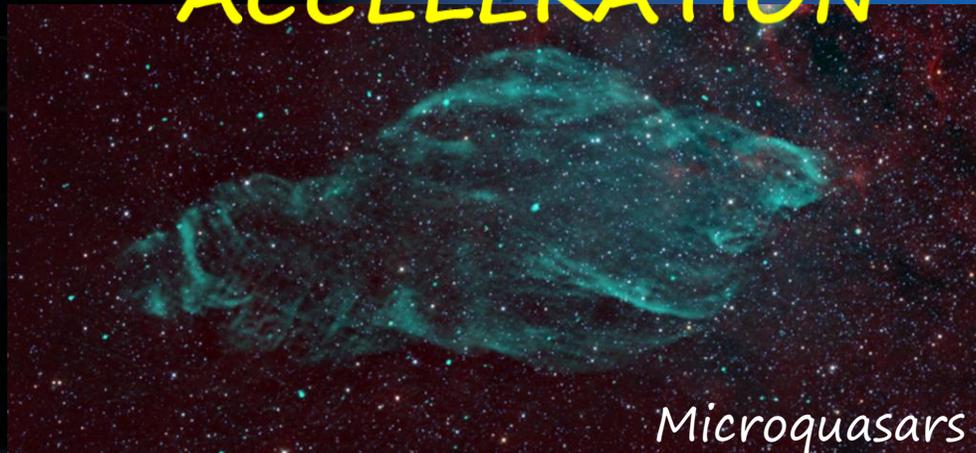
Star Formation Regions



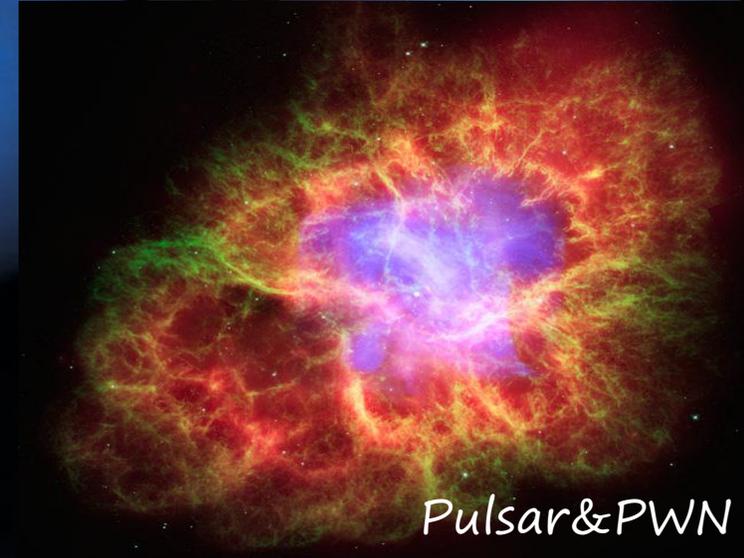
Novae



SNRs



Microquasars



Pulsar & PWN

# Pevatrons

## HIGH-ENERGY ASTROPHYSICS

PEVATRON = an object capable of accelerating PARTICLES (hadrons or leptons) up to the PeV ( $=10^{15}$  eV) range

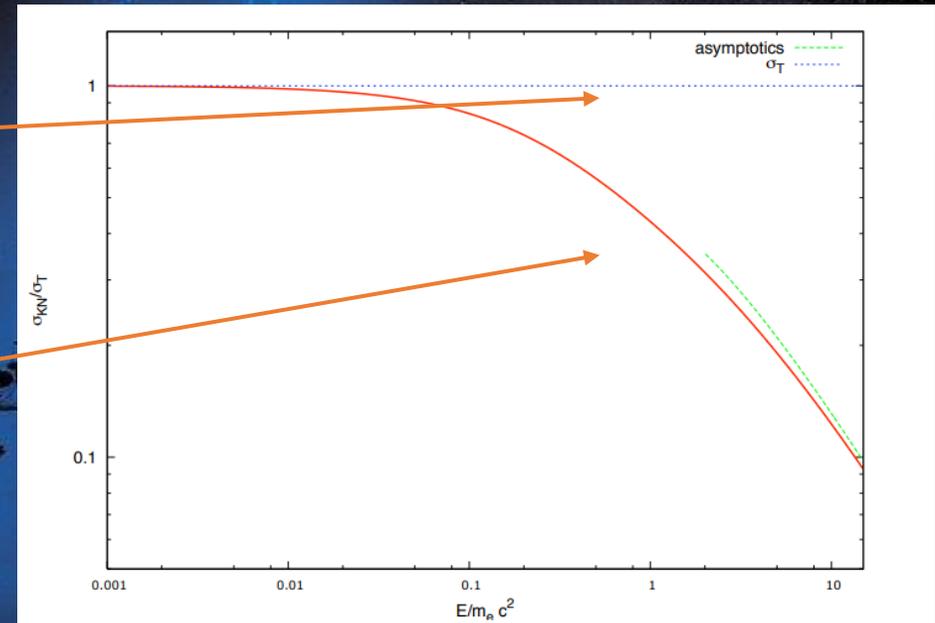
### INVERSE COMPTON (leptonic)

#### Thomson scattering ( $h\nu_i \ll m_e c^2$ )

- transfer small,
- scattering almost elastic,
- Thomson cross-section applied

#### Klein-Nishina scattering ( $h\nu_i \gg m_e c^2$ )

- transfer large,
- scattering deeply inelastic,
- need to use cross-section derived from QED.

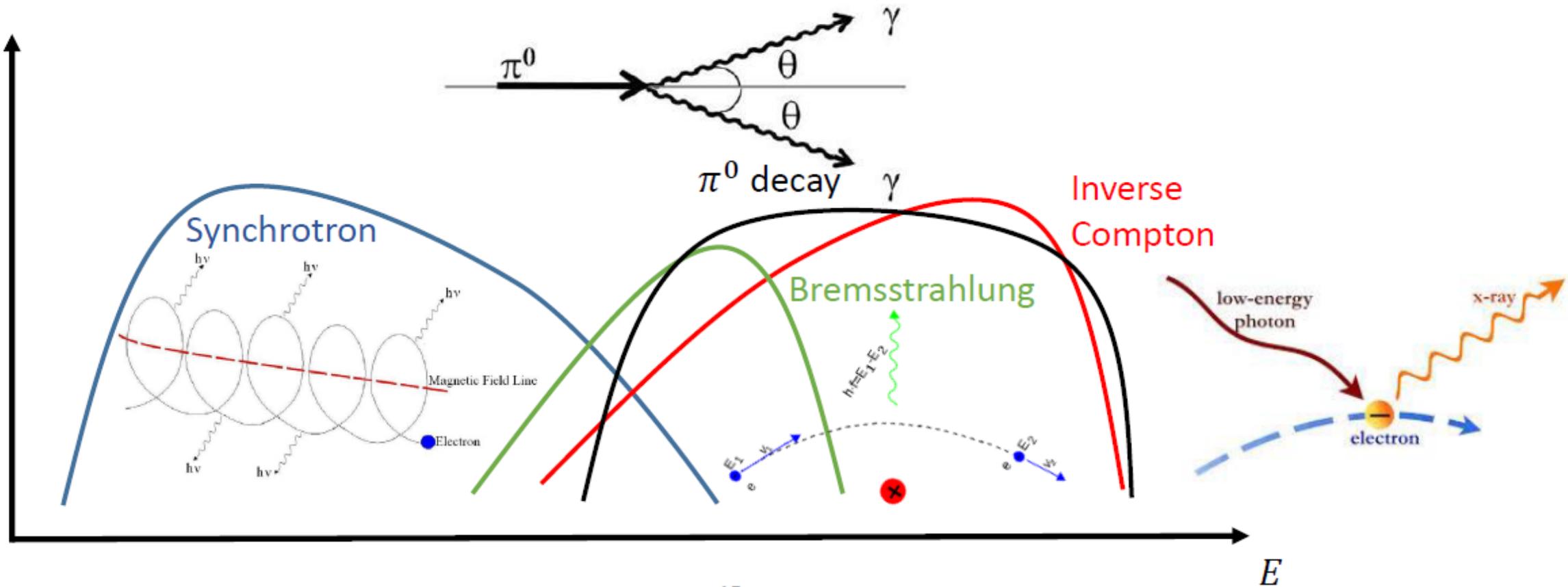


## COSMIC RAY CONTEXT

PEVATRON = an object capable of accelerating HADRONS up to the PeV ( $=10^{15}$  eV) range

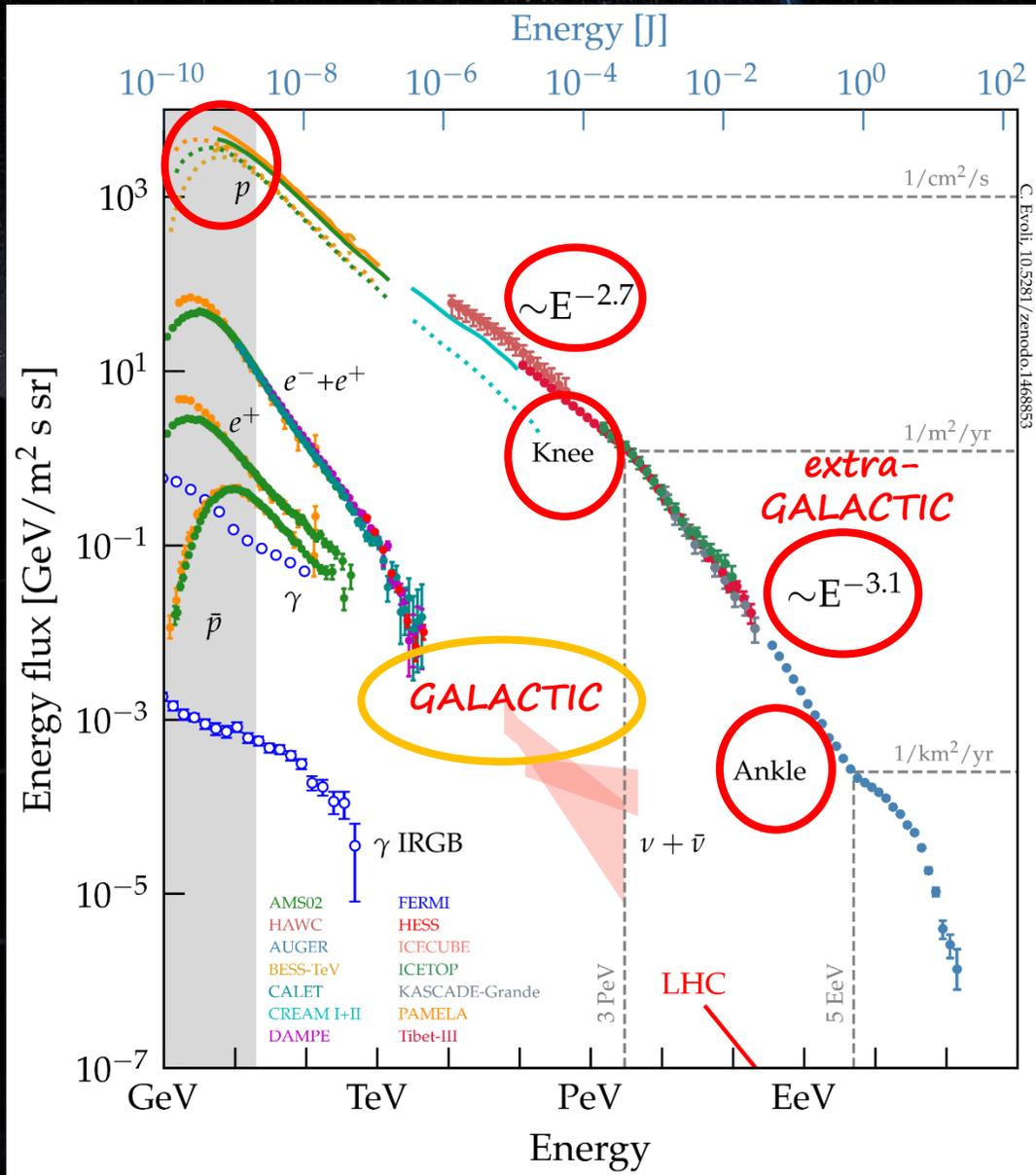
# Radiative processes: very quick look

$E^2 F(E)$



# Cosmic Ray Overview

Evoli 2021



➤ High-energy particles (mostly protons and nuclei) up to  $10^{21}$  eV

➤ Bending below 30 GeV due to solar modulation

➤ Power-law distribution with an index  $\alpha \approx 2.7$  up to PeV energies → No thermal → acceleration

➤ Two main features:

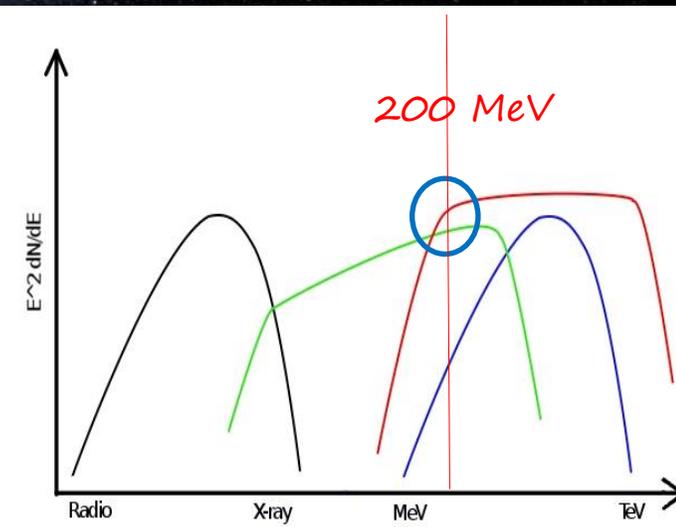
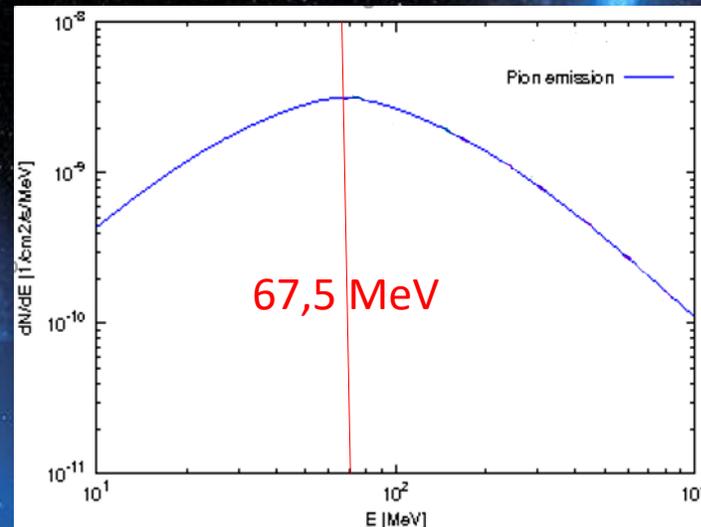
- Steepening at PeV energies,  $\alpha \approx 3.1$  (Knee, 1 part/m<sup>2</sup>/yr)
- Hardening at about  $E=10^{18}$  eV (Ankle, 1 part/km<sup>2</sup>/yr)

➤ Knee due to rigidity-dependent acceleration mechanism →  $E_{knee,Z} = Z E_{knee,p}$

# CR Acceleration: direct evidences

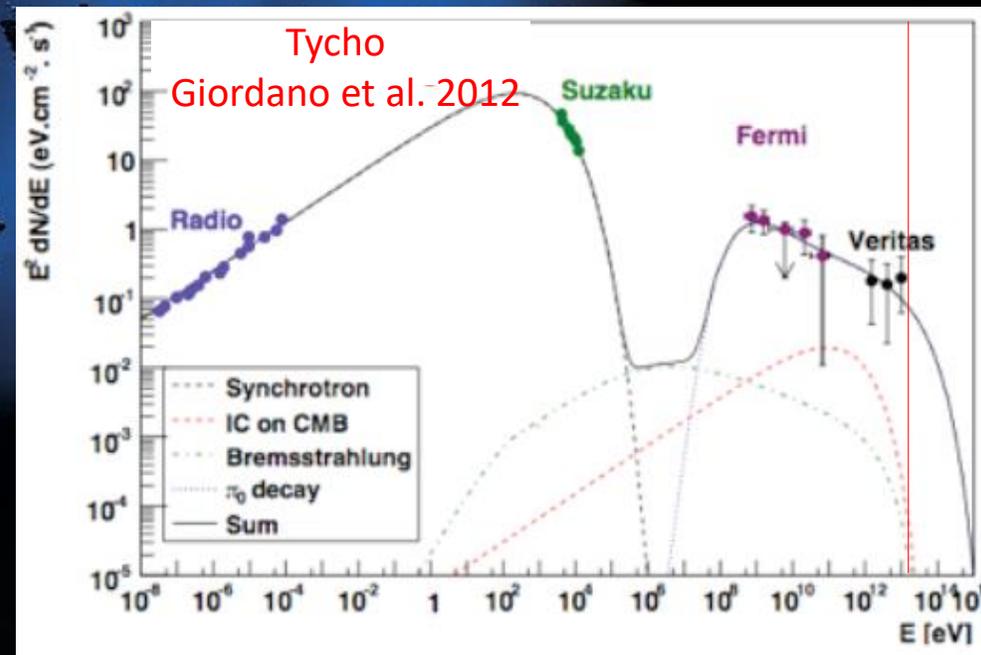
## Low-Energies

→ Pion bump detection:  
distinction leptonic from  
hadronic component only at  
 $E < 200$  MeV



## High-Energies

**Pevatrons** → gamma-ray at  
 $E > 100$  TeV can be only of  
hadronic origin  
(theoretically...)



# Pevatrons Shopping list (Hilton seminar 2022):

- ❖ Detected VHE-UHE Emission
- ❖ Spectral curvature
  - Signature of  $E_{\text{max}}$ , KN, spectral breaks
- ❖ Spatially-resolved emission
- ❖ Correlation with target material
  - Not perfect: i.e. emission is convolution of CR distribution with gas
- ❖ Energy-dependent morphology
  - Expected in general due to energy dependence of transport and/or cooling
- ❖ A multi-wavelength counterpart!

HIGHEST  
ENERGY  
SENSITIVITY

WIDE BAND  
SENSITIVITY

GOOD  
ANGULAR  
RESOLUTION

THE RIGHT  
LOCATION

# Current Cherenkov Facilities

From Ribot presentation at Gamma 2022



VERITAS

HAWC



HESS



LHAASO



LST  
MAGIC

No Pevatron emission up to 2021 when...

# "PeVatrons" storm from LHAASO

## OUR GALAXY IS FULL OF "PEVATRONS"!!!!!!

LHAASO, Nature, 594, p.33-36, 2021

12 "PeVatrons" discovered with high significance ( $>7$ )!!

LEPTONIC  
Or  
HADRONIC?

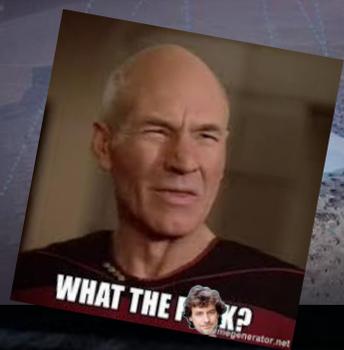
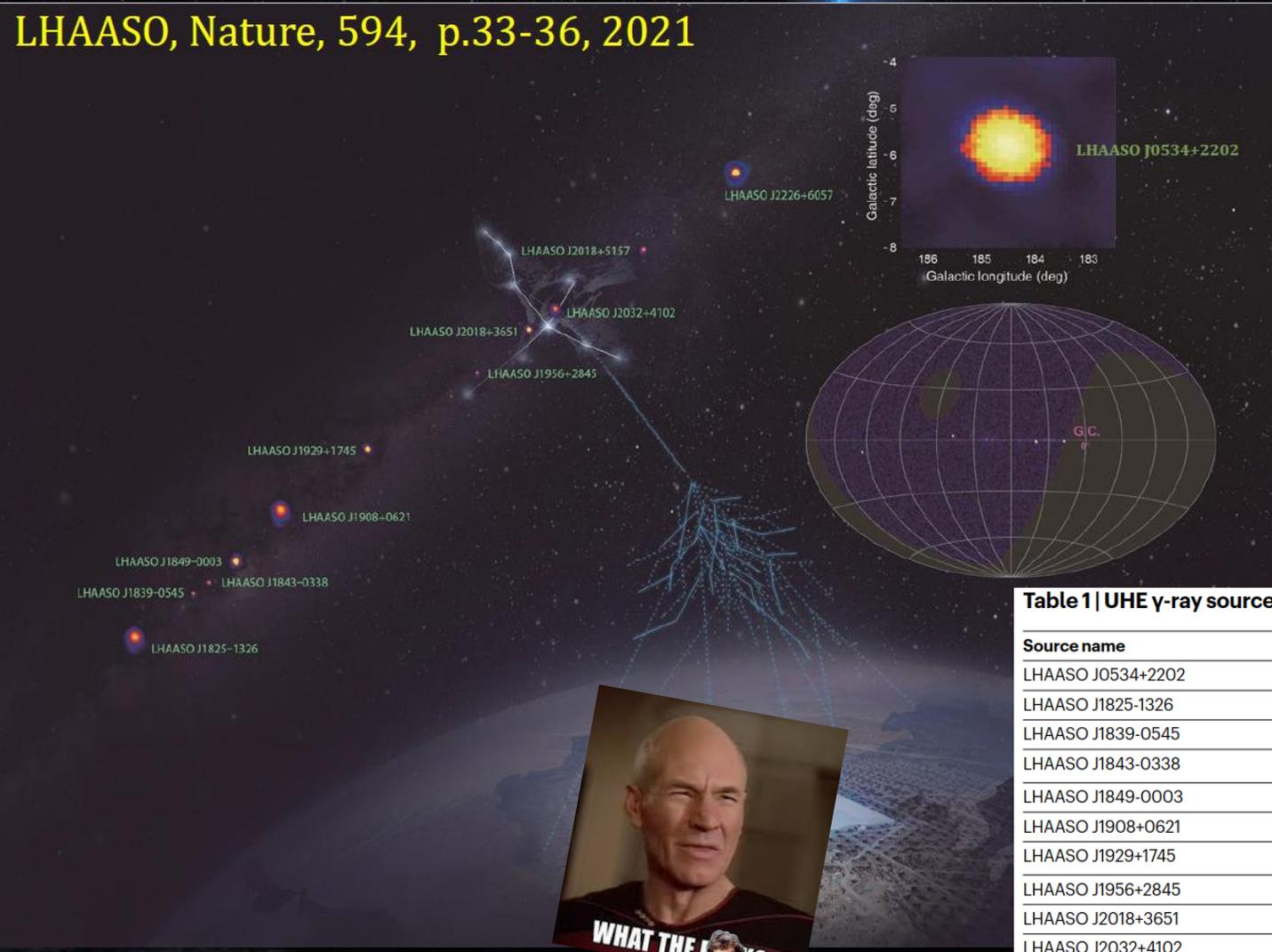


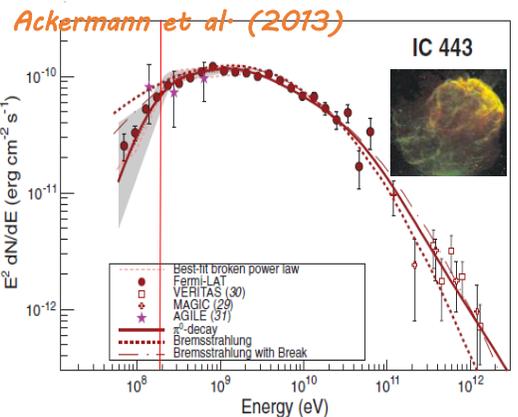
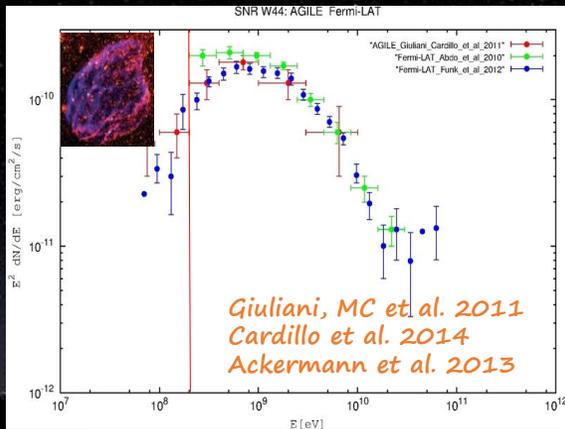
Table 1 | UHE  $\gamma$ -ray sources

Source name	RA (°)	dec. (°)	Significance above 100 TeV ( $\times\sigma$ )	$E_{\max}$ (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	$0.88 \pm 0.11$	1.00(0.14)
LHAASO J1825-1326	276.45	-13.45	16.4	$0.42 \pm 0.16$	3.57(0.52)
LHAASO J1839-0545	279.95	-5.75	7.7	$0.21 \pm 0.05$	0.70(0.18)
LHAASO J1843-0338	280.75	-3.65	8.5	$0.26 - 0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	-0.05	10.4	$0.35 \pm 0.07$	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	$0.44 \pm 0.05$	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 - 0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	$0.42 \pm 0.03$	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	$0.27 \pm 0.02$	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	$1.42 \pm 0.13$	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	$0.43 \pm 0.05$	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	$0.57 \pm 0.19$	1.05(0.16)

See Orlando Talk

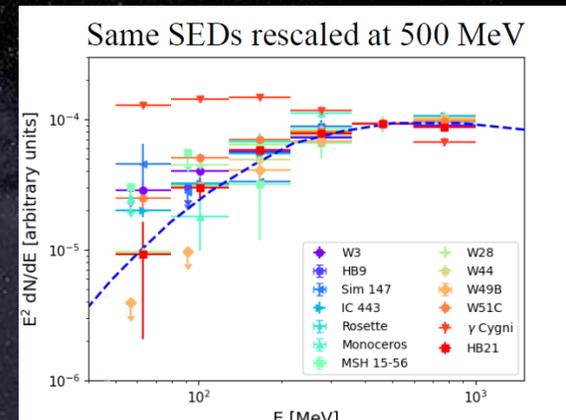
# Supernova Remnants

Lemoine-Goumard talk  
Gamma2022

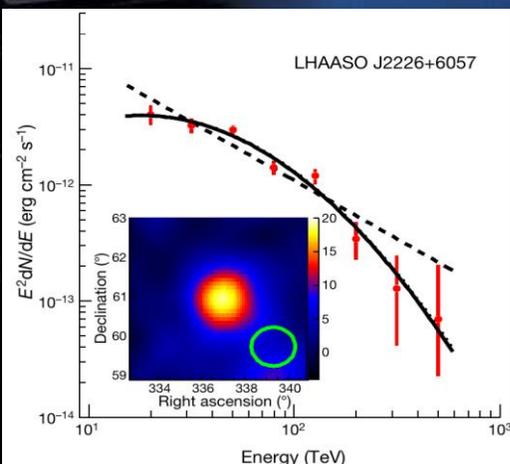
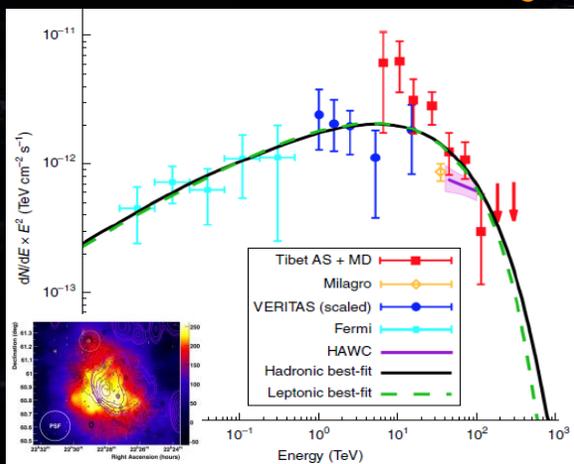


## Low Energies

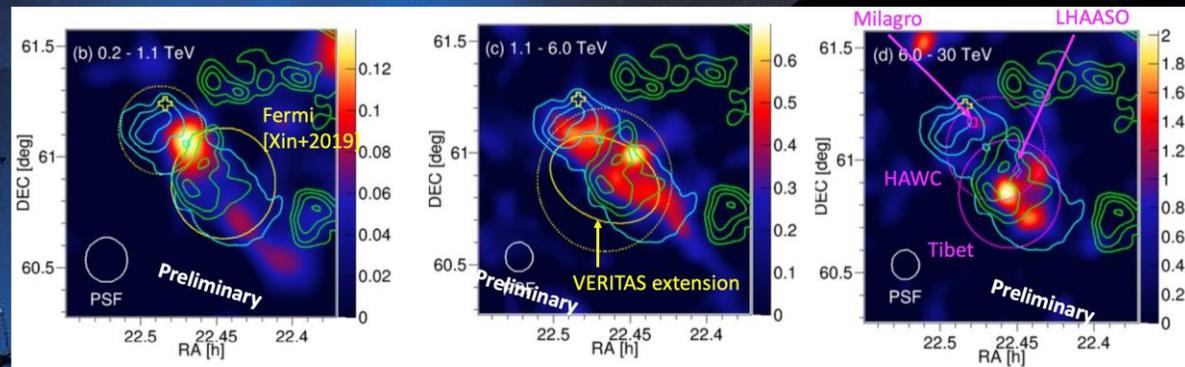
Presence of CRs confirmed but not confirmation of freshly accelerated CRs (likely RE-accelerated)  
 [Cardillo et al. 2016, Celli et al. 2019]



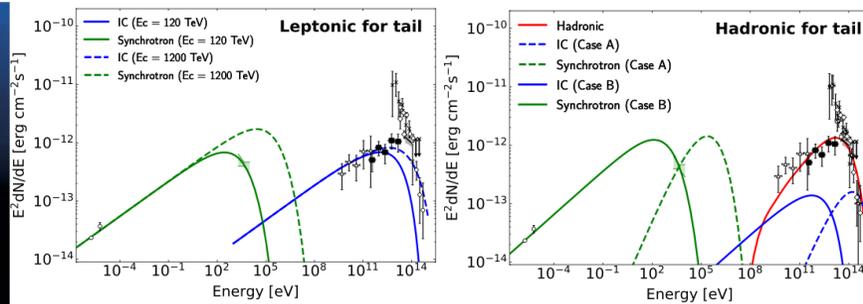
## G106.3+2.7/Boomerang/LHAASO J2226+6057



Tibet AS collaboration 2021 - Cao et al. 2021



MAGIC study (Saito talk Gamma2022)



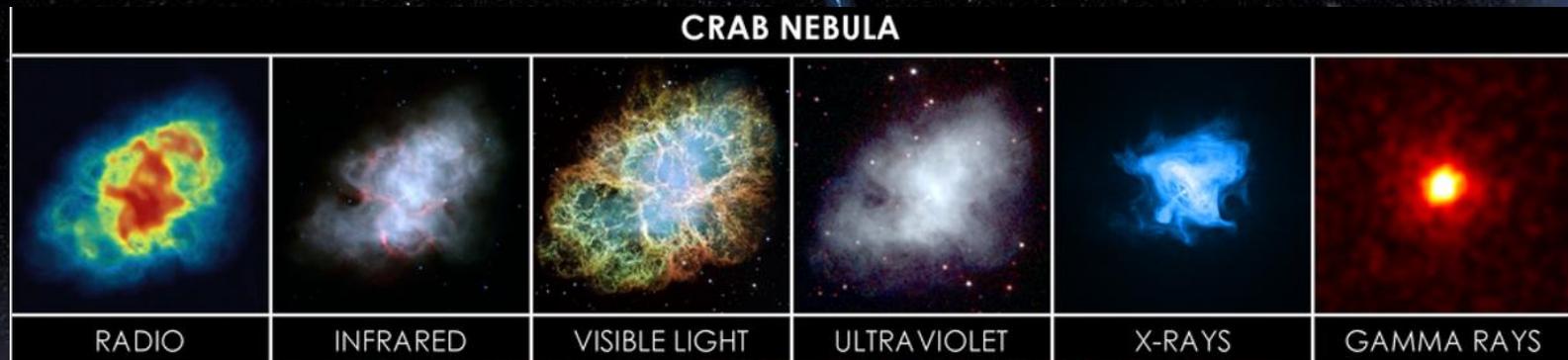
## High Energies

See Giuliani Talk for ASTRI performances

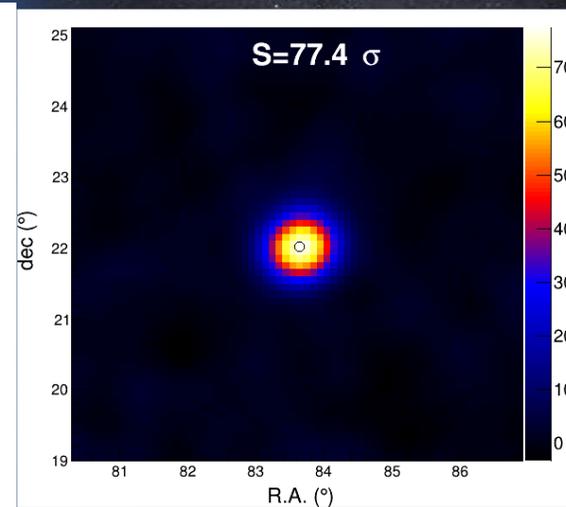
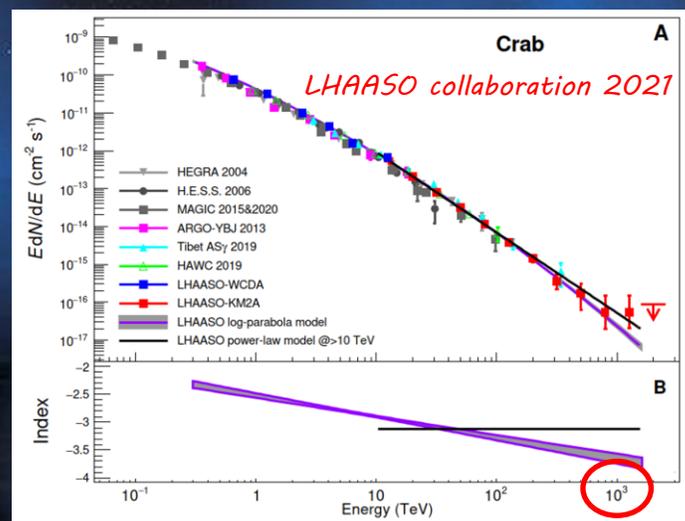
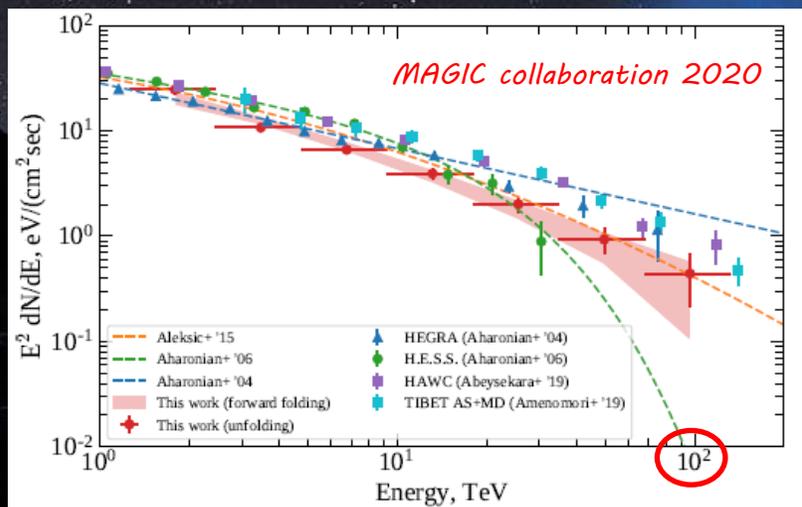
## Propagation study



# CRAB NEBULA

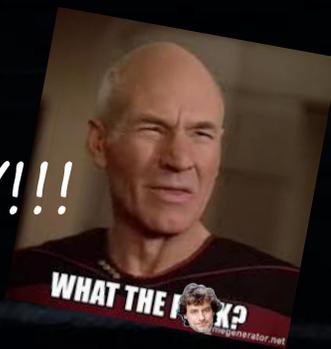


Standard Candle for Gamma-ray astronomy (when it is not flaring)



Detection above 1 PeV!!!

See Giuliani Talk for ASTRI performances



but...

Crab is a PWN (leptonic source)

So...

Leptons Or Hadrons?

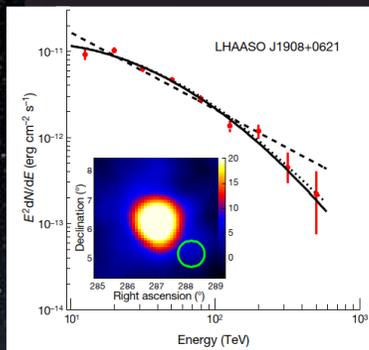
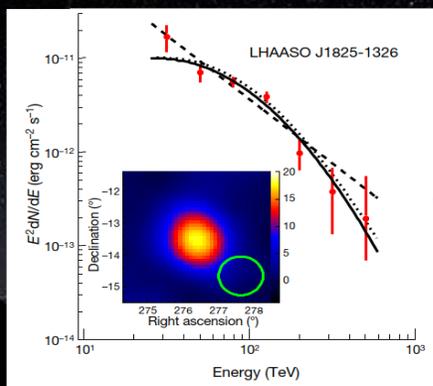
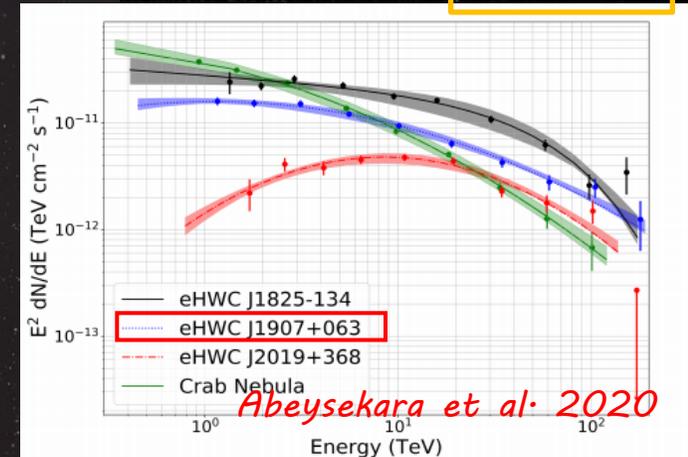
# Pulsar Wind Nebulae

See Giuliani Talk for ASTRI performances

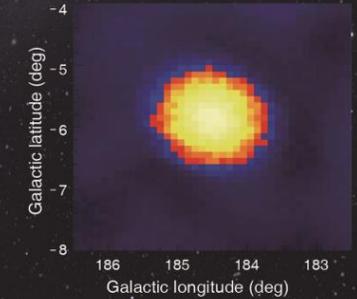
See Amato talk

HAWC

The majority could be PWN!!!



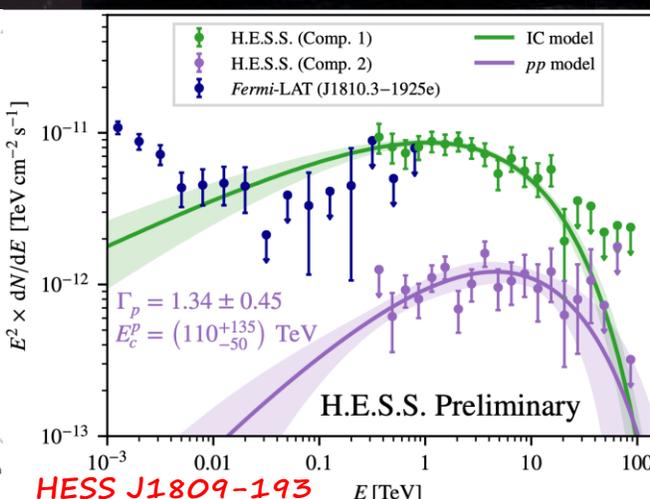
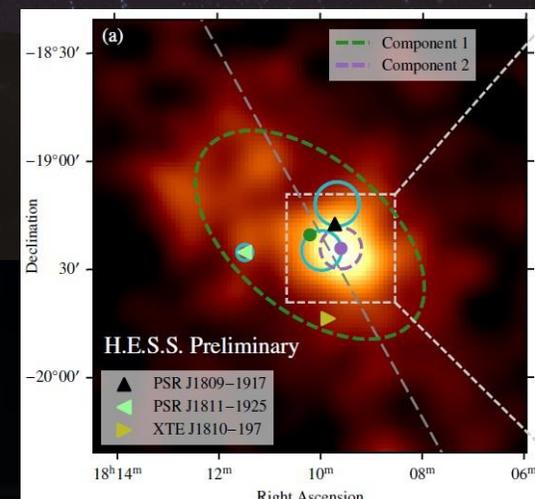
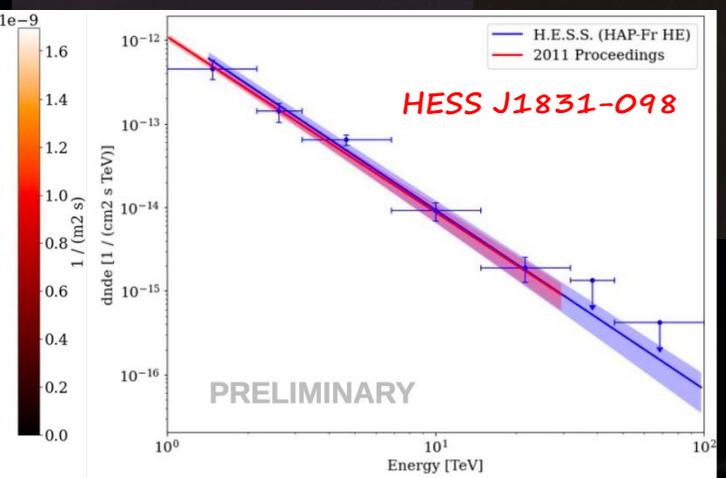
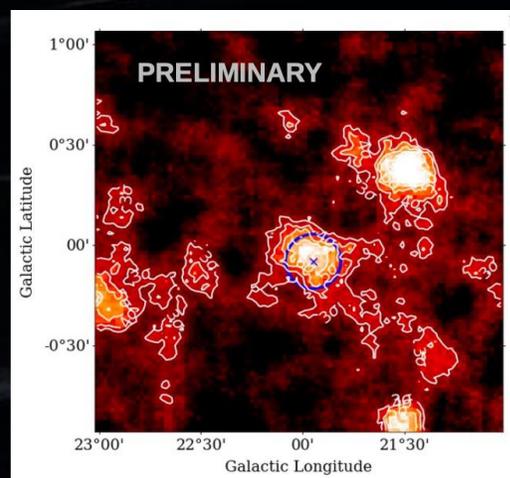
See Crestan talk



HESS J1831-098  
Several possible associations:  
PWN? SNR?  
[Lypova talk Gamma2022]

Complex environment

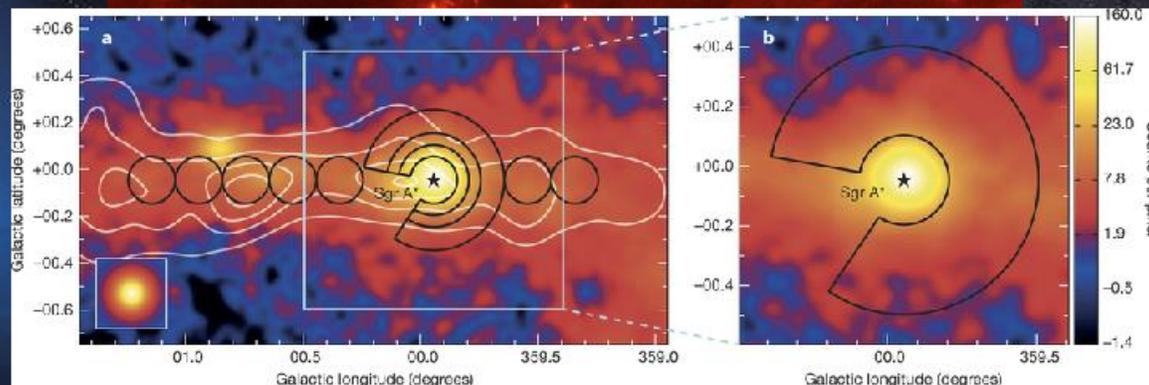
HESS J1809-193  
Extended component → PWN or PWN+SNR  
Compact Component  
[Mohrmann talk Gamma2022]



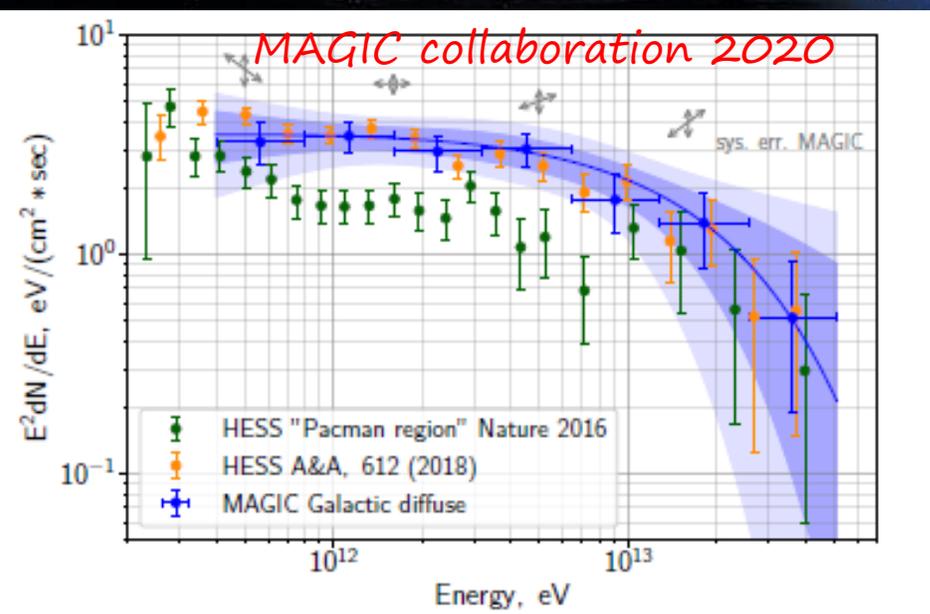
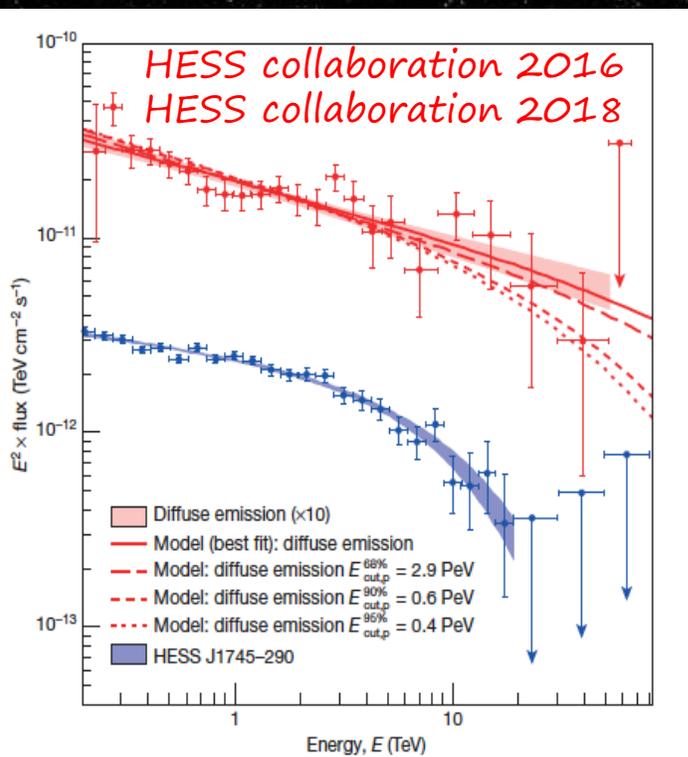
# Galactic Center Region

See Giuliani Talk  
for ASTRI performances

APEX+Planck  
: Dust



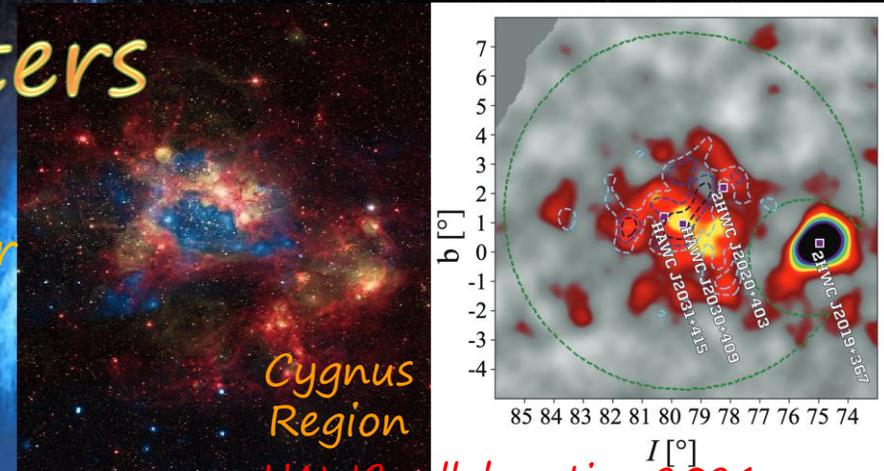
HESS  
collaboration  
2016



- Perfect correlation between molecular gas distribution and gamma-ray emission seen by HESS
- CR energy density 10 times greater than CR sea
- CR spectrum with and index  $\gamma E = 2.3-2.4$  up to 100 TeV (but with large error bars)
- Spatial distribution with  $1/r$  (continuous injection)
- Maybe from Sgr A\* (Rodríguez-Ramírez et al., 2019)
- **First spectro-morphological analysis on-going (Devin talk Gamma 2022)**

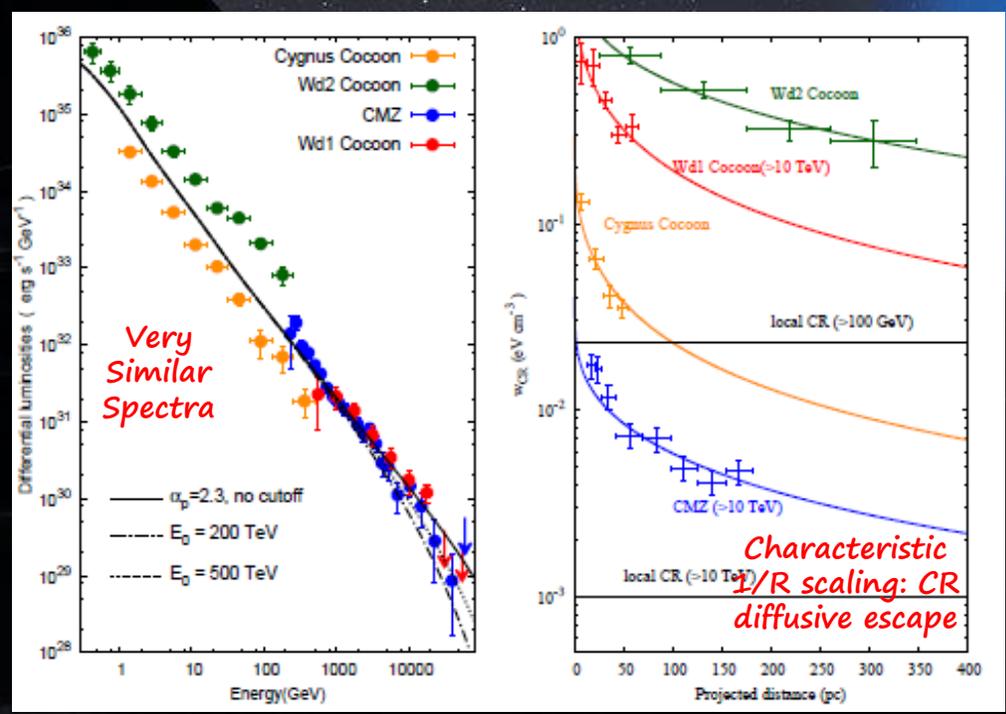
# Massive Star Clusters

- Multiple shocks and winds → enhanced turbulence and acceleration
- No radiative phase → larger acceleration efficiency
- Low-energy spectrum slope similar to the one measured by Voyager
- Explanation of some CR composition anomalies → Be abundances [Tatischeff 2018]
- Spatial and spectral behavior similar to the GC one [Aharonian 2018]
- Acceleration at 1 PeV possible at Wind Termination Shocks [Vieu talk & Gabici talk Gamma2022, Vieu et al. 2022]

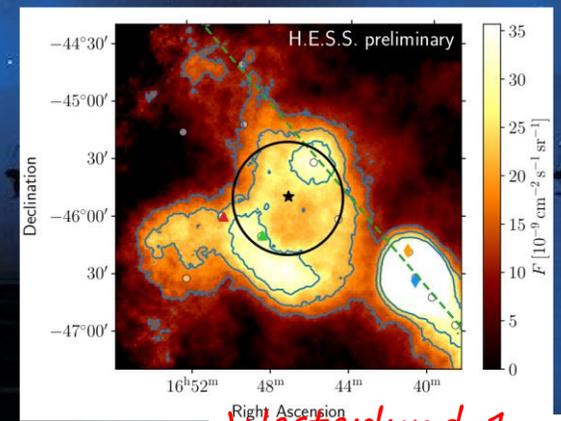


Cygnus Region

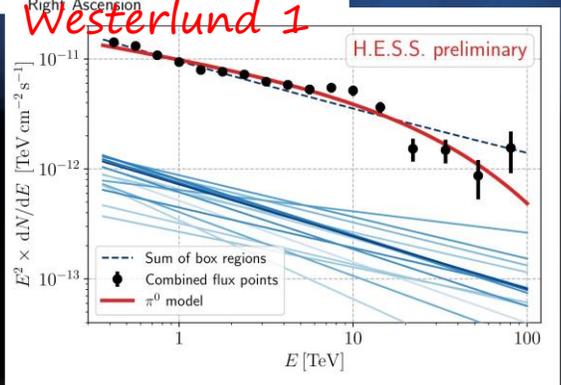
HAWC collaboration 2021



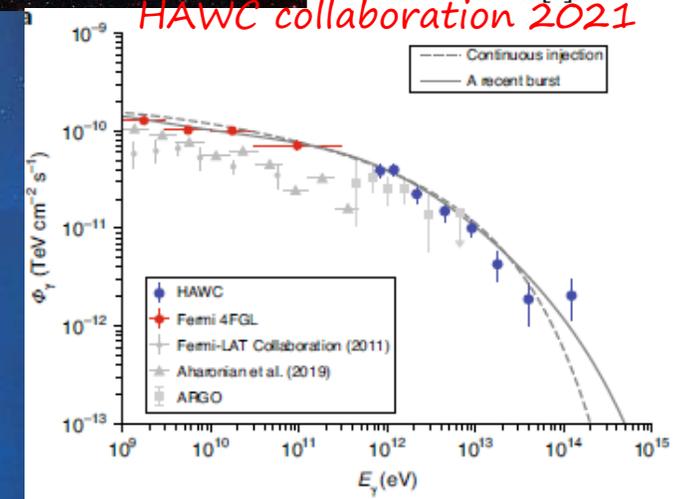
Aharonian et al. 2018



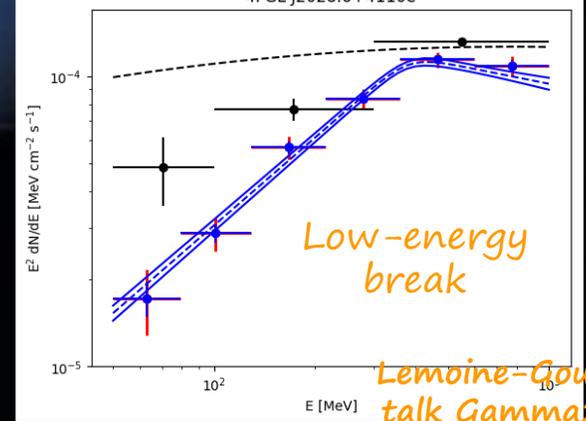
Harer poster & Vieu talk Gamma 2022



Westerlund 1



4FGL J2028.6+4110e



Lemoine-Goumard talk Gamma2022

# Gamma-ray binaries example: Microquasars

Binary stellar systems (BS/BH+Companion)

Cyg X-1, Cyg X-3 and **SS 433** (emitting X-rays) show HE emission up to GeV.

See Egron Talk

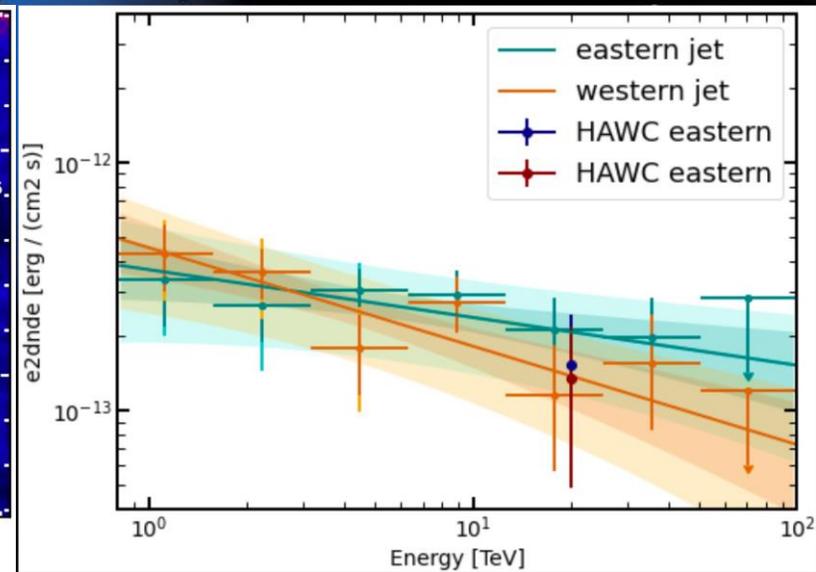
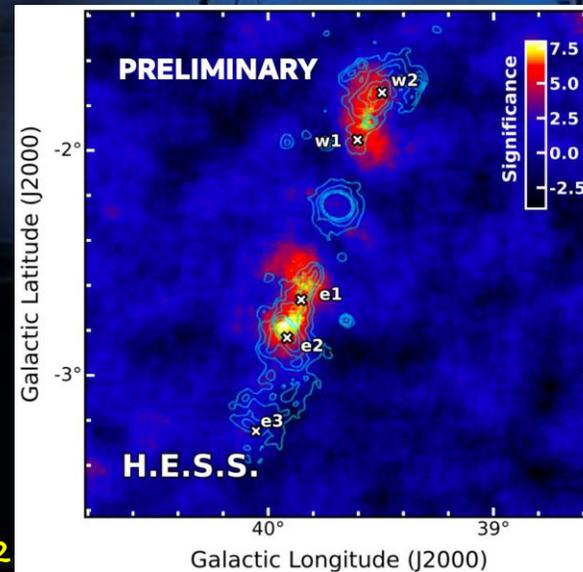
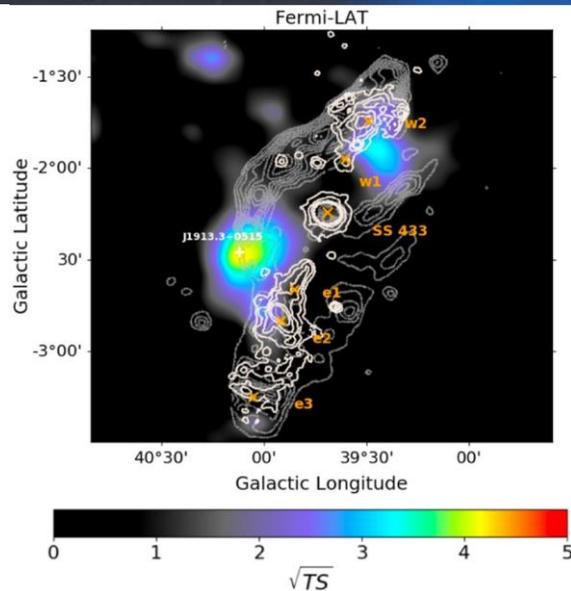
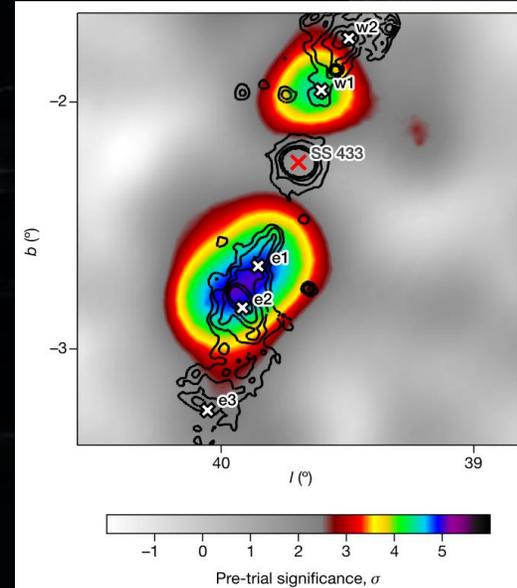
SS 433



HAWC (HAWC2018)

Fermi-LAT (Fang+2020)

HESS



# What we need in the next future?

- Wide FoV with almost homogeneous off-axis acceptance
  - ✓ Multi-target fields, surveys, and extended sources (GC, SNRs, TeV halos)
  - ✓ Enhanced chance for serendipitous discoveries
- Sensitivity: better than current IACTs ( $E > 10$  TeV):
  - ✓ Extended spectra for PeVatron confirmation and lepto/hadro origin discerning (SNRs, Micro-quasars, PWN)
  - ✓ Diffusion coefficient constraints (Gamma-Cygni, SNRs, TeV halos)
- Energy/Angular resolution:  $\leq 10\%$  /  $\leq 0.1^\circ$  ( $E \leq 10$  TeV)
  - ✓ Characterize extended sources morphology and MW association (Jets, SNRs, GC, TeV halos)

And we would like also  
a neutrino detection, thanks!





cherenkov  
telescope  
array

the observatory for  
ground-based  
gamma-ray astronomy



Serra La Nave  
(Sicily)

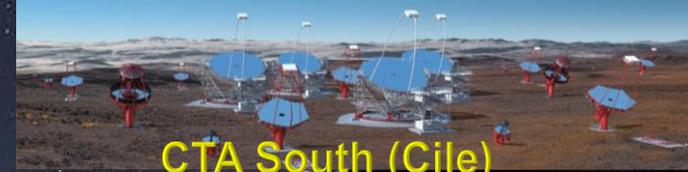
Teide Observatory  
(Tenerife)

*Giuliani Talk*

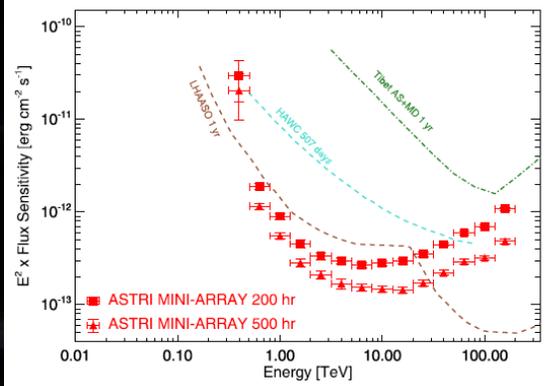
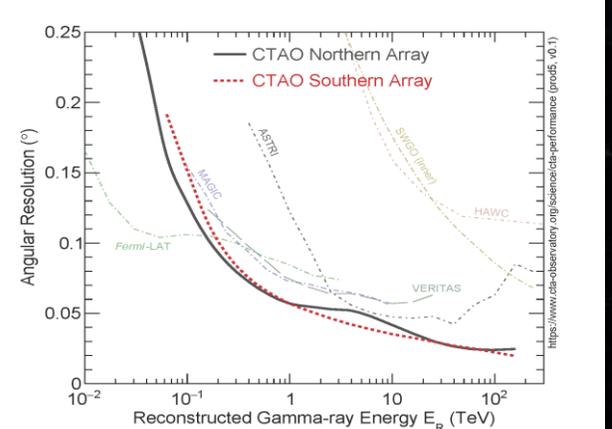
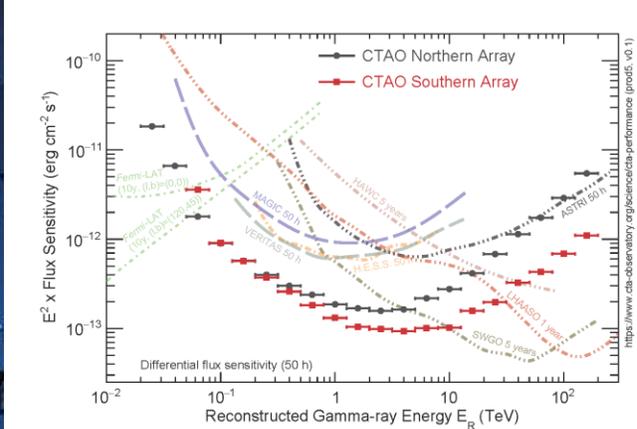
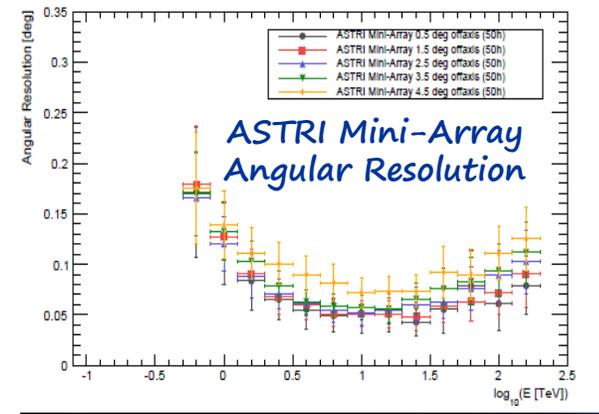
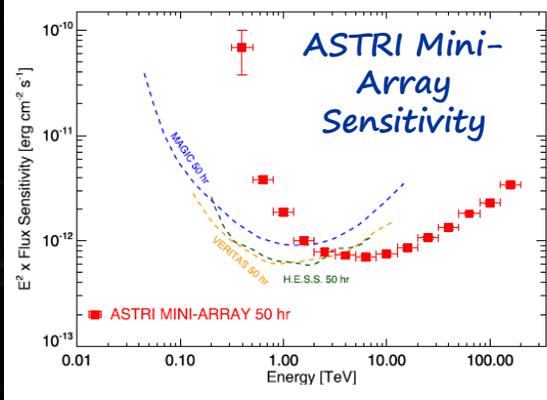
*Cappi Talk*



CTA North (La Palma)



CTA South (Cile)



1 telescope operative → early 2023 (already on-site!!)

3 telescopes operative → by 2023

Complete Array → by the end of 2024

- Scuderi et al., 2022, JHEAP, 35, 52
- Vercellone et al., 2022, JHEAP, 35, 1-42
- D'Ai et al., 2022, JHEAP, 35, 139

CTA Sensitivity

CTA Angular Resolution

CTA website (<https://www.cta-observatory.org/science/ctao-performance/#147256315764891558872-faf1>)

LST1, La Palma  
(Canarian Islands)



# IMPORTANT MESSAGES

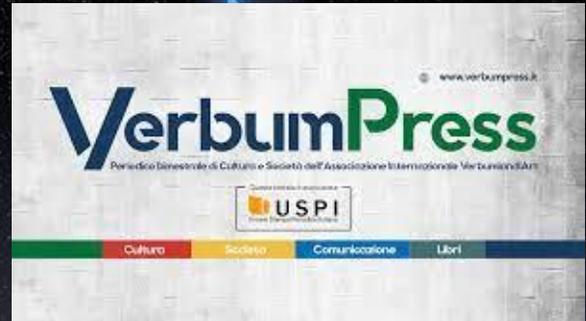
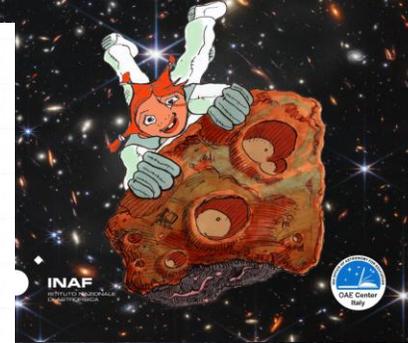
- ✧ One of the "hot" topic of the High Energy Astrophysics is "Particle Acceleration" and, in particular, the search of hadronic Pevatrons (**Origin of Cosmic Rays!!!!**)
- ✧ A very brilliant future with **ASTRI Mini-Array** and **CTA** and synergy with current VHE instruments
- ✧ **Multiwavelength** work will be fundamental
- ✧ **A lot of work to do**: from simulation and software to data analysis to theoretical interpretation

**ENJOY THE  
HIGH-ENERGY SIDE!**

You Tube



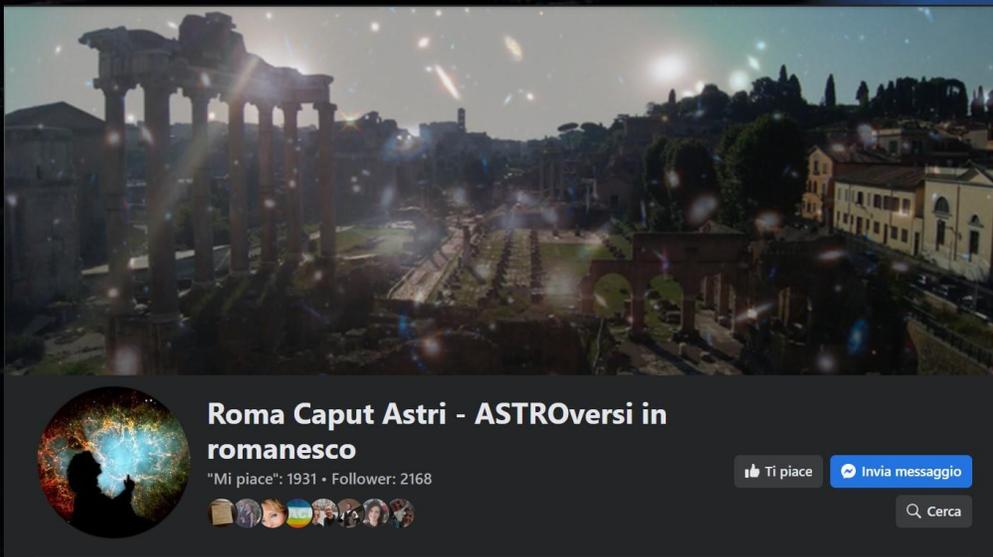
MARTINA TREMENDA NELLO SPAZIO



Rubrica "Bolle spaziali"



Facebook



Divulgazione fatta col cuore...



"A Spazio Con Marty"



ASTRONOMITALY LA RETE DEL TURISMO ASTRONOMIC



Grazie

a tutti voi!