HANDS ON THE EXTREME UNIVERSE WITH HIGH ENERGY GAMMA RAYS

July, 18-22, 2022

The fascinating Galactic Science to understand with future Cherenkov Telescopes

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Sorry if I'm not there in presence.

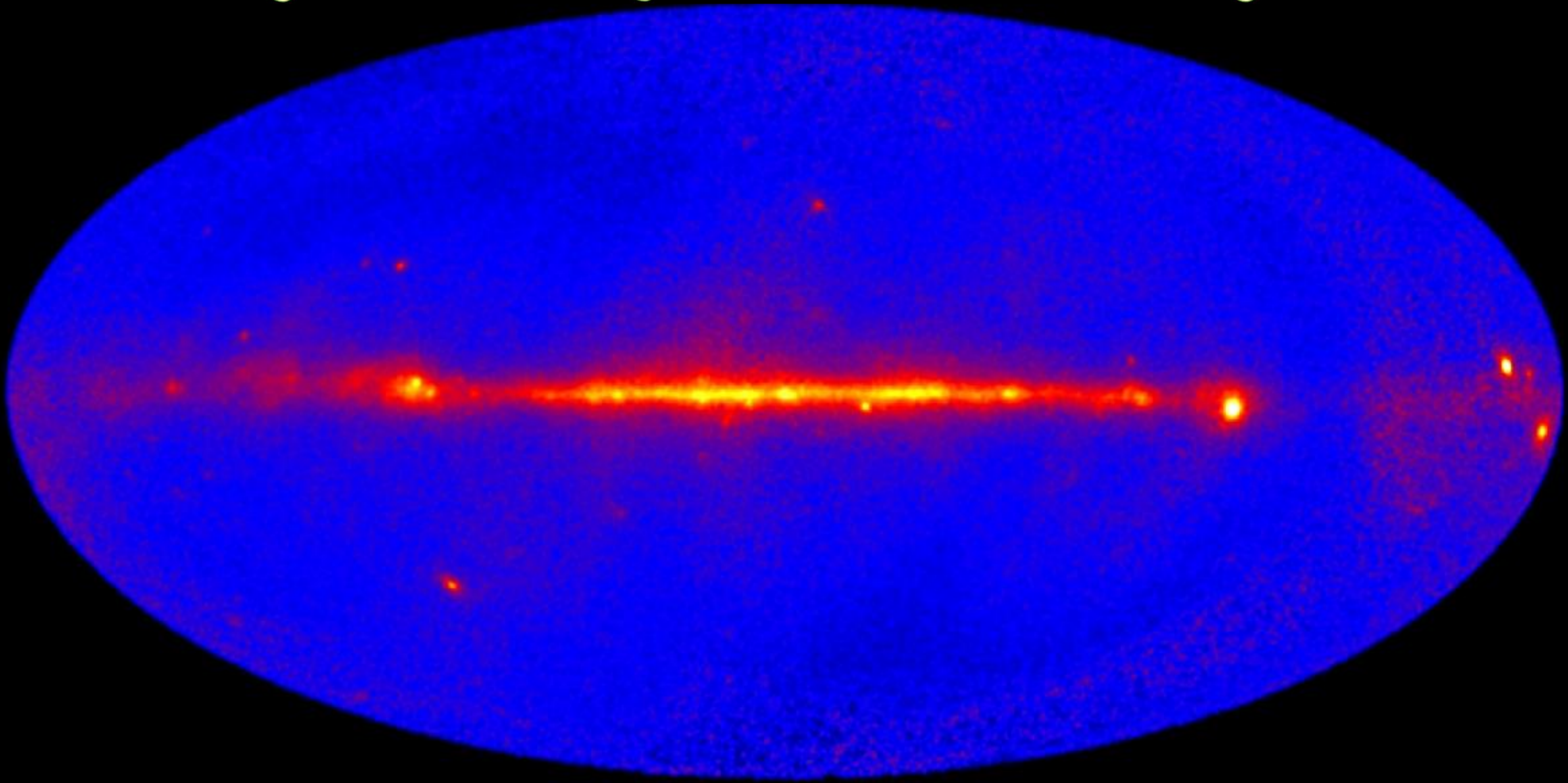
July 20, 2022


AFTER THE TERRIFIC IMAGES OF JWT
WE, GAMMA-RAY SCIENTISTS, NEED A MOTIVATIONAL MOMENT

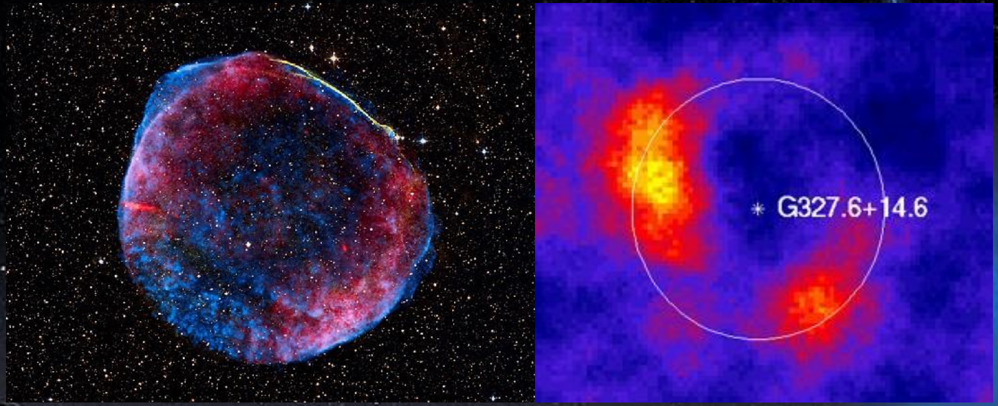
Sadly true:

the beautiful images in the optical (and not only) band…

...in the gamma-ray band we can forget them!

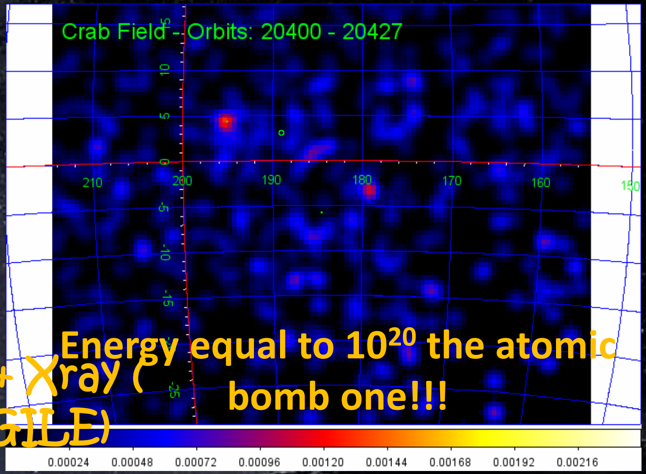


But remember, our sources are ugly but very cool!!!



SNR 1006 by Chandra (X ray) and HESS (gamma-rays)

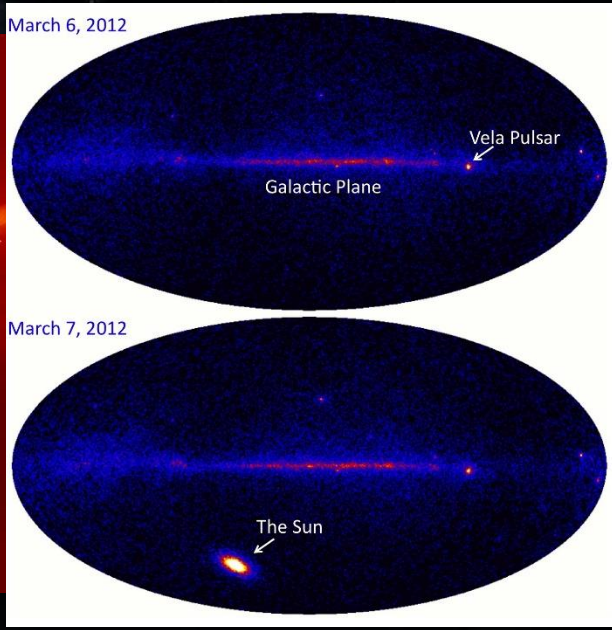
Crab nebula: optical (Hubble) + Xray (Chandra) and Gamma-ray (AGILE)



Energy equal to 10^{20} the atomic bomb one!!!

AGILE revealed the brighter gamma-ray source in the sky: the black hole CRAZY DIAMOND, December 3-4, 2009

The Sun seen by SOHO



And we are very cool, don't forget it!

VHE: Messengers and Instruments

Direct Detection (E<100 GeV) — **Space Based**

Particles
- Proportional tubes and scintillators (e.g. CREAM, TRACER)
- Magnetic Spectrometers and silicon tracker (e.g. PAMELA, AMS-02)

Gamma-rays
- Silicon Tracker and calorimeter (AGILE, Fermi-LAT)

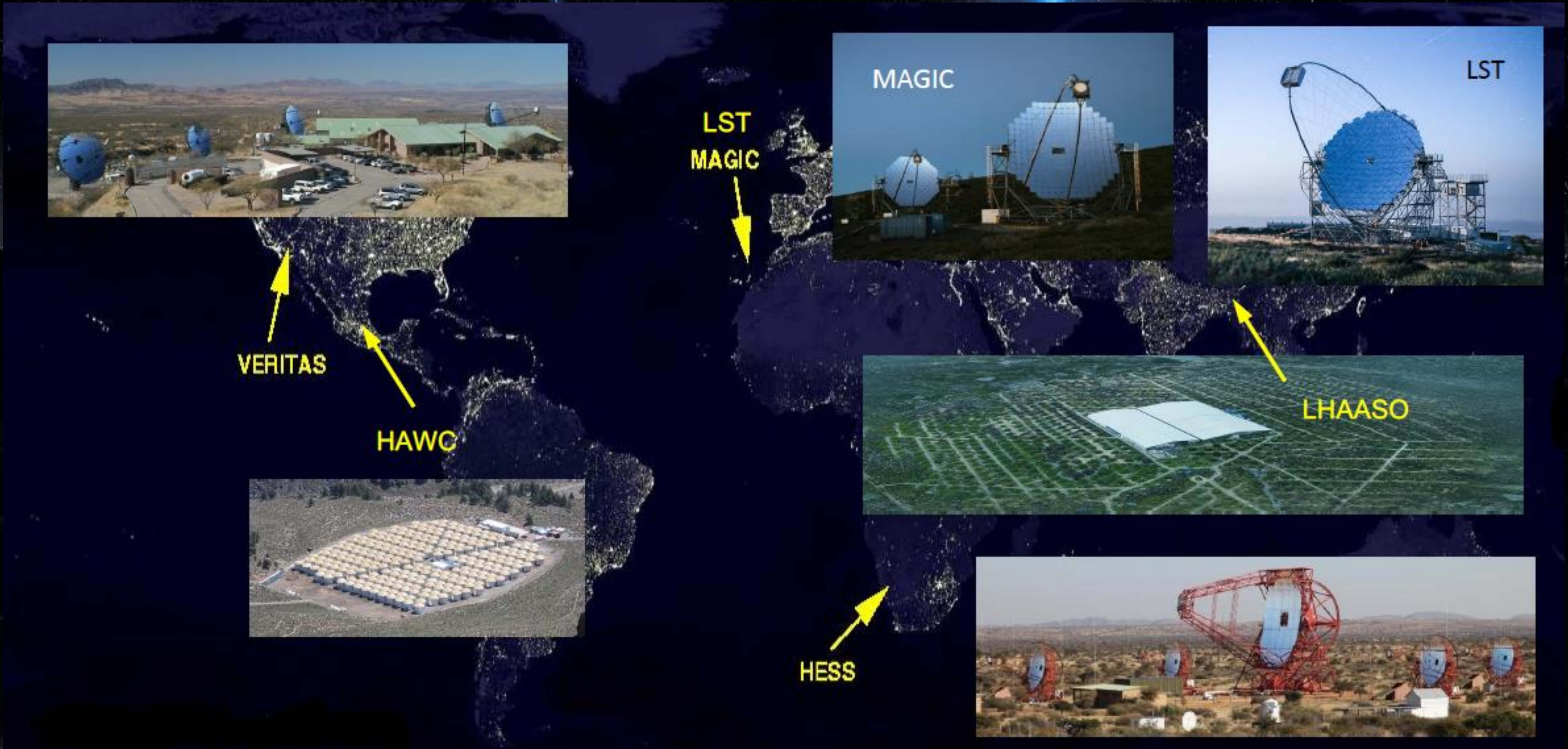
NEUTRINOS

Indirect Detection (E>100 GeV) — **Ground Based**

Particles&Gamma
- Scintillators and Multiple Resistive plate chambers (e.g. KASCADE-Grande, Tibet_AS gamma, Argo)
- Water Cherenkov (e.g. Milagro, HAWC)
- Hybrid: water Cherenkov and fluorescence (e.g. Auger) or scintillators (e.g. LHAASO)

Gamma-rays
- Imaging Atmospheric Cherenkov Telescope (e.g. HESS, VERITAS, MAGIC → ASTRI-MA, CTA)

Current Cherenkov Facilities

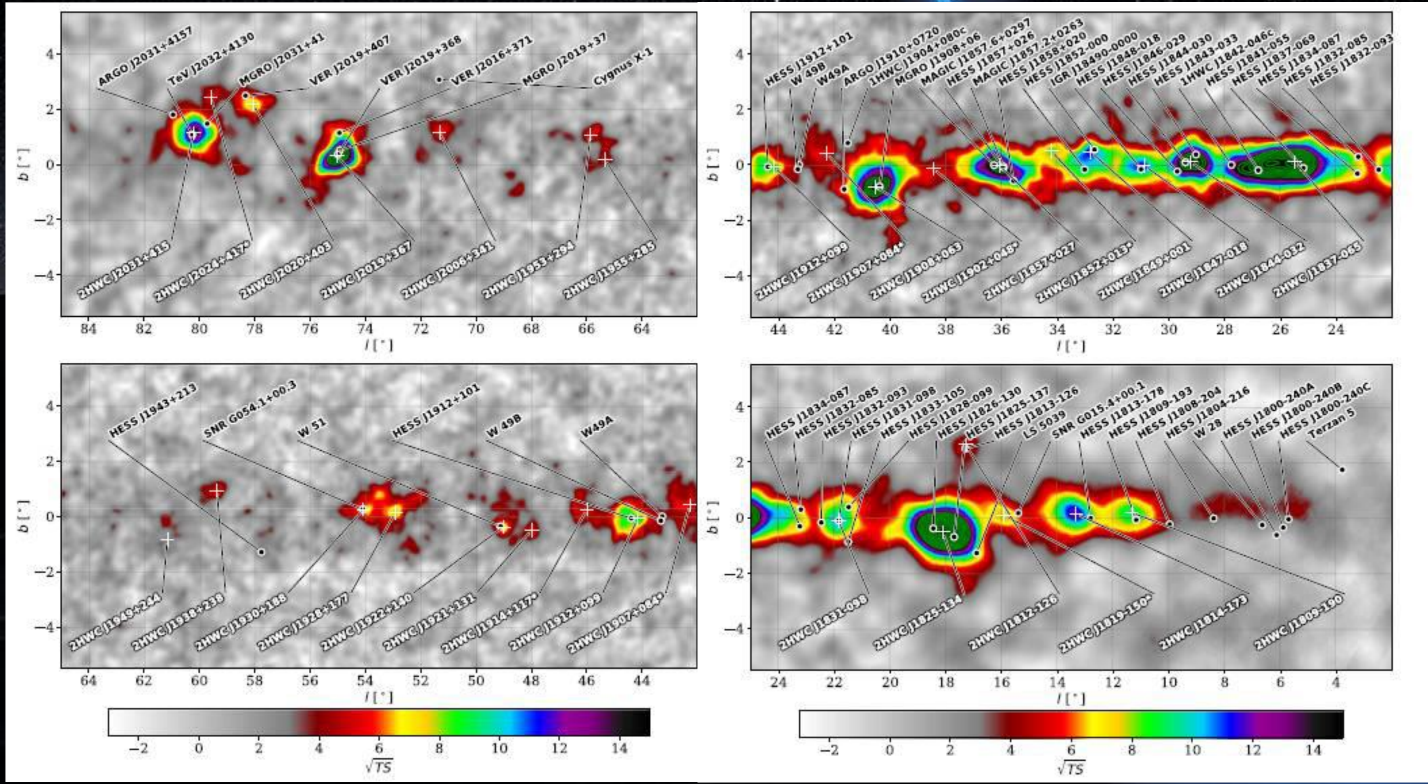


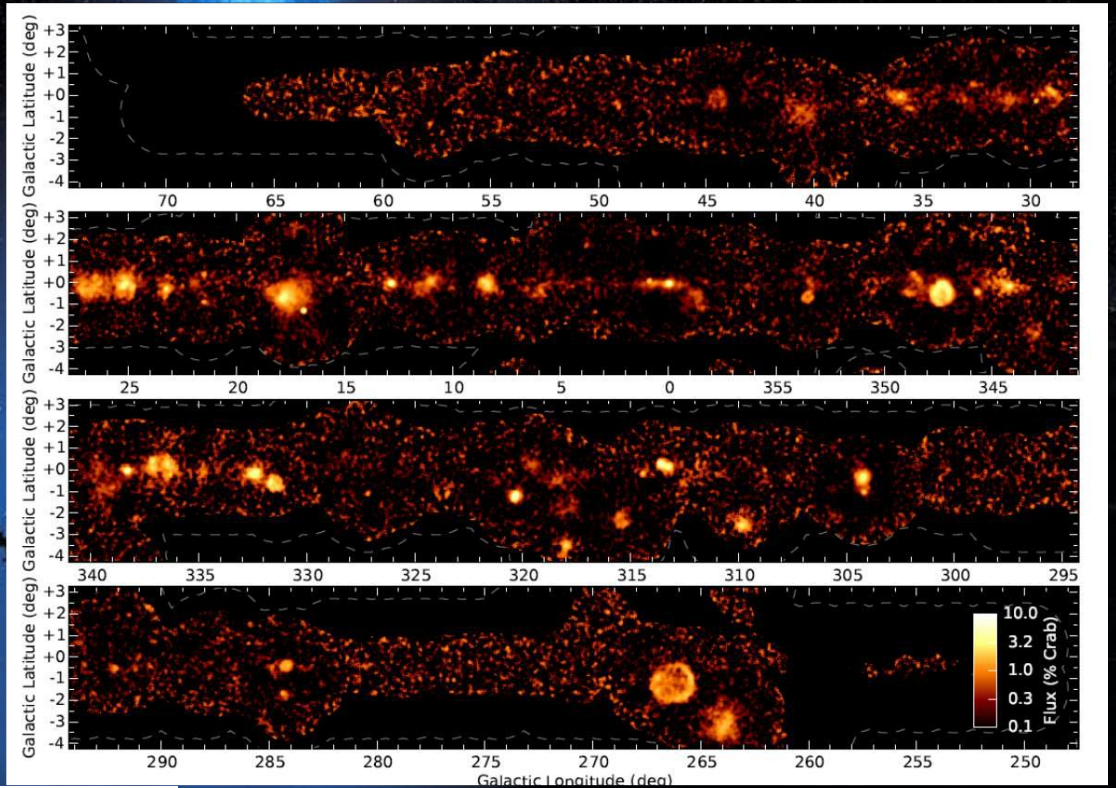
From Ribot presentation at Gamma 2022

Galactic Plane Survey

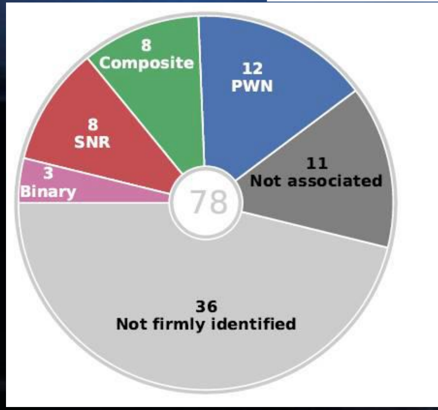
Abeysekara et al. 2017

Deil et al. 2015
HESS 2018





39 sources → 17 new
Some with no <10 TeV countepart



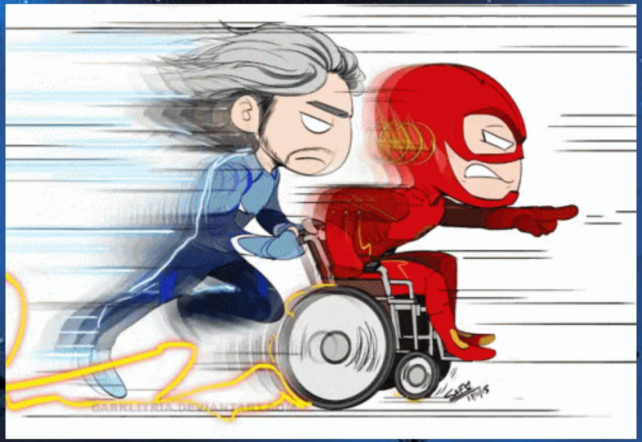
78 sources → 13 new

From Rowell presentation 2019

Galactic Science Questions

PARTICLE ACCELERATION


Star Formation Regions

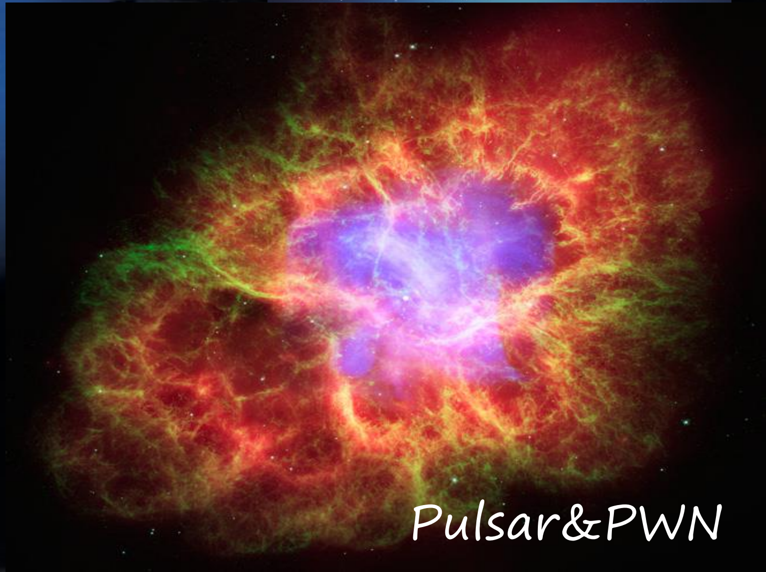


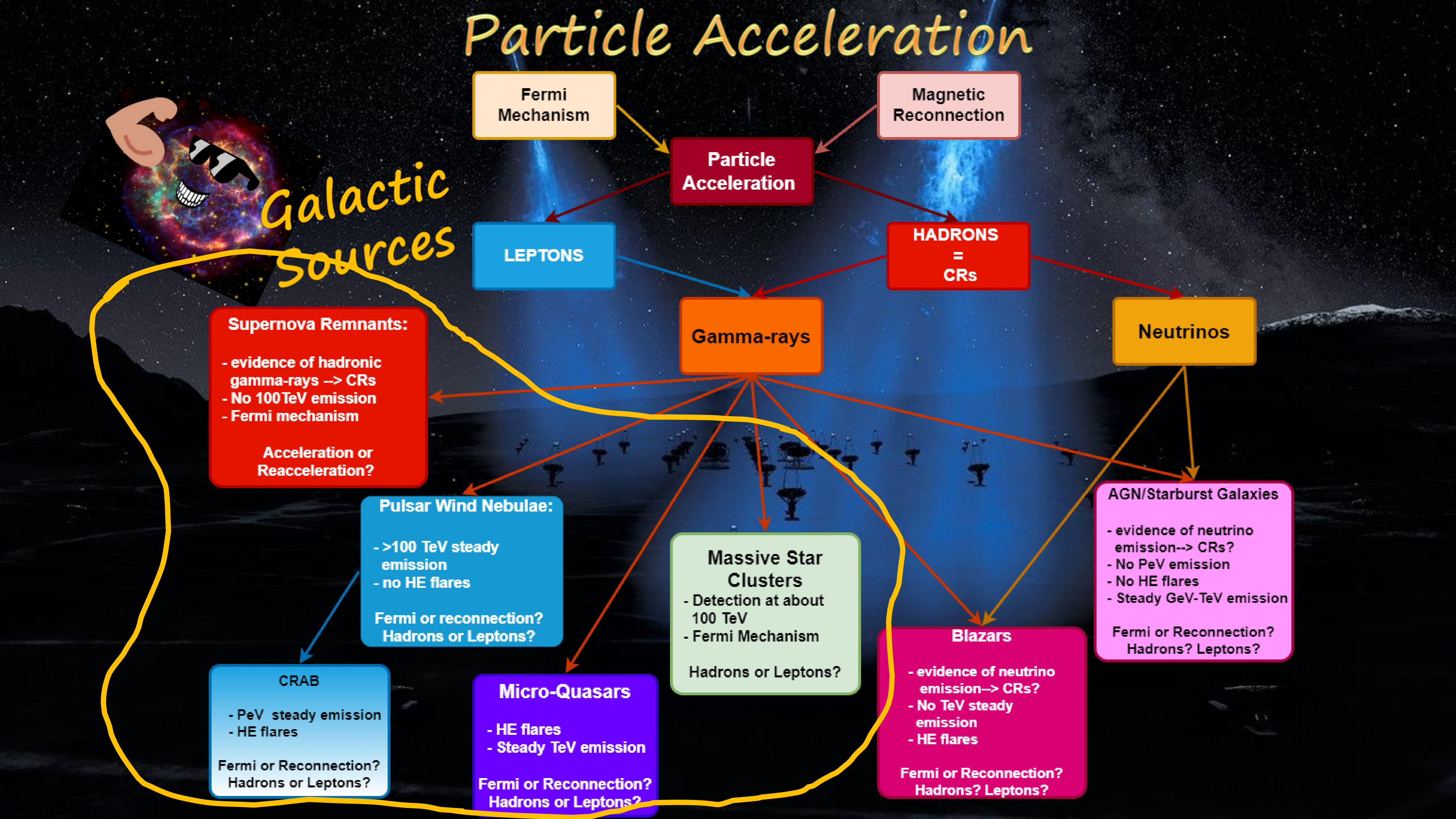
Morlino Talks


Novae

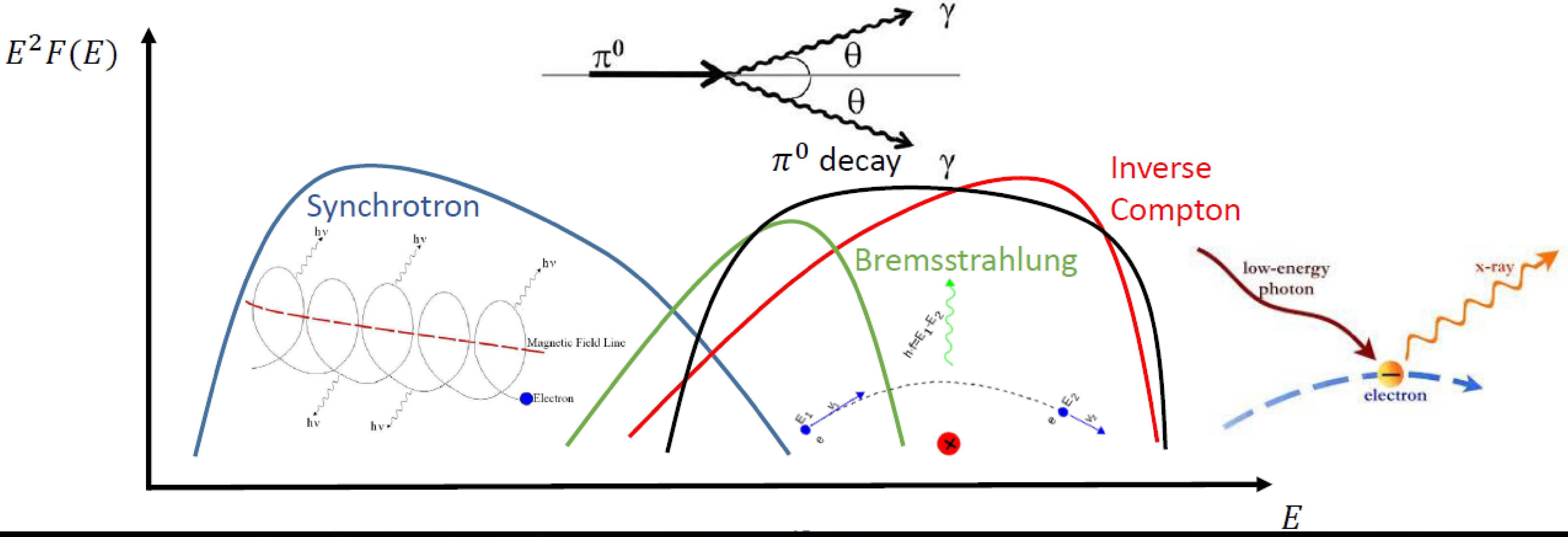

SNRs


Microquasars


Pulsar&PWN


Particle Acceleration
Fermi Mechanism
Magnetic Reconnection
Particle Acceleration
LEPTONS
HADRONS = CRs
Gamma-rays
Neutrinos
Galactic Sources
Supernova Remnants:
- evidence of hadronic gamma-rays --> CRs
- No 100TeV emission
- Fermi mechanism
Acceleration or Reacceleration?
Pulsar Wind Nebulae:
- >100 TeV steady emission
- no HE flares
Fermi or reconnection? Hadrons or Leptons?
CRAB
- PeV steady emission
- HE flares
Fermi or Reconnection? Hadrons or Leptons?
Micro-Quasars
- HE flares
- Steady TeV emission
Fermi or Reconnection? Hadrons or Leptons?
Massive Star Clusters
- Detection at about 100 TeV
- Fermi Mechanism
Hadrons or Leptons?
Blazars
- evidence of neutrino emission--> CRs?
- No TeV steady emission
- HE flares
Fermi or Reconnection? Hadrons? Leptons?
AGN/Starburst Galaxies
- evidence of neutrino emission--> CRs?
- No PeV emission
- No HE flares
- Steady GeV-TeV emission
Fermi or Reconnection? Hadrons? Leptons?

Radiative procesess: very quick look



See the next Morlino Talk for all you have to know about PeVatrons!!!

Pevatrons

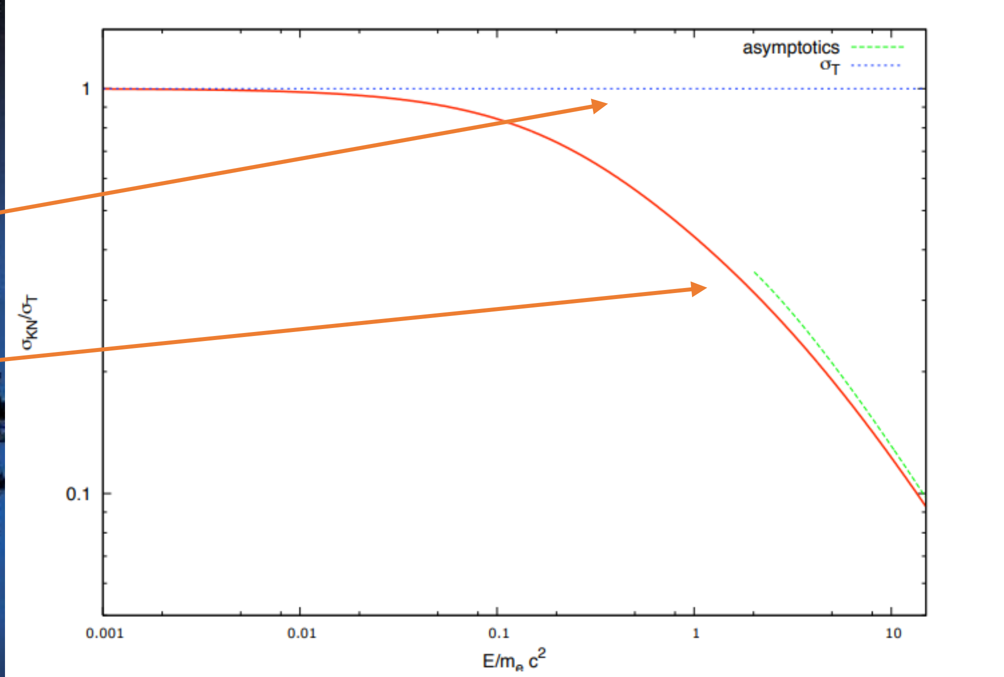
HIGH ENERGY ASTROPHYSICS

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 applies

Klein-Nishina scattering ($h\nu_i \gg m_e c^2$)
- transfer large,
- scattering deeply inelastic,
- need to use cross-section derived from QED.

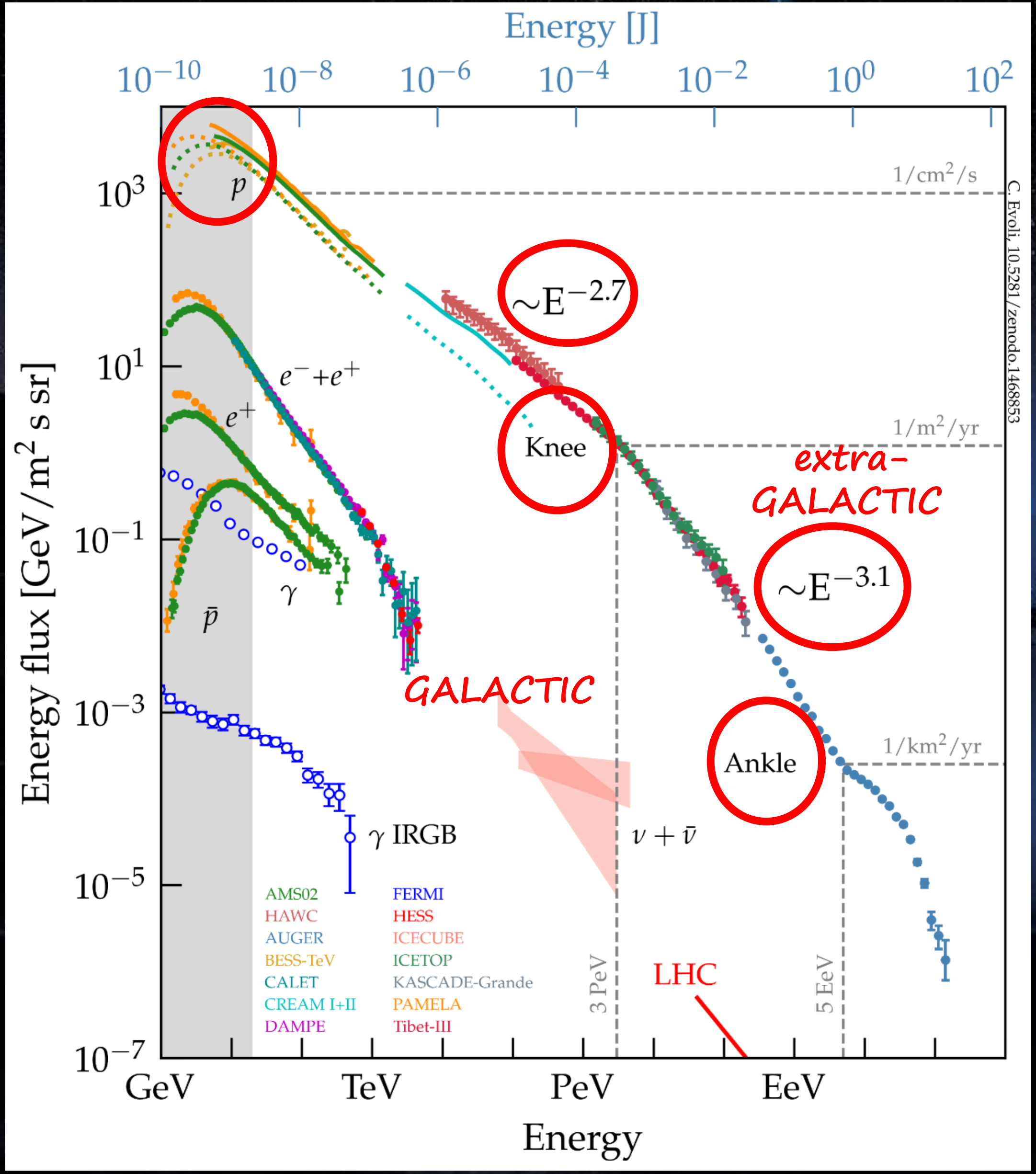


COSMIC RAY CONTEXT

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

Cosmic Ray Overview

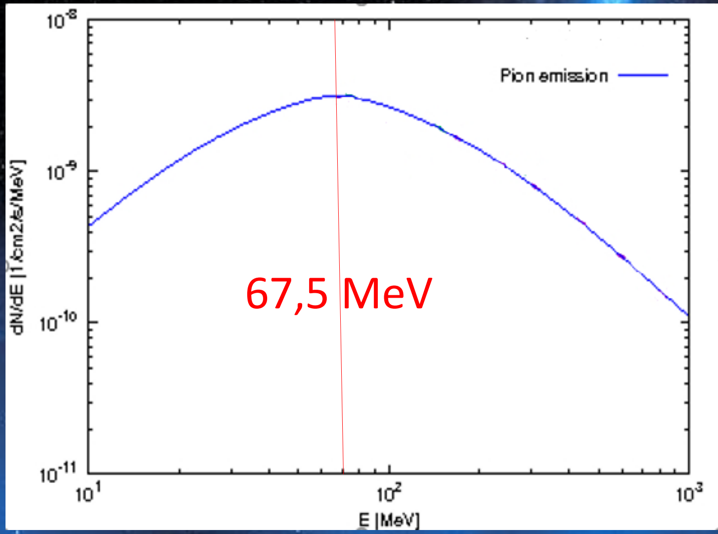
Evoli 2021

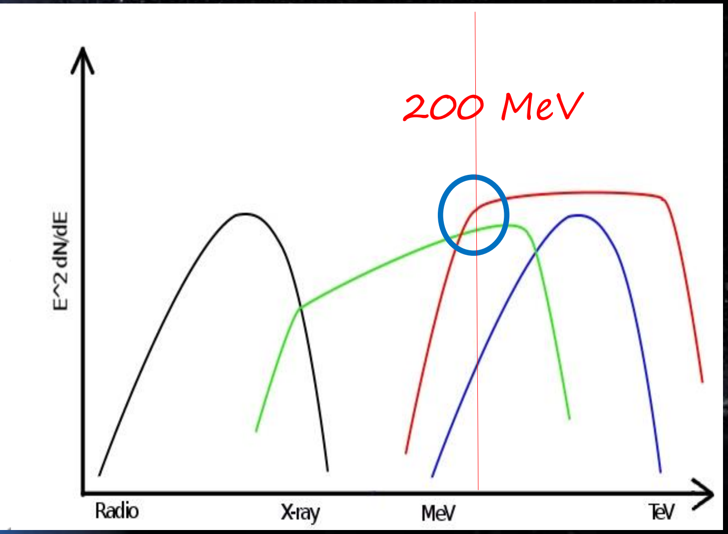


- High-energy particles (mostly protons and nuclei) up to 10^{21} eV
- Bending below 30 GeV due to solar modulation
- Power-law distribution with an index $\alpha \simeq 2.7$ up to PeV energies → No thermal → acceleration
- Two main features:
  - Steepening at PeV energies, $\alpha \simeq 3.1$ (*Knee*, 1 part/m²/yr)
  - Hardening at about E=10^{18} eV (*Ankle*, 1 part/km²/yr)
- Knee due to rigidity-dependent acceleration mechanism → $E_{knee,Z} = Z\, E_{knee,p}$

CR Acceleration: direct evidences

Low-Energies → **AMEGO (2029)**

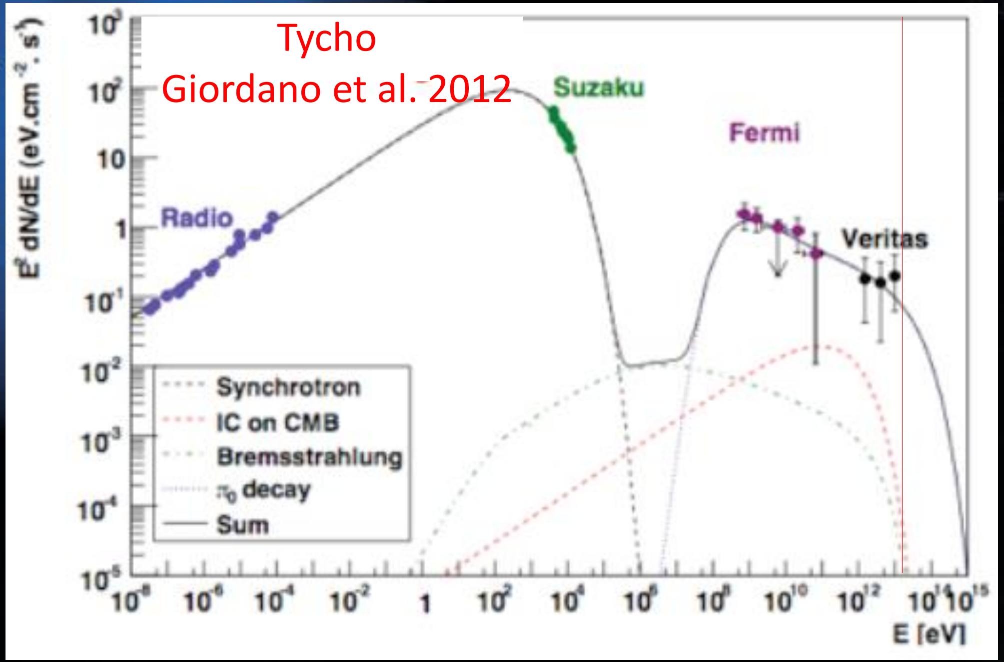




Hadronic or Leptonic?

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

High-Energies → **ASTRI MA** (3 out of 9 telescopes within 2023)
CTA SST (first telescopes within 2024)



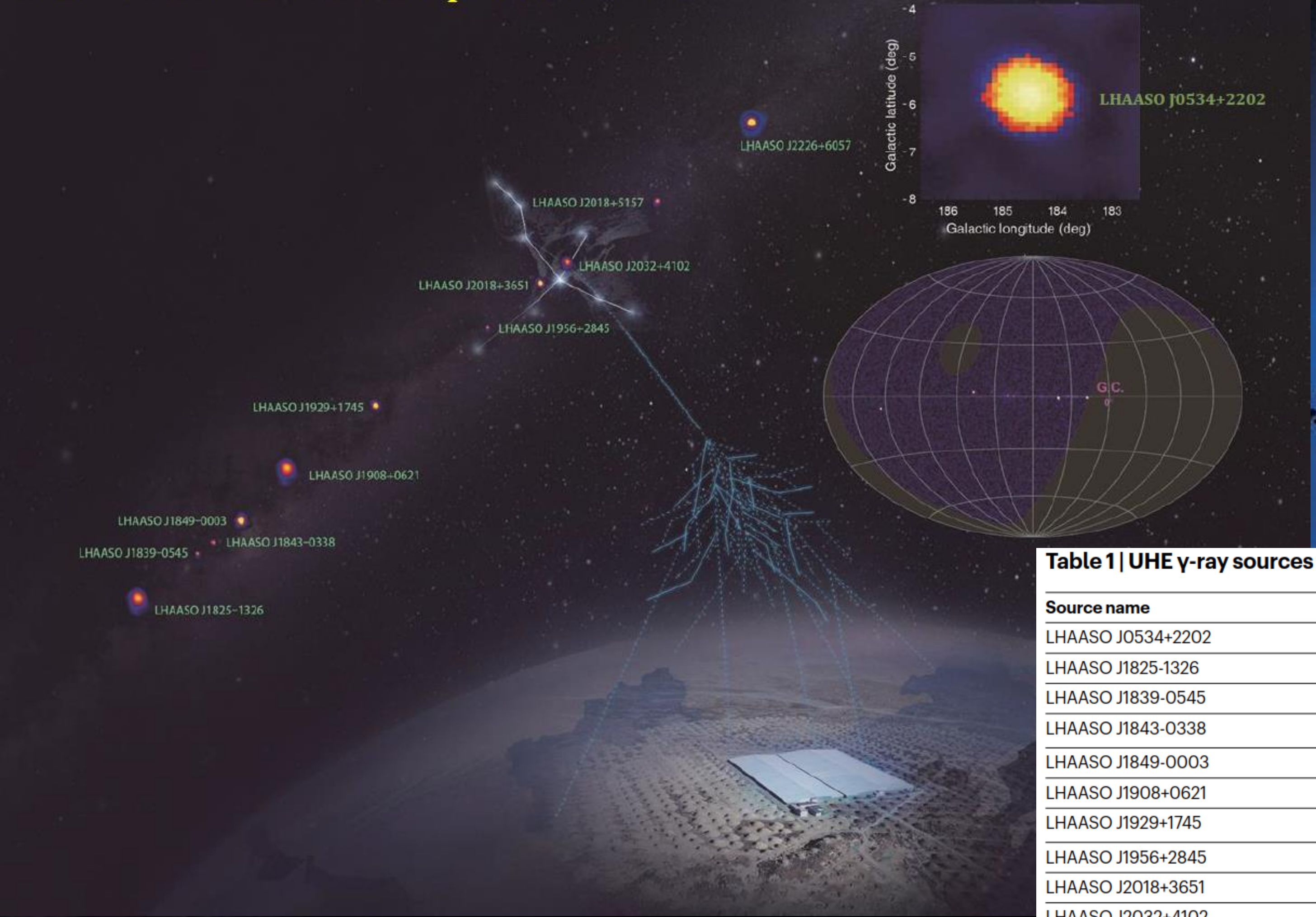
Pevatrons?

→ gamma-ray at E>100 TeV can be only of hadronic origin (theoretically…)

"PeVatrons" storm from LHAASO

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

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



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

Table 1 | UHE γ-ray sources

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 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 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 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 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

Cao ICRC 2021

VHE Shopping list (Hilton seminar 2022):

- Detected VHE-UHE Emission
- Spectral curvature
  - Signature of Emax, 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

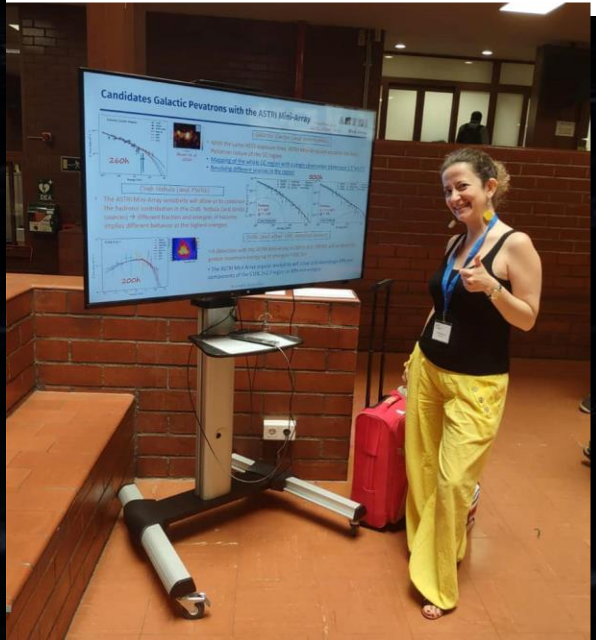
THE RIGHT LOCATION

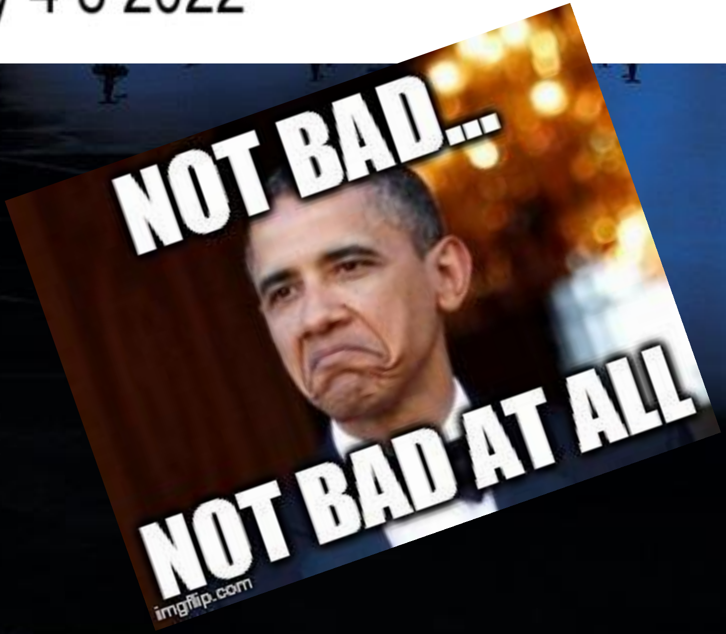
A lot of results from this beautiful Conference...

https://indico.icc.ub.edu/event/46/overview

γ 2022

7th Heidelberg International Symposium on
High Energy Gamma-Ray Astronomy
Barcelona, July 4-8 2022



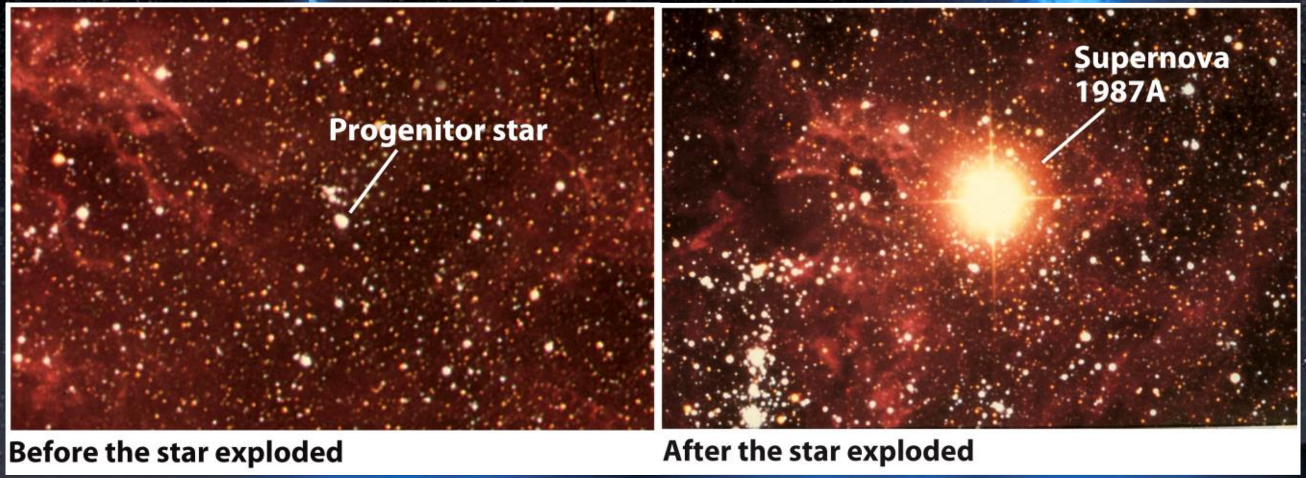


...where I got the COVID.!

Supernova Remnants

PERFECT CR ACCELERATORS CANDIDATES

1934 Zwicky & Baade
(SNR hypothesis)



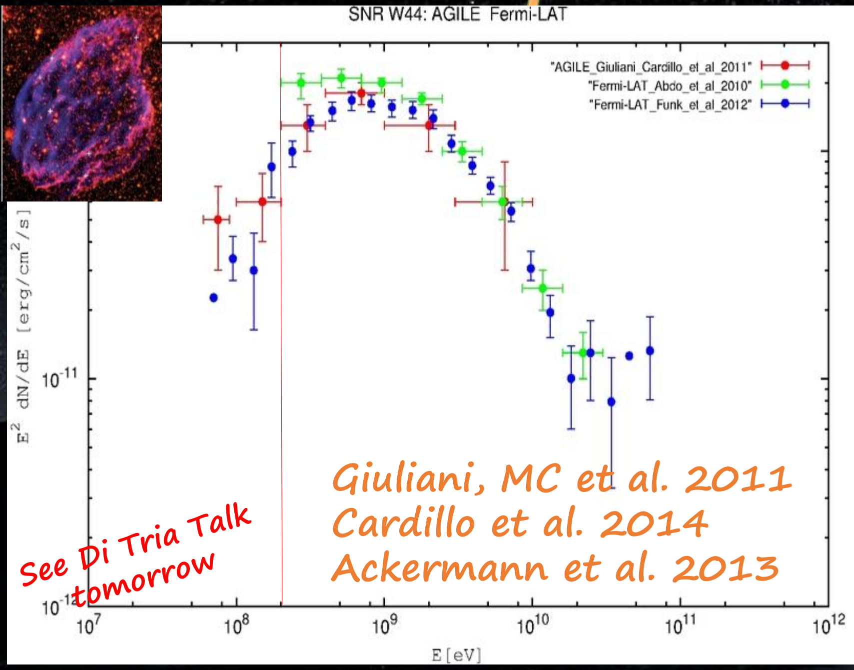
1959. V.Ginzburg
(quantitative)

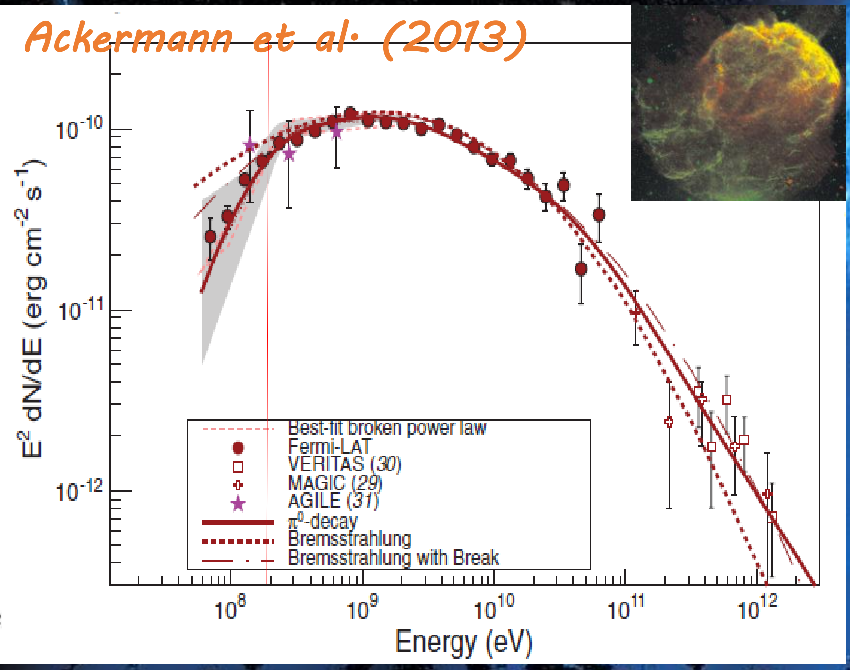
$$\begin{cases} L_{SN} = R_{SN}E_{kin} \approx 3 \times 10^{41} \text{erg/s} \\ L_{CR,gal} \sim 3 \times 10^{40} \text{erg/s} \end{cases}$$

→ *Efficiency of order 10% per SN is sufficient to accomodate CR energetics.*

- *COLLISIONLESS SHOCKS*:
  energy dissipated via wave–particle interaction instead of particle–particle collisions.
- *STRONG SHOCKS AND DSA*: $\mathcal{R} = \frac{u_u}{u_D} = \frac{4M_s^2}{3 + M_s^2}$ $\quad M_s \to \infty \,,\ \mathcal{R} \to 4$
- *MAGNETIC FIELD AMPLIFICATION*

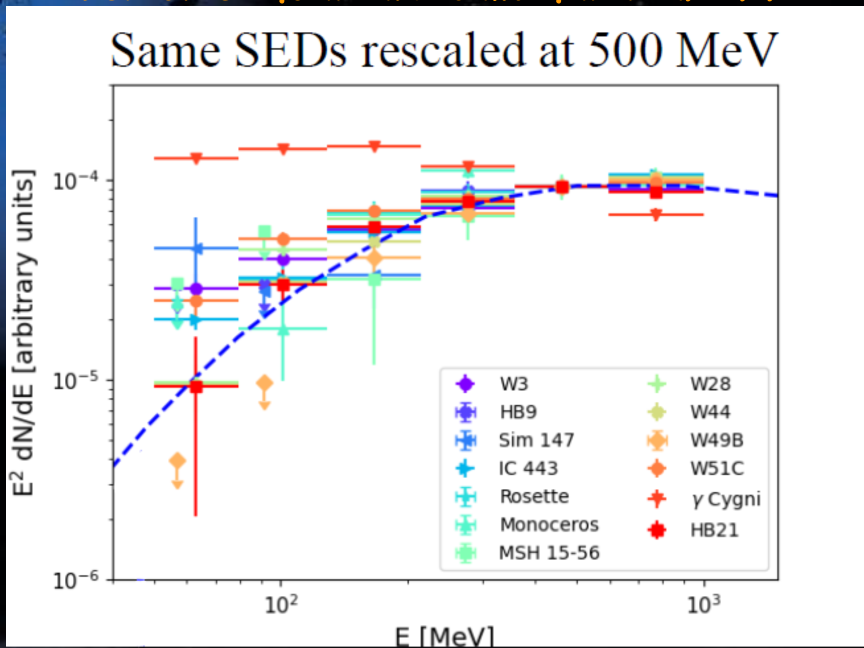
Supernova Remnants: Low-Energies





Gamma-ray emission below 200 MeV detected by AGILE from the SNR W44, then confirmed by Fermi-LAT also in IC443

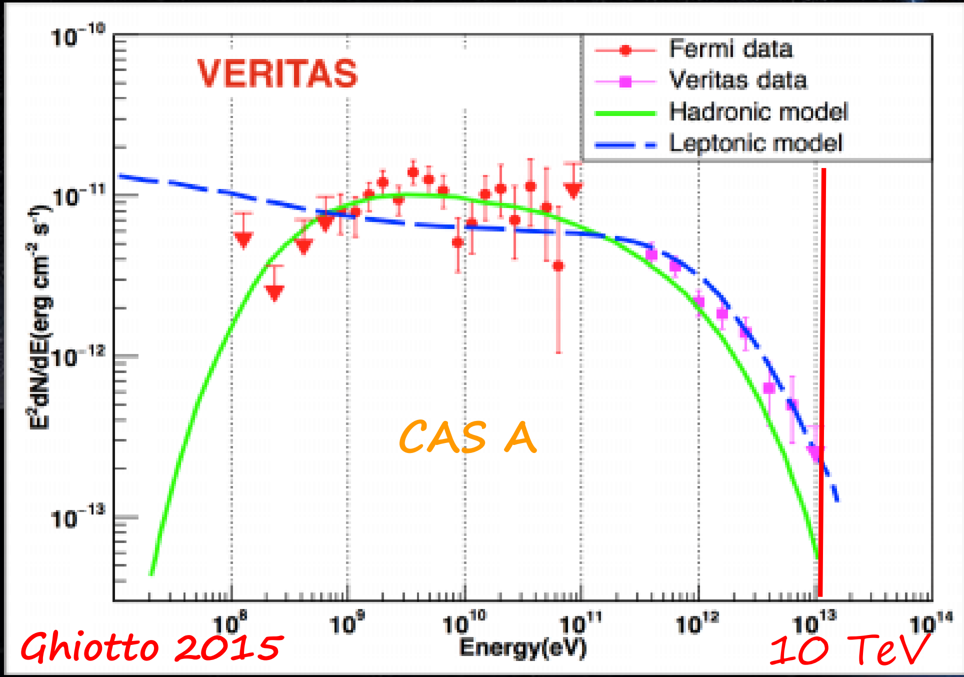
Lemoine-Goumard talk Gamma2022

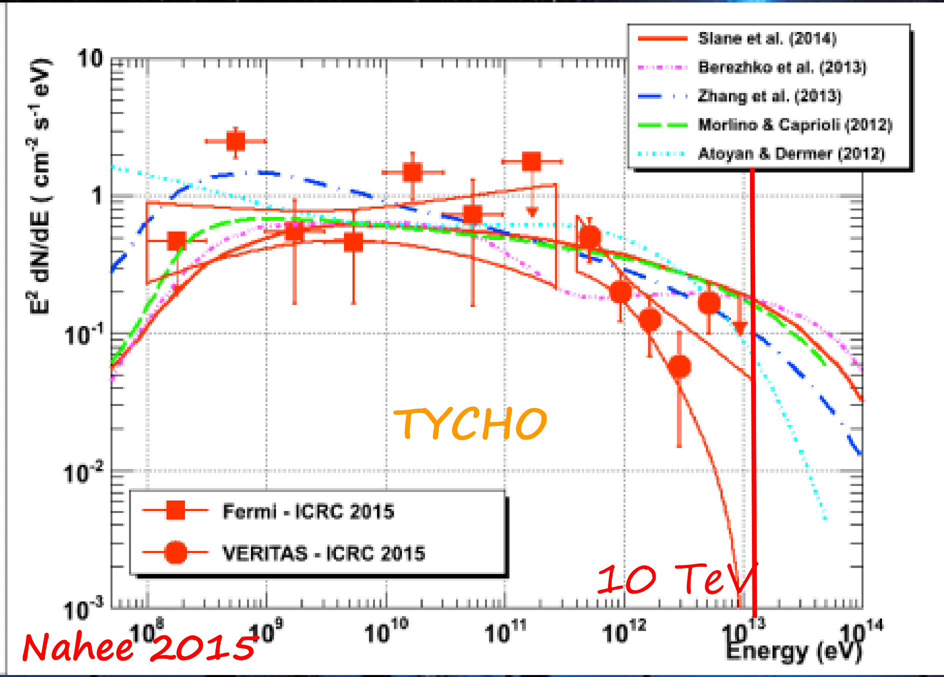


- Presence of a broken PL and of a very steep HE spectral index → *not expected from diffusive shock acceleration theory;*
- The shock of middle-aged remnants are slow (vs < 100 km/s)→ *acceleration efficiency ξ_{CR} has to be too high in order to explain the emission:* $P_{CR} = \xi_{CR} \rho v_{sh}^2$

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

Supernova Remnants: High-Energies

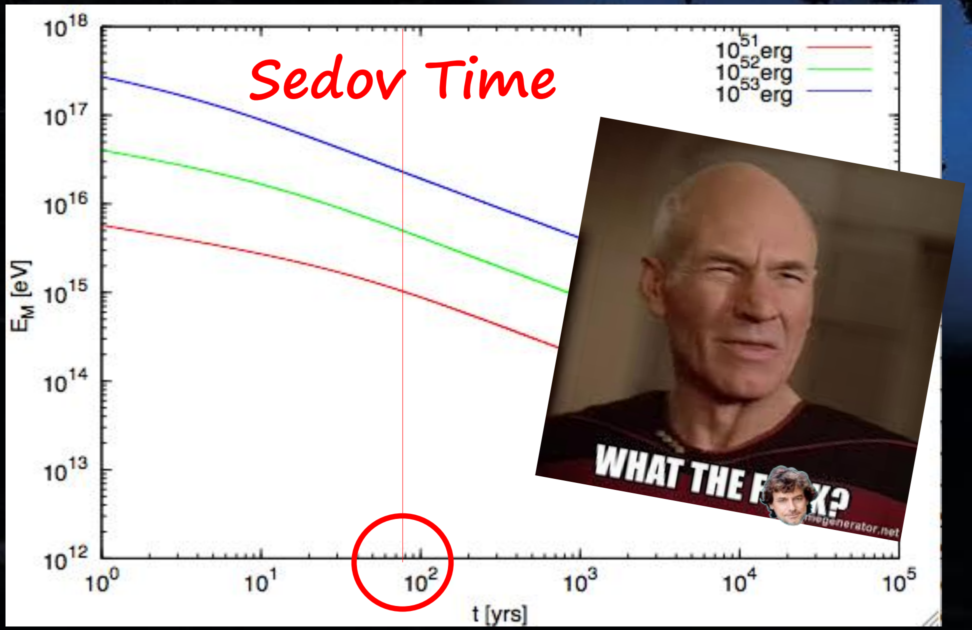




Despite the great amount of SNRs detected in the gamma-ray band, no young SNRs show gamma-ray emission up to $E \geq 100\,TeV$

What is probability to detect SNR emitting Pevatron gamma-rays?

Cardillo, Amato, Blasi 2015

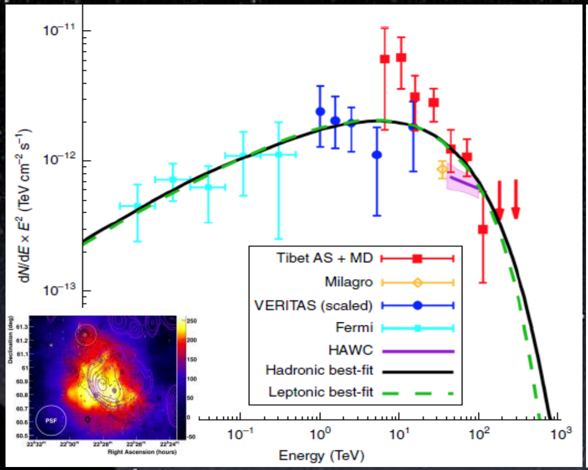


Distant MCs could be "the only hope" of a a SNR PeVatron detection (Gabici 2009)

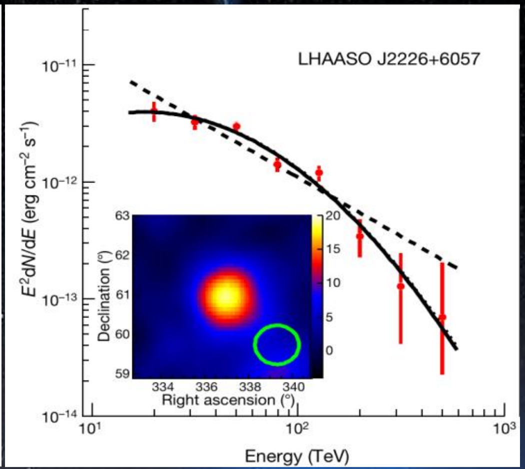
See Giuliani Talk for ASTRI perfomances

Supernova Remnants: high-energies

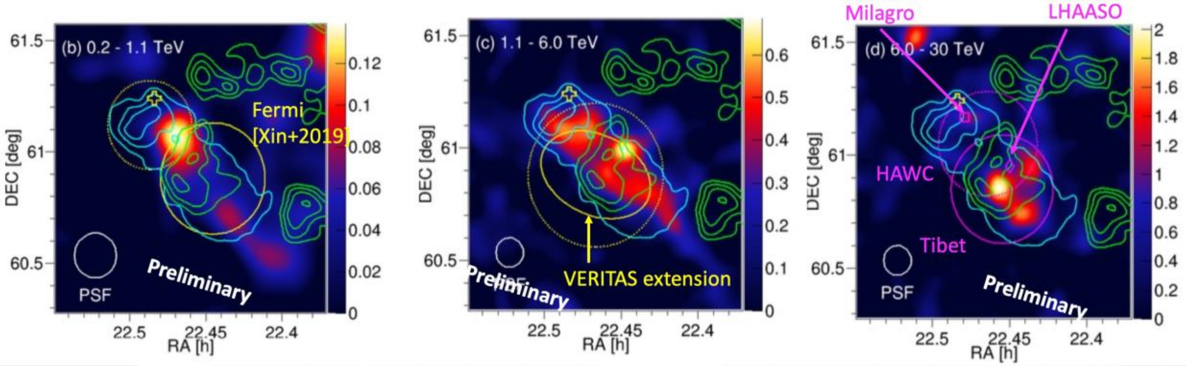
G106.3+2.7/Boomerang/LHAASO J2226+6057

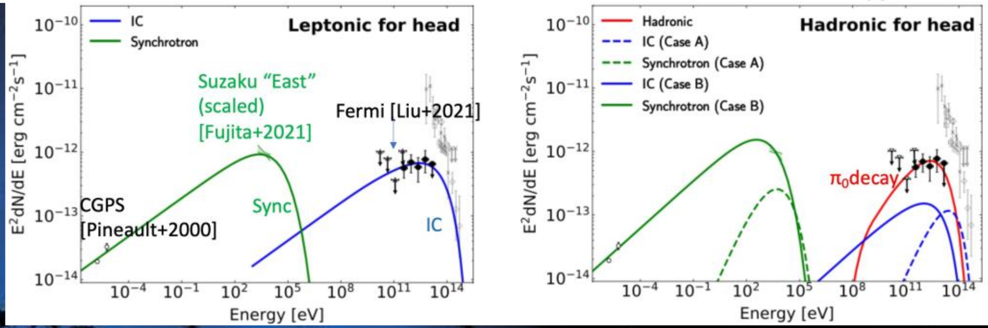


Tibet AS collaboration 2021



Cao et al. 2021

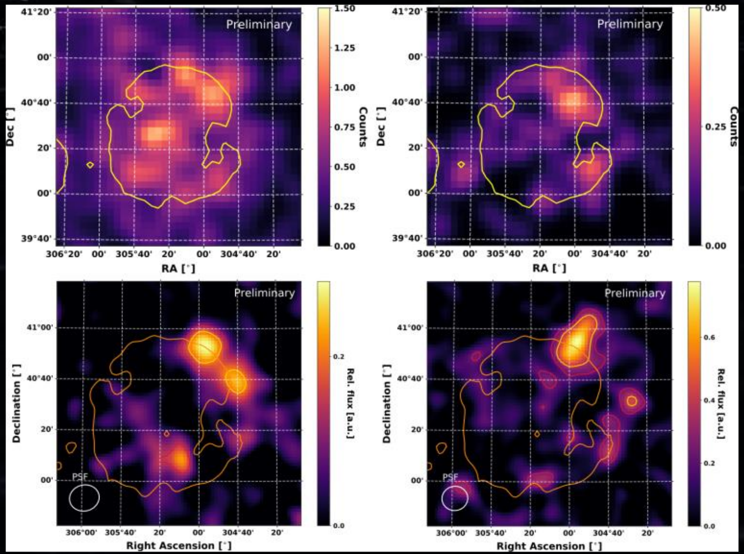




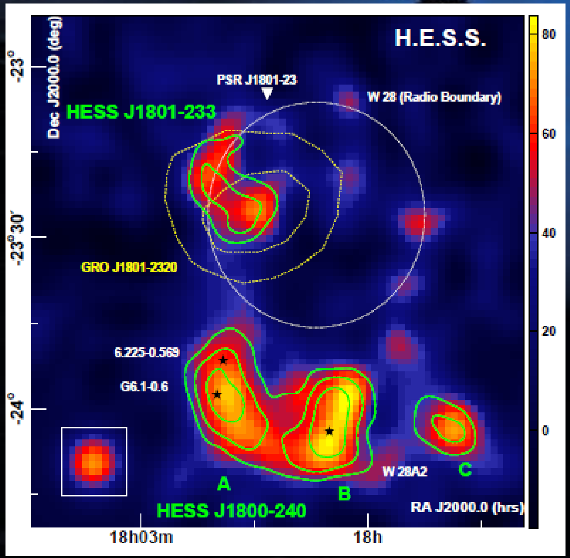
MAGIC study (Saito talk Gamma2022)

Propagation study

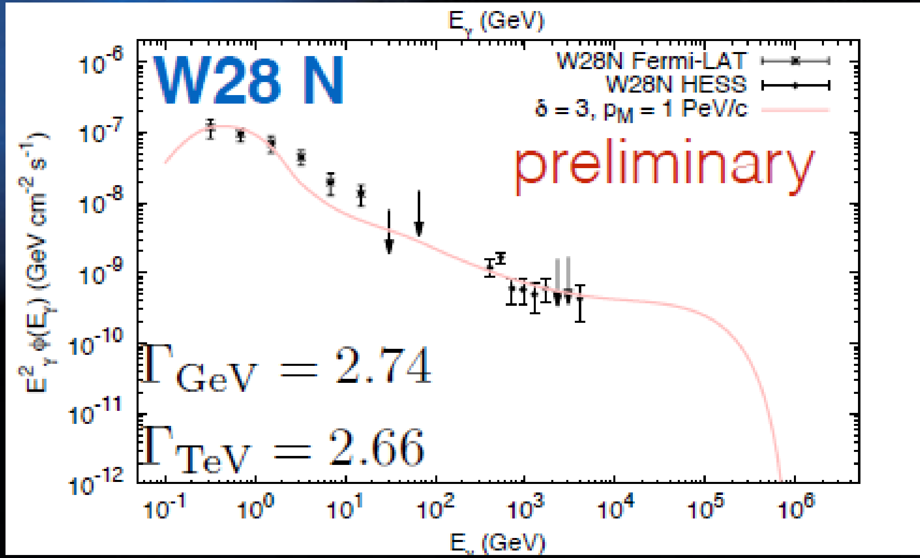
Gamma Cygni (MAGIC collaboration 2019)



W28 (Aharonian et al. 2008)

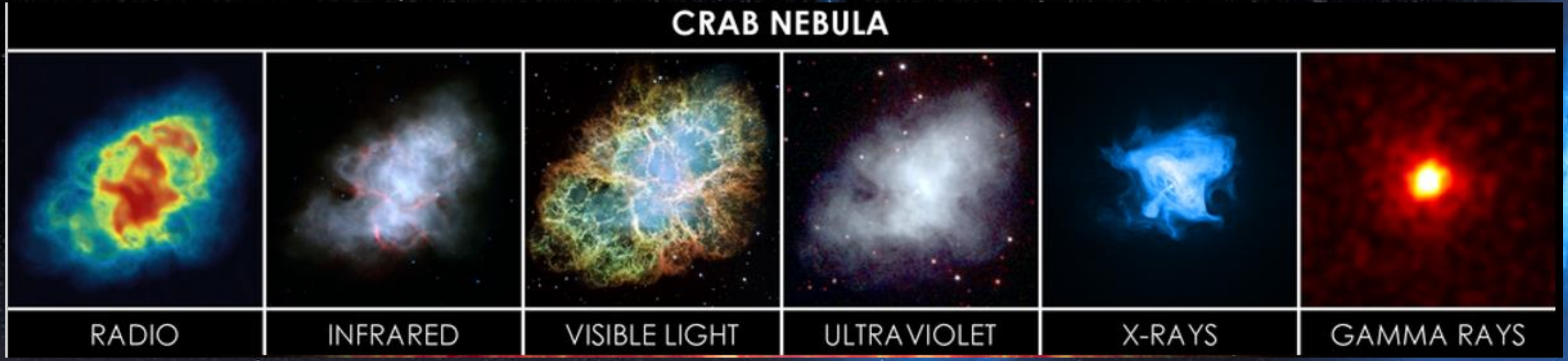


Celli Talk Gamma2022

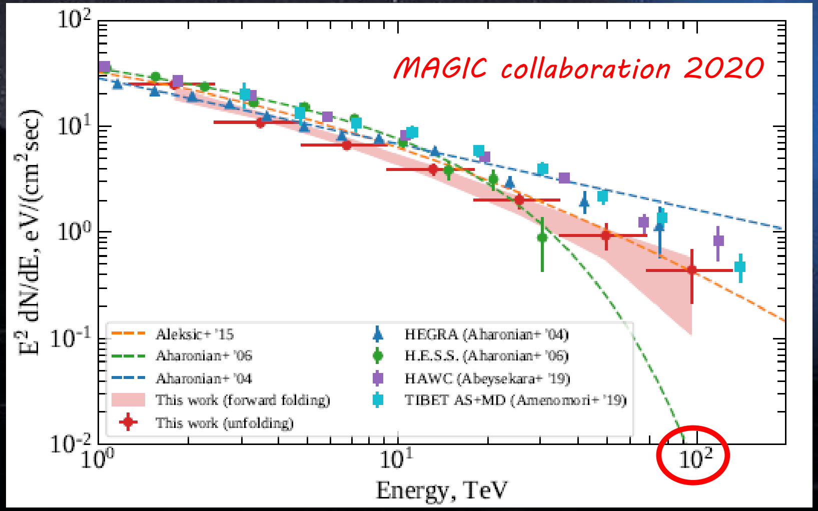


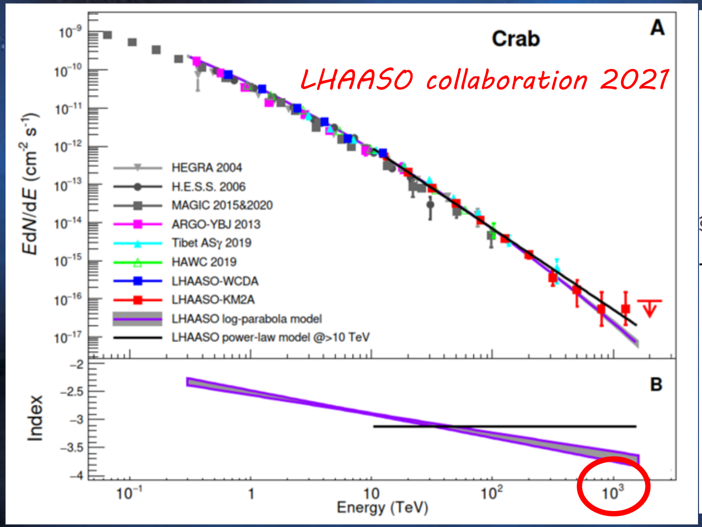
CRAB NEBULA

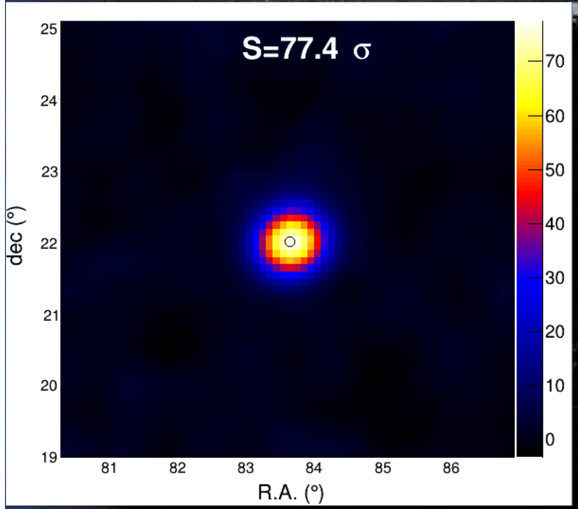
See Giuliani Talk
for ASTRI perfomances



Standard Candle for Gamma-ray astronomy







Detection above 1 PeV!!!

but...

Crab is a PWN (leptonic source)

So...

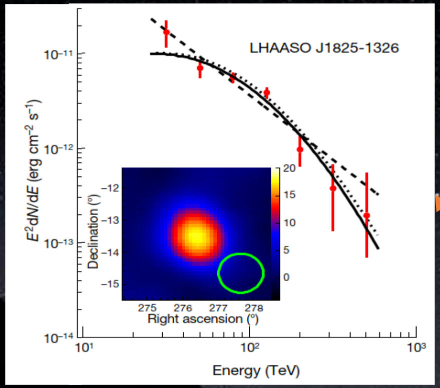
Leptons Or Hadrons?

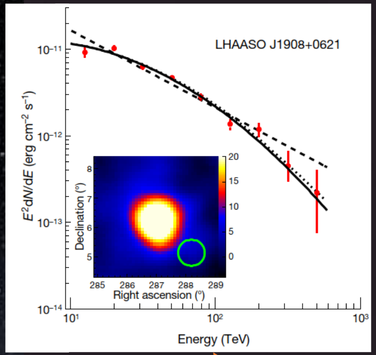
Pulsar Wind Nebulae

HAWC

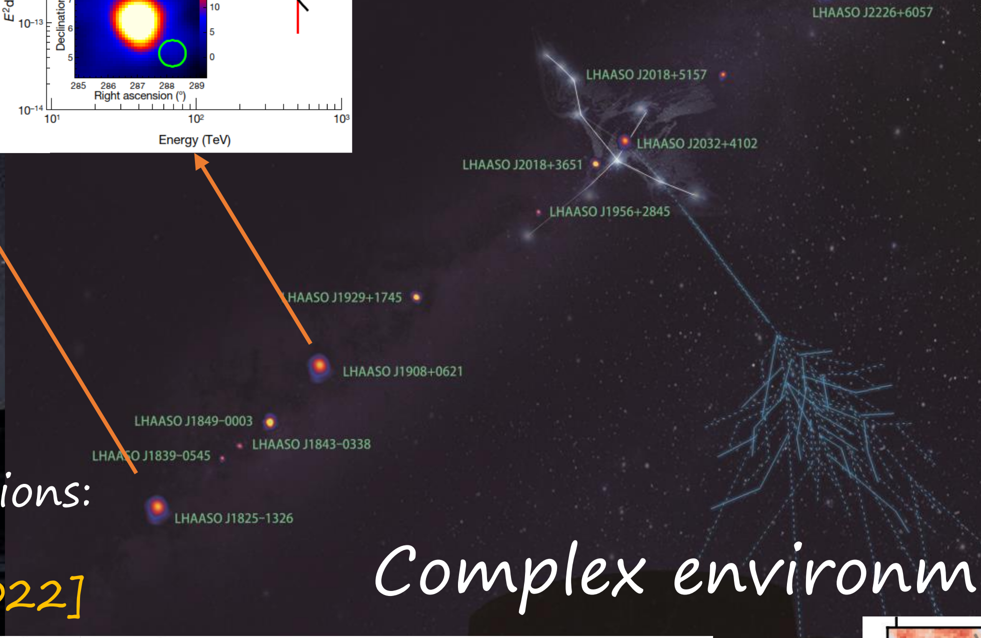
See Giuliani Talk
for ASTRI perfomances

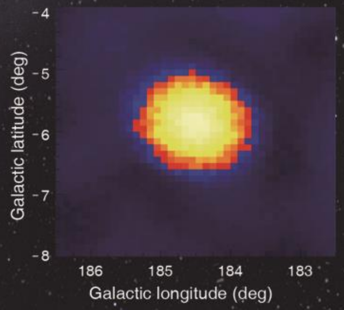
Cao et al. 2021



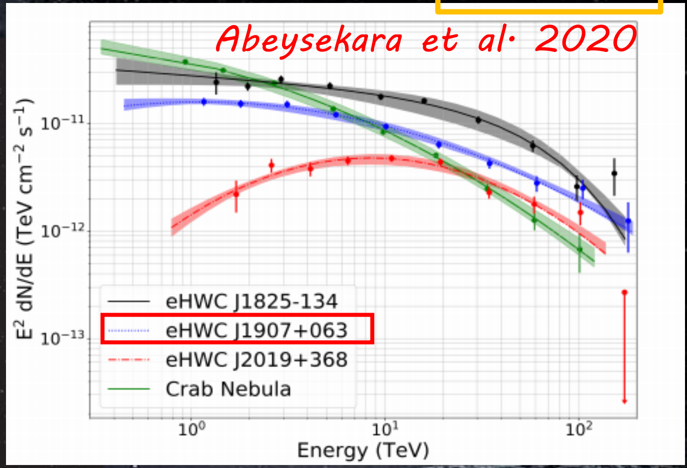


The majority
could be PWN!!!





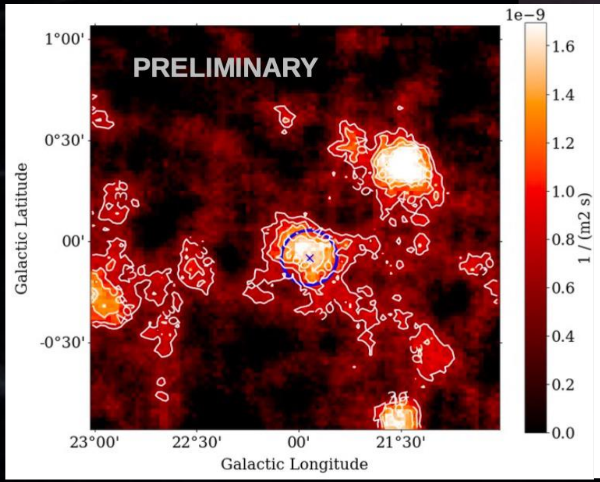
Abeysekara et al. 2020

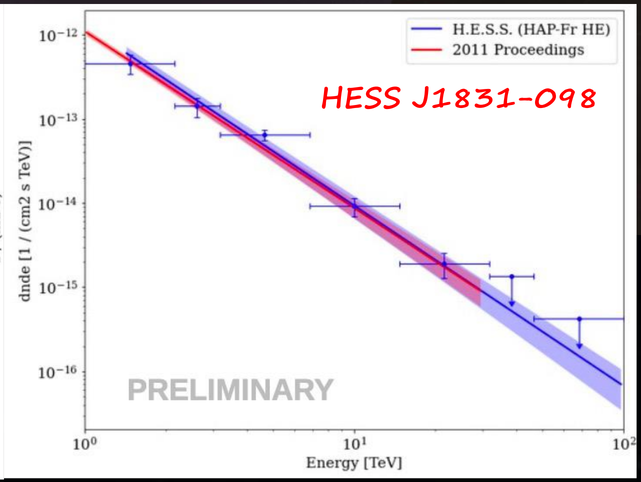


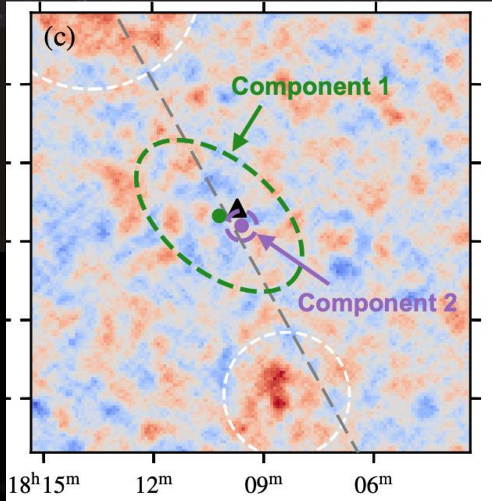
HESS J1831-098
Several possible associations:
PWN? SNR?
[Lypova talk Gamma2022]

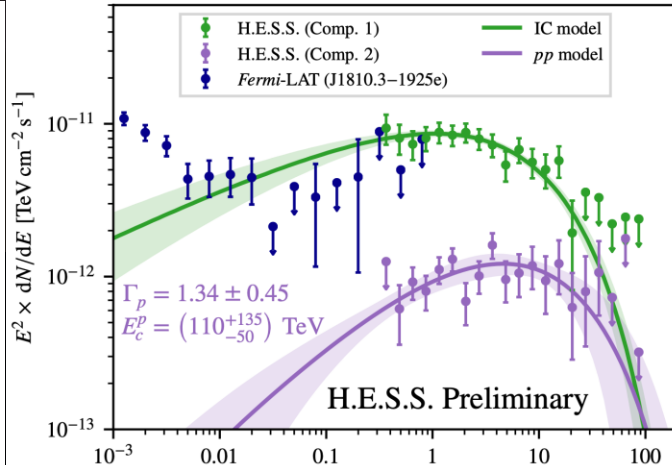
Complex environment

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





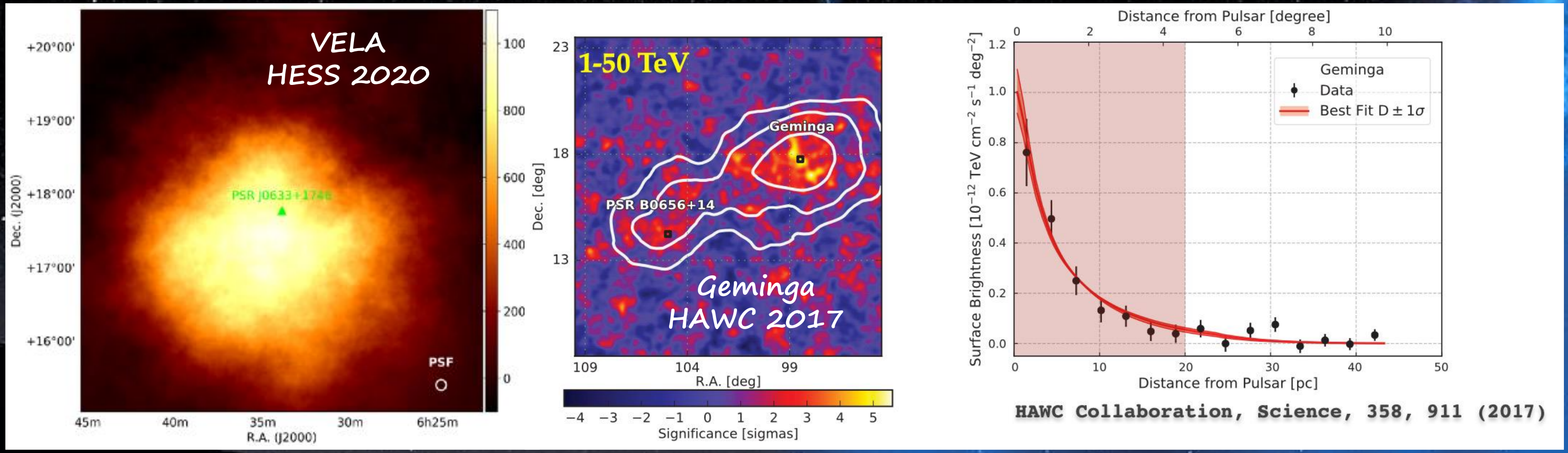




HESS J1809-193

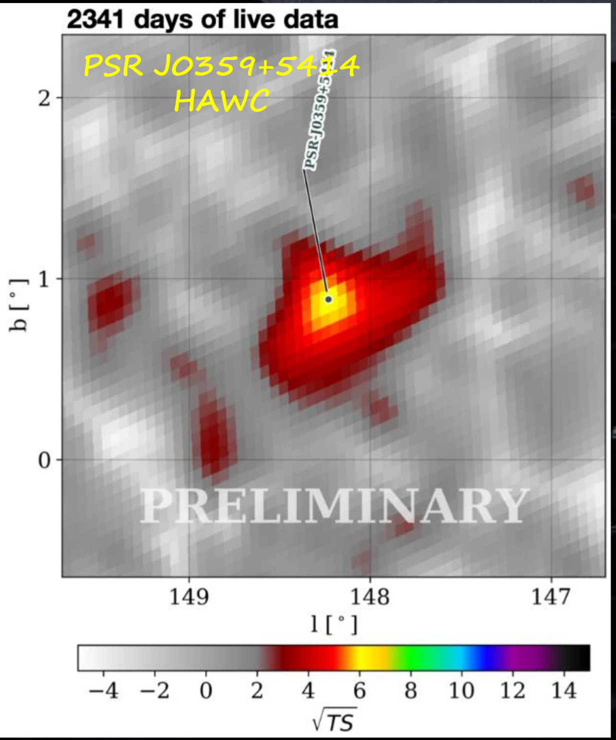
TeV HALOS

See Giuliani Talk for ASTRI perfomances



HAWC Collaboration, Science, 358, 911 (2017)

- Both pulsar and extended emission evaded detection for a long time
- Escaping electrons and positrons form an extended halo of GeV and TeV gamma-rays



- TeV halo candidate near the Galactic plane in a non-crowded region.
- This TeV halo candidate shares similar characteristics to others, suggesting that TeV halos could be a general feature of middle-age pulsars.

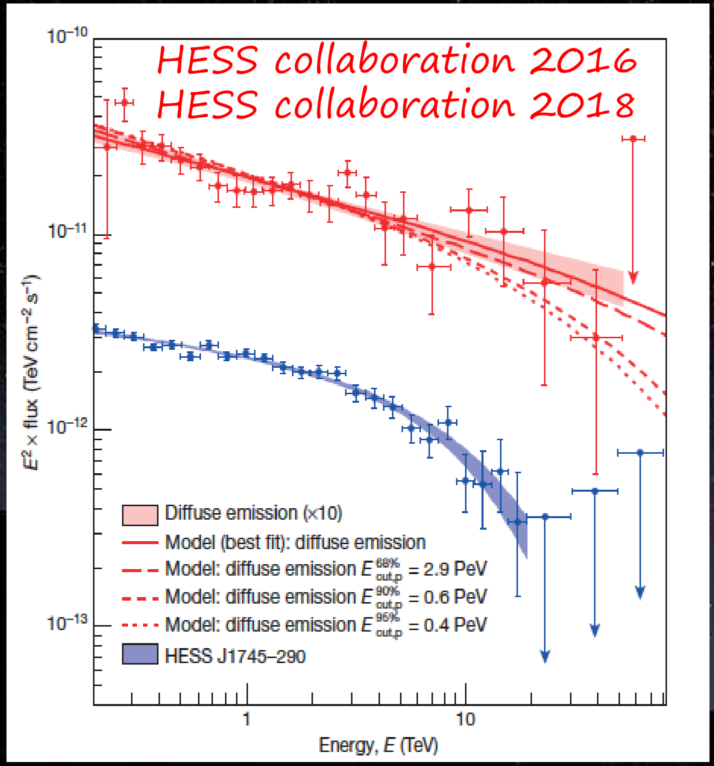
TeV Halos as new source class

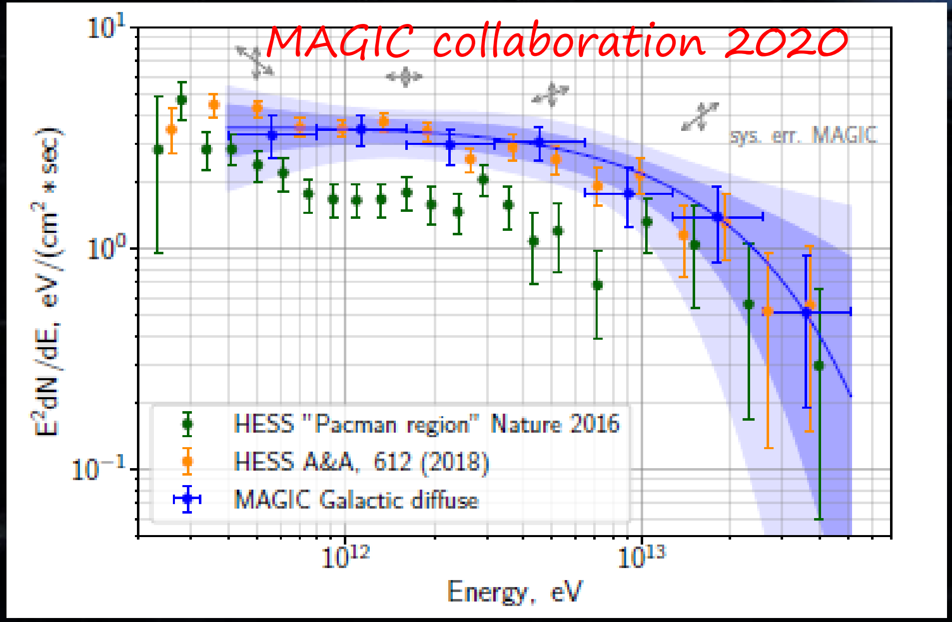
Propagation study

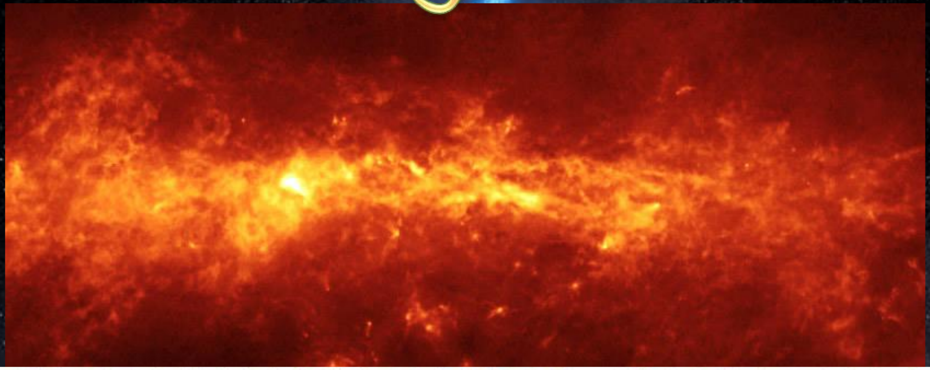
De Leon talk Gamma2022

Galactic Center Region

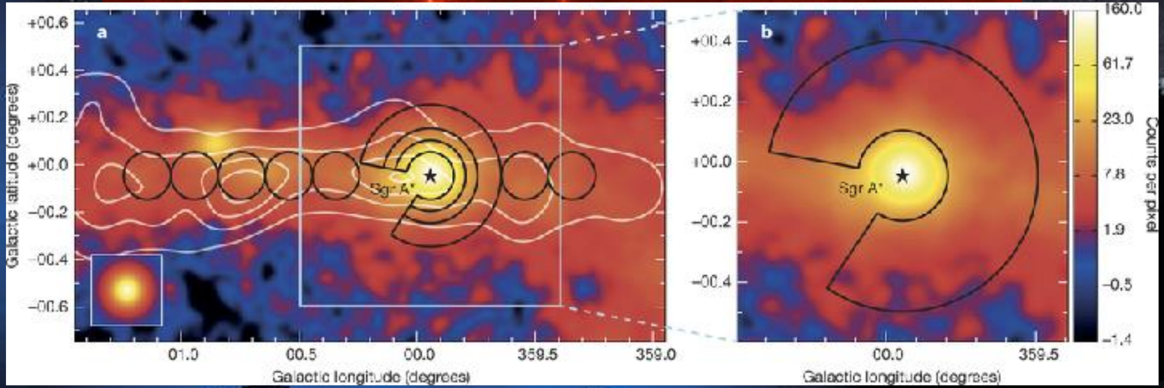
See Giuliani Talk for ASTRI perfomances







APEX+Planck : Dust



HESS collaboration 2016

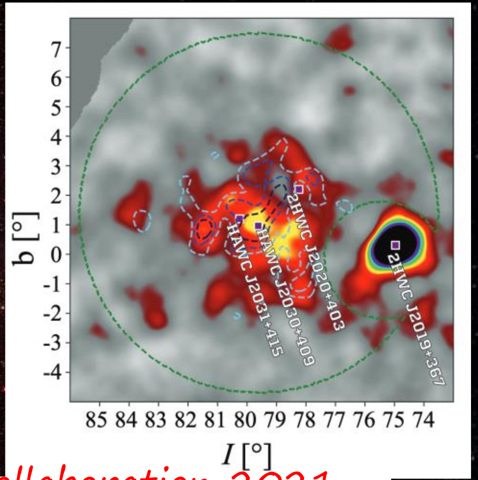
- Perfect correlation between molecular gas distribution and gamma-ray emission seen by HESS
- CR energy density 10 times greater than CR sea
- CR spectrum with and index γE =2.3-2.4 up to 100 TeV (but with large error bars)
- Spatial distribution with 1/r (continuous injection)
- Maybe from Sgr A* (Rodríguez-Ramírez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

Massive Star Clusters

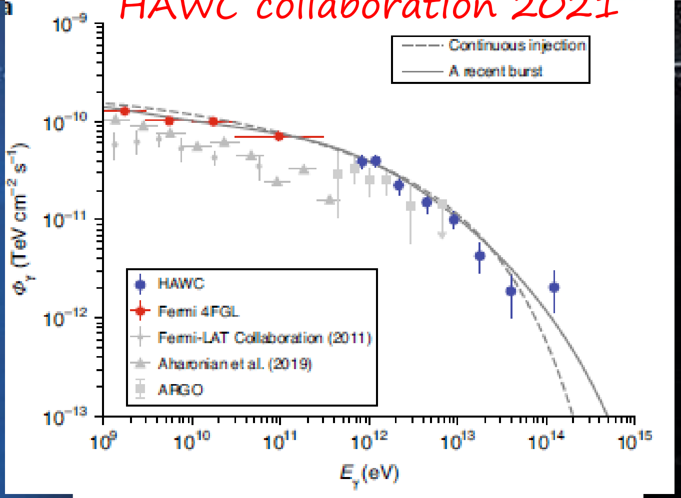
- Multiple shocks and winds → enhanced turbulence and acceleration
- No radiative phase → larger acceleration efficiency
- Low-energy spectrum slope similar to the one measured by Voyager
- Explanation of some CR composition anomalies → Be abundances [Tatischeff 2018]
- Spatial and spectral behavior 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]

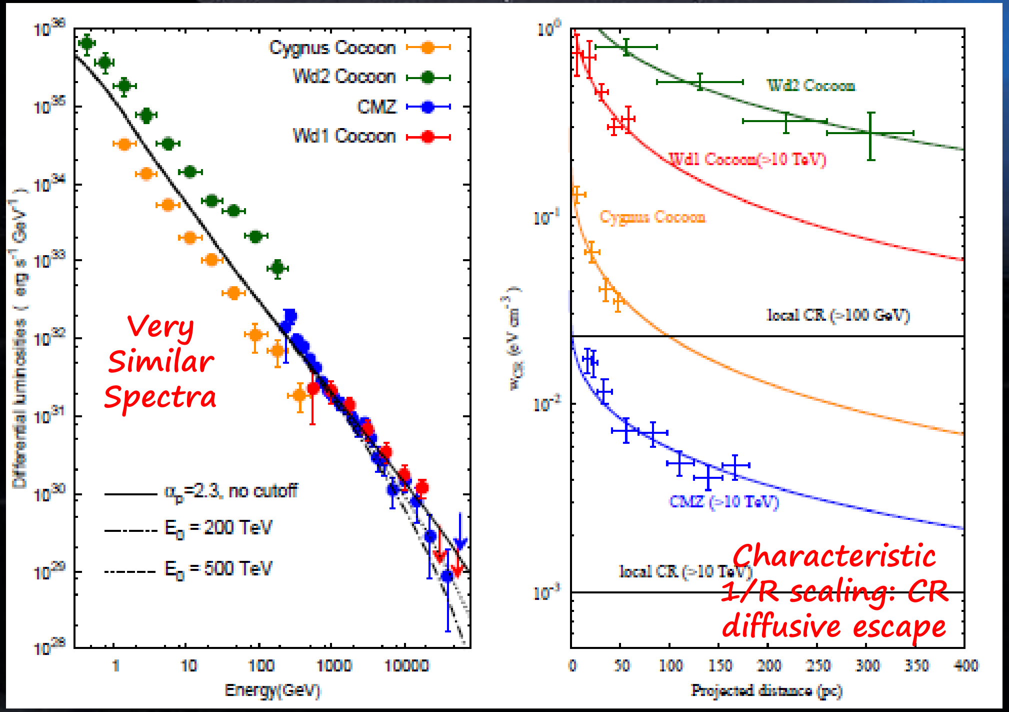
See Menchiari Talk tomorrow

Cygnus Region

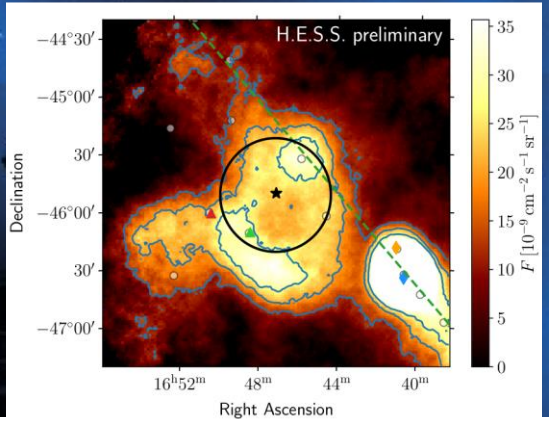


HAWC collaboration 2021

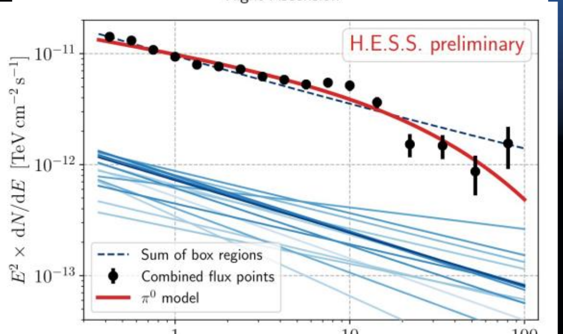




Aharonian et al. 2018

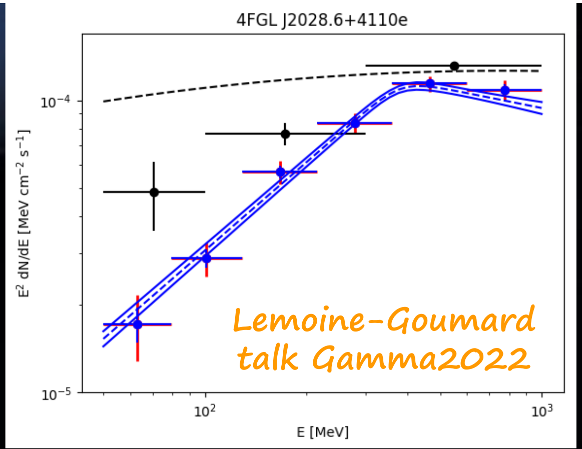


Harer poster Gamma 2022



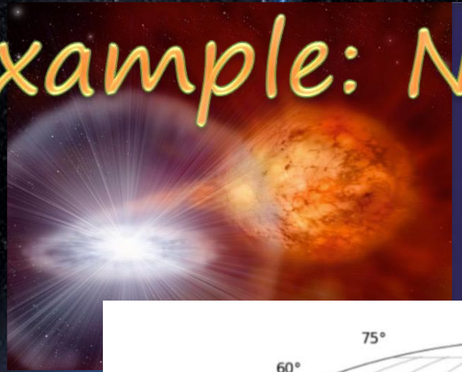
Westerlund 1

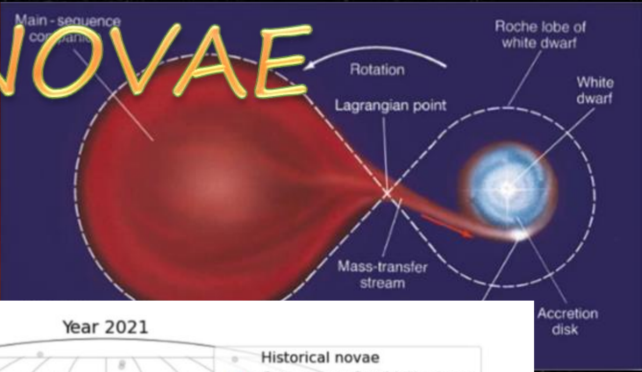
Vieu talk Gamma 2022



Lemoine-Goumard talk Gamma2022

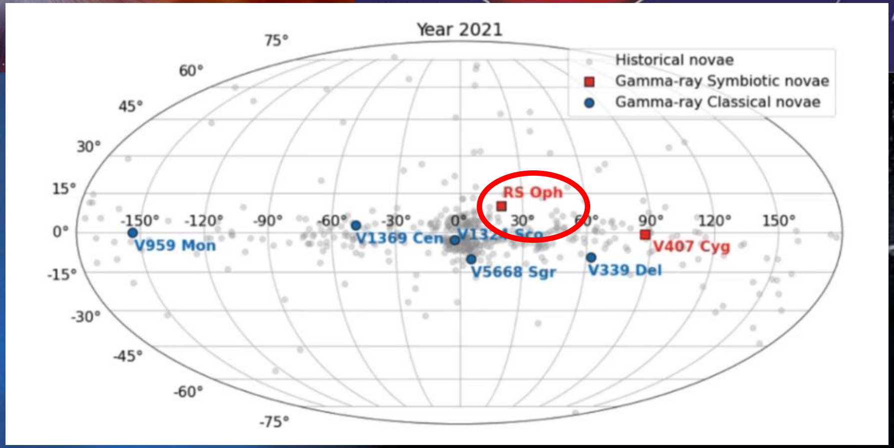
Gamma-ray binaries example: NOVAE



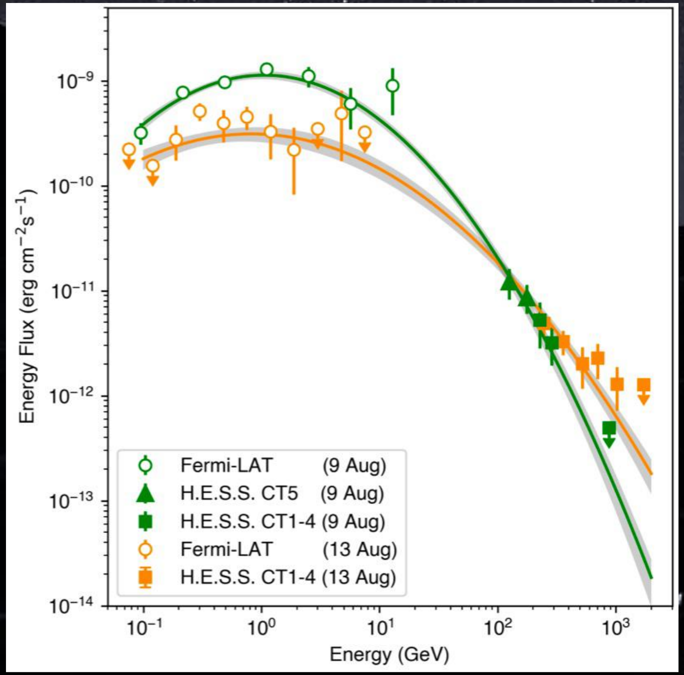


Sub-class of Cataclysmic variable stars (WD+companion)

- Thermonuclear explosion
- Recently detected in the GeV gamma-ray band (2010)
- If companion is a Red Giant → Symbiotic or recurrent Novae
- First detection at VHE with MAGIC&HESS → **Rs Oph**

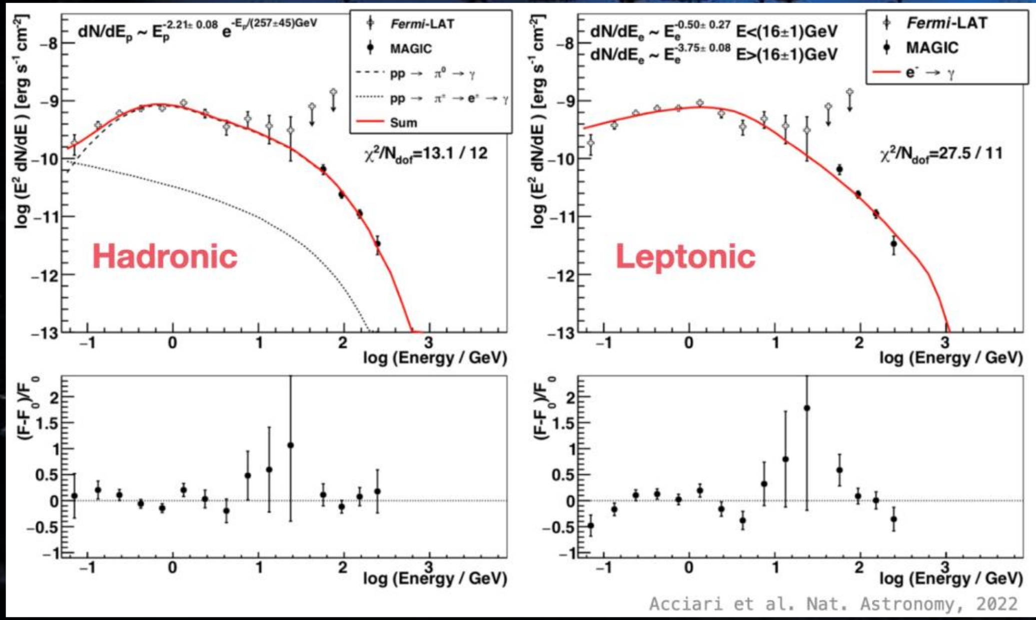


RS OPH

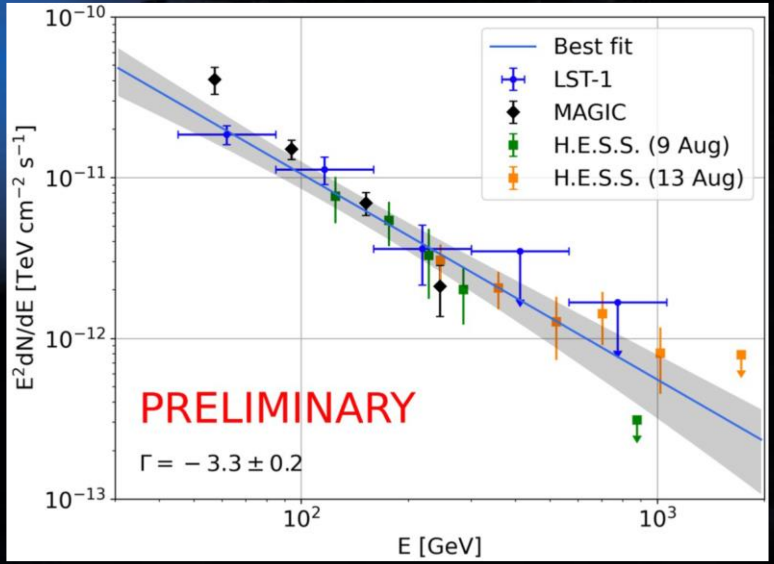


HESS+Fermi
[Steinmassi talk Gamma2022]

MAGIC+Fermi
[Acciari et al. 2022
Lopez-Oramas Gamma2022]



LST1 [Aguasca-Cabot Gamma2022
Teshima Sexten School 2022]



Gamma-ray binaries example: Microquasars

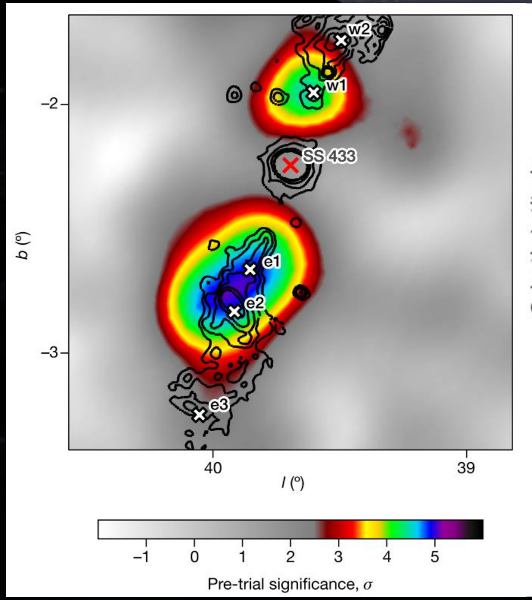
Binary stellar systems (BS/BH+Companion)

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

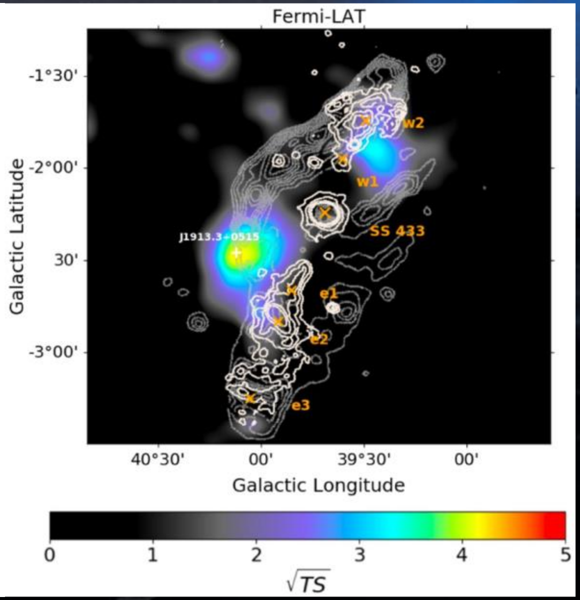
Safi-Arb Gamma2022

SS 433

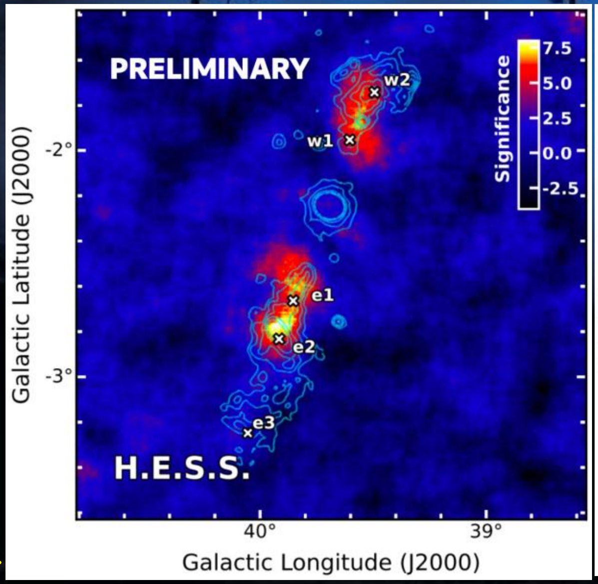
HAWC (HAWC2018)

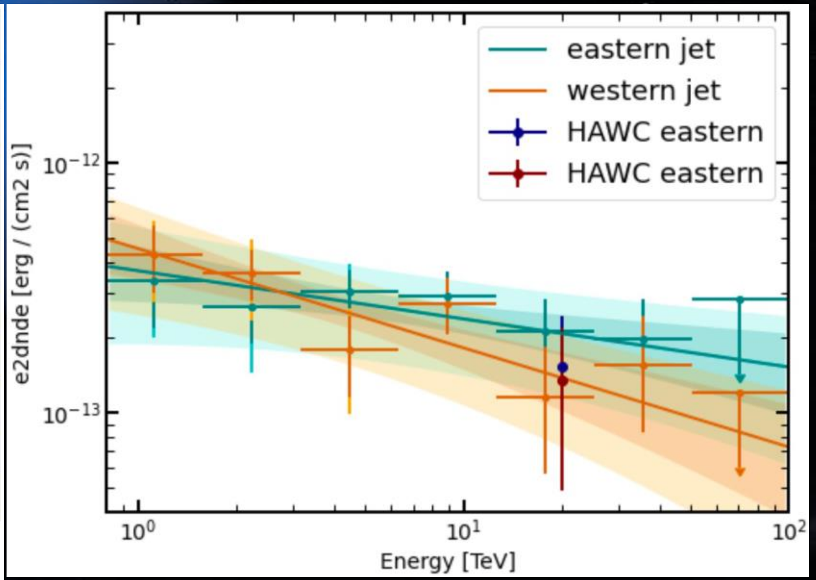


Fermi-LAT (Fang+2020)



HESS





Olivera-Nieto Gamma2022

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 (Boomerang, SS443, PWN)
  - ✓ Diffusion coefficient constraints (Gamma-Cygni, W28, TeV halos)

- Energy/Angular resolution: $\leq 10\%$ / $\leq 0.1°$ ($E \leq 10$ TeV)
  - ✓ Characterize extended sources morphology and MW association (Jets, SNRs, GC, TeV halos)

ASTRI Mini-Array

cta cherenkov telescope array
the observatory for ground-based gamma-ray astronomy

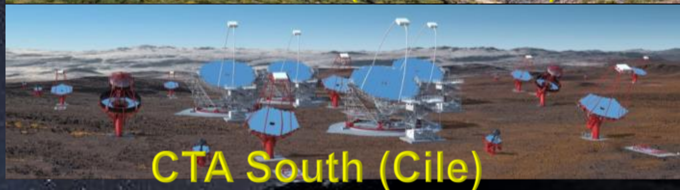
Serra La Nave (Sicily)

Teide Observatory (Tenerife)

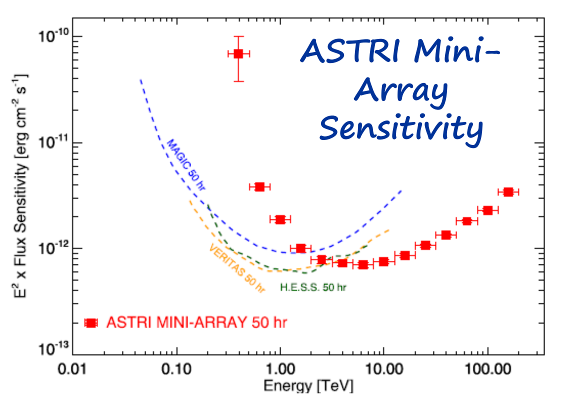
Giuliani Talk
Sironi Talk

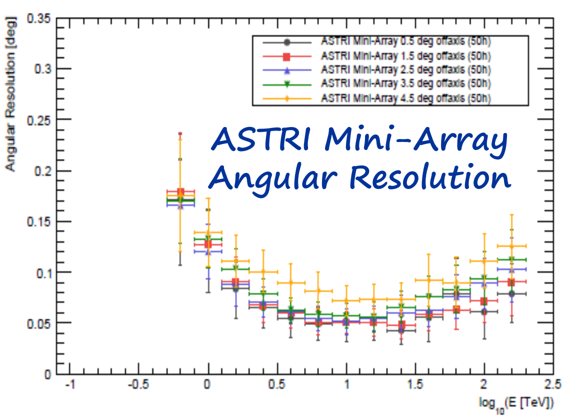
Hoffman Talk
Longo Talks
Teshima Talk
Glicestein Talk
Bissaldi Talk

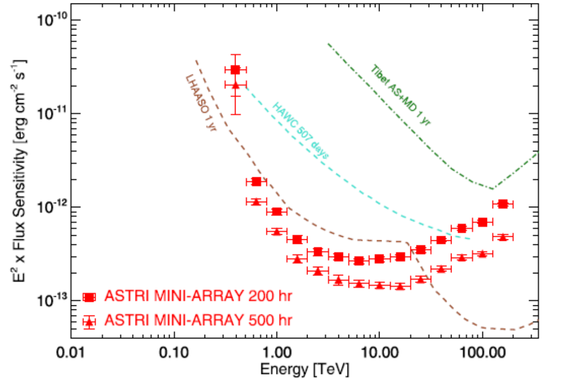
CTA North (La Palma)



CTA South (Cile)





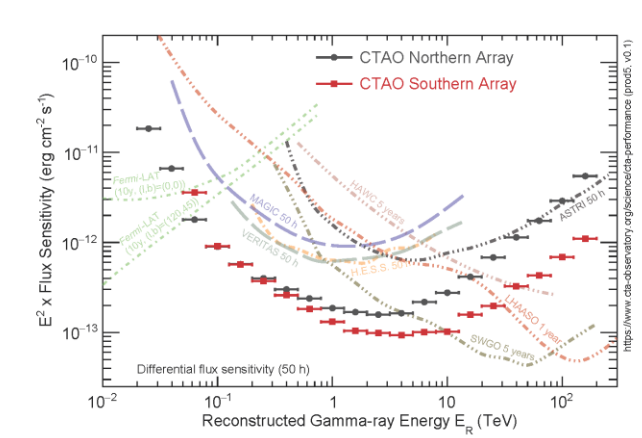


1 telescope operative → early 2023 (already on-site!!)

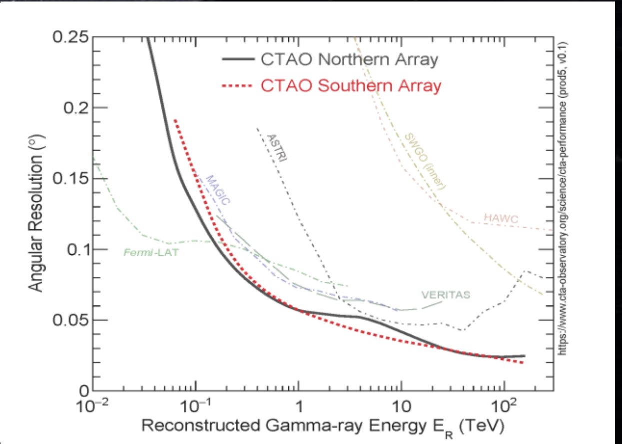
3 telescopes operative → by 2023

Complete Array→ by 2024

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



CTA Sensitivity



CTA Angular Resolution

CTA website (https://www.cta-observatory.org/science/ctao-performance/#1472563157648 91558872-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 MiniArray and CTA and synergy with current VHE instruments
- A lot of work to do: from simulation and software to data analysis to theoretical interpretation

ENJOY THE
HIGH-ENERGY SIDE!

Thank you very much!

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