



Conferenza Italiana di Plasmi
3-6 febbraio 2026

1° Conferenza
Italiana Plasmi

The Origin of cosmic Rays: the importance of multi- communities

- LHAASO J1849-0003
- LHAASO J1839-0545
- LHAASO J1843-0338
- LHAASO J1825-1326

LHAASO J1908+0621

LHAASO J1929-1741

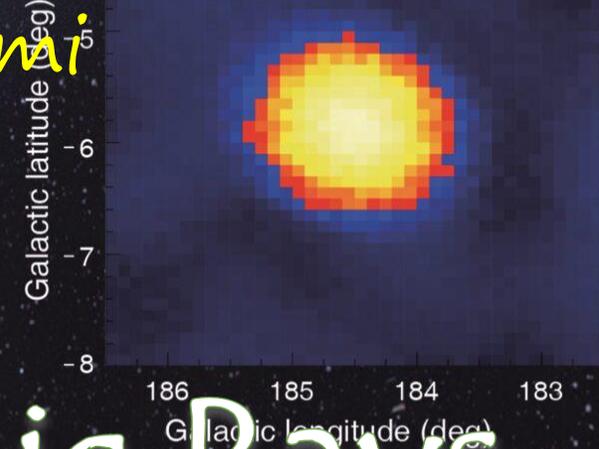
LHAASO J2018+3651

LHAASO J1956+1145

LHAASO J2032-1702

LHAASO J2018+5157

LHAASO J2216+6057



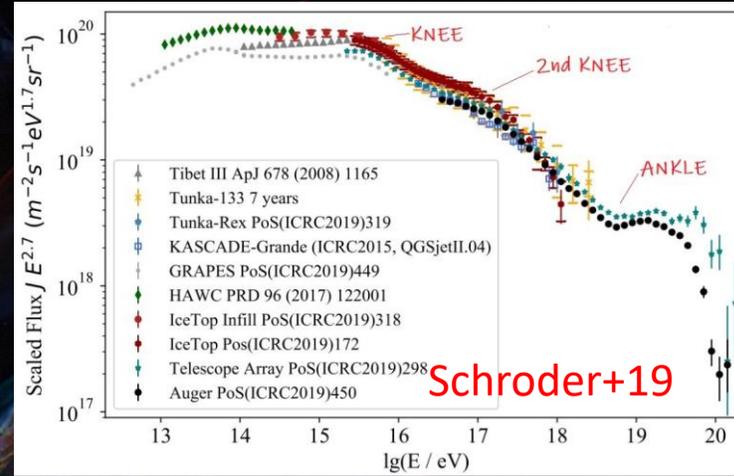
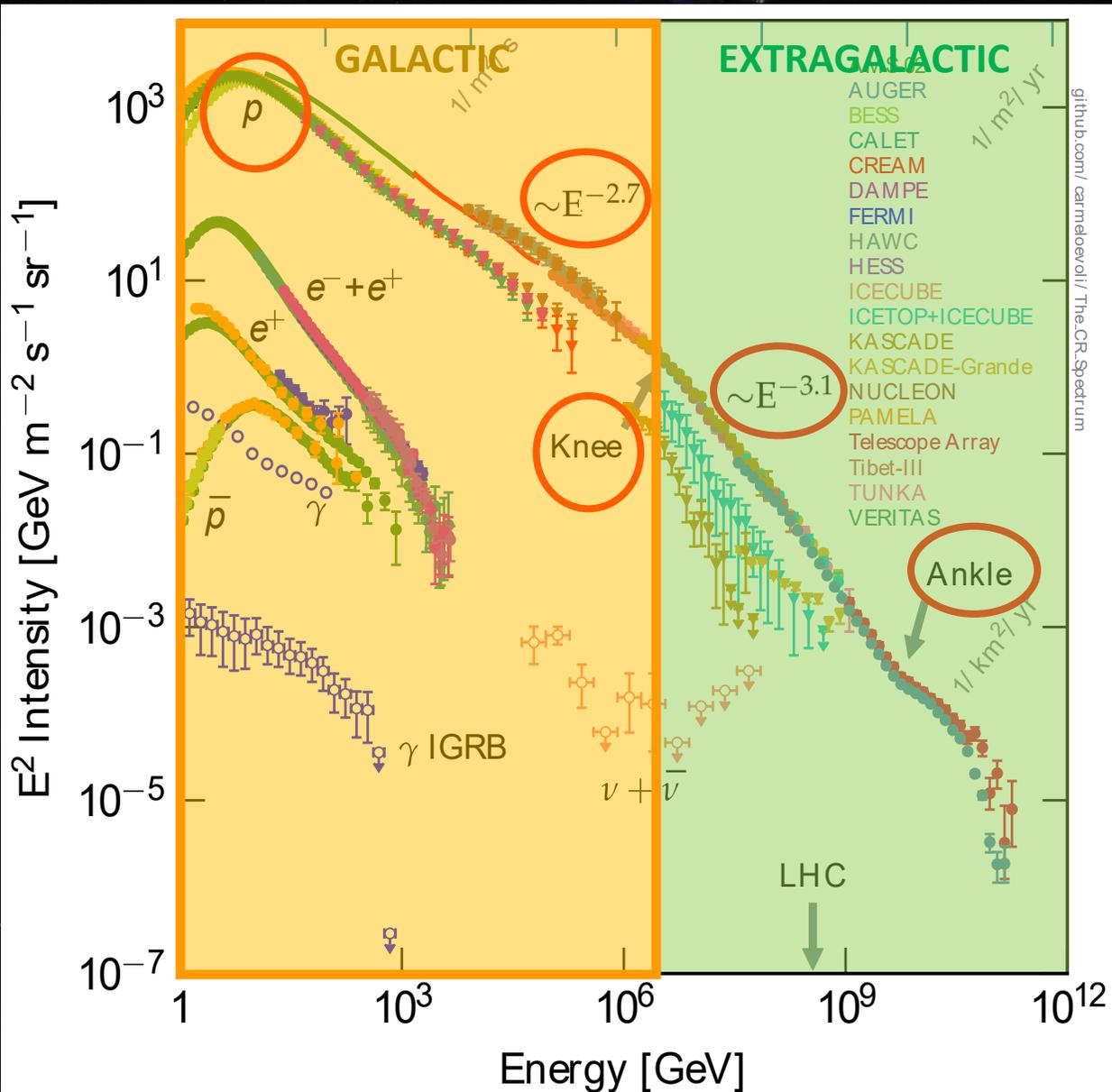
Martina Cardillo
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TOPIC: Cosmic Rays (from 1912)

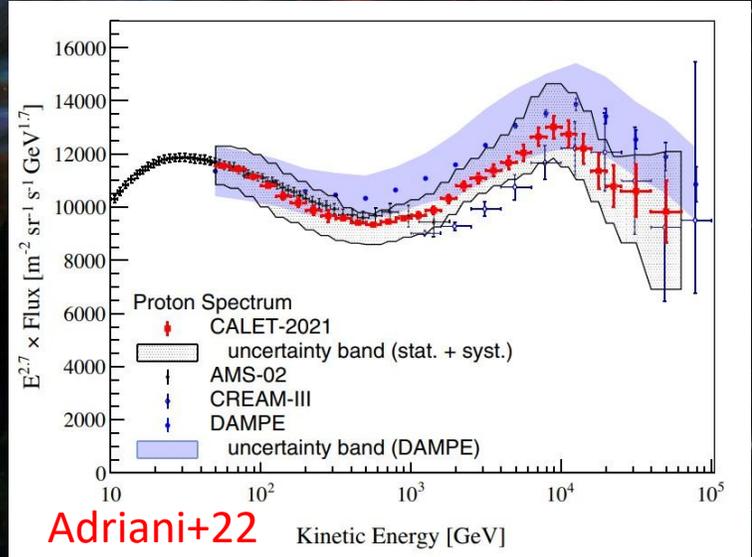
Credits: C.Evoli



Between the knee and the second knee (10^{17} eV) should be transition from Galactic to extragalactic component (Vieu+2023 and ref therein)

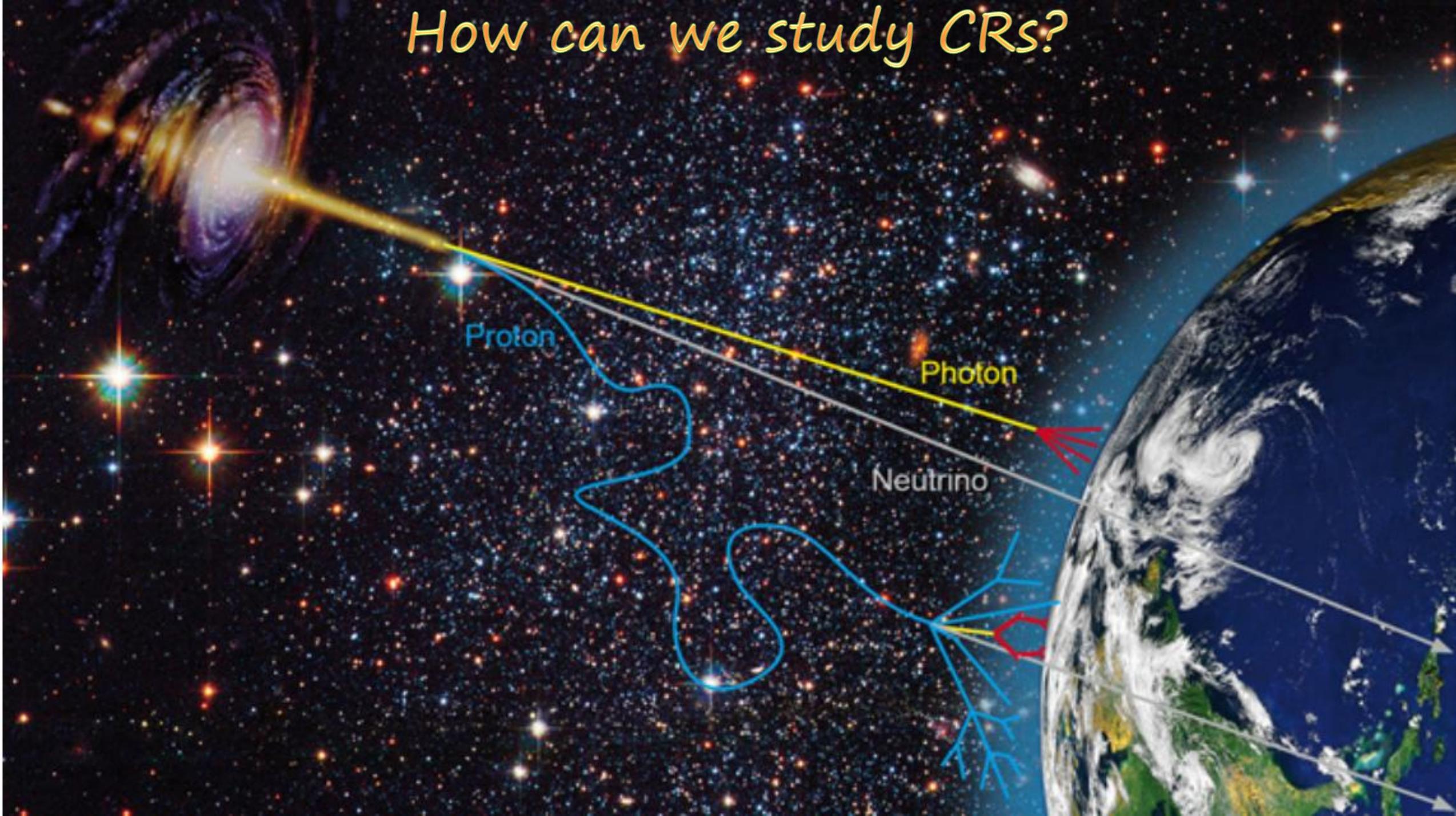
But also the Galactic Component is not so bright and clear

Recent results by CALET/DAMPE show that the region below 1 PeV may not be as featureless as we thought, showing hardening and steepening between 100 GeV and 100 TeV and a bump at 10 TeV (Malkov+2022 for theoretical interpretation)



Adriani+22

How can we study CRs?



How can we study CRs?

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)

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)

NEUTRINOS
(IceCube, Baikal
→ KM3Net,
IceCube-Gen2)

The issue: Cosmic Ray origin (in a nutshell)

The main candidates:
Supernova Remnants

- **ENERGY SUPPLY:** $L_{CR} = 10\% L_{SN}$
- **COLLISIONLESS SHOCKS:** energy dissipated via wave-particle interaction instead of particle-particle collisions.
- **STRONG SHOCKS & Diffusive Shock Acceleration**
- **MAGNETIC FIELD AMPLIFICATION**
- Indirect evidences in the X-ray and optical bands

Direct evidences

"Help us Molecular Clouds: you are our only hope."



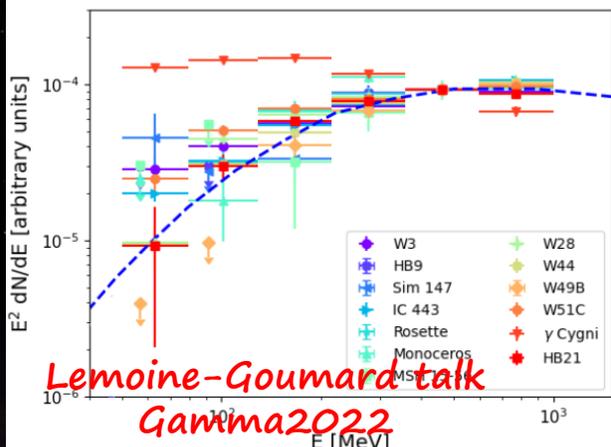
Low-Energies (from space)

Pion bump detection: distinction leptonic/hadronic only at $E < 200$ MeV

Pevatrons \rightarrow γ -ray at $E > 100$ TeV only of hadronic origin (maybe...)

High-Energies (from Earth)

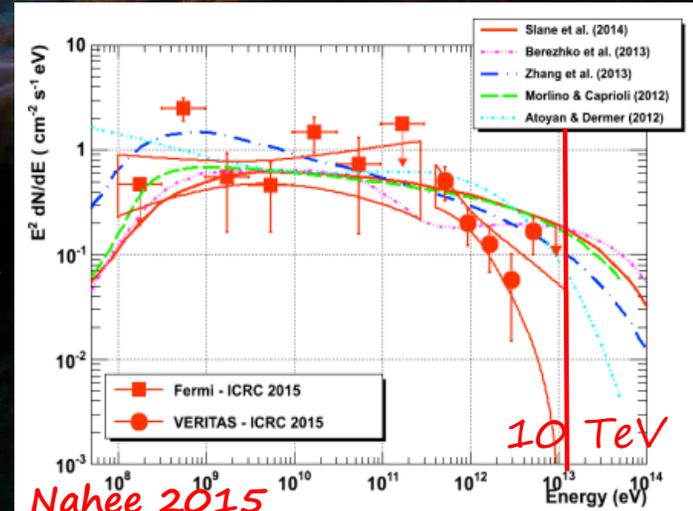
Same SEDs rescaled at 500 MeV



Confirmation of the presence of CRs [Giuliani, Cardillo+2011] but no SNRs detected at $E > 100$ TeV

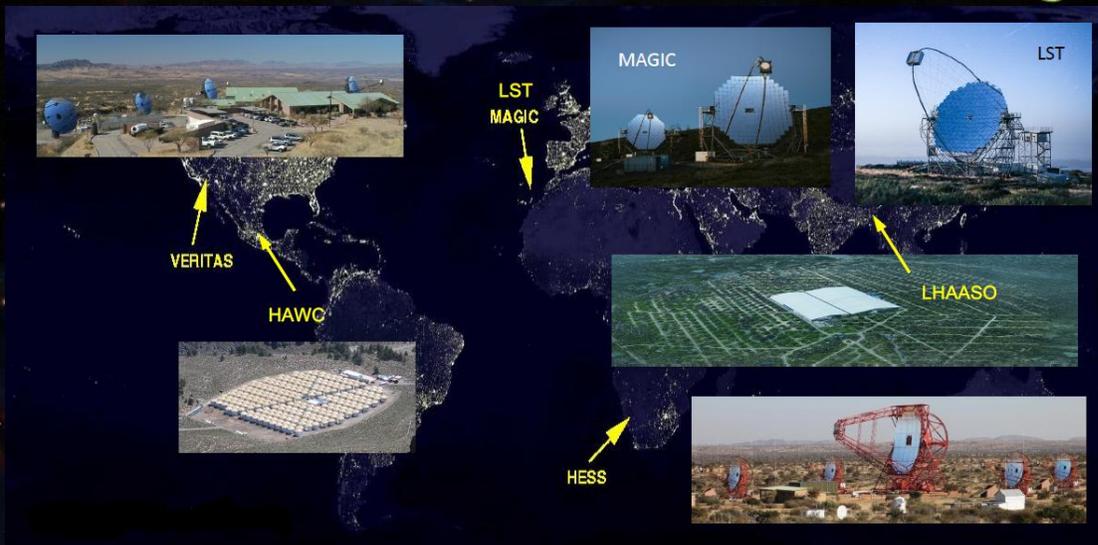
Possible Detection problem \rightarrow PeVatrons only in the first 100 years [MC+2015]

Gamma-ray from MCs illuminated by escaped CRs (Gabici 09, Mitchell 21, Celli 23)



Nahee 2015

The issue: Cosmic Ray origin (in a nutshell)



OTHER SOURCES?

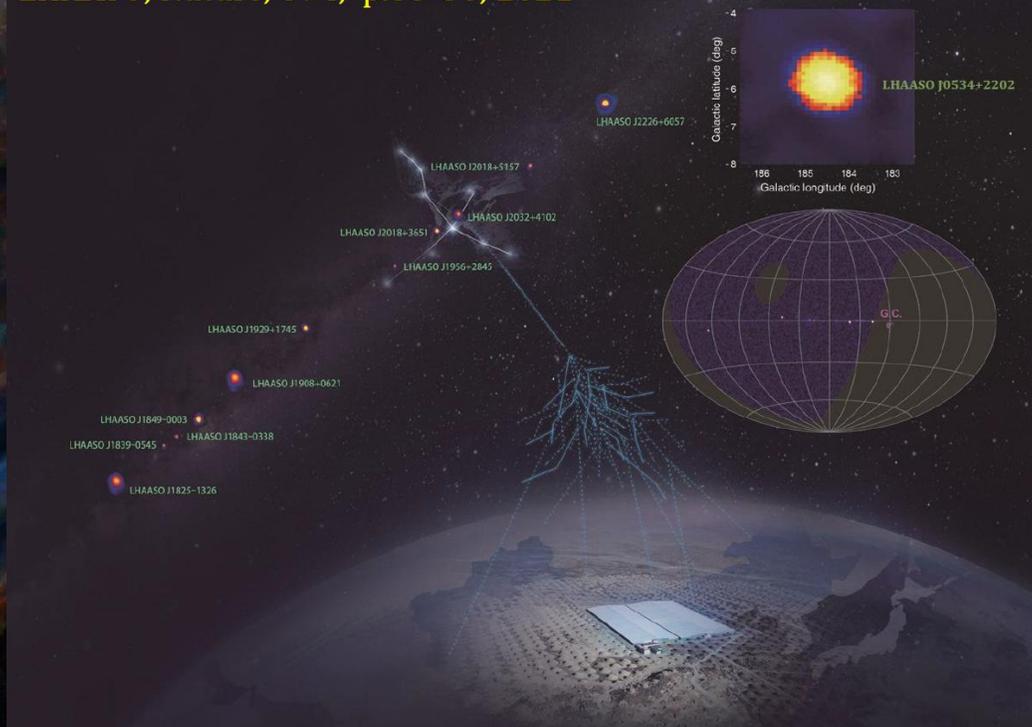
Some first hints of PeVatron emission from different source typology but only in the Crab were seen gamma photons > 100 TeV

LHAASO detected a lot of PeVatron regions!

(Cao+21, Cao+24)

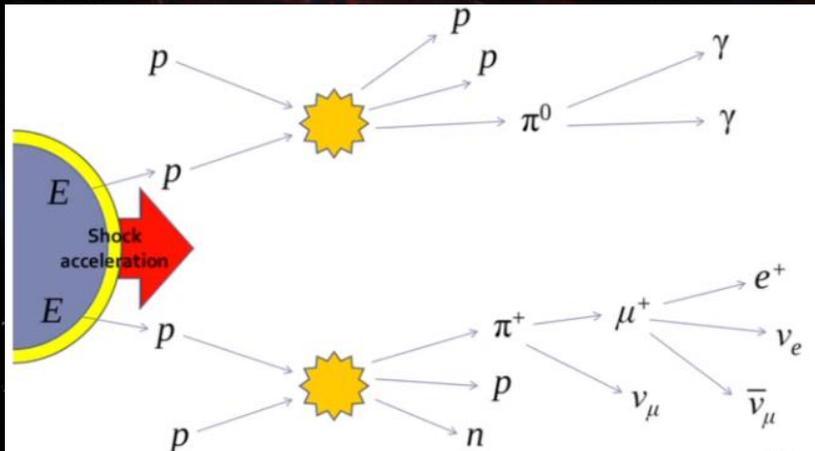
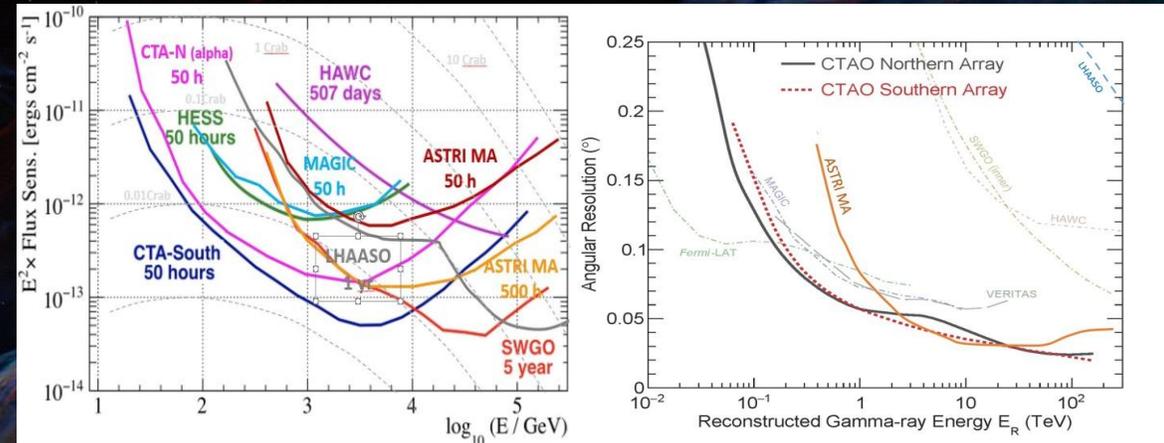
- **Good news:**
 - There are a lot of possible candidates PeVatrons (PWNe, MQs, YMCs, MQs)
- **Bad news:**
 - Also electrons reach $E > 100$ TeV \rightarrow Pevatron emission is no more a hint of CR acceleration
 - Very low angular Resolution \rightarrow it is very difficult to understand the source typology

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



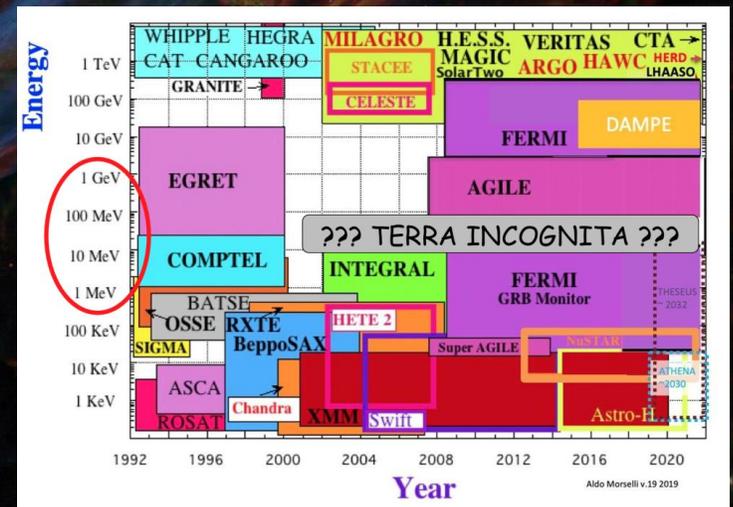
Cosmic Ray origin: what we need

- **Better Angular Resolution** → in this way we can limited the PeV gamma-ray emission
 - **ASTRI Mini-Array and the Cherenkov Telescope Array Observatory (CTAO)** → important need to multi-frequency view



- **Neutrino detection** → If in correspondence of gamma-ray emission, it can be due only to CRs
 - **Problem:** Current neutrinos detector have no sufficient sensitivities and data format totally different from the gamma-rays

- **An MeV-focused Mission** → in order to detect the pion bump in correspondence of the LHAASO candidates PeVatrons
 - **Problem:** no proposed MeV missions have passed any selection criteria → MeV gap





cherenkov
telescope
array

the observatory for
ground-based
gamma-ray astronomy

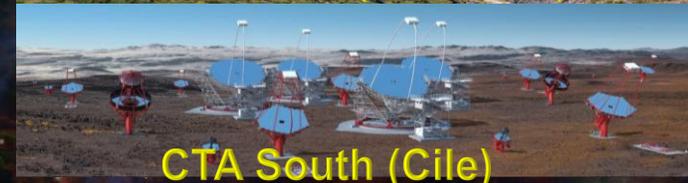


Serra La Nave
(Sicily)

Teide Observatory
(Tenerife)



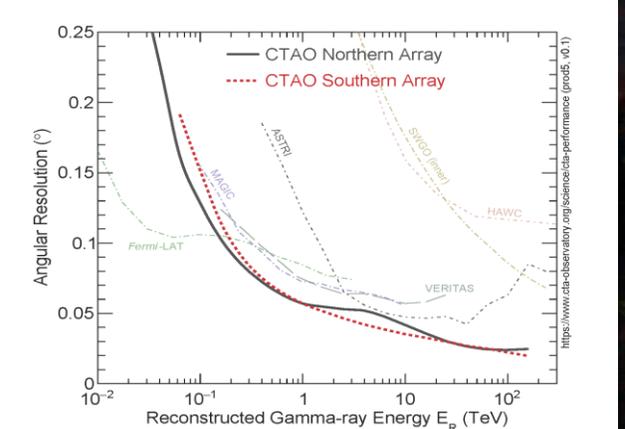
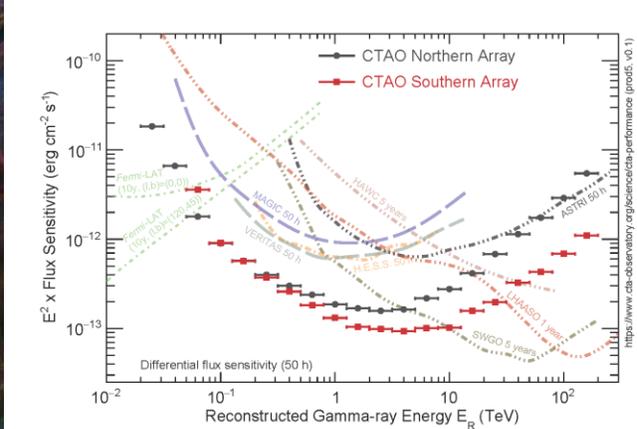
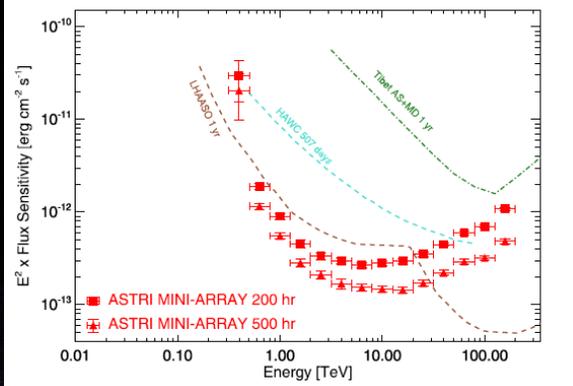
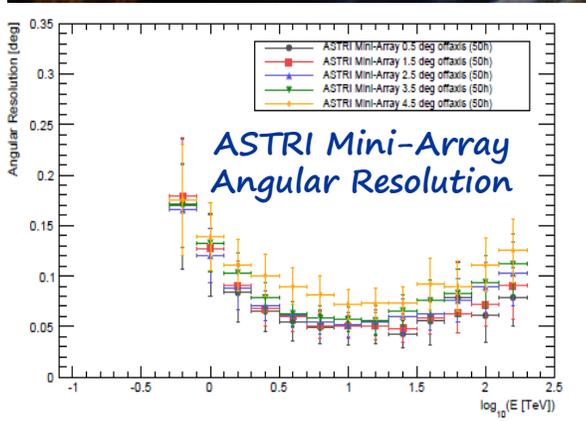
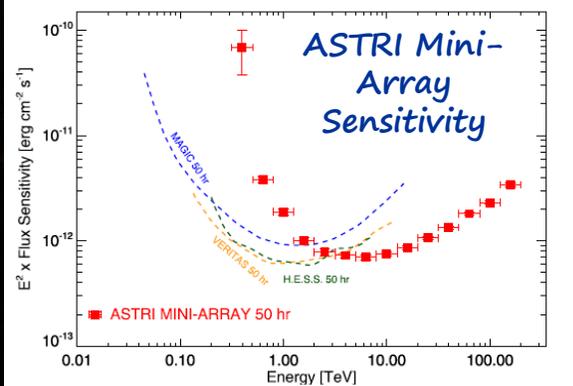
CTA North (La Palma)



CTA South (Cile)

Hoffman&Zanin
2023

Scuderi et al. 2022, JHEAP, 35, 52
Vercellone et al., 2022, JHEAP, 35, 1
D'Ai et al., 2022, JHEAP, 35, 139
Saturni et al. 2022, JHEAP, 35, 91



CTA Sensitivity

CTA Angular Resolution

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

- End to end approach
- Core Science program in the first 4 yrs
- Important synergies with Northern ground based gamma-ray facilities

LST1, La Palma
(Canarian Islands)



Multi-frequency and multi-messengers: FAIR Data policy and standard Format

Toward an Open Observatory:

- **MAGIC, HESS, VERITAS:**
internally managed and no archives
- **LHAASO**
releases science-ready products such as source catalogs; direct access only for the collaboration.
- **ASTRI Mini-Array**
initially internally managed experiment, but it is designed to evolve into an open observatory
- **CTAO is designed as an open observatory**, data and software available to the scientific community according to FAIR principles (Findable, Accessible, Interoperable, Reusable).

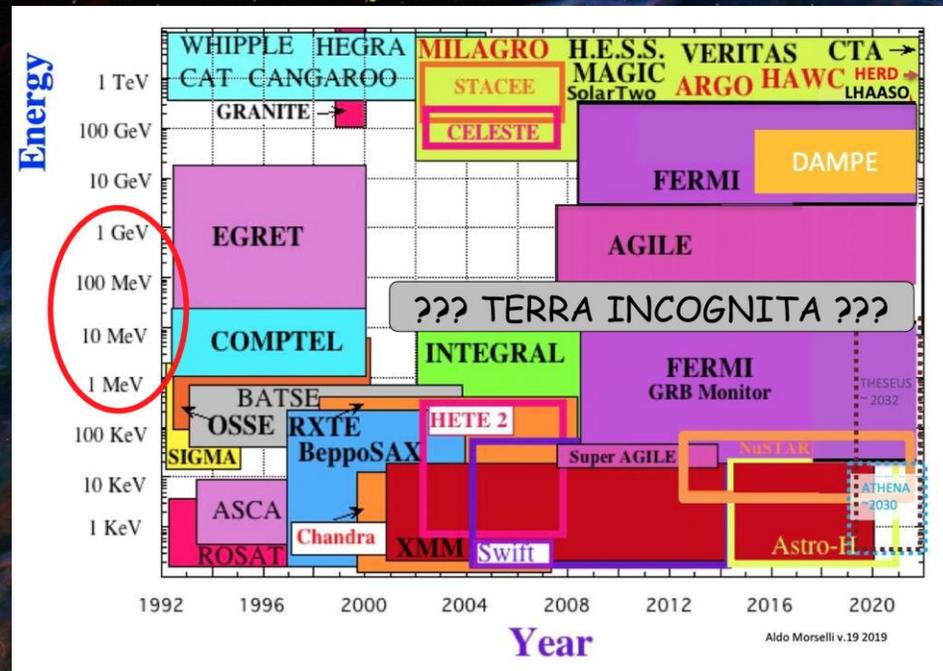
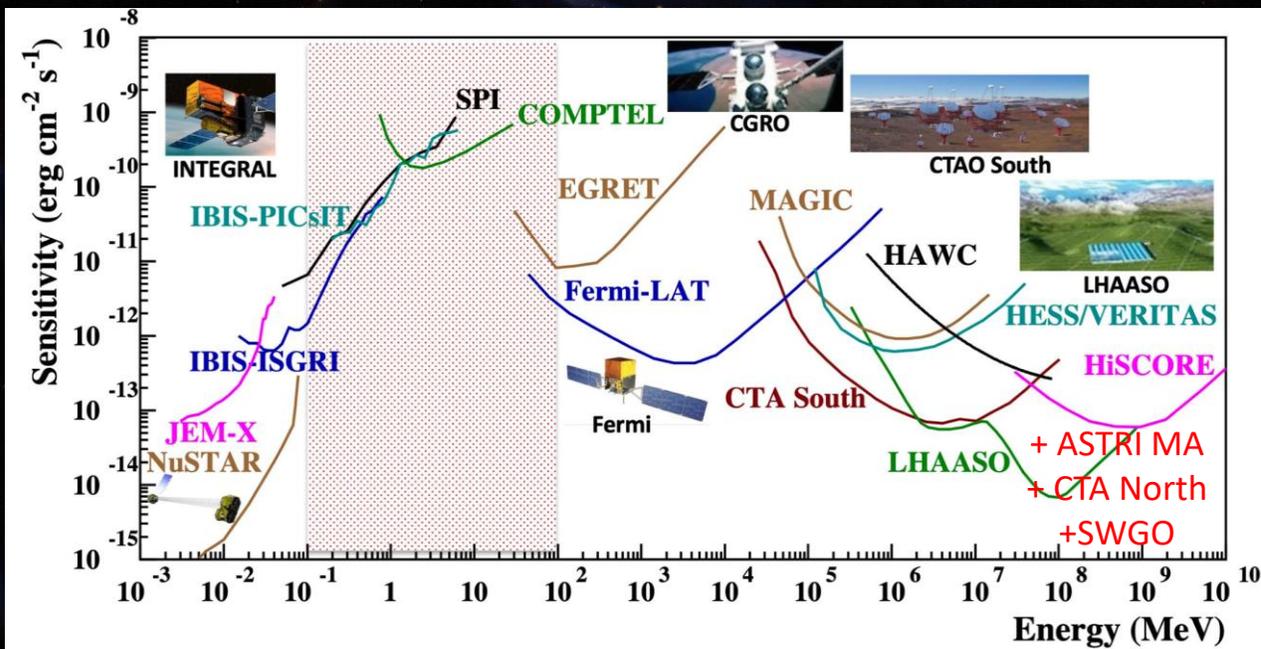
From GADF to VODF

GADF - Gamma-ray Astro Data Formats: first step toward standardization of high-level IACT gamma-ray data → **Limitations:** gamma-only, instrument-oriented, not multi-messenger ready

VODF - Very-High-Energy Open Data Format for VHE gamma-ray & neutrino astronomy: open data model & format.

- **Standardizes data** from reconstructed events to high-level products (maps, spectra, light curves, catalogs).
- **A community-driven** initiative (CTAO, ASTRI, H.E.S.S., MAGIC, VERITAS, HAWC, Fermi-LAT, IceCube, KM3NeT, SWGO, FACT)
- Designed for interoperability, **IVOA compliance**, and **FAIR data** principles.
- Common tools - multi-instrument analyses across the VHE and multi-messenger landscape.

We need to fill the MeV gap



0.2-5 MeV

**YES
(2027)**

100 KeV - 1GeV

NO

NO

15 KeV-3 GeV

new ASTROGAM
Closing the MeV gap

Waiting for big missions... do Small missions

IMPORTANT MESSAGES

- ❖ Cosmic-ray origin: *a Very Hot Topic since 1912!!*
- ❖ Several candidates hadronic PeVatrons
 - *Pulsar Wind Nebulae, Supernova Remnants (with MCs), Young Massive Star Clusters and Microquasars*
- ❖ The future in the VHE domain is related to *LHAASO, ASTRI-MA and CTA* and their synergy with other instruments
 - *multi-frequency approach and FAIR data policy*
- ❖ The *collaboration between gamma-ray and neutrino communities* will be fundamental in order to solve the CR origin issue
 - *importance of VODF*
- ❖ We need *satellite for the MeV energies*
 - *pion bump detection from PeV candidates*

*Collaboration, cross-correlation, transparency and bottom-up approach.
Will it be ever possible?*



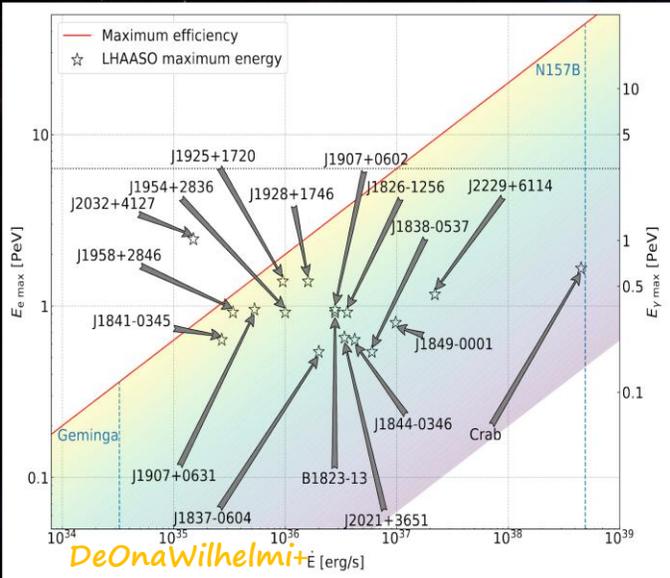
Thank you
very much!



BACKUP SLIDES

PWNe:

The majority! (statistics)



Leptonic origin of gamma-rays > 100 TeV is possible!!!
 → IC on BKG photon field [Breuhaus+ 2022]

If there are protons (hadrons): ~few % of the total energy (Guepin+ (2020)) and pp emission may show up in the high energy tail of IC emission

Very Complex Environment and low angular resolution

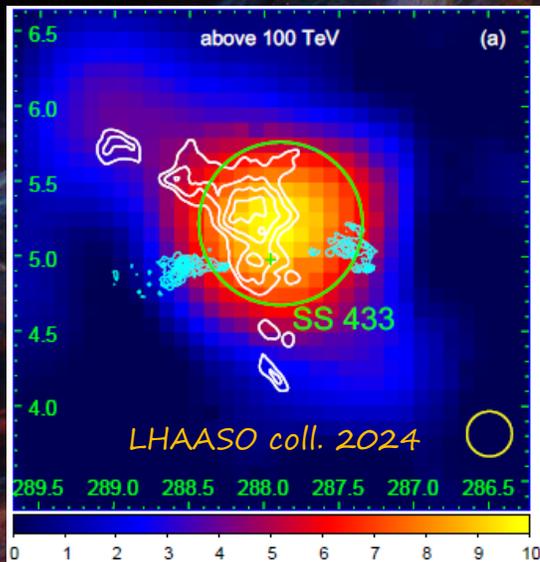
DeOnaWilhelmi+ 2022

Microquasars

5 MQs detected at $E > 100$ TeV

SS433 possible hadronic emission

MQs seem to provide natural interpretation of both CR and gamma-ray data [Kaci, Giacinti, Aharonian 2025]



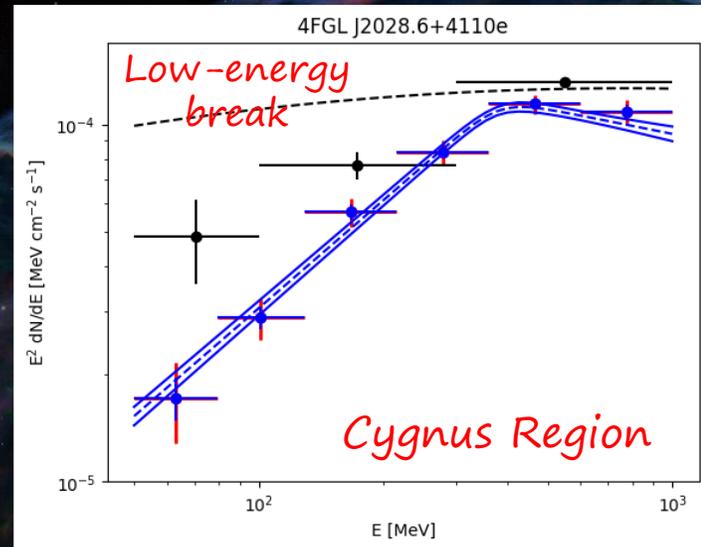
Young Massive Clusters ($t < \text{Myrs}$)

Acceleration at 1 PeV at Wind Termination Shocks [Morlino 2021, Vieu et al. 2022]

Collective effects can generate a collective outflows (right amount of power [Vink 2022])

Several physical ingredients to a deep analysis [Morlino CTAO general meeting]

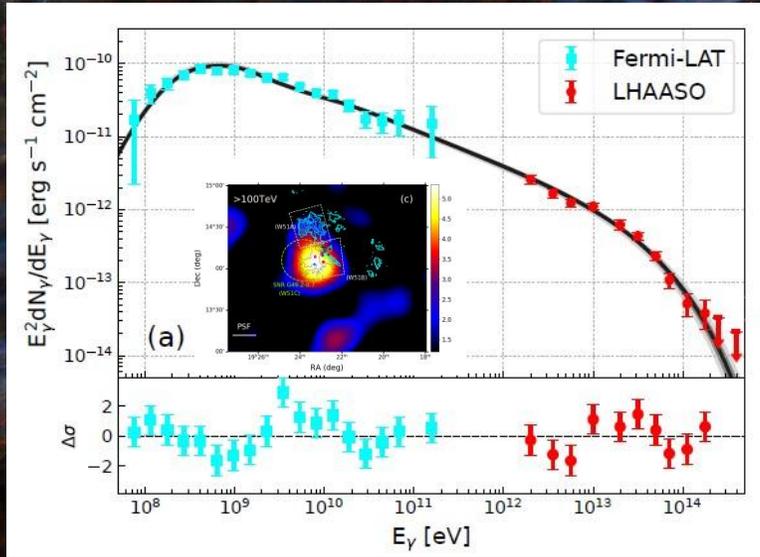
Little contribution to the CR production to avoid a new understanding of the GCR transport [Blasi 2025]



Lemoine-Goumard, talk Gamma2022

Supernova Remnants

Cao+ (LHAASO coll) 2024

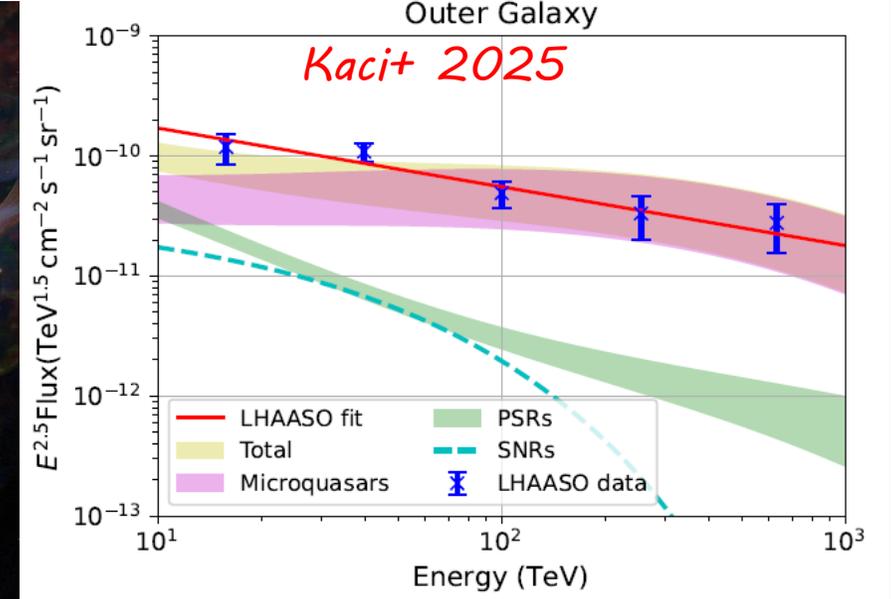
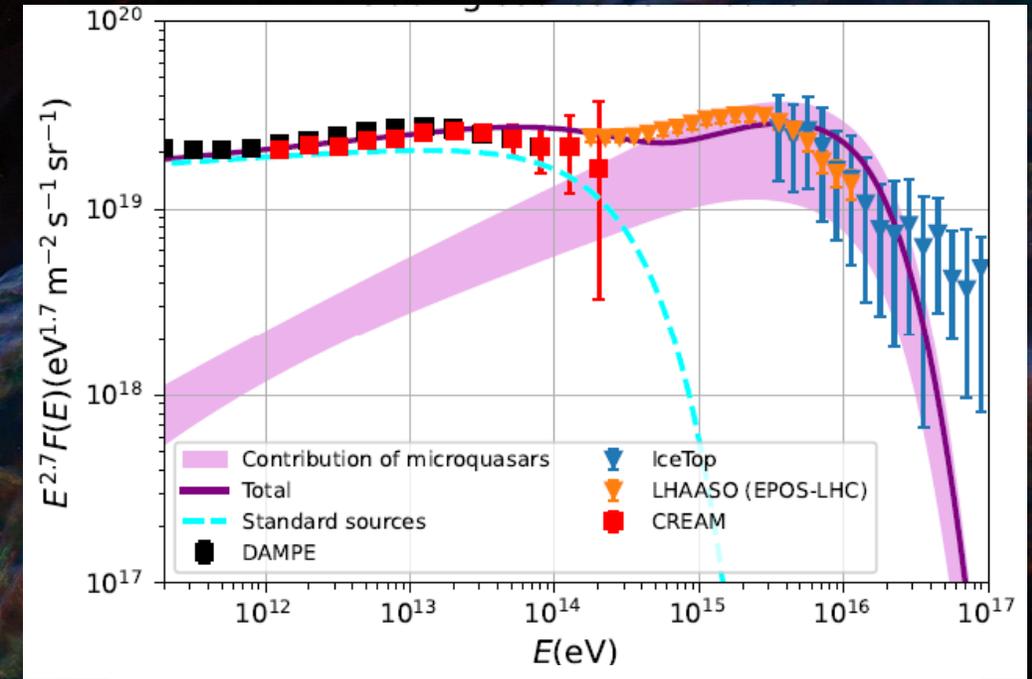
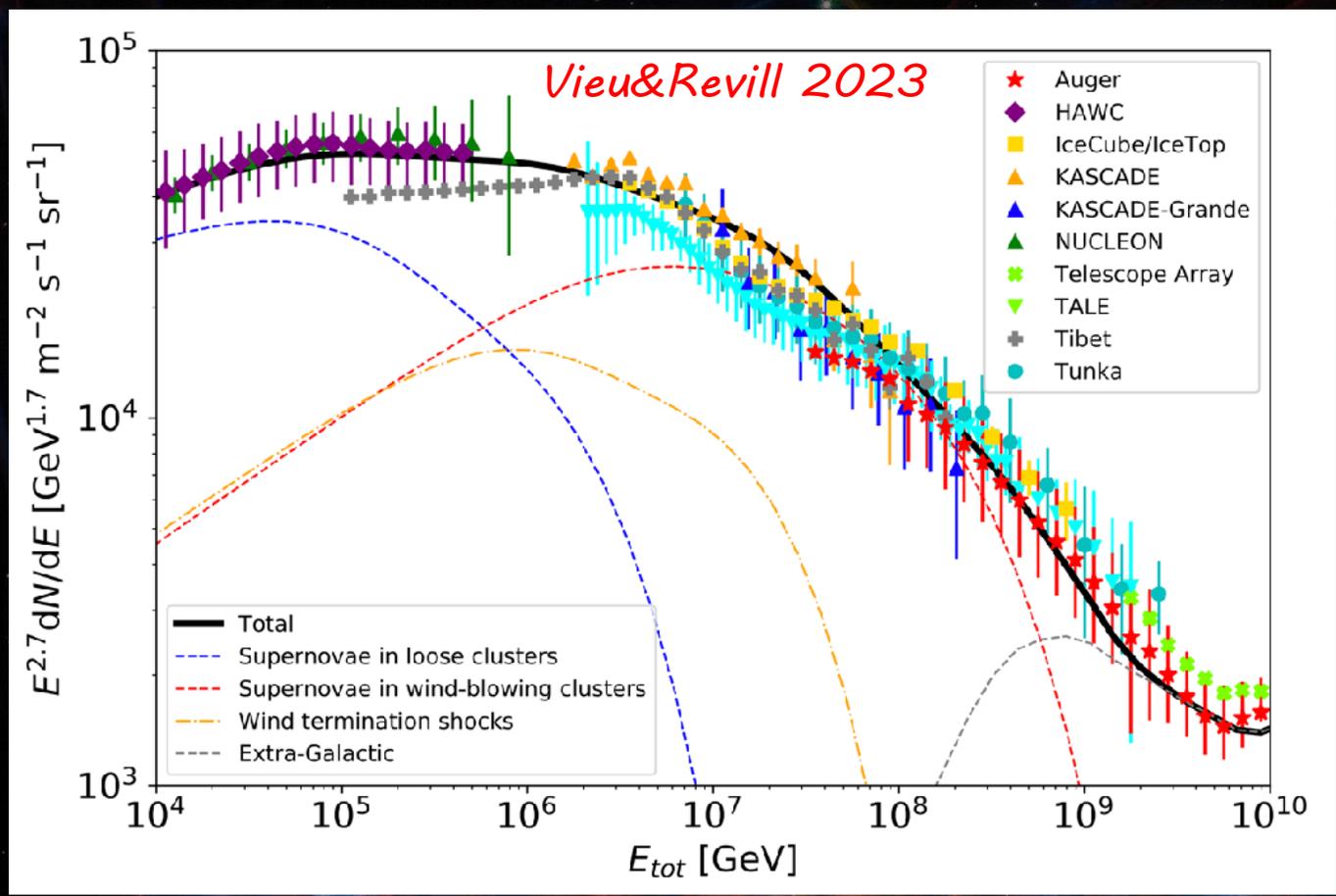


Several middle aged → how is it possible?

1. Something wrong in theoretical models
2. illuminated clouds scenario

W51 region: Likely, due to SNR/MC interaction or trapped CR emission [Mitchell+Celli24, Sunny, Cardillo + iun prep.] → possible first case of SNR with "pion bump" and PeVatron emission

More kinds of sources are better than one



Pevatrons shopping list

- 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
 - ✓ Energy dependence
 - ✓ Identification acceleration regions
 - ✓ MW association
 - ✓ Spectral Shape (hadrons vs leptons)

Li et al. ICRC23 (Neutrino/
LHAASO diffuse emission)
Burley et al. ICRC23 (Neutrino
promising target and SNRs)

And we would like also
a neutrino detection, thanks!



Galactic Cosmic Rays: from source to us



ACCELERATION

Very well studied phase due to the “reflection” of particles back and forward through a source shock
[first order Fermi acceleration]

ESCAPE

The detection of emission from particles in this phase is very difficult → theoretical complexity.



PROPAGATION

The last phase before reaching our Earth. Consequently, it takes almost all our attention thanks to a lot of data collected in the last years.

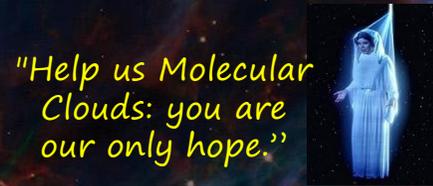
The issue: Cosmic Ray origin

The main candidates:
Supernova Remnants

- **ENERGY SUPPLY:** $L_{CR} = 10\% L_{SN}$
- **COLLISIONLESS SHOCKS:** energy dissipated via wave-particle interaction instead of particle-particle collisions.
- **STRONG SHOCKS & Diffusive Shock Acceleration:**
- **MAGNETIC FIELD AMPLIFICATION**

$$\mathcal{R} = \frac{u_u}{u_D} = \frac{4M_S^2}{3 + M_S^2} \quad M_S \rightarrow \infty, \mathcal{R} \rightarrow 4$$

Direct evidences



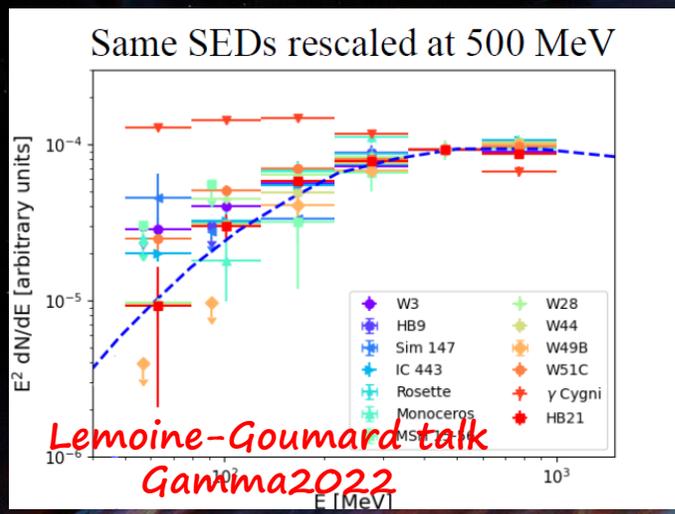
"Help us Molecular Clouds: you are our only hope."

Low-Energies (from space)

Pion bump detection: distinction leptonic/hadronic only at $E < 200$ MeV

Pevatrons \rightarrow g-ray at $E > 100$ TeV only of hadronic origin (maybe...)

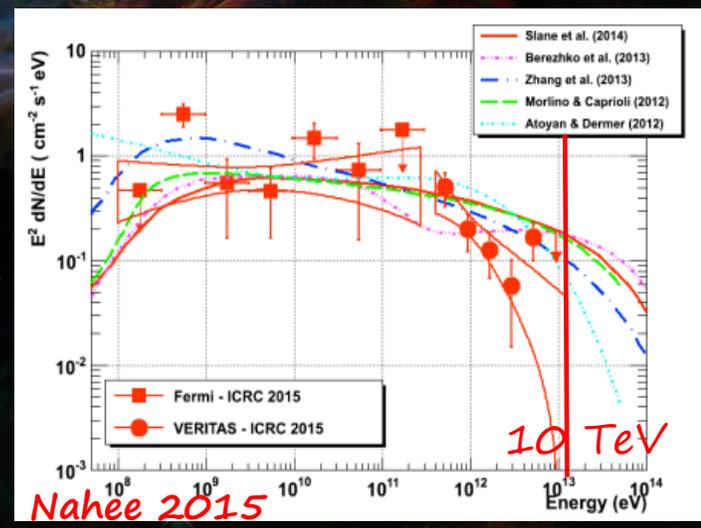
High-Energies (from Earth)



Confirmation of the presence of CRs but not of fresh acceleration (likely RE-accelerated or D suppression) [MC+2016, Celli+2019]

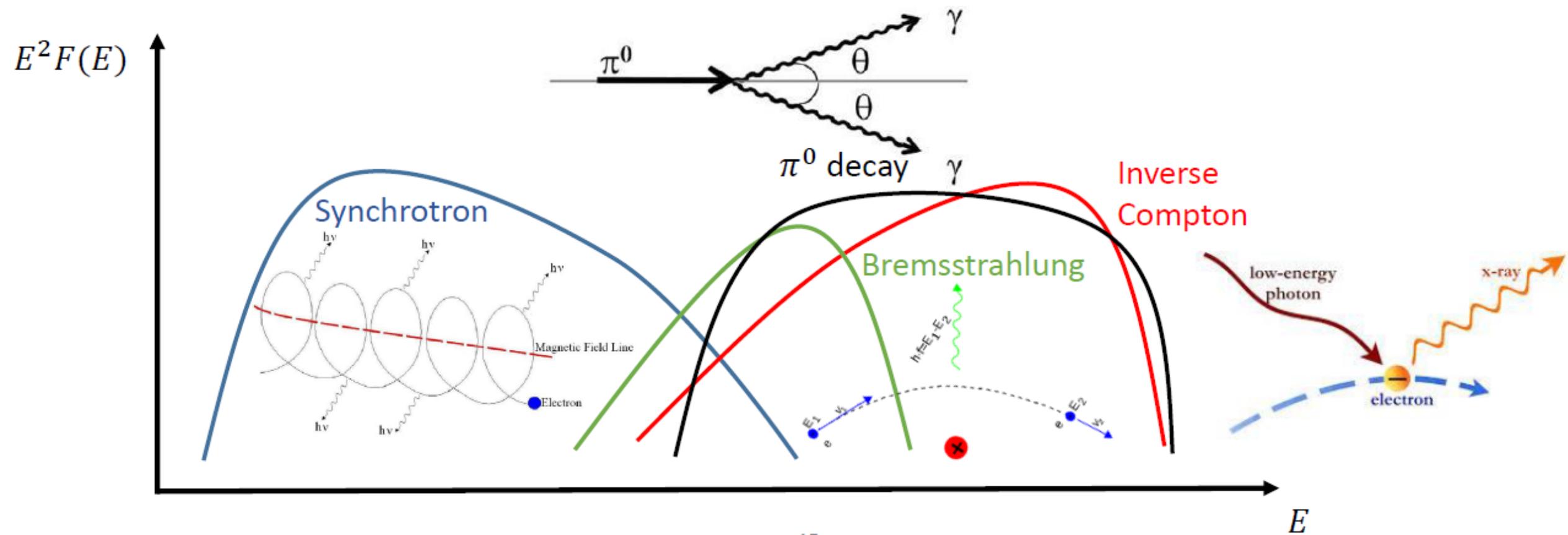
Possible Detection problem \rightarrow PeVatrons only in the first 100 years [MC+2015]

Gamma-ray from MCs illuminated by escaped CRs (Gabici 09, Mitchell 21, Celli 23)



Radiative processes: leptonic vs hadronic problem

Disentangle leptonic and hadronic contributions in the gamma-ray band

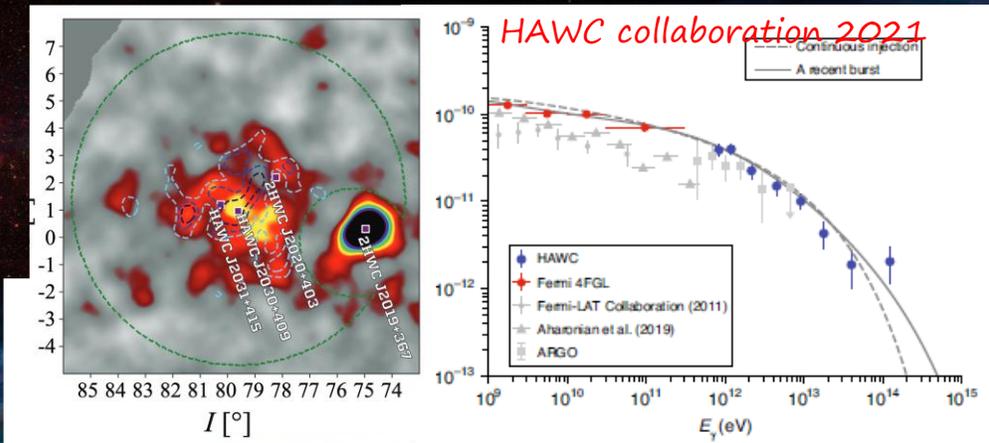
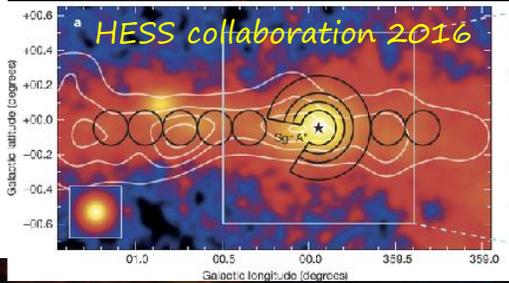


Galactic Center

APEX+Planck: Dust
(ATLASGAL-
Konsortium/Csengeri+ 2016)

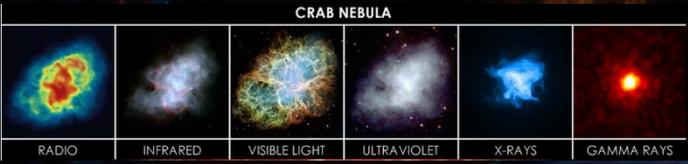


Cygnus Region



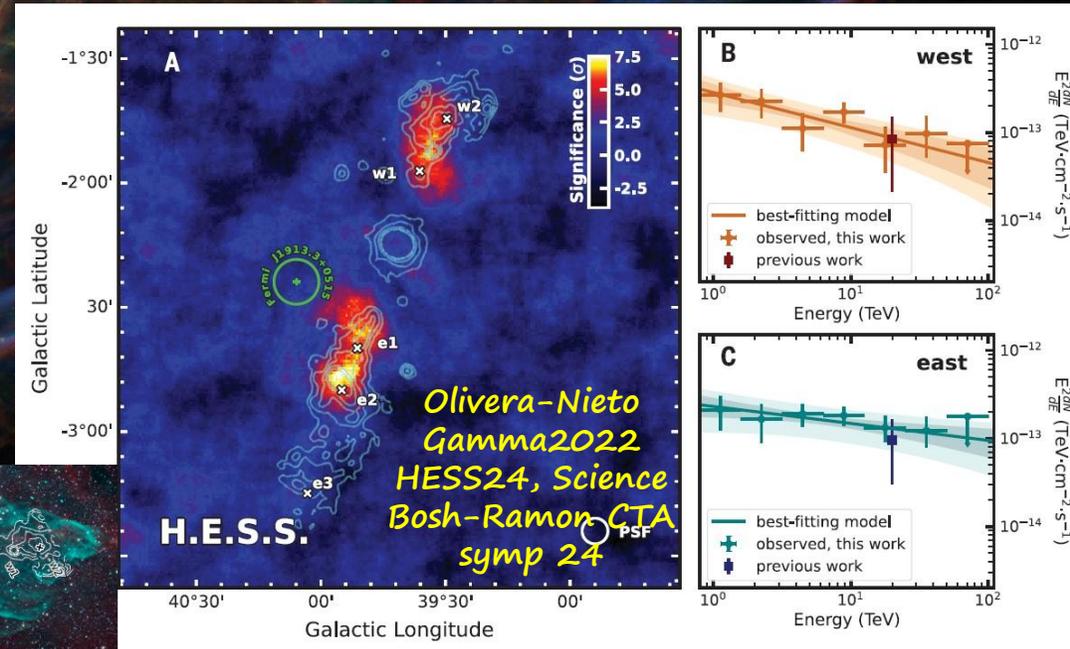
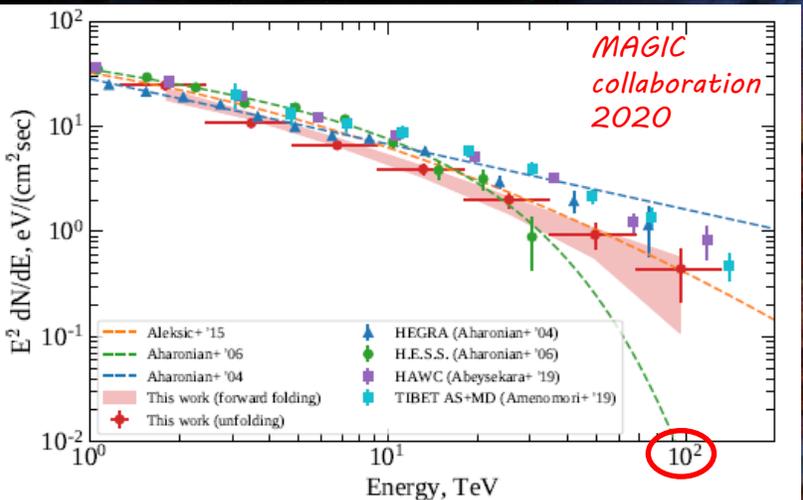
Young Massive Clusters

Crab Nebula



Right physics environment and spectral behavior but no PeV emission from most of these sources

Microquasars



"PeVatrons" storm from LHAASO

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

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

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

LEPTONIC
Or
HADRONIC?



Table 1 | UHE γ -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 ± 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)

Extended Data Table 2 | List of energetic astrophysical objects possibly associated with each LHAASO source

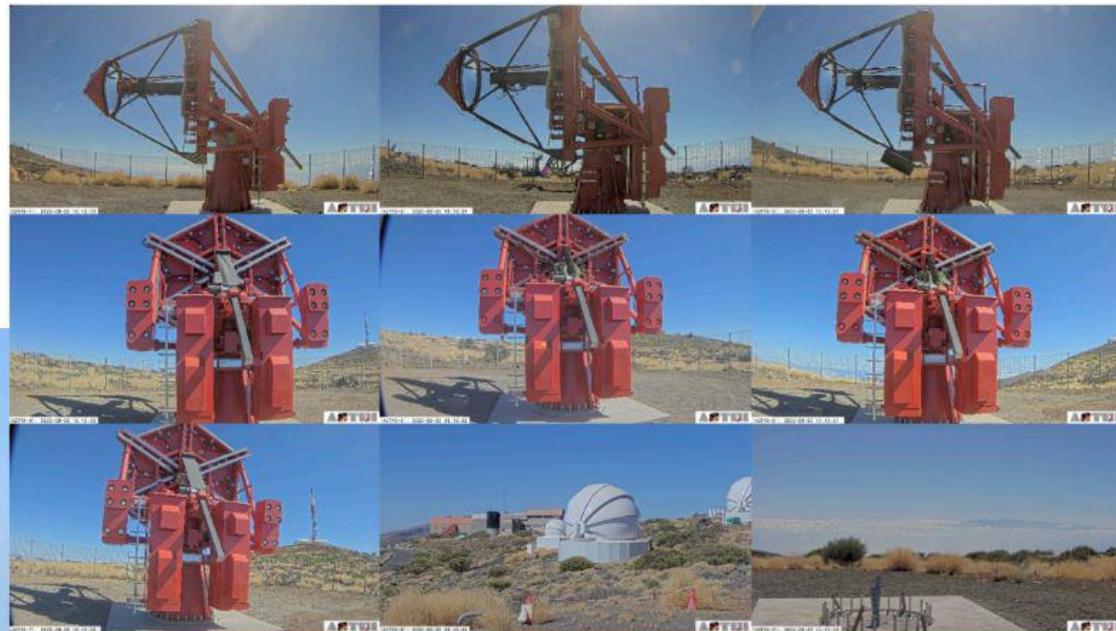
LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr) ^a	L_s (erg/s) ^b	Potential TeV Counterpart ^c
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030,
						2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0601	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8}_-0.7^d$	$1.8 - 3.3^k$	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7}_-1.4^l$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

LHAASO first catalog (Cao+2024)

To keep in mind:
only in the Northern
Emisphere!!!

Source name	Components	α_{2000}	δ_{2000}	$\sigma_{p,fit,stat}$	$r_{3\sigma}$	TS	N_0	Γ	TS ₁₀₀	Assoc.(Sep.[$^\circ$])	Source name	Components	α_{2000}	δ_{2000}	$\sigma_{p,fit,stat}$	$r_{3\sigma}$	TS	N_0	Γ	TS ₁₀₀	Assoc.(Sep.[$^\circ$])	Source name	Components	α_{2000}	δ_{2000}	$\sigma_{p,fit,stat}$	$r_{3\sigma}$	TS	N_0	Γ	TS ₁₀₀	Assoc.(Sep.[$^\circ$])	Source name	Components	α_{2000}	δ_{2000}	$\sigma_{p,fit,stat}$	$r_{3\sigma}$	TS	N_0	Γ	TS ₁₀₀	Assoc.(Sep.[$^\circ$])
ILHAASO J0007+5659a	KM2A	1.86	57.00	0.12	<0.18	86.5	0.33±0.05	3.10±0.20	43.6		ILHAASO J1219+2915	WCDA	184.98	29.25	0.09	<0.08	50.4	0.34±0.06	2.67±0.17			ILHAASO J1857+0203a	KM2A	284.38	2.06	0.07	0.28±0.03	475.2	1.78±0.10	3.31±0.10	112.4	HESS J1858+020 (0.21)	ILHAASO J1956+2921	WCDA	299.24	29.35	0.38	0.99±0.07	161.3	1.47±0.16	2.09±0.06		LHAASO J1956+2845 (0.63)
ILHAASO J0007+7303a	KM2A	1.91	73.07	0.07	0.17±0.03	961.0	3.41±0.27	3.40±0.12	171.6	CTA 1 (0.12)	ILHAASO J1653+3943	WCDA	253.43	39.73	0.01	<0.04	4121.6	3.77±0.08	2.94±0.02		Mrk 501 (0.04)	ILHAASO J1858+0330	KM2A*	284.59	3.51	0.12	0.43±0.04	299.3	1.56±0.10	3.78±0.15			ILHAASO J1959+2846a	KM2A	299.78	28.78	0.09	0.29±0.03	213.2	0.84±0.07	2.90±0.10	74.0	
ILHAASO J0056+6346a	KM2A	14.10	63.77	0.08	0.24±0.03	380.2	1.47±0.10	3.33±0.10	94.1		ILHAASO J1727+5016	WCDA	261.89	50.28	0.10	<0.08	43.6	0.49±0.08	3.09±0.21		1ES 1727+502 (0.14)	ILHAASO J1902+0648	WCDA	285.58	6.80	0.10	<0.15	46.2	0.45±0.13	2.39±0.18			ILHAASO J1959+1129a	KM2A	299.82	11.49	0.10	<0.21	94.1	0.27±0.04	2.69±0.17	60.8	
ILHAASO J0206+4302a	KM2A	31.70	43.05	0.13	<0.27	96.0	0.24±0.03	2.82±0.16	82.8		ILHAASO J1740+0948a	KM2A	265.03	9.81	0.07	<0.11	156.2	0.41±0.04	3.13±0.15	37.2	3HWC J1739+099(0.13)	ILHAASO J1906+0712	WCDA	286.56	7.20	0.21	0.21±0.05	57.8	1.01±0.25	2.72±0.15			ILHAASO J2002+3244a	WCDA	300.64	32.74	0.09	<0.16	74.0	0.34±0.06	2.21±0.11		
ILHAASO J0212+4254a	KM2A	33.01	42.91	0.20	<0.31	38.4	0.12±0.03	2.45±0.23	30.2		ILHAASO J1809-1918a	KM2A	272.38	-19.30	0.13	<0.22	134.6	0.46±1.27	3.51±0.26	88.4	HESS J1809-193 (0.24)	ILHAASO J1907+0826	WCDA*	286.96	8.44	0.31	0.43±0.08	51.8	1.34±0.29	2.62±0.14		2HWC J1907+084* (0.18)	ILHAASO J2005+3415*	WCDA	300.69	32.64	0.11	<0.08	43.6	0.15±0.03	2.70±0.22	28.1	
ILHAASO J0216+4237a	KM2A	34.10	42.63	0.10	<0.13	102.0	0.18±0.03	2.58±0.17	65.6		ILHAASO J1813-1245	KM2A	272.66	-12.75	0.22	<0.31	42.2	1.42±0.27	3.66±0.34		HESS J1813-126 (0.07)	ILHAASO J1908+0615a	KM2A	287.05	6.26	0.03	0.36±0.01	3410.6	6.86±0.16	2.82±0.03	912.0	MGRO J1908+06 (0.07)	ILHAASO J2005+3050	KM2A	301.45	30.85	0.13	0.27±0.05	110.2	0.46±0.05	3.62±0.21		3HWC J2005+311(0.32)
ILHAASO J0249+6022	KM2A	42.39	60.37	0.16	0.38±0.08	148.8	0.93±0.09	3.92±0.18			ILHAASO J1814-1719a*	WCDA	273.69	-17.33	0.27	0.71±0.07	118.8	26.50±2.46	2.83±0.06		2HWC J1814-173 (0.16)	ILHAASO J1910+0516*	KM2A	287.55	5.28	0.15	<0.30	74.0	0.57±0.08	3.15±0.18		SS 433 w-1 (0.26)	ILHAASO J2018+3643a	KM2A	304.65	36.72	0.04	0.24±0.01	2362.0	3.93±0.11	3.46±0.05	139.2	MGRO J2019+37 (0.11)
ILHAASO J0339+5307	KM2A	54.79	53.13	0.11	<0.22	144.0	0.58±0.06	3.64±0.16		LHAASO J0341+5258 (0.37)	ILHAASO J1814-1636a	KM2A	273.27	-16.62	0.30	0.68±0.08	132.2	11.90±1.30	3.74±0.20	50.4	2HWC J1814-173 (0.72)	ILHAASO J1912+1014a	WCDA	288.22	10.25	0.08	0.36±0.03	585.6	3.07±0.24	2.68±0.06		HESS J1912+101 (0.10)	ILHAASO J2020+4034	WCDA	305.03	40.57	0.08	0.38±0.03	458.0	2.36±0.16	2.91±0.06		VER J2019+407 (0.19)
ILHAASO J0343+5254a*	KM2A	55.79	52.91	0.08	0.20±0.02	388.1	1.07±0.07	3.53±0.10	20.2	LHAASO J0341+5258 (0.28)	ILHAASO J1825-1418	WCDA	276.29	-14.32	0.19	0.81±0.05	210.2	39.20±2.30	2.98±0.05		HESS J1825-137 (0.56)	ILHAASO J1913+0501	KM2A	288.28	5.03	0.11	<0.10	96.0	0.45±0.06	3.30±0.18		SS 433 e1 (0.15)	ILHAASO J2020+3638	WCDA	305.14	36.63	0.34	1.27±0.11	88.4	3.59±0.43	2.62±0.09		VER J2019+368 (0.28)
ILHAASO J0359+5406	KM2A	59.78	54.10	0.10	0.30±0.04	299.2	0.85±0.06	3.34±0.15			ILHAASO J1825-1256a	KM2A	276.41	-12.94	0.08	<0.20	299.2	5.08±0.42	3.33±0.13	121.0	HESS J1826-130 (0.14)	ILHAASO J1914+1150a	KM2A*	288.73	11.84	0.09	0.21±0.04	289.2	0.79±0.06	3.41±0.13	26.0	2HWC J1914+117* (0.13)	ILHAASO J2020+3649a	KM2A	305.23	36.82	0.04	0.12±0.02	912.0	2.29±0.09	3.31±0.06	86.5	VER J2019+368 (0.30)
ILHAASO J0428+5531	WCDA	67.23	55.33	0.36	1.18±0.12	153.8	4.73±0.63	2.66±0.10			ILHAASO J1825-1337a	KM2A	276.35	-13.73	0.05	<0.18	493.7	10.10±0.61	3.28±0.09	249.6	HESS J1825-137 (0.15)	ILHAASO J1914+1556	WCDA	289.78	15.93	0.32	<0.44	37.2	0.24±0.04	4.71±0.53		3HWC J1914+159(0.09)	ILHAASO J2020+3657	KM2A	306.88	36.95	0.23	0.38±0.05	84.6	0.50±0.06	3.21±0.17		
ILHAASO J0500+4454	WCDA	75.01	44.92	0.28	0.41±0.07	43.6	0.69±0.16	2.53±0.20			ILHAASO J1831-1007a*	WCDA	277.75	-10.12	0.16	0.78±0.04	378.4	17.80±1.08	2.71±0.04		HESS J1831-098 (0.25)	ILHAASO J1922+1403	WCDA	290.70	14.06	0.07	0.18±0.02	258.0	1.37±0.10	2.62±0.07		W 51 (0.15)	ILHAASO J2028+3352	KM2A	307.21	33.88	0.86	1.70±0.23	75.7	1.61±0.19	3.38±0.19		
ILHAASO J0534+3533	KM2A	83.53	35.56	0.18	<0.36	60.8	0.19±0.03	4.89±0.53			ILHAASO J1831-1029	KM2A	277.31	-9.83	0.12	0.26±0.05	128.4	2.56±0.27	3.30±0.14	53.3	HESS J1833-105 (0.35)	ILHAASO J1924+1609	WCDA*	291.09	16.15	0.43	1.45±0.11	169.0	4.44±0.41	2.51±0.08		3HWC J1923+169(0.86)	ILHAASO J2031+4052a	WCDA	307.90	40.88	0.19	0.25±0.05	57.8	0.77±0.12	2.81±0.16		LHAASO J2032+4102 (0.20)
ILHAASO J0534+2200a	WCDA	83.629	22.012	0.004	<0.04	73603.7	21.10±0.11	2.69±0.01		Crab (0.01)	ILHAASO J1834-0831	WCDA	278.62	-8.53	0.22	0.40±0.07	96.0	5.99±1.09	3.08±0.13		HESS J1834-087 (0.24)	ILHAASO J1928+1813a	KM2A	292.07	18.23	0.14	0.63±0.03	306.2	2.48±0.16	3.24±0.08	44.9	2HWC J1928+177 (0.46)	ILHAASO J2031+4127a	KM2A	308.14	40.88	0.13	<0.08	33.6	0.68±0.02	2.13±0.27	38.4	
ILHAASO J0542+2811a	KM2A	85.71	28.20	0.14	0.98±0.05	745.3	2.93±0.12	3.74±0.09	21.2	HAWC J0543+233 (0.21)	ILHAASO J1837-0654a	KM2A*	279.39	-6.90	0.06	0.34±0.01	1048.8	15.50±0.54	2.92±0.03		HESS J1837-069 (0.05)	ILHAASO J1928+1746a	WCDA	292.14	17.78	0.07	0.17±0.02	196.0	0.79±0.05	2.22±0.05		2HWC J1928+177 (0.01)	ILHAASO J2031+4127a	WCDA	307.95	41.46	0.03	0.22±0.01	1933.6	2.56±0.08	3.45±0.06	136.9	TeV J2032+4130 (0.12)
ILHAASO J0617+2231	WCDA	86.07	23.19	0.50	1.45±0.18	136.9	2.08±0.54	1.96±0.13			ILHAASO J1839-0545a	KM2A	279.39	-5.81	0.06	0.22±0.02	364.8	3.03±0.20	3.24±0.09	127.7	LHAASO J1839-0545 (0.17)	ILHAASO J1929+1846a	WCDA	292.17	18.99	0.07	<0.16	129.7	0.72±0.07	3.10±0.12	44.9		ILHAASO J2034+4434	KM2A*	311.92	44.58	0.23	0.42±0.09	62.4	0.46±0.06	3.17±0.20		
ILHAASO J0622+3754	KM2A	95.50	37.90	0.08	0.46±0.03	615.0	1.42±0.07	3.68±0.10		LHAASO J0621+3755 (0.63)	ILHAASO J1841-0519	WCDA	280.33	-5.33	0.09	0.60±0.03	519.8	15.20±0.84	2.88±0.04		HESS J1841-055 (0.25)	ILHAASO J1931+1653	KM2A	292.79	16.90	0.11	<0.10	51.8	0.22±0.04	3.15±0.25			ILHAASO J2108+5153a	KM2A	317.10	51.90	0.04	0.19±0.02	942.5	1.38±0.07	2.97±0.07	282.8	LHAASO J2108+5157 (0.06)
ILHAASO J0631+1040	WCDA	97.77	10.67	0.11	<0.30	141.6	0.54±0.06	3.33±0.16		3HWC J0631+107(0.06)	ILHAASO J1843-0335a	KM2A	280.21	-3.23	0.37	0.62±0.12	82.8	2.10±0.25	3.85±0.20		HESS J1843-033 (0.06)	ILHAASO J1928+1746a	WCDA	292.14	17.78	0.07	0.17±0.02	196.0	0.79±0.05	2.22±0.05		2HWC J1928+177 (0.01)	ILHAASO J2200+5643a	KM2A	330.08	56.73	0.13	0.54±0.05	368.6	1.70±0.10	3.44±0.10	38.4	
ILHAASO J0634+1741a	KM2A	98.57	17.69	0.10	0.89±0.04	1043.3	4.42±0.15	3.69±0.06	23.0	Geminga (0.54)	ILHAASO J1848-0153a	WCDA	281.01	-3.50	0.06	0.40±0.02	1162.8	9.01±0.43	2.58±0.03		HESS J1848-018 (0.11)	ILHAASO J1945+2424*	WCDA	296.36	24.30	0.37	1.29±0.11	262.4	4.27±0.51	2.56±0.08		2HWC J1949+244 (0.97)	ILHAASO J2228+6100a	WCDA	336.79	61.02	0.05	0.25±0.02	676.0	2.37±0.16	2.26±0.04		SNR C106.3+02.7 (0.13)
ILHAASO J0635+0619	WCDA	98.51	17.72	0.28	1.16±0.17	193.2	1.53±0.65	1.65±0.15			ILHAASO J1848-0001a	KM2A*	282.02	-1.78	0.11	0.56±0.03	542.9	3.29±0.17	3.69±0.10	36.0		ILHAASO J1951+2608	KM2A*	297.42	26.97	0.20	0.36±0.06	7.2	0.40±0.05	3.93±0.30			ILHAASO J2229+5927a	WCDA	339.54	59.00	0.09	0.43±0.03	353.4	2.03±0.12	3.55±0.09		
ILHAASO J0709+1405	WCDA	105.83	14.10	0.26	1.88±0.09	841.0	6.30±0.23	3.98±0.08		2HWC J0709+143 (0.72)	ILHAASO J1850-0004a*	WCDA	282.74	-0.07	0.08	0.46±0.02	800.9	5.30±0.32	2.49±0.04		HESS J1852-000 (0.36)	ILHAASO J1952+2922	WCDA	298.05	29.38	0.07	<0.12	104.0	0.55±0.05	2.52±0.													

- 7 out of 9 telescopes fully assembled
- Remaining 2 telescopes to be delivered next year
- Second camera scheduled for installation next month
- Subsequent cameras to be deployed in the following months



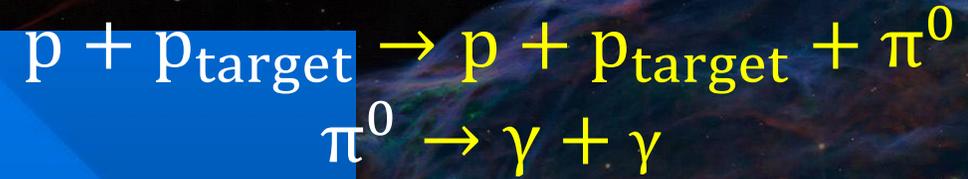
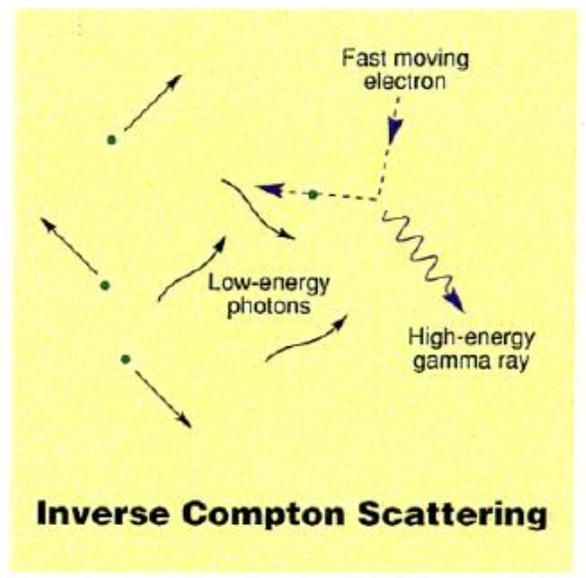
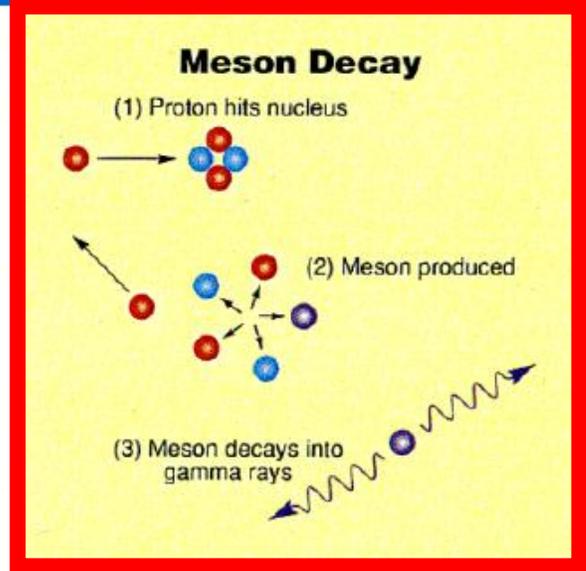
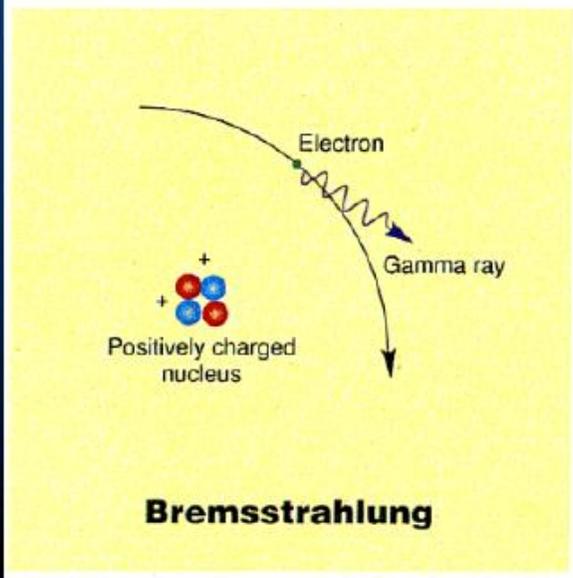
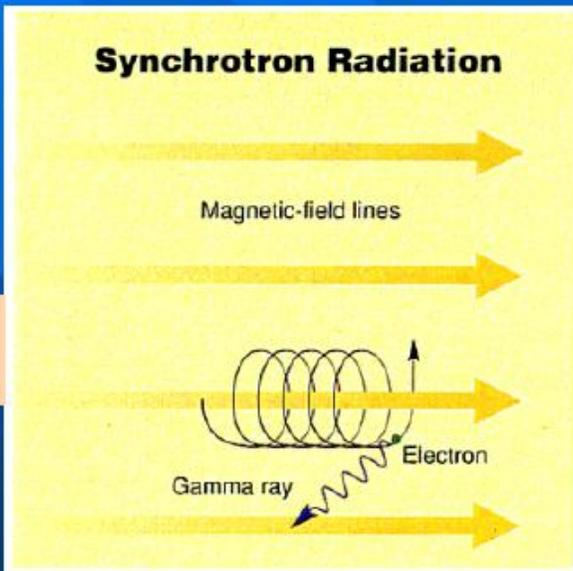
ASTRI Mini-Array: ASTRI-1



Radiative processes (MW importance)

$e^\pm + B$

$e^\pm + \text{matter}$

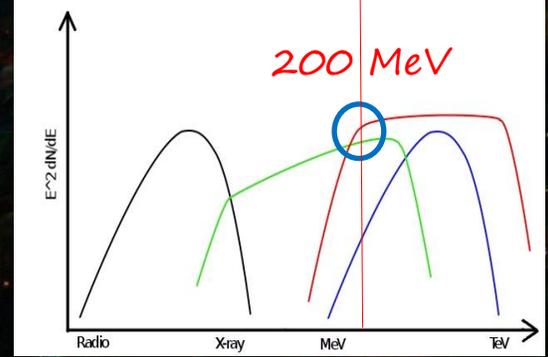
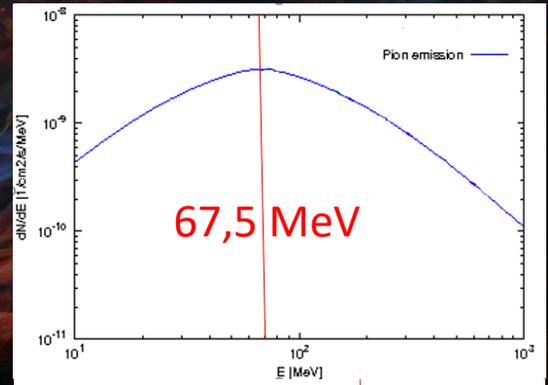


$p + \text{matter}$

$e^\pm + h\nu$

But we have a big problem...

- No deviations \rightarrow source direction
- Same spectrum of primary protons
- $E_{\gamma, M} \approx 10\% E_{p, M}$
- Evidence: Pion bump



Theory

Where do most CRs come from?

Observations

- ❖ Energetics
 - $P_{CR} \sim 10^{40} - 10^{41}$ erg/s
- ❖ Power-law injected spectrum
 - Required from DSA theory
- ❖ Maximum energy
 - They must explain the PeV proton energies
- ❖ Anisotropy
 - Source distribution has to be correlated with CR anisotropy (at PeV, $\sim 10^{-3}$)
- ❖ Composition
 - They must explain CR composition and its energy dependence

Receipt to be a CR source

MC&Giuliani 2023

- ❖ Detected VHE-UHE Emission
- ❖ Spectral curvature
 - Signature of E_{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!

A visualization of the cosmic web, showing a complex network of filaments and voids. The filaments are colored in shades of blue, purple, and red, set against a dark background filled with numerous small stars. The overall structure is intricate and three-dimensional.

Other sources?
B.L.

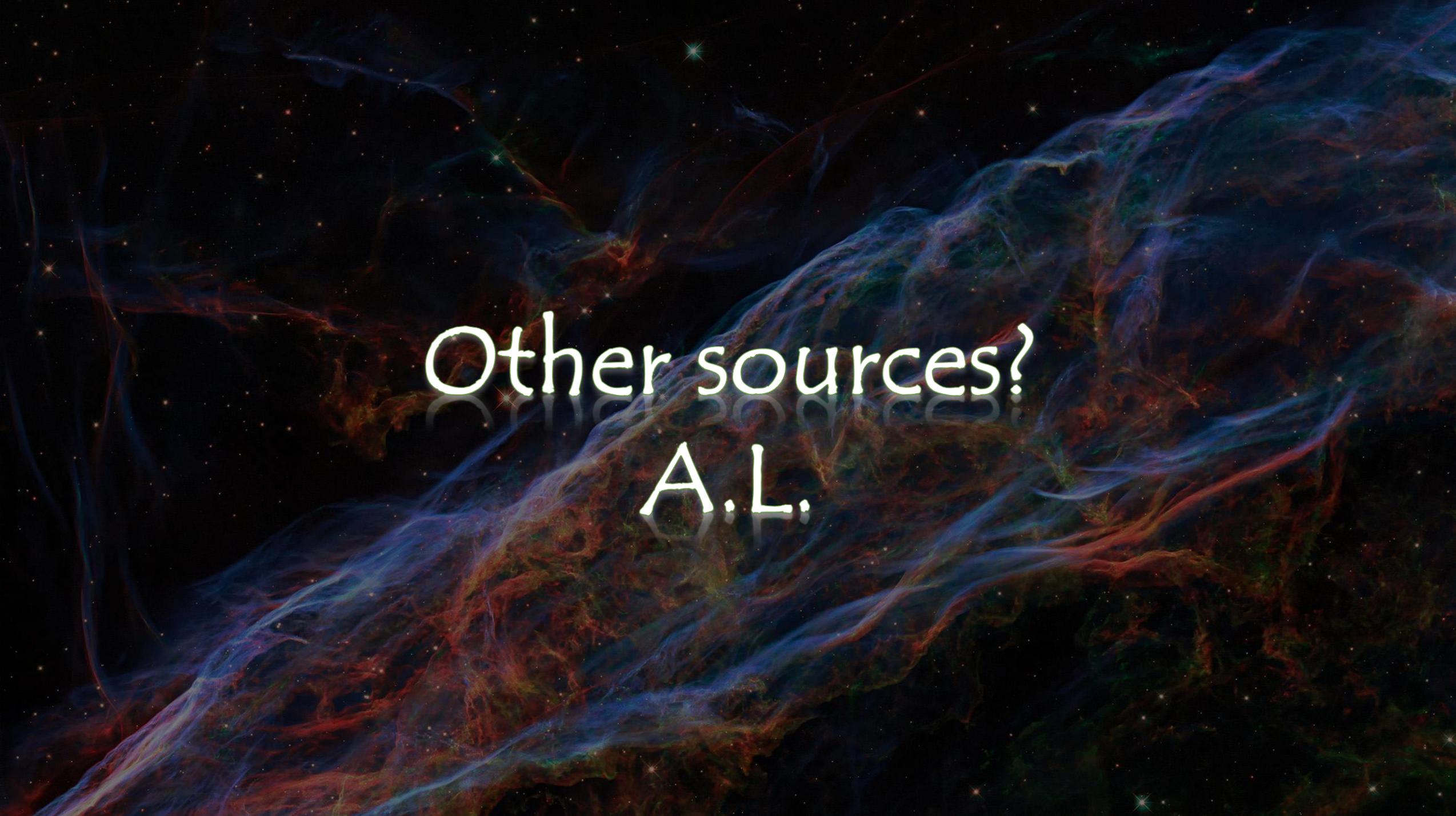
Ok...

We have some hints of
emission around 100 TeV...
but just one PeVatron (the
Crab)...

And it could be a leptonic
one...



...when suddenly...

A visualization of the cosmic web, showing a complex network of filaments and voids. The filaments are colored in shades of blue, purple, and red, set against a dark background filled with numerous small, distant stars.

Other sources?
A.L.

Vercellone+, 2022

ASTRI Mini-Array



	ASTRI Mini-Array	MAGIC	VERITAS	H.E.S.S.	HAWC	LHAASO
Location	28° 18' 04" N 16° 30' 38" W	28° 45' 22" N 17° 53' 30" W	31° 40' 30" N 110° 57' 7.8" W	23° 16' 18" S 16° 30' 00" E	18° 59' 41" N 97° 18' 27" W	29° 21' 31" N 100° 08' 15" E
Altitude [m]	2,390	2,396	1,268	1,800	4,100	4,410
FoV	9.6°	~ 3.5°	~ 3.5°	~ 5°	2 sr	2 sr
Angular Res.	0.05° (10 TeV)	0.07° (1 TeV)	0.07° (1 TeV)	0.06° (1 TeV)	(0.15–1) ^(a)	~ 0.2 ^(b) (10 TeV)
Energy Res.	(12)% (10 TeV)	16% (1 TeV)	17% (1 TeV)	15% (1 TeV)	30% (10 TeV)	60% (10 TeV) ^(b)
Energy Range	(0.3-200) TeV	(0.05-20) TeV	(0.08-30) TeV	(0.02-30) TeV ^(c)	(0.1-100) TeV	(0.1-1,000) TeV

- *Wide FoV with homogeneous off-axis acceptance*
 - ✓ Multi-target fields, surveys, and extended sources
 - ✓ Enhanced chance for serendipitous discoveries



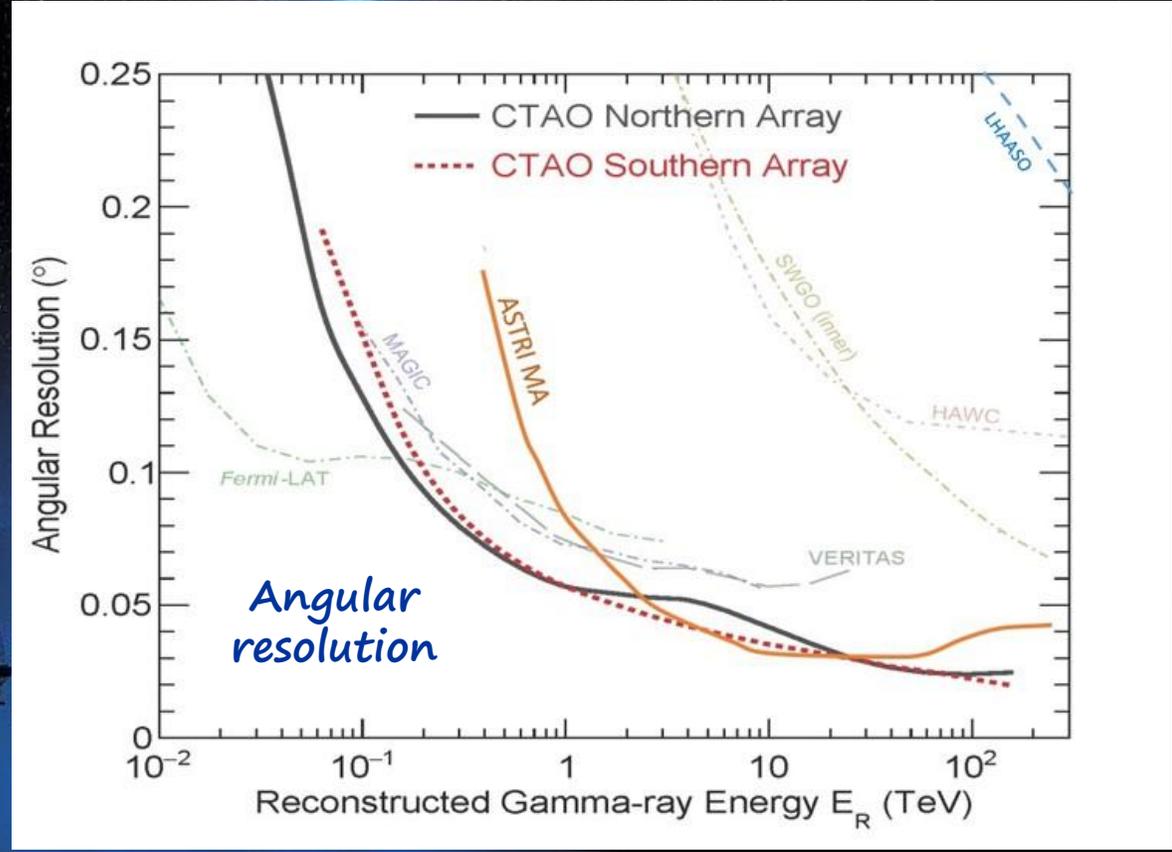
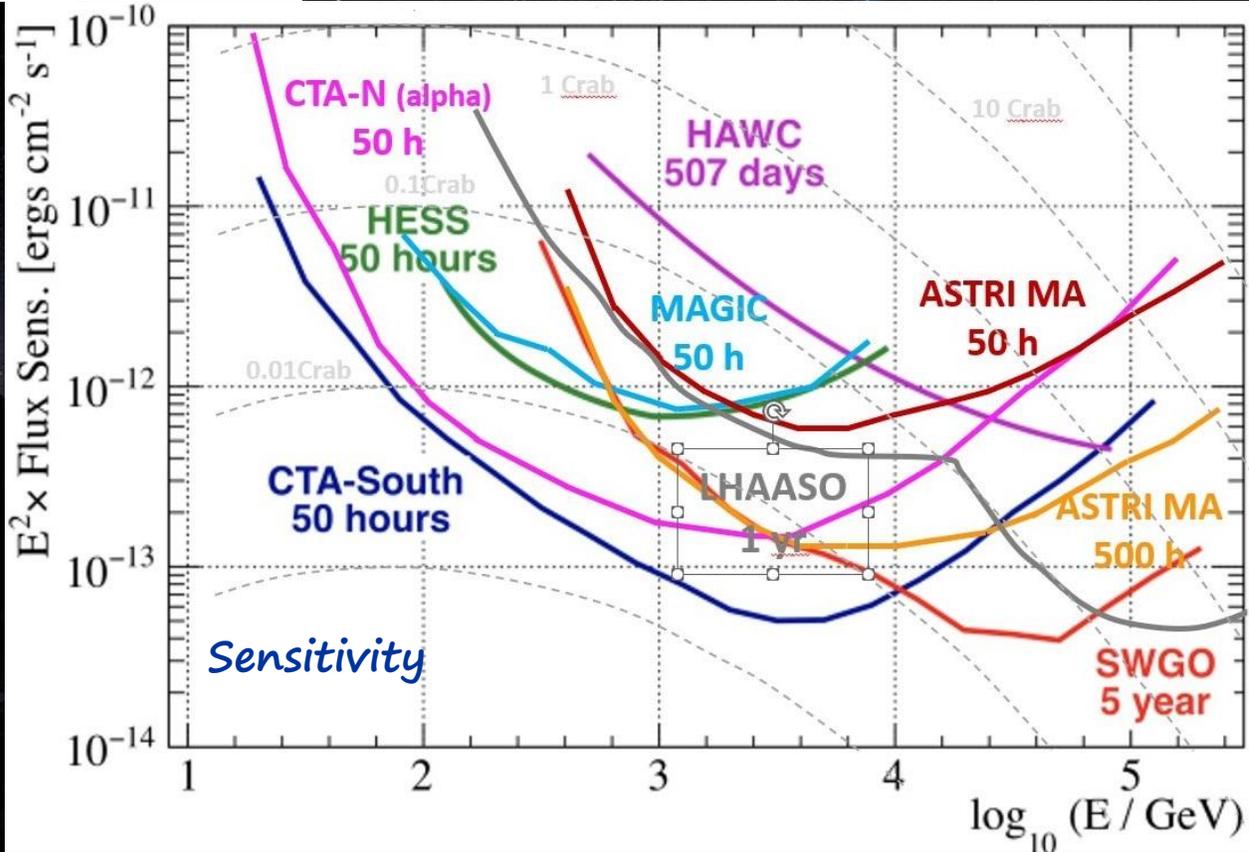
ASTRI Mini-Array and CTA



cherenkov
telescope
array

the observatory for
ground-based
gamma-ray astronomy

Mini-Array



- **Sensitivity: better than current IACTs ($E > 10$ TeV):**
 - ✓ Extended spectra and cut-offs constraints
- **Energy/Angular resolution: $\leq 10\%$ / $\leq 0.1^\circ$ ($E \leq 10$ TeV)**
 - ✓ Characterize extended sources morphology

Vercellone+ 2022,
Scuderi+ 2022,
CTA website,
MC&Giuliani 2023

IMPORTANT MESSAGES

- ❖ Cosmic-ray origin: a *Very Hot Topic since 1912!!*
- ❖ The main candidates hadronic PeVatrons are *Pulsar Wind Nebulae, Supernova Remnants, Young Massive Star Clusters and Microquasars*
- ❖ The future in the VHE domain is related to *LHAASO, ASTRI-MA and CTA* and their synergy with other instruments
- ❖ We need *satellite for the MeV energies* (pion bump detection) [*Ackermann+ 2025*]
- ❖ The *collaboration between gamma-ray and neutrino communities* will be fundamental in order to solve the CR origin issue → importance of VODF (Very-high-energy Open Data Format [*Khelifi+2023 ICRC23 proc., Unbenhaum+23*])
- ❖ *A lot of work to do*: from simulation and software to data analysis to theoretical interpretation

Total known galactic SNRs: 310 (*Green 2025, Ferrand and Safi-Harb 2012*)

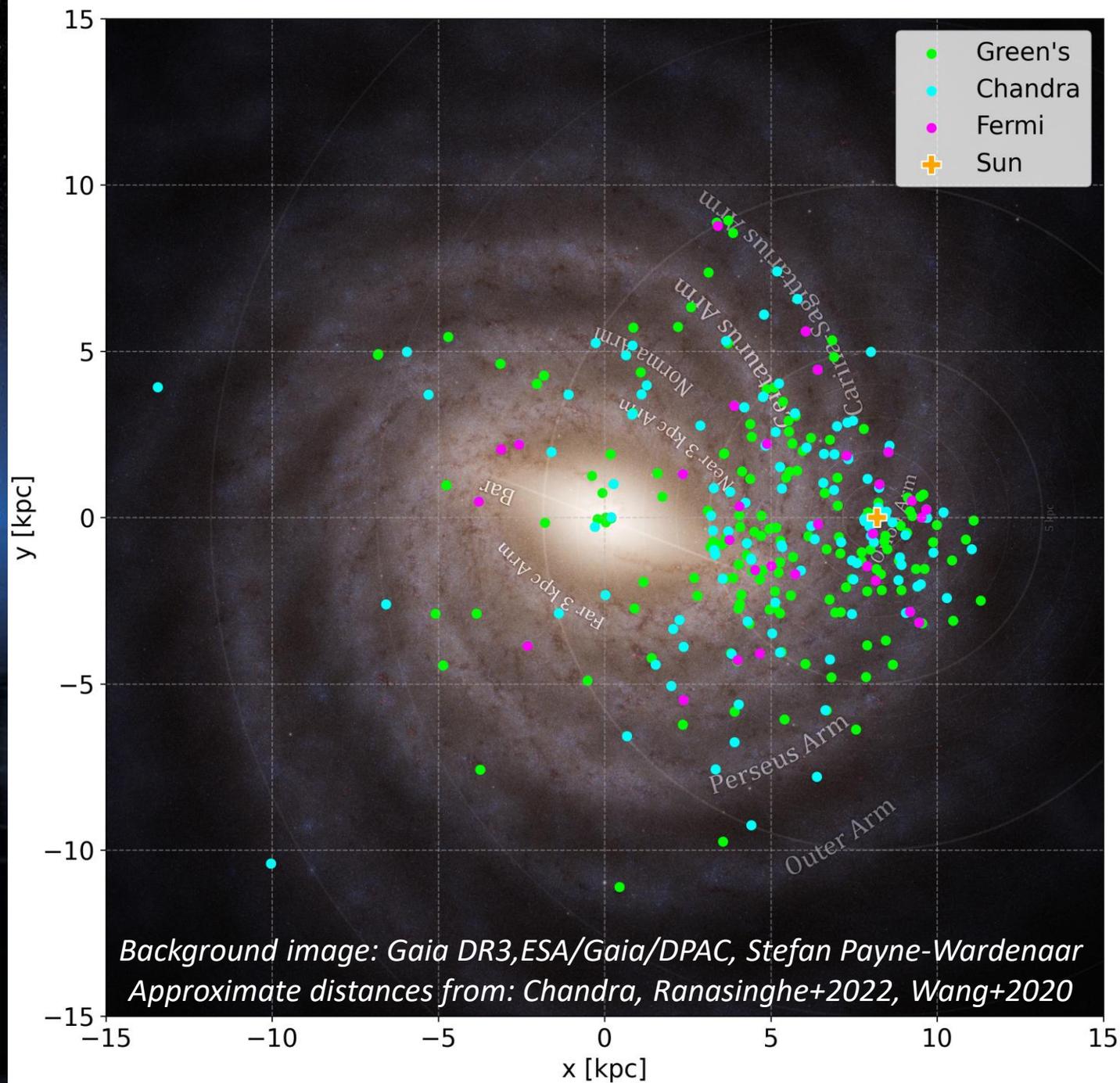
Chandra X-rays: 144 (*Chandra SNR catalog*)

Fermi -rays: 30 + several candidates (*Fermi's First SNR catalog, Acero+2016*) γ

+Additional data from HESS, HAWC, VERITAS, MAGIC, and LHAASO

Sort into three catalogs

- **Tier 1:** Extremely likely to be hadronic
- **Tier 2:** Hadronic at low energies, inconclusive at TeV
- **Tier 3:** Possible sub-dominant hadronic component with relatively high flux



Radiative processes: pp interaction

NB Here the acceleration index is called "delta"

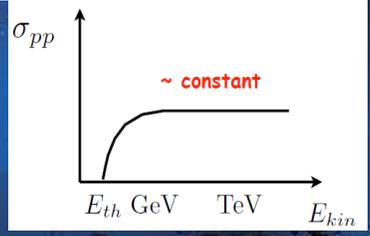
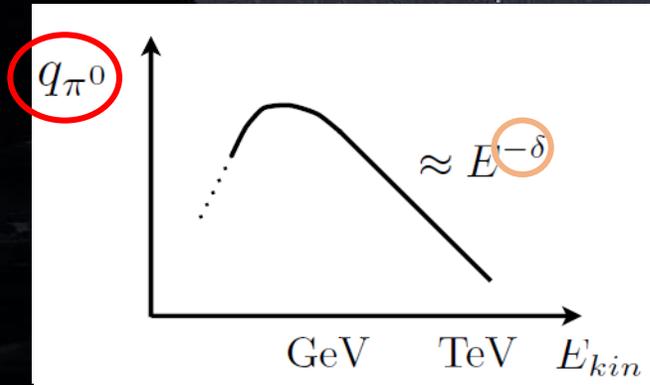
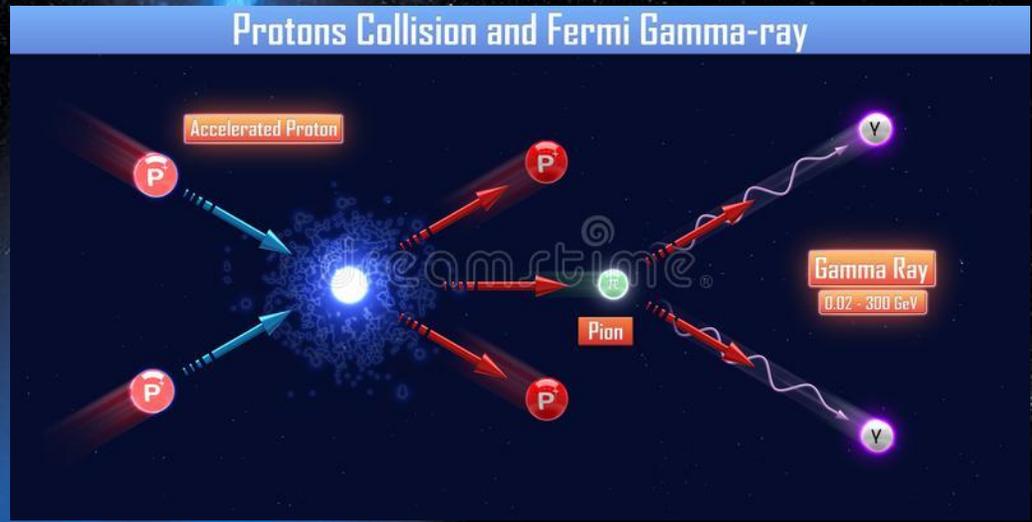


Kelner 2006, Cardillo+ 2016

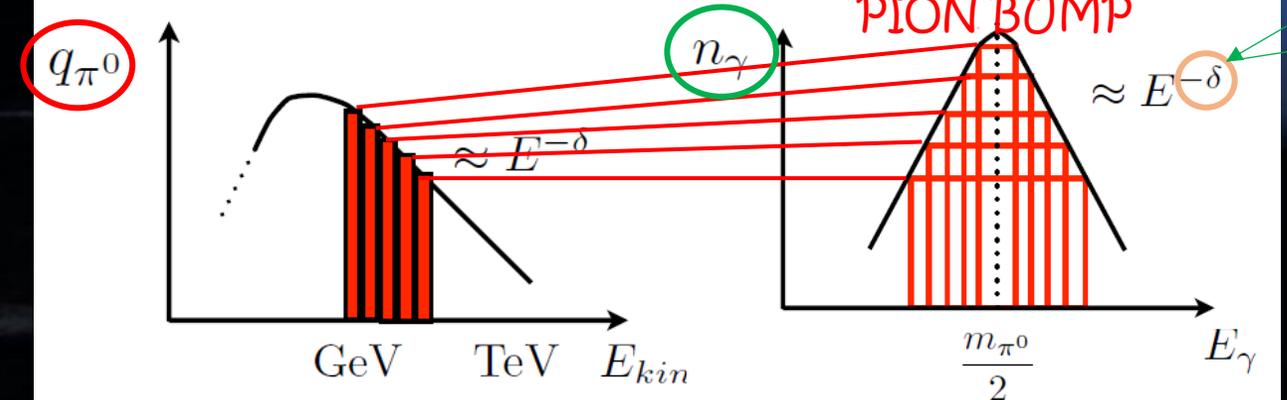
Delta approximation

$$J_{\pi}(E_{\pi}) = \int dE_p N_p(E_p) \delta(E_{\pi^0} - f_{\pi^0} E_{p,kin}) \sigma_{pp}(E_p) n_{gas} c$$

$N_p(E_p) \propto E_p^{-\delta}$ $f_{\pi^0} \approx 0.17$ $\sigma_{pp} \sim \text{constant}$



$$J_{\gamma}(\epsilon_{\gamma}) = 2 \int_{\epsilon_{\gamma} + m_{\pi}^2/4\epsilon_{\gamma}}^{\infty} dE_{\pi} \frac{J_{\pi}(E_{\pi})}{\sqrt{E_{\pi}^2 - m_{\pi}^2}}$$



- Gamma-ray spectrum reflects the proton one
- Gamma-ray spectrum is symmetric with respect to $\frac{m_{\pi^0}}{2} \sim 70 \text{ MeV}$ (neutral pion rest mass)
- Known relation between energies: $E_{\gamma} \approx \frac{E_{CR}}{10}$

Indirect evidences



X-RAY BAND



Magnetic Field Amplification

In the X-ray band, young SNRs show very thin rims of about 0.01 pc due to Synchrotron emission. In Bohm diffusion limit

$$[\delta B \rightarrow B_0 \Rightarrow D(E) = \frac{1}{3} r_L(E) c]$$

$$\sqrt{D(E) \tau_{sync}} \approx 0.04 B_{100\mu G}^{-\frac{3}{2}} pc \Rightarrow B \approx 100 \mu G$$

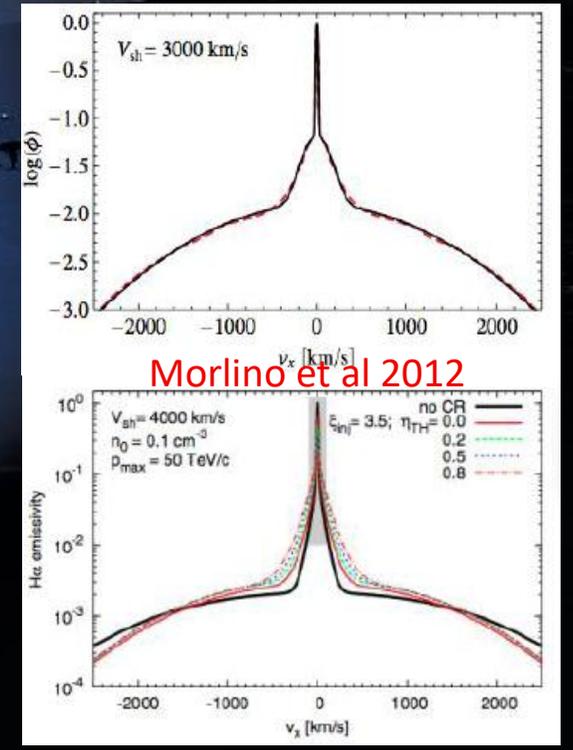
OPTICAL BAND



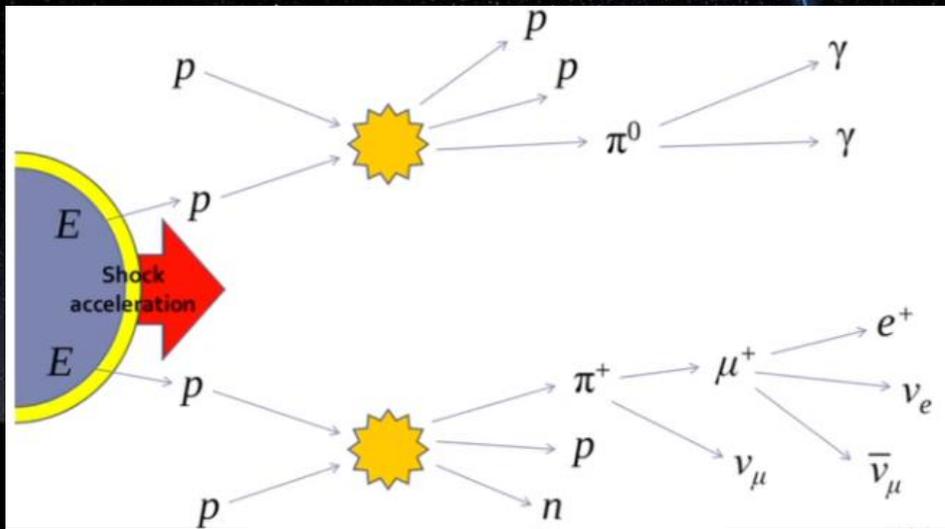
CR acceleration

- Neutrals leads to a third component in the **Balmer lines** spectrum due to Neutral return flux
- In presence of accelerated CR
 - Narrower broad line $\rightarrow T_{down} \rightarrow$ CR pressure
 - Broader narrow line
- Steepening of CR spectrum

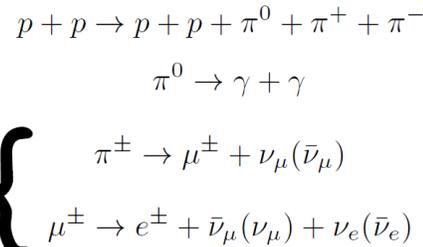
NOT SUFFICIENT!!



pp interaction: not only gamma-rays



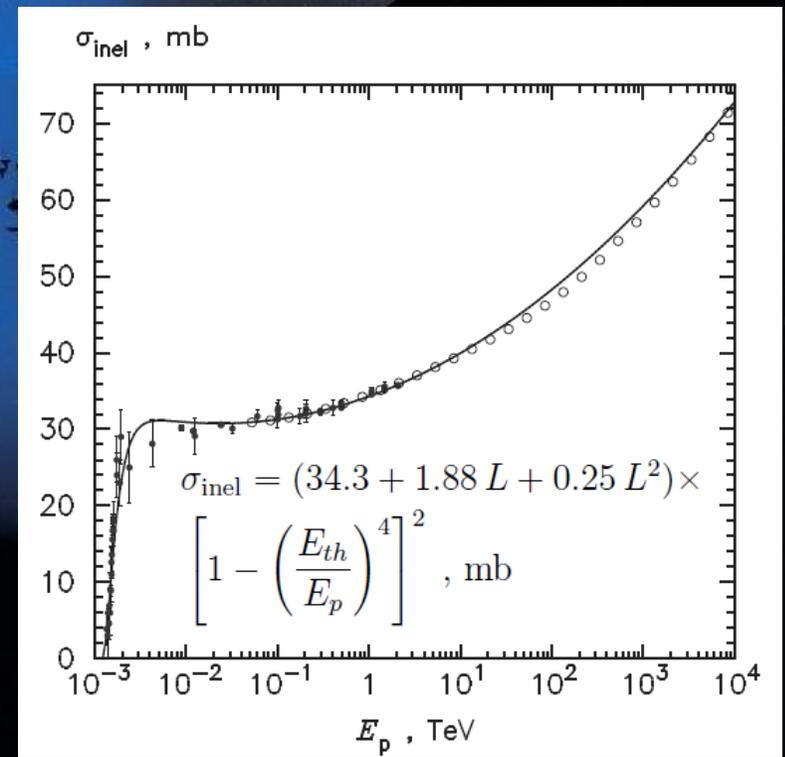
Final products of proton-proton interactions are not only gamma ray photons but also **neutrinos**, **anti-neutrinos**, **electrons** and **positrons**



$$E_e \approx E_\nu \approx \frac{E_{CR}}{20}$$

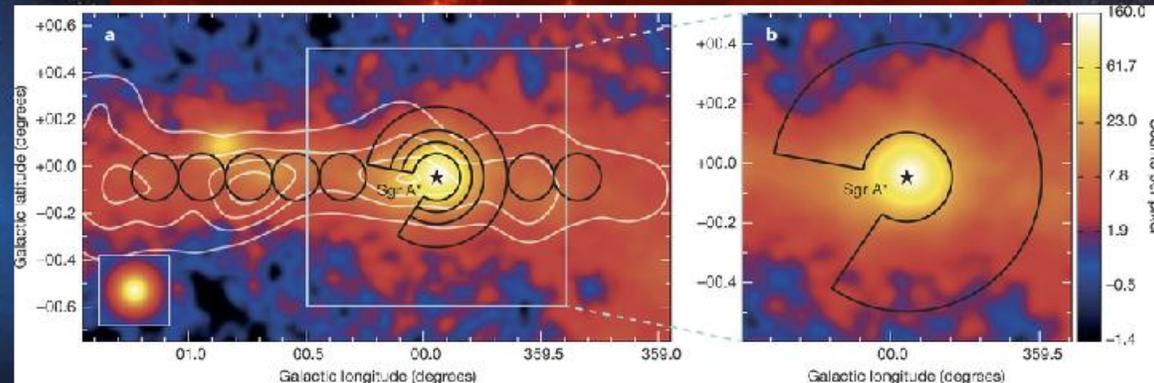
$$\Phi_{s,high}(E_s) = v n_0 \int_0^1 \sigma_{inel}(E_s/x) f(E_s/x) F_s(x, E_s/x) \frac{dx}{x}$$

$$\sigma_{inel} = (34.3 + 1.88L + 0.25L^2) \left[1 - \left(\frac{E_{th}}{E_p} \right)^4 \right]^2 \text{ mb}$$

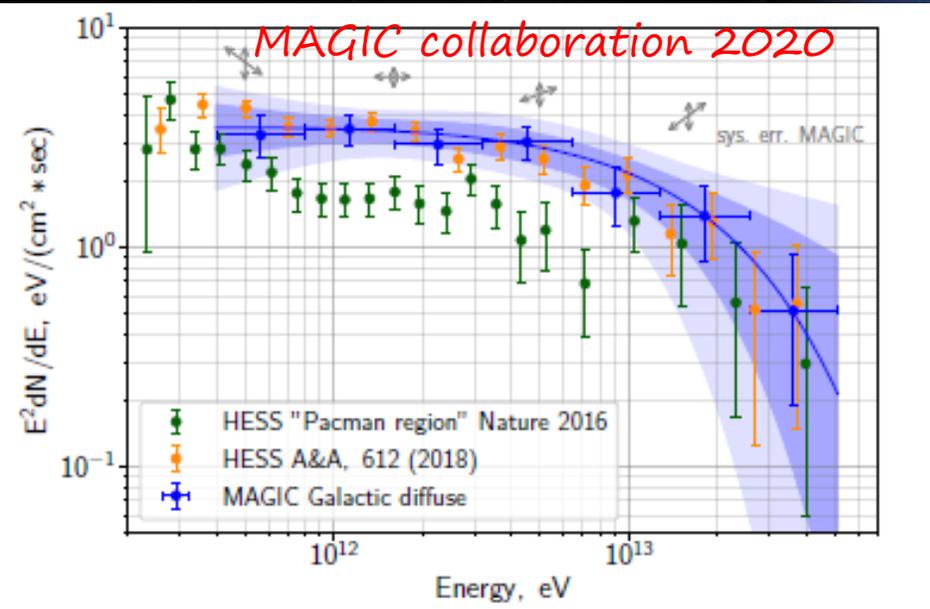
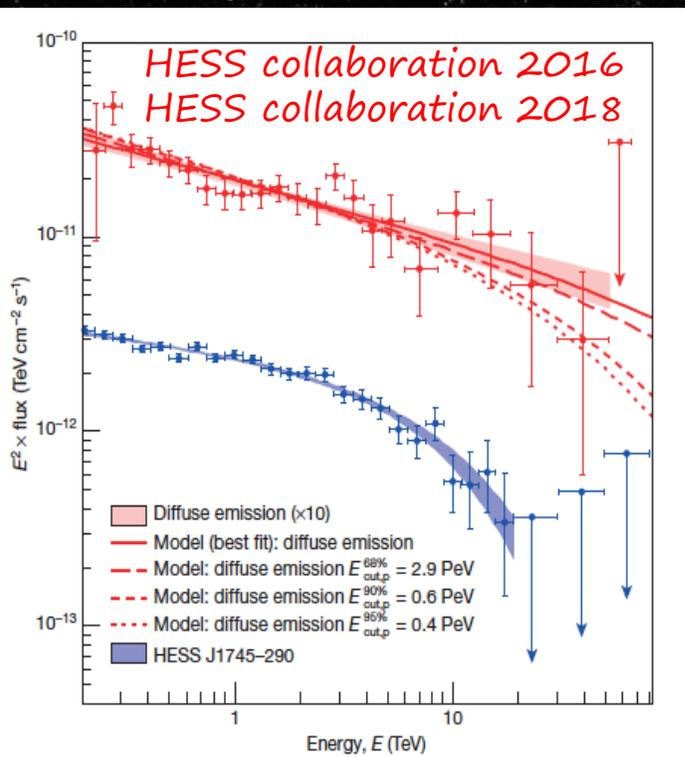


Other Sources? - Galactic Center Region

APEX+Planck:
Dust
(ATLASGAL-
Konsortium/Cse-
ngeri+ 2016)



HESS
collaboration
2016



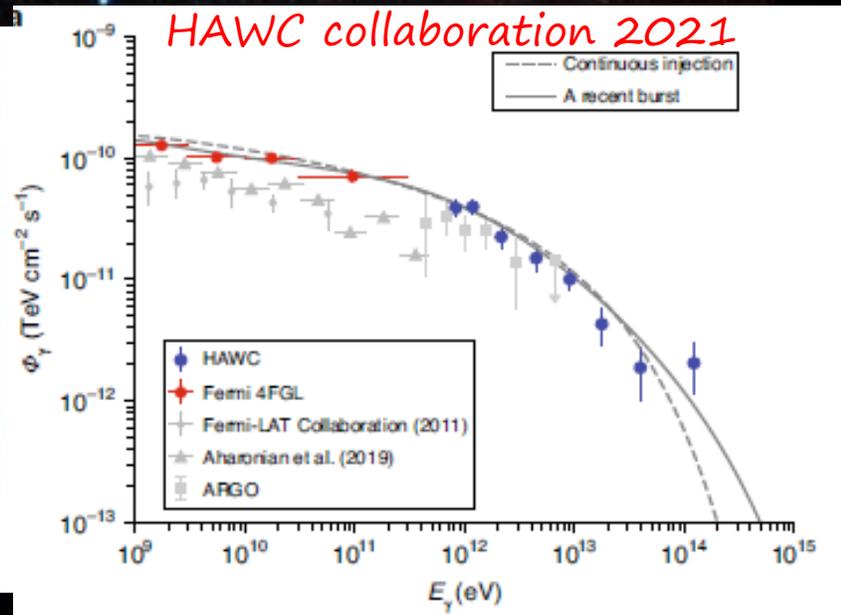
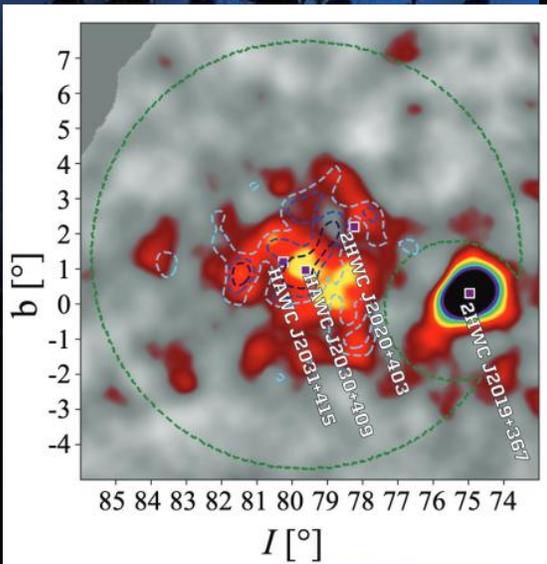
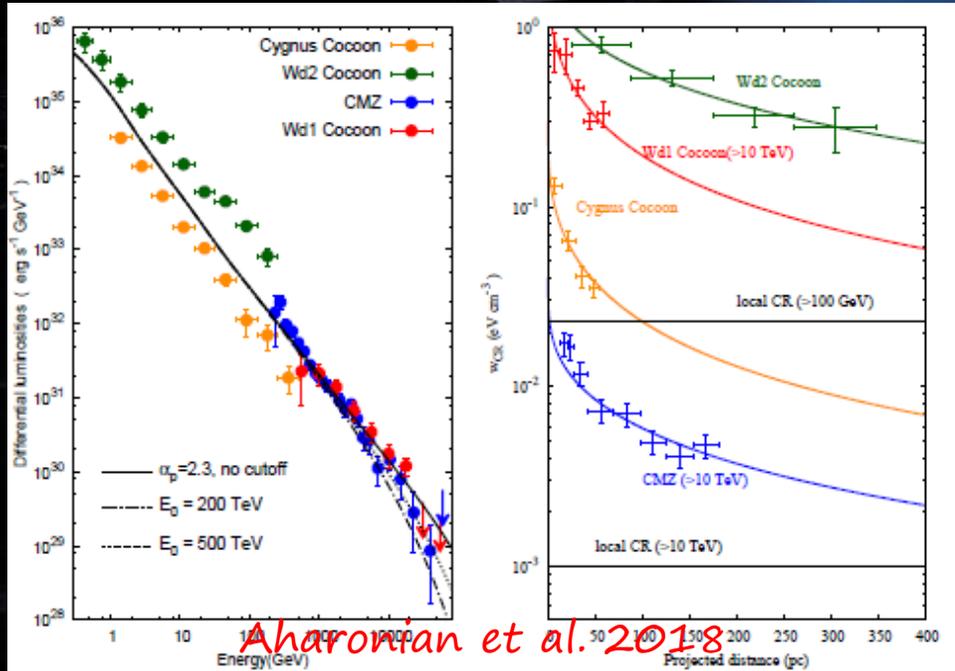
- Perfect correlation between molecular gas distribution and gamma-ray emission seen by HESS
- CR energy density 10 times greater than CR sea
- CR spectrum with and index $\gamma_E = 2.3-2.4$ up to 100 TeV (but with large error bars)
- Spatial distribution with $1/r$ (continuous injection)
- Maybe from Sgr A* (Rodríguez-Ramírez et al., 2019)
- **First spectro-morphological analysis (HESS2018, Devin talk Gamma 2022)**

Other sources? – From GCR to Superbubbles

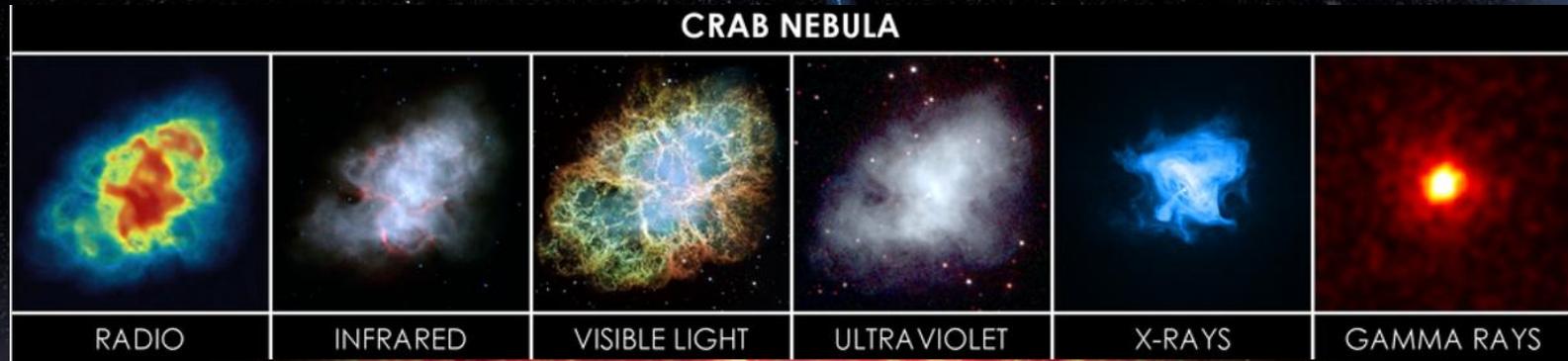
Hot and rarefied extended cavities formed by OB stars winds [Bykov 1992]:

- 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]

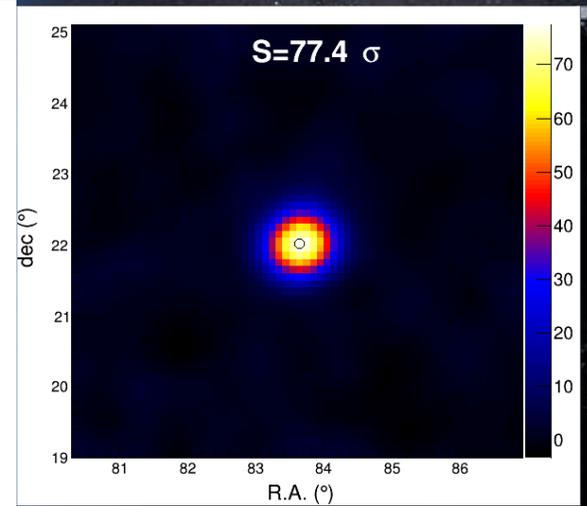
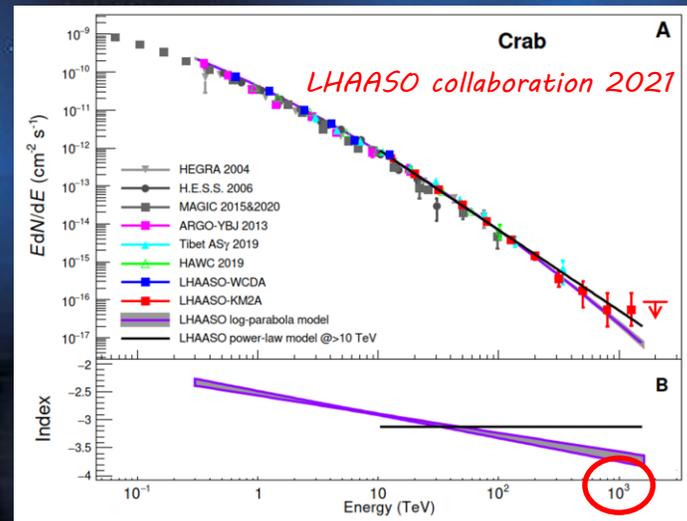
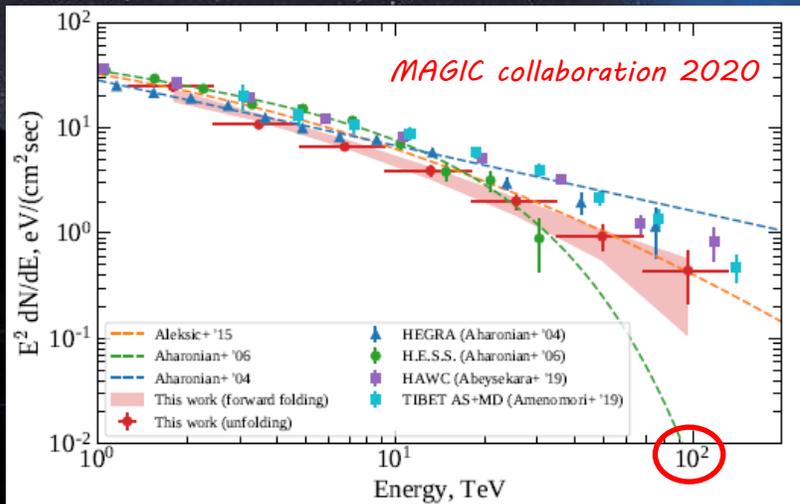
DIRECT PROOF?



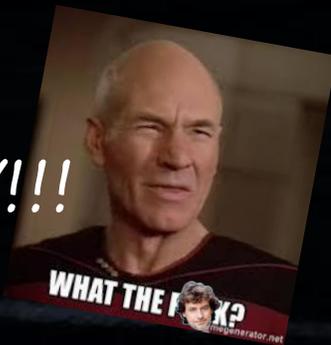
Other Sources? - CRAB NEBULA



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



Detection above 1 PeV!!!



but...

Crab is a PWN (leptonic source)

So...

Leptons Or Hadrons?

Acceleration or Reacceleration (Spencer+23)

Other sources? - Gamma-ray binaries & 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.

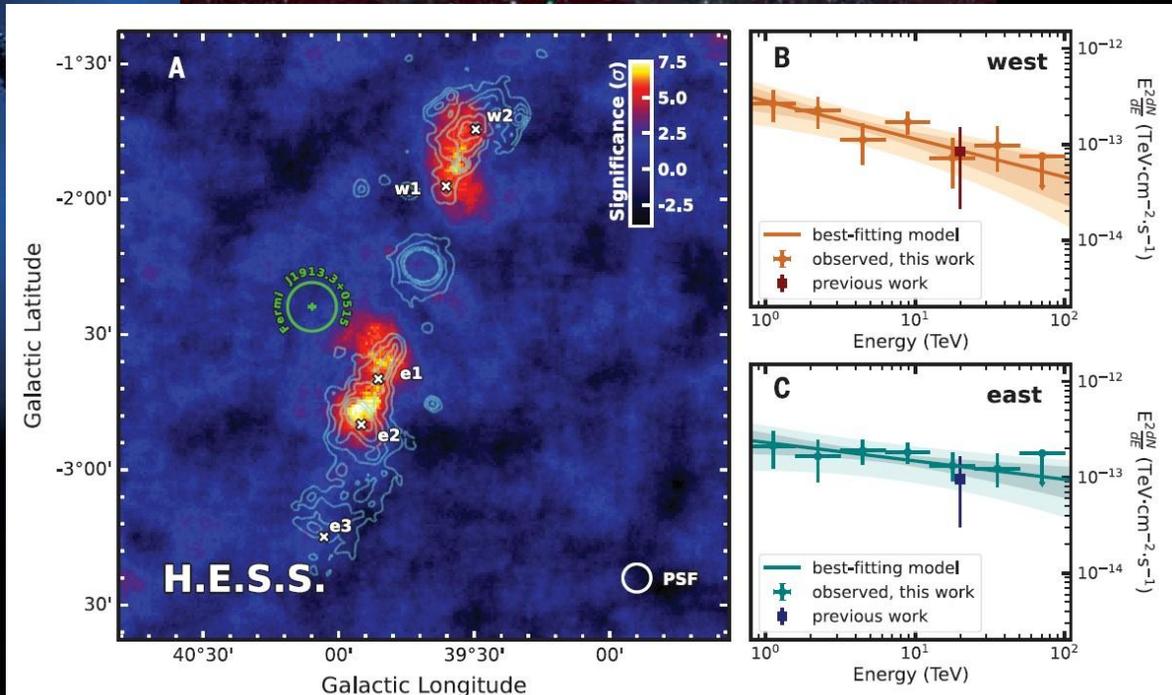
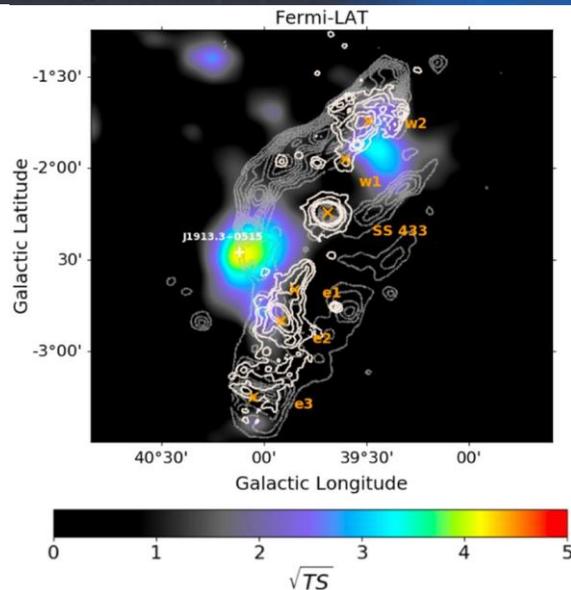
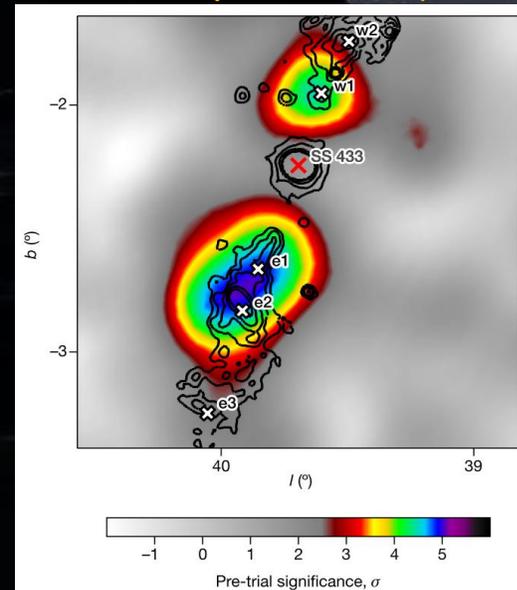
SS 433



HAWC (HAWC2018)

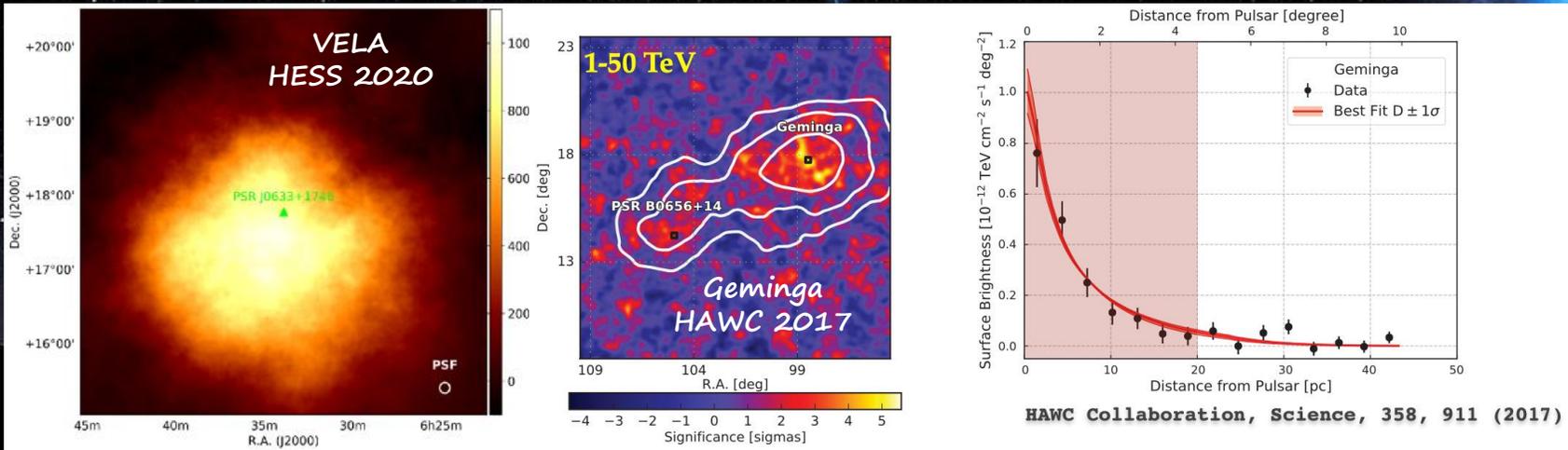
Fermi-LAT (Fang+2020)

HESS

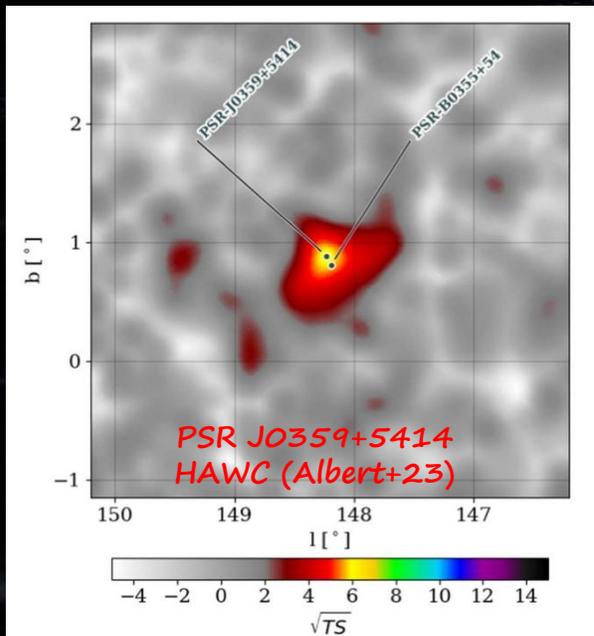


Olivera-Nieto Gamma2022
HESS24, Science
Bosh-Ramon CTA symp 24

And for the propagation: TeV HALOS



- 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



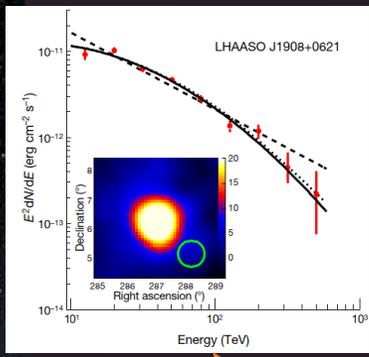
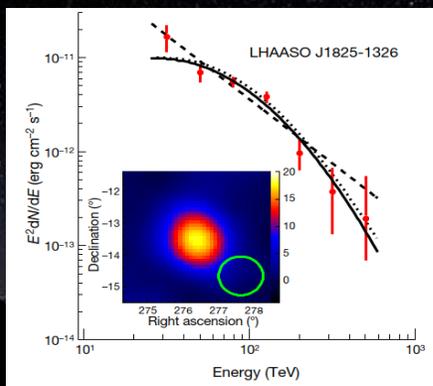
Propagation study



Pulsar Wind Nebulae

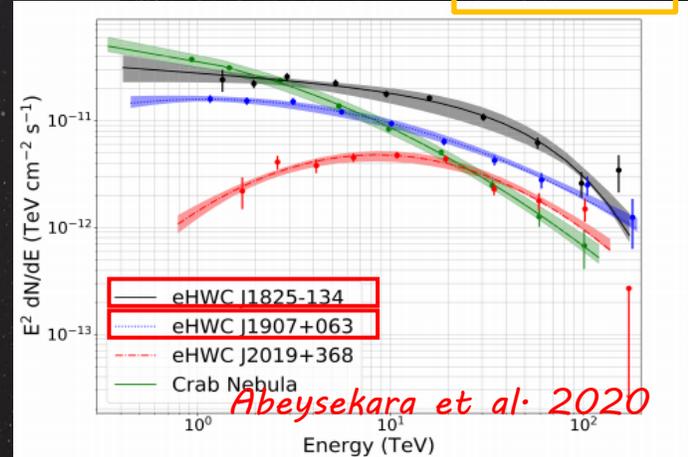
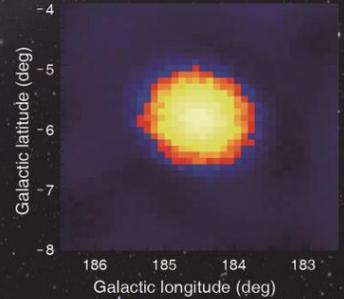
HAWC

Cao et al. 2021



The majority could be PWN!!! (statistics)

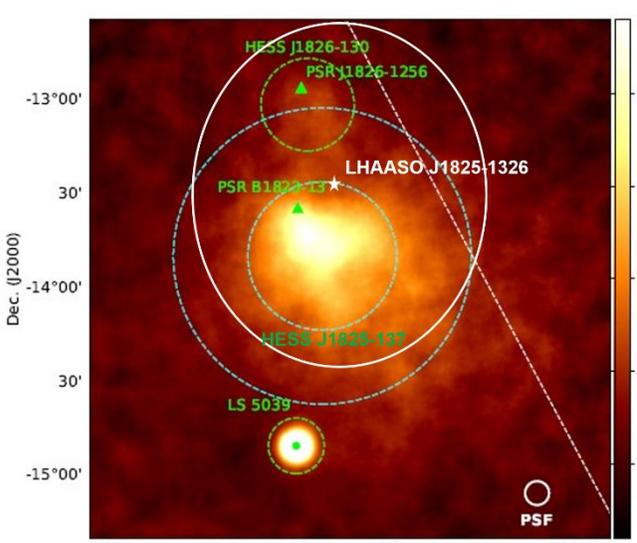
LHAASO J2226+6057



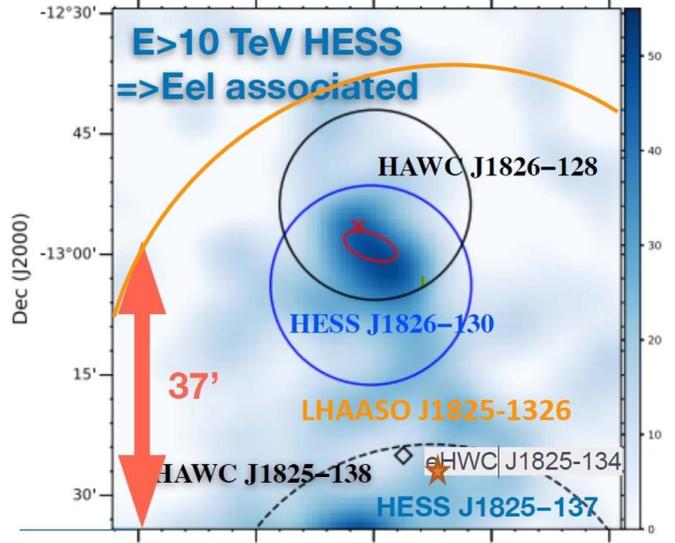
Abeysekara et al. 2020

LHAASO J1825-1326
PWN? SNR?
[MC&Giuliani 2023]

LHAASO J1908+621
PWN?SNR?
[MC&Giuliani 2023]

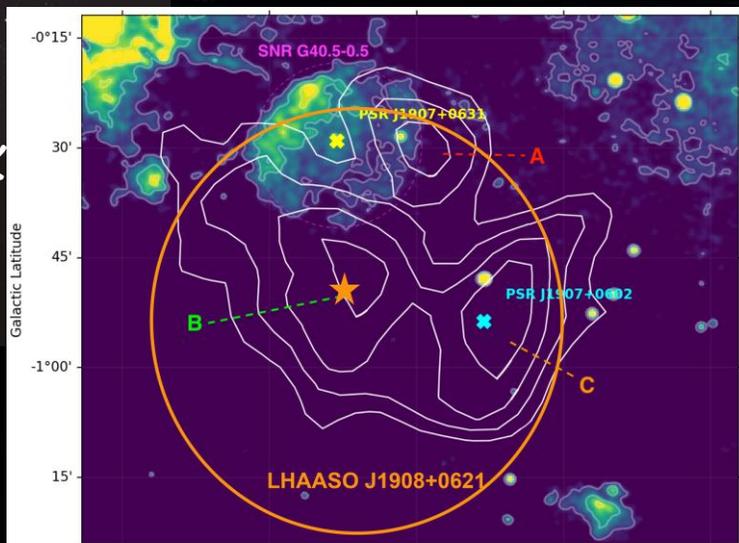


HESS coll. 2019



Burgess+ 2022

Very Complex Environment and low angular resolution



Crestani+ 2021

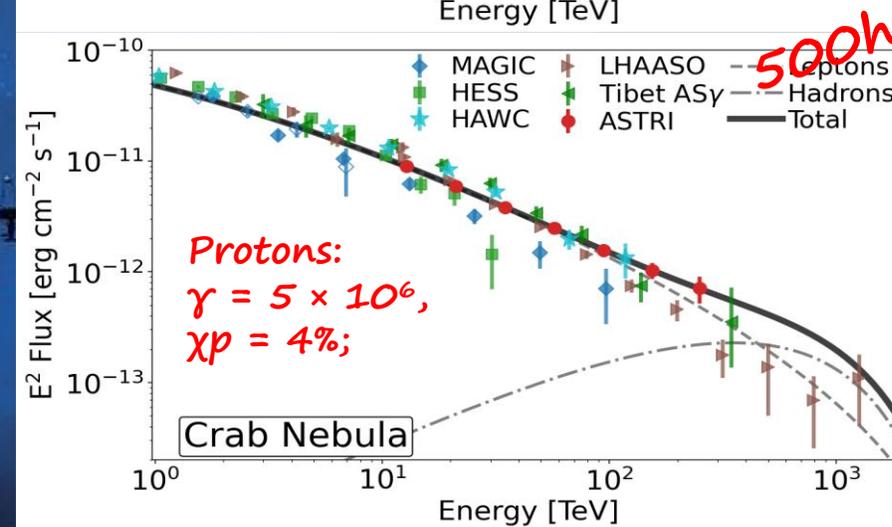
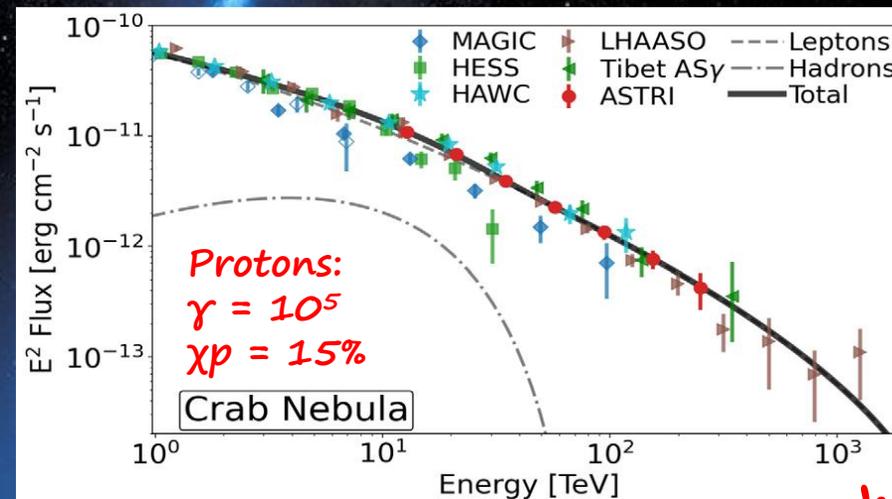
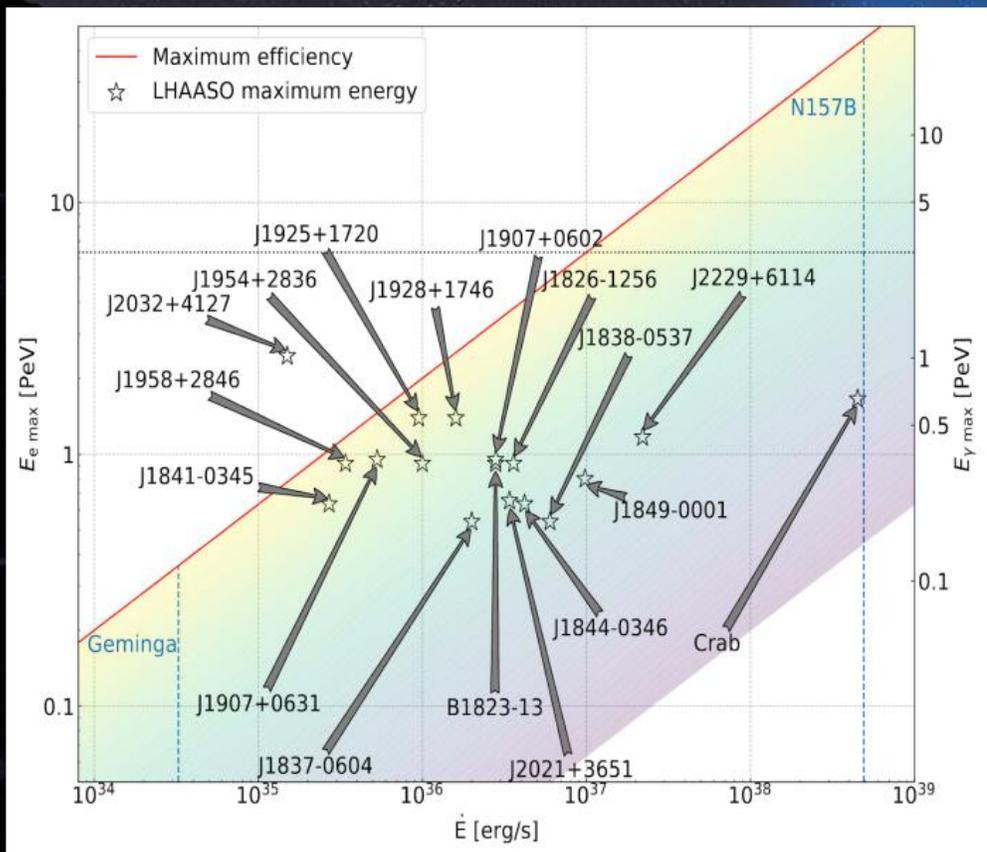
Pulsar Wind Nebulae

Vercellone+ 2022

Leptonic origin of gamma-rays > 100 TeV is possible!!!

→ IC on BKG photon field (no KN effect due to an increase of the cooling time in radiation dominated environments [low B]) [Breuhaus+ 2022]

Acceleration is limited by the maximum potential drop (not in the Crab)



If there are protons (hadrons):

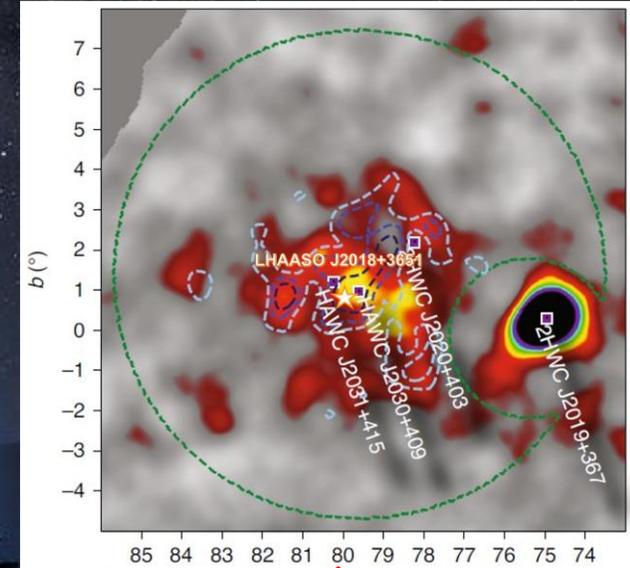
- ~few % of the total energy (Guepin+ (2020))
- pp emission may show up in the high energy tail of IC emission

DeOnaWilhelmi+ 2022

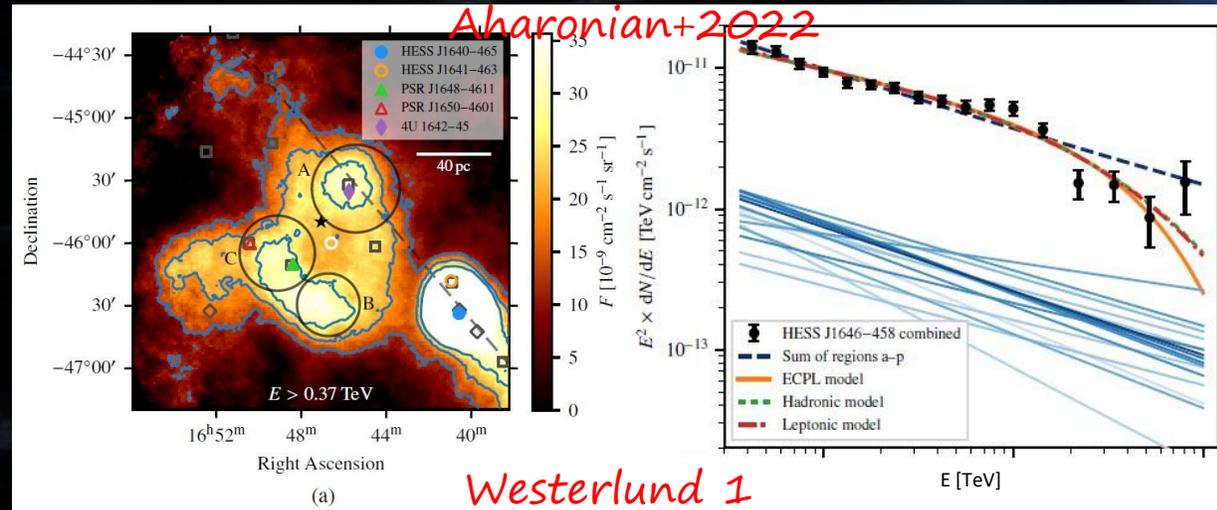
Young Massive Star Clusters (inside superbubbles)

- Clusters with age < few Myrs that can reach M up to 6×10^4 Solar masses
- Acceleration at 1 PeV possible at Wind Termination Shocks [Morlino 2021, Vieu et al. 2022]
- Collective effects in the most compact clusters (size of a few pc) can generate a collective outflows (right amount of power [Vink 2022])
- Several physical ingredients to a deep analysis (cluster population, stellar population inside, stellar wind, cluster wind, PA model, gas distribution) [Morlino CTAO general meeting]
- Recent estimations (based on the grammage) implies that YMCs can contribute only with a little percentage to the CR production otherwise we need a new understanding of the GCR transport [Blasi 2025]

Abeyssekara+ 2021 (HAWC coll)

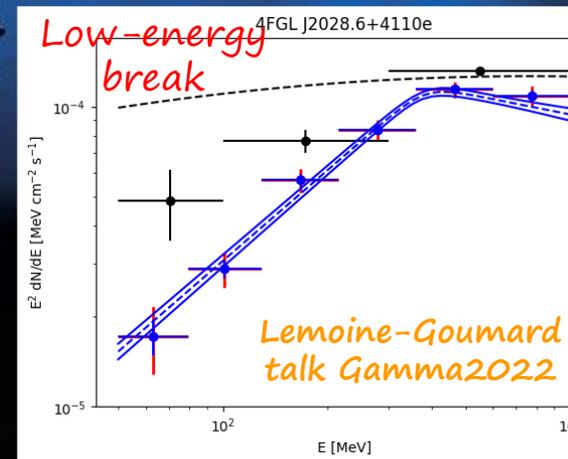


Cygnus Region



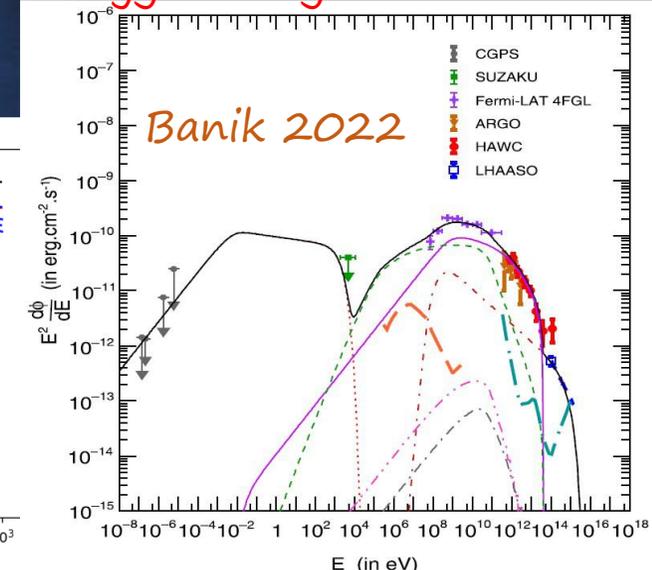
Aharonian+2022

Westerlund 1



Low-energy break

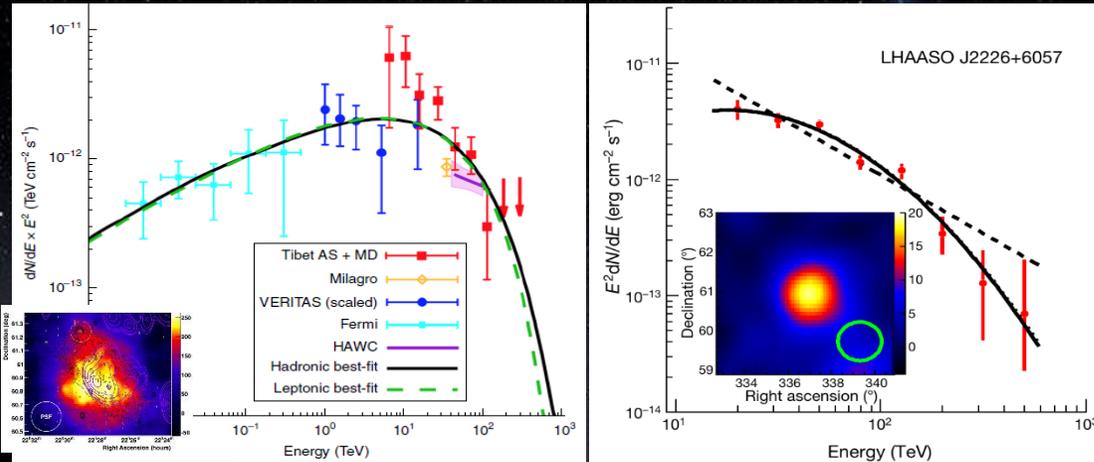
Lemoine-Goumard talk Gamma2022



Banik 2022

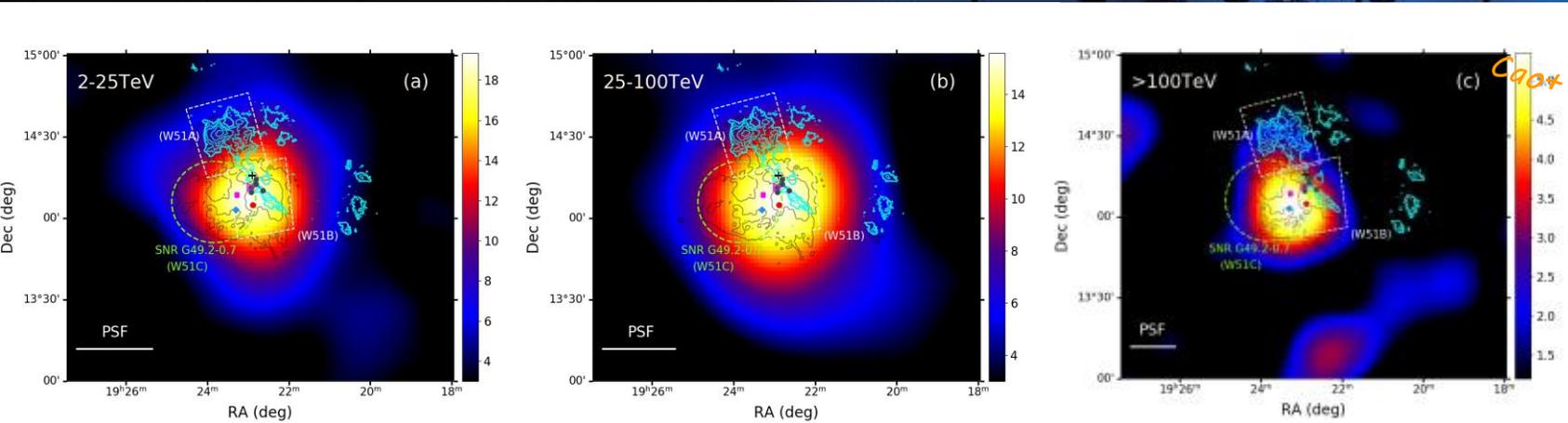
And finally... The Supernova Remnants

LHAASO J2226+6057 (direct interaction SNR/MC)

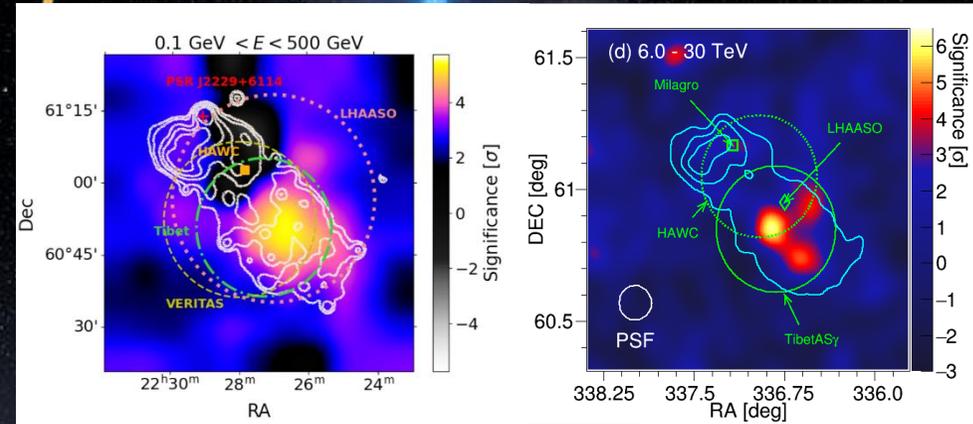


Tibet AS collaboration 2021 Cao+ (LHAASO coll) 2021

W51 REGION (illuminated MCs?)



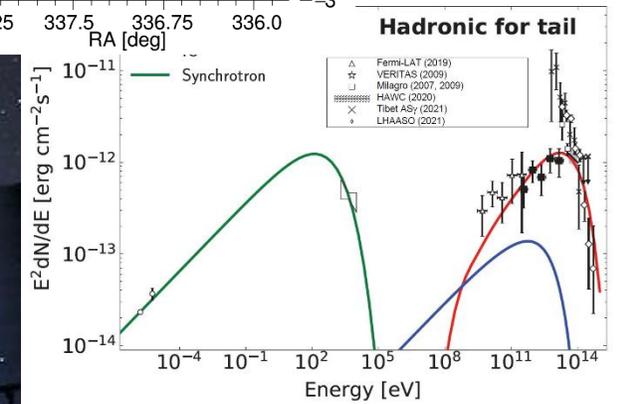
Likely, due to SNR/MC interaction or trapped CR emission [Mitchell&Celli24] → possible first case of SNR with "pion bump" and PeVatron emission



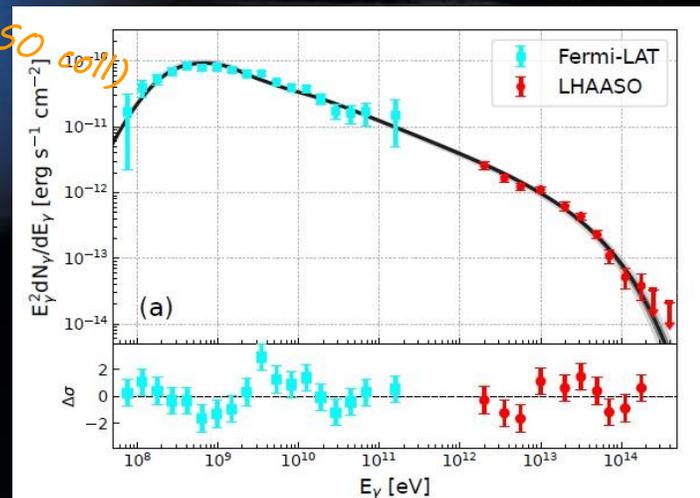
Fang+ 2022

MAGIC coll. 2023

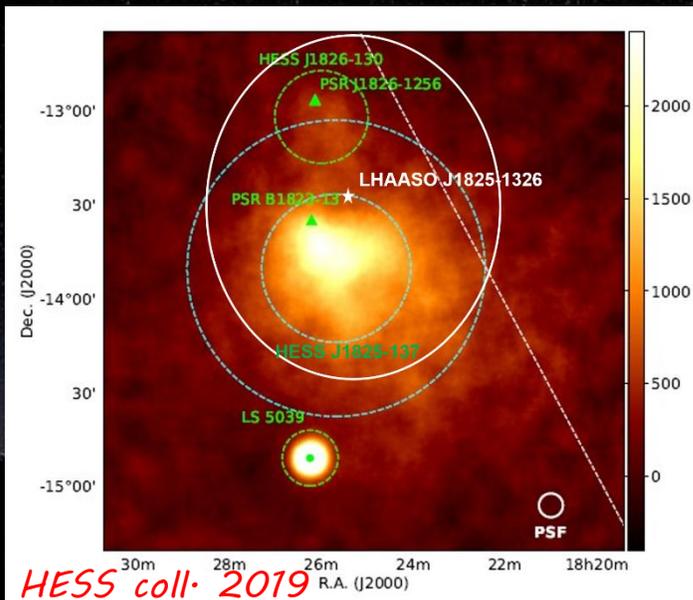
Fermi-LAT and MAGIC detection favoured hadrons from SNR/MC interaction



Cao+ (LHAASO coll) 2024



LHAASO J1825-1326



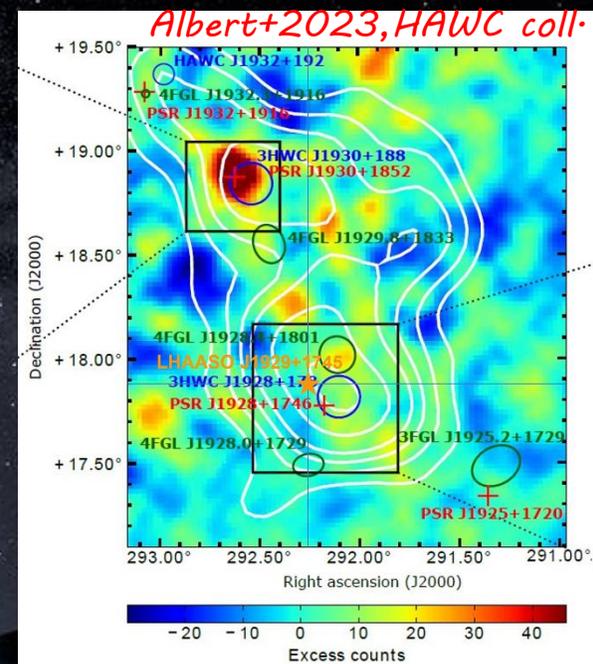
HESS coll. 2019

TeV HALOS

Several LHAASO sources could be TeV halos!

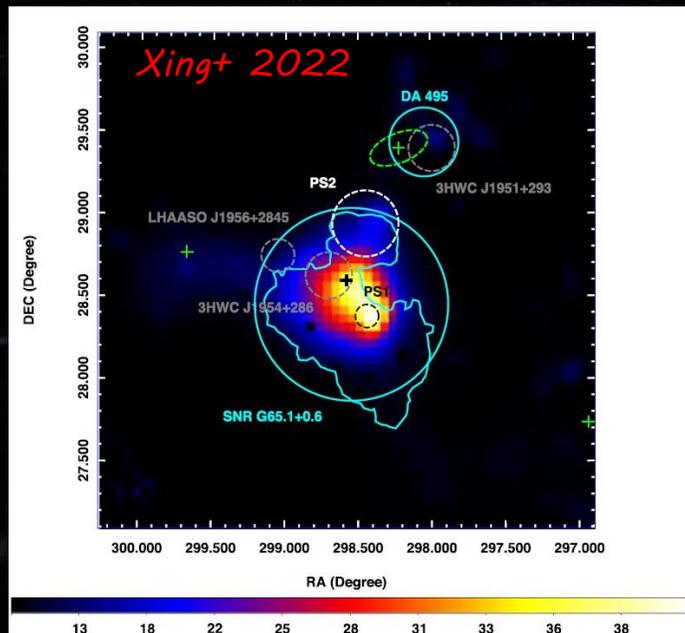
[MC&Giuliani 2023]

LHAASO J1929+1745



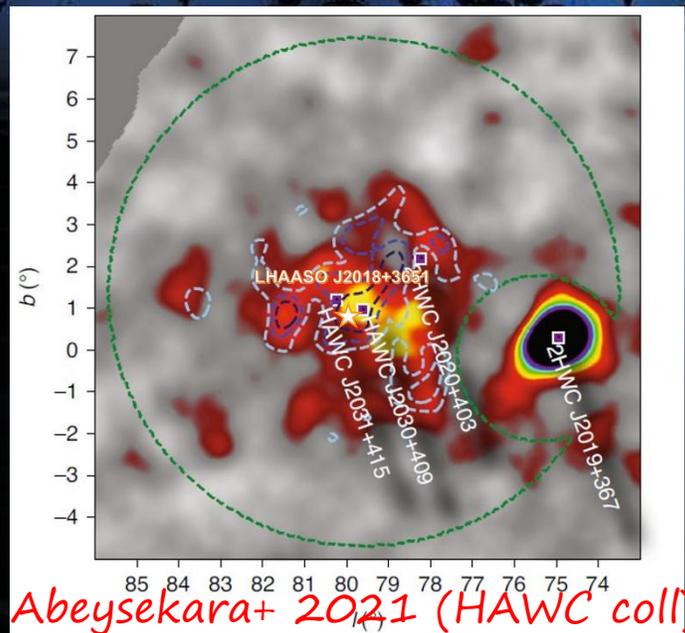
Albert+2023, HAWC coll.

LHAASO J1956+2845



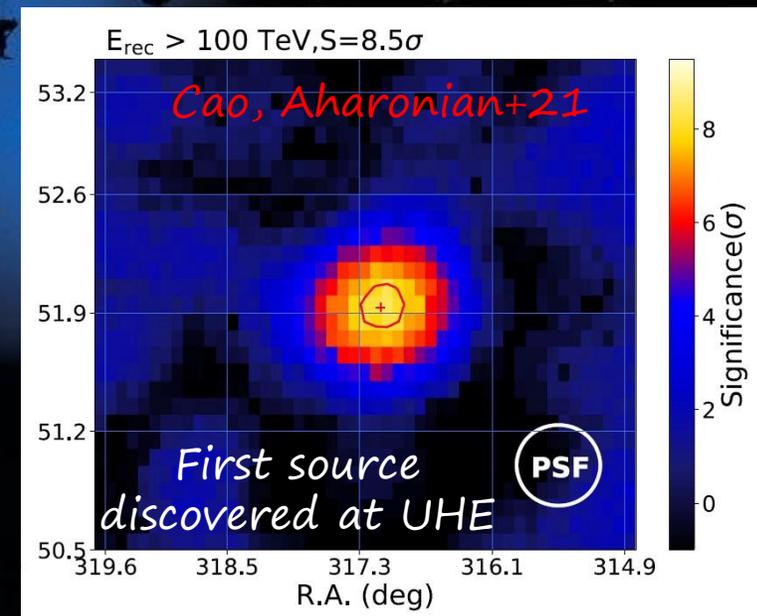
Xing+ 2022

LHAASO J2032+4102



Abeysekara+ 2021 (HAWC coll)

LHAASO J2108+3651



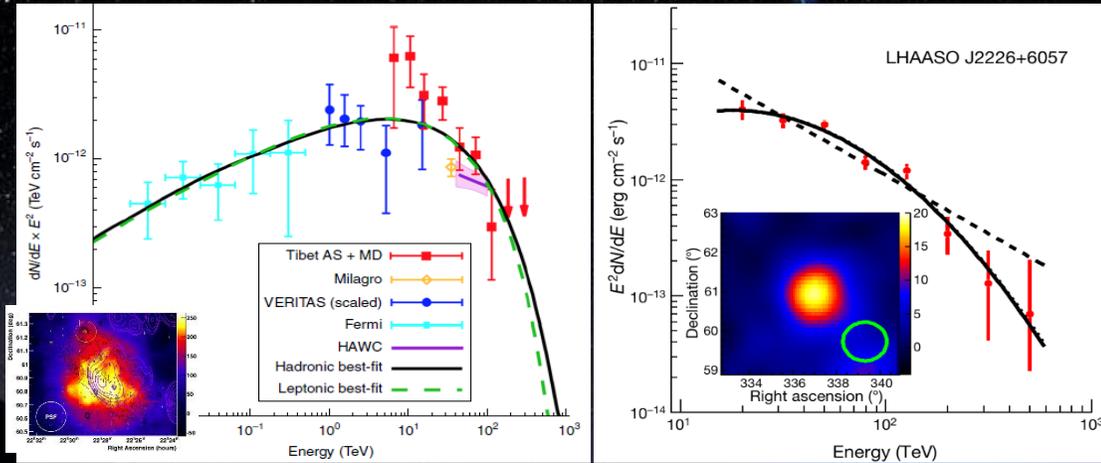
$E_{rec} > 100 \text{ TeV}, S=8.5\sigma$

Cao, Aharonian+21

First source discovered at UHE

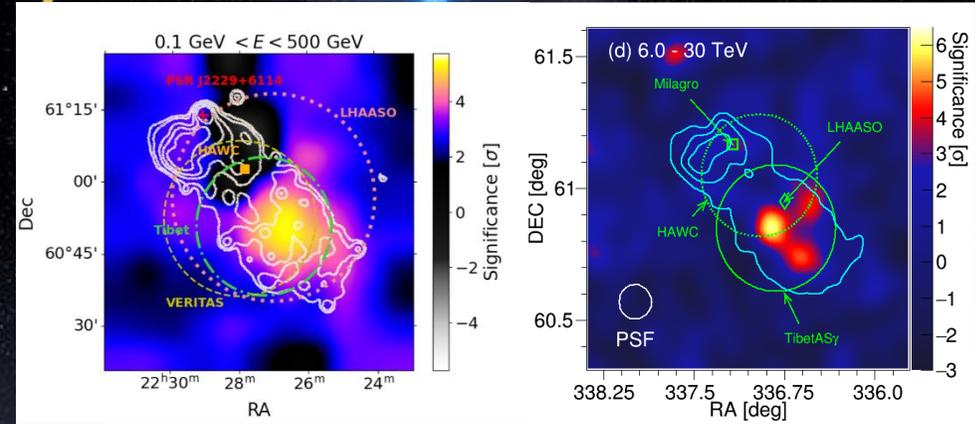
And finally... The Supernova Remnants

LHAASO J2226+6057



Tibet AS collaboration 2021

Caot (LHAASO coll) 2021



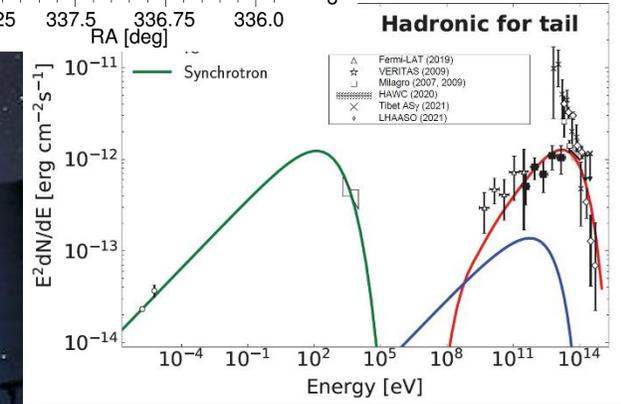
Fang+ 2022

MAGIC coll. 2023

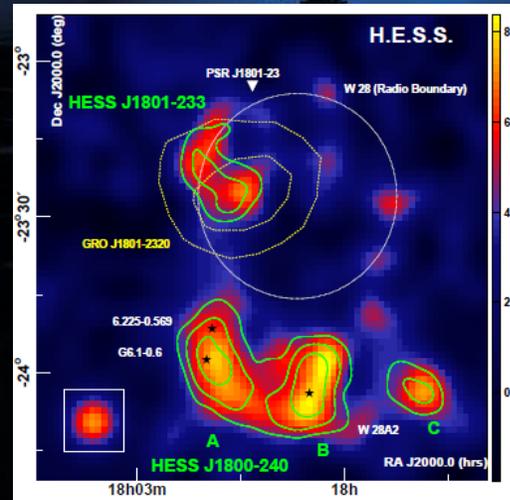
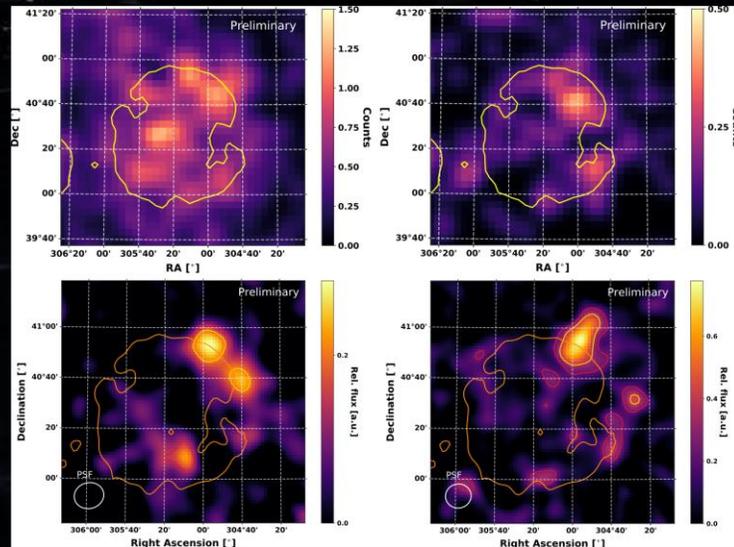
Propagation study



Fermi-LAT and MAGIC detection favoured hadrons from SNR/MC interaction

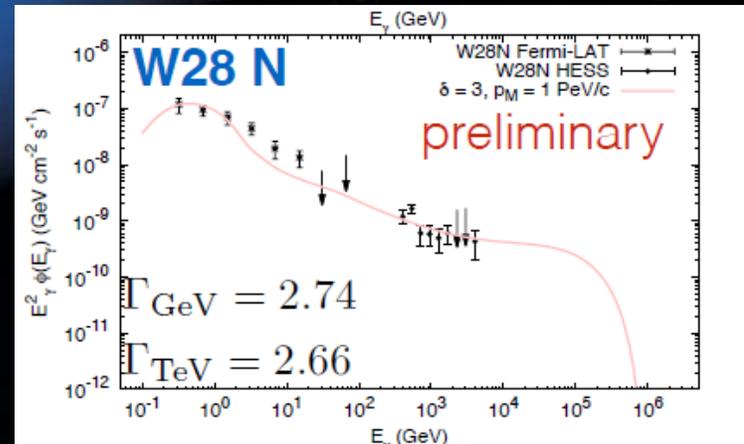


Gamma Cygni (MAGIC collaboration 2019)



W28 (Aharonian et al. 2008)

Celli Talk Gamma2022



Sources	Ra (°)	Dec (°)	σ >100 TeV	E _{max} (PeV)	Origin	Neutrino constraints	Favoured model
LHAASO J0341+5258	55.34	52.97	6 at 25 TeV	not defined	not identified	no	few information
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	Crab PWN	yes (Huang+22a,b, Abbasi+23)	Lepto-Hadronic (Nie+22, Vercellone+22)
LHAASO J00621+3755	95.47	37.92	3.1	not defined	TeV halo, PWN	no	challenging
LHAASO J1825-1326	276.45	-13.45	16.4	0.42 ± 0.16	TeV halo, PWN, SNR	yes (Huang+22a)	Leptonic (Burgess+22)
LHAASO J1839-0545	279.95	-5.75	7.7	0.21 ± 0.05	PWN, MSC	no	Hadronic (Banik+21)
LHAASO J1843-0338	280.75	-3.65	8.5	$0.26^{+0.16}_{-0.10}$	PWN, SNR	no	challenging
LHAASO J1849-0003	282.35	-0.05	10.4	0.35 ± 0.07	PWN, MSC	no	challenging
LHAASO J1908+621	287.05	6.35	17.2	0.44 ± 0.05	PWN, SNR	yes (Huang+22a)	Lepto-Hadronic (DeSarkar+22)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71^{+0.16}_{-0.07}$	PWN, TeV halo, SNR	no	challenging
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	PWN, TeV halo, SNR	no	challenging
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	PWN, YMC	no	Leptonic (Yang+23)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	YMSC, PWN, TeV halo	yes (Banik+22)	Hadronic (Banik+22)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	TeV halo	yes (Kar+22)	Hadronic (Kar+22)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	SNR, PWN	no	Hadronic (Fang+22, MAGIC23)

HIGHEST
ENERGY
SENSITIVITY

WIDE BAND
SENSITIVITY

GOOD
ANGULAR
RESOLUTION

NEUTRINOS

MC&Giuliani
2023

Very recent results (especially from ICRC 2023)

Yao TeVPa 2023,
LHAASO Highlight ICRC2023,
Lemoine-Goumard GA
highlights ICRC2023

- ✧ 12 PeVatrons studied with LHAASO-WCDA [Chuangdong ICRC23]
 - LHAASO J1908+621 shows a break in the spectrum
 - LHAASO J2032+4102 shows a possible Cut-Off

Importance to combine GeV-TeV energies

- ✧ First LHAASO catalog with a total of 43 candidate PeVatrons! (WCDA+KM2A) <https://arxiv.org/abs/2305.17030>

A lot of SNRs! (young but also middle aged)

- LHAASO J2002+3238 coincident with SNR G69.7+1.0 [Hou et al. ICRC23]
- LHAASO J1959+2850 coincident with PSR J1958+2845 and SNR G66.0-0.00 + associated MC [Yu et al. ICRC23]
- LHAASO J1740+1000: could be a bow-shock pulsar tail [Xu et al. ICRC23]
- LHAASO J1922+1403: W51c up to 300 TeV! [Chen et al ICRC2023]
- SNR G150.3+4.5: coincident with 4FGL J0426.5, could be a PWN or a SNR/MC [Zeng et al ICRC23]
- GAMMA CYGNI: KM2A detected PeV emission! [Feng et al. ICRC23]



- ✧ Further studies from the other instruments (see ICRC23 presentations) → the most analysed:

Importance of cross-correlation

- LHAASO J2108+5157 (VERITAS&HAWC [Kumar et al. ICRC23] and MC [Toledano-Juarez ICRC23])
- LHAASO J2226+6057 (HAWC [Son et al. ICRC23] and VERITAS [Park et al. ICRC23])
- LHAASO J1825-1326 (HAWC [Goksu talk])