TeVPa
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The LHAASO PeVatron bright sky: what we learned

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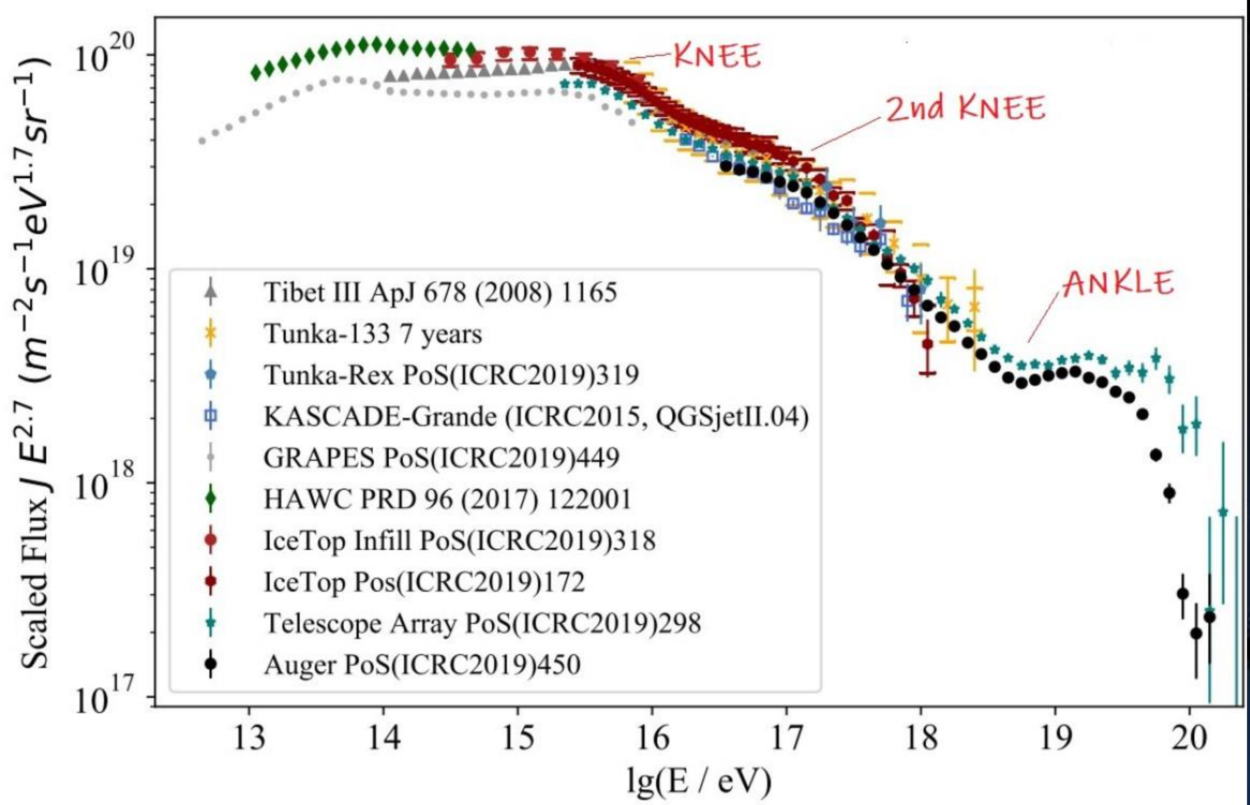
Cosmic Ray Overview

Schroder+19

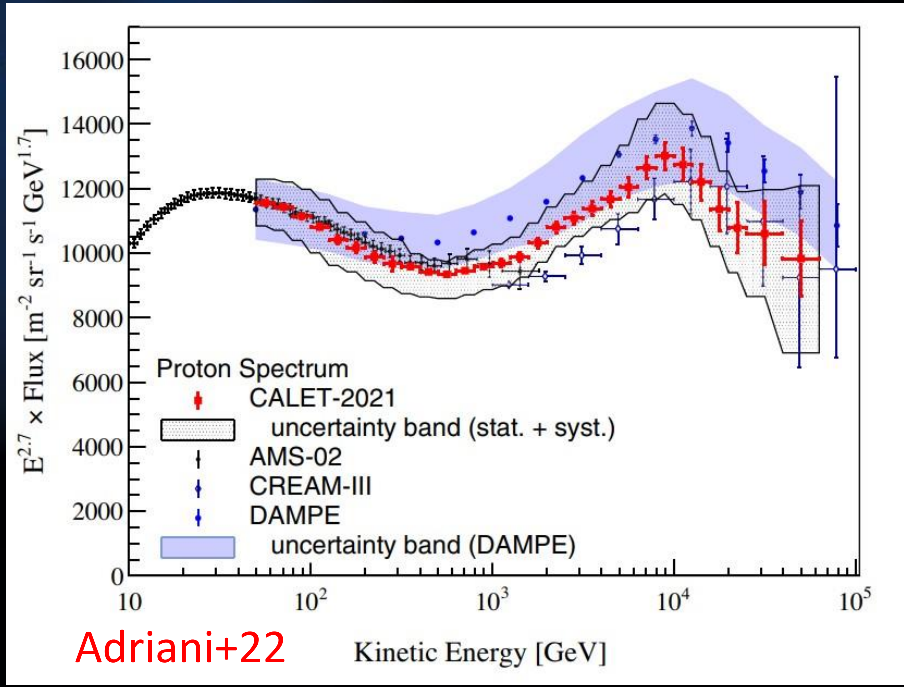


Between the knee and the second knee ($\sim 10^{17}$ eV) should be the transition from Galactic to extragalactic component.

Extra-Galactic component

- Limited information
- Extra-Galactic magnetic field
- Origin connected to transition region

But also the Galactic Component is not so bright and clear



Adriani+22

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

Galactic Cosmic Ray origin

GENOLINI talk

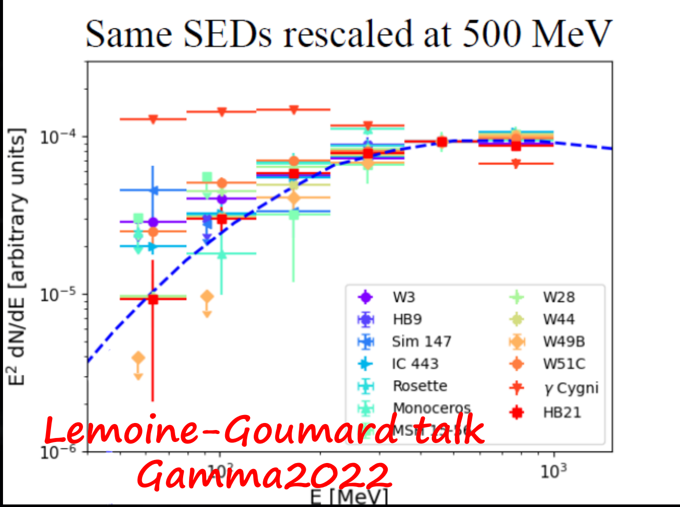
The main candidates: Supernova Remnants

- *ENERGY SUPPLY*: $L_{CR} = 10\% \, L_{SN}$
- *COLLISIONLESS SHOCKS*:
- energy dissipated via wave–particle interaction instead of particle–particle collisions.
- *STRONG SHOCKS AND DSA*: $\mathcal{R} = \frac{u_u}{u_D} = \frac{4M_s^2}{3+M_s^2}$ $M_s \to \infty \ , \mathcal{R} \to 4$
- *MAGNETIC FIELD AMPLIFICATION*

Direct evidences

Low-Energies

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



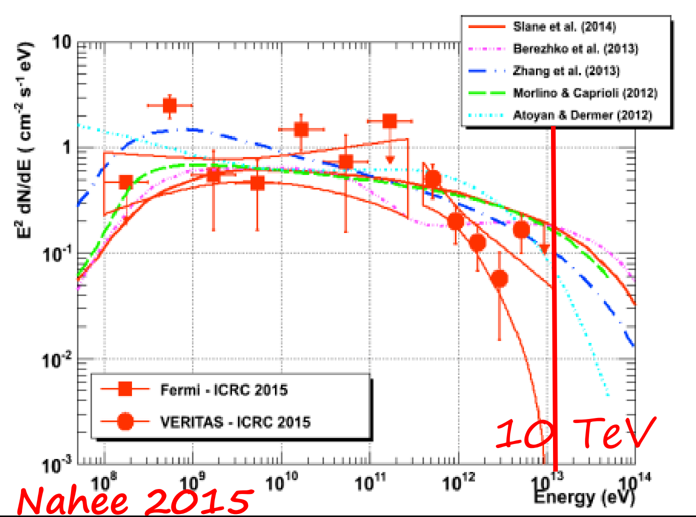
Lemoine-Goumard talk Gamma2022

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

High-Energies

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

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



Nahee 2015

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

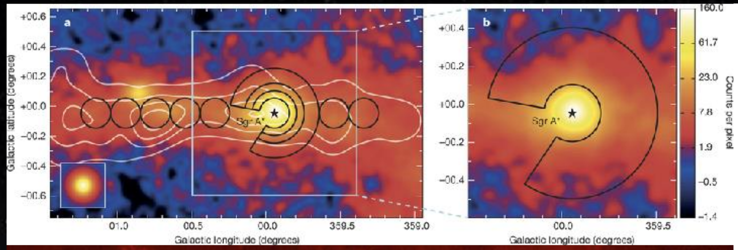
Receipt to be a CR source

MC&Giuliani 2023

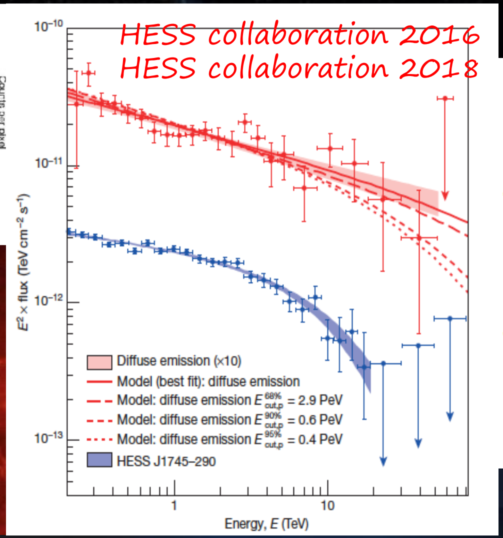
- Detected VHE-UHE Emission
- Spectral curvature
  - Signature of Emax, KN, spectral breaks
- Spatially-resolved emission
- Correlation with target material
  - Not perfect: i.e. emission is convolution of CR distribution with gas
- Energy-dependent morphology
  - Expected in general due to energy dependence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

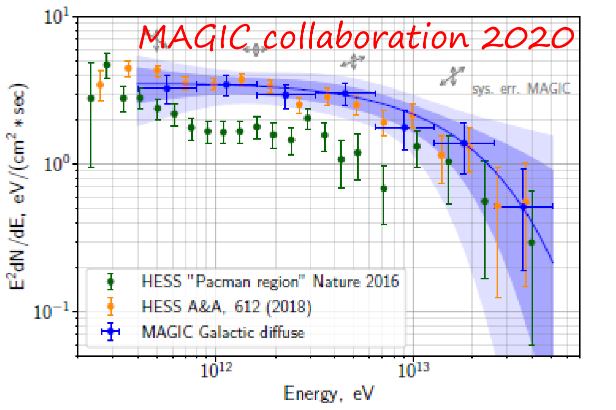
Other sources – Before LHAASO

Galactic Center Region



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





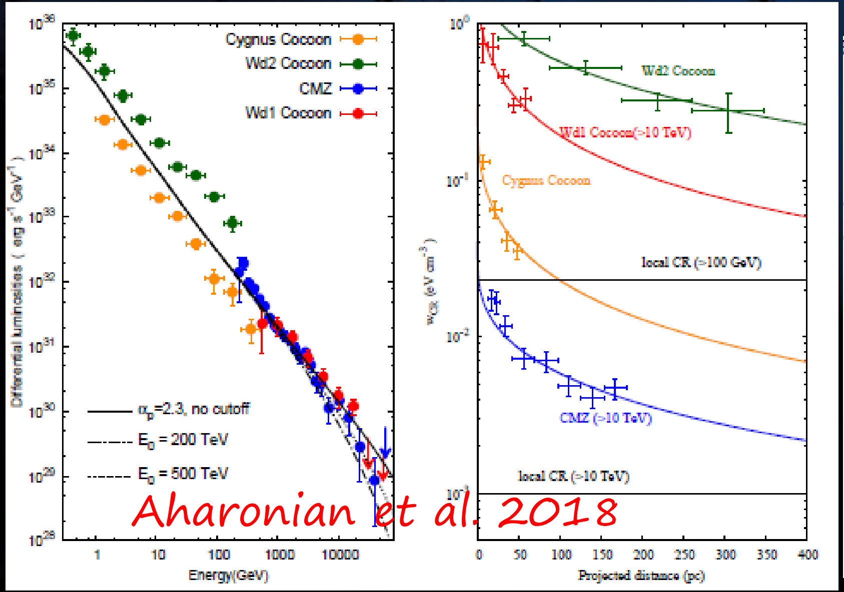
- Correlation molecular gas and gamma-ray
- CR energy density 10 CR sea
- CR spectrum → γ_E =2.3-2.4 up to 100 TeV (large error bars)
- Spatial distribution → 1/r
- First spectro-morphological analysis on-going (Devin talk Gamma 2022)

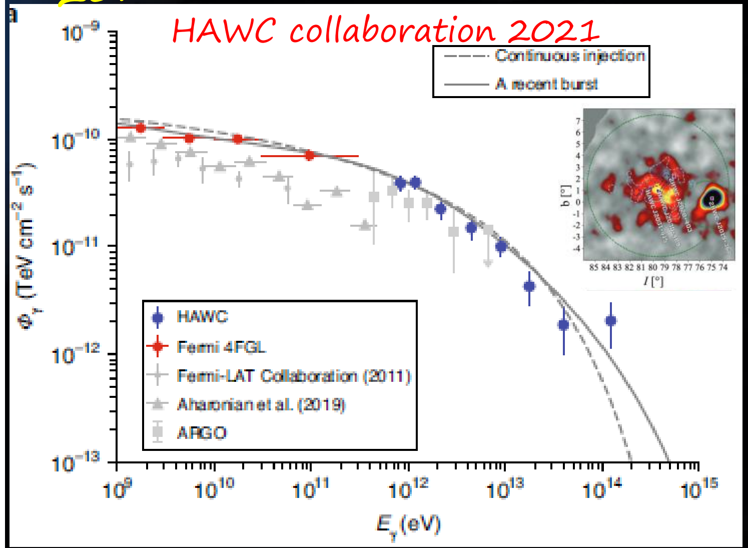
Superbubbles

Vieu thesis 2023

Hot and rarefied extended cavities (OB stars winds and SNRs [Bykov 1992]:

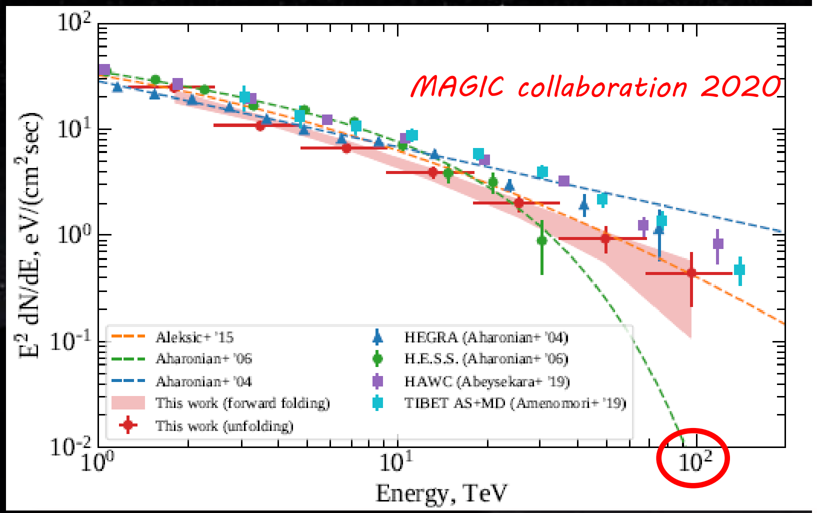
- Multiple shocks and winds
- No radiative phase
- Low-energy spectrum slope similar to the one measured by Voyager
- Explanation of some CR composition anomalies[Higdon+ 2003, Tatischeff 2018]
- Spatial and spectral behavior similar to the GC one [Aharonian 2018]

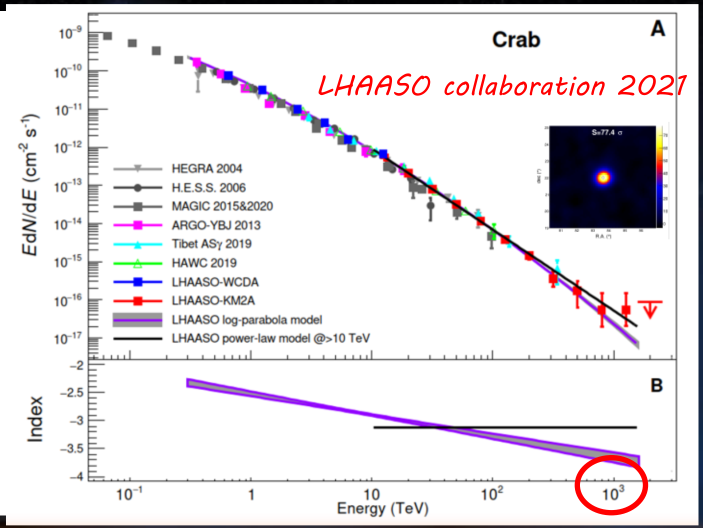




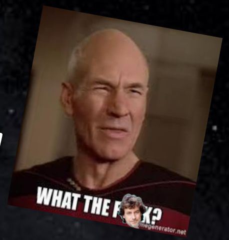
Other sources - Before LHAASO

Crab Nebula & the others





Detection above 1 PeV!!!



but...

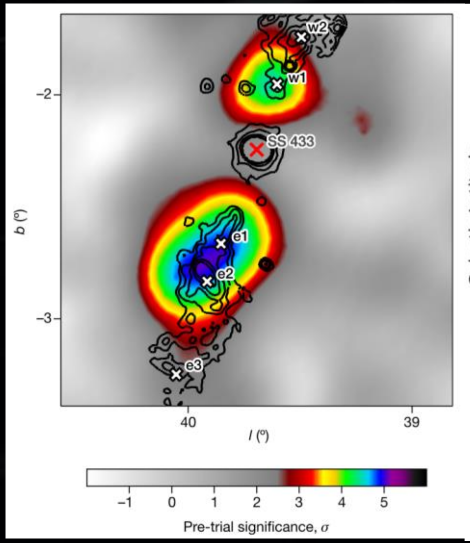
Crab is a PWN
(leptonic source)

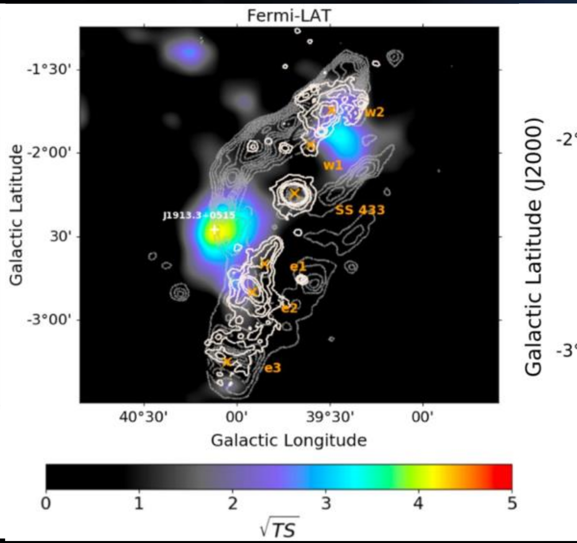
so...

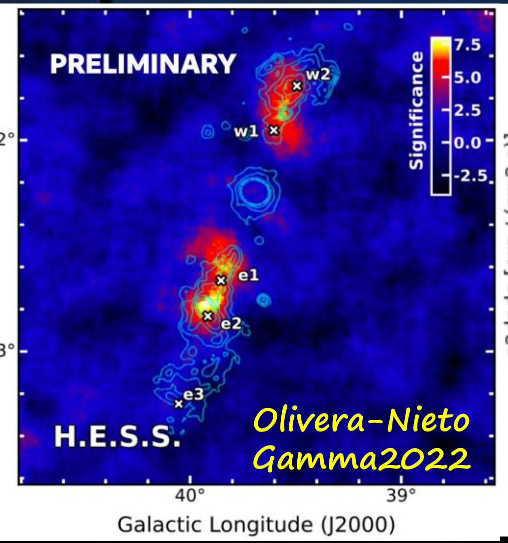
- Leptonic origin of gamma-rays possible!!
- There is a hadronic component?

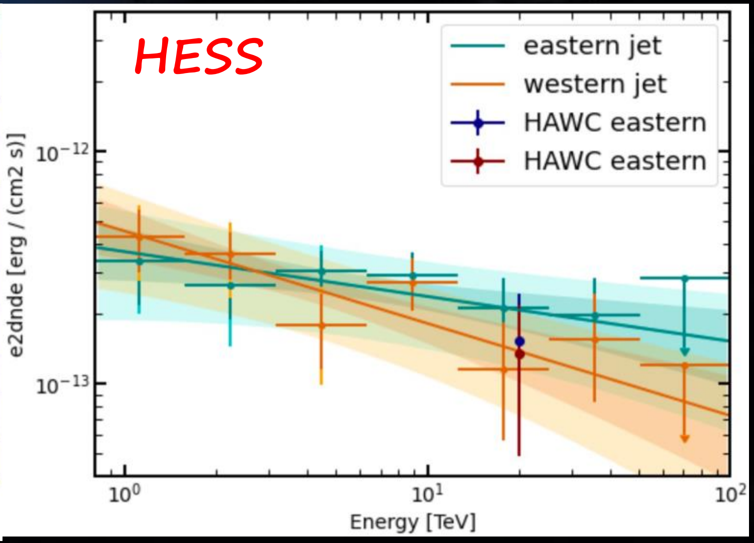
Binaries & Microquasars

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

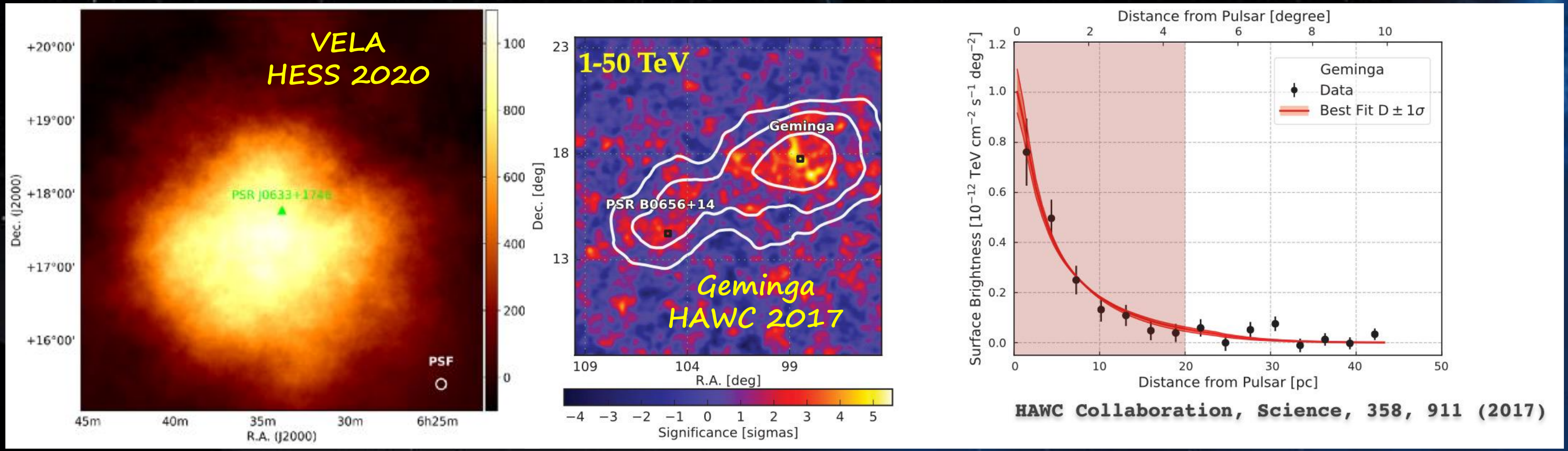








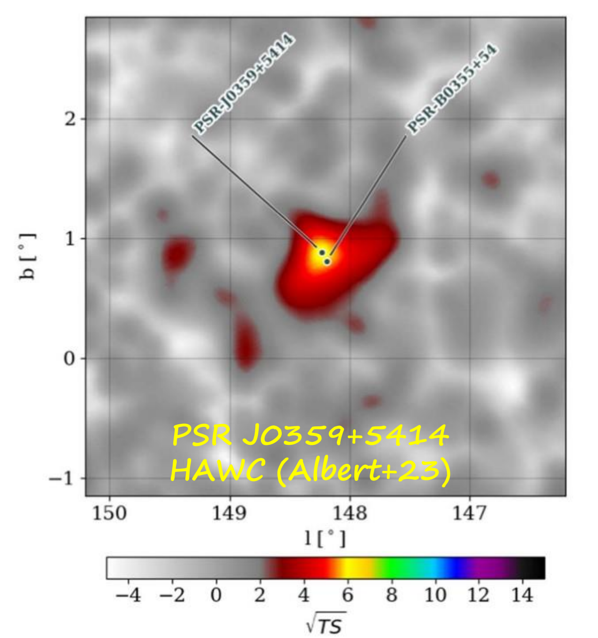
And for the propagation: TeV HALOS



- Both pulsar and extended emission evaded detection for a long time
- Escaping electrons and positrons (due to RS that disrupts PWN) form an extended halo of GeV and TeV gamma-rays

TeV Halos as new source class

Propagation study



- 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.

Pevatrons

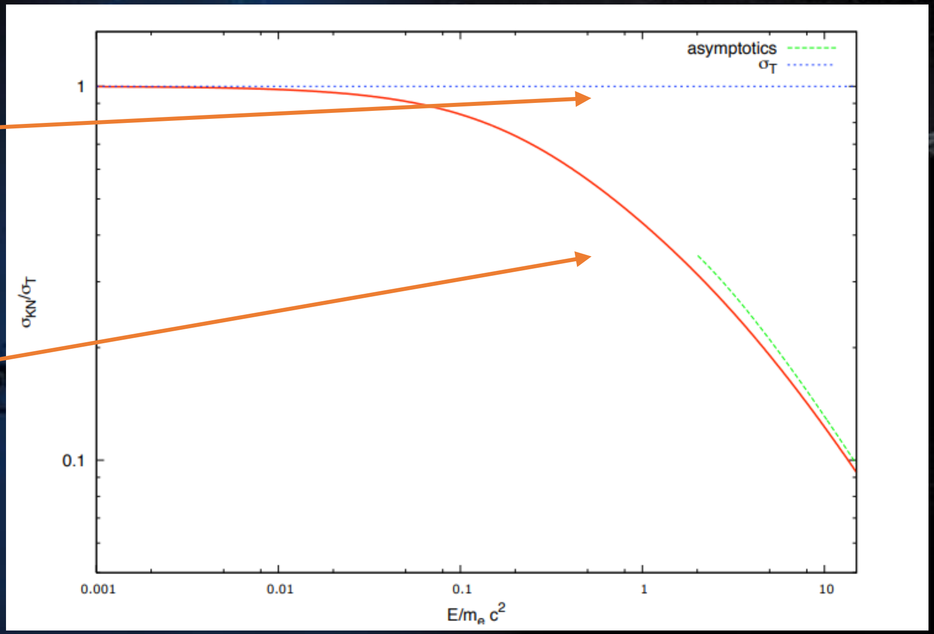
HIGH-ENERGY ASTROPHYSICS

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

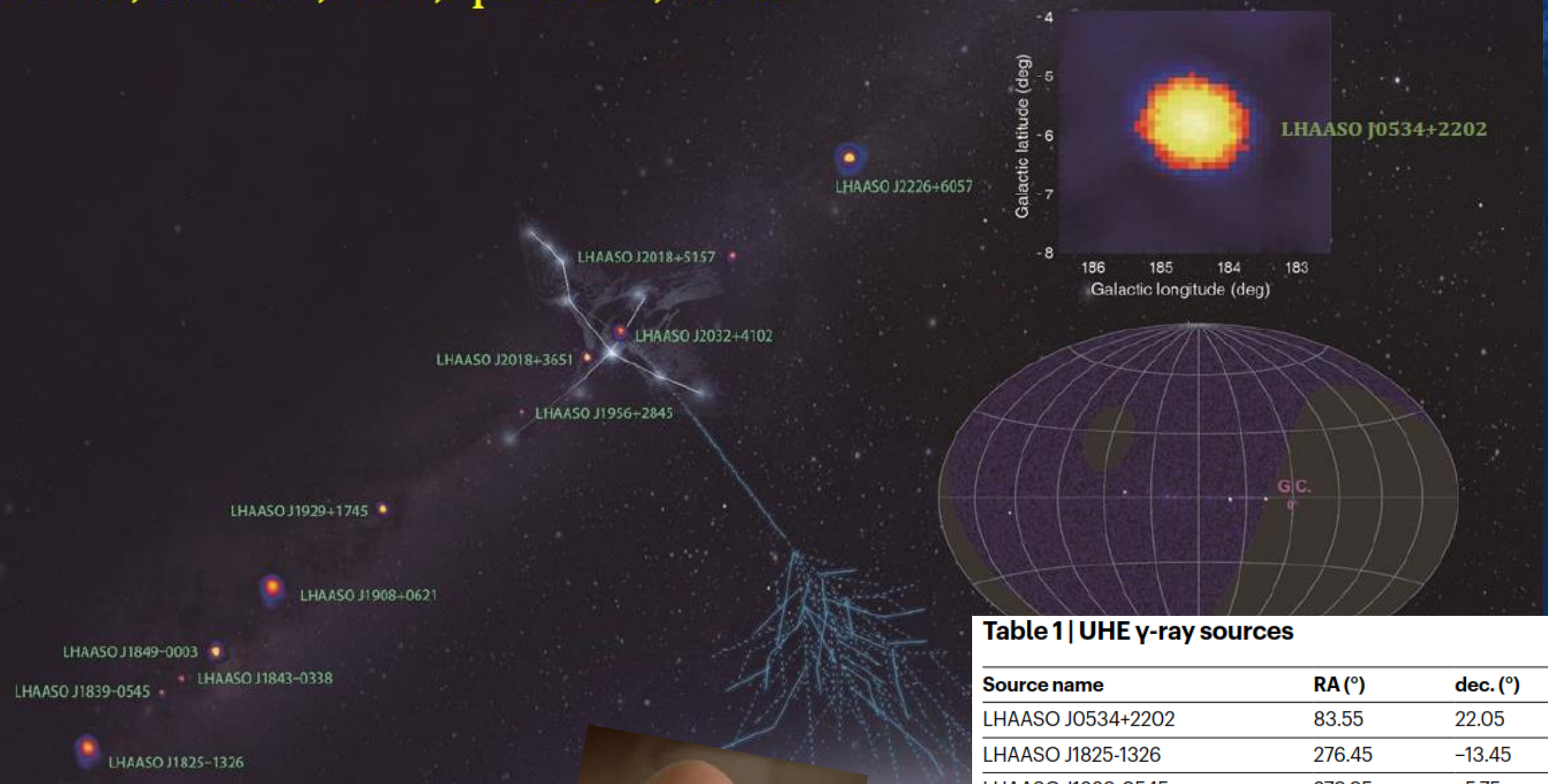
Ok…
We have some hints of emission around 100 TeV…
…but just one PeVatron (the Crab)…
And it could be a leptonic one…

…when suddenly…

"PeVatrons" storm from LHAASO

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

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



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

LEPTONIC
Or
HADRONIC?

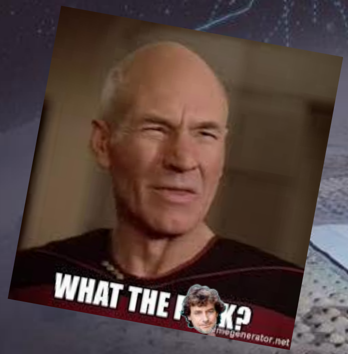


Table 1 | UHE γ-ray sources

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

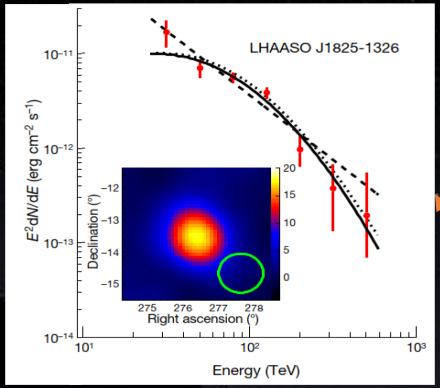
Extended Data Table 2 | List of energetic astrophysical objects possibly associated with each LHAASO source

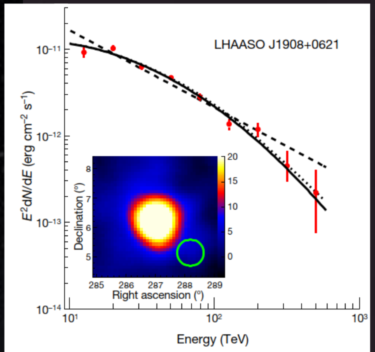
LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	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+0631	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	$6.3^{+0.8\ d}_{-0.7}$	$1.8 - 3.3^k$	—	
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	$1.8^{+1.7\ l}_{-1.4}$	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}	

Pulsar Wind Nebulae

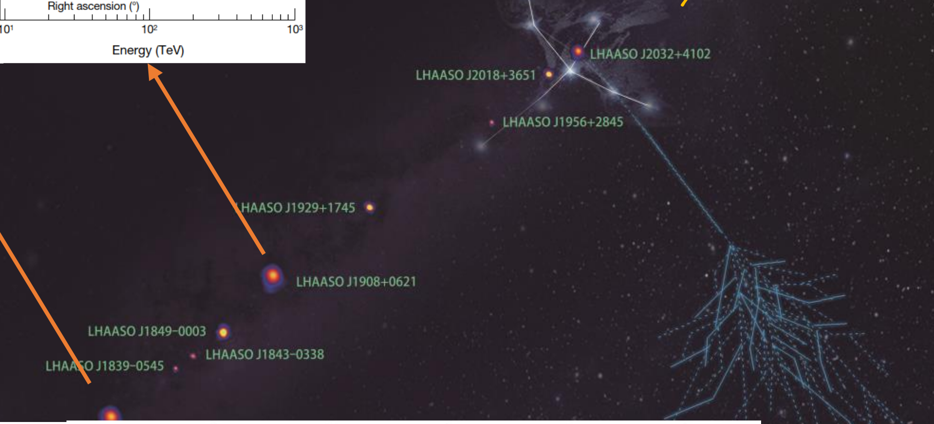
HAWC

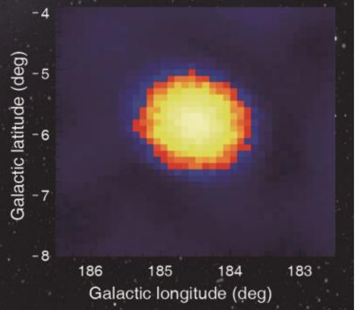
Cao et al. 2021

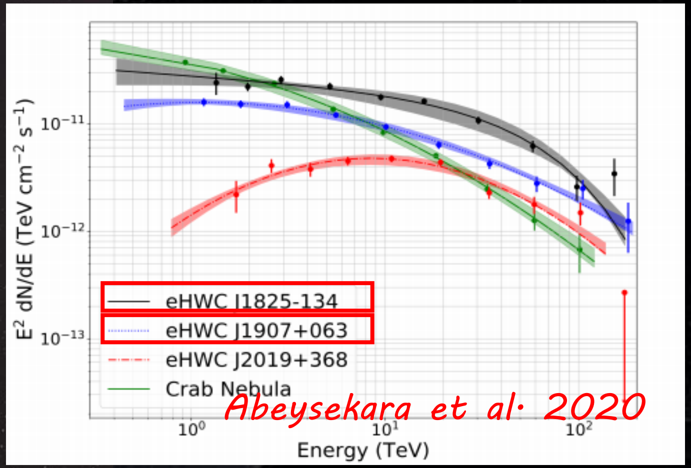




The majority could be PWN!!! (statistics: more numerous and long last)



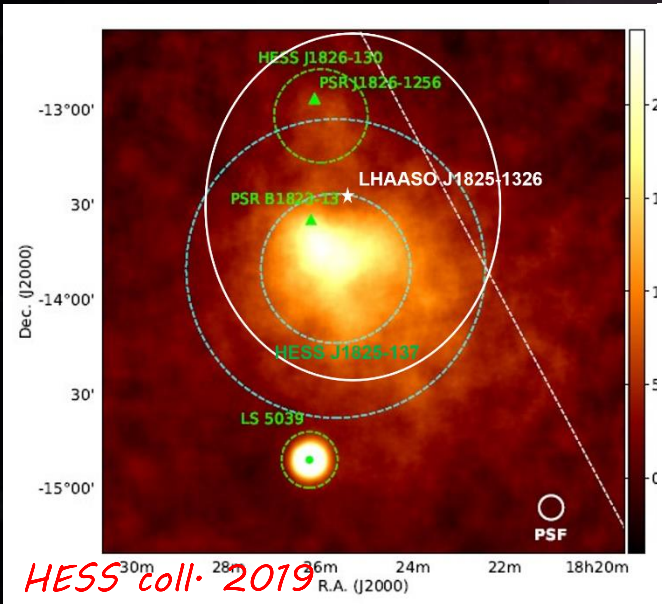




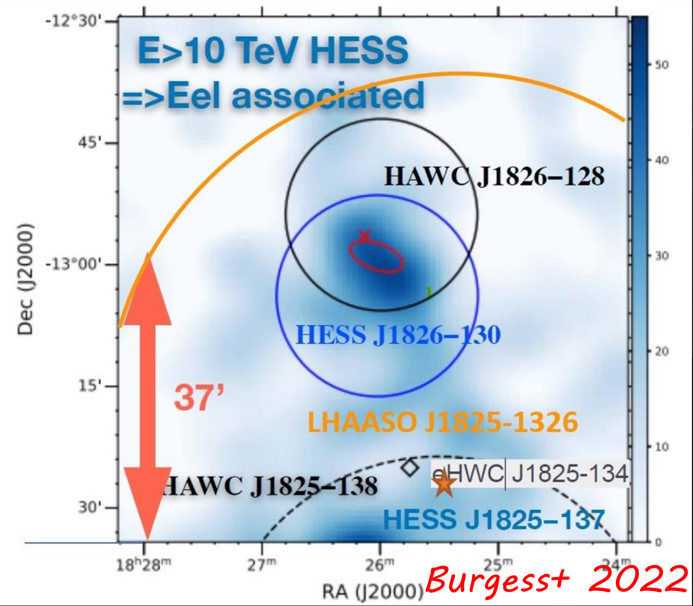
Abeysekara et al. 2020

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

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

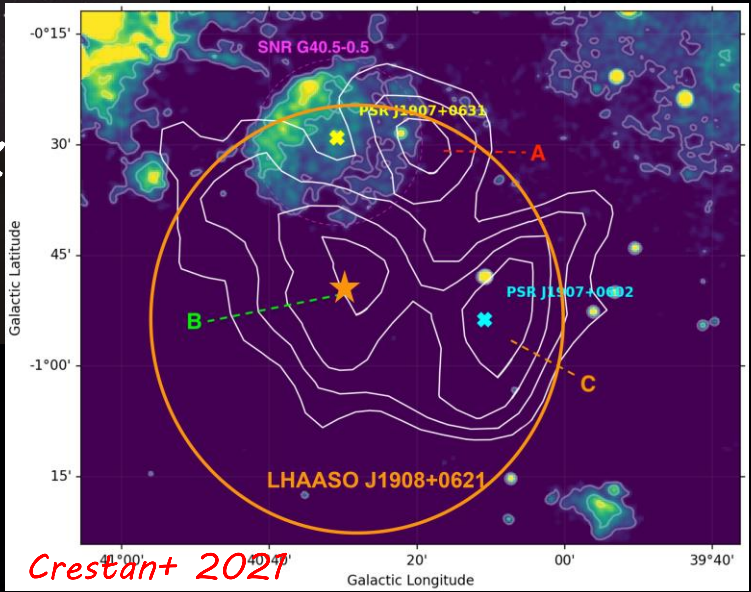


HESS coll. 2019



Burgess+ 2022

Very Complex Environment and low angular resolution



Crestan+ 2021

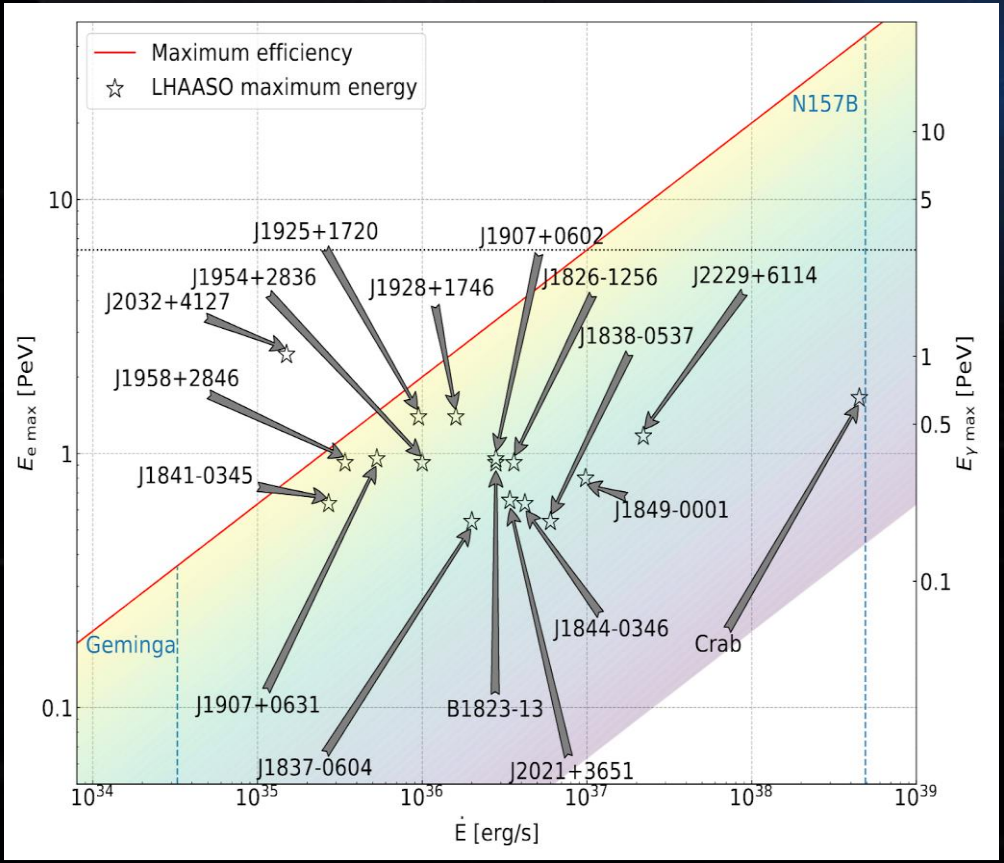
Pulsar Wind Nebulae

Vercellone+ 2022

Leptonic origin of gamma-rays > 100 TeV is possible

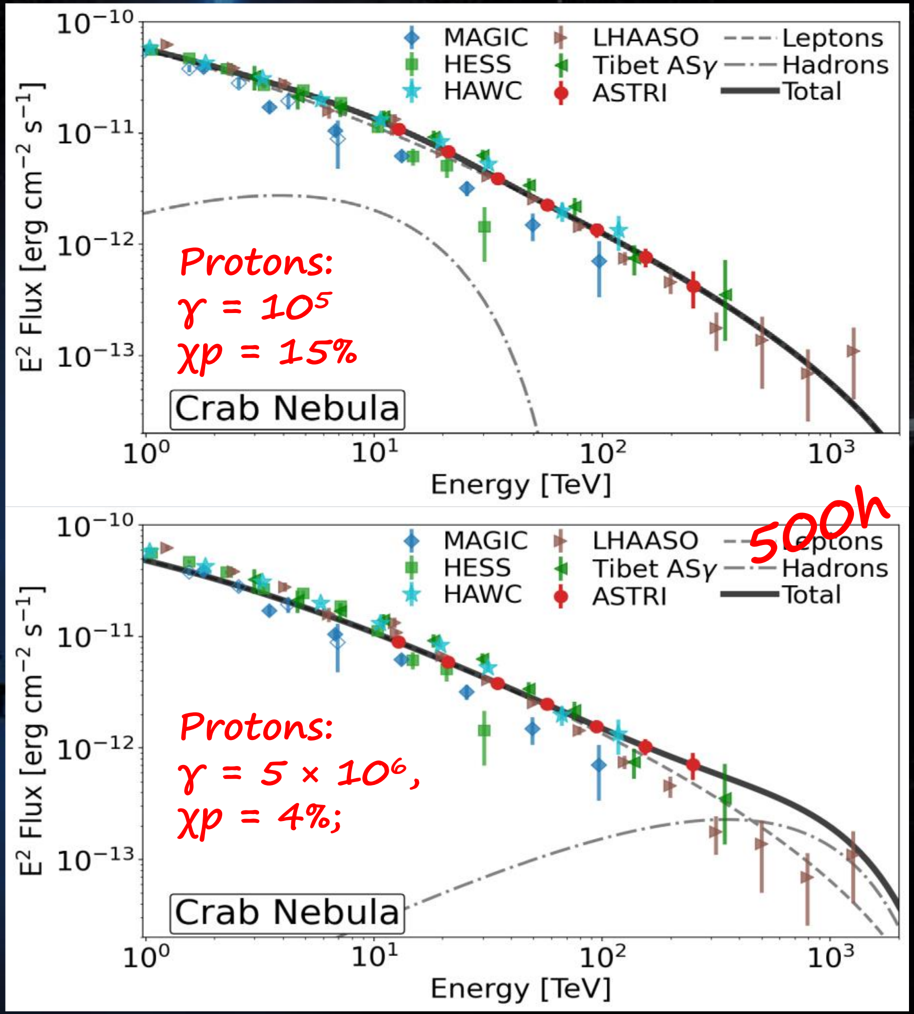
→ IC on BKG photon field (no KN effect due to an increase of the cooling time in radiation dominated environments [low B]) [Breuhaus+ 2022]

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



CARIBELLA talk
MOHRMANN talk
GOKSU talk

DeOnaWilhelmi+ 2022



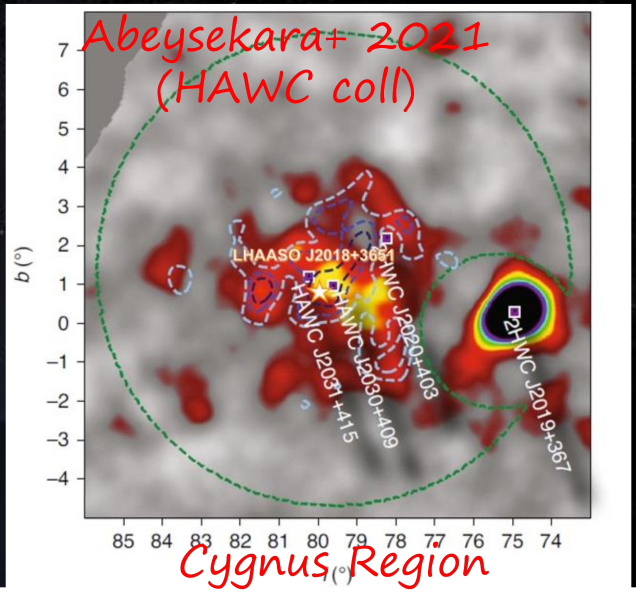
If there are protons (hadrons):

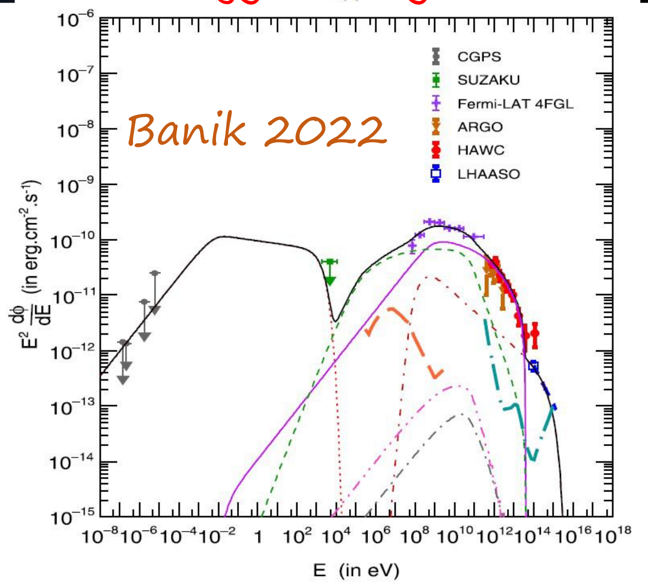
- ~few % of the total energy (Guepin+ (2020))
- pp emission may show up in the high energy tale of IC emission

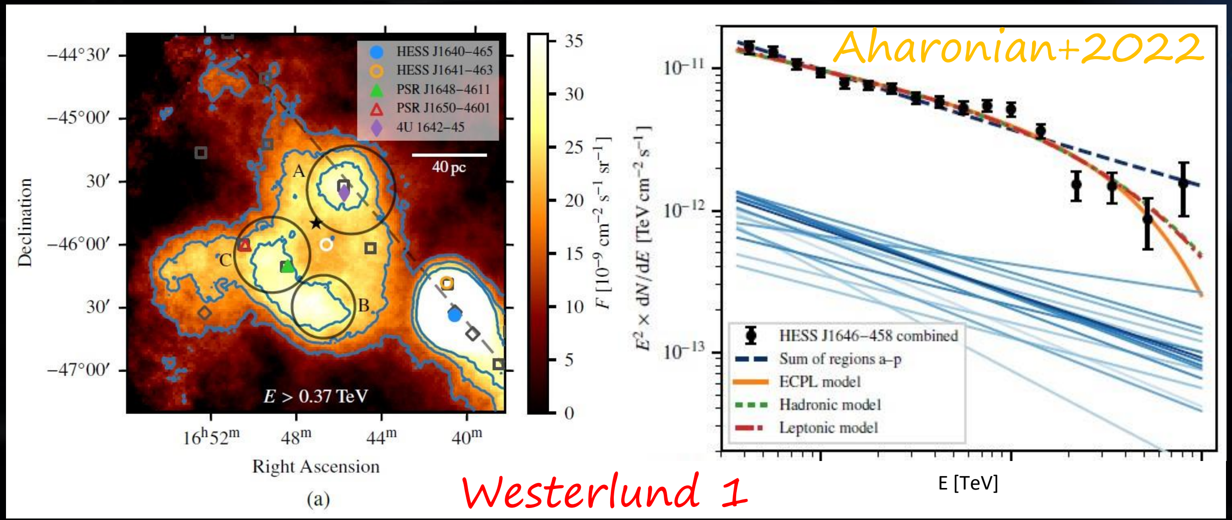
Young Massive Star Clusters (inside superbubbles)

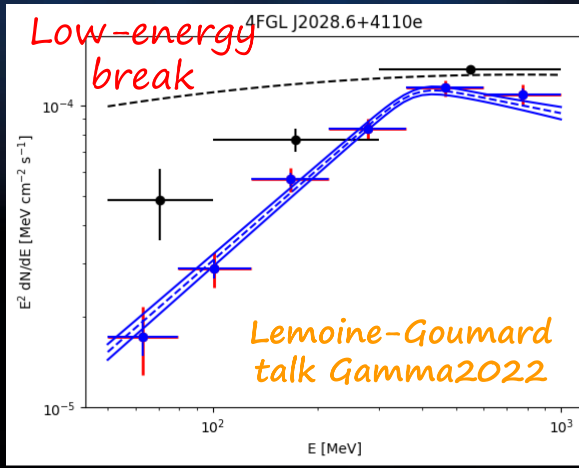
MOHRMANN talk
MENCHIARI talk

- 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 ourflows (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]









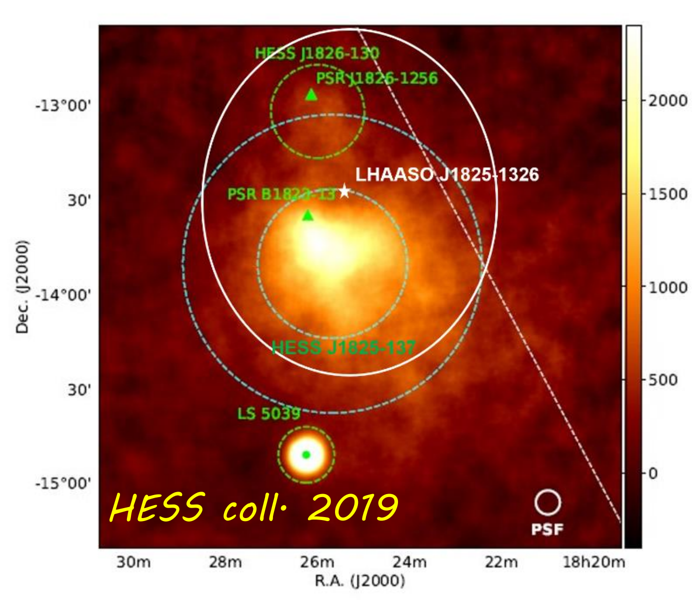
TeV HALOS

Several LHAASO sources could be TeV halos!

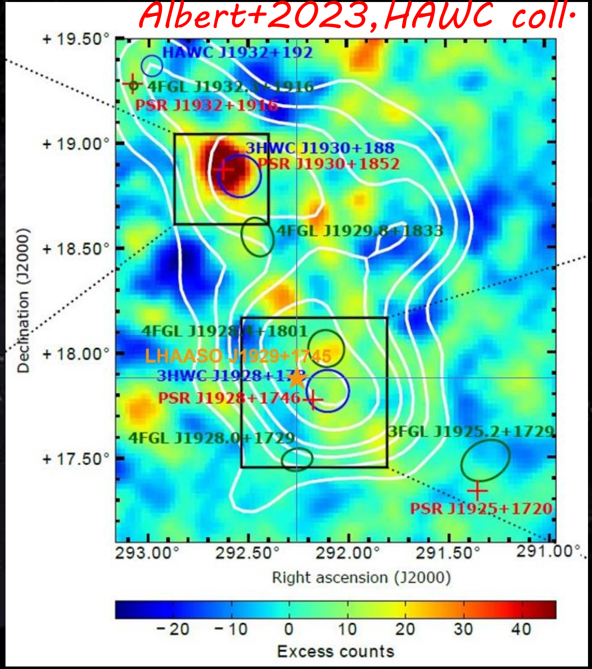
[MC&Giuliani 2023]

PINETTI talk
LINDEN talk

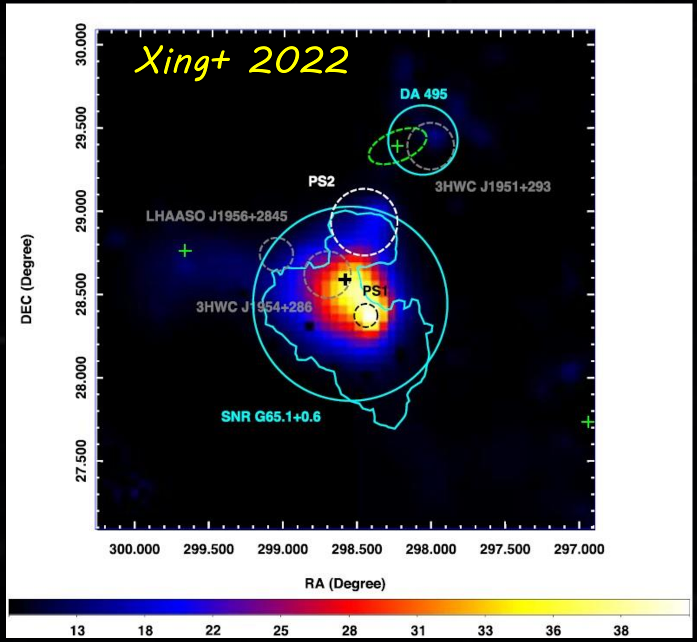
LHAASO J1825-1326



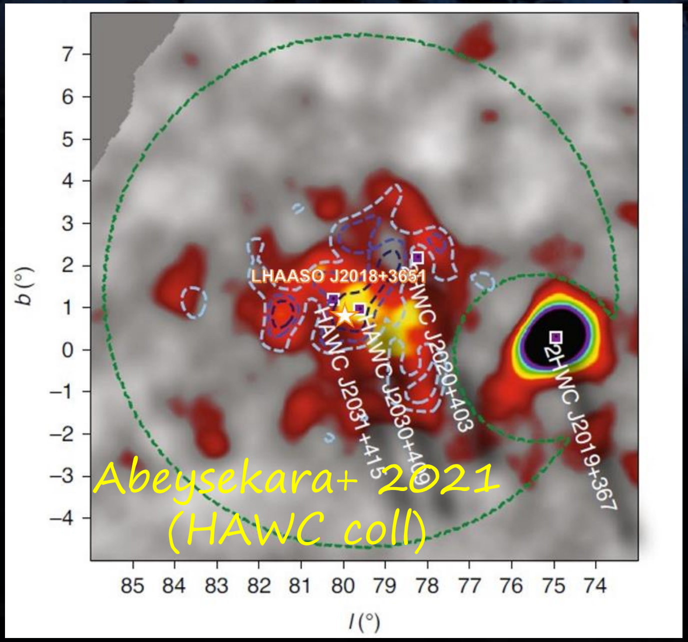
LHAASO J1929+1745



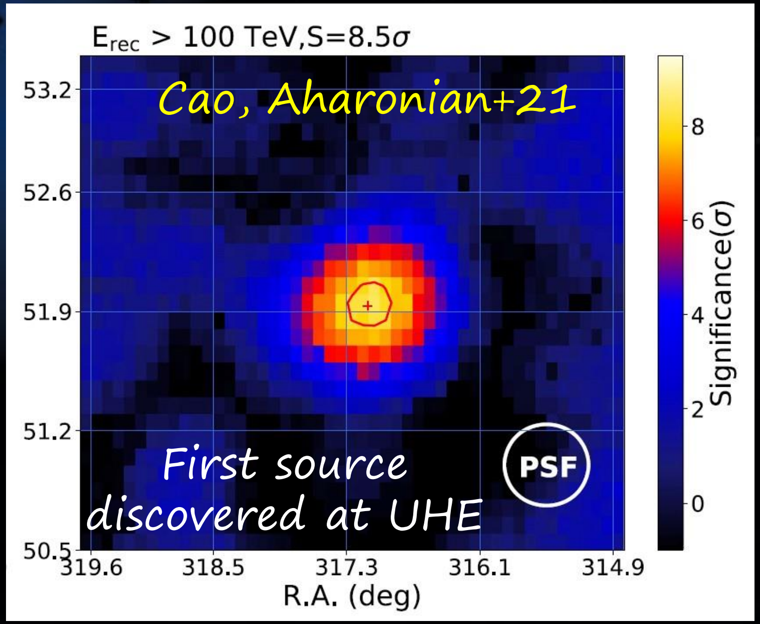
LHAASO J1956+2845



LHAASO J2032+4102



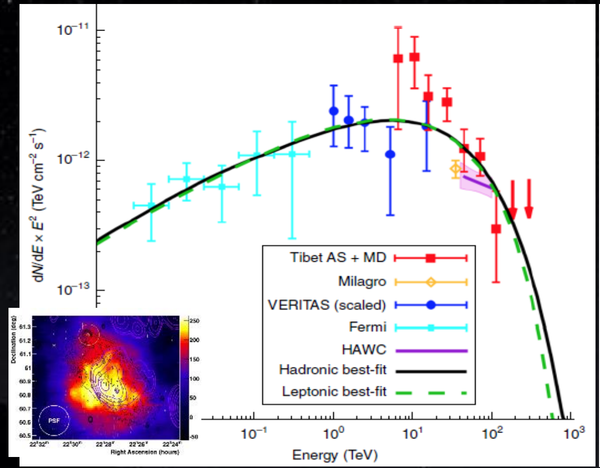
LHAASO J2108+3651



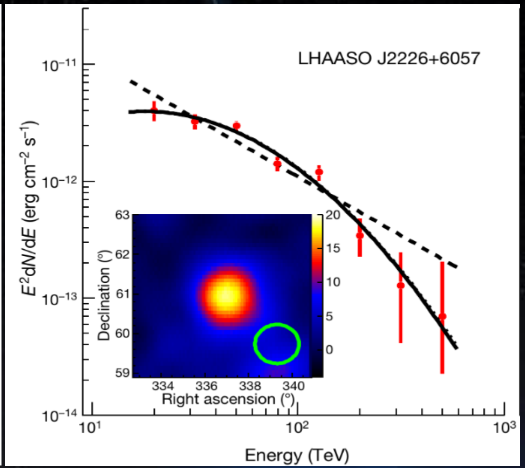
And finally… The Supernova Remnants

Almost all the talks in this session

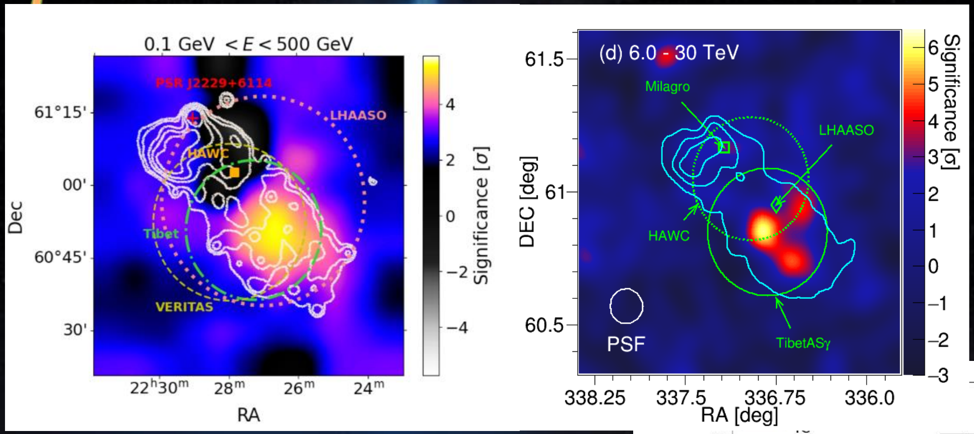
LHAASO J2226+6057



Tibet AS collaboration 2021

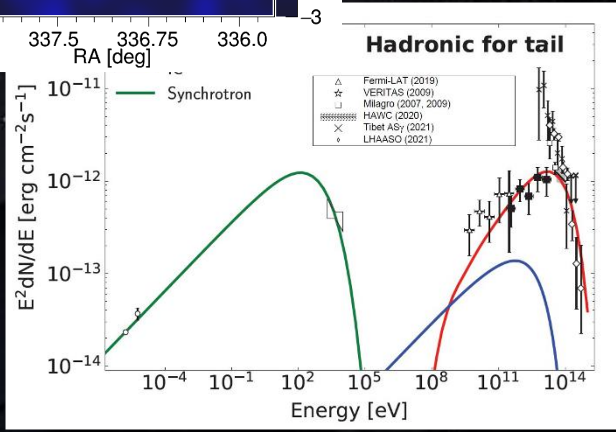


Cao+ (LHAASO coll) 2021



Fang+ 2022

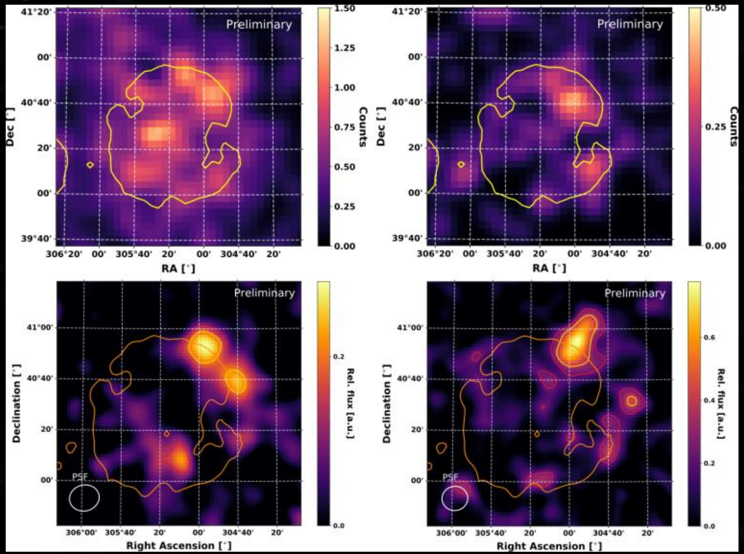
MAGIC coll. 2023

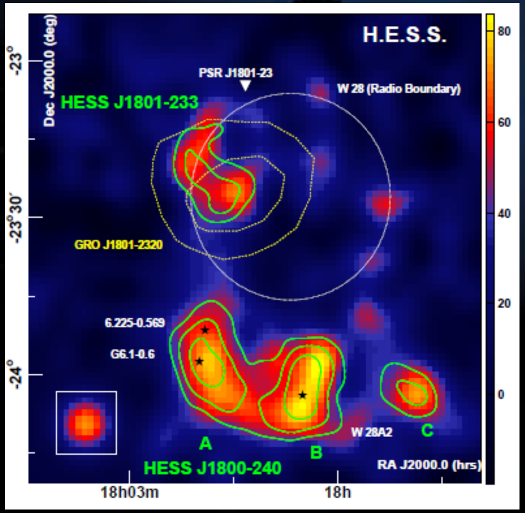


Fermi-LAT and MAGIC detection favoured hadrons from SNR/MC interaction

Propagation study

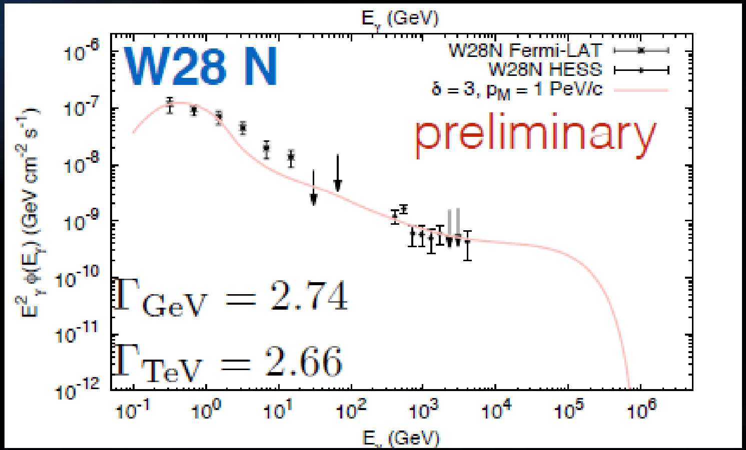
Gamma Cygni (MAGIC collaboration 2019)



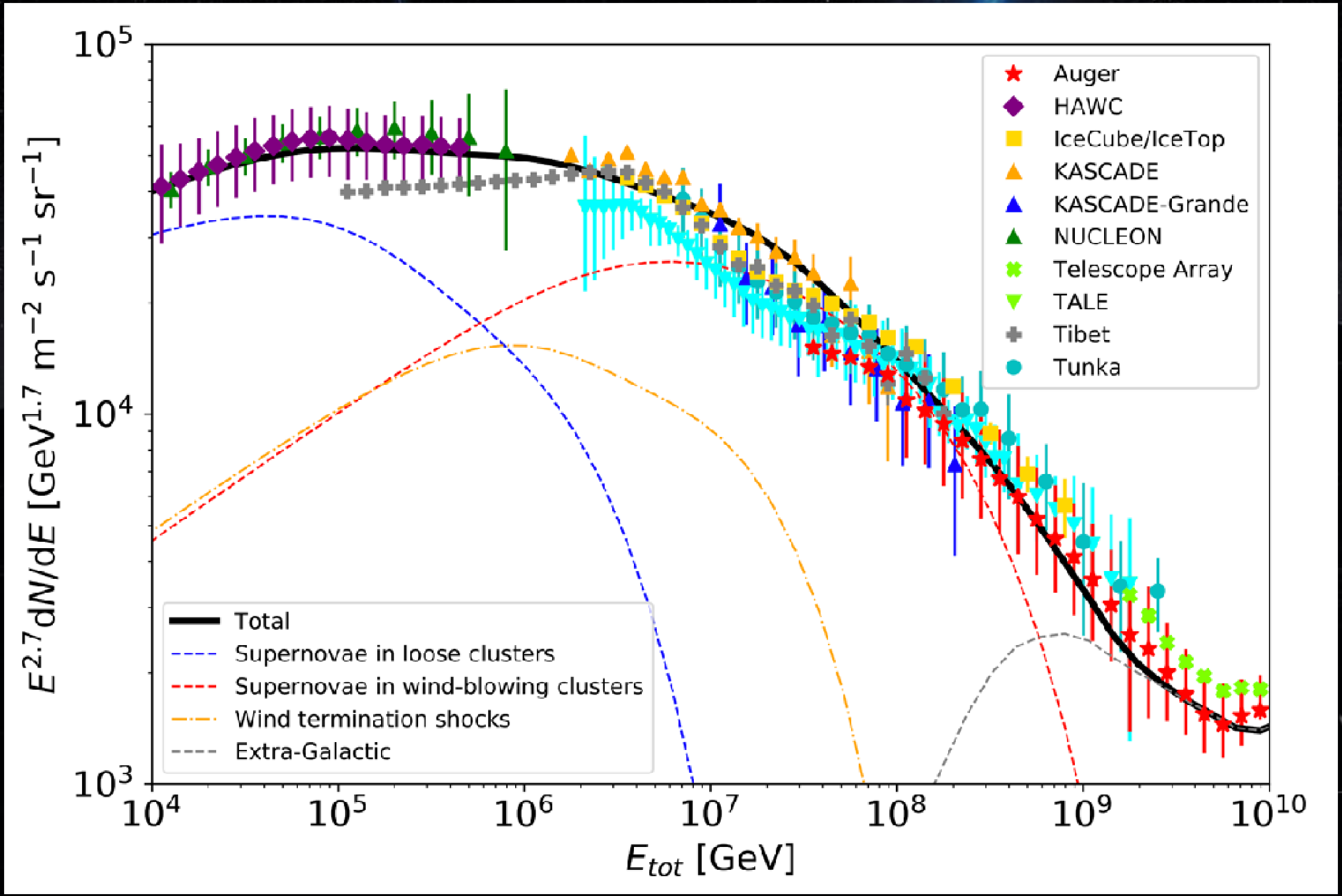


W28 (Aharonian et al. 2008)

Celli Talk Gamma2022



More kinds of source is better than one



Vieu&Revill 2023

Sources	Ra (°)	Dec (°)	σ >100 TeV	Emax (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 ANGUKAR RESOLUTION

NEUTRINOS

MC&Giuliani 2023

Very recent results (especially from ICRC 2023)

Yao talk, LHAASO Highlight ICRC2023, Lemoine-Goumard GA highlights ICRC2023

- 12 PeVatrons studied with LHAASO-WCDA [Chuandong 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
  - 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]

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

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

Importance of cross-correlation

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: ≤ 10% / ≤ 0.1° (E ≤ 10 TeV)
  - ✓ Characterize extended sources morphology
    - ✓ Energy dependence
    - ✓ Identification acceleration regions
  - ✓ MW association
  - ✓ Spectral Shape (hadrons vs leptons)

Several Talks in the TeVPa neutrino sessions

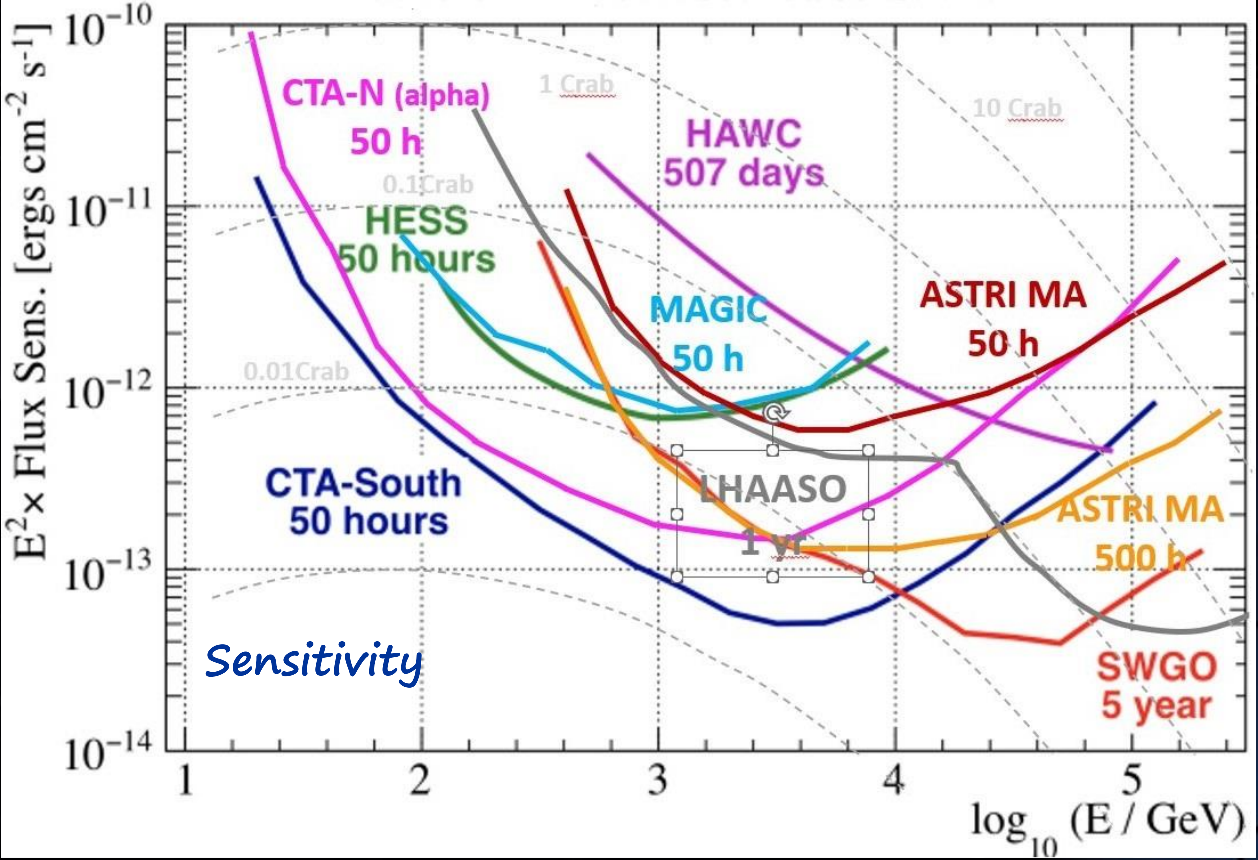
Li et al. ICRC23 (Neutrino/ LHAASO diffuse emission)
Burley et al. ICRC23 (Neutrino promising target and SNRs)

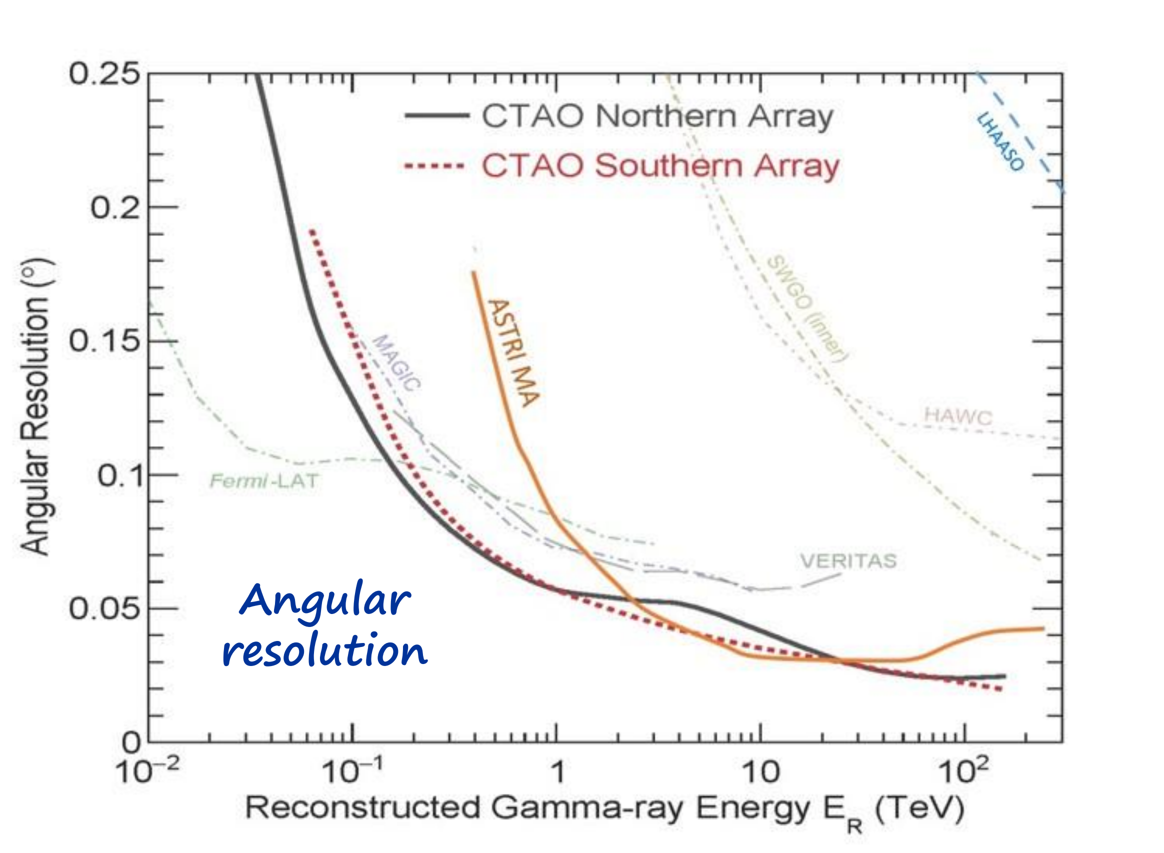
And we would like also a neutrino detection, thanks!

ASTRI Mini-Array and CTA

ASTRI Mini-Array

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





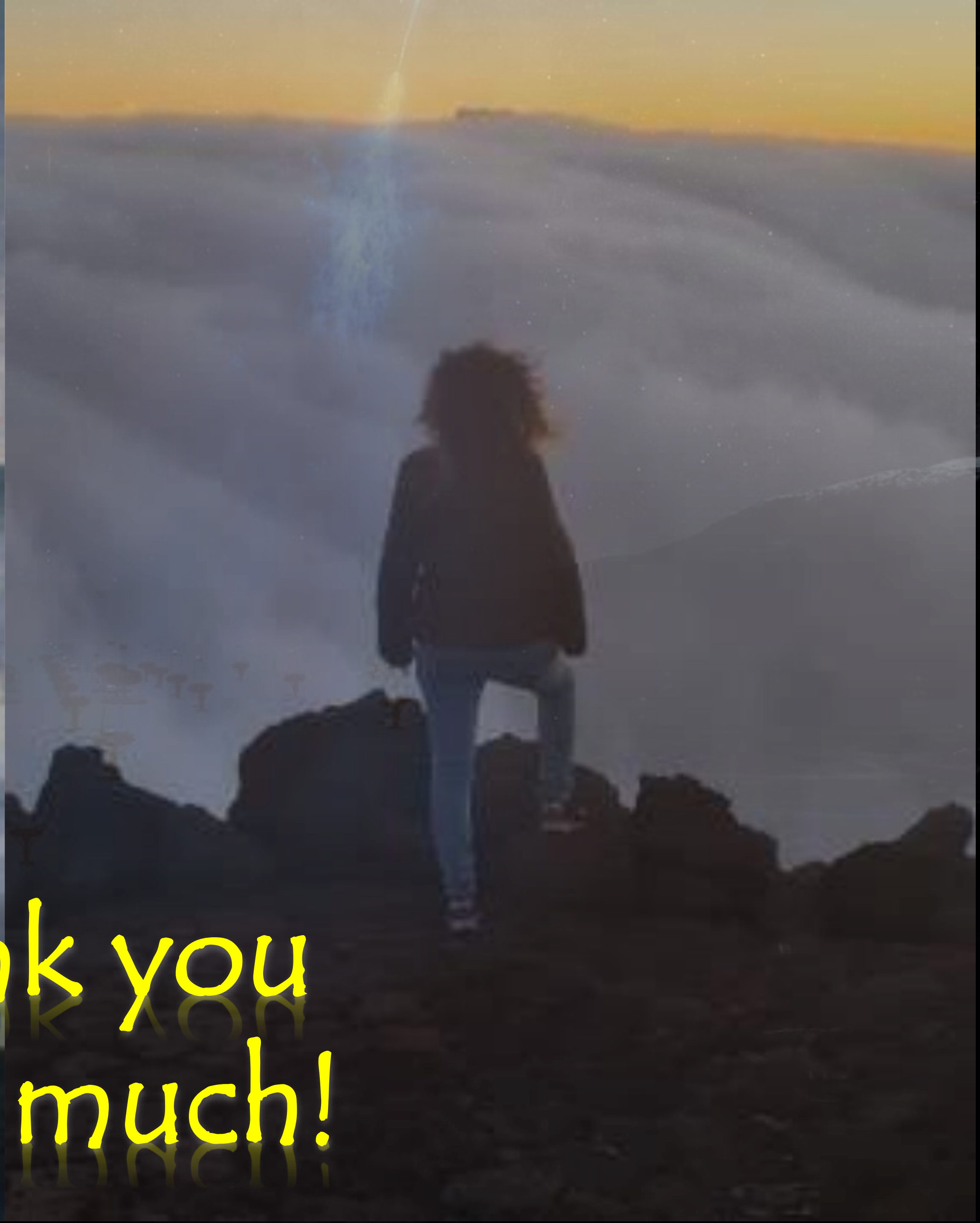
- Sensitivity: better than current IACTs (E > 10 TeV):
  - ✓ Extended spectra and cut-offs contsraints
- Energy/Angular resolution: ≤ 10% / ≤ 0.1° (E ≤ 10 TeV)
  - ✓ Characterize extended sources morphology

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

Tutone talk

IMPORTANT MESSAGES

- Cosmic-ray origin: a Very Hot Topic since 1912!!
- The three main candidate hadronic PeVatrons are Pulsar Wind Nebulae, Supernova Remants and Massive Star Clusters
- The future in the VHE domain is related to LHAASO, ASTRI-MA and CTA and their synergy with other instruments
- 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])
- Look at the ICRC2023 and TeVPa presentations and proceedings with a lot of new observations and modeling of PeVatron candidate sources
- A lot of work to do: from simulation and software to data analysis to theoretical interpretation



Thank you very much!