LHAASO galactic sources review

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PeVatrons - gamma-ray sources with energy spectra extending beyond **100 TeV (0.1 PeV)**

a reasonable definition for both hadronic and leptonic PeVatrons

Hadronic origin:

pp or pγ: $< E_\gamma > \approx 0.1 E_p$

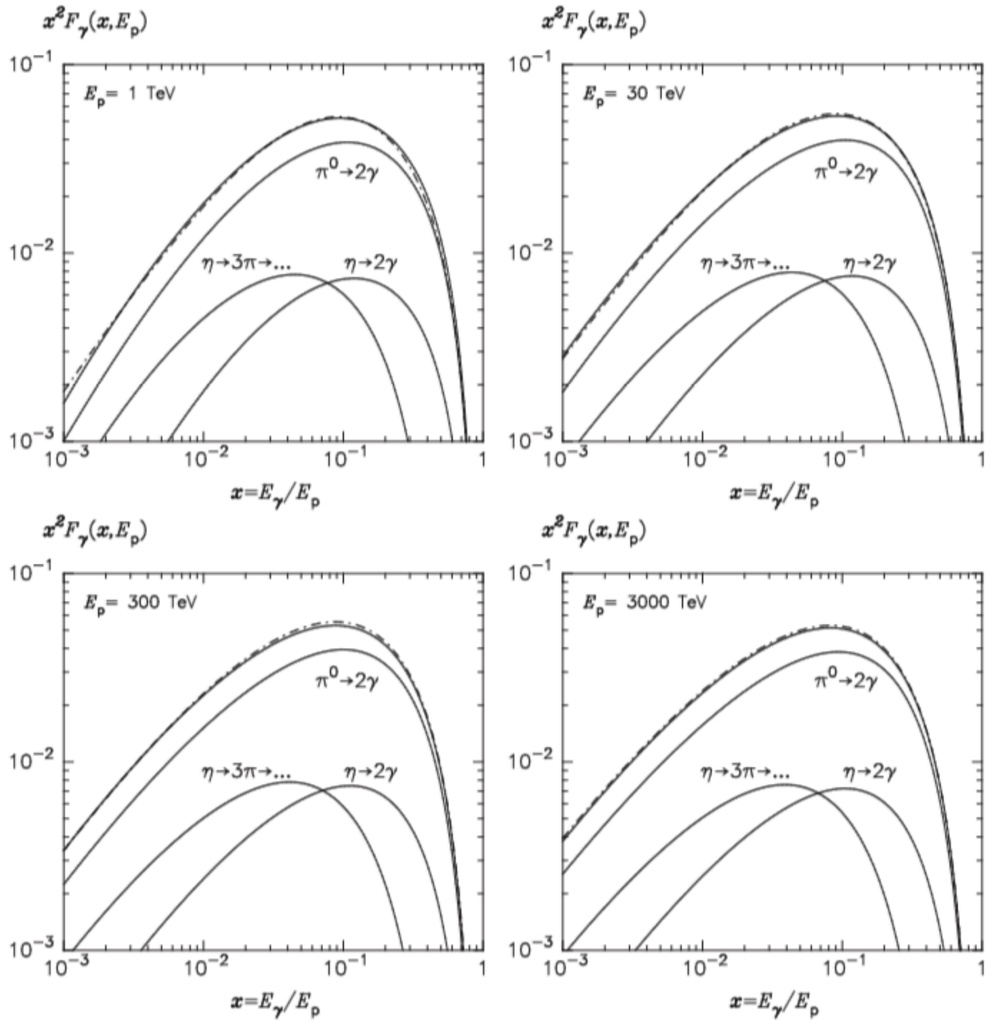
Leptonic origin: UHE γ-rays are (typically) produced at IC on 2.7 K

$$E_e \simeq 0.37\,(E_\gamma/100\,\mathrm{TeV})^{0.77}\,\mathrm{PeV}$$

- the requirement of of strict $E_{p(e)} \geq 1\,\mathrm{PeV}$ is an exaggeration;
  $E_{p,e} \gg 0.1\,\mathrm{PeV}$ makes more sense
- for E_γ one should use the highest energy point in the spectrum but not the (exponential) cutoff energy: $E^{max}_{p(e)}$ can be $\gg 100\,\mathrm{TeV}$ while $E_0 \leq 100\,\mathrm{TeV}$

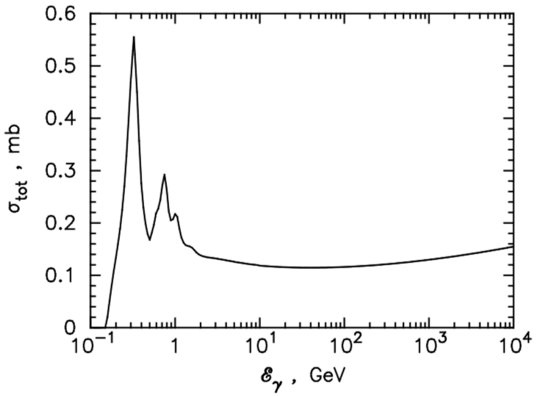
- statistically significant (i.e. $\geq 5\sigma$) detection of $\geq 100\,\mathrm{TeV}$ γ-rays
  => directly measured spectral points but not based on “standard” fits e.g.
  power-law with cutoffs (with strongly correlated Γ and E_{cutt}) or breaks

$pp \rightarrow \gamma$



$$< E_\gamma > \approx 0.1 E_p$$

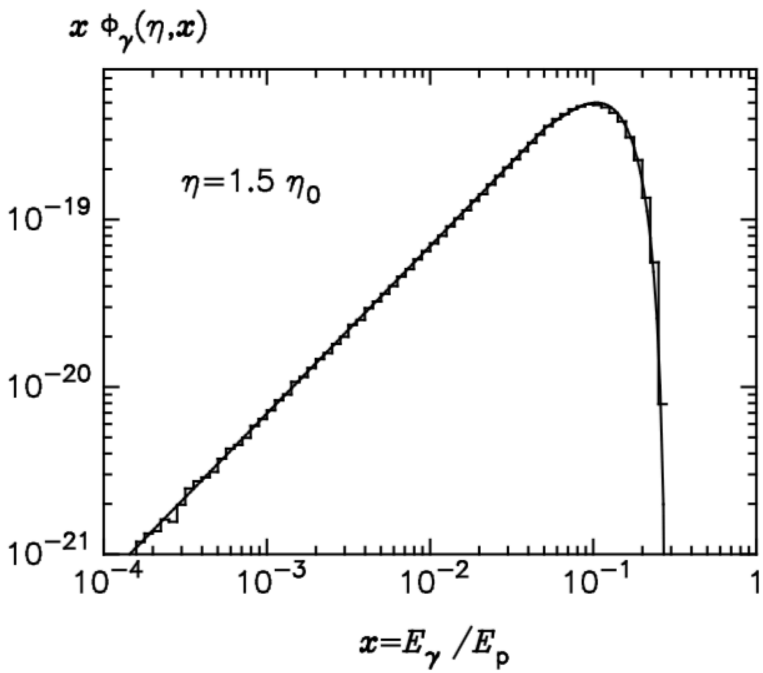
Kelner, FA, Bugaev 2006
calculations based on SIBYIL code

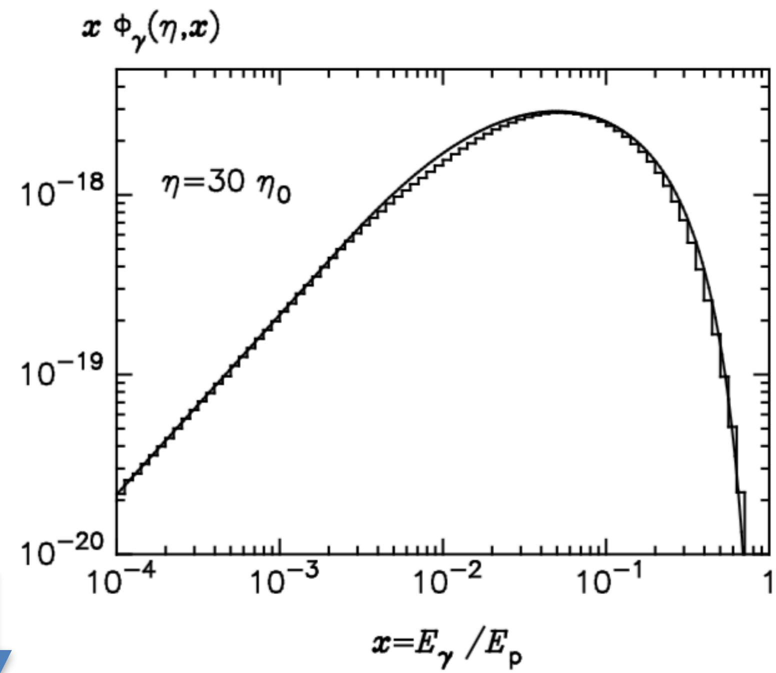


$p\gamma \rightarrow \pi^0 \rightarrow \gamma$

in the isotropic field of target photons of energy η
γ-ray spectrum is characterized by the ratio η/η_0

$$\eta = \frac{\epsilon E_p}{m_p^2 c^4} \qquad \eta \geq \eta_0 = 2\frac{m_\pi}{m_p}\left(1 + \frac{m_\pi}{m_p}\right) \approx 0.313$$





Kelner,FA 2008

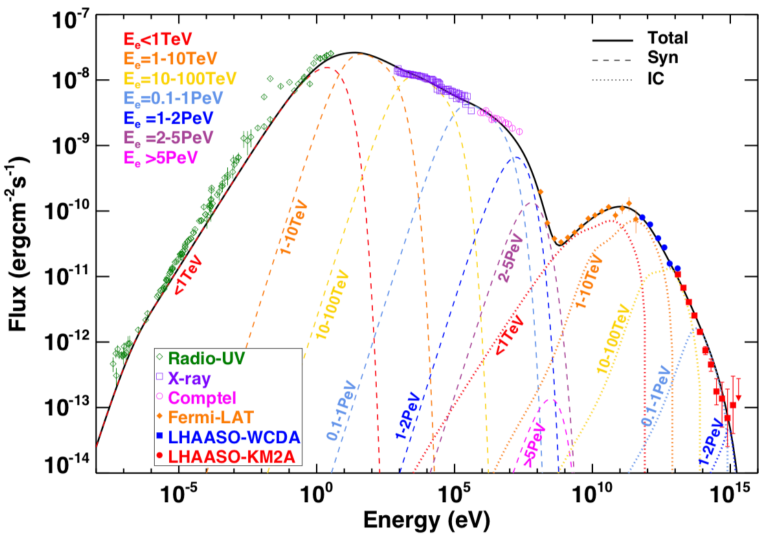
$$< E_\gamma > \approx 0.1 E_p$$

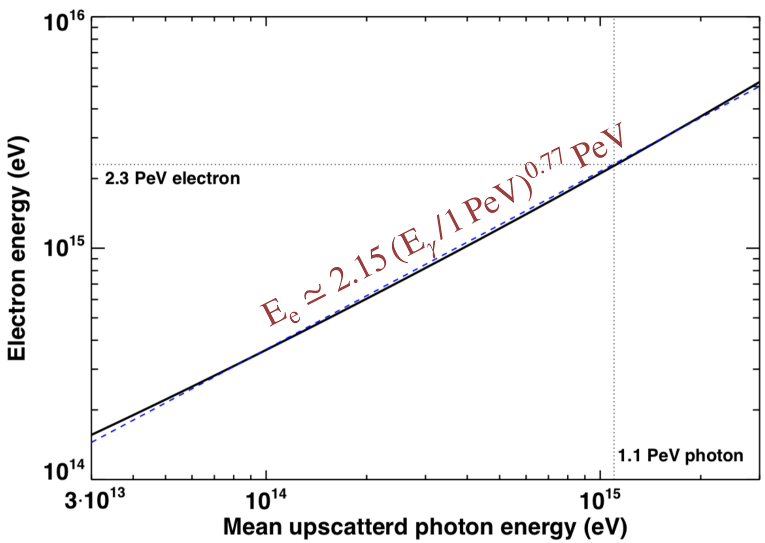
IC scattering

$E_\gamma \propto \varepsilon \gamma_e^2$ in Thomson limit

$E_\gamma \to E_e = \gamma_e mc^2$ in KN limit

for effective production of UHE gamma-rays $\varepsilon \sim 0.01 - 0.001\mathrm{eV}$ - 2.7 K CMBR!





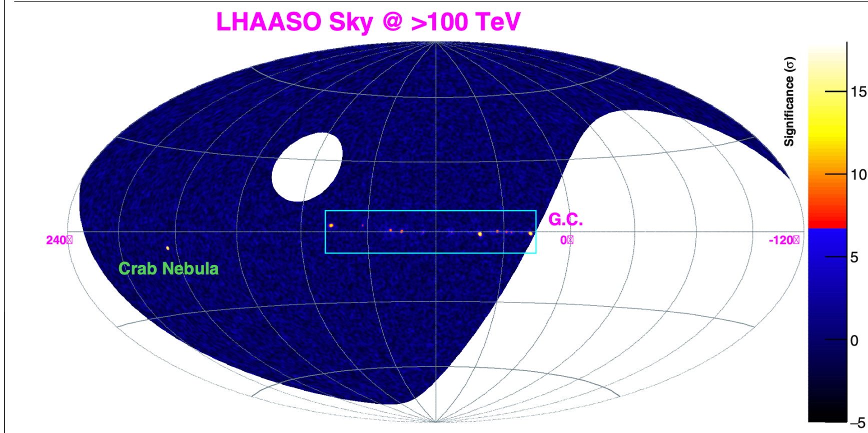
electron PeVatrons?

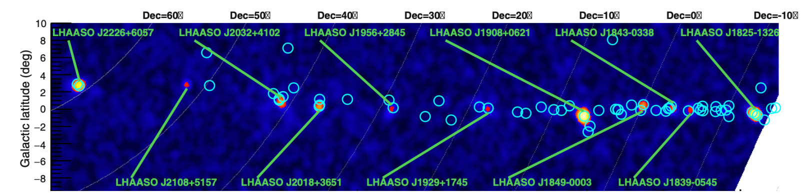
$E_\gamma \geq$ several 100 TeV

First PeVatrons!

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources (Nature, June 3rd 2021)

LHAASO Collaboration



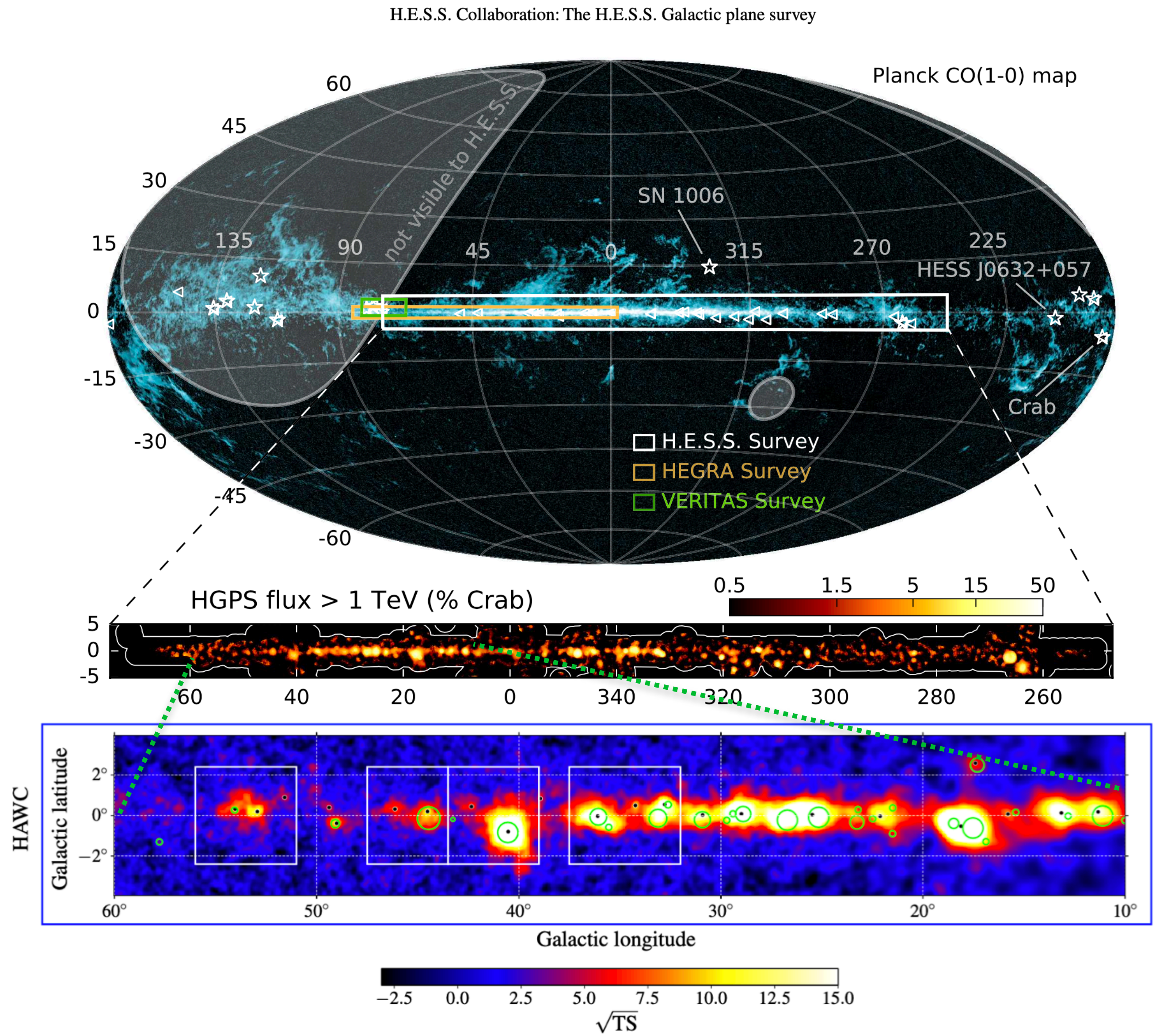


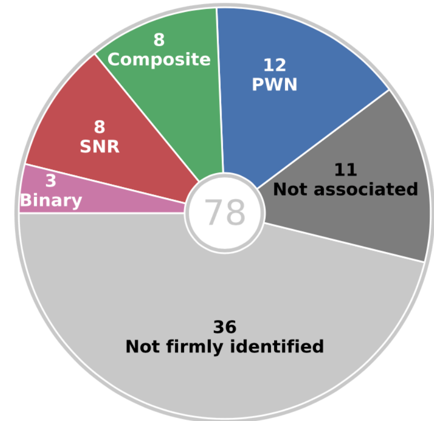
first results/conclusions - many > UHE or PeV sources!

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)

Celestial coordinates (RA, dec.); statistical significance of detection above 100 TeV (calculated using a point-like template for the Crab Nebula and LHAASO J2108+5157 and 0.3° extension templates for the other sources); the corresponding differential photon fluxes at 100 TeV; and detected highest photon energies. Errors are estimated as the boundary values of the area that contains ±34.14% of events with respect to the most probable value of the event distribution. In most cases, the distribution is a Gaussian and the error is 1σ.





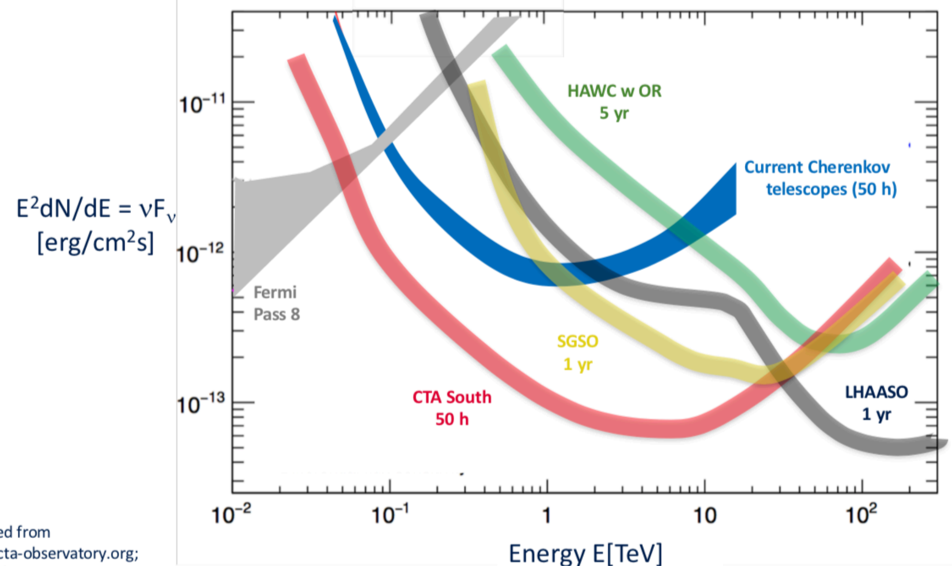
Galactic Plane is full of TeVatrons!

LHAASO - GP is full of PeVatrons !!!

HAWC - sources with spectra up to 100 TeV!

IACTs and LHAASO

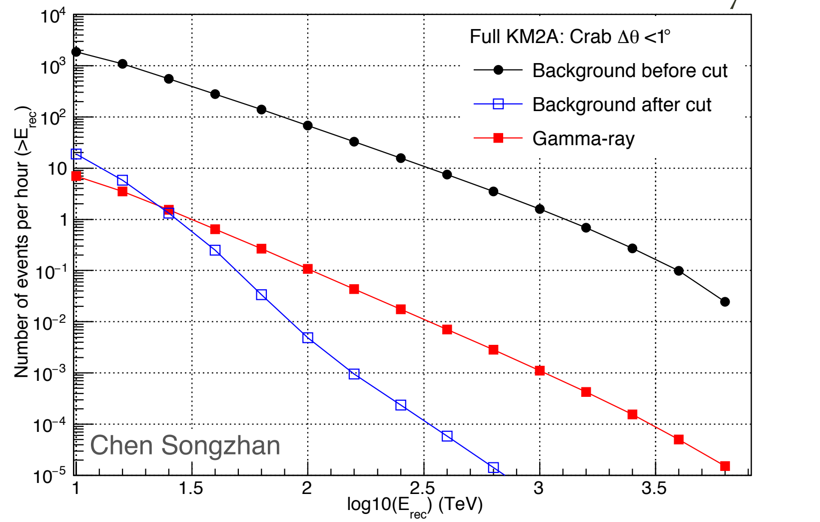
sensitivities of current and future detectors



adapted from
www.cta-observatory.org;
J. Goodman, COSPAR 2018;
Z. Cao, La Palma 2018

CTA - PSF: 2′-3′ from 100 GeV to 100 TeV
energy resolution 10-0%
sensitivity - best between 1-10 TeV
($\sim 3 \times 10^{-14}$ erg/cm^{2}s)

detection rate of the full KM2A array



KM2A - PSF: 25′ at 20 TeV, 12′ at 100 TeV
energy resolution better than 20%
sensitivity => 10^{-14} erg/cm^{2}s

extremely "fast" detectors
very good photon statistics for sources > 0.1 Crab
very good for spectrometry, morphology, timing

background-free detection of extended 1deg sources of >100 TeV gamma-rays of strength 0.1 Crab by KM2A with a rate 1 ph/100 h
very good for diffuse/extended sources

In the AstroParticle Physics community "LHAASO" is associated with PeVatrons, but LHAASO's legacy will not be solely linked to the discovery of PeVatrons

LHAASO is a powerful **TeV to PeV** detector that covers **4+** energy decades

with nice performance - for “homogeneous” studies of angular and spectral properties of TeV/PeV sources from **0.3 TeV to 3 PeV**

very good sensitivity at TeV energies - competitive with CTA (especially for extended sources) - LHAASO (WCDA) is a powerful TeV detector as well

“correct” energy dependence of sensitivity - significant improvement with energy allowing high quality of spectral measurements in the (for many cases, critically important) cutoff region, study of the energy-dependent morphology with energy, *etc*.

what is missing? arcmin (or better) angular resolution for source identification

solution ? - multi-TeV IACTs and large FoV X-ray detectors (eROSITA) “slope or intrinsic power-low index” $\Leftrightarrow$ “pure PL or with a cutoff” ?

a dilemma when searching PeVatrons

formally any (typical) γ-ray spectrum in a limited (e.g. 1 decade or less) energy interval can be presented in the PL with exponential cutoff form:

$$dN/dE = AE^{-\Gamma} \exp[-(E/E_0)^{\alpha}]$$

but with large parameter space (Γ, E_0, α)

$\Gamma \sim 1.5$ Eo < 10 TeV => Ep < 100 TeV “is not a PeVatron”

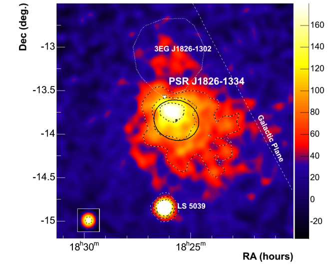
$\Gamma \sim 2.3$ Eo > 10 TeV => Ep > 100 TeV “can be a PeVatron”

for a definite answer one should have adequate spectral measurements at

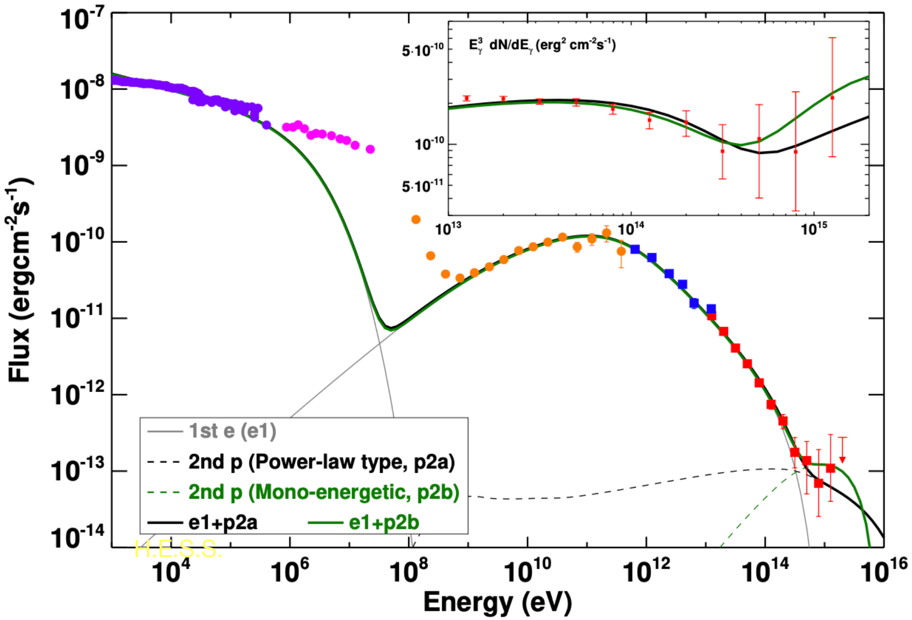
(1) $E_\gamma \geq 100\,\mathrm{TeV}$ and (2) $E_\gamma \ll E_0$ down to TeV energies

the “smart” energy-dependence of LHAASO’s sensitivity provides such measurements over 4+ decades (LHAASO already has beautiful examples)

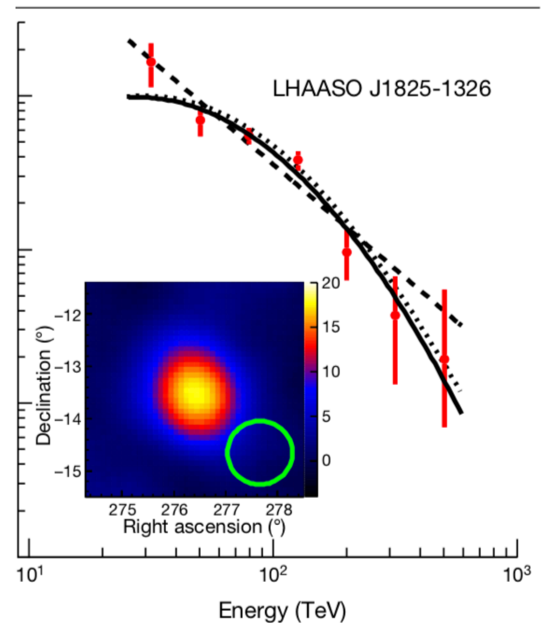
Detection of > 100 TeV photons from PWNe



Crab Nebula



LHAASO J1825-1326



Crab Nebula: **effective electron accelerator** but **not effective γ-ray emitter**:

"standard" PWNe with B ~ (1 – 10) μG) are not only **effective accelerators**

but also **effective UHE emitters !**

while this is explained naturally, a surprise is that spectra from some potential

PWNe/Pulsar Halos extend beyond 100 TeV

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}	

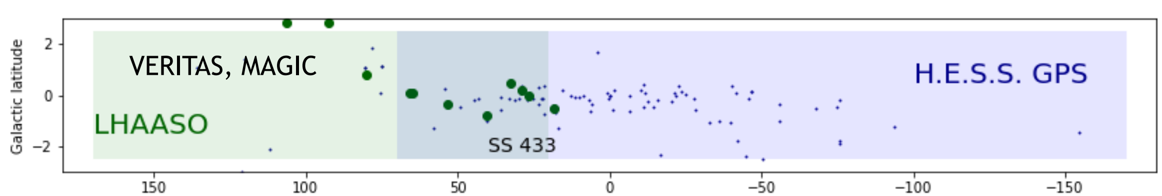
- firmly identified - Crab (Nebula)
- PWNe and/or PHs?
- no young SNRs (Cas A, Tycho)
- middle-age SNRs (nearby GMCs)?
- Young Massive Clusters (YMCs)
- - - - - -

> 100 TeV γ-ray sources: regions of concentration of CRs and high density target but not the locations of PeVatrons which should be yet localised and identified

>100 TeV gamma-rays should be detected to claim the presence of PeVatrons

for bright sources **30-300 TeV** interval can be covered by future multi-TeV **IACTs (ASTRI/CTA)**

with PSF ~ several arcmin - critical for source identifications

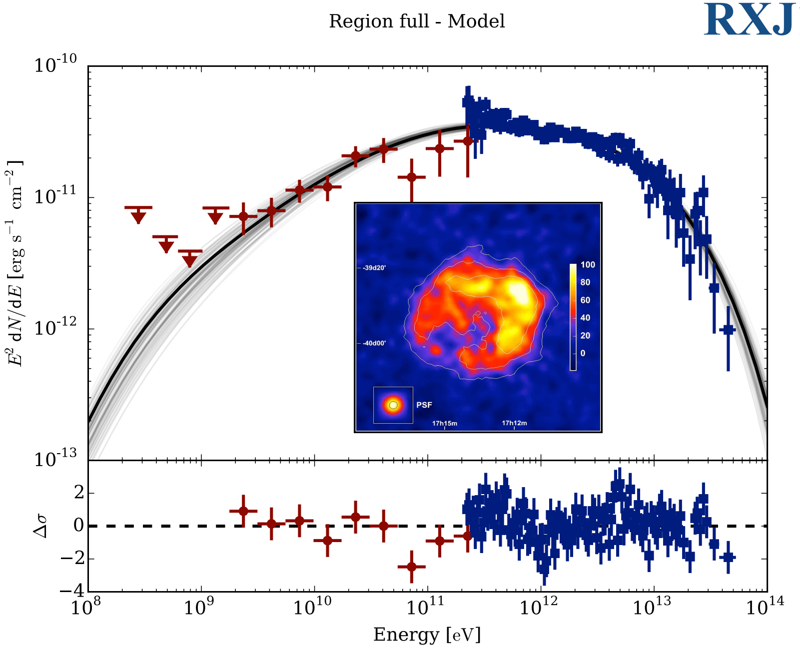


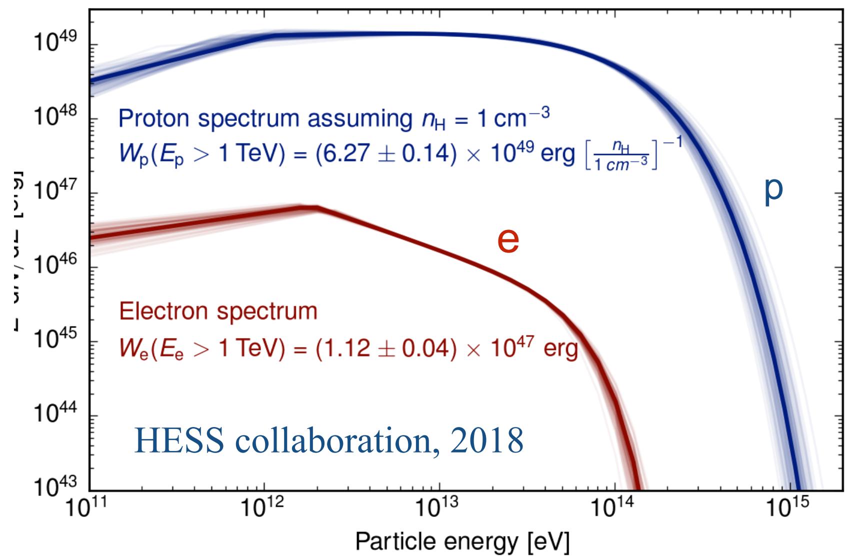
Probing the distributions of accelerated particles in SNRs

Fermi+HESS measurements

derived spectra of e and p

RXJ1713.7-3946

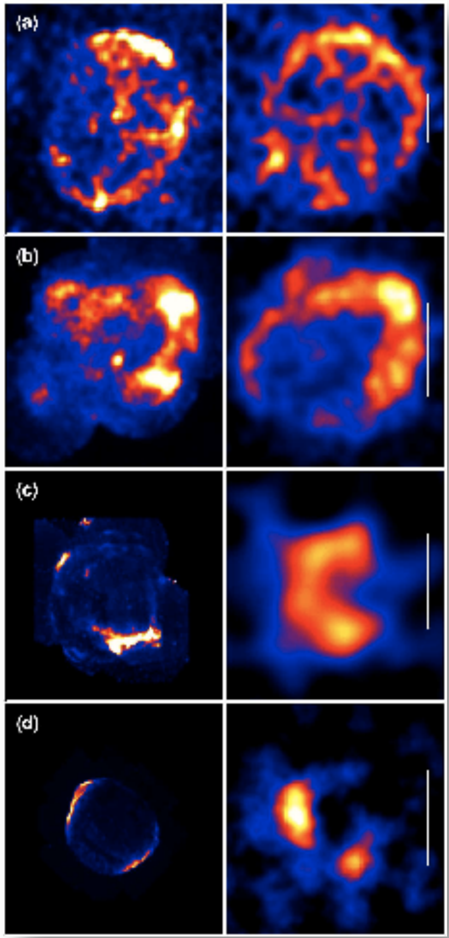




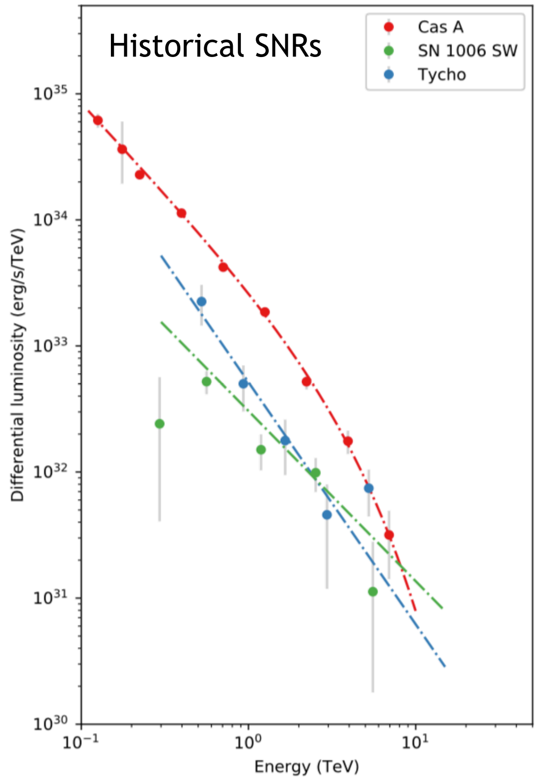
clear spectral steepening above 10 TeV - cutoff ? or a break ? in the proton spectrum at 100 TeV with principally different implications

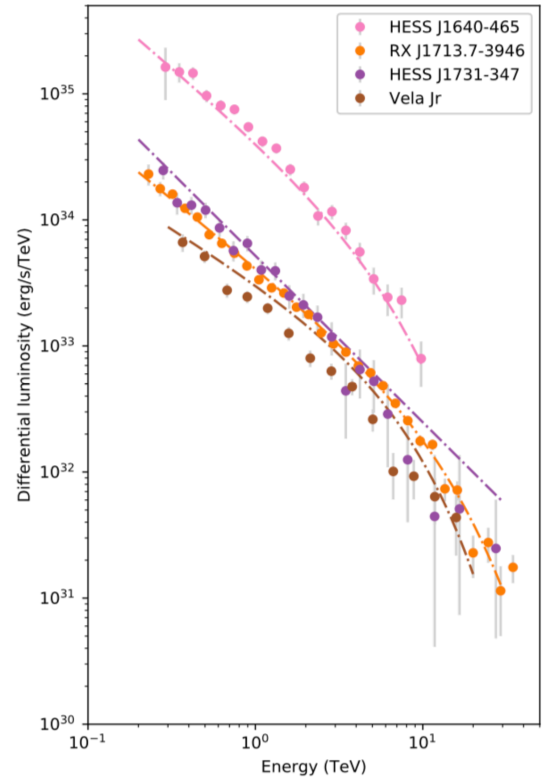
recent exciting (software) developments - detection of many HESS sources well beyond 10 TeV (up to 100 TeV) => revisiting RXJ1713.7-3946 (seems to me) very promising

spectra of young SNRs above 1 TeV - steep with Γ= 2.3-2.6



TeV photons from from >10 young SNRs: support SNR paradigm of galactic CRs, but it is not yet clear whether SNRs can provide the CR flux up to the *knee* (~1 PeV)





steep spectra or 'early' cutoffs ? studies should be extended to 100 TeV

LHAASO is able to answer to this question

?

two options

- $\Gamma \geq 2.3$ according to recent theoretical studies (Malkov, Bell, Caprioli, …) more realistic than $\Gamma \sim 2$ of the "standard" DSA

  no strong constrains on the proton maximum energy from gamma-ray data:

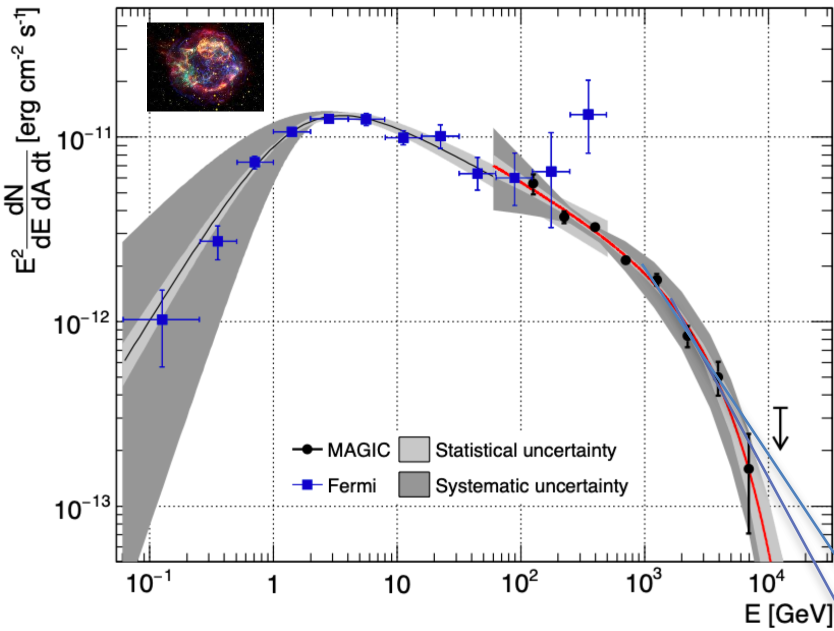
  $E_{max} \sim 1$ PeV - very difficult, but feasible

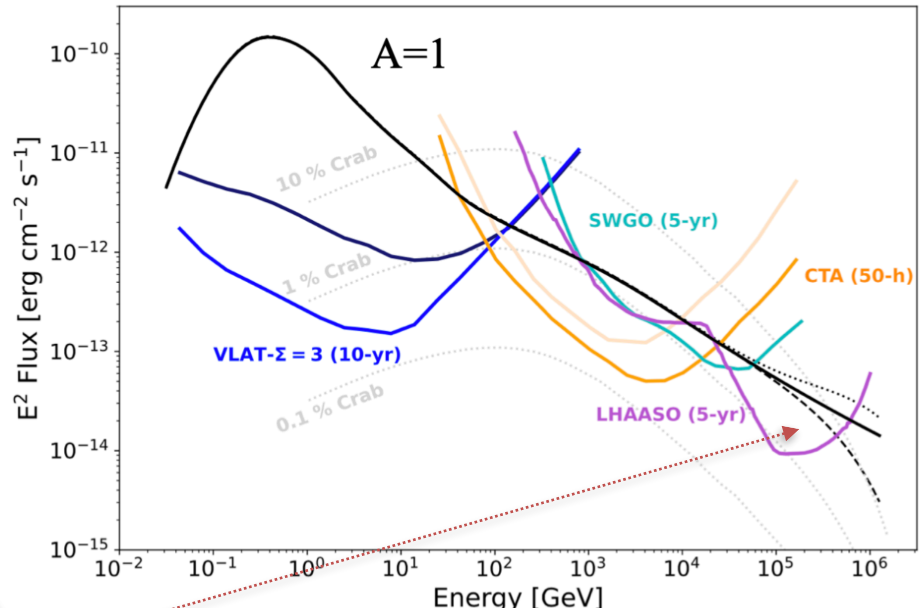
e.g. Type II SN shocks propagating through the dense wind of the progenitor star … but "PeVatron phase" can be accomplished only during the first years of explosion

- "early cutoff" standard DSA with (exponential) cutoff, $E_0 \sim 10 - 100$ TeV
  - relax and accept that SNRs are main contributors to CRs but only at TeV energies (Laggage and Cesarsky 1983); above 100 TeV they are overtaken by other source population ("PeVatrons") responsible for the knee region?
  - relate it to the early "PeVatron Phase" - years after SN explosion (T. Bell+, Zirakashvili, …) and the escape of >1 PeV particles from the remnant

"large Γ or small Eo ?" - extension of observations to 100 TeV

Cas A, a benchmark SNR-PeVatron candidate?





$dN/dE \propto E^{-3} \rightarrow F_E \sim 10^{-14}$ erg/cm^{2}s at $E_\gamma \sim 100$ TeV at the margin of sensitivity of LHAASO

no detection - acceleration at very early epochs (< 10 yr) because CRs already left the remnant ?

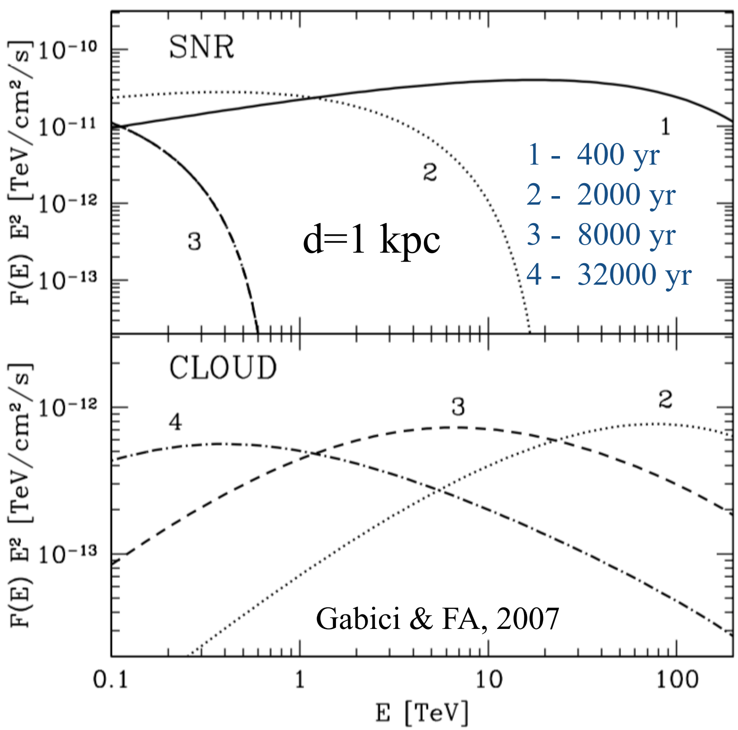
even moving ballistically R~100 pc (angular size $\sim 2^0$) but the γ-ray image would be a point like;

for "slow diffusion" R < 10 pc, angular size comparable with PSF of LHAASO

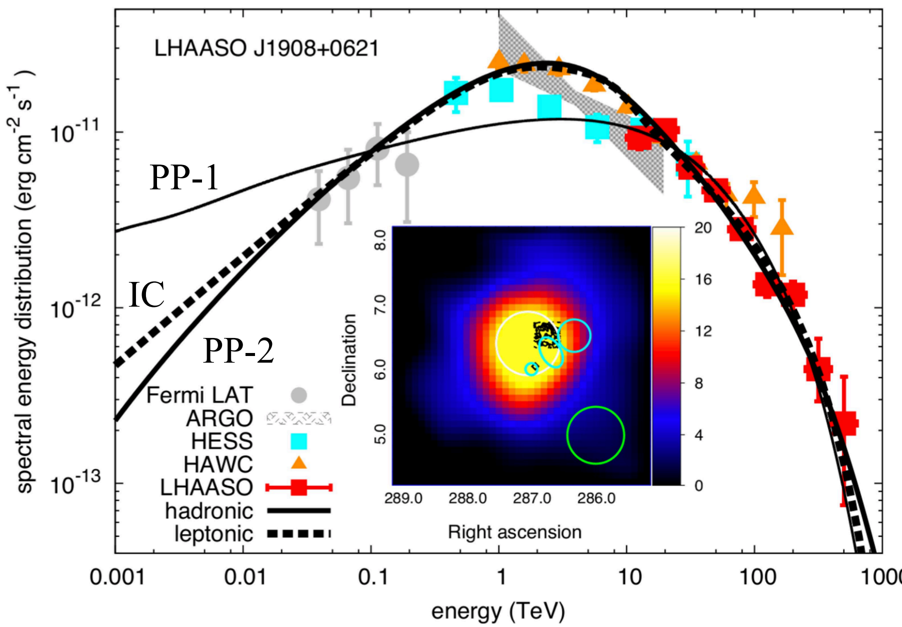
=> LHAASO upper limit (or detection) of 100 TeV γ-rays - at the level of 10^{-14} erg/cm^{2}s

decisive "PeVatron test" independent of the acceleration epoch

GMCs as "smoking guns" within <100 pc of mid-age SNRs (FA&Atoyan 1996)



SNR G40.5-0.5 + GMC ?



SNR: $W=10^{51}$ erg $n=1$ cm^{-3}
$f(p)\sim p^{-4}$ $p_{max}=5$ PeV
$p_{max}\sim t^{-2.4}$

Cloud: R=100 pc, $M=10^4 M_o$
$D(E)=3\times10^{29}(E/1\mathrm{PeV})^{0.5}$ cm^2/s

— PP-1: $dN/dE \propto E^{-1.85}\exp[-(E/380\mathrm{TeV})]$

— PP-2: $dN/dE \propto E^{-1.2}$ $E \leq 25$TeV;
$\propto E^{-2.7}\exp[-(E/1.3\mathrm{PeV})]$ above 25 TeV

After decades of recognition as the major CR production sites, SNRs are still considered the primary sources of Galactic CRs, but the CR community is less confident about in their substantial contribution to the *knee* (PeV) region

The deep γ-ray probes of SNRs by LHAASO will provide a decisive verdict on their ability to perform as PeVatrons.

Meanwhile, the exploration of alternative sources/scenarios of production highest energy CRs becomes a “hot topic” in the context of new sensitive VHE/UHE γ-ray observations and theoretical studies.

Stellar Clusters operate as PeVatrons ?

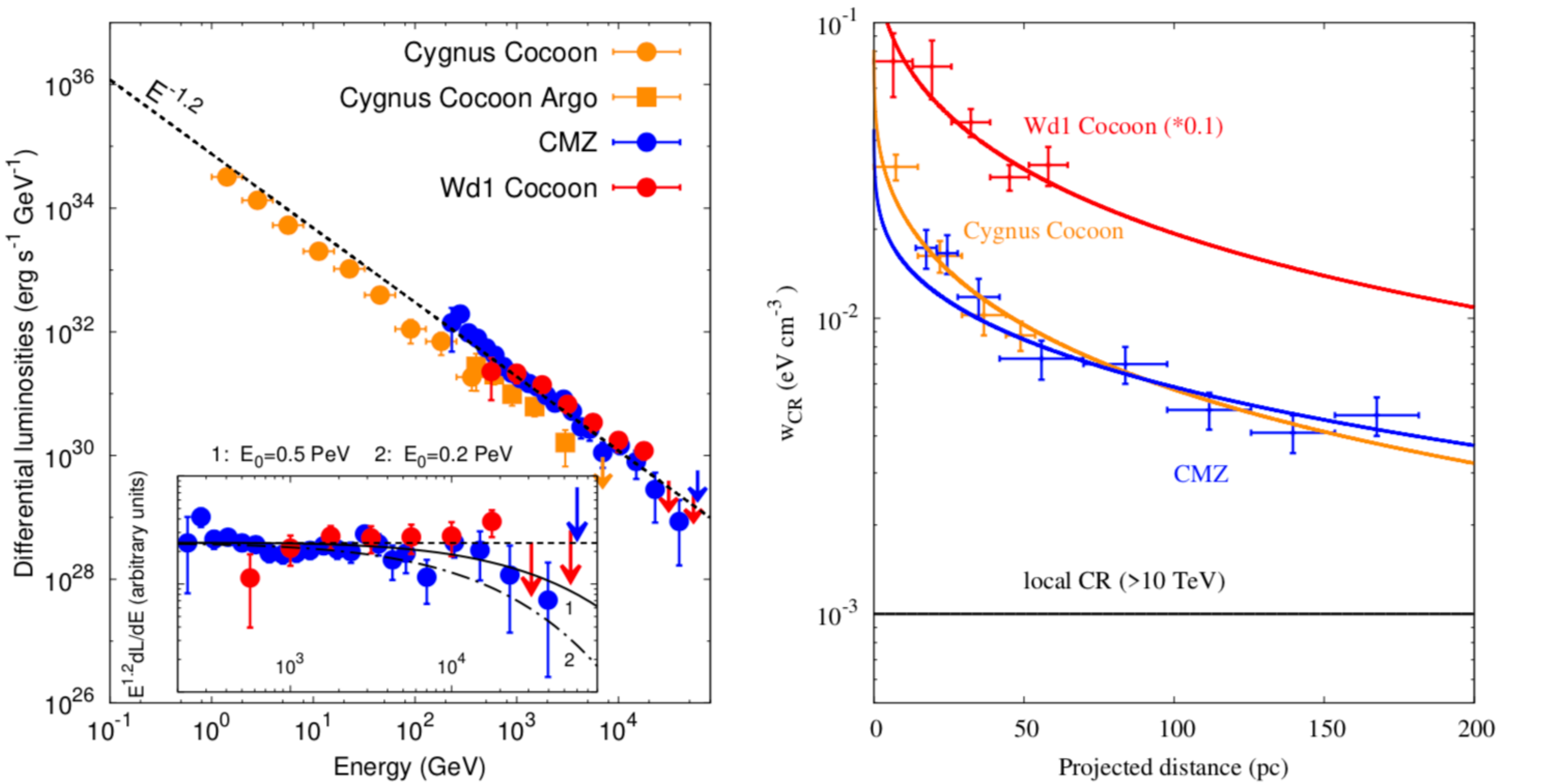


Figure 1: Gamma-ray luminosities and CR proton radial distributions in extended regions around the star clusters Cyg OB2 (Cygnus Cocoon) and Westerlund 1 (Wd 1 Cocoon), as well as in the Central Molecular Zone (CMZ) of the Galactic Centre assuming that CMZ is powered by CRs accelerated in *Arches*, *Quintuplet* and *Nuclear* clusters.

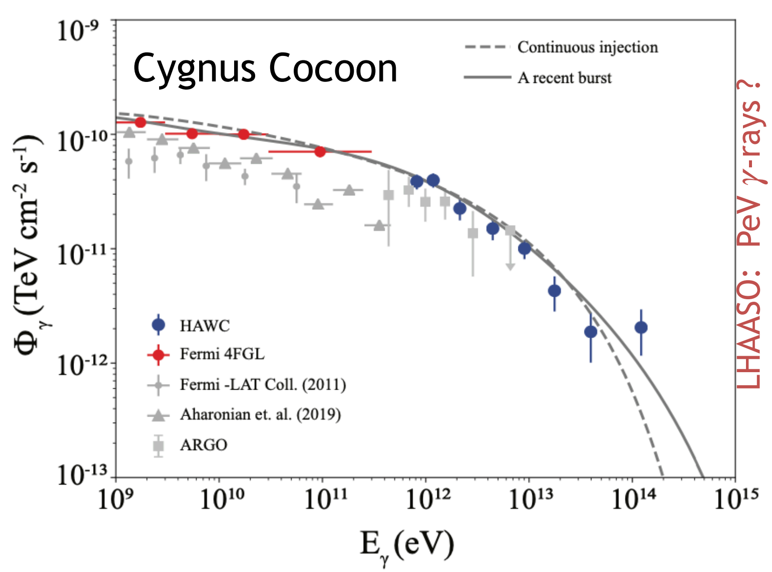
FA, Yang, Ona de Wilhelmi, 2018

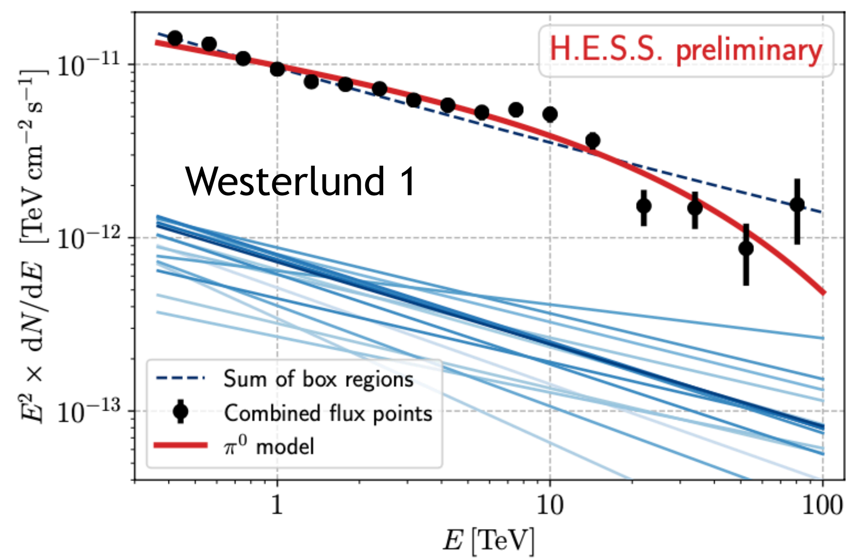
Extended Regions surrounding Clusters of Young Massive Stars are sources sources of GeV, TeV and … PeV gamma-rays!

Westerlund 1, *Westerlund 2*, *30 Dor C* (in LMC)

CygnusOB2, *W43*, *NGC3603*

Arches, *Quintuplet* and *Nuclear* ultracompact clusters



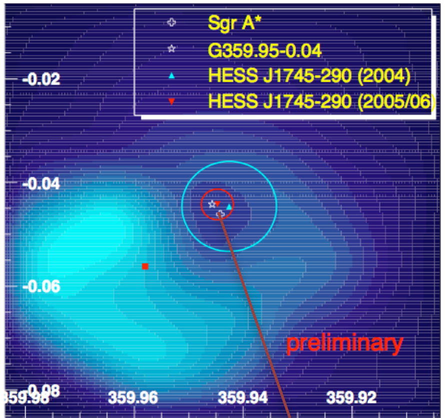


Origin of TeV/PeV γ-rays ? Hadronic!

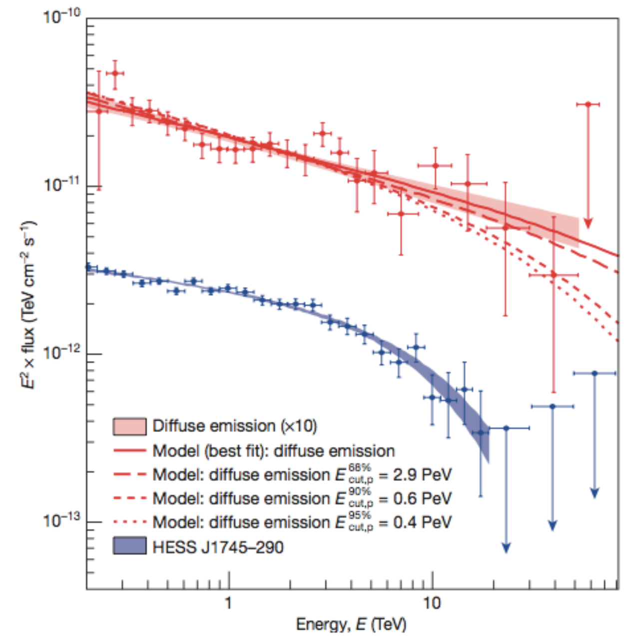
IC (almost) excluded - only PWNe can accelerate electrons >> 100 TeV

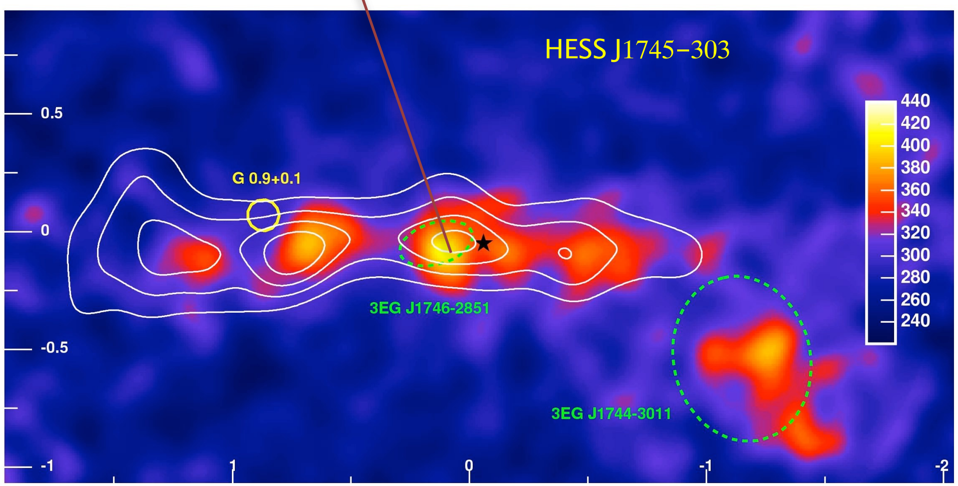
- γ-ray morphology

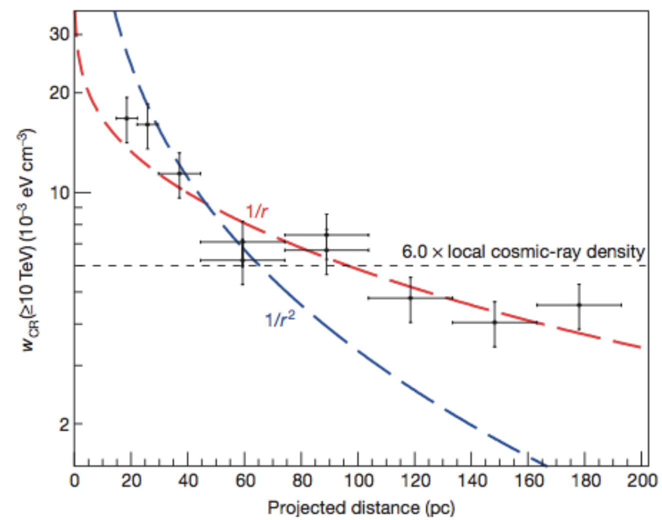
PeVatron(s) in the Galactic Center!



continuous injection of protons into CMZ up to ~1/2 PeV : a PeVatron(s) within 10 pc of GC







SMBC in GC (Sgr A*) operating as a PeVatron ?

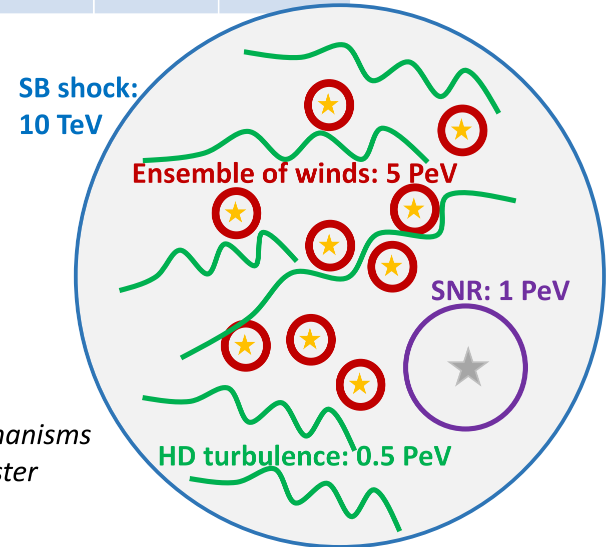
or particles are accelerated in the Arches, Quintuplet, Nuclear ultra-compact YMCs ?

Stellar Clusters as factories of Galactic Cosmic Rays out of 1 (10) PeV ?

$E_{p,max}$ in different scenarios of the stellar clusters and related superbubbles

Acceleration mechanism	*U* [km/s]	*B* [μG]	*R* [pc]	Emax, reasonable [PeV]	Emax, optimistic [PeV]	Particle injection?
SB forward shock	30	1 – 10	50 – 100	**0.01**	0.1	N
SNR inside SB	3000	10 – 50	10 – 30	**1**	1 – 3	Y
WTS around a compact cluster	2000	1 – 10	1 – 10	**1**	1 – 3	Y
HD turbulence	100	1 – 10	50 – 100	**0.5**	1	N
Collection of individual winds	2000	10 – 30	1 – 20	**3**	10	Y

Vieu et al., Preliminary!



Maximum proton energies reasonably expected for various acceleration mechanisms in a superbubble carved by a loose cluster

PeVatrons and Super-PeVatrons in Milky Way

do we expect acceleration of particles to PeV energies and well beyond?

multi-PeV accelerators in our Galaxy?

extension of the cosmic ray spectrum well beyond 1 PeV =>
super-PeVatrons should exist in the Milky Way

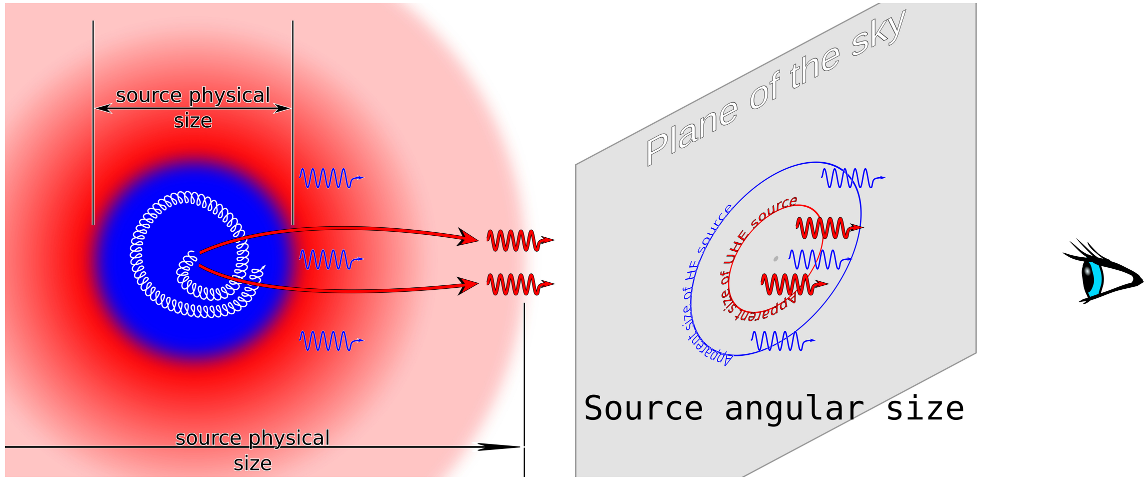
Supper-Bubbles ?

SNRs ? ?

Pulsars: $E = 20\,\eta_B^{1/2}\,L_{38}^{1/2}$ PeV

Binary systems, Microquasars - ?

SMBH in the Galactic Center: $E = eBR \simeq 100(B/10\,\mathrm{kG})\,(M/3\times10^6 M_\odot)$ PeV



"physical size versus apparent angular size of γ-ray image"

in diffusive-to-ballistic transition regime of propagation of parent charged particles

apparent angular size decreases with increase of energy !

"standard" diffusion coefficient particles propagate the first tens of the trajectory

in (quasi) ballistic regime => gamma-ray image coincides with the accelerator !

eROSITA with 10'' PSF could be critical in localization of LHAASO PeVatrons

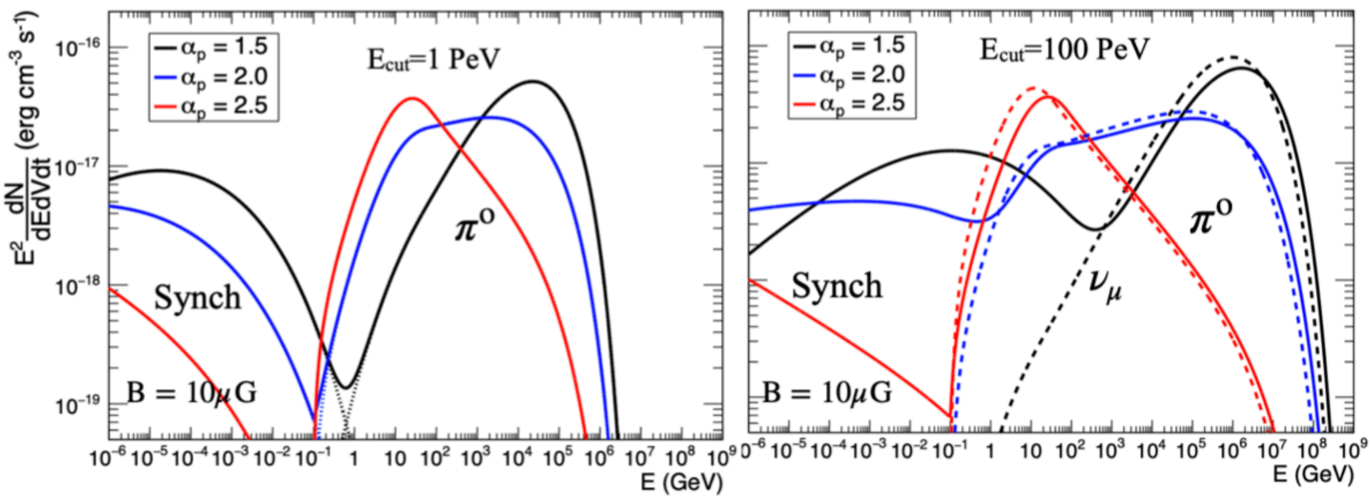
LHAASO and

synchrotron radiation of secondary electrons: $pp \to \pi^{\pm} \to e^{\pm} + B \to \gamma$

$\epsilon \simeq 20(B/100\mu\mathrm{G})(\mathrm{E}/100\,\mathrm{TeV})^2\,\mathrm{keV}$ characteristic energy of the synch. photon

$t_{\mathrm{synch}} \approx 15(B/100\mu\mathrm{G})^{-3/2}(\epsilon/10\mathrm{keV})^{-1/2}\,\mathrm{yr}$ cooling time of electrons

synchrotron radiation almost "prompt" - counterparts of gamma-rays and neutrinos!

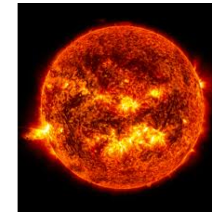


emissivities of secondary products - gamma-rays and secondary synchrotron photons:
$\mathrm{d}N/\mathrm{d}E \propto E^{-\alpha_p} \exp -(E/E_{cut})$, $\mathrm{w_p}(\geq 100\,\mathrm{GeV}) = 1\,\mathrm{erg/cm^3}$ $\mathrm{n} = 1\,\mathrm{cm^{-3}}$ $\mathrm{B} = 10\mu\mathrm{G}$

$\mathrm{F}(10\,\mathrm{keV})/\mathrm{F}(100\,\mathrm{TeV}) \sim 0.1 - 1$; strongest LHAASO sources $\mathrm{F}(100\,\mathrm{TeV}) \approx 10^{-12}\,\mathrm{erg/cm^2s}$

X-rays can help to localize and identify **PeVatrons**
Gamma-rays (below 100 GeV) can be very helpful for Super PeVatrons

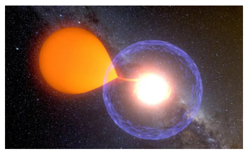
Relativistic Matter (CR ray) Factories and potential LHAASO-ASTRI sources



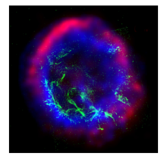
nonthermal processes in Universe proceed everywhere on almost all astronomical *space* (sub-pc to Mpc) and *energy* (GeV to PeV) scales

G

Stars



Novae

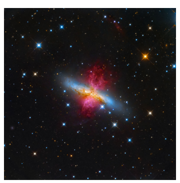


SNRs

Microquasars

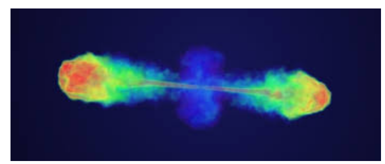
Neutron Stars*

EXG

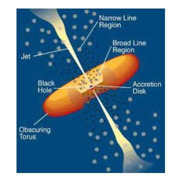


Galaxies

Galaxy Clusters

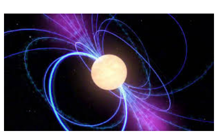


Large Scale Jets of AG

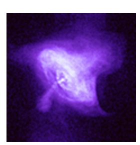


Blazars

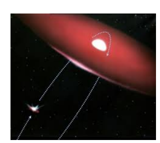
* accelerators associated with Neutron Stars



Pulsars



Pulsar Wind Nebula



Binary pulsars

(BNS mergers)

(short) GRBs

SNRs, SCs and PWNe will be covered by SG, GM , and EA

a few words about Binaries:

Binary Pulsar — PWN in a binary system - PSR B 1259-63 (detected)

Microquasars (BH jets) — *extended*: SS433 (detected - HAWC, HESS)

episodic events: GRS 1915 (HEGRA), Cyg X-1 (MAGIC), Cyg X-3 (?)

Unidentified binaries — LS 5039, LS 61° 303 - binary pulsars ?

Leptonic scenarios - natural, effective, but difficult to imagine > 100 TeV

LS5039 and PSR 1259-63: γ-rays - well beyond 10 TeV

Hadronic scenarios - have not been considered and studied in depth, only (phenomenological) speculations (since 1980s)

The first (to my knowledge) particle acceleration model - A. Bykov et al. : acceleration of hadrons in the colliding pulsar and stellar winds

leptonic scenarios - $e\gamma$, hadronic scenarios - pp or $p\gamma$

binary systems - unique high energy laboratories

binary pulsars - a special case with strong effects associated with the optical star on both the dynamics of the pulsar wind and and the radiation before and after its termination

the same 3 components - *Pulsar/Pulsar Wind/Synch.Nebula* - as in PWNe both the electrons of the cold wind and shocke-accelerated electrons are illuminated by optical radiation from the companion star detectable IC γ-rays

"on-line watch" of the MHD processes of creation and termination of the ultrarelativistic pulsar wind, as well as particle acceleration by relativistic shock waves, through spectral and temporal studies of γ-ray emission

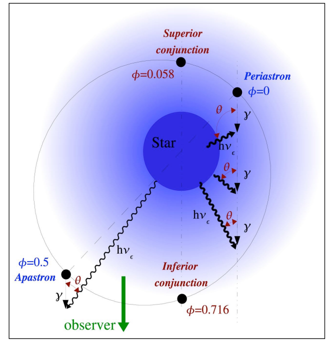
(characteristic timescales 1 h or shorter !)

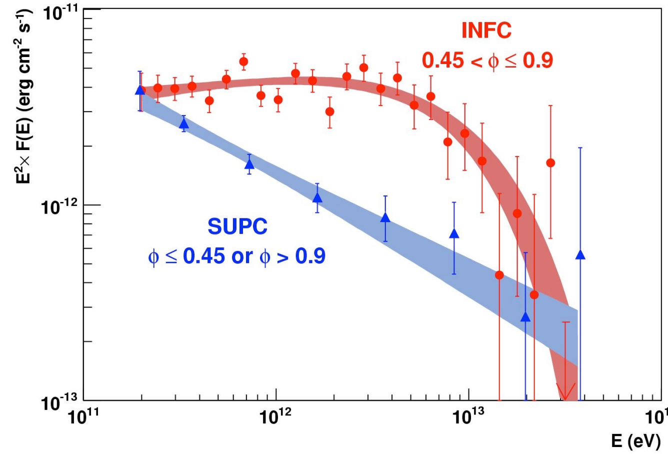
the target photon field is function of time, thus the only (?) unknown parameter is B-field => predictable gamma-ray emission?

LS 5039

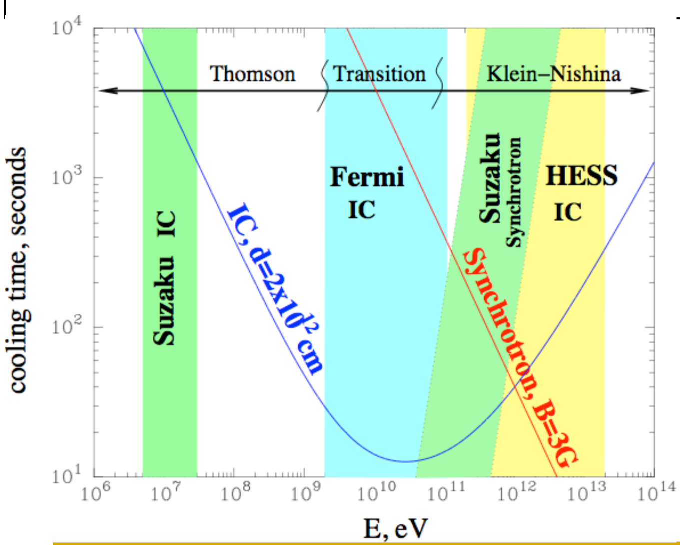
works as a perfect TeV clock
and an extreme accelerator

close to inferior conjuction - maximum
close to superior conjuction – minimum





modulation of the gamma-ray signal? *a quite natural reason (because of γ–γ absorption), but we see a different picture… anisotropic IC scattering? yes, but perhaps some additional factors (adiabatic losses, modest Doppler boosting) also play a non-negligible role*



can electrons be accelerated to energies up to 20 TeV in presence of dense radiation? *yes, but accelerator should not be located deep inside binary system; even at the edge of the system* $\eta < 10$ => *although* the origin of the compact object is not yet known (pulsar or BH) and we do not understand many details,.

do we deal with proton PeVatrons?

Future measurements - timing and spectrum up to and beyond 100 TeV

Bykov et al - acceleration of > 1 PeV protons in binary systems ?

PeV Photon and Neutrino Flares from Galactic Gamma-Ray Binaries

Abstract: The high-energy radiation from short period binaries containing a massive star with a compact relativistic companion was detected from radio to TeV γ-rays. We show here that PeV regime protons can be efficiently accelerated in the regions of collision of relativistic outflows of a compact object with stellar winds in these systems. The accelerated proton spectra in the presented Monte Carlo model have an upturn in the PeV regime and can provide very hard spectra of sub-PeV photons and neutrinos by photomeson processes in the stellar radiation field. The recent report of a possible sub-PeV γ-ray flare in coincidence with a high-energy neutrino can be understood in the frame of this model. The γ-ray binaries may contribute substantially to the Galactic component of the detected high-energy neutrino flux

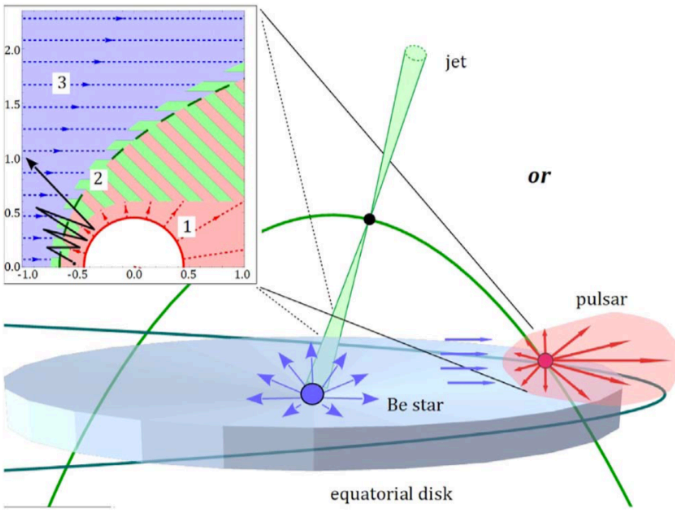


Figure 1. Sketch of the interaction of mildly relativistic flows produced by a compact object (pulsar or black hole) with the equatorial disk of a Be star. Inset: spatial structure of the Monte Carlo model diffusion zones. (1) Pink: shocked pulsar wind. (2) Cross-hatched with green: zone around the contact discontinuity (approximate position—dashed green line). (3) Blue: stellar wind. The white zone is the cold pulsar wind. The red solid line shows the termination shock of the pulsar wind, dashed lines with arrows are the directions of flows. Lengths are normalized to 2.5×10^{14} cm. The black imposed polygonal line illustrates a trajectory of a particle accelerated in the colliding flows.

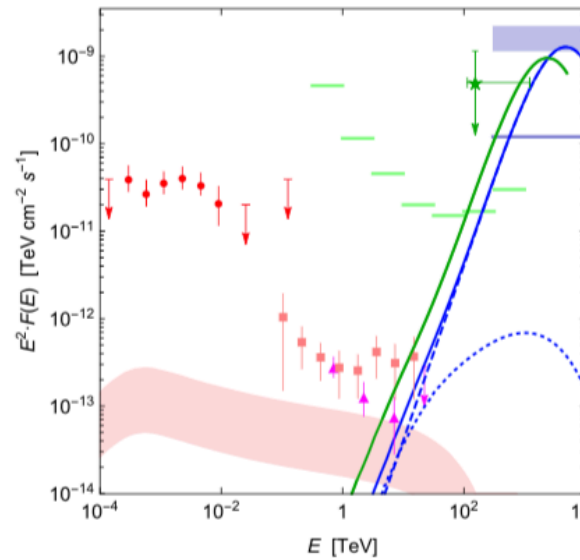
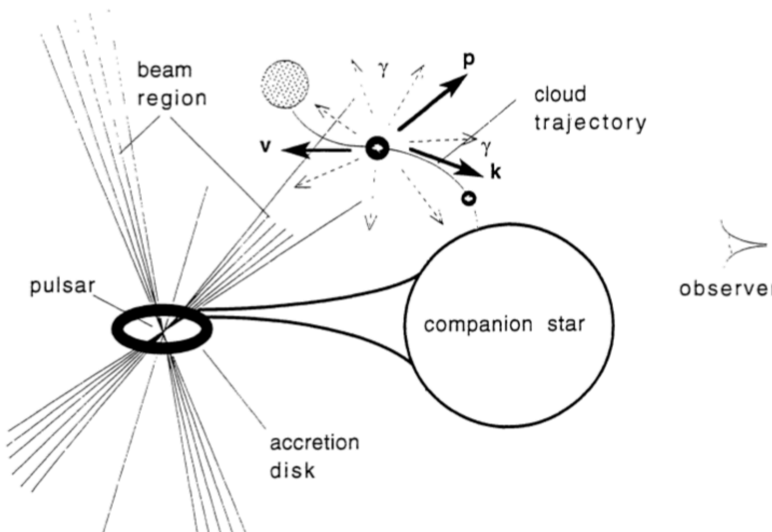


Figure 3. High-energy emissions from the source in the Cygnus region. Blue: photons from the total (full curve) simulated flare flux; contributions from p–p (dotted) and p–γ (dashed) interactions of protons accelerated in colliding winds. Red shaded area: photons from the p–p interaction of the injection spectrum protons (within the source parameter uncertainties). Violet shaded area: Carpet-2 flare flux. Magenta and pink data points: VERITAS and MAGIC steady-state fluxes (Abeysekara et al. 2018); red points in the GeV range are Fermi/LAT steady-state data (Chernyakova et al. 2020). Violet horizontal line: Carpet-2 95% CL upper limit on the steady-state flux. Green: neutrinos' estimated total flare flux (full curve); horizontal lines represent the 90% CL IceCube (IceCube Collaboration et al. 2021) upper limit on the steady-state neutrino flux of Cyg X-3, which is expected to be similar to that of PSR J2032 +4127. Star: an order-of-magnitude estimate (Dzhappuev et al. 2021) of the flare flux from the detection of one 150 TeV neutrino (IceCube Collaboration 2020).

flares ? - because of possible variation of magnetic field, conditions in the disk

an interesting (old) model of VHE/UHE episodic gamma-rays from binaries

Episodic VHE/UHE gamma-ray emission: *Moving (fragile) target crosses proton beam*



$$\frac{\Delta\nu}{\nu_0} = \beta\,\frac{\cos(\mathbf{k}\wedge\mathbf{v}) - \cos(\mathbf{p}\wedge\mathbf{v})}{1 - \beta\cos(\mathbf{k}\wedge\mathbf{v})}$$

Fig. 1. The cartoon of the scenario "moving target crosses beam". The shift of the frequency of pulsations relative to the spin frequency of the pulsar, $\Delta\nu/\nu_0$, due to the double Doppler effect is shown, where **p** and **v** are the unit vectors in directions of the proton beam and the cloud velocity, respectively, and **k** is the unit vector in the direction of the photon pointed from the cloud to observer. The frequency shift, depending on the orientation of **p** and **k** relative to **v** , is of order of $\beta = v/c$; $\Delta\nu = 0$ if $\mathbf{p} \parallel \mathbf{k}$.

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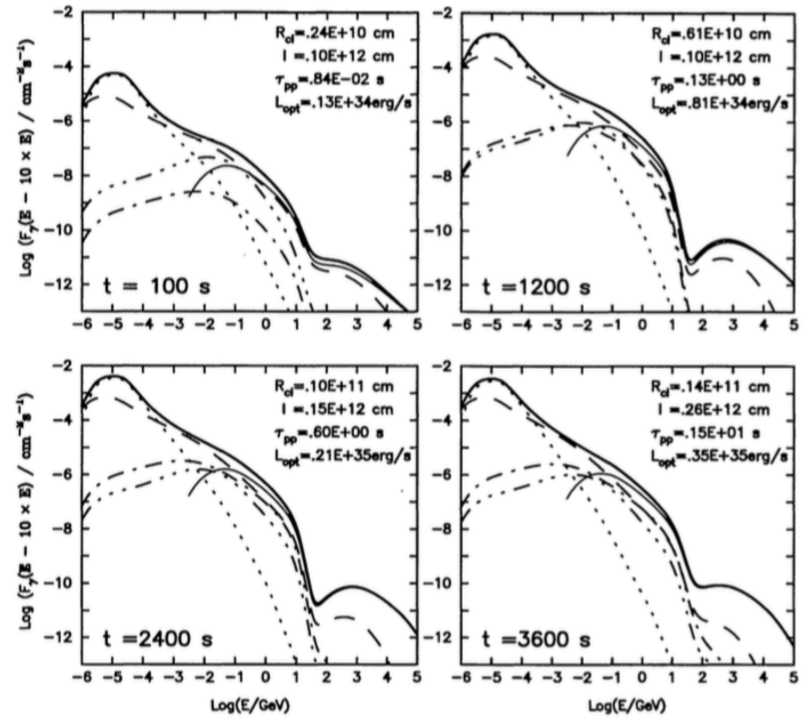

Fig. 2. The evolution of the radiation spectra expected during a γ-ray episode from Her X-1. The fluxes and principle parameters of the cloud (the radius R_{cl}, the distance l from the pulsar, the $p-p$ interaction time τ_{pp}, and the thermal optical luminosity within $300-600$ nm are presented at 4 different instances t after entrance of the gas cloud into the propagation cone of the beam. The contributions of different processes are shown by solid line (π^0 decays), dashed line (synchrotron radiation), dot-dashed line (inverse Compton), fancy line (electron bremsstrahlung), dotted line (multiple Compton scattered radiation in the cold gas). The heavy solid line is the total spectrum emerging from the cloud. The mass of the cloud, its initial radius and distance from the pulsar are $M_{cl} = 2 \cdot 10^{22}$ g, $R_{cl} = 2 \cdot 10^9$ cm, and $l = 10^{11}$ cm, respectively. The luminosity of the proton beam is $L_p = 2 \cdot 10^{39}$ erg s^{-1}sr^{-1}. The distance to Her X-1 is taken $d = 3$ kpc.

Summary:

LHAASO discovered that Milky Way is full of PeVatrons (a big surprise!). Possible associations of the already detected PeVatrons with PWNe (Crab), Stellar Clusters (Cygnus), SNRs (“echoes" from GMCs ?), but most of the reported PeVatrons are still not firmly identified.

Next few years, we anticipate a substantial (dramatic?) increase in the number of detected PeVatrons and exciting identifications with known astronomical objects with important implications generally supporting the current paradigms and concepts. Still, we should be prepared for surprises and challenges…