2nd LHAASO Symposium, Hong Kong, March 20-25, 2025

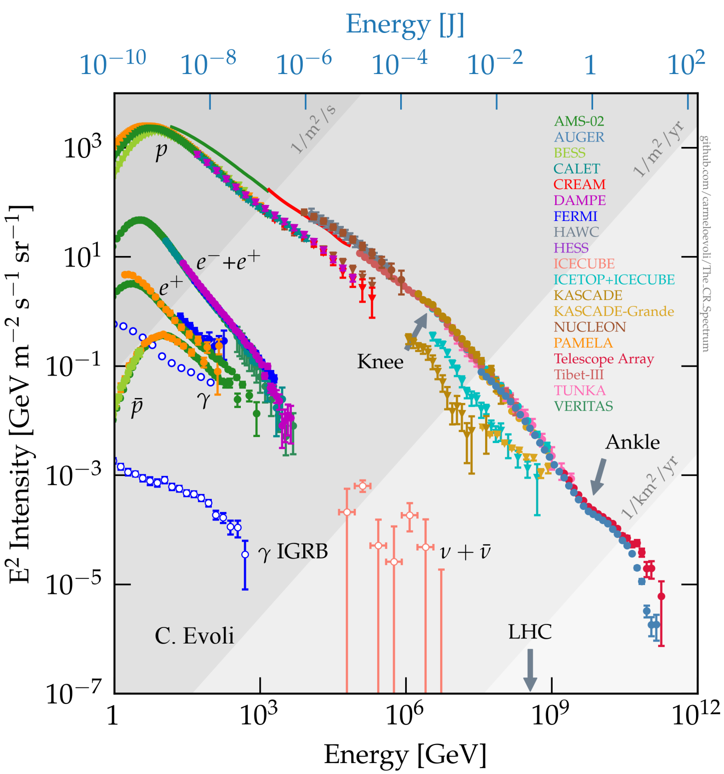
Super-Accreting Microquasars: Super PeVatron Candidates in Milky Way ?

Felix Aharonian

Henri Cheng International Conference Center, March 21, 2025

"After 100+ years of the discovery of cosmic rays, their origin remains a mystery"

somewhat exaggerated assessment - but of course there are serious challenges …



| below 10^{15} eV - **G** | beyond 10^{18} eV - **EXG** |

between 10^{15}-10^{18} eV **G/EXG ?**

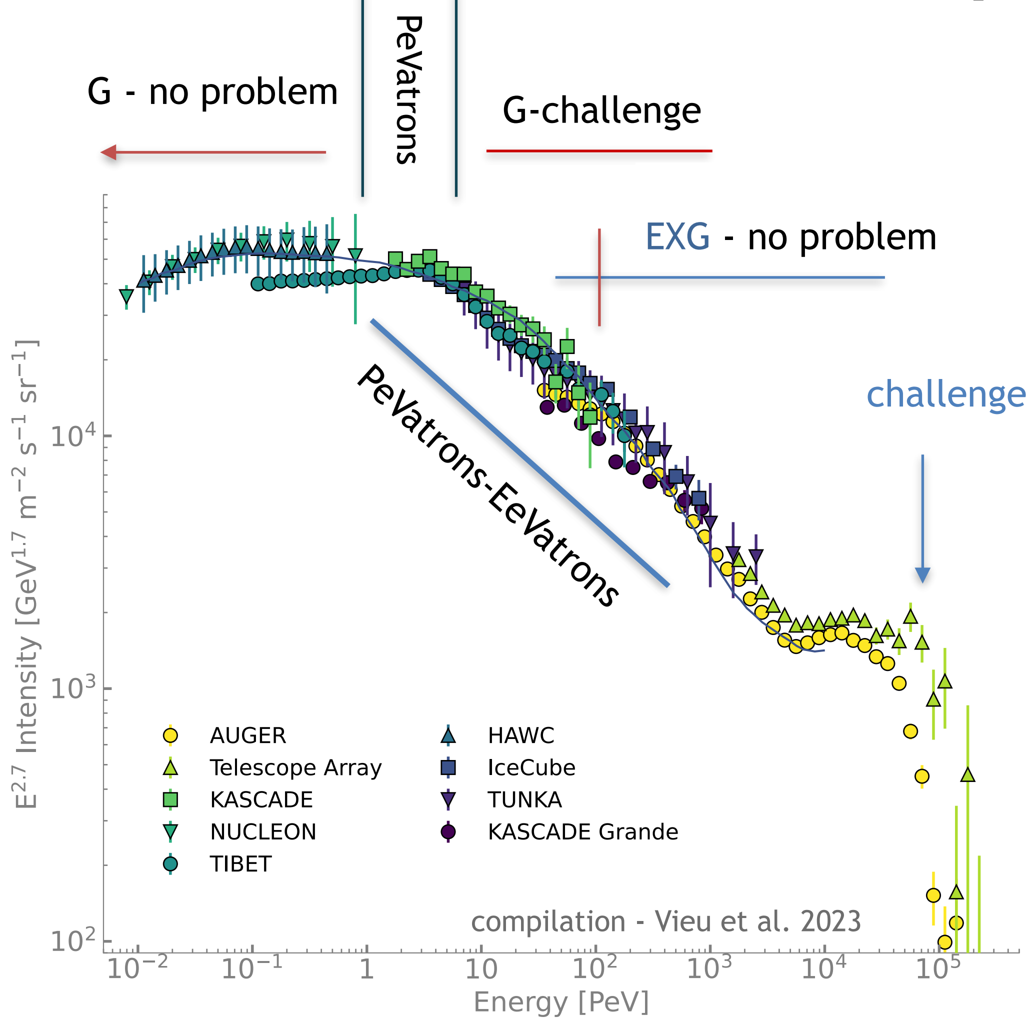
until recently we faced a challenge and uncertainty regarding contributors to the "knee", but now we have several candidates:
SNR, Stellar Clusters, PWNe, SMBH in GC, Micoquasars

latest findings have revealed new possibilities that allow for relaxation, at the same time, complicate the overall picture with outstanding questions

- SNRs - no direct evidence but nearby regions as "smoking guns"?
- Stellar Clusters - more representatives detected >100 TeV needed
- PWNe (Crab?) - rather "no" than "yes" ($e^{\pm}$ winds, lumonosities)
- Sgr A* - exciting, but what about 3 ultracompact clusters in GC
- Microquasars - emerged as plausible candidates with several attractive features - jet power & speed (!)

an intrigue remains for the energy interval 10-100 PeV

10 PeV - 100 PeV: most problematic energy range



“challengness” level of explanation of Cosmic Rays

two options:

- Galactic Pevatrons contributing to the knee but not much beyond

  above 10 PeV - EXG from nearby objects - Galaxy Clusters, Starburst Galaxies, nearby AGN - M87/Cen A

- Galactic Super-PeVatrons up to 100 PeV or even 1 EeV

  above 100 PeV (1 EeV) EXG

Galactic Super-Pevatrons:
protons at least up to 0.1 EeV ?

CR production rate above 3 PeV:
10^{38} erg/s – 10^{39} erg/s

an order of magnitude uncerttainty caused by uncetainty in the diffusion coefficient intex $D(E) \propto E^{\delta}$; but the energetics is not a serious problem, the real challenge is highest energy E_{max}

Requirements to Galactic Super PeVatrons

$E_{max} = Ze\,B\beta R$

$L_B = \frac{B^2}{4\pi}\beta c\,A$ - Pointig flux

$A_{eff} = \omega\pi R^2$

ω - geometrical factor of oder of 1

$L_K = (\Gamma - 1)\rho c^2\beta c\,A \equiv L_B/\sigma$

$\sigma = B^2/[4\pi(\Gamma - 1)\rho c^2]\,\Gamma$
bulk Lorentz factor

$\Rightarrow$

$E_{max} \approx 100Z\,(\sigma/\omega)^{1/2}\,(\beta L_{K,39})^{1/2}$ PeV

$L_K \geq 10^{37}\,(E_{max}/10\,\mathrm{PeV})^2\,(\beta\sigma/\omega)^{-1}$ erg/s

these conditions silently assume that acceleration proceeds with maximum rate: $\dot{E} = e\mathscr{E}c = \eta eBc$

$\mathscr{E}_{eff} = \eta B$ projection of the electric field on the particle's trajectory averageds as particle moves along this trajectory

$\eta \leq 1$ - acceleration efficiency

CR acceleration beyond 100 PeV in Milky Way more challenging than beyond 100 EeV by powerful AGN jets !

Galactic Super PeVatron: E_{max} significantly exceeding 10 PeV

$$\beta L_K \sim 10^{37} (E_{max}/10\,\mathrm{PeV})^2 \sigma^{-1} \eta^{-1}\,\mathrm{erg/s}$$

relativistic outflows $\beta \sim 1$ optimal magnitzation $\sigma \sim 0.5$ extreme accelerator $\eta = 1$

Kinetic Energy Power $10^{39}\,\mathrm{erg/s}$ for $E_{max} \sim 100\,\mathrm{PeV}$

$10^{41}\,\mathrm{erg/s}$ for $E_{max} \sim 1\,\mathrm{EeV}$

Super PeVatrons:

extreme accelerators associated with *highly magnetized relativistic outflow*

with mechanical power exceeding $10^{39}\,\mathrm{erg/s}$ more realistically $10^{40}\,\mathrm{erg/s}$

this requirement aplies to *individual objects*

required power is relevant to episodic ("high state") activity (as well)

even with 10 % of duty cicle of "high states", only a few Super PeVatrons needed to explain the local Cosmic Ray flux above the "knee" assuming $\dot{W}_{CR} \sim 0.1 L_K$

questions beyond the origin of local CRs: *physics of* Extreme Accelerators - EA

cosmic facilities where acceleration proceeds with efficiency close to 100%

- fraction of available energy converted to nonthermal particles
  in PWNe and perhaps also in SNRs can be as large as 50 %
- maximum possible energy achieved by individual particles
  acceleration rate close to the maximum (theoretical) marjin

acceleration rate: $\dot{E} = e\mathscr{E}c = \eta eBc \quad \eta = 1$ is determined by classical ED & ideal MHD

combined with the Synchrotron energy lose rate => E_{max}

radiation signature: synch. peak at $h\nu = \frac{9}{4}\frac{mc^2}{\alpha_f}\eta$

($\alpha_f = 1/137$, m - particle mass)

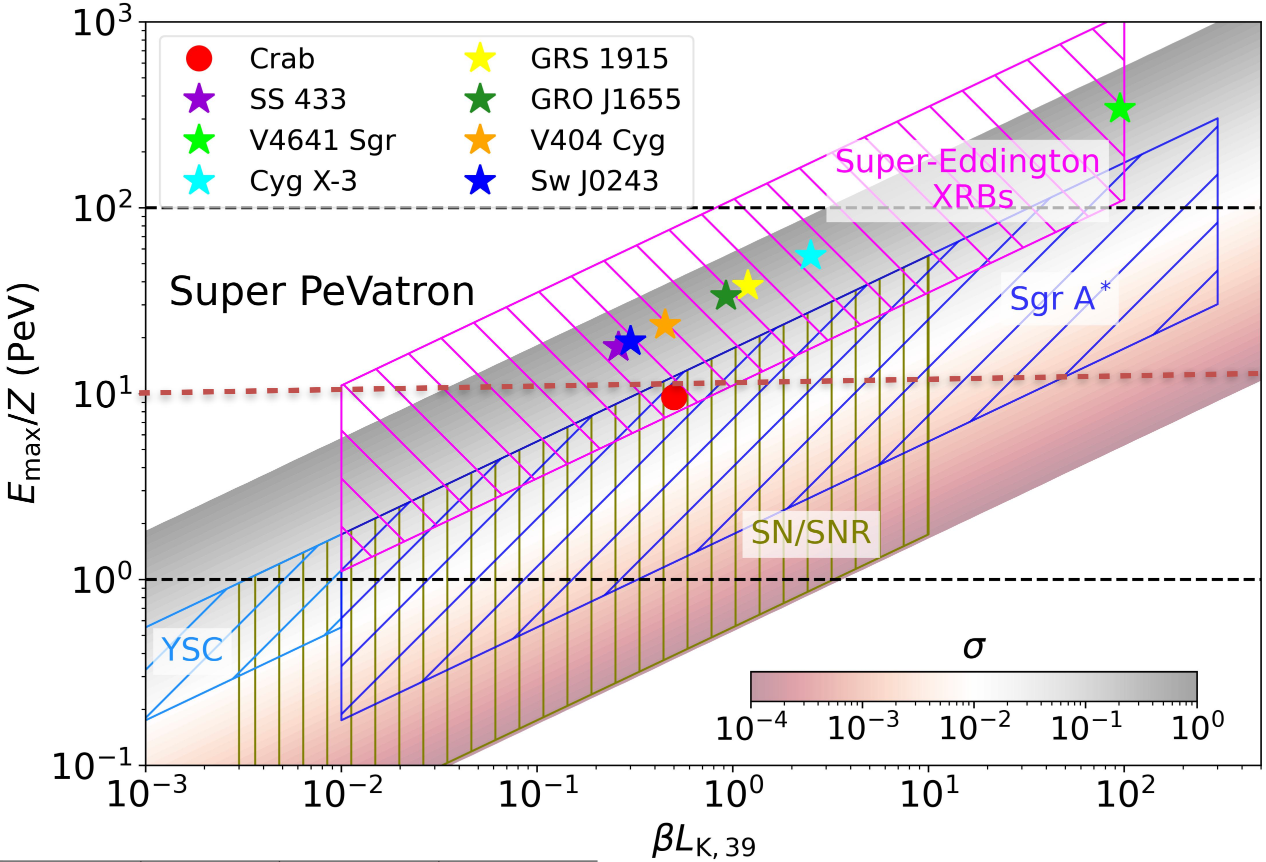
electrons synchrotron ≈ 0.15 GeV proton synchrotron: ≈ 0.3 TeV

Crab Nebula is (almost) EA $h\nu_{synch} \geq 10$MeV; during flares ≥ 1GeV;

more robust conclusion based on the detection of > 1 PeV photons (LHAASO)

Blazars can be EAs? if one interprets TeV emissioin as proton-synchrotron

Potential Super Pevatrons in Milky Way



J.Wang, B.Reville, FA

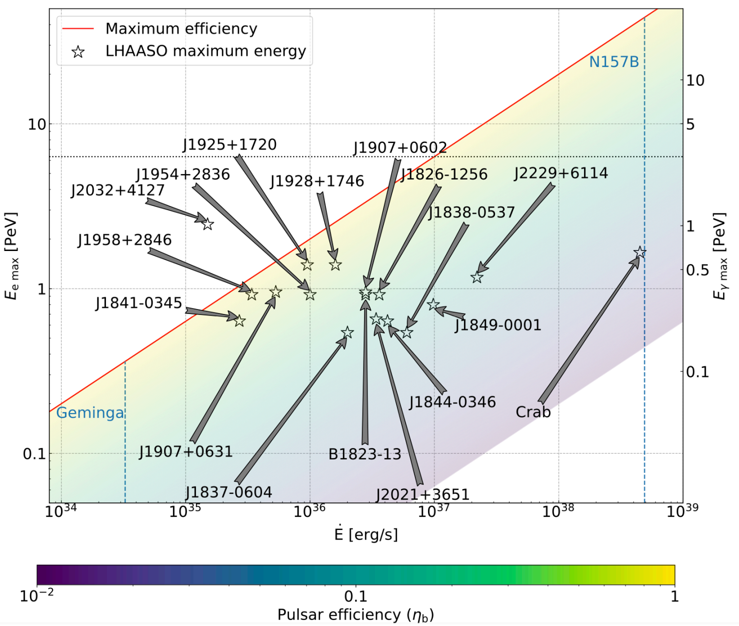
Sources	Power (10^{39} erg/s)	Velocity (c)	Magnetization	E_{max}/Z (PeV)
YSC[a]	$0.1-1$	$0.003-0.01$	$0.01-0.1$	$0.1-2$
SN/SNR[b]	$0.1-10^3$	$0.03-0.1$	$10^{-4}-0.1$	$0.03-55$
Sgr A* [c]	$10-3\times10^3$	$10^{-3}-0.1$	$10^{-3}-0.1$	$0.2-300$
XRB[d]	$0.1-10^2$	$0.1-1$	$0.01-1$	$1-10^3$
Carb[e]	0.5	1	0.06	10
SS 433[f]	1	0.26	0.1	$18\sigma_{-1}^{1/2}$
V4641 Sgr[g]	10^2	0.95	0.1	$350\sigma_{-1}^{1/2}$
Cyg X-3[h]	5	0.5	0.1	$55\sigma_{-1}^{1/2}$
GRS 1915+105[i]	1.7	0.95	0.1	$31\sigma_{-1}^{1/2}$
GRO J1655-40[j]	1	0.92	0.1	$34\sigma_{-1}^{1/2}$
V404 Cyg[k]	0.9	0.5	0.1	$23\sigma_{-1}^{1/2}$
Swift J0243.6+6124[l]	1.5	0.2	0.1	$19\sigma_{-1}^{1/2}$

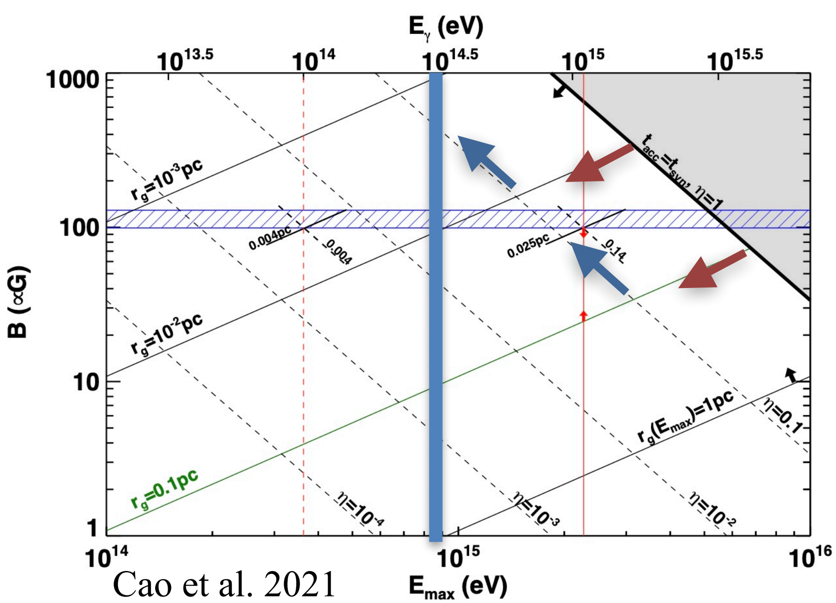
$E \rightarrow E_{max}$ $\eta \rightarrow 1$

extreme acceleration regime

a comment on PWNe (see talk by Ruoyu Liu at this meeting)

Ona De Wilhelmi et al. 2022





Cao et al. 2021

$$E_{max} \approx 20\,\sigma_B^{1/2}\,L_{38}^{1/2}\ \mathrm{PeV}$$

no energy losses - works as long as $t_{acc} \leq t_{synch}$ and requires $\sigma \to 1$

PWNe with $L_{SD} \geq 10^{37}$ erg/s: ***potential electron PeVatrons***

upper limit $E_{e,max}$ based on two conditions:

synchrotron loss domionated

$$E_{e,max} \approx 6\,\eta^{1/2}(B/100\mu G)^{-1/2}\ \mathrm{PeV}$$

accelerator size-dominated

$$E_{e,max} \leq 1\,(B/1\,\mu G)\,(R/1\,pc)\ \mathrm{PeV}$$

PWNe - at early stages $L_{SD} \geq 10^{39}$ erg/s

=> Proton Super PeVatrons (?)

Definitions: γ-rays above 100 TeV => UHE γ-rays

UHE gamma-ray sources - stastically significant detections above 100 TeV

PeVatrons - objects accelerating protons/electrons to > 1 PeV but not $E_0 \to 1\,\mathrm{PeV}$ from the "power-law+exponential cutoff" fits

Radiation mechanisms: 'π^0 - decay' - pp and pγ interactions in both $E_\gamma \approx 0.1 E_p$

'IC' - inverson Compton on 2.7 K MBR

30 TeV - 3 PeV: $E_e \approx 0.37 (E_\gamma / 100\mathrm{TeV})^{0.7}\,\mathrm{PeV}$

detection of UHE γ-rays implies presence of proton or electron PeVatrons!

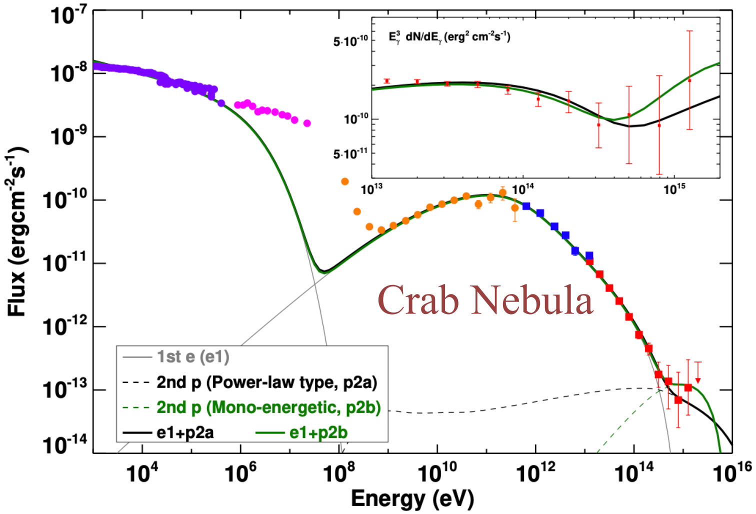
UHE γ-ray souce do not imply detection of a PeVatron but localization of a PeV γ-ray emitter in association with PeVatron(s) - it is crucial to derive the spatial and energy distributions of e/p

Energy Distributions of electrons and protons - straightforward (model-independent) & accurate !

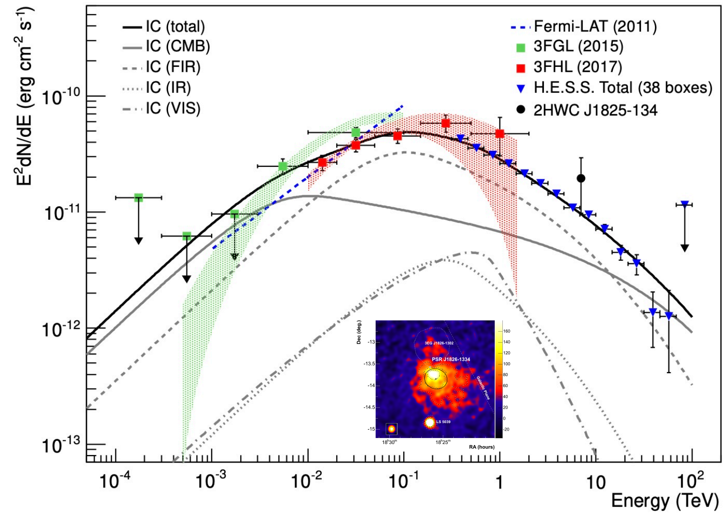
Spatial Distribution of electrons $\equiv$ spatial distribution of γ-rays

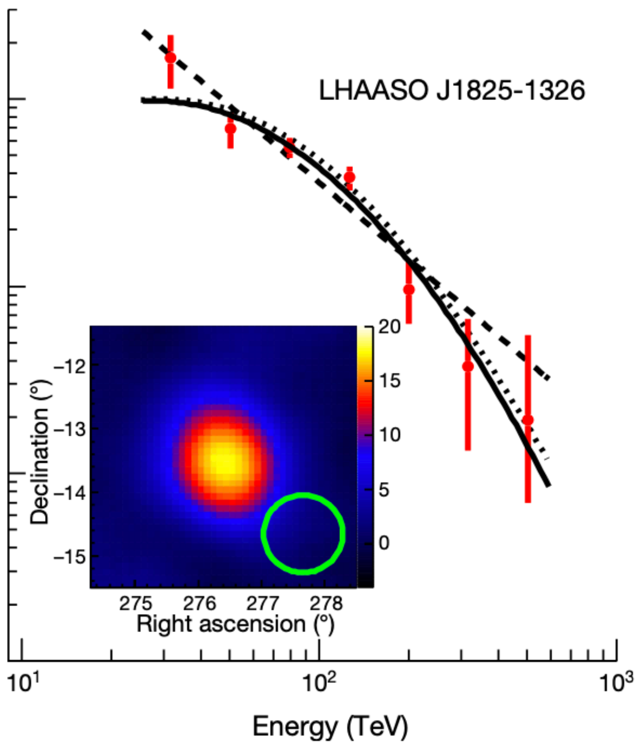
Spatial Distribution of protons $n_\gamma(r) \propto n_p(r)\, n_{gas}(r)$ - gas distribution is a key component

LHAASO collaboration 2021

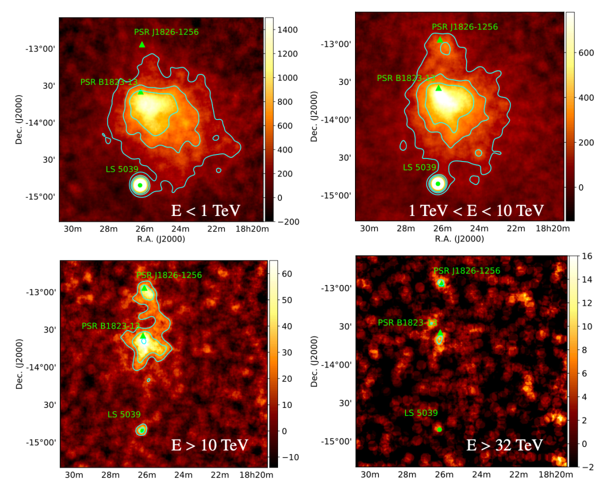


H.E.S.S. collaboration 2019

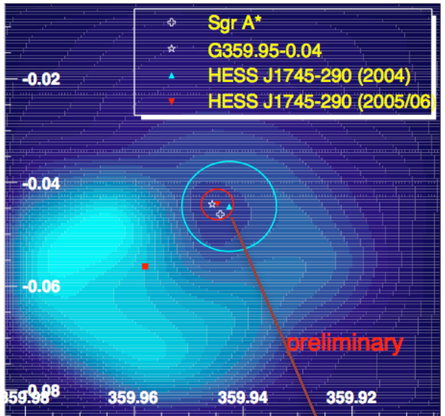




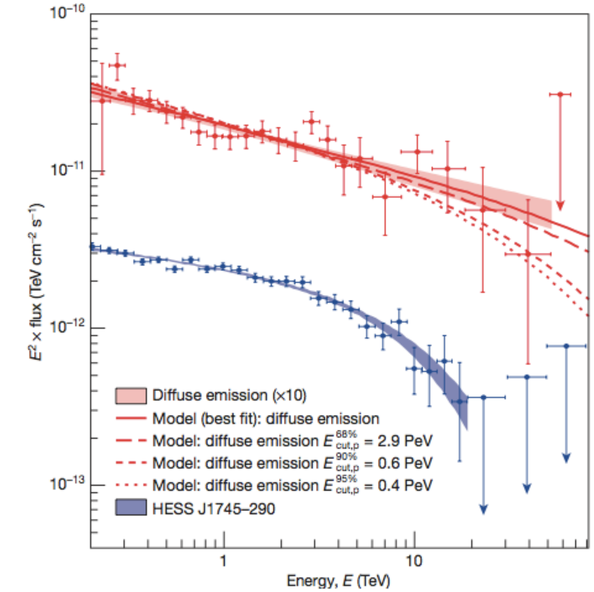
$E_\gamma \sim 500$ TeV gamma-rays => $E_e \geq 1$ PeV electrons accelerated in a PWN or protons?



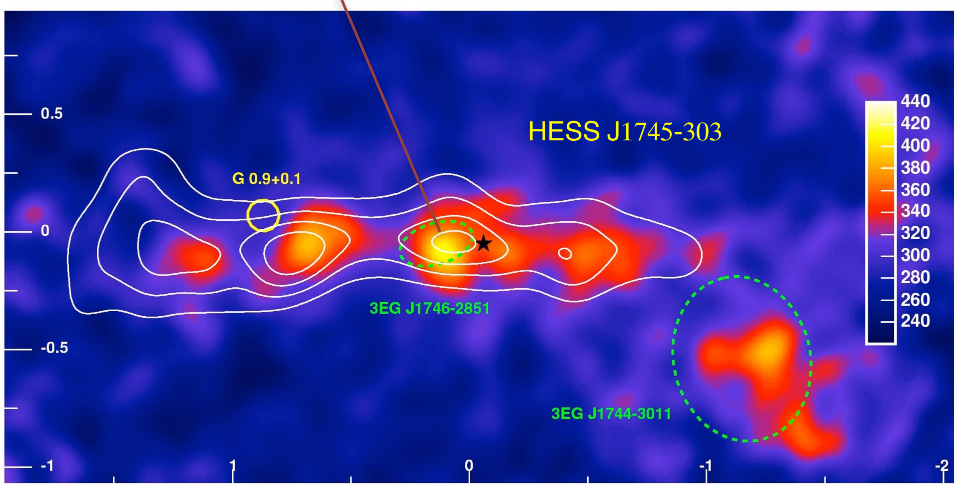
a comment on SMBH in GC

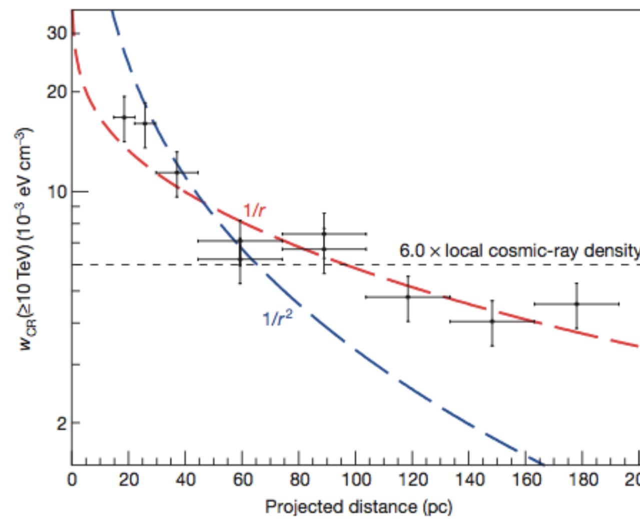


First Pevatron(s) claimed - based on diffuse emission of CMZ in Galactic Center



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



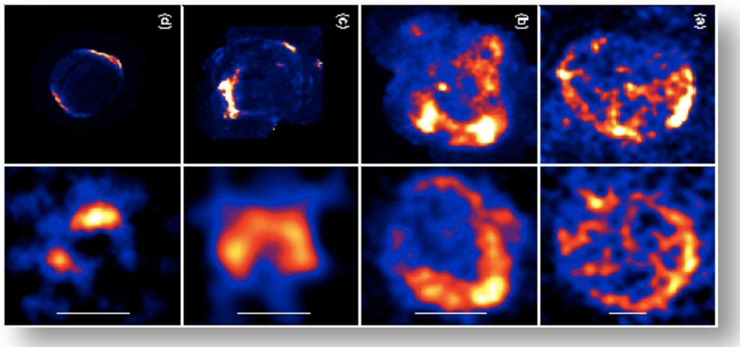


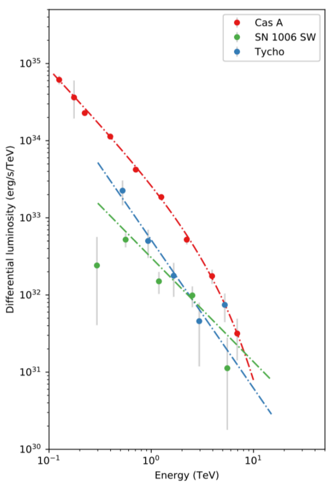
SMBC in GC (Sgr A*) operating as a PeVatron ? potentially $L_K \rightarrow 10^{44}$ erg/s **!**

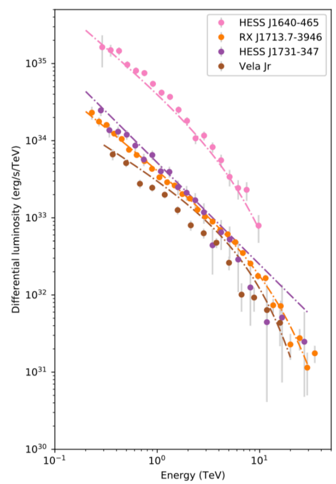
or particles are accelerated in the Arches, Quintuplet, Nuclear ultra-compact YMCs ?

a comment on SNRs (see talks by Zhen Cao and Pasquale Blasi at this meeting)

young SNRs >1 TeV - steep spectra; Γ= 2.3-2.6





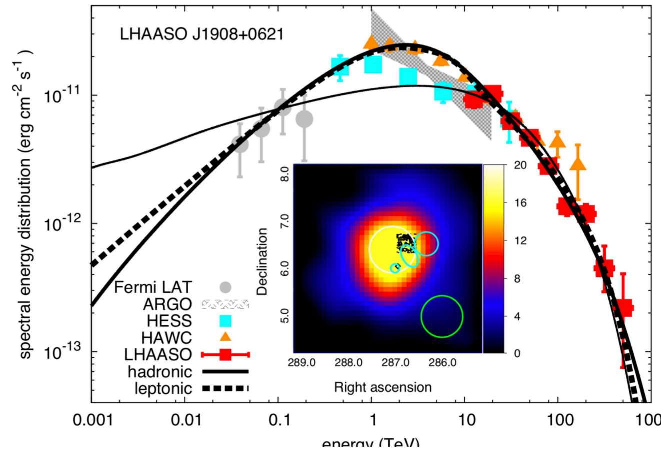


steep TeV spectra - trouble?

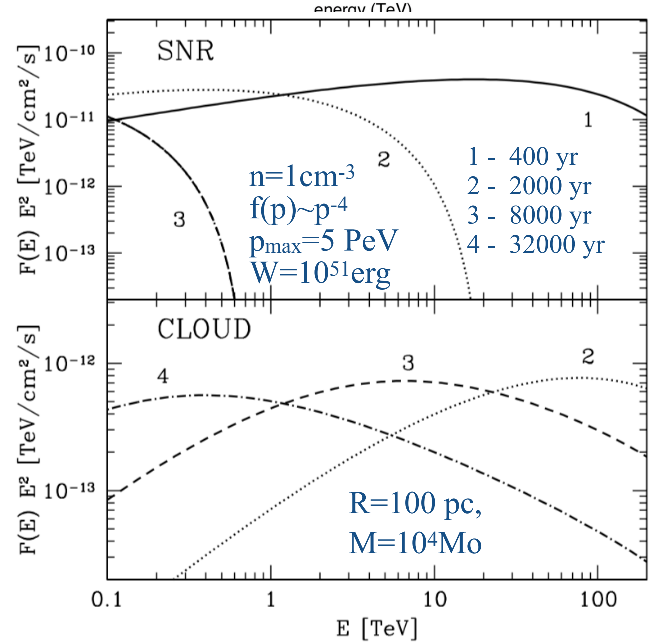
- not dramatic from perspsctives of theory;
- premature to discard SNRs as PeVatrons

challenging for observations > 100 TeV

GMCs in vicinity of middle-aged SNRs: "smoking gun" with spectra >> 100 TeV



Cao et al. 2021



Gabici&FA

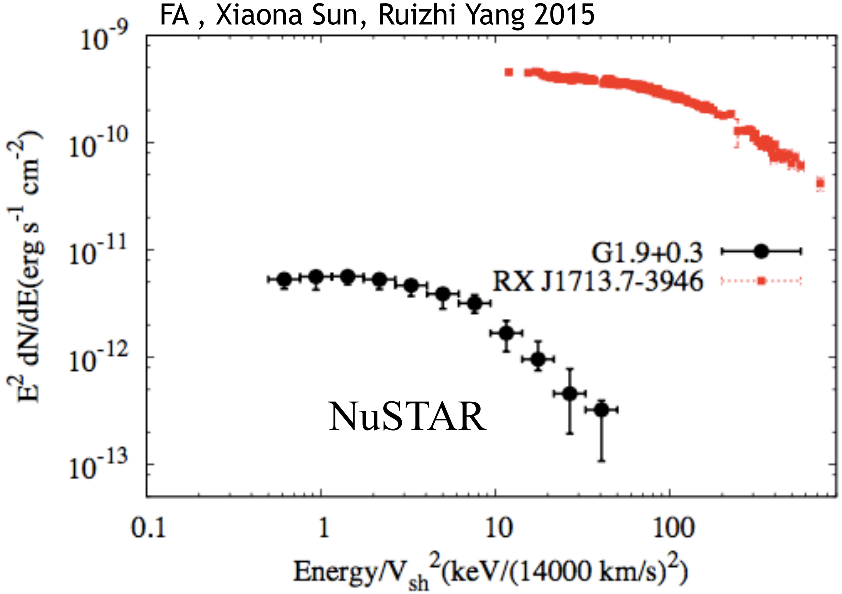
Very young SNRs as Super PeVatrons?

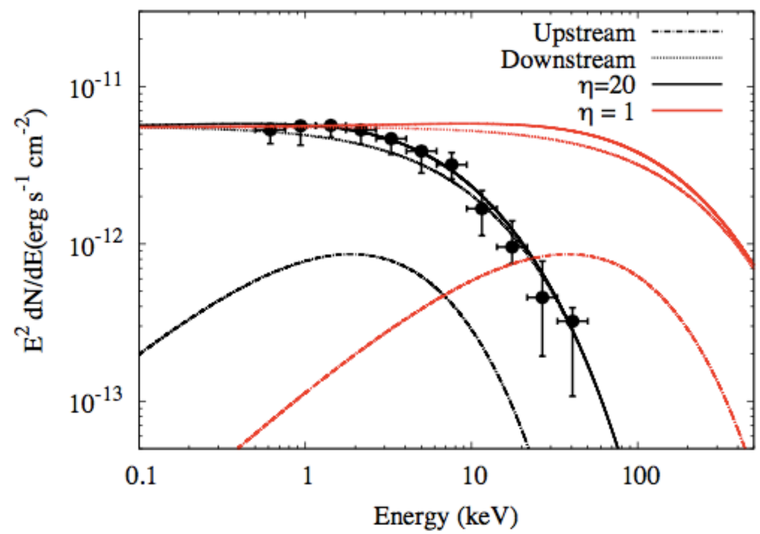
G1.9+0.3 - youngest (100yr-old) known SNR in Galaxy
with the current shock speed $v \approx 14000$ km/s

$h\nu_{max} \simeq 1\,(v_{shok}/3000\,\mathrm{km/s})^2\,\mathrm{keV}$ independent of B-field (!)

in the Bohm diffusion limit the peak should be around 20 keV but is detected at 1 keV as SNR RXJ1713 (but with a speed ≈ 4000 km/s)

FA , Xiaona Sun, Ruizhi Yang 2015





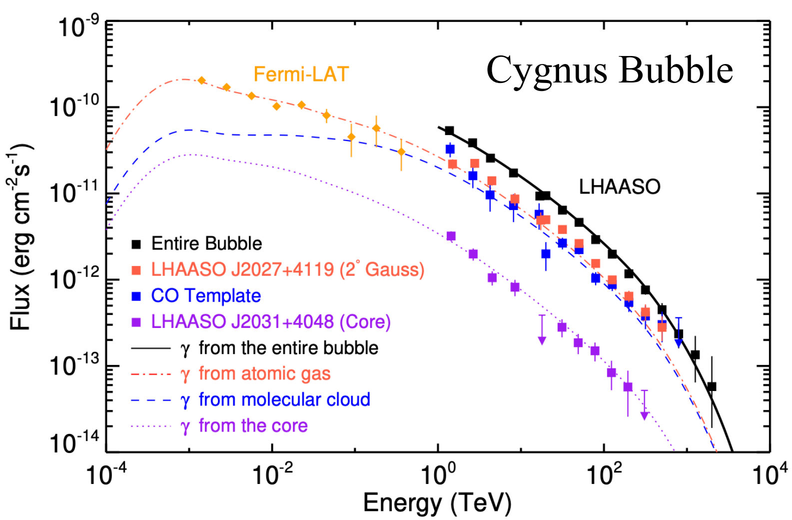
G1.9+0.3 does not operate as PeVatron (as many other young SNRs as well - Tsuji et al 2021) !

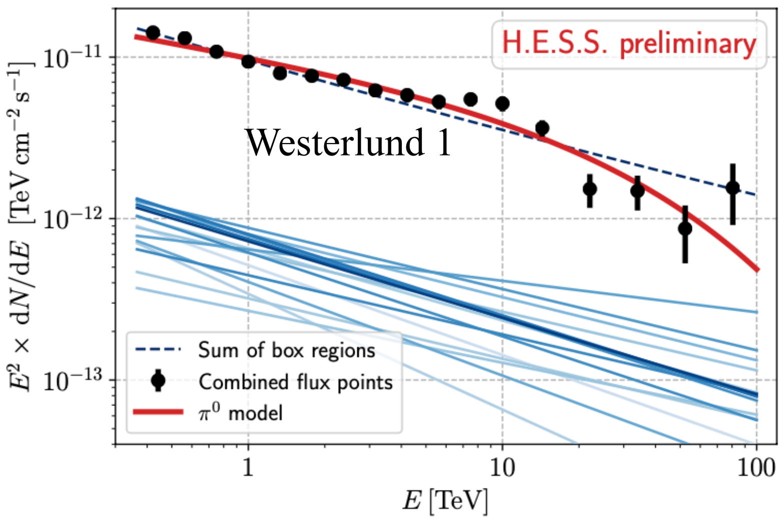
very disappointing… should be taken seriously a comment on Stellar Clusters (see talk by Giovanni Morlino)

Extended gamma-ray bubbles surrounding Clusters of Young Massive Stars

West 1, West 2, 30 Dor C (in LMC) Cygnus OB2, W43, NGC3603, …

also possibly Arches, Quintuplet and Nuclear ultracompact clusters (?)





Theory: PeVatrons ? Yes

Super PeVatrons? - challenging despite all atrtractive features

what to do with Cygnus Bubble ?

X-ray Binaries

Four decades ago, compact binary systems, in particular Cyg X-3, have been claimed to be TeV/PeV γ-ray sources. However, after failing to confirm the early reports, they have no longer been treated as important targets for γ-ray astronomy. Nevertheless… see e.g.

A MODEL OF PULSED GAMMA RADIATION FROM THE X-RAY BINARY HERCULES X-l/HZ HERCULIS

F. A. Aharonian and A. M. Atoyan

Abstract:

A model of pulsed very high energy and ultrahigh energy y-radiation from X-ray binaries is proposed, which implies that the γ-rays are due to the bombardment of a cloud ejected from the companion normal star by the relativistic proton beam stationarily accelerated by the pulsar. In the framework of this model all the peculiarities of the γ-radiation observed from the X-ray binary Hercules X-l/HZ Herculis are naturally explained, namely, (a) the y-pulsation frequency shift with respect to the X-ray frequency; (b) the episodic nature of γ-ray events with typical burst duration < 1 hr; (c) the absence of any correlation between the γ-ray events and the orbital phase of the binary; and (d) the observation of γ -ray events in the phase of the deep eclipse of the pulsar. The expected γ-ray spectra in a wide energy range of 100 MeV < E < 1 PeV, as well as the possibilities of experimental verification of the model proposed, are discussed.

Astrophysical Journal v.381, p.220, 1991

"Moving Fragile Target Crosses Relativistic Particle Beam"

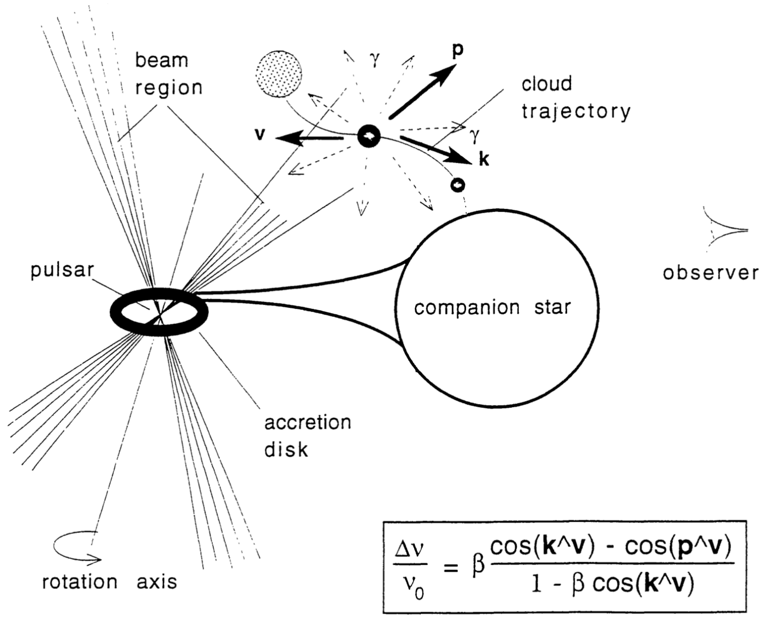


Fig. 1. The cartoon of the scenario "moving target crosses beam". The shift of the frequency of pulsations relative to the spin frequency of the pulsar, $\Delta\nu/\nu_0$, due to the double Doppler effect is shown, where **p** and **v** are the unit vectors in directions of the proton beam and the cloud 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 **p** $\parallel$ **k** .

Microquasars

The stance, however, has been changed after discovery of galactic sources with relativistic jets dubbed Microquasars (GRS 1915, Mirabel and Rodrigez 1994)

paricles can be accelerated and effectively radiate both inside and outsiude binary systems

μQSOs have been trendy sources in mid-1990s/2000s - tens of papers have been written predictiing GeV/TeV gamma-rays primarily from Microquasar jets

also a papers on gamma-rays from extended regions surrounding Microquasars:

- leptonic origin - IC gamma-rays from X-ray lobes of SS433 (FA & Atoyan 1998) *
- hadronic origin - regions surrounding μQSOs (Bosch-Ramon, FA, Paredes 2006) **

* at VHE/UHE energies the efficiency of IC determines by the w_r/w_B ratio (high)

** impact of the μQSO's outflows (winds/jets) on the environment => slow diffusion resulting in reasonably high $\pi^0-\mathrm{decay}$ gamma-ray production efficiency

Hyper-Eddington accretion - regime in which a black hole (neutron star) accretes matter at a rate much beyond the Eddington limit

Nominal Accretion - Eddington limit: $L_{Edd} = \frac{4\pi GMc}{k} = 1.3 \times 10^{39} \, (M/10M_{\odot}) \text{ erg/s}$

Eddington limit arises from the balance between radiation pressure and gravitational attraction

Super-Eddington accretion without significant radiation pressure feedback :

Photon Trapping in Accretion Disks Anisotropic Radiation (Beaming Effects)

Strong Magnetic Fields (Magnetically Arrested Disks)

Optically Thick, Radiatively Inefficient Flows

……..

Outflows & Winds

SS 433: a high priority target of TeV gamma-ray observations

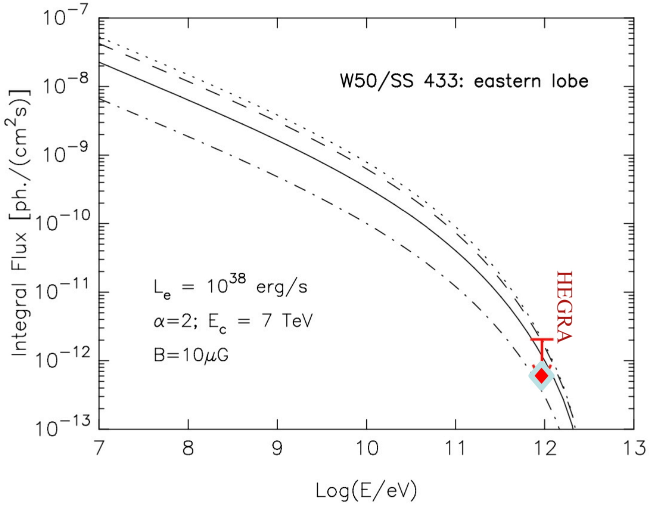
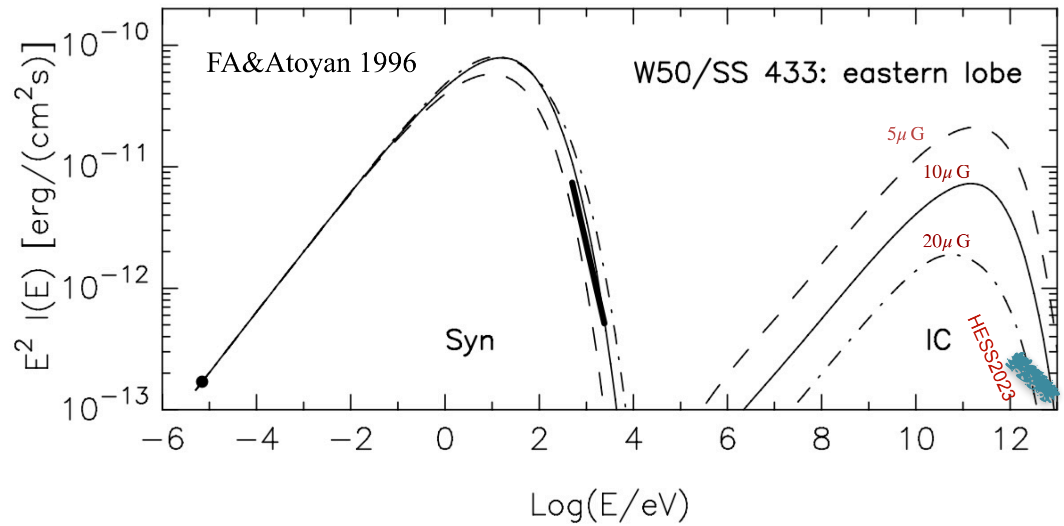
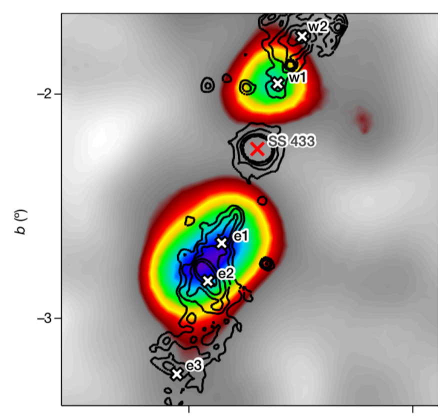


Fig. 7.10 The integral fluxes of γ-rays expected from the direction of the eastern ra
"ear" of W50/SS 433 within different opening angles: 0.1° (dot-dashed), 0.25° (sol
the size of the "ear"), 0.5° (dashed), and 2° (dots). The upper limit on the TeV flux
by the HEGRA IACT system is also shown. (From Aharonian and Atoyan, 1998b).

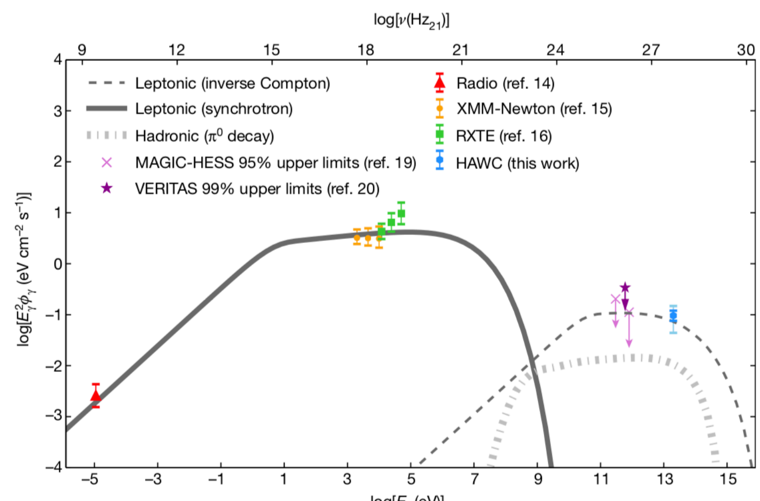


HEGRA : flux u.l. @ 1 TeV $\rightarrow$ B $\leq 19\mu$G

HAWC - single point at 20 TeV
HESS/MAGIC - upper limits
=> spectrum as flat as E^{-2}

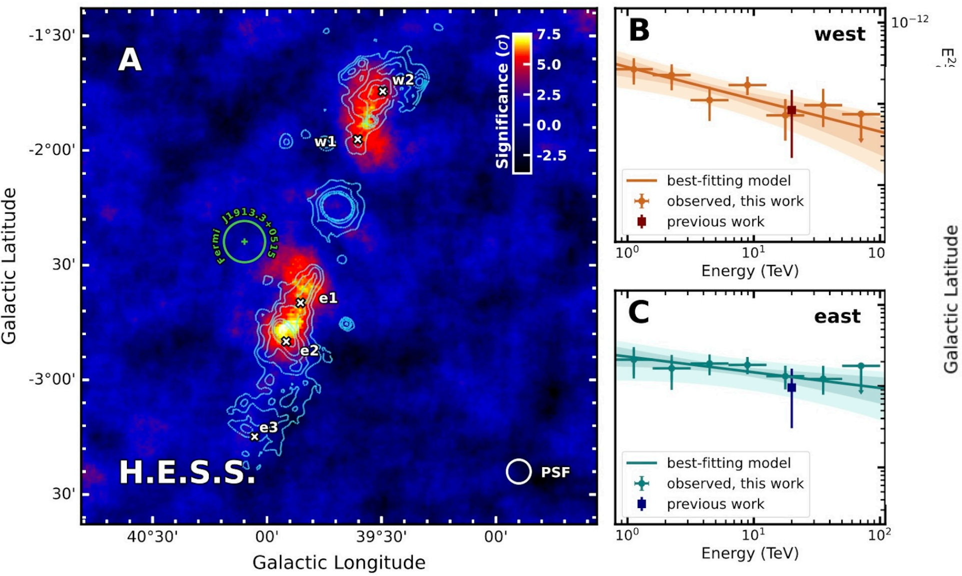


HAWC coll. Nature 2018

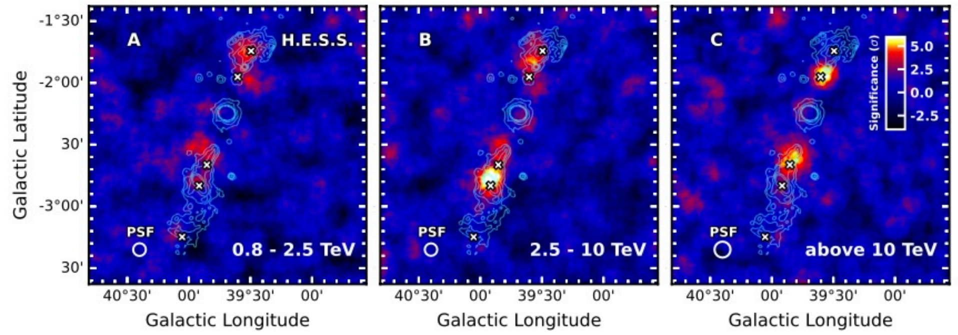


Detection of TeV gamma-rays from X-ray lobes of SS 433

H.E.S.S. collaboration 2023

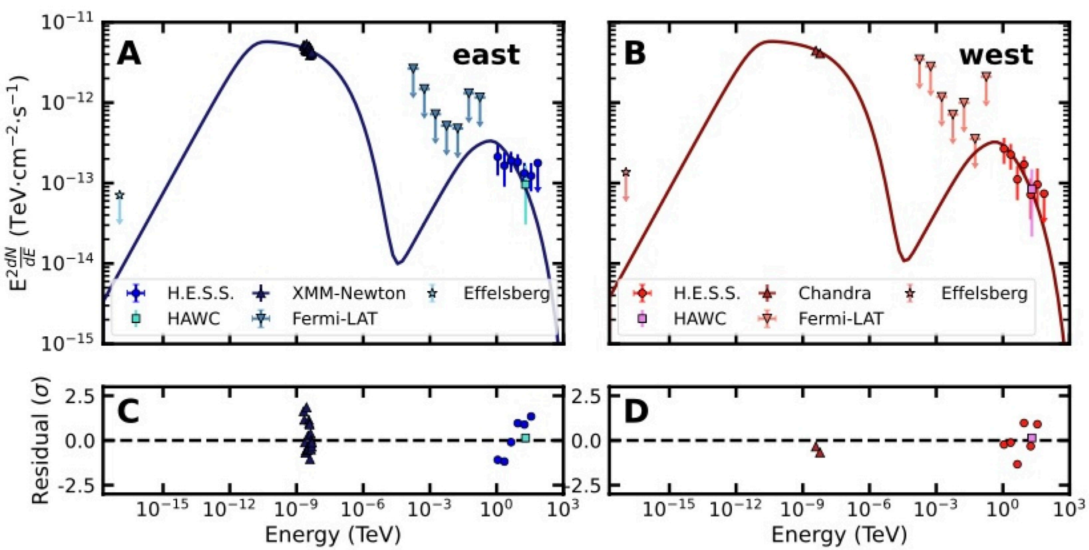


Energy-dependent morphology !



SED fitting with synchrotron and IC radiation of ultrarelativistic electrons

	east	west	shared	fixed
Γ_e	2	2	yes	yes
$E_{\rm cut}$ (TeV)	>200		yes	no
α	$(1.287 \pm 0.029)\cdot 10^{-3}$		yes	no
B (μG)	19.5±2.7	21.1±1.8	no	no



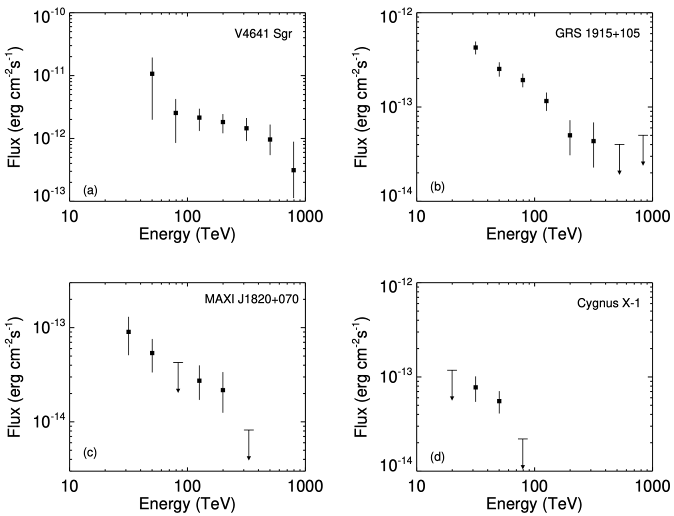
LHAASO 2024

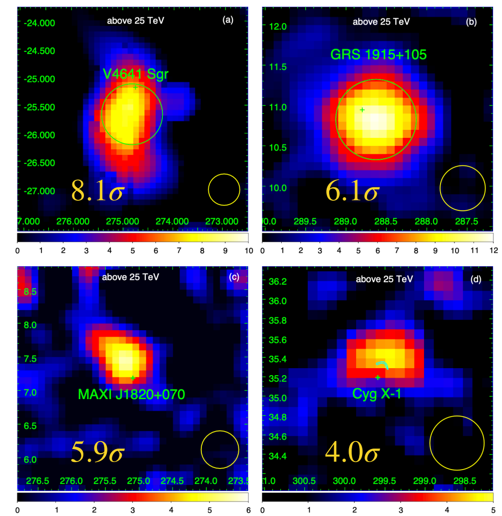
spectra extend out of 100 TeV

IC - still is OK

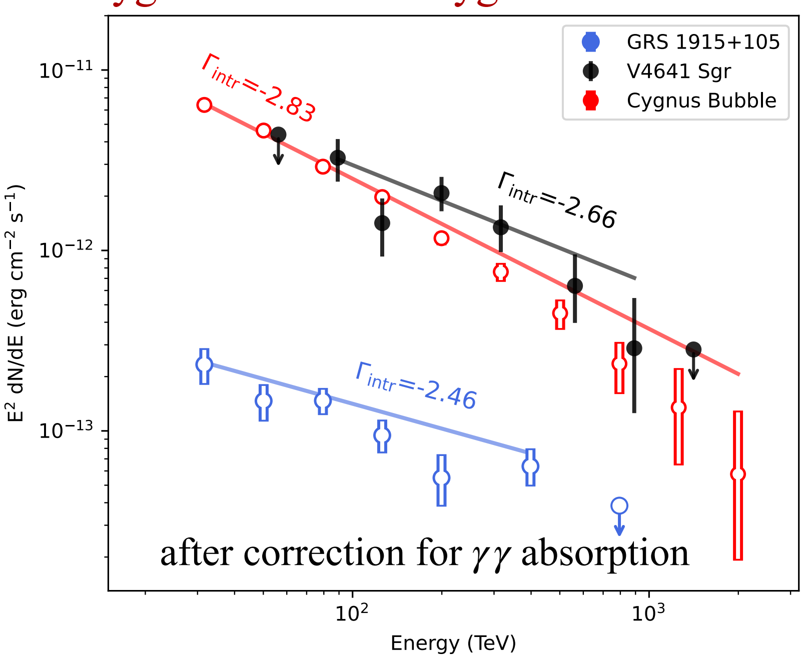
π^0 - not excluded

four more microquasars detected by LHAASO





Cygnus Bubble as Cygnus X-3 Bubble?



Observational & theoretical advantages rather than disadvantages if locating the source furter

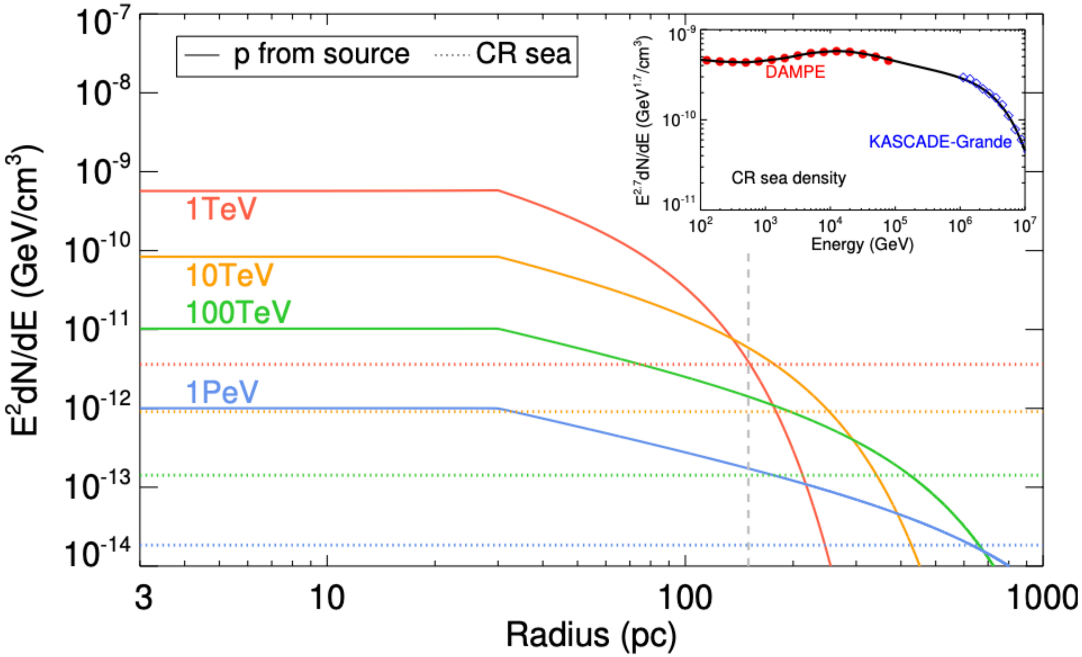
$$L_\gamma(E) = \dot{W}_p(\sim 10\,E)\, t_{conf} t_{pp}^{-1} \propto \dot{W}_p\, nR^2/D$$

$$R = \theta d \quad F_\gamma = L_\gamma/4\pi d^2 \;\propto \theta^2\,(\dot{W}_p\, n/D)$$

for given θ, results do not depend on the distance

for fixed density and diffusion coefficient, same requiremnent to $\dot{W}_p$ as long as $\theta \le \sqrt{DT}/d$

deriving the radial profile of CR proton energy densities



from "Cygnus Bubble" paper (Cao et al. 2024)

what will change if Cygnus Bubble is Cygnus X-3 Bubble

x 6 Cygnus X-3

diffusion coefficient $D(E_p) = 3 \times 10^{26}\ (E_p/1\ \mathrm{TeV})^{0.7}\ \mathrm{cm^2 s^{-1}}$

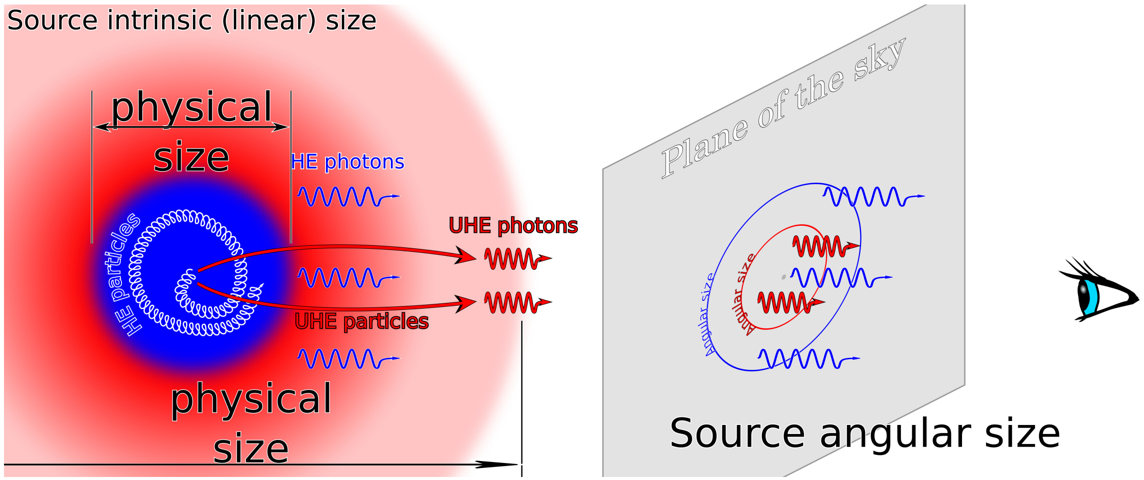
proton injection spectrum $Q(E_p) \propto E^{-2.25}\ \exp(-E_p/5\ \mathrm{PeV})$

proton injection power $\dot{W}_p = 1.1 \times 10^{37}\ \mathrm{erg/s}$

energy density of > 100 TeV protons exceeds the level of "CR sea" up to several 100 pc (>1 kpc for Cygnus X-3) !!!

Scaling factor $(\dot{W}_p\, n/D)$

transition from ballistic motion to diffusion - critical multi-PeV energies



propagation time in difffusion regime $R^2/2D$

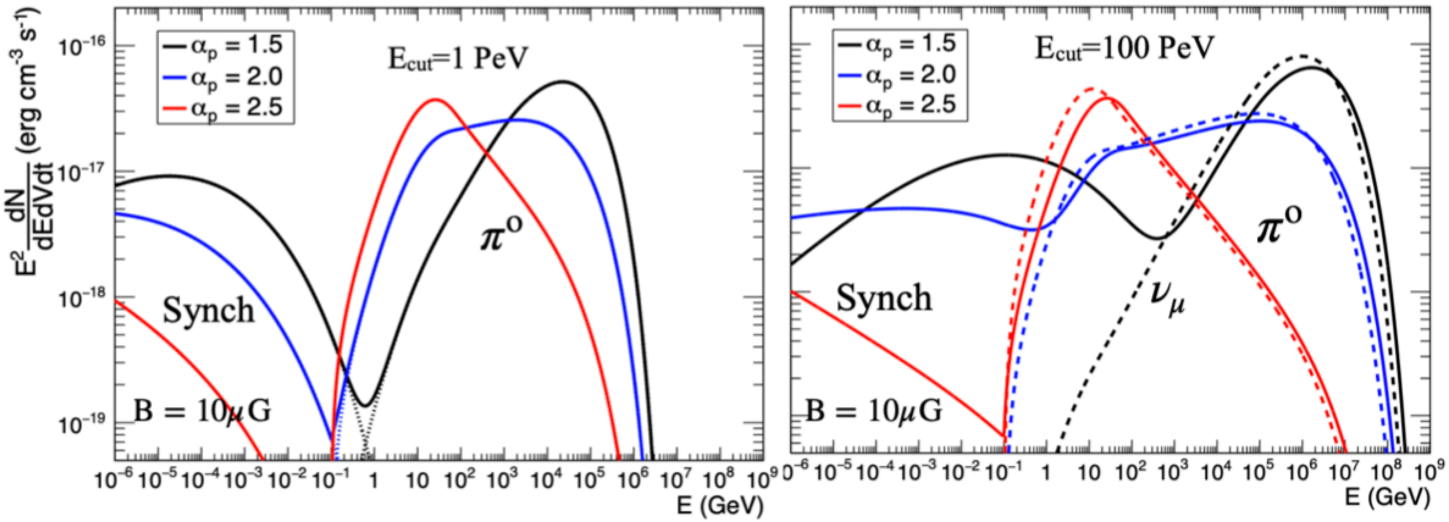
ballistic (rectlinear) propagation time R/c

=> diffusion after $R_0 \sim 2D/c \simeq 20\, D_{30}\, \mathrm{pc}$

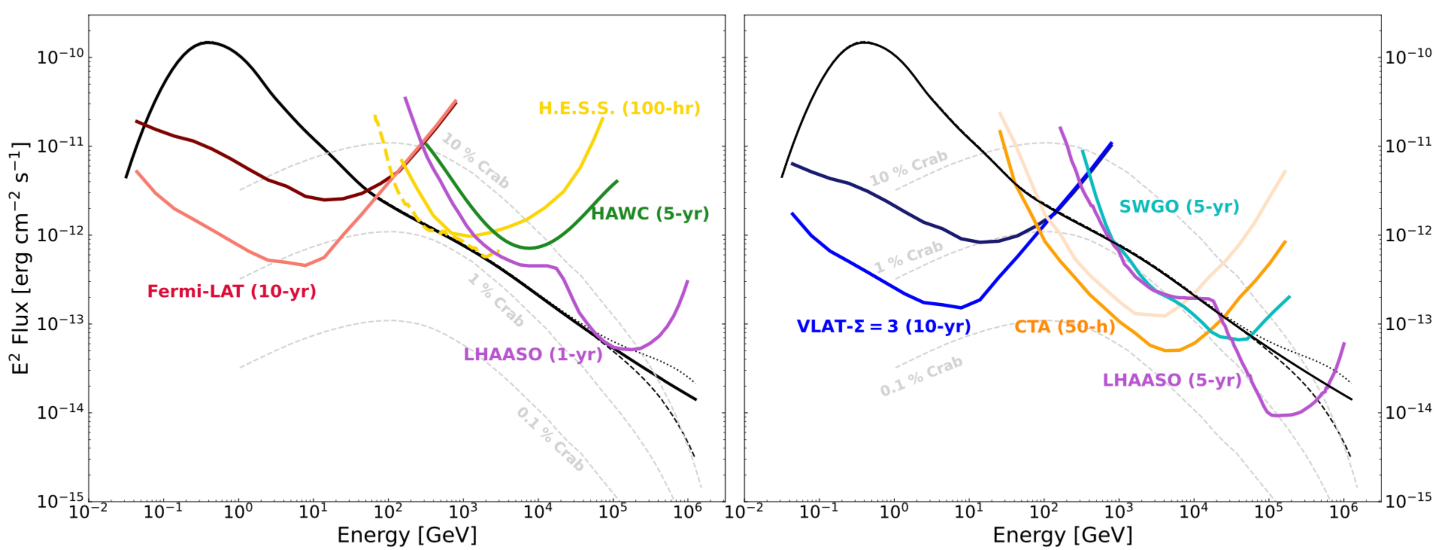
How detect Super PeVatrons? with synchrotron GeV/TeV gamma-rays ?

Celli, Aharonian, Gabici, 2022

$$\epsilon \simeq 20(B/100\mu\mathrm{G})(\mathrm{E}/100\,\mathrm{TeV})^2\ \mathrm{keV}$$



G. Peron and F. Aharonian: Probing the galactic cosmic-ray density with current and future γ-ray instruments



Summary:

Hyper-accreting Microquasars acting as SuperPeVatrons? yes

The major (only) feasibly option to explain GCRs well above 10 PeV: yes (?)