Stellar Clusters as Major contributors to Galactic Cosmic Rays at PeV Energies ?
or
"*Young Stars versus Dead Stars*"

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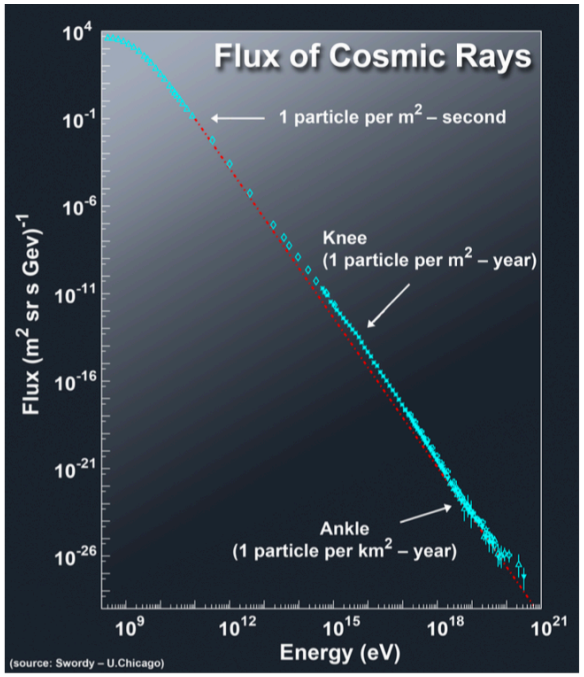
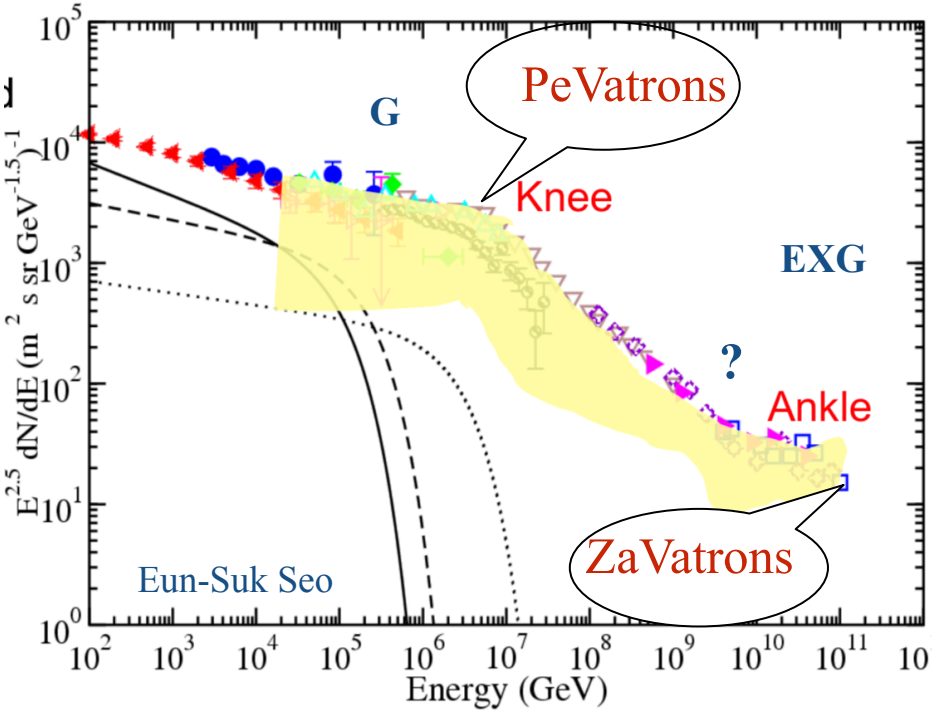
"Origin of cosmic rays remains a mystery…"





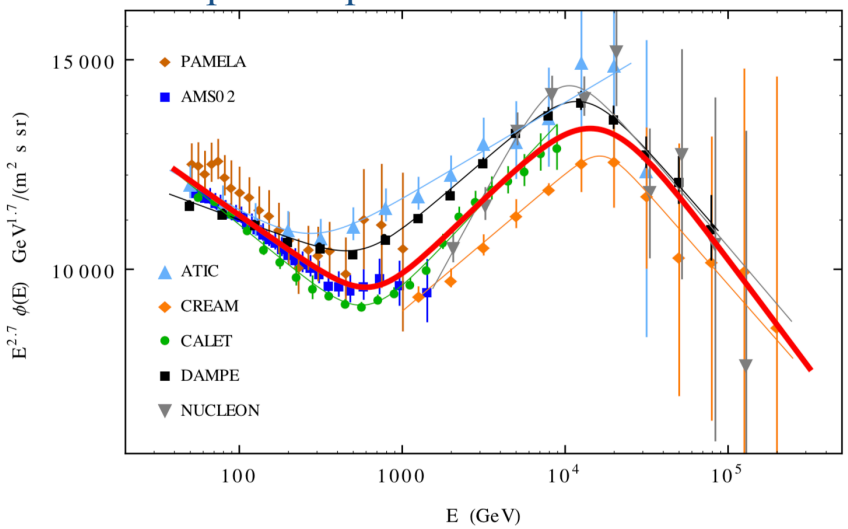
below 10^{15} eV - **G** - from GeV to ~1 PeV - **a single source population (SNRs?)**

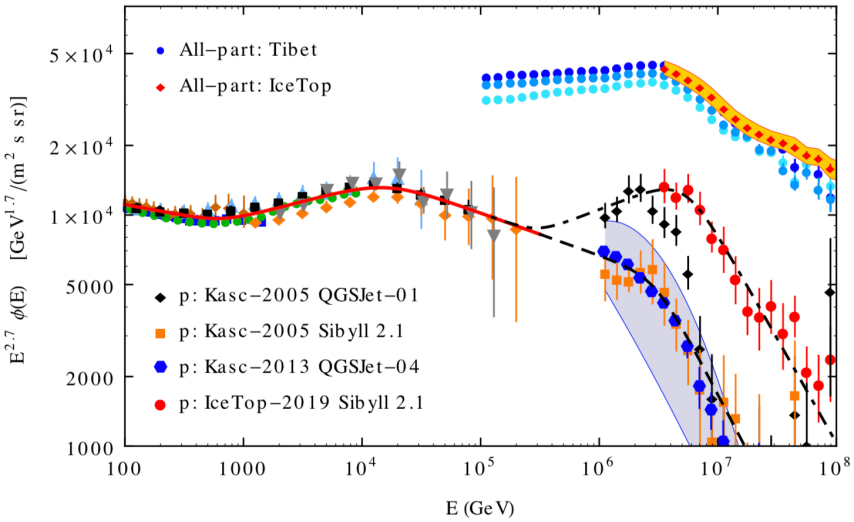
beyond 10^{18} eV - **EXG** between 10^{15} and 10^{18} eV **G-to-EXG** transition

"mystery" is an exaggeration but the origin of sources of Cosmic Rays around 1 PeV and beyond ("PeVatrons") indeed remains uncertain …

structures in HE GCR spectrum: contributions by two or more source populations?

CR proton spectrum





Lipari and Vernetto 2019

the spectrum is not single power-law; it contains (at least) two spectral features:

- hardening above a few 100 GeV
- steepening above 10 TeV
- hardening above 100 TeV ?

do we need PeVatrons ?

- **quasi-PeVatrons**
  up to 0.1 PeV and more

- **nominal - PeVatrons**
  up to 1 PeV

- **super-PeVatrons (of Galactic origin?)**
  >10 PeV up to 100 PeV

Galactic Cosmic Rays

Cosmic Rays: primary component + secondary component

primary: directly accelerated p, A, e^-, e^+

secondary: A, γ , ν, e^+, $\bar{p}$ produced in interactions of primary CRs with ISM

secondary/primary fraction X => "grammage" Λ

=> confinement time T => diffusion coefficient $D(E) \propto E^{\delta}$

source - injection spectrum into ISM $S(E) \propto E^{-\alpha}$

CR spectrum in ISM - modulated $\Phi(E) \propto E^{-\Gamma};\ \Gamma = \alpha + \delta$

Galactic Cosmic Rays

basic facts based on direct measurements:

energy density: ~ **1eV/cm^3** assuming that "CR sea"=locally measured CRs

accumulated "grammage" - several g/cm^2 from secondary-to-primary ratio

=> age: To ~ **$10^{6\text{-}7}$ yrs**

diffusion coefficient: $D(E) = Do(E/1\ GeV)^{-\delta}$;

$Do \sim 10^{28}$ cm^2/s; $\delta \sim 0.3\text{-}0.5$

production rate: $Lcr = wV/To \sim$ **$(0.3\text{-}1) \times 10^{41}$ erg/s**,

source spectrum: $Q(E) \sim E^{-\alpha}$; $\alpha = \Gamma - \delta$; $\Gamma \sim 2.7\text{-}2.8$; **$\alpha \sim 2.3\text{-}2.5$**

Galactic Cosmic Rays

Sources ?

SNRs as prime candidates - over decades the conviction has been based on phenomenological arguments and theoretical meditations

- as early as 1933 W. Baade and Zwicky recognized the comparable energetics characterizing SN explosions and CRs and envisaged a link between

  $E_{SN} \sim 10^{51}$ erg, $R \sim 0.03$ yr $^{-1}$, $P_{SN} \sim 10^{42}$ erg/s => 10 % to CRs ?

- Diffusive Shock Acceleration theory applied to SNRs - viable mechanism for acceleration of particles with in young (< 1 kyr) SNRs up to 1 PeV ?
  Difficult but (in principle) possible - fast (> 0.01 c) shocks, Bohm diffusion, amplification of the magnetic field in upstream are critical conditions

- direct prove - **gamma-rays** and **neutrinos**

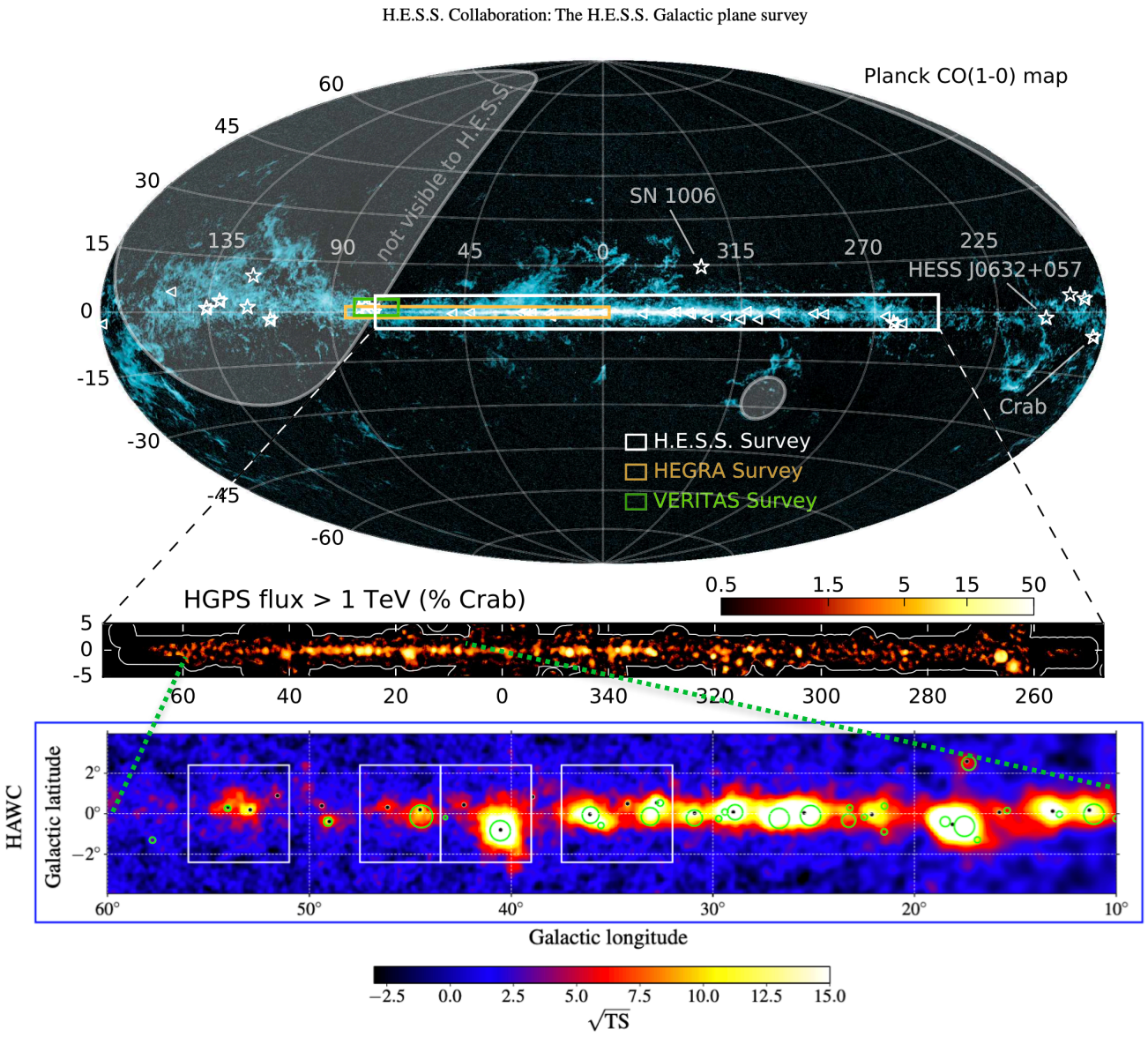
Origin of CRs: one of the key issues:

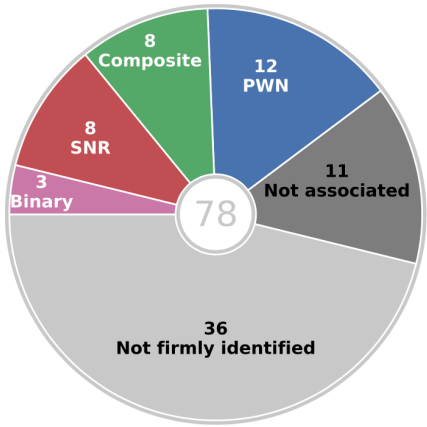
identification of the major contributors to the 'local fog'

cannot be addressed by observations of charged Cosmic Rays …

straightforward (the only feasible!) approach:

revealing sources of Galactic Cosmic Rays
through detection of γ-rays and neutrinos





Galactic Plane is full of TeVatrons!

HAWC - sources with spectra up to 100 TeV!

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!

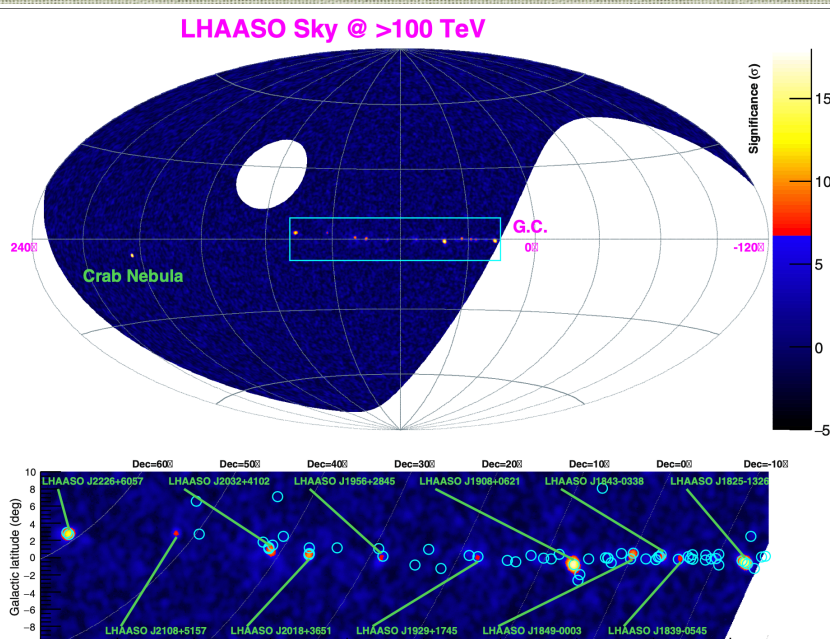


Table 1 | UHE γ-ray sources

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	$0.26\ ^{+0.16}_{-0.10}$	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	$0.71\ ^{+0.16}_{-0.07}$	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.

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	$6.3^{+0.8}_{-0.7}{}^{d}$	$1.8 - 3.3^{k}$	—	
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}	

- 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 PeVatrions which should be yet localised and identified

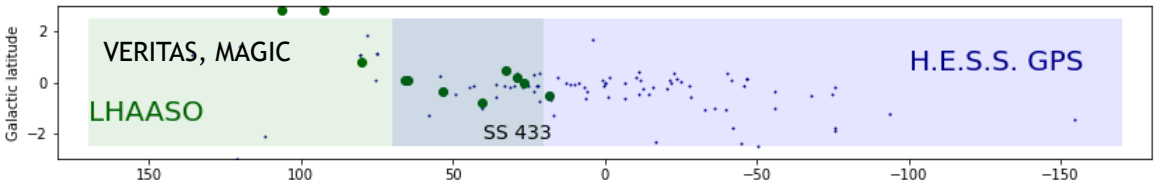
all reported UHE sources have steep γ-ray spectra: $dN/dE \propto E^{-\Gamma}$; $\Gamma \geq 3$

two radiation mechanisms: IC on 2.7 K and $pp \rightarrow \pi^0 \rightarrow \gamma\gamma$

pp: $E_p \approx 3E_\gamma$; **IC**: $E_e \approx 360(E_\gamma/100\,\mathrm{TeV})^{0.77}$ TeV (within 30 TeV to 3 PeV)

>300 TeV gamma-rays should be detected to claim the presence of PeVatrons

IACTs and LHAASO - complementary (PSF ~ several arcmin critical for source identifications)

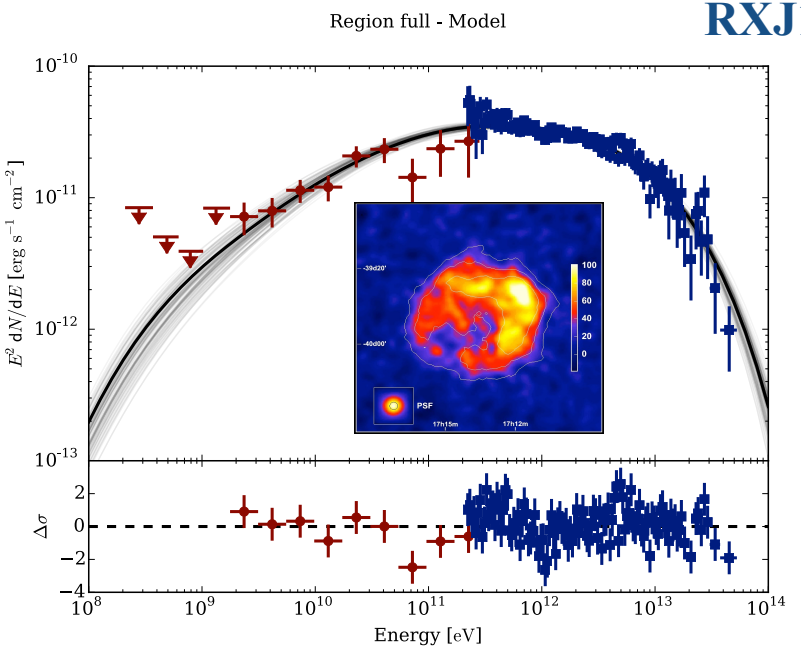


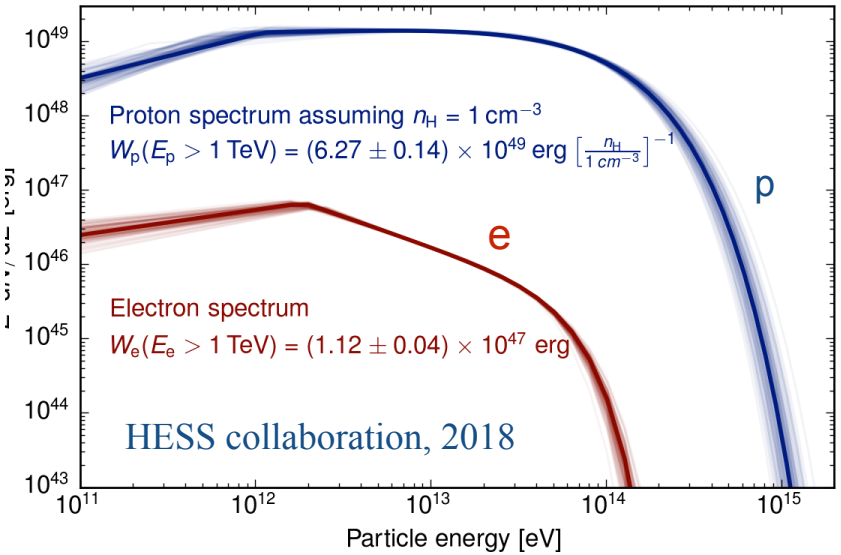
Probing the distributions of accelerated particles in SNRs

Fermi+HESS measurements

derived spectra of e and p

RXJ1713.7-3946

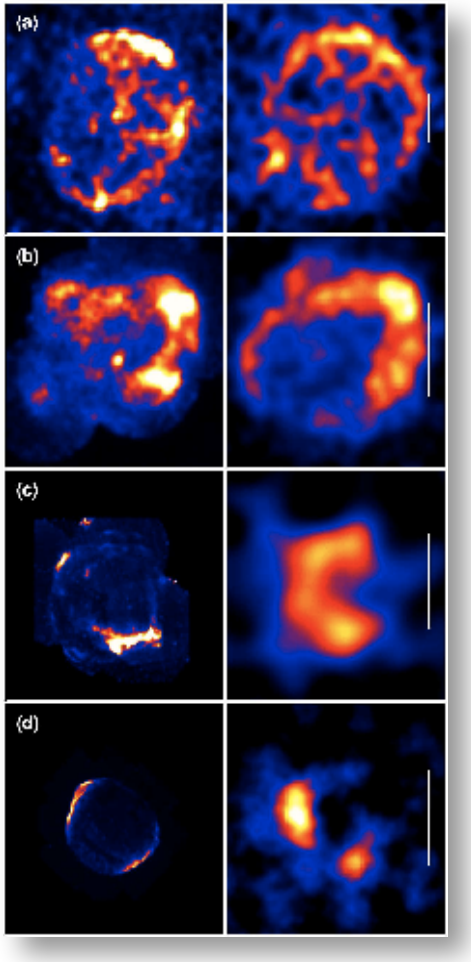




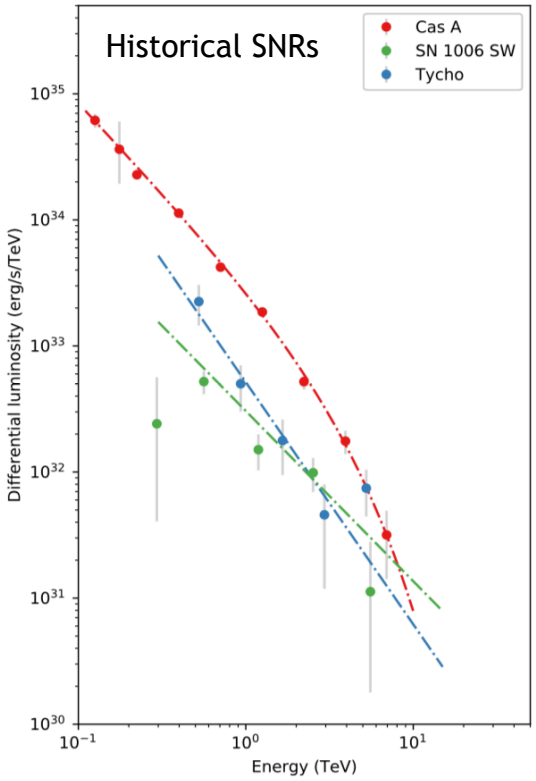
cutoff or break in the proton spectrum at 100 TeV

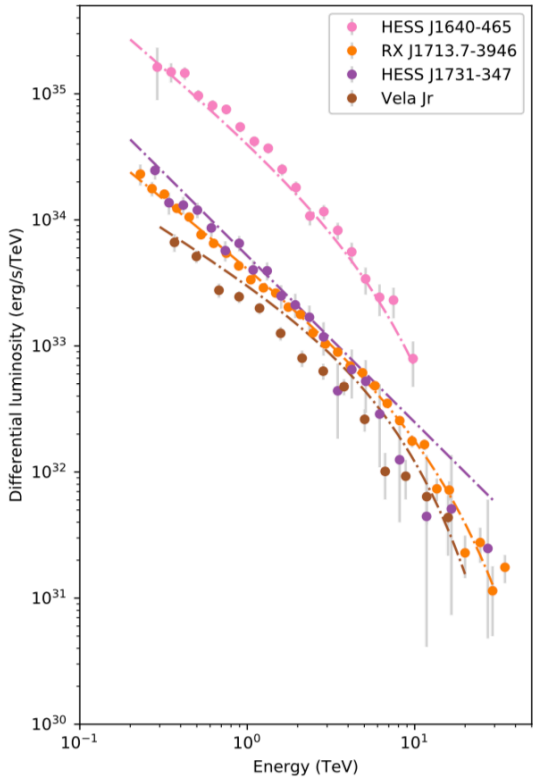
recent exciting (software) developments - detection of many HESS sources well beyond 10 TeV (up to 100 TeV) => revisiting RXJ1713.7-3946 (seems to me) very promising

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 ? The studies should be extended to 100

LHAASO (and CTA ?) is able to answer to this question

slope or intrinsic power-low index?

formally the γ-ray spectra
can be presented in the form: $dN/dE \propto E^{-\Gamma} \exp[-(E/E_0)^{\beta}]$

with reasonable combination of E_0 and β, Γ=2 could be an option

price?

Eo < 10 TeV => Ep < 100 TeV is not a PeVatron

Eo > 10 TeV => Ep > 100 TeV and $\Gamma > 2.3$ can be a PeVatron

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 constrains on the proton maximum energy from gamma-ray data:

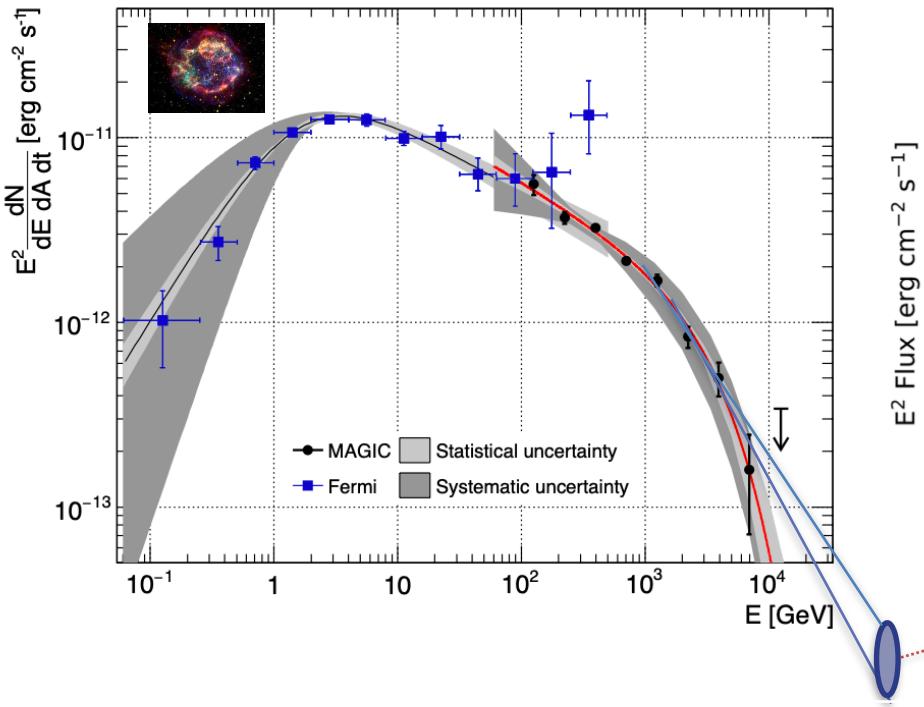
$E_{max} \sim 1$ PeV - very difficult, but feasible

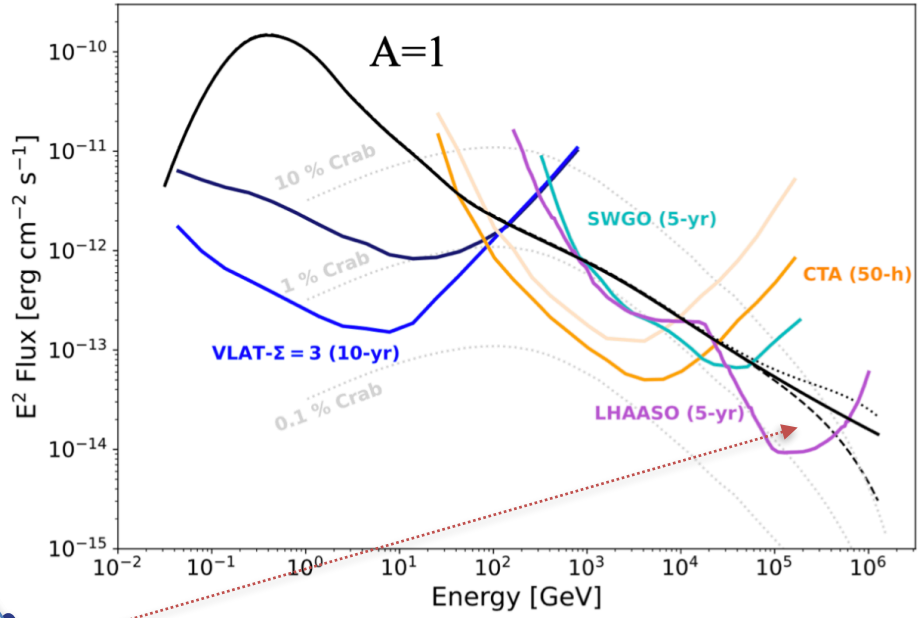
e.g. Type II SN shocks propagating through the dense wind of the progenitor star …
but "PeVatron phase" can be accomplished only during the first years of explosion

- "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?





$dN/dE \propto E^{-3} \rightarrow F_E \sim 10^{-14}\,\mathrm{erg/cm^2 s}$ at $E_\gamma \sim 100\,\mathrm{TeV}$ 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;

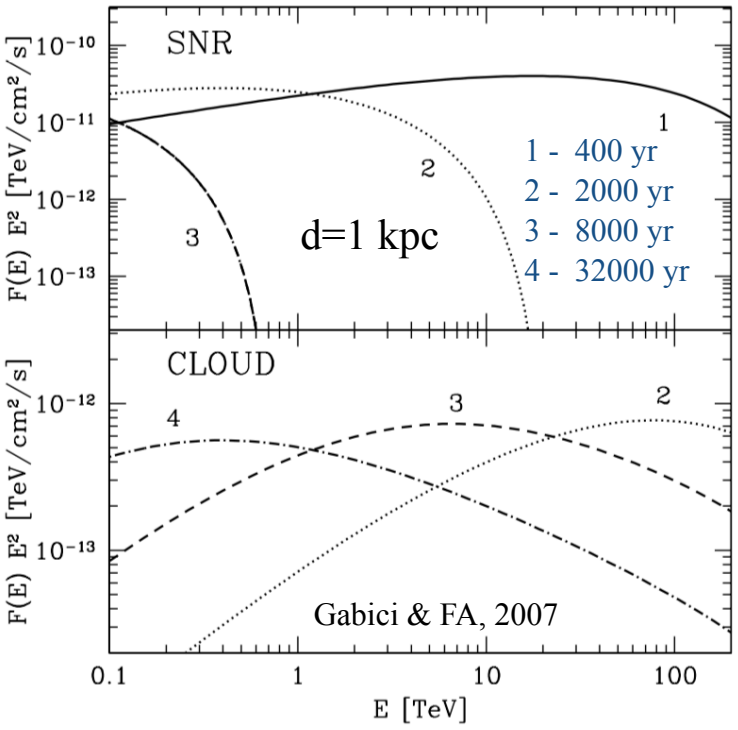
for "slow diffusion" R < 10 pc, angular size comparable with PSF of LHAASO

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

decisive "PeVatron test" independent of the acceleration epoch

"smoking gun" from dense environments in <100 pc vicinities of mid-age SNRs

(Aharonian&Atoyan 1996)



SNR: $W=10^{51}$ erg $n=1$ cm^{-3}

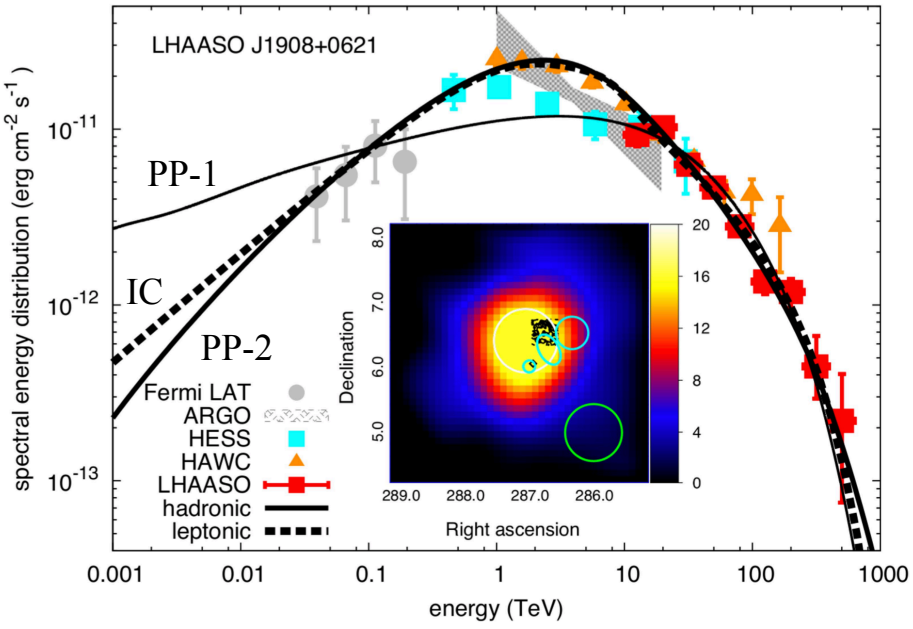
$f(p)\sim p^{-4}$ $p_{max}=5$ PeV

$p_{max}\sim t^{-2.4}$

Cloud: R=100 pc, M=10^4Mo

$D(E)=3\times10^{29}(E/1\text{PeV})^{0.5}$ cm^2/s

SNR G40.5-0.5 + GMC ?



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

— PP-2: $dN/dE \propto E^{-1.2}$ $E \leq 25$TeV;

$\propto E^{-2.7}\exp[-(E/1.3\text{PeV})]$ above 25 TeV

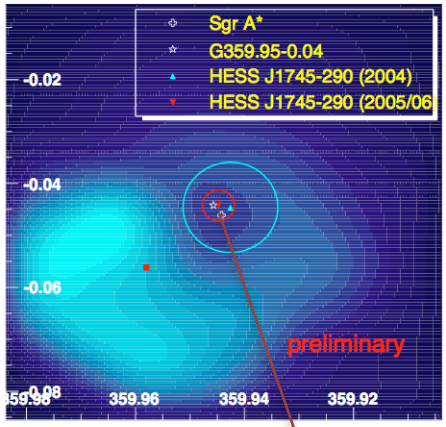
Interim Summary

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

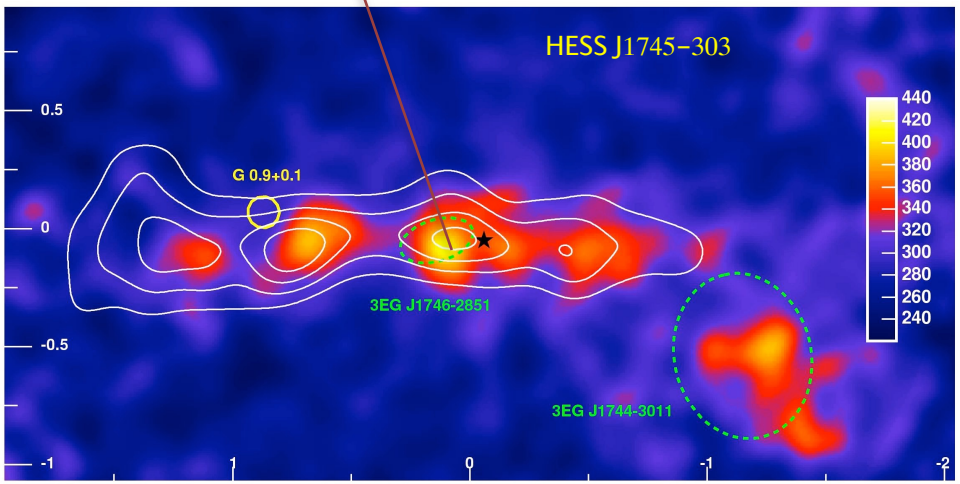
The deep γ-ray probes of SNRs by LHAASO will provide a decisive verdict on their ability to perform as PeVatrons.

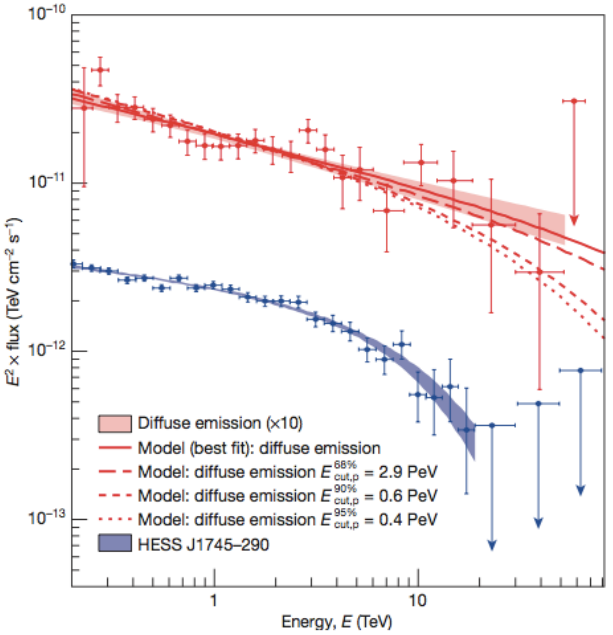
Meanwhile, the exploration of alternative sources/scenarios of production highest energy CRs becomes a "hot topic" in the context of new sensitive VHE/UHE γ-ray observations and theoretical studies.

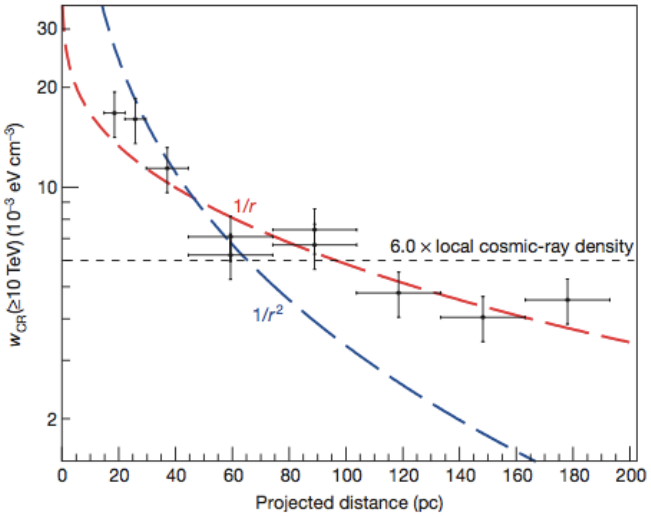
PeVatron(s) in the Galactic Center!



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



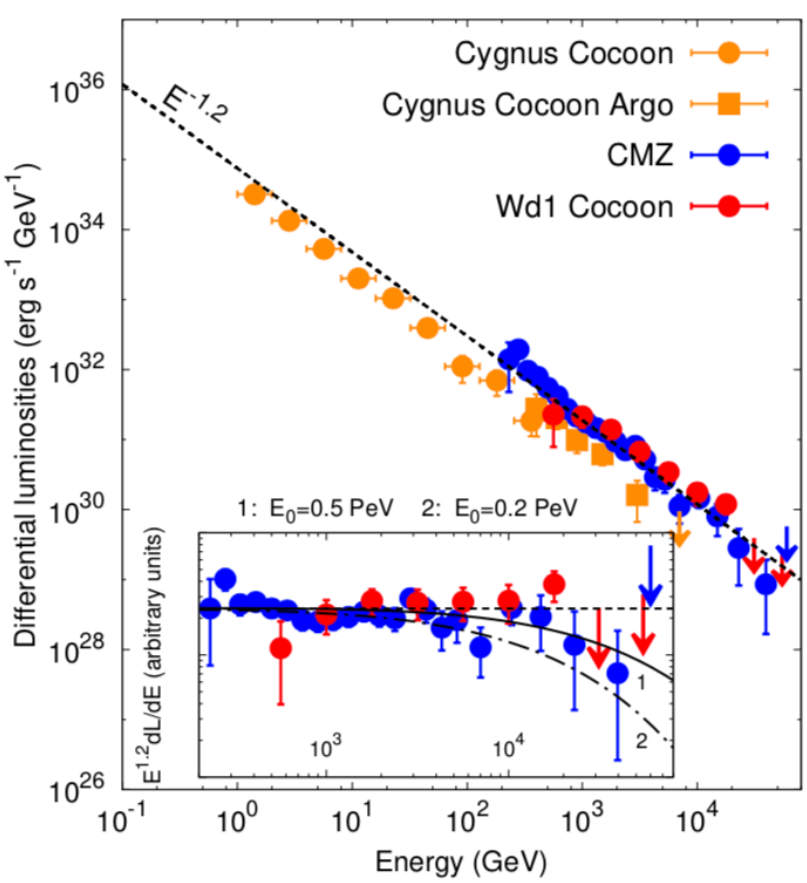




SMBC in GC (Sgr A*) operating as a PeVatron ?

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

Stellar Clusters operate as PeVatrons ?



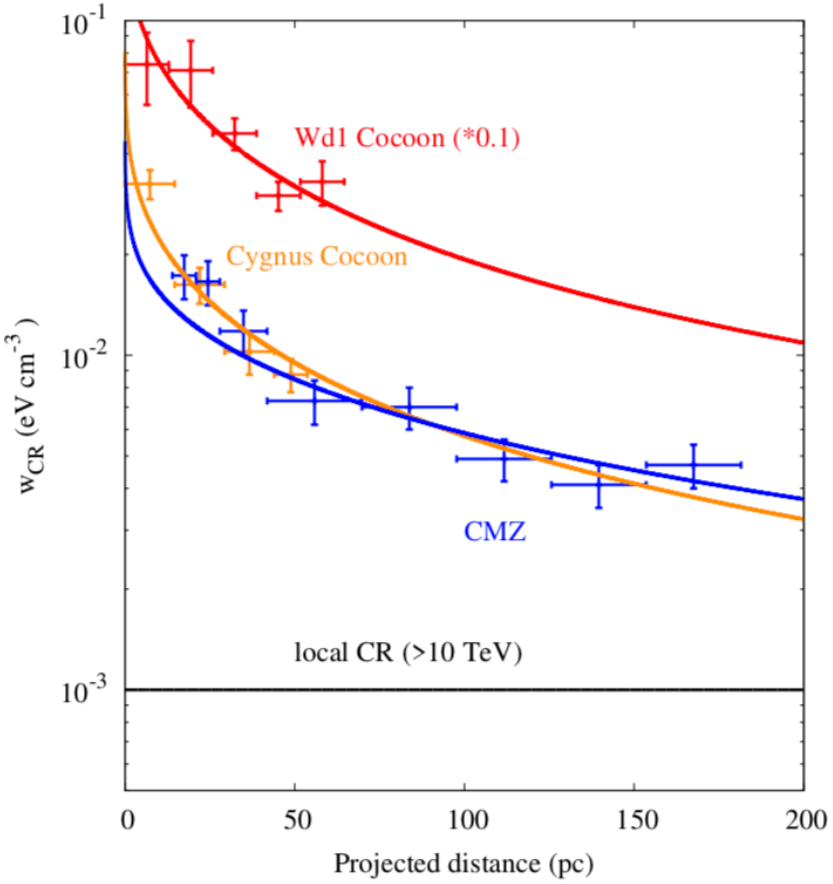


Figure 1: Gamma-ray luminosities and CR proton radial distributions in extended regions around the star clusters Cyg OB2 (Cygnus Cocoon) and Westerlund 1 (Wd 1 Cocoon), as well as in the Central Molecular Zone (CMZ) of the Galactic Centre assuming that CMZ is powered by CRs accelerated in *Arches*, *Quintuplet*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

FA, Yang, Ona de Wilhelmi, 2018

Stellar Clusters as factories of Galactic Cosmic Rays up to 1 PeV ?

Cesarsky and Montmerle 1983; A. Bykov - since 1990s, R. Lingenfelter - since 2000s
recent reviews: R. Lingenfelter 2018, A. Bykov et al 2020, T. Vieu 2021 (PhD thesis)

massive stars produced at the collapse of GMCs form compact groups consisting of tens of massive (O, WR type) stars and remain linked during their life (1-10 Myr)

SWs and SN explosions => *superbubbles* filled with turbulent plasma shocks
=> particle acceleration by interacting SWs, termination shocks in the vicinity of stars or in superbubbles

collective power in stellar winds 10^{38} - 10^{39} erg/s; speeds 3×10^3 km/s

at PeV energies - conditions can be more favourable than in individual SNRs

other motivations:

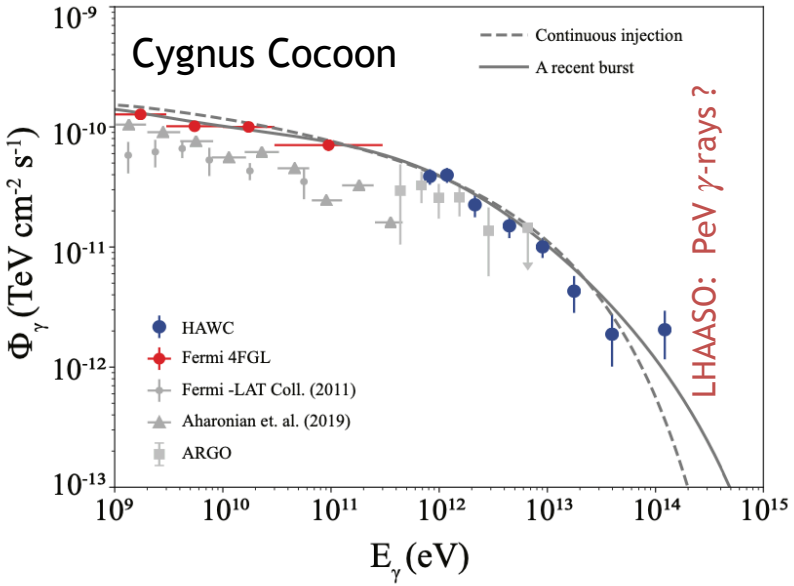
- $^{22}Ne/^{20}Ne$ ratio
- gamma-rays from a number of YMCs from GeV to TeV (and PeV ?)

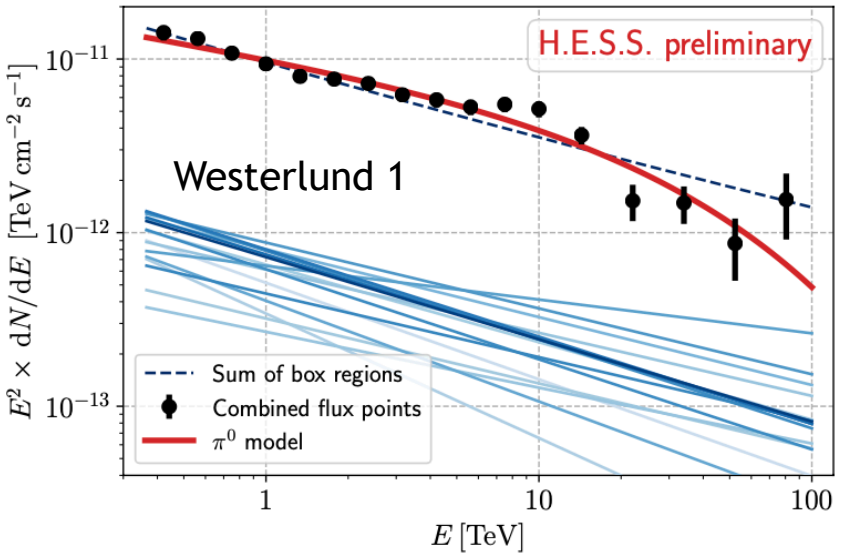
Extended Regions surrounding Clusters of Young Massive Stars are sources sources of GeV, TeV and … PeV gamma-rays !

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!

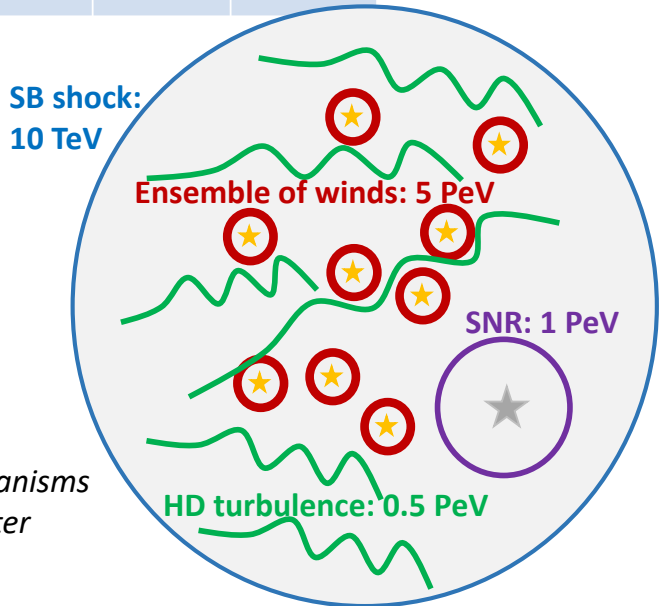
IC (almost) excluded - only PWNe can accelerate electrons >> 100 TeV

- γ-ray morphology

$E_{p,max}$ 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

extension of the cosmic ray spectrum well beyond 1 PeV =>

Super-PeVatrons in Milky Way ?

- YMCs/Supper-Bubbles ?
- SNRs ? ?
- Pulsars: $E = 20\,\eta_B^{1/2}\,L_{38}^{1/2}$ PeV
- Binary systems, Microquasars - ?
- SMBH in the Galactic Center: $E = eBR \simeq 100(B/1\,kG)\,(M/3\times 10^6 M_\odot)$ PeV

other messengers

Neutrinos:

similar to gamma-rays, but there are principal differences

1. production only in hadronic interactions - no uncertainty regarding the origin of radiation

2. interact weakly with the surrounding matter and magnetic and radiation fields

=> information about "hidden" sources; extragalactic PeVatrons, …

3. because of small cross-sections, small detection areas even for km^3 scale detectors

even for strongest ("1 Crab") sources with spectra extending beyond 100 TeV only ~1 ν for several years

upgrade of IceCube and the on-going new projects aim to discover the first neutrino sources

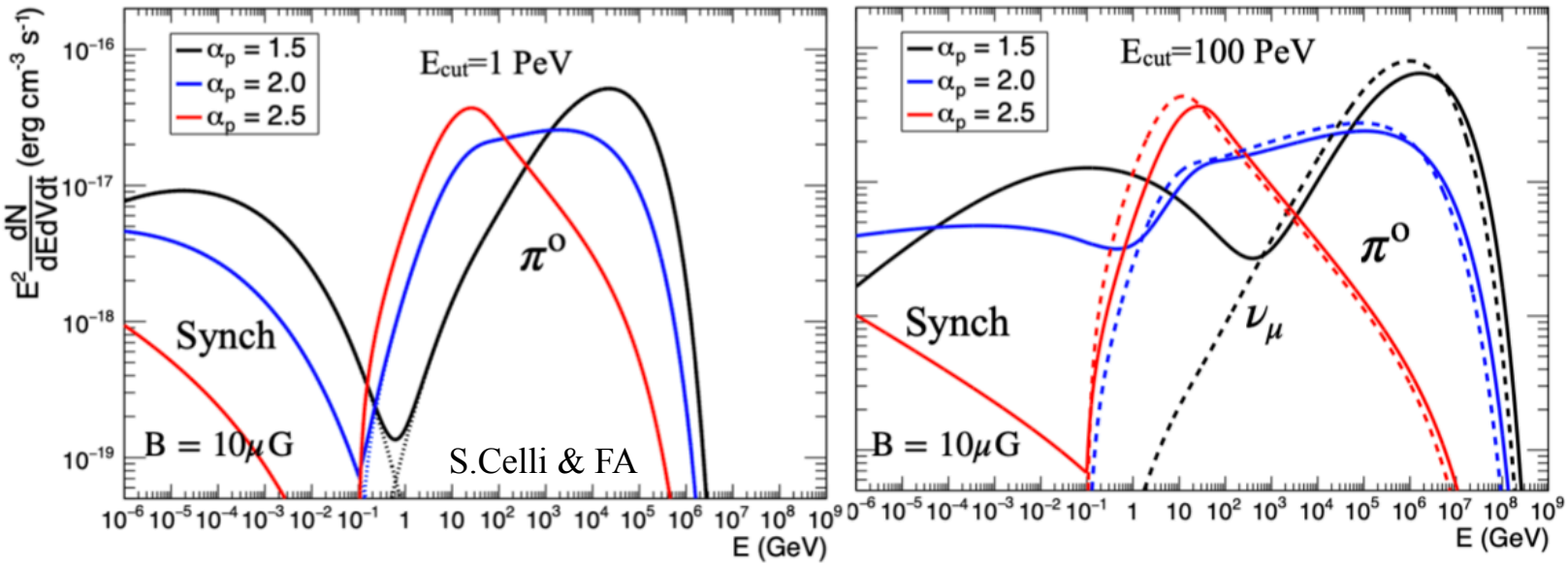
LHAASO and eROSITA

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

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



normalisation: $\mathrm{n} = 1\,\mathrm{cm}^{-3}$; $\mathrm{w_p}(\geq 100\,\mathrm{GeV}) = 1\,\mathrm{erg/cm}^{-3}$

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

eROSITA can help to localise and identify LHAASO sources !

warning: don't be tricked by propagation effects!

transition from rectilinear to diffusive regime of propagation

$$f(r,\mu) = \frac{Q}{4\pi c}\left(\frac{1}{r^2} + \frac{c}{rD}\right)\frac{1}{2\pi Z}\exp\left(-\frac{3D(1-\mu)}{rc}\right)$$

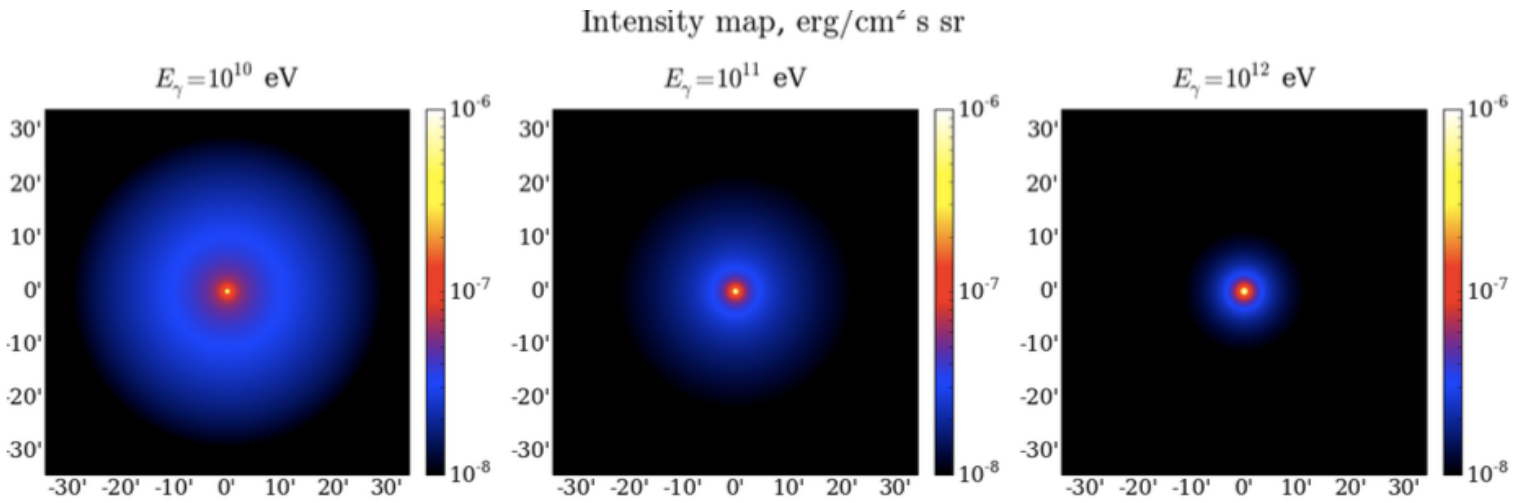
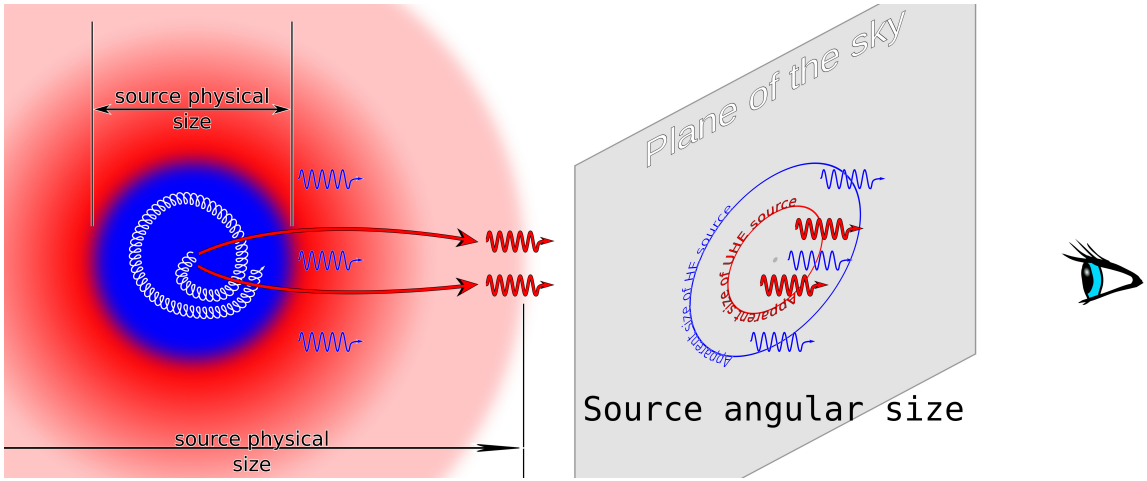


Figure 2: The intensity maps of gamma-ray emission at different energies. The spherical cloud with homogeneous density distribution is irradiated by the cosmic-ray source located in its centre. The gas density inside the accelerator is assumed very low, so the contribution of the accelerator to the gamma-ray emission is negligible. The maps are produced for the case of small diffusion coefficient (for details, see the text). For the distance to the source $d = 1$ kpc, the region of $\sim 1^\circ \times 1^\circ$ corresponds to the area $\sim 20 \times 20$ pc^2.

Prosekin, Kelner, Aharonian 2015



"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 localisation of LHAASO PeVatrons