19th Rencontres du Vietnam: Theory meeting Experiment

Multi-messenger signals from Galactic Pevatrons

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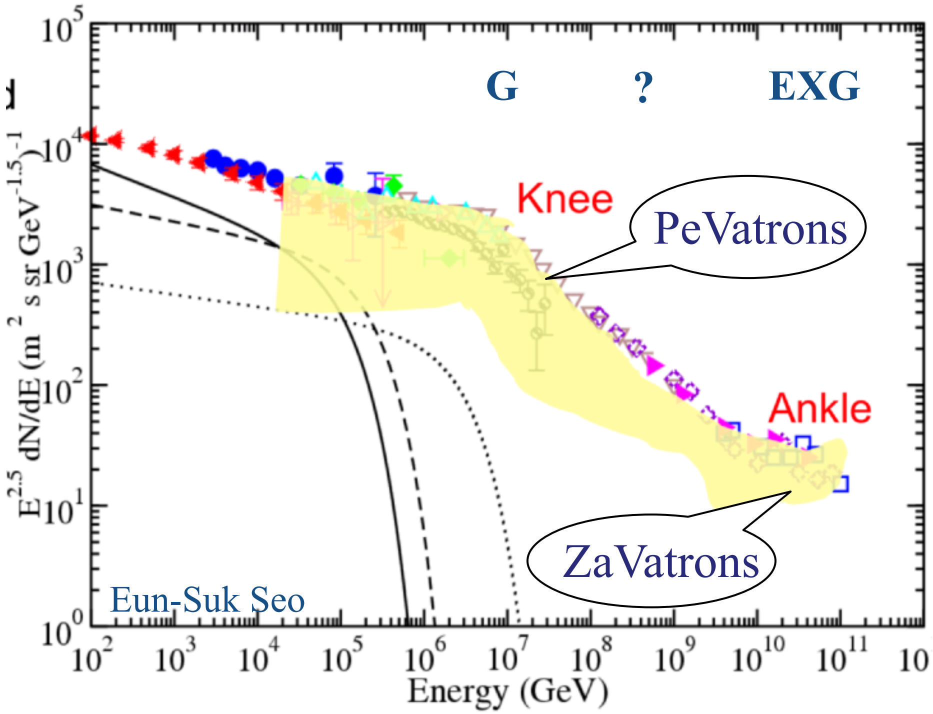
Why "PeVatrons" getting super popular?



Cosmic Ray spectrum over 11 decades

below 10^{15} eV - G challenge: > 10^{15} eV

beyond 10^{18} eV - EXG challenge: > 10^{20} eV

between 10^{15}-10^{18} eV ???

two mysteries:

origin of PeVatrons and ZeVatrons

PeVatrons - Cosmic Ray Factories accelerating particles to 1 PeV

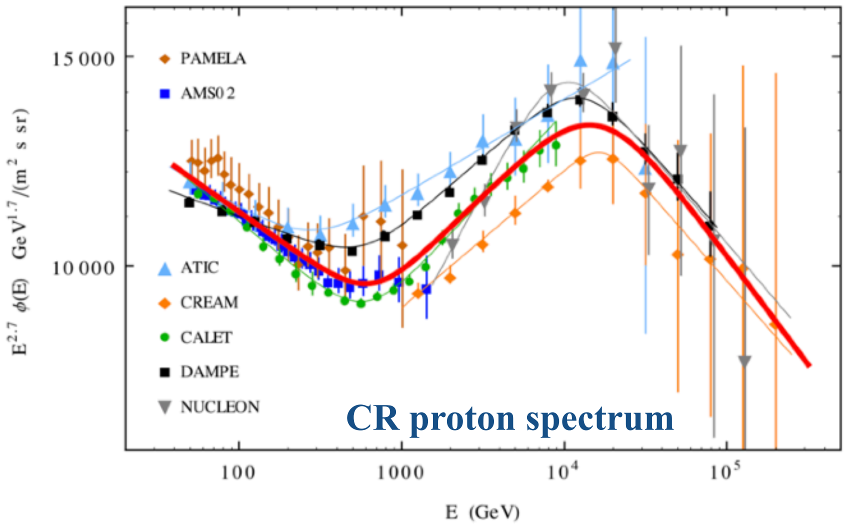
interest to PeVatrons? (i) **astrophysics** - contributors to GCRs in the *knee* region
(ii) **physics** - theoretical challenges

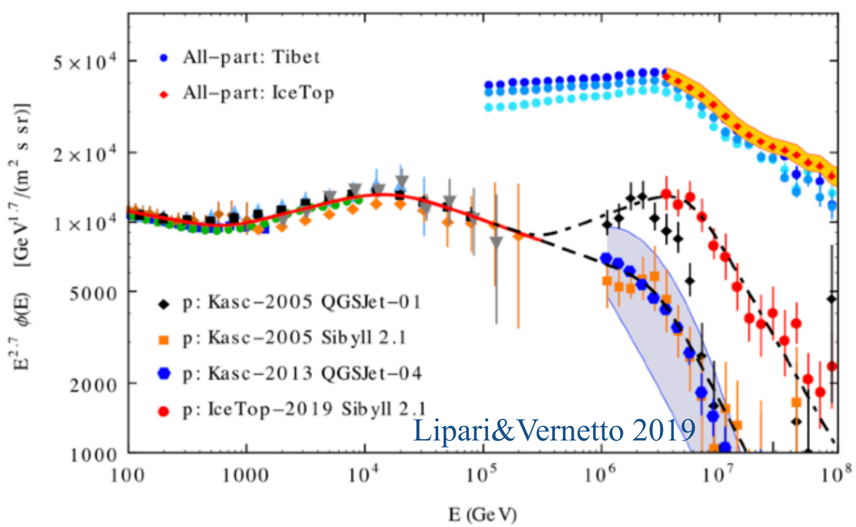
Galactic PeVatrons:

- until recently - no robust evidence of presence of PeVatrons
- theoretical challenges for acceleration of protons to 1 PeV, and especially to >> 1 PeV "SuperPeVatrons"

CR Spectrum - presence of PeVatrons (!) and super-PeVatrons (?) in Milky Way

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





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

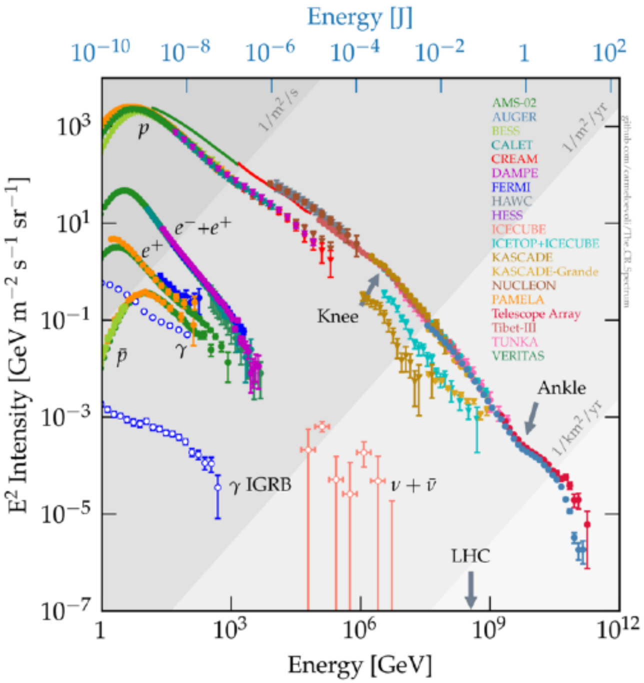
- hardening above a few 100 GeV
- steepening above 10 TeV
- hardening above 100 TeV ?

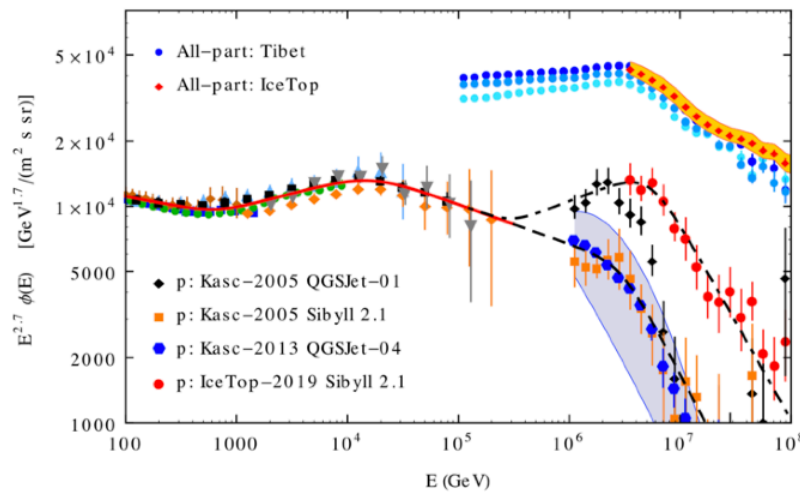
- **quasi-PeVatrons**
  up to 0.1 PeV and more

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

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

a key issue - *separating protons from nuclei*





Lipari and Vernetto 2019

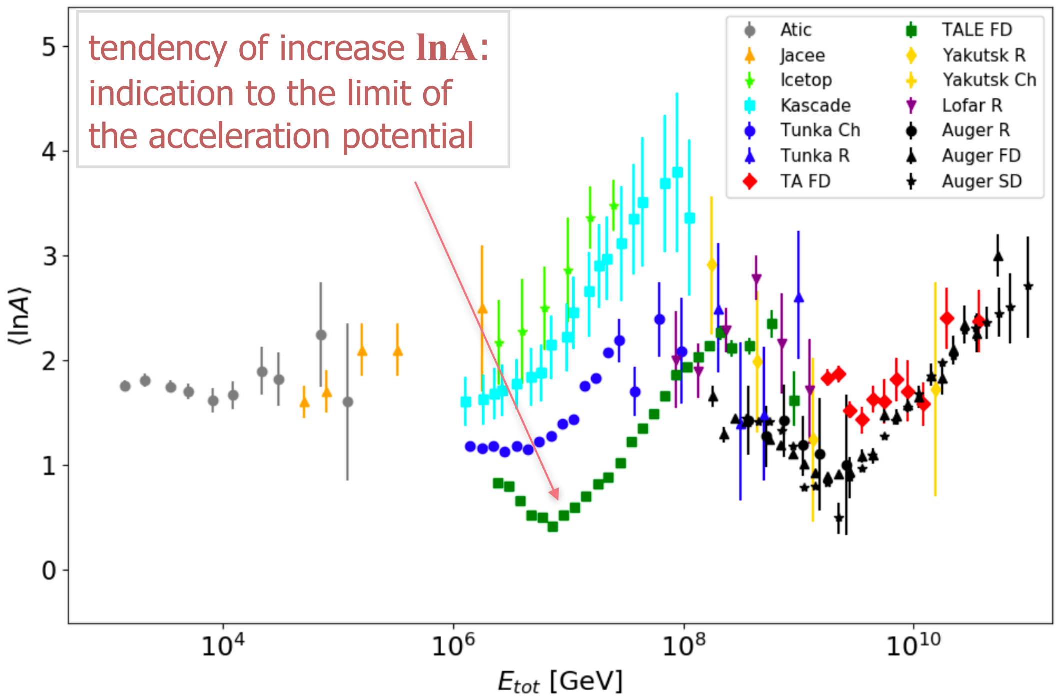
separating protons from nuclei:

below 100 TeV - significant progress (space-based experiments)

above 100 TeV - large ambiguity; certain expectations from LHAASO but challenges with EAS (indirect) measurements will remain…

measurements of diffuse UHE gamma-rays with LHAASO: a promising and complementary approach

PeVatrons - acceleration of protons to 1 PeV (nuclei to 1 PeV/A)



“proton superPeVatrons” ? <lnA> increases with energy but no reasonable agreement between different experiments. CR data. Nevertheless there is no doubt that the energy of the GCR component extends at least 1 PeV/nucleon

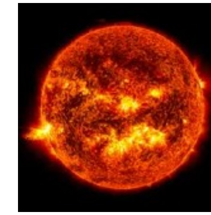
“Origin of Cosmic Rays” ?

Origin of CRs generally is reduced to the identification of major contributors (SNRs, pulsars, GC, etc.) to the locally measured Cosmic Rays

however, term “Cosmic Rays” itself has two meanings:

- locally detected nonthermal/relativistic particles - a “local fog”
- the ”4th substance” of the visible Universe (after the matter, radiation and magnetic fields) - a *more fundamental issue*

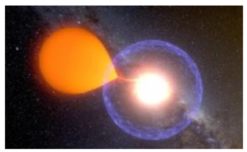
Relativistic Matter Factories



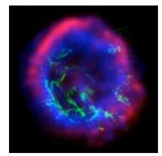
nonthermal processes in Universe proceed everywhere and on all astronomical scales:

G

Stars

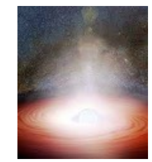


Novae



SNRs

Microquasars

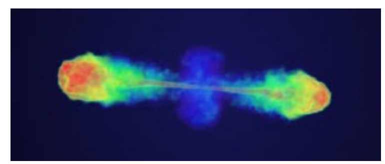


Neutron Stars*

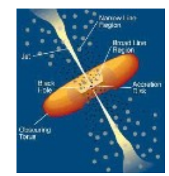
EXG

Galaxies

Galaxy Clusters

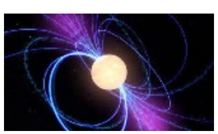


Large Scale Jets of AG



Blazars

* accelerators associated with Neutron Stars



Pulsars

Pulsar Wind Nebula

Binary pulsars

(BNS mergers)

(short) GRBs

MM & MWL in the context of PeVatrons

UHE γ-rays - principal messengers: adequate sensitivity of LHAASO!

TeV/PeV neutrinos - complementary to UHE γ-rays; marginally detectable

HE & VHE gamma-rays - important; a lot of data already available

X-rays - multi-purpose: synchrotron of directly accelerated electrons:
peak - acceleration rate ;
synchrotron of secondary electrons:
complementary to UHE ; new developments - eROSITA!

Gas distribution - atomic hydrogen (21cm),
molecular hydrogen (mm; though CO), dust
recent developments:
dense clumps as targets for gamma-ray production;
3D distributions of gas around accelerators

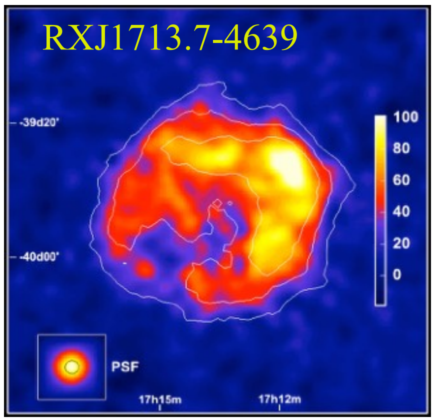
Cosmic Ray Factories in the Milky Way

accelerating particles to $E \geq 1\,\mathrm{PeV/nucleon}$

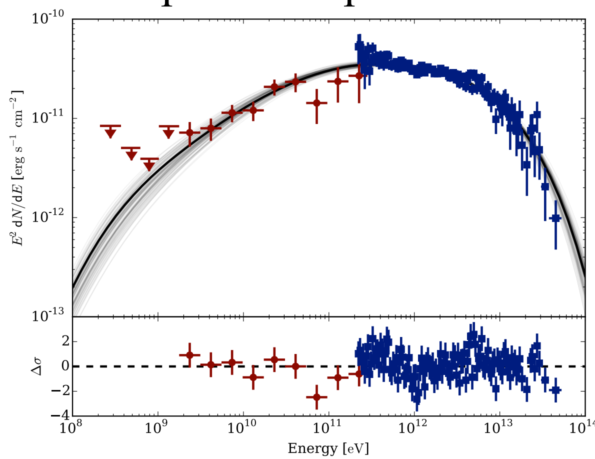
SNRs as the major contributors to GCRs? -

for decades this conviction has been based on phenomenological/theoretical arguments

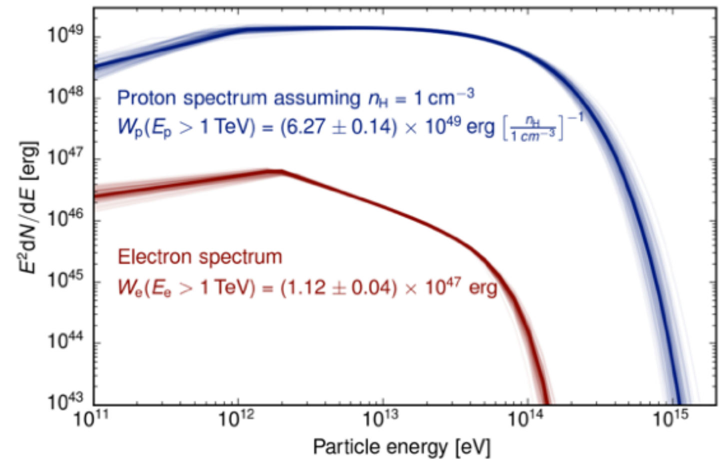
morphology - shell!

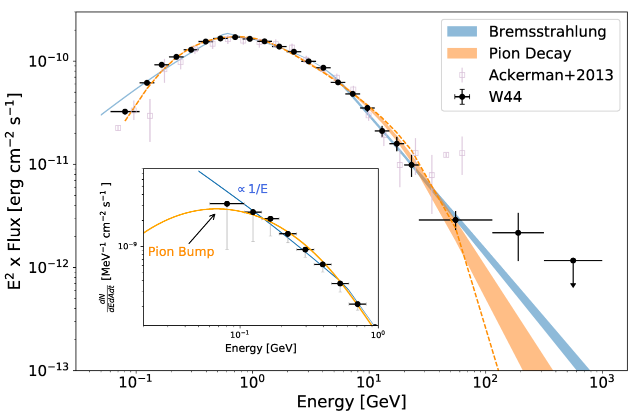


spectrum up to 60 TeV



spectra of electrons and protons



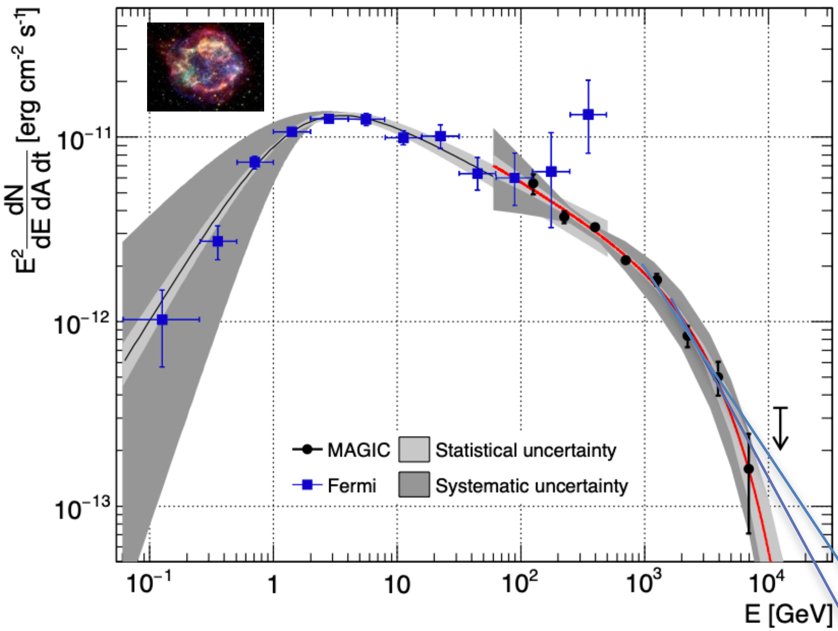


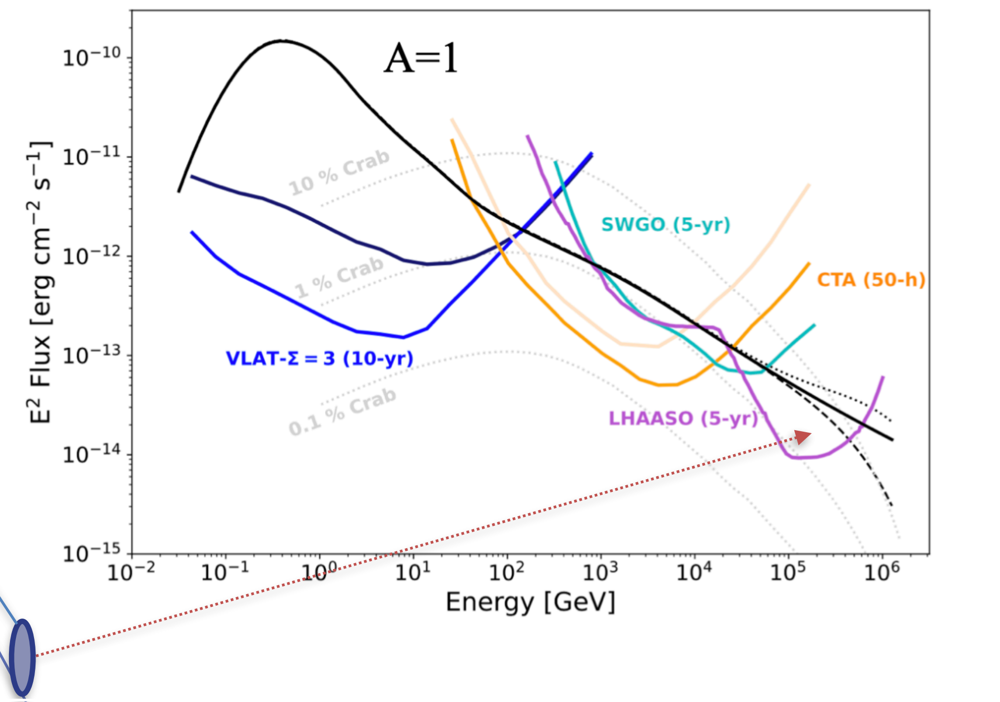
- *lepton vs. hadronic* - not yet solved at VHE energies
- if hadronic - protons accelerated out to 0.5 PeV although the cutoff in the spectrum is ~100 TeV
- exponential cutoff or a break?

RXJ 1713 can be a PeVatron ! (?)

π^0 bump detected - hadronic! but cannot be extrapolated to TeV/PeV energies

Cas A, a benchmark SNR-PeVatron candidate?





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

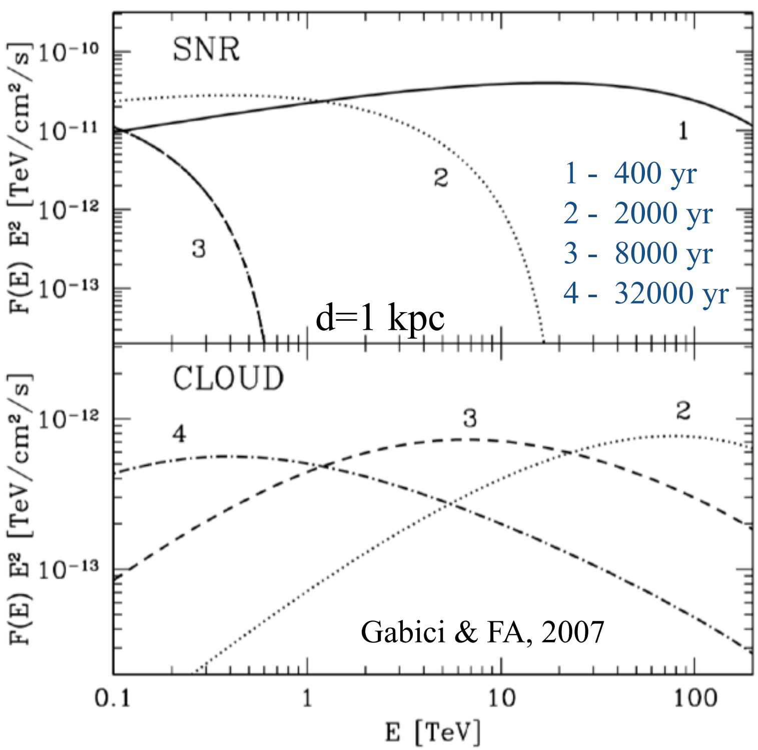
=> LHAASO upper limit (or detection) of 100 TeV γ-rays - at the level of $10^{-14}\,\mathrm{erg/cm^2 s}$

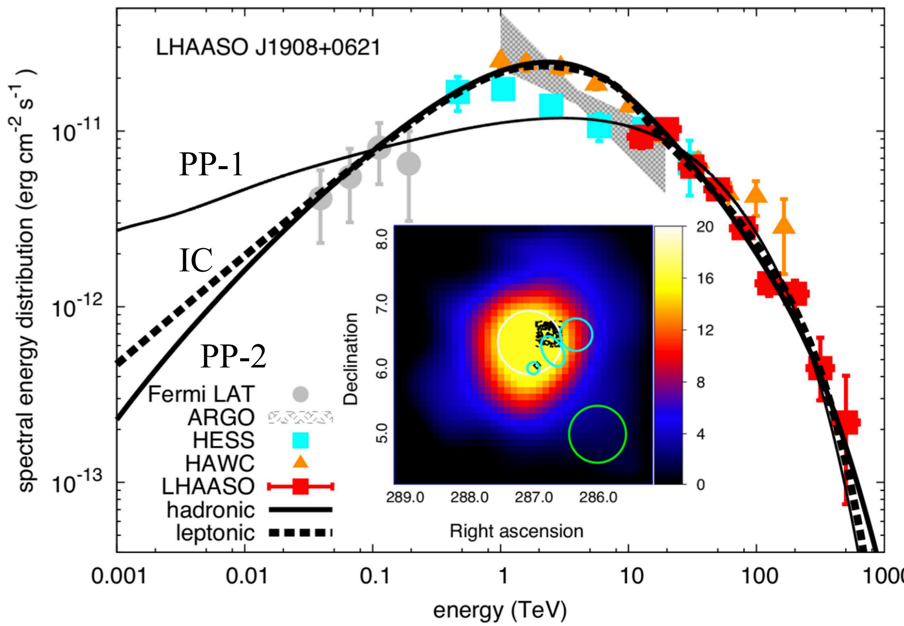
decisive "PeVatron test" independent of the acceleration epoch

"smoking gun" from dense environments in <100 pc vicinities of middle-aged SNRs

"Searching for Galactic Cosmic-Ray **PeVatrons** with Multi-TeV Gamma Rays and neutrinos"

SNR G40.5-0.5 + GMC ?





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

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

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

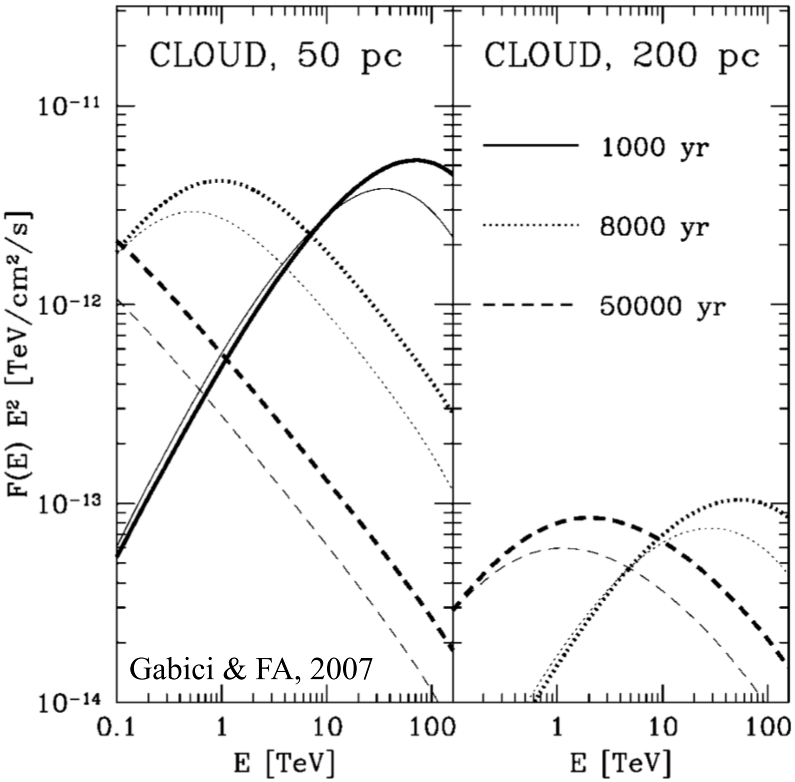
Cloud: R=100 pc, $M=10^4 M_o$
$D(E)=3\times10^{29}(E/1\mathrm{PeV})^{0.5}\ \mathrm{cm}^2/\mathrm{s}$

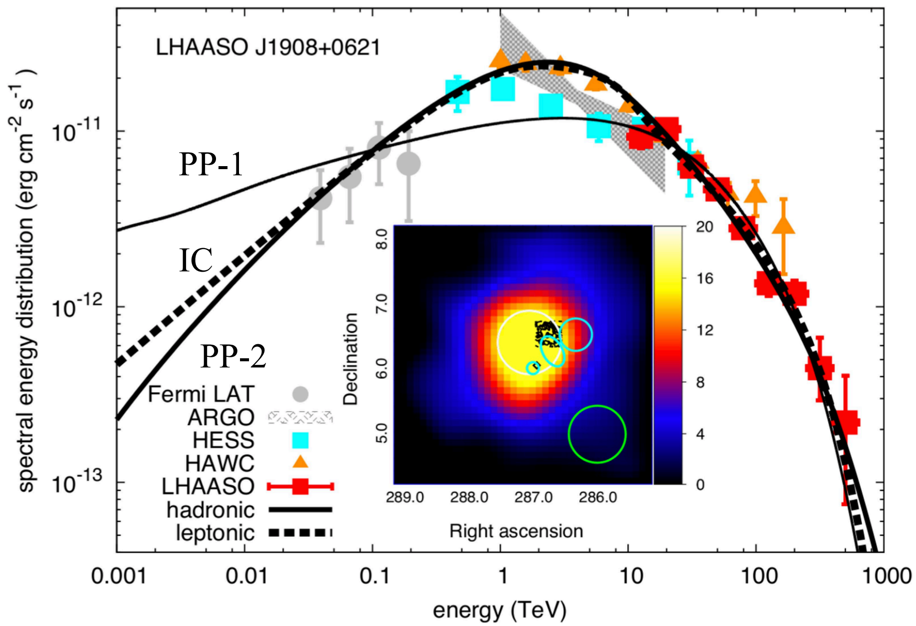
spectrum typical for IC gamma-rays but very hard spectrum below 1 TeV is naturally formed in "SNR - nearby GMC" scenario as well

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

“Searching for Galactic Cosmic-Ray **PeVatrons** with Multi-TeV Gamma Rays and neutrinos”

SNR G40.5-0.5 + GMC ?





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Very hard ($\Gamma \sim 1.5$) and very steep ($\Gamma \sim 3$) spectra at GeV-TeV energies may characterise the “echo” of PeVatrons, but detection of photons out of 100 TeV is crucial in the hunts of PeVatrons. Complementary information is provided by multi-TeV to PeV neutrinos and “hadronic” X-rays

Intermediate Summary:

Lack of reliable detection of γ- rays well beyond 10 TeV raised doubt in the CR community regarding the ability of SNRs to accelerate protons to PeV energies

But, it is *premature to draw a verdict*, given the limited sensitivity of the current IACT arrays in the key energy regime UHE photons, $E_\gamma \geq 100$ TeV.

LHAASO is able to give definite answers to this principal question - *soon*!

Meanwhile, the recent reports of giant gamma-ray structures around a few Young Stellar Clusters, e.g. around Westerlund 1 and especially Cygnus OB2 demonstrate the potential of these objects to act as PeVatrons.

"young stars versus dead stars"

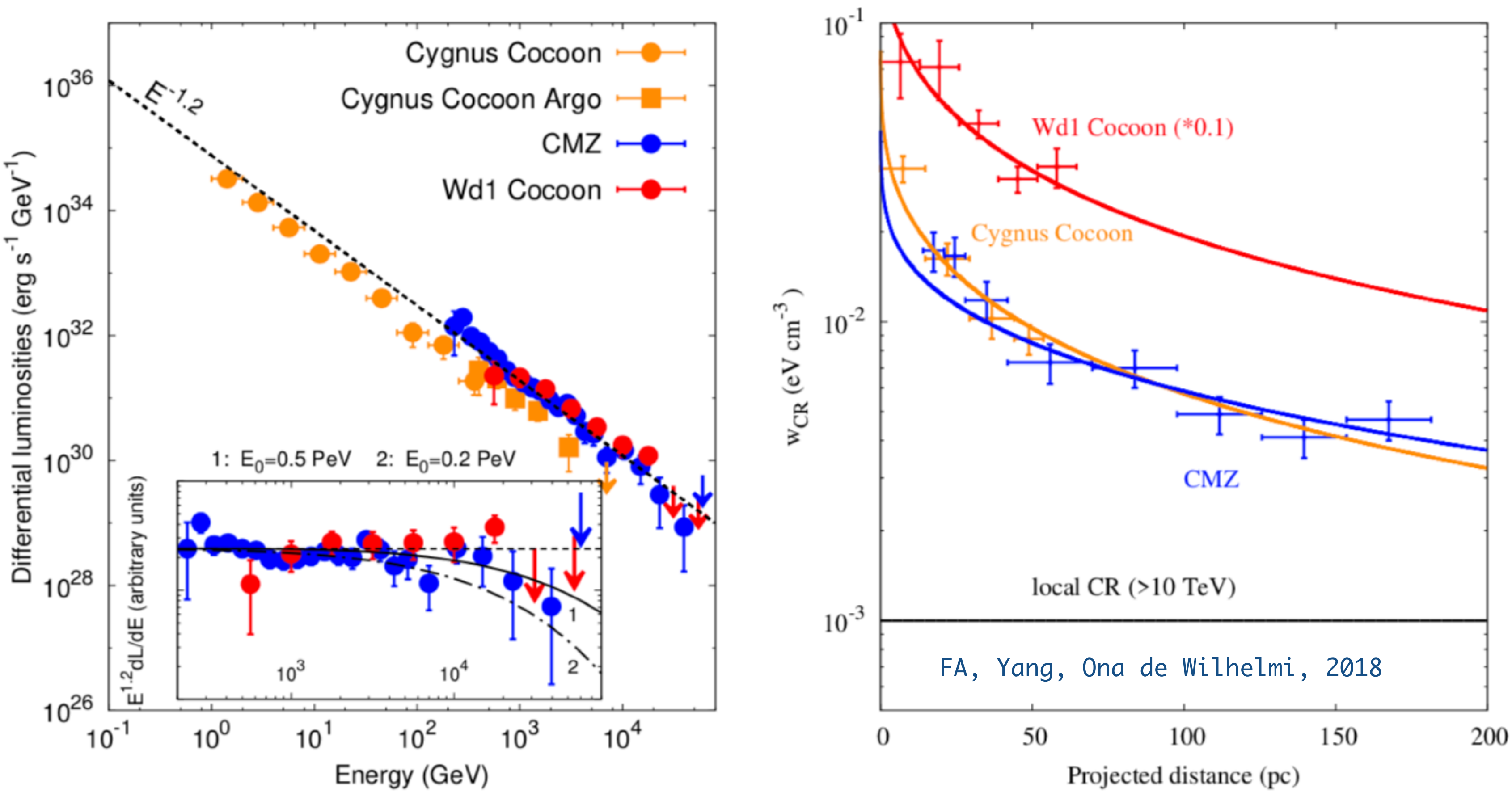


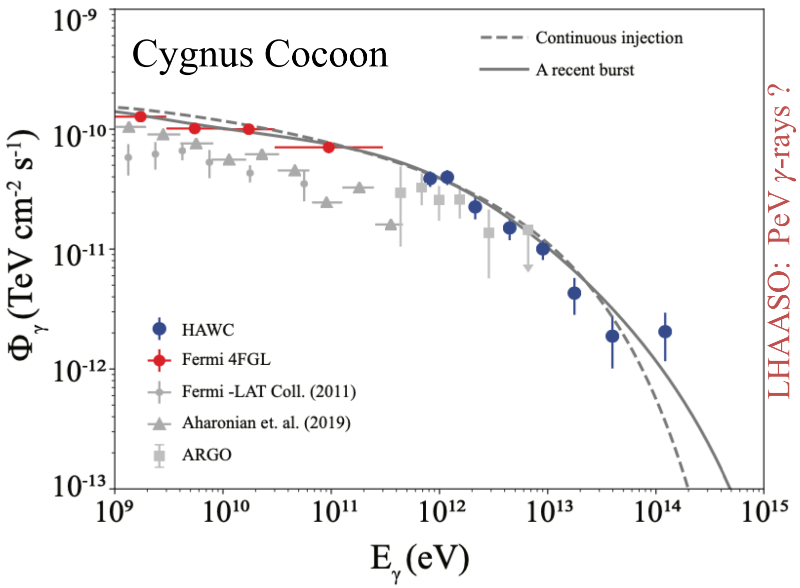
Figure 1: Gamma-ray luminosities and CR proton radial distributions in extended regions around the star clusters Cyg OB2 (Cygnus Cocoon) and Westerlund 1 (Wd 1 Cocoon), as well as in the Central Molecular Zone (CMZ) of the Galactic Centre assuming that CMZ is powered by CRs accelerated in *Arches*, *Quintuplet*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

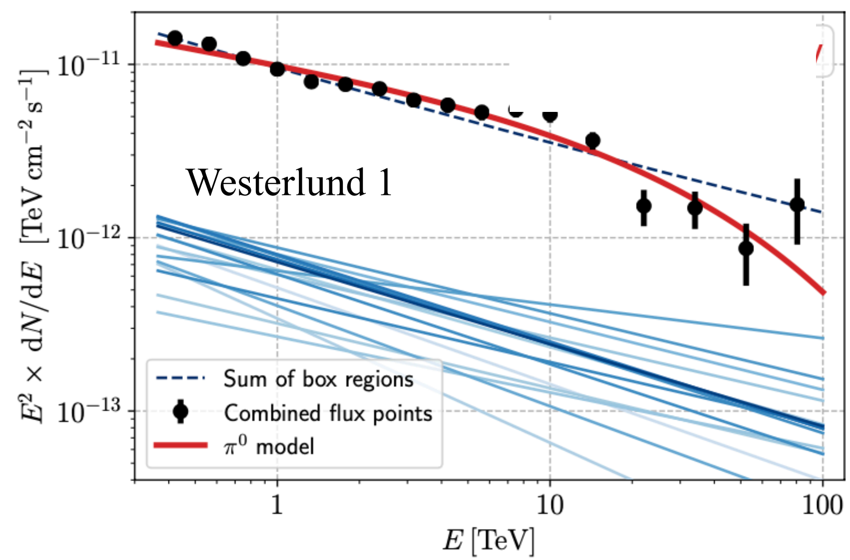
do Stellar Clusters operate as PeVatrons ?

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), W43, NGC3603, **CygnusOB2

Arches, Quintuplet and Nuclear ultracompact clusters in GC (?)

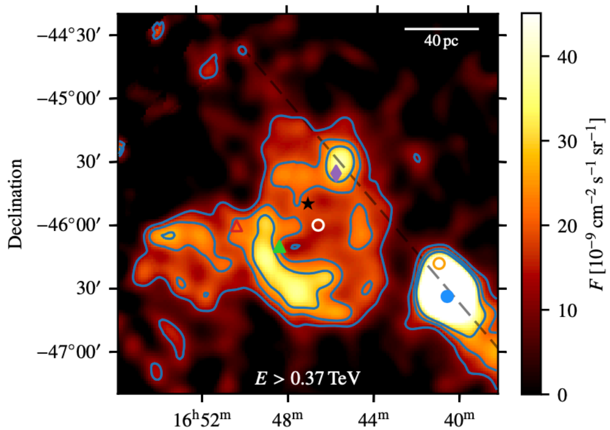




Origin of TeV/PeV γ-rays ? **Hadronic!**

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

Westerlund 1

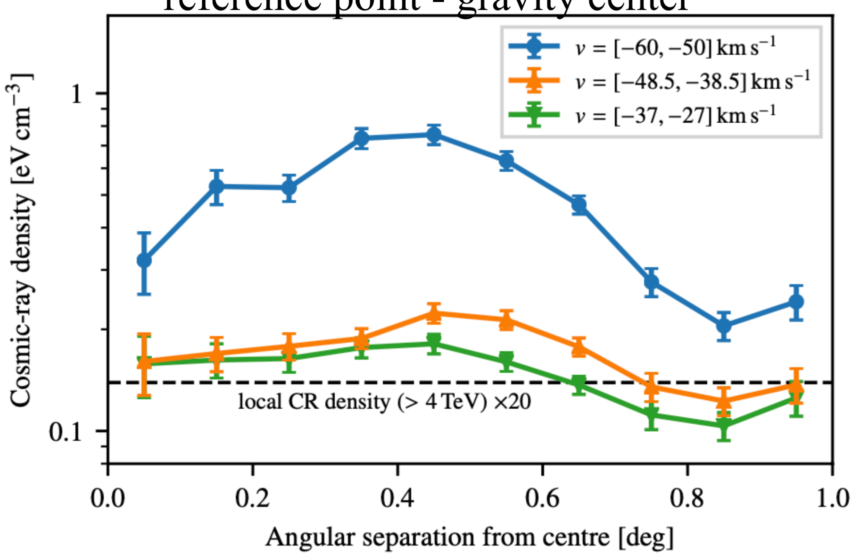


γ-ray distribution is the result of product of CRs and gas distributions: $F_\gamma(r) \propto n(r) \times w_{CR}(r)$

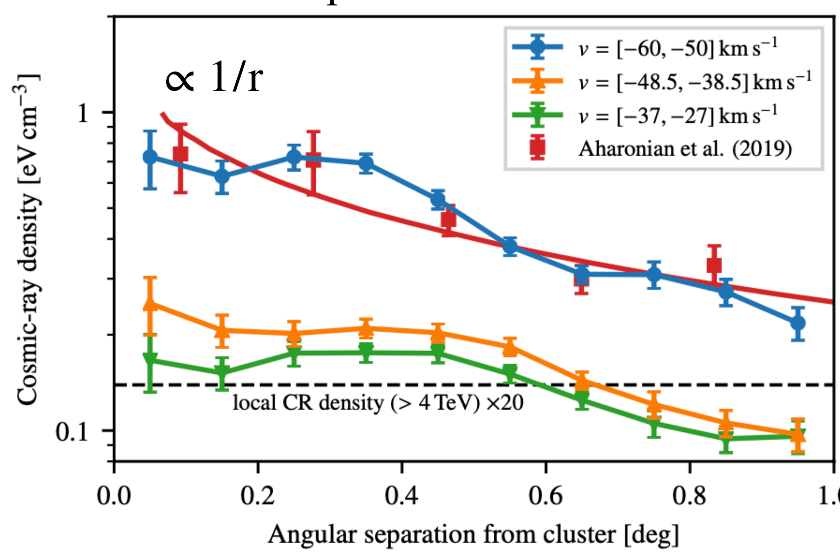
objective information is contained in $w_{CR}(r)$ but not in $F_\gamma(r)$

conclusion is sensitive to the position of the reference point

reference point - gravity center



reference point - Westerlund 1



1/r CR distribution implies continuous CR injection: accelerator is located in Westerlund 1?

alternative/additional 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 do exist in the Milky Way

Pulsars, PWNe: ? - cannot be excluded

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

Binary systems, Microquasars: ?

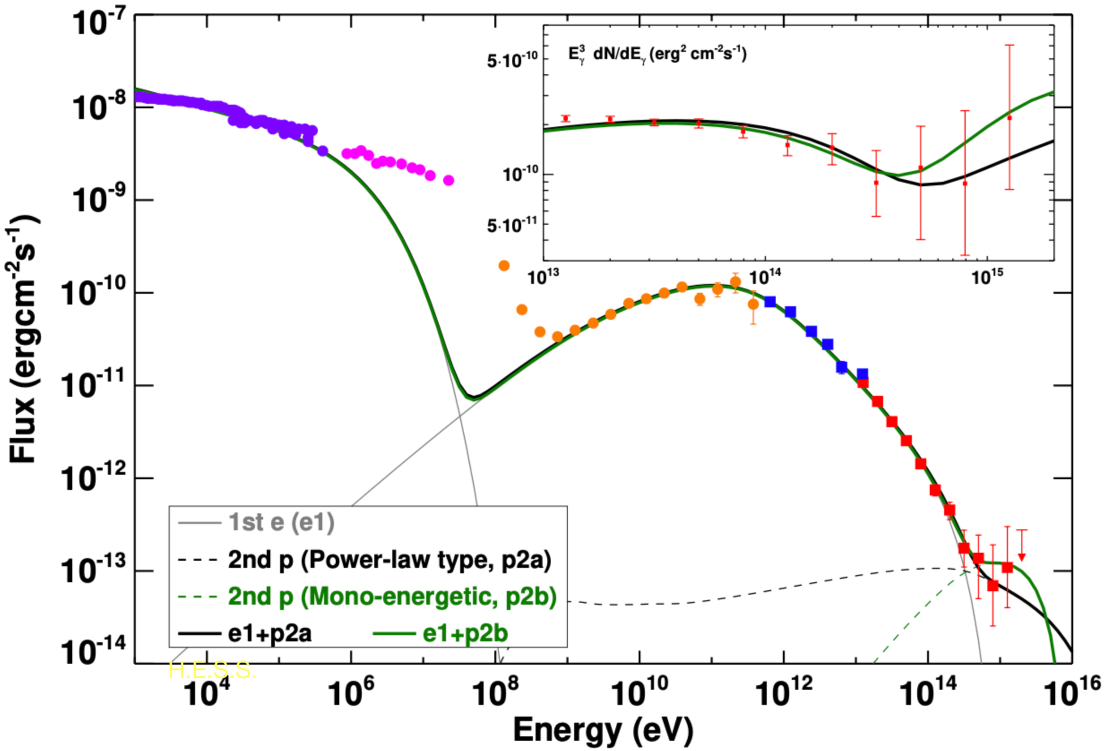
power of SS433 jets exceeds 10 times the required injection rate

SMBH in the Galactic Center:

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

Detection of > 1 PeV photons from Crab by LHAASO

mechanism: Inverse Compton on 2.7 K CMBR: direct relation $E_e \simeq 2.15(E_\gamma/1\,\mathrm{PeV})^{0.77}$ PeV



$E_\gamma = 1.1\,\mathrm{PeV} \rightarrow E_e \simeq 2.5\,\mathrm{PeV}$

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

$\eta = 0.14(B/100\mu G)(E_\gamma/1\,\mathrm{PeV})^{1.54}$

$E_\gamma \geq 1.1\,\mathrm{PeV} \rightarrow \eta \geq 0.16$

for comparison, in SNRs: $\eta \sim 10^{-4}$

Crab: pulsar/wind/nebula: an *extreme e-accelerator*

- conversion of the rotational energy of pulsar to non-thermal energy with efficiency ~50 %
- acceleration rate close to maxim possible

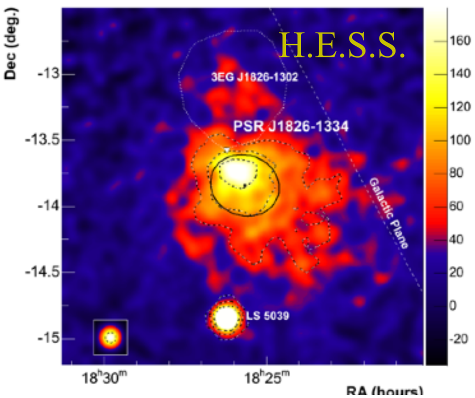
or PeV γ-rays of hadronic origin?

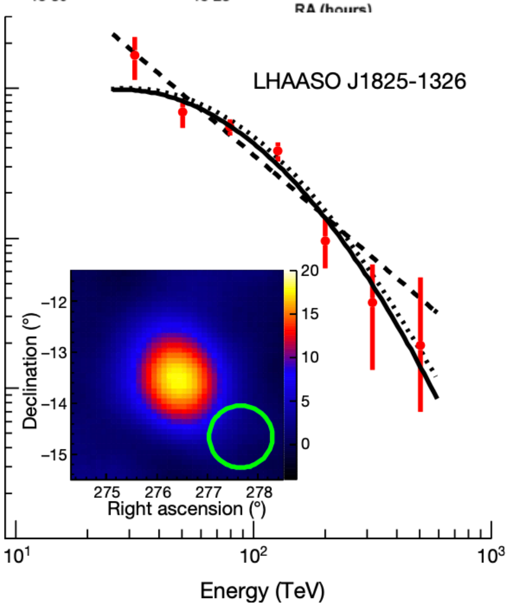
Crab Nebula: **effective electron accelerator** but **not effective γ-ray emitter**:

γ-ray efficiency: $\kappa = t_{Sy}/t_{IC} \approx 1(B/3\mu G)^{-2}$; because of $B \simeq 100\,\mu G$, $\kappa \sim 10^{-3}$

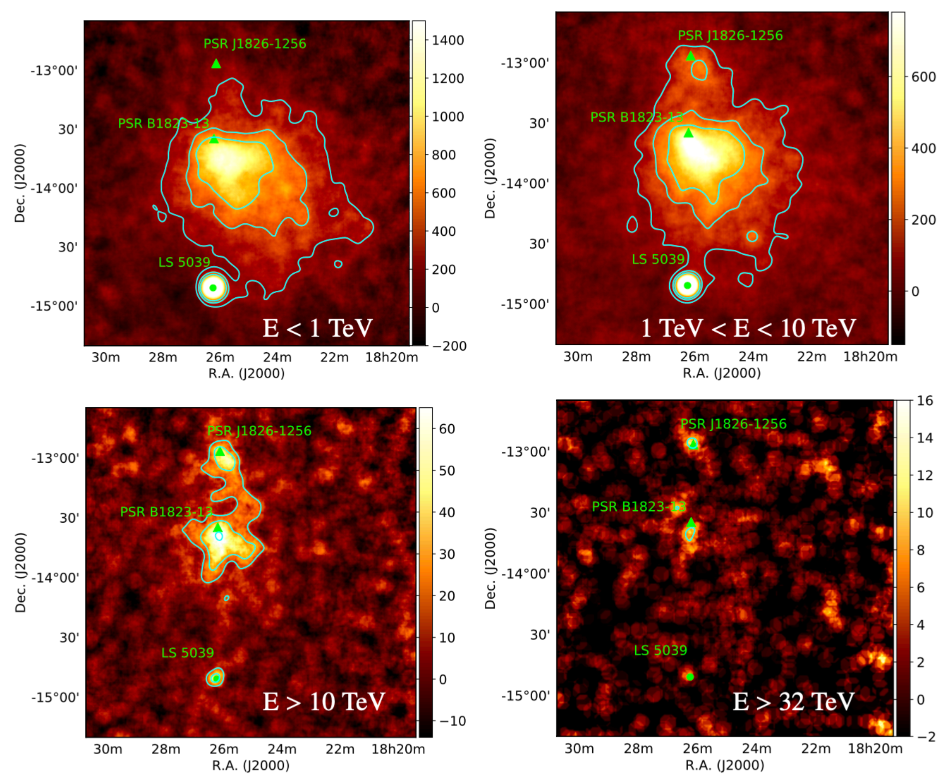
"standard" PWNe ($B \sim$ a few μG) are **effective accelerators/effective emitters** :

large $\kappa \sim 1$ in most of PWNe compensates smaller pulsars' spin-down luminosities



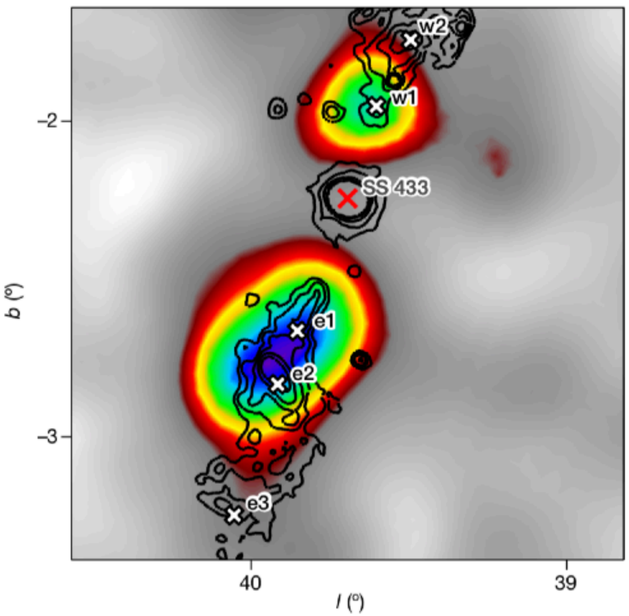


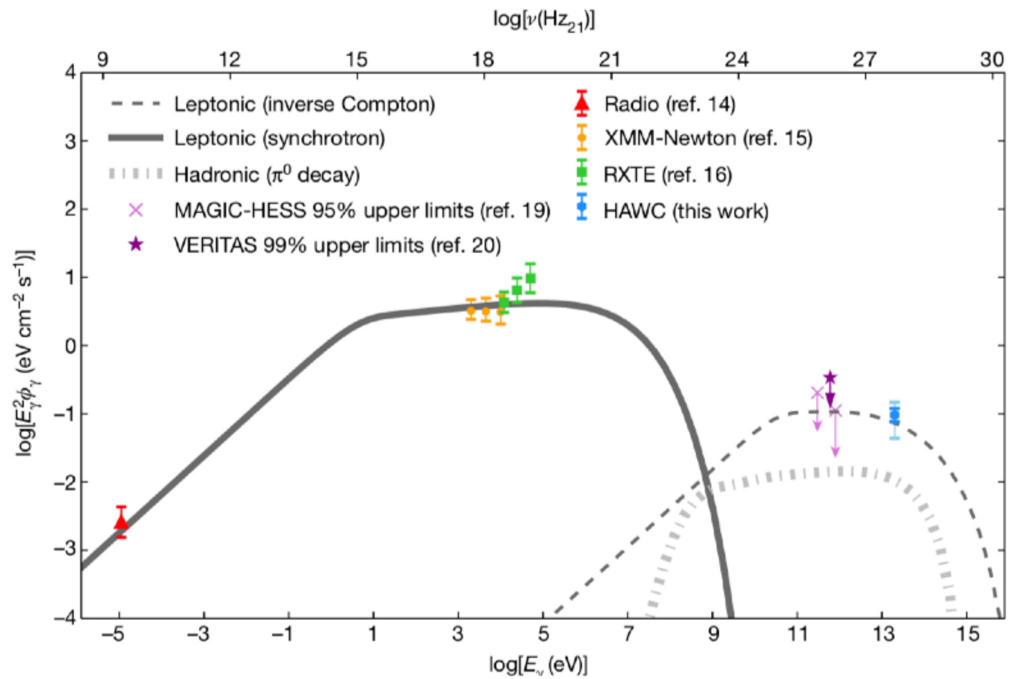
energy dependent morphology



Compact Binary Systems - Microquasars, Binary pulsars, etc.

detection of >10 TeV gamma-rays from SS 433

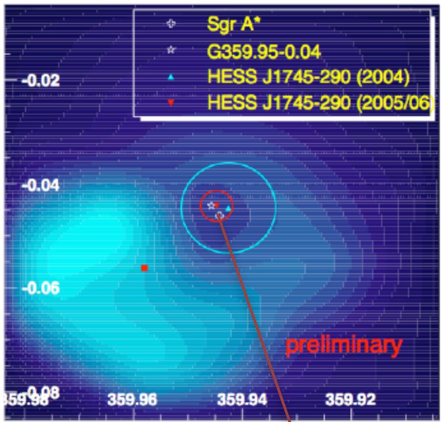




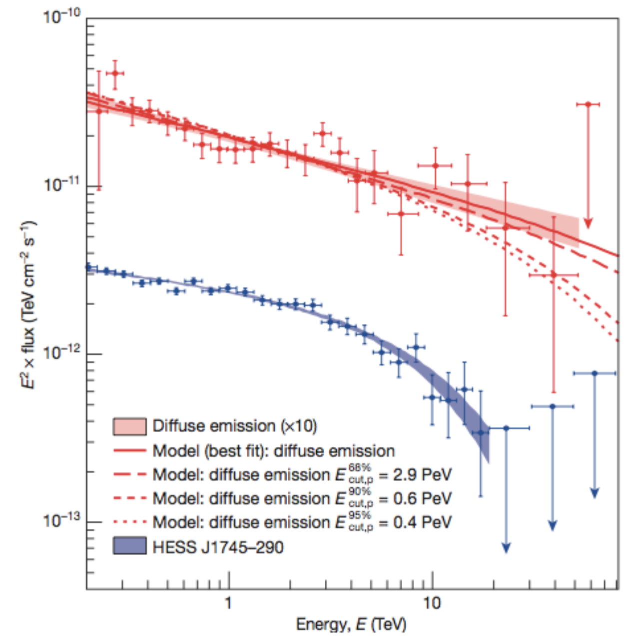
more is coming!

HAWC - HESS/MAGIC upper limits

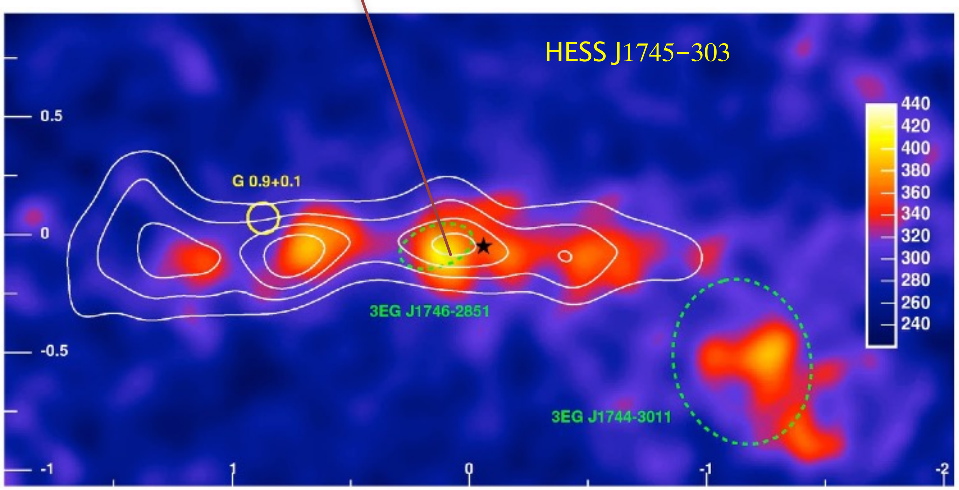
spectrum as flat as E^{-2} extending 20 TeV

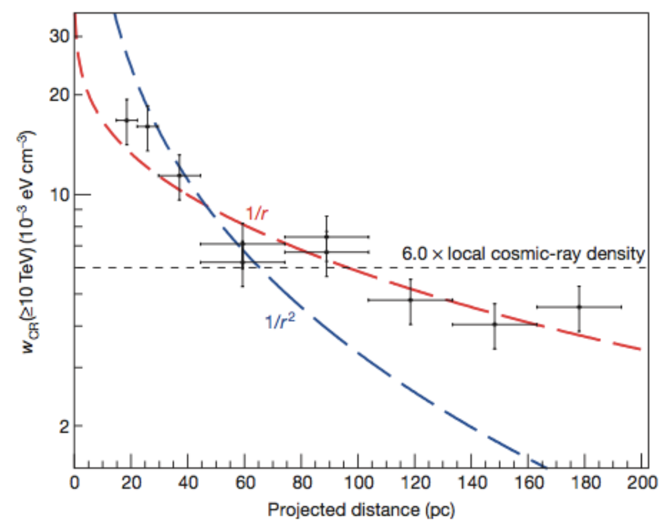


PeVatron(s) in the Galactic Center!



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

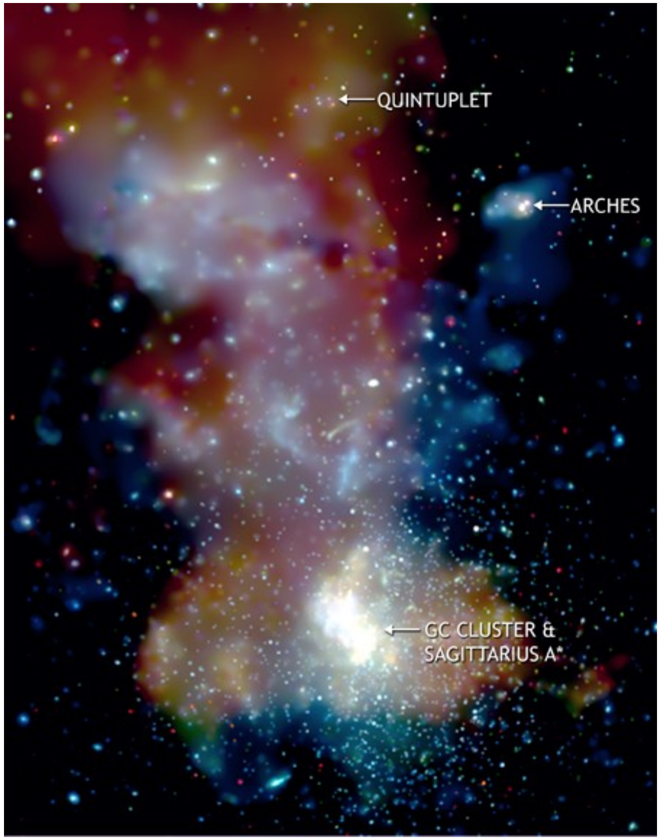




SMBC in GC (Sgr A*) operating as a PeVatron ?

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

CR injection into CMZ of GC from three centres:
Arches, Quintuplet, Nucler Clusters



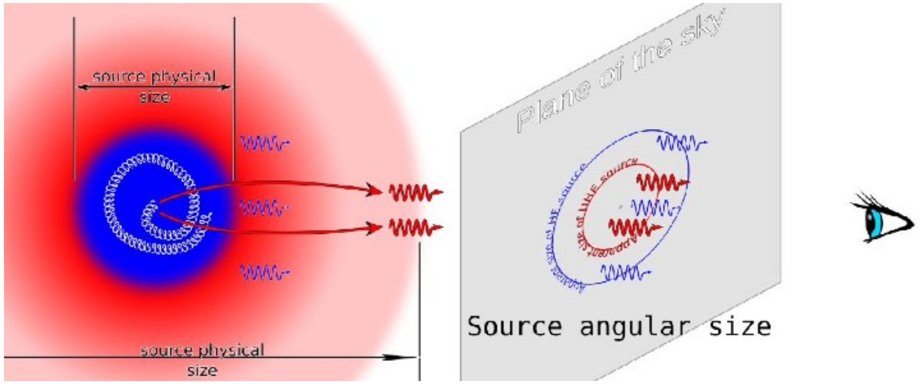
- demonstrate that γ-ray morphology in CMZ is better described when CRs are injected from three sites than from the center - can be done with IACT Arrays (HESS, CTA ASTRI): PSF comparable with distances between clusters

- search for variability of the central source; but one cannot exclude that the diffuse component is powered by 3 clusters and the central source is associated with SMBH (Sgr A)

at highest energies, $E_\gamma \gg 10\,\mathrm{TeV}$, a unique opportunity to localize the accelerators and measure the initial (acceleration) spectrum before distortion due to the CR diffusion

Localising the accelerator and deriving the initial acceleration spectrum with UHE gamma-rays produced by CRs at the stage of their ballistic motion

propagation of particles in the ballistic-to diffusive transition regime and its impact on the angular size of gamma-ray image



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

for the diffusion coefficient $D(E) = D_0(E/1\,\mathrm{GeV})^{\delta}$

ISM: $D_0 \approx 10^{28}\,\mathrm{cm^2/s}$; $\delta \approx 0.5$
at 1 PeV => $D \simeq 10^{31}\,\mathrm{cm^2/s}$

condition of the diffusive propagation: $R^2/2D \leq R/c$ => $R \geq 2D/c \simeq 200\,\mathrm{pc}$

even if the diffusion coefficient is suppressed by order of magnitude, first tens of parsecs protons with energy $E \geq 1$ PeV move in the (quasi)ballistic regime

in diffusive-to-ballistic transition regime of propagation of parent charged particles the apparent angular size of radiation *decreases* (!) with energy; at highest energies corresponding to ballistically moving protons/electrons, the source becomes point-like

localization of PeVatrons inside the LHAASO UHE sources;
high precision γ-ray studies with CTA and ASTRI, …

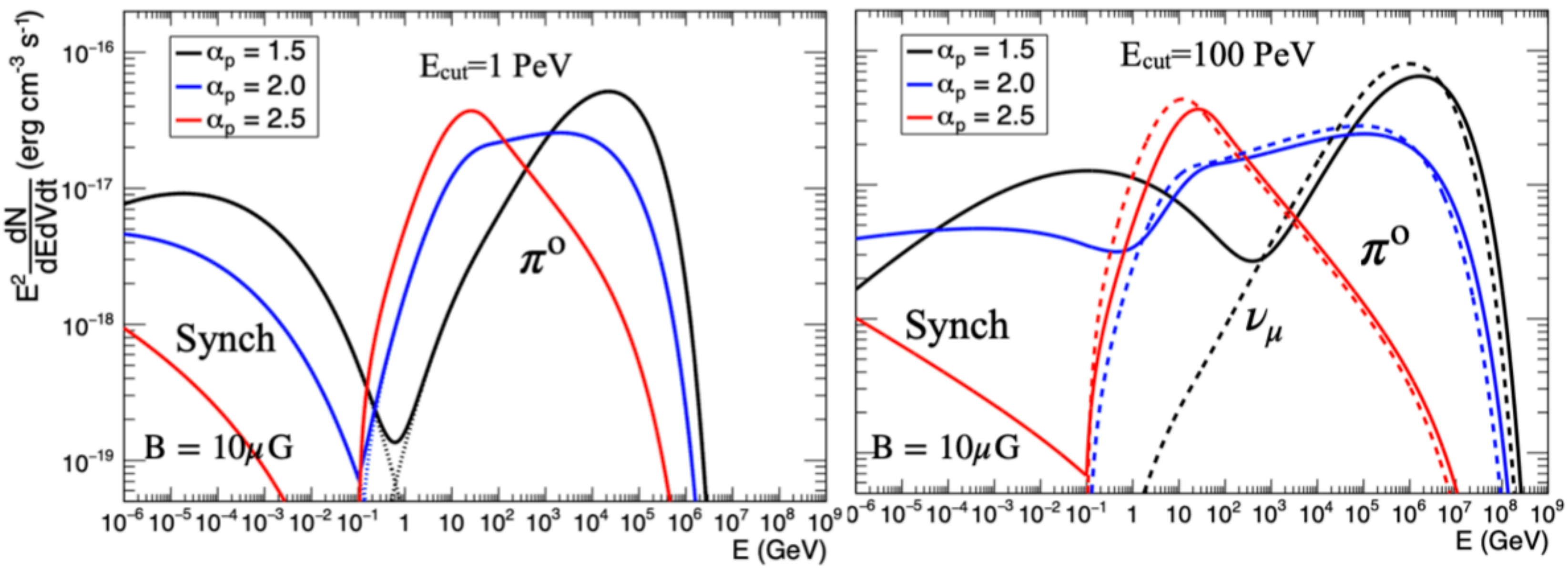
Proton PeVatrons and eROSITA

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!



S.Celli, FA, Gabici 2021

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 $\mathrm{F}(100\,\mathrm{TeV}) \approx 10^{-12}\,\mathrm{erg/cm^2s}$

eROSITA can help to localize and identify LHAASO sources !