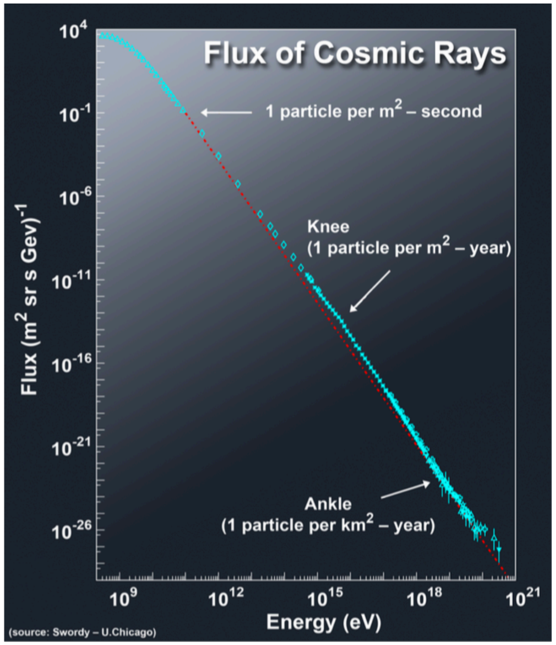
HONEST 2: PeVatrons and their environments

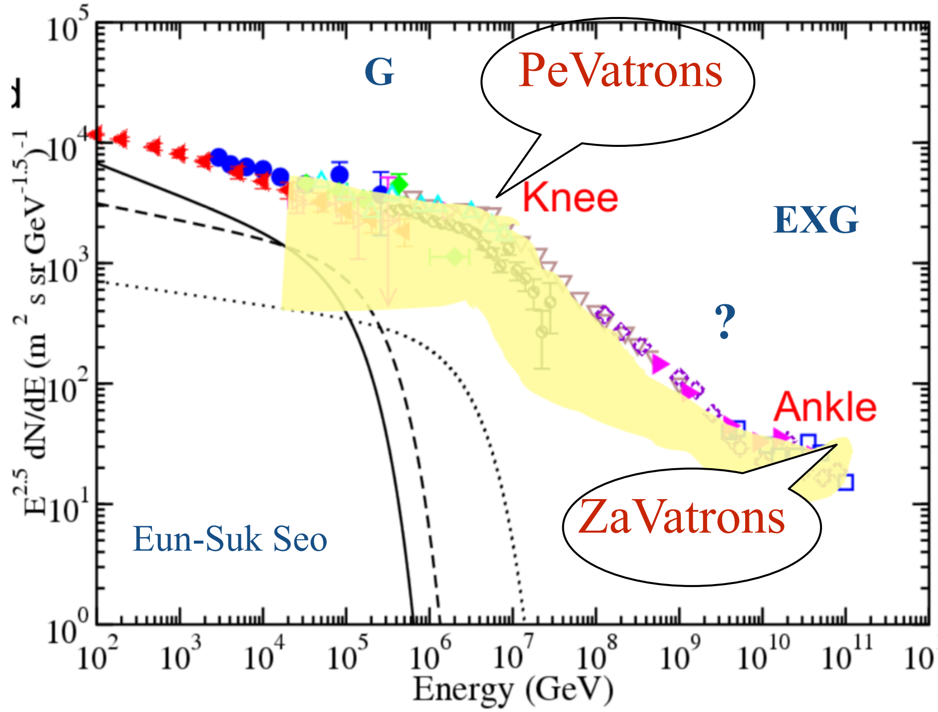
On the identification and localisation of Cosmic Ray PeVatrons inside extended UHE gamma-ray sources

Felix Aharonian
DIAS/Dublin & MPIK/Heidelberg

Nov 29- Dec 1, 2022on-line workshop

Cosmic Ray spectrum over 11 decades





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

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

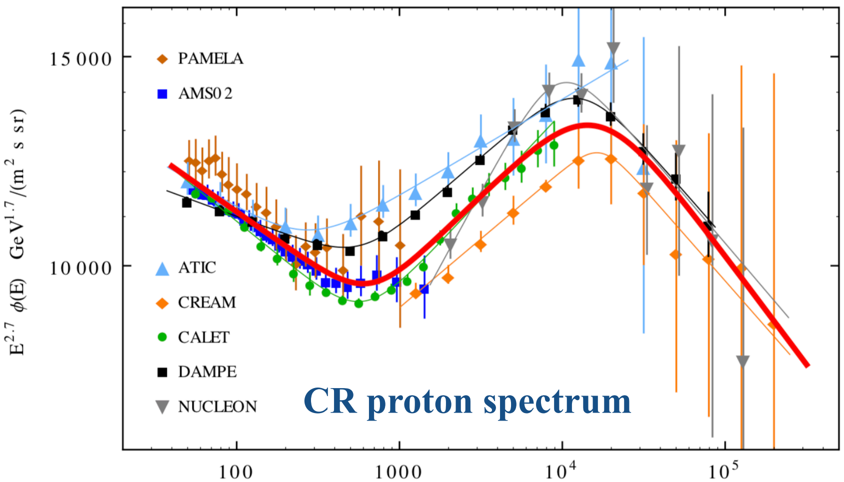
between 10^{15}-10^{18} eV transition ???

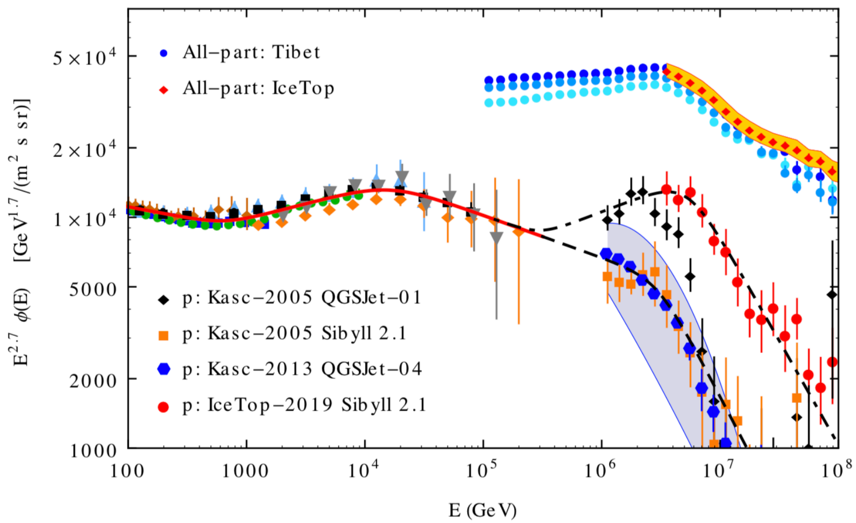
interest to PeVatrons? (i) astrophysics - contributors to GCRs in the *knee* region

(ii) physics - theoretical challenges

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

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





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 ?

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

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

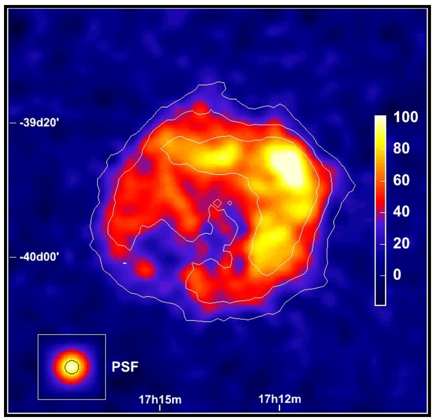
- **super-PeVatrons (of Galactic origin?)**
  >10 PeV up to 100 PeV

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

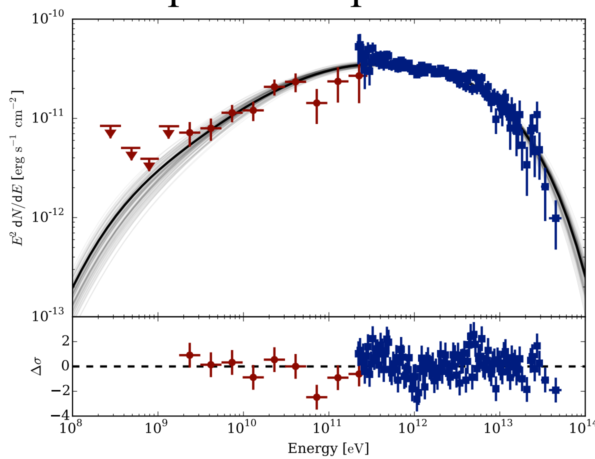
RXJ1713.7-4639

γ-ray observations - great achievements!

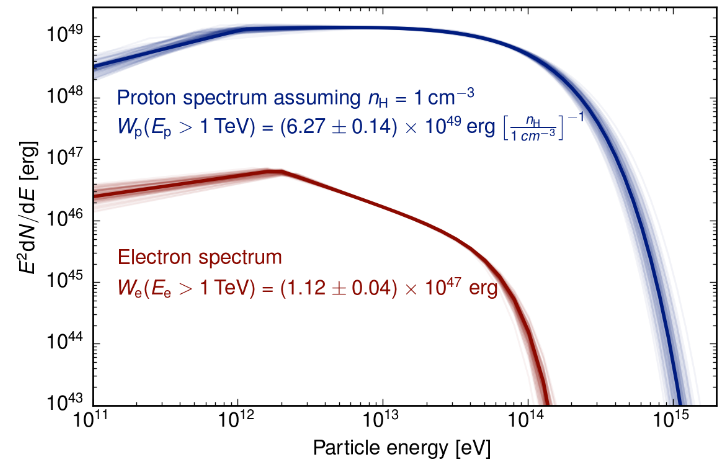
morphology - shell!

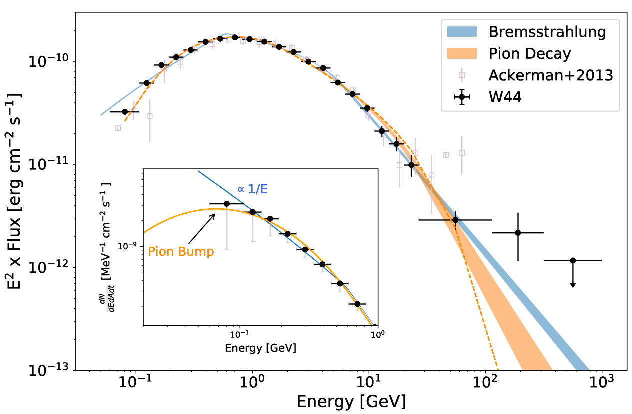


spectrum up to 60 TeV



spectra of electrons and protons



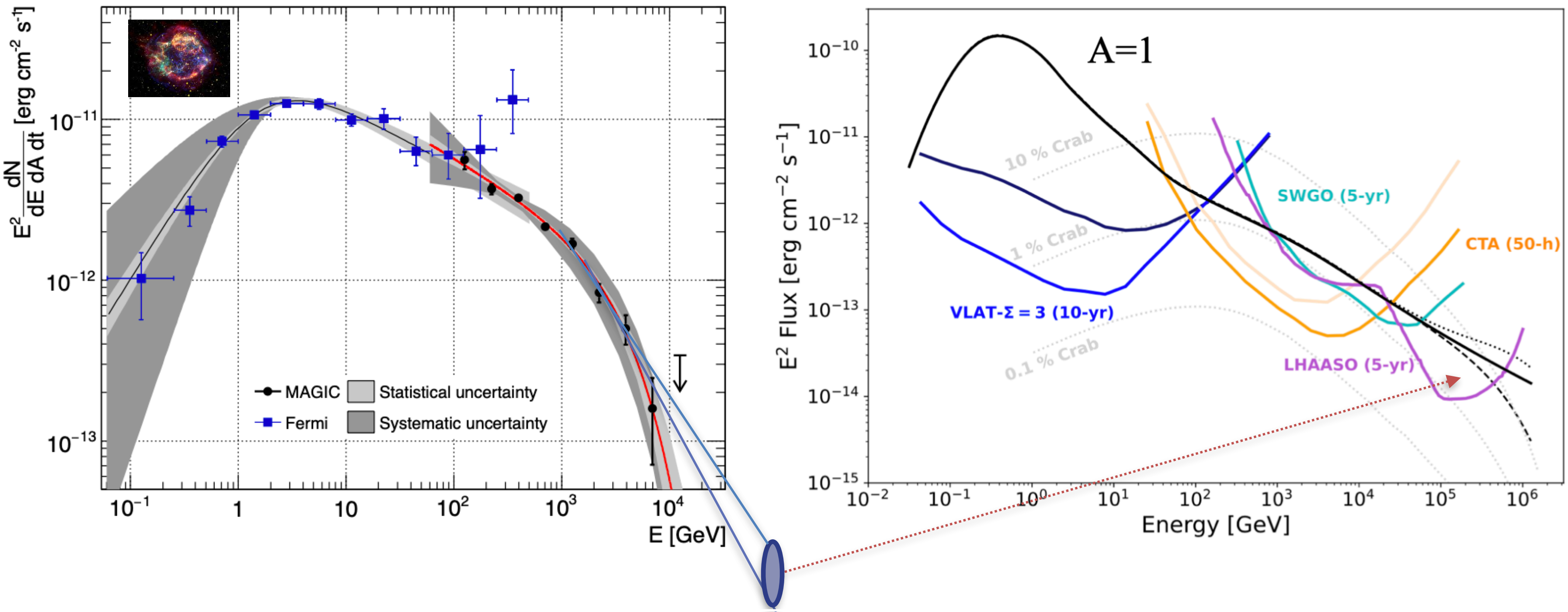


- *lepton vs. hadronic* - not yet solved at VHE energies
- if hadronic - protons accelerated out go 0.5 PeV although the cutoff in the spectrum around 100 TeV
- exponential cutoff or break?

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 $E_\gamma \sim 100\,\mathrm{TeV}$ 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

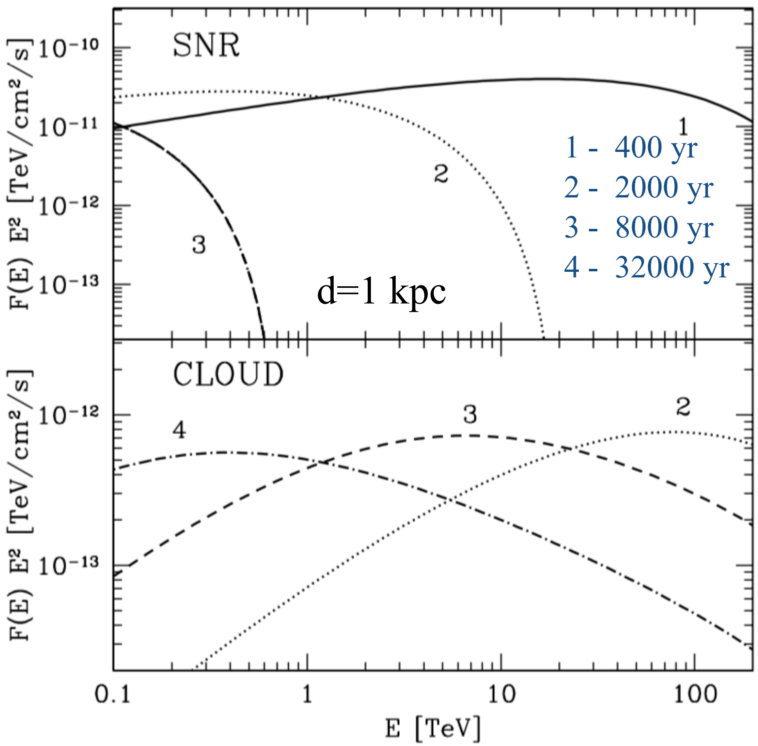
=> LHAASO upper limit (or detection) of 100 TeV γ-rays - at the level of $10^{-14}\,\mathrm{erg/cm^2 s}$

decisive "PeVatron test" independent of the acceleration epoch

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

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

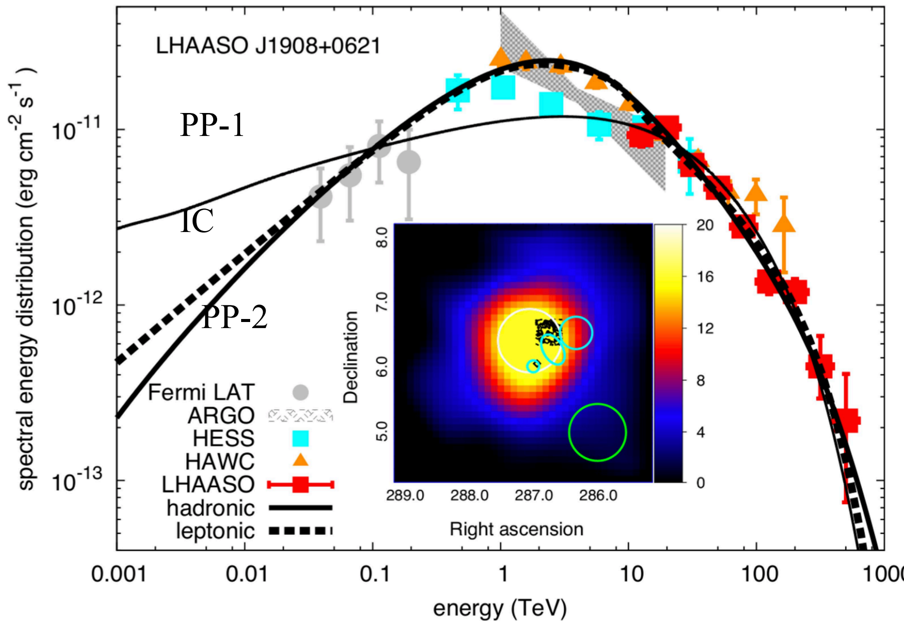
Gabici & FA, 2007



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

SNR G40.5-0.5 + GMC ?



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

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

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

Stellar Clusters operate as PeVatrons ?

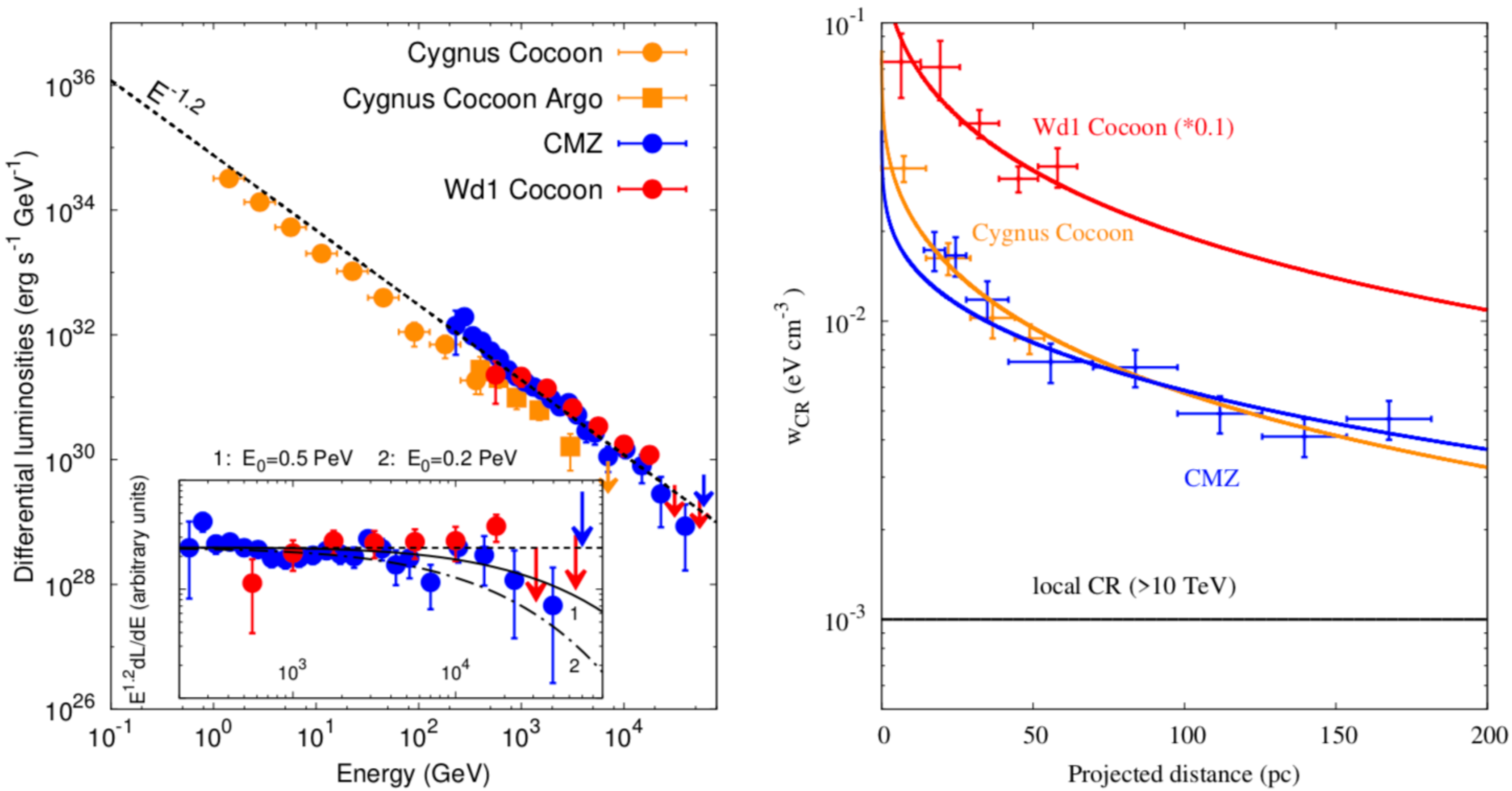


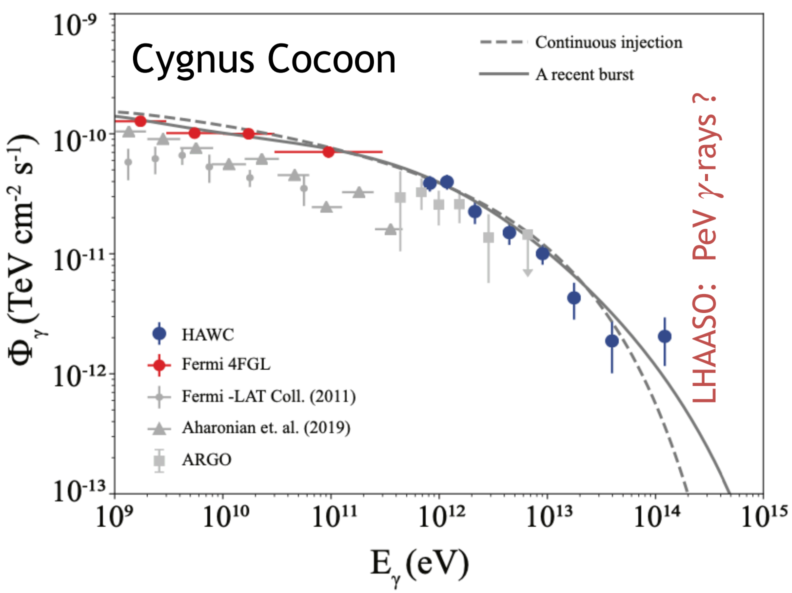
Figure 1: Gamma-ray luminosities and CR proton radial distributions in extended regions around the star clusters Cyg OB2 (Cygnus Cocoon) and Westerlund 1 (Wd 1 Cocoon), as well as in the Central Molecular Zone (CMZ) of the Galactic Centre assuming that CMZ is powered by CRs accelerated in *Arches*, *Quintuplet*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

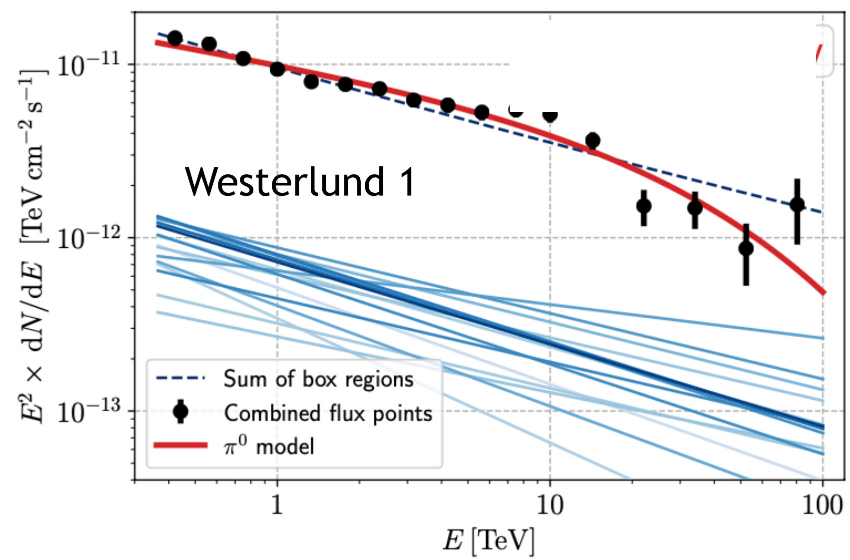
FA, Yang, Ona de Wilhelmi, 2018

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), W43, NGC3603,* ***CygnusOB2***

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

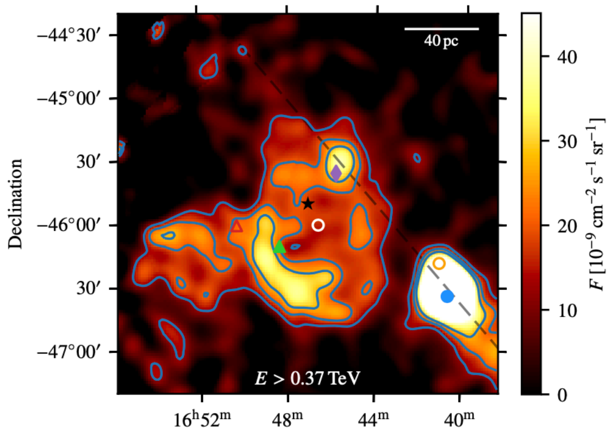




Origin of TeV/PeV γ-rays ? **Hadronic!**

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

Westerlund 1

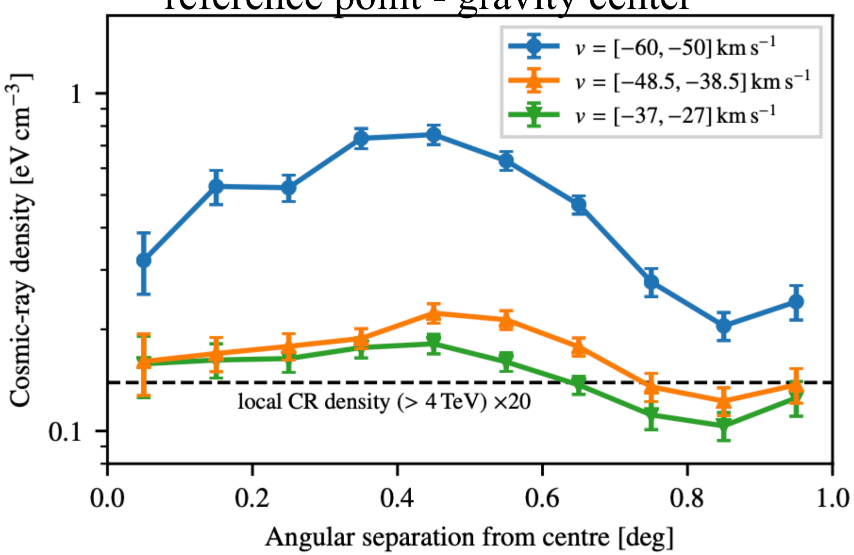


γ-ray distribution is the result of product of CRs and gas distributions: $F_\gamma(r) \propto n(r) \times w_{CR}(r)$

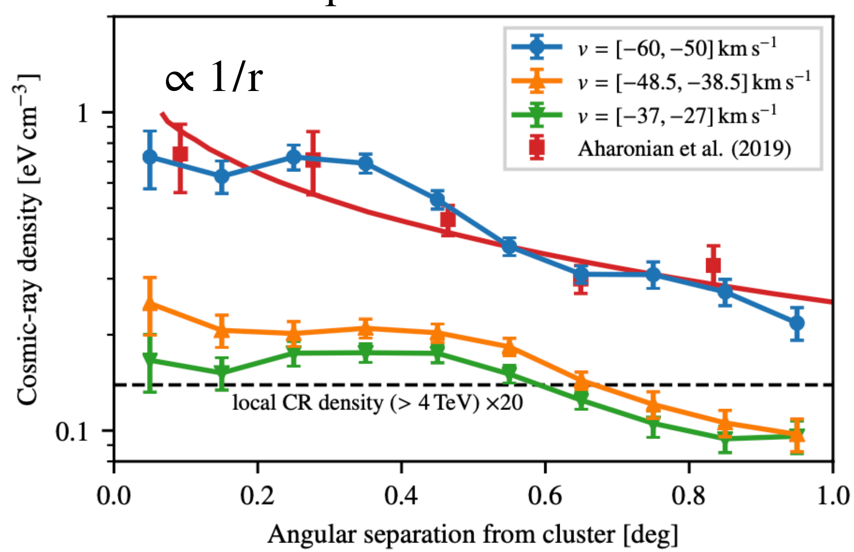
objective information is contained in $w_{CR}(r)$ but not in $F_\gamma(r)$

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: ?

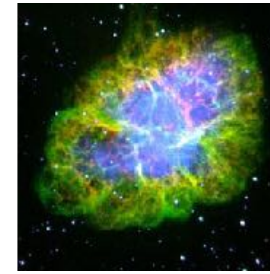
power of SS433 jets exceeds 10 times the required injection rate

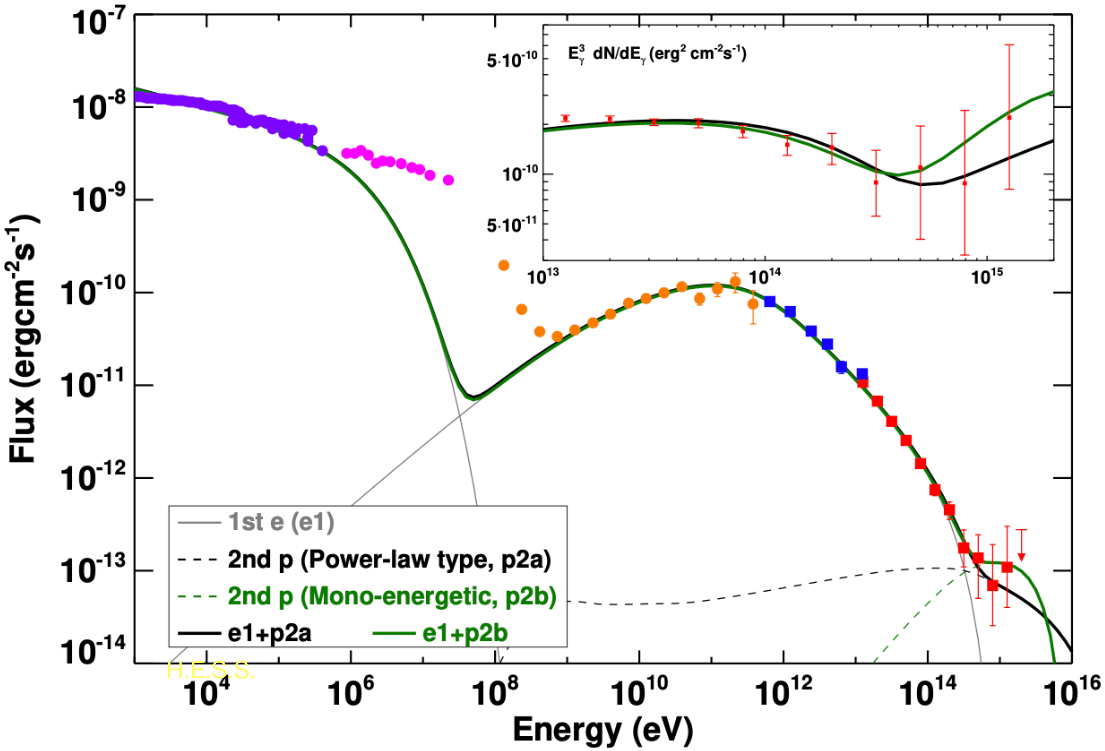
SMBH in the Galactic Center:

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

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: Extreme Accelerator

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

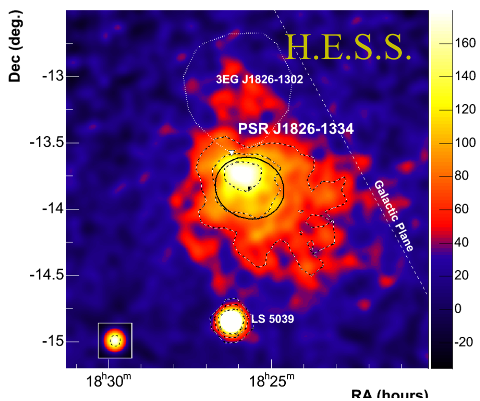
or PeV γ-rays of hadronic origin?

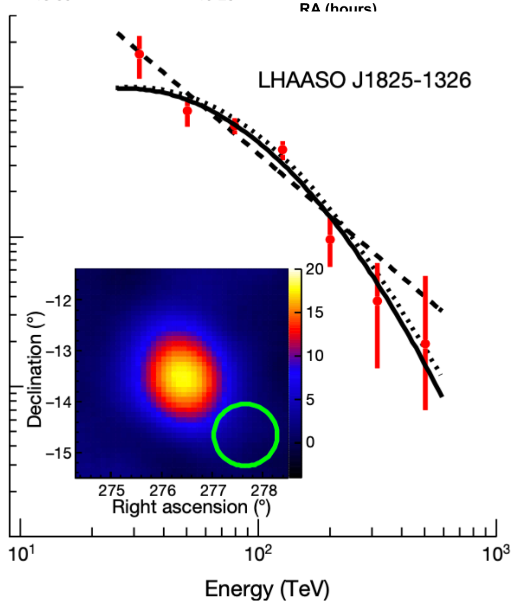
Crab Nebula: **effective electron accelerator** but **not effective γ-ray emitter**:

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

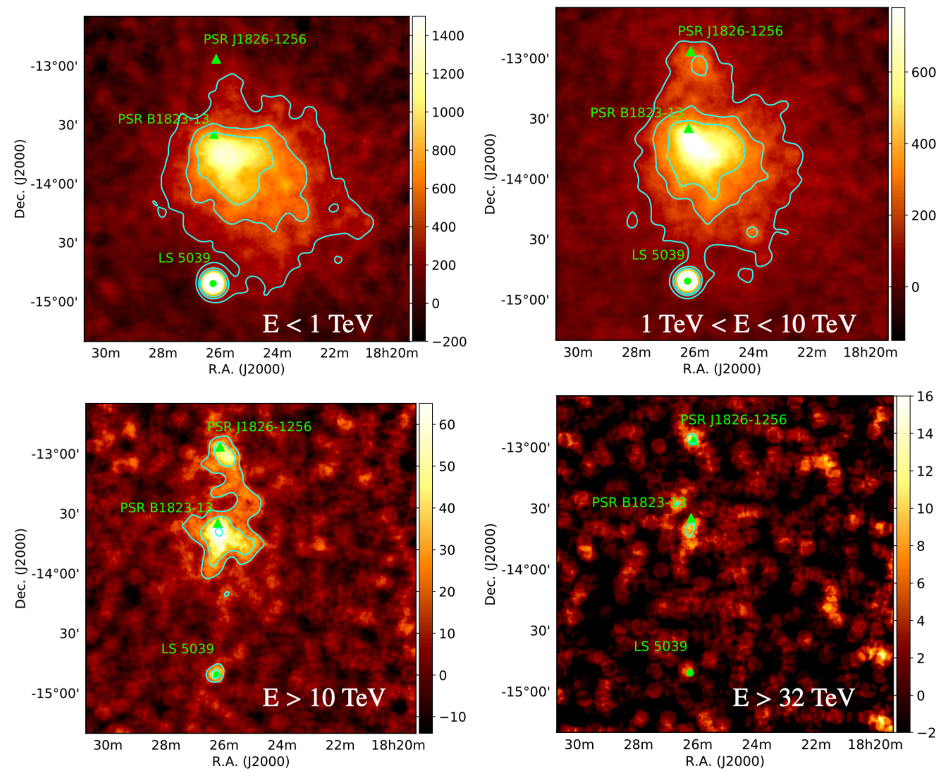
"standard" PWNe ($B \sim$ a few μG) are **effective accelerators/effective emitters** :

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

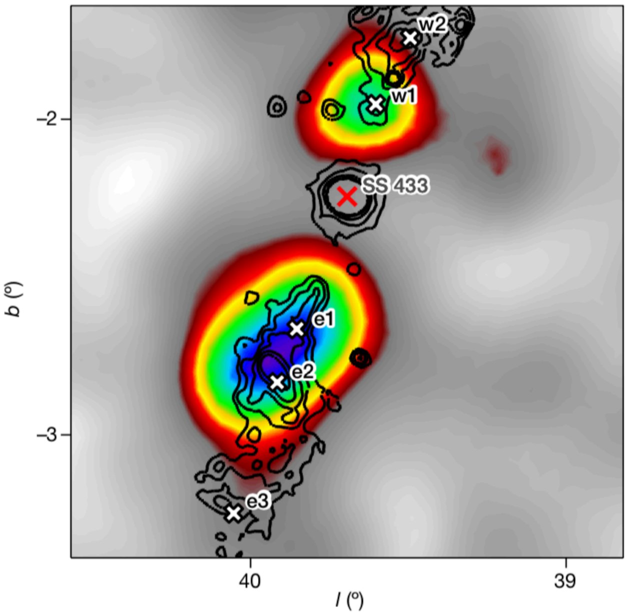




energy dependent morphology

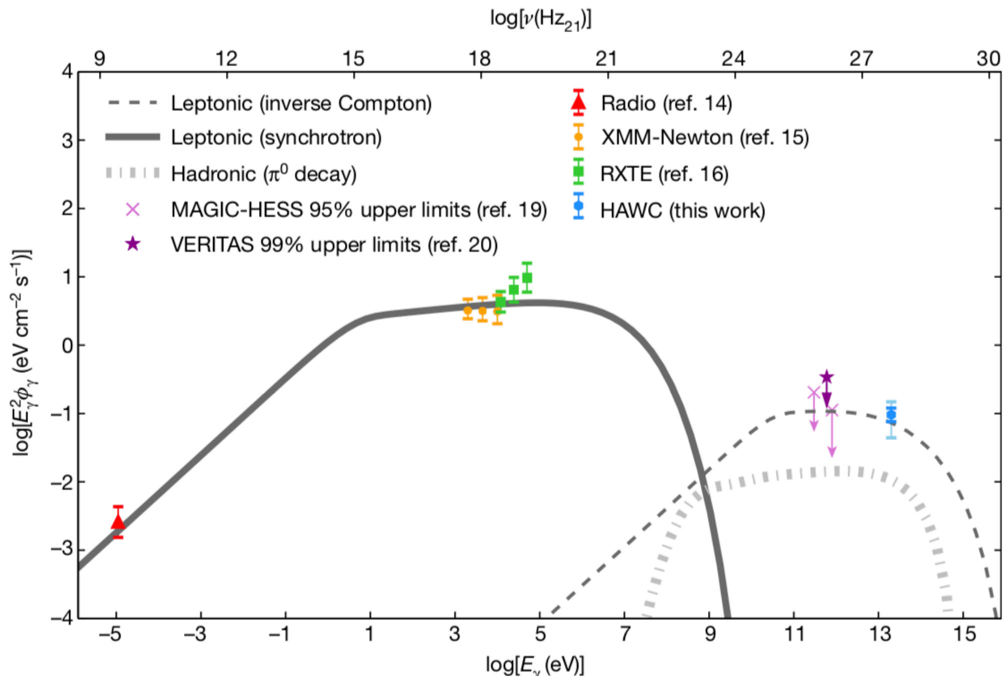


detection of >10 TeV hard spectrum gamma-rays from SS 433

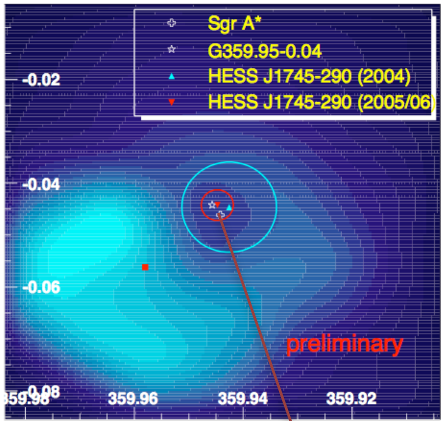


HAWC - HESS/MAGIC upper limits

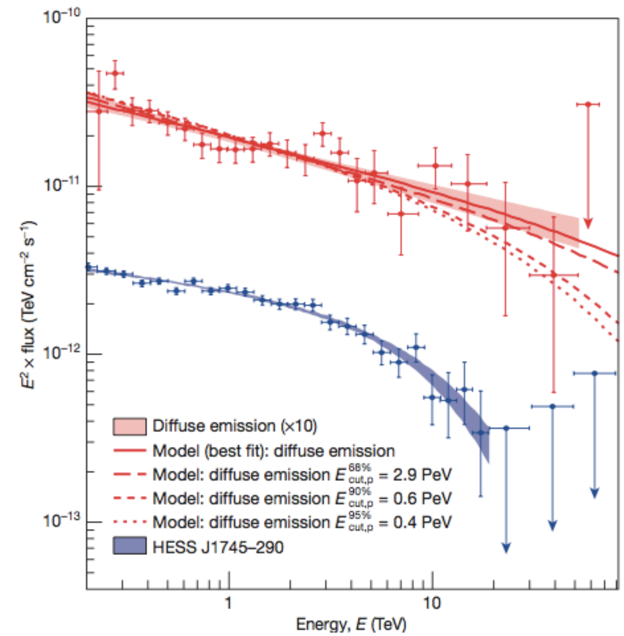
spectrum as flat as E^{-2} extending 20 TeV



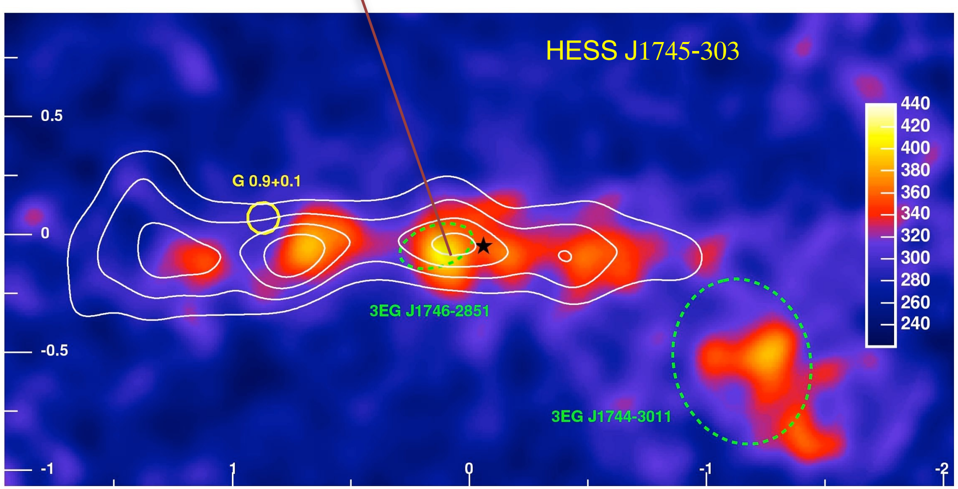
more is coming!

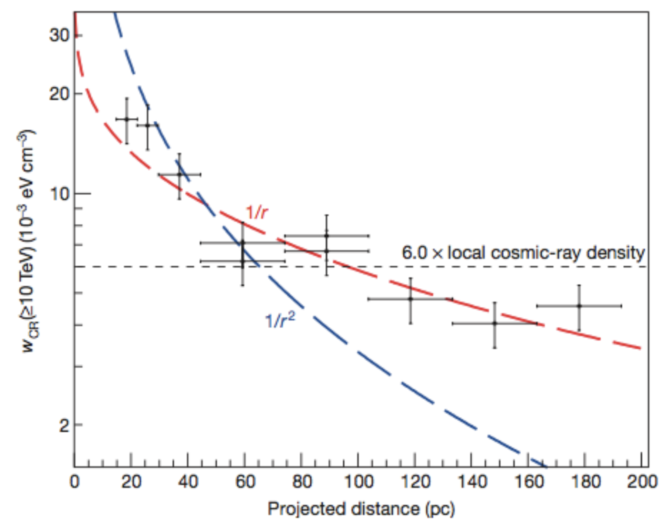


PeVatron(s) in the Galactic Center!



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





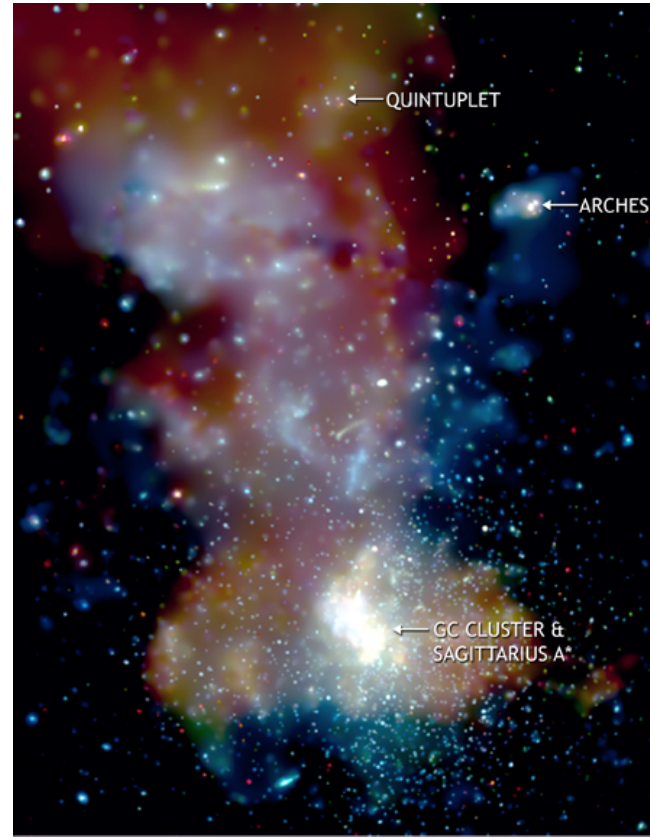
SMBC in GC (Sgr A*) operating as a PeVatron ?

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

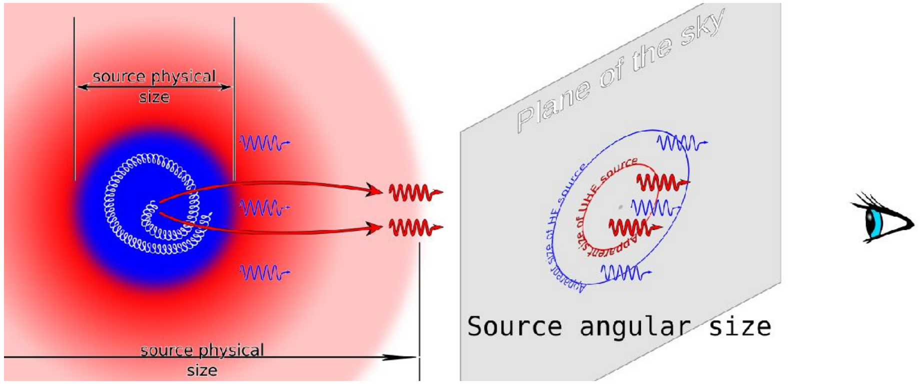
- search for variability of the central source; but one cannot exclude that the diffuse component is powered by 3 clusters and the central source is associated with SMBH (Sgr A)



at highest energies, $E_\gamma \gg 10\,\mathrm{TeV}$, a unique opportunity to localise 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: $D_0 \approx 10^{28}\,\mathrm{cm}^2/\mathrm{s};\ \delta \approx 0.5$
at 1 PeV => $D \simeq 10^{31}\,\mathrm{cm}^2/\mathrm{s}$

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

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

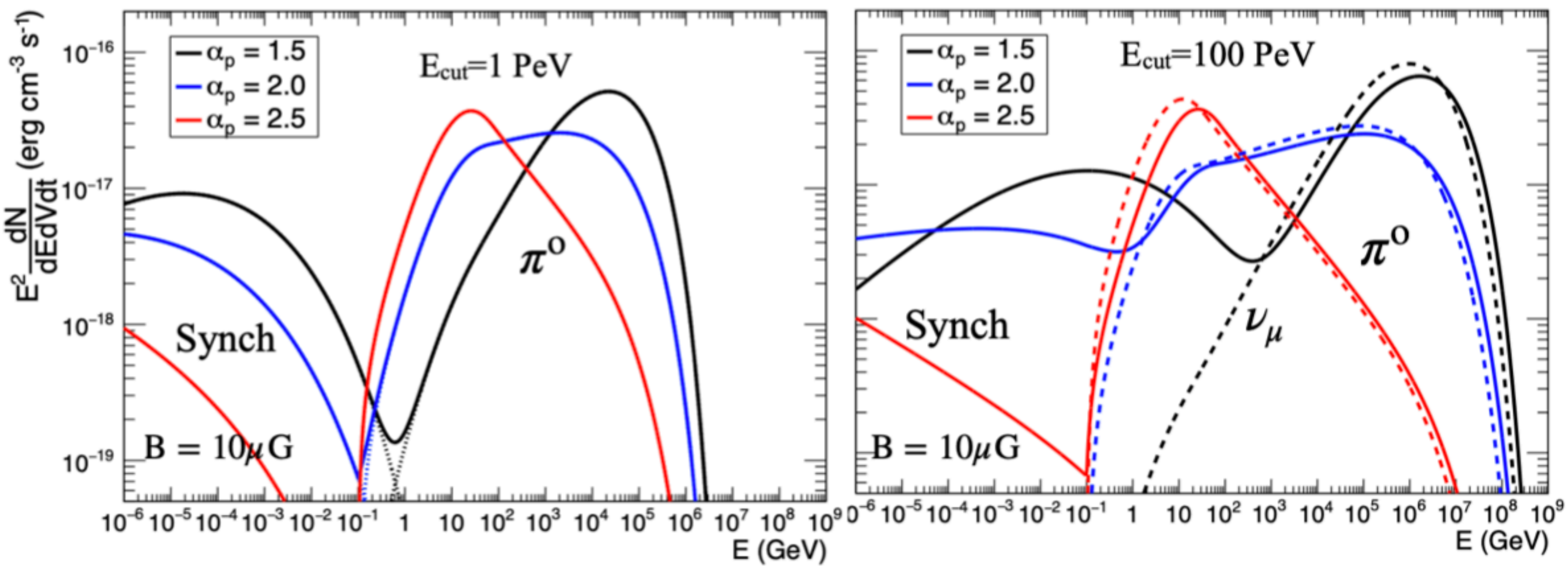
Proton PeVatrons and eROSITA

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!



S.Celli, FA, Gabisi 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 localise and identify LHAASO sources !