γ 2024 8th Heidelberg International Gamma Ray Symposium on
High Energy Gamma Ray Astronomy, Milano, Sep 2-6, 2024

Galactic Gamma Ray Sources
@
Very and Ultra High Energies

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September 2, 2024, Milan, Italy

First Heidelberg Gamma Ray Astrophysics Symposium (workshop) - Oct 3-7, 1994
Theory and Observations

approx 130 participants: SOC: F.Aharonian, M. Begelman, C. Ceasarsky, Ph. Goret, W. Hofmann, G. Kanbach, T. Kifune, J. Kirk, G. Krymsky, R. Lamb, H. Meyer, A. Watson, T. Weeks, G. Yodh, H. Voelk

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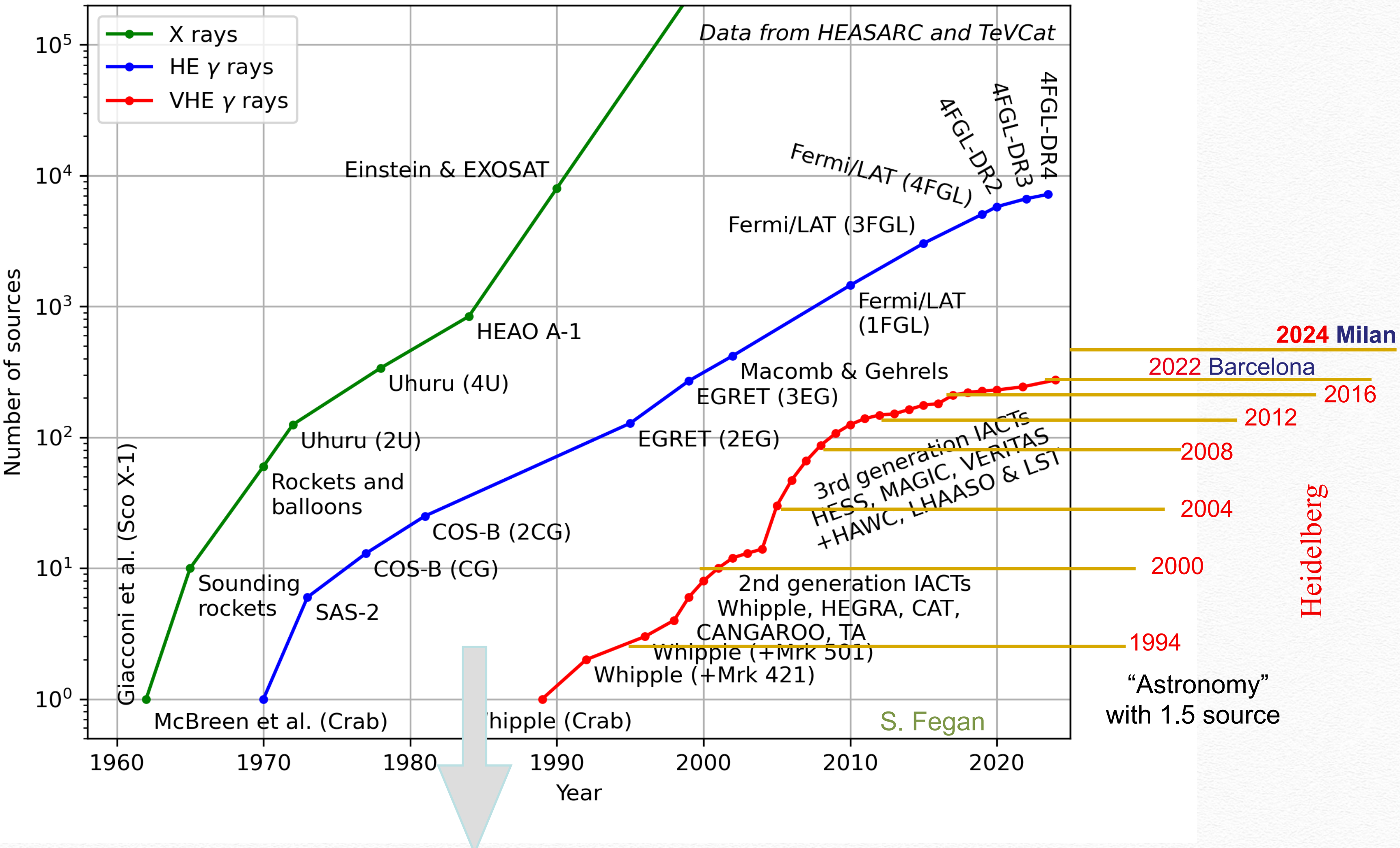
balanced coverage of the detection technique, observations, and theory !

detection technique - great progress; *observations* - 2 sources;
theory/phenomenology - discussion of topics which constitute core of today's discussions - *SNR, Pulsars, PWNe, Binaries, Starburst Galaxies, Galaxy Clusters, AGN, EBL, IGMF, ...*

“Kifune’s plot”: number of sources vs years



“exciting” (“dark”) years with Cyg X-3

Ground-Based Gamma-Ray Astronomy - *a success story*

over the last two decades the field has been revolutionized

before – *"astronomy" with several sources - Astroparticle Physics rather than Astronomy*

now – *a truly astronomical discipline with*

hundreds (> 300) of detected VHE/UHE gamma-ray sources representing at least 14 Galactic and Extragalactic source populations:

SNRs, GMCs, Massive Stellar Clusters, Novae, Pulsars, PWN, Pulsar Halos, Binary Pulsars, Microquasars, Galactic Center, ...

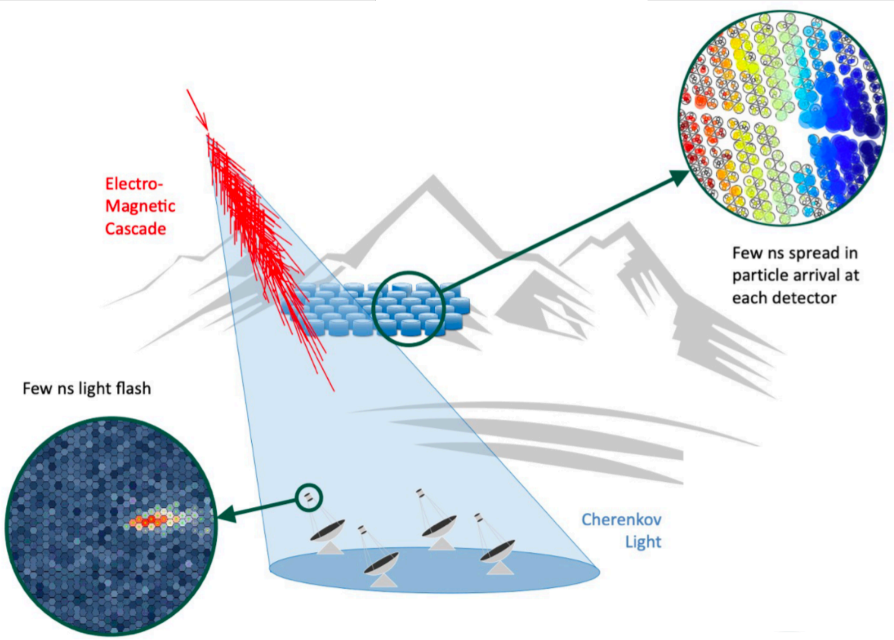
Starburst Galaxies, Radiogalaxies, Blazars, GRB afterglows…

and

two effective detection techniques:

- *Stereoscopoic IACT Arrays*
- *Particle (EAS) Detectors*

Particle Detector Arrays



Imaging Cherenkov Telescope Arrays

Gamma Ray Astronomy and Origin of Cosmic Rays

Historically, the main motivations for experimental study of cosmic γ-rays, have been formulated in the context of the origin of galactic cosmic rays

In the 1960s, the pioneers of the field recognized the great potential of γ-ray astronomy to solve the "50-year-old puzzle" of Cosmic Rays, i.e., to reveal sites of particle accelerators responsible for the locally measured CR fluxes.

since then, we have witnessed the birth of *observational* γ-ray astronomy at

HE in 1970/80s **VHE** 1990s/2000s , **UHE** in 2020s

over the last two decades thousands of GeV, hundreds of TeV, and tens of PeV γ-ray sources have been discovered and (partly) identified with famous astronomical objects!

Yet … we keep talking about the potential of gamma-ray astronomy to solve the "110+ years old puzzle" of the Origin of Cosmic Rays

disappointing?

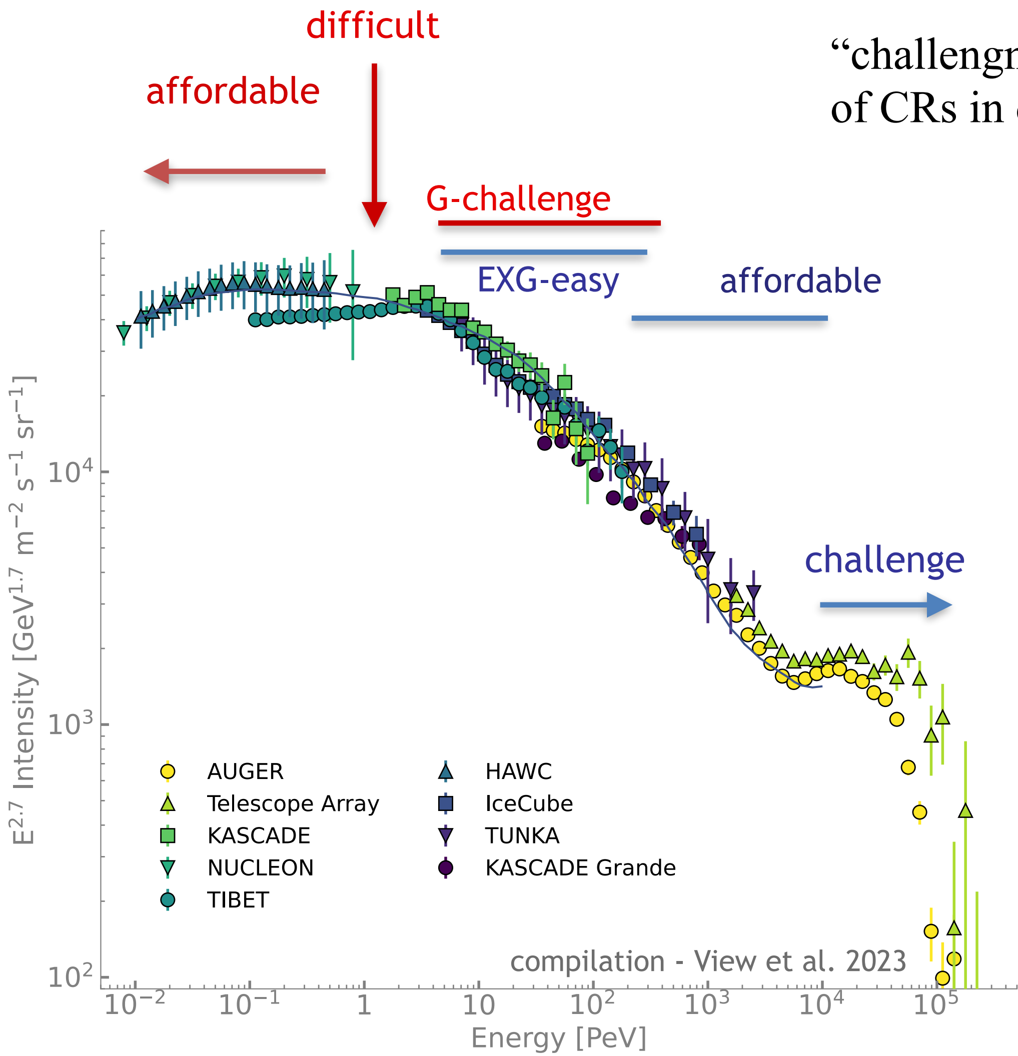
Gamma Ray Astronomy - a discipline in its own right

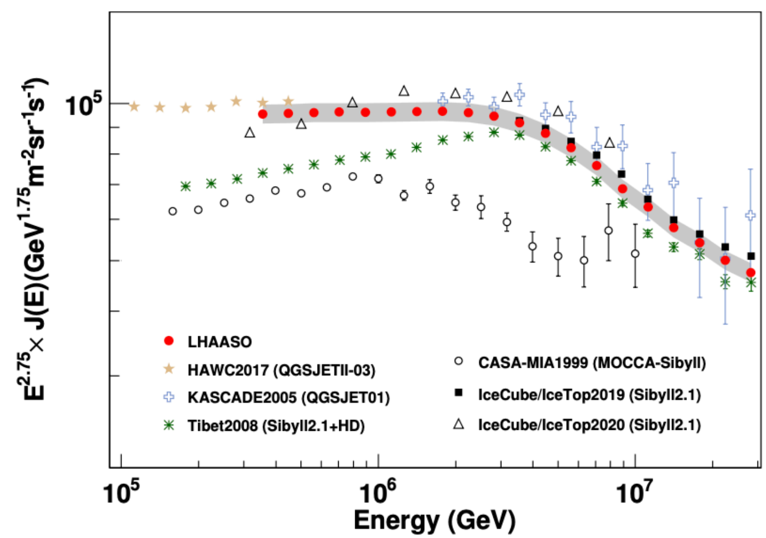
The motivation of γ-ray observations cannot be reduced to a specific (though important) scientific objective - the "Origin of Cosmic Rays", especially since it is often understood as the identification of the principal contributors to the directly measured local CR flux

- in the context of galactic sourcers, the great γ-ray discoveries tell us that Milky Way is full of TeVatrons and PeVatrons - we deal with Cosmic Ray Factories - effective accelerators of electrons, protons/nuclei linked, directly or indirectly, to star formation processes, the results of explosive events like SNRs, compact objects - neutron stars/pulsars and black holes/microquasars, SMBH (Sgr A*) in the GC, *etc*

- not necessarily all these sources can be responsible for the local "CR fog"; the importance of exploration of diversity of particle accelerators on *source-by-source* basis (like "laboratory experiments") goes beyond the issue of "Origin of CRs"

Regarding the origin of *Galactic Cosmic Rays*, the recent discovery of UHE gamma-ray observations gives us optimism that we are close to solution of the "century old problem", and, it is likely that the outcome could be different than what we anticipated for decades “challengness” level of explanation of CRs in different energy intervals

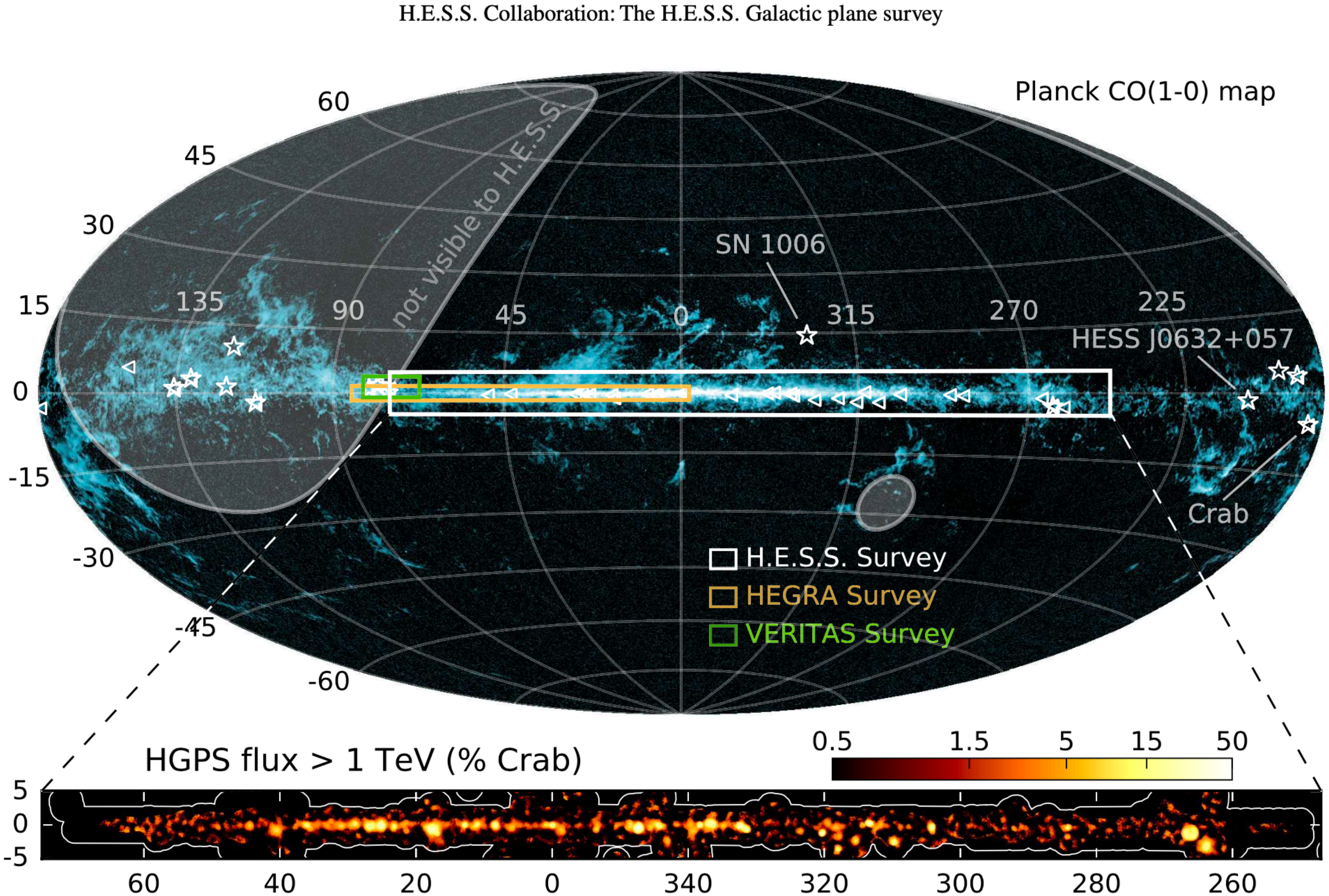


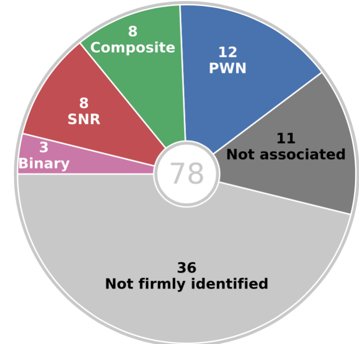


LHAASO - all particle CR spectrum

what do we understand under solution of the “century-old puzzle” ?

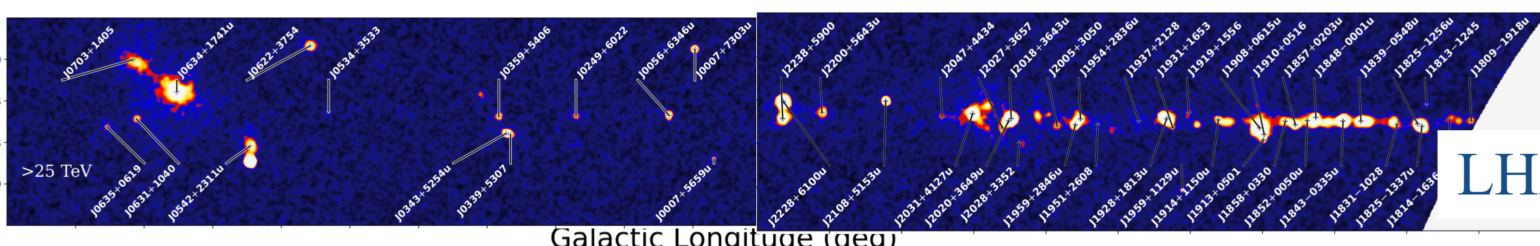
identification of Galactic and Extragalactic source populatios as major contributors to the locally measured Cosmic Rays fluxes (local CR fog”)





HESS

Milky Way is
full of TeVatrons



LHAASO

Milky Way is
full of PeVatrons

UHE gamma-ray sources, $E_\gamma \geq 100$ TeV, unambiguously *indicate* the presence of electron or proton PeVatrons since the all effective γ-ray production mechanism

IC (on 2.7 K) $\quad p\,p \rightarrow \pi^0 \rightarrow \gamma \quad p\gamma \rightarrow \pi^0 \rightarrow \gamma$

require an order of magnitude larger energy of parent particles

but UHE gamma-ray sources cannot be considered (*a priori*) as PeVatrons; they are *γ-ray emitters* - the products of CR interactions with surrounding gas and radiation

γ -rays can be effectively produced inside the accelerators (young SNRs, PWNe, compact binaries), but often more effectively outside accelerators leading to the formation of extended γ-ray structures - "bubbles", "halos", offset "hot spots" …

Localization and identification of PeVatrons is the aim no. 1 - it is hard task that requires broad-band γ-ray morphology and spectrometry with adequate precision, multiwavelemgth observations, careful modeling of confinement and escape of particles, their propagation outside the accelerator, etc. etc.

For compact objects, the timing is an additional if not the most decisive tool

Galactic γ-ray sources at VHE/UHE energies

- **Supernova Remnants (SNRs)**
- **Giant Molecular Clouds (GMCs)**
- **Young Stellar Clusters**
- **Supermassive Black Hole (Sgr A*) at GC**
- **Galaxy itself (the Disk and the Hallo)**
- **Pulsars,**
- **Pulsar Winds,**
- **Pulsar Wind Nebulae (PWNe)**
- **Pulsar Halos**
- **Binary Pulsars**
- **Microquasars (accreting Black Holes)**
- **Central Molecular Zone**

=> *all are Cosmic Ray Factories, but not all of them are responsible for directly measured local CR fluxes*

SNRs as sources of Galactic Cosmic Rays (*"SNR paradigm of GCR"*)

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 characterising **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 in young (< 1 kyr) SNRs up to 1 PeV ?
  Difficult but (in principle) possible - *fast (> 0.01 c) shocks waves, Bohm diffusion,* amplification of B-field in upstream are critical conditions

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

Two approaches:

- Probing γ-ray emission of **young SNRs** (e.g. Cas A, SN 1006**)** up to 100 TeV

  model-independent conclusions on PeV protons *inside and outside* SNRs

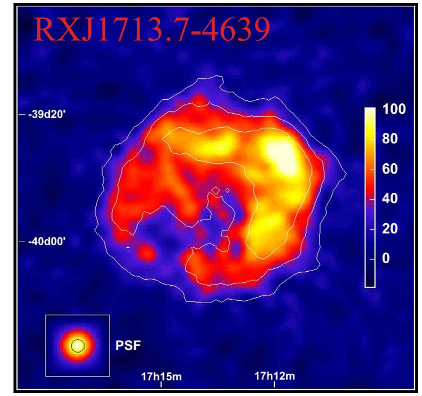
=> decisive tests whether these objects have operated as PeVatrons
at any stage of their evolution

- Exploring links of some of the extended UHE sources with **middle-aged** (~10,000 yr old) SNR having nearby (R $\leq$ 100 pc) massive (M $\geq 10^4 M_\odot$) gas clouds - "smocking guns" radiating γ-rays initiated by CRs that already have left the accelerator (SNR) and presently interact with the cloud(s)

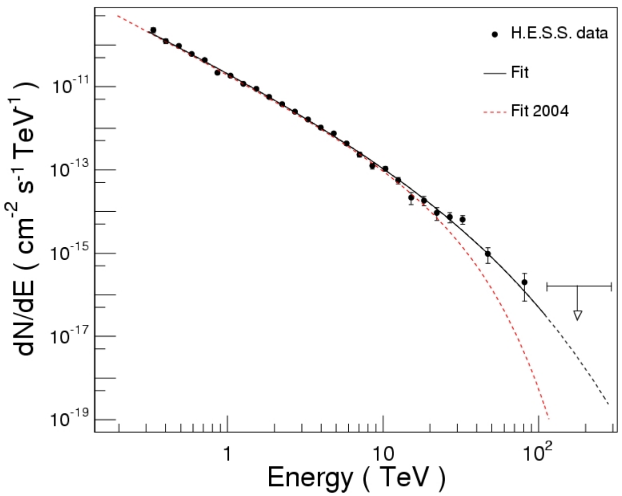
detection of TeV γ-rays from young and middle-aged SNRs by IACT arrays has been predicted in mid 1990s

detected from many representatives of both classes in 2000s

RXJ1713.7-4639 - ~ 1000 yr old SNR at ‘optimal” distance of 1 kpc



TeV γ-rays and shell type morphology: acceleration of protons and/or electrons in shell up to, at least, several 100TeV



Fit: $dN/dE = K\, E^{-\alpha} \exp[-(E/E_o)^{\beta}]$

$\alpha=2.0$ $E_o=17.9$ TeV $\beta=1$

$\alpha=1.79$ $E_o=3.7$ TeV $\beta=0.5$

A. *Hadronic*: γ-rays from $pp \rightarrow \pi^0 \rightarrow 2\gamma$

with ”right” total energy: $W_p=10^{50}\,(n/1cm^{-3})^{-1}$ erg

B. *Leptonic:* IC gamma-rays because of

- TeV-X correlations
- lack of thermal X-ray component
- comfortable (~ 1/100) e/p ratio
- very hard γ-ray spectrum at GeV energies

both models are not free of problems/challenges

=> MWL data - important but should be taken with care otherwise they could be misleading

=> need in deep theoretical studies

broad-band SEDs

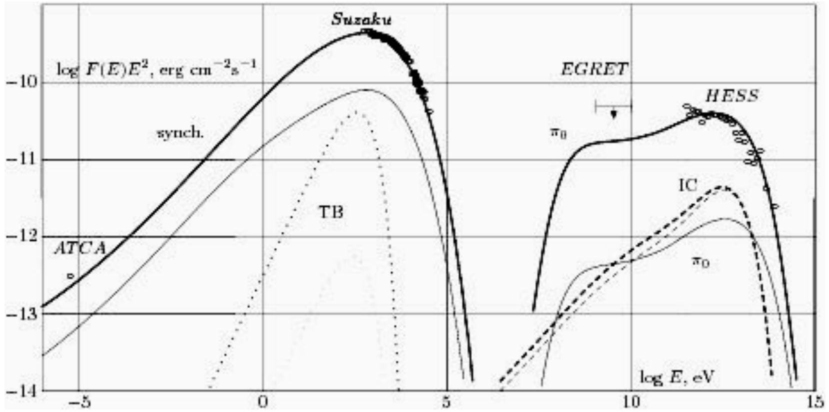
good spectral fit, reasonable radial profile, support for amplification of B-field but …

(1) lack of thermal emission - possible explanation?
>70% energy is released in acceleration of protons!
or gamma-rays are produced in clumps

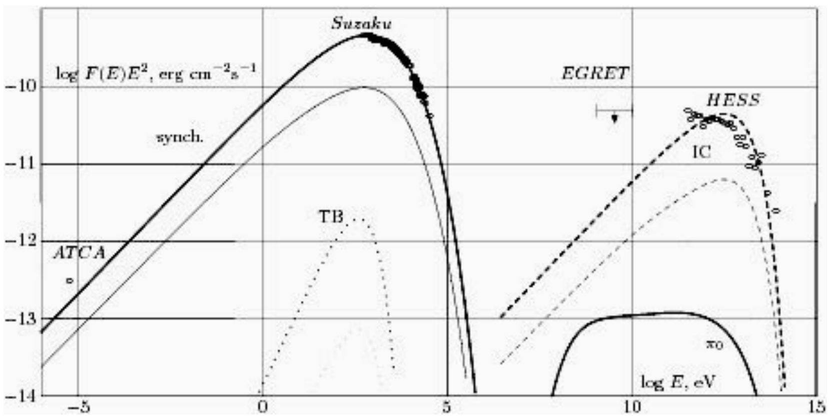
(2) very high p/e ratio (10^4)
E_{max} ~ 100 TeV (not 1 PeV) – escape ?

not perfect, but still acceptable, fits for spectral and spatial distributions of IC gamma-rays; suppressed thermal emission, comfortable p/e ratio (~10^2); small large-scale B-field (~ 10 μG)
2zone-model?: IC gamma-rays in reverse shock,
Synchrotron X-rays – forward shock

hadronic model

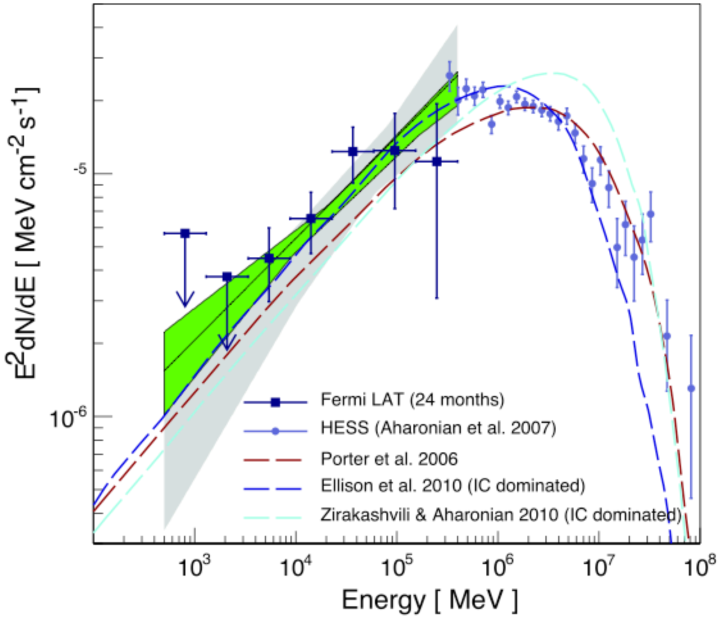


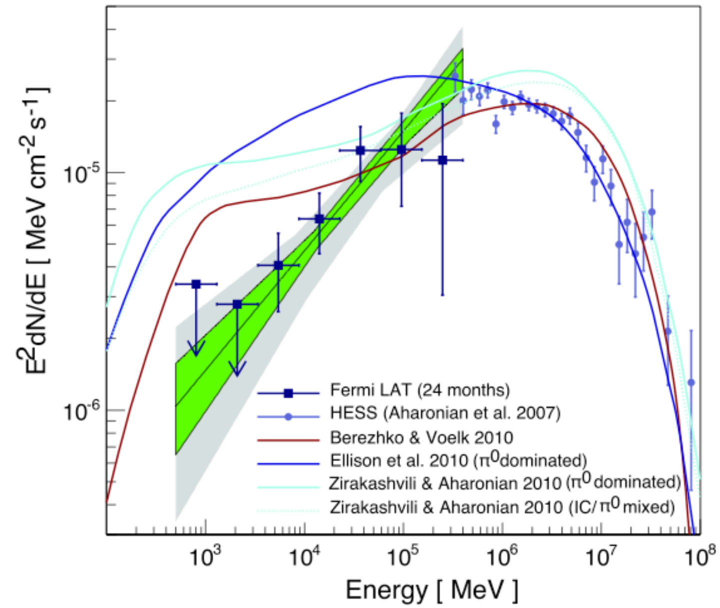
leptonic model



Zirakashvili and FA 2010

Fermi-LAT: GeV data contradict hadronic origin of γ-rays ! (?)





leptonic models

hadronic models

Questions: (i) can we compare GeV and TeV fluxes within one-zone models?

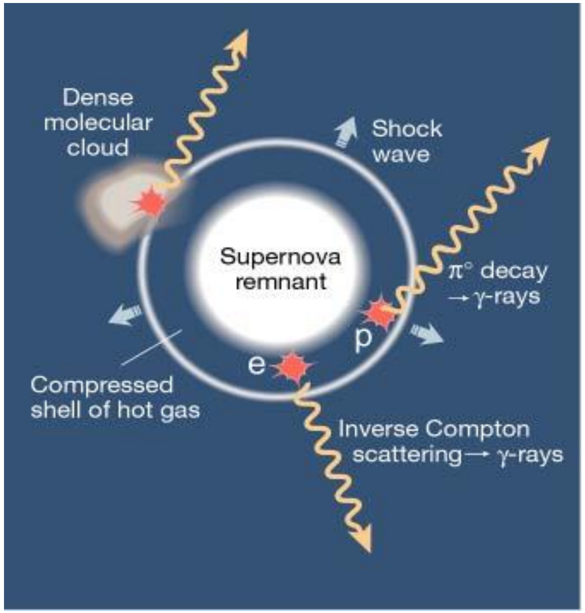
they could come from quite different regions

(ii) cannot we assume hard proton spectra ?

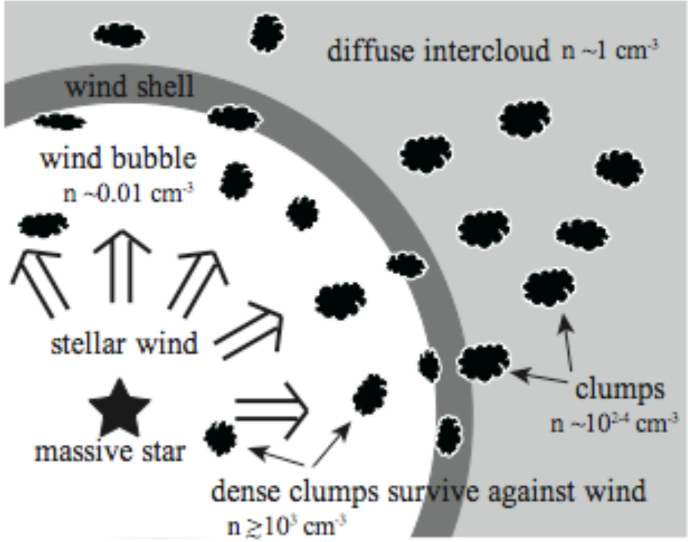
nonlinear theories do predict very hard spectra with α -> 1.5

Fermi LAT - important, but only neutrinos, ultra-high energy gamma-rays and hard synchrotron X-rays from secondary electrons can provide decisive conclusions

IC gamma-rays from (i) the entire shell with average small B-field and (ii) π^0 -decay gamma-rays from dense clouds/clumps inside the shell



FA 2002,
Nature **416**,797



Fermi LAT results - important, but only ultra-high energy gamma-rays and neutrinos can provide decisive conclusions propagation effects in clumps can explain the Fermi LAT – HESS spectral points from 1 GeV to 100 TeV (Gabici & F.A, Celli et al., Sato et al.) as well as the suppressed thermal X-ray emissio

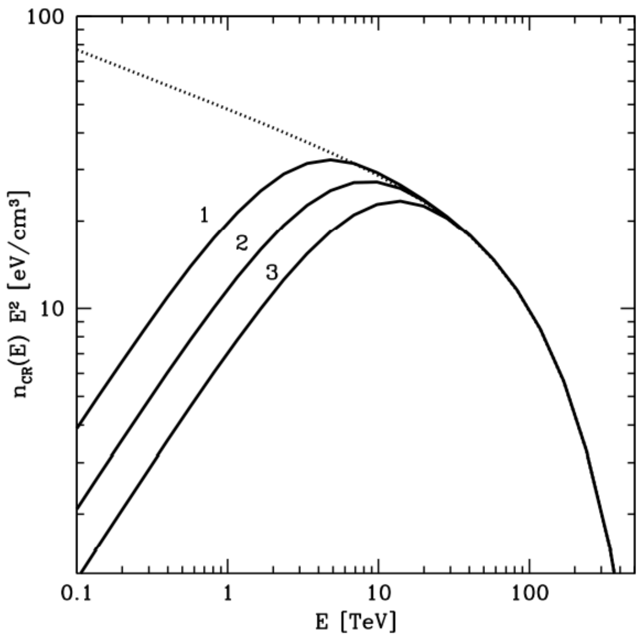


Figure 1. Spectrum of CRs in the SNR shell (dotted line) and inside a clump that entered the shock at t_c = 1400, 1500, and 1550 yr (solid line 1, 2, and 3 respectively).

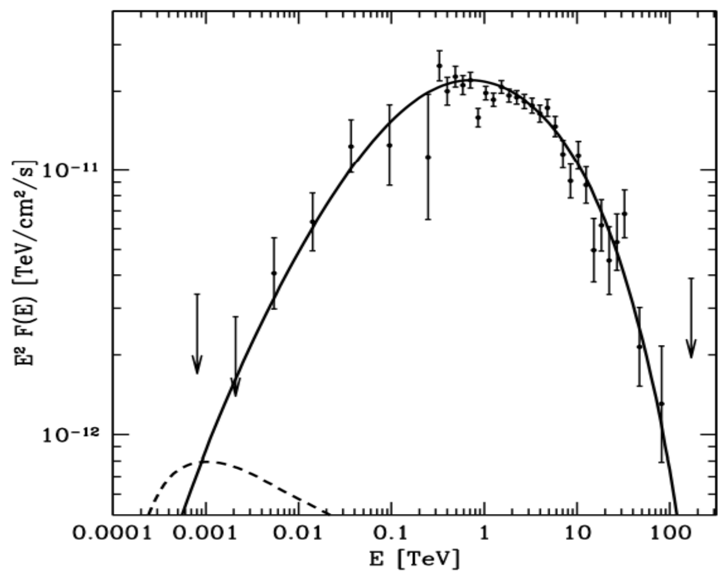


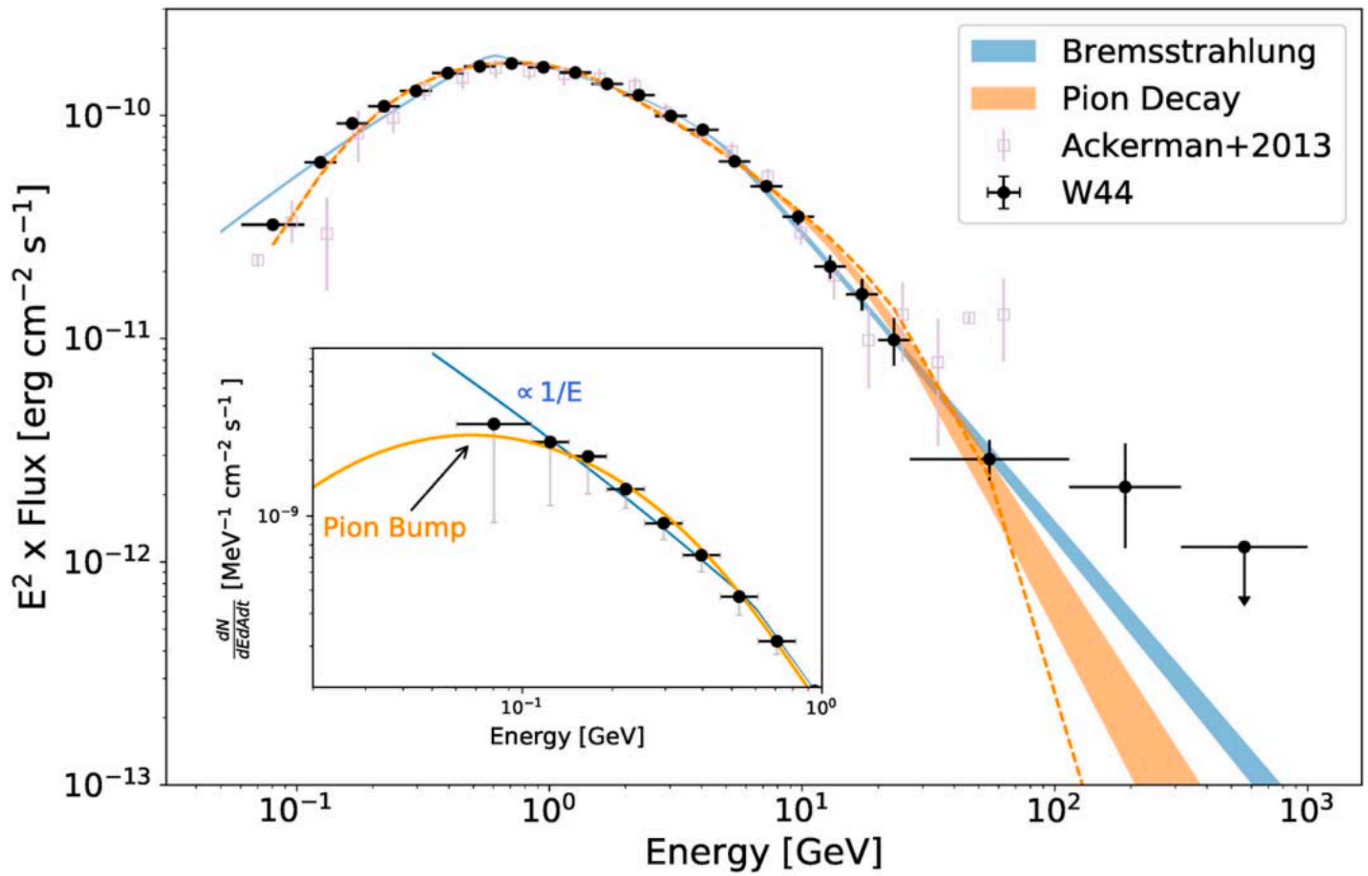
Figure 2. Gamma–rays from RX J1713.7-3946. The emission from the clumps is shown as a solid line, while the dashed line refers to the emission from the diffuse gas in the shell. Data points refer to *FERMI* and *HESS* observations.

definite answer – detect neutrinos: **very difficult** *but not hopless*

γ-ray approach: **morphology** *with 1-2 arcmin resolution*

spectrometry *with 10 -20 % resolution and well above 10 TeV*

π^0 bump in the spectrum of a middle age SNR W44 !

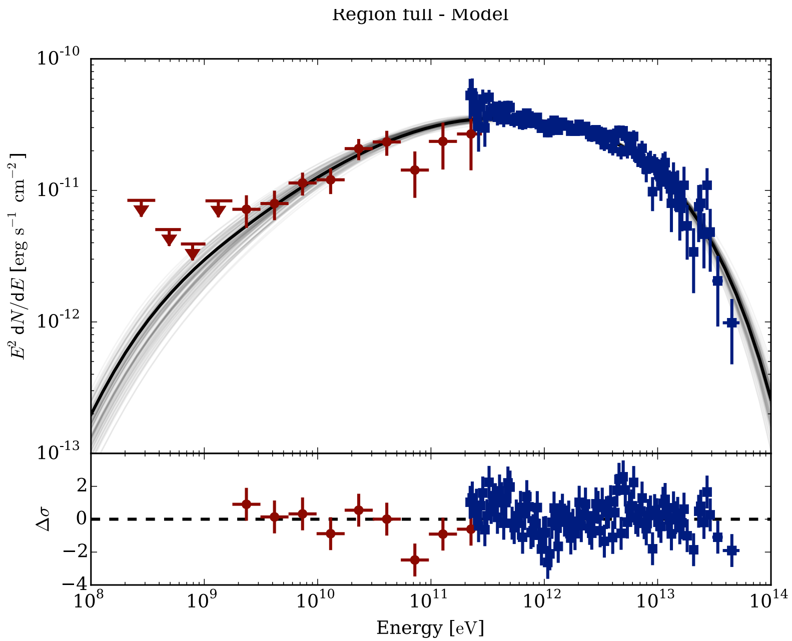


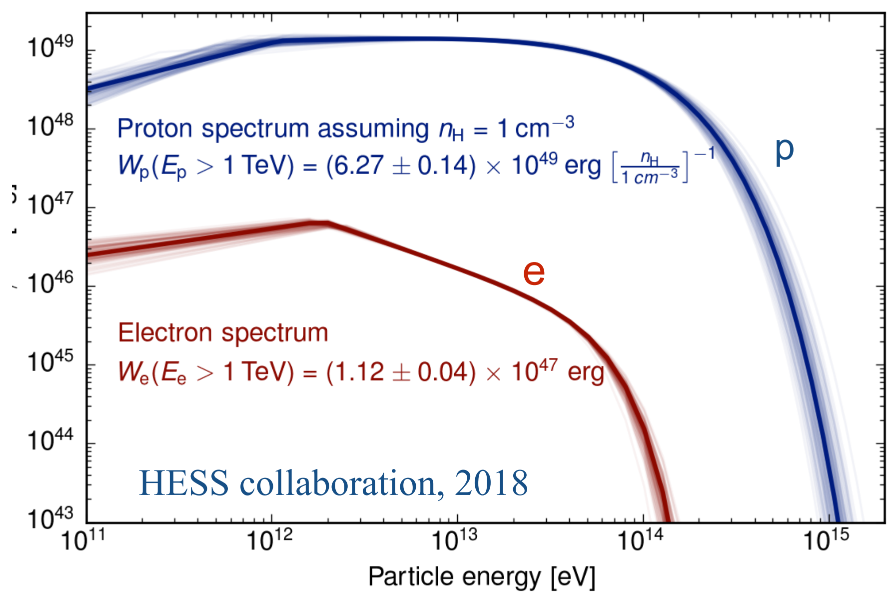
G. Peron

detection of π^0 - bump - important, but only neutrinos, ultra-high energy gamma-rays and hard synchrotron X-rays from secondary electrons can provide decisive conclusions about the ability of SNRs to operate as PeVatrons and contribute to the CR flux around the "knee"

Probing the energy distributions of accelerated particles in SNRs

Fermi+HESS measurements **RXJ 1713** derived spectra of e and p





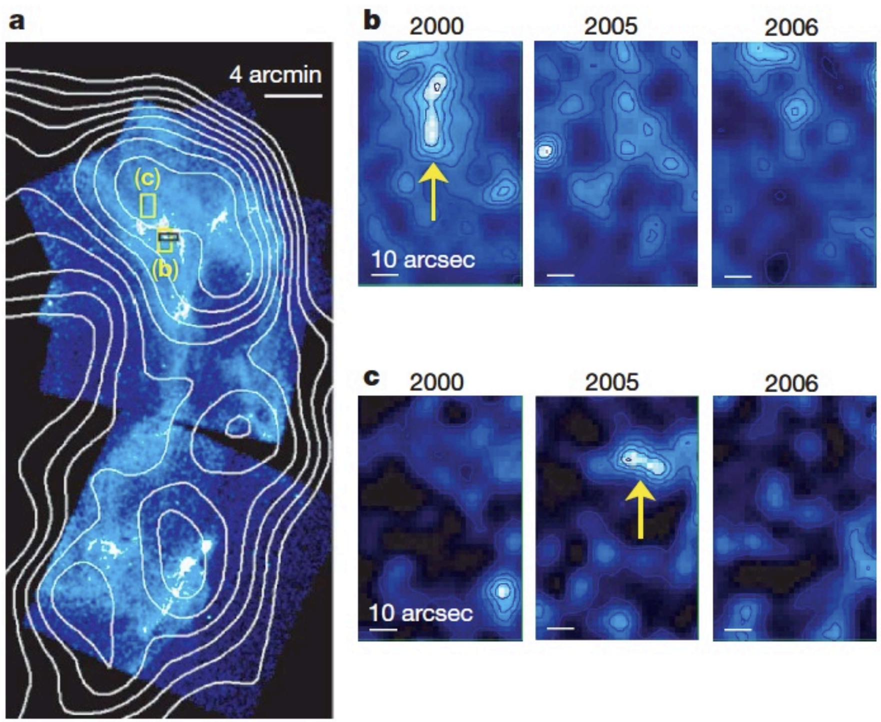
cutoff /break in the proton spectrum at 100 TeV

Detection of 60 TeV gamma-rays: IC on 2.7 K approx 100 -200 TeV electrons

$pp \rightarrow \pi^0 \rightarrow \gamma\gamma$ approx 200-300 TeV protons

Variability of X-rays on year timescales -

strong magnetic field and particle acceleration in real time



flux increase - particle acceleration

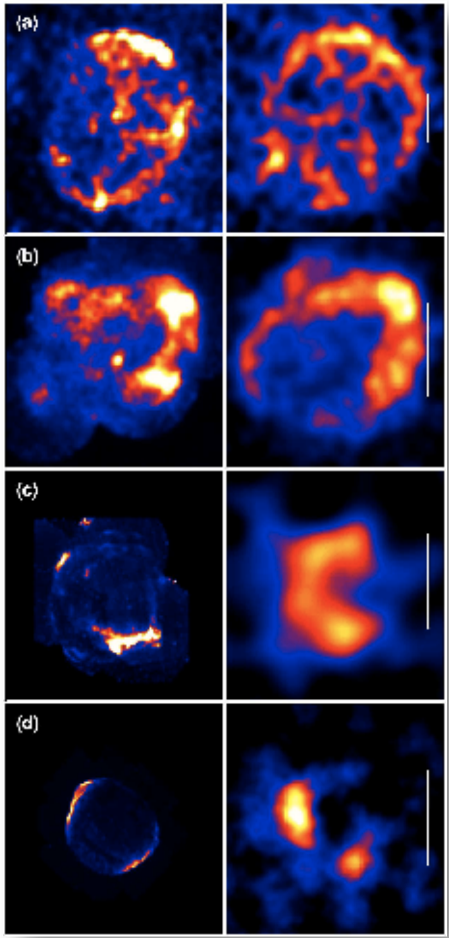
flux decrease - synchrotron cooling *)

both require B-field of order 100μG, at least in hot spots

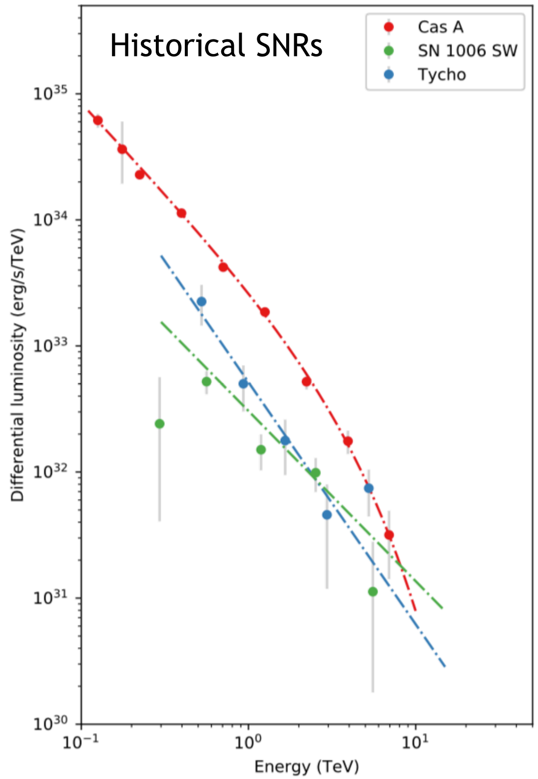
Uchiyama et al, Nature **449**, 576

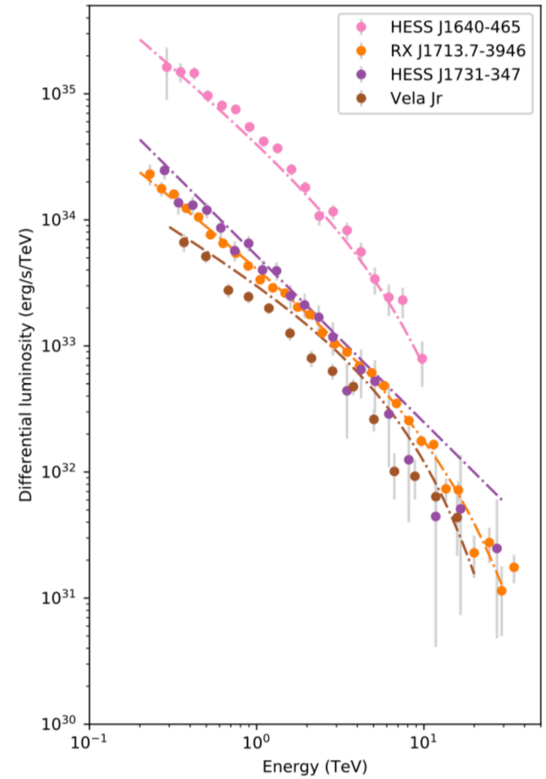
strong support of the idea of amplification of B-field by in strong nonlinear shocks through non-resonant streaming instability of charged particles

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 TeV

LHAASO (and CTA ?) is able to answer to this question "slope or intrinsic power-low index" , i.e. "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 broad-band spectral measurements at (1) $E_\gamma \geq 100\,\mathrm{TeV}$ and (2) $E_\gamma \ll E_0$ down to TeV energies

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:

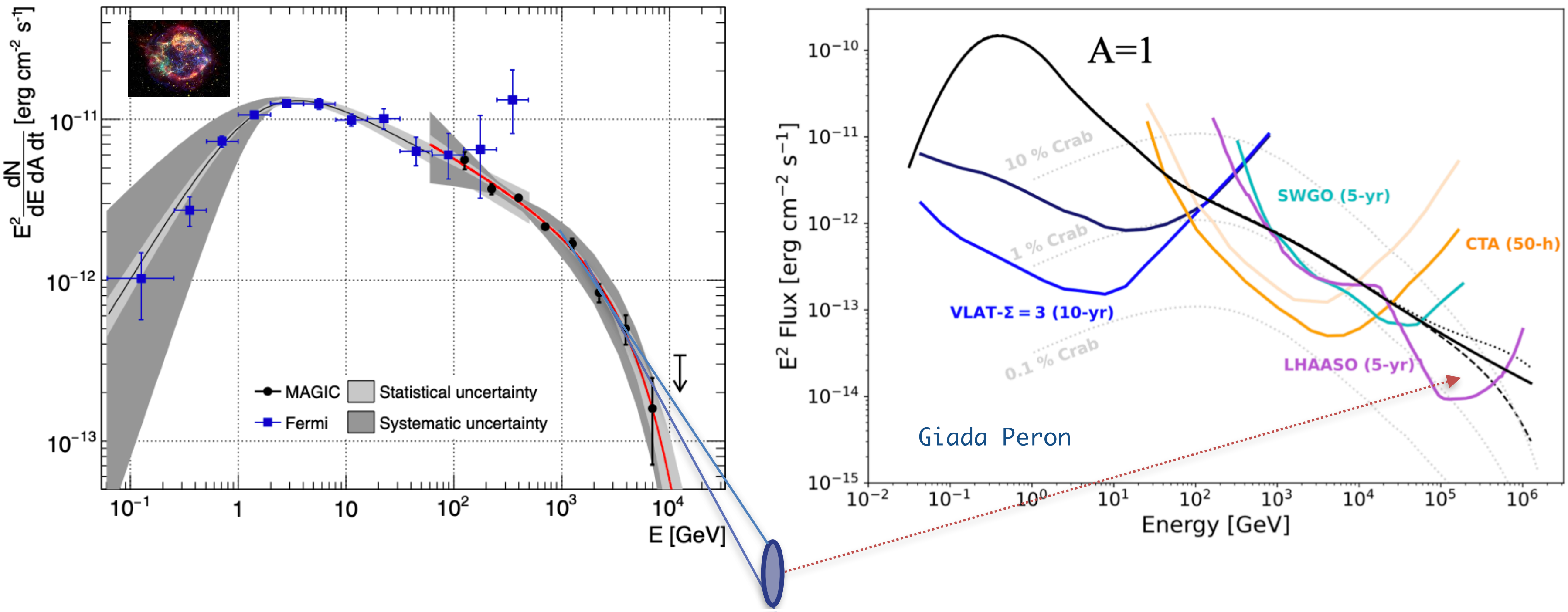
$E_{max} \sim 1$ PeV - very difficult, but feasible

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, Blasi, …) 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 ?

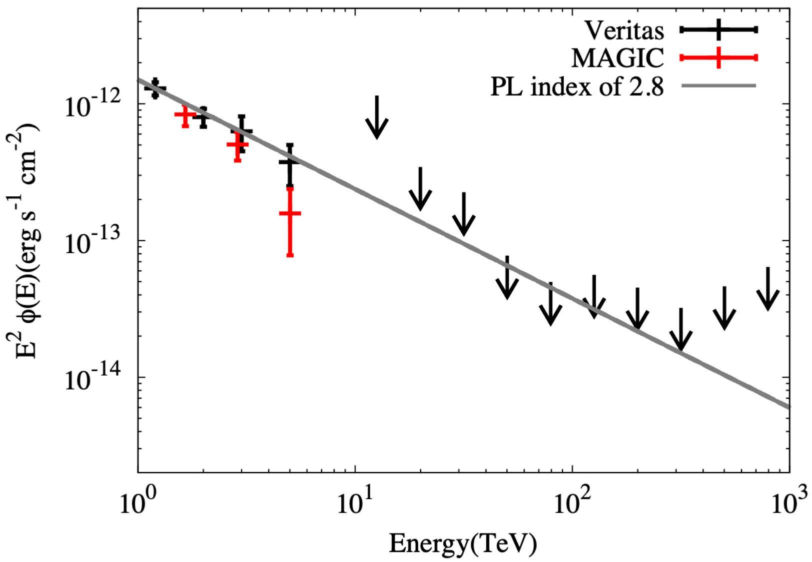
even moving ballistically R~100 pc (angular size $\sim 2^0$) but the γ-ray image would be a point like;

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

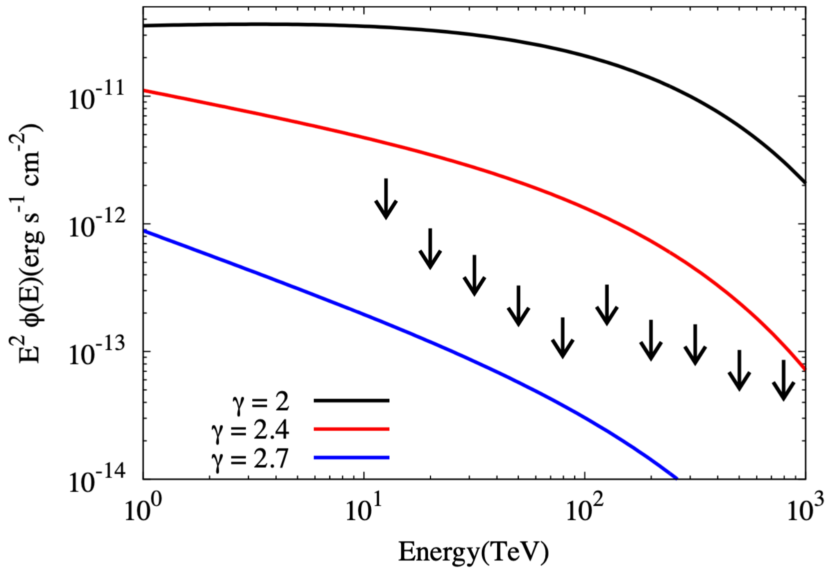
=> LHAASO upper limit (or detection) of 100 TeV γ-rays - at the level of 10^{-14} erg/cm^{2}s

decisive "PeVatron test" independent of the acceleration epoch

Cas A - LHAASO upper limits

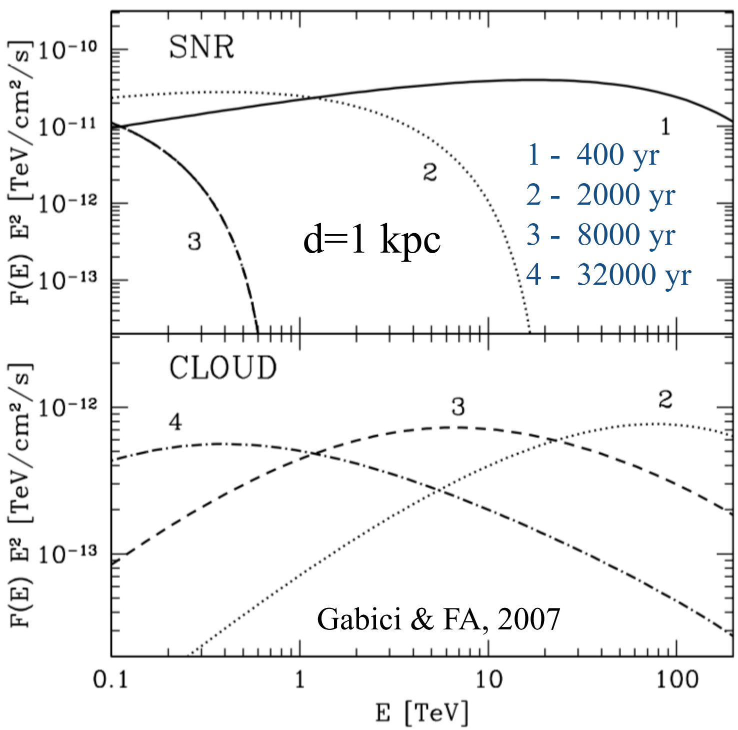


UHE γ-ray flux upper limits assuming Cas A is a point source. Low energy measuremts from MAGIC and VERITAS. The grey curve is the power law function with the index of 2.8.

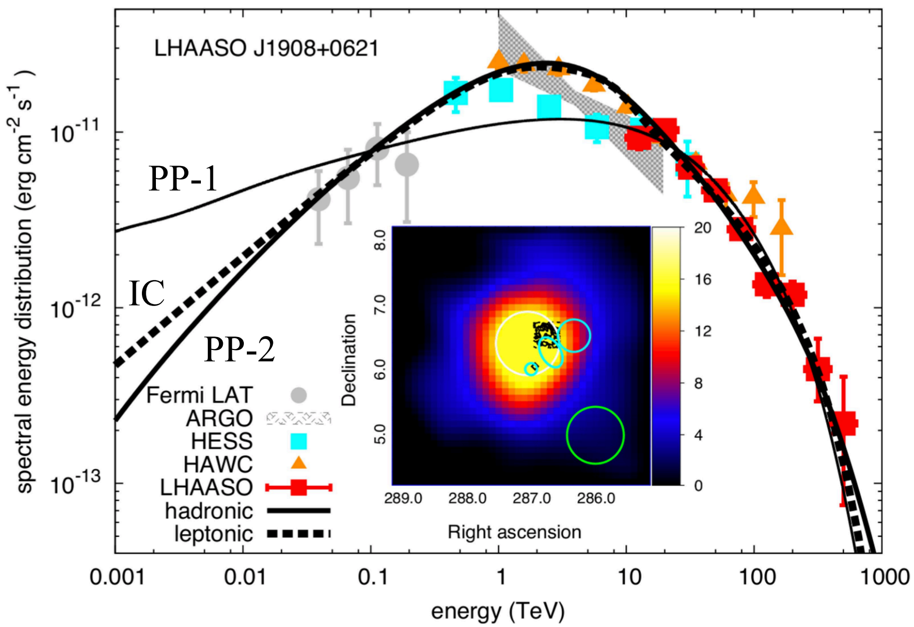


UHE γ-ray flux upper limits within 1.8 degree. Black, red and blue curves correspond to the predicted pion-decay γ-ray fluxes for the proton index of 2.0, 2.4 and 2.7, respectively. Total CR proton energetics in 100 – 1000 TeV are 5×10^{49} erg, 3×10^{48} erg and 1×10^{47} erg, respectively, which are the CR energy budget expected if Cas A type SNR produce all the PeV CRs in our Galaxy.

GMCs as "smoking guns" within <100 pc of mid-age SNRs



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, $M=10^4 M_o$

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

— 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

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.

alternative CR factories?

☑ collective stellar winds and SNR shocks in clusters and of massive stars, superbubbles
- speeds off stellar winds - several 1000 km/s - comparable to young SNR power
- 10^{41} erg/s (comparable or a factor of 2 less than mechanical power of SN)
accel. efficiency should be at least 10 % - much less is needed for the knee region

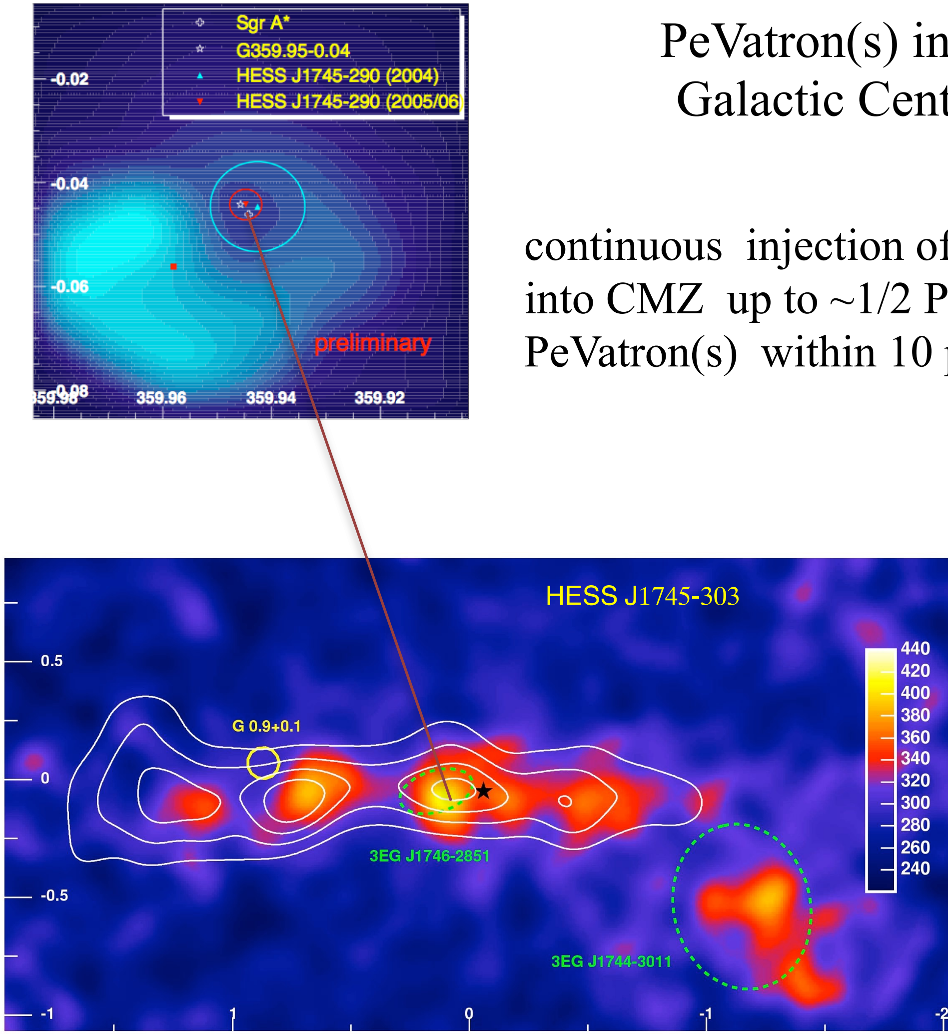
☑ Galactic Center - significant contribution could come only from the Supermassive

☑ Black Hole (Sgr A*) . 5 x 10^{6} solar masses can formally provide a power as large as 10^{43} erg/s (assuming 10 % acceleration efficiency). But presently the accretion rate does not exceed 10^{39} erg/s (bolometric luminosity of Sgr A* is less than 10^{36} erg/s)

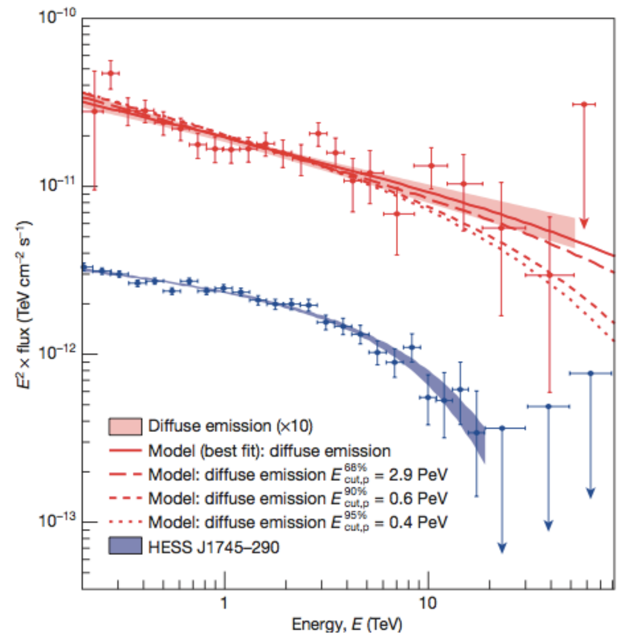
☑ Pulsars/pulsar wind nebulae? prolific accelerators of electrons and positrons … and protons?

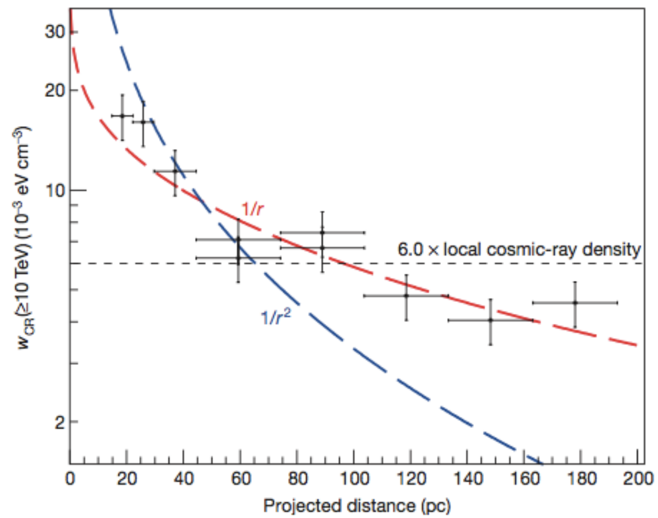
☑ Microquasars - very attractive also for acceleration beyond 10 PeV

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 ?

implications?

- Galactic Center (GC) harbors a hadronic PeVatron within a few pc region around Sgr A* (a SMBH in GC)

- 1/r type distribution of the CR density implies (quasi)continuous regime of operation of the accelerator with a power 10^{38} erg/s (on timescales 1 to 10 kyr) - a non negligible fraction of the current accretion power

- this accelerator alone can account for most of the flux of Galactic CRs around the “knee” if its power over the last 10^{6} years or so, has been maintained at average level of 10^{39} erg/s

- escape of particles into the Galactic halo and their subsequent interactions with the surrounding gas, can be responsible for the sub-PeV neutrinos recently reported by the IceCube collaboration

SMBH or young massive-star clusters?

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

Cesarsky and Montmerle 1983; R. Lingenfelter - since 2000s

- gamma-rays from a number of stellar clusters GeV to TeV energies

  (Fermi-LAT, HESS - E. de ona Wilhelmi, R. Yang, L. Mohrmann)
- gamma-rays from stellar clusters up to 1 PeV

  (LHAASO collaboration 2023)

recent extensive work by several groups - A. Bykov et al. (Ioffe), Gabici et al. (APC), T. Vieu et al. (Heidelberg), G. Morlino, E. Amato, P. Blasi (Arcetri-GSSS), etc.

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)

SN explosions => termination shocks in the vicinity of stars or in superbubbles

Stellar Winds => collective power in SWs 10^{38} - 10^{39} erg/s; speeds 3×10^3 km/s

favorable conditions, particles can be accelerated up to 10 PeV?

Stellar Clusters operate as PeVatrons ?

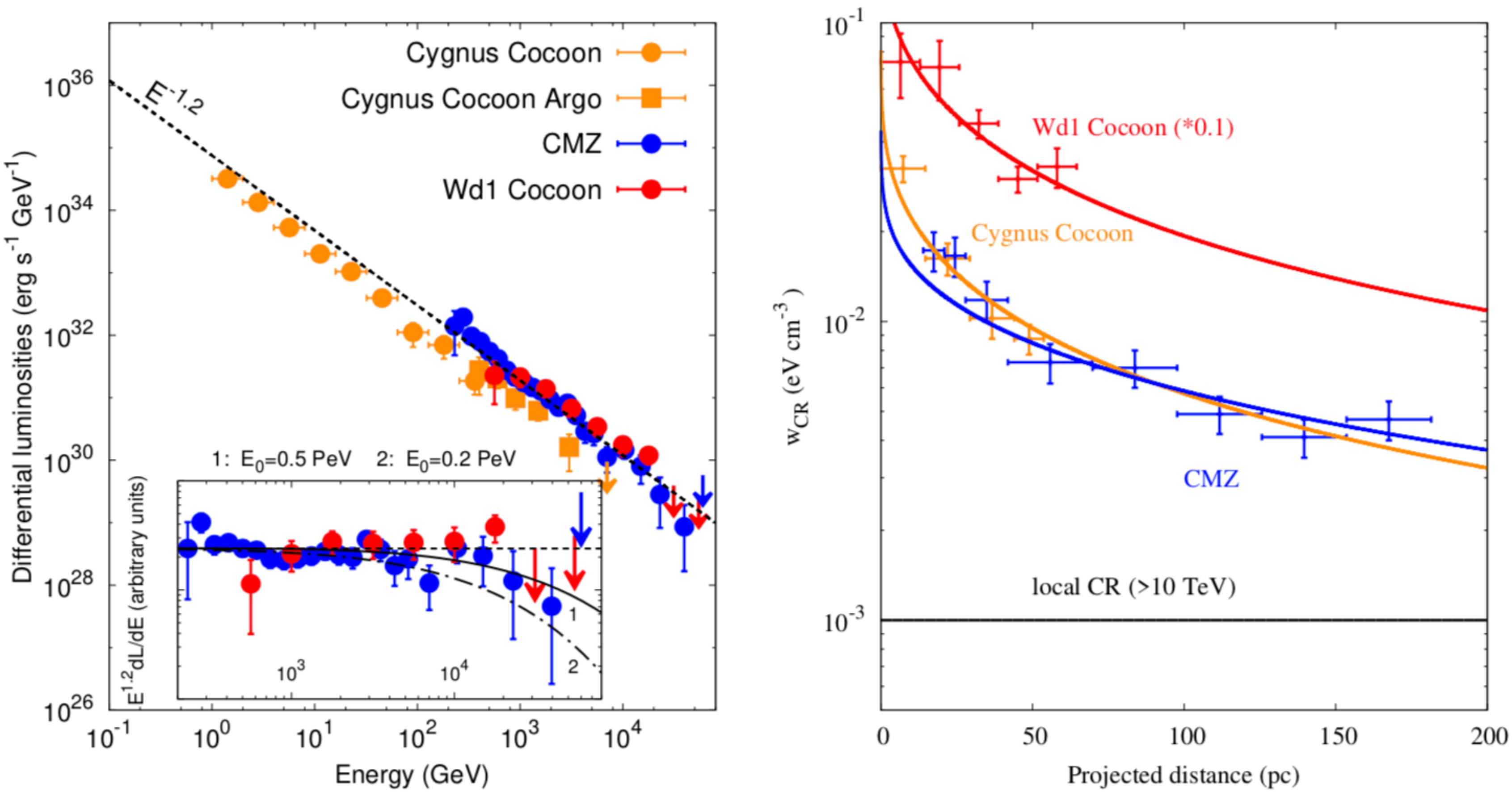


Figure 1: Gamma-ray luminosities and CR proton radial distributions in extended regions around the star clusters Cyg OB2 (Cygnus Cocoon) and Westerlund 1 (Wd 1 Cocoon), as well as in the Central Molecular Zone (CMZ) of the Galactic Centre assuming that CMZ is powered by CRs accelerated in *Arches*, *Quintuplet*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

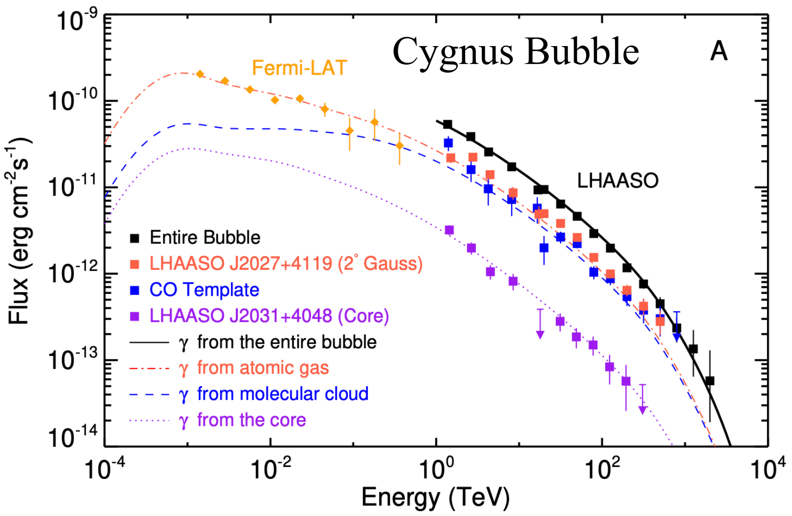
FA, Yang, Ona de Wilhelmi, 2018

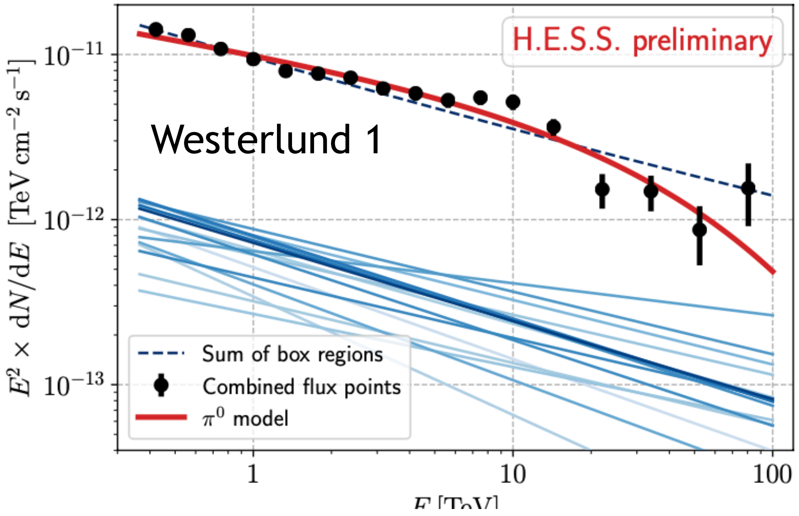
Extended Regions surrounding Clusters of Young Massive Stars are sources sources of GeV, TeV and … PeV gamma-rays!

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

CygnusOB2, W43, NGC3603

Arches, Quintuplet and Nuclear ultracompact clusters

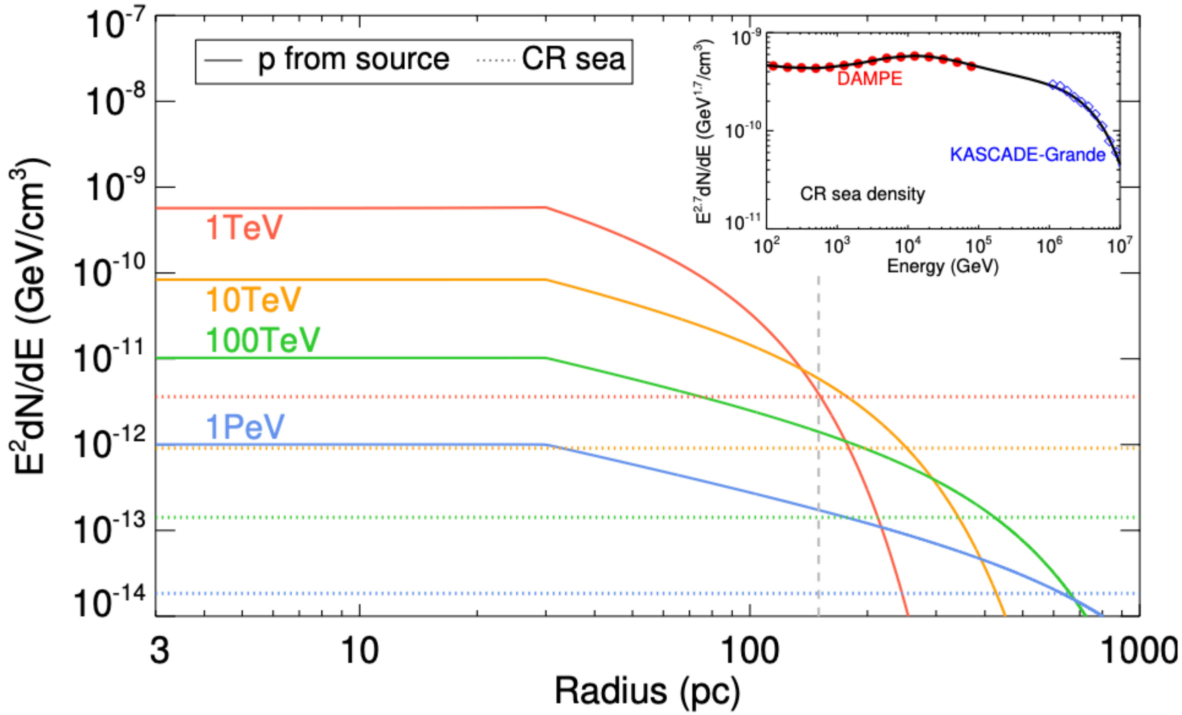




Origin of TeV/PeV γ-rays ? Hadronic!

IC is excluded - only PWNe can accelerate electrons >> 100 TeV; γ-ray morphology

deriving the radial profile of CR proton energy densities



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

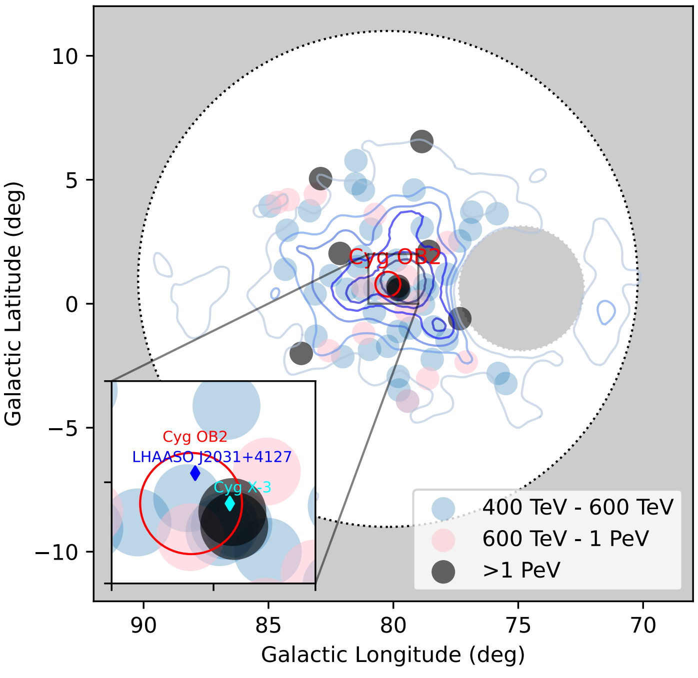
proton injection spectrum $Q(E_p) \propto E^{-2.25}\ \exp(-E_p/5\,\mathrm{PeV})$

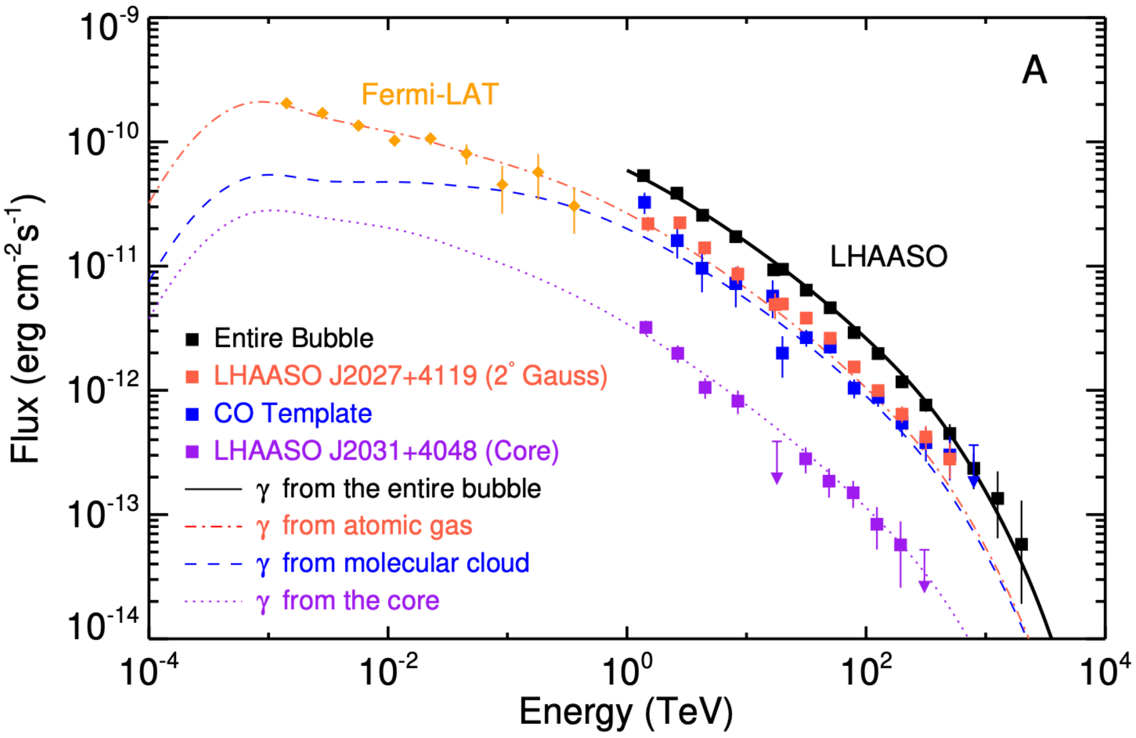
proton injection power $\dot{W}_p = 1.1 \times 10^{37}\,\mathrm{erg/s}$

energy density of > 100 TeV protons exceeds the level of “CR sea”
up to several 100 pc !!!

Potential of LHAASO: detecting gamma-rays out of 1 PeV

Detecting a Super Bubble in the Cygnus Region



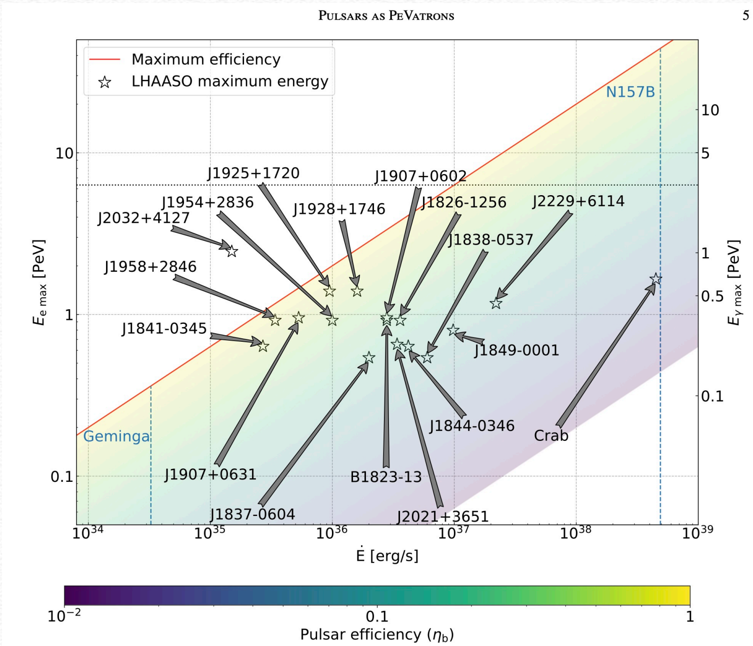


extension of the cosmic ray spectrum well beyond 1 PeV =>

Super-PeVatrons in Milky Way ?

- YMCs/Supper-Bubbles yes!
- SNRs ? ?
- Pulsars: $E = 20\,\eta_B^{1/2}\,L_{38}^{1/2}$ PeV
- Binary systems, Microquasars - why not?
- SMBH in the Galactic Center: $E = eBR \simeq 100(B/1\,\mathrm{kG})\,(M/3 \times 10^6 M_\odot)$ PeV

$\gg 10\,\mathrm{PeV}$ protons in powerful outflows?



E. de Ona Wilhelmi et al. 2022

maxiumum energies:

e (p) $E_{\max} \approx 2\,\eta_e\,\eta_B^{1/2}\,\dot{E}_{36}^{1/2}$ PeV

γ $E_{\gamma\ \max} \approx 0.9\,\eta_e^{1.3}\,\eta_B^{0.65}\,\dot{E}_{36}^{0.65}$ PeV

For electrons: synchrotron losses
=> additional constrains

η_e : electric-field to magnetic-field ratio
η_B : fraction of wind's kinetic energy converted to magnetic field

$E_{\max,e} \propto (\eta_B \dot{E}_{36})^{-1/2}$

protons in the pulsar winds ??? pulsar winds consists of electrons and positrons

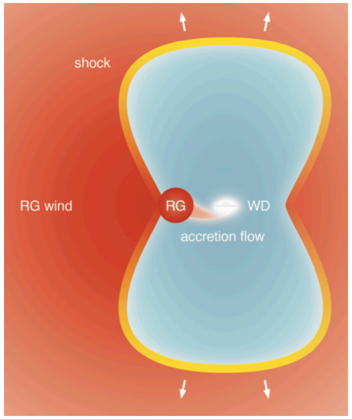
protons in outflowes of X-ray binaries? Ultraluminous X-ray Binaries (SS 433, Cyg X-3)
kinnetic energy luminosity can be as large as
$E_{\mathrm{kin}} \geq 10^{39}\,\mathrm{erg/s} => \mathrm{E_p} \rightarrow\ 100\,\mathrm{PeV}$ (!)

watching particle acceleration in "online regime"

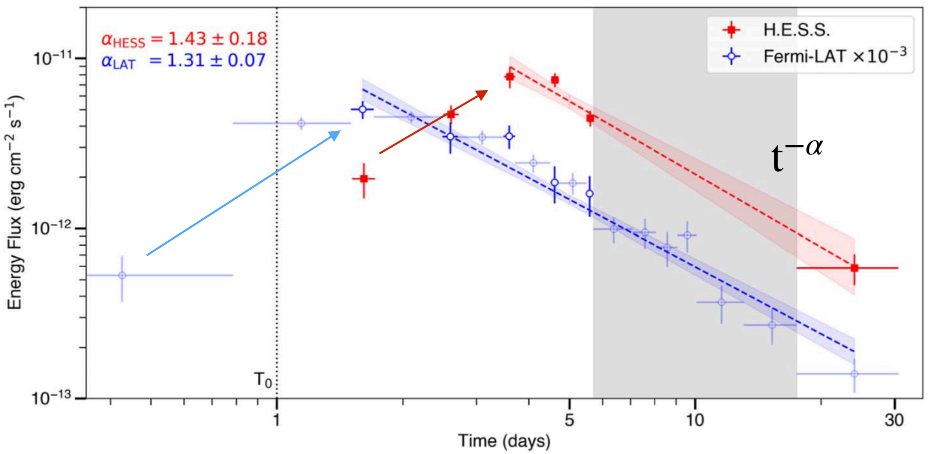
RS Ophiuchi : recurrent nova in the constellation Ophiuchus - binary system: White Dwarf (**WD**) and Red Giant (**RG**); eruptions in 1898, 1933, 1958, 1967, 1985, 2006 and 2021

2021 explosion in August has been detected in γ-rays by Femi LAT, HESS and MAGIC

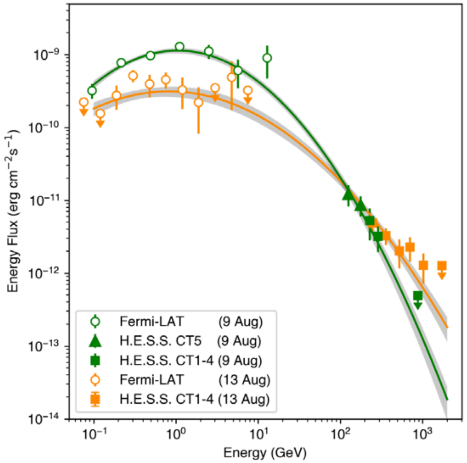
1.48 AU separation of starts - close enough for WD to continually accrete material from RG to trigger recurrent thermonuclear explosions and drive shock (v~ 5000 km/s) into RG's wind



The explosion originates at WD's surface. Within one day, shock is expanding as bipolar blast wave moving orthogonal to accretion disk, into RG' wind.



Light curves: Fermi LAT (0.06- 500 GeV) and HESS (0.25-2.5 TeV) after the peaks $F \propto t^{-\alpha}$. T_0 - peak of optical emission. Fermi LAT flux peak - $T_0 + 2\,\text{day}$; H.E.S.S. flux peak is delayed by two days

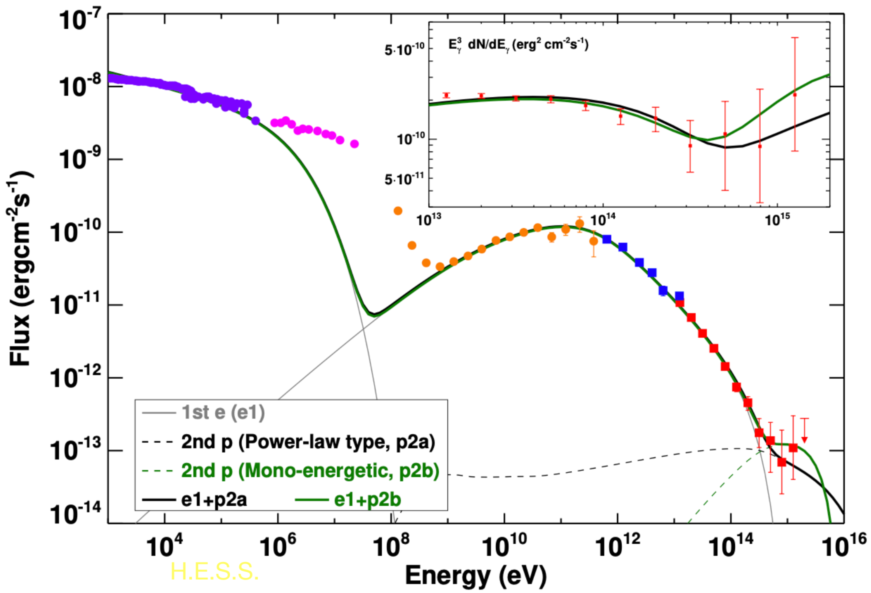


Energy spectra: curves are fits with Log-parabola. Hadronic models requires $\approx 10^{33}$erg in CRs

electron PeVatrons

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



$E_\gamma = 1.1$ PeV $\rightarrow E_e \simeq 2.5$ PeV

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

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

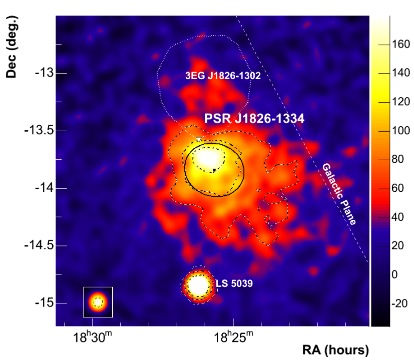
$E_\gamma \geq 1.1$ PeV $\rightarrow \eta \geq 0.16$

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 gamma-rays of hadronic origin?

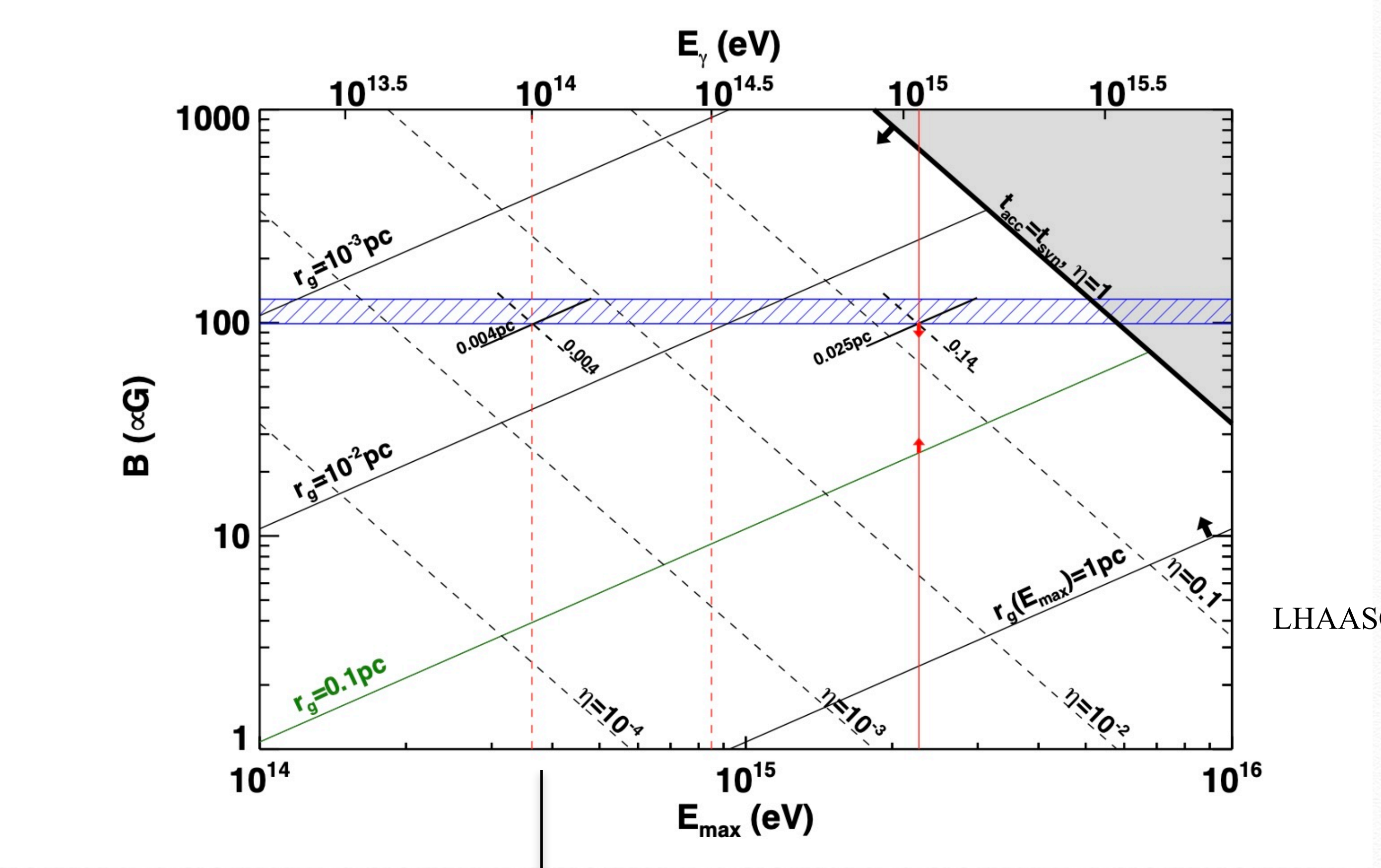


Crab Nebula: **effective electron accelerator** but **not effective γ-ray emitter**:

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



LHAASO collaboration 2021

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

$t_{acc} = t_{synch} \rightarrow \quad E_{max} \approx 6\eta^{1/2}(B/100\mu G)^{-1/2}$ PeV

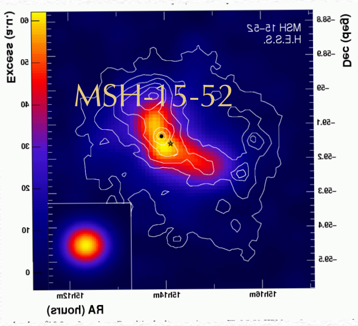
$r_g = R \qquad \rightarrow \quad E_{e,max} \leq 1\,(B/1\,\mu G)\,(R/1\,pc)$ PeV

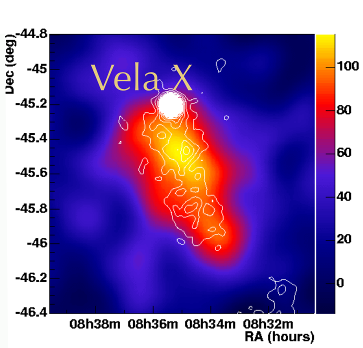
absolute limit based on L_{SD}

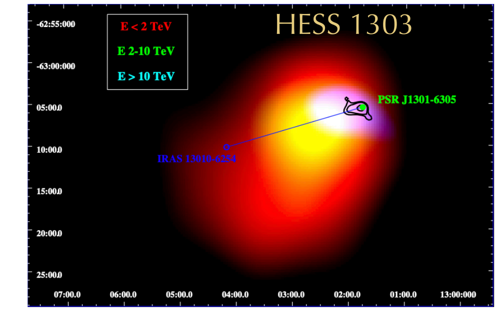
$E = 20\,\eta_B^{1/2}\,L_{38}^{1/2}$ PeV

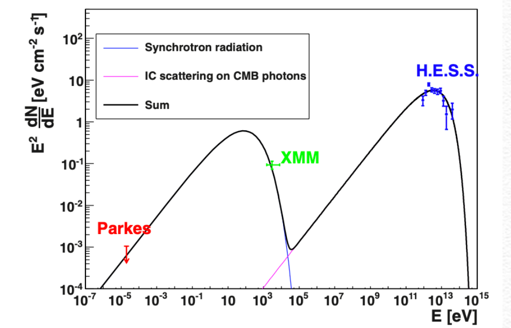
extended TeV structures around pulsars:

PWNe (MHD structures) or PWN+ Pulsar Halos (IC of electrons after they escape PWN)

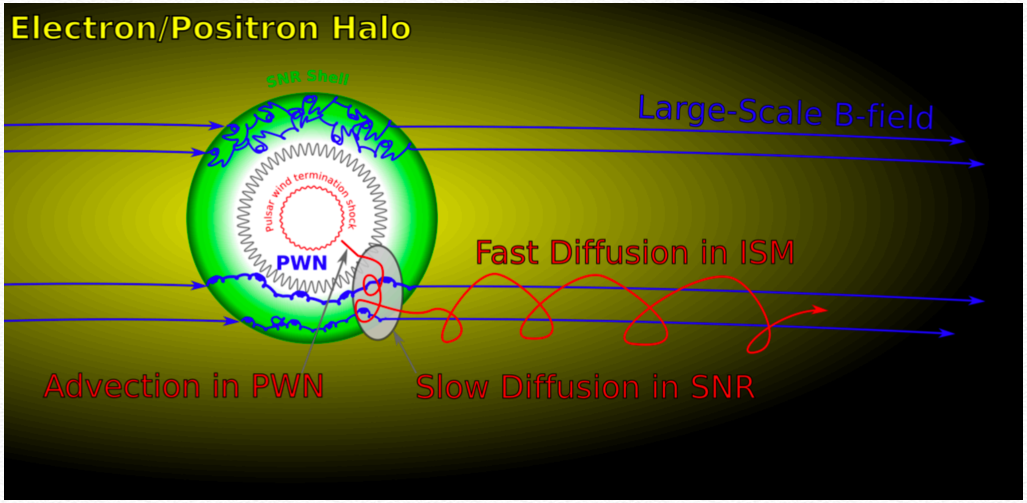








Energy dependent morphology
very low B-field $B \sim 1.4\mu G$

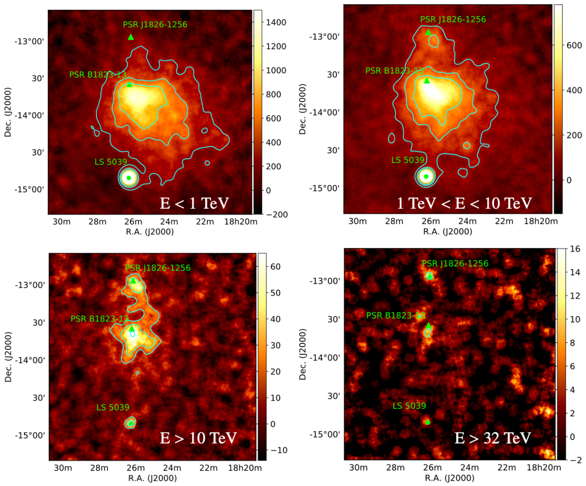


PWNe - MHD structure

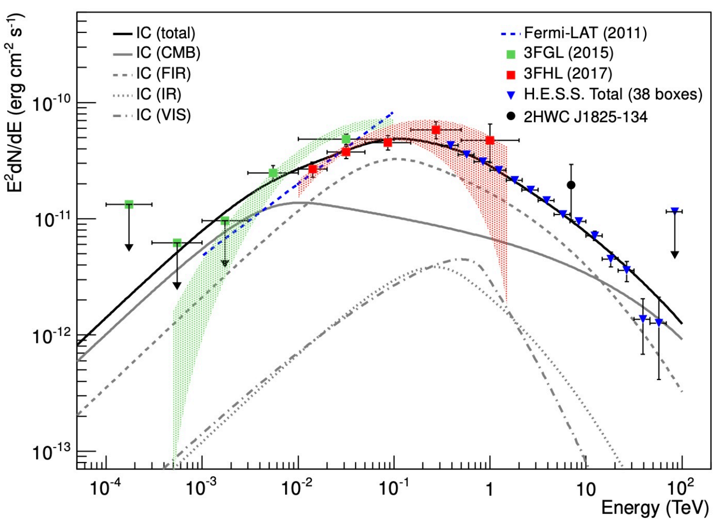
PHs - diffusively expanding cloud of electrons

reduction of the size with energy - because of energy losses or ballistic motion?

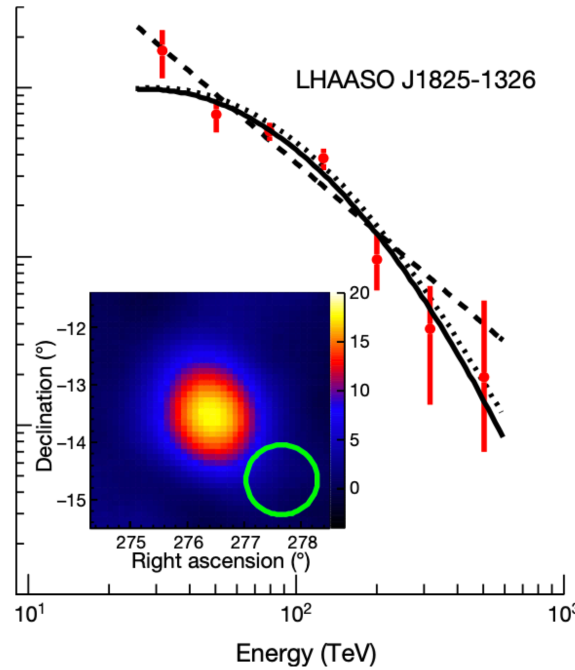
H.E.S.S. collaboration 2019



1.5 deg source at 4 kpc => L ~ 100 pc
unrealitically large for a PWN => PH ?



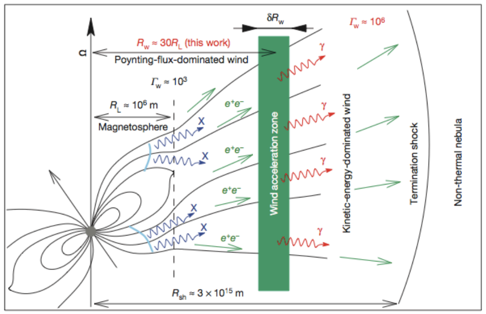
LHAASO collaboration 2021

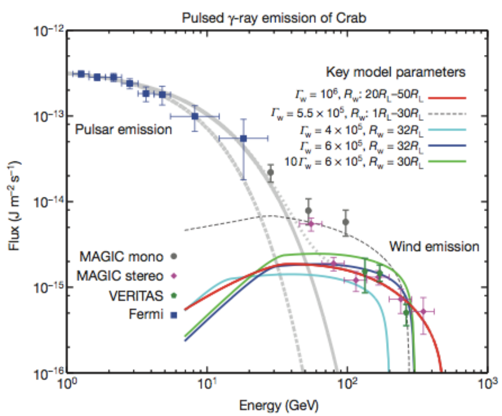


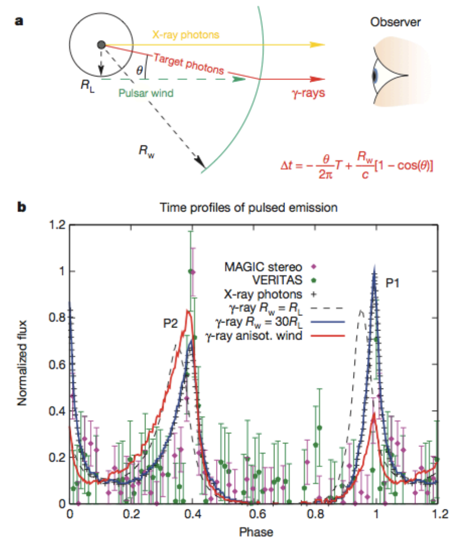
$E_\gamma \sim 500$ TeV gamma-rays => $E_e \geq 1$ PeV electrons accelerated in a PWN ?

Pulsed TeV gamma-rays from Crab and Vela pulsars !

Pulsed VHE gamma-rays from the Crab – Comptonization of the cold ultrarelativistic pulsar wind?

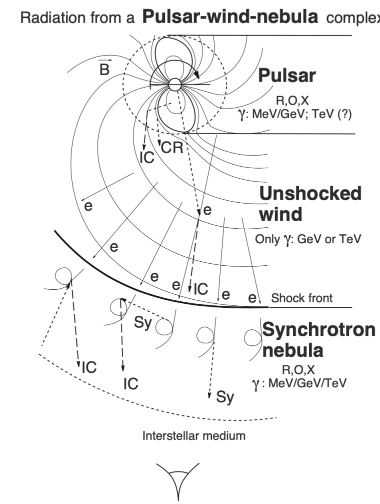






FA, Bogovalov, Khangulyan (Nature 2012)

$\Gamma \sim 10^6$; R ~ 30 L



MAGIC/VERITAS VHE p ulsed γ-ray emission from Crab pulsar

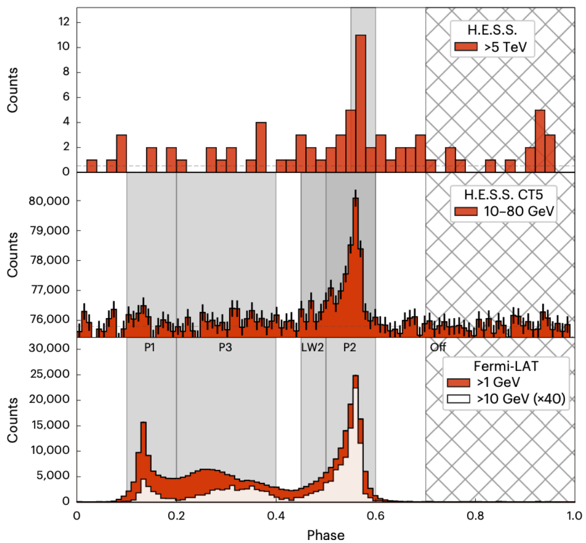
Comptonization of the cold wind? Looks a simple/elegant solution …

but not up to 2 TeV ? $E_{\gamma,max} = \Gamma_w \times m_e c^2 \approx 0.5\ (\Gamma_w/10^6)$ TeV

Lorentz factor of the cold wind $\Gamma_w \sim (1-2)\ 10^6$

Detection of multi-TeV pulsed gamma-rays from the Vela pulsar !

HESS collaboration (New Astronomy 2023)



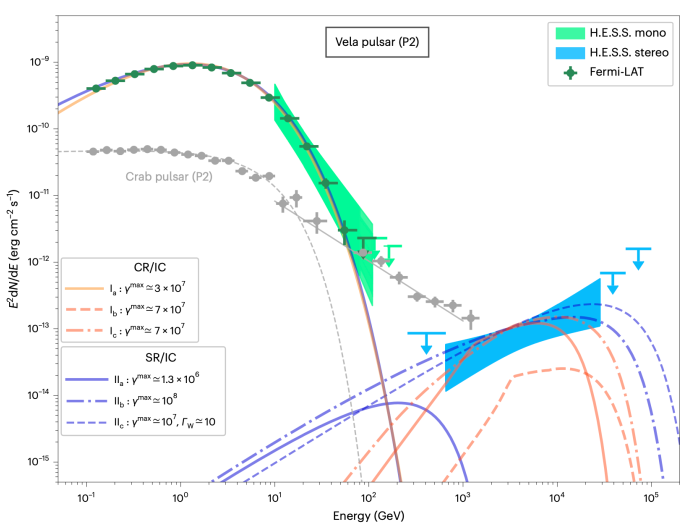
Comptonization of the “hot” pulsar wind ?

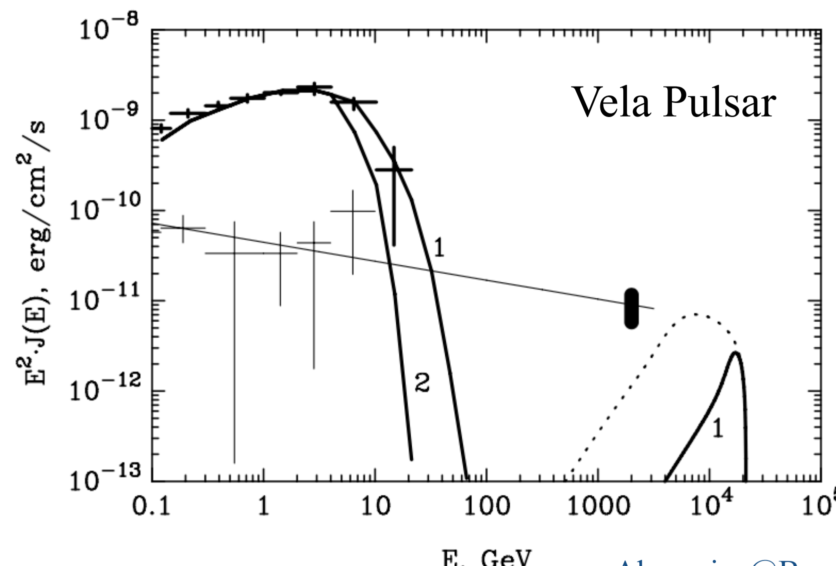
or

IC scattering in the magnetosphere by electrons responsible for the curvature radiation at MeV/GeV ?

or

something else? (see A. Harding’s talk)



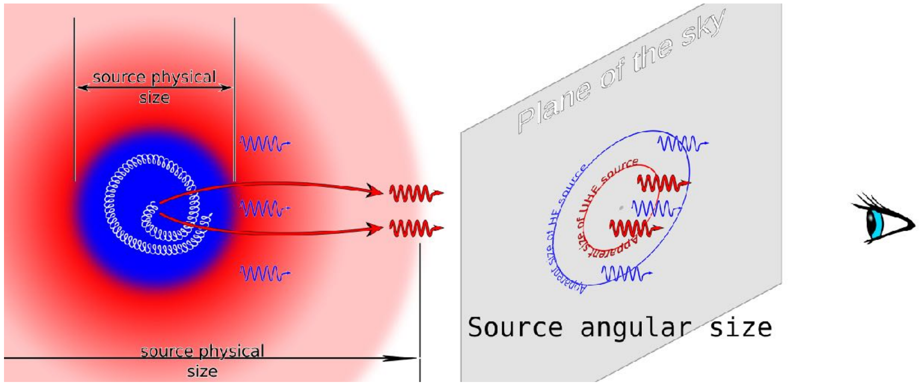


Aharonian@Bogovalov 2002

Unique tool to localise the accelerator and derive the initial acceleration spectrum

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

$R^2/D \geq R/c \rightarrow R \geq D/c \sim 10\,(D/10^{30}\,\mathrm{cm}^2/\mathrm{s})\,\mathrm{pc}$



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

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

unique opportunity to localise the PeVatron and measure the (undistorted) acceleration spectrum

observations of CTA & ASTRI and eROSITA could be very helpful in localisation of PeVatroins inside the LHAASO UHE gamma-ray sources with high precision

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 illu-minated 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

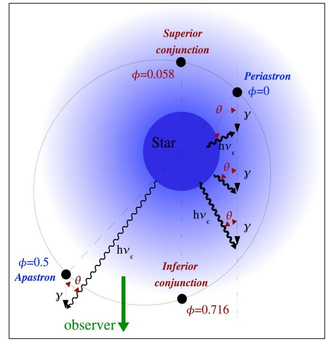
(characteristic timescales 1 h or shorter !)

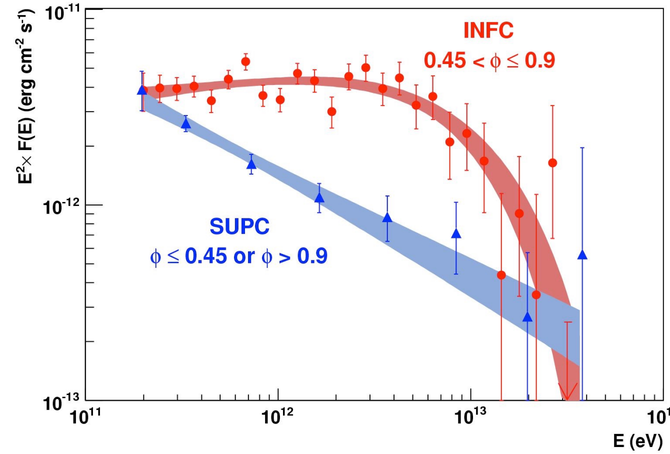
the target photon field is function of time, thus the only unknown parameter is B-field => predictable gamma-ray emission?

LS 5039

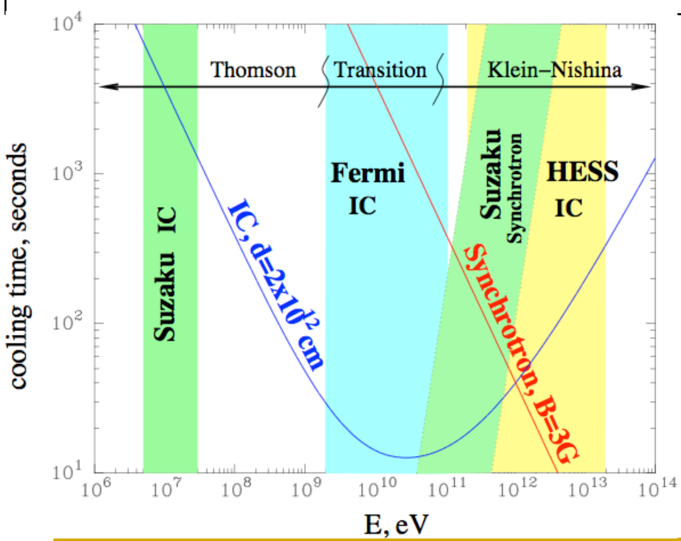
works as a perfect TeV clock
and an extreme accelerator

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 (super) PeVatrons

not published results (rumors) - spectrum up to 100 TeV?

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

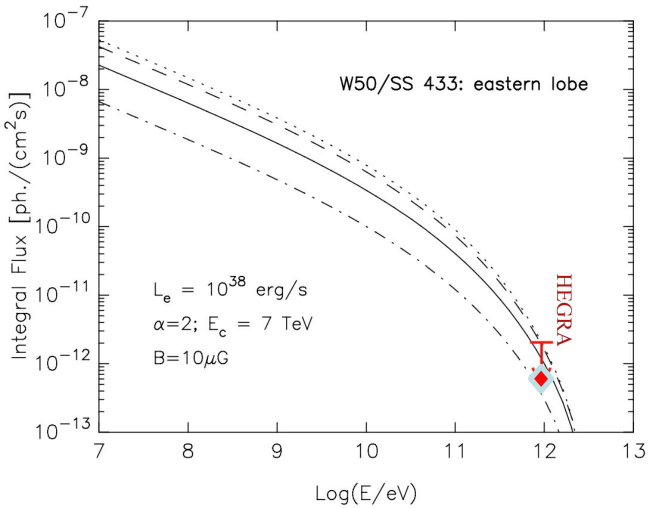
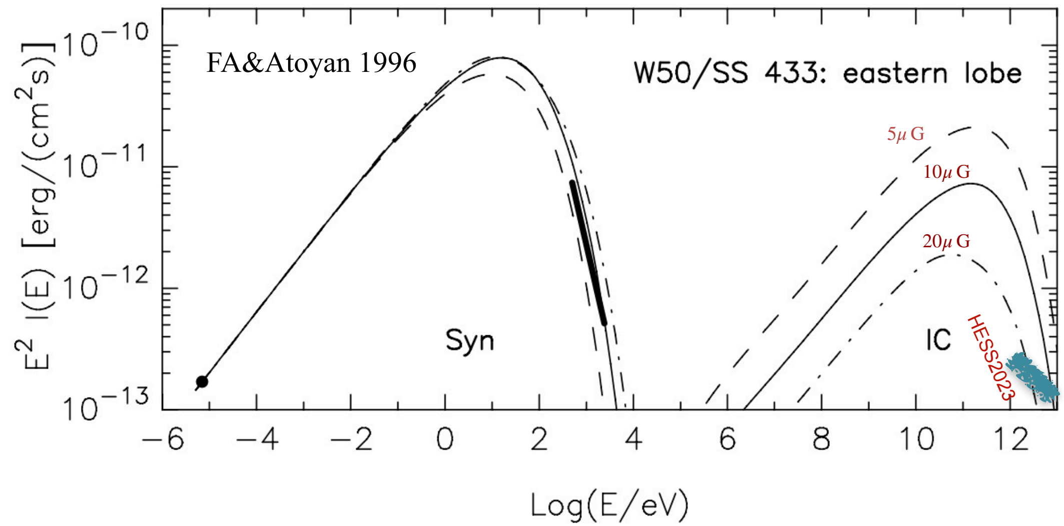
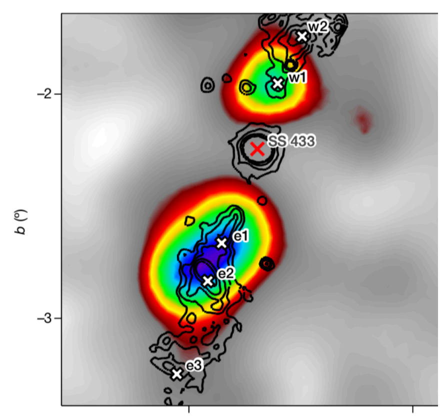


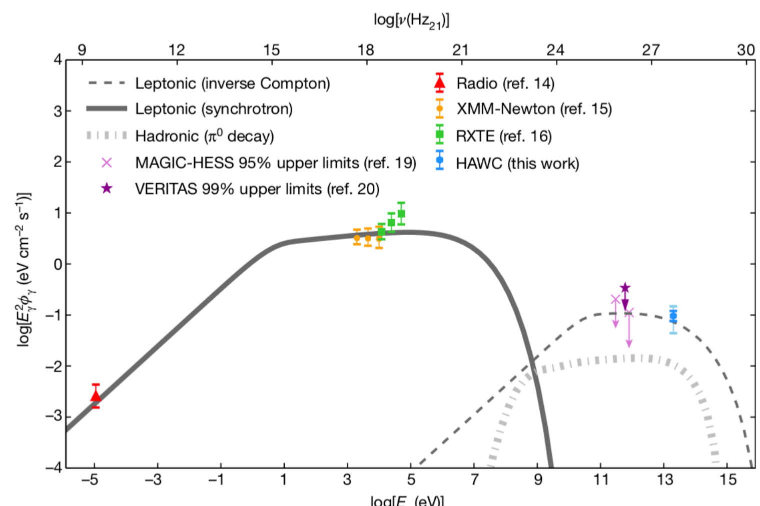
Fig. 7.10 The integral fluxes of γ-rays expected from the direction of the eastern ra "ear" of W50/SS 433 within different opening angles: 0.1° (dot-dashed), 0.25° (sol the size of the "ear"), 0.5° (dashed), and 2° (dots). The upper limit on the TeV flux by the HEGRA IACT system is also shown. (From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



HEGRA : flux u.l. @ 1 TeV → B ≤ 19μG



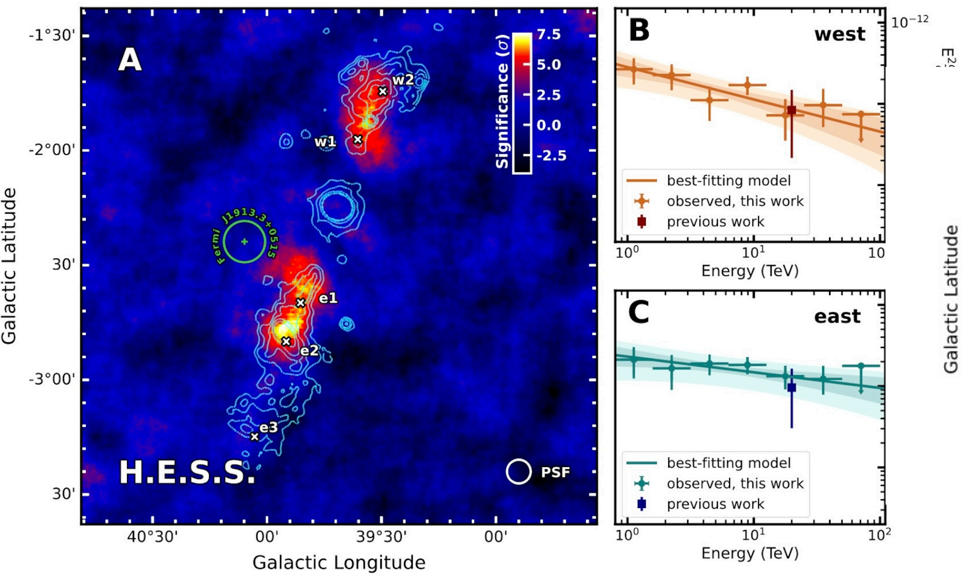
HAWC coll. Nature 2018



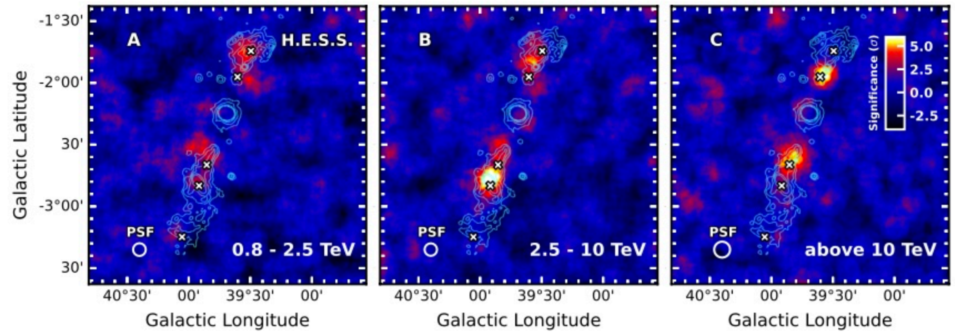
HAWC - single point at 20 TeV
HESS/MAGIC - upper limits
=> spectrum as flat as E^{-2}

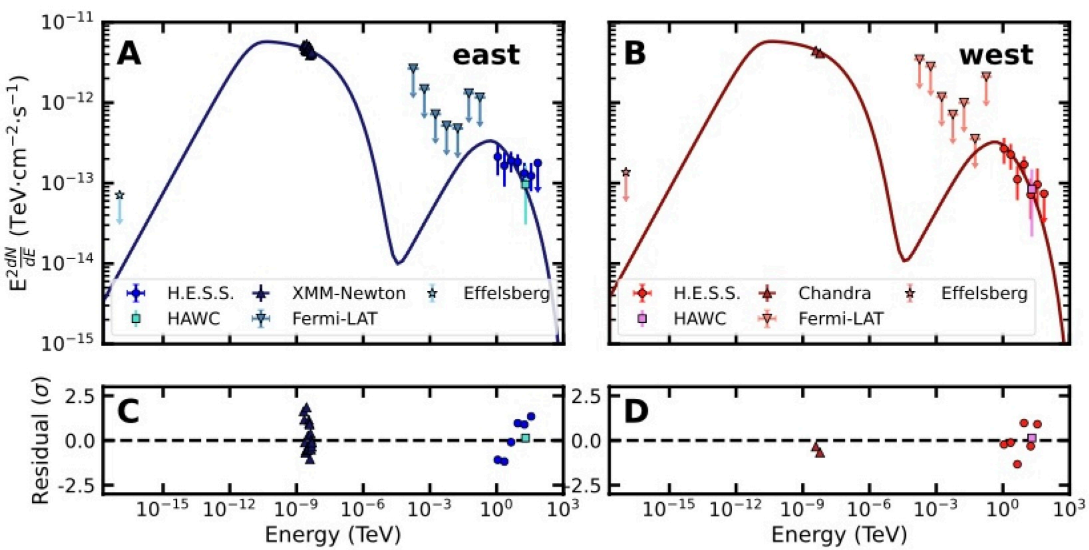
Detection of TeV gamma-rays from X-ray lobes of SS 433

H.E.S.S. collaboration 2023



Energy-dependent morphology

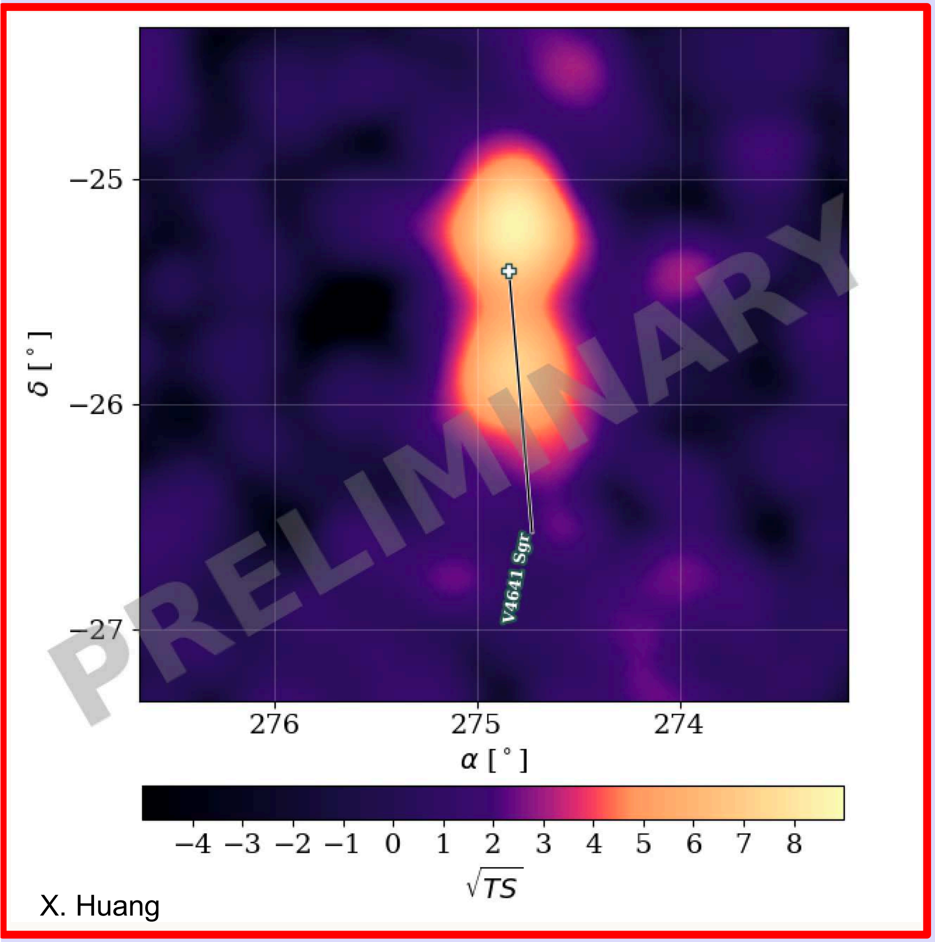




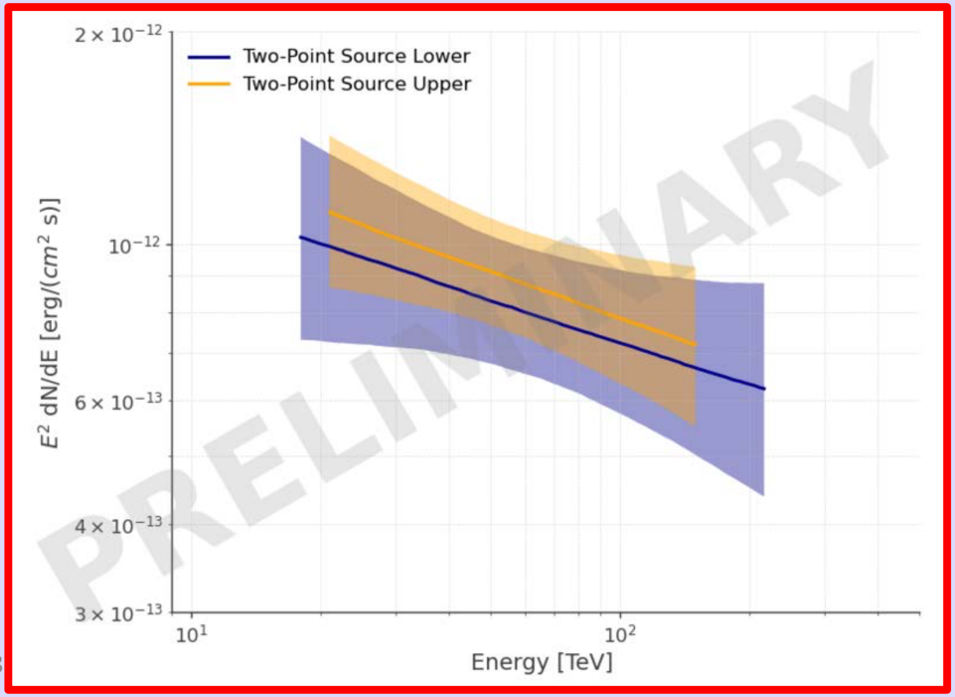
SED fitting with synchrotron and IC radiation of ultrarelativistic electrons

	east	west	shared	fixed
Γ_e	2	2	yes	yes
E_{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

VHE Photons coincident with V4641 Sgr



- Newly discovered TeV source at the boundaty of HAWC fov
- High zenith angle for HAWC - 45° off zenith
- Coincident with one of the fastest superluminal jets in the Milky Way galaxy
- 9.7σ in Pass 5 7 σ above 56 TeV
- Morphology: two sources or a 100 pc extended one
- Highest energy measured: 220 TeV



S. Casanova 2023

Summary

The Milky Way is full of Cosmic Ray Factories - TeVatrons and PeVatrons - that accelerate particles with extremely high efficiency. These factories initiate γ-ray production - inside the accelerators and, more often, outside the acceleration sites, resulting in several types of gamma-ray emitters.

The physics of these perfect devices producing ultrarelativistic nonthermal plasma can be explored through high-quality gamma-ray observations and comprehensive modeling.

The recent achievements of ground-based --ray astronomy are impressive. We anticipate more in the coming years. To a certain extent, the outcome is predictable in the sense of great expectations based on the current observations and a good understanding of the performance of future detectors. We expect breakthrough (if not revolutionary) results that might require significant modifications or even revisions of the current concepts and paradigms linked to several areas of Galactic Astronomy: SNRs, SFR, GMC, ISM, Pulsars, PWNe, Microquasars,…

Finally, the new observations will bring us closer, hopefully in the coming years, to the solution to the century-old mystery of the origin of galactic cosmic rays.