International School of Physics ”Enrico Fermi” - Varenna 2022

Foundations of Cosmic Ray Astrophysics

High Energy Cosmic Rays and Gamma Radiation

Lecture 2. Galactic and Extragalactic Cosmic Ray Accelerators

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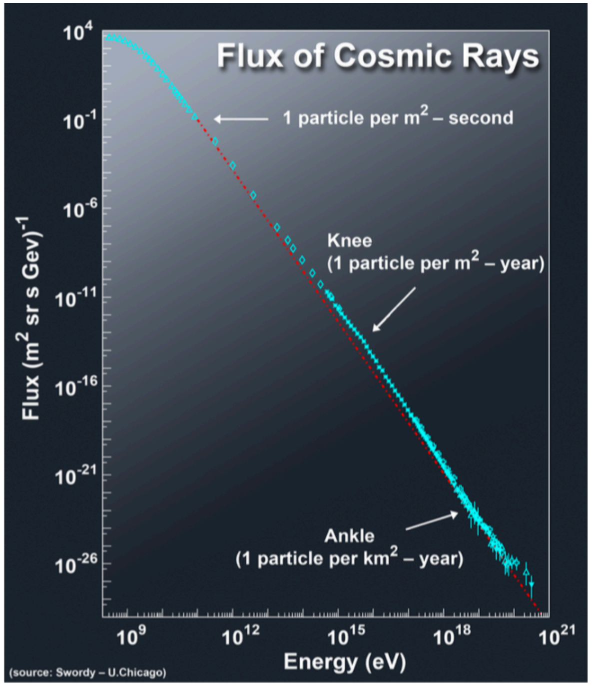
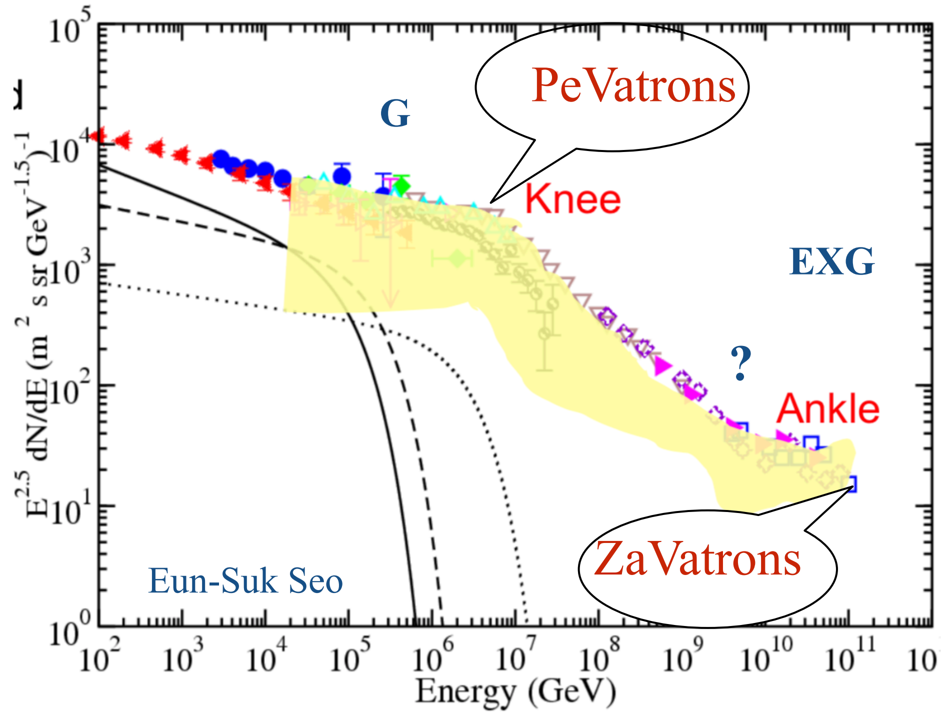
Villa Monastero Varenna, June 25, 2022

"Origin of cosmic rays remains a mystery…"

a standard statement used in reviews/textbooks over many decades





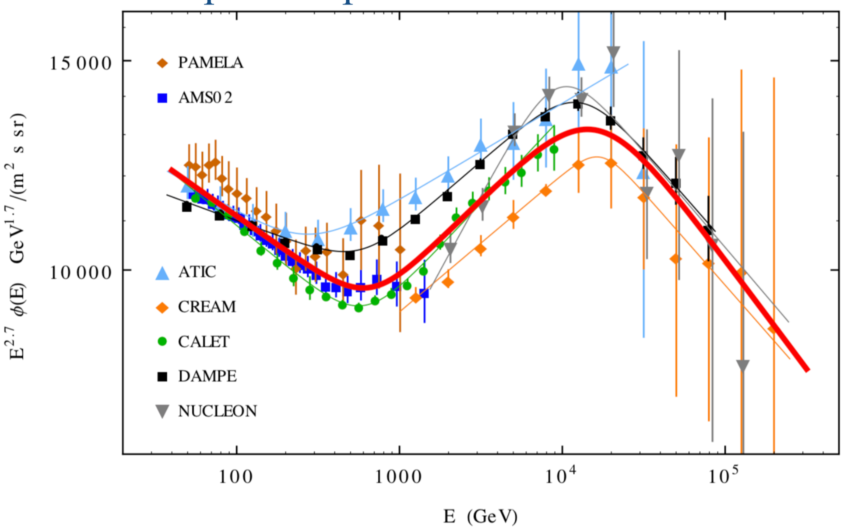
below 10^{15} eV - G challenge : > 10^{15} eV

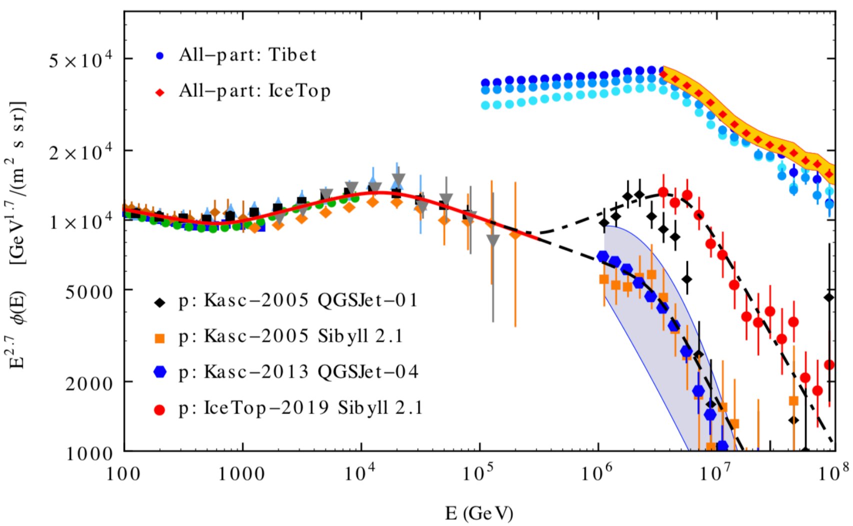
beyond 10^{18} eV - EXG challenge: > 10^{20} eV

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

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 ?

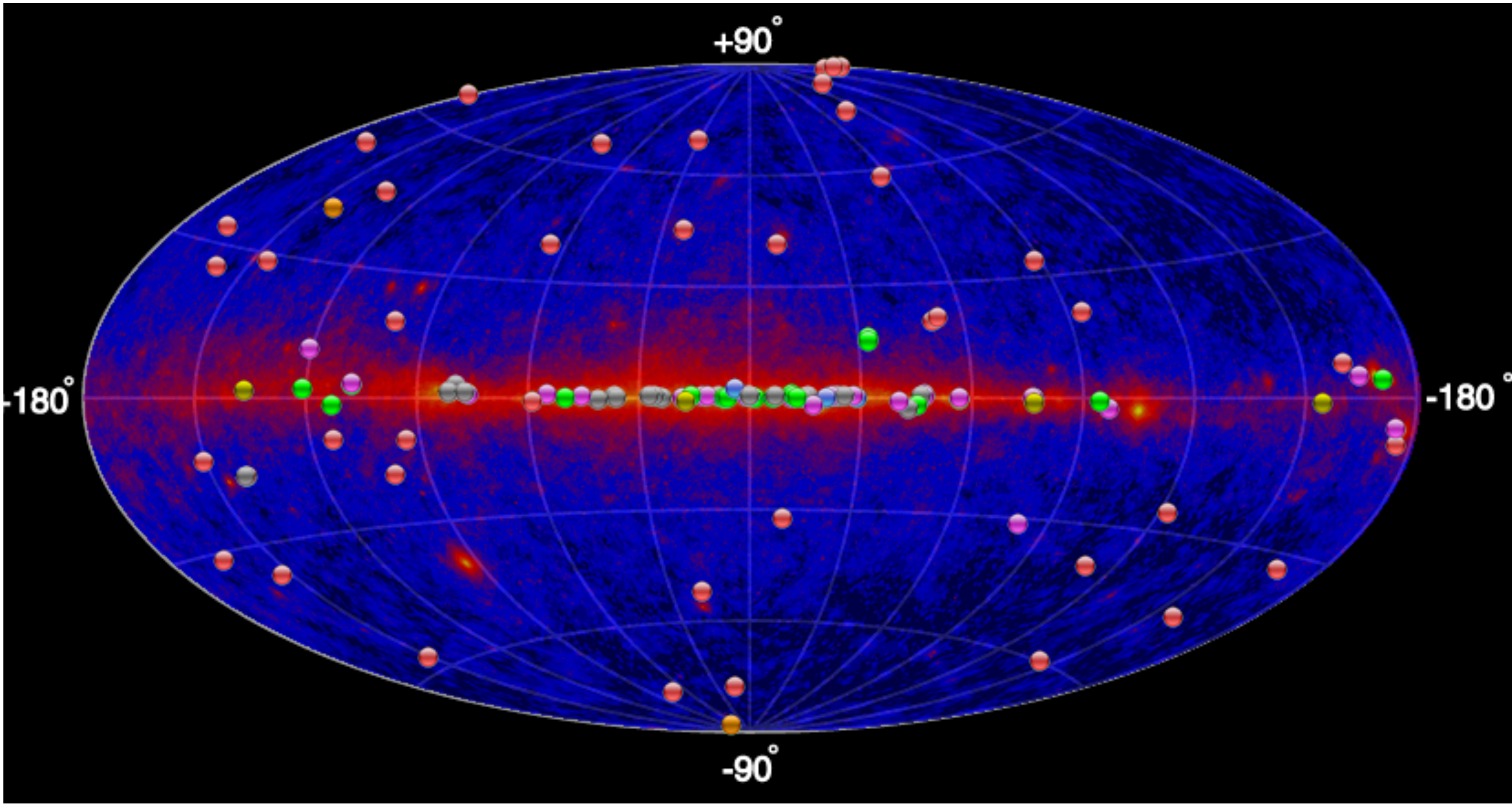
do we need PeVatrons ?

- **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

TEVCAT + Fermi LAT Skymap



galactic gamma-ray sources

- 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)
- Binary Pulsars
- Microquasars (accreting Black Holes)
- …

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$^{6-7}$ yrs**

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

Do~10^{28} cm^2/s; δ ~ 0.3-0.5

production rate: Lcr = wV/To ~ **(0.3-1) x 10^{41} erg/s**,

source spectrum: $Q(E) \propto E^{-\alpha}$

$\alpha=\Gamma-\delta$; Γ~2.7-2.8 ; **α ~2.3-2.5**

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 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**

Two primary objectives:

- Probing γ-ray emission of **young SNRs** (Cas A and Tycho) up to 100 TeV

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

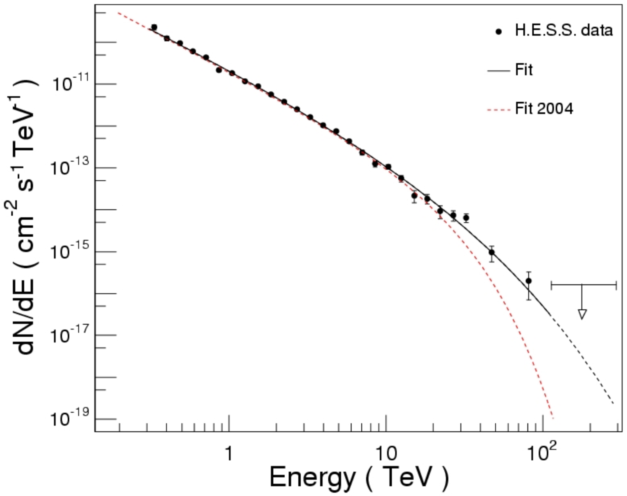
=> decisive tests whether these objects have operated as PeVatrons
at any stage of their evolution

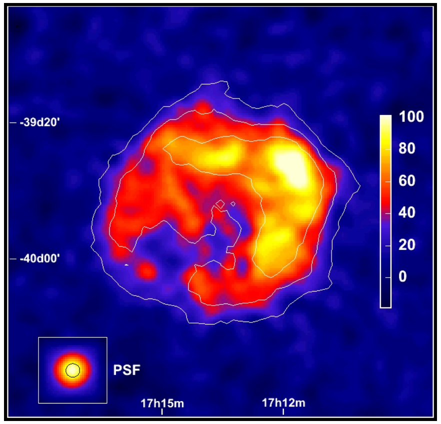
- Exploring links of some of the extended UHE sources with **middle-aged** (~10,000 yr old) SNR having nearby ($R \leq 100$ pc) massive ($M \geq 10^4 M_\odot$) gas clouds - "smocking guns" radiating γ-rays initiated by CRs that already have left the accelerator (SNR) and presently interact with the cloud(s)

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

RXJ1713.7-4639

TeV γ-rays and shell type morphology: acceleration of protons and/or electrons in shell up to 100TeV (not much higher)





can be explained by γ-rays from pp -> π^o -> 2γ

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

α=2.0 Eo=17.9 TeV β=1

α=1.79 Eo=3.7 TeV β=0.5

with just "right" energetics:

$Wp = 10^{50}\, (n/1cm^{-3})^{-1}$ erg

but IC models generally are more preferred… because of TeV-X correlations (?)

IC origin of γ-rays cannot indeed be excluded, but this is not a convincing argument

definite answer – detect neutrinos (very difficult)

more realistic approach: γ-ray: morphology with 1-2 arcmin resolution and spectrometry, especially above 10 TeV

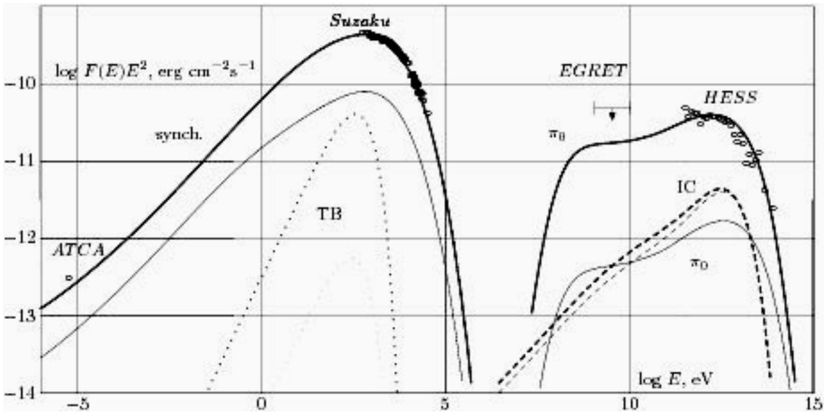
broad-band SEDs

hadronic model

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

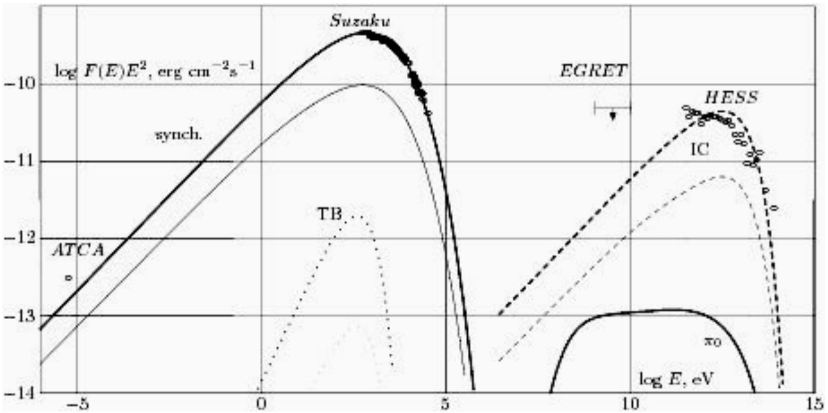
(1) lack of thermal emission - possible explanation?
>70% energy is released in acceleration of protons!
or gamma-rays are produced in clumps

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



leptonic model

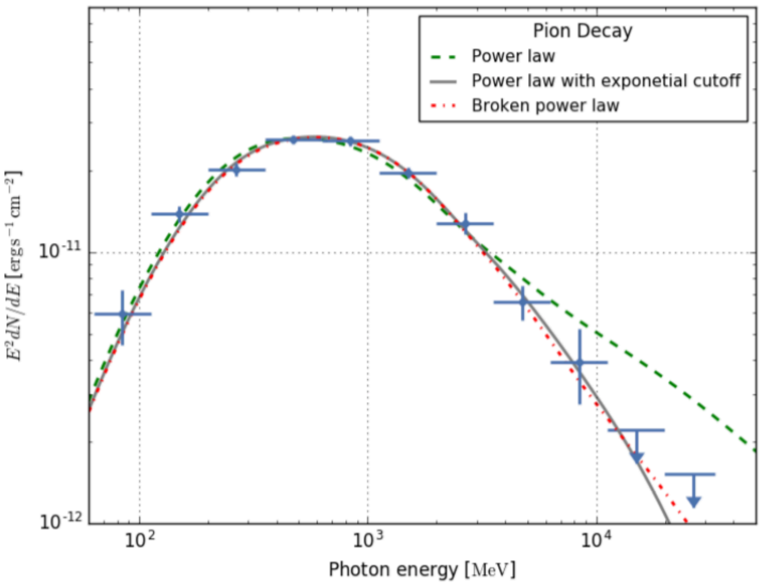
not perfect, but still acceptable, fits for spectral and spatial distributions of IC gamma-rays;
suppressed thermal emission, comfortable p/e ratio (~10^2);small large-scale B-field (~ 10 μG)
2zone-model?: IC gamma-rays in reverse shock,
Syncrotron X-rays – forward shock

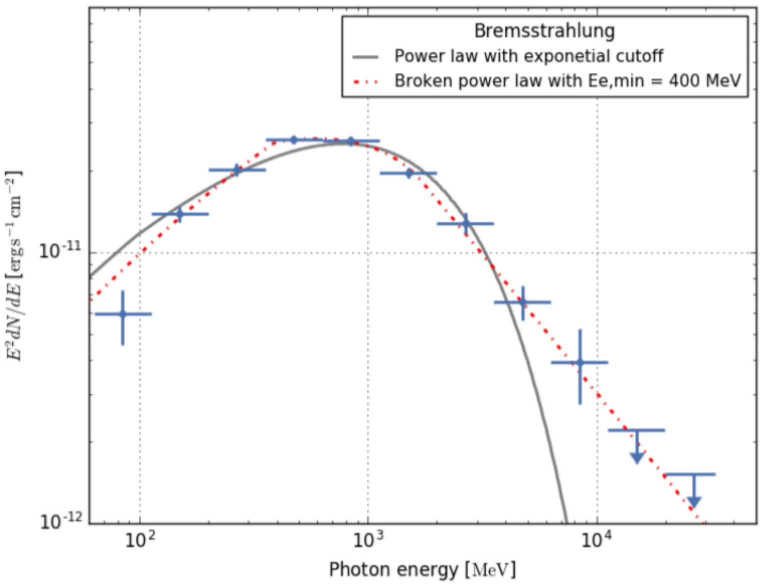


detection of ‘π^0’ bump in middle-aged SNRs

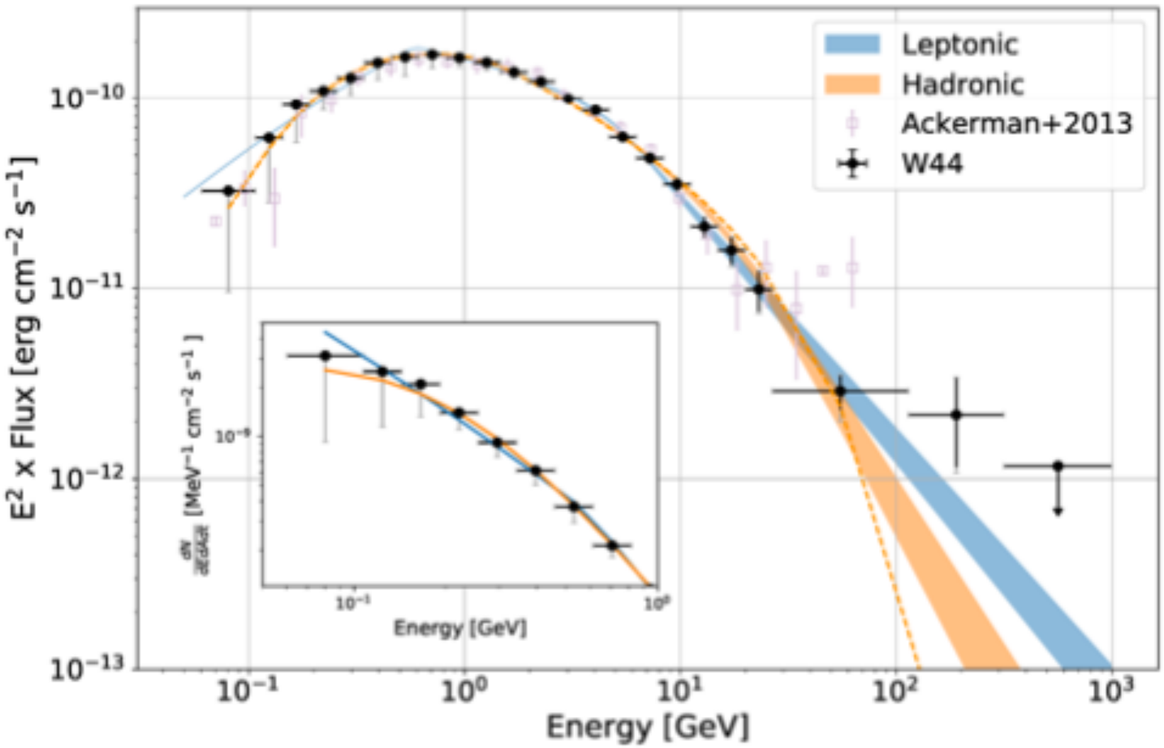
in principle, ’pi-0’ bump in SED can be reproduced by bremsstrahlung of electrons with broken power-law spectrum close to the one observed in the interstellar medium

π^0 origin of the bump is important for estimates of the content of low-energy CR protons and nuclei, but it is not a critical issue for the origin of Galactic CRs





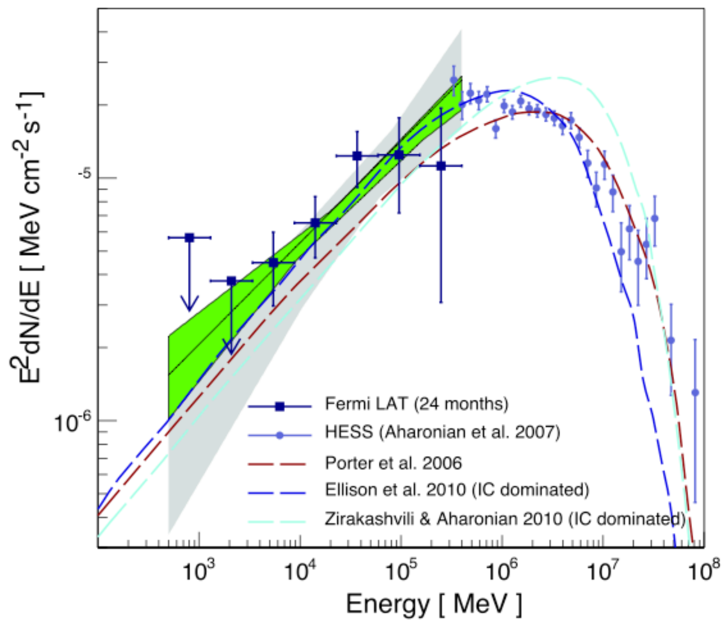
π^0 bump in the spectrum of W44 !

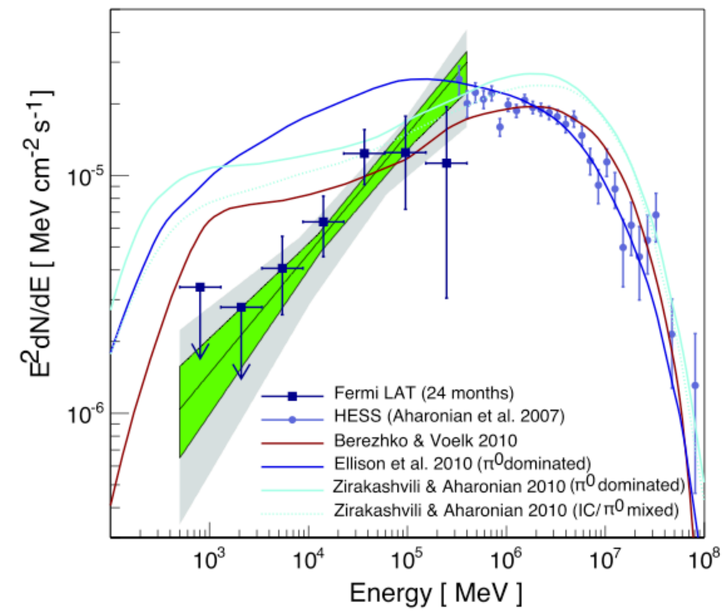


G. Peron

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

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?

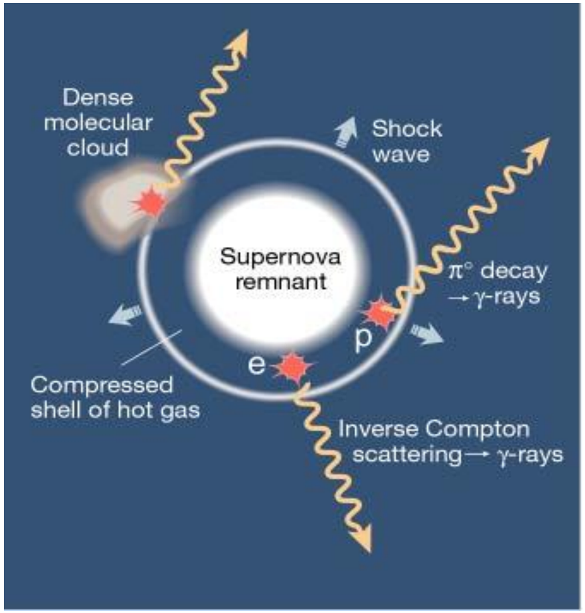
they could come from quite different regions

(ii) cannot we assume hard proton spectra ?

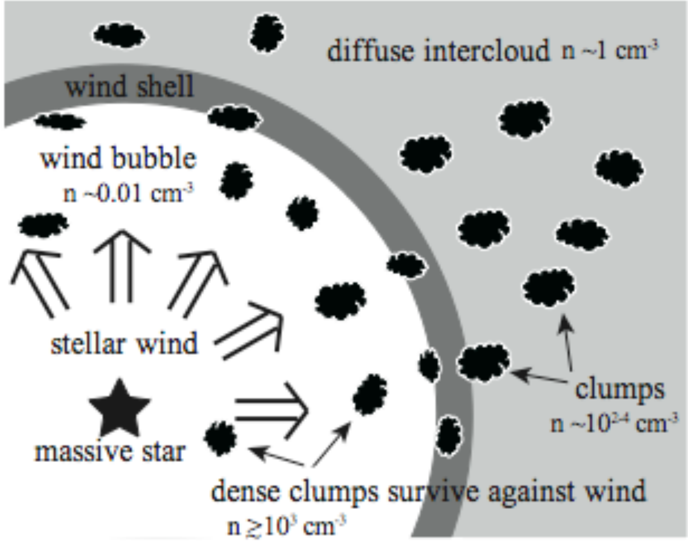
nonlinear theories do predict very hard spectra with α -> 1.5

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

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



Inoue et al. 2011, ApJ

Fermi LAT results - important, but only neutrinos, ultra-high energy gamma-rays and hard synchrotron X-rays from secondary electrons can provide decisive conclusions propagation effects in clumps can, in principle, explain Fermi LAT – HESS spectral points from 1 GeV to 100 TeV (Gabici & F.A. 2014) and, possibly, also the lack of thermal X-ray emission

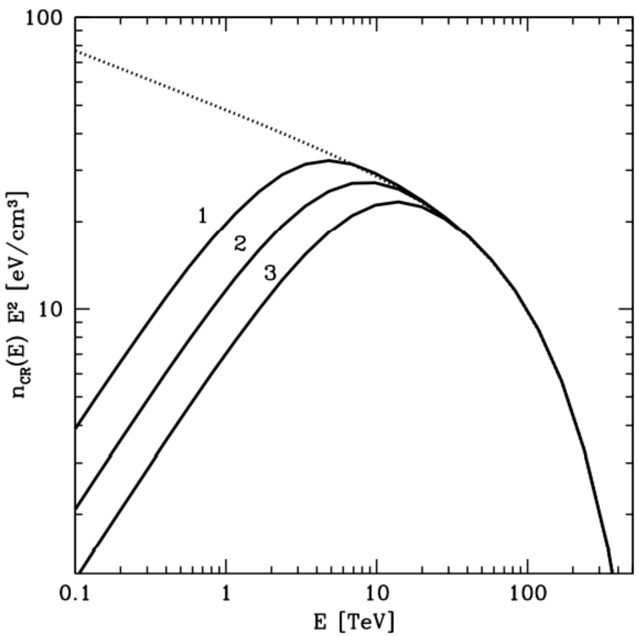


Figure 1. Spectrum of CRs in the SNR shell (dotted line) and inside a clump that entered the shock at t_c = 1400, 1500, and 1550 yr (solid line 1, 2, and 3 respectively).

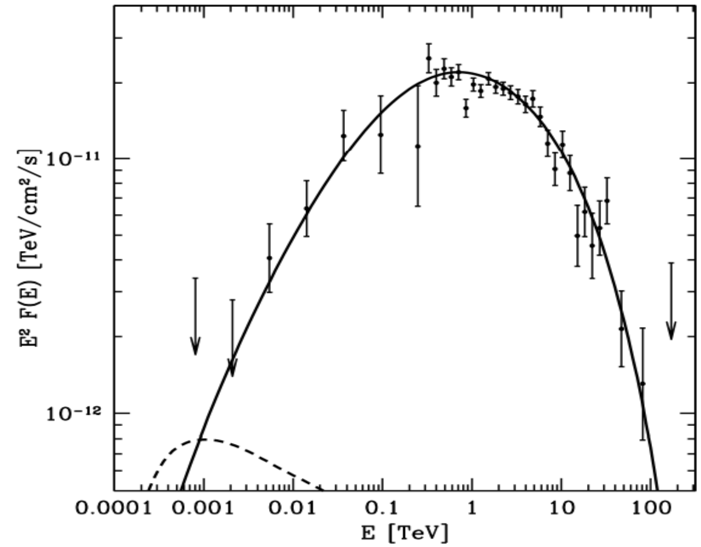
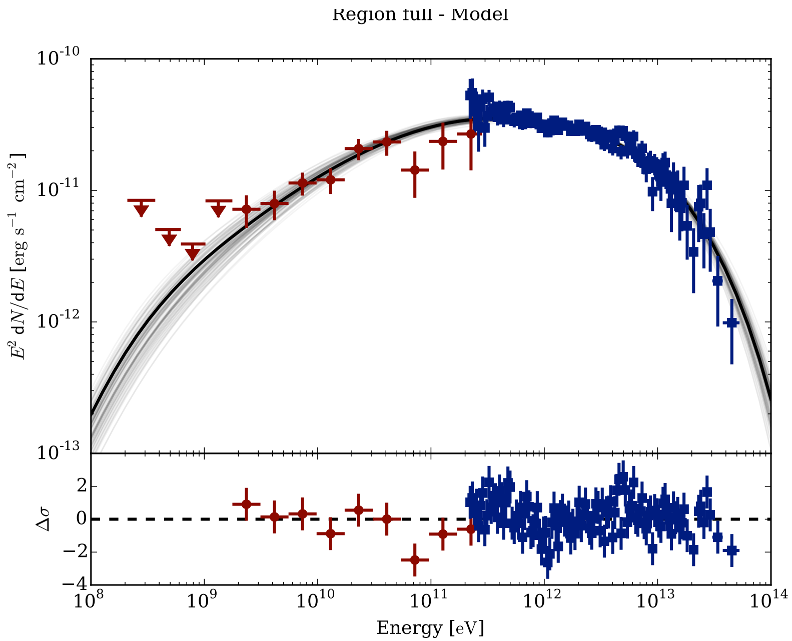


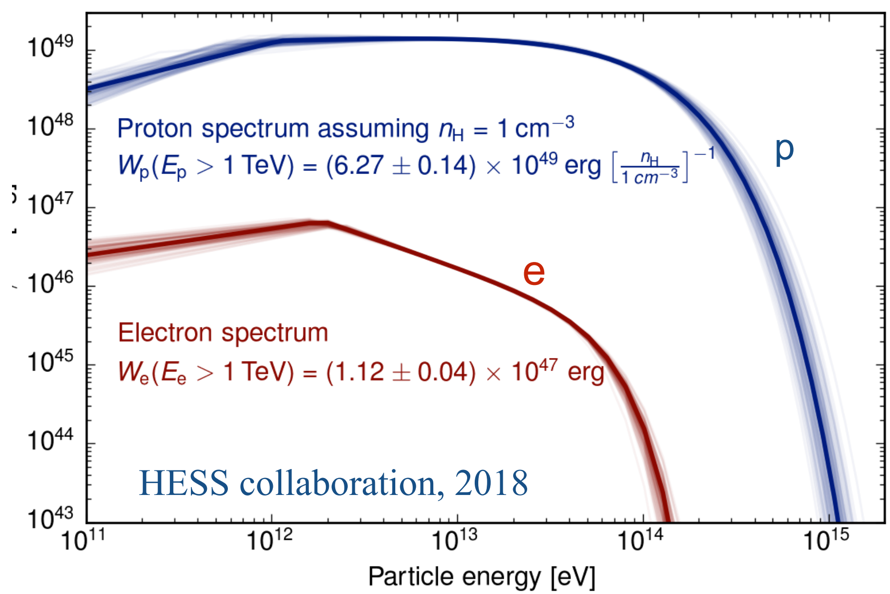
Figure 2. Gamma–rays from RX J1713.7-3946. The emission from the clumps is shown as a solid line, while the dashed line refers to the emission from the diffuse gas in the shell. Data points refer to *FERMI* and *HESS* observations.

!

Probing the distributions of accelerated particles in SNRs

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

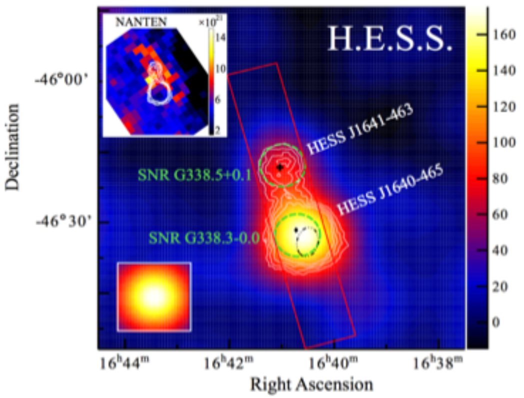




cutoff /break in the proton spectrum at 100 TeV

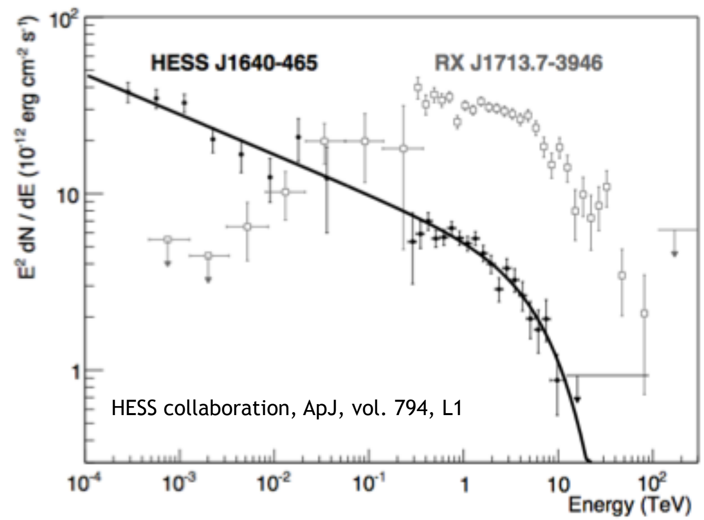
HESS J 1640-465/HESS J1641-463

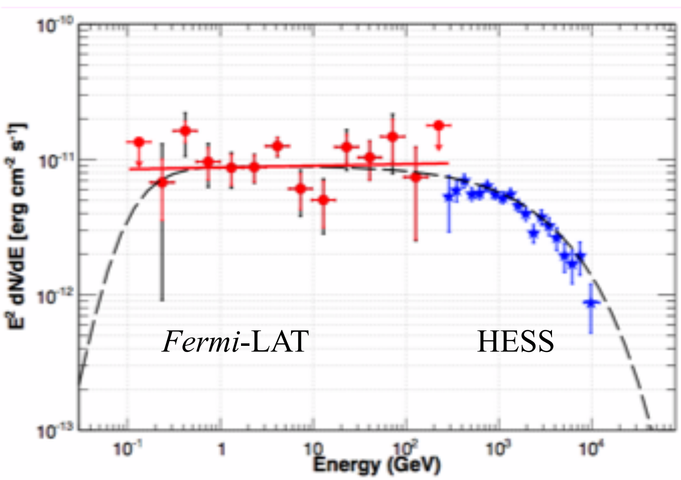
γ-ray production in dense environment



HESS 1640-465: one of the most luminous galactic VHE sources !

1-2 kyr old SNR G338.3-00 @10 kpc



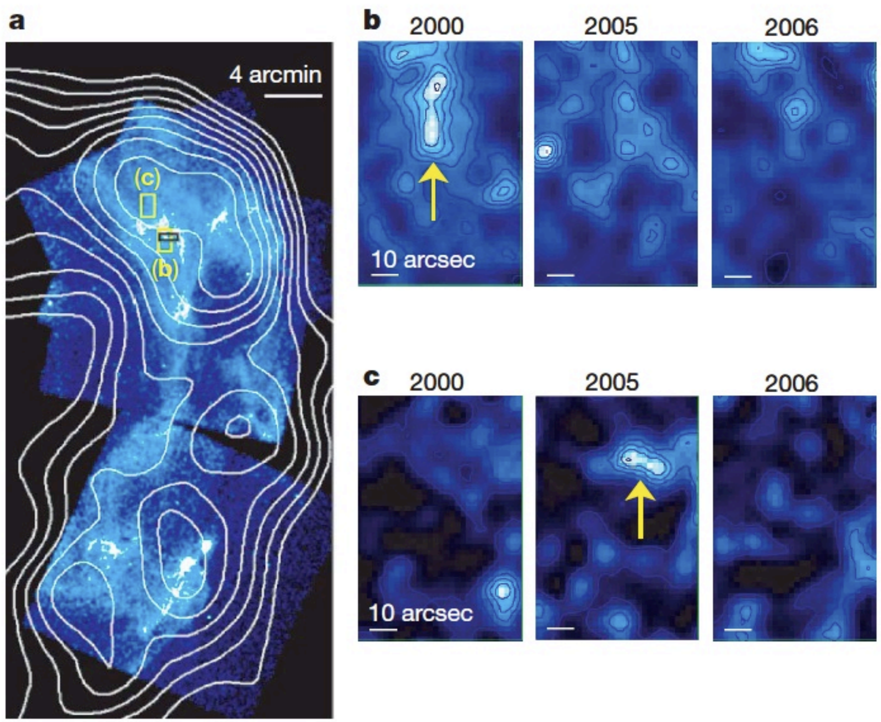


strong argument in favor of hadronic origin of gamma-rays in a SNR?

L_γ=4.8 10^{35} erg/s ; Wcr ~10^{50} erg => target gas density n > 100 cm^{-3} !

another very luminous SNR N132 D in LMC - L_γ=10^{35} erg/s - origin of the target?

Variability of X-rays on year timescales -
strong magnetic field and particle acceleration in real time



flux increase - particle acceleration

flux decrease - synchrotron cooling *)

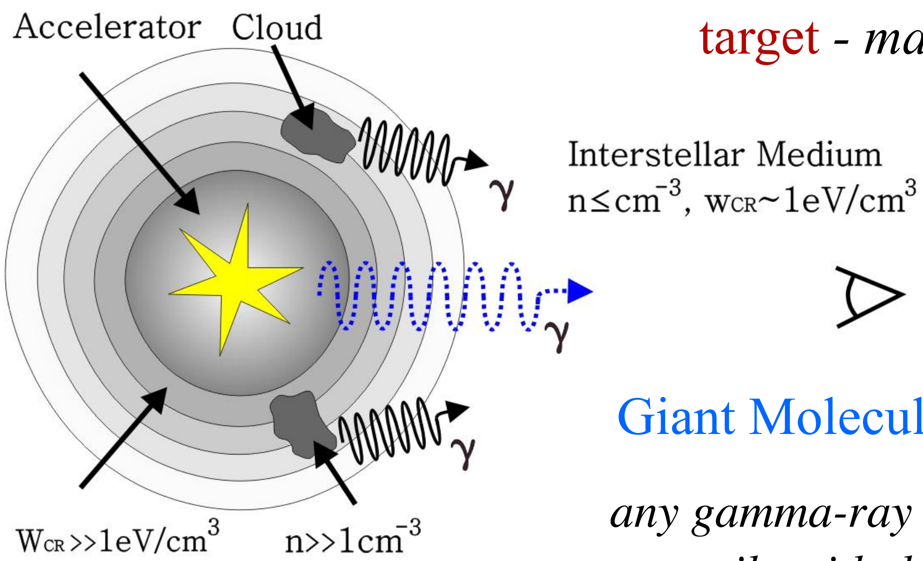
both require B-field of order 100μG, at least in hot spots

strong support of the idea of amplification of B-field by in strong nonlinear shocks through non-resonant streaming instability of charged energetic particles (T. Bell)

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

gamma-ray production: particle accelerator + target

existence of a powerful particle accelerator by itself is not sufficient for γ-radiation; an additional component – a dense target - is required



target - *matter, radiation, magnetic field*

Giant Molecular Clouds as barometers of CRs

any gamma-ray emitter coincides with the target, but not necessarily with the "primary" source/particle-accelerator

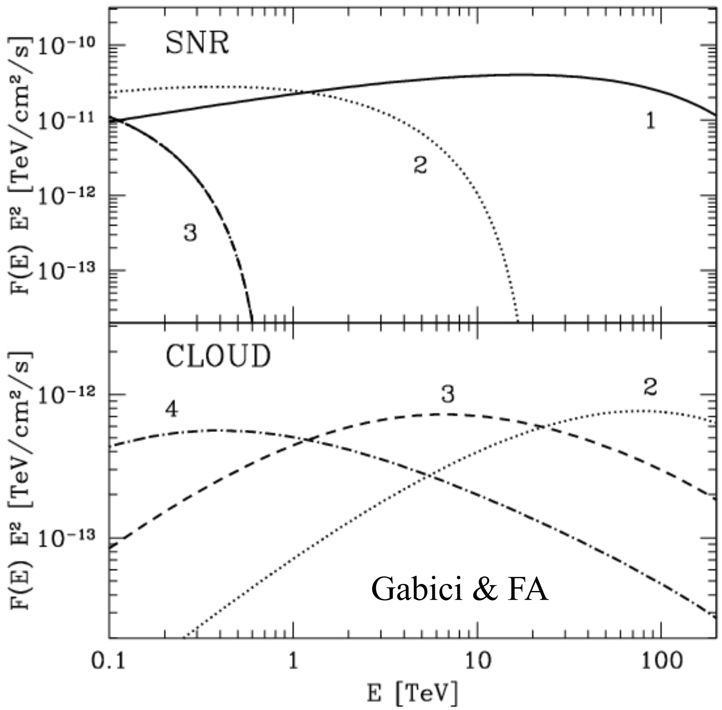
"passive" GMCs - level of the sea of GCRs

"active" GMCs – nearby accelerators – history, escape, propagation, etc…

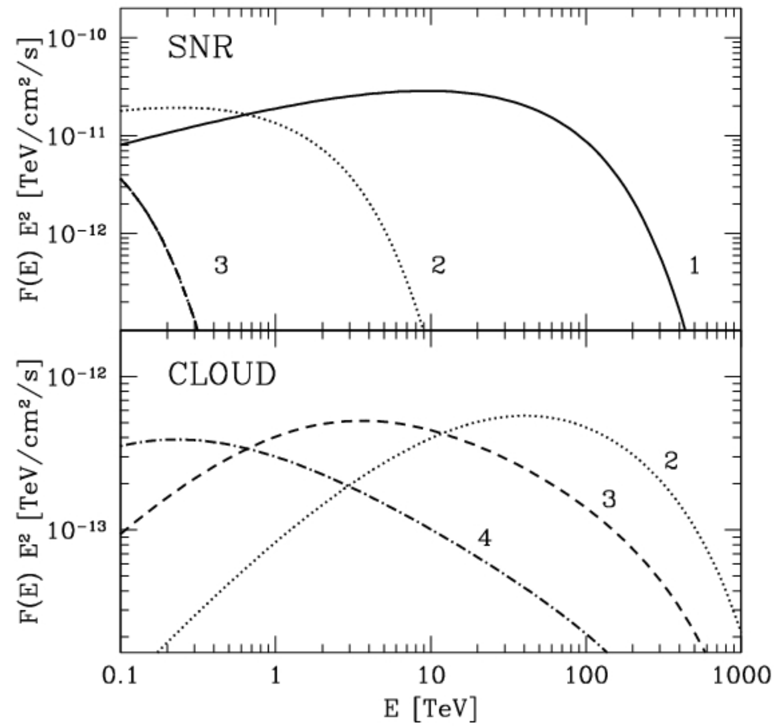
Gamma-rays and neutrinos inside and outside of SNRs

1 - 400yr, 2 - 2000yr, 3 - 8000yr, 4 - 32,000 yr

gamma-rays



neutrinos



SNR: $W_{51}=n_1=u_9=1$ d=1 kpc

GMC: $M=10^4\ M_o$ d=100pc

ISM: $D(E)=3x10^{28}(E/10TeV)^{1/2}$ cm²/s

how to find the “missing PeV protons in SNRs?

highest energy particles, E > 100 TeV, are confined in the shell only during a few 100 years => most promising search for PeVatrons? multi-TeV γ-rays from dense gas clouds in the near neighborhood

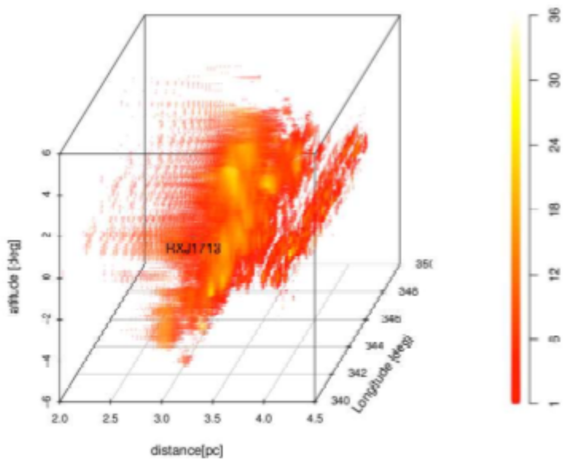
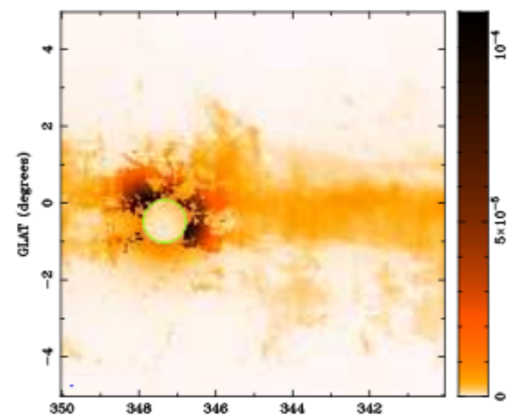


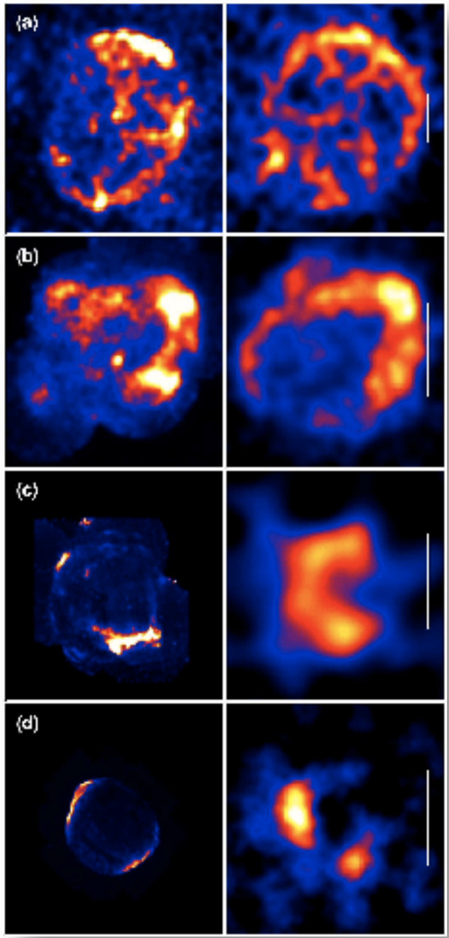
Fig. 1. The gas distribution in the region which spans Galactic longitude $340^\circ < l < 350^\circ$, Galactic latitude $-5^\circ < b < 5^\circ$ and heliocentric distance 50 pc $< l_d <$ 30 kpc, as observed by the NANTEN and LAB surveys, expressed in protons cm^{-3}. The distance axis is logaritmic in base 10. A value for the gas density is given every 50 pc in distance, which is reflected in the apparent slicy structure for distances below 100 pc. For sake of clarity only densities above 1 protons cm^{-3} are shown. Also indicated the position of the historical SNR, RX J1713.7-3946.



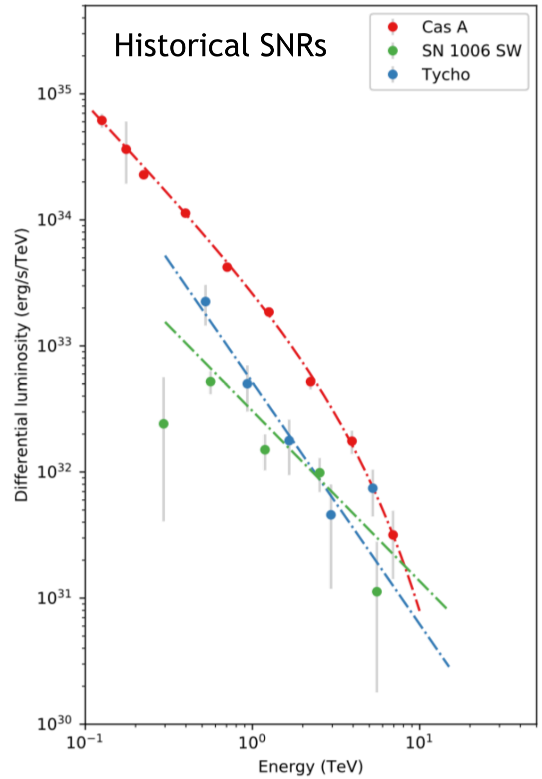
surrounding gas density:
NANTEN data
age:
1600 yr
escape of protons:
model of Zirakashvili&Ptuskin 2008
diffusion coefficient outside SNR:
$D=10^{26}$ $(E/10GeV)^{0.5}$ cm^2/s

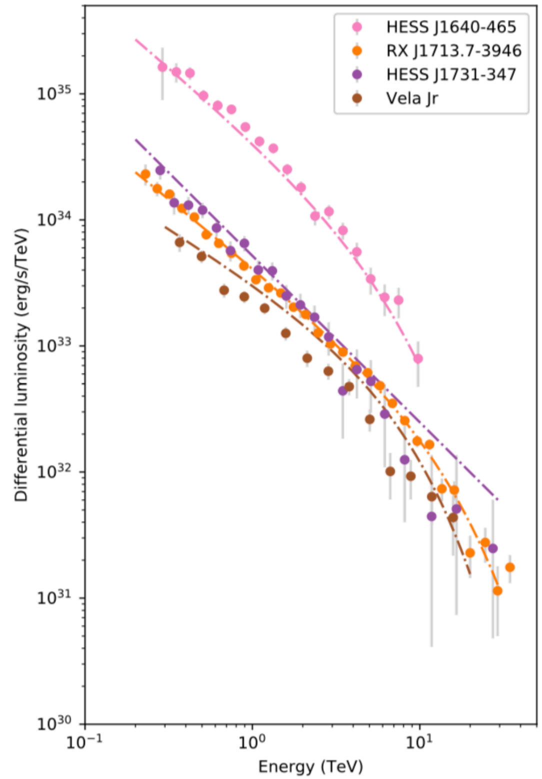
required angular resolution as good as 1-2 arcmin can be achieved at 10 TeV !

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?

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, $\Gamma=2$ 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

- large power-law indices

deviation from DSA or its modification?

presently - no constrains on the proton maximum energy from gamma-ray data

- "early cutoff"

standard DSA but low-energy cutoff

should we relax and accept that SNRs are main contributors to CRs but at TeV energies are overtaken by other source population ("PeVatrons") responsible for the knee region?

or

relate it to the much early "PeVatron Phase" - first << 100 years after the SN explosion and the escape of highest energy particles from the remnant e

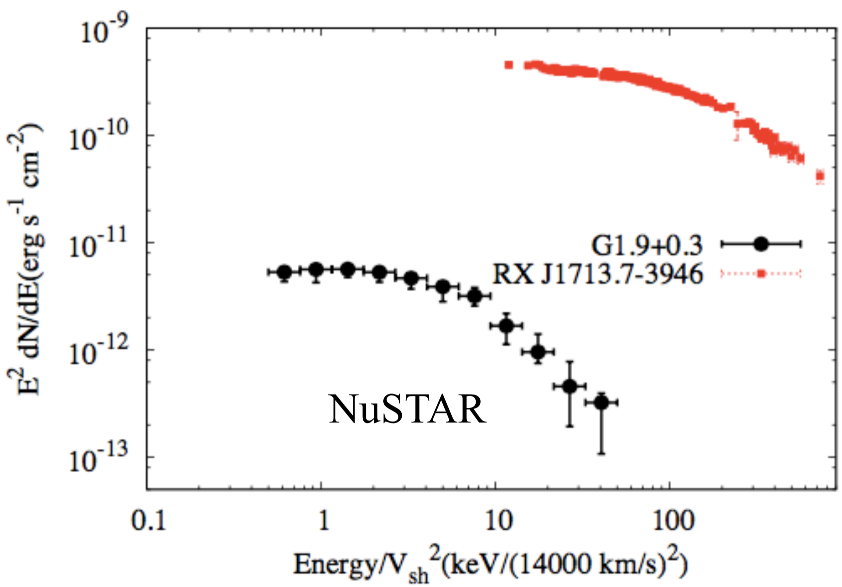
"large Γ or small Eo ?" - extension of observations to 10 TeV

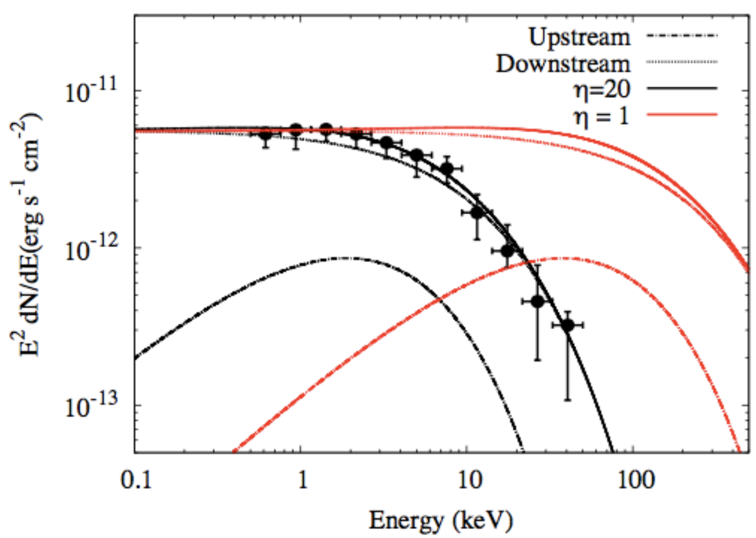
Very young SNRs as PeVatrons?

G1.9+0.3 - youngest (100yr-old) known SNR in Galaxy with the current shock speed v=14,000 km/s

$$h\nu_{\rm max} \approx 1(\mathrm{v_{sh}}/3000~\mathrm{km/s})^2~\mathrm{keV}$$

in the Bohm diffusion limit the peak should be around 20 keV but is detected at 1 keV





Presently G1.9+0.3 does not operate as a PeVatron!

PeV protons have been accelerated at earlier epochs, but, because of the particle escape, the remnant is already emptied =>

early acceleration and escape reduce the chances of finding PeVatrons ?

in very young (SN 1987a and G1.9+0.3) SNRs, multi-TeV particles cannot run

far away, thus the current upper limits can be applied to the "escape regions"

G1.9+0.3 in GC region:

propagation of **R > 10 TeV** protons cannot exceed 30 pc (for **D ~ 10^{30} cm^2/s**)

for **d=8.5 kpc** the angular sized less than **10 arcmin**

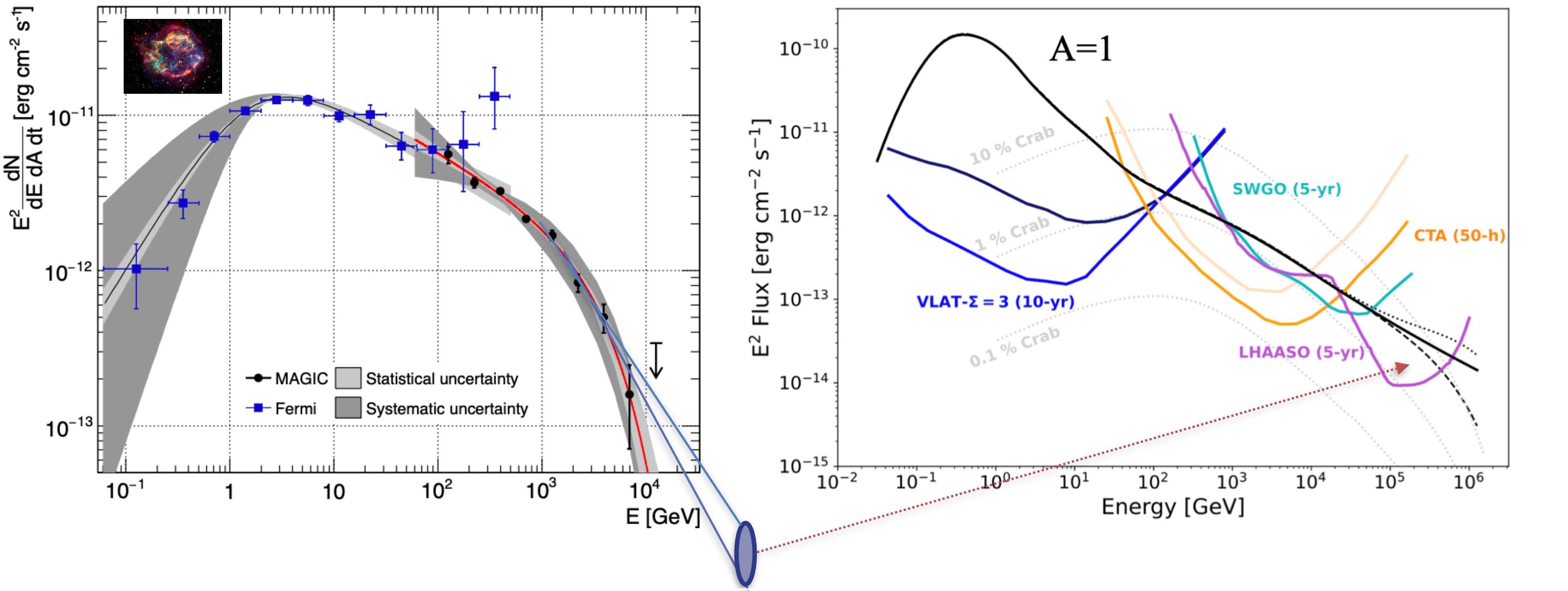
HESS upper limit on the γ-ray luminosity $L_\gamma(\geq 1\ \mathrm{TeV}) \leq 2 \times 10^{32}$ erg/s

can be applied to the content of >10 TeV protons within R=30 pc region

for n~100 cm^{-3} $W_p(\geq 10E) = L_\gamma(\geq E) t_\pi$ or **$W_p < 10^{45}$ erg**

=> G1.9+0.3 was not an effective PeVatron also in the past !

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 ?

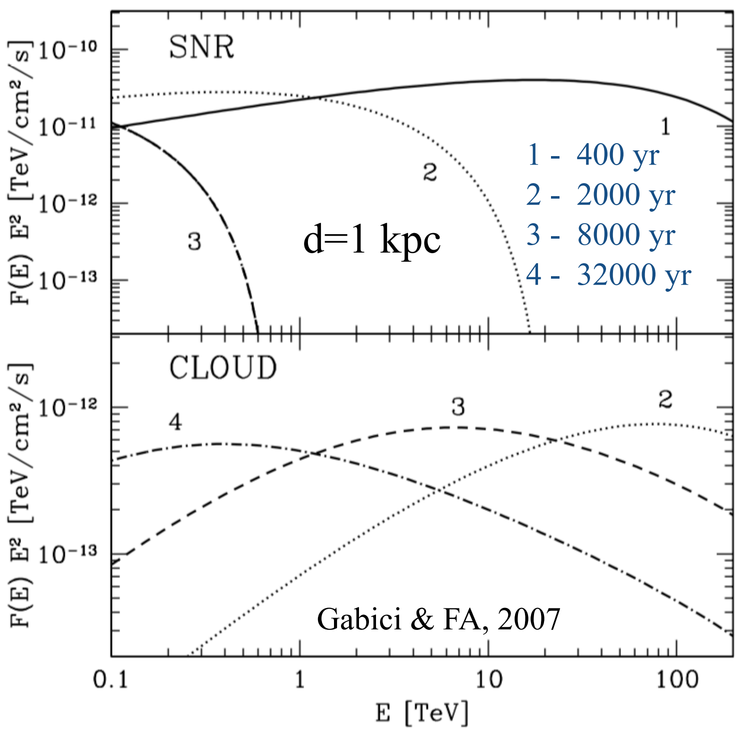
even moving ballistically R~100 pc (angular size $\sim 2^0$) but the γ-ray image would be a point like;

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

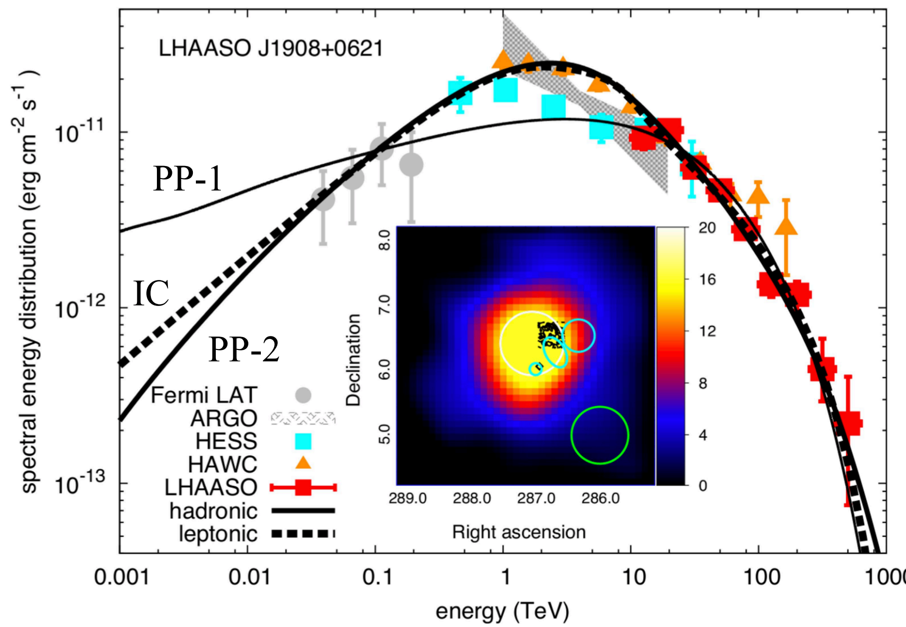
=> LHAASO upper limit (or detection) of 100 TeV γ-rays - at the level of $10^{-14}\, erg/cm^2 s$

decisive “PeVatron test” independent of the acceleration epoch

“smoking gun” from dense environments in <100 pc vicinities 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?

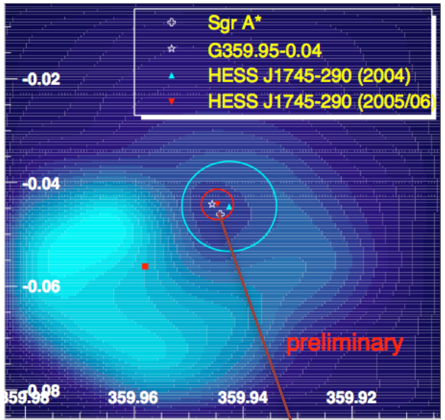
✓ collective stellar winds and SNR shocks in clusters and of massive stars, superbubbles
- speeds off stellar winds - several 1000 km/s - comparable to young SNR shock speeds
- 10^{41} erg/s (comparable or a factor of 2 less than mechanical power of SN)
accel. efficiency should be at least 10 % - much 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;
potential, but, most likely, not the major contributors to CR electrons

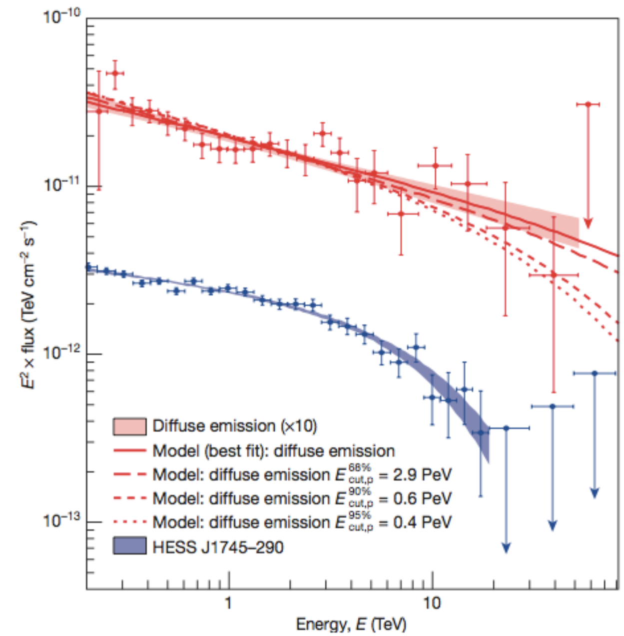
one cannot exclude that the observed CR flux up to 10^{15}eV is significantly contributed by a single (or a few) local sources. This is the case of TeV electrons

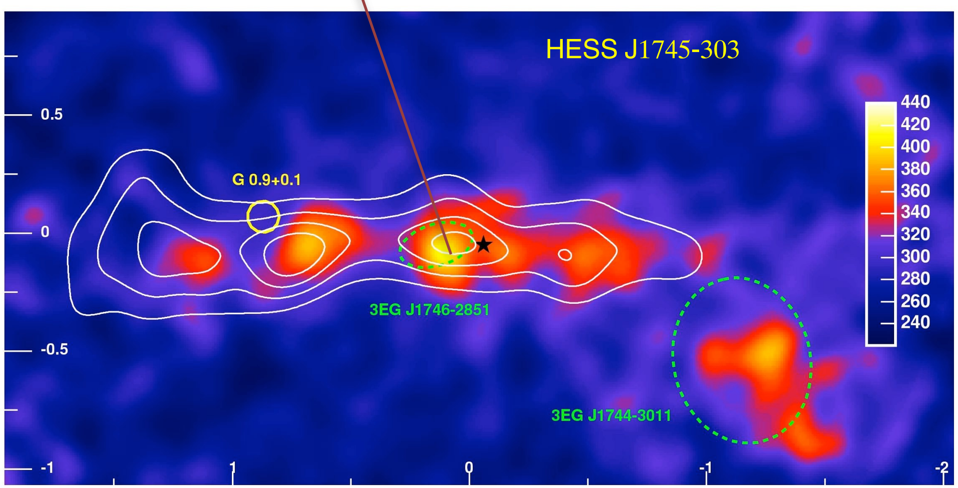
PeVatron(s) in the Galactic Center!

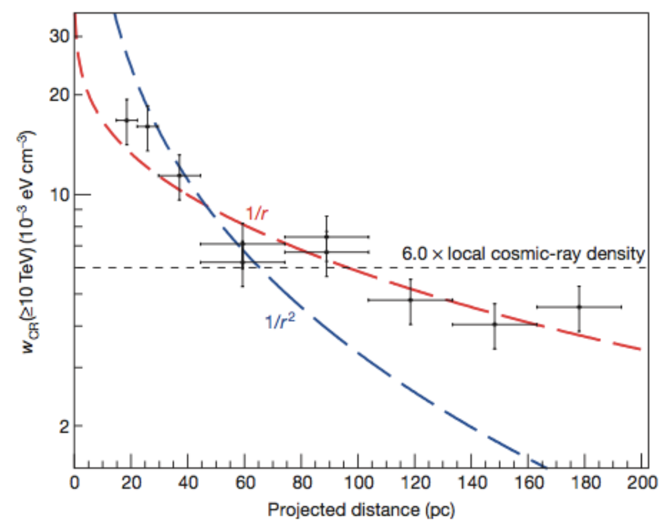


PeVatron(s) in the Galactic Center!

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)

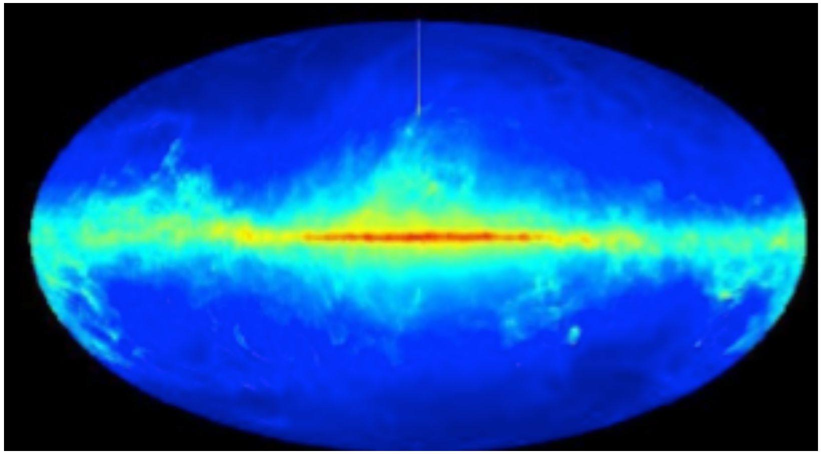
- 1/r type distribution of the CR density implies (quasi)continuous regime of operation of the accelerator with a power 10^{38} erg/s (on timescales 1 to 10 kyr) - a non negligible fraction of the current accretion power

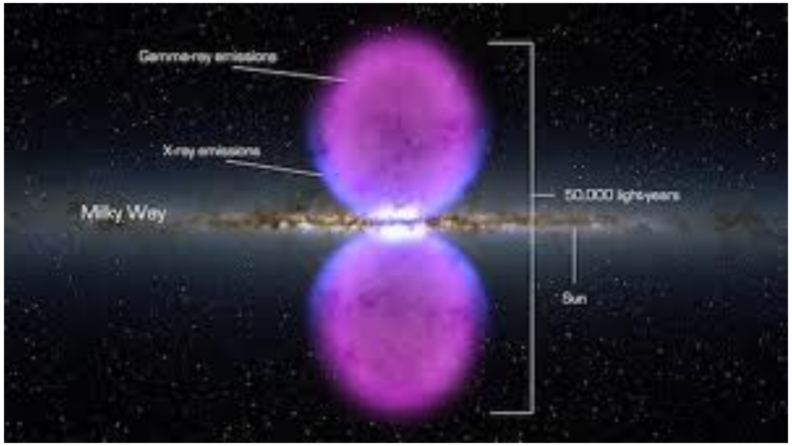
- this accelerator alone can account for most of the flux of Galactic CRs around the "knee" if its power over the last 10^6 years or so, has been maintained at average level of 10^{39} erg/s

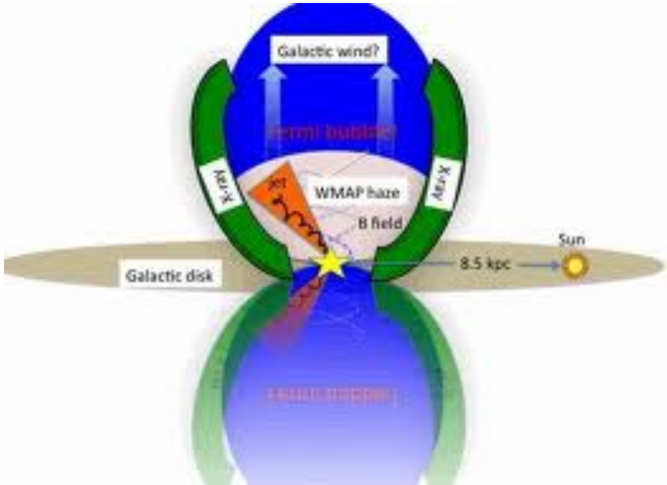
- escape of particles into the Galactic halo and their subsequent interactions with the surrounding gas, can be responsible for the sub-PeV neutrinos recently reported by the IceCube collaboration

SMBH or young massive-star clusters?

Fermi Bubbles !







Finkbeiner and collaborators 2010

Fermi Bubbles - result of pp interactions of CRs produced in the GC and accumulated in R ~10 kpc regions over 10Gyr comparable to the age of the Galaxy? (Crocker&FA 2011)

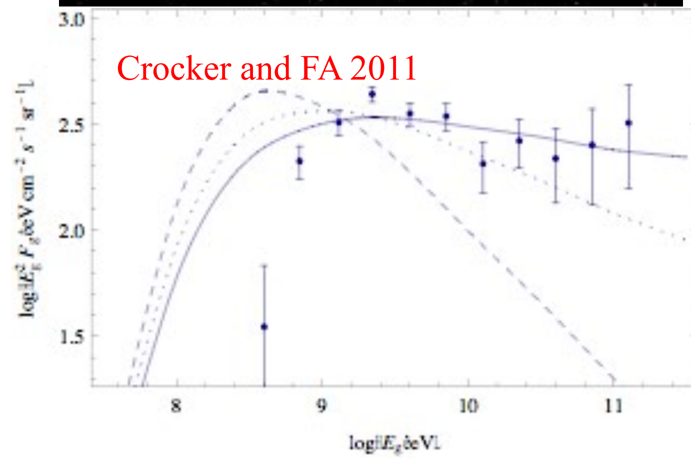
Size - because of slow diffusion in turbulent environment (10 times slower than in the Galactic Disk)

plasma density: n~0.01 cm^{-3} timescale: $t_{pp} \sim 5$ Gyr $< t_{Galaxy}$

saturation (calorimetric) regime can explains:

generally homogeneous distribution of gamma-rays (local γ-ray production rate does not depend on density), unless possible gradients in the CR spatial distribution, e.g. due to propagation effects ; if the sharp edges tentatively found in the Fermi images is a real effect, they can be naturally explained by higher turbulence introduced by shocks => slower diffusion => accumulation of CRs close to the edges

modest requirements to CR rate : Lp ~ 10^{39} erg/s



Fermi Bubbles as a ν-source ? if γ-ray spectrum extends to 100 TeV, Km3NeT should be able to detect neutrinos

are FBs sites (reservoirs or accelerators) of PeV CRs? The answer can can be provided by γ-ray observation at multi-Tev energies, and CTA and LHAASO are the best hope!

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 ?)

Stellar Clusters operate as PeVatrons ?

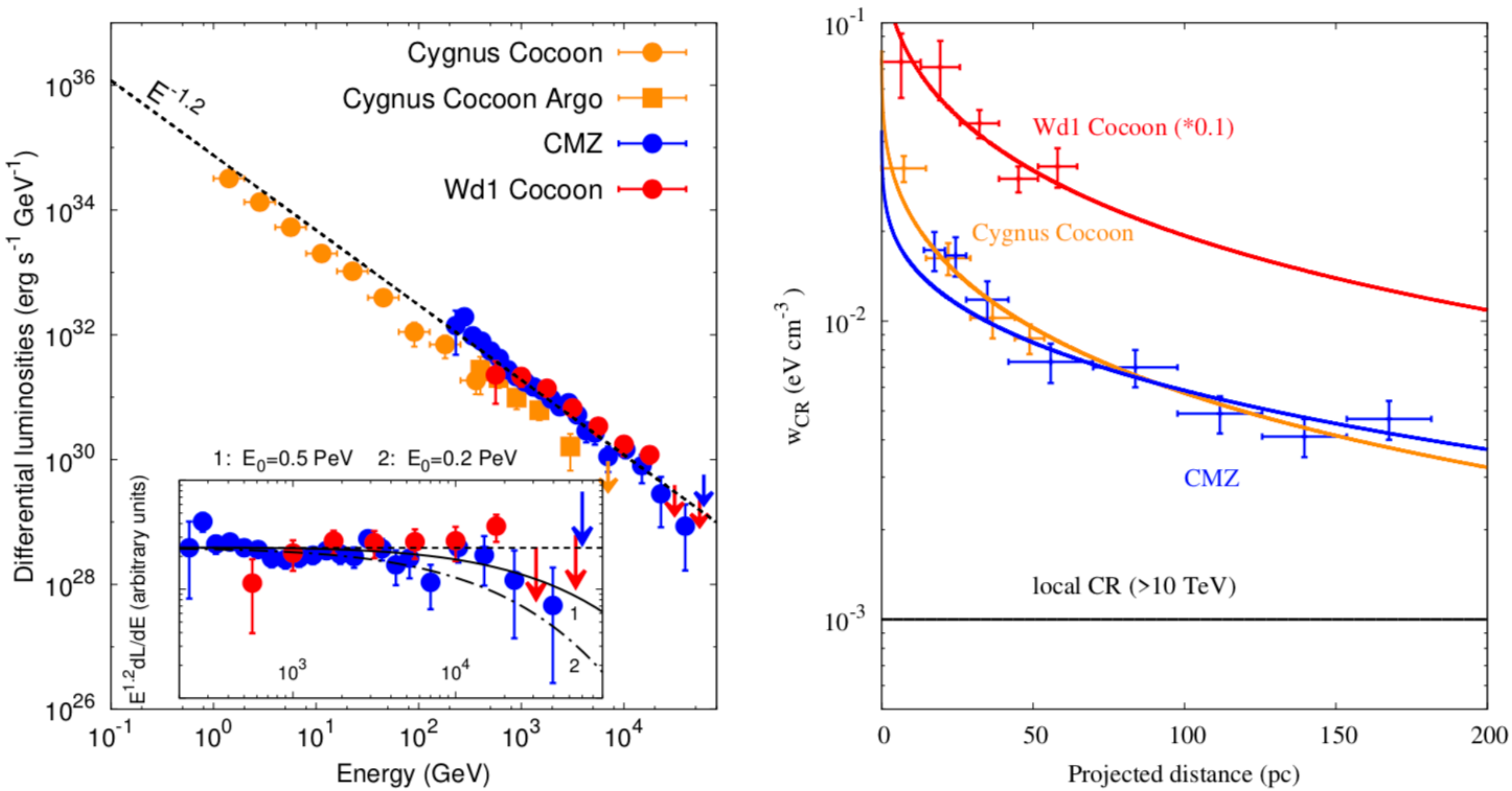


Figure 1: Gamma-ray luminosities and CR proton radial distributions in extended regions around the star clusters Cyg OB2 (Cygnus Cocoon) and Westerlund 1 (Wd 1 Cocoon), as well as in the Central Molecular Zone (CMZ) of the Galactic Centre assuming that CMZ is powered by CRs accelerated in *Arches*, *Quintuplet*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

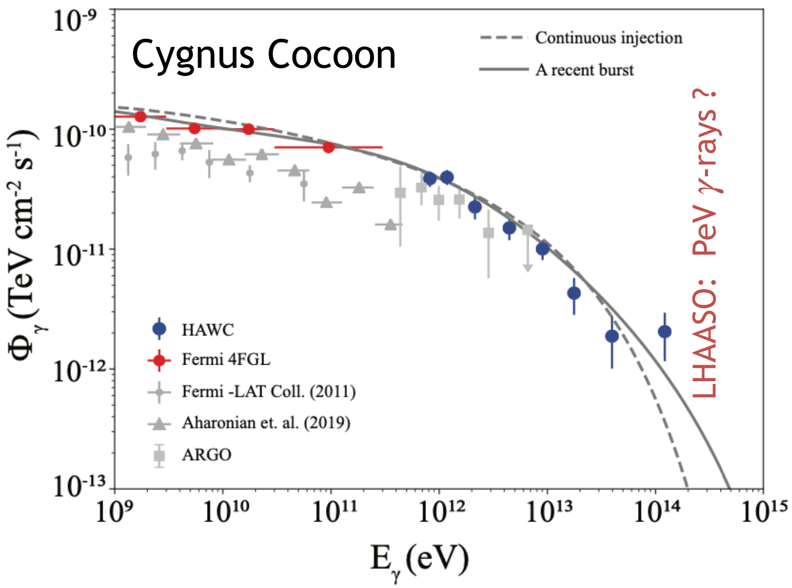
FA, Yang, Ona de Wilhelmi, 2018

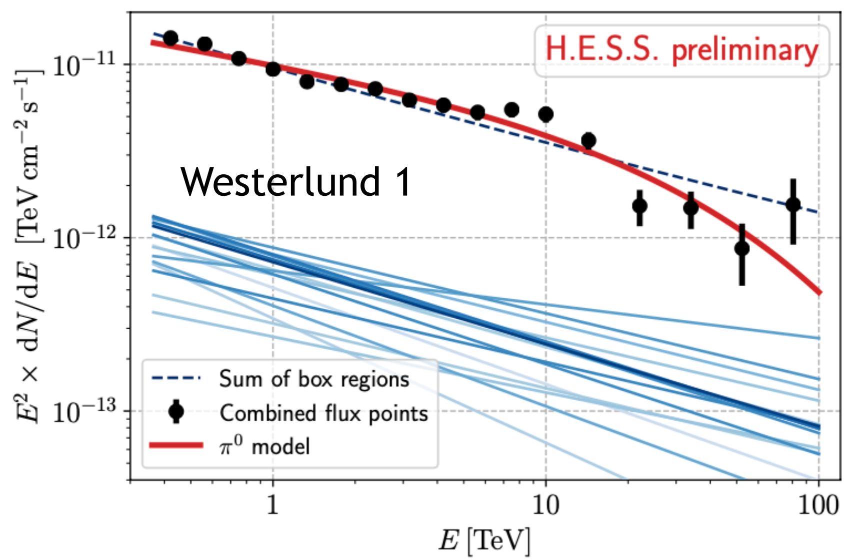
Extended Regions surrounding Clusters of Young Massive Stars are sources sources of GeV, TeV and … PeV gamma-rays!

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

- γ-ray morphology

Total energy in CRs within the size of radius Ro

$$W_{\rm p} = 4\pi \int_0^{R_0} w(r) r^2 \, {\rm d}r \approx 2.7 \times 10^{47} (w_0/1 \ {\rm eV/cm^3}) ({\rm R_0}/10 \ {\rm pc})^2 \ {\rm erg}$$

Size of emission region - depends on D and To

$$R_{\rm D} = 2\sqrt{T_0 D(E)} \approx 3.6 \times 10^3 (D_{30} T_6)^{1/2} \ \ {\rm pc}$$

Efficiency of conversion of the wind kinetic energy to CRs

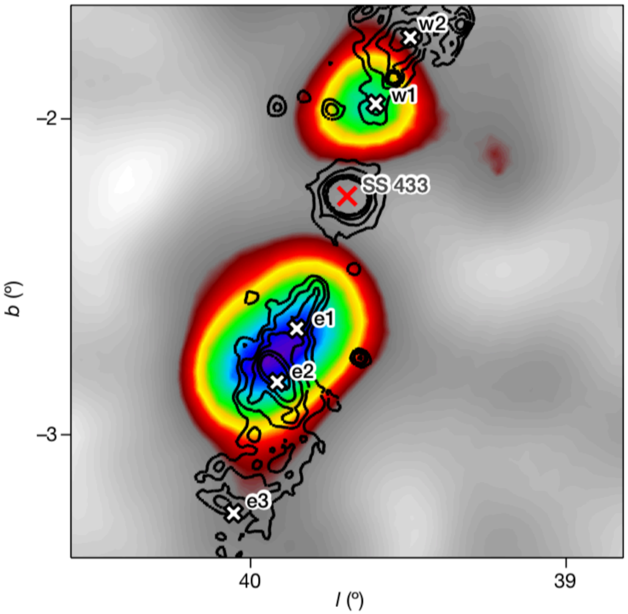
$$f(\geq 10 \ {\rm TeV}) \approx 1 w_0 D_{30} L_{39}^{-1}$$

For $E^{-2.3}$ proton spectrum, f(>10TeV) does not significantly exceed 1%
the diffusion coefficient D_{30} cannot be larger than 0.01; $R_D \sim 300$ pc

CTA - unique measurements of D and consequently f

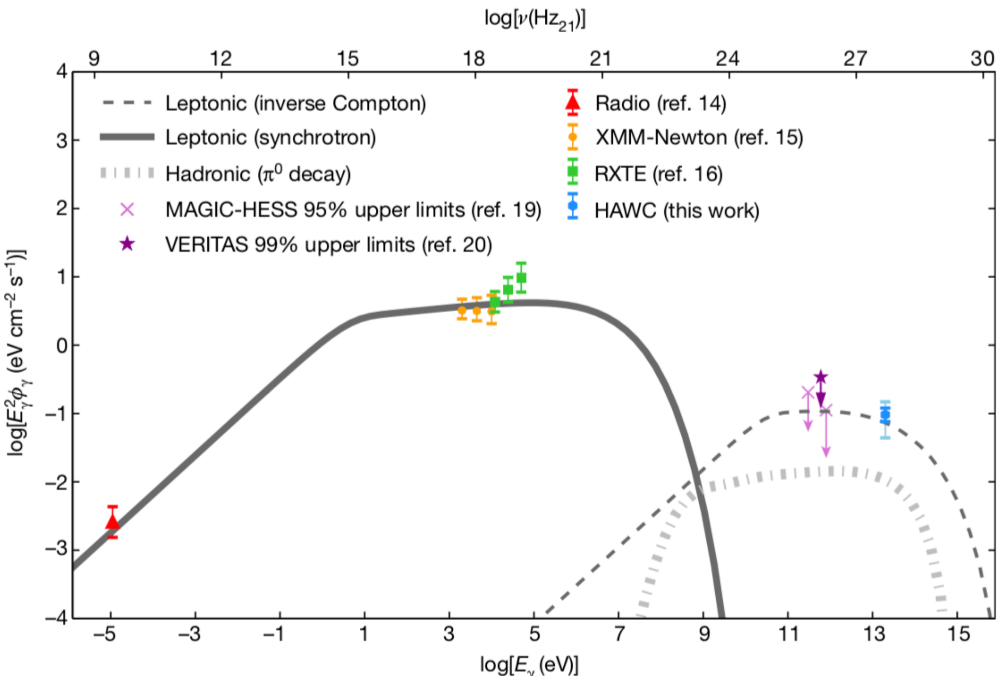
Other Pevatron candidates

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



- E^{-2} electron spectrum with Eo=2 PeV
- gas density - not sufficient?

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

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 should exist in the Milky Way

Supper-Bubbles ?

SNRs ? ?

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

Binary systems, Microquasars - ?

SMBH in the Galactic Center: $E = eBR \simeq 100(B/10\,\mathrm{kG})\,(M/3\times 10^6 M_\odot)$ PeV

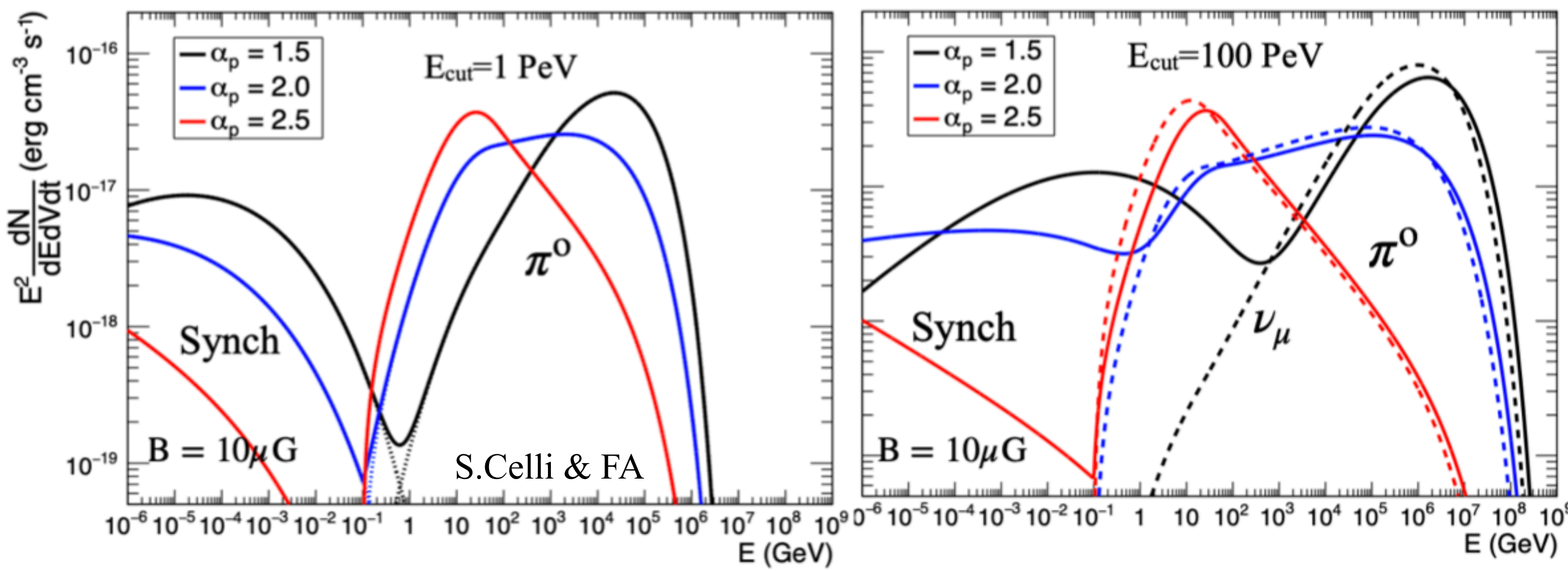
LHAASO and eROSITA

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!



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 !

electron PeVatrons

Detection of > 1 PeV photons from Crab by LHAASO

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

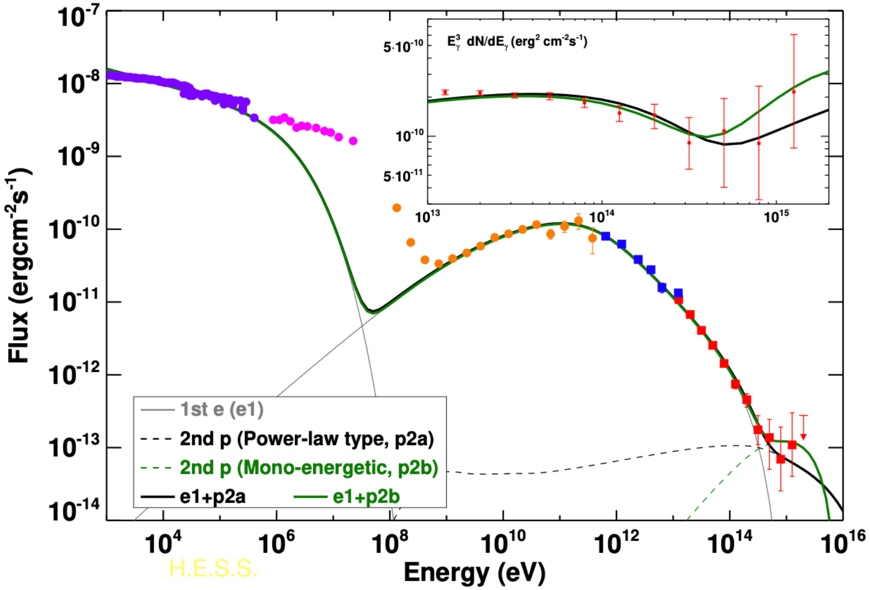
$E_\gamma = 1.1\,\mathrm{PeV} \rightarrow E_e \simeq 2.5\,\mathrm{PeV}$

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

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

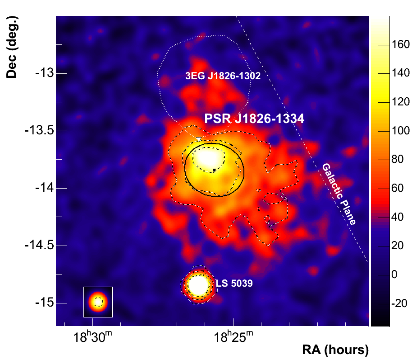
$E_\gamma \geq 1.1\,\mathrm{PeV} \rightarrow \eta \geq 0.16$

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 gamma-rays of hadronic origin?



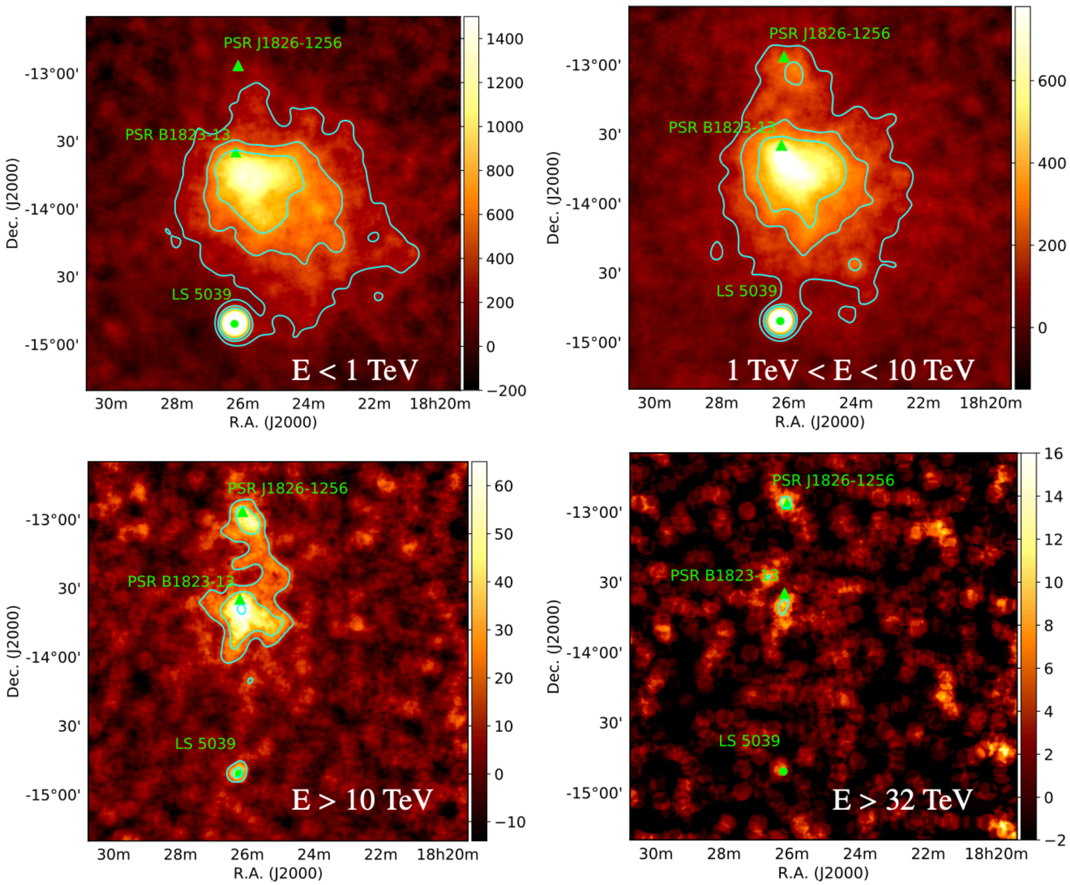
Crab Nebula: **effective electron accelerator** but **not effective γ-ray emitter**:

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

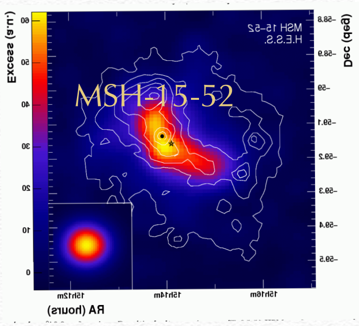
HESS collaboration 2019

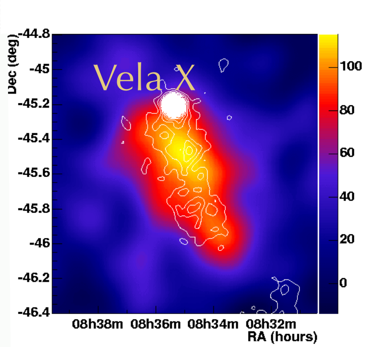


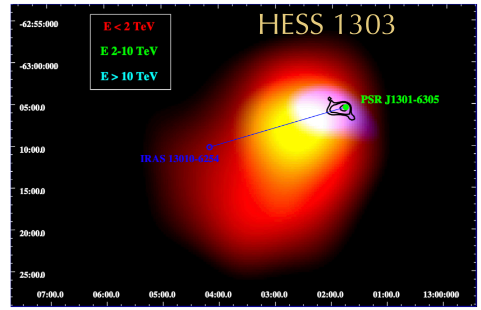
future measurements - morphology+spectrum up to 100 TeV and beyond

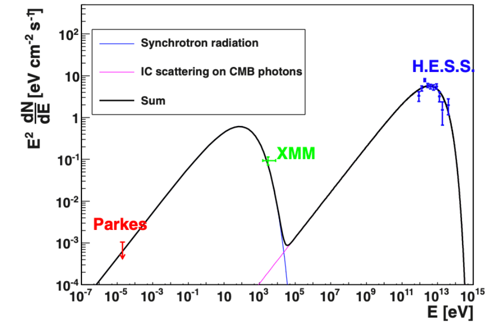
extended TeV structures around pulsars:

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

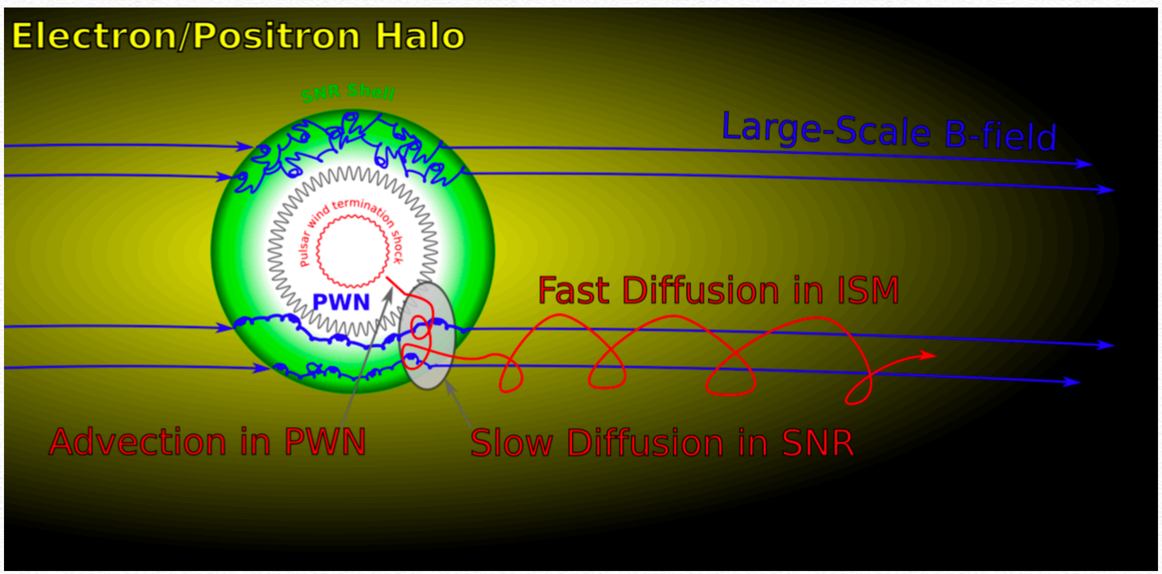








Energy dependent morphology
very low B-field $B \sim 1.4\mu G$



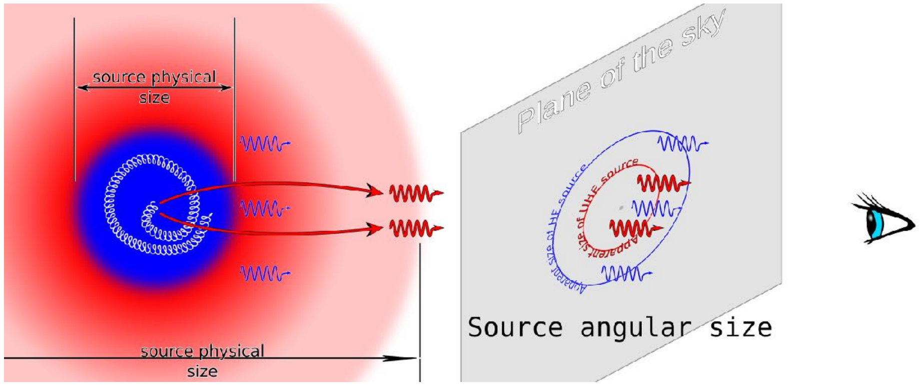
PWNe - MHD structure

PHs - diffusively expanding cloud of electrons

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

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



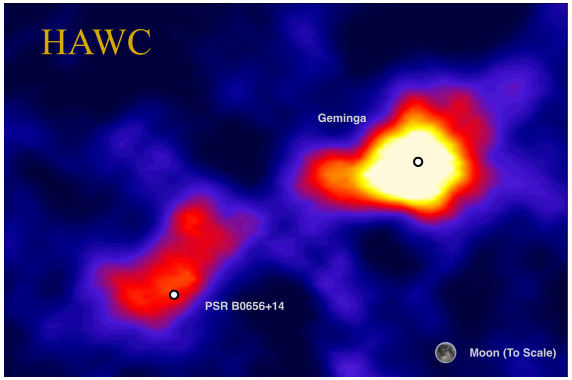
physical size versus apparent angular size of the γ-ray image

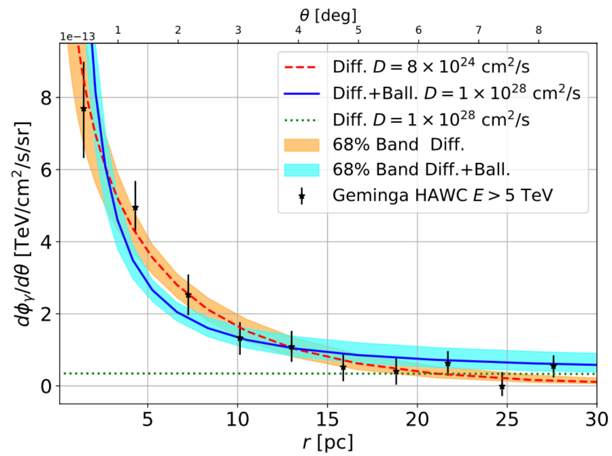
in diffusive-to-ballistic transition regime of propagation of parent charged particles the apparent angular size of radiation *decreases* (!) with energy; at highest energies corresponding to ballistically moving protons/electrons, the source becomes point-like

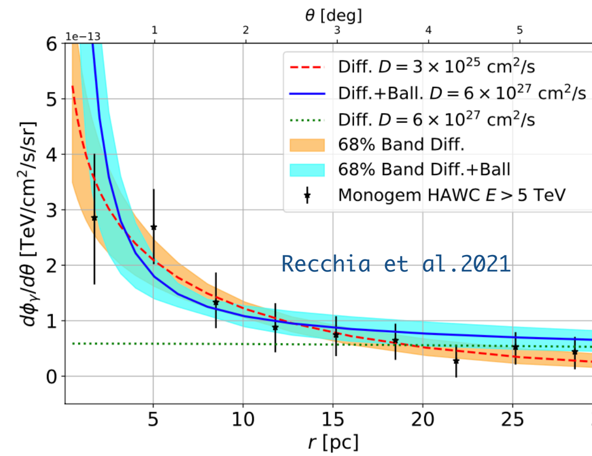
unique opportunity to localise the PeVatron and measure the (undistorted) acceleration spectrum

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

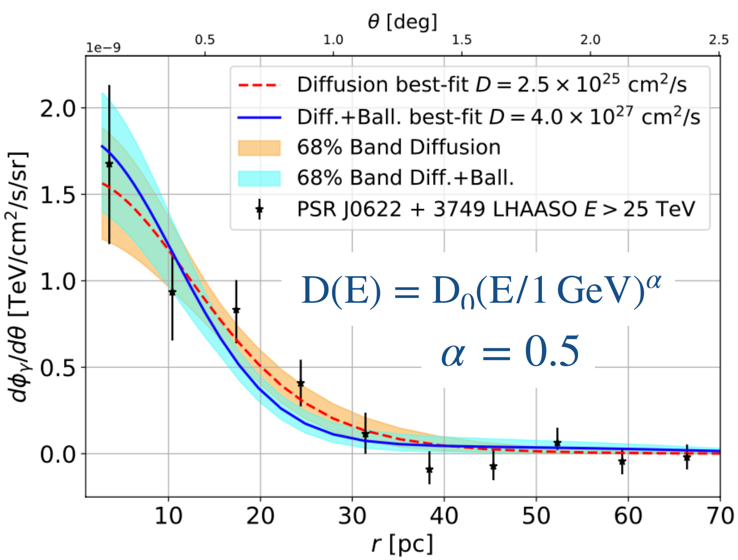
extended gamma-ray emission from the direction of two nearby pulsars







gamma-ray profiles require (i) very slow or (ii) "standard" (as in ISM) diffusion taking into account the effect o f (quasi) ballistic motion at the initial stage of propagation



$D(E) = D_0(E/1\,\mathrm{GeV})^{\alpha}$

$\alpha = 0.5$

Chalenges:

(i) small diffusion coefficient versus $D_{ISM} \approx 10^{28}\ \mathrm{cm^2/s}$

(ii) efficiency, $f = \dot{W}_e/L_{rot} > 1$?

f, slow/fast %

	$\dot{E}$ [erg/s]	T [kyr]	l [kpc]	τ_0 [kyr]	n	f, slow/fast %
Geminga	3.25×10^{34}	342	0.19	12.0	3	3-5/180-200
Monogem	3.8×10^{34}	111	0.288	12.0	3	2-6/60-100
PSR J0622+3749	2.7×10^{34}	208	1.6	12.0	3	6-10/40-100
Injection Spectrum	spectral index			E_c		
	1.5			150 TeV		

enhancement of the turbulence on scales of up to ~100 pc ?
efficiency close to ~50% is more realistic than ~5 % ?

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

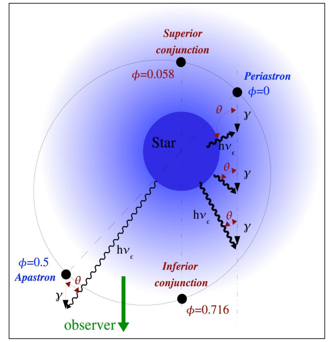
(characteristic timescales 1 h or shorter !)

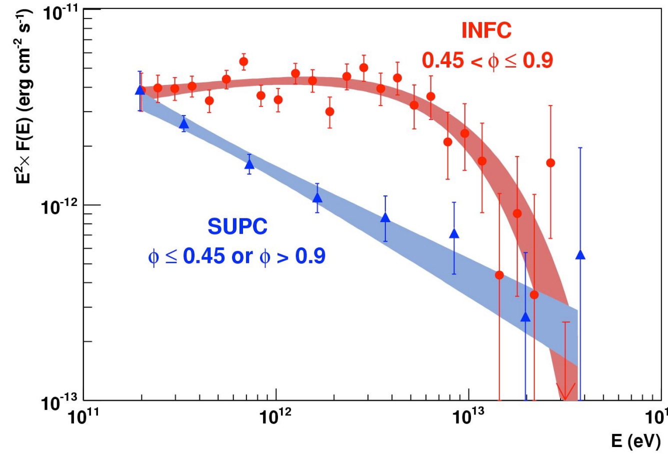
the target photon field is function of time, thus the only unknown parameter is B-field => predictable gamma-ray emission?

LS 5039

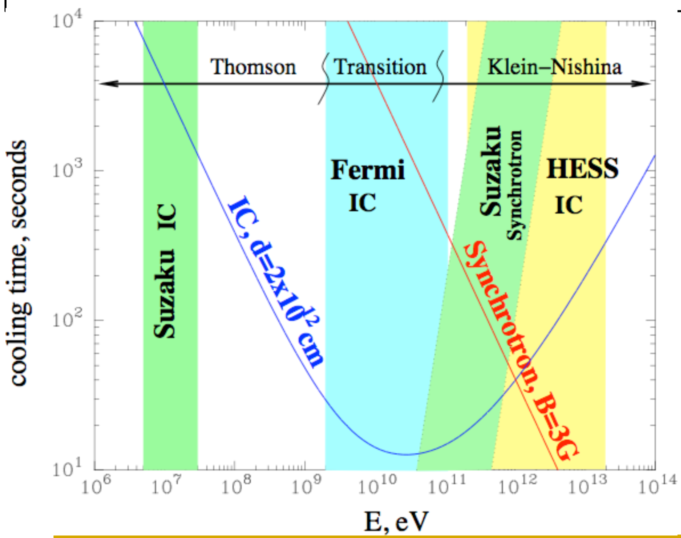
works as a perfect TeV clock
and an extreme accelerator

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, it is clear that this binary system works as an extreme accelerator

Future measurements - timing and spectrum up to and beyond 10 TeV

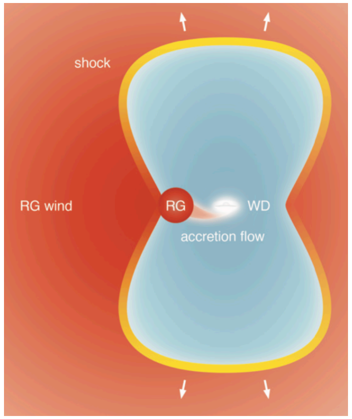
new!

watching particle acceleration in "online regime"

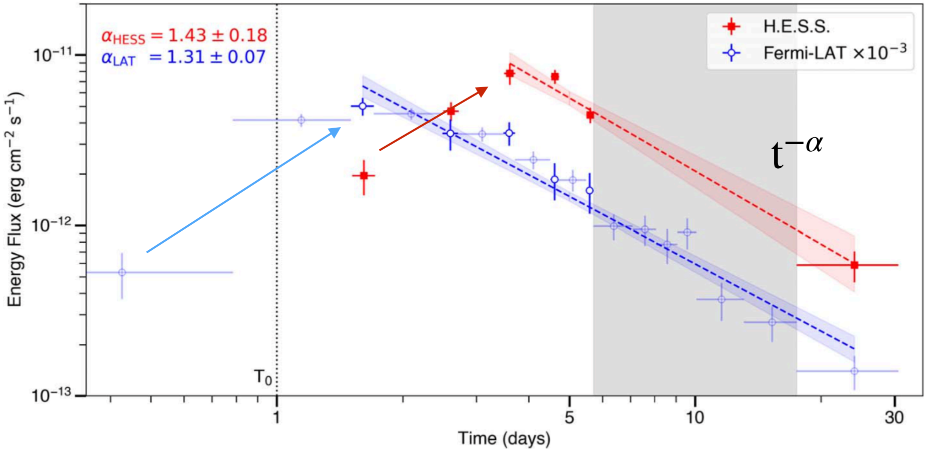
RS Ophiuchi : recurrent nova in the constellation Ophiuchus - binary system: White Dwarf (**WD**) and Red Giant (**RG**); eruptions in 1898, 1933, 1958, 1967, 1985, 2006 and 2021

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

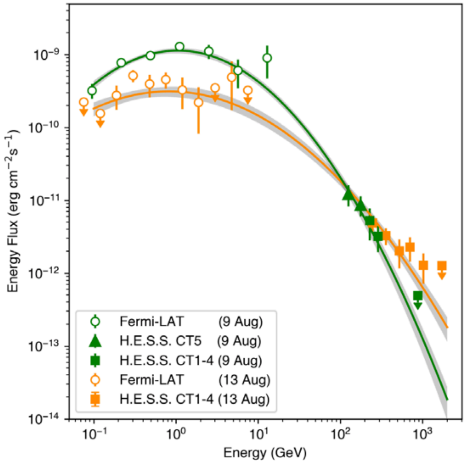
1.48 AU separation of starts - close enough for WD to continually accrete material from RG to trigger recurrent thermonuclear explosions and drive shock (v~ 5000 km/s) into RG's wind



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

Highest Energy Cosmic Rays

Extragalactic Sources and Highest Energy Cosmic Rays

potential sites of 10^{20} eV cosmic rays based on the condition:
source size > Larmor radious: $(R/1pc)(B/1G) > 0.1\ (E/10^{20}eV)$:

necessary but not sufficient; it implies:

(1) minimum acceleration time $t_{acc}=R_L/c=E/eBc$

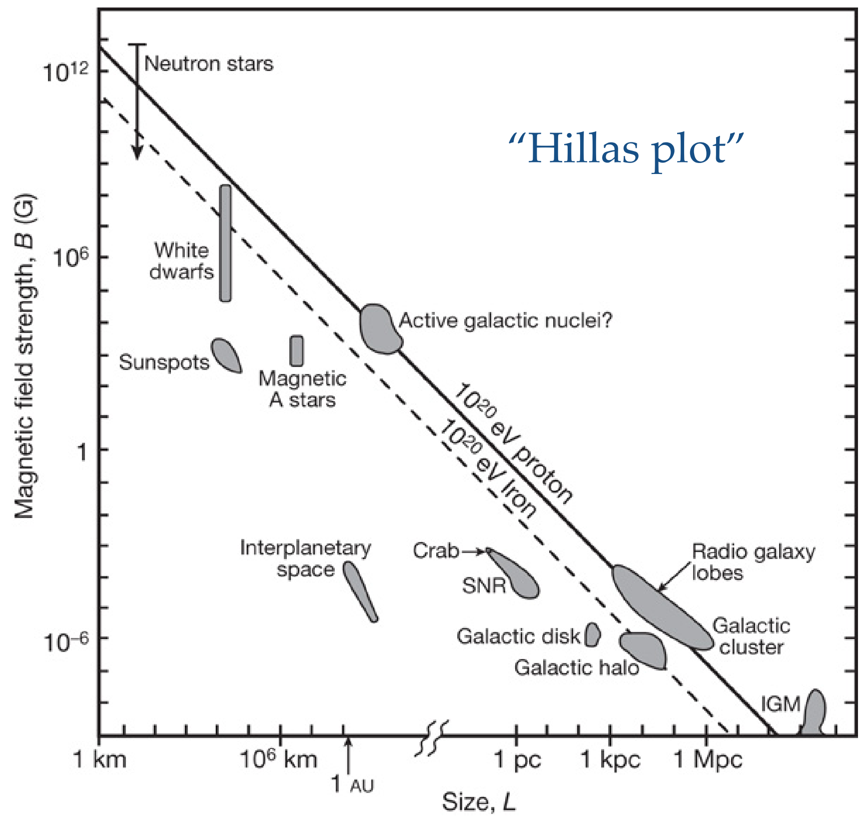
acceleration in fact is slower:

$t_{acc}=(1\text{-}10)\eta\ R_L/c\ (c/v)^2$

with $\eta>1$ and shock/bulk-motion speed $v<c$ ($\eta=1$ - Bohm diffusion)

(2) no energy losses

synchrotron/curvature losses in compact objects become severe limiting factor



PM Bauleo & JR Martino Nature 458, 847-851 (2009

acceleration sites of 10^{20} eV CRs ?

$$t_{\rm acc} = \frac{R_L}{c}\eta^{-1}$$

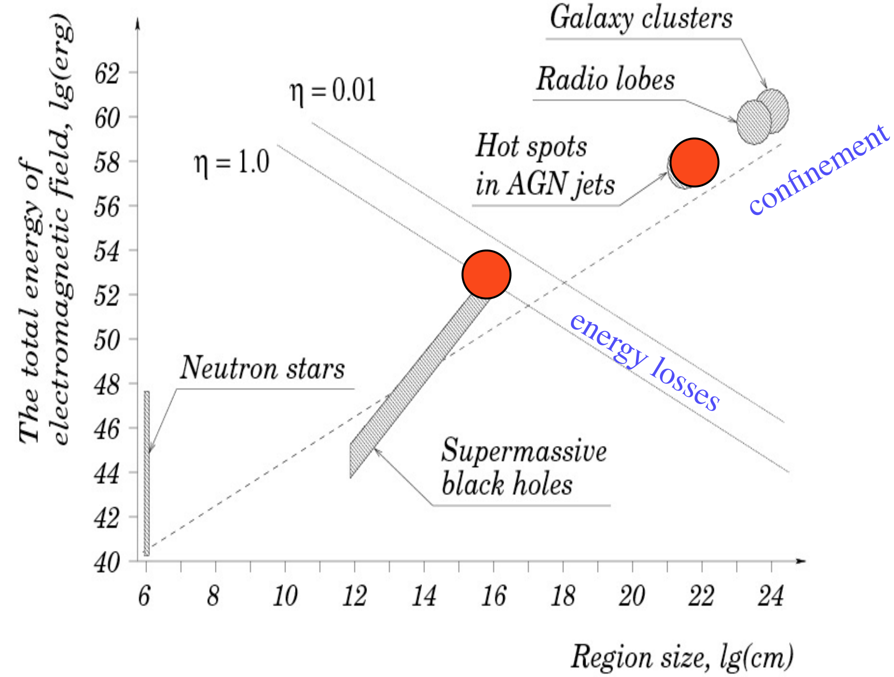
signatures of extreme accelerators?

✓ synchrotron self-regulated cutoff:

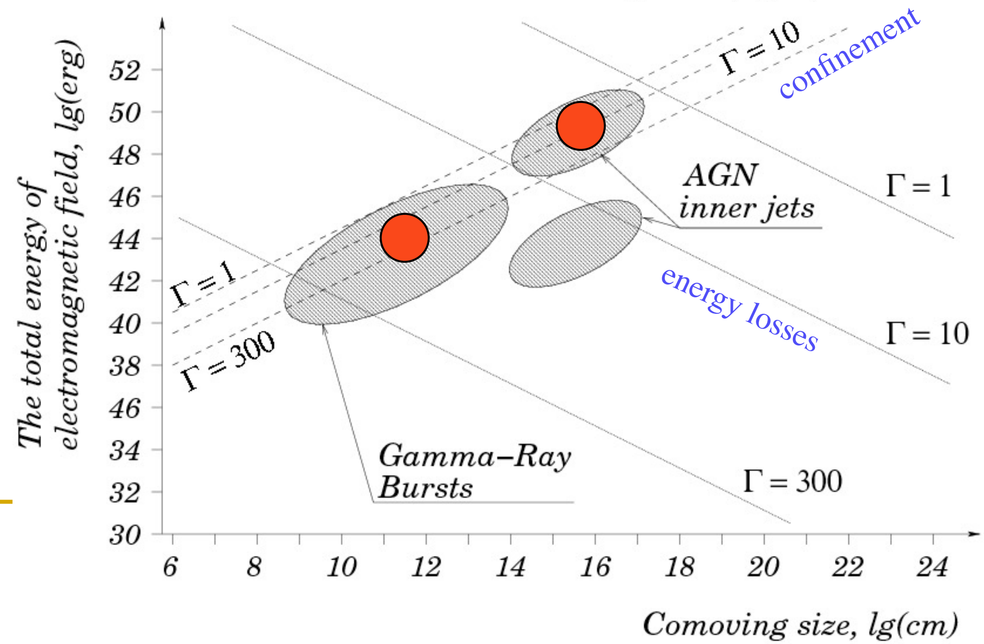
$$h\nu_{\rm cut} = \frac{9}{4}\alpha_f^{-1} mc^2 \eta :$$

$\simeq$ 300GeV proton synchrotron
$\simeq$ 150MeV electron synchrotron

a viable "hadronic" model applicable for TeV γ-ray blazars if B ~ 100 G or so



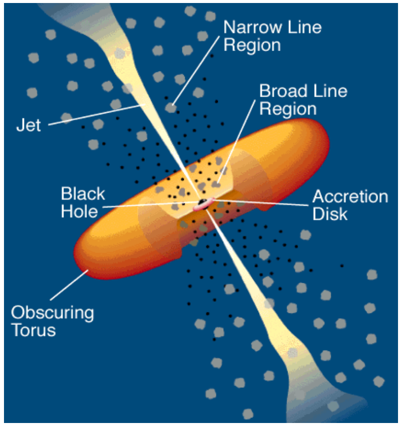
✓ neutrinos (through "converter" mechanism) production of neutrons (through pγ interactions) which travel without losses and at large distances convert again to protons => Γ^2 energy gain! (Deerishev et al. 2003)



✓ observable off-axis radiation
radiation pattern can be much broader than $1/\Gamma$

*) in nonrelativistic shocks $\eta \approx 0.1(v_{\rm shock}/c)^2$

Blazars - sub-class of AGN dominated by nonthermal/variable broad band (from R to γ) radiation produced in relativistic jets close to the line of sight, with massive Black Holes as central engines



GeV/TeV gamma-ray observations

strong impact on

- Blazar physics and astrophysics
- Diffuse Extragalactic Background (EBL) Intergalactic Magnetic fields (IGMF)

most exciting results of recent years

- ultra short time variability (on min scales)
- Jet power exceeds Eddington luminosity
- extremely hard (harder than E-1.5) energy spectra
- VHE blazars up to z~1!

"leptonic" versus "hadronic" models of TeV Blazars

leptonic (Inverse Compton) models: SSC or external IC

attractive: easy to accelerate electrons to TeV energies; easy to produce IC γ-rays

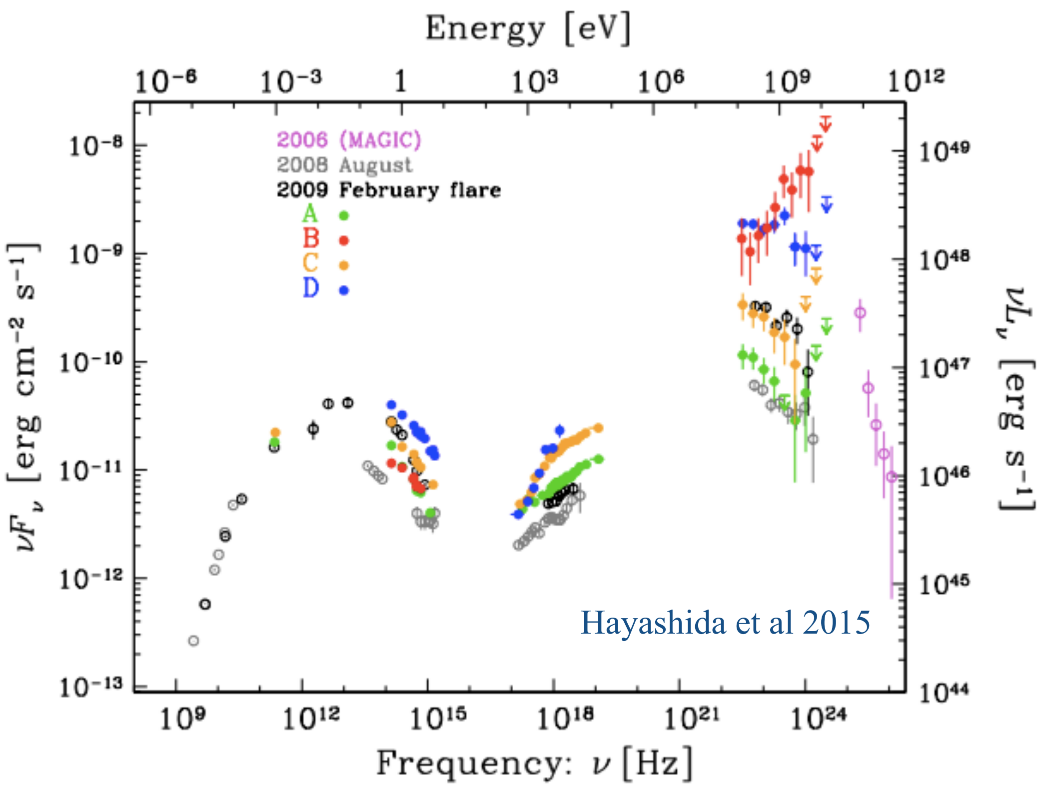
problems: B-field very small - 1-10 mG (in the inner parts of the jet): $W_e >> W_B$

hadronic models

- interactions with matter ("pp") - *very slow process*
- interactions with photons ("pγ") - *low efficiency & severe γγ absorption*
- interactions with B-field (synchrotron) - (very?) large B-field, $W_B >> W_p$

  & max. acceleration rate ~ R_L/c

can be realized only in the extreme accelerators (sources of 10^{20}eV CRs)



2013-14 flares of 3C 273:

Δt ~ less than 1 hour
Lapp ~ 10^{49} erg/s
unusually hard spectra

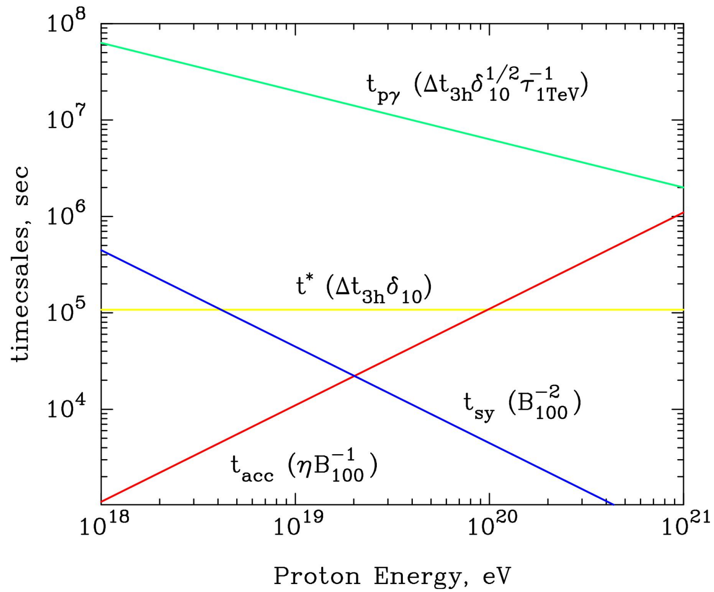
"leptonic versus hadronic" - of course it's important to clarify

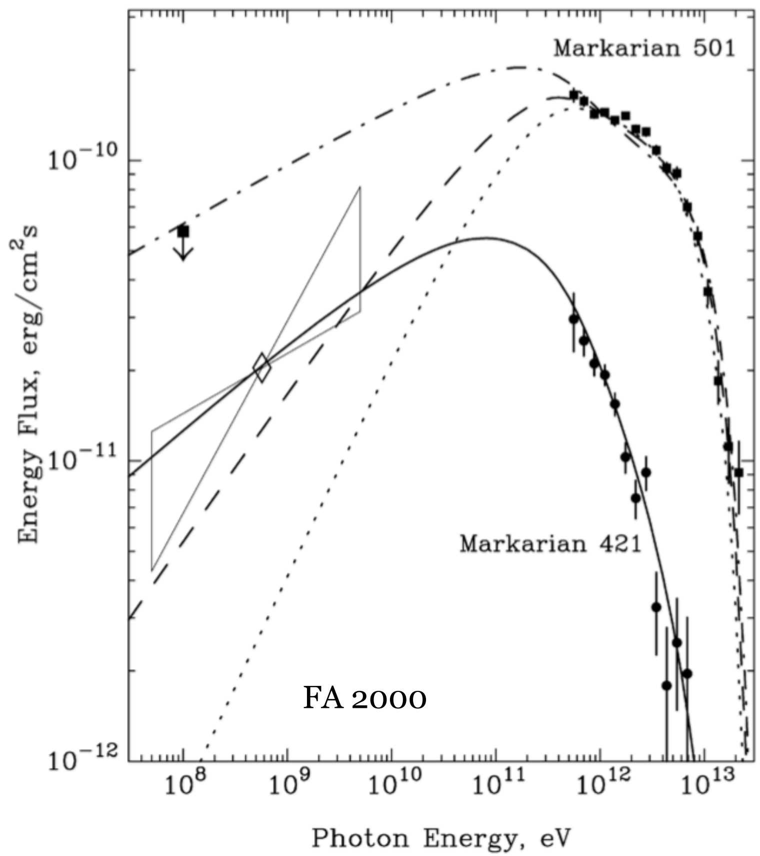
but now we face more serious challenges (for all models):

1. ultrafast variability ~ Rg/c

2. jet power > Eddington luminosity

Synchrotron radiation of an extreme proton accelerator





E_{cut}=90 (B/100G)(Ep/10^{19} eV)^2 GeV

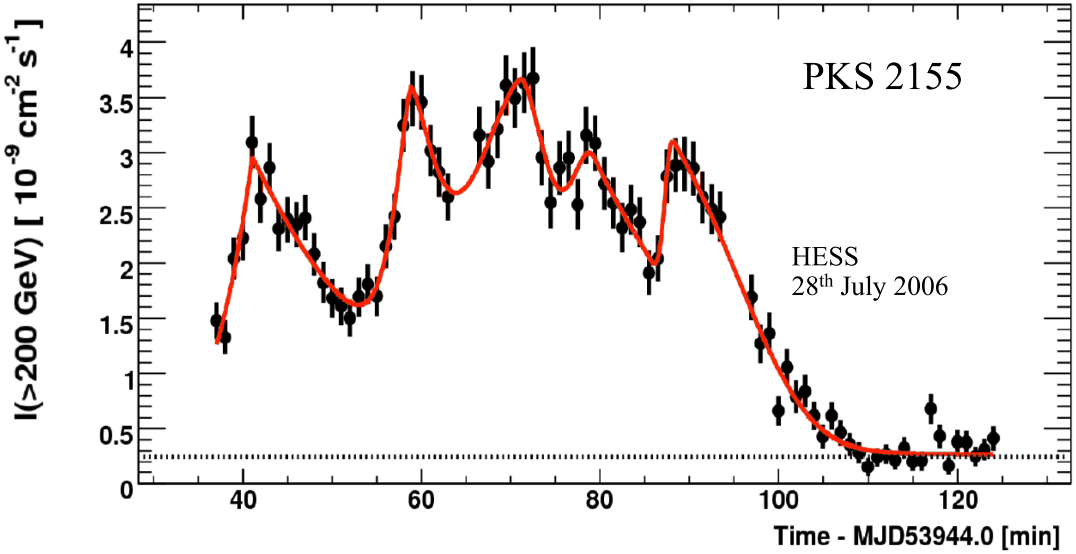
t_{synch}=4.5x10^4(B/100G) $^{-2}$ (E/10^{19} eV)$^{-1}$ s

t_{acc}=1.1x10^4 (E/10^{19}) (B/100G) $^{-1}$ s

cooling time of pγ interactions >> synchrotron cooling time => negligible neutrons flux

Light curve of PKS 2155-304 during 2006 July flare

variability timescale $\Delta t \sim$ 3 min: L< $c\Delta t \sim 6\ 10^{12}$ cm!



it is convenient to express the variability through

$$\Delta t = R_g/c \sim 10\ (M/10^8 M_o)\ \text{min}$$

$R_g = GM_{BH}/c2 = 1.5\ 10^{13} M_8$ cm is gravitation radius of Kerr BH

how the ultrafast ("sub-horizon") flares can be explained?

1. γ-rays are produced in (parts of) BH magnetospheres?

   perhaps in M87, but certainly not for distant blazers

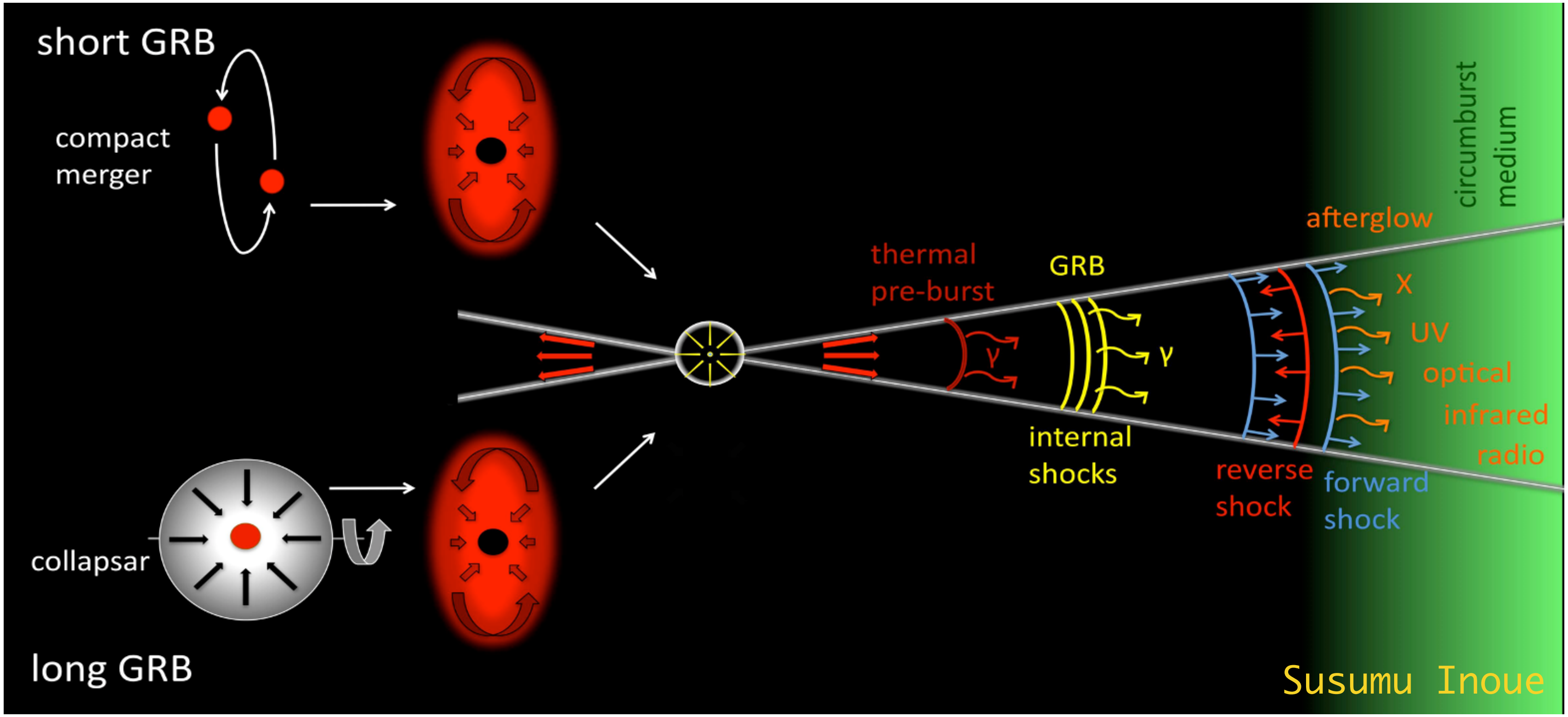
2. obviously one needs yo invoke relativistic effects, and the perturbations in the jets responsible for flares should have external origin (not directly linked to central black hole)

   two possibilities are under discussion:

   - "jet in jet"

   - "star - jet interactions"

Detection of Short and long GRBs and their afterglows



GRBs - mini "Big Bangs" allowing studies of most powerful relativistic phenomena in the "online" regime

uniqueness:

disadvantage - solitary events (no chance to repeat the "experiment"), this is compensated, to some extent, by the large GRB statistics

advantage - no pollution from the past (related) activities => "pure experiment"

Similarity with other objects/phenomena

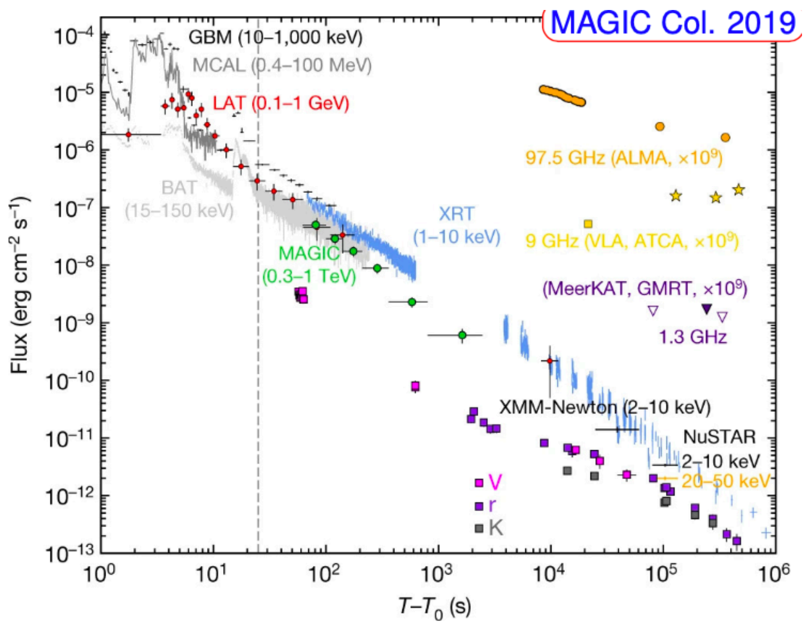
AGN flares - most spectacular in (very) high-energy γ-rays

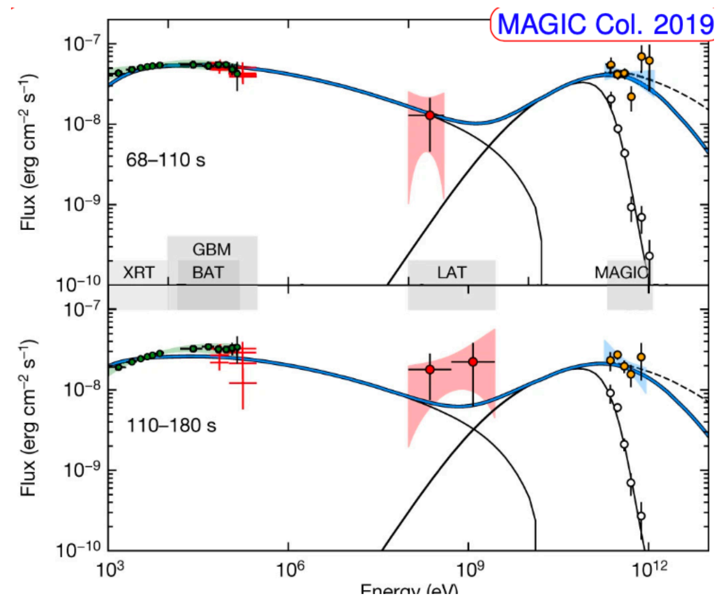
time-scales: $\Delta t \sim R_g/c \sim 10^{-5}(M/M_\odot)\ \delta^{-1}$ sec

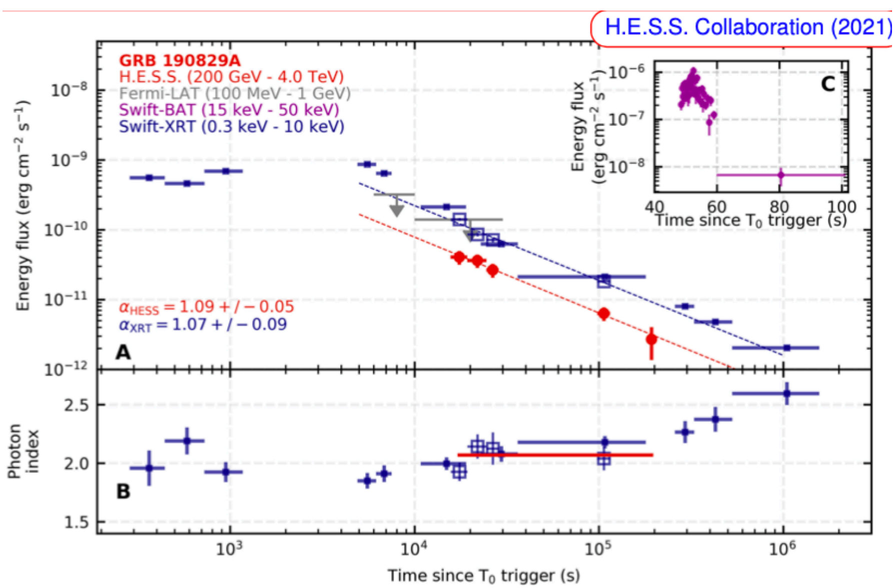
Crab (synchrotron) flares

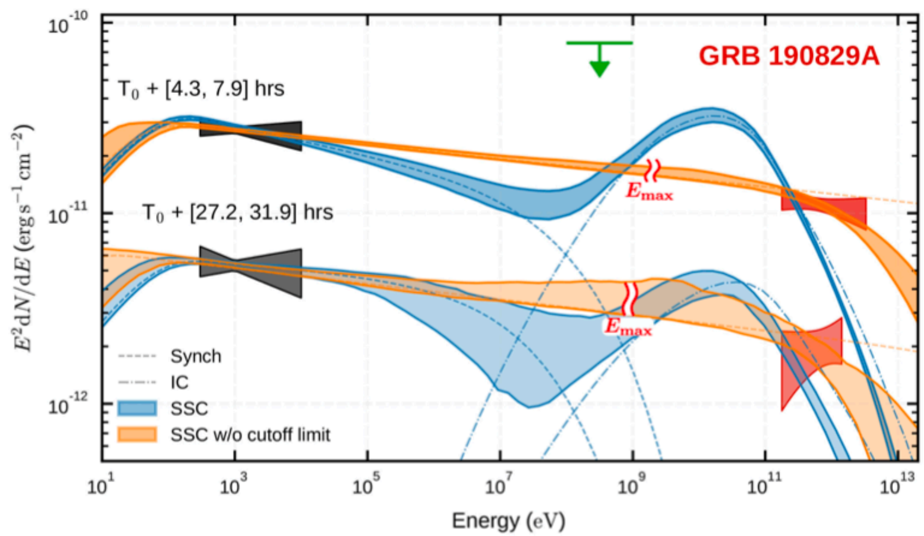
ground-based γ-ray detectors - "very fast" tools to explore the transient/eruptive phenomena on shortest time scales !

Detecting GRB afterglows - finally!









- On the potential and prospects of ground-based gamma-ray detectors for exploration of GRBs and their afterglows

CTA/ASTRI, LHAASO/WCDA and SWGO, very low threshold (GeV) IACTs

- multi-wavelength and multi-messenger aspects of GRB studies

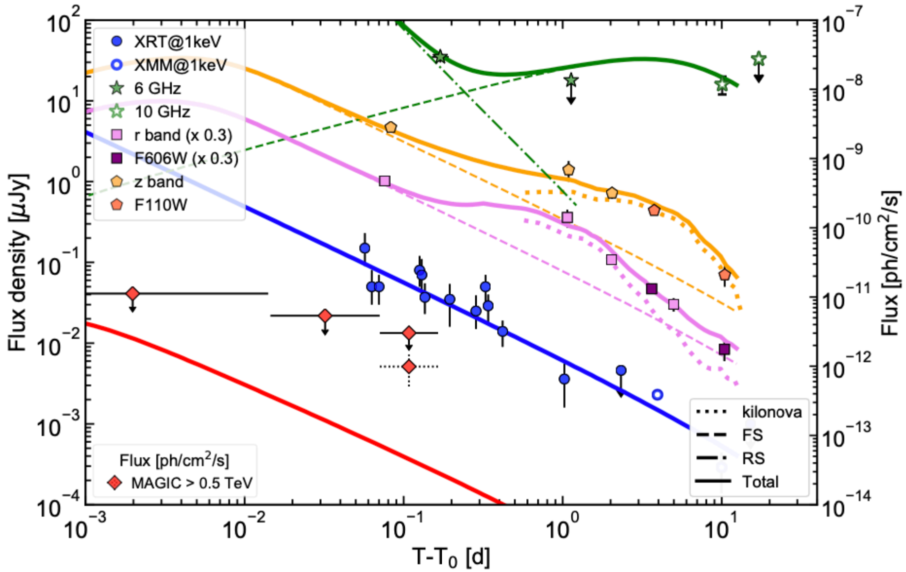
detection perspectives with arrival of CTA and low-threshold WCDs:

afterglows - dramatic increase of the chance of detection by CTA detection > 1 week (s);
much better spectrometry including the Synch-IC transition region

prompt ? possible but difficult with CTA
WCDA ? if spectrum extends to >100 GeV and flux exceeds $\geq 10^{-7} \mathrm{erg/cm^2 s}$

short GRB afterglow at VHE energies?

Acciari et al. 2021 (MAGIC collaboration)



GRB 160821B: ~0.5 sec GRB => classified as a short GRB
MWL observations => a kilo nova component
=> BNS merger - short GRB

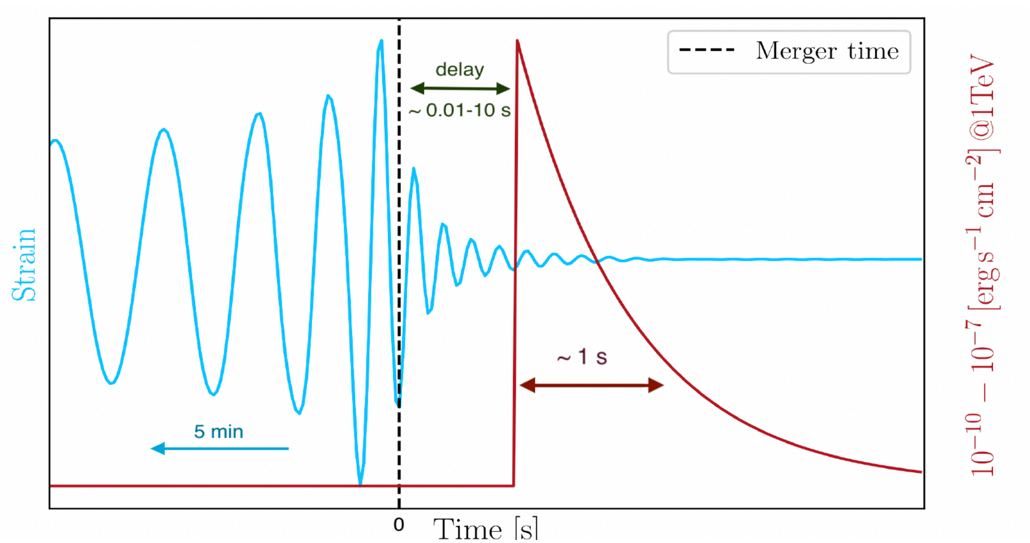
No difference between long and short GRB afterglows as long as it concerns particle acceleration and radiation?

If so, simultaneous detections of GW events and short GRB afterglows by CTA and WCDA => important contribution towards understanding the link between BNS mergers and GRBs

Detecting prompt emission of short GRBs with gamma-rays?

Fermi LAT - FoV is OK but too small detection area
WCDA-LHAASO, SWGO - FoV is OK but sensitivity and high energy threshold
CTA - adequate sensitivity, low energy threshold, but small FoV

Solution? Coordinated studies by CTA and third generation of GW detectors - Einstein Telescope (ET) and Cosmic Explorer (CE)



The Idea: ET can localise GW events in the inspiral phase (before the BNS merger) and thus provide an early-warning (**minutes**) alert for upcoming short GRBs: ET can observe large fraction of GW events with a sky-localization **a few tens of square degrees** compatible with a sky area that CTA is able to promptly and deeply cover

GSSI GW-GRB team (courtesy of Gor Oganesyan)

would be great to have very-low threshold (a few GeV) IACTs at several locations

Summary:

Over the last two decades, we have seen two revolutions in gamma-ray astronomy with surprise discoveries of hundreds and thousands sources at GeV and TeV energies, respectively. The detailed study of these objects representing more than a dozen astronomical source populations contributed substantially to our knowledge about the most energetic and violent phenomena in the Universe. Presently we are witnessing a new revolution, this time at PeV energies. The recent results promise a breakthrough in a few areas, in particular towards the solution of the century-old mystery of the Origin of Cosmic Rays.