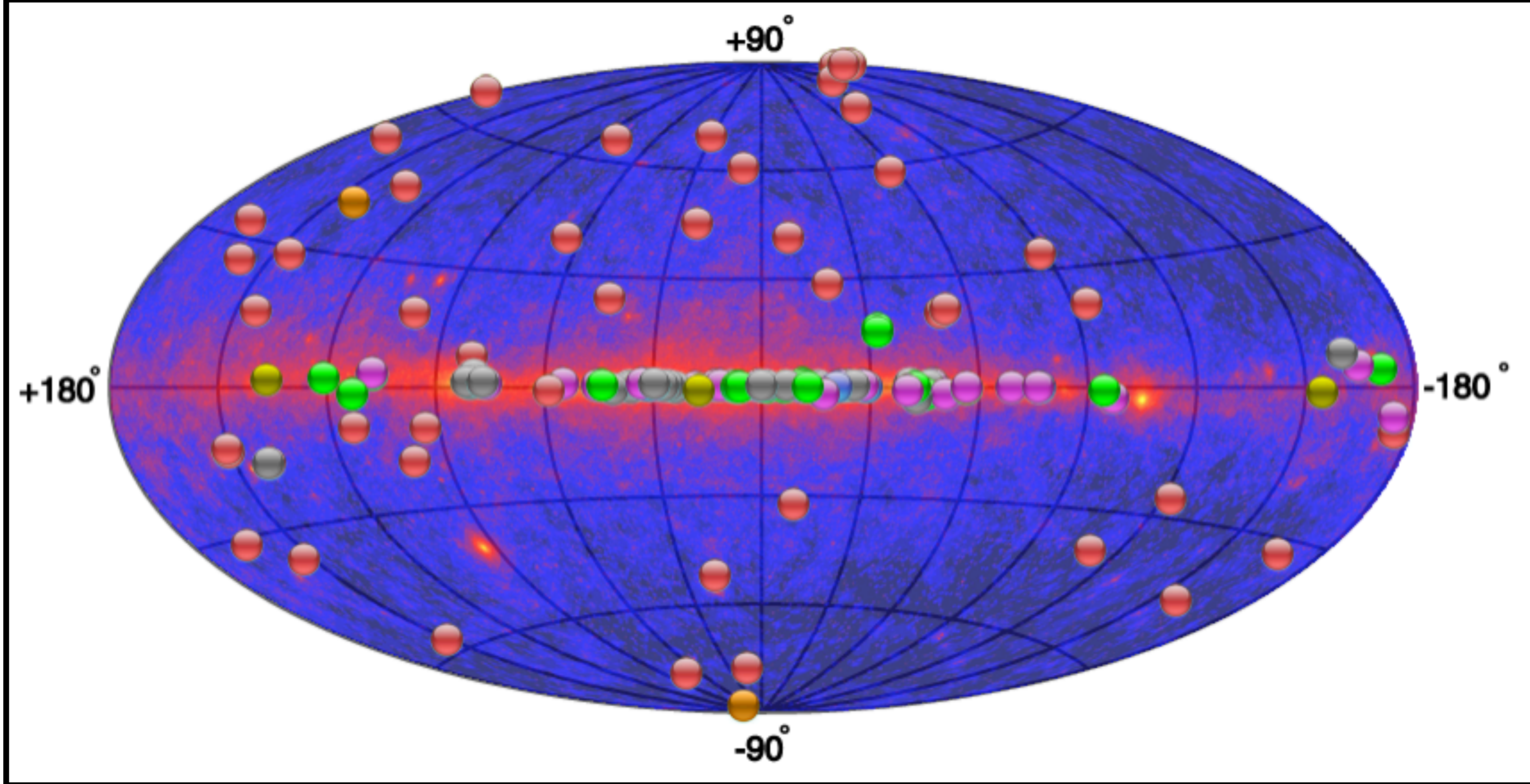
On the importance of morphological studies to reveal the cosmic ray accelerators

Felix Aharonian

Dublin Institute for Advanced Studies, Dublin, Ireland
Max-Planck Institut f. Kernphysik, Heidelberg, Germany

Rome, May 18, 2018

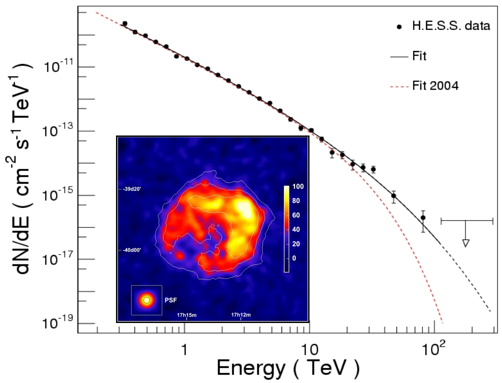
TeV Sky



blue-to-red colors – > 0.1 GeV – Fermi gamma-ray sky

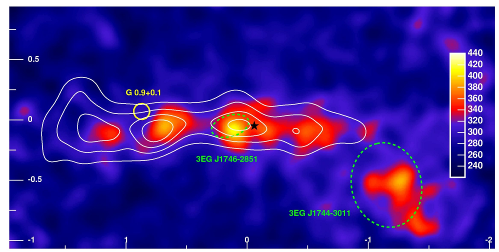
spectrometry, morphology, timing

RXJ 1713.7-3946



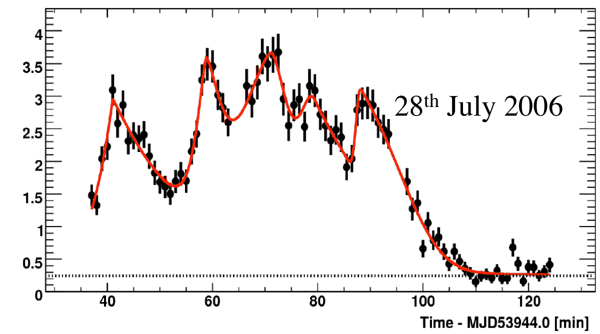
TeV image and energy spectrum of a SNR

Galactic Center



resolving GMCs in the Galactic Center 100pc region

PKS 2155-309



variability of TeV flux of a blazar on minute timescales

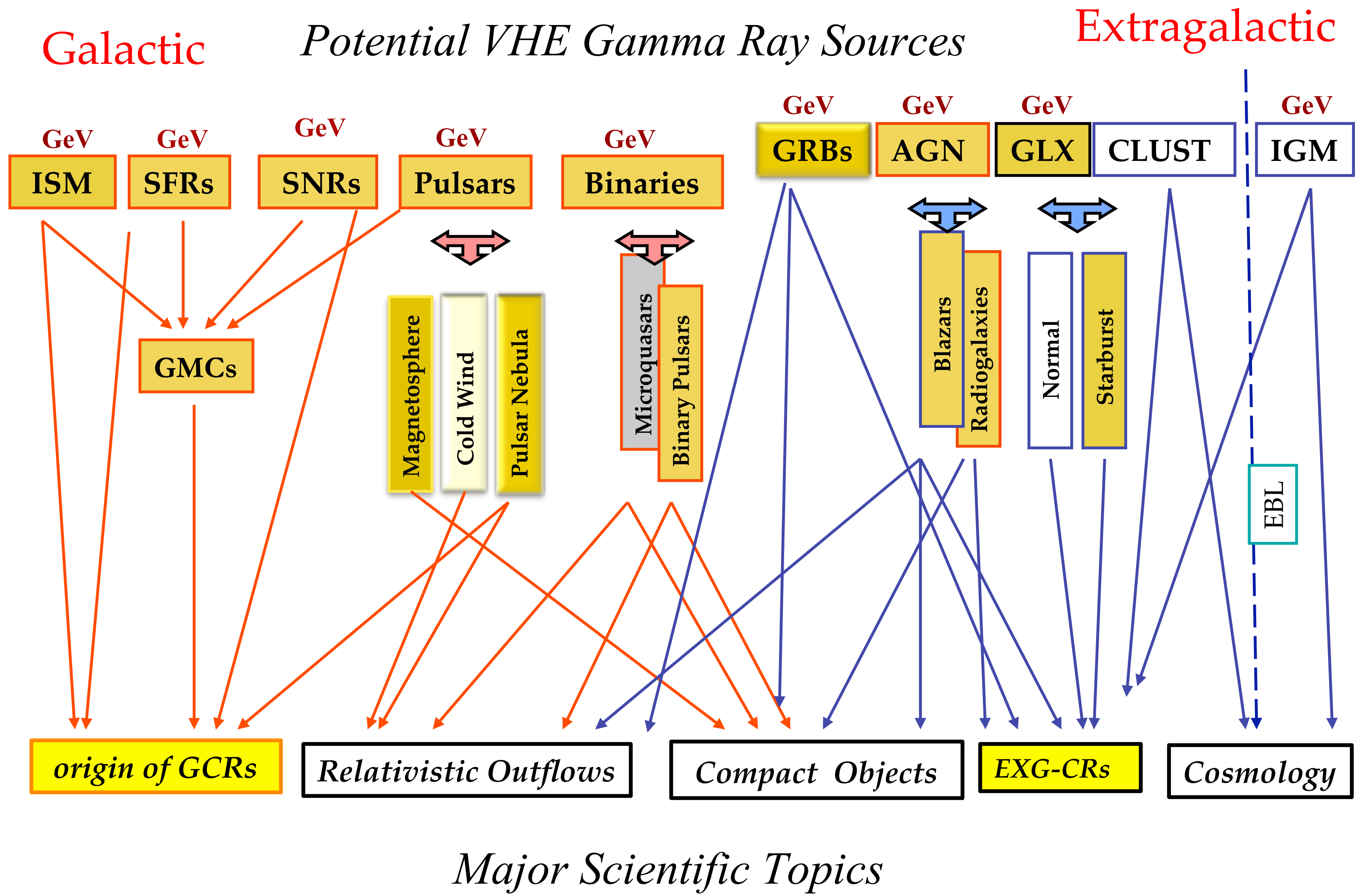
multi-functional tools: *spectrometry* *temporal studies* *morphology*

✓ extended sources: *from SNRs to Clusters of Galaxies*

✓ transient phenomena *μQSOs, AGN, GRBs, ...*

Galactic Astronomy | Extragalactic Astronomy | Observational Cosmology

many objects and objectives are related,
in one way or another, to origin of GCR



the strength and uniqueness

- unique for specific topics e.g. for the solution of
  Origin of Galactic and Extragalactic Cosmic Rays

- may provide key insight into a number of principal issues e.g.
  paradigm of *"Pulsar/Pulsar-Wind/Pulsar-Wind-Nebula"*
  physics and astrophysics of Supermassive Black Holes

- contribution to fundamental physics, e.g. *violation of Lorentz invariance,* search for *Dark Matter*, or exotic issues, like *Relativistic MHD* (e.g. in PWNe and AGN)

- established detection technique - *IACT arrays* - for adequate *spectrometry, morphology, timing, surveys*, with a clear plan (no saturation yet) for next steps (CTA and beyond) all particle cosmic ray spectrum

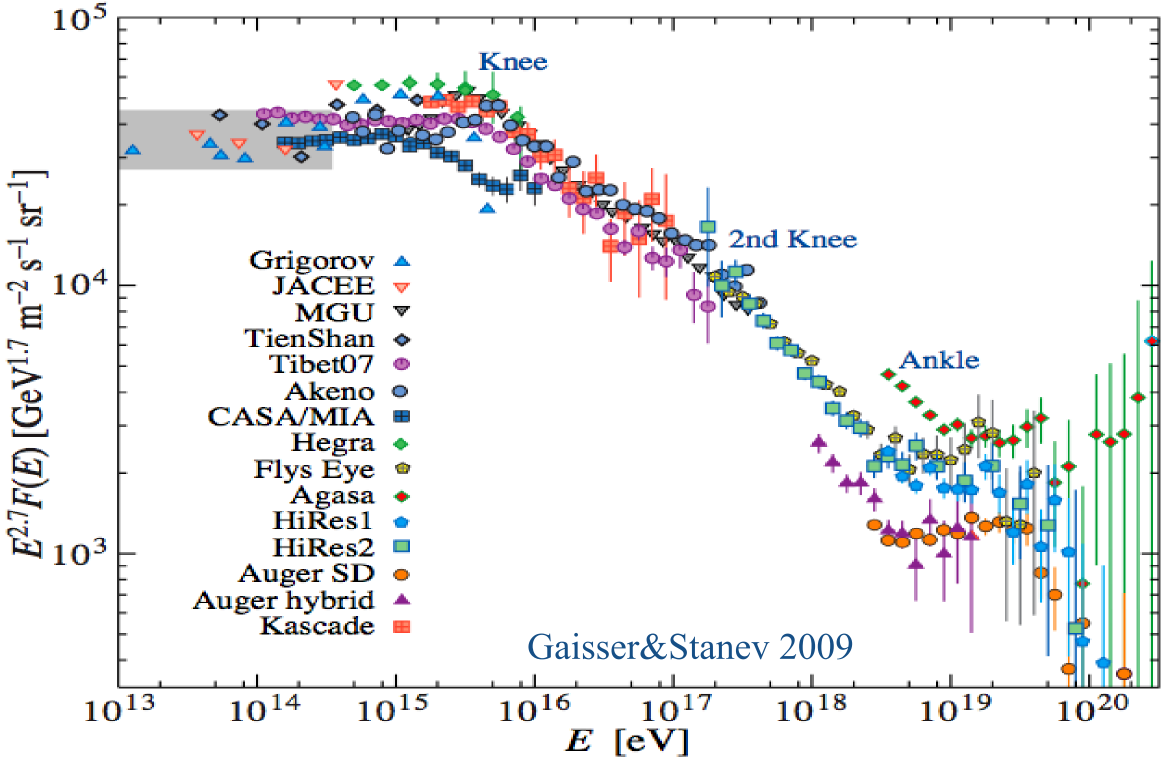


Figure 24.8: The all-particle spectrum from air shower measurements. The shaded area shows the range of the the direct cosmic ray spectrum measurements.

a standard (for many decades, statement)
"*origin of cosmic rays still is a mystery*"

Cosmic Ray Astrophysics with CRs?

a lot of information about the locally measured primary and secondary components of CRs but still no definite conclusions about the accelerators

it <u>is not</u> a big surprise that the origin of CRs is yet a mystery!

charged CRs do not provide information about the acceleration sites

CR factories can be revealed only by *astronomical means;*
the astronomical messengers should be *neutral & stable*:*

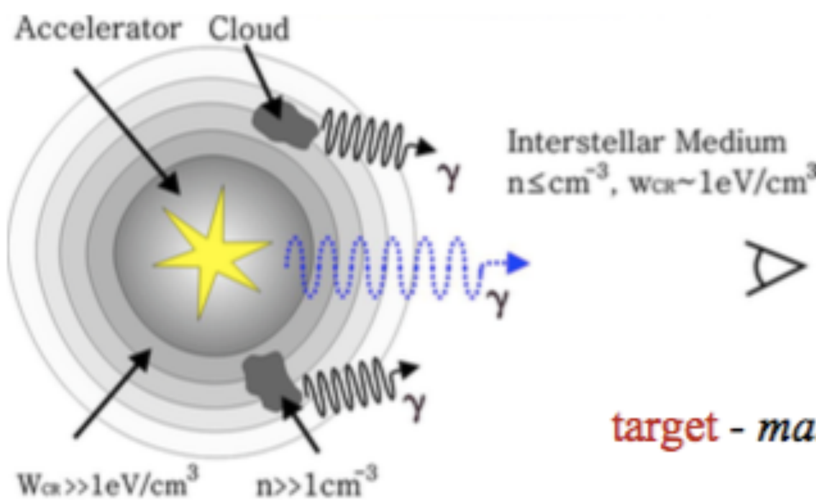
photons and neutrinos, but partly also neutrons

$$d < (E_n/m_nc^2)\, c\, t_o \;\; \Rightarrow \;\; E_n > 10^{17}(d/1\ \mathrm{kpc})\ \mathrm{eV}$$

do satisfy fully to these condition

gamma-ray production: 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*

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

Galactic Cosmic Rays:

basic facts:

energy density: ~ 1eV/cm^3 ; age: ~ 10^7 yrs,

production rate: (0.3-1) x 10^{41} erg/s, source spectrum: hard $Q(E) \sim E^{-2}$

sources ?

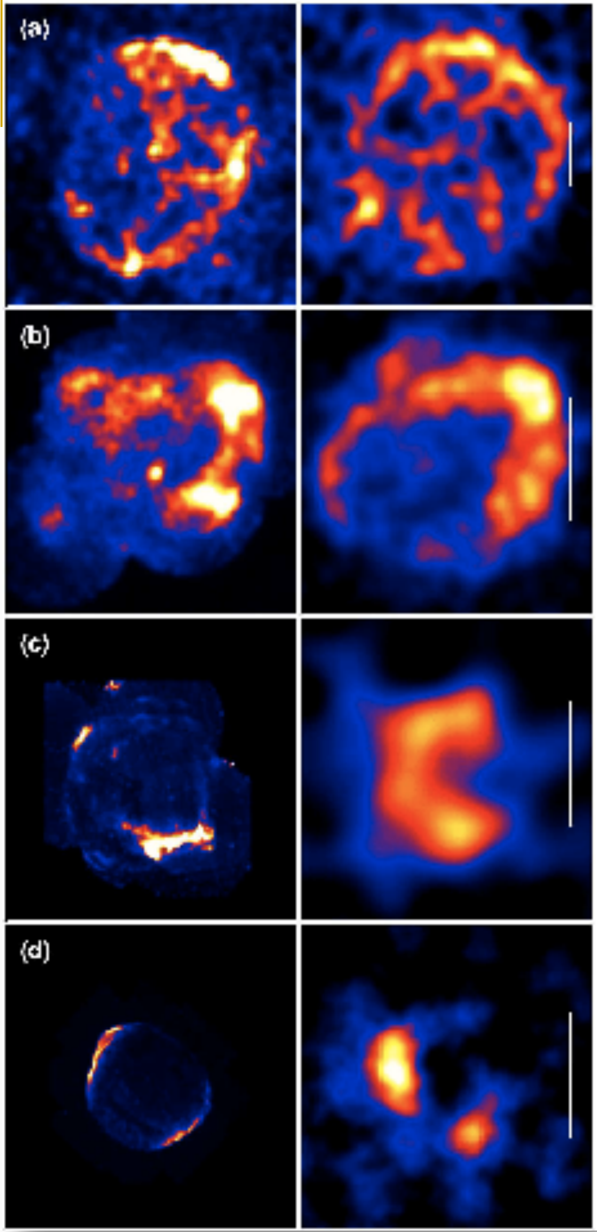
- ✓ SNRs: up to 10^{15} or even 5×10^{18} eV for Fe for type IIb SNe but so far we do not have decisive evidence of SNRs operating as CR PeVatrons…

- ✓ collective stellar winds and SNR shocks in clusters and associations of massive stars

- ✓ other potential sources? Galactic Center (Sgr A*)? "GRB remnants", pulsars?

one cannot exclude that the observed CR flux up to 10^{15}eV is significantly contributed (or even dominated) by a single (or a few) local sources (e.g. Erlykin&Wolfendale 2010); this is the case of TeV electrons (e.g. Aharonian et al 1995)

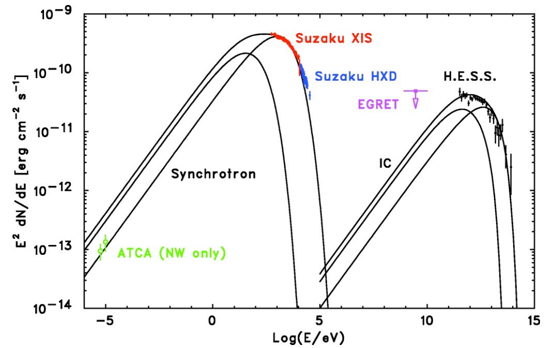
gamma-ray morphology: a key for identification of GCR accelerators

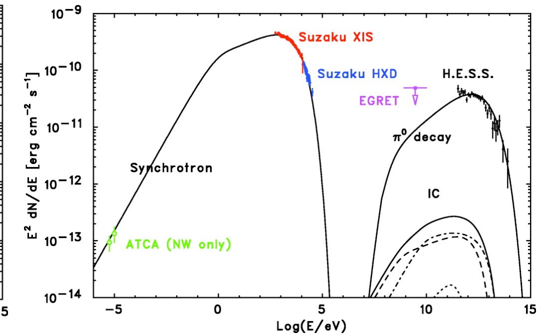


=>

acceleration of protons and/or electrons in SNR shells to energies up to 100TeV

leptonic or hadronic?





RXJ1713.7-4639

inverse Compton scattering of electrons on 2.7K CMBR

$B=15\mu G$

$We \approx 3.4\ 10^{47}$ erg/cm^3

γ-rays from pp $\to \pi^o \to 2\gamma$

$dN/dE = A\ E^{-\alpha} \exp(-E/Eo)$

with $\alpha=1.7$, $Eo \approx 25$ TeV,

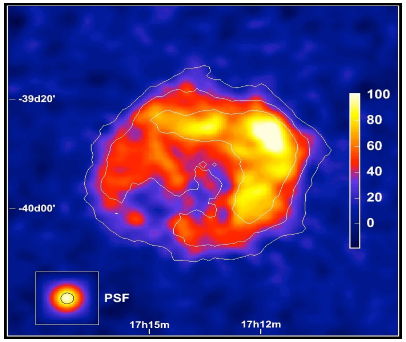
$B=200\mu G$

$Wp \approx 2\ 10^{50} (n/1cm^{-3})^{-1}$erg/cm^3

unfortunately we cannot give preference to hadronic or leptonic models - both have attractive features but also serious problems

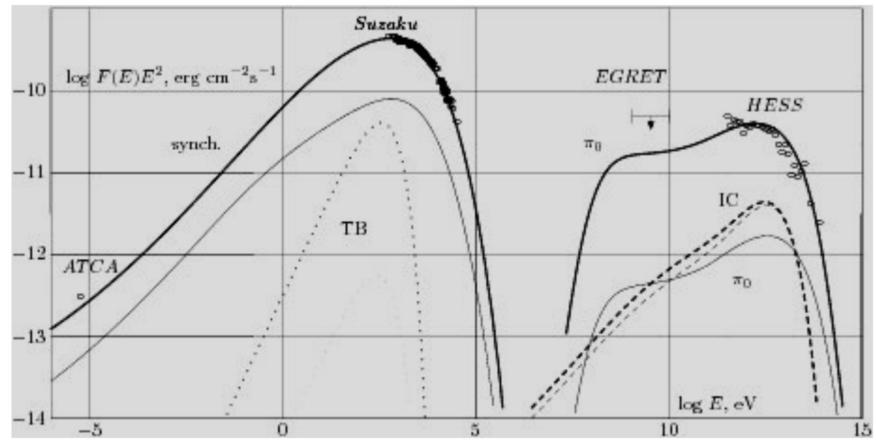
solution? detection of more sources, broader energy coverage, and search for neutrinos

RXJ 1713.7-4639



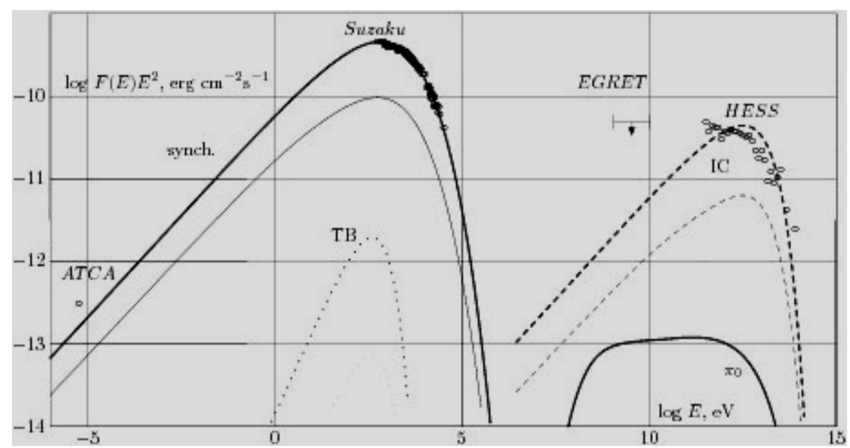
modeling of broad-band SEDs:

hadronic model



good spectral fit, reasonable radial profile, but …
(1) lack of thermal emission - possible explanation?
>70% energy is released in acceleration of protons!
(2) very high p/e ratio (10^4)

leptonic model



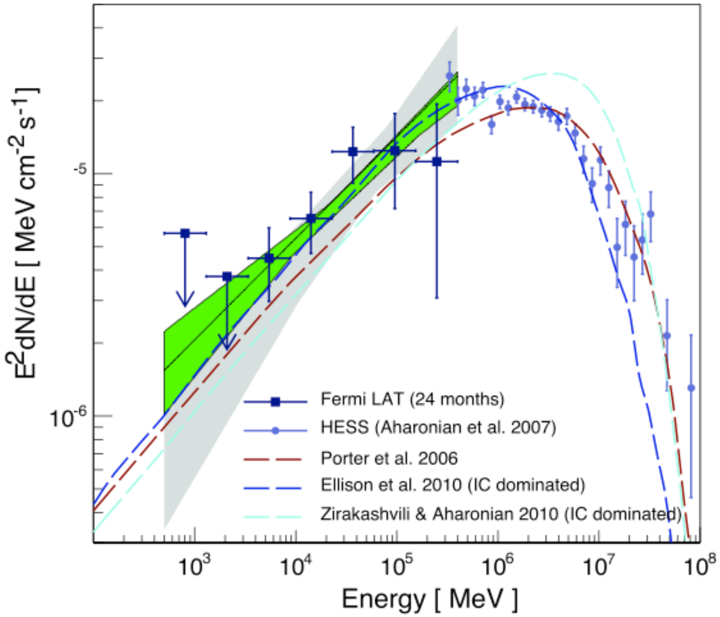
not perfect, but still acceptable, fits for spectral and spatial distributions of IC gamma-rays; suppressed thermal emission, comfortable p/e ratio (~10^2);small large-scale B-field (~ 10 μG)

both forward&reverse shock contribute to γ-rays

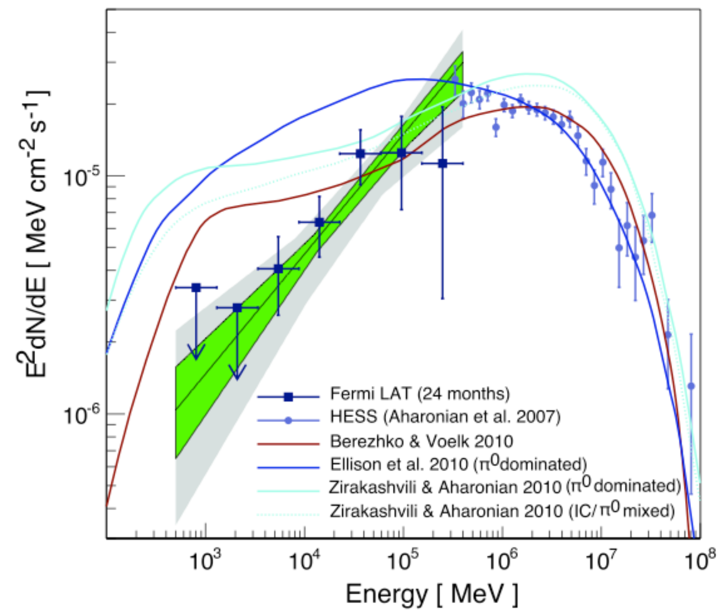
Zirakashvili, FA 2010

gamma-rays detected by Fermi? very important… but not decisive

Fermi: GeV data contradict hadaronic origin of γ-rays (?)



leptonic models



hadronic models

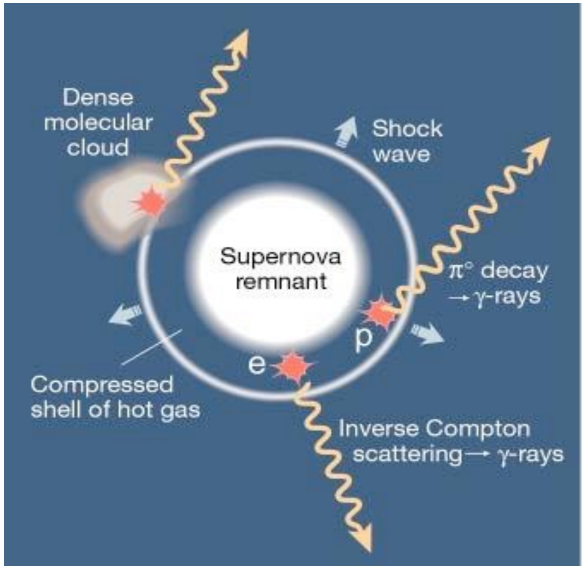
Questions: (i) can we compare GeV and TeV fluxes within one-zone models?

they could come from quite different regions

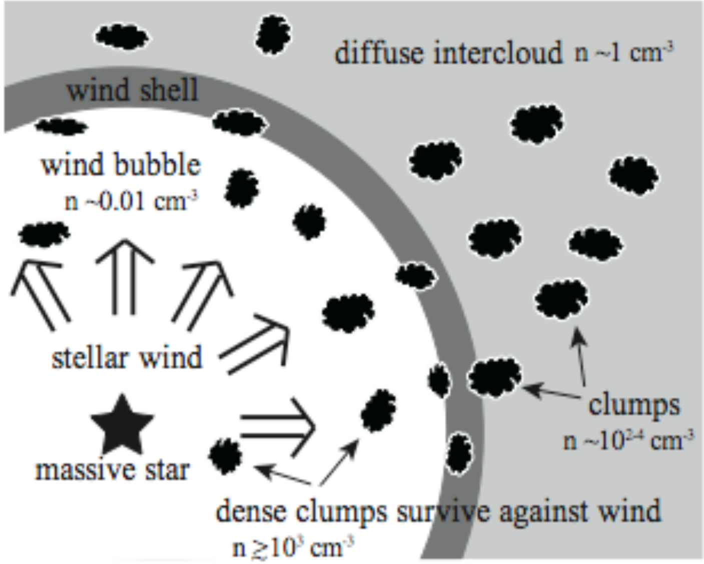
(ii) cannot we assume hard proton spectra ?

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

GeV gamma-rays can be suppressed because low energy protons cannot cannot penetrate deep into the dense clouds/clumps Zirakashvili&FA 2010, Gabici et al. 204, Celli et al 2018)



FA 2002, Nature 416,797



Inoue et al. 201, ApJ

Fermi LAT - 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 and, possibly, also the lack of thermal X-ray emission

Gabici&FA 2014

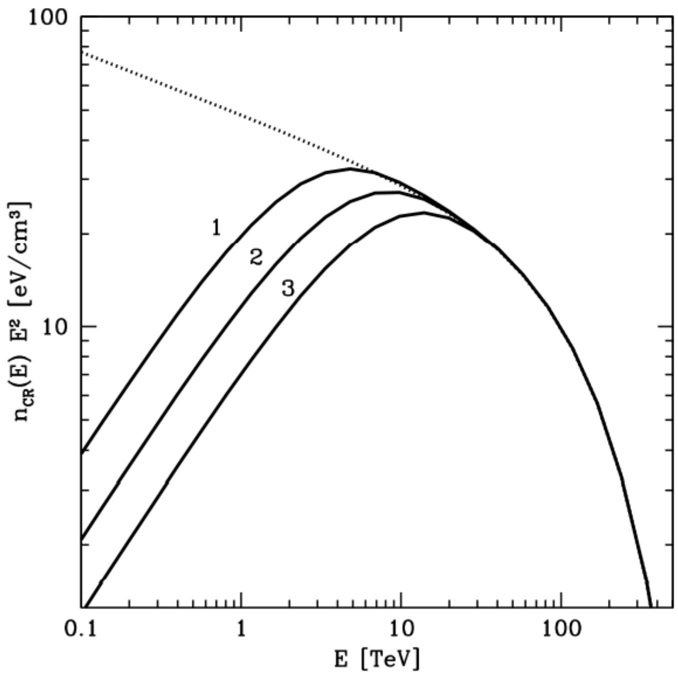


Figure 1. Spectrum of CRs in the SNR shell (dotted line) and inside a clump that entered the shock at $t_c = 1400$, 1500, and 1550 yr (solid line 1, 2, and 3 respectively).

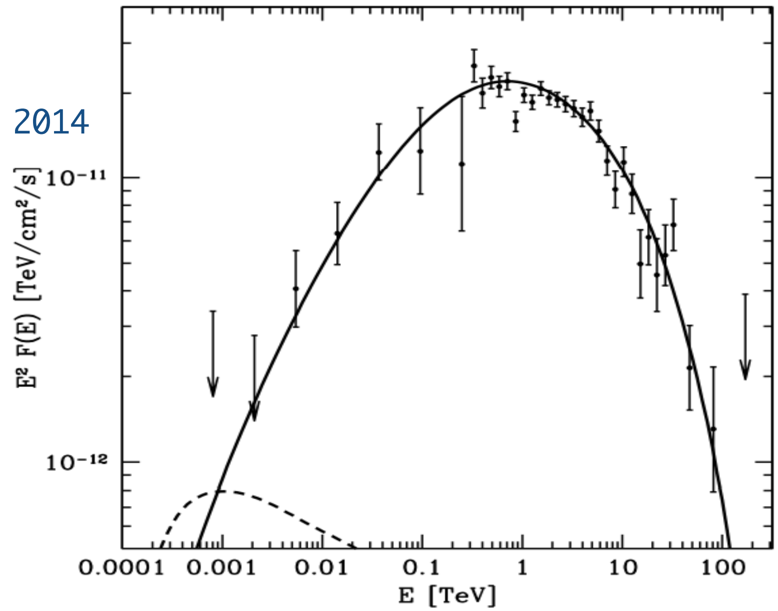


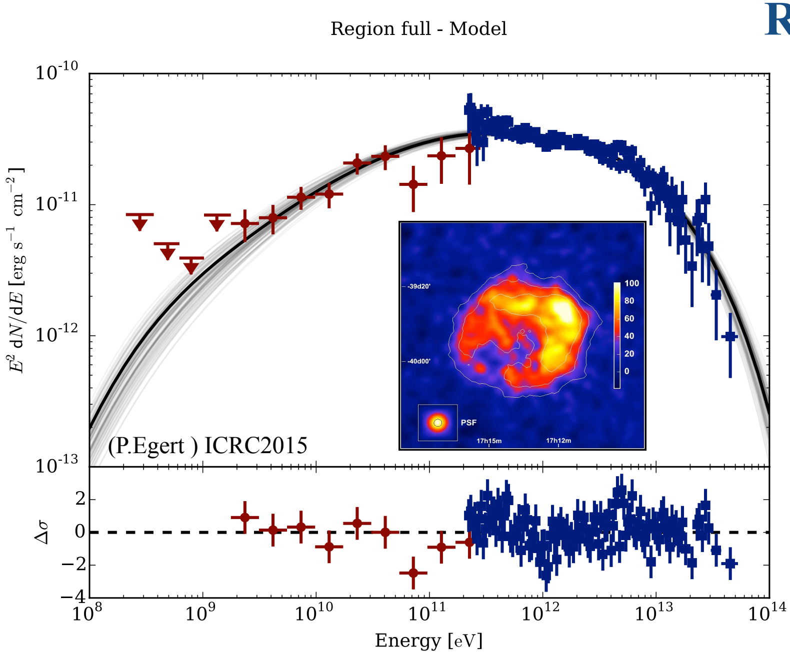
Figure 2. Gamma–rays from RX J1713.7-3946. The emission from the clumps is shown as a solid line, while the dashed line refers to the emission from the diffuse gas in the shell. Data points refer to *FERMI* and *HESS* observations.

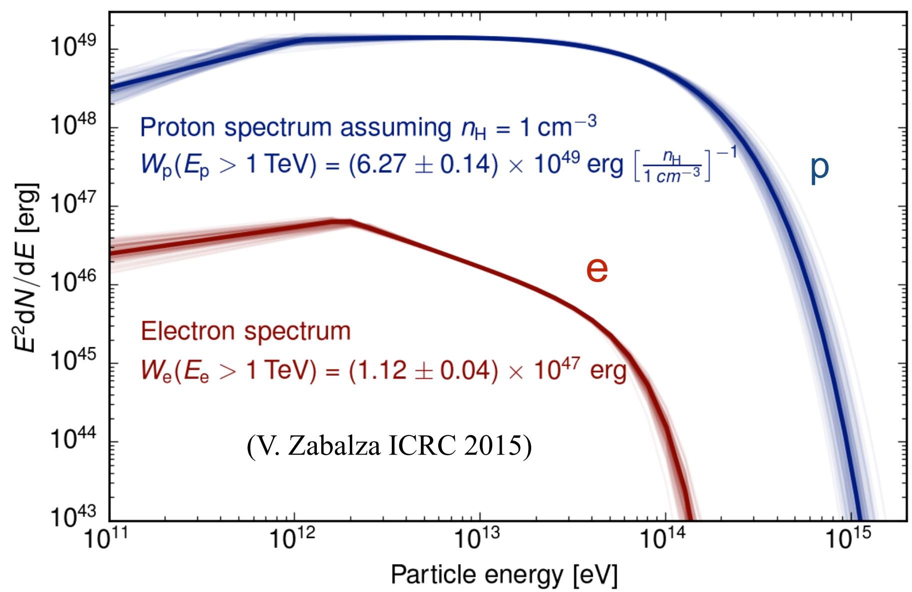
Probing the distributions of accelerated particles in SNRs

HESS measurements

derived spectra of e and p

RXJ 1713



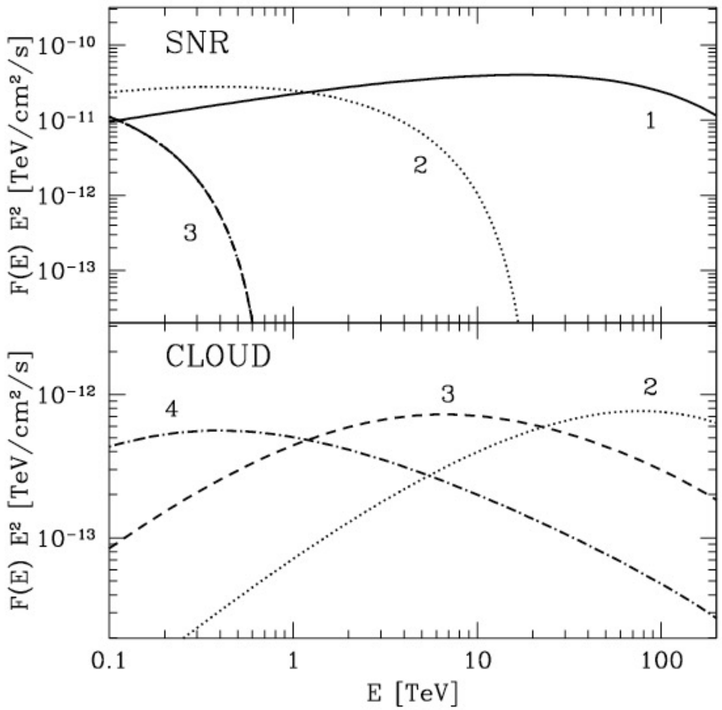


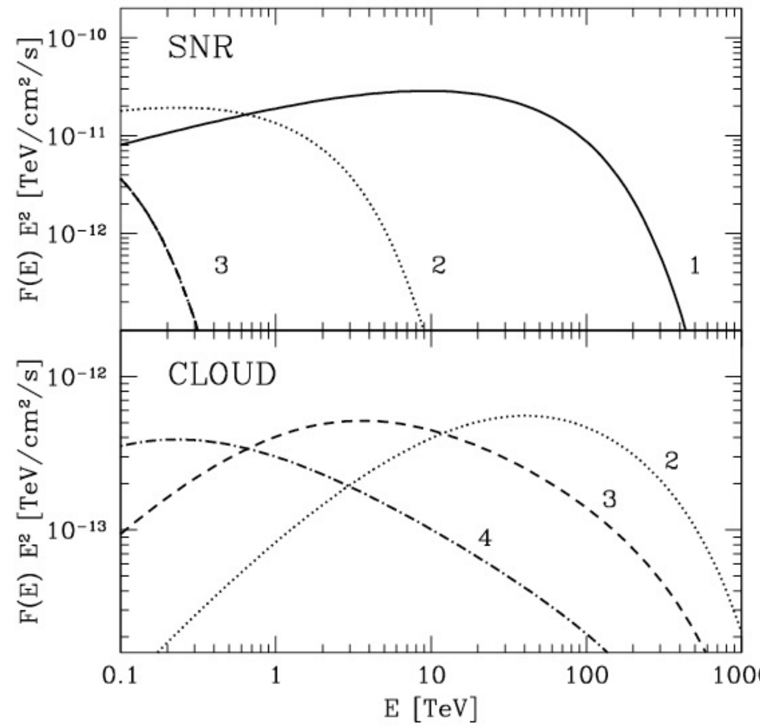
important !!! extension of measurements to arcimin (sub-pc) structures both inside and outside the shells

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: $D(E)=3\mathrm{x}10^{26}(E/10\mathrm{TeV})^{1/2}$ cm^2/s

S. Gabici & FA 2007

warning: don't be tricked by propagation effects!

transition from rectilinear to diffusive regime of propagation

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

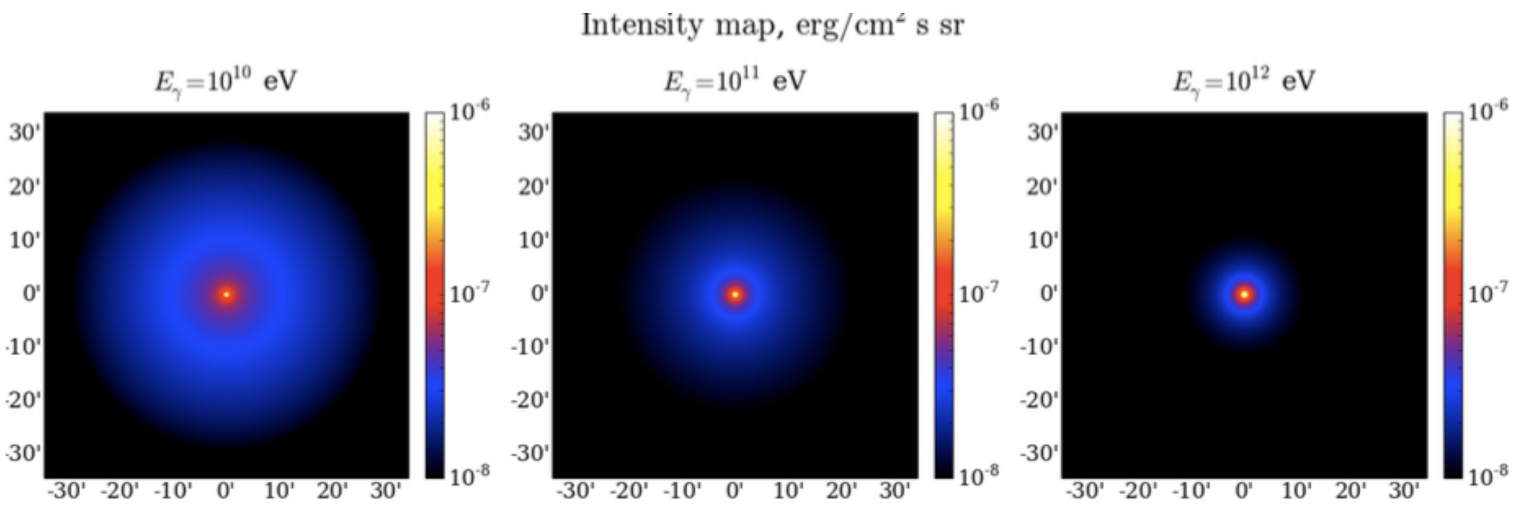


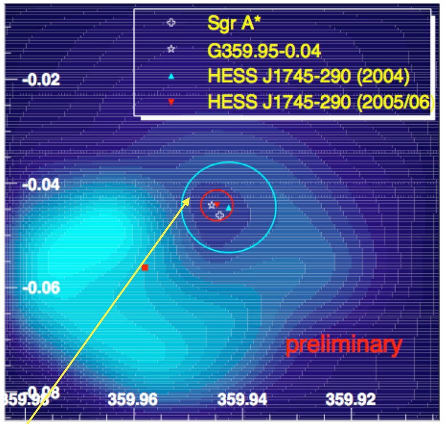
Figure 2: The intensity maps of gamma-ray emission at different energies. The spherical cloud with homogeneous density distribution is irradiated by the cosmic-ray source located in its centre. The gas density inside the accelerator is assumed very low, so the contribution of the accelerator to the gamma-ray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

Prosekin, Kelner, FA 2015

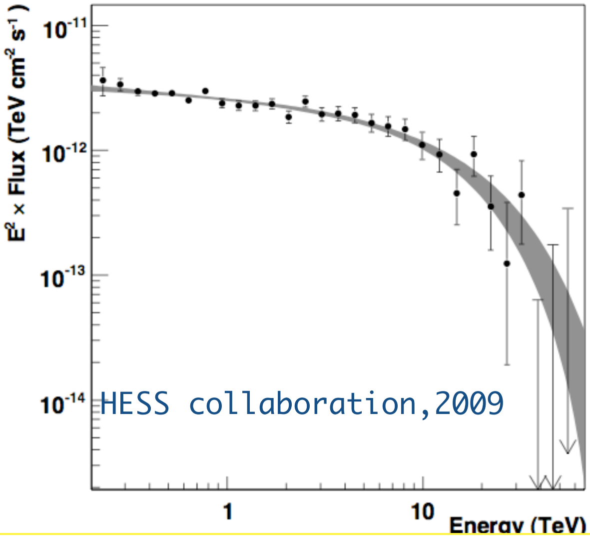
PeVatron(s) in the Galactic Center!

TeV gamma-rays from GC

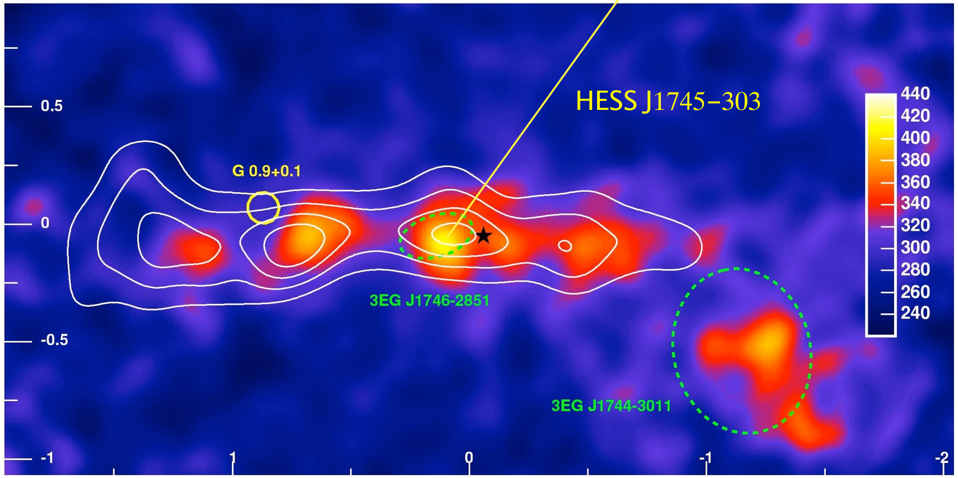
90 cm VLA radio image



Sgr A* or the central diffuse < 10pc region or a plerion?



γ-ray emitting clouds



HESS collaboration,2006

Energy spectrum:

$dN/dE = AE^{-\Gamma} \exp[(-E/E_{0)})^{\beta}]$

$\beta=1$ $\Gamma=2.1$; $E_0=15.7$ TeV

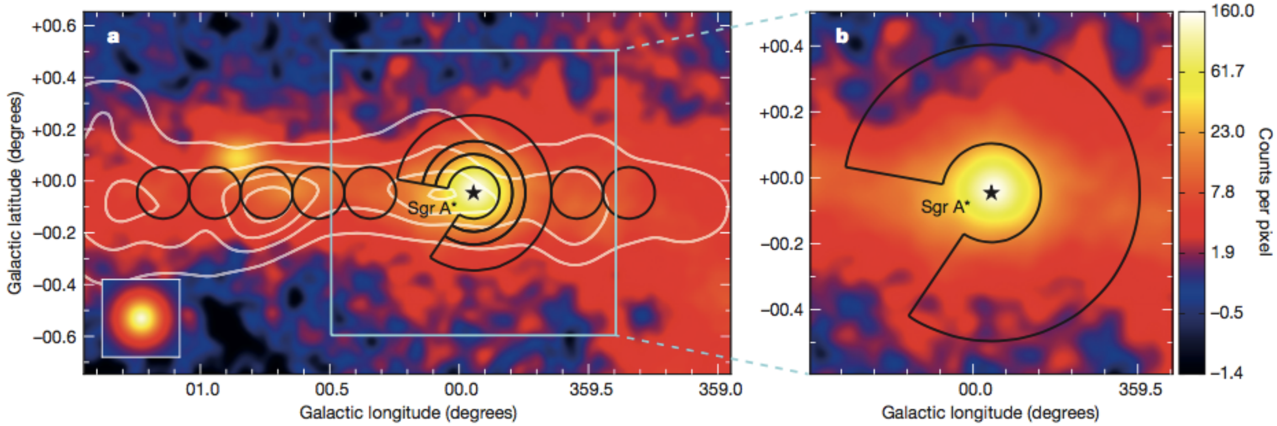
$\beta=1/2$ $\Gamma=1.9$ E0=4.0 TeV

important finding by HESS

a proton PeVatron - a machine accelerating particles up to 10^{15} eV and beyond presently operates in $R<10$ pc region of the Galactic Center with acceleration rate of protons above energy 10TeV at level $10^{37\text{-}38}$ erg/s

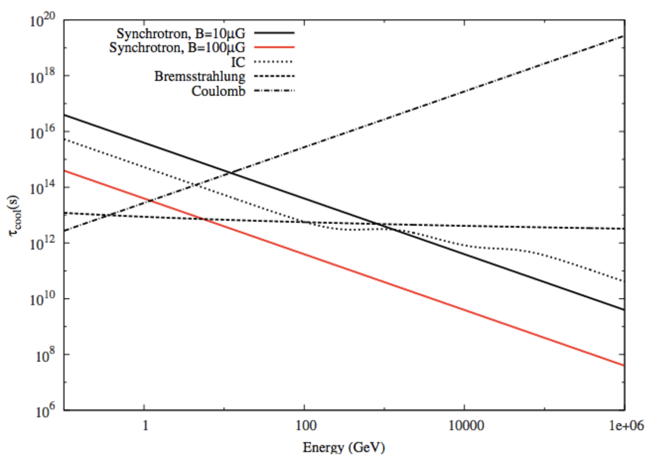
this conclusion is based on spectroscopic and morphological studies of diffuse VHE gamma-ray component in so-called ~200 pc radius Central Molecular Zone (CMZ) of the GC

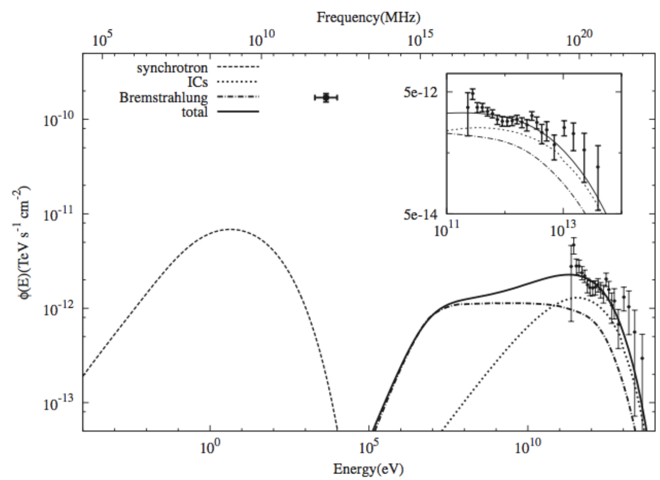
- for the first time, a gamma-ray spectrum is registered that continues without a cutoff or a break up to 20-30 TeV (most likely, 50 TeV)
- for the first time, the density profile of parent protons is derived based on analysis of spatial distributions of VHE gamma-rays and the gas in GC



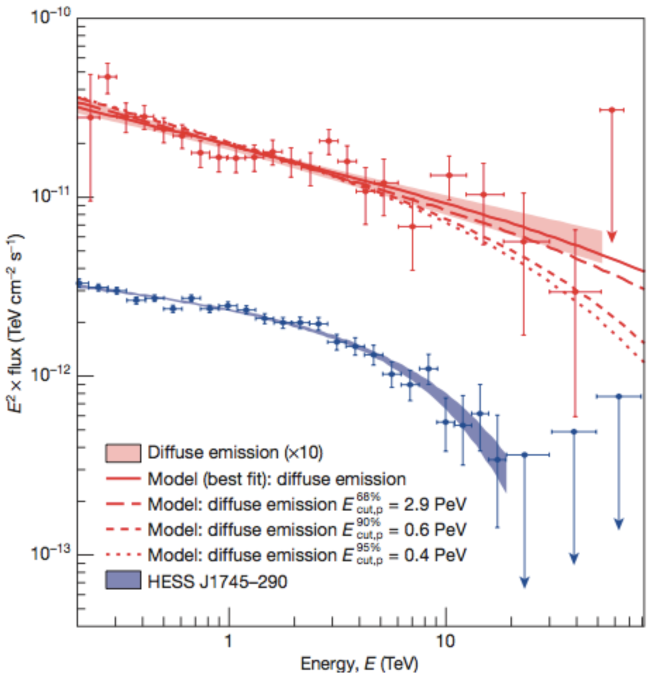
gamma-rays are of hadronic (pp) origin:

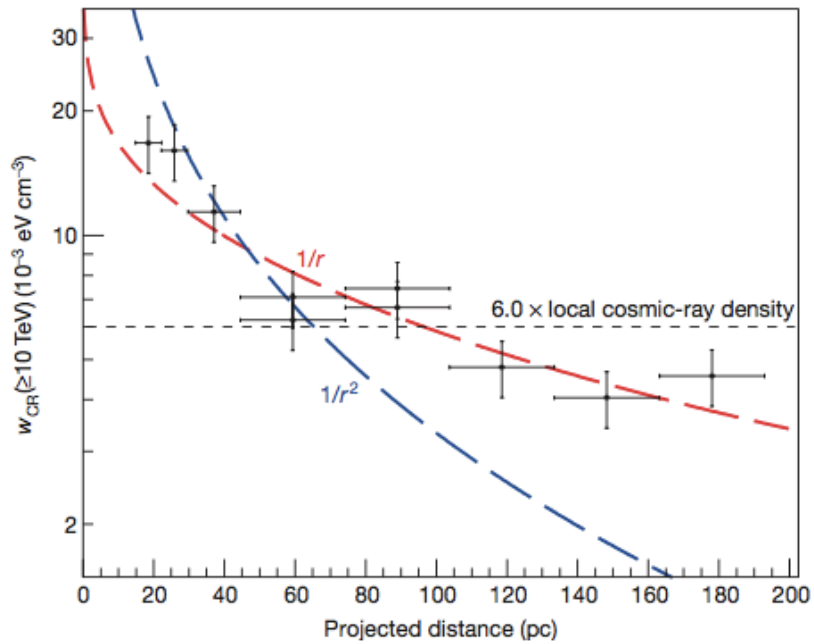
- gamma-ray brightness correlates with gas density (but not linearly!)
- mean free paths of 100 TeV gamma-rays cannot exceed a few pc
- because of cooling of electrons the IC spectrum breaks below 10TeV





PeVatron located within R<10 pc and operating continuously over > 10^3 yr





no-cutoff in the gamma-ray spectrum up to **25 TeV**
=> *no-cutoff* in the proton spectrum up to ~ **1 PeV**

what do we expect?

1/r continuous source
$1/r^2$ wind or ballistic motion
constant burst like source

derived: **1/r** distribution
=> continuous acceleration !

Conclusions:

- 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

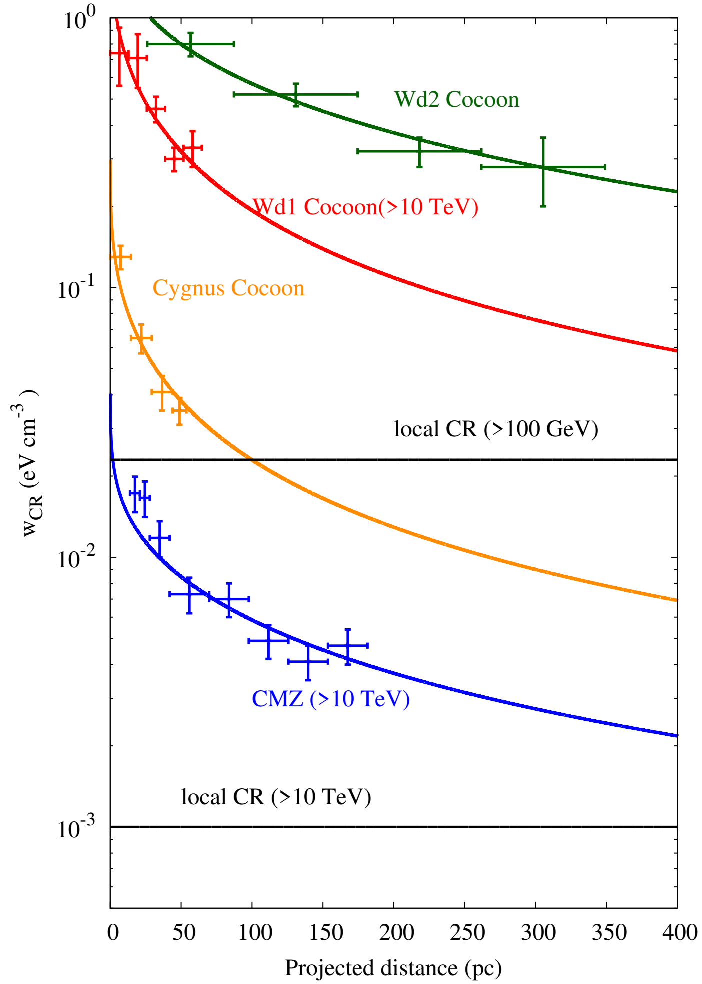
- this accelerator alone can account for most of the flux of Galactic CRs around the “knee” if its power over the last 10^{6} years or so, has been maintained at average level of 10^{39} erg/s.

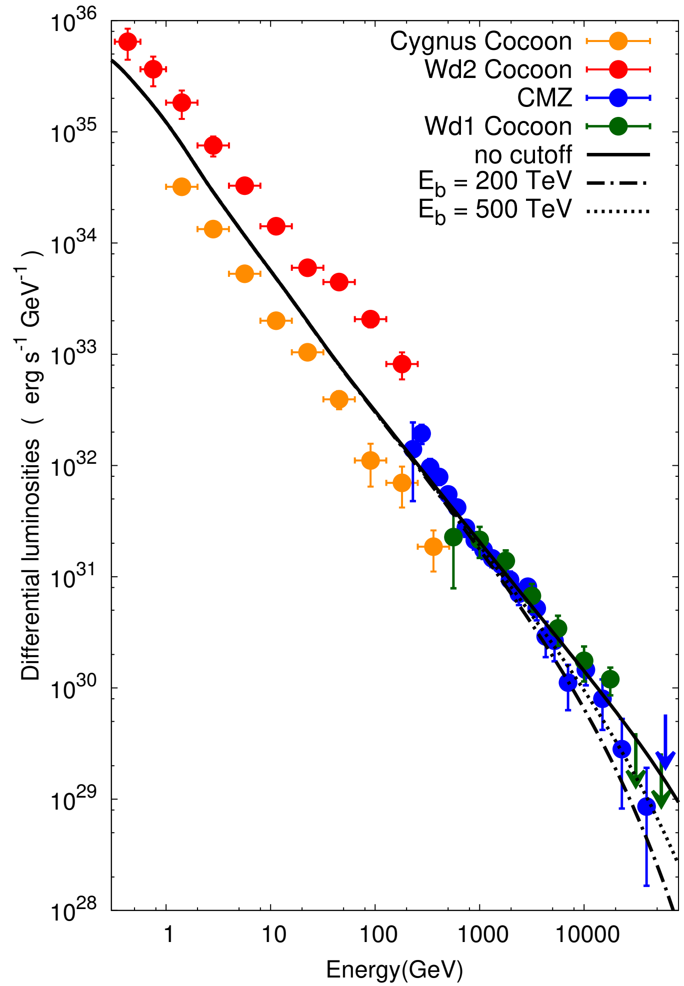
- escape of particles into the Galactic halo and their subsequent interactions with the surrounding gas, can be responsible for the sub-PeV neutrinos recently reported by the IceCube collaboration

- SMBH or young massive clusters?

Clusters of Young Massive stars as major sources of CRs?

FA, Yang, Ona de Wilhelmi, 2018

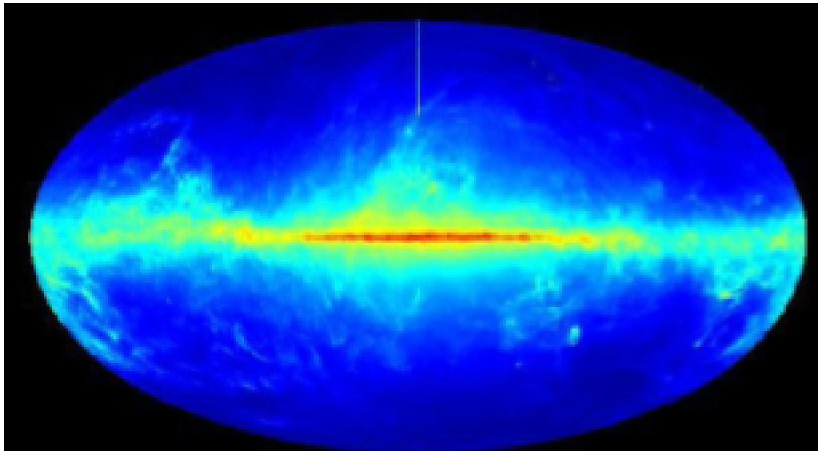


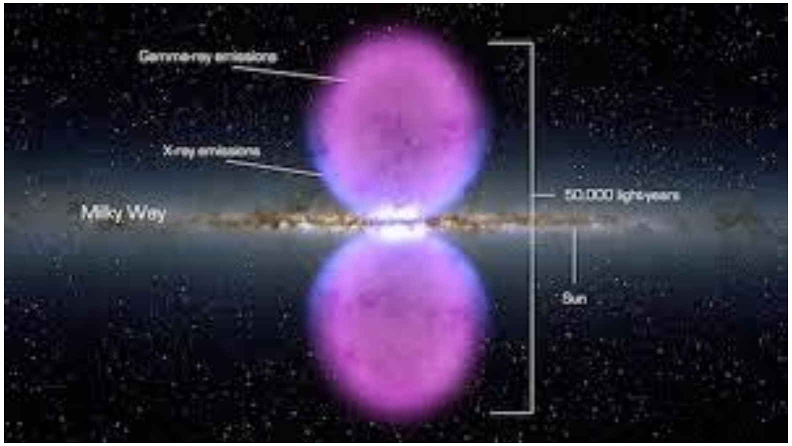


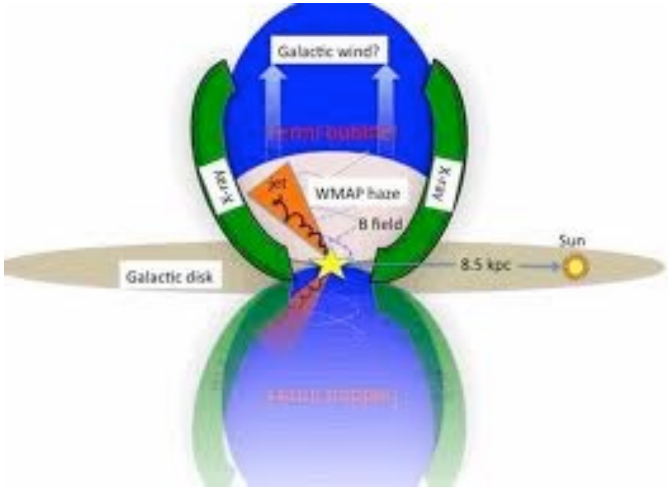
1/r - continuous accelerator!

gas density, gamma-ray flux and image extension - constraints on diffusion coefficient and CR production efficiency

CRs from GC responsible for Fermi Bubbles?







and “IceCube Neutrinos” from a larger >>10 kpc halo (Taylor, Gabici, FA 2015) ?

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)

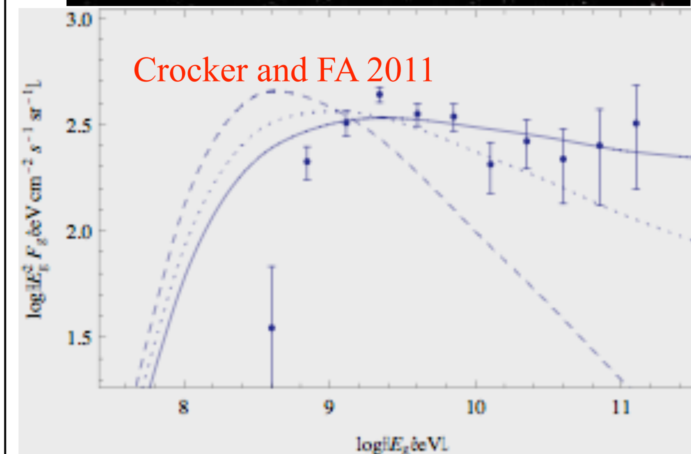
Size - because of slow diffusion in turbulent environment (10 times slower than in the Galactic Disk)

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

saturation (calorimetric) regime can explains:

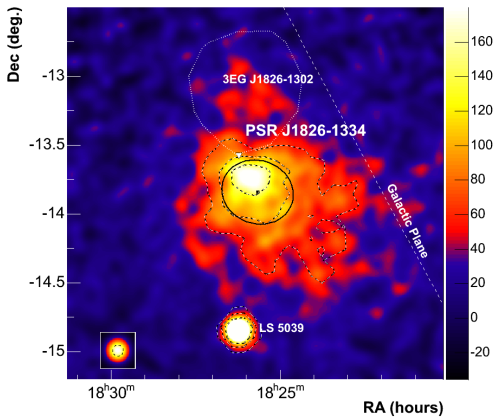
generally homogeneous distribution of gamma-rays (local γ-ray production rate does not depend on density), unless possible gradients in the CR spatial distribution, e.g. due to propagation effects ; if the sharp edges tentatively found in the Fermi images is a real effect, they can be naturally explained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

modest requirements to CR rate : $L_p \sim 10^{39}$ erg/s



Fermi Bubbles
as a VHE neutrino source?

Pulsar Wind Nebulae:
electron PeVatrons



since TeV gamma-rays are produced in interactions of multi-TeV electrons with 2.7 K CMBR => γ-ray images give direct information about the spatial distribution of ultrarelativistic electrons

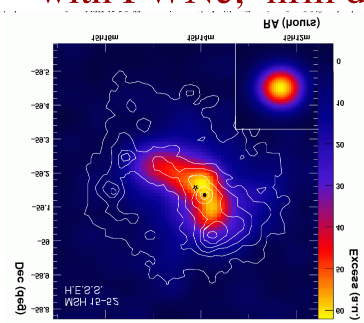
Crab Nebula is a very effective accelerator
but not an effective IC γ-ray emitter

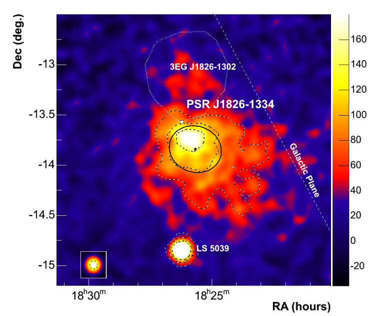
we do see TeV γ-rays from the Crab Nebula because of very large spin-down flux: $f_{rot}=L_{rot}/4\pi d^2=3x10^{-7}\ erg/cm^2\ s$

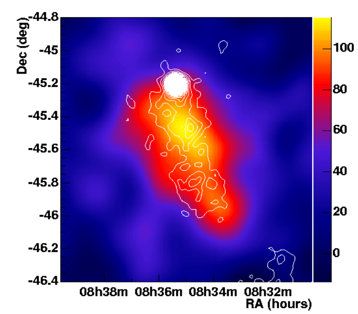
gamma-ray flux << "spin-down flux" *because of large B-field*

if the B-field is small (environments with small external gas presure)

higher γ-ray efficiency ➡ detectable γ-ray fluxes from other plerions
HESS confirms this prediction – many (20+) candidates associated with PWNe; firm detections - MSH 15-52, PSR 1825, Vela X, ... N157B!







Summary:

morphological studies of galactic sources with future major gamma-ray instruments - CTA and high altitude particle arrays:

a (the) key for the solution of the 100-yr old puzzle of the origin of Galactic Cosmic Rays and for deeper understanding of the physics/astrophysics of Cosmic Ray factories in the Milky Way