Gamma Rays and Cosmic Rays:

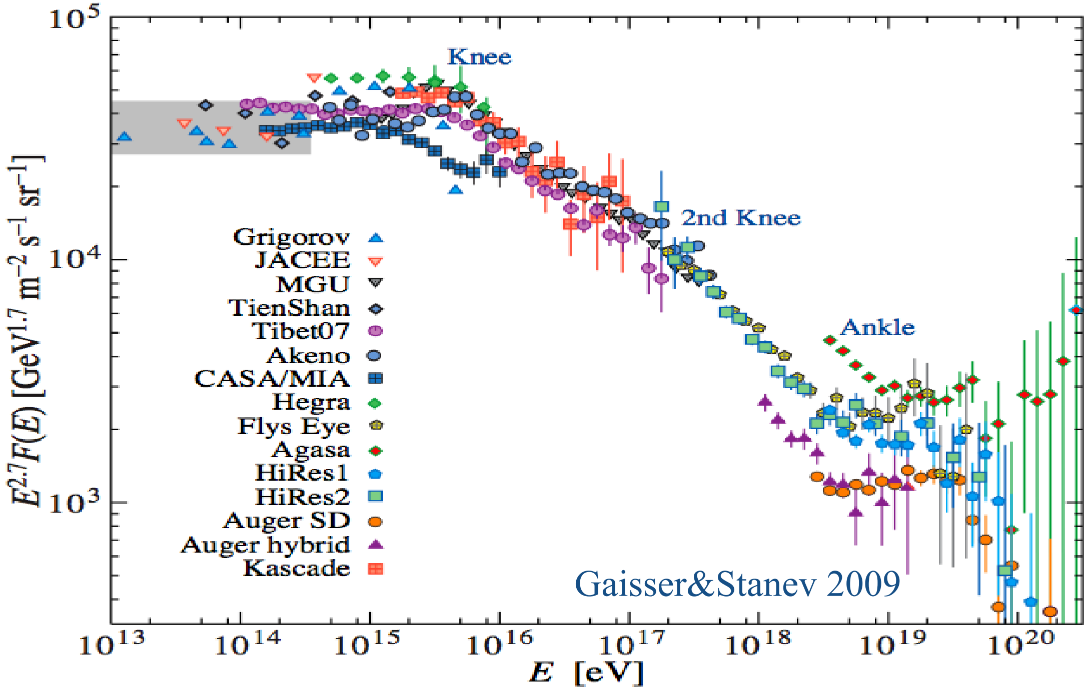
Gamma Rays as the key to reveal the origin of Galactic Cosmic Rays

Felix Aharonian

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

Vulcano 2018, May 22, 2018

"origin of cosmic rays - still is a mystery"



the all-particle CR spectrum

after 100+ years of discovery of CRs, the origin of these relativistic particles extending over 11+ decades in energy is not fully understood and established:

this concerns both the Galactic (G) and Extragalactic (EXG) components of CRs

(1) G - up to at least 10^{15} eV (2) Extragalactic (for sure, above 10^{18} eV)

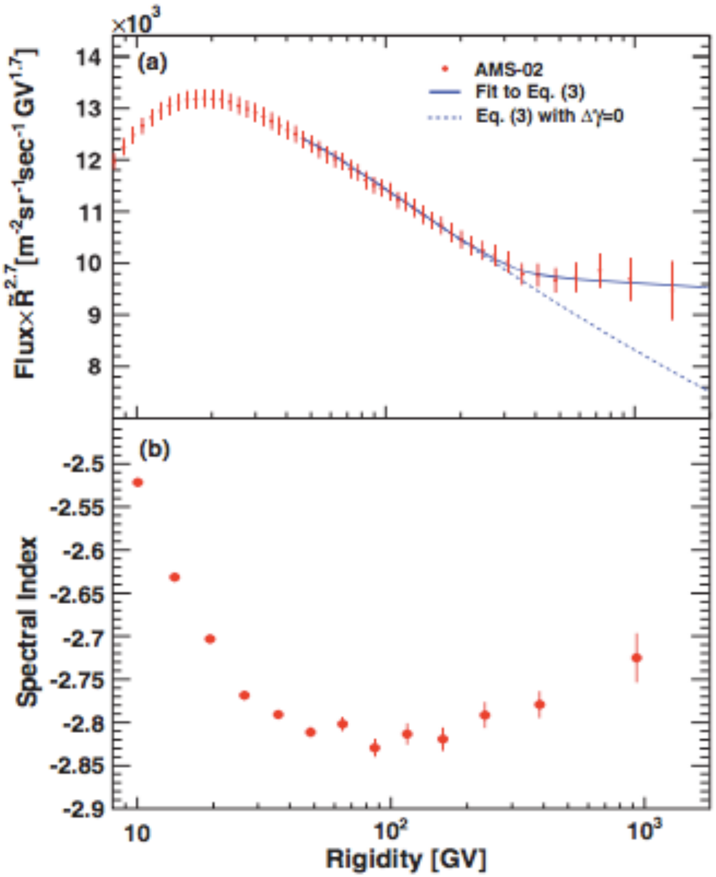
what does imply "Origin of Cosmic Rays" ?

the term "Cosmic Rays" itself has two meanings

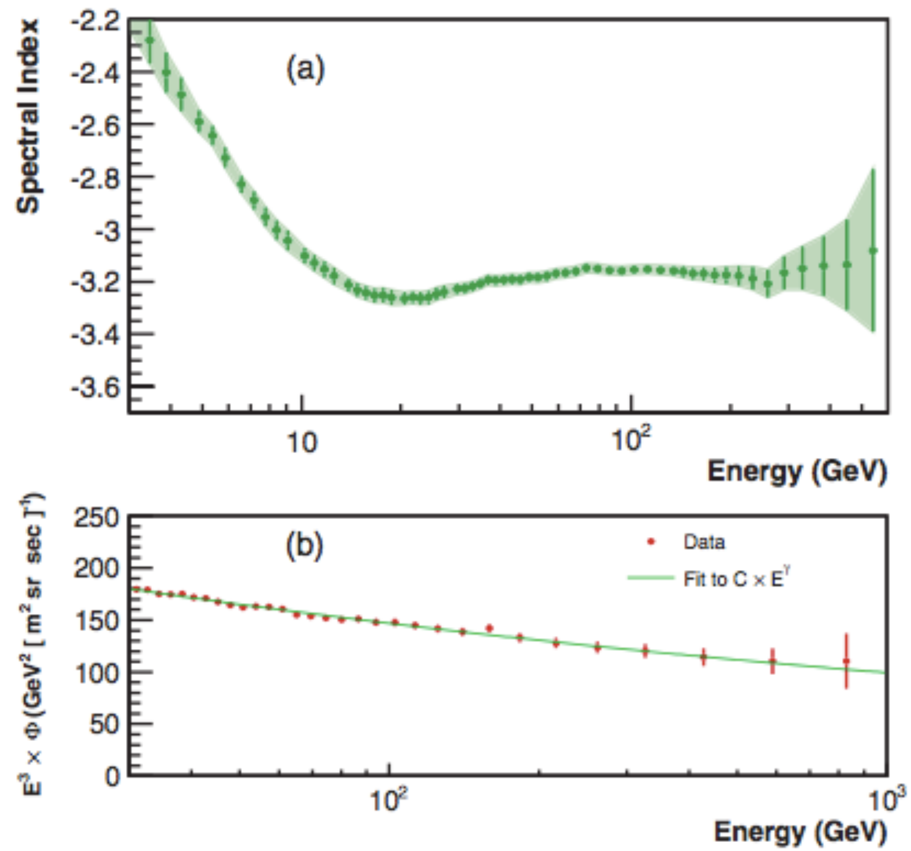
- locally detected nonthermal/relativistic particles - a *"local fog"*
- the 4th substance of the visible Universe (after the matter, radiation and magnetic fields) - a *more fundamental issue*

Recent remarkable success of CR studies

protons



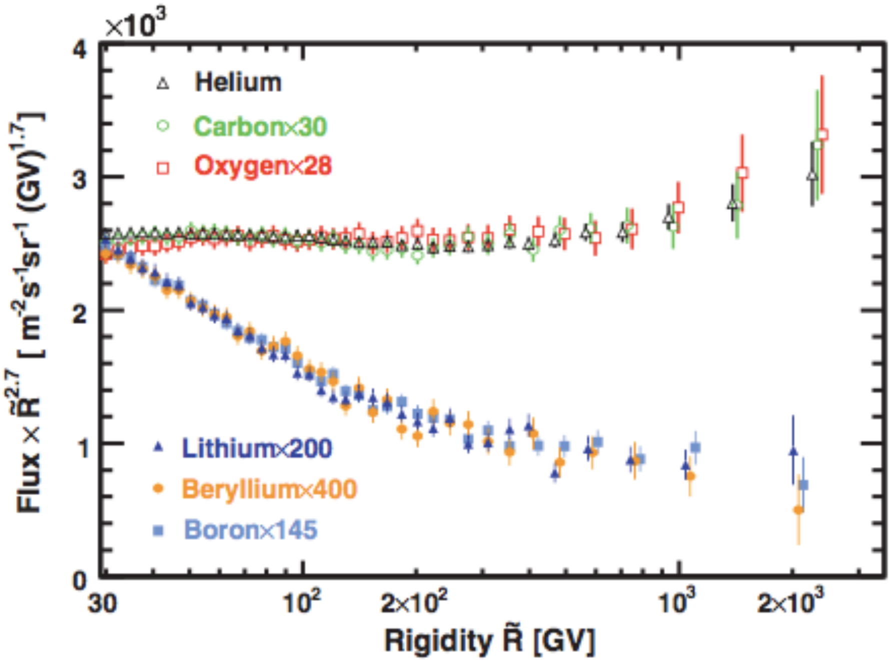
electrons

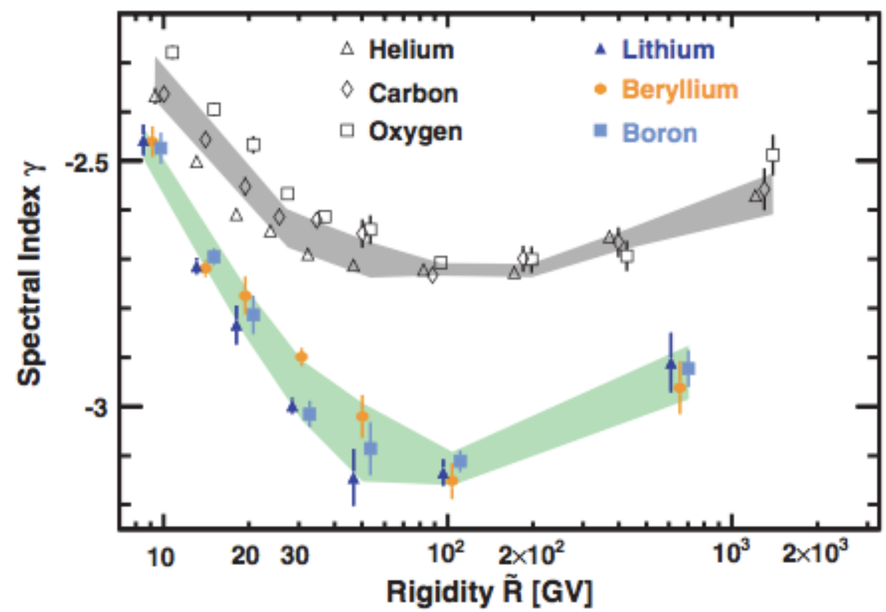


AMS

Recent remarkable success of CR studies

primary and secondary nuclei

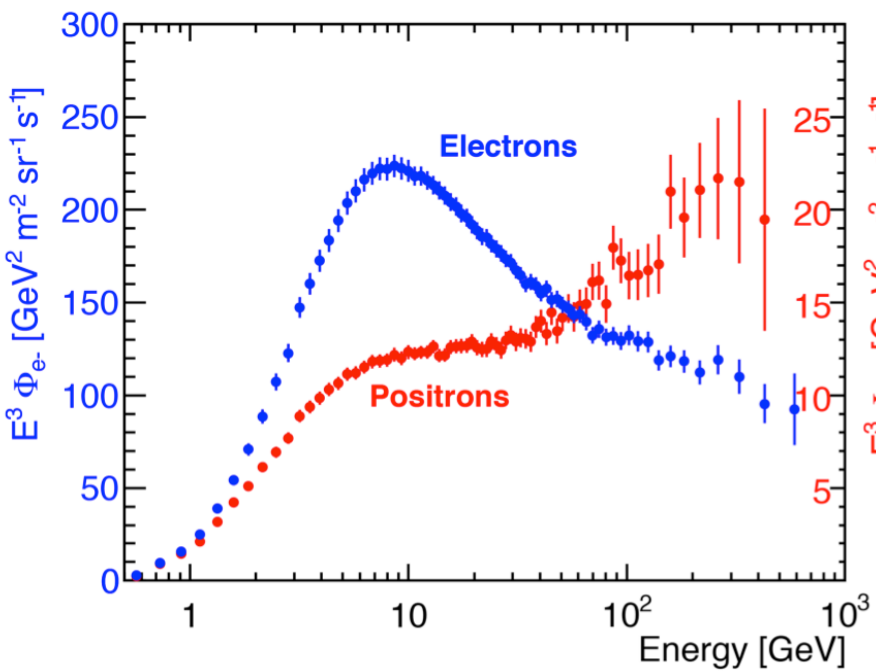


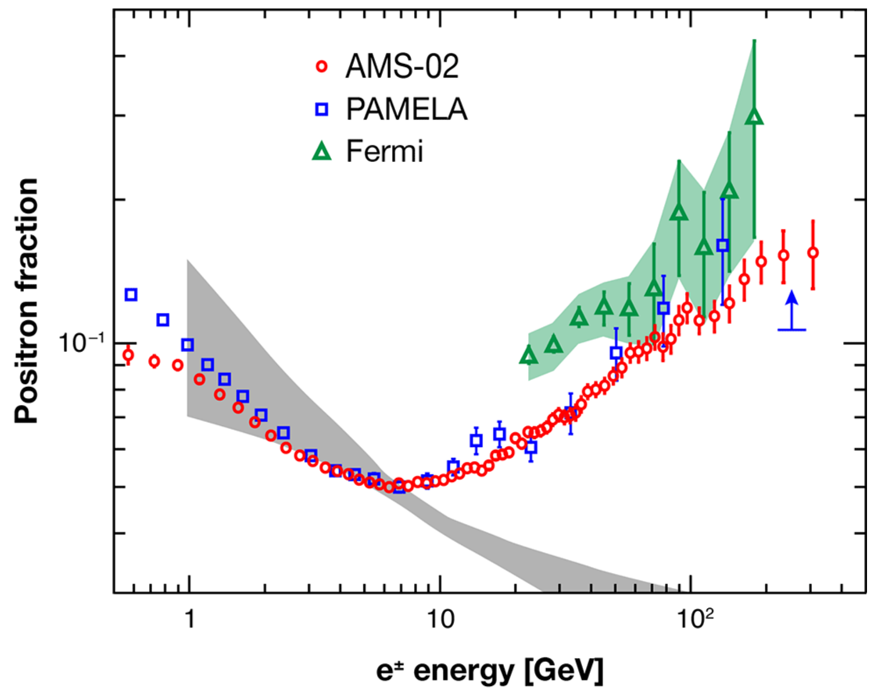


AMS

Recent remarkable success of CR studies

electrons and positrons





"positron" excess! trouble? not really - primary (nearby) sources of electrons and positrons positrons

AMS

What do we know about the Galactic Cosmic Rays?

basic facts:

energy density: $\sim$ 1eV/cm^3 ; age: $\sim 10^7$ yrs,

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

modulated during propagation (energy dependent diffusion) in the ISM

sources ?

- ✓ Supernova Remnants (**SNRs**): at least up to 10^{15}

  we do not have decisive evidence of SNRs operating as CR PeVatrons…

- ✓ collective stellar winds and SNR shocks in

  Clusters of Young Massive Stars (**YMS**)

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

- ✓ local sources of electrons and positrons - pulsars/PWNe

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*:*

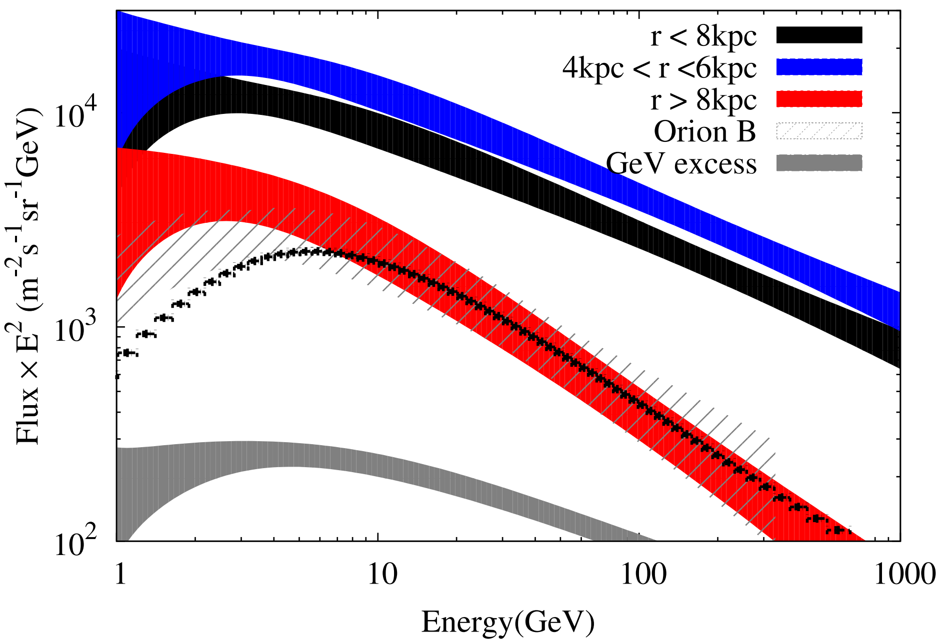
photons and neutrinos, but partly also neutrons

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

do satisfy fully to these condition

Gamma Rays messengers of information about cosmic rays

- diffuse gamma rays => propagation of Cosmic Rays



CR flux in different parts of the Galaxy derived from Fermi LAT γ-ray data

- gamma rays from sources => Cosmic Ray Accelerators

questions beyond the origin of CRs - physics of Extreme Accelerators (MHD, electrodynamics, plasma physics…)

machines where acceleration proceeds with efficiency close to 100%

(i) fraction of available energy converted to nonthermal particles

in PWNe and perhaps also in SNRs and AGN <u>can be as large as 50 %</u>

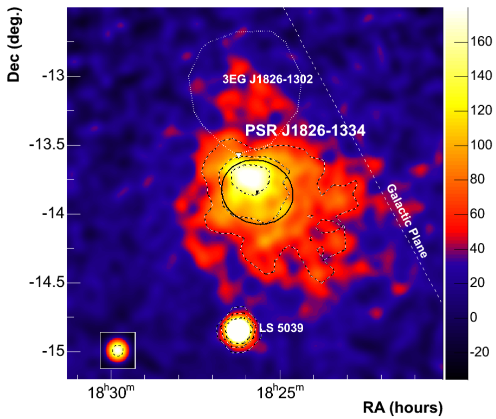
(ii) maximum possible energy achieved by individual particles

acceleration rate close to the <u>maximum (theoretically) possible rate</u>

sometimes efficiency can even "exceed" 100% ?

(no violation of conservation laws - but due to non-linear effects)

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 <u>effective accelerator</u>

but <u>not an effective IC γ-ray emitter</u>

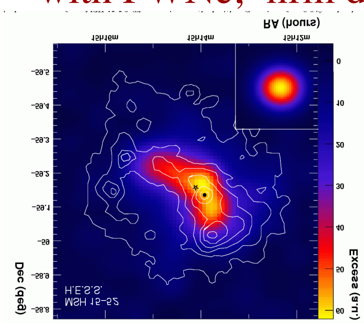
we do see TeV γ-rays from the Crab Nebula because of very large spin-down flux: $f_{rot}=L_{rot}/4\pi d^2=3\times10^{-7}$ erg/cm^2 s

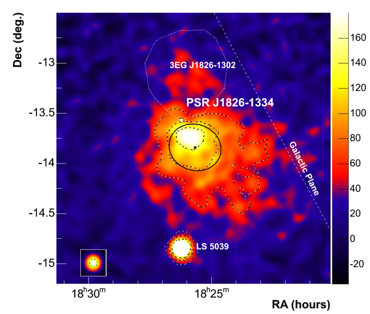
gamma-ray flux << "spin-down flux" *because of large B-field*

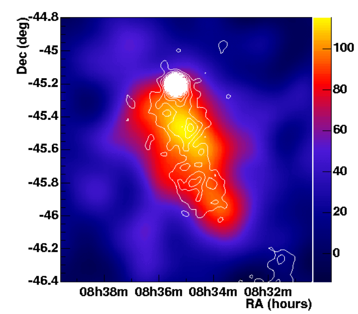
if the B-field is small (environments with small external gas presure)

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!





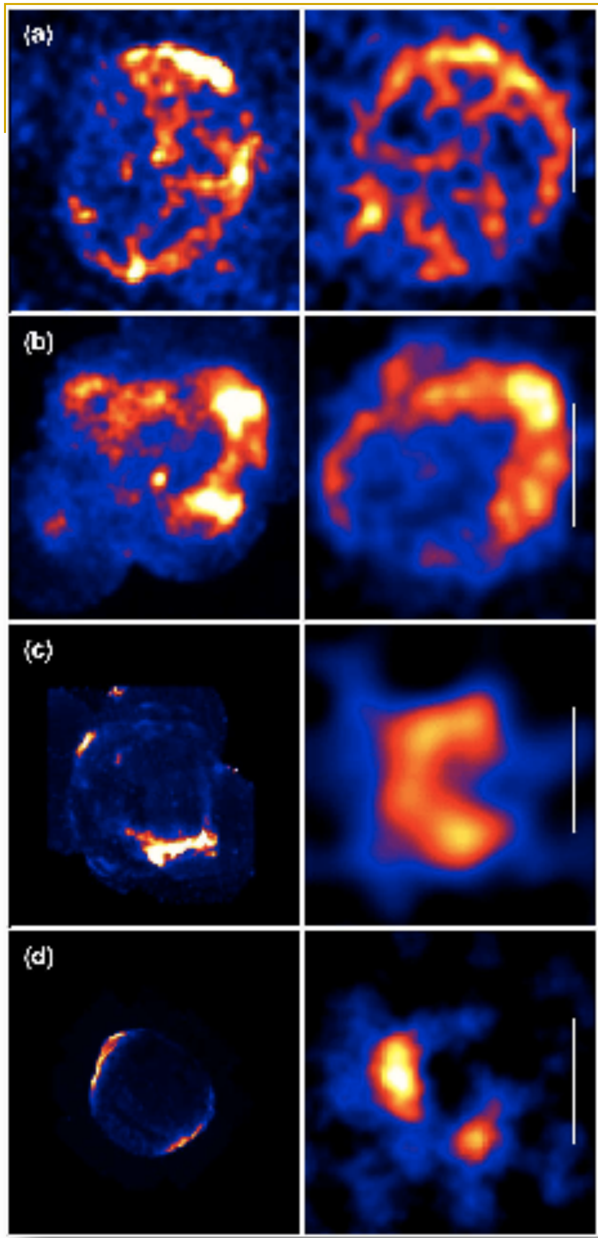


SNRs and Galactic Cosmic Rays

SNRs as the most likely sources
of galactic cosmic rays?

main hope is related to gamma-ray observations:

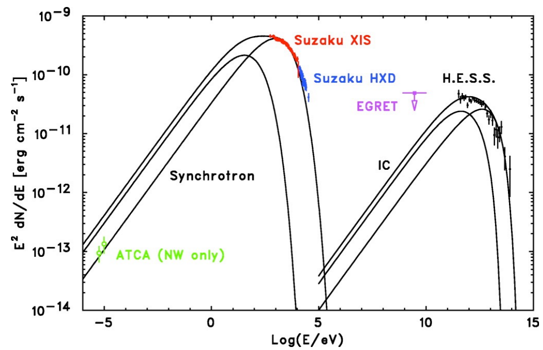
- detect VHE gamma-rays from SNRs
- demonstrate that they have hadronic origin
- demonstrate that proton spectra continue up to 1 PeV

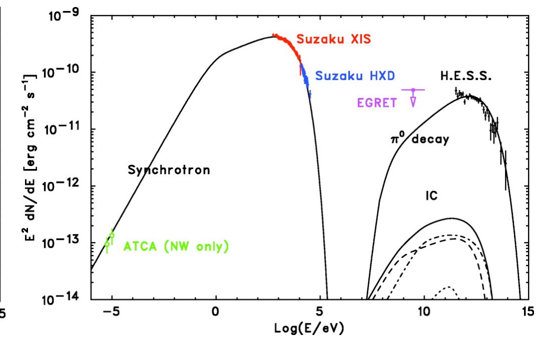


=>

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

$B=15\mu G$

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

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

$dN/dE = A\ E^{-\alpha} \exp(-E/E_o)$
with $\alpha=1.7$, $E_o \approx 25$ TeV,
$B=200\mu G$

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

a few comments on the hadronic scenario

- lack of thermal emission in RXJ 1713.7-3946

  almost the entire available energy goes to acceleration?

  very low gas density but γ rays are produced in "clumps" ?

- p/e ratio > 10^3 - cosmic rays p/e ~ 100

  in Cas A p/e in principle could be 100, but could be also less than 10

- "early cutofs" - in all SNRs Ecut < 100 TeV

should we relax and accept that SNRs are the main contributors to GCRs but until 10-100 TeV, and that there should be other sources (PeVatrons) responsible for the knee around 1 PeV ?

perhaps but we should explore other possibilities as well,

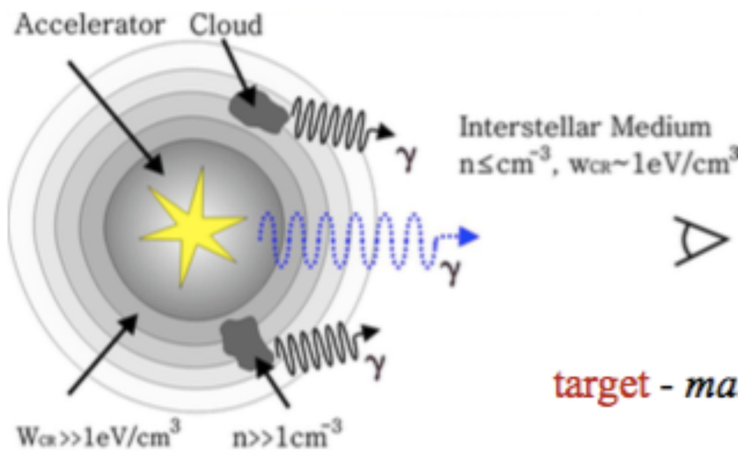
in particular the role of the *escape*

HESS: it seems there is a component beyond the shell in RXJ1713 if so

it would be important to measure the gamma-ray (and the secondary hard synchrotron X-ray) spectra related to the escaping protons

gamma-ray production: accelerator+target

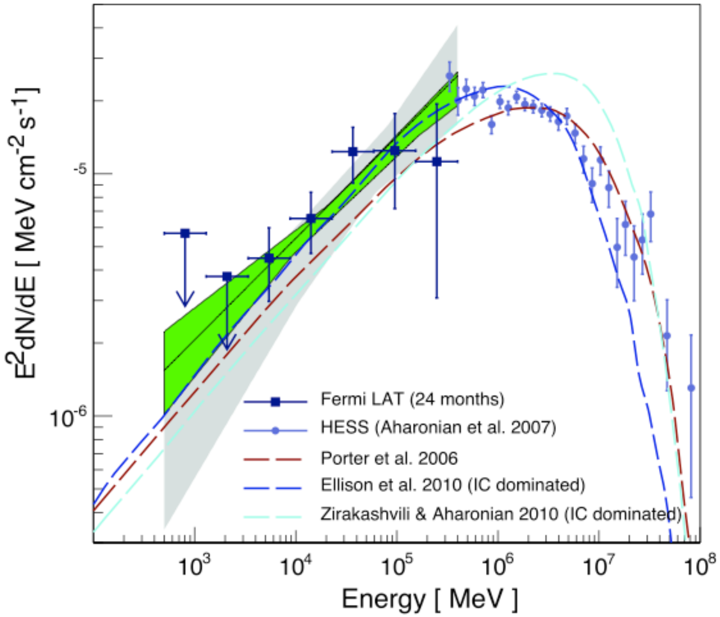
existence of a powerful particle accelerator by itself is not sufficient for γ-radiation; an additional component – a dense target - is required

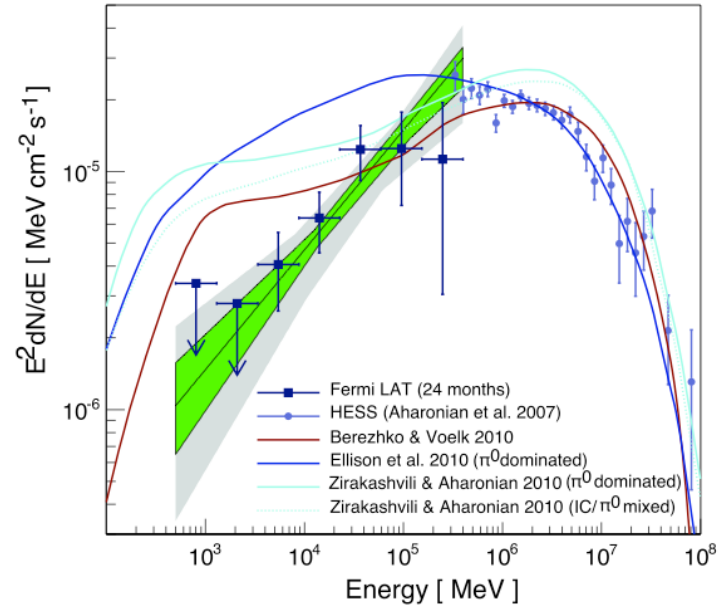


target - *matter, radiation, magnetic field*

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

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

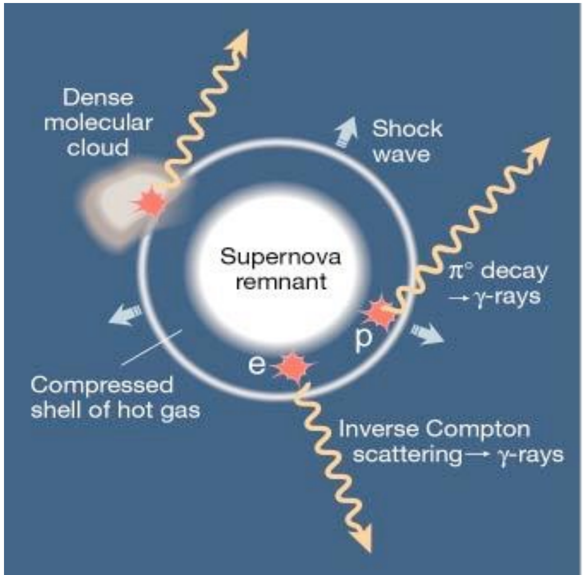




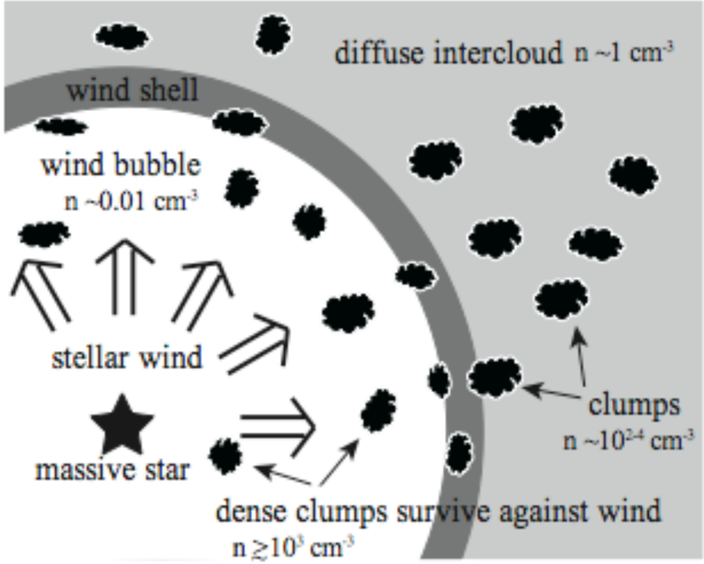
leptonic models   hadronic models

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

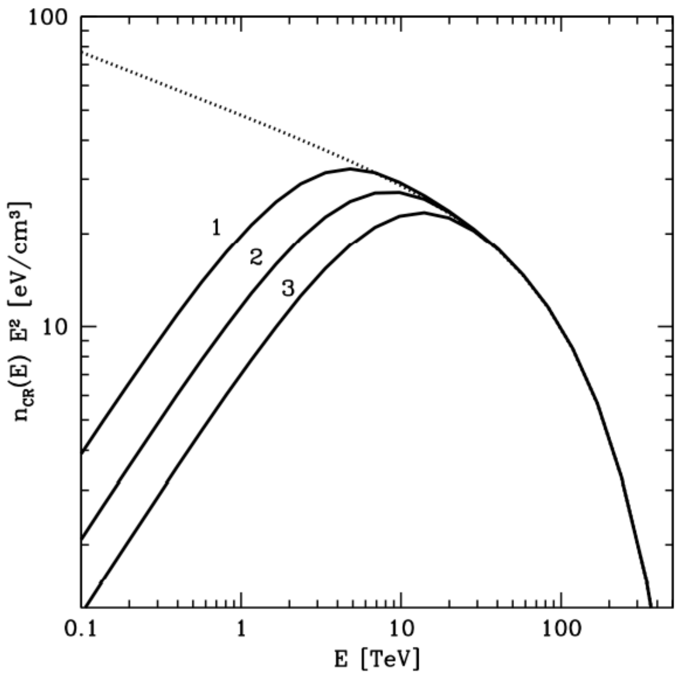


Figure 1. Spectrum of CRs in the SNR shell (dotted line) and inside a clump that entered the shock at t_c = 1400, 1500, and 1550 yr (solid line 1, 2, and 3 respectively).

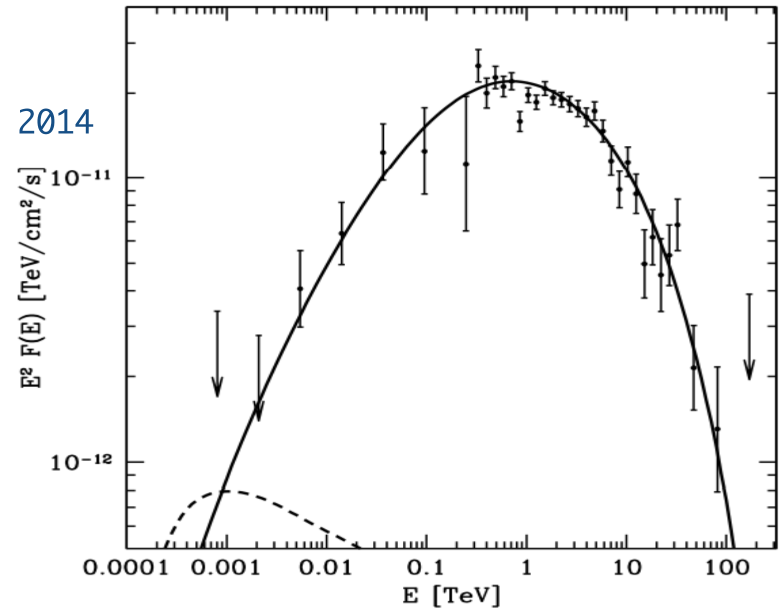


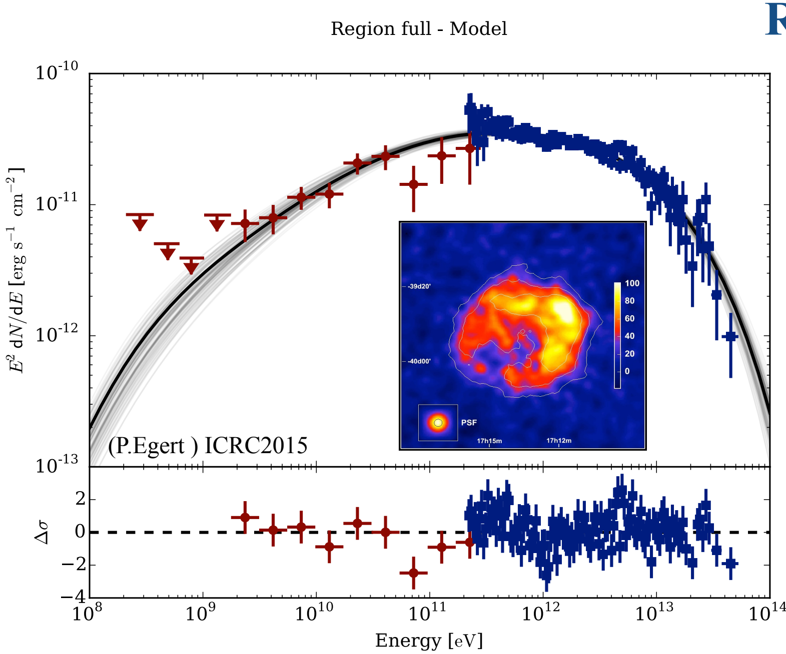
Figure 2. Gamma–rays from RX J1713.7-3946. The emission from the clumps is shown as a solid line, while the dashed line refers to the emission from the diffuse gas in the shell. Data points refer to *FERMI* and *HESS* observations.

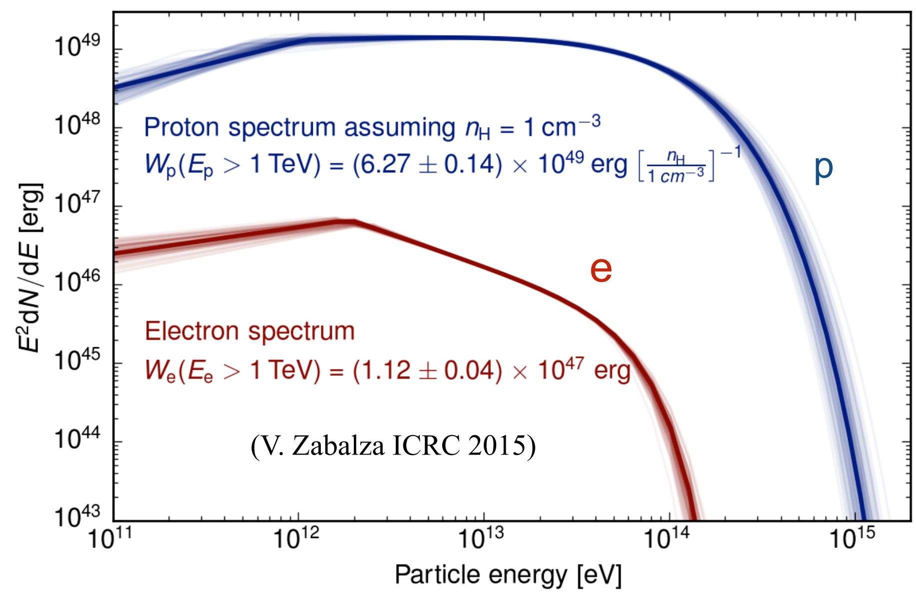
Probing the distributions of accelerated particles in SNRs

HESS measurements

derived spectra of e and p

RXJ 1713



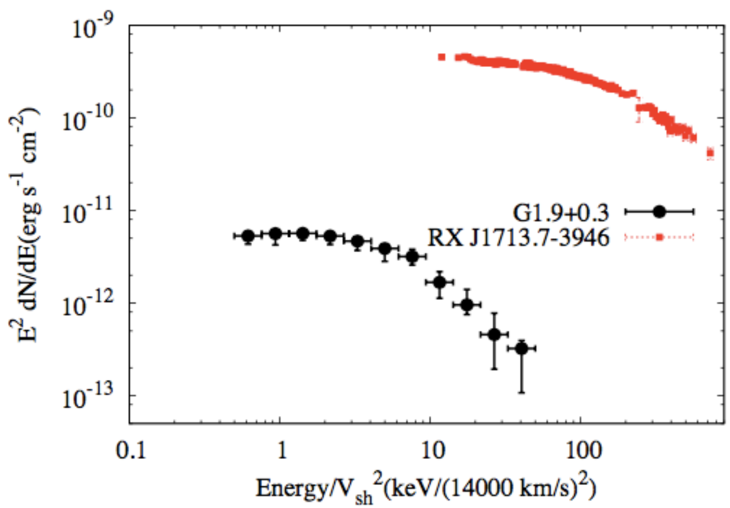


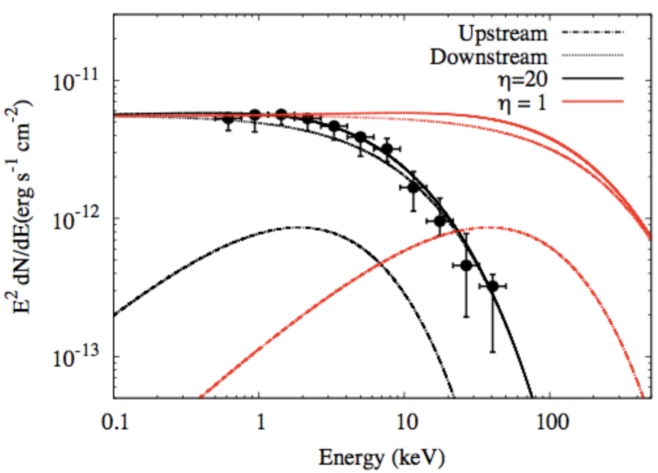
important !!! extension of measurements to arcimin (sub-pc) structures both inside and outside the shells

Very young SNRs as PeVatrons?

G1.9 - 100 yr old SNR in our Galaxy with v=14,000 km/s

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

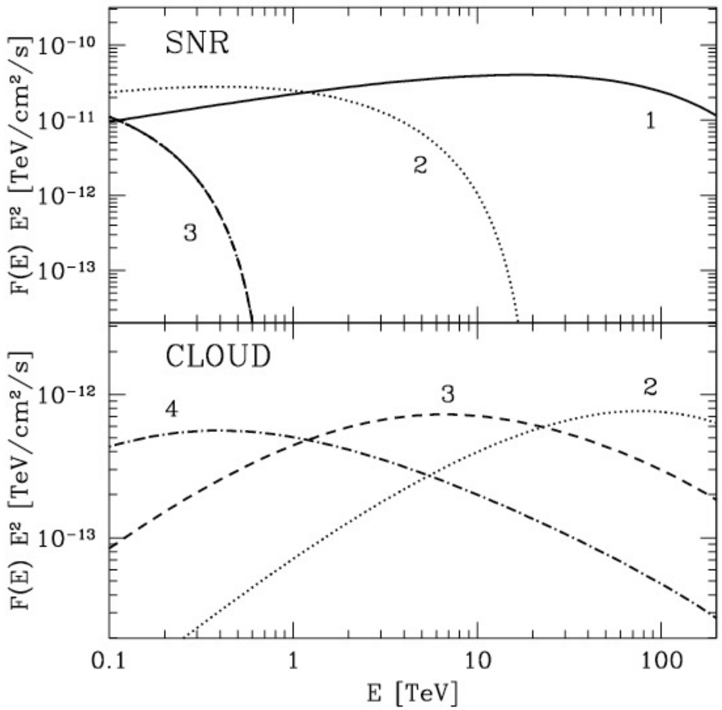




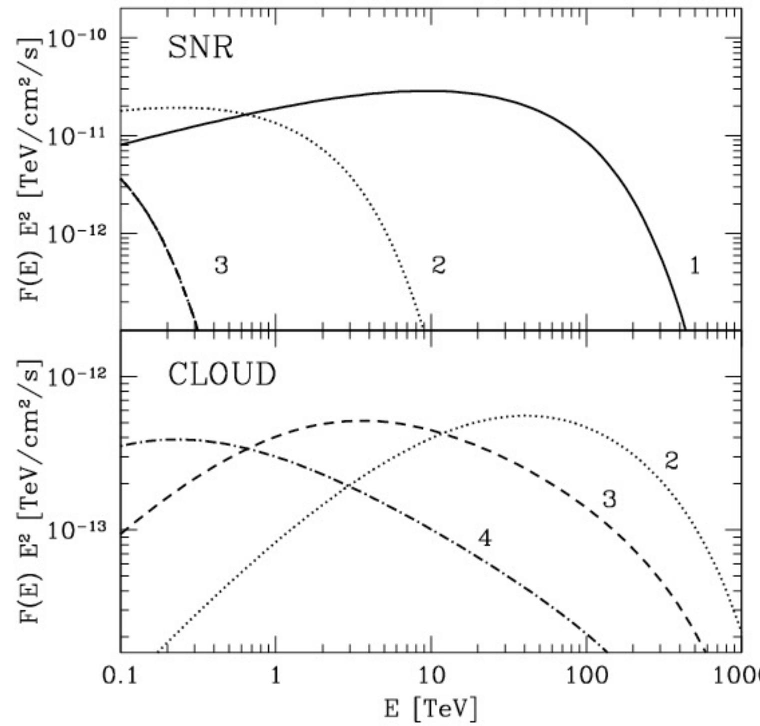
Gamma-rays and neutrinos inside and outside of SNRs

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: $D(E)=3x10^{26}(E/10TeV)^{1/2}\ cm^2/s$

S. Gabici & FA 2007

warning: don't be tricked by propagation effects!

transition from rectilinear to diffusive regime of propagation

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

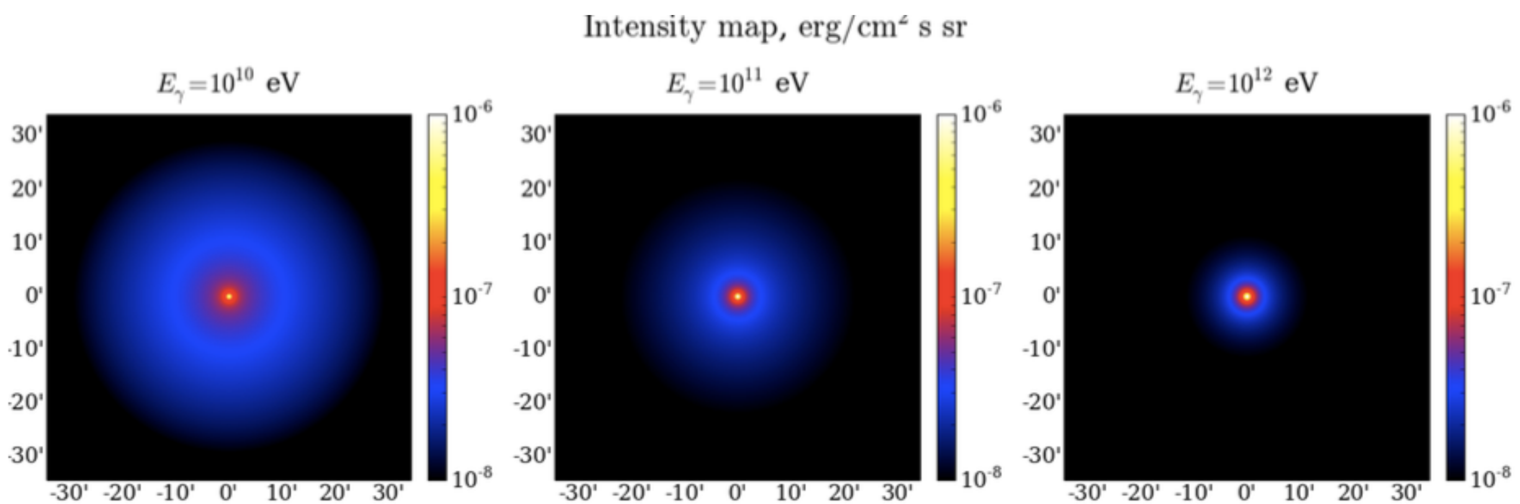


Figure 2: The intensity maps of gamma-ray emission at different energies. The spherical cloud with homogeneous density distribution is irradiated by the cosmic-ray source located in its centre. The gas density inside the accelerator is assumed very low, so the contribution of the accelerator to the gamma-ray 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 $\sim 1^\circ \times 1^\circ$ corresponds to the area $\sim 20 \times 20$ pc^2.

Prosekin, Kelner, FA 2015

warning: don’t be tricked by propagation effects!

transition from rectilinear to diffusive regime of propagation

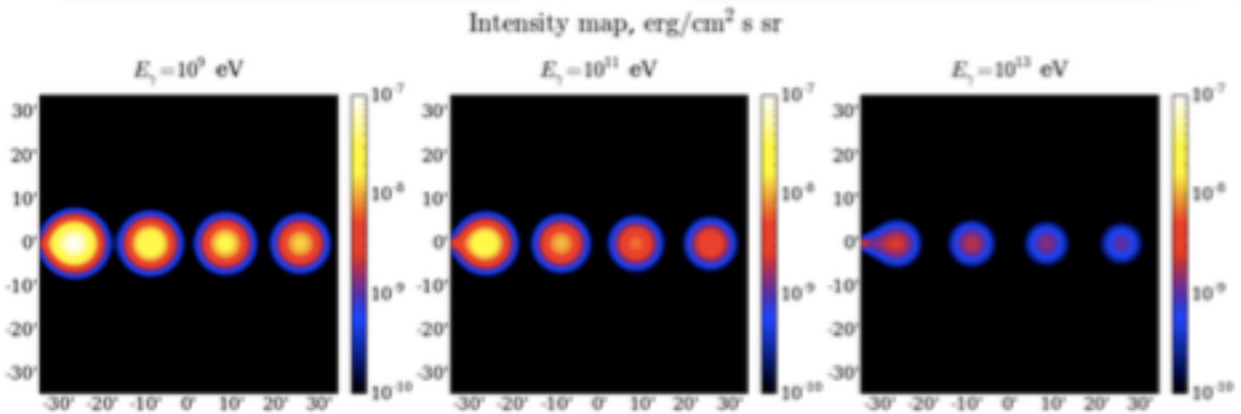


Figure 5: The intensity maps of gamma-ray emission from the group of clouds (without background) at various energies for the case of low diffusion coefficient. The cosmic-ray source is located in the centre of the left side.

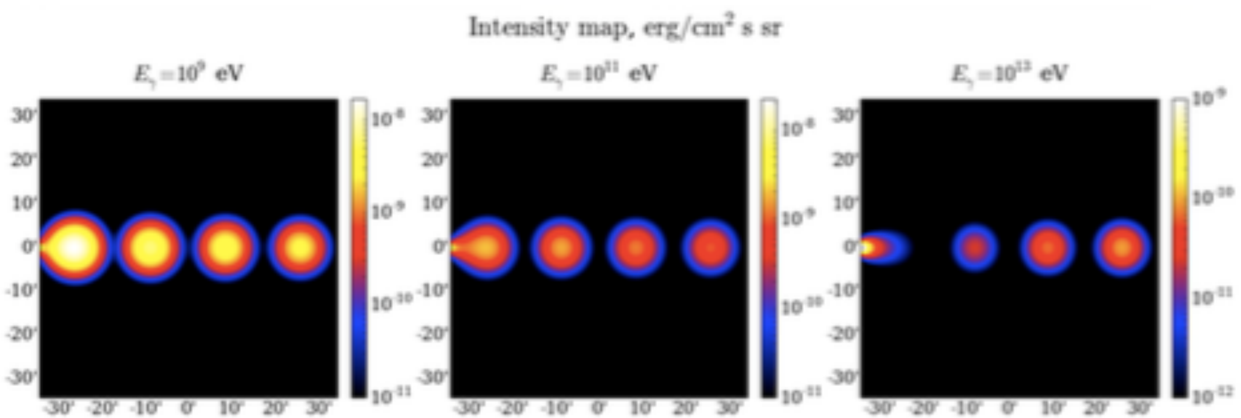


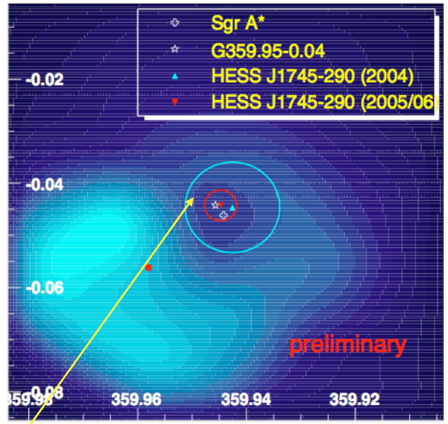
Figure 6: The same as in Fig. 5 for the case of high diffusion coefficient.

Prosekin, Kelner, FA 2015

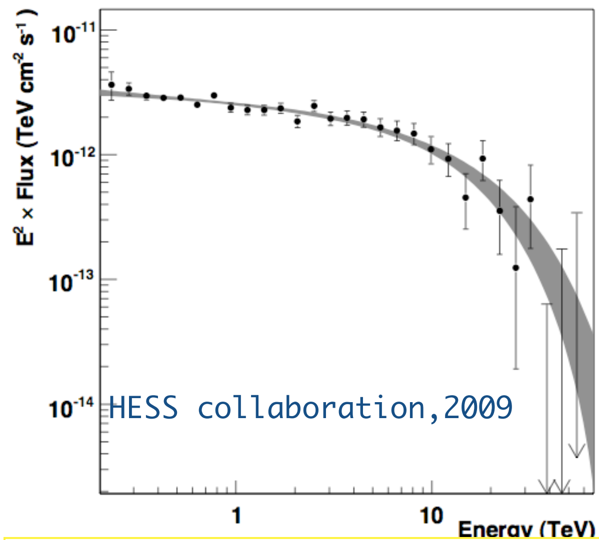
PeVatron(s) in the Galactic Center!

TeV gamma-rays from GC

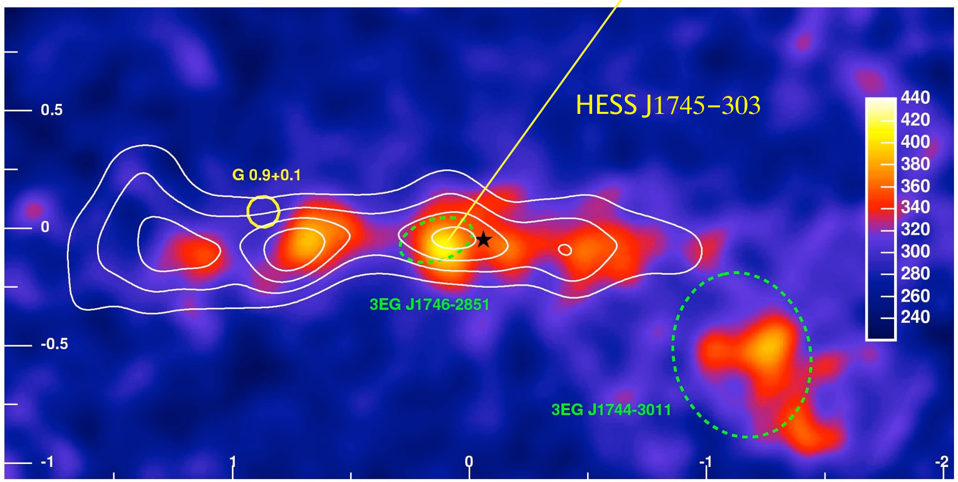
90 cm VLA radio image



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

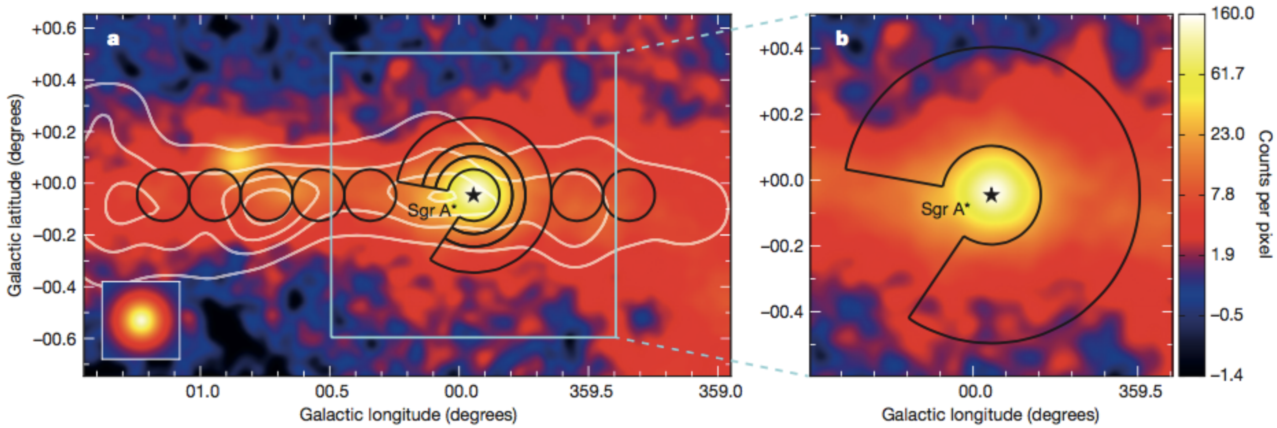
$\beta=1/2$ $\Gamma=1.9$ $E0=4.0$ TeV

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^{37-38} erg/s

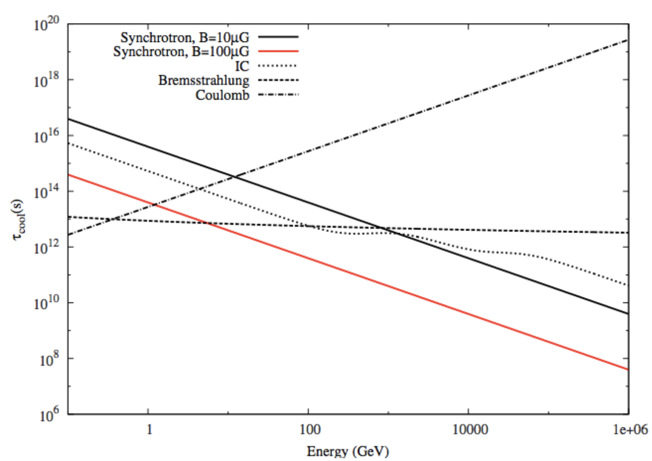
this conclusion is based on spectroscopic and morphological studies of diffuse VHE gamma-ray component in so-called ~200 pc radius Central Molecular Zone (CMZ) of the GC

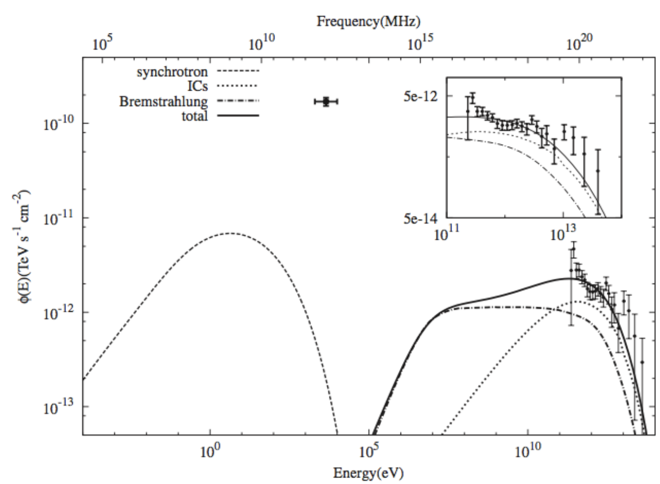
- for the first time, a gamma-ray spectrum is registered that continues without a cutoff or a break up to 20-30 TeV (most likely, 50 TeV)
- for the first time, the density profile of parent protons is derived based on analysis of spatial distributions of VHE gamma-rays and the gas in GC



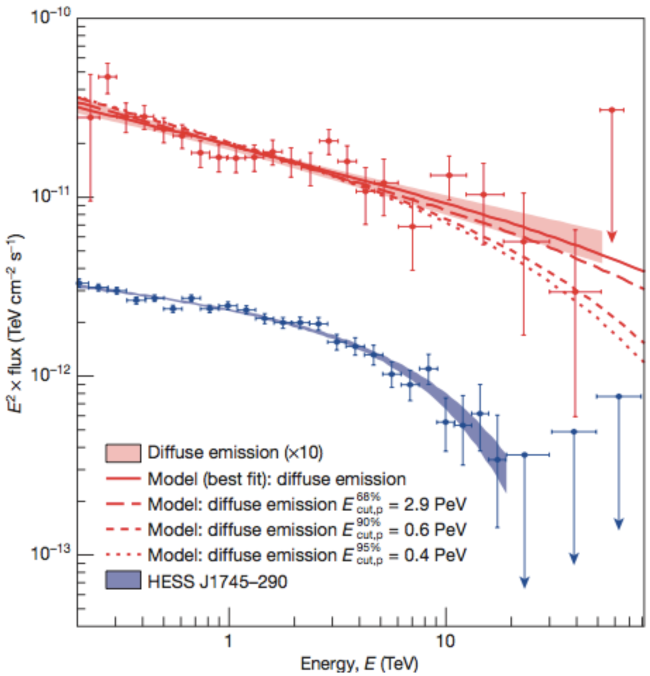
gamma-rays are of hadronic (pp) origin:

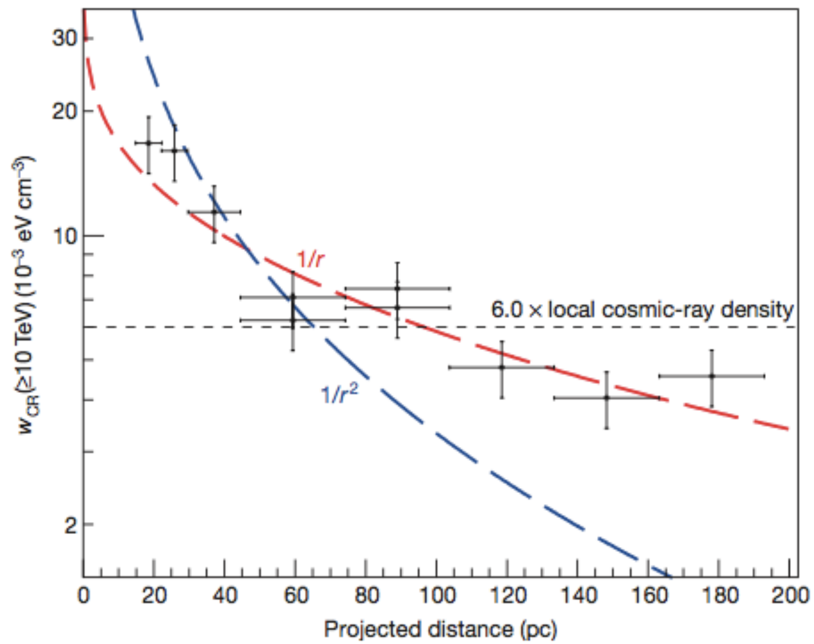
- gamma-ray brightness correlates with gas density (but not linearly!)
- mean free paths of 100 TeV gamma-rays cannot exceed a few pc
- because of cooling of electrons the IC spectrum breaks below 10TeV





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

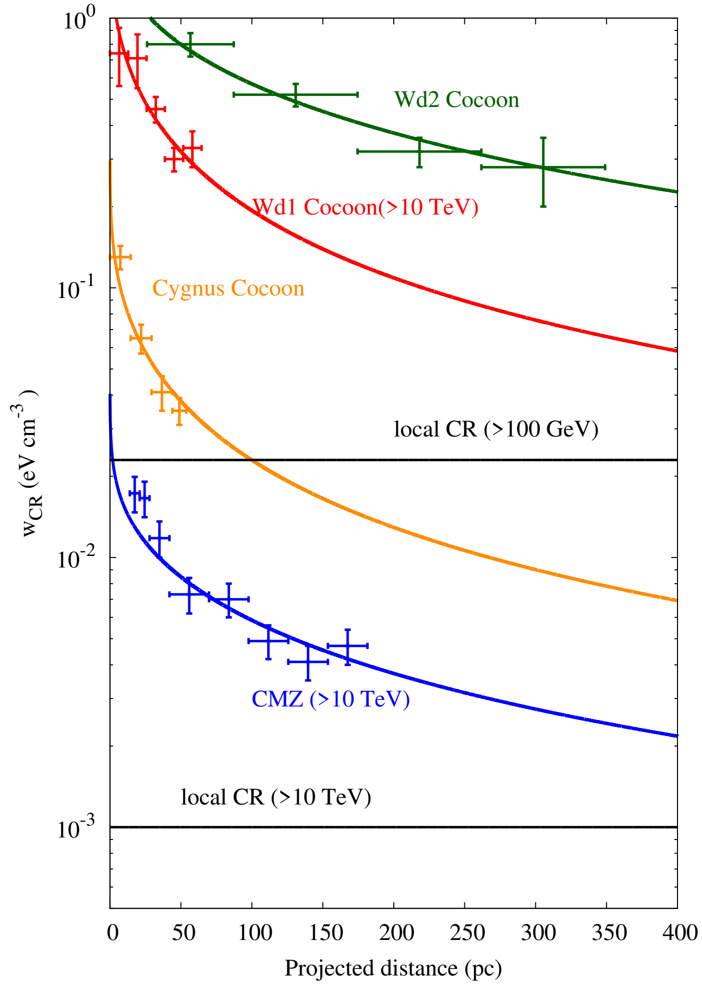
derived: **1/r** distribution

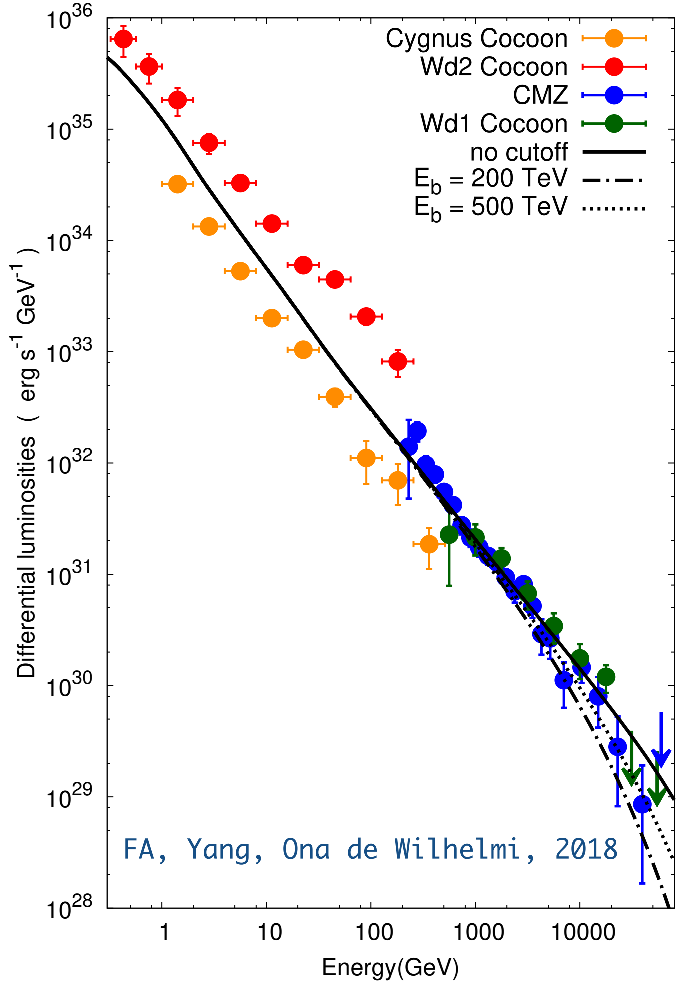
=> continuous acceleration !

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?





1/r - continuous accelerator!

gas density, gamma-ray flux and image extension - constraints on diffusion coefficient and CR production efficiency for WD2 - at least 10-20 %

Summary:

(1) γ-ray studies of galactic sources with future ground-based instruments - CTA and high-altitude particle arrays will help to solve, in one way or another, the 10-year old puzzle of the origin of Galactic CRs, and understand deeper the physics and astrophysics of Cosmic Rays in the Milky Way

(2) my personal (apparently, biased) opinion:

- we are very close to the solution; the **current (SNR) paradigm will be modified or revised**

- in the **new paradigm, Clusters of YMS** will be the major sources of CR, at least at TeV energies

Galactic Cosmic Rays are produced by young/energetic rather than dead stars