Galactic PeVatrons

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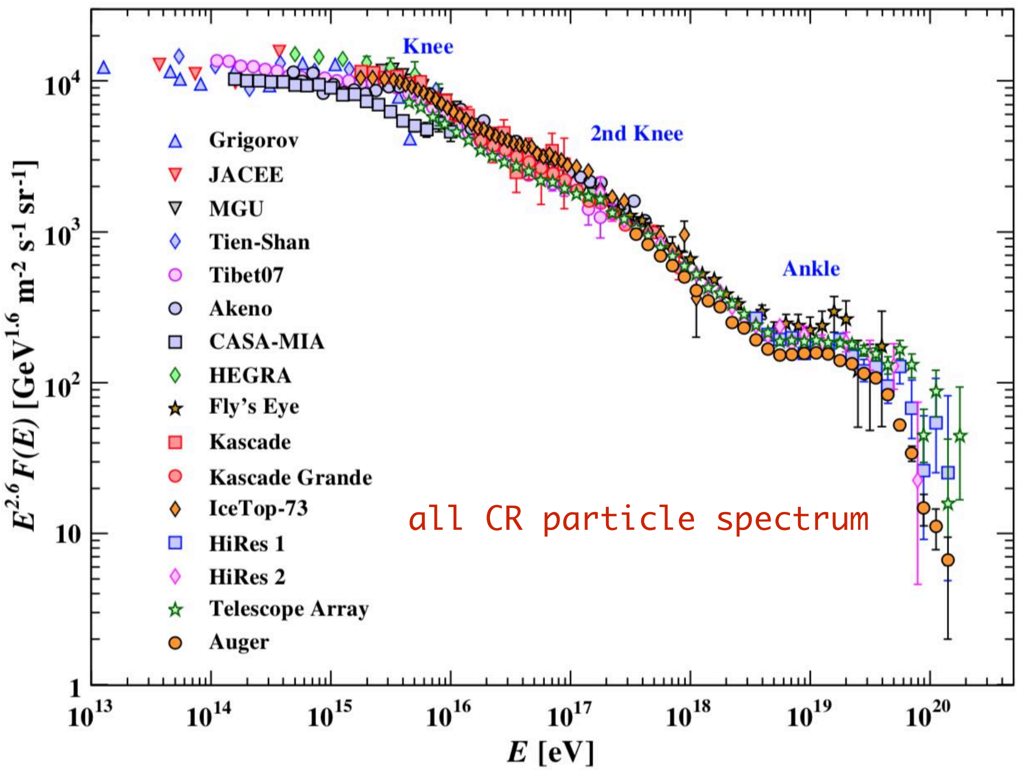
far, far away, something – somewhere – is creating particles with crazy amounts of energy

physicsworld 31 July 2018

"…after 100+ years of the discovery, the origin of Cosmic Rays remains a mystery…"



this is an exaggeration - wee know a lot of about CRs, in particular we know that

up to (at least) 10^{15} eV - CRs are produced in our Galaxy

above (at least) 10^{18} eV - CRs. are produced outside the Galaxy

what does imply "Origin of Cosmic Rays" ?

the term "Cosmic Rays" itself has two meanings

- locally detected nonthermal/relativistic particles - a *"local fog"*

often it is reduced to the identification of the main contributors to CRs

- the 4th substance of the visible Universe (after the matter, radiation and magnetic fields) - a *more fundamental issue*

factories of CRs are perfectly designed accelerators operating at the margin of maximum possible efficiency in the sense of (1) conversion of the available energy to CRs and (2) the energies achieved by individual particles

"misteries" ?

several - one of them the existence of **Galactic PeVatrons**

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 is not a big surprise that major contributors to CRs are not yet firmly identified

charged CRs do not provide information about the acceleration sites

CR factories can be revealed only by *astronomical* means:

messengers should be neutral & stable: photons and neutrinos

observations:

GeV-TeV gamma-rays => several populations of CR accelerators in our Galaxy - *among them the major suspects:* **SNRs**

multi-TeV neutrinos => *if* galactic - messengers of galactic PeVatrons

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)

sources of Galactic Cosmic Rays?

basic facts:

energy density: ~ 1eV/cm^3 ; age: ~ 10^6 - 10^7 yrs,

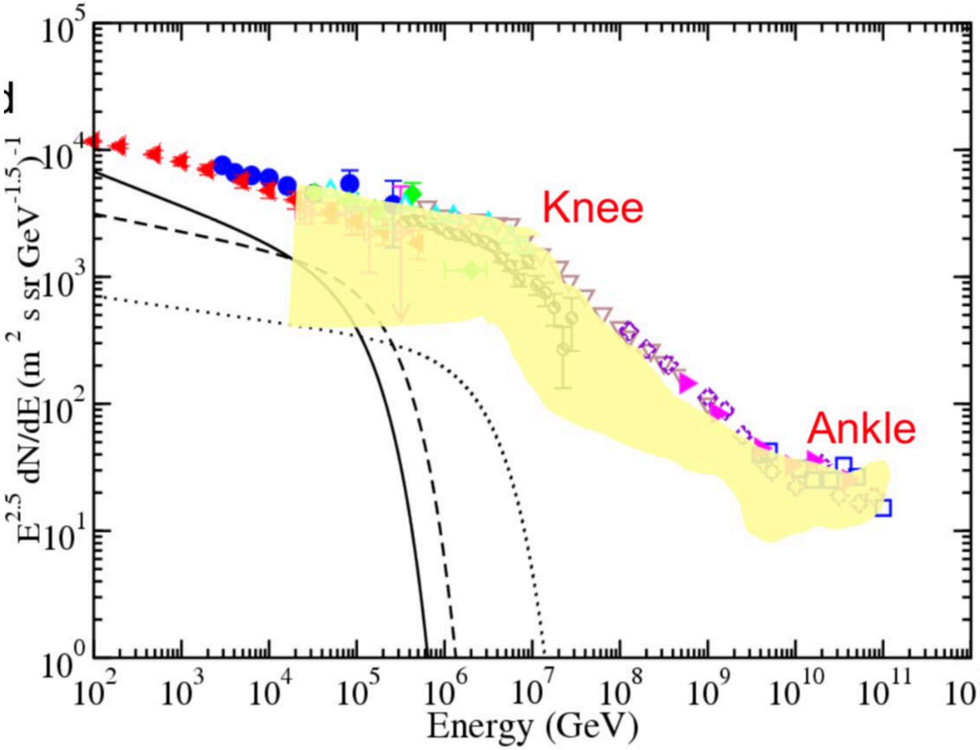
production rate: **(0.3-1) x 10^{41} erg/s**, source spectrum: harder than the locally observed because of modulation during propagation $E^{-\alpha-\delta}$ (energy dependent diffusion) in the ISM

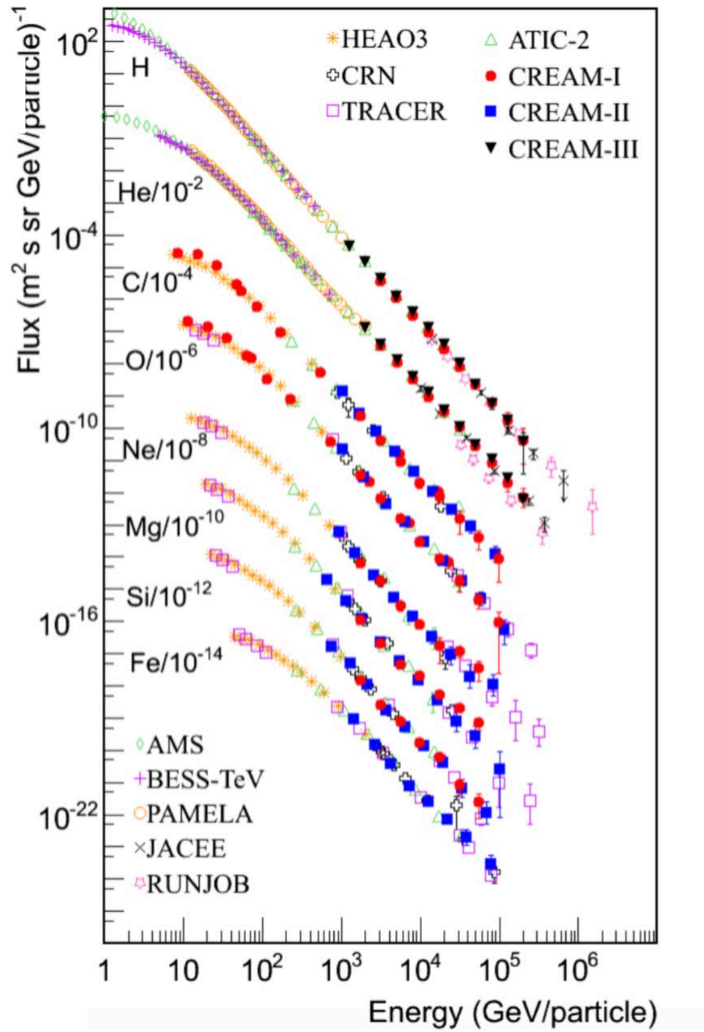
sources ? should have power not much less than **10^{42} erg/s**

- ✓ Supernova Remnants (**SNRs**)**:** at least up to 10 TeV or more
  we do not have decisive evidence of SNRs operating as CR PeVatrons…
- ✓ stellar winds in Clusters of Young Massive Stars (**CYMS**)
- ✓ Galactic Center (**Sgr A***)? presently 10^{39} erg/s, potentially $>10^{43}$ erg/s
- ✓ pulsars/magnetars ….

Galactic Cosmic Rays: up to 1 PeV (and beyond?)

Eun-Suk Seo 2018



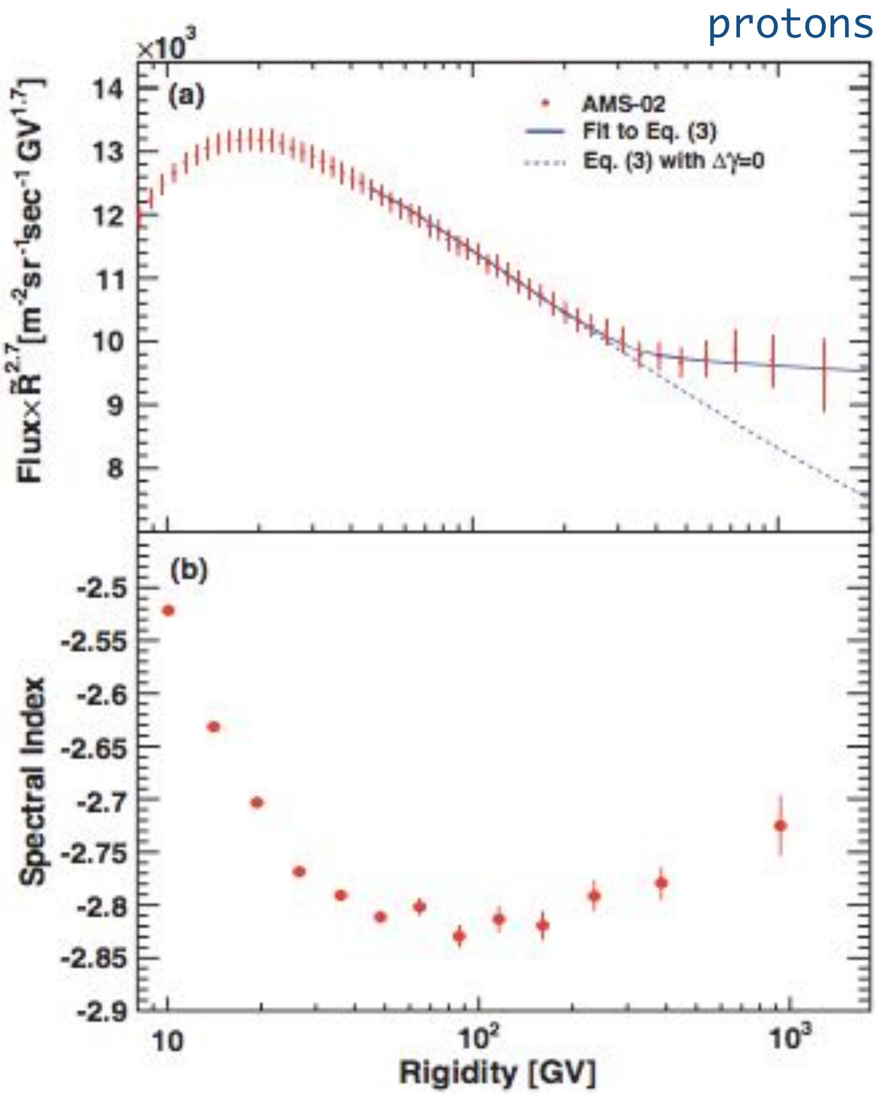


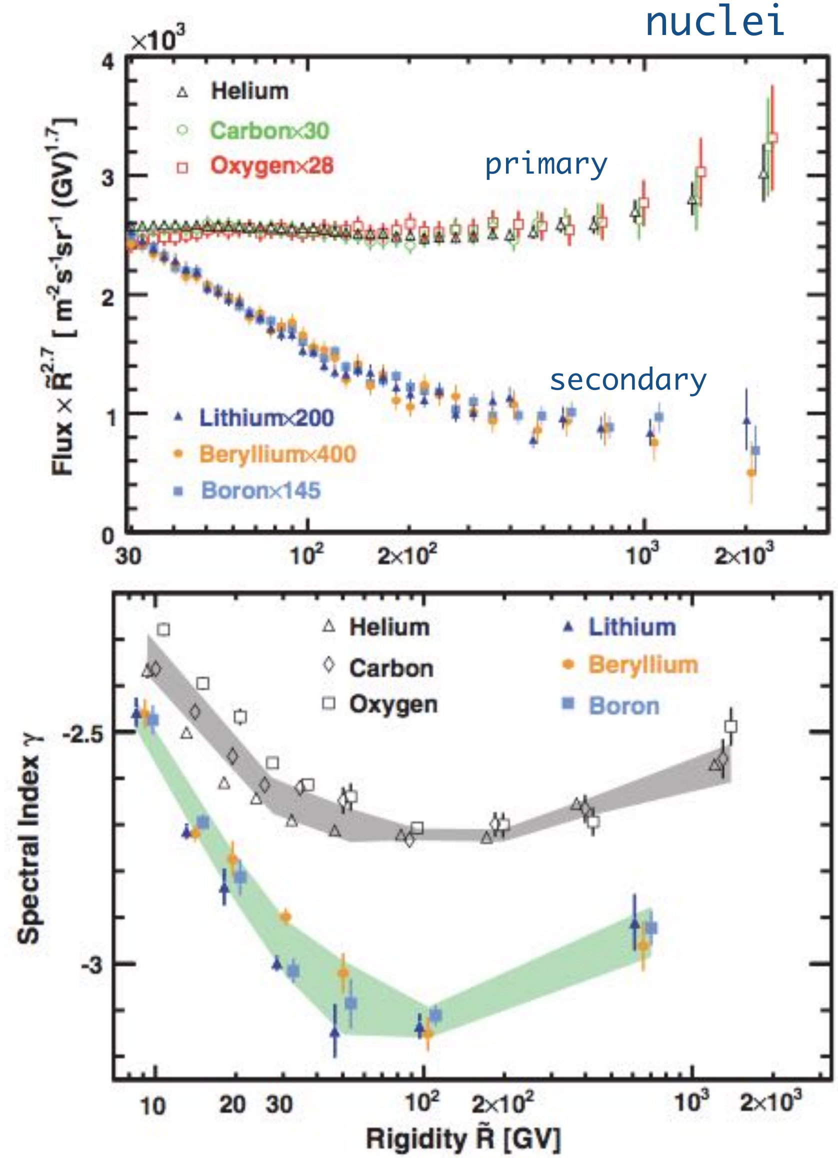
single power-law up to 1 PeV ?

(1) a dominant source-population?

(2) main contributors are PeVatrons

recent remarkable achievements





a new spectral structure seen in GCRs

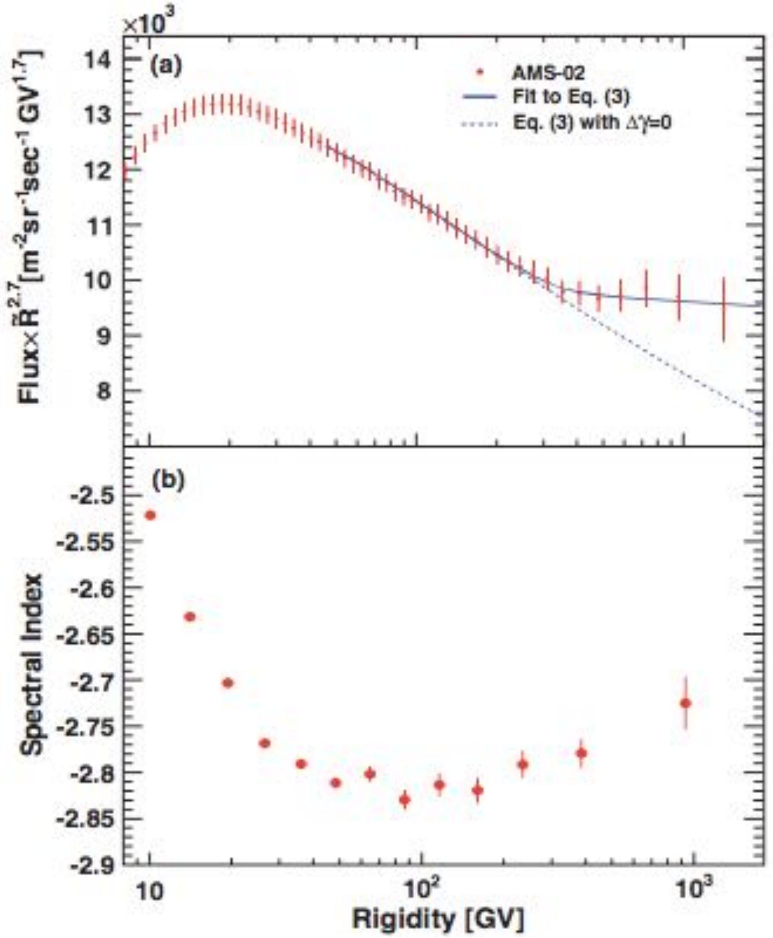
hardening of **energy spectra of all CR species above 100 GeV/nuc**

reason?

- change of the acceleration character

- change of the Diffusion Coefficient in ISM

- a new c component



- two or more source populations as major contributors to the "local fog"?

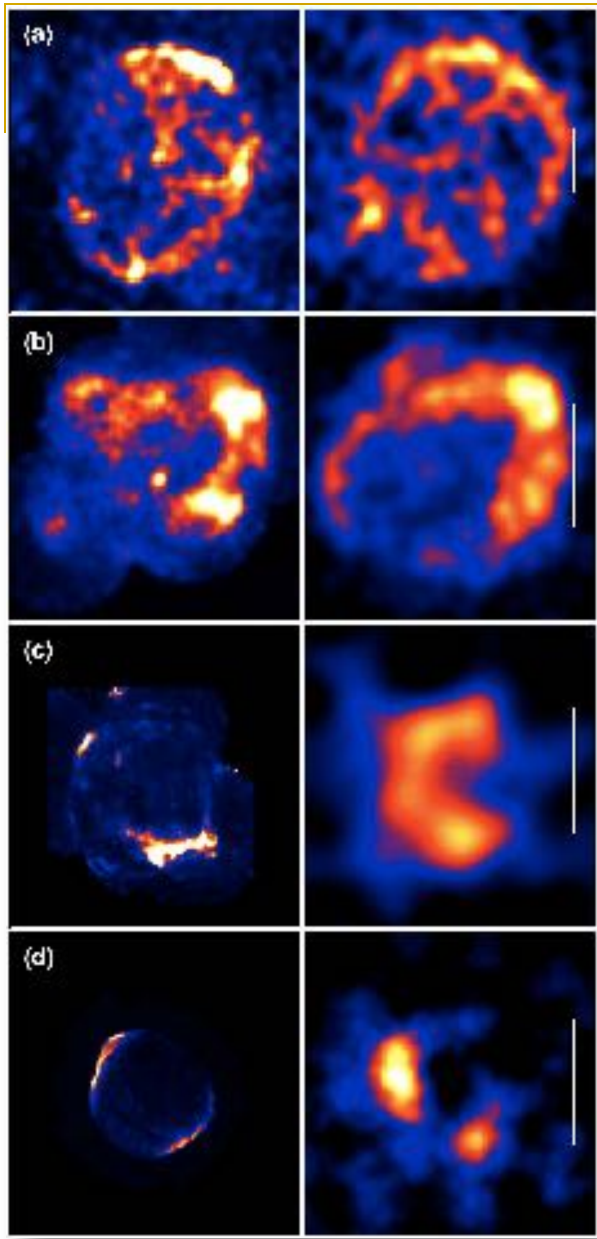
- spectra of CRs injected into ISM - noticeably steeper than E^{-2} (?!)

SNRs and Galactic Cosmic Rays

SNRs as the most likely sources
of galactic cosmic rays?

main hope is related to gamma-ray observations:

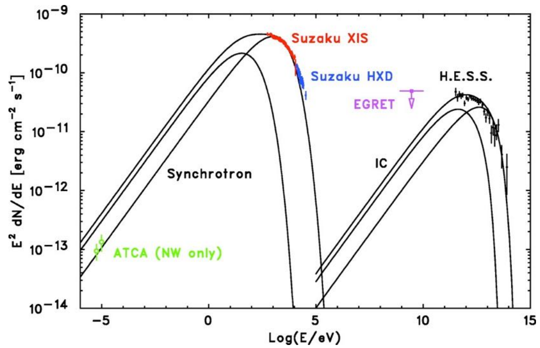
- detect VHE gamma-rays from SNRs
- demonstrate that they have hadronic origin
- demonstrate that proton spectra continue up to 1 PeV

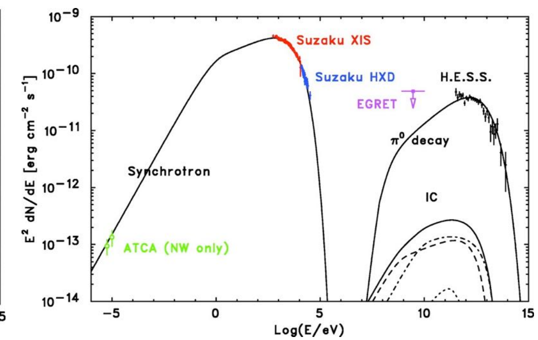


acceleration of protons and/or electrons in SNR shells to energies up to 100TeV

leptonic or hadronic?

=>





RXJ1713.7-4639

inverse Compton scattering of electrons on 2.7K CMBR

B=15μG

We ≈3.4 10^{47} erg/cm^3

γ-rays from pp ->π^o ->2γ

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

with α=1.7, Eo ≈ 25 TeV,

B=200μG

Wp ≈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

- 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

  only in Cas A p/e in principle could be 100

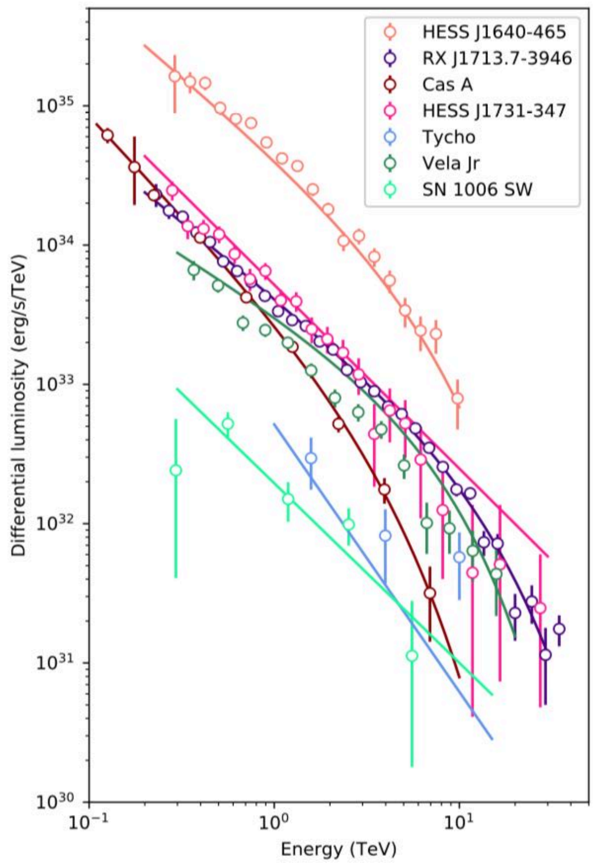
- "early cutoffs" - so far, in all SNRs Ecut < 100 TeV
  - IC gamma-rays; we do not see the hadronic component (?!)

- should we relax and accept that SNRs are main contributors to GCRs but at TeV energies are overtaken by other source population (PeVatrons) responsible for the knee? (Laggage and Cesarsky 1983) ?

or

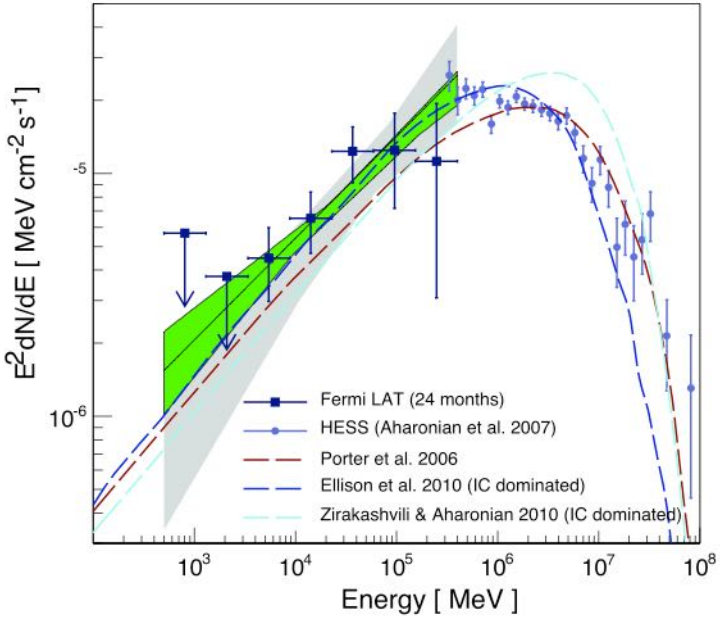
- relate it to the much early "PeVatron Phase" - first 10 to 100 years after the SN explosion (Bell+,Blasi+,Zirakashvili+) and the escape of highest energy particles from the remnant

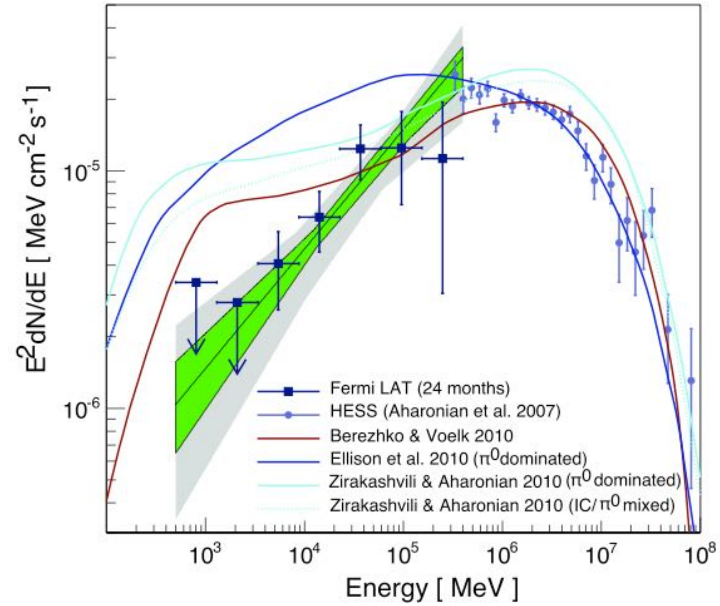
Energy spectra of young supernova remnants



this figure tells us something different than we would like to see…

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?

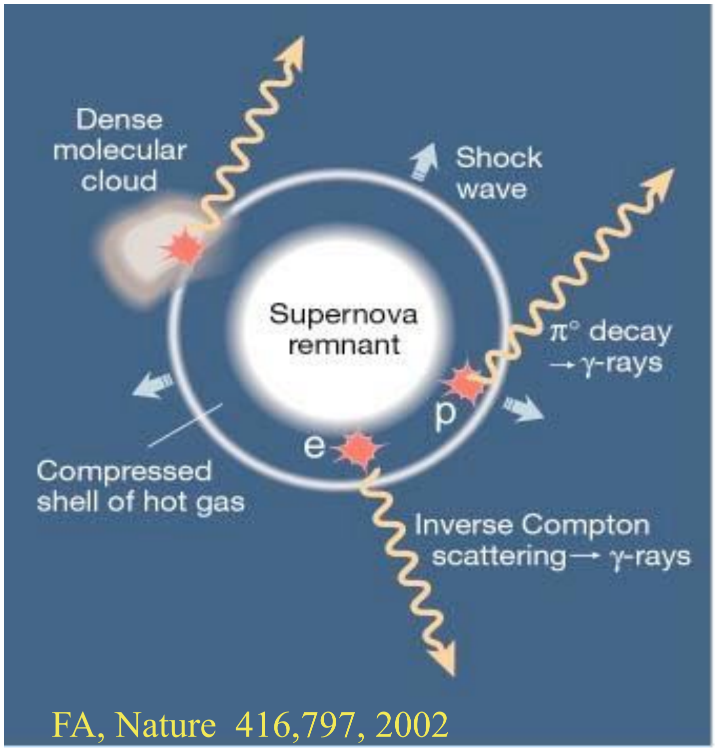
they could come from quite different regions

(ii) cannot we assume hard proton spectra ?

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

SNR emission with suppressed spectrum at GeV energies

GeV gamma-rays can be suppressed because low energy protons cannot cannot penetrate deep into the dense clouds/clumps Zirakashvili&FA 2010, Inoue et al. 2011, Gabici et al. 2014) => see talk by S. Celli (this afternoon)



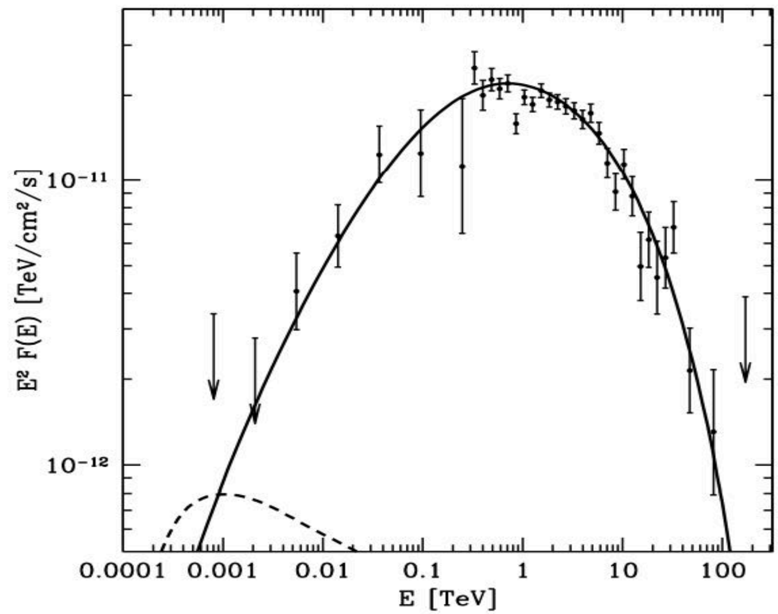


Figure 2. Gamma–rays from RX J1713.7-3946. The emission from the clumps is shown as a solid line, while the dashed line refers to the emission from the diffuse gas in the shell. Data points refer to *FERMI* and *HESS* observations.

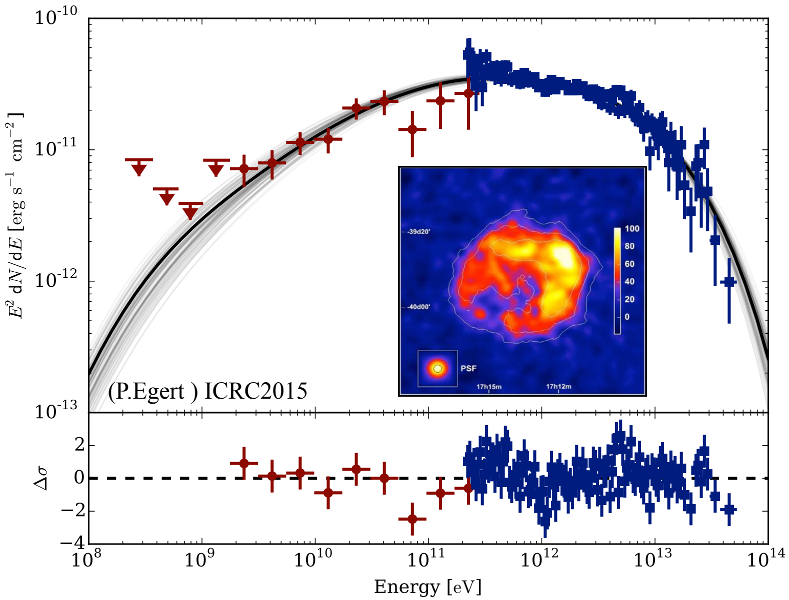
MeV/GeV gamma-rays - important, but only neutrinos, ultra-high energy gamma-rays and hard synchrotron X-rays from secondary electrons can provide decisive conclusions

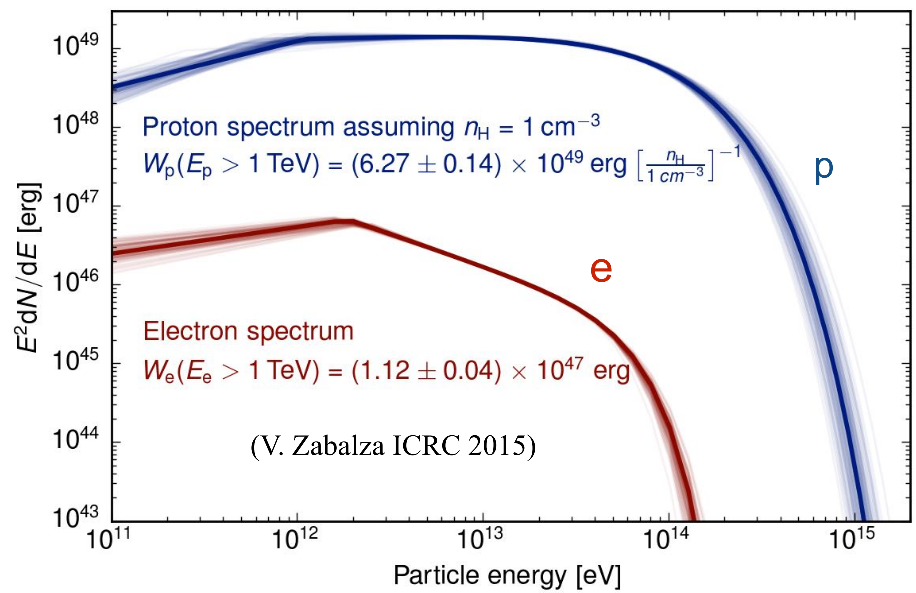
Probing the distributions of accelerated particles in SNRs

HESS measurements

derived spectra of e and p

RXJ 1713





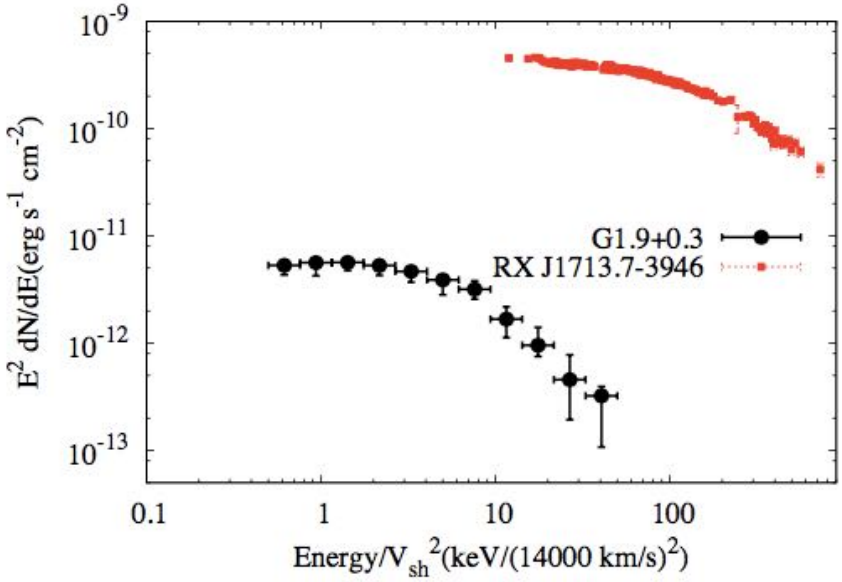
important !!! extension of measurements to arcimin (sub-pc) structures both inside and outside the shells

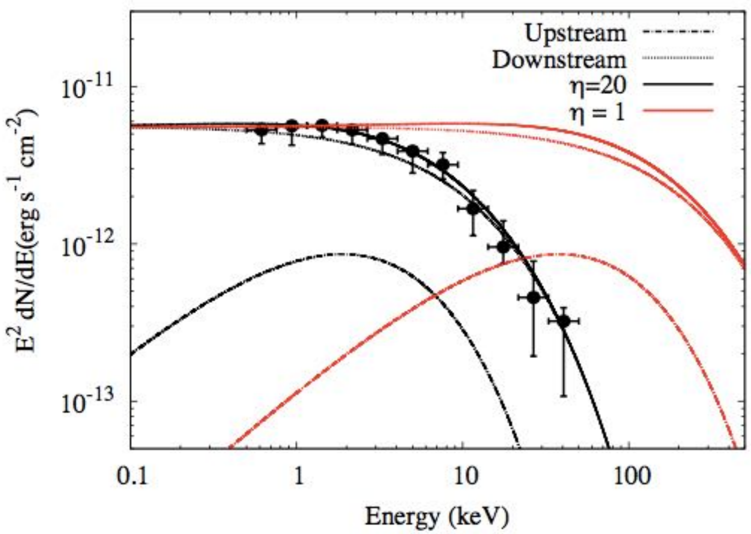
Very young SNRs as PeVatrons?

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

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

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

fortunately, NOT

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 even for **D ~ 10^{30} cm^2/s**

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

therefore the 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

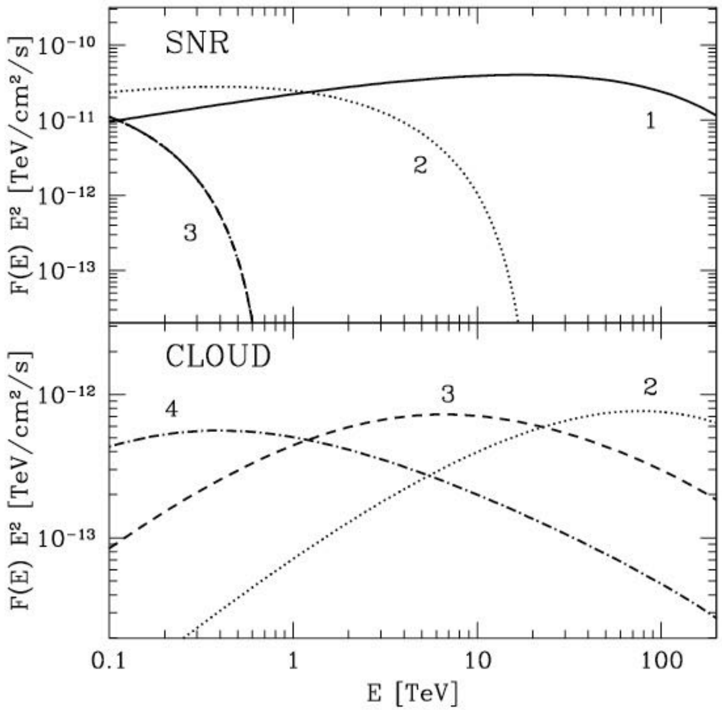
for $n \sim 100\ \mathrm{cm}^{-3}$ $W_p(\geq 10E) = L_\gamma(\geq E) t_\pi$ or **$W_p < 10^{45}$ erg**

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

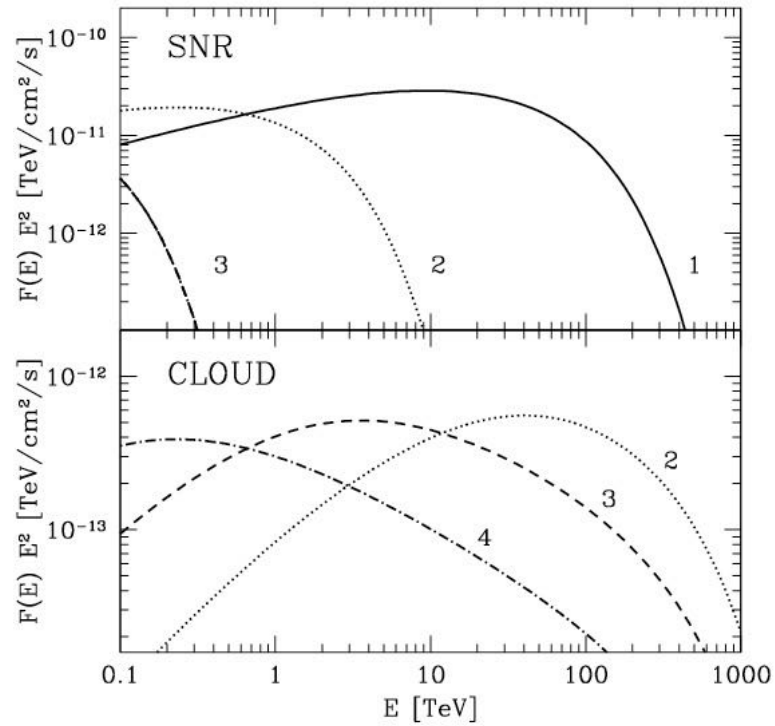
Gamma-rays and neutrinos inside and outside of SNRs

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

S. Gabici & FA 2007

warning: don't be tricked by propagation effects!

transition from rectilinear to diffusive regime of propagation

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

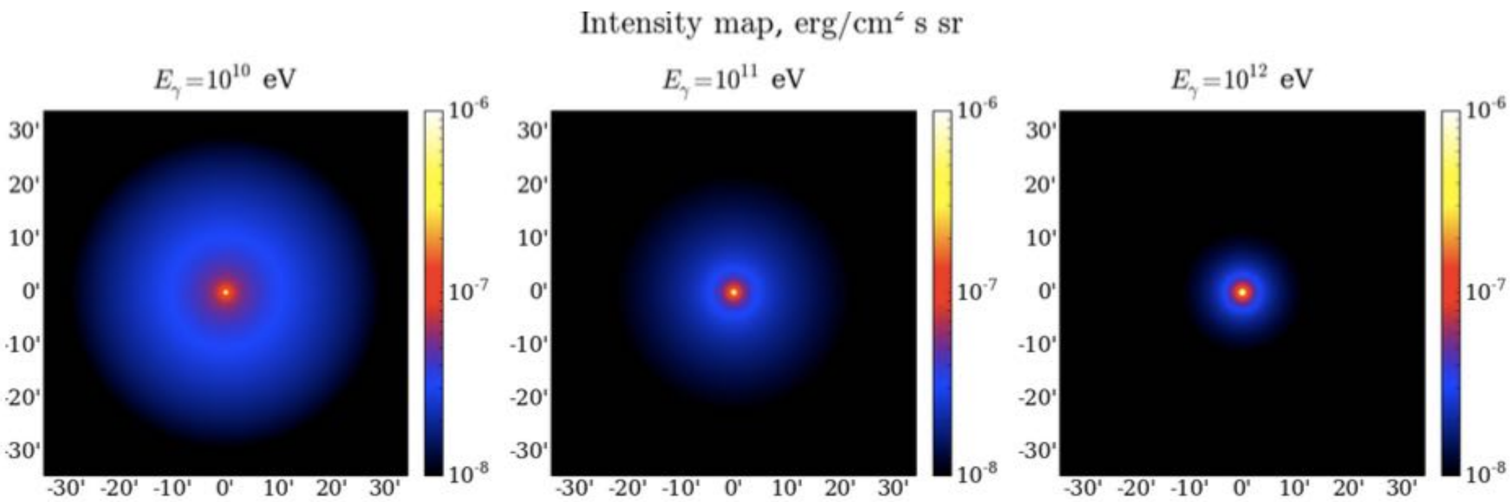
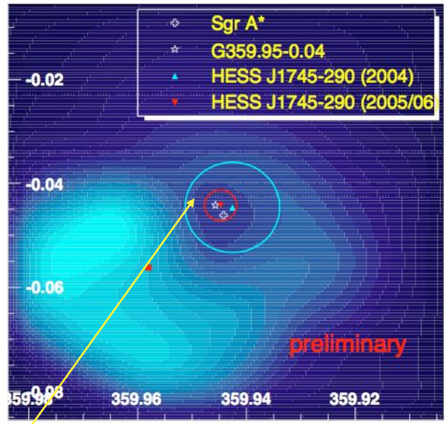


Figure 2: The intensity maps of gamma-ray emission at different energies. The spherical cloud with homogeneous density distribution is irradiated by the cosmic-ray source located in its centre. The gas density inside the accelerator is assumed very low, so the contribution of the accelerator to the gamma-ray 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.

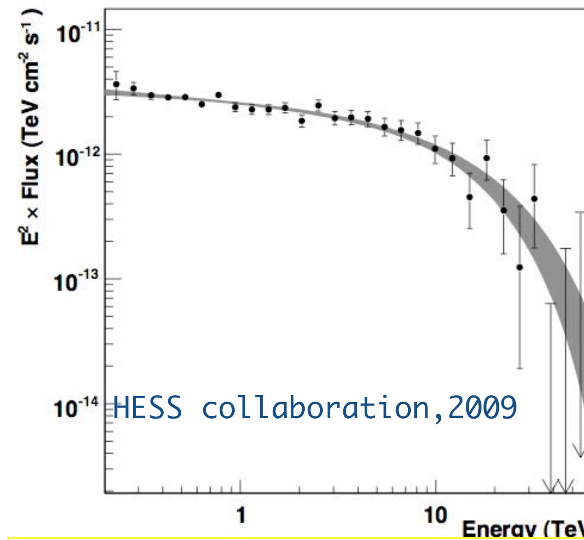
Prosekin, Kelner, FA 2015

TeV gamma-rays from GC

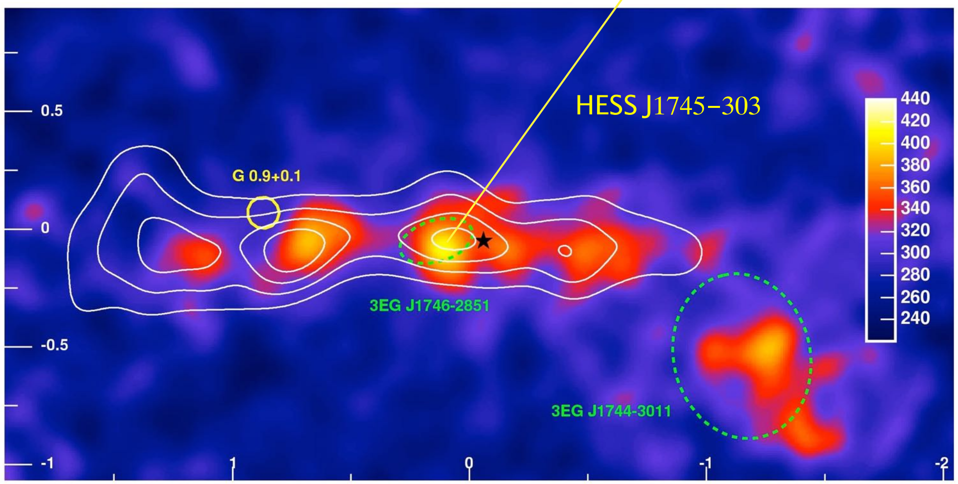
90 cm VLA radio image



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

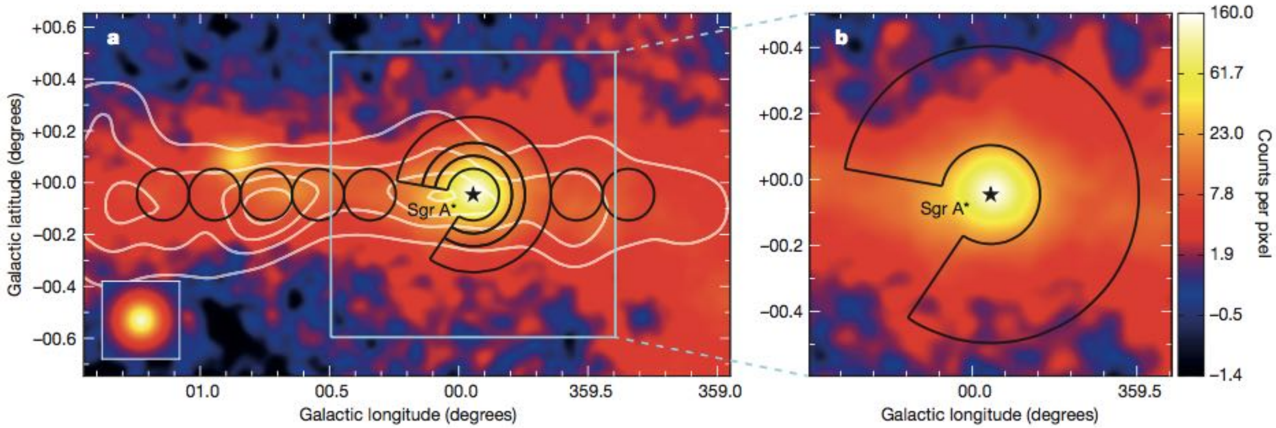
$\beta=1/2$ $\Gamma=1.9$ E0=4.0 TeV

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

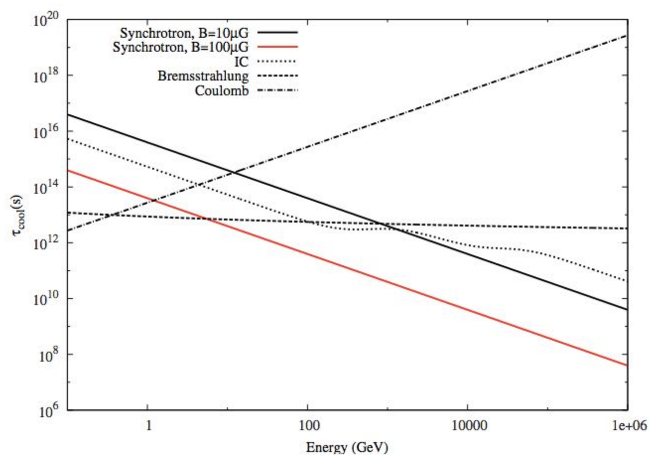
this conclusion is based on spectroscopic and morphological studies of diffuse VHE gamma-ray component in so-called ~200 pc radius Central Molecular Zone (CMZ) of the GC

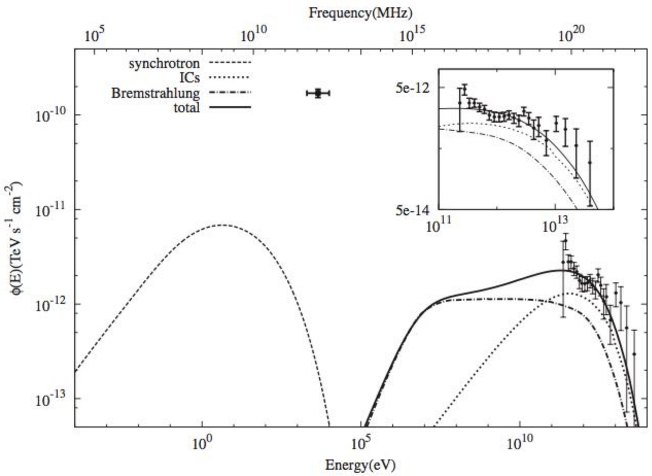
- for the first time, a gamma-ray spectrum is registered that continues without a cutoff or a break up to 20-30 TeV (likely, 50 TeV)
- for the first time, the density profile of parent protons is derived based on analysis of spatial distributions of VHE gamma-rays and the gas in GC



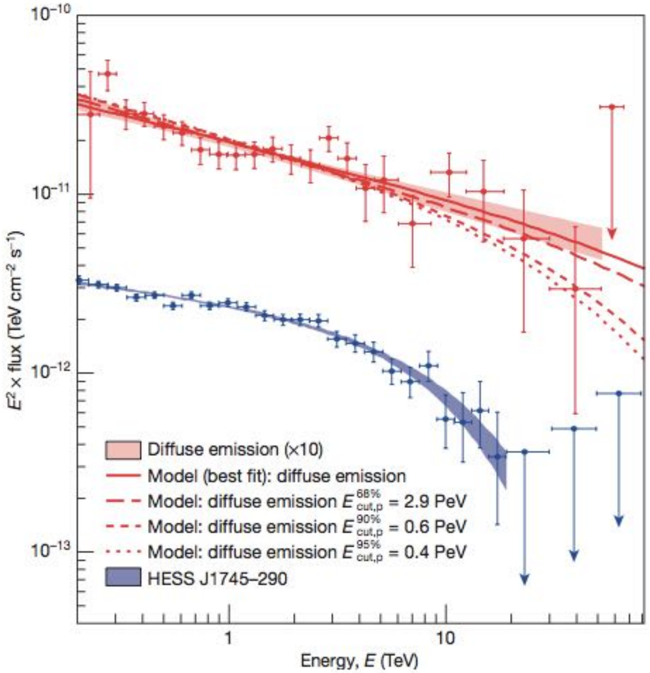
gamma-rays are of hadronic (pp) origin:

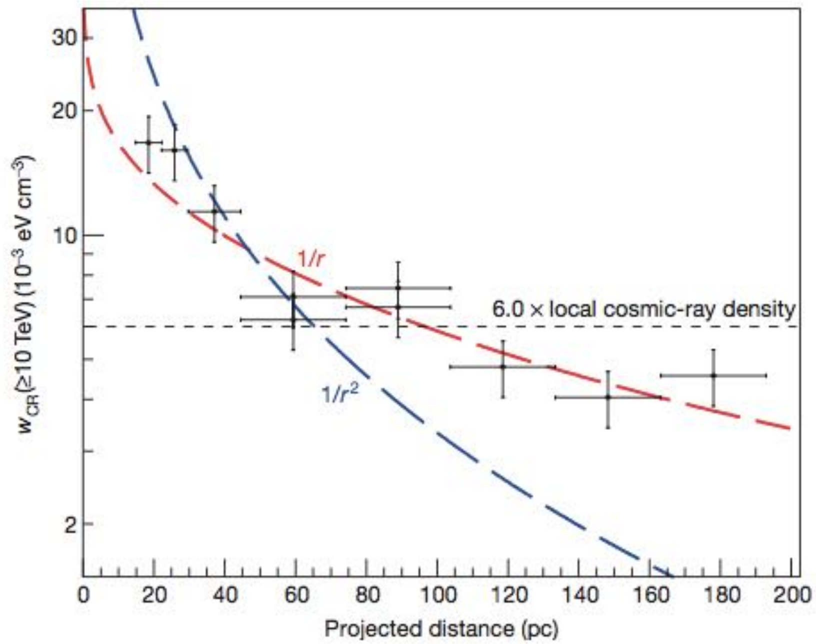
- gamma-ray brightness correlates with gas density (but not linearly!)
- mean free paths of 100 TeV gamma-rays cannot exceed a few pc
- because of cooling of electrons the IC spectrum breaks below 10TeV





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-star clusters?

Extended Regions surrounding Clusters of Young Massive Stars sources of GeV and TeV gamma-rays

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

CygnusOB2, *Westerlund 2*, *NGC3603*

Arches, *Quintuplet* and *Nuclear* clusters in GC

- collective power in stellar wind 10^{38} - 10^{39} erg/s
- typical speeds of stellar winds several 1000 km/s

continuous injections of CRs into ISM over (2-5) x 10^{6} yrs

formation of $\sim 1/r$ radial distribution of CRs up to 100 pc and beyonds

Diffuse (typically irregular) gamma-ray morphology

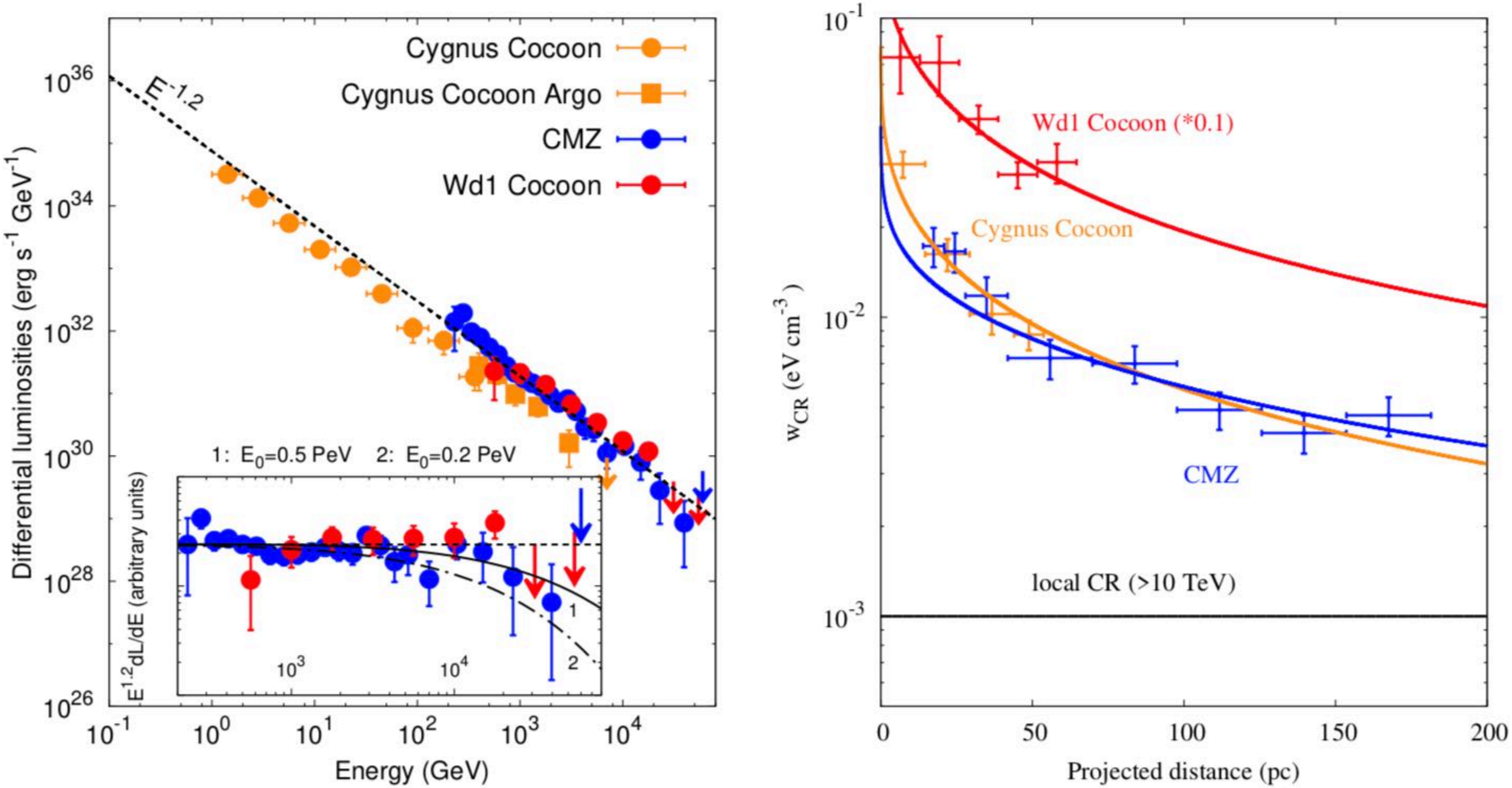


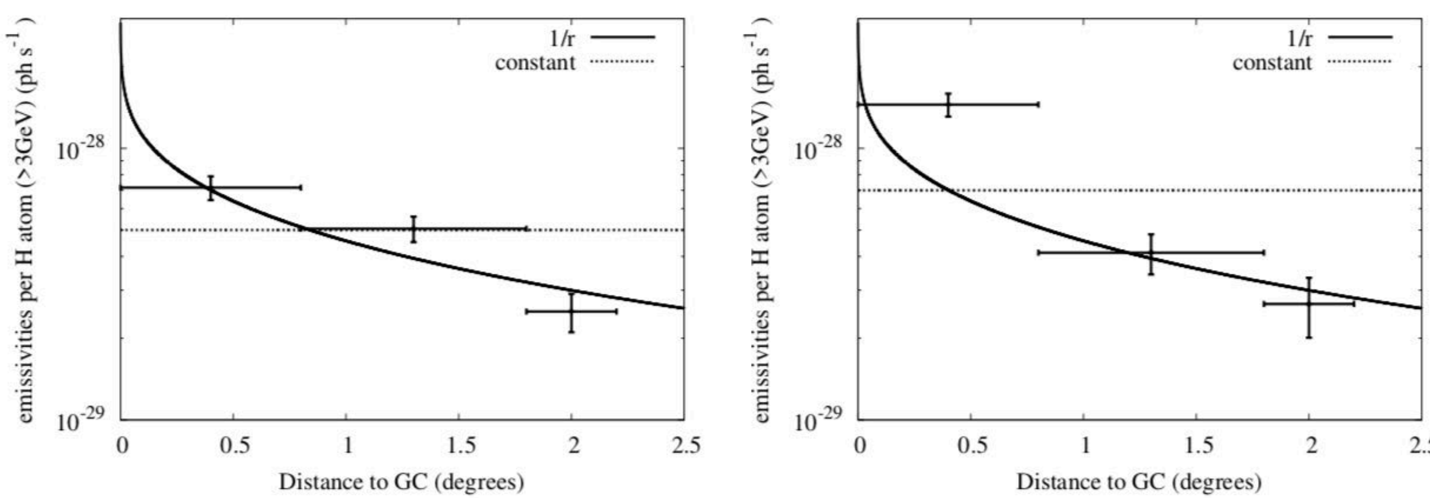
Figure 1: Gamma-ray luminosities and CR proton radial distributions in extended regions around the star clusters Cyg OB2 (Cygnus Cocoon) and Westerlund 1 (Wd 1 Cocoon), as well as in the Central Molecular Zone (CMZ) of the Galactic Centre assuming that CMZ is powered by CRs accelerated in *Arches*, *Quintuplet*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

FA, Yang, Ona de Wilhelmi, 2018

$$w(r) = w_0(r/r_0)^{-1}$$

Source	Cyg Cocoon	CMZ	Wd 1 Cocoon
Extension (pc)	50	175	60
Age of cluster (Myr)[27]	3–6	2–7	4–6
L_{kin} of cluster (erg/s)	2×10^{38} [17]	1×10^{39} [28]	1×10^{39} [29]
Distance (kpc)	1.4	8.5	4
$\omega_o(> 10\text{TeV})$ (eV/cm^3)	0.05	0.07	1.2

Table 1: Physical parameters of four extended γ-ray structures and the related stellar clusters



Extended Data Figure 2: The radial profiles of γ-ray emissivities (per H-atom) above 10 GeV with respect to the position of Cygnus OB2 in the south (left panel) and north (right panel) hemisphere of Cygnus Cocoon.

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

Summary

Major Sources of Galactic Cosmic Rays?

<u>Clusters of Young Massive Stars</u> vs <u>Supernova Remnants</u>

- SNRs ?
- CYMSs ?
- SNRs (low energies) + CYMSs (highest energies)
- role of Sgr A* ?

high priority topics for next generation gamma-ray detectors