Probing Cosmic Accelerators with Gamma Rays

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CRIS2016, Ischia, July4-8, 2016

gamma-ray astronomy - a discipline in its own right

- gamma-ray astronomy as one of the branches of Astroparticle Physics
- gamma-ray astronomy as an established *truly* Astronomical discipline

to a large extent, Gamma Ray Astronomy is a *discipline in its own right*:

it is an interdisciplinary field of research at interface of *Physics, Astrophysics and Cosmology* strongly supported by both the (Astro)Particle and Astronomy&Astrophysics communities

HE&VHE gamma-rays - effectively *detectable* messengers of crucial information about "most energetic and violent phenomena in the Universe"

<u>the strength and uniqueness of gamma-ray astronomy</u>

crucial - for specific topics e.g. for the solution of the *Origin of Galactic an Extragalactic Cosmic Rays*

unique - 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 - *violation of* ***Lorentz invariance,*** *search for* ***Dark Matter,*** *or less exotic issues, like* ***Relativistic MHD*** **"experiments"** (e.g. in PWNe and AGN)

established detection technique - *IACT arrays* - for adequate *spectrometry, morphology, timing, surveys*, with a clear plan for the next steps; in the foreseeable future - **CTA**

Gamma Rays and Origin of Cosmic Rays

all particle cosmic ray spectrum

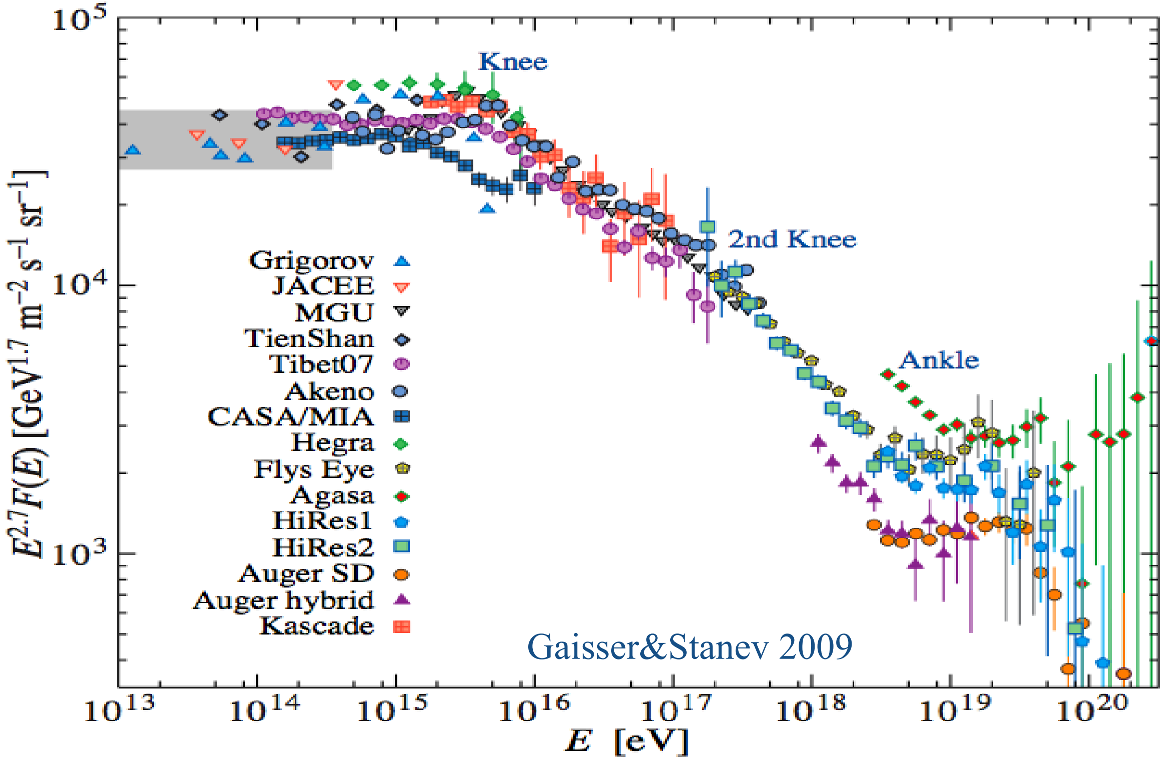


Figure 24.8: The all-particle spectrum from air shower measurements. The shaded area shows the range of the the direct cosmic ray spectrum measurements.

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

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*

for the origin of the locally detected Cosmic Rays

the problem is somewhat exaggerated; perhaps it should not be characterized as a "mystery" but rather as an annoying "uncertainty" regarding the *major contributors* (astrophysical sources) to the *local fog*

moreover, it is not clear what should be done to solve the problem since they cannot be identified by means of detection of Cosmic Ray:

even super-AUGER cannot tell us more about the origin of 10^{20} eV particles than the simple *Hillas plot* and the *GZK effect* (unless the IGMF are very small)

the CR measurements could be infinitely improved which would initiate new ideas and concepts but the origin of the "local fog" never could be ultimately solved

Cosmic Ray Astrophysics with CRs?

an attempt to extract information from the "smell" (energy spectrum and chemical composition of CRs) of a "soup" (isotropic CRs flux) cooked from different ingredients over huge $T > 10^7$ (10^{10})yr timescales…

it is not a big surprise that the origin of CRs is yet a mystery!

origin of CRs can be revealed only by *astronomical means;*
the astronomical messengers should be *neutral & stable*:*

photons and neutrinos, but partly also neutrons

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

do satisfy fully to these conditions;

*astronomy with protons?: only for $E \sim 10^{20}$ eV if IGMF $B < 10^{-12}$ G

what do we know about Cosmic Rays?

- we know that ultra-relativistic particles, in general sense (not only CRs!), represent an equally important (in addition to matter, radiation and magnetic fields), substance of the visible Universe.

- CRs play crucial role in many (not necessarily related to nonthermal) phenomena (ionization/chemistry, star formation, etc.)

- synchrotron radio emission (since 1950s) and X-ray emission (over the last 20 years) - relativistic and ultrarelativistic electrons are accelerated almost everywhere

- gamma-ray observations of recent years revealed 10+ classes of effective Galactic and Extragalactic particle accelerators, some of them are feasible candidates to be called sources of CRs

what do we expect from gamma-ray studies?

the next generation gamma-ray detectors will result in discoveries and surprises the significance of which certainly will go beyond the specific objective of identification of the main contributors to Cosmic Rays

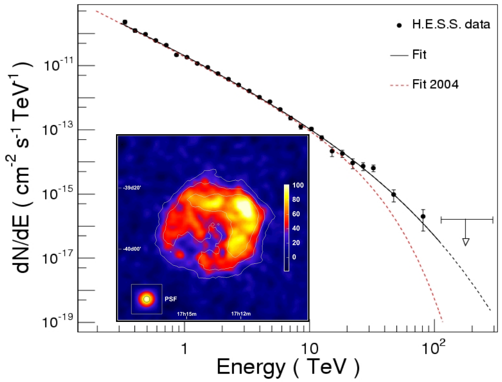
in this regard, one of the main objectives of the major future detector CTA is considered the dramatic increase of the number of detected sources and the population studies. But equally (or even more) important is the study of physics of individual **TeVatrons & PeVatrons** (for Galactic accelerators), and **EeVatrons** (for Extragalactic accelerators)

- current VHE gamma-ray observations demonstrate that particle acceleration to multi-TeV energies is widely spread phenomenon taking place with remarkable diversity; this concerns the acceleration mechanisms, type of sources, energetics, etc.

- some VHE sources are studied quite comprehensively, but even in the case of the strongest ones (">0.1 Crab") many important details (in lightcures, energy spectra, images) are missing - the clarification of these details should be one of the highest priorities of future VHE observations ("the devil is in details")

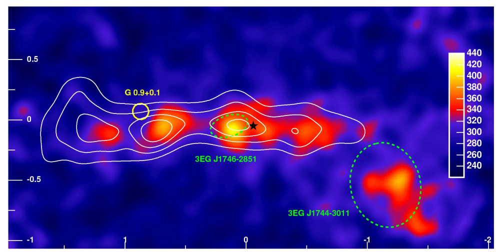
good performance/high quality data => modeling/theory

RXJ 1713.7-3946



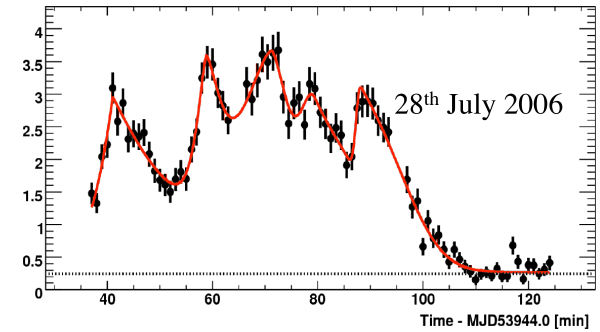
TeV image and energy spectrum of a SNR

Galactic Center



resolving GMCs in the Galactic Center 100pc region

PKS 2155-309



variability of TeV flux of a blazar on minute timescales

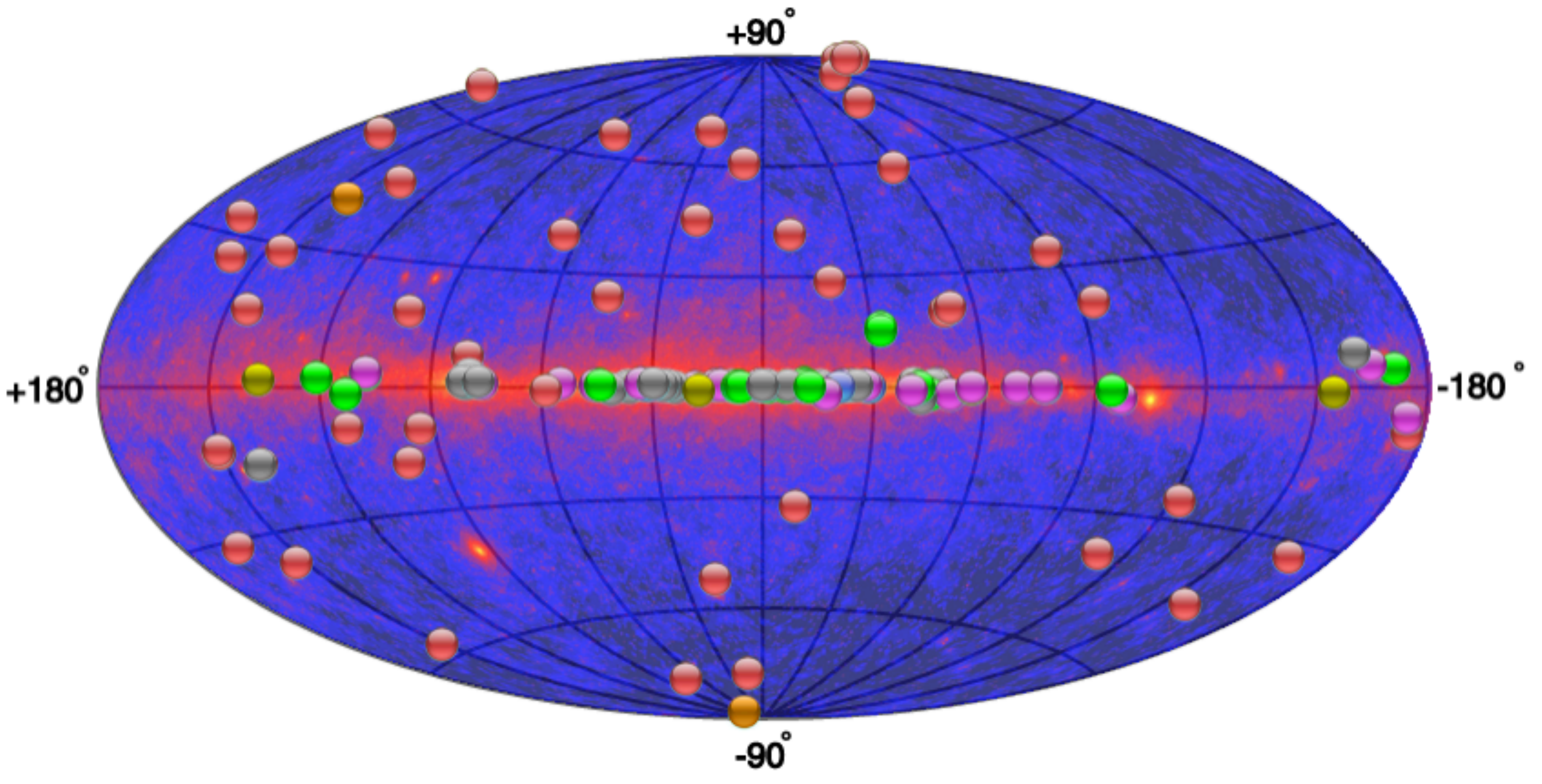
multi-functional tools: *spectrometry* *temporal studies* *morphology*

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

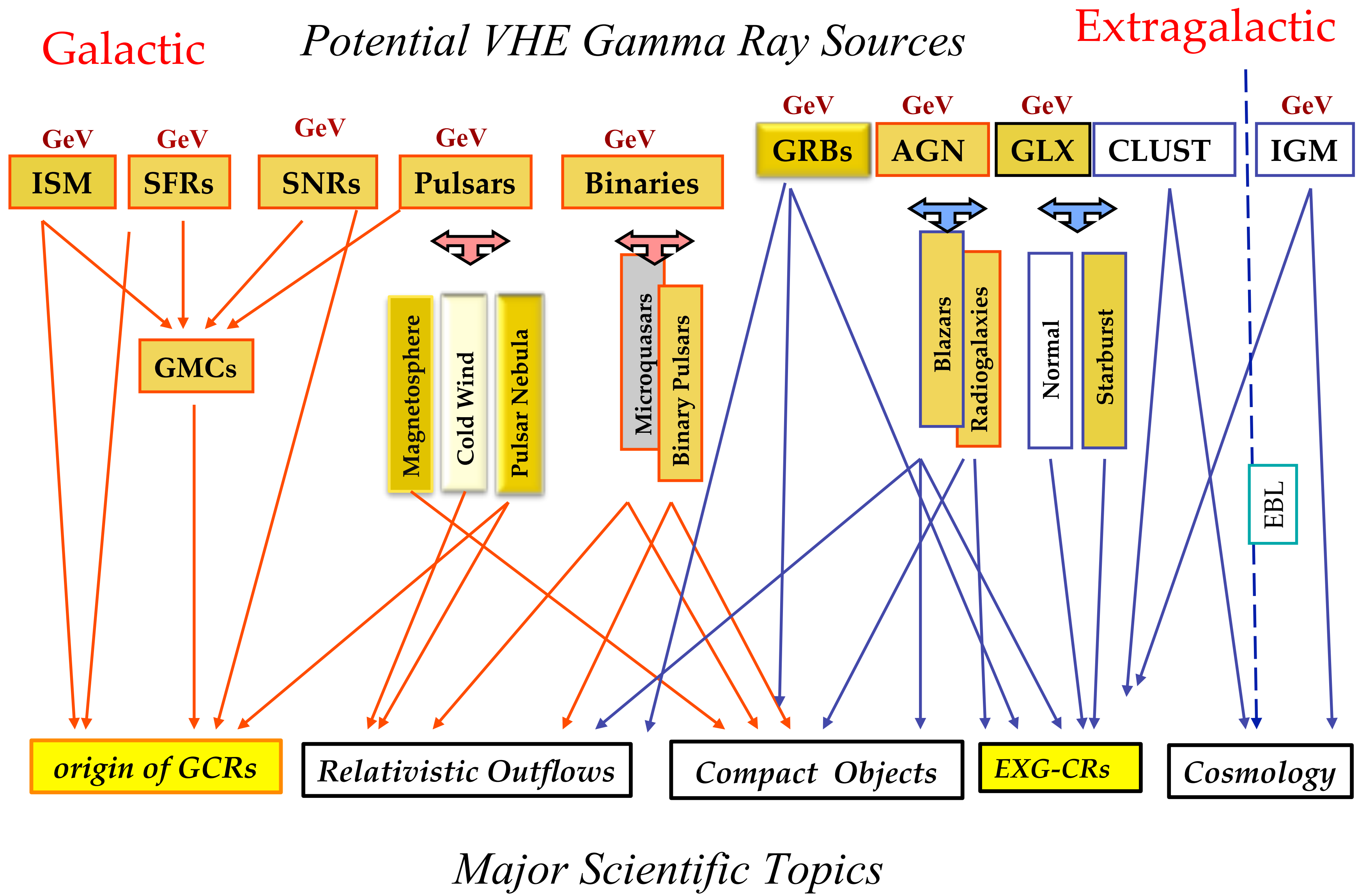
✓ transient phenomena *μQSOs, AGN, GRBs, ...*

Galactic Astronomy | Extragalactic Astronomy | Observational Cosmology

TeV Sky



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



Galactic
Potential VHE Gamma Ray Sources
Extragalactic
GeV
ISM
GeV
SFRs
GeV
SNRs
GeV
Pulsars
GeV
Binaries
GeV
GRBs
GeV
AGN
GeV
GLX
CLUST
GeV
IGM
GMCs
Magnetosphere
Cold Wind
Pulsar Nebula
Microquasars
Binary Pulsars
Blazars
Radiogalaxies
Normal
Starburst
EBL
origin of GCRs
Relativistic Outflows
Compact Objects
EXG-CRs
Cosmology
Major Scientific Topics

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)

Extragalactic Cosmic Rays

EXG origin of CRs? certainly above 10^{19} eV or perhaps even above 10^{17} eV;

at lower energies? problematic: $t \sim R^2/D$; for any reasonable diffusion coefficient, the propagation time from multi-Mpc distances exceeds Hubble time $\sim 10^{10}$ yr

actually, because of interactions with 2.7 K MBR, the highest energy (10^{20}eV) CRs also represent a "local fog" (nearby universe): <u>$R \sim 100$ Mpc or less</u>:

"GZK cutoff" is not a cosmological effect!

paradoxically only particles of $E < 10^{18}$ eV can (in principle) carry cosmological information- in the case of extremely weak intergalactic magnetic fields $<10^{-15}$ G

sources ?

go to the "Hillas Plot", but don't be mislead - viable options are quite limited -

it implies acceleration of particles at maximum possible rate: $t_{acc} \sim c/R_L$.

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 (theoretically) 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 relativistic and non-linear effects)

<u>analogy with X-ray Astronomy:</u>

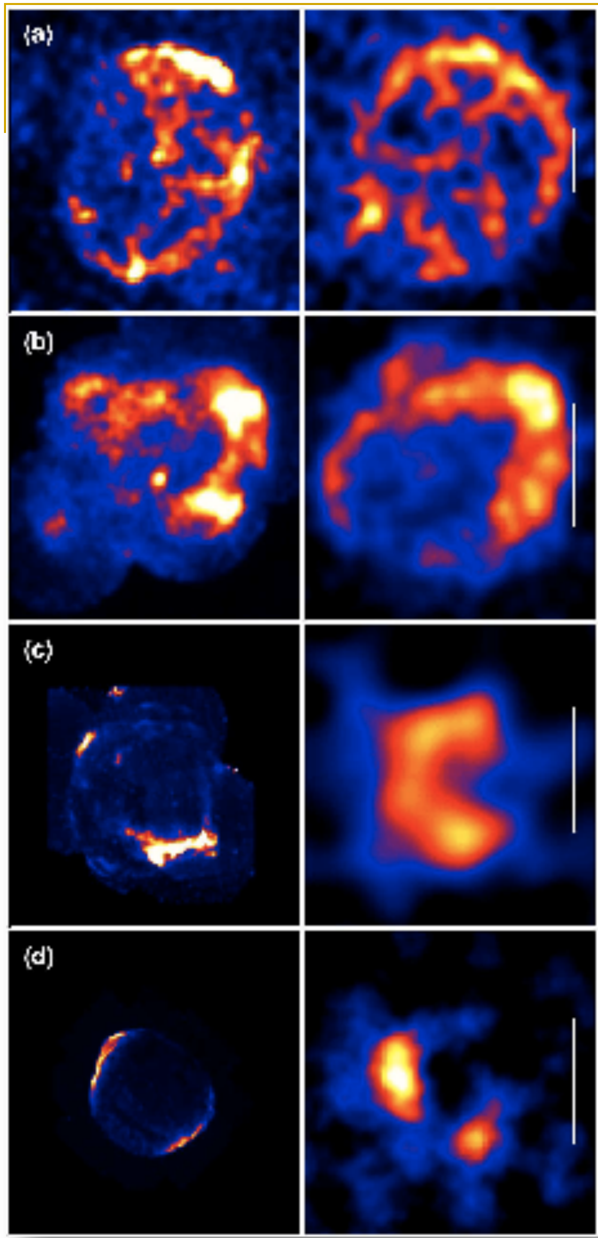
as cosmic plasmas are easily heated up to keV temperatures - almost everywhere, particles (electrons and protons) can be easily accelerated to TeV energies - almost everywhere, especially in objects containing relativistic outflows -jets & winds

SNRs and Galactic Cosmic Rays

SNRs as the most likely sources
of galactic cosmic rays?

main hope is related to gamma-ray observations:

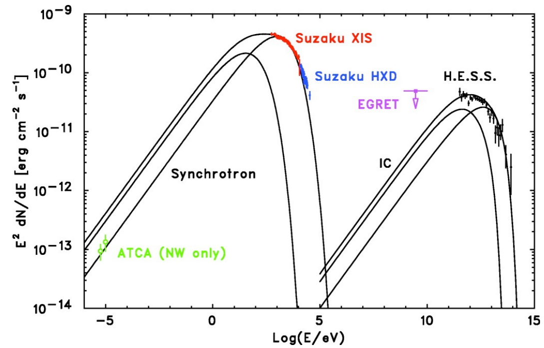
- detect VHE gamma-rays from SNRs
- demonstrate that they have hadronic origin
- demonstrate that proton spectra continue up to 1 PeV

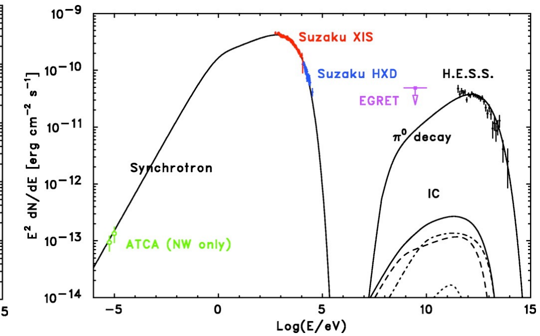


=>

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/cm³

γ-rays from pp ->π^o ->2γ

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

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

$B=200\mu G$

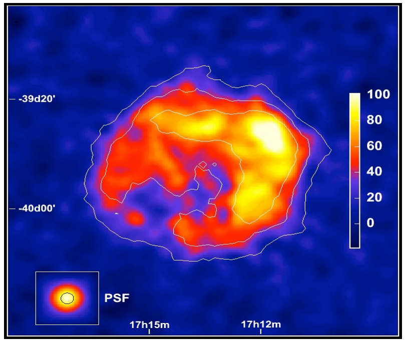
$W_p \approx 2\ 10^{50} (n/1cm^{-3})^{-1}$ erg/cm³

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

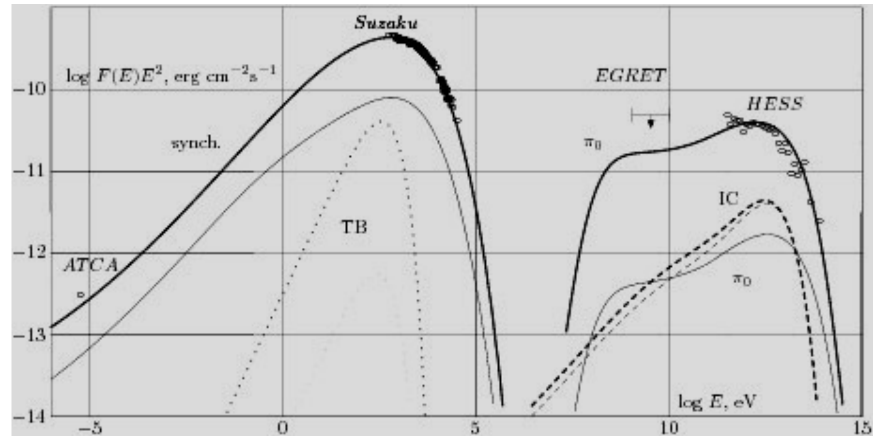
RXJ 1713.7-4639

modeling of broad-band SEDs:



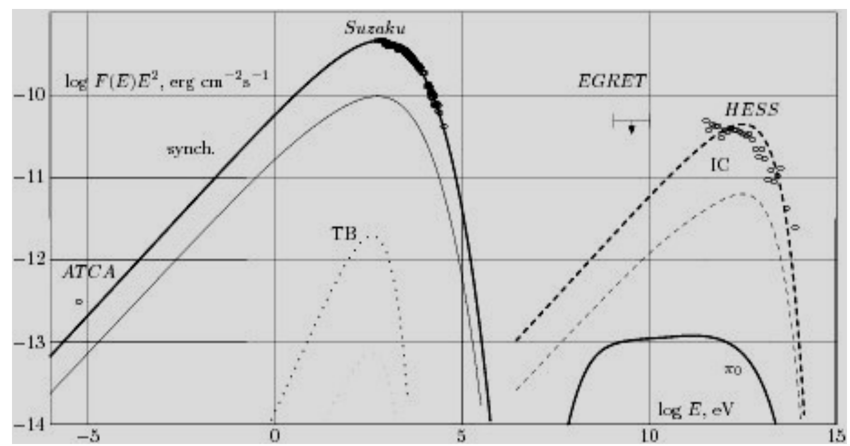
Berezhko&Voelk, Blasi et al. ,
Ellison et al., Zirakashvili&FA

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



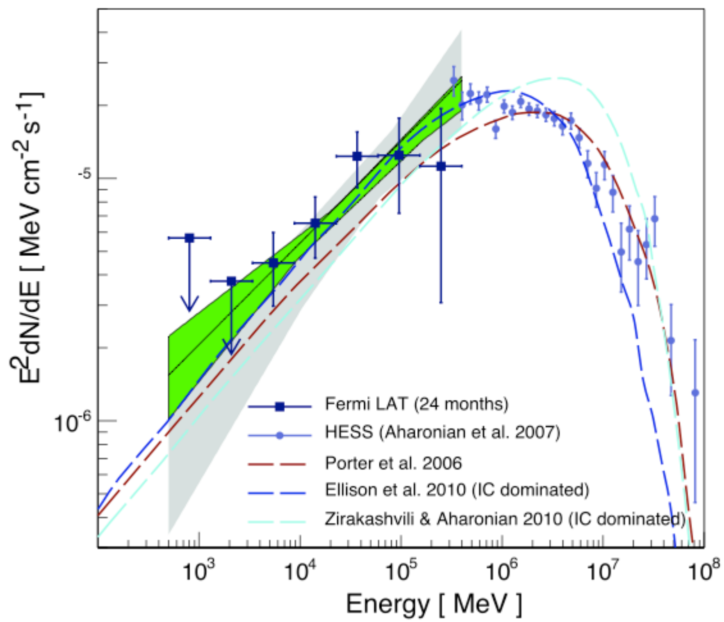
not perfect, but still acceptable, fits for spectral and spatial distributions of IC gamma-rays; suppressed thermal emission, comfortable p/e ratio (~10^2);small large-scale B-field (~ 10 μG)

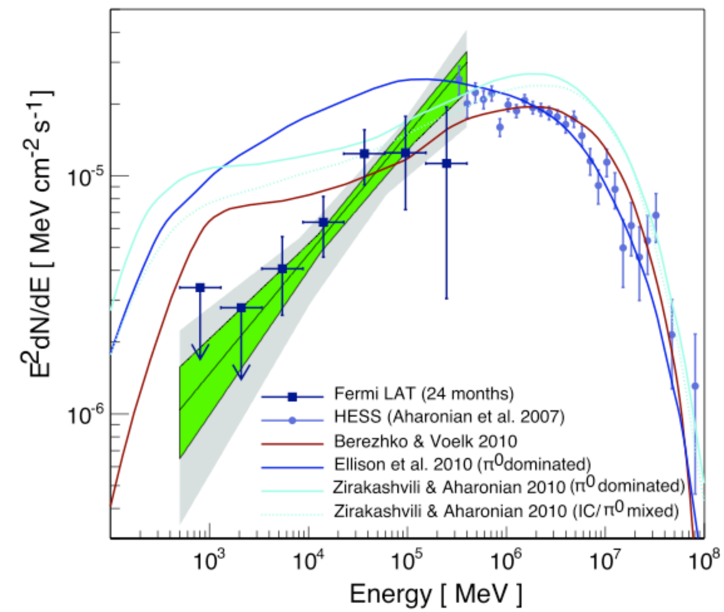
both forward&reverse shock contribute to γ-rays

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

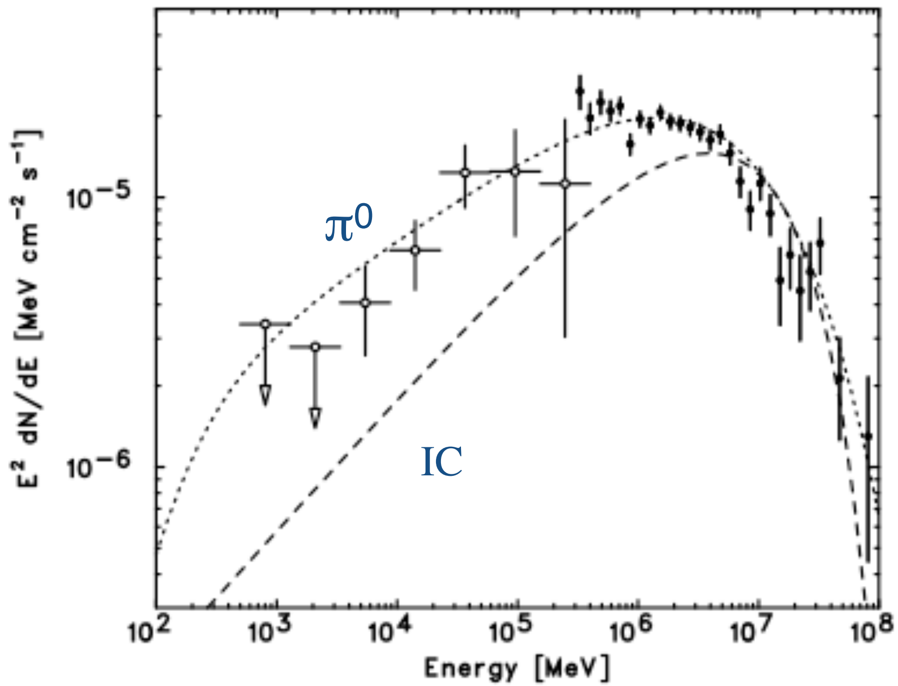
Questions: (i) can we compare GeV and TeV fluxes within one-zone models?

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-TeV data can be explained by protons with spectral index s=1.8



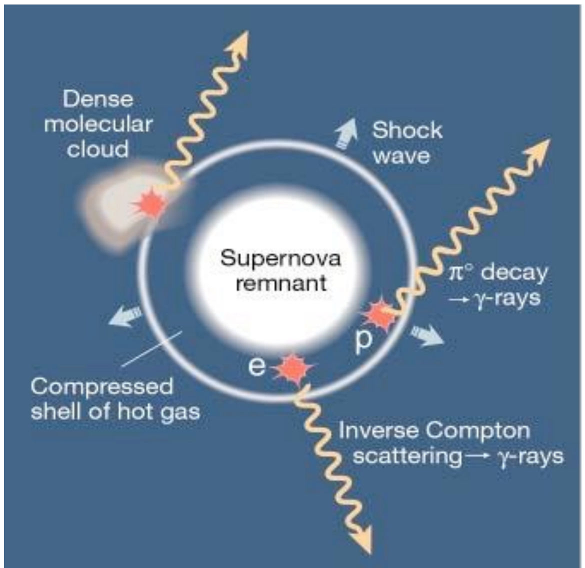
data: HESS and Fermi LAT

thenomenological curves: Tanaka et al. 2008

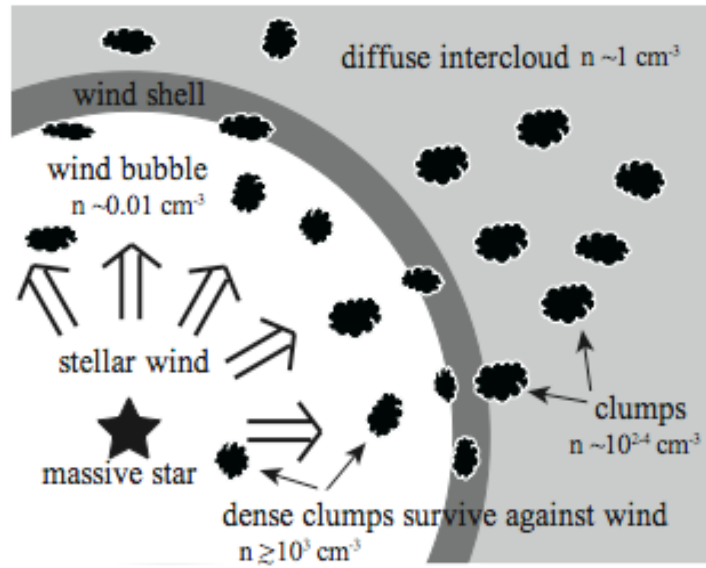
extremely efficient DSA theory predicts s=1.5 (Malkov 1999) but Abdo et al. 2011 *argued that "...such a proton energy distribution is not observed in the current models of DSA (Ellison et al. 2010)"* (a key sentence in the Fermi LAT official paper !?)

"the story of the death of hadronic origin of γ-rays has been greatly exaggerated"

GeV gamma-rays can be suppressed because low energy protons cannot reach the dense target (Malkov et al. 2005) or cannot penetrate deep into the dense clouds/clumps Zirakashvili&FA 2010)



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

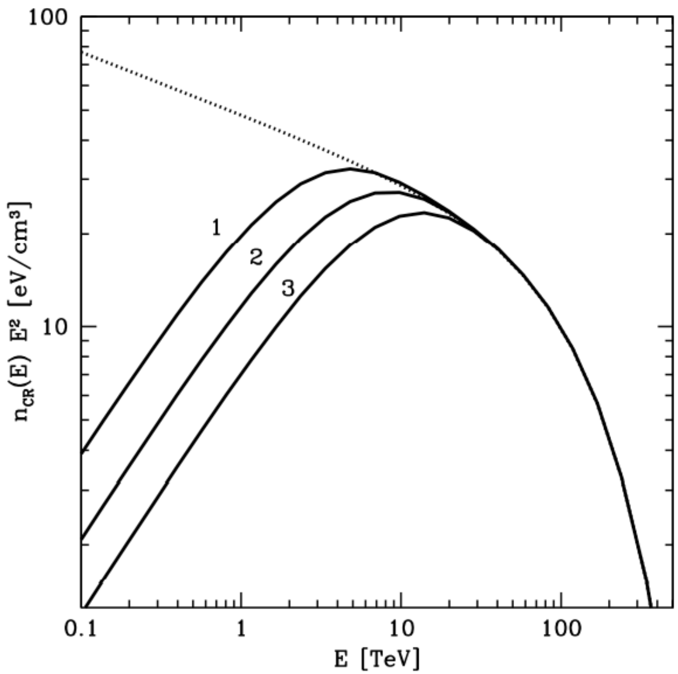


Figure 1. Spectrum of CRs in the SNR shell (dotted line) and inside a clump that entered the shock at t_c = 1400, 1500, and 1550 yr (solid line 1, 2, and 3 respectively).

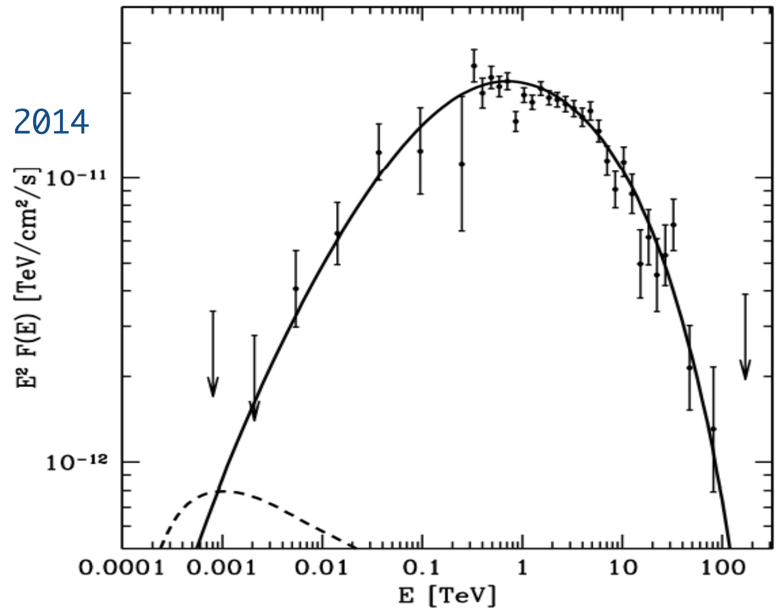


Figure 2. Gamma–rays from RX J1713.7-3946. The emission from the clumps is shown as a solid line, while the dashed line refers to the emission from the diffuse gas in the shell. Data points refer to *FERMI* and *HESS* observations.

a few comments on the hadronic scenario:

- lack of thermal emission in RXJ 1713.7-3946

  almost all available energy goes to particle acceleration? (Drury et al 2010)

- 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,

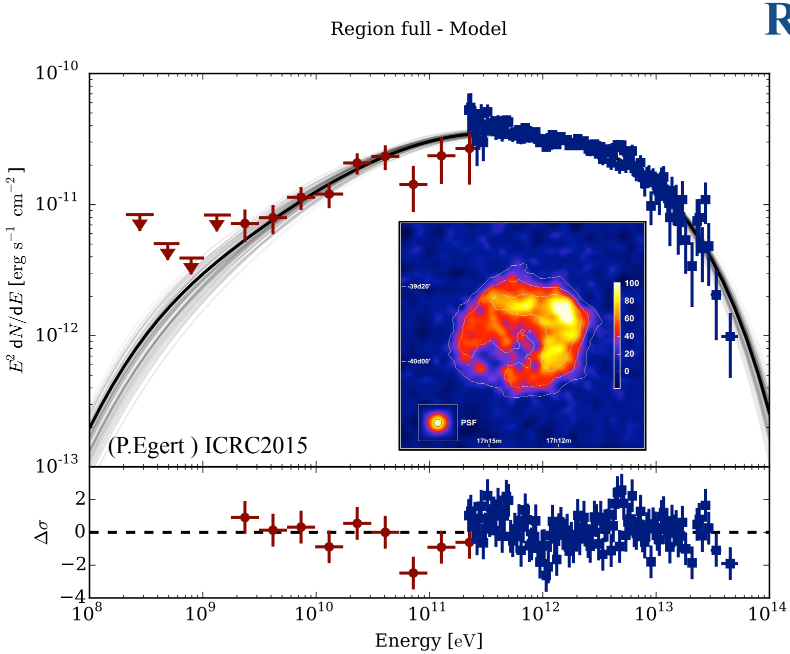
  in particular the role of the **escape**

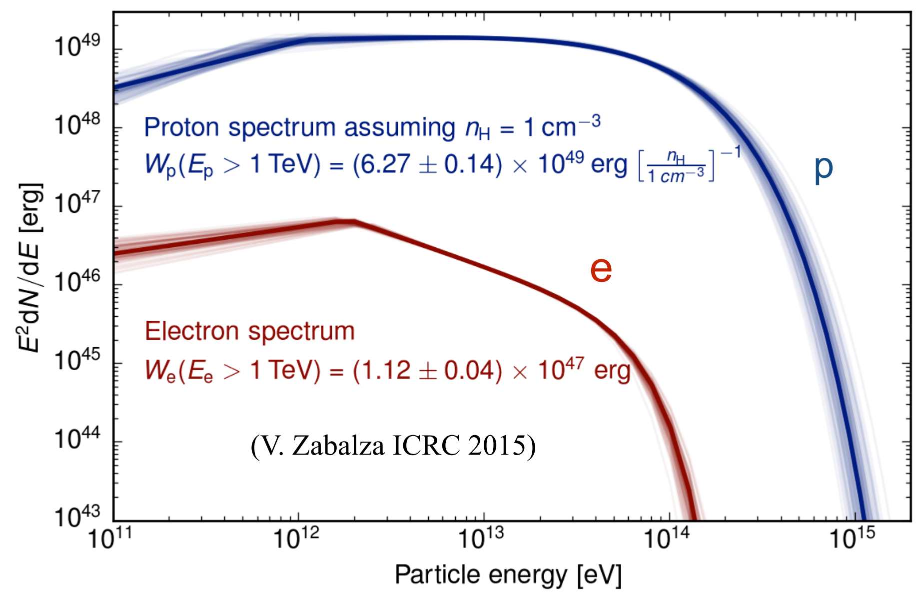
HESS: it seems there is a component beyond the shell in RXJ1713 if so it would be important to measure the gamma-ray (and the secondary hard synchrotron X-ray) spectra related to the escaping protons

Probing the distributions of accelerated particles in SNRs

HESS measurements derived spectra of e and p

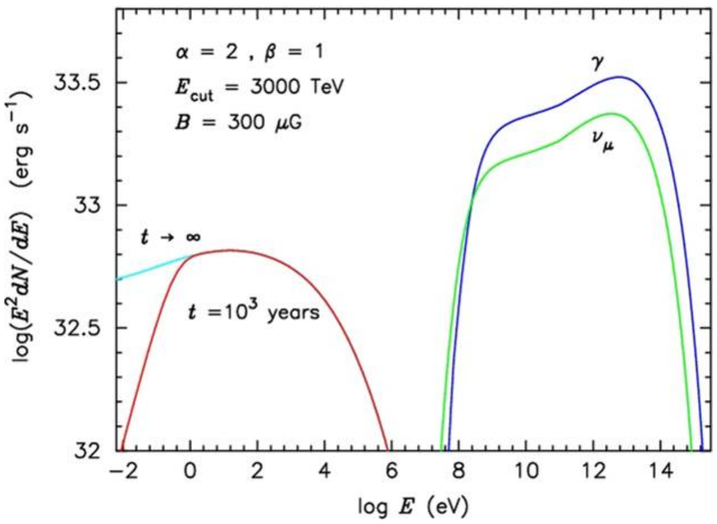
RXJ 1713





CTA can do much better; extension of measurements to >100 TeV
a few arcimin (sub-pc) structures
particles beyond the shell

a Galactic PeVatron: E~10^{15}eV



three channels of information
about cosmic PeVatrons:

10-1000 TeV gamma-rays
10-1000 TeV neutrinos

10 -100 keV hard X-rays

- γ-rays: difficult, but possible with future “10km^2“ area multi-TeV IACT arrays

- neutrinos: marginally detectable by IceCube, Km3NeT - don’t expect spectrometry, morphology; uniqueness - unambiguous signatute!

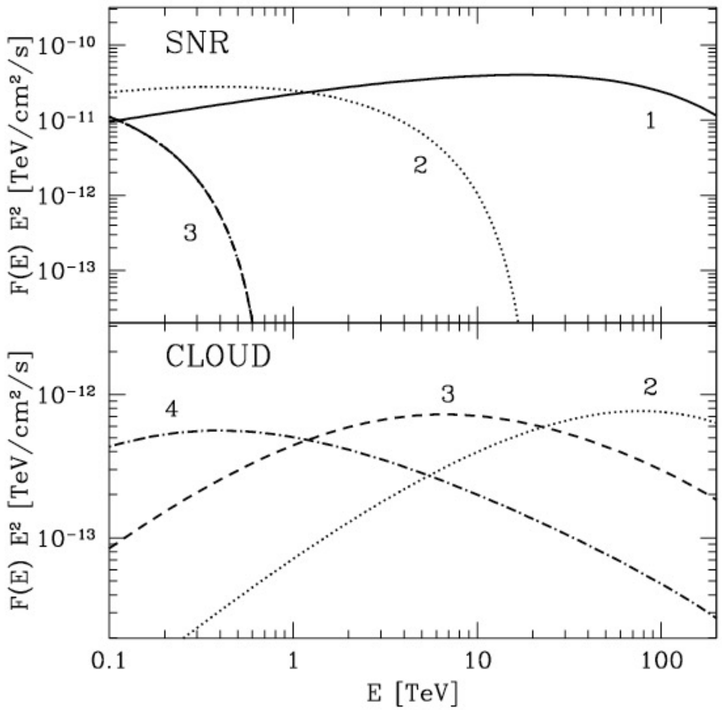
- “prompt“ synchrotron X-rays: smooth spectrum
a very promising channel - quality!

$\sim \varepsilon^{-(\alpha/2+1)} \exp[-(\varepsilon/\varepsilon_0)^{1/5}]$

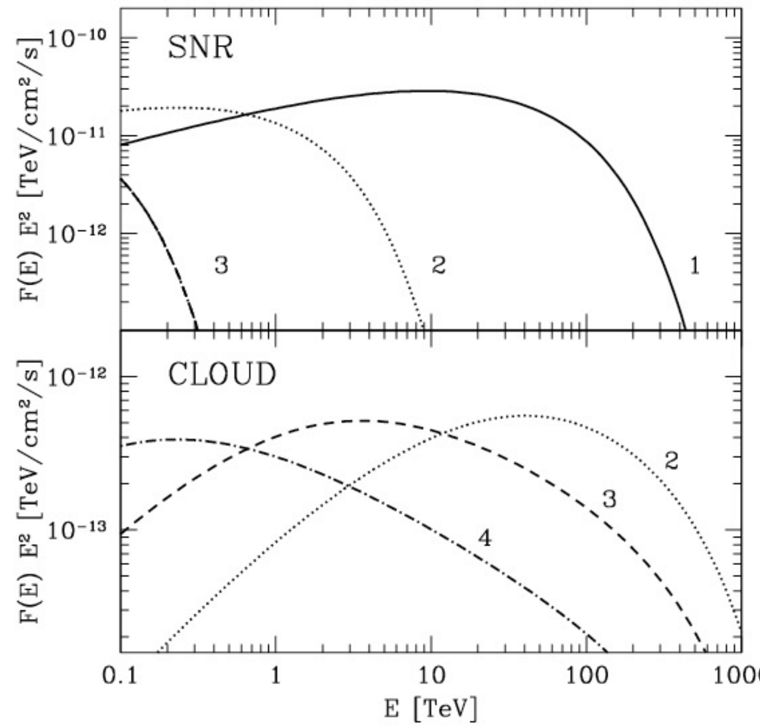
Gamma-rays and neutrinos inside and outside of SNRs

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

gamma-rays



neutrinos



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

d=1 kpc

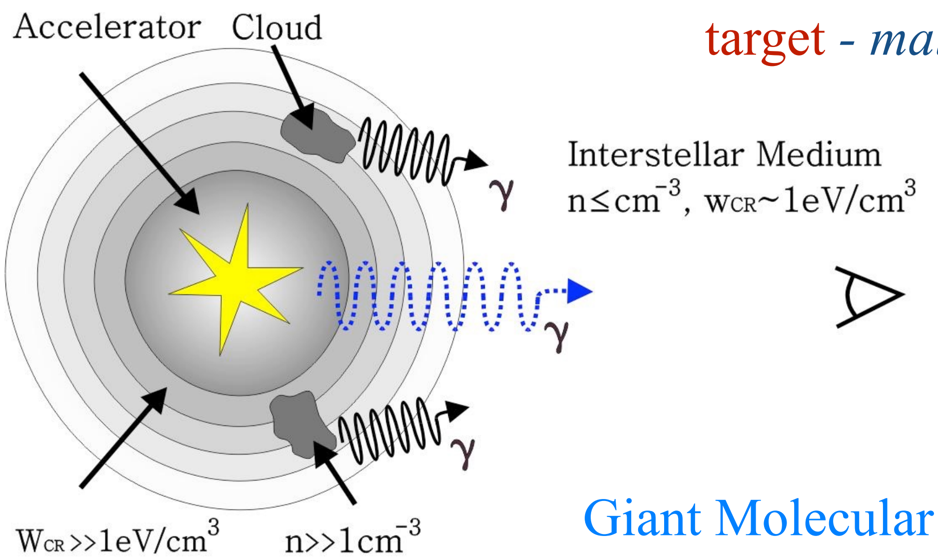
GMC: $M=10^4\ M_o$ d=100pc

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

S. Gabici & FA 2007

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

warning: don't be tricked by propagation effects!

transition from rectilinear to diffusive regime of propagation

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

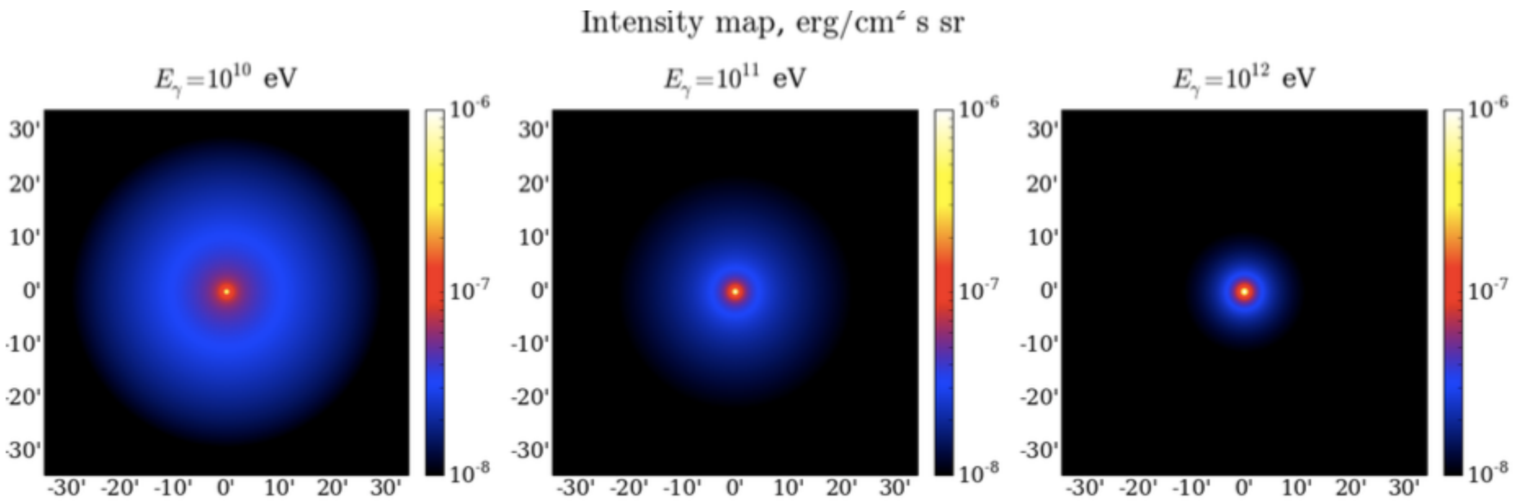
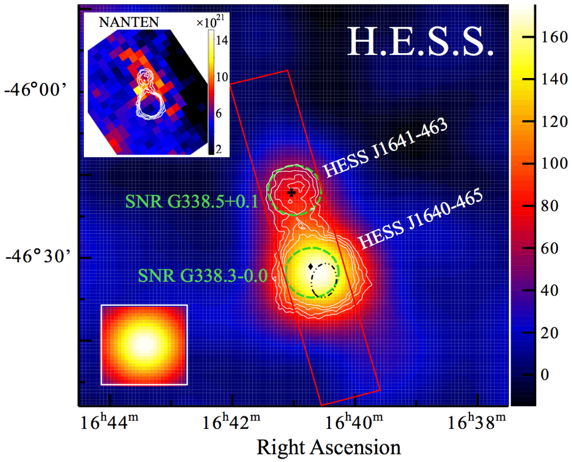


Figure 2: The intensity maps of gamma-ray emission at different energies. The spherical cloud with homogeneous density distribution is irradiated by the cosmic-ray source located in its centre. The gas density inside the accelerator is assumed very low, so the contribution of the accelerator to the gamma-ray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

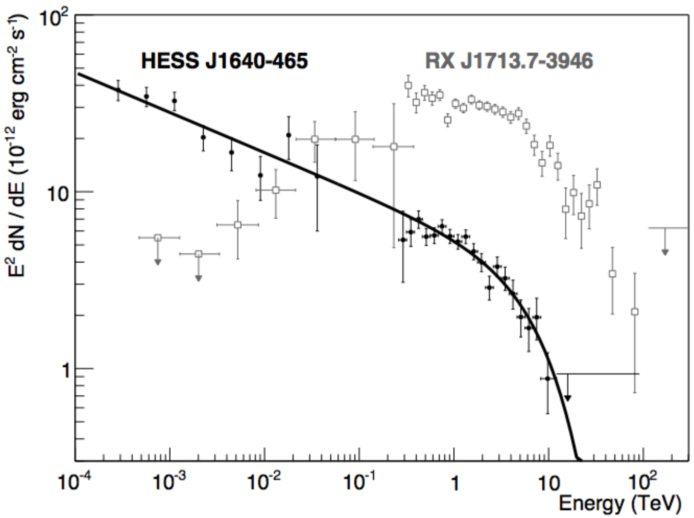
Prosekin, Kelner, FA 2015

HESS 1640-465: the most luminous galactic VHE source !

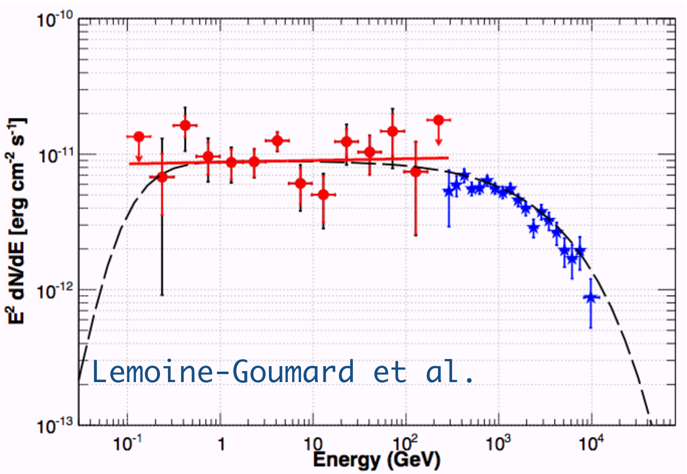
HESS J 1640-465/HESS J1641-463



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



HESS collaboration, ApJ, vol. 794, L1



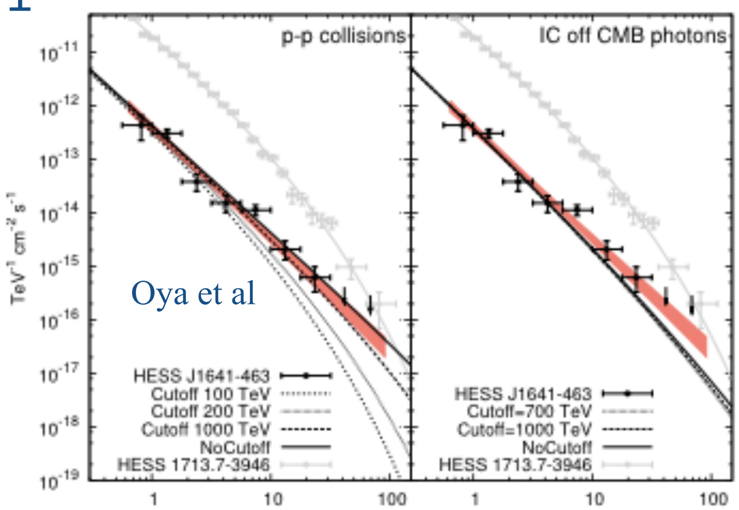
strong argument in favor of hadronic origin of gamma-rays in a SNR?

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?

1 HESS 1641-463

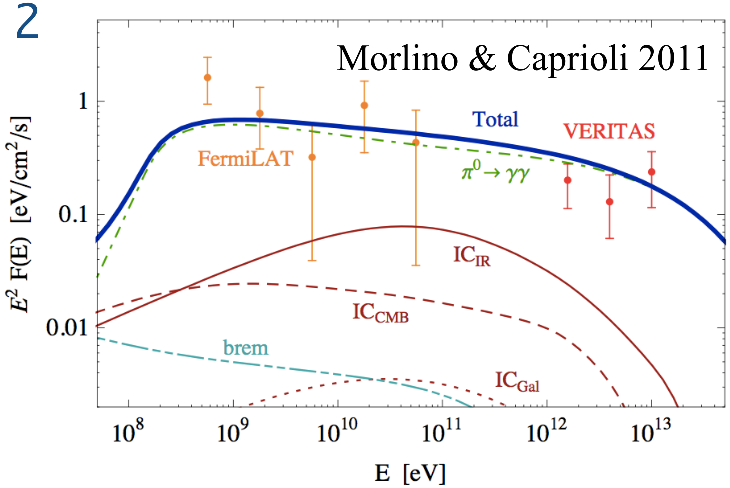
SNR candidates for PeVatrons?



a weak but very hard spectrum up to 20 TeV

what is special with this source?
"delayed" emission from escaped CRs interacting with a cloud?

2



Tycho ?
deserves more observations for a better statistics/quality -

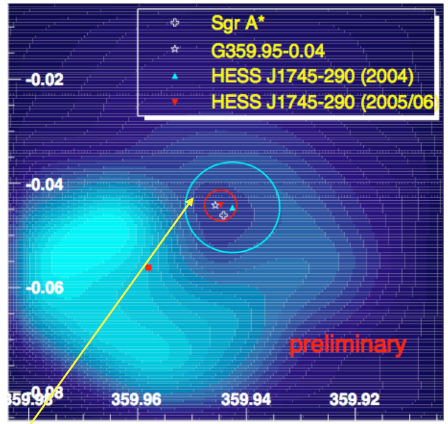
gone! new VERITAS results - much steeper spectrum

Westerlund 1 - a hard HESS source with a spectrum up to ~10 TeV:
a starburst regions with multiple powerful winds of young massive stars and a supernova remnant - favorable sites for high-energy CR acceleration and gamma-ray and neutrino production (Bykov et al. 2015)

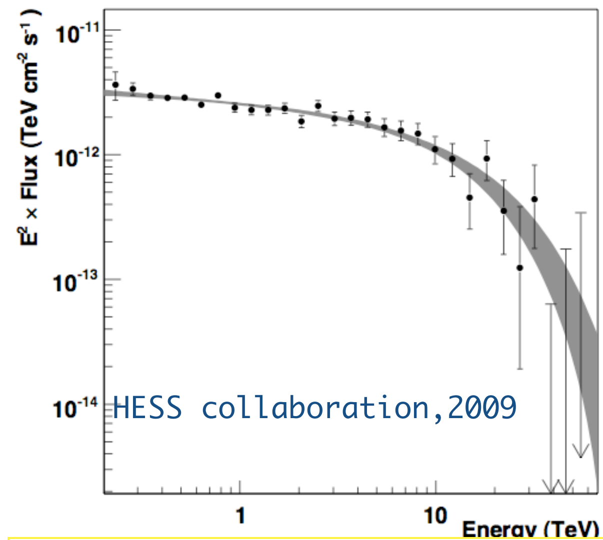
a PeVatron in the Galactic Center!

TeV gamma-rays from GC

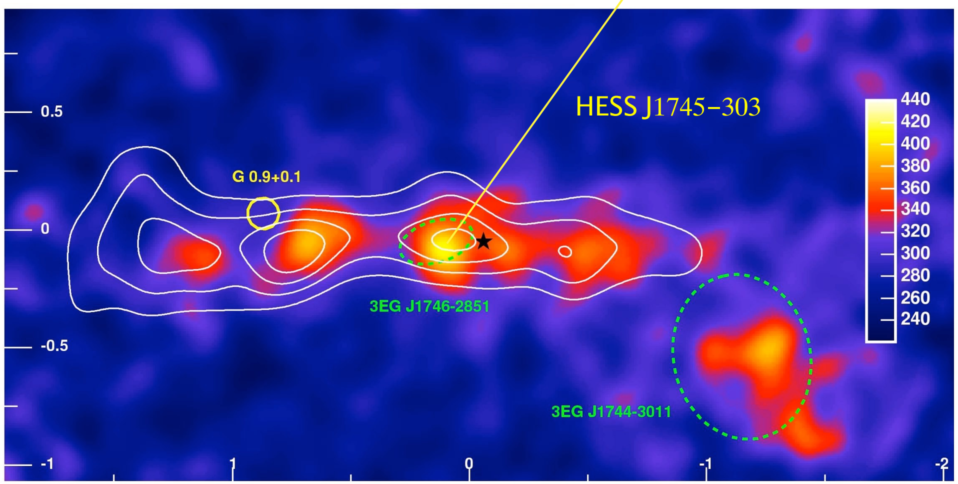
90 cm VLA radio image



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

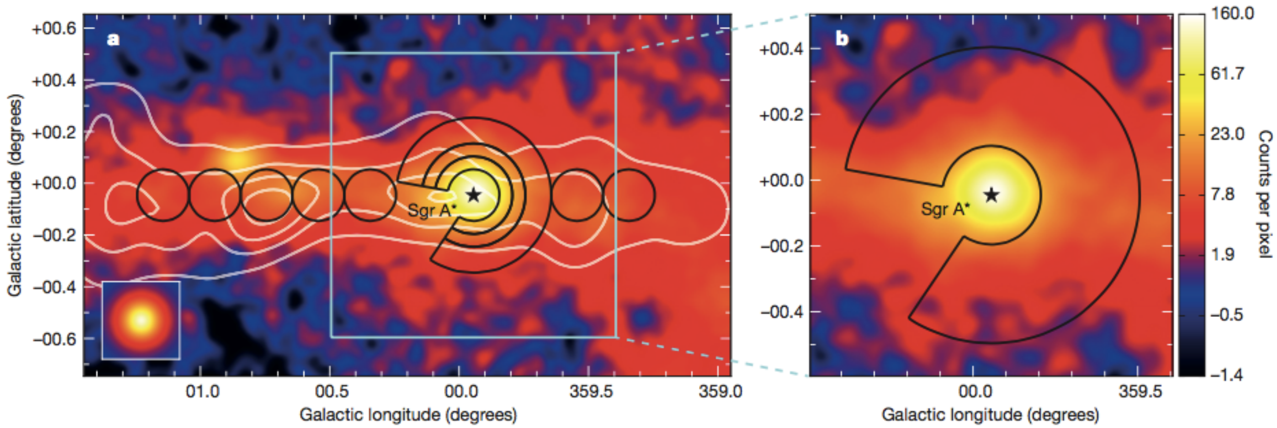
$\beta=1/2$ $\Gamma=1.9$ $E0=4.0$ TeV

New - HESS collaboration

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

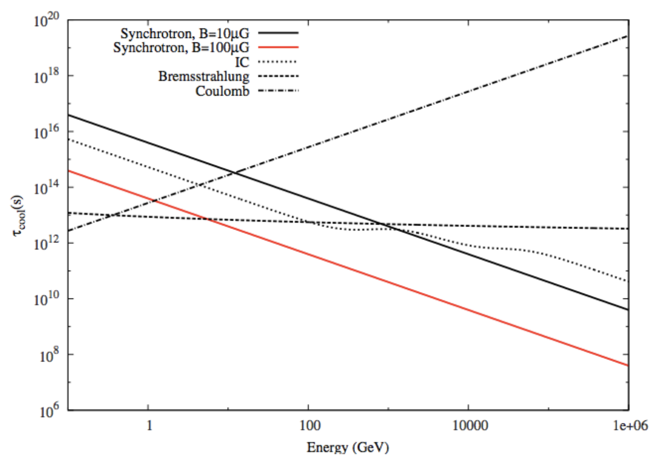
this conclusion is based on spectroscopic and morphological studies of diffuse VHE gamma-ray component in so-called ~200 pc radius Central Molecular Zone (CMZ) of the GC

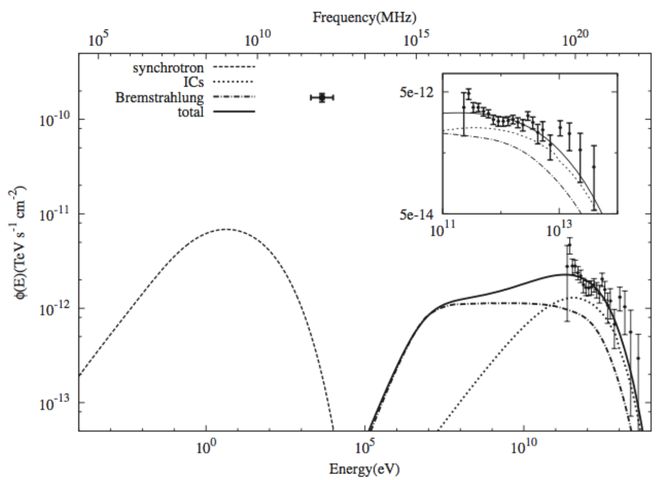
- for the first time, a gamma-ray spectrum is registered that continues without a cutoff or a break up to 20-30 TeV (most likely, 50 TeV)
- for the first time, the density profile of parent protons is derived based on analysis of spatial distributions of VHE gamma-rays and the gas in GC



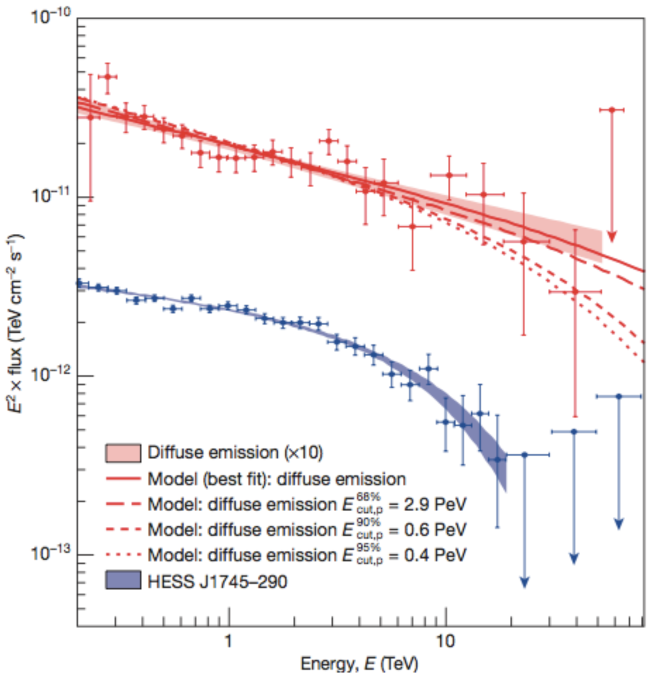
gamma-rays are of hadronic (pp) origin:

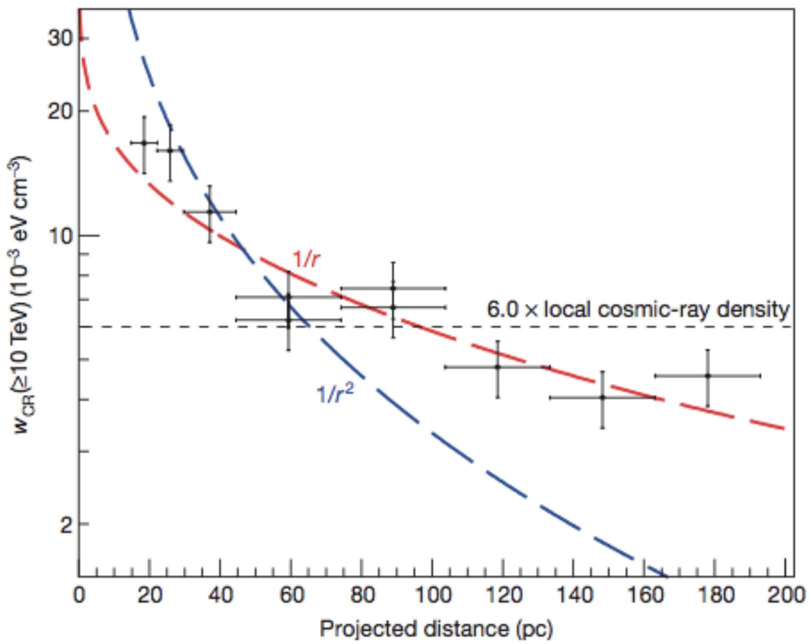
- gamma-ray brightness correlates with gas density (but not linearly!)
- mean free paths of 100 TeV gamma-rays cannot exceed a few pc
- because of cooling of electrons the IC spectrum breaks below 10TeV





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

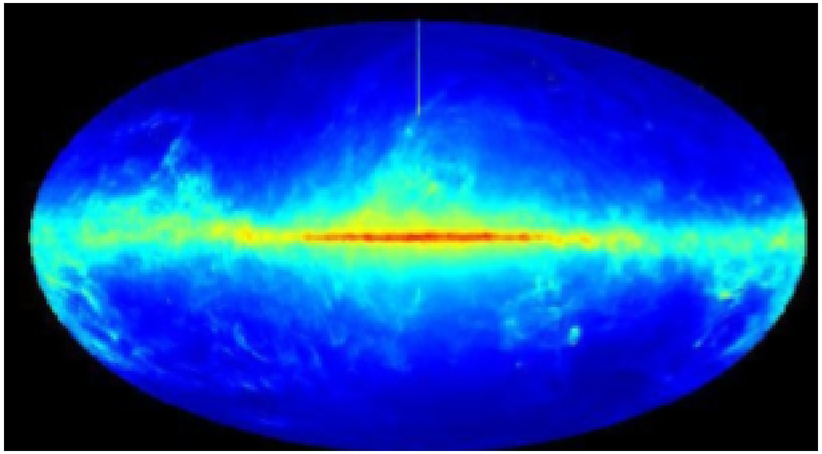
- this accelerator alone can account for most of the flux of Galactic CRs around the "knee" if its power over the last 10^6 years or so, has been maintained at average level of 10^{39} erg/s.

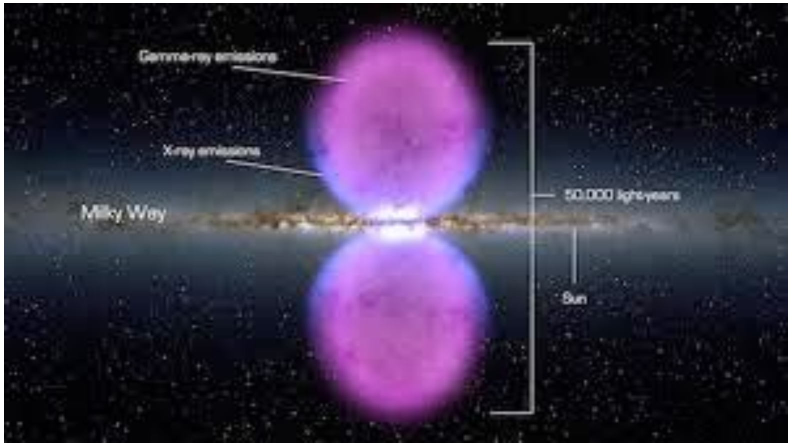
- escape of particles into the Galactic halo and their subsequent interactions with the surrounding gas, can be responsible for the sub-PeV neutrinos recently reported by the IceCube collaboration

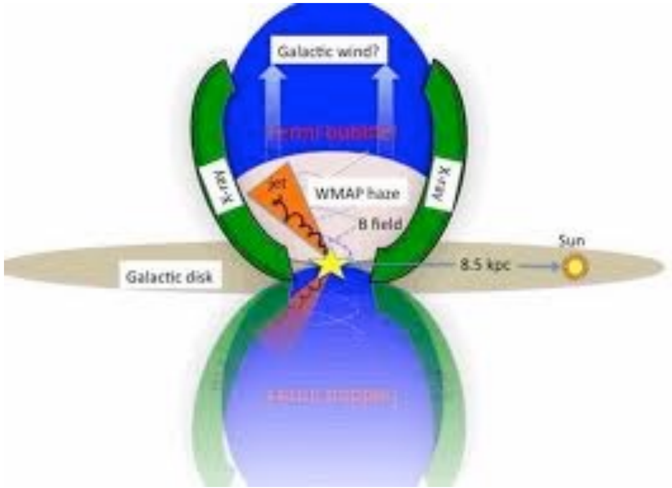
- the expected >10 TeV neutrino flux is within the range of sensitivity of a several km^3 volumee neutrino detector

- perfect target for CTA - to search for the variability of the central source, to measure the spectrum of diffuse (CMZ) gamma-rays up to 100 TeV and beyond

CRs from GC responsible for Fermi Bubbles?







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

Fermi Bubbles - alternative explanation:
IC scattering of electrons:
age: 10^7 yr, electron inj. rate $10^{38\text{-}39}$ erg/s

Problem: how transport E >1 TeV electrons to distances 10 kpc - in situ acceleration?

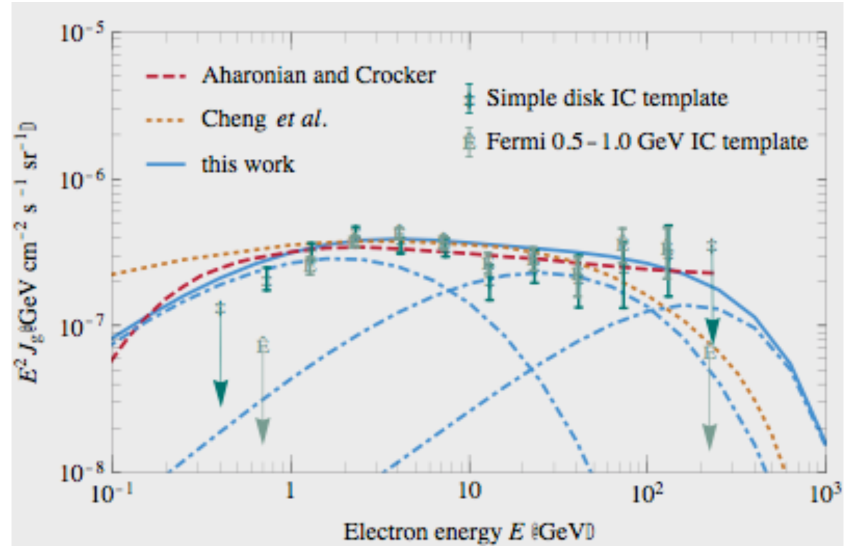
stochastic (2nd order Fermi) most viable option (Mertsch & Sarkar 2011)

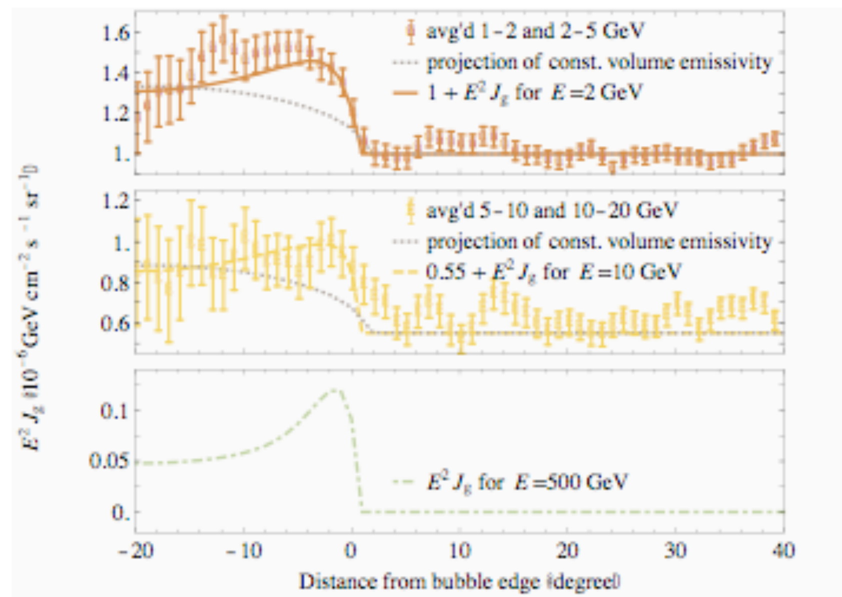
shock fronts at Bubble edges (ROSAT) => higher turbulence - concentration of electrons close to the edges => sharp γ-ray edges

narrow electron distribution+limited E_{max}~1TeV
only 2.7K MBR as a target cannot for IC explain the 1-100 GeV γ-radiation: galactic FIR/O target field helps to explain the average 1-100 GeV E^{-2} type flat gamma-ray spectrum

distinct feature of the model - much steeper energy spectra of gamma-rays at large heights compared to region close to the galactic plain.

is not supported (!) by recent measurements of Fermi LAT (Yang, FA, Crocker 2015) - we see **hardening of the spectrum with distance**





Mertsch & Sarkar 2011

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)

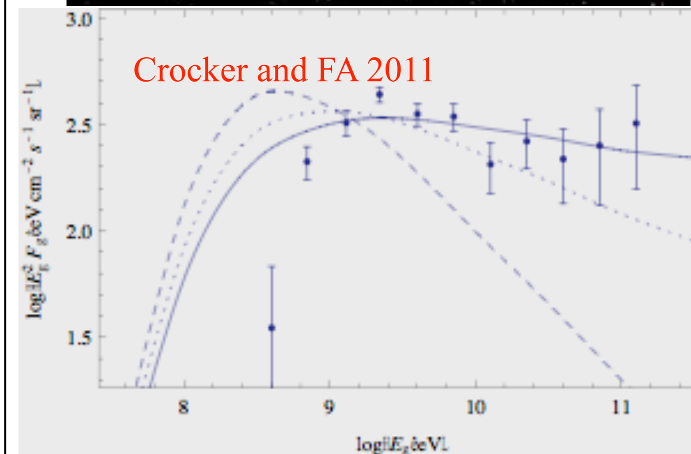
Size - because of slow diffusion in turbulent environment (10 times slower than in the Galactic Disk)

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

saturation (calorimetric) regime can explains:

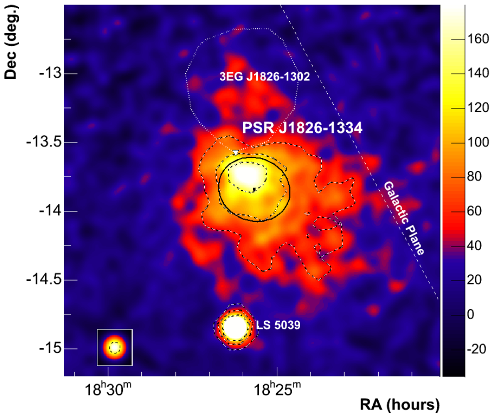
generally homogeneous distribution of gamma-rays (local γ-ray production rate does not depend on density), unless possible gradients in the CR spatial distribution, e.g. due to propagation effects ; if the sharp edges tentatively found in the Fermi images is a real effect, they can be naturally explained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

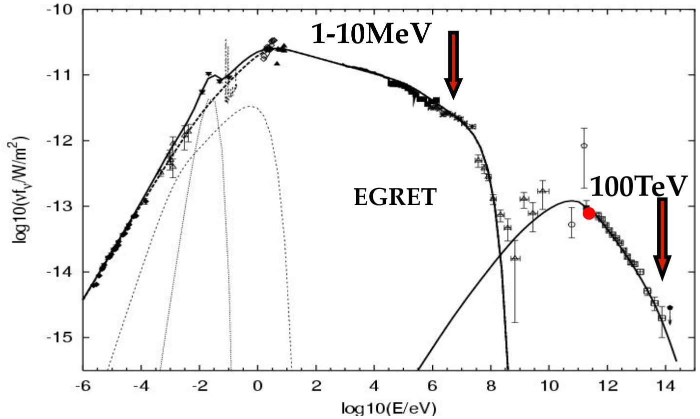


Fermi Bubbles
as a VHE neutrino source?

Pulsar Wind Nebulae:
electron PeVatrons



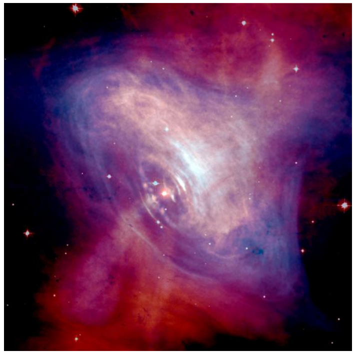
Crab Nebula – *a perfect electron PeVatron*



standard MHD theory (Kennel&Coroniti)

cold ultrarelativistc pulsar wind terminates by reverse shock resulting in acceleration of multi-TeV electrons

synchrotron radiation => nonthermal optical/X nebula
Inverse Compton => high energy gamma-ray nebula

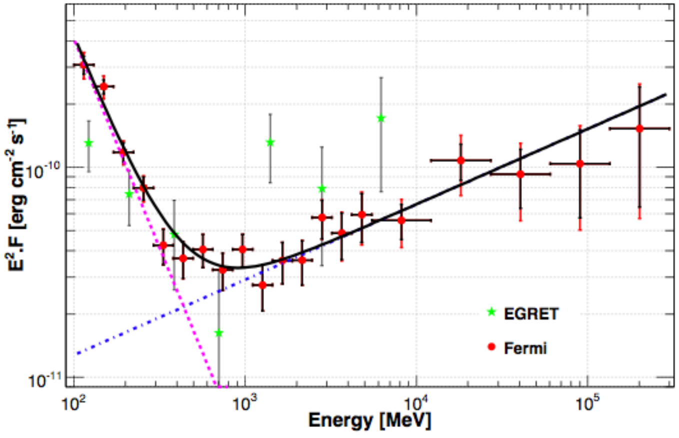


Crab Nebula – a powerful $L_e=1/5L_{rot} \sim 10^{38}$ erg/s
and extreme accelerator: Ee >> 100 TeV

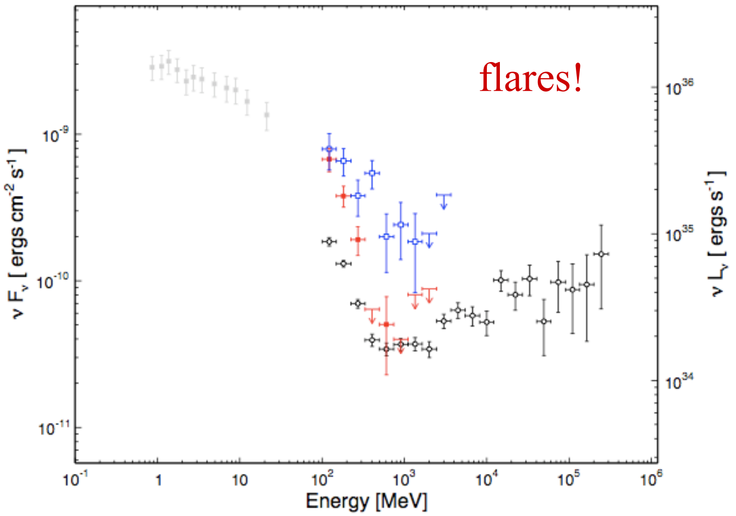
$E_{max}=60\ (B/1G)^{-1/2}\ \eta^{-1/2}$ TeV and $h\nu_{cut} \sim 150\eta^{-1}$ MeV

Cutoff at $h\nu_{cut} > 10$ => $\eta < 10$ - acceleration at 10 % of the maximum rate
γ-rays: $E_\gamma \sim 50$ TeV (HEGRA, HESS) => $E_e > 200$ TeV
B-field ~100 mG => $\eta \sim 10$ - independent and more robust estimate
1 mG => $\eta \sim 1$?

Flares of Crab (Nebula) :



IC emission consistent with average nebular B-field: B ~ 100μG-150μG

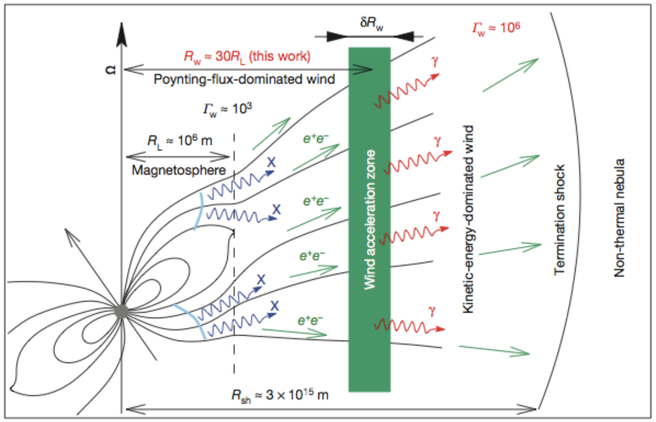


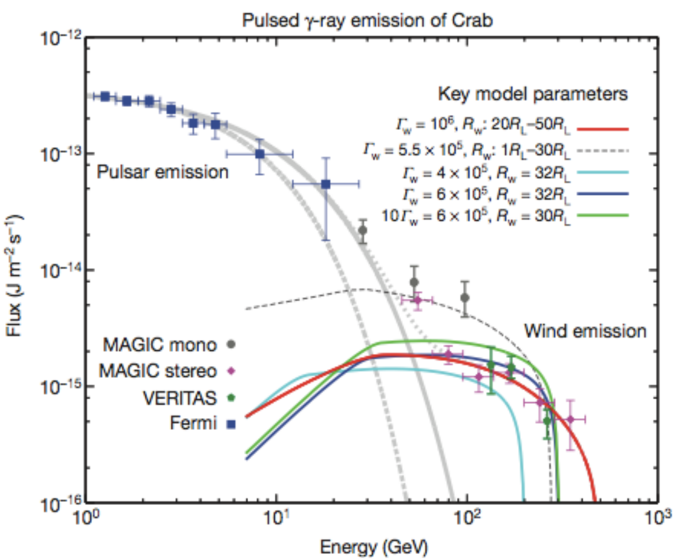
seems to be in agreements with the standard PWN picture, but … MeV/GeV flares!!

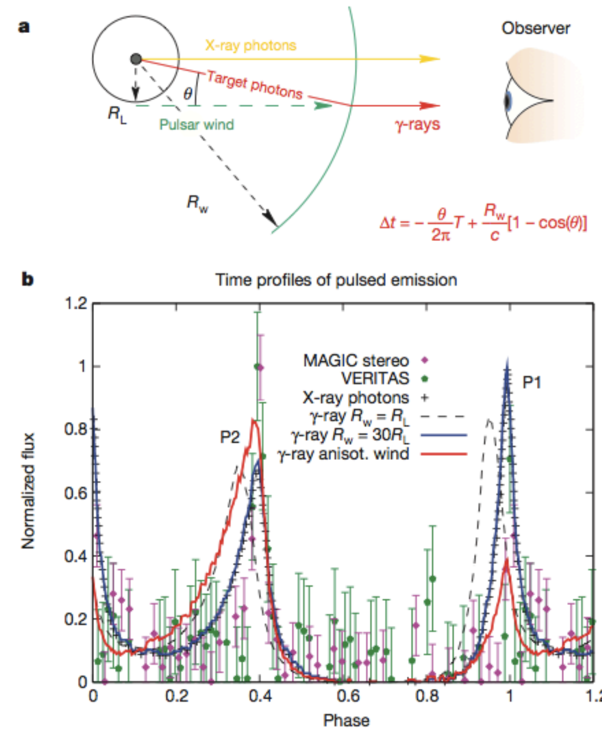
although the reported flares perhaps can be explained within the standard picture - no simple answers to several principal questions - extension to GeV energies, B>1mG, etc.

<u>observations of 100TeV gamma-rays</u> - IC photons produced by electrons responsible for synchrotron flares - a key towards understanding of the nature of MeV/GeV flares

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







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

Crab Nebula is a very effective accelerator

but not an effective IC γ-ray emitter

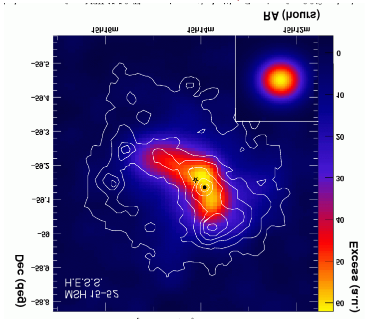
we do see TeV γ-rays from the Crab Nebula because of very large spin-down flux: $f_{rot}=L_{rot}/4\pi d^2=3\times10^{-7}$ erg/cm^2 s

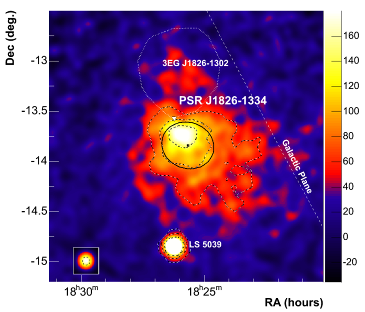
gamma-ray flux << "spin-down flux" *because of large B-field*

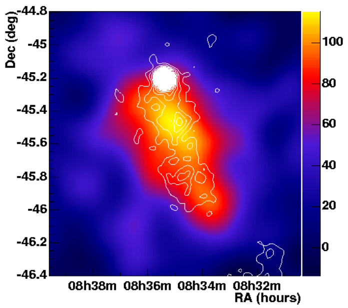
if the B-field is small (environments with small external gas presure)

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!







binary systems - unique high energy laboratories

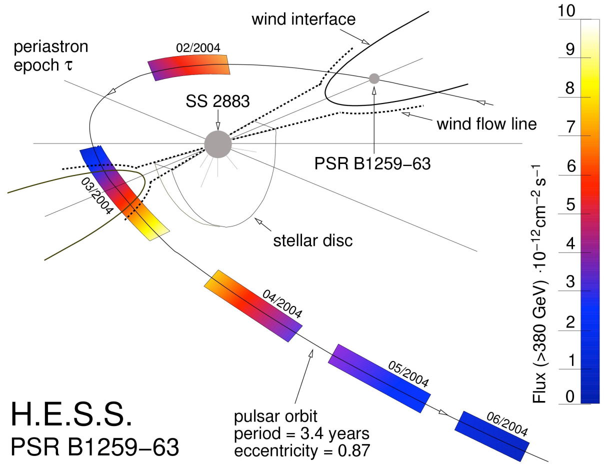
binary pulsars - a special case with strong effects associated with the optical star on both the dynamics of the pulsar wind and and the radiation before and after its termination

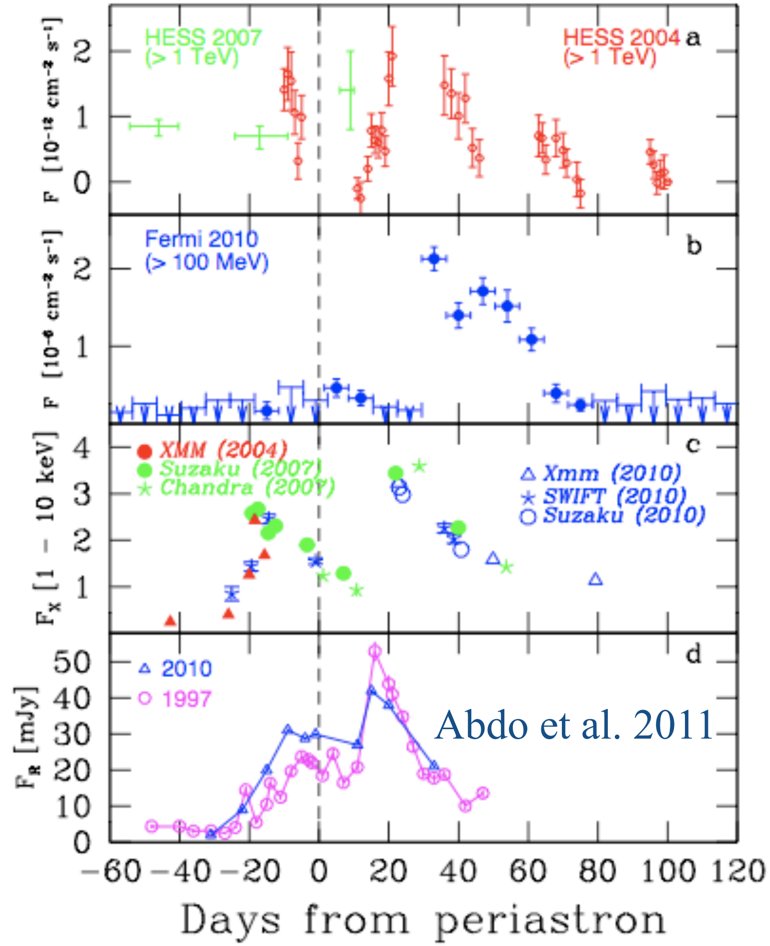
the same 3 components - *Pulsar/Pulsar Wind/Synch.Nebula* - as in PWNe both the electrons of the cold wind and shocke-accelerated electrons are illu-minated by optical radiation from the companion star detectable IC γ-rays

“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?





HESS: detection of γ-rays at < 0.1Crab level - tendency of minimum flux close to periastron;

Several possible explanations, but many things uncertain and confusing.

Special expectations/hopes from Fermi related to the periastron passage in Dec 2010

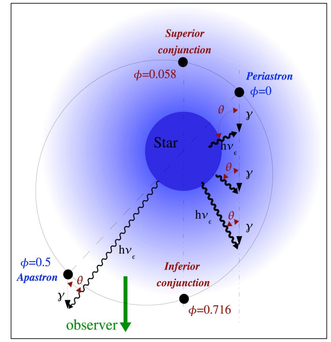
Fermi LAT - weak signal faround periastron, but flares after 1 month!

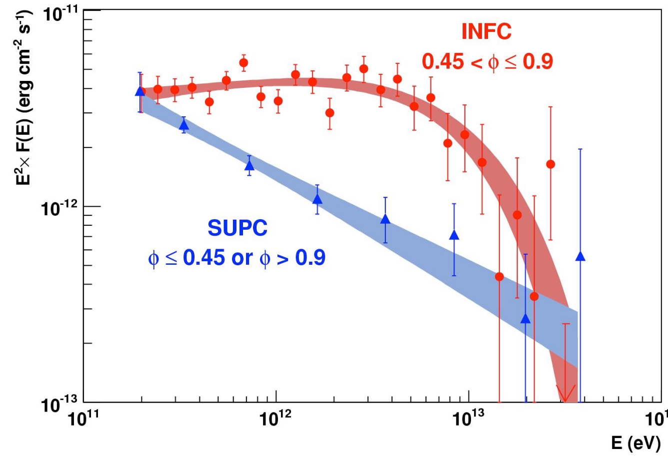
IC emission of unshocked wind with Lorentz factor 10^4 ?

LS 5039

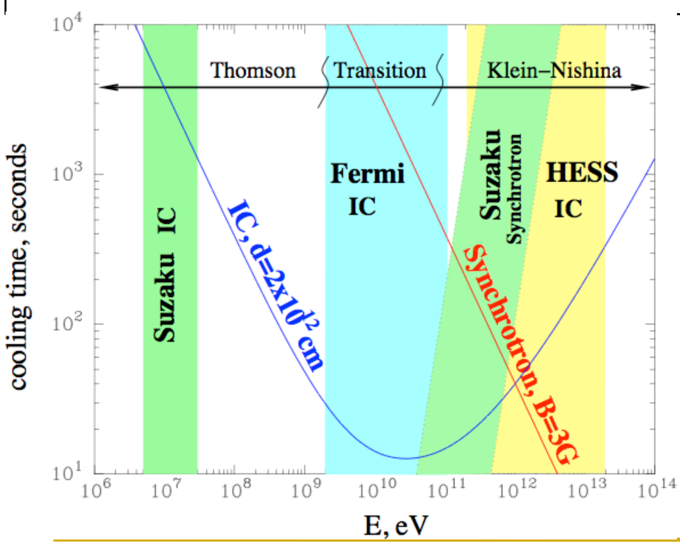
works as a perfect TeV clock
and an extreme accelerator

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 η < 10 => although* the origin of the compact object is not yet known (pulsar or a BH) and we do not understand many details, it is clear that this binary system works as an extreme accelerator

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
$t_{acc}=R_L/c=E/eBc$

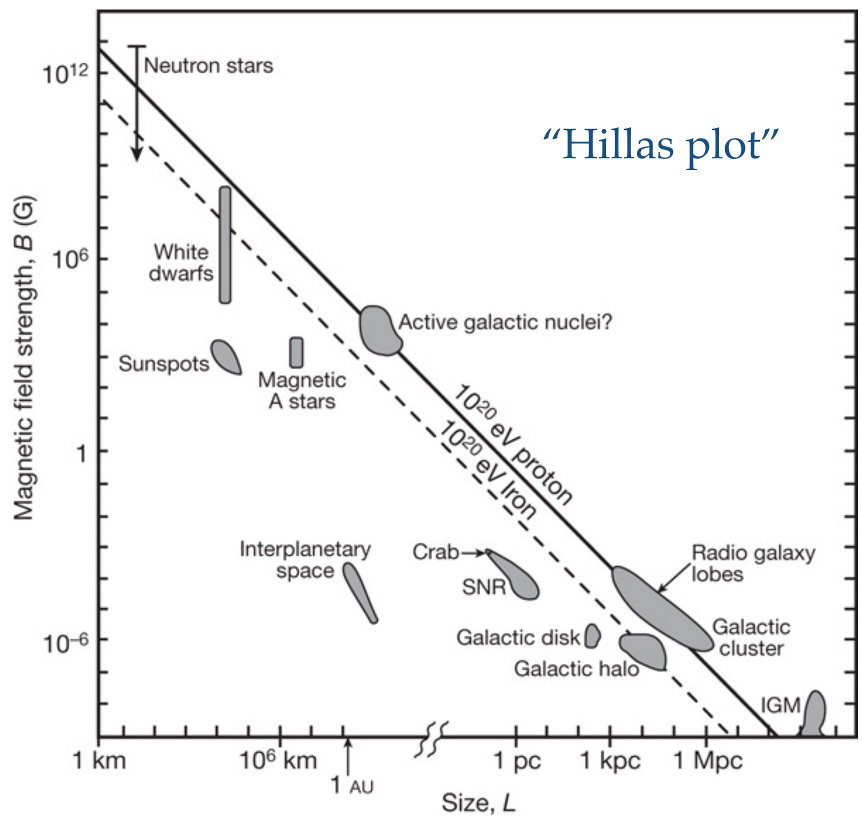
acceleration in fact is slower:

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

with η>1 and shock/bulk-motion speed v<c (η=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

Particle Acceleration in Galaxy Clusters

Several ingredients for effective acceleration to highest energies

- ✓ formation of strong accretion shocks
- ✓ magnetic field of order 0.1-1 μG
- ✓ shock velocity - few 1000 km/s
- ✓ acceleration time ~ Hubble time

but protons cannot be acceleratedto beyond 10^{19} eV (Kang et al., Vannoni et al) because of (Bethe-Heitler) pair production

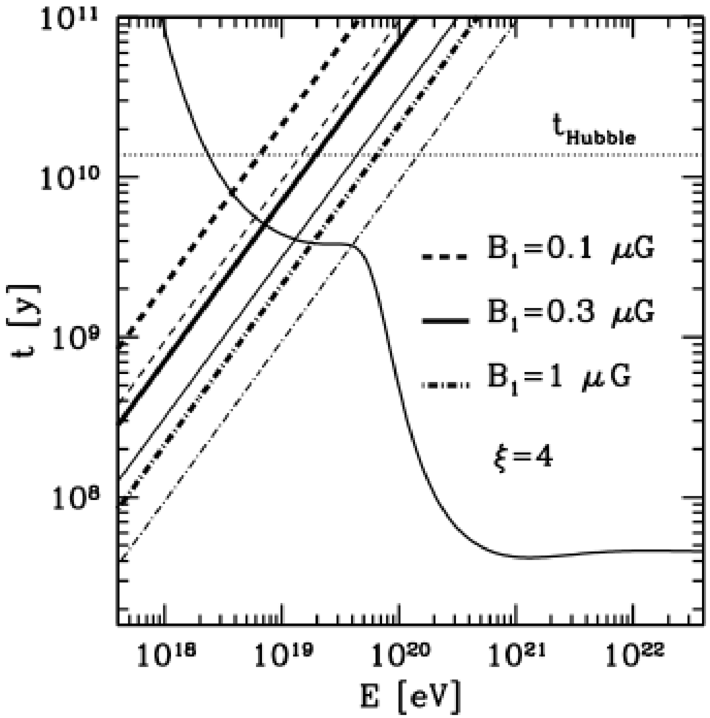


Fig. 1. Acceleration and energy loss time scales as a function of the proton energy. The acceleration time scales are obtained for the values of the upstream magnetic field B_1 reported in figure and a downstream magnetic field $B_2 = 4B_1$. The thick lines correspond to a shock velocity of 2000 km/s, the thin lines to a velocity of 3000 km/s. As an horizontal dotted line we report the estimated age of the Universe, for comparison.

Vannoni et al. 2009

acceleration sites of 10^{20} eV CRs ?

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

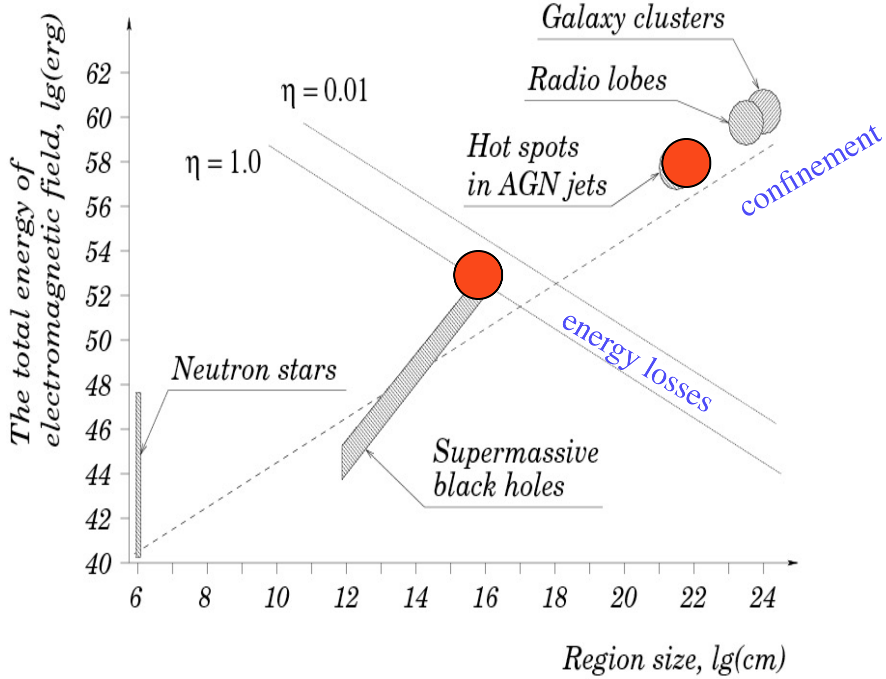
signatures of extreme accelerators?

✓ synchrotron self-regulated cutoff:

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

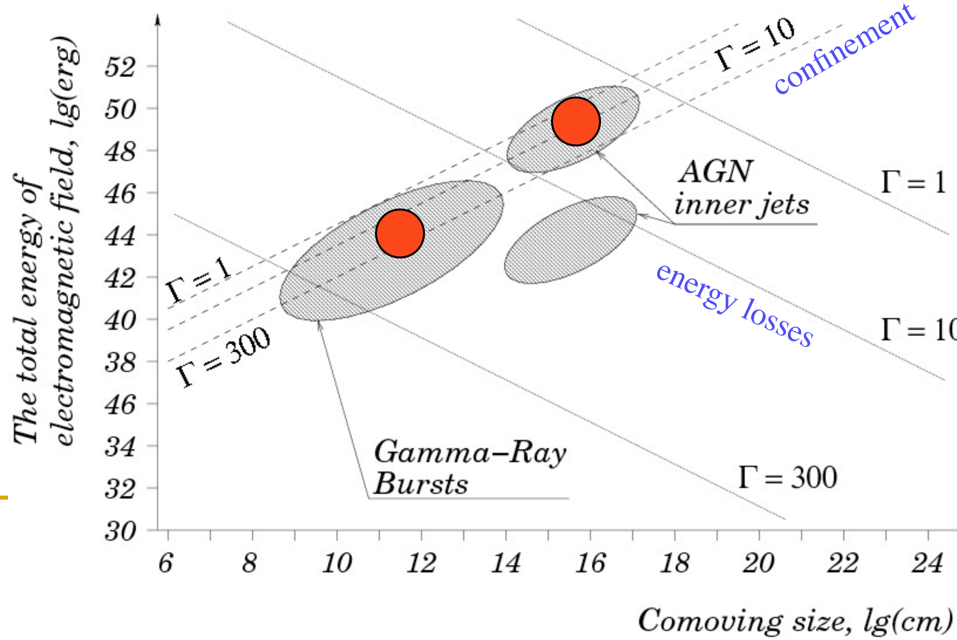
$\simeq 300$GeV proton synchrotron
$\simeq 150$MeV electron synchrotron

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



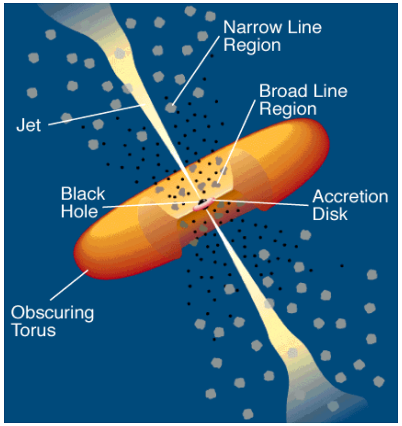
✓ neutrinos (through "converter" mechanism) production of neutrons (through pγ interactions) which travel without losses and at large distances convert again to protons => Γ^2 energy gain! (Deerishev et al. 2003)

✓ 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! (MAGIC)

Hadronic vs. Electronic models of TeV Blazars

SSC or external Compton *– currently most favoured models*:

- easy to accelerate electrons to TeV energies
- easy to produce synchrotron and IC gamma-rays

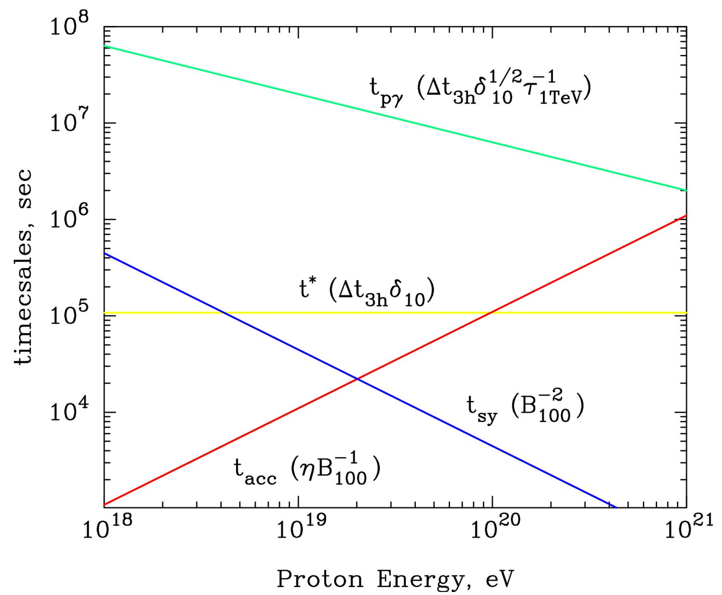
recent results require extremely small B~1mG

Hadronic Models:

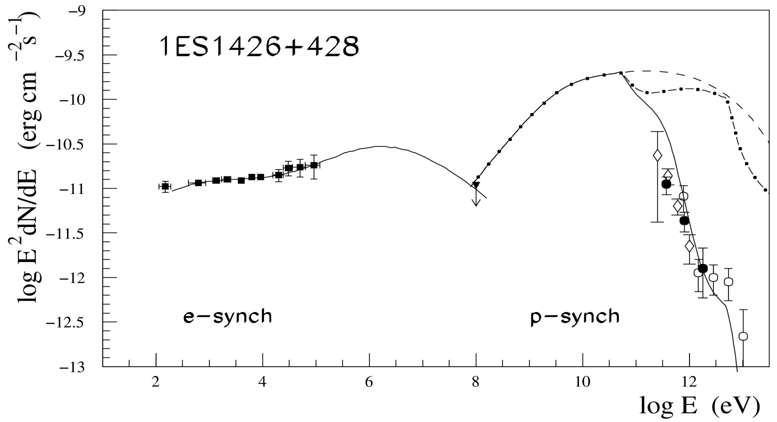
- protons interacting with ambient plasma — neutrinos
  very slow process:
- protons interacting with photon fields — neutrinos
  low efficiency + severe absorption of TeV γ-rays
- proton synchrotron — no neutrinos
  very large magnetic field B=100 G + accelaration rate c/r_g

"extreme accelerator" with Poynting flux dominated flow

Synchrotron radiation of an extreme proton accelerator



FA 2004



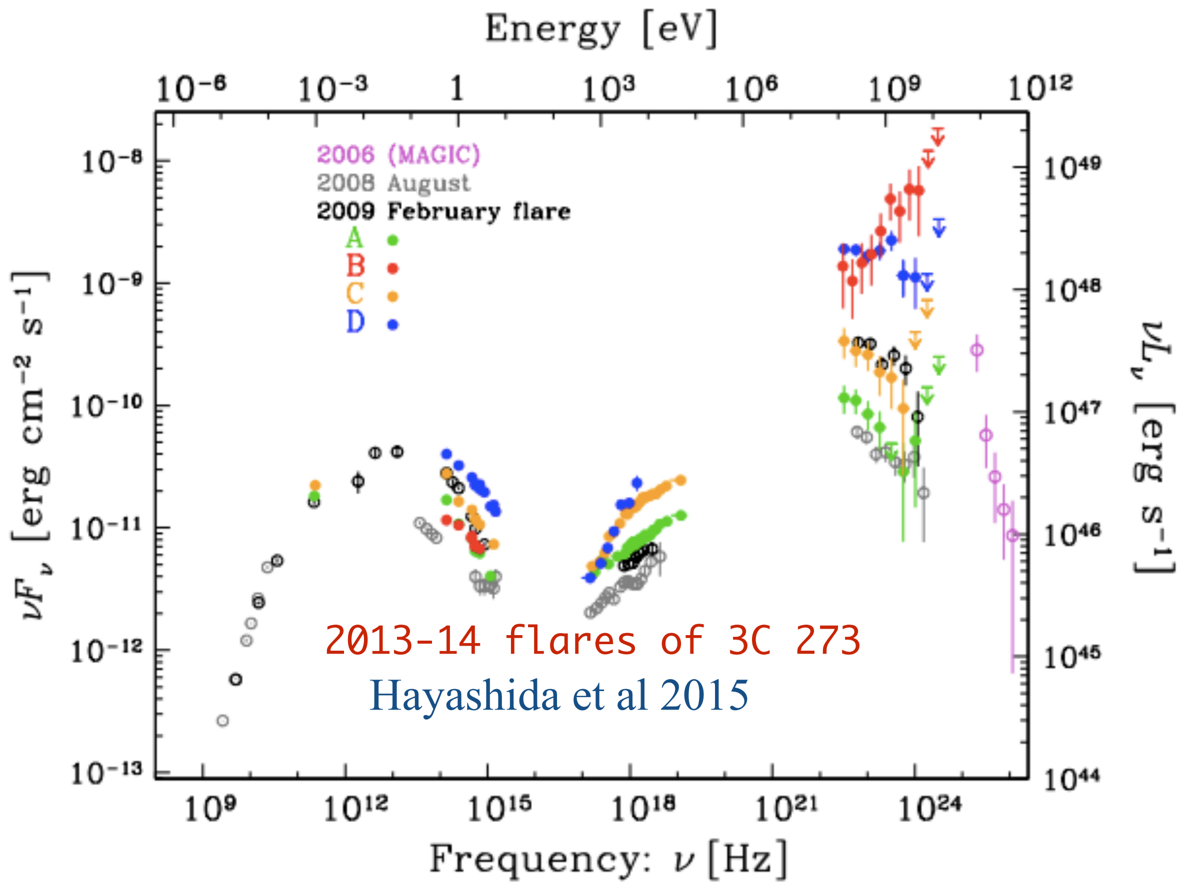
synchrotron radiation of protons:
a viable radiation mechanism

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

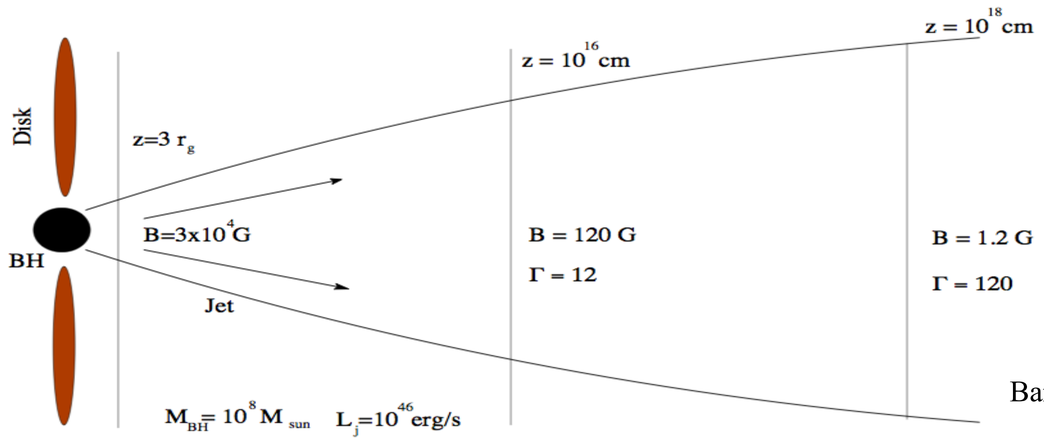
E_{max} =300 η^{-1} δj GeV
requires extreme accelerators: $\eta \sim 1$



Leptonic model: LB/Lj < 10-4, electron power-law index p=1 !
hadronic (photo-meson processes) model: not realistic
proton synchrotron - can explain the GeV gamma-ray peak

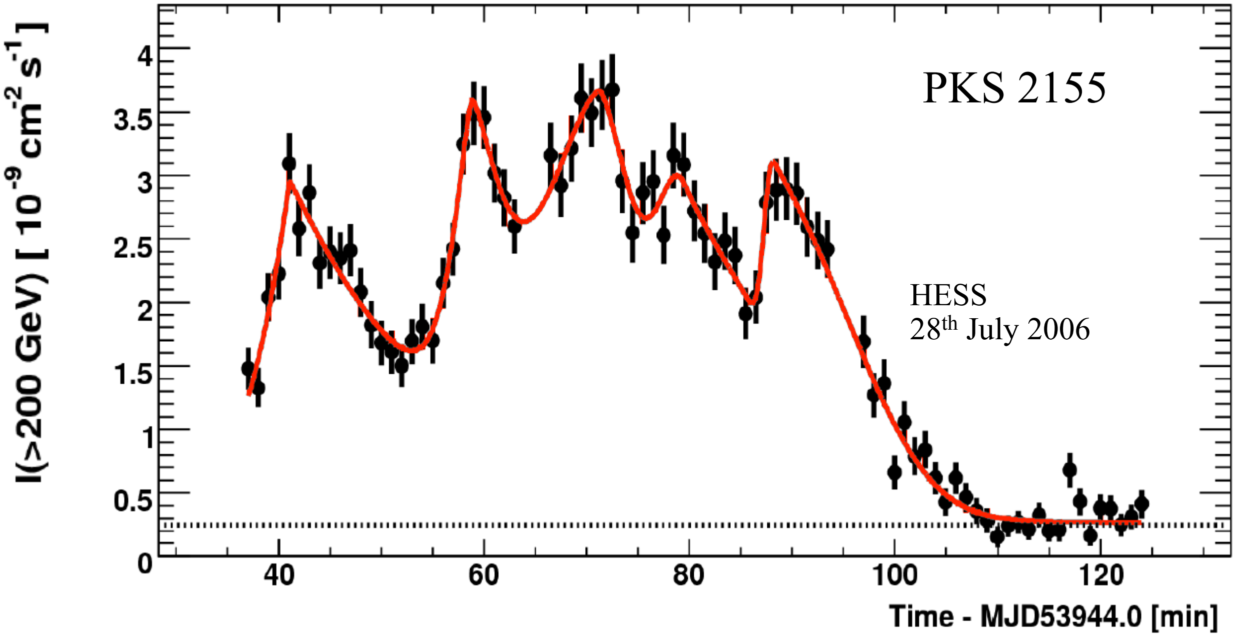
variability t~ 7 10^3 sec vs t_h ~ (3-8) 10^3 sec !

B-field: very large or very small?



Barkov et al 2010

in powerful blazars at subparsec scales B-field cannot be smaller than 1G, a serious constraint for the simplified one-zone "leptonic models, several min (200s) variabiliry timescale => R=c $\Delta t_{var}\ \delta_j = 10^{14}\delta_{10}$ cm for a 10^9Mo BH with 3Rg = 10^{15} cm => δj > 100, i.e. close to the accretion disk (the base of the jet), the bulk motion $\Gamma > 100$



it is convenient to express the variability in timescale

$$t_h = \frac{r_g}{c} = 10^{-5}(M_{\rm BH}/M_\odot)s$$

on the Doppler boosting and mass of BH

- several min variability timescale => $R=ct_{var}\delta_j \sim 10^{13}\delta_j$ cm for a 10^9Mo BH with $3Rg \sim 10^{15}$ cm => $\delta j > 100$, i.e. close to the accretion disk (the base of the jet), the Lorenz factor of the jet $\Gamma > 50$ - this hardly can be realized close to Rg!

- the (internal) shock scenario: shock would develop at $R=Rg\,\Gamma^2$, i.e. minimum γ-ray variability would be $R_g/c=10^4(M/10^9Mo)$ sec, although the γ-ray production region is located at $R_g \sim ct_{var}\Gamma^2$ (e.g. Chelotti, Fabian, Rees 1998) - this is true for any other scenario with a "signal-pertubaution" originating from the central BH

- thus for the observed $t_{var} < 200$ s, the mass of BH cannot significantly exceed 10^7Mo. On the other hand the "BH mass–host galaxy bulge luminosity" relation for PKS2155-304 gives $M > 10^9$Mo.

Solution? perturbations are coused by external sources, e.g. by magnetized condensations ("blobs") that do not have direct links to the central BH;

do we deal with the scenario "star crosses the relativistic e^+e^- jet" ?

Summary:

- VHE gamma-rays are perfect carriers of information about the sites and processes of particle acceleration on both galactic and extragalactic scales

- the contribution to the field of CR studies with the current ground-based detectors HESS/MAGIC/VERITAS/HAWC is substantial, unique and impressive

- CR related studies will be one of the highest priority tasks for the generation of ground-based detectors, first of all CTA