Very High Energy Gamma Rays *and* Origin of Galactic Cosmic Rays

F.A. Aharonian (MPI-K, Heidelberg)

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Solution of the Problem of Origin of Galactic Cosmic Rays

one of the highest priorities of TeV γ-ray Astronomy tightly connected with many research areas related to

Shell type SNRs, Star Formation Regions/Giant Molecular Clouds, Interstellar Medium, as well as Plerions, Microquasars, GRBs ....

Origin of Cosmic Rays:

a mystery since the discovery in 1912 by V.Hess …

but now we are quite close (hopefully) to the solution of the (galactic) component below the energy 1PeV (10^{15}eV)

thanks to the new generation of ground and space-based gamma-ray detectors , in particular

HESS and **GLAST**

Cosmic Ray Studies with Cosmic Rays

what do we know about Cosmic Rays ?

- energy spectrum $dN/dE=kE^{-2.6-2.7}$ up to the "knee" (10^{15} eV)
- chemical composition → $\lambda=5\ (E/10GeV)^{-0.6}\ g/cm^2$

little doubt that up to (at least) 10^{15} eV they have Galactic Origin*

→ source spectrum close to $E^{-2.0-2.1}$

production rate $3 \times 10^{40}\ erg/s$

* CRs above 10^{19} eV most likely of extrargalactic origin,
CRs between 10^{15} eV and 10^{19} eV ? both G- and EXG are possible

γ-rays as tracers of CRs

what we do not know about Galactic Cosmic Rays ?

acceleration sites, source populations, acceleration mechanisms

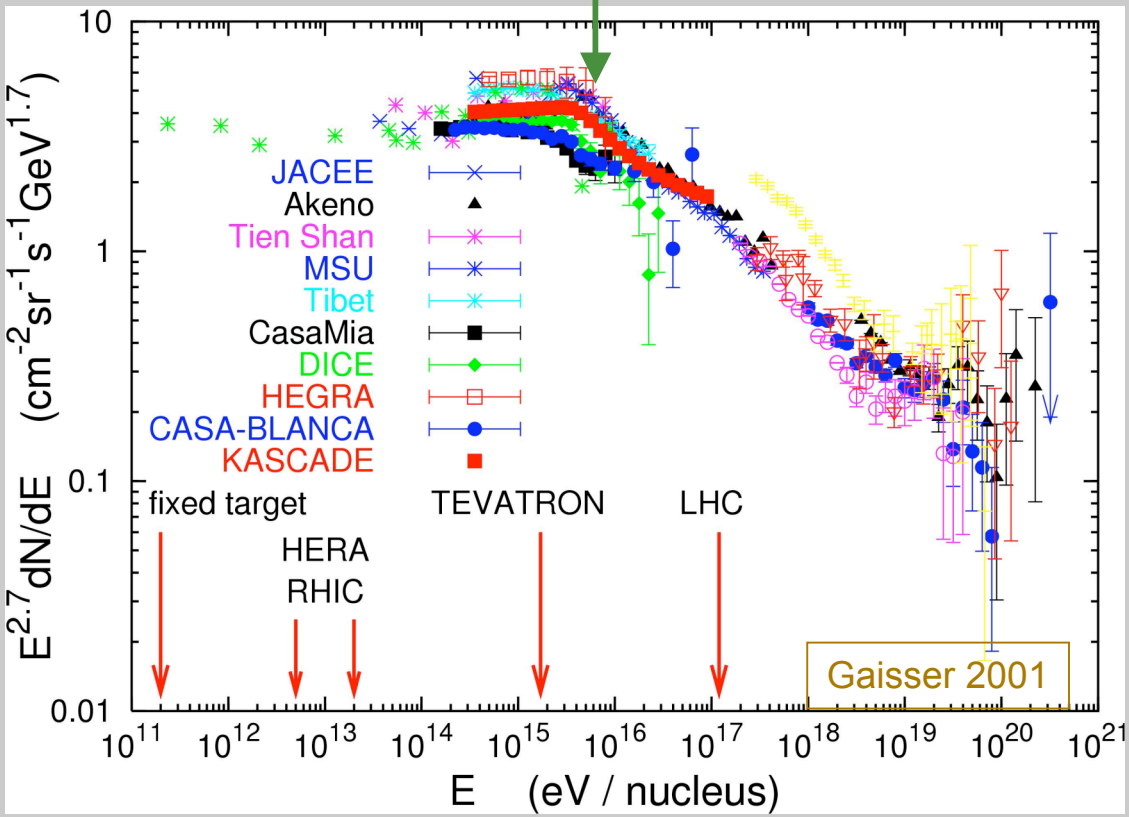
reason ? ***deflection (diffusion) of CRs in interstellar B-fields***

solution ? ***probing CRs with high energy gamma-rays:***

discrete γ-ray sources – productions sites oF CRs
diffuse γ-ray emission – propagation of CRs in ISM

the major (historical) motivation of gamma-ray astronomy

Galactic **PeVatrons** – accelerators responsible for CRs up to (at least) 1 PeV (=10^{15} eV) *



SNRs ?

Pulsars/Plerions ?

O & B stars ?

Microquasars ?

Galactic Center ?

. . .

* the source population responsible for the bulk of GCRs are PeVatrons ?

SNRs – the most probable factories of GCRs ?

(almost) common belief based two arguments:

- necessary amount of available energy – 10^{51} erg
- Diffusive Shock Acceleration – **10% efficiency and E^{-2} type spectrum up to ? at least 10^{15} eV**

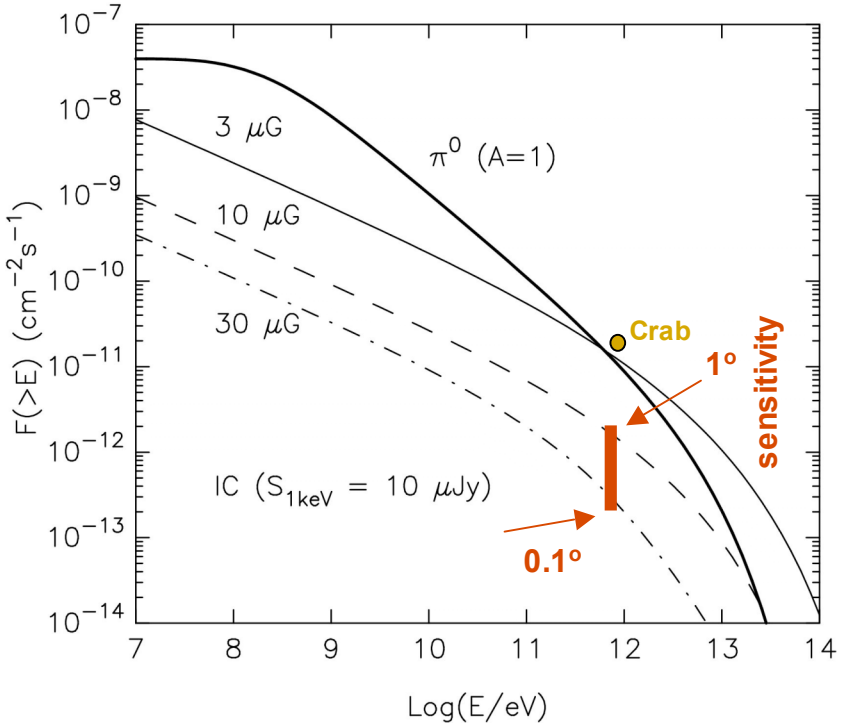
Straightforward proof: detection of gamma-rays (and neutrinos) from pp interactions (as products of decays of secondary pions)

Objective: to probe the content of nucleonic component of CRs in SNRs at d < 10 kpc at the level 10^{49} -10^{50} erg

Realiztion: sensitivity of detectors - down to 10^{-13} erg/cm^2 s

crucial energy domain - VHE/UHE (up to 100 TeV)

Visibility of SNRs in high energy gamma-rays



for CR spectrum with $\alpha=2$

$F_\gamma(>E)=10^{-11}\ A\ (E/1TeV)^{-1}$ ph/cm^{2}s

$A=(W_{cr}/10^{50}erg)(n/1cm^{-3})(d/1kpc)^{-2}$

1000 yr old SNRs (in Sedov phase)

Detectability ? compromise between
angle θ (r/d) and flux F_γ $(1/d^2)$

TeV γ-rays – detectable if A > 0.1

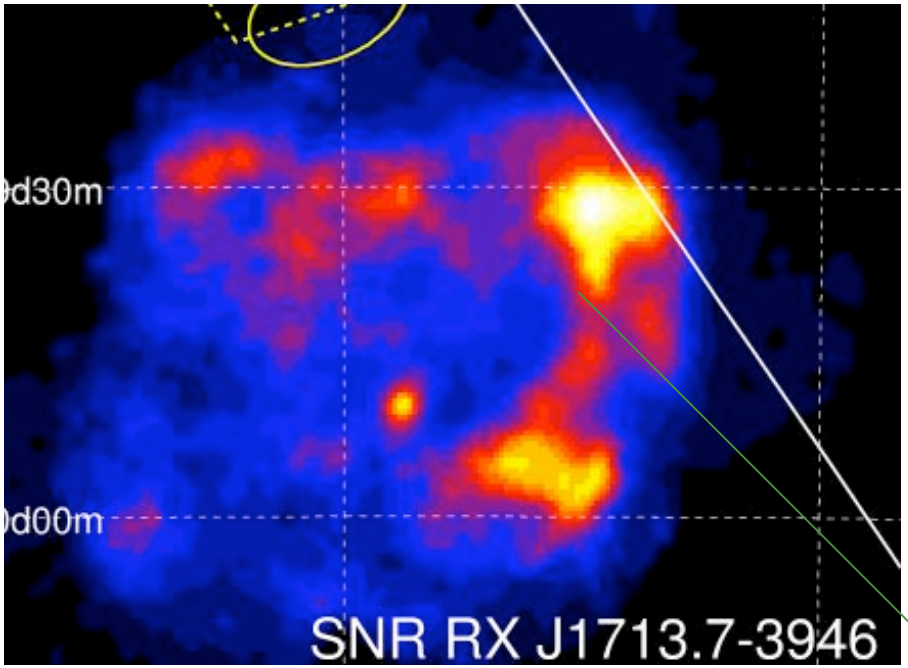
π^o component dominates if $A > 0.1\ (S_x/10\ \mu J)(B/10\ \mu G)^{-2}$

nucleonic component of CRs - "visible" through TeV (and GeV) gamma-rays !

Cosmic Ray Accelerators ?

SNRs in our Galaxy: 231(Green et al. 2001

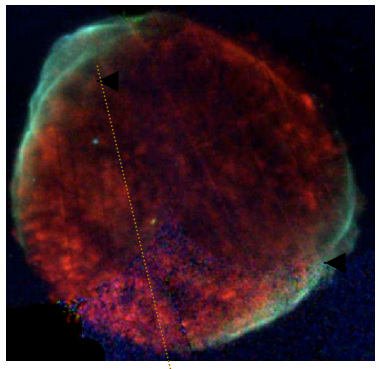
with nonthermal X-ray emission - 10 or so



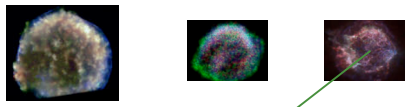
best candidate - young SNRs

with synchrotron X-rays

SN1006



Tycho Kepler CasA



?

30 arcmin

TeV emission

H.E.S.S. PSF

SN 1006 - *a good candidate for particle source acceleration*

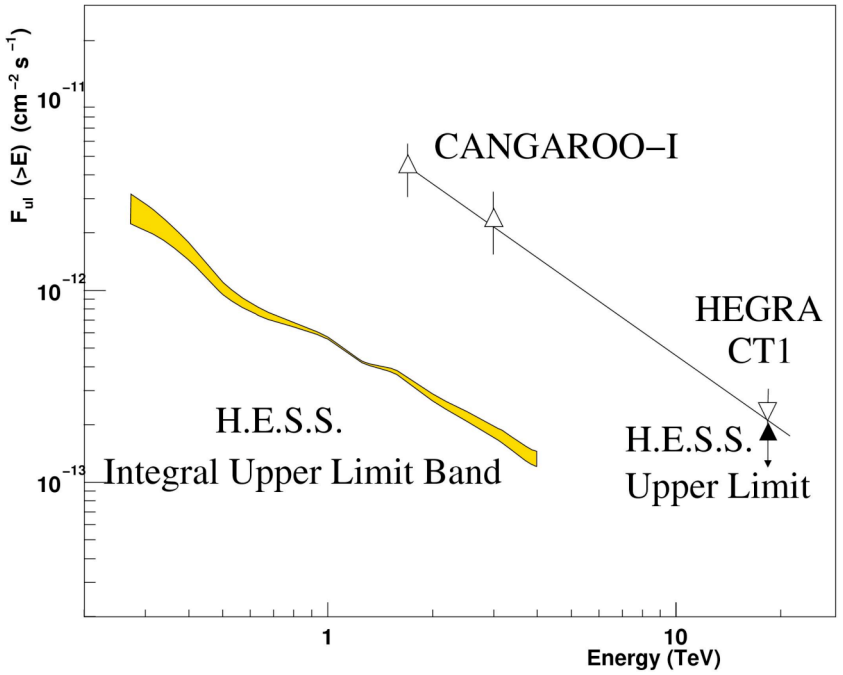
H.E.S.S. upper limits - an order of magnitude below the flux reported by CANGAROO

a trouble ? not at all …

HESS upper limits imply

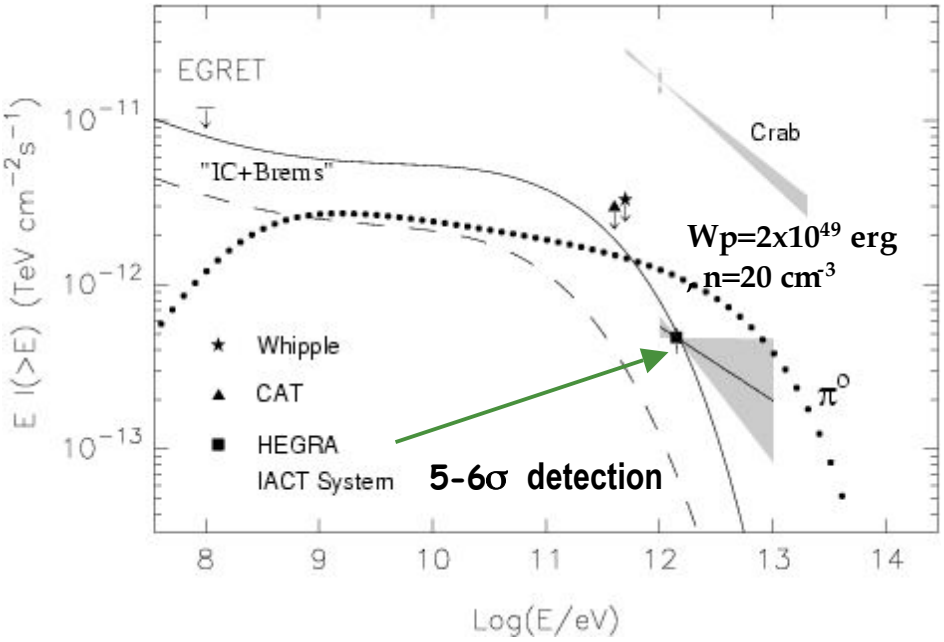
IC : B > 25 μG

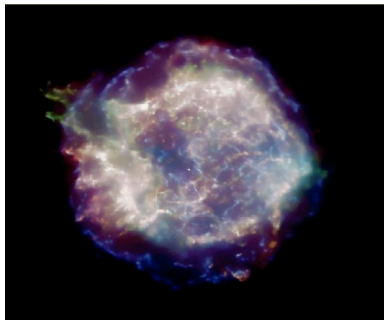
π° : W_p<(0.2-2) x 10^{50} erg



no problem for the hypothesis of SNR origin of Galactic CRs …

Cas A – *a proton accelerator*





B > 0.1 mG ⟹ IC origin is unlikely;

TeV gamma rays of hadronic origin ?

yes, although Wp =10^{49}erg (only)

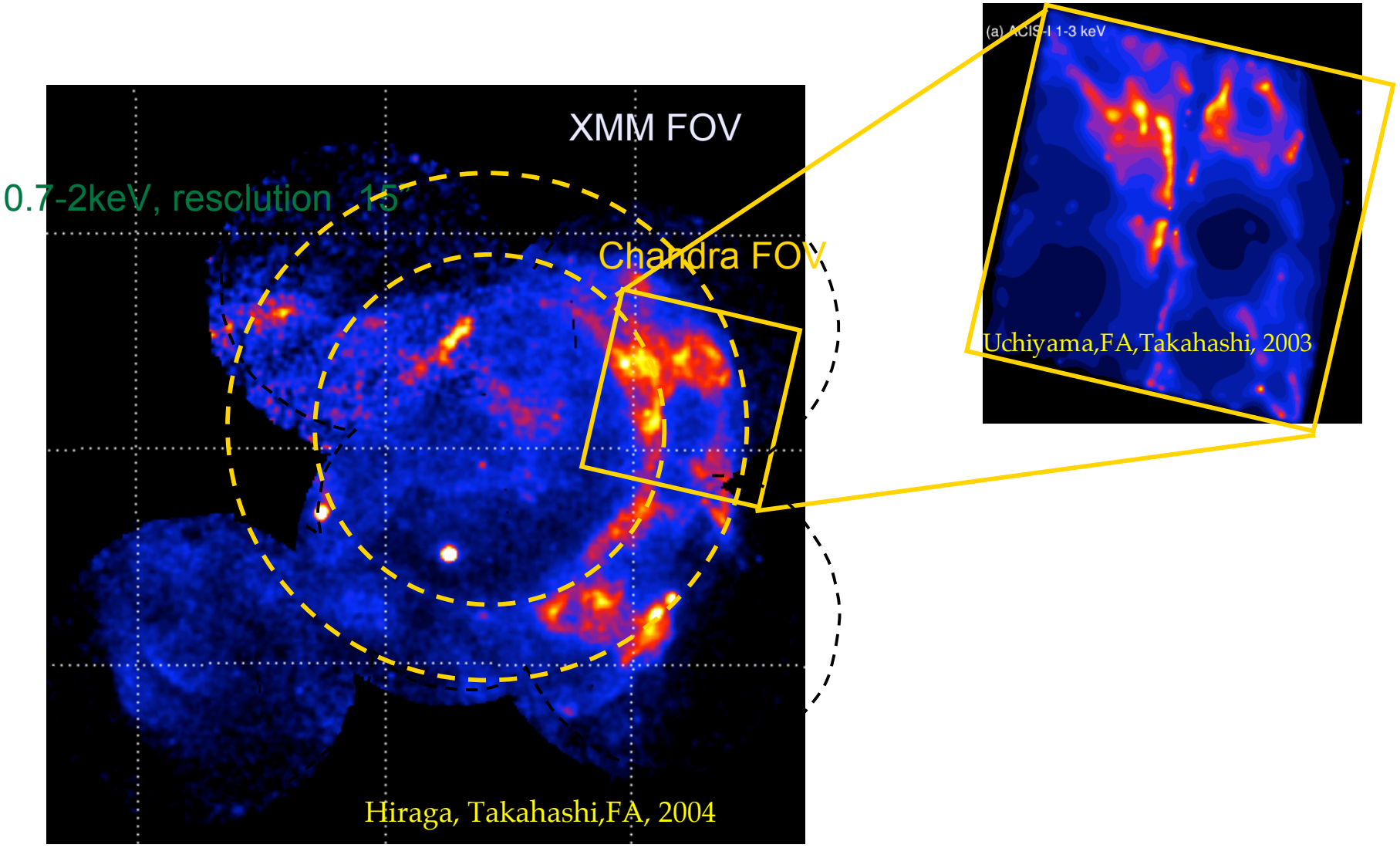
Cas A is well designed for acceleration of protons to 10^{15} eV !

can be checked with >10 TeV γ -ray and neutrino (?) detectors

important target for VERITAS and MAGIC

***GLAST* should detect GeV γ-ray emission in any case**

RX J1713.7-3946



RX J1317.7-3946

- discovered during the ROSAT all sky survey

  (*Pfefferman & Ashebach 1996*)

- 1 degree diameter remnant with very large, $5x10^{-10}$ erg/cm^{2}s flux consisting of only nonthermal (synchrotron) component - ASCA

  (*Koyama et al., 1997, Slane et al. 1999*)

  no convincing evidence yet for a thermal component !

- distance to the source - around 1 kpc (no anymore 6 kpc) – from CO observations of the interacting cloud - NANTEN (*Fukui et al. 2003*)

- age - s 1 kyr - 1611 yr as the remnant of the AD 393 SN event ?

  (*Wang et al. 1997*)

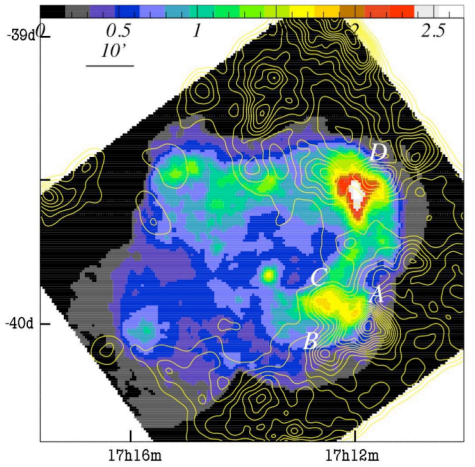
X-ray properties

- Chandra - striking small – scale (s 10") structure (of the NW part) in the forms of filaments and hotspots embedded in a diffuse plateau
  sites of particle acceleration ?

also, a noticeable spatial variation of N_H - from X –ray spectral fits

- XMM - surprisingly positive correlation between X –ray brightness and N_H along the western portion

Reason ? massive molecular cloud(s) interacting with the shell of SNR ?

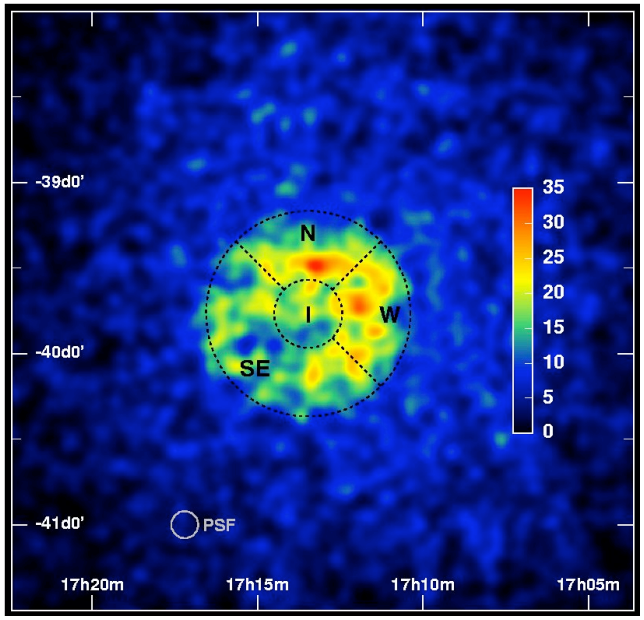


Direct evidence of high energy particle acceleration in the shell of RXJ 1713.7-3946*

H.E.S.S collaboration

first image of an astronomical object obtained in γ-rays on arcmin scales

Nature, in press



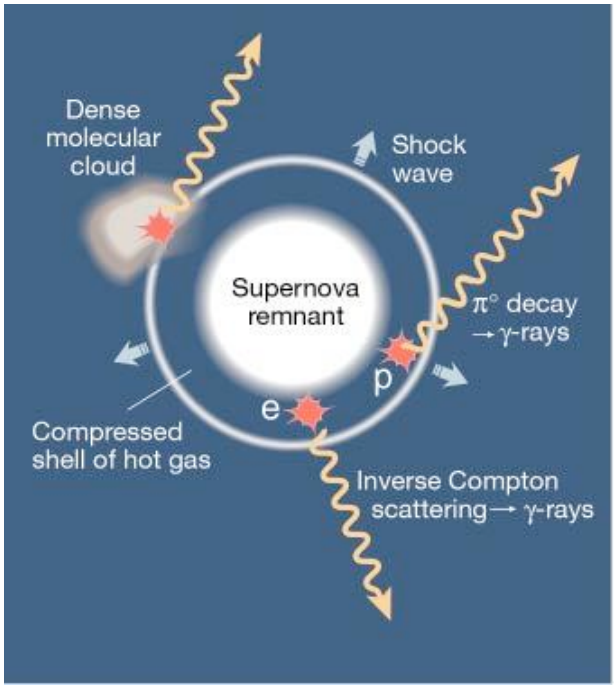
COSPAR 2004, Paris, July 22

Origin of radiation ?

- hadronic origin seems preferable given the high density environment:

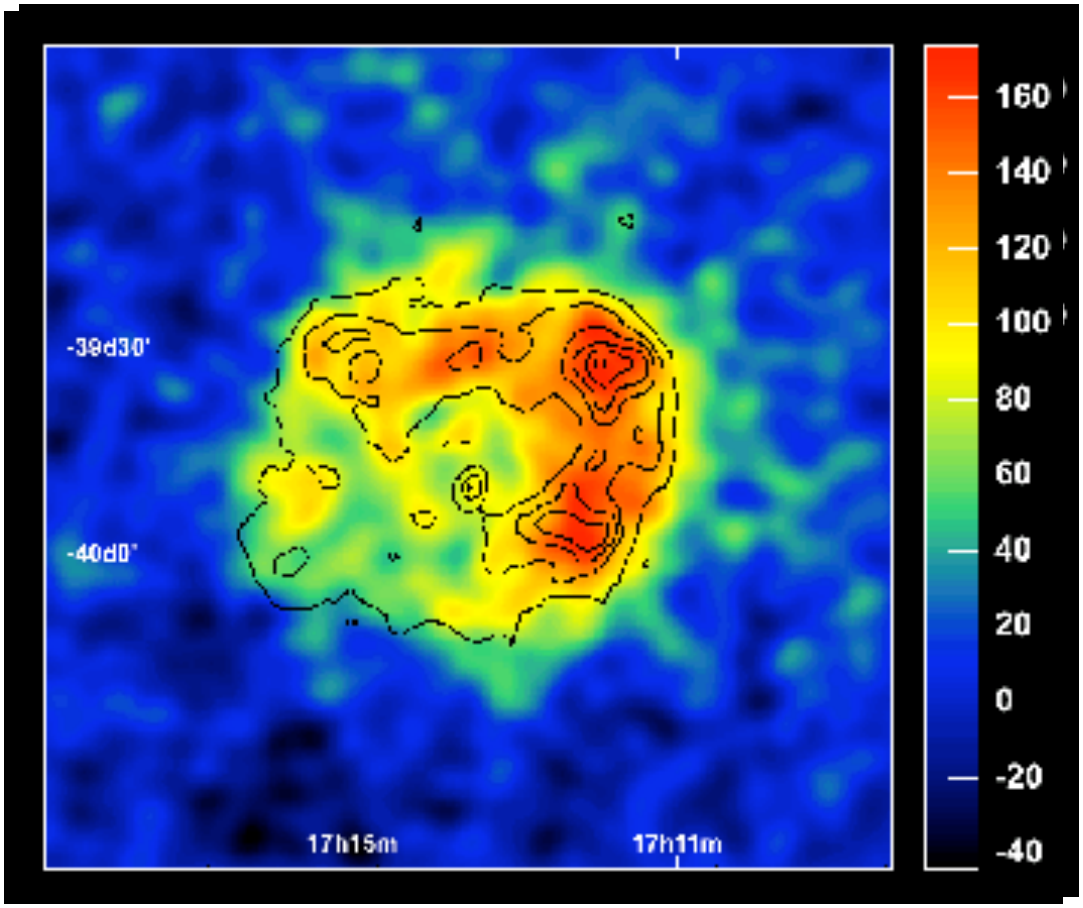
W_p (above 10 TeV) = 3×10^{47} (n/100 cm^{-3}) $^{-1}$ erg

- IC origin is not excluded, but this model requires B – field less than 10-20 μG



More complex scenario, e.g. γ-rays from NW+SW are contributed by protons while gamma-rays from remaining parts are due to IC γ-rays, cannot be excluded

TeV-keV correlations … what this could mean?



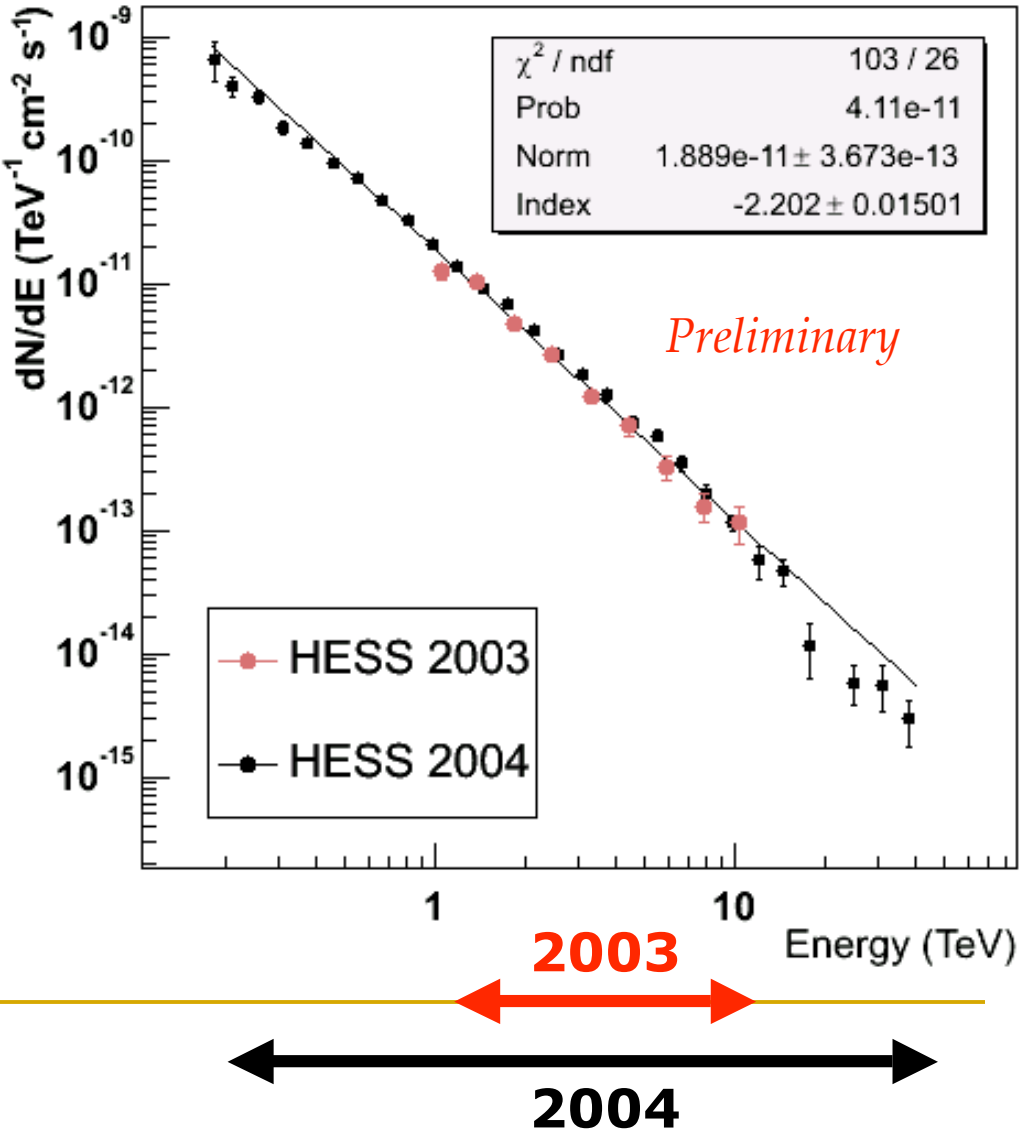
Energy Spectrum

- 2003:

  $\Gamma = 2.19 \pm 0.09 \pm 0.15$

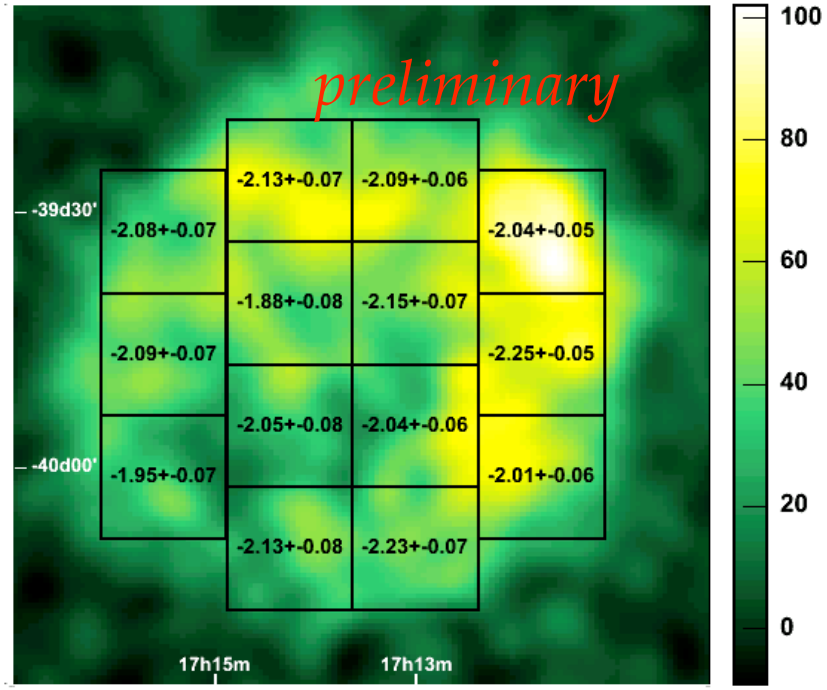
- 2004:

  $\Gamma = 2.20 \pm 0.02 \pm 0.15$



spatially resolved spectra

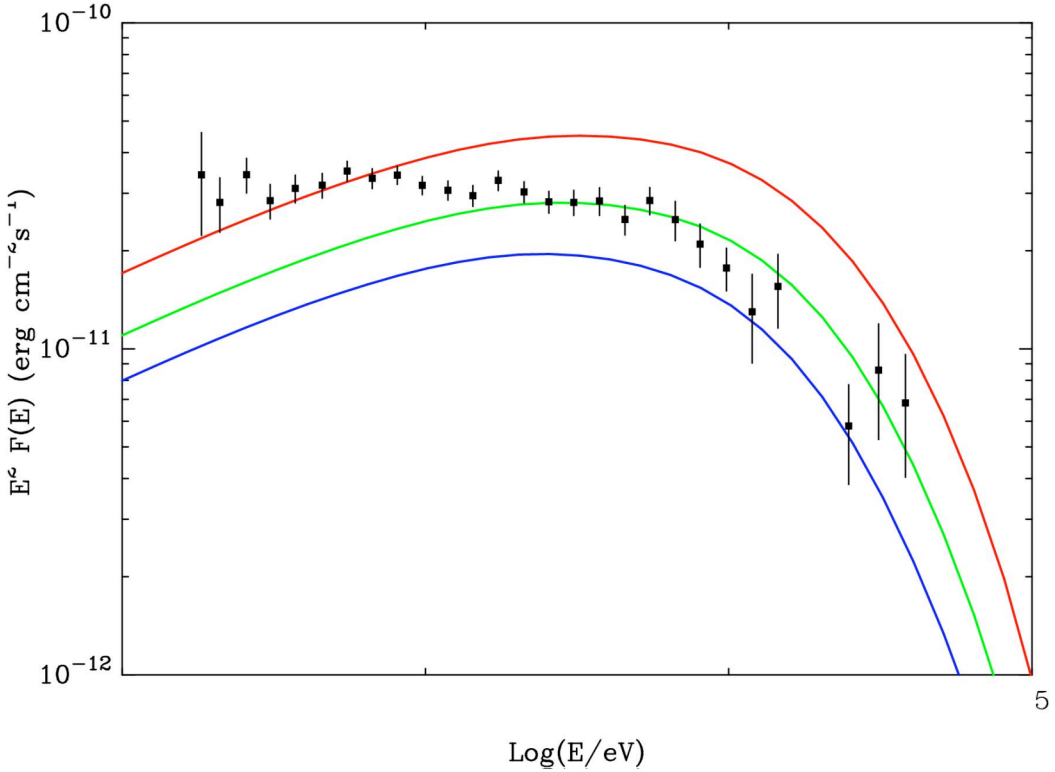
- **Spectral shape – quite stable**
- **flux variation - a factor of 2**



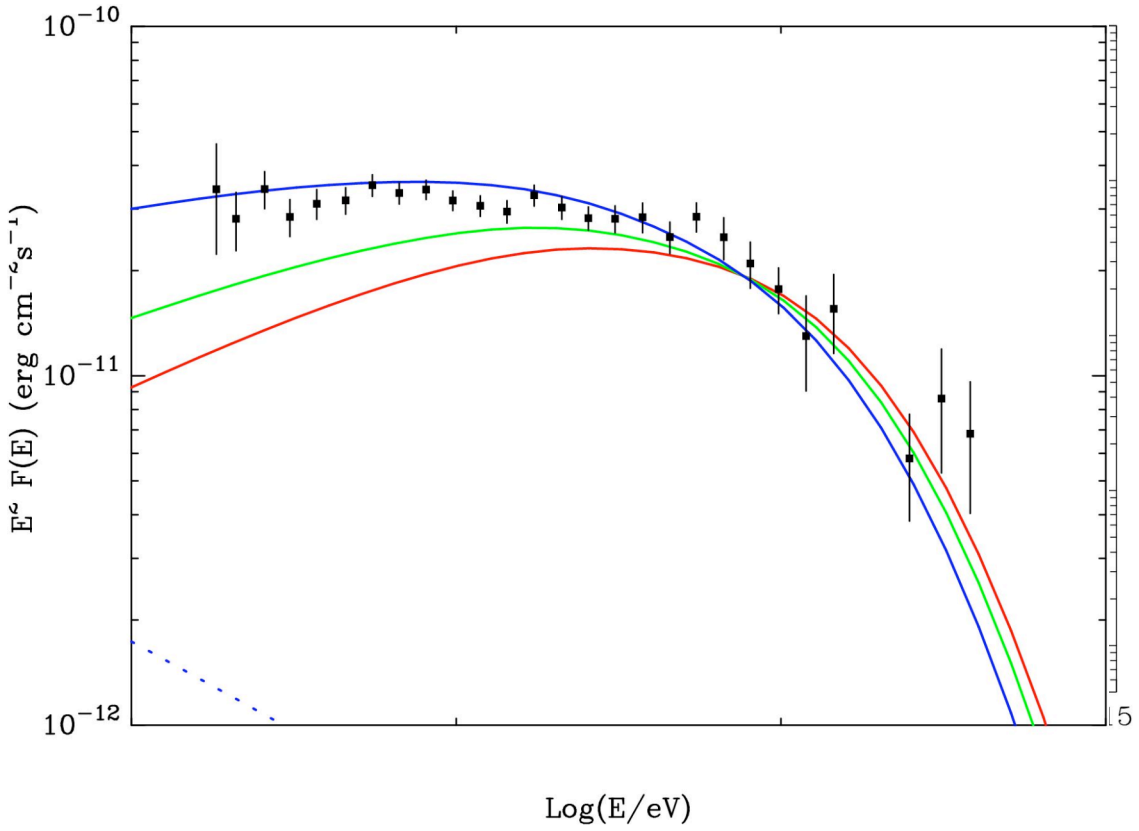
a (quasi) homogeneous X- and g-radiation production region ?

well … not a bad (completely wrong) approximation

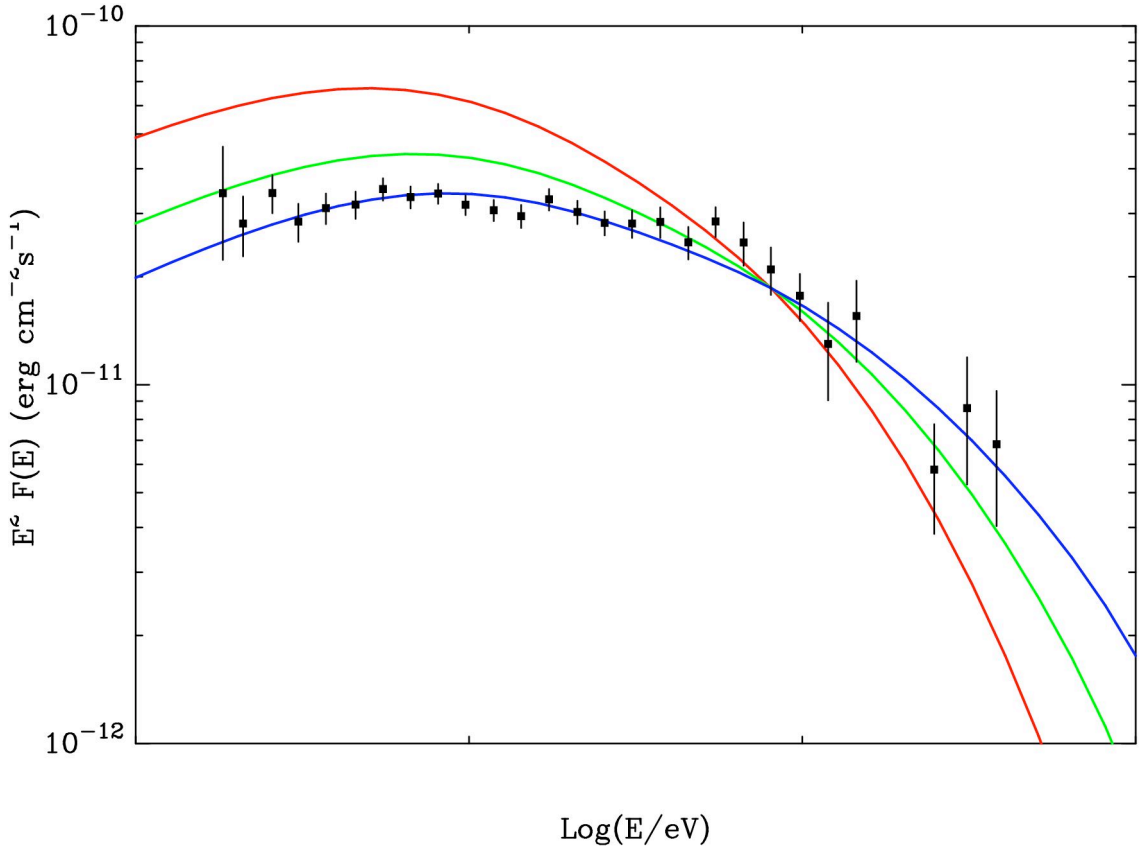
IC model: B-field cannot exceed 10 mG and …
does not provide good spectral fit



steeper electron acceleration spectra ? now a better fit, but conflict with radio and 2 orders of magnitude larger energetics

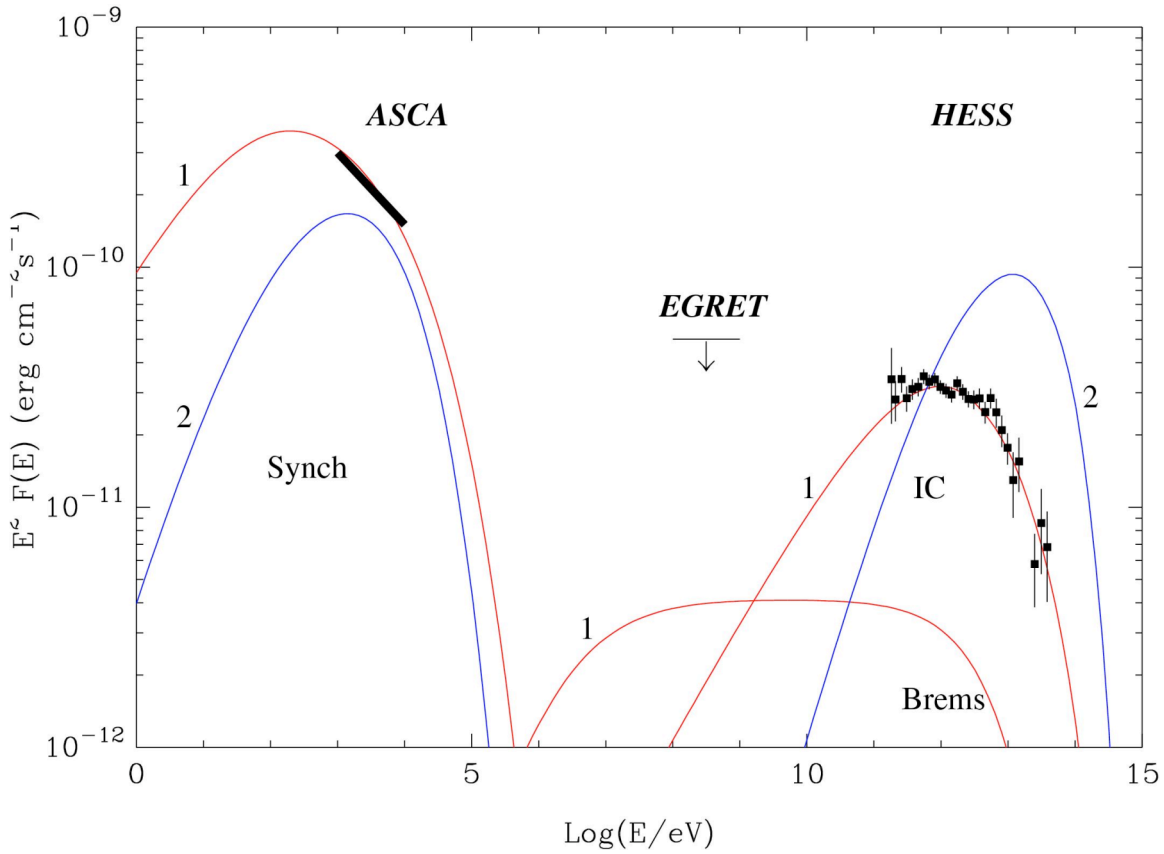


older source ?

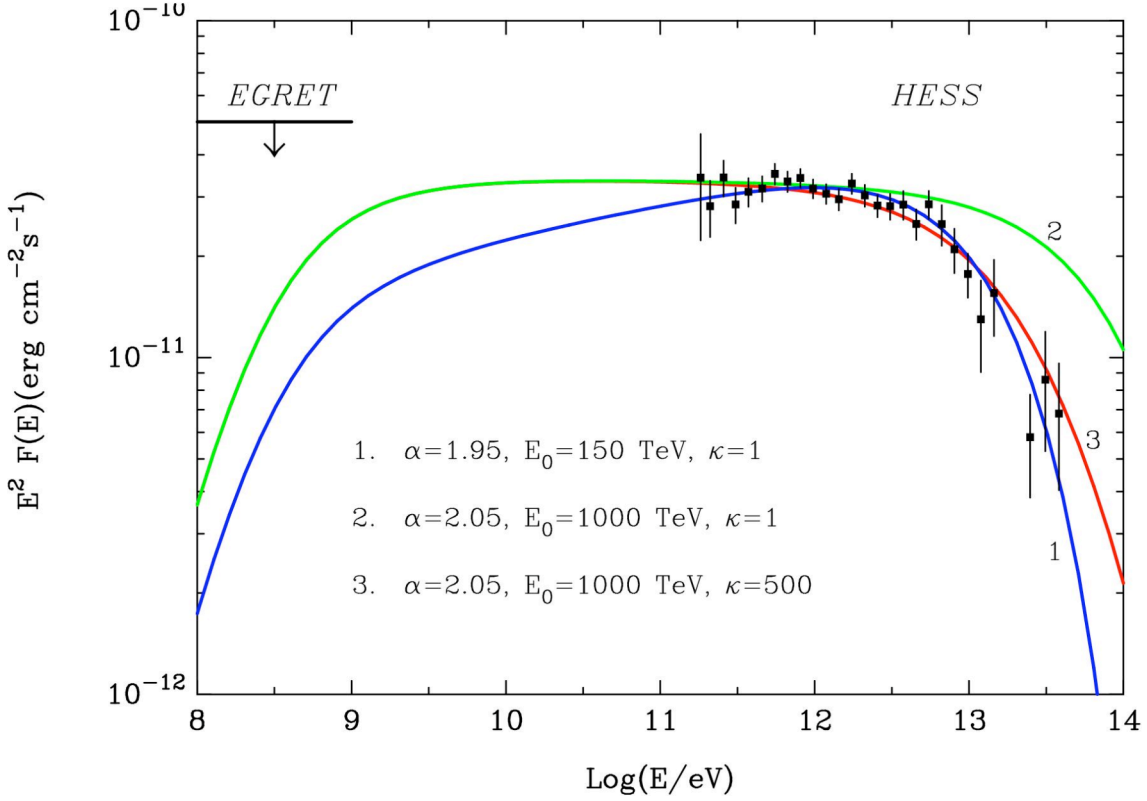


two zone model ?

$t_{esc}=50\ t_B$ (prop. 1/E); $B_1=3$ mG, $B_2=15$mG; R=3 pc



Hadrons - reasonable fit and modest energetics



$W_p = 10^{50}\ (n/1cm^{-3})^{-1}$ erg ; n close to 1 cm^{-3} ? preferable -

can explain the production rate of GCRs by SNRs

Eo significantly smaller than 100 TeV ?, yes, although

that could be connected with the fast escape of protons from

accelerator, so RXJ 1713 still could be treated as a

Probing PeV protons with X-rays

SNRs shocks can accelerate CRs to <100 TeV (Cesarsky&Lagage 1984)

unless magnetic field significantly exceeds 10 μG

Recent theoretical developments: applification of the B-field up to 1 mG is possible through plasma waves generated by CRs

(Bell and Lucek 2000)

$>10^{15}$ eV protons ⇒ $>10^{14}$ eV gamma-rays and electrons

$$t(\epsilon) \simeq 1.5(\epsilon/1\mathrm{keV})^{-1/2}(B/1\mathrm{mG})^{-3/2}\mathrm{yr} \ll t_{SNR}$$

⇒ prompt synchrotron X-rays

L_X/L_γ

L_X/L_γ

typically in the range between 1 and 100 keV with the ratio (for E^{-2} type spectra), but for very hard proton component as large as 30% can exceed 1

detection of the hard synchrotron X-rays of (hadronic) secondary origin from 10 keV to 100keV is possible with INTEGRAL, ASTRO-E2

Basic Features

- morphology: sharp thin structures – due to shock compression of the ambient gas and B-field and severe energy losses

"hadronic" X-rays and VHE gamma-rays - similar morphologies !

- energy spectra: assuming for p: $Q_p(E) = Q_o E^{-\Gamma} \exp[-(E/E_o)^{\beta}]$

X-ray spectrum: $\propto \nu^{-(\Gamma/2+1)} \exp[-(\nu/\nu_o)^{\beta/2}] \quad (\nu_o \propto E_o B^2)$

smoother than the gamma-ray spectrum $\propto E_\gamma^{-\Gamma} \exp[-(E_\gamma/E_{\gamma,o})^{\beta}]$

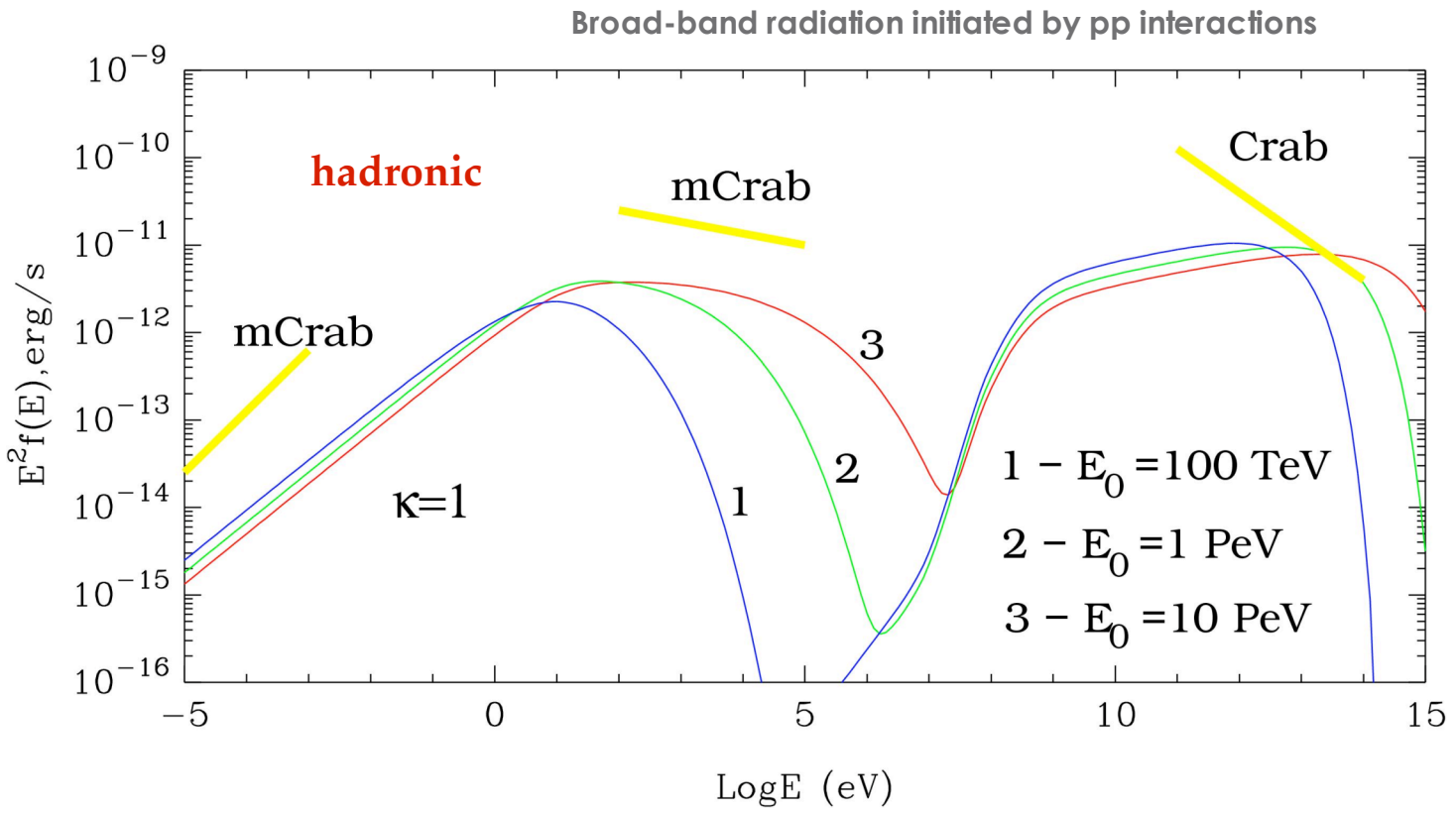
- cutoff: $h\nu_o \propto B E_o^2 \propto B^3$ above the synchrotron cutoff of X-rays produced by primary electrons $h\nu_o \simeq 2(v/2000\mathrm{km/s})^2 \mathrm{keV}$

cutoff energies in X- and γ-ray spectra → $B = a(h\nu_o/E_{\gamma,o})^{1/2}$

two-bump structure in pure hadronic model ?

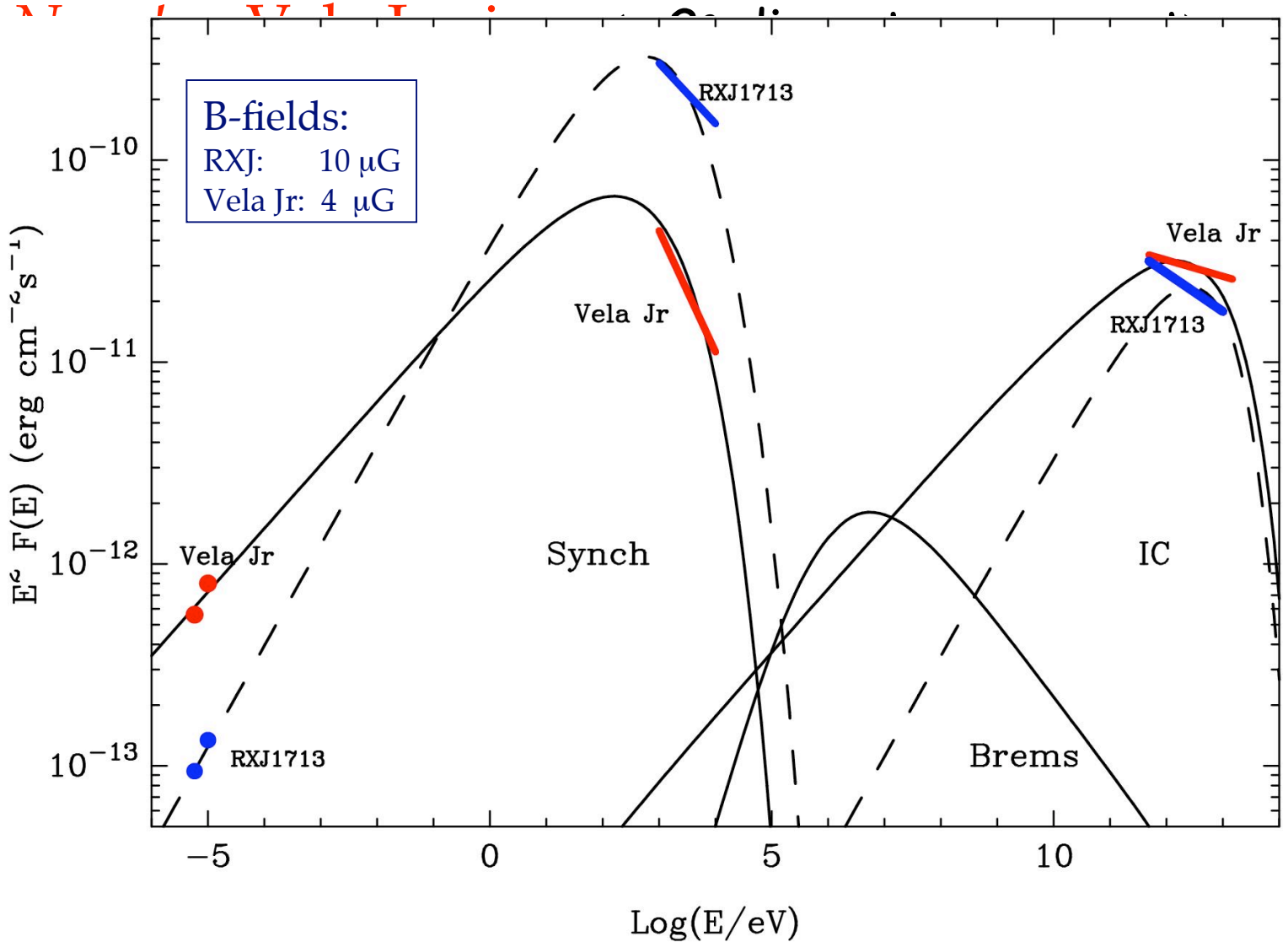
yes, especially in the case of dense clouds

interacting with the west portion of the shell



Lp=10^{37} (n/300cm^{-3}) erg/s, Γ=1.9, T=10^3 yr

X-rays in RXJ1713 of secondary origin ? Would be great, but does not work , Lx > Lγ



IC ? – very small magnetic field at the level of < 4 μG

searching for galactic PeVatrons ...

TeV gamma-rays from Cas A and RX1713.7-3946, Vela Jr –
a proof that SNRs are responsible for the bulk of GCRs ?- not yet

the hunt for galactic PeVatrons continues

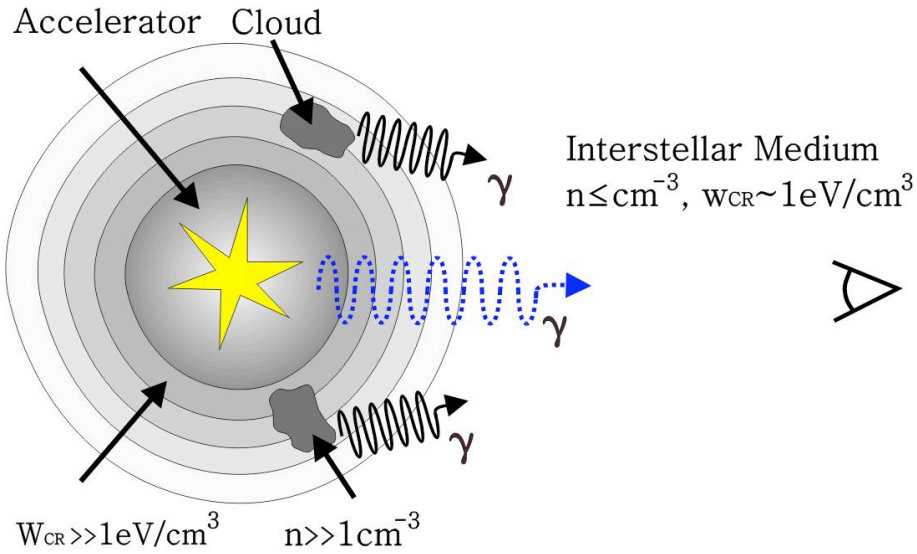
unbiased approach – deep survey of the Galactic Plane – not to miss any recent (or currently active) acceleration site:

SNRs, Pulsars/Plerions, Microquasars...

not only from accelerators, but also from nearby dense regions

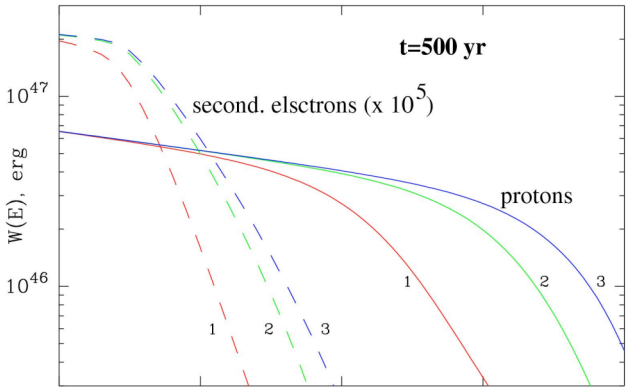
Gamm-rays/X-rays from dense regions surrounding accelerators

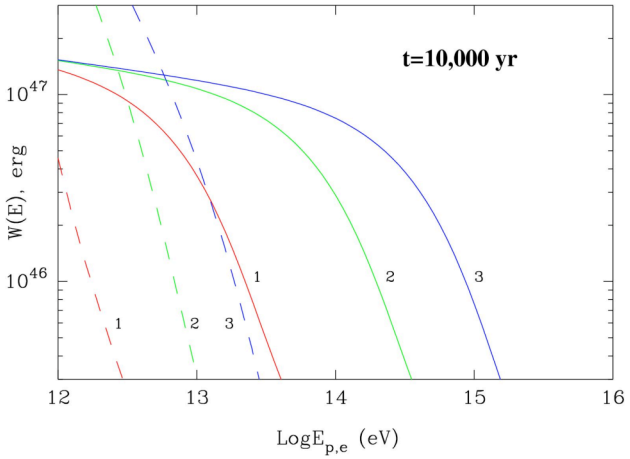
the existence of a powerful accelerator by itself is not sufficenrt for gamma radiation; an additional component – a dense gas target - is required

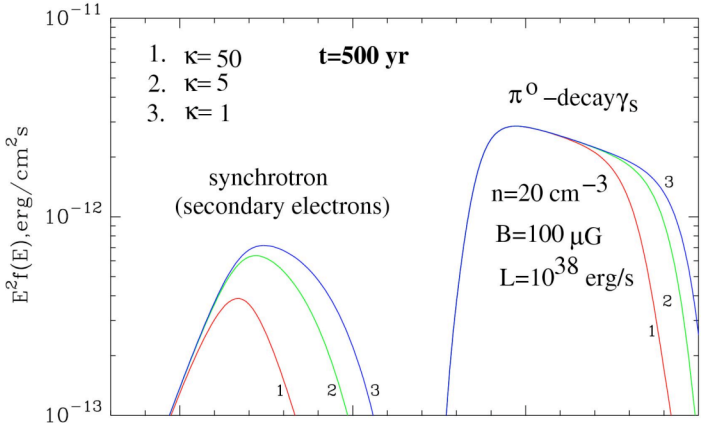


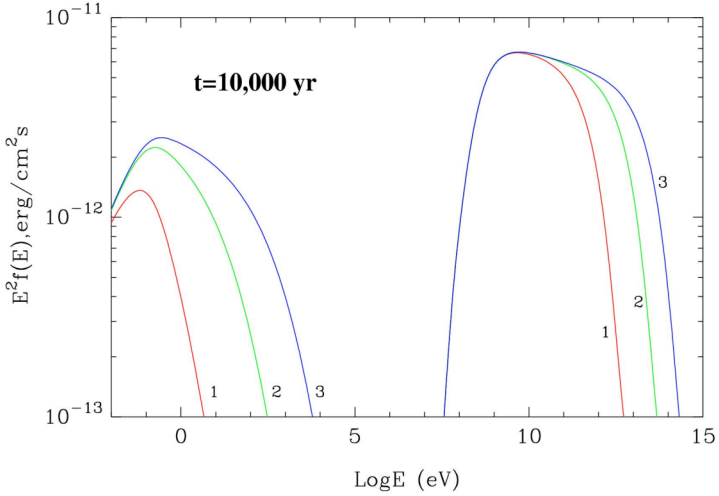
gamma-rays from surrounding regions add much to our knowledge about highest energy protons which quickly escape the accelerator and therefotr do not signifi-cantly contribute to gamma-ray production inside the proton accelerator-PeVatron

older source - steeper gamma-ray spectrum









$t_{esc} = 4 \times 10^5 (E/1TeV)^{-1} \kappa^{-1} yr \ \ (R = 1 \ pc)$ $\kappa = 1 -$ Bohm Difussion

$\dot{Q}_p \propto E^{-2.1} \exp(-E/1PeV)$ $L_p = 10^{38}(1 + t/1{,}000yr)^{-1} \ erg/s$

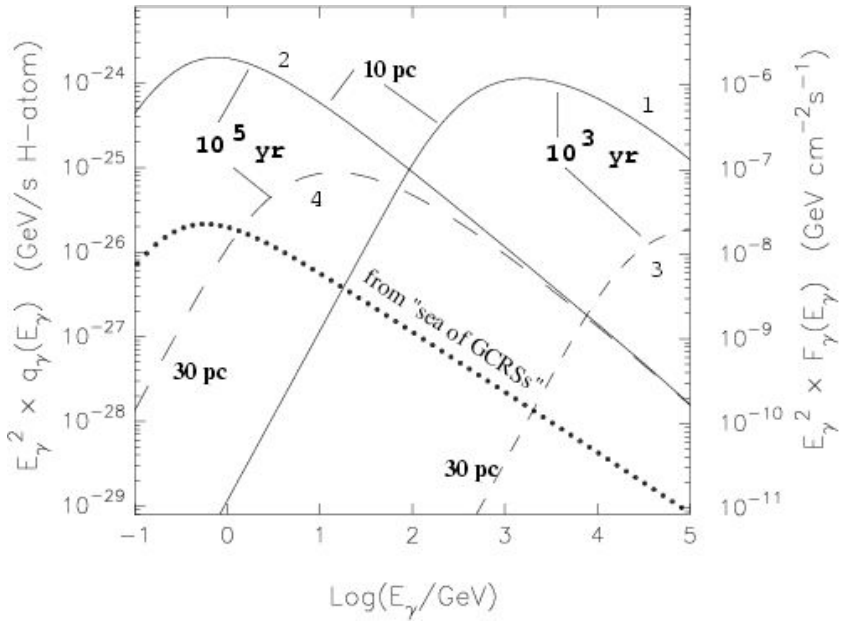
Giant Molecular Clouds (GMCs) as tracers of Galactic Coismic Rays

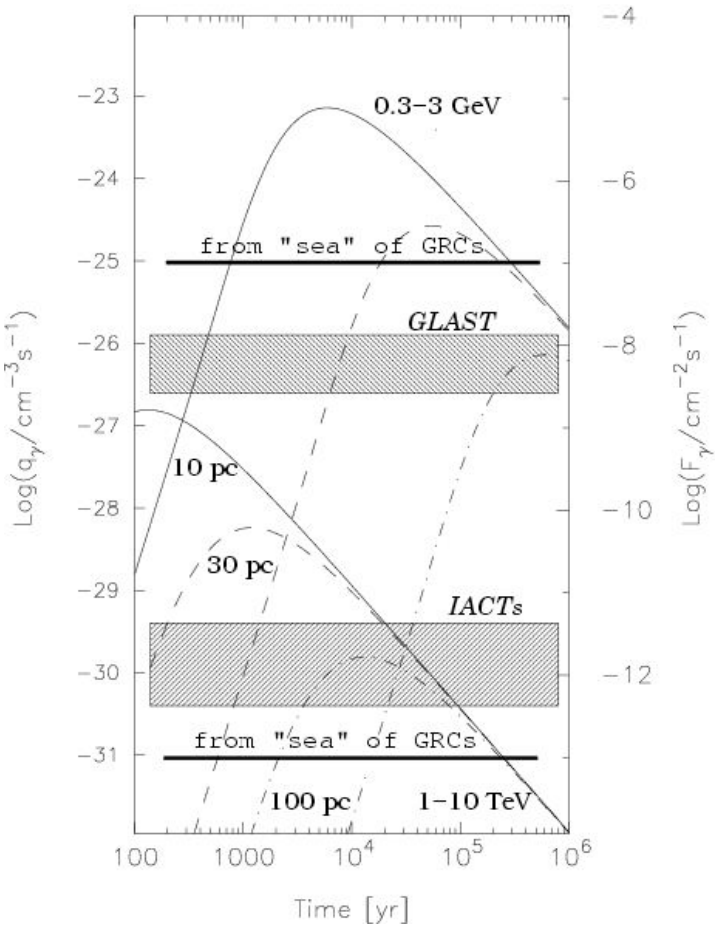
GMCs - 10^3 to 10^5 solar masses clouds physically connected with *star formation regions* - the likely sites of CR accelerators (with or without SNRs) - perfect objects to play the role of targets !

While travelling from the accelerator to the cloud the spectrum of CRs is a strong function of time t, distance to the source R, and the (energy-dependent) Diffusion Coefficient D(E)

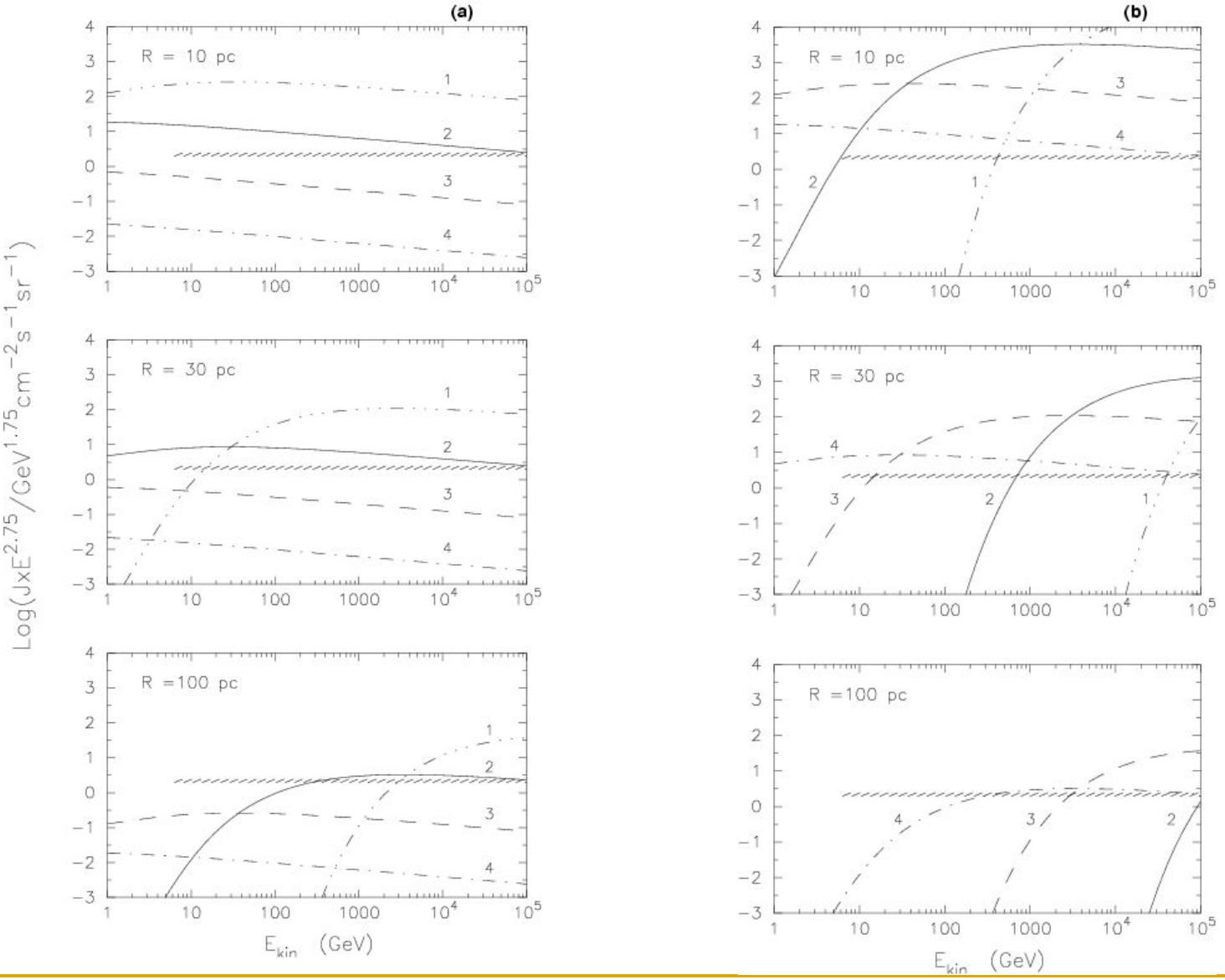
depending on t, R, D(E) one may expect any proton, and therefore gamma-ray spectrum – very hard, very soft, without TeV tail, without GeV counterpart ...

Propagation Effects on the spectrum of Gamma Rays

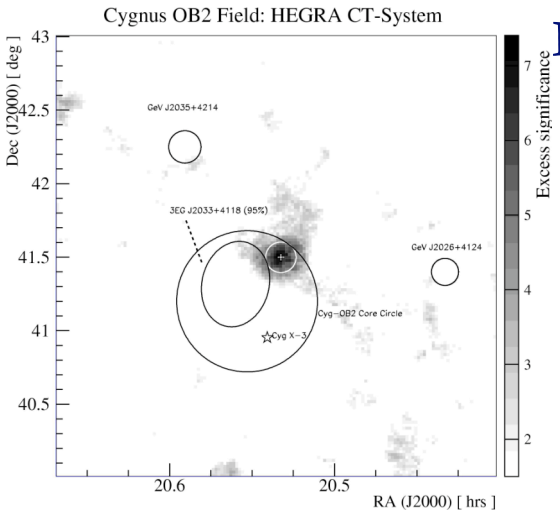


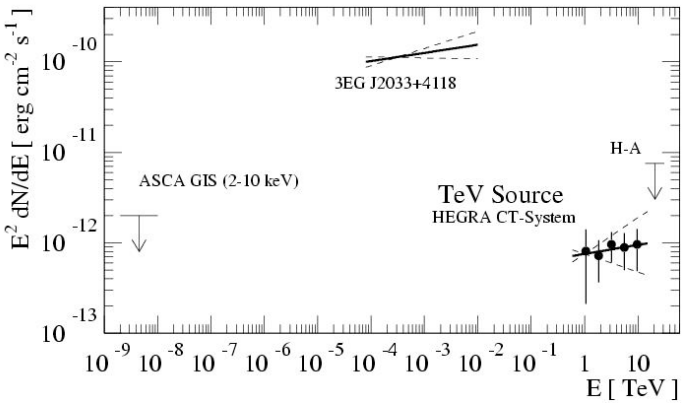


emissivities and fluxes (M_5/d^2_{kpc}) of gamma rays from a cloud at different times and distances from an impulsive accelerater with ~~$W=10^{50}$ erg [$D(E)=10^{26}$ $(E/10GeV)^{0.5}$ cm^2/s]~~


(a)
(b)
R = 10 pc
R = 30 pc
R =100 pc
Log(JxE^2.75/GeV^1.75cm^-2s^-1sr^-1)
E_kin (GeV)
1
2
3
4

First Unidentified TeV source TeV J2032+4130 *





Found by HEGRA seredipiously (6 sigma signal accumulated 100h from the Cygnus region and confirmed in 2002 by pointing observations (130 h)

Basic features – hard power-law spectrum (photon index 1.9), constant flux and slightly extended (about 5 arcmin) source

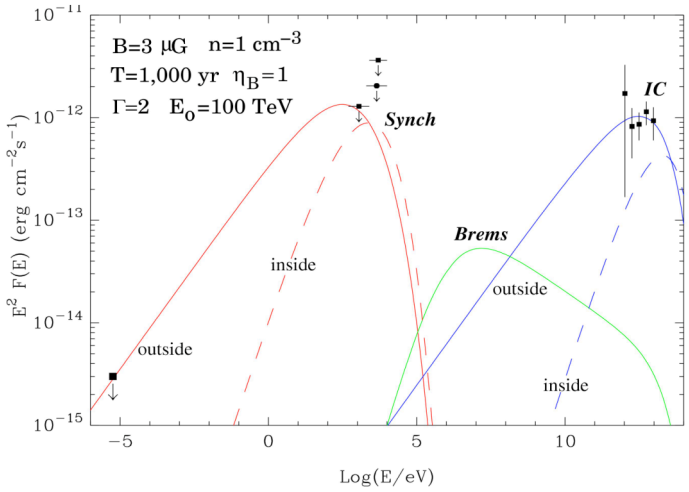
Origin ? leptonic (IC) origin is almost excluded

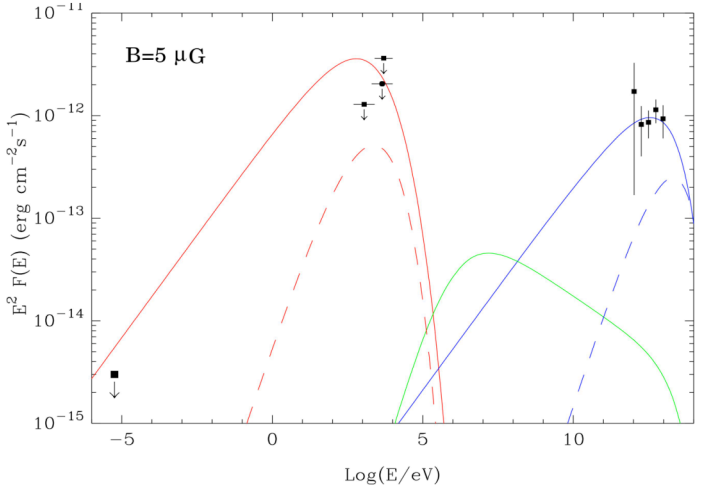
dense gas cloud(s) illuminated by protons arriving from a recent nearby Pevatron ?

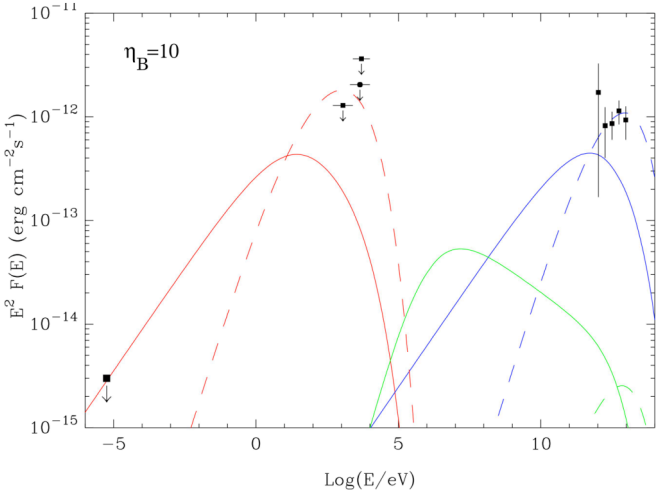
if this object is a representative of a large source population, the planned survey of the Galactic Disk by H.E.S.S. should reveal reveal many such hot spots

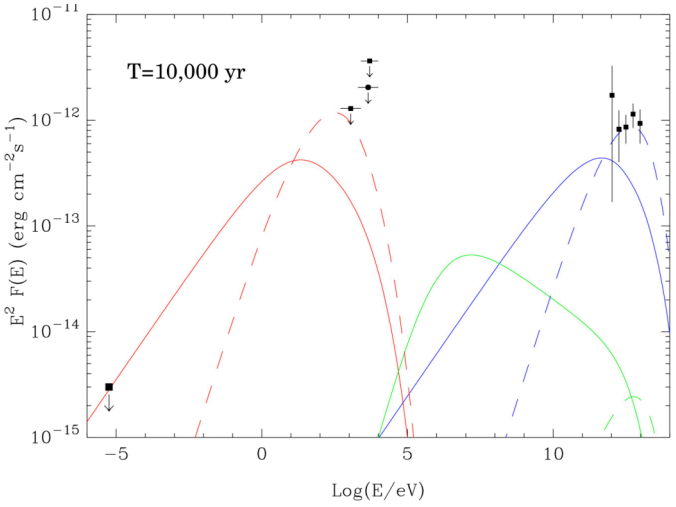
detected earlier by the HEGRA array and Crimea and "recently" by Whipple (?)

Electrons


B=3 μG n=1 cm^{-3}
T=1,000 yr η_B=1
Γ=2 E_o=100 TeV
Synch
IC
Brems
inside
outside
outside
inside
E^2 F(E) (erg cm^{-2}s^{-1})
Log(E/eV)


B=5 μG
E^2 F(E) (erg cm^{-2}s^{-1})
Log(E/eV)


η_B=10
E^2 F(E) (erg cm^{-2}s^{-1})
Log(E/eV)


T=10,000 yr
E^2 F(E) (erg cm^{-2}s^{-1})
Log(E/eV)

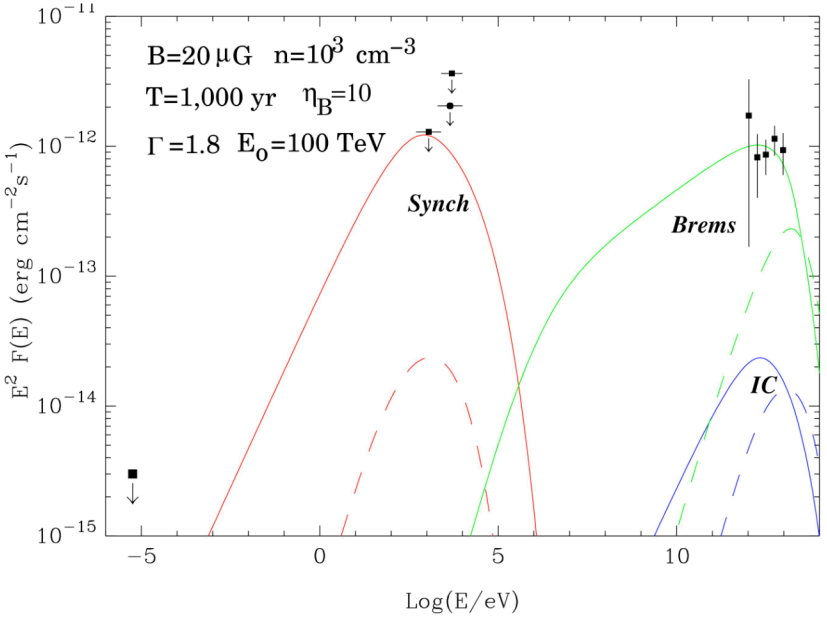
Electronic Models

Inverse Compton

B-field smaller than 3 10^{-6} G (!)
source age less than 1000 yr (!)

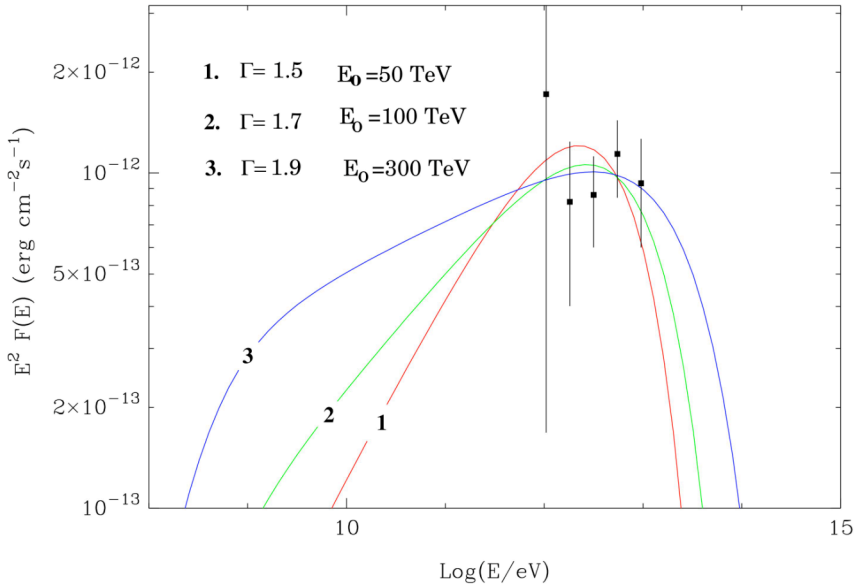
Otherwise even for very slow (Bohm !) diffusion gamma ray source should be largder than 5 arcmin (for d=1.6 kpc) !

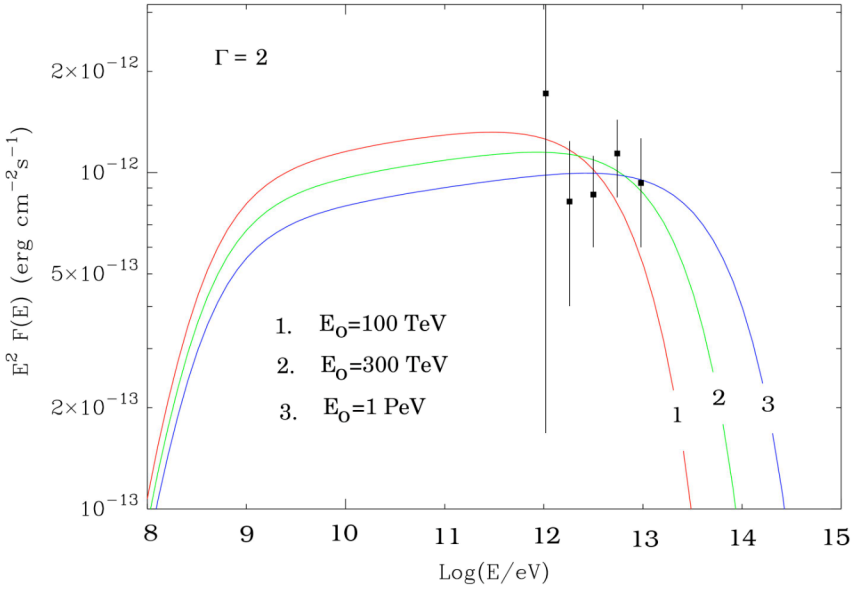
Bremsstrahlung



better - more "comfortable"

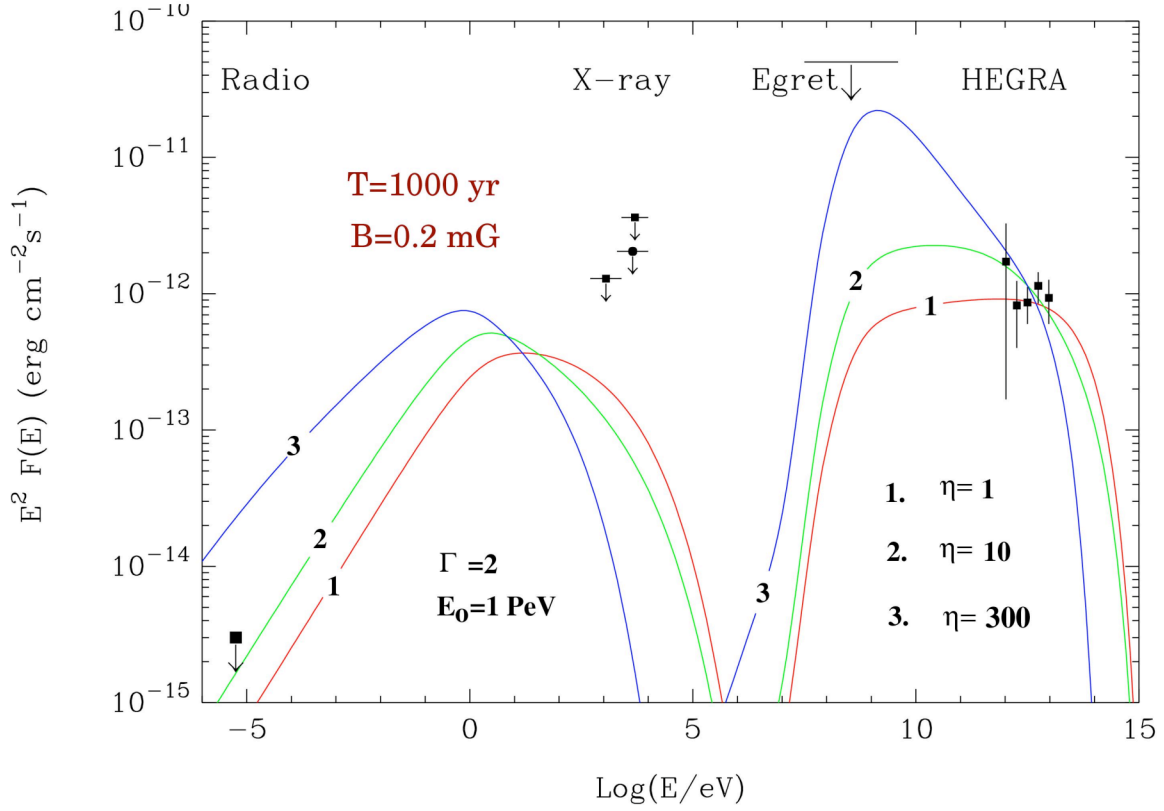
Protons ? spectrum should extend at least to 100 TeV





Hadrons…

young source

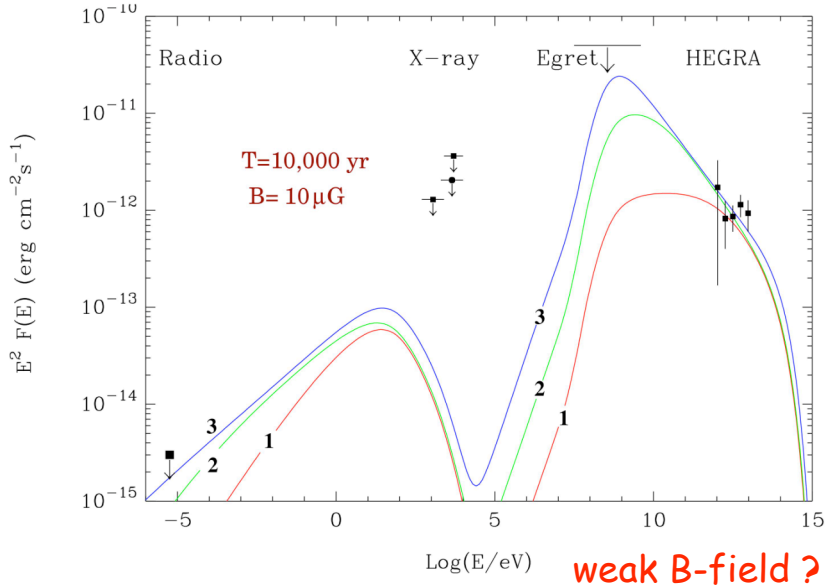


Gamma-ray spectrum strongly depends on the diffusion (escape)

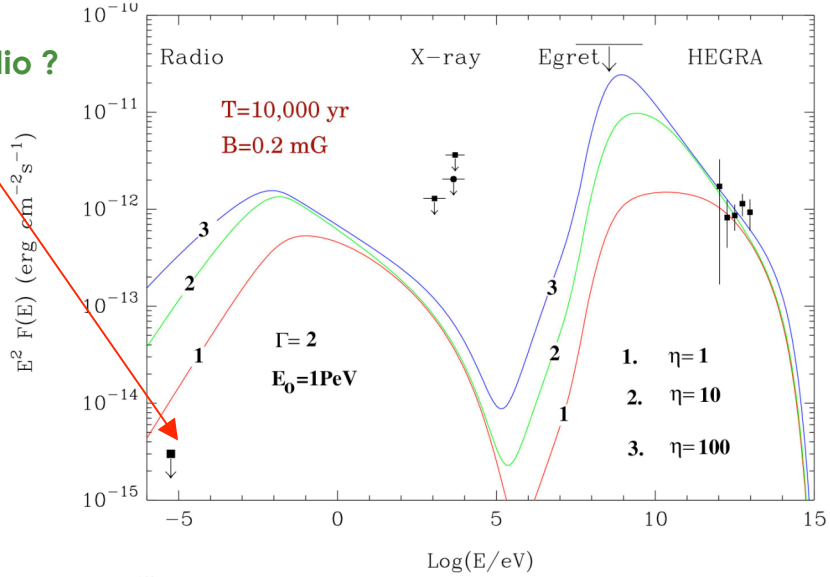
$$D(E) = 10^{24}(E/1\ GeV)^{0.5}\ \eta\ cm^2/s$$

older source

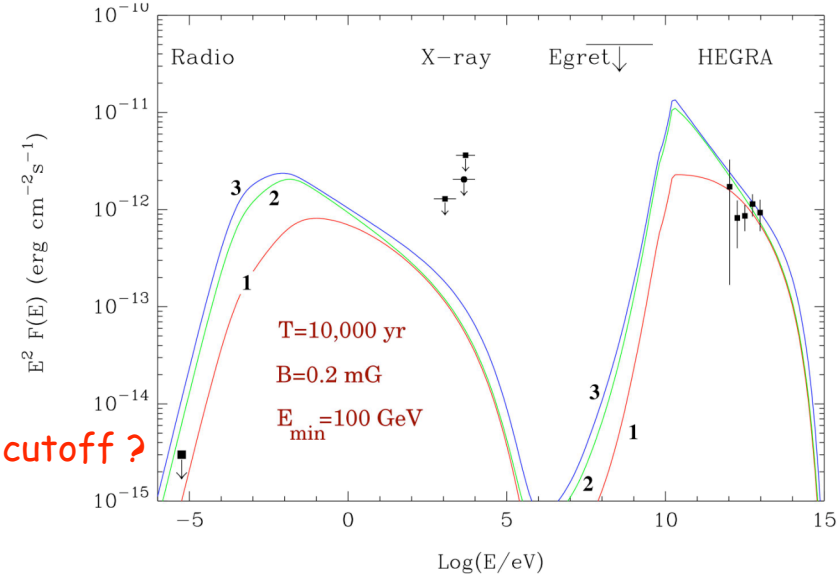
conflict with radio ?



weak B-field ?

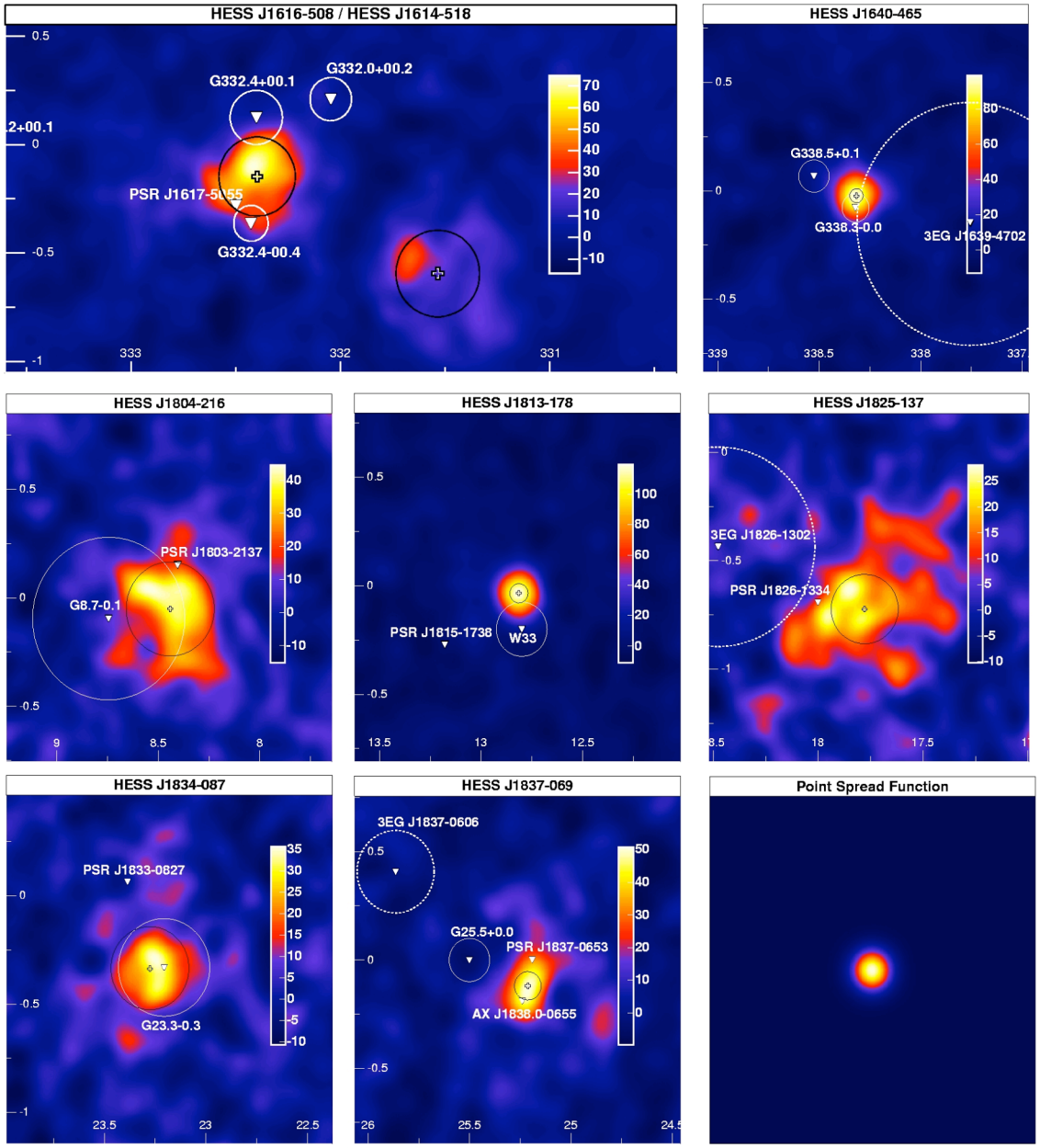


or low-energy cutoff ?

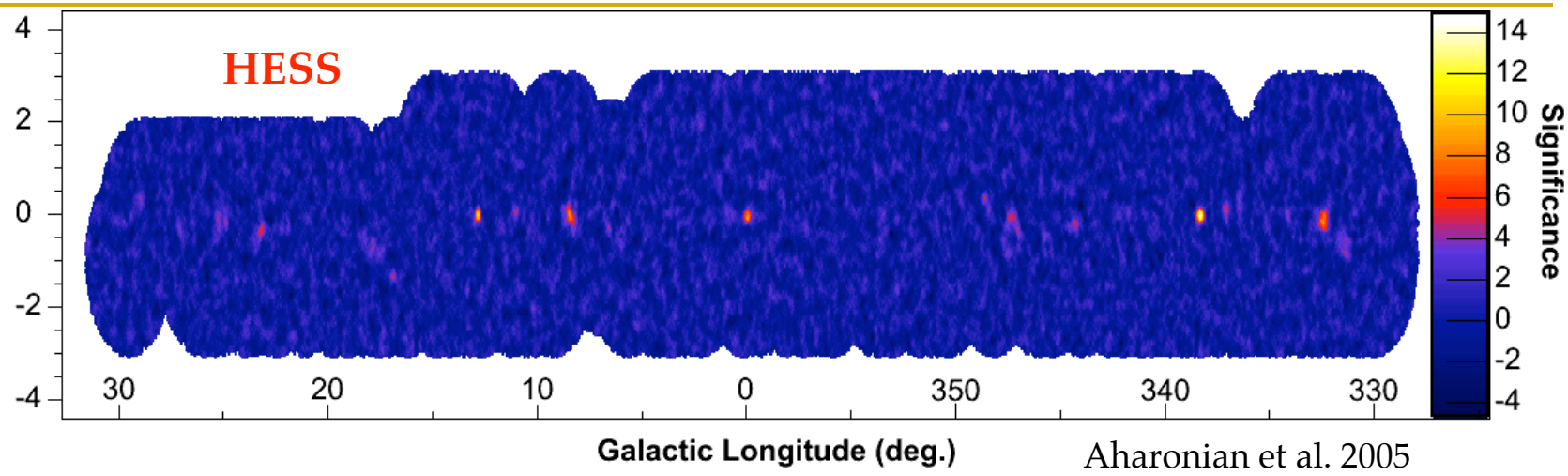


conclusion:

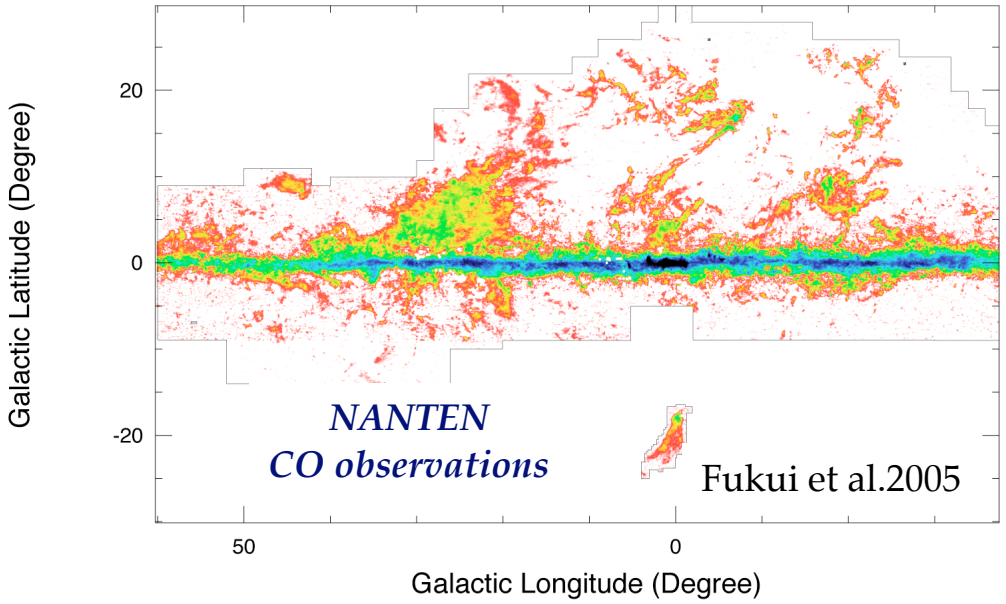
the PeVatron should be young, B-field – large, confinement - effective



unidentified HESS sources

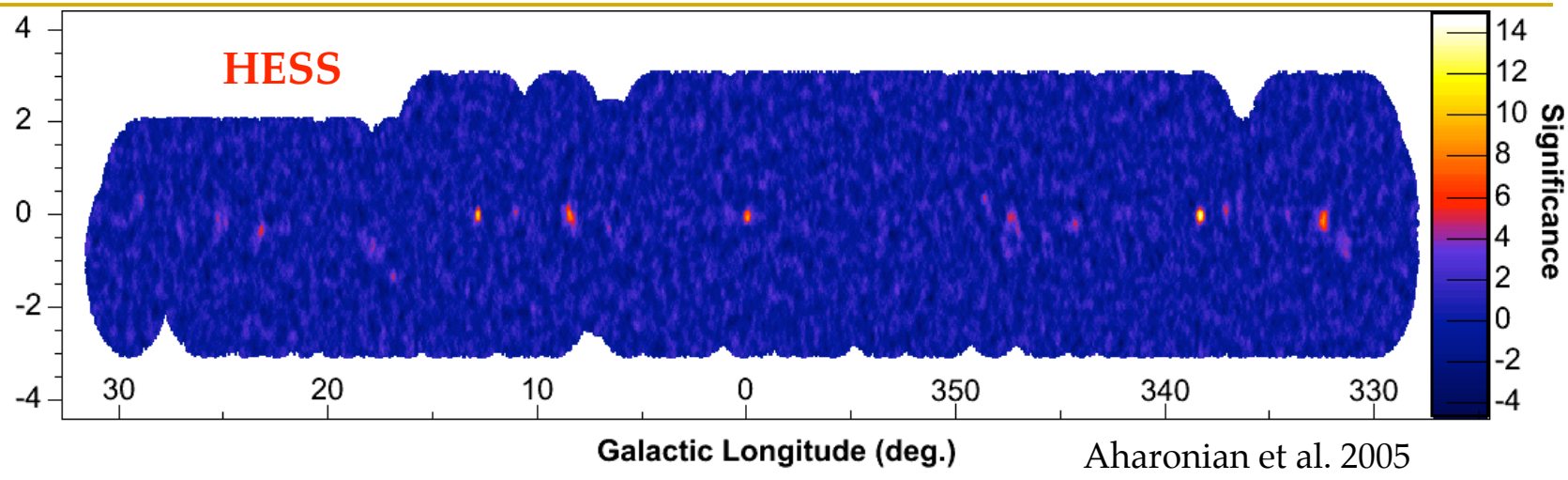


Aharonian et al. 2005

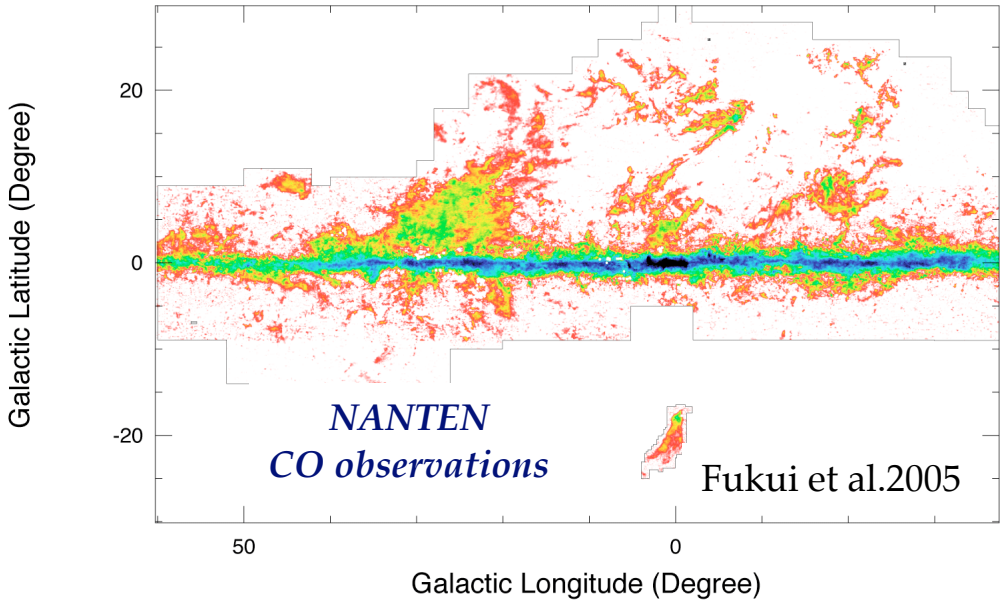


TeV and CO data:
narrow distributions
in the Galactic Plane:

because of **GMCs** ? or
Star Formation Regions ?
or (*most likely*) **both ?**



Aharonian et al. 2005



TeV and CO data:
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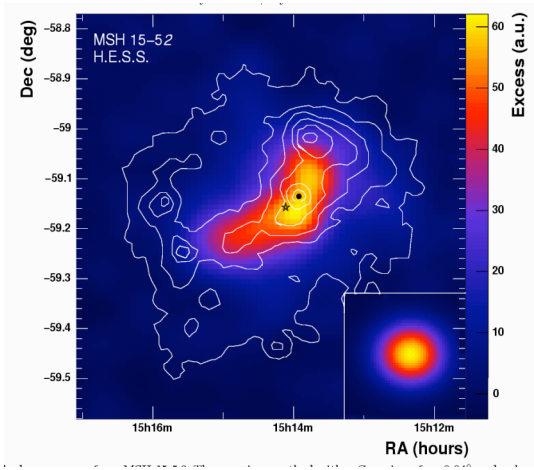
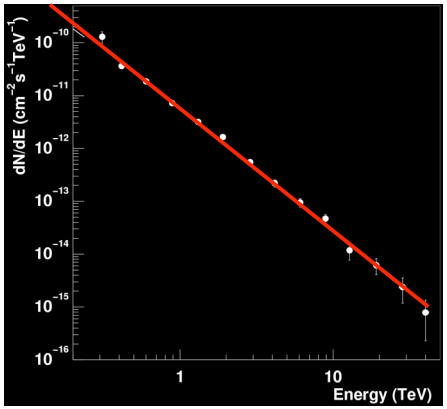
other potential sources of hadronic CRs

Plerions (PWN) ?

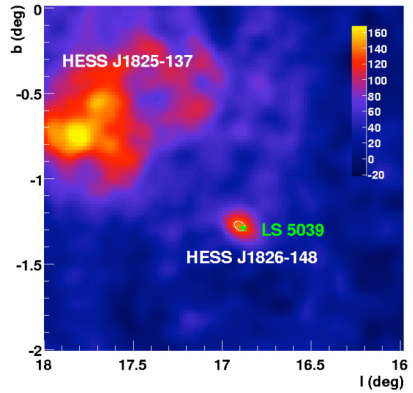


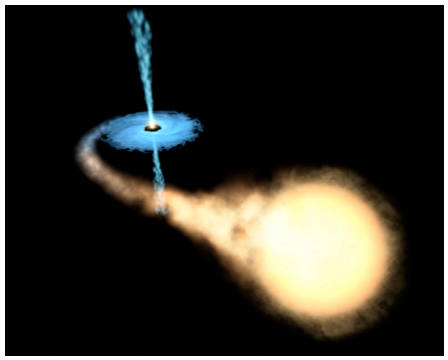


perfect power-law with
Γ=2.2-2.3 over 2 decade

cannot be easily explained by IC
=> hadronic origin of γ-rays ?

mQSOs ?





LS5039 is a TeV source !

huge density of starlight seed photons provides prolific γ−ray production through IC and pγ channels, but also severe $\gamma\gamma$ absorption …

GRBs …

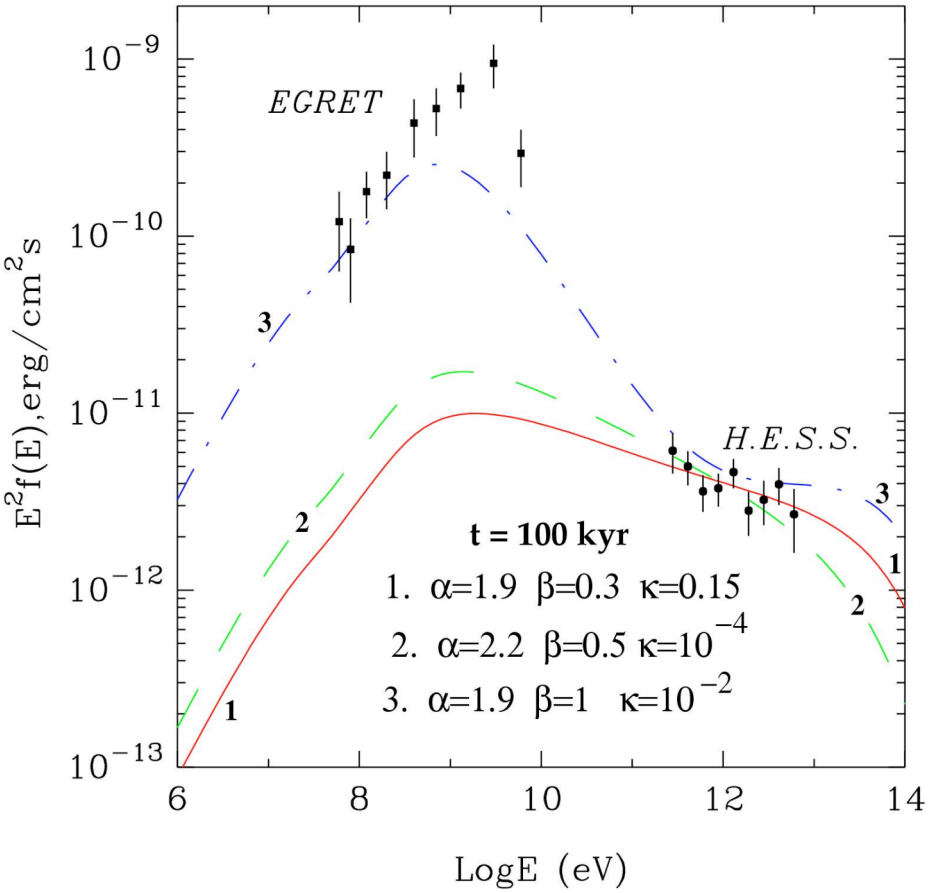
GC as a unique site of CR production

TeV Gamma Ray Emission from GC due to pp

interactions in dense (1000 cm^{-3}) gas regions

Power of CR acceleration in GC :

$Q_p(E)=Q_o\, E^{-\alpha}\, \exp(-E/1\ \text{PeV})$, $D(E)=10^{28}(E/1\text{GeV})^{\beta}\ \kappa\ \text{cm}^2/\text{s}$ $\kappa=1$, $\beta=0.5\text{-}0.6$ -diffusion in GD



$t_{pp} = 50$ kyr $\quad (n=10^3\ \text{cm}^{-3})$

$T_{esc} = 300\,(E/100\text{TeV})^{-1}\,(B/100\mu\text{G})$ kyr
(Bohm Diffusion)

1. fast diffusion : $\Gamma \rightarrow \alpha+\beta$
   $Lp=7.5 \times 10^{37}$ erg/s
2. slow diffusion: $\Gamma \rightarrow \alpha$
   $Lp=6.9 \times 10^{36}$ erg/s
3. Diffusion-to-rectlinear prop.
   $\Gamma \quad \alpha+\beta \Rightarrow \Gamma \quad \alpha$
   $Lp=1.1 \times 10^{39}$ erg/s

Summary

recent HESS discoveries of Galactic TeV sources is a serious step towards solution of the problem of origin of GCRs, but the current data do not yet allow definite answers ...

the hunt for galactic PeVatrons continues