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

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TEXAS@Stanford, Dec 17, 2004

Major objectives of VHE astronomy*

- **Origin of Galactic Cosmic Rays**

  SNRs, Molecular clouds, Diffuse radiation of the Galactic Disk, ...

- **Galactic and Extragalactic Sources with relativistic flows**

  Pulsar Winds, Microquasars, Small and Large Scale jets of AGN, ...

- **Observational Gamma Ray Cosmology**

  Large Scale Structures (Clusters of Galaxies), Dark Matter Halos,
  Diffuse Extragalactic Background radiation,

....

....

*energy domain E > 0.1 TeV (VHE astronomy =TeV astronomy)

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

H.E.S.S.* and ***GLAST***

and *CANGAROO, MAGIC,VERITAS*

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 ⇒ ● $=5\ (E/10GeV)^{-0.6}$ 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 3×10^{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

♑-rays as tracers of CRs

what we do not know about Galactic Cosmic Rays ?

acceleration sites, source populations, acceleration mechanisms

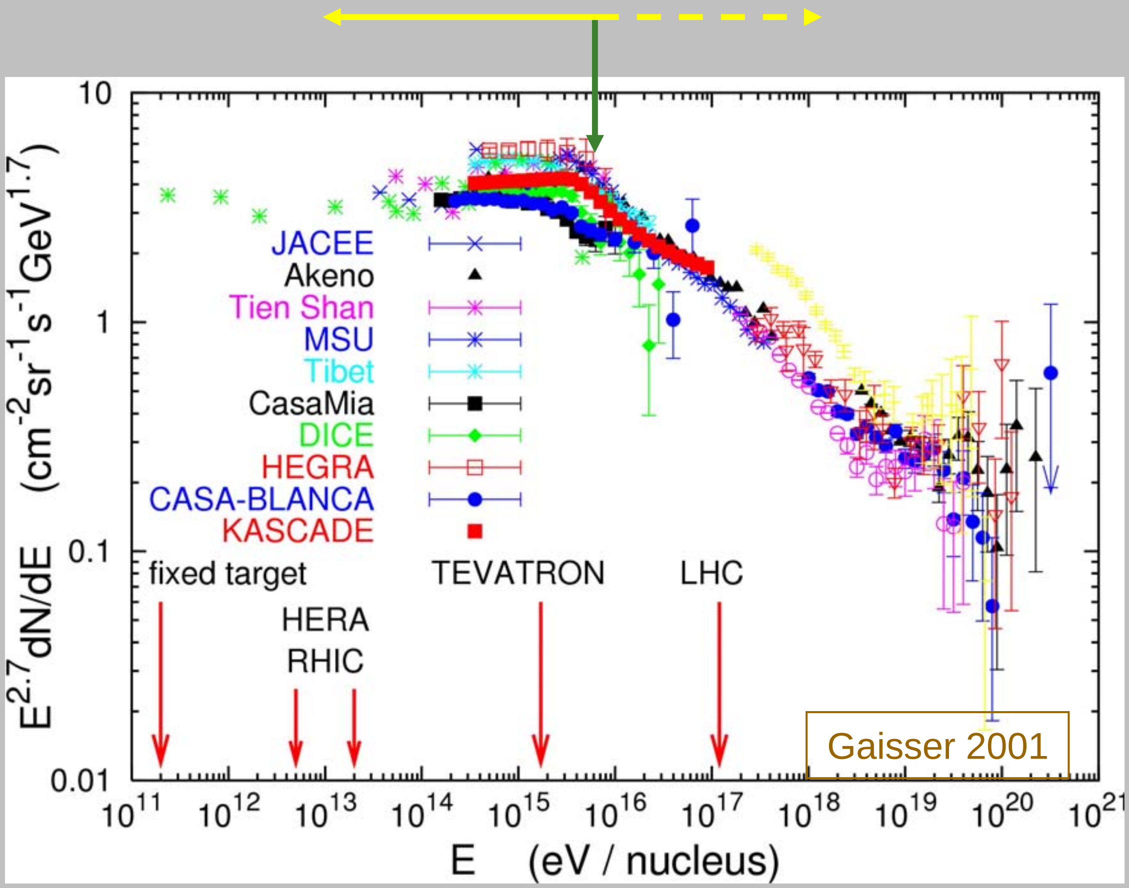
reason ?   ***deflection (diffusion) of CRs in interstellar B-fields***

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

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

the major (historical) motivation of gamma-ray astronomy
(P. Morrison, V. Ginzburg, S. Hayakawa, ...)

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 ? <u>at least 10^{15} eV</u>

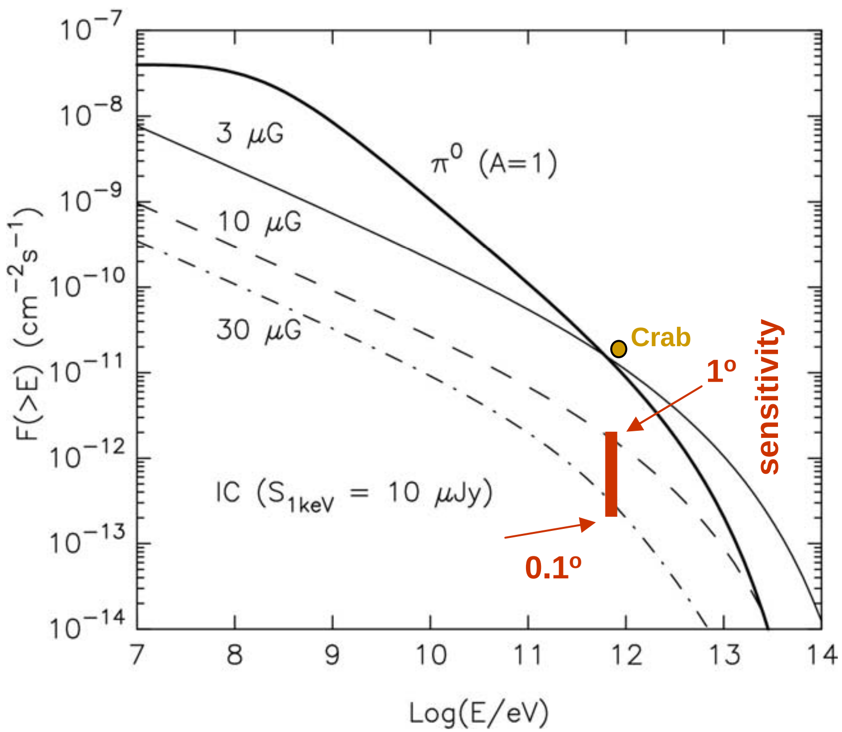
<u>Straightforward proof:</u> detection of gamma-rays (and neutrinos) from pp interactions (as products of decays of secondary pions)

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

<u>Realiztion:</u> ***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 ♋=2

$F_g(>E)=10^{-11}$ 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 ❑ (r/d) and flux $F_{♍}$ $(1/d^2)$

typically A: 0.1-0.01 ❑ : 0.1°

TeV ♍-rays – detectable if A > 0.1

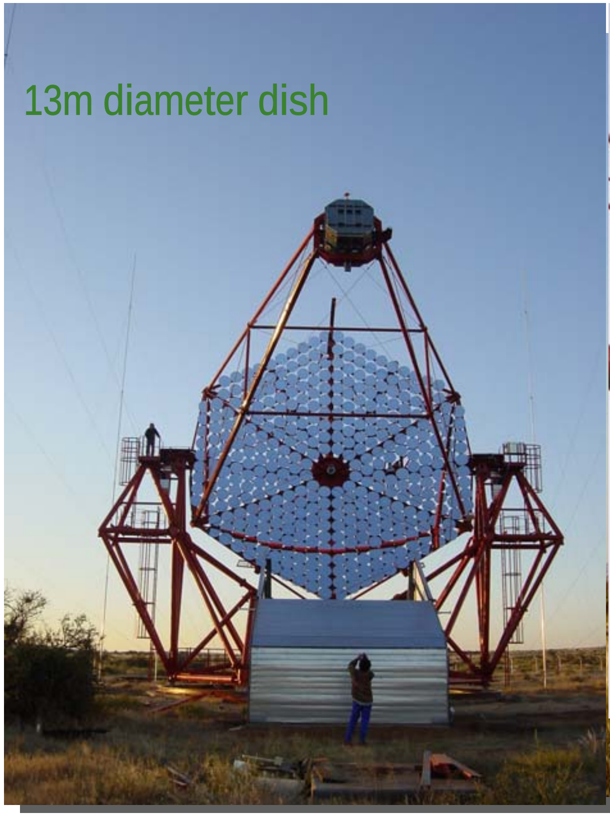
◘° component dominates if A > 0.1 (S_x/1

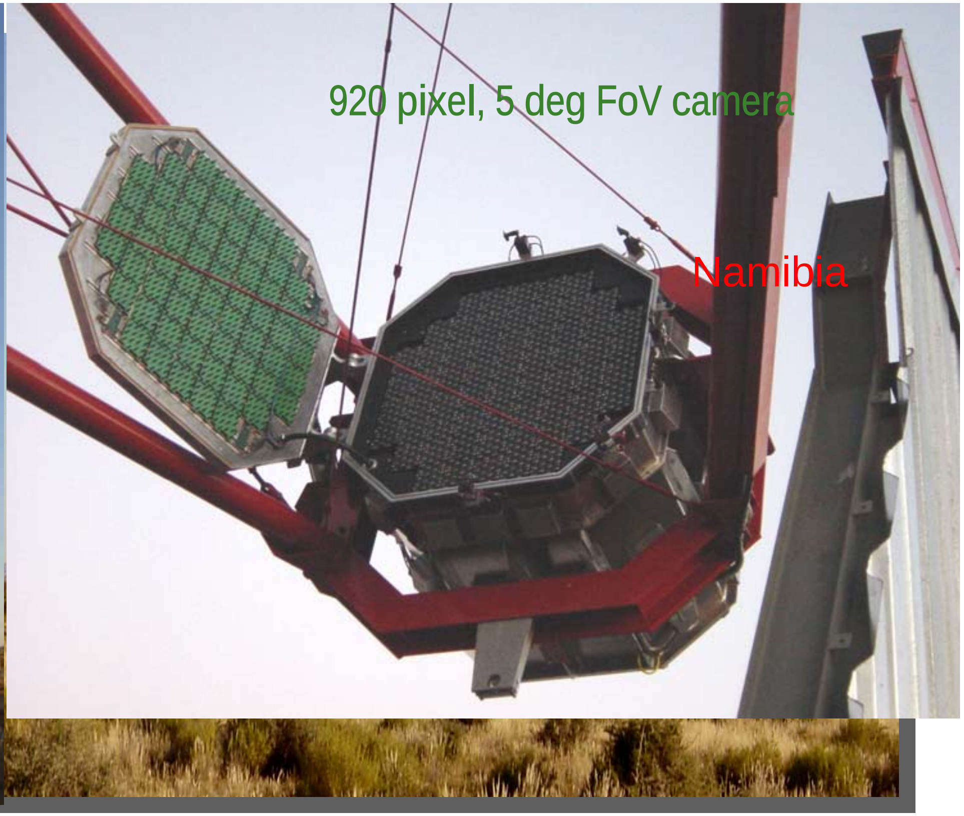
♍'s

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

main target photon field 2.7 K: $F_{♍,IC}/F_{x,sinch}=0.1\ (B/10❍G)^{-2}$

H.E.S.S. - *High Energy Stereoscopic System*





"stereoscopic imaging of air showers with large mirrors and large FoV cameras"

- Energy range

  100 GeV - 10 TeV
- Energy resolution

  15 - 20%
- Angular resolution

  3 - 6 arcmin

- Sensitivity:

1 Crab *	**30 sec**
0.1 Crab	20min
0.01 Crab	**25 hours**
10 Crab	1 sec

***1 Crab =3 x 10^{-11} erg/cm^2 s**

- Field of View 5^o

✓ 0.1 Crab - detection time 20 min

for HEGRA/CAT/Whipple – 50-100 hour

✓ 0.003 Crab requires 200 h

10^{-13} erg/cm^2 s level

deeper probe than Chandra/XMM for >0.1 deg objects !

✓ 10 Crab (i) strong flares of Mkn 421/501

(ii) energy flux sensitivity of EGRET

(iii) several orders of magnitude less than typical GRB fluxes

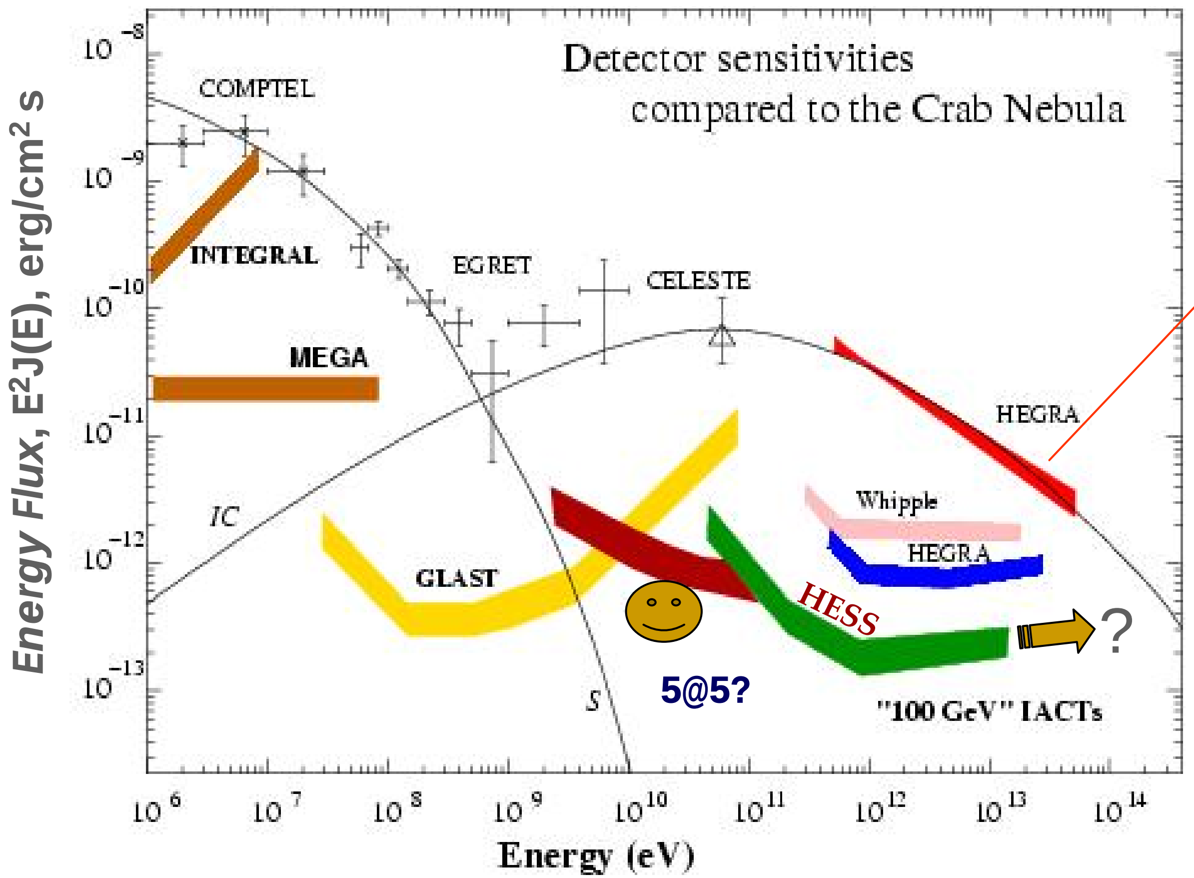
✓ 3 arcmin - angular resolution of ASCA

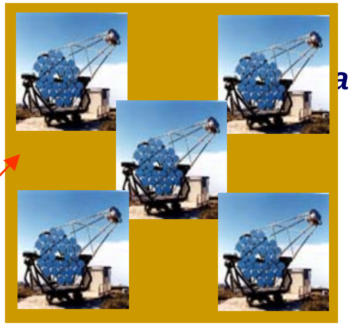
5^o FoV plus 0.1 Crab for < 1 h –

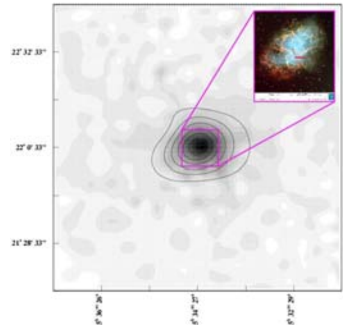
sufficient for effective surveys !

Potential of IACT Arrays

sensitivity → 10^{-13} erg/cm^{2}s   angular resolution: 3-5 arcminutes
energy resolution 10 to 20 %   dynamical range : 3 GeV to 100TeV



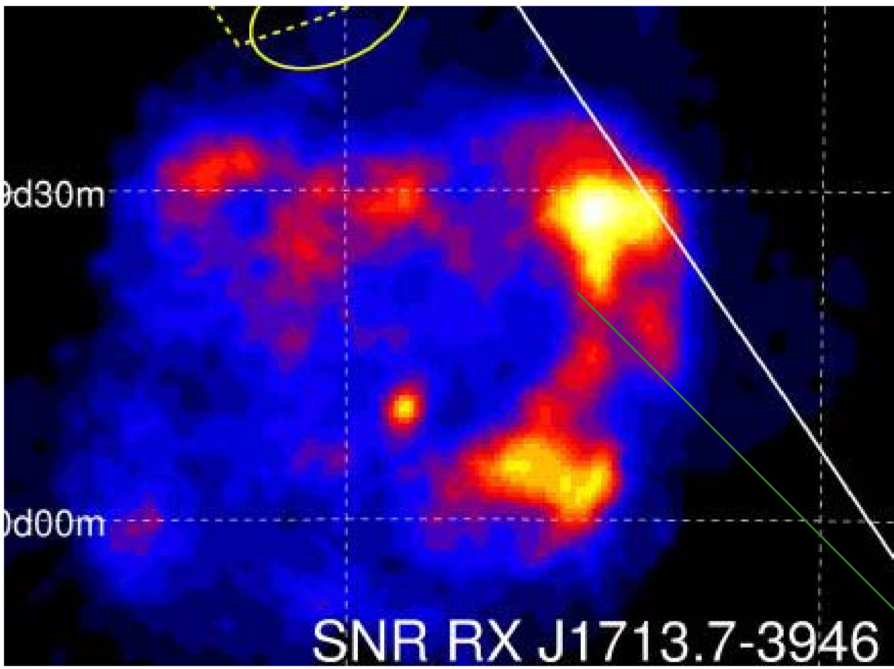




Cosmic Ray Accelerators ?

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

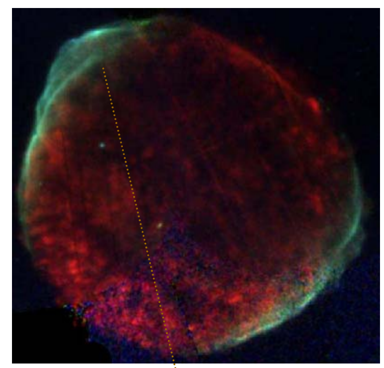
with nonthermal X-ray emission - 10 or so



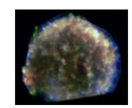
30 arcmin

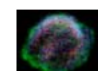
best candidate - young SNRs
with synchrotron X-rays

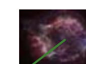
SN1006



Tycho Kepler CasA







?

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

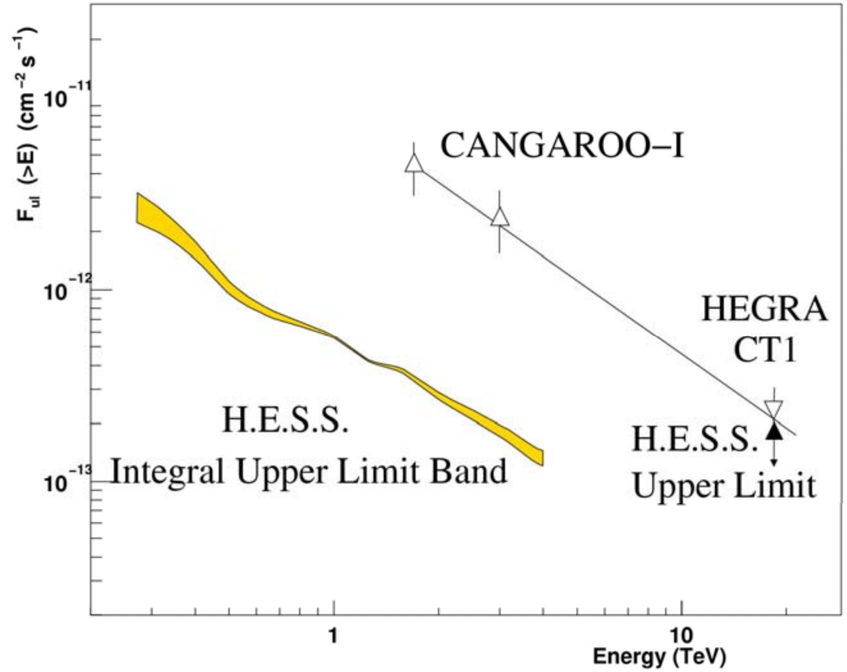
a trouble ? not at all ...

HESS upper limits imply

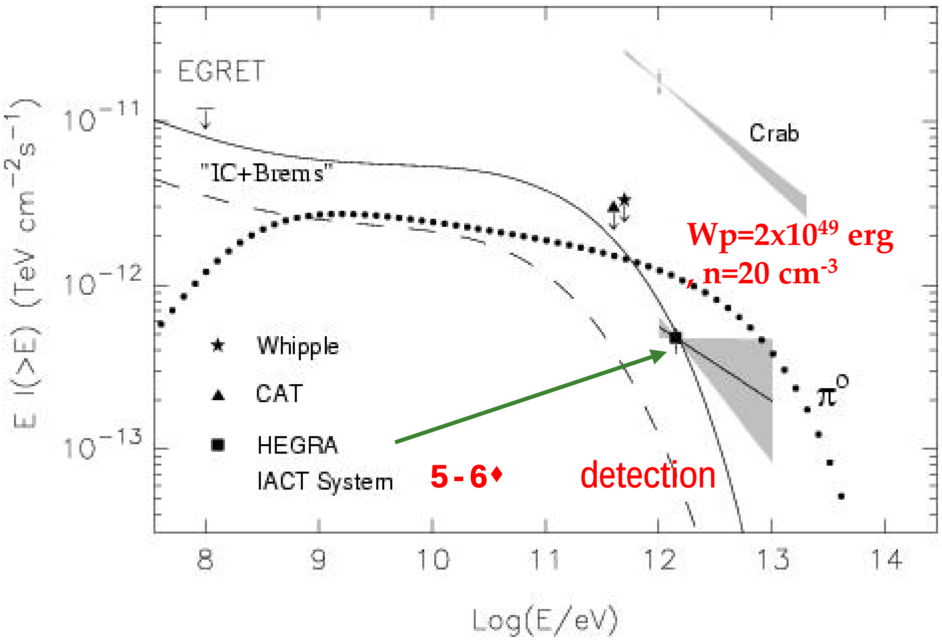
IC : B > 25 ❍G

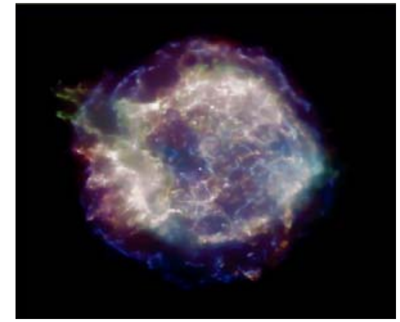
□ ° : W_p<(0.2-2) x 10^{50} erg

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 !

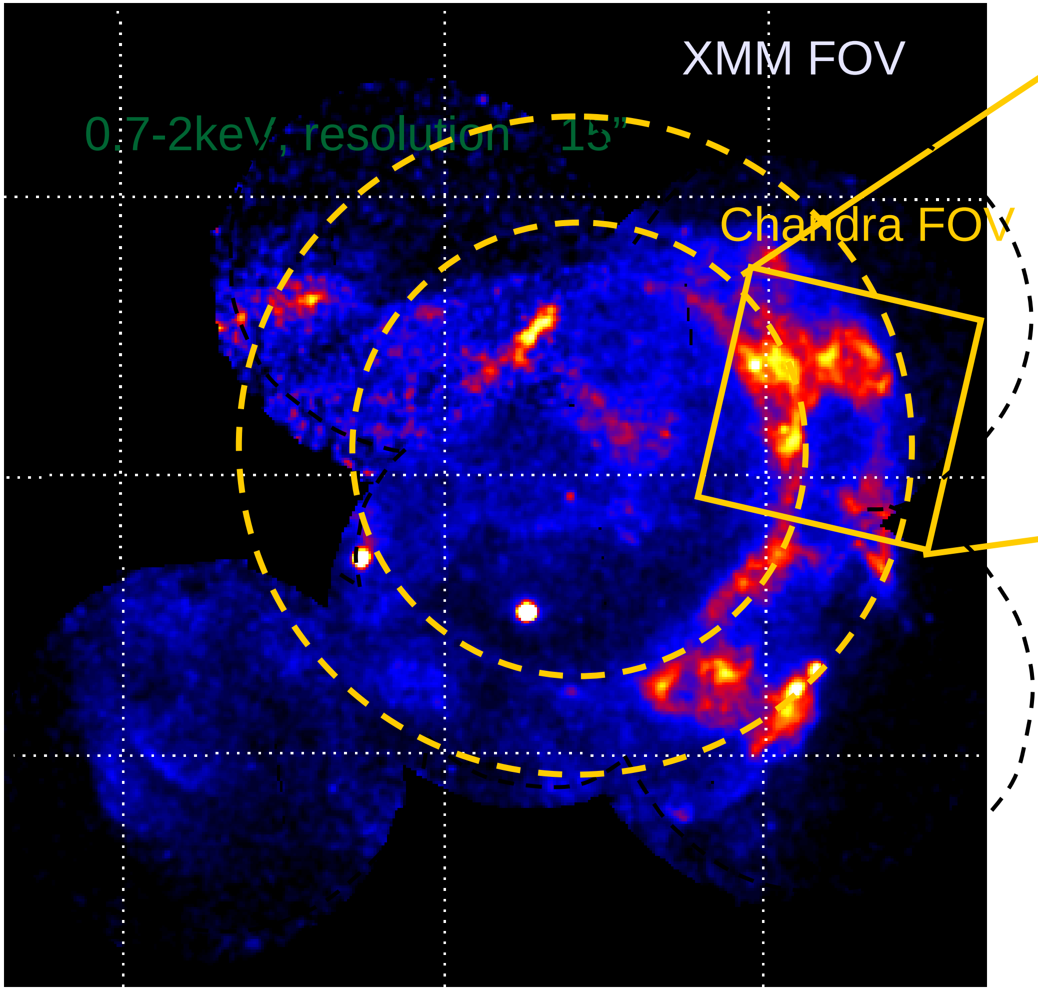
can be checked with >10 TeV γ *-ray and neutrino (?) detectors*

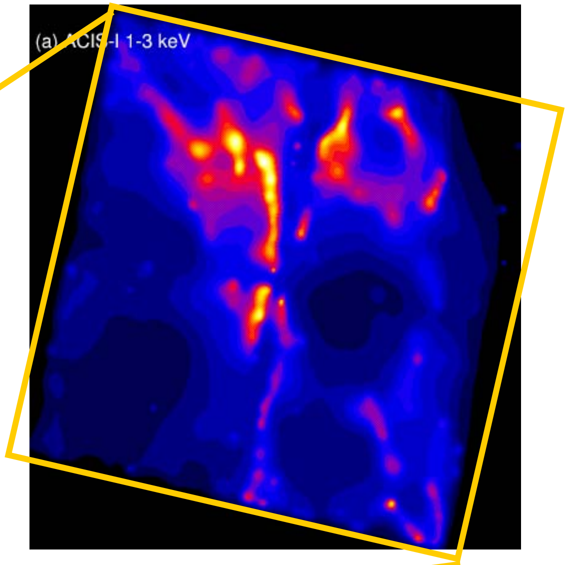
highest priority souce for *VERITAS* and *MAGIC*

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

RX J1713.7-3946

structure of the entire remnant (XMM-*Newton*)





Chandra image

only non-thermal X-rays are detected !

RX J1317.7-3946

- discovered during the ROSAT all sky survey

  (Pfefferman & Ashebach 1996)

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

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

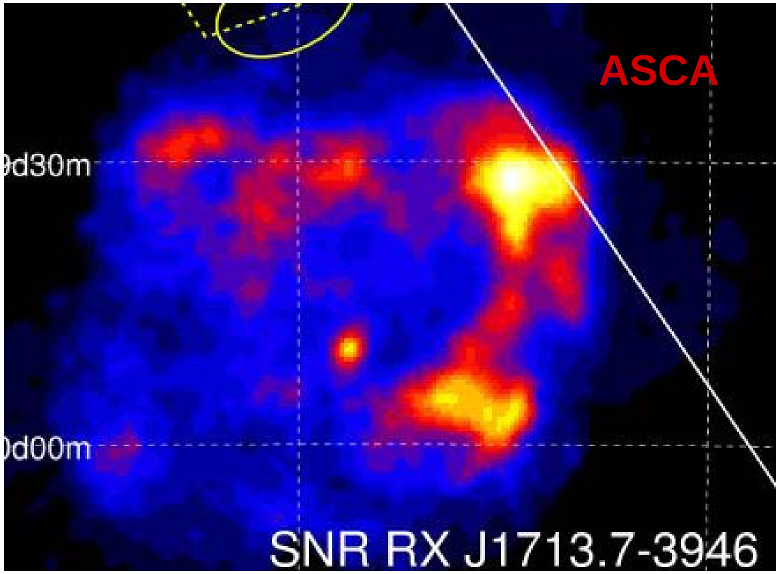
  no convincing evidence yet for a thermal component !

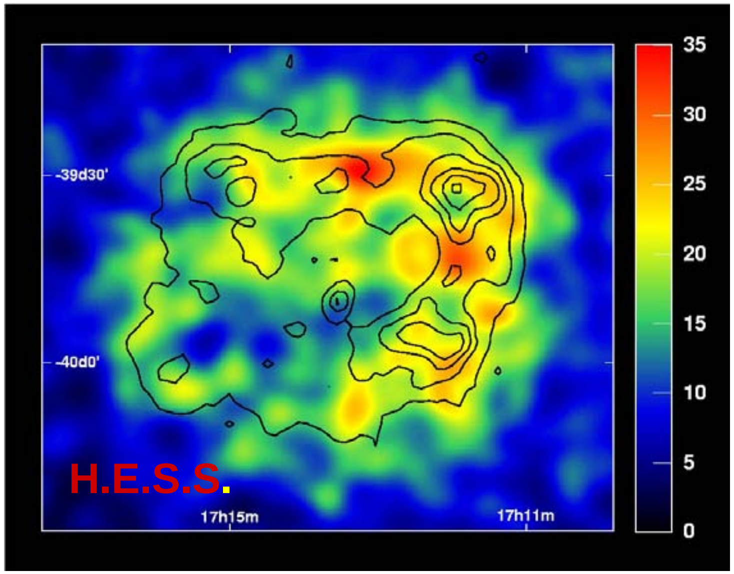
- distance to the source - around 1 kpc (no anymore 6 kpc) – from CO observations of the interacting cloud - NANTEN *(Fukui et al. 2003)*

- age - $\sim$ 1 kyr - 1611 yr as the remnant of the AD 393 SN event ?

  (Wang et al. 1997)

Nonthermal X-rays and TeV gamma-rays from RXJ1713.7-3946



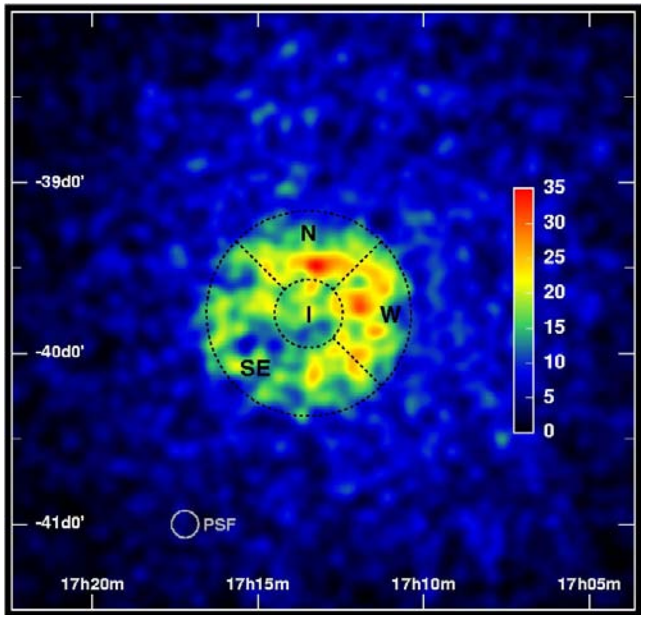


Direct evidence of high energy particle acceleration in the shell of RXJ 1713.7-3946*

H.E.S.S collaboration

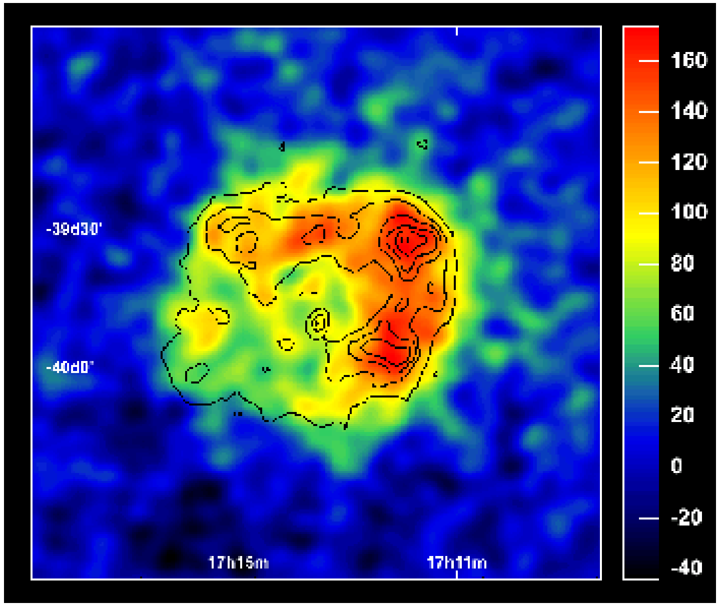
first image of an astronomical object obtained in γ-rays on arcmin scales

Nature, Nov 4, 2004



morphology and energy spectrum obtained with H.E.S.S.

2004 Data (4 telescope system)



flux from the entire remnant :

J(>1 TeV)=1.46 +/- 0.17 (stat.)+/-0.30 (sy

F(1-10 TeV)=5.5 x 10^{-11} erg /cm^2 s, L_γ

soon - energy spectra from 150GeV to > 10TeV
from different parts - *NW, S W, E,C*

a key issue - identification of γ-ray emission
mechanisms: – □^{0} or IC ?

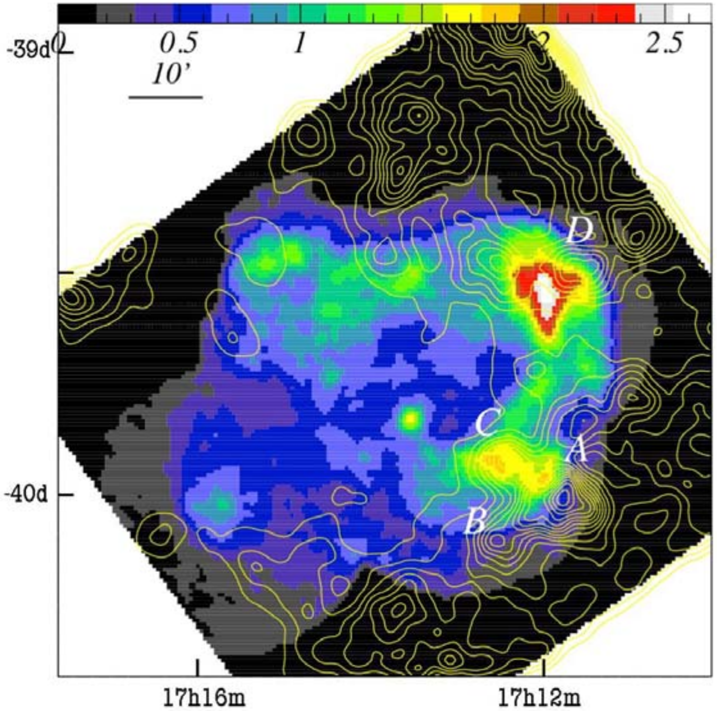
if single power law from 100 GeV to 10 TeV
hardly can be explained by IC

implications ?

if □^{0} - hadronic component is detected !
estimate of Wp (with an uncertainty
related to the uncertainty in n/d^2)

if IC - model independent estimate of We
(multi-TeV electrons)
- model independent estimate of Le=Lx
- model independent map of B-field

X-ray properties



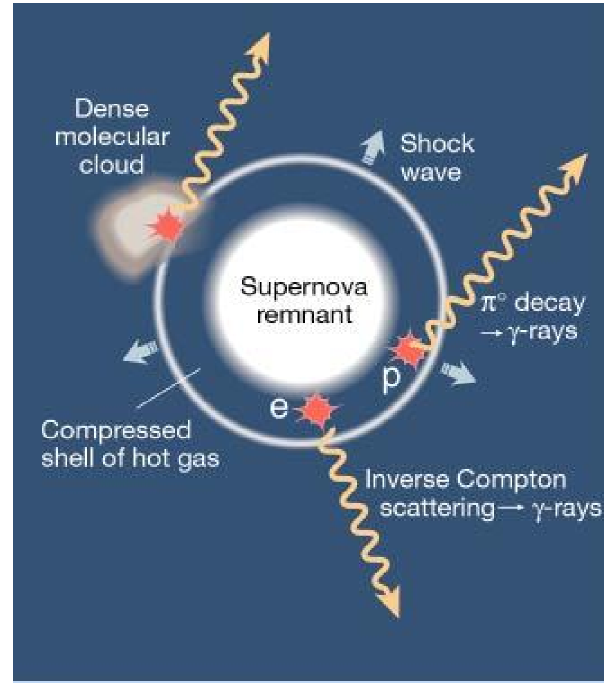
- Chandra – striking small – scale (s 10
  forms of filaments and hotspots emb
  sites of partic

  Chandra - noticeable spatial variatior

- XMM - surprising positive correlatio
  N_H along the western portior

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

Origin of radiation ?



- hadronic origin seems preferable given the high density environment:

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

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

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

HESS observations with 4 telescope in 2004

may provide certain answers or … bring new puzzles

Electronic origin of TeV emission of RX J1713.7-3946 ?

morphology of synch. X- rays requires large B-field

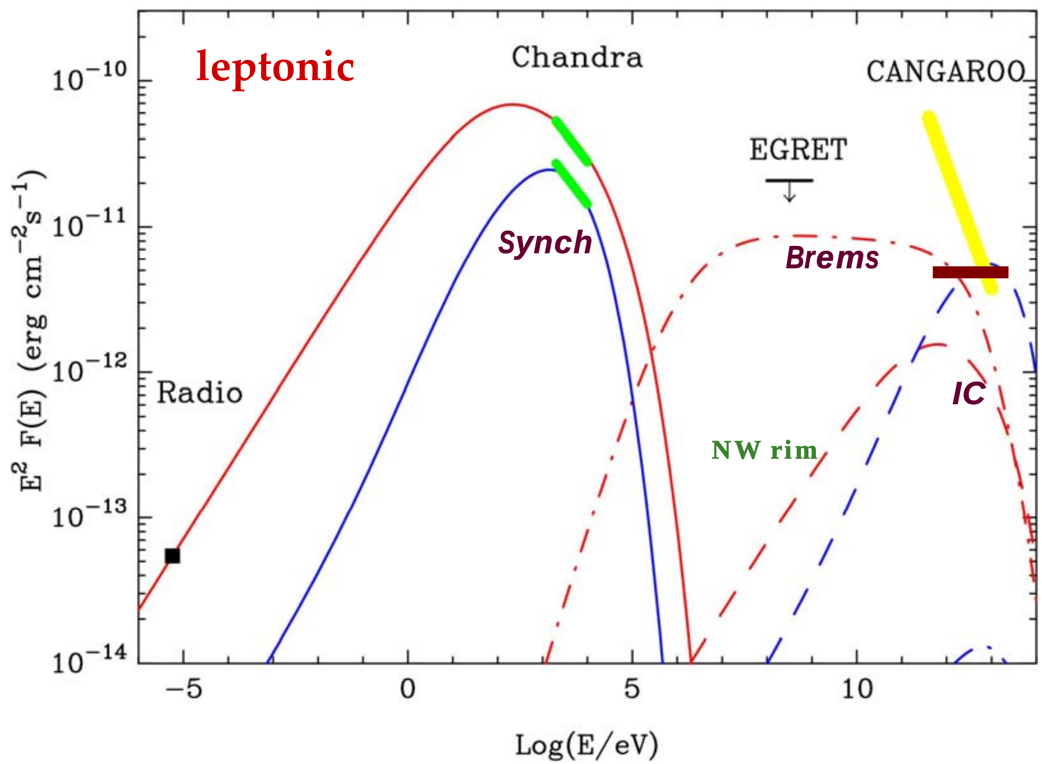
➡ IC should be significantly suppressed*

d=1 kpc
T=1000 yr

B_{int} =5 ❍G
B_{rim} =20 ❍G *
n_{int} =1 cm^{-3}
n_{cloud} =300 cm^{-3}

electron injection spectrum
$Q(E)=Q_0\, E^{-2} \exp(-E/100\ \mathrm{TeV})$
L_e =2.3 x 10^{36} erg/s
Bohm type diffusion

* minimum (shock-compressed
value of B-field in the shell)



**but because of very dense region bremsstrahlung could be significant*

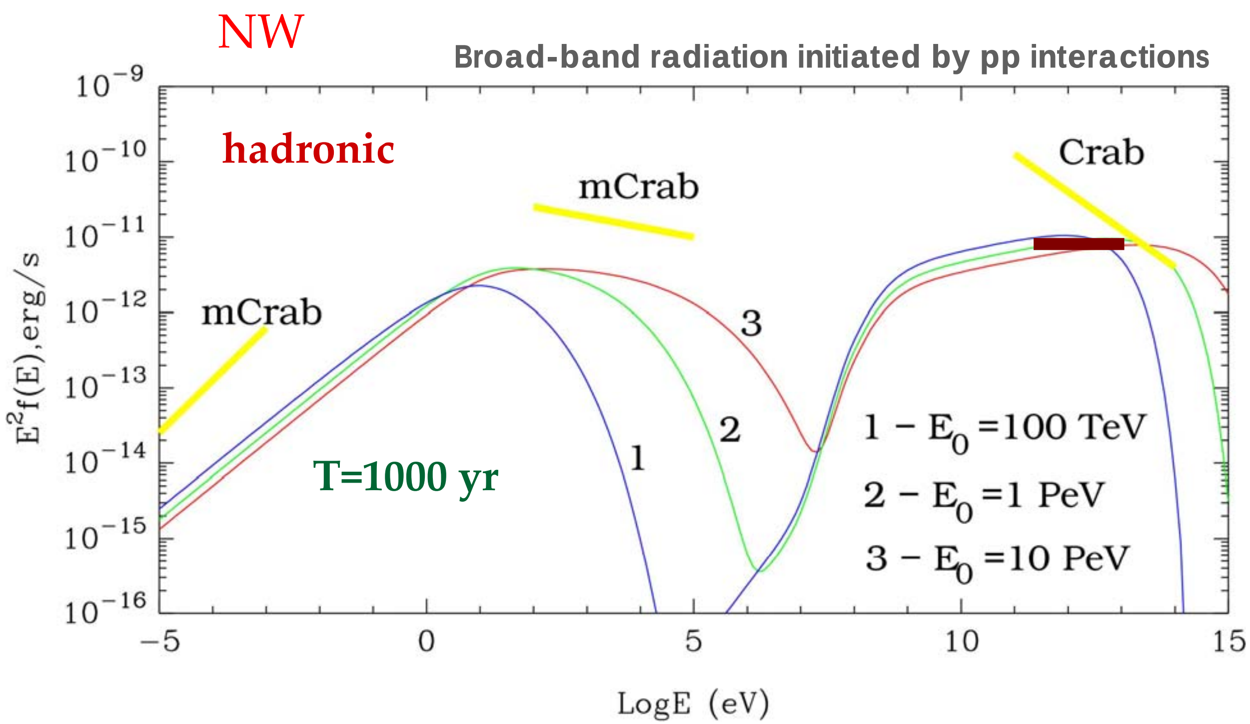
Hadronic Origin of TeV emission ?

yes, especially of the reported dense clouds

interacting with the west portion of the shell

X-rays of secondary origin ? Would be great, but $L_X/L_\gamma \geq 10$ while

one should expect $L_X/L_\gamma \leq 1$



$L_p = 10^{37}(n/300\mathrm{cm}^{-3})^{-1}$ erg/s; $\Gamma = 1.9$

for t=1 kyr and n >10 cm^{-3} Wp < 10^{49} erg

Probing PeV protons with X-rays

SNRs shocks can accelerate CRs to <100 TeV (Cesarsky&Lagage 1984) unless magnetic field significantly exceeds 10 ❍G

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
⟹ “prompt“ synchrotron X-rays

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

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

Detection of the hard synchrotron X-rays of (hadronic) secondary origin From 10 keV to 100keV from RX J1713.7-3946 is possible with 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: $\propto \nu^{-(\Gamma/2+1)} \exp[-(\nu/\nu_o)^{\beta/2}] \quad (\nu_o \propto E_o B^2)$

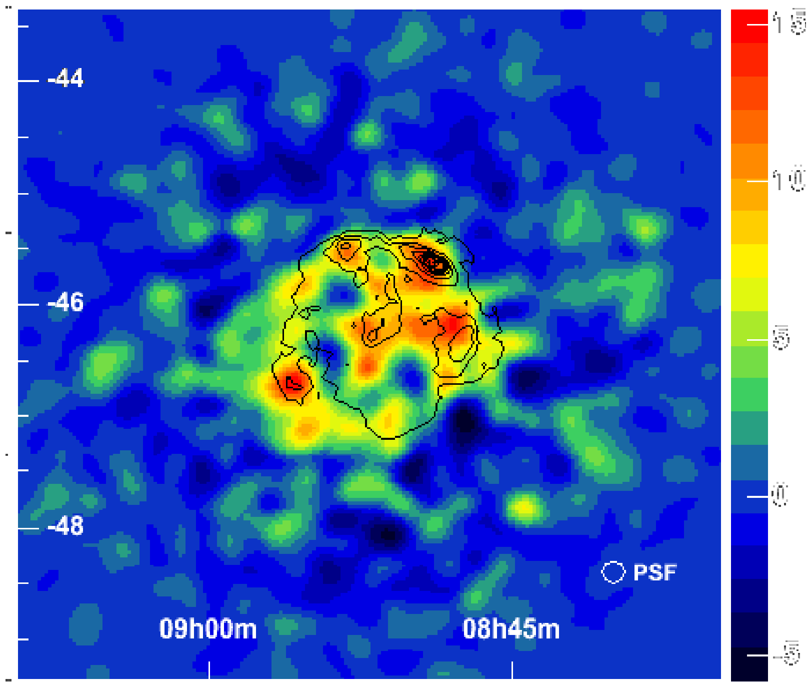
smoother than the gamma-ray spectrum $\propto E_\gamma^{-\Gamma} \exp[-(E_\gamma/E_{\gamma,o})^\beta]$

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

cutoff energies in X- and γ-ray spectra ➡

$B=a(h\nu_o/E_{\gamma,o})^{1/2}$

Vela Junior (a 2^o diameter remnant)



CANGAROO - 5 sigma (or so) 2003

HESS - 12 sigma after 4.5 h obs. time in 2004!

Flux - 1 Crab at 1 TeV

H.E.S.S. will observe the source for ca 100 h, so one should expect perfect data to estimate energy in p and/or e

uncertainty in **d** as large as factor of 3, n – poorly known
nevertheless if no nearby clouds - Wp could be as large as 10^{50} erg

IC ? – very small magnetic field at the level of **< 10 ❍G**

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

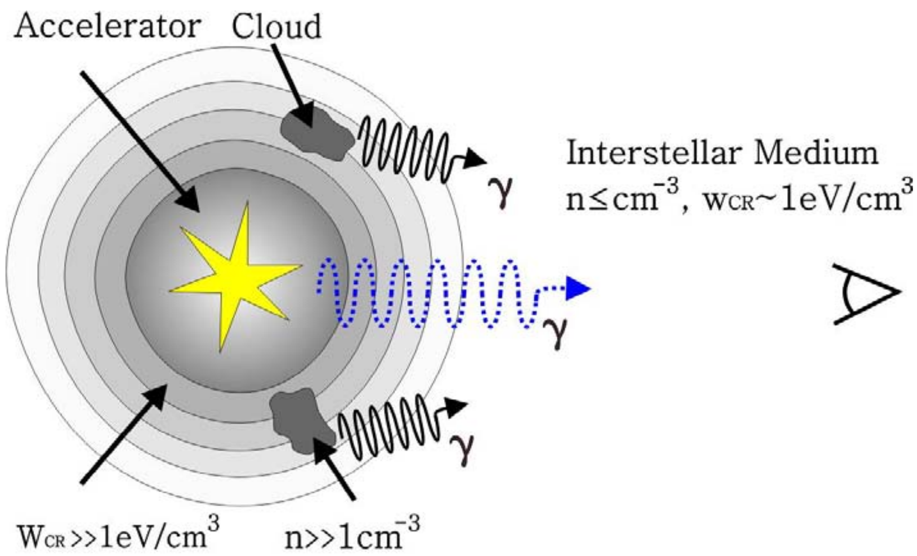
unbiased approach – deep survey of the Galactic Plane – not to miss any recent (or currently active) acceleration site:

SNRs, Pulsars/Plerions, Microquasars...

not only from accelerators, but also from nearby dense regions

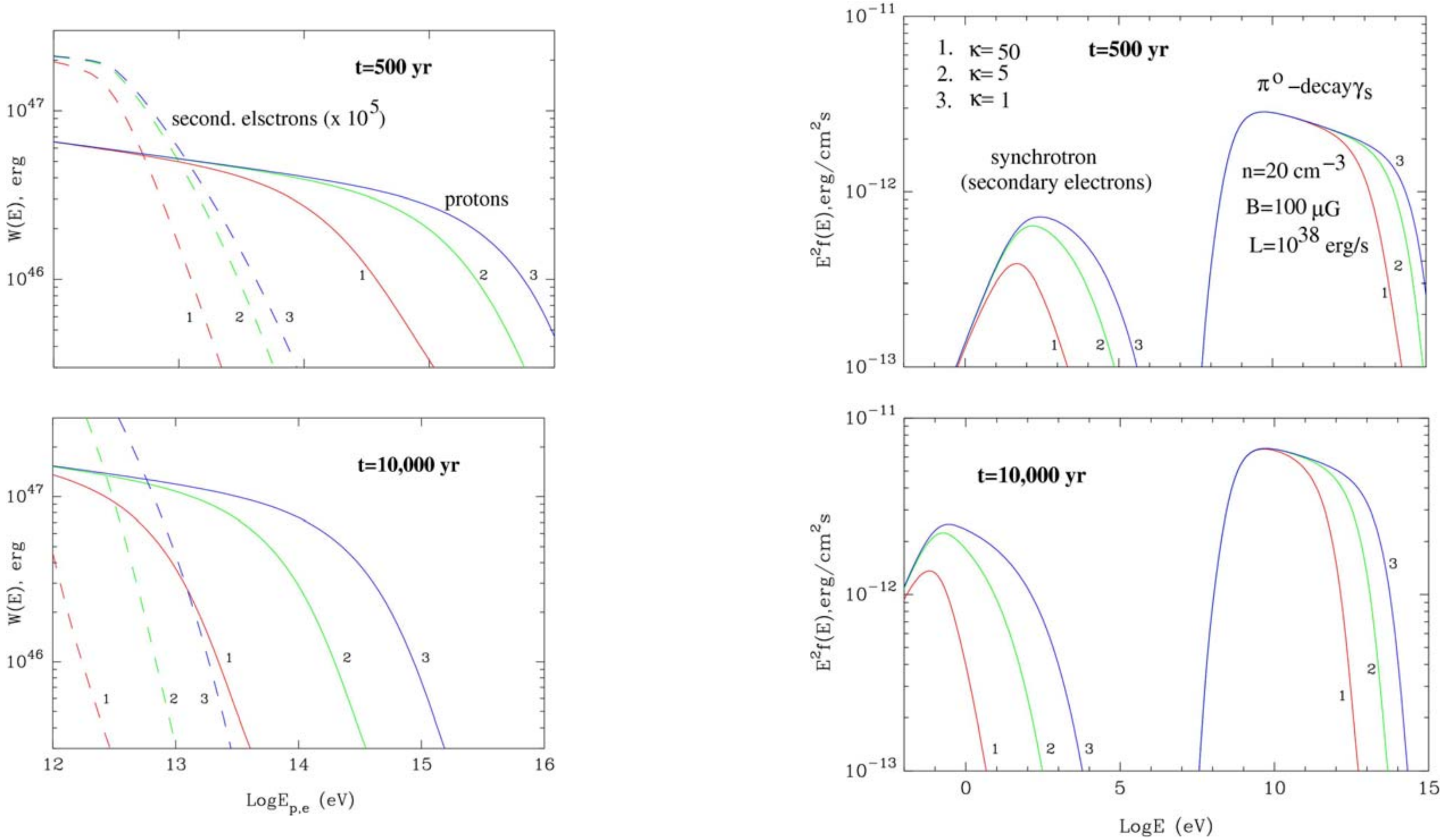
Gamm-rays/X-rays from dense regions surrounding accelerators

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 significantly 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

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

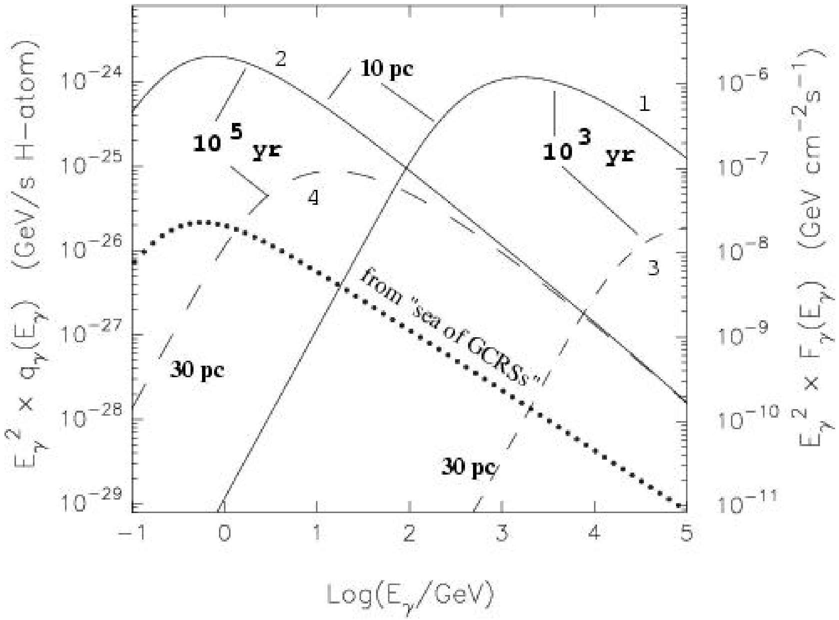
Giant Molecular Clouds (GMCs) as tracers of Galactic Coismic Rays

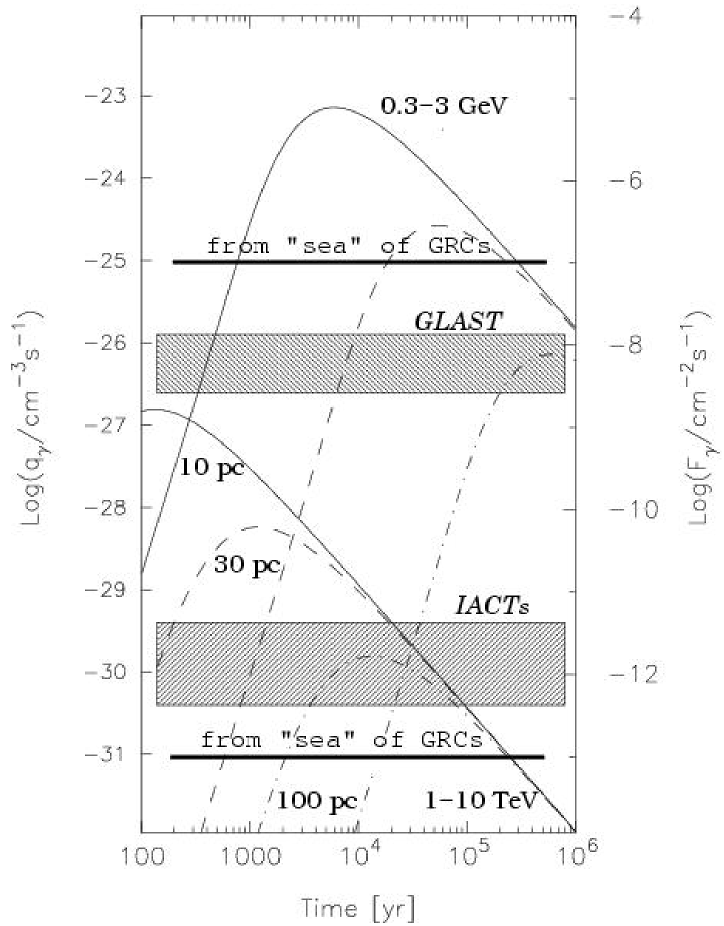
GMCs - 10^3 to 10^5 solar masses clouds physically connected with *star formation regions* - the likely sites of CR accelerators (with or without SNRs) - perfect objects to play the role of targets !

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)

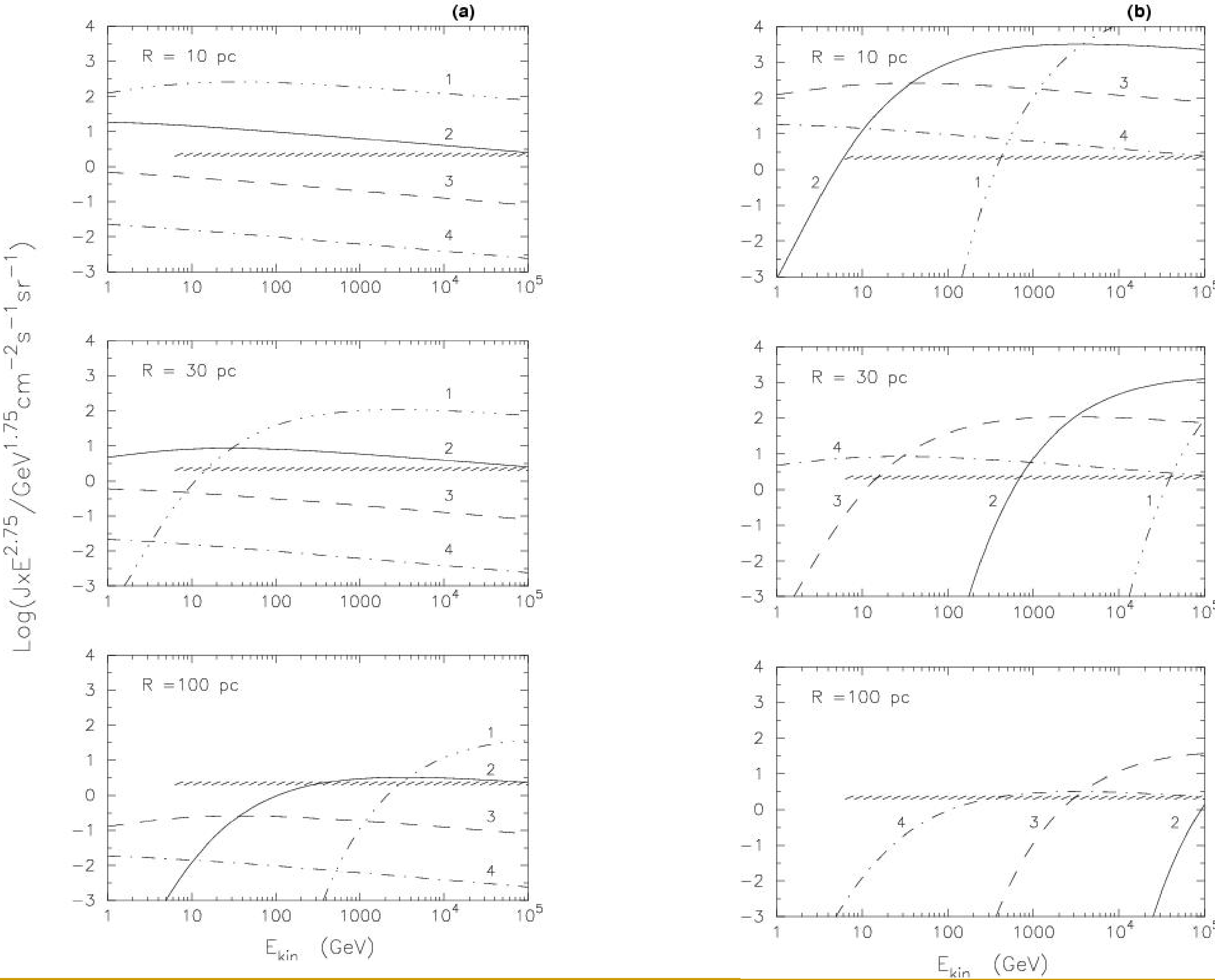
→ depending on t, R, D(E) one may expect any proton, and therefore gamma-ray spectrum – very hard, very soft, without TeV tail, without GeV counterpart ...

Propagation Effects on the spectrum of Gamma Rays

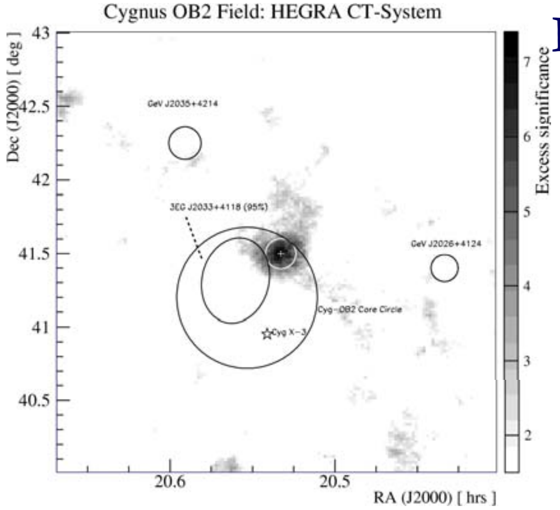


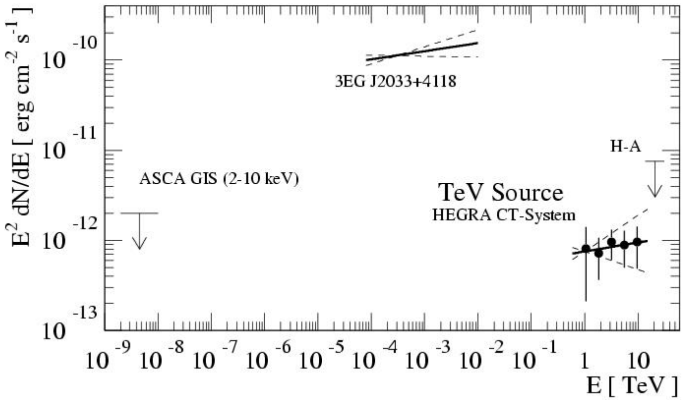


emissivities and fluxes (M_5/d^2_{kpc}) of gamma rays from a cloud at different times and distances from an impulsive accelerater with $W=10^{50}$ erg [$D(E)=10^{26}$ $(E/10GeV)^{0.5}$ cm^2/s]


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

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

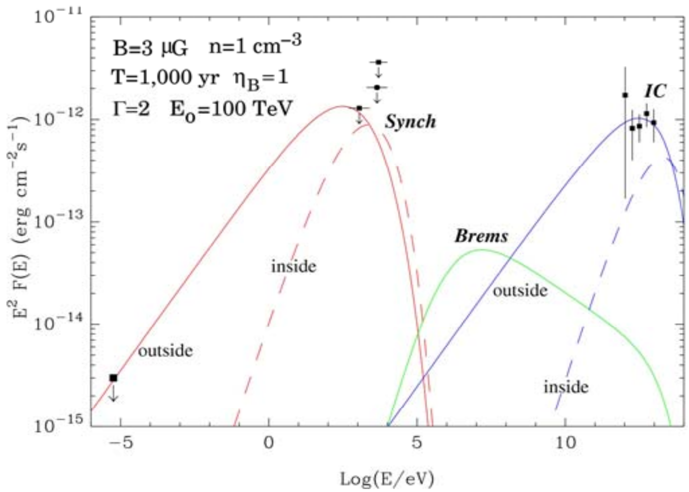
Origin ? leptonic (IC) origin is almost excluded

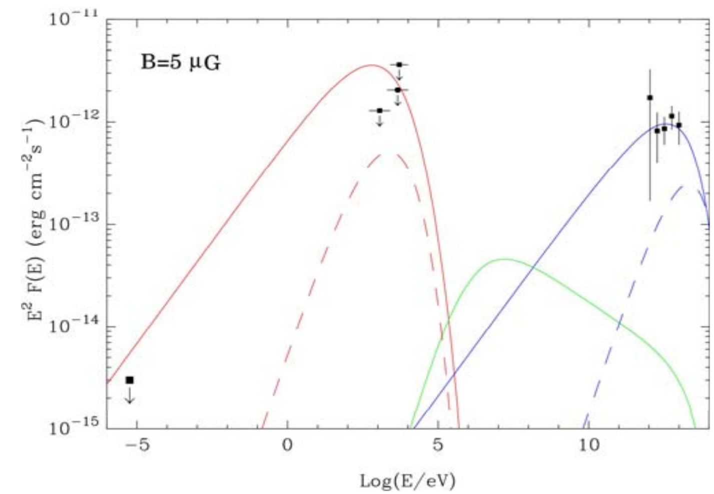
dense gas cloud(s) illuminated by protons arriving from a recent nearby Pevatron ?

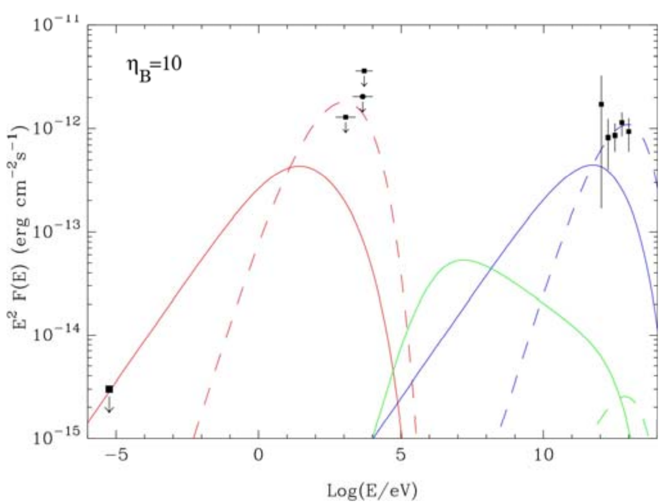
if this object is a representative of a large source population, the planned survey of the Galactic Disk by H.E.S.S. should reveal reveal many such hot spots

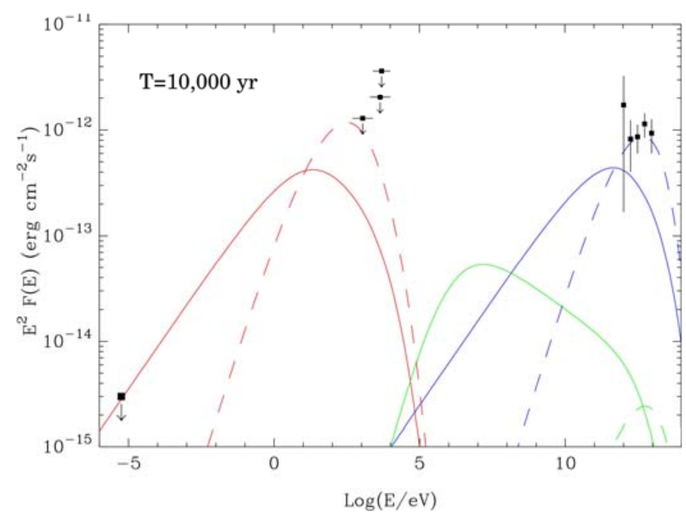
detected earlier by the HEGRA array and Crimea and “recently” by Whipple (?)

Electrons


B=3 μG n=1 cm^{-3}
T=1,000 yr η$_B$=1
Γ=2 E$_0$=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)

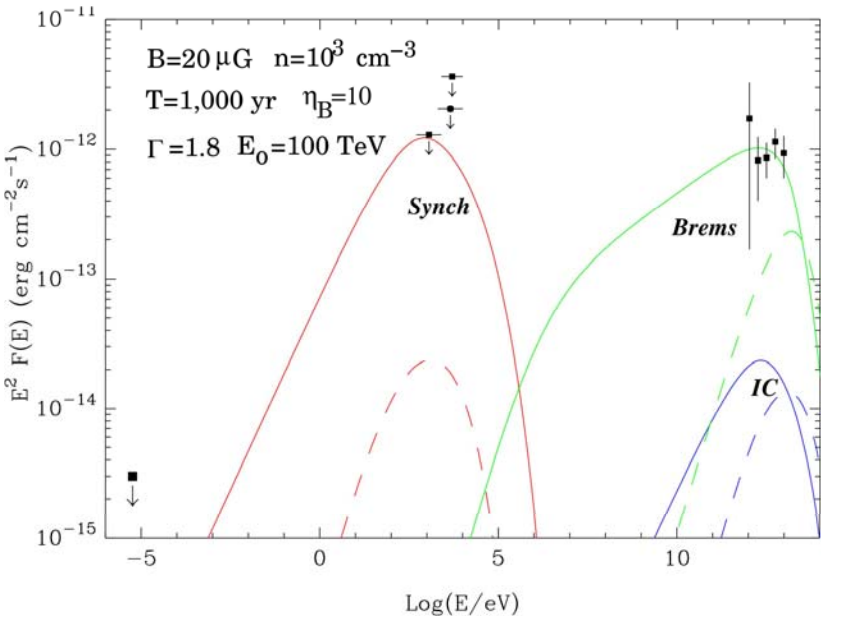
Electronic Models

Inverse Compton

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

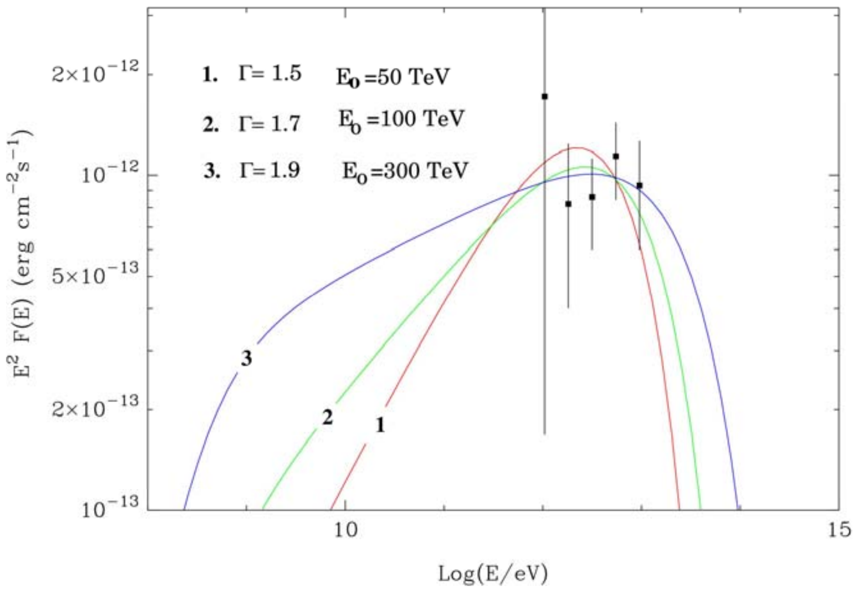
Otherwise even for very slow (Bohm !) diffusion gamma ray source should be largder than 5 arcmin (for d=1.6 kpc) !

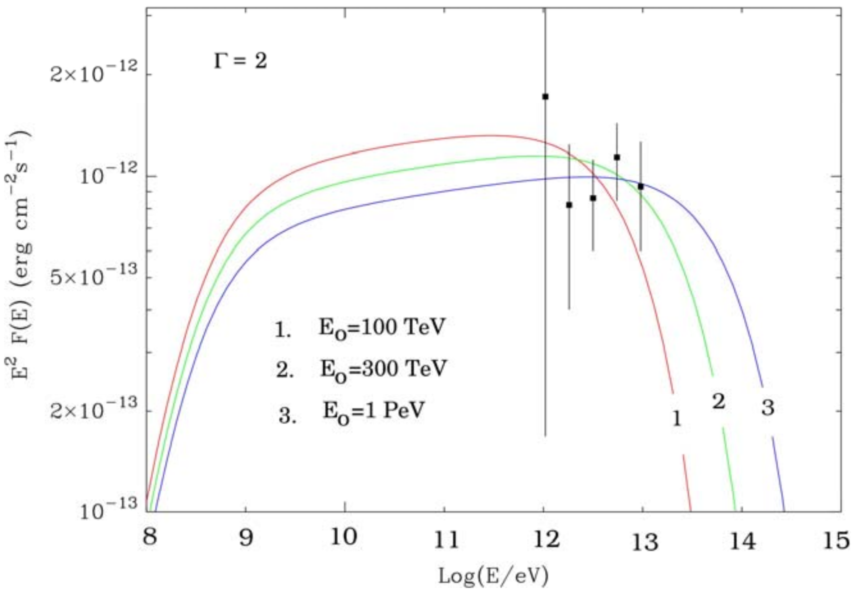
Bremsstrahlung



better - more "comfortable"

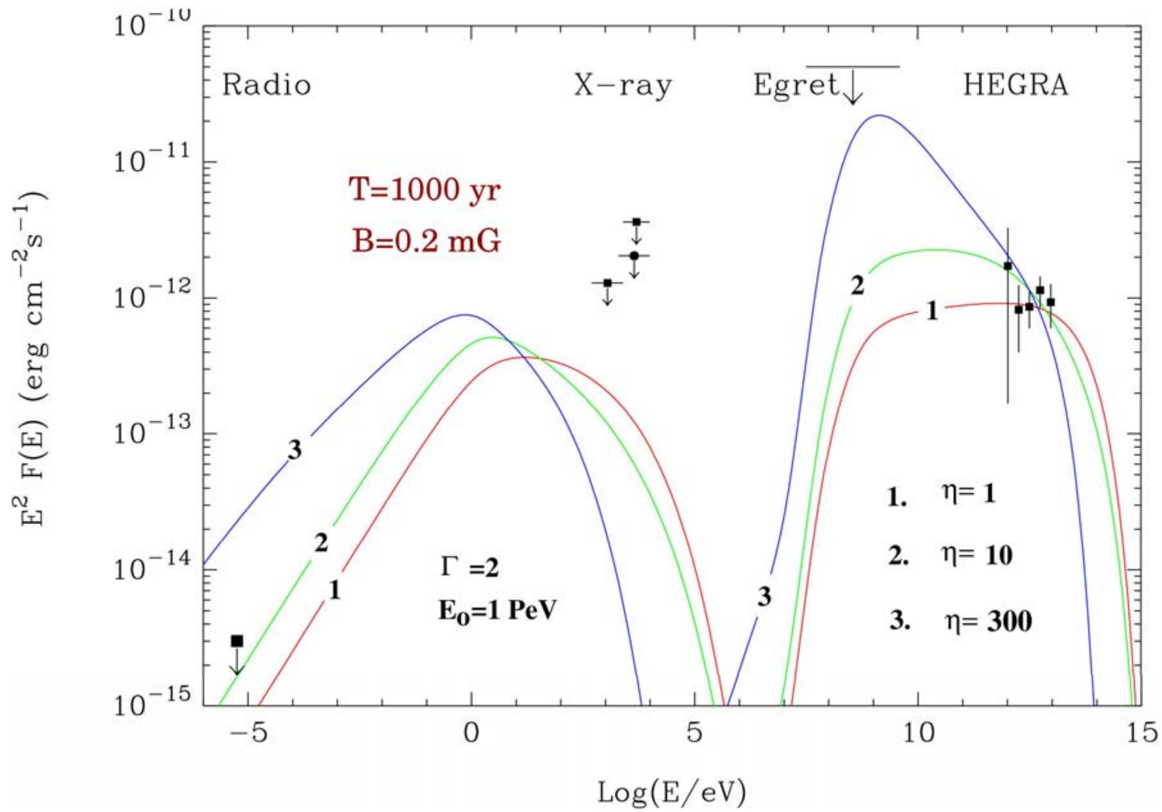
Protons ? spectrum should extend at least to 100 TeV





Hadrons…

young source

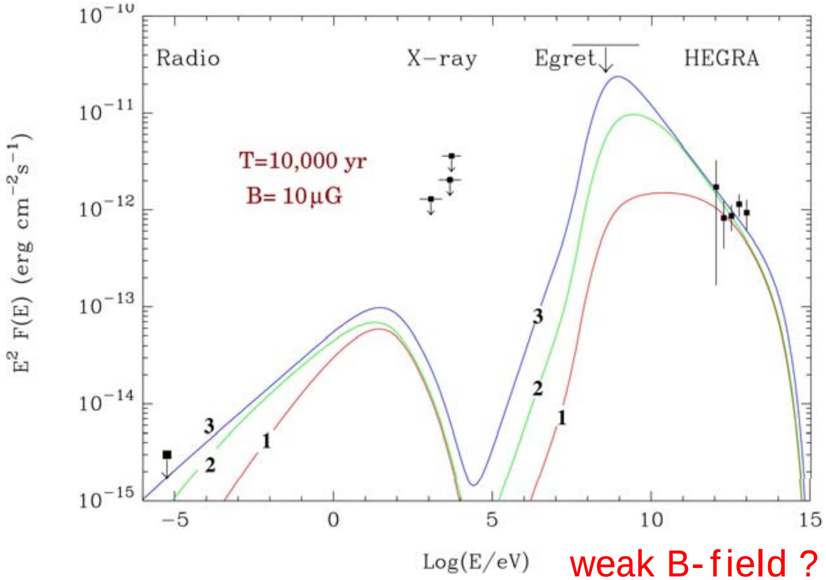


Gamma-ray spectrum strongly depends on the diffusion (escape)

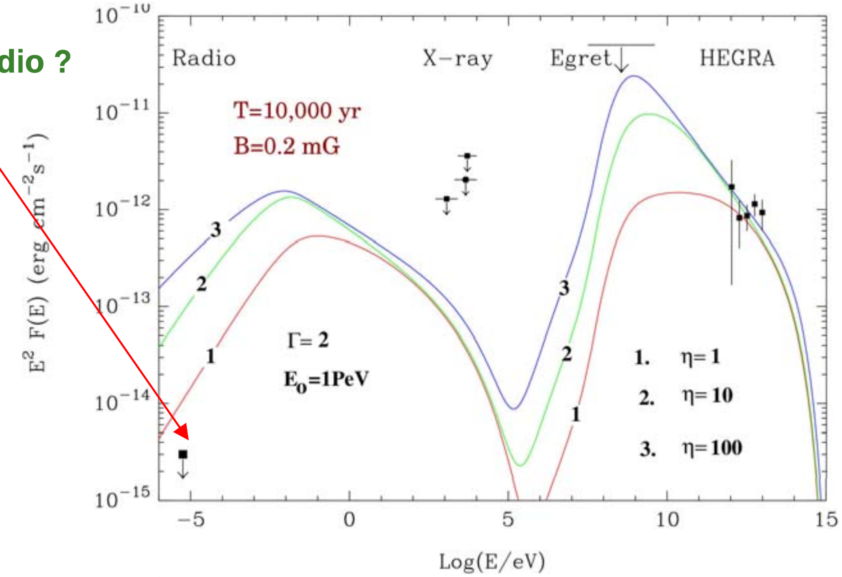
$$D(E) = 10^{24}(E/1\ GeV)^{0.5}\ \eta\ cm^2/s$$

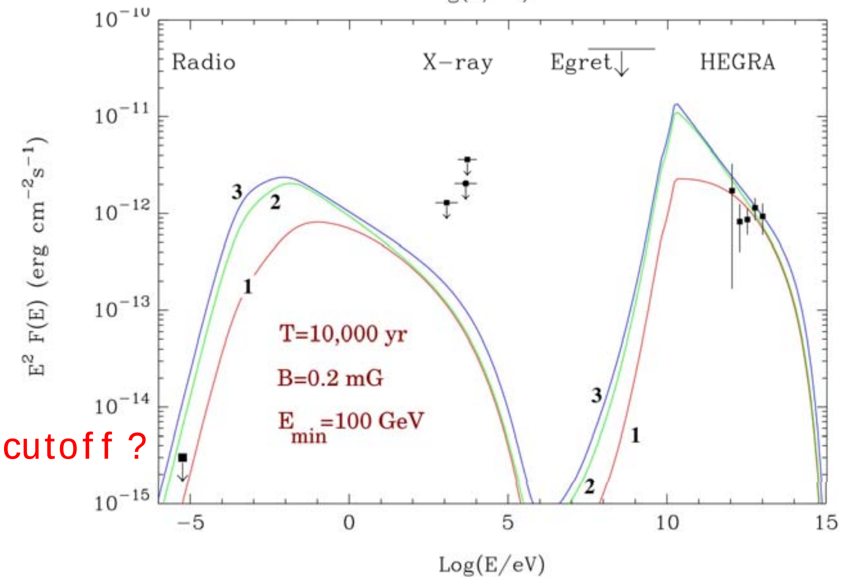
older source

conflict with radio ?



weak B-field ?



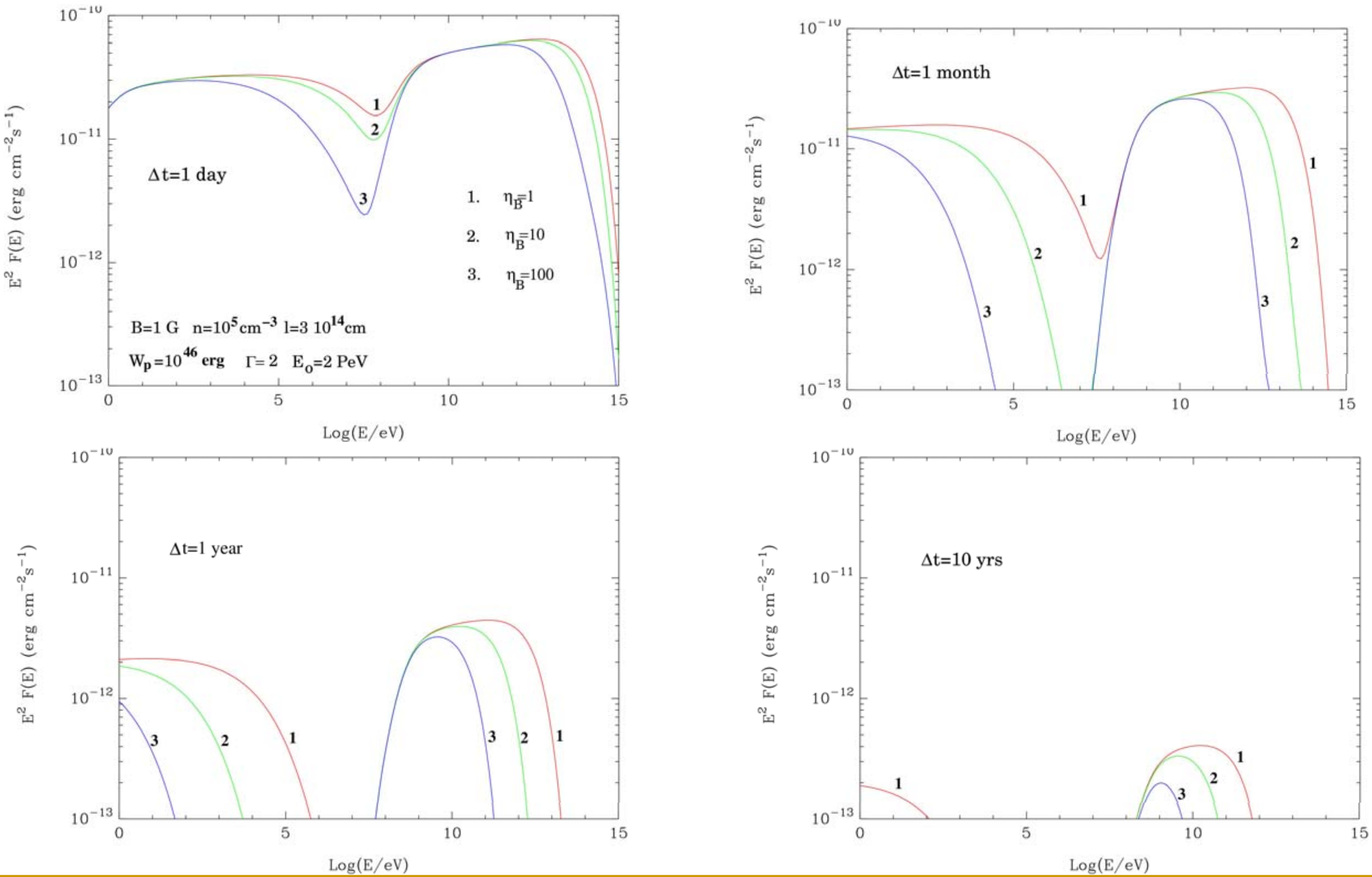


or low-energy cutoff ?

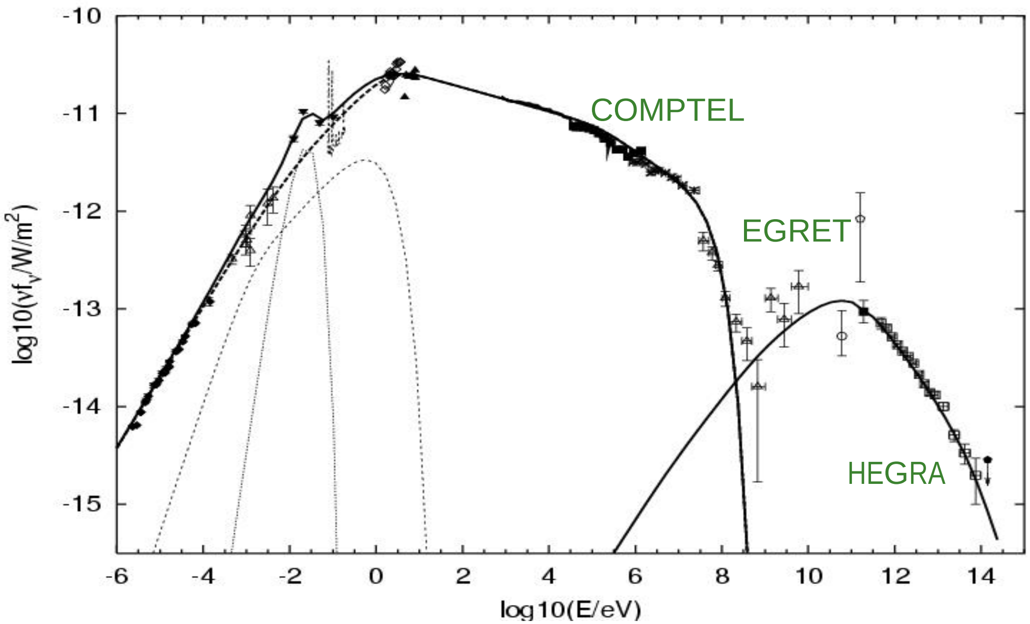
conclusion:

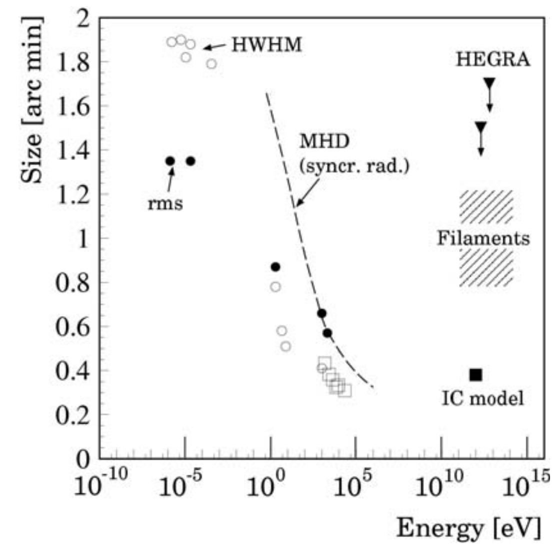
the PeVatron should be young, B-field – large, confinement - effective

Source - transient proton accelerator inside the dense core ?



Crab Nebula – gamma-rays up to 50 TeV and beyond !





Standard MHD theory – cold ultrarelativistc pulsar wind terminates by a reverse shock resulting in (re)acceleration of electrons up to 10^{16} eV

Synchrotron radiation => nonthermal optica and X-ray nebula
Inverse Compton scattering => high energy gamma-ray nebula

Crab Nebula – a very powerful

and "extreme" accelerator

$$W = L_{rot} = 5 \times 10^{38}\ ergs$$
$$h\nu_{cut} = 0.1 h\nu_{max} \sim 0.1 m_e c^2/\alpha_f \sim 10 MeV$$

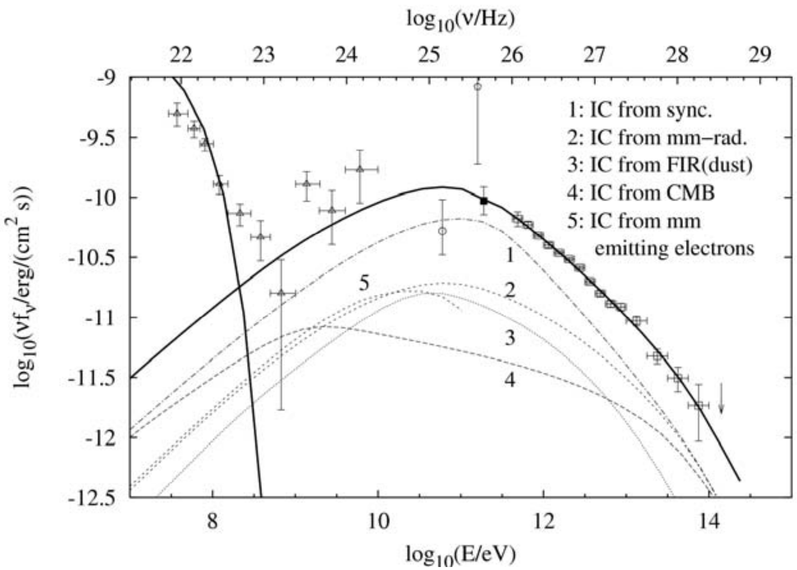
Acceleration takes place at 10 % of the maximum possible rate c/r_g !

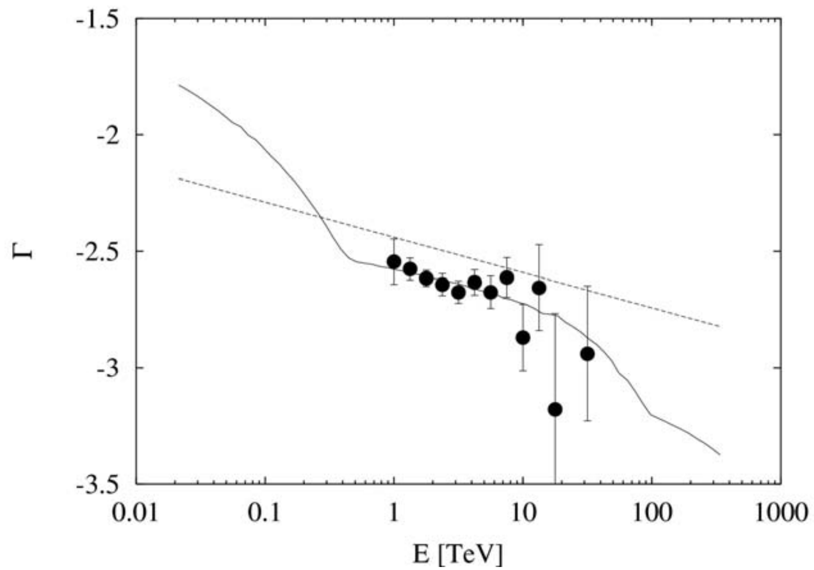
PeV electrons are responsible for MeV synchrotron and >30 TeV IC components

Crab Nebula – a perfect (extreme) electron accelerator

spectrum can be described by a power-law $E^{-2.6}$ from 500 GeV to 80 TeV while stanfard IC models predict noticeable steepening above 20 TeV

closer examination based on recent HEGRA data shows that indeed the spectrum becomes steeper especially above 10 TeV





no much room (less than 10-20 % of L_0) for protons in the pulsar wind

TeV gamma-rays from other Pulsar Driven Nebulae

Crab Nebula is very effective accelerator but not effective IC gamma-ray emitter (because of large B)

less powerful pulsars ⟹ weaker magnetic field ⟹ higher gamma-ray efficiency ⟹ detectable gamma-ray fluxes from a number of plerions

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

similar to other pulsars with three components/sites *- Pulsar, Pulsar Wind, Synchrotron Nebula -* the cold wind and the shocked accelerated electrons are illuminated by optical radiation from the companion star ⟹ detectable IC gamma-ray emission

new ! detection of TeV gamma-rays from PSR1259-63 at 0.1Crab level by H.E.S.S. a few days before the periastron (March 7)

(see H.E.S.S. poster and short presentation by G.Heinzelmann)

Challenges

A. Probing possible hadronic component

spectrum is explained nicely from 500 GeV to 80 TeV energies by IC scattering within the MHD theory of Kennel and Coroniti (1980)

additional hadronic component with narrow energy spectrum with characteristic energy 10^{15} eV is not excluded, but the energy content of protons in the wind cannot exceed 10 %

B. **Probing the site of creation and the Lorentz factor of the kinetic-energy dominated wind through inverse Compton scatering of wind electrons**

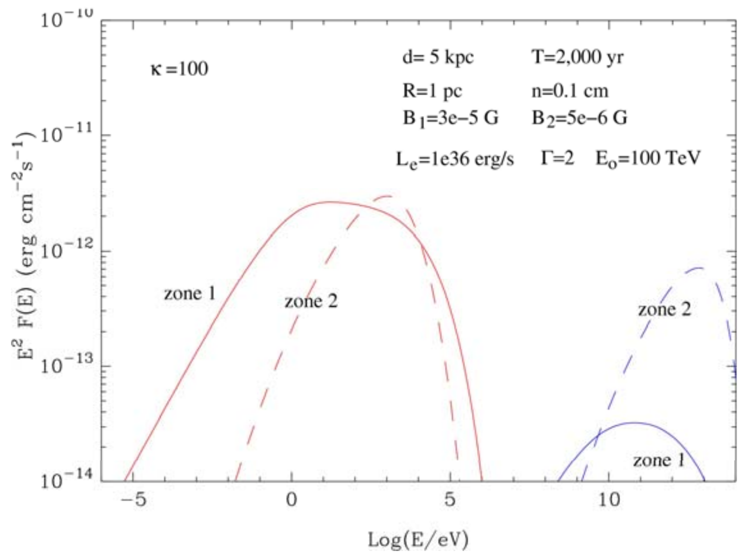
unique feature of VHE gamma-ray astronomy - ***discovery of ultrarelativistic flows through bulk motion Comptonzation***

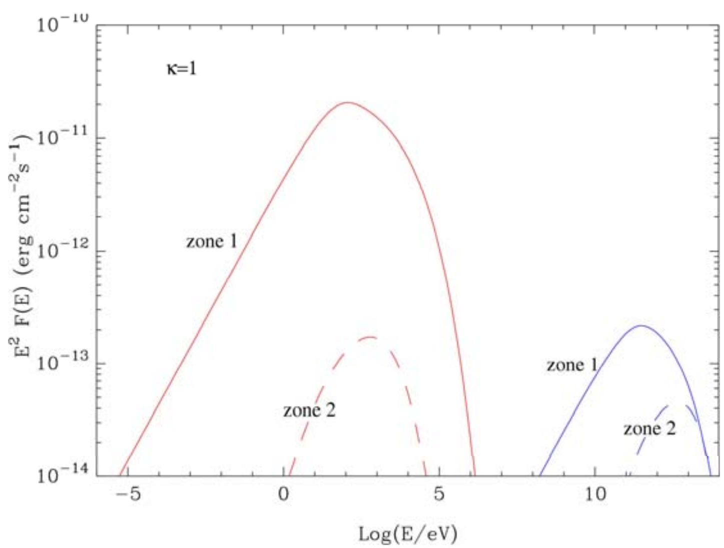
on the L_x/L_γ ratio in plerions

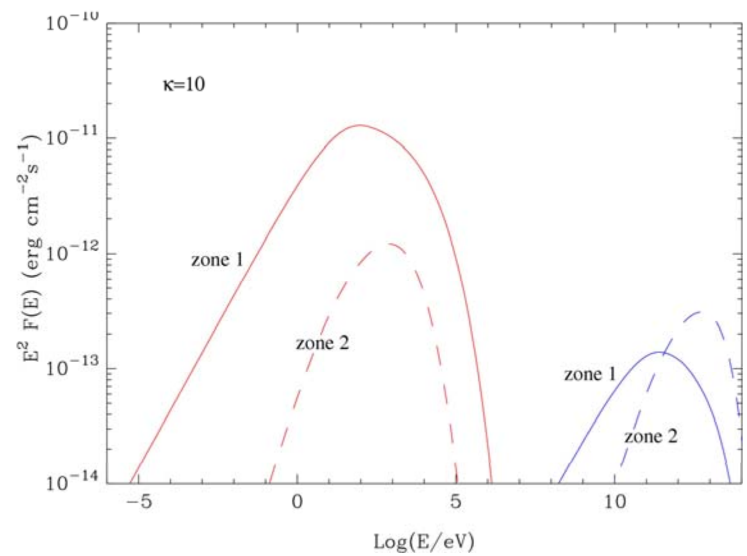
$$\frac{L_\gamma}{L_x} = \frac{B^2/8\pi}{w_{2.7K}} = 0.1(B/10\mu G)^{-2}$$

for B-fields exceeding 30 microGauss
TeV/X ratio less than 1 percent ?

Yes, but outside the source
L_{γ_0} could be much higher

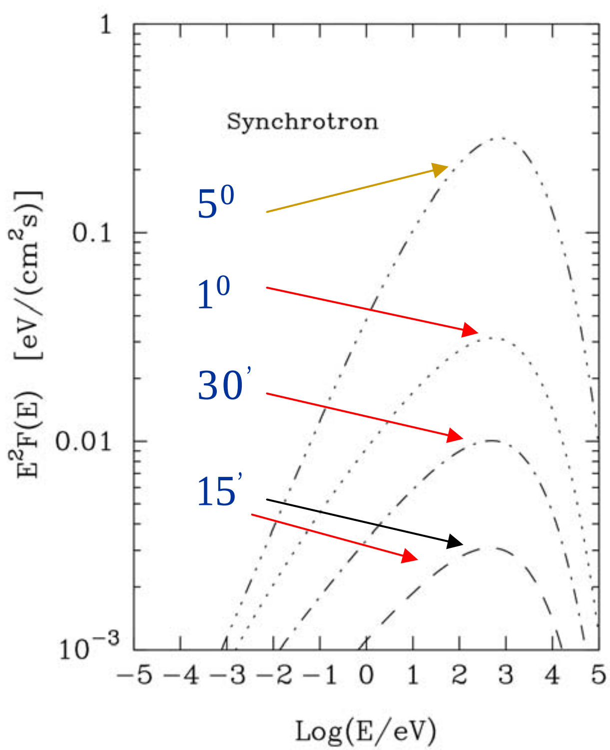


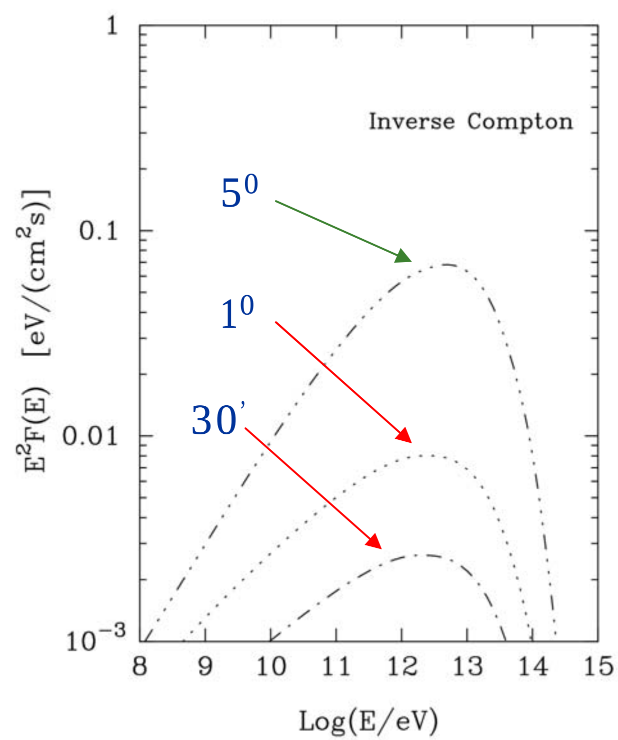




morphology of X and TeV gamma-rays in ISM (*outside the plerion*)

B_{ISM}=5 ❍G (or so): morphology depends only on the source age T and the diffusion coefficient D(E) *

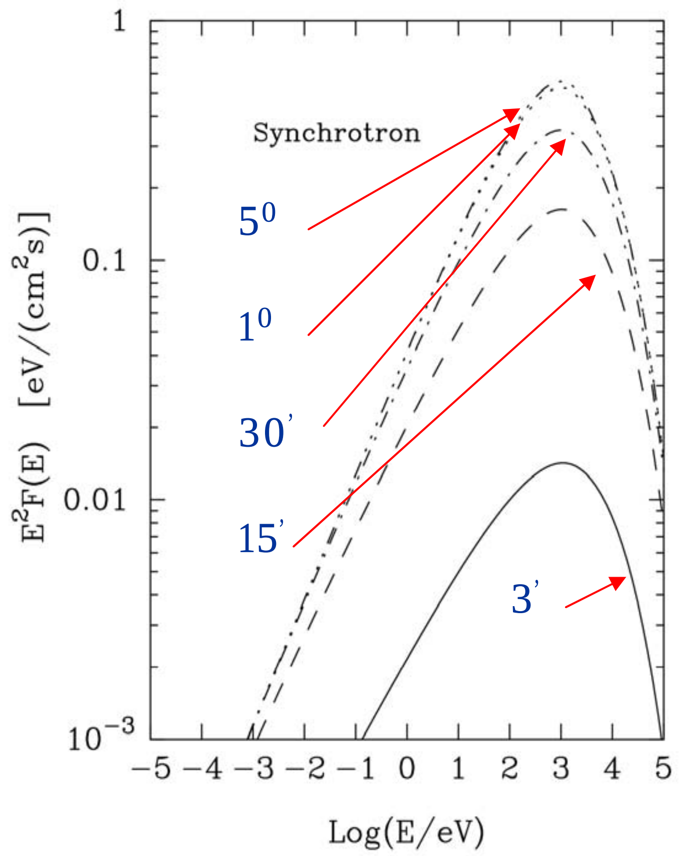


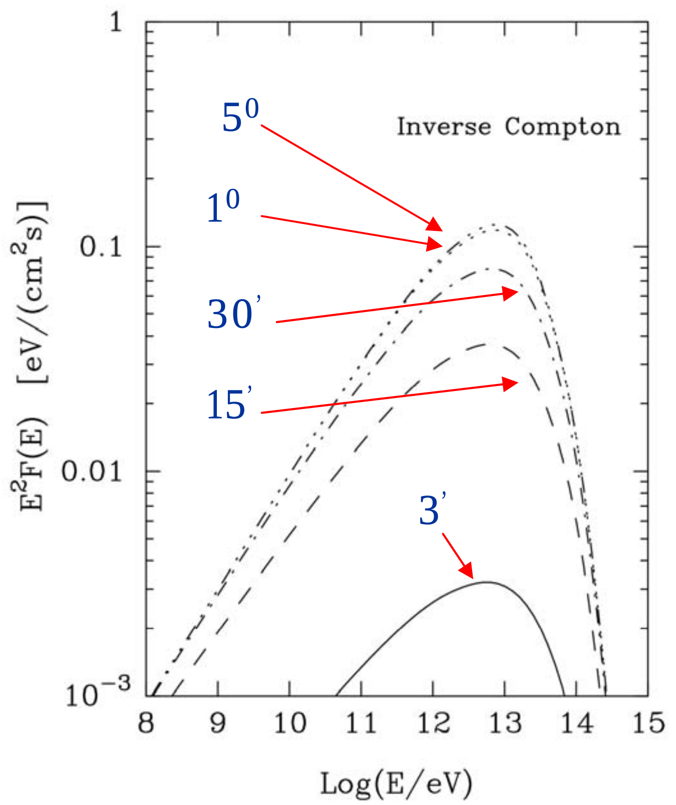


fast diffusion/young source

* $D(E)=D_0\ (E/10\ GeV)^s$

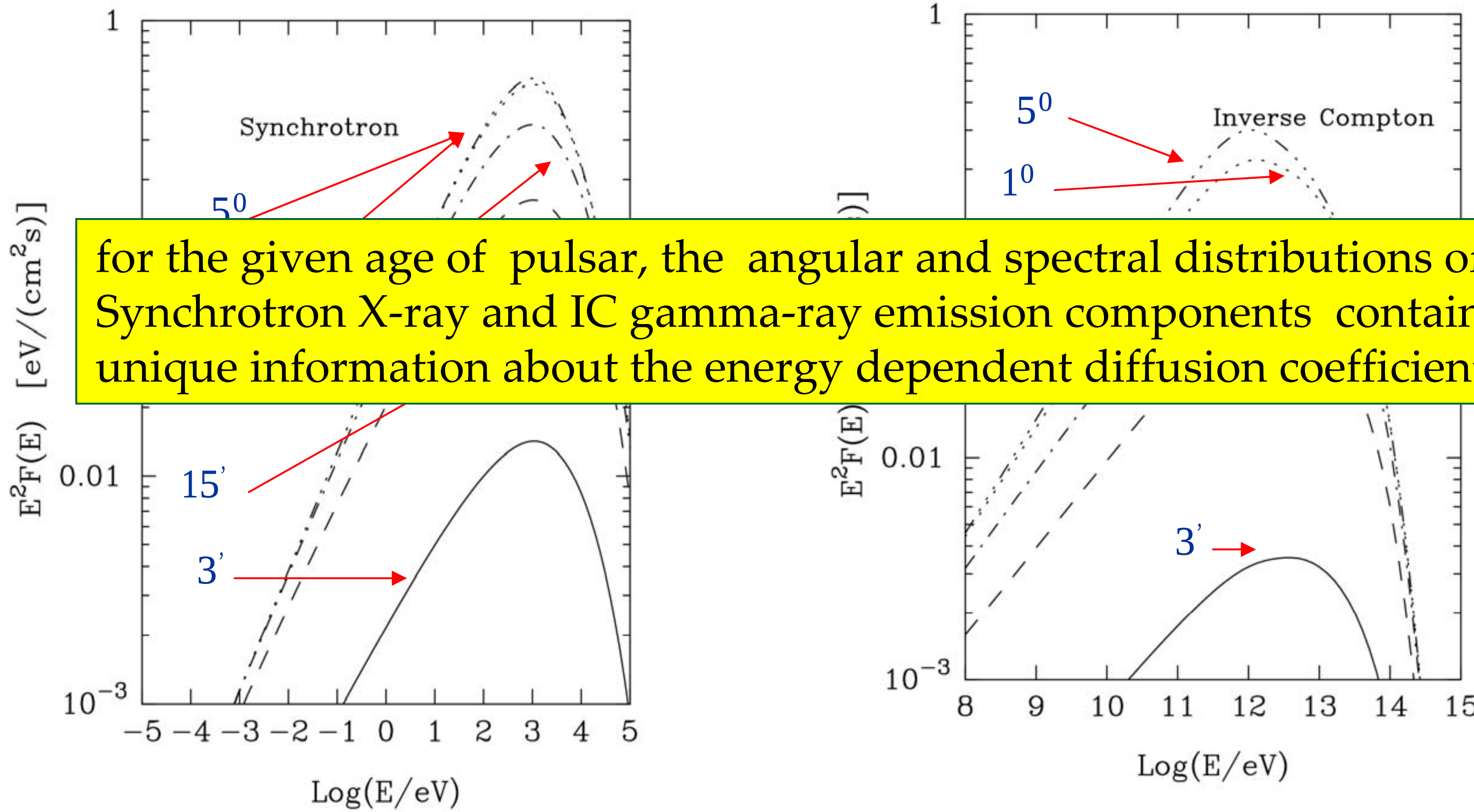
$D_0=10^{28}\ cm^2/s$, s=0.65, T=2,000 yr





slow diffusion/young source

$D_0=10^{27}$ cm^2/s, s=1/3, T=2,000 yr



for the given age of pulsar, the angular and spectral distributions of Synchrotron X-ray and IC gamma-ray emission components contain unique information about the energy dependent diffusion coefficient

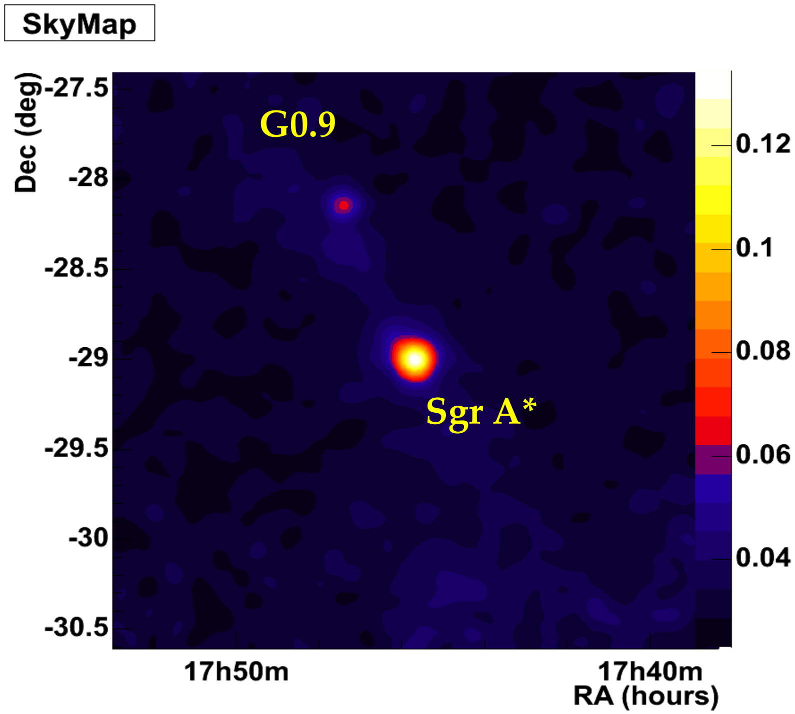
slow diffusion/older source

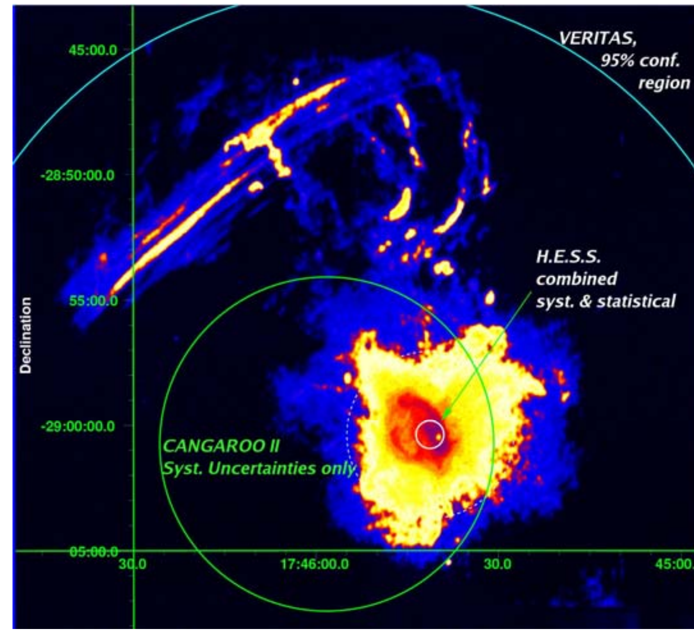
$D_0=10^{27}$ cm^2/s, s=1/3, T=10,000 yr

Galactic Center as an alternative source of the bulk of Galactic CRs

Galactic Center as an alternative source of the bulk of Galactic CRs ?

TeV ♑-rays from Galactic Center





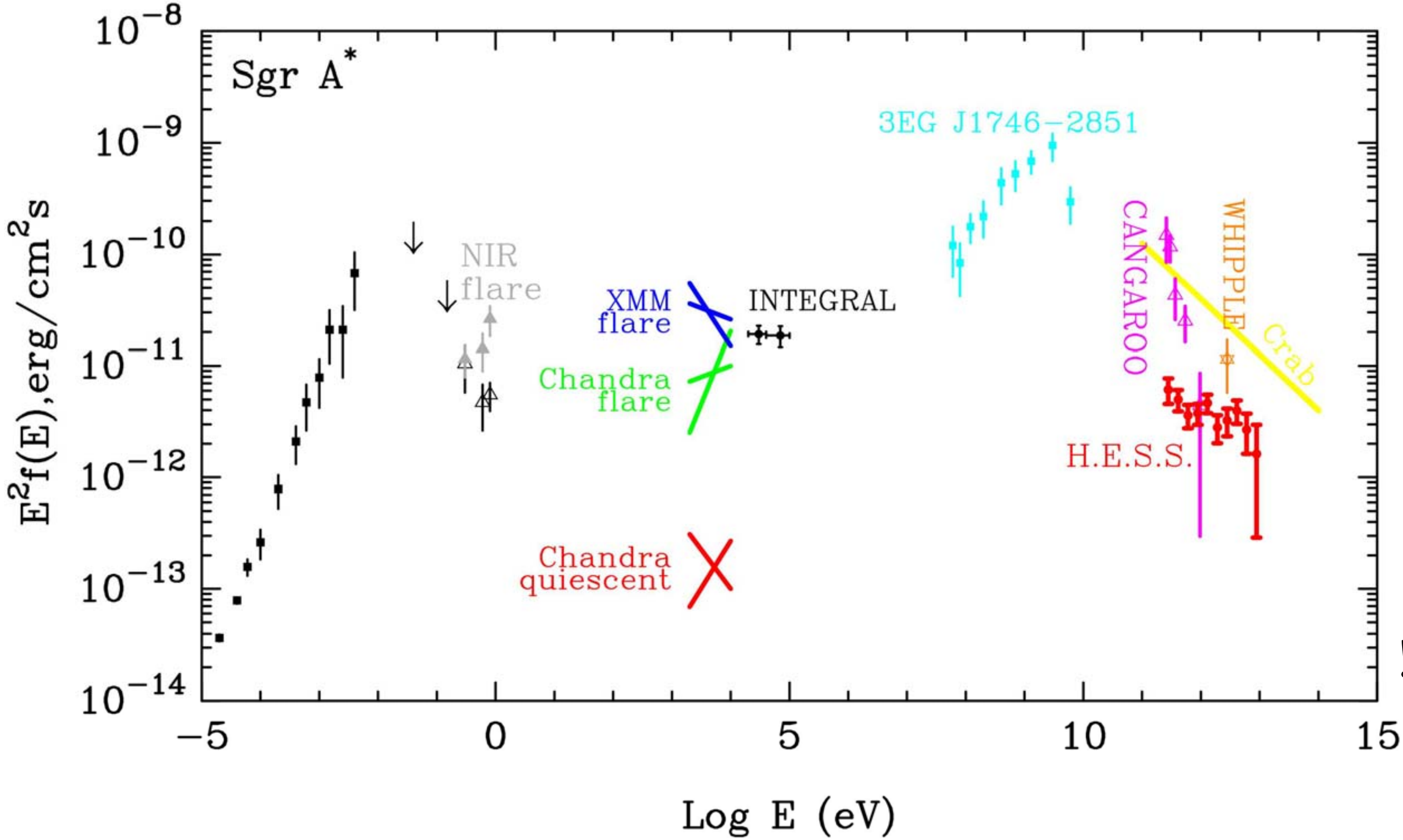
if extended source - size less than 3’ (7 pc)
if point-like source – position within 1’ around Sgr A*

TeV γ-rays from central <10 pc region of GC

- Annihilation of DM ? *mass of DM particles > 12 TeV ?*
- *Sgr A* :* 3 10^6 M_o BH ? *somewhat speculative but possible*
- SNR Sgr A East ? *why not ?*
- Plerionic (IC) source(s) *why not* ?
- Interaction of CRs with dense molecular gas (clouds) ? *easily*

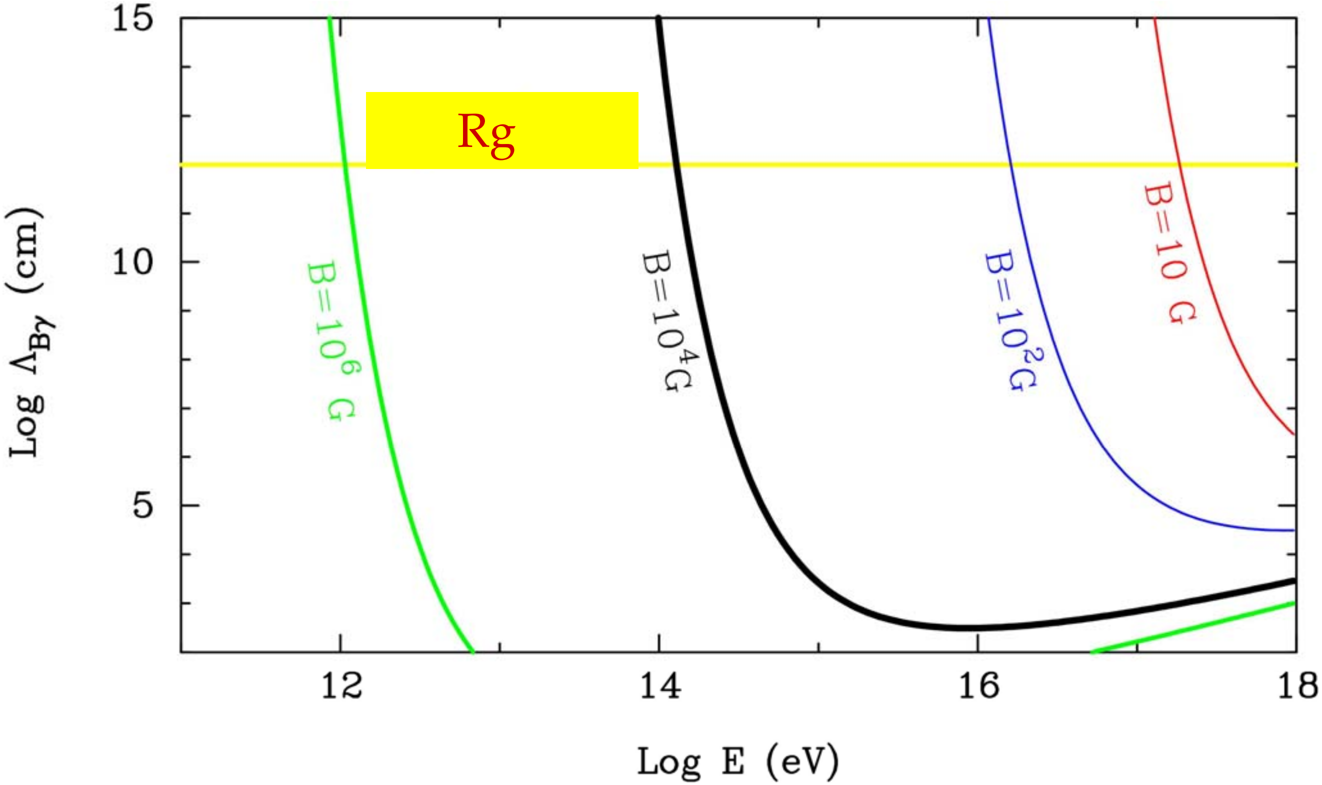
BH in GC – unique with extremely low luminosity

nice present for (gamma-ray) astronomers …



!

transparent also in magnetic field if $B < 10^5$ G



Mean free path is a function of ♍◘☎☜✉$m_e c^2$)(B/B_{crit}); B_{crit}=4.4e13 G

Radiation Processes associated with *Protons*

maximum acceleration rate: $t_{acc} = \kappa r_g/c; \quad r_g = E/300B; \quad \kappa \geq 1$

(i) in rotation-induced magnetic field (Levinson 2001) : k=1

(ii) by shocks (DSA): $k \sim \not\subsetneq 10\ (c/v)^2$

$$E_p \approx 10^{18}(B/10^4 G)(M/3\times 10^6 M_\odot)\ \kappa^{-1}\ \text{eV}\ .$$

- *Synchrotron radiation ?* $\varepsilon_{max} = (9/4)\alpha_f^{-1} m_p c^2 \approx 300\kappa^{-1}$ GeV

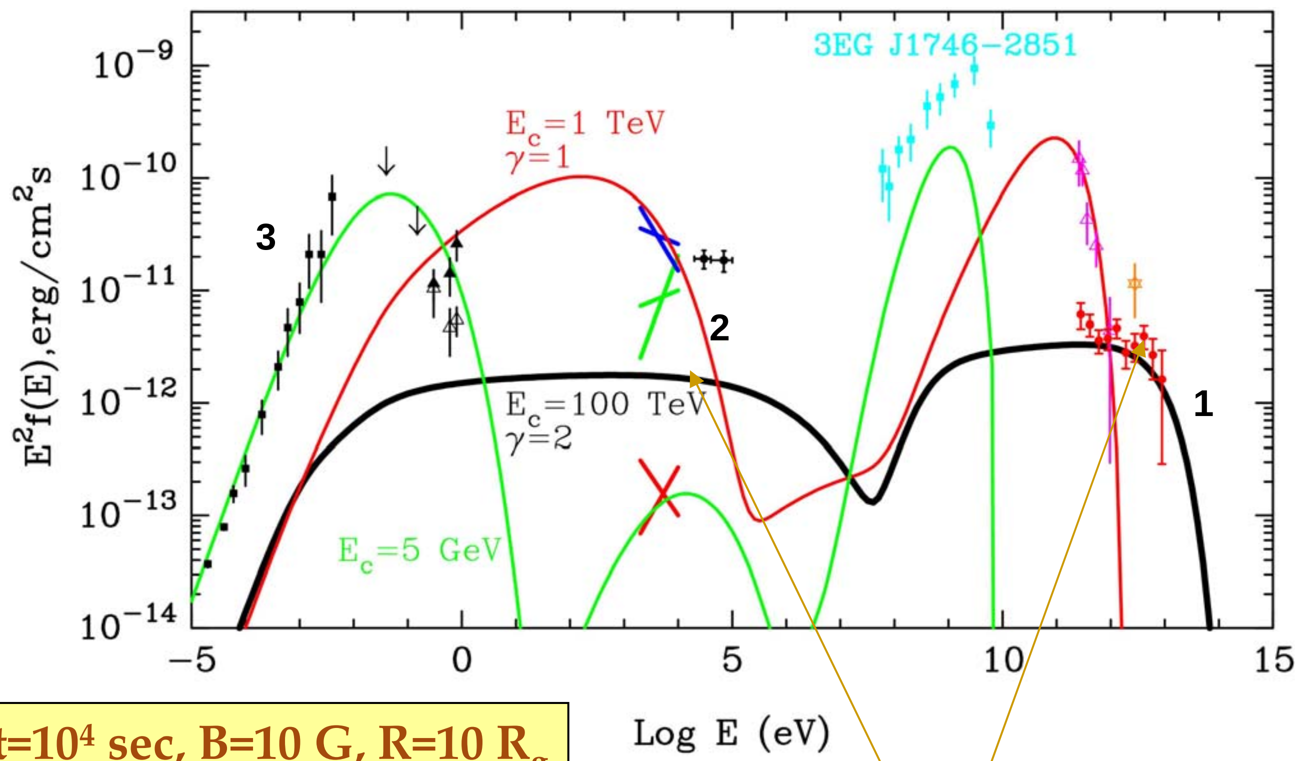
  unlikely unless in the jet with ♎ ✇ 🗁🗀

- *Curvature radiation ?* $0.2(B/10^4 G)^{3/4}$ TeV

  possible if B >10^5 G , but in such fields TeV gamma-rays cannot escape

- pp interactions ?
- p ♑ (photomeson) interactions ?

p-p interactions in the accretion disk



n=10^8 cm^{-3}, t=10^4 sec, B=10 G, R=10 R_g

=2, E_c=100 TeV, L_p=5e38 erg/s
=1. E_c=1 TeV, L_p=1e40erg/s
=0, E_c=5 GeV, L_p=1e40 erg/s

$(h■)_{synch} \sim 100\ (E_\gamma/1\text{TeV})^2\ (B/10\ \text{G})$ ke

p-p interactions in the accretion disk ?

Broad-band radiation due to TeV protons

acceleration by induced electric field
or by strong shocks in the accretion flow

correlated TeV-X-IR flares

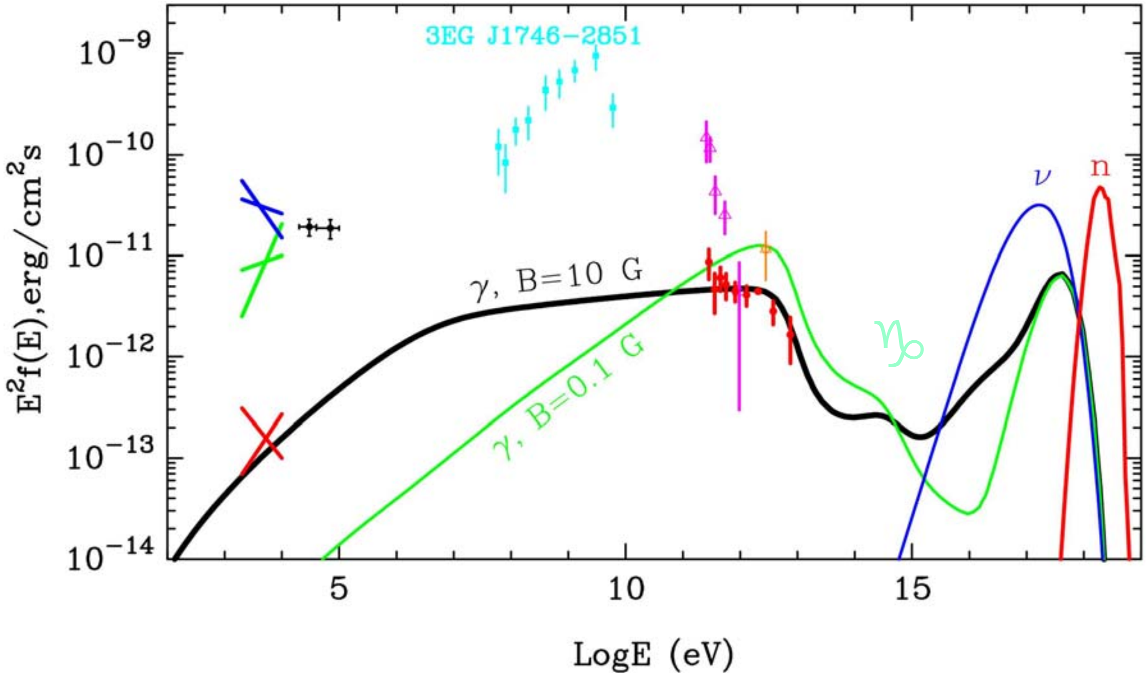
Can be easily checked by simultaneous X-TeV observations:
TeV energy flux can be only a factor of few higher than X-ray flux !
(unless B << 1G)

$n=10^8$ cm^{-3}, $t=10^4$ sec, $R=10\ R_g$

Low efficiency: tpp= 10^7 $(n/10^8\ \mathrm{cm}^{-3})^{-1}$ sec => ♒ < 0.1 %

TeV neutrino fluxes detectable by km^3 class detectors ?

E-M cascades initiated by p-γ interactions



Acceleration to 10^{18} eV close to the gravitational radius (10^{12} – 10^{13} cm)

interaction with IR and mm photons (and B) fields
=> E-M cascades

requires 10 kG B-field at 1-2 Rg

no conflict with X-rays !

UHE neutrinos – detectable by AUGER ?,
UHE neutrons and γ-rays detectable by AUGER

electronic models = IC models

1. SSC type models in relativistic jet ?

maximum electron energy in random field:

$$E_{e,max} \approx 5 \times 10^{13} (B/1G)^{-1/2} \kappa^{-1/2} \text{ eV}$$

=> random B-field << 1 G unless & ~ 1

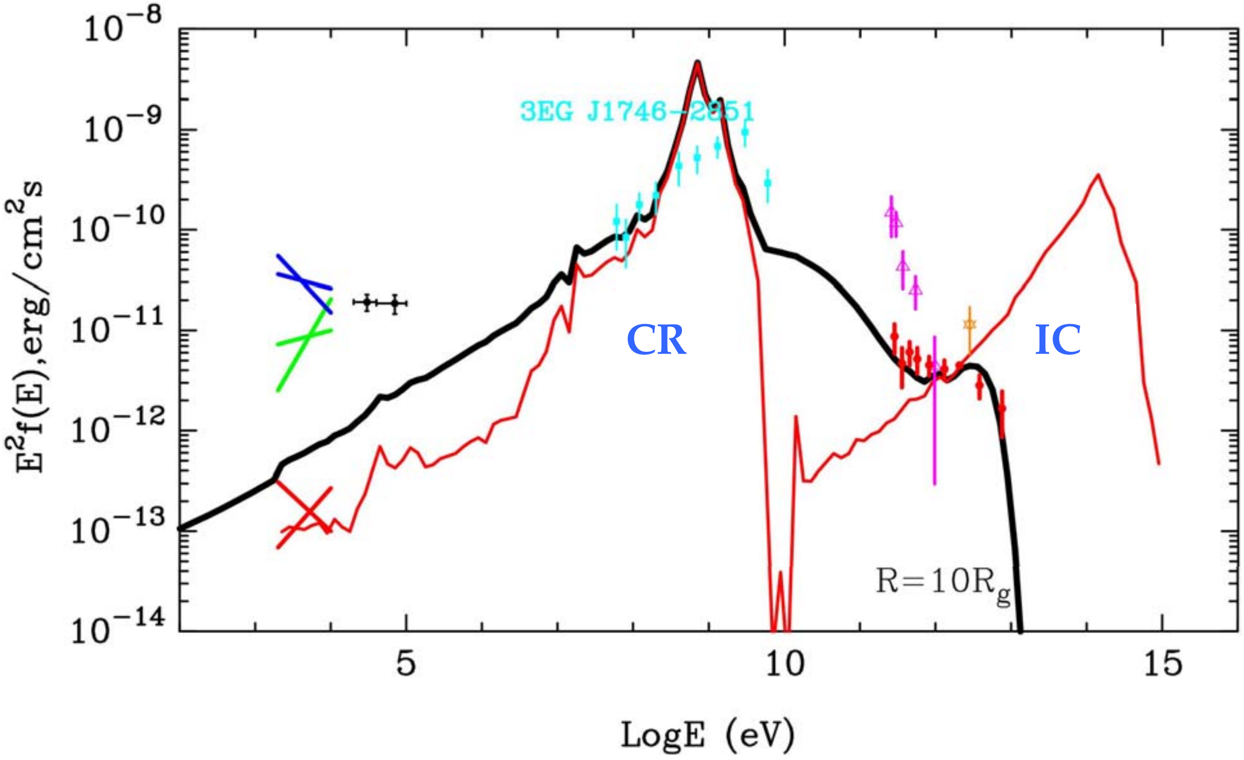
2. Curvature Radiation – IC model

acceleration in a regular B-field:

$$E_{e,max} \approx 10^{14} (B/10G)^{1/4} \text{ eV}$$

100 TeV IC gamma-rays initiate E-M cascade in IR source

electronic models: "IC/Curvature radiation" cascades)



no neutrons, no neutrinos, relatively weak X-ray emission

Summary

- At least 3 process can provide non-negligible fractions of the detected TeV flux

Tests:

- Variability on timescales less than 1 hour

  HESS detects every night statistically significant signal from GC

- MWL campaigns

  planned observations with Chandra

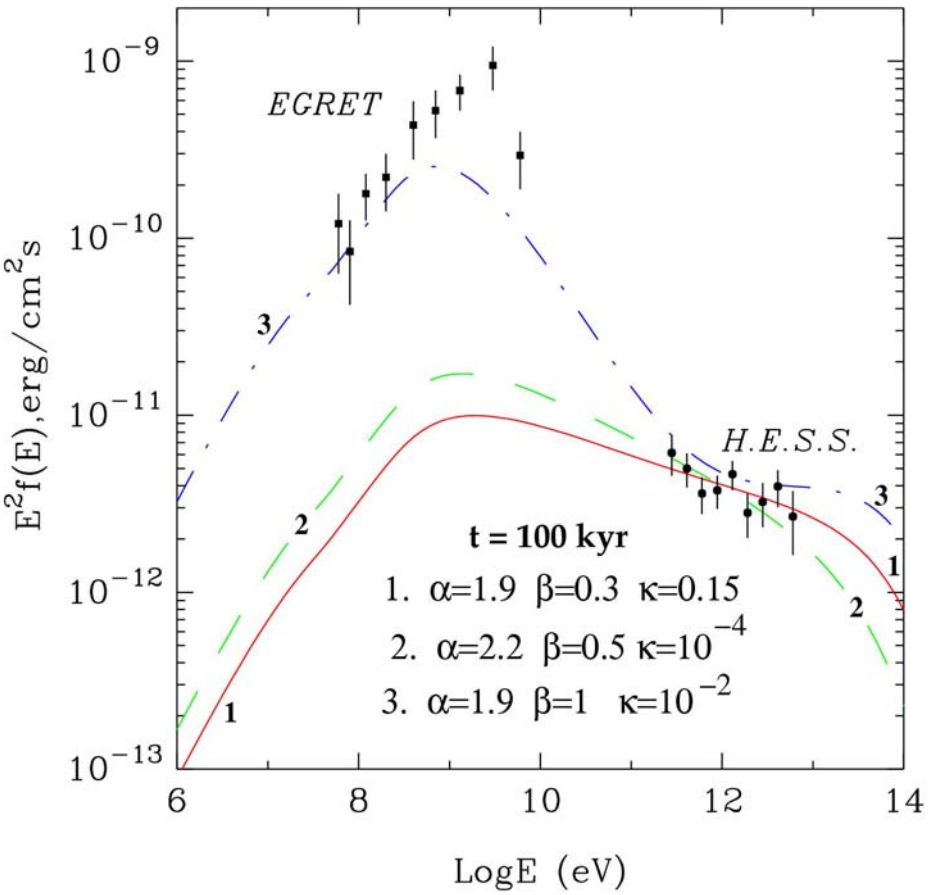
Diffuse Emission of the central 10 pc region

1. **due to pp interactions in dense (1000 cm^{-3}) gas regions**

2. **due to Inv. Compton in dense (2.5 keV/cm^{-3}) FIR regions**

pp gamma-rays in the central 10 pc region

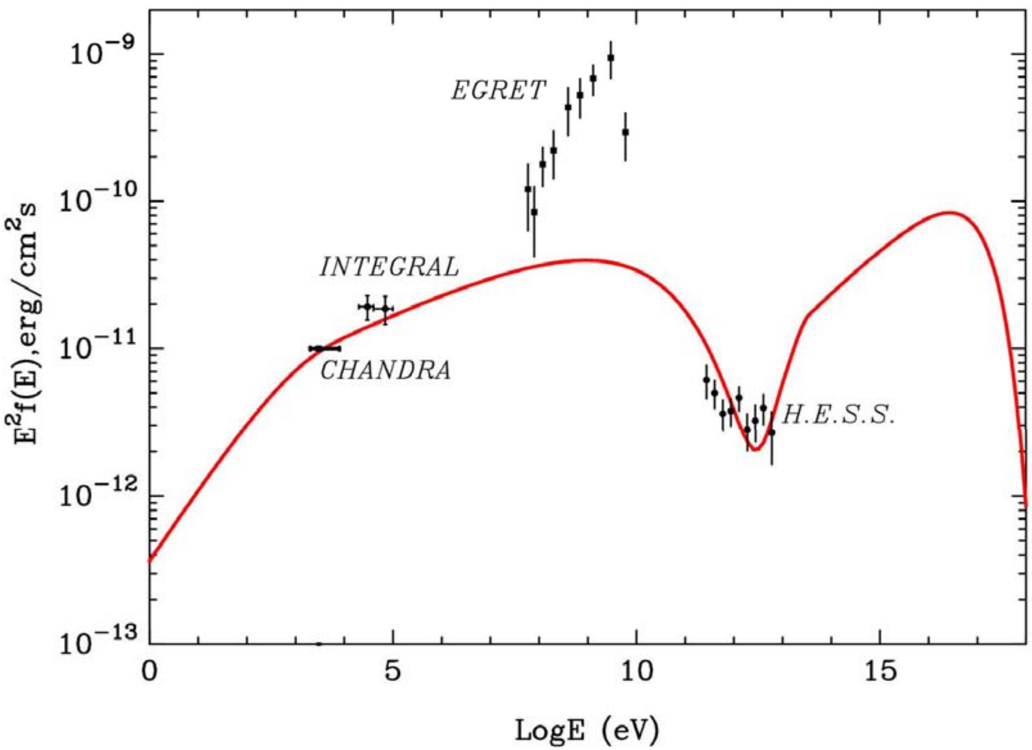
$Q_p(E)=Q_o$ $E^{-♋}$ exp(-E/1 PeV), $D(E)=10^{28}(E/1GeV)$ ♌ & cm^2/s & =1, ♌=0.5-0.6 - diffusion in GD



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

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

1. fast diffusion : ☝ →
   Lp=7.5 x 10^{37} erg/s
2. slow diffusion: ☝ → 9
   Lp=6.9
3. Diffusion-to-rectlinear prop.
   ☝→ ⟹ ♋→♌
   Lp=



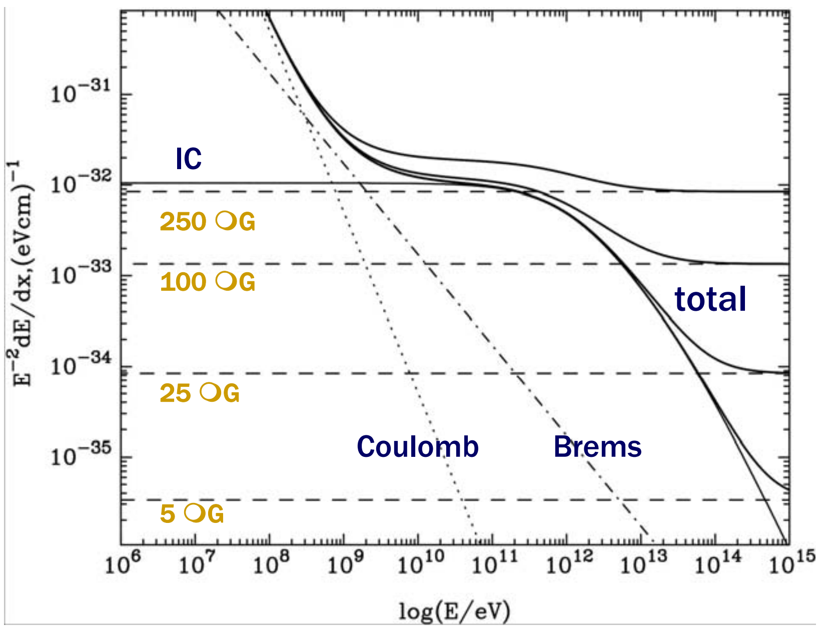
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
EGRET
INTEGRAL
CHANDRA
H.E.S.S.
0
5
10
15
LogE (eV)
$E^2f(E)$,erg/cm^{2}s

IC emission of plerionic or SNR origin*

Energy Losses of electrons in the Galactic Disk and the GC region

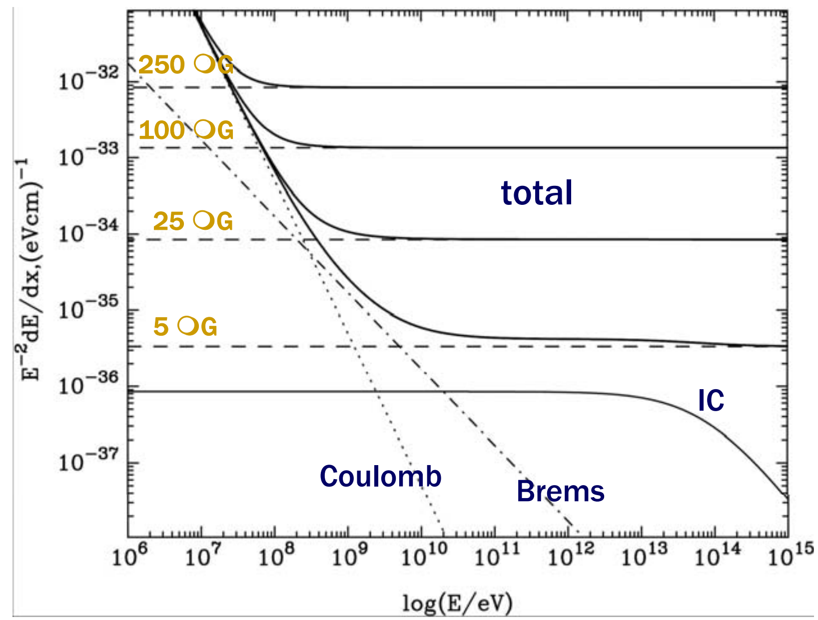
Central 1 pc region of GC

T=160K, w=2500 eV/cm^3, n=1000 cm^{-3}

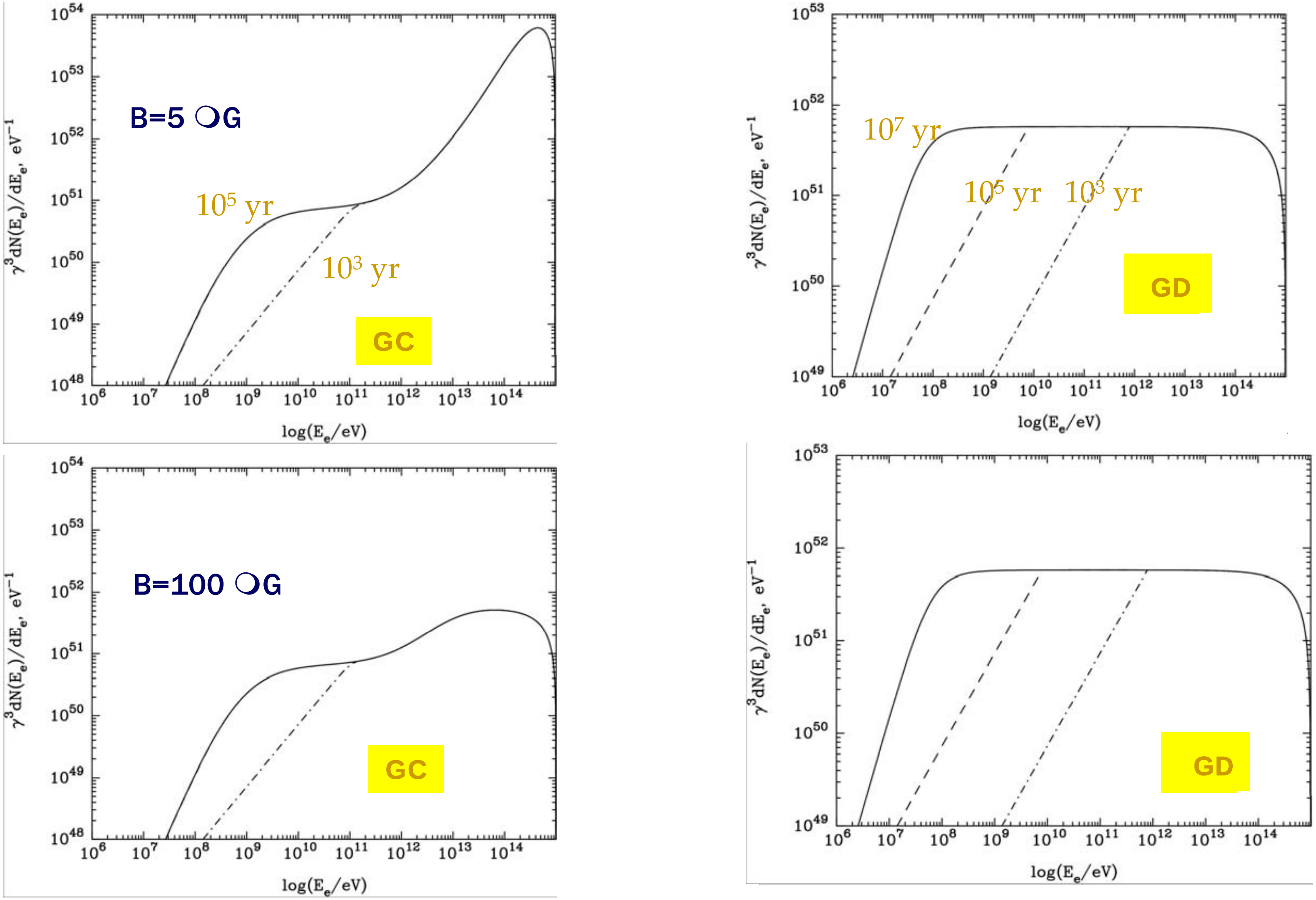


"standard" region of GD

T=2.7K, w=0.25 eV/cm^{-3}, n=1 cm^{-3}

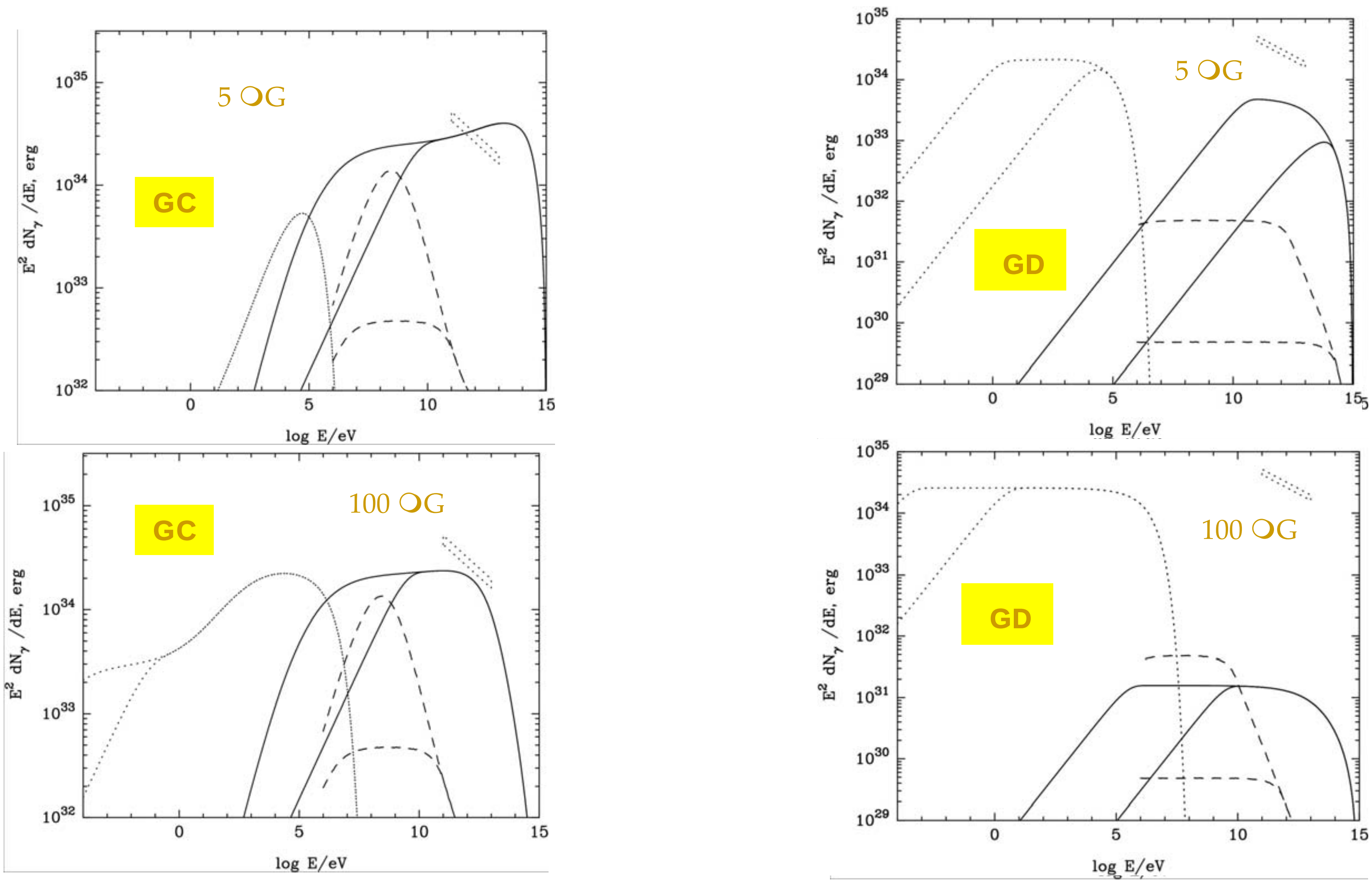


Electron spectra at different epochs in 1pc region around GC and in GD



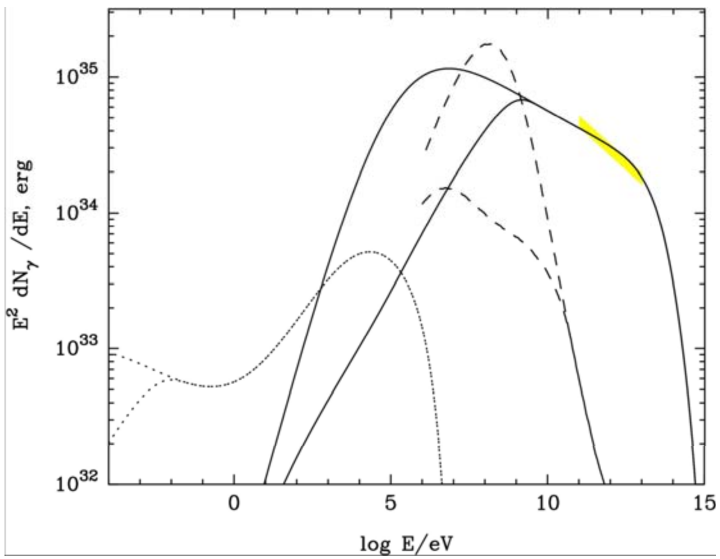
$L_e=10^{36}$ erg/s, ☝=2, E_{cut}=100 TeV

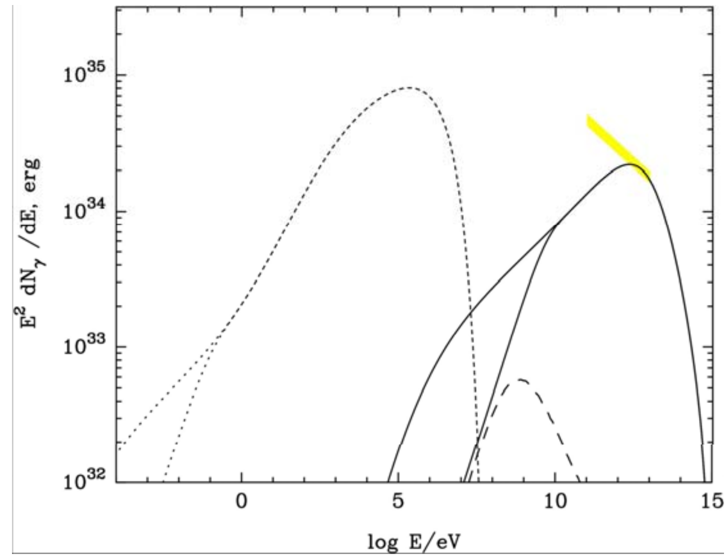
Broad-band E-M radiation from a source within 1pc of GC and in GD



$L_e=10^{36}$ erg/s, ☝=2, E_{cut}=100 TeV

Gamma Rays from GC of IC Origin ? *





Le=1.1e37 erg/s, B=25 ❍G, ☝=2.3

Le=1.2e36 erg/s, B=100 ❍G, ☝=1.6

* SNR Sgr A East or a "plerion" around Sgr A*