High energy γ-rays from SNRs
or SNR-GCR connections

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SN and GRB Remnants, KITP, SB, Feb 10, 2006

Solution of the Problem of Origin of Galactic Cosmic Rays

[*the major (historical) motivation of gamma-ray astronomy*]

remains the highest priority objective of TeV γ-ray astronomy in the context of several research areas related to high energy particle acceleraton and radiation processes in (first of all)

Shell type SNRs

as well as in Star Formation Regions/Giant Molecular Clouds, Pulsar Wind Nebulae (Plerions), Microquasars, GRB remnants ....

Origin of Cosmic Rays:

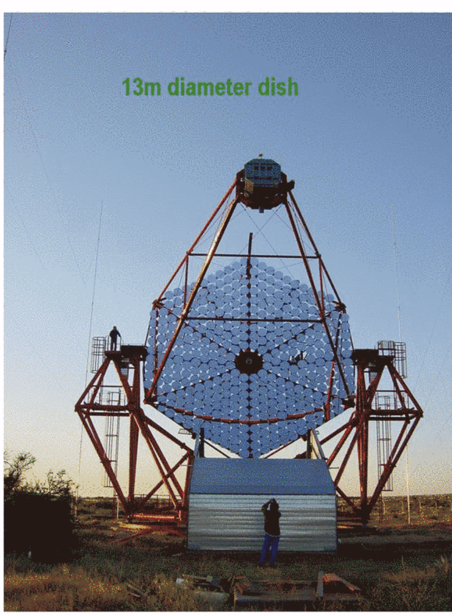
a mystery since the discovery of CRs in 1912 by V.Hess ...

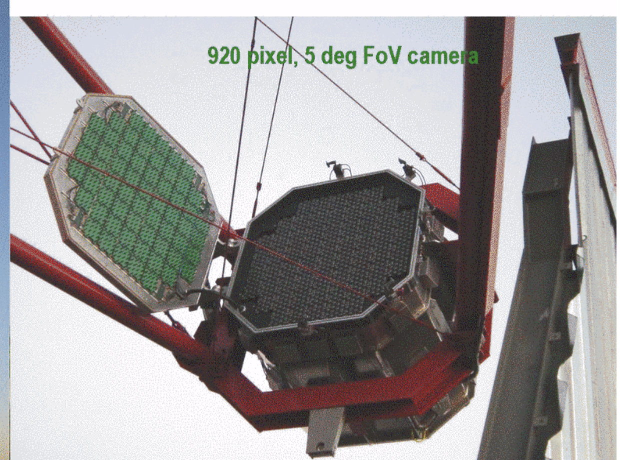
but now we are quite close (hopefully) to the solution of the (galactic) component of CRs below the energy 10^{15} eV

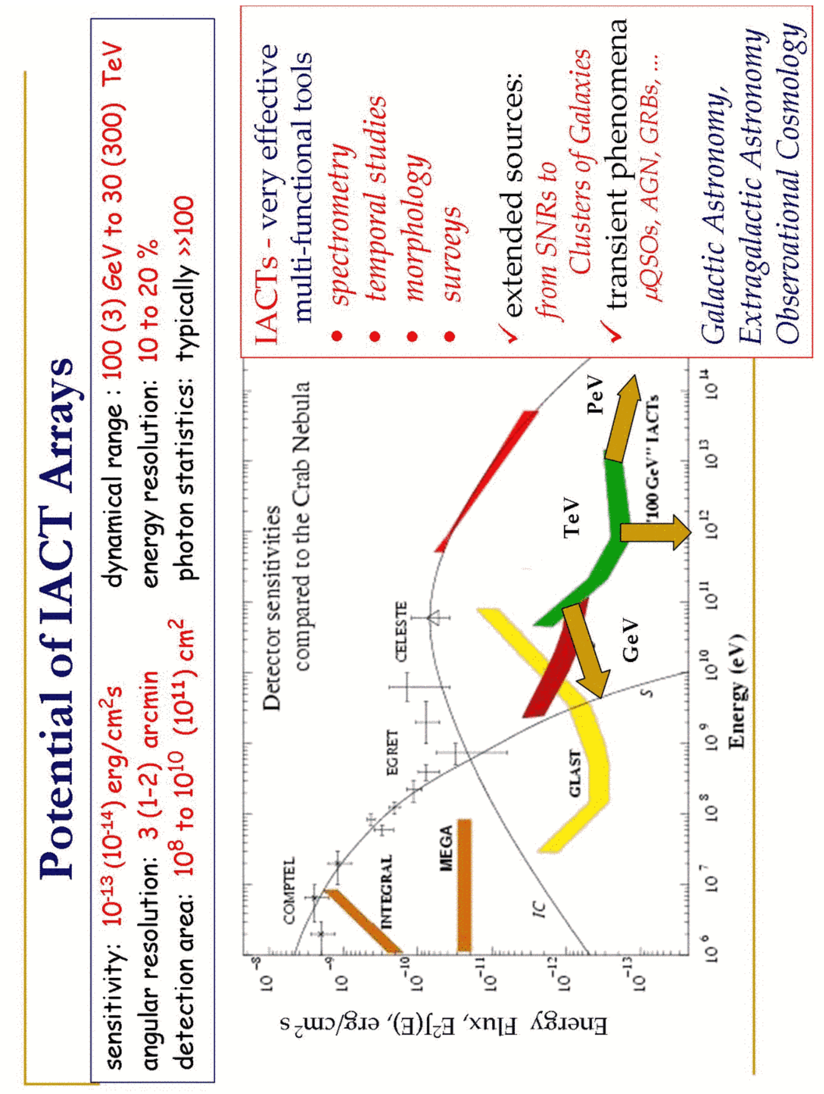
thanks to the H.E.S.S. (first important probes) and

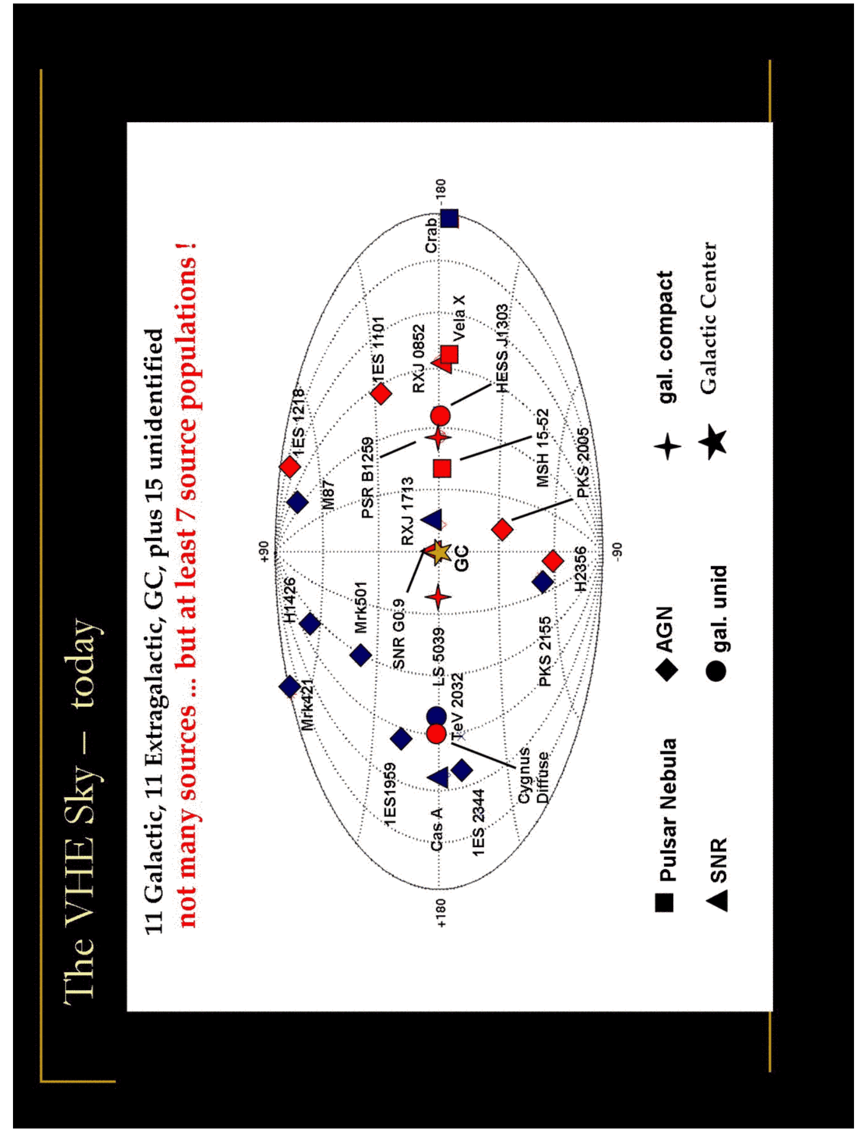
- next generation of IACT Arrays (beyond HESS)
- km3 scale neutrino telescopes (IceCube, Km3Net)
- next generation hard X-ray missions

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






Potential of IACT Arrays
sensitivity: 10-13 (10-14) erg/cm2s
angular resolution: 3 (1-2) arcmin
detection area: 108 to 1010 (1011) cm2
dynamical range : 100 (3) GeV to 30 (300) TeV
energy resolution: 10 to 20 %
photon statistics: typically >>100
Detector sensitivities
compared to the Crab Nebula
Energy Flux, E2J(E), erg/cm2 s
Energy (eV)
COMPTEL
INTEGRAL
MEGA
EGRET
GLAST
CELESTE
IC
S
GeV
TeV
PeV
"100 GeV" IACTs
IACTs - very effective
multi-functional tools
spectrometry
temporal studies
morphology
surveys
extended sources:
from SNRs to
Clusters of Galaxies
transient phenomena
μQSOs, AGN, GRBs, ...
Galactic Astronomy,
Extragalactic Astronomy
Observational Cosmology


The VHE Sky – today
11 Galactic, 11 Extragalactic, GC, plus 15 unidentified
not many sources ... but at least 7 source populations !
Crab
Vela X
RXJ 0852
HESS J1303
1ES 1101
1ES 1218
M87
PSR B1259
RXJ 1713
MSH 15-52
PKS 2005
GC
H2356
H1426
Mrk501
SNR G0.9
LS 5039
PKS 2155
Mrk421
TeV 2032
Cygnus Diffuse
1ES1959
Cas A
1ES 2344
Pulsar Nebula
SNR
AGN
gal. unid
gal. compact
Galactic Center

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 ⇒ $\lambda = 5\ (E/10\mathrm{GeV})^{-0.6}\ \mathrm{g/cm^2}$

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 extragalactic 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 ?

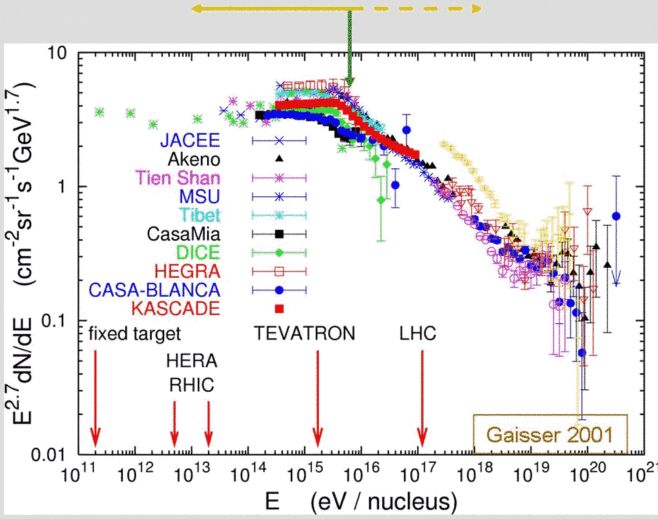
acceleration sites, source populations, acceleration mechanisms

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

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 in 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

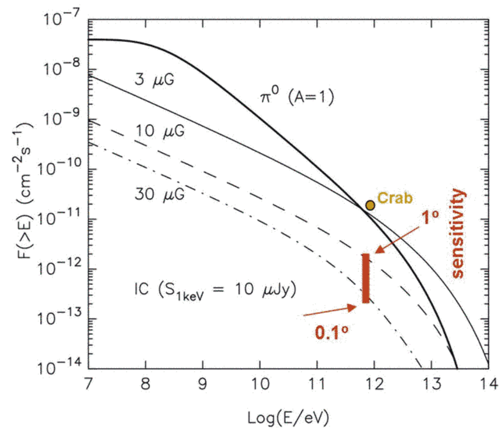
Straightforward proof: detection of gamma-rays and neutrinos from pp interactions (as products of decays of secondary pions)

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

Realization: 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 α=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)

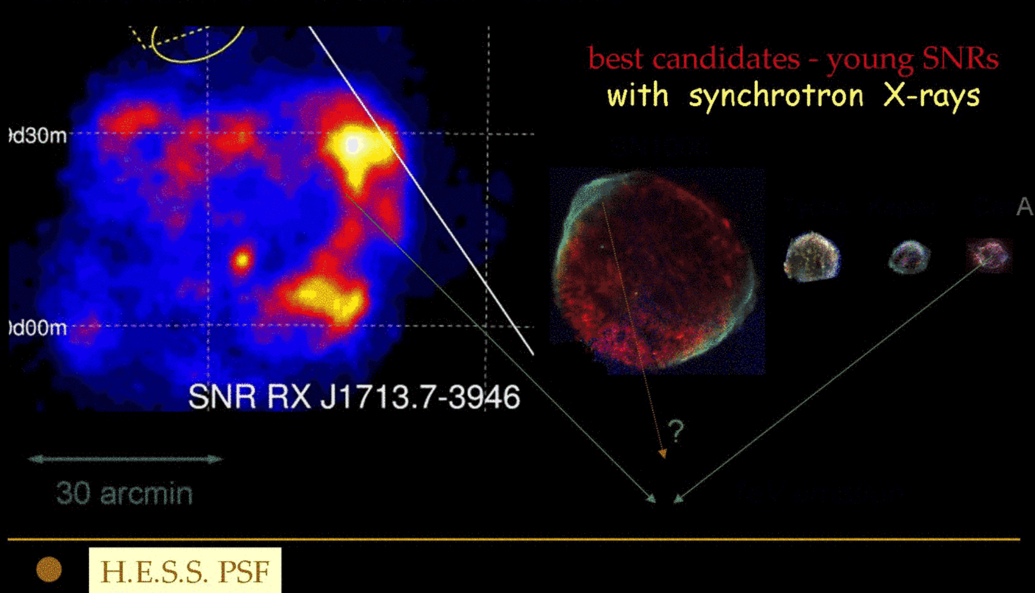
typically A: 0.1-0.01 θ: 0.1° - 1°

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 ?



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

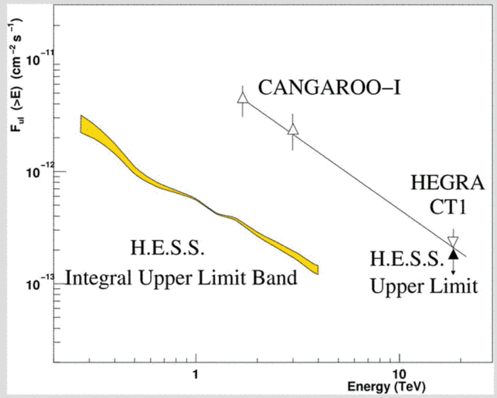
H.E.S.S. upper limits - an order of magnitude below the flux reported by CANGAROO

a trouble ? not at all ...

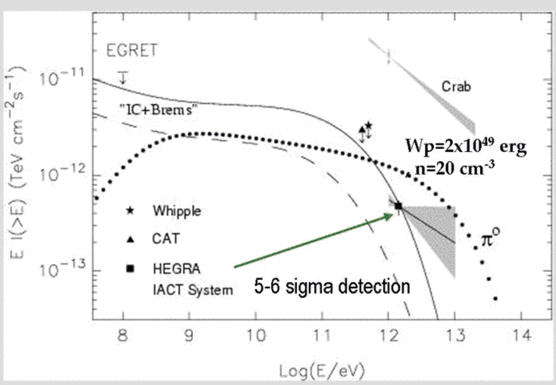
HESS upper limits imply

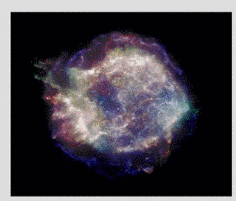
IC : B > 25 μG
π^0 : $W_p<(0.2\text{-}2) \times 10^{50}$ erg

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



Cas A – *a proton accelerator*



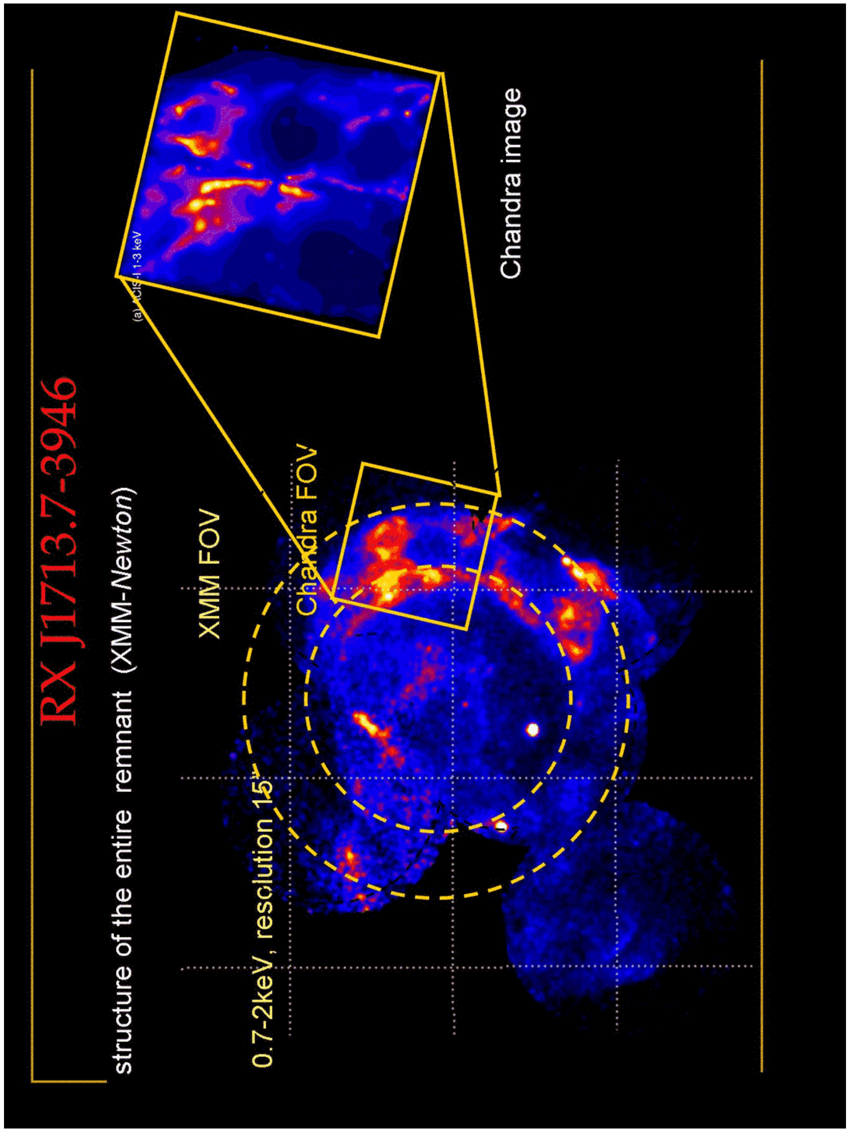


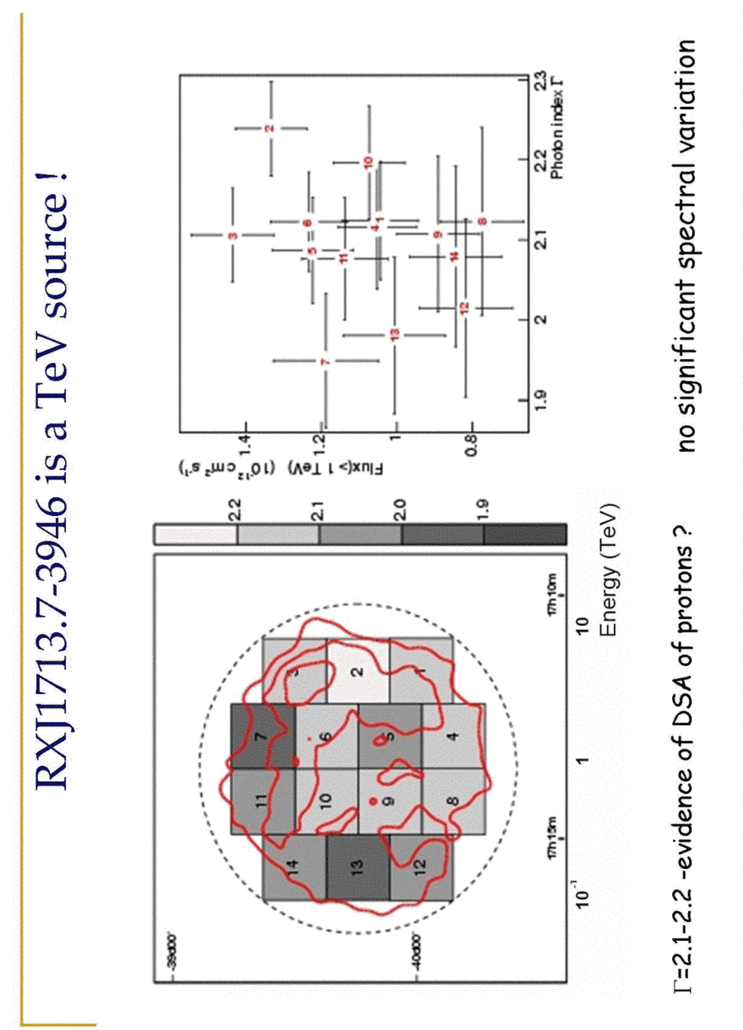
B > 0.1 mG → IC origin is unlikely;
TeV gamma rays of hadronic origin ?
yes, although Wp $=10^{49}$ erg (only)

Cas A is well designed for acceleration of protons to 10^{15} eV !
can be checked with >10 TeV γ -ray and neutrino (?) detectors

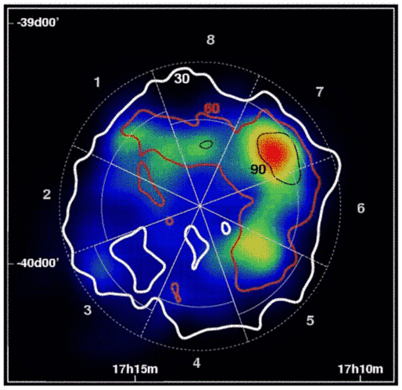
important target for VERITAS and MAGIC

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


RX J1713.7-3946
structure of the entire remnant (XMM-*Newton*)
XMM FOV
Chandra FOV
0.7-2keV, resolution 15''
Chandra image


RXJ1713.7-3946 is a TeV source !
Energy (TeV)
Photon index Γ
Flux(> 1 TeV) (10^-12 cm^-2 s^-1)
Γ=2.1-2.2 -evidence of DSA of protons ?
no significant spectral variation

RX 1713.7-3946:
interpretation



TeV-keV correlations ...
what this could mean?

the key issue - identification of γ-ray emission mechanisms: – π^0 or IC ?

new! - energy spectra 150GeV-30 TeV from different parts - *NW, S W, E,C*

coordinate-independent from 0.2 to 10 TeV difficult to explain by IC (?)

implications ?

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

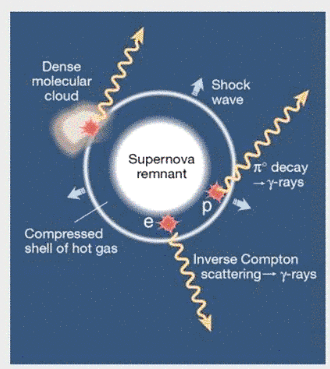
if IC - model independent estimate of We (multi-TeV electrons) Le=Lx and model independent map of B-field

Origin of radiation ?

- hadronic origin preferable given the high density environment:

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

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

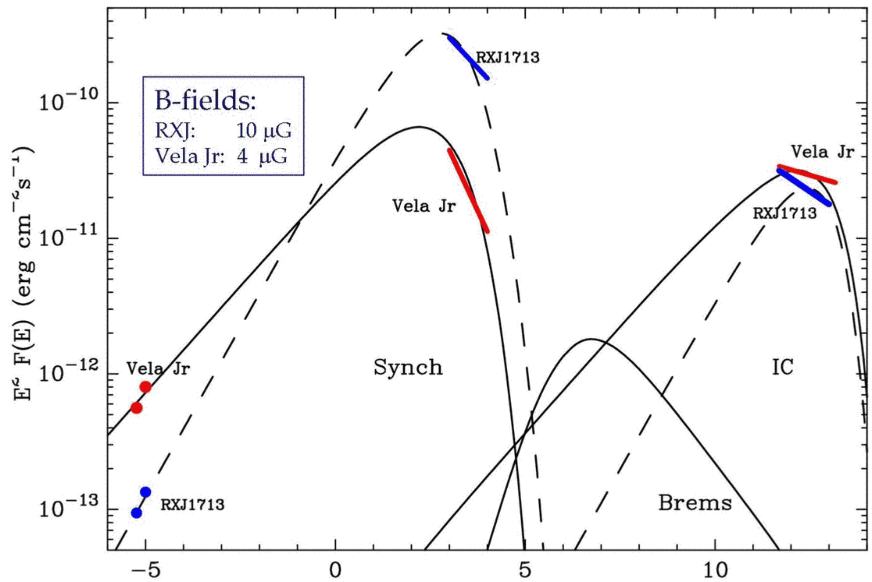


more complex scenarios ? SNR shell interacting with a dense cloud ?

if so - γ-rays from NW+SW are contributed by protons while γ-rays from remaining parts are due to IC ?

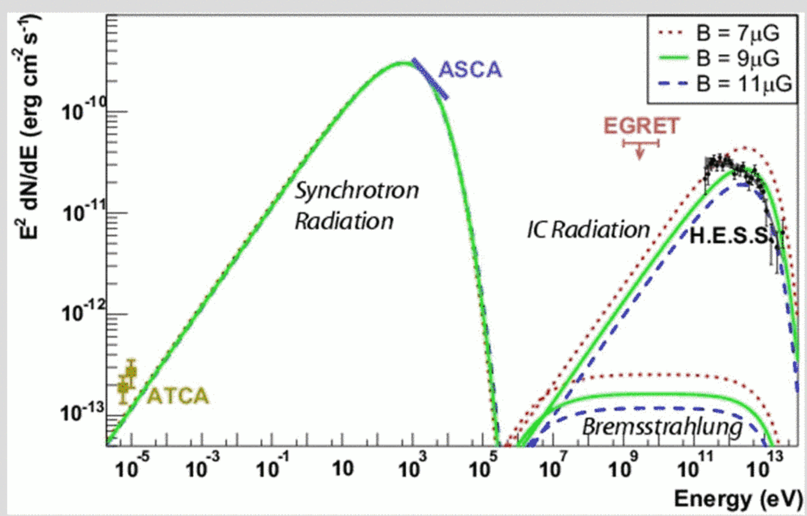
then why we do not see (significant) changes of the energy spectrum ?

Vela Junior (a 2° diameter remnant)



IC origin ? – very small B-field, $B < 10\ \mu G$, and
very large $E_{max} > 100$ TeV
two assumptions hardly can co-exists within standard DSA models

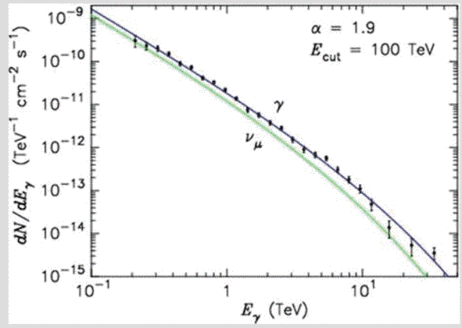
IC model: B-field cannot exceed 10 μG and ...
does not provide good spectral fit

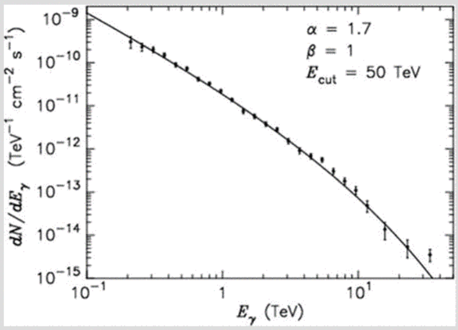


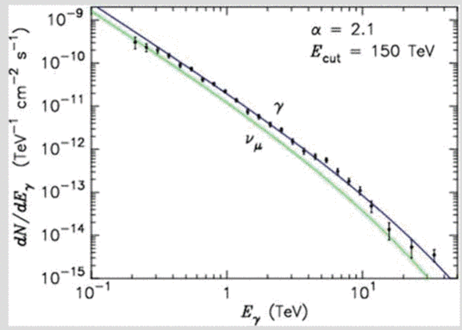
pp ⇒ π^o ⇒ γγ – perfect spectral fits, reasonable energetics !

protons:
dN/dE=K $E^{-\alpha}$ exp[-$(E/Ecut)^{\beta}$]

γ-rays:
dN/dE v $E^{-\Gamma}$ exp[-$(E/E_0)^{\beta\gamma}$]
Γw α+δα, δα w 0.1, βγ w β/2, E_0 . Ecut/20



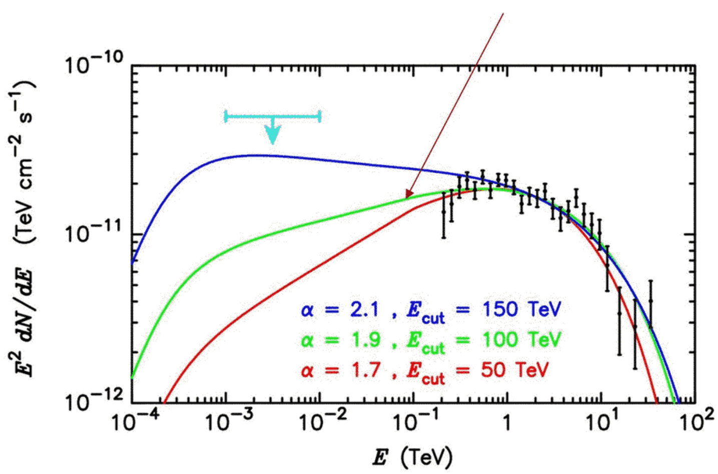




Wp(>1 TeV) w 0.5x10^{50} (n/1cm^{-3})$^{-1}$ (d/1kpc)^2

spectrum of protons ?

GLAST, HESS Phase-2



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

E_o significantly smaller than 1000 TeV ?, yes, although that could be connected with the fast escape of protons from accelerator, so RXJ 1713 still could be treated as a PeVatron

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

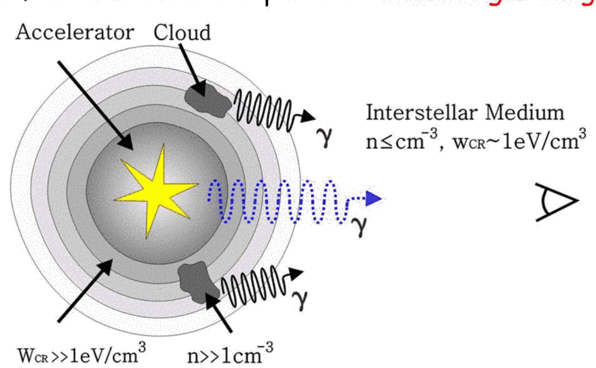
unbiased approach – deep survey of the Galactic Plane – not to miss any recent (or currently active) acceleration site:

SNRs, Pulsars/Plerions, Microquasars...

not only from accelerators, but also from nearby dense regions

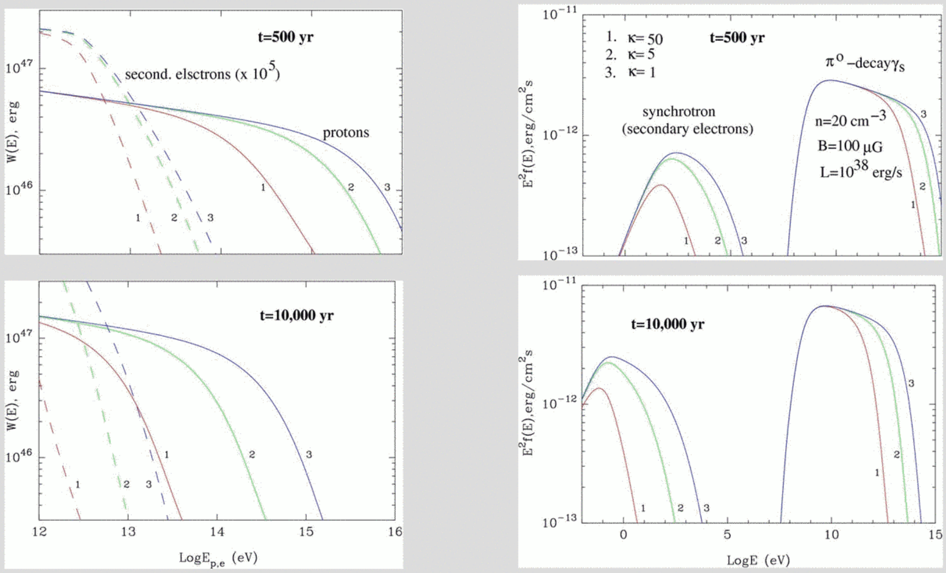
Gamm-rays/X-rays from dense regions surrounding accelerators

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 γ-ray spectrum



t_{esc}=4x10^5(E/1 TeV) $^{-1}$ κ^{-1} yr (R=1pc); κ=1 – Bohm Difussion

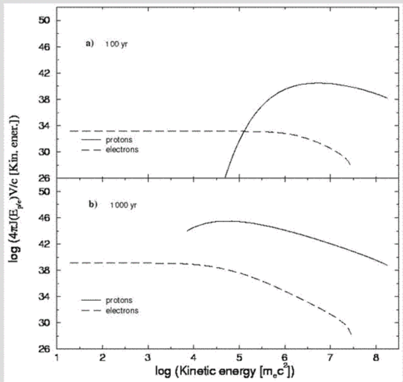
Qp / E$^{-2.1}$ exp(-E/1PeV) Lp=10^{38}(1+t/1kyr) $^{-1}$ erg/s

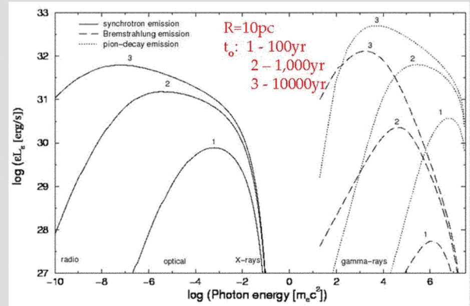
Giant Molecular Clouds (GMCs) as tracers of Galactic Coismic Rays

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 ...

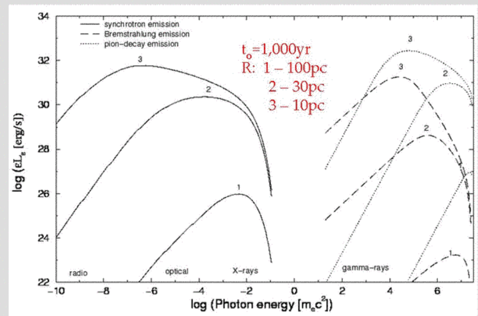




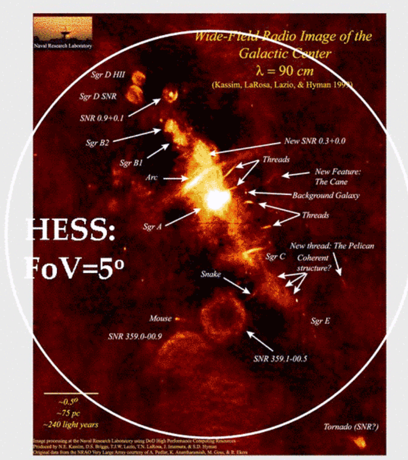
continuous accelerator
:
$Lp=10^{37}$ erg/s, α_p=2, E_{max}=100 TeV,

diff.coef. $D(E)=10^{27}(E/10GeV)^{1/2}$ cm^2/s

Cloud at a distance d=30 pc and density 10^4 cm^{-3}



TeV γ-rays from GC



GC – a unique site that harbors many interesting sources packed with un-usually high density around the most remarkable object $3x10^6$ Mo SBH – Sgr A*

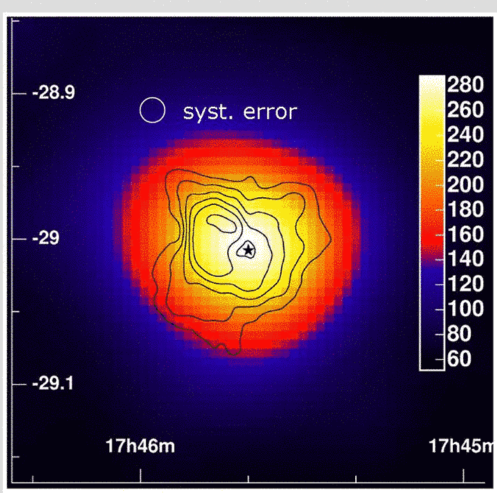
*many of them are potential γ-ray emitters - Shell Type SNRs Plerions, Giant Molecular Clouds Sgr A * itself, Dark Matter …*

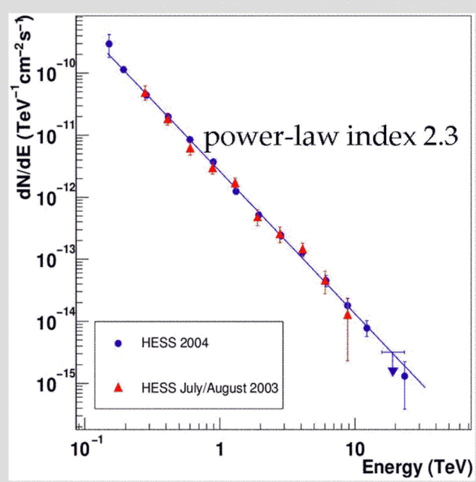
all of them are in the FoV HESS ! and can be probed down to a flux level 10^{-13} erg/cm^2 s and localized within << 1 arcmin

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

- Annihilation of DM ? mass of DM particles > 10 TeV ?
- Sgr A* : 3 10^6 M_o BH ? yes, but lack of variability …
  even the inner R < 10 Rg region is transparent for TeV γ-rays !
- SNR Sgr A East ? why not ?
- Plerionic (IC) source(s) why not ?
- Interaction of CRs with GMCs ? easily

Sagittarius A - point-like but not variable …

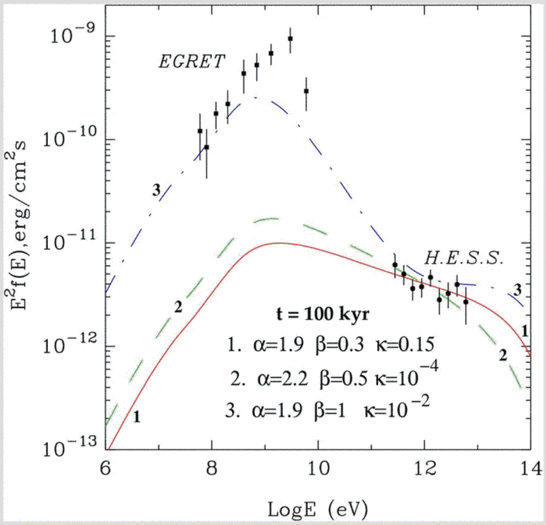




Colors: H.E.S.S.
Contours: Radio

pp gamma-rays in the central 10 pc region

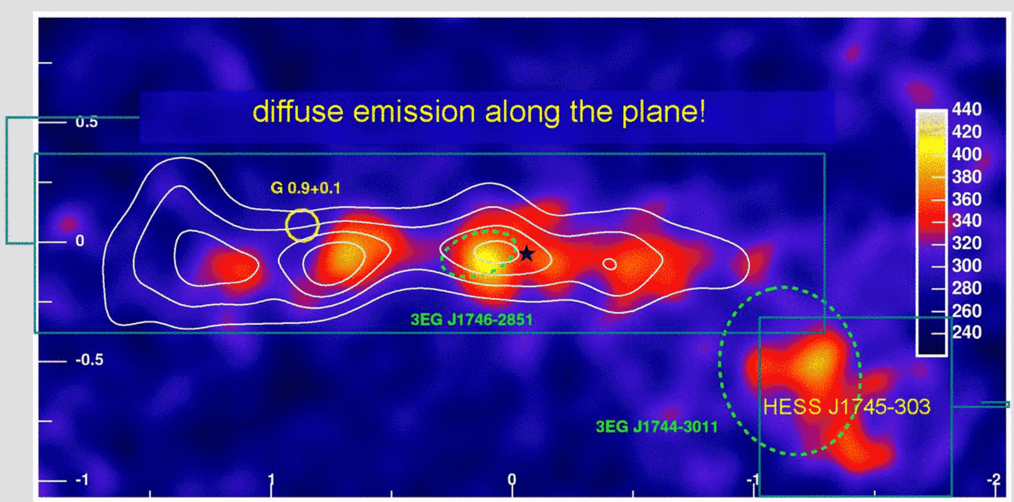
$Q_p(E)=Q_o E^{-\alpha} \exp(-E/1\ \mathrm{PeV})$, $D(E)=10^{28}(E/1\mathrm{GeV})^{\beta}\ \kappa\ \mathrm{cm^2/s}$; $\kappa=1$, $\beta=0.5$-0.6 -diffusion in GD



if $t_{pp} < t_{esc}$ => π^o-decay γ-ray production in "saturated" regime => $L\gamma = 1/3\ Lp$, otherwise the flux and spectrum of γs depend not only on CR injection power and spectrum, but also on the (energy dependent) propagation of CRs in ISM

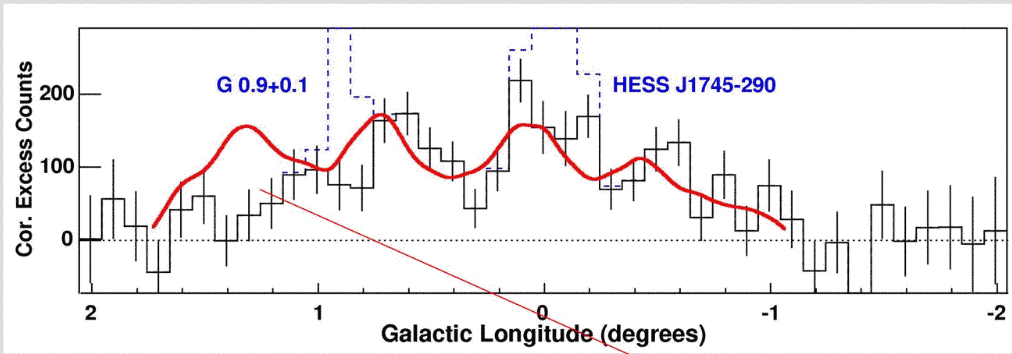
1. fast diffusion : $\Gamma \rightarrow \alpha+\beta$
   $Lp=7.5 \times 10^{37}$ erg/s
2. slow diffusion: $\Gamma \rightarrow \alpha$
   $Lp=6.9 \times 10^{36}$ erg/s
3. Diffusion-to-rectlinear prop.
   $\Gamma=\alpha+\beta \Rightarrow \Gamma=\alpha$
   $Lp=1.1 \times 10^{39}$ erg/s

Residuals after source subtraction



HESS collaboration: Nature Feb 9, 2006

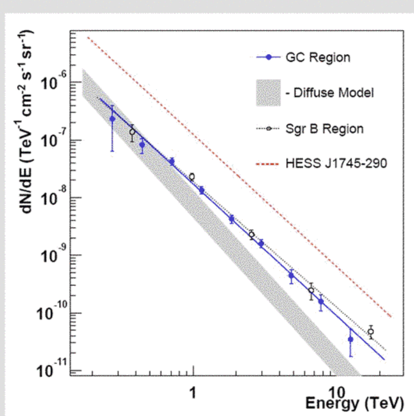
Longitudinal Slice



reasonable agreement overall but deficit around l = 1.3°

interpretation ? protons accelerated (relatively) recently in Sgr A* or Sgr A East interact with GMCs : the cloud at l=1.3° is too far

Diffuse emission from the GC ridge



Photon index 2.3

Harder CR spectrum
Compared to local CRs

Higher CR density
above 10 TeV

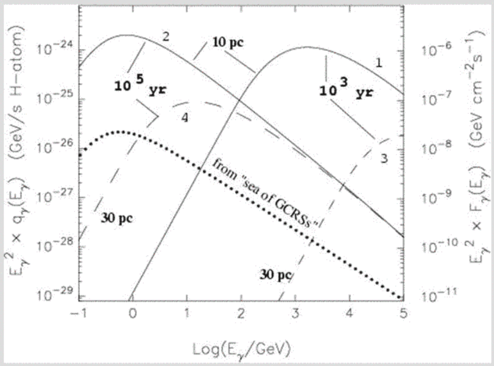
Source of CRs ?

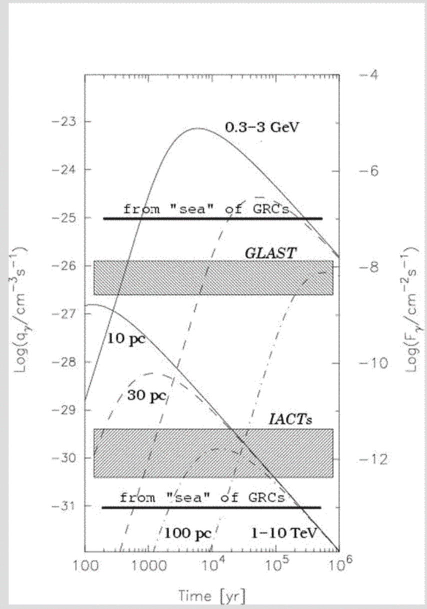
CR diffusion like in ISM –
2 to 10 kyr SNR Sgr A East

*slower diffusion – Sgr A**

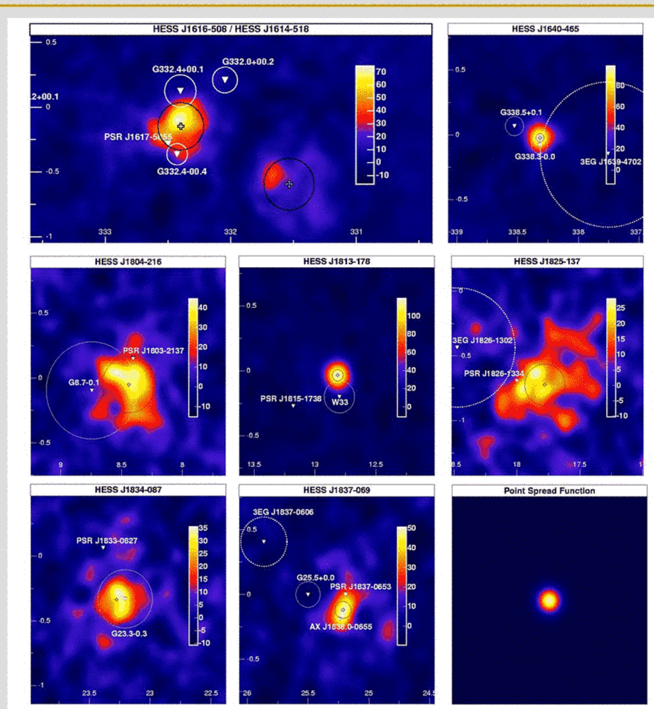
very important – detection of E > 10 TeV gamma-rays , hard X-rays, neutrinos (?)

Propagation Effects on the spectrum of Gamma Rays

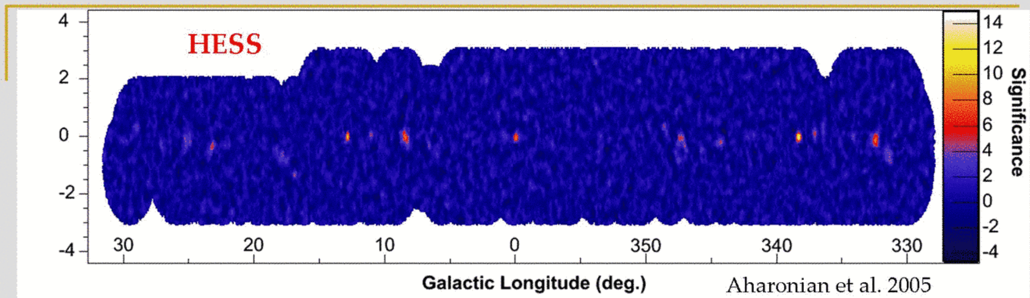


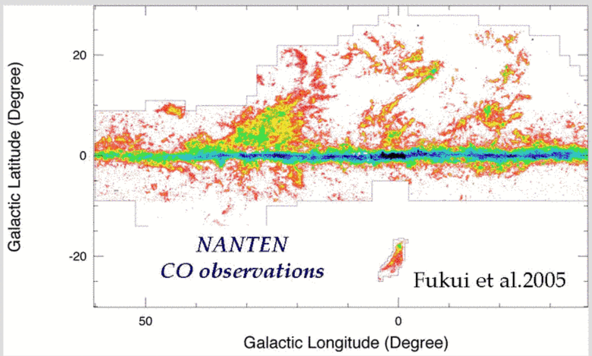


emissivities and fluxes (M_5/d^2_{kpc}) of gamma rays from a cloud at different times and distances from an impulsive accelerater with $W=10^{50}$ erg [$D(E)=10^{26}\ (E/10GeV)^{0.5}\ cm^2/s$]



unidentified HESS sources





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

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

Origin of Extended HESS TeV sources

three basic mechanisms of γ-ray production in extended sources:

characteristic timescales:

$p+p \rightarrow \pi^0 \rightarrow \gamma\gamma$	$t_{pp} = 1 \times 10^{15}\ (n/1cm^{-3})^{-1}$ sec
$e+2.7$ K $\rightarrow e\gamma$	$t_{IC} = 4 \times 10^{12}\ (E/10\ TeV)^{-1}$ sec
e-bremsstrahlung	$t_{br} = 3 \times 10^{14}\ (n/1cm^{-3})^{-1}$ sec

- IC is very effective as long as magnetic field $B < 10\ \mu G$
- Bremsstrhlung important in dense, $n > 10^2\ cm^{-3}$, environments
- pp interactions dominate over Bremsstrahlung if the ratio of energy densities of protons to electrons $w_p/w_e > 10$, and Inverse Compton component if $w_p/w_e > 500\ (n/1cm^{-3})^{-1}$ (at energies above 10 TeV)

Morphology vs. Energy Spectrum

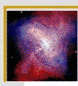
morphology: pp: depends on spatial distributions of CR and gas: $n_H(r) \times Np(r)$
IC: depends only on spatial distribution of electrons: $N_e(r)$

energy spectra: depends on acceleration spectrum Q(E), energy losses dE/dt, age of accelerator t_o, and character of propagation/diffusion coefficient D(E)

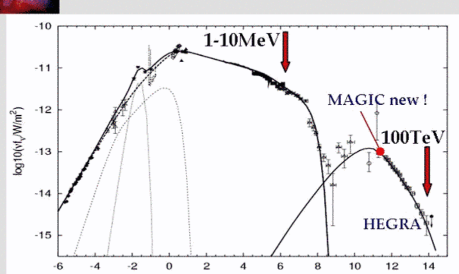
pp: generally energy spectrum independent of morphology, but for young objects energy spectrum could be harder at larger distances than near the accelerator → angular size increases with energy

IC: very important are synchrotrin energy losses;
weak B-field (<10 μG) and/or fast diffusion
→ angular size increases with energy
strong B-field (100 μG) and/or slow diffusion
→ angular size decreases with energy

irregular shapes of γ-ray images : because of inhomogeneous distrubition of gas (pp) or unisotropic propagation of cosmic rays (pp or IC)



Crab Nebula – a perfect PeVatron of electrons (and protons ?)



Standard MHD theory

cold ultrarelativistc pulsar wind terminates by a reverse shock resulting in acceleration with an unprecedented rate: $t_{acc}=\eta r_L/c$, $\eta < 100$ *)

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

Crab Nebula – a very powerful $W=L_{rot}=5\times10^{38}$ erg/s
and extreme accelerator: Ee > 1000 TeV

$E_{max}=60\ (B/1G)^{-1/2}\ \eta^{-1/2}$ TeV and $h\nu_{cut}=(0.7\text{-}2)\ \alpha_f^{-1} mc^2\ \eta^{-1} = 50\text{-}150\ \eta^{-1}$ MeV

η=1 – minimum value allowed by classical electrodynamics
Crab: $h\nu_{cut}$= 10MeV: acceleration at 1 to 10 % of the maximum rate (η=10-100)

maximum energy of electrons: E_γ=100 TeV => E_e > 100 (1000) TeV → B=0.1-1 mG
– very close the value independently derived from the MHD treatment of the wind

* for comparison, in shell type SNRs DSA theory gives $\eta=10(c/v)^2=10^4\text{-}10^5$

TeV gamm-rays from other Plerions ?

Crab Nebula is a very <u>effective accelerator</u>
but <u>not an effective IC γ-ray emitter</u>

We see TeV gamma-rays from the Crab Nebula because of
very large spin-down flux $f_{rot} = L_{rot}/4\pi d^2$

but gamma-ray flux << "spin-down flux"
because of large magnetic field

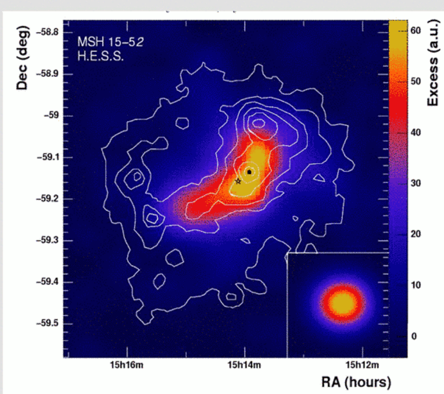
$\dot{W}_e \approx L_{rot}$ but the strength of B-field also depends on L_{rot}

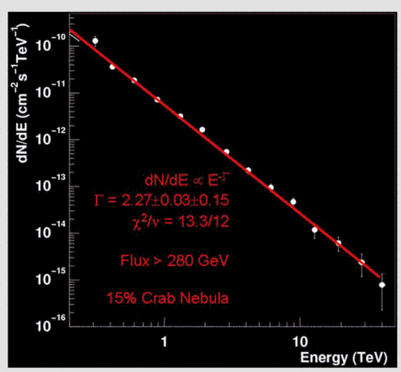
less powerful pulsar ➡ weaker magnetic field
➡ higher gamma-ray efficiency
➡ <u>detectable gamma-ray fluxes from other plerions</u>

HESS confirms this prediction ! (?)

* Plerions – Pulsar Driven Nebulae

MSH 15-52





since 2.7 K MBR is the main target field, TeV images reflect spatial distributions of electrons Ne(E,x,y); coupled with synchrotron X-rays, TeV images allow measurements of B(x,y)

the energy spectrum - a perfect hard power-law with photon index Γ=2.2-2.3 over 2 decades !

- cannot be easily explained by IC… (unless intense IR sources around)
- hadronic (π^o-decay) origin of γ-rays ?

HESS J0835-456 (Vela X) – *do we see the Compton peak ?*

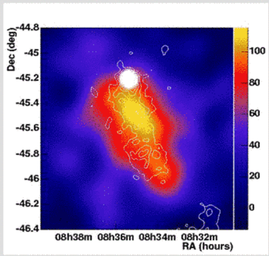
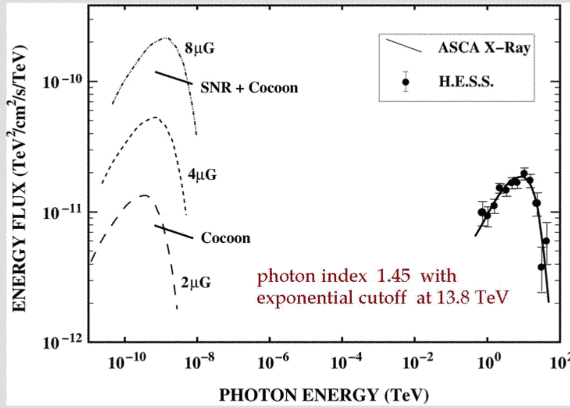


image of TeV electrons ! (?)

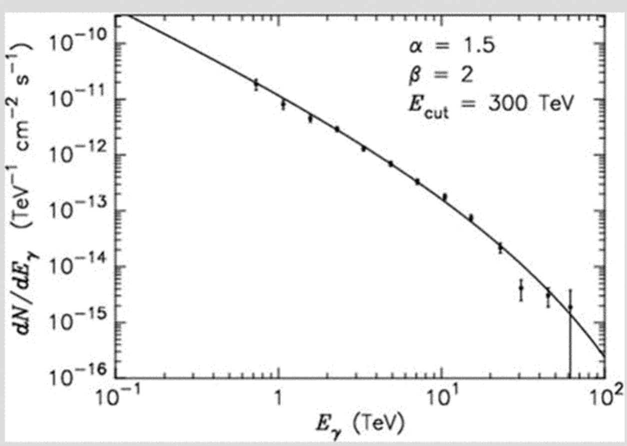
spectral index Γ=2 with a
break around 70 TeV
total energy We=2 x 10^{45} erg



questions:
B-field – as weak as several μG or even less ?
energy in ultrarelativistic electrons only 2×10^{45} erg ?
integrated energy over 11kyr: $>2.5\times10^{48}$ erg – in which form the "dark energy" is released?

low energy electrons or in ultrarelativistic protons ? (!)

Vela X as a proton PeVatron ?



for d=300 pc, n < 1cm^{-1}, Wp > 10^{49} erg – *protons from early epochs ?*

Summary:

The hunt for Galactic Cosmic Ray PeVatrons just started (HESS !)
but we need more sensitive specialized instruments above 10 TeV:

- **sensitivity ?** — **F_E => 10^{-13} erg/cm^2 s (and less) above 10 TeV**
- **realization ?** — **10 km^2 scale IACT arrays of small (<5 m diamter) IACTs**
- **timescales ?** — **short (years) - no technological challenges ***
- **efforts ?** — **relatively modest including**
- **problems ?** — **other urgent issues (super-HESS, low energy IACT arrays) and very limited resources**

TeV-PeV neutrinos — **IceCube and KM3NeT under construction !**

Hard X-rays — **complementary approch using 10-100 keV synchrotron radiation of secondary electrons from pp interactions** ***(NexT, NuSTAR, SIMBOL-X)***

Goal: *certain answers concerning the origin of Galactic CRs before 2012*