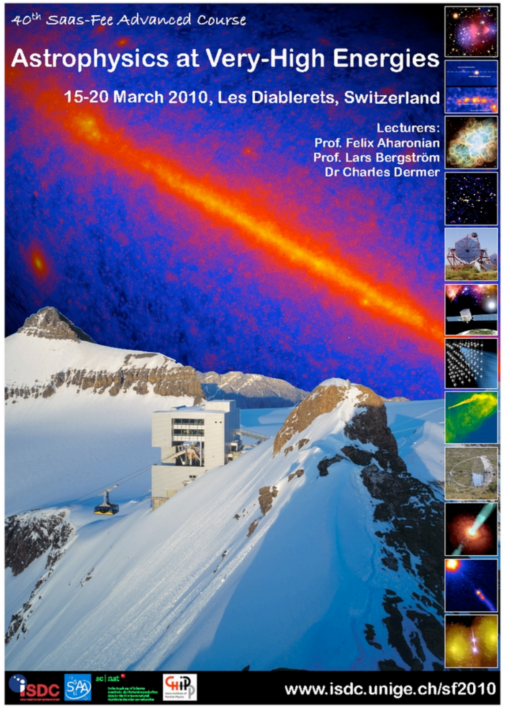
Lecture 6: Nonthermal Processes in Supernova Remnants

(and related topics)



F.A. Aharonian, *DIAS (Dublin)* & *MPIK (Heidelberg)*

Les Diablerets, March 15-20, 2010

Origin of Cosmic Galactic Rays:

a mystery since the discovery in 1912 by V. Hess … but now we are close (hopefully) to the solution of the origin of the (galactic) component below 10^{15} eV

Ground-based gamma-ray detectors

capability for deep spectrometric, morphological and temporal studies of VHE gamma-ray sources in the crucial energy band

100 GeV to 100 TeV

Fermi additional (complementary) information about the energy domain

100 MeV-100 GeV

km^3 volume scale TeV neutrino detectors

unambiguous information about hadronic omponent of CRs

1 TeV to 100 TeV

new generation imaging hard X-ray detectors

capability for deep/sensitive study of highest energy protons through synchrotron radiation of secondary ($\pi^{+/-}$-decay) electrons

10 TeV - 10 PeV

Cosmic Ray Studies with Cosmic Rays

or what do we know about Cosmic Rays?

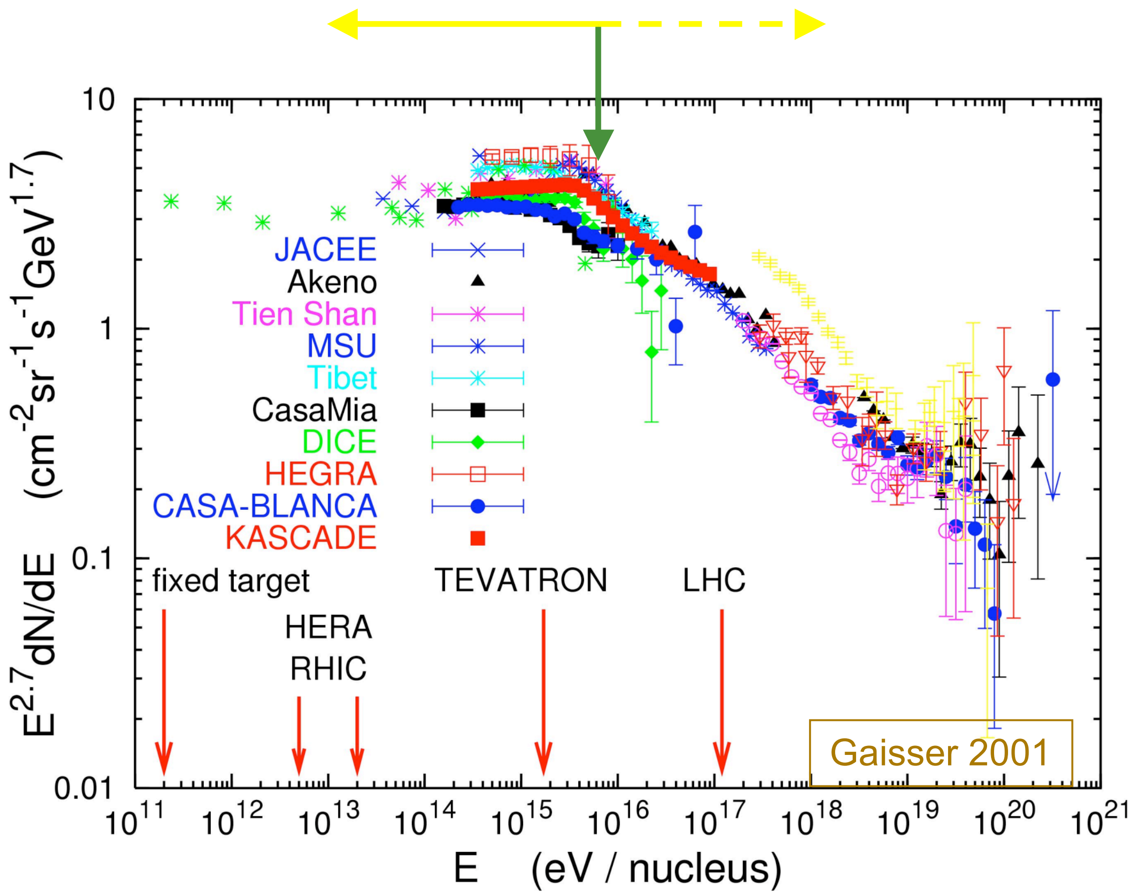
- flux is dominated by hadronic component
- energy spectrum $dN/dE = kE^{-2.6-2.7}$ up to the "knee"
- content of secondaries: $\lambda = 5\ (E/10\mathrm{GeV})^{-0.6}\ \mathrm{g/cm^2}$

source (acceleration) spectrum close to $E^{-2.0-2.1}$

CR production rate in the Galaxy 3×10^{40} erg/s

because of deflections in ambient random magnetic fields the information about production sites is lost …nevertheless there is little doubt that up to (at least) 10^{15} eV Cosmic Rays have galactic origin

Galactic PeVatrons – particle accelerators responsible for Cosmic Rays with energies up to 10^{15} eV



SNRs ?

Pulsars/Plerions ?

OB, W-R Stars ?

Microquasars ?

Galactic Center ?

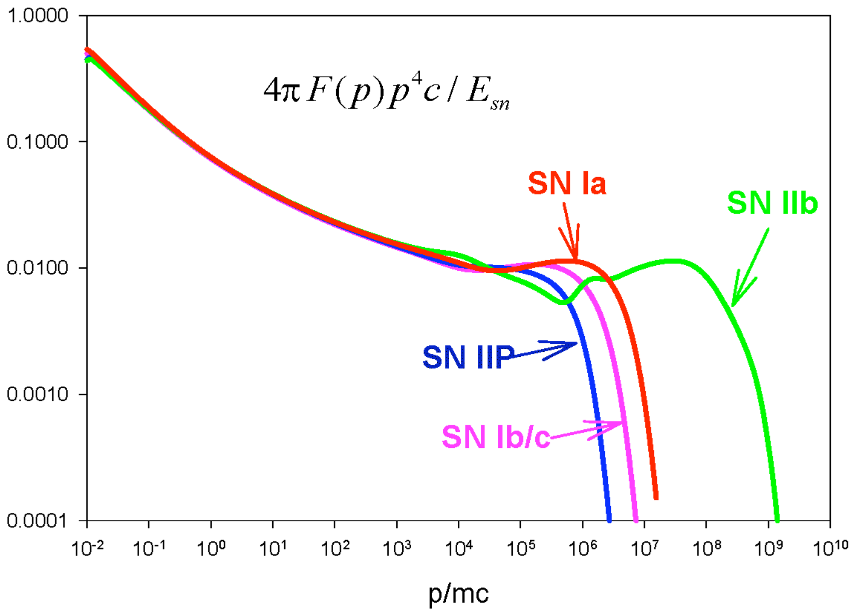
. . .

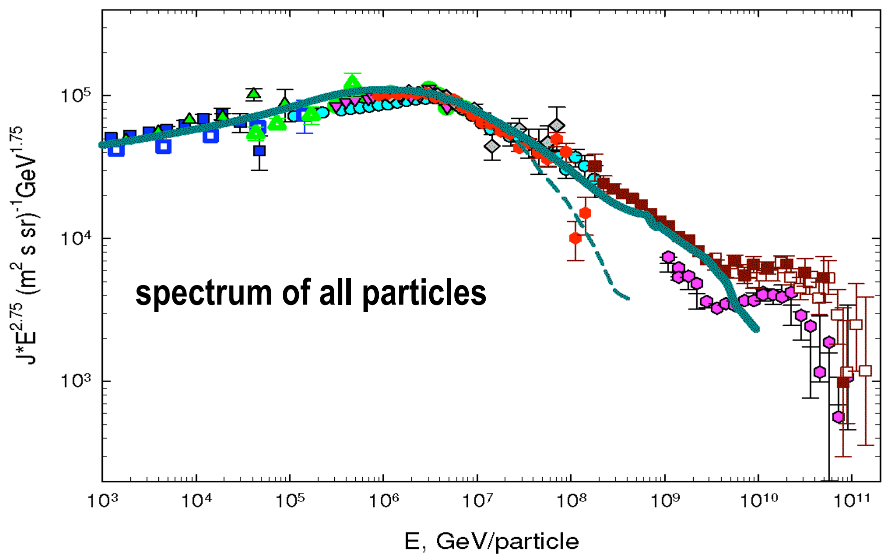
* the source population responsible for the bulk of GCRs are PeVatrons ?

empirical escape length $X_e = 11.8\beta\left(p/4.9Z\ \mathrm{GV}\right)^{-0.54}\ \mathrm{g/cm^2}$ at $p/Z > 4.9$ GV

Jones et al 2001

calculated interstellar spectra (normalized at 10^3 GeV)





data from ATIC 1/2, Sokol, JACEE, Tibet, HEGRA, Tunka, KASCADE, HiRes and Auger experiments

SNRs – the most probable factories of GCRs ?

(almost) a common belief based on two arguments:

- necessary amount of available energy – 10^{51} erg
- Diffusive Shock Acceleration (DSA) – > 10% efficiency and E^{-2} type spectrum to very high energies

but…

(i) DSA theory cannot provide robust predictions concerning the conversion efficiency
(ii) for acceleration of particles to 10^{15}eV, the acceleration efficiency should exceed 100%

SNRs – the most probable factories of GCRs ?

straightforward proof: detection and identification of gamma-rays, neutrinos and hard X-rays from p-p interactions (as products of decays of secondary neutral and charged pions)

objective: (i) to probe the content of nucleonic component of CRs in SNRs at d < 10kpc at the level 10^{49} -10^{50} erg, and (ii) to demonstrate that at least in some SNRs particles are accelerated to 10^{15} eV

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

crucial energy domains: γ: up to 100+ TeV

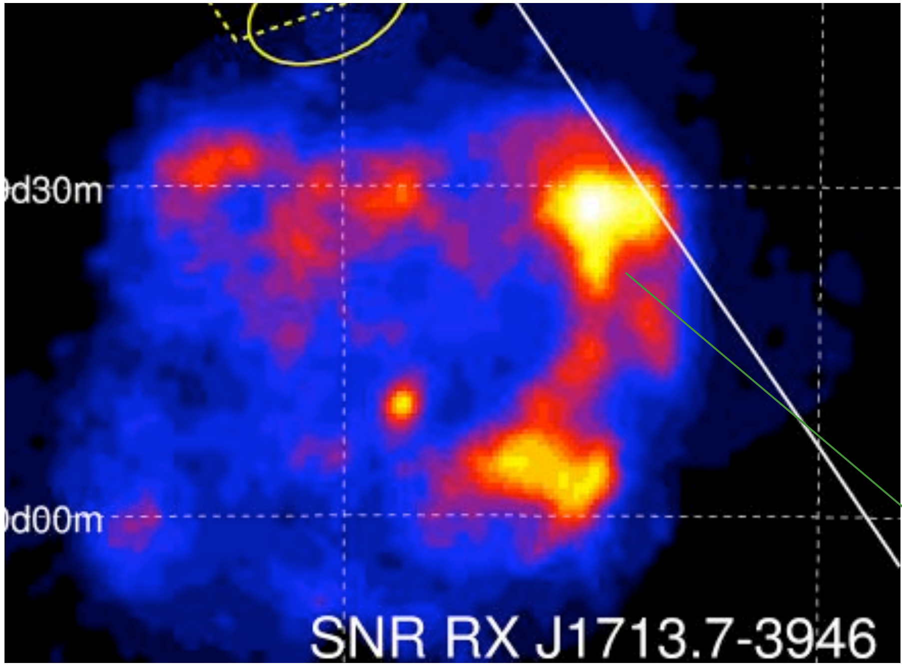
ν: 1 - 100 TeV

X: 10 - 100 keV

SNRs as Cosmic Ray Accelerators - TeVatrons !

SNRs in our Galaxy: more than 230 (Green et al. 2001)

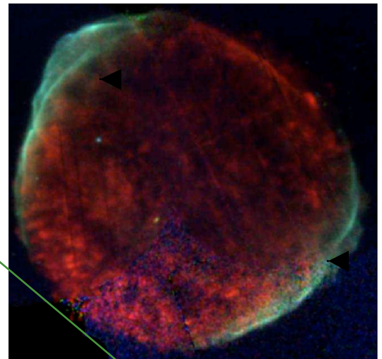
with nonthermal X-ray emission - 10 or so



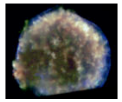
30 arcmin

best candidates - young SNRs with nonthermal synchrotron X-rays

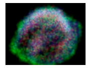
SN1006



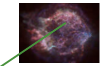
Tycho



Kepler



CasA

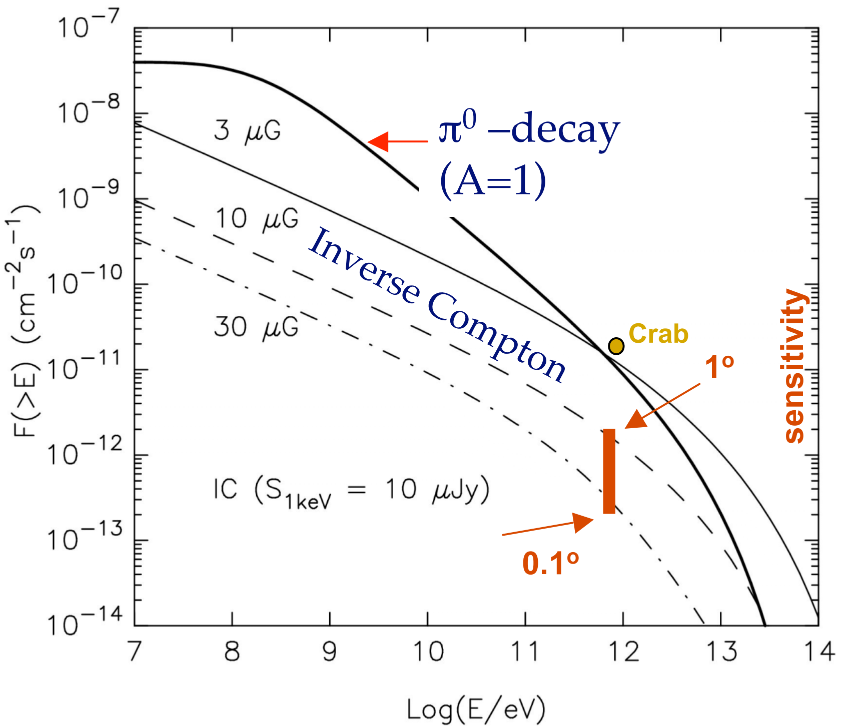


TeV γ-ray emission

synchrotron X-rays - presence of multi-TeV electrons,

but only TeV γ-rays provide mode-independent evidence

Visibility of SNRs in high energy gamma-rays



for CR spectrum with α=2

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

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

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

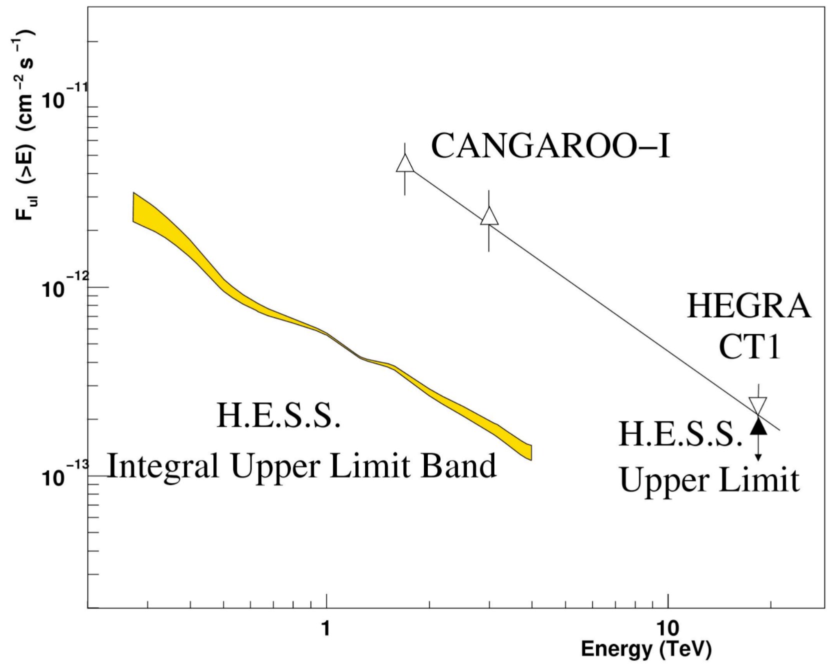
π^o component dominates if A > 0.1 $(S_x/10\ \mu J)(B/10\ \mu G)^{-2}$

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

SN 1006 - a potential TeV gamma-ray source

claim of detection of quite high TeV gamma-ray flux by CANGAROO (mid 90s)
=> excitements and hopes, but instead …. the H.E.S.S. shocking upper limits

although no problem for the hypothesis of SNR origin of Galactic Cosmic Rays - to some extent just opposite; the reported TeV fluxes were uncomfortably high…



On the other hand there were all reasons to believe that SN1006 should be a TeV γ-rays source … "heroical" effort of HESS finally resulted to clear detection of TeV emission

SN 1006 is a TeV gamma-ray source: HESS 2003-2008, t~100h

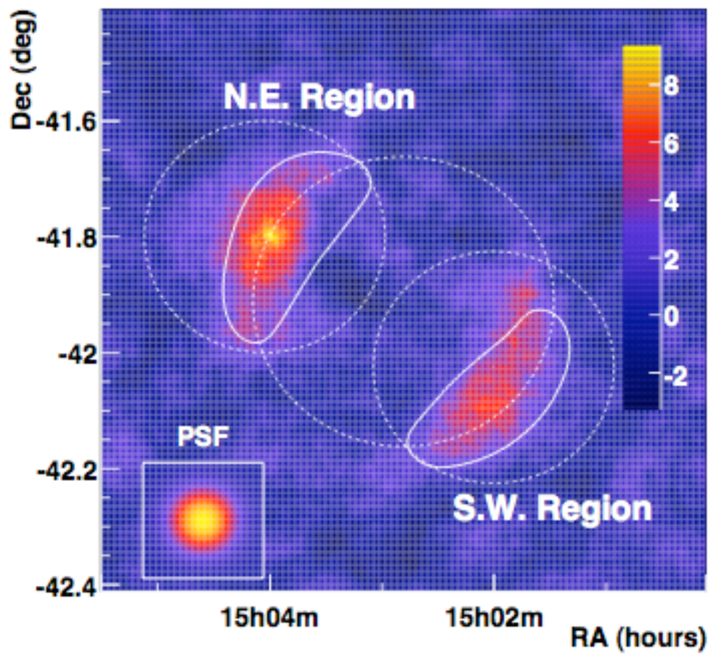


Fig. 1. *H.E.S.S. γ-ray significance map of SN 1006 using an integration radius of 0.05°. The linear colour scale is in units of standard deviations. The white solid contours correspond to the regions which contain 80% of the non-thermal X-ray emission from the XMM-Newton flux map in the 2 - 4.5 keV energy range after smearing with the H.E.S.S. PSF, shown in the inset. The white dashed circles correspond to the regions that are excluded from background determination.*

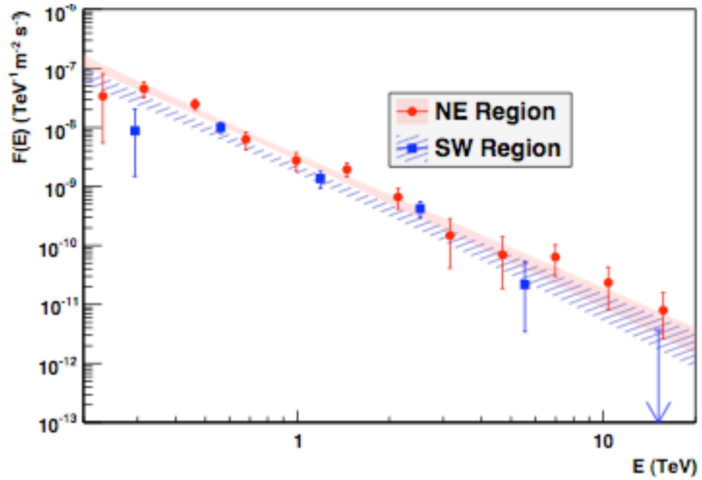
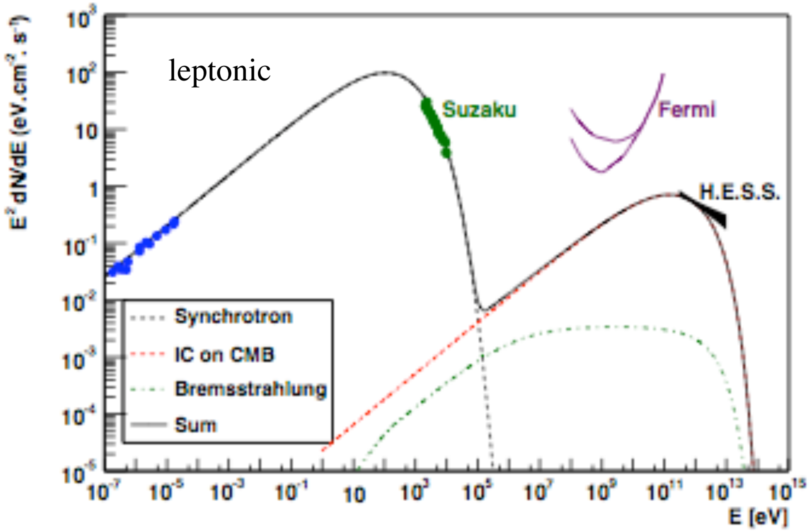
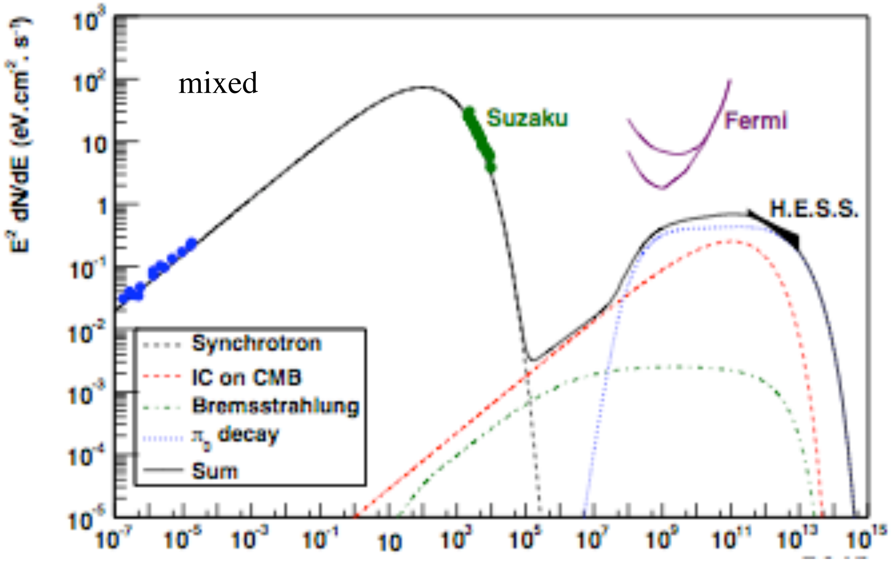
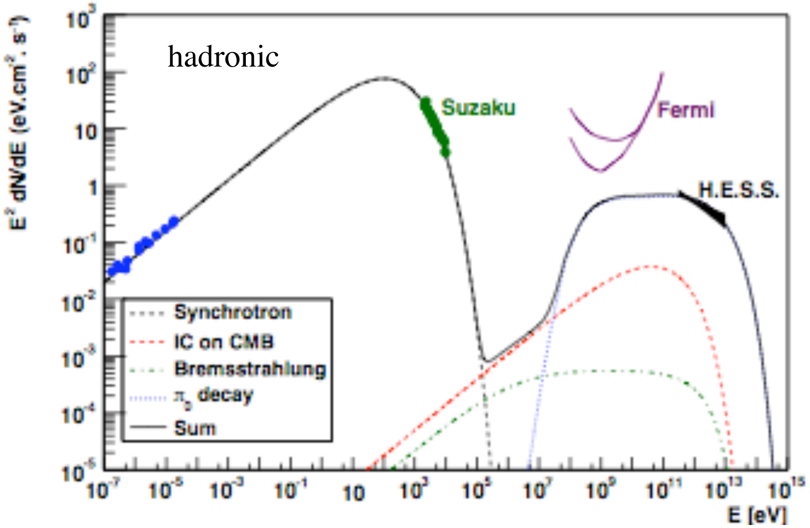


Fig. 7. *Differential energy spectra of SN 1006 extracted from the two regions NE and SW as defined in Section 2. The shaded bands correspond to the range of the power-law fit, taking into account statistical errors.*

Region	photon index Γ	$\Phi(> 1\mathrm{TeV})$ $(10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1})$
NE	$2.35 \pm 0.14_{stat} \pm 0.2_{syst}$	$0.233 \pm 0.043_{stat} \pm 0.047_{syst}$
SW	$2.29 \pm 0.18_{stat} \pm 0.2_{syst}$	$0.155 \pm 0.037_{stat} \pm 0.031_{syst}$







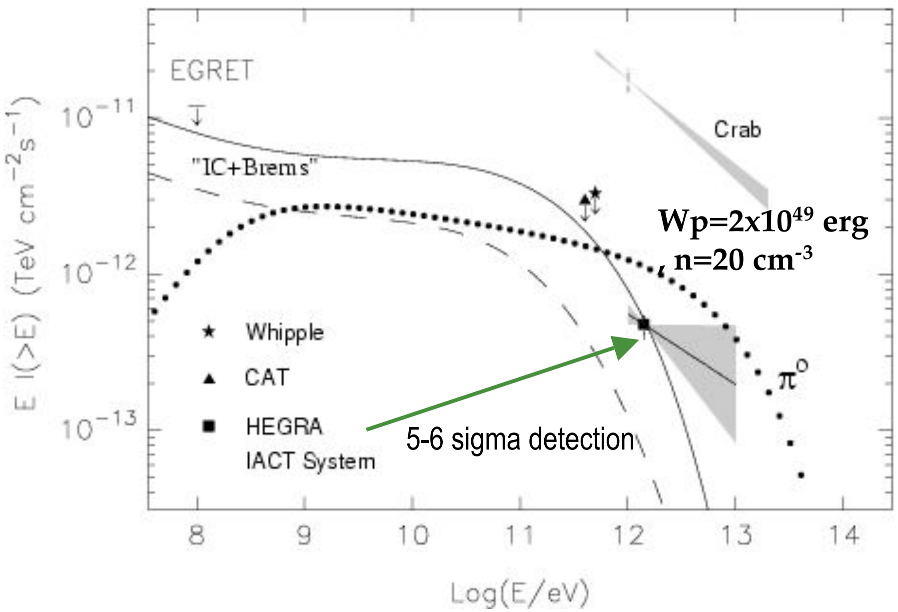
Model	$E_{cut,e}$ [TeV]	$E_{cut,p}$ [TeV]	W_e [10^{47}erg]	W_p [10^{50}erg]	B [μG]
Leptonic	10	-	3.3	-	30
Hadronic	5	80	0.3	3.0	120
Mixed	8	100	1.4	2.0	45

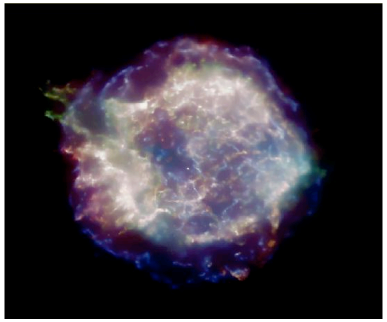
α_p=2; α_e=2.1

one-zone model

HESS collaboration, A&A, 2010 (in press)

Cas A – *a proton accelerator ?*





γ(100MeV)/radio => B > 0.1 G

IC origin is unlikely

TeV gamma-rays of hadronic origin ?

yes, but $W_p(>1\text{TeV}) = 10^{49}$ erg and very small proton/electron ratio (<10)

Cas A is well designed to operate as a PeVatron ?

with a "right" combination of B-field, shock speed and age to accelerate and confine particles up to 1 PeV - a source of >1TeV gamma -rays and neutrinos?

- very important target for VERITAS and MAGIC
- GLAST should detect GeV gamma-ray emission in any case
- no way to detect TeV neutrionos even with km^3 scale detectors

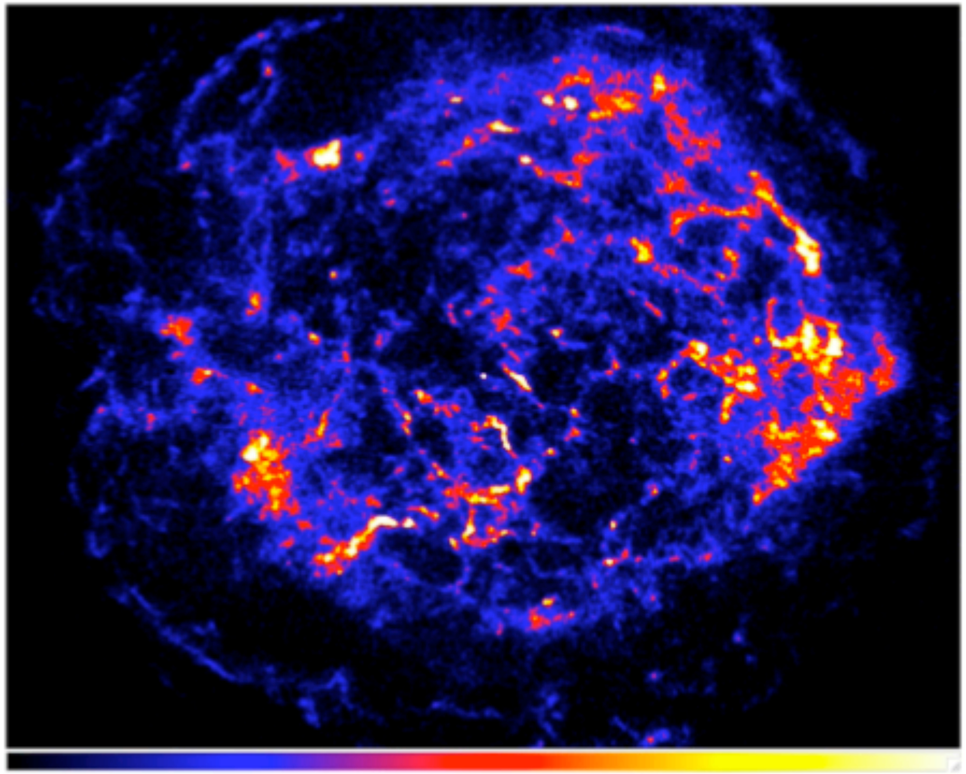
Cassiopeia A: Variable Filaments

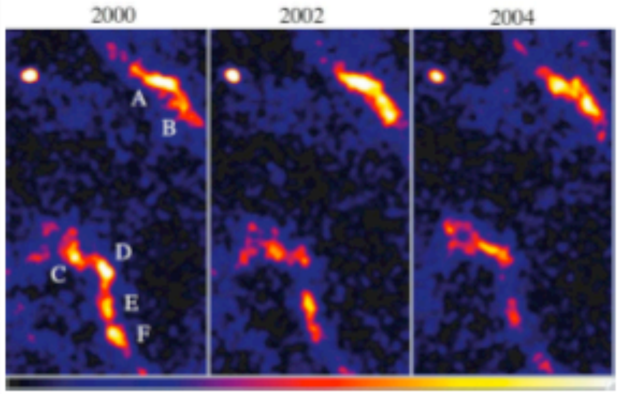
Continuum (4-6 keV) year-scale variability

thermal bremsstrahlung from shock-heated ejecta

\+ **synchrotron** component: knots/filaments brightening/decaying 10%/yr

(Uchiyama & Aharonian 2008)





Chandra Observations in 2000, 2002, and 2004

see also Patnaude & Fesen 2009

Cas A: Magnetic Field Strength

Synchrotron X-ray Variability gives a new probe of B-field in SNRs.

(Uchiyama & Aharonian 2008)

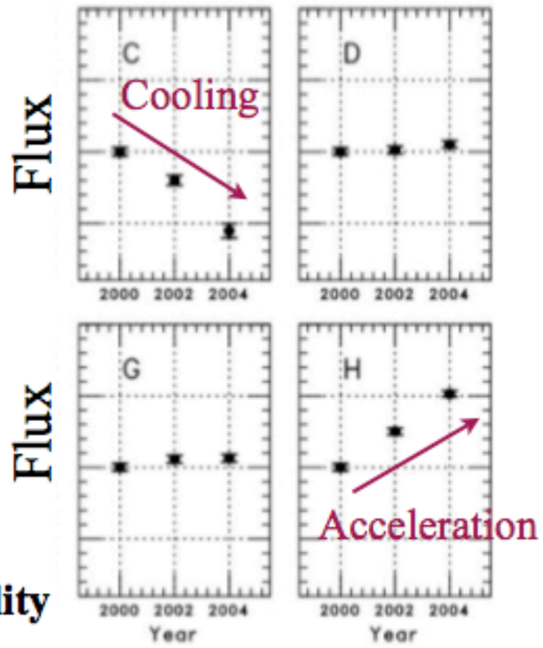
Decaying = Synchrotron Cooling

$$t_{\rm sync} \sim 1.5 \left(\frac{B}{\rm mG}\right)^{-1.5} \left(\frac{\epsilon}{\rm keV}\right)^{-0.5} \text{ year} \longrightarrow \text{B} \sim 0.5 \text{ mG}$$

Brightening = Acceleration of Fresh Electrons

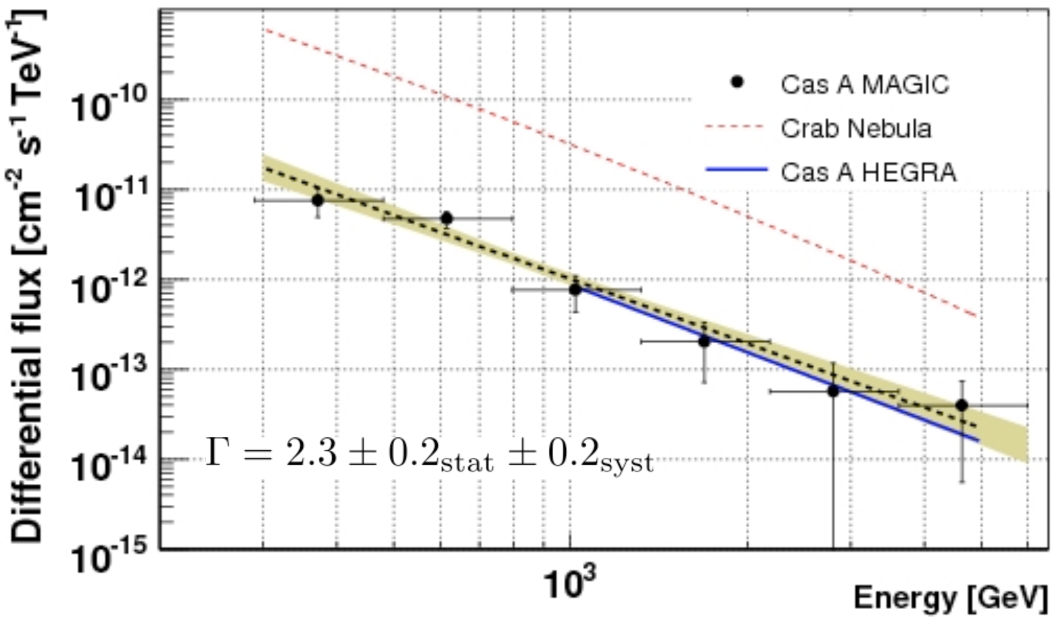
Fermi Acceleration Theory

$$t_{\rm acc} \sim 1\ \eta \left(\frac{B}{\rm mG}\right)^{-1.5} \left(\frac{\epsilon}{\rm keV}\right)^{0.5} \left(\frac{V_s}{3000\ {\rm km\ s^{-1}}}\right)^{-2} \text{ years}$$



NOTE:
radio synchrotron shows much slower variability
→ B-field change alone cannot explain the variability

recent news from Magic

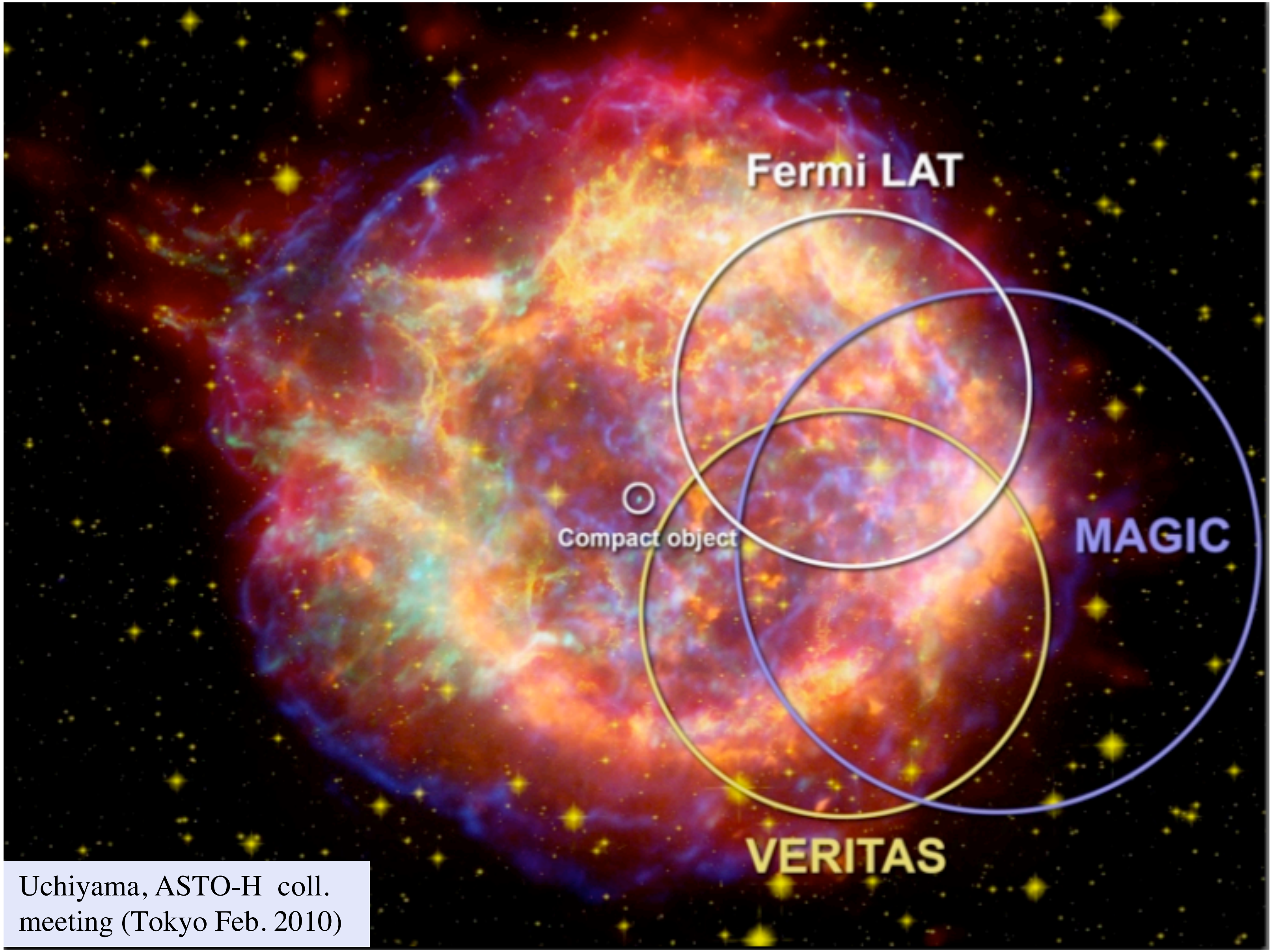


$E^{-\alpha}$ exp(-E/Eo) type proton spectrum with (i) α=2 and cutoff energy Eo <10 TeV
or (ii) α=2.3 (or so) and Eo >> 10 TeV

implications?

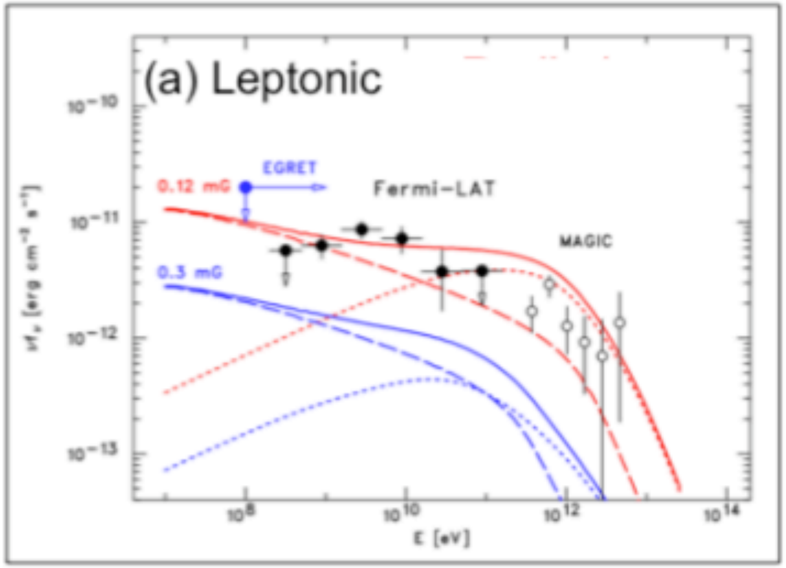
(i) protons are not accelerated to > 10 TeV energies despite large B and v_{shock}
(ii) total energy in protons (down to 1 GeV) close to 10^{50} erg (as expected)

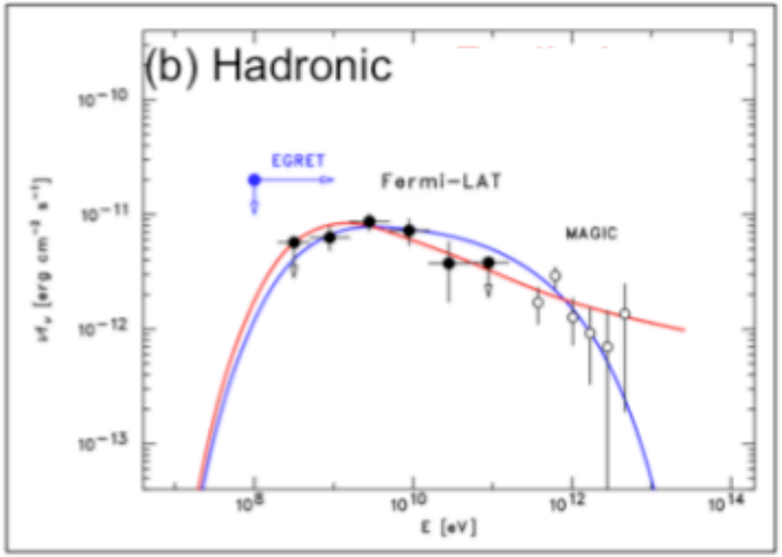
obseravations with VERITAS/MAGIC and GLAST will soon tell us a lot about Cas A



Uchiyama, ASTO-H coll. meeting (Tokyo Feb. 2010)

Cas A Spectrum





(a) Leptonic (Bremsstrahlung + IC)

B = 0.12 mG

CR electron: $W_e = 1 \times 10^{49}$ erg

(b) Hadronic (π^0 decay)

B > 0.12 mG

CR proton: $W_p = 5 \times 10^{49}$ erg

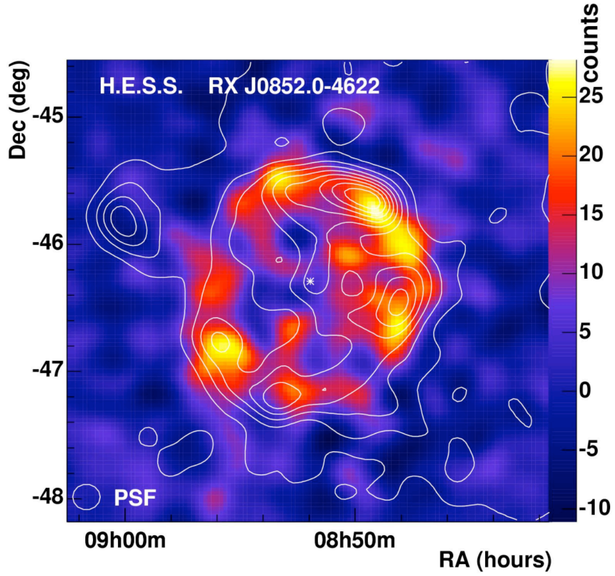
B~0.5 mG inferred by X-ray data prefers (b) Hadronic (π^0 decay)

CR content: 2% of E_{SN}

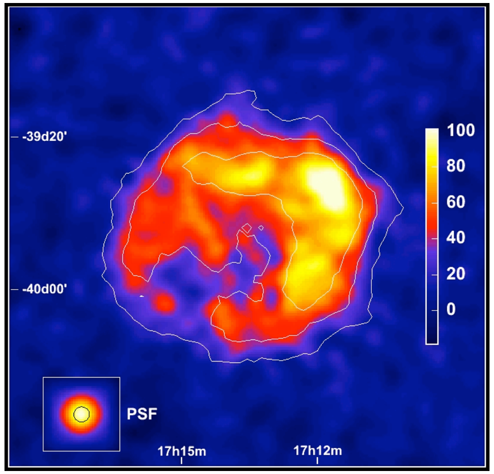
Uchiyama, ASTO-H coll. meeting (Tokyo Feb. 2010)

TeV images of two young "1Crab" strength shell type SNRs

Vela Junior



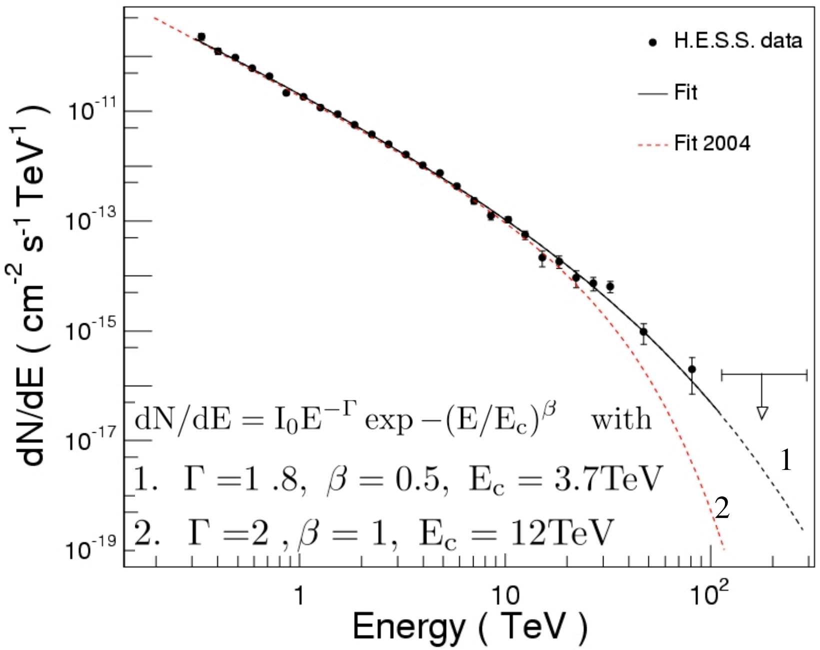
RXJ1713.7-3946

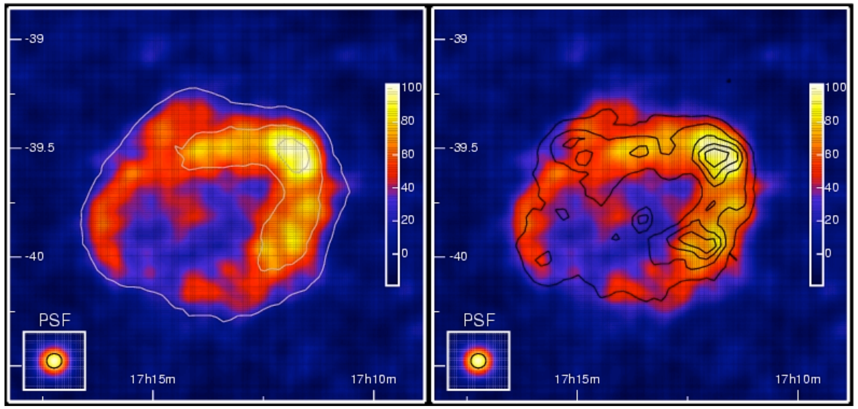


flux and spectra - similar, morphology – shell type

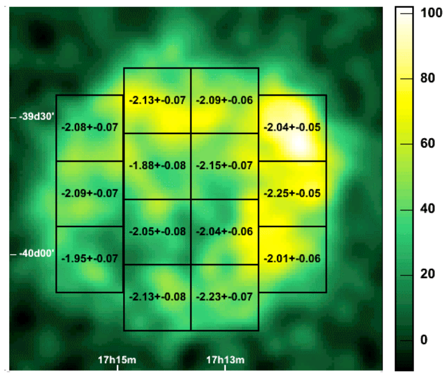
RXJ1713.7-4639

> 30 TeV γ-rays and shell type morphology: acceleration of protons and/or electrons in the shell to energies (well) exceeding 100 TeV





very good correlation with X-rays

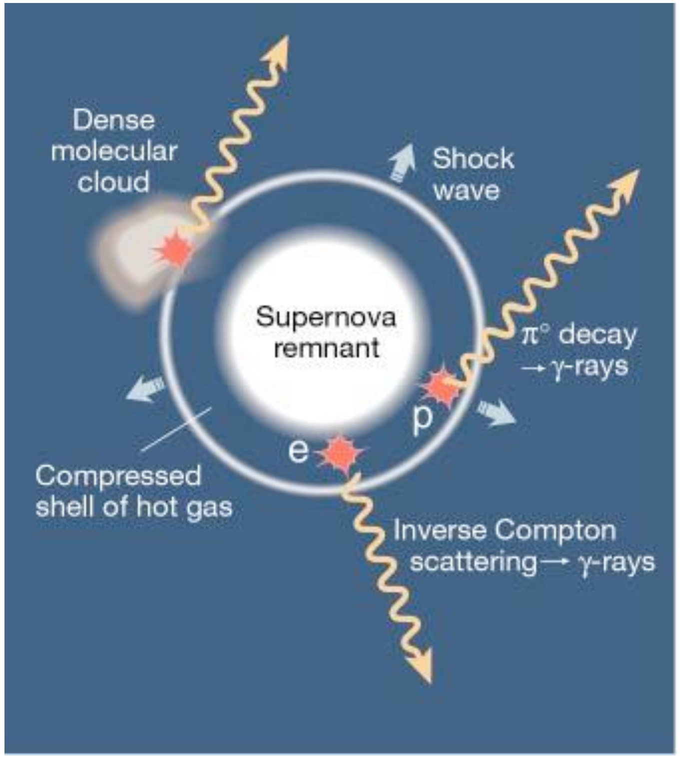


almost constant photon index !

for π^0-meson decay gamma-rays: $J(E_p) = J_0 E^{-\alpha} \exp\left[-(E/E_0)^{\beta_0}\right]$

$$\alpha \approx \Gamma - 0.1,\ E_0 \approx 20E_c,\ \beta_0 \approx 2\beta$$

origin of gamma-rays…



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

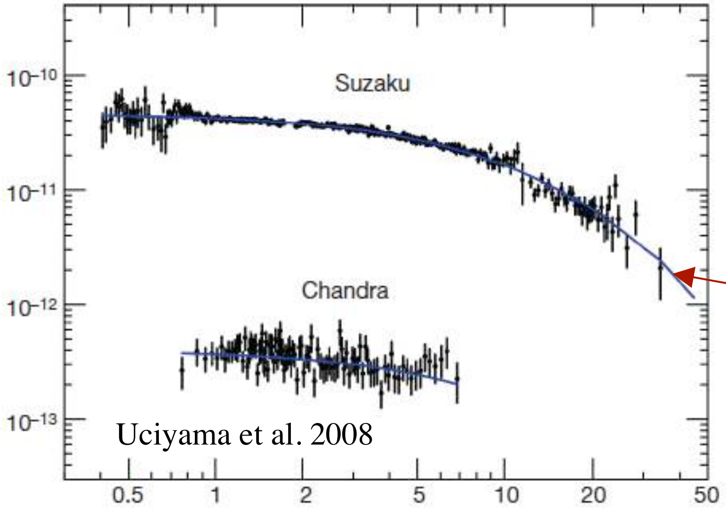
π^0 hadronic origin of gamma-ray

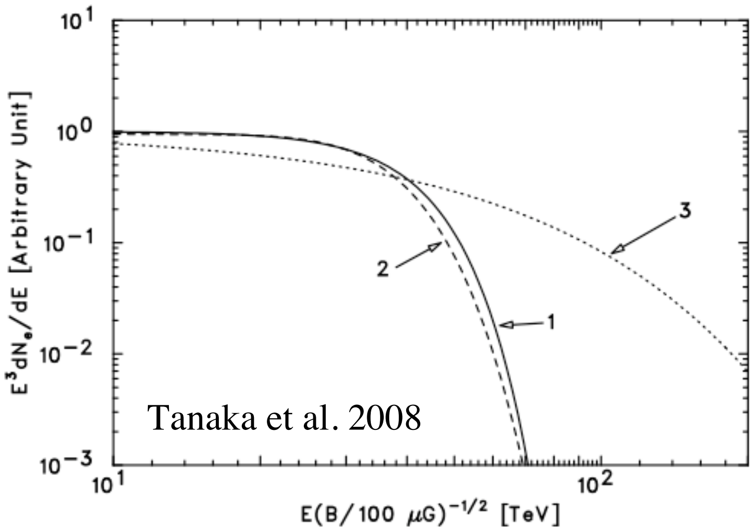
derivation of the energy spectrum and the total energy Wp (with an uncertainty related to the uncertainty in n/d^2)

IC leptonic origin of gamma-rays

model-independent derivation of the spatial and spectral distributions of electrons and, in combination with X-ray data - model independent map of the B-field

SNRs





energy spectrum of synchrotron radiation of electrons in the framework of DSA

$$J_\nu \propto \nu^{-1}[1+0.46(\nu/\nu_0)^{0.6}]^{11/4.8} \exp\left[-(\nu/\nu_0)^{1/2}\right]$$

$$h\nu_0 \approx 1(v/3000 km/s)^2 \eta^{-1} \text{ keV}$$

$h\nu_0$=0.55 keV

strong support for acceleration in Bohm diffusion regime (η ~ 1) - from postion of synchrotron cutoff given that the shock speed v < 4000 km/s *(Chandra)*

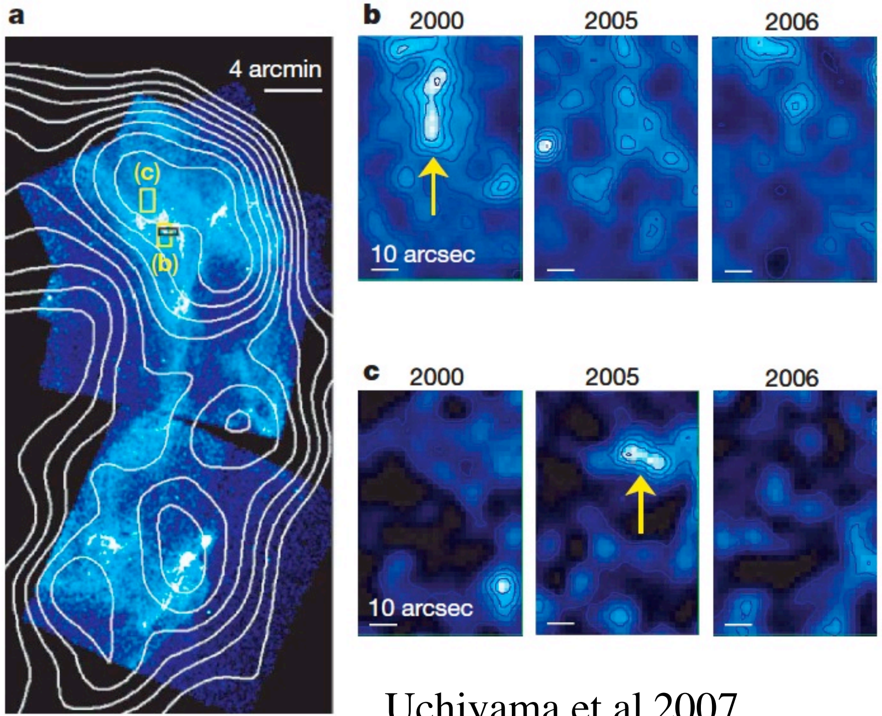
1. electron spectrum derived from Suzaku data
2. DSA prediction
3. "standard E^{-3} exp($-E/E_0$) type elec. spectrum

broad coverage of X-rays: very important!

ASTRO-H!

derived electron spectrum allows model-independent calculations of IC spectrum !

Variability of X-rays on year timescales - *strong magnetic field and particle acceleration in real time*



Uchiyama et al 2007

flux increase - particle acceleration

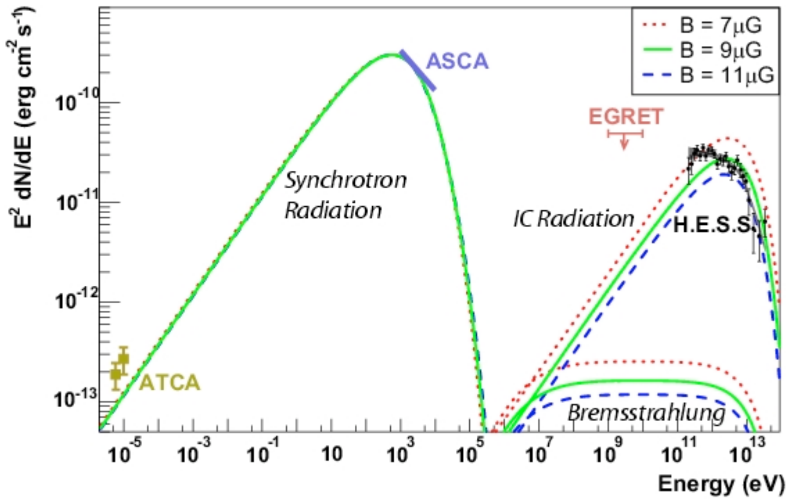
flux decrease - synchrotron cooling *)

both require B-field of order 100μG, at least in hot spots

strong support of the idea of amplification of B-field by in strong nonlinear shocks through non-resonant streaming instability of charged energetic particles (T. Bell)

*) explanation by variation of B-field does't work as demonstrated for Cas A (Uciyama&FA, 2008)

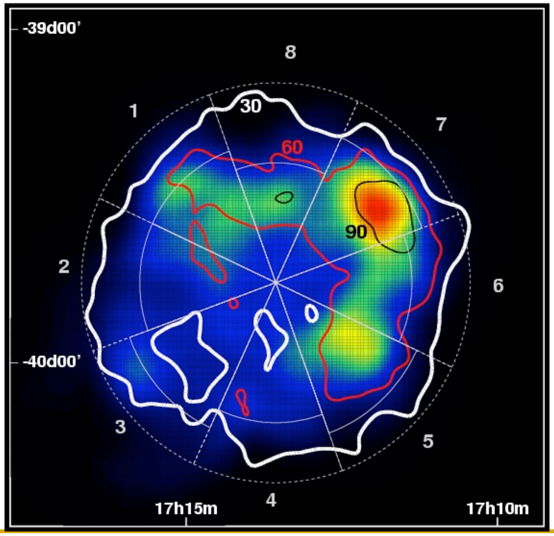
leptonic model - IC on 2.7 K



argument in favor of IC origin of γ-rays:

- *existence of multi-TeV electrons from synchrotron radiation*
- *nice spatial correlation with X-rays*
- *argument against hadronic models*

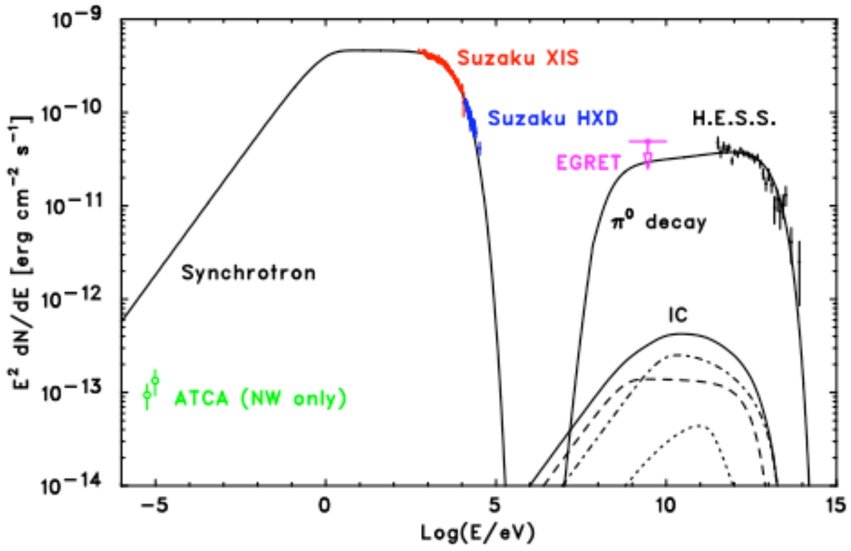
IC origin ? – very small B-field, $B < 10\ \mu G$, and very large $E_{max} > 100$ TeV

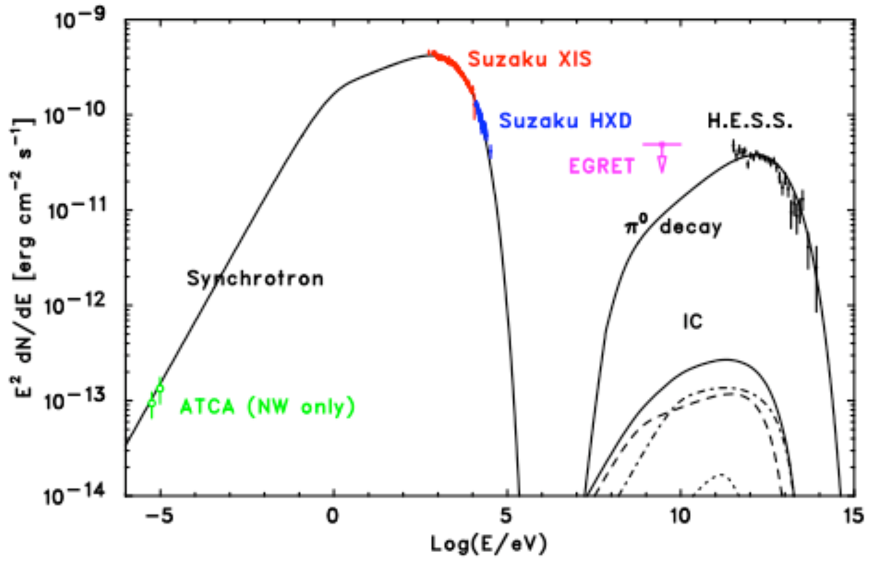


two assumptions marginally co-exists within standard DSA models; bad spectral fit below a few TeV, but most likely we deal with multi-zone models

IC origin of γ-rays implies that we see distribution of electrons => nice correlation of electron distribution with synchrotron X-ray distribution => homogeneous magnetic field, but distinct spatial variation of electrons

hadronic origin of TeV gamma-rays





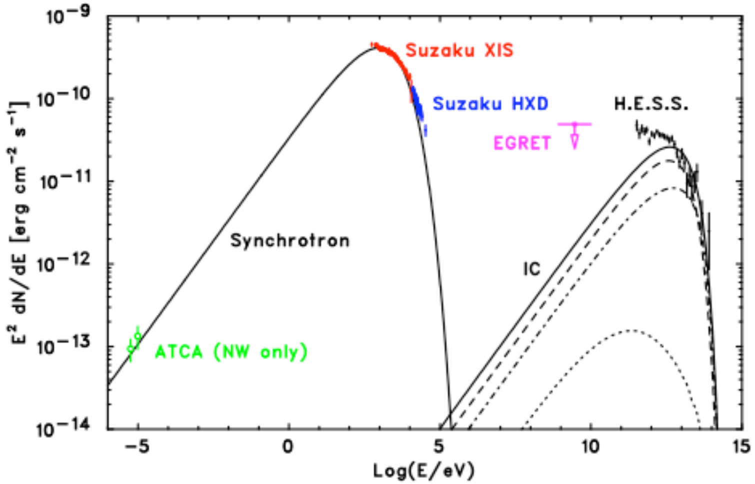
acceleration spectrum with power-law index α=2; B=200 μG, age: 1000 years
Wp=2.7 x 10^{50} (n/1cm^{-3})$^{-1}$ erg
We=3.1 x 10^{46} erg

the same, except for
α=1.7
Wp=1.6 x 10^{50} (n/1cm^{-3})$^{-1}$ erg
We=6.0 x 10^{45} erg

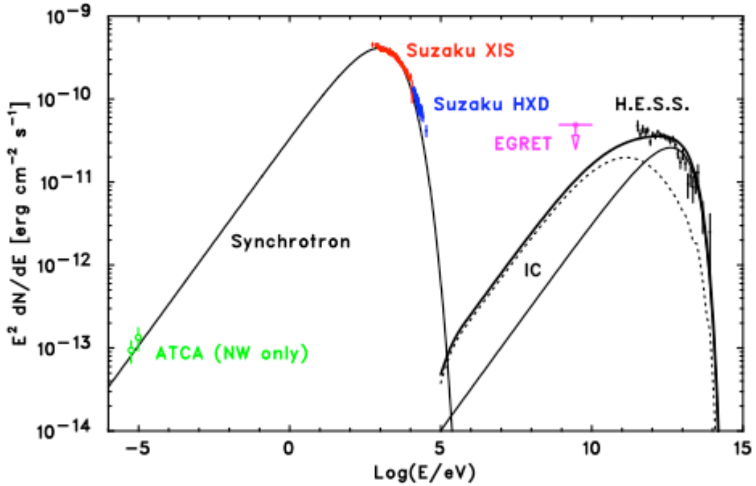
Tanaka et al. 2008

IC calculations based on Suzaku data

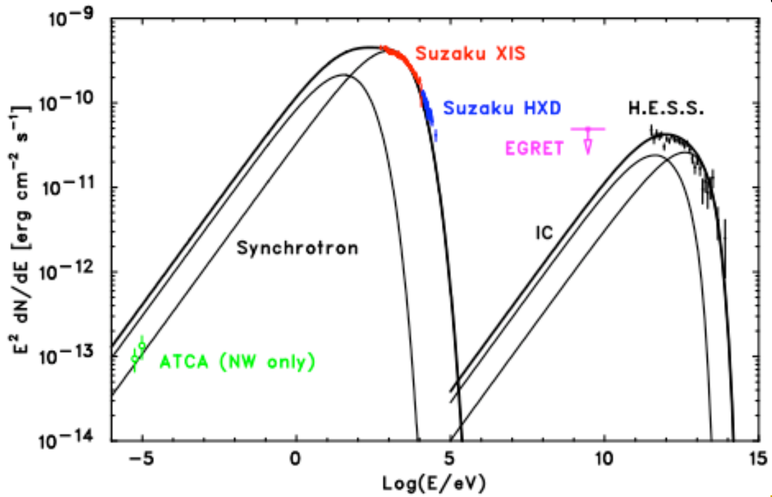
1. Solid - total 2. IC on 2.7 3. IC on FIR 4. IR on optical



Standard ISM radiation fields B=14μG



density of Optical field: 140 eV/cm3



second electron component with a cutoff at 10 TeV

or should adopt that the source is $>10^4$ years old

Tanaka et al. 2008

*challenges for hadronic models *):*

- strong X-TeV correlaton

  in fact this can have natural explanation - it could be an indication that electrons and protons are accelerated in the same sites, they can also reflect the links between the gas density and the magnetic field

- weak radio emission, very large p/e ratio

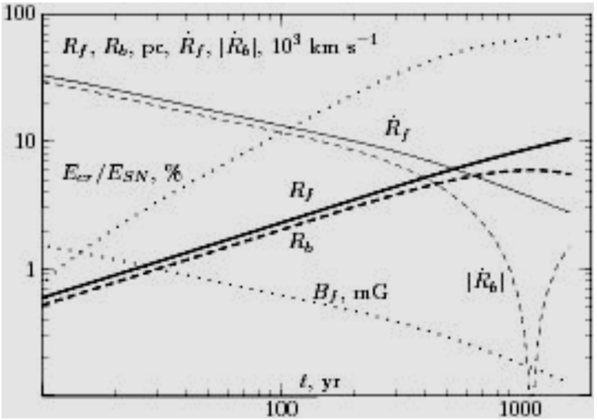
  different from other SNRs, but why should be it the same in all SNRs? Acceleration of low energy electrons at later epochs? Eectrons in GCRs are contributed by other source populations, e.g. by plerions? After all the p/e~100 ratio is a result of a specific realization in the Disk of our Galaxy

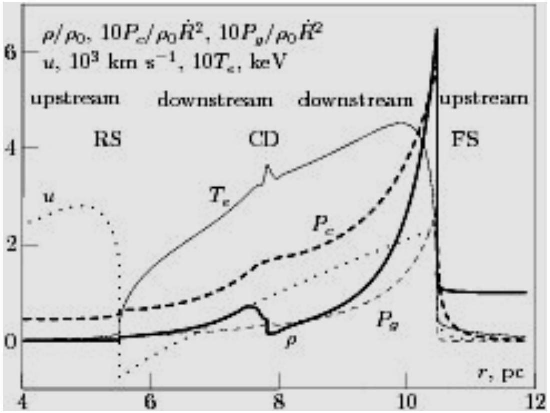
- lack of thermal X-ray emission

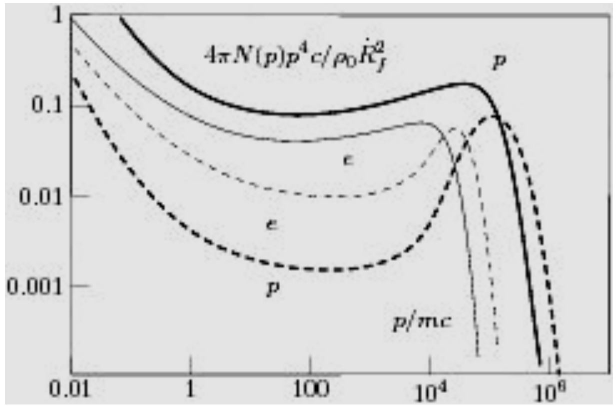
  a serious argument - strong shocks should lead to Te $>10^7$ K. One can avoid the conflict with thermal bremsstrahlung assuming low density n ~ $0.1 cm^{-3}$, but line emission will be still observable n << $0.1 cm^{-3}$. In the hadronic models density cannot be <<$0.1 cm^{-3}$ because of limited available energy budget. Deficit of heavy elements? Another possibility - extremely effective (>50%) non-linear shock acceleration - shock energy goes to acceleration rather than to heating. Finally the sites of proton acceleration and gamma-ray production regions can be separated

*) often two different issues are mixed up - hadronic orgin of gamma-rays and SNR origin of Galactic Cosmic Rays

theoretical modeling of hydrodynamics, acceleration and propagation of cosmic rays in a young SNR (including forward and reverse shocks)







<u>time-dependences</u> of basic parameters (shock speed, temperature, position of the shock, B-field)

<u>radial-dependences</u> of basic parameters (shock speed, temperature, position of the shock, B-field)

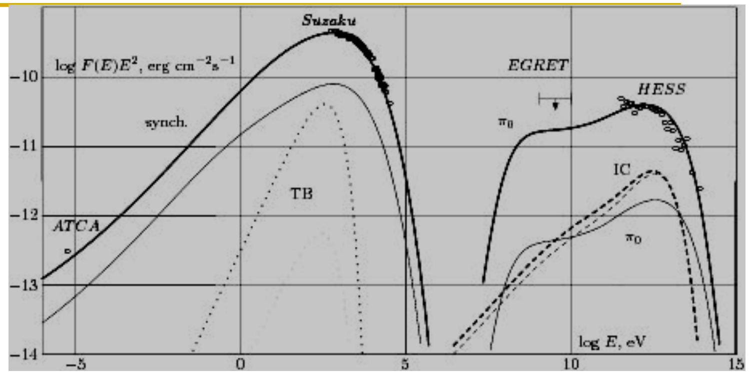
<u>energy distributions</u> of protons & electrons

V. Zirakashvili

broad-band SEDs

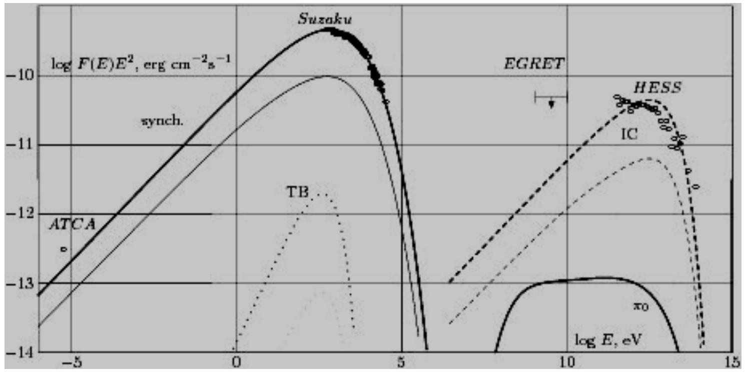
hadronic model

good spectral fit, reasonable radial profile, but …
(1) thermal emission - conflict with expectations !
(2) very high p/e ratio (10^4)



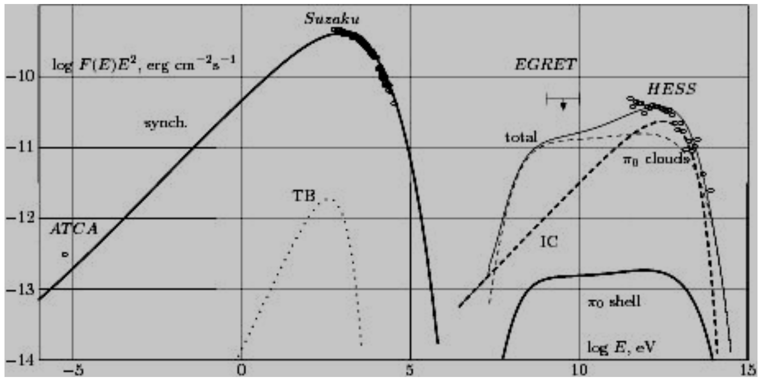
leptonic model

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



“composite” model?

gamma-rays detected by Fermi?
very important…



Zirakashvili, FA 2010

radial profiles

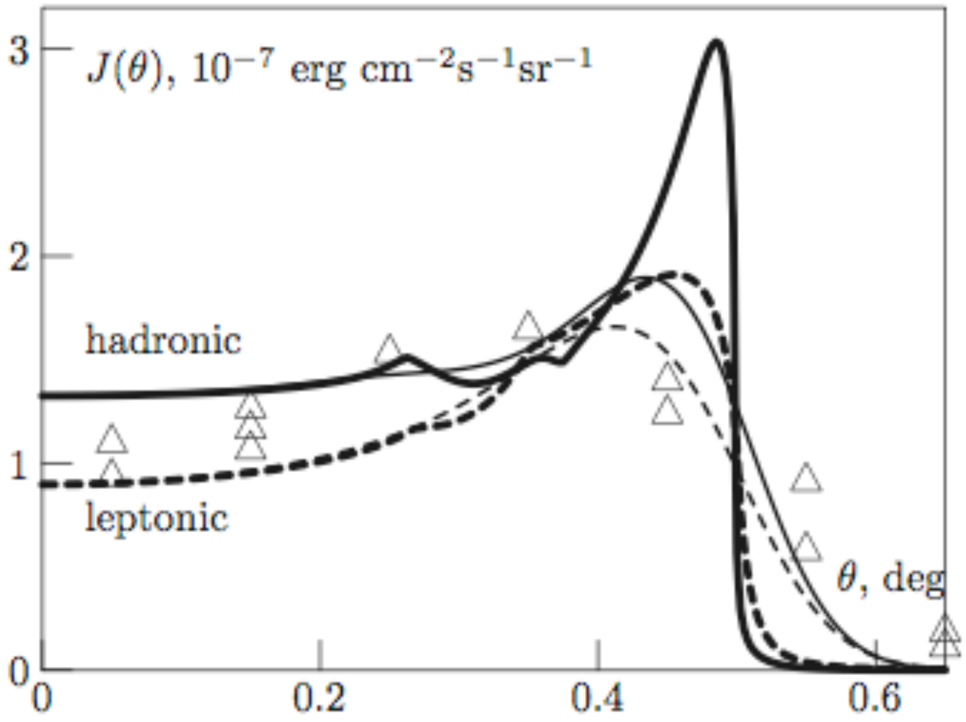
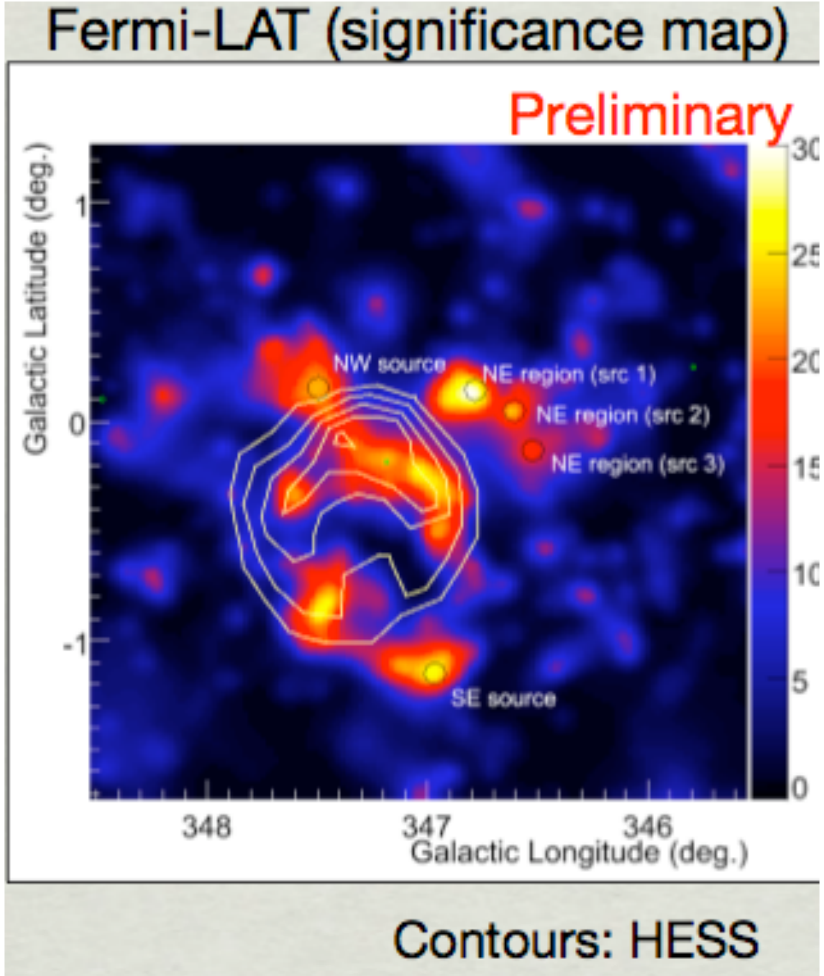


Figure 13. Radial profiles of 1 TeV gamma rays for the hadronic scenario in the uniform medium (solid) and for the leptonic scenario with the non-modified forward shock (dashed). The profiles smoothed with a Gaussian point-spread function with $\sigma = 0^\circ.05$ are also shown (thin lines). The triangles show the azimuthally averaged TeV gamma-ray radial profile observed by HESS (Aharonian et al. 2007a).

Zirakashvili&FA, ApJ 2010

Fermi detected GeV gamma-rays from RXJ1713.7-4639?



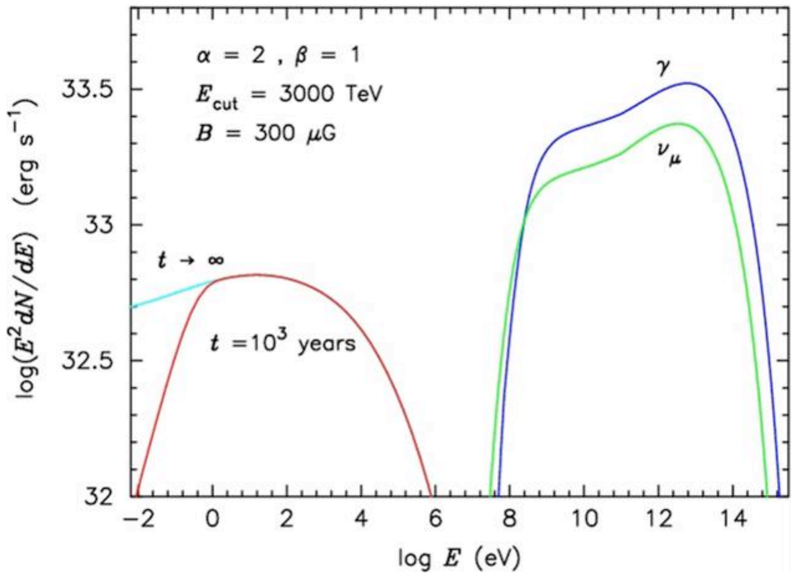
Y. Uchiyama 2010

SNRs as Cosmic PeVatrons ?

3 channels of information about cosmic PeVatrons:

10-100 TeV gamma-rays
10-100 TeV μ-neutrinos
10 -100 keV hard X-rays

sensitivities ?
better than 10^{-12} erg/cm^{2}s



- γ-rays: difficult, but possible with future "10km^2" area multi-TeV IACT arrays
- neutrinos: difficult, but KM3NeT should be able to see (marginal) signals from SNRs RX 1713.7-3946 and Vela Jr
- "prompt" synchrotron X-rays: a very promising channel

Probing PeV protons with X-rays

SNRs shocks can accelerate CRs to <100 TeV (e.g. Cesarsky&Lagage 1984)
unless magnetic field significantly exceeds 10 μG

Recent theoretical developments: applification of the B-field up to >100 μG is possible through plasma waves generated by CRs (Bell and Lucek 2000)

$>10^{15}$ eV protons $\Rightarrow$ $>10^{14}$ eV gamma-rays and electrons
"prompt" synchrotron X-rays

cooling time: $t(\varepsilon) = 1.5\ (\varepsilon/1\mathrm{keV})^{-1/2}\ (B/1\mathrm{mG})^{-3/2}\ \mathrm{yr} \ll t_{SNR}$

energy range: typically between 1 and 100 keV with the ratio L_x/L_γ larger than 20% (for E^{-2} type spectra)

"hadronic" hard X-rays and (multi)TeV γ-rays – similar morphologies !

“hadronic“ X-rays versus synchrotron radiation of primary electrons:

electron injection spectrum $Q_e(E_e)=Q_o E_e^{-\alpha} \exp[(-E_e/E_{e,o})^{\sigma}]$

spectrum of synchrotron radiation of cooled electrons

$\varepsilon^{-(a/2+1)} \exp[(-\varepsilon/\varepsilon_o)^{\lambda}]$ with $\lambda = \sigma/\sigma+2$; $\sigma=0.5$, $\lambda=1/5$

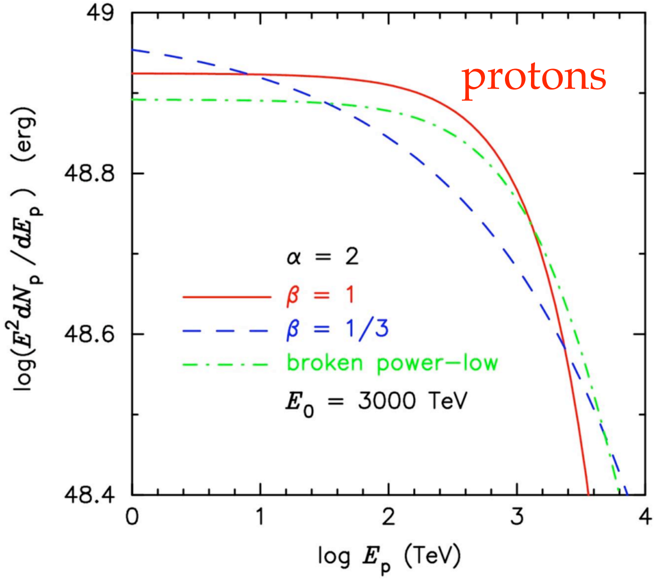
synchrotron spectrum of primary electrons: $\lambda=2/(2+2)=1/2$

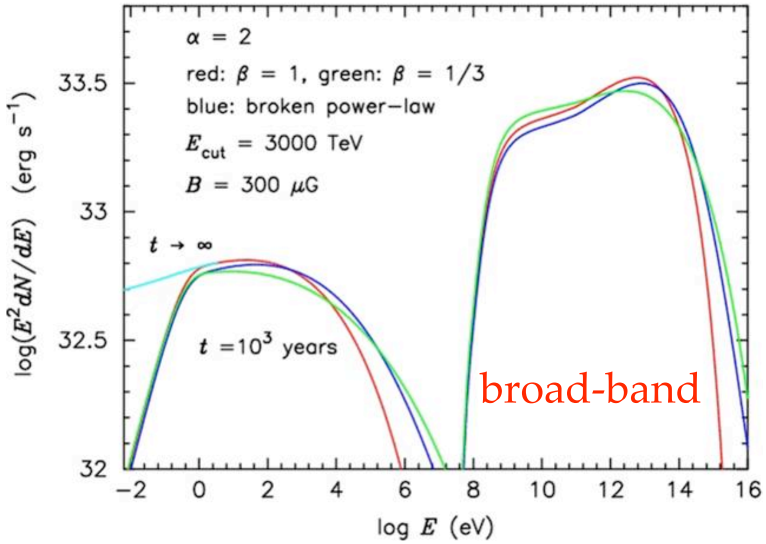
ε_o : characteristic synchrotron frequency proportional BE_0^2(prop. to B^3)

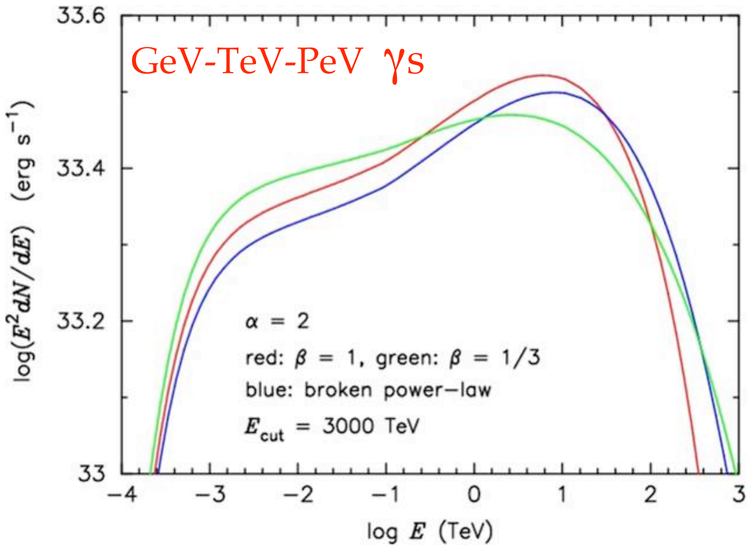
for Eo =1 PeV, B=1 mG X-ray emission extends well beyond 10 keV

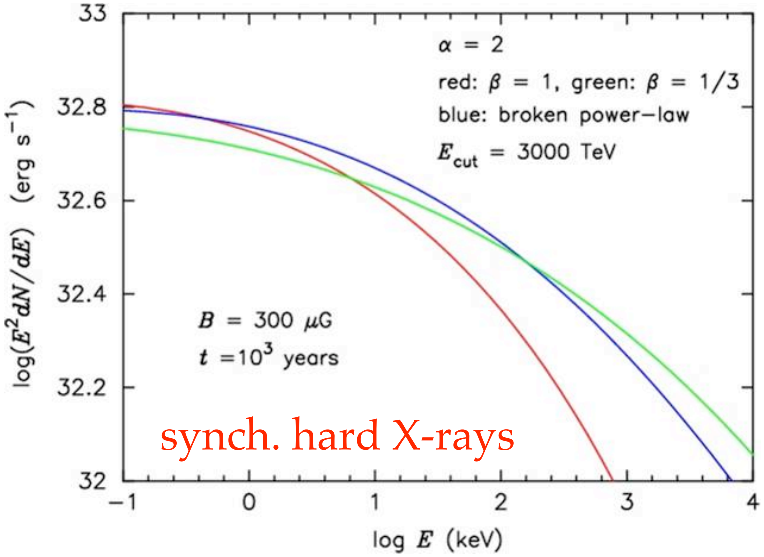
while the cutoff energy in the synchrotron spectrum from directly accelerated electrons is expected around 1 keV

simultaneous measurements of π^0-decay γ-rays and associated synchrotron radiation provide unambiguous estimate of B-field in the acceleration region !









broad-band emision initiated by pp interactiosn : Wp=10^{50} erg, n=1cm^{-3}

key observations to prove the hadronic origin of gamma-rays

- large ($\gg 10\mu G$) magnetic field

  X-ray studies (Chandra)

- gamma-rays to and beyond 100 TeV

  UHE gamma-ray studies (arrays for detection multi-TeV gamma-rays)

- neutrinos

  detection of neutrins (IceCube and KM3NeT)

- hard X-rays produced by secondary electrons

  detection of gamma-rays from 10keV to 100 keV (NuSTAR, ASTRO-H)

key observations to prove the hadronic origin of gamma-rays

population studies (CTA, AGIS, and radio and X-ray detectors)

searching for galactic PeVatrons ...

TeV gamma–rays from Cas A and RX1713.7-3946, Vela Jr, SN1006 – a proof that SNRs are responsible for the bulk of GCRs ?– not yet

the hunt for galactic PeVatrons continues

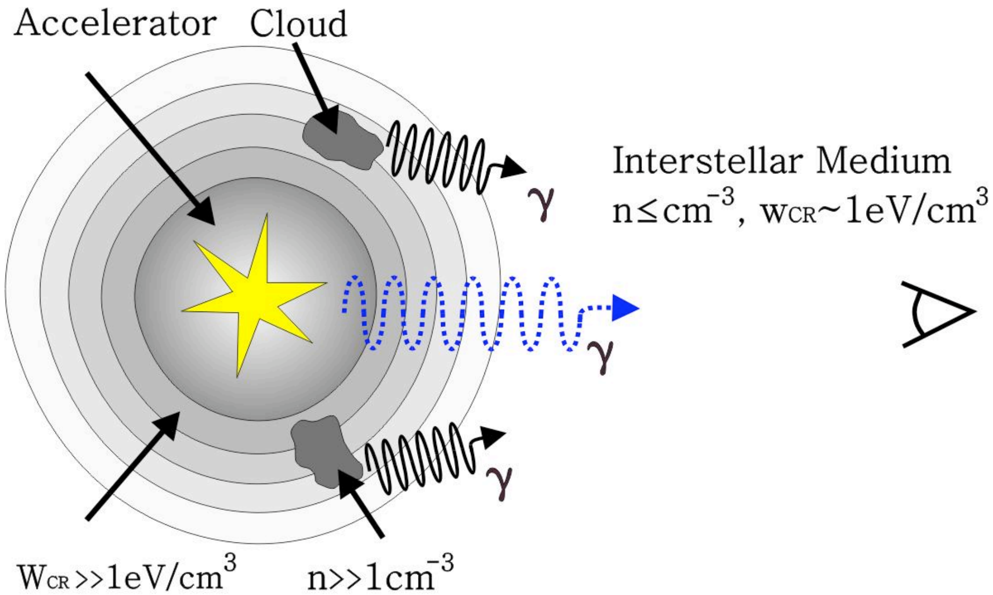
unbiased approach – deep survey of the Galactic Plane – not to miss any recent (or currently active) acceleration site:

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

Giant Molecular Clouds (GMCs)

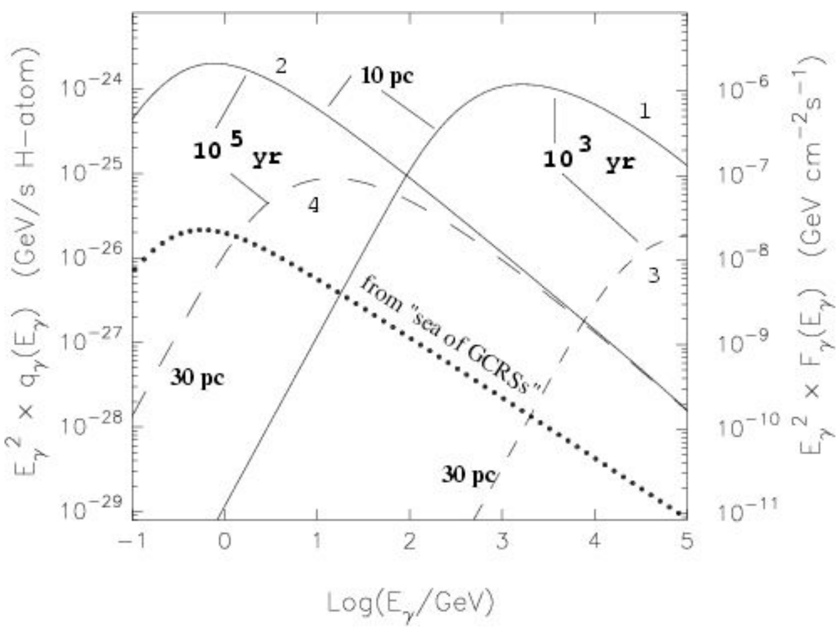
as tracers of Galactic Cosmic Rays

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 !

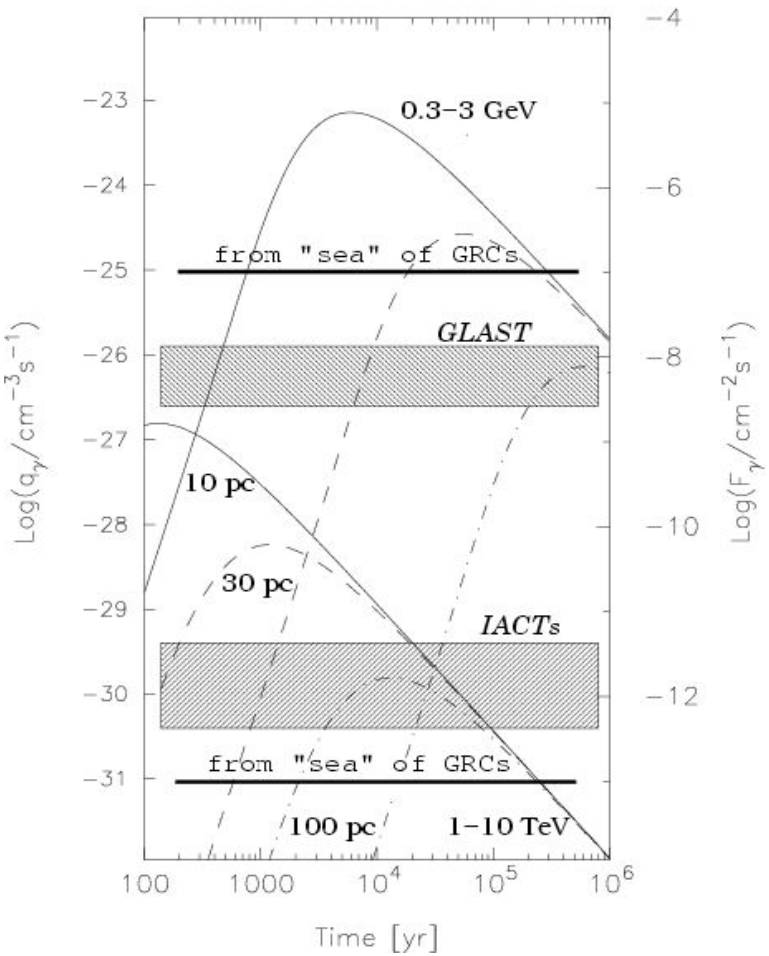
While travelling from the accelerator to the cloud the spectrum of CRs is a strong function of time t, distance to the source R, and the (energy-dependent) Diffusion Coefficient D(E)

⇨ 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 ...

Impact of Propagation Effects



GeV-TeV anti-correlations



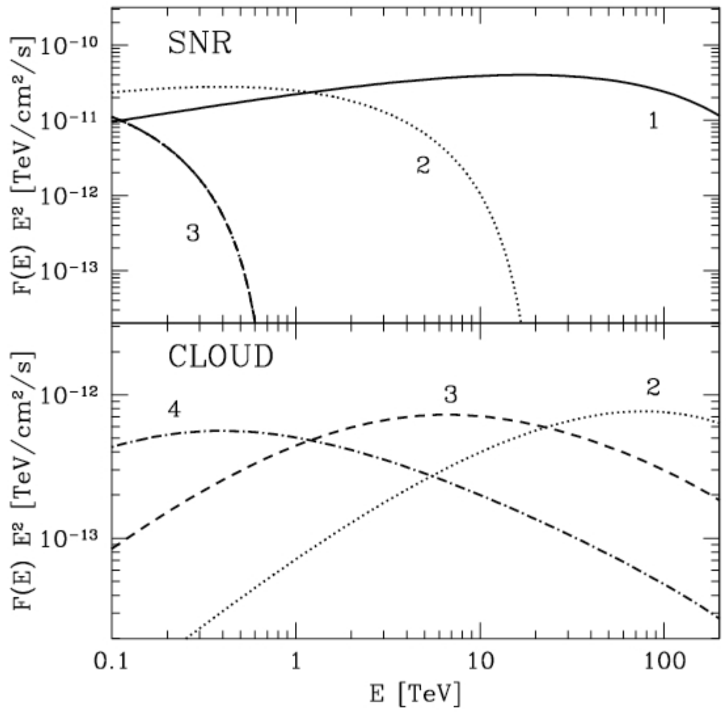
emissivities and fluxes (for M_5/d^2_{kpc}) of γ-rays from a cloud at different times and distances from impulsive accelerater with $W=10^{50}$ erg ; $D(E)=10^{26}\,(E/10\,GeV)^{0.5}$ cm^2/s]

FA 1995

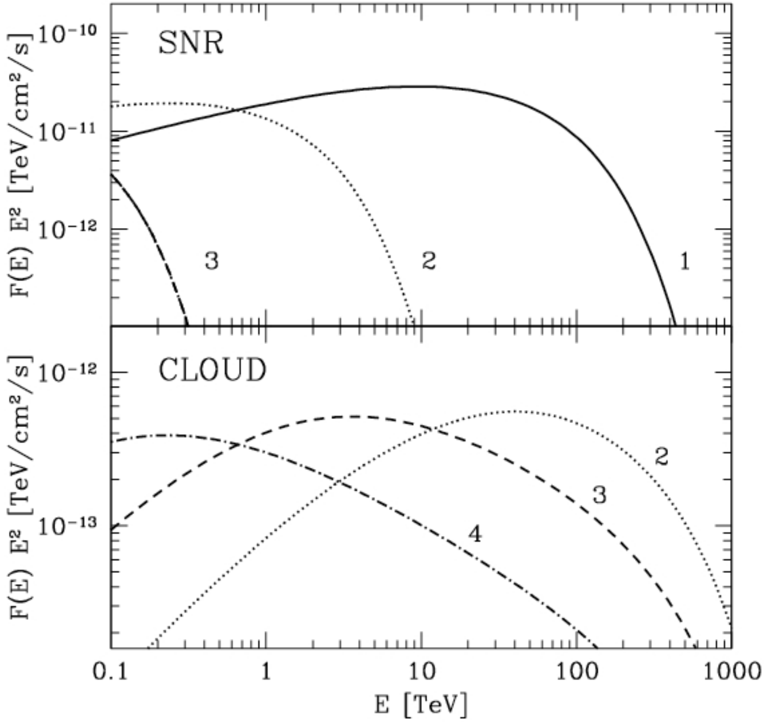
Gamma-rays and neutrinos inside and outside of SNRs

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

gamma-rays



neutrinos



SNR: $W_{51}=n_1=u_9=1$ d=1 kpc   GMC: $M=10^4\ M_o$ d=100pc

ISM: $D(E)=3\times10^{28}(E/10\mathrm{TeV})^{1/2}\ \mathrm{cm^2/s}$

Gabici, FA 2007

highest energy particles escape quickly

T=100 yr

T=1620 yr

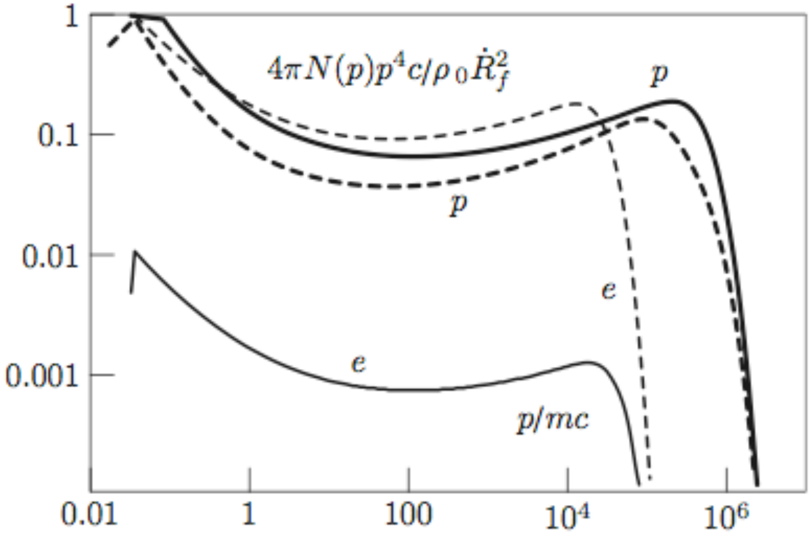


Figure 4. Energy distributions of accelerated protons (thick lines) and electrons (multiplied to the factor of 5000; thin lines) at $t = 100$ yr. Spectra at both the forward shock (solid lines) and the reverse shock (dashed lines) are shown.

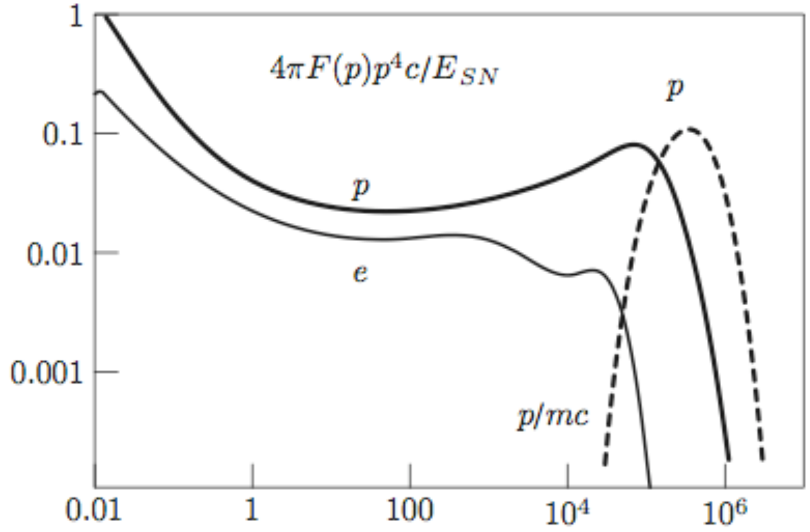


Figure 5. Spatially integrated spectra of accelerated protons (solid line) and electrons (multiplied to the factor of 5000; thin solid line) at $t = 1620$ yr. Spectrum of runaway particles, which have left the remnant is also shown (dashed line).

expected gamma-ray emission from interactions of protons which escaped the shell of SNR and interact with dense gas surrounding RXJ1713.7-3946

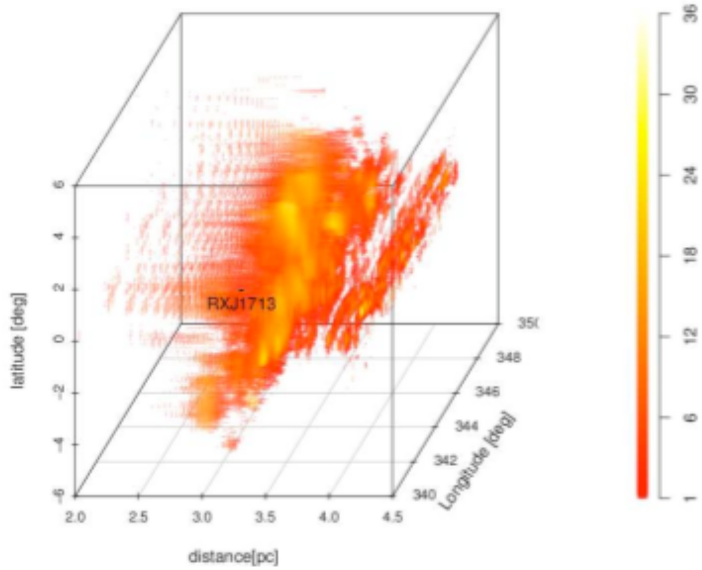
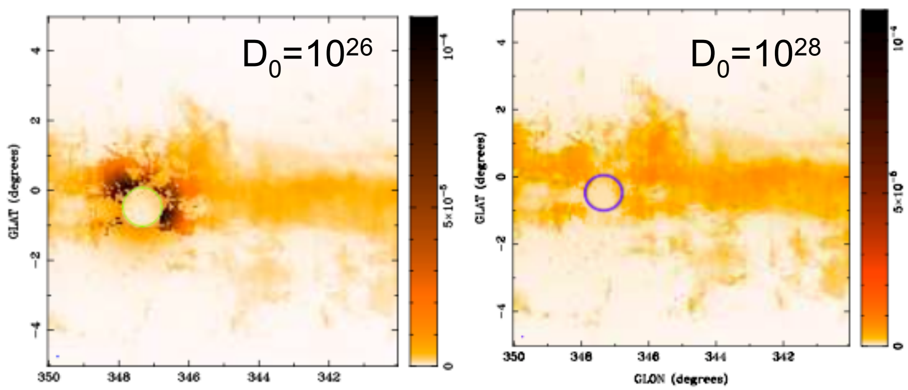


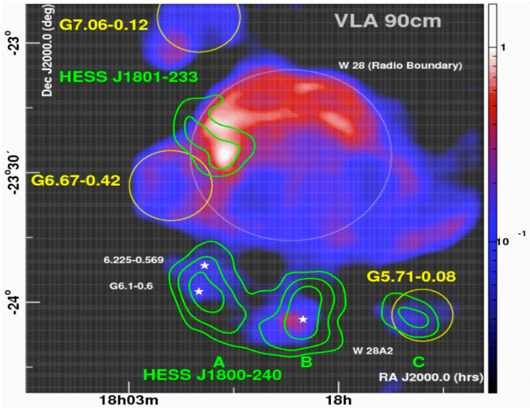
Fig. 1. The gas distribution in the region which spans Galactic longitude $340^\circ < l < 350^\circ$, Galactic latitude $-5^\circ < b < 5^\circ$ and heliocentric distance 50 pc $< l_d <$ 30 kpc, as observed by the NANTEN and LAB surveys, expressed in protons cm^{-3}. The distance axis is logaritmic in base 10. A value for the gas density is given every 50 pc in distance, which is reflected in the apparent slicy structure for distances below 100 pc. For sake of clarity only densities above 1 protons cm^{-3} are shown. Also indicated the position of the historical SNR, RX J1713.7-3946.

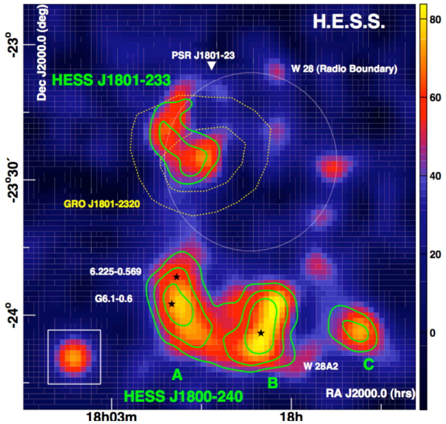


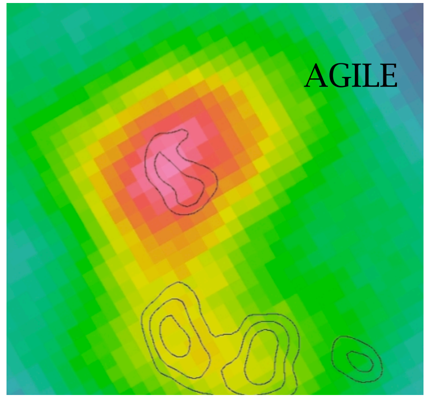
surrounding gas density:
NANTEN data **age:** 1600 yr
escape of protons: Zirakashvili&Ptuskin 2008
diffusion coefficient outside SNR:
$D=D_0(E/10\mathrm{GeV})^{0.5}$ cm^2/s

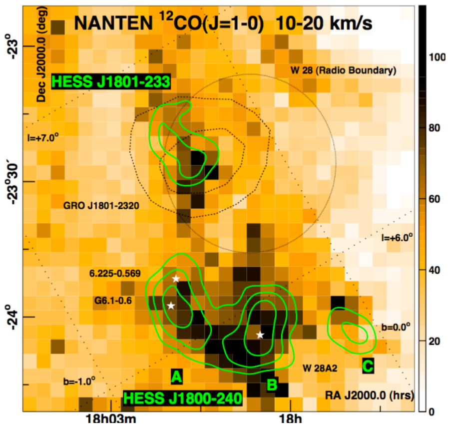
Casanova et al. 2010

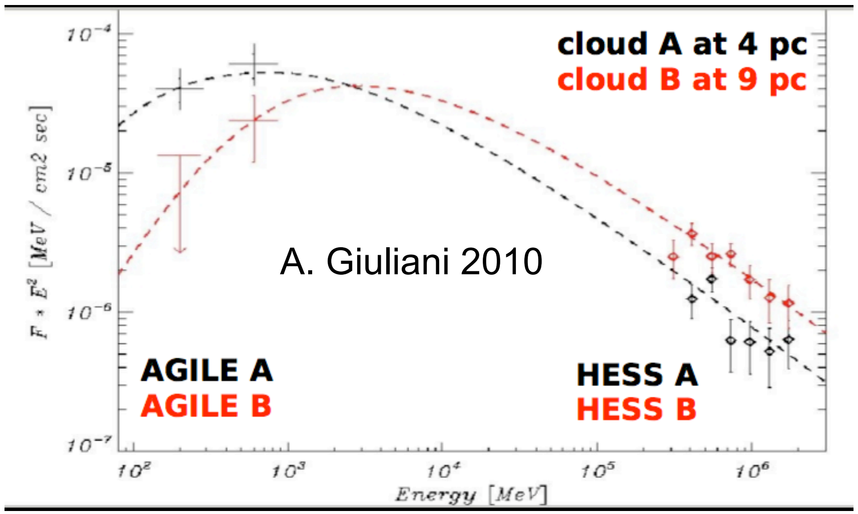
TeV gamma-ray sources around W28:
CRs from an old SNR interacting with nearby clouds?



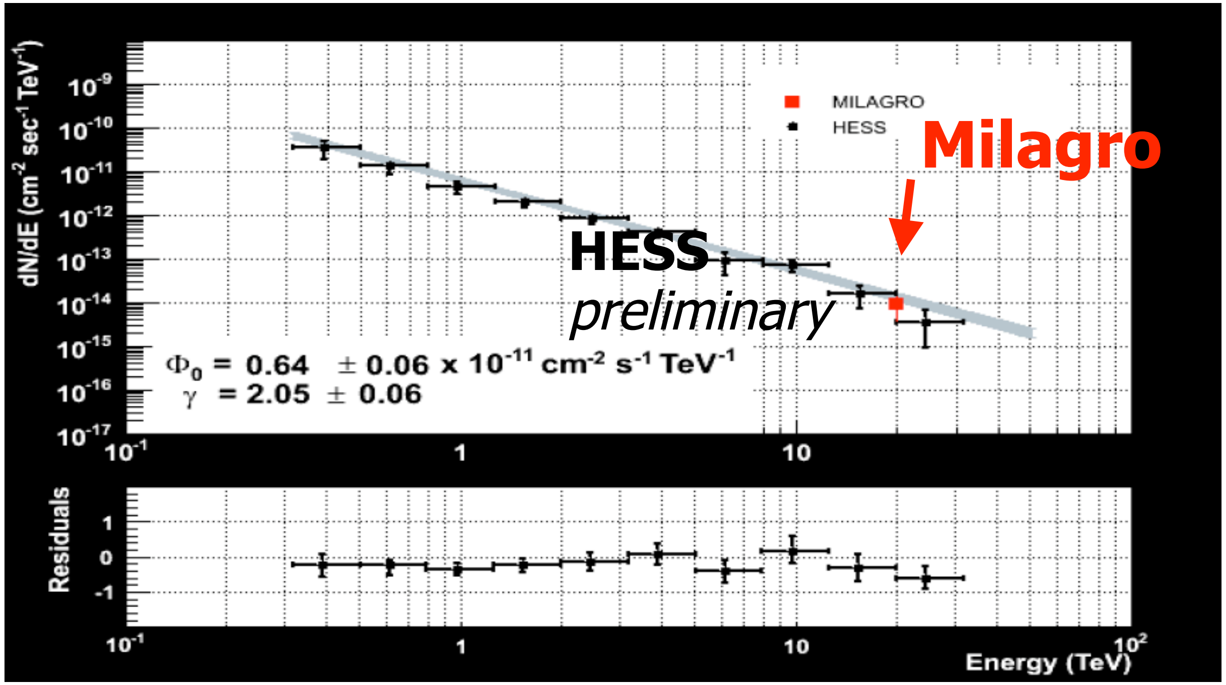




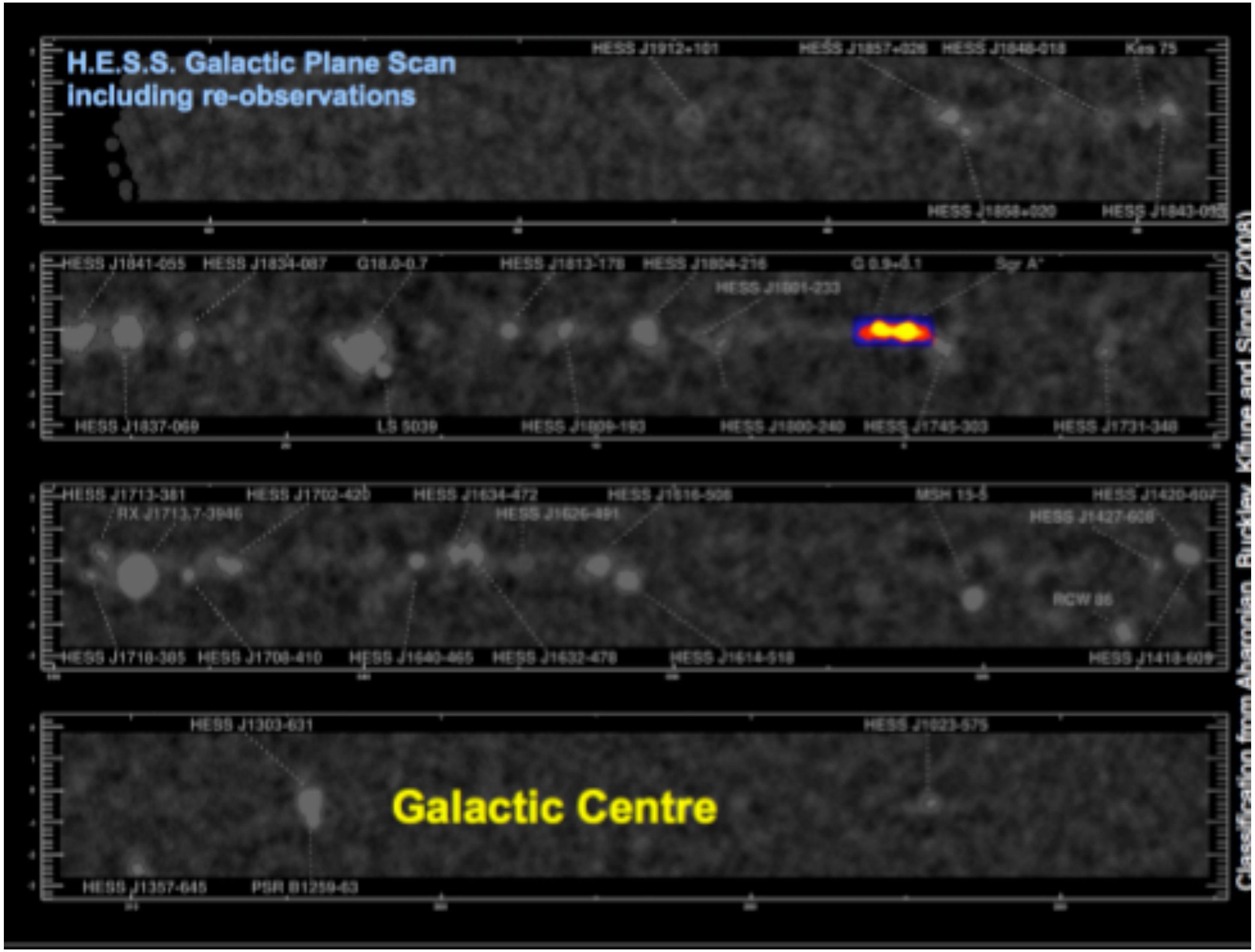


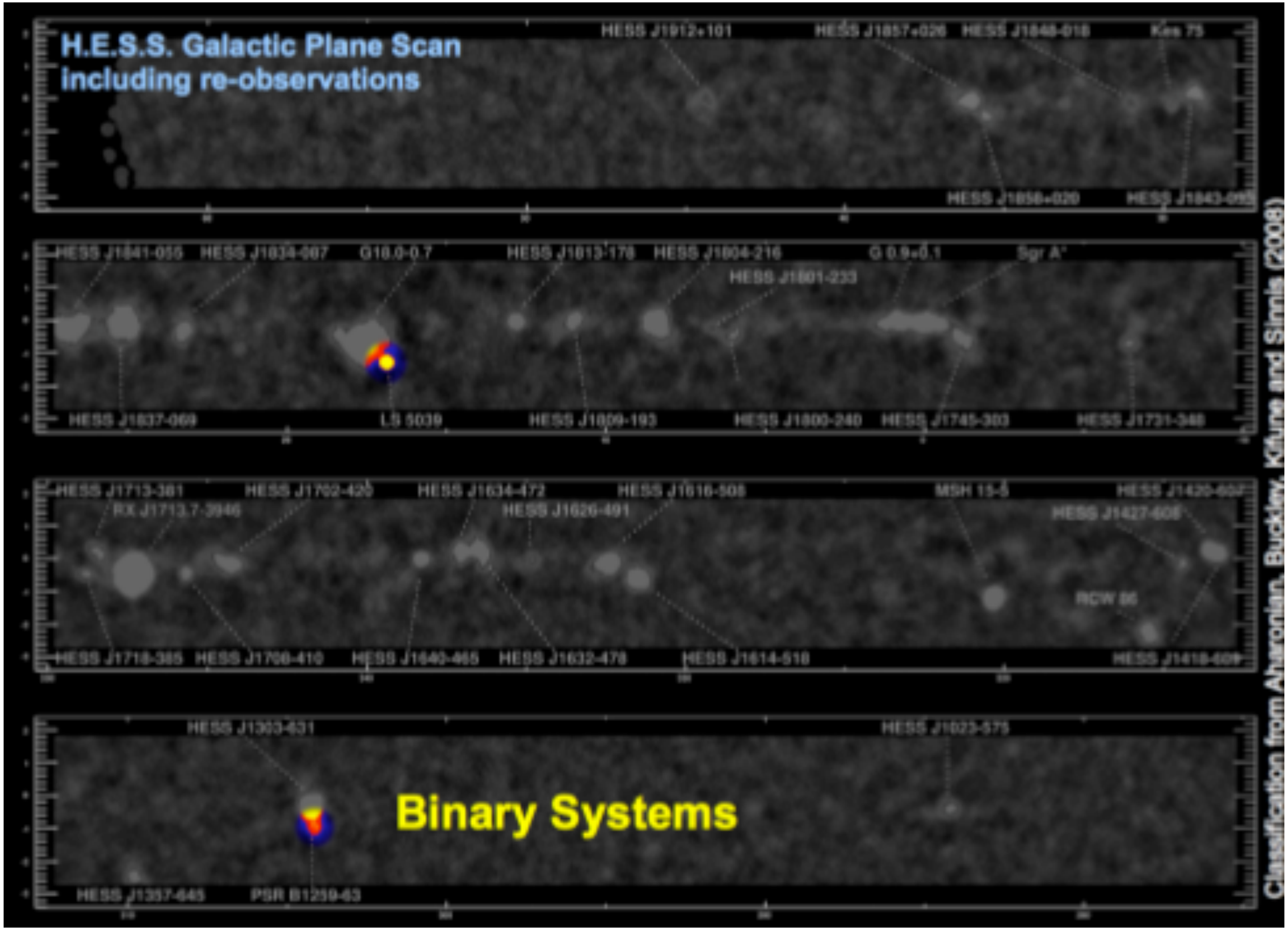


MGRO J1908+06 - a hadronic PeVatron?

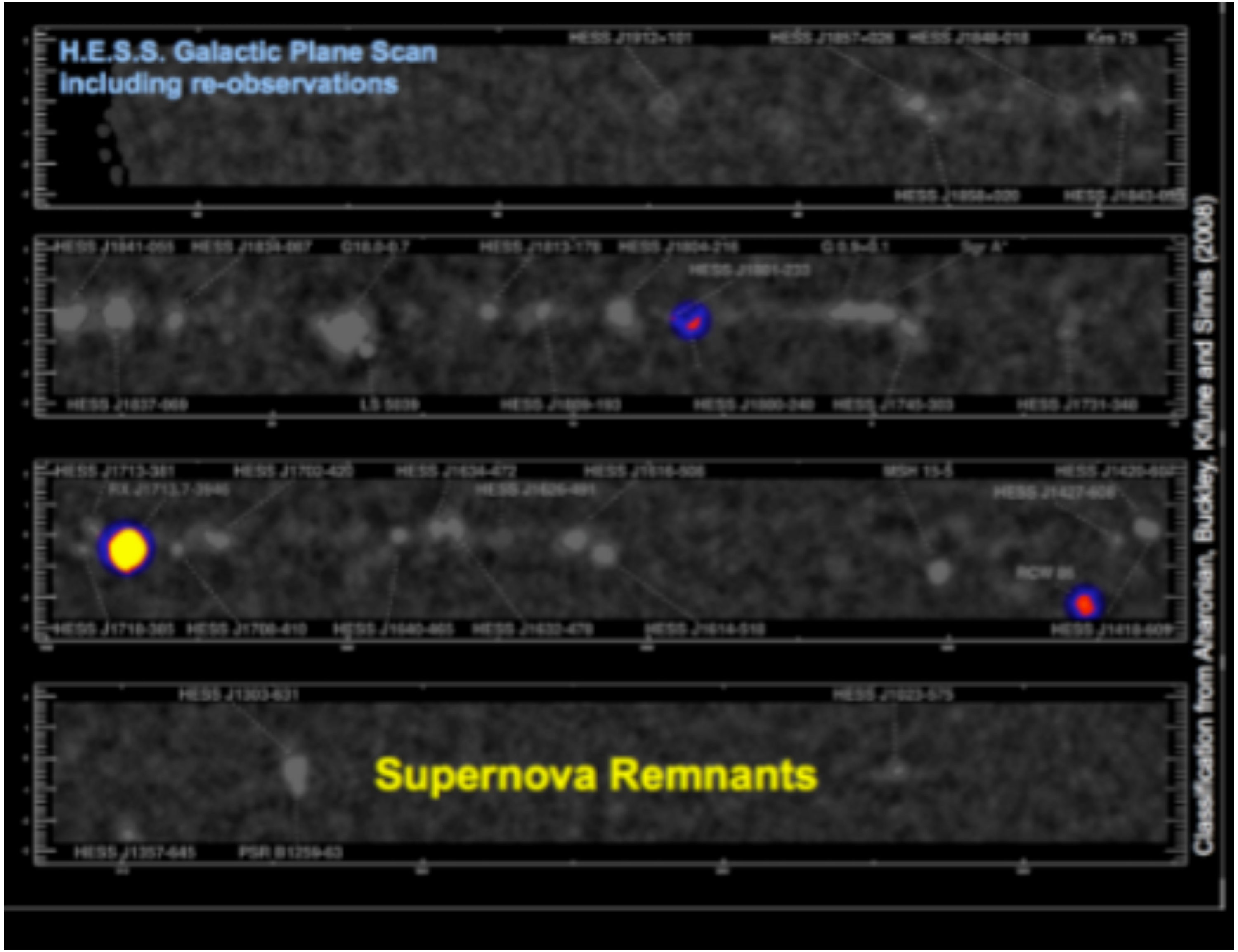


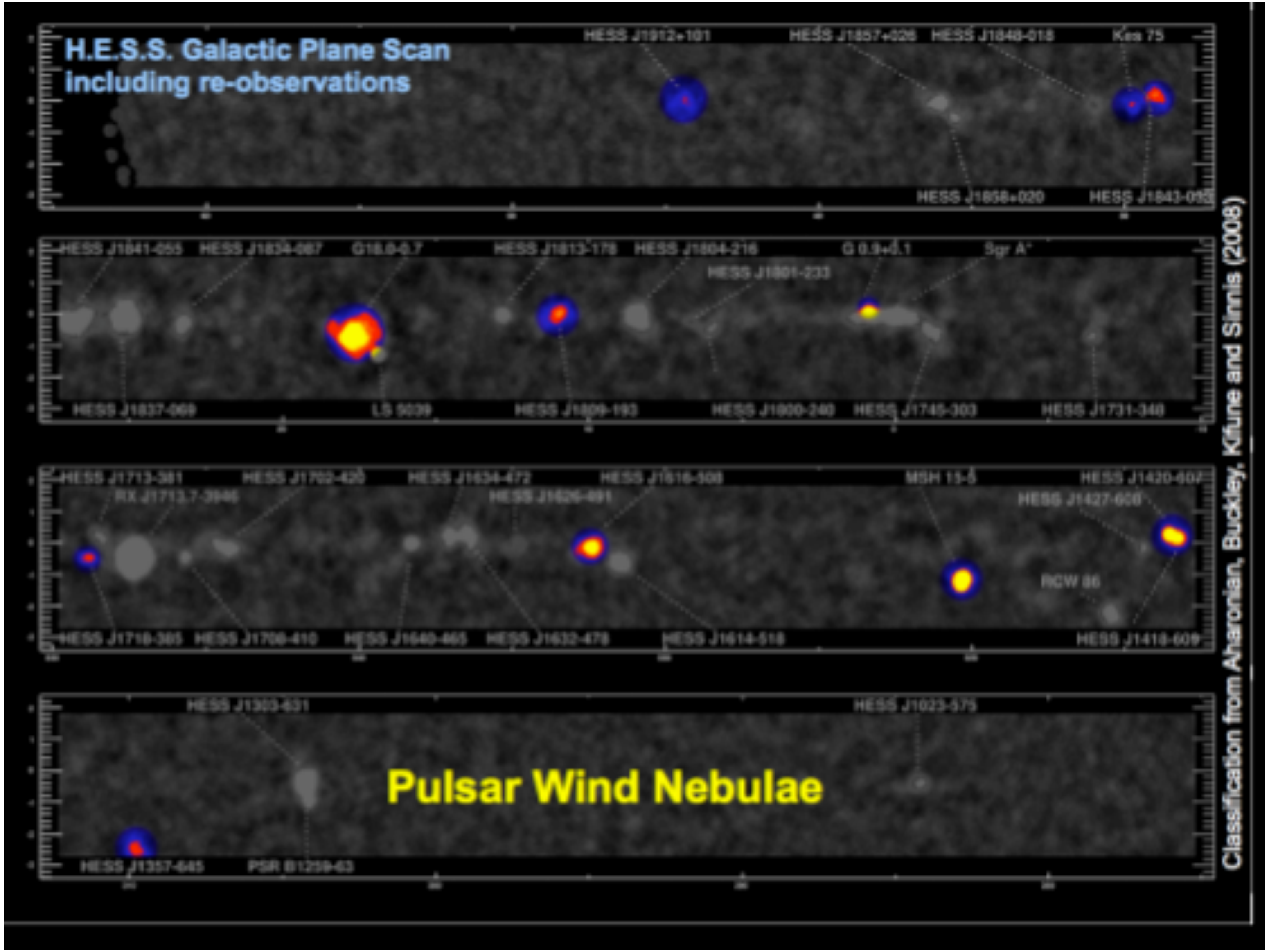
or a Pulsar Wind Nebula?


H.E.S.S. Galactic Plane Scan
including re-observations
HESS J1912+101
HESS J1857+026
HESS J1848-018
Kes 75
HESS J1858+020
HESS J1841-055
HESS J1834-087
G18.0-0.7
HESS J1813-178
HESS J1804-216
HESS J1801-233
Sgr A*
HESS J1837-069
LS 5039
HESS J1809-193
HESS J1800-240
HESS J1745-303
HESS J1731-348
HESS J1713-381
RX J1713.7-3946
HESS J1702-420
HESS J1634-472
HESS J1626-491
HESS J1616-508
MSH 15-52
HESS J1420-607
HESS J1427-608
RCW 86
HESS J1718-385
HESS J1708-410
HESS J1640-465
HESS J1632-478
HESS J1614-518
HESS J1418-609
HESS J1303-631
HESS J1023-575
Galactic Centre
HESS J1357-645
PSR B1259-63
Classification from Aharonian, Buckley, Kifune and Sinnis (2008)

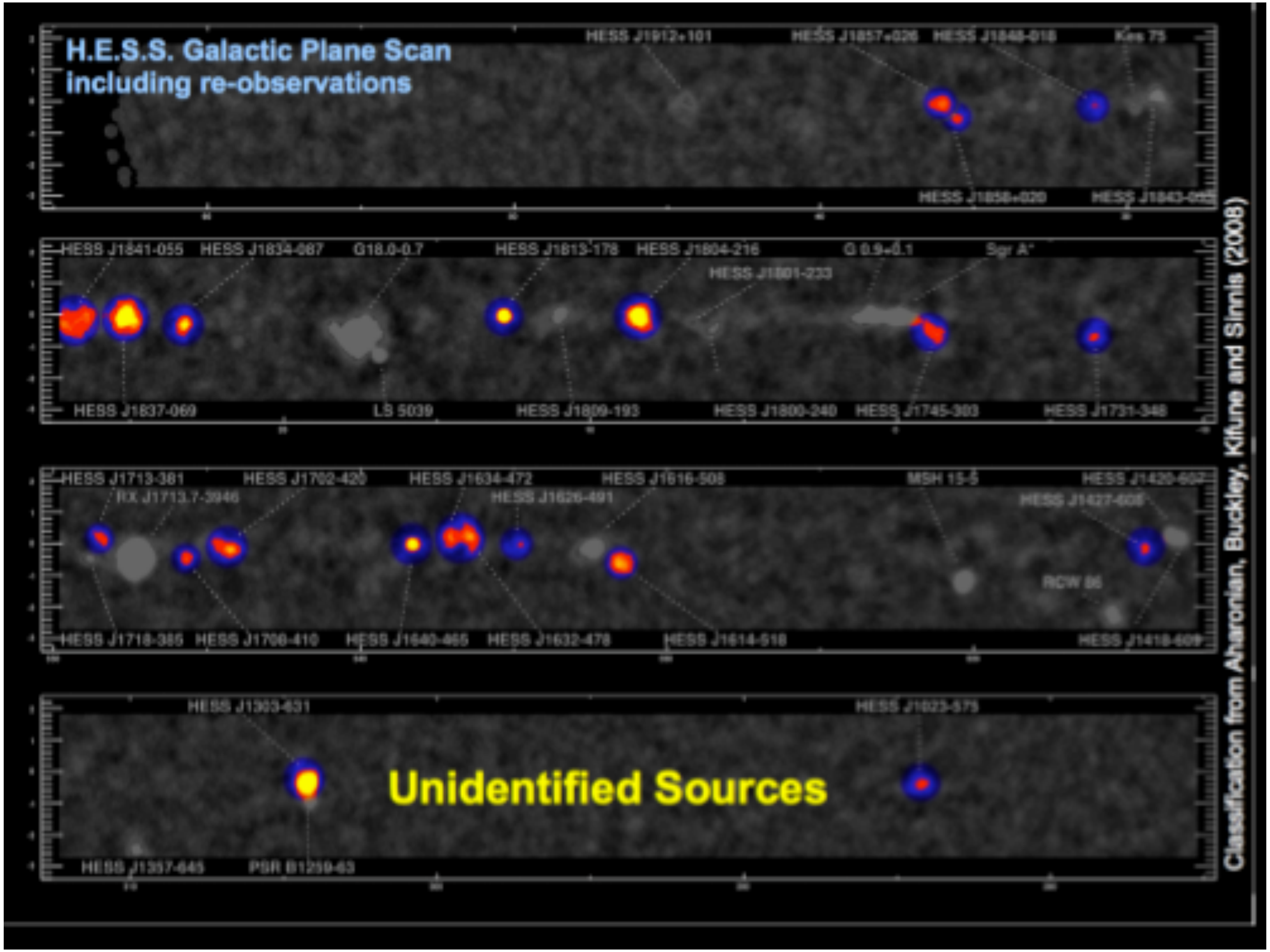


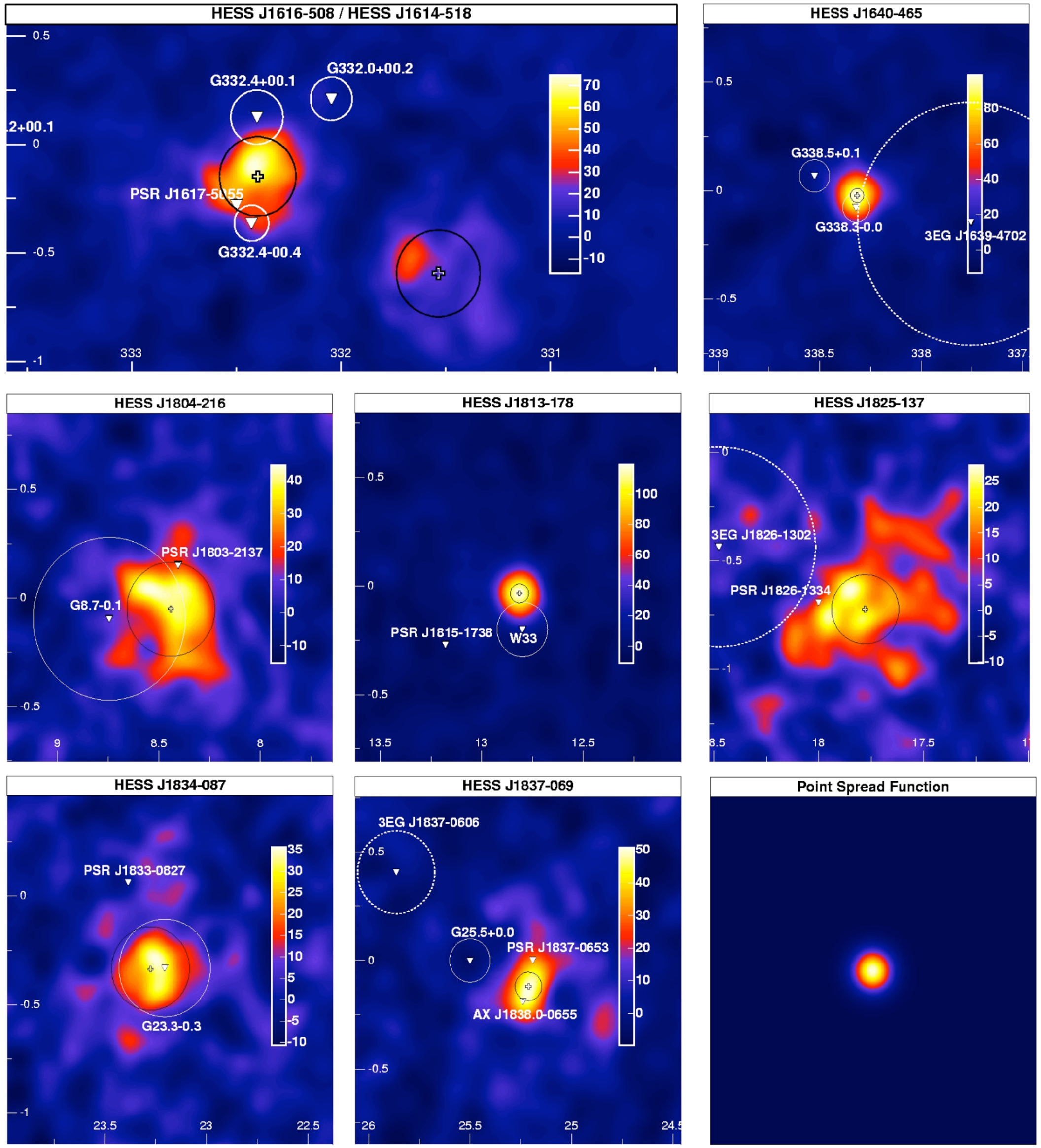
H.E.S.S. Galactic Plane Scan
including re-observations
Binary Systems
LS 5039
PSR B1259-63
Classification from Aharonian, Buckley, Kifune and Sinnis (2008)


H.E.S.S. Galactic Plane Scan
including re-observations
Supernova Remnants
Classification from Aharonian, Buckley, Kifune and Sinnis (2008)



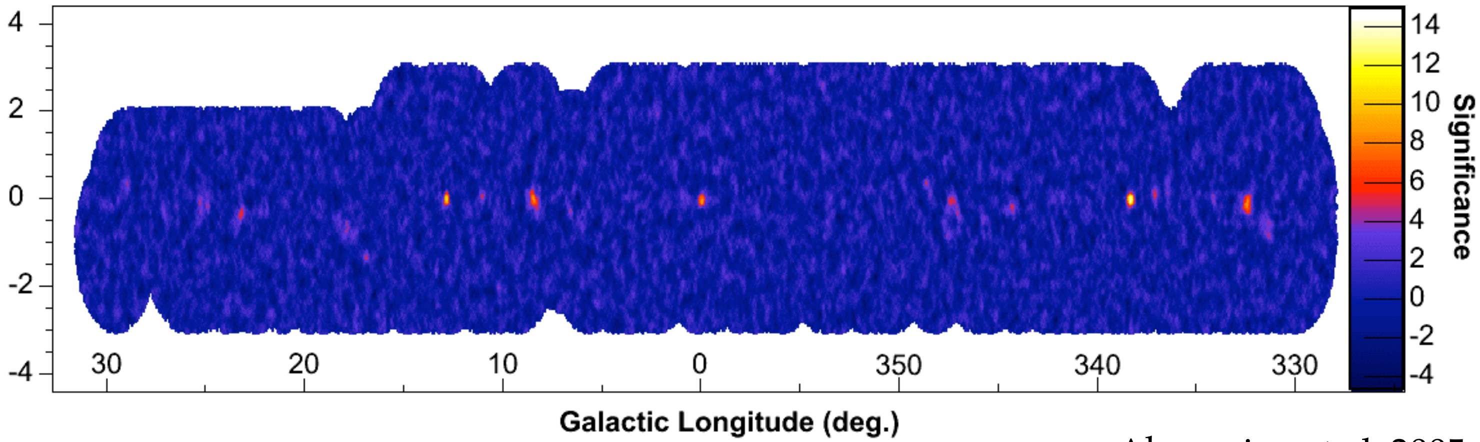
H.E.S.S. Galactic Plane Scan
including re-observations
HESS J1912+101
HESS J1857+026
HESS J1848-018
Kes 75
HESS J1858+020
HESS J1843-033
HESS J1841-055
HESS J1834-087
G18.0-0.7
HESS J1813-178
HESS J1804-216
HESS J1801-233
G 0.9+0.1
Sgr A*
HESS J1837-069
LS 5039
HESS J1809-193
HESS J1800-240
HESS J1745-303
HESS J1731-348
HESS J1713-381
RX J1713.7-3946
HESS J1702-420
HESS J1634-472
HESS J1626-491
HESS J1616-508
MSH 15-5
HESS J1420-607
HESS J1427-608
RCW 86
HESS J1718-385
HESS J1708-410
HESS J1640-465
HESS J1632-478
HESS J1614-518
HESS J1418-609
HESS J1303-631
HESS J1023-575
Pulsar Wind Nebulae
HESS J1357-645
PSR B1259-63
Classification from Aharonian, Buckley, Kifune and Sinnis (2008)


H.E.S.S. Galactic Plane Scan
including re-observations
HESS J1912+101
HESS J1857+026
HESS J1848-018
Kes 75
HESS J1858+020
HESS J1843-033
HESS J1841-055
HESS J1834-087
G18.0-0.7
HESS J1813-178
HESS J1804-216
G 0.9+0.1
Sgr A*
HESS J1801-233
HESS J1837-069
LS 5039
HESS J1809-193
HESS J1800-240
HESS J1745-303
HESS J1731-348
HESS J1713-381
RX J1713.7-3946
HESS J1702-420
HESS J1634-472
HESS J1626-491
HESS J1616-508
MSH 15-52
HESS J1420-607
HESS J1427-608
RCW 86
HESS J1718-385
HESS J1708-410
HESS J1640-465
HESS J1632-478
HESS J1614-518
HESS J1418-609
HESS J1303-631
HESS J1023-575
Unidentified Sources
HESS J1357-645
PSR B1259-63
Classification from Aharonian, Buckley, Kifune and Sinnis (2008)

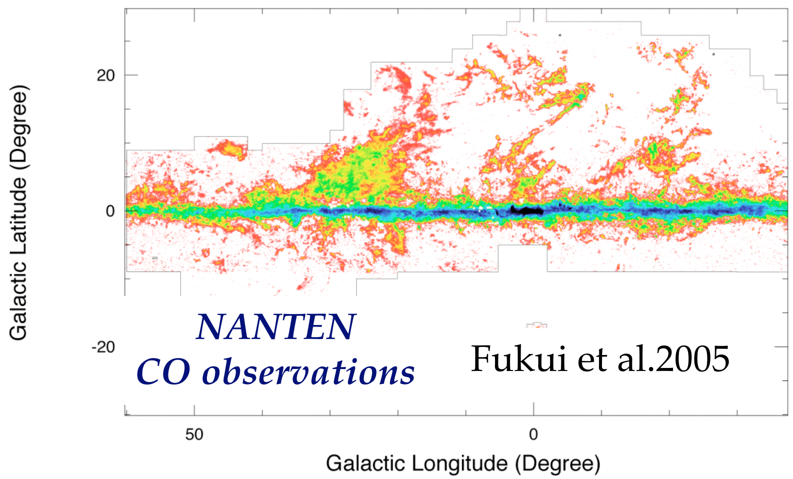


TeV galactic gamma-ray sources

distribution of HESS sources HESS



Aharonian et al. 2005



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

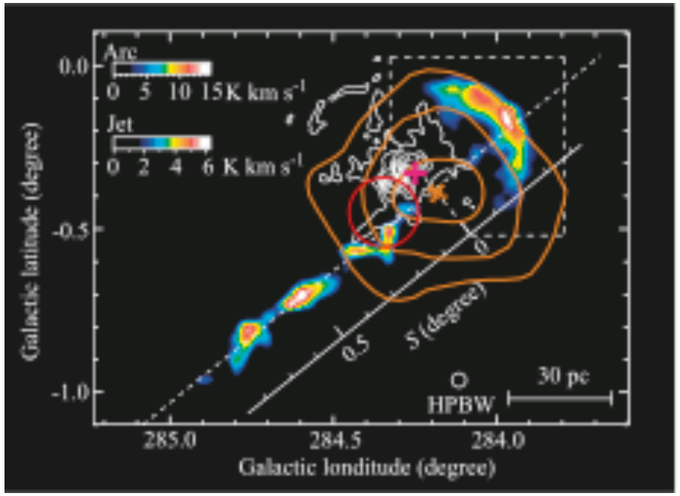
because of **GMCs** ?
Star Formation Regions ?

Westerlund-2: a rich young star cluster

gamma-ray source? - *colliding stellar winds, supernova shocks, PWN*

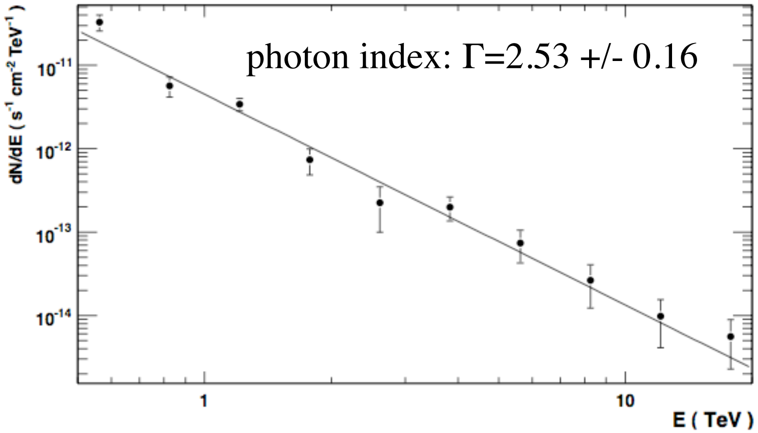
electrons, protons, nuclei, …

$L_\gamma=1.5\times10^{35}$ erg/s (d=8kpc)



NANTEN 2:

"jet" and "arc" in CO
anisotropic SN explosion
(a hypernova remnant?)



HESS:

IC ? a steep electron spectrum; $\alpha>4$
or a cutoff; modest energetics
L_X (1-10keV) < 5 10^{34} erg/s

Protons? $W_p=10^{50}\,(n\,/1\mathrm{cm}^{-3})^{-1}$ erg
a SN? provided flattening below 1TeV
steep spectrum - old source?

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

characteristic timescales:

$p+p \rightarrow \pi^0 \rightarrow \gamma\gamma$ $\quad t_{pp} \sim 10^{15}\,(n/1\mathrm{cm}^{-3})^{-1}$ sec

$e+2.7\,\mathrm{K} \rightarrow e\gamma$ $\quad t_{IC} \sim 4 \times 10^{12}\,(E/10\,\mathrm{TeV})^{-1}$ sec

e-bremsstrahlung $\quad t_{br} \sim 3 \times 10^{14}\,(n/1\mathrm{cm}^{-3})^{-1}$ sec

- IC is very effective as long as magnetic field $B < 10\,\mu G$
- Bremsstrhlung important in dense, $n > 10^2\ \mathrm{cm}^{-3}$, environments
- pp interactions dominate over Bremsstrahlung if the ratio of energy densities of protons to electrons $w_p/w_e > 10$ (almost always if the emitter is located far from the accelrator)

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, therefore angular size increases with energy

IC: very important are synchrotron energy losses;
generally angular size decreases with energy

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