

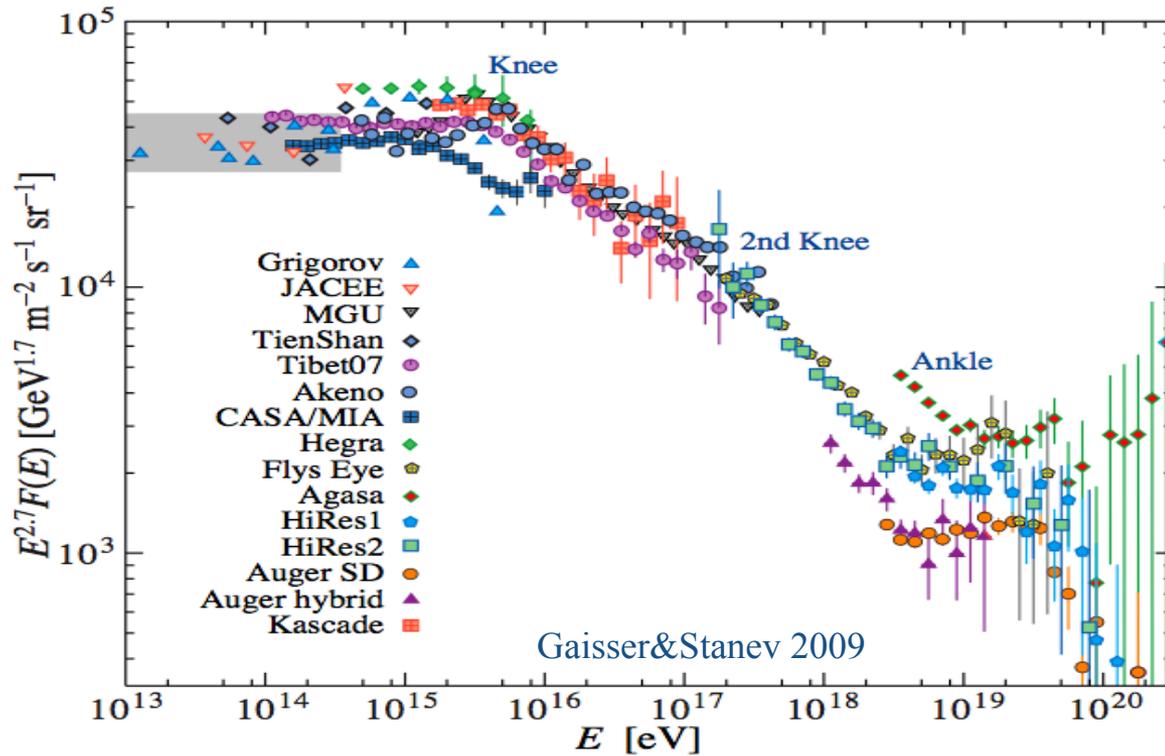
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# Cosmic particle acceleration after a decade of VHE gamma-ray observations

Felix Aharonian

Dublin Institute for Advanced Studies, Dublin, Ireland  
Max-Planck Institut f. Kernphysik, Heidelberg, Germany

## all particle cosmic ray spectrum



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

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

## introductory remarks

the problem, however, is somewhat exaggerated... perhaps it should not be anymore characterized as a “mystery” but rather as an “annoying uncertainty” regarding the major contributors to flux of the locally detected relativistic particles (aka CRs)

- now we know that ultra-relativistic particles, in general sense (not only CRs!), represent an equally important (in addition to matter, radiation and magnetic fields), substance of the visible Universe.
- gamma-ray observations of recent years revealed 10+ classes of effective Galactic and Extragalactic particle accelerators, some of them are feasible candidates to be called sources of CRs
- but the major contributors are not yet firmly identified; and this remains a high priority task for gamma-ray astronomy
- CTA is well designed to address this issue through deep(er) population studies, but this is not going to be an easy task

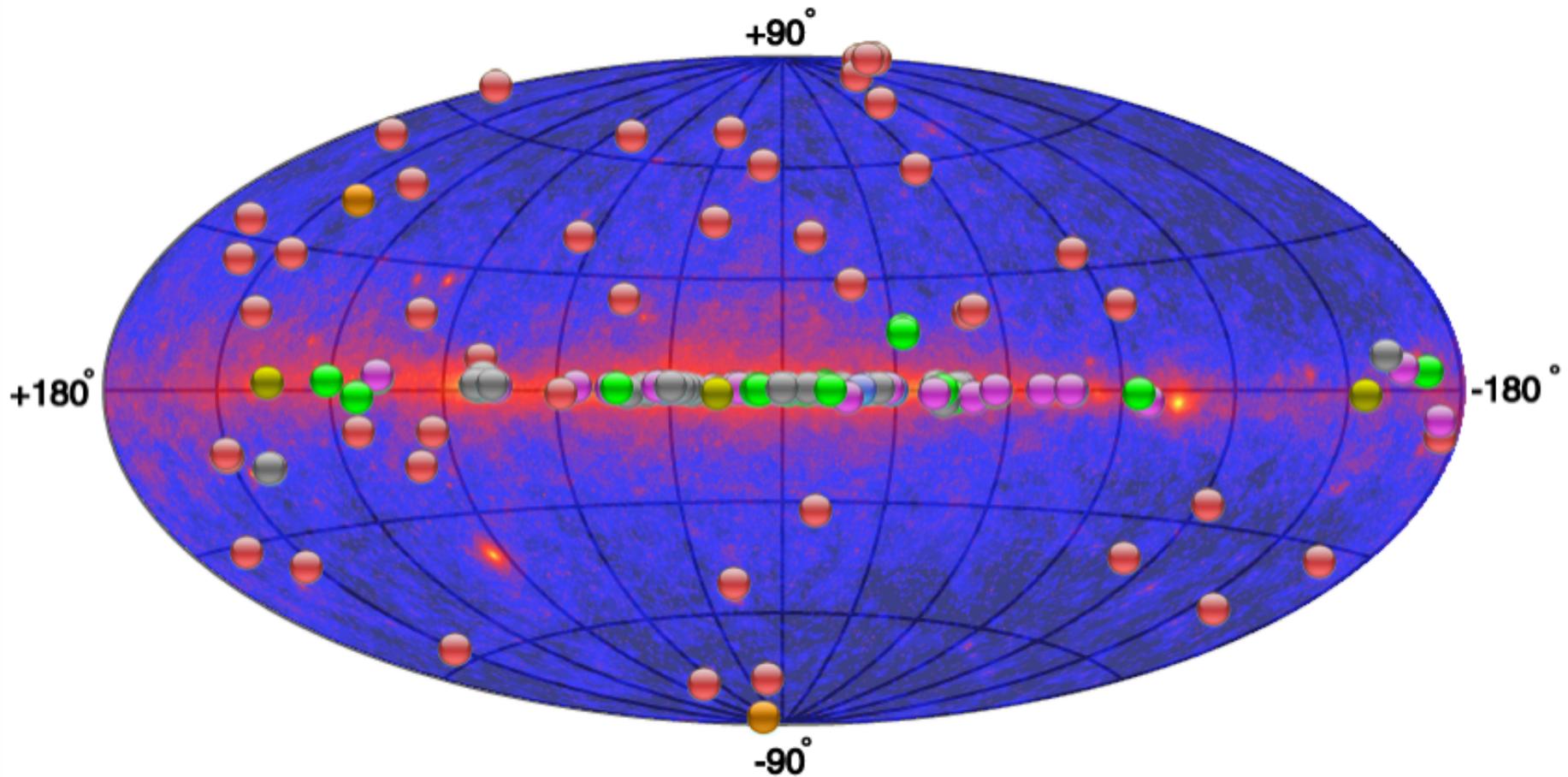
## introductory remarks

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

equally (or even more) important is the study of physics of individual TeVatrons & PeVatrons (for Galactic accelerators), and EeVatrons (for Extragalactic accelerators)

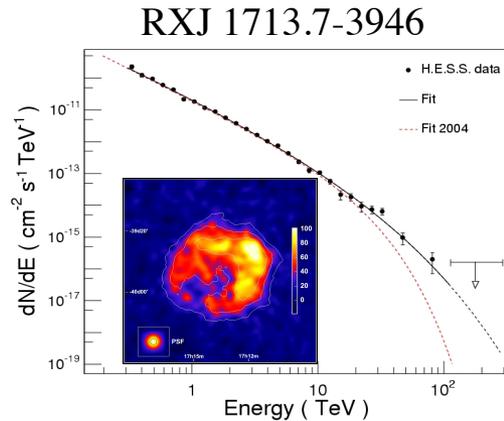
- current VHE gamma-ray observations demonstrate that particle acceleration to multi-TeV energies is widely spread phenomenon taking place with remarkable diversity; this concerns the acceleration mechanisms, type of sources, energetics, etc.
- some VHE sources are studied quite comprehensively, but even in the case of the strongest ones (“>0.1 Crab”) many important details (in lightcures, energy spectra, images) are missing - the clarification of these details should be one of the highest priorities of future VHE observations (“devil is in details”)

# TeV Sky

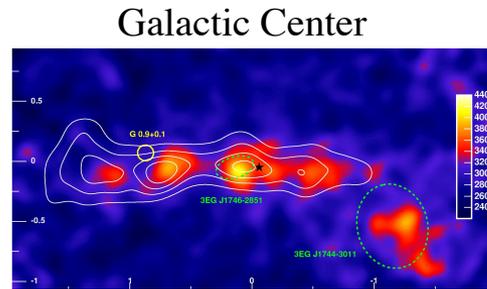


blue-to-red colors  $\rightarrow$  0.1 GeV – Fermi gamma-ray sky

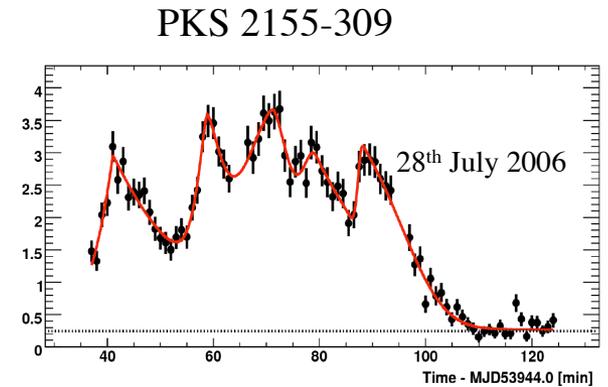
good performance/high quality data => modeling/theory



TeV image and energy spectrum of a SNR



resolving GMCs in the Galactic Center 100pc region



variability of TeV flux of a blazar on minute timescales

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

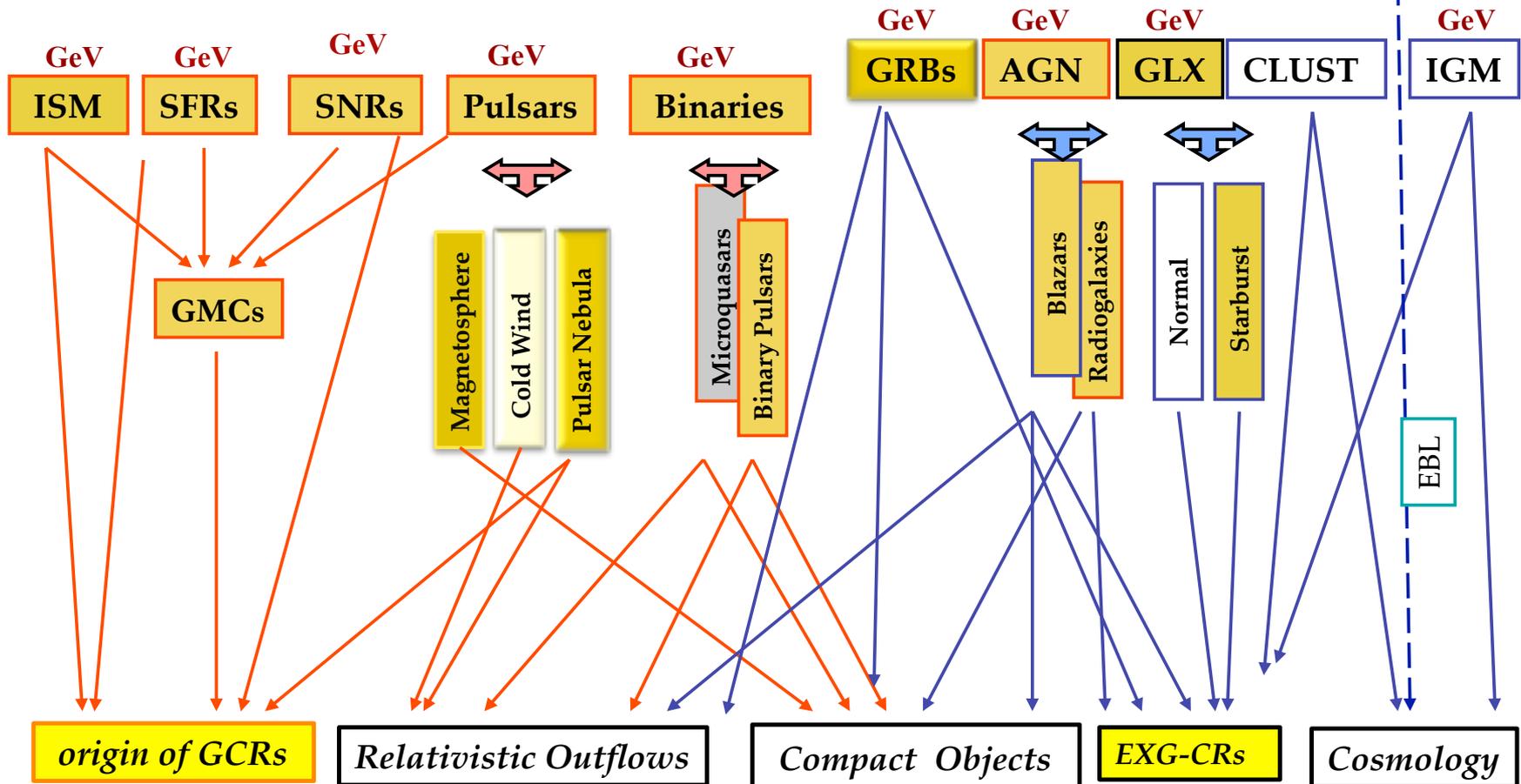
- ✓ **extended sources:** *from SNRs to Clusters of Galaxies*
- ✓ **transient phenomena**  *$\mu$ QSOS, AGN, GRBs, ...*

*Galactic Astronomy* | *Extragalactic Astronomy* | *Observational Cosmology*

Galactic

Potential VHE Gamma Ray Sources

Extragalactic



Major Scientific Topics

# VHE gamma-ray source populations

## Galactic Objects

- ✓ Shell Type SNRs
- ✓ Giant Molecular Clouds
- ✓ Star formation regions
- ✓ Pulsar Wind Nebulae
  
- ✓ Pulsars magnetospheres and/or Pulsar untouches winds
- ✓ Binary pulsars ( PRB 1259-63, also LS5039, LSI 61 303... ?)
- ✓ Accreting BHs/Microquasars? (Cyg X-1 ?)
- ✓

## Galactic Center

## Extragalactic objects

- ✓ Starburst galaxies (NGC 253 and M82)
- ✓ Radiogalaxies (M87, Cen A, NGC 1275) -
- ✓ TeV Blazars – with redshift from 0.03 to  $\sim 1$
- ✓ GRBs (Fermi LAT; photons of tens of GeVs at  $z > 1$ )

# Galactic Cosmic Rays:

## basic facts:

energy density:  $\sim 1\text{eV/cm}^3$ ; age:  $\sim 10^7$  yrs,

production rate:  $(0.3-1) \times 10^{41}$  erg/s, source spectrum: hard  $Q(E) \sim E^{-2}$

## sources ?

- ✓ SNRs: up to  $10^{15}$  or even  $5 \times 10^{18}$  eV for Fe for type IIb SNe (e.g. Ptuskin&Zirakashvili) but so far we do not have decisive evidence of SNRs operating as CR PeVatrons...
- ✓ collective stellar winds and SNR shocks in clusters and associations of massive stars (e.g. Cesarsky and Montmerle 1982, Bykov & Toptygyn 2001) GC?
- ✓ other potential sources? Galactic Center (Sgr A\*)? “GRB remnants”, pulsars?

*one cannot exclude that the observed CR flux up to  $10^{15}$  eV is significantly contributed (or even dominated) by a single (or a few) local sources (e.g. Erlykin&Wolfendale 2010), i.e. we see a “local fog”; this is the case of TeV electrons (e.g. Aharonian et al 1995)*

# Extragalactic Cosmic Rays

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

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

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

*“GZK cutoff” is not a cosmological effect!*

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

sources ?

go to the “Hillas Plot”, but don’t be misled - viable options are quite limited -

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

# Cosmic Ray Astrophysics with CRs?

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

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

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

**gamma-rays** and **neutrinos**, but partly also **neutrons**

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

do satisfy fully to these conditions;

\*astronomy with **protons?**: only for  $E \sim 10^{20}$  eV if IGMF  $B < 10^{-11}$  G

## why gamma-rays?

gamma-rays are unique carriers of astrophysical/cosmological information about high energy phenomena related to galactic and extragalactic sources

- ✓ are effectively produced in E-M and hadronic interactions
- ✓ are effectively detected by space- and ground-based instruments

(but... are fragile - effectively interact with matter, radiation and B-fields => information could arrive after significant distortion)

VHE gamma-ray detection technique - huge detection areas - potentially  $\gg 1\text{km}^2$  => huge photon statistics coupled with good ( $\sim 10\%$ ) energy resolution and good angular resolution (down to 1-2 arcmin) => spectrometry, morphology, timing sensitivity for point-like sources down to  $10^{-14}$  erg/cm<sup>2</sup>s; impressive by standards of modern astronomical instruments

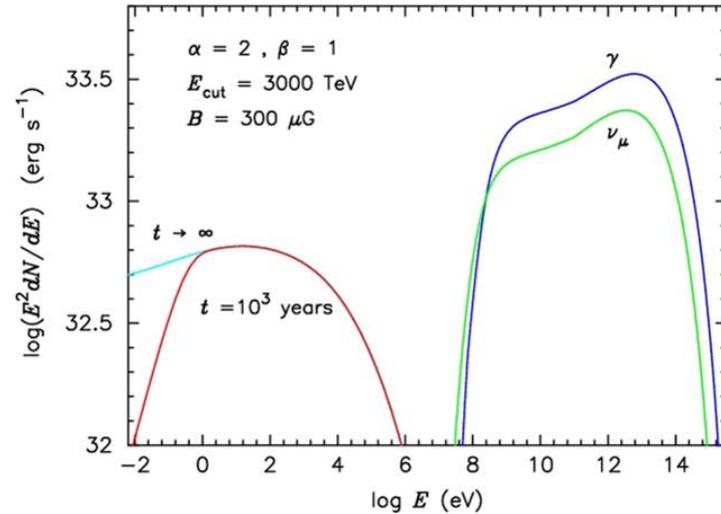
# a Galactic PeVatron: $E \sim 10^{15} \text{eV}$

three channels of information  
about cosmic PeVatrons:

10-1000 TeV gamma-rays

10-1000 TeV neutrinos

10 -100 keV hard X-rays



➤ **γ-rays:** difficult, but possible with future “10km<sup>2</sup>” area multi-TeV IACT arrays

➤ **neutrinos:** marginally detectable by IceCube, Km3NeT - don't expect spectrometry, morphology; uniqueness - unambiguous signature!

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

$$\sim \epsilon^{-(\alpha/2+1)} \exp[-(\epsilon/\epsilon_0)^{1/5}]$$

## a new window

# Probing hadrons with secondary hard X-rays

complementary to gamma-ray and neutrino telescopes

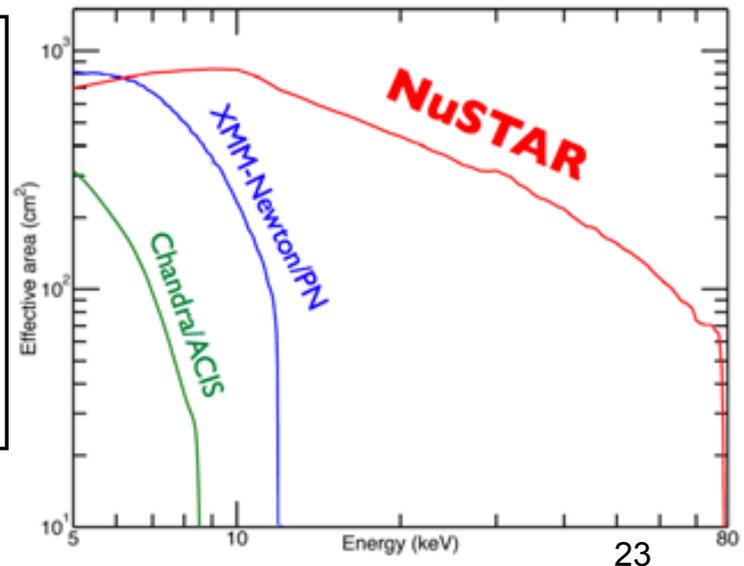
advantage - (a) comparable or better performance  
(b) compensates lack of neutrinos and gamma-rays at “right energies”

disadvantage - ambiguity of origin of X-rays

**Energy Band:** 3 - 80 keV  
**Angular resolution :**  
58" (HPD), 18" (FWHM)  
**Energy Resolution:** 0.4 keV  
at 6 keV, 0.9 keV at 60 keV  
(FWHM)



- X-ray imaging and spectroscopy in the hard X-ray band
- angular resolution one arcmin (10")
- Minimum detectable energy flux down to  $10^{-14}$  erg/cm<sup>2</sup>s !



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## questions beyond the origin of CRs - physics of Extreme Accelerators (MHD, electrodynamics, plasma physics...)

*machines where acceleration proceeds with efficiency close to 100%*

(i) fraction of available energy converted to nonthermal particles

*in PWNe and perhaps also in SNRs and AGN can be as large as 50 %*

(ii) maximum (theoretically) possible energy achieved by individual particles

*acceleration rate close to the maximum (theoretically) possible rate*

sometimes efficiency can even “exceed” 100% ?

(no violation of conservation laws - but due to relativistic and non-linear effects)

analogy with X-ray Astronomy:

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

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# SNRs and Galactic Cosmic Rays

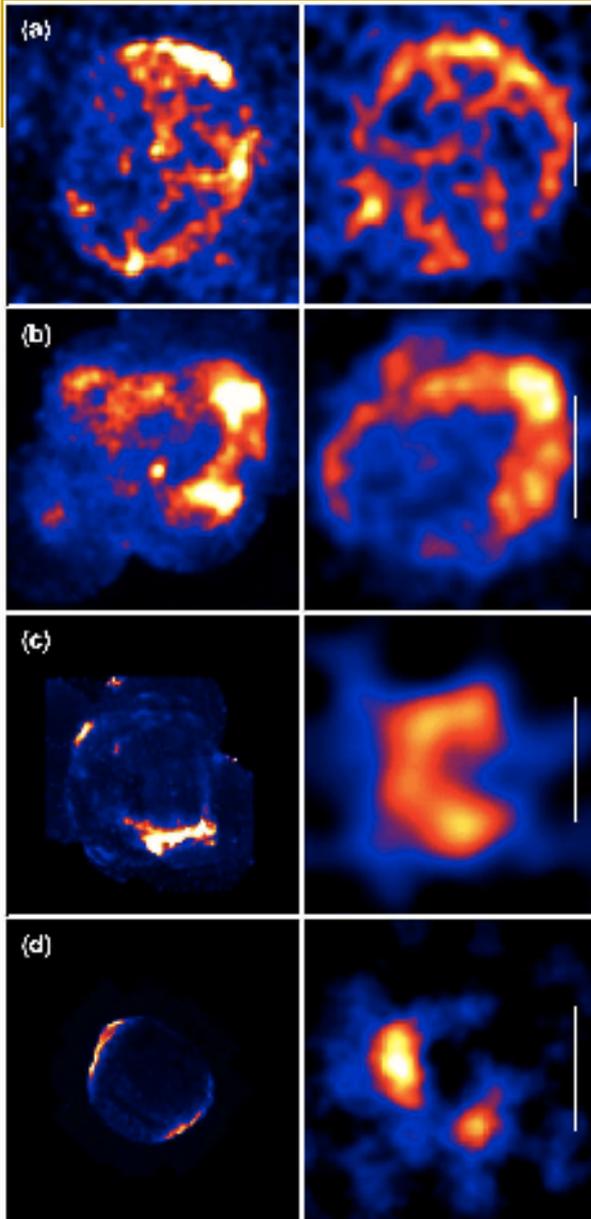
SNRs as the most likely sources  
of galactic cosmic rays?

main hope is related to gamma-ray observations:

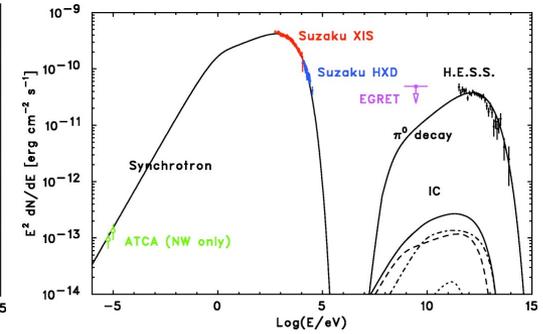
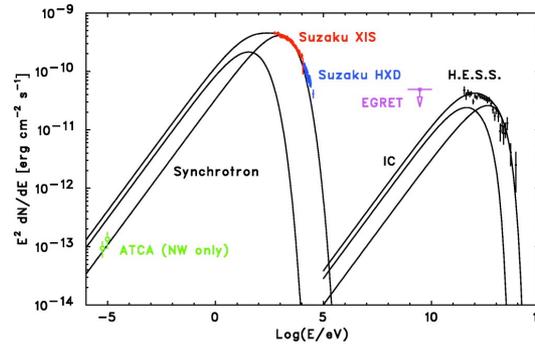
- ❑ detect VHE gamma-rays from SNRs
  - ❑ demonstrate that they have hadronic origin
  - ❑ demonstrate that proton spectra continue up to 1 PeV
-

# acceleration of protons and/or electrons in SNR shells to energies up to 100TeV

leptonic or hadronic?



⇒



inverse Compton scattering  
of electrons on 2.7K CMBR

$\gamma$ -rays from  $pp \rightarrow \pi^0 \rightarrow 2\gamma$

$$B=15\mu\text{G}$$

$$dN/dE=A E^{-\alpha} \exp(-E/E_0)$$

with  $\alpha=1.7$ ,  $E_0 \approx 25 \text{ TeV}$ ,

$$B=200\mu\text{G}$$

$$W_e \approx 3.4 \cdot 10^{47} \text{ erg/cm}^3$$

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

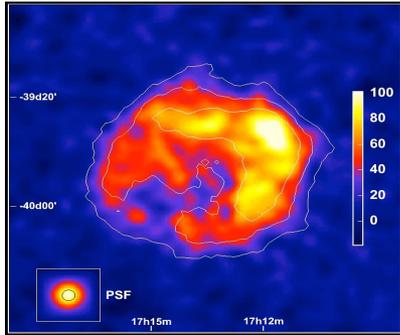
unfortunately we cannot give preference to  
hadronic or leptonic models - both have  
attractive features but also serious problems

solution? detection of more sources, broader energy coverage, and search for neutrinos

RXJ 1713.7-4639

# modeling of broad-band SEDs:

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



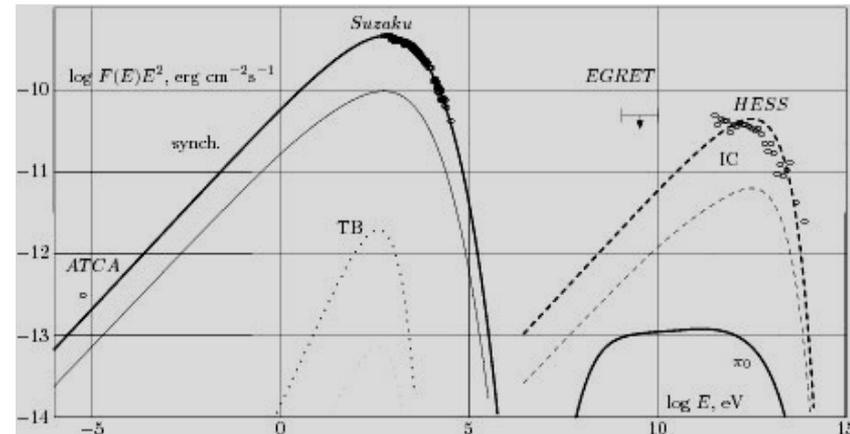
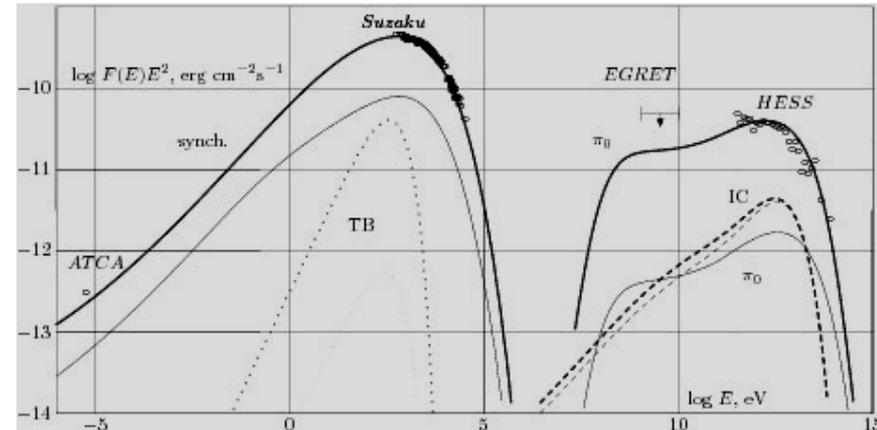
## hadronic model

- good spectral fit, reasonable radial profile, but ...
- (1) lack of thermal emission - possible explanation?  
>70% energy is released in acceleration of protons!
- (2) very high p/e ratio ( $10^4$ )

## leptonic model

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

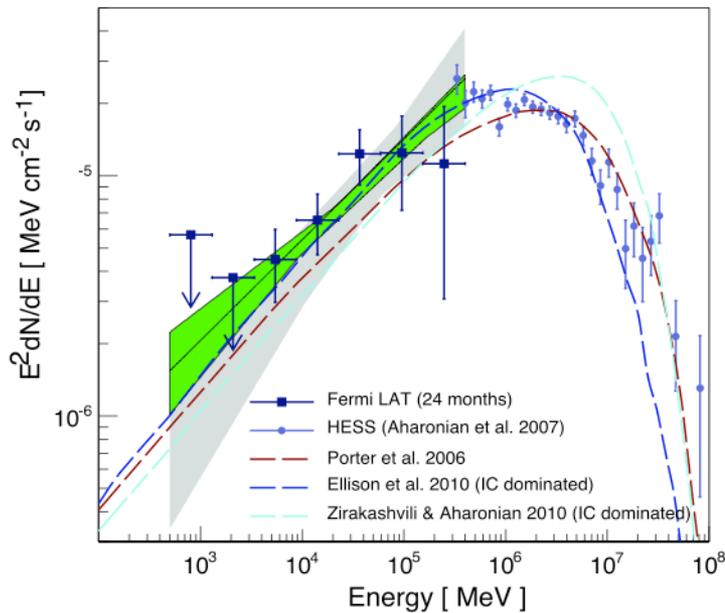
both forward&reverse shock contribute to  $\gamma$ -rays



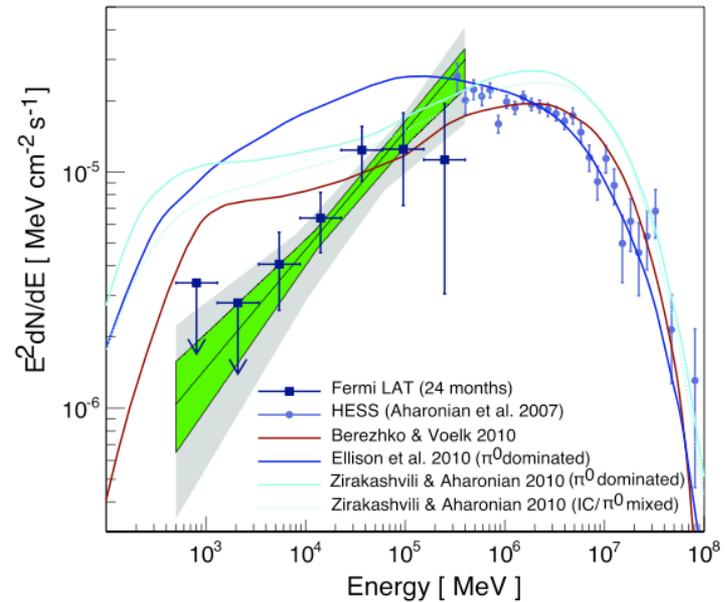
Zirakashvili, FA 2010

gamma-rays detected by Fermi? very important... but not decisive

# Fermi: GeV data contradict hadronic origin of $\gamma$ -rays (?)



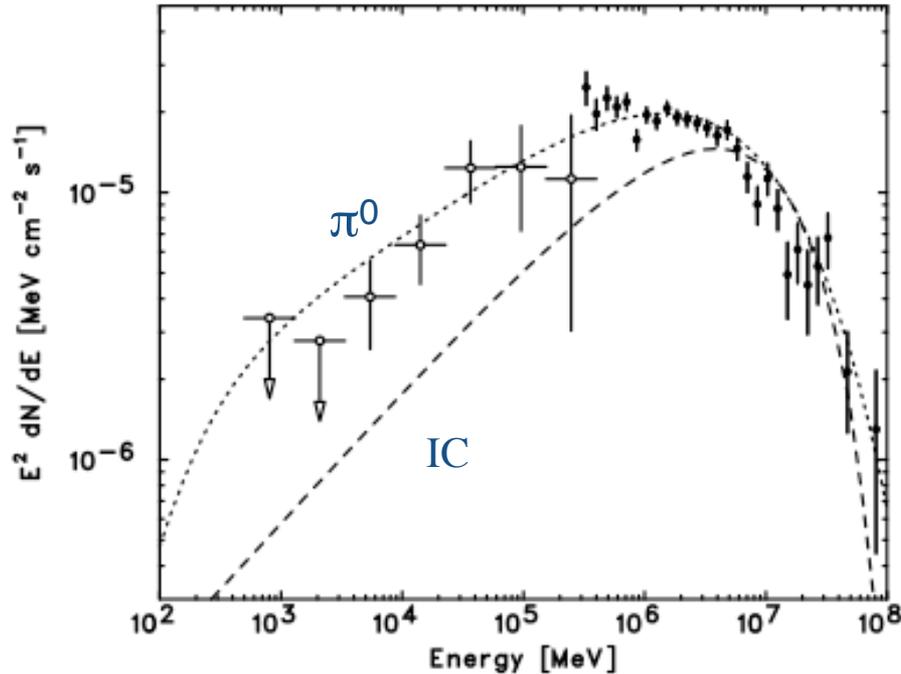
leptonic models



hadronic models

- Questions:
- (i) can we compare GeV and TeV fluxes within one-zone models?  
*they could come from quite different regions*
  - (ii) cannot we assume hard proton spectra ?  
*nonlinear theories do predict very hard spectra with  $\alpha \rightarrow 1.5$*

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



data: HESS and Fermi LAT

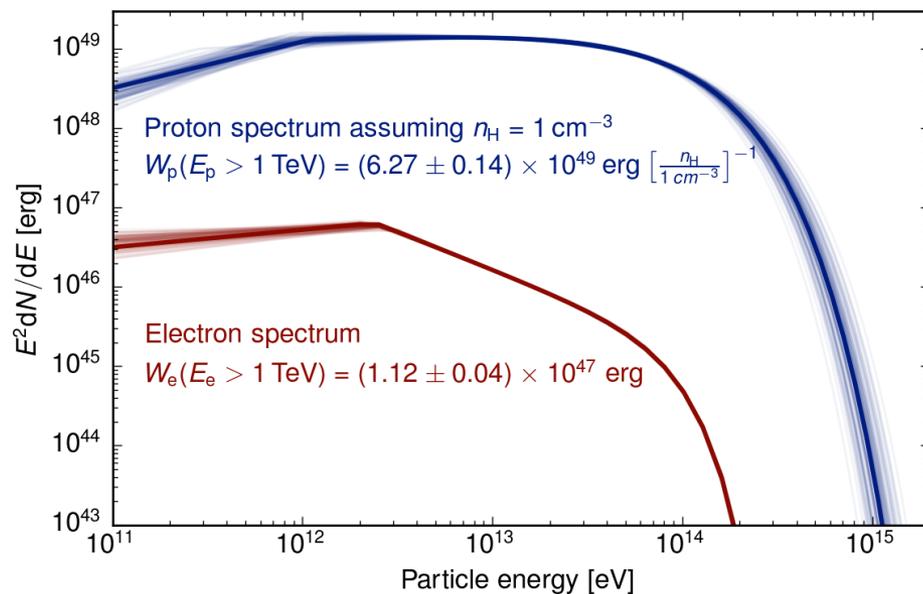
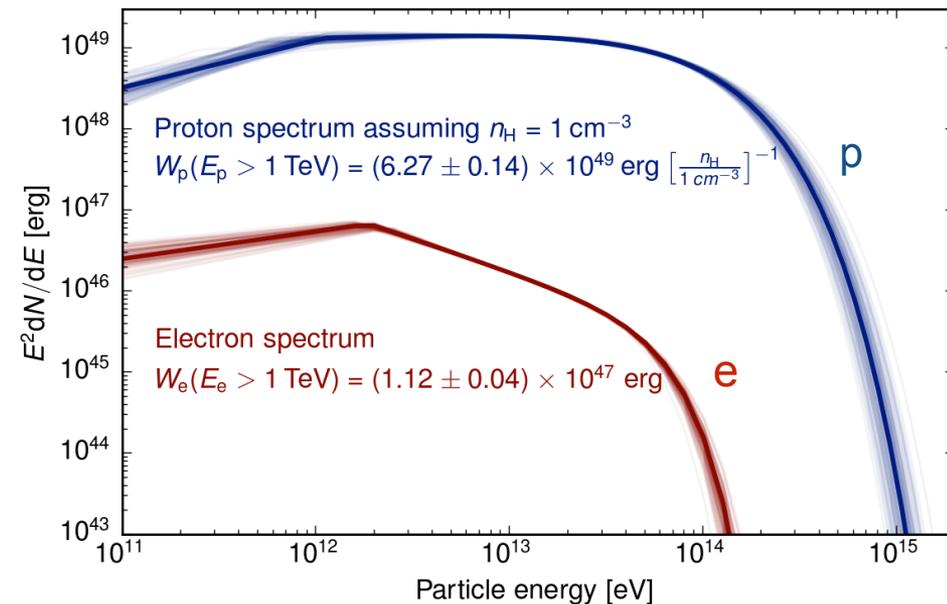
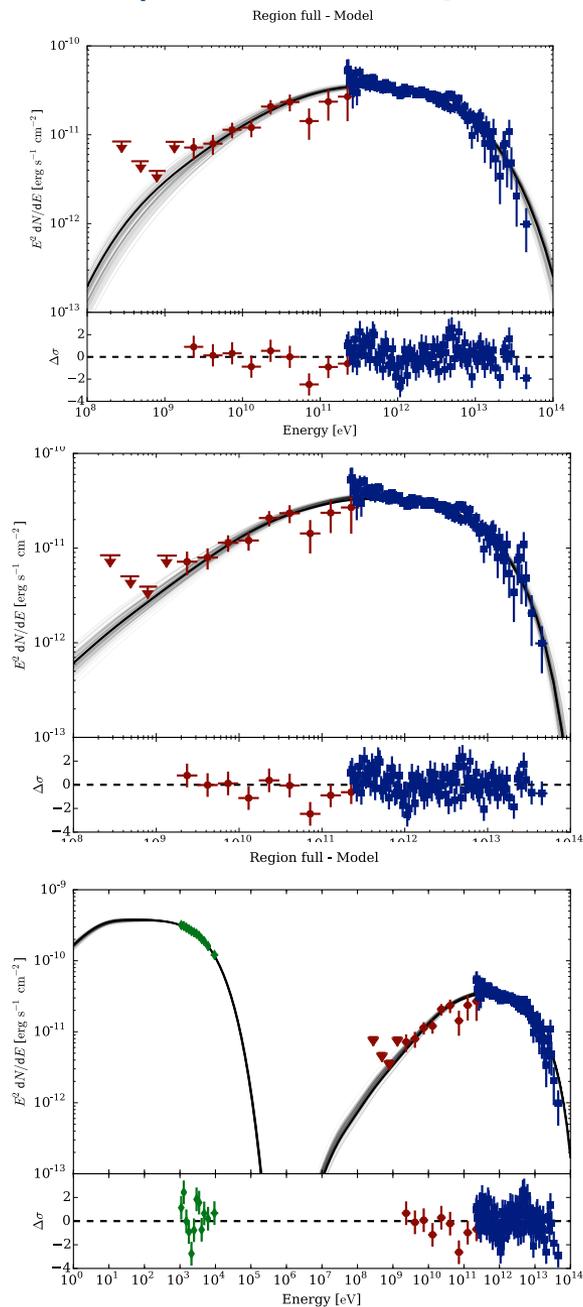
phenomenological curves: Tanaka et al. 2008

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

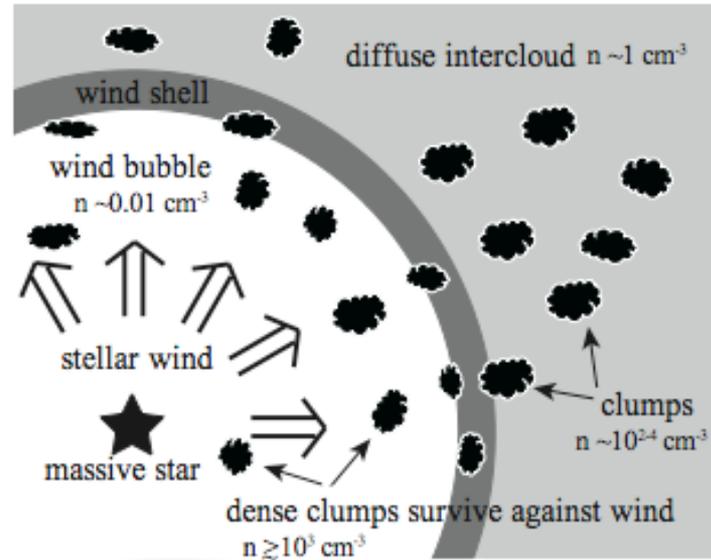
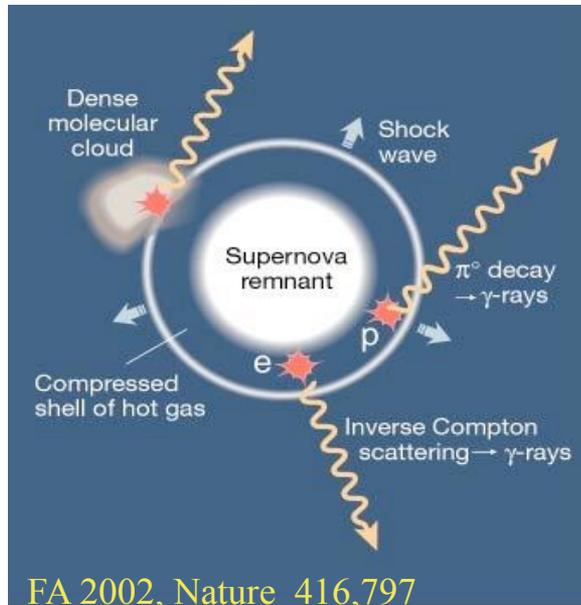
“the story of the death of hadronic origin of  $\gamma$ -rays has been greatly exaggerated”

# HESS update (see Egert et al.)

# model-independent spectra of p and e (see V. Zabalza)



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

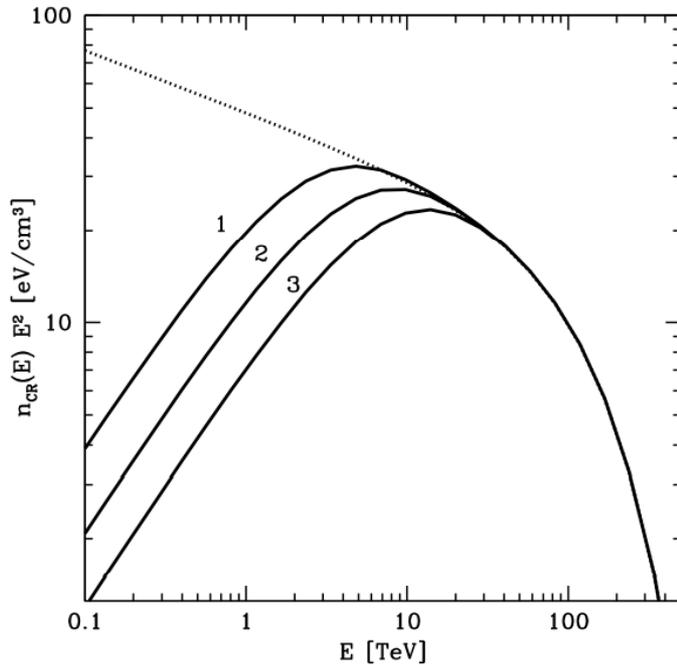


Inoue et al. 201, ApJ

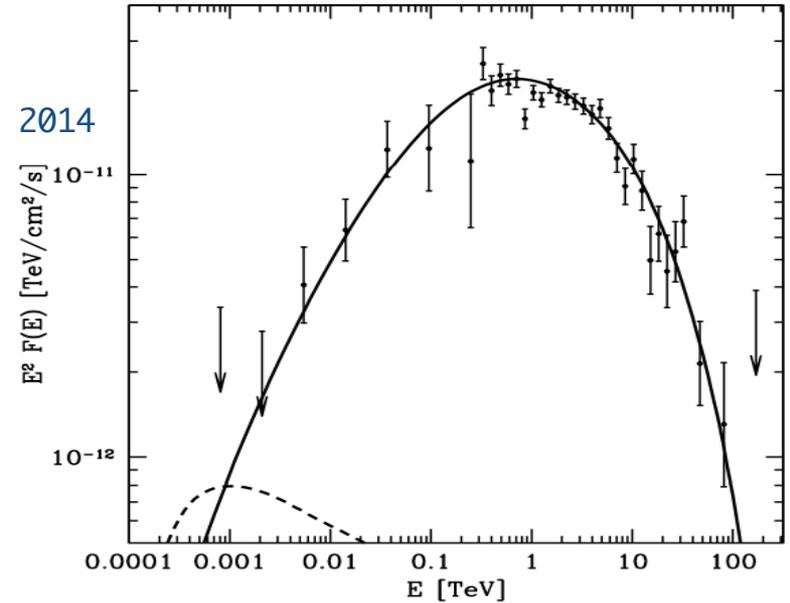
*Fermi LAT - important, but only neutrinos, ultra-high energy gamma-rays and hard synchrotron X-rays from secondary electrons can provide decisive conclusions*

*propagation effects in clumps* can, in principle, explain Fermi LAT – HESS spectral points from 1 GeV to 100 TeV and, possibly, also the lack of thermal X-ray emission

Gabici&FA 2014



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



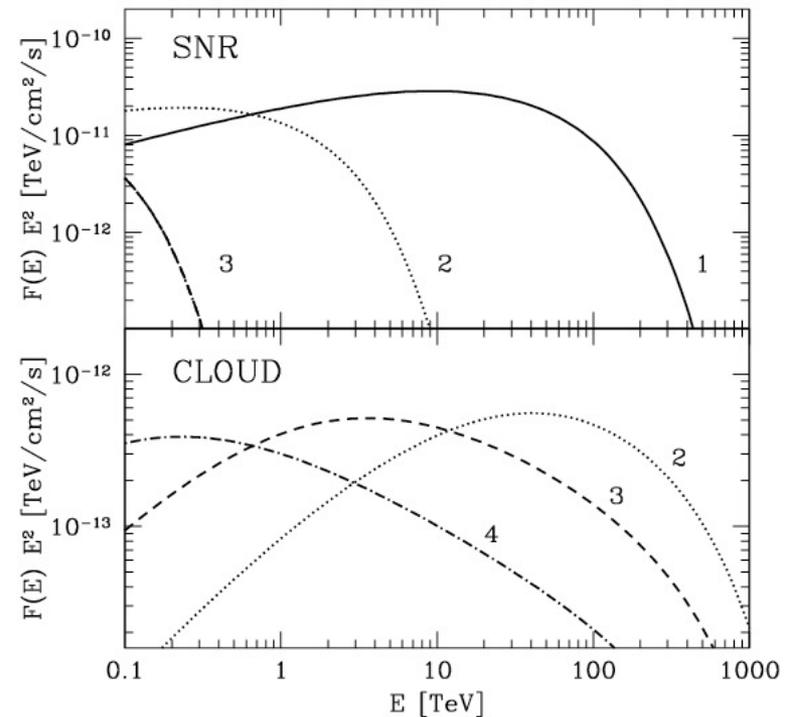
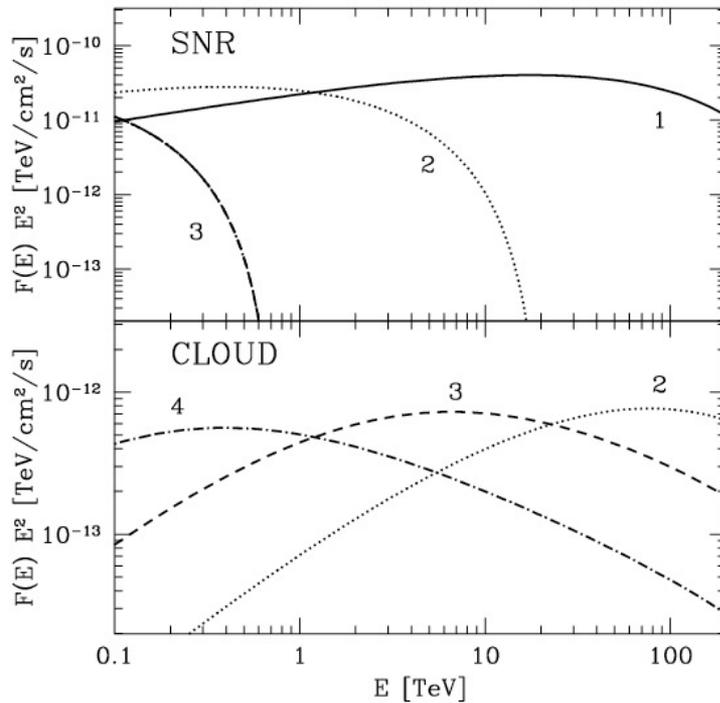
**Figure 2.** Gamma-rays from RX J1713.7-3946. The emission from the clumps is shown as a solid line, while the dashed line refers to the emission from the diffuse gas in the shell. Data points refer to *FERMI* and *HESS* observations.

# 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

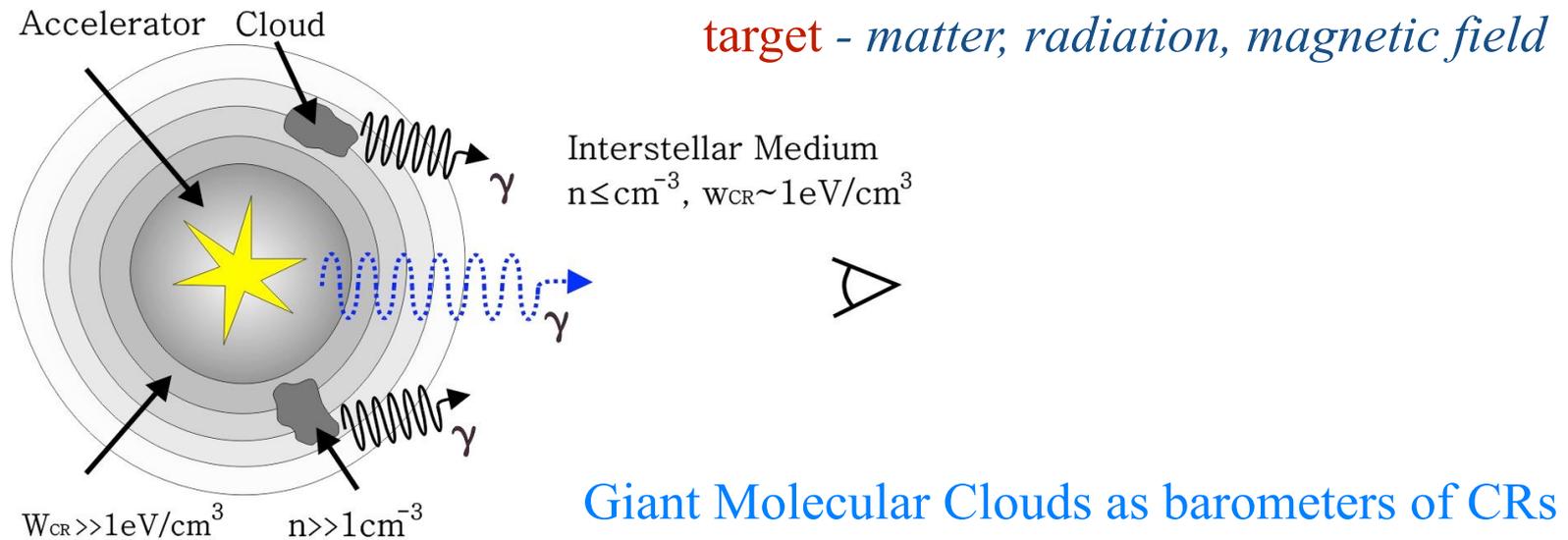
GMC:  $M=10^4 M_\odot$   $d=100$ pc

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

S. Gabici & FA 2007

gamma-ray production: particle accelerator + target

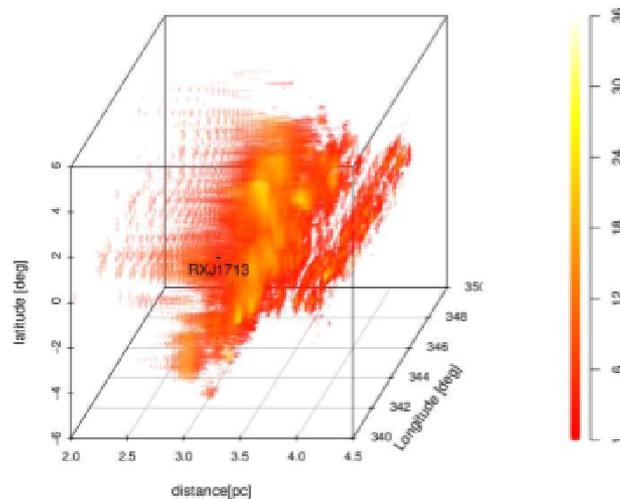
existence of a powerful particle accelerator by itself is not sufficient for  $\gamma$ -radiation; an additional component - a dense target - is required



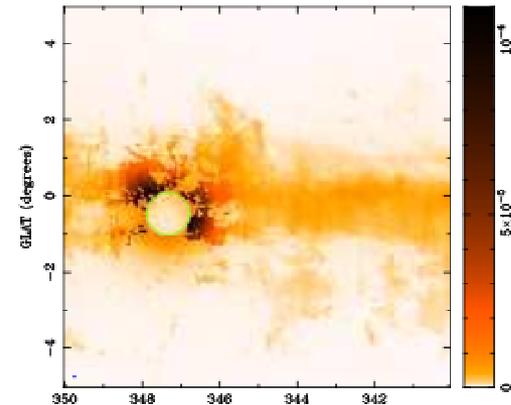
*any gamma-ray emitter coincides with the target, but not necessarily with the “primary” source/particle-accelerator*

# how to find the “missing PeV protons in SNRs?”

highest energy particles,  $E > 100$  TeV, are confined in the shell only during a few 100 years => most promising search for PeVatrons?  
multi-TeV  $\gamma$ -rays from dense gas clouds in the near neighborhood



**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  $50 \text{ pc} < l_d < 30 \text{ kpc}$ , as observed by the NANTEN and LAB surveys, expressed in protons  $\text{cm}^{-3}$ . The distance axis is logarithmic 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  $\text{cm}^{-3}$  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:**

model of Zirakashvili&Ptuskin 2008

**diffusion coefficient outside SNR:**

$$D=10^{26} (E/10\text{GeV})^{0.5} \text{ cm}^2/\text{s}$$

## a few comments on the hadronic scenario:

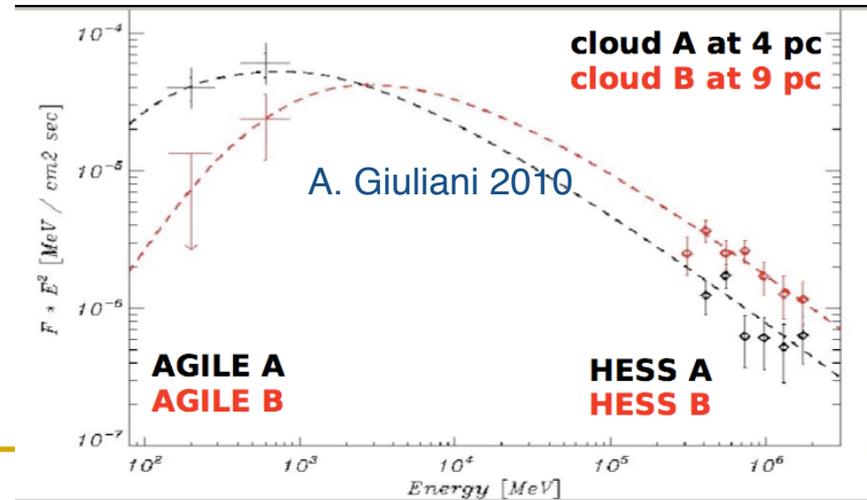
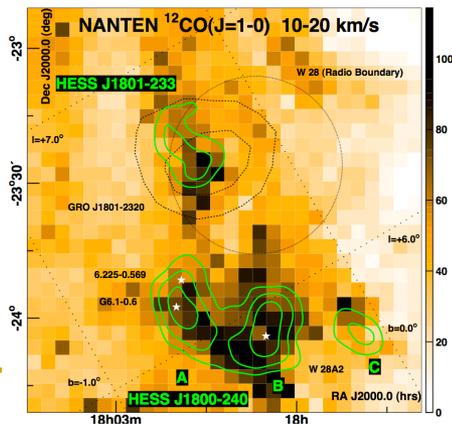
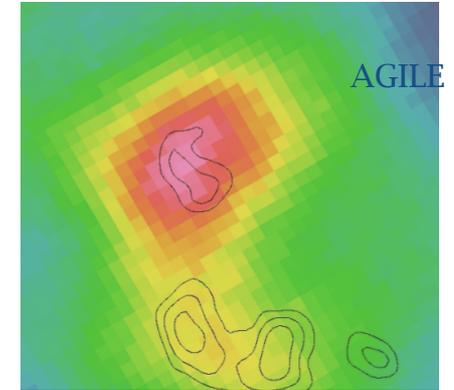
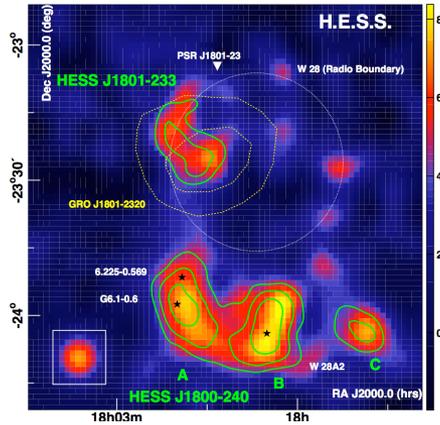
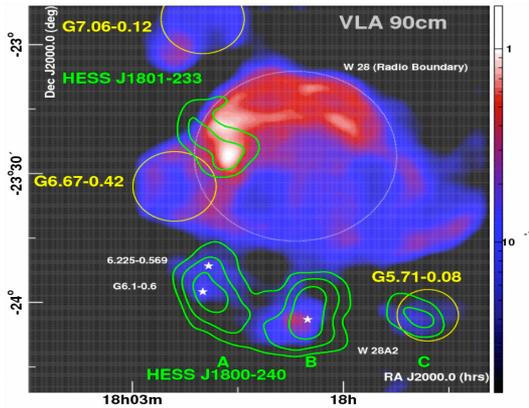
- **lack of thermal emission** in RXJ 1713.7-3946  
*almost all available energy goes to particle acceleration?* (Drury et al 2010)
- **p/e ratio  $> 10^3$**  - cosmic rays p/e  $\sim 100$   
*in Cas A p/e in principle could be 100, but could be also less than 10*
- **“early cutoffs”** - in all SNRs  $E_{\text{cut}} < 100 \text{ TeV}$

because of escape? do they contribute to the the region around the “knee”  
HESS: it seems there is a component beyond the shell in RXJ1713 if so

- it would be important to measure the gamma-ray (and the secondary hard synchrotron X-ray) spectrum related to the escaping protons
- to derive the diffusion coefficient from the hard X-ray data from the shell (NuSTAR, ASTRO-H) compare with the gamma-ray spectrum inside and outside the shell (CTA?)

# GeV TeV gamma-ray sources around mid age W28:

*CRs from an old SNR interacting with nearby clouds?*



# warning: don't be tricked by propagation effects!

transition from rectilinear to diffusive regime of propagation

Aloisio, Berezhinsky, Gazizov 2009, Prosekin, Kelner, FA 2015

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

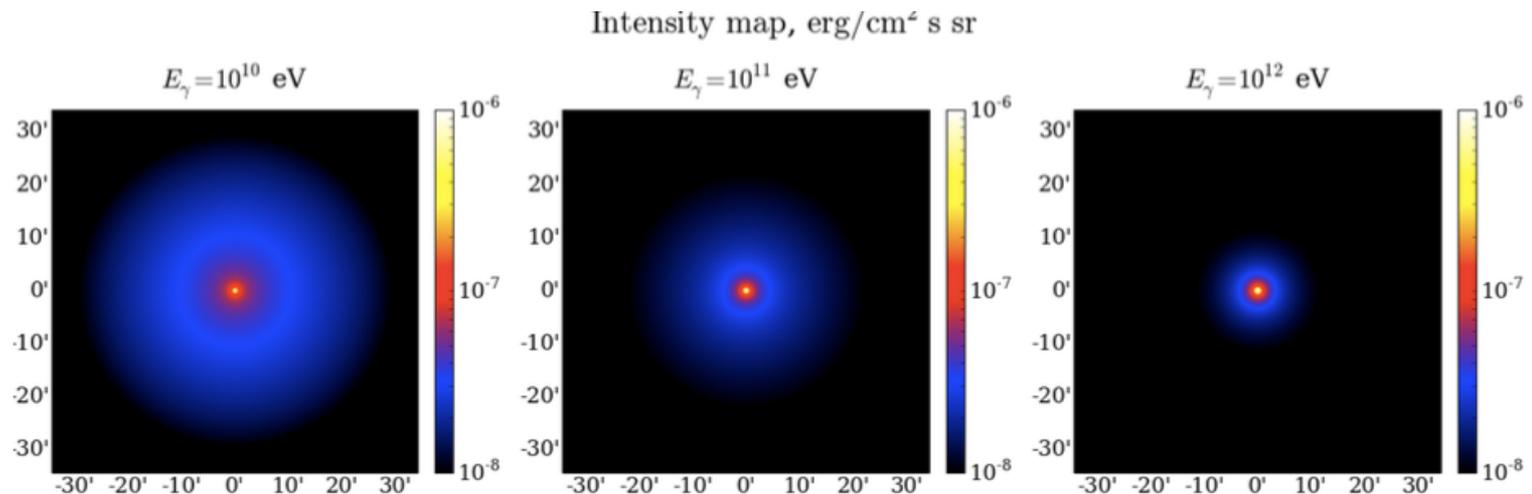
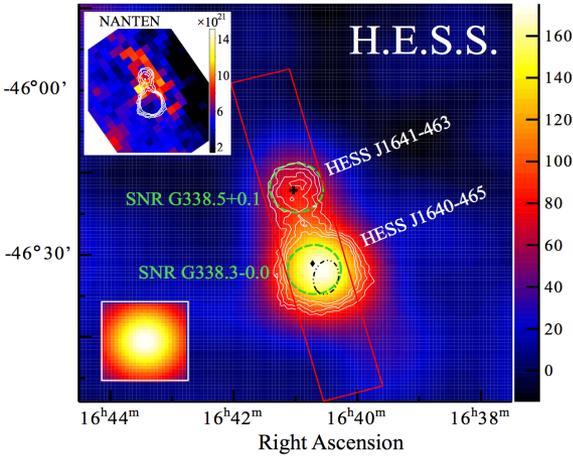


Figure 2: The intensity maps of gamma-ray emission at different energies. The spherical cloud with homogeneous density distribution is irradiated by the cosmic-ray source located in its centre. The gas density inside the accelerator is assumed very low, so the contribution of the accelerator to the gamma-ray emission is negligible. The maps are produced for the case of small diffusion coefficient (for details, see the text). For the distance to the source  $d = 1$  kpc, the region of  $\sim 1^\circ \times 1^\circ$  corresponds to the area  $\sim 20 \times 20$  pc<sup>2</sup>.

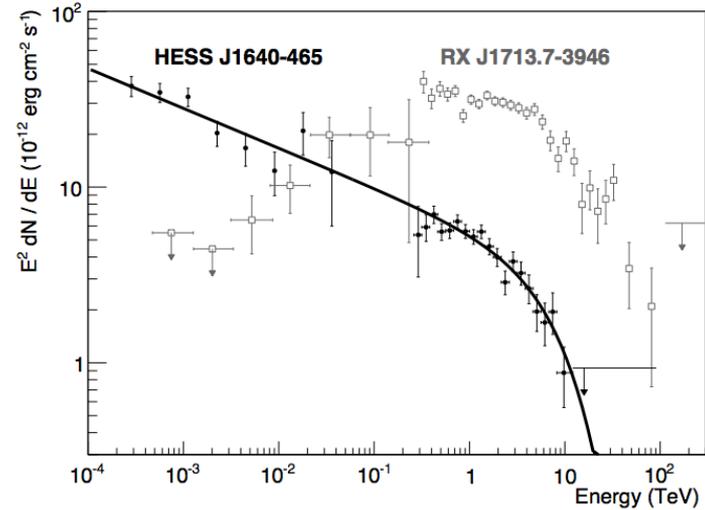
Prosekin et al. 2015

HESS J 1640-465/HESS J1641-463

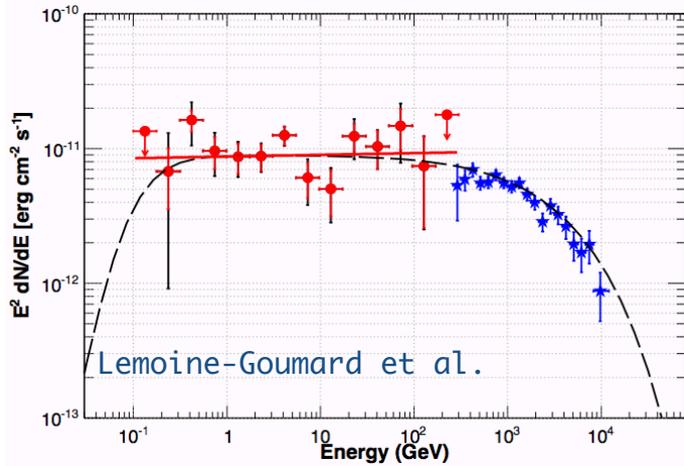
HESS 1640-465: the most luminous galactic VHE source !



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



HESS collaboration, ApJ, vol. 794, L1

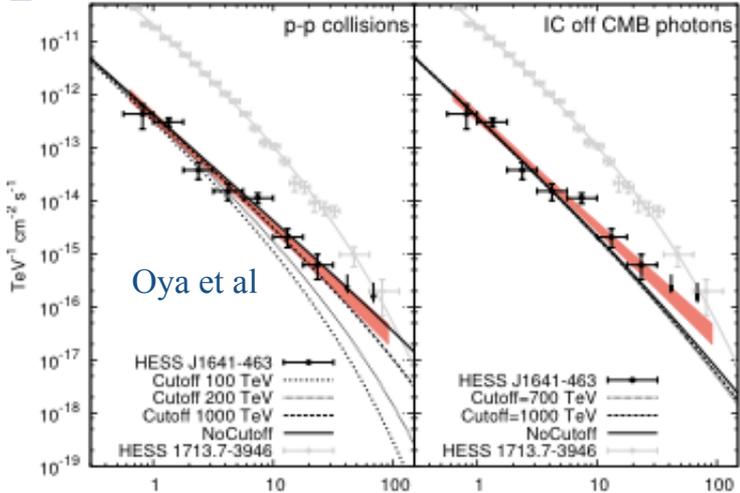


strong argument in favor of hadronic origin of gamma-rays in a SNR?

$L_\gamma = 4.8 \cdot 10^{35}$  erg/s ;  $W_{cr} \sim 10^{50}$  erg  $\Rightarrow$  target gas density  $n > 100$   $cm^{-3}$  !

another very luminous SNR N132 D in LMC -  $L_\gamma = 10^{35}$  erg/s - origin of the target?

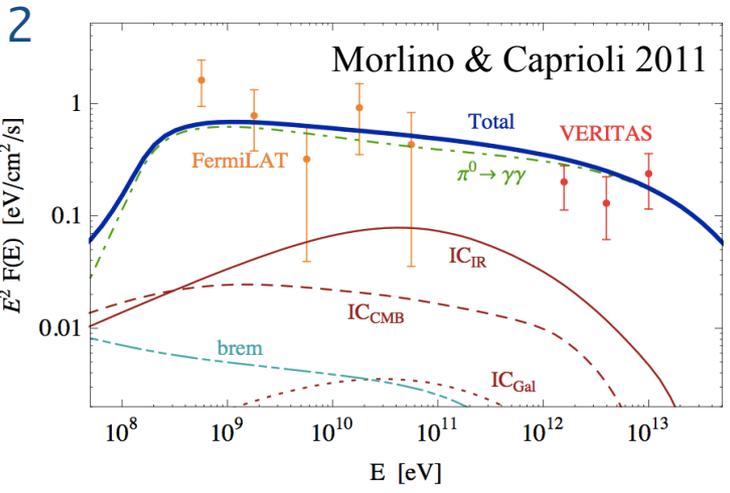
# 1 HESS 1641-463



# SNR candidates for PeVatrons?

a weak but very hard spectrum up to 20 TeV

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



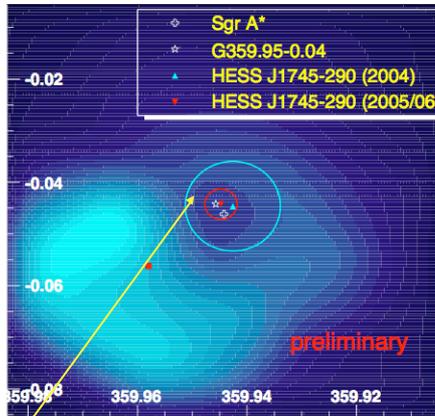
Tycho !

deserves more observations  
 for a better statistics/quality

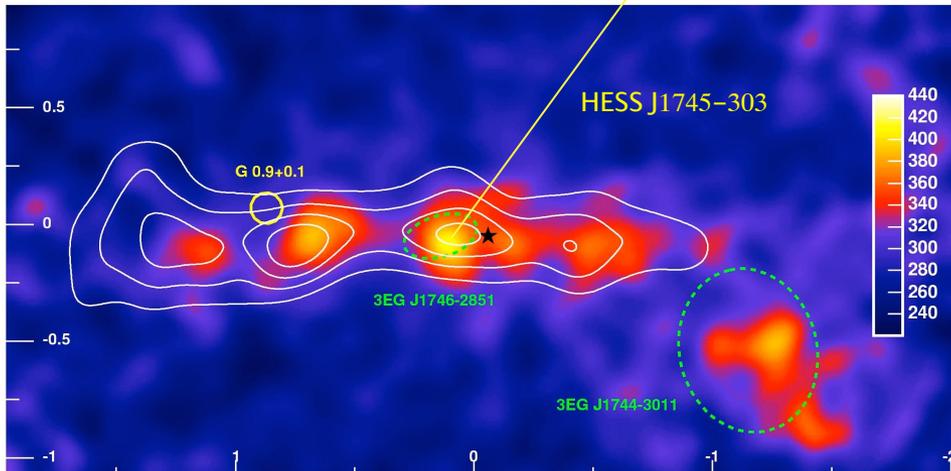
3 Westerlund 1 - a hard HESS source with a spectrum up to ~10 TeV:  
 a starburst regions with multiple powerful winds of young massive stars and  
 a supernova remnant - favorable sites for high-energy CR acceleration  
 and gamma-ray and neutrino production (Bykov et al. 2015)

# TeV gamma-rays from GC

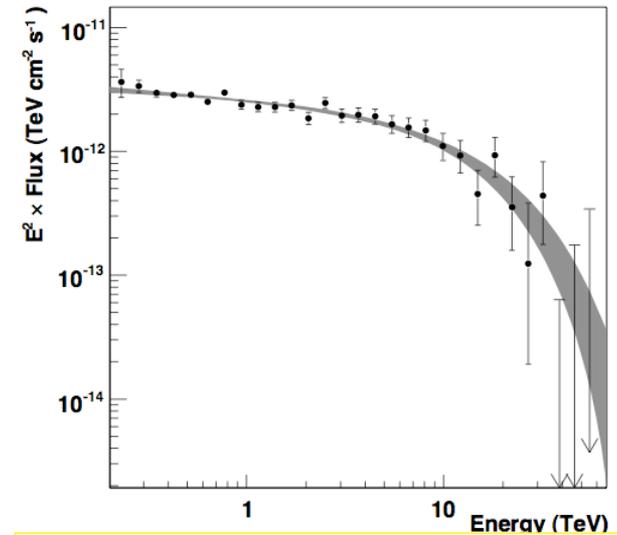
90 cm VLA radio image



$\gamma$ -ray emitting clouds



Sgr A\* or the central diffuse < 10pc region or a plerion?



Energy spectrum:

$$dN/dE = A E^{-\Gamma} \exp[(-E/E_0)^\beta]$$

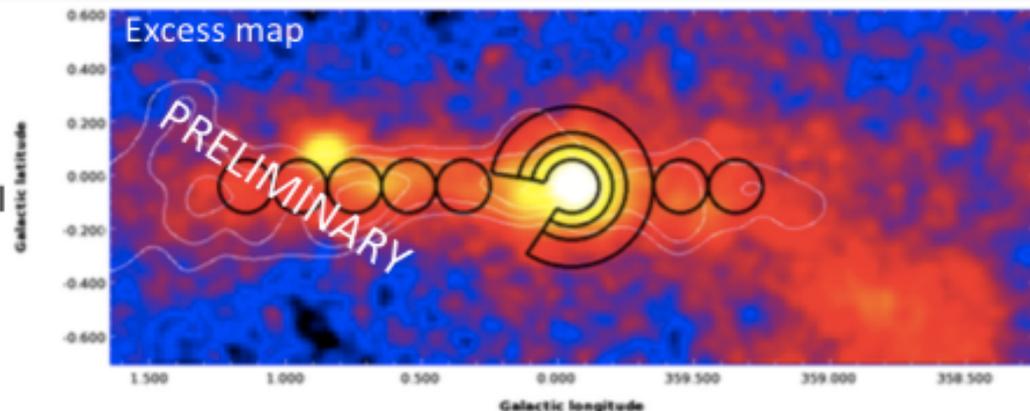
$$\beta=1 \quad \Gamma=2.1; E_0=15.7 \text{ TeV}$$

$$\beta=1/2 \quad \Gamma=1.9 \quad E_0=4.0 \text{ TeV}$$

new!

# Cosmic-ray density distribution

- Correlation with molecular clouds  
=> pp interaction target mass (M)
- Gamma-ray luminosity (L) in several regions
- => CR density  $\propto L/M$

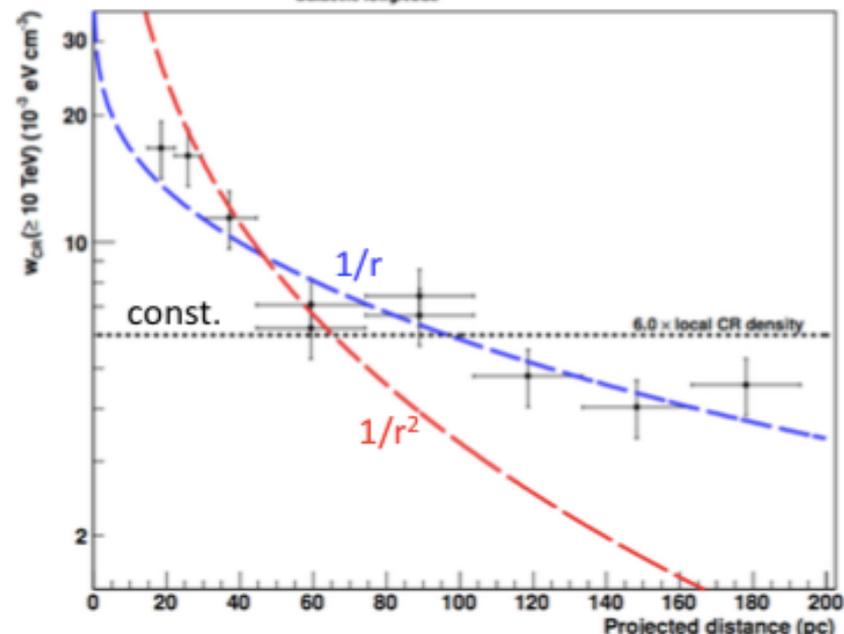


CR density radial distributions:

- Homogeneous => Impulsive injection of CRs and diffusive propagation
- $1/r^2$  => Wind-driven propagation
- $1/r$  => continuous injection and diffusive propagation

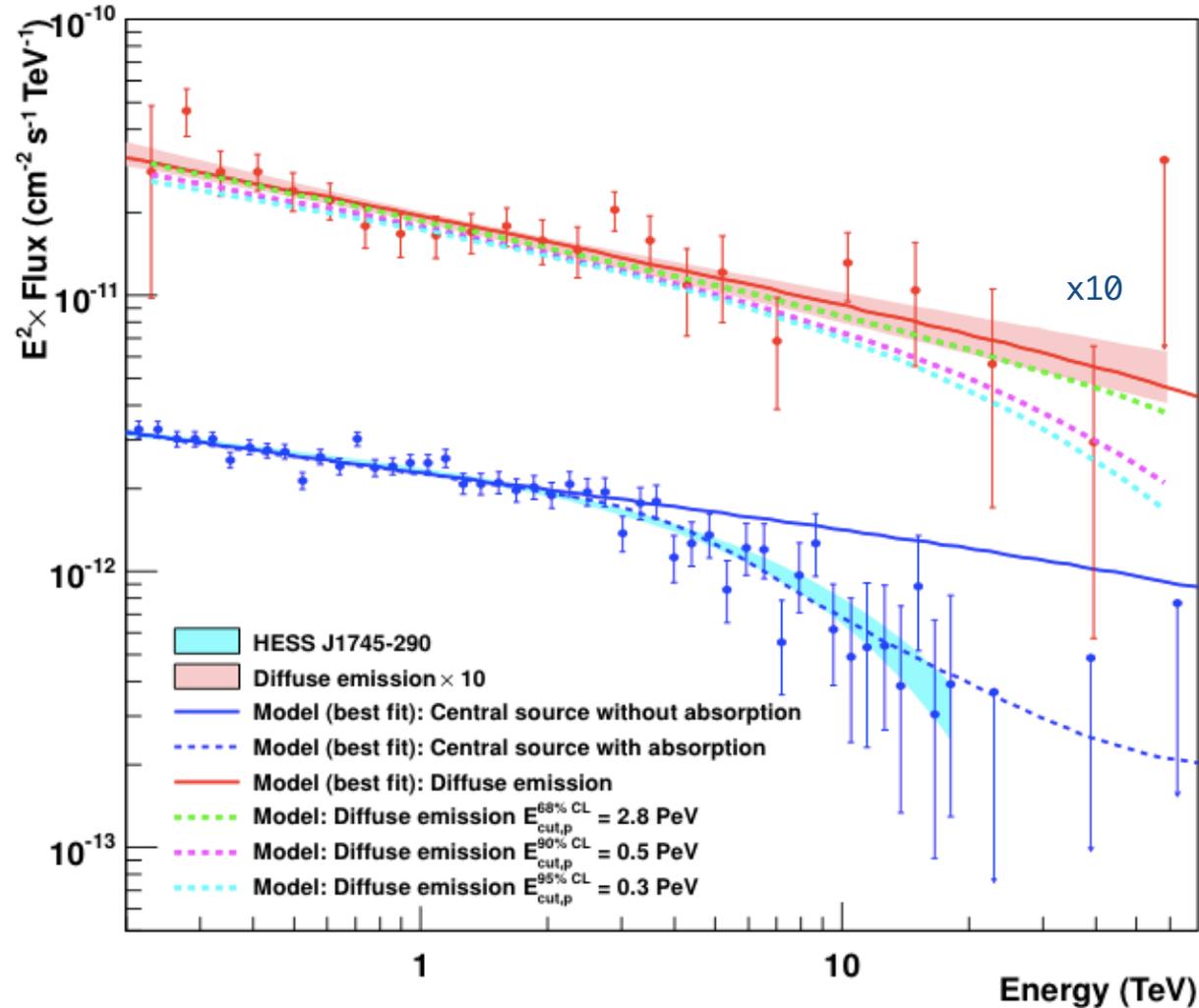


**Central accelerator located within 10 pc and injecting CRs continuously for > 1 kyrs**

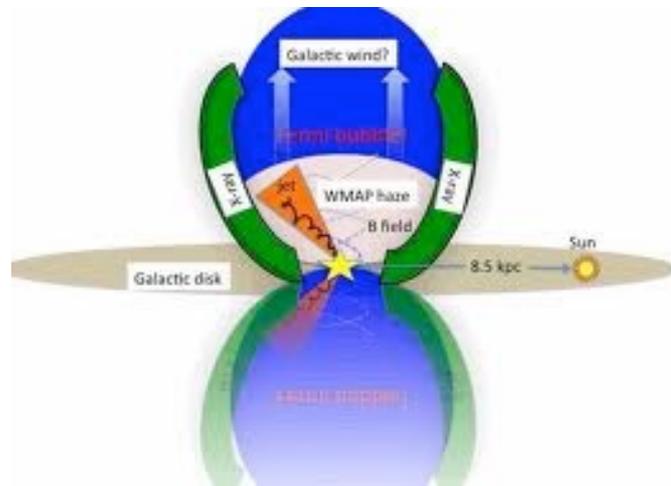
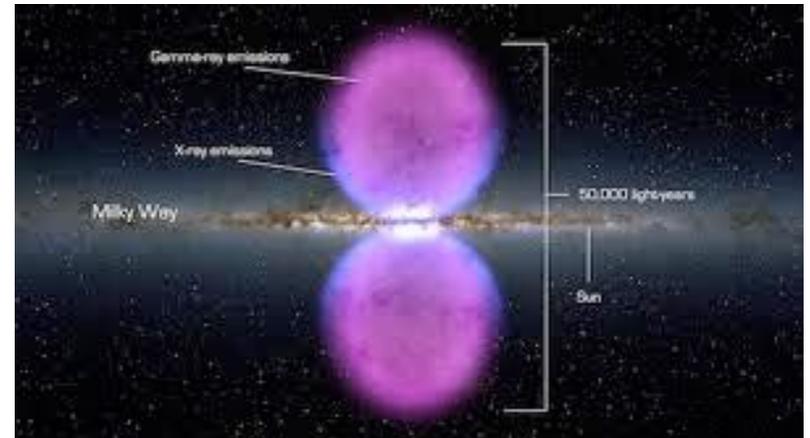
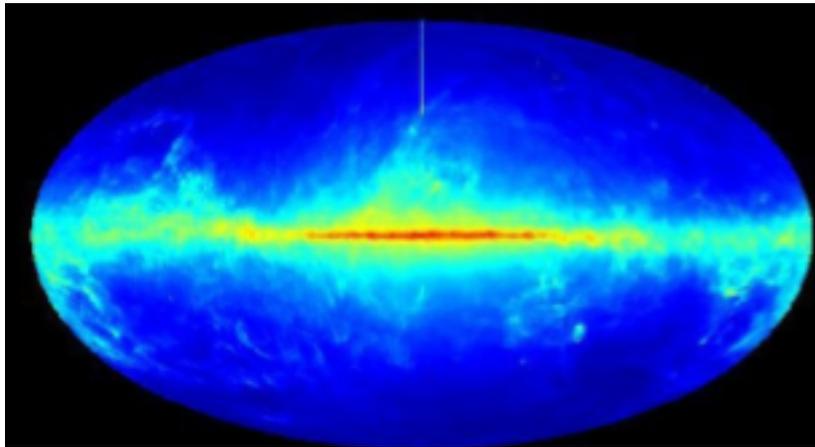


new!

## GC: the central source and the diffuse emission of CMZ



# CRs from GC responsible for Fermi Bubbles?

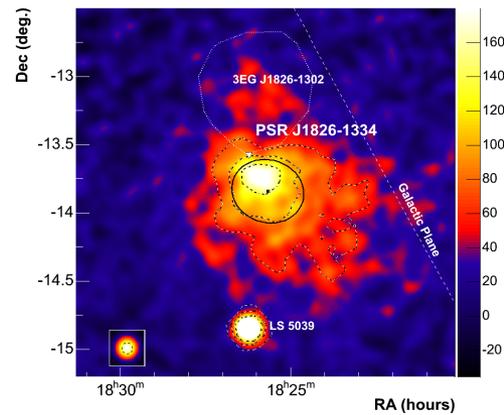


## Conclusions:

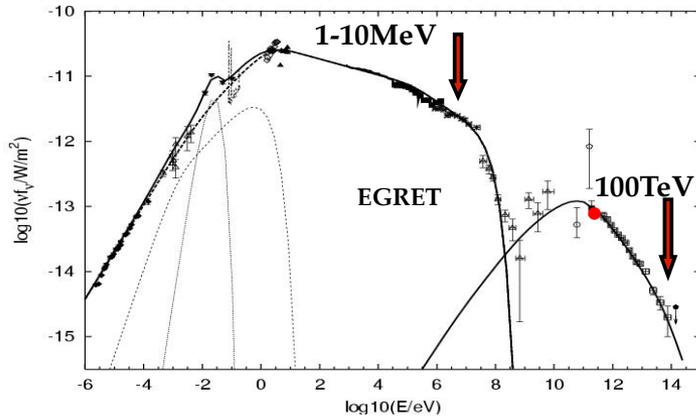
- Galactic Center (GC) harbors a hadronic PeVatron within a few pc region around Sgr A\* a suspected SMBH
- $1/r$  type distribution of the CR density implies (quasi)continuous regime of operation of the accelerator with a power  $10^{38}$  erg/s (on timescales 1 to 10 kyr) - a non negligible fraction of the current accretion power
- this accelerator alone can account for most of the flux of Galactic CRs around the “knee” if its power over the last  $10^6$  years or so, has been maintained at average level of  $10^{39}$  erg/s.
- escape of particles into the Galactic halo and their subsequent interactions with the surrounding gas, can be responsible for the sub-PeV neutrinos recently reported by the IceCube collaboration
- the expected  $>10$  TeV neutrino flux is within the range of sensitivity of a several  $\text{km}^3$  volume neutrino detector
- perfect target for CTA - to search for the variability of the central source, to measure the spectrum of diffuse (CMZ) gamma-rays up to 100 TeV and beyond

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# Pulsar Wind Nebulae: electron PeVatrons



## Crab Nebula – a perfect electron PeVatron



standard MHD theory (Kennel&Coroniti)  
 cold ultrarelativistic pulsar wind terminates by reverse  
 shock resulting in acceleration of multi-TeV electrons  
 synchrotron radiation => **nonthermal optical/X nebula**  
 Inverse Compton => **high energy gamma-ray nebula**

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

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

Cutoff at  $h\nu_{\text{cut}} > 10 \Rightarrow \eta < 10$  - acceleration at 10 % of the maximum rate

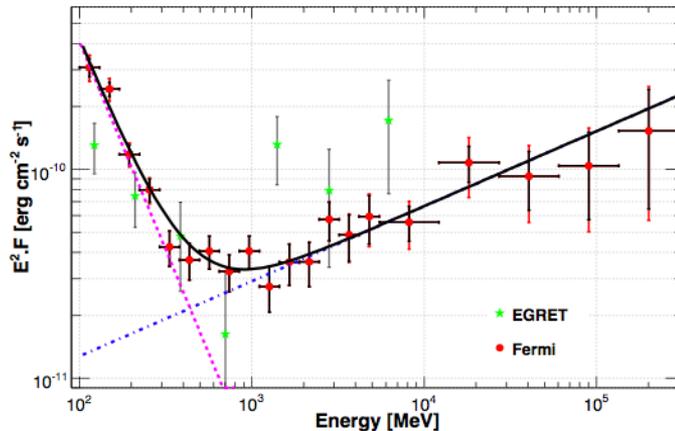
$\gamma$ -rays:  $E_\gamma \sim 50$  TeV (HEGRA, HESS)  $\Rightarrow E_e > 200$  TeV

B-field  $\sim 100$  mG  $\Rightarrow \eta \sim 10$  - independent and more robust estimate

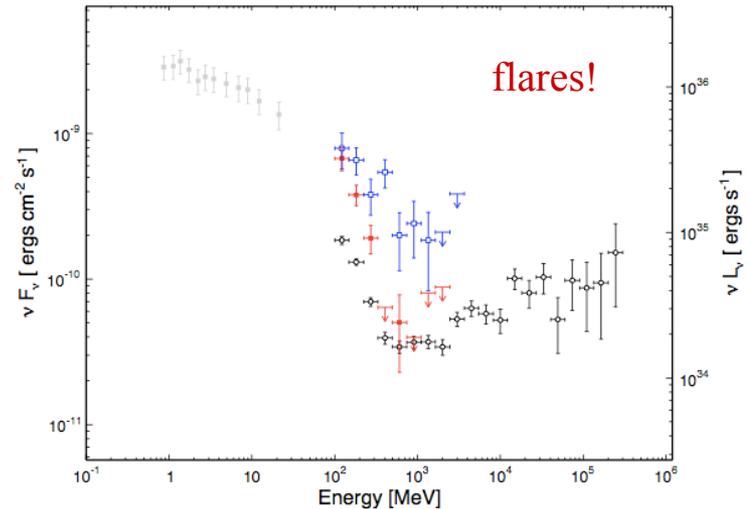
1 mG  $\Rightarrow \eta \sim 1$  ?



## Flares of Crab (Nebula) :



IC emission consistent with average  
nebular B-field:  $B \sim 100\mu\text{G}-150\mu\text{G}$

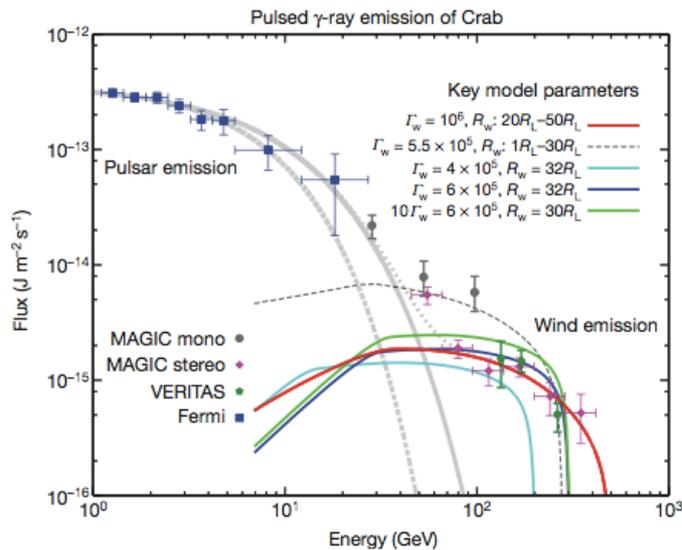
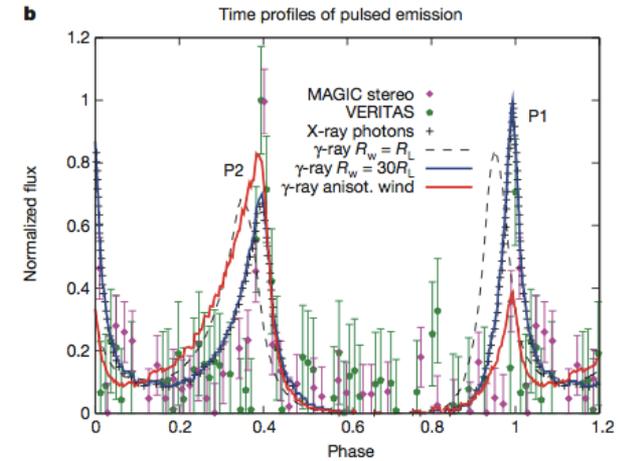
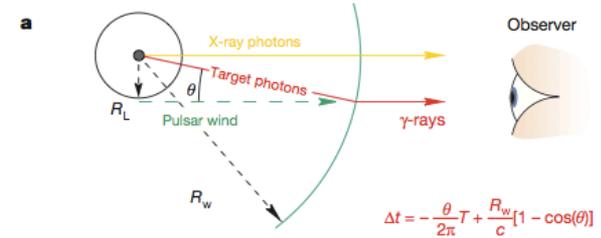
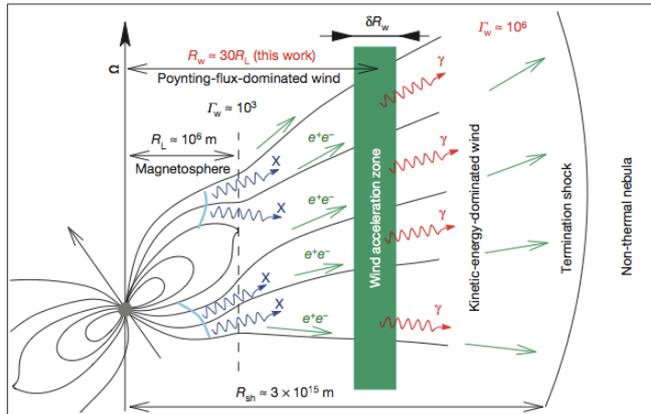


seems to be in agreements with the standard PWN picture, but ... **MeV/GeV flares!!**

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

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

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



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

Crab Nebula is a very effective accelerator  
but not an effective IC  $\gamma$ -ray emitter

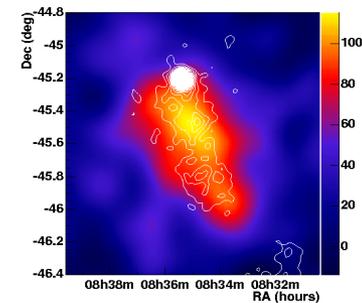
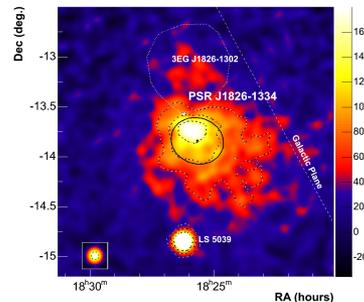
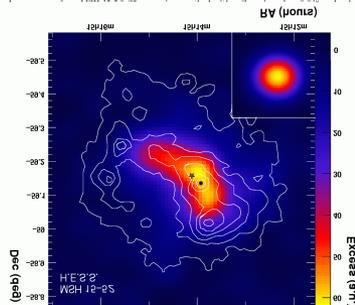
we do see TeV  $\gamma$ -rays from the Crab Nebula because of very large spin-down flux:  $f_{\text{rot}} = L_{\text{rot}} / 4\pi d^2 = 3 \times 10^{-7} \text{ erg/cm}^2 \text{ s}$

gamma-ray flux  $\ll$  “spin-down flux“ *because of large B-field*

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

higher  $\gamma$ -ray efficiency  $\rightarrow$  detectable  $\gamma$ -ray fluxes from other plerions

**HESS confirms this prediction – many (20+) candidates associated with PWNe; firm detections - MSH 15-52, PSR 1825, Vela X, ... N157B!**



## binary systems - unique high energy laboratories

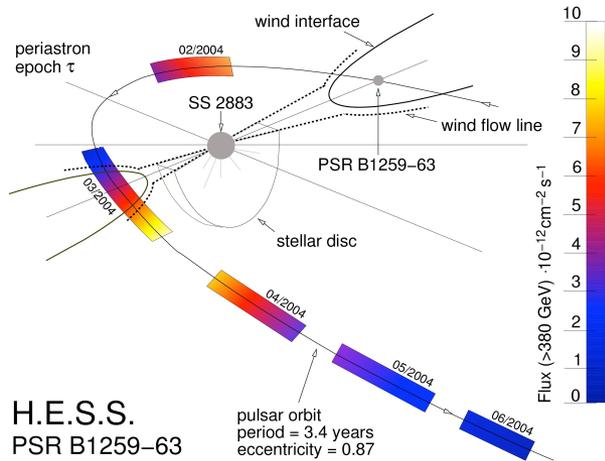
binary pulsars - a special case with strong effects associated with the optical star on both the dynamics of the pulsar wind and the radiation before and after its termination

the same 3 components - *Pulsar/Pulsar Wind/Synch.Nebula* - as in PWNe  
both the electrons of the cold wind and shock-accelerated electrons are illuminated by optical radiation from the companion star detectable IC  $\gamma$ -rays

“on-line watch“ of the MHD processes of creation and termination of the ultrarelativistic pulsar wind, as well as particle acceleration by relativistic shock waves, through spectral and temporal studies of  $\gamma$ -ray emission

(characteristic timescales 1 h or shorter !)

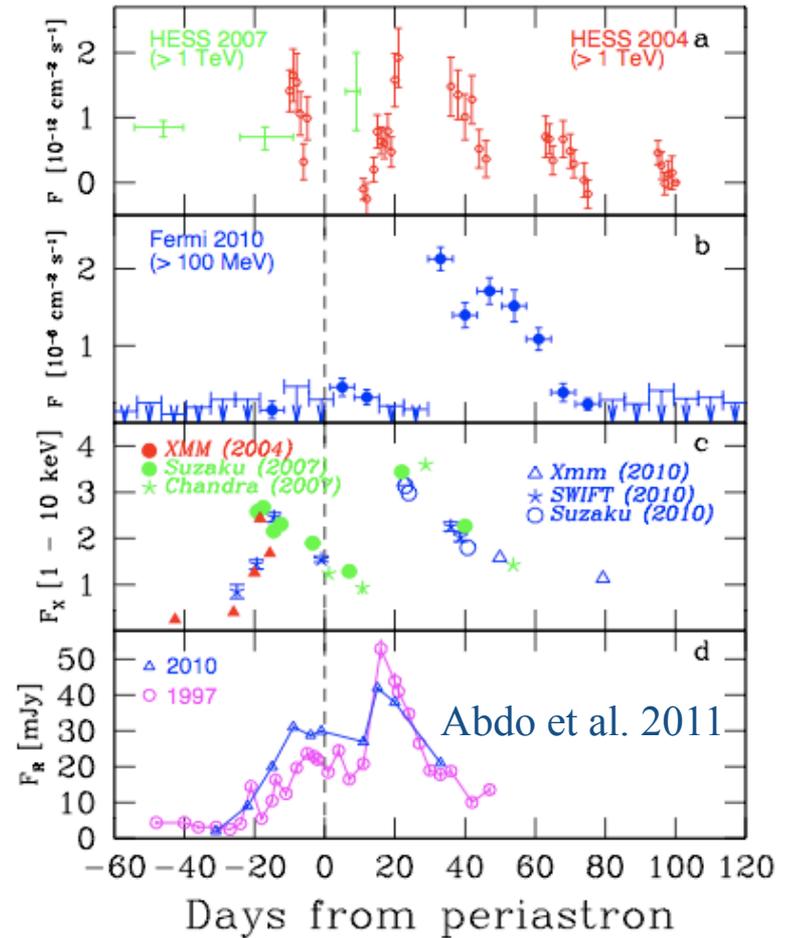
the target photon field is function of time, thus the only unknown parameter is B-field => predictable gamma-ray emission?



*H.E.S.S.: detection of  $\gamma$ -rays at  $< 0.1 \text{ Crab}$  level - tendency of minimum flux close to periastron;*

*Several possible explanations, but many things uncertain and confusing.*

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



Abdo et al. 2011

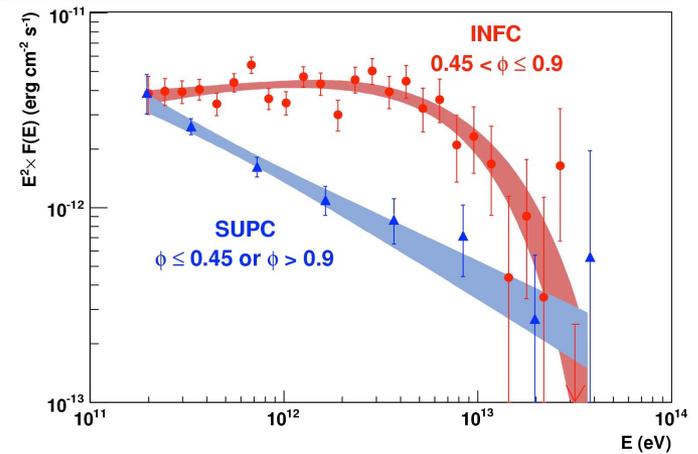
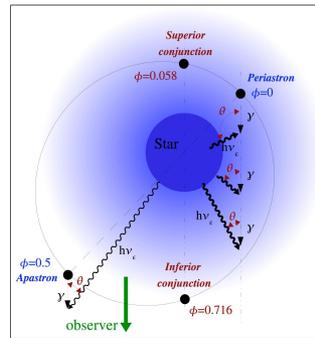
**Fermi LAT - weak signal far around periastron, but flares after 1 month!**

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

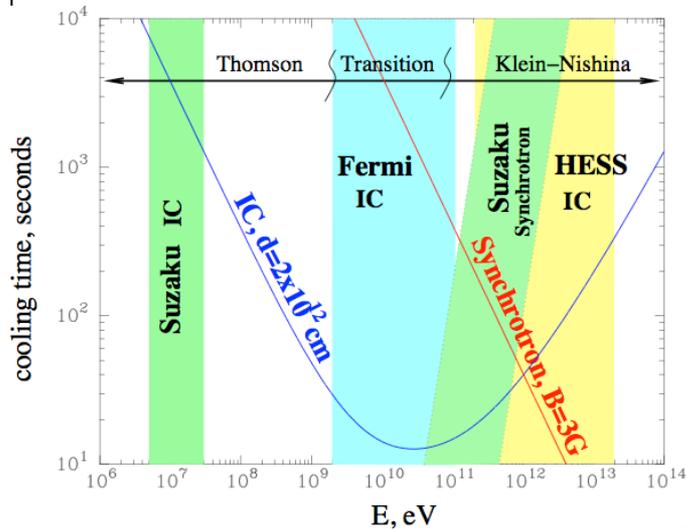
# LS 5039

works as a perfect TeV clock  
and an extreme accelerator

close to inferior conjunction - maximum  
close to superior conjunction - minimum



*modulation of the gamma-ray signal? a quite natural reason (because of  $\gamma$ - $\gamma$  absorption), but we see a different picture... anisotropic IC scattering? yes, but perhaps some additional factors (adiabatic losses, modest Doppler boosting) also play a non-negligible role*



*can electrons be accelerated to energies up to 20 TeV in presence of dense radiation? yes, but accelerator should not be located deep inside binary system; even at the edge of the system  $\eta < 10 \Rightarrow$  although the origin of the compact object is not yet known (pulsar or a BH) and we do not understand many details, it is clear that this binary system works as an extreme accelerator*

*potential sites of  $10^{20}$  eV cosmic rays based on the condition:*  
 source size  $>$  Larmor radius:  $(R/1\text{pc})(B/1\text{G}) > 0.1 (E/10^{20}\text{eV})$  :

necessary but not sufficient; it implies:

(1) minimum acceleration time

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

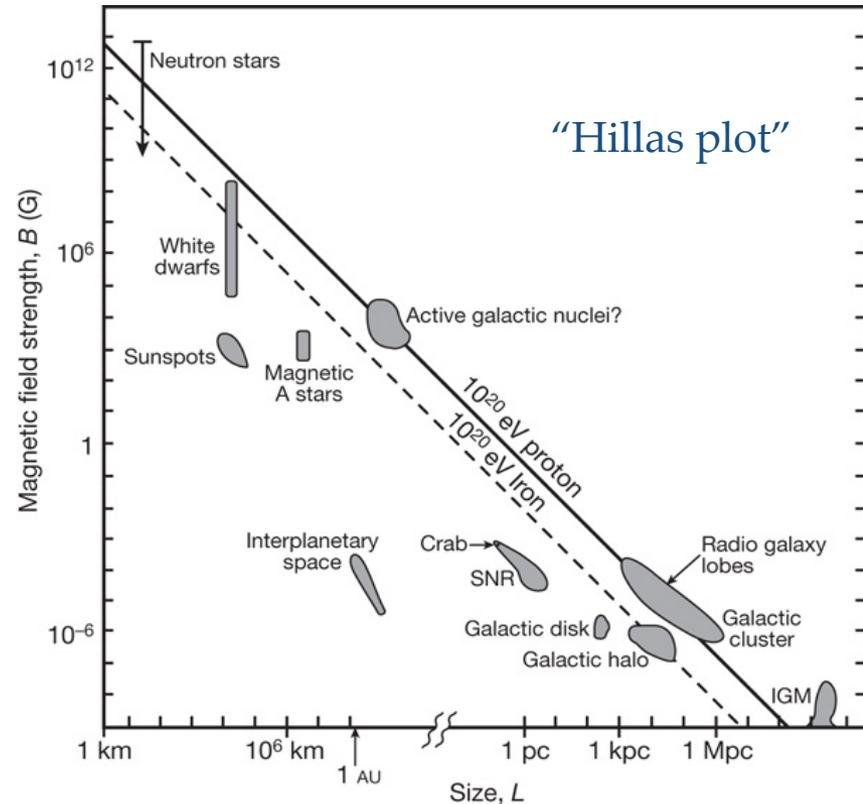
acceleration in fact is slower:

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

with  $\eta > 1$  and shock/bulk-motion speed  $v < c$  ( $\eta = 1$  - Bohm diffusion)

(2) no energy losses

synchrotron/curvature losses in compact objects become severe limiting factor

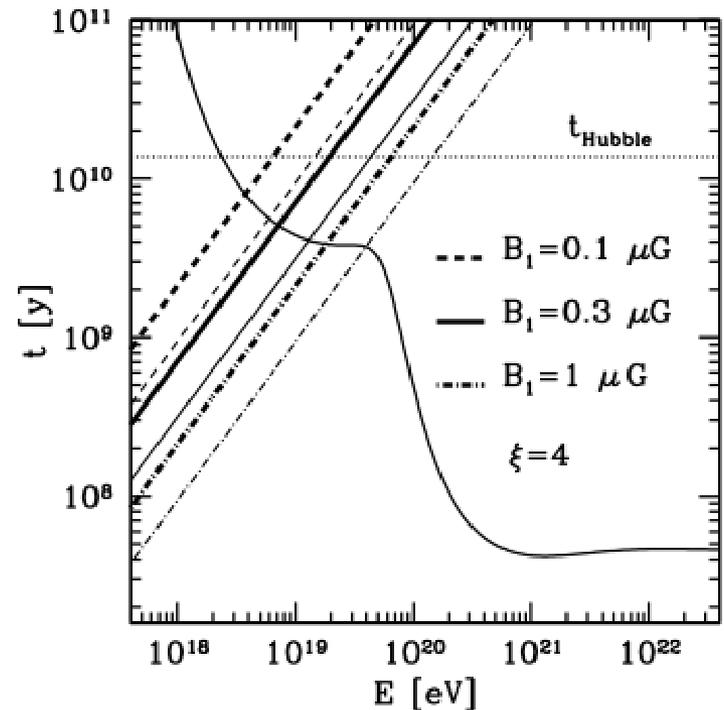


# Particle Acceleration in Galaxy Clusters

Several ingredients for effective acceleration to highest energies

- ✓ formation of strong accretion shocks
- ✓ magnetic field of order 0.1-1  $\mu\text{G}$
- ✓ shock velocity - few 1000 km/s
- ✓ acceleration time  $\sim$  Hubble time

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



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

## acceleration sites of $10^{20}$ eV CRs ?

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

signatures of extreme accelerators?

✓ **synchrotron self-regulated cutoff:**

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

$\simeq 300\text{GeV}$  proton synchrotron

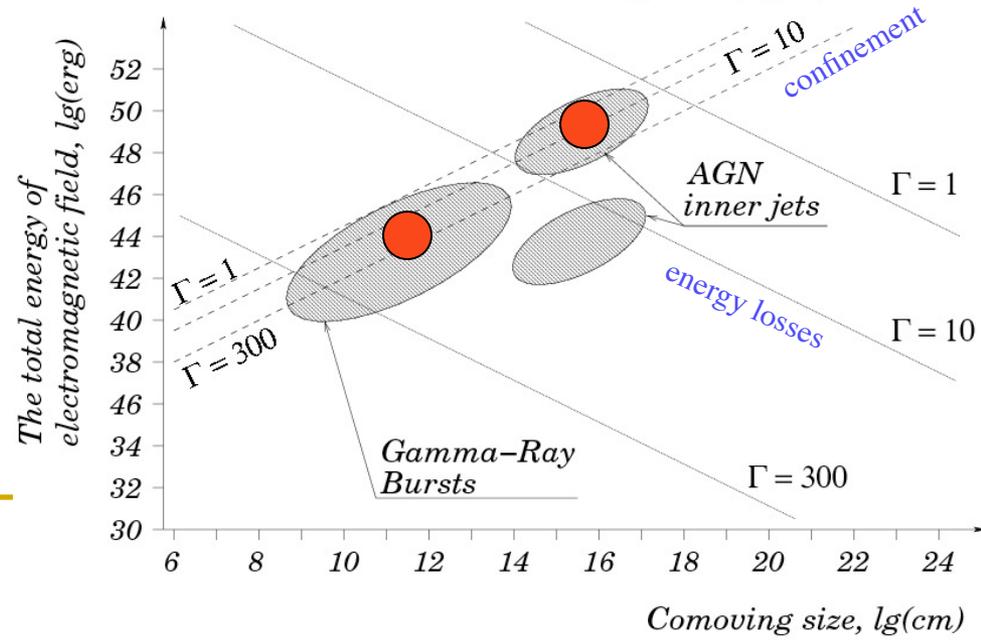
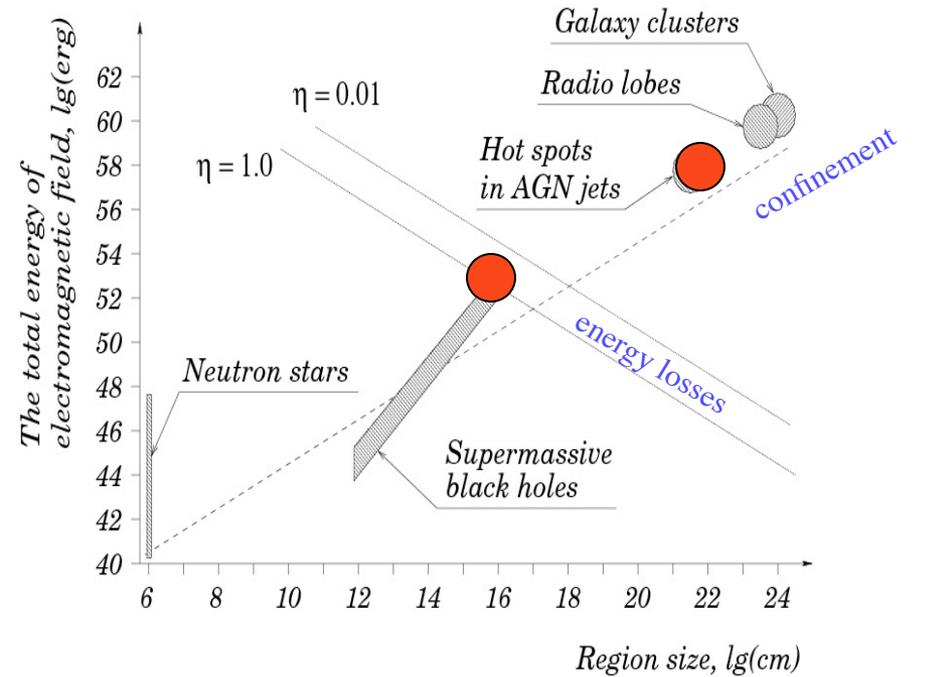
$\simeq 150\text{MeV}$  electron synchrotron

a viable “hadronic” model applicable for TeV  $\gamma$ -ray blazars if  $B \sim 100$  G or so

✓ **neutrinos** (through “converter” mechanism) production of neutrons (through  $p\gamma$  interactions) which travel without losses and at large distances convert again to protons  $\Rightarrow \Gamma^2$  energy gain! (Deerishev et al. 2003)

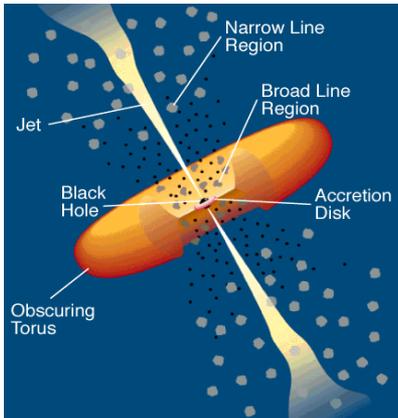
✓ **observable off-axis radiation**

radiation pattern can be much broader than  $1/\Gamma$



\*) in nonrelativistic shocks  $\eta \approx 0.1(v_{\text{shock}}/c)^2$

**Blazars** - sub-class of AGN dominated by nonthermal/variable broad band (from R to  $\gamma$ ) radiation produced in relativistic jets close to the line of sight, with massive Black Holes as central engines



## GeV/TeV gamma-ray observations

*strong impact on*

- Blazar physics and astrophysics
- Diffuse Extragalactic Background (EBL)  
Intergalactic Magnetic fields (IGMF)

most exciting results of recent years

- ultra short time variability (on min scales)
- Jet power exceeds Eddington luminosity
- extremely hard (harder than E-1.5) energy spectra
- VHE blazars up to  $z \sim 1$ ! (MAGIC)

# Hadronic vs. Electronic models of TeV Blazars

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

- easy to accelerate electrons to TeV energies
  - easy to produce synchrotron and IC gamma-rays
- recent results require extremely small  $B \sim 1 \text{ mG}$

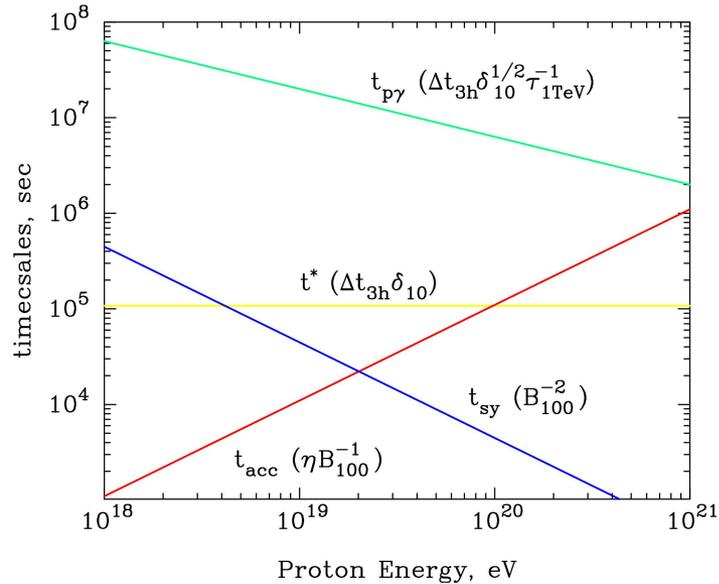
**Hadronic Models:**

- **protons interacting with ambient plasma**      neutrinos  
very slow process:
- **protons interacting with photon fields**      neutrinos  
low efficiency + severe absorption of TeV  $\gamma$ -rays
- **proton synchrotron**      no neutrinos  
very large magnetic field  $B = 100 \text{ G}$  + acceleration rate  $c/r_g$



“extreme accelerator” with Poynting flux dominated flow

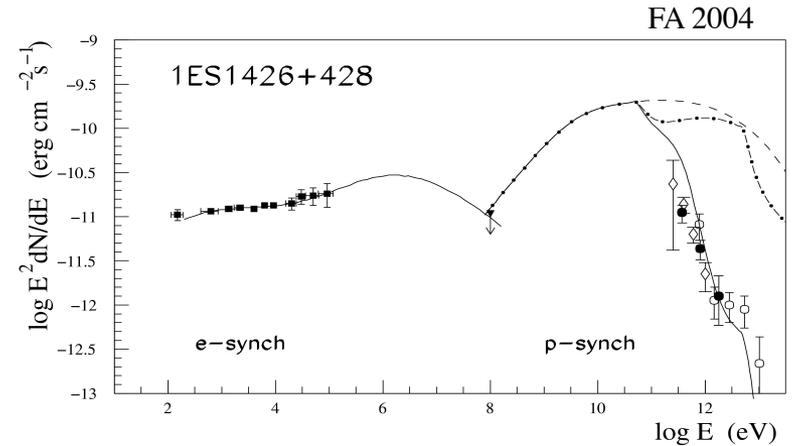
# Synchrotron radiation of an extreme proton accelerator



$$E_{cut} = 90 (B/100G)(E_p/10^{19} \text{ eV})^2 \text{ GeV}$$

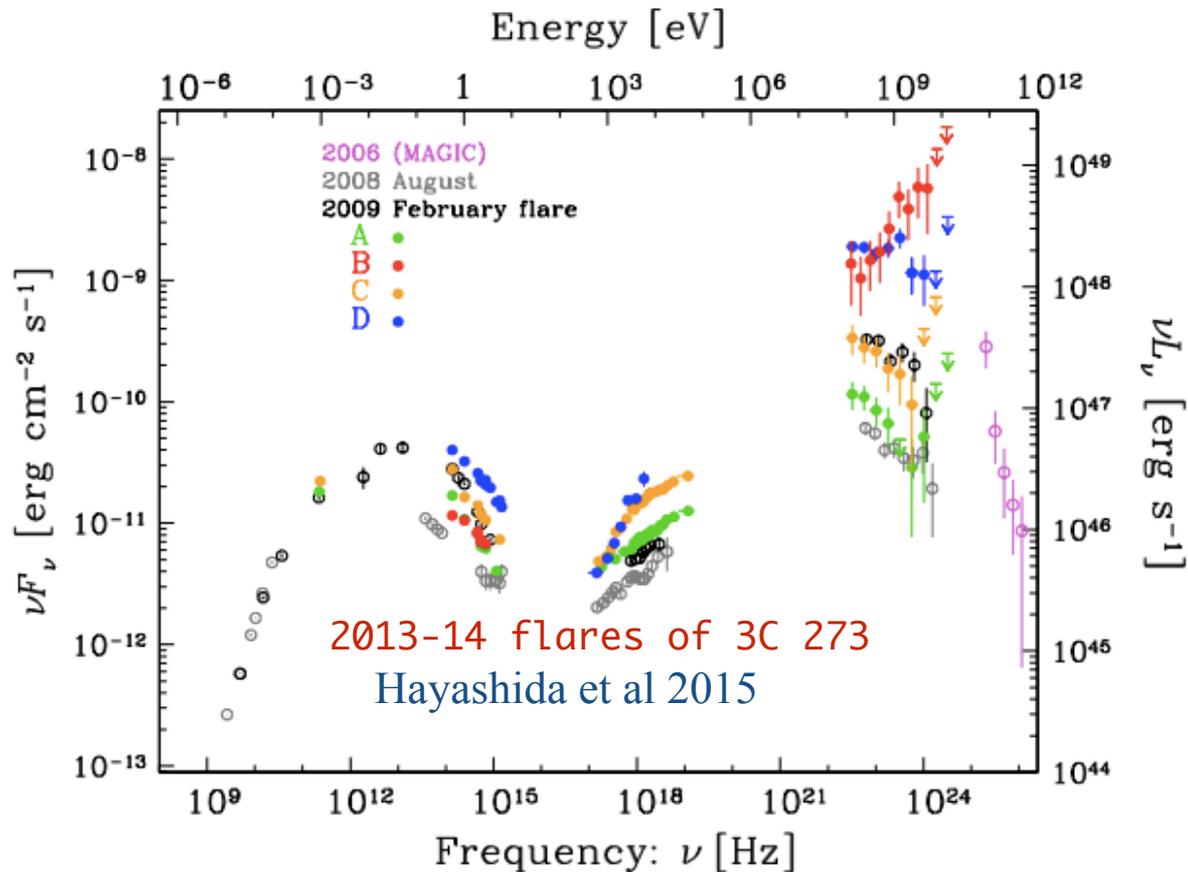
$$t_{synch} = 4.5 \times 10^4 (B/100G)^{-2} (E/10^{19} \text{ eV})^{-1} \text{ s}$$

$$t_{acc} = 1.1 \times 10^4 (E/10^{19}) (B/100G)^{-1} \text{ s}$$



*synchrotron radiation of protons:  
a viable radiation mechanism*

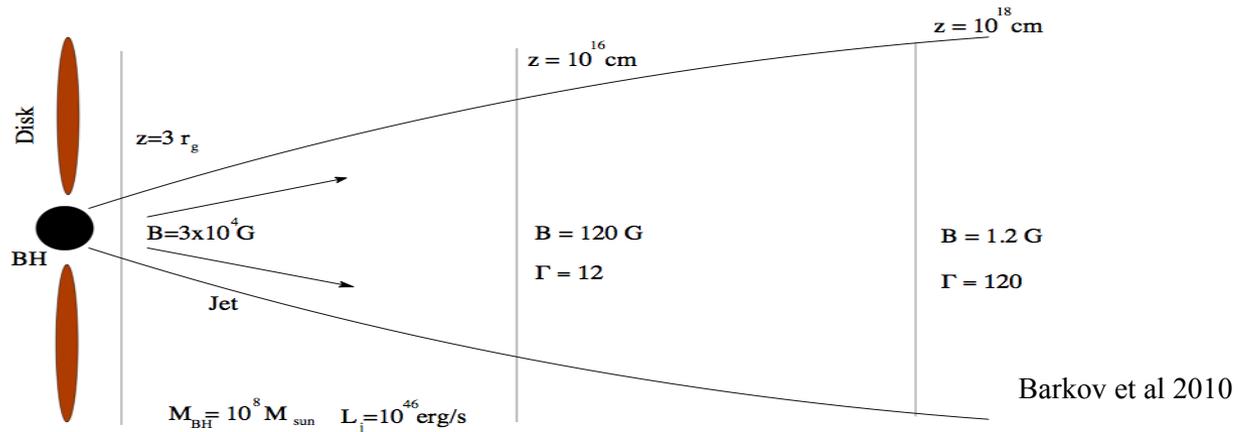
$E_{max} = 300 \eta^{-1} \delta_j \text{ GeV}$   
requires extreme accelerators:  $\eta \sim 1$



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

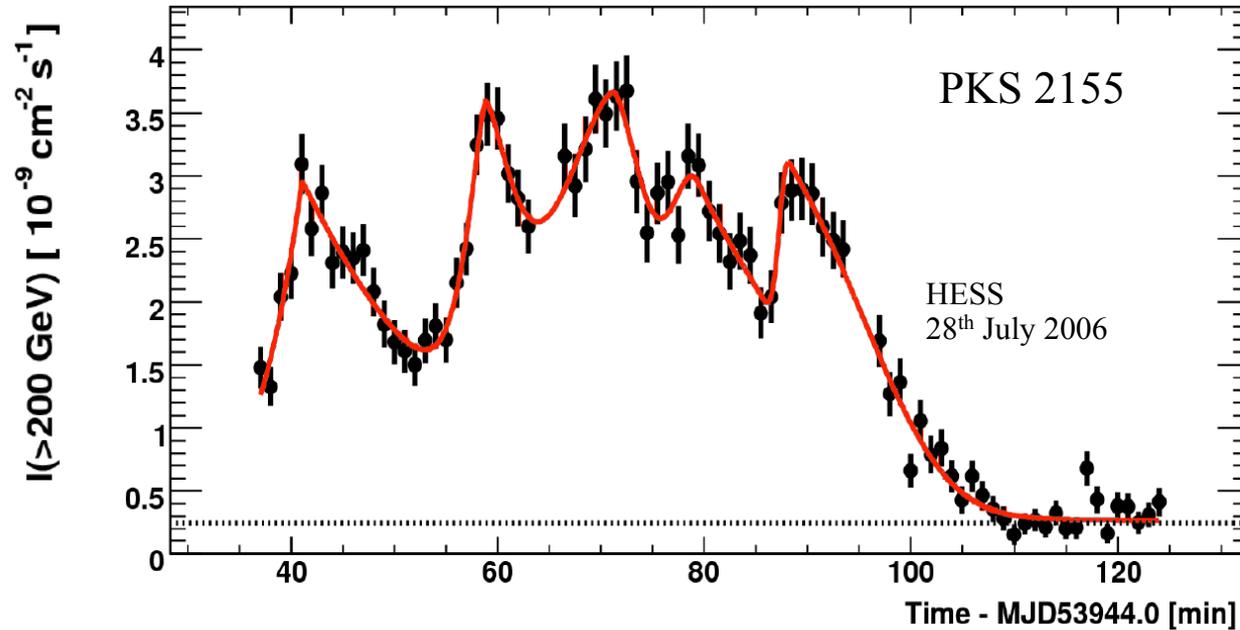
variability  $t \sim 7 \cdot 10^3$  sec vs  $t_h \sim (3-8) \cdot 10^3$  sec !

## B-field: very large or very small?



in powerful blazars at subparsec scales B-field cannot be smaller than 1G, a serious constraint for the simplified one-zone “leptonic models,

several min (200s) variability timescale  $\Rightarrow R=c \Delta t_{\text{var}} \delta_j=10^{14}\delta_{10}$  cm  
 for a  $10^9 M_{\odot}$  BH with  $3R_g = 10^{15}$  cm  $\Rightarrow \delta_j > 100$ , i.e. close to the  
 accretion disk (the base of the jet), the bulk motion  $\Gamma > 100$



it is convenient to express the variability in timescale

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

## on the Doppler boosting and mass of BH

- several min variability timescale  $\Rightarrow R = ct_{\text{var}} \delta_j \sim 10^{13} \delta_j$  cm for a  $10^9 M_{\odot}$  BH with  $3R_g \sim 10^{15}$  cm  $\Rightarrow \delta_j > 100$ , i.e. close to the accretion disk (the base of the jet), the Lorentz factor of the jet  $\Gamma > 50$  - this hardly can be realized close to  $R_g$ !
- the (internal) shock scenario: shock would develop at  $R = R_g \Gamma^2$ , i.e. minimum  $\gamma$ -ray variability would be  $R_g/c = 10^4 (M/10^9 M_{\odot})$  sec, although the  $\gamma$ -ray production region is located at  $R_g \sim ct_{\text{var}} \Gamma^2$  (e.g. Chelotti, Fabian, Rees 1998) - this is true for any other scenario with a “signal-perturbation” originating from the central BH
- thus for the observed  $t_{\text{var}} < 200$  s, the mass of BH cannot significantly exceed  $10^7 M_{\odot}$ . On the other hand the “BH mass–host galaxy bulge luminosity“ relation for PKS2155-304 gives  $M > 10^9 M_{\odot}$ .

**Solution?** perturbations are caused by external sources, e.g. by magnetized condensations (“blobs”) that do not have direct links to the central BH;  
do we deal with the scenario “star crosses the relativistic  $e^+e^-$  jet” ?

## Summary:

- VHE gamma-rays are perfect carriers of information about the sites and processes of particle acceleration on both galactic and extragalactic scales
- the contribution to the field of CR studies with the current ground-based detectors HESS/MAGIC/VERITAS/HAWC is substantial, unique and impressive
- CR related studies will be one of the highest priority tasks for the generation of ground-based detectors, first of all CTA