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Probing Cosmic Accelerators with Very High Energy Gamma Rays

Felix Aharonian

Dublin Institute for Advanced Studies, Dublin

Max-Planck Institut fuer Kernphysik, Heidelberg

VHE gamma-ray astronomy - *a success story*

over last several years the field has bee revolutionized

before – "astronomy with several sources"

(an activity related to *Astroparticle Physics rather than Astronomy*)

now – a truly astronomical discipline with characteristic key words:

energy spectra, images, lightcurves, surveys...

with more than 100 reported gamma-ray sources representing more than 10 Galactic & Extragalactic populations in the energy interval 0.1 TeV to 100 TeV

remains - as one of the most advanced research areas of Astroparticle Physics

=> *enjoys strong support of both Astrophysics and Particle Physics communities - very important for the next generation major IACT array project - CTA*

main factors which make possible this success?

several factors… but basically thanks to lucky combination of two

- ✓ full realization of the great potential of the detection technique

  imaging, stereoscopic approach, large FoV

- ✓ effective acceleration of TeV/PeV particles on all astronomical scales coupled with favourable conditions for production of gamma-rays

first conclusions from VHE gamma-ray observations:

Universe is full of *Extreme Accelerators* - TeVatrons and PeVatrons ?

Extreme Accelerators

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 <u>*can be as large as 50 %*</u>

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

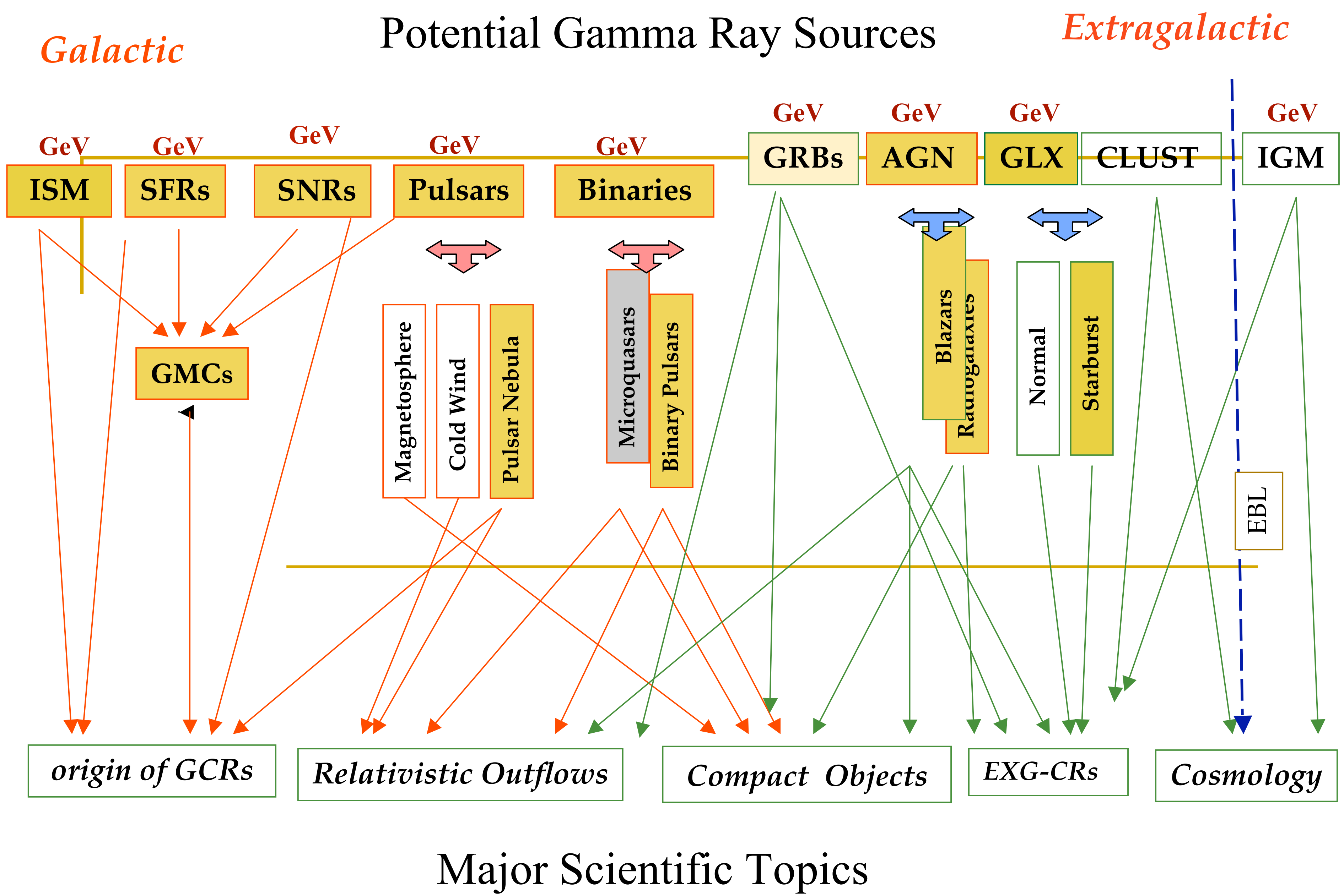
acceleration rate close to the <u>*maximum (theoretically) possible rate*</u>

sometimes efficiency can even "exceed" 100% ?

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

<u>analogy with X-ray Astronomy:</u>

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


Potential Gamma Ray Sources
Galactic
Extragalactic
GeV
ISM
SFRs
SNRs
Pulsars
Binaries
GRBs
AGN
GLX
CLUST
IGM
GMCs
Magnetosphere
Cold Wind
Pulsar Nebula
Microquasars
Binary Pulsars
Blazars
Radiogalaxies
Normal
Starburst
EBL
origin of GCRs
Relativistic Outflows
Compact Objects
EXG-CRs
Cosmology
Major Scientific Topics

Major topics related to Astrophysics and Cosmology

- Origin of Galactic and Extragalactic Cosmic Rays

  SNRs, GMCs, Center of Galaxy, Starburst Galaxies, Active Galactic Nuclei

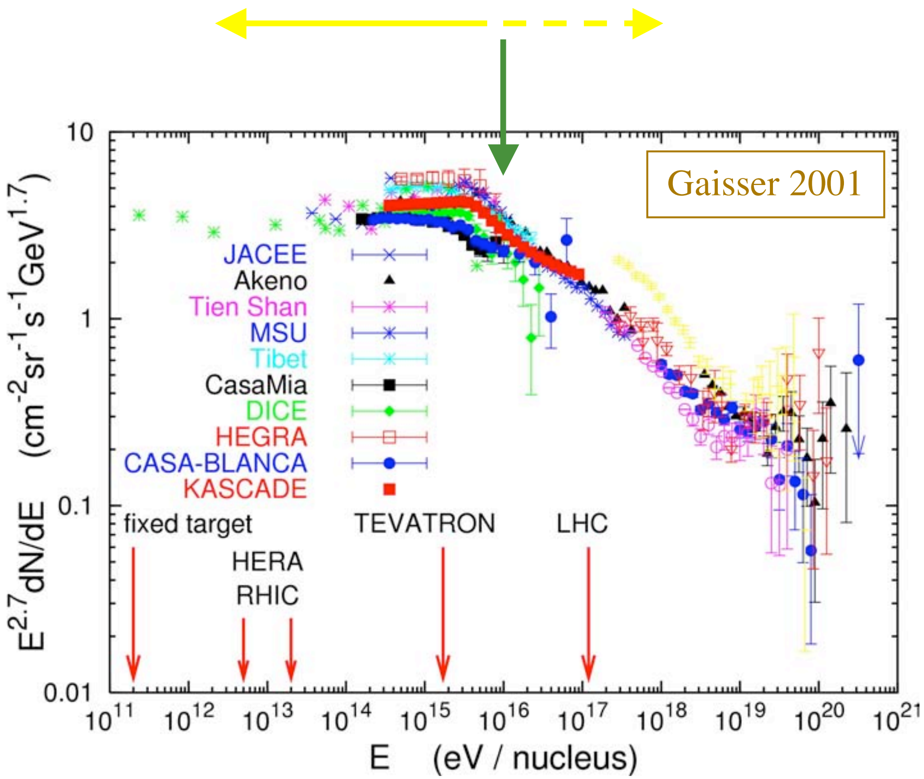
- Physics and Astrophysics of Relativistic Outflows

  Pulsar Winds and Black Hole Jets

- Observational Cosmology

  Intergalactic radiation and magnetic fields, Dark Matter

Galactic TeVatrons and PeVatrons - particle accelerators responsible for cosmic rays up to the “knee” around 1 PeV



SNRs ?

one of the key objectives of the high energy gamma-ray astronomy: confirmation that SNRs operate as PeVatrons, and can provide the bulk of Galactic CRs up to $E \sim 10^{15}$ eV

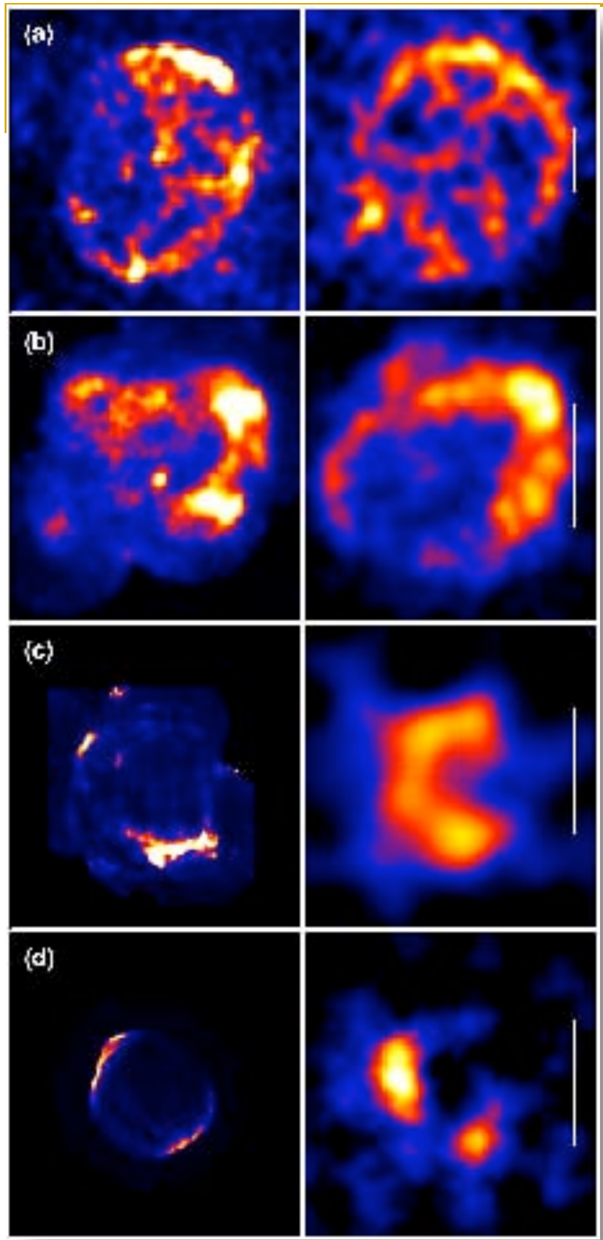
other possible sources?

Pulsars/Plerions

OB, W-R Stars

Microquasars

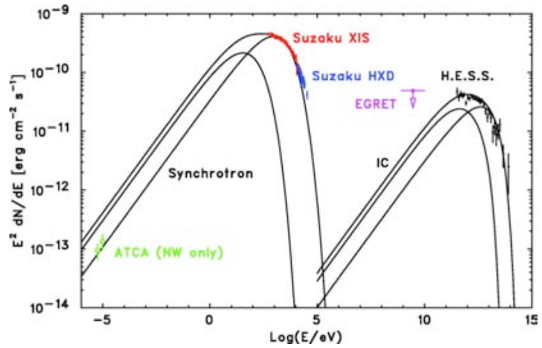
Galactic Center

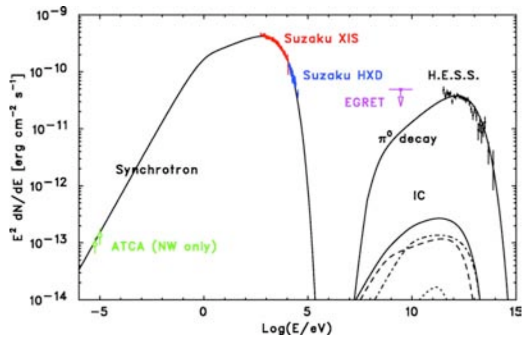


acceleration of protons and/or electrons in SNR shells to energies up to 100TeV

leptonic or hadronic?

=>





RXJ1713.7-4639

inverse Compton scattering of electrons on 2.7K CMBR

B=15μG
We ≈3.4 10^{47} erg/cm^3

γ-rays from pp ->π^o ->2γ

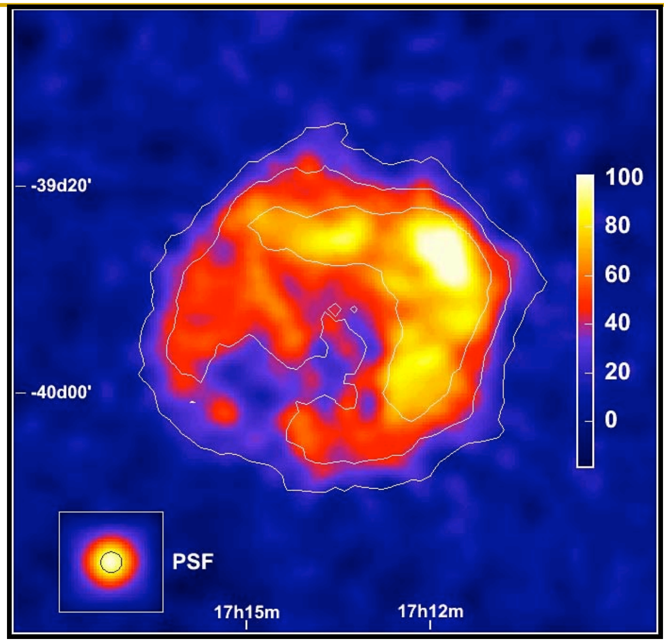
dN/dE=A $E^{-\alpha}$ exp(-E/Eo)
with α=1.7, Eo ≈ 25 TeV,
B=200μG
Wp ≈2 10^{50}(n/1cm^{-3})$^{-1}$erg/cm^3

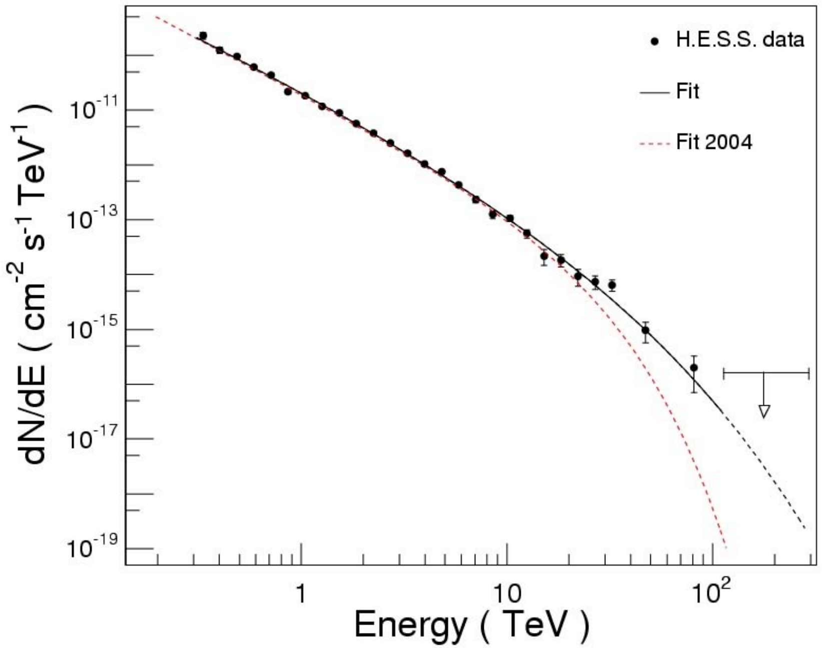
unfortunately we cannot give preference to hadronic or leptonic models - both have attractive features but also serious problems

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

RXJ1713.7-4639

TeV γ-rays and shell type morphology: acceleration of p or e in the shell to energies exceeding 100TeV





can be explained by γ-rays from pp ->π^{0} ->2γ

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

$\alpha=2.0$ $\quad$ Eo=17.9 TeV $\quad$ $\beta=1$

$\alpha=1.79$ $\quad$ Eo=3.7 TeV $\quad$ $\beta=0.5$

and with just "right" energetics

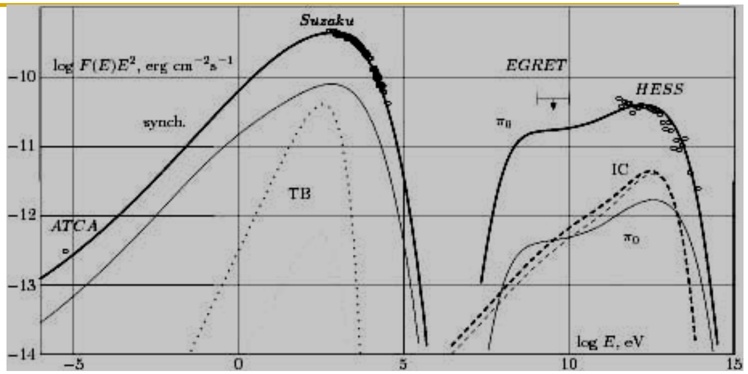
$Wp=10^{50}\,(n/1cm^{-3})^{-1}$ erg/cm^{3}

but IC canot be immediately excluded…

broad-band SEDs

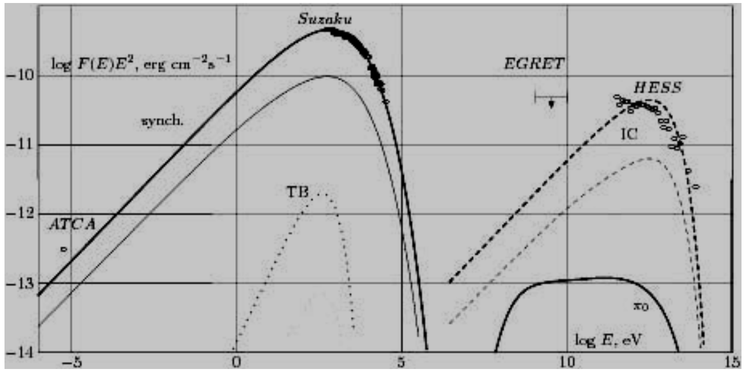
hadronic model

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)



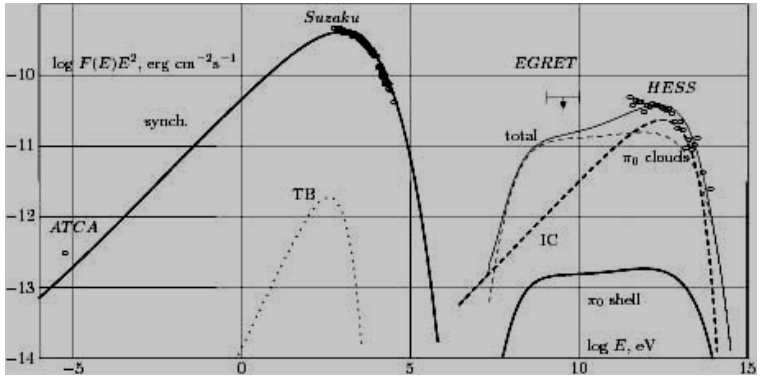
leptonic model

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 μG)



"composite" model?

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

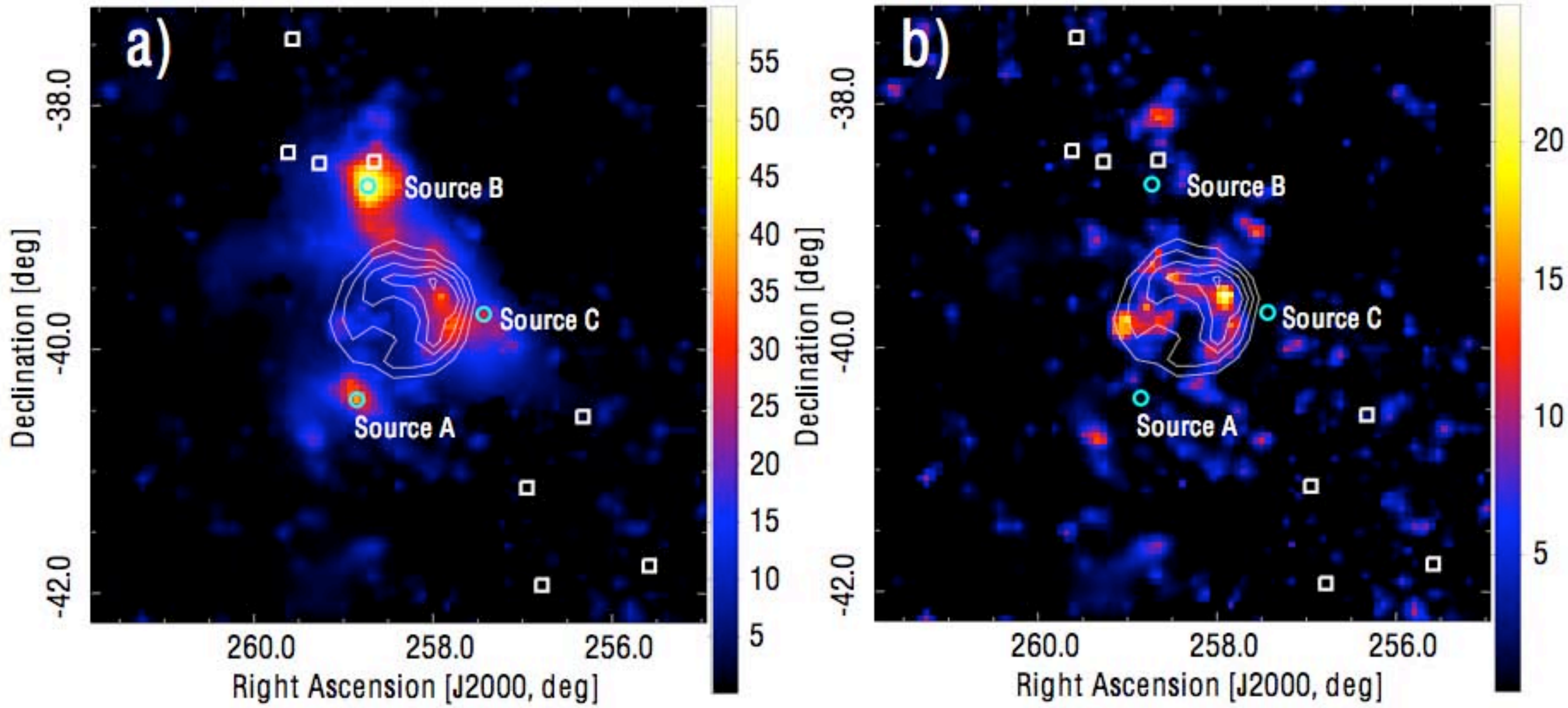


both forward and reverse shock contribute to γ-rays

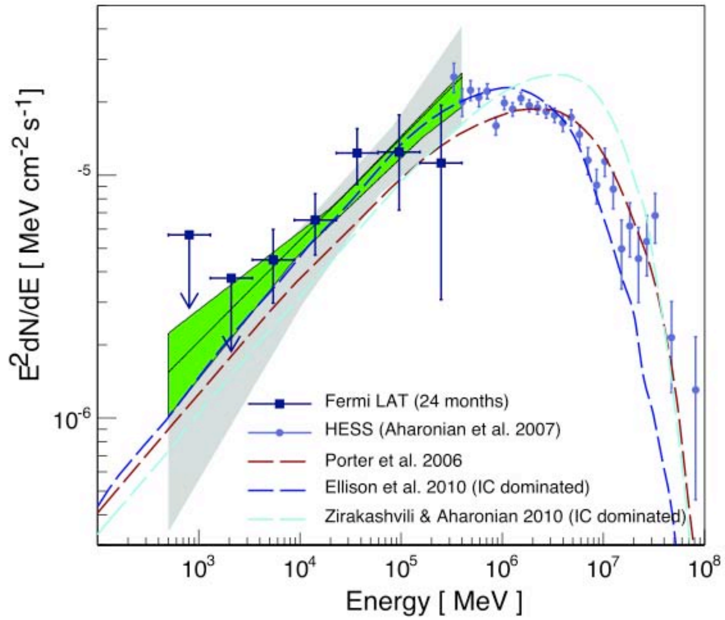
Zirakashvili, FA 2010

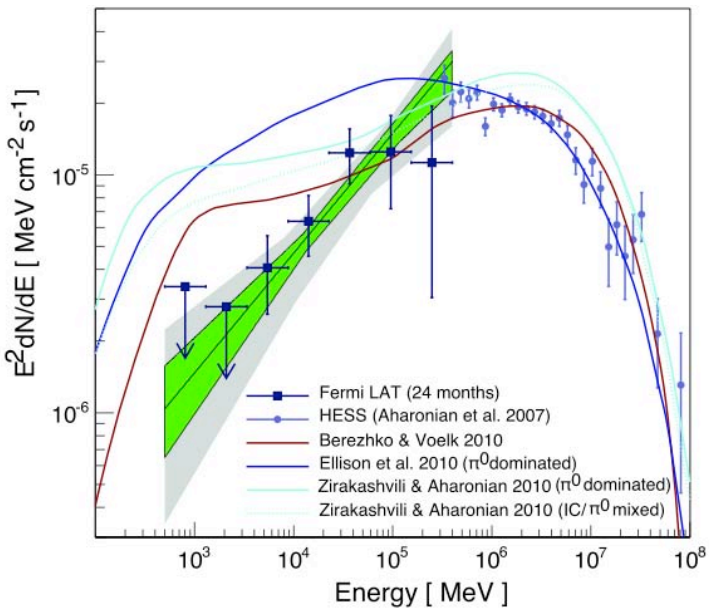
Recent Fermi report

GeV gamma-ray images



Fermi: GeV data contradict daronic origin of γ-rays ! (?)





leptonic models hadronic models

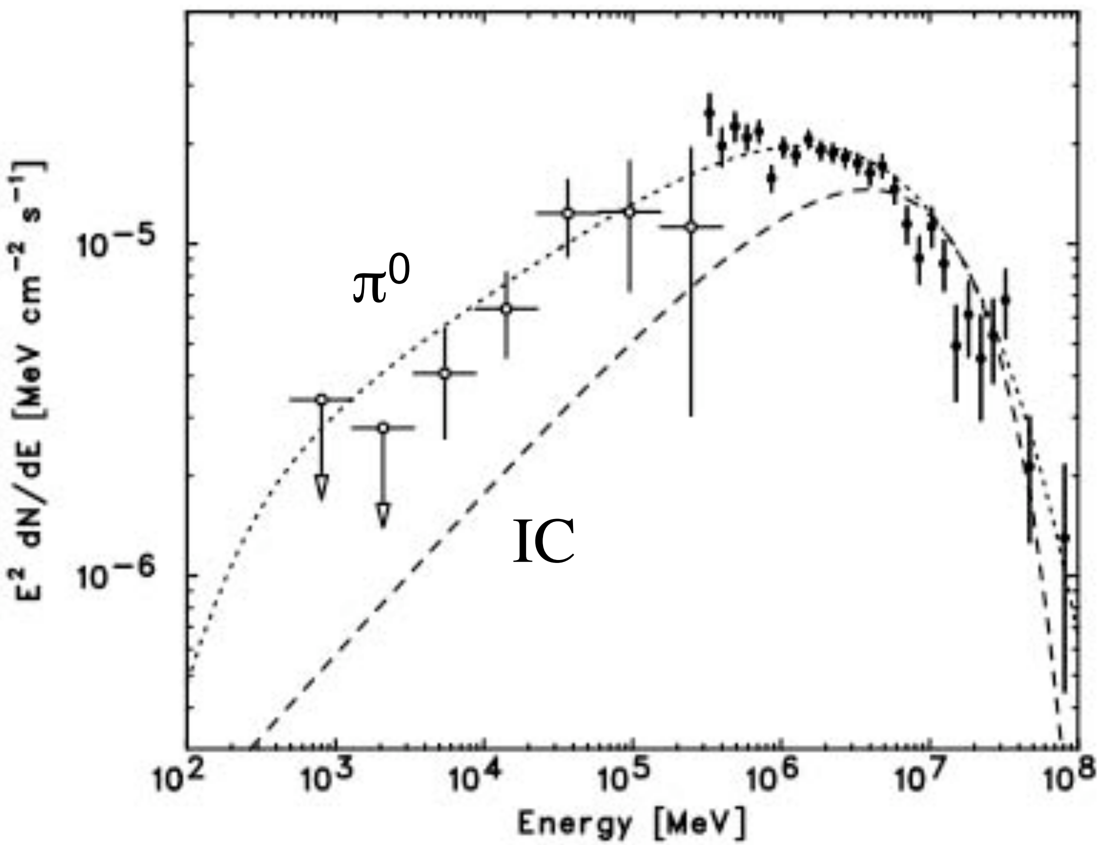
Questions: (i) can we compare GeV and TeV fluxes within one-zone models?

they could come from quite different regions

(ii) cannot we assume hard proton spectra ?

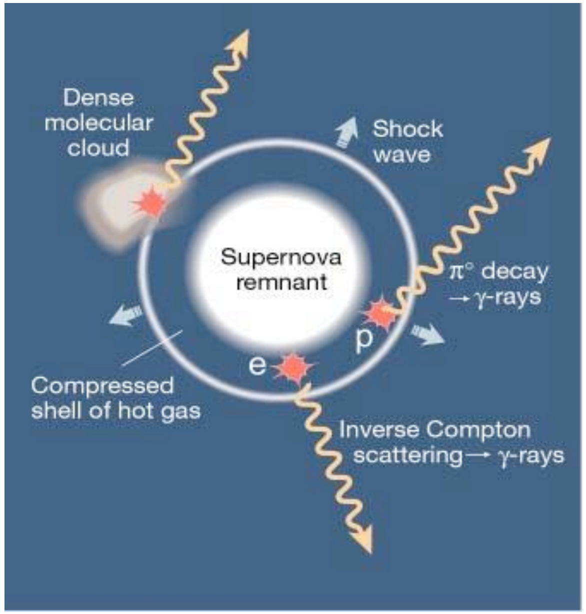
nonlinear theories do predict very hard spectra with α -> 1.5

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



theoretical curves from Tanaka et al. 2008 *the "composite" model*

IC gamma-rays from (i) the entire shell with average small B-field and (ii) π^0 -decay gamma-rays from dense clouds inside the shell



not strong correlation is expected between GeV and with TeV gamma-ray images

<10 GeV and E >10 TeV gamma-rays should correlate with dense CO clouds

GeV gamma-rays can be suppressed because low energy protons cannot penetrate deep into the dense clouds

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

problems with hadronic models:

- lack of thermal emission in RXJ 1713.7-3946

  almost all available energy goes to particle acceleration?

- p/e ratio > 10^3 - cosmic rays p/e ~ 100

  in Cas A p/e in principle could be 100, but could be also less than 10

- "early cutofs" - in all SNRs Ecut < 100 TeV

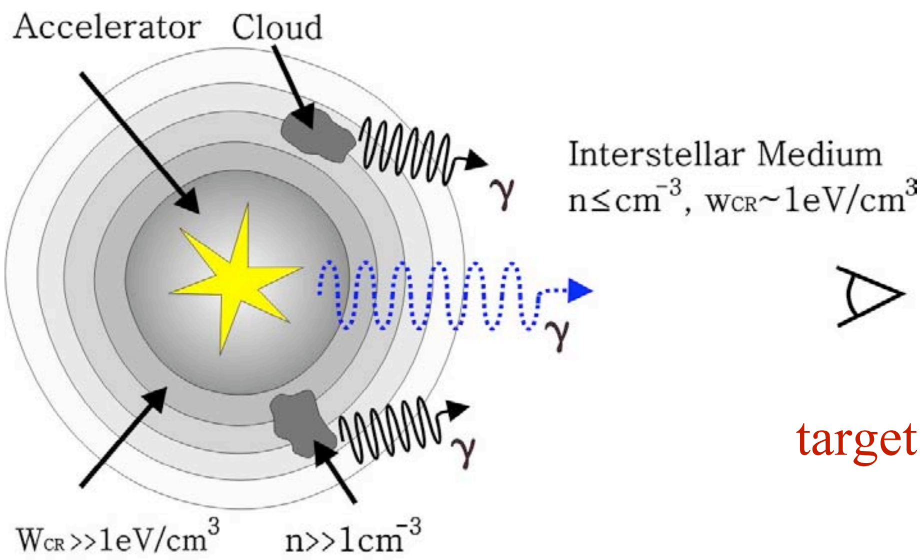
  because of escape? do they contribute to the the region around the "knee"

paradoxical conclusion: from the point of view of the SNR paradigm of CRs are preferable leptonic (but not hadronic!) models of gamma-rays

=> there are protons in SNRS with spectra up to 1 PeV but ….

we do not "see" them because of the low density ambient gas *gamma-ray production:* particle accelerator + target

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



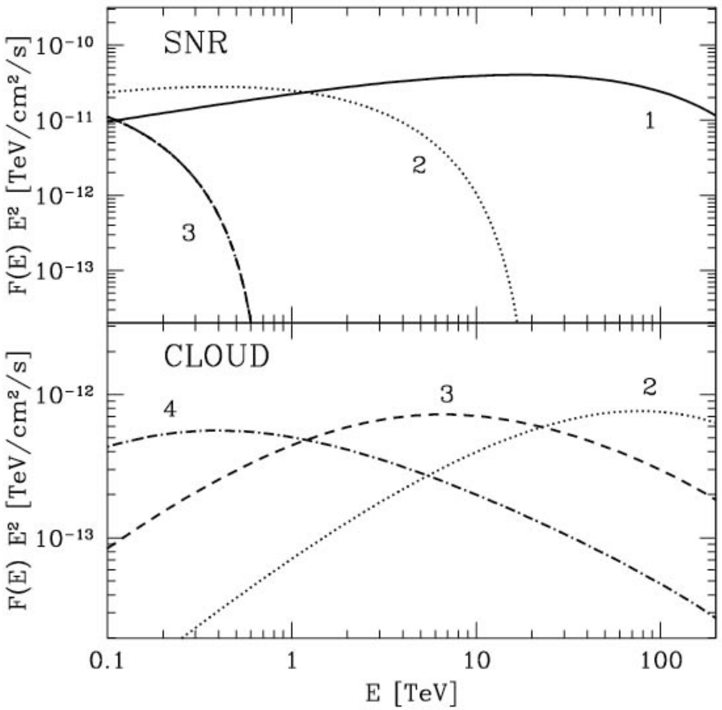
target - *matter, radiation, magnetic field*

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

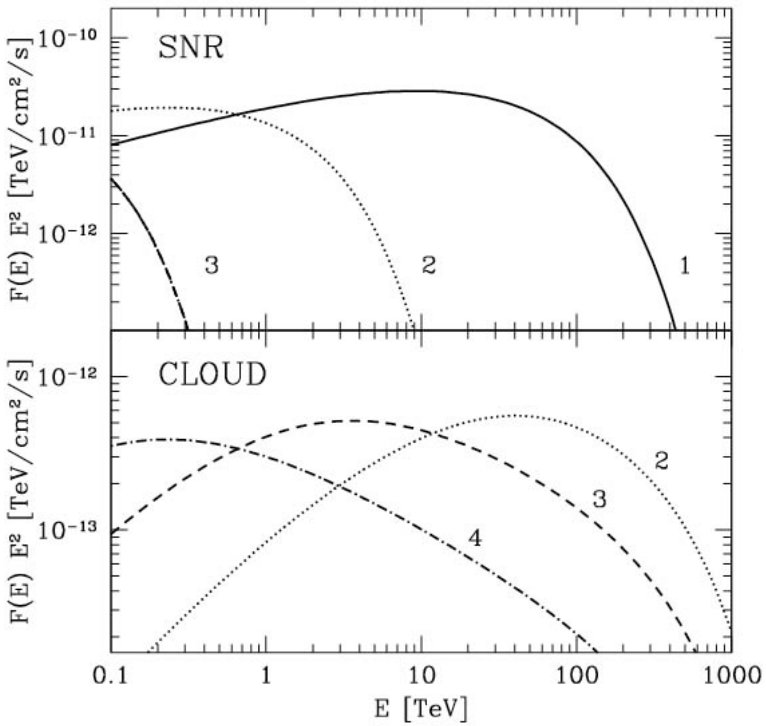
Gamma-rays and neutrinos inside and outside of SNRs

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

[S. Gabici, FA 2007]

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 γ-rays from dense gas clouds in the near neighborhood

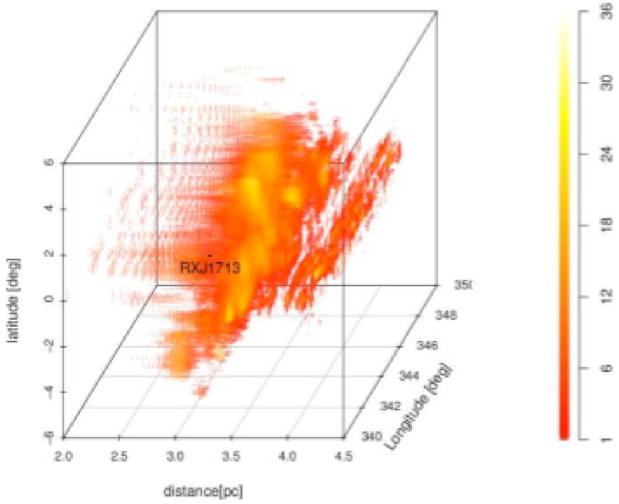
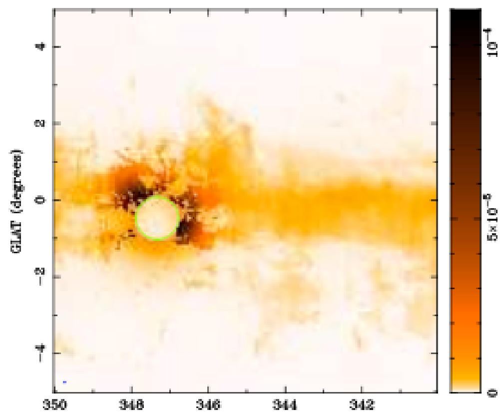


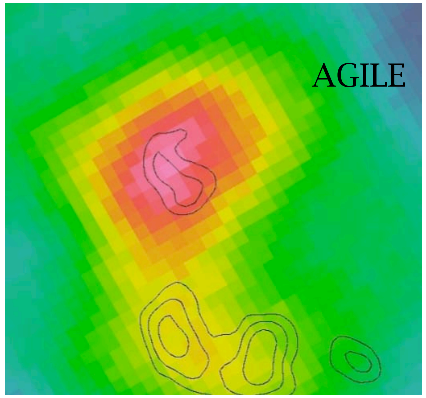
Fig. 1. The gas distribution in the region which spans Galactic longitude $340^\circ < l < 350^\circ$, Galactic latitude $-5^\circ < b < 5^\circ$ and heliocentric distance 50 pc $< l_d <$ 30 kpc, as observed by the NANTEN and LAB surveys, expressed in protons cm^{-3}. The distance axis is logaritmic 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.

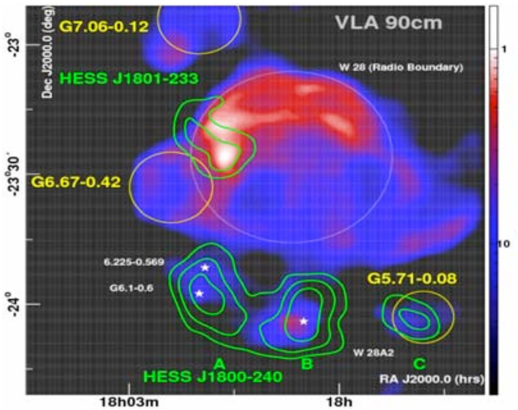


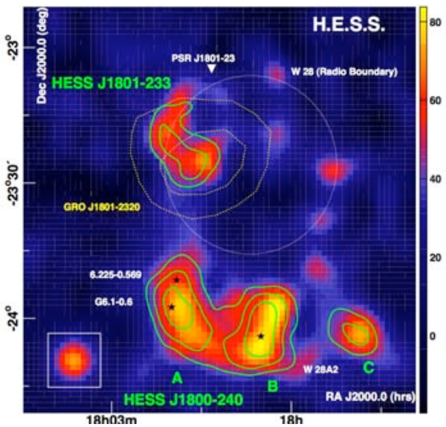
surrounding gas density:
NANTEN data
age:
1600 yr
escape of protons:
model of Zirakashvili&Ptuskin 2008
diffusion coefficient outside SNR:
$D = 10^{26}\ (E/10\text{GeV})^{0.5}\ \text{cm}^2/\text{s}$

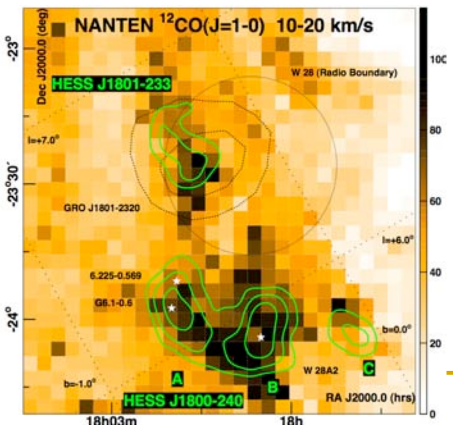
GeV TeV gamma-ray sources around mid age W28:

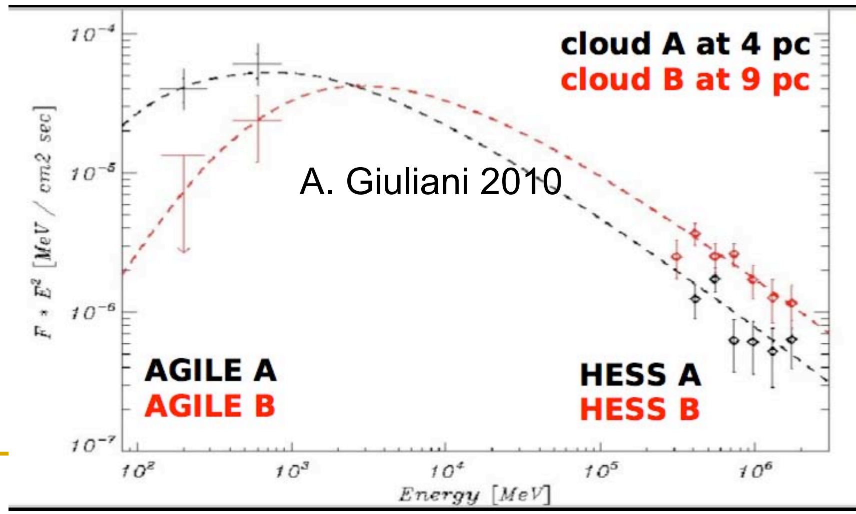
CRs from an old SNR interacting with nearby clouds?





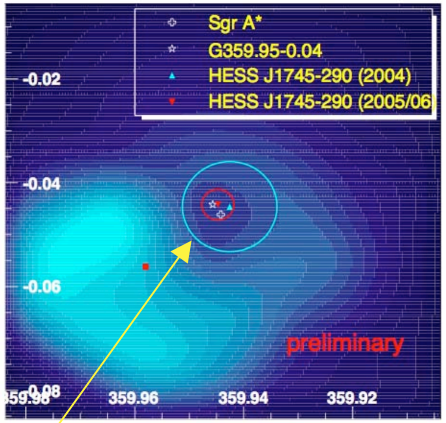




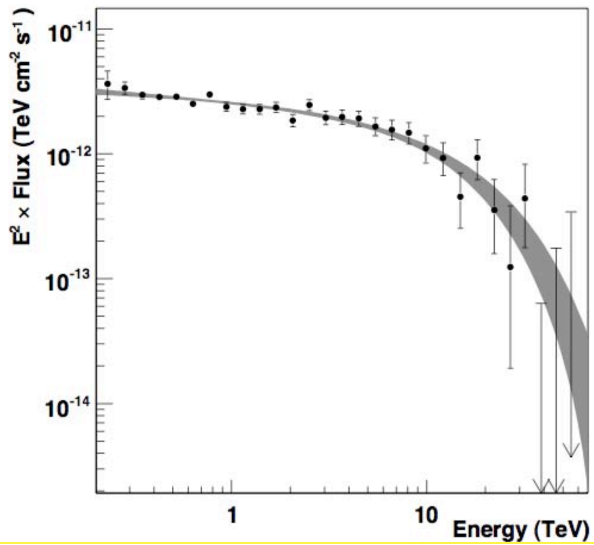


Galactic Center

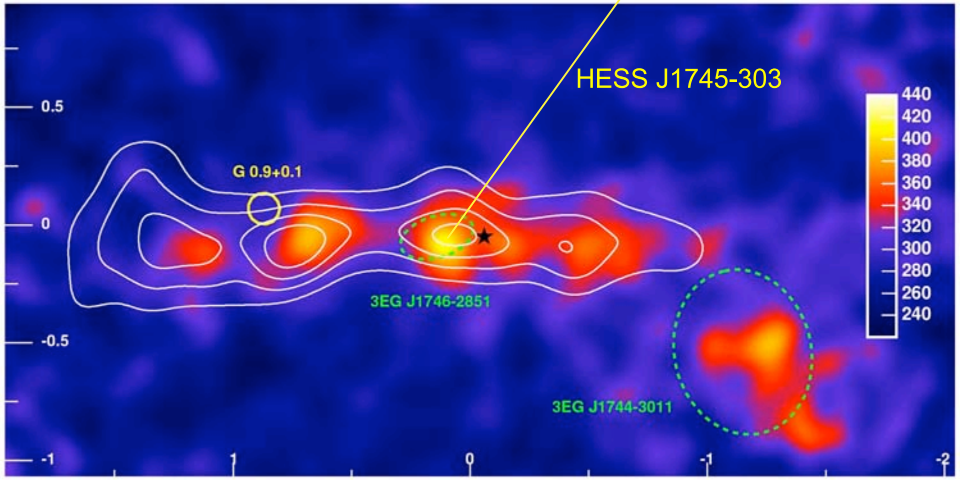
90 cm VLA radio image



Sgr A* or the central diffuse < 10pc region or a plerion?
[no indication for variation]



γ-ray emitting clouds



Energy spectrum:

$dN/dE=AE^{-\Gamma} \exp[(-E/E_{0)})^{\beta}]$

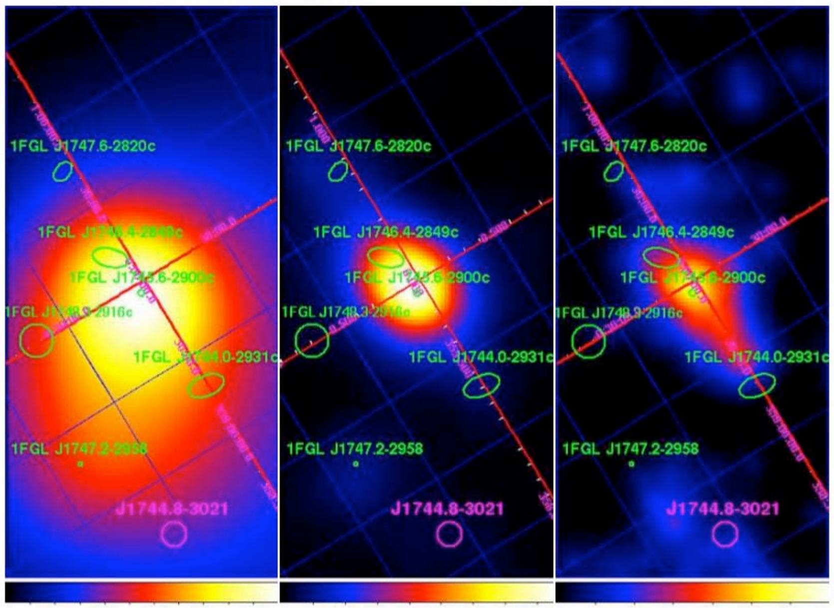
$\beta=1$	$\Gamma=2.1$; $E_0=15.7$ TeV
$\beta=1/2$	$\Gamma=1.9$ E0=4.0 TeV

γ-rays from GMCs in GC: a result of an active phase in Sgr A* with acceleration of CRs some 10^4yr ago?

GALACTIC CENTER AT VERY HIGH-ENERGIES.

CHERNYAKOVA, M.[1], MALYSHEV, D.[1], AHARONIAN, F. A.[1,2], CROCKER, R. M.[2], JONES, D I.[2]

0.3-3 GeV   3-30 GeV   30-300 GeV



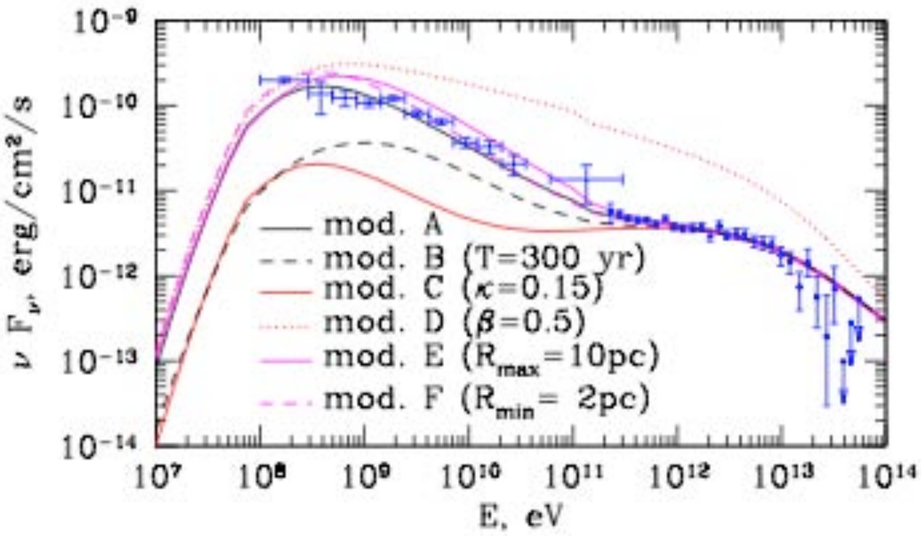
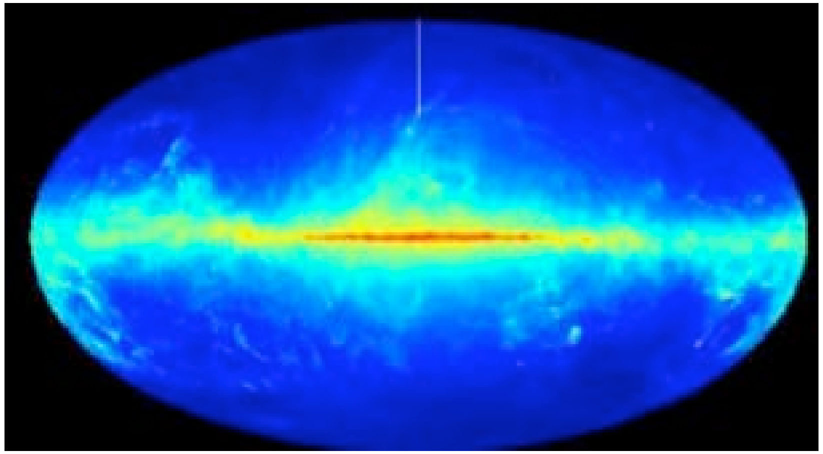
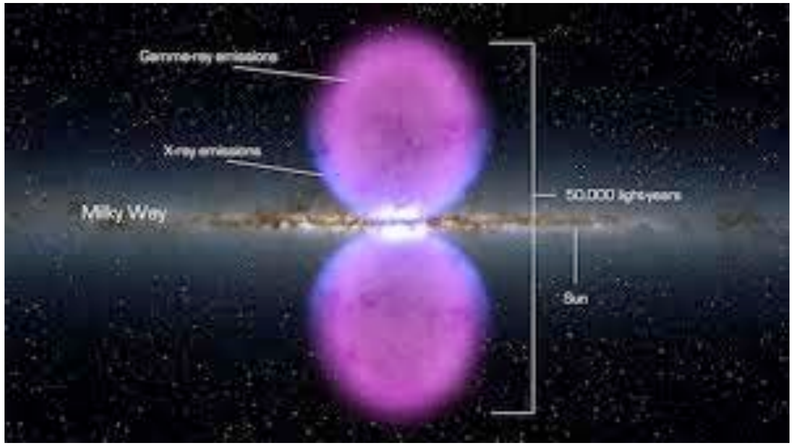


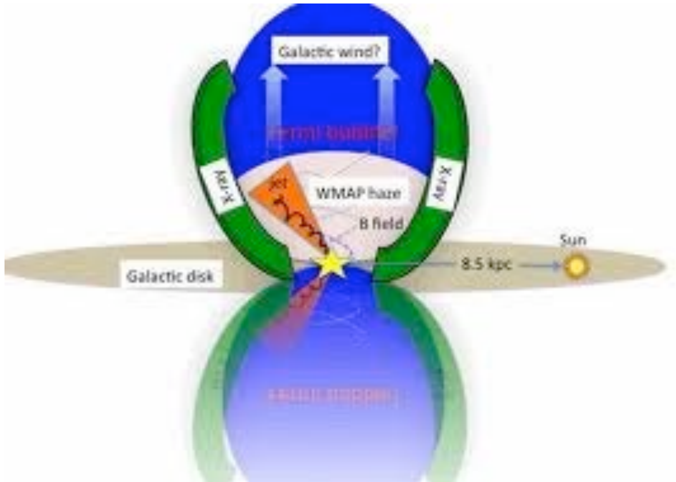
FIG. 5.— Spectral energy distribution of gamma-rays expected from a region filled with relativistic and non-relativistic protons within different assumptions concerning the injection, diffusion and the region geometry (see text for a discussion of parameters for each specific model). The data points have been derived from the Fermi and HESS data

$L_p \approx 10^{39}$ erg/s

Fermi Bubbles !







Finkbeiner and collaborators 2010

Fermi Bubbles - *result of pp interactions of CRs produced in the GC and accumulated in R ~10 kpc regions over 10 Billion year comparable to the age of the Galaxy? (Crocker&FA, PRL 2011)*

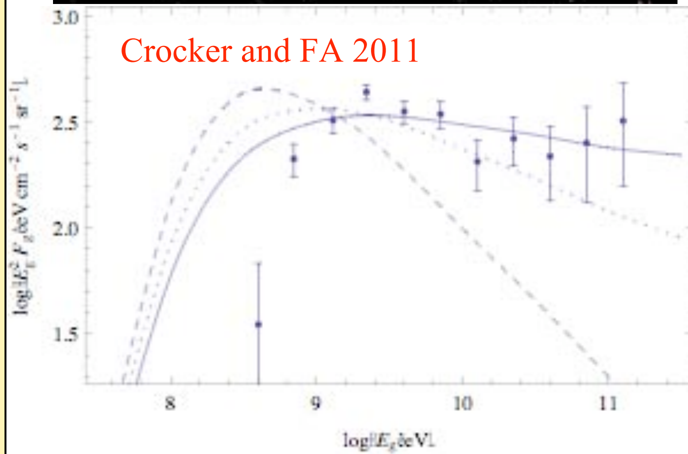
Size - because of slow diffusion in a very turbulent plasma (10 times slower than in Galactic Disk)

plasma density: n~0.01 cm^{-3} t_{pp} ~ 5 Gyr < t_{Galaxy}

saturation (calorimetric) regime explains:

modest requirements to CR rate : *Lp ~ 10^{39} erg/s*
homogeneous radiation - γ-ray production rate does not depend on n

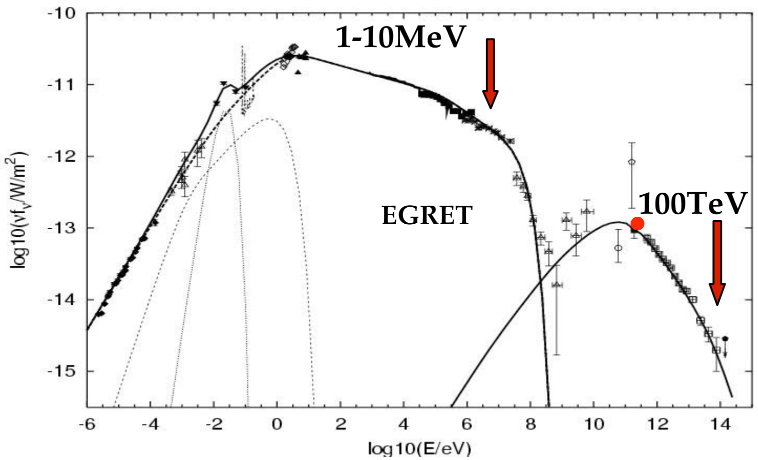
other explanations - *IC scattering of electrons*
problems - how transport>1 TeV electrons to distances 10 kpc - in situ acceleration?



Fermi Bubbles as a neutrino source ?

Crucial test - detection of neutrinos - see talk by Piera Sapienza

Crab Nebula – *a perfect electron PeVatron*



standard MHD theory (Kennel&Coroniti)

cold ultrarelativistc pulsar wind terminates by reverse shock resulting in acceleration of multi-TeV electrons

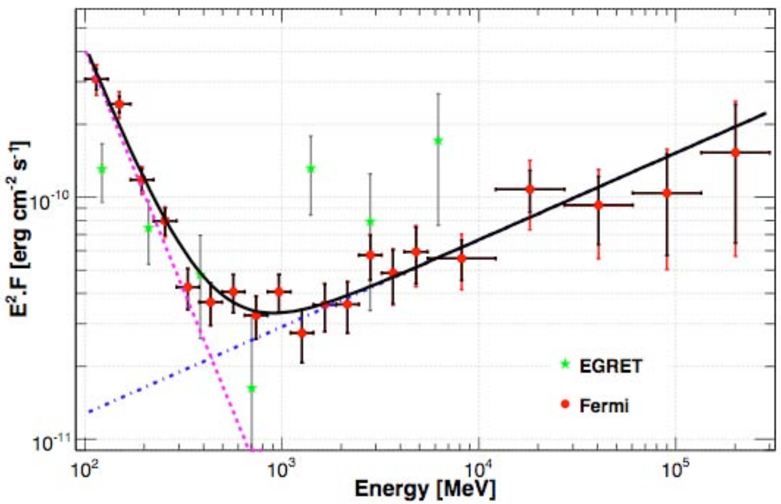
synchrotron radiation => nonthermal optical/X nebula
Inverse Compton => high energy gamma-ray nebula

Crab Nebula – a powerful L_e=1/5L_{rot} ~ 10^{38} erg/s
and extreme accelerator: Ee >> 100 TeV

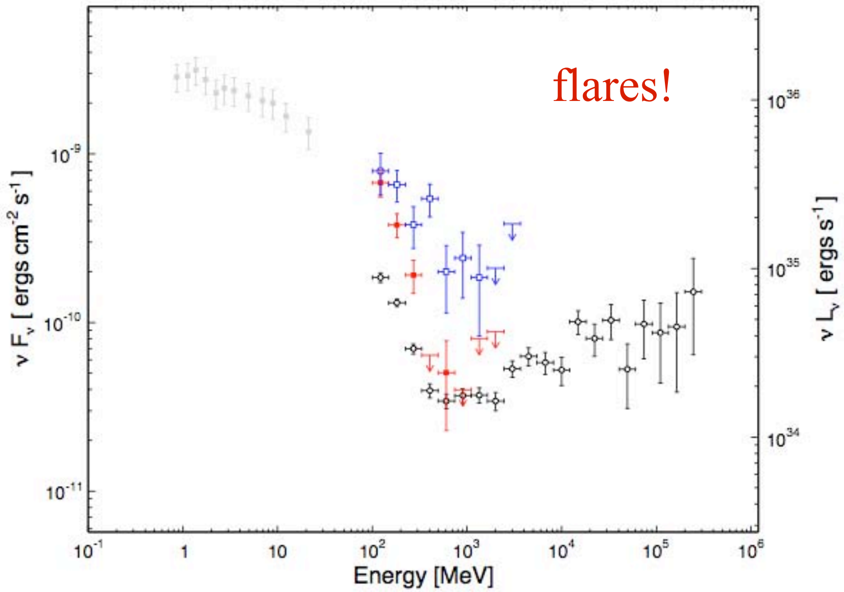
E_{max}=60 $(B/1G)^{-1/2}$ $\eta^{-1/2}$ TeV and $h\nu_{cut}$ ~150η^{-1} MeV

Cutoff at $h\nu_{cut}$ =10-20 MeV => η ~10 - acceleration at 10 % of the maximum rate
γ-rays: E_γ ~ 50 TeV (HEGRA, HESS) => E_e > 200 TeV
B-field ~100 mG => h ~ 10 - independent and more robust estimate
1 mG => η ~ 1 ?

Crab Nebula - news from AGILEE and Fermi LAT :



IC emission consistent with average
nebular B-field: B ~ 100μG-150μG



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>1mG, etc.

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

Crab Nebula is a very <u>effective accelerator</u>

but <u>not an effective IC γ-ray emitter</u>

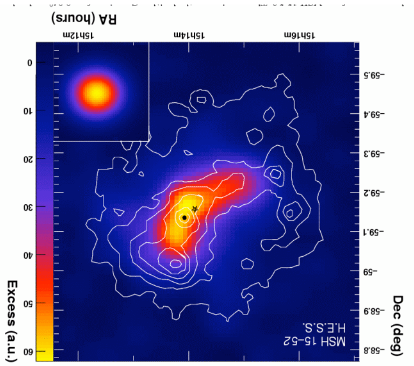
we do see TeV γ-rays from the Crab Nebula because of very large spin-down flux: $f_{rot}=L_{rot}/4\pi d^2=3\mathrm{x}10^{-7}$ erg/cm^2 s

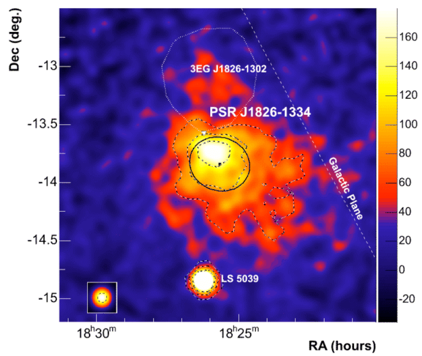
gamma-ray flux << "spin-down flux" *because of large B-field*

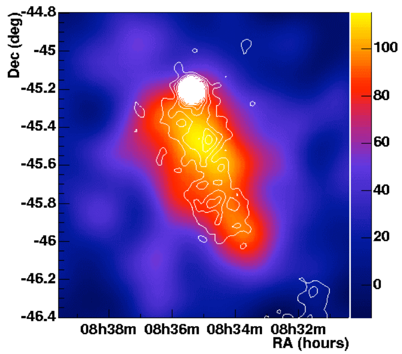
if the B-field is small (environments with small external gas presure)

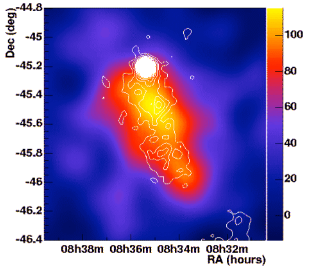
higher γ-ray efficiency ➡ detectable γ-ray fluxes from other plerions

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

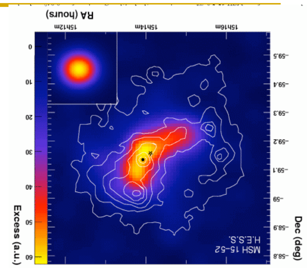




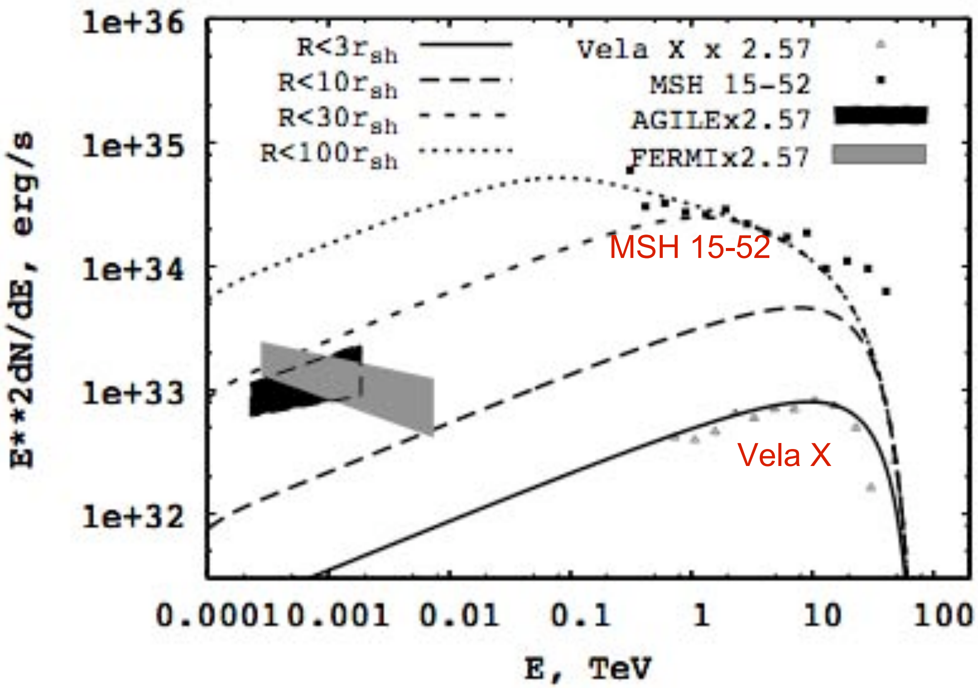




Vela X and MSH-15-52



both are of almost same age (10kyr), same power L_{rot}~10^{37} erg/s, and angular size, but very different luminosities, energy spectra, distances and … sizes!



because the small distance to Vela X, we see only a very small part of the nebula => very low luminosity, but also because of quick escape of electrons from this small area - we see IC spectrum of uncooled electrons

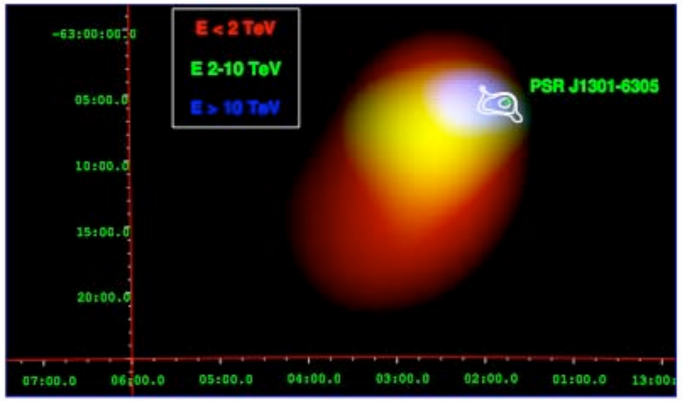
$L=1.8\ 10^{37}$ erg/s, $r_{sh}=5\ 10^{18}$s, $\sigma=3\ 10^{-3}$, $Q(E)=E^{-2.2}\exp(-E/300\mathrm{TeV})$

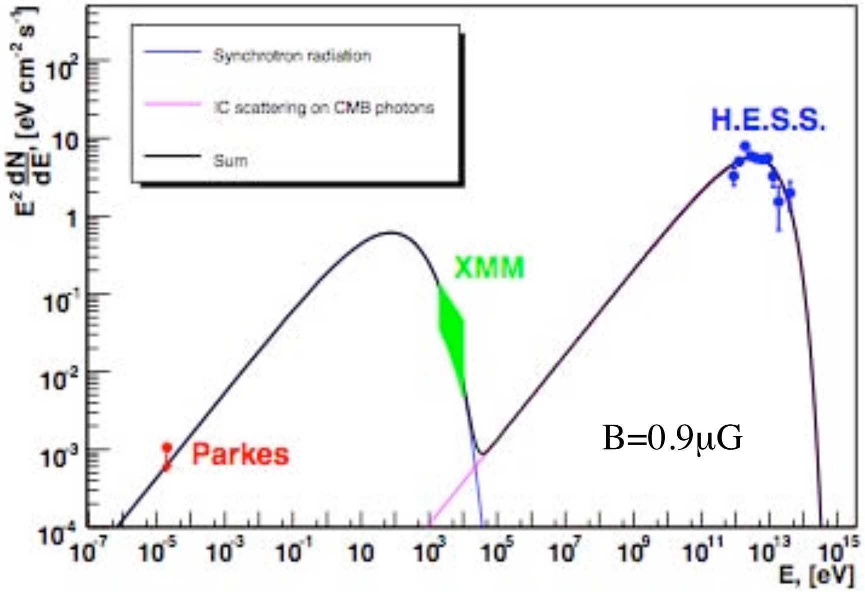
Khangulyan, FA, Bogovalov 2010

PWNe - *perfect electron accelerators and perfect γ-ray emitters!*

(1) rot. energy => (2) Poynting flux => (3) cold ultrarelativistic wind =>
(4) termination of the wind/acceleration of electrons => gamma-radiation:
efficiency at each stage >50% !

HESS J 13030-62 = PSR J1301-6305?



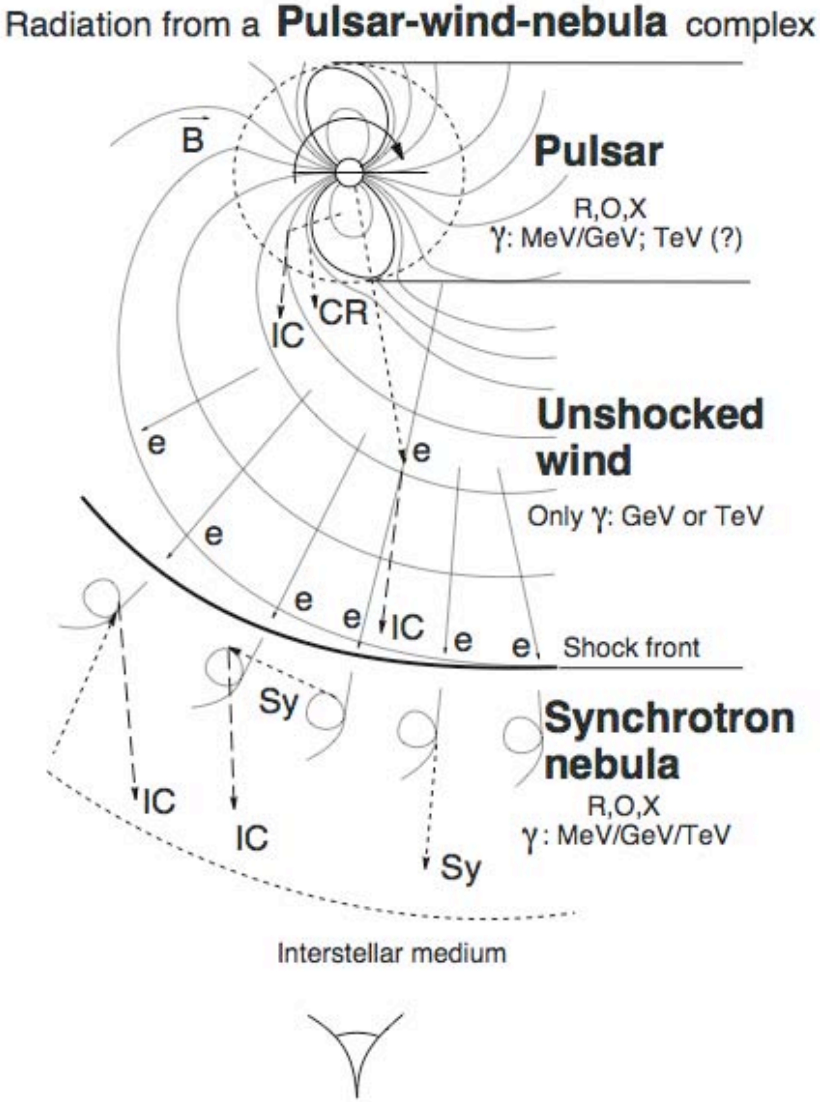


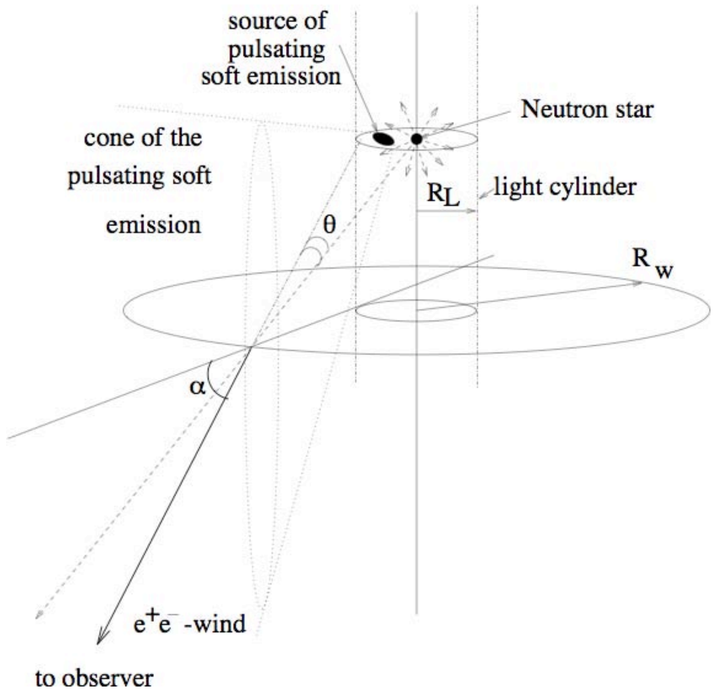
dramatic reduction of the angular size with energy:strong argument in favor of the IC origin of the γ-ray nebula

very small average B-field; for d=12.6kpc
L_γ/L_{SD} = 0.07; 3arcmin ~ 10 pc

because of small B-field we see "relic" electrons produced at early epochs of the pulsar

3-zones in pulsars

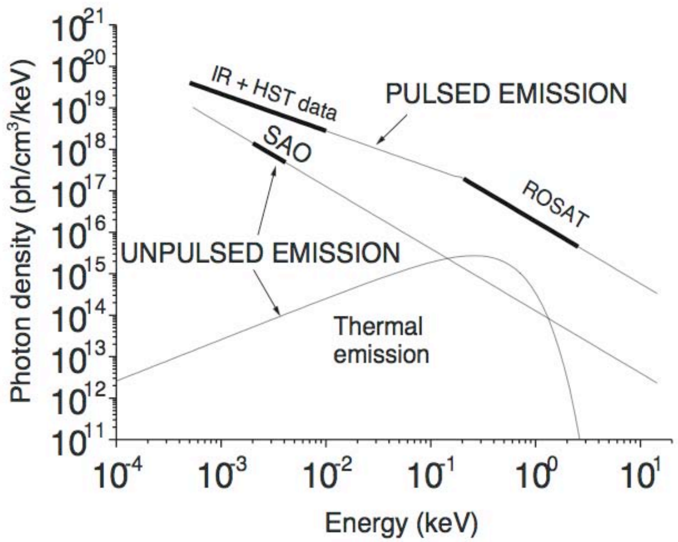


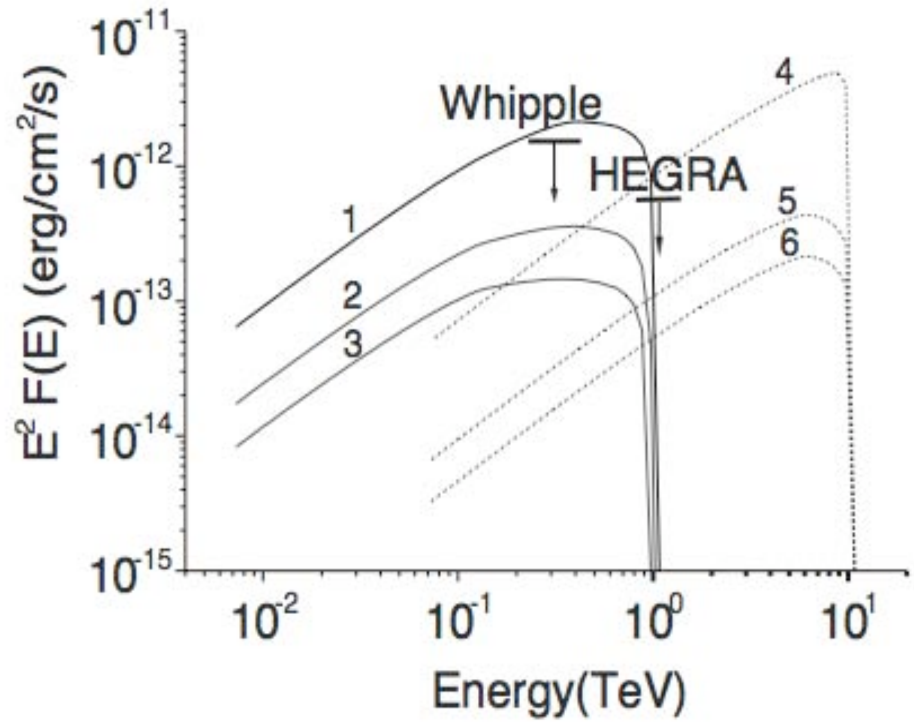


Bogovalov & FA 2000

VERITAS - VHE pulsed emission from Crab ?

only reasonable explanation - IC of unshocked wind





1,2,3 - R/R_L=30, 50, 70; Γ=3 10^6

4,5,6 - R/R_L=30, 50, 70; Γ=3 10^7

Bogovalov & FA 2000

binary systems - unique high energy laboratories

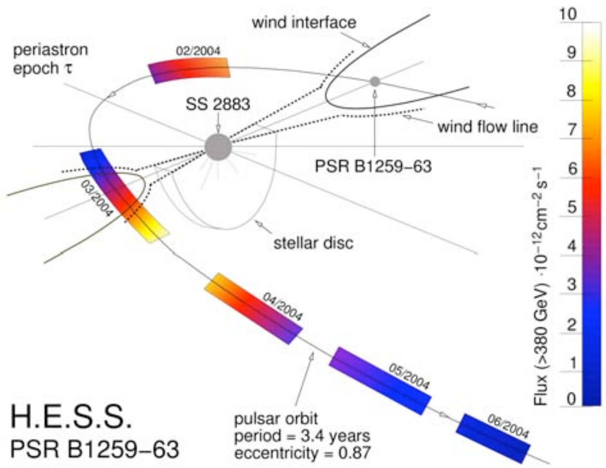
binary pulsars - a special case with strong effects associated with the optical star on both the dynamics of the pulsar wind and and the radiation before and after its termination

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

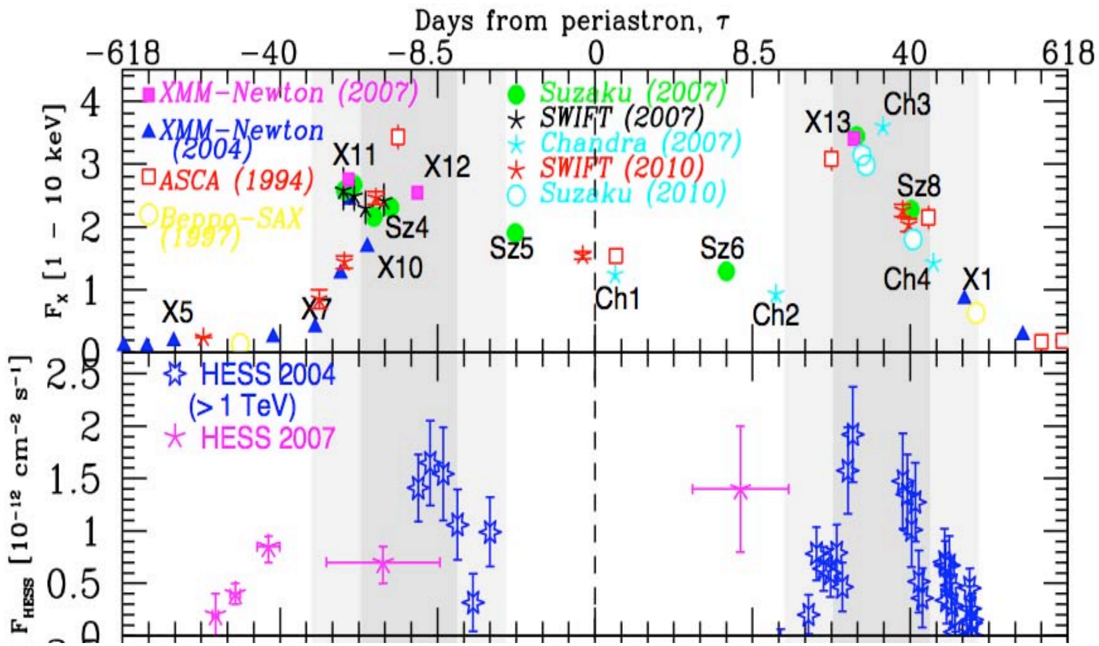
‘‘on-line watch‘‘ of the MHD processes of creation and termination of the ultrarelativistic pulsar wind, as well as particle acceleration by relativistic shock waves, through spectral and temporal studies of γ-ray emission

(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?



energy flux of starlight close to periastron:
~ 1 erg/cm^3 B-field is estimated: 0.1-1 G



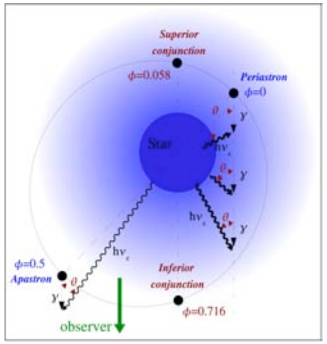
HESS: detection of γ-rays from PSR1259-63 at < 0.1Crab level - tendency of minimum of TeV gamma-ray flux close to the periastron; *several possible explanations* - *but* many things remain uncertain and confusing

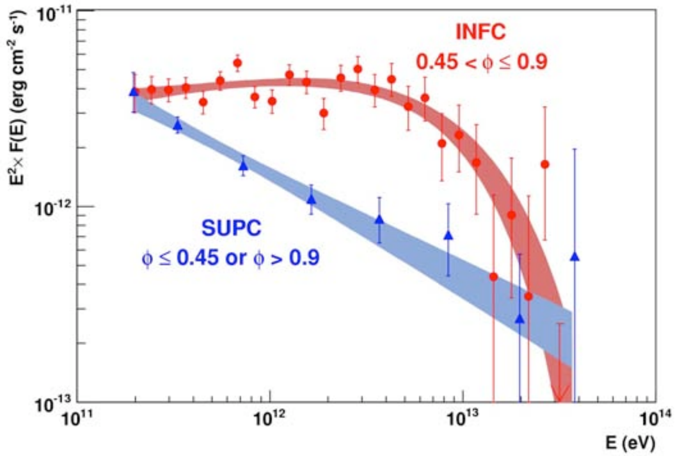
now we have a new puzzle - flares at GeV energies !!!

LS 5039

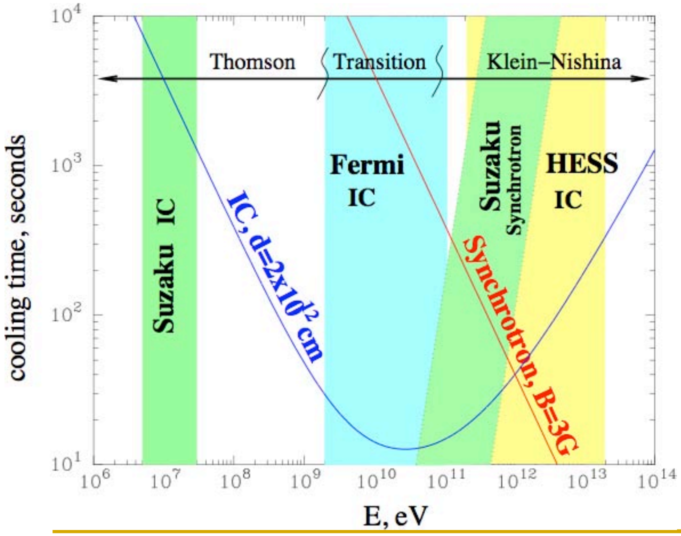
works as a perfect TeV clock
and an extreme accelerator

close to inferior conjuction - maximum
close to superior conjuction – minimum



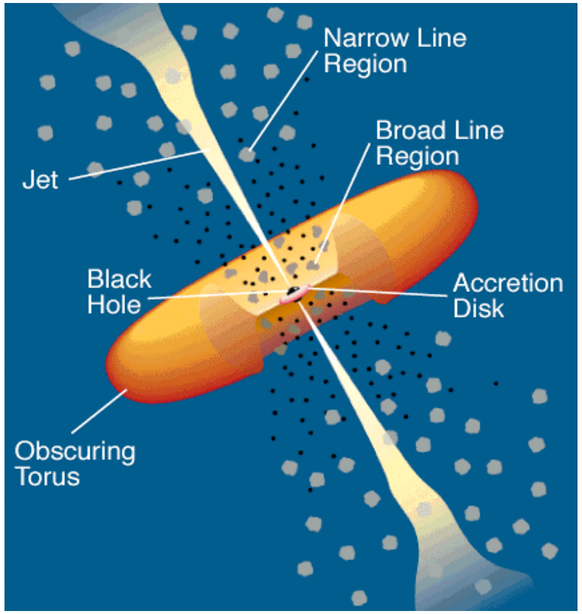


modulation of the gamma-ray signal? *a quite natural reason (because of $\gamma-\gamma$ absorption), but we see a different picture… anisotropic IC scattering? yes, but perhaps some additional factors (adiabatic losses, modest Doppler boosting) also play a non-negligible role*



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 $\eta < 10$ => 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

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



before 2004:

detection of 6 TeV Blazars, extraordinary outbursts of Mkn 501 in 1999, variations on <1h timescales;

=> initiated huge interest in AGN and EBL communities

today:

more than three dozens TeV blazars; quite unexpectedly TeV γ-rays from distant blazars;

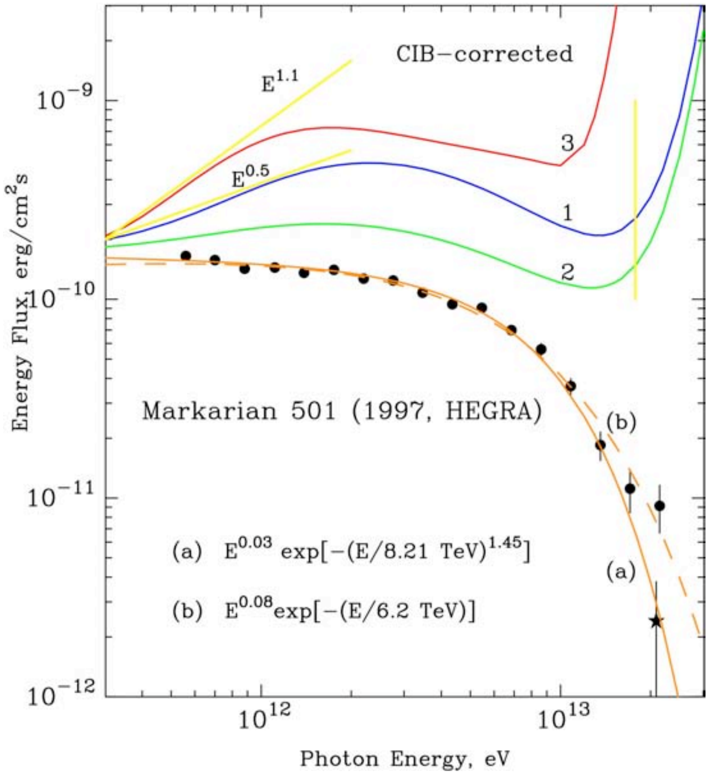
=> strong impact on both blazar physics and on the Diffuse Extragalactic Background (EBL) models

most exciting results - variability on 2-3 min timescales

unusually hard gamma-ray spectra

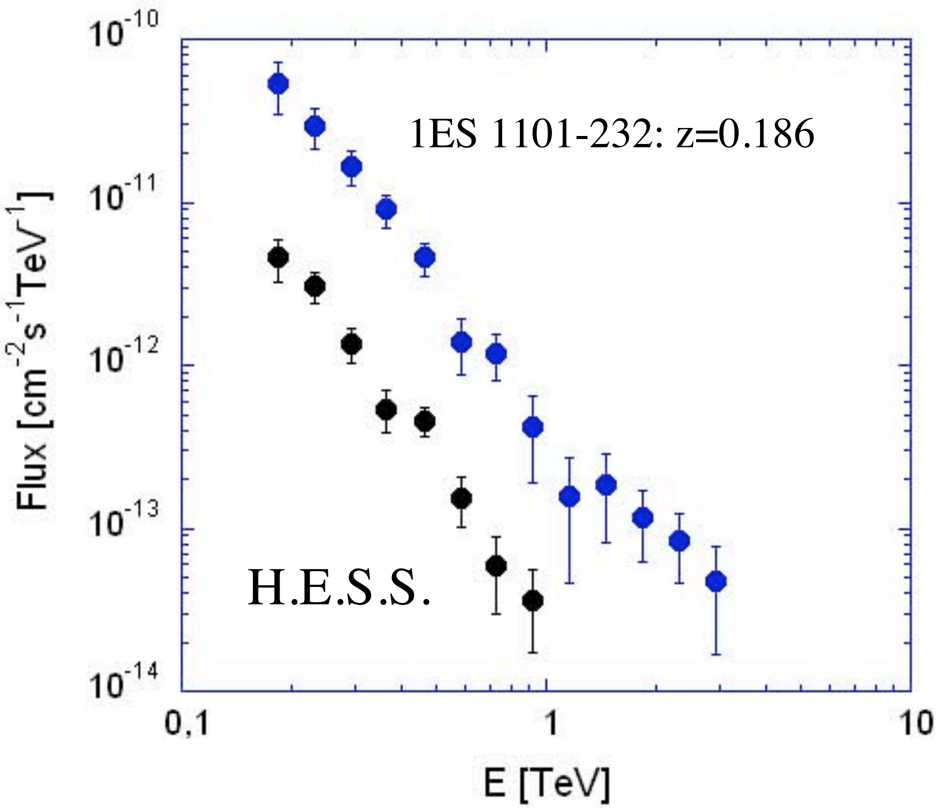
Blazars and EBL

Mkn 501: z=0.031: an "infrared crisis", but with a happy end…



reported EBL flux at FIR have not been confirmed

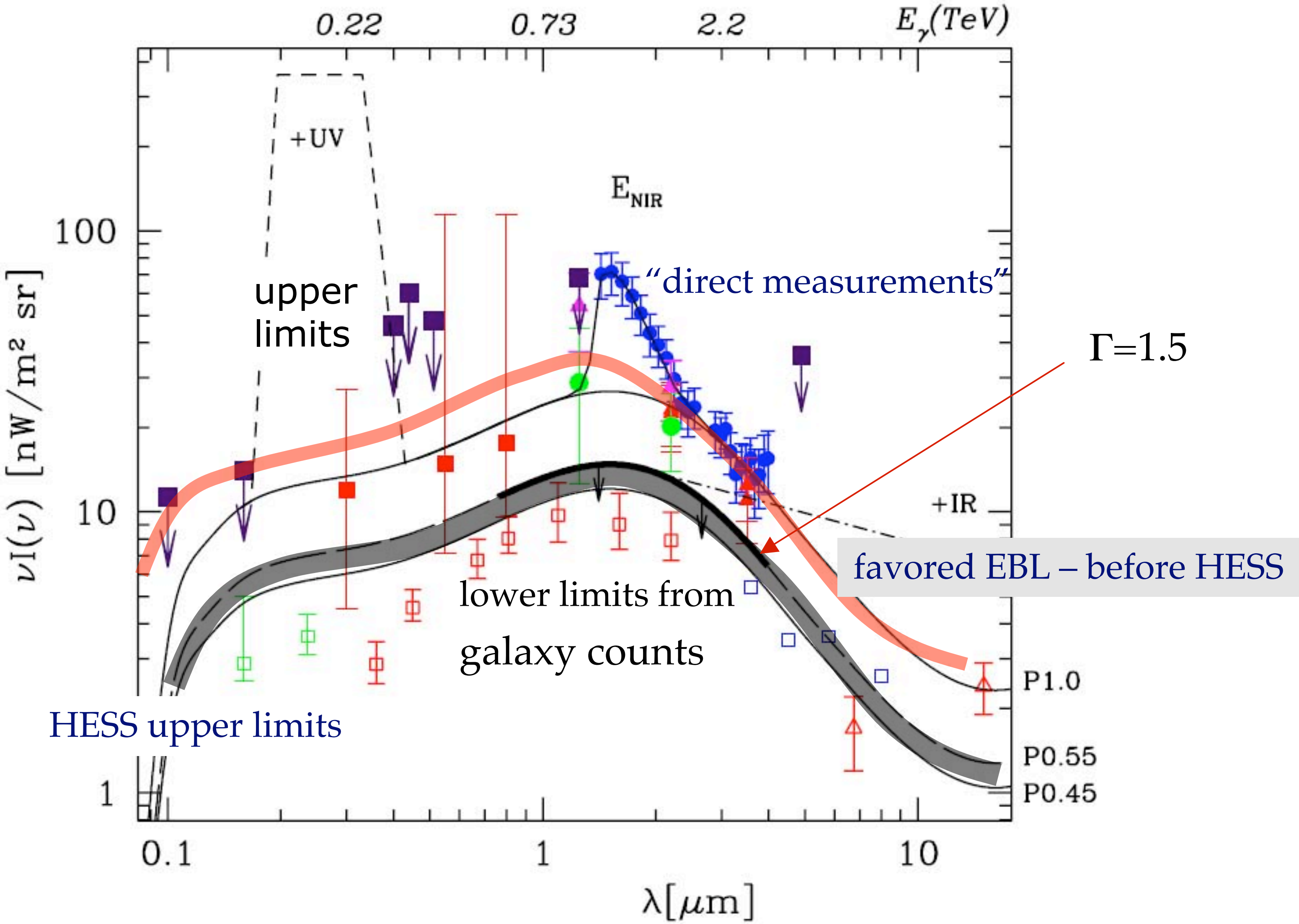
TeV blazars detected by HESS at z> 0.15 !



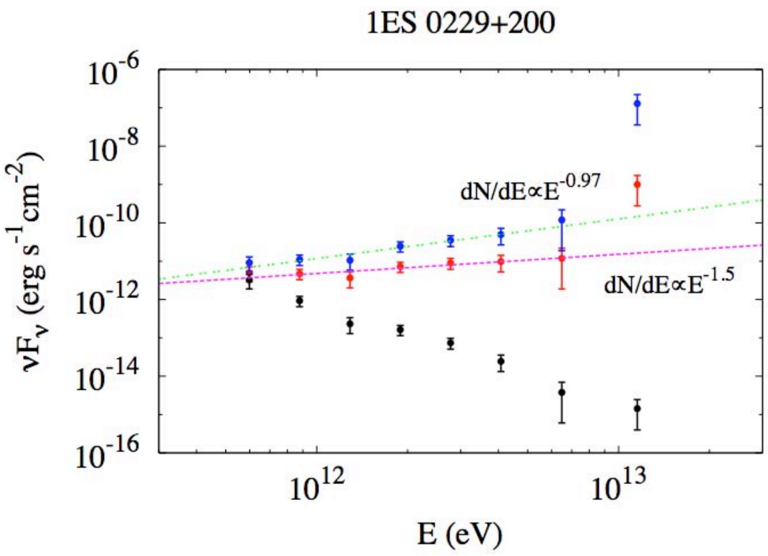
corrected for EBL absorption γ-ray spectrum not harder than $E^{-\Gamma}$ (Γ=1.5) => **u.l. EBL**

HESS upper limits on EBL - good agreement with recent EBL studies

EBL (almost) resolved at NIR ?



1ES 0229+200 - *a new "trouble-maker"*

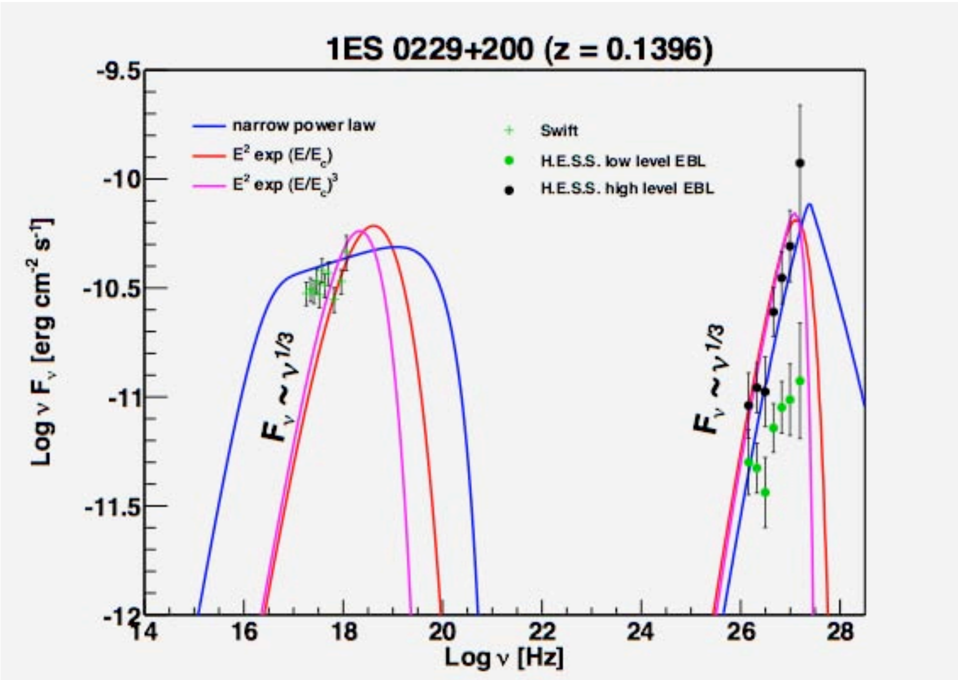


z= 0.14, but spectrum extends to >5 TeV !
even slight deviation from the "standard" EBL
=> extremely hard γ-ray spectra with $\Gamma < 1$

possible explanations:

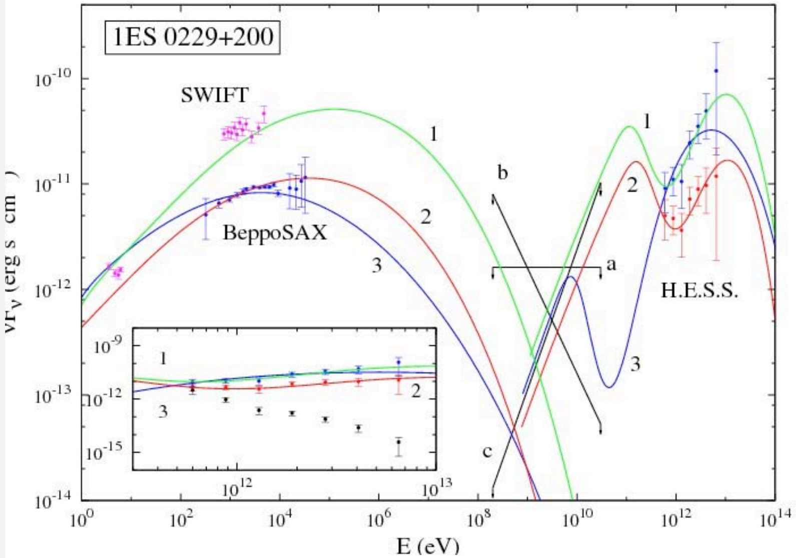
- very narrow electron distribution - no significant radiative energy losses =>
  typically very small B-field: 0.001G
  mechanism: External IC or SSC
- cold ultrarelativistic electron wind?
  mechanism: External IC
- internal γ–γ absorption =>
  very strong magnetic field, B >10 G
  mechanism: proton synchrotron

Synchrotron Self Compton



E. Lefa

Proton synchrotron plus internal γ–γ absorption

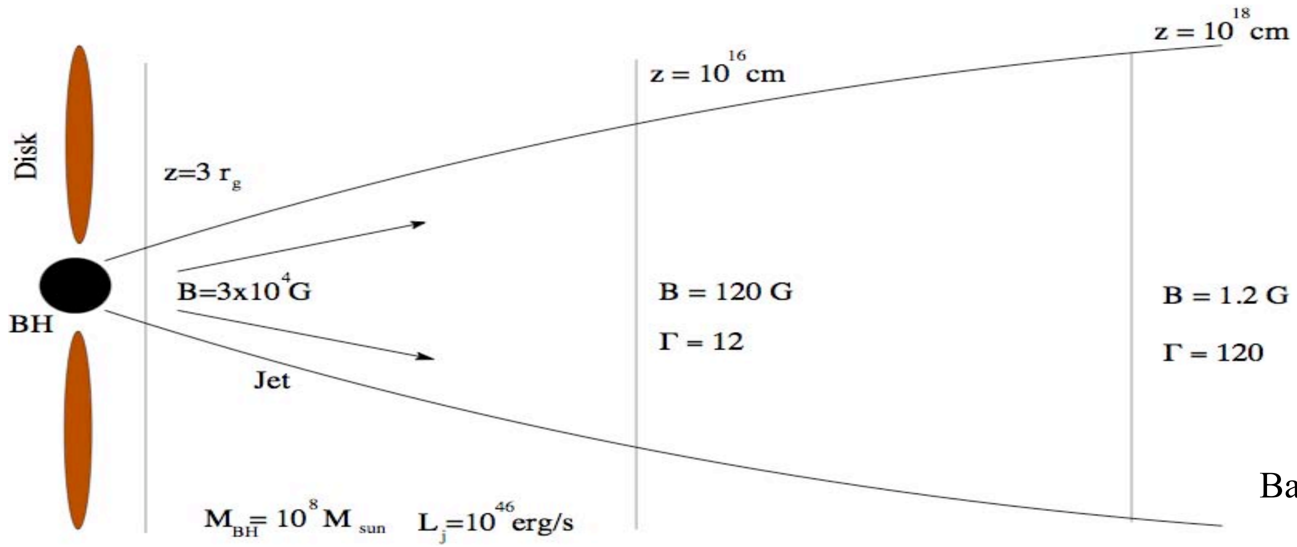


O. Zacharopoulou

narrow electron distribution
plus weak magnetic field
B < 0.1 G

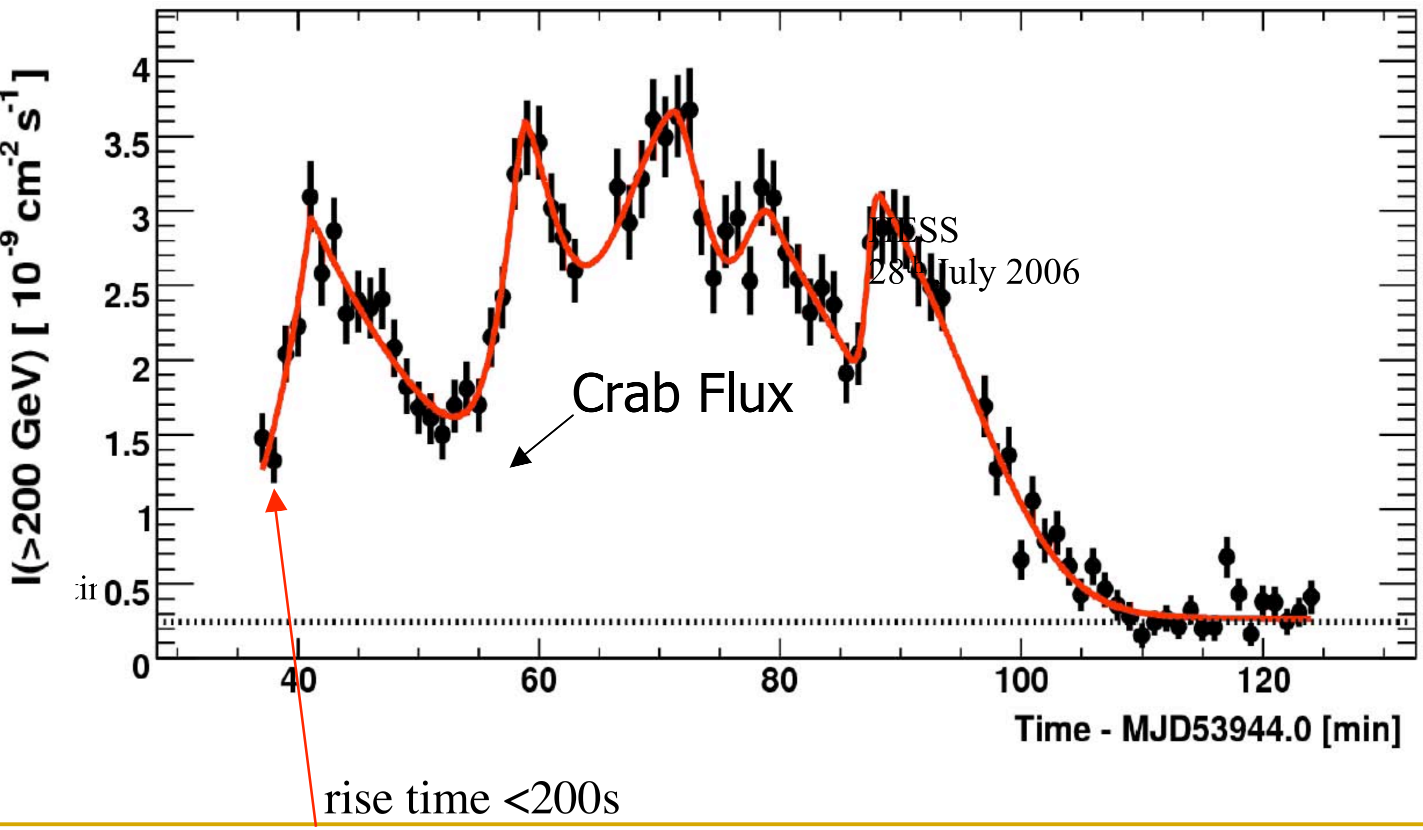
strong magnetic field:
B > 10 G

B-field: very large or very small?



Barkov et al 2010

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) variabiliry timescale => R=c Δt_{var} δ_j=$10^{14}\delta_{10}$ cm for a 10^9Mo BH with 3Rg = 10^{15} cm => δj > 100, i.e. close to the accretion disk (the base of the jet), the bulk motion Γ > 100



on the Doppler boosting and mass of BH in PKS2155-309

- several min variability timescale => $R=ct_{var}\delta_j \sim 10^{13}\delta_j$ cm for a 10^9Mo BH with $3Rg \sim 10^{15}$ cm => $\delta j > 100$, i.e. close to the accretion disk (the base of the jet), the Lorenz factor of the jet $\Gamma > 50$ - this hardly can be realized close to Rg!

- the (internal) shock scenario: shock would develop at $R=Rg\,\Gamma^2$, i.e. minimum γ-ray variability would be $R_g/c=10^4(M/10^9Mo)$ sec, although the γ-ray production region is located at $R_g \sim ct_{var}\Gamma^2$ (e.g. Chelotti, Fabian, Rees 1998) - this is true for any other scenario with a "signal-pertubaution" originating from the central BH

- thus for the observed $t_{var} < 200$ s, the mass of BH cannot significantly exceed 10^7Mo. On the other hand the "BH mass–host galaxy bulge luminosity" relation for PKS2155-304 gives $M > 10^9$Mo.

Solution? perturbations are cased 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" ?