Short Course on High Energy Astrophysics
"Exploring the Nonthermal Universe
with High Energy Gamma Rays"

Lecture 5: **Galactic Sources of VHE Gamma Rays**

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potential galactic gamma-ray sources

- ✓ Supernova Remnants (SNRs)
- ✓ Colliding Stellar Winds
- ✓ Giant Molecular Clouds (GMCs)
- ✓ Galaxy itself (the Disk and the Hallo)
- ✓ Pulsars, Pulsar Winds, Pulsar Wind Nebulae (PWNe)
- ✓ Binary Pulsars
- ✓ Microquasars (accreting Black Holes)

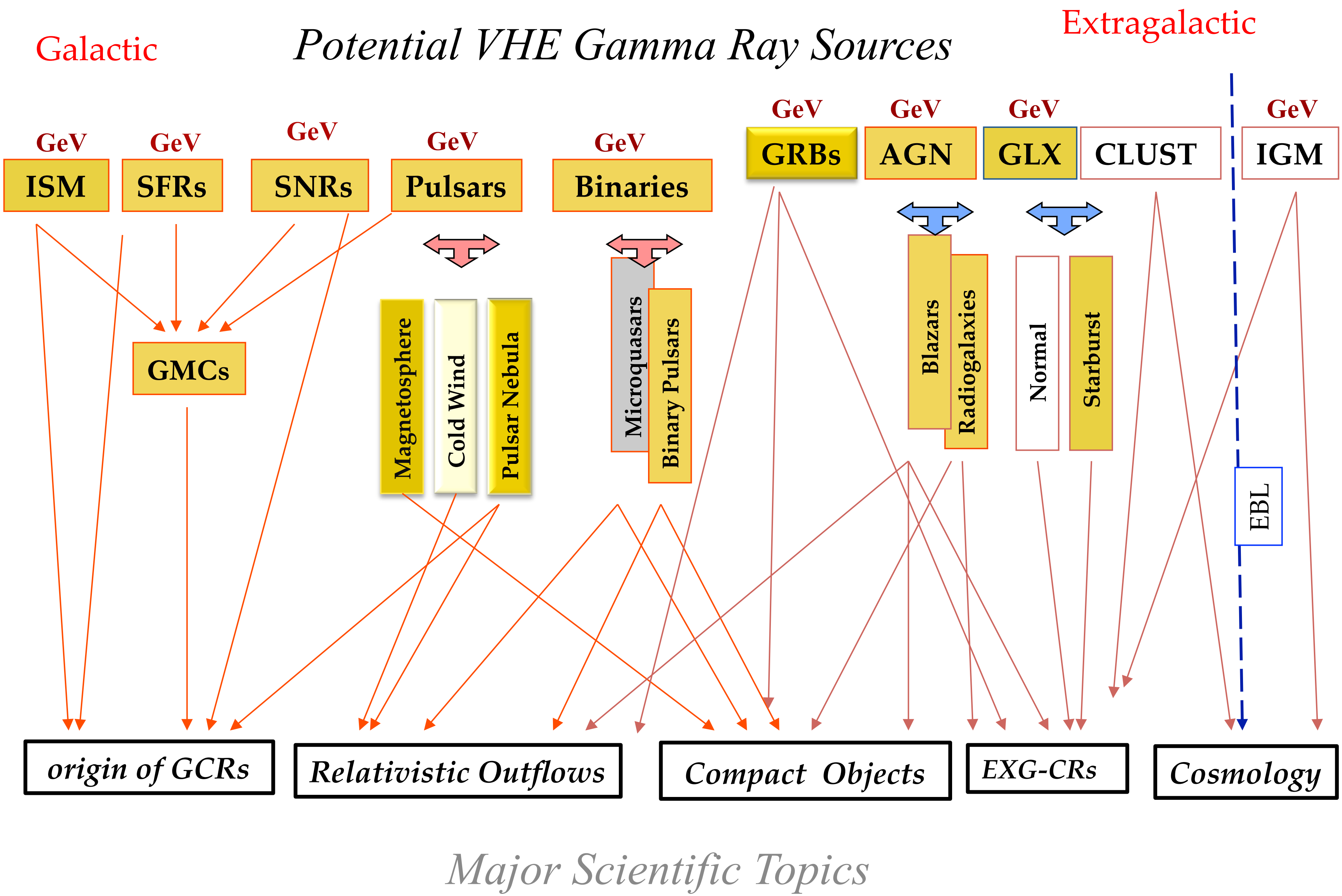
Topics

Theory of Particle Acceleration
Origin of Galactic Cosmic Rays

Structure of our Galaxy
Physics of the Interstellar Medium
Star Formation

Physics of Pulsar Magnetospheres and Winds
Relativistic hydrodynamics in PWNe and in Binary Pulsars

Nonthermal aspects of Accreting Black Holes

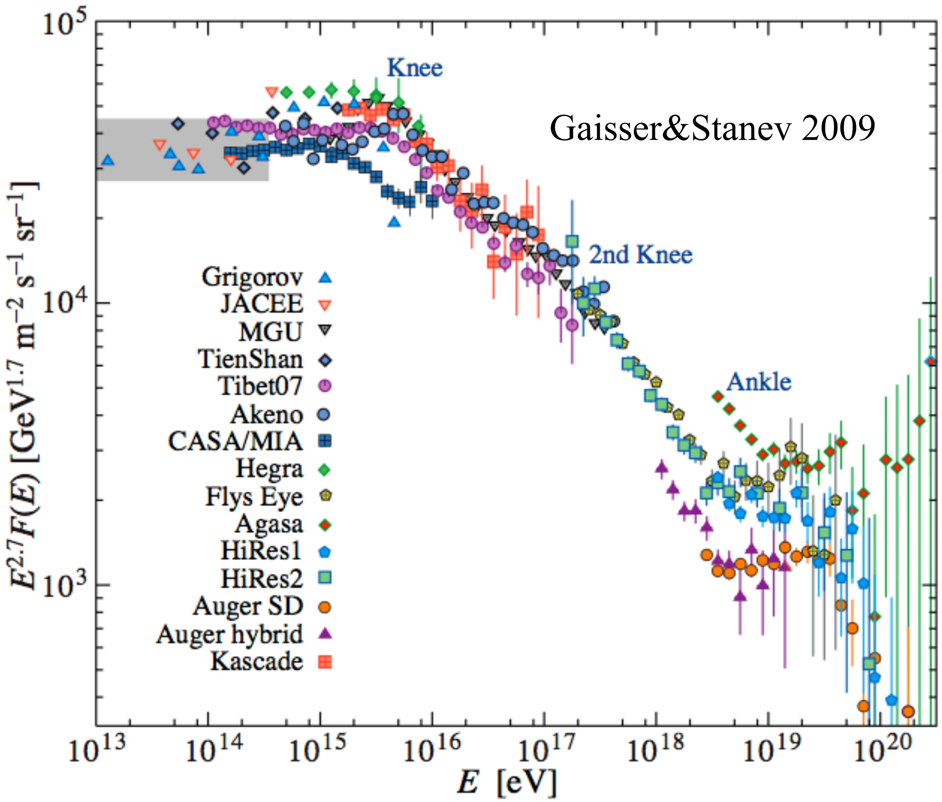

Galactic
Potential VHE Gamma Ray Sources
Extragalactic
GeV
ISM
GeV
SFRs
GeV
SNRs
GeV
Pulsars
GeV
Binaries
GeV
GRBs
GeV
AGN
GeV
GLX
CLUST
GeV
IGM
GMCs
Magnetosphere
Cold Wind
Pulsar Nebula
Microquasars
Binary Pulsars
Blazars
Radiogalaxies
Normal
Starburst
EBL
origin of GCRs
Relativistic Outflows
Compact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

Origin of Cosmic rays - "after 100yr of the discovery still a mystery"

energy range: 10^9 to 10^{20} eV

what do we know about CRs:

- before the knee - galactic
- after the ankle - extragalactc
- between knee and ankle ?



all particle cosmic ray spectrum

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

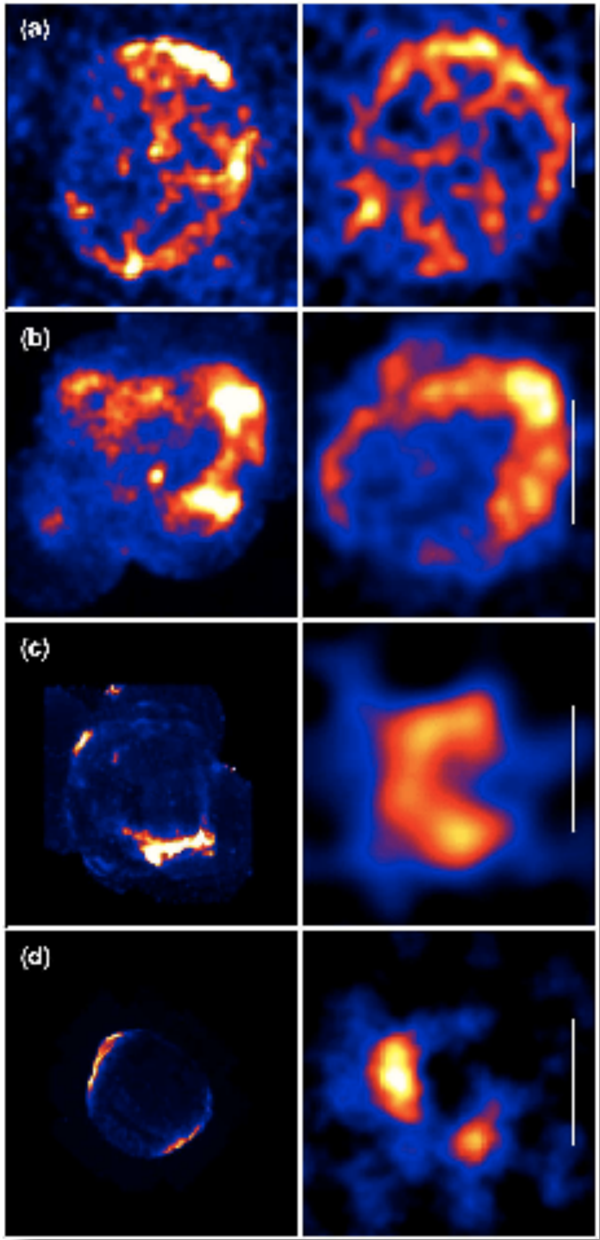
Supernova Remnants? two attractive features:

- ✓ *available energy:* $W_{CR} \sim 0.1 E_{SN}$
- ✓ *effective mechanism* Diffusive Shock Acceleration

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

other possible sources?

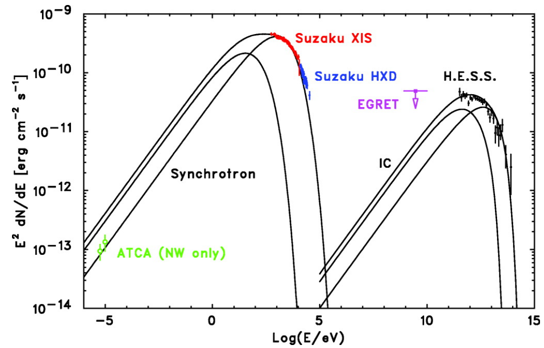
Pulsars/PWNe OB stars Binaries Galactic Center …

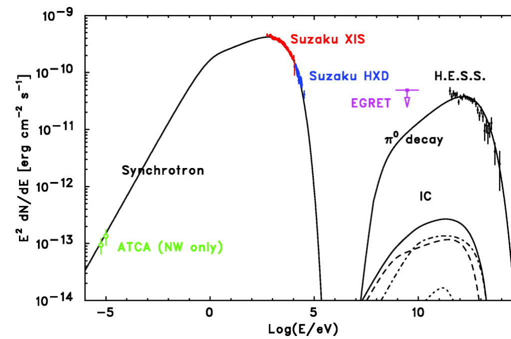


acceleration of protons and/or electrons in SNR shells to energies up to 100TeV

leptonic or hadronic?

=>





RXJ1713.7-4639

$e + 2.7K \Rightarrow \gamma$ $\qquad$ $pp \Rightarrow \pi^o \Rightarrow 2\gamma$

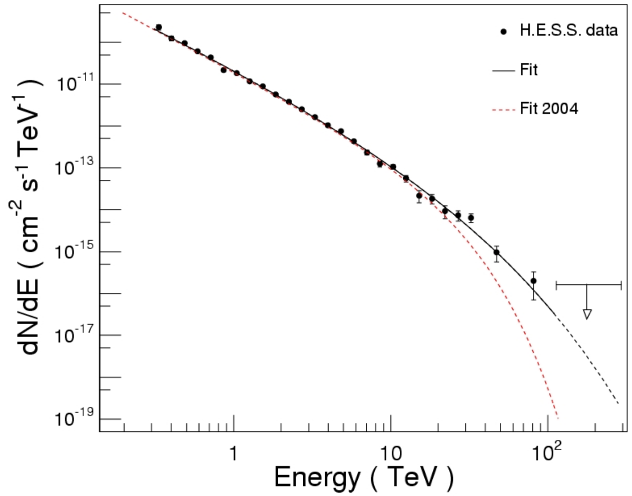
B=15μG
We ≈3 10^{47} erg

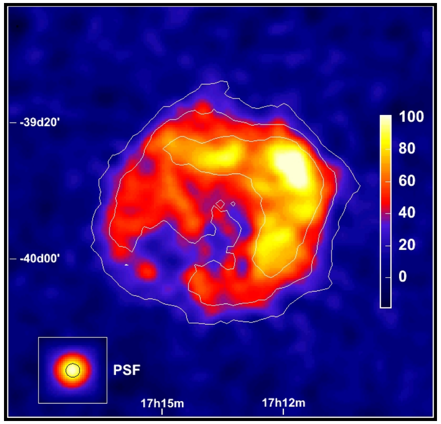
B=200μG
Wp ≈ $10^{50}(n/1cm^{-3})^{-1}$ erg

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

RXJ1713.7-4639

TeV γ-rays and shell type morphology: acceleration of protons and/or electrons in shell up to 100TeV (not much higher)





can be explained by γ-rays from pp ->π^o ->2γ

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

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

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

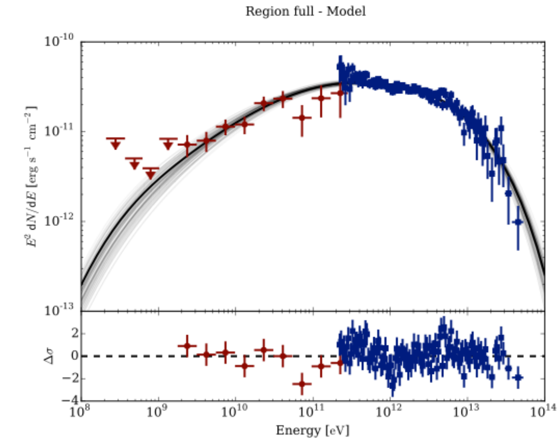
with just "right" energetics:
$Wp=10^{50}\,(n/1cm^{-3})^{-1}$ erg

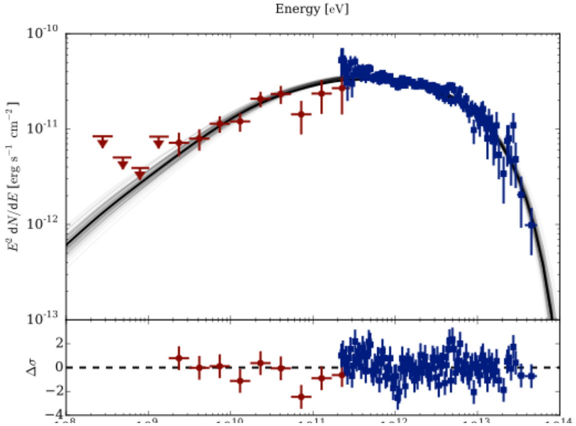
but IC models generally are more preferred… because of TeV-X correlations (?)

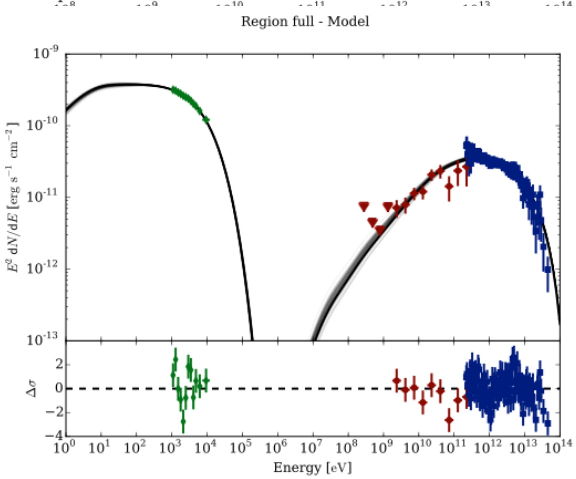
IC origin of γ-rays cannot indeed be excluded, but this is not a good argument

definite answer – detect neutrinos (very difficult)
more realistic approach – γ-ray: morphology with 1 arcmin resolution and spectrometry, especially above 10 TeV

HESS update (see Egert et al.)

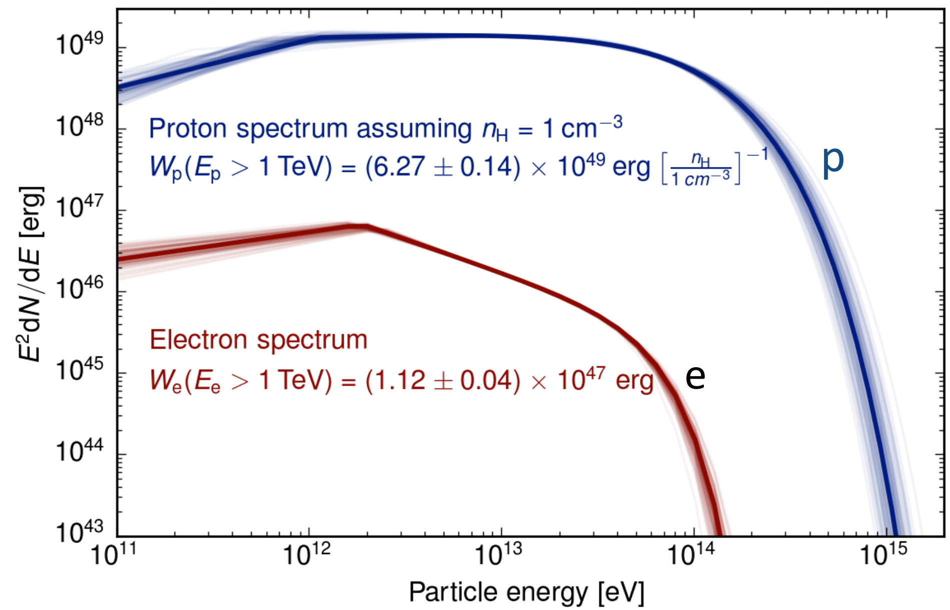


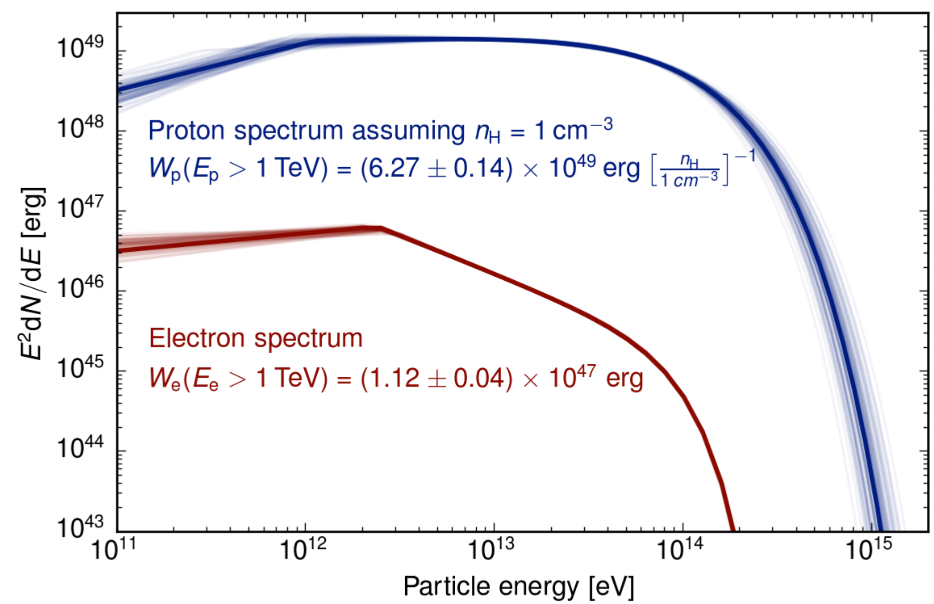




model-independent spectra of p and e

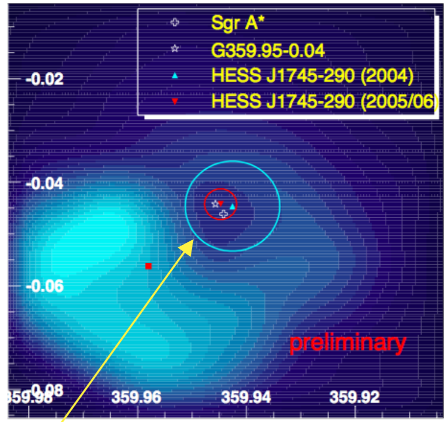
(see V. Zabalza)





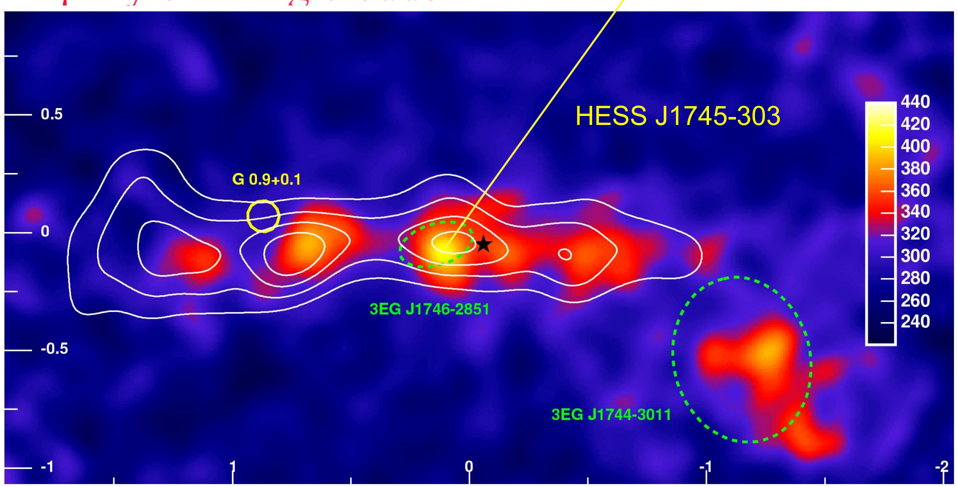
Galactic Center

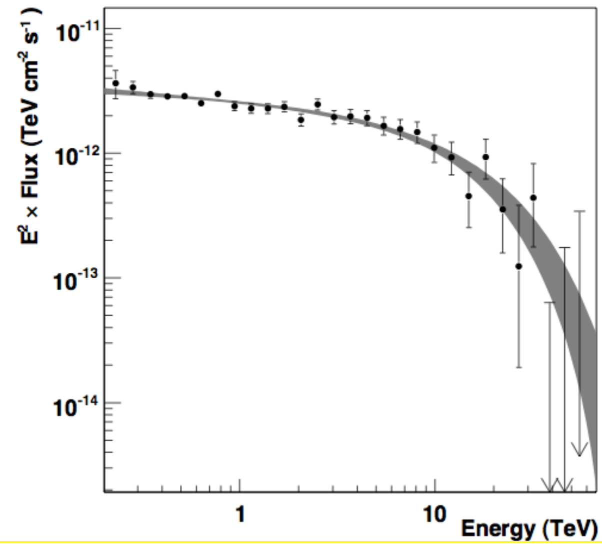
90 cm VLA radio image



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

γ-ray emitting clouds





Energy spectrum:

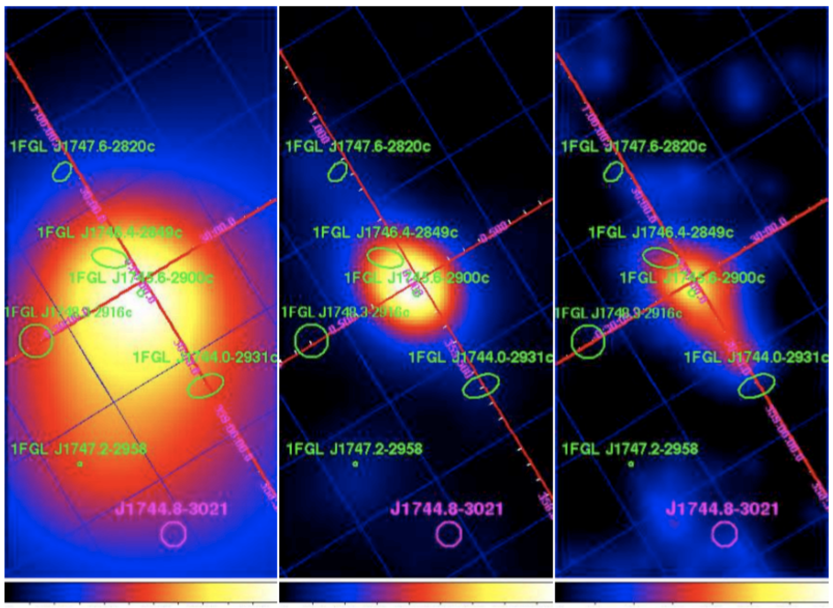
$dN/dE=AE^{-\Gamma} \exp[(-E/E_{0)})^{\beta}]$

$\beta=1$ $\Gamma=2.1$; $E_0=15.7$ 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 high energies

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



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

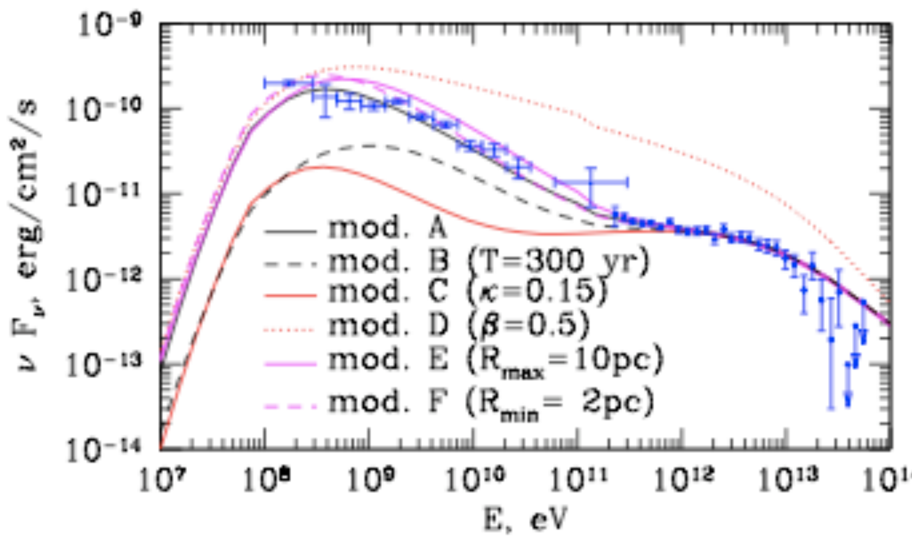
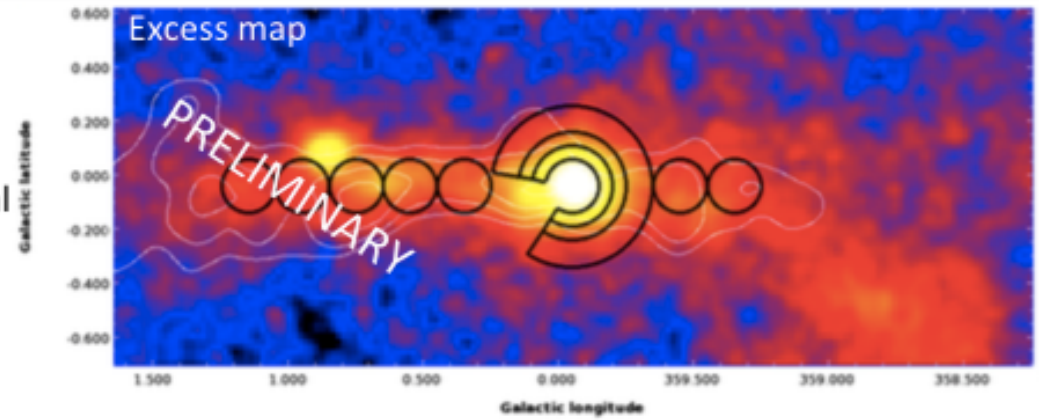


FIG. 5.— Spectral energy distribution of gamma-rays expected from a region filled with relativistic and non-relativistic protons within different assumptions concerning the injection, diffusion and the region geometry (see text for a discussion of parameters for each specific model). The data points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

new!

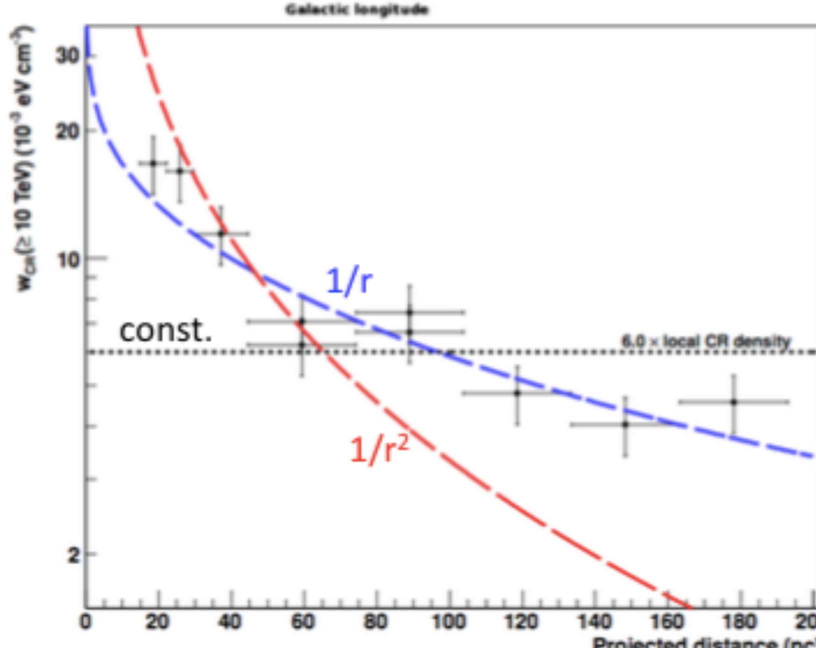
Cosmic-ray density distribution

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



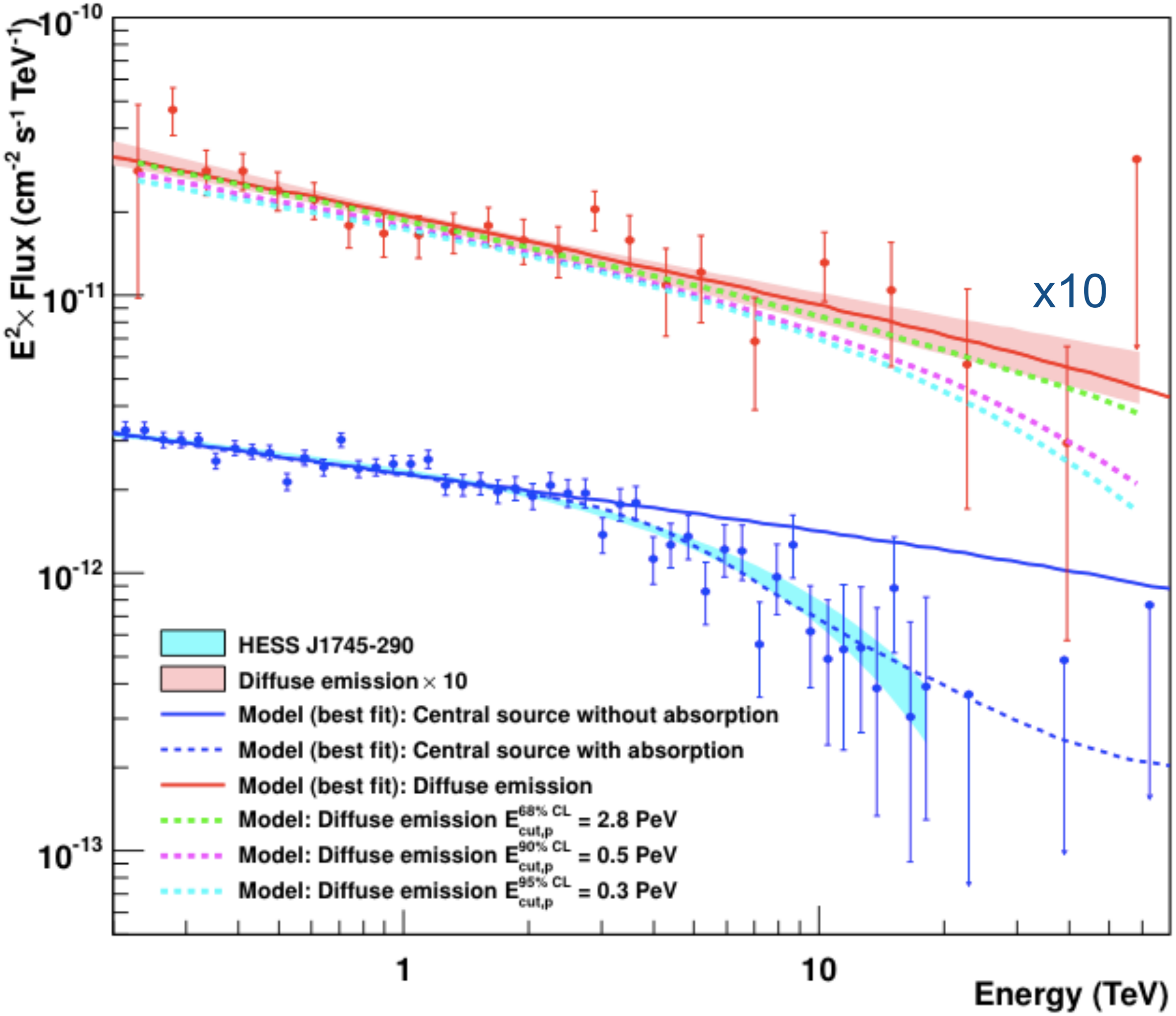
CR density radial distributions:
- Homogeneous => Impulsive injection of CRs and diffusive propagation
- 1/r2 => Wind-driven propagation
- 1/r => continuous injection and diffusive propagation

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



new!

GC: the central source and the diffuse emission of CMZ



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

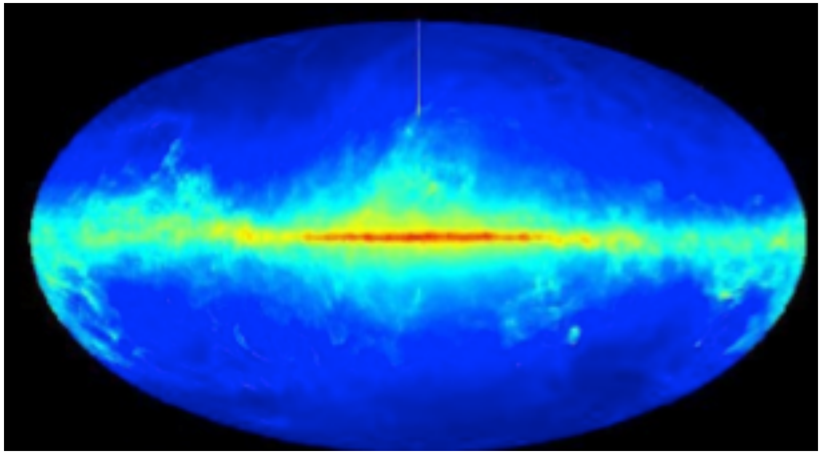
- this accelerator alone can account for most of the flux of Galactic CRs around the "knee" if its power over the last 10^6 years or so, has been maintained at average level of 10^{39} erg/s.

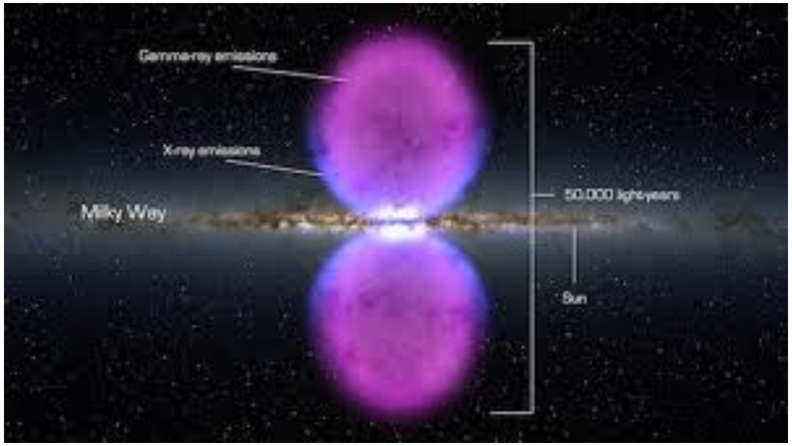
- escape of particles into the Galactic halo and their subsequent interactions with the surrounding gas, can be responsible for the sub-PeV neutrinos recently reported by the IceCube collaboration

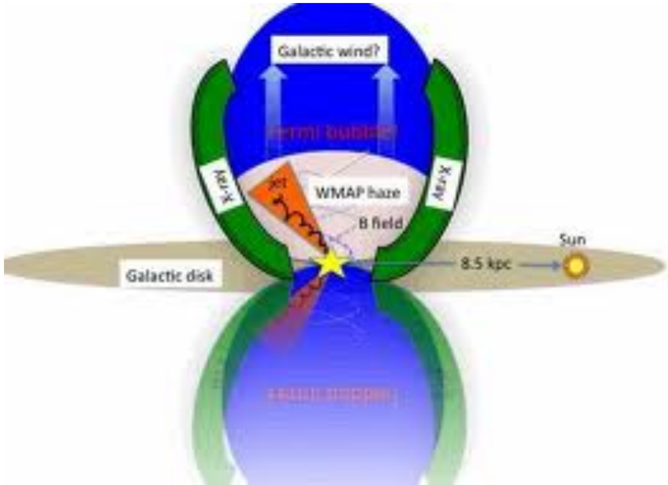
- the expected >10 TeV neutrino flux is within the range of sensitivity of a several km^3 volumee neutrino detector

- 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

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 10Gyr comparable to the age of the Galaxy? (Crocker&FA 2011)

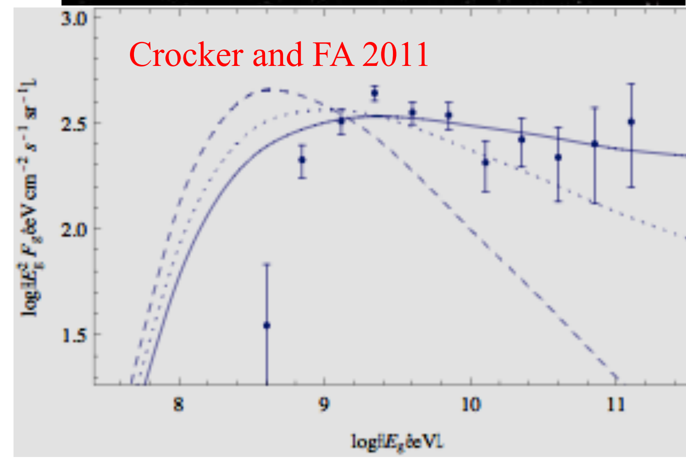
Size - because of slow diffusion in turbulent environment (10 times slower than in the Galactic Disk)

plasma density: $n \sim 0.01\ cm^{-3}$ timescale: $t_{pp} \sim 5$ Gyr $< t_{Galaxy}$

saturation (calorimetric) regime can explains:

generally homogeneous distribution of gamma-rays (local γ-ray production rate does not depend on density), unless possible gradients in the CR spatial distribution, e.g. due to propagation effects ; if the sharp edges tentatively found in the Fermi images is a real effect, they can be naturally explained by higher turbulence introduced by shocks => slower diffusion => accumulation of CRs close to the edges

modest requirements to CR rate : $L_p \sim 10^{39}$ erg/s



Fermi Bubbles as a ν-source ?
if γ-ray spectrum extends to 100 TeV, Km3NeT should be able to detect neutrinos

are FBs sites (reservoirs or accelerators) of PeV CRs? The answer can can be provided by γ-ray observation at multi-Tev energies, and CTA is the best hope!

Fermi Bubbles - alternative explanation:

IC scattering of electrons:

age: 10^7 yr, electron inj. rate $10^{38\text{-}39}$ erg/s

Problem: how transport E >1 TeV electrons to distances 10 kpc - in situ acceleration?

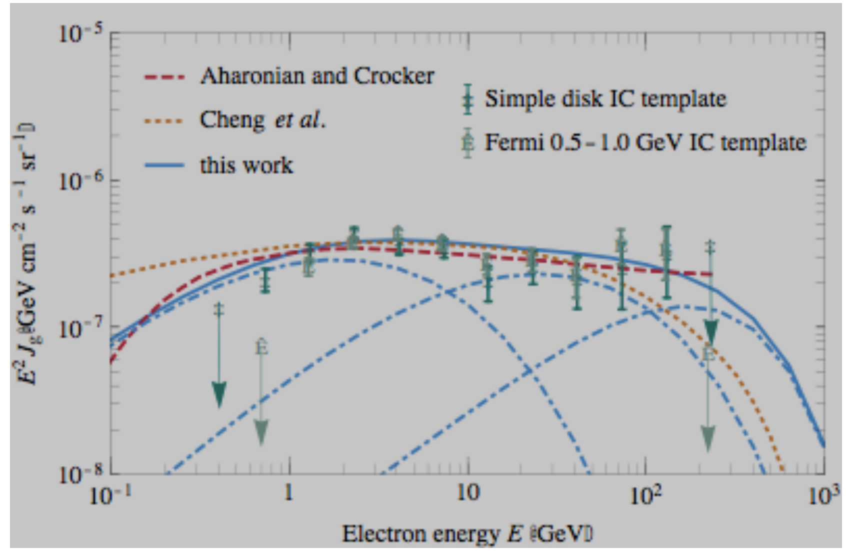
stochastic (2nd order Fermi) most viable option (Mertsch& Sarkar 2011)

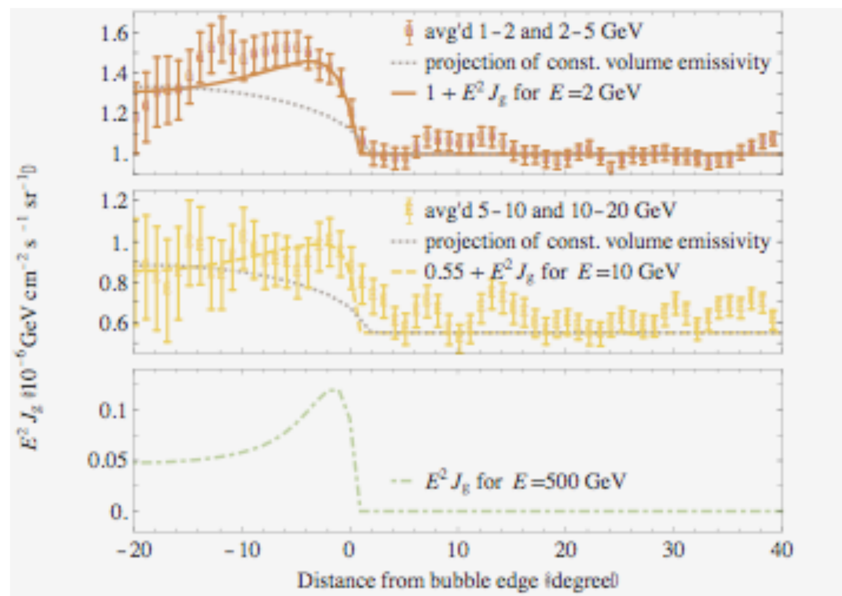
shock fronts at Bubble edges (ROSAT) => higher turbulence - concentration of electrons close to the edges => sharp γ-ray edges

narrow electron distribution+limited E_{max}~1TeV only 2.7K MBR as a target cannot for IC explain the 1-100 GeV γ-radiation: galactic FIR/O target field helps to explain the average 1-100 GeV E^{-2} type flat gamma-ray spectrum

distinct feature of the model - much steeper energy spectra of gamma-rays at large heights compared to region close to the galactic plain.

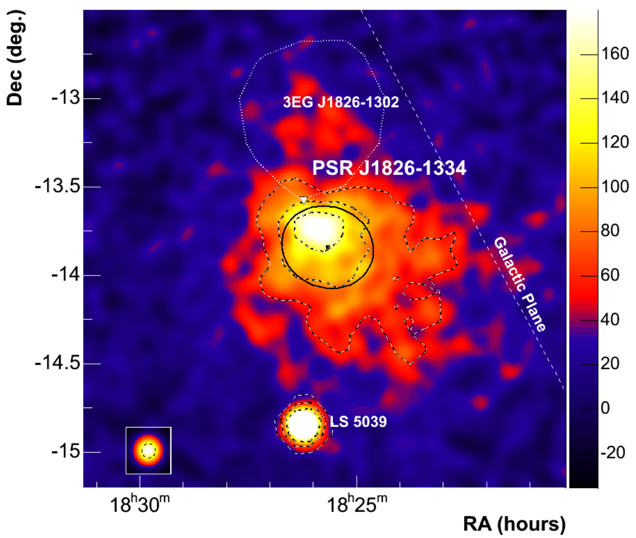
can be checked very soon …





Pulsar Wind Nebulae:

electron PeVatrons



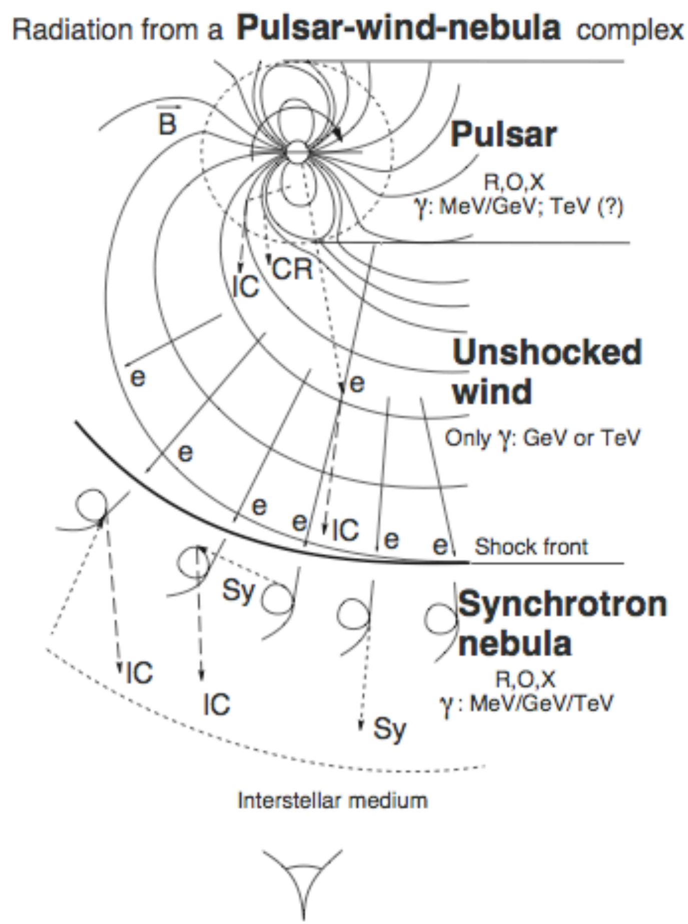
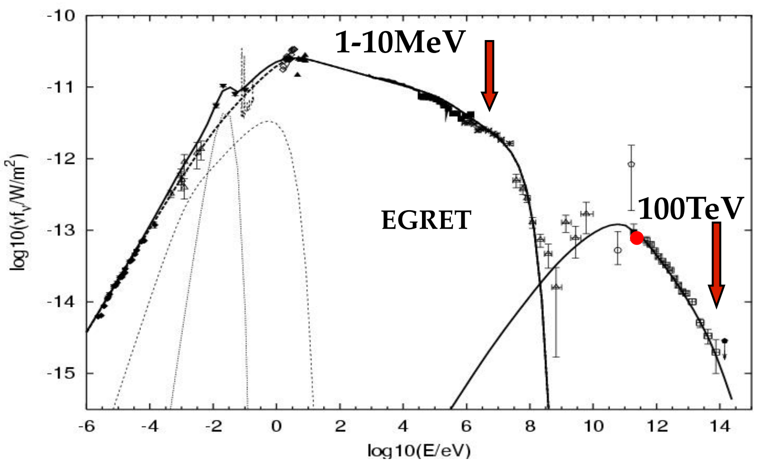


Fig. 1.8 Three regions of nonthermal radiation associated with a rotation powered pulsar: *pulsar* – magnetospheric pulsed γ-ray emission produced within the light cylinder due to the curvature, synchrotron, and inverse Compton processes; *unshocked wind* – gamma-radiation of the cold wind at GeV and TeV energies through the relativistic bulk-motion Comptonization; *synchrotron nebula* – broad-band, synchrotron and IC emission of the nonthermal nebulae (from Aharonian and Bogovalov, 2003).

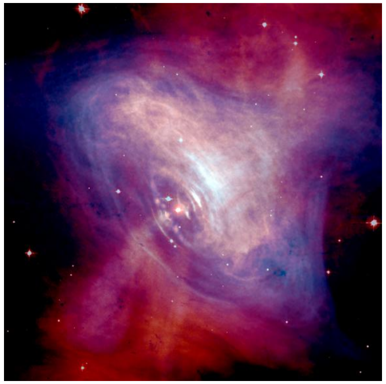
Crab Nebula – *a perfect electron PeVatron*



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

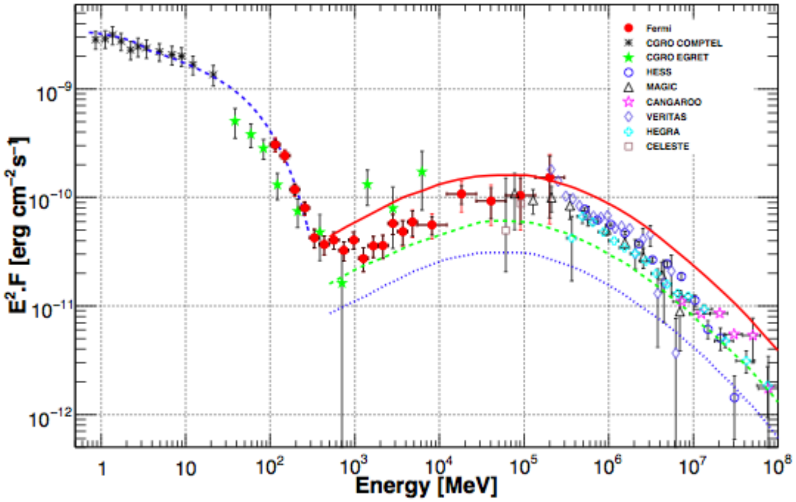


Crab Nebula – a powerful $L_e=1/5L_{rot} \sim 10^{38}$ erg/s
and extreme accelerator: Ee >> 100 TeV

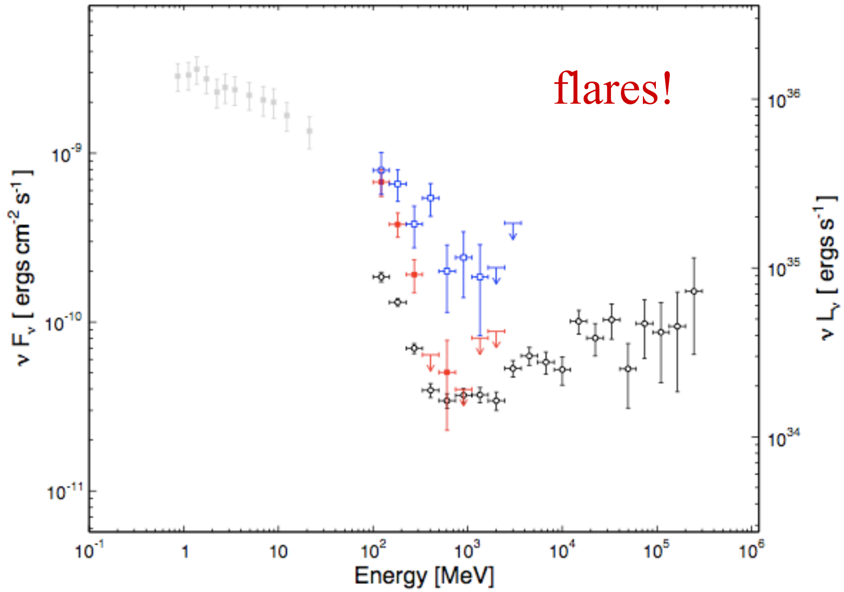
$E_{max}=60\ (B/1G)^{-1/2}\ \eta^{-1/2}$ TeV and $h\nu_{cut} \sim 150\eta^{-1}$ MeV

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

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.

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

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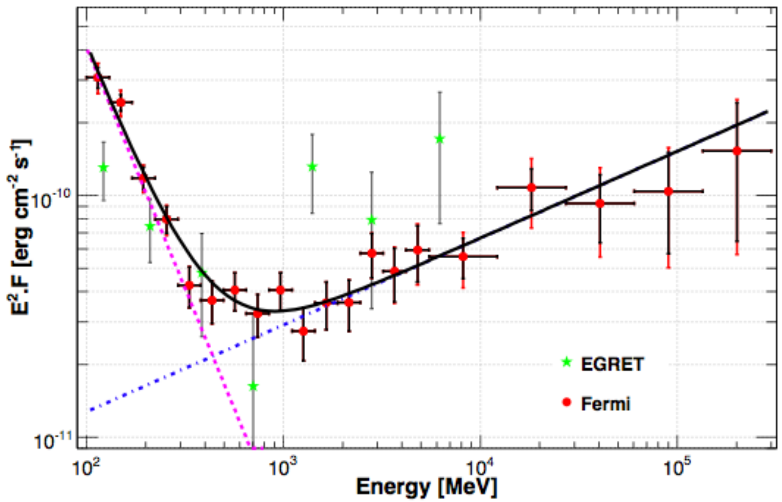

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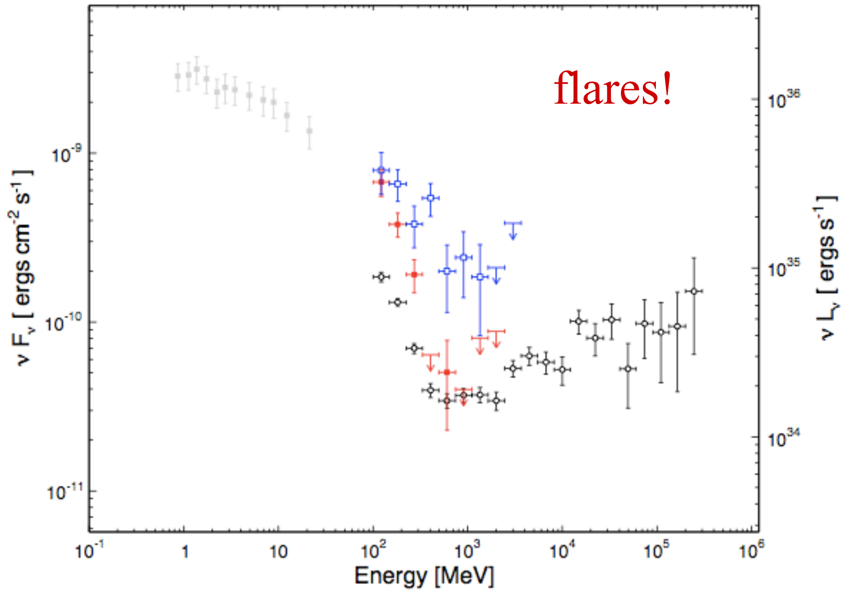

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<u>observations of 100TeV gamma-rays</u> - IC photons produced by electrons responsible for synchrotron flares - a key towards understanding of nature of MeV/GeV flares

Crab Nebula is a very effective accelerator

but not an effective IC γ-ray emitter

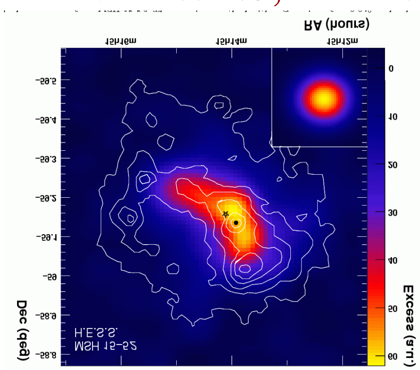
we do see TeV γ-rays from the Crab Nebula because of very large spin-down flux: $f_{rot}=L_{rot}/4\pi d^2=3\mathrm{x}10^{-7}$ erg/cm^2 s

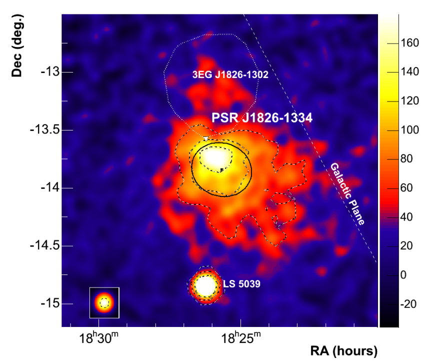
gamma-ray flux << "spin-down flux" *because of large B-field*

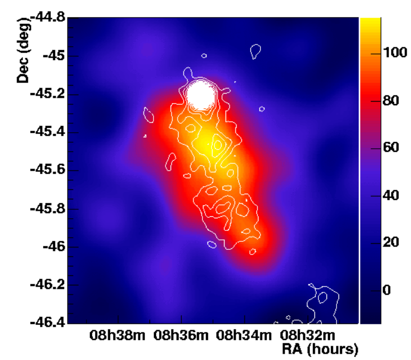
if the B-field is small (environments with small external gas presure)

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, ...



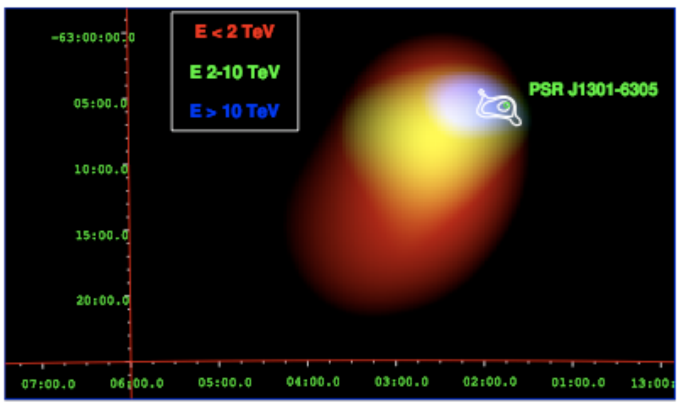


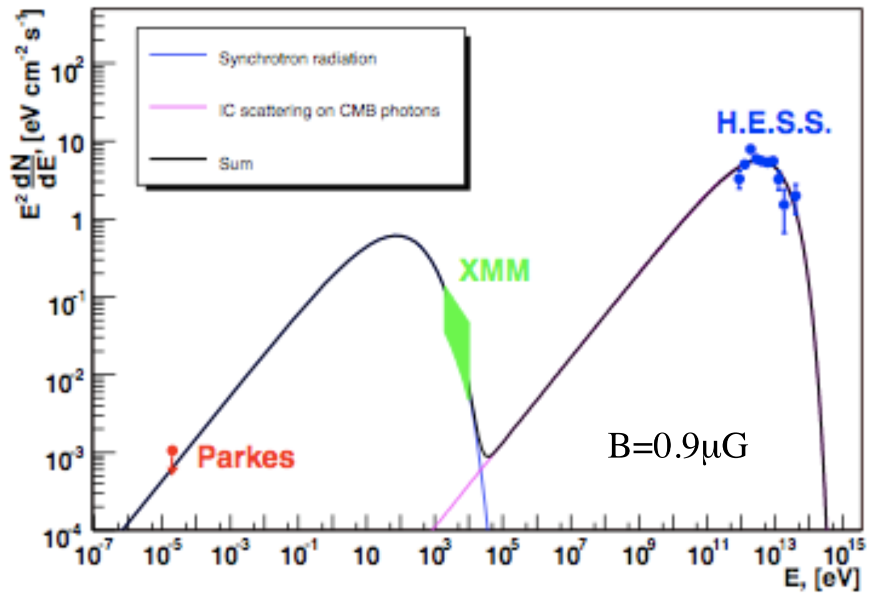


PWNe - *perfect electron accelerators and perfect γ-ray emitters!*

(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?



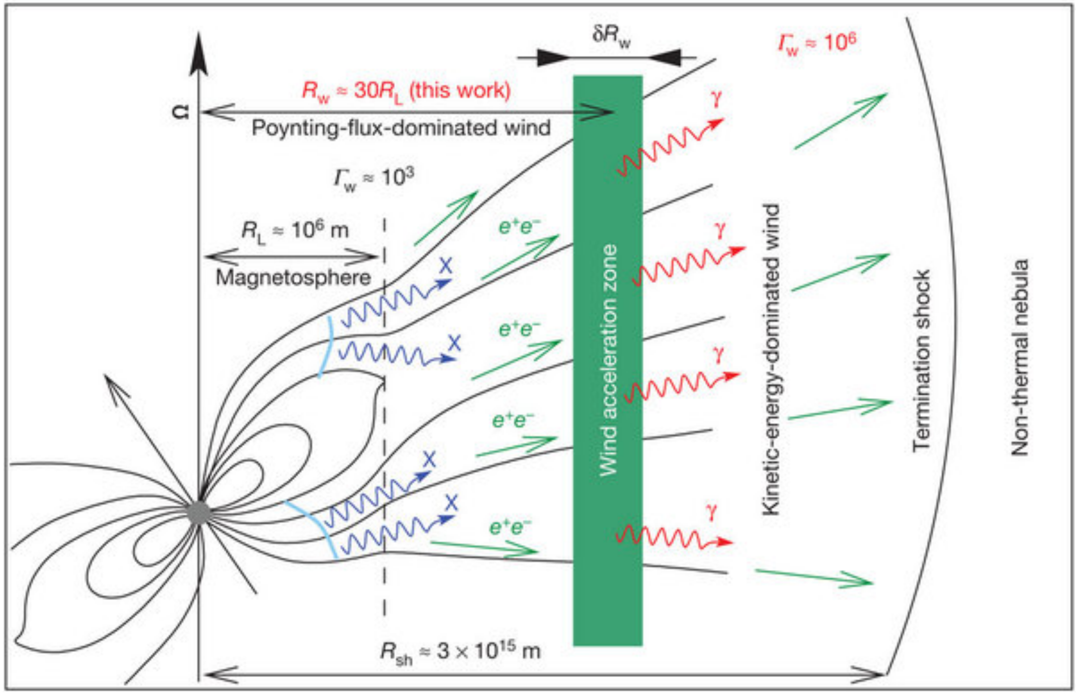


dramatic reduction of the angular size with energy:strong argument in favor of the IC origin of the γ-ray nebula

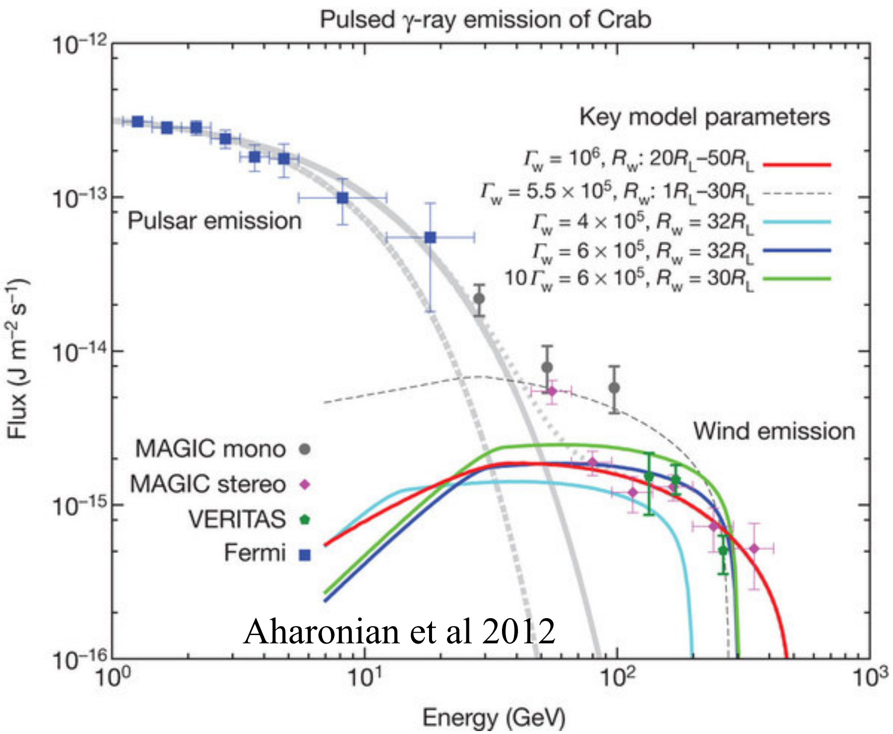
very small average B-field; for d=12.6kpc
$L_\gamma/L_{SD} = 0.07$; 3arcmin ~ 10 pc

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

pulsar–wind–nebula paradigm



Pulsed component extends to VHE energies!



where pulsed VHE signal is produced:

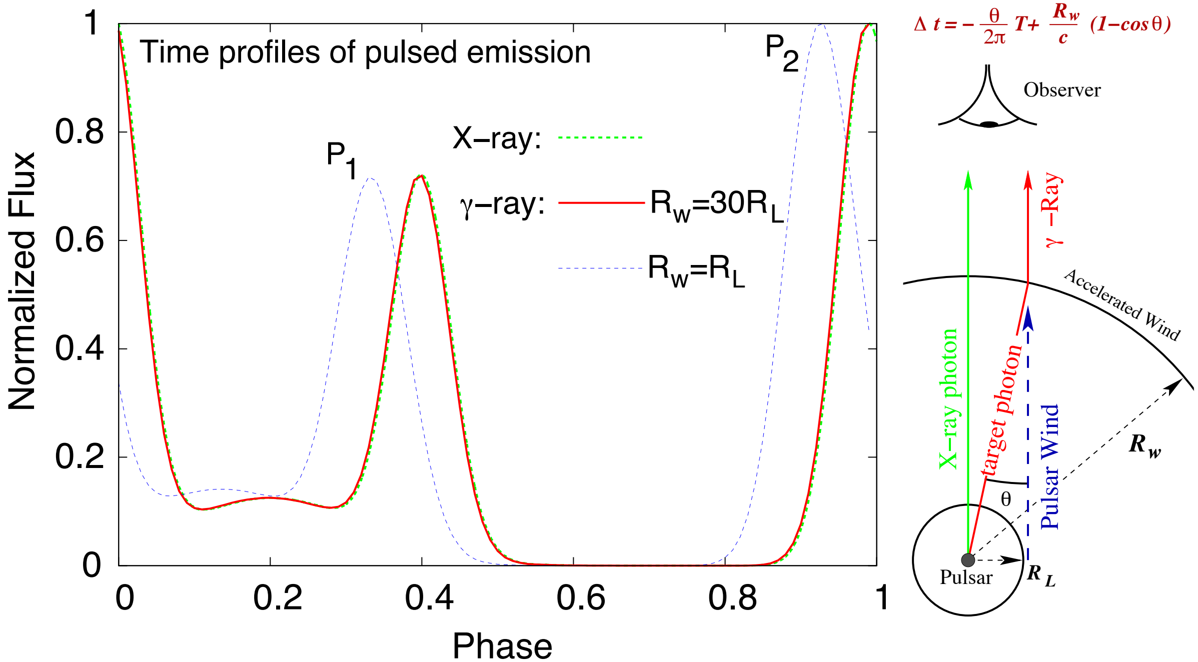
in the magnetosphere
or in the pulsar wind?

very low fluxes – for adequate spectrometry and lightcurve – we need more sensitive instruments between 10 GeV and 1000 GeV

if the VHE gamma-ray emission is due to the "cold" wind

- ✓ wind is accelerated at R~ $30R_L$ to bulk motion Lorentz factor Γ~0.5-1 x 10^6
- ✓ no need to revise dramatically the magnetospheric models of GeV emission

time structure of the periodic signal



TeV pulsed emission mimics the lightcurve of soft X-rays:

at $R_w >> R_L$, $\Delta t \approx T/4\pi\ (R_L/R_w)$, for $R_w=30R_L$, $\Delta t \sim 0.003T$

binary systems - unique high energy laboratories

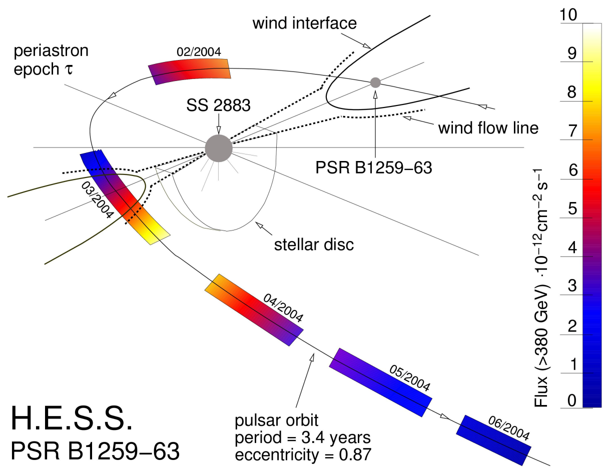
binary pulsars - a special case with strong effects associated with the optical star on both the dynamics of the pulsar wind and and the radiation before and after its termination

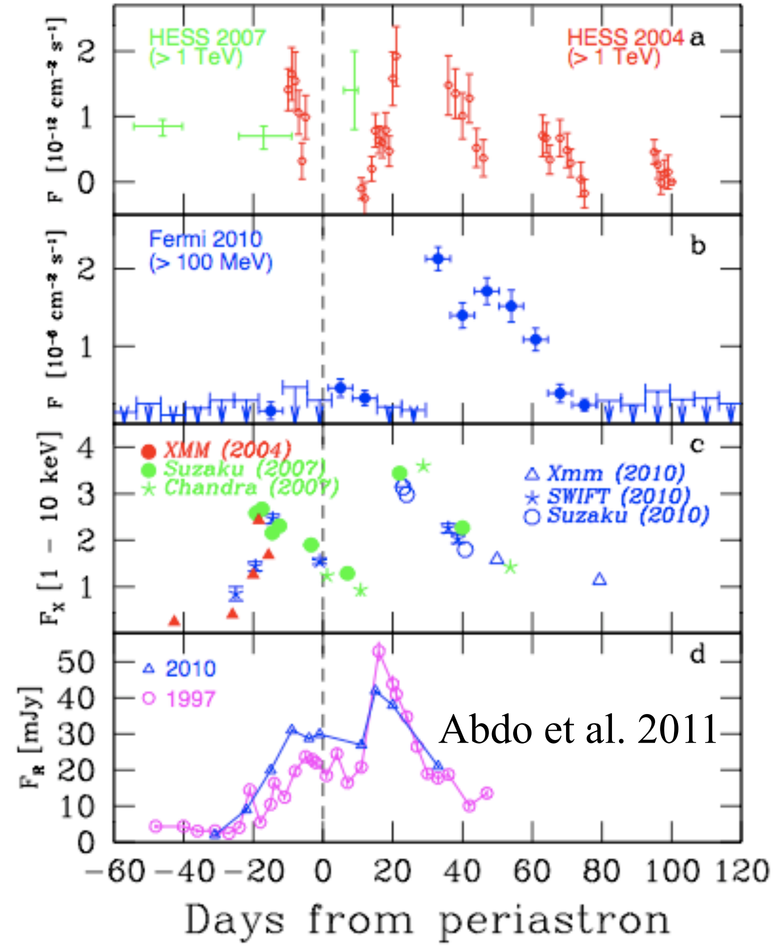
the same 3 components - *Pulsar/Pulsar Wind/Synch.Nebula* - as in PWNe both the electrons of the cold wind and shocke-accelerated electrons are illuminated by optical radiation from the companion star detectable IC γ-rays

"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?





HESS: detection of γ-rays at < 0.1Crab level - tendency of minimum flux close to periastron;

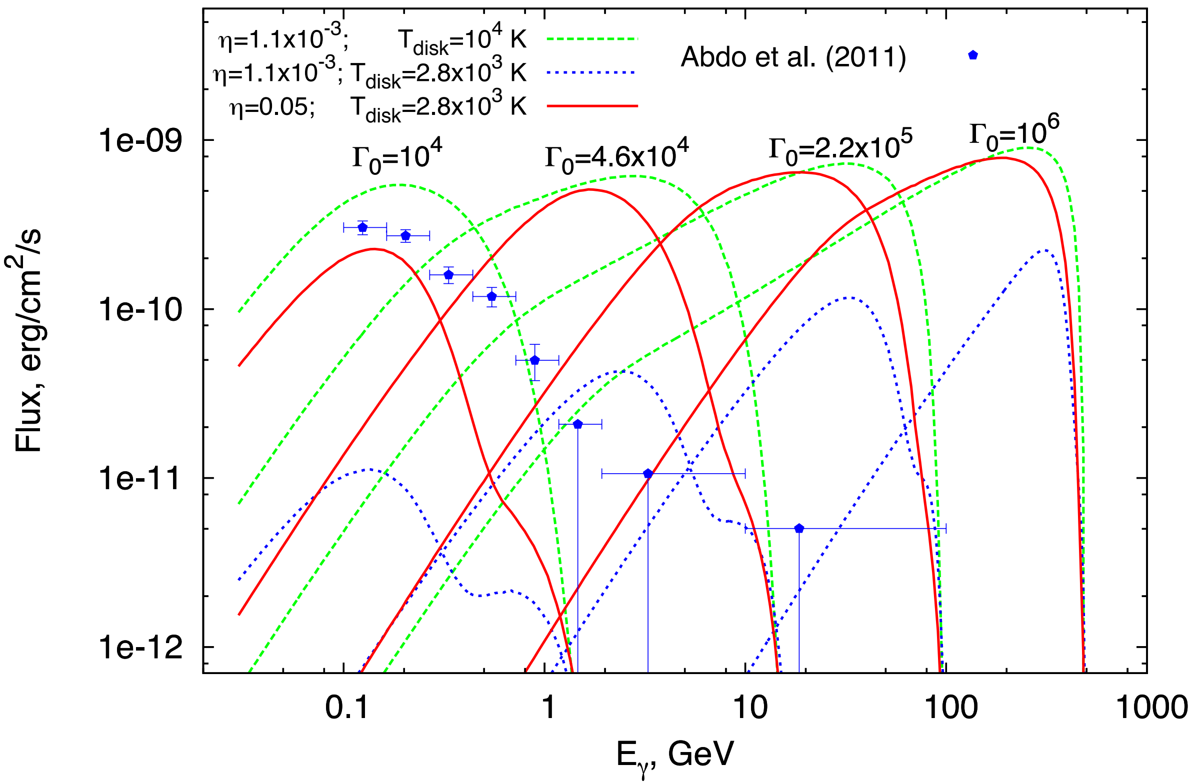
Several possible explanations, but many things uncertain and confusing.

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

Fermi LAT - weak signal faround periastron, but flares after 1 month!

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

GeV Flare in PSR1259

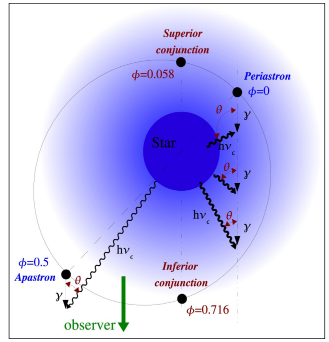


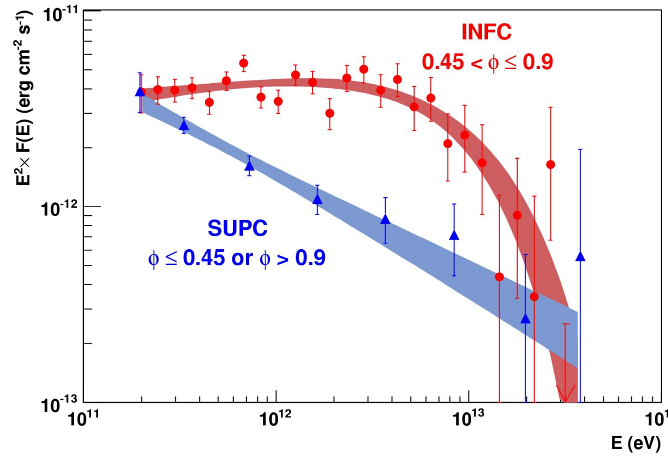
flare – Comptonization of the unshocked wind by IR of the disk just after the exit of the pulsar from the disk => $\Gamma \sim 10^4$

LS 5039

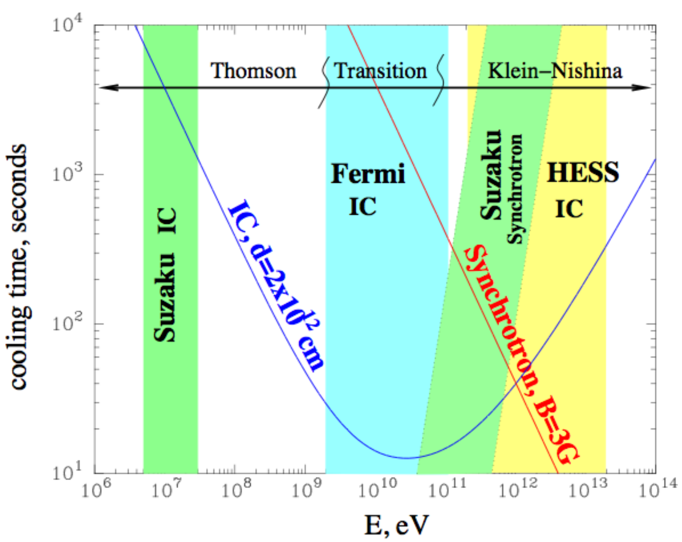
works as a perfect TeV clock
and an extreme accelerator

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 η < 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