2019 ISAPP summer school: The dark side of the Universe

Heidelberg, 2019 May 28 – June 4

# High Energy Universe (theory)

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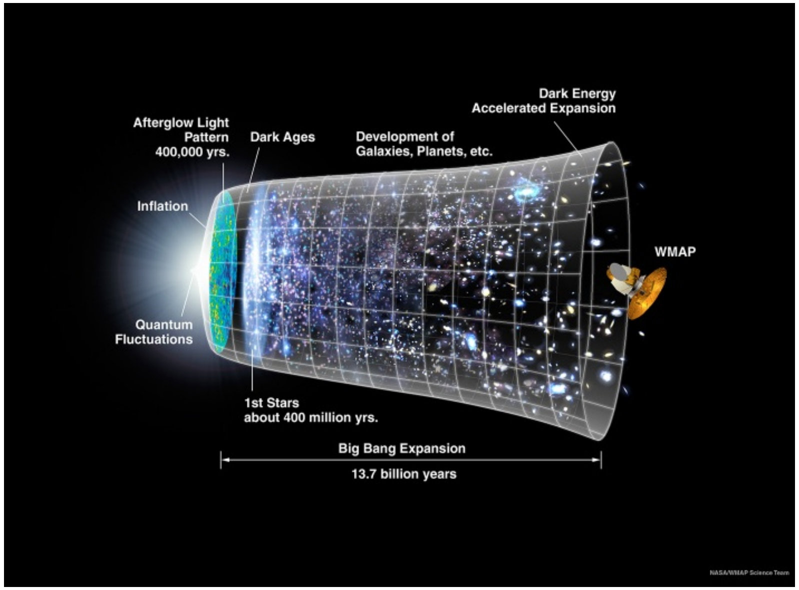
MPI-K, Heidelberg, June 3, 2019

# Universe as a high energy phenomenon




*in the framework of "Big Bang Theory"*

- the "Universe" itself is a high energy phenomenon
- its birth was an incredibly energetic event
- quite a long time it was "hot soup" consisting of relativistic particles and radiation ($E > m_e c^2$); 2.7 K MBR (~$10^{-3}$ eV) as remnant of that "soup"

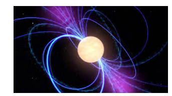
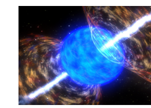
now it is cold but contains *Cosmic Ray Factories* - particle accelerators producing the 4th substance - after *matter, radiation and magnetic fields* - of the visible Universe

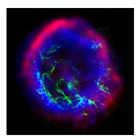
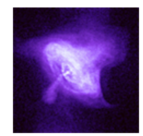
*Relativistic Plasma* ("Cosmic Rays")

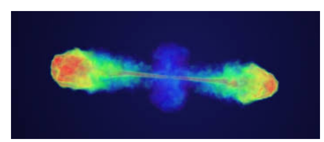
pressure (energy density) in Cosmic Rays in many objects can be comparable or even exceed the pressure contributed by the thermal gas, turbulent motion, radiation, B-fields

# Relativistic Matter Factories

*nonthermal processes* in Universe proceed everywhere and on all astronomical scales:

solar-mass black holes  neutron stars/pulsars  γ-ray bursts 

supernova remnants  pulsar wind nebulae  massive stars 

starburst galaxies  AGN Jets  galaxy clusters 

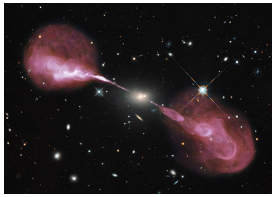
## Messengers of Nonthermal Universe

- ✓ *cosmic rays (relativistic electrons, protons, nuclei)*
- ✓ *photons (radio, O/IR, X-rays, gamma-rays)*
- ✓ *neutrinos*
- ✓ *(gravitational waves)*

multi-wavelength and multi-messenger astronomy some comments

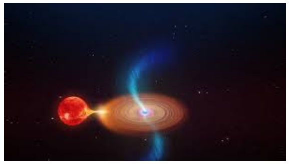
## high energy phenomena - *not necessarily high energy (γ) radiation*

e.g. radio emission of synchrotron radiation of sub to multi-GeV electrons until recently was the main window on nonthermal/high-energy universe



## high energy γ-rays - *not necessarily imply non-thermal origin*

e.g. plasma accreting onto black closer to event horizon could be heated to temperatures $10^{11}$ - $10^{12}$ K - characteristic thermal radiation in the γ-ray band

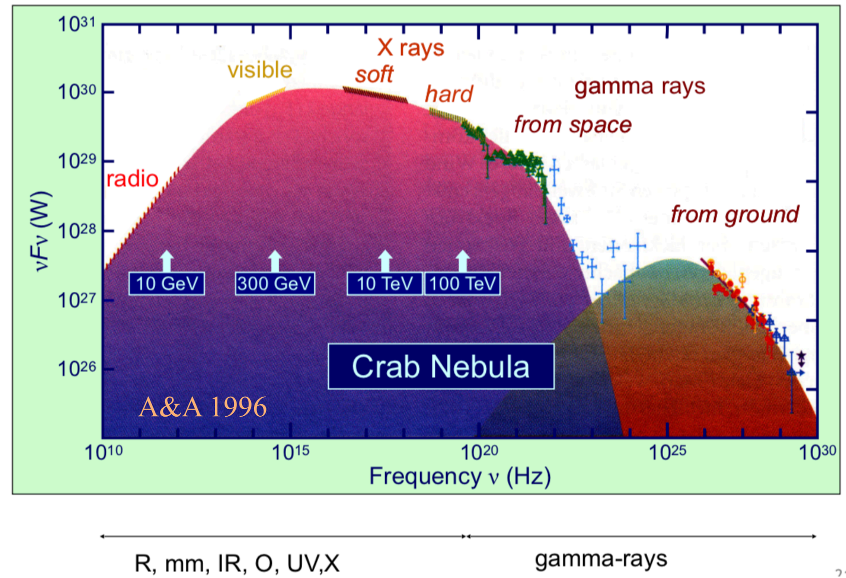


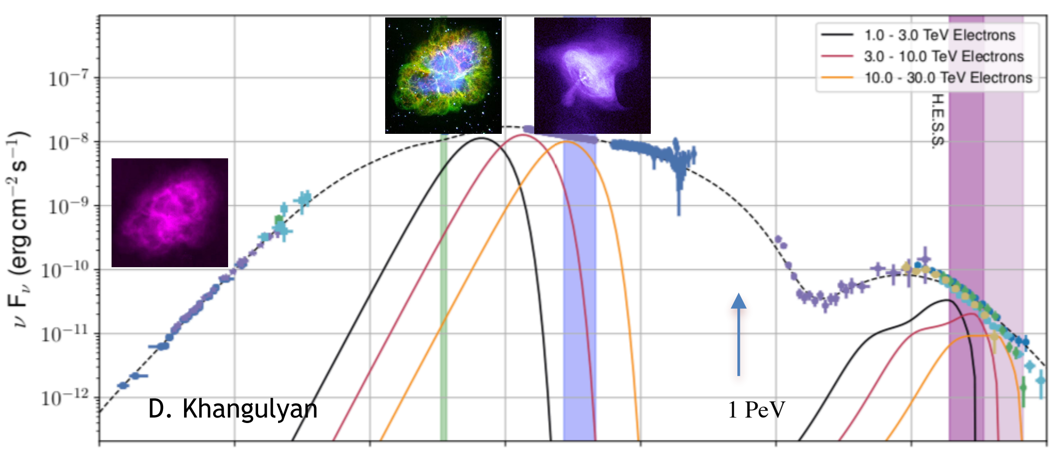
# Crab pulsar/wind/nebula:

*an extreme non thermal source*

- conversion of the rotational energy of pulsar to non-thermal energy with efficiency ~50 %
- electron acceleration  with 100 % efficiency

a non-thermal astrophysical object seen over 20 energy decades



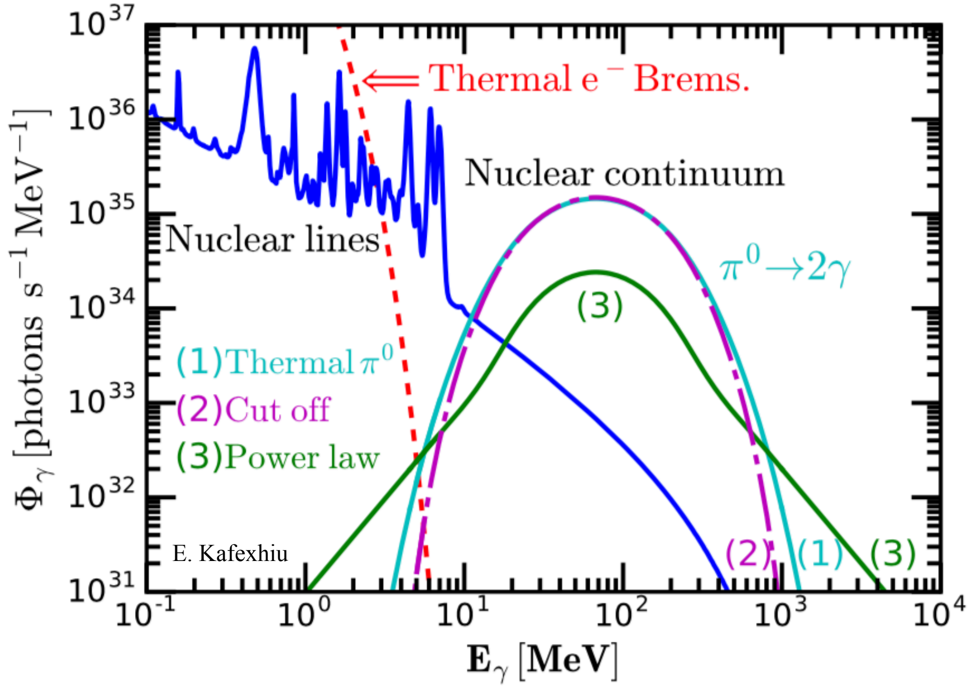




almost half of  rotational energy of the pulsar is released in form of accelerated electrons/positrons and radiated away via synchrotron and inverse Compton channels of radiation over 20 decades !

electrons are accelerated to ~1 PeV (!)
The acceleration rate should be at the margin allowed by theory (classical electrodynamics)

Gamma-ray emission of hot two-temperature thermal plasma formed at accretion of gas onto a 10 solar masses black hole

microquasar




unique measure of the ion temperature in the accretion flow close to the gravitational radius

radiation efficiency - less than $10^{-4}$ (fraction of the Eddington luminosity)
but could be higher in the case of acceleration in the accretion flow or by the jet

some comments

## Maxwellian (type) particle distribution - *not necessarily thermal*

when interpreting γ-ray spectra sometimes we need a Maxwellian type distribution. It does not mean, however, that we see the emission of thermal plasma. Some specific ("stochastic" or Fermi II type) mechanisms of particle acceleration can lead to a Maxwellian type distributions of particles

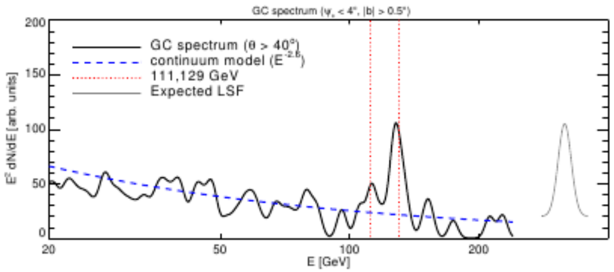
## Sources of nonthermal emission - *do not necessarily coincide with accelerators*

nonthermal emission is a result of interaction of a beam of relativistic particles with a target (gas, B-field, photons), therefore the emission source (= target) and the accelerator can be separated

## Dark Matter as "smoking gun " ? - *often unnecessary exaggeration*

such strong claims in the context of one of the most fundamental objectives of modern physics and astrophysics require a careful judgment through the "Occam's razor" principle, i.e. exploration of other more conventional (and natural) interpretations

# narrow GeV/TeV gamma-ray lines of astrophysical origin

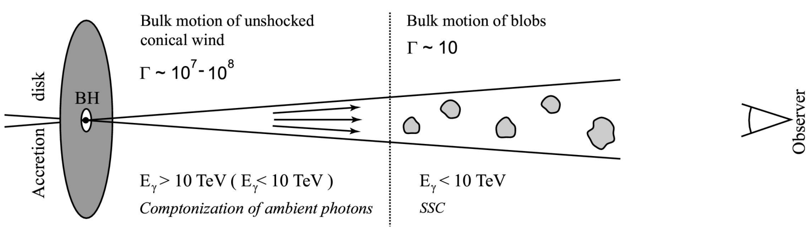


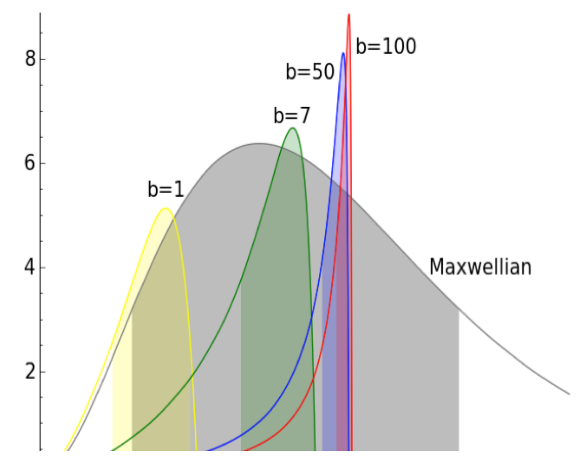

~100 GeV gamma-ray line detected by Fermi LAT? *

cosmological interpretation - DM as the only option?

No! can be interpreted as Inverse Compton scattering of monoenergetic electrons and cold ultra relativistic (e.g.) pulsar winds in the deep Klein-Nishina regime

often confusion between acceleration of bulk motion and particle acceleration !




* later not confirmed

# High Energy Astrophysics

addresses an impressively broad range of topics related to the high energy processes in the Universe, including acceleration, propagation and radiation of relativistic particles on all astronomical scales: from compact objects like (neutron-stars and solar mass black holes) to huge rado jets and large-scale cosmological structures (galaxy clusters)

# links to many areas of physics and astrophysics

a coherent description and interpretation of high energy phenomena requires deep knowledge of many areas of modern physics and astronomy  and physics:

- ✓ *special and general relativity*
- ✓ *quantum and classical electrodynamics*
- ✓ *atomic and molecular physics*
- ✓ *nuclear and particle physics*
- ✓ *plasma physics*
- ✓ *magneto(hydrodynamics)*
- ✓ *galactic and extragalactic astronomy*
- ✓ *cosmology*

…..

# High Energy Astrophysics

a major objective: study of *nonthermal* phenomena in

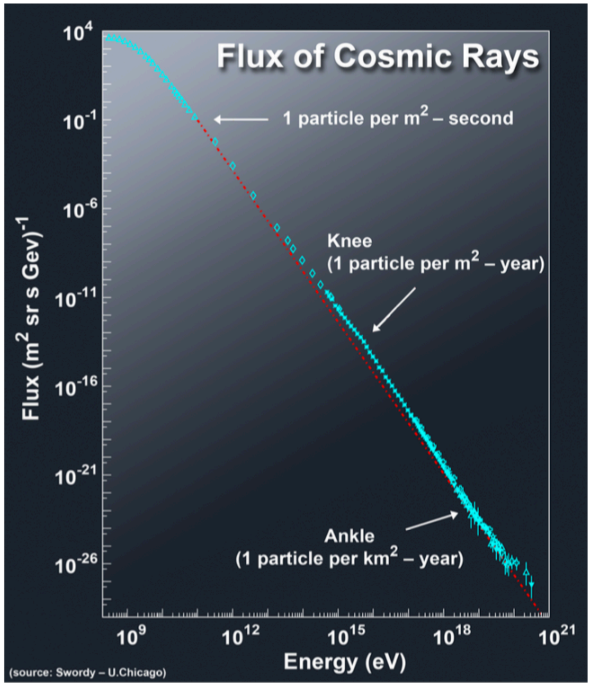
most energetic and violent forms in the Universe

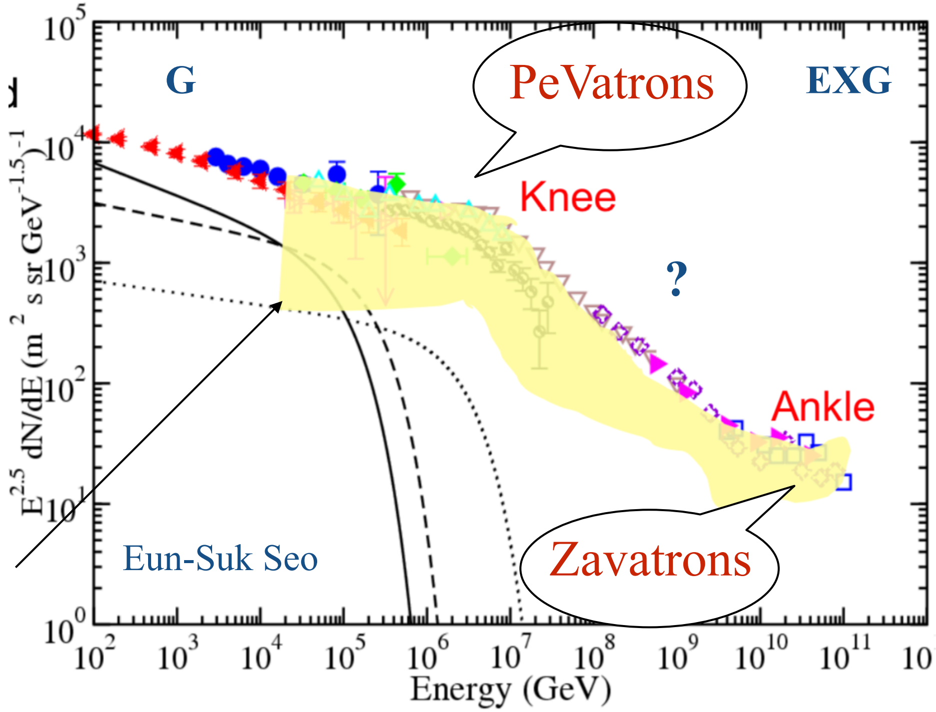
many research topics are related, in one way or another,
to exploration of Nature's perfectly designed machines:

Extreme Particle Accelerators

# "Origin of cosmic rays remains a mystery…"

*a standard statement used in reviews/textbooks over many decades*




below $10^{15}$ eV - G
beyond $10^{18}$ eV - EXG
between $10^{15}$-$10^{18}$ eV ?

PeVatrons and Zevatrons
are extreme Accelerators

what does mean "Origin of Cosmic Rays" ?

*term "Cosmic Rays" itself has two meanings:*

- locally detected nonthermal/relativistic particles - a "local fog"
- the "4th substance" of the visible Universe (after the matter, radiation and magnetic fields) - a *more fundamental issue*

"origin of CRs" generally is reduced to the identification of the major contributors (SNRs, pulsars, GC, etc.) to the 'local fog'

this issue principally cannot be addressed by observations of charged CRs

sources can be identified only by neutral stable messengers:
photons and neutrinos
also neutrons with $E>10^{14}(d/1pc)$ eV, axions…

# recent gamma-ray discoveries - a breakthrough in the field

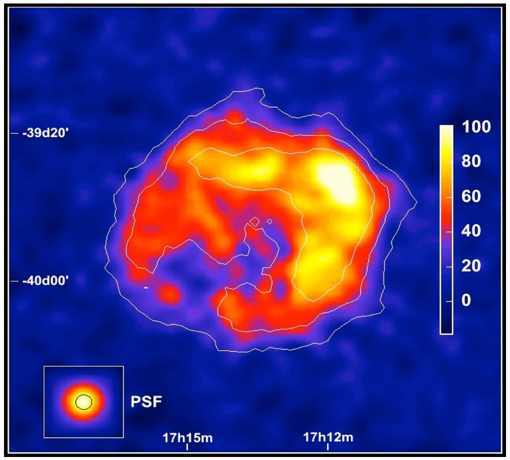
*hundreds of GeV and/or TeV gamma-ray emitters have been discovered representing 10+ source populations:*

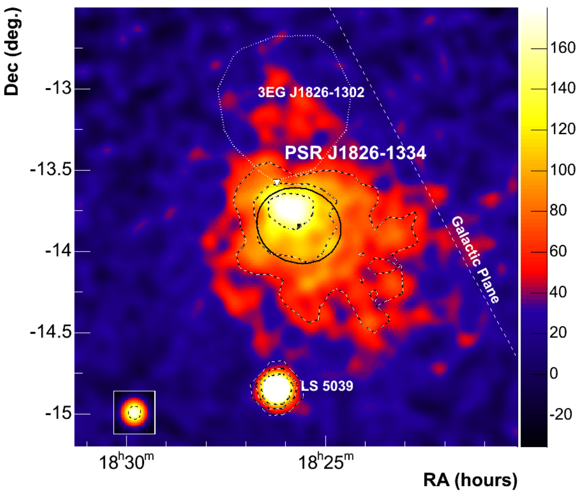
- SNRs, Stellar Clusters, GMCs
- Pulsars, PWNe
- Binaries (Binary Pulsars, Microquasars)
- Galaxies, Starburst Galaxies,
- Radiogalaxies,
- AGN, GRBs

**analogy with thermal X-rays:**
as cosmic plasmas are easily heated up to keV temperatures - almost everywhere, particles (electrons and protons/nuclei) can be easily accelerated to TeV energies - almost everywhere!

not all of them contribute to local CR flux but all are Particle Accelerators - *factories* of relativistic matter how it works?

## Gamma Ray images of Galactic TeVatrons




**Supernova Remnant**

(the) major contributors to galactic cosmic rays:

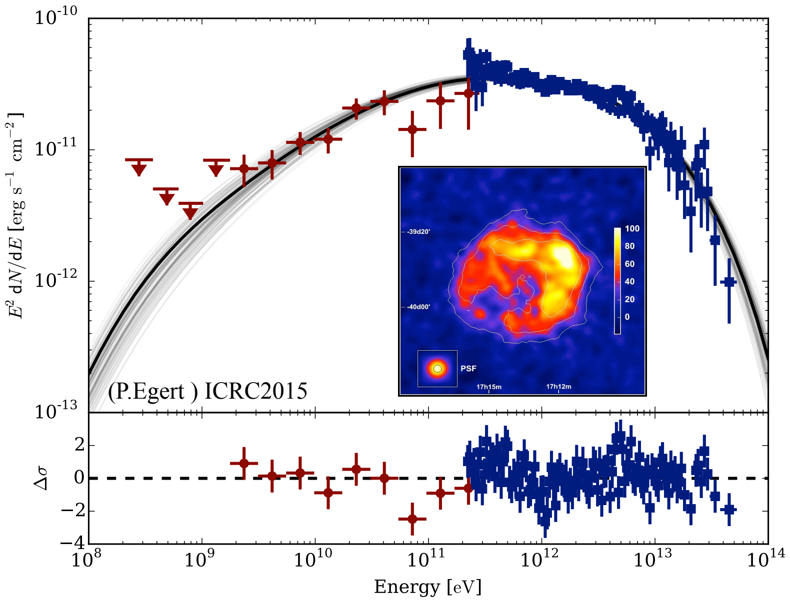
**Pulsar Wind Nebula**

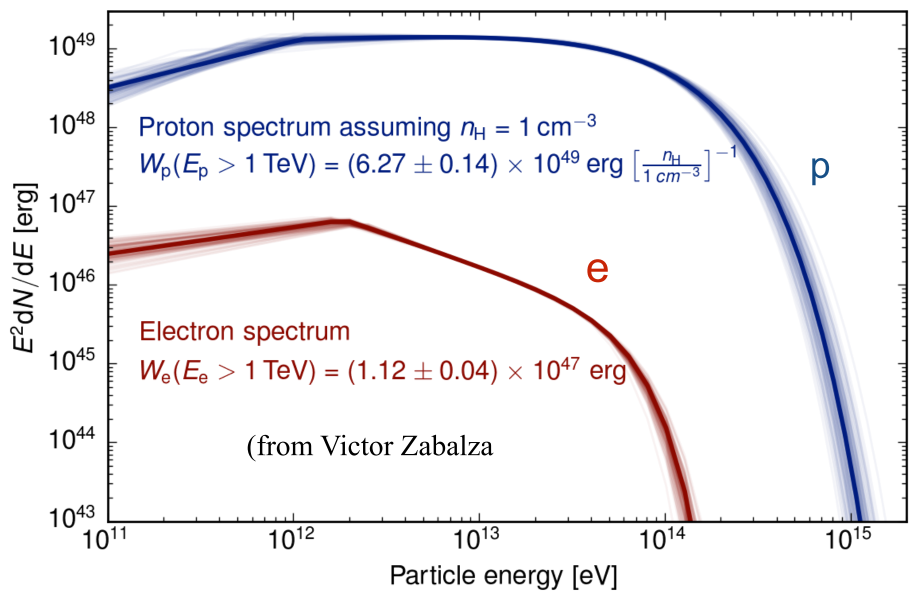
contributors to cosmic ray electrons and positrons

# how it works?

*Probing the distributions of accelerated particles in SNRs*

HESS measurements **RXJ 1713** derived spectra of e and p

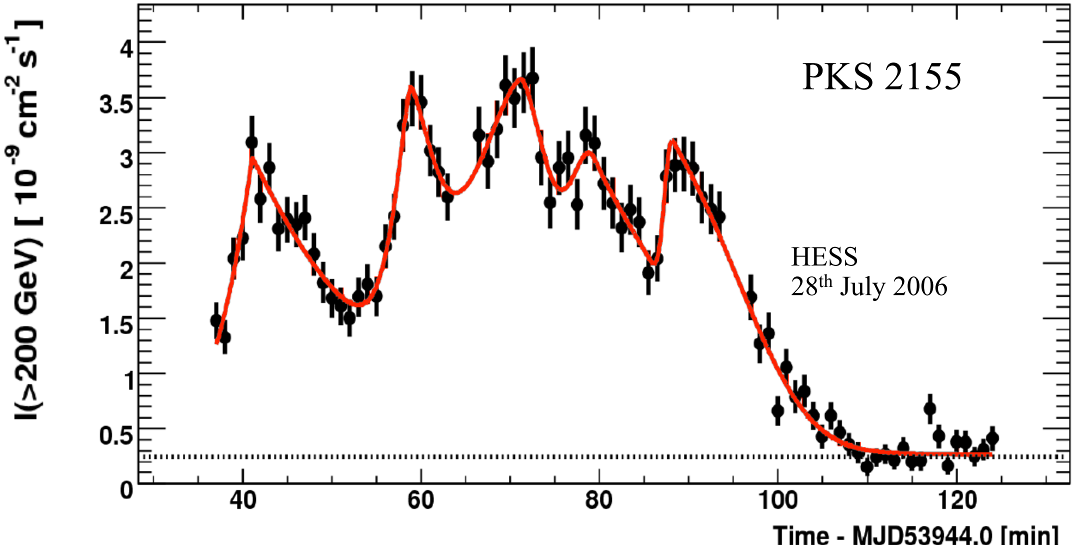



CTA can do much better; extension of measurements to >100 TeV
a few arcimin (sub-pc) structures
particles beyond the shell

how it works?

Light curve of PKS 2155-304 during 2006 July flare
variability timescale $\Delta t\sim$ 3 min: L< $c\Delta t\sim 6\ 10^{12}$cm!




it is convenient to express the variability through

$$\Delta t = R_g/c \sim 10\ (M/10^8 M_o)\ \text{min}$$

$R_g = GM_{BH}/c2 = 1.5\ 10^{13} M_8$ cm is gravitation radius of Kerr BH recent detection of "astrophysical" neutrinos by IceCube

great discovery with (potentially) great implications

is the detected flux of truly diffuse origin ?

if yes, where the neutrinos are produced ?

in the Interstellar Medium (ISM) or in Intergalactic medium (IGM) *

or it is superposition of individual sources ?

Starburst galaxies? Active Galactic Nuclei?

many questions - no definite answers

but one thing is clear - neutrinos are unique messengers about the galactic and extragalactic cosmic PeVatrons, EeVatrons, ZeVatrons

* I think in the ~100 kpc Halo of the Milky Way

questions beyond the origin of local CRs for example
the physics of 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* *<u>can be as large as 50 %</u>*

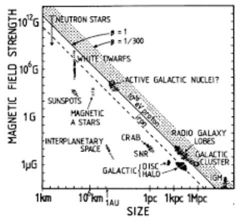
(ii) maximum possible energy achieved by individual particles

*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)

detection of $10^{20}$ eV CRs implies that
they are produced by extreme accelerators !

1984

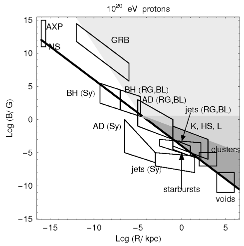


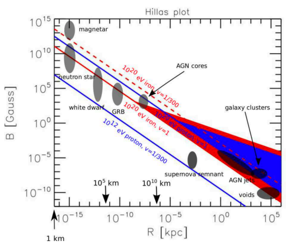

# Hillas Plot: trivial and non-trivial implications

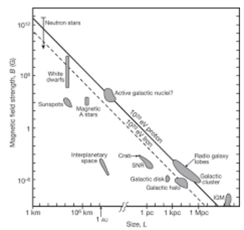
Ann. Rev. Astron. Astrophys. 1984, 22:425-444

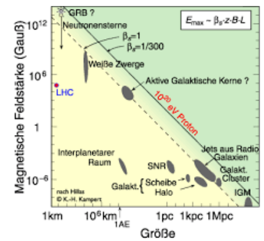
Hillas Plot : B – L relation based on the condition $L > r_L$

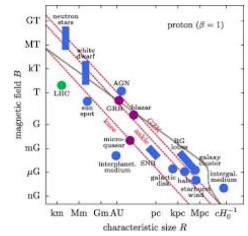
tens of “Hillas Plots” have been produced since 1984 ...

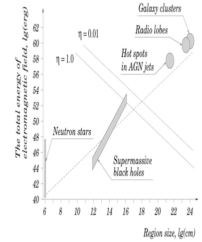












$$B_{\mu G} L_{\rm Mpc} > 2E_{21}/Z(v/c)$$

works both for “gradual modes of acceleration” and for “one shot acceleration”

“Clearly, very few sites remain as possibilities: either one wants highly condensed objects with huge B or enormously extended object. In either case, very high speeds are required”

*v* - characteristic velocity of scattering centers - *v* -> *c* - relativistic outflows (shocks) !
*Z* - large Z (nuclei) - preferred!

extended objects - Clusters of Galaxies - does’t work ; Large Scale structures in the AGN Jets - marginally !

compact objects - BH magnetospheres or Small Scale AGN Jets - energy losses !

Top-Down scenario (TDs etc.) - robustly closed (overproduction of the universal gamma-ray background )

Hillas Plot - "severe filter" but not "green light"

acceleration time:

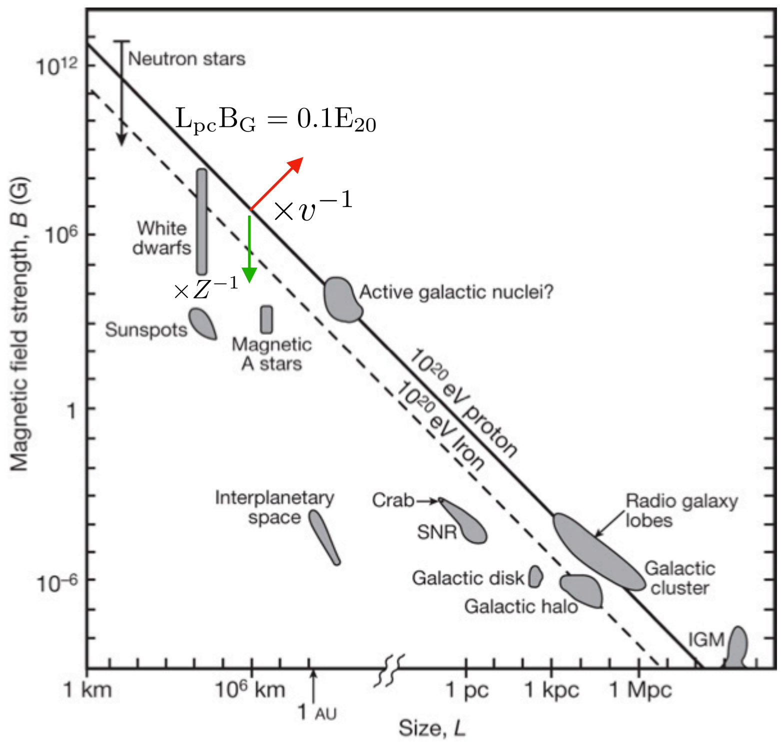
$$t_{acc} = \eta \frac{E}{eBc} = \eta \frac{r_L}{c} \qquad h\nu_{\max} = \frac{9}{4}\alpha^{-1} mc^2 \eta^{-1}$$

$\eta^{-1}B = \mathcal{E}_{eff}$ projection of electric field on particle trajectory averaged as particle moves along the trajectory

$\eta \geq 1$ $\qquad$ $\eta \approx 1 \rightarrow$ extreme accelerator

signature : $h\nu_{\max} = 160$ MeV for electrons

300 GeV for protons




absolute minimum set my classical ED:

DSE: $\eta = (1 - 10)(c/v)^2$

e.g. in young SNRs $\eta \approx 10^5$

effective accelerator : $t_{conf} \geq t_{ac}$

best confinement – in Bohm Diffusion regime with $D = \frac{r_L c}{3}$

$$t_{conf} = \frac{L^2}{3D} = \frac{L^2}{r_L c} \Rightarrow L \geq \eta^{1/2} r_L$$

$L=r_L$ condition implies an extreme accelerator

trivial condition - non-trivial solutions

replacement of $10^{20}$ by $10^{19}$ eV would be a significant but not sufficient relief to relax

# Basics of the Galactic CR paradigm

Cosmic Rays: primary component + secondary component

primary: directly accelerated p, A, $e^-$, $e^+$

secondary: A, γ , ν, $e^+$, $\bar{p}$ produced in interactions of primary CRs with ISM

secondary/primary fraction X => "grammage" Λ
=> confinement time T => diffusion coefficient $D(E) \propto E^{\delta}$

source - injection spectrum into ISM $S(E) \propto E^{-\alpha}$

CR spectrum in ISM - modulated $\Phi(E) \propto E^{-\Gamma}; \ \Gamma = \alpha + \delta$

# Galactic Cosmic Rays

*basic facts based on direct measurements:*

energy density: ~ $1 eV/cm^3$ assuming that "CR sea=locally measured CR density"

accumulated "grammage" - several $g/cm^2$ from secondary-to-primary ratio

=> *age:* $T_o \sim 10^7$ yrs

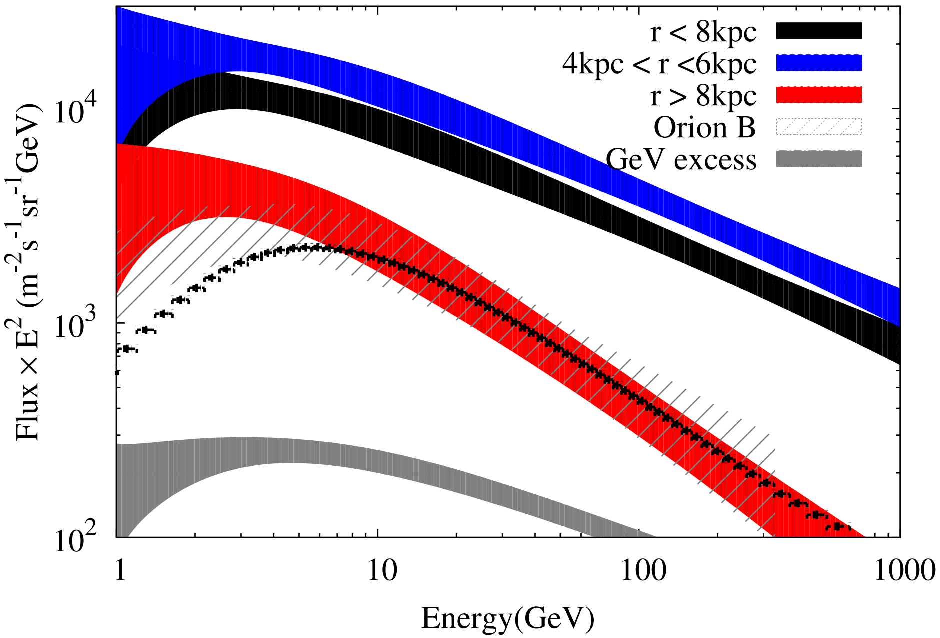
*diffusion coefficient:* $D(E) = D_o(E/1\ GeV)^{-\delta}$ ; $D_o \sim 10^{28}\ cm^2/s$; $\delta \sim 0.3\text{-}0.5$

*production rate:* $L_{cr} = w\ V/T_o \sim (0.3\text{-}1) \times 10^{41}$ erg/s,

*source spectrum:* $Q(E) \sim E^{-\alpha}$ ; $\alpha=\Gamma-\delta$; $\Gamma \sim 2.7\text{-}2.8$ ; $\alpha \sim 2.3$

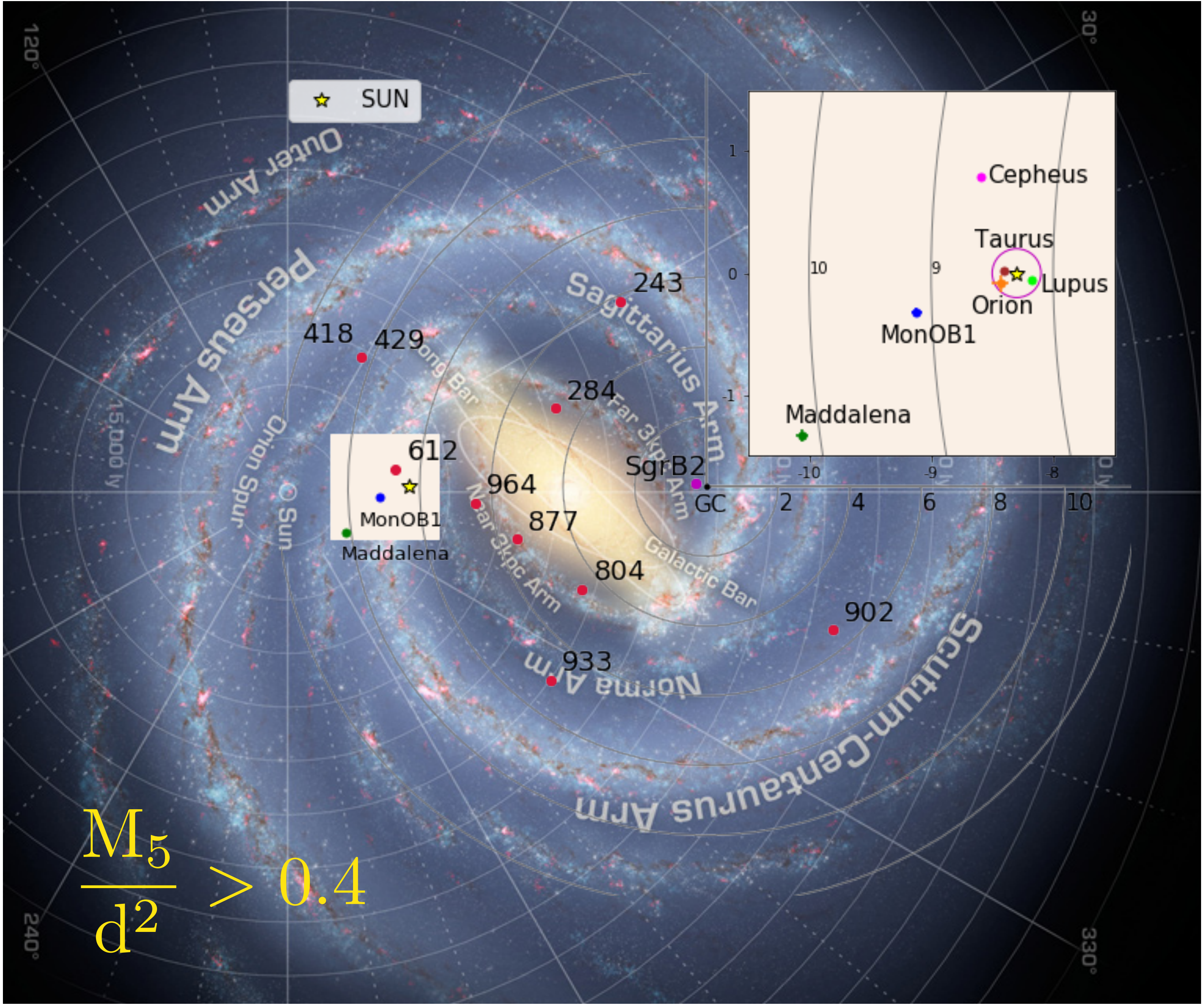
# Gamma Rays messengers of information about cosmic rays

**- diffuse gamma rays => propagation of Cosmic Rays**




CR flux in different parts of the Galaxy derived from Fermi LAT γ-ray data

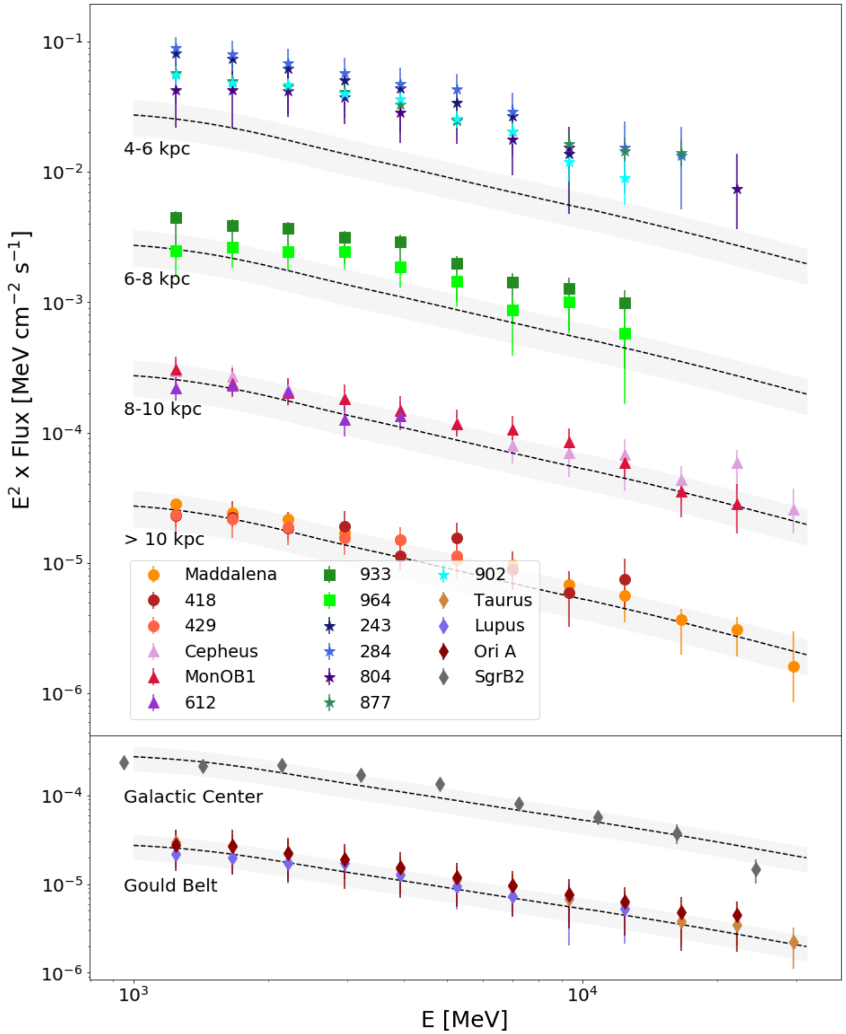
**- gamma rays from sources => Cosmic Ray Accelerators**



SUN
Outer Arm
Perseus Arm
Orion Spur
Sun
15,000 ly
Sagittarius Arm
Long Bar
Far 3kpc Arm
Near 3kpc Arm
Galactic Bar
Norma Arm
Scutum-Centaurus Arm
243
418
429
284
612
964
877
804
902
933
SgrB2
GC
MonOB1
Maddalena
Cepheus
Taurus
Lupus
Orion
2
4
6
8
10
-10
-9
-8
1
0
-1
120°
30°
240°
330°

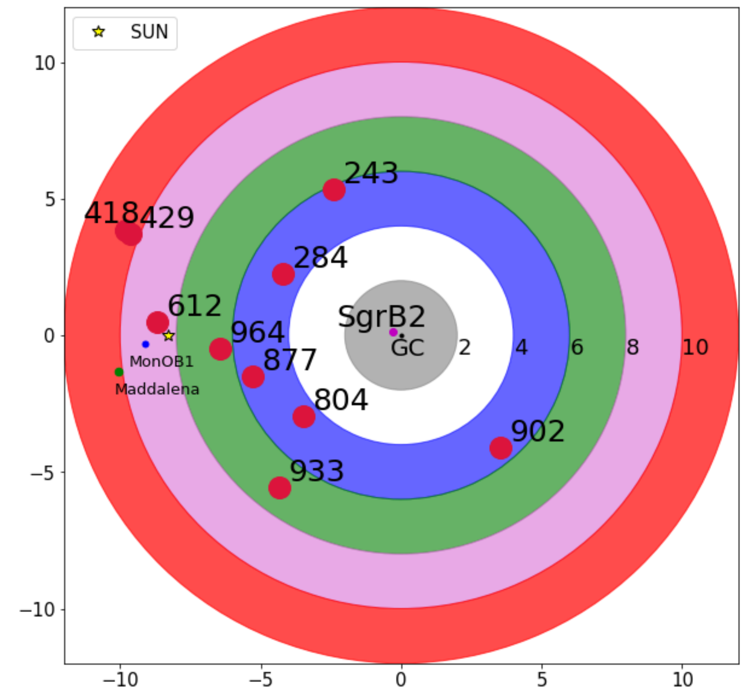

$$\frac{M_5}{d^2} > 0.4$$

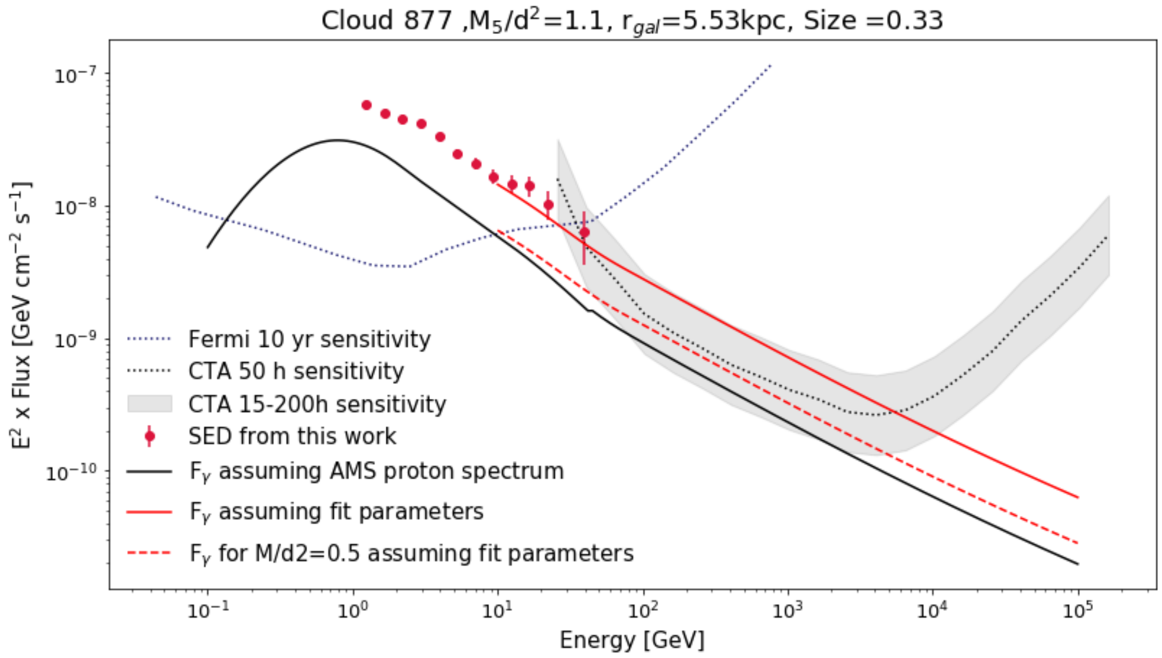
# The CR sea is resolved; everywhere is the same and coincides with the AMS 02 spectrum except perhaps the 4-6 ring (?)




## clouds detectable by Fermi

$$\frac{M_5}{d^2} > 0.4; \quad M_5 = M/10^5 M_\odot; \; d_{kpc} = d/1kpc$$






future? would be great to have CR barometers for GeV, TeV and PeV energies

GeV - should be more more sensitive than Fermi LAT by an order of magnitude

TeV - CTA - can marginally detect the CR sea at TeV energies !

PeV - would be great to have a CR “barometer” for >0.1 PeV protons

# Galactic Cosmic Rays: sources ?

SNRs as prime candidates - over decades the conviction has been based on phenomenological arguments and theoretical meditations

- as early as 1933 W. Baade and Zwicky recognized the comparable energetics characterizing SN explosions and CRs and envisaged a link between

  $E_{SN} \sim 10^{51}$ erg, $R \sim 0.03$ yr $^{-1}$, $P_{SN} \sim 10^{42}$ erg/s => 10 % to CRs ?

- Diffusive Shock Acceleration theory applied to SNRs - viable mechanism for acceleration of particles with hard $E^{-2}$ type spectrum in young (< 3 kyr) SNRs up to 1 PeV ? Difficult but in principle possible - amplification of the magnetic field in upstream is a critical issue

- direct prove - gamma-rays, neutrinos

# Probing SNRs with gamma-rays

SNRs as the most likely sources

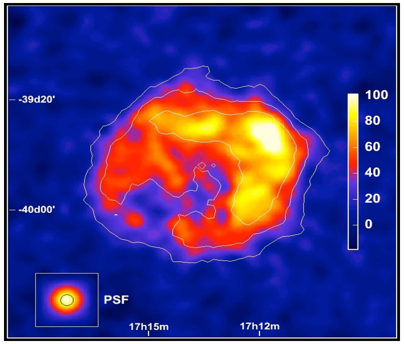
of galactic cosmic rays up to 1 PeV?

main hope is related to gamma-ray observations:

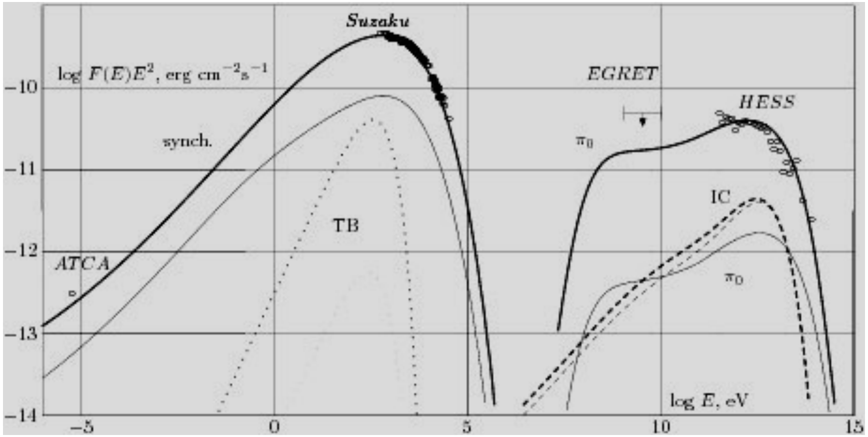
- detect VHE gamma-rays from SNRs
- demonstrate that they have hadronic origin
- demonstrate that proton spectra continue up to 1 PeV

RXJ 1713.7-4639

# *modeling of broad-band SEDs:*

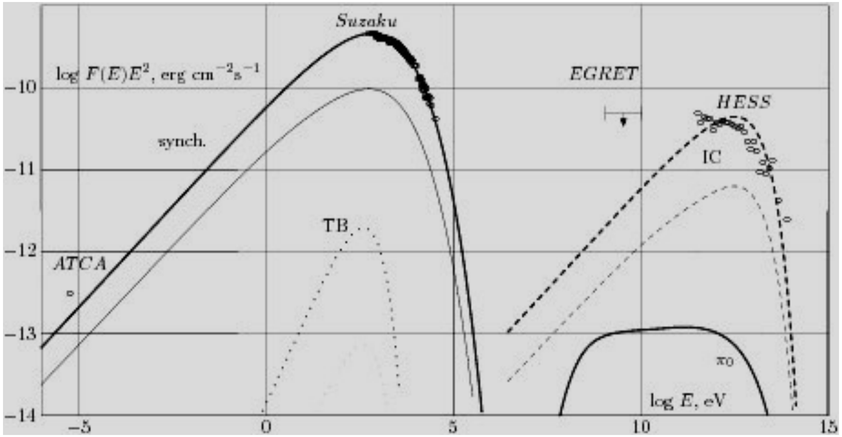



hadronic model




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

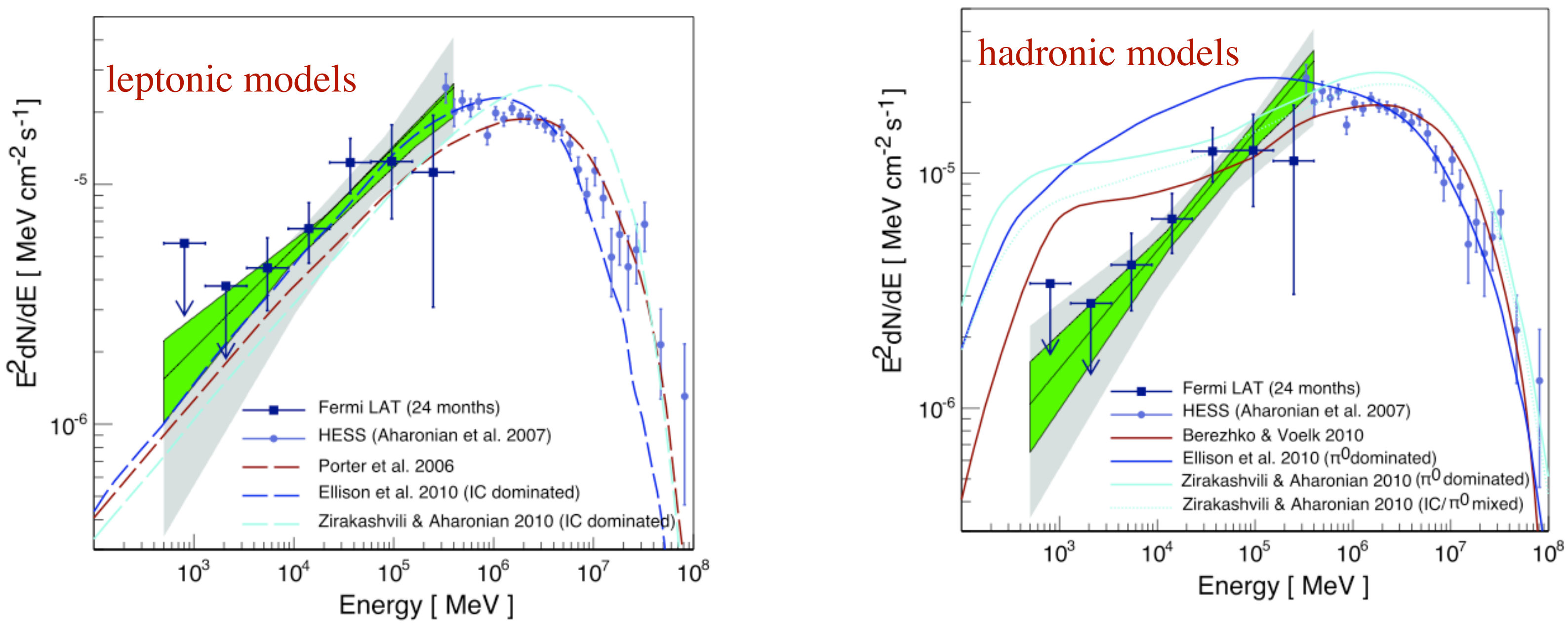



not perfect, but still acceptable, fits for spectral and spatial distributions of IC gamma-rays; suppressed thermal emission, comfortable p/e ratio (~$10^2$);small large-scale B-field (~ 10 μG)

both forward&reverse shock contribute to γ-rays

Zirakashvili, FA 2010

# Fermi: GeV data contradict hadronic origin of γ-rays (?)




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

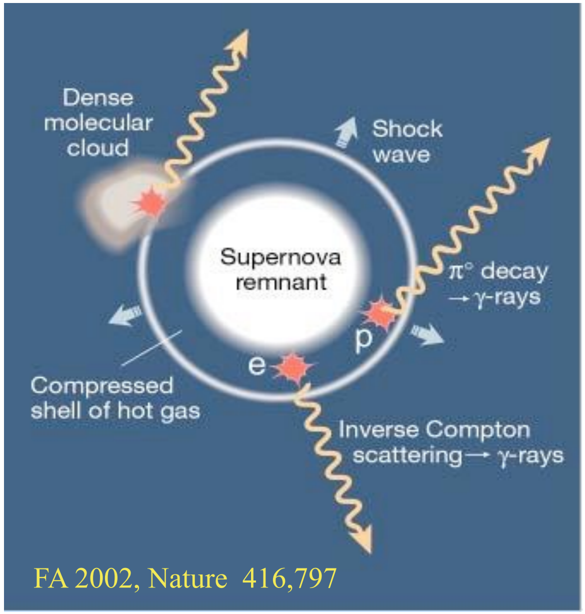
*they could come from quite different regions*

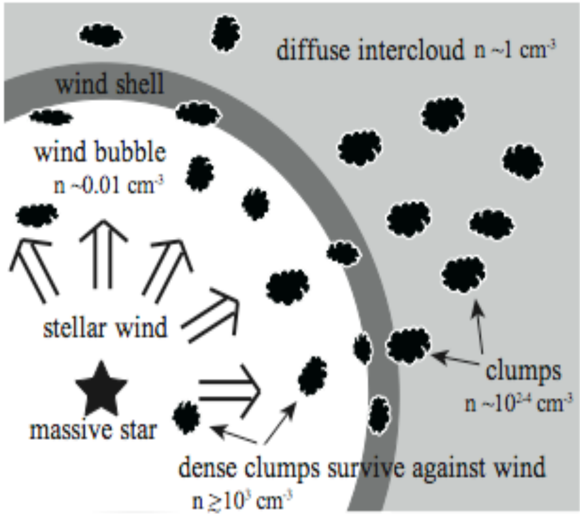
(ii) cannot we assume hard proton spectra ?

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

(iii) there could be a simple/natural solution

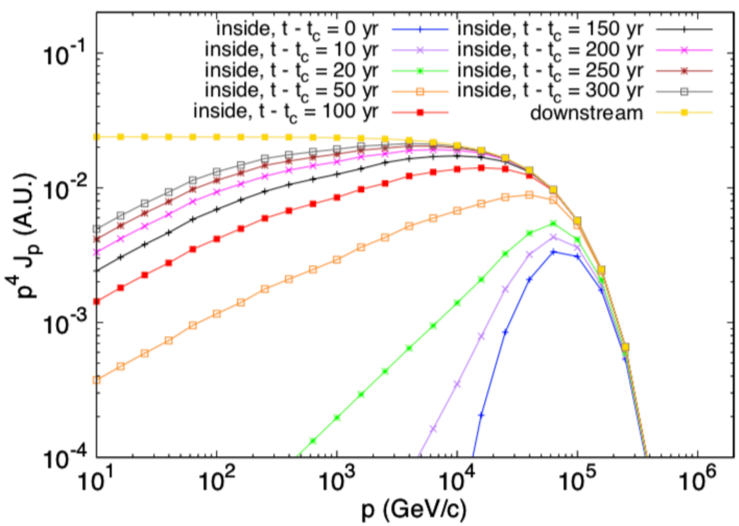
GeV γ-rays can be suppressed because low energy protons cannot reach the dense target (Malkov et al. 2005) or cannot penetrate deep into the dense clouds/clumps Zirakashvili&FA 2010)



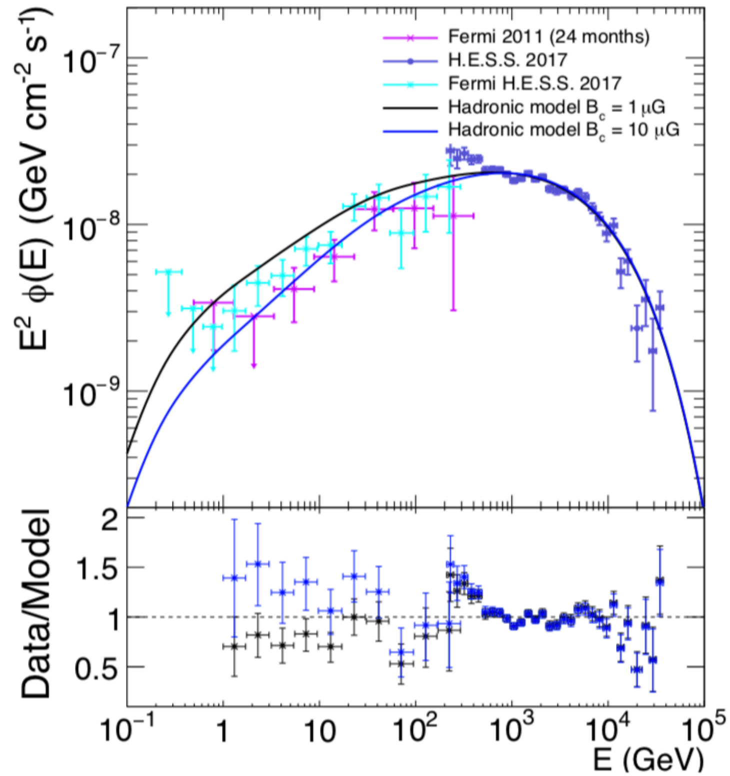




Inoue et al. 2011, ApJ

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

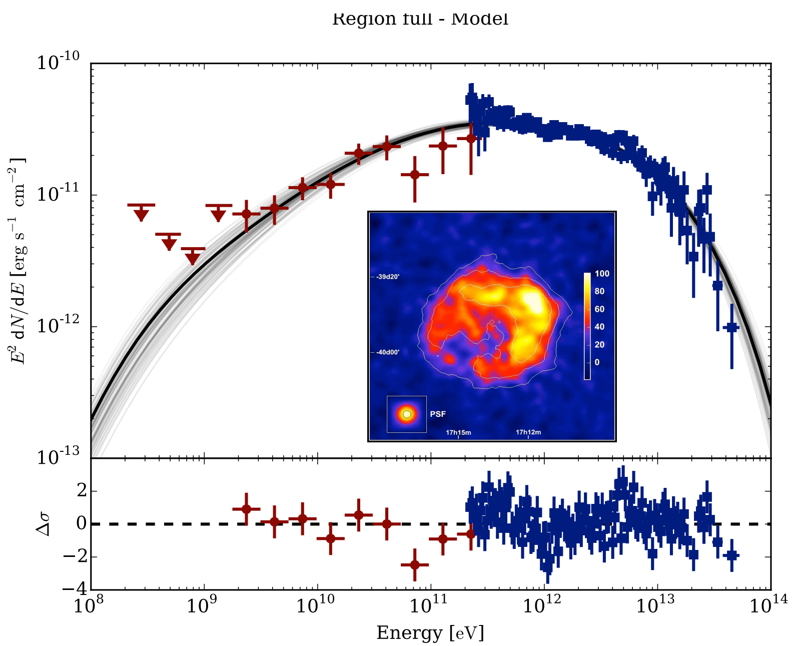


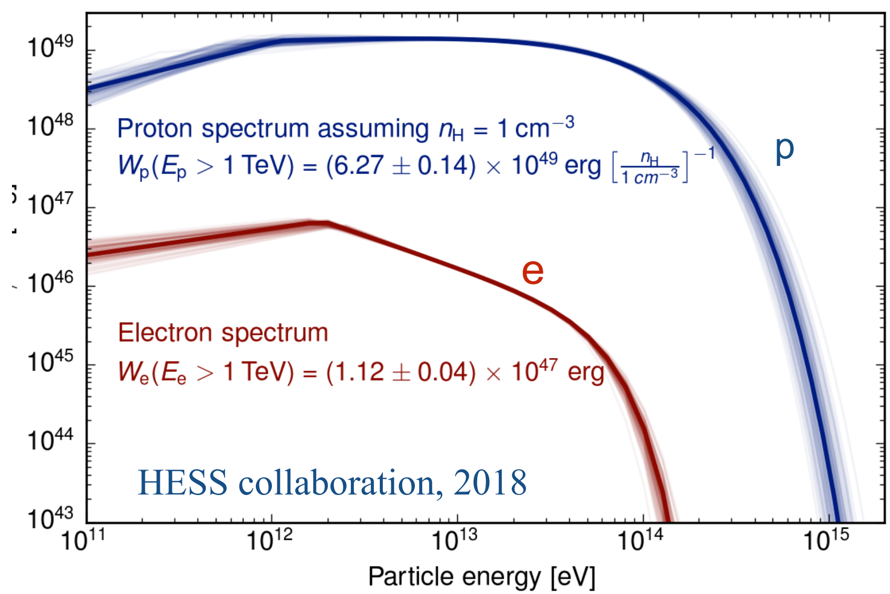

S. Celli 2018



# Probing the distributions of accelerated particles in SNRs

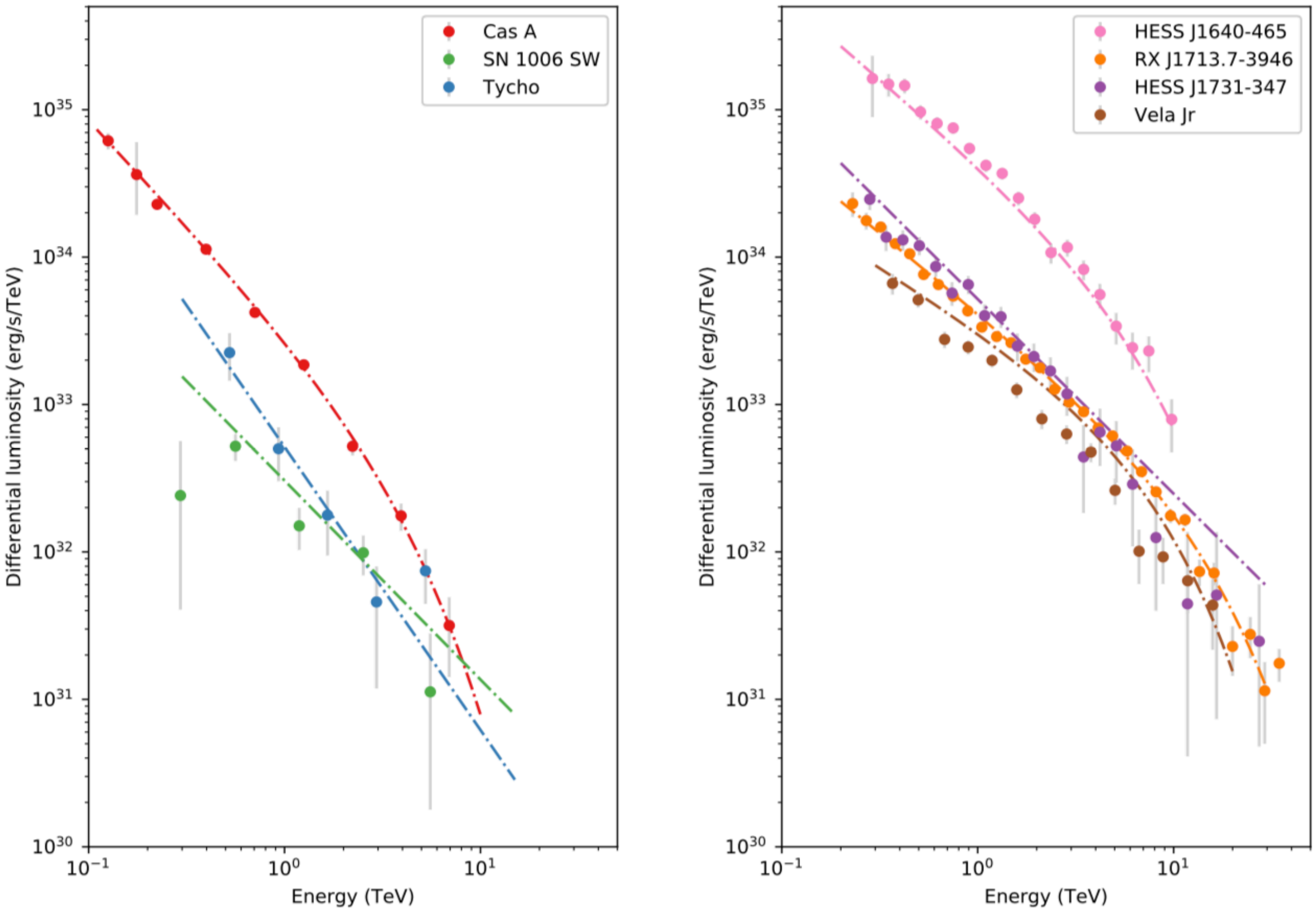
Fermi+HESS measurements **RXJ 1713** derived spectra of e and p




cutoff /break in the proton spectrum at 100 TeV

# spectra of young SNRs above 1 TeV - steep with $\Gamma = 2.3\text{-}2.6$



# slope or intrinsic power-low index?

formally the spectra can be presented in the form:

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

with reasonable combination of $E_0$ and $\beta$, $\Gamma=2$ could be an option

price?

Eo < 10 TeV => Ep < 100 TeV - is not a PeVatron ?

Eo > 100 TeV (no early cutoff) and $\Gamma > 2.3$

can be a PeVatron

- large power-law indices

deviation from DSA or its modification?

presently - no constrains on the proton maximum energy from gamma-ray data

- "early cutoff"

standard DSA but low-energy cutoff

should we relax and accept that SNRs are main contributors to CRs but at TeV energies are overtaken by other source population ("PeVatrons") responsible for the knee region? (Laggage and Cesarsky 1983) ?

or

relate it to the much early "PeVatron Phase" - first 10 to 100 years after the SN explosion (Bell+, Ptuskin & Zirakashvili) and the escape of highest energy particles from the remnant energy particles

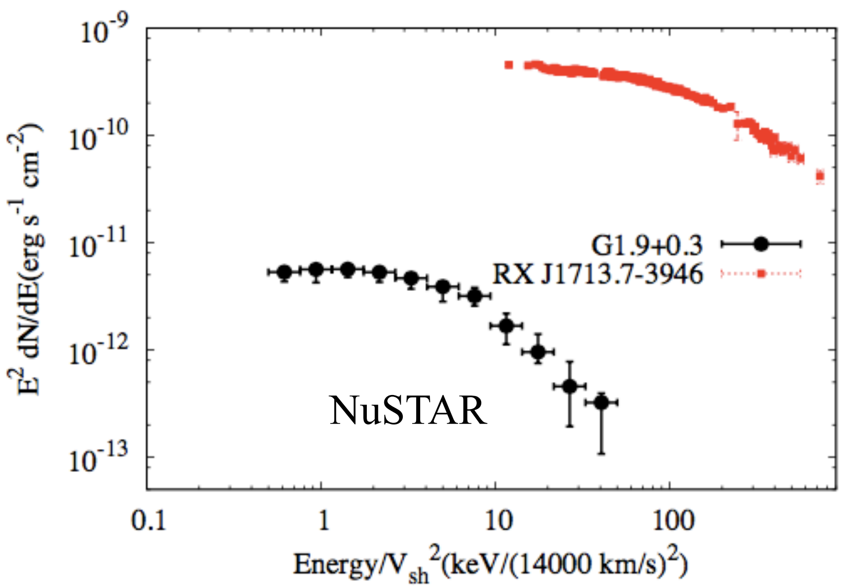
"large Γ or small Eo ?" - extension of observations to 10 TeV

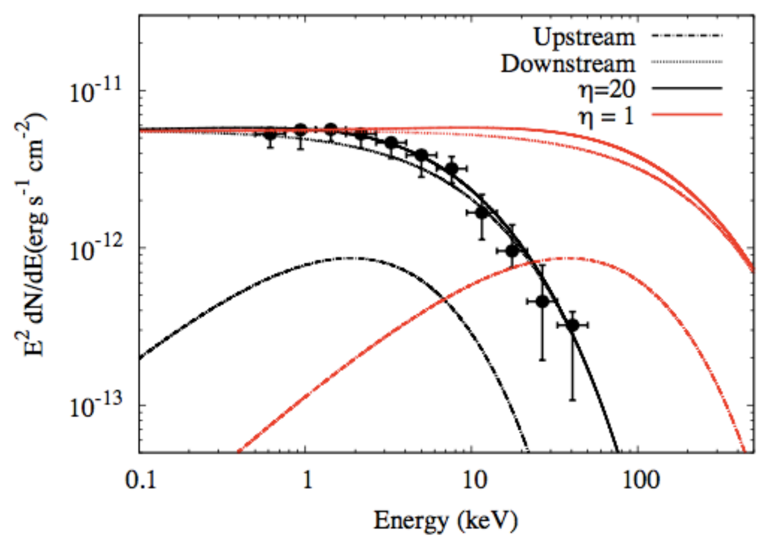
# Very young SNRs as PeVatrons?

G1.9+0.3 - youngest (100yr-old) known SNR in Galaxy with the current shock speed v=14,000 km/s

$$h\nu_{\rm max} \approx 1 (v_{\rm sh}/3000~{\rm km/s})^2~{\rm keV}$$

in the Bohm diffusion limit the peak should be around 20 keV but is detected at at 1 keV




Presently G1.9+0.3 does not operate as a PeVatron!

PeV protons have been accelerated at earlier epochs, but, because of the particle escape the remnant is already emptied =>

early acceleration and escape reduce the chances of finding PeVatrons ?

in very young (SN 1987a and G1.9+0.3) SNRs, multi-TeV particles cannot run far away, thus the current upper limits can be applied to the "escape regions"

G1.9+0.3 in GC region:

propagation of **R > 10 TeV** protons cannot exceed 30 pc (for **D ~ $10^{30}$ cm$^2$/s** )

for **d=8.5 kpc** the angular sized less than **10 arcmin**

HESS upper limit on the γ-ray luminosity $L_\gamma(\geq 1\ \mathrm{TeV}) \leq 2 \times 10^{32}$ erg/s

can be applied to the content of >10 TeV protons within R=30 pc region

for n~100 $\mathrm{cm}^{-3}$ $W_p(\geq 10E) = L_\gamma(\geq E) t_\pi$ or **Wp < $10^{45}$ erg**

=> G1.9+0.3 was not an effective PeVatron also in the past !

# alternative CR factories?

- ✓ collective stellar winds and SNR shocks in clusters and of massive stars, superbubbles
  - speeds off stellar winds - several 1000 km/s - comparable to young SNR shock speeds
  - $10^{41}$ erg/s (comparable or a factor of 2 less than mechanical power of SN)
    accel. efficiency should be at least 10 % - much less is needed for the knee region

- ✓ Galactic Center - significant contribution could come only from the Supermassive Black Hole (Sgr A*) . 5 x $10^{6}$ solar masses can formally provide a power as large as $10^{43}$ erg/s (assuming 10 % acceleration efficiency). But presently the accretion rate does not exceed $10^{39}$ erg/s (bolometric luminosity of Sgr A* is less than $10^{36}$ erg/s)

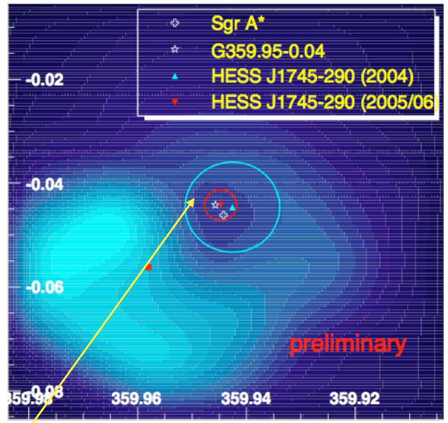
- ✓ pulsars/pulsar wind nebulae? prolific accelerators of electrons and positrons;
  potential, but, most likely, not the major contributors to CR electrons

one cannot exclude that the observed CR flux up to $10^{15}$eV is significantly contributed by a single (or a few) local CR accelerators. This is the case of TeV electrons

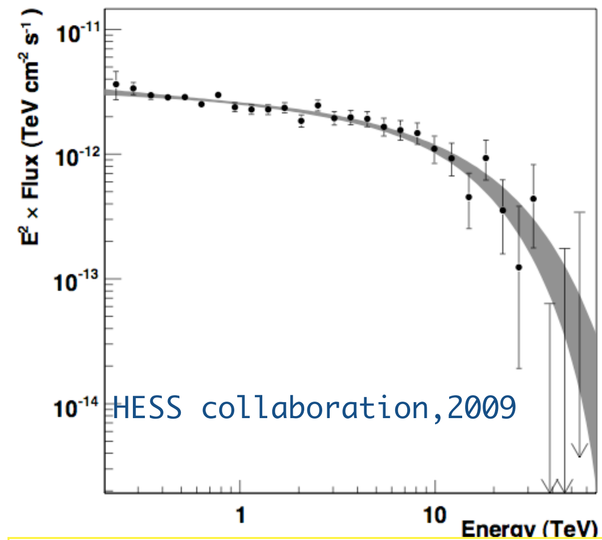
# PeVatron(s) in the Galactic Center!

# TeV gamma-rays from GC

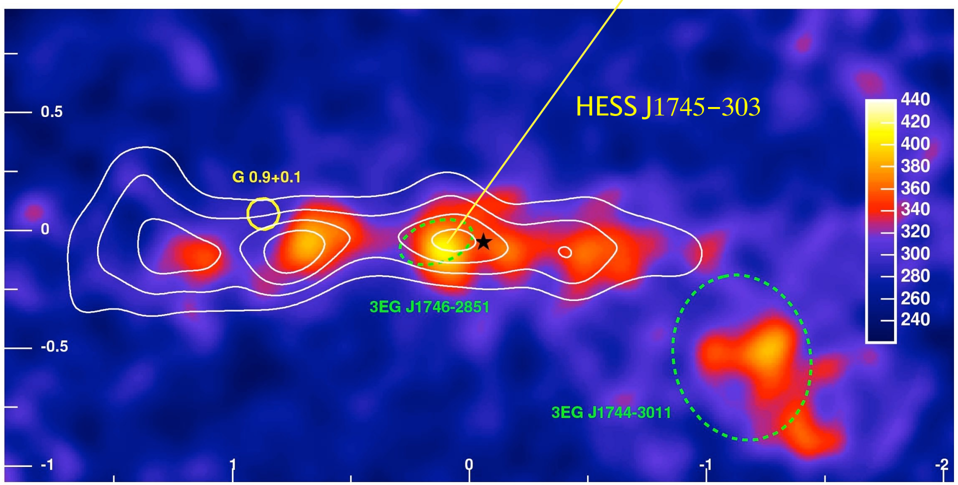
90 cm VLA radio image




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




γ-ray emitting clouds




HESS collaboration,2006

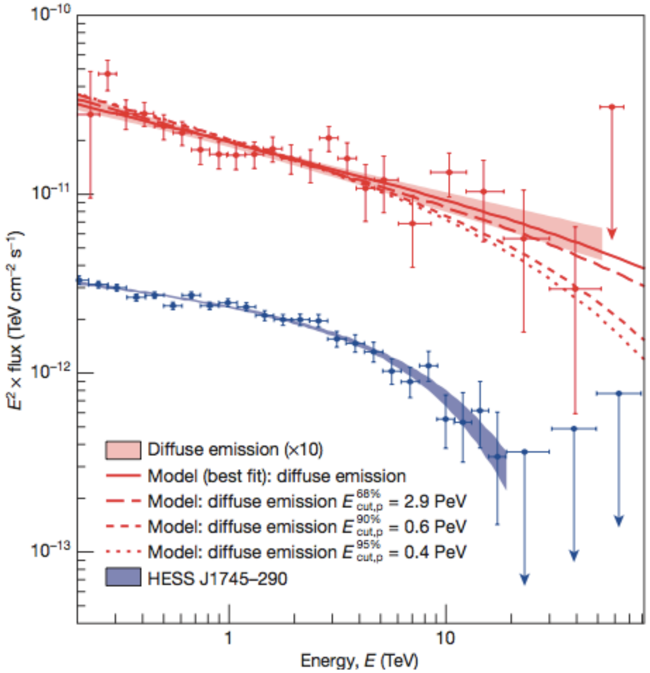
Energy spectrum:

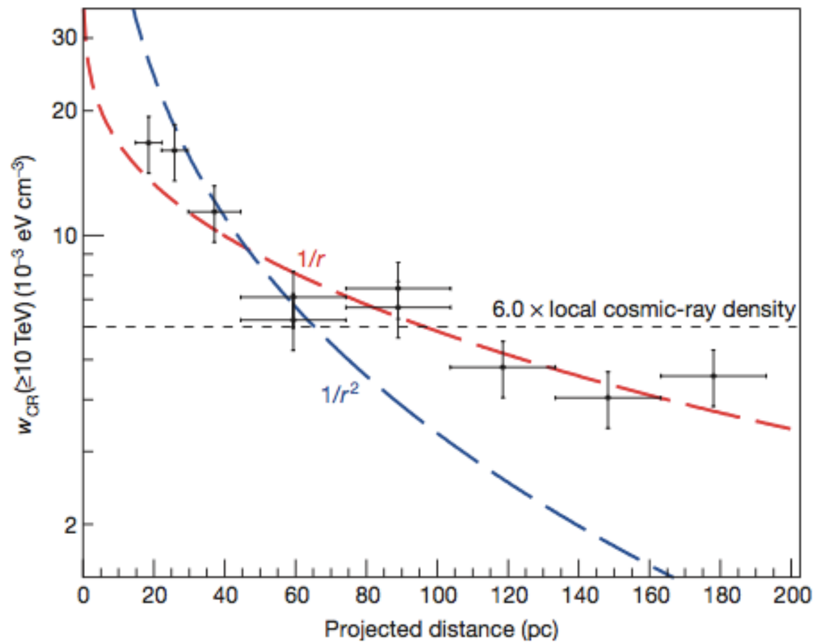
$dN/dE = AE^{-\Gamma} \exp[(-E/E_{0)})^{\beta}]$

$\beta=1$ $\Gamma=2.1$; $E_0=15.7$ TeV

$\beta=1/2$ $\Gamma=1.9$ E0=4.0 TeV

# PeVatron located within R<10 pc and operating continuously over > $10^3$ yr




*no-cutoff* in the gamma-ray spectrum up to **25 TeV**
=> *no-cutoff* in the proton spectrum up to ~ **1 PeV**

*what do we expect?*

1/r continuous source
$1/r^2$ wind or ballistic motion
constant burst like source

*derived*: **1/r** distribution
**=> continuous acceleration !**

## implications?

- Galactic Center (GC) harbors a hadronic PeVatron within a few pc region around Sgr A* (a SMBH in GC)

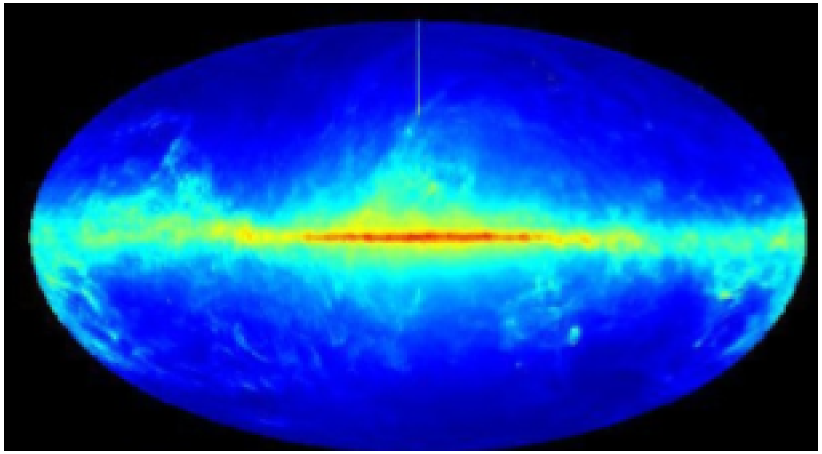
- 1/r type distribution of the CR density implies (quasi)continuous regime of operation of the accelerator with a power $10^{38}$ erg/s (on timescales 1 to 10 kyr) - a non negligible fraction of the current accretion power

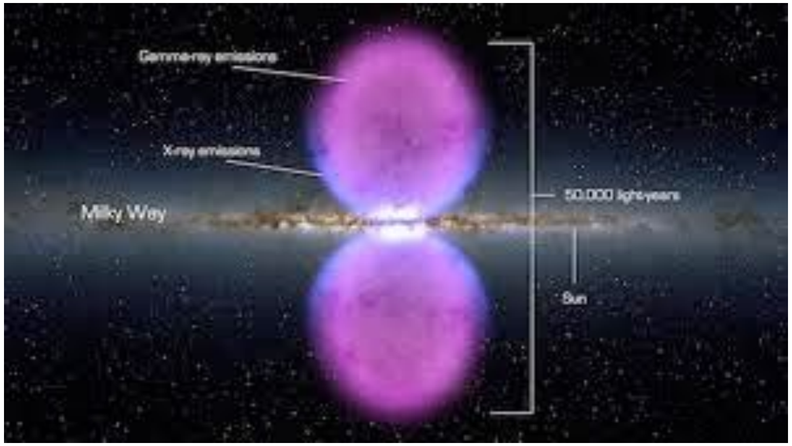
- this accelerator alone can account for most of the flux of Galactic CRs around the “knee” if its power over the last $10^6$ years or so, has been maintained at average level of $10^{39}$ erg/s

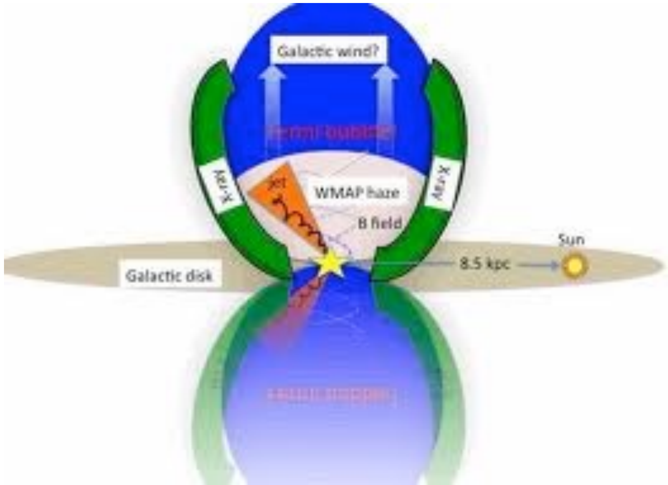
- escape of particles into the Galactic halo and their subsequent interactions with the surrounding gas, can be responsible for the sub-PeV neutrinos recently reported by the IceCube collaboration

SMBH or young massive-star clusters?

# CRs from GC responsible for Fermi Bubbles?






and “IceCube Neutrinos” from a larger >>10 kpc halo  ?

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)

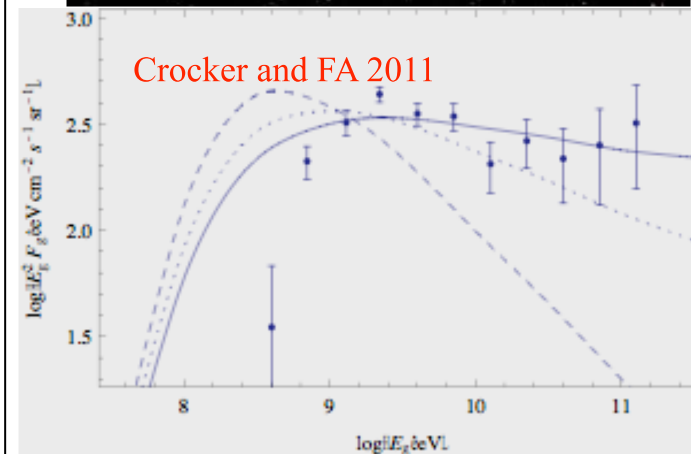
*Size - because of slow diffusion in turbulent environment (10 times slower than in the Galactic Disk)*

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 : $L_p \sim 10^{39-40}$ erg/s




Fermi Bubbles
as a VHE neutrino source?

# Clusters of Young Massive Stars as major sources of CRs?

# Extended Regions surrounding Clusters of Young Massive Stars sources of GeV and TeV gamma-rays

*Westerlund 1*, *Westerlund 2*, *30 Dor C* (in LMC)

*CygnusOB2*, *Westerlund 2*, *NGC3603*

*Arches*, *Quintuplet* and *Nuclear* ultracompact clusters in GC

- collective power in stellar wind $10^{38}$ - $10^{39}$ erg/s
- typical speeds of stellar winds several 1000 km/s

continuous injections of CRs into ISM over (2-5) x $10^6$ yrs formation of ~ 1/r radial distribution of CRs up to 200 pc; diffuse (typically irregular) gamma-ray morphology

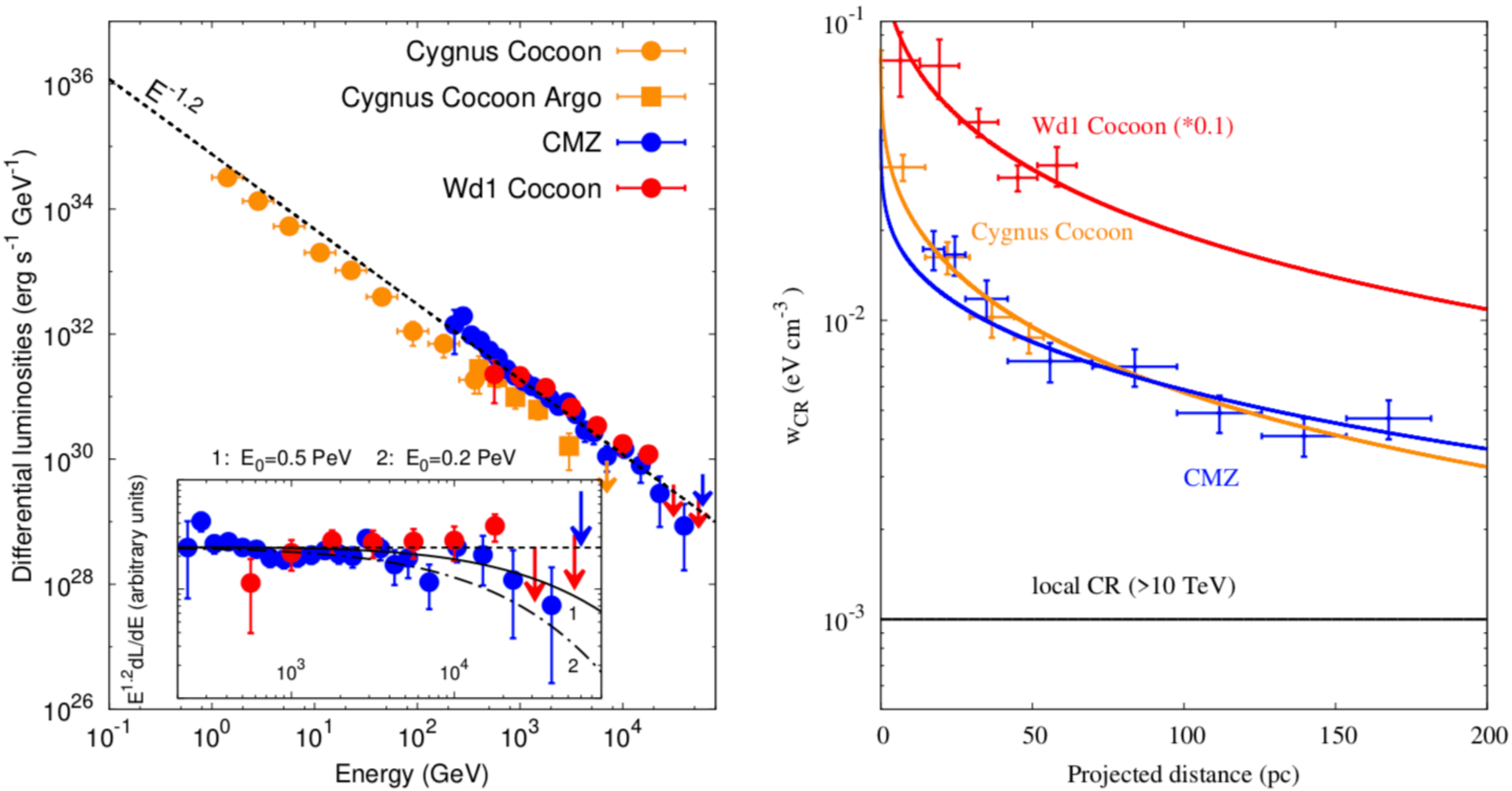



Figure 1: Gamma-ray luminosities and CR proton radial distributions in extended regions around the star clusters Cyg OB2 (Cygnus Cocoon) and Westerlund 1 (Wd 1 Cocoon), as well as in the Central Molecular Zone (CMZ) of the Galactic Centre assuming that CMZ is powered by CRs accelerated in *Arches*, *Quintuplet* and *Nuclear* clusters.

FA, Yang, Ona de Wilhelmi, 2018

Total energy in CRs within the size of radius Ro

$$W_p = 4\pi \int_0^{R_0} w(r) r^2 \, dr \approx 2.7 \times 10^{47} (w_0/1 \text{ eV/cm}^3)(R_0/10 \text{ pc})^2 \text{ erg}$$

Size of emission region - depends on D and To

$$R_D = 2\sqrt{T_0 D(E)} \approx 3.6 \times 10^3 (D_{30} T_6)^{1/2} \text{ pc}$$

Efficiency of conversion of the wind kinetic energy to CRs

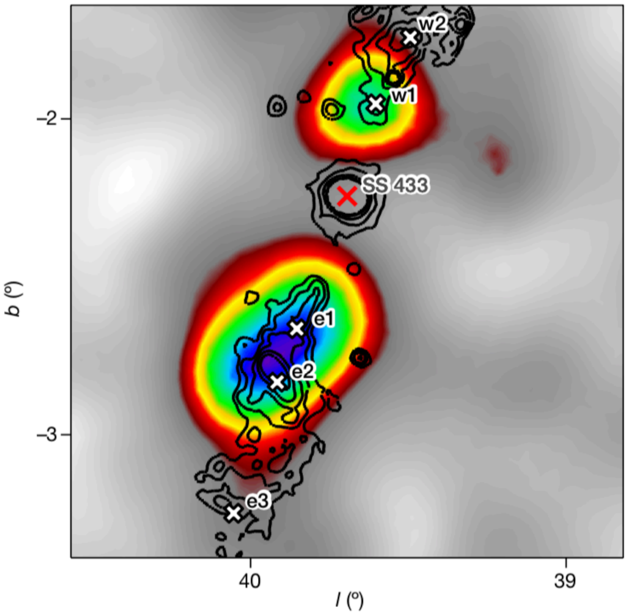
$$f(\geq 10 \text{ TeV}) \approx 1 w_0 D_{30} L_{39}^{-1}$$

For $E^{-2.3}$ proton spectrum, f(>10TeV) does not significantly exceed 1%
the diffusion coefficient $D_{30}$ cannot be larger than 0.01; $R_D$ ~ 300 pc

CTA - unique measurements of D and consequently f

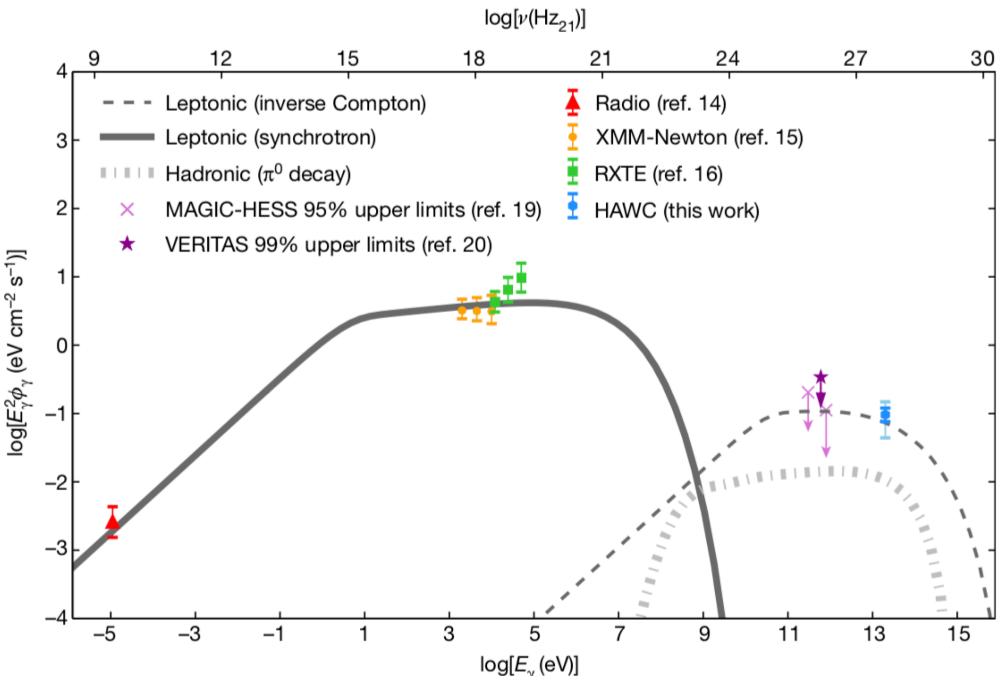
# Other Pevatron candidates

# detection of >10 TeV hard spectrum gamma-rays from SS 433



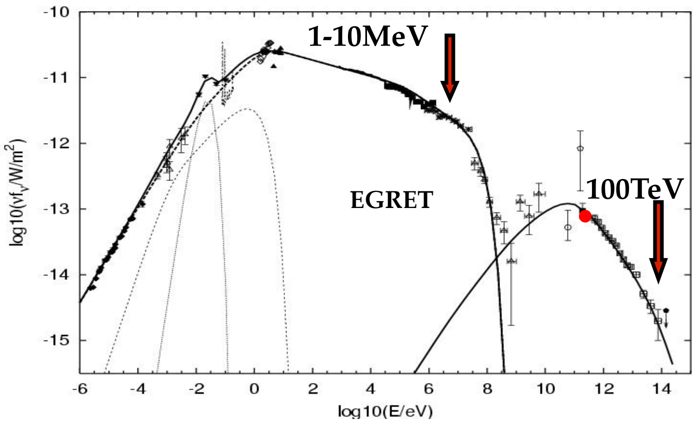

HAWC - HESS/MAGIC upper limits

spectrum as flat as $E^{-2}$ extending 20 TeV




- $E^{-2}$ electron spectrum with Eo=2 PeV
- gas density - not sufficient?

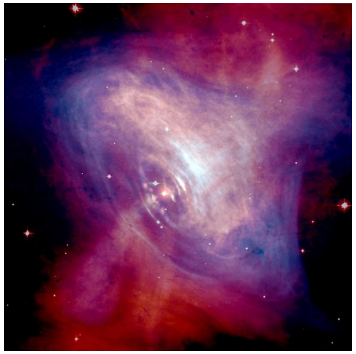
# Crab Nebula – *a perfect electron PeVatron*




**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

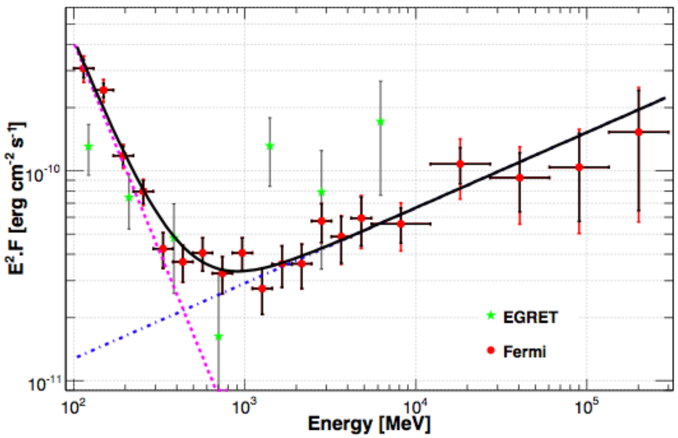


Crab Nebula – a powerful $L_e=1/5L_{rot} \sim 10^{38}$ erg/s
and extreme accelerator: Ee >> 100 TeV

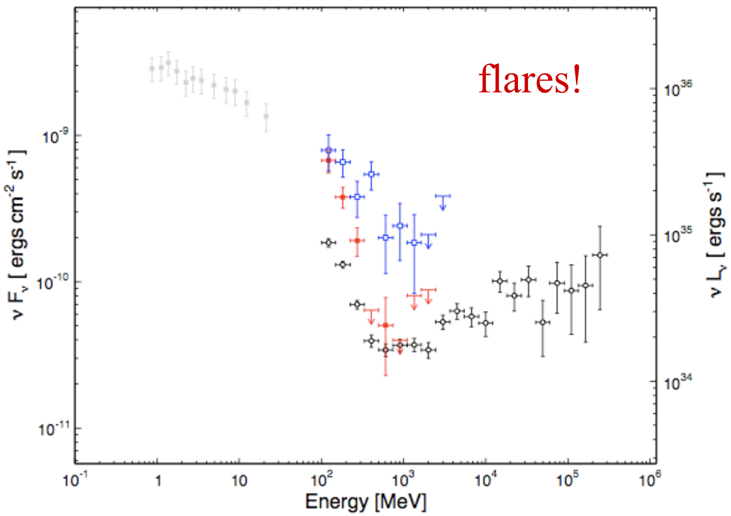
$E_{max}=60\ (B/1G)^{-1/2}\ \eta^{-1/2}$ TeV and $h\nu_{cut} \sim 150\eta^{-1}$ MeV

Cutoff at $h\nu_{cut}$ > 10 => $\eta$ < 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 => $\eta \sim 1$ ?

## Flares of Crab (Nebula) :




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>

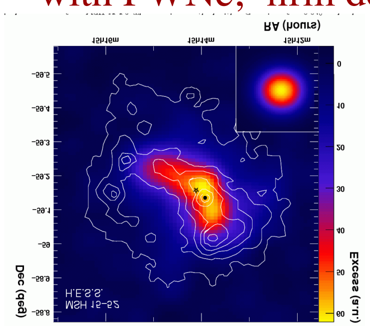
we do see TeV γ-rays from the Crab Nebula because of very large spin-down flux: $f_{rot}=L_{rot}/4\pi d^2=3\text{x}10^{-7}$ erg/cm$^2$ s

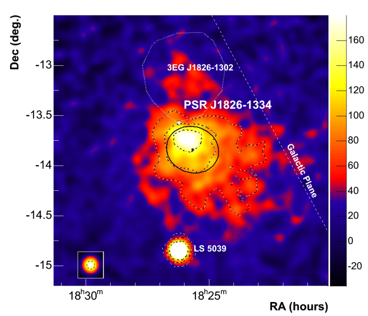
gamma-ray flux << “spin-down flux“ *because of large B-field*

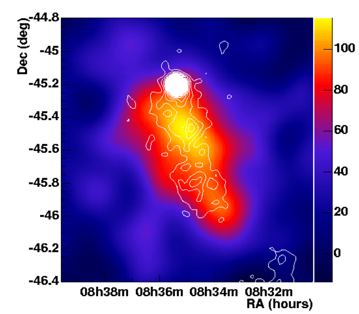
if the B-field is small (environments with small external gas presure)

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

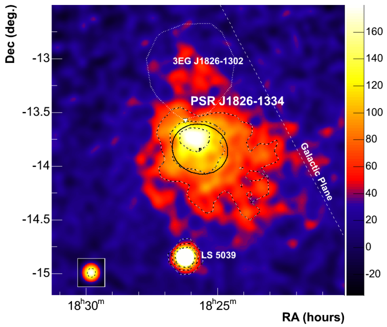
HESS confirms this prediction – many (20+) candidates associated with PWNe; firm detections - MSH 15-52, PSR 1825, Vela X, ... N157B!





# Galactic Sources

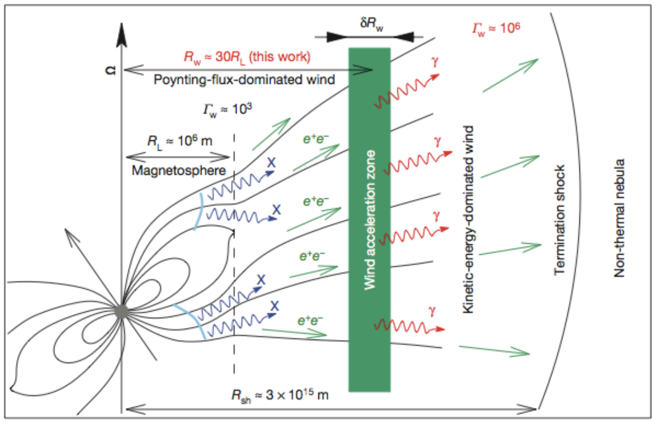


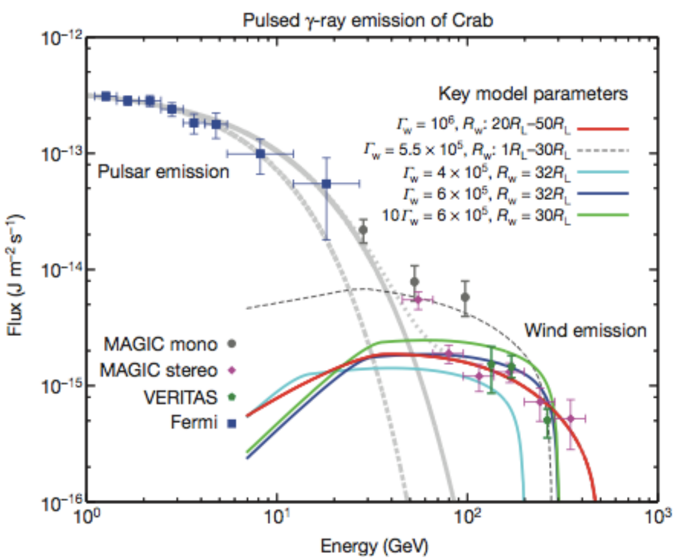

- **PWNe** - spatial and energy distribution of electrons without any assumption (unique in astrophysics), spatial distribution of the average B-field by adding the X-ray results, turbulence of the magnetic field, size of the regions filled by electrons, propagation of electrons (transition from PWN to ISM)

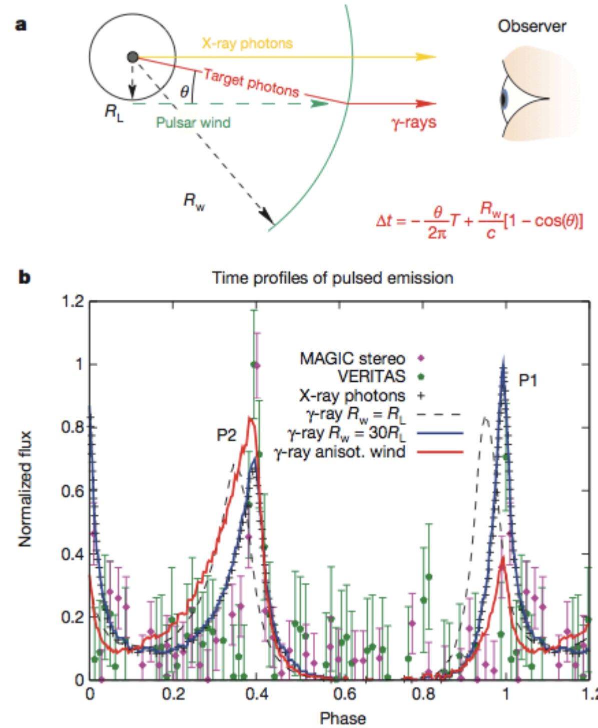
- **Pulsars/Pulsar-Windsm -** pulsed TeV emission - magnetospheres or cold winds?

- **Binary Pulsars -** termination of pulsar winds, formation of relativistic shocks, acceleration of electrons in *on-line* regime, study the sites and mechanisms of acceleration

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




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

# 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 $\gamma$-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

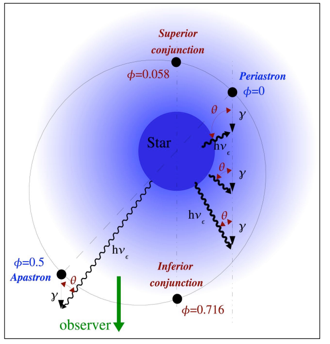
(characteristic timescales 1 h or shorter !)

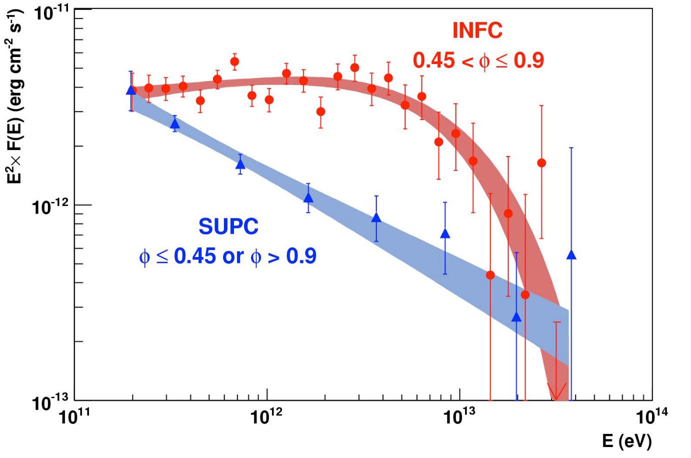
the target photon field is function of time, thus the only unknown parameter is B-field => predictable gamma-ray emission?

# LS 5039

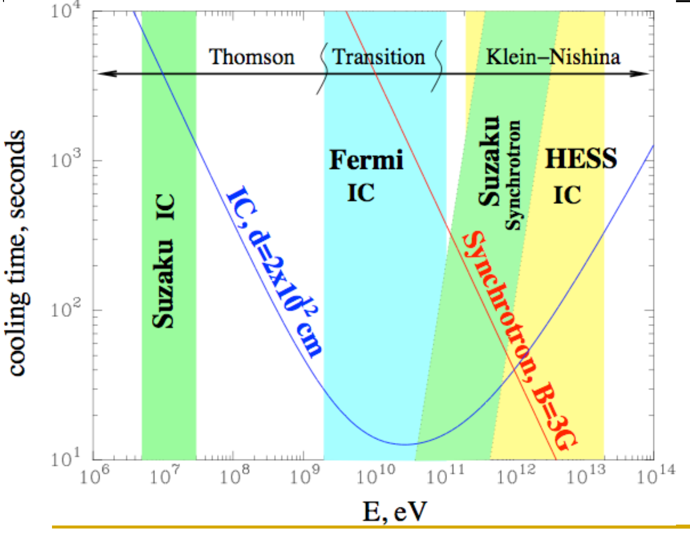
works as a perfect TeV clock
and an extreme accelerator

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



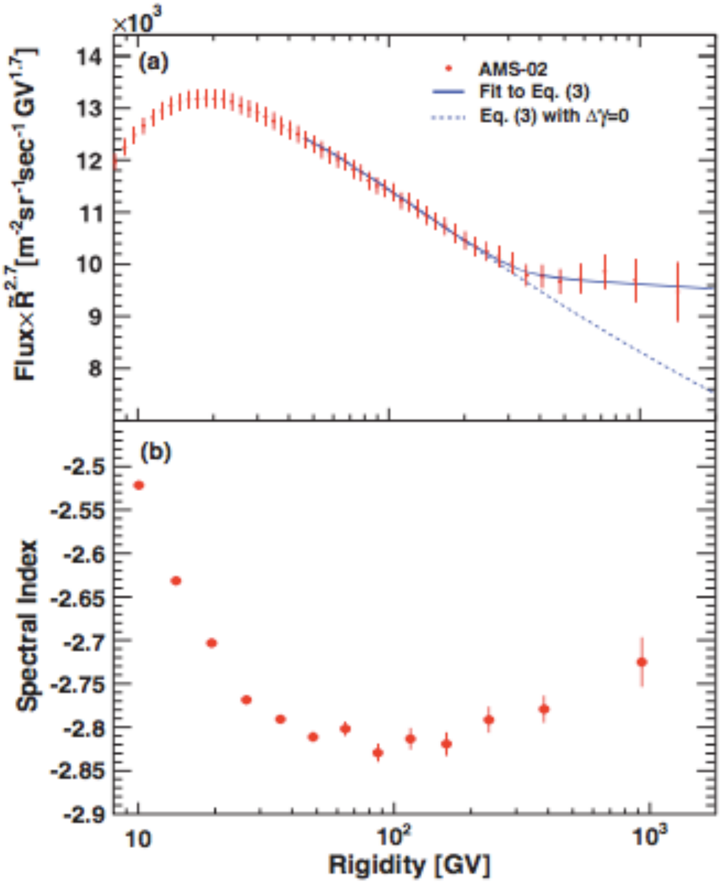

*modulation of the gamma-ray signal?* *a quite natural reason (because of γ–γ absorption), but we see a different picture… anisotropic IC scattering? yes, but perhaps some additional factors (adiabatic losses, modest Doppler boosting) also play a non-negligible role*




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

## recent great progress in Cosmic Ray Studies: precise measurements and implications

# recent primary CR measurements - *second component* ?




most natural explanation -
Superposition of two CR components

alternative explanations?

- change of energy dependence of diffusion coefficient
- acceleration efficiency increases with energy

# anomalously high content of antiparticles in CRs
# - because of the the seecond CR component ?

spectrum of secondary particle close to the projectiles:

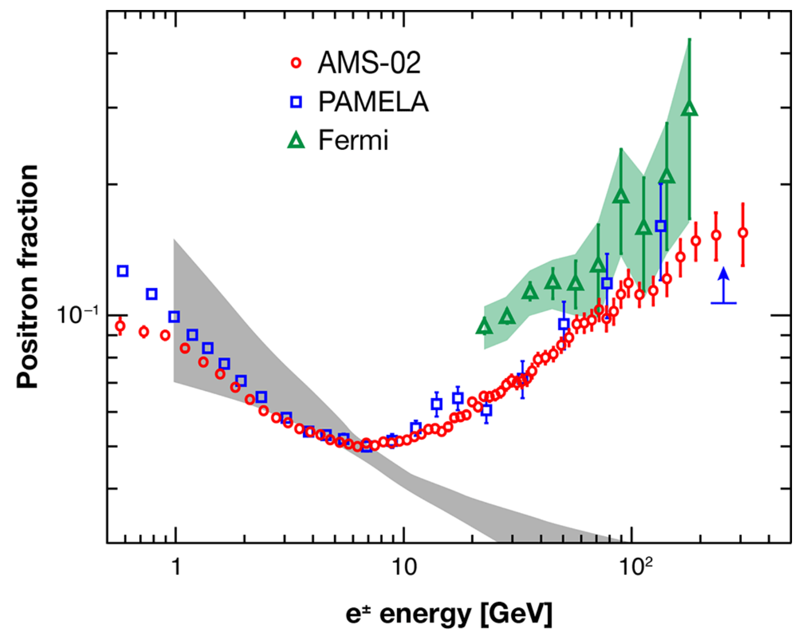
production spectrum of secondaries $S(E) \propto E^{-\Gamma}$

charged secondaries - modulated once more $\Phi(E) \propto E^{-(\Gamma+\delta)}$

secondary-to-primary ratio $\Phi''(E)/\Phi'(E) \propto E^{-\delta}$

decreases with energy because of the “double-modulation”

opposite dependence is observed !



# additional source(s) for antiparticles is needed!

Dark Matter?

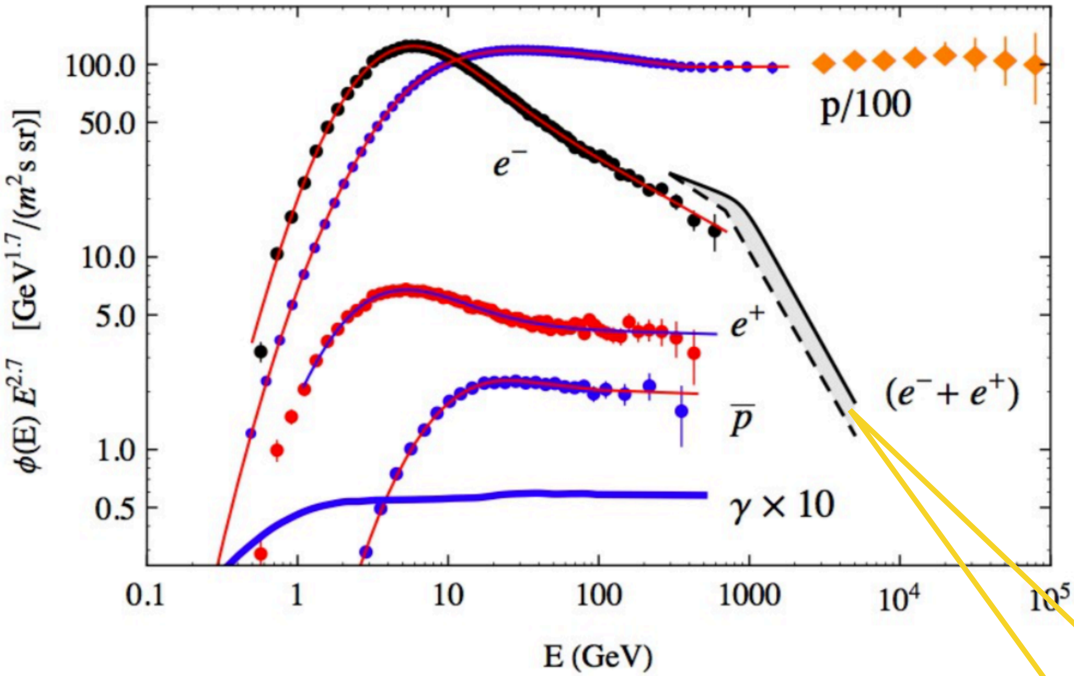
for positrons exist a more natural source - pulsars/PWNe

but it does not work for antiprotons - Dark Matter?

$e^+/\bar{p}$ ratio is almost energy-independent - should be an intrinsic link between positrons and antiprotons

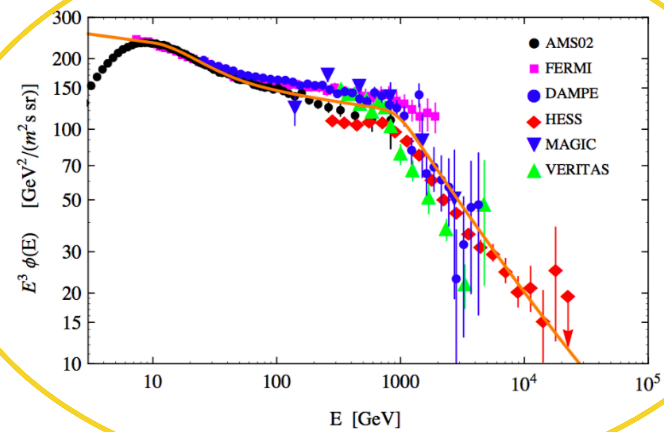
more realistic possibility - interactions of primary CRs with ambient gas, but inside or close to accelerators

secondary antiparticles with hard spectra together with primaries are injected into ISM - no double modulation!




positrons from pulsars?

multi-TeV electrons
from a nearby source




protons, positrons, antiprotons

similar spectra !

conclusion: positrons and positrons
are products of interactions of
primary particles but not in ISM

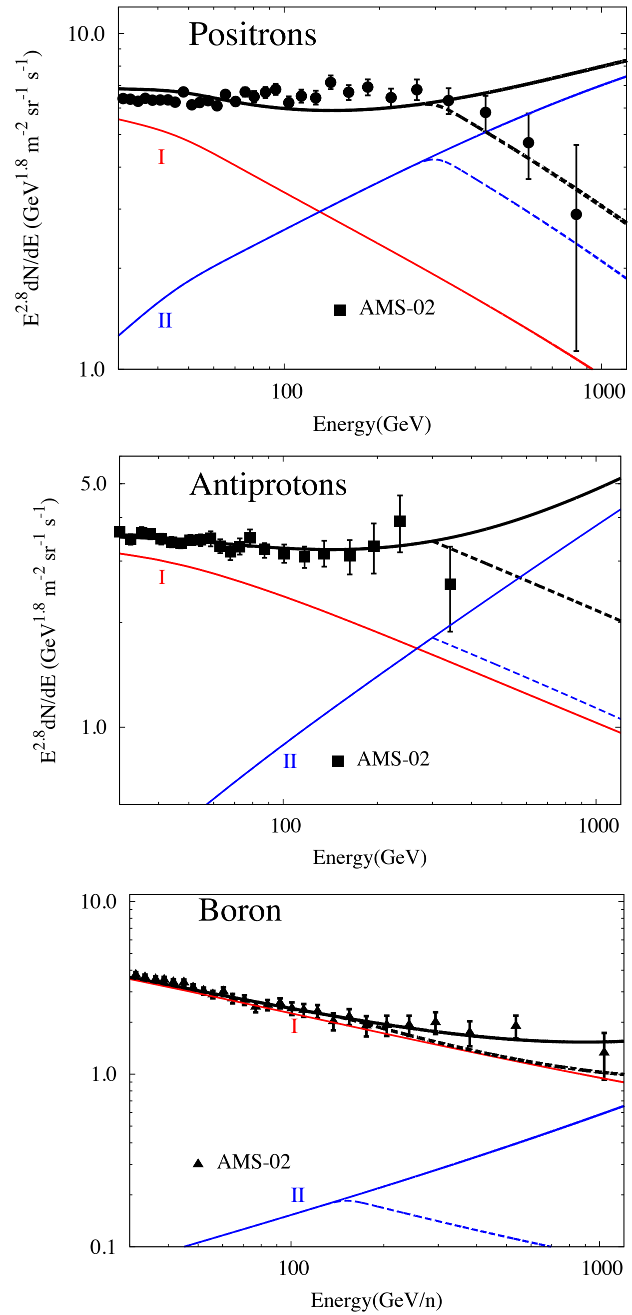
## a simple solution

by adding new assumptions to the 'standard' paradigm of Galactic CRs

- antiparticles are effectively produced in interactions of primary CRs with gas not only in ISM but also inside accelerators

- two source populations inject CRs into ISM with soft (1) $E^{-2.3}$ and (2) hard $E^{-1.8}$ spectra

- CRs in 2nd population accelerators accumulate "grammage" ~1 g/cm2 before leakage into ISM



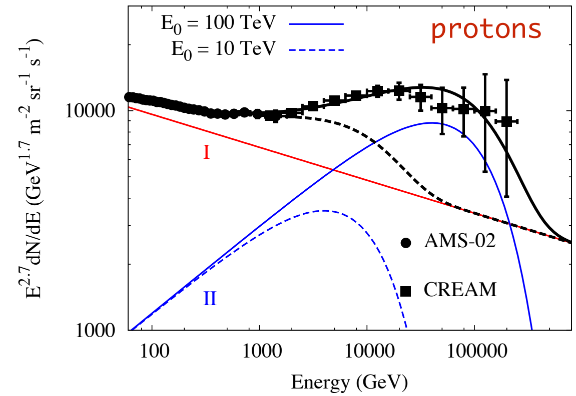
superposition of contributions of two- source populations explains:

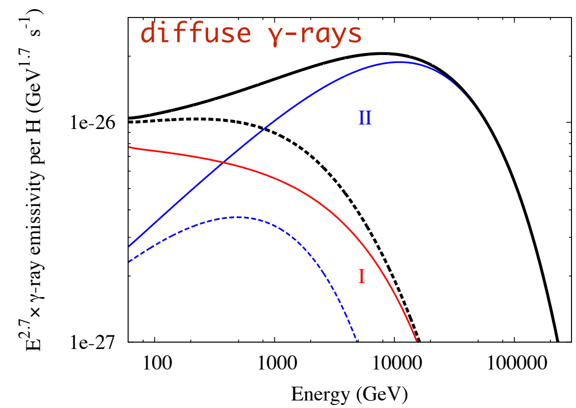
the hardening  of spectra of CR protons and nuclei around 200 GeV

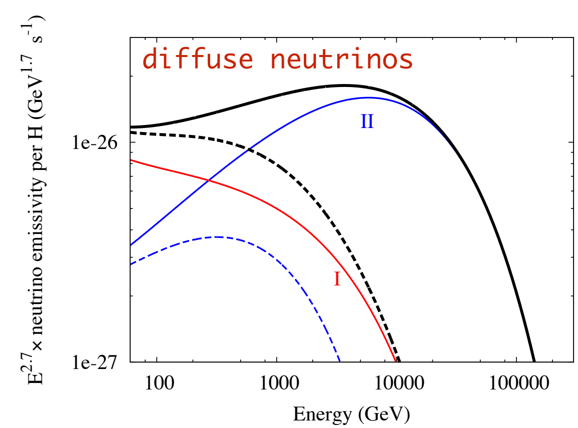
required power in 2nd source population < 10 % of power of 1st population, W ~$10^{39}$ erg/s

2nd population -  PeVatrons?

responsible for the highest energy particle in galactic CRs up to the “knee”  around $10^{15}$ eV but should around 100-200 TeV cutoff



# Extragalactic Sources

*see lectures of Frank Rieger - a nice overview of the field with comprehensive description of sources and acceleration processes*

*I will add only a few comments basically in the context of*

*Extreme Accelerators*

# Extragalactic Sources

nearby AGN - so far  M87 (variability on timescales of days,
Cen A  (central source and radiolobes at  GeV energies)

*next steps:*  detailed spectral/spatial distributions, timing
*topics:*   BH physics,  jets,   EBL at MIR-FIR

# Extragalactic Sources

Starburst Galaxies - so far NGC 253 and M82 have been detected both at GeV and TeV energies with very high proton-to gamma conversion factor > 0.1 (almost "calorimetric" ), hard spectra

*next step:* detailed spectral measurements up to 100 TeV, angular distribution up to 1 deg (to map ~100 kpc halos), search for VHE emission from most powerful representatives - Arp 220, Mkn 279

topics: origin of CRs, EBL at MIR-FIR

# ExtraGalactic Sources

- Clusters of Galaxies

**so far** - no detections at GeV and TeV, but there is little doubt (?) that gamma-rays will appear at some level because of pp, IC and "p -2.7K + IC of Bethe-Heitler electrons" interactions

**reasons for optimism?** accretion shocks with $v > 1000$ km/s
**objects:** Clusters of Galaxies - Coma, Perseus A, …
**topics:** large-scale cosmological structures in the context of nonthermal phenomena, B-fields, accretion shocks, …

- Large scale structures of different origin

Radio lobes of powerful radiogalaxies; Synchrotron Halos of secondary electrons; Giant $e^+e^-$ pair Halos around AGN; photon beams broadened in the very week B-fields of IGMFs

# 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 μG
- ✓ shock velocity - few 1000 km/s
- ✓ acceleration time ~ Hubble time

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

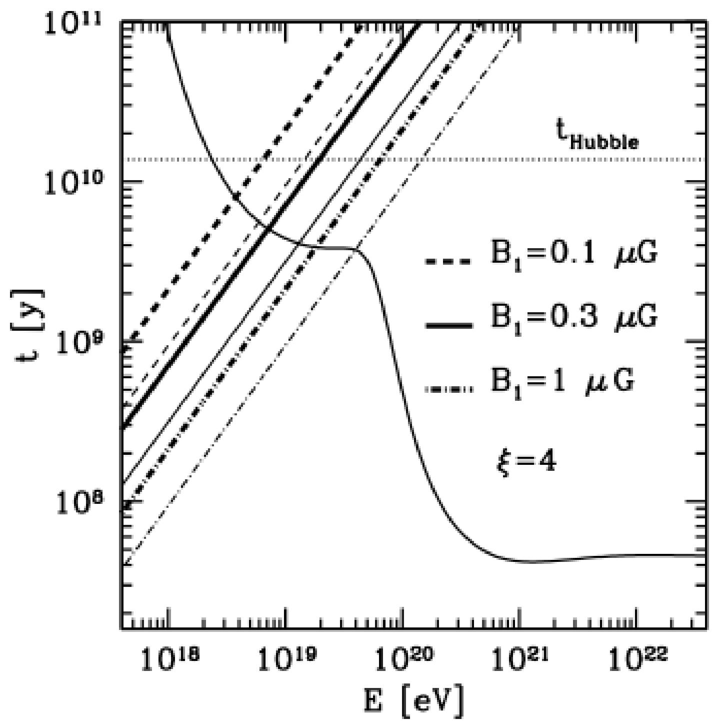
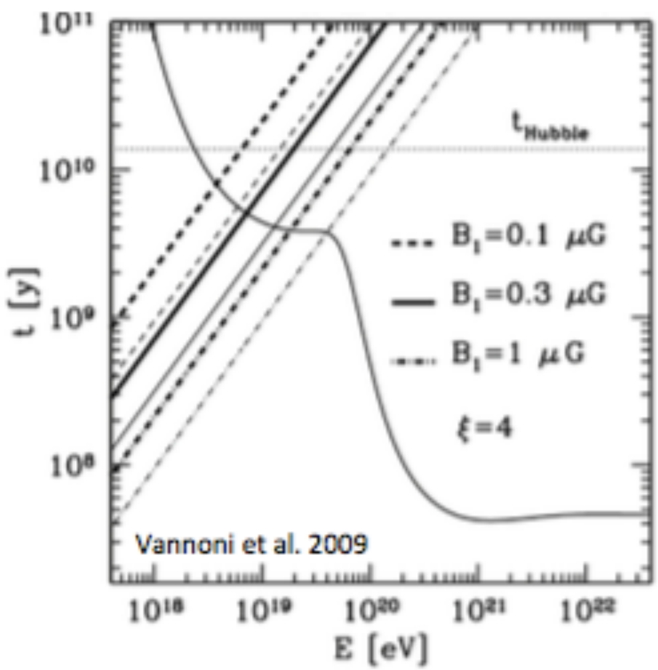



**Fig. 1.** Acceleration and energy loss time scales as a function of the proton energy. The acceleration time scales are obtained for the values of the upstream magnetic field $B_1$ reported in figure and a downstream magnetic field $B_2 = 4B_1$. The thick lines correspond to a shock velocity of 2000 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.

Vannoni et al. 2009

*Clusters of Galaxies accelerating protons to* $10^{18}$eV

DSA acceleration of protons=> interactions of protons with 2.7K CMBR
=> $e^+e^-$ pair production => Synchrotron and IC of secondary electrons

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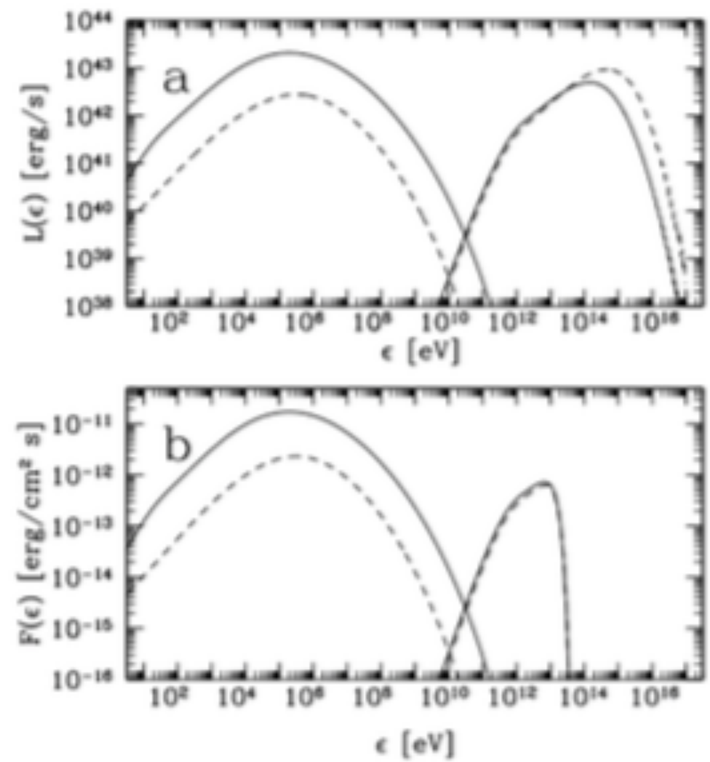



**Fig. 13. a)** Broadband radiation spectra produced at the source by the electron distributions in Fig. 12**b**, downstream (solid line) and upstream (dashed line). **b)** Energy flux at the observer location, after absorption in the EBL, for a source distance of 100 Mpc.

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

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

signatures of extreme accelerators?

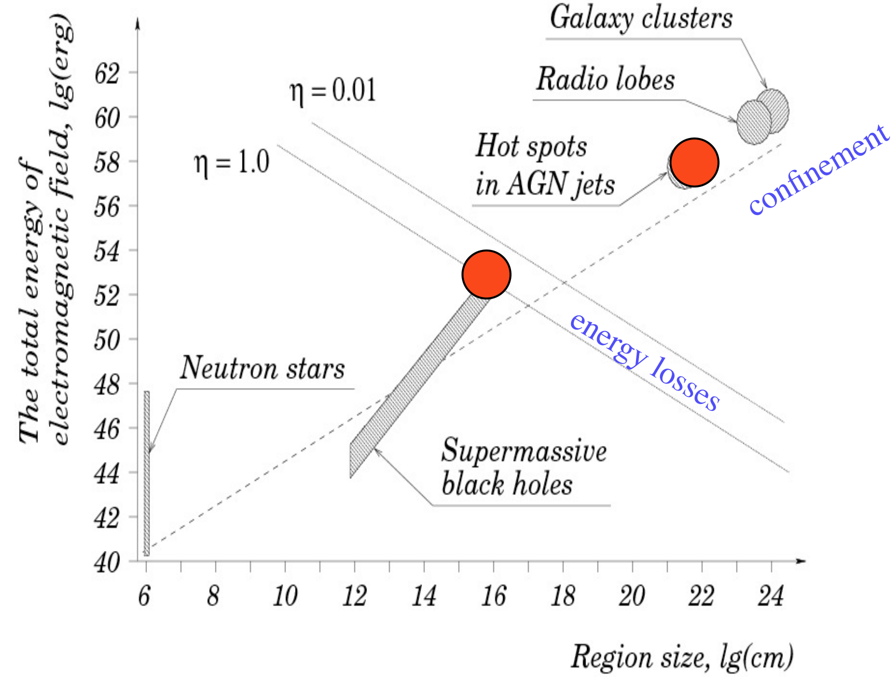
✓ synchrotron self-regulated cutoff:

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

$\simeq$ 300GeV proton synchrotron

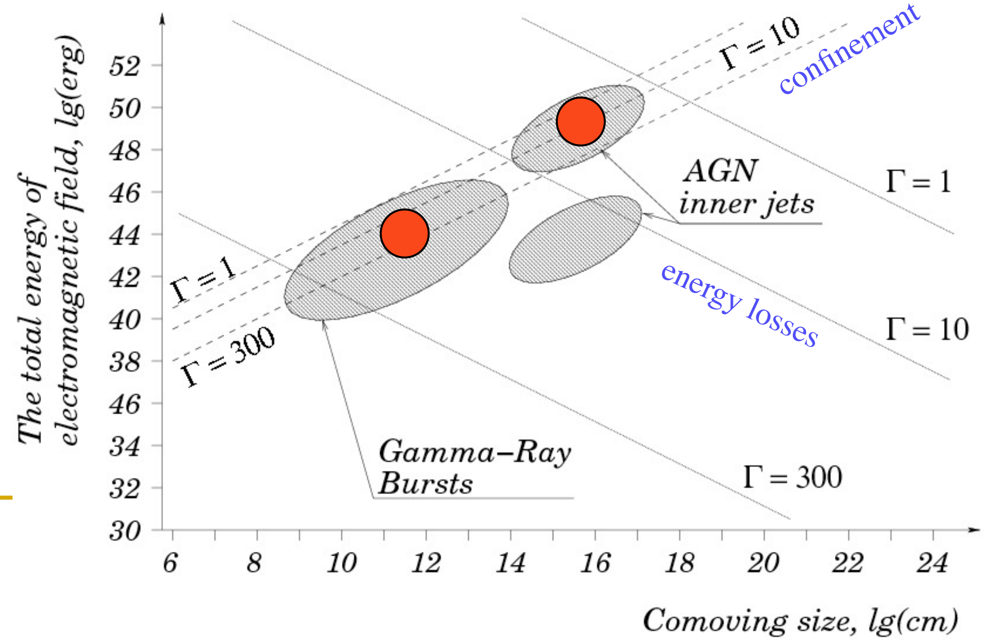
$\simeq$ 150MeV electron synchrotron

a viable "hadronic" model applicable for TeV γ-ray blazars if B ~ 100 G or so



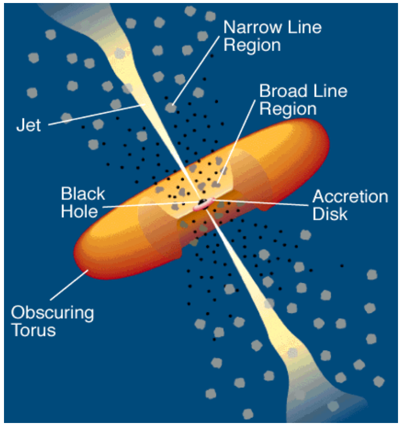

✓ neutrinos (through "converter" mechanism) production of neutrons (through pγ interactions) which travel without losses and at large distances convert again to protons => $\Gamma^2$ energy gain! (Deerishev et al. 2003)

✓ observable off-axis radiation
radiation pattern can be much broader than 1/Γ




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

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




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~1!

# "leptonic" versus "hadronic" models of TeV Blazars

**leptonic** (Inverse Compton) models: SSC or external IC

attractive: easy to accelerate electrons to TeV energies; easy to produce IC γ-rays

problems: B-field very small - 1-10 mG (in the inner parts of the jet): $W_e >> W_B$

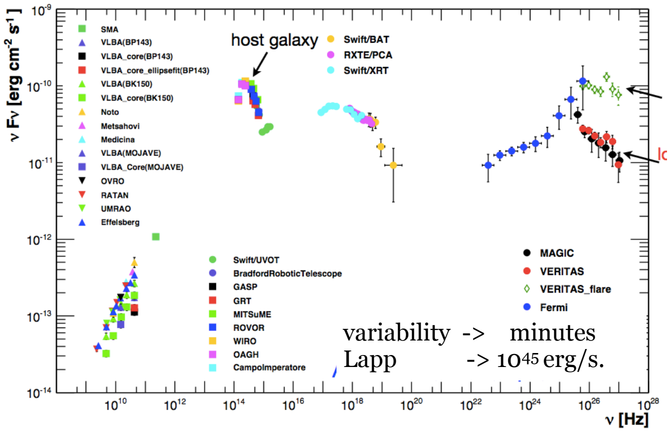
**hadronic** models

- interactions with matter ("pp") - *very slow process*
- interactions with photons ("pγ") - *low efficiency & severe γγ absorption*
- interactions with B-field (synchrotron) - (very?) large B-field, $W_B >> W_p$ & max. acceleration rate ~ $R_L/c$

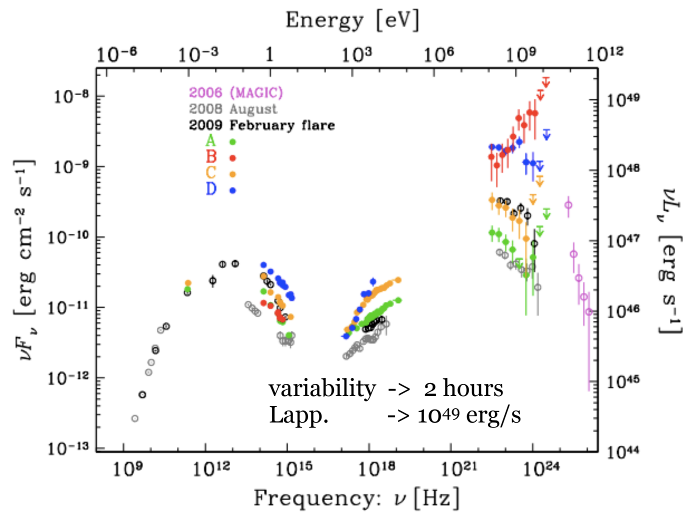
can be realized only in the extreme accelerators (sources of $10^{20}$eV CRs)

# EHE CRs and GeV/TeV gamma-ray emission of Blazars?

*a typical TeV blazar:* Mkn 501




*a typical GeB blazar: 3C 279*




"standard" SSC or IC model for gamma-rays

if this is the case - nothing to do with EHE CRs - too small B-field (B << 1 G)

synchrotron cutoff at IR (GeV blazars) and X-ray (TeV blazers) => $\eta \sim (h\nu/100\ \mathrm{MeV})^{-1}\ \Gamma^{-1}$ <<< 1

independent of the EHE CR related issue, B << 1 G and η << 1 is a big problem

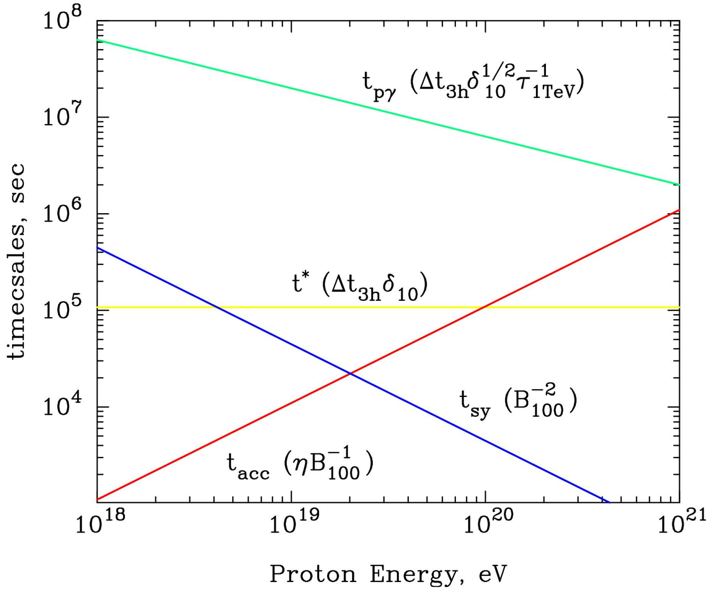
hadronic models in synchrotron-loss dominated regime

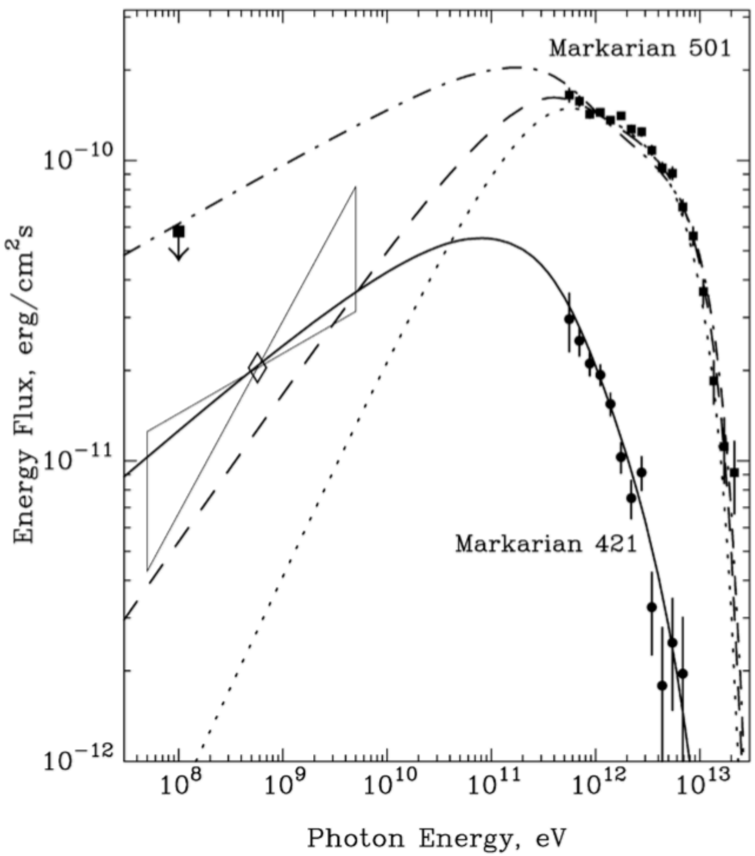
$$\mathrm{E_{p,max}} = 3/2(\mathrm{e^3 B}\eta)^{-1/2}\mathrm{m_p^2 c^4} \approx 1.8\times 10^{19}\mathrm{B_{100}^{-1/2}}\eta^{-1/2}\mathrm{eV}$$

for $\mathrm{L} \leq 10^{-3}$pc B should be as large as 300G => $\mathrm{E_{p,max}} \approx 10^{19}$ eV

bulk motion Lorentz factor exceeding Γ=10 is needed !

# Synchrotron radiation of an extreme proton accelerator




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

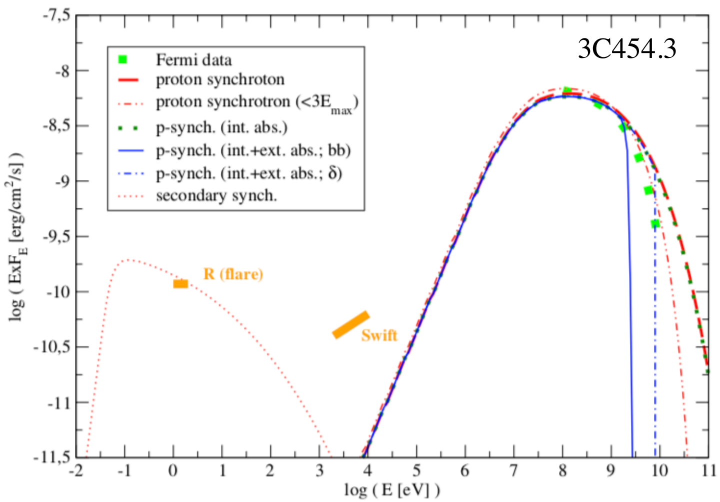
$t_{synch}$=4.5x$10^4$(B/100G)$^{-2}$ (E/$10^{19}$ eV)$^{-1}$ s

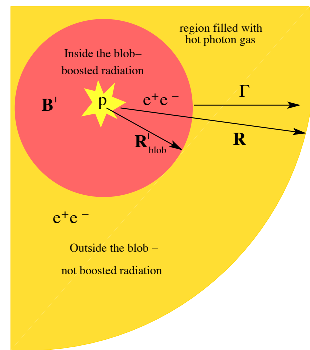
$t_{acc}$=1.1x$10^4$ (E/$10^{19}$) (B/100G)$^{-1}$ s

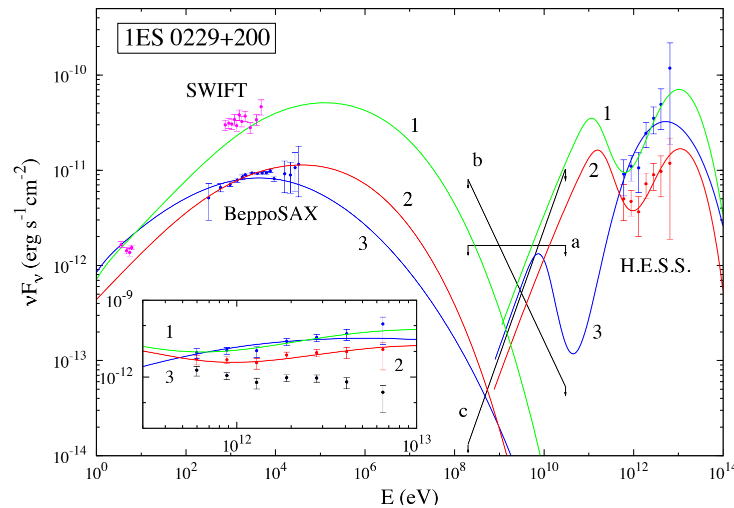
cooling time of p$\gamma$ interactions >> synchrotron cooling time => negligible neutrons flux

FA 2000

low-frequency synchrotron peak produced by secondary electrons



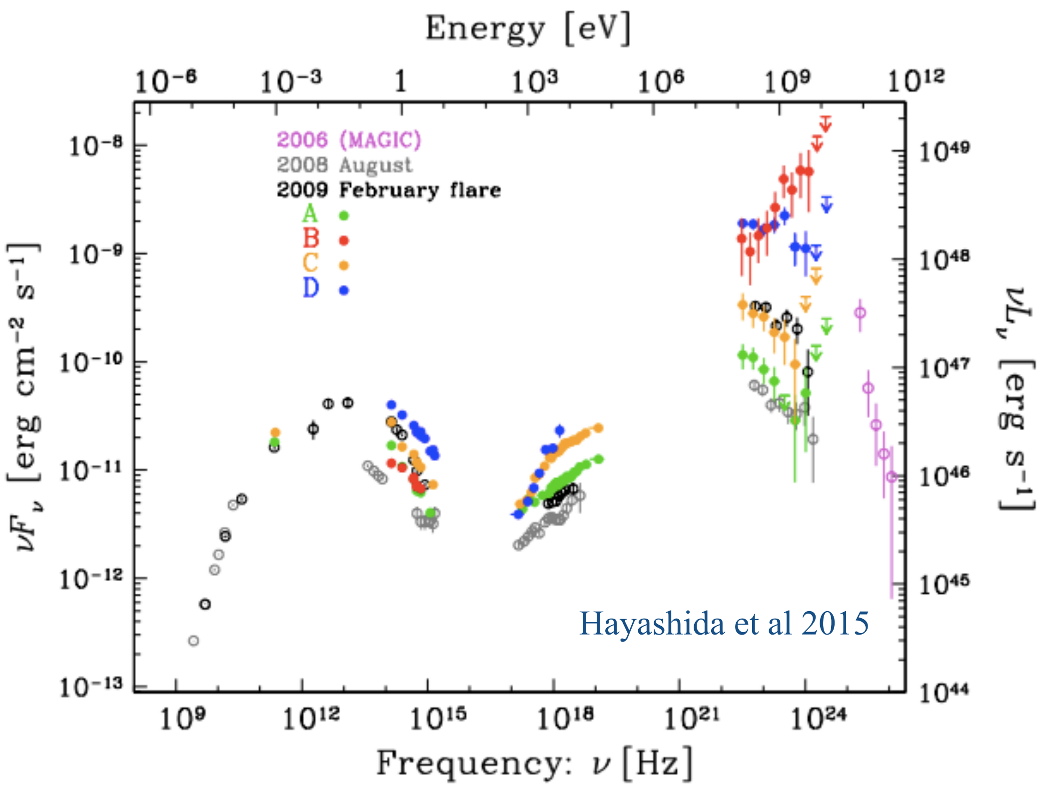




$$\text{in TeV blazers } \eta \sim 1 \text{ while in GeV blazers } \eta \sim 10^{-3}$$

explains the puzzle of location of the “second” (synchrotron) peaks at X-ray and IR bands

TeV blazers as extreme accelerators and sources of $10^{20}$ protons ?




2013-14 flares of 3C 273:

Δt ~ 2 hours
Lapp ~ $10^{49}$ erg/s
unusually hard spectra

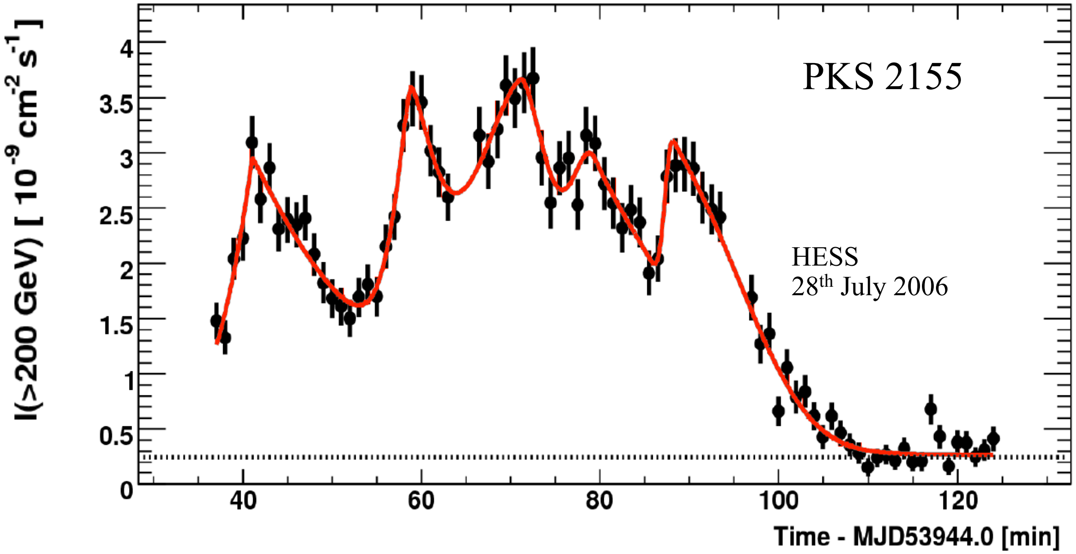
"leptonic versus hadronic" - of course it's important to clarify

but now we face more serious challenges (for all models):

1. ultrafast variability ~ Rg/c
2. jet power > Eddington luminosity

Light curve of PKS 2155-304 during 2006 July flare

variability timescale $\Delta t \sim 3$ min: $L < c\Delta t \sim 6\ 10^{12}$ cm!




it is convenient to express the variability through

$$\Delta t = R_g/c \sim 10\ (M/10^8 M_o)\ \text{min}$$

$R_g = GM_{BH}/c2 = 1.5\ 10^{13} M_8$ cm is gravitation radius of Kerr BH

# how the ultrafast ("sub-horizon") flares can be explained?

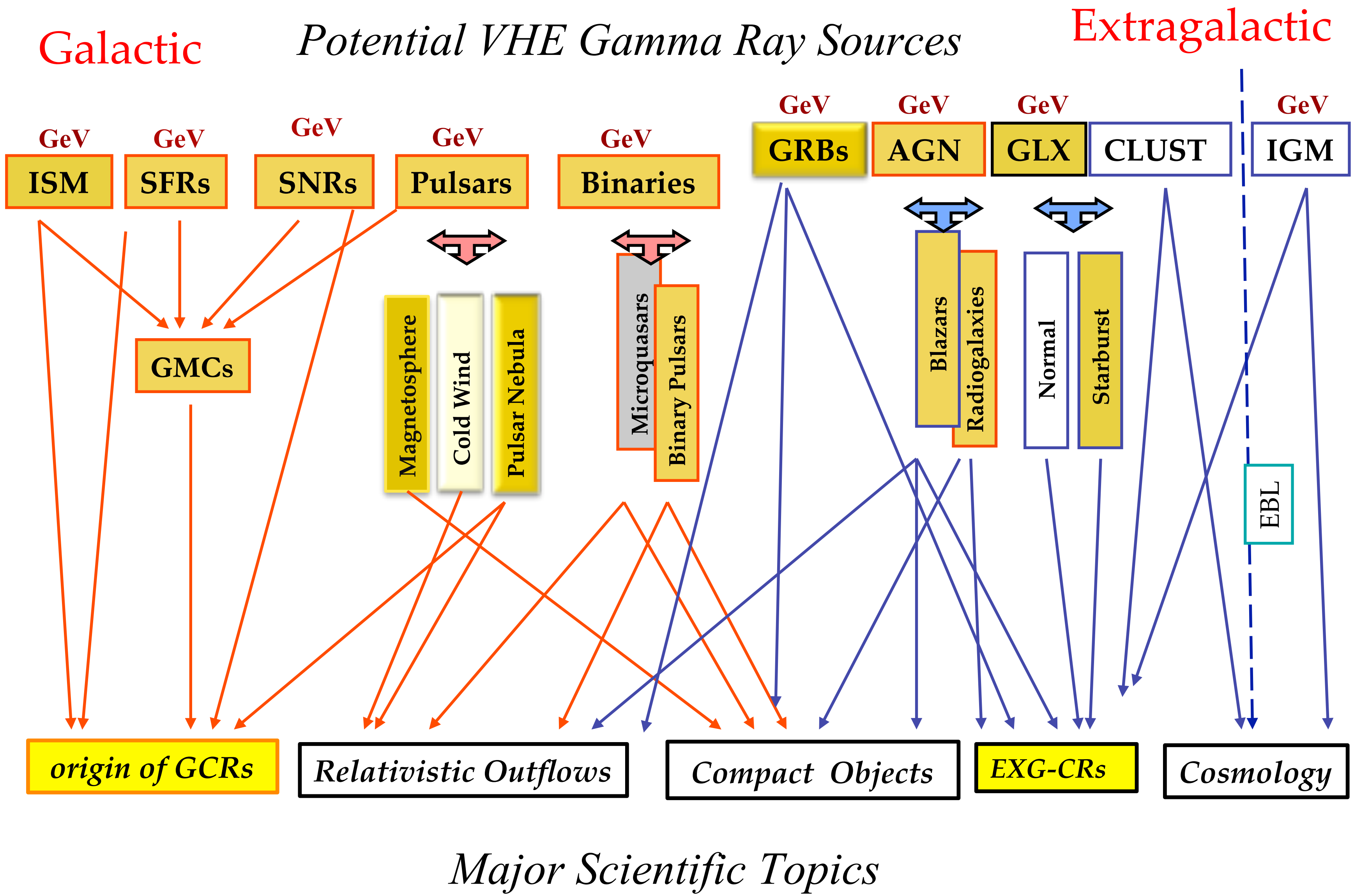
1. γ-rays are produced in (parts of) BH magnetospheres?

   perhaps in M87, but certainly not for distant blazers

2. obviously one needs yo invoke relativistic effects, and the perturbations in the jets responsible for flares should have external origin (not directly linked to central black hole)

   two possibilities are under discussion:

   - "jet in jet"
   - "star - jet interactions"



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

# Summary:

future of high energy astrophysics? bright !

- solid predictions (based on the current data and theory)
- exciting expectations which can dramatically change our present understanding of the nonthermal Universe