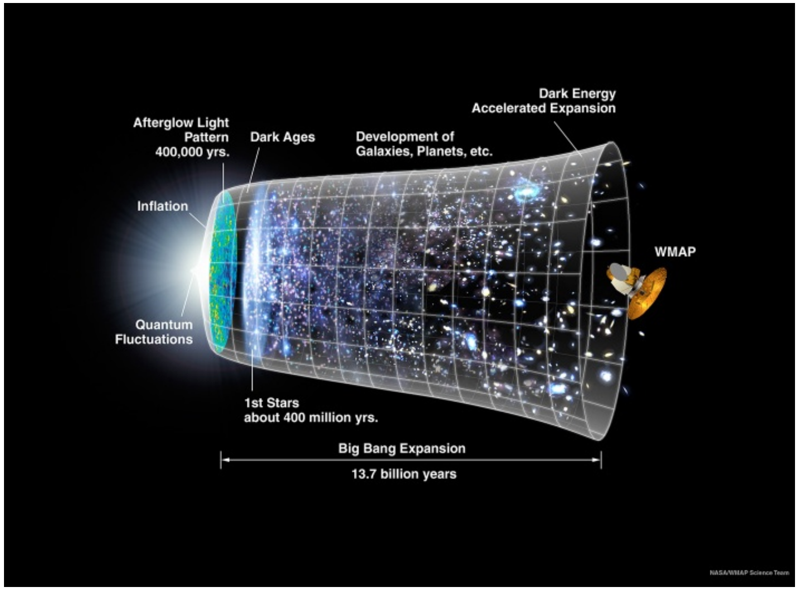
Gordon Godfrey Workshop on Astroparticle Physics

Extreme Particle Accelerators

Felix Aharonian
DIAS/Dublin and MPIK/Heidelberg

Dec 1, 2020 (9am, "Sydney")

Universe as high energy phenomenon



in the framework of "Big Bang Theory"

- the "Universe" is a high energy phenomenon
- its birth was the result of an incredibly energetic event
- quite a long time it was a "hot soup" consisting of relativistic particles and radiation

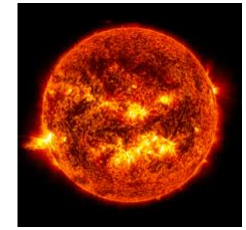
2.7 K MBR (~10^{-3} eV) is the remnant of that "soup"

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

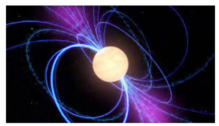
Relativistic Nonthermal Plasma or "Cosmic Rays"

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

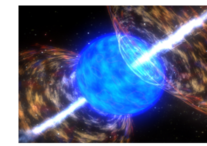
Relativistic Matter Factories

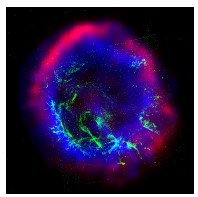


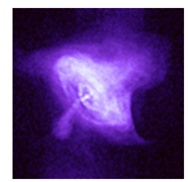
nonthermal processes in Universe proceed everywhere and on all astronomical scales:

Neutron Stars/Pulsars 

Black Holes 

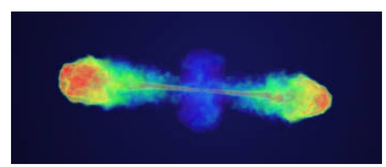
γ-ray Bursts 

Supernova Remnants 

Pulsar Wind Nebulae 

Massive Stars 

Galaxies
Starburst Galaxies 

AGN Jets 

GalaxyClusters 

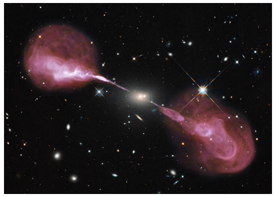
messengers of Nonthermal Universe

- ✓ 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

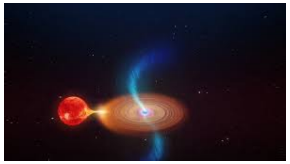
high energy phenomena - *not necessarily high energy (γ) radiation*

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



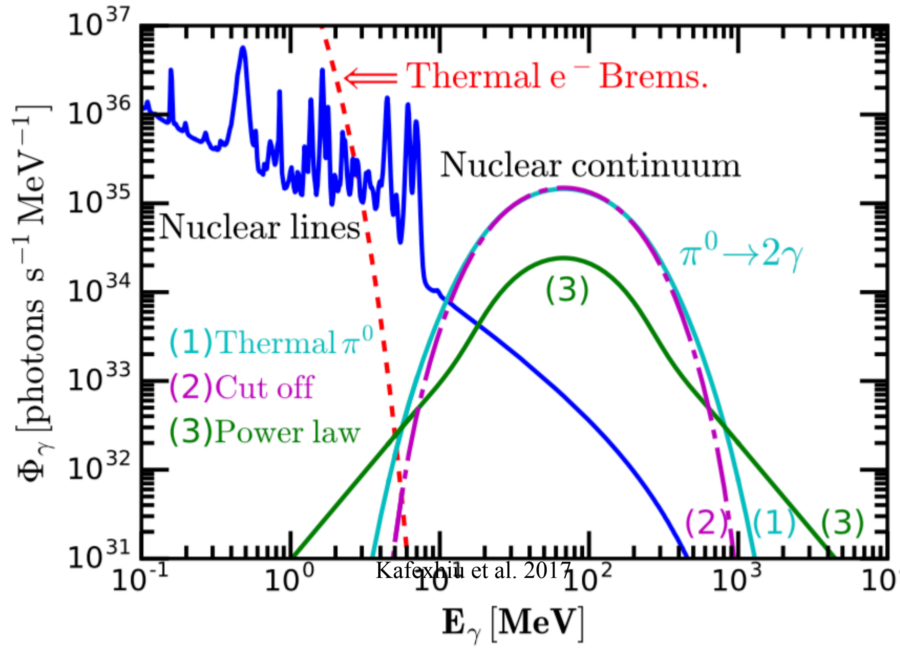
high energy γ-rays - *not necessarily imply non-thermal origin*

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



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

accreting Black Hole



measure of ion temperature in accretion flow close to the gravitational radius
radiation efficiency - less than 10^{-4} (fraction of the Eddington luminosity)

In AGN powered by SMBHs the power of the jet can exceed the Eddington luminosity
In AGN jets, nonthermal processes not only dominate but can be extremely effective

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

more general: narrow-distribution $E^{-\Gamma}\exp[-(E/E_0); \Gamma < 2$: all energy is concentrated around E_0 ;
In fact, a nominal power-law distribution which can be realised at shock acceleration in colliding winds

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

High Energy Astrophysics

a (the) 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

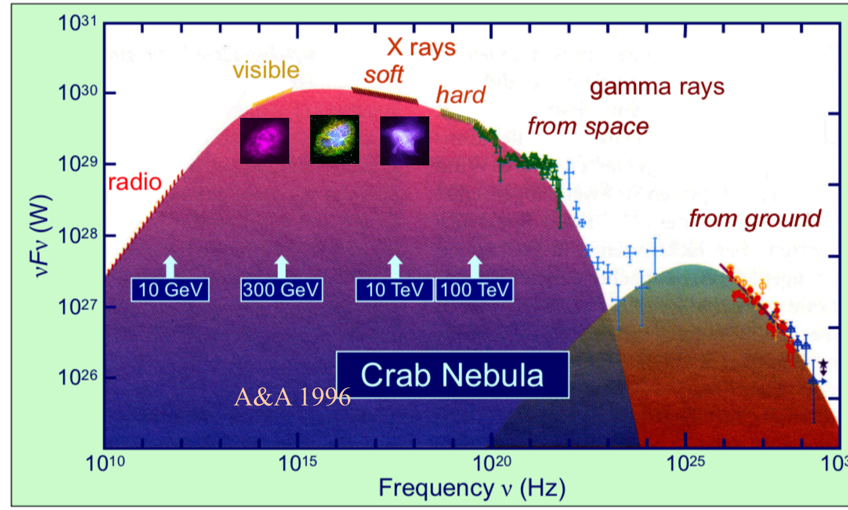
a non-thermal astrophysical object seen over 20 energy decades

Crab pulsar/wind/nebula:

absolute extreme accelerator !

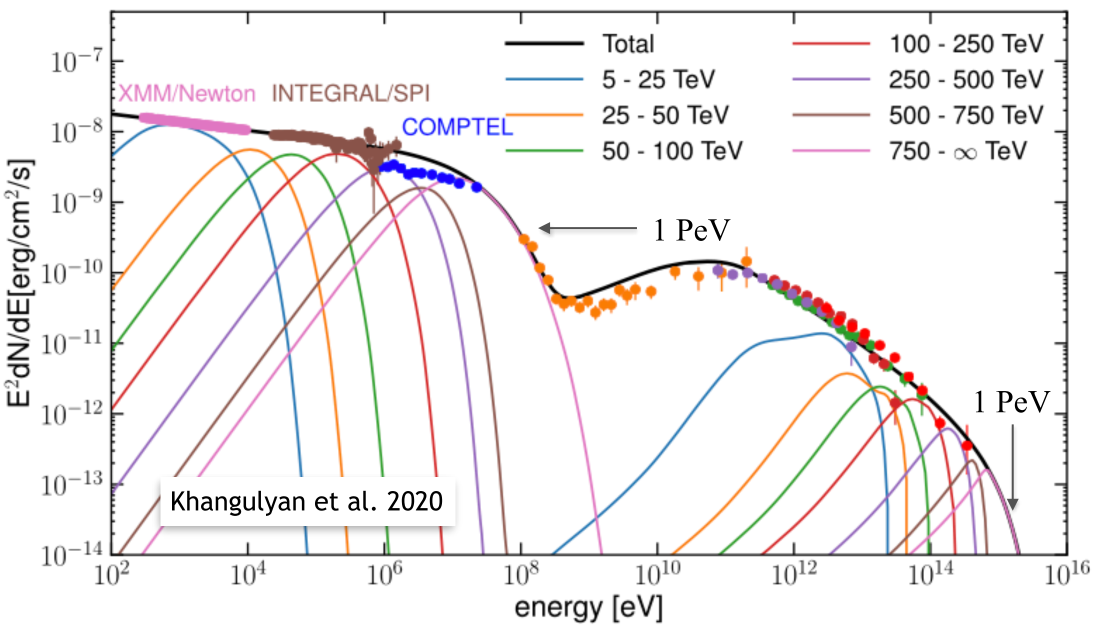
conversion of the rotational energy of pulsar to non-thermal energy with efficiency ~50 %

electron acceleration with 100 % efficiency



R, mm, IR, O, UV,X

gamma-rays



~ half of rotational energy of pulsar is released in form of accelerated e^+e^- radiated away via synchrotron and IC channels of radiation over 20 decades !

e^+e^- are accelerated to >1 PeV (!) acceleration rate be at the margin allowed by theory ("ideal MHD")

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 can be as large as 50 %

(ii) maximum possible energy achieved by individual particles

acceleration rate close to the maximum (theoretically) possible rate

sometimes efficiency can even "exceed" 100% ?

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

Extreme Accelerators and Absolute Extreme Accelerators

"Extreme Accelerator": maximum possible acceleration rate achieved for given parameters is achieved under extreme conditions

for example, within the Diffusive Shock Acceleration Theory (DSA), the acceleration of protons in a SNR to 1 PeV is possible if diffusion proceeds in the Bohm limit and magnetic field is amplified by order of magnitude

young, less than 1000 yr old SNRs operate as (almost) extreme accelerators

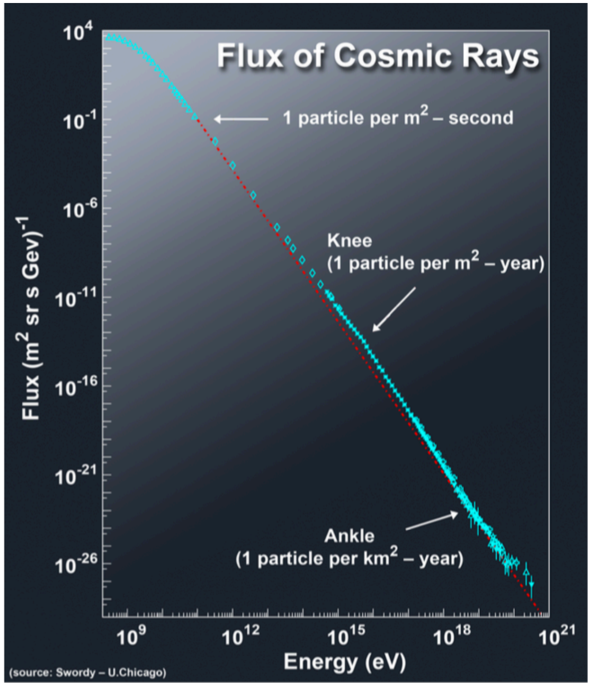
"Absolute Extreme Accelerator": maximum possible acceleration rate allowed by classical electrodynamics and ideal MHD

Pulsar Wind Nebulae operate as Absolute Extreme Accelerators of electrons

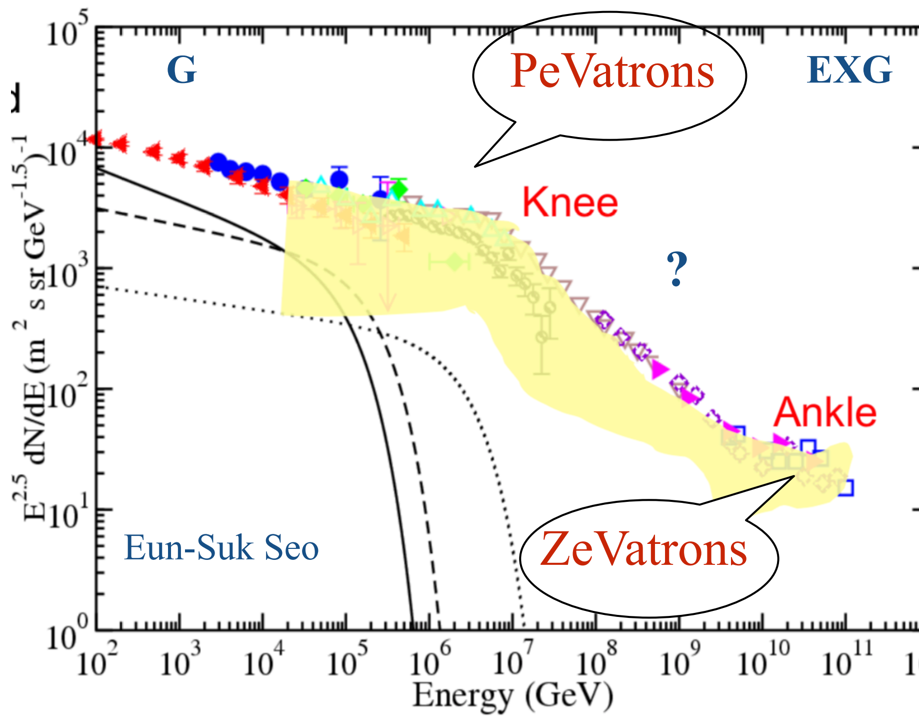
Sources of 10^{20} eV protons (of unknown origin) are, most likely, Absolute Extreme Accelerators of protons

“Origin of cosmic rays remains a mystery…”

a standard statement used in reviews/textbooks over many decades



1PeV = 10^{15}eV 1EeV = 10^{18}eV 1ZeV = 10^{21}eV



below	10^{15} eV	G	
beyond	10^{18} eV	EXG	
between	10^{15}-10^{18} eV	?	most problematic parts of the spectrum 10^{15} eV and 10^{19} eV

PeVatrons and ZeVatrons are Extreme Accelerators!

what does mean "Origin of Cosmic Rays" ?

term "Cosmic Rays" 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
neutrons with $E>10^{17}$(d/1kpc) eV

Presently: MeV-GeV-TeV gamma-rays exciting results from 10+ source populations
TeV - PeV neutrinos first detections; no identifications of sources

ground based gamma-ray observations

provide the VHE window in the spectrum of cosmic E-M radiation

0.1 TeV and 100 TeV => TeV (VHE) γ-ray Astronomy

with a great potential for extension of the energy domain

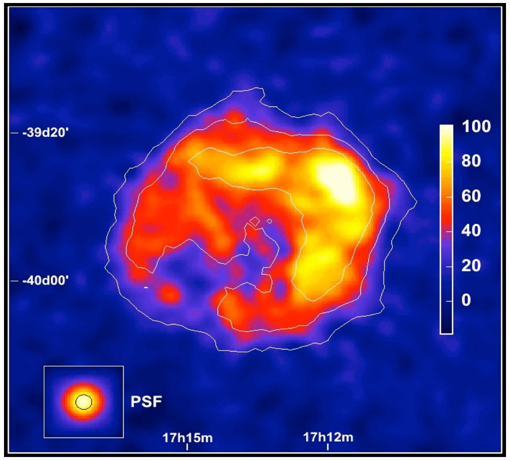
below 100 GeV down to 10 (1) GeV: multi-GeV (HE) Astronomy

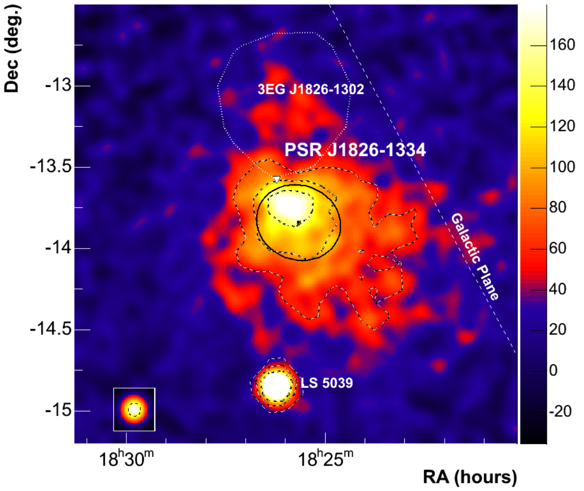
above 0.1 PeV (1 PeV): PeV (UHE) Astronomy

=> GeV-TeV-PeV astronomy

morphology, spectrometry, timing - all are needed for the search of extreme accelerator morphology

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

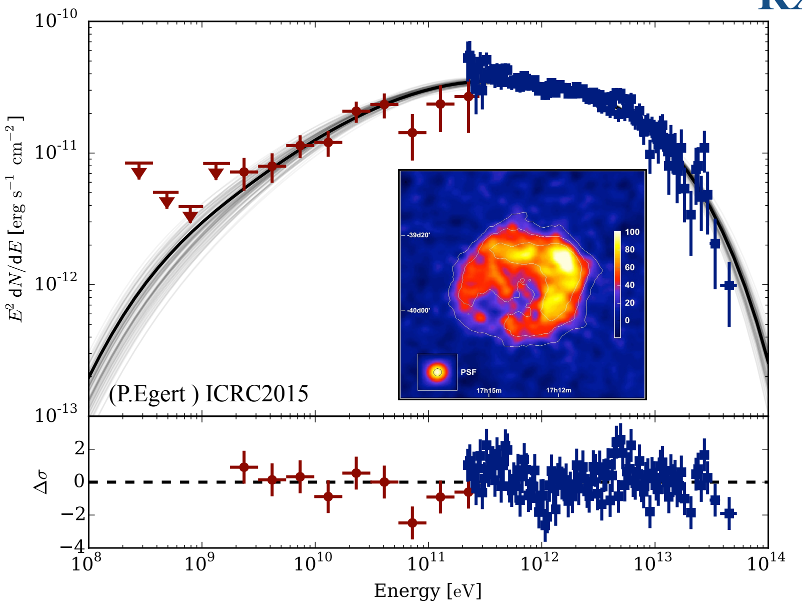
spectrometry

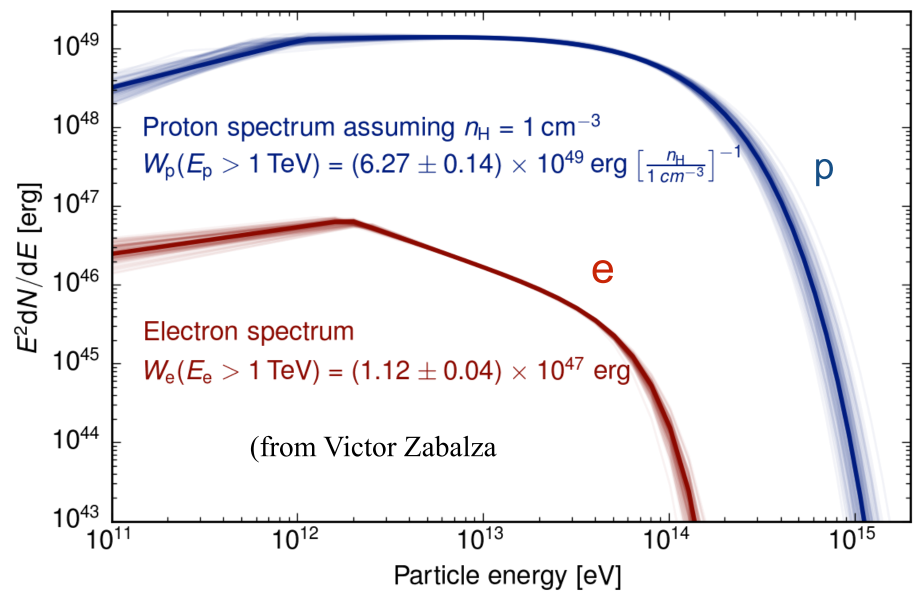
Probing the distributions of accelerated particles in SNRs

HESS measurements

RXJ 1713

derived spectra of e and p





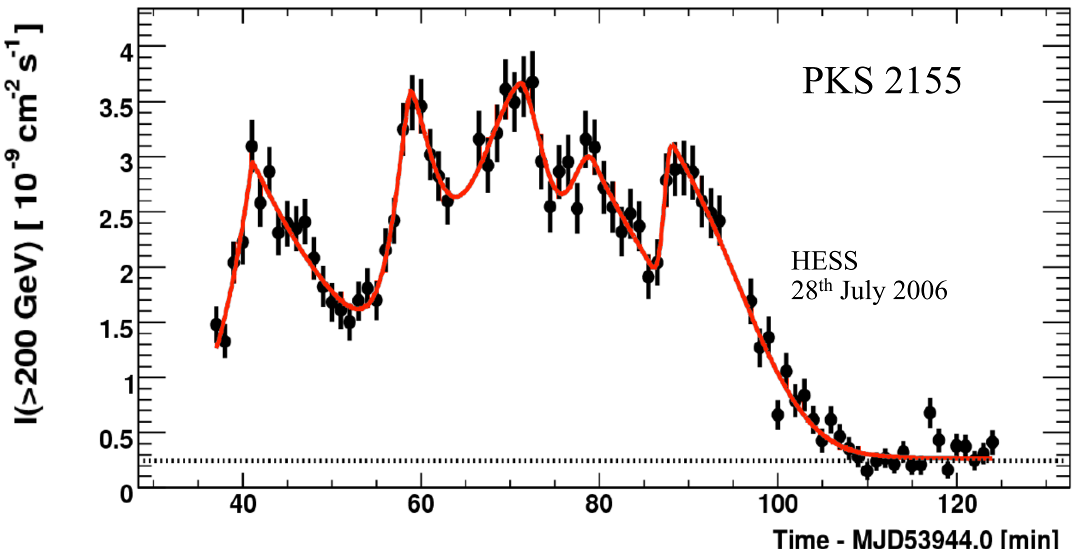
CTA can do much better; extension of measurements to >100 TeV

a few arcimin (sub-pc) structures

particles beyond the shell

Timing

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

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

$R_g = GM_{BH}/c^2 = 1.5\ 10^{13}\ M_8$ cm is gravitation radius of Kerr BH 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:

—————— G ——————

- SNRs, Stellar Clusters, GMCs
- Pulsars, PWNe, Pulsar Halos
- Binaries (Binary Pulsars, Microquasars)

—————— EXG ——————

- 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
some of them are Extreme Accelerators

neutrinos

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

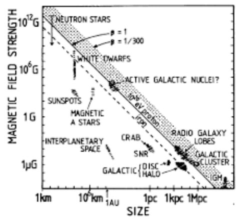
or it is superposition of individual sources ?

Starburst galaxies? Active Galactic Nuclei?

many questions - no definite answers

but no doubt that neutrinos are unique messengers from galactic and extragalactic Cosmic PeVatrons, EeVatrons, ZeVatrons

1984



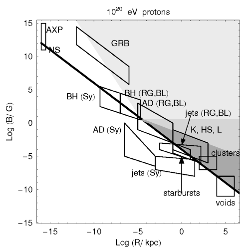
Hillas Plot:
trivial and non-trivial implications

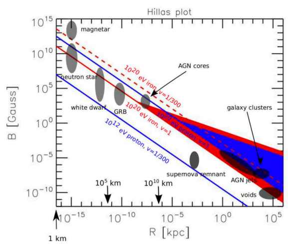
Ann. Rev. Astron. Astrophys. 1984, 22:425-444

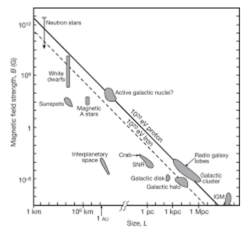
Hillas Plot : B – L relation based on the condition $L > r_L$

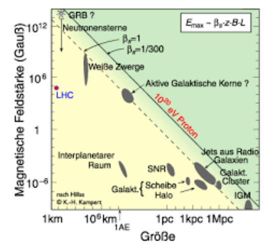
$$B_{\mu G} L_{\rm Mpc} > 2E_{21}/Z(v/c)$$

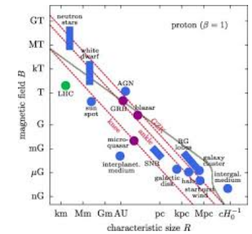
tens of “Hillas Plots” have been produced since 1984 ...

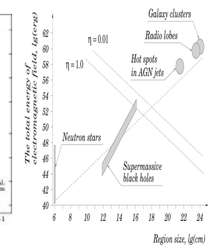












works both for “gradual modes of acceleration” and for “one shot acceleration”

“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) !

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

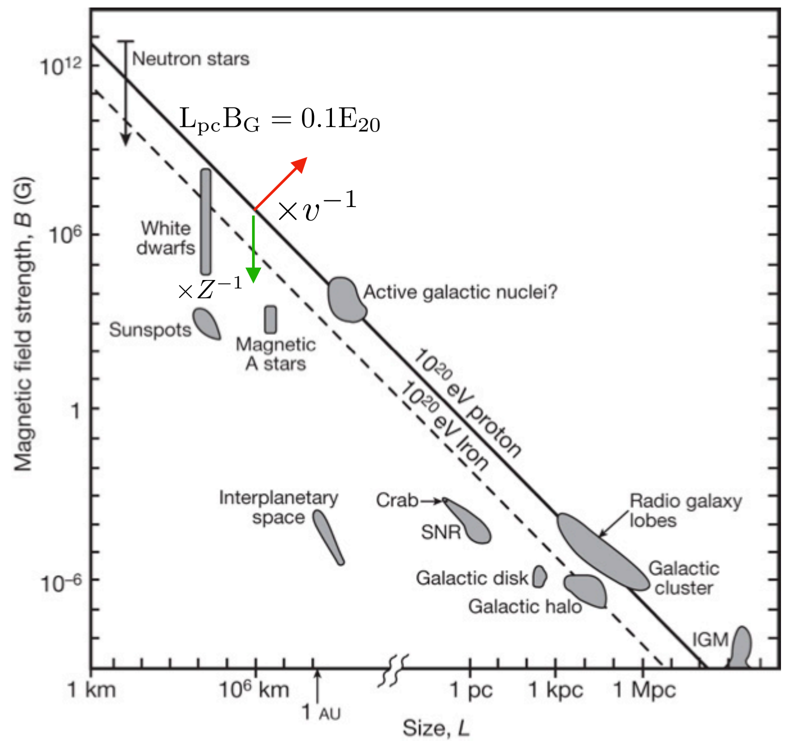
$\eta \geq 1$ $\qquad$ $\eta \approx 1 \rightarrow$ extreme accelerator

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

absolute minimum set by classical ED:

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

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



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

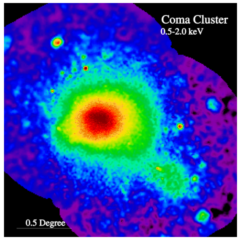
best confinement – in Bohm Diffusion regime with $D = \frac{r_L c}{3}$

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

$L=r_L$ 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



Clusters of Galaxies - sources of 10^{20} eV protons?

so far no firm gamma-ray detections but there are reasons to believe that gamma-rays will appear at some level because of pp, IC and "p -2.7K" 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, …

detailed studies - protons cannot be effectively accelerated beyond 10^{19} eV

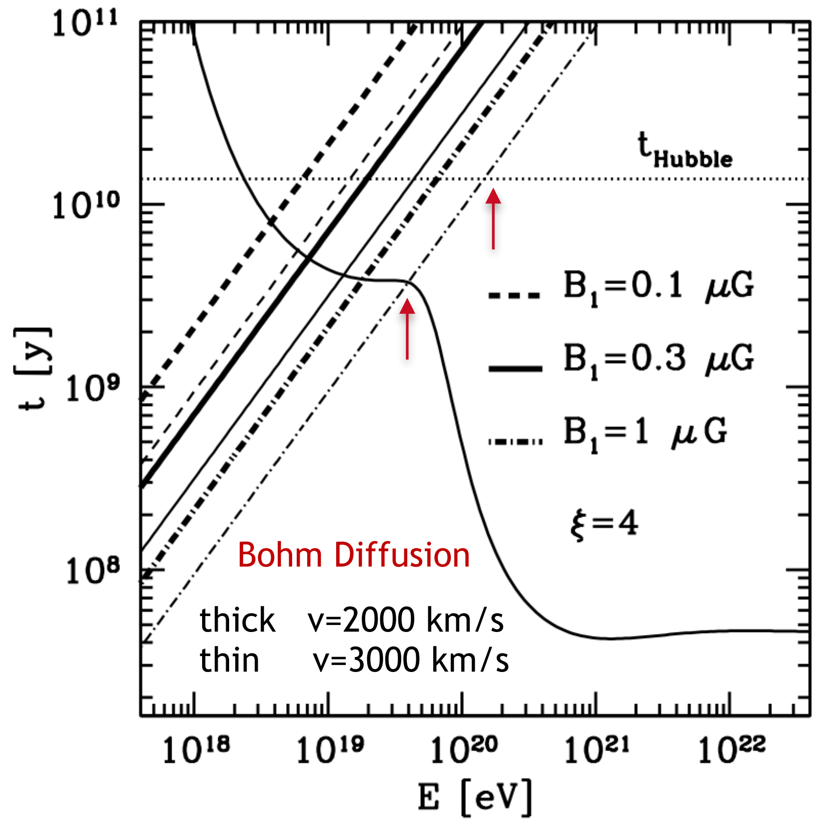
Shock acceleration of particle in Galaxy Clusters

several ingredients for effective acceleration to highest energies

- ✓ formation of strong accretion shocks
- ✓ magnetic field of order 0.1-1 μG
- ✓ shock velocity - few x1000 km/s
- ✓ acceleration time ~ Hubble time

but protons cannot be accelerated beyond 10^{19} eV (Kang et al., Vannoni et al 2011) because of (Bethe-Heitler) pair production

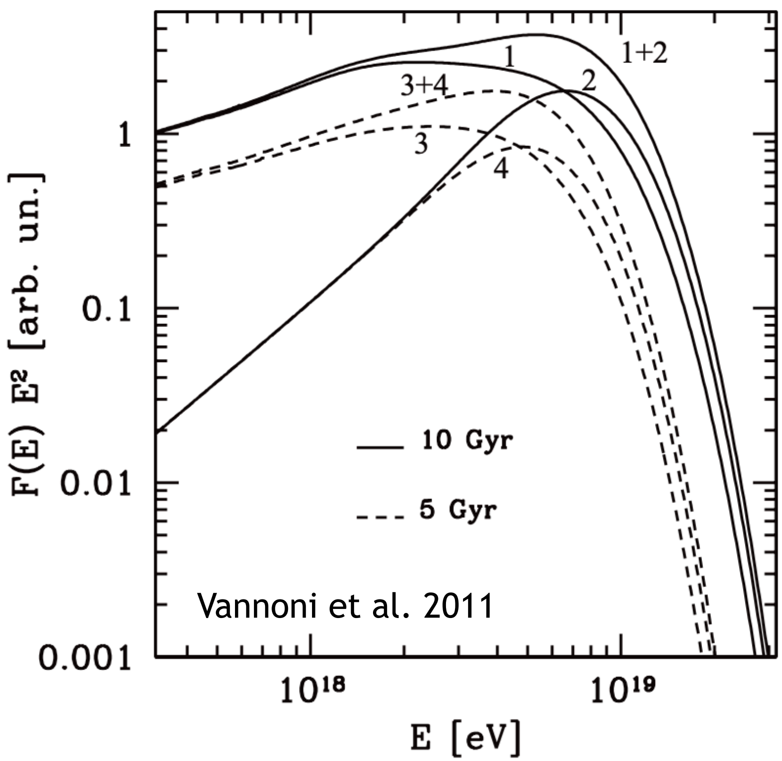
DSA in the Coma cluster



Vannoni et al. 2011

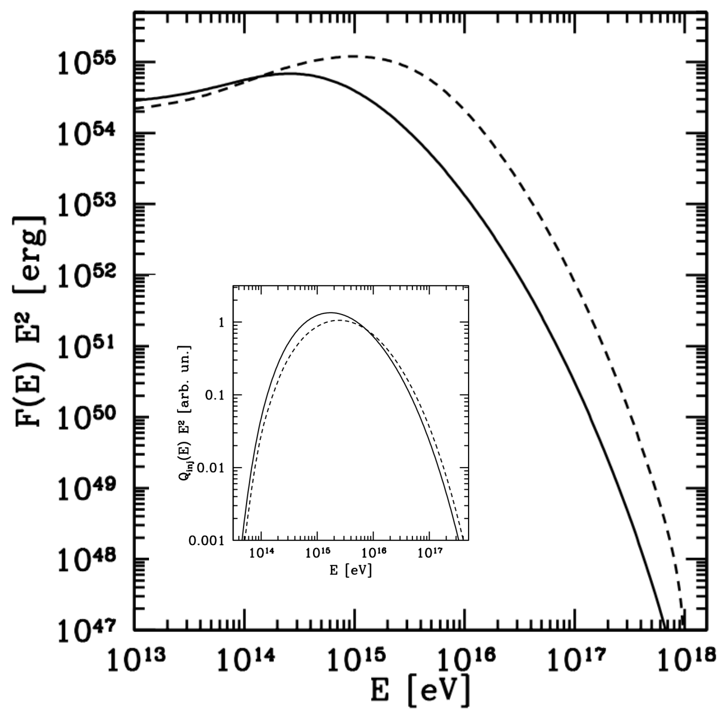
Coma

protons

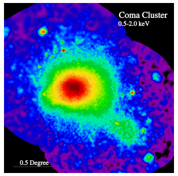


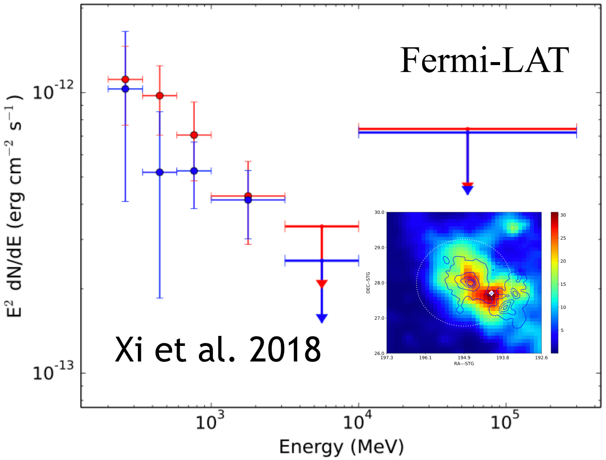
spectra of accelerated protons

Bethe-Heitler electrons

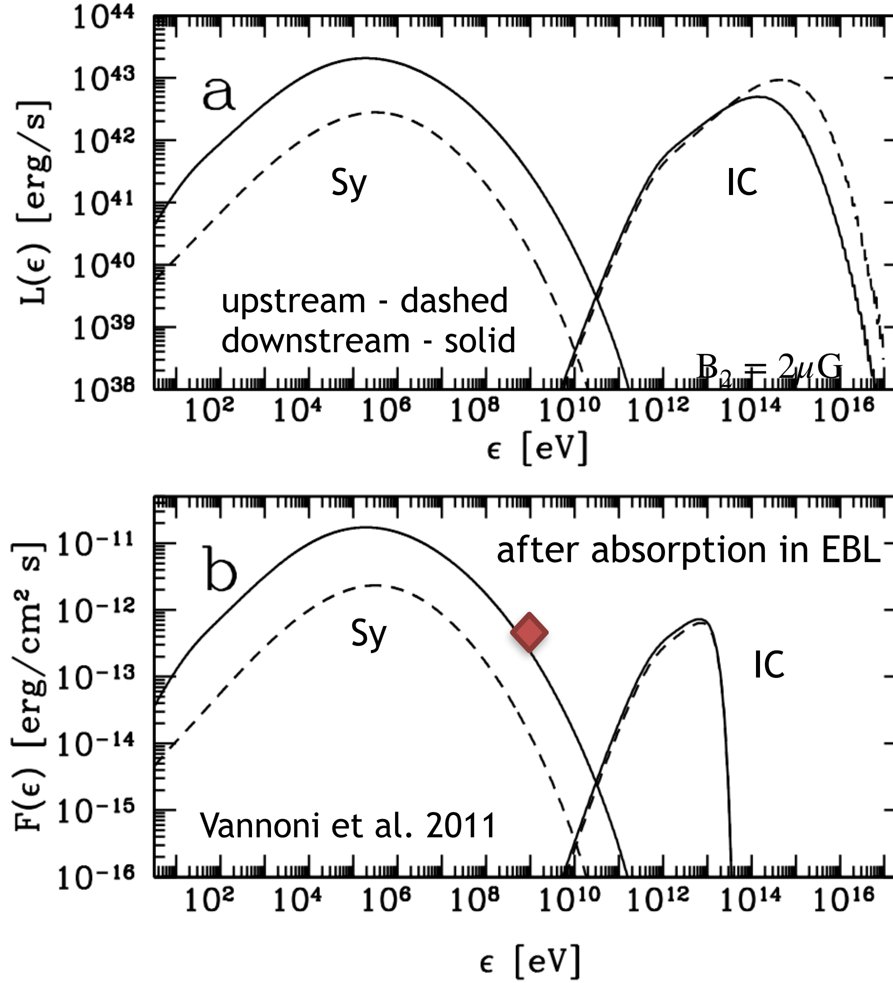


production and cooled spectra
of Bethe-Heitler electrons





depending on the choice of templates
5-7sigma detection of extended source:
energy flux 2×10^{-12} erg/cm^{2}s with
steep power-law spectrum between
0.2-300 GeV; $\Gamma \approx 2.7$



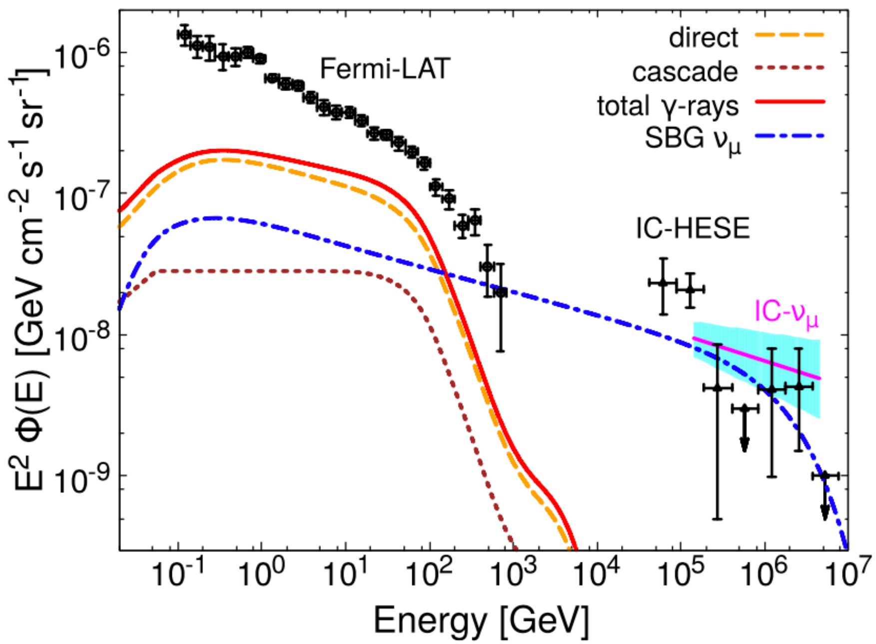
3 channels of gamma-radiation:
- IC of primary accelerated electrons - break in the electron spectrum < 100 GeV - modest acceleration
- pp interactions - break in the spectrum of accelerated protons < 10 GeV - very modest acceleration
- Synchrotron emission of secondary Bethe-Heitler electrons - extreme acceleration

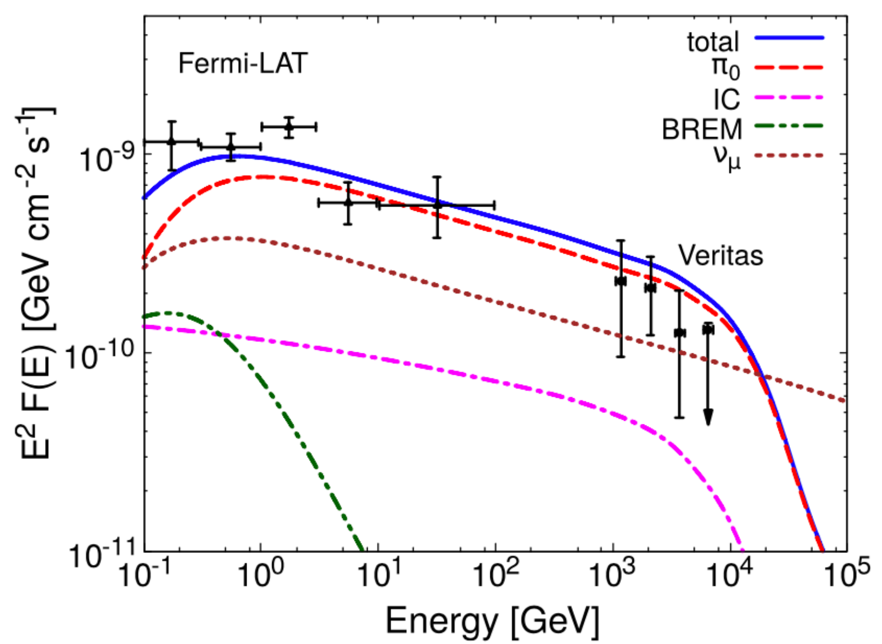
Star Burst Galaxies - sources of >10 PeV CRs ?

extraterrestrial PeV neutrinos - SBG as potential sites of production ?
If so, the energy spectrum of protons should continue up to 100 PeV

Accelerators? SNR in SBG have some advantage compared to SNRs in Milky Way
larger turbulence and B-field in the ISM => Emax~100 PeV - very difficult but not unrealistic

Key observations?   PeV neutrinos from individual SBGs





acceleration sites of 10^{20} eV CRs ?

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

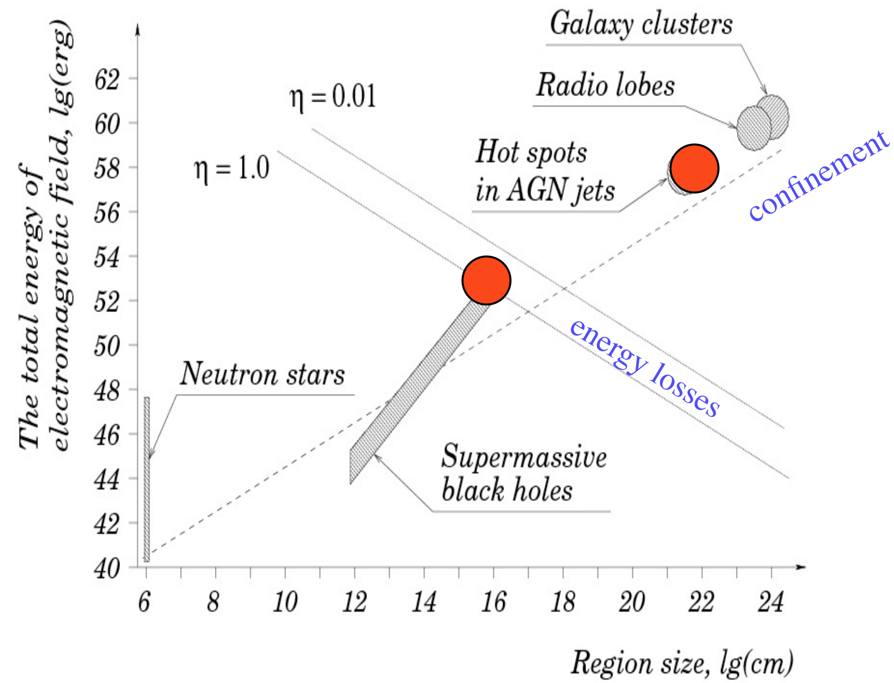
signatures of extreme accelerators?

✓ synchrotron self-regulated cutoff:

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

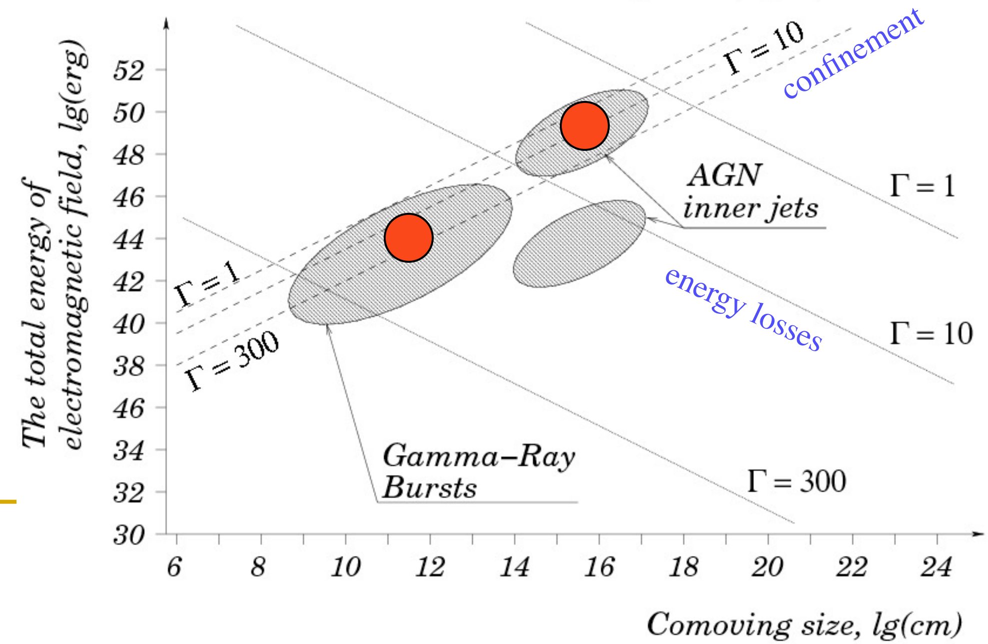
$\simeq$ 300GeV proton synchrotron
$\simeq$ 150MeV electron synchrotron

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



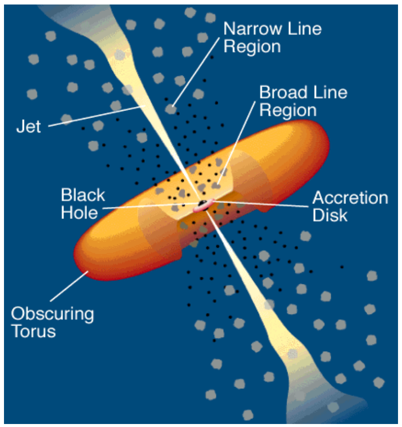
✓ neutrinos (through "converter" mechanism) production of neutrons (through pγ interactions) which travel without losses and at large distances convert again to protons => Γ^2 energy gain! (Derishev et al. 2003)

✓ 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

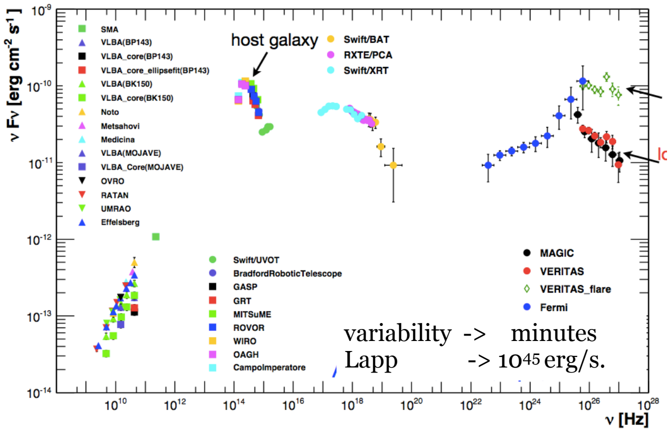
- Blazar physics and astrophysics
- Diffuse Extragalactic Background (EBL)
  Intergalactic Magnetic fields (IGMF)

most exciting results of recent years

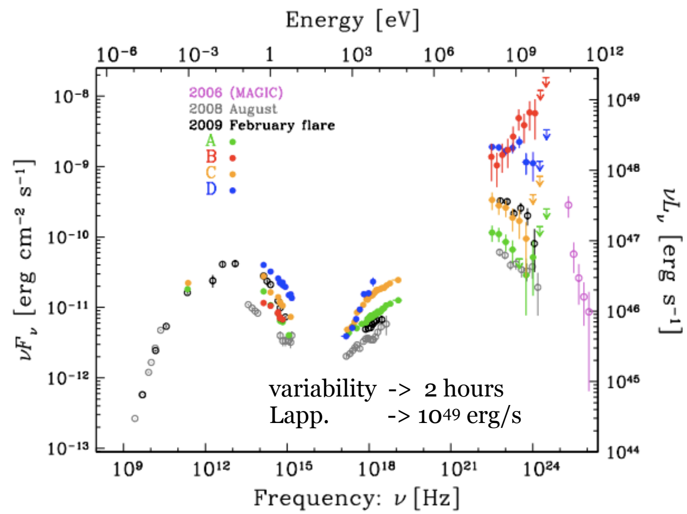
- ultra short time variability (on min scales)
- Jet power exceeds Eddington luminosity
- extremely hard (harder than E-1.5) energy spectra
- VHE blazars up to z~1!

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) => $\eta \sim (h\nu/100\ \mathrm{MeV})^{-1}\ \Gamma^{-1} \lll 1$

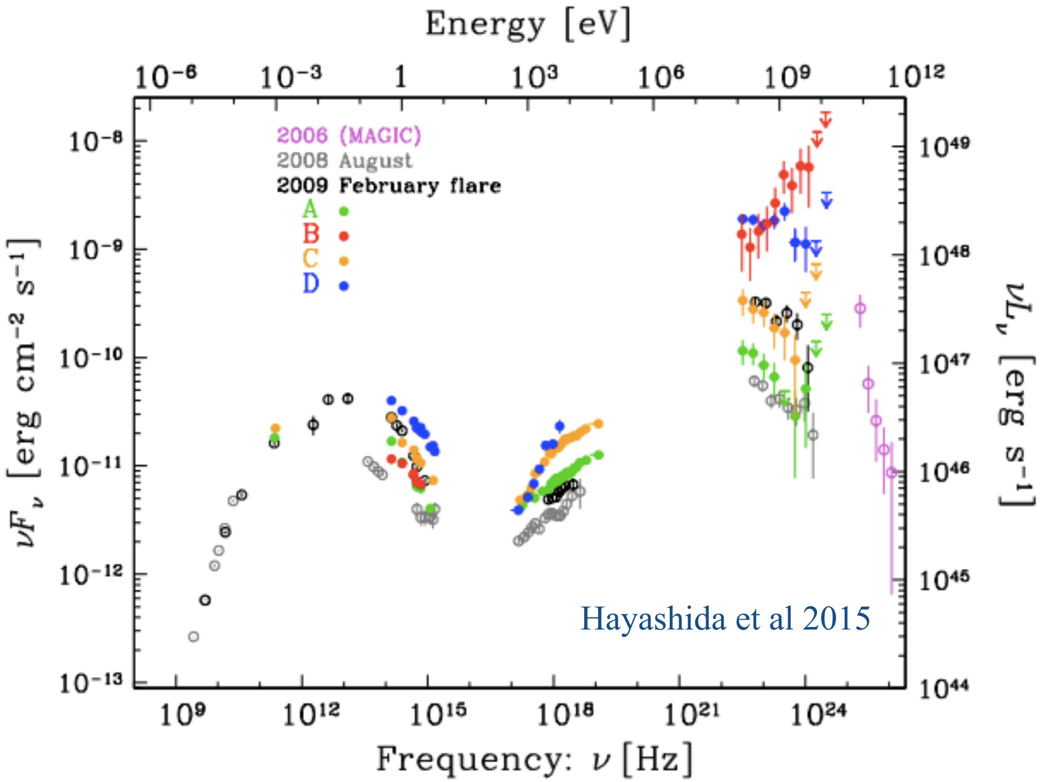
independent of the EHE CR related issue, B << 1 G and η << 1 is a big problem

hadronic models in synchrotron-loss dominated regime

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

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

bulk motion Lorentz factor exceeding Γ=10 is needed !



2013-14 flares of 3C 273:

$\Delta t \sim 2$ hours
Lapp ~ 10^{49} erg/s
unusually hard spectra

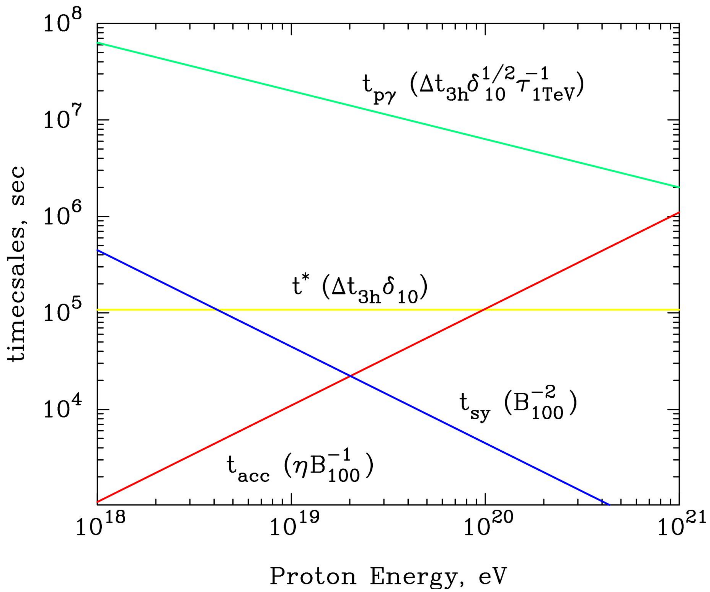
"leptonic versus hadronic" - of course it's important to clarify

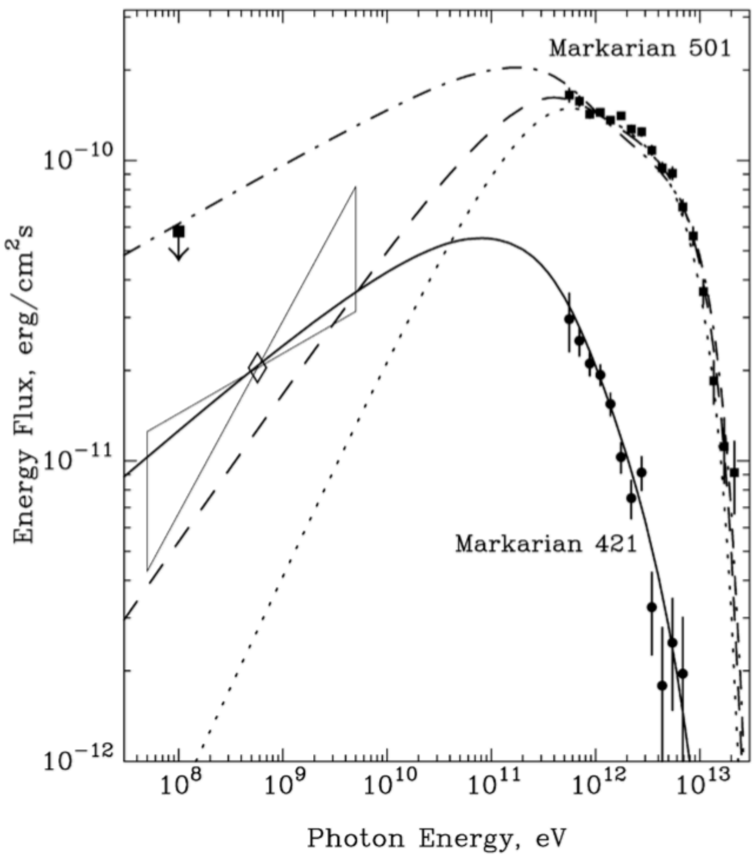
but now we face more serious challenges (for all models):

1. ultrafast variability ~ Rg/c

2. jet power > Eddington luminosity

Synchrotron radiation of an extreme proton accelerator





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

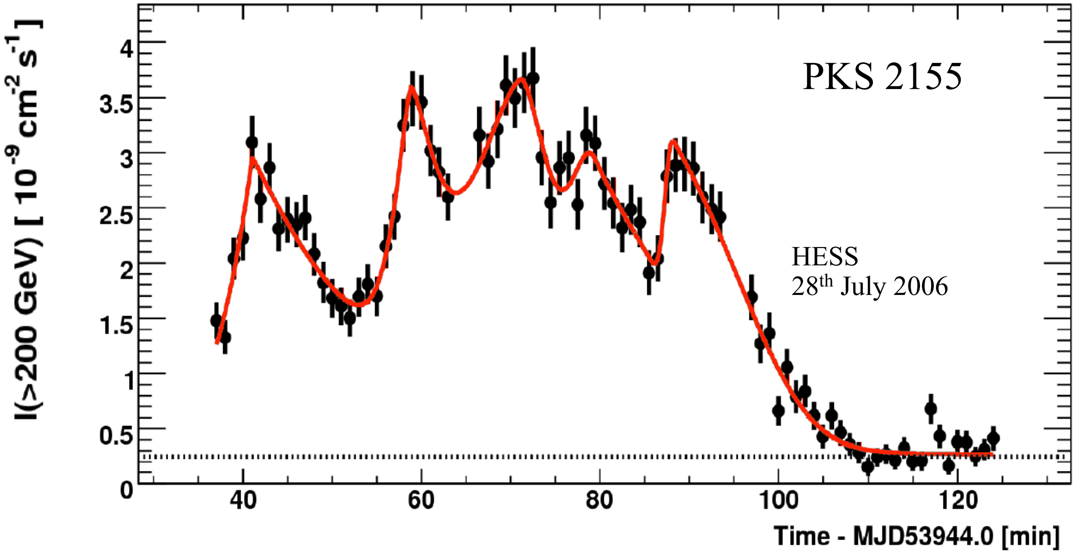
t_{synch}=4.5x10^4(B/100G)$^{-2}$ (E/10^{19} eV)$^{-1}$ s

t_{acc}=1.1x10^4 (E/10^{19}) (B/100G)$^{-1}$ s

cooling time of pγ interactions >> synchrotron cooling time => negligible neutrons flux

FA 2000

Light curve of PKS 2155-304 during 2006 July flare
variability timescale Δt~ 3 min: L< cΔt~6 10^{12}cm!



it is convenient to express the variability through

$$\Delta t = R_g/c \sim 10\ (M/10^8 M_\odot)\ \mathrm{min}$$

$R_g = GM_{BH}/c2 = 1.5\ 10^{13} M_8$ 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 Cosmic Rays

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

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

=> *age:* To ~ 10^7 yrs

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

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

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

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

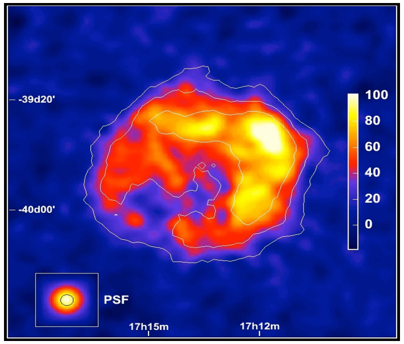
of galactic cosmic rays up to 1 PeV?

main hope is related to gamma-ray observations:

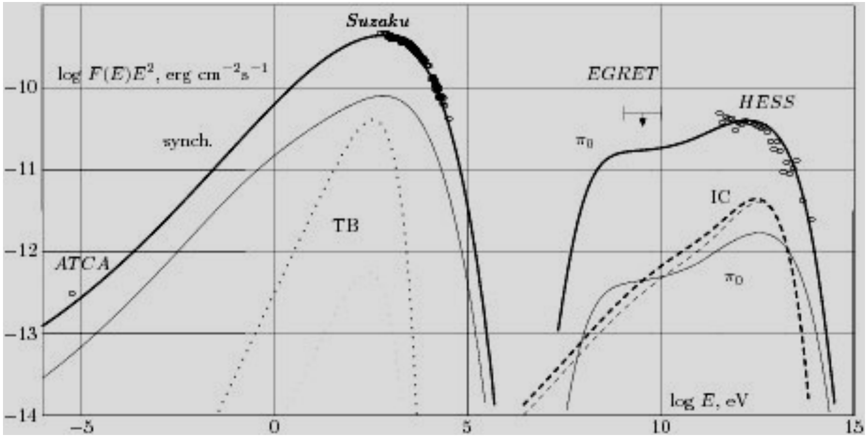
- detect VHE gamma-rays from SNRs
- demonstrate that they have hadronic origin
- demonstrate that proton spectra continue up to 1 PeV

RXJ 1713.7-4639

modeling of broad-band SEDs:

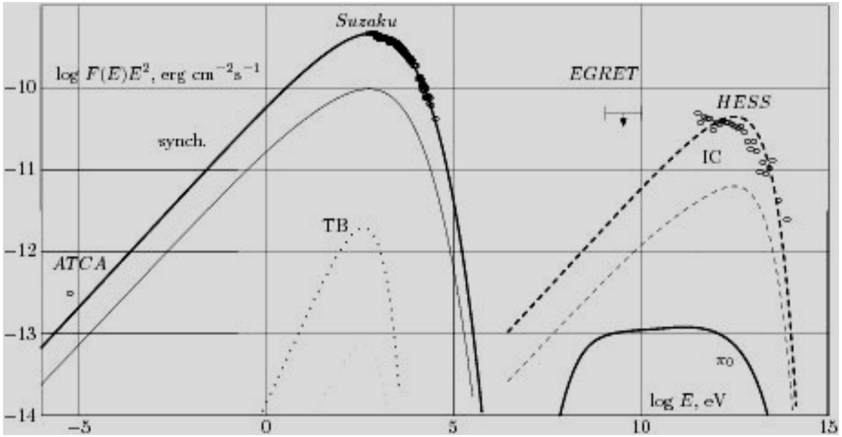


hadronic model



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



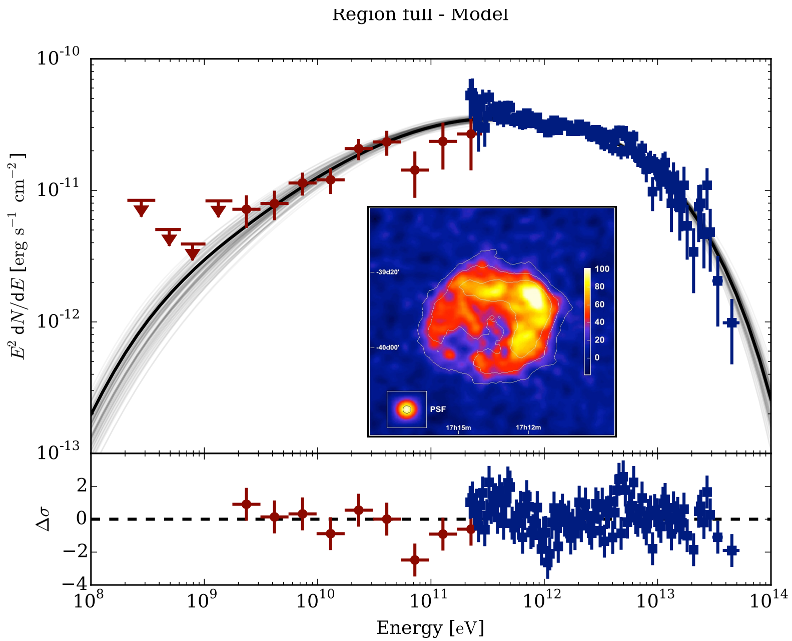
not perfect, but still acceptable, fits for spectral and spatial distributions of IC gamma-rays; suppressed thermal emission, comfortable p/e ratio (~10^2);small large-scale B-field (~ 10 μG)

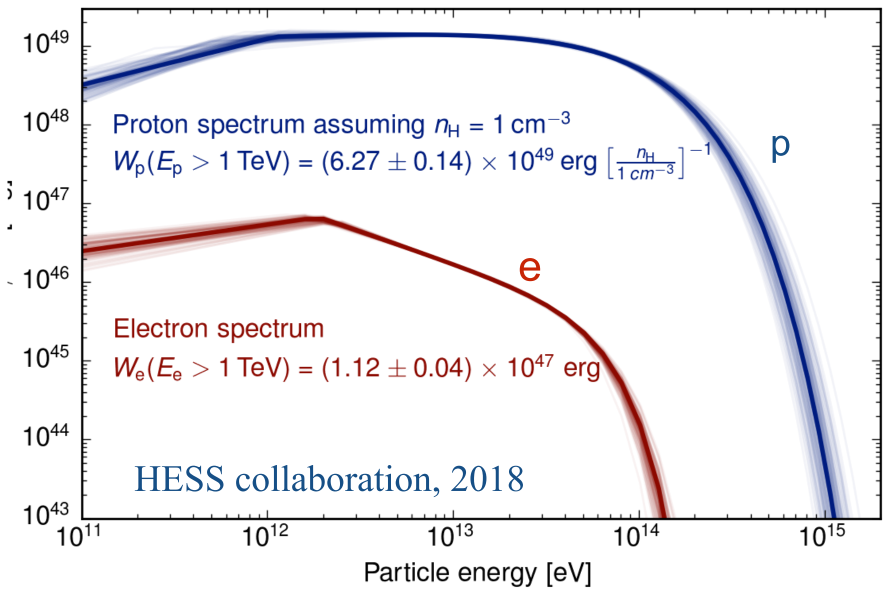
both forward&reverse shock contribute to γ-rays

Zirakashvili, FA 2010

Probing the distributions of accelerated particles in SNRs

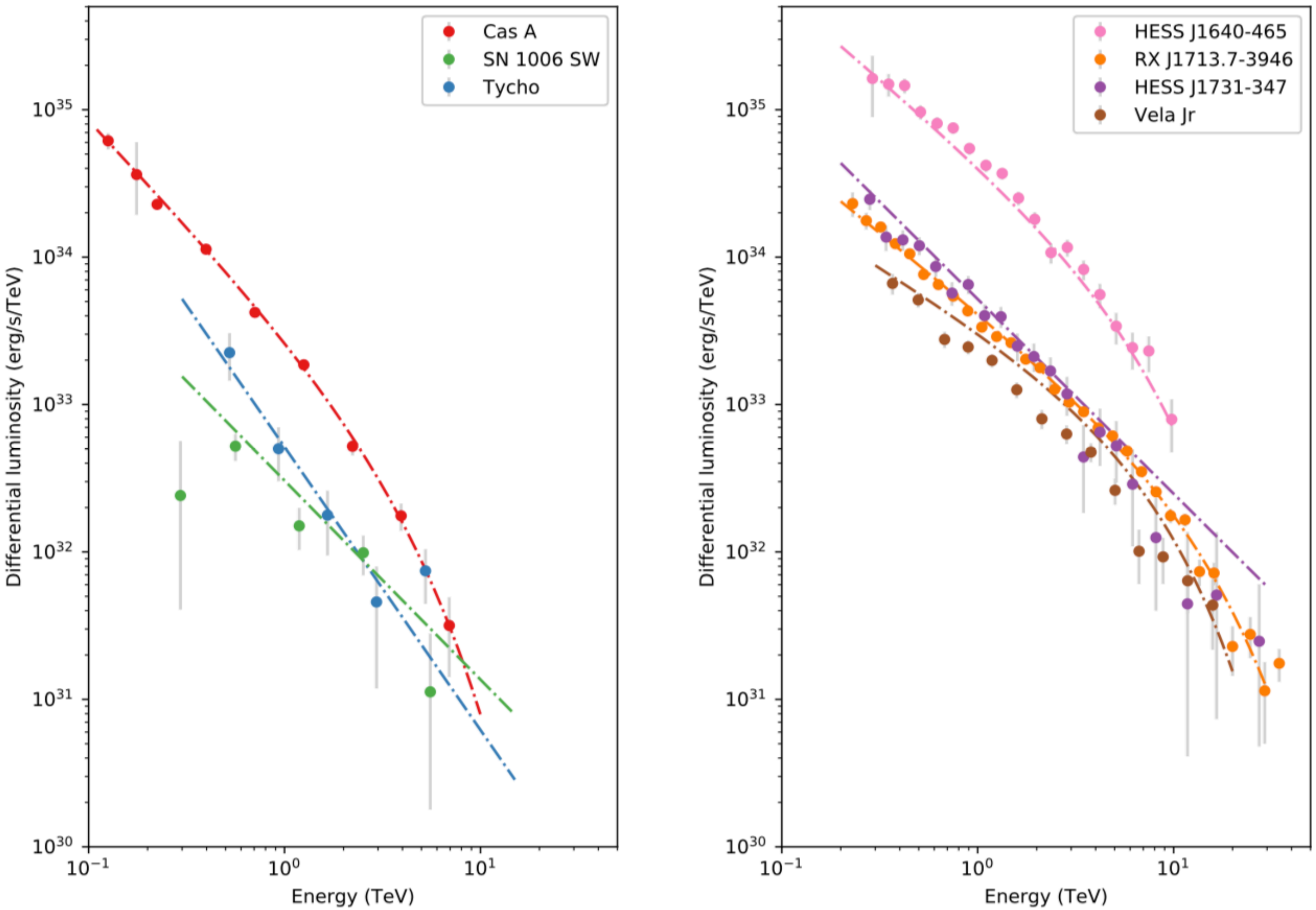
Fermi+HESS measurements **RXJ 1713** derived spectra of e and p





cutoff /break in the proton spectrum at 100 TeV

spectra of young SNRs above 1 TeV - steep with Γ= 2.3-2.6



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 β, $\Gamma=2$ 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

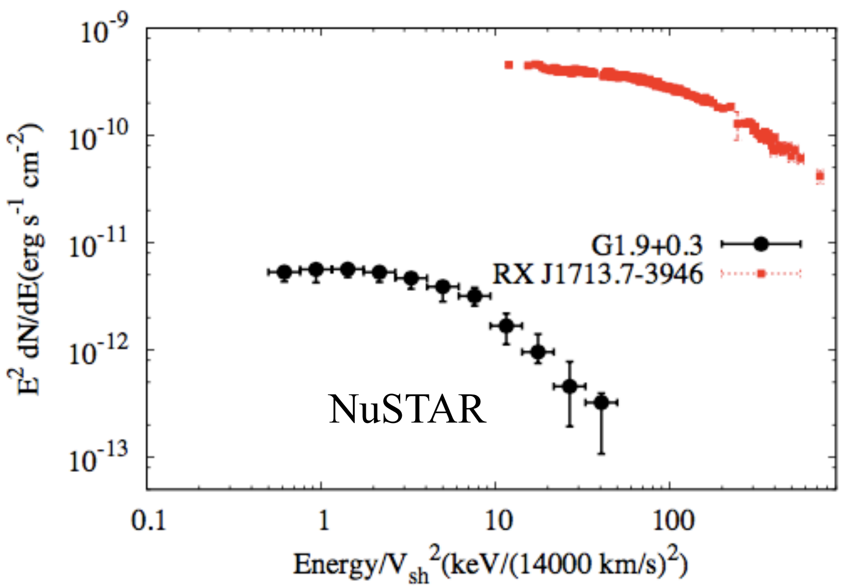
"large Γ or small Eo ?" - extension of observations to 10 TeV

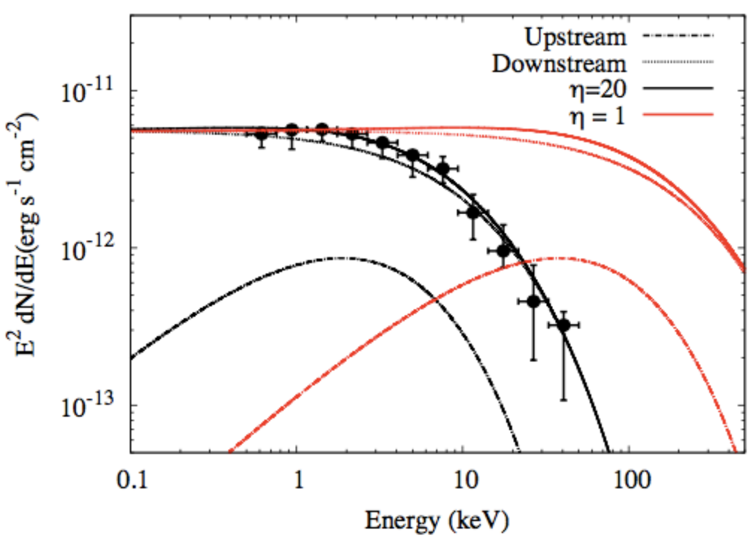
Very young SNRs as PeVatrons?

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

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

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 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*) . 5×10^6 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;

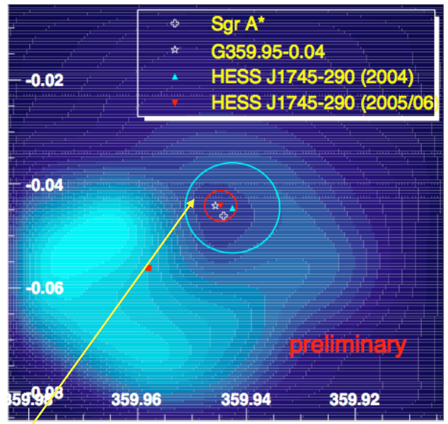
  potential, but, most likely, not the major contributors to CR electrons

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!

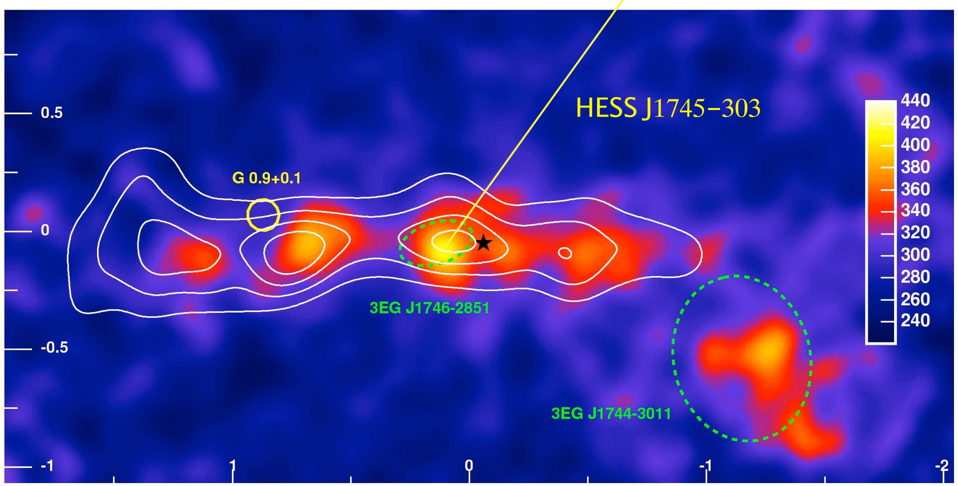
TeV gamma-rays from GC

90 cm VLA radio image

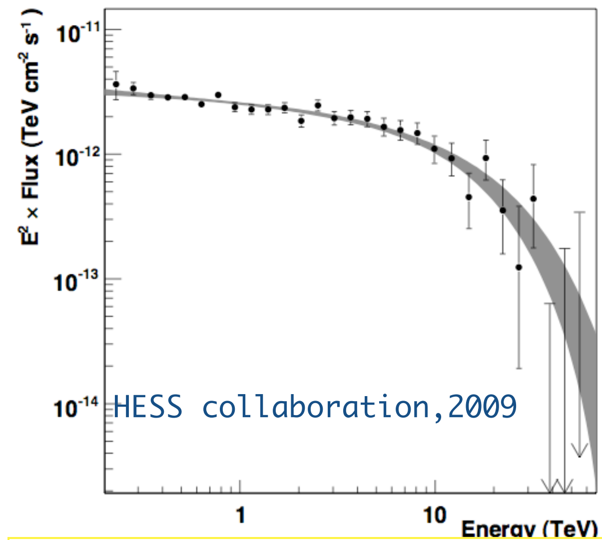


Sgr A* or the central diffuse < 10pc region or a plerion?

γ-ray emitting clouds



HESS collaboration,2006



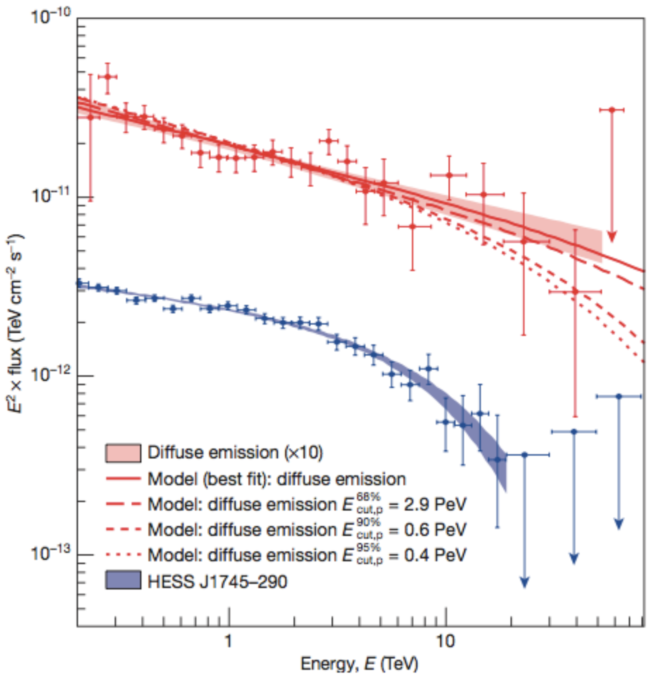
Energy spectrum:

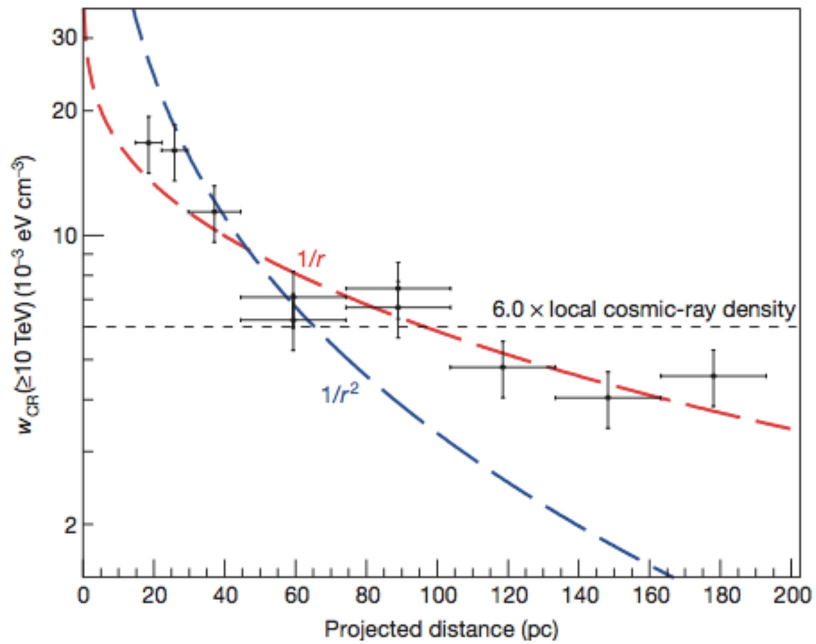
$dN/dE=AE^{-\Gamma} \exp[(-E/E_{0)})^{\beta}]$

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

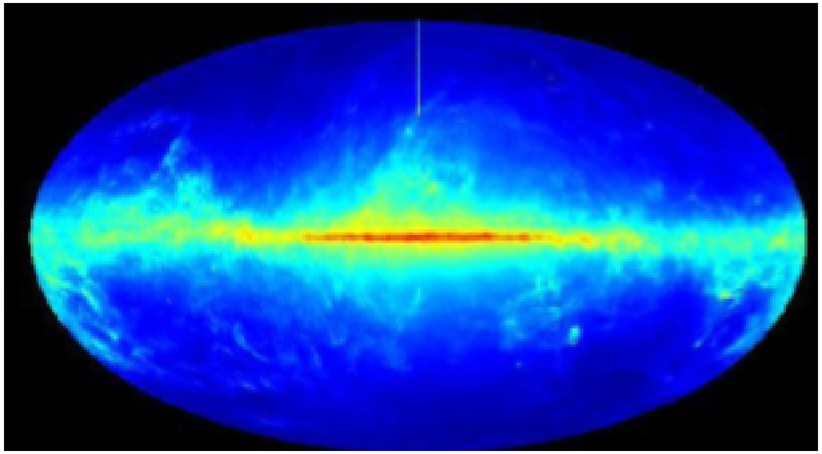
- 1/r type distribution of the CR density implies (quasi)continuous regime of operation of the accelerator with a power 10^{38} erg/s (on timescales 1 to 10 kyr) - a non negligible fraction of the current accretion power

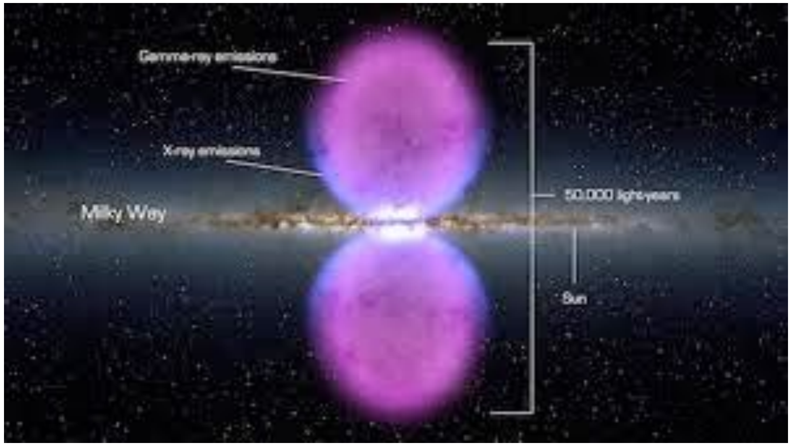
- this accelerator alone can account for most of the flux of Galactic CRs around the "knee" if its power over the last 10^6 years or so, has been maintained at average level of 10^{39} erg/s

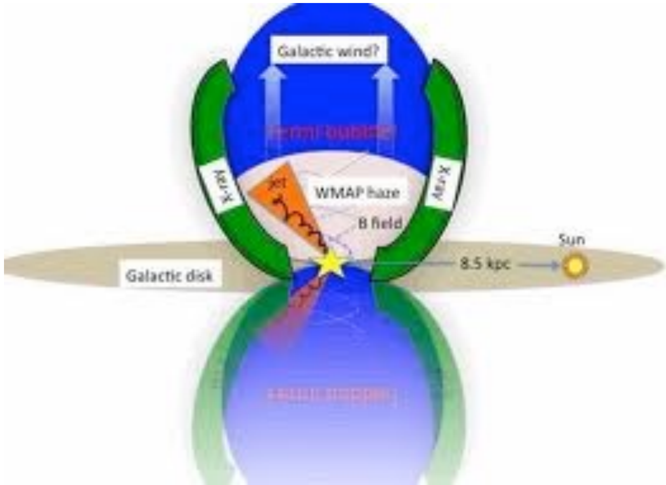
- escape of particles into the Galactic halo and their subsequent interactions with the surrounding gas, can be responsible for the sub-PeV neutrinos recently reported by the IceCube collaboration

SMBH or young massive-star clusters?

CRs from GC responsible for Fermi Bubbles?







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

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 times 1000 km/s

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

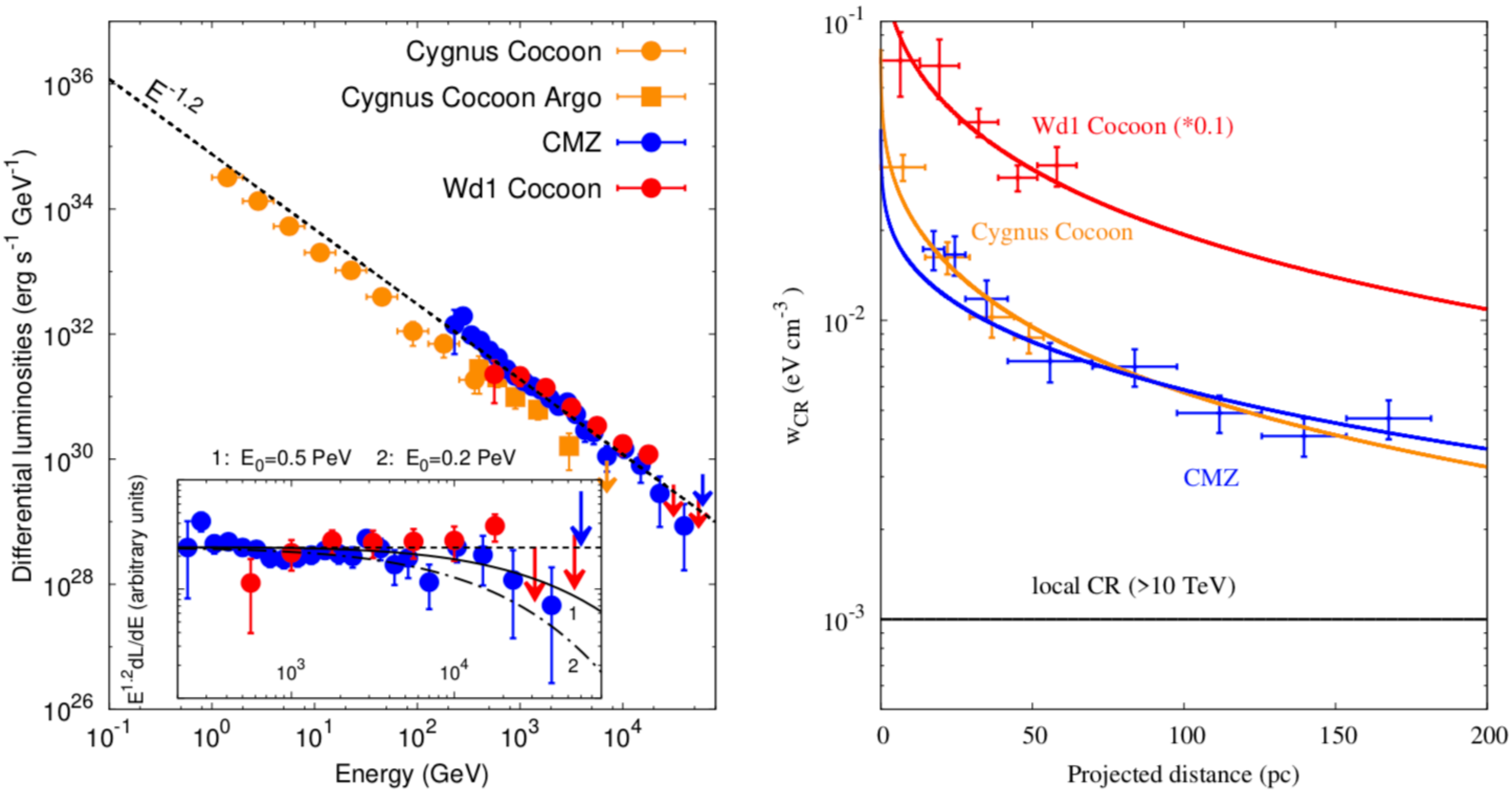


Figure 1: Gamma-ray luminosities and CR proton radial distributions in extended regions around the star clusters Cyg OB2 (Cygnus Cocoon) and Westerlund 1 (Wd 1 Cocoon), as well as in the Central Molecular Zone (CMZ) of the Galactic Centre assuming that CMZ is powered by CRs accelerated in *Arches*, *Quintuplet*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

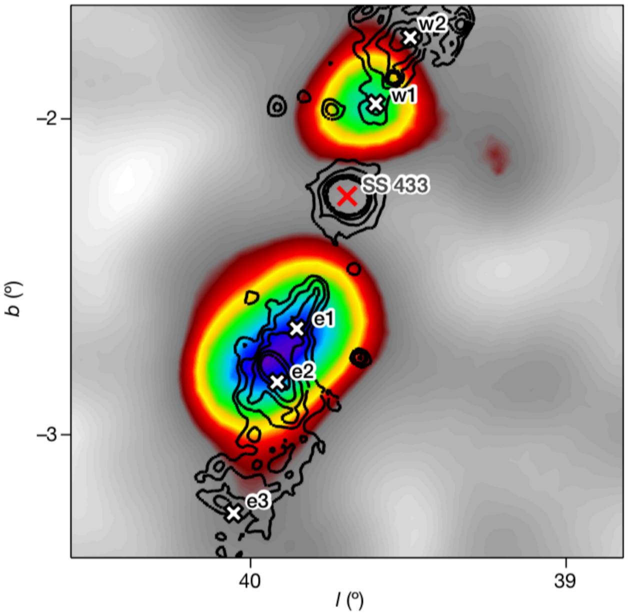
$$f(\geq 10 \text{ TeV}) \approx 1 w_0 D_{30} L_{39}^{-1}$$

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

CTA - unique measurements of D and consequently f

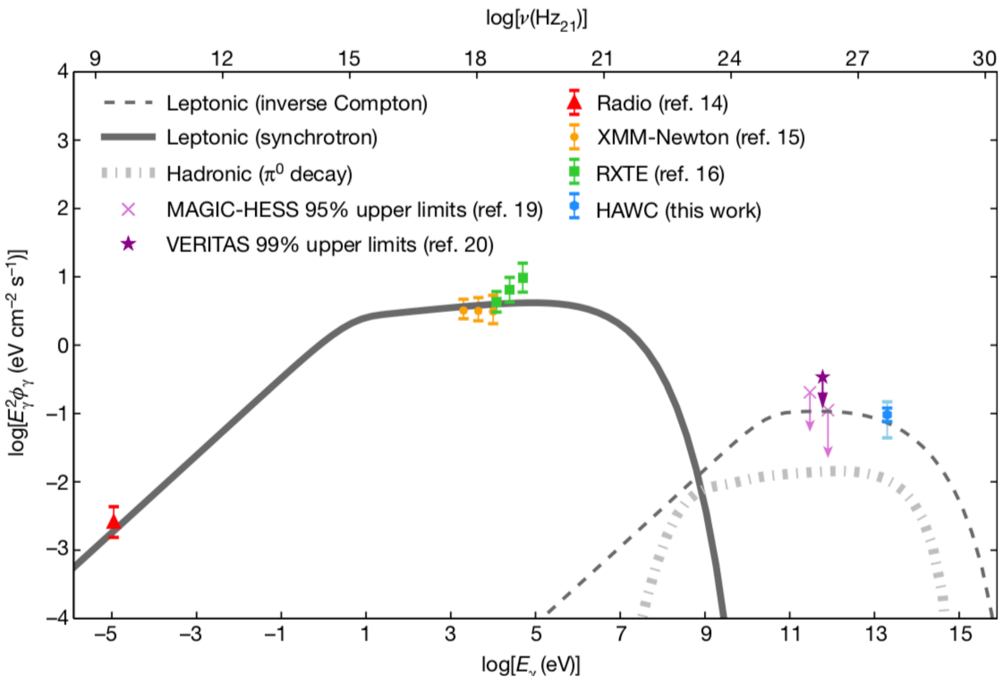
Other Pevatron candidates

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



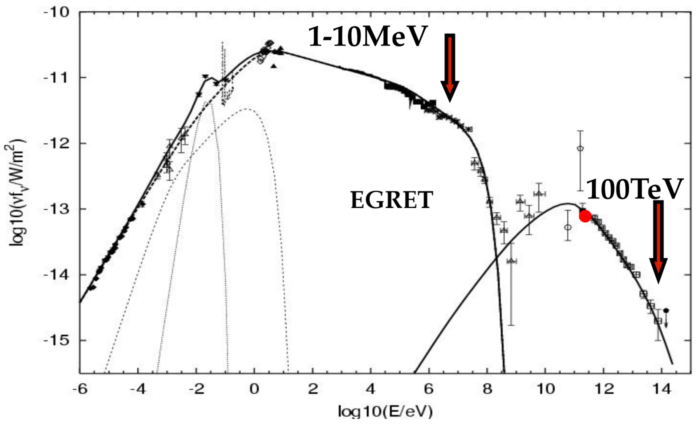
HAWC - HESS/MAGIC upper limits

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



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

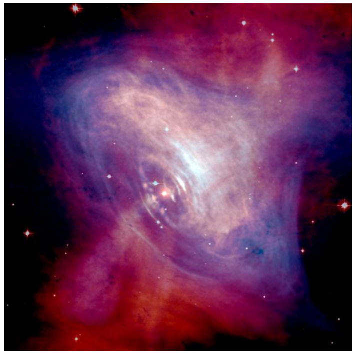
Crab Nebula – *a perfect electron PeVatron*



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

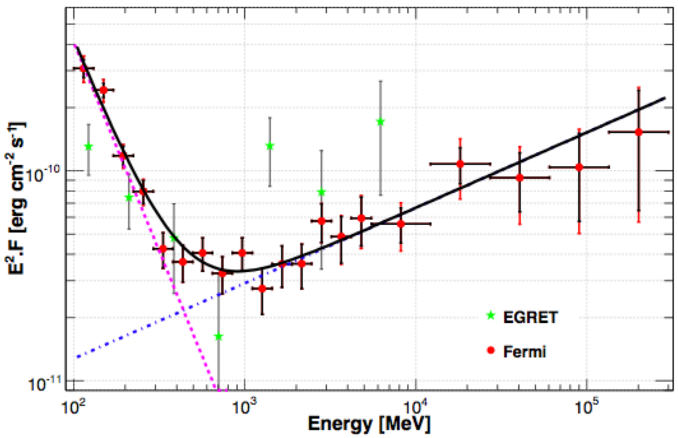


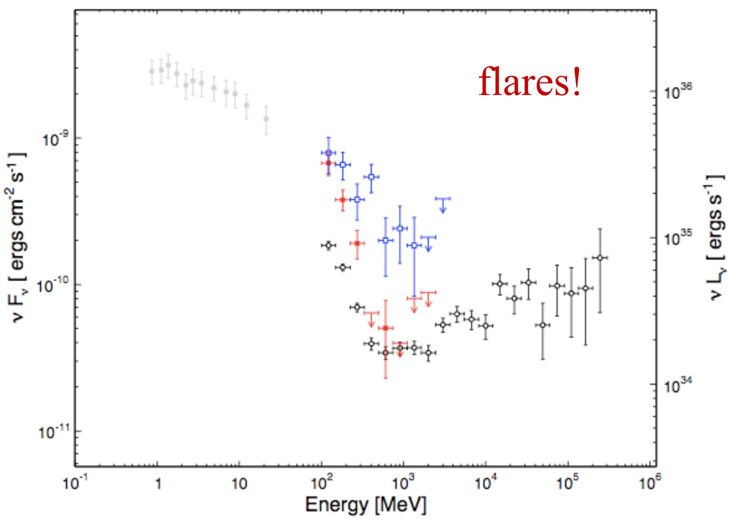
Crab Nebula – a powerful L_e=1/5L_{rot} ~ 10^{38} erg/s
and extreme accelerator: Ee >> 100 TeV

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

Cutoff at $h\nu_{cut}$ > 10 => 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 => η ~ 10 - independent and more robust estimate
1 mG => η ~ 1 ?

Flares of Crab (Nebula) :





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

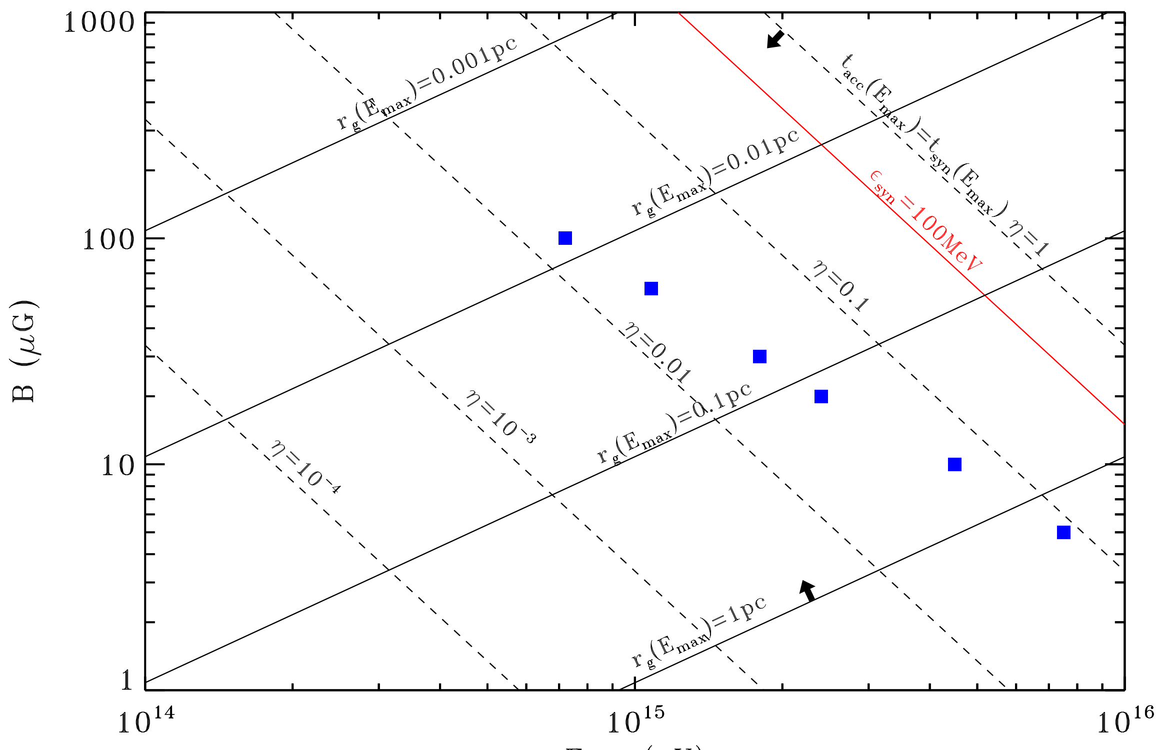
seems to be in agreements with the standard PWN picture, but … MeV/GeV flares!!

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

PWNe as an electron PeVatrons ?

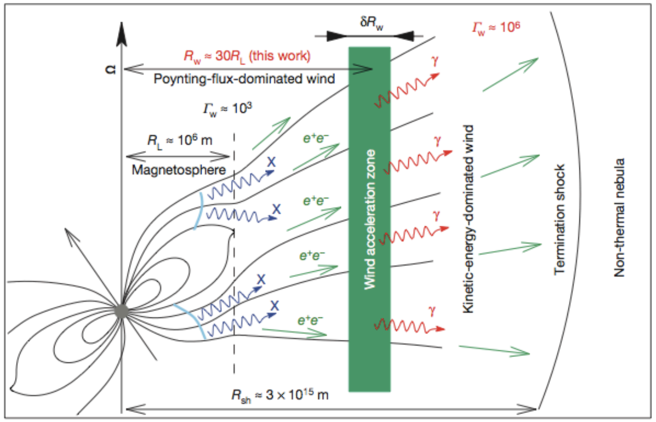
E_{max} versus B, R, and η

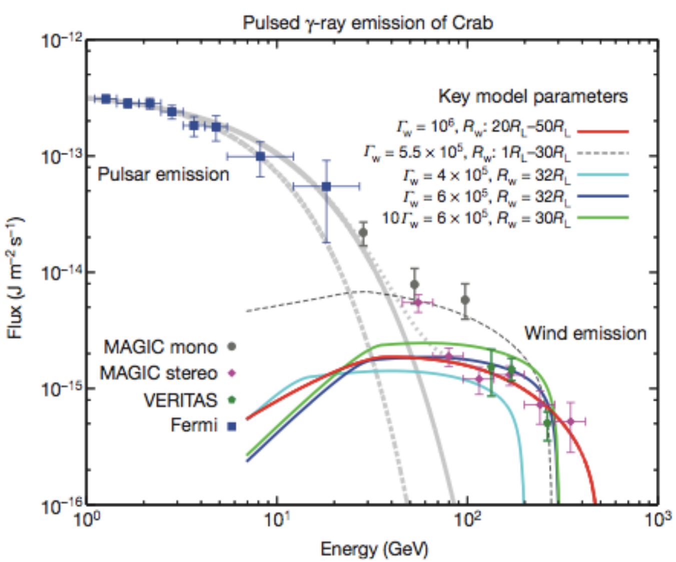


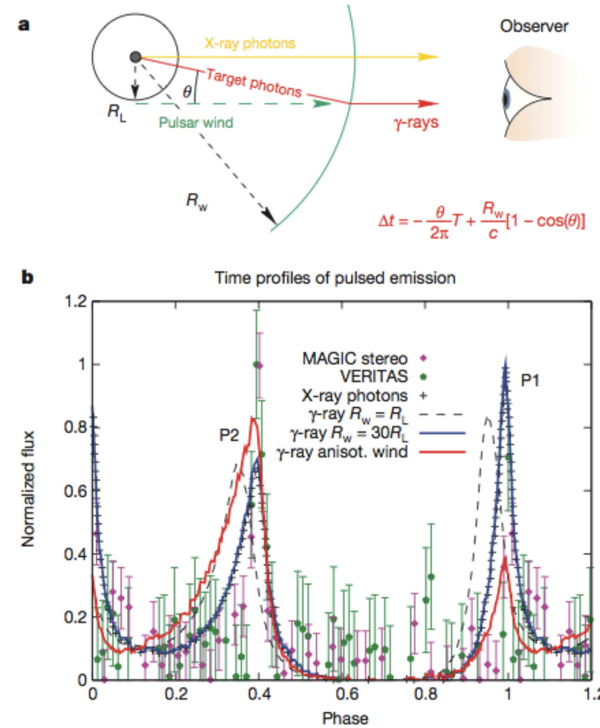
Ruoyu Liu

> 100 TeV gamma-rays: critical and unbiased to find Emax

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







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

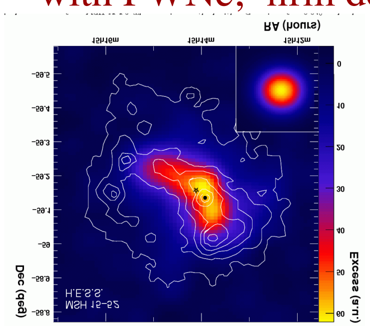
Crab Nebula is a very effective accelerator
but not an effective IC γ-ray emitter

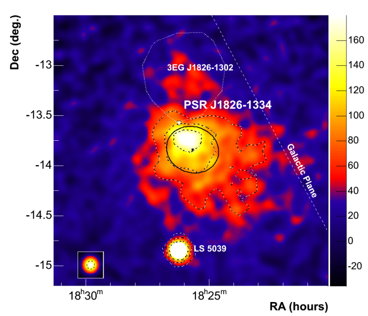
we do see TeV γ-rays from the Crab Nebula because of very large spin-down flux: $f_{rot}=L_{rot}/4\pi d^2=3\text{x}10^{-7}$ erg/cm^2 s

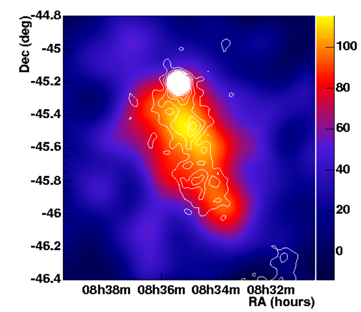
gamma-ray flux << “spin-down flux“ *because of large B-field*

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!







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

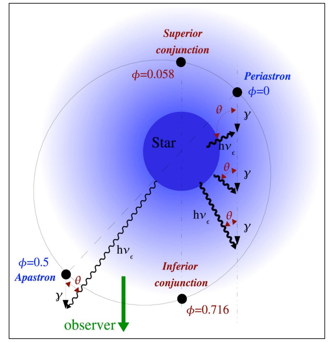
(characteristic timescales 1 h or shorter !)

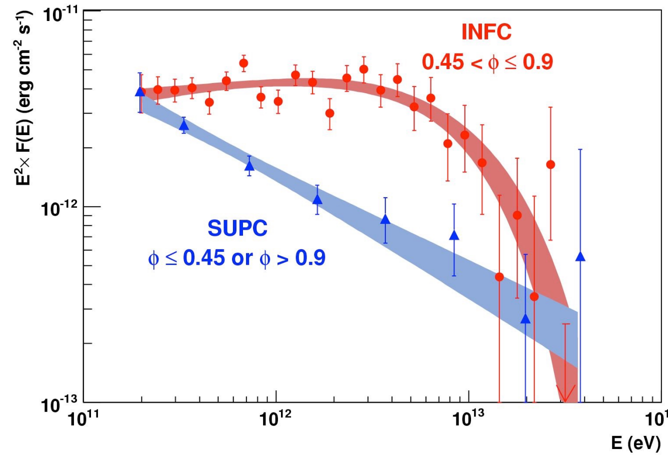
the target photon field is function of time, thus the only unknown parameter is B-field => predictable gamma-ray emission?

LS 5039

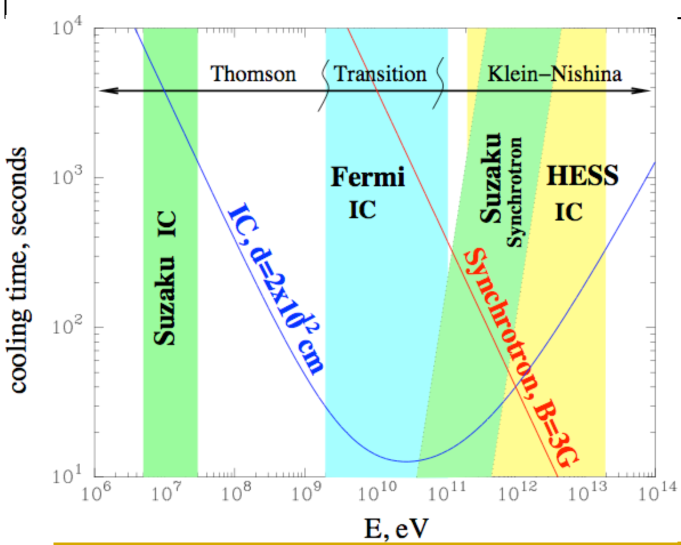
works as a perfect TeV clock
and an extreme accelerator

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



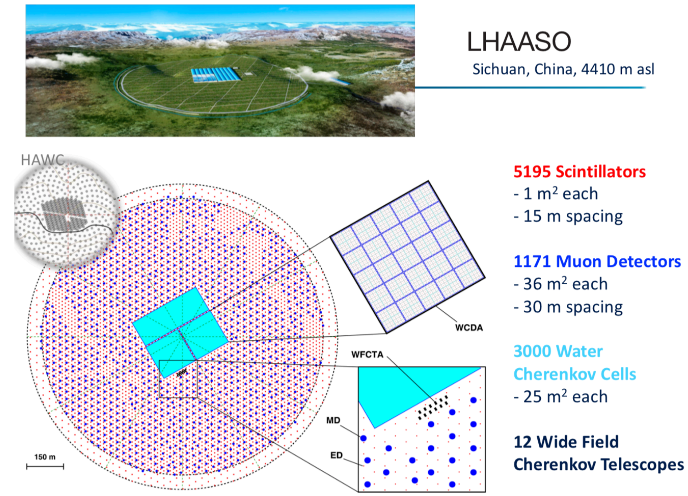


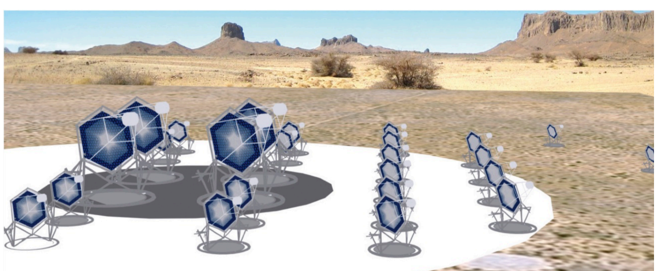
modulation of the gamma-ray signal? *a quite natural reason (because of γ−γ absorption), but we see a different picture… anisotropic IC scattering? yes, but perhaps some add-itional factors (adiabatic losses, modest Doppler boosting) also play a non-negligible role*



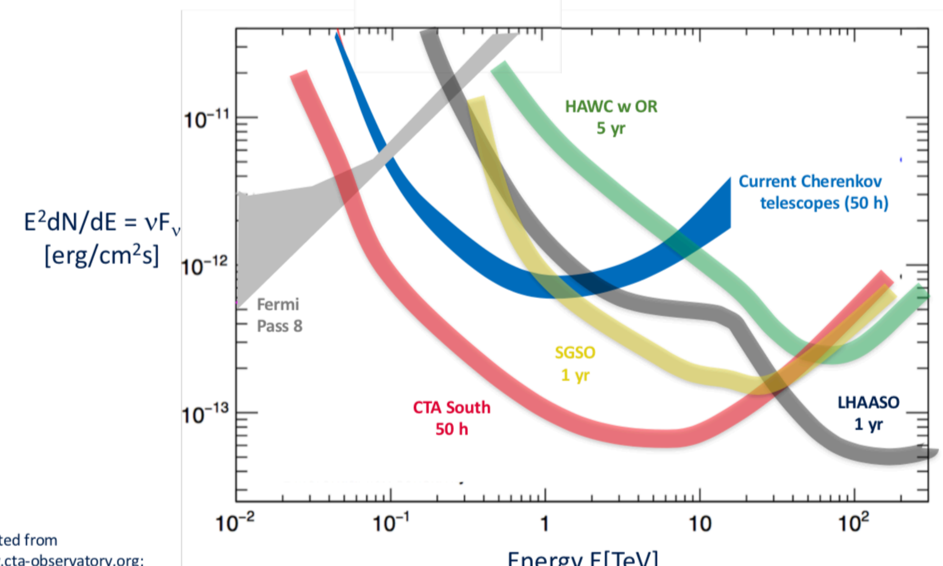
can electrons be accelerated to energies up to 20 TeV in presence of dense radiation? *yes, but accelerator should not be located deep inside binary system; even at the edge of the system* $\eta < 10$ => *although* the origin of the compact object is not yet known (pulsar or a BH) and we do not understand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

UHE gamma-rays as key messengers from Extreme Accelerators





CTA



adapted from
www.cta-observatory.org;
J. Goodman, COSPAR 2018;
Z. Cao, La Palma 2018