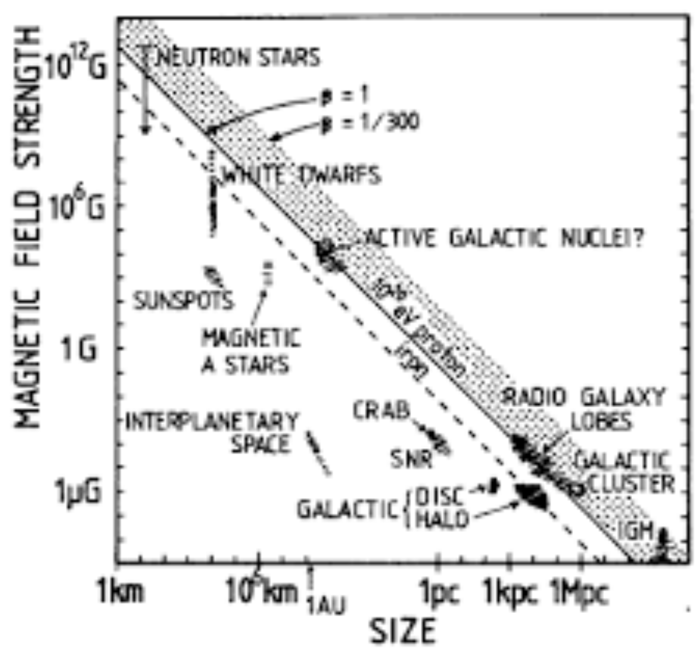
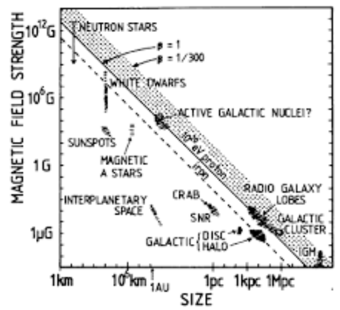


Hillas Plot:
trivial and non-trivial implications

Felix Aharonian

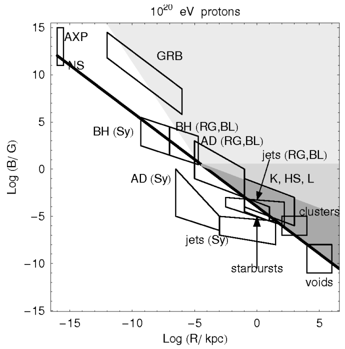
1984

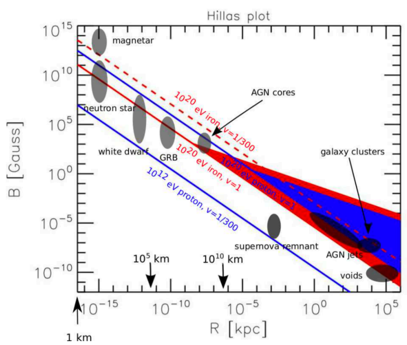


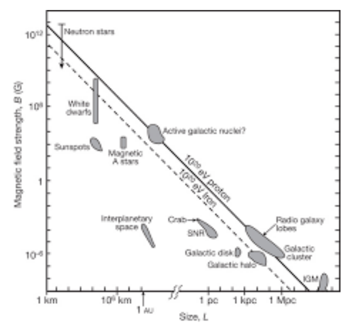
Hillas Plot : B – L relation based on the condition $L > r_L$

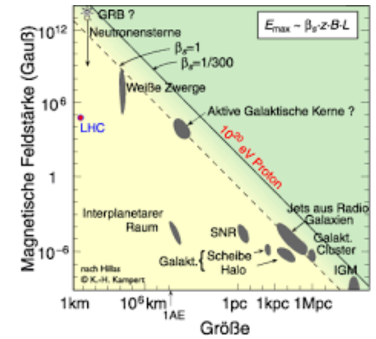
Ann. Rev. Astron. Astrophys. 1984, 22:425-444

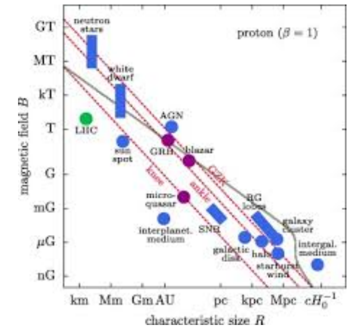
tens of "Hillas Plots" have been produced since 1984 ...

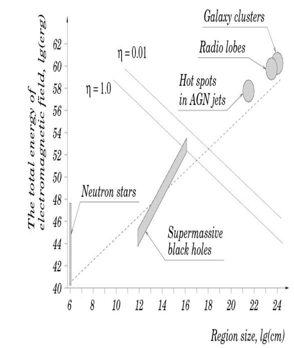












$$B_{\mu G} L_{\mathrm{Mpc}} > 2E_{21}/Z(v/c)$$

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 - $v \to c$ - 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:

$$t_{acc} = \eta \frac{E}{eBc} = \eta \frac{r_L}{c}$$

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

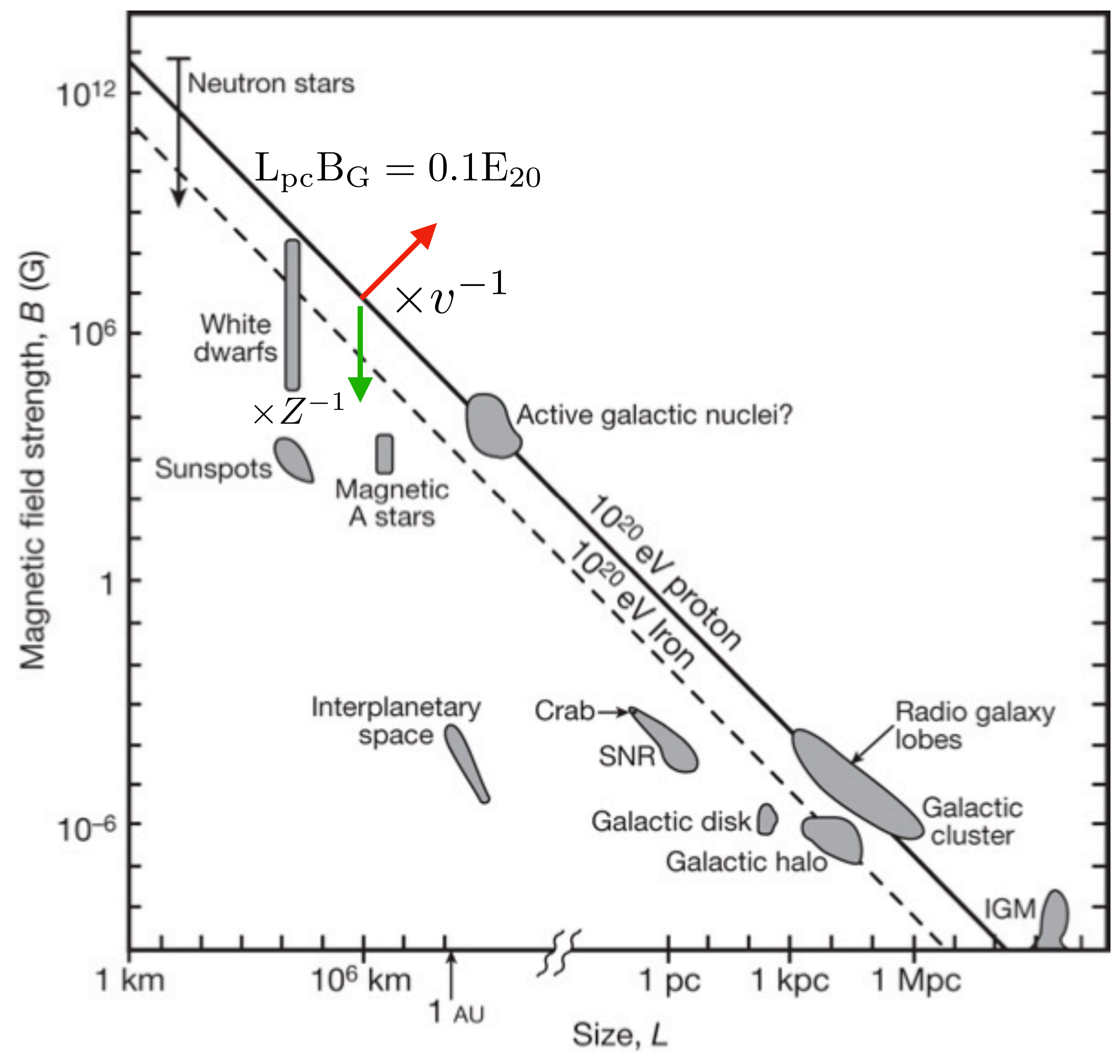
absolute minimum set my classical ED: $\eta \geq 1$

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

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

$\boxed{\eta \approx 1 \to \text{extreme accelerator}}$

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



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

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

$L = r_L$ condition implies an extrem accelerator

trivial condition - non-trivial solutions

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

$\boxed{Ep=10^{19}\ eV}$

extended structures

- are Galaxy Clusters ruled out?
- large scale structures in AGN jets ? *knots, lobes, entire multi-kpc jets*

losses ? yes (in Galaxy Clusters) interactions with 2.7 K MBR (Bethe-Heitler pair-production)
signature? unusual Synchrotron (low/high) and IC (VHE) radiation

$\boxed{Ep=10^{20}\ eV}$

compact objects

should we be scared of “extreme accelerators” ? *well, we know at least one* - Crab

small scale jets in AGN - attractive features - relativistic flows, GeV/TeV gamma-rays

unusual features - super-Eddington power, fast variability...

losses ? yes ! synchrotron/curvature losses determine the maximum energy
signature? GeV and TeV radiation of the e- and p- synchrotron components

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 times 1000 km/s
- ✓ acceleration time ~ Hubble time

protons cannot be accelerated beyond 10^{19} eV (Kang et al., Vannoni et al) because of losses on pair production

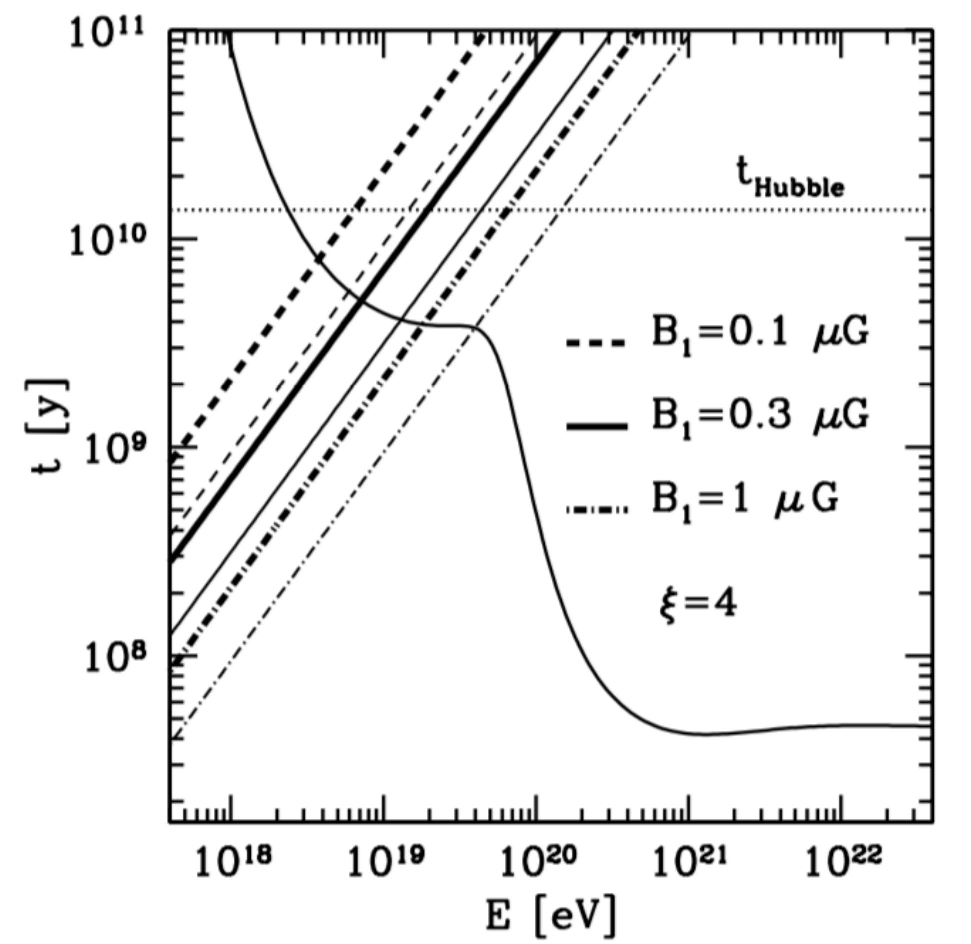


Fig. 1. Acceleration and energy loss time scales as a function of the proton energy. The acceleration time scales are obtained for the values of the upstream magnetic field B_1 reported in figure and a downstream magnetic field $B_2 = 4B_1$. The thick lines correspond to a shock velocity of 2000 km s^{-1},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

Vannoni et al. 2009

Acceleration of Cosmic Rays by Accretion Shocks in Clusters if Galaxies

DSA => interactions of p with 2.7 K => pair production - IC and Synchrotron emission

protons: up to several times 10^{18} eV

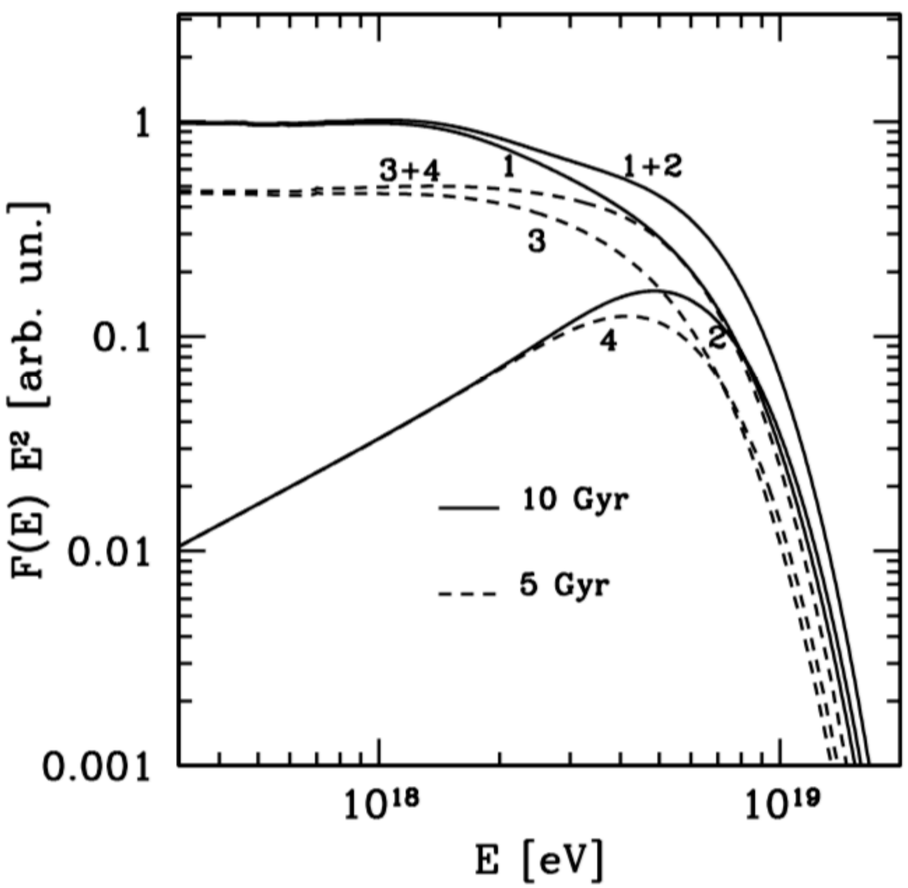


Fig. 3. Spatially integrated spectra for the proton distributions in Fig. 2 for an accelerator age of 10 Gyr (solid lines) and 5 Gyr (dashed lines). The lines 1 and 3 represent the downstream contributions, 2 and 4 the upstream ones, and 1+2 and 3+4 the sum of each pair.

MeV/GeV synchrotron and multi-TeV IC

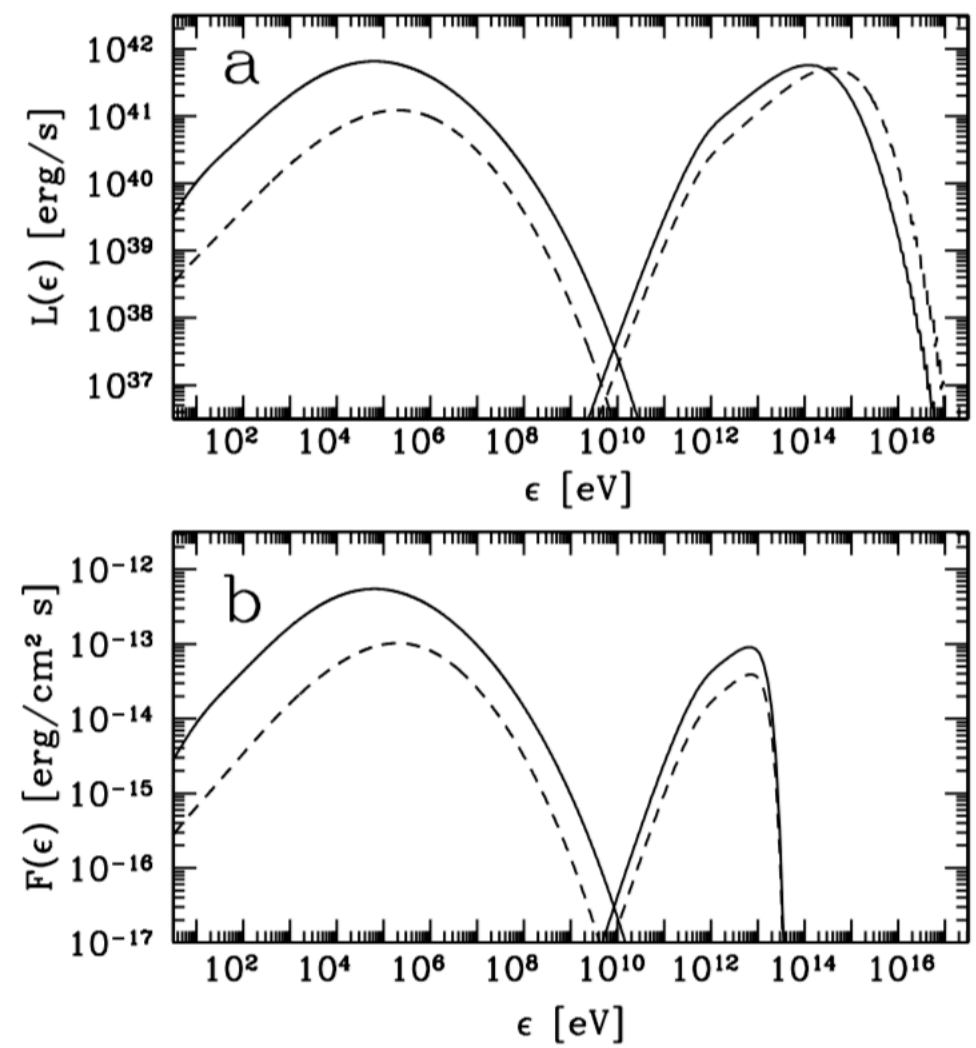


Fig. 7. a) Broadband electromagnetic emission produced at the source location via synchrotron and IC cooling by the electron distributions in Fig. 6**b**). The solid curve refers to the downstream component and the dashed curve to the upstream one. **b)** Expected flux at Earth for a source located at a distance D = 100 Mpc. The effect of photon-photon absorption during propagation has been taken into account.

acceleration sites of 10^{20} eV CRs ?

$$t_{acc} = \frac{r_L}{c}\eta$$

signatures of extreme accelerators?

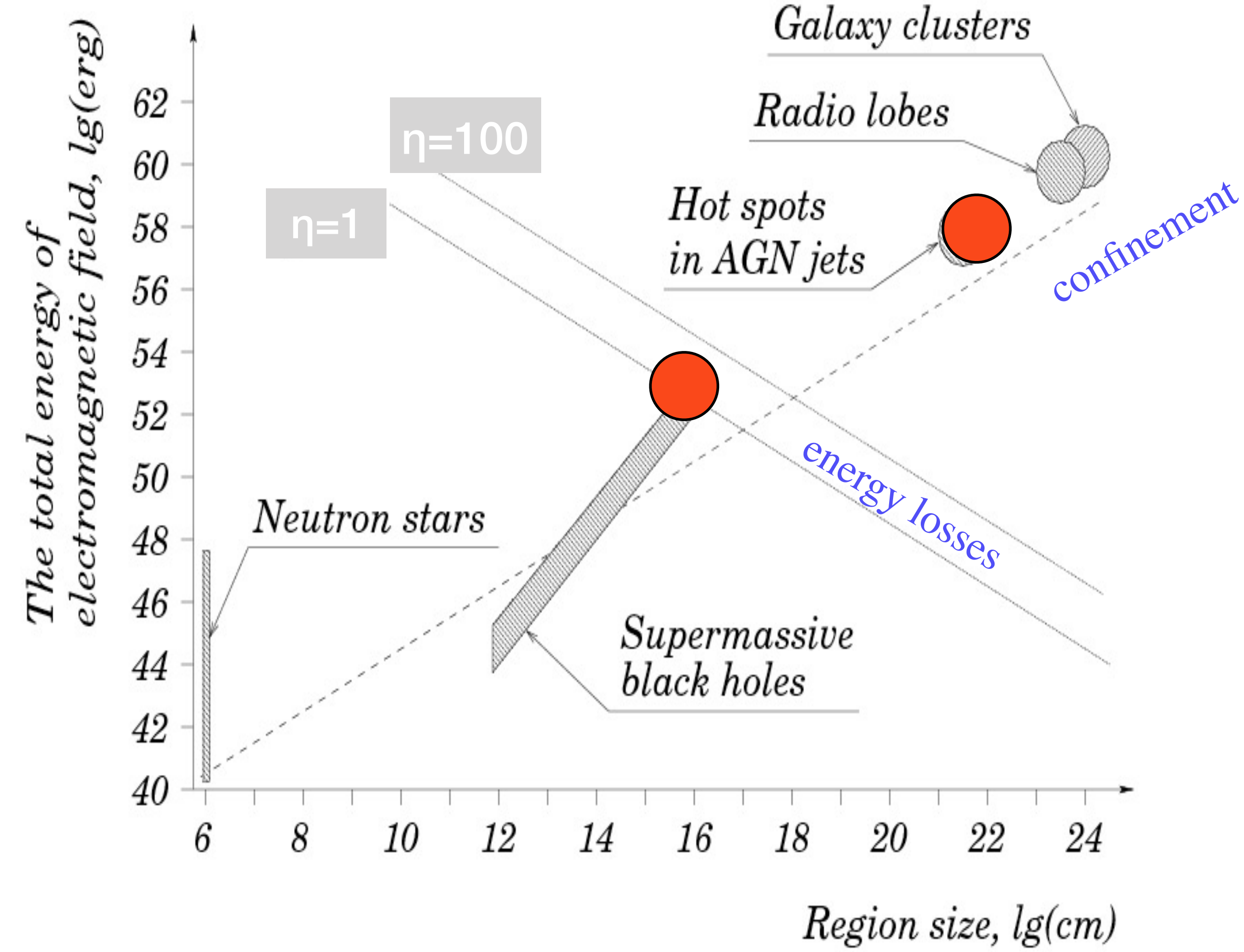
✓ synchrotron self-regulated cutoff:

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

≈ 150 MeV for electrons

≈ 300 GeV for protons

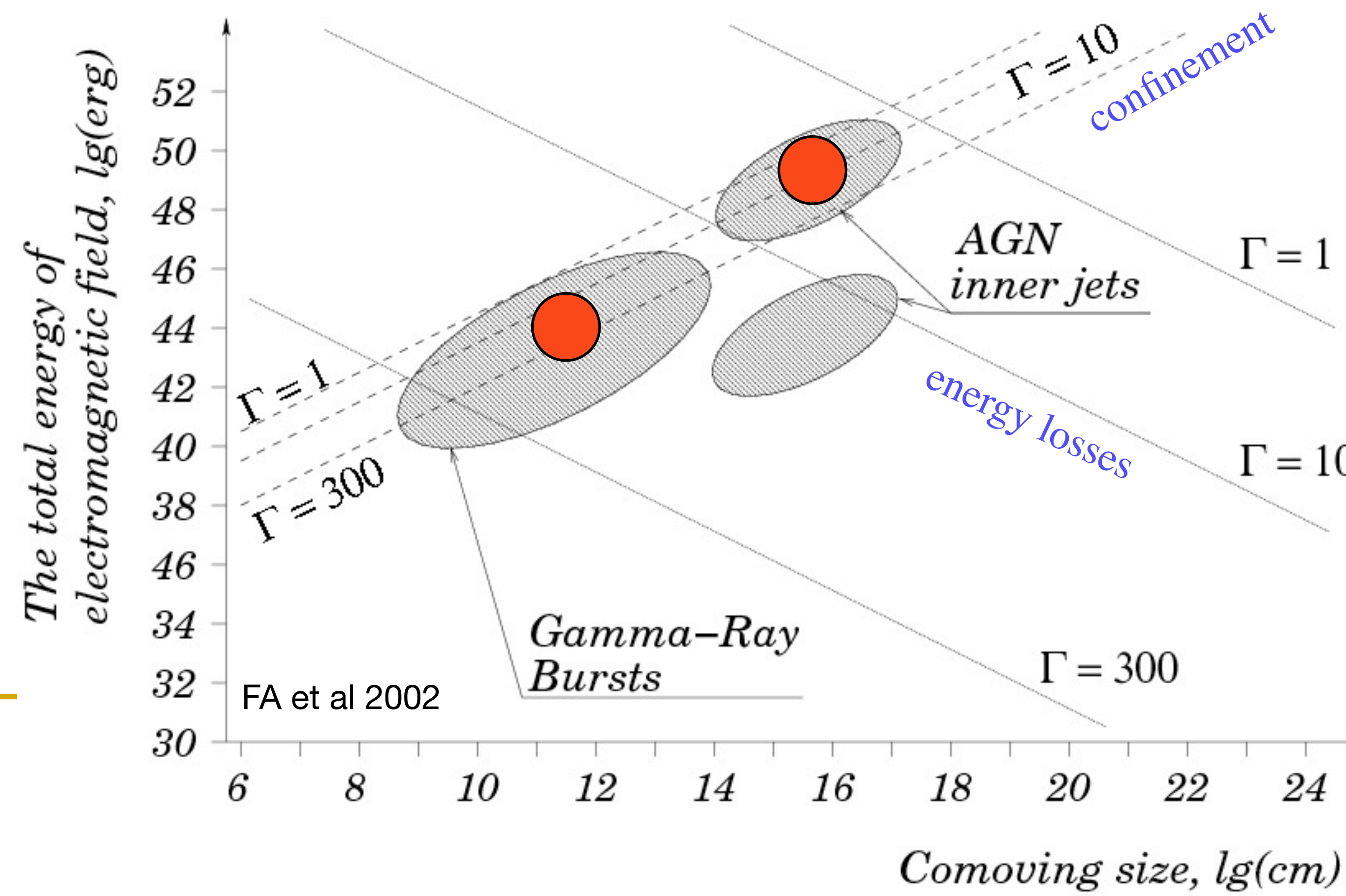
a viable "hadronic" model applicable for TeV γ-ray blazars if B ~ 100 G or so



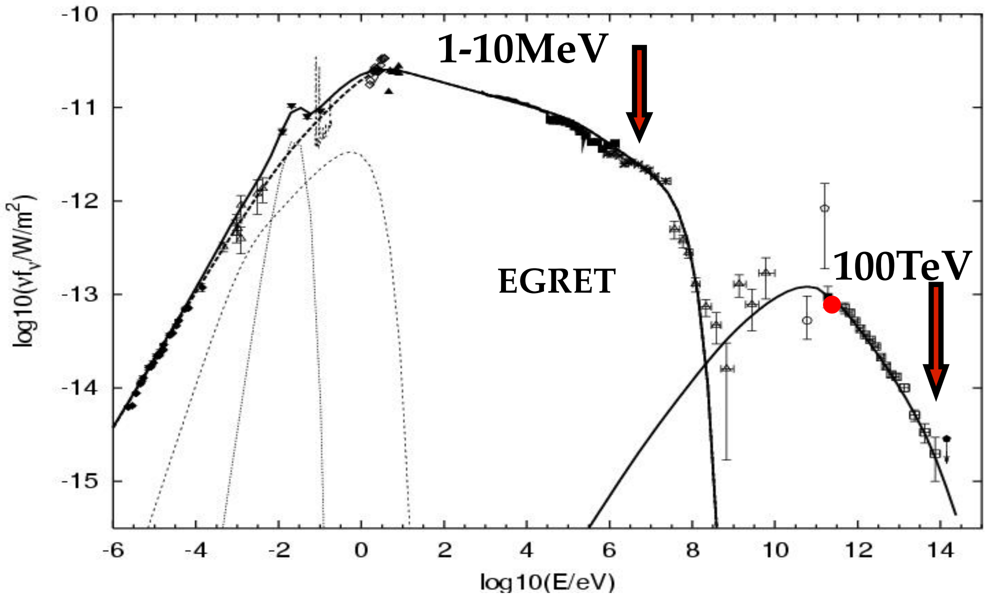
✓ neutrinos (through "converter" mechanism) production of "pγ" neutrons which travel to large distances and convert again to protons => Γ^2 energy gain! (Derishev et al. 2003)

(a possible solution to the problem of acceleration by relativistic shocks

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



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

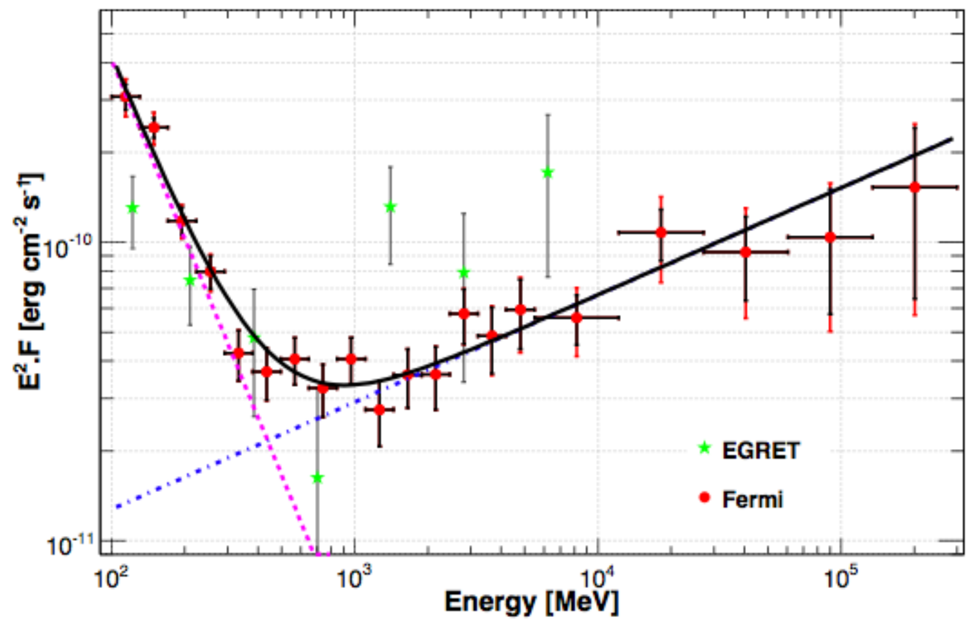
synchrotron radiation => nonthermal optical/X nebula
Inverse Compton => high energy gamma-ray nebula

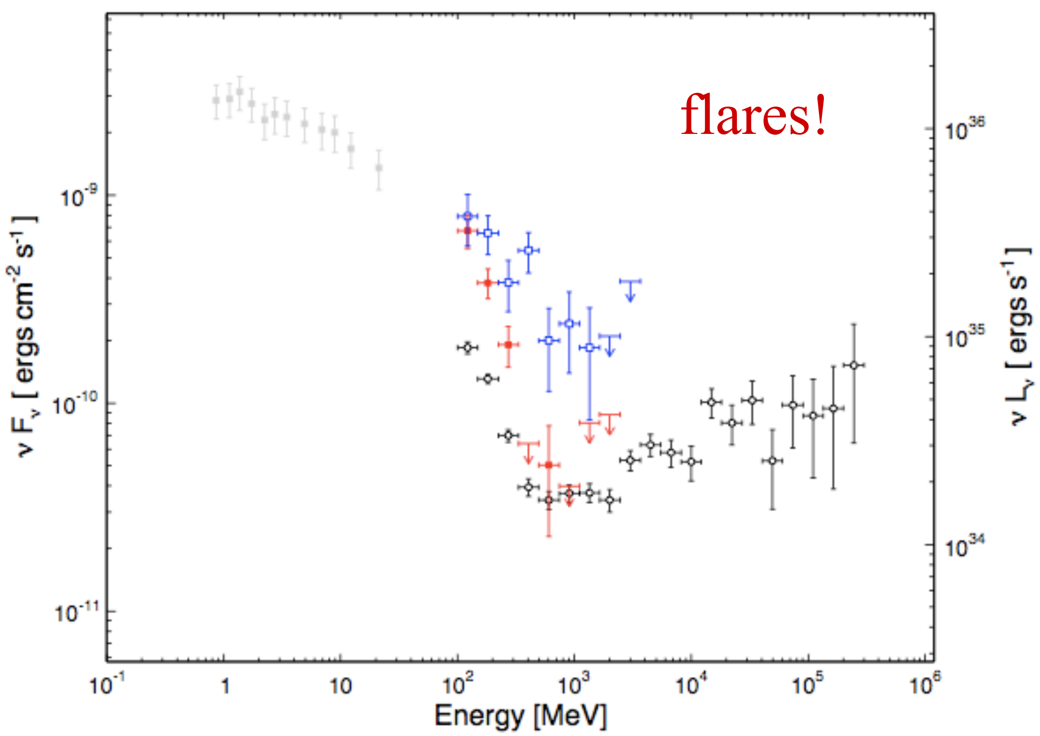
Crab Nebula – a powerful $L_e = 1/5 L_{rot} \sim 10^{38}$ erg/s
and extreme accelerator: Ee >> 100 TeV

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

Cutoff at $h\nu_{cut} > 10 \Rightarrow \eta < 10$ - 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

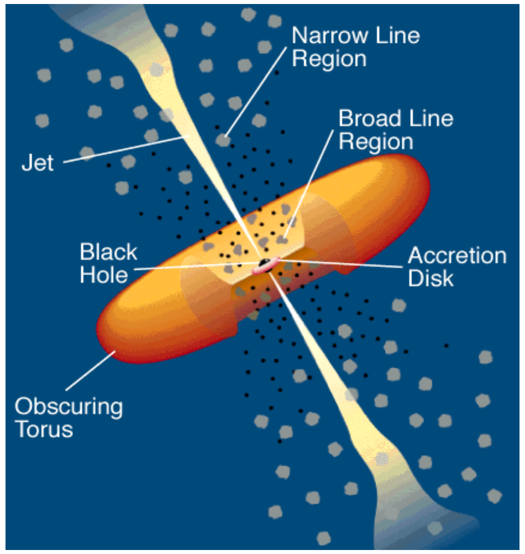
seems to be in agreements with the standard PWN picture, but … MeV/GeV flares!!

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

Blazars as sources of EHE CRs?

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

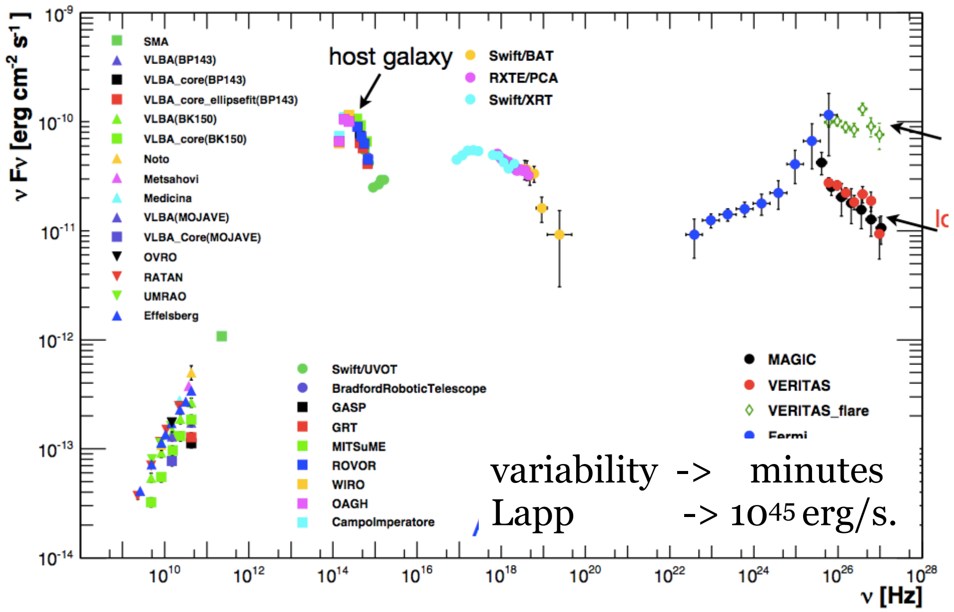
- Blazar physics and astrophysics
- Diffuse Extragalactic Background (EBL)
  Intergalactic Magnetic fields (IGMF)

most exciting results of recent years

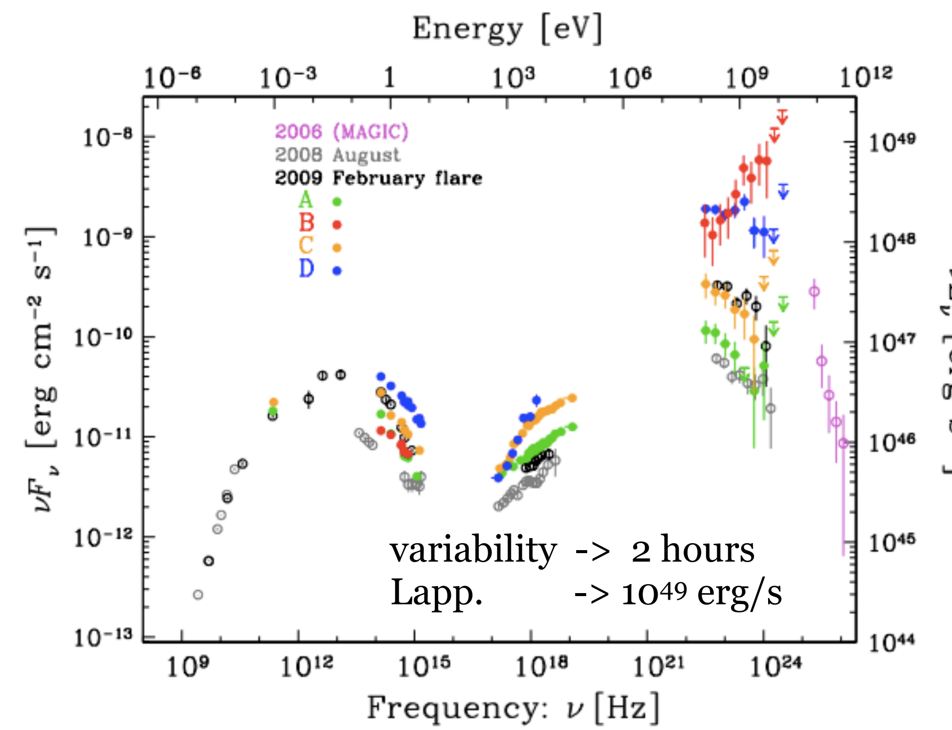
- ultra short time variability (on min scales)
- Jet power exceeds Eddington luminosity
- extremely hard (harder than E-1.5) energy spectra

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

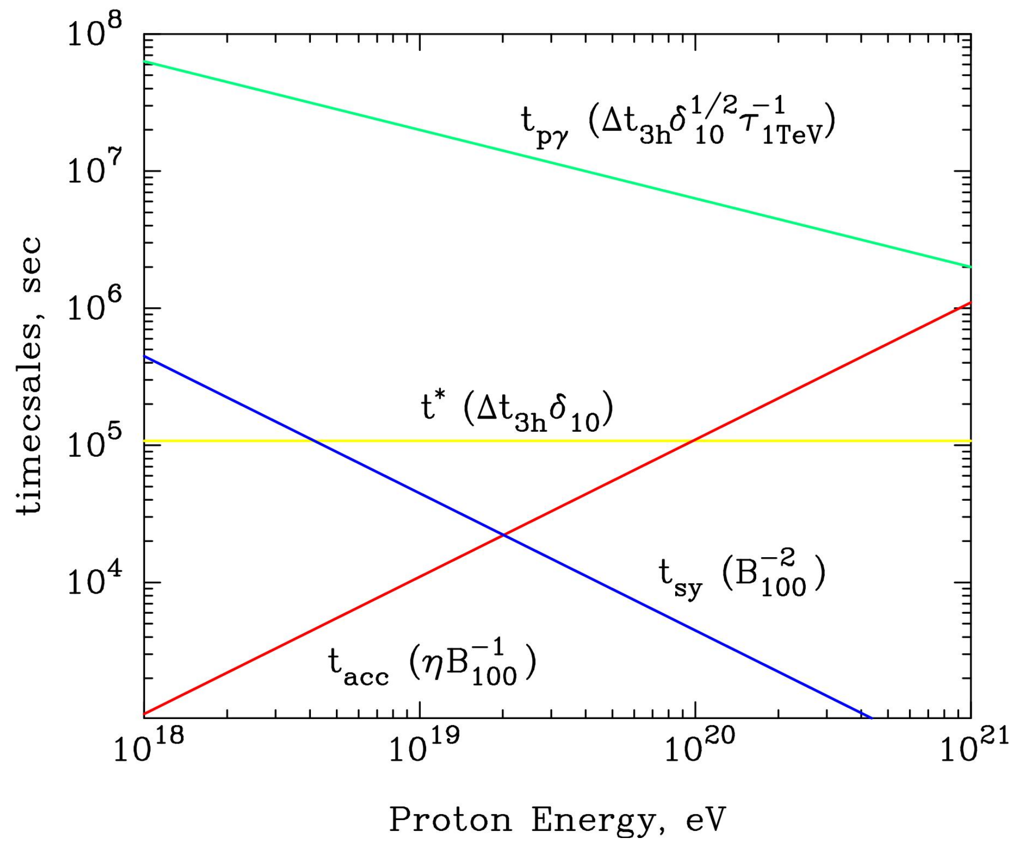
hadronic models in synchrotron-loss dominated regime

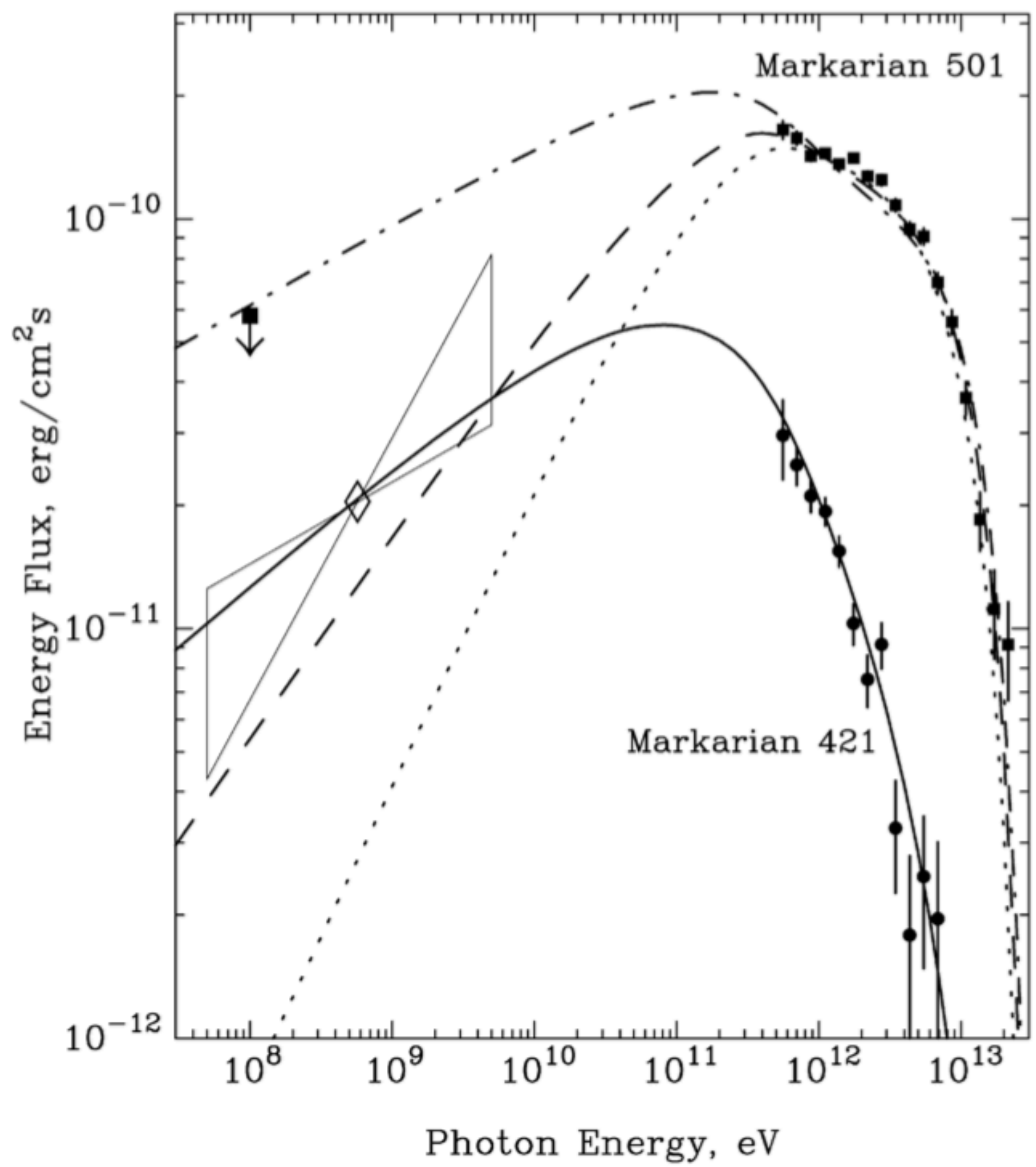
$$\mathrm{E_{p,max}} = 3/2(\mathrm{e^3 B}\eta)^{-1/2}\mathrm{m_p^2 c^4} \approx 1.8\times10^{19}\mathrm{B_{100}^{-1/2}}\eta^{-1/2}\mathrm{eV}$$

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

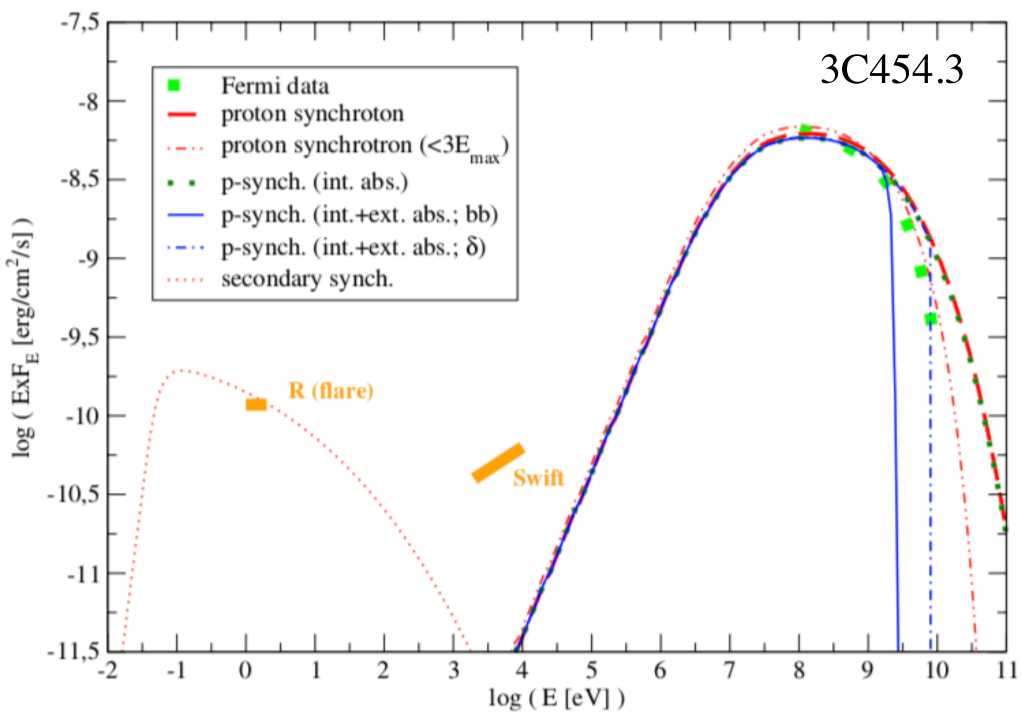
t_{synch}=4.5x10^4(B/100G) $^{-2}$ (E/10^{19} eV)$^{-1}$ s

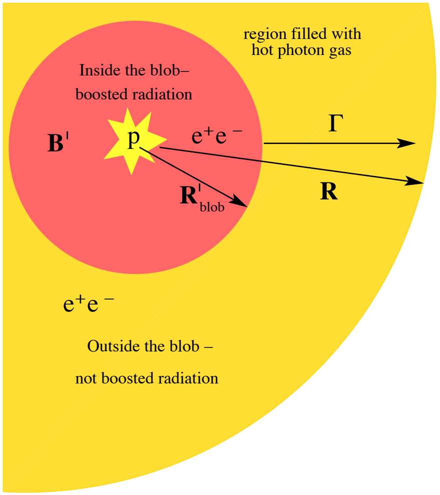
t_{acc}=1.1x10^4 (E/10^{19}) (B/100G) $^{-1}$ s

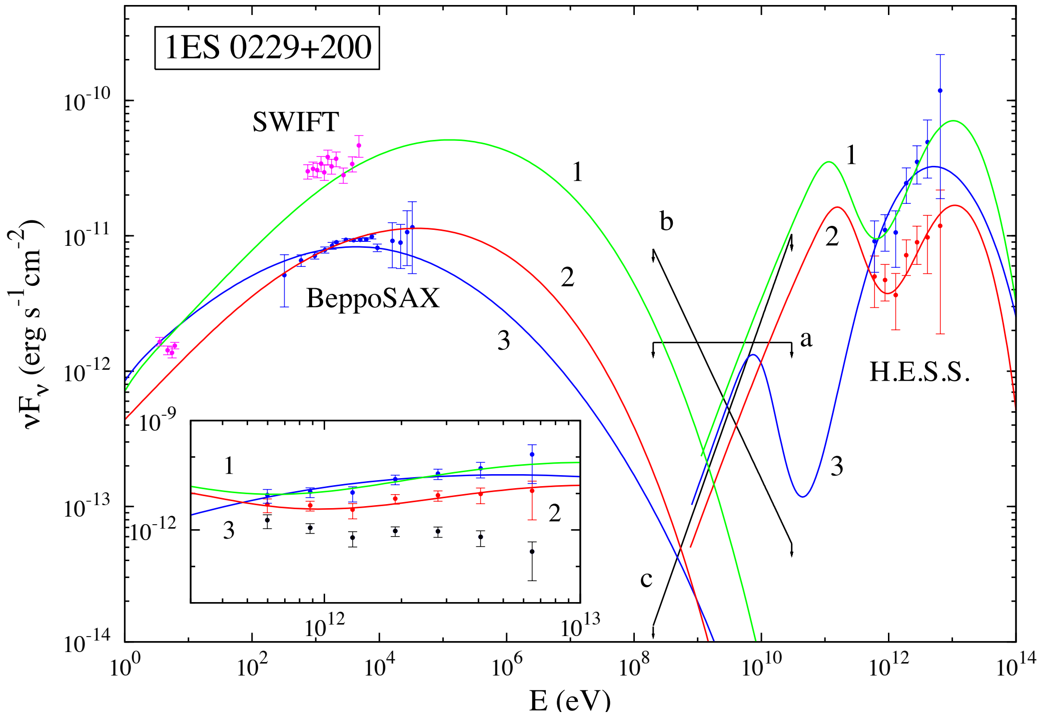
cooling time of pγ interactions >> synchrotron cooling time => negligible neutrons flux

FA 2000

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

$$\mathrm{h}\nu_2 \propto \eta^{-1} \text{ while } \mathrm{h}\nu_2 \propto \eta^{-2}$$

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

last remark:

source(s) responsible for observed EHE CRs should be located in our (<100 Mpc) neighbourhood (independent of arguments based on GZK cutoff !); otherwise we should require a (strange) “negative evolution” of the relevant source populations

do we have nearby objects - candidates for the detected “local fog” of EHE CRs?

M87 - as a 6×10^9 Mo SMBH, a misaligned blazer,
a radiogalaxy and a galaxy cluster ?

Can A - inner jets and/or huge radio lobes ?