Gamma Rays from Active Galactic Nuclei:

I. *Production sites, acceleration/radiation mechanisms*
II. *Cosmological implications*

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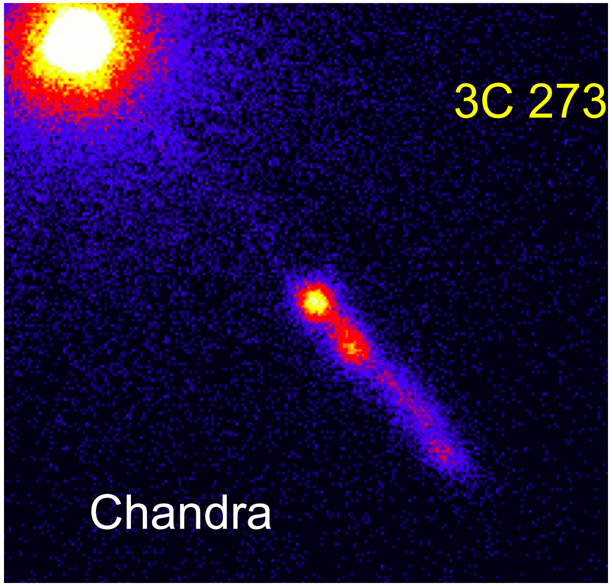
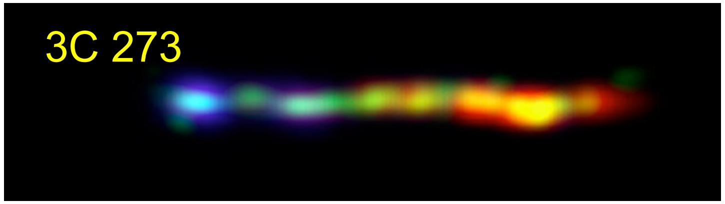
Nice, September 14, 2012

Production Sites, Scenarios, Mechanisms





Chandra X
Hubble O
Spitzer IR

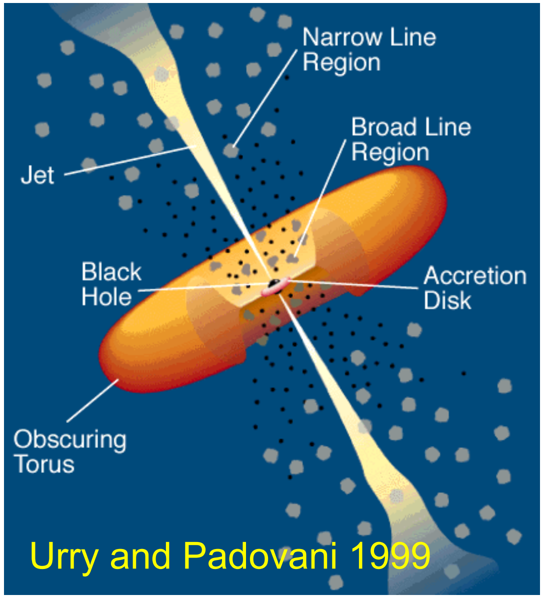
jet – approximately 20 arcsec

1 arcsec =3 kpc (z=0.158, Ho= 65 km/s Mpc

from R to X rays - nonthermal emission:
one should expect also gamma-rays on all
from sub-pc scales to multi-kpc scales!

high (GeV) and very high (TeV) energy γ-rays have been reported from hundreds and tens of AGN, respectively !

almost all of them are blazars – objects with relativistic jets directed towards the observer sites



Urry and Padovani 1999

BH
magnetosphere
sub-parsec jet
pc-scale
multi-pc jet
radio lobes
magnetized Mpc

acceleration

(sub) relativistic shocks
convertor mechanism
stochastic (Fermi II)
magnetic reconnection,
……..

radiation

Inverse Compton
electron synchrotron
Proton synchrotron
photomeson processes
(and subsequent cascades)
γ-γ pair production

plus very complex magnetohydrodynamics

$\Rightarrow$ broad range of possible realization (scenarios)

unfortunately, γ-ray images of AGN – not possible,
information only though energy spectra and variability

Active Galactic Nuclei: AGN

- Active Galaxies - galaxies with a compact, variable bright core (nucleus) the radiation of which is comparable or dominates over the emission of the host galaxy produced by stars (and partly reproduced by dust)

- AGN – central engines powered by Black Holes of 10^6 to 10^{10} M_o

- Radiation of AGN: thermal emission of the accretion flow and nonthermal emission of the relativistic jet

- several types of AGN - distinction between them sometimes arbitrary, but it is clear that we deal with several AGN populations – Seyfert galaxies, Quasars, Radio galaxies, BL Lac Objects,…

difference between these classes?

spectral lines e.g. Seyferts – rich line spectra, BL Lacs – featureless continuous
large scale morphology e.g. radio galaxies – often with tween-lobed structures
luminosity e.g. Seyferts – 10^{43}-10^{45} erg/s; QSO: > 10^{46} erg/s
polarization, variability, etc.

classification and unification of AGN?

classification of source populations is not a trivial task in astronomy, especially for AGN with very diverse spectral and temporal characteristics:

they can be biased because of different selection effects, e.g. because of strongly variable behavior of AGN. This is true especially for γ-ray emitting compact, short-lived nonthermal structures (solitary events) with highly variable parameters which contain large uncertainties (e.g. strength of the magnetic field, the speed and viewing angle of the moving emitter, etc.)

e.g. recently Giommi et al (2012) demonstrated, based on the WMAP, Planck and Fermi LAT data that the so called (very popular) "blazar sequence" (correlation between the luminosity L and the position of the synchrotron peak ν) is a selection effect "arising from the comparison of shalow radio and X-ray surveys".

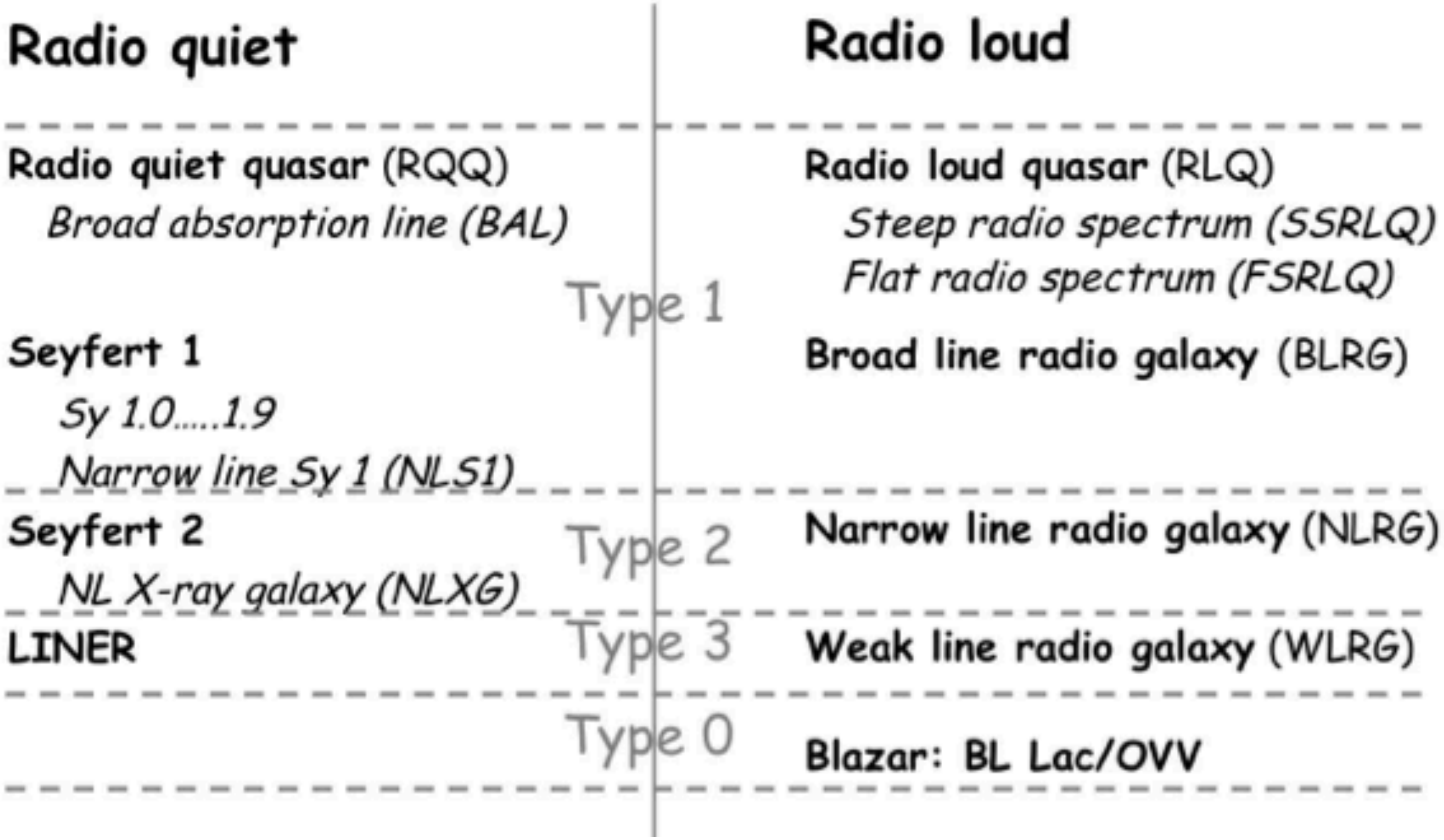
classification and unification of AGN?

Unification of AGN:

- AGN basically are of two types – Seyferts and Quasars – and difference between them is in the luminosity ($L_{QSO}/L_{Sey} > 100$)
- Seyfert 1 and Seyfert 2 galaxies are intrinsically the same sources. In the case of Seyfert 2 galaxies we do not see the nuclear source because of absorption of optical lines due to the unfavorable viewing angle
- Blazars - radio loud AGN when jet axis is close to the line of sight

Unification approach based on anisotropy due to orientation of jets (nonthermal emission) and absorption of thermal emission in dusty torus, generally provides a useful tool for systematization of large data sets, but still it seems to be a simplification of the real picture

AGN classifications: an example

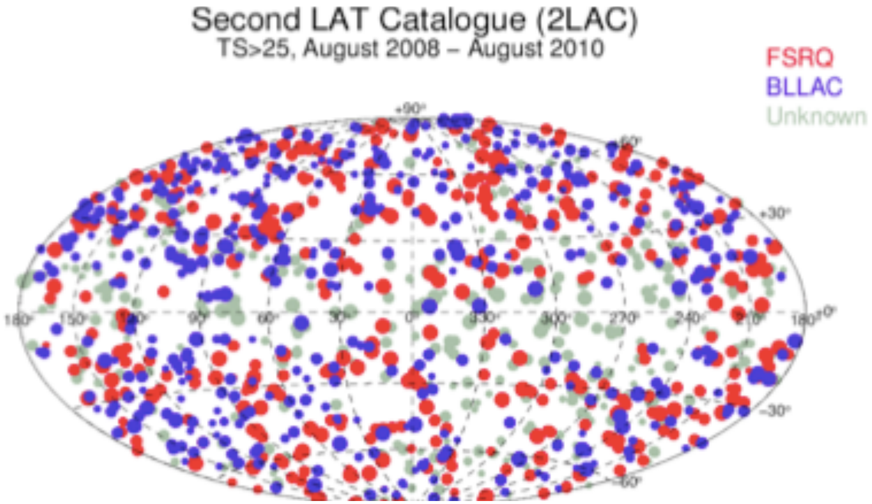


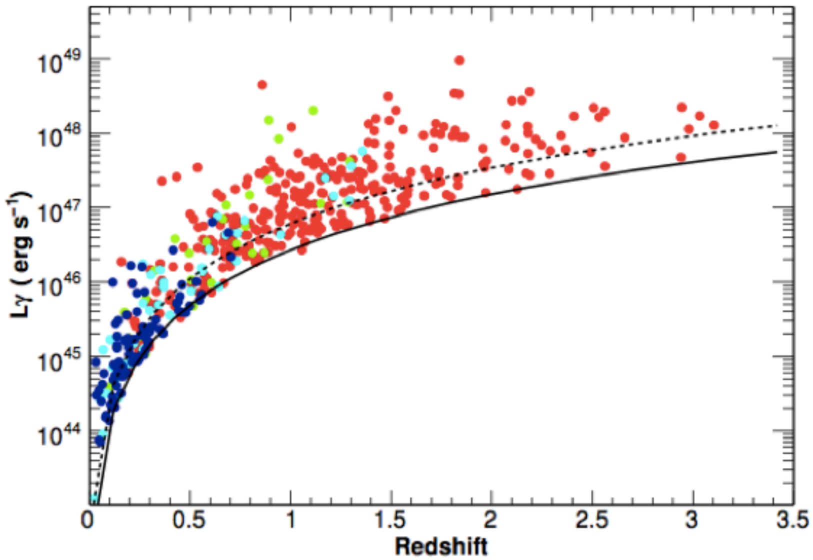
Radio quiet		**Radio loud**
Radio quiet quasar (RQQ) *Broad absorption line (BAL)* **Seyfert 1** *Sy 1.0.....1.9* *Narrow line Sy 1 (NLS1)*	Type 1	**Radio loud quasar** (RLQ) *Steep radio spectrum (SSRLQ)* *Flat radio spectrum (FSRLQ)* **Broad line radio galaxy** (BLRG)
Seyfert 2 *NL X-ray galaxy (NLXG)*	Type 2	**Narrow line radio galaxy** (NLRG)
LINER	Type 3	**Weak line radio galaxy** (WLRG)
	Type 0	**Blazar: BL Lac/OVV**

from C. Tadhunter, New AR 2008

most of gamma-ray emitting AGN are BL Lac Objects at GeV and TeV energies or Optically Violently Variable (OVV) quasars at GeV (in a few cases at TeV) energies

GeV AGN





only most powerful QSOs can be detected from large z: $L_\gamma = 10^{46}\,(f_\gamma/10^{-10}\ \mathrm{erg/cm^2\ s})\,(d/3\mathrm{Gpc})^2$ erg/s

FERMI AGN: 310 FSRQs
395 BL Lacs
156 unknown type
26 other AGN

these are apparent luminosities; “true” (intrinsic) luminosities cannot exceed 10^{48} erg/s even for 10^{10} Mo SBH; we see Doppler boosted radiation:

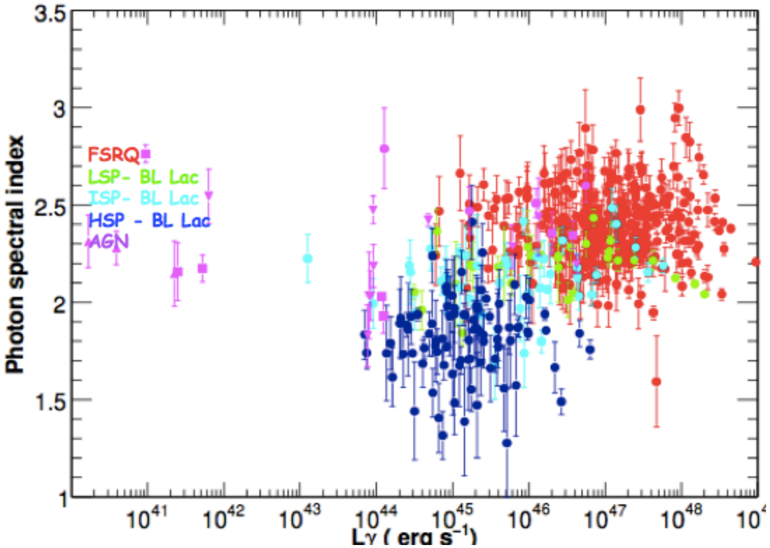
$L_{int} \to \delta^{-4} L_{app}$

$E \to \delta^{-1} E_{obs}$ δ – Doppler factor: 10-100

$\Delta t \to \delta\, \Delta t_{obs}$

D. Gasparrini, GAMMA2012

FERMI LAT: higher luminosity – harder spectrum

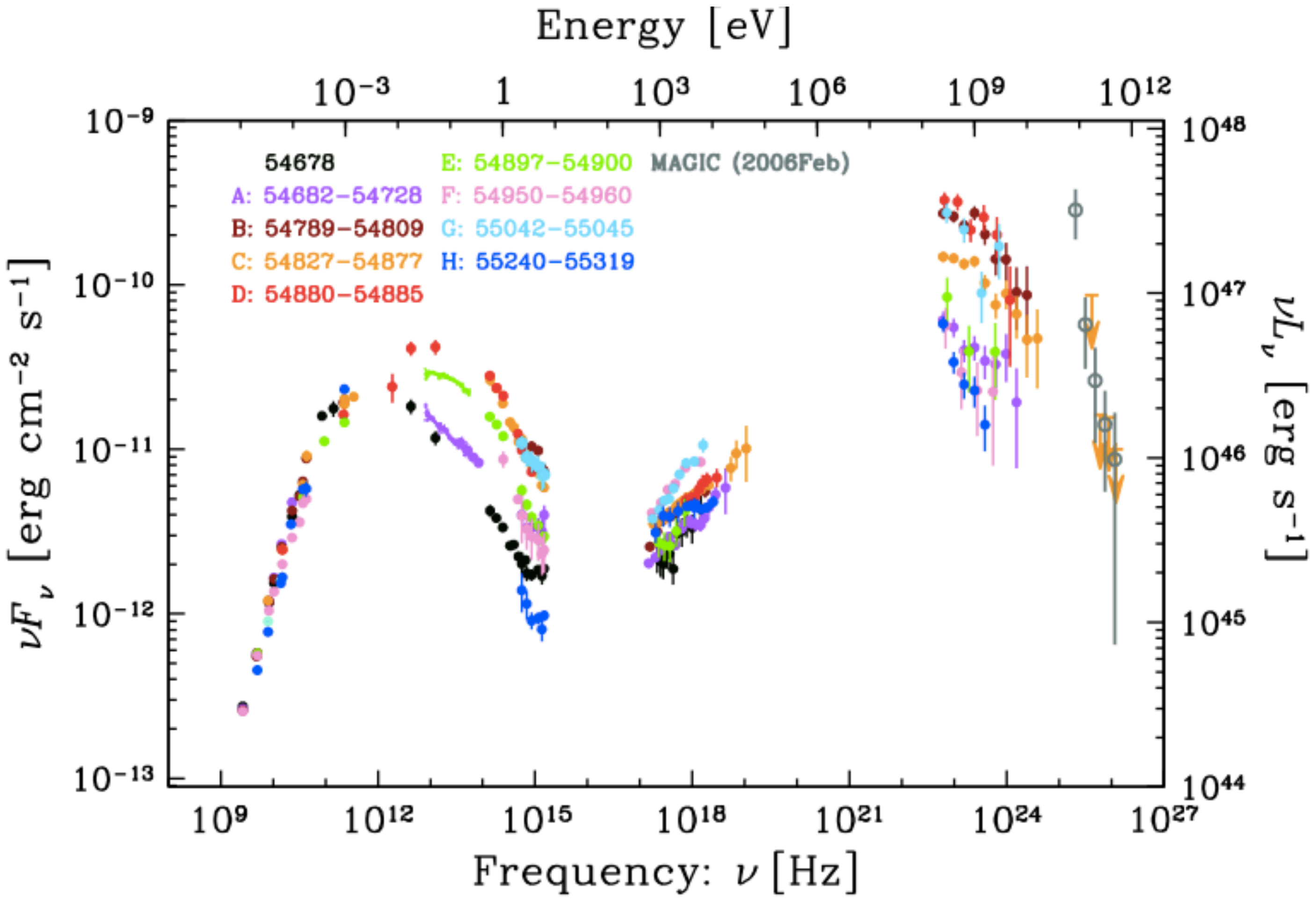


this confirms to some extent the fact that the TeV source population is dominated by less powerful BL Lacs

Reason? could be more than one reason, e.g.

- Quasars are distant sources, thus VHE γ-rays are absorbed due to interactions with EBL
- Quasars are very powerful sources - high density radiation fields may lead to
  - (1) "early" cutoffs in the electron spectra (due to enhanced Compton cooling) and correspondingly in the IC gamma-ray spectra
  - (2) internal phton-photon absorption
  - (3) could be both, but also something else

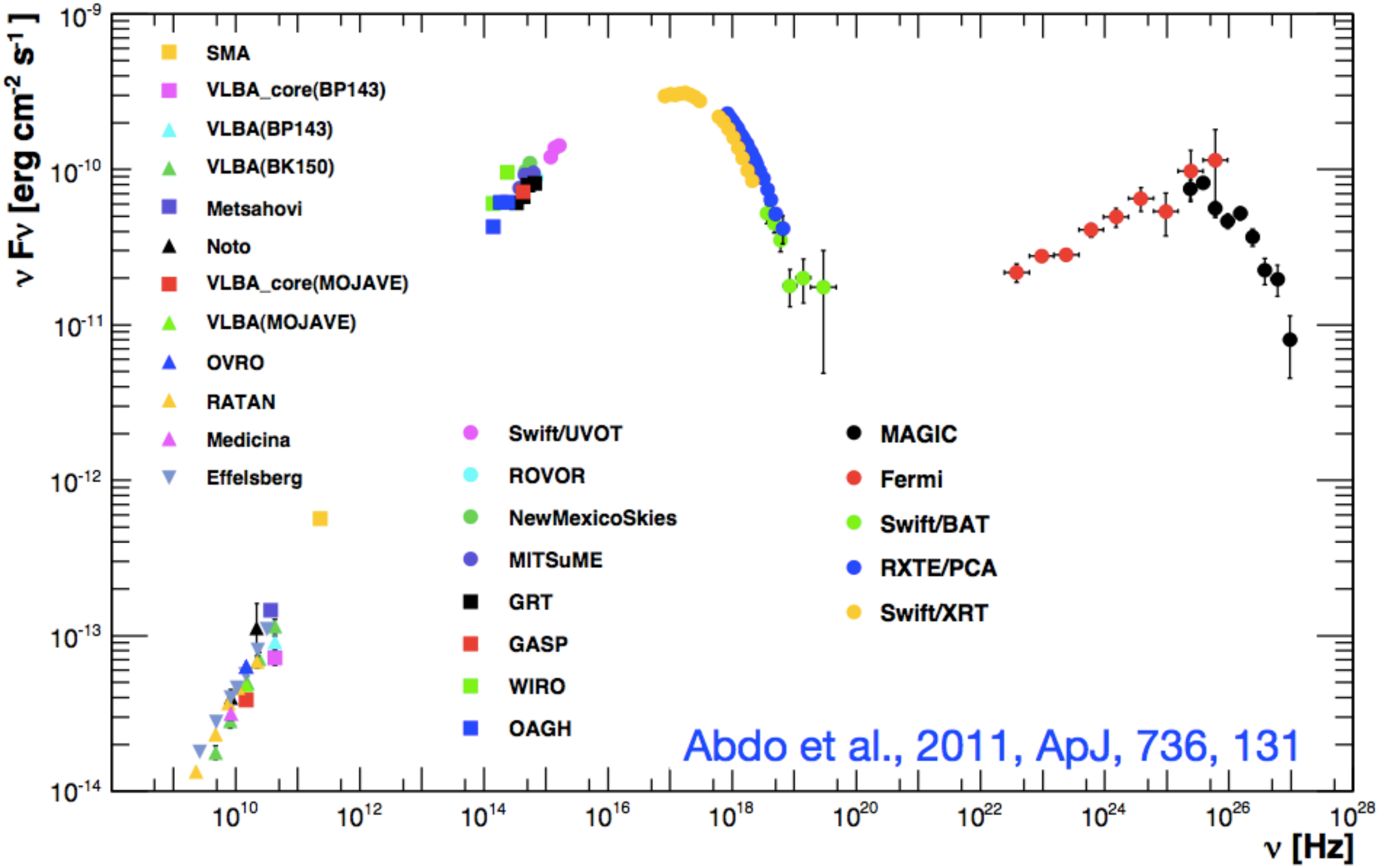
SED of 3C 279 – a classical GeV blazar



$L_\gamma/L_S > 10$ | Synchrotron peak at mm & MIR | X-rays of IC origin | variability - days

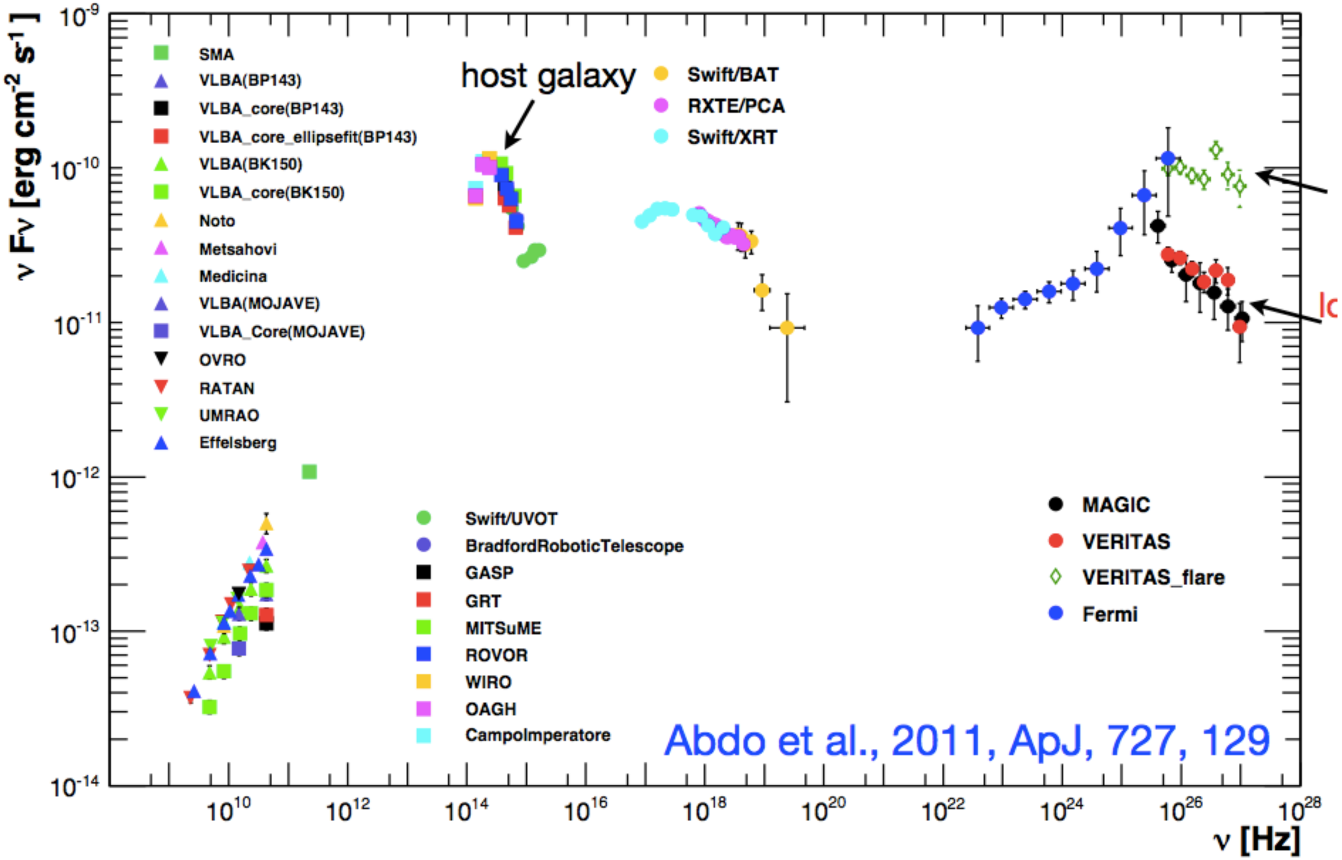
TeV emission?

a typical TeV blazar: Mkn 421



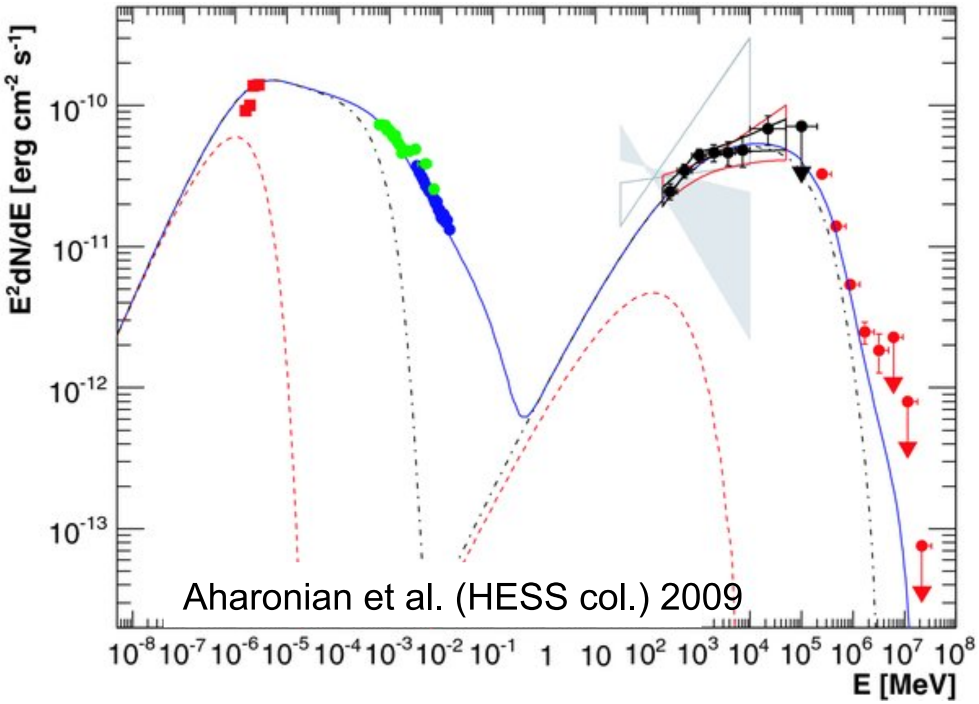
Abdo et al., 2011, ApJ, 736, 131

a typical TeV blazar: Mkn 501



Abdo et al., 2011, ApJ, 727, 129

TeV blazar PKS 2155-304 in a low state



Aharonian et al. (HESS col.) 2009

one zone SSC model

electron spectrum:
power-law with two breaks:
p1=1.3, p2=3.2, p2=4.3
$\gamma_1=1.4\times10^4$, $\gamma_2=2.3\times10^5$
and cutoff at $\gamma_{max}=3\times10^6$
B=0.02 G, R=2×10^{17}cm, $\delta=32$

with a standard remark:
"SSC is a simplification but it satisfactorily explains the SED and gives correct parameters"

my opinion: *I cannot agree with such a statement: it is poorly justified and misleading if* the low-state SED in reality is a superposition of of weak flares – the parameters will be different; also usually the role of multiple "breaks" is overestimated, while the shape at cutoff is underestimated. What to do? Better nothing, rather than `one-zone model' "industry".

When we deal with AGN we should remember that

generally the phenomena relevant to compact relativistic objects proceed under extreme physical conditions in environments characterized with

- *huge gravitational, magnetic and electric fields,*
- *very dense background radiation,*
- *relativistic bulk motions (black-hole jets and pulsar winds)*
- *shock waves, highly excited (turbulent) media, etc.*

any coherent description and interpretation of phenomena related to high energy cosmic gamma-rays requires knowledge and deep understanding of many disciplines of experimental and theoretical physics, including

nuclear and particle physics,
quantum and classical electrodynamics,
special and general relativity,
plasma physics, (magneto) hydrodynamics, etc.
and (of course) Astronomy&Astrophysics

gamma-ray emitting AGN

everything should proceed with an extreme efficiency!

conversion of gravitationl, thermal, bulk motion, electromagnetic forms of energy to nonthermal relativistic particles, i.e. effective acceleration of particles coupled with favorable conditions for production of γ-rays

SMBH and relativistic Doppler boosting – not sufficient: we need

extremely effective particle accelerators and effective emitters

Extreme Accelerators

machines where acceleration proceeds with efficiency close to 100%

(i) fraction of available energy converted to nonthermal particles

in PWNe and perhaps also in SNRs and AGN *<u>can be as large as 50 %</u>*

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

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

$t_{acc}=\eta(\varepsilon)\, E/ecB = \eta(\varepsilon)\, r_L/c$; $E_{eff}=\eta^{-1} B$ - projection of the electric field on the particle trajectory averaged when particle moves along trajectory; generally $E \ll B$, i.e. $\eta \gg 1$

$\eta=1$ extreme accelerator ($\eta < 1 \Rightarrow E > B$ – cannot be excluded)

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

as cosmic plasmas are easily heated up to keV temperatures - almost everywhere, particles (electrons and protons) can be easily accelerated to TeV energies - almost everywhere, especially in objects containing relativistic outflows -jets & winds

AGN and 10^{20} eV Cosmic Rays

the very fact of existence of such particles implies existence of extragalactic extreme accelerators…

the "Hillas condition" - $l > R_L$ - an necessary but not sufficient condition…

(i) maximum acceleration rate allowed by classical electrodynamics
$t^{-1}=\eta qBc$ or c/R_L with $\eta \sim 1$ and $\sim (v/c)^2$ in shock acceleration scenarios)

(ii) B-field cannot be arbitrarily increased - the synchrotron and curvature radiation losses become a serious limiting factor, unless we assume perfect linear accelerators …

only a few options survive from the original Hillas ("l-B") plot:
$>10^9$ M_o BH magnetospheres, small and large-scale AGN jets, GRBs

suspected sites of 10^{20} eV cosmic rays based on the condition: source size > Larmor radious

$$(R/1pc)(B/1G) > 0.1\ (E/10^{20}eV)$$

necessary but not sufficient condition: it implies

(1) minimum acceleration time

$$t_{acc}=R_L/c=E/eBc$$

acceleration in fact is slower:

$$t_{acc}=(1\text{-}10)\eta\ R_L/c\ (c/v)^2$$

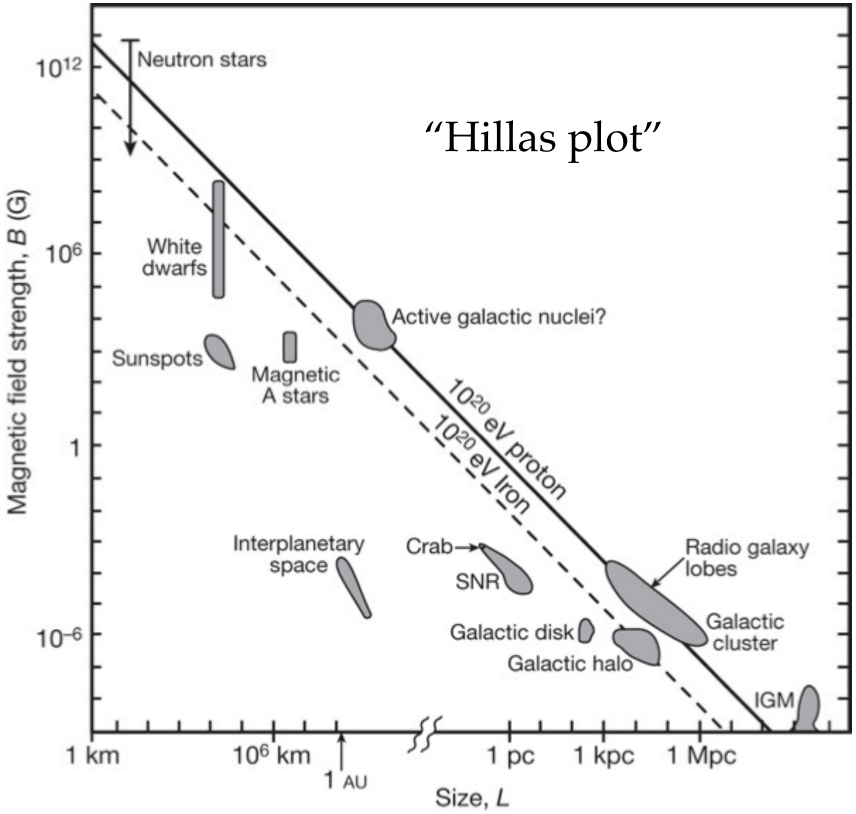
with $\eta>1$ and shock/bulk-motion speed $v<c$ ($\eta=1$ - Bohm diffusion)

Compact objects like AGN and GRBs are the best candidates

(2) no energy losses

but synchrotron/curvature losses in compact objects become severe limiting factor

“Hillas plot”



PM Bauleo & JR Martino Nature 458, 847-851 (2009

acceleration sites of 10^{20} eV CRs ?

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

signatures of extreme accelerators?

✓ synchrotron self-regulated cutoff:

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

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

✓ 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, FA et al. 2003, Phys Rev D **68** 043003*

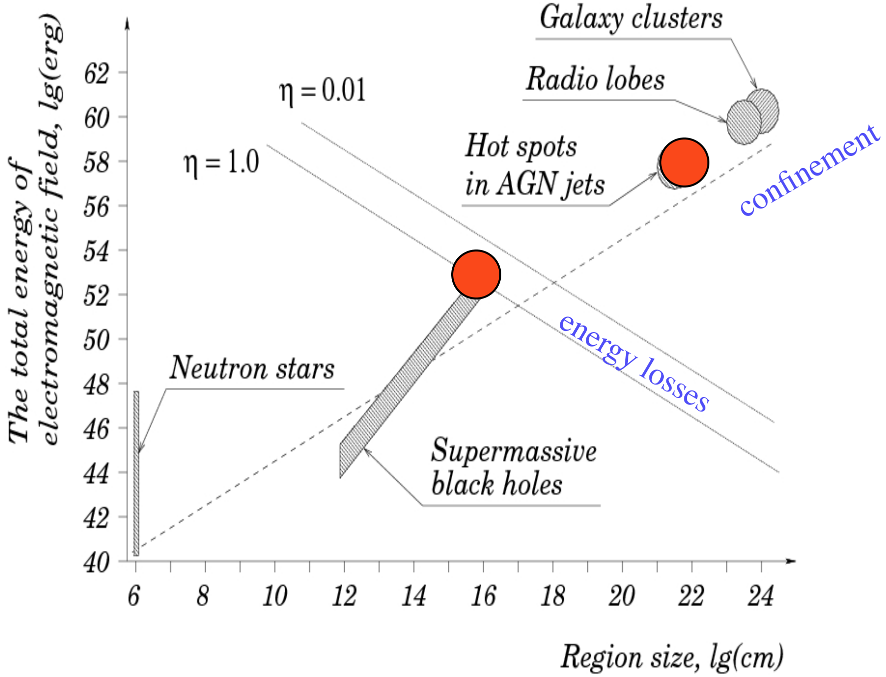
✓ observable off-axis radiation

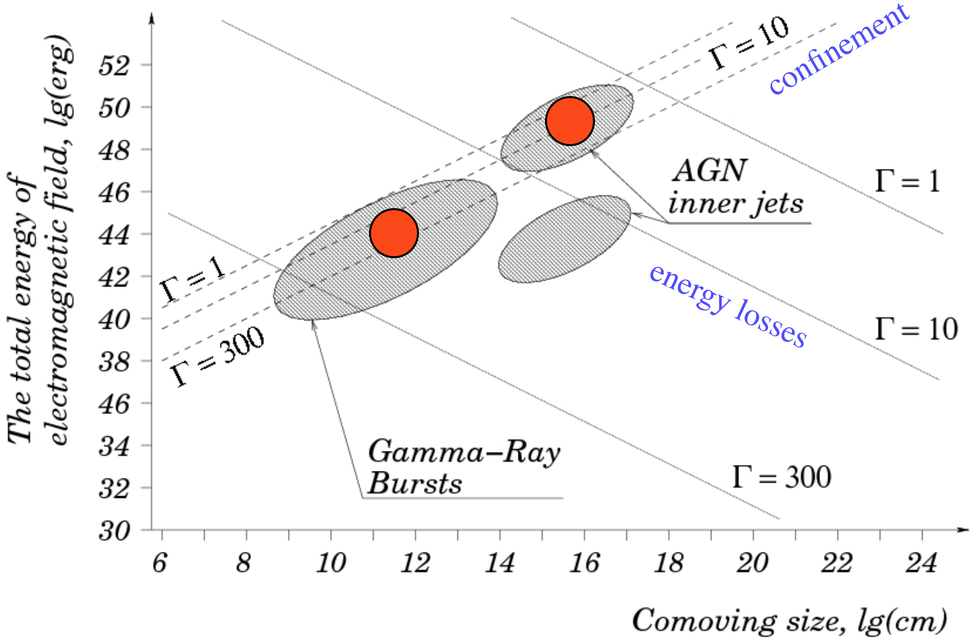
radiation pattern can be much broader than 1/Γ

*Derishev, FA et al. 2007, ApJ, **655**, 980*

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

*FA, Belyanin, Derishev 2002, Phys Rev D, **66**, id. 023005*





radiation and absorption processes

any interpretation of an astronomical observation requires

- ✓ unambiguous identification of radiation mechanisms and
- ✓ good knowledge of radiation and absorption processes

gamma-ray production and absorption processes:
several but well studied

interactions with matter

E-M:		VHE	
bremsstrahlung:	$e\ N(e) => e'\ \gamma\ N(e)$	*	$E\gamma \sim 1/2 E_e$
pair production	$\gamma\ N(e) => e^+ e^-\ N(e)$	*	
e+e- annihilation	$e^+ e^- => \gamma\ \gamma$ (511 keV line)		

Strong/week: pp (A) $=> \pi, K, \Lambda, \ldots$ ** $E\gamma \sim 1/10 E_p$

$\pi, K, \Lambda => \gamma, \nu, e, \mu$

$\mu => \nu$

also in the low energy region

Nuclear: $p\ \ A => A^* => A'\ \gamma, n$

$n\ p => D\ \gamma$ (2.2 MeV line)

interactions with radiation and B-fields

Radiation field **VHE**

E-M:
inverse Compton: $e\ \gamma\ (B) => e'\ \gamma$ ** $E\gamma \sim \varepsilon(Ee/mc^2)^2$ (T) to ~Ee (KN)
$\gamma\gamma$ pair production $\gamma\ \gamma\ (B) => e^+e^-$ **

Strong/week $p\ \gamma => \pi, K, \Lambda, \ldots$ *
$\pi, K, \Lambda => \gamma, \nu, e, \mu$ $E\gamma \sim 1/10Ep$
$\mu => \nu$
$A\ \gamma => A^* => A'\ \gamma$ * $E\gamma \sim 1/1000A\ Ep$

B-field
synchrotron $e\ (p)\ B => \gamma$ *
pair production $\gamma\ B => e+e-$ * $E\gamma \sim BE_e^2$; $h\nu_{max} \sim \alpha^{-1}\ mc^2$

leptonic or hadronic?

gamma-rays produced in interactions of electrons and protons/nuclei often are called leptonic and hadronic interactions
but it is more appropriate to call them as E-M (electromagnetic) and S (strong)

examples:

(i) synchrotron radiation of protons - pure electromagnetic process
interaction of hadrons without production of neutrinos

(ii) photon-photon annihilation => μ+μ- => neutronos, antineutrinos
production of neutrinos by photons as parent particles

E-M are calculated with high accuracy and confirmed experimentally
S are well studied experimentally and explained theoretically

often several processes proceed together => cascades in matter, radiation and B-fields

gamma-ray production efficiency

many reported TeV gamma-ray sources require not only extreme particle accelerators but also effective production of gamma-rays

effective gamma-ray production?

cooling time of the given gamma-ray production process is shorter than

(1) timescales of radiative and non-radiative (e.g. adiabatic) losses

(2) intrinsic dynamical (source age, acceleration time, particle escape time)

Note*:* high efficiency is an important but not sufficient/decisive condition for a gamma-ray sources to be detected. The detectability depends also on

- ✓ power and distance to the source ($\sim W/d^2$)
- ✓ beaming factor, e.g. Doppler boosting ($\sim \delta^4$)
- ✓ Sensitivity of the instrument in the given energy domian

inefficient!

Nonthermal X-ray Bremsstrahlung

at first glance quite attractive (*"why should I invoke multi-TeV electrons to produce X-rays when can I use keV electrons to produce keV X photons?"*) in fact only less than 10^{-5} fraction of the kinetic energy of electrons (protons) is released in X-rays; 99.99…% goes to the ionization and heating of the gas

$$L_e > 10^5 \, L_X = 10^{37} (f_X / 10^{-12} \text{ erg/s}) \, (d/1\text{kpc})^2 \text{ erg/s}$$

the same is true for gamma-ray line emission due to excitation of nuclei by sub-relativistic protons - both mechanisms "work" during Solar flares, otherwise it typically leads to unreasonably high requirements for production rate of sub-relativistic electrons - this makes the extremely interesting issues like detection of gamma-ray lines, in particular from ISM, SNRs, GMCs, etc (information about the sub-relativistic CRs !) observationally very difficult

we are unlucky with prompt gamma-ray line astronomy!

pp -> π^0 -> 2γ

not very efficient

no competing dissipation mechanisms - in "calorimetric scenarios": $L_\gamma \sim L_p/3$
but the process itself is not very fast/relatively slow: $t_\pi \sim 10^{15}\ (n/1\mathrm{cm}^{-3})^{-1}$ s
usually the source age or particle escape is a big issue !

SNRs: typical density: $n \sim 1\mathrm{cm}^{-3}$, magnetic field $B \sim 100\mu G$, size $R \sim 3$ pc assuming Bohm diffusion, $D(E)=r_L c/3=10^{25}(E_p/10\mathrm{TeV})^{-1}\ \mathrm{cm}^2/\mathrm{s}$, escape time of protons which produce 1 TeV gamma-rays: $t_{esc} \sim R^2/D \sim 10^{13}$ s $\sim 0.01 t_\pi$

GMCs: typical densities $n > 100\mathrm{cm}^{-3}$, size $R > 10$pc, but >1000 times faster diffusion : $t_{esc} \sim 10^{11}$ s $\sim 0.01 t_\pi$ => the same ~1% effcinecy

Galaxy Clusters: densities $n \sim 10^{-3}$ s, size R>1Mpc - full confinement!
$t_\pi < 10^{18}\ (n/1\mathrm{cm}^{-3})^{-1}$ s - comparable to the age (Hubble time) !

γBinaries: protons accelerated by the compact object and interacting with the dense stellar disk of companion: $n \sim 10^{13}\ \mathrm{cm}^{-3}$; the cooling time could be shorter than escape time => potentially effective production of gamma-rays and νs

higher efficiencies at MeV/GeV energies because of problem of confinement

Synchrotron radiation

very efficient

especially in extreme particle accelerators where acceleration proceeds at the maximum (theoretically possible) rate and the further acceleration is limited by synchrotron losses

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

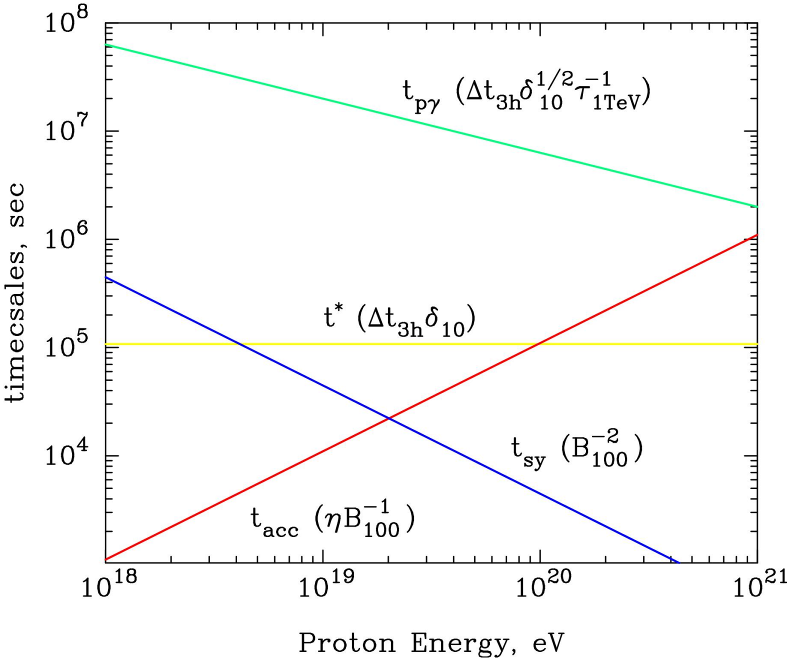
=> self regulated cutoff

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

$\simeq 300$GeV proton synchrotron

$\simeq 150$MeV electron synchrotron

proton-synchrotron is effective in compact objects with large B-fields (when $t_{\rm coo} < R/c$)



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

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

$E_{\rm max} \sim B^{-1/2}$, but $h\nu_{\rm cut}$ - independent of B

$t(h\nu_{\rm cut})=2.4{\rm x}10^4\ ({\rm B}/100{\rm G})^{-3/2}\ \eta^{1/2}$ s $< R/c$

$B> 100(R/10^{15}{\rm cm})^{-2/3}\ \eta^{1/3}$ G

Synchrotron radiation

very efficient

do we have evidence for signatures of extreme accelerators?

electron synchrotron - most likely in the spectrum of the Crab Nebulae
protons synchrotron - in some blazers, GRBs ?

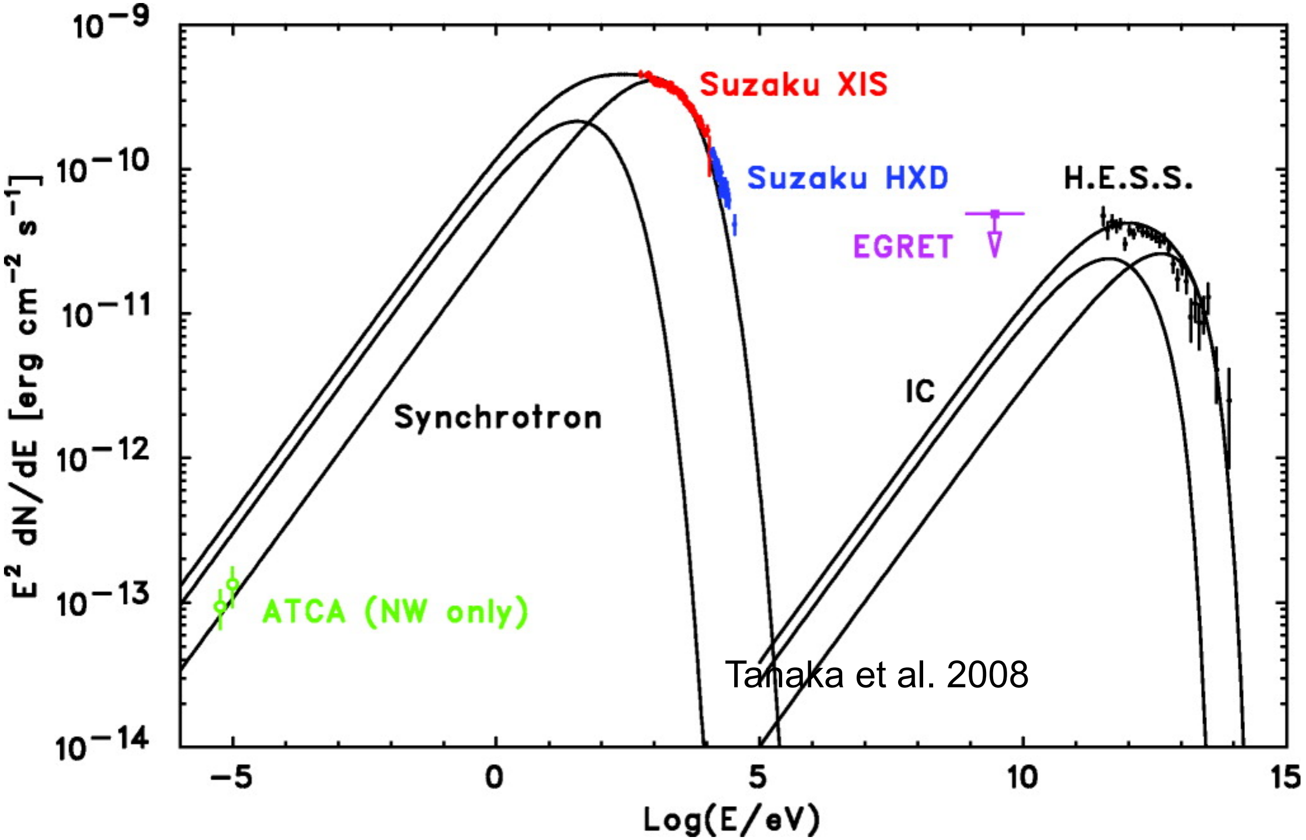
factors reducing the maximum energies of the synchrotron cutoff?

- *radiative losses in the case of electrons-synchrotron (in binaries)*
- *not sufficiently strong B-fields in the case of proton-synchrotron*

position of the synchrotron peak as indicator of acceleration efficiency

electron synchrotron efficiency could be close 100% even in non-extreme accelerators though the radiation at lower energies, e.g. in young SNRs

Sy-IC SED of SNR RXJ 1713-4639



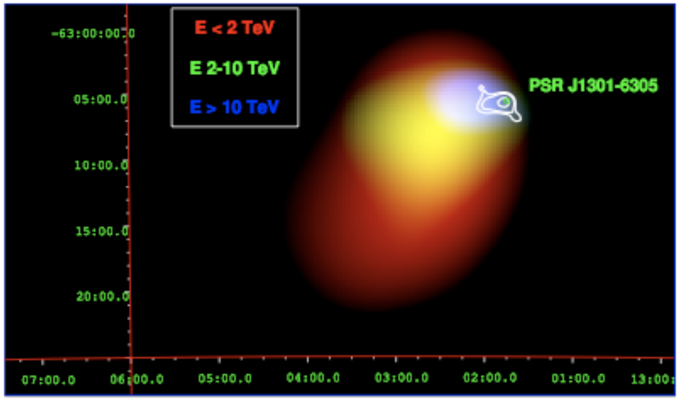
Tanaka et al. 2008

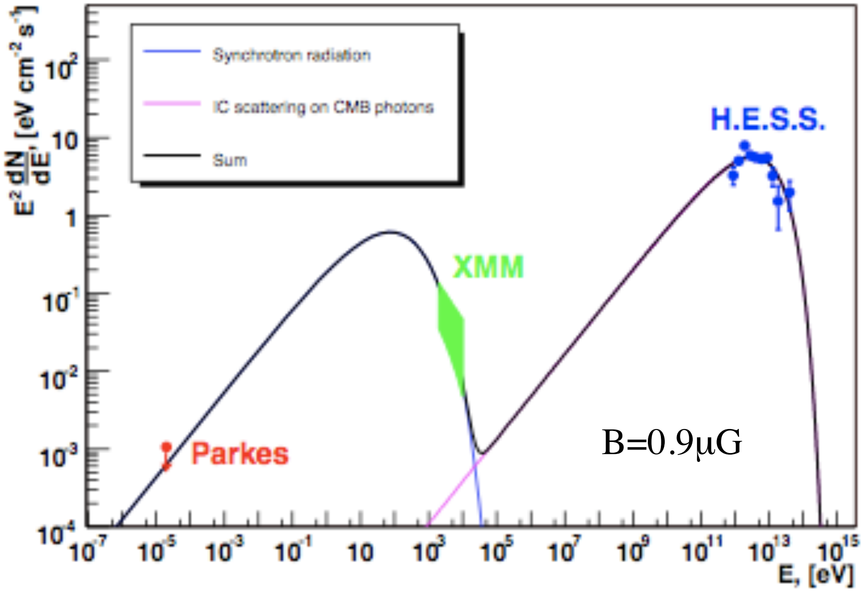
two characteristic Synchrotron and IC peaks; $h\nu_{max}$ ~ 1 (v/3000km/s)2 κ keV;
κ= 1 implies maximum effective Bohm diffusion regime for DSA

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

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

HESS J 13030-62 = PSR J1301-6305?



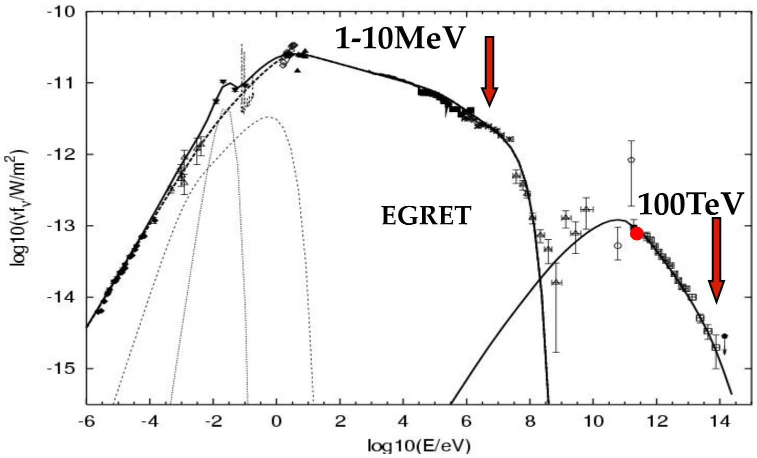


dramatic reduction of the angular size with energy:strong argument in favor of the IC origin of the γ-ray nebula

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

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

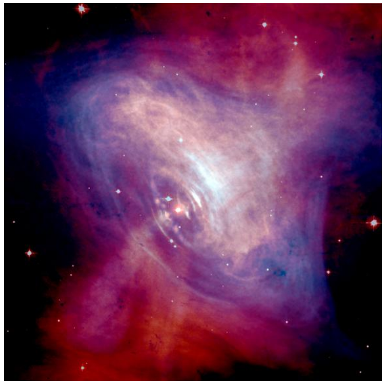
Crab Nebula – *a perfect electron PeVatron and an extreme accelerator*



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 $h\nu_{cut} \sim 100$ MeV => $\eta \sim 1$ – acceleration at the maximum rate

Flares! maximum of SED beyond 100 MeV => $h < 1$ (or $E > B$) or Doppler boosting?

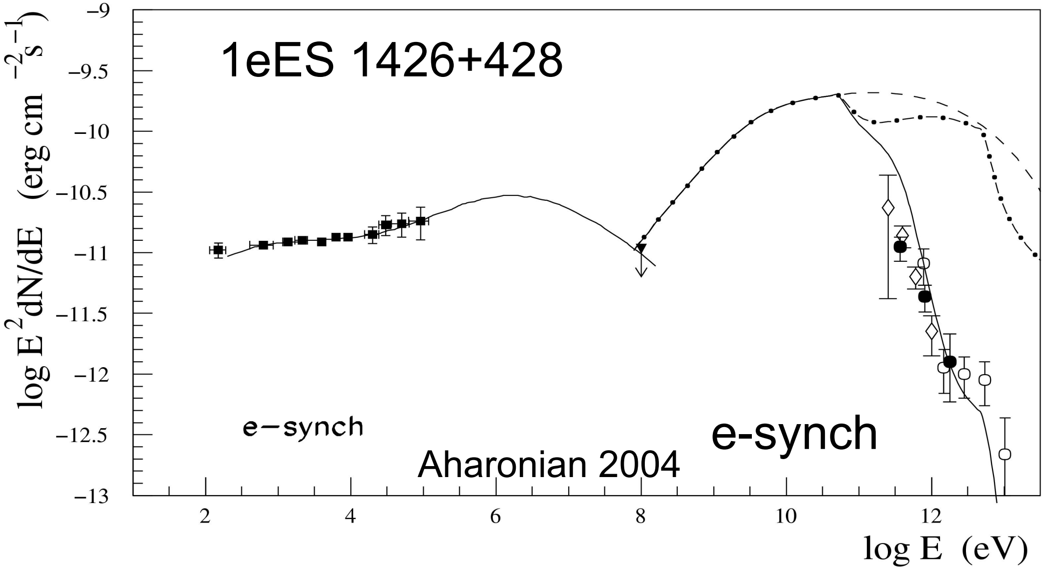
(see lecture of M. Tavani)

Can AGN operate like the Crab Nebula

proton synchrotron as an alternative for explanation of the TeV emission spectra of BL LACs ?

boosted electron synchrotron can explain the GeV emission of FSRQ?

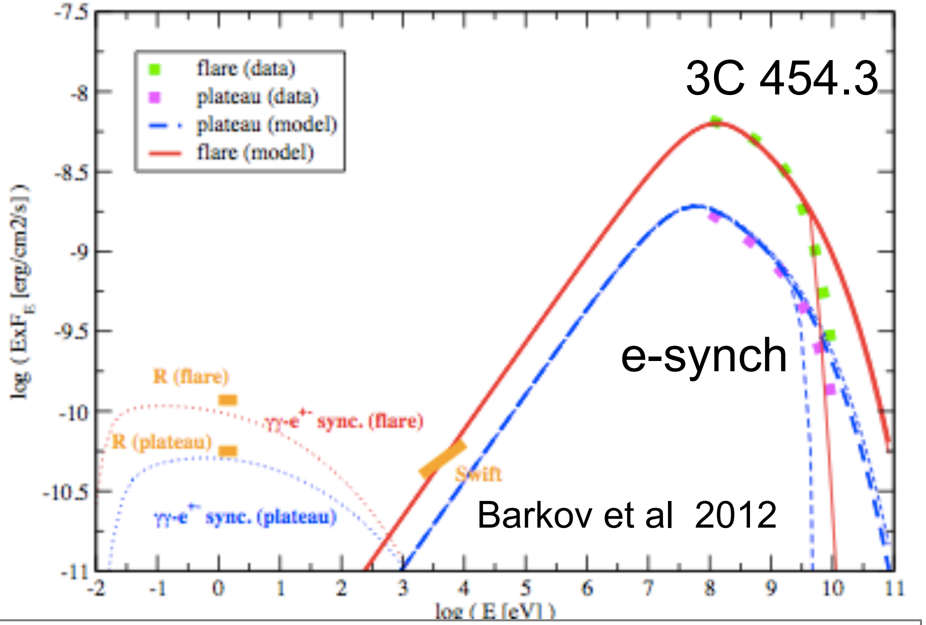
Internal γ-γ absorptions provides Better fit, and explains the low-energy radiation by synchrotron radiation of secondary electrons



1eES 1426+428

e-synch

Aharonian 2004



3C 454.3

e-synch

Barkov et al 2012

SSC or EXC models: while the production of nonthermal radiation is efficient, location of the synchrotron peak below X-ray band implies very low, $\eta < 10^{-6}$ (!?) acceleration rate?

IC: eγ -> e+γ'

very efficient

- ✓ compact objects - binaries, AGN… -
  very effective with some exceptions

- ✓ PWNe with very small B-field: $L_{IC}=Le(w_{2.7K}/w_B)=L_e(B/3mG)^{-1} \sim L_e$ if B <3mG; thanks to very effective (relativistic shock?) acceleration
  electrons still can be accelerated to 100 TeV or beyond

- ✓ Clusters of Galaxies - despite small B-field (~ 1μG) and limited shock speed (~ 2000 km/s), thanks to the large size and age of these cosmological structures, protons can be accelerated to 10^{18}-10^{19} eV, produce secondary (Bethe-Heilter) pairs at interactions with 2.7K CMBR, and the secondary electrons can produce effective IC gamma-rays upscattering 2.7K CMBR

- ✓ many other realizations….

when in the Klein-Nishina regime, IC is accompanied by γ-γ pair-production

Hadronic vs. Electronic models of TeV Blazars

SSC or external Compton *– currently most favoured models*:

- easy to accelerate electrons to TeV energies
- easy to produce synchrotron and IC gamma-rays

recent results require more sophisticated leptonic models

Hadronic Models:

- protons interacting with ambient plasma — neutrinos
  very slow process:

unlikely

- protons interacting with photon fields — neutrinos*
  low efficiency + severe absorption of TeV γ-rays

- proton synchrotron — no neutrinos
  very large magnetic field B=100 G + accelaration rate c/r_g

"extreme accelerator" (of EHE CRs) Poynting flux dominated flow

*detectable neutrinos from EGRET AGN but not from TeV blazars

Gamma-ray emission of Blazars

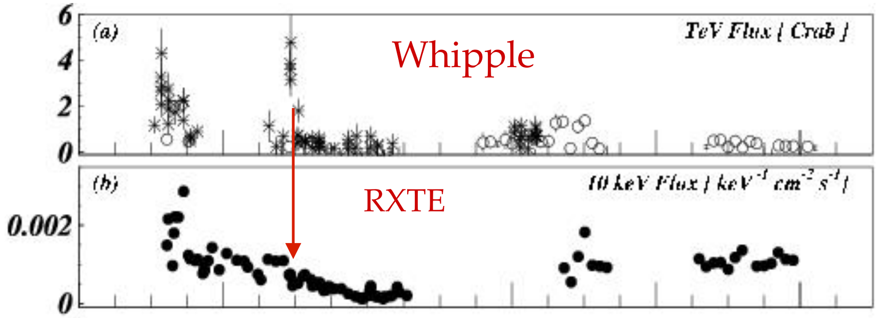
large Doppler factors: make more comfortable the interpretation of variability timescales (larger source size, and longer acceleration and radiation times), reduces (by orders of magnitude) the energy requirements, allow escape of GeV and TeV γ-rays ($t_{\gamma\gamma} \sim \delta_j^6$)

uniqueness: Only TeV radiation tells us unambigiously that particles are accelerated to high energies (one needs at least a TeV electron to produce a TeV photon) in the jets with Doppler factors > 10 otherwise gamma-rays Cannot escape the source due to severe internal photon-photon pair production

combined with synchrotron: derivation of several basic parameters like B-field, total energy budget in accelerated particles, thus to develope a quanititative theory of MHD, particle acceleration and radiation in relativistic jets, although yet with many conditions, assumptions, caveats...

deviations from standard concepts

1ES 1959+650



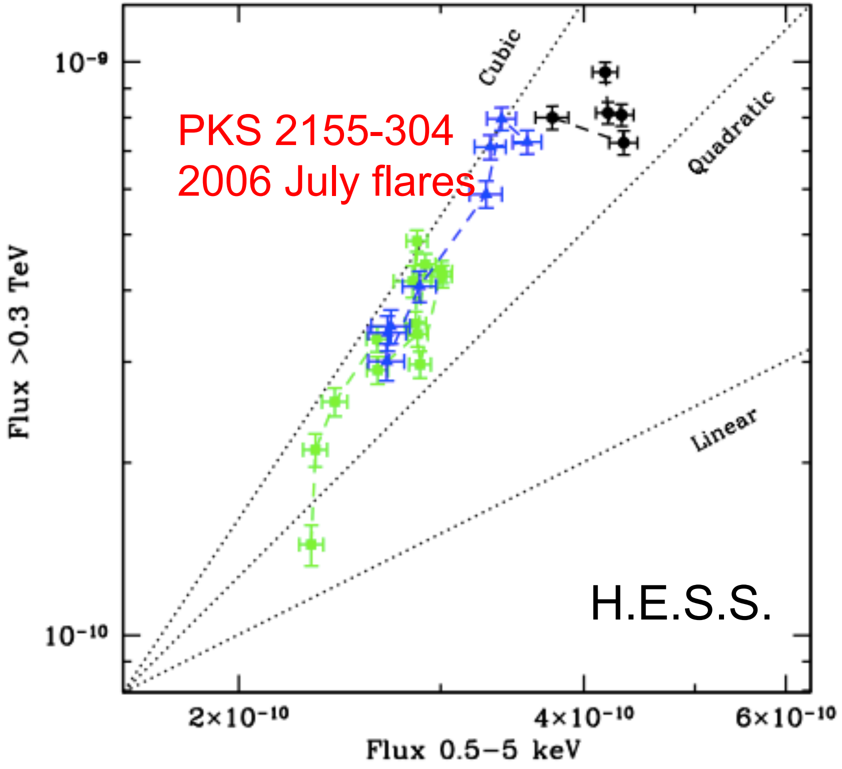
"orphan" TeV flare:

no X-TeV correlations

contradicts to the concept of
the Compton origin of γ-rays ?

not really… there could be several natural explanations within the leptonic models

generally in IC scenarious one can expect quite unusual/nonstandard X-TeV relation



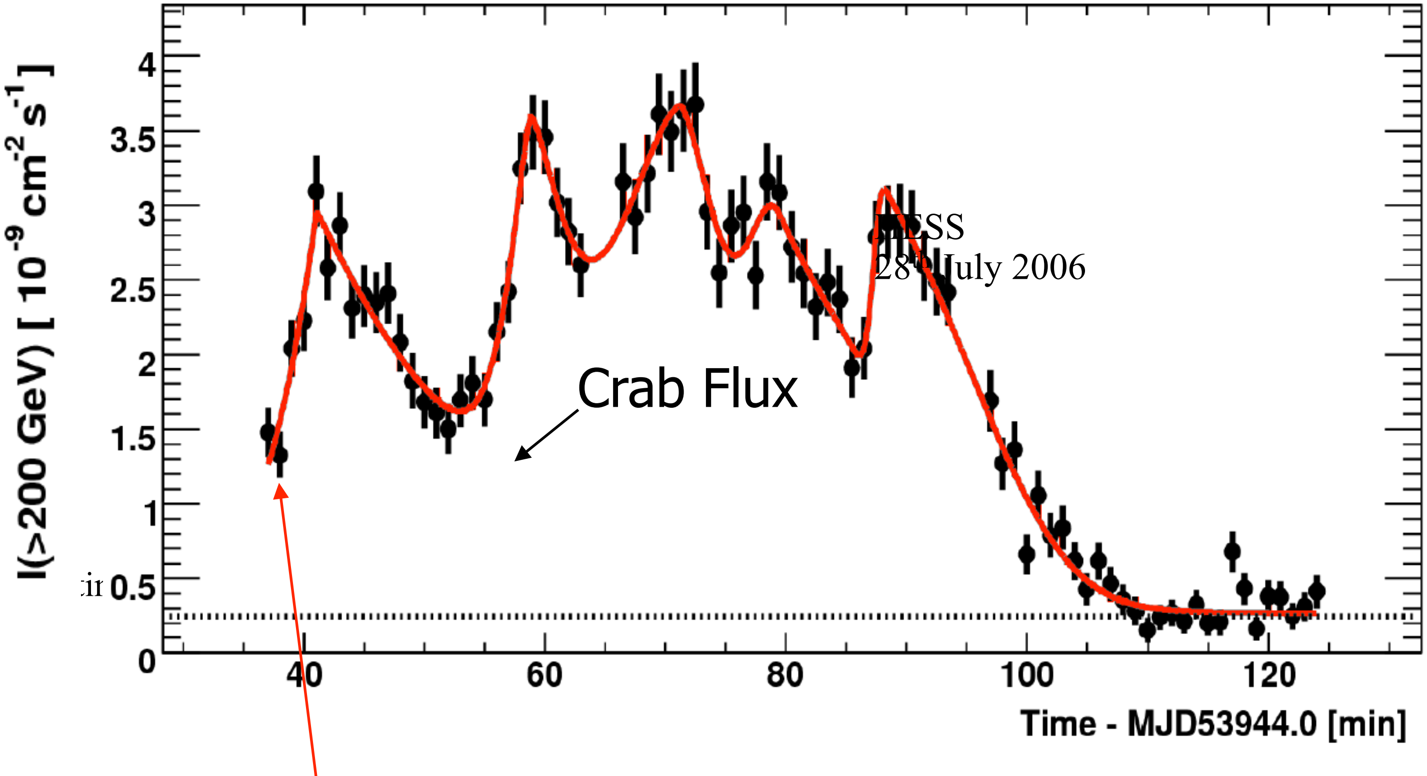
increase of TeV flux by a factor of 20, while X-ray and optical fluxes have been increased only by a factor of 2 and 15%, respectively

TeV-X cubic dependence against the simple SSC model

most exciting results of recent years

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

several min (200s) variabiliry timescale => $R = c\,\Delta t_{var}\,\delta_j = 10^{14}\delta_{10}$ cm for a 10^9Mo BH with $3R_g = 10^{15}$ cm => $\delta_j > 100$, i.e. close to the accretion disk (the base of the jet), the bulk motion $\Gamma > 50$



HESS
28th July 2006

Crab Flux

rise time <200s

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

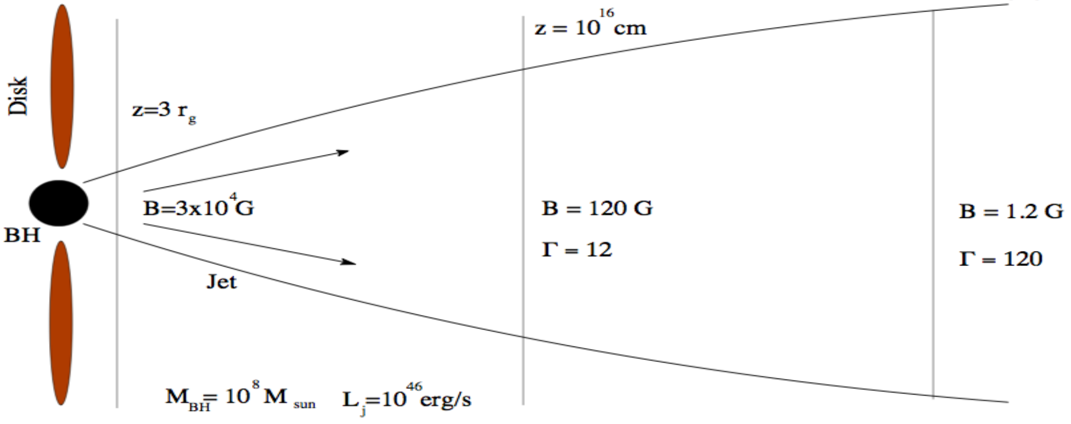
- several min variability timescale => $R=ct_{var}\delta_j \sim 10^{13}\delta_j$ cm for a 10^9Mo BH with 3Rg ~ 10^{15} cm => δj > 100, i.e. close to accretion disk (the base of the jet), the Lorenz factor of the jet $\Gamma > 50$ - this hardly can be realized close to Rg!

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

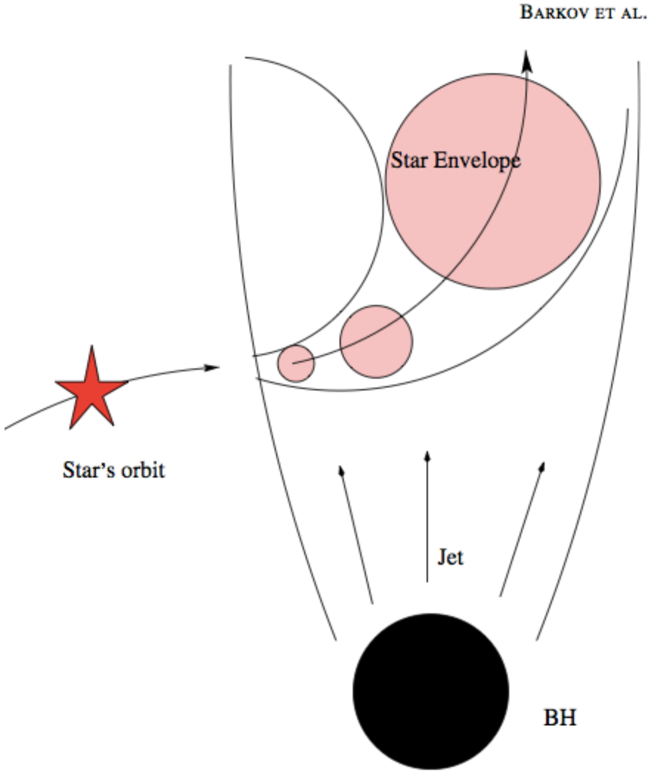
- thus for the observed $t_{var} < 200$ s, the mass of BH cannot significantly exceed 10^7Mo. On the other hand the "BH mass–host galaxy bulge luminosity" relation for PKS2155-304 gives $M > 10^9$Mo.

Solution? perturbations are cased by external sources, e.g. by magnetized condensations ("blobs") that do not have direct links to the central BH; do we deal with the scenario "star crosses the relativistic e^+e^- jet" ?

“star crosses the relativistic e^+e^- jet”



Barkov et al 2010



B-field: very large or very small?

in powerful blazars at subparsec scales B-field cannot be smaller than 1G, a serious constraint for the simplified one-zone “leptonic models,

M 87 – evidence for production of TeV gamma-rays close to BH ?

- Distance: ~16 Mpc

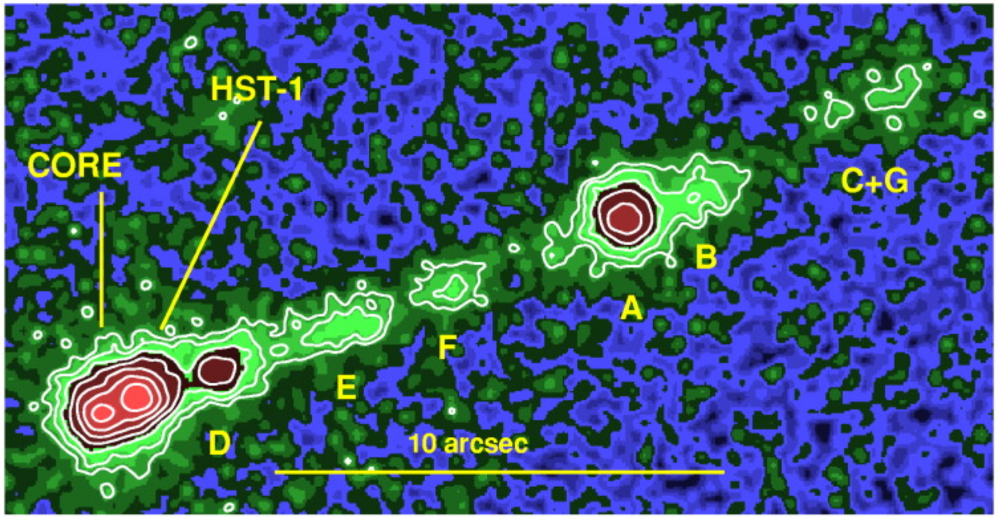
- central BH: $3\times10^9\ M_O$ *)
- Jet angle: ~30°

  => *not a blazar*!

discovery (>4σ) of TeV γ-rays by HEGRA (1998) and confirmed recently by HESS/VERITAS, MAGIC

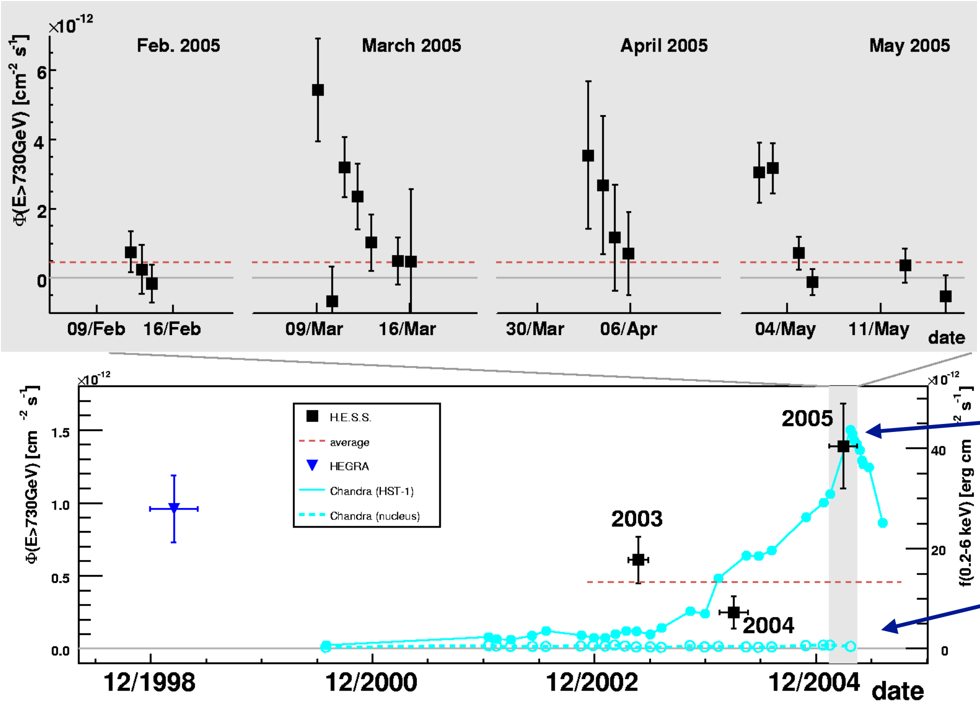
*) recently 6.4 x $10^9\ M_o$

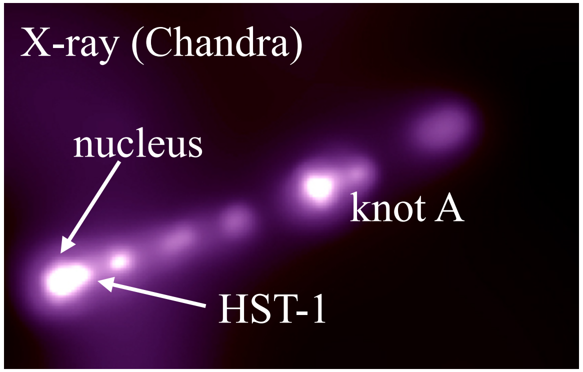
arXiv: 0906.1492 (2009)



M87: light curve and variabiliy

HESS Collaboration 2006, Science, **314**,1427





HST-1

core

I>730 GeV [cm^{-2} s^{-1}]

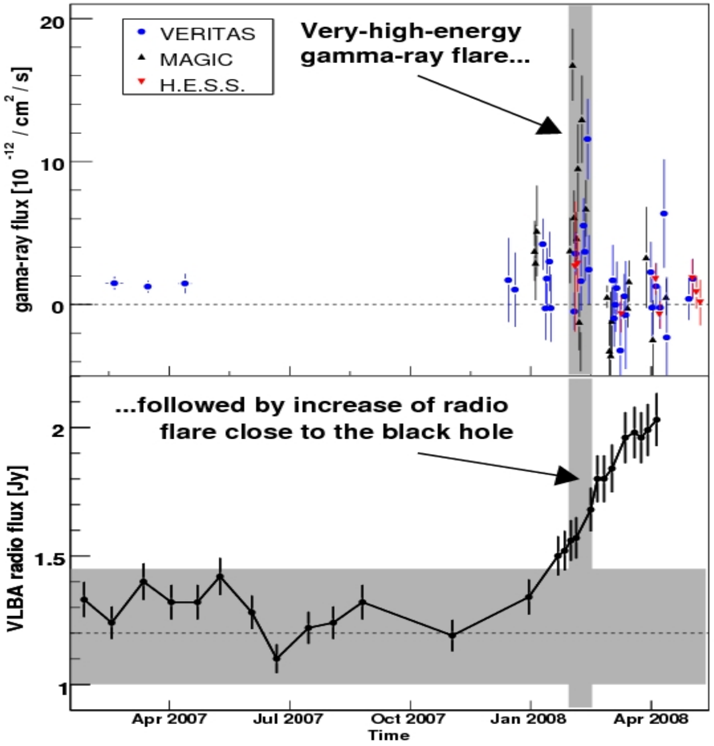
Site ? - the core (nucleus) - BH magnetosphere or the base of the jet

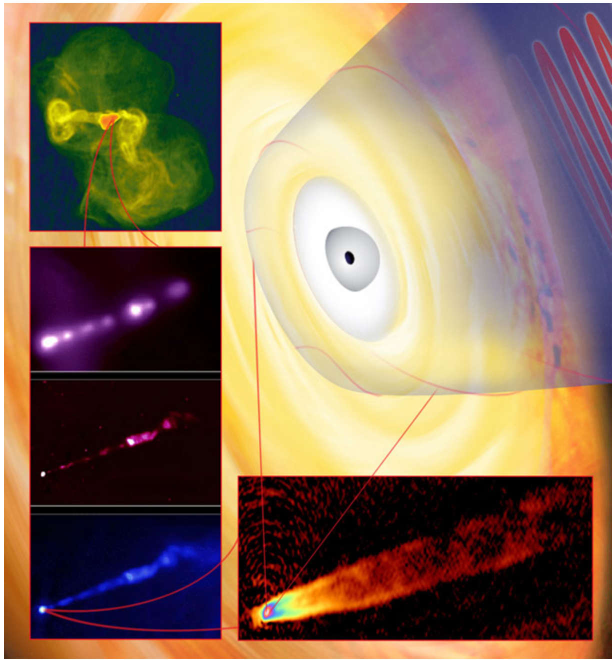
short-term variability on 1-2 day scales => emission region R ~ $5 \times 10^{15} \delta_j$ cm
=> production of gamma-rays very close to the ‘event horizon’ of BH?

because of very low luminosity of the core in O/IR:
TeV gamma-rays can escape the production region

$$L_{IR} \approx 10^{-8} L_{Edd}$$

New! NRAO and VERITAS/MAGIC/HESS: *Science, July 2, 2009*
Simultaneous TeV and radio observations allow localization of gamma-ray production region within 50 R_s





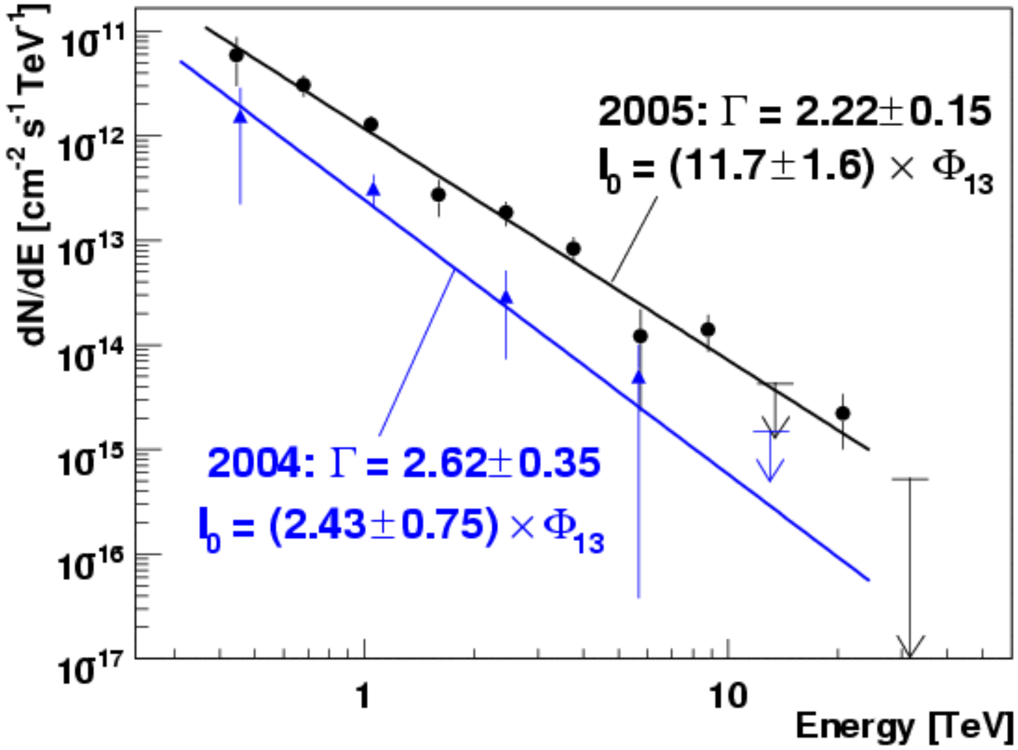
monitoring of the M87 inner jet with VLBA at 43 GHz (ang. res. 0.21x0.43 mas) revealed increase of the radio flux by 30 to 50% correlated wit the increase in TeV gamma-ray flux in Feb 2008

conclusion? *TeV gamma-rays are produced in the jet collimation region within 50 Rs around BH*

energy spectra

energy spectra for 2004 ($\sim 5\sigma$) and 2005 ($\sim 10\sigma$)

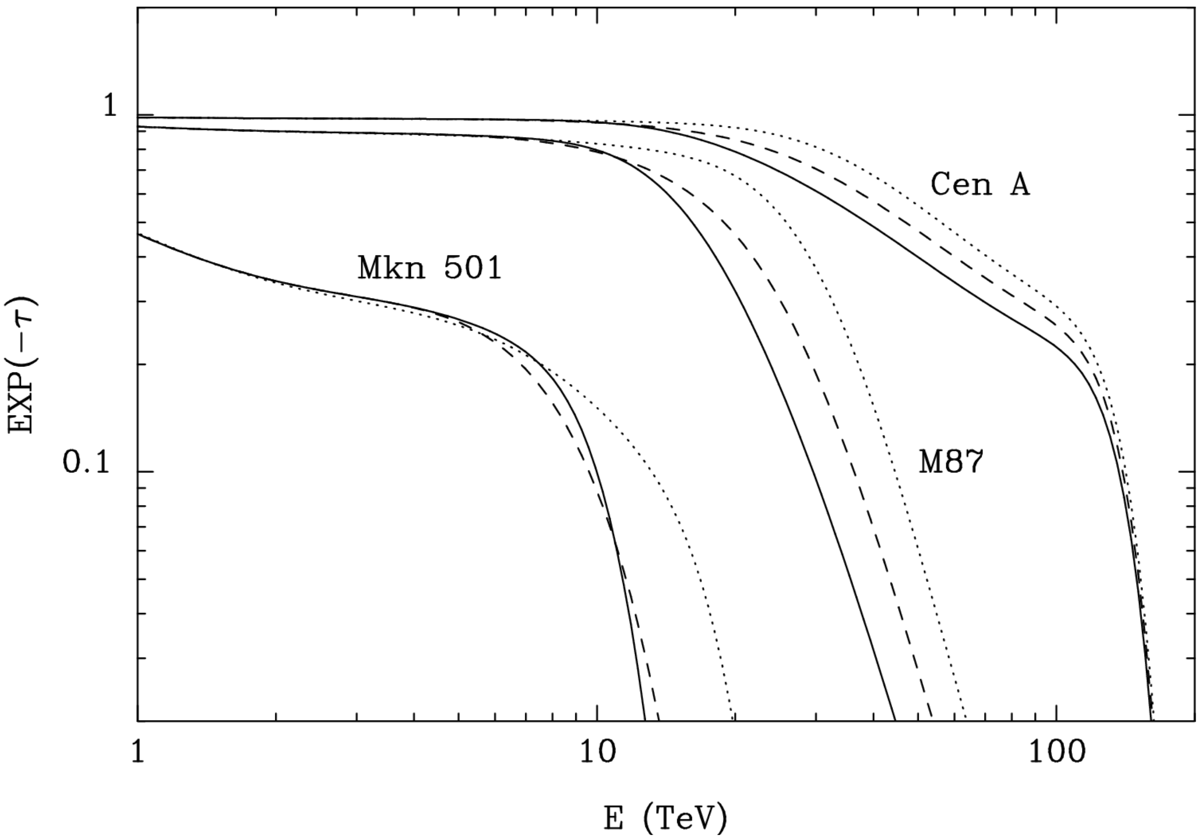
Differential spectra well described by power-laws:



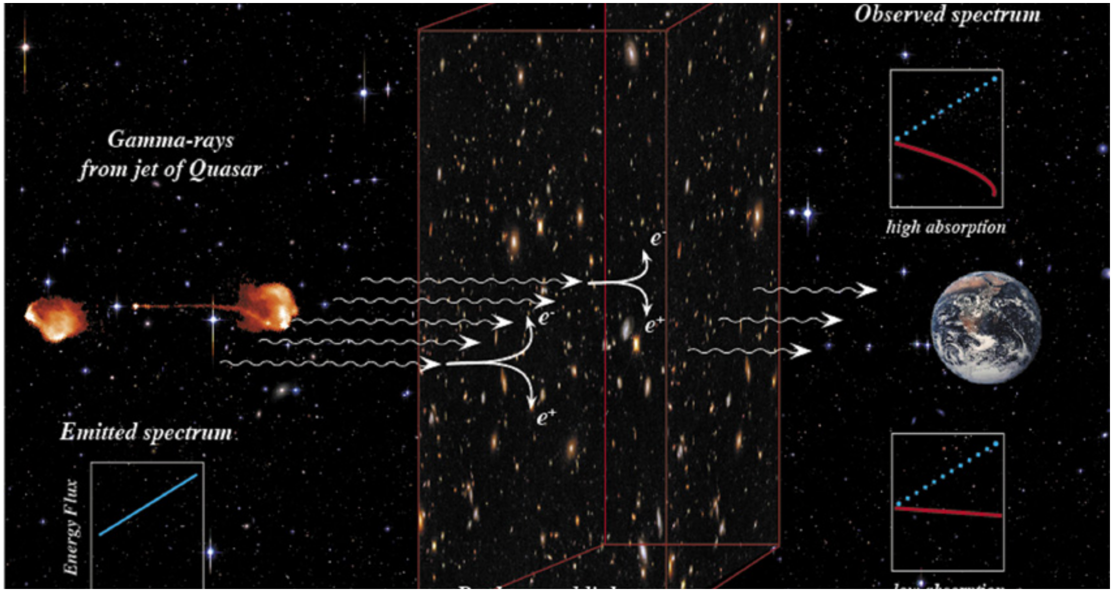
$\Phi_{13} = 10^{-13}$ cm^{-2} s^{-1} TeV^{-1}

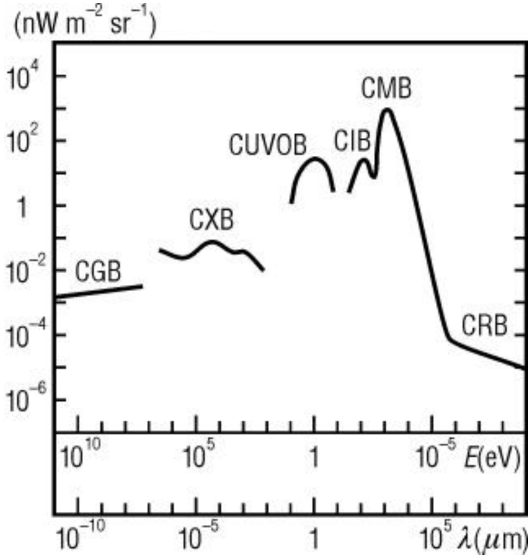
2004 vs. 2005:
Photon indices compatible, but different flux levels

Probing DEBRA at MIR /FIR with E_γ > 10 TeV γ-rays from nearby extragalactic sources (d < 100 Mpc)



gamma-ray blazars and EBL





energy-dependent gamma-ray absorption => information about EBL

cascades in CMB/EBL => total high energy luminosity of the Universe
=> EBL and total energy in relativistic electrons
=> evidence of extremely low IGMFs

Blazars and **EBL** - two different but tightly connected topics

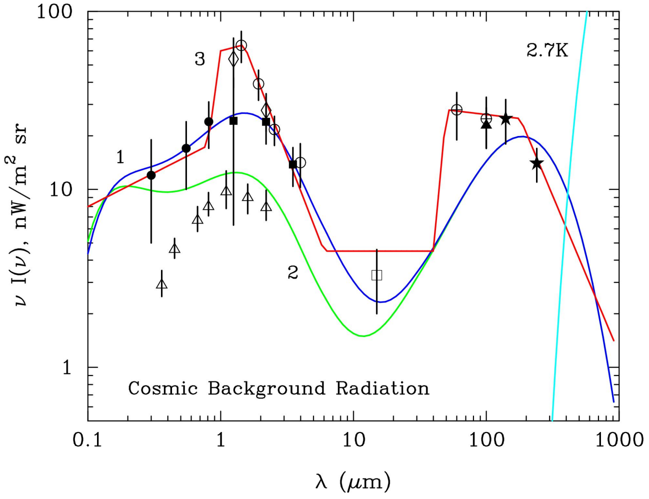
GeV/TeV gamma-ray observations:
strong impact on

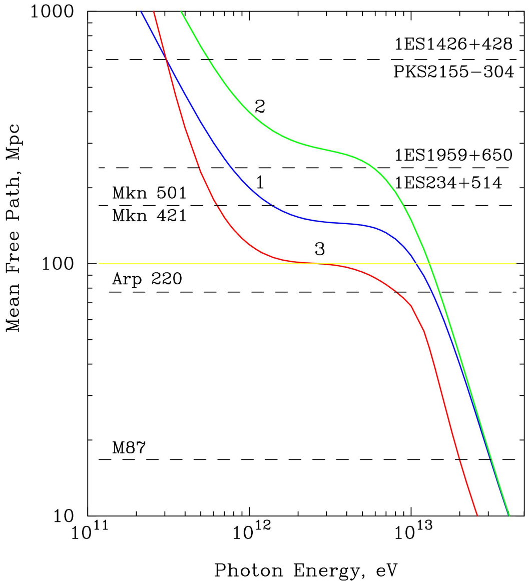
- ✓ Blazar physics and astrophysics
- ✓ Diffuse Extragalactic Background (EBL)
  Intergalactic Magnetic fields (IGMF)

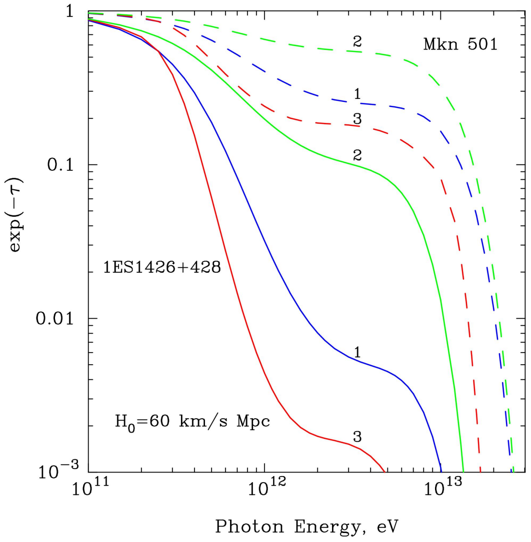
most exciting results of recent 2-3 years

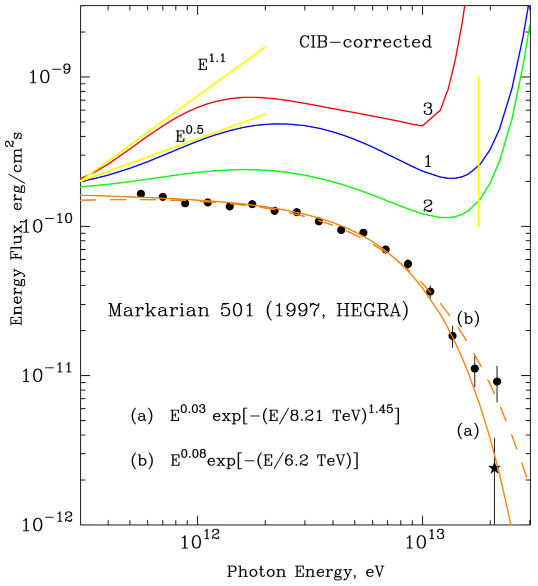
- ◆ *variability on 2-3 min timescales*
- ◆ *jet power exceeds Eddington luminosity?*
- ◆ *unusually hard gamma-ray spectra*

intergalactic absorption of gamma-rays









FA 2001

unusuall gamma-ray spectra? two options:

claim that EBL is “detected“ between O/NIR and MIR

or

propose *extreme* hypotheses, e.g.
violation of Lorentz invariance, non-cosmological origin of z ...

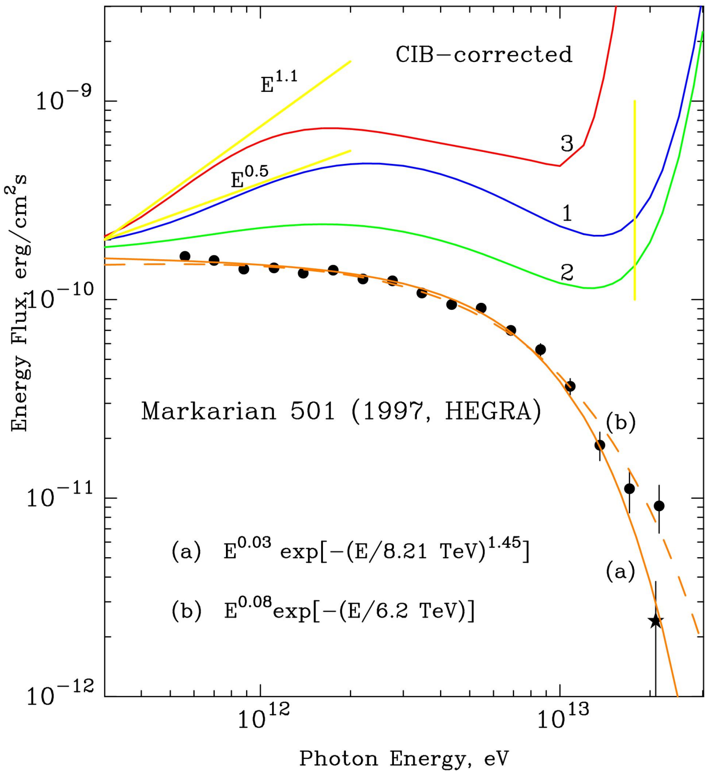
or

propose *less dramatic (more reasonable)* ideas, e.g.

- very specific spectrum of electrons -> $\nu F \nu \sim E_{\gamma}^{1.33}$
- TeV emission from blazars due to comptonization of cold relativistic winds with bulk Lorentz factor $\Gamma > 10^6$
- internal gamma-ray absorption

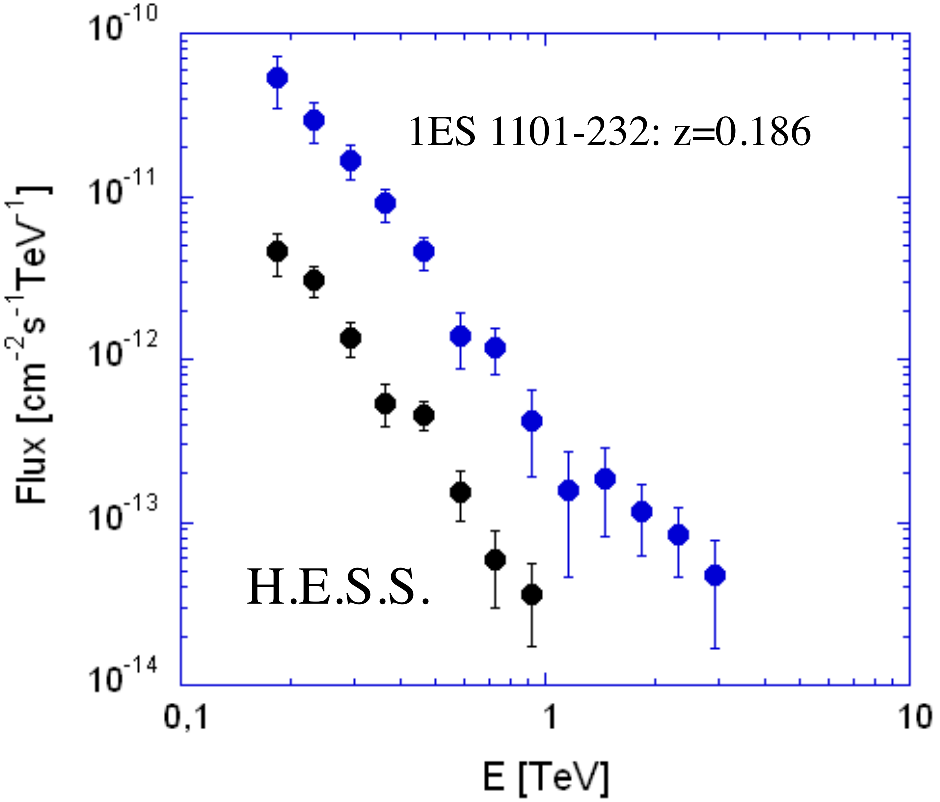
Blazars and EBL

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



reported EBL flux at FIR have not been confirmed

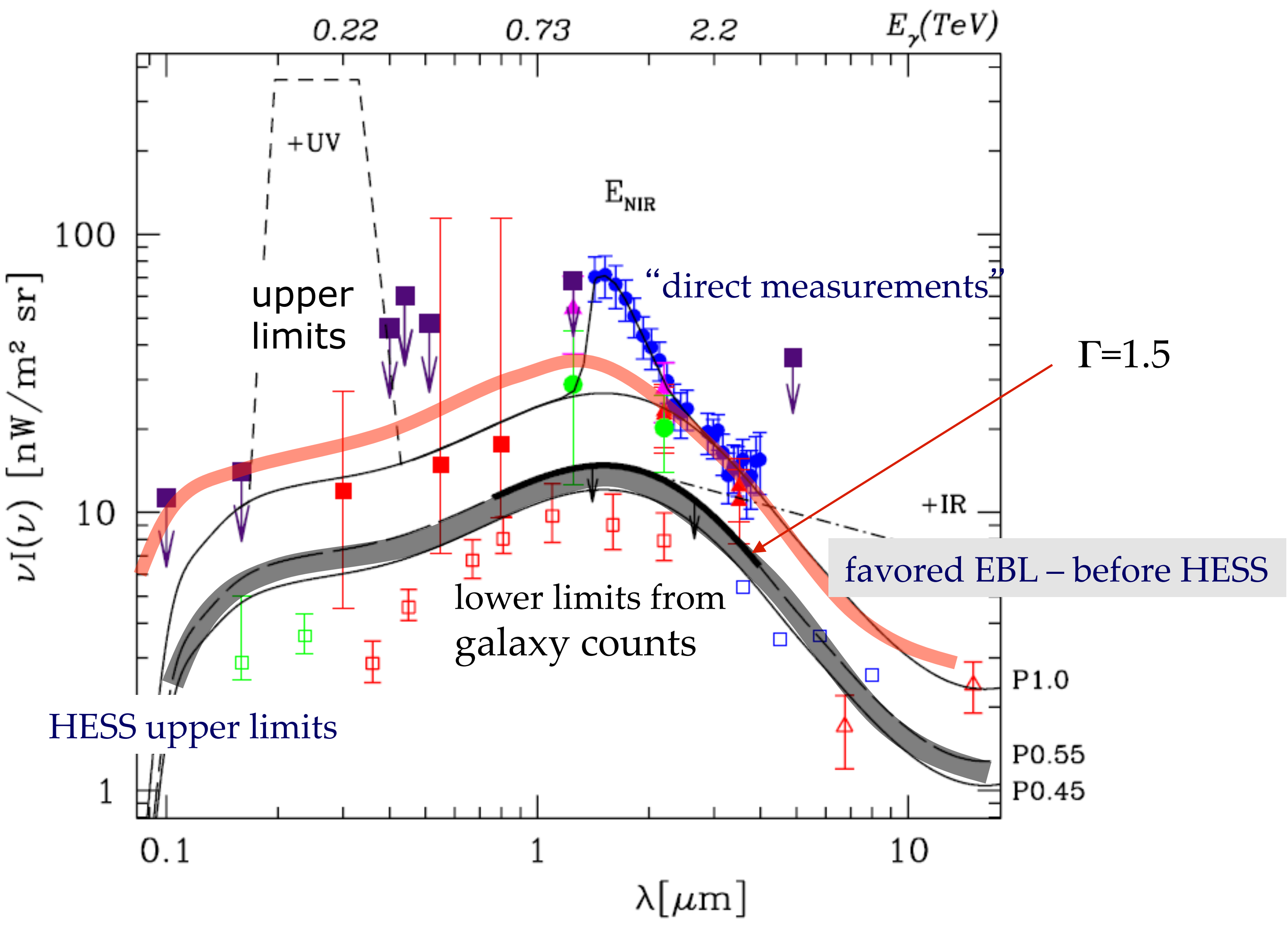
TeV blazars detected by HESS at z> 0.15 !



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

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

EBL (almost) resolved at NIR ?



upper limits

"direct measurements"

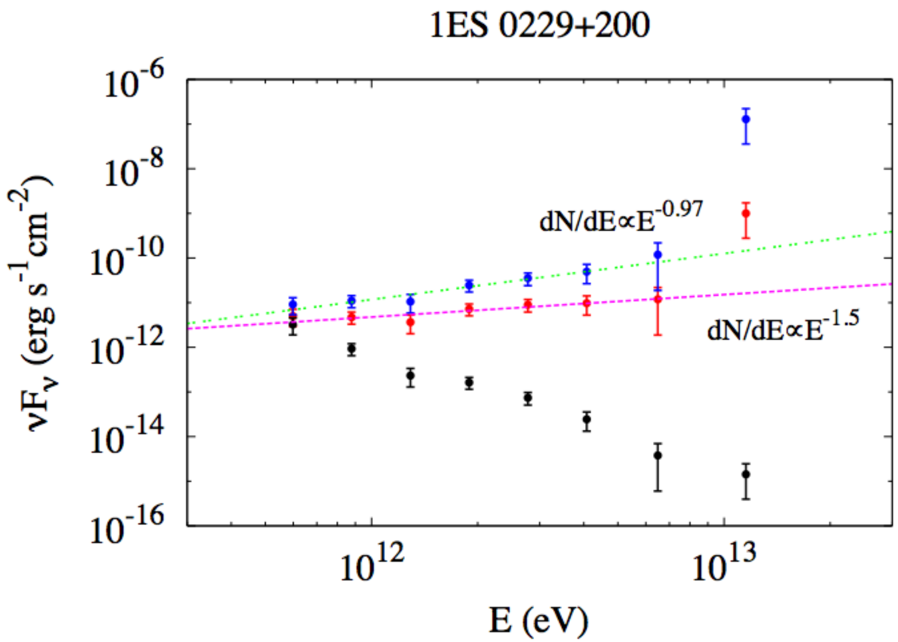
Γ=1.5

favored EBL – before HESS

lower limits from galaxy counts

HESS upper limits

new "problematic" sources



possible explanations:

- ✓ very narrow electron distribution - no significant radiative energy losses =>

  typically very small B-field: 0.001G

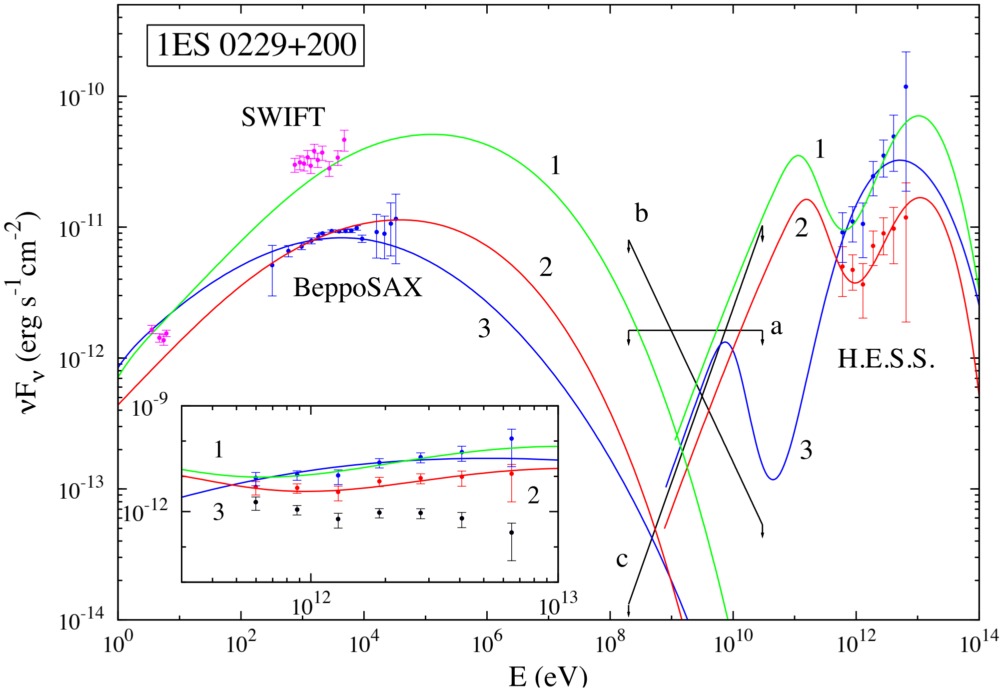
  introduce adiabatic losses or assume stochastic (Fermi II type) acceleration with Maxwellian type distribution

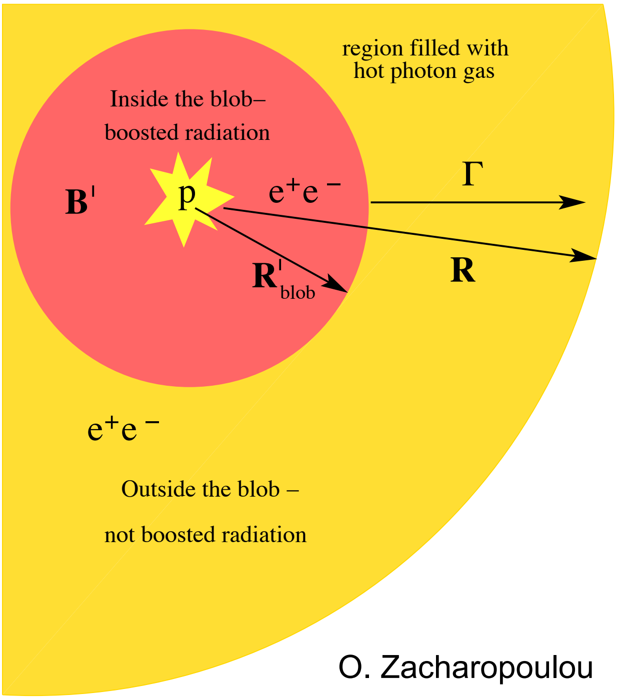
- ✓ internal γ-γ absorption =>

  very strong magnetic field, B >10 G mechanism: proton synchrotron

1ES 0229+200: z= 0.14 spectrum extends to >5 TeV ! even slight deviation from the "standard" EBL => extremely hard γ-ray spectra with Γ ~ 1

Proton synchrotron and internal γ-γ absorption





region filled with
hot photon gas

Inside the blob–
boosted radiation

Outside the blob –

not boosted radiation

O. Zacharopoulou

very strong magnetic field: B > 10 G !

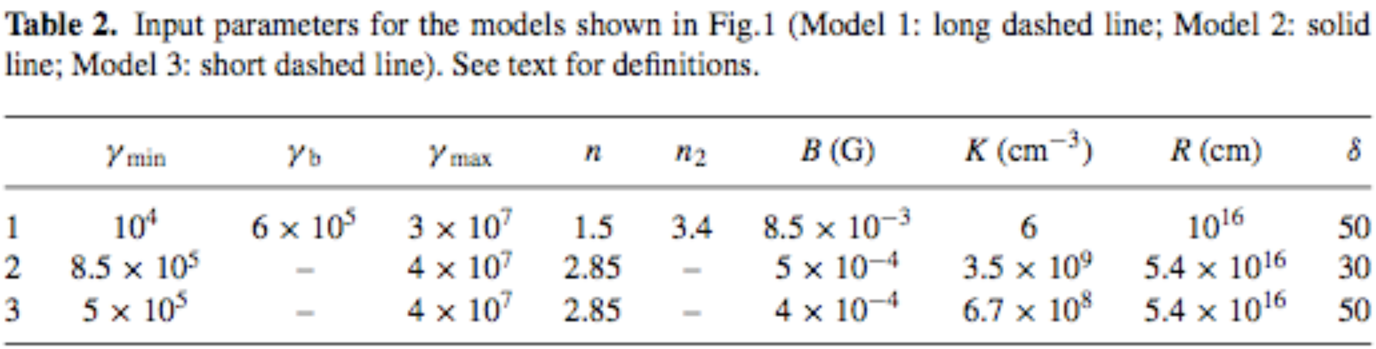
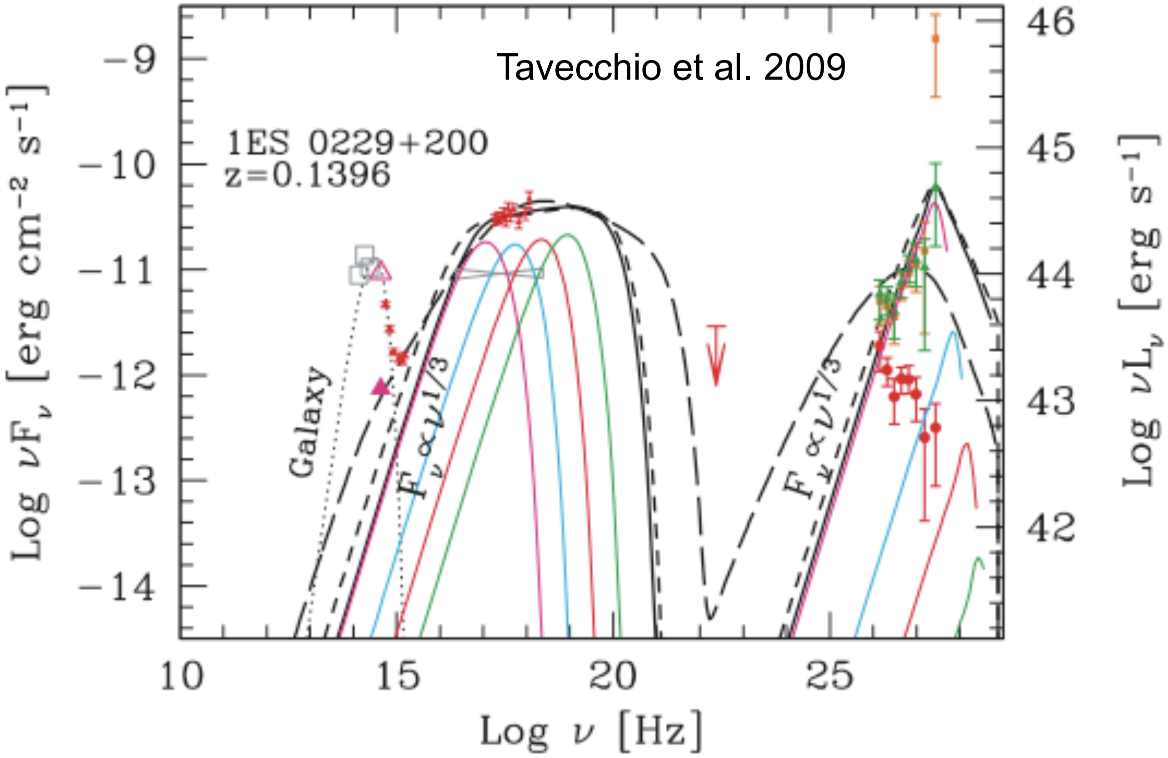


Table 2. Input parameters for the models shown in Fig.1 (Model 1: long dashed line; Model 2: solid line; Model 3: short dashed line). See text for definitions.

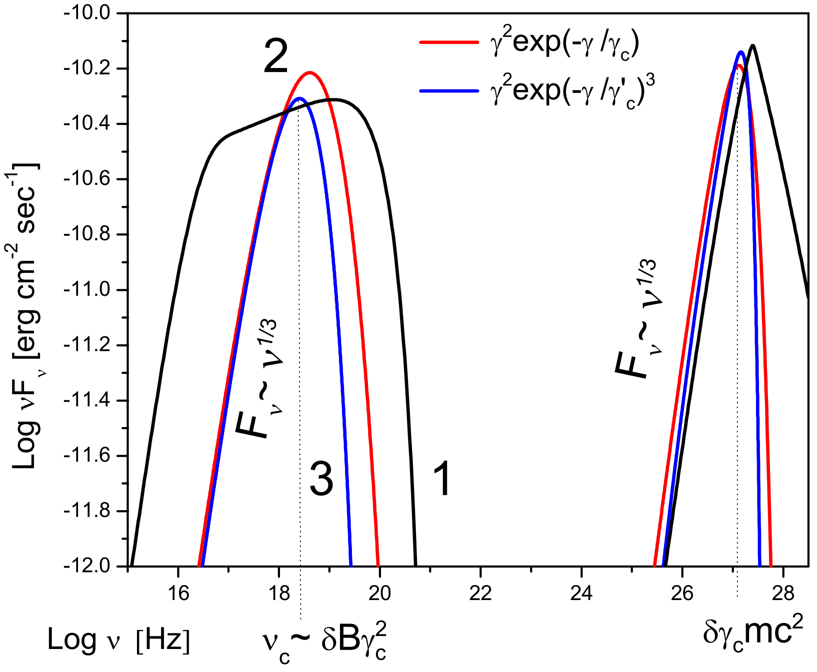
	$\gamma_{\rm min}$	$\gamma_{\rm b}$	$\gamma_{\rm max}$	n	n_2	B (G)	K (cm^{-3})	R (cm)	δ
1	10^4	6×10^5	3×10^7	1.5	3.4	8.5×10^{-3}	6	10^{16}	50
2	8.5×10^5	–	4×10^7	2.85	–	5×10^{-4}	3.5×10^9	5.4×10^{16}	30
3	5×10^5	–	4×10^7	2.85	–	4×10^{-4}	6.7×10^8	5.4×10^{16}	50

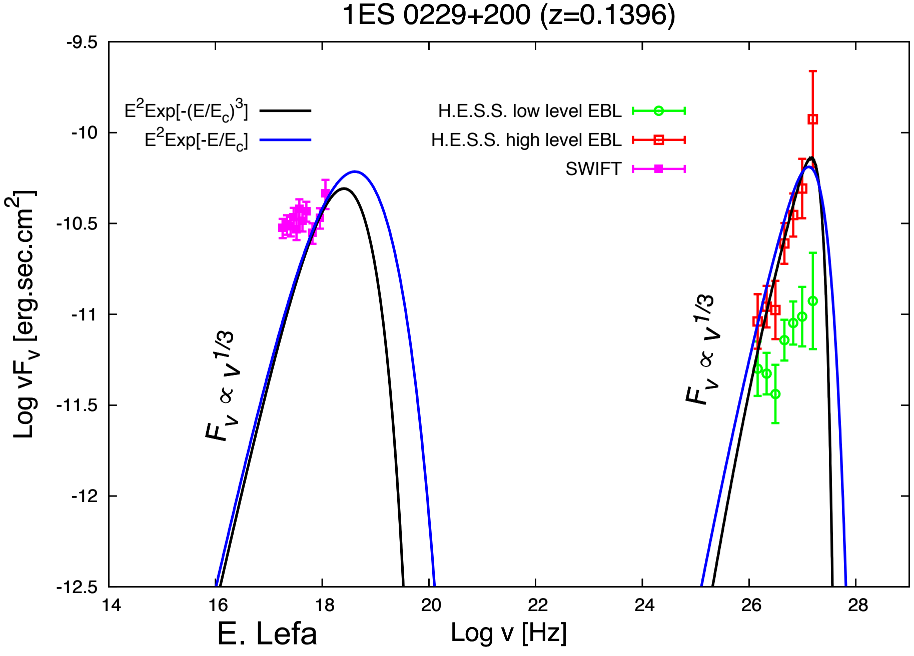


Tavecchio et al. 2009

B~10^{-3} G: deviation from equipartition by many orders of magnitude!

Synchrotron Self Compton: narrow distribution of electrons



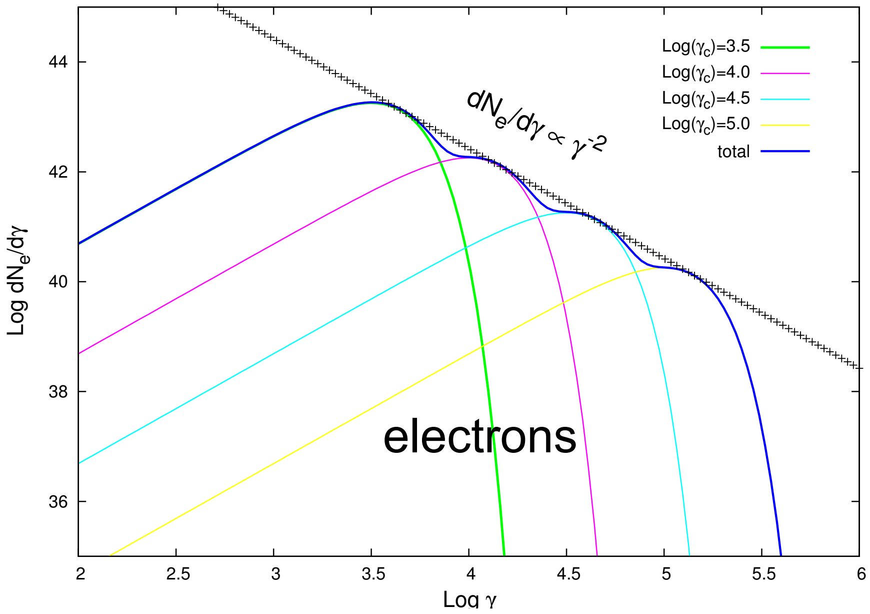


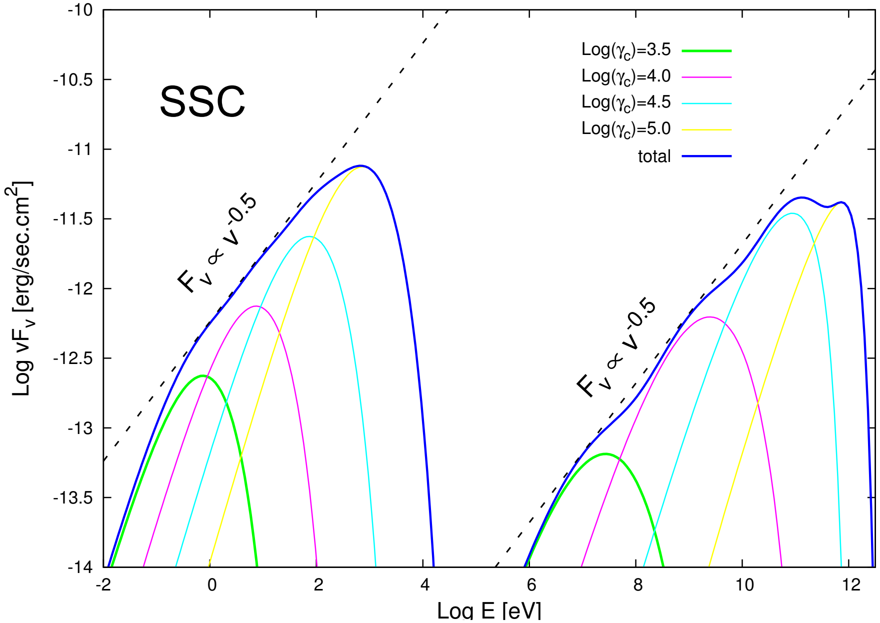
1. γ_{min}=5 10^5; γ_{max}=4$10^7$; B=0.4mG; δ=50
2. γ_c=1.5 10^5; B= 70mG; δ=33
3. γ_c=5.3 10^5; B=0.4mG; δ=33

small or very small B-field!

E.Lefa

multi-zone (multi-blob) concept

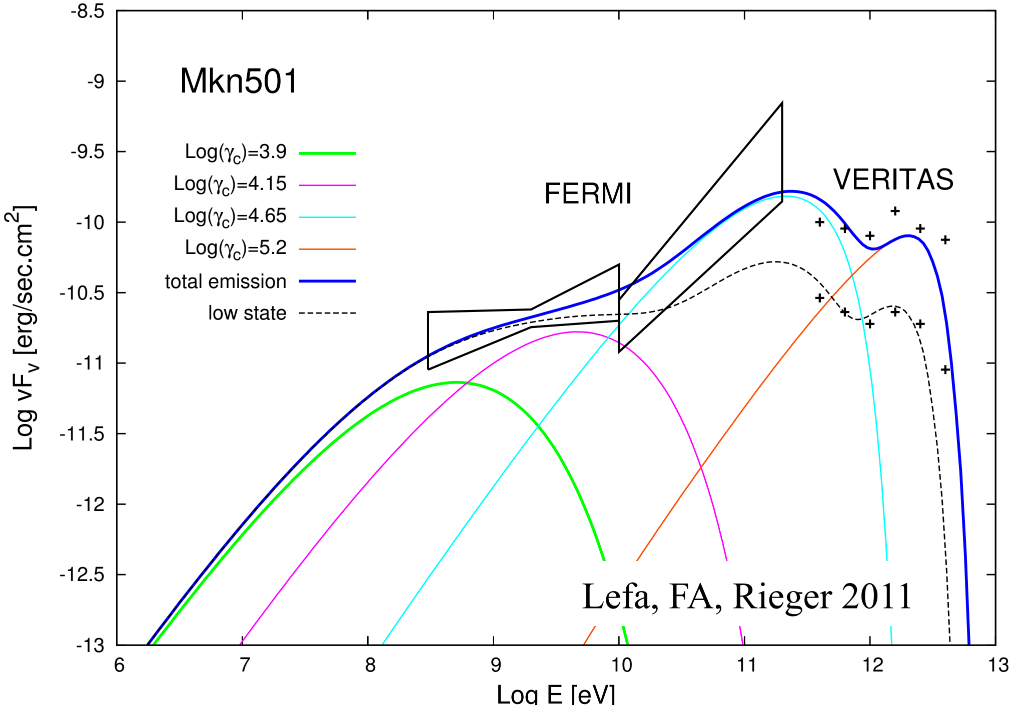




$$\frac{dN}{d\gamma} = A\gamma^2 \exp[-(\gamma/\gamma_0)^2] \qquad \mathrm{E_i} = 2\times 10^{44}\mathrm{erg},\ \mathrm{B} = 0.1\mathrm{G},\ \delta = 30,\ \mathrm{R} = 3\times 10^{14}\mathrm{cm}$$

depending on E_i and γ_{0i} => arbitrary total electron spectrum
for E_i=const, but different γ_0 and i >>1 almost ideal γ^{-2} spectrum

Very hard spectrum of Mkn 5011 during 2009 flare



Lefa, FA, Rieger 2011

Fermi LAT: flat spectrum in a low state and very hard $dN/dE \sim E^{-1}$ type during 2009 flare (Abdo et al. 2010 and Neronov et al 2011)

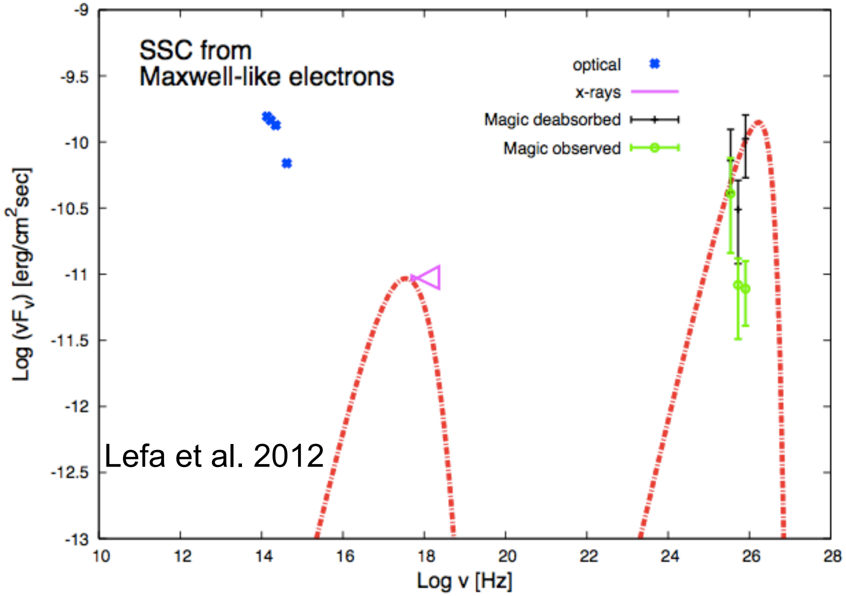
can be explained by change δ=30 to 40 of two “hottest” blobs; B=0.1G, $R=10^{14}$ cm

we can expect g-ray spectrum of arbitrary form; in flaring state as hard as E^{-1}

conclusions: do not try to get ‘smooth’ spectral fits, especially in low-states
do not overestimate the potential of “single-zone” models
do not overestimate the potential of γ-rays for derivation of EBL

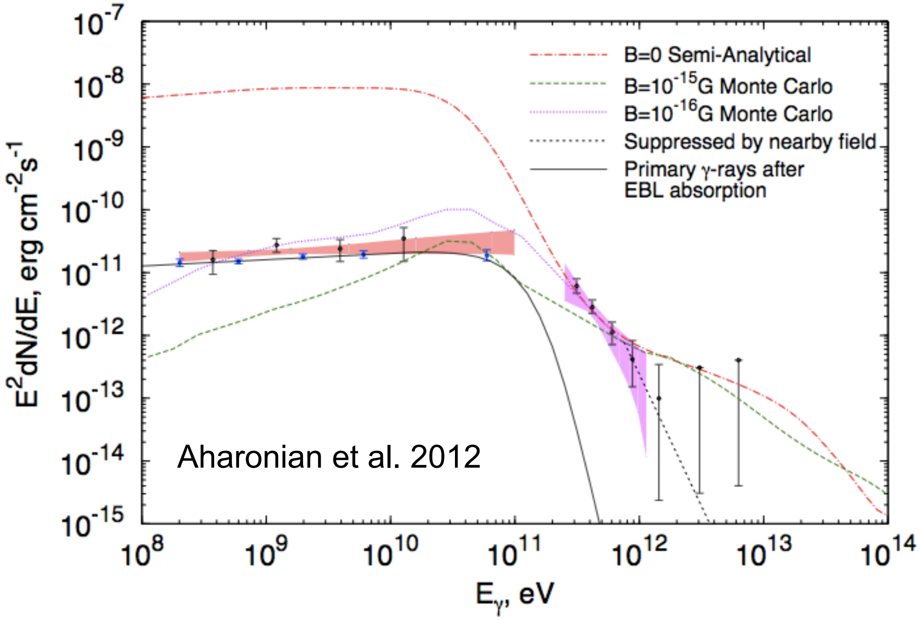
approaching to the threshold of ``trouble”?

3C279: z=0.536



Lefa et al. 2012

PKS 0447-439: z=1.26?

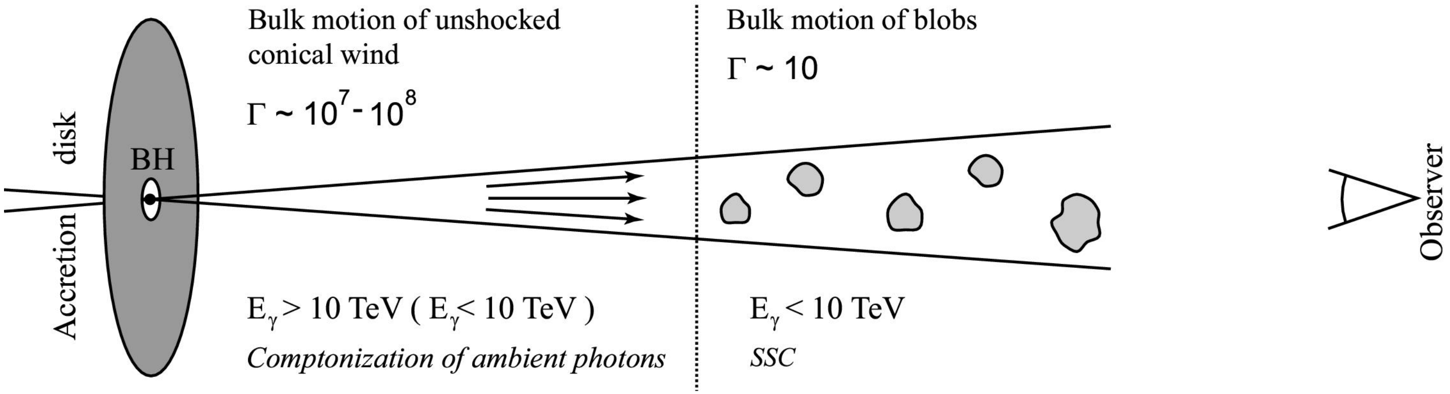


Aharonian et al. 2012

SSC with Maxwellian type electron distributuin: B=0.3G, δ=40; γo= 7x10^4

possible explanations: γ-rays due to cascades in induced by >1018eV protons in IGM with B < 10^{-15} G? or the claimed redshift is wrong

Gamma Rays from a cold ultrarelativistic wind ?



Bulk motion of unshocked conical wind

$\Gamma \sim 10^7 - 10^8$

$E_\gamma > 10$ TeV ($E_\gamma < 10$ TeV)

Comptonization of ambient photons

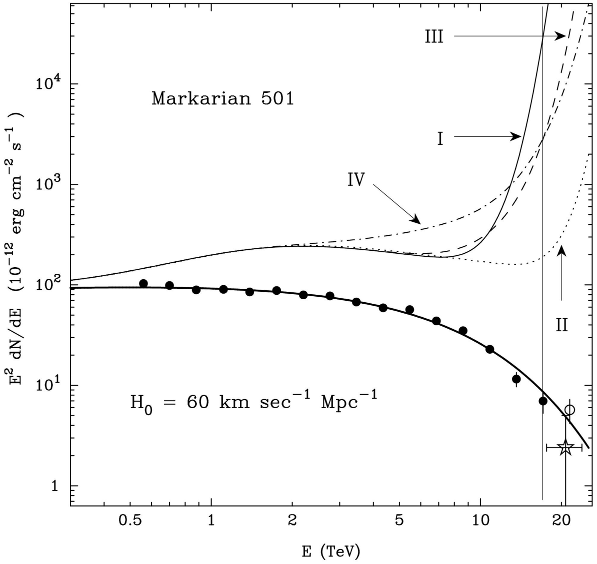
Bulk motion of blobs

$\Gamma \sim 10$

$E_\gamma < 10$ TeV

SSC

in fact not a very exotic scenario ...



Aharonian 2001

Pair Halos

TeV Gamma-rays from distant extragalactic sources, d > 100 Mpc interact effectively with Extragalactic Background Radiation (EBL; (0.1-100 mm)

when a gamma-ray is absorbed its energy is not lost !
absorption in EBL leads to E-M cascades suppoorted by

- Inverse Compton scattering on 2.7 K CMBR photons
- photon-photon pair production on EBL photons

if the intergalactic field is sufficiently strong, $B > 10^{-11}$ G,
the cascade e^+e^- pairs are promptly isotropised

➡ formation of extended structures – Pair Halos

how it works ?

energy of primary gamma-ray

$$E_{\gamma,0} \simeq 10(E_\gamma/100\mathrm{GeV})^{1/2}\ \mathrm{TeV}$$

mean free path of parent photons

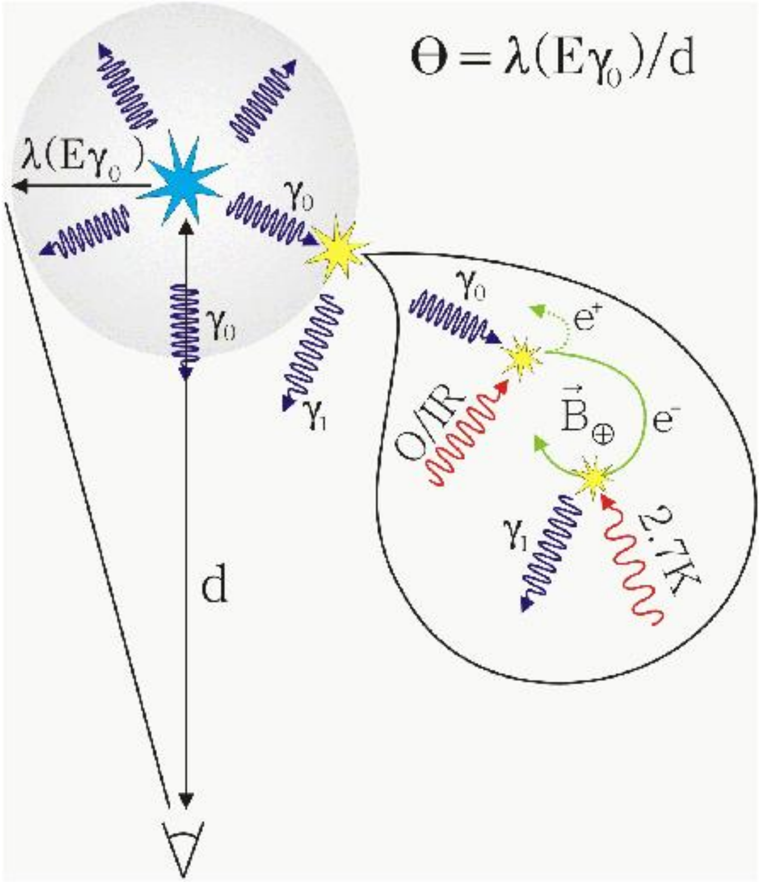
$$\lambda(E_{\gamma,0}) \sim d \times \Theta$$

information about EBL flux at

$$\lambda \simeq 10(E_\gamma/100\mathrm{GeV})^{1/2}\ \mu\mathrm{m}$$

gamma-radiation of pair halos can be recognized by its distinct variation in spectrum and intensity with angle, and depends rather weakly (!) on the features of the central VHE source

two observables – <u>angular</u> and <u>energy</u> distributions allow to disentangle two variables $u_{EBL}(\lambda, z)$ and $d\ (H_0)$!



Pair Halos as Cosmological Candles

- informationabout EBL density at fixed cosmological epochs given by the redshift of the central source unique !

- estimate of the total energy release of AGN during the active phase

- objects with jets at large angles - many more g-ray emitting AGN

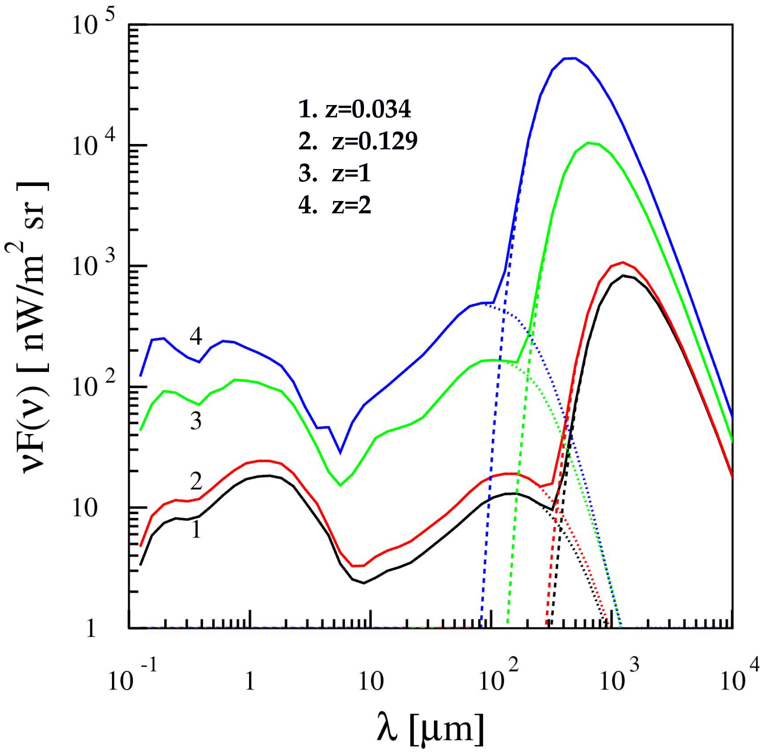
but the advantage of the large Doppler boosting of blazars disapeares: beam => isotropic source

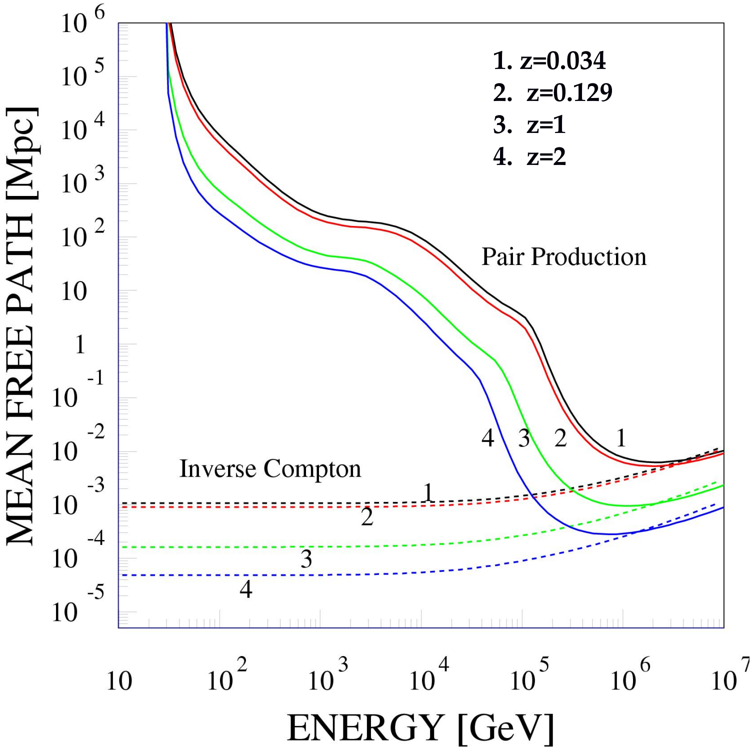
therefore very powerful central objects needed

QSOs and Radiogalaxies (sources of EHE CRS ?) as better candidates for Pair Halos

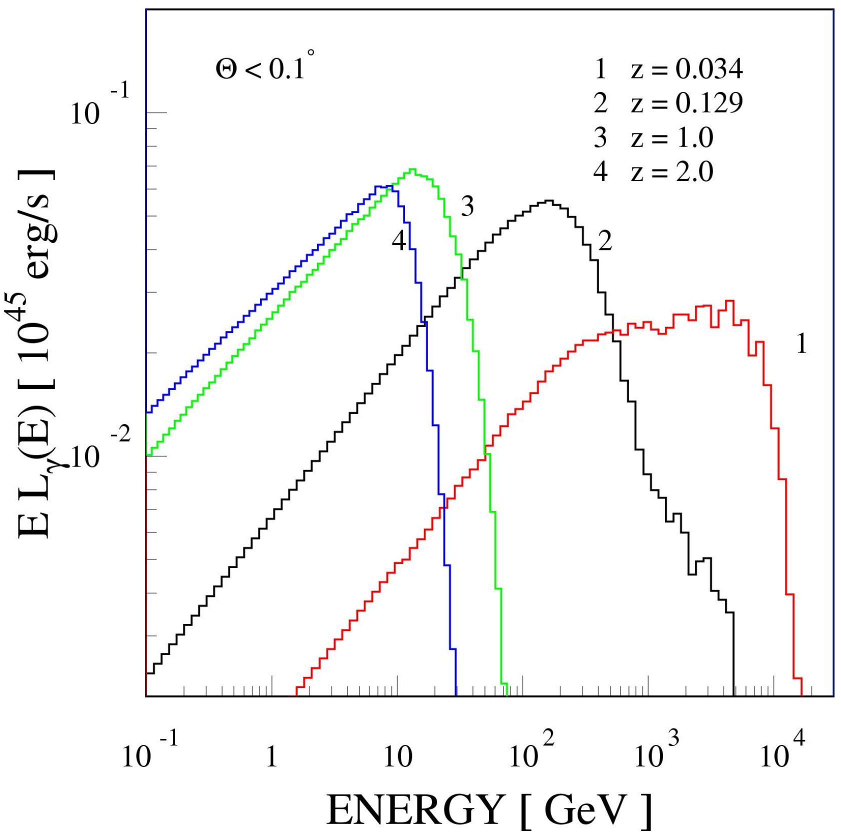
this requires low-energy threshold detectors

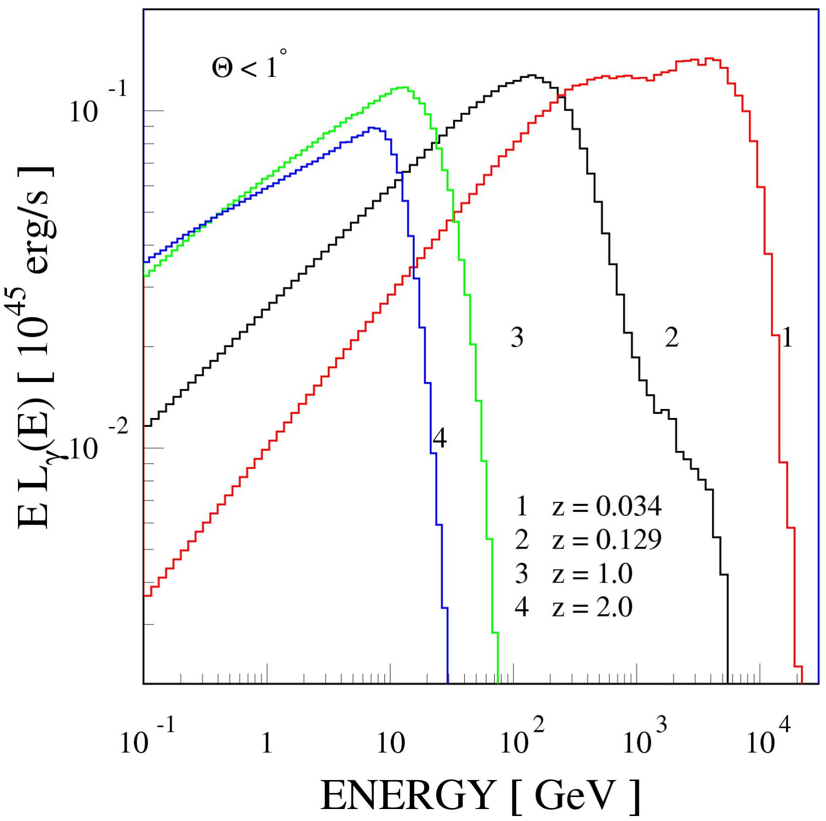
EBL at different z and corresponding mean freepaths





SEDs for different z within 0.1^o and 1^o

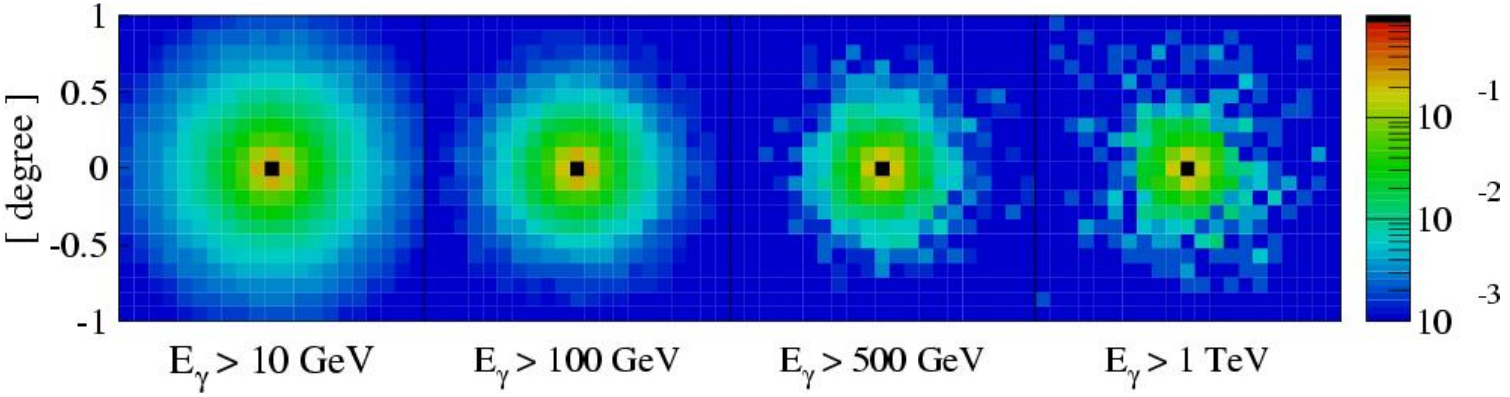




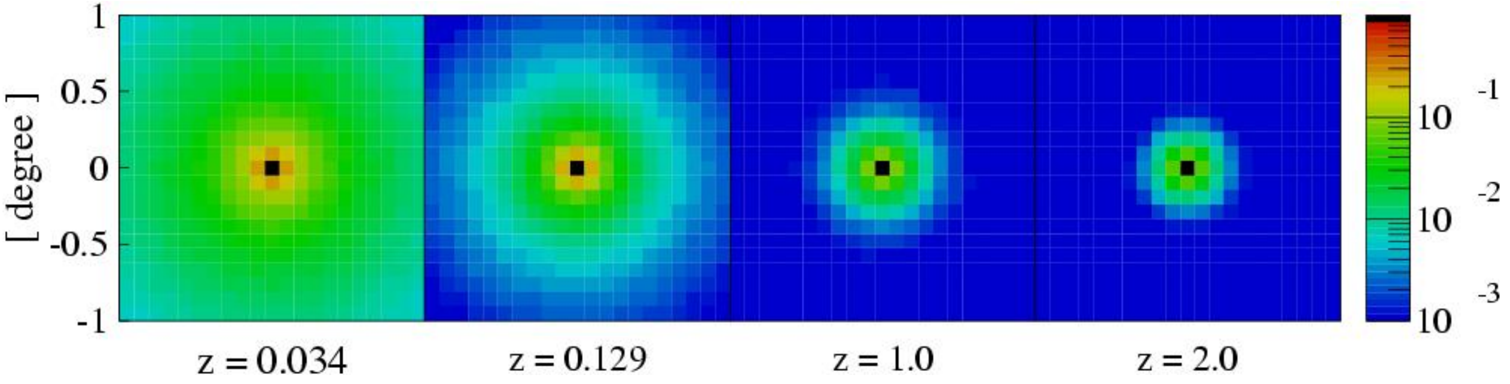
EBL model – Primack et al. 2000

$L_o = 10^{45}$ erg/s

Brightness distributions of Pair Halos

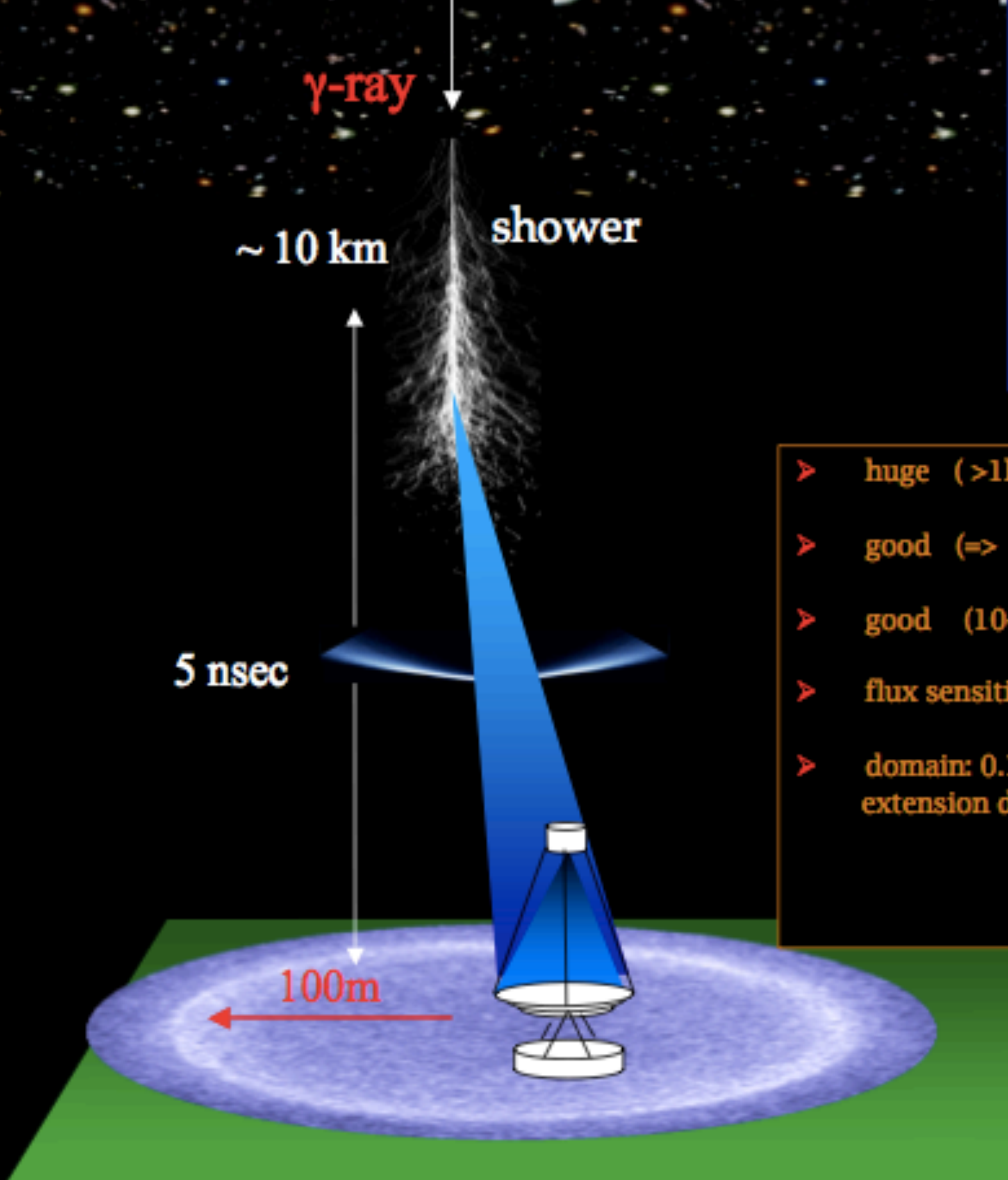


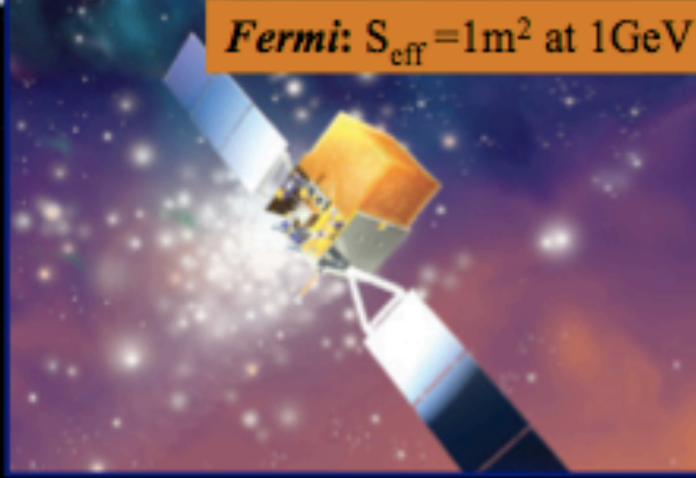
z=0.129



E=10 GeV

A. Eungwanichayapant, PhD thesis, Heidelberg, 2003

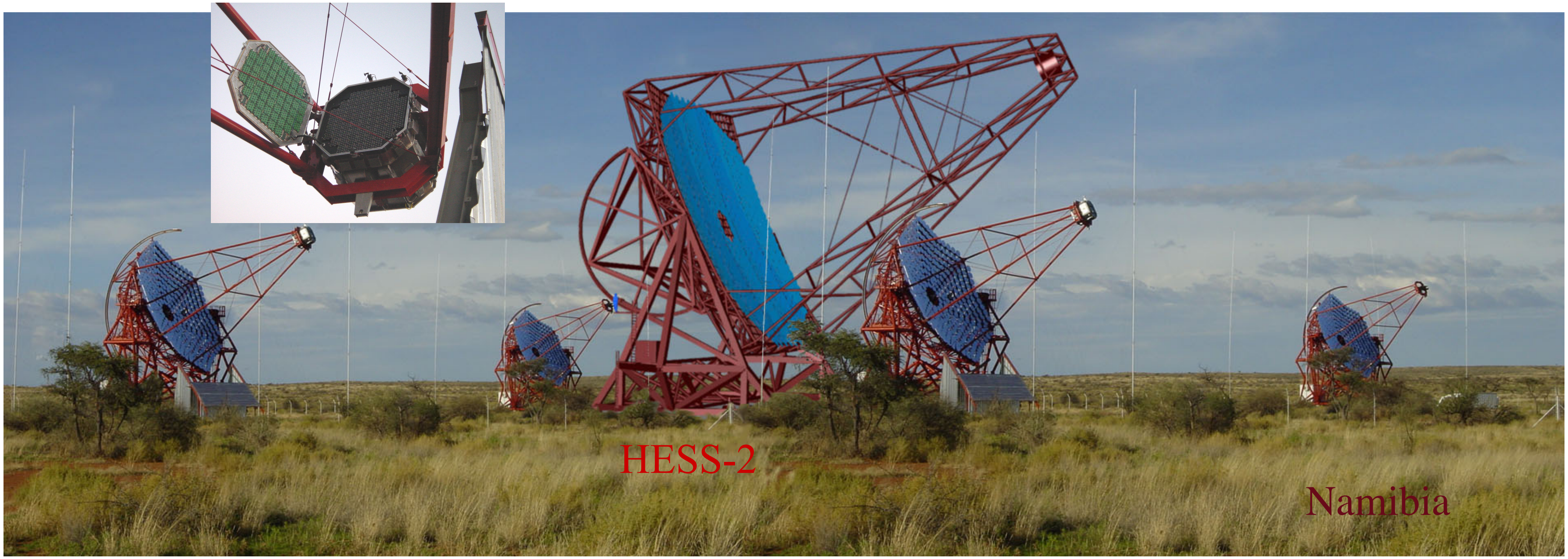




Fermi: $S_{\mathrm{eff}} = 1\mathrm{m}^2$ at 1GeV

- huge (>$1\mathrm{km}^2$ or larger) detection area
- good (=> 1arcmin) angular resolution
- good (10-25 %) energy resolution
- flux sensitivity => 10^{-14} erg/cm^2 s
- domain: 0.1 - 100 TeV with a potential of extension down to 10GeV and up to 1PeV

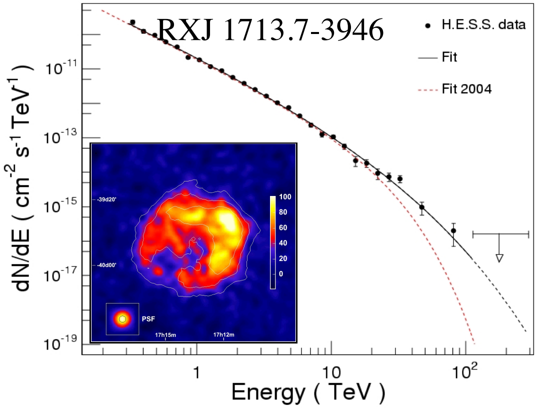
H.E.S.S. - *High Energy Stereoscopic System*



one of the current 3 (HESS, MAGIC, VERITAS) major IACT arrays

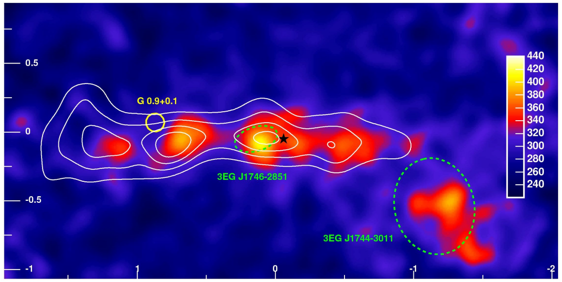
good performance => high quality data => solid basis for physics studies

spectrometry



TeV image and energy spectrum of a SNR

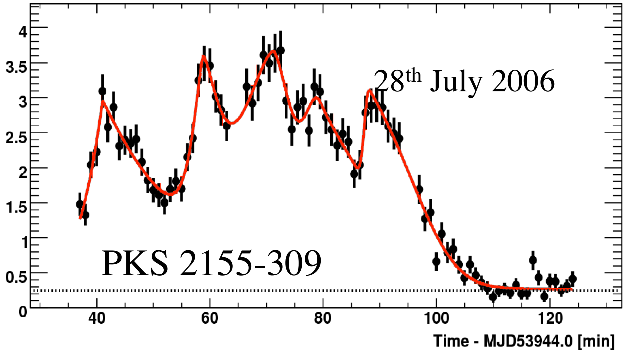
imaging



Galactic Center

resolving GMCs in the Galactic Center 100pc region

timing



variability of TeV flux of a blazar on minute timescales

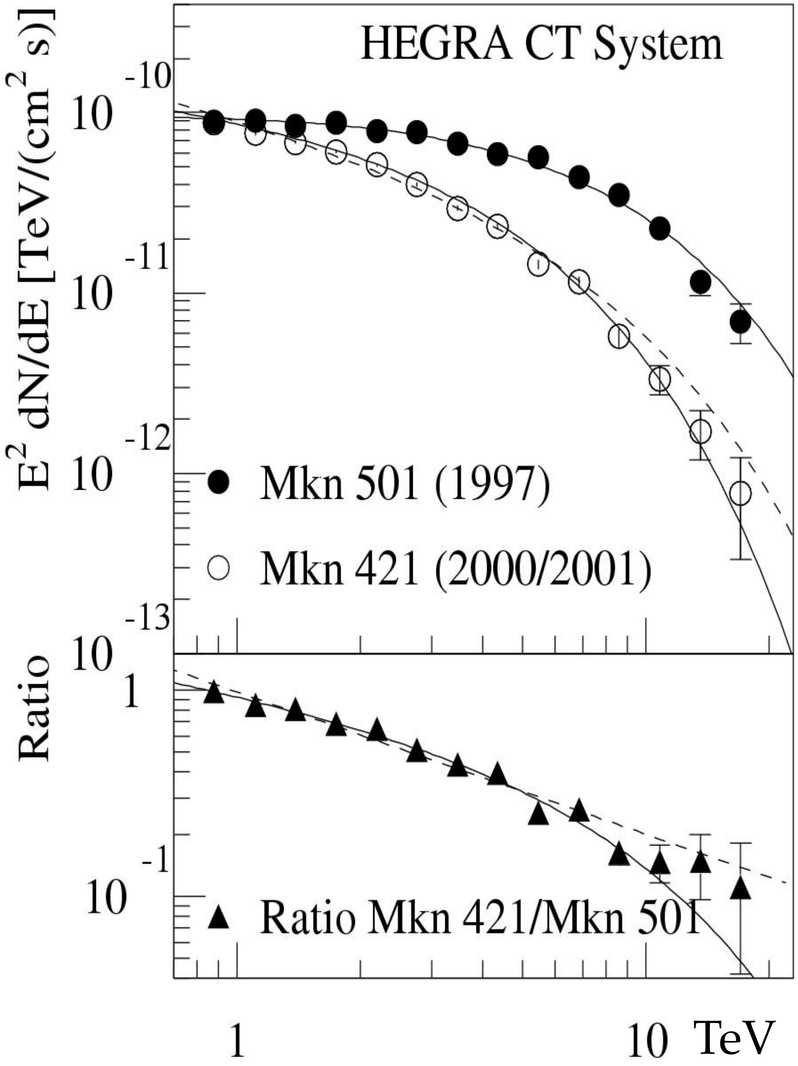
multi-functional tools: *spectrometry* *temporal studies* *morphology*

✓ extended sources: *from SNRs to Clusters of Galaxies*

✓ transient phenomena *μQSOs, AGN, GRBs, ...*

Galactic Astronomy | Extragalactic Astronomy | Observational Cosmology

Spectrometry with HEGRA beyond 3E_{cutoff} !



Unprecedented photon statistics

Mkn 421 – 60,000 TeV photons
detected in 2001

Mkn 501 – 40,000 TeV photons
detected in 1997

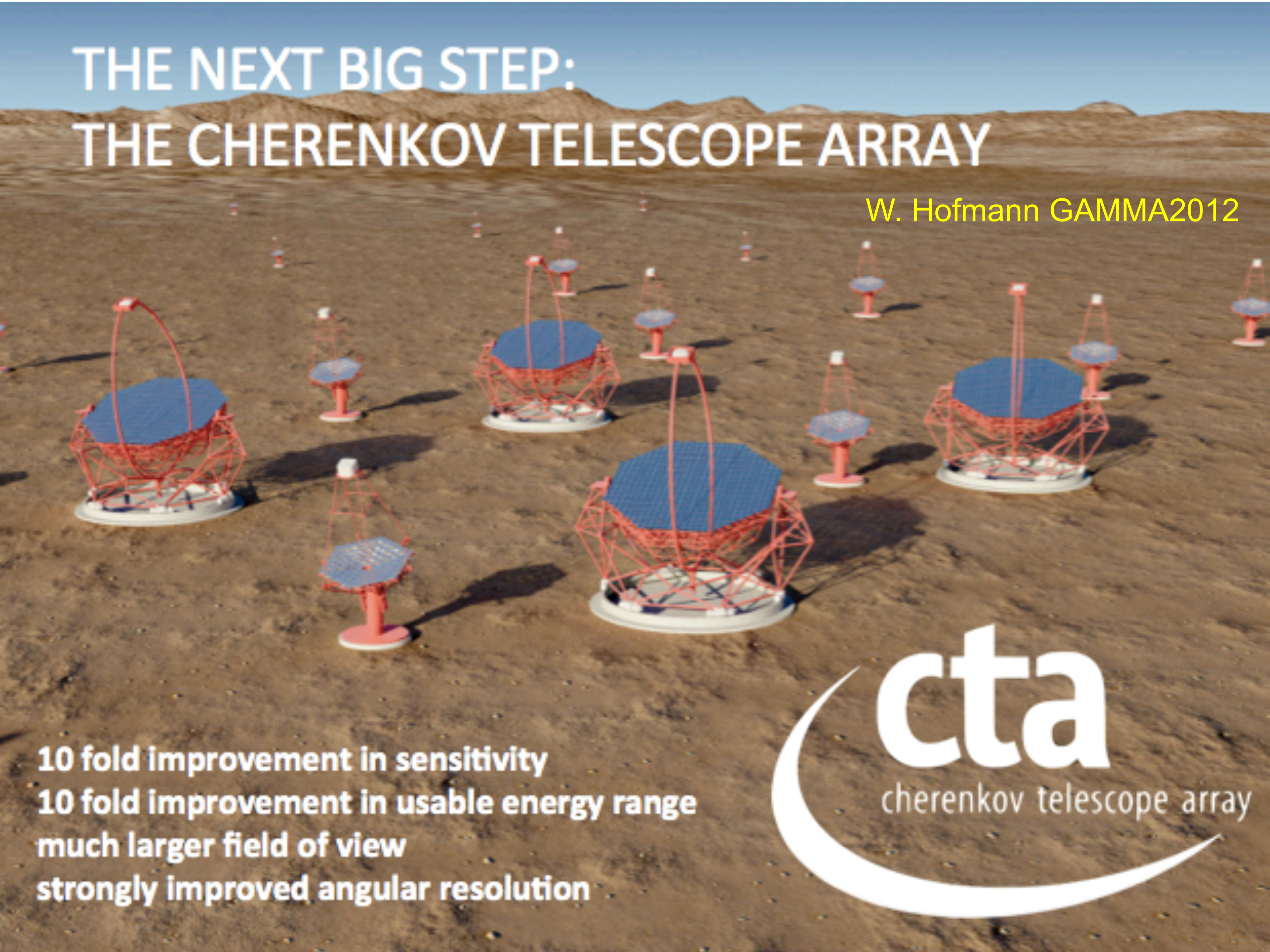
spectra: canonical power-law
with exponential cutoff

Cutoff = 6.2 TeV and 3.8 TeV
for Mkn 501 and Mkn 421

time average spectra of
Mkn 421 and Mkn 501

THE NEXT BIG STEP:
THE CHERENKOV TELESCOPE ARRAY

W. Hofmann GAMMA2012

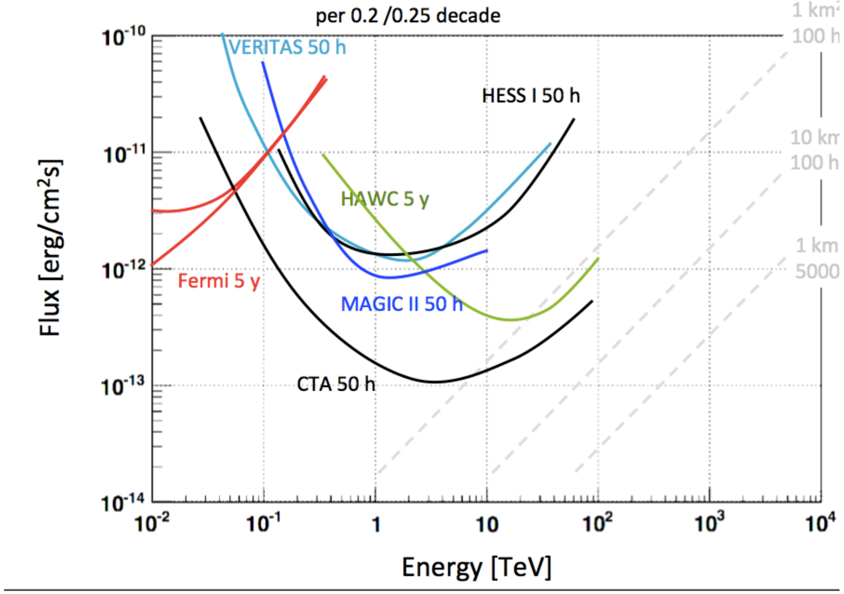


10 fold improvement in sensitivity
10 fold improvement in usable energy range
much larger field of view
strongly improved angular resolution

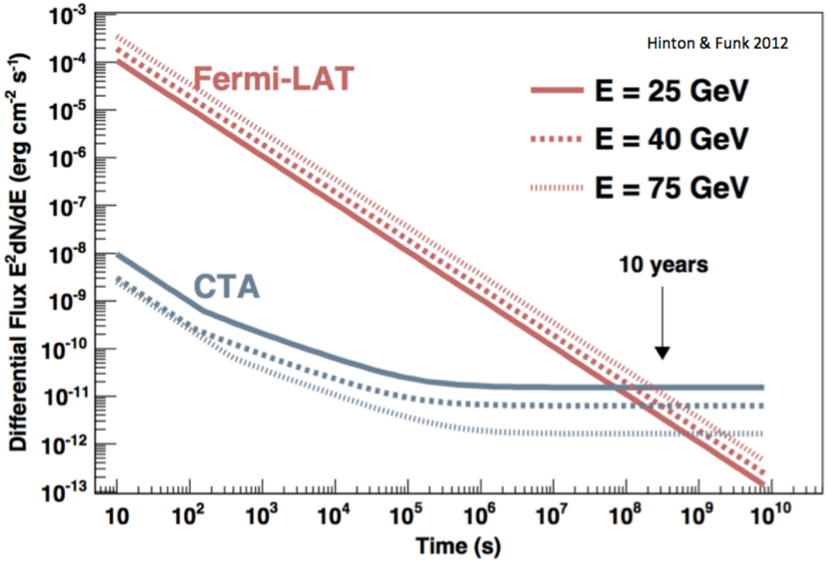
cta
cherenkov telescope array

CTA – a powerful tool for AGN studies

DIFFERENTIAL SENSITIVITY



CTA VERSUS FERMI – TRANSIENT SOURCES



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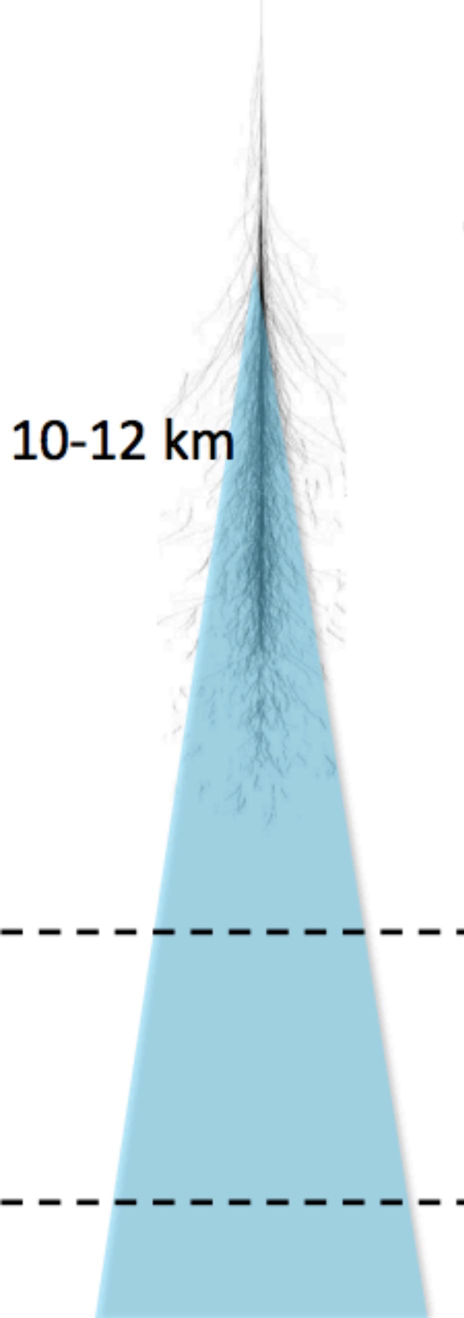
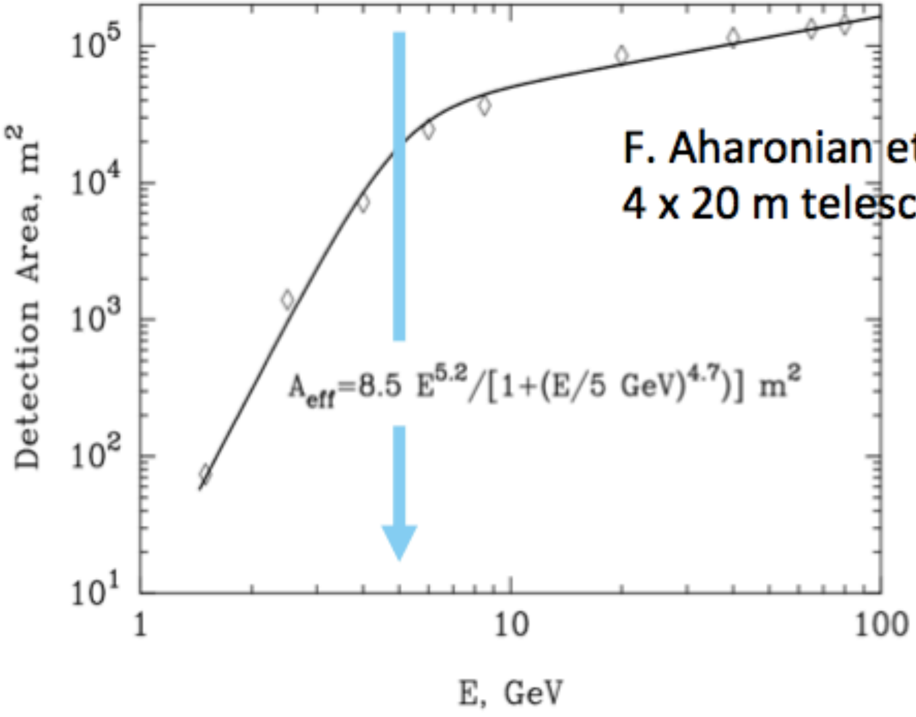
Detection of `nominal' (Fermi/AGILE) AGN for just 1 min, but above several tens of Ge
the emission could be is strongly suppressed at tens of GeV – low threshold is critical

HIGH-ALTITUDE CHERENKOV TELESCOPES





F. Aharonian et al., astro-ph/0006163
4 x 20 m telescopes @ 5000 m asl

higher light intensity (5000 m: x2)
➔lower threshold
smaller light pool area (5000 m: /2)

Reference height ~2000 m

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current status of AGN studies in gamma-rays

almost one thousand GeV and several dozens TeV γ-ray emitting AGN!

`GeV-to-TeV' ratio is not too large given the continuous monitoring of AGN by Fermi LAT and AGILE of a significant fraction of the sky

GeV – large *source* statistics – good for population studies

TeV - large *photon* statistics – good for physics studies

the field is not yet saturated:

- ✓ *Fermi/AGILE and HESS/MAGIC/VERITAS will bring more results*
- ✓ *CTA will elevate the status of the field to a new level*
- ✓ *10 GeV (or so) threshold IACT arrays – new surprises and challenges*