Short Course on High Energy Astrophysics

“Exploring the Nonthermal Universe
with High Energy Gamma Rays”

Lecture 6: **Extragalactic Sources of VHE Gamma Rays**

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Florianopolis, Brazil, March 2016

potential extragalactic gamma-ray sources

- ✓ Normal Galaxies (nearby, within a few Mpc)
- ✓ Starburst Galaxies (<100 Mpc) like M82 and NGC 253
- ✓ Nearby Radio Galaxies (M87 and Cen a)
- ✓ Blazars (up to z~1-2)
- ✓ Clusters of Galaxies (within 100 Mpc - Coma, Perseus)
- ✓ GRBs ? (the tails > 20 GeV)
- ✓ something unexpected

Topics

Theory of Particle Acceleration

Origin of Extragalactic Galactic Cosmic Rays (above 10^{18} eV)

Physics and Astrophysics of Supermassive Black Holes

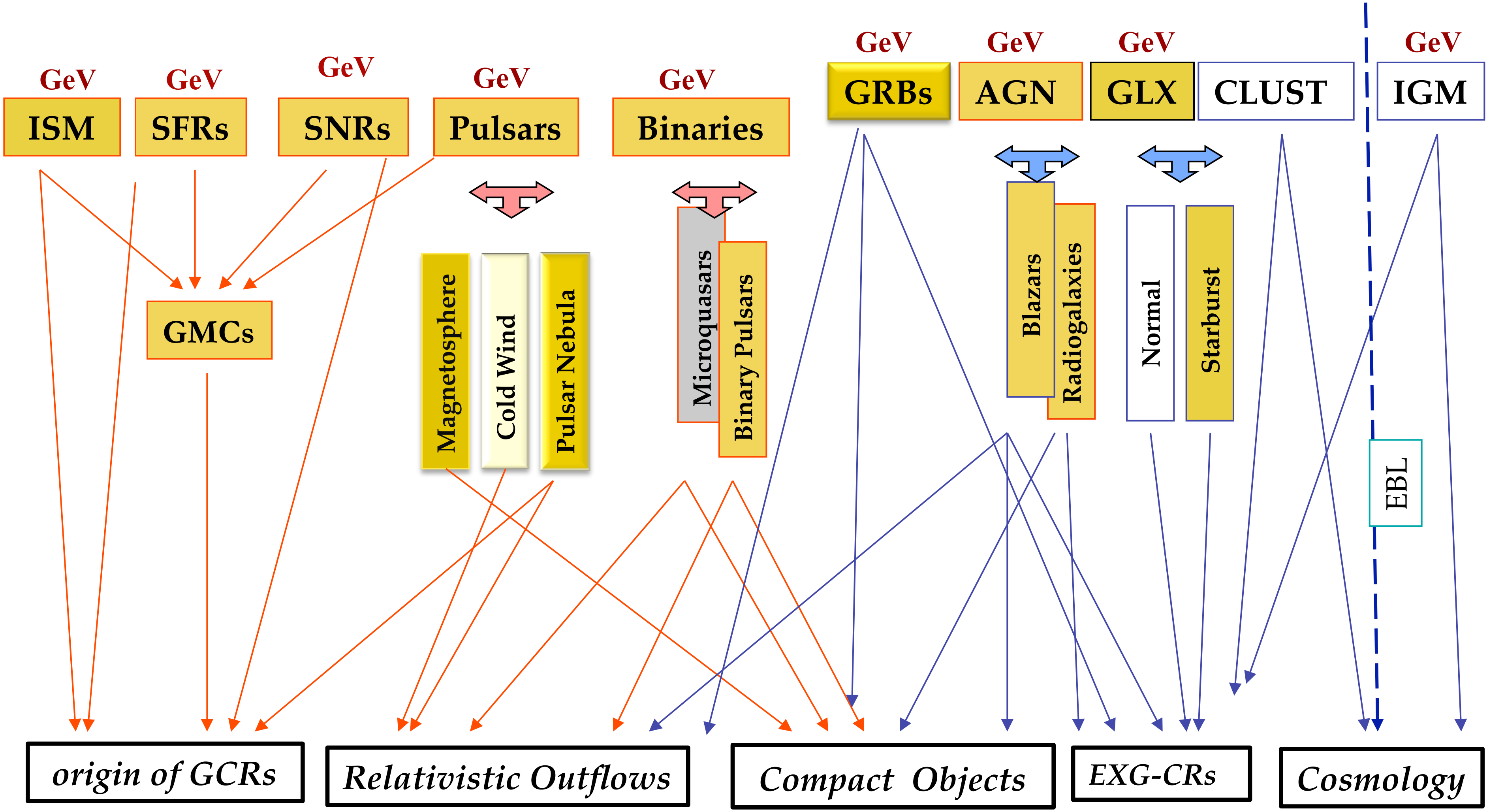
Relativistic hydrodynamics of Relativistic Jets

Extragalactic Radiation Fields (*First Stars, Galaxy Formation*)

Structure of the IGM (Magnetic Fields, Large Scale Structure)

Tests of Fundamental Physics

Potential VHE Gamma Ray Sources



Galactic

Extragalactic

GeV **ISM**

GeV **SFRs**

GeV **SNRs**

GeV **Pulsars**

GeV **Binaries**

GMCs

Magnetosphere

Cold Wind

Pulsar Nebula

Microquasars

Binary Pulsars

GeV **GRBs**

GeV **AGN**

GeV **GLX**

CLUST

GeV **IGM**

Blazars

Radiogalaxies

Normal

Starburst

EBL

origin of GCRs

Relativistic Outflows

Compact Objects

EXG-CRs

Cosmology

Major Scientific Topics

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?

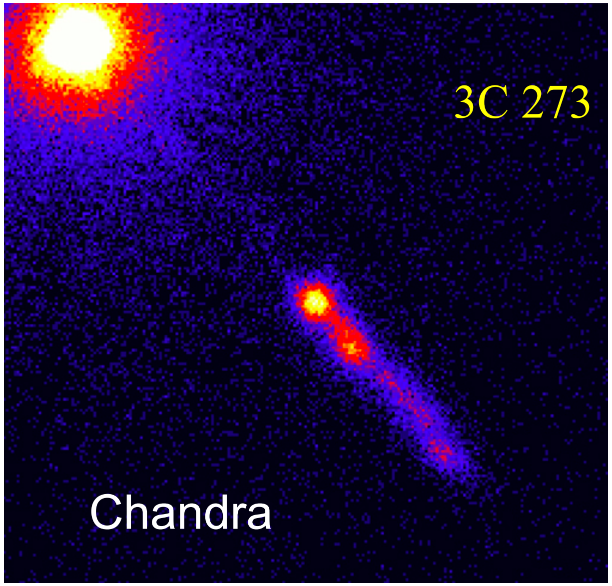
spectral lines e.g. Seyferts – rich line spectra, BL Lacs – featureless continuous

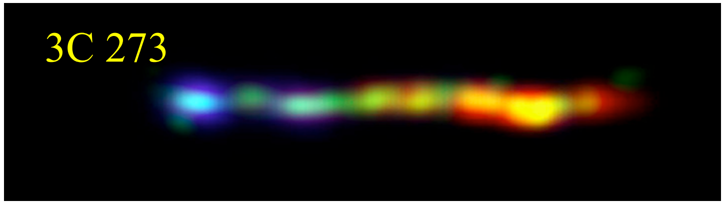
large scale morphology e.g. radio galaxies – often with tween-lobed structures

luminosity e.g. Seyferts – 10^{43}-10^{45} erg/s; QSO: > 10^{46} erg/s

polarization, variability, etc.

Nonthermal features: Particle *Production Sites, Scenarios, Mechanisms*





Chandra X
Hubble O
Spitzer IR

jet – approximately 20 arcsec

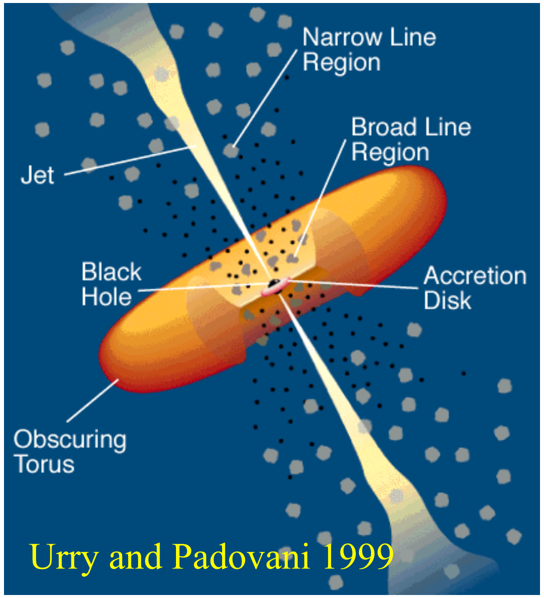
1 arcsec =3 kpc (z=0.158, Ho= 65 km/s Mpc

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 g-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	*acceleration*	*radiation*
	(sub) relativistic shocks convertor mechanism stochastic (Fermi II) magnetic reconnection, ……..	Inverse Compton electron synchrotron Proton synchrotron photomeson processes (and subsequent cascades) γ-γ pair production



Urry and Padovani 1999

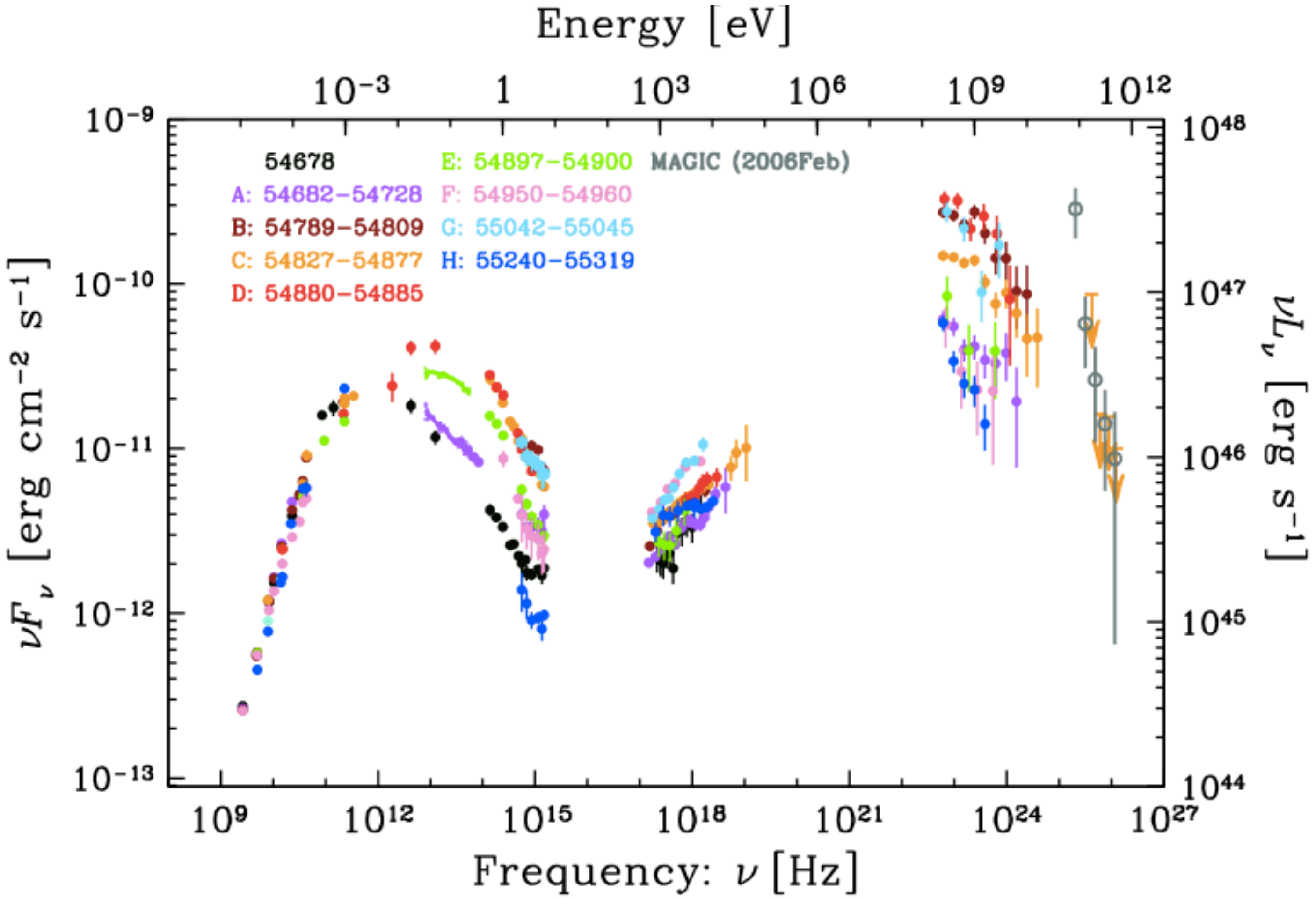
plus very complex *magnetohydrodynamics*

BH magnetosphere
sub-parsec jet
pc-scale jet
multi-pc jet
multi-kpc lobes

gamma-ray images of AGN – not possible, the only information through energy spectra and variability

⇒ broad range of possible realization (scenarios)

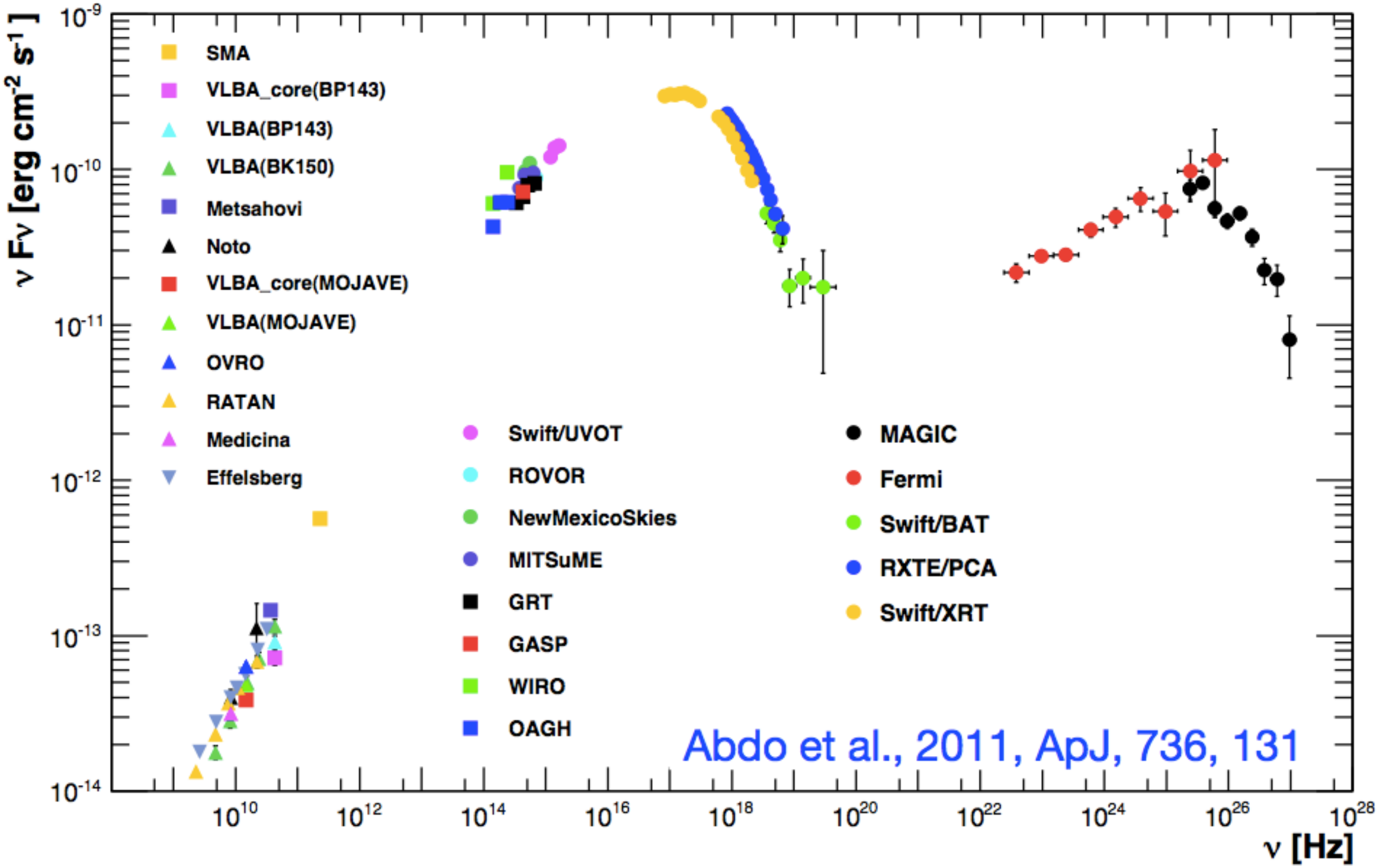
SED of 3C 279 – a classical GeV blazar



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

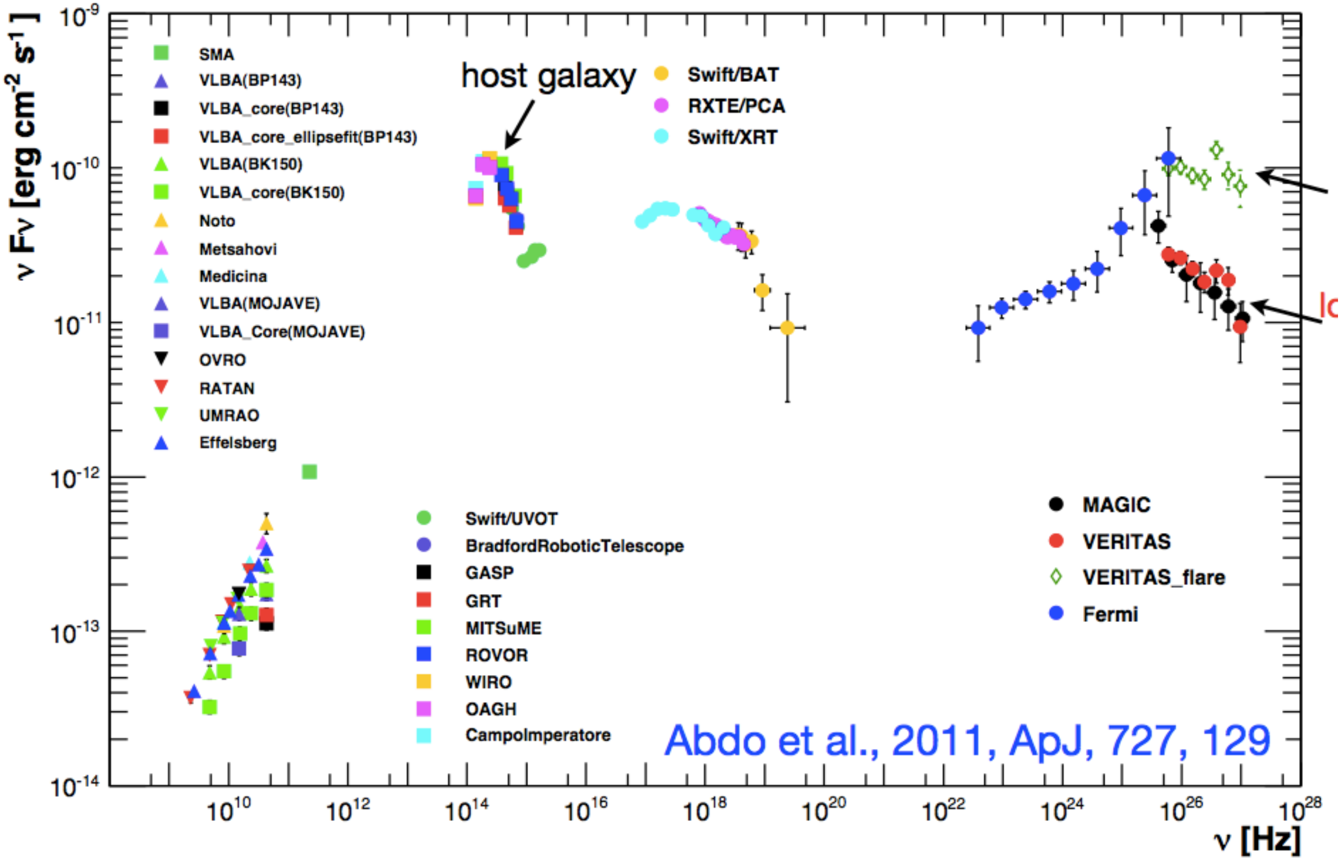
TeV emission?

a typical TeV blazar: Mkn 421



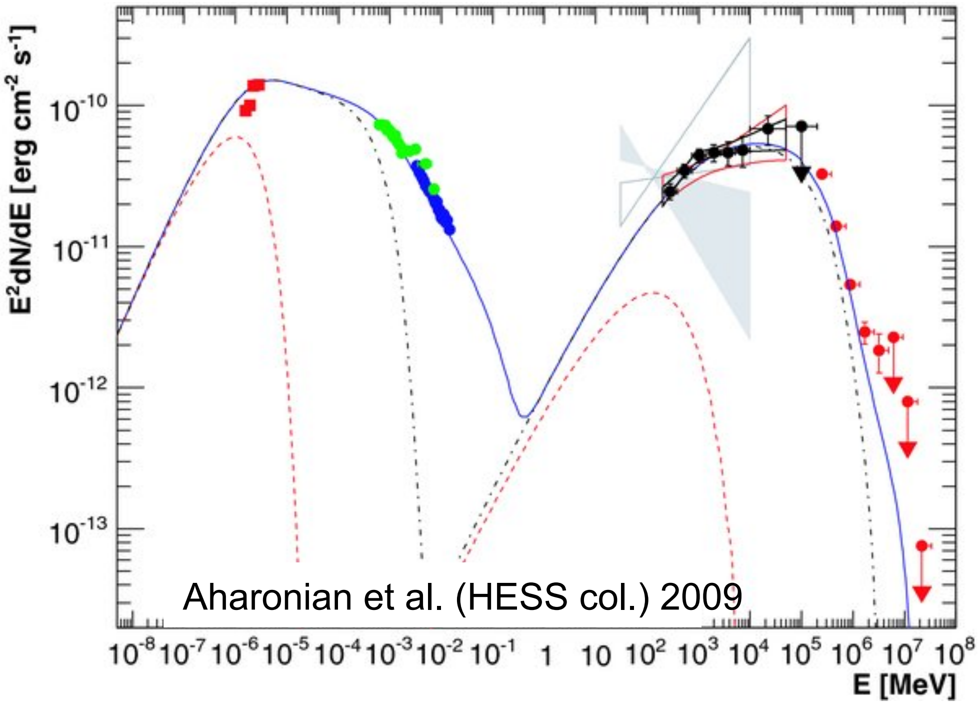
Abdo et al., 2011, ApJ, 736, 131

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, p3=4.3
$\gamma_1=1.4\mathrm{x}10^4$, $\gamma_2=2.3\mathrm{x}10^5$
and cutoff at $\gamma_{max}=3\mathrm{x}10^6$
B=0.02 G, R=2x10^{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 acceleration and radiation processes proceed under extreme physical conditions in environments characterized with

huge gravitational, magnetic and electric fields (in the cores)
very dense background radiation
relativistic bulk motions (black-hole jets with $\delta > 10$
shock waves, highly excited (turbulent) media, etc.

in γ-ray emitting AGN everything should proceed with an extreme efficiency:

conversion of the gravitationl, thermal, bulk motion, electromagnetic forms of energy to nonthermal relativistic particles, i.e. effective acceleration of GeV/TeV/PeV/EeV particles coupled with favourable conditions for production of gamma-rays

SMBH and relativistic Doppler boosting – not sufficient:

AGN - extremely effective particle accelerators and effective emitters

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

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

necessary but not sufficient condition: it implies

(1) minimum acceleration time

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

acceleration in fact is slower:

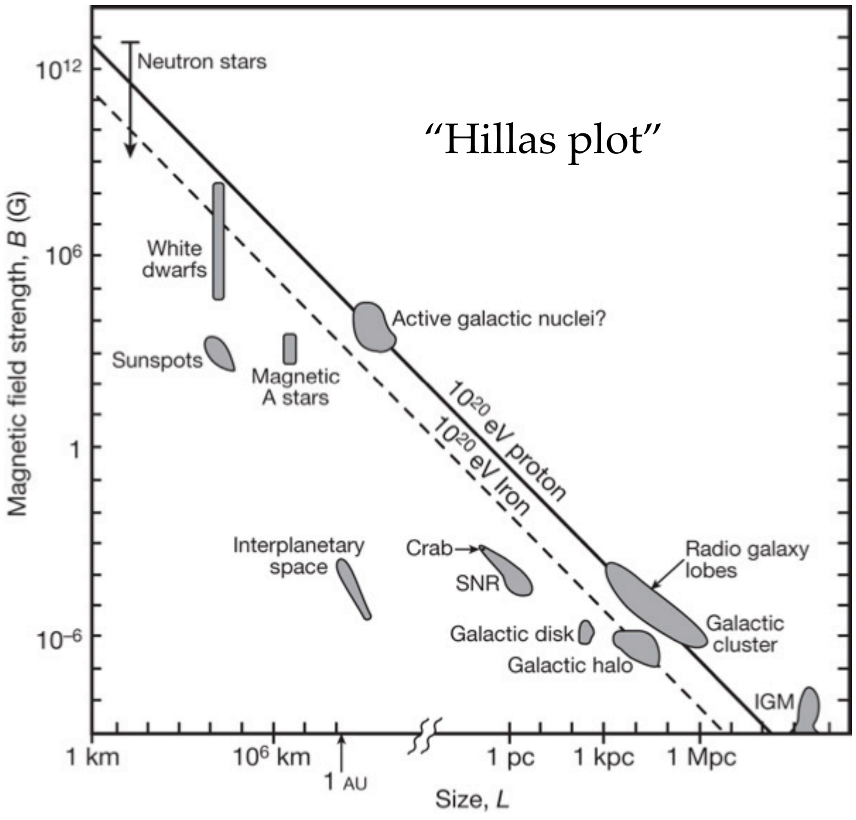
$$t_{acc}=(1\text{-}10)\eta\ R_L/c\ (c/v)^2$$

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:

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

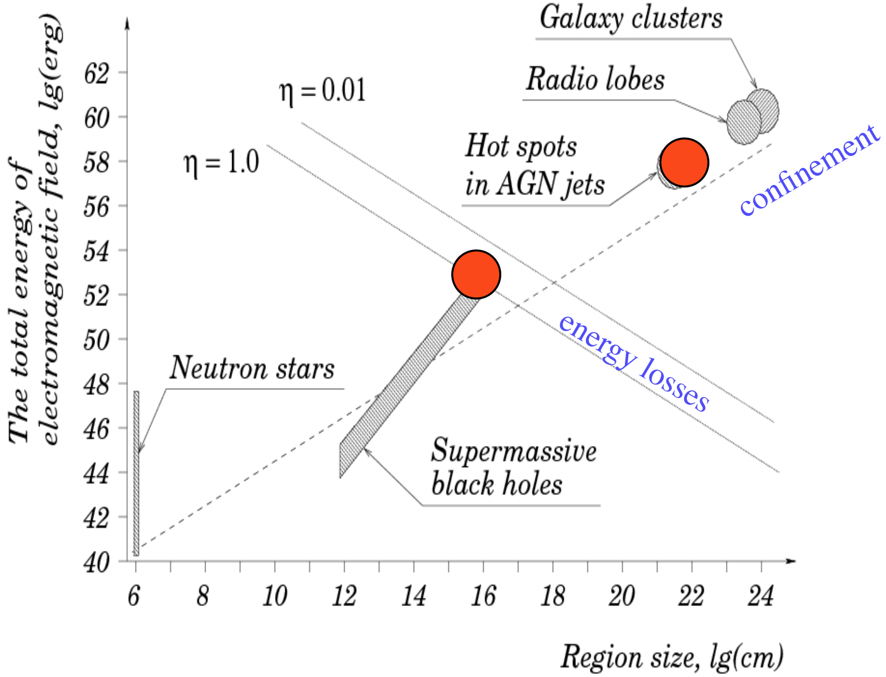
$\simeq$ 300GeV proton synchrotron
$\simeq$ 150MeV electron synchrotron

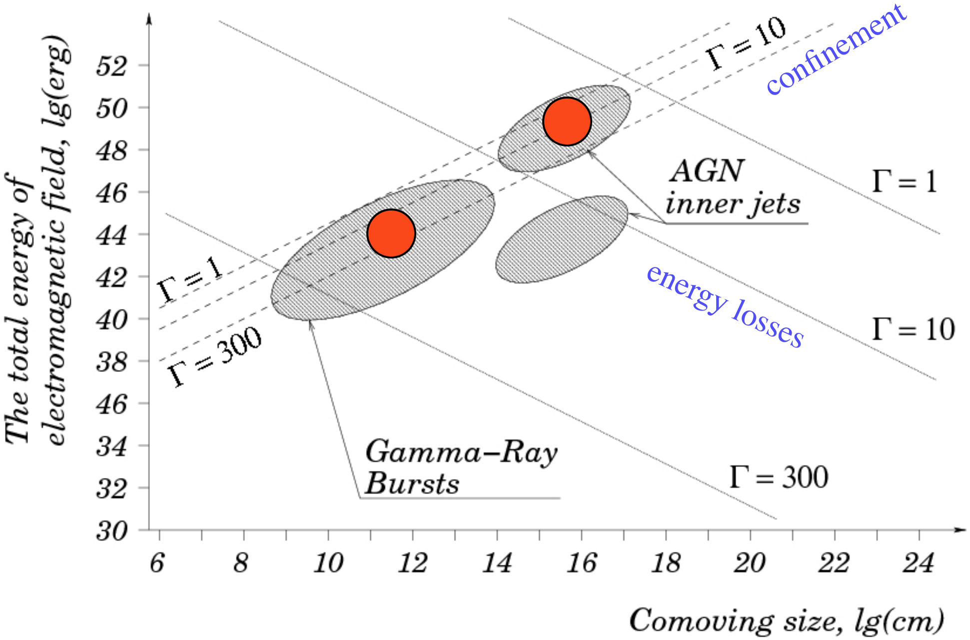
✓ neutrinos (through "converter" mechanism) production of neutrons (through pγ interactions) which travel without losses and at large distances convert again to protons => Γ^2 energy gain !
Derishev, FA et al. 2003, Phys Rev D ***68*** *043003*

✓ observable off-axis radiation
radiation pattern can be much broader than 1/Γ
Derishev, FA et al. 2007, ApJ, ***655****, 980*

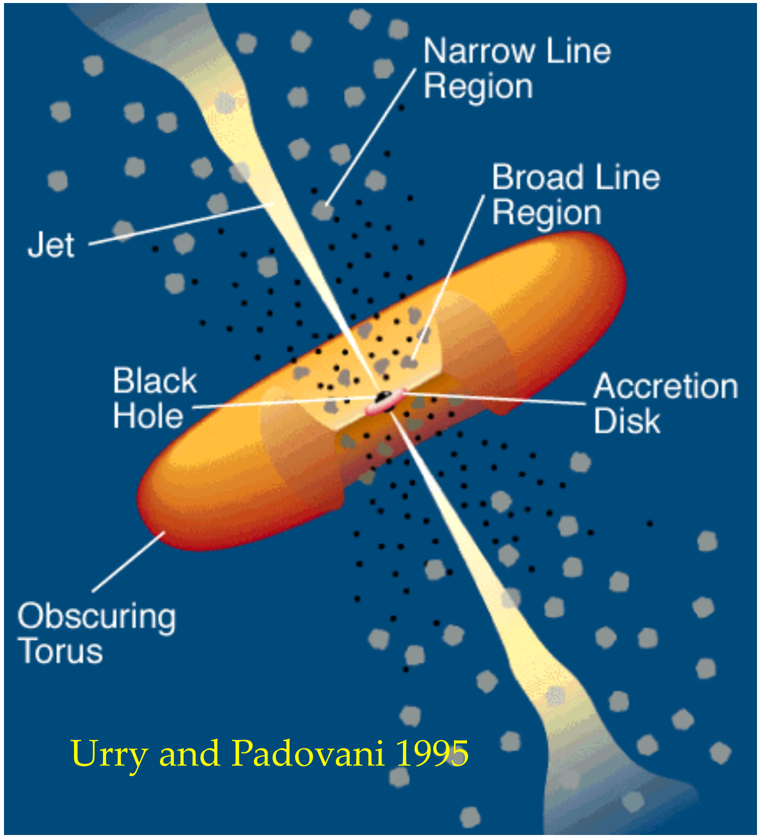
*) in nonrelativistic shocks $\eta \approx 0.1(v_{\rm shock}/c)^2$

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



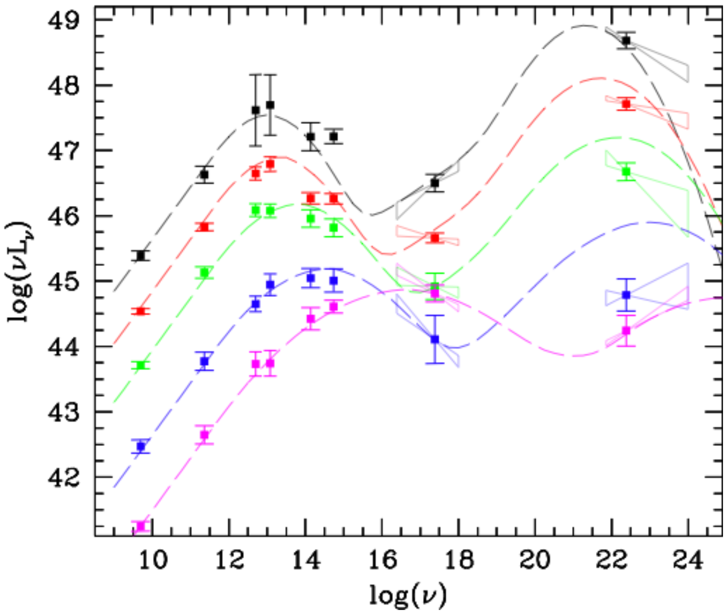


Blazars - sub-class of AGN dominated by nonthermal/variable broad band (from R to gamma) adiation produced in relativistic jets close to the line of sight, with massive Black Holes as central engines



Urry and Padovani 1995

two-peaks (Synchrotron-IC) paradigm



typically small B-field, B <1G

gamma-rays from >100 Mpc sources - detectable because of Doppler boosting

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 ($\tau_{\gamma\gamma} \sim \delta_j^6$)

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...

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

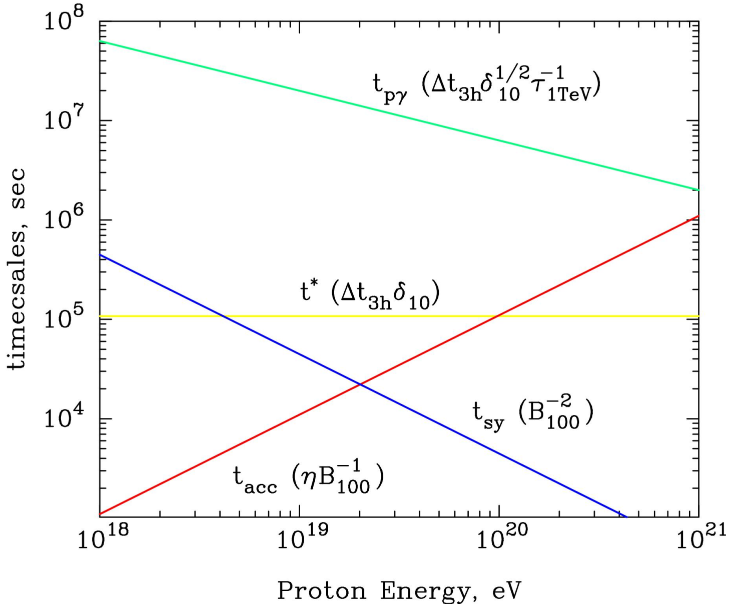
unlikely

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

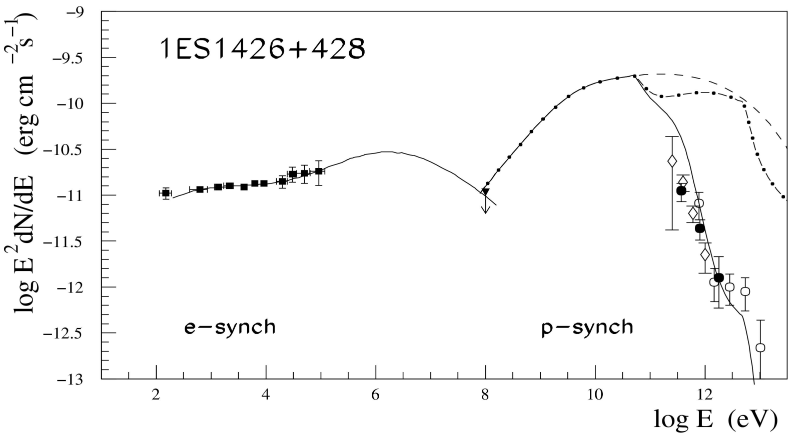
"extreme accelerator" (of EHE CRs) Poynting flux dominated flow

*detectable neutrinos from EGRET AGN but not from TeV blazars

Synchrotron radiation of an extreme proton accelerator



FA 2004



synchrotron radiation of protons:
a viable radiation mechanism

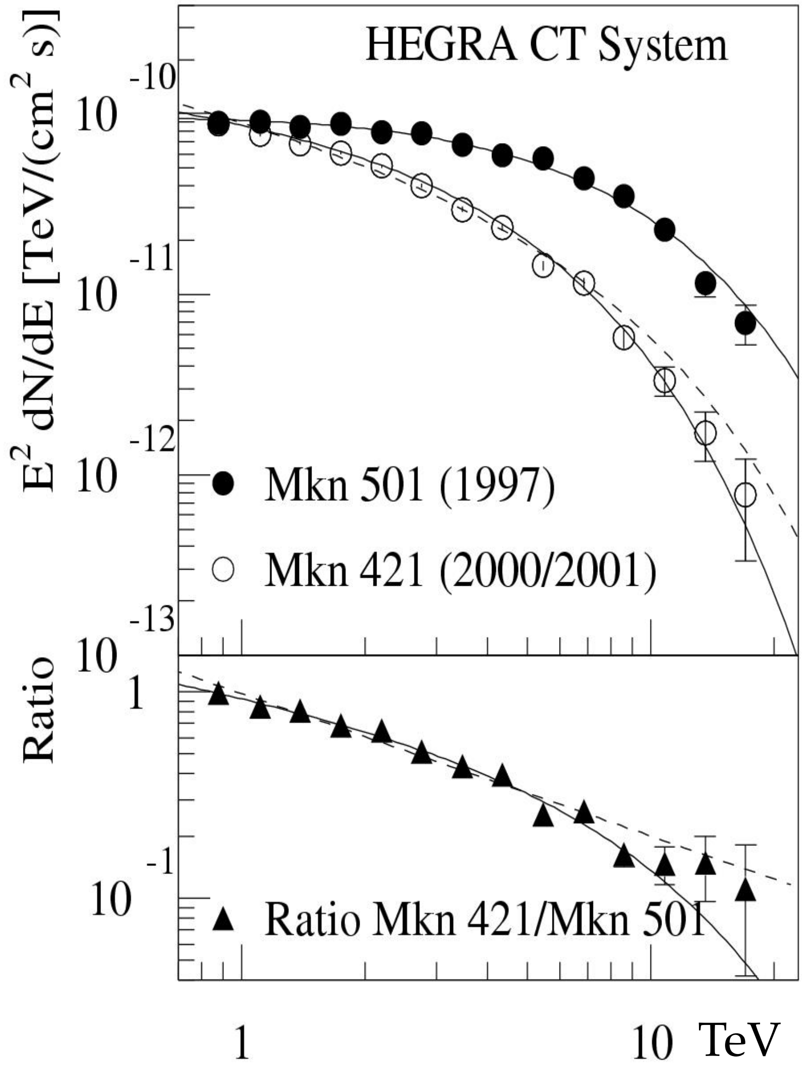
E_{cut}=90 (B/100G)(Ep/10^{19} eV)^{2} GeV

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

E_{max} =300 η^{-1} δj GeV
requires extreme accelerators: η ~ 1

Spectrometry beyond $3E_{cutoff}$!



Unprecedented photon statistics

Mkn 421 – 60,000 TeV photons
detected in 2001

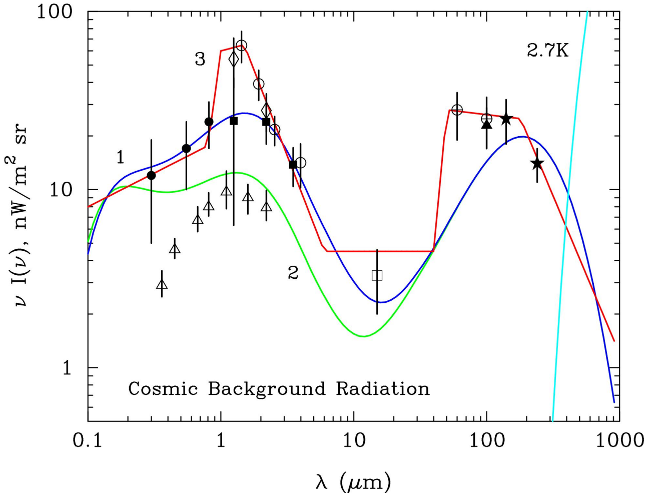
Mkn 501 – 40,000 TeV photons
detected in 1997

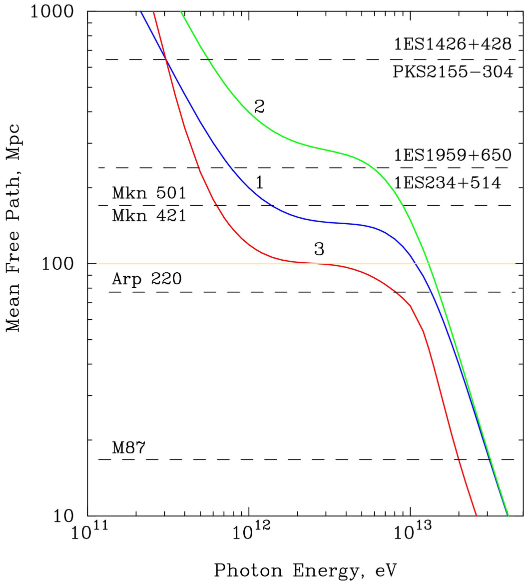
spectra: canonical power-law
with exponential cutoff

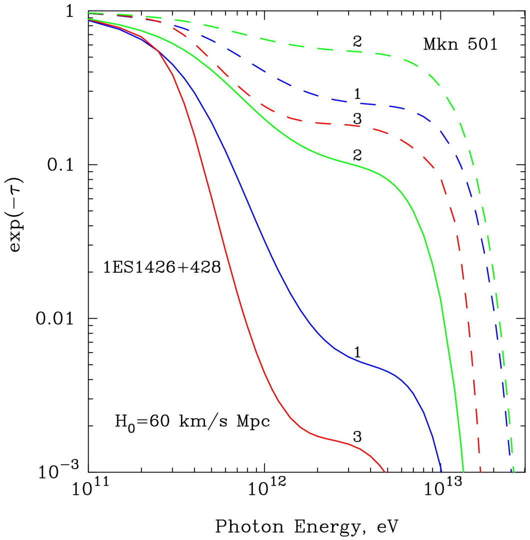
Cutoff = 6.2 TeV and 3.8 TeV
for Mkn 501 and Mkn 421

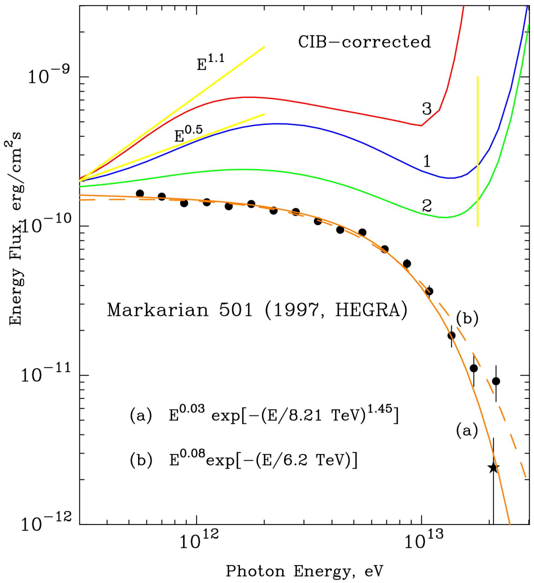
time average spectra of
Mkn 421 and Mkn 501

intergalactic absorption of gamma-rays



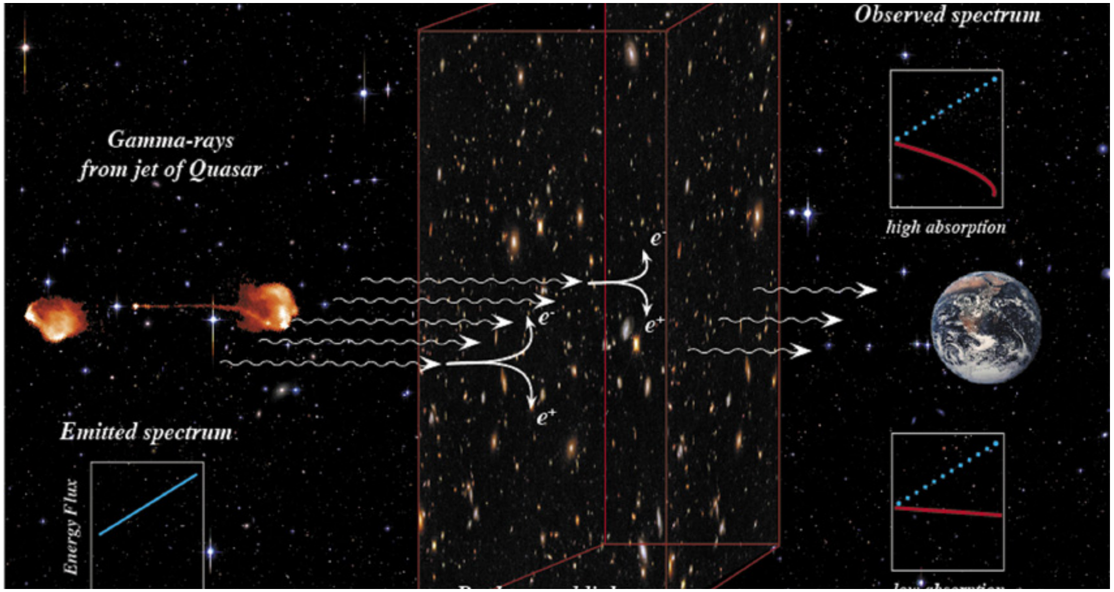


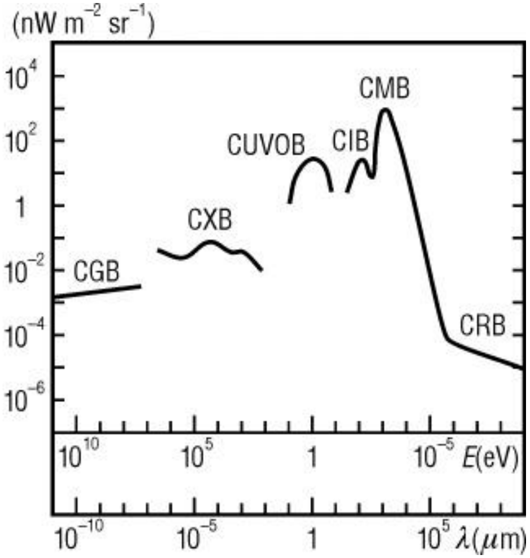




FA 2001

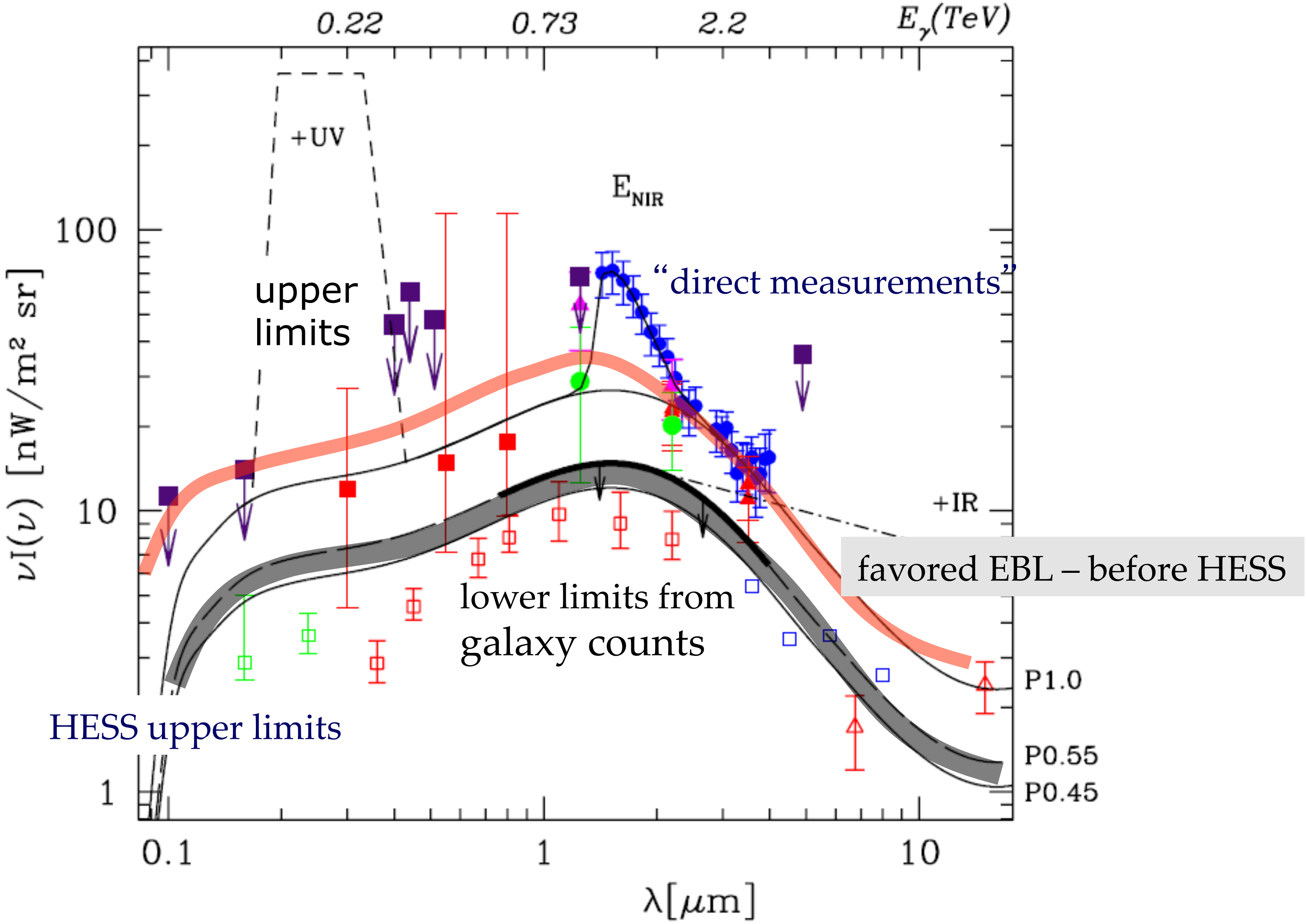
gamma-ray blazars and EBL





HESS – upper limits on EBL at O/NIR:

EBL (almost) resolved at NIR ?



upper limits

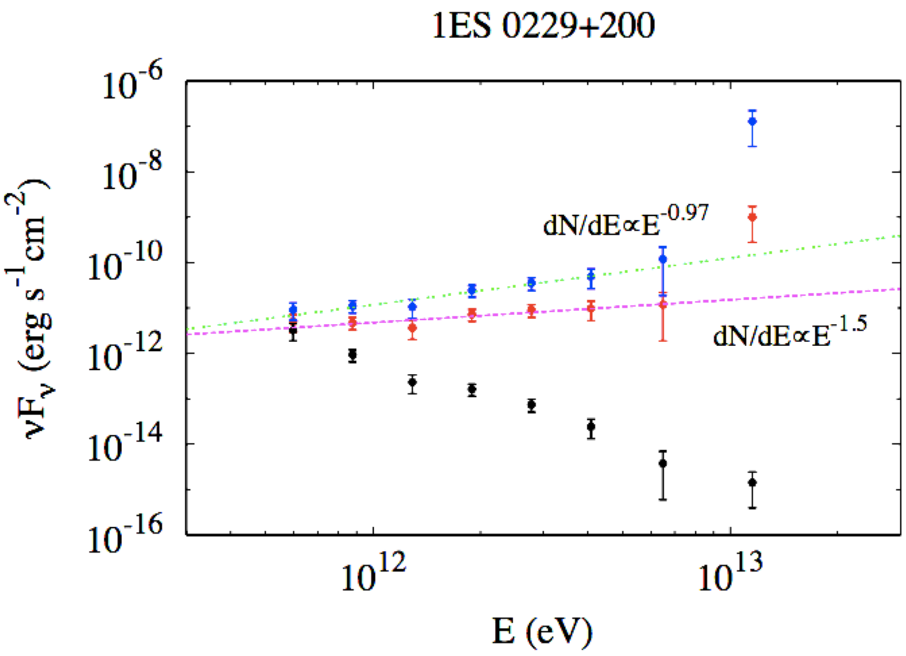
“direct measurements”

favored EBL – before HESS

lower limits from galaxy counts

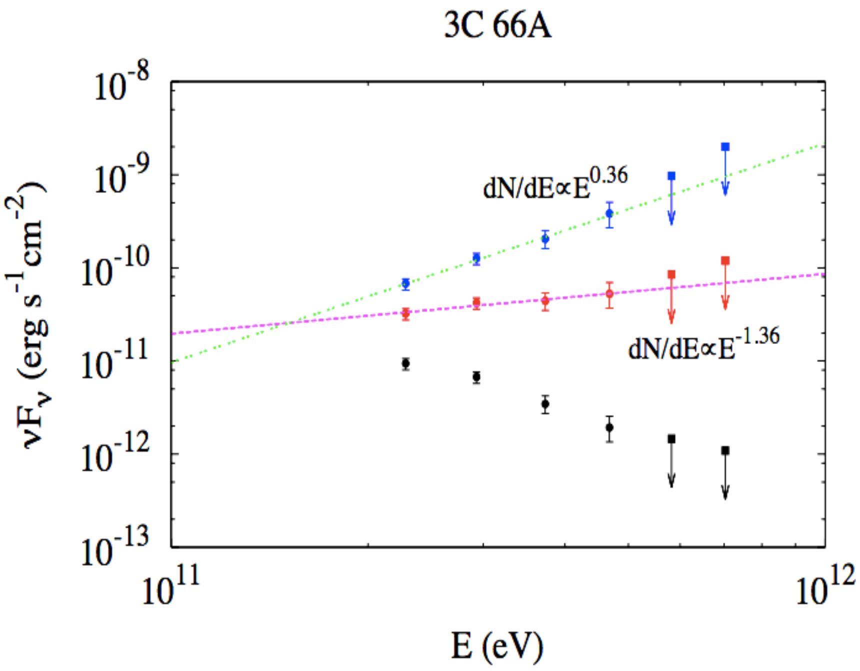
HESS upper limits

new “trouble-makers”


1ES 0229+200

1ES 0229+200: z= 0.14, but spectrum extends to >5 TeV ! (HESS collaboration) !

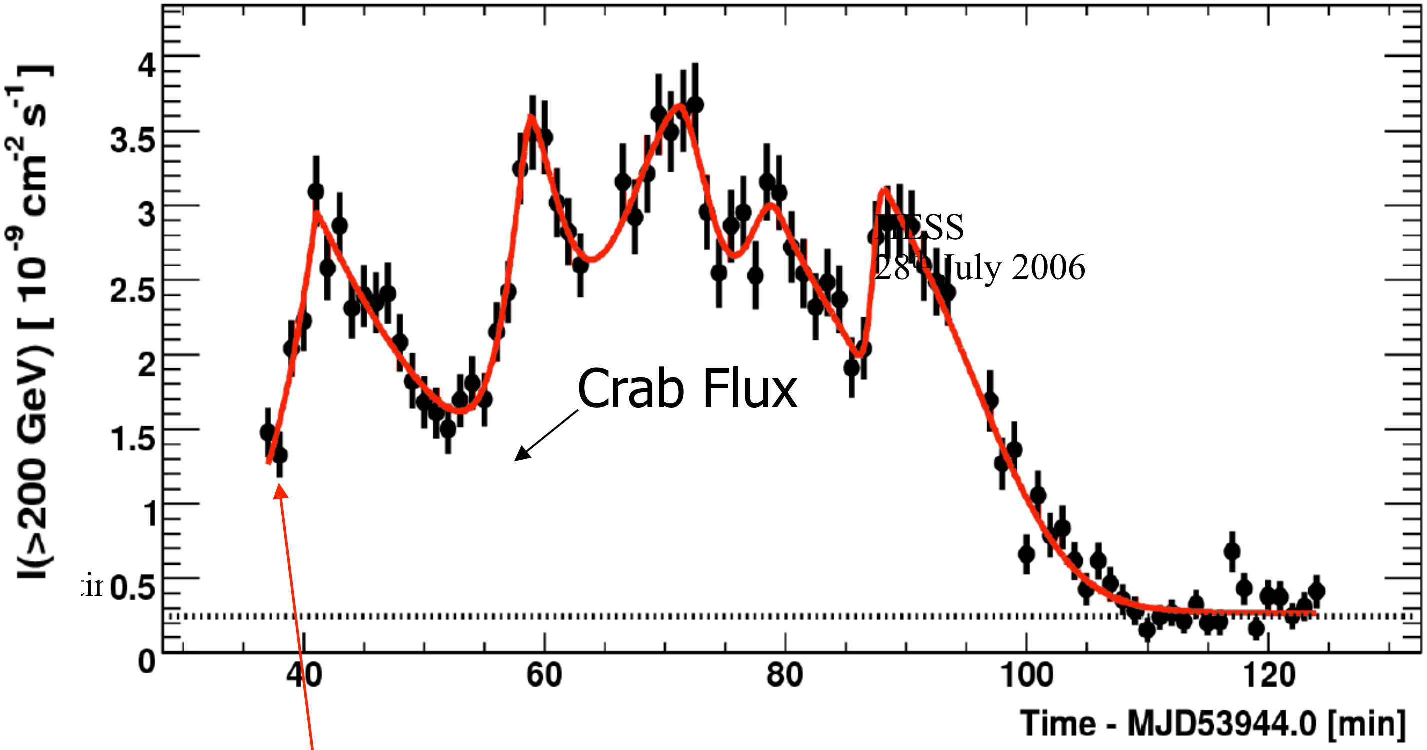
3C 66A z=0.44 ! (VERTAS collaboration)


3C 66A

most exciting results of recent years

- ultra short time variability (on min scales)
- Jet powers could exceed Eddington luminosity
- extremely hard energy spectra

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



rise time <200s

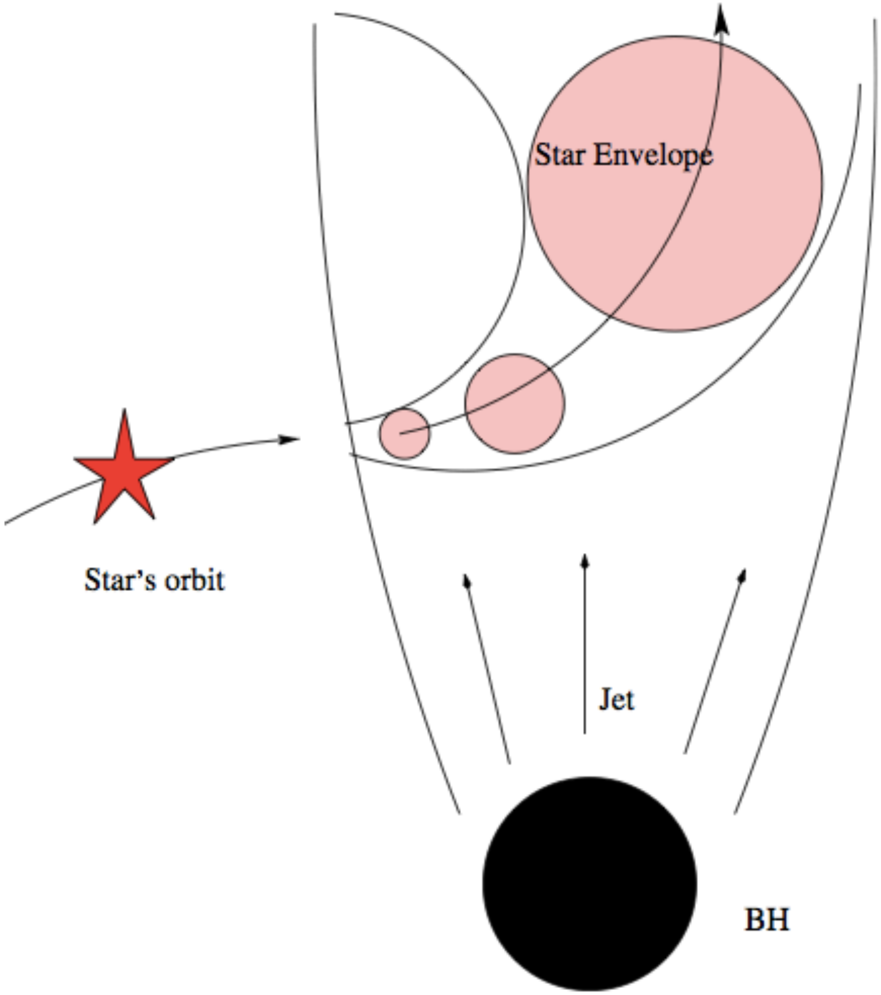
on the Doppler boosting and mass of BH in PKS2155-309

- 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 the accretion disk (the base of the jet), the Lorenz factor of the jet $\Gamma > 50$ - this hardly can be realized close to Rg!

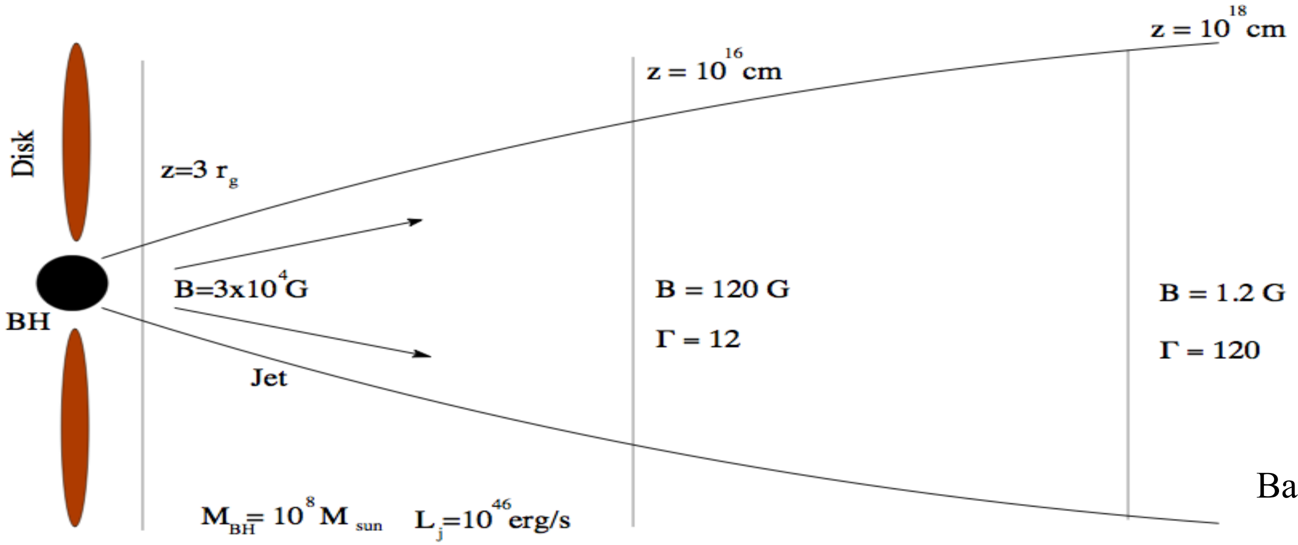
- the (internal) shock scenario: shock would develop at $R=Rg\,\Gamma^2$, i.e. minimum γ-ray variability would be $R_g/c=10^4(M/10^9Mo)$ sec, although the γ-ray production region is located at $R \sim ct_{var}\Gamma^2$ (e.g. Chelotti, Fabian, Rees 1998) - this is true for any other scenario with a "signal-pertubaution"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

B-field: very large or very small?



Barkov et al 2010

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*!

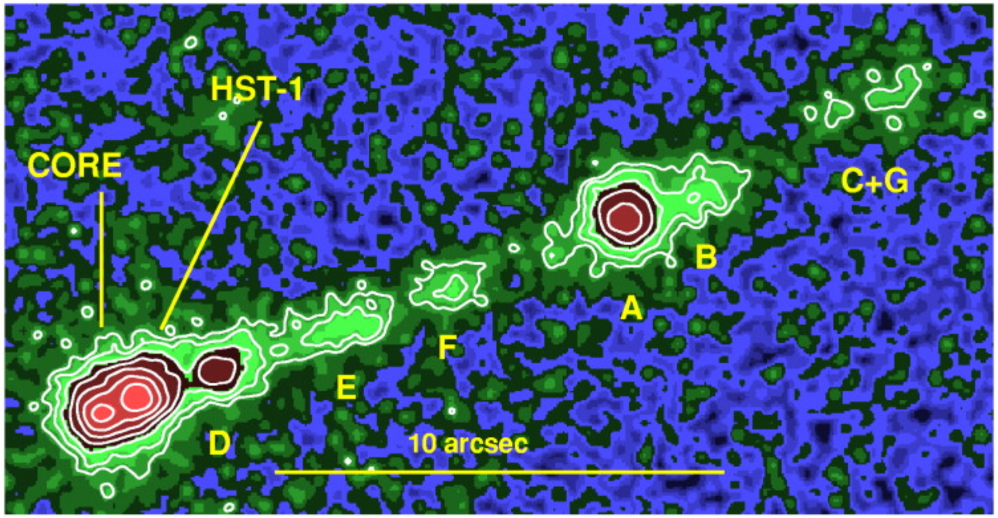
discovery (>4σ) of TeV γ-rays

by HEGRA (1998) and confirmed

recently by HESS/VERITAS, MAGIC

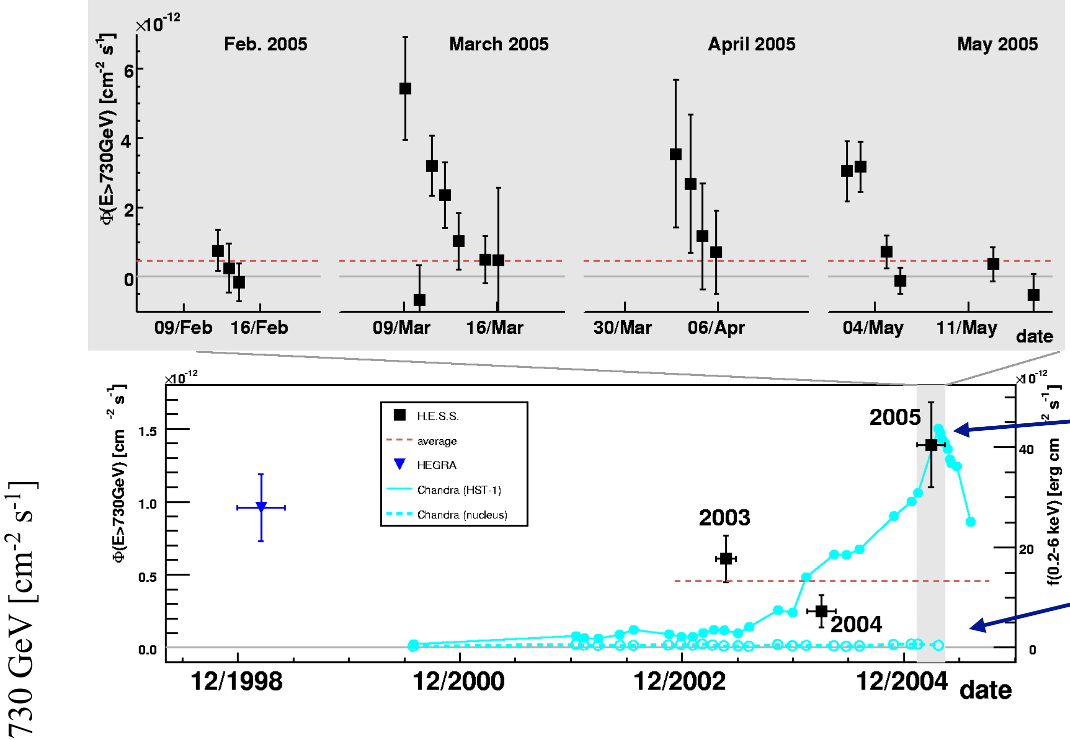
*) recently $6.4 \times 10^9\ M_o$

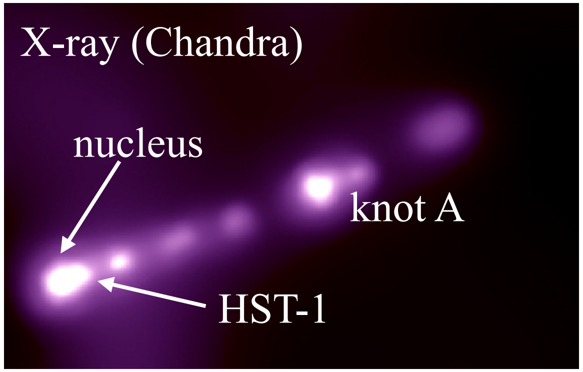
arXiv: 0906.1492 (2009)



M87: light curve and variabiliy

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





HST-1

core

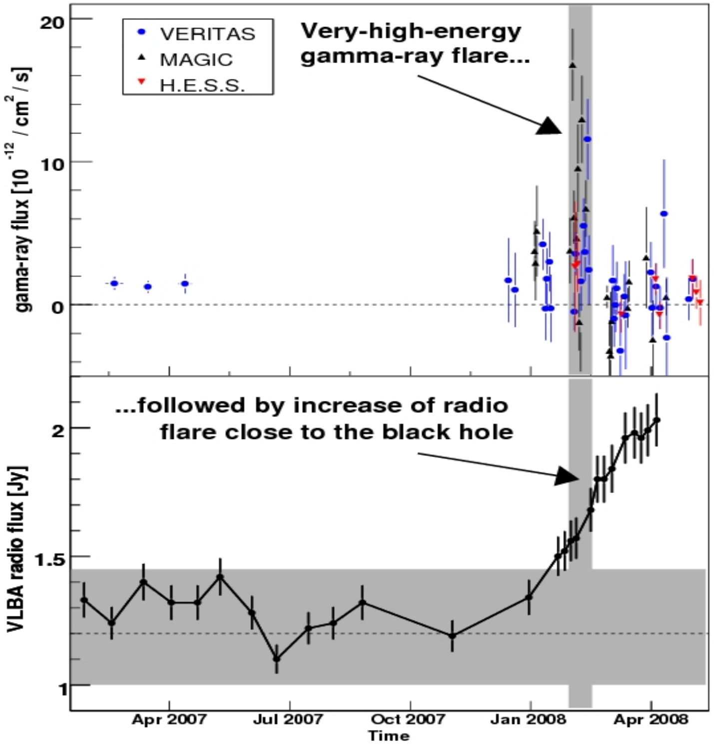
short-term variability on 1-2 day scales => emission region R ~ 5x10^{15}δj cm
=> production of gamma-rays very close to the ‘event horizon’ of BH?

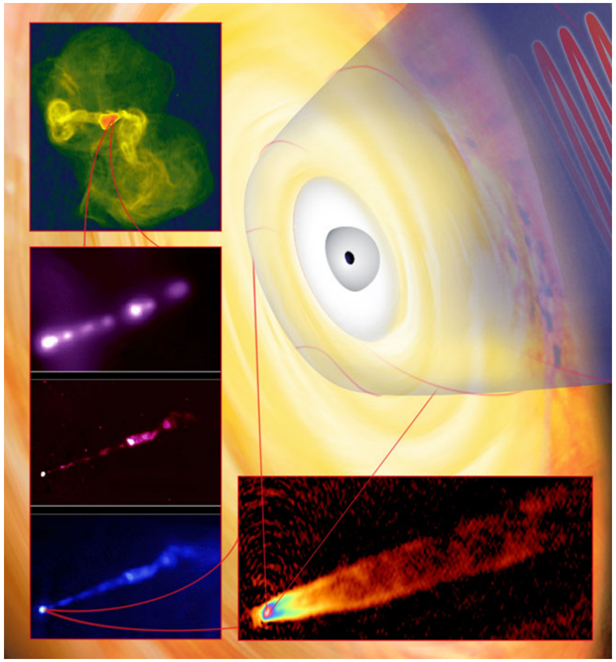
because of very low luminosity of the core in O/IR:
TeV gamma-rays can escape the production region

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

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*

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

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

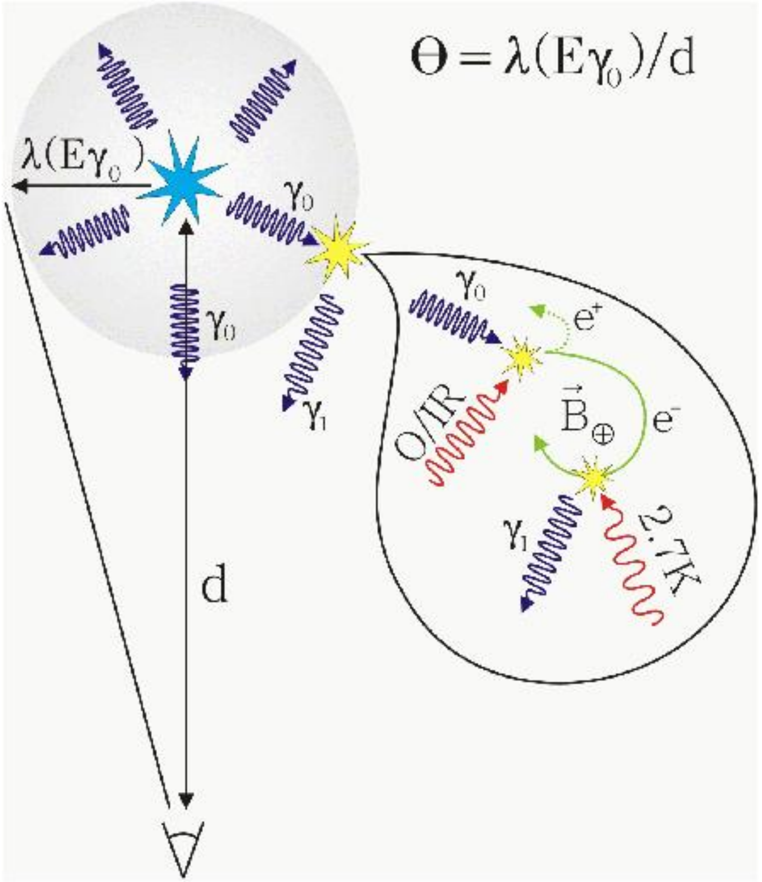
mean free path of parent photons

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

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

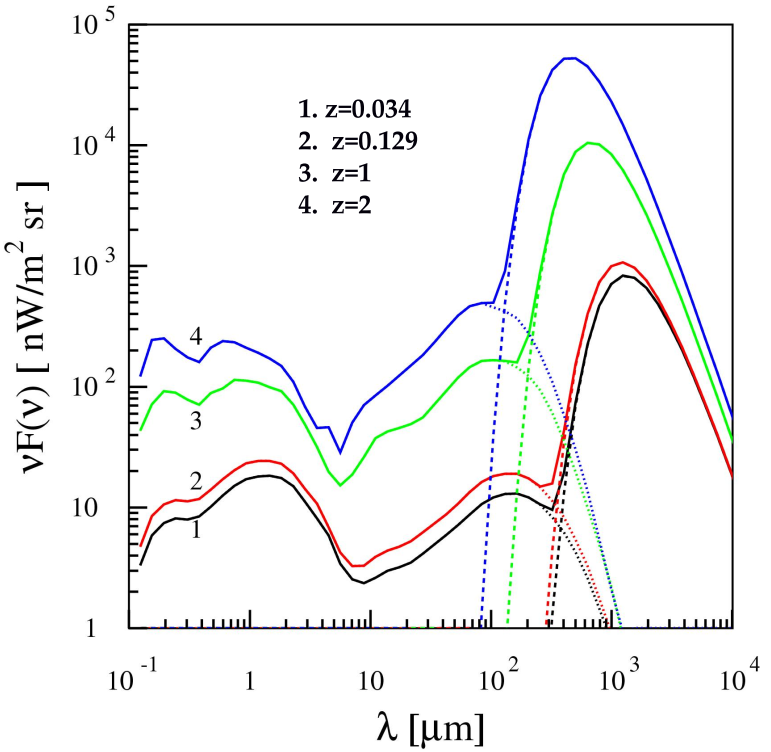
but the advantage of the large Doppler boosting of blazars disapeares: beam => isotropic source

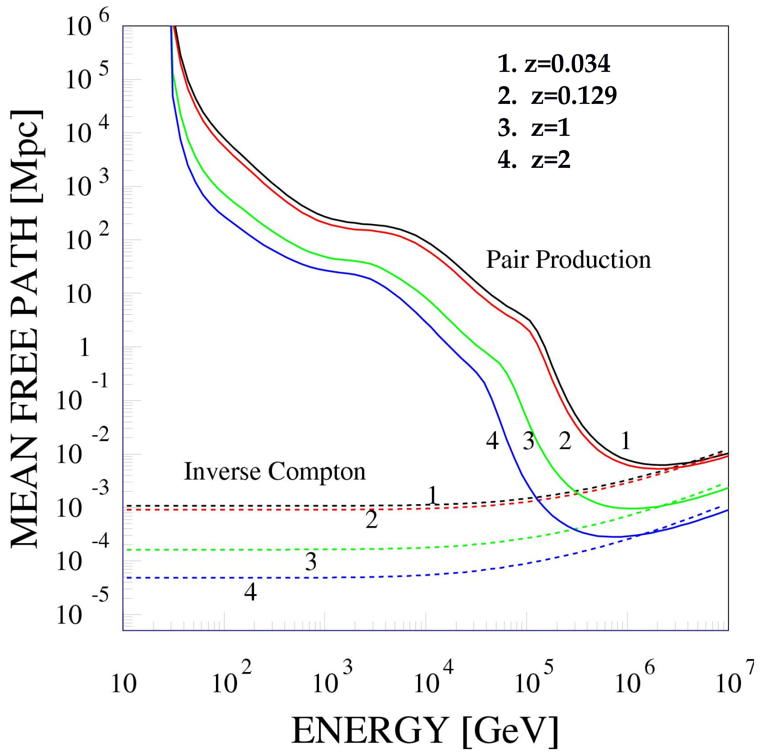
therefore very powerful central objects needed

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

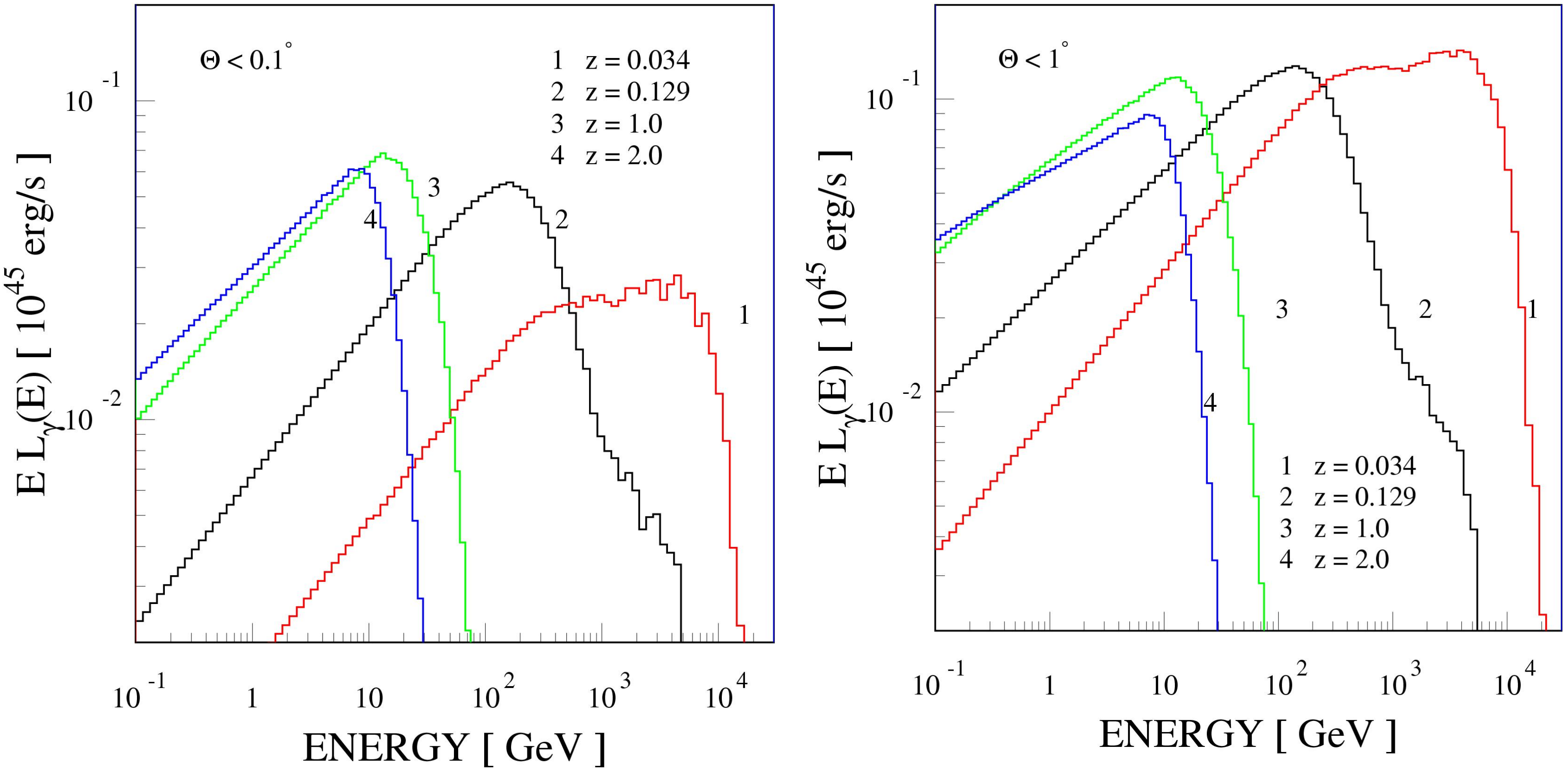
this requires low-energy threshold detectors

EBL at different z and corresponding mean freepaths





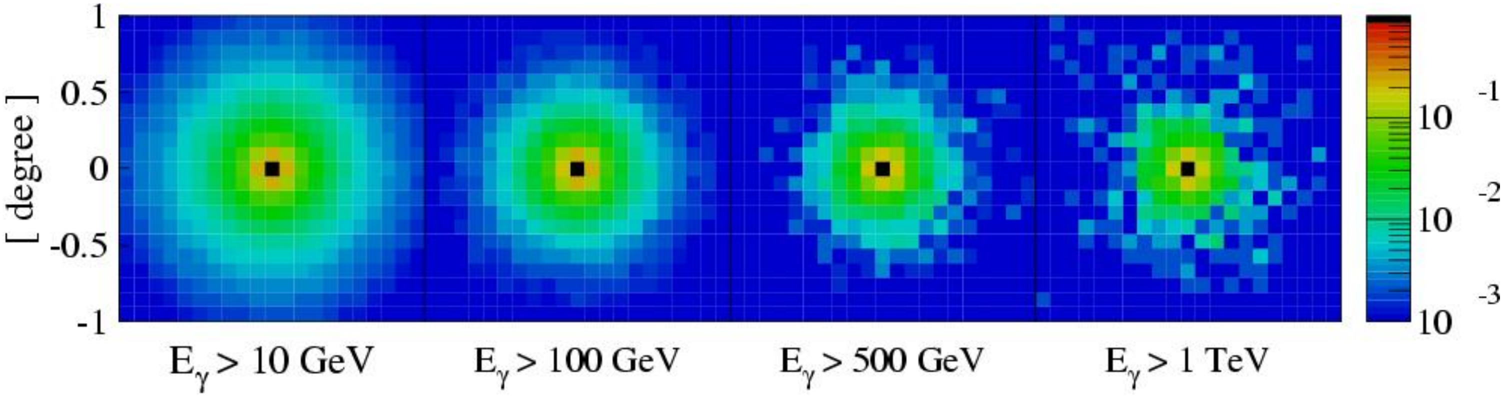
SEDs for different z within 0.1^{o} and 1^{o}



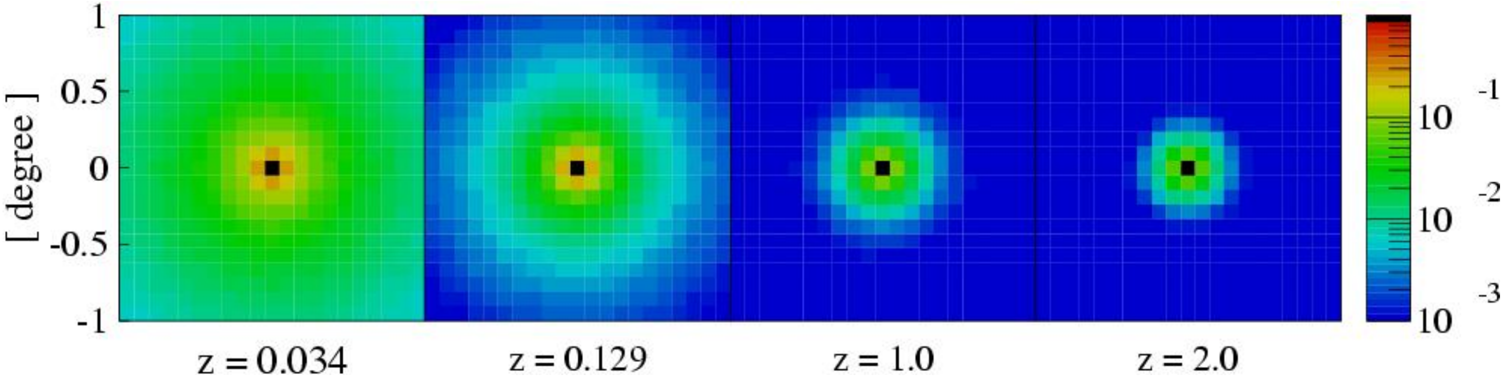
EBL model – Primack et al. 2000

L_o=10^{45} erg/s

Brightness distributions of Pair Halos



z=0.129



E=10 GeV