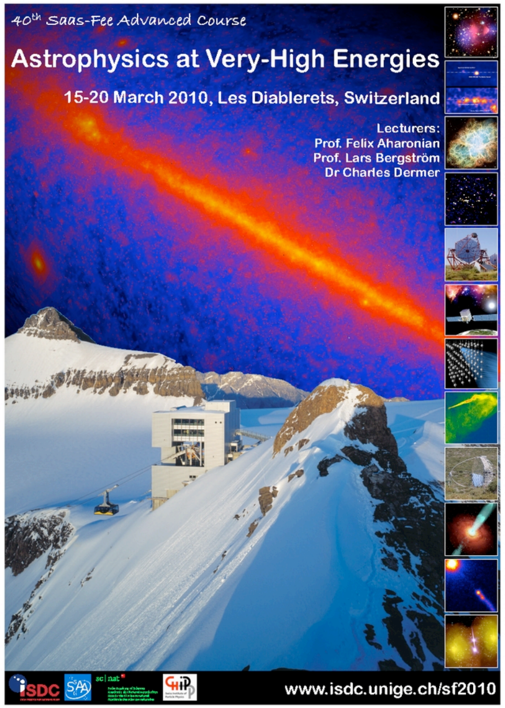
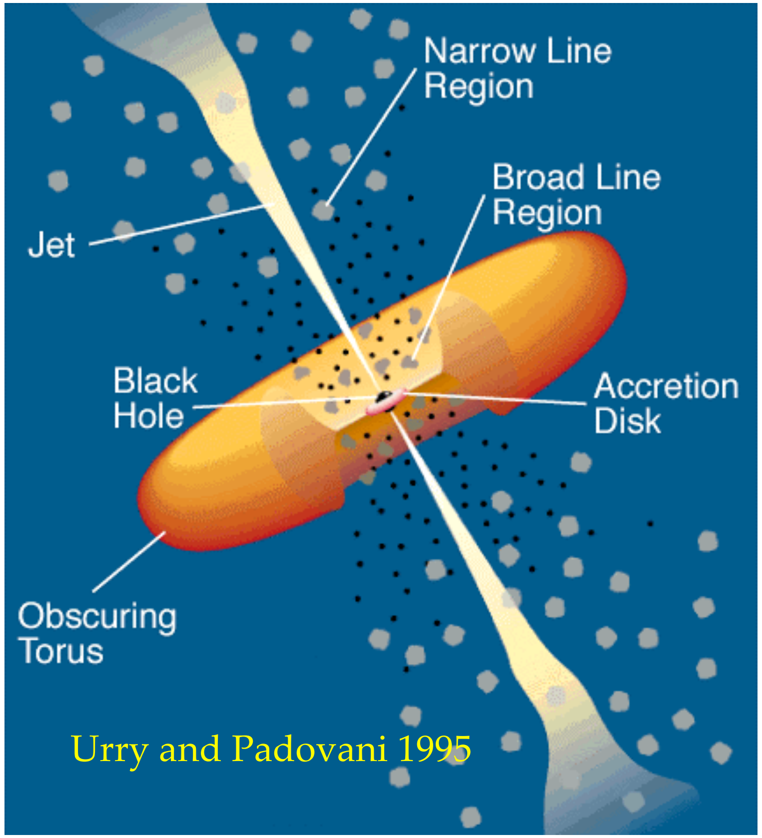
Lecture 10: TeV Blazars and EBL



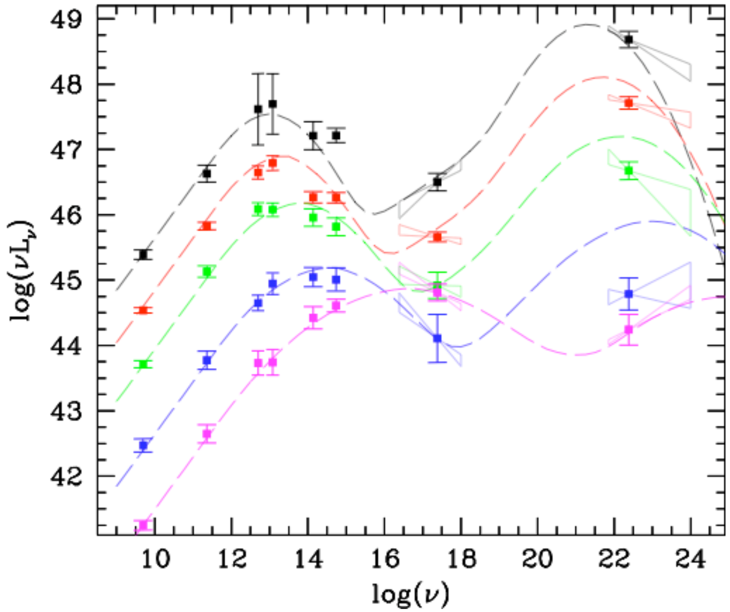
F.A. Aharonian, *DIAS (Dublin)* & *MPIK (Heidelberg)*

Les Diablerets, March 15-20, 2010

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



two-peaks (Synchrotron-IC) paradigm



typically small B-field, B <1G

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

TeV emission from 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 X-rays: 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...

important results

before 2004 (current generation of IACTs - HESS/MAGIC/VERITAS)

- detection of 6 TeV Blazars, extraordinary outbursts of Mkn 501 in 1999, Mkn 421 in 2001, and 1ES 1959+650 in 2002 with overall average flux at > 1 Crab level; variations on <1h timescales; good spectrometry; first simultaneous X/TeV observations

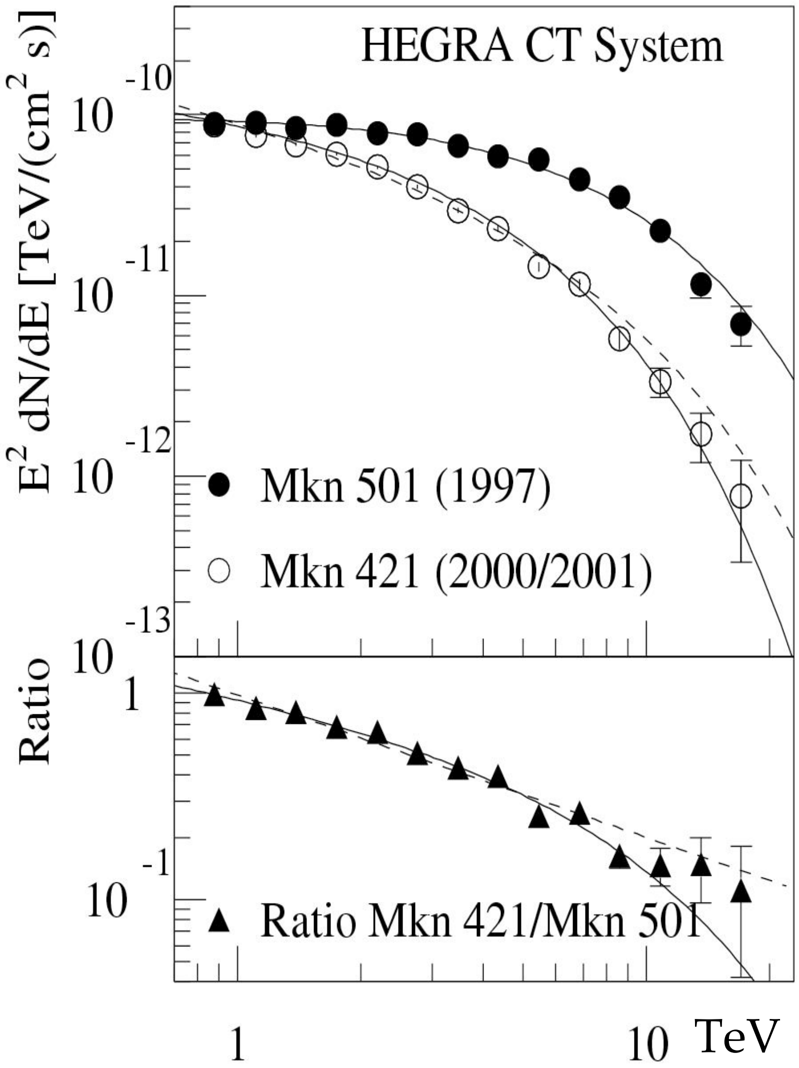
  => initiated huge interest - especially in AGN and EBL communities

today

- detection of >25 TeV blazars, most importantly γ-rays from distant blazars; remarkable flares of PKS2155-305 - detection of variability on min timescales

  => strong impact on both blazar physics and on the Diffuse Extragalactic Background (EBL) models

Spectrometry beyond $3E_{cutoff}$!



Unprecedented photon statistics

Mkn 421 – 60,000 TeV photons detected in 2001

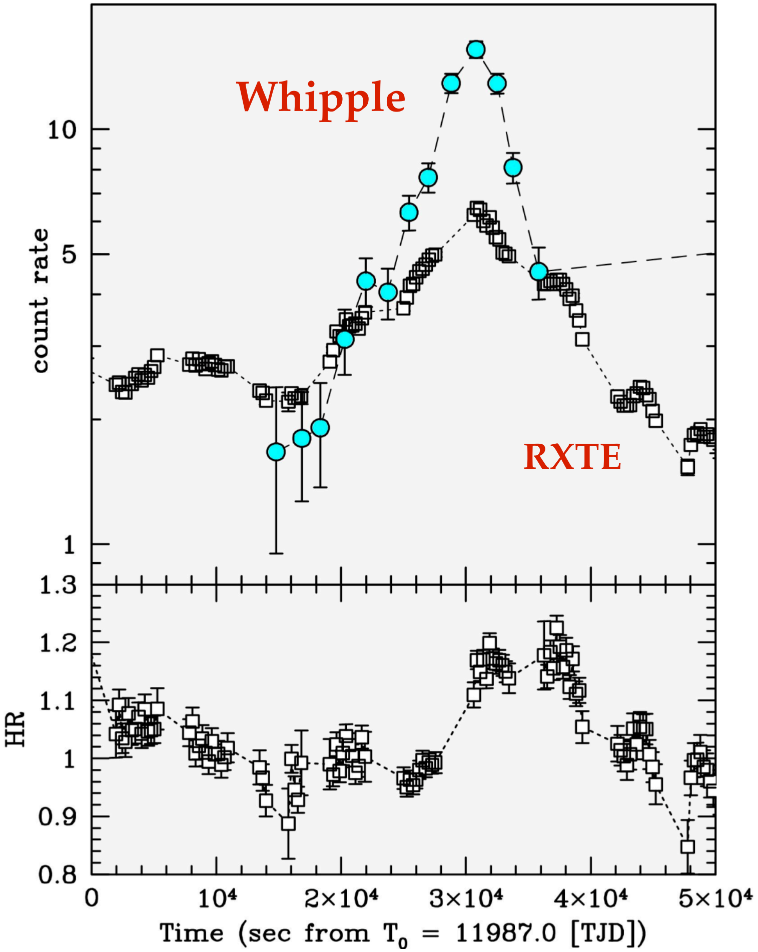
Mkn 501 – 40,000 TeV photons detected in 1997

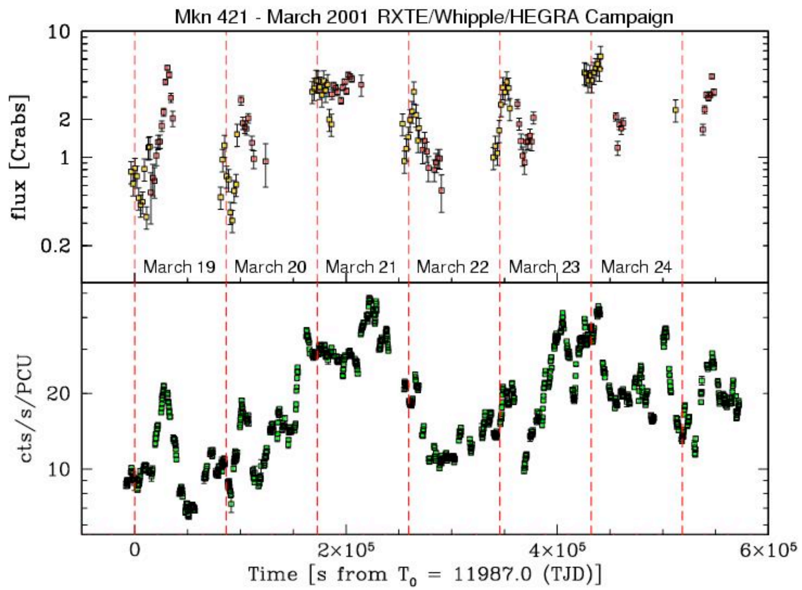
spectra: canonical power-law with exponential cutoff

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

time average spectra of Mkn 421 and Mkn 501

time variations on sub-hour timescales !

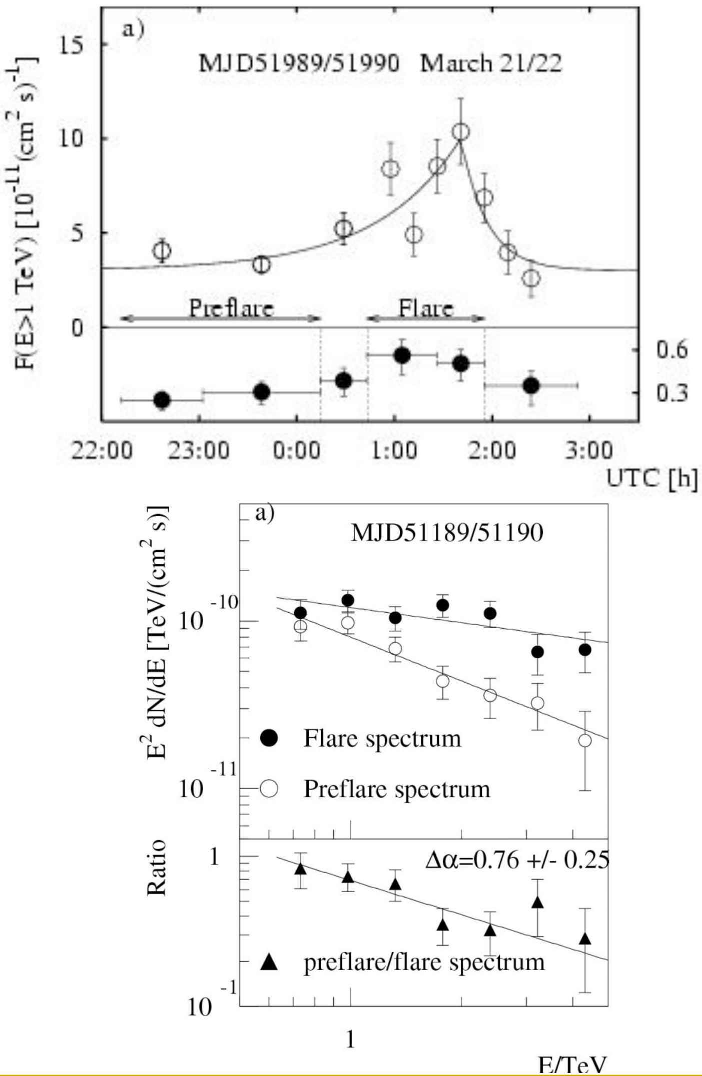




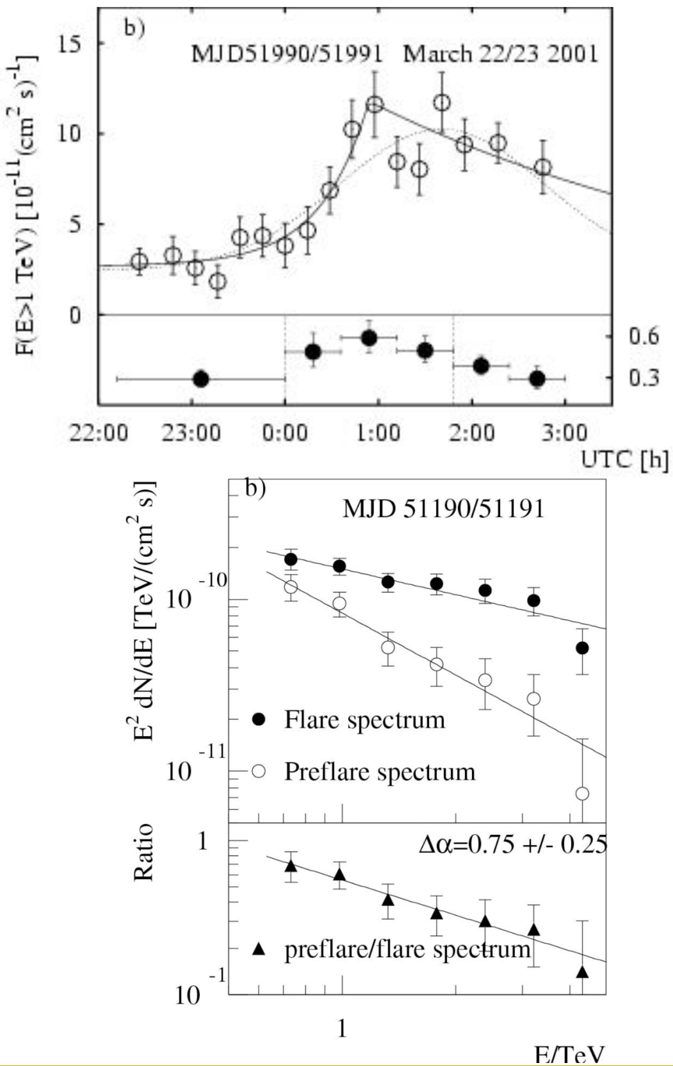
Mkn 421 – extraorginary
high state in 2001

Mkn 421 March-2001 flares - spectroscopy on hour timescales (**HEGRA)**

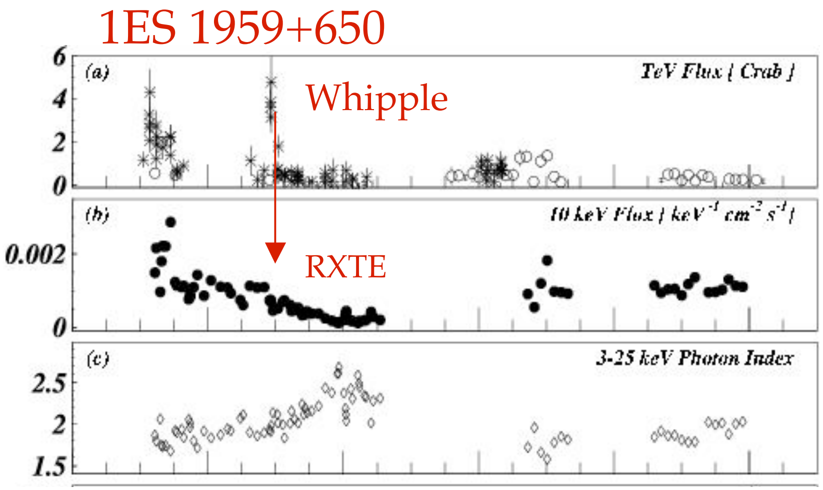
rise time - 45min, decay time - 15min

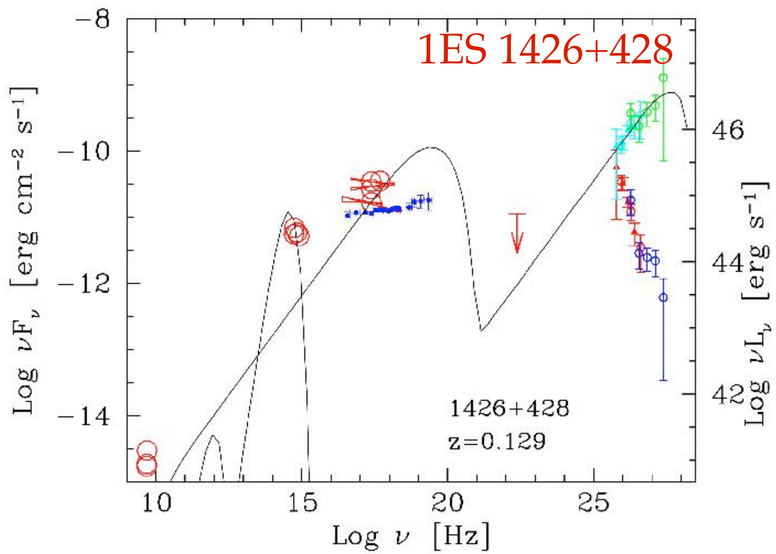


rise time - 21min decay time - 4.5hour



deviations from standard concepts





"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

after correction for IG absorption the γ-ray peak higher than the X-ray peak

violation of the concept that while in GeV blazars Compton peak dominates over the synchrotron peak (in IR domain) in TeV blazars synchrotron peak (in X-ray domain) dominates over the inverse Compton peak

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

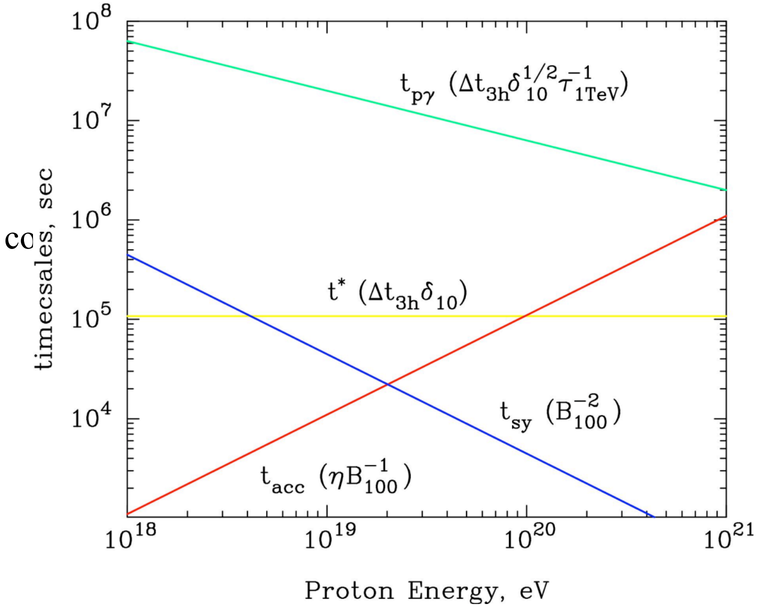
- proton synchrotron — no neutrinos

  very large magnetic field B=100 G + accelaration rate c/r_g

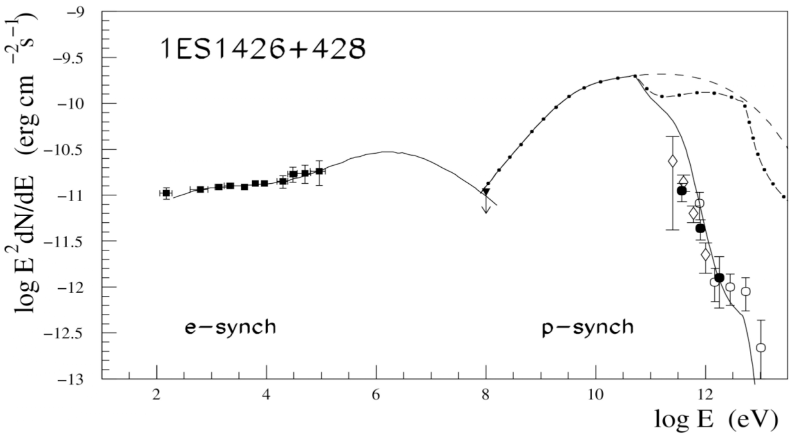
"extreme accelerator" (of EHE CRs) Poynting flux dominated flow

*detectable neutrinos from EGRET AGN but not from TeV blazars

Synchrotron radiation of an extreme proton accelerator



FA 2004



synchrotron radiation of protons: a viable radiation mechanism

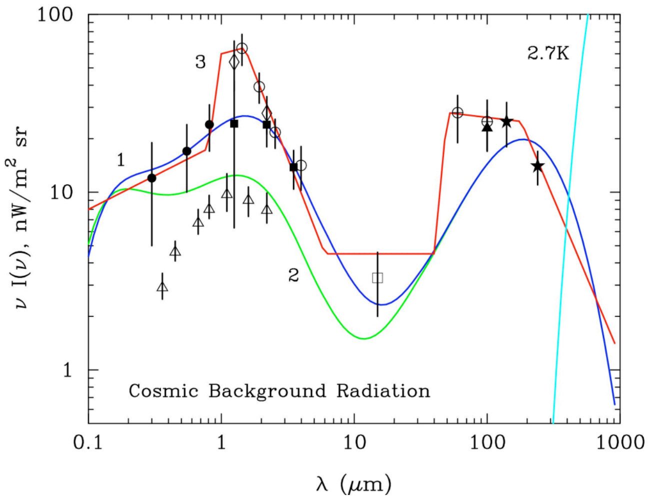
E_{cut}=90 (B/100G)(Ep/10^{19} eV)^2 GeV

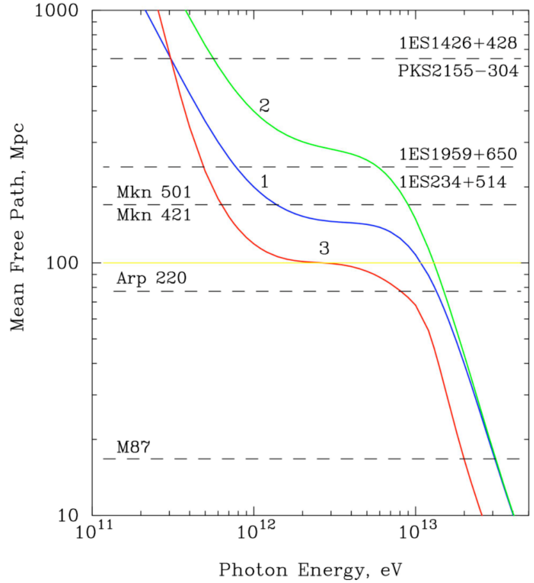
t_{synch}=4.5x10^4(B/100G)$^{-2}$ (E/10^{19} eV)$^{-1}$ s

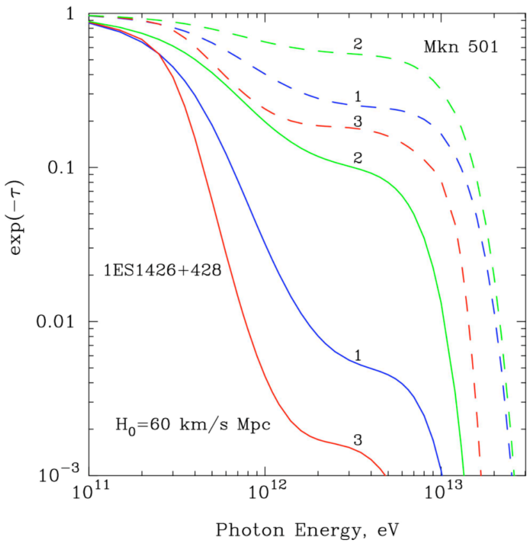
t_{acc}=1.1x10^4 (E/10^{19}) (B/100G)$^{-1}$ s

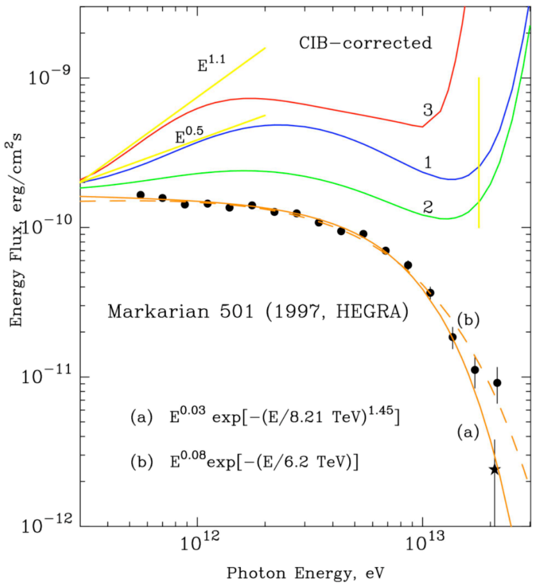
E_{max} =300 η^{-1} δj GeV
requires extreme accelerators: $\eta \sim 1$

intergalactic absorption of gamma-rays



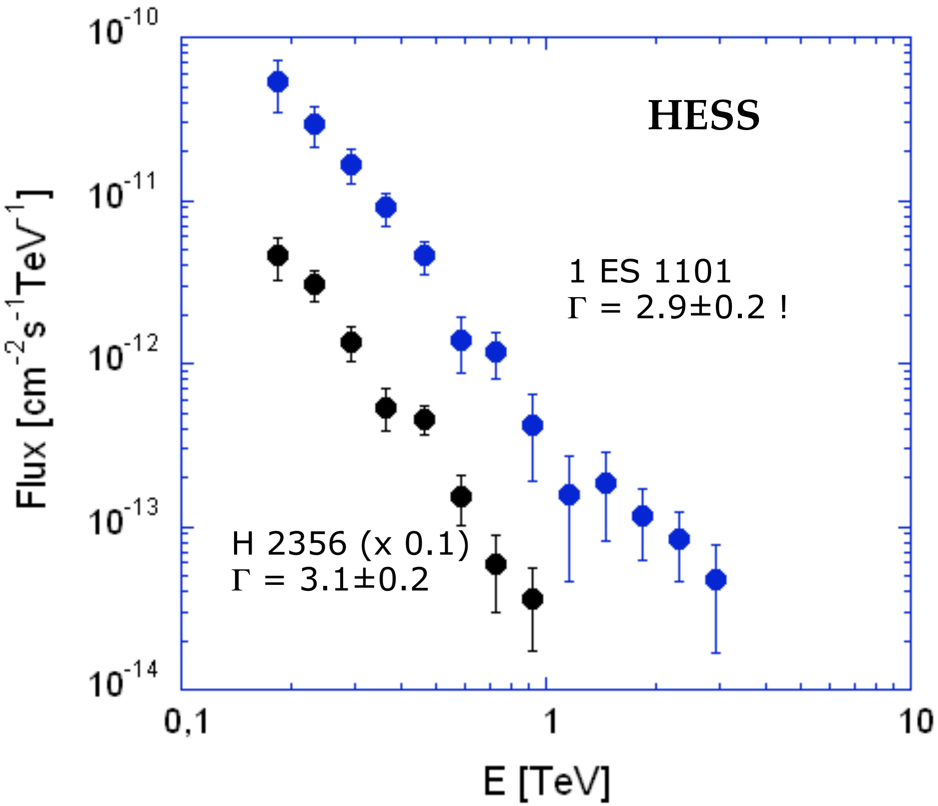






FA 2001

new blazars detected at large z:
HESS/MAGIC at z> 0.15 !

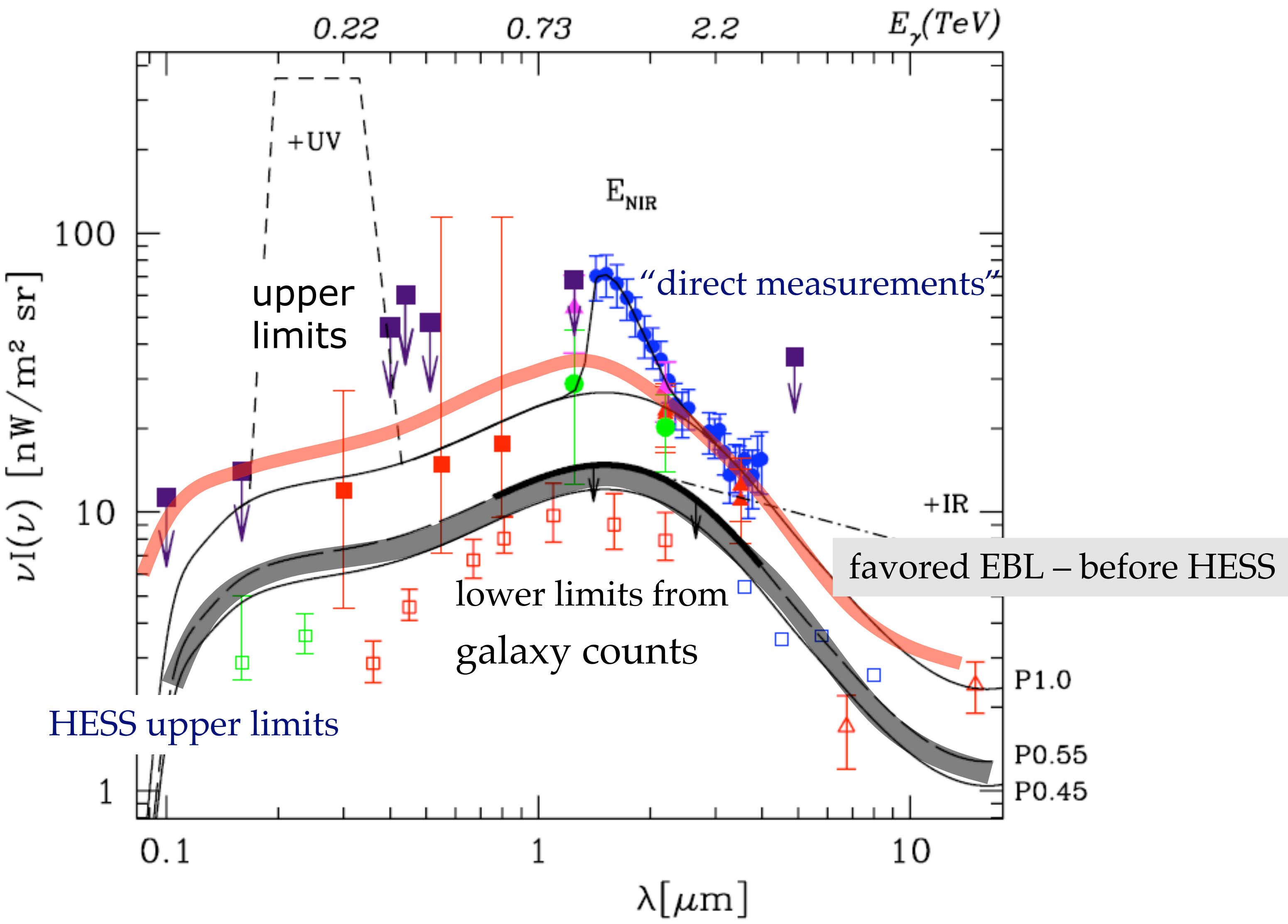


condition: corrected for IG absorption γ-ray spectrum not harder than $E^{-\Gamma}$ ($\Gamma=1.5$)

➔ **upper limit on EBL**

HESS – upper limits on EBL at O/NIR:

EBL (almost) resolved at NIR ?



two options:

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

or

propose *extreme* hypotheses, e.g.

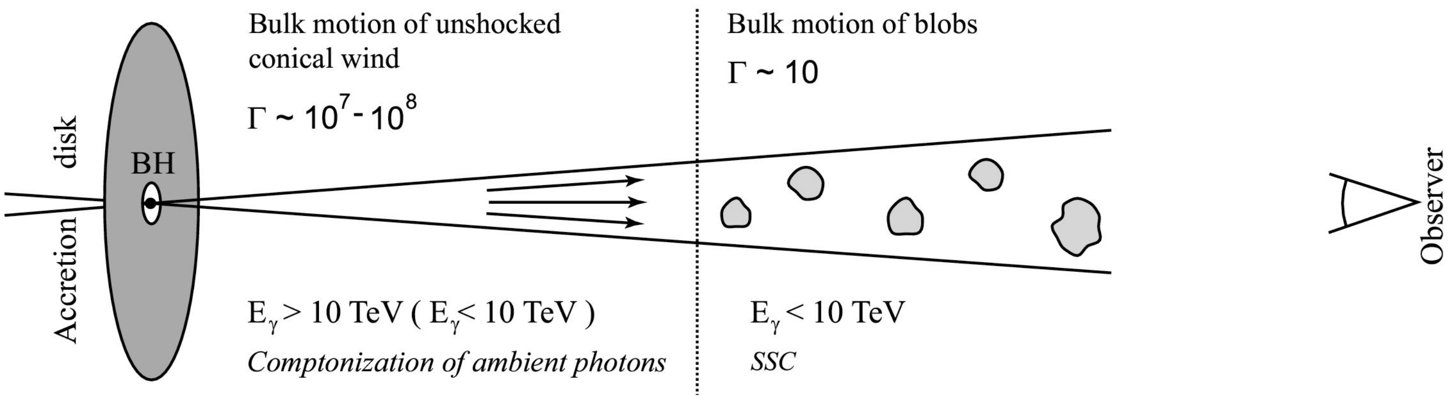
violation of Lorentz invariance, non-cosmological origin of z ...

or

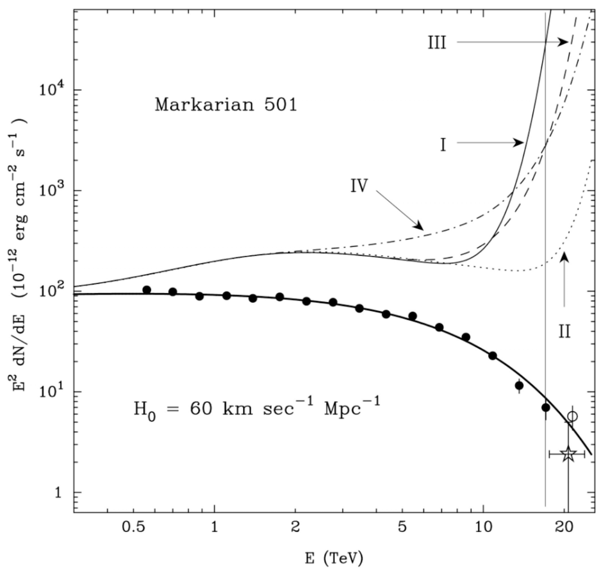
propose ***less dramatic (more reasonable)*** ideas, e.g.

- 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

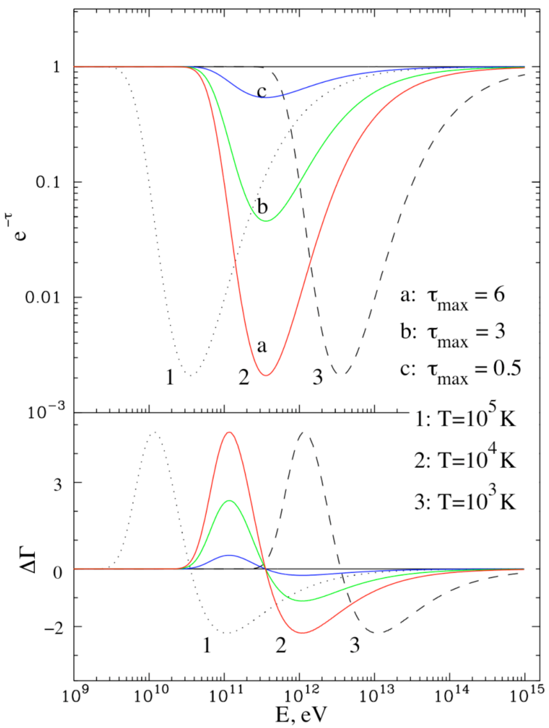
Gamma Rays from a cold ultrarelativistic wind ?

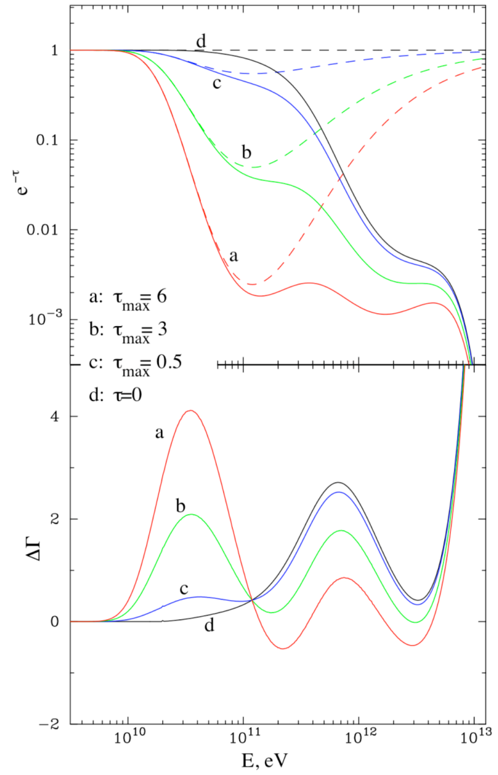


in fact not a very exotic scenario ...



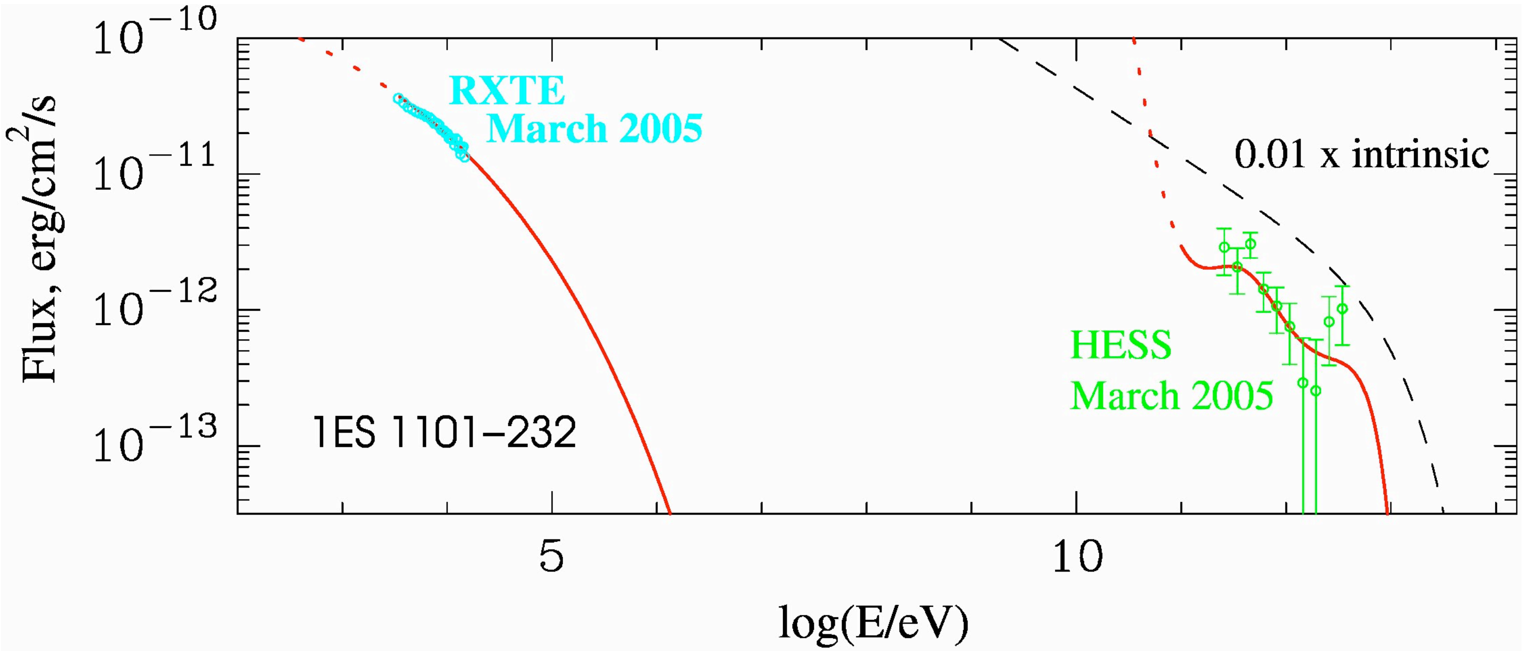
internal gamma-gamma absorption





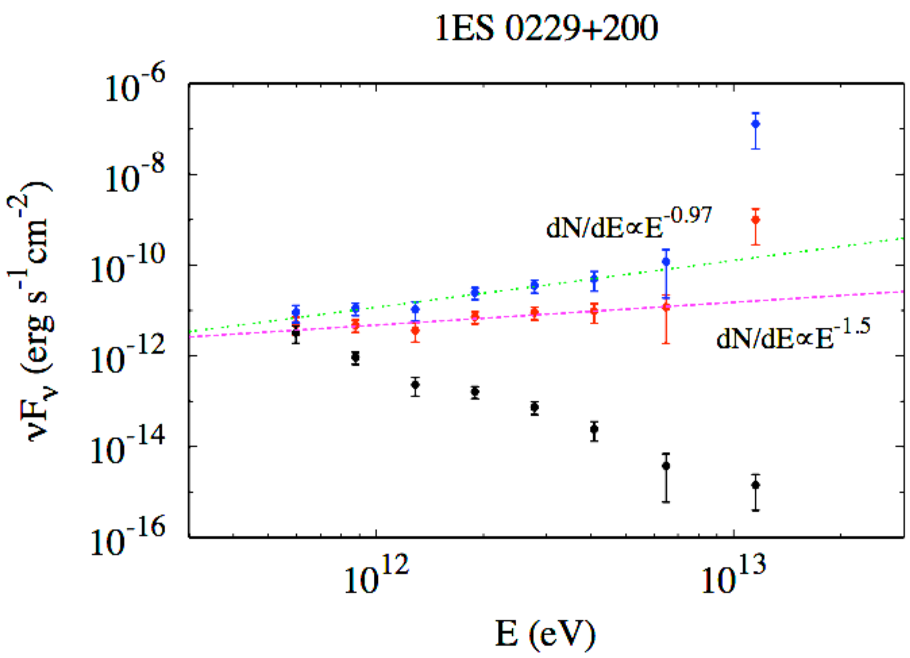
can make the intrinsic spectrum arbitrary hard without any real problem from the point of view of energetics, given that it can be compensated by large Doppler factor, $\delta j > 30$

TeV gamma-rays and neutrinos (?) and secondary X-rays



2-3 orders of magnitude suppression of TeV gamma-rays !
if gamma-rays are of hadronic origin => neutrino flux >10 Crab
should be detected by cubic-kilometer scale neutrino detectors

new "trouble-makers"



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

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

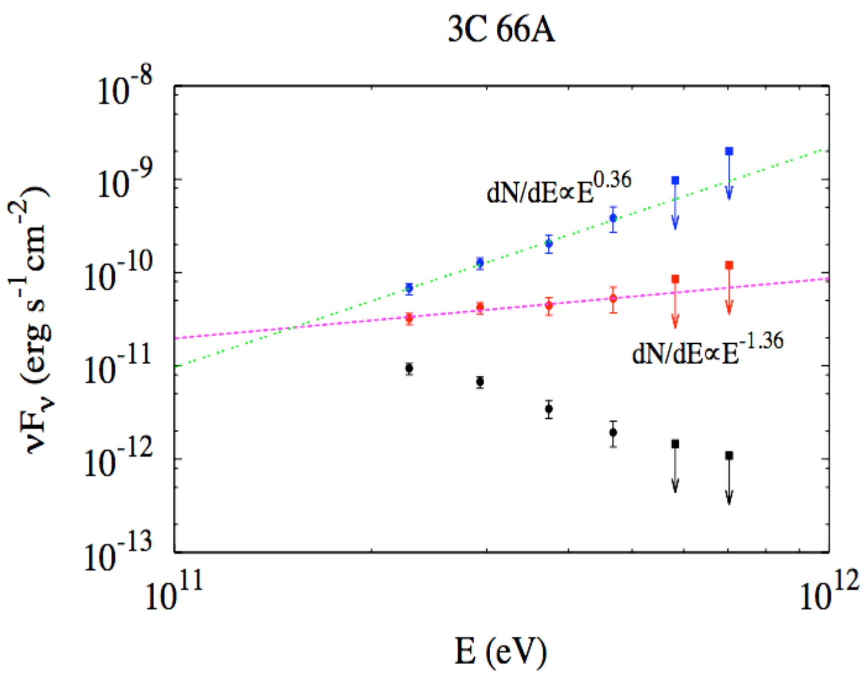
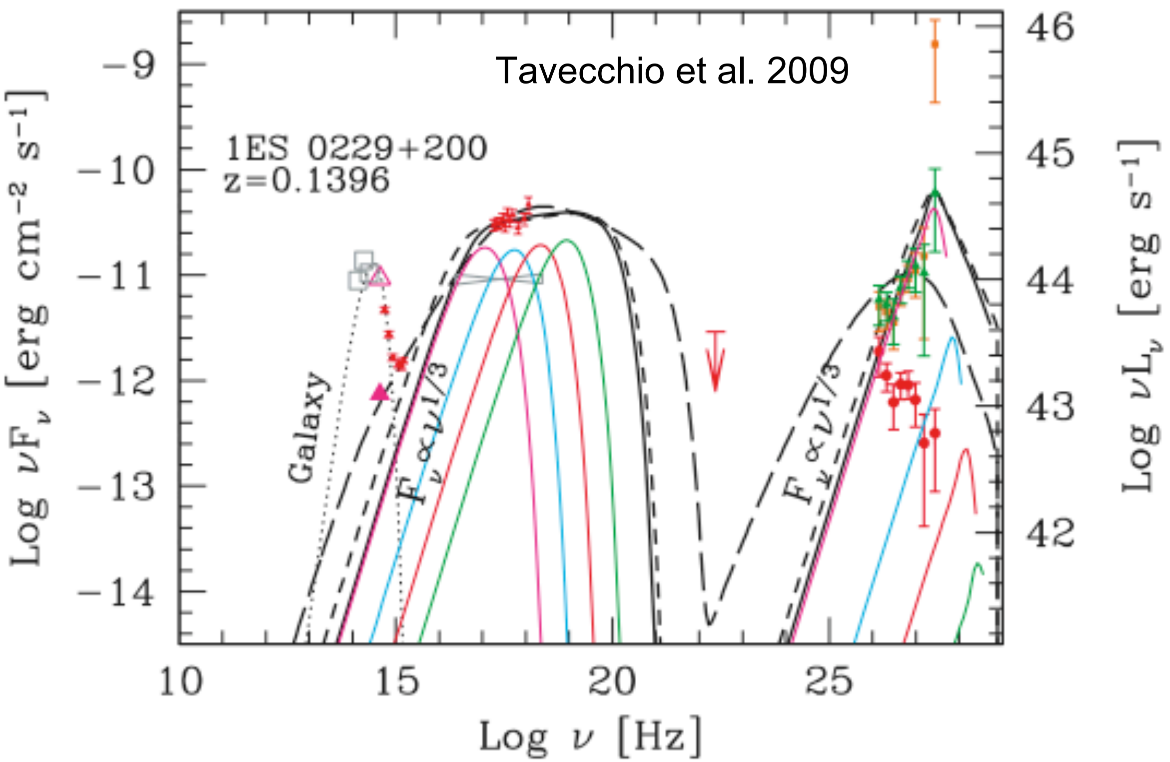
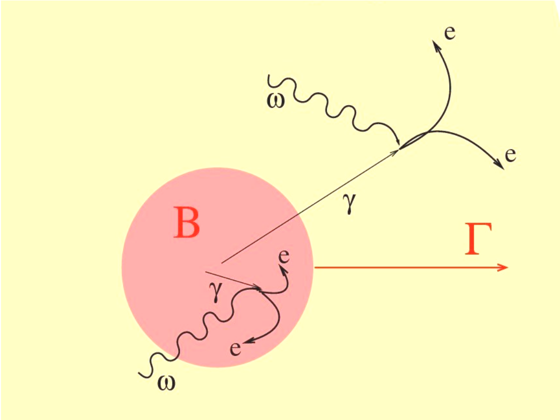


Table 2. Input parameters for the models shown in Fig.1 (Model 1: long dashed line; Model 2: solid line; Model 3: short dashed line). See text for definitions.

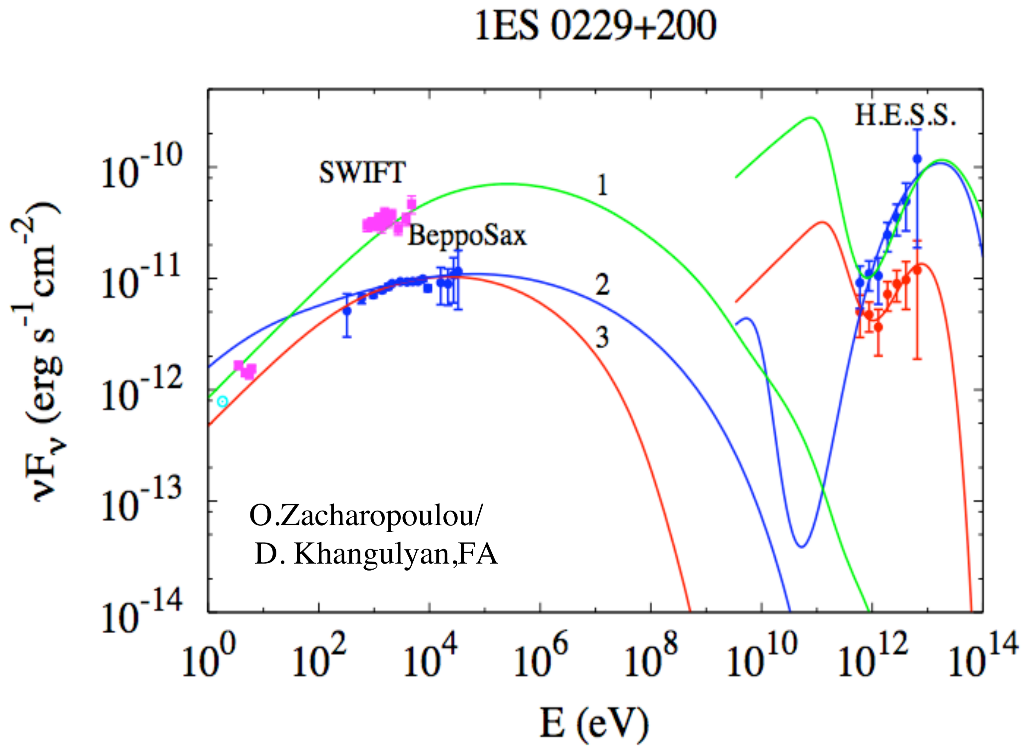
	γ_{min}	γ_b	γ_{max}	n	n_2	B (G)	K (cm^{-3})	R (cm)	δ
1	10^4	6×10^5	3×10^7	1.5	3.4	8.5×10^{-3}	6	10^{16}	50
2	8.5×10^5	–	4×10^7	2.85	–	5×10^{-4}	3.5×10^9	5.4×10^{16}	30
3	5×10^5	–	4×10^7	2.85	–	4×10^{-4}	6.7×10^8	5.4×10^{16}	50



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



magnetized compact blobs (B~100G) in blazar jets with Γ~10 as accelerators of protons to E~10^20 eV ?



- gamma-ray spectrum partly absorbed inside the source and in IGM
- X-ray emission from synchrotron radiation of secondary e+e- pairs

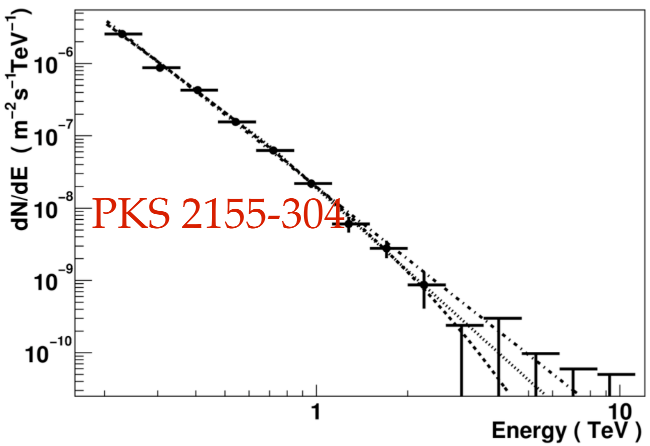
assuming optical depth $\tau_{\gamma\gamma}$ ~ 3-7, Γ ~ 10, one can explain not only gamma-ray spectra (after) correction for intergalactic absorption), but also the synchrotron emission by secondary e^+e^-

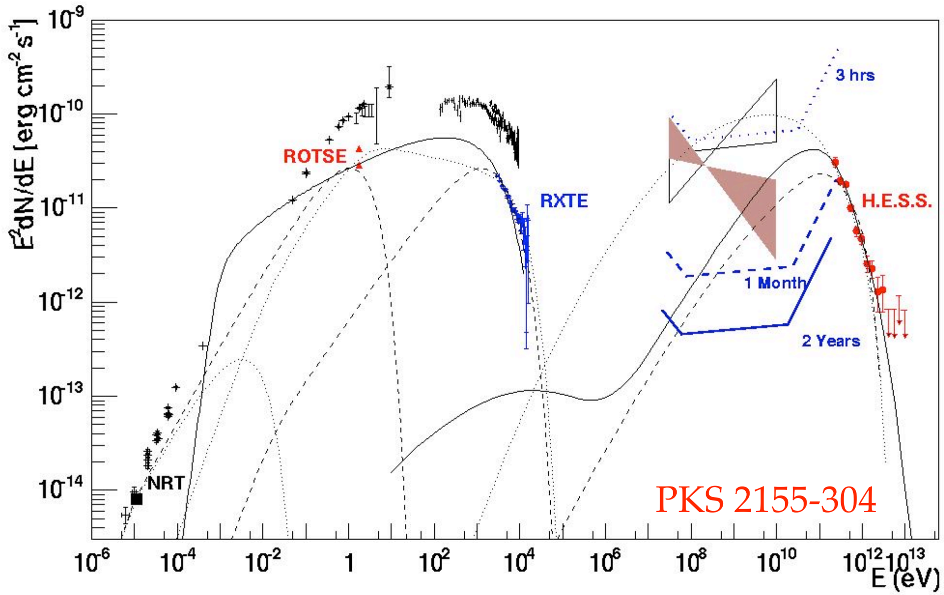
Model: *internal γ−γ absorption inside and outside the blob* (Aharonian et al. 2008)

PKS 2155-304

2003-2005 HESS observations:
variable flux within 5 to 40 % of Crab

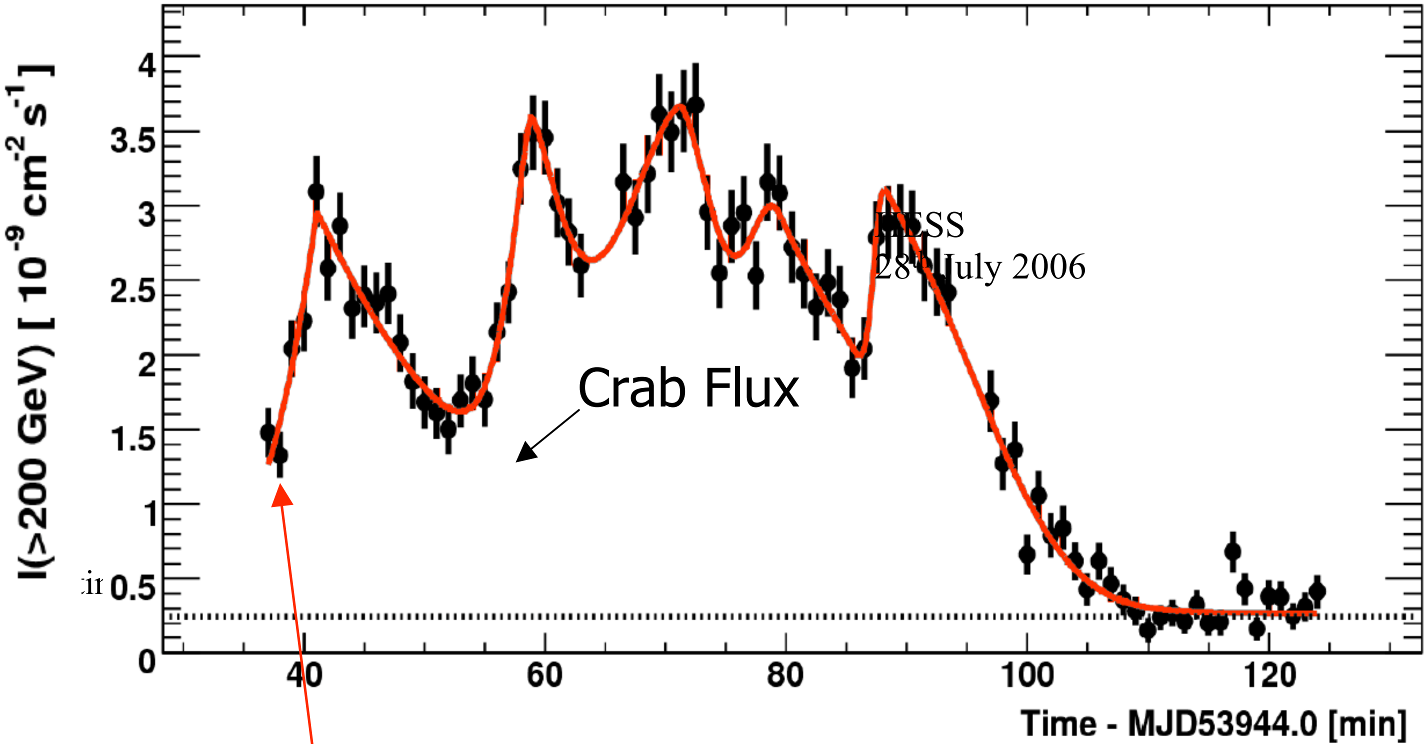
$\Gamma = 3.32$ +/- 0.06 +/- 0.1





a standard phrase in Whipple, HESS, MAGIC papers "SED can be explained within both electronic and hadronic models" ...

several min (200s) variabiliry timescale => R=c $\Delta t_{var}\ \delta_j=10^{14}\delta_{10}$ 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 $\Gamma > 100$



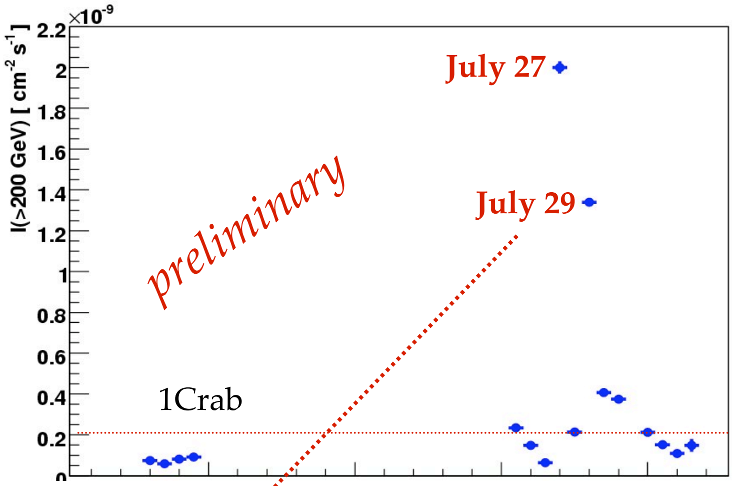
rise time <200s

Relativistic Jets as powerful particle accelerators and gamma-ray emitters

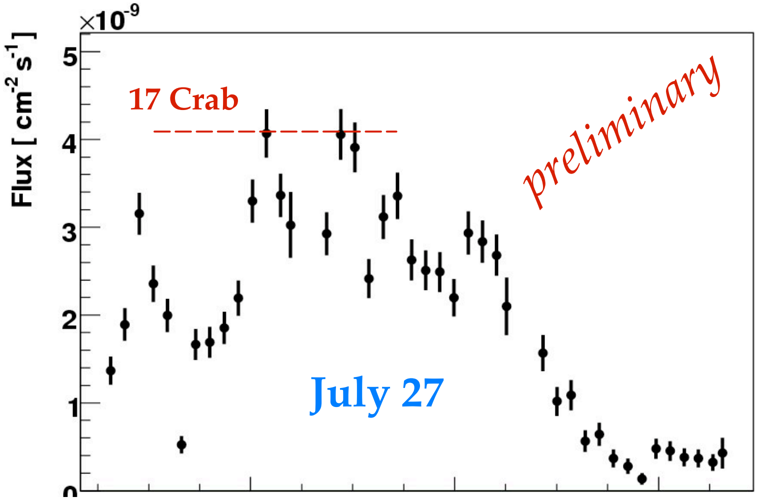
F.A. Aharonian (MPIK, Heidelberg/DIAS, Dublin)

HEAD 2006, San Francisco, October 5, 2006

PKS 2155-304: remarkable flares in July/August 2006



night by night lightcurve July-August 2006



2 minute binning lightcurve

X-ray (RXTE, Swift, Chandra) observations available:
Chandra – simultaneous coverage for 6 continuous hours !
strong variability - a factor of 2 timescales – 10 minutes or so)

strong evidence for variability on a few minute timescales !
on average 70 γ/min rate ➔ *spectrometry on minute timescales*

see poster by L. Costamante

on the mass of BH in PKS2155-309

- several min (300s) variabiliry timescale ➔ $R = c\,\Delta t_{var}\,\delta_j = 10^{14}\delta_{10}$ cm for a 10^9Mo BH with 3Rg ~ 10^{15} cm ➔ $\delta_j > 100$, i.e. close to the accretion disk (the base of the jet), the bulk motion **$\Gamma > 100$**

- the (internal) shock scenario: shock would develope at $R = Rg\,\Gamma^2$, i.e. minimum gamma-ray variability would be $Rg/c = 10^4 (M/10^9 Mo)$ cm, although the gamma-ray production region region is located at $R\gamma \sim ct_{var}\,\Gamma^2$ (e.g. Chelotti, Fabian, Rees 1998)

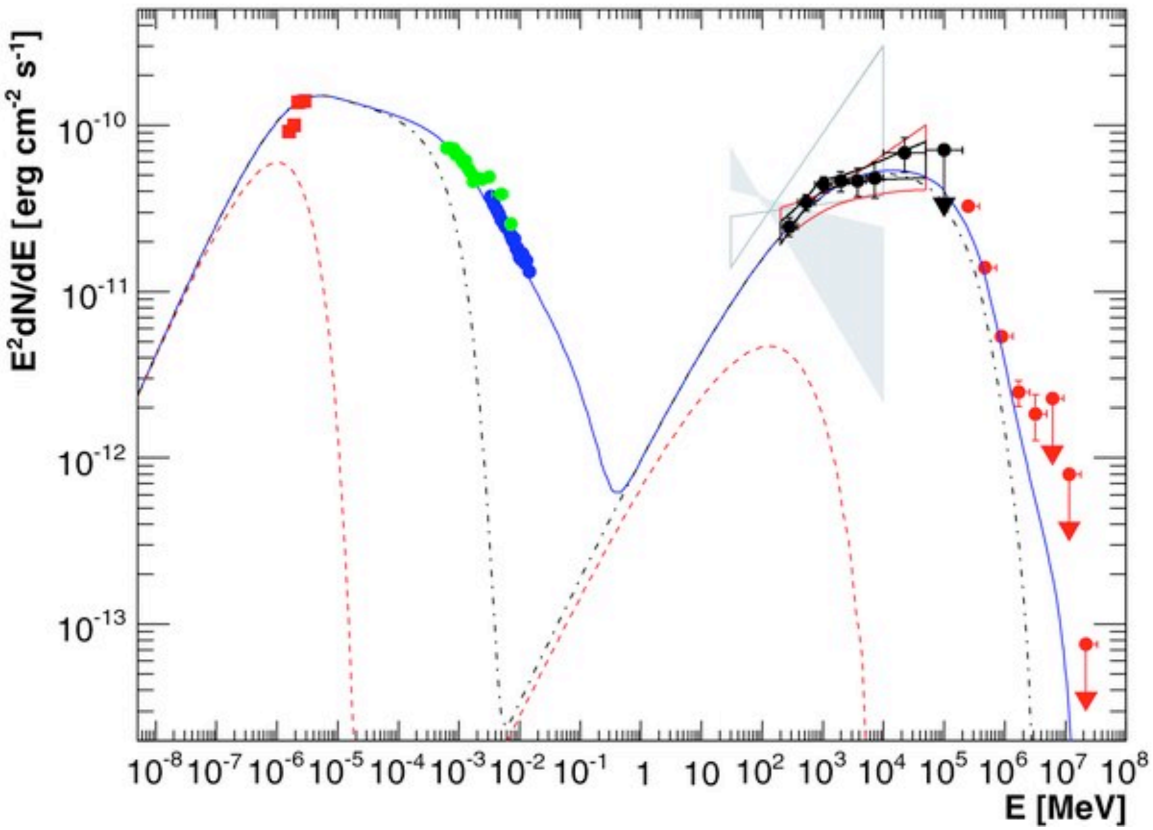
thus for the observed $t_{var} < 300$ s, the mass of BH cannot exceed 3×10^7Mo. On the other hand the "BH mass–host galaxy bulge luminosity" relation for PKS2155-304 gives $M > 10^9 M_o$

Conclusions? smaller mas of BH or a non-shock scenario ?

Simultaneosly measured spectrum of PKS2155-309 by *RXTE/Fermi/HESS*

-

typically B<1 G



why the synchrotron cutoff is located below 1 keV ? - inefficient accelerator?

Gamma-rays of IC origin?

synchrotron peak of PKS2155-409 is located at <100 eV; comparison with $h\nu_{cut}$=100 η^{-1} δ_j MeV ➔ $\eta > 10^6\ \delta_j$ - quite a large number, i.e.
very low efficieny of acceleration ...

acceleration rate of TeV electrons (needed to produce the IC peak in the SED at energies 10GeV or so (for large Doppler factors, 10-100):

$$t_{acc}=\eta\ R_L/c = 10^5\ \delta_j\ (B/1G)^{-1}\ \text{sec}$$

Since B < 1 G ➔ cannot explain the TeV variability (rise time)
in the frame of the jet $t_{var}=300\ \delta_j$ sec

conclusion: hadronic origin of TeV gamma-rays?

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*!

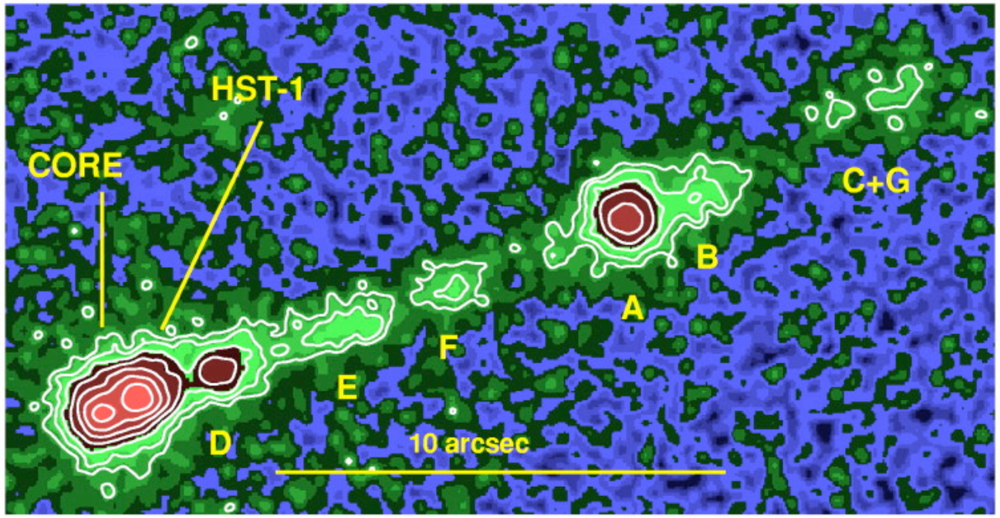
discovery (>4σ) of TeV γ-rays

by HEGRA (1998) and confirmed

recently by HESS/VERITAS, MAGIC

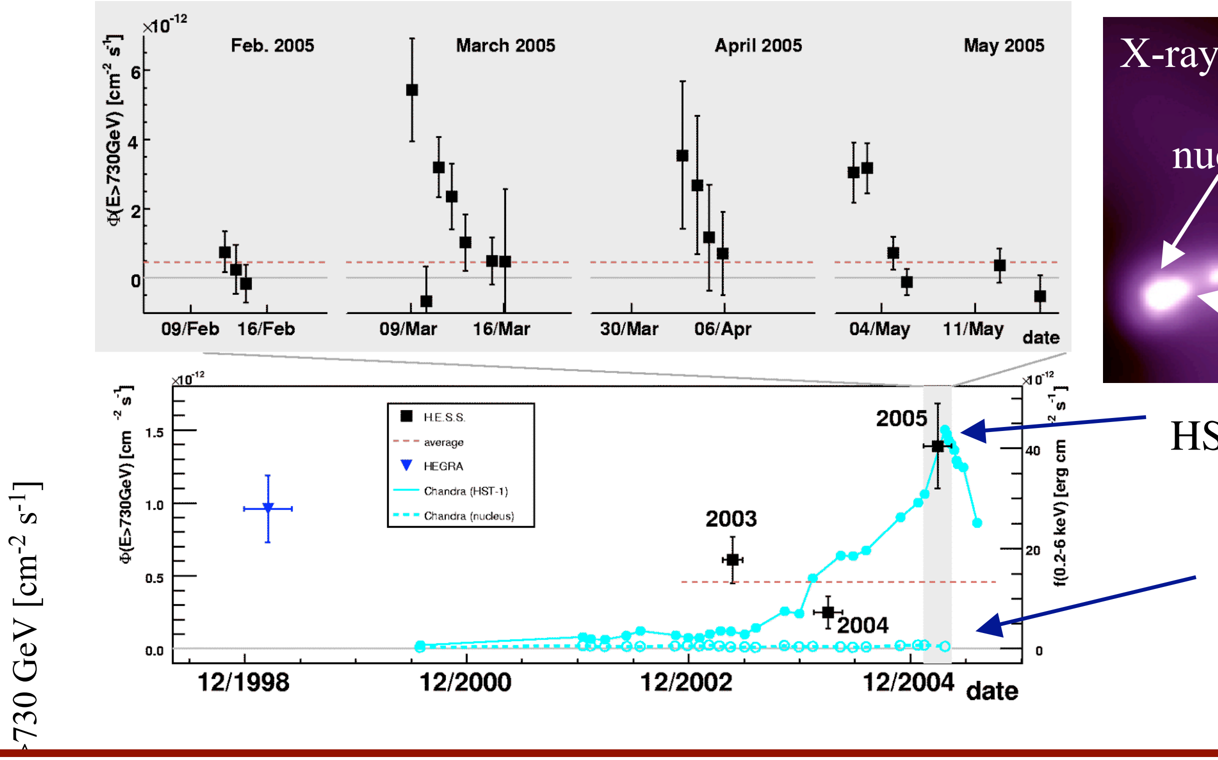
*) recently $6.4 \times 10^9\ M_o$

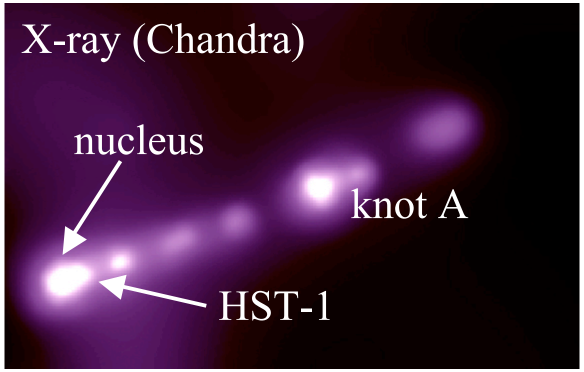
arXiv: 0906.1492 (2009)



M87: light curve and variabiliy

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



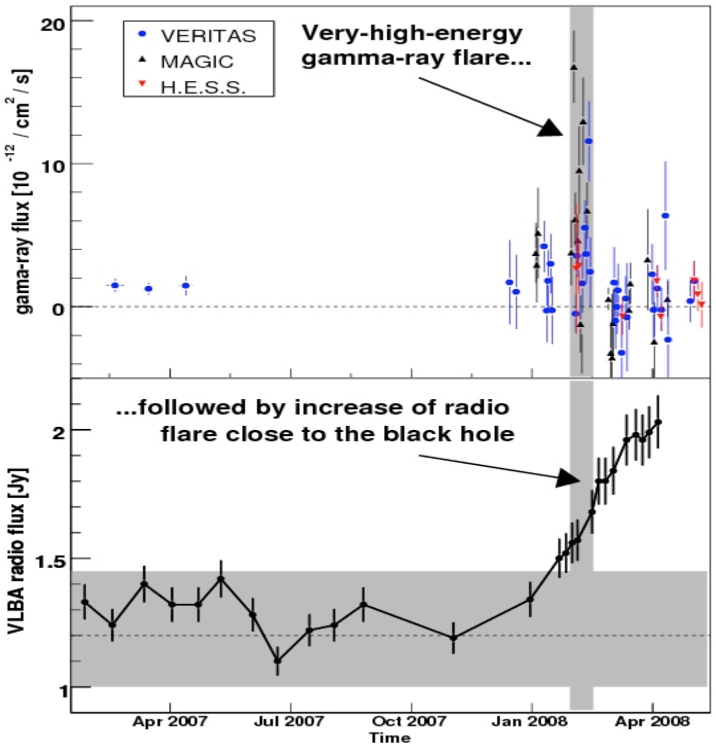


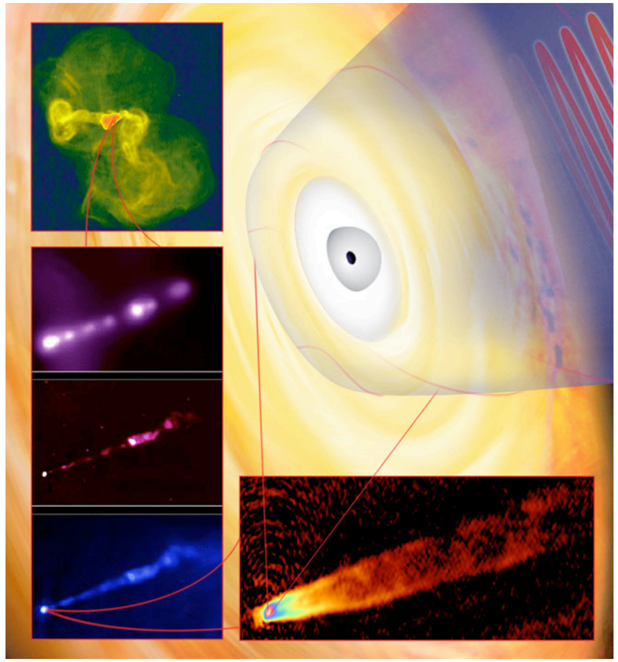
short-term variability on 1-2 day scales => emission region R ~ $5\times10^{15}\delta_j$ cm
=> production of gamma-rays very close to the 'event horizon' of BH?

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





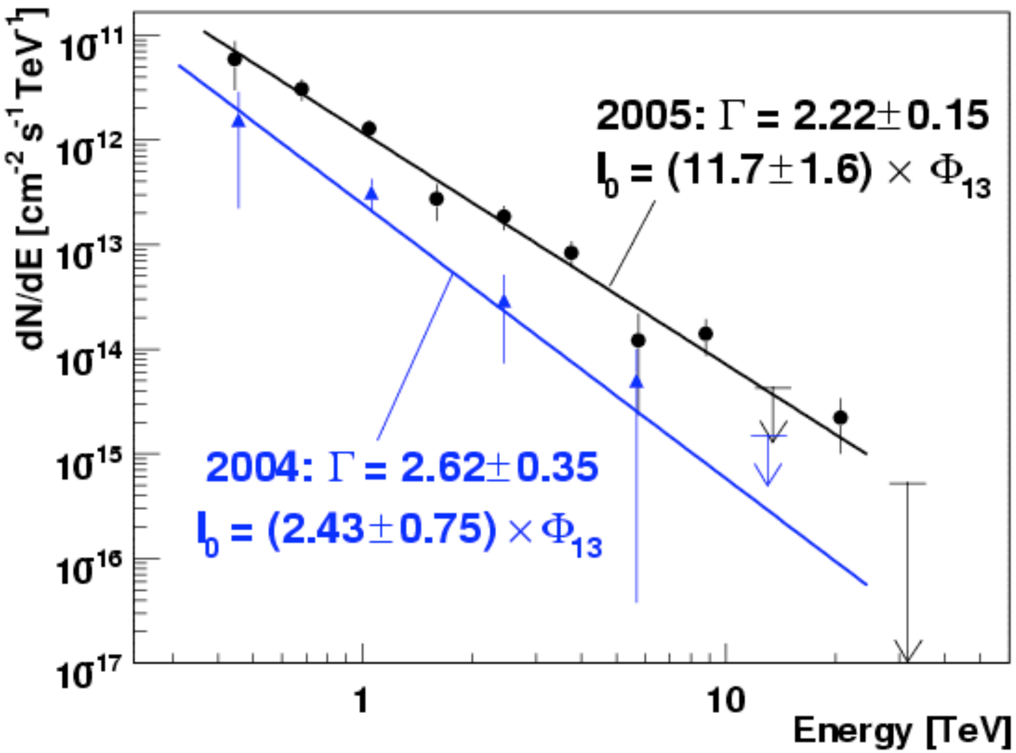
monitoring of the M87 inner jet with VLBA at 43 GHz (ang. res. 0.21x0.43 mas) revealed increase of the radio flux by 30 to 50% correlated wit the increase in TeV gamma-ray flux in Feb 2008

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

energy spectra

energy spectra for 2004 (~5σ)
and 2005 (~10σ)

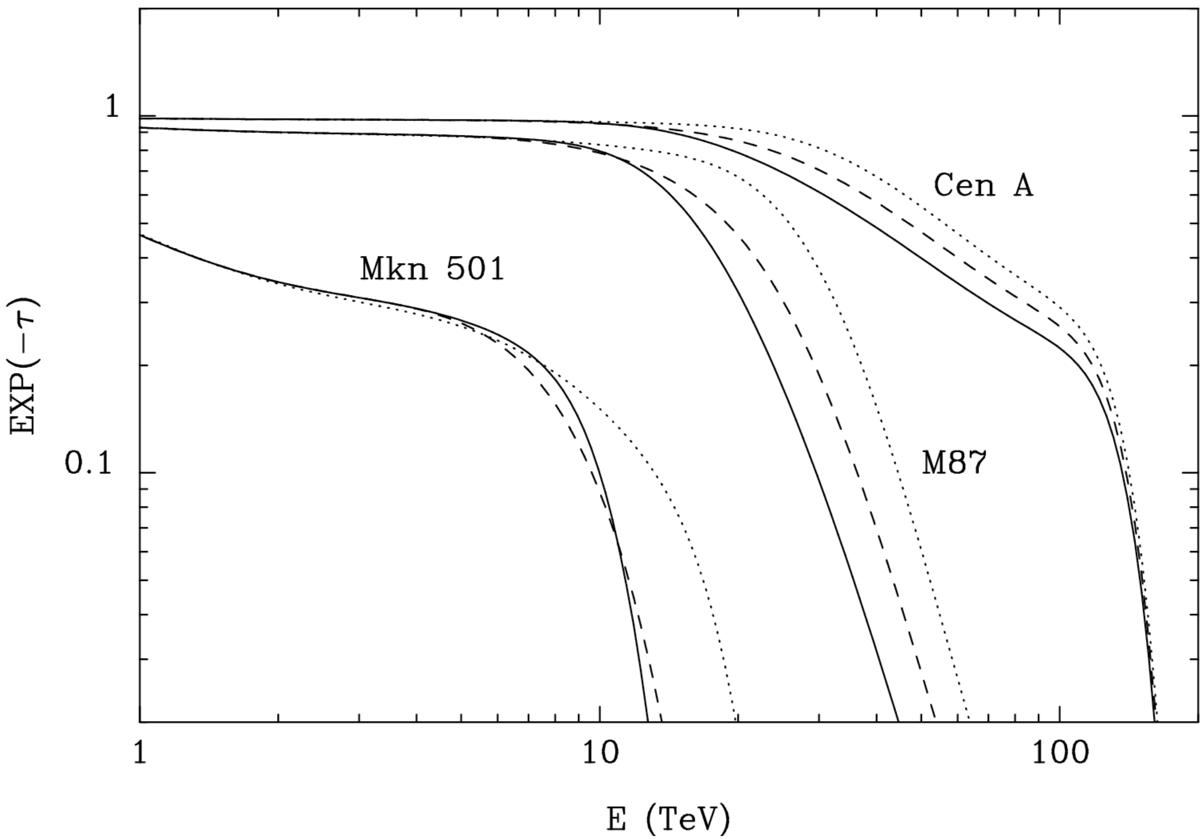
Differential spectra well described by power-laws:



$\Phi_{13} = 10^{-13}$ 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)



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

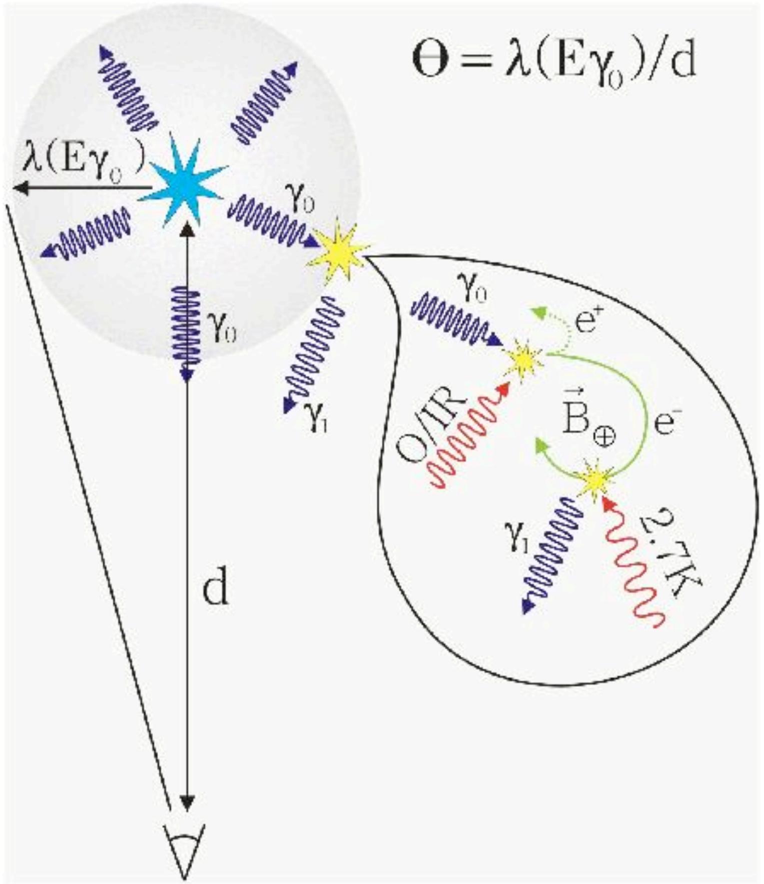
$$\lambda(E_{\gamma,0}) \sim d \times \Theta$$

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 – angular and energy 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 γ-ray emitting AGN

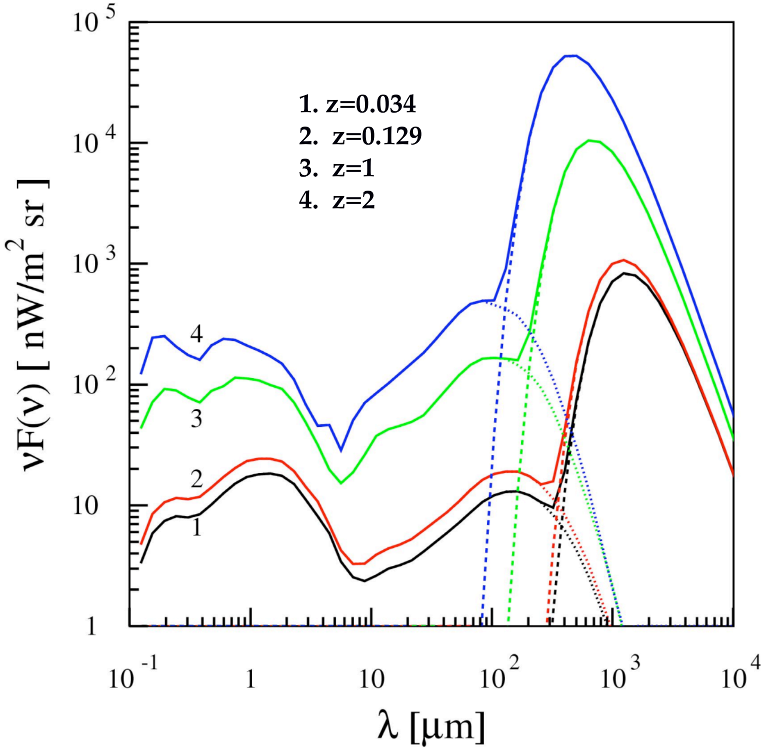
but the advantage of the large Doppler boosting of blazars disapeares: beam => isotropic source

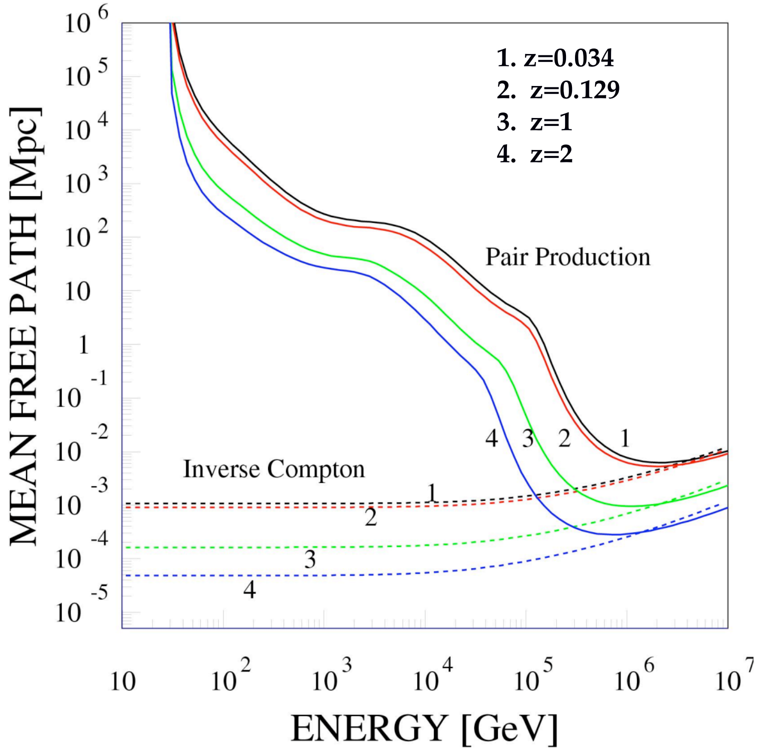
therefore very powerful central objects needed

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

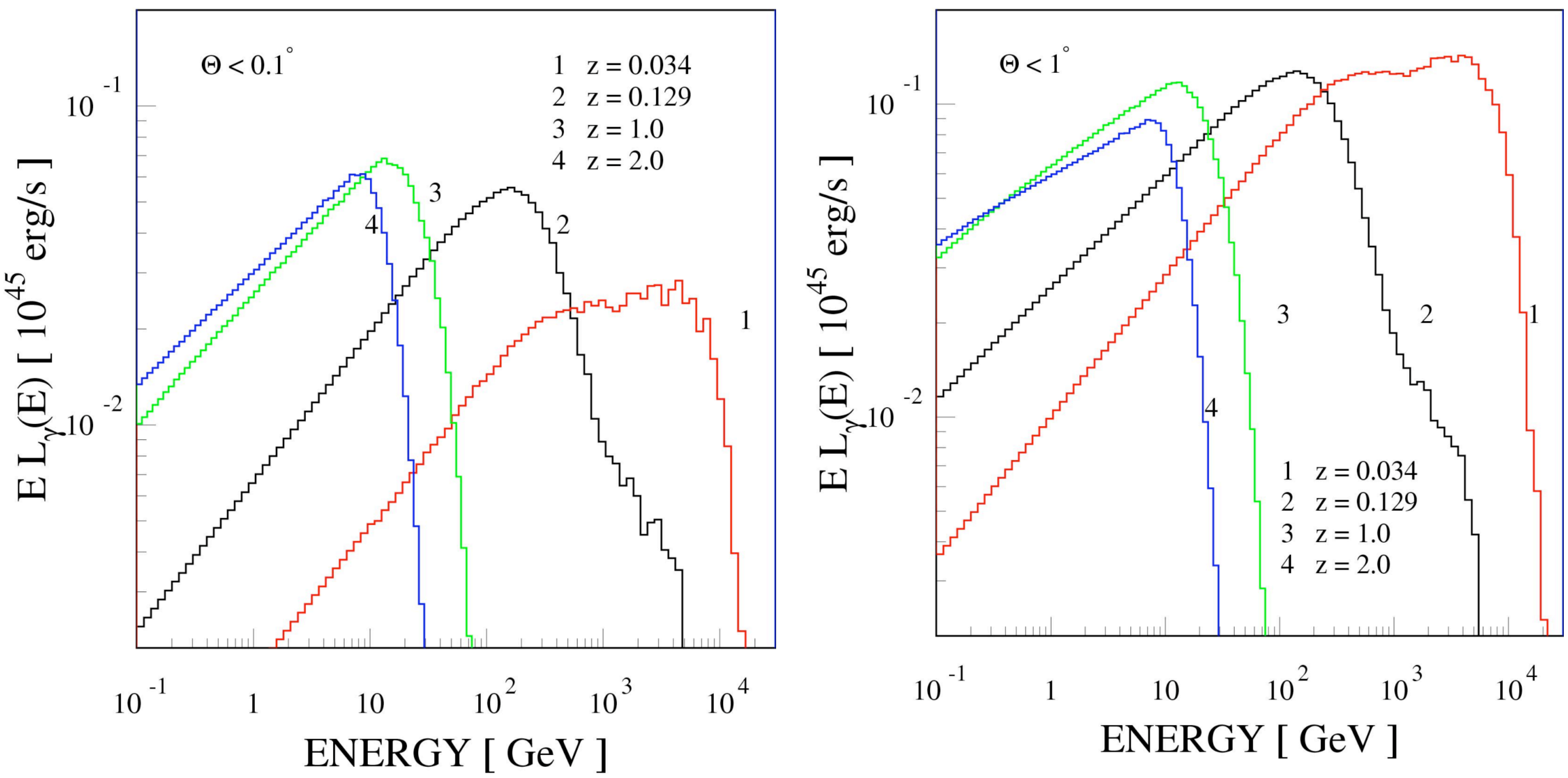
this requires low-energy threshold detectors

EBL at different z and corresponding mean freepaths





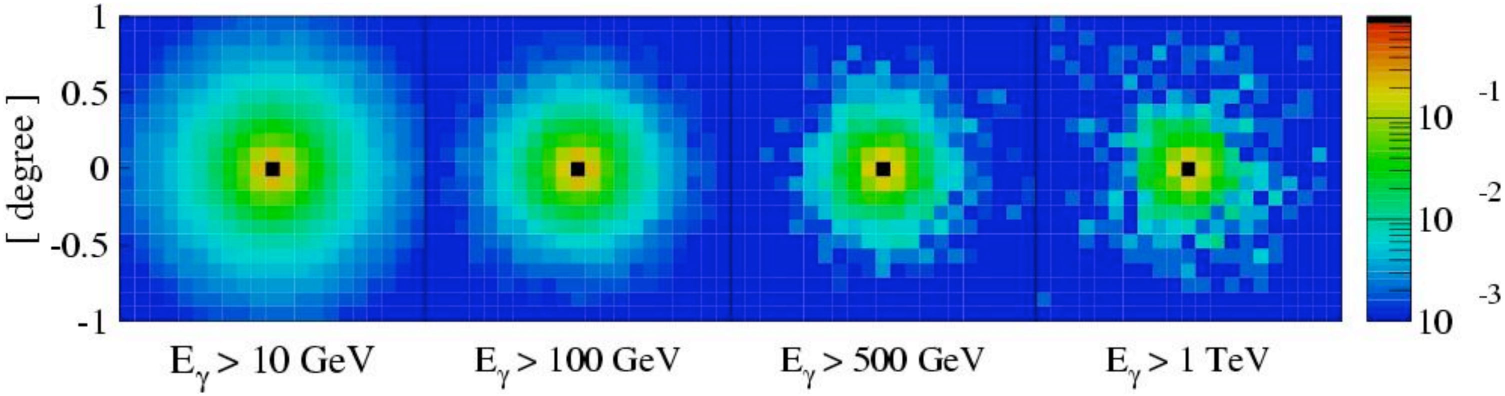
SEDs for different z within 0.1° and 1°



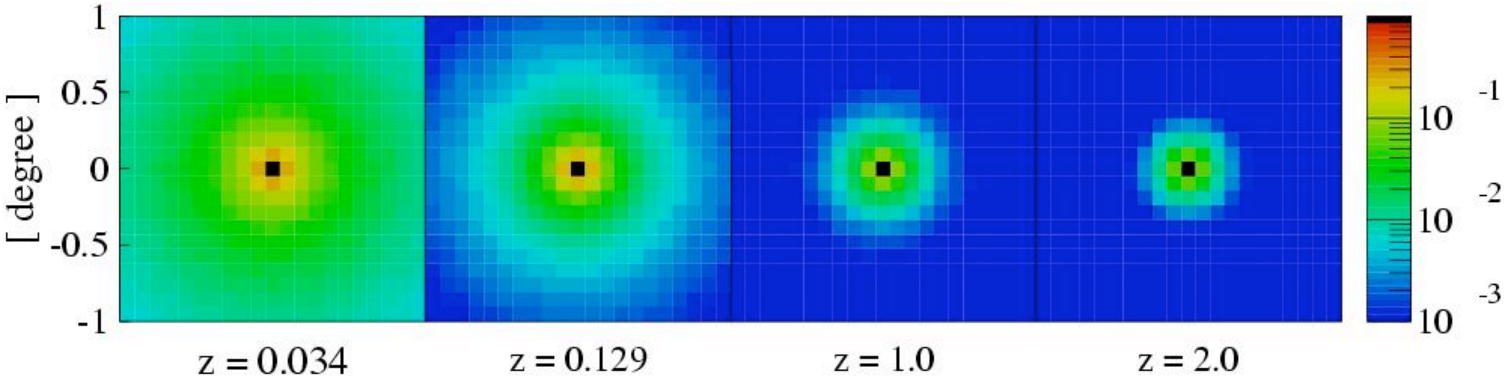
EBL model – Primack et al. 2000

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

Brightness distributions of Pair Halos



z=0.129



E=10 GeV

A. Eungwanichayapant, PhD thesis, Heidelberg, 2003 *thanks to the organizers and participants of this nice school*!

I encourage all of you to attend the TEXAS Symposium 2010

* reduced conference fee for PhD Students