The 2006 Giant Flare in PKS 2155-304 and Unidentified TeV Sources

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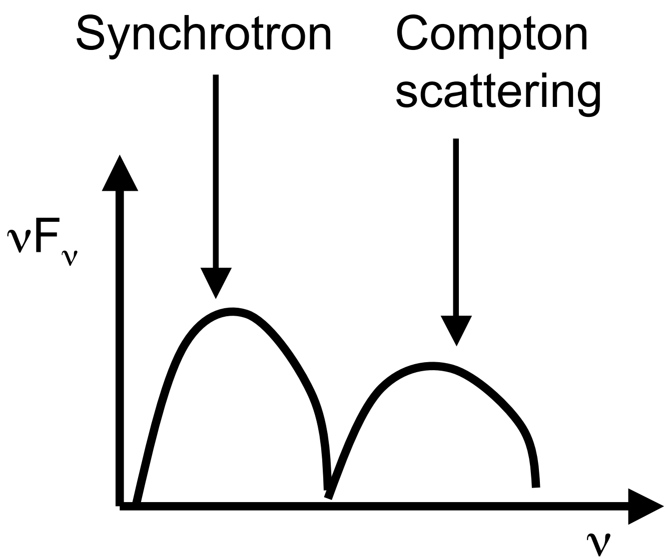
Outline

- Part I: The SSC Model
- Part II: The giant flare in PKS 2155-304
- Part III: Blazars as UnID TeV sources

Finke, J. D., Dermer, C. D., Böttcher, M., (2008), ApJ, submitted,
arXiv: 0802.1529

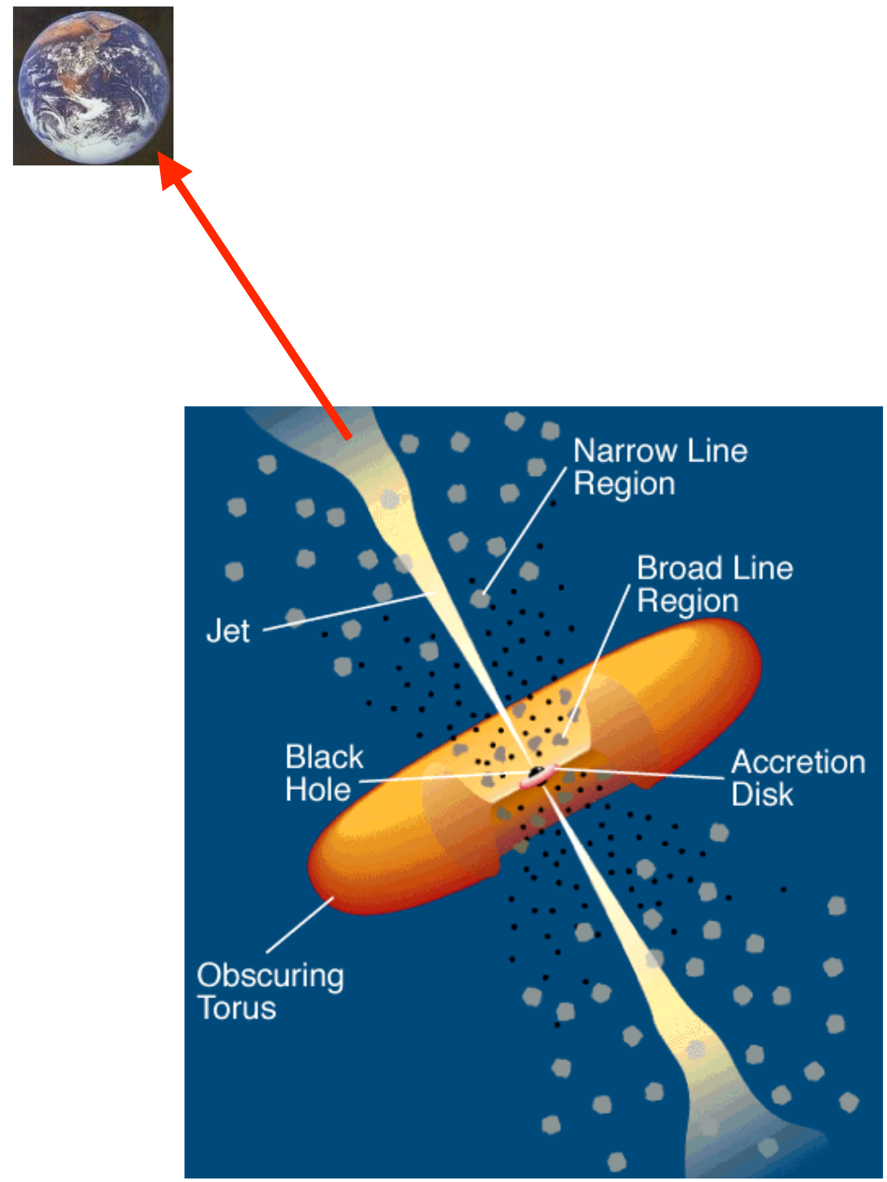
BL Lac Objects



Compton scattering of:

- synchrotron
- disk radiation
- broad line regions
- torus radiation
- slow sheath surrounding blob

(Ghisellini et al. 2005)

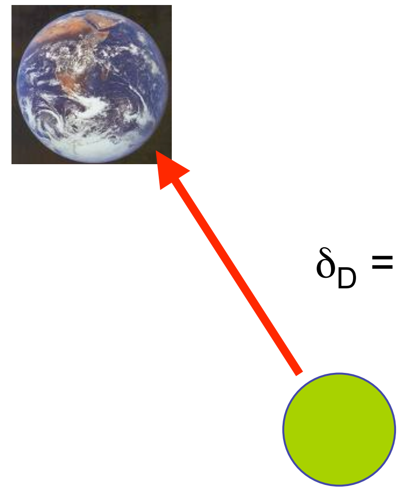


The One-Zone SSC Model

In blob frame:
- Tangled, homogeneous B-field
- homogenous, randomly oriented electron distribution

Radiation is Doppler boosted along our line of sight.

Compton scattering synchrotron photons from the same blob.

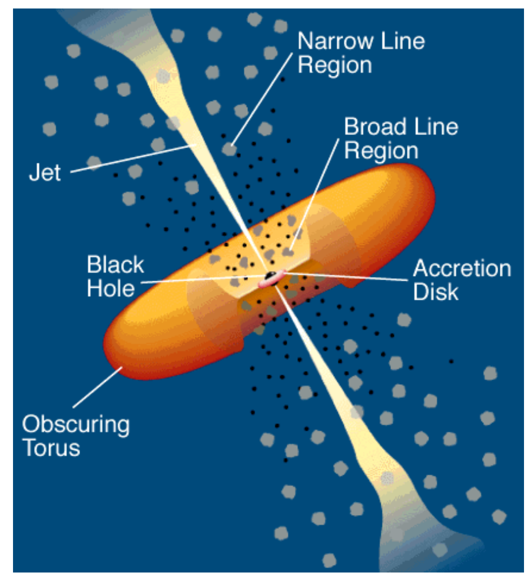


$\delta_D = \Gamma \, [\, 1 - \beta \cos(\theta) \,]$

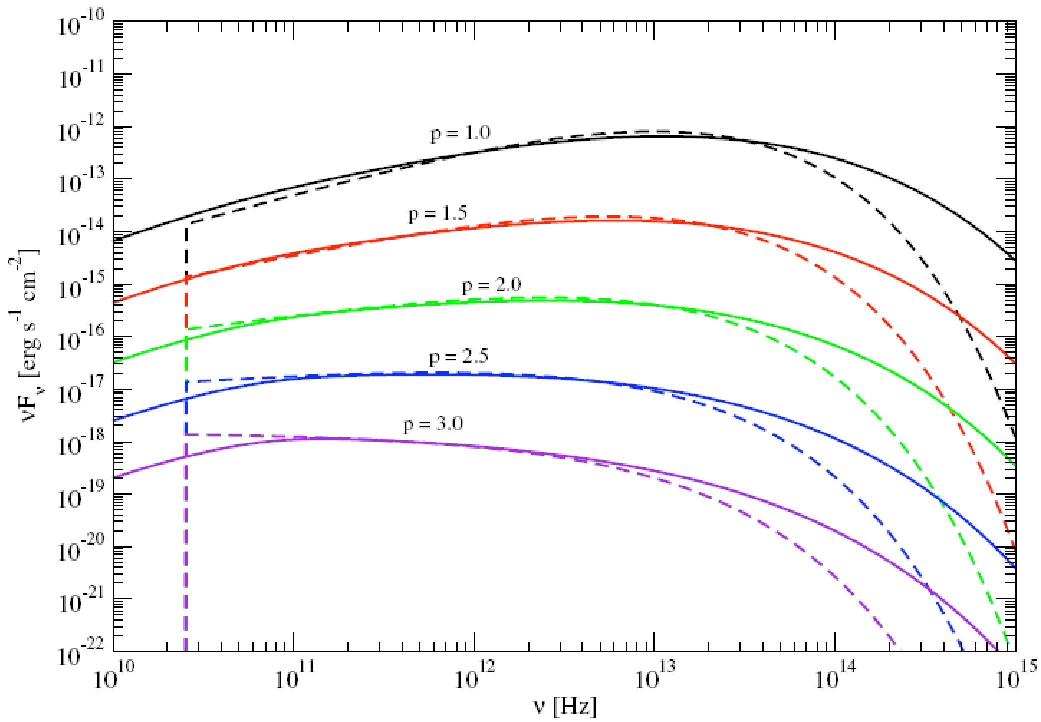
Write SSC as a function of:
δ_D, B, R_b', z, $N_e(\gamma)$.

Can constrain R_b' based on observations:

$$R_b' \le \frac{\delta_D c t_{\mathrm{var}}}{(1+z)}$$



δ-approximation and Exact Synchrotron



Dashed: δ-approx.
Solid: exact.

Exact expression from Crusius & Schlickeiser (1986).

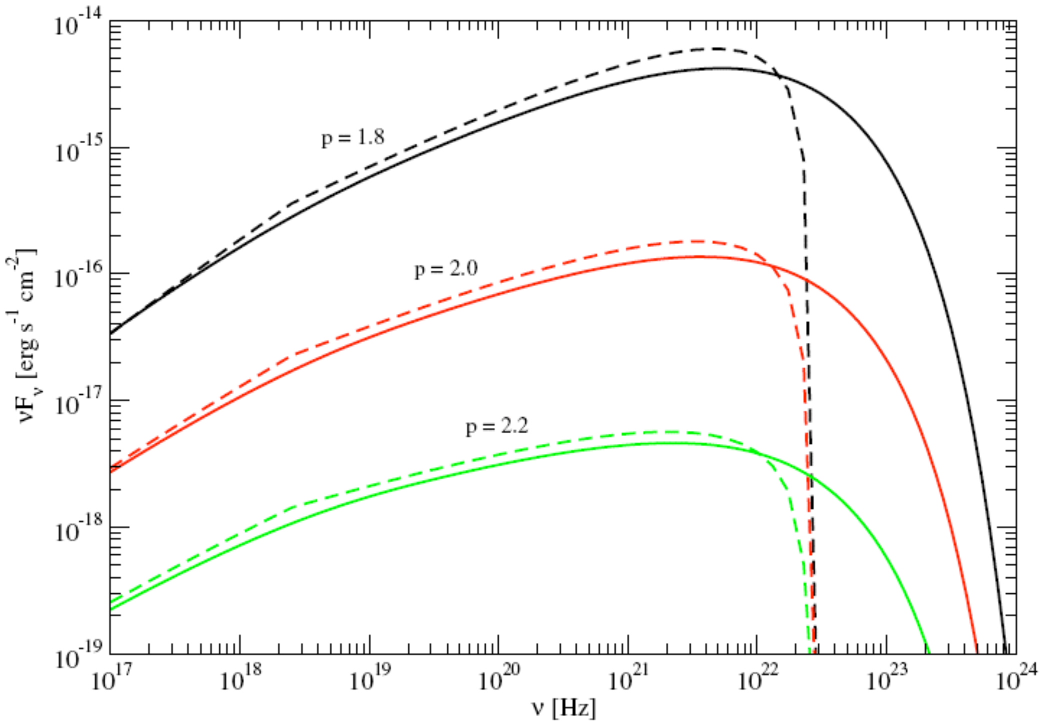
δ-approx. not a good fit at the endpoints.

Exact expression in needed.

$$N'_e(\gamma') = K_e\ \gamma'^{-p}\ \exp\left(\frac{-\gamma'}{\gamma'_c}\right)\ H(\gamma' - \gamma'_1)$$

δ_D = 100, B = 10 mG, t_v = 300 s

Thomson and Compton cross-sections



Dashed: Thomson + cutoff
Solid: Compton

Full Compton expression from Jones (1968).

Full Compton expression needed to accurately represent SSC spectrum.

$$N_e'(\gamma') = K_e \; \gamma'^{-p} \; \exp\left(\frac{-\gamma'}{\gamma_c'}\right) \; H(\gamma' - \gamma_1')$$

δ_D = 100, B = 10 mG, t_v = 300 s

Fitting Technique

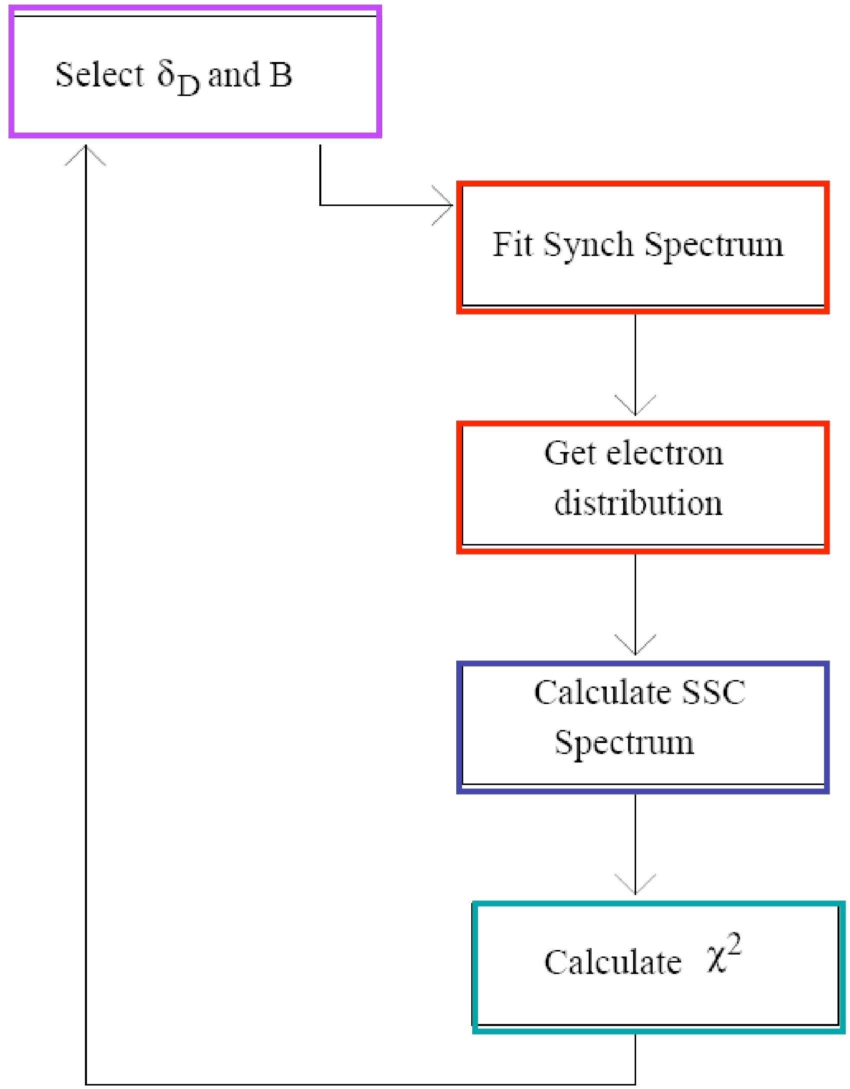
Select δ_D and B

f_e^{syn} gives $N_e(\gamma)$.
(delta-approx. or CS86 expression)

Use this $N_e(\gamma)$ with B and δ_D to calculate SSC.

How good is the fit?

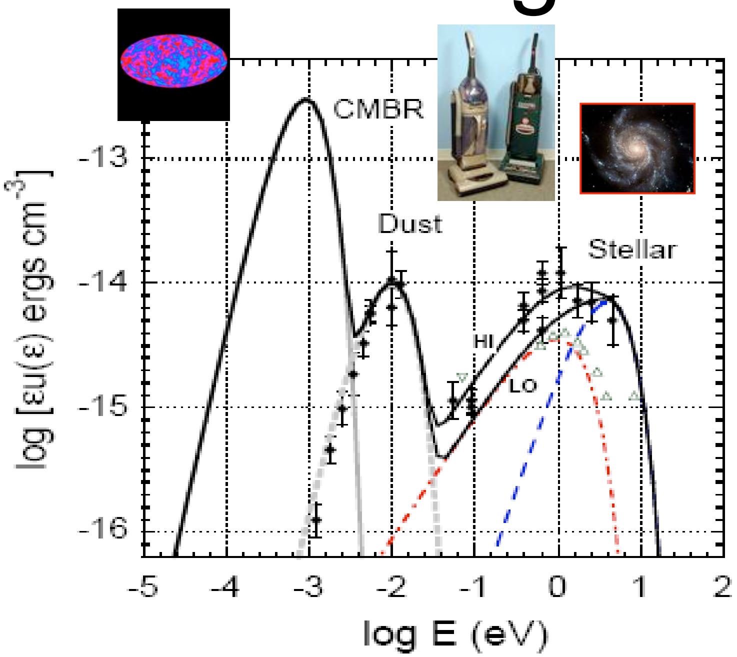
Repeat until adequate χ^2 is found.

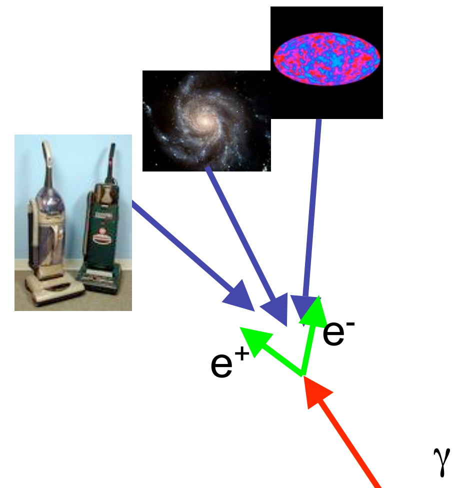


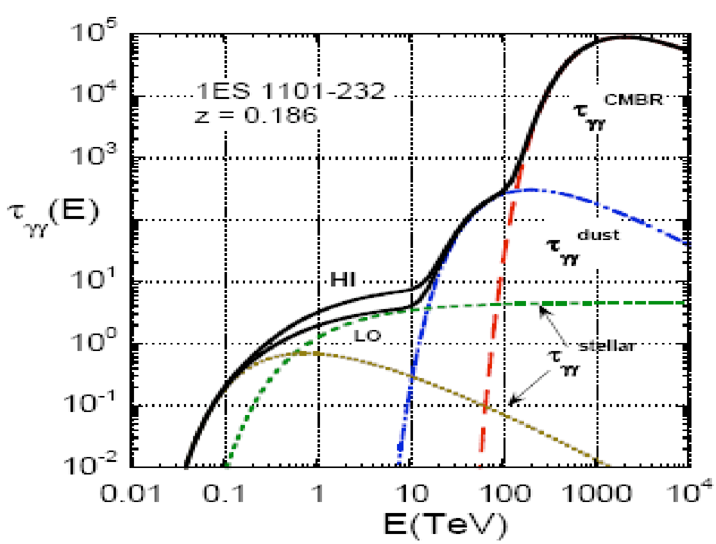
Jet Power

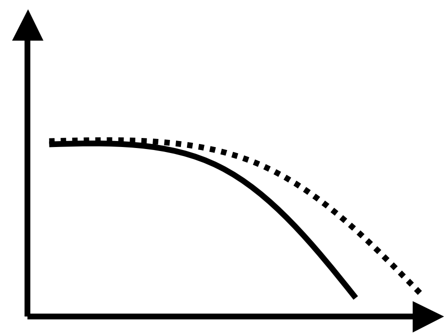
- Jet power: total power available in jet (in observer frame)
- $L_j = 2\pi R'_b{}^2 \beta \Gamma^2 c(u'_B + u'_p)$ (Celotti & Fabian 1993)
- $dL_j / dB = 0 \rightarrow B_{min}$ (equipartition)
- $B < B_{min} \rightarrow u'_p >> u'_B$

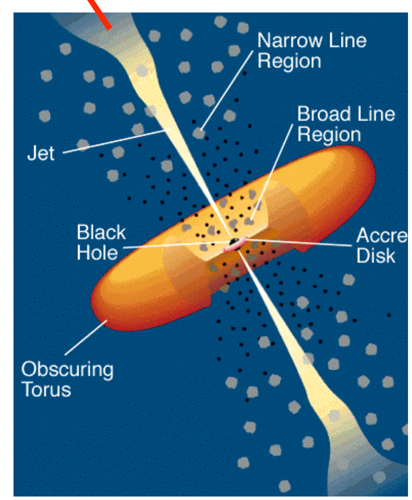
γγ absorption by Extragalactic Background Light (EBL)





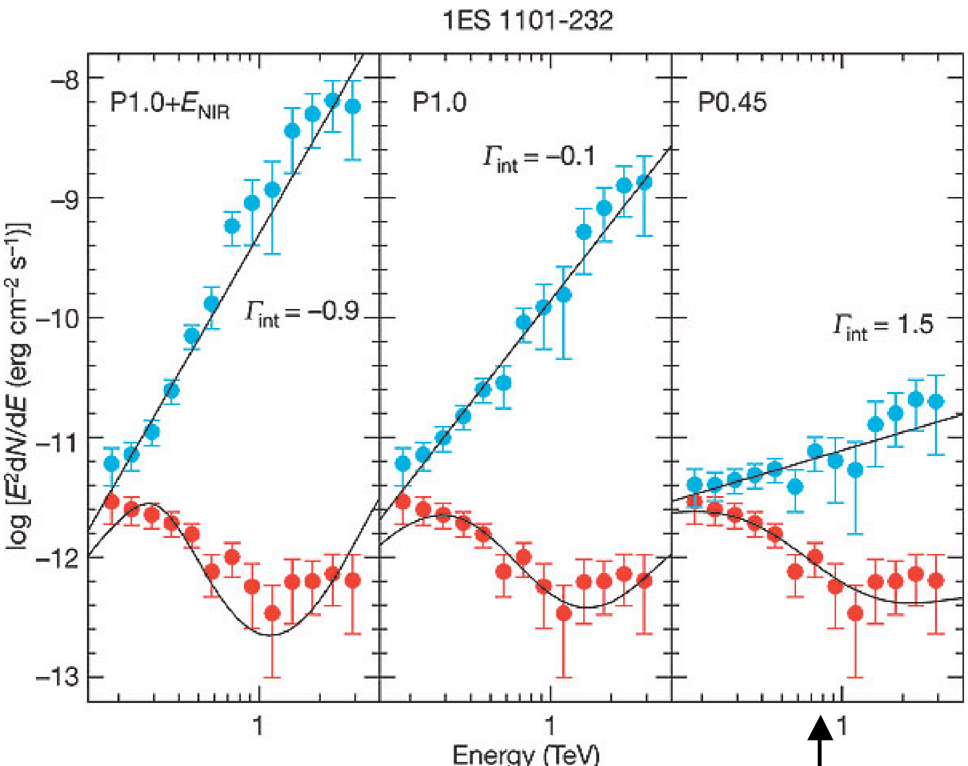






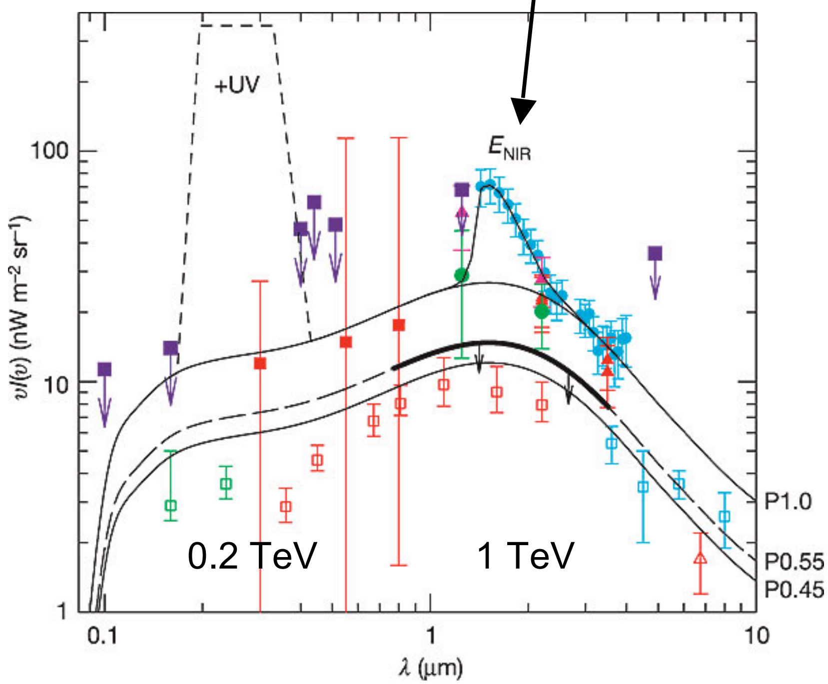
Primack et al. (2005)
Stecker et al. (2006)
Dermer (2007)
Razzaque et al. (2008)

EBL Controversy



Γ_{obs} = 2.9

Questionable NIR from IRTS (Matsumoto et al. 2004). May be Pop III stars.



EBL to give Γ_{int} = 1.5

Alter normalization of EBL until reasonable fit Γ is obtained.

Open symbols are lower limits.

Seems consistent with lower limits on EBL.

Simultaneous XMM-Newton observations: Γ_X ~ 2

Aharonian et al. (2006), *Nature*, 440, 101

Conclusions (Part I)

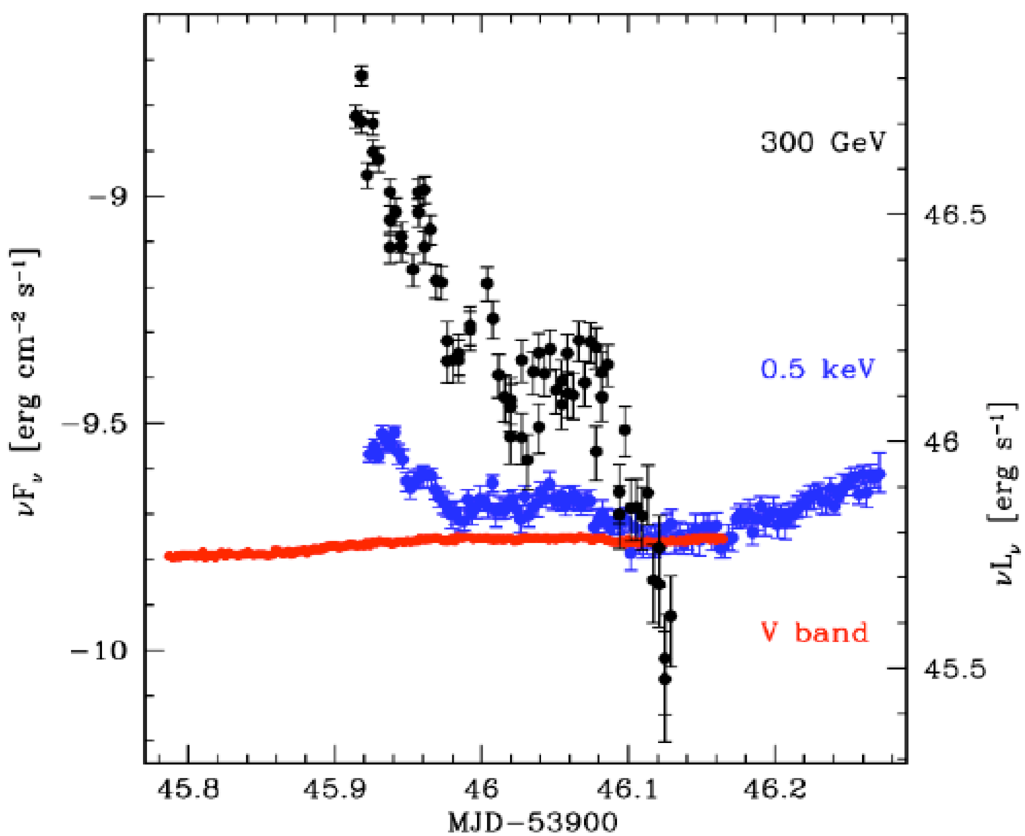
- The level of the EBL and explanations for hard VHE γ-ray spectra from blazars is controversial, but seems to be quite low.

- Accurate expressions for the synchrotron and Compton cross sections are necessary to do precision spectral modeling.

PKS 2155-304

- X-ray selected BL Lac
- $z = 0.116$, $d_L = 540$ Mpc
- Detected by EGRET
- August 2006: bright flares, detected by
  - HESS (Aharonian et al. 2007)
    - Variability timescale: ~5 minutes
    - $\Gamma_{obs} \sim 3.5$
  - Followed up with:
    - Swift (Foschini et al. 2007) (3 ks/day)
    - Chandra (Costemante 2007)
    - Ground based optical telescopes (Costemante 2007)

Correlated Variability



Besides Swift and HESS, giant flare was observed with Chandra and ground-based optical telescopes.

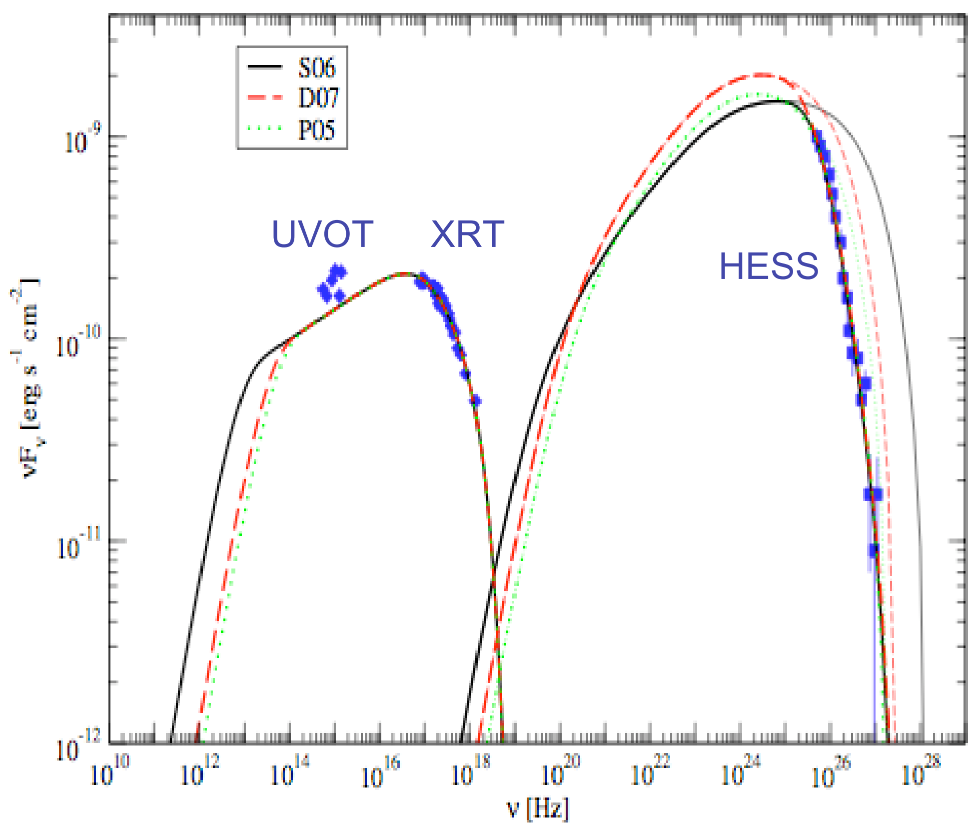
HESS and X-rays correlated, but optical is not.

γ-rays and X-rays likely from the same blob, but optical is not.

Very little optical variability.

Costemante (2007), presented in “High Energy Phenomena in Relativistic Outflows”, Dublin, Ireland

Results



Electron distribution: broken power law, p_1=2.7, p_2=3.7

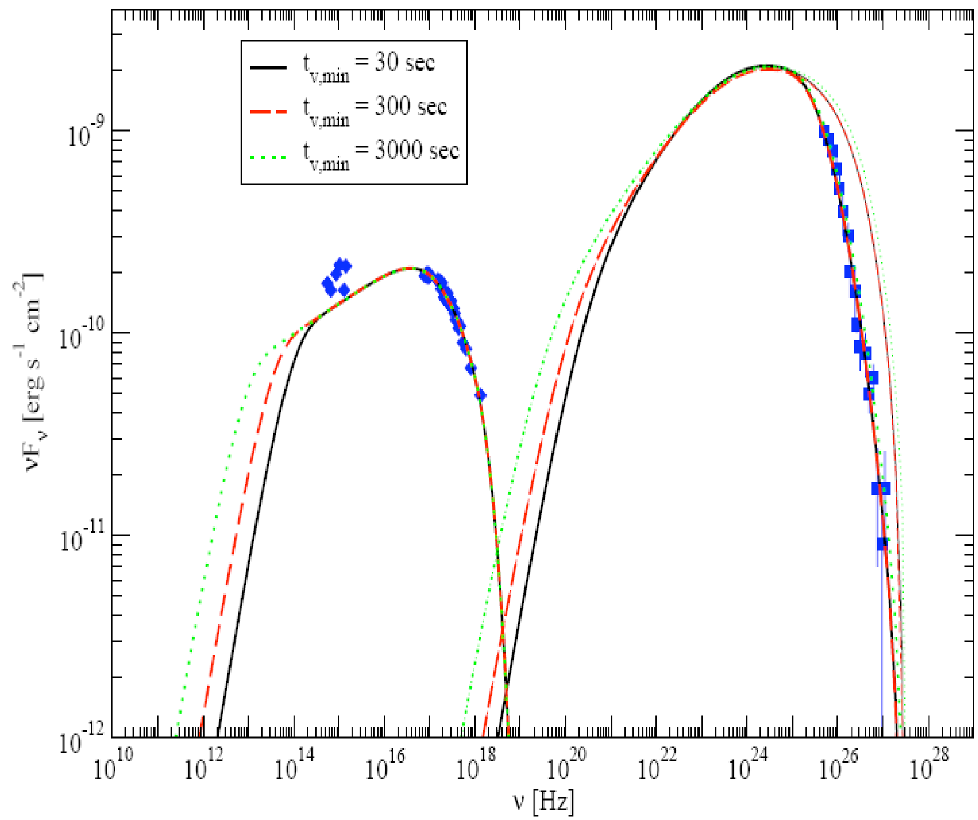
EBL Model	δ_D	B [mG]	t_{var} [s]	L_j [10^{46} erg s^{-1}]
S06	278	5.9	300	34
D07	124	58	300	5.0
P05	58	100	300	4.0

Unreasonably high δ_D and L_j, ζ_B ~0.01.

$L_{Edd} = 10^{47}$ erg s^{-1} M_9
From radio obs., $\delta_D < 10$

Lower EBL leads to more reasonable parameters, but still excessive.

Results



D07 EBL

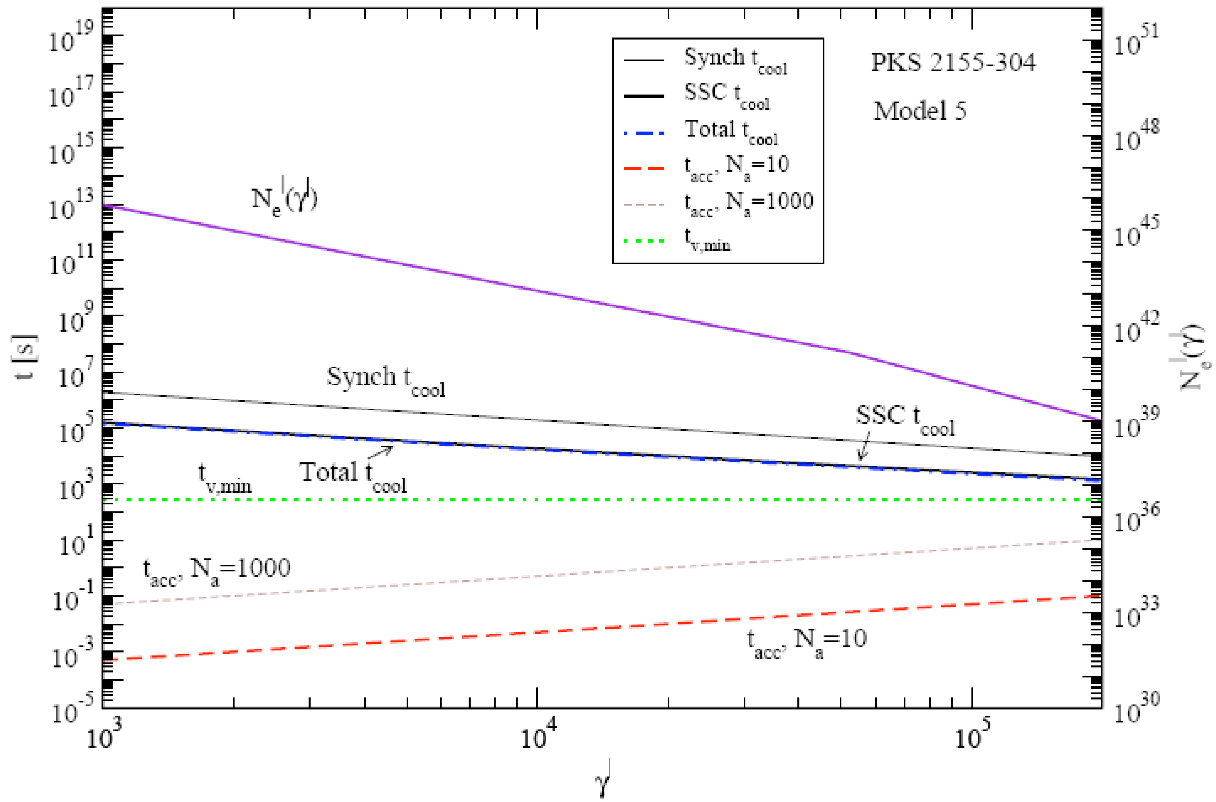
δ_D	B [mG]	t_{var} [s]	L_j [10^{46} erg s^{-1}]
230	88	30	3.8
124	58	300	5.0
67	35	3000	7.3

Greater variability timescale (larger blob sizes) lead to more reasonable Doppler factors.

GLAST could distinguish between these models!

Variability

- Variability can't be attributed to cooling.
- Adiabatic expansion or acceleration-dominated variability?
- $t'_{acc} = N_a \gamma' / \nu_B$
- $N_a > 10^5$, not unreasonable.



Robustness of Models

Jet power and certainty contours.

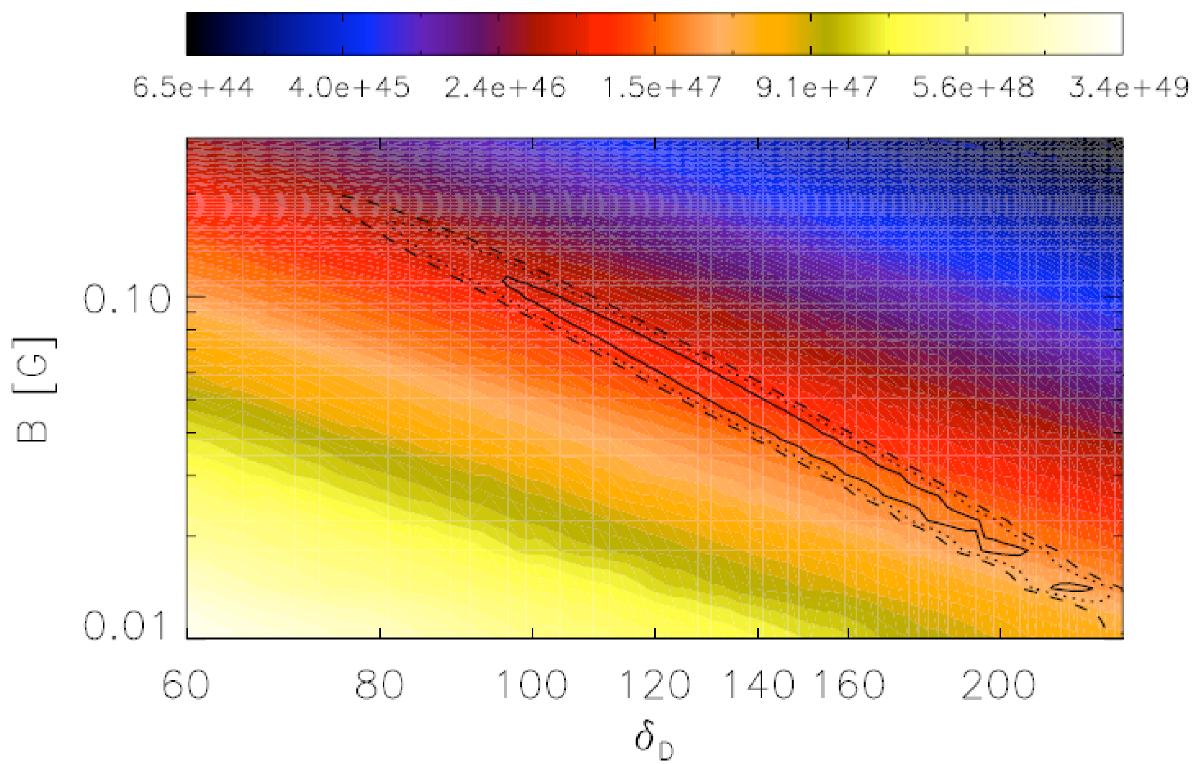
Parameters δ_D and B have fairly broad ranges.

Jet power, however, does not.

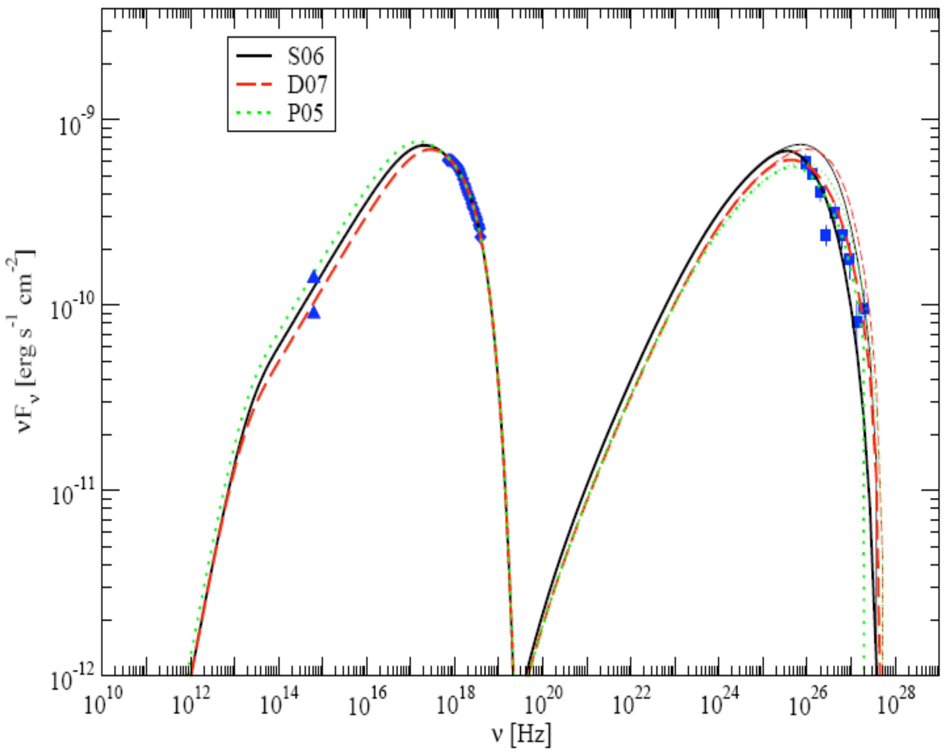
L_j contours follow $B \sim \delta_D^{-1.5}$

Uncertainty contours follow $B \sim \delta_D^{-2.6}$ rather than $B \sim \delta_D^{-3}$ (Tavecchio et al. 1998). This can be explained with KN cross section.

D07 EBL, t_v = 300 sec



Mrk 421



EBL is small but not negligible.

Parameters more reasonable than PKS 2155-304.

$z = 0.03$, $d_L = 130$ Mpc

March 2001 flare observed by RXTE, Whipple, HEGRA, & ground-based optical telescopes (Fossati et al. 2008).

Variability observed down to 1000 sec (Aharonian et al. 2002).

EBL Model	δ_D	B [mG]	t_{var} [s]	L_j [10^{45} erg s^{-1}]
S06	31	22	10^4	3.1
D07	34	27	10^4	3.7
P05	37	38	10^4	3.7

Conclusions (Part II)

- High Doppler factors, jet luminosities and cooling timescales indicates SSC has trouble explaining γ-rays from 2006 PKS 2155-304 flare.
  - Compare to Begelman et al. (2008)
- Resolution of this problem?
  - External source for Compton scattering needed?
  - One zone model not correct? Another blob (Georganopoulos et al. 2003)?
  - Lower EBL energy density?
- *GLAST* will significantly detect similar flares in PKS 2155-304 in ~ 1-2 ksec in scanning mode. *GLAST* will distinguish between EBLs if SSC model is correct.
- PKS 2155-304 giant flare was ~ 10 times brighter in TeV than in X-rays or optical. Could unID TeVs be blazars?

Can any of the UnID TeV Sources be blazars?

- Costamante & Ghisellini (2002) estimate that latest VHE telescopes should see ~ 100 blazars on the whole sky.

$$\frac{100\ \text{blazars}}{41{,}200\ \text{deg}^2} = \frac{N\ \text{blazars}}{360\ \text{deg}^2}$$

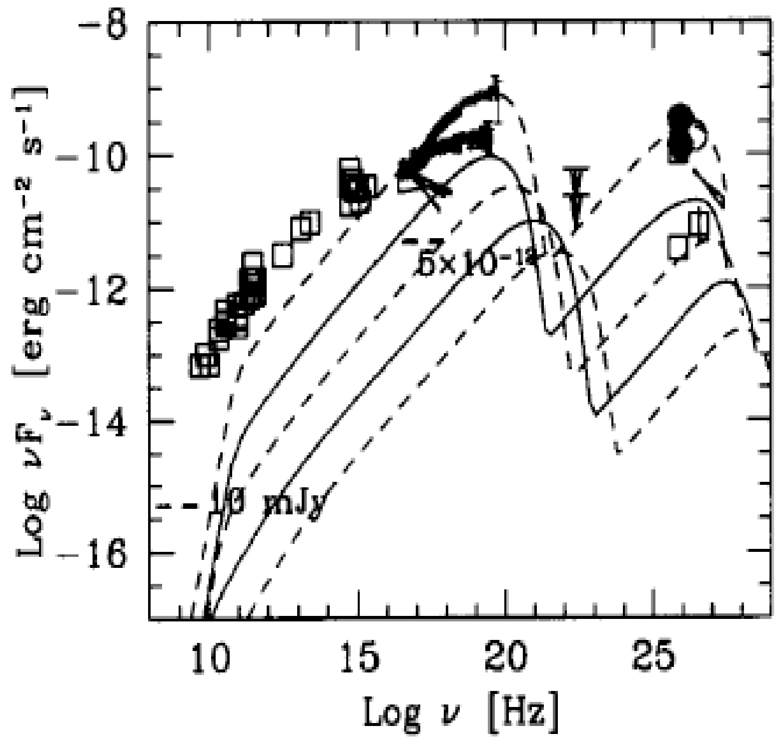
- So there should be ~ 1 TeV blazar in HESS (6 deg x 60 deg) Galactic survey (Aharonian 2006, 2008).

- Point Source UnID TeVs are seen out to very high energies, > 50 TeV. Problems for blazars?
  - Electrons with high enough energies to scatter to these high energies.
  - Absorption by EBL.

- Can variability distinguish between blazars and other phenomena?

A new class of blazars?

- Ghisellini (1999) suggests existence of higher energy class of blazar.
- FSRQ → LBL → HBL sequence
- Extend sequence to lower fluxes, higher energies. Highest energy blazars should be the weakest.
- Emission out to several tens of TeV.
- Energetics seem to allow this.
- Mukherjee et al. (2003) suggest UnID TeV J2032+4130 might be such a blazar.
- This source only seen up to ~10 TeV (Aharonian et al. 2002, 2005; Albert et al. 2008)



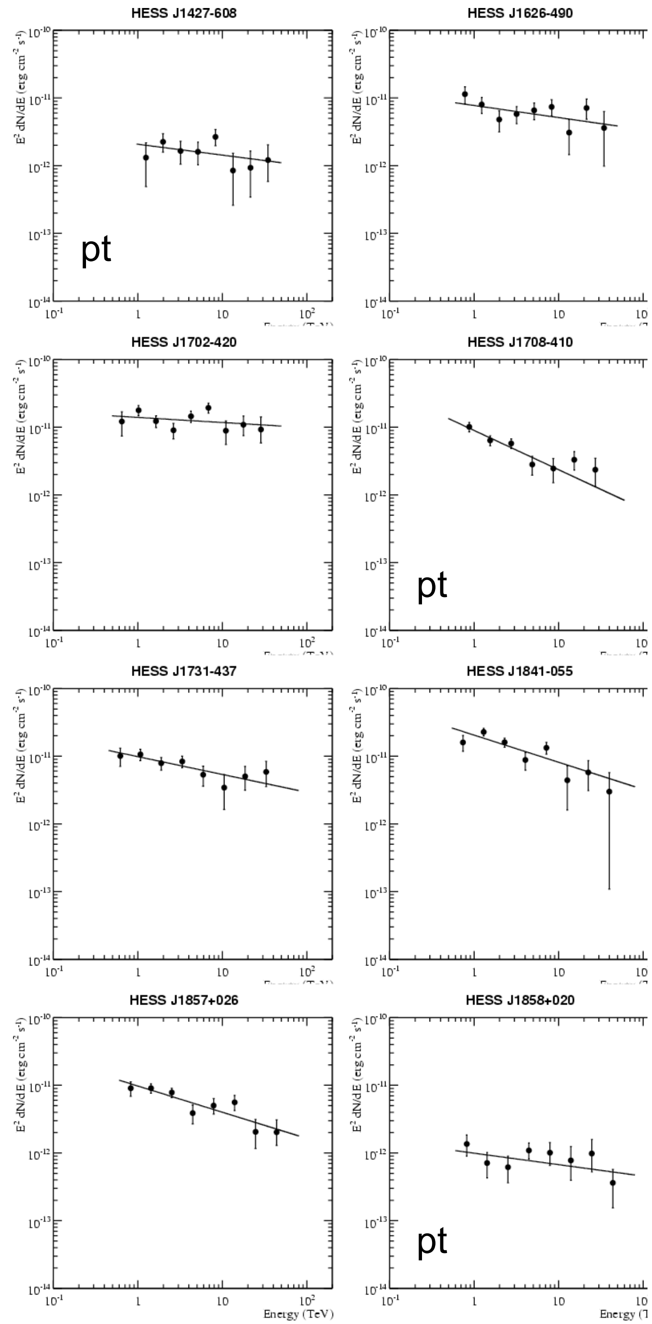
Ghisellini (1999), Aph, 11, 11

TeV Spectra

Spectra for eight sources followed up with HESS.

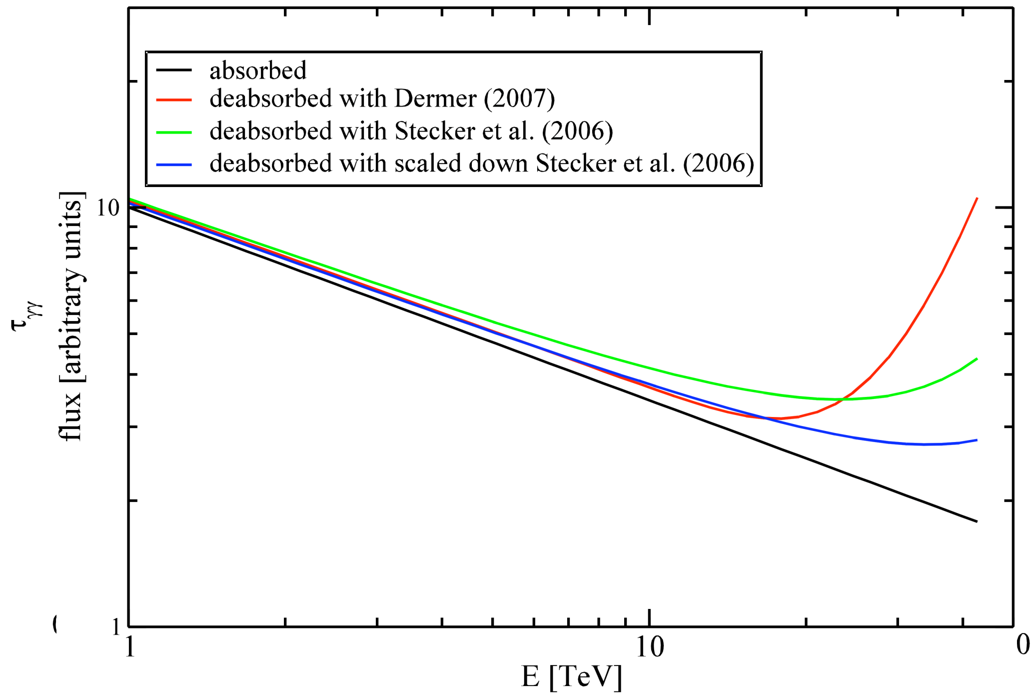
All sources followed up have spectra to > 50 TeV .

Evidence for high energy cutoffs?



Aharonian et al. (2008), 477, 353

Absorption by EBL



Closest blazar is Mrk 421 at z=0.03 (130 Mpc).

Closest TeV-loud AGN is M87 at z=0.003 (13 Mpc).

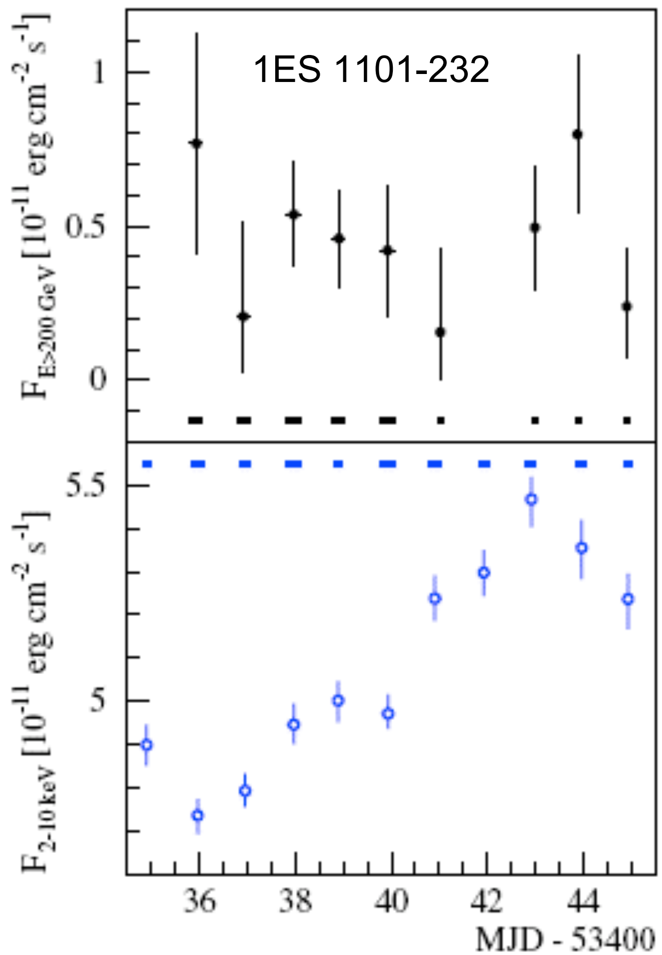
M87 seen out to ~20 TeV (Aharonian et al. 2006)

Mrk 501 seen out to ~20 TeV (Aharonian et al. 1999)

Deabsorb UnID TeV source with Γ = 2.4 from 0.9—50 TeV with various EBLs. Assume z=0.003.

Rapid Variability

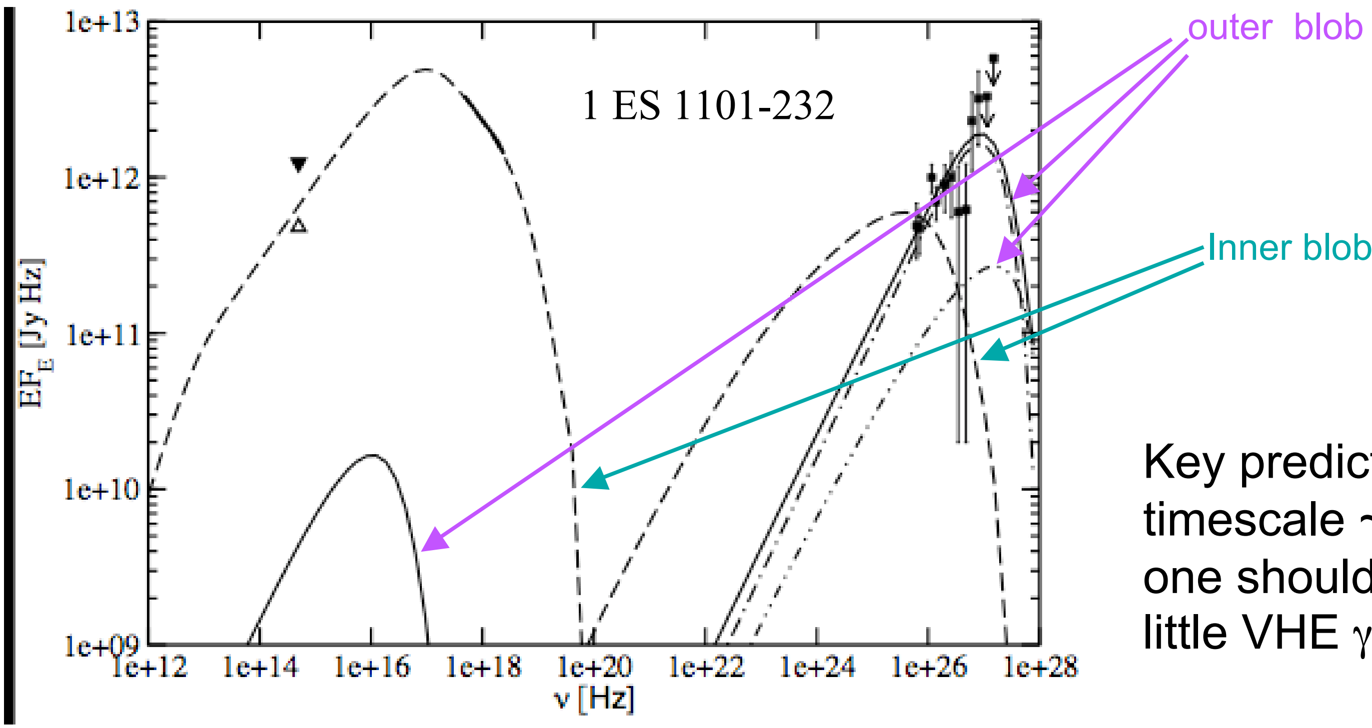
- PKS 2155-304 and Mrk 501 have been observed with rapid TeV variability (t_v ~ 300 sec).
- Other blazars, however, (e.g., 1ES 1101-232, 1ES 0229+200), have little or no TeV variability for several months.

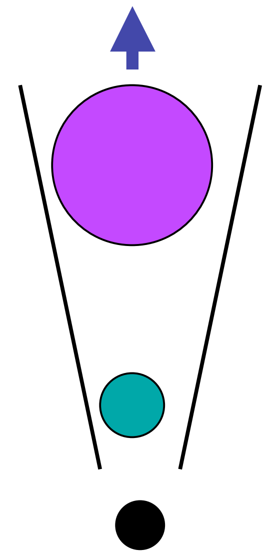


Aharonian et al. (2007), 470, 475

Compton Scattering of CMB

- Shock accelerates electrons to $\gamma > 10^6$ in jet at 100s of parsecs.
- $B \sim 10\ \mu G$, $\Gamma = 15$, $R'_b = 2 \times 10^{18}$ cm, $q = 1.5$

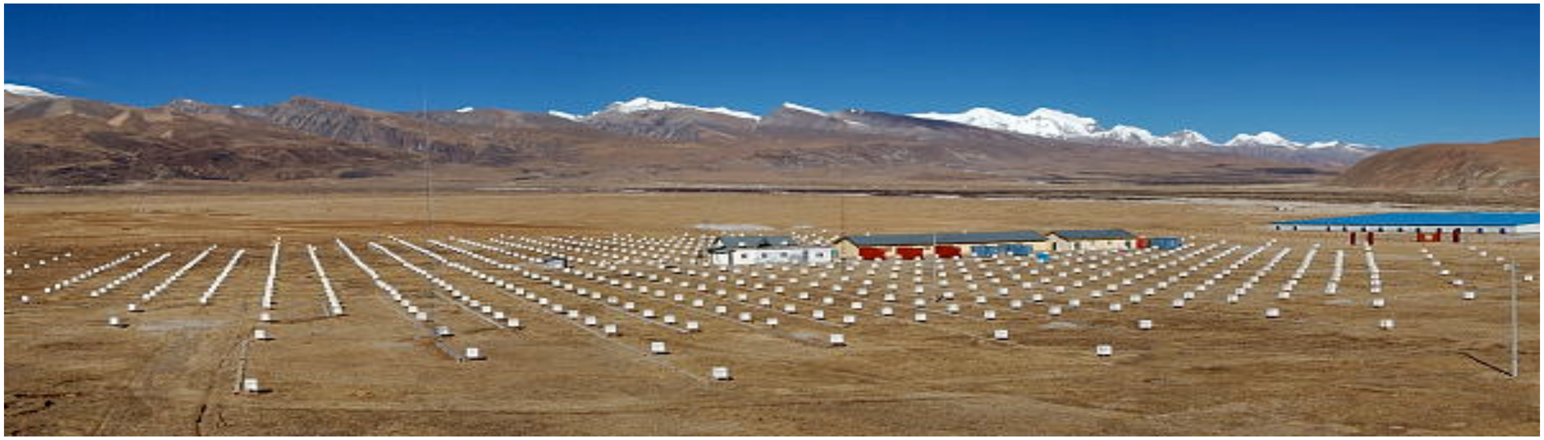




Key prediction: Cooling timescale ~ 10^3 years, so one should observe very little VHE γ-ray variability.

Böttcher et al. (2008), ApJ, 2008, 679, L9

Tibet Air Shower Array Sources



- Tibet ASA (Wang et al. 2008; arXiv: 0804.1862) sees three (questionable) UnID TeVs with E_{max} > 10 TeV.

source	*l* (deg)	*b* (deg)	σ
1	133	-8.3	4.6
2	155	-46	4.7
4	153	-25	4.8

- Two are quite far from Galactic plane, and could be AGN.
- Probability of observing more than 3 sources at > 4.5σ is 26%.

Conclusions (Part III)

- Tibet ASA sources and J2032+4130 (E_{max} ~ 10 TeV) could possibly be AGN.
- Other point source UnID TeVs are probably not blazars, based on E_{max} > 50 TeV.
- Rapid variability:
  - may be a signature of blazars but probably won't rule out microquasars.
  - Lack of rapid variability doesn't rule out AGNs as UnID TeVs.