

Secondary signal from ultra-high energy cosmic rays produced by distant blazars. Time variability.

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Outline

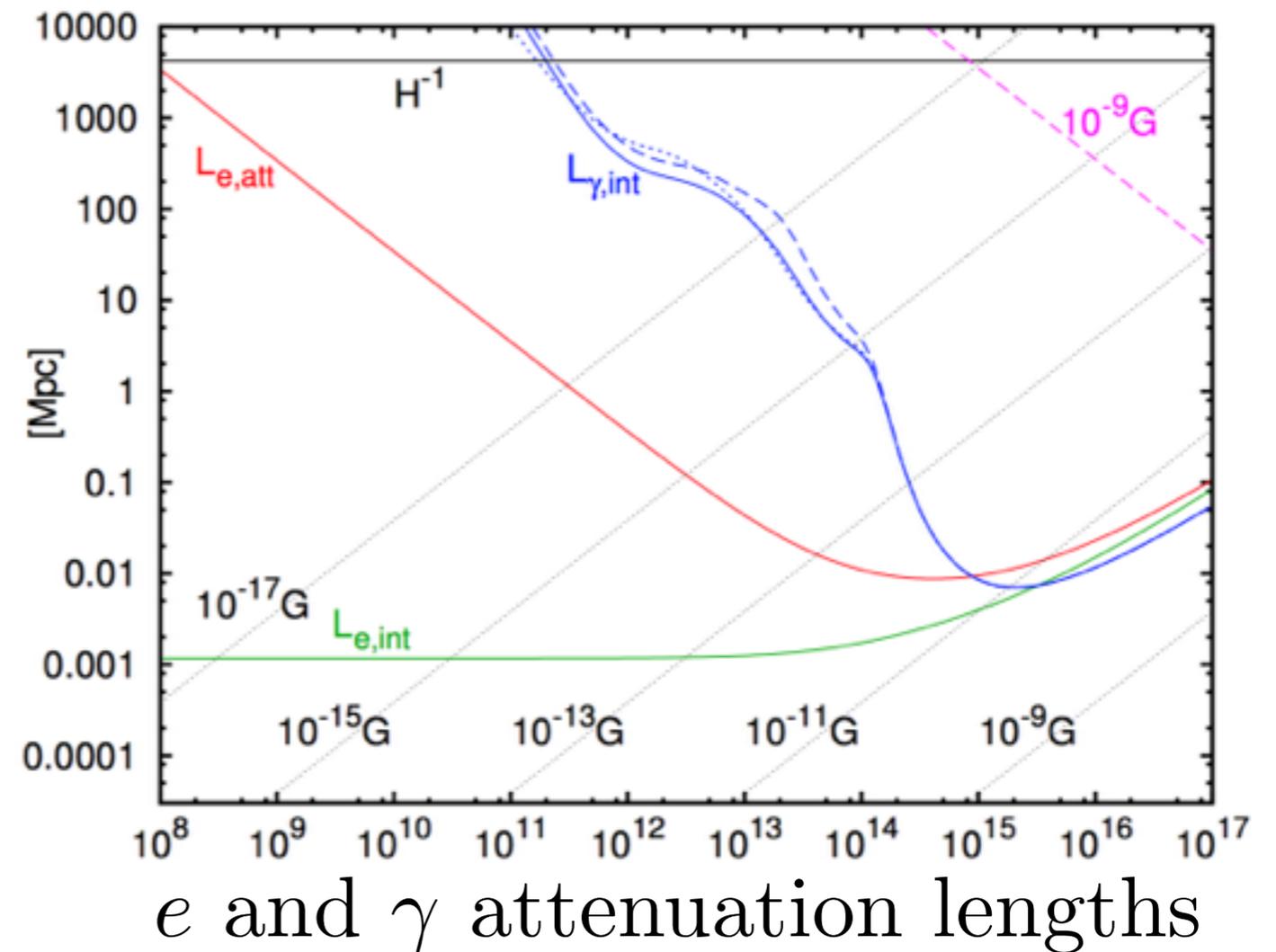
- Introduction. Primary and secondary gamma-rays from distant blazars.
- Testing hypothesis with time variability.

Opacity of Universe to gamma rays

$$\gamma\gamma_b \rightarrow e^+e^-$$

For $E_\gamma > 0.2\text{TeV}$

remote sources flux should
be suppressed



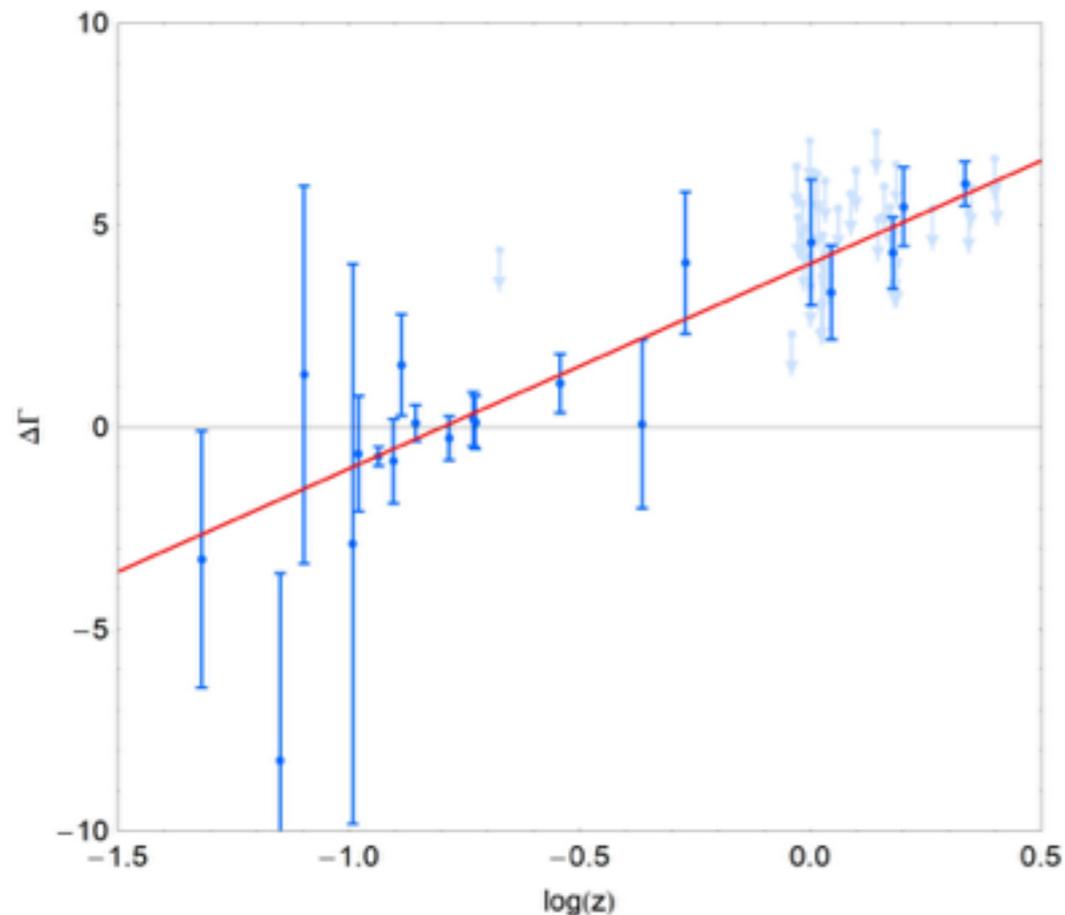
However

TeV gamma-rays have been detected from the remote
blazars $z > 0.15$ (HESS, VERITAS)

”Anomalous” Universe transparency for γ -rays

Possible solutions:

- Hardening spectra at sub-TeV energies
- Very low EBL
- Secondary component from cosmic rays emitted by the same sources
- New physics (ALP, Lorentz invariance violation)



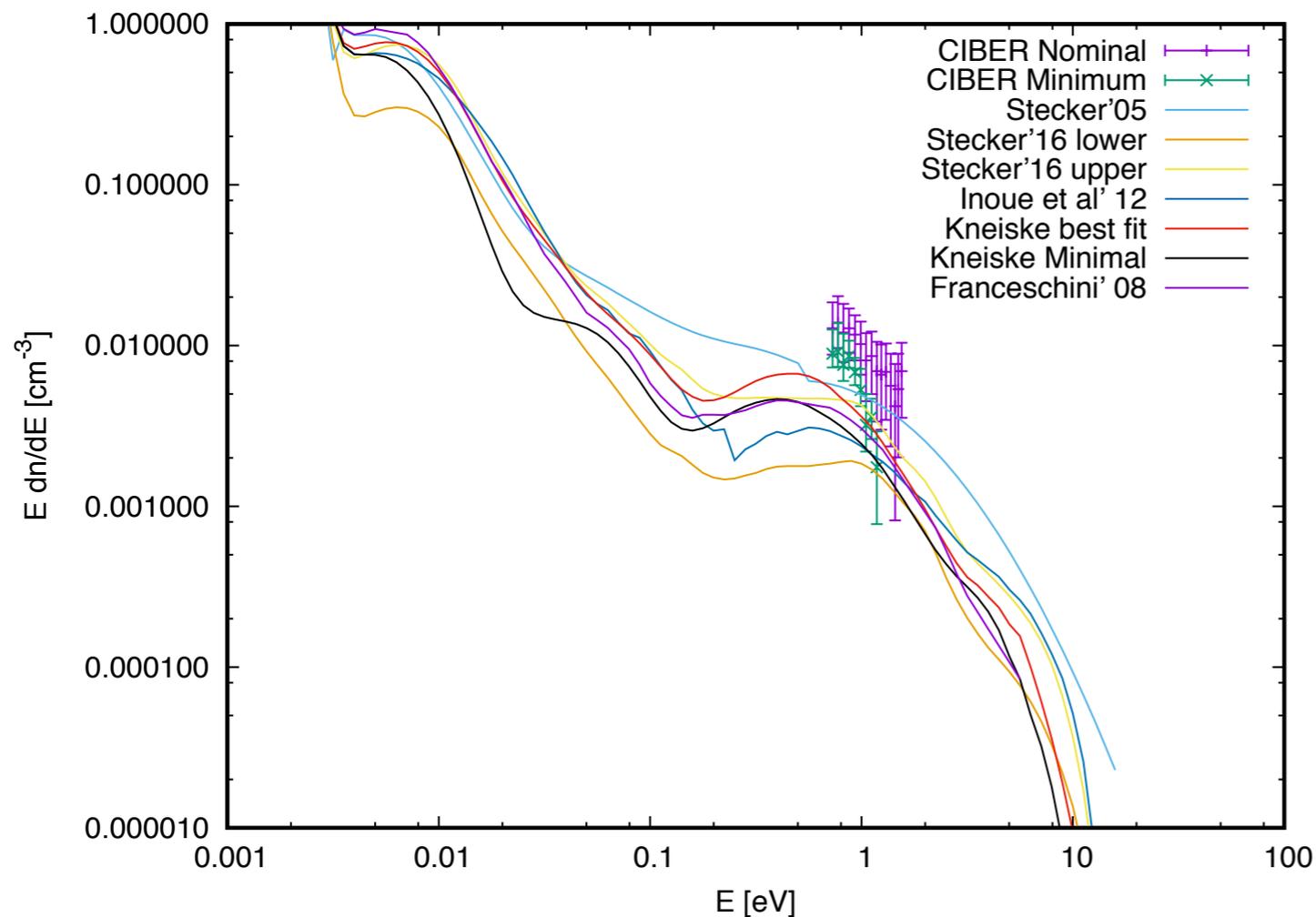
Power law spectrum break Γ
grows with redshift

Rubtsov, Troitsky 2014

”Anomalous” Universe transparency for γ -rays

Possible solutions:

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- Secondary component from cosmic rays emitted by the same sources
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Secondary γ -rays from UHECR

$$p\gamma_b \rightarrow \pi.. \rightarrow \gamma$$

$$p\gamma_b \rightarrow e^+ e^- \rightarrow \gamma \quad \text{Essey et. al 2010}$$

Flux scaling with distance

Primary γ :

$$F_{\text{prim},\gamma}(r) \propto \frac{1}{r^2} \exp\{-r/\lambda_\gamma\}$$

Secondary γ :

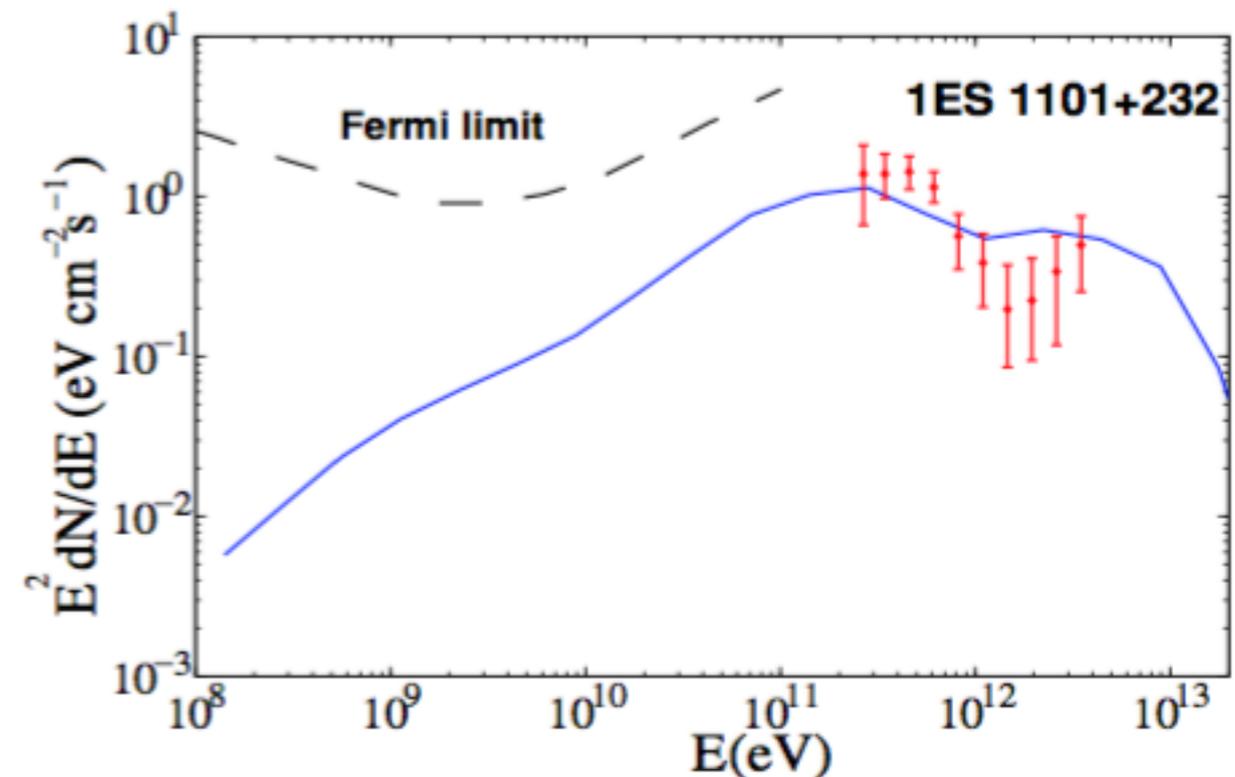
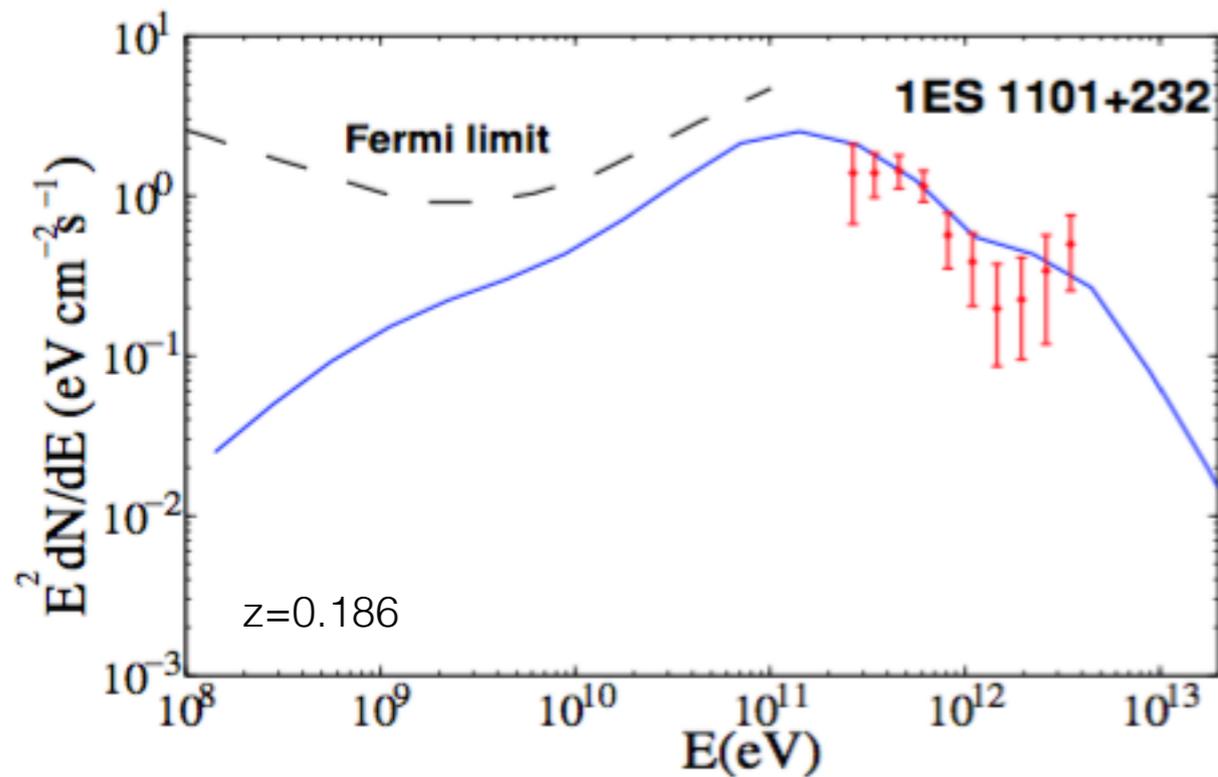
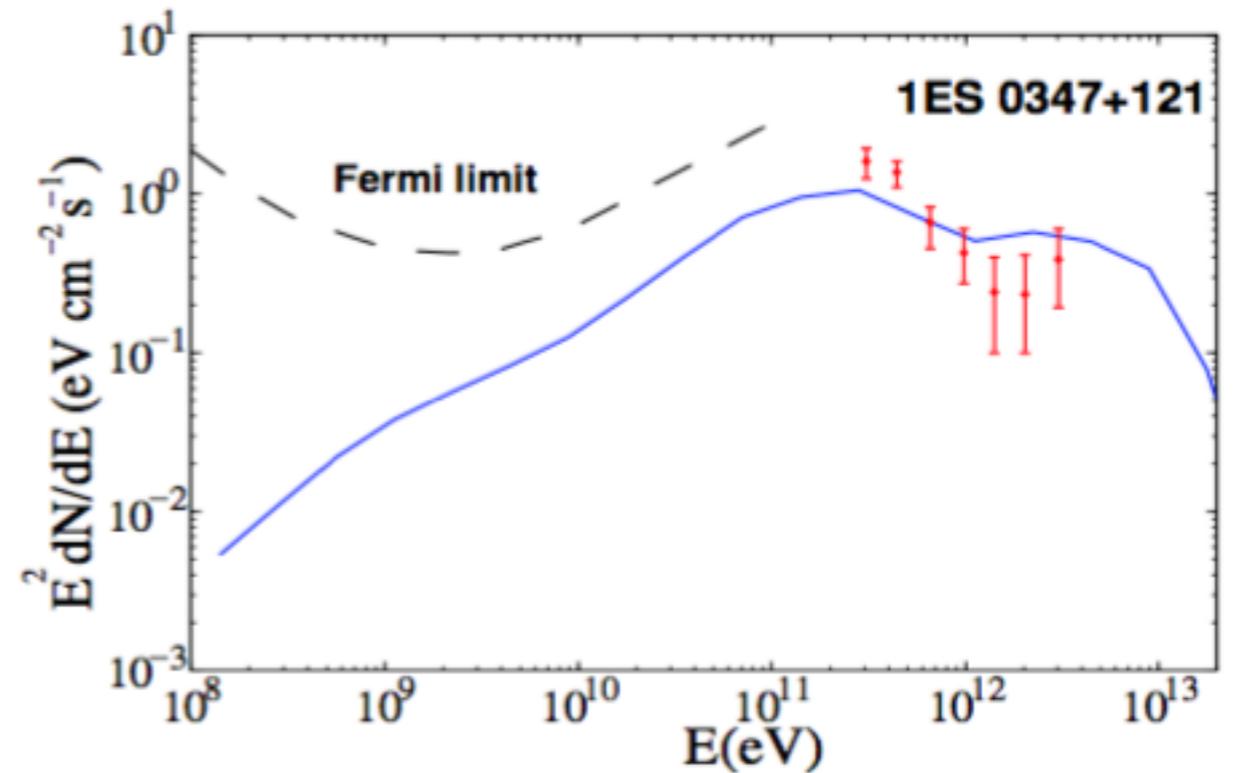
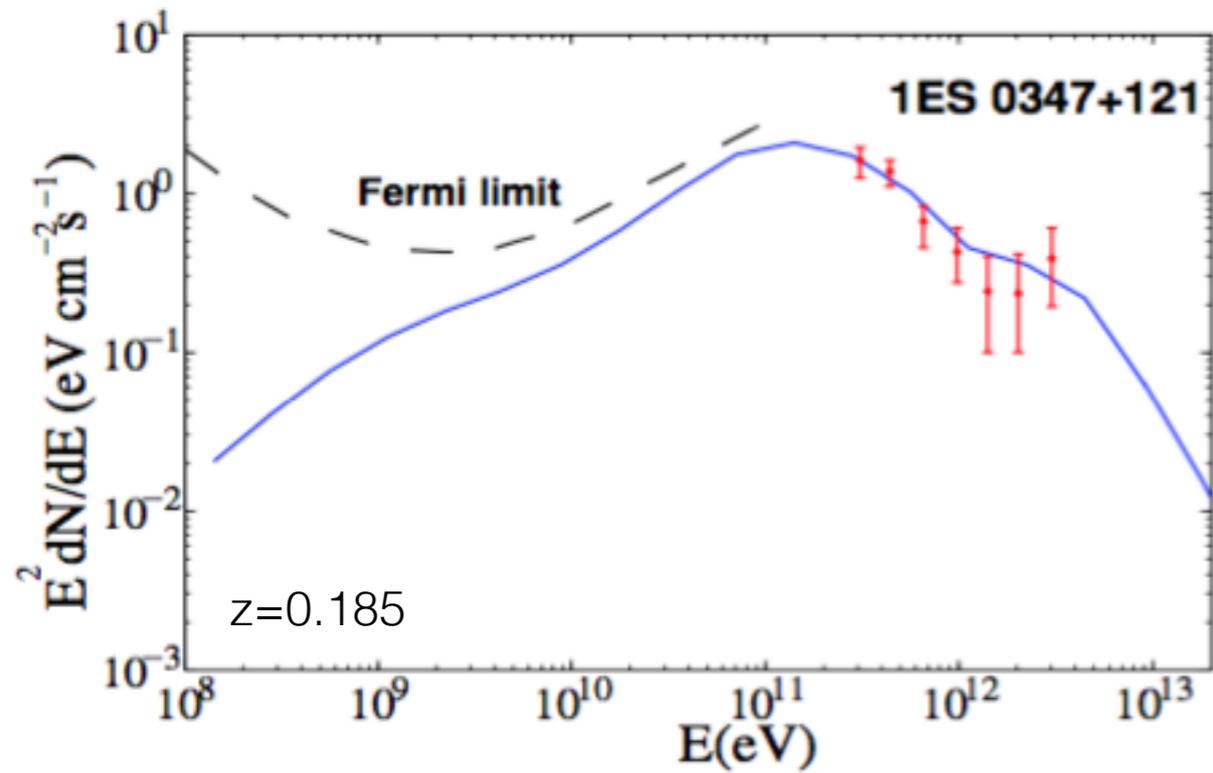
$$F_{\text{cr}} \times r^2 \simeq \text{const}, \quad \frac{d}{dr}(F_\gamma \times r^2) = \eta(F_{\text{cr}} \times r^2) - \frac{1}{\lambda_\gamma} F_\gamma \times r^2$$

$$F_{\text{sec},\gamma}(r) = \frac{\eta\lambda_\gamma}{4\pi r^2} [1 - e^{-r/\lambda_\gamma}] \propto \begin{cases} 1/r, & \text{for } r \ll \lambda_\gamma, \\ 1/r^2, & \text{for } r \gg \lambda_\gamma. \end{cases}$$

Deflection of protons

$$\Delta\theta \sim 0.1^\circ \left(\frac{B}{10^{-14}\text{G}} \right) \left(\frac{4 \times 10^7 \text{GeV}}{E} \right) \left(\frac{D}{1 \text{Gpc}} \right)^{1/2} \left(\frac{l_c}{1 \text{Mpc}} \right)^{1/2}.$$

Sample calculations



Low EBL

High EBL

Primary vs. secondary

Primary photons

- Very low EBL
- No limitation on IGMF
- Time variability?
- Limitations on the intrinsic background level

Secondary photons

- Low IGMF
- EBL - any reasonable ?
- Time variability can be destroyed by IGMF
- Sensitive to filaments

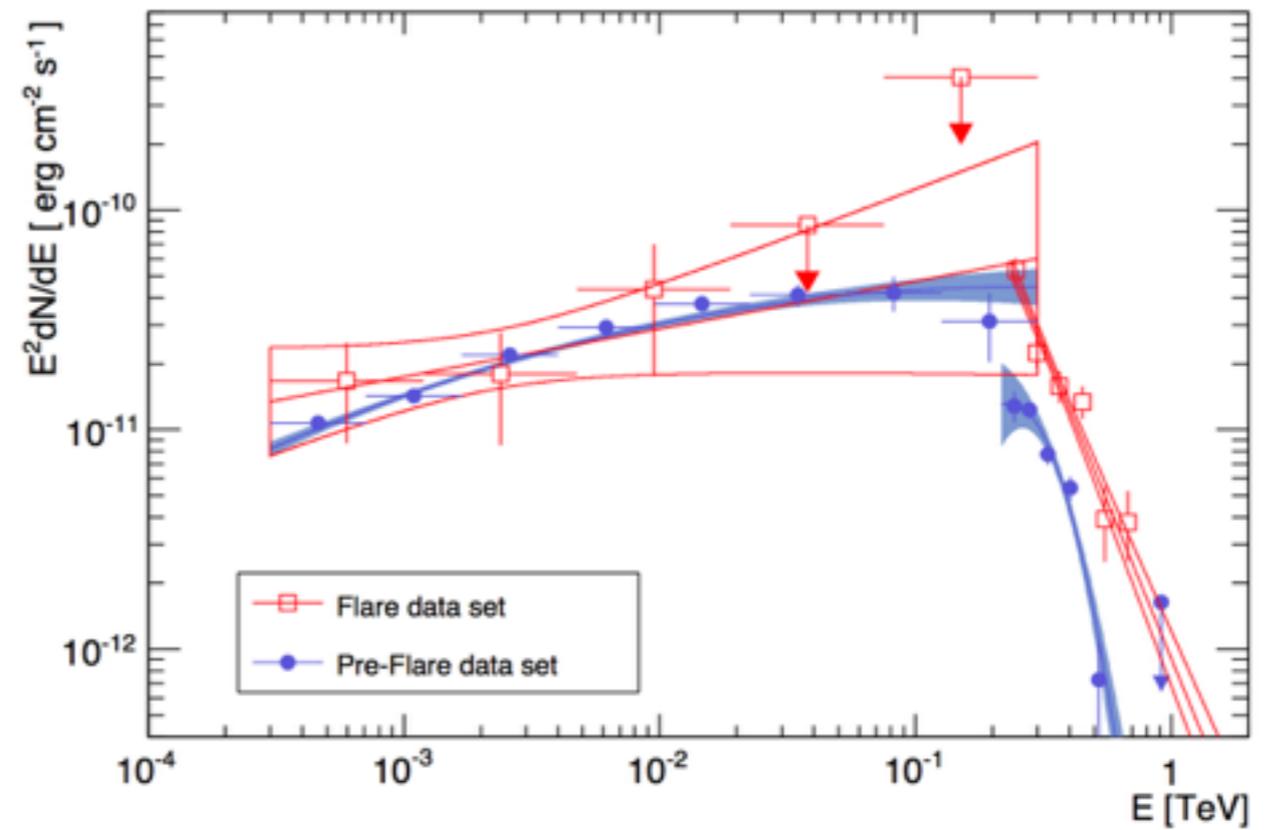
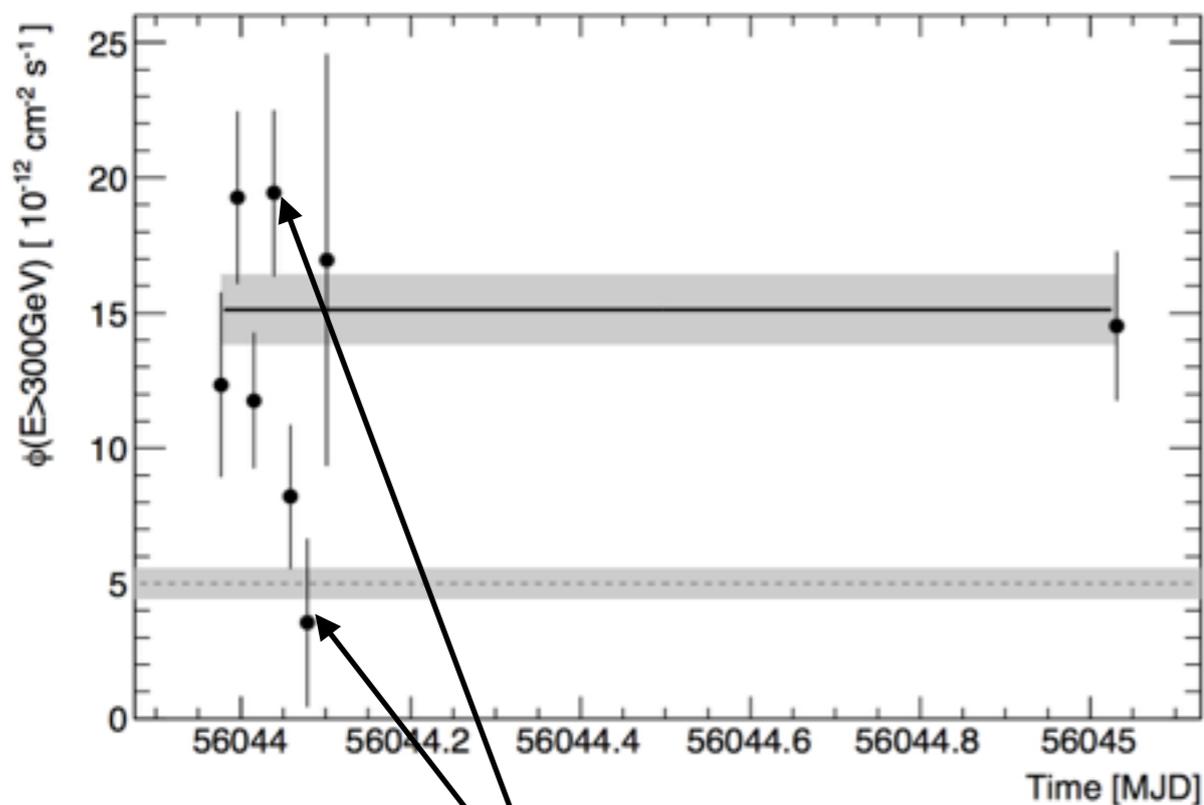
Conservative time variability test

- **Deabsorbed** spectrum $\Phi_d(E) = \Phi(E) \times e^{\tau(E,z)} \propto E^\Gamma$

must have positive break $\Delta\Gamma > 0$

- Time variability must be observed in the energy range **above** the deabsorbed spectrum break (otherwise we don't need secondary photons)

The 2012 flare of Bl Lac object PG 1553+113



H.E.S.S. 2015

Flux drop by more than 60% in 2 h above 300 GeV

PG 1553+113

Deabsorbed spectrum

Depends on:

- redshift assumed

$0.43 < z < 0.58$ Danforth et al. (2010)

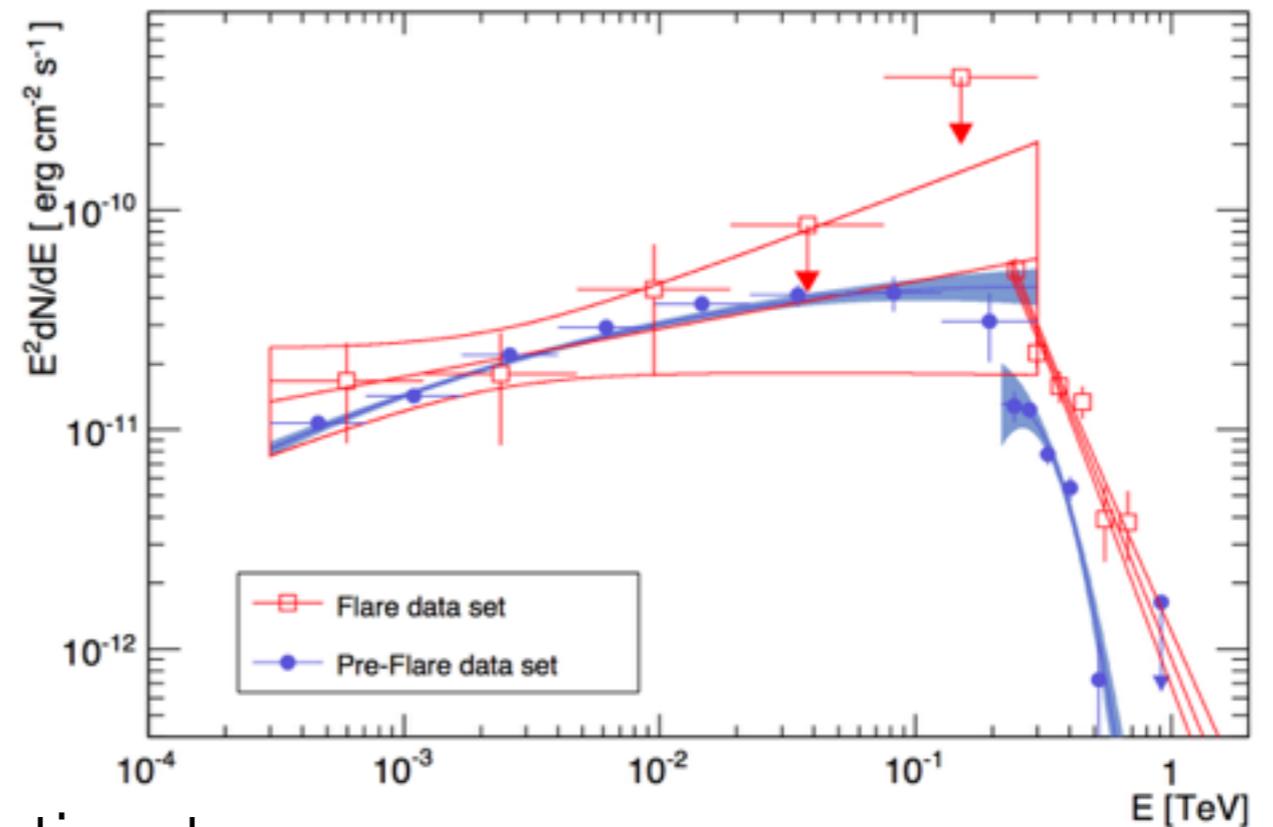
far-UV spectroscopy

$z = 0.49 \pm 0.04$ H.E.S.S. 2015

derived for specific EBL

we use $z=0.43$ for conservative estimate

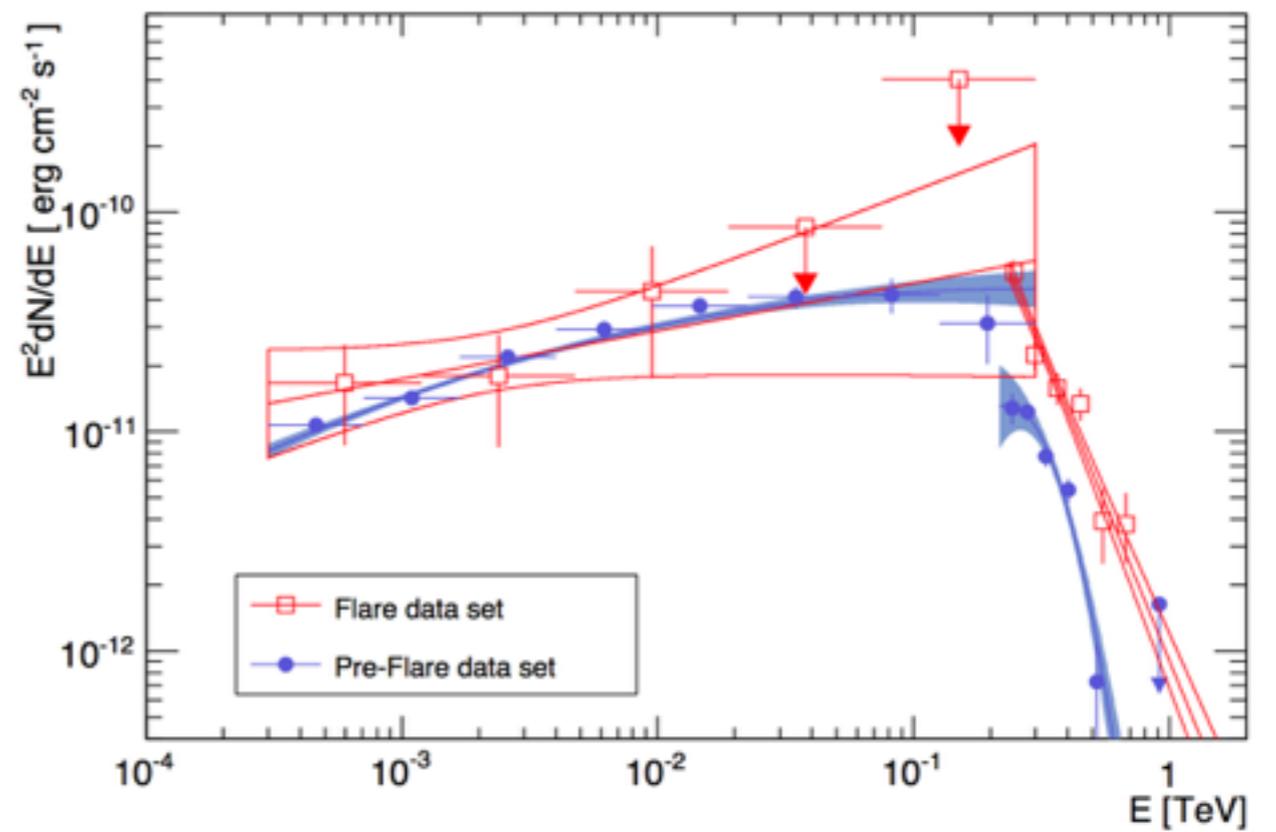
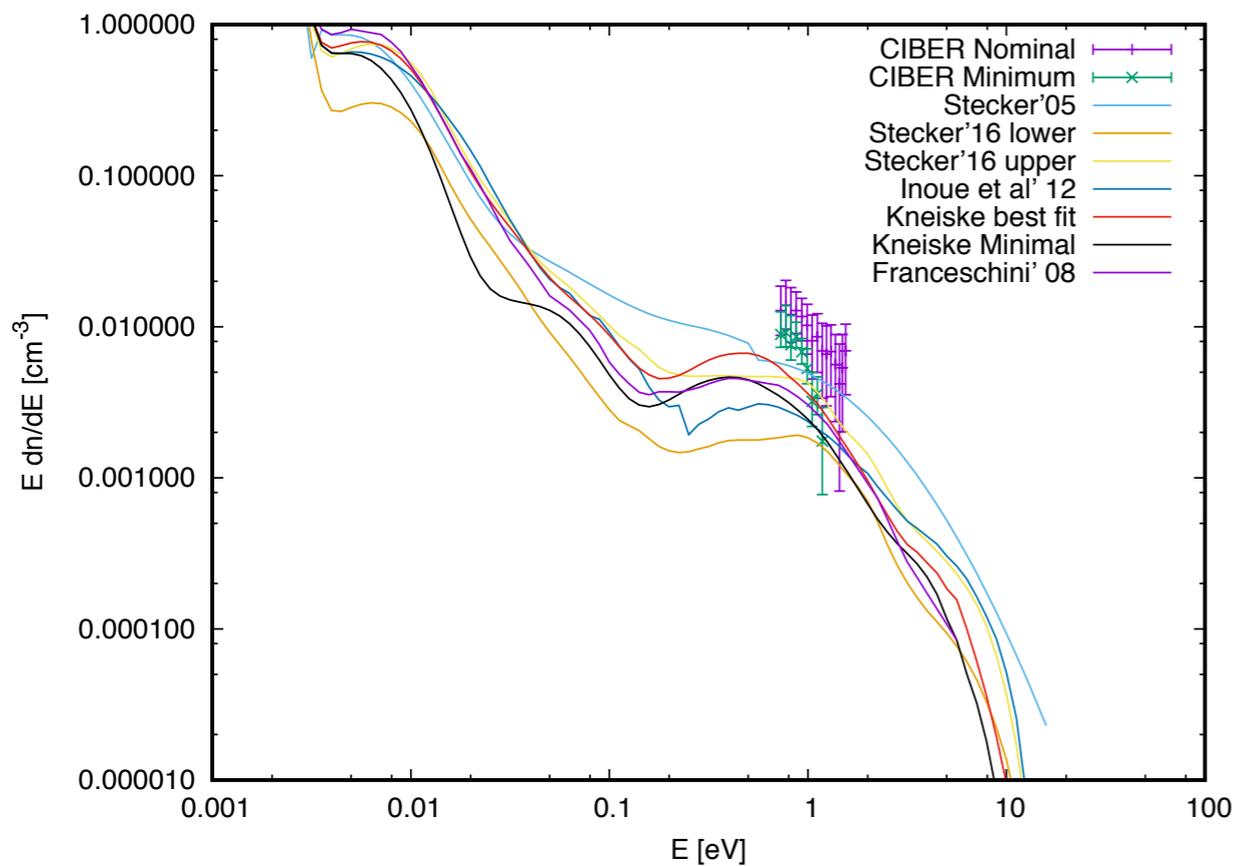
- EBL assumed



PG 1553+113

Deabsorbed spectrum

Depends on:

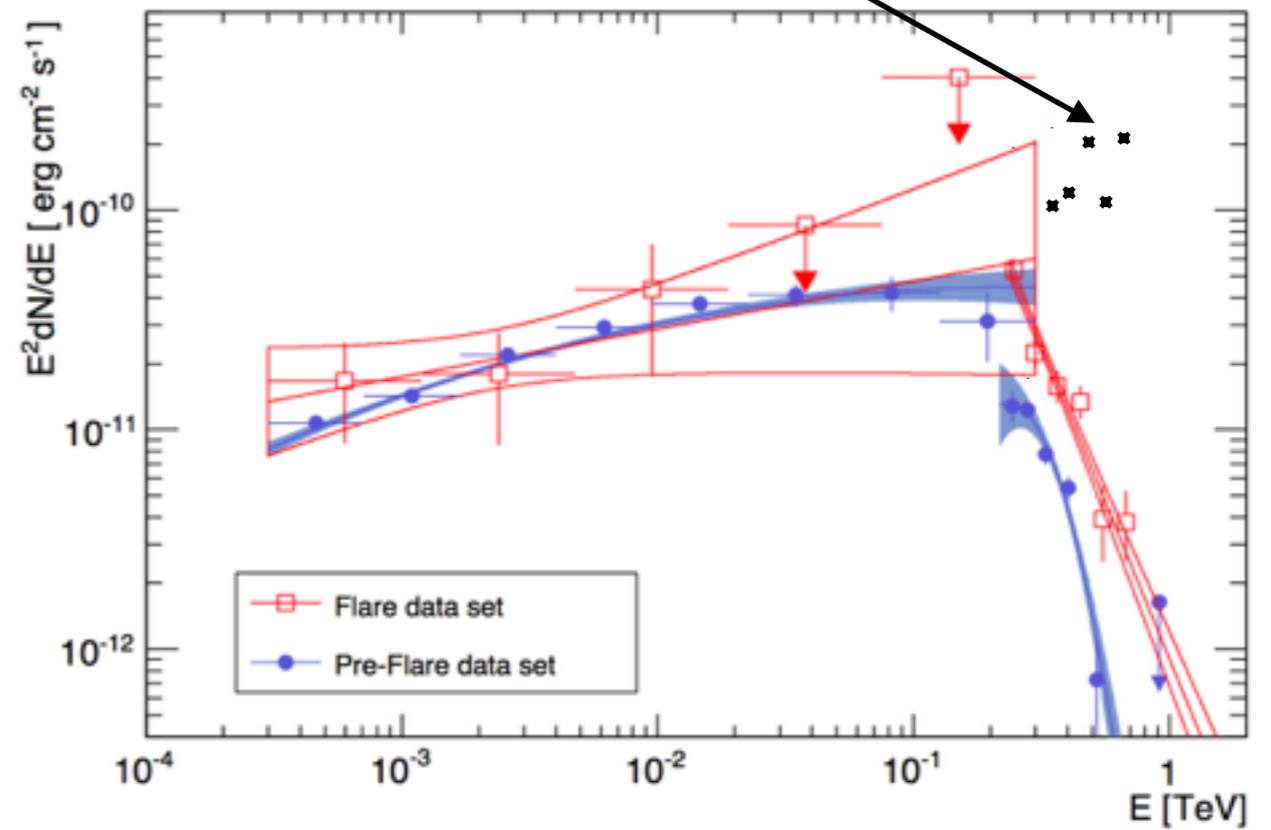
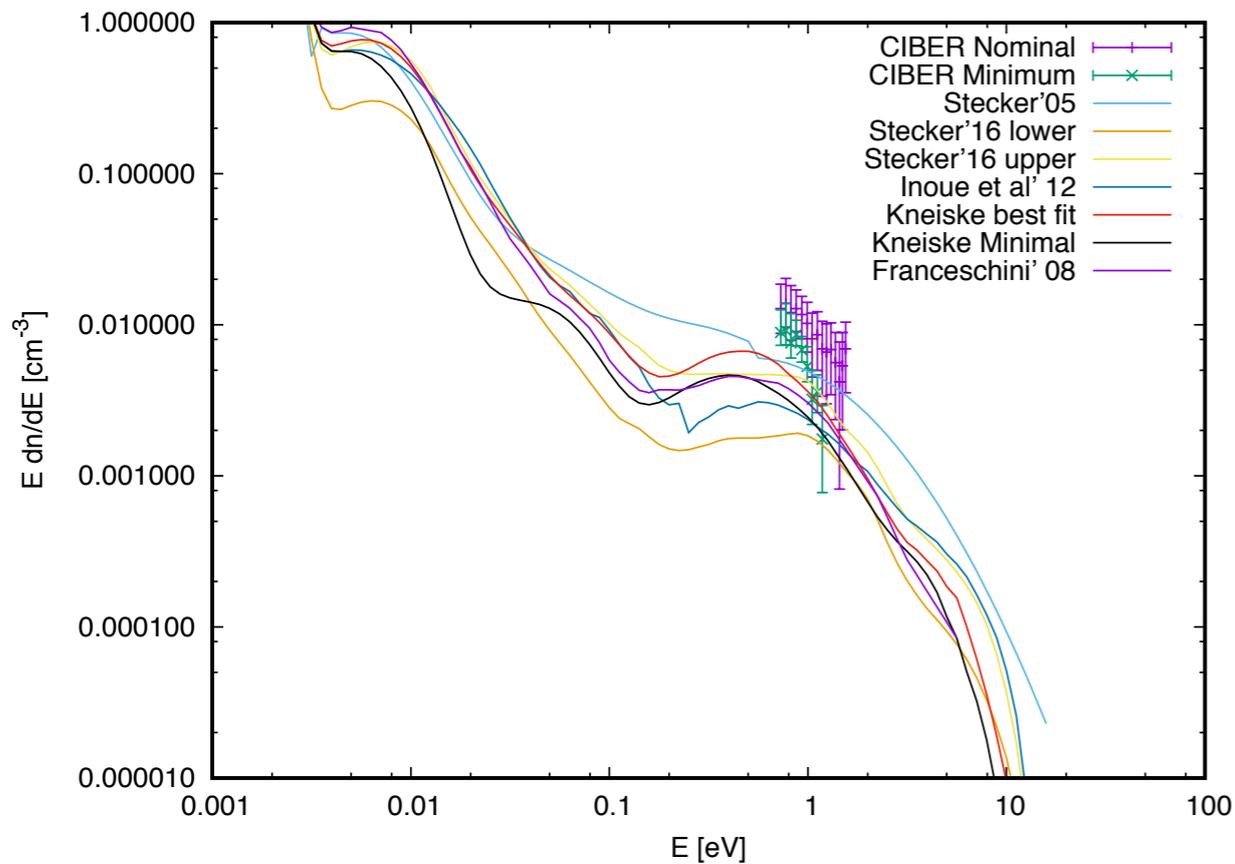


- EBL assumed

PG 1553+113

Deabsorbed spectrum

Depends on:



- EBL assumed

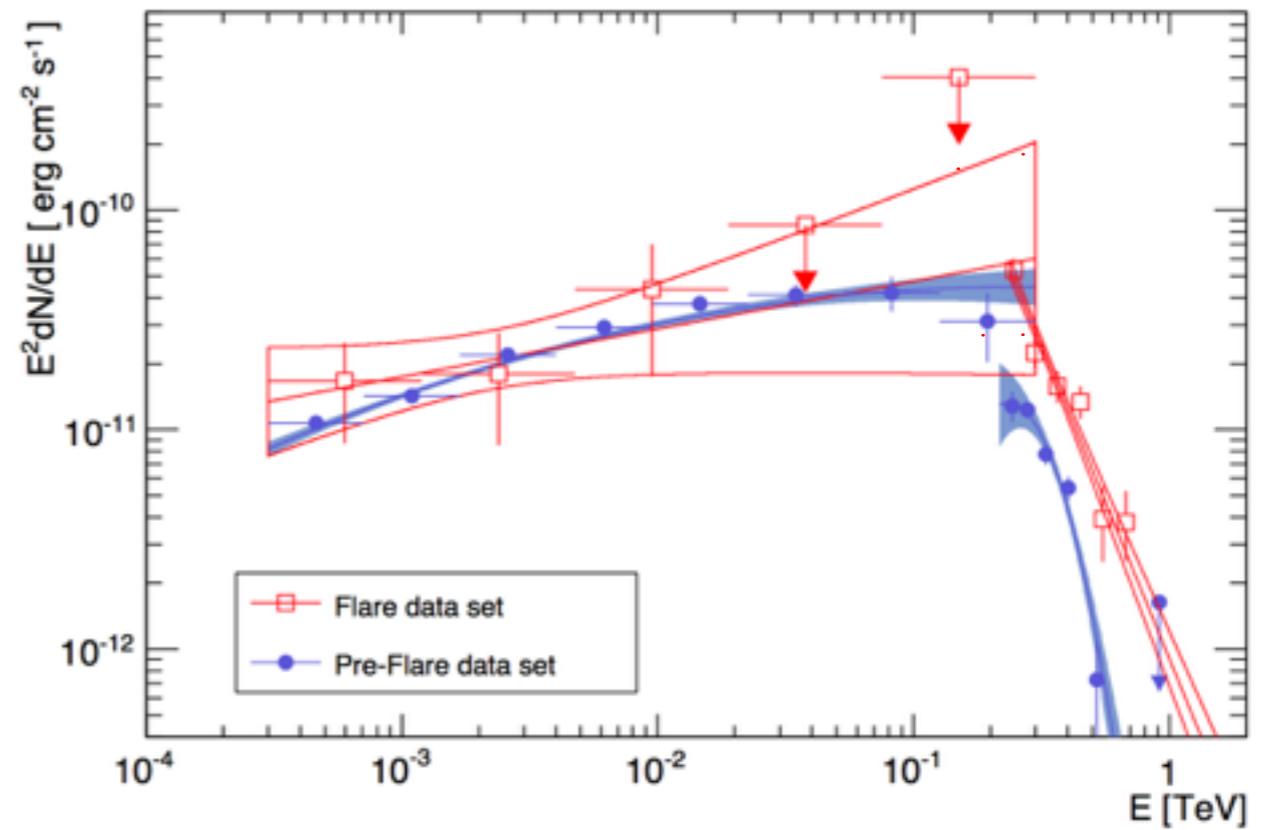
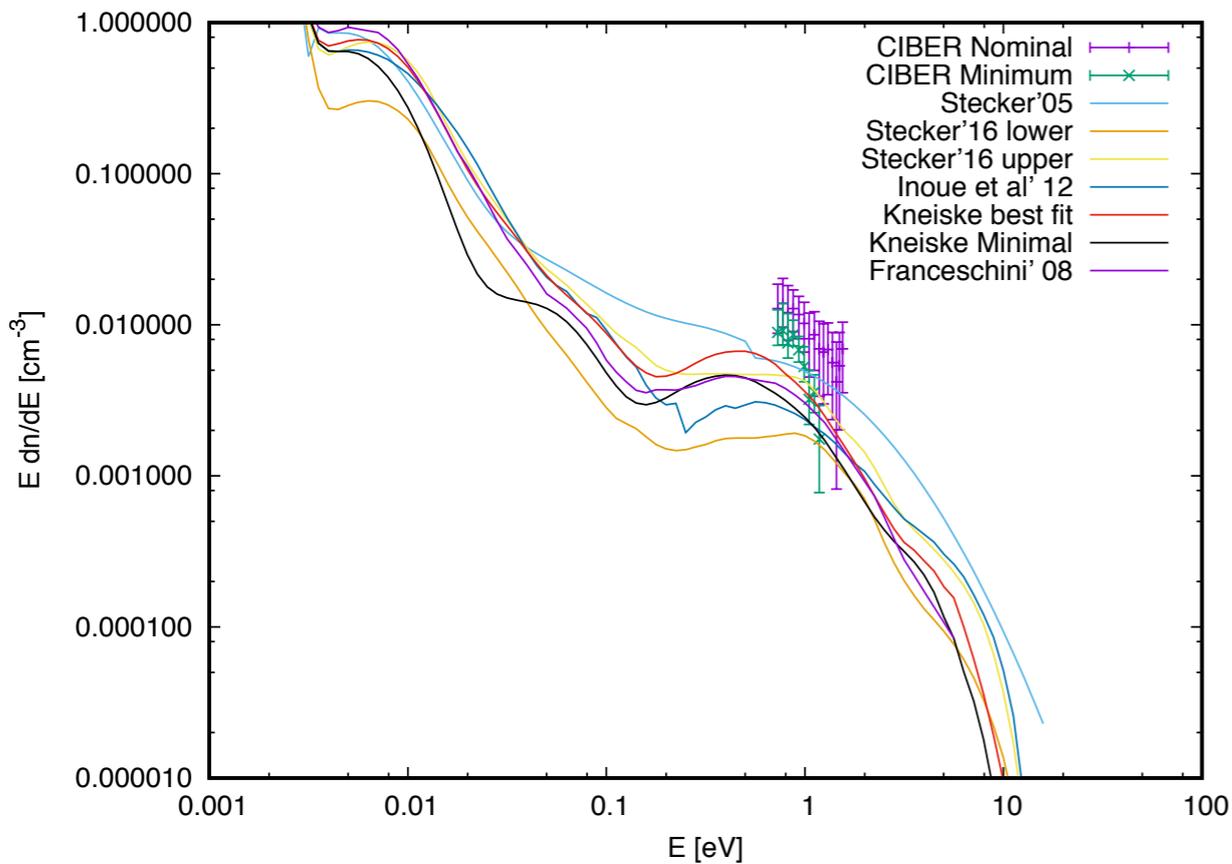
Francischohini et. al 2017 EBL

No Break - No Contradiction

PG 1553+113

Deabsorbed spectrum

Depends on:



- EBL assumed

CIBER EBL *Astrophys.J.* 839 7

Break exists

PG 1553+113

Deabsorbed spectrum

Depends on:

- redshift assumed

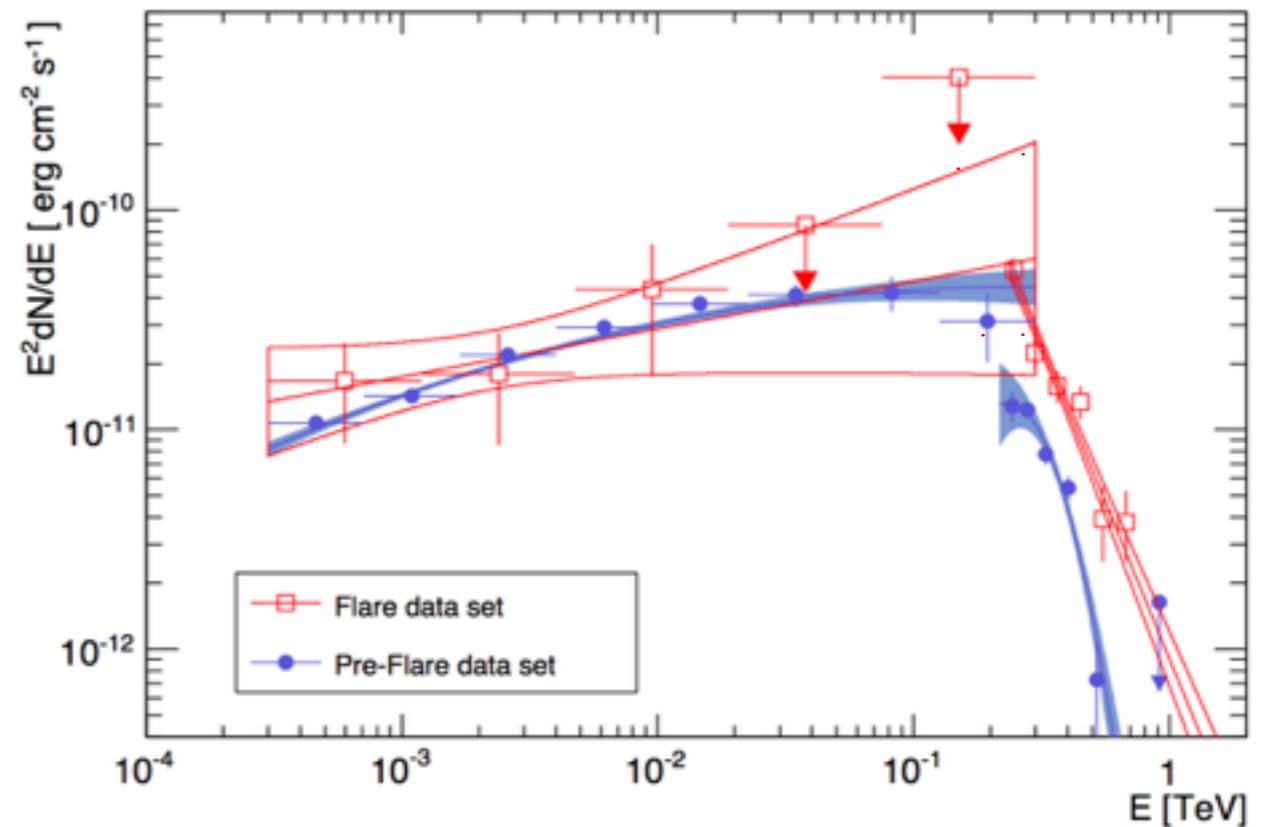
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CIBER EBL *Astrophys.J.* 839 7

Break exists

Variability. Conservative Test

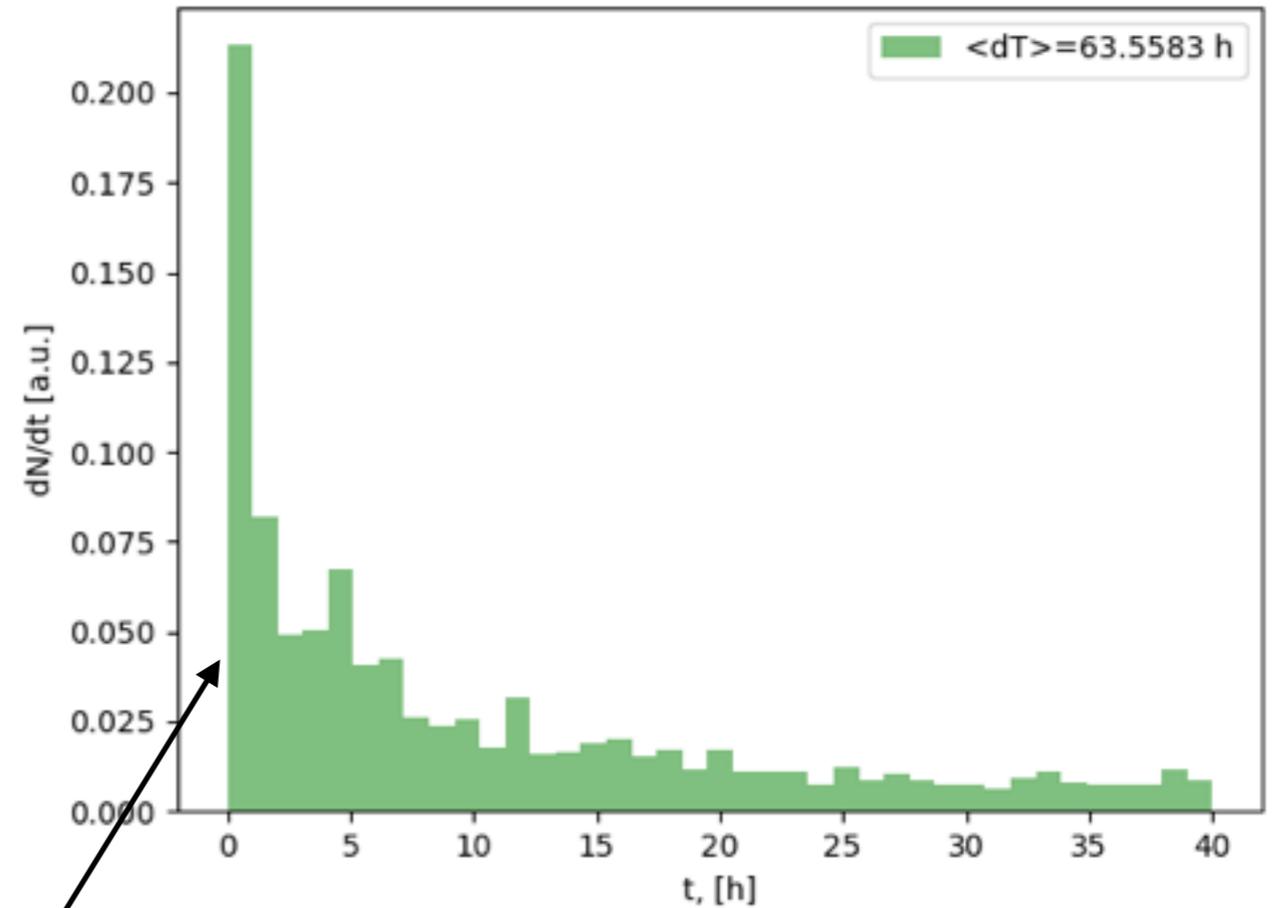
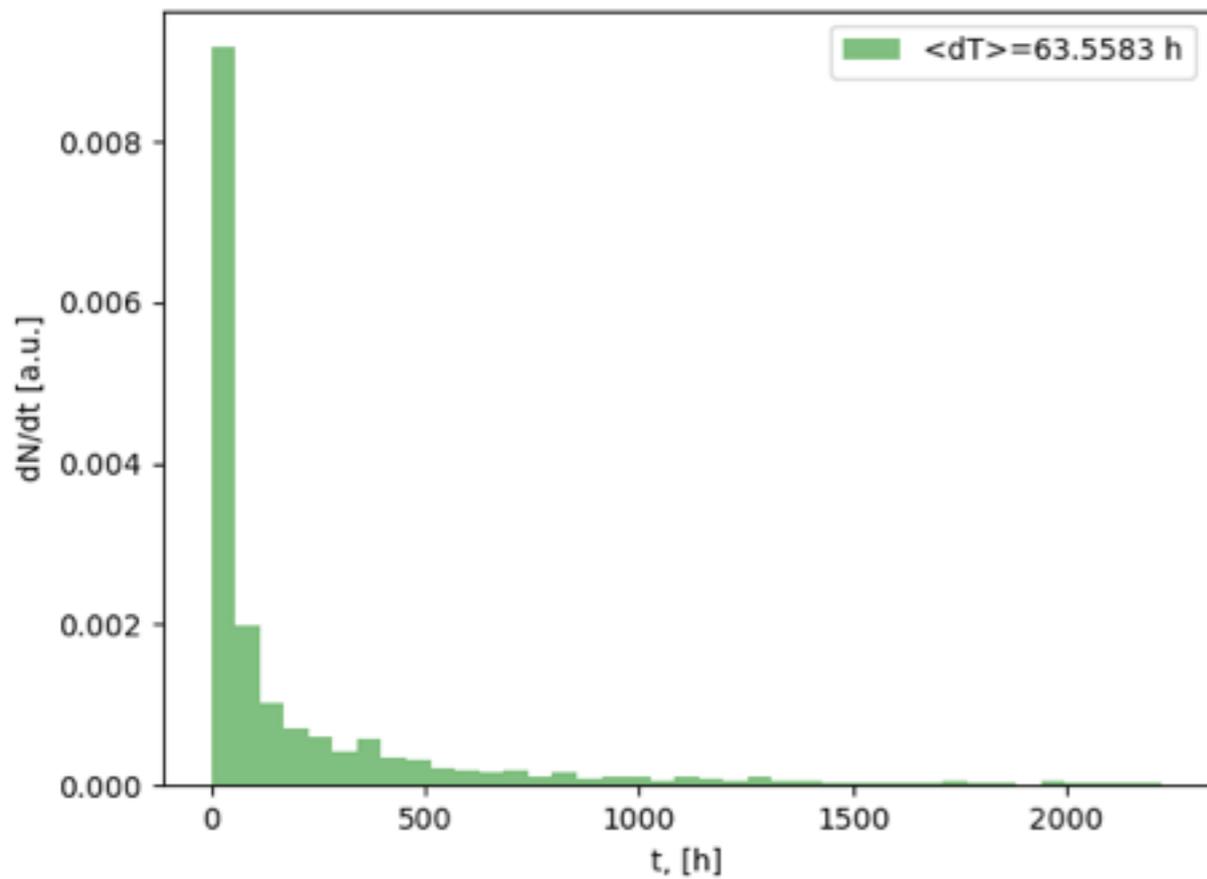
Minimize deflections

- Proton UHECR primaries
- $E_p=40$ EeV (just below GZK threshold)
- Consider allowed range of B and L_{cor}
- Jet opening angle 5°

Using MC code for trajectory calculation *(V. Beresinsky, O.K. 2016)*

- Proton interactions and secondaries calculation
- EM cascade development
- 3D - particle trajectories
- Turbulent magnetic field model (J. Giacalone' 99)

Time Delay Calculations



$B = 10^{-17} \text{ G}$, $L_{\text{cor}} = 1 \text{ Mpc}$

Leading component - underdeveloped cascade
produced at distances $< 10 \text{ Mpc}$

Models, preserving variability at 2h scale (preliminary)

$B=10^{-17}G$

$B=10^{-16}G$

$B=10^{-15}G$

$B=10^{-14}G$

maximal
 L_{cor}

>1 Mpc

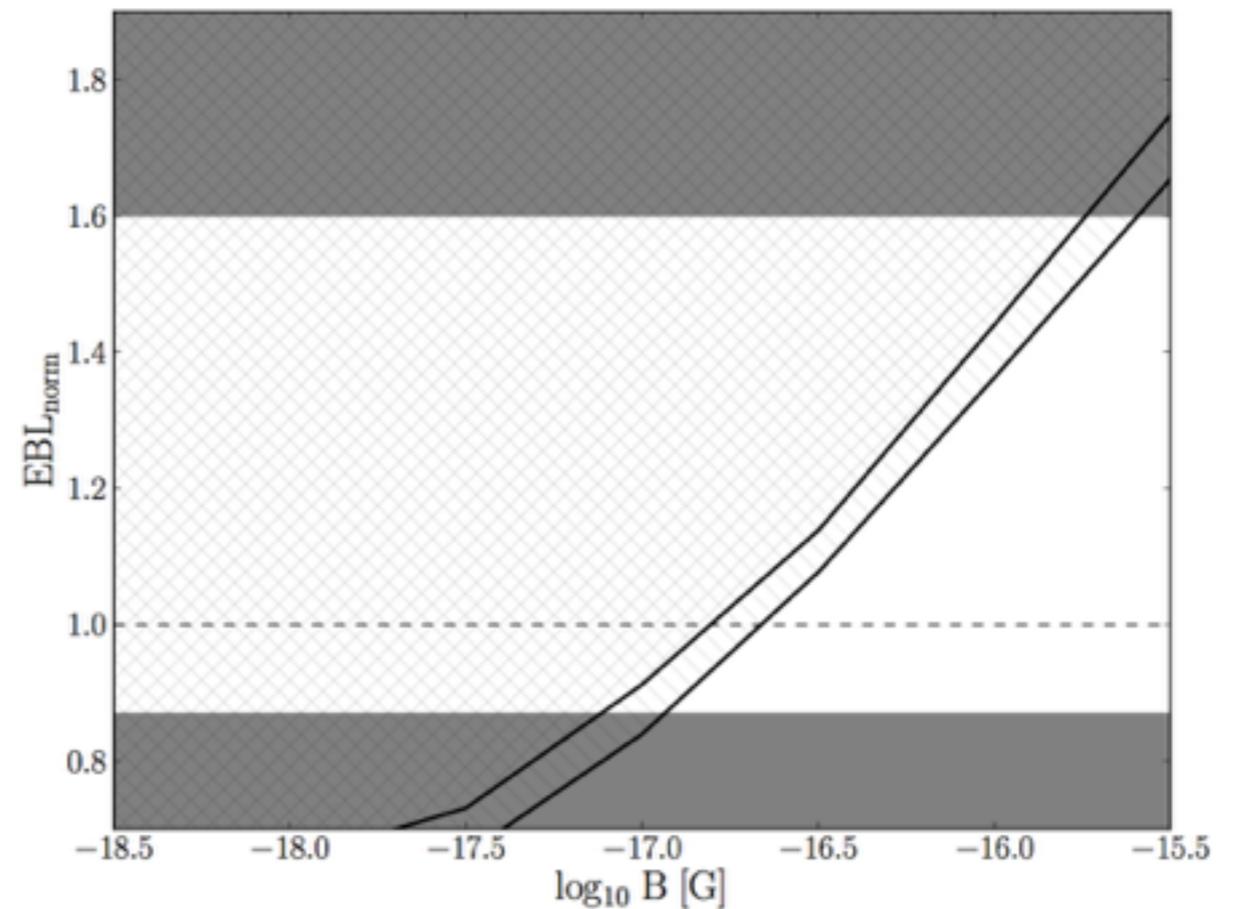
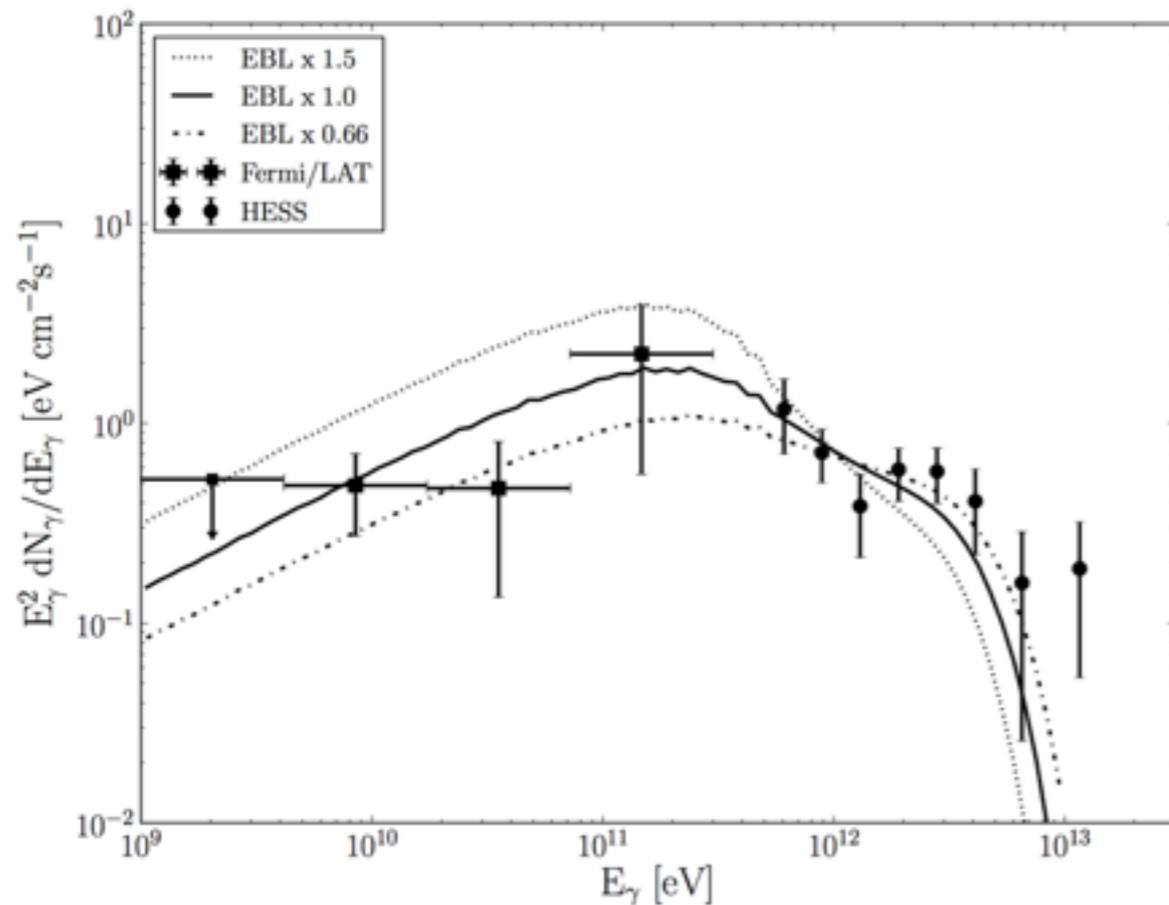
10 Kpc

10 pc

<1 pc

Comparison to lower limits on IGMF

FERMI/LAT and HESS observations of 1ES 0229+200



Vovk et al 2011

- Cascade photon flux is too low - constraining B from below
- Limits depend on the EBL level assumed
- Limits on B scale with correlation length as $L_{\text{cor}}^{-1/2}$

Compare limits on B and L_{cor}

$B=10^{-17}G$

$B=10^{-16}G$

$B=10^{-15}G$

$B=10^{-14}G$

maximal L_{cor}
(PG1553+113 variability)

>1 Mpc

10 Kpc

10 pc

<1 pc

minimal L_{cor}
(1ES 0229+200 spec.)

-

700 Kpc

7 Kpc

70 pc

Limits are mutually exclusive

Secondary gamma-ray scenario. Conclusions

- Variability tests can probe both IGMF and EBL
- EBL can not be too high even in secondary gamma-ray scenario. CIBER serves as illustration.

Thank you

Appendix

Source luminosities in cosmic rays

for slide 7 plots

| Source | Redshift | EBL Model | L_p | $L_{p,iso}$ | χ^2 | DOF |
|-------------|----------|-----------|----------------------------|----------------------------|----------|-----|
| 1ES0229+200 | 0.14 | Low | 1.3×10^{43} erg/s | 4.9×10^{45} erg/s | 6.4 | 7 |
| 1ES0229+200 | 0.14 | High | 3.1×10^{43} erg/s | 1.1×10^{46} erg/s | 1.8 | 7 |
| 1ES0347-121 | 0.188 | Low | 2.7×10^{43} erg/s | 1.0×10^{46} erg/s | 16.1 | 6 |
| 1ES0347-121 | 0.188 | High | 5.2×10^{43} erg/s | 1.9×10^{46} erg/s | 3.4 | 6 |
| 1ES1101-232 | 0.186 | Low | 3.0×10^{43} erg/s | 1.1×10^{46} erg/s | 16.1 | 9 |
| 1ES1101-232 | 0.186 | High | 6.3×10^{43} erg/s | 2.3×10^{46} erg/s | 4.9 | 9 |