Disentangling Hadronic and Leptonic Cascade Scenarios from the Very-high-energy Gamma-ray Emission from Hard-spectrum Blazars

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HT, Murase, Dermer 2013, ApJ 771, L32
Murase, Dermer, HT, Gigliori 2012, ApJ 749, 107

JSPS 独立行政法人 日本学術振興会 Japan Society for the Promotion of Science

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Outline

- Extreme high-frequency peaked BL Lac objects (HBLs) and electromagnetic cascades

- Electromagnetic cascade induced by hadronic components

- Distant hard gamma-ray blazars

- How to disentangle leptonic and hadronic origins?

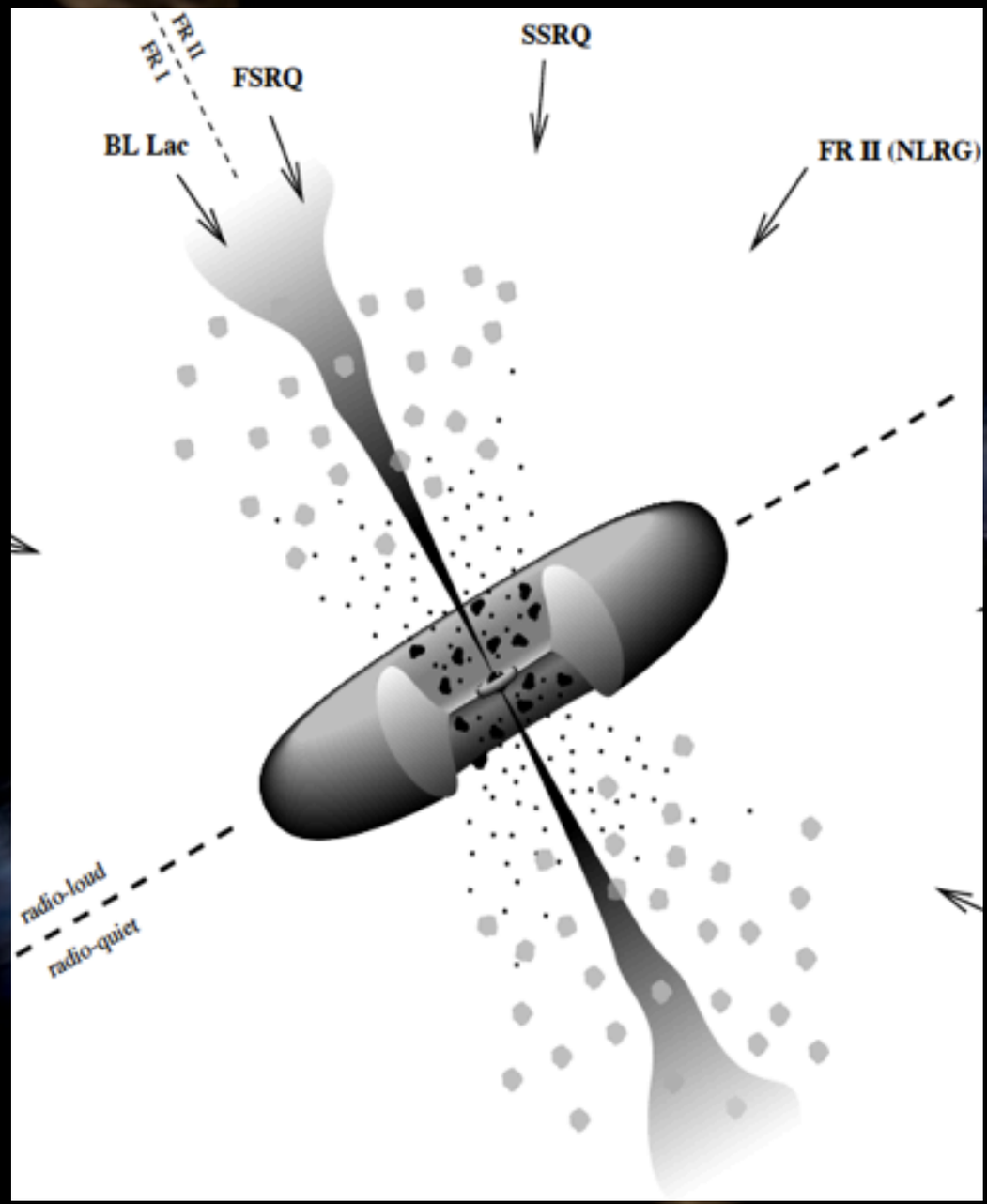
Active Galactic Nuclei

- Luminous nucleus comparable with the whole galaxy
- Powered by accretion onto supermassive black holes
- Some AGN (radio galaxies) have jets.

Unification Hypothesis

The diversity of AGN originates from the viewing angle of observers.

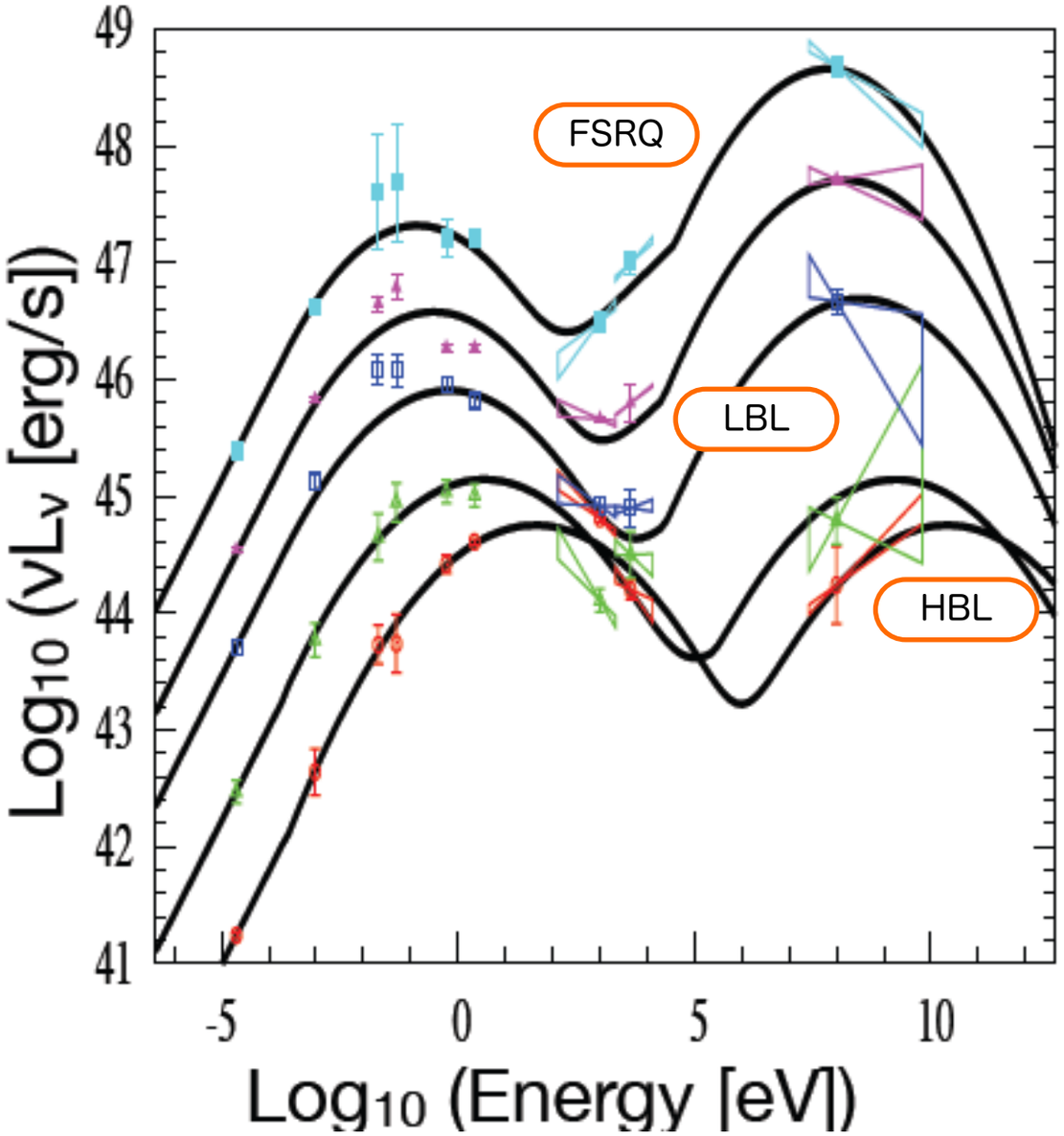
Urry & Padovani 1995



Blazars - AGN with jets directed to observers

Relativistic jets
--> Relativistic beaming is essentially important.

Typical SED and Blazar Sequence



Fossati+ 1998

Spectral Energy Distribution

Two humps

- Lower freq. - Electron synchrotron radiation
- Higher freq. - Inverse Compton / Hadronic

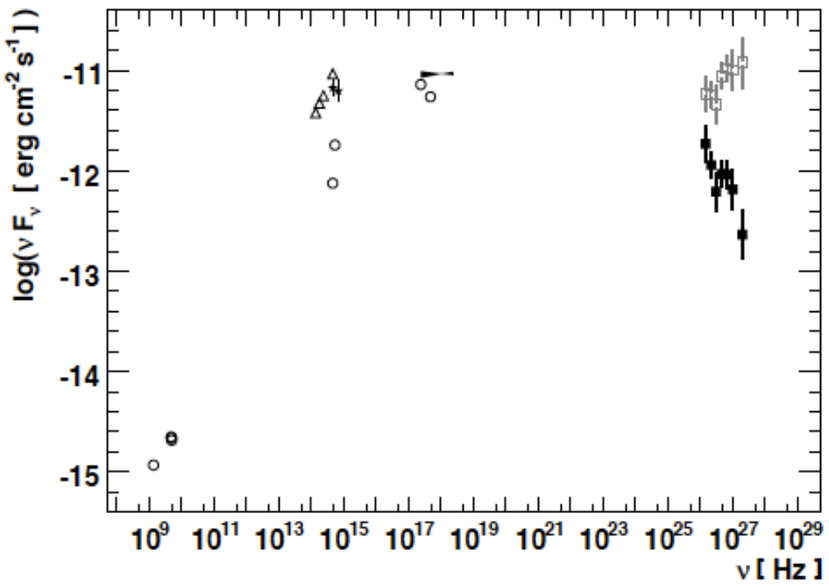
Blazar sequence

Empirical relation:

The lower peak frequency is, the higher luminosity is.

Extreme HBL

Highest-frequency-end of the blazar sequence



Aharonian et al. 2007

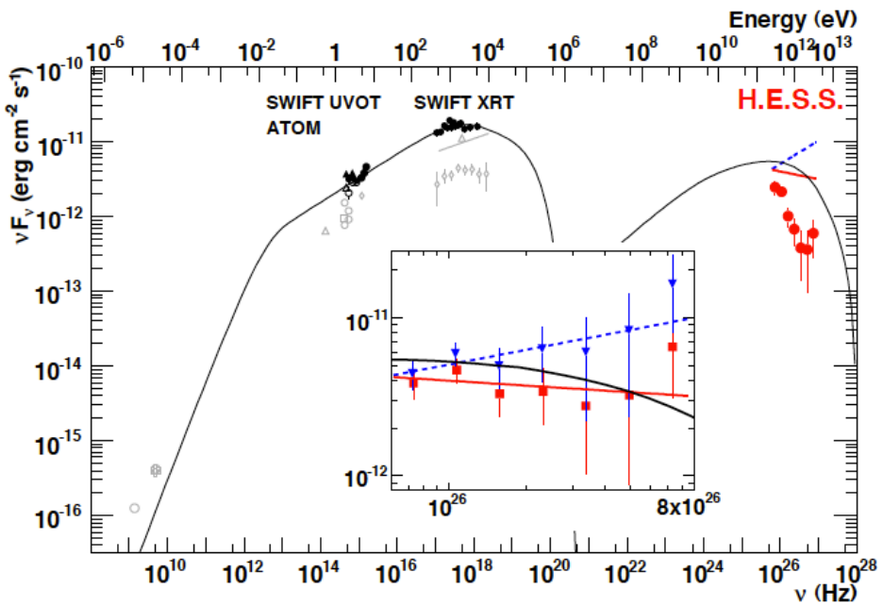
1ES 0229+200 (z = 0.14)
$\Gamma = 2.50 \pm 0.19_{stat} \pm 0.10_{sys}$
(500 GeV - 15 TeV)

z ~ 0.2

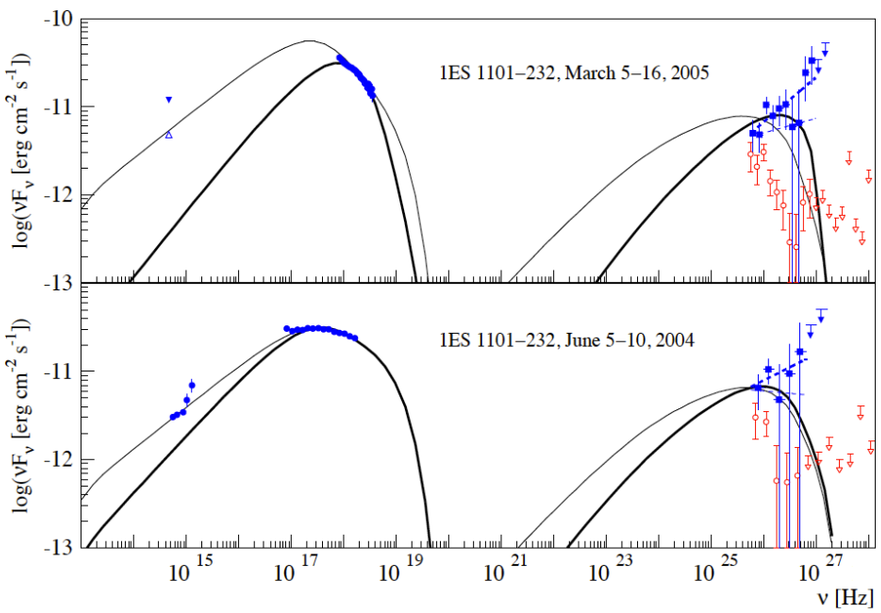
- Very hard TeV spectra beyond ~10 TeV
- No significant variability
- Faint in the Fermi range

1ES 0347-121 (z = 0.188)
$\Gamma = 3.10 \pm 0.23_{stat} \pm 0.10_{sys}$
(250 GeV - 3 TeV)

1ES 1101-232 (z = 0.186)
$\Gamma = 2.94 \pm 0.20$
(> 225 GeV)



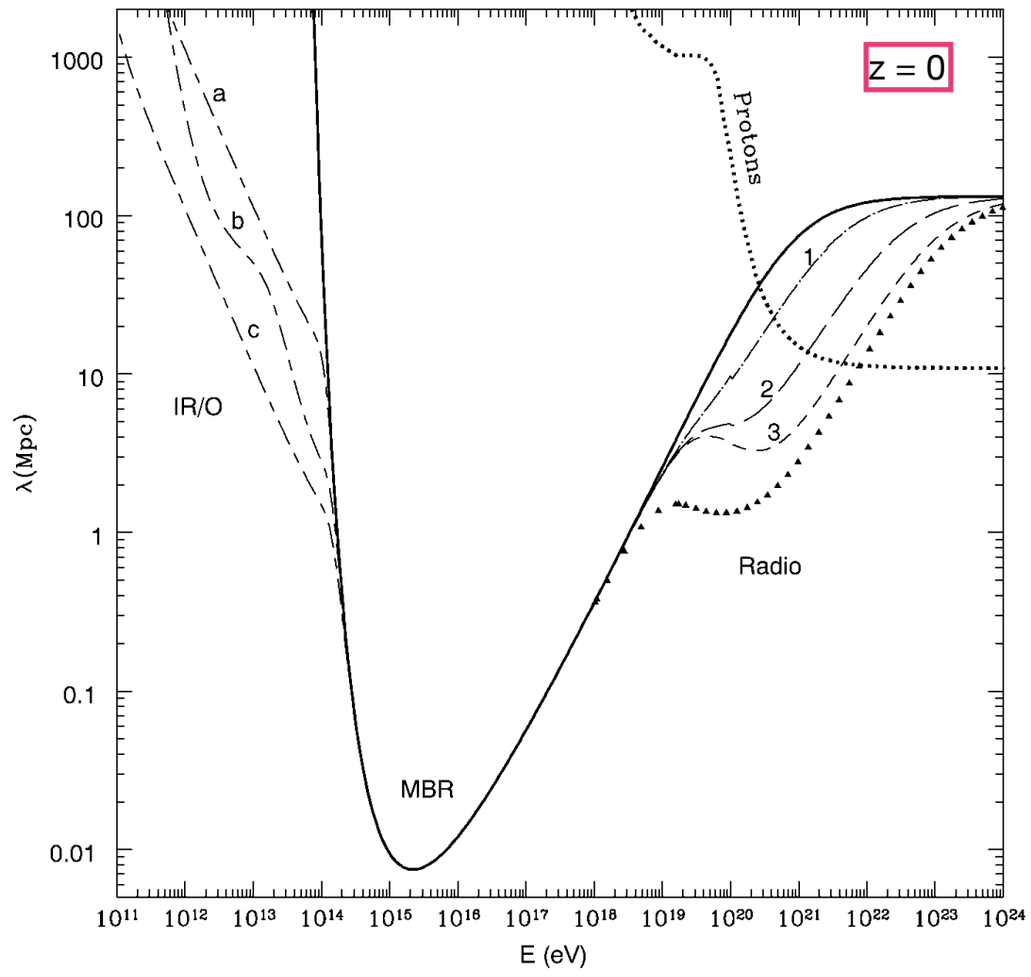
Aharonian et al. 2007



Aharonian et al. 2007

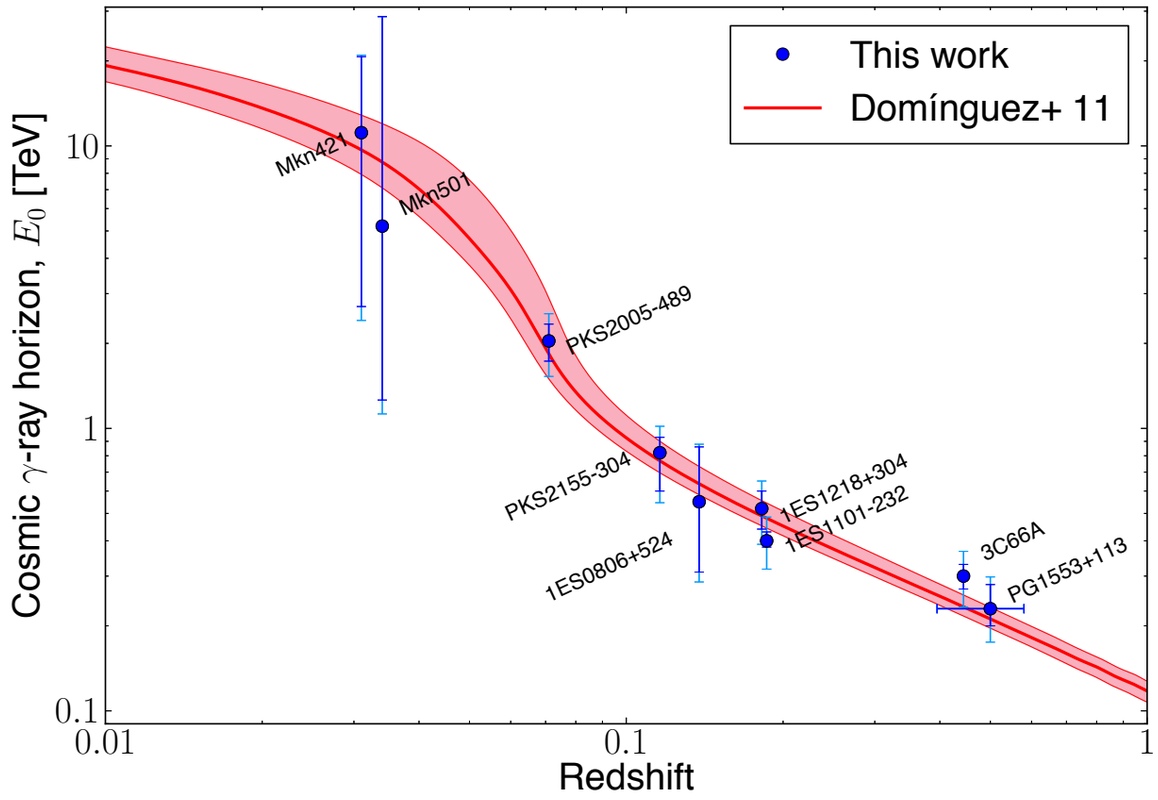
Mean free path and optical depth of gamma rays

Mean free path



Coppi & Aharonian 1997

Attenuation energy [τ(E,z)=1]



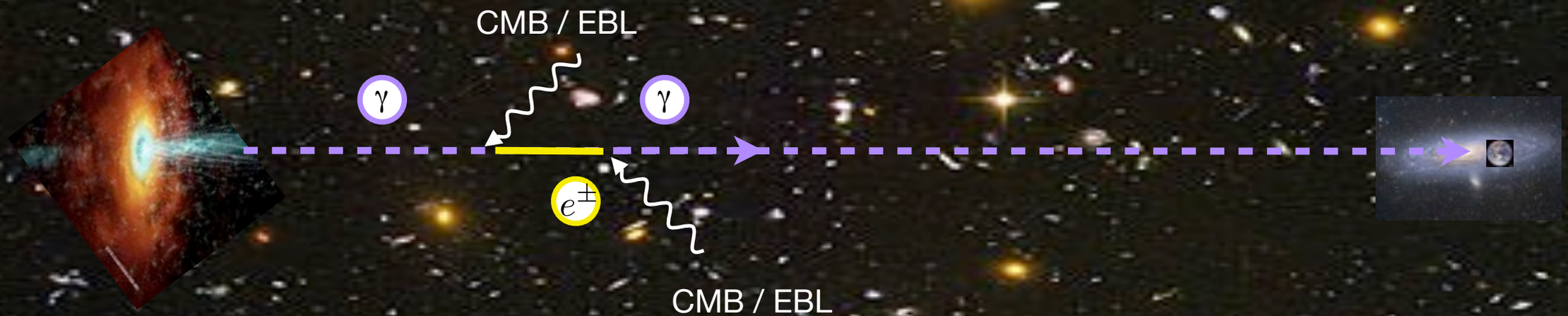
Dominguez et al. 2013

Very-high-energy photons (>100 GeV) are absorbed via pair creation, depending on source redshift, by extragalactic background light.

Gamma-ray-induced Cascade

Pair creation

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

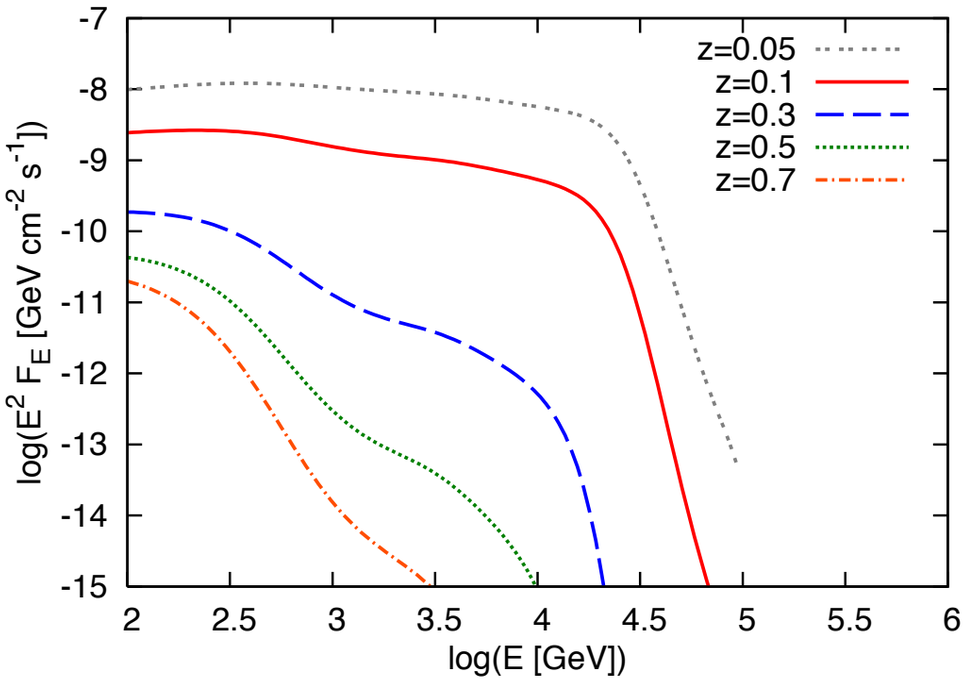


Created pairs are affected by intergalactic magnetic magnetic fields if they are strong enough.

- Pair-halo : image spread (e.g., Aharonian Coppi, Völk 1994, Elyiv et al. 2009)
- Pair-echo : delayed secondary gamma rays (e.g., Plaga 1995, Murase et al. 2008, Ichiki et al. 2008)

- IGMF study : gamma rays from deflected pairs do not reach the earth if IGMF is sufficiently strong (e.g., Neronov et al. 2009, Dermer et al. 2011, Dolag et al. 2011), but possible plasma instability causes the deflection (under debate; e.g., Schlickeiser et al. 2013 for a recent discussion)

Gamma-ray-induced Cascade



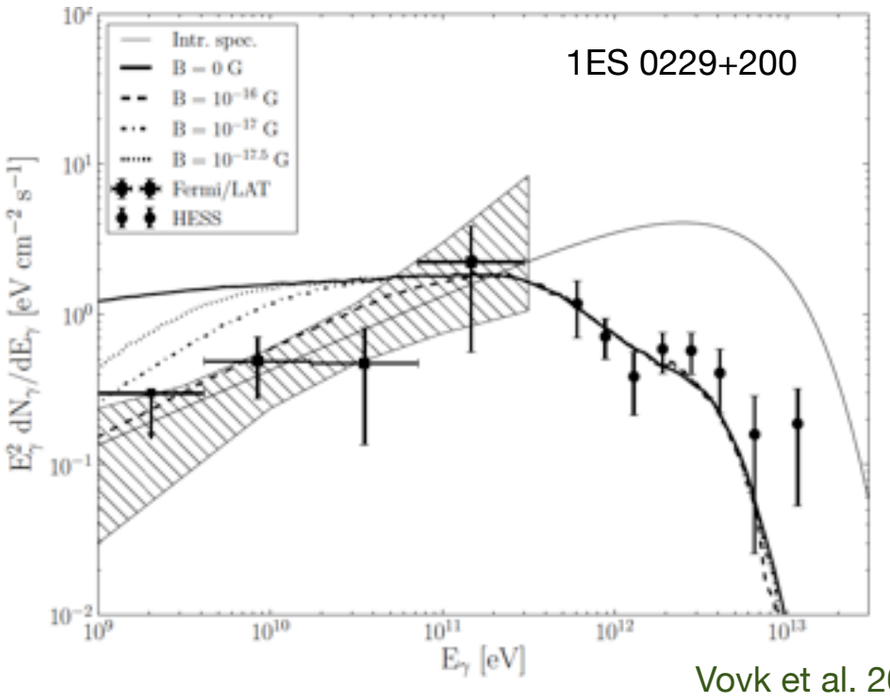
Murase, Dermer, HT, Migliori 2012

• The cascaded spectra are strongly attenuated above energies defined from $\tau_{\gamma\gamma}(E,z) = 1$.

• A spectral shape at around the characteristic EBL absorption energy is essentially determined by the spectral shape of EBL.

• The hard spectra of extreme HBLs can be well reproduced even after strong EBL absorption.

• A lot of >10 TeV photons are required to compensate the absorption.



Vovk et al. 2012

Cosmic-ray-induced Cascade

Photomeson production

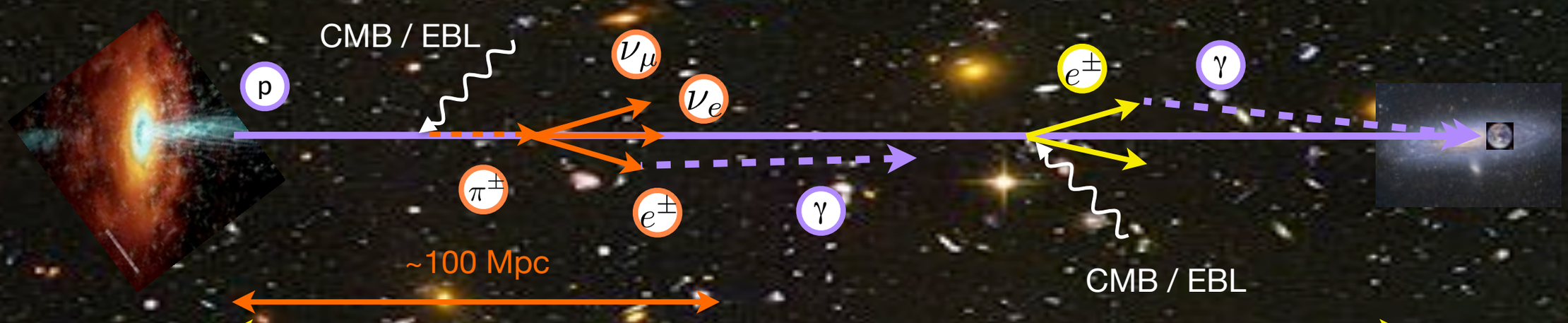
$$p\gamma \to p\pi^0 \to p + 2\gamma$$
$$p\gamma \to n\pi^+ \to ne^+\nu_\mu\nu_e\bar{\nu}_\mu$$

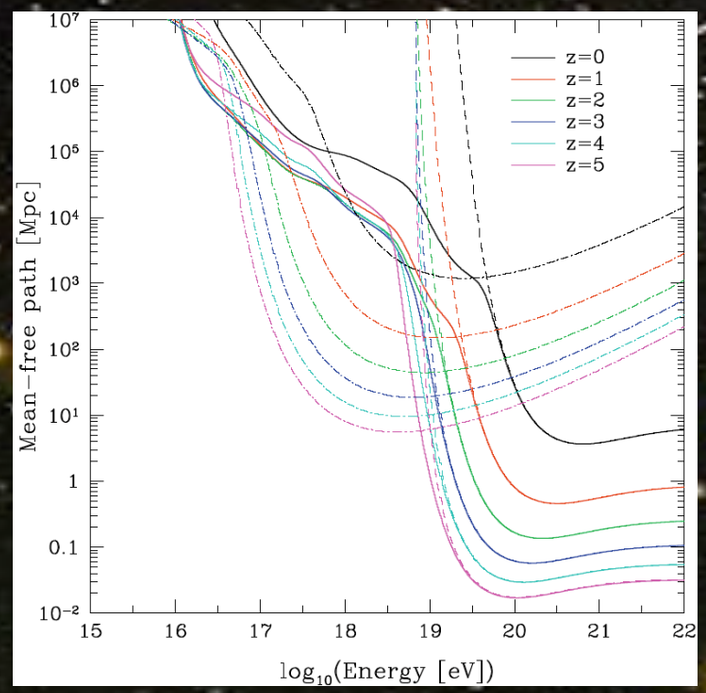
E > 6 x 10^{19} eV for CMB

Bethe-Heitler Pair Creation

$$p\gamma \to pe^+e^-$$

E > 6 x 10^{16} eV for CMB

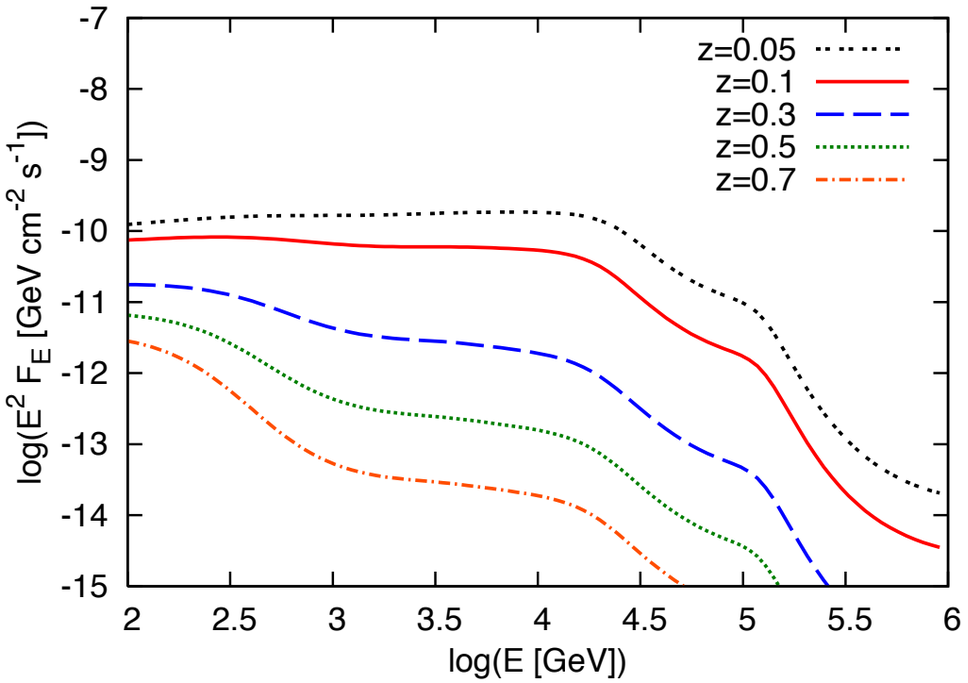




Higher energy photons than EBL attenuation remain because of $e^\pm$ supply even near observers.

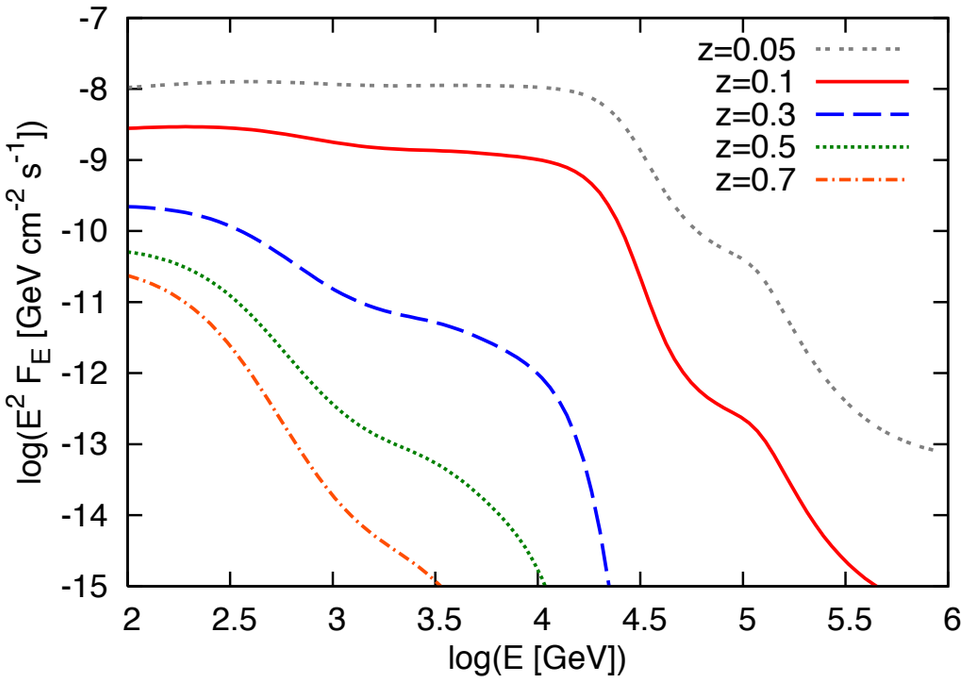
Gamma rays induced by cosmic rays

Cosmic-ray-induced cascade



- $dN/dE \propto E^{-2}$; $10^{18} < E < 10^{19}$ eV
- No IGMF is assumed.

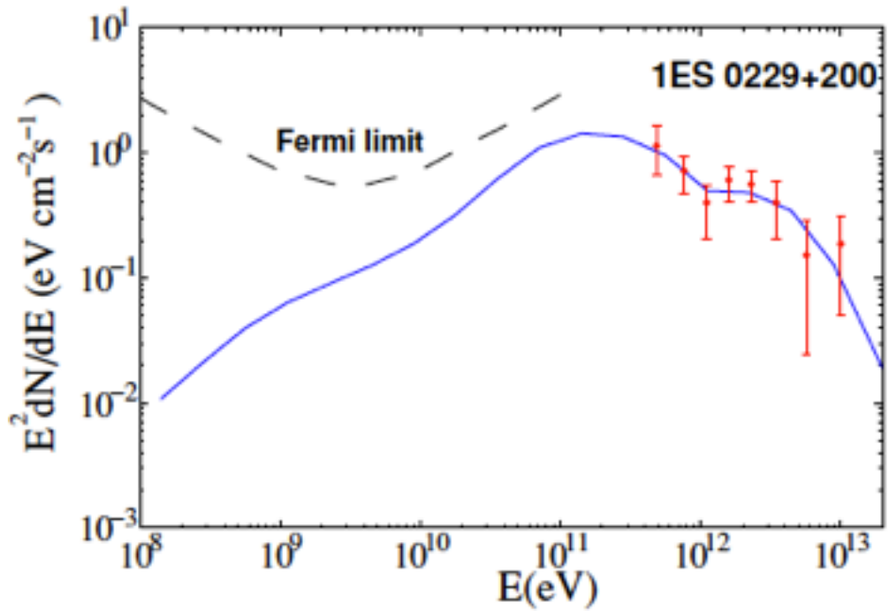
Gamma-ray-induced cascade



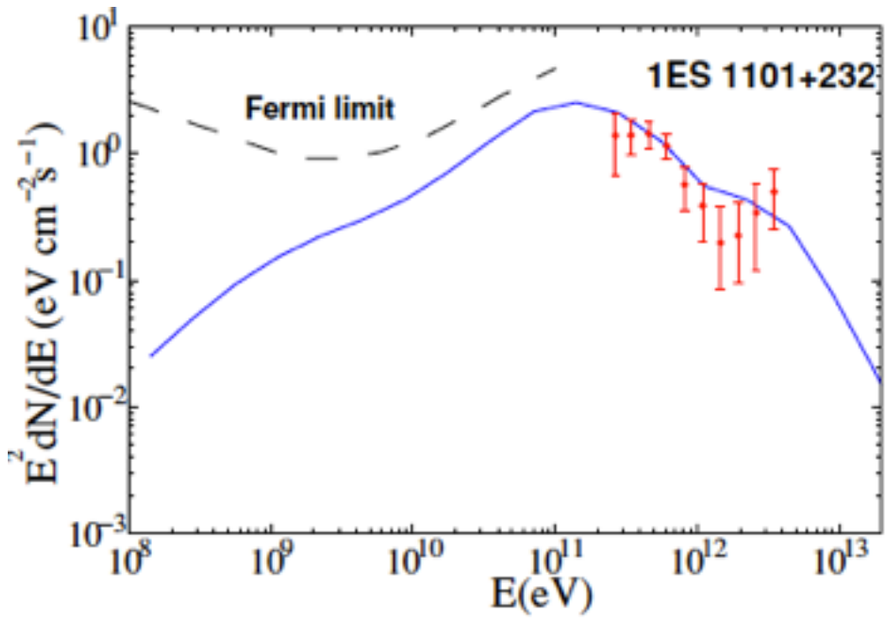
- Gamma-rays with 10^{19} eV induces the cascades.
- No IGMF is assumed.

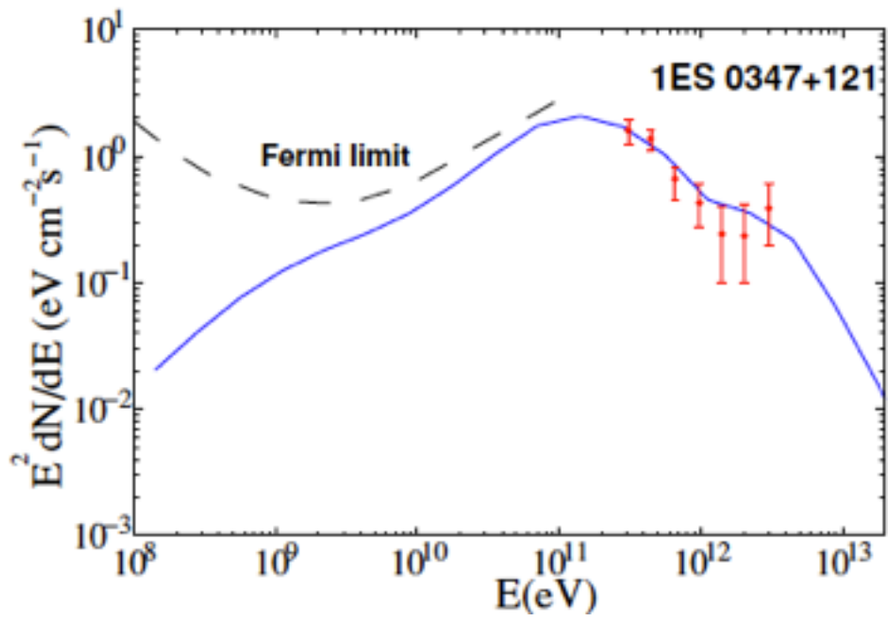
Hard spectra are predicted above energies defined from $\tau_{\gamma\gamma}(E,z) = 1$ from cosmic-ray-induced cascade due to the long energy-loss length of Bethe-Heitler pair creation.

γ-rays from Line-of-sight Cascade



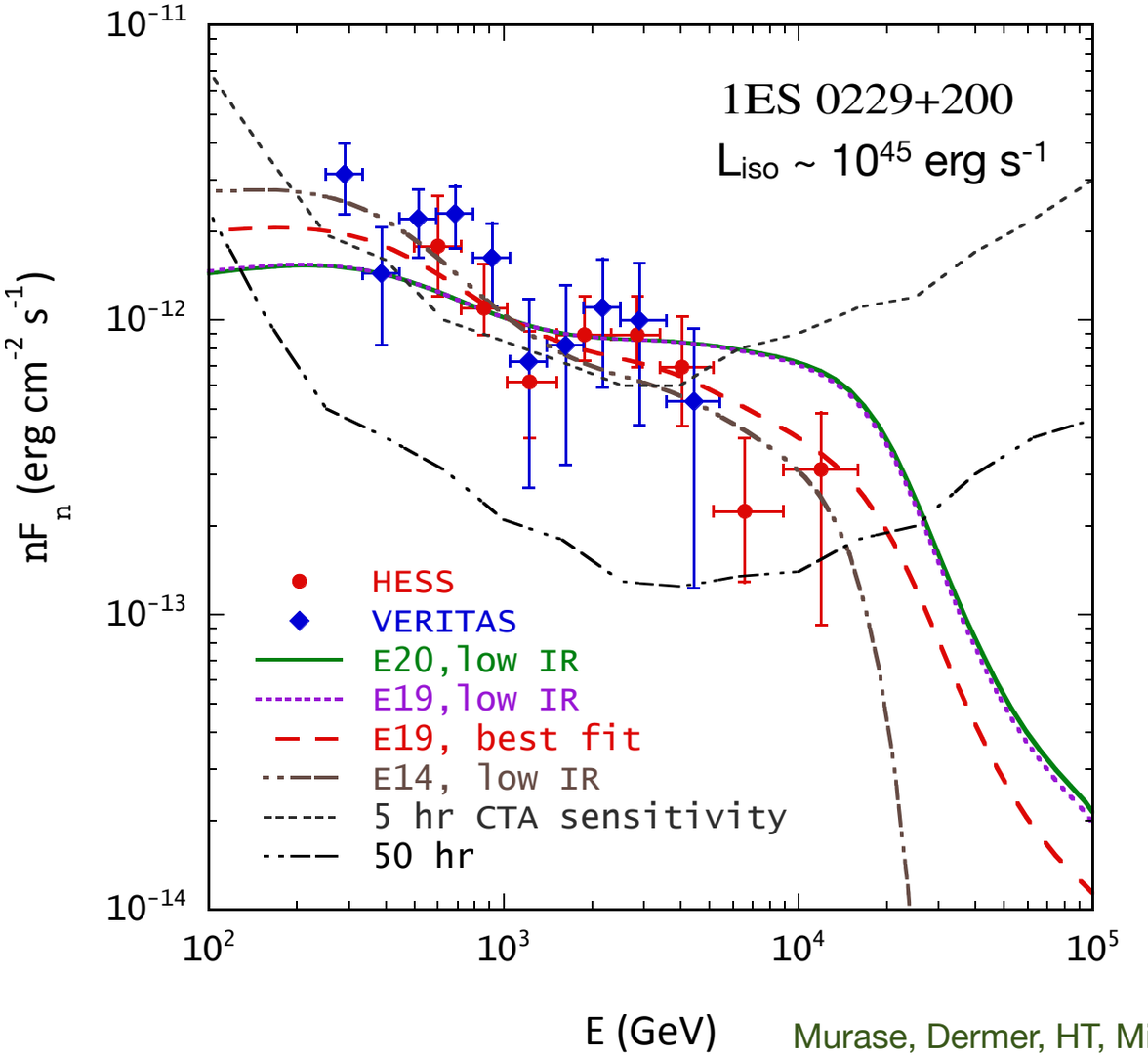
- The observed spectra are well reproduced.
- Intergalactic magnetic field reduces γ-ray flux at the Fermi energy range.





Essey et al. 2011

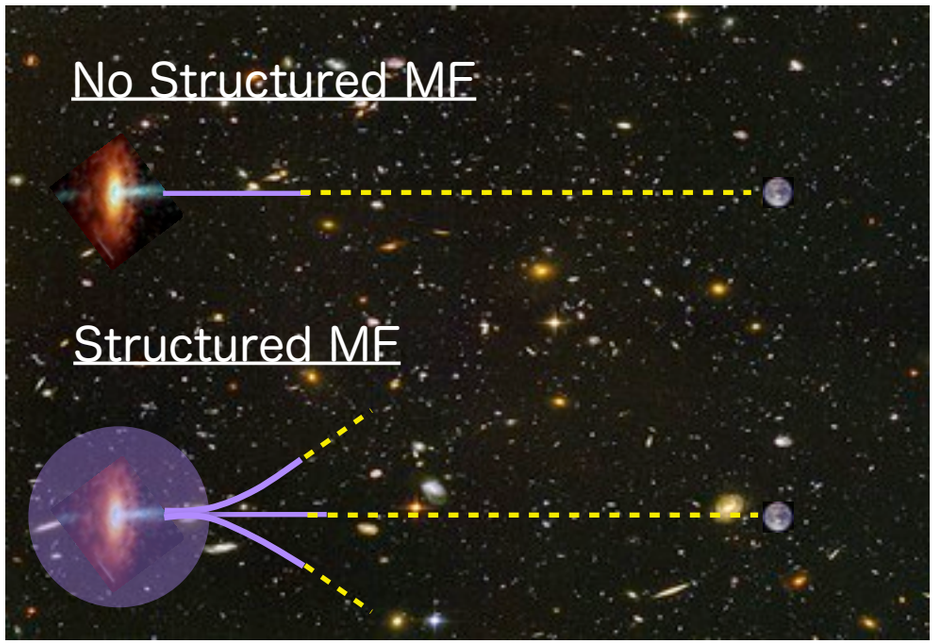
SED Modeling of a Extreme HBL



Murase, Dermer, HT, Migliori 2012

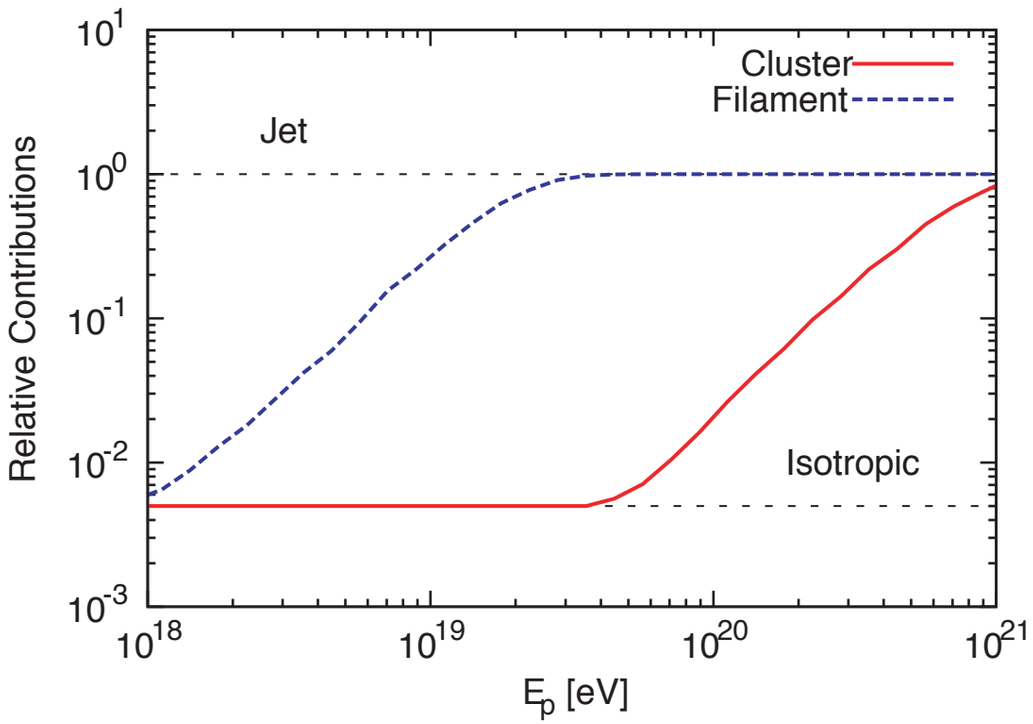
- Spectral shape is essentially determined by the spectral shape of EBL.
- 100 TeV γ-ray emitter can also reproduce the observed spectrum.
- Difference between hadronic cascade scenarios and leptonic cascade scenarios appears above 20 TeV
- CTA and HAWK have a potential to distinguish these scenarios.

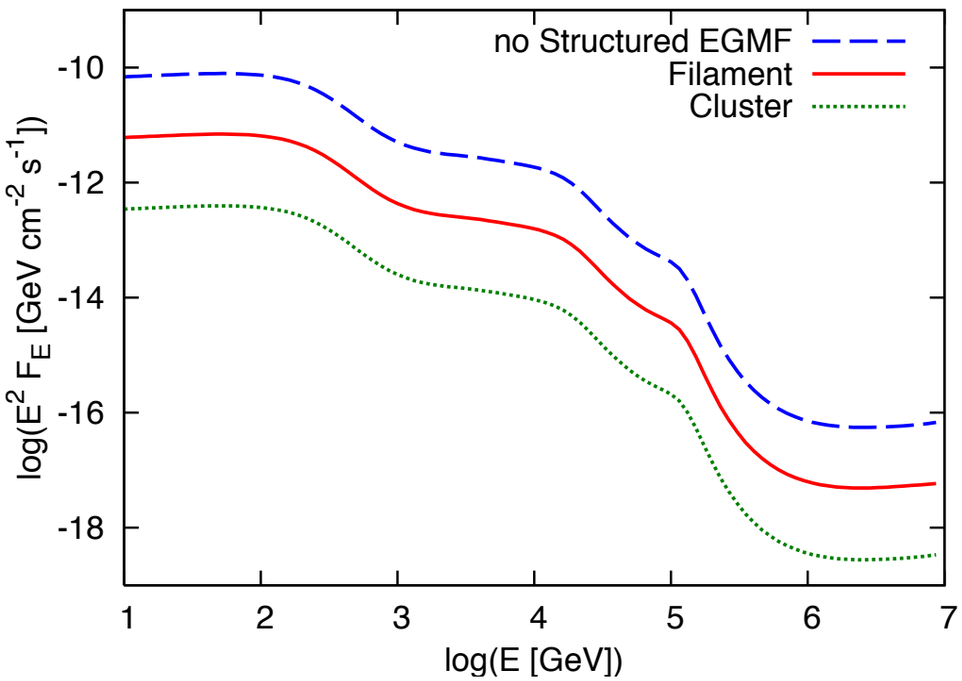
Role of Embedding Magnetic Fields



• EGMF around a blazar deflects the trajectories of UHECRs emitted from the source.

• Stronger EGMF requests higher UHECR luminosity in order to compensate UHECRs propagating in different directions from observers.

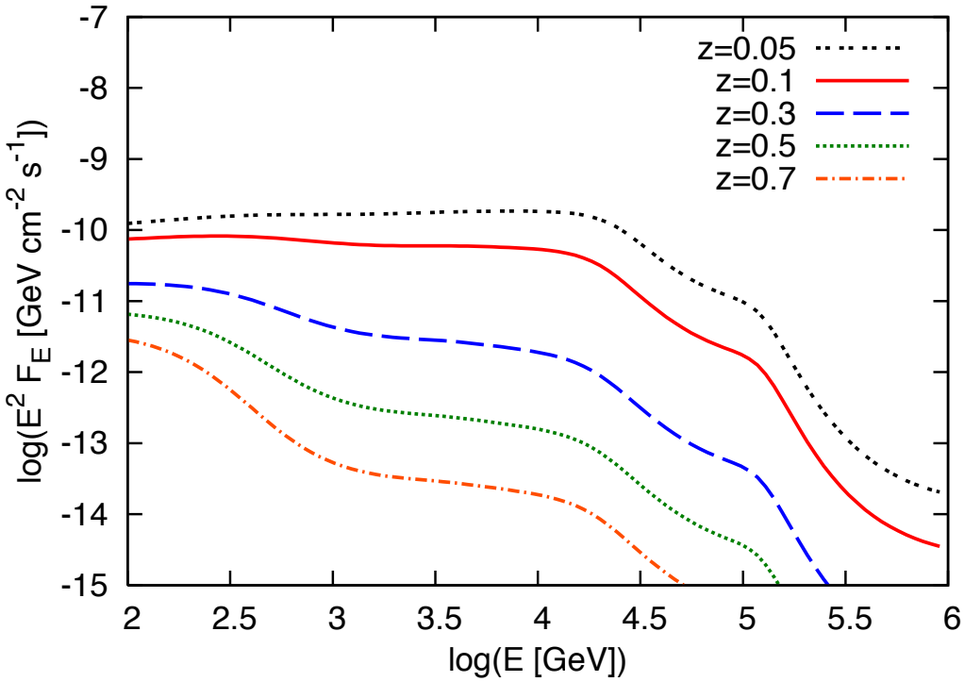




Murase, Dermer, HT, Migliori 2012

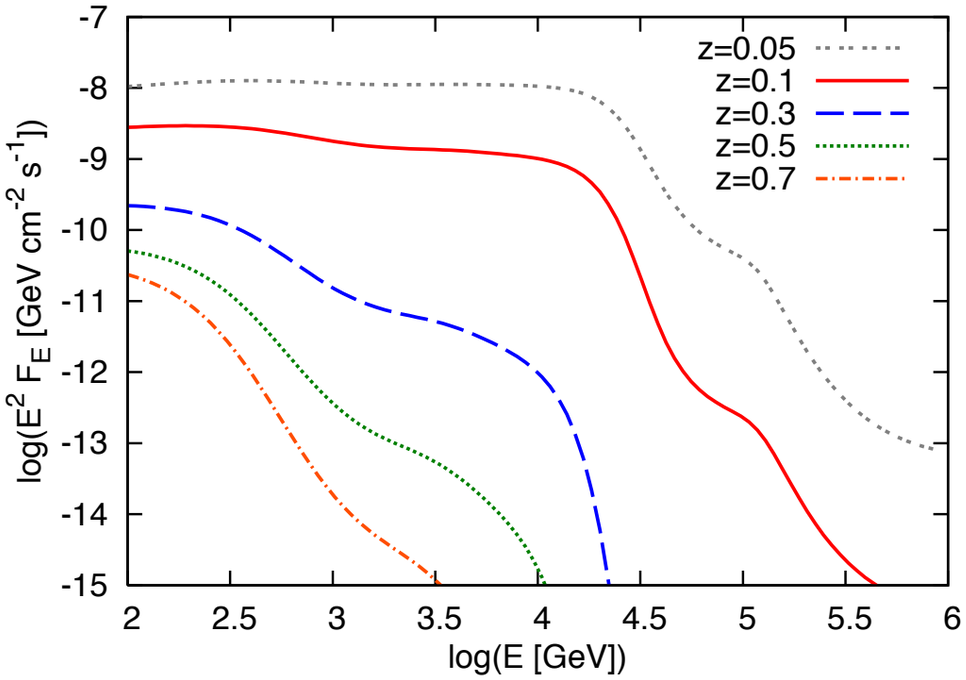
Gamma rays induced by cosmic rays

Cosmic-ray-induced cascade



- $dN/dE \propto E^{-2}$; $10^{18} < E < 10^{19}$ eV
- No IGMF is assumed.

Gamma-ray-induced cascade



- Gamma-rays with 10^{19} eV induces the cascades.
- No IGMF is assumed.

Distant hard gamma-ray spectrum blazars may result from cosmic-ray-induced cascades, which become evidence for ultra-high-energy cosmic-ray sources.

List of distant VHE gamma-ray emitters

Fermi sources associated with VHE photons, but not identified by IACTs (z>0.5)

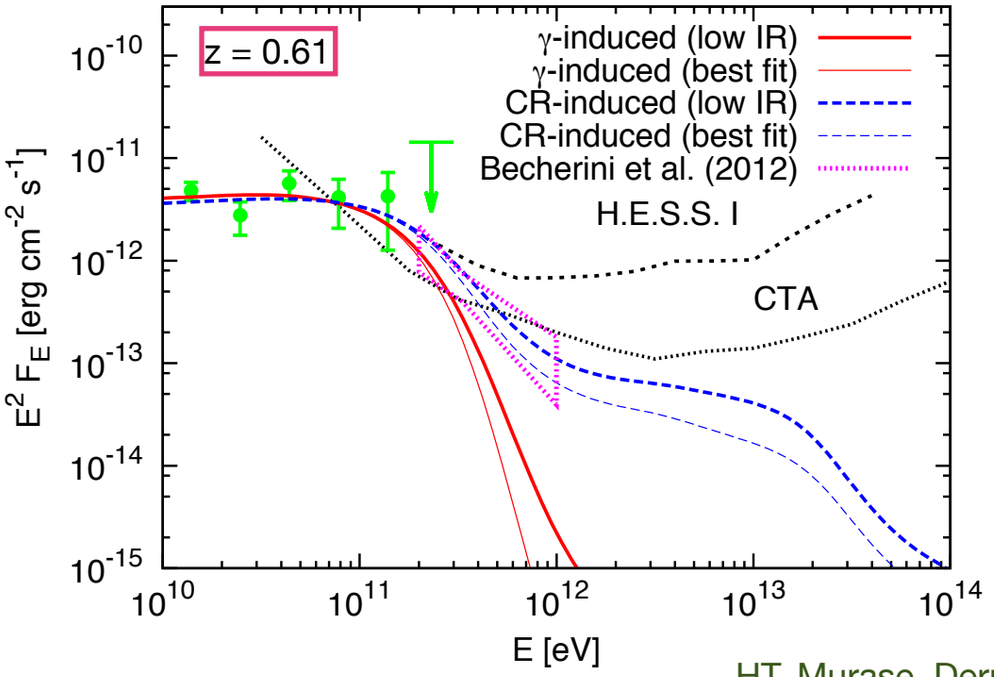
	Name	RA	DEC	Type	z	N_{30-100}	$N_{0.1}$	$N_{0.2}$	E_{max}	$L/L_{\rm Mrk421}$	P	Index
1	TXS 0138-097	25.3576	-9.4788	BL	0.733	2	1f	0	138	44.5	1.1e-3	2.033
2	PKS 0426-380	67.1685	-37.9388	BL	1.11	13	1f	0	134	151	0.9e-3	1.946
3	B2 0912+29	138.9683	29.5567	BL	1.521	5	1f	0	126	405	0.7e-3	1.875
4	Ton 116	190.8031	36.4622	BL	1.065	11	1b	0	114	133	0.7e-3	1.698
5	PG 1246+586	192.0783	58.3413	BL	0.847	9	1b	0	104	67.5	1.2e-3	1.949
6	B3 1307+433	197.3563	43.0849	BL	0.69	4	1f	0	104	37.5	0.8e-3	1.839
7	4C +55.17	149.4091	55.3827	FSRQ	0.8955	14	1b	0	141	84.0	1.6e-3	Log PB
8	TXS 1720+102	260.6857	10.2266	FSRQ	0.732	0	1f	0	168	46.8	1.9e-3	2.23
9	PKS 1958-179	300.2379	-17.8160	FSRQ	0.65	2	1b	0	118	33.5	2.3e-3	2.38
10	PKS 2142-75	326.8030	-75.6037	FSRQ	1.139	1	1f	0	135	173	1.5e-3	2.517
11	KUV 00311-1938	8.3933	-19.3594	BL	0.61	11	0	2b	152	53.2	8e-6	1.758
12	RGB J0250+172	42.6567	17.2067	BL	1.1	3	0	1b	358	147	7.6e-3	1.836
13	PKS 1130+008	173.190067	0.5744	BL	1.223	1	0	1f	140	204	4.4e-3	2.178

Neronov et al. 2012

(The 1FHL catalog may include more sources with VHE photons.)

- They have rather hard spectra.
- The hard spectra motivates possible hadronic origin.

Example: KUV 00311-1938



HT, Murase, Dermer 2013

Models

EBL: Kneiske et al. (2004) for low and best-fit EBL

Leptonic model

- $dN/dE \propto E^{-s}$; $E > 10^{9.75}$ eV, $E_{max} = 10^{14}$ eV
- No suppression from IGMF (10^{-20} G < B < 10^{-15} G)

Hadronic model

- $dN/dE \propto E^{-2.6} \exp(-E/E_c)$; $E > 10^{18}$ eV, $E_c = 10^{19}$ eV
- No suppression from IGMF (B < 10^{-14} G for protons)

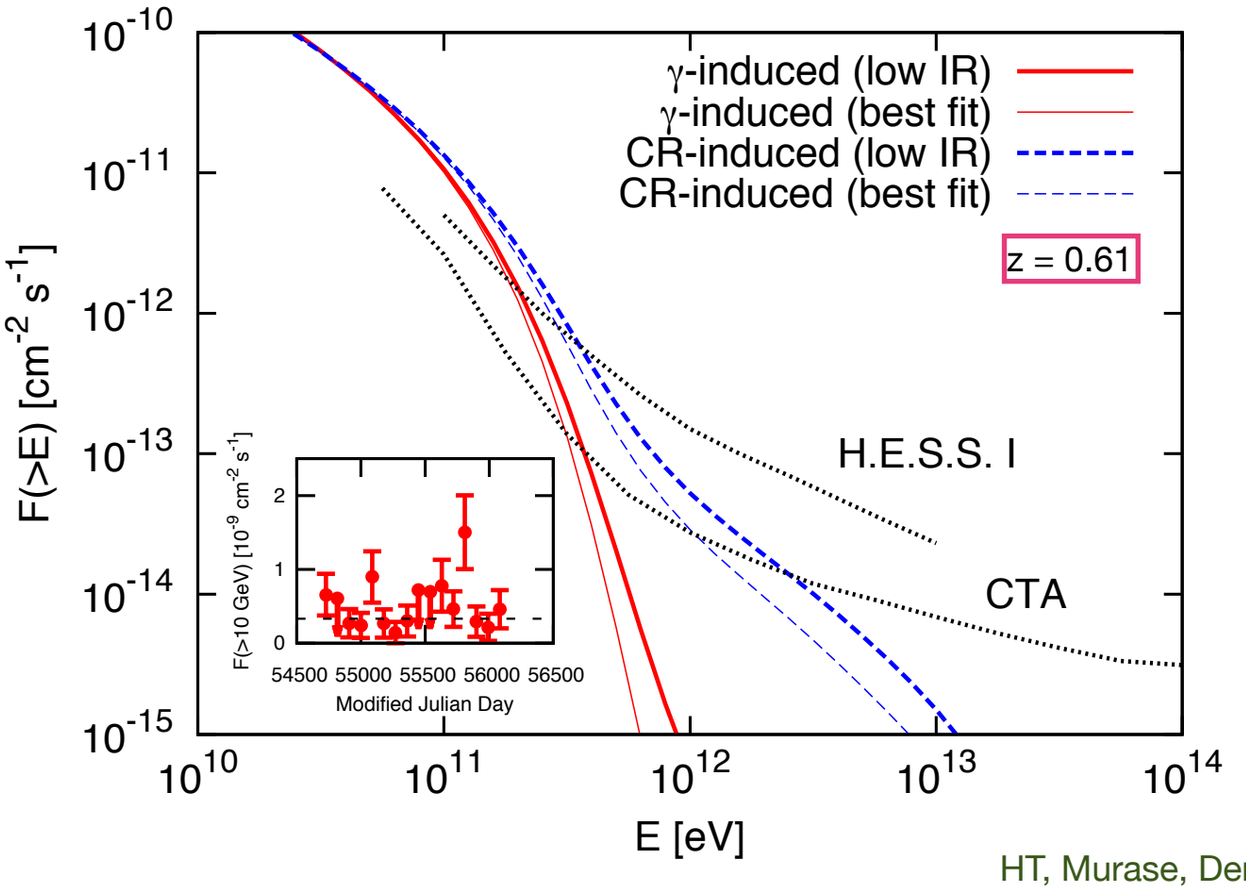
KUV 00311-1938

- Distant hard-source in the Fermi-LAT
- Recently detected by H.E.S.S. Becherini et al. 2012
- z=0.61 is quoted, but recent optical spectroscopy indicates only z>0.506. Pita et al. 2012

- Both models reproduce the Fermi spectrum.
  - The sources in the sample except PKS 0426-380 and 2142 are also reproduced.
- These models are distinguishable above ~500 GeV even considering the uncertainty of EBL models.
- The hadronic model is favored if z = 0.61 is correct.
  - Redshift measurement is important for confirmation.

Example: KUV 00311-1938 ~ integral flux ~

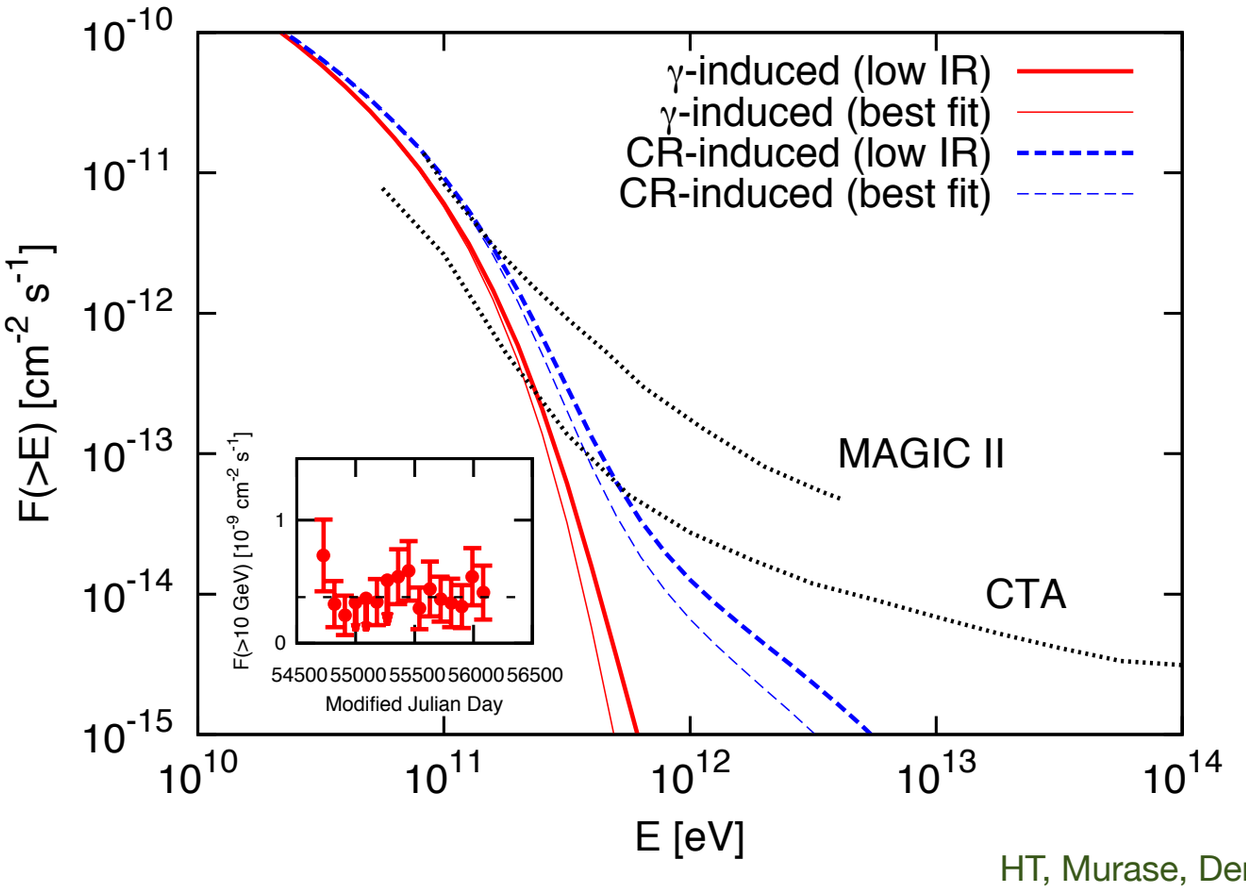
Integral flux is sensitive to the hard component in the hadronic model.



HT, Murase, Dermer 2013

- Integral flux above ~500 GeV can clearly distinguish these two scenarios.
- The light curve (with ~3 month bins) is consistent with constant flux (χ^2/d.o.f. = 0.94)

Example: PG 1246+586 (z=0.847)



HT, Murase, Dermer 2013

- Even for z~0.85 sources, hadronic origin can be investigated by CTA.
- The light curve (with ~3 month bins) is consistent with constant flux (χ^2/d.o.f. = 0.40)

Summary

• A hadronic model in which electrons and gamma rays induced by the propagation of ultra-high-energy cosmic rays produce gamma rays has been discussed. If confirmed, it may be strong evidence for the origin of ultra-high-energy cosmic rays.

• The cosmic-ray luminosity required to reproduce the observed flux of extreme HBLs is affected by cosmic magnetic fields around the sources.

• The spectra of distant hard gamma-ray blazars can be reproduced by the hadronic cascade model as well as the cases of extreme HBLs.

• The measurements of integrated flux above ~500 GeV, depending on source redshift, allow us to distinguish leptonic and hadronic models.

• In the case of the recently-detected KUV 00311-1938, the hadronic cascade model is favored if the often quoted redshift (z=0.61) is correct.