Multi-TeV flarings: an evidence of the photohadronic process

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Presentation program

Multi-TeV observations in the universe

Blazars as gamma-ray sources

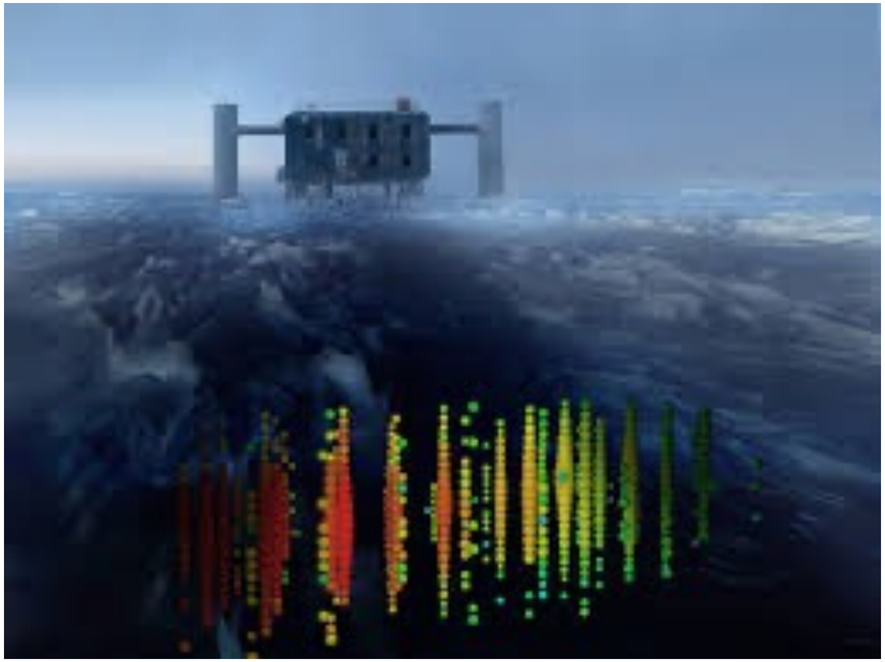
Photohadronic model

Description of HBL VHE spectra

Indirect determination of redshift

Future perspectives

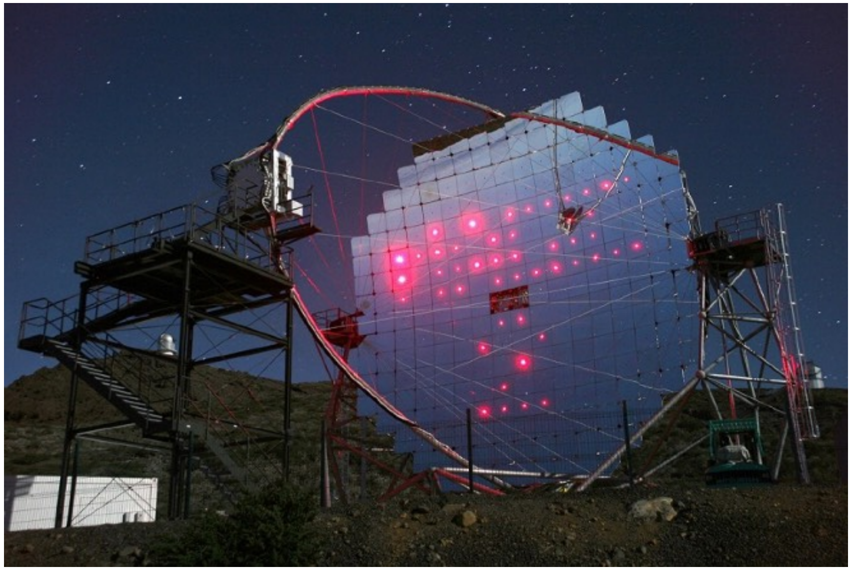
Cosmic Ray Observatories



IceCube Neutrino Observatory
Amundsen-Scott South Pole Station

Very Energetic Radiation Imaging Telescope (VERITAS)
Mouth Hopkins, Arizona, USA

Cosmic Ray Observatories



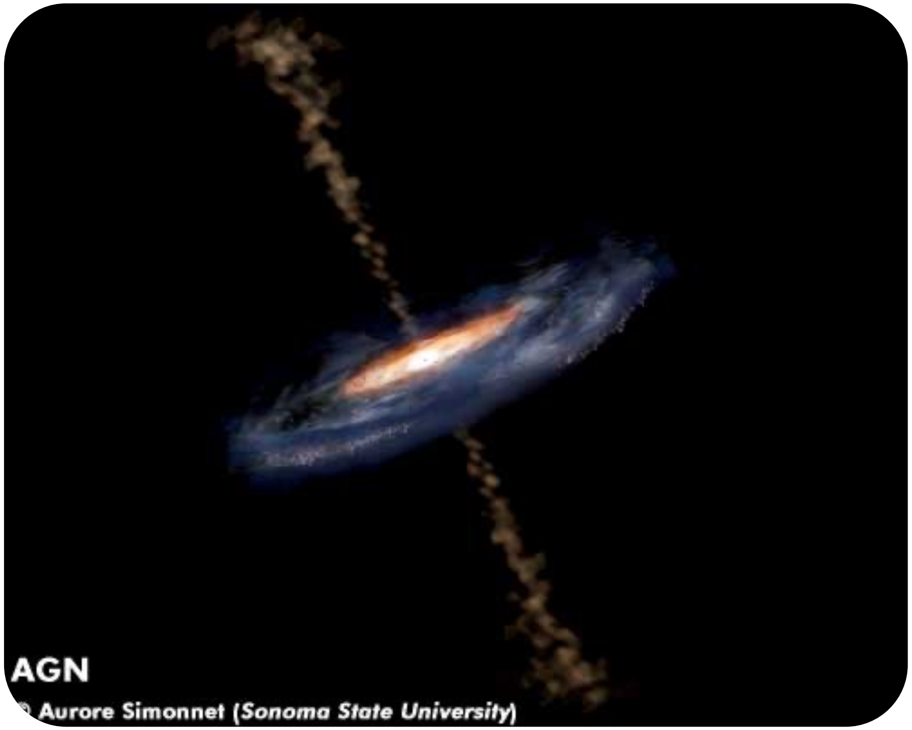
Major Atmospheric Gamma Imaging Cherenkov Telescopes (MAGIC)
La Palma, Spain

High Altitude Water Cherenkov Experiment (HAWC)
Sierra Negra, Puebla, Mexico

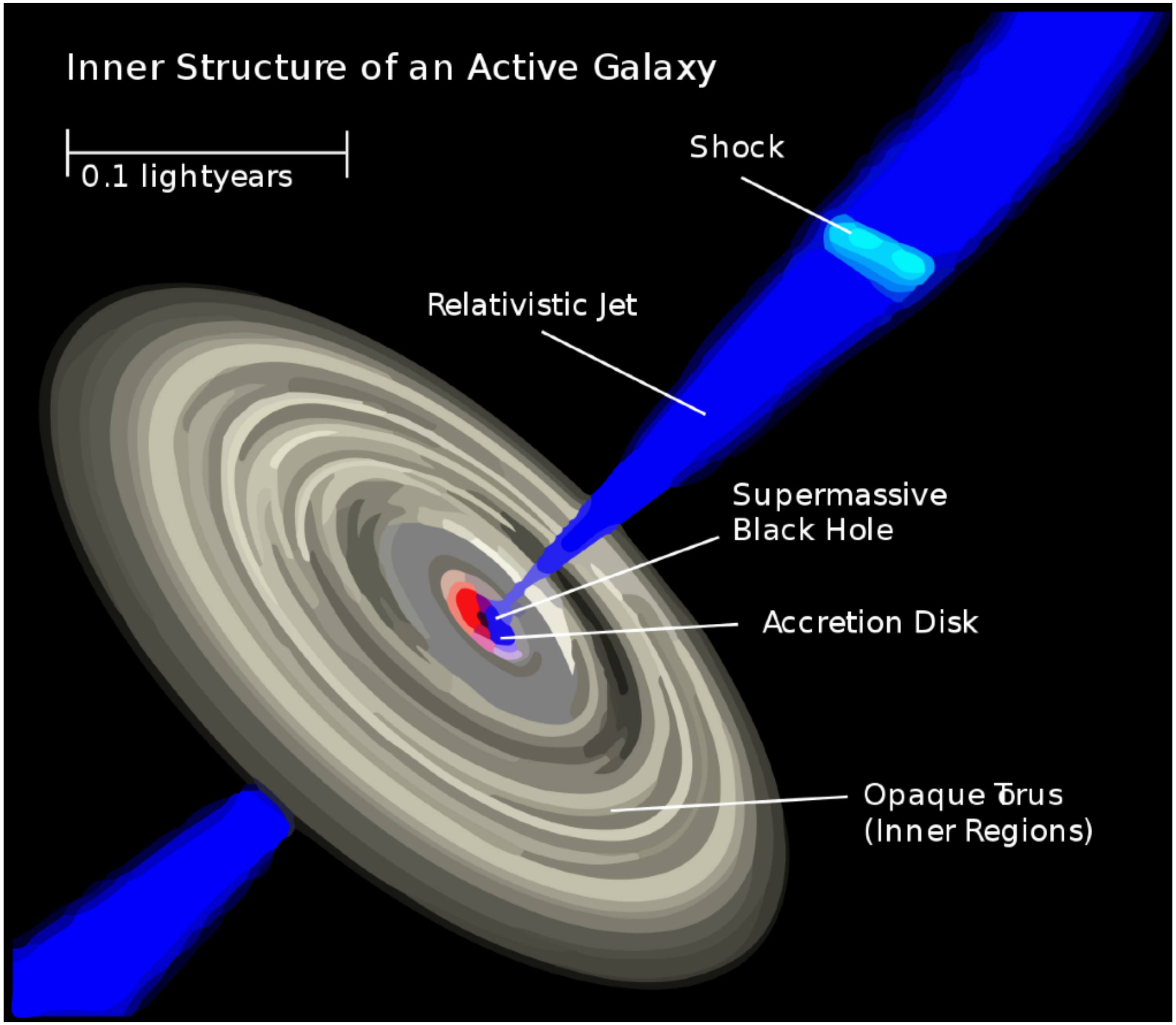
Active Galactic Nuclei

Compact regions at the center of a galaxy with very high luminosity

Non-stellar radiation due to matter accretion in central supermassive black hole



Active Galactic Nuclei

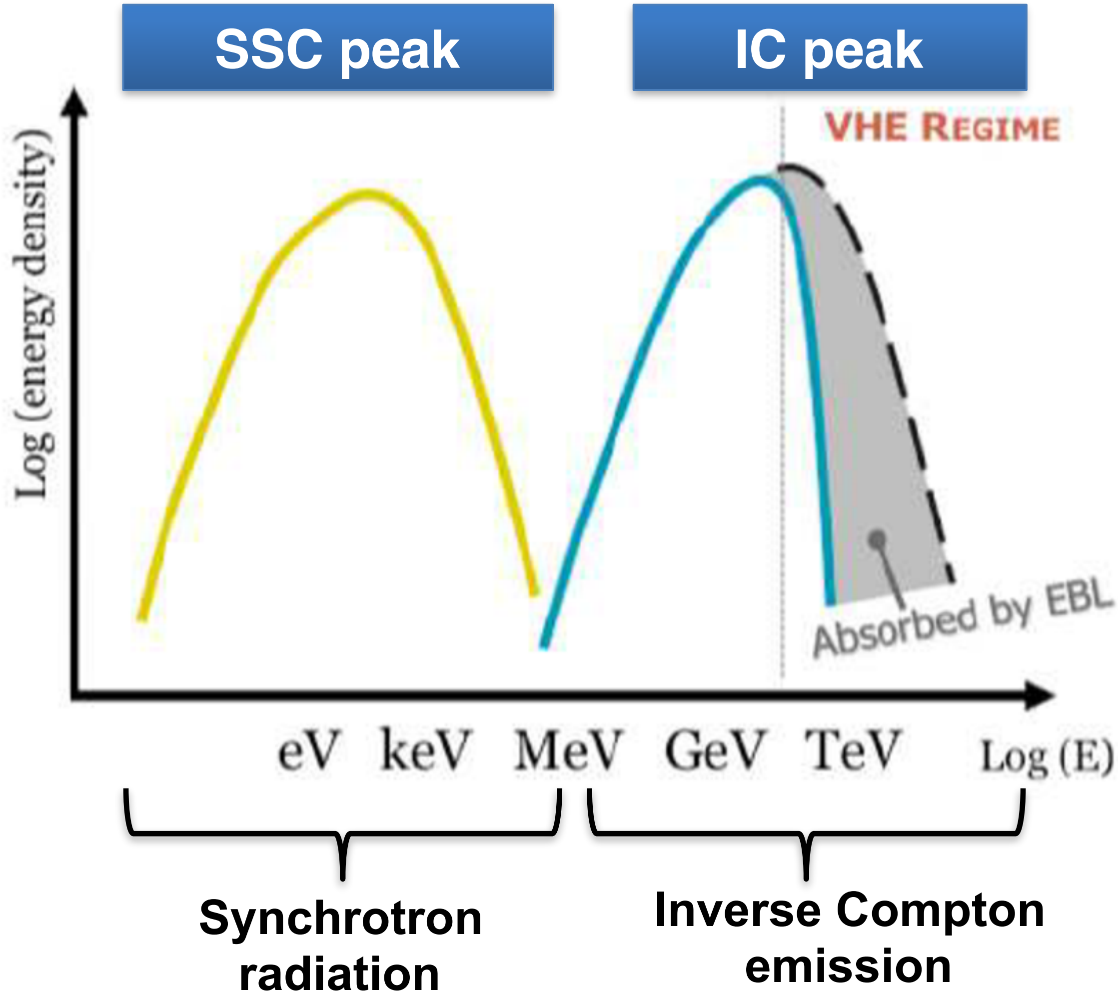


Types of AGNs

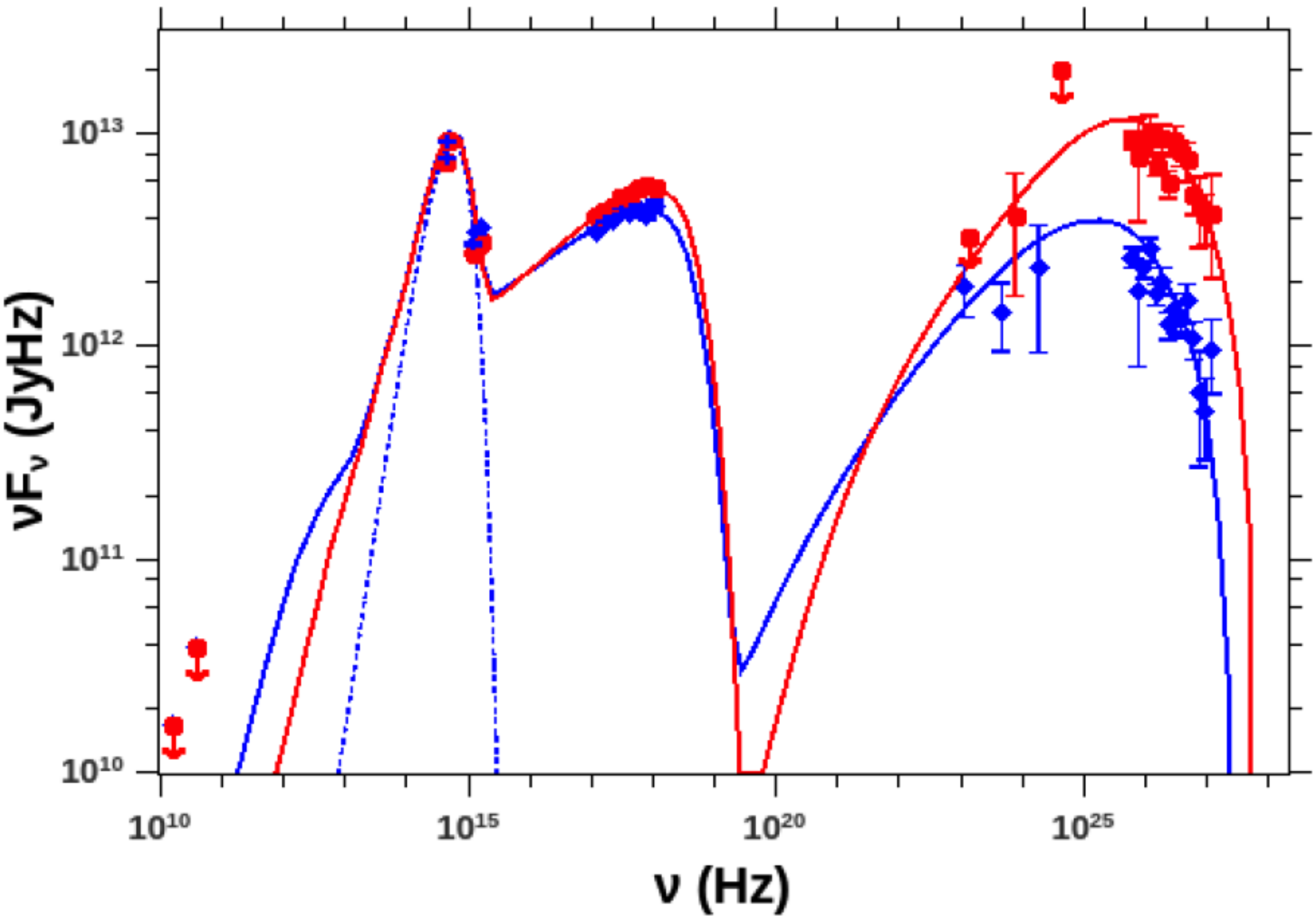
Active Galactic Nuclei
(A few % of all galaxies)

Most common gamma-ray sources

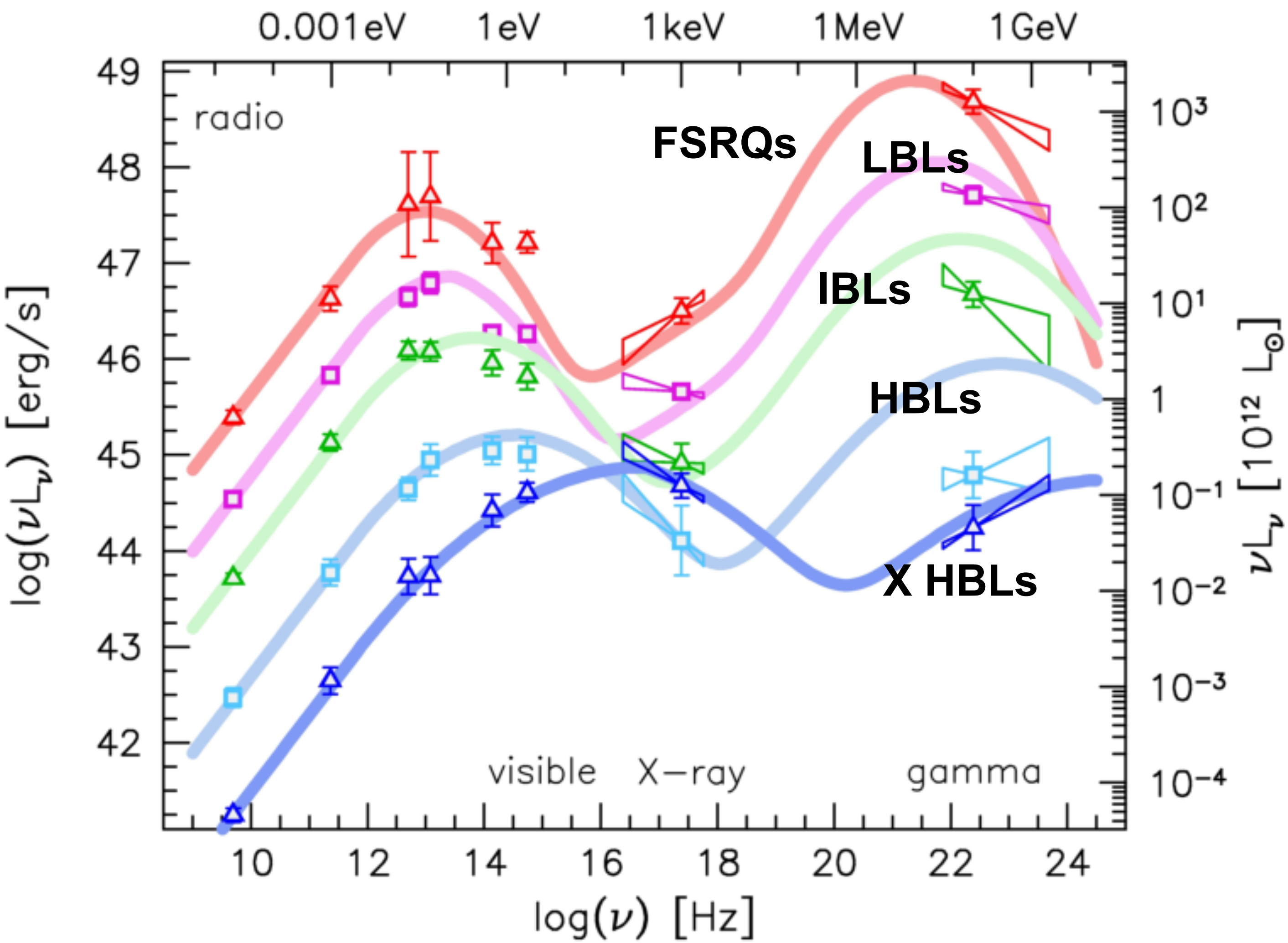
Spectral energy distribution (SED)



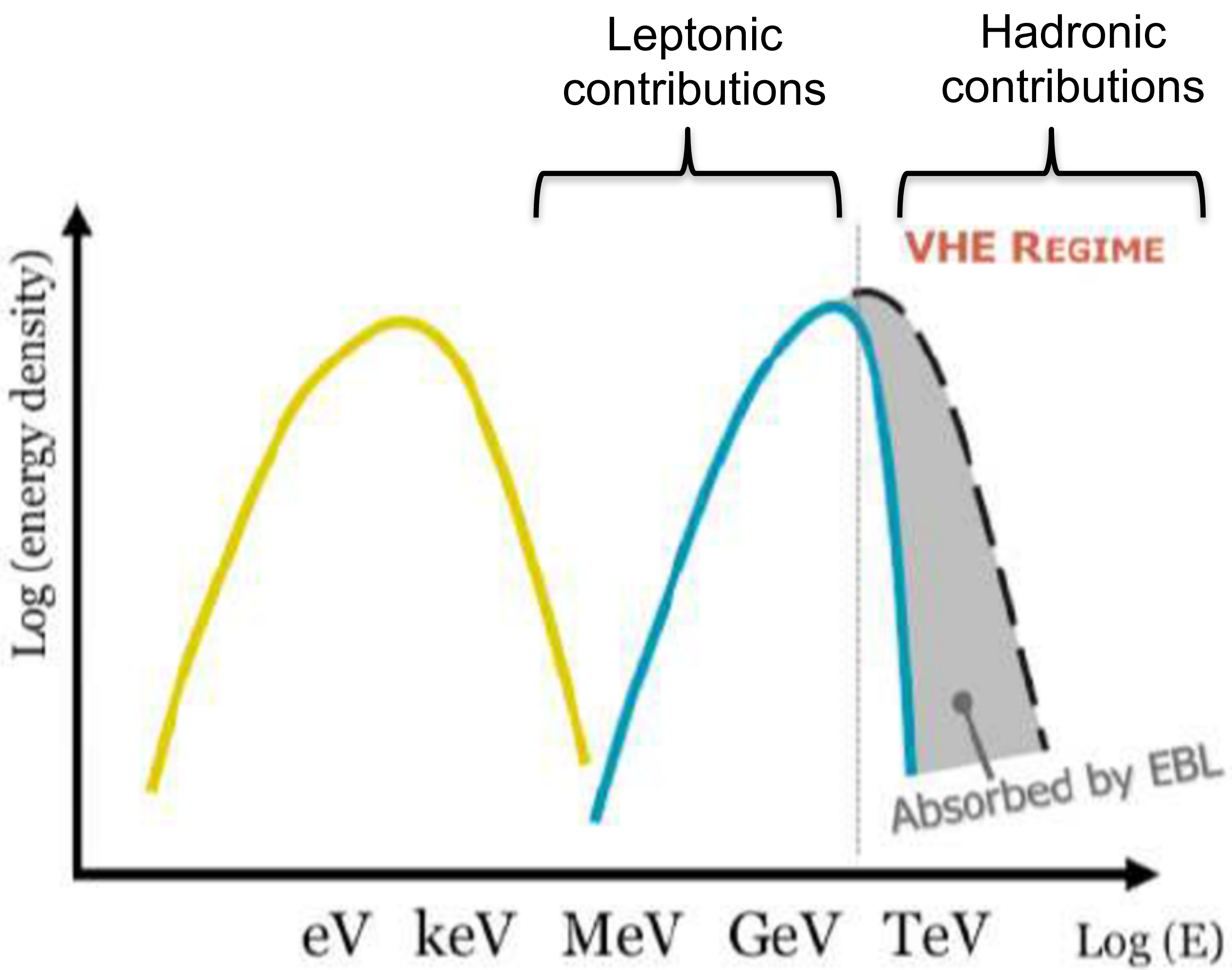
VHE Spectrum of Mrk 501 (VERITAS Colab, 2016)



Blazar clasification



Particle acceleration mechanisms?



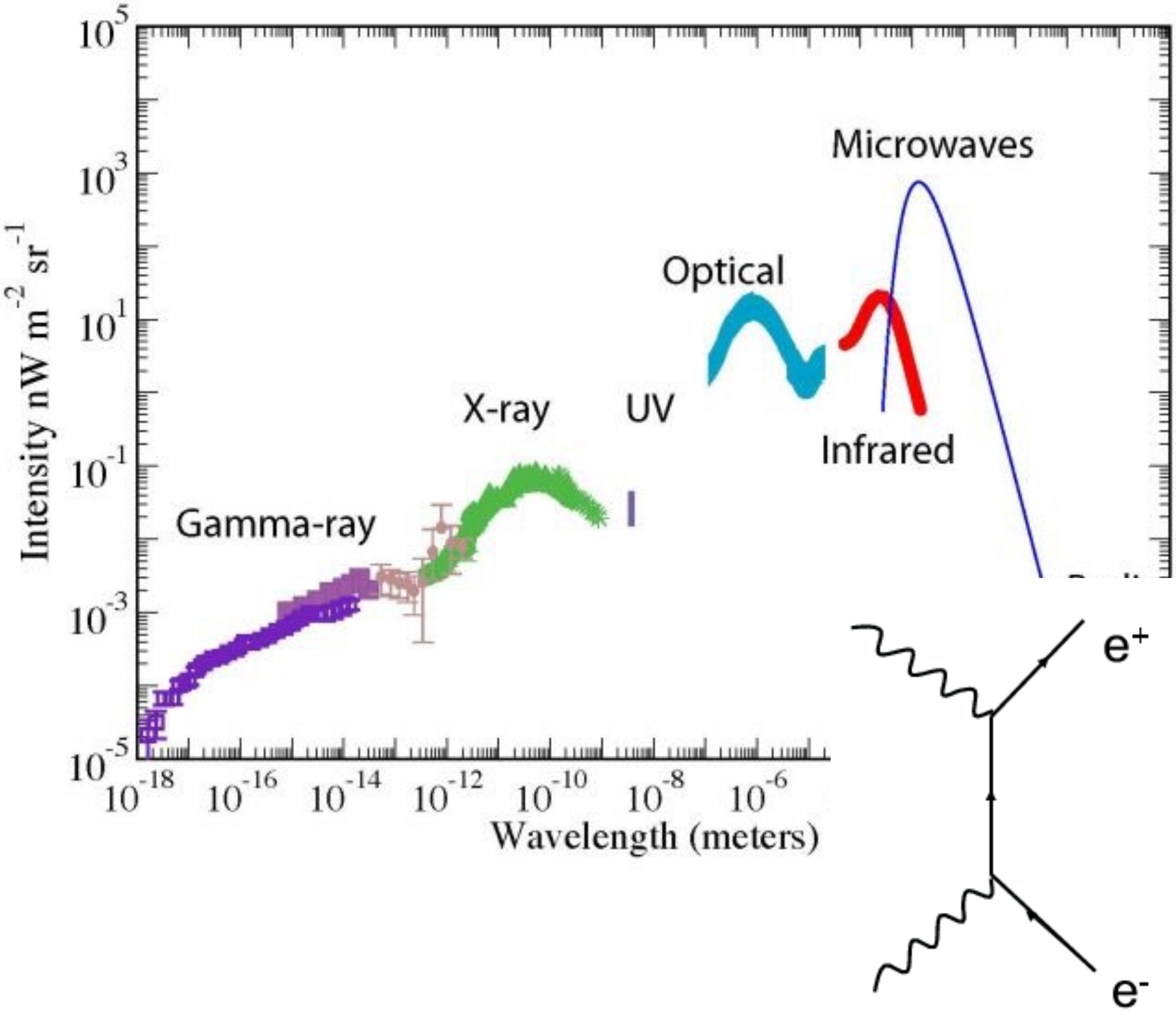
VHE emission mechanism?

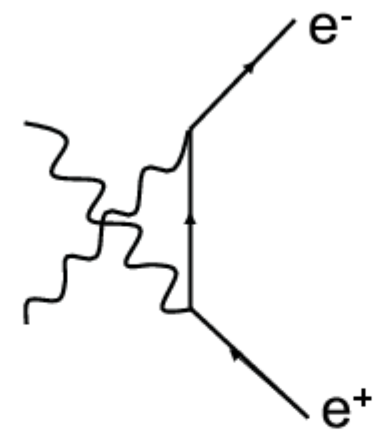
Leptonic
(Bottcher, Aleksic et al.)

Leptohadronic
(Reynoso, Cerruti et al.)

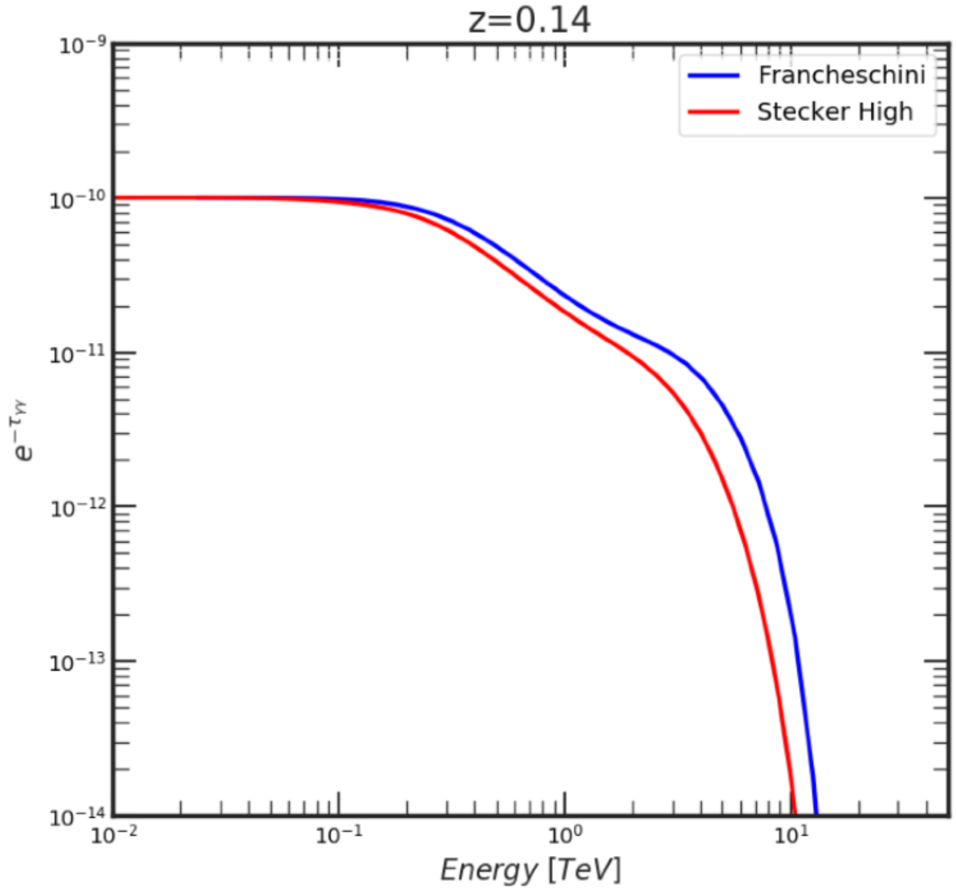
Hadronic
(Kusenko et al,
Giannios et al.)

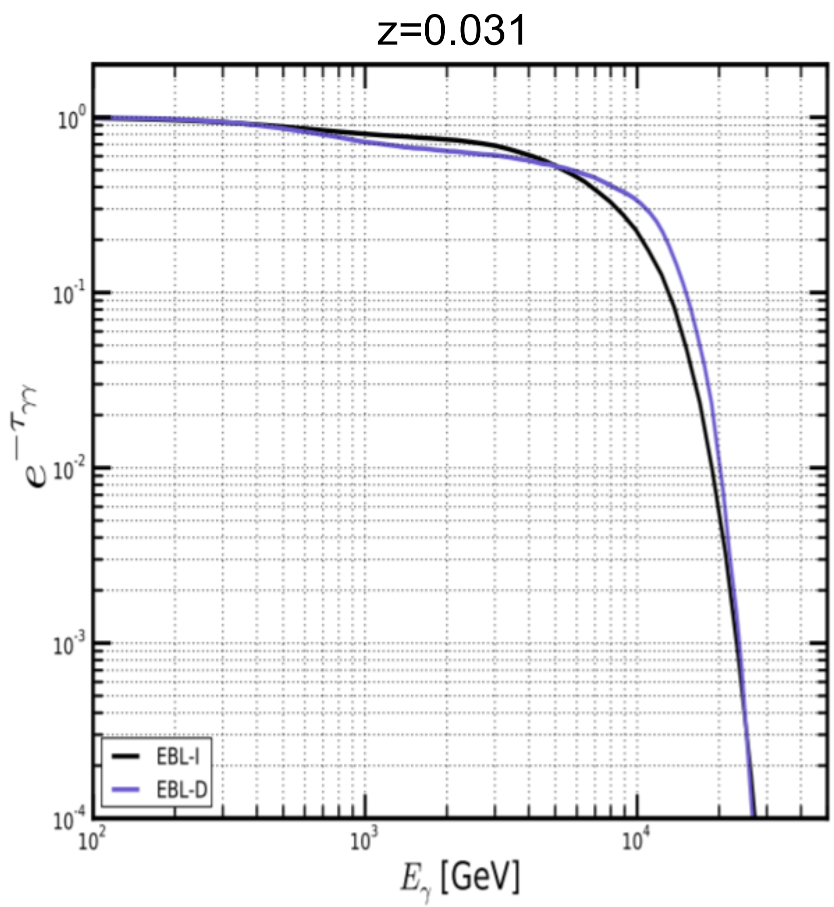
Extragalactic background light (EBL)





Extragalactic background light (EBL)





Leptonic standard interpretation

Emitting region is a blob with comoving radius R'_b moving with velocity β with a bulk Lorentz factor Γ and seen at an angle θ_{ob}.

Isotropic electron population and randomly oriented B'. The electrons and Fermi-accelerated protons follow a **power-law spectrum**.

Limited electron acceleration, UHE hadronic acceleration possible

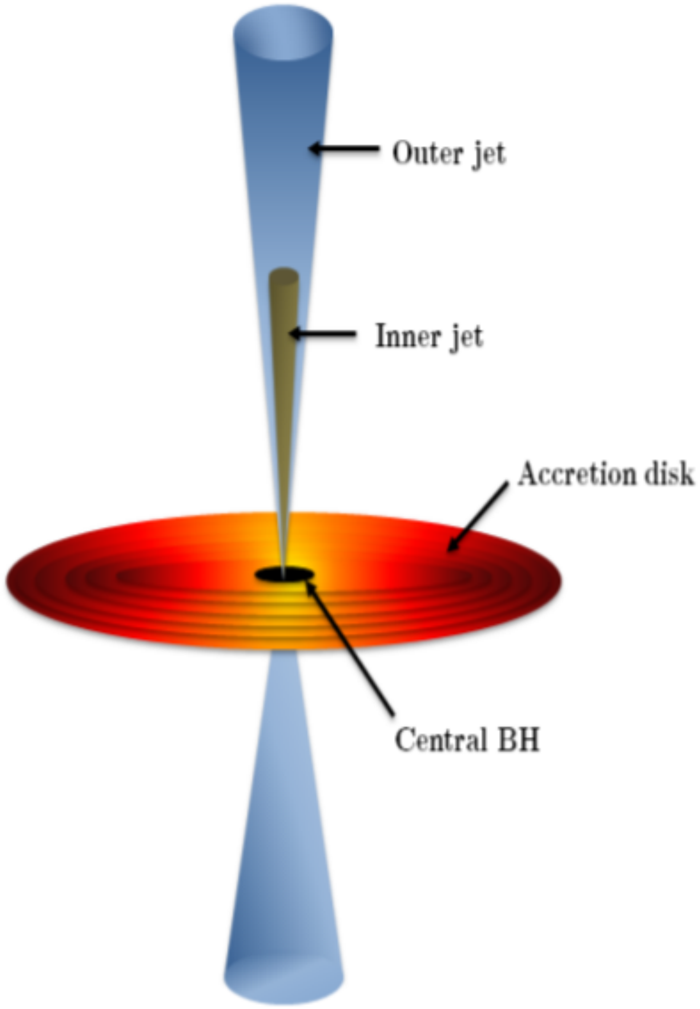
Photohadronic model

Flaring occurs within a compact volume R'_f inside the blob.

The internal and external jet move with almost the same Γ as the blob.

Fermi-accelerated protons

$$\frac{dN}{dE_p} \propto E_p^{-\alpha} \ , \ \alpha \geq 2$$



Photohadronic model

Photohadronic scenario

$$p + \gamma \to \Delta^+ \to \begin{cases} p\,\pi^0, & \text{fraction } \; 2/3 \\ n\,\pi^+, & \text{fraction } \; 1/3 \end{cases}$$

$$\sigma_\Delta \sim 5 \times 10^{-28}\,\mathrm{cm}^2$$

<u>Gamma-rays</u>

$$\pi^0 \to \gamma\gamma$$

<u>Neutrinos</u>

$$\pi^+ \to e^+\nu_e\nu_\mu\bar{\nu}_\mu$$

Double jet structure -> no need for super-Eddington power

(inner photon density) $n_{\gamma,f} > n_\gamma$ (outer photon density)

Photohadronic model

Minimum kinematical condition

$$E_p' \epsilon_\gamma' = \frac{(m_\Delta^2 - m_p^2)}{2(1 - \beta_p \cos\theta)} \simeq 0.32\,\mathrm{GeV}^2$$

For high energy protons, we assume $\beta_p \sim 1$. We average collision of all directions as $(1 - cos\theta) \sim 1$.

Photohadronic model

In the observer frame,

$$E_p \epsilon_\gamma \simeq 0.32 \, \frac{\Gamma \mathcal{D}}{(1+z)^2} \, \mathrm{GeV}^2$$

where,

$$\epsilon_\gamma = \frac{\mathcal{D} \epsilon'_\gamma}{(1+z)} \qquad\qquad E_p = \frac{\Gamma E'_p}{(1+z)}$$

Each pion carries ~ 0.2 of the proton energy, and pions decay into two γ-rays. Therefore,

$$E_\gamma = \frac{1}{10} \frac{\mathcal{D}}{(1+z)} E'_p = \frac{\mathcal{D}}{10\,\Gamma} E_p$$

Photohadronic model

The matching condition between the $\pi 0$-decay photon energy E_γ and the target photon energy ϵ_γ becomes,

$$E_\gamma \epsilon_\gamma \simeq 0.032 \, \frac{\mathcal{D}\Gamma}{(1+z)^2} \, \mathrm{GeV}^2$$

The VHE γ-ray flux is proportional to the background seed photon density n'_γ and the proton flux $F_p = E_p^2 (dN/dE_p)$

$$F_\gamma = E_\gamma^2 \frac{dN}{dE_\gamma} \propto E_p^2 \frac{dN}{dE_p} n'_{\gamma,f}$$

Photohadronic model

To constrain the seed photon density, we compare the dynamical time scale $t'_d = R'_f$ with the $p\gamma$ interaction time scale $t'_{p\gamma} = \left(n'_{\gamma,f} \sigma_\Delta K_{p\gamma} \right)^{-1}$.

The optical depth of the $p\gamma$ process is,

$$\tau_{p\gamma} = n'_{\gamma,f} \sigma_\Delta R'_f$$

For moderate efficiency, we have $t'_{p\gamma} > t'_d$ and thus

$$\tau_{p\gamma} < 2$$

Photohadronic model

Photon density is also limited by the Eddington luminosity

$$n'_{\gamma,f} \ll \frac{L_{Edd}}{8\pi R'^2_f \epsilon'_\gamma}$$

For the outer jet, it is well known that,

$$n'_\gamma(\epsilon_\gamma) = \eta \frac{L_{\gamma,SSC}(1+z)}{\mathcal{D}^{2+\kappa} 4\pi R'^2_b \epsilon_\gamma}$$

where the SSC photon luminosity is,

$$L_{\gamma,SSC} = \frac{4\pi d_L^2 \Phi_{SSC}(\epsilon_\gamma)}{(1+z)^2}$$

Photohadronic model

Using the kinematical condition, we can express the ratio,

$$\frac{n'_\gamma(\epsilon_{\gamma_1})}{n'_\gamma(\epsilon_{\gamma_2})} = \frac{\Phi_{SSC}(\epsilon_{\gamma 1})}{\Phi_{SSC}(\epsilon_{\gamma 2})} \frac{E_{\gamma_1}}{E_{\gamma_2}}$$

Scaling behavior

$$\frac{n'_{\gamma,f}(\epsilon_{\gamma_1})}{n'_{\gamma,f}(\epsilon_{\gamma_2})} \simeq \frac{n'_\gamma(\epsilon_{\gamma_1})}{n'_\gamma(\epsilon_{\gamma_2})}$$

Due to the adiabatic expansion of the inner jet, the photon density will decrease when it crosses into the outer region

Photohadronic model

To recall, the observed VHE flux is,

$$F_\gamma = E_\gamma^2 \frac{dN}{dE_\gamma} \propto E_p^2 \frac{dN}{dE_p} n'_{\gamma,f}$$

The observed flux taking into account EBL effect,

$$F_\gamma(E_\gamma) = F_{int}(E_\gamma) e^{-\tau_{\gamma\gamma}(E_\gamma, z)}$$

Photohadronic model

Putting everything together,

$$F(E_\gamma) = A_\gamma \Phi_{SSC}(\epsilon_\gamma) \left(\frac{E_\gamma}{TeV} \right)^{-\alpha+3} e^{-\tau_{\gamma\gamma}(E_\gamma, z)}$$

where the proportionality constant is,

$$A_\gamma = \left(\frac{F(E_{\gamma_2})}{\Phi_{SSC}(\epsilon_{\gamma 2})} \right) \left(\frac{TeV}{E_{\gamma_2}} \right)^{-\alpha+3} e^{\tau_{\gamma\gamma}(E_{\gamma_2}, z)}$$

and,

α: proton spectral index ($\alpha \geq 2$)

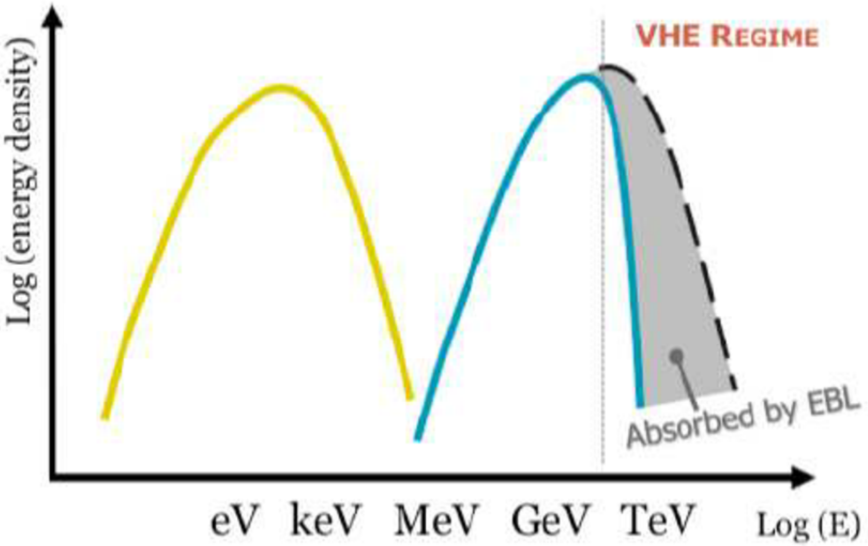
Photohadronic model

For HBLs and extreme HBLs, it has been shown that the SSC flux falls on the tail region and follows a simple power law,

$$\Phi_{SSC}(\epsilon_\gamma) = \Phi_0\, E_\gamma^{-\beta}$$

β: seed photon spectral index

$(\beta \leq 1)$



Photohadronic model

Therefore for the VHE spectra of HBL, we have the general expression in terms of a single parameter,

$$F_{\gamma,obs}(E_\gamma) = F_{\gamma,int}(E_\gamma)\, e^{-\tau_{\gamma\gamma}(E_\gamma,z)}$$

where the intrinsic flux is given by,

$$F_{\gamma,int}(E_\gamma) = F_0 \left(\frac{E_\gamma}{TeV}\right)^{-\delta+3} e^{-\tau_{\gamma\gamma}(E_\gamma,z)}$$

and,

F_0 : Normalisation constant

$\delta = \alpha + \beta$: photohadronic spectral index

Results

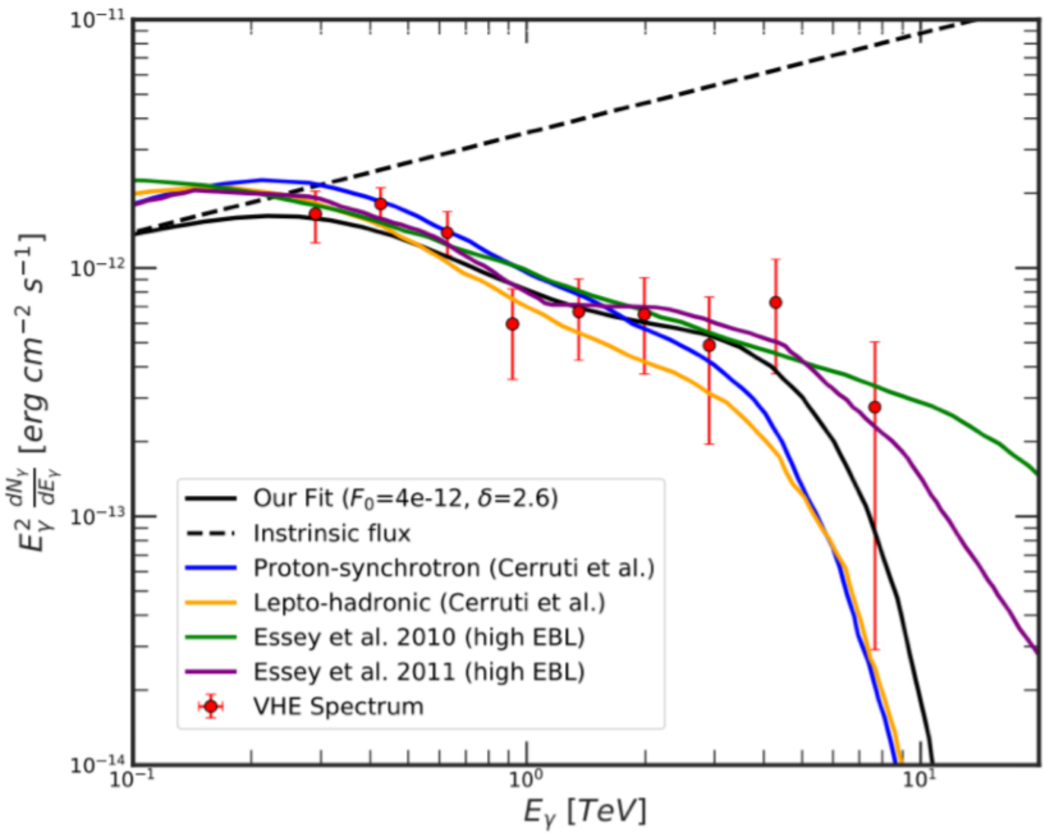
We fitted the observed VHE spectra of 42 emission epochs of 23 HBLs of different redshifts very well with the free parameter δ is in the range $2.5 \leq \delta \leq 3.0$.

We have roughly classified:

- Very high state: $\delta \in [2.5, 2.6]$
- High state: $\delta \in \,]2.6, 3.0[$
- Low state: $\delta = 3.0$

EBL template: Francheschini et al (2008).

VHE Spectrum (low redshift)



1ES 0229+200 (z=0.1396)

It was observed by VERITAS telescopes during a long-term observation over three seasons between October 2009 and January 2013, for a total of 54.3 hours

Energy range:

$$0.29\ TeV \leq E_\gamma \leq 7.6\ TeV$$

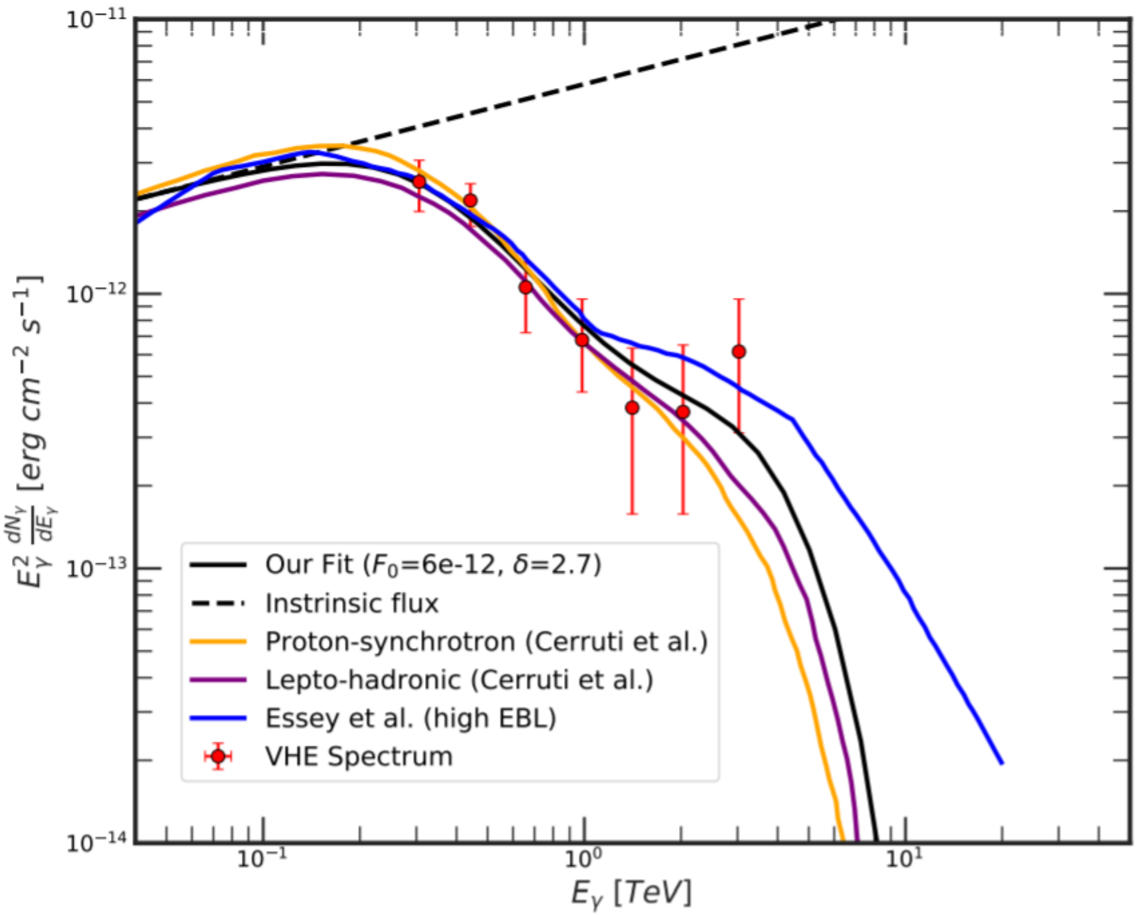
VHE Spectrum (low redshift)

1ES 0347-121 (z=0.188)

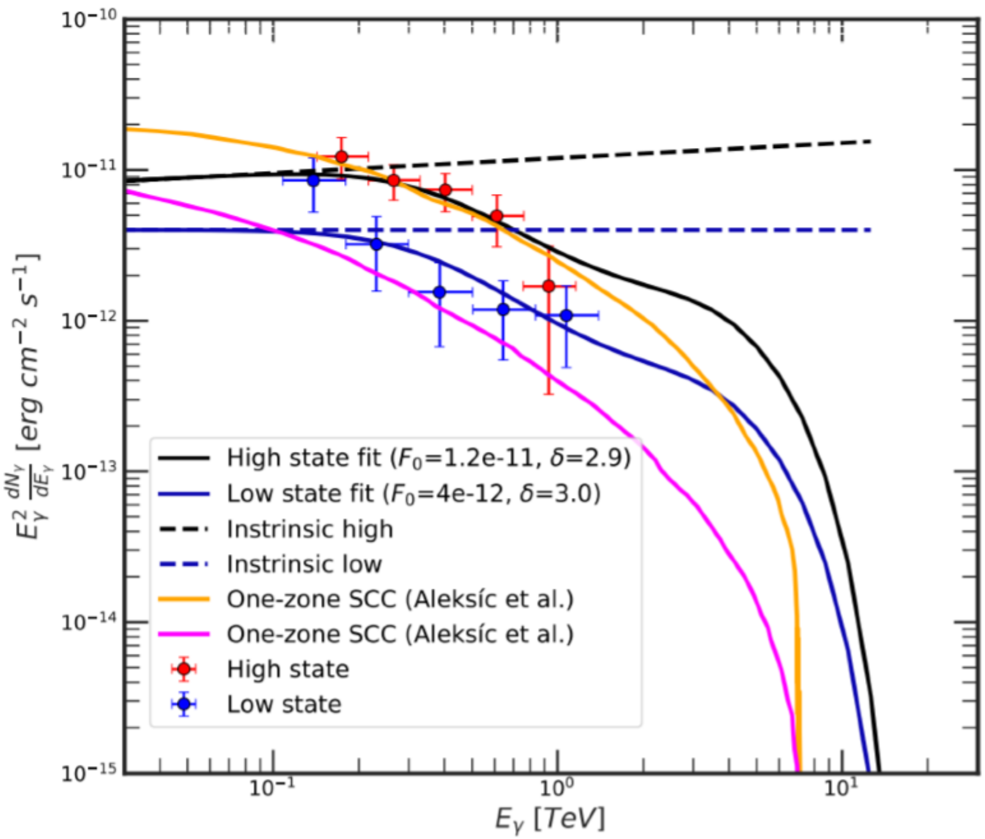
The HESS telescopes observed this blazar between August and December 2006 for a total of 25.4 hours.

Energy range:

$$0.25\ TeV \leq E_\gamma \leq 3.0\ TeV$$



VHE Spectrum (low redshift)



1ES 0806+524: (z=0.138)

A multiwavelength campaign was performed by MAGIC telescopes from January to March 2011 for 13 nights for about 24 hours and, on February 24, observed a flaring event for 3 hours.

Energy range:

$$0.17\ TeV \leq E_\gamma \leq 0.93\ TeV$$

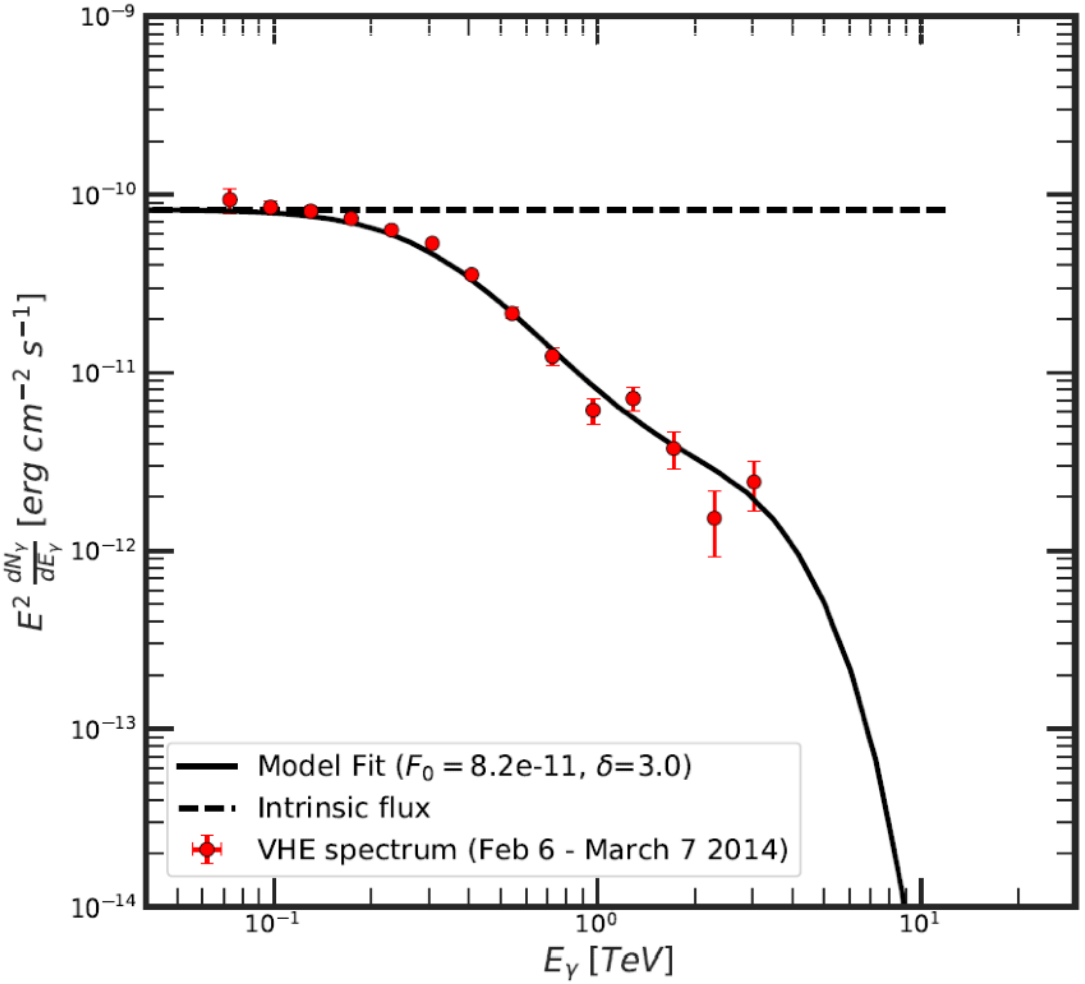
VHE Spectrum (medium redshift)

1ES 1011+496 (z=0.212)

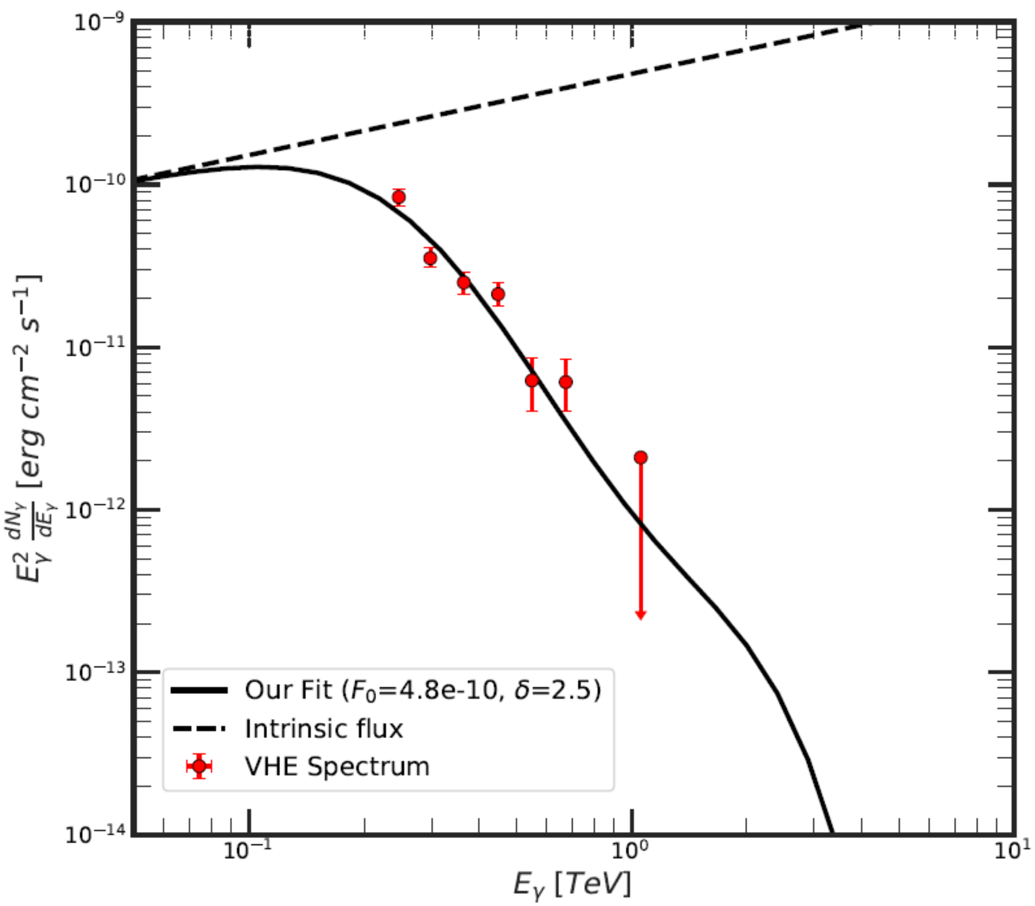
It was observed by the MAGIC telescopes during a aring event between February and March 2014, for a total of 17 nights.

Energy range:

$$0.1\ TeV \leq E_\gamma \leq 3\ TeV$$



VHE Spectrum (high redshift)



PG 1553+113 (z=0.5)

A multi-TeV faring event was observed from PG 1553+113 during the nights of April 26 and 27 of 2012 by the HESS telescopes for a total of 3.5 hours.

Energy range:

$$0.25\ TeV \leq E_\gamma \leq 0.6\}\ TeV$$

Predicting unknown redshifts

HESS J1943+213 (z=?)

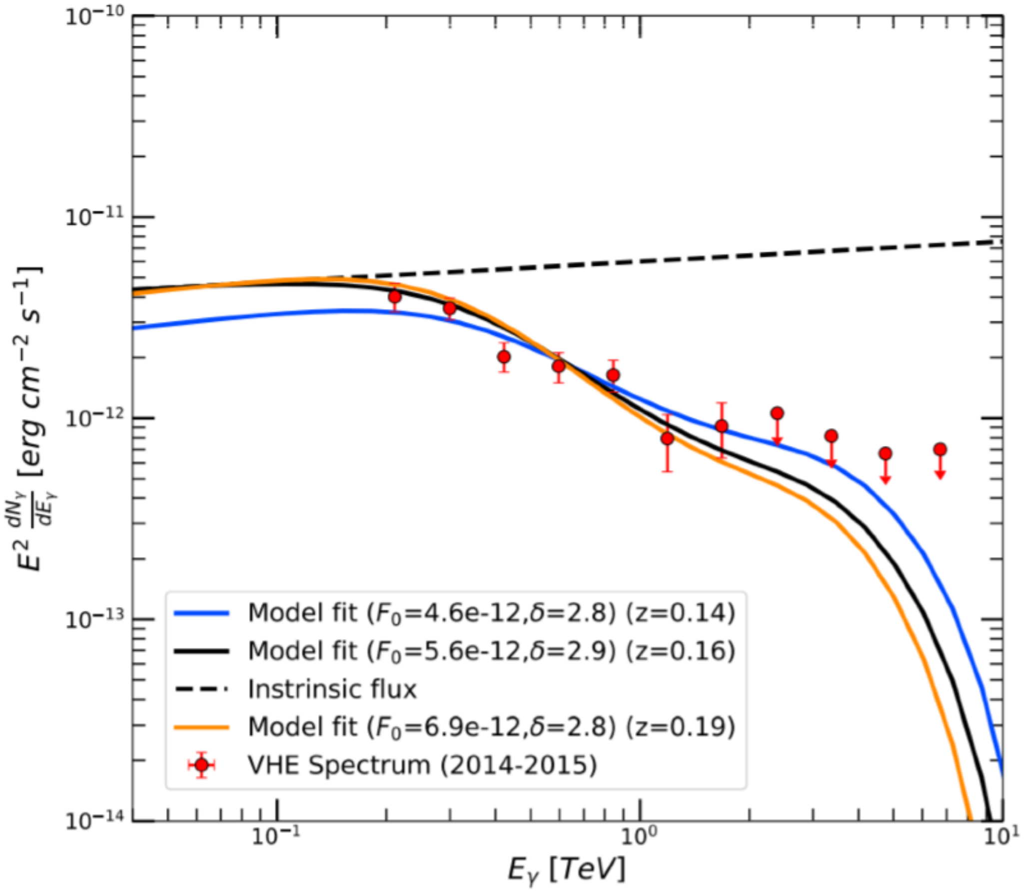
In VHE, it was observed by VERITAS telescopes from 27 May to 2 July 2014 and from 20 April to 9 November 2015, for a total exposure time of 37.2 hours.

Previously constrained to,

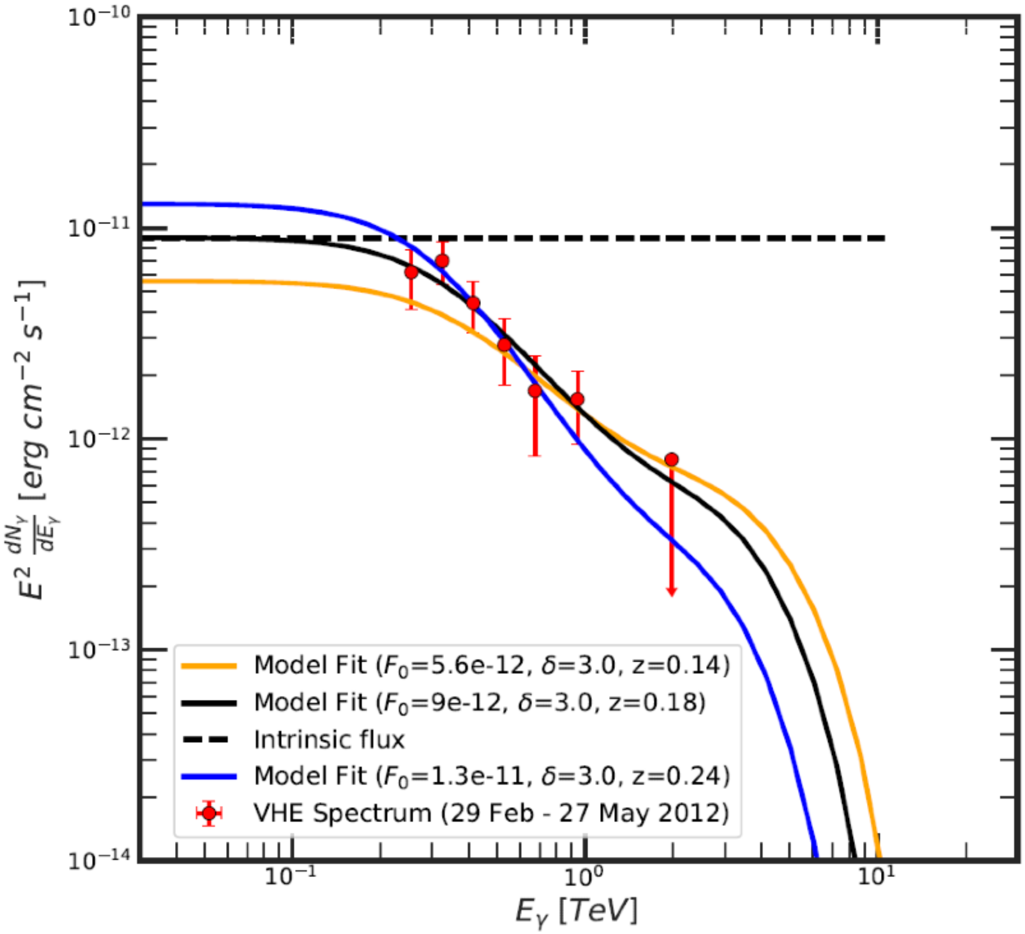
$$0.03 < z < 0.45$$

by applying the photohadronic model we found more stringent bounds for the redshift,

$$\mathbf{0.14 \leq z \leq 0.19}$$



Predicting unknown redshifts



PKS 1440-389 (z=?)

This HBL was observed by HESS telescopes between 29 February to 27 May 2012 for a total of ~12 hours.

Previously constrained to,

$$0.14 < z < 0.2.2$$

by applying the photohadronic model we found more stringent bounds for the redshift,

$$\mathbf{0.14 \leq z \leq 0.24}$$

Results

Only model to consistently describe up to 40+ VHE spectra of HBLs.

Photohadronic spectral index can predict state and photon density (since $\beta = \delta - \alpha$)

Name	Redshift(z)	Period	$F_{0,11}$	δ	State
Mrk 421	0.031	2004	51.3	2.95	High
		22 Apr 2006	5.2	2.95	High
		24 Apr 2006	10.7	3.0	Low
		25 Apr 2006	6.9	2.95	High
		26 Apr 2006	5.2	3.0	Low
		27 Apr 2006	16	2.95	High
		28 Apr 2006	5.0	3.0	Low
		29 Apr 2006	4.9	3.0	Low
		30 Apr 2006	13.5	2.5	Very High
		16 Feb 2010	12	3.0	Low
		17 Feb 2010	1.5	3.0	Low
		10 Mar 2010	21	2.6	Very High
		10 Mar 2010	16.5	3.0	Low
		28 Dec 2010	6.7	3.00	Low
Mrk 501	0.034	22 - 27 May 2012	6.3	2.9	High
		23 - 24 Jun 2014	28	2.93	High
1ES 2344+514	0.044	4 Oct 2007 - 11 Jan 2008	0.8	3.0	Low
1ES 1959+650	0.048	May 2002	12	3.0	Low
		Nov 2007 - Oct 2013	2.2	3.0	Low
		21-27 May 2006	1.1	3.0	Low
		20 May 2012	80	2.9	High
1ES 1727+502	0.055	1-7 May 2013	0.9	3.0	Low
PKS 1440-389	$0.14 \leq z \leq 0.24$	29 Feb - 27 May 2012	0.90	3.0	Low
1ES 1312-423	0.105	Apr 2004 - Jul 2010	0.20	3.0	Low
B32247+381	0.119	30 Sep - 30 Oct 2010	0.17	3.0	Low
RGB J0710+591	0.125	Dec 2008 - Mar 2009	0.5	2.9	High
1ES 1215+303	0.131	Jan - Feb 2011	90	3.0	Low
1RXS J101015.9-311909	0.14	Aug 2008 - Jan 2011	0.2	2.8	High
1ES 0229+200	0.14	2005 - 2006	0.4	2.6	Very High
H 2356-309	0.165	Jun - Dec 2004	0.3	2.9	High
1ES 1218+304	0.182	Dec 2008 - 2013	1.5	2.9	High
1ES 1101+232	0.186	2004 - 2005	0.60	2.75	High
1ES 1011+496	0.212	6 Feb - 7 Mar 2014	8.2	3.0	Low
1ES 0414+009	0.287	Aug 2008 - Feb 2011	0.70	2.9	High
RGB J0152+017	0.80	30 Oct - 14 Nov 2007	0.3	3.0	Low
RGB J2243+203	$0.75 \leq z \leq 1.1$	21 - 24 Dec 2014	0.28	2.6	Very High

Summary

AGNs represent important sources to probe for the origin of cosmic rays through multi-TeV gamma-ray observations.

Leptonic, hadronic, and hybrid models allow a phenomenological description of VHE spectra but are limited to multiple parametrizations and other physical constraints (i.e. efficiency, B)

Photohadronic scenario provides a simple yet consistent explanation for VHE γ production through $p\gamma$ interaction via intermediary Δ^+

Double jet scenario provides necessary seed photon density to account for moderate efficiency of the process

Summary

Photohadronic model only requires the adjustment of one free parameter (photohadronic spectral index):

- Predict emission state (low, high, very high)
- Predict photon density (assuming known α)
- Constraint HBL redshift from VHE spectrum
- Constraint EBL model from VHE spectrum

Future work:

- Extension to IBLs and LBLs (unified model?)
- Description of IceCube neutrino events

Thank you for your ατtention