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Temporary Extreme High Energy BL Lac Objects: A New classification and their Very High Energy Spectra

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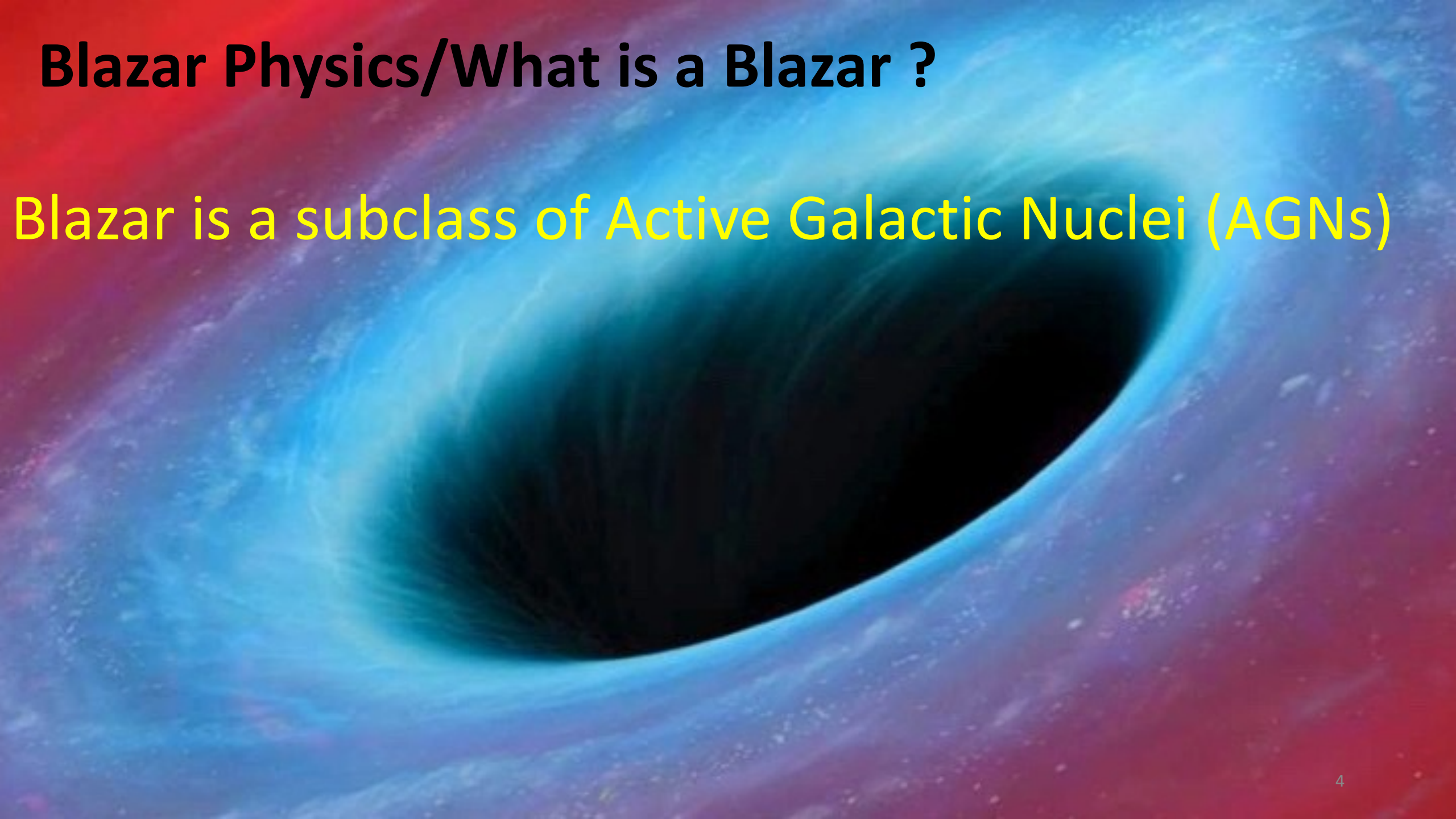
- Introduction
- Blazar Physics
- Flaring of BL Lac Objects
- Extragalactic Background Light (EBL)
- Gamma-ray production mechanisms

  Photohadronic Model
- Extreme High Energy BL Lac (EHBL) and Temporary EHBL
- Results
- Conclusions

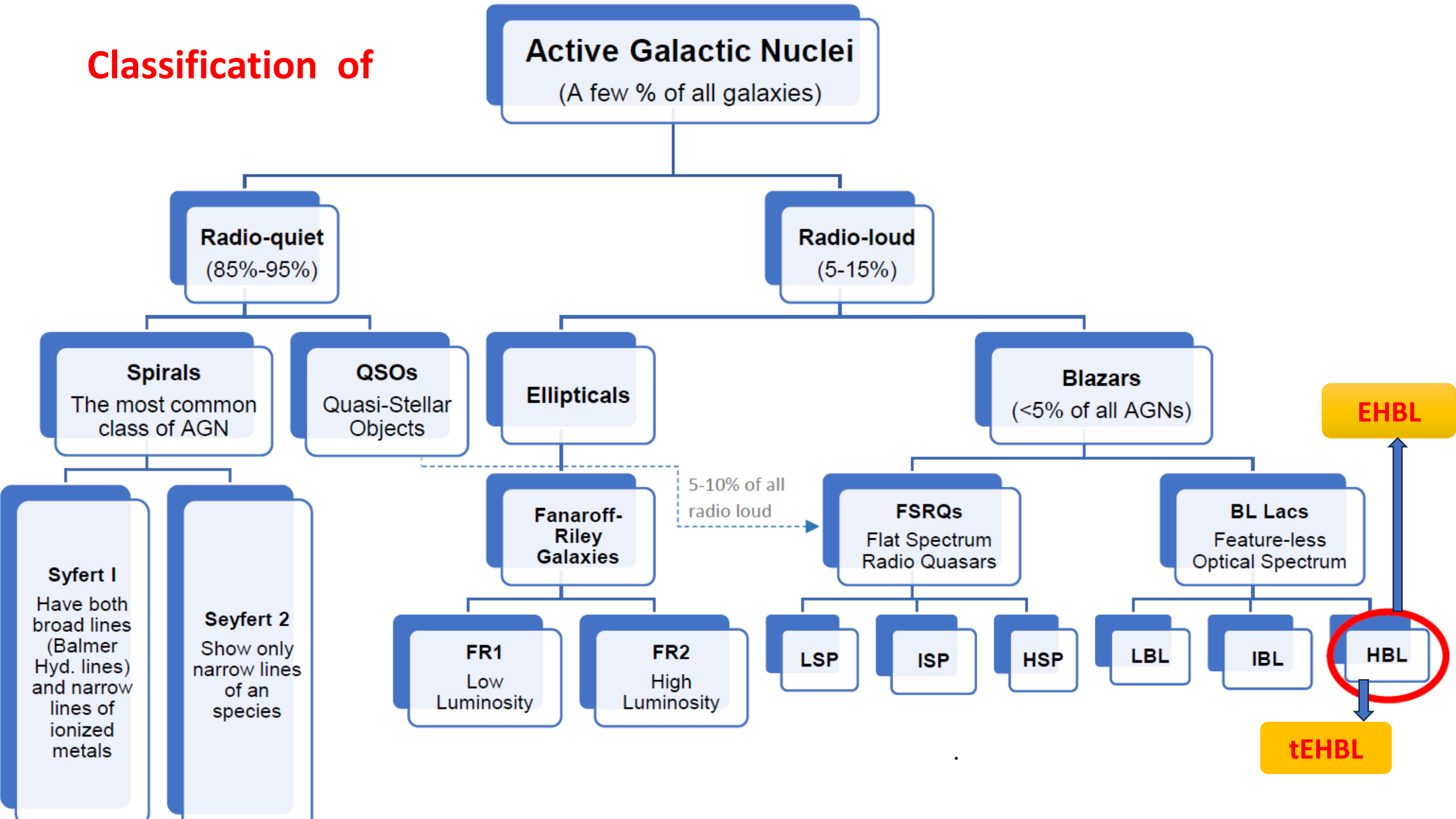
- Introduction
- Blazars make up the dominant extragalactic population in gamma-rays. Emit in all wavelengths.
- Recent observation of some neutrino events by IceCube neutrino detector in South Pole seems have positional and temporal correlation with many blazars.

Blazar Physics/What is a Blazar ?

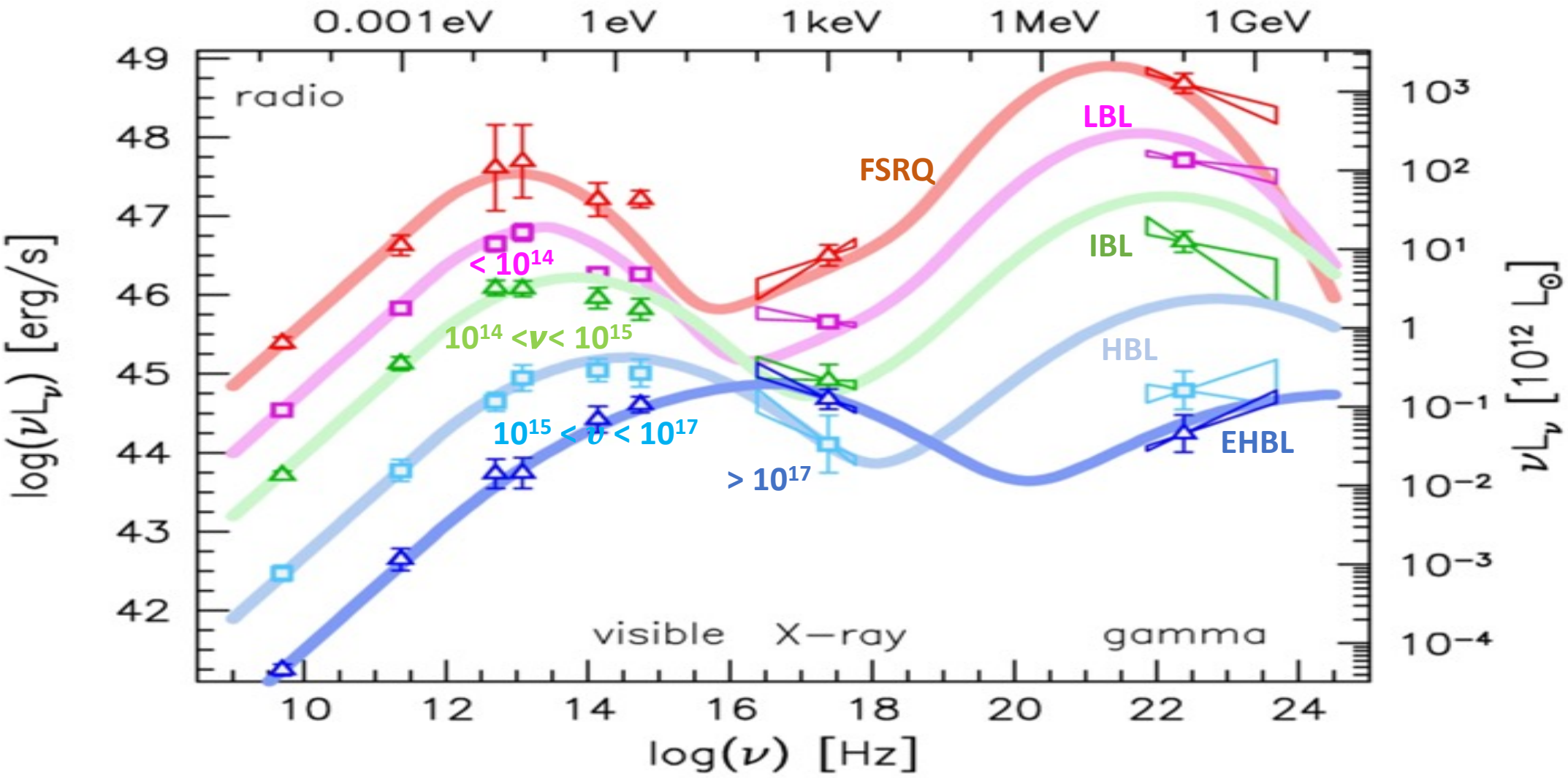
Blazar is a subclass of Active Galactic Nuclei (AGNs)



Classification of



AGN spectrum ?

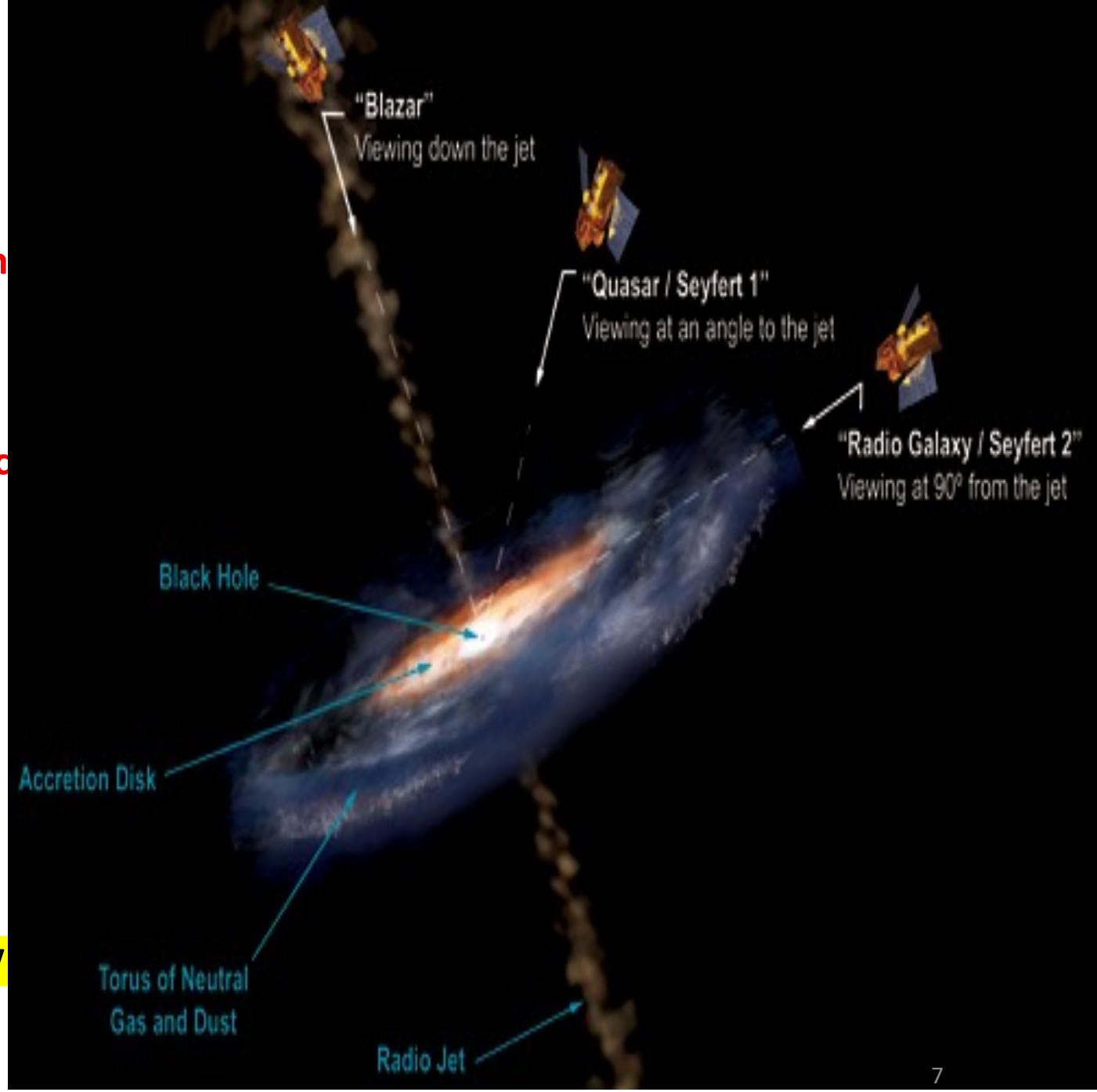


Blazars

- Nonthermal spectra,
- Rapid variability across the entire em spectrum (Radio to ɣ-Ray)
- Highly relativistic plasma jet pointing along the
- line of sight to the observer.
- Small viewing angle of the jet, strong relativistic effects ➔
- Boosting of the emitted power
- Shortening of the time scale (minutes)

Reason to Study these Objects:

- Energy extraction mechanisms from the central supermassive Black Hole
- Physical properties of the Astrophysical Jets
- Accleration of the charged particles in the Jet
- Production of UHECRs, VHE Neutrinos, multi-TeV gamma-rays etc.
- Constraint the Extragalactic Background Light (EBL).



Spectral Energy Distribution (SED) of blazars

TWO nonthermal bumps

1st peak

Near infra-Red/optical (Low energy peaked blazars LBL)

OR

UV/X-ray (HBL)

2nd peak

GeV Range

Power-Law

$$\frac{dN}{dE} \propto E^{-\alpha}$$

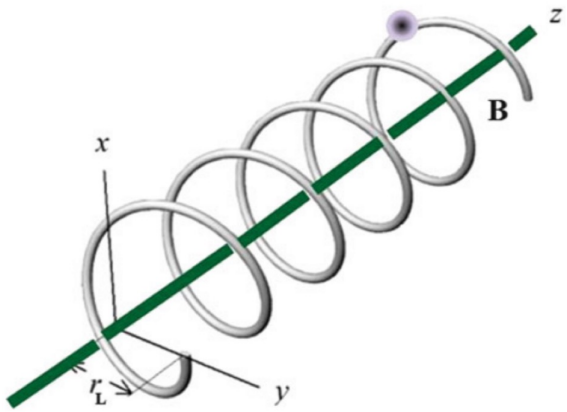
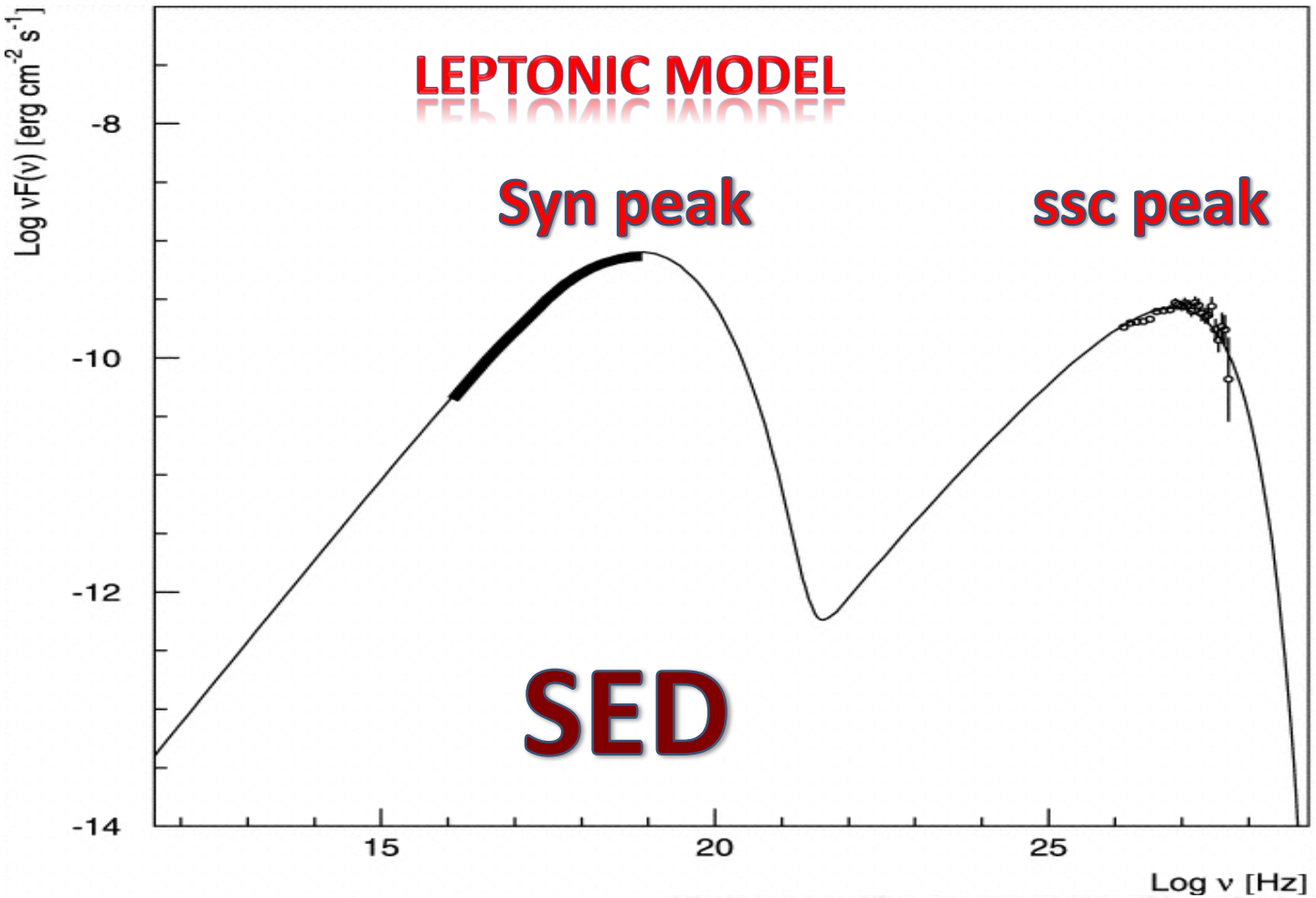
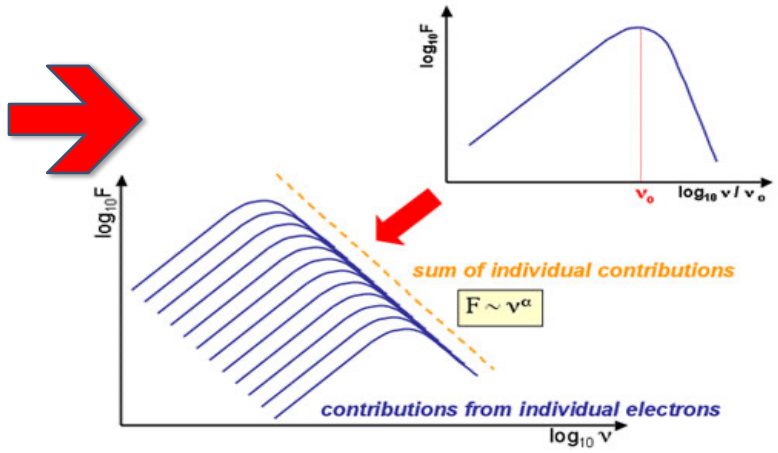
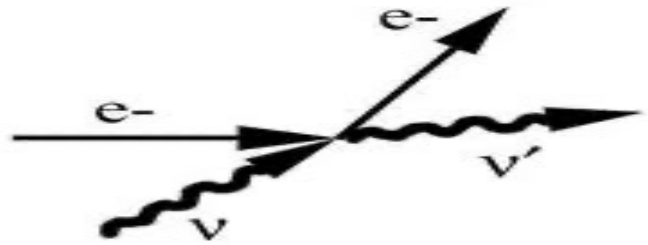


Figure 8: The motion of a charged particle along the $\vec{B}$ field line.





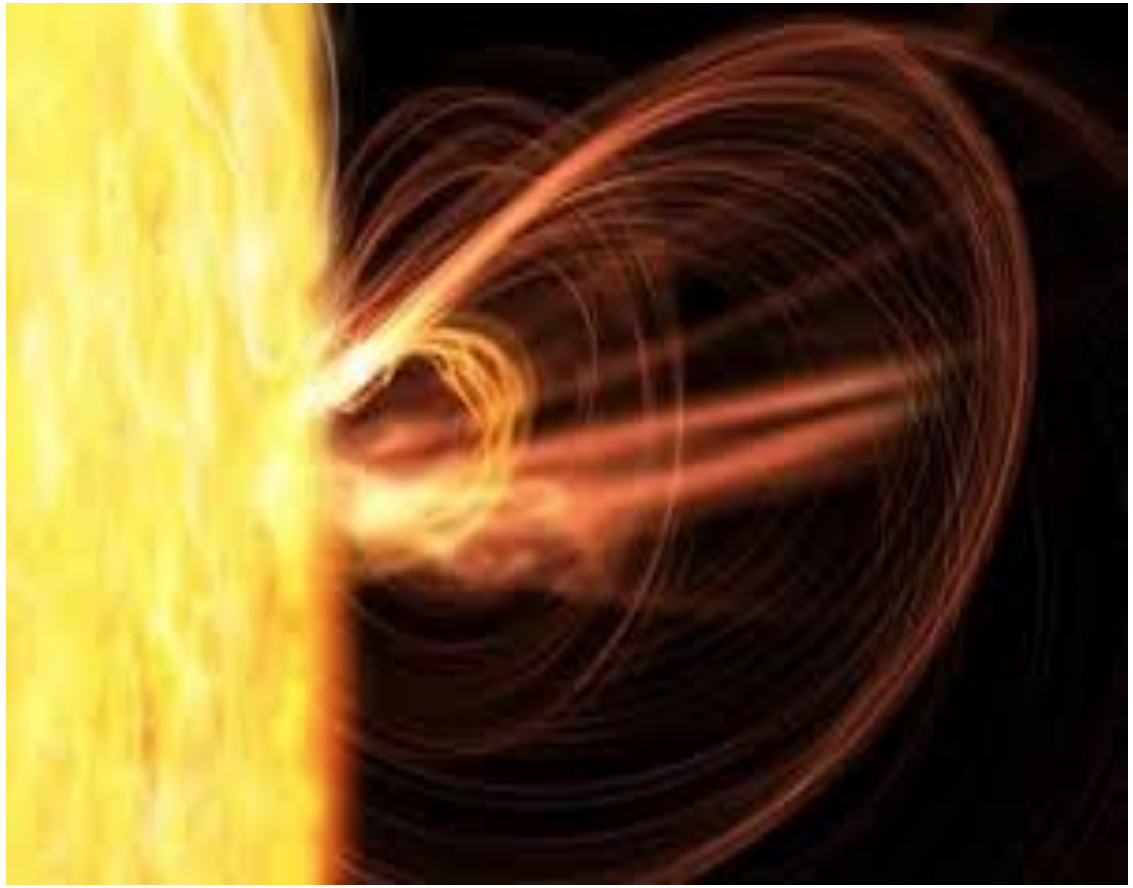
Inverse Compton scattering



ν′ > ν

High energy e- initially e- loses energy

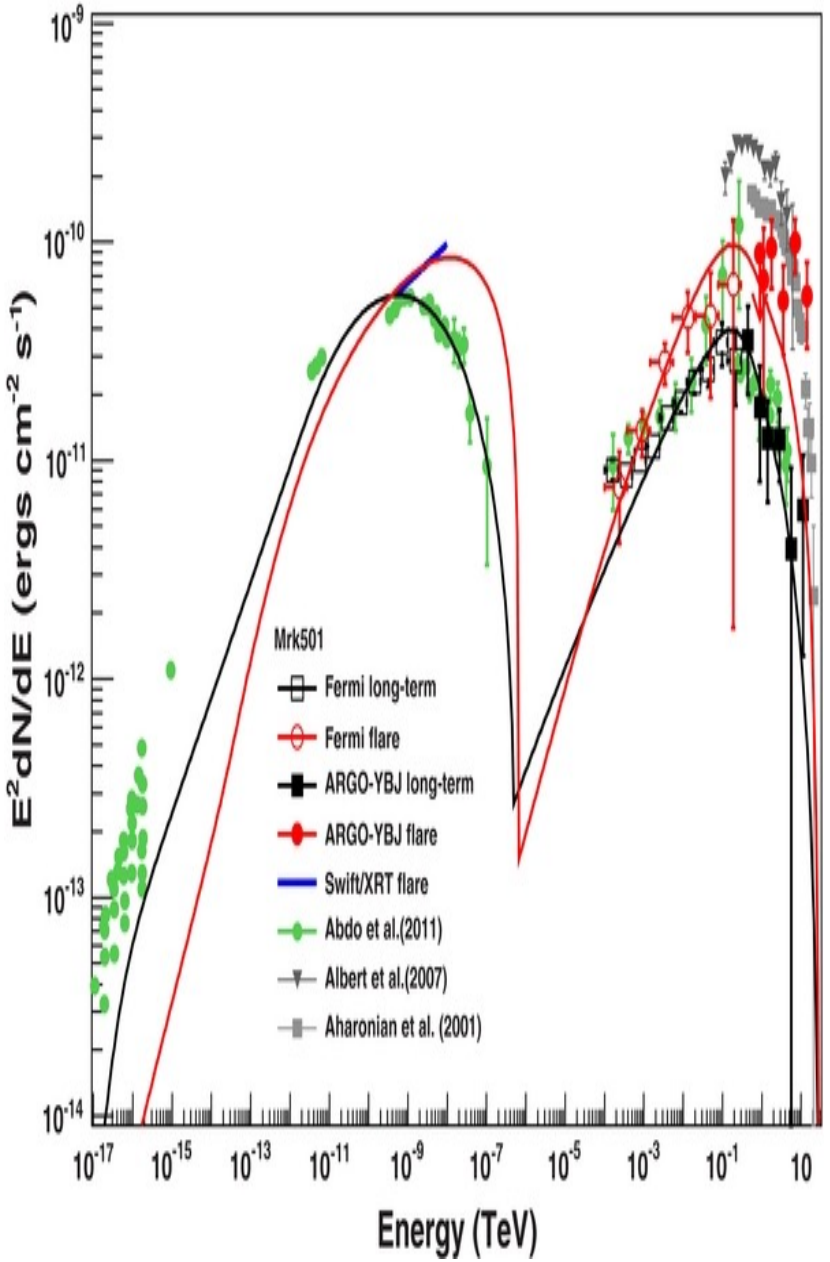
Flaring

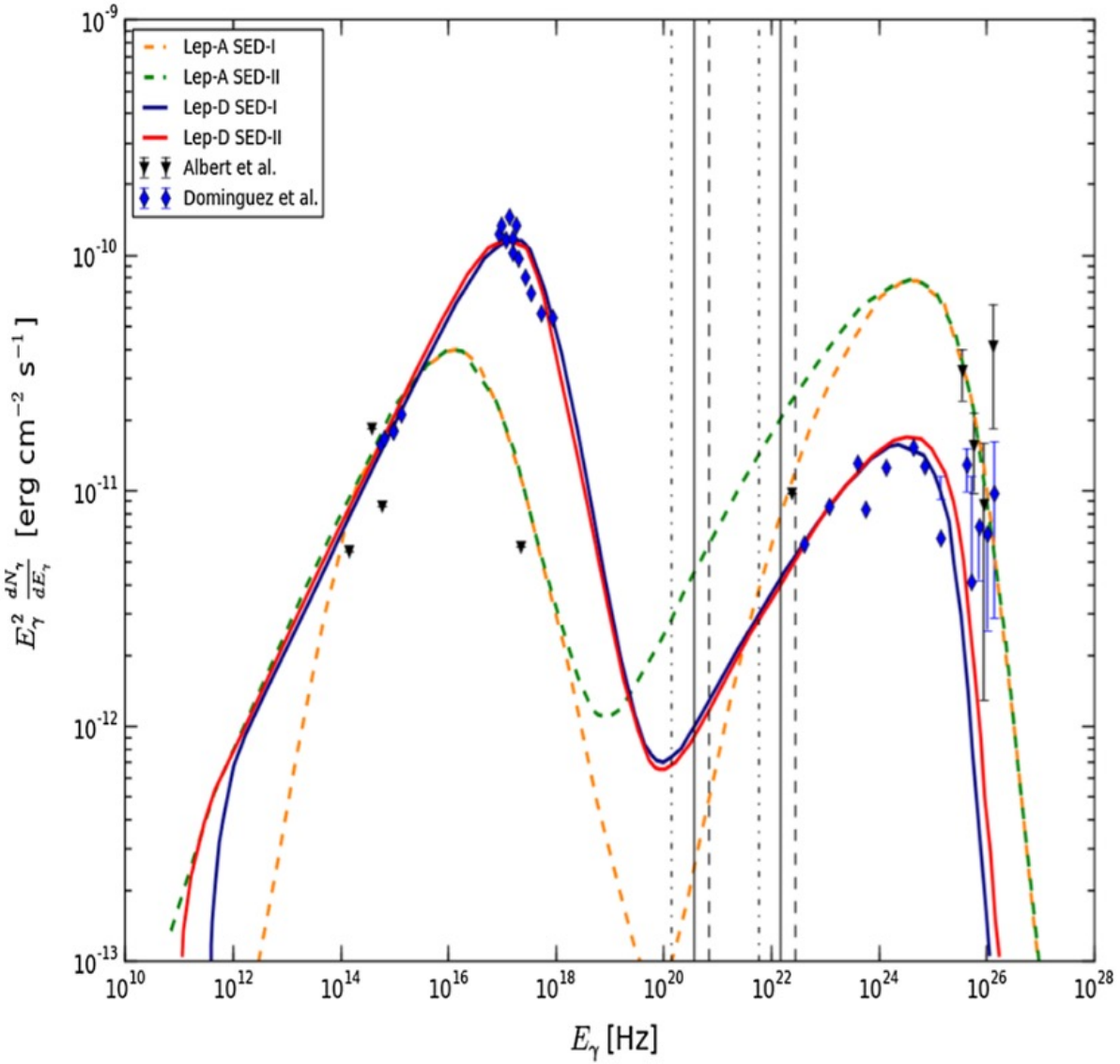


Flaring seems to be major activity of the blazars, which is unpredictable and switches between quiescent and active states involving different time scales

Intense eruption, increase in flux in short interval of time, in Blazar

⇛ Production of multi-TeV gamma-rays, CR, neutrinos ??





[redacted] The leptonic SED of the HBL 1ES 1011+496 is shown by using

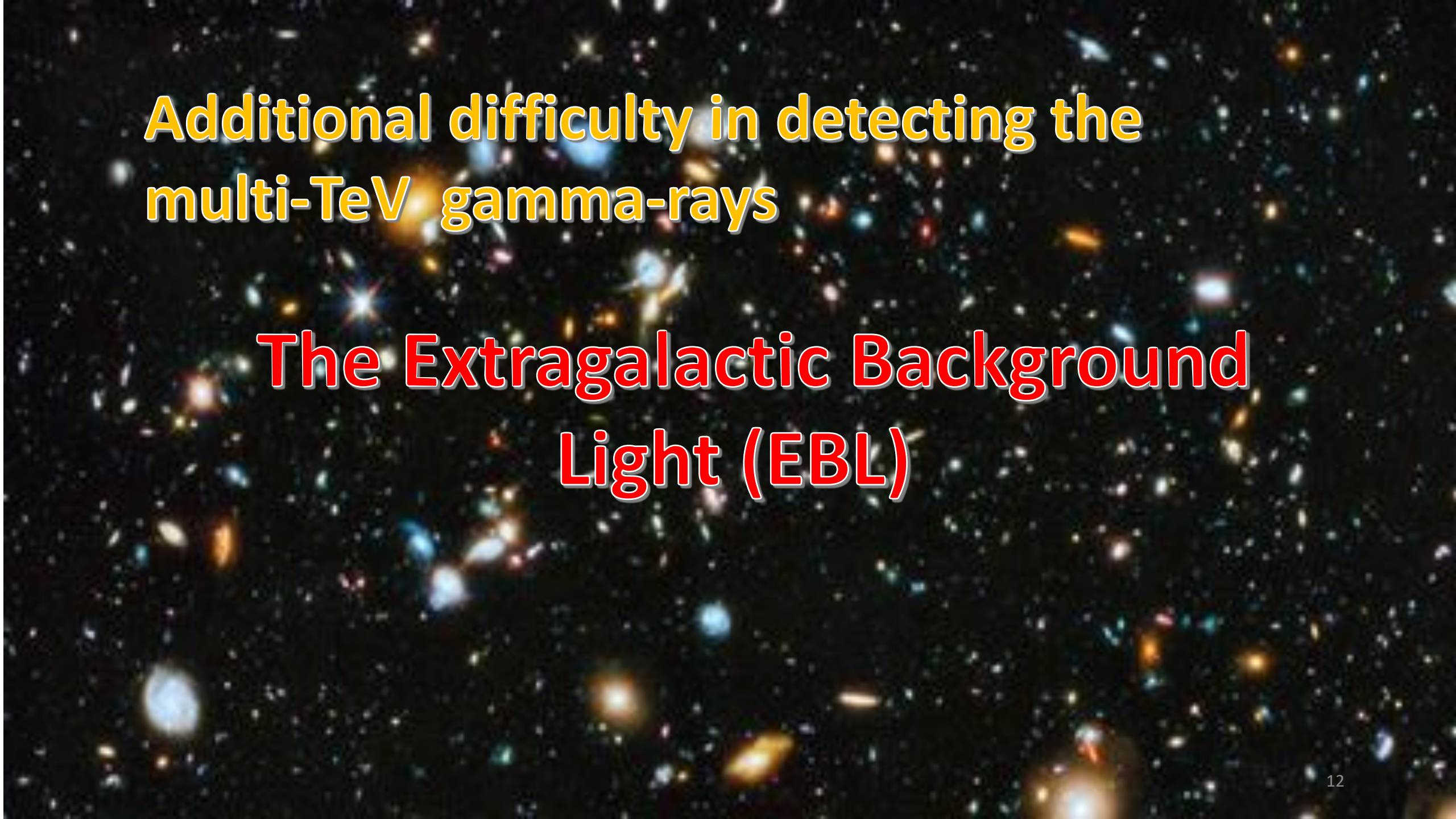
Sources of these gamma-radiation

Sources of High/Very High energy γ-rays

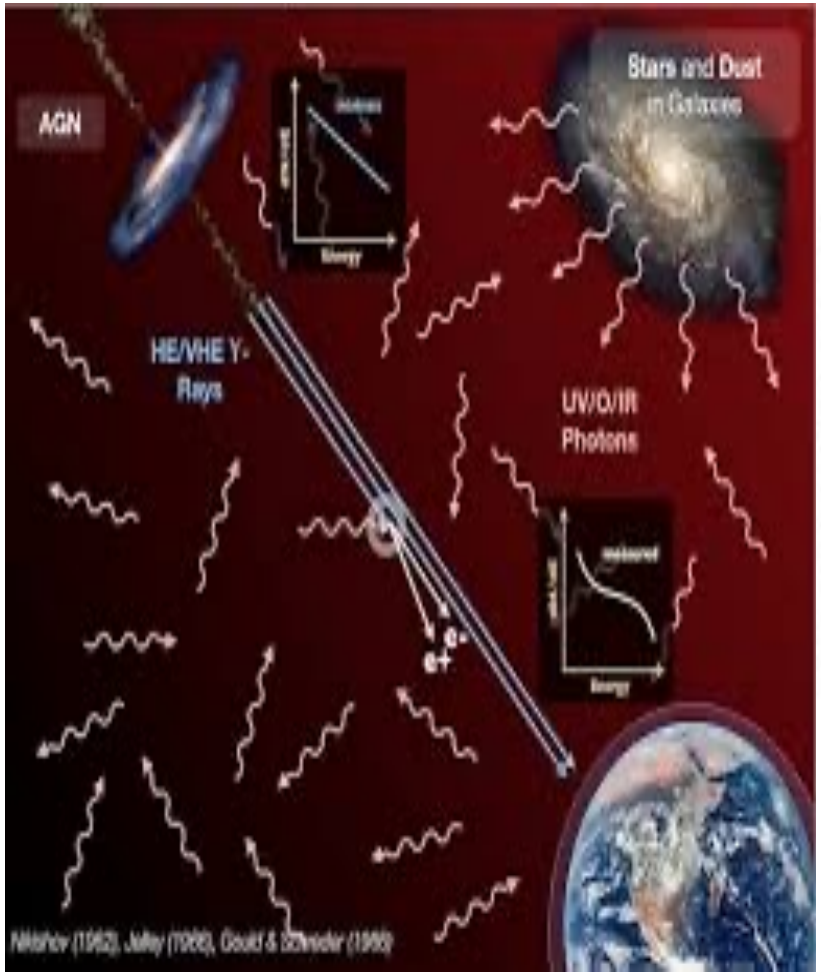
- **Active Galactic Nuclei (Black Hole at the center of a galaxy)**
- **Gamma-ray Bursts (GRBs)**
- **Pulsars**
- **Decay of dark Matter**

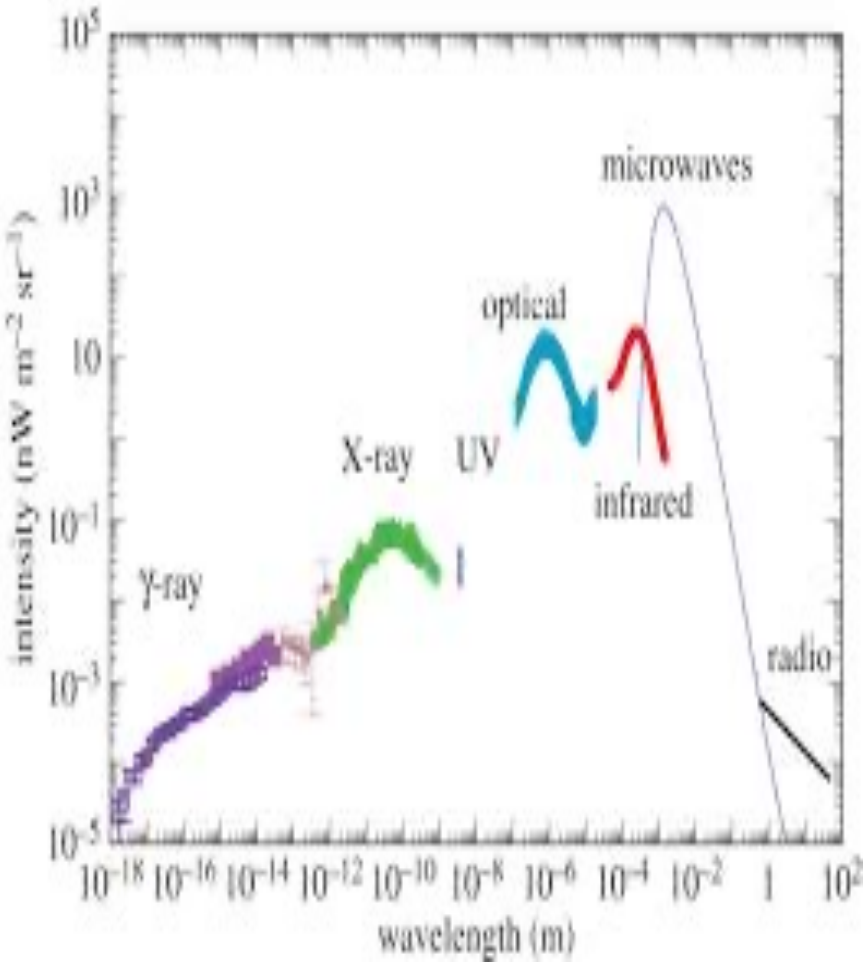
VHE Gamma-Ray Detectors around the World

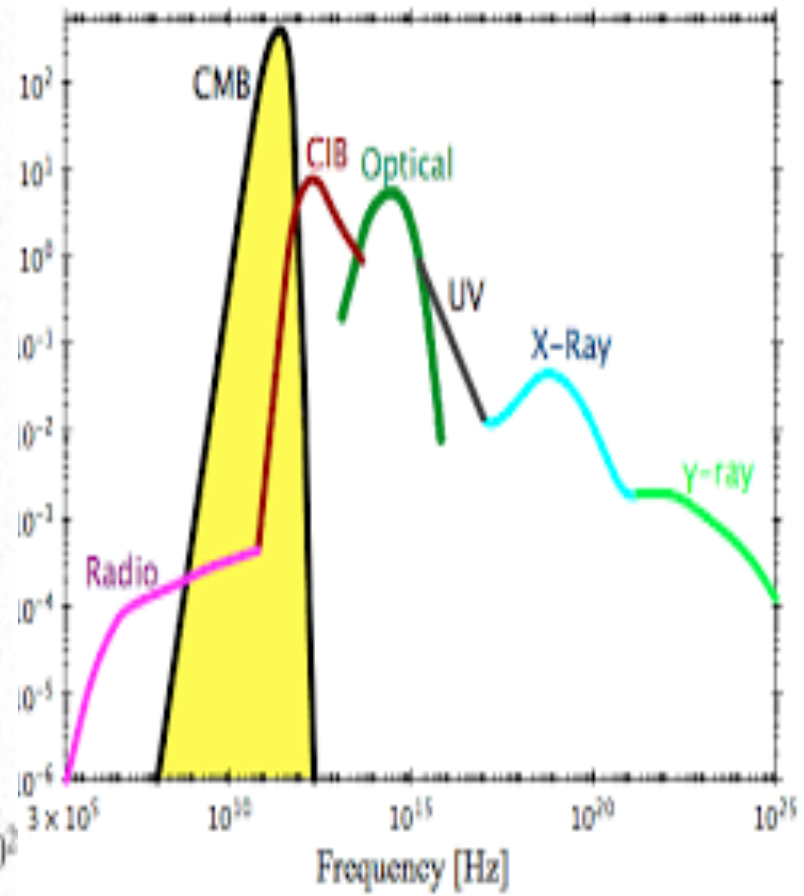
MAGIC-- Major Atmospheric Gamma-ray Imaging Cherenkov Telescope (La Palma, Spain)
VERITAS—Very High Energy Radiation Imaging Telescope Array System (USA)
HESS --- High Energy Stereoscopc System (Namibia)
HAWC – High Altitude Water Cherenkov (Mexico)


Additional difficulty in detecting the multi-TeV gamma-rays
The Extragalactic Background Light (EBL)

Extragalactic Background Light (EBL)

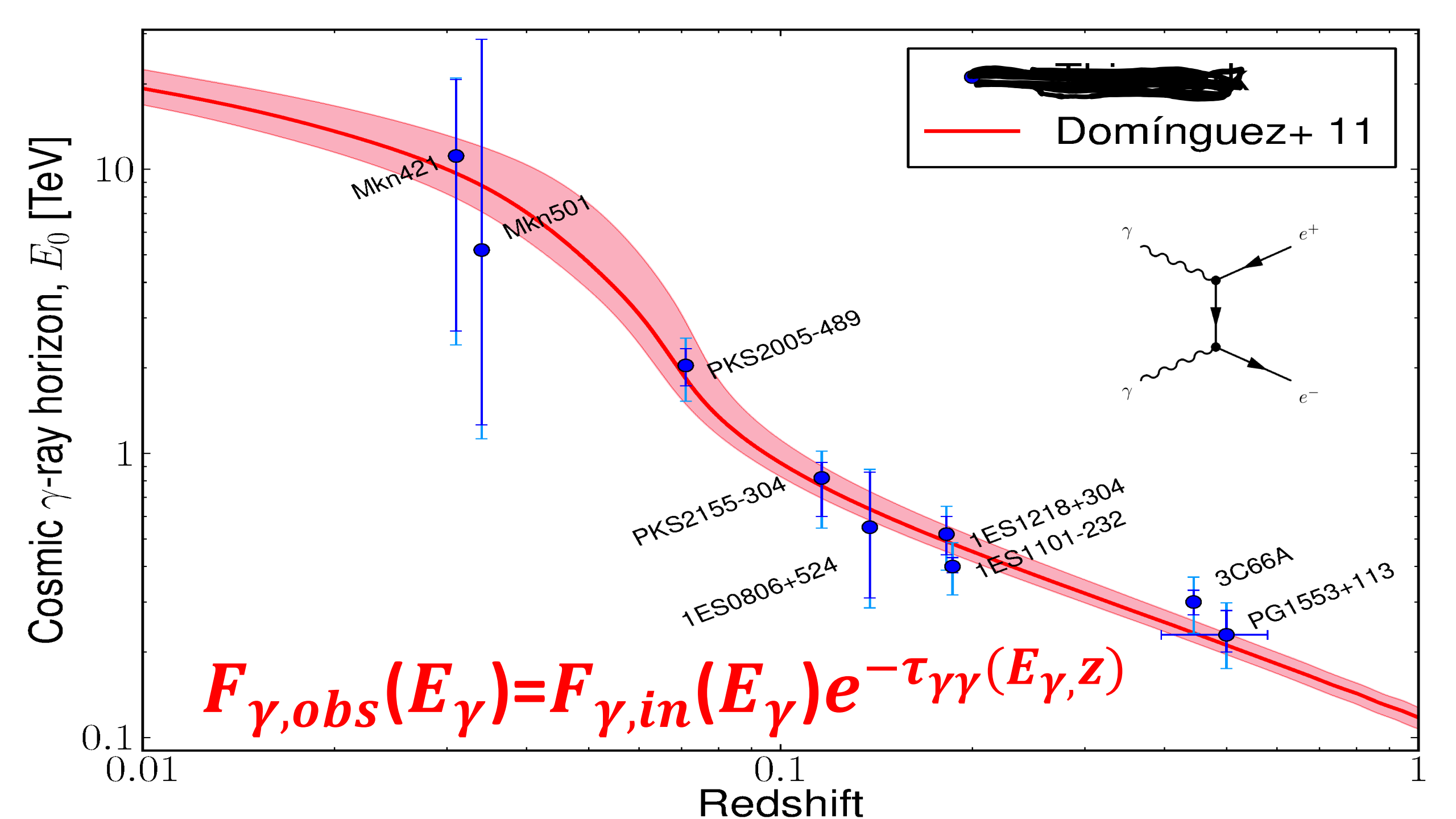




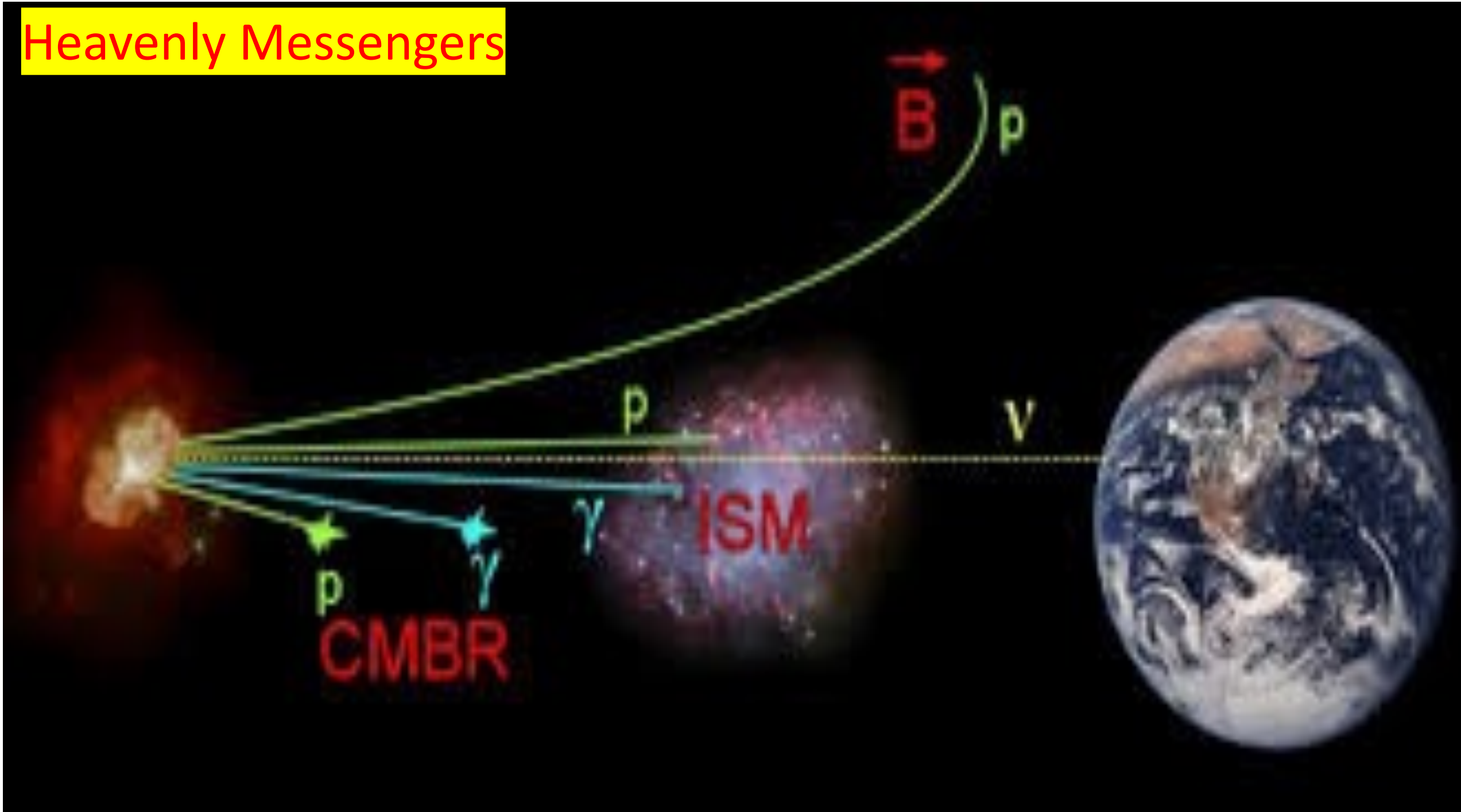


0.1-100 μm wavelength range emitted by stars, galaxies, from nucleosynthesis in AGN, reprocessed by dust.

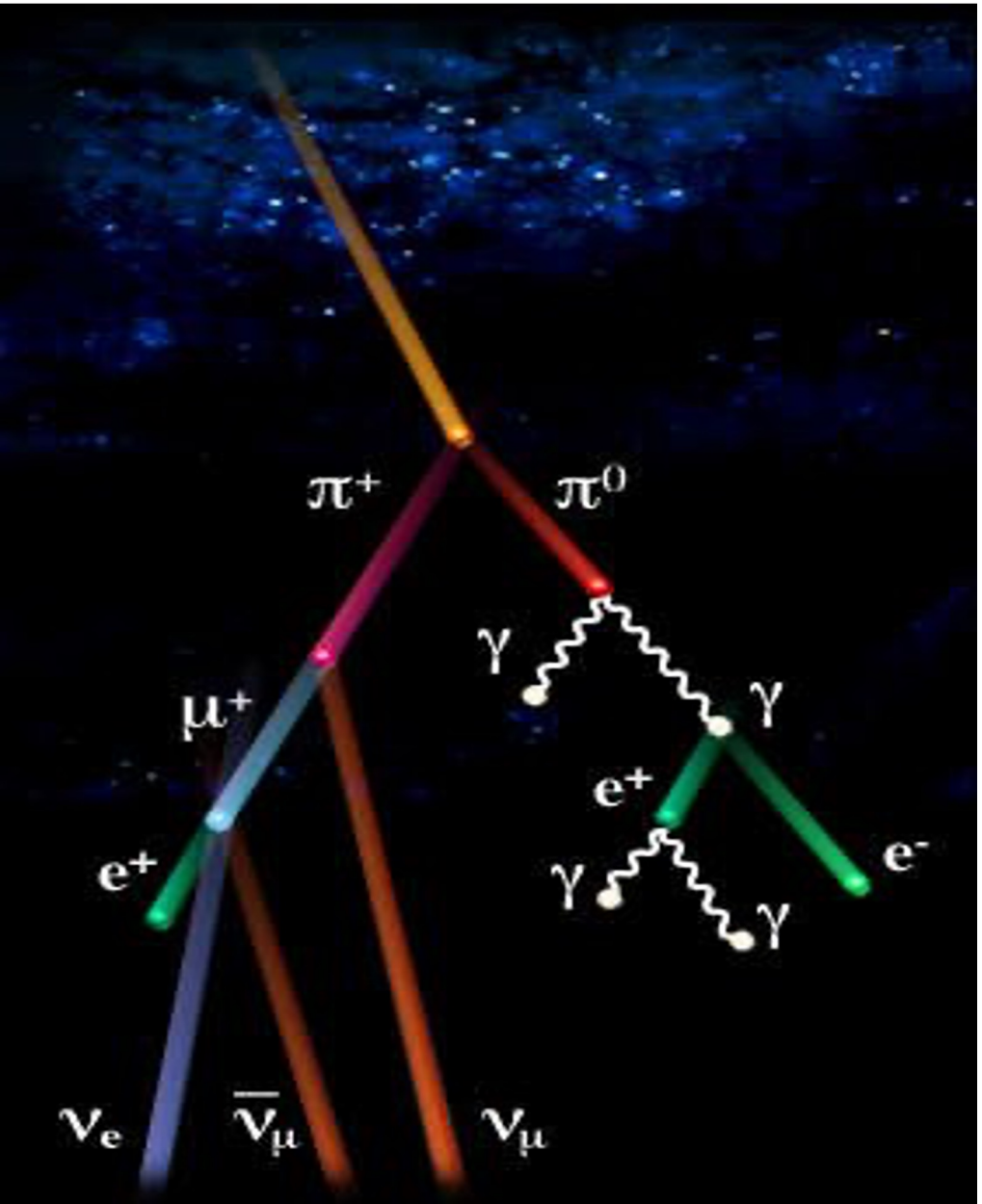
This diffuse background is called EBL


[redacted]
Domínguez+ 11
Mkn421
Mkn501
PKS2005-489
PKS2155-304
1ES0806+524
1ES1218+304
1ES1101-232
3C66A
PG1553+113
γ
e^+
γ
e^-
Cosmic γ-ray horizon, E_0 [TeV]
10
1
0.1
0.01
0.1
1
Redshift
$F_{\gamma,obs}(E_\gamma)=F_{\gamma,in}(E_\gamma)e^{-\tau_{\gamma\gamma}(E_\gamma,z)}$

Heavenly Messengers



Photohadronic Model (Sahu et al.)



We have developed a photohadronic model which can explain the multi-TeV flaring from high energy blazars

The Fermi accelerated high energy protons interact with the background photons to produce Δ-Resonance.

Photohadronic Model

The Fermi accelerated high energy protons interact with the background photons in the jet to produce Δ-Resonance.

Photohadronic scenario

To produce pions through Δ-resonance

$$p+\gamma \rightarrow \Delta^{+} \rightarrow \begin{cases} p\pi^{0} \rightarrow p\gamma\gamma & \text{fraction 2/3} \\ n\pi^{+} \rightarrow ne^{+}\nu_{e}\nu_{\mu}\bar{\nu}_{\mu} & \text{, fraction 1/3.} \end{cases}$$

In comoving frame each π carries ~0.2 (20%) of the proton energy.

$$\sigma_{\Delta} \approx 5.10^{-28}\, cm^{2}$$

Jet structure during flaring

What we assume ……

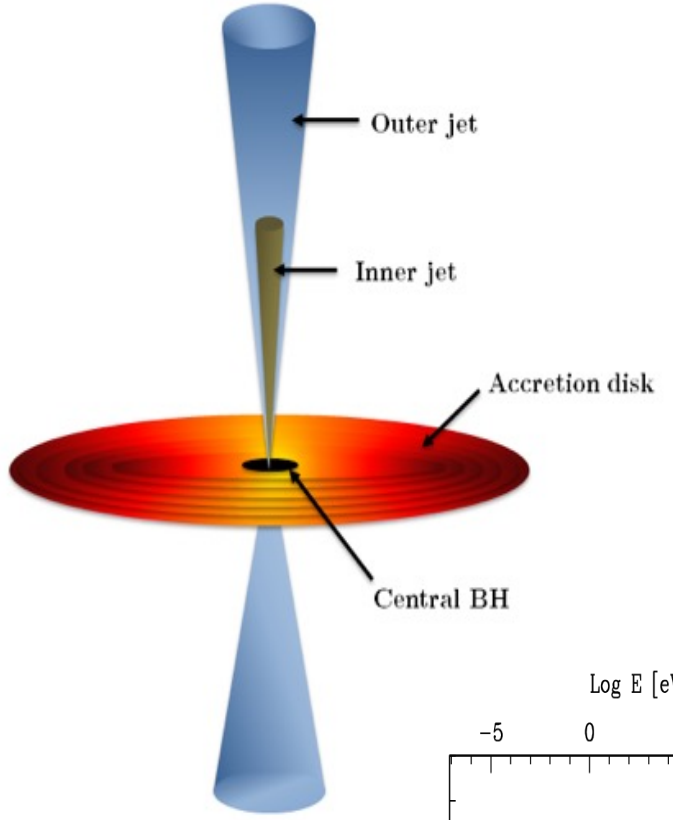
Photohadronic scenario

To produce pions through Δ-resonance

$$p+\gamma \longrightarrow \Delta^{+} \longrightarrow \begin{cases} p\pi^{0} \rightarrow p\gamma\gamma \\ n\pi^{+} \rightarrow ne^{+}\nu_{e}\nu_{\mu}\bar{\nu}_{\mu} \end{cases}$$

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

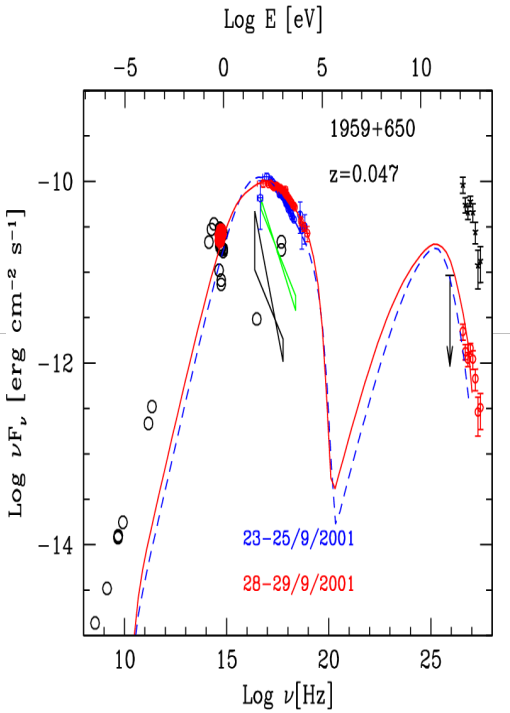
$$\frac{n'_{\gamma,f}(\epsilon_{\gamma,1})}{n'_{\gamma,f}(\epsilon_{\gamma,2})} \simeq \frac{n'_{\gamma}(\epsilon_{\gamma,1})}{n'_{\gamma}(\epsilon_{\gamma,2})}.$$



Photon density in the inner region >> outer region during a flaring.

In comoving frame each π carries ~0.2 (20%) of the proton energy.

$$\sigma_{\Delta} \approx 5.10^{-28} cm^2$$



Kinematical Condition

$$E_p \varepsilon_\gamma = 0.32 \Gamma \delta (1+z)^{-2} GeV^2$$

$$E_\nu \varepsilon_\gamma = 0.016 \Gamma \delta (1+z)^{-2} GeV^2$$

$$E_\gamma \varepsilon_\gamma = 0.032\ \Gamma\ \delta\ (1+z)^{-2}\ GeV^2$$

What do we assume & Propose ?

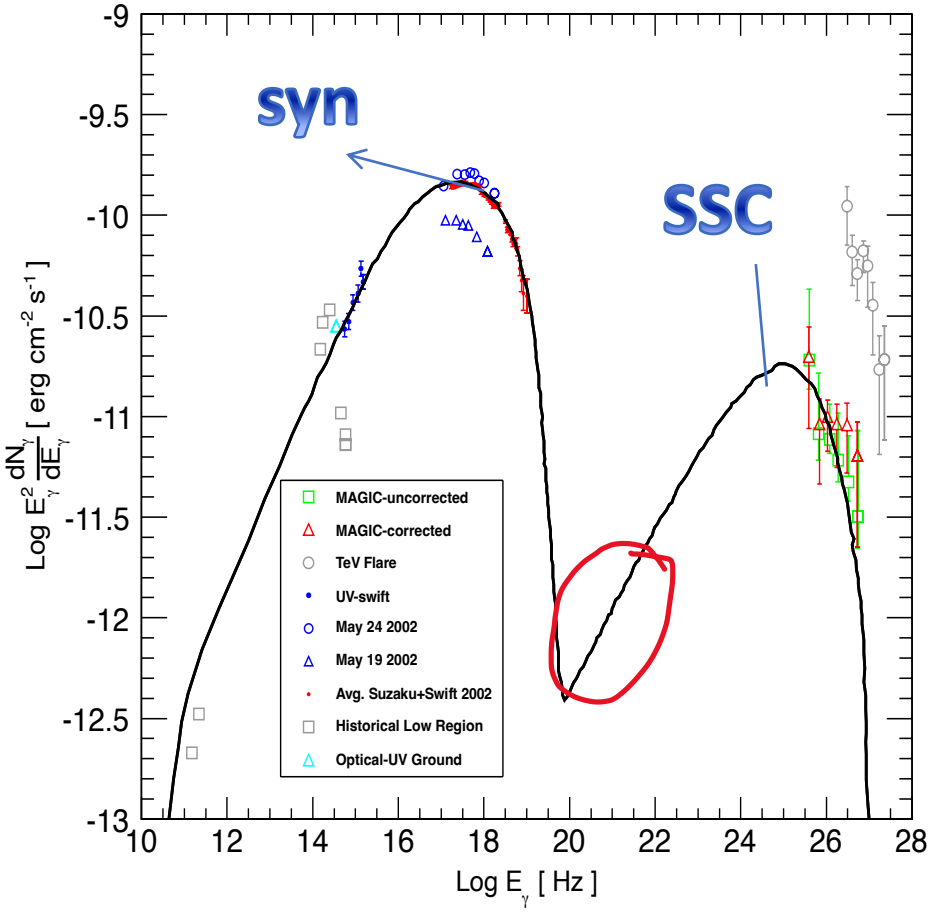
Assume:

Standard Leptonic model which explains both low and high energy peaks (syn, ssc) by

Synchrotron,
SSC photons as in the case of many HBLs

We propose:

Low energy tail of the SSC photons in the jet serves as the target for the Fermi acc. HE protons.



The γ-ray flux due to pion decay will be

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

Final formula

$$\mathrm{F}_\gamma(E_\gamma) = F_0 \left(\frac{E_{\gamma 1}}{E_0}\right)^{-\boldsymbol{\delta}+3} e^{-\boldsymbol{\tau\gamma\gamma}}$$

TeV photon and the HE protons are related through

$$F(E_p) = 5 \times \frac{3}{2} \times \frac{F(E_\gamma)}{\tau_{p\gamma}(E_p)}$$

20%

2/3 prob.

Neutrino

$$F_\nu = \frac{3}{8} F_\gamma$$

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

$\tau_{\gamma\gamma}$ is the optical depth which depends on both energy and the redshift of the object. Optical depth is NATURAL in attenuating the High Energy Flux from the object.

Classification of the flaring states:

1. **Low emission state :** $\delta = 3.0$
2. **High emission state** $2.6 < \delta < 3.0$
3. **Very high emission state** $2.5 \leq \delta \leq 2.6$

Extreme HBL (EHBL) have Synchrotron spectrum $peak\ \nu_s > 10^{17}$ Hz

It is observed that their spectra follows the same behavior as the HBLs !!!!

Occasionally a HBL has a synchrotron spectrum peak above $\nu_s > 10^{17}$ Hz , signifies that this behavior is of EHBL type. However, after sometime its spectrum jumps back to HBL type i.e. $\nu_s < 10^{17}$ Hz.

This behavior is difficult to comprehend and needs further explanation.

Results:

1. **Flaring events of 2005 and 2012 in Markarian 501 (Mrk 501), Sahu et al, ApJ (2020)**
2. **Flaring events of June 13, 14 and July 1, 2016 in 1ES 1959+650, Sahu et al, ApJ (2021)**
3. **Flaring events of March 10 (MJD 55265) to March 22 (MJD 55277), 2010 in Markarian 421 (Mrk 421) for 13 consecutive nights, Sahu et al, ApJ (2021)**

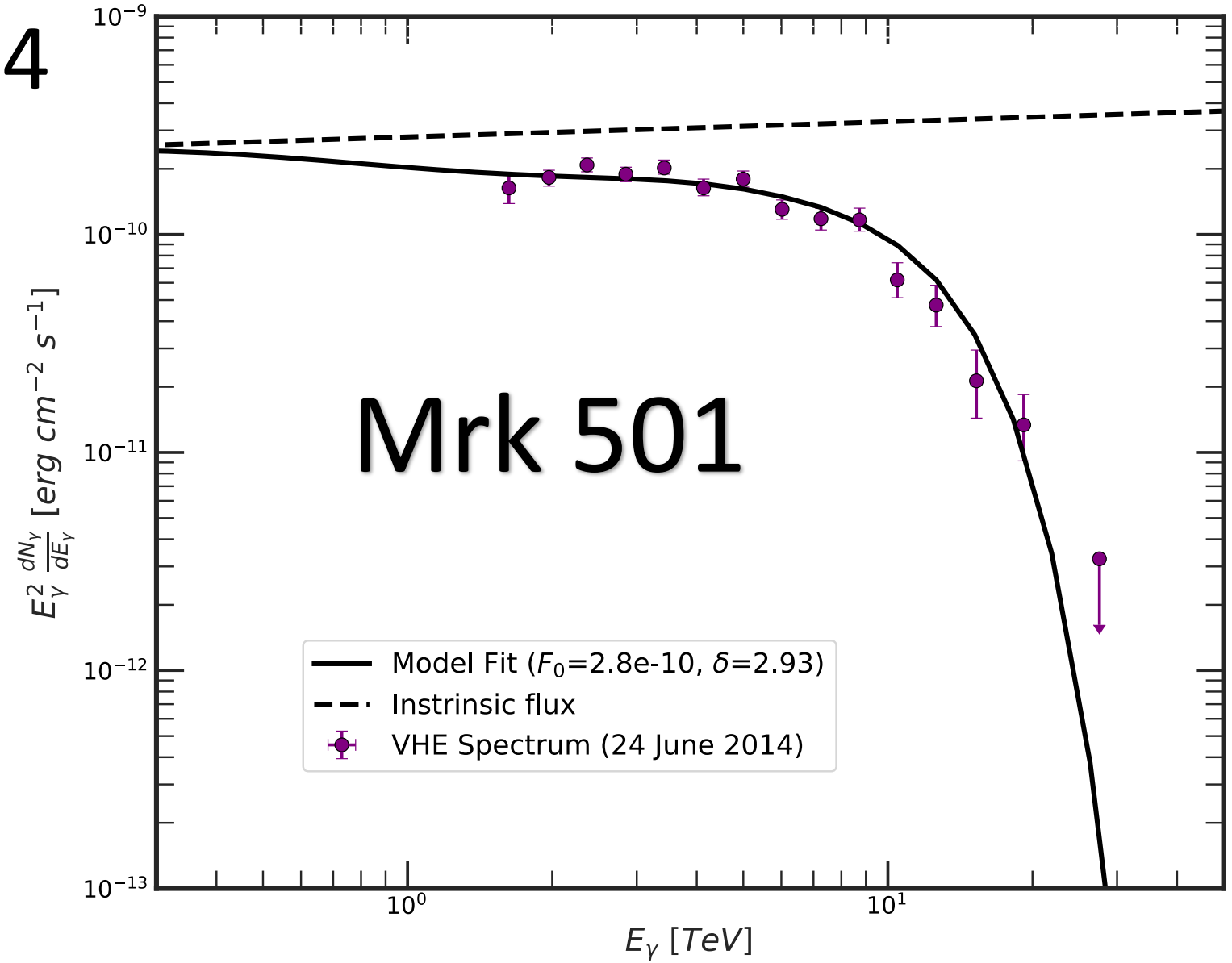
In the above three articles we have developed and fine tuned the Two-Zone Photohadronic model by explaining the observed flaring events successfully.

Mrk 501

- Discovered in 1996, next nearest BL Lac object (after Mrk 421)
- Extensively studied in multiwavelengths HBL by several telescopes in low, high and very high energies.
- Two episodes of very-high-energy gamma-ray flaring events during 2005 May–July and 2012 June are of special significance, as the source exhibited extreme HBL-like behavior.
- The successful standard photohadronic model does not adequately explain these extraneous behaviors.

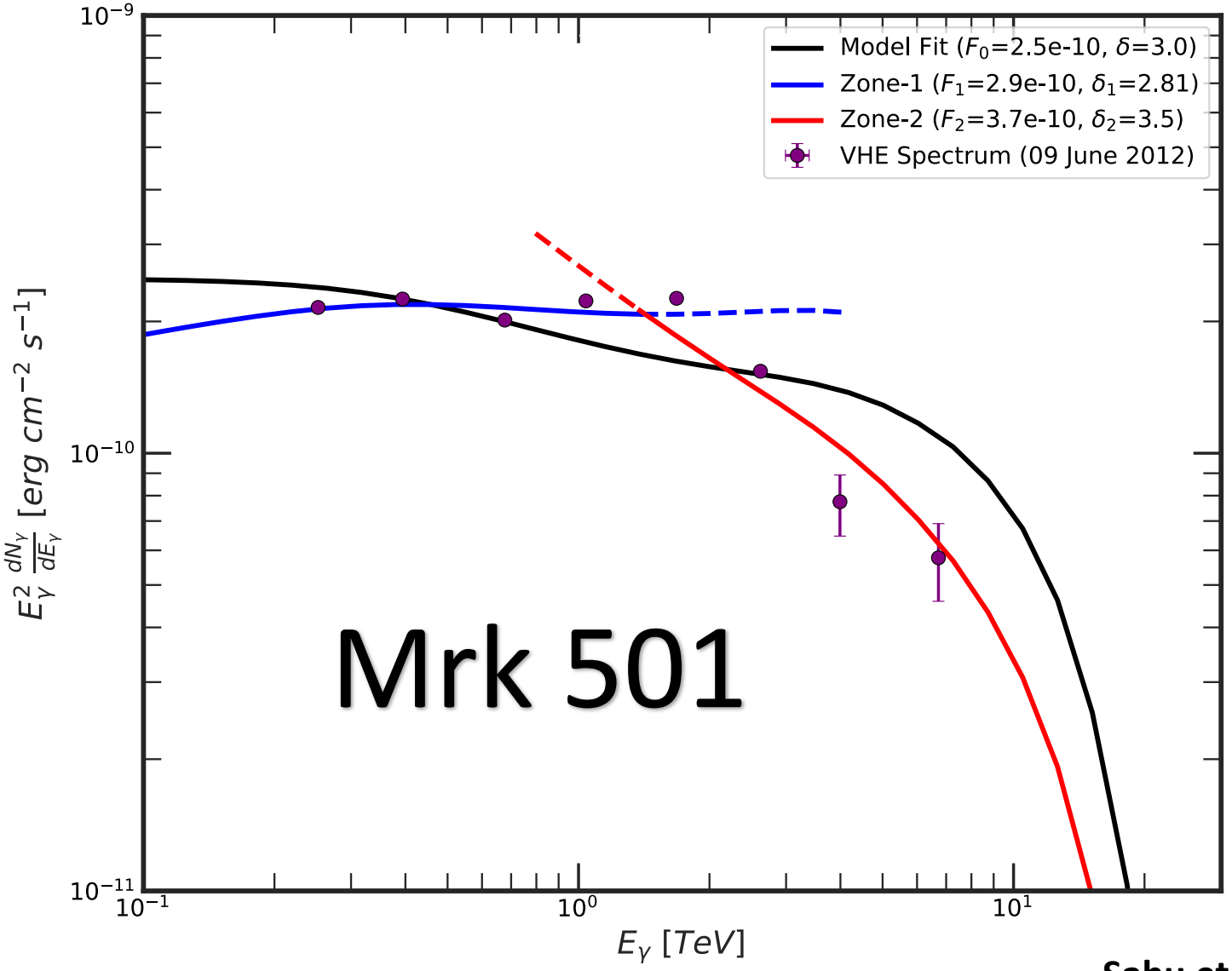
For Normal HBL Behavior

z=0.034



Sahu et al., ApJL (2019)

Temporary EHBL-Like



MAGIC

Sahu et al, ApJ (2020)

Extending the Photohadronic Model to include Two-Zones

$$\Phi_{SSC} \propto \begin{cases} E_\gamma^{-\beta_1}, & 100\,\mathrm{GeV} \lesssim \mathrm{E}_\gamma \lesssim \mathrm{E}_\gamma^{\mathrm{intd}} \\ E_\gamma^{-\beta_2}, & \mathrm{E}_\gamma \gtrsim \mathrm{E}_\gamma^{\mathrm{intd}} \end{cases} . \qquad (\beta_1 \neq \beta_2).$$

$$F_{\gamma,obs} = e^{-\tau_{\gamma\gamma}} \times \begin{cases} F_1 \left(\frac{E_\gamma}{TeV}\right)^{-\delta_1+3}, & 100\,\mathrm{GeV} \lesssim \mathrm{E}_\gamma \lesssim \mathrm{E}_\gamma^{\mathrm{intd}} \quad (\text{zone-1}) \\ F_2 \left(\frac{E_\gamma}{TeV}\right)^{-\delta_2+3}, & \mathrm{E}_\gamma \gtrsim \mathrm{E}_\gamma^{\mathrm{intd}} \quad (\text{zone-2}) \end{cases},$$

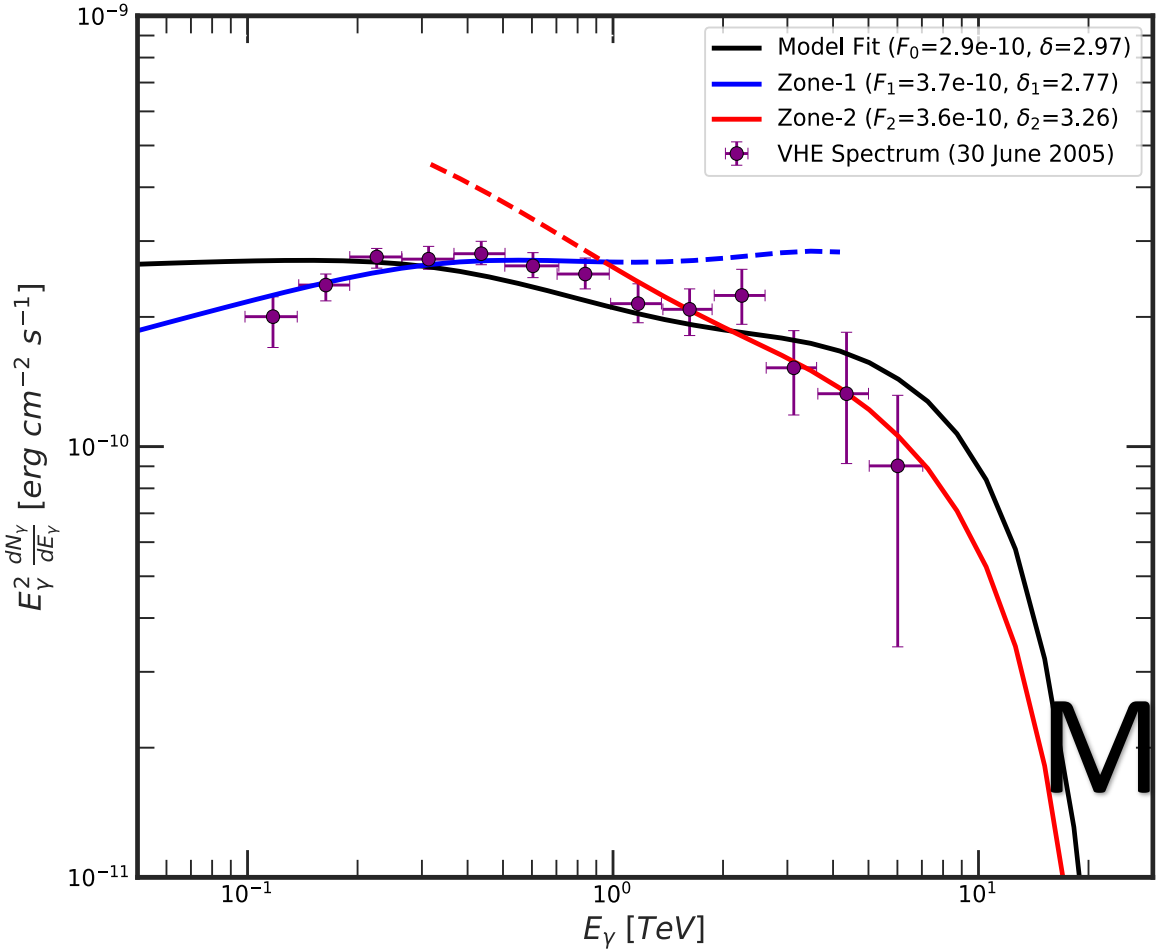
$$\delta_i = \alpha + \beta_i \ (i = 1, 2)$$

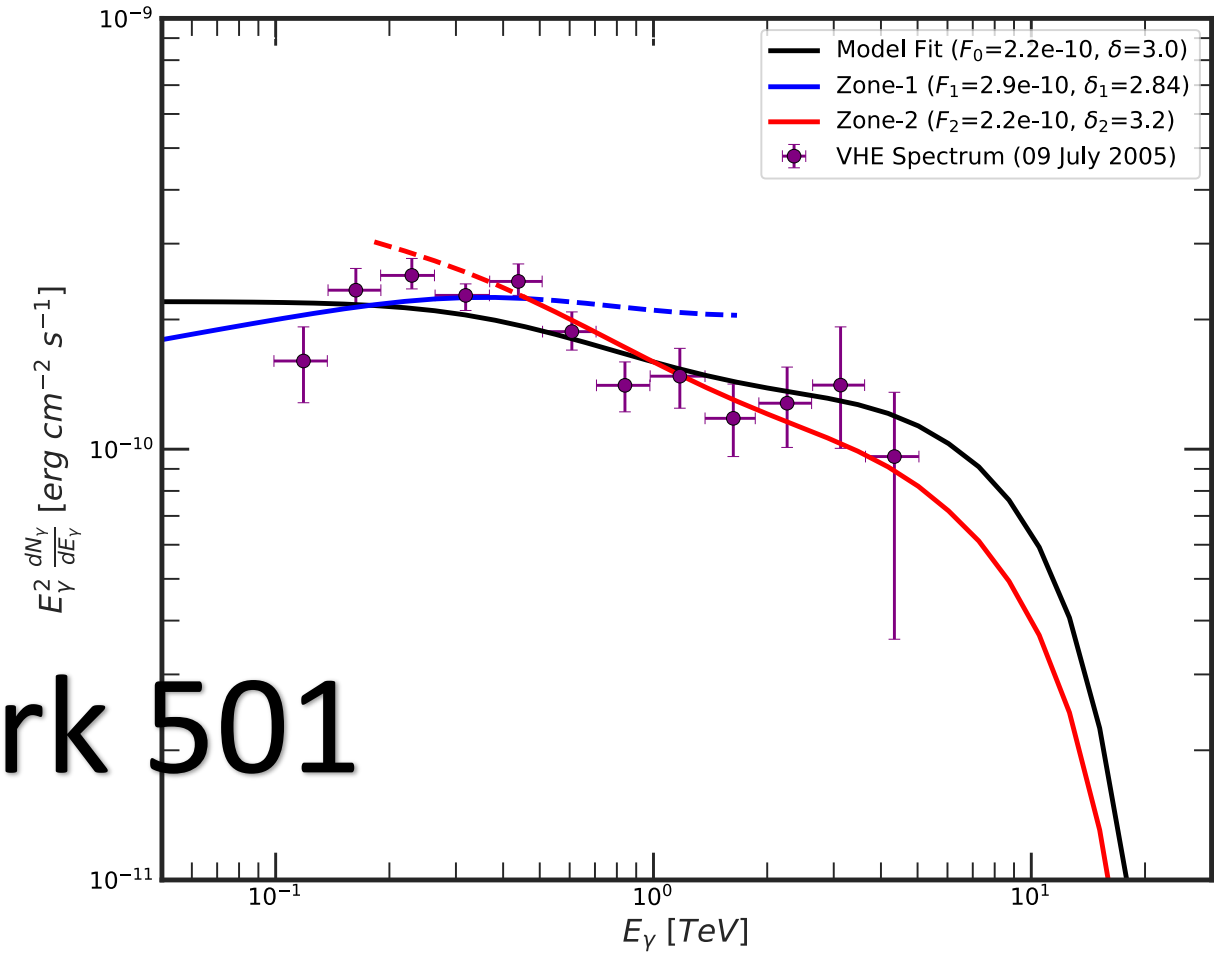
$2.5 \leq \delta_1 \leq 3.0$ Same as HBL

$3.0 < \delta_2 \leq 3.5$ New Branch

E_γ^{intd} → Energy scale around which the transition between Zone-1 and Zone-2 takes place

Temporary EHBL-Like





Mrk 501

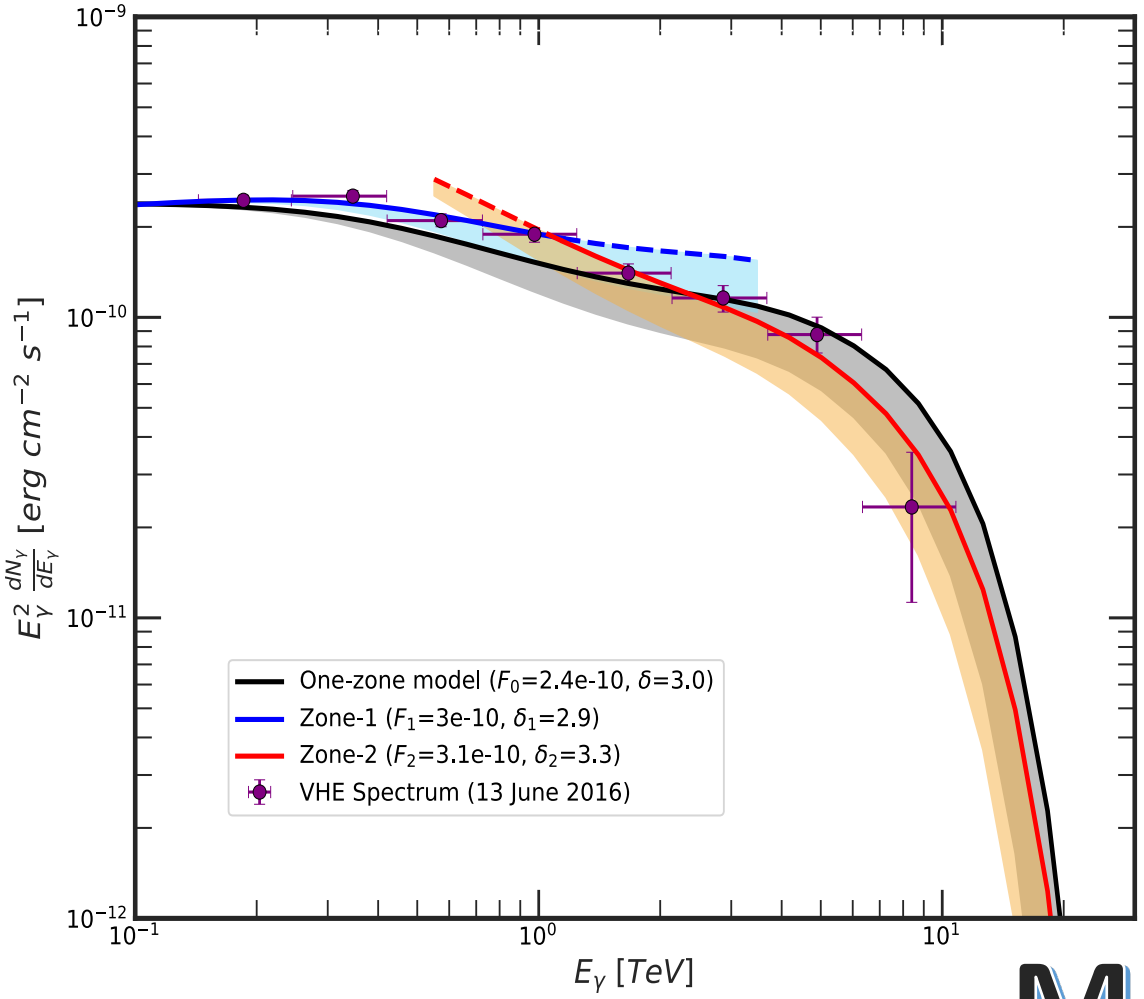
MAGIC

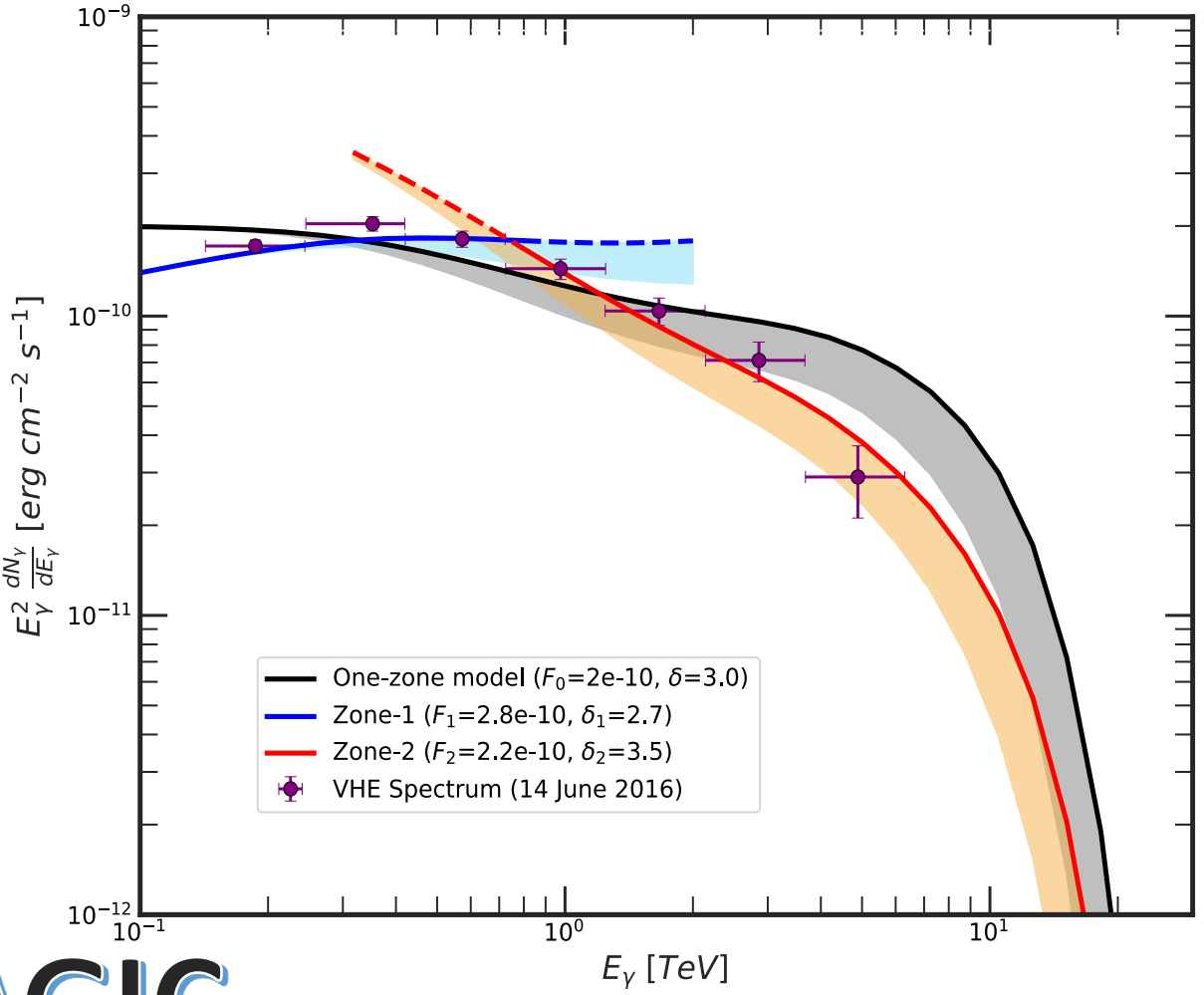
Sahu et al, ApJ (2020)

1ES 1959+650

- It is a well-known and well studied HBL and undergone several eipsodes of multi-TeV flaring.
- During a multiwavelength campaign from 2016 April 29 to November 21, MAGIC telescopes observed multi-TeV flarings during the nights of 2016 June 13 and 14 and July 1 when the position of the synchrotron peak was found to be above 10^{17} Hz.

1ES 1959+650 (z=0.048)

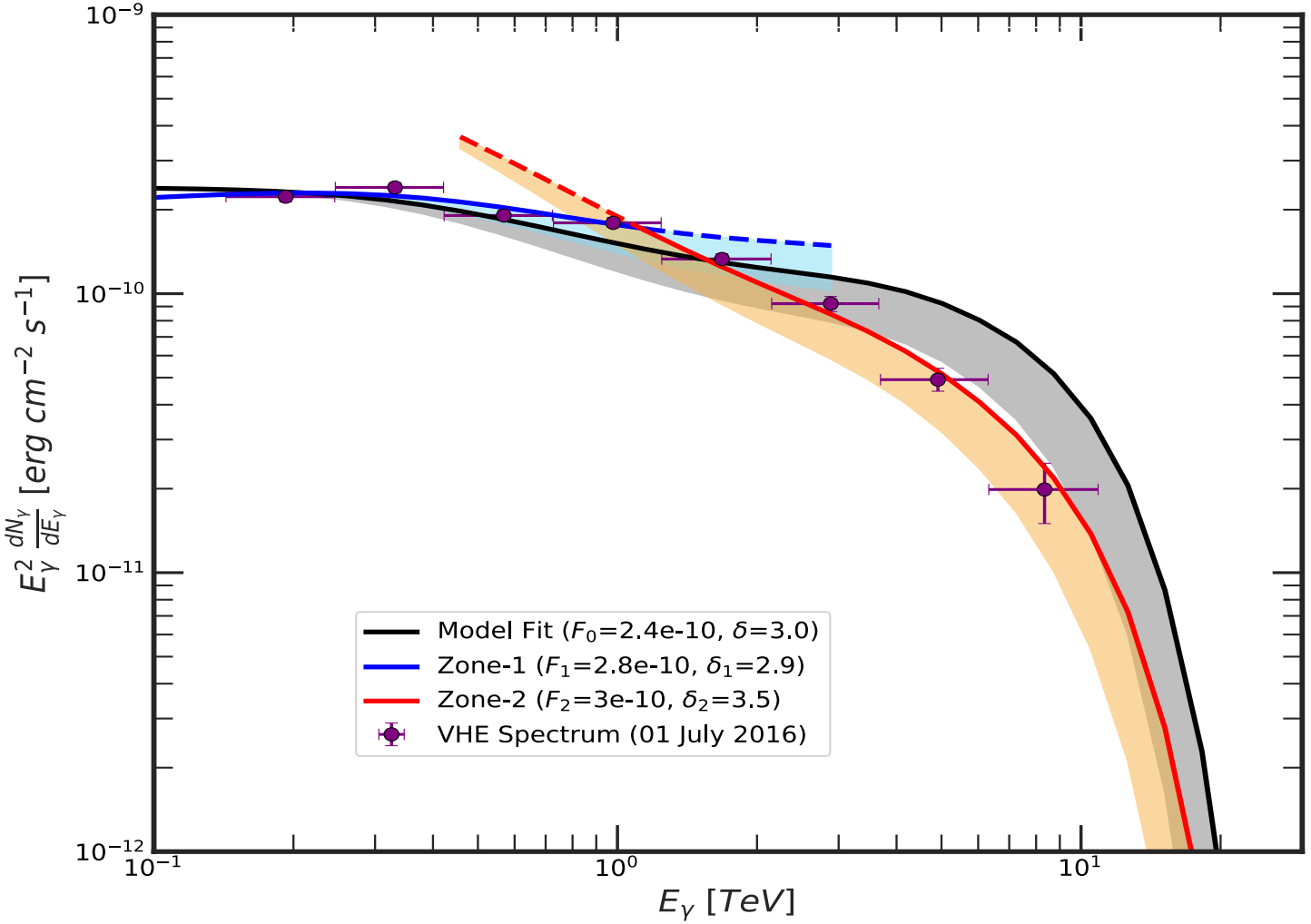




MAGIC

1ES 1959+650

Sahu et al, ApJ (2021)



MAGIC

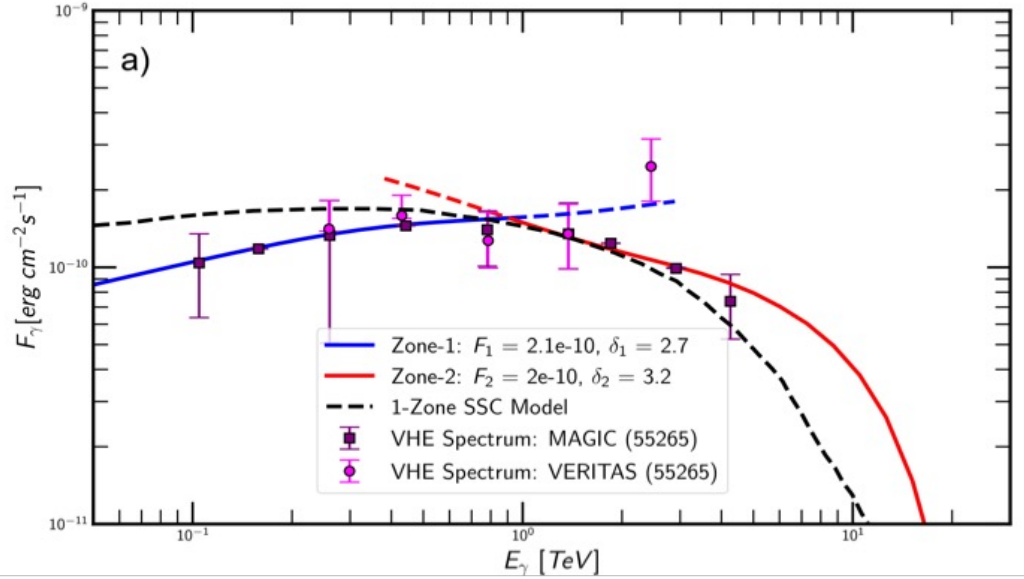
Mrk 421

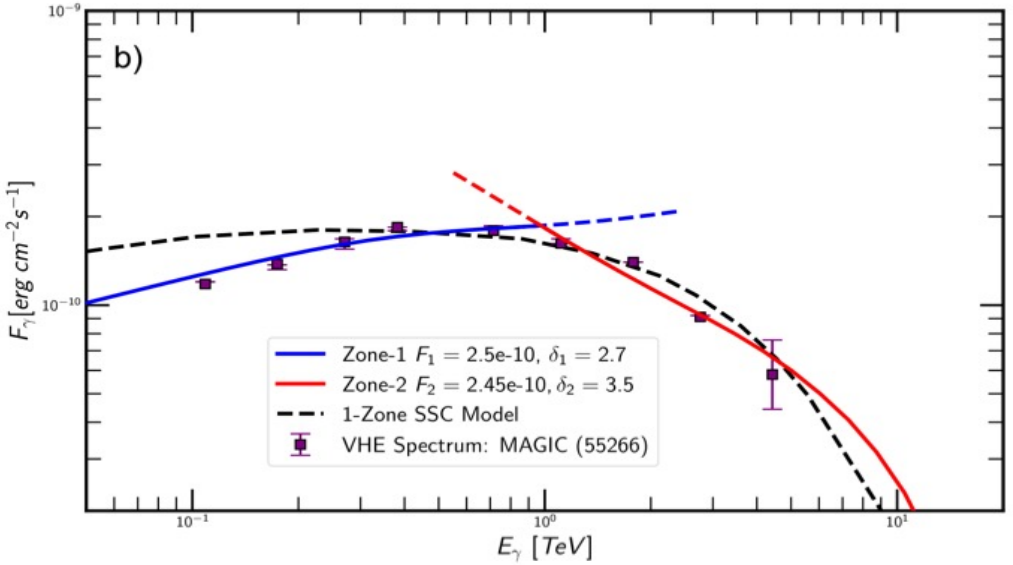
- Markarian 421 is the nearest high-energy peaked blazar and is also the first extragalactic source to be detected in multi-TeV γ-rays.
- It has been observed in multiwavelength for an exceptionally long period of time with dense monitoring and several major outbursts have been detected from this source.
- In 2010 March, the source was in a high state of activity and was observed in multiwavelength by various telescopes for 13 consecutive days.
- During this period the position of the synchrotron peak was found to be above 10^{17} Hz and also the position of the second peak was shifted toward higher energy, a signature of extreme HBL-like behavior.

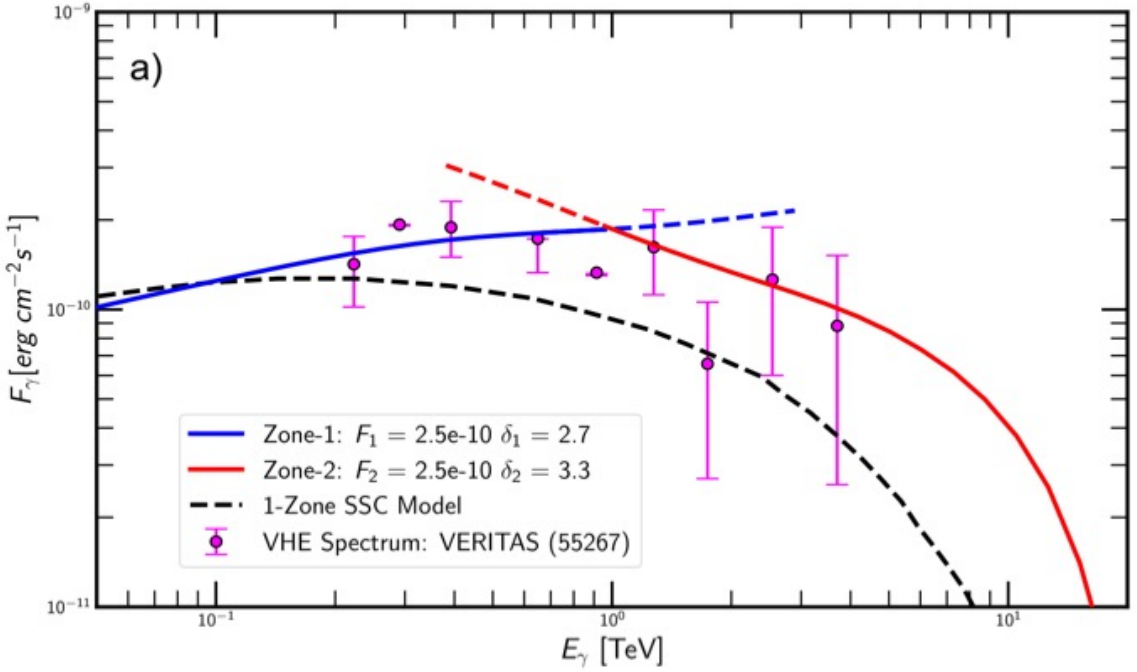
Mrk 421 (z=0.031)

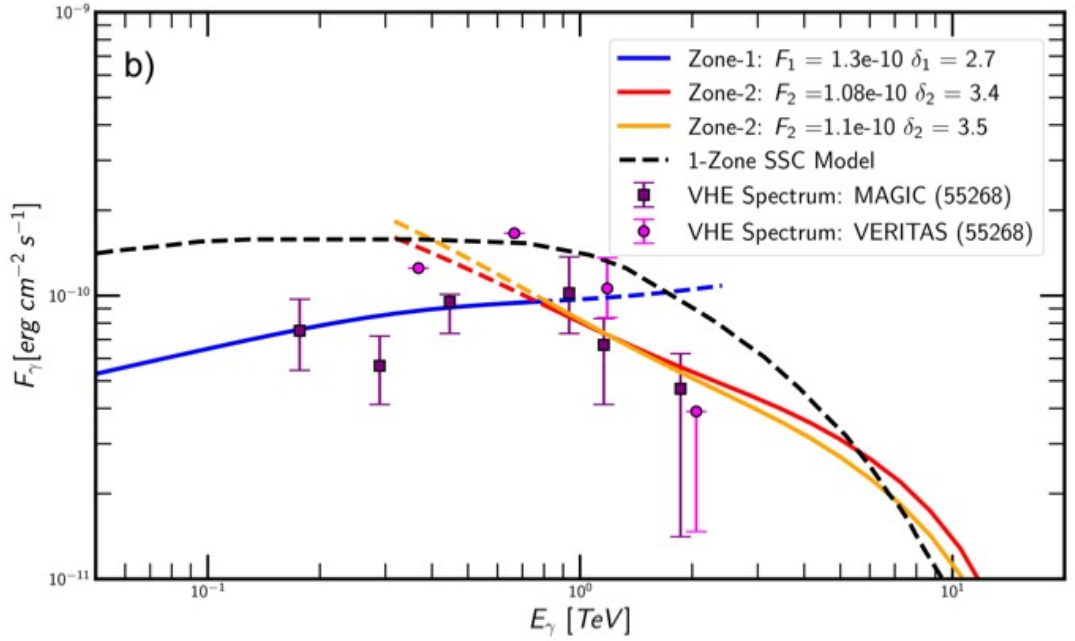
Observed for 13 consecuitive nights in 2010 March 10 (MJD 55265) to March 22 (55277) by MAGIC and VERITAS Telescopes

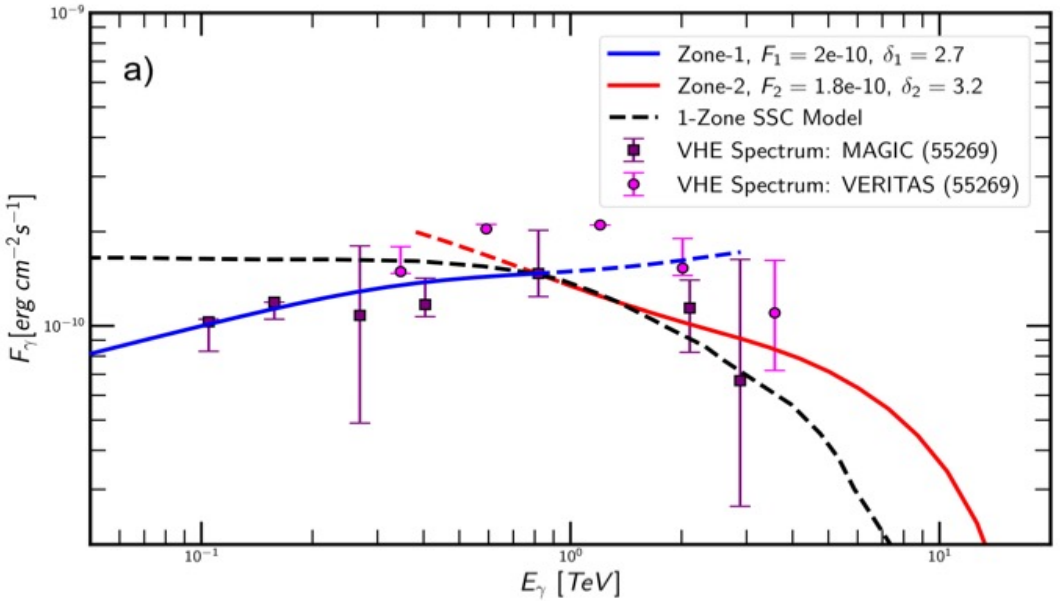
Sahu et al, ApJ (2021)

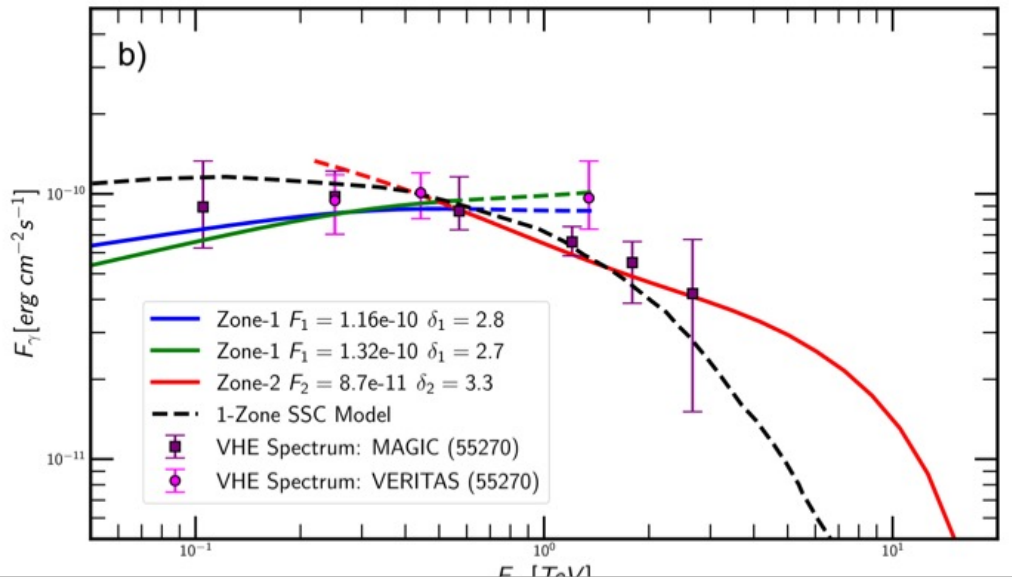

a)
Zone-1: F_1 = 2.1e-10, δ_1 = 2.7
Zone-2: F_2 = 2e-10, δ_2 = 3.2
1-Zone SSC Model
VHE Spectrum: MAGIC (55265)
VHE Spectrum: VERITAS (55265)
$F_\gamma [erg\ cm^{-2} s^{-1}]$
E_γ [TeV]

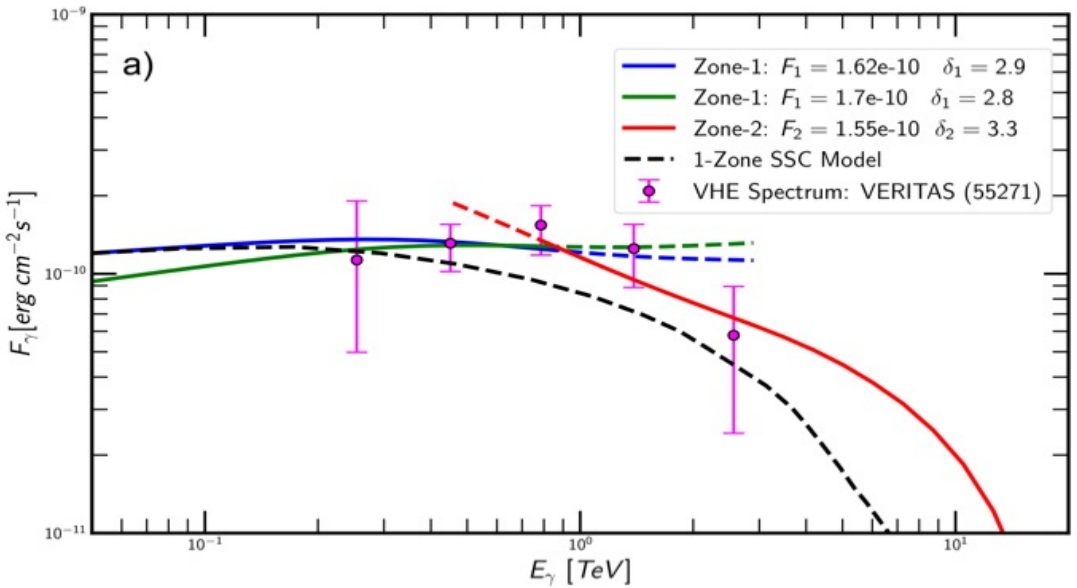

b)
Zone-1 F_1 = 2.5e-10, δ_1 = 2.7
Zone-2 F_2 = 2.45e-10, δ_2 = 3.5
1-Zone SSC Model
VHE Spectrum: MAGIC (55266)
$F_\gamma [erg\ cm^{-2} s^{-1}]$
E_γ [TeV]

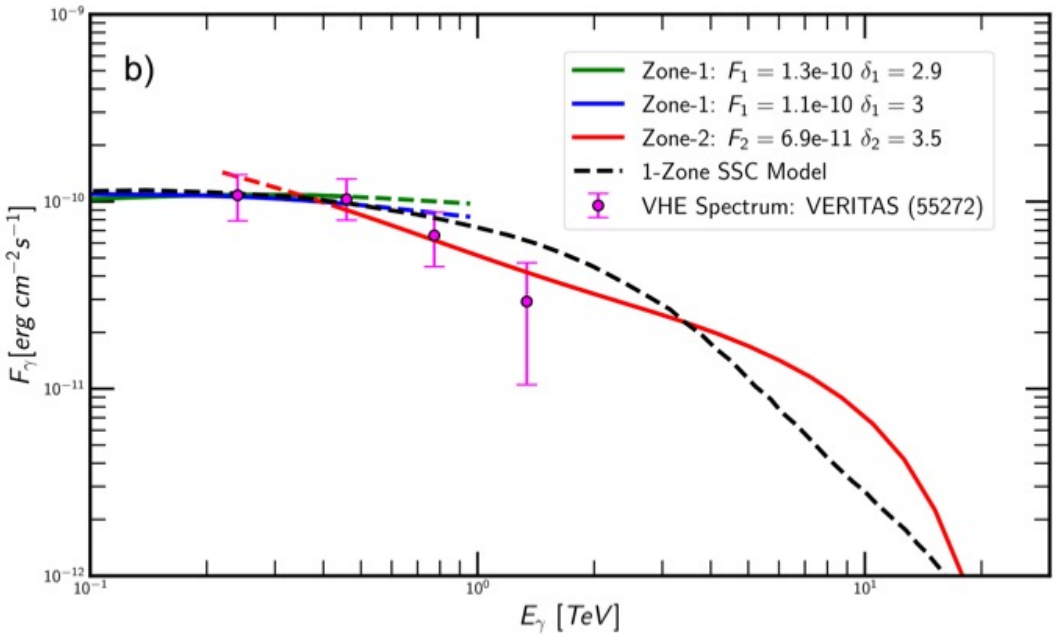

a)
Zone-1: F_1 = 2.5e-10 δ_1 = 2.7
Zone-2: F_2 = 2.5e-10 δ_2 = 3.3
1-Zone SSC Model
VHE Spectrum: VERITAS (55267)
$F_\gamma [erg\ cm^{-2} s^{-1}]$
E_γ [TeV]

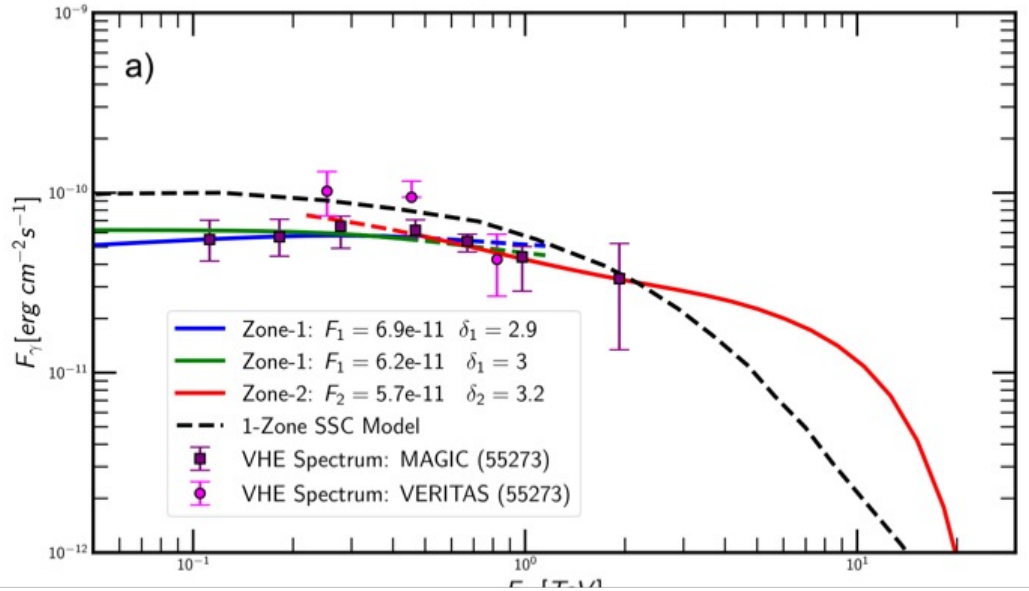

b)
Zone-1: F_1 = 1.3e-10 δ_1 = 2.7
Zone-2: F_2 =1.08e-10 δ_2 = 3.4
Zone-2: F_2 =1.1e-10 δ_2 = 3.5
1-Zone SSC Model
VHE Spectrum: MAGIC (55268)
VHE Spectrum: VERITAS (55268)
$F_\gamma [erg\ cm^{-2} s^{-1}]$
E_γ [TeV]

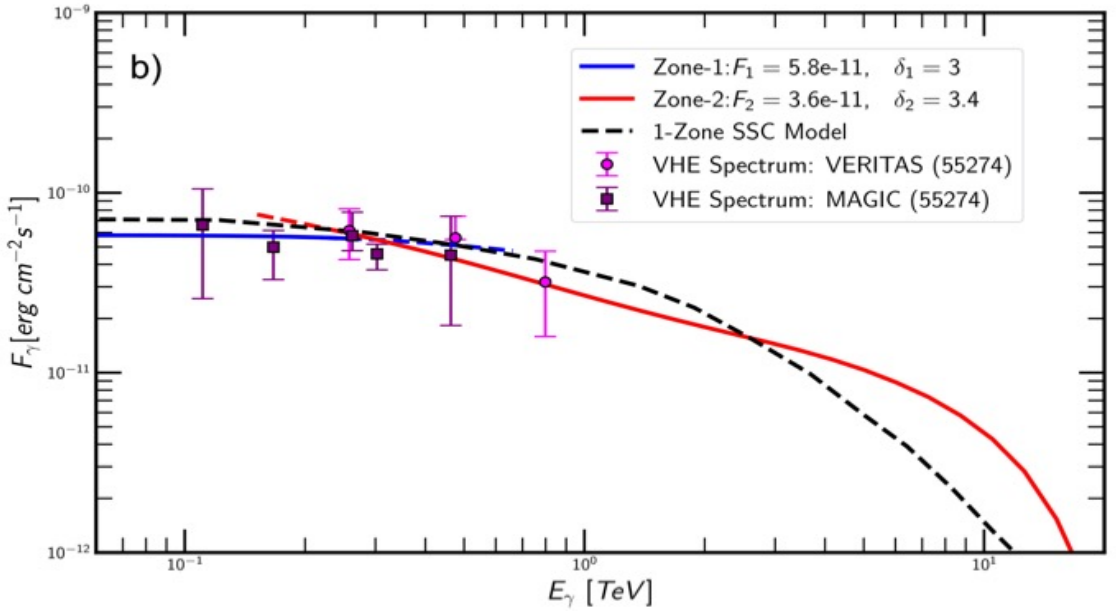

a)
Zone-1, F_1 = 2e-10, δ_1 = 2.7
Zone-2, F_2 = 1.8e-10, δ_2 = 3.2
1-Zone SSC Model
VHE Spectrum: MAGIC (55269)
VHE Spectrum: VERITAS (55269)
$F_\gamma [erg\ cm^{-2} s^{-1}]$
E_γ [TeV]

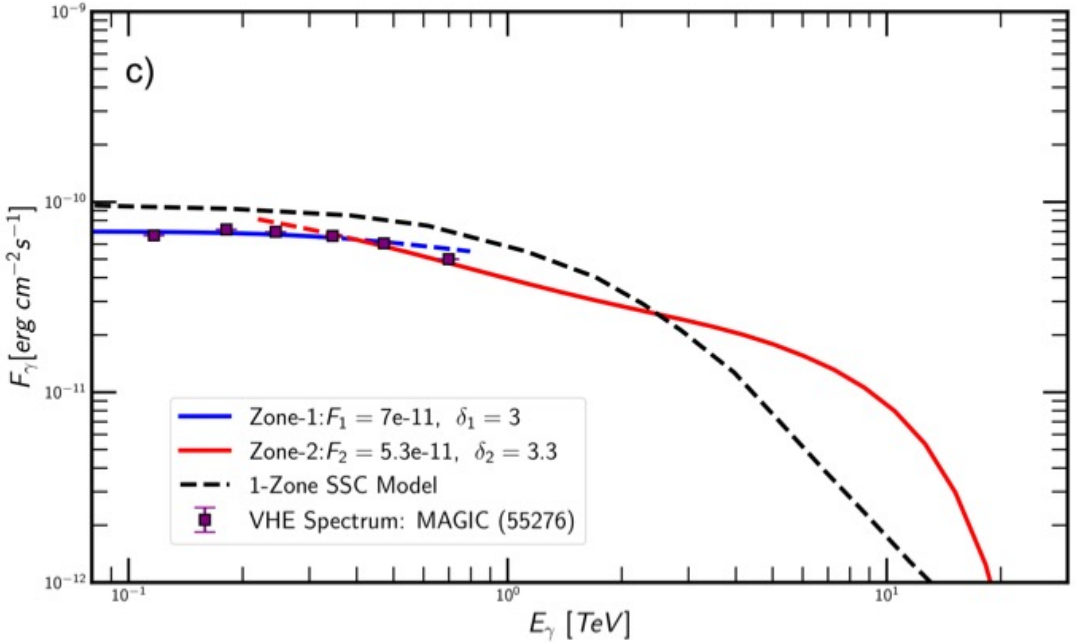

b)
Zone-1 F_1 = 1.16e-10 δ_1 = 2.8
Zone-1 F_1 = 1.32e-10 δ_1 = 2.7
Zone-2 F_2 = 8.7e-11 δ_2 = 3.3
1-Zone SSC Model
VHE Spectrum: MAGIC (55270)
VHE Spectrum: VERITAS (55270)
$F_\gamma [erg\ cm^{-2} s^{-1}]$

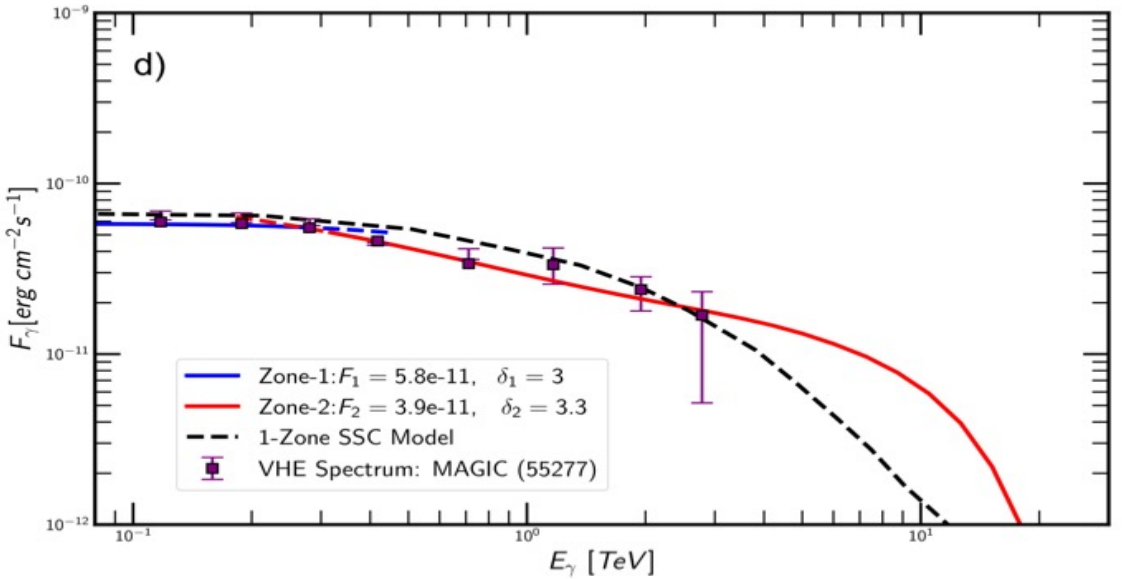

a)
Zone-1: F_1 = 1.62e-10 δ_1 = 2.9
Zone-1: F_1 = 1.7e-10 δ_1 = 2.8
Zone-2: F_2 = 1.55e-10 δ_2 = 3.3
1-Zone SSC Model
VHE Spectrum: VERITAS (55271)
$F_\gamma [erg\ cm^{-2} s^{-1}]$
E_γ [TeV]


b)
Zone-1: F_1 = 1.3e-10 δ_1 = 2.9
Zone-1: F_1 = 1.1e-10 δ_1 = 3
Zone-2: F_2 = 6.9e-11 δ_2 = 3.5
1-Zone SSC Model
VHE Spectrum: VERITAS (55272)
$F_\gamma [erg\ cm^{-2} s^{-1}]$
E_γ [TeV]


a)
Zone-1: $F_1 = 6.9e\text{-}11$ $\delta_1 = 2.9$
Zone-1: $F_1 = 6.2e\text{-}11$ $\delta_1 = 3$
Zone-2: $F_2 = 5.7e\text{-}11$ $\delta_2 = 3.2$
1-Zone SSC Model
VHE Spectrum: MAGIC (55273)
VHE Spectrum: VERITAS (55273)
$F_\gamma [erg\ cm^{-2} s^{-1}]$


b)
Zone-1:$F_1 = 5.8e\text{-}11$, $\delta_1 = 3$
Zone-2:$F_2 = 3.6e\text{-}11$, $\delta_2 = 3.4$
1-Zone SSC Model
VHE Spectrum: VERITAS (55274)
VHE Spectrum: MAGIC (55274)
$F_\gamma [erg\ cm^{-2} s^{-1}]$
E_γ [TeV]


c)
Zone-1:$F_1 = 7e\text{-}11$, $\delta_1 = 3$
Zone-2:$F_2 = 5.3e\text{-}11$, $\delta_2 = 3.3$
1-Zone SSC Model
VHE Spectrum: MAGIC (55276)
$F_\gamma [erg\ cm^{-2} s^{-1}]$
E_γ [TeV]


d)
Zone-1:$F_1 = 5.8e\text{-}11$, $\delta_1 = 3$
Zone-2:$F_2 = 3.9e\text{-}11$, $\delta_2 = 3.3$
1-Zone SSC Model
VHE Spectrum: MAGIC (55277)
$F_\gamma [erg\ cm^{-2} s^{-1}]$
E_γ [TeV]

Conclusions:

A new class: Occasionally/Temporarily some (maybe all) HBLs cross their Synchrotron limits $\nu_s > 10^{17}$ Hz and similarly their VHE emission also go beyond few TeVs. (tEHBL)

This clearly shows that the Bulk Lorentz Factor of the Jet moving in the forward direction is very high compared to the HBL. This corresponds to high proton energy and can be a Ultra High Energy Cosmic Ray (UHECR). But we have not seen such UHECR.

Also, this can be responsible for the protonduction of High Energy neutrinos observed by IceCube. There are some indications, but statistically not so relevant.

We have to wait many more years ……

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Thank You