Are Blazars sources of high energy neutrinos ?

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- Introduction
- IceCube Neutrino Telescope
- Classification of AGN
- Observations
  - Neutrino
  - GeV-TeV Gamma-ray
- Possible theoretical interpretation
- Future observations

- Introduction

- Birth place of ultra-high energy cosmic rays (UHECRs) in the Universe is a long standing mystery.
- The observed distribution of the arrival directions of UHECRs in the sky favor *predominantly extragalactic* origin.
- Among the numerous candidates (AGN, GRBs, starburst galaxies etc.) most promising are active galactic nuclei (AGN) which eject powerful relativistic jets and high energy particles can be accelerated in it.
- Interaction of these UHECRs with background protons or photons produce charged and neutral pions which subsequently produce neutrinos and gamma-rays.
- Apart from solar and supernova neutrinos we are able to see neutrinos from other cosmological source(s) for the first time.

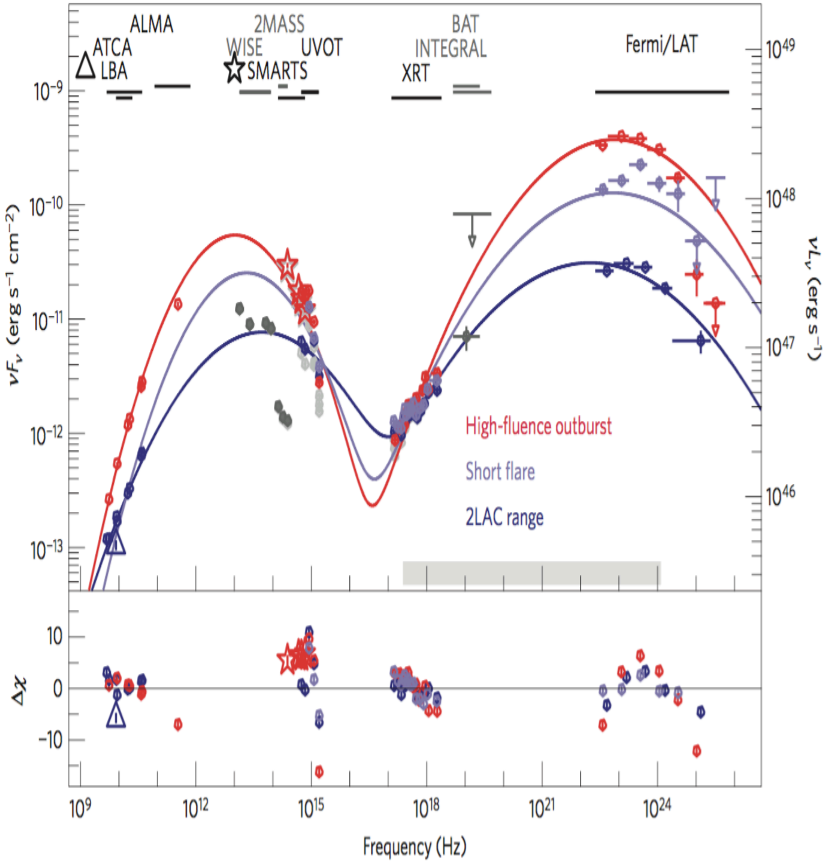
Previous Observations:

Nature 12, 807 (2016)

nature physics
ARTICLES
PUBLISHED ONLINE: 18 APRIL 2016 | DOI: 10.1038/NPHYS3715

Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event

M. Kadler[1*], F. Krauß[1,2], K. Mannheim[1], R. Ojha[3,4,5], C. Müller[1,6], R. Schulz[1,2], G. Anton[7], W. Baumgartner[3], T. Beuchert[1,2], S. Buson[8,9], B. Carpenter[5], T. Eberl[7], P. G. Edwards[10], D. Eisenacher Glawion[1], D. Elsässer[1], N. Gehrels[3], C. Gräfe[1,2], S. Gulyaev[11], H. Hase[12], S. Horiuchi[13], C. W. James[7], A. Kappes[1], A. Kappes[7], U. Katz[7], A. Kreikenbohm[1,2], M. Kreter[1,7], I. Kreykenbohm[2], M. Langejahn[1,2], K. Leiter[1,2], E. Litzinger[1,2], F. Longo[14,15], J. E. J. Lovell[16], J. McEnery[3], T. Natusch[11], C. Phillips[10], C. Plötz[12], J. Quick[17], E. Ros[18,19,20], F. W. Stecker[3,21], T. Steinbring[1,2], J. Stevens[10], D. J. Thompson[3], J. Trüstedt[1,2], A. K. Tzioumis[10], S. Weston[11], J. Wilms[2] and J. A. Zensus[18]



e 2 | Dynamic SED of PKS B1424-418. The multi-epoch SEDs are fitted with two log parabolas for the 2LAC period (purple), the short 2010 flare

- In 2016 reported a PeV neutrino event (IC35) from the Blazar PKS B1424-418, detected by IceCube. A shower event (angular error 16^0)

Previous Observations:

- 2017 Lucareli et al.   Reported a gamma-ray precursor flare with AGILE, coincidence with IceCube tarck-like neutrino event but the significance was very marginal (**AGILE** (**A**stro-Rivelatore **G**amma a **I**mmagini **Le**ggero) is an X-ray and Gamma ray astronomical satellite of the Italian Space Agency (ASI) 30 MeV-50 GeV).

AGILE Detection of a Candidate Gamma-Ray Precursor to the ICECUBE-160731 Neutrino Event

F. Lucarelli[1,2], C. Pittori[1,2], F. Verrecchia[1,2], I. Donnarumma[3], M. Tavani[4,5,6], A. Bulgarelli[7], A. Giuliani[8], L. A. Antonelli[1,2], P. Caraveo[8], P. W. Cattaneo[9]Show full author list

Published 2017 September 8 •

The Astrophysical Journal, Volume 846, Number 2

- Recent Observation

On 22nd of September 2017, IceCube neutrino telescope in South Pole detected a track-like neutrino event with energy ~ 290 TeV (IceCube-170922A). It observed a upward-going muon E_{μ}=23.7±2.8 TeV

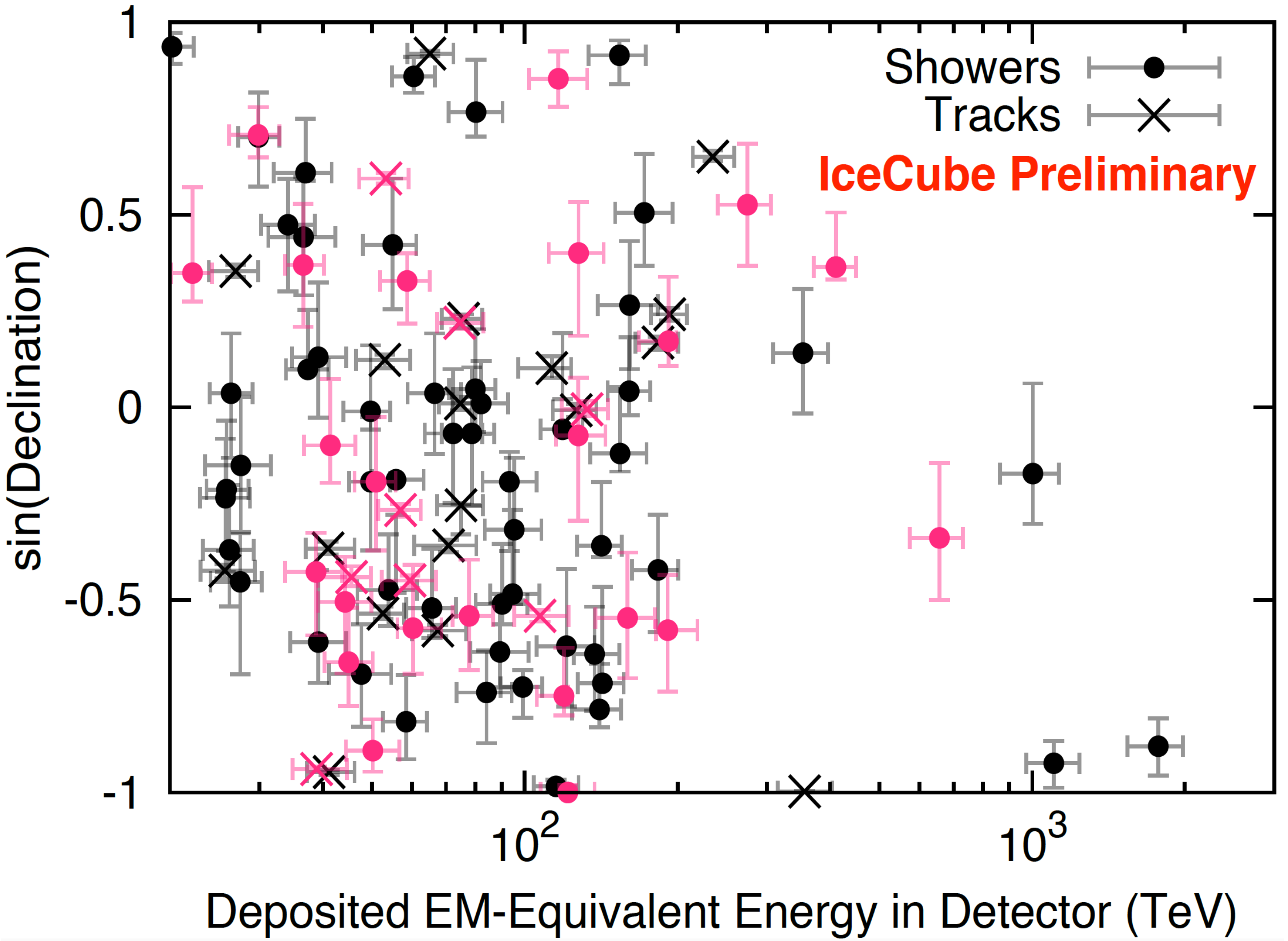
For the first time

- ❖This neutrino event is spatially and temporally associated with a Blazar TXS 056+056 (z=0.3365) which was in a flaring state in gamma-rays at that vary moment.
- ❖Extensive follow-up observation from Radio to TeV ⇛ Enhanced emission in all these energy bands.
- ❖Fermi-LAT (satellite) observed high state in GeV energy.
- ❖Major Atmospheric Gamma Imaging Telescope (MAGIC) observed > 100 GeV.
- ❖High-Energy Stereoscopic System (HESS) & Very Energetic Radiation Imaging Telescope Array System (VERITAS) did not observe any event.

Prior result 6 years ICRC 2017
arXiv:1710.01191

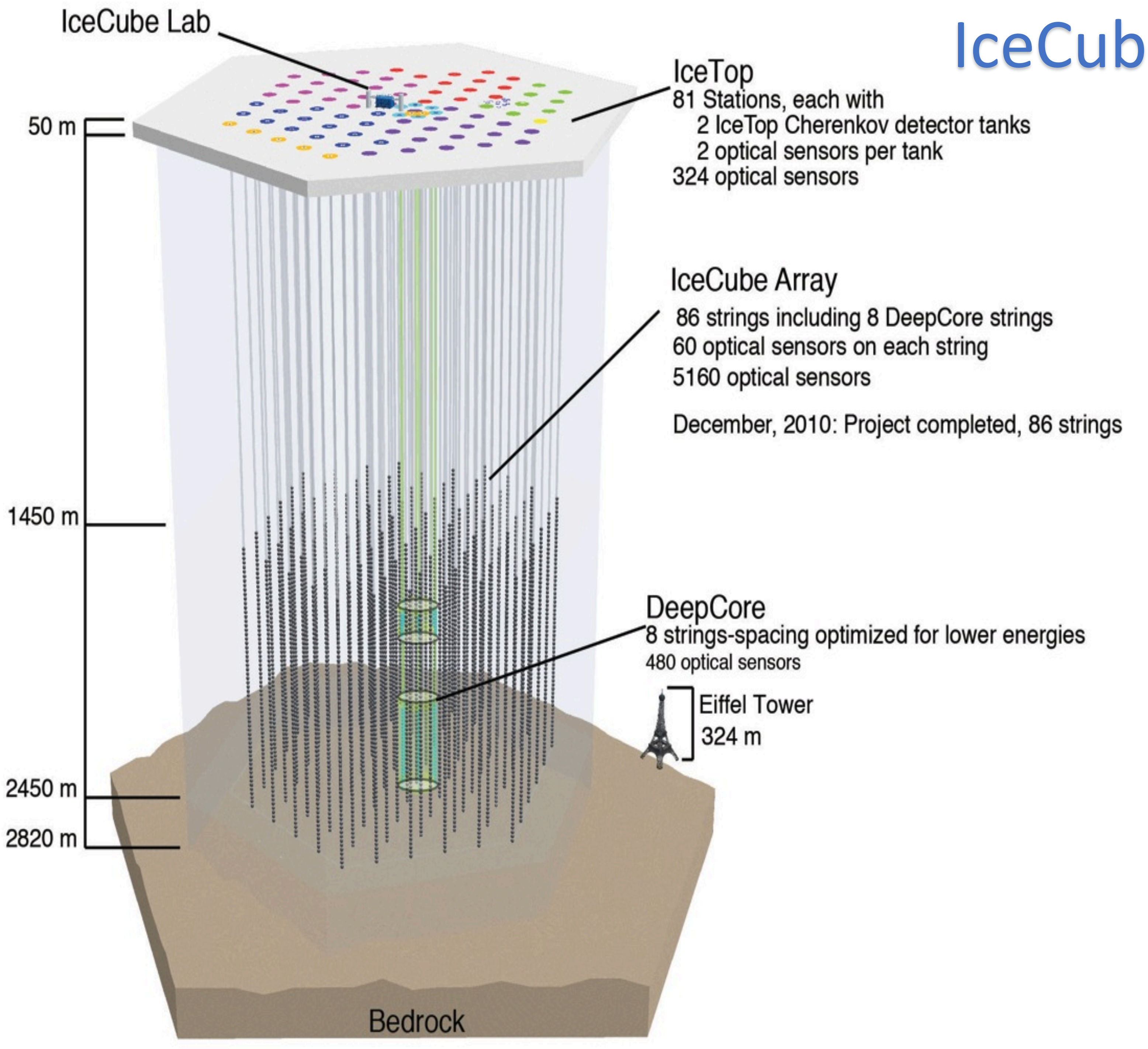
Updates to calibration and ice optical properties

103 events, with 60 events >60 TeV



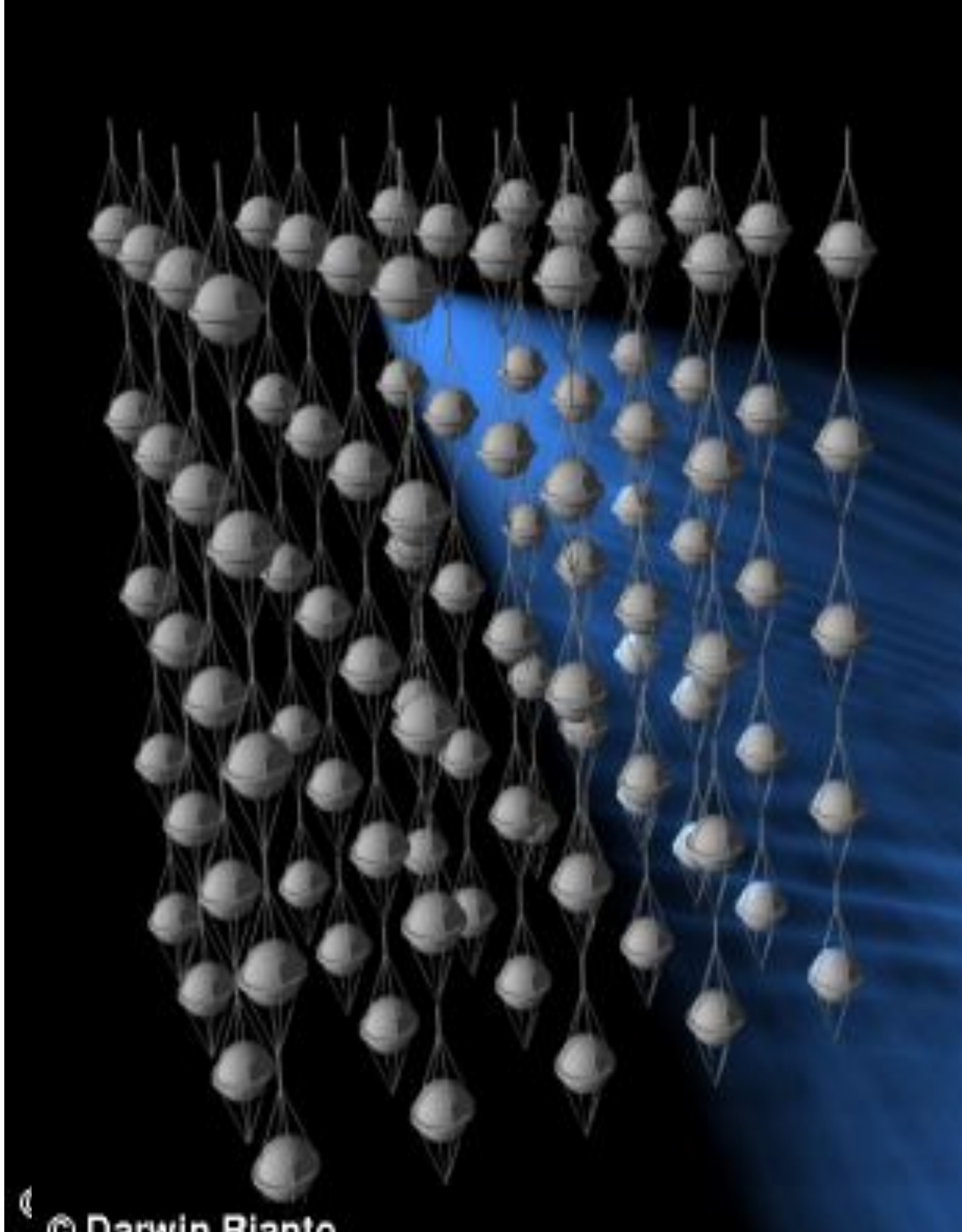
Association of IceCube-170922A with blazar TXS 0506+056 provides direct evidence that AGN can accelerate high energy CR and produce neutrinos from pp and/or pγ interactions.

IceCube Neutrino Telescope



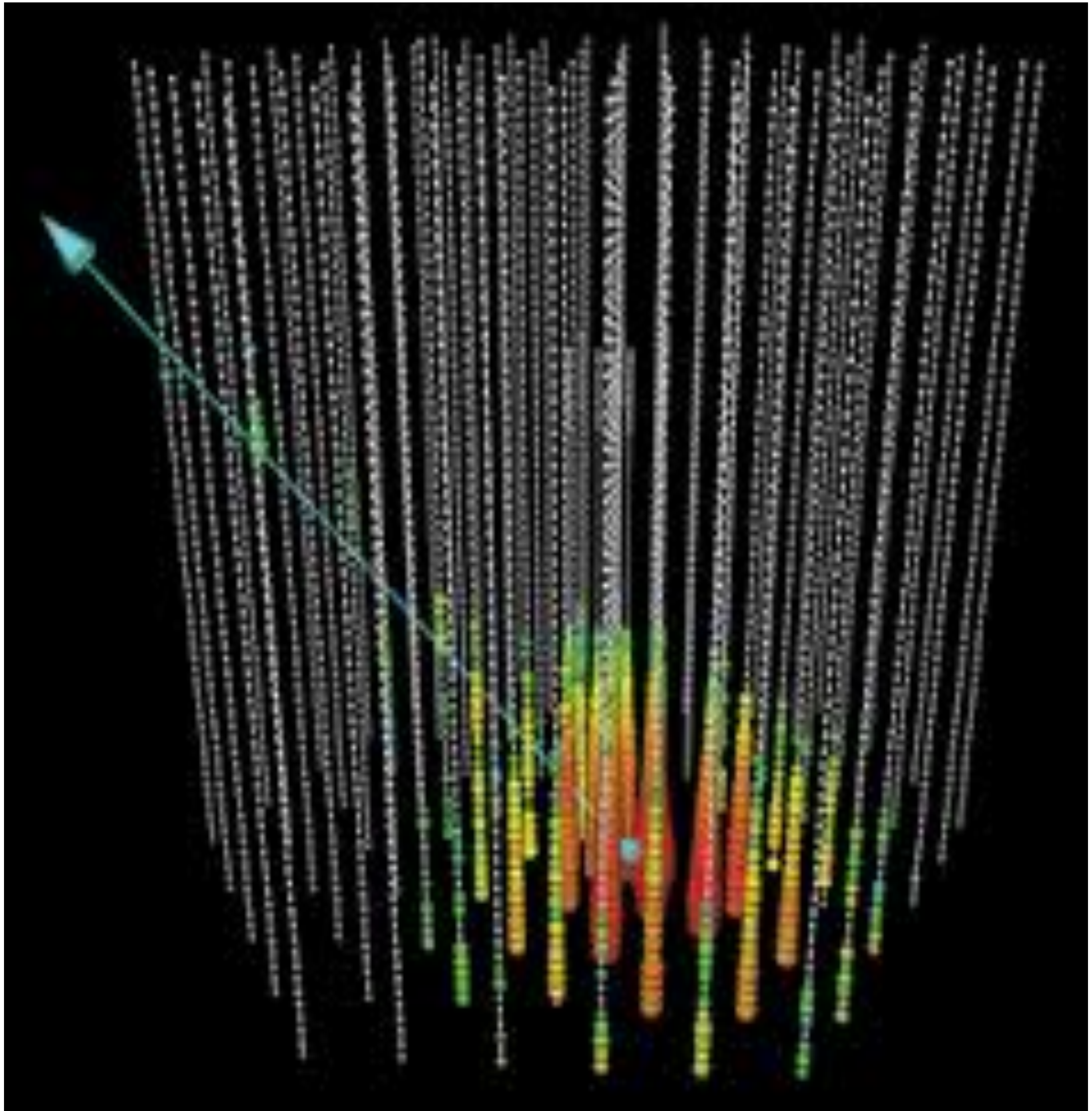
125 m apart

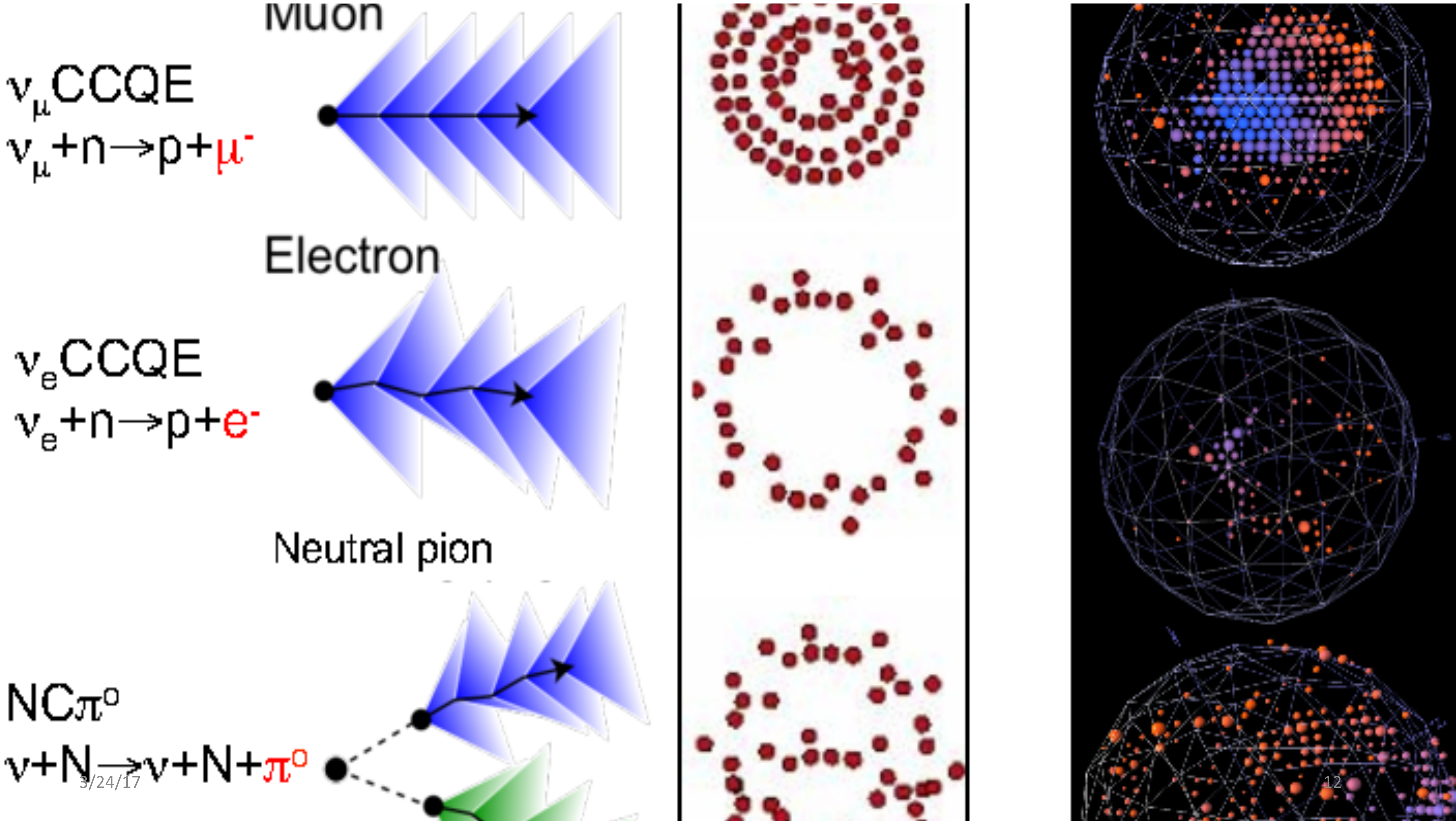
- Neutrino Telescope
  86 Strings
  160 IceTop tanks
  5480 Digital Optical Modules
  1 km^3 of instrumented volume
  completed on December 18th, 2010
  took approximately 7 years to complete
  Cost Approx. 279 million USD
  Collaboration:> 300 members, 48 Institutions, 12 countries



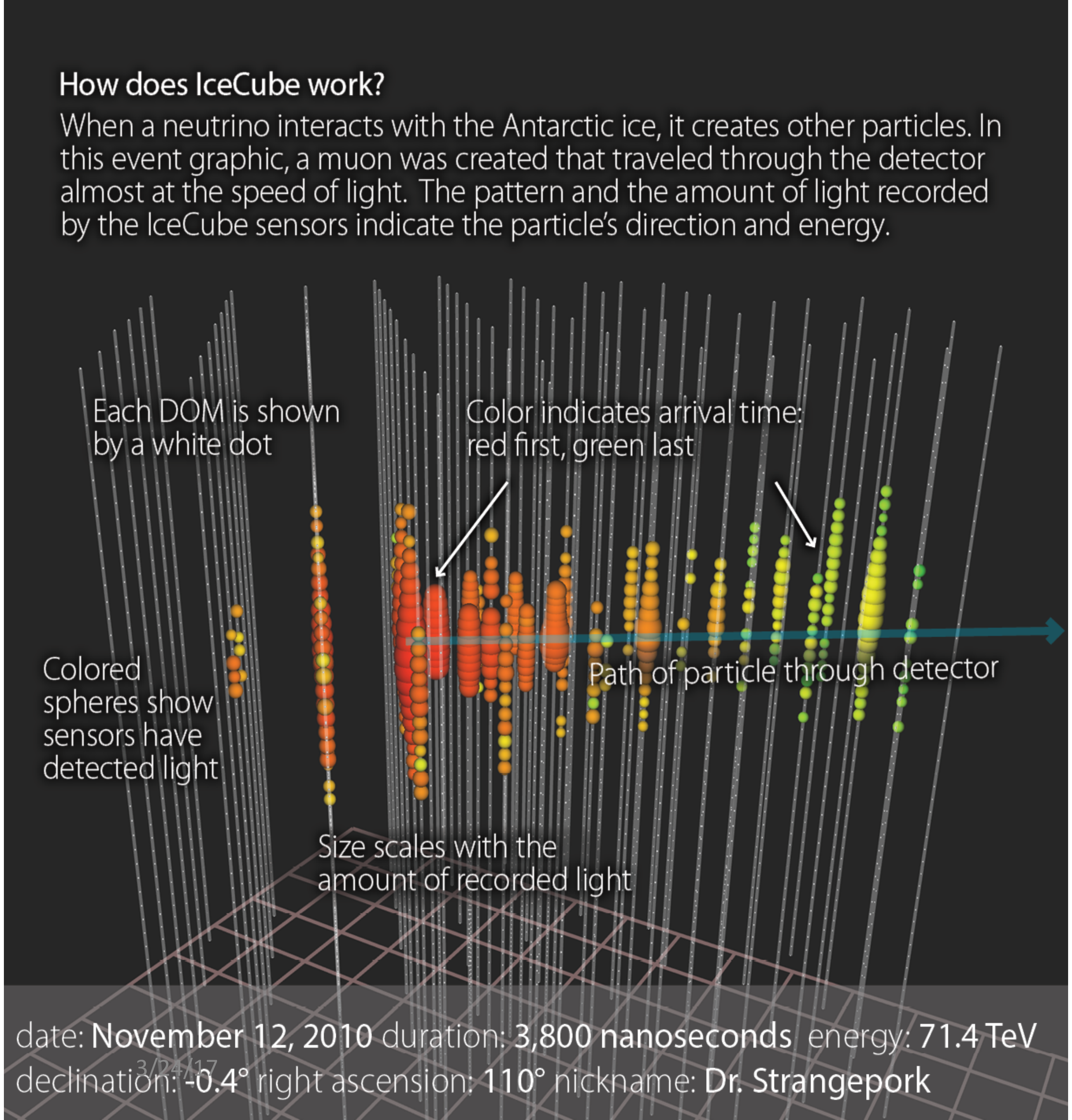
Two types of events:

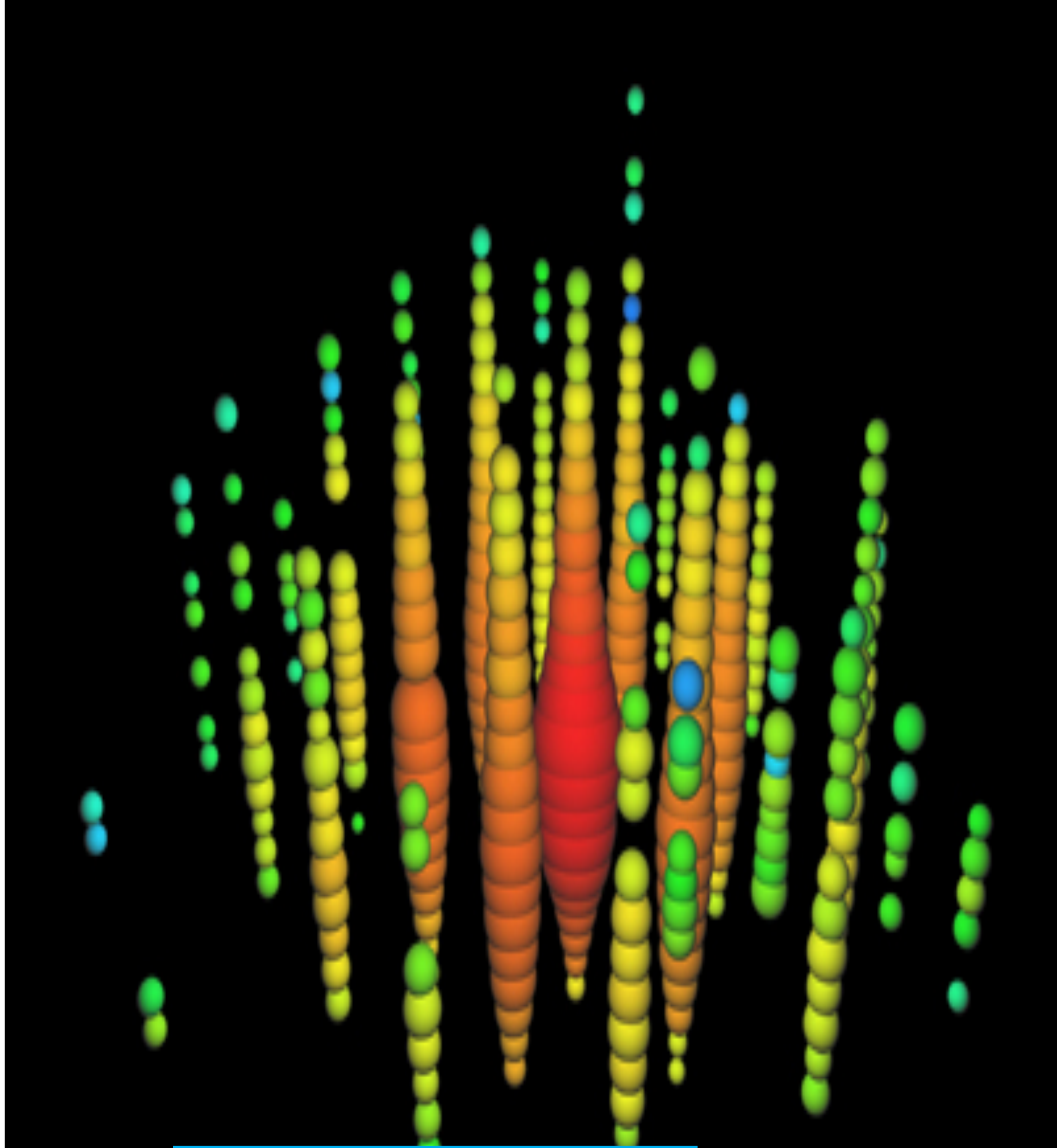
1. Shower Events
2. Track Events





Muon
ν_μCCQE
$\nu_\mu + n \rightarrow p + \mu^-$
Electron
ν_eCCQE
$\nu_e + n \rightarrow p + e^-$
Neutral pion
NCπ^o
$\nu + N \rightarrow \nu + N + \pi^o$

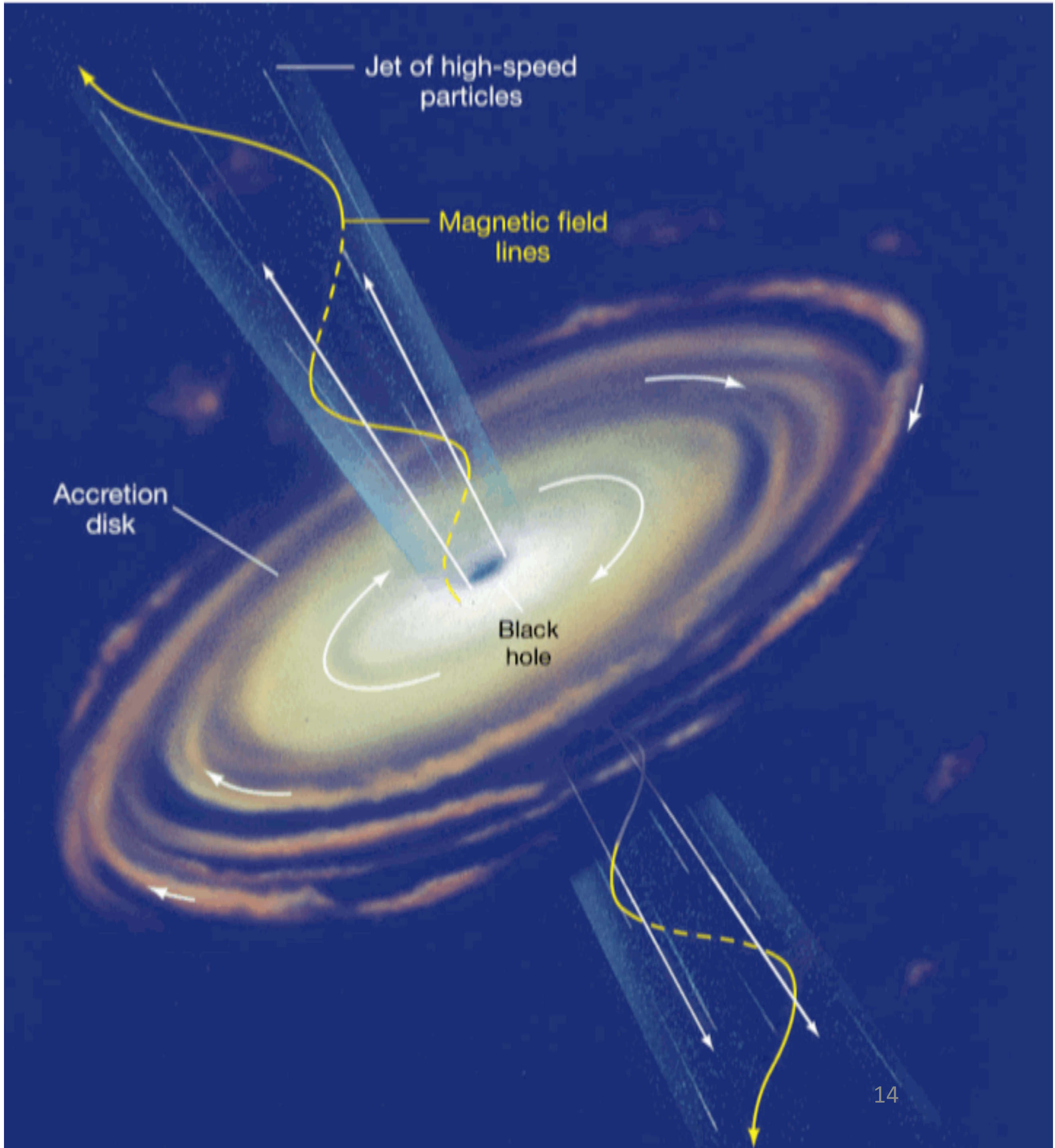




A shower called Ernie

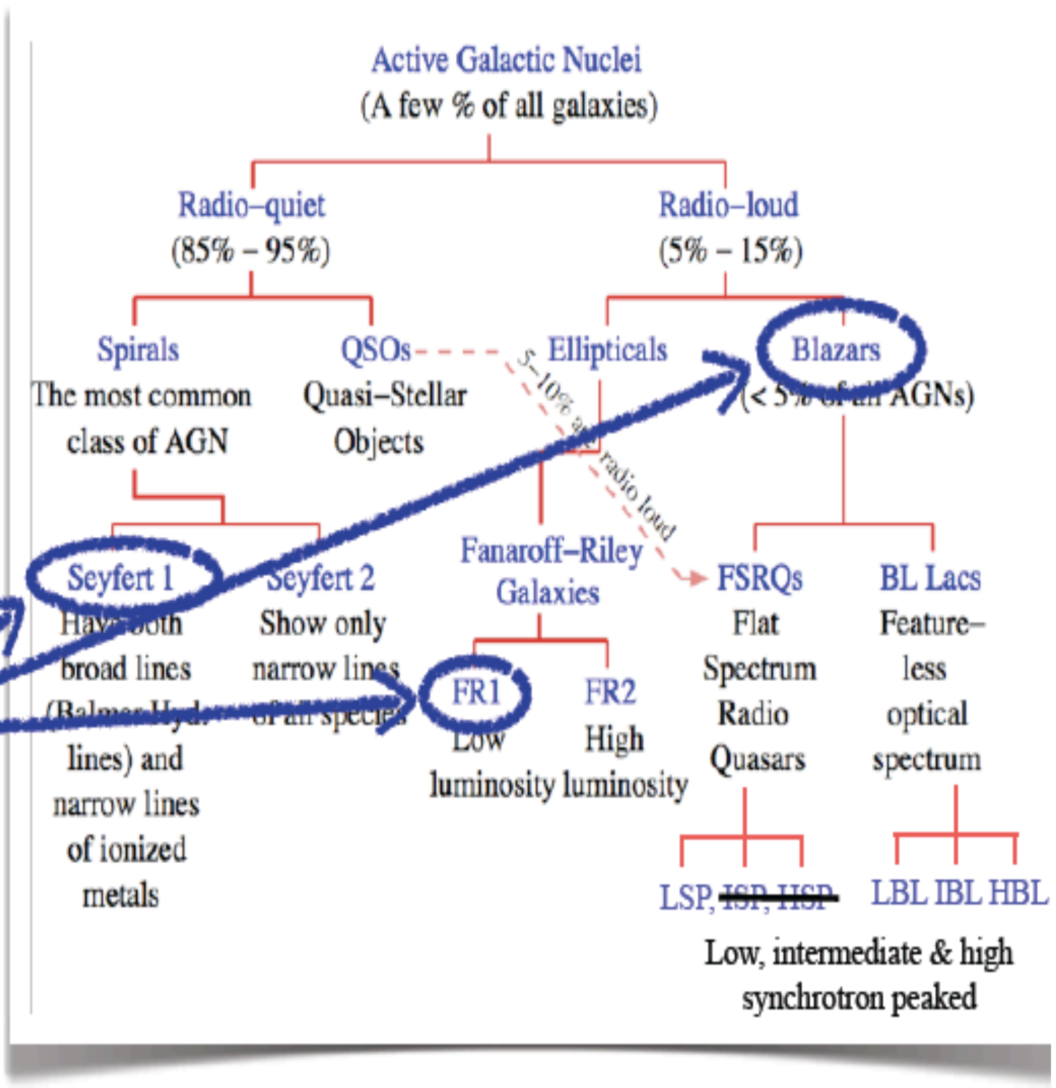
AGN

- AGN emits EM radiation and its spectrum span from radio to gamma-rays
- A super massive BH is believed to sit at the center of the AGN surrounded by an accretion disk.
- Oppositely directed Jets ⊥ to accretion disk .
- Unification scheme of AGN: Blazars and Radio galaxies are same objects viewed at different angles w.r.t. jet axis.

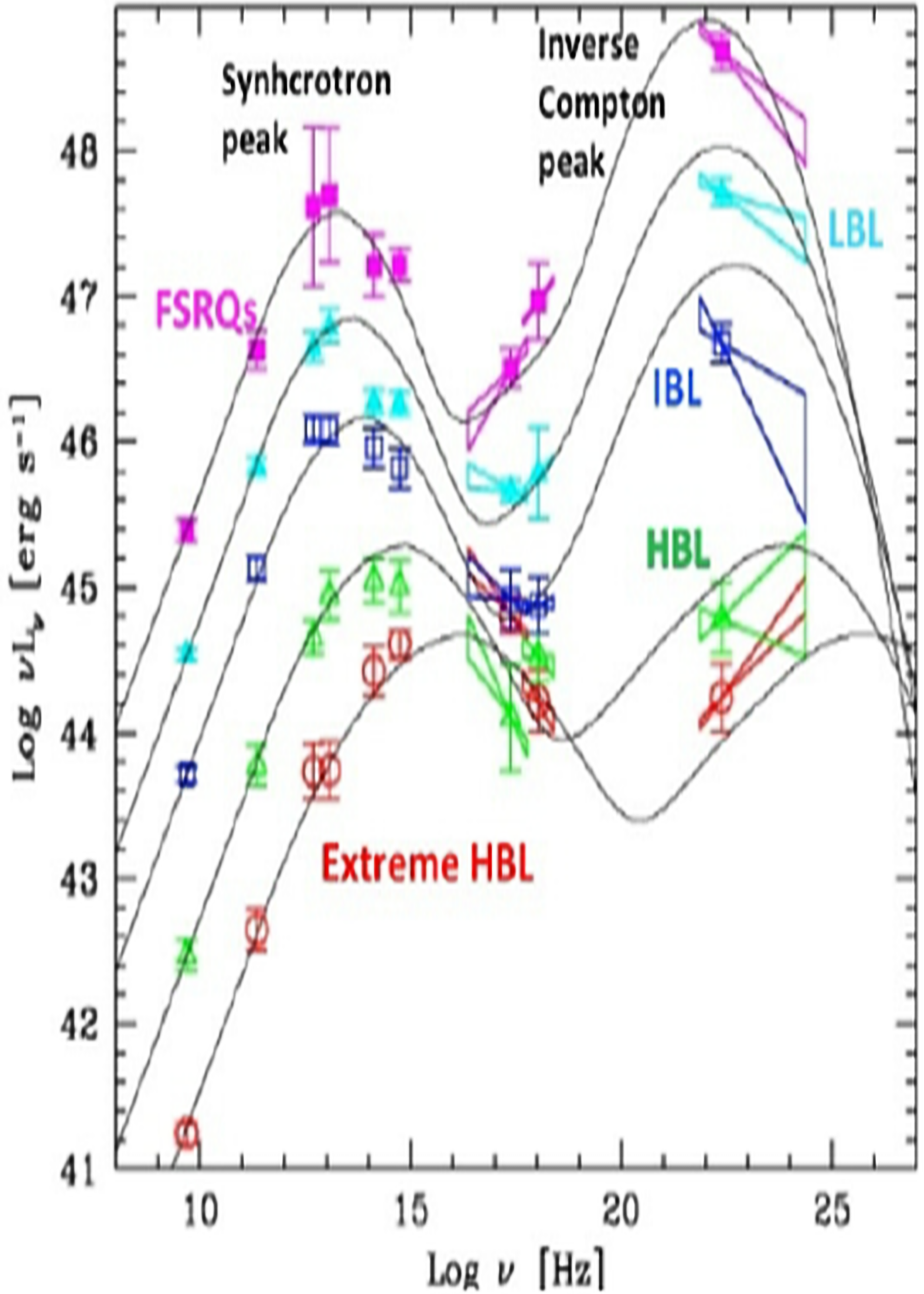


Active Galactic Nuclei

CLASSIF



identified as Fermi sources

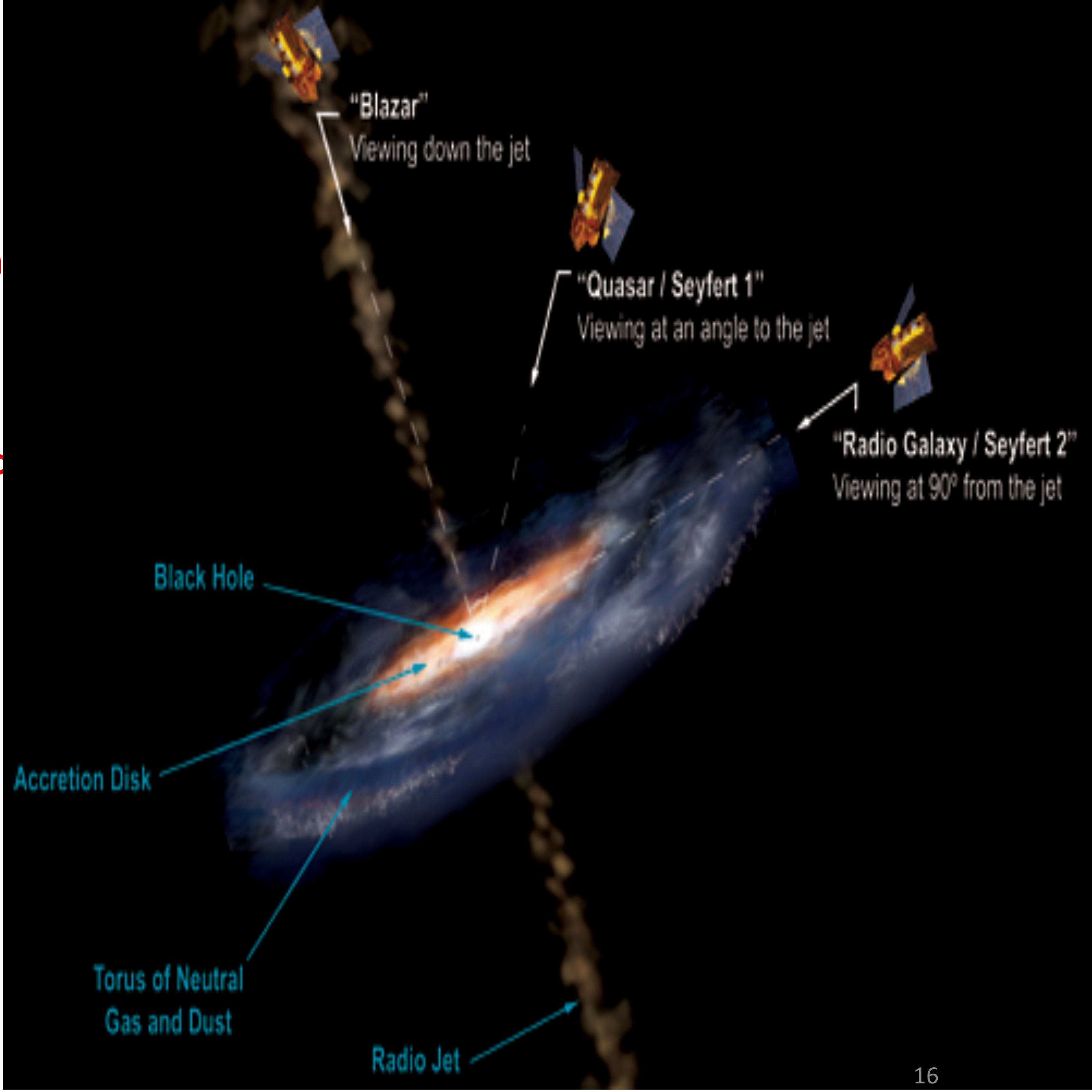


Blazars

- 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

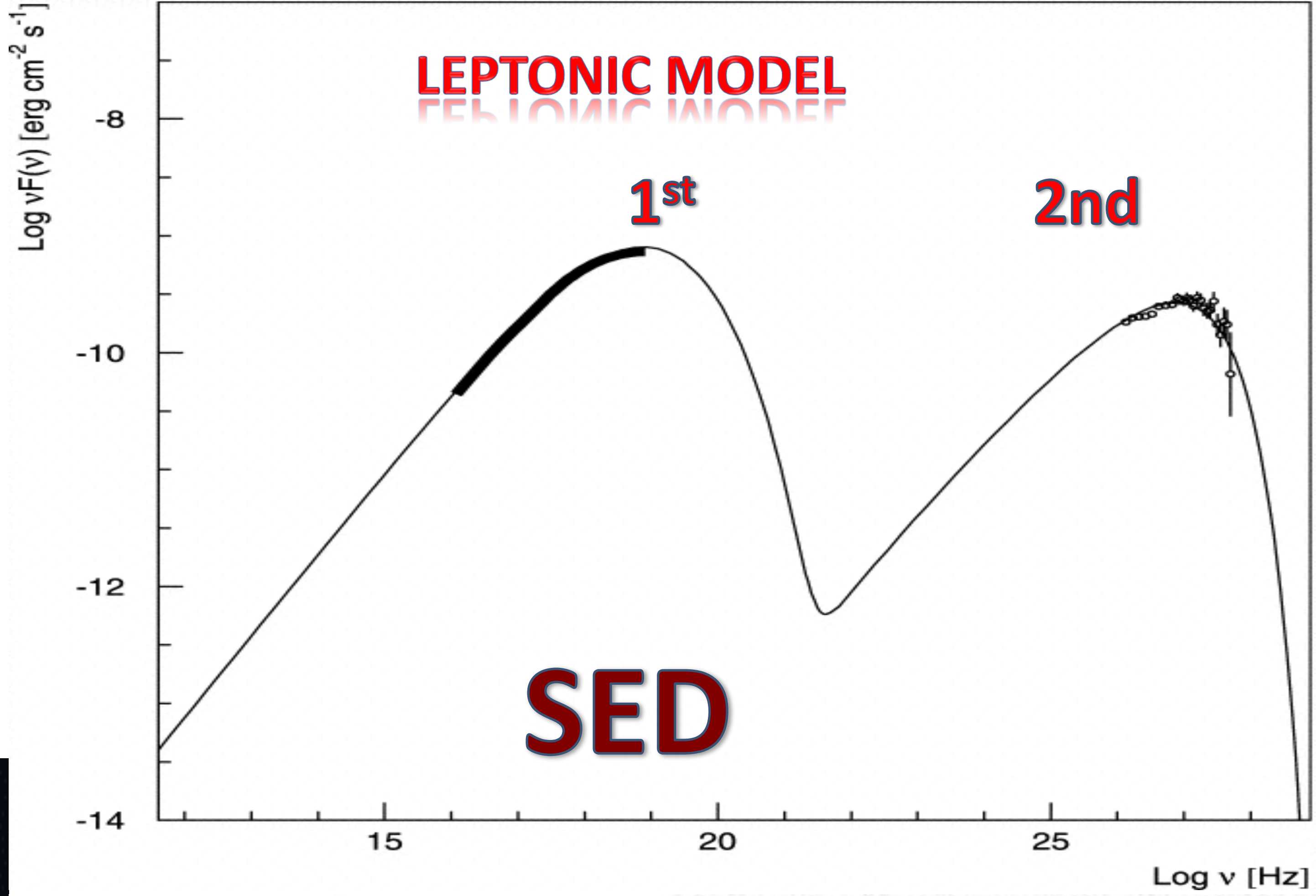
Near infra-Red/optical (Low energy peaked blazars LBL)

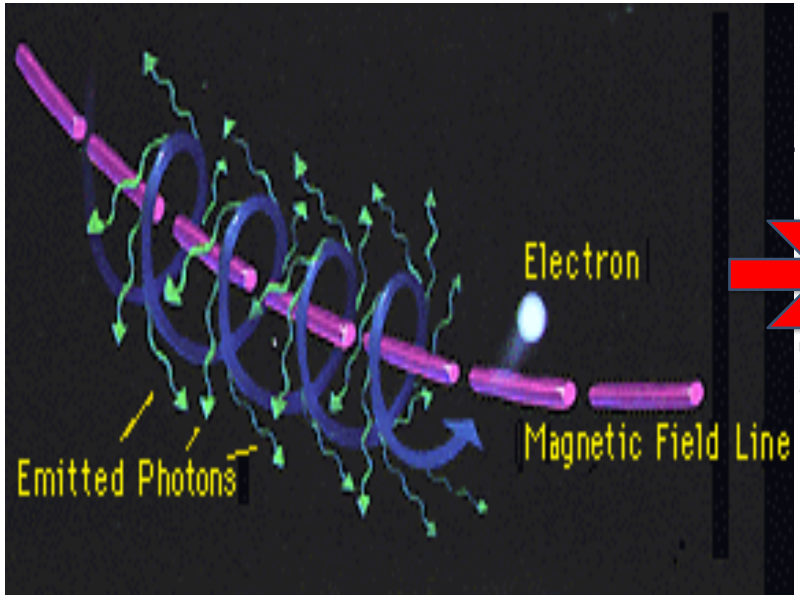
OR

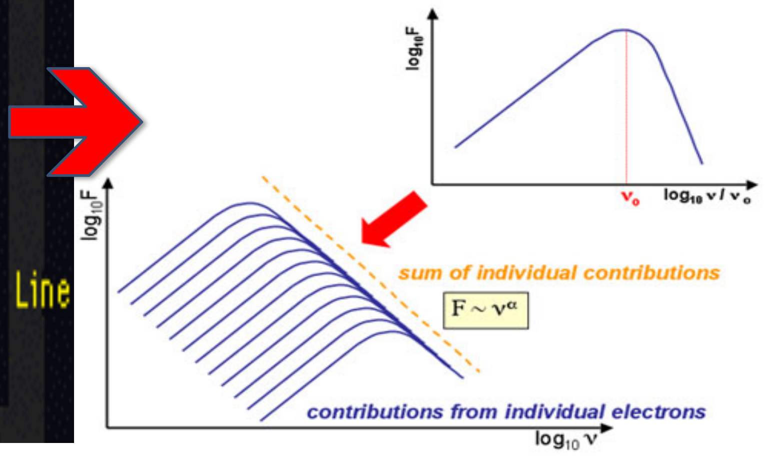
UV/X-ray (HBL)

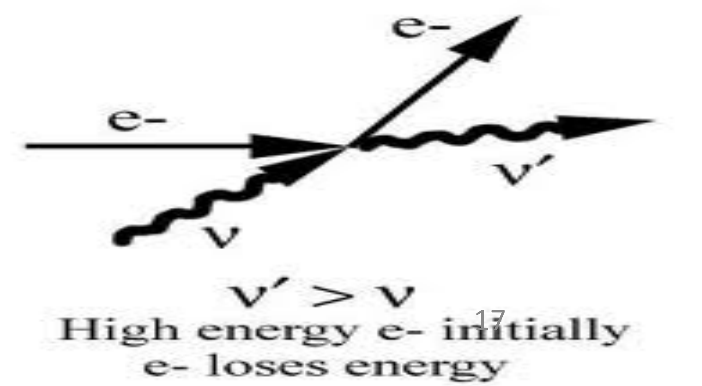
2nd peak

GeV Range

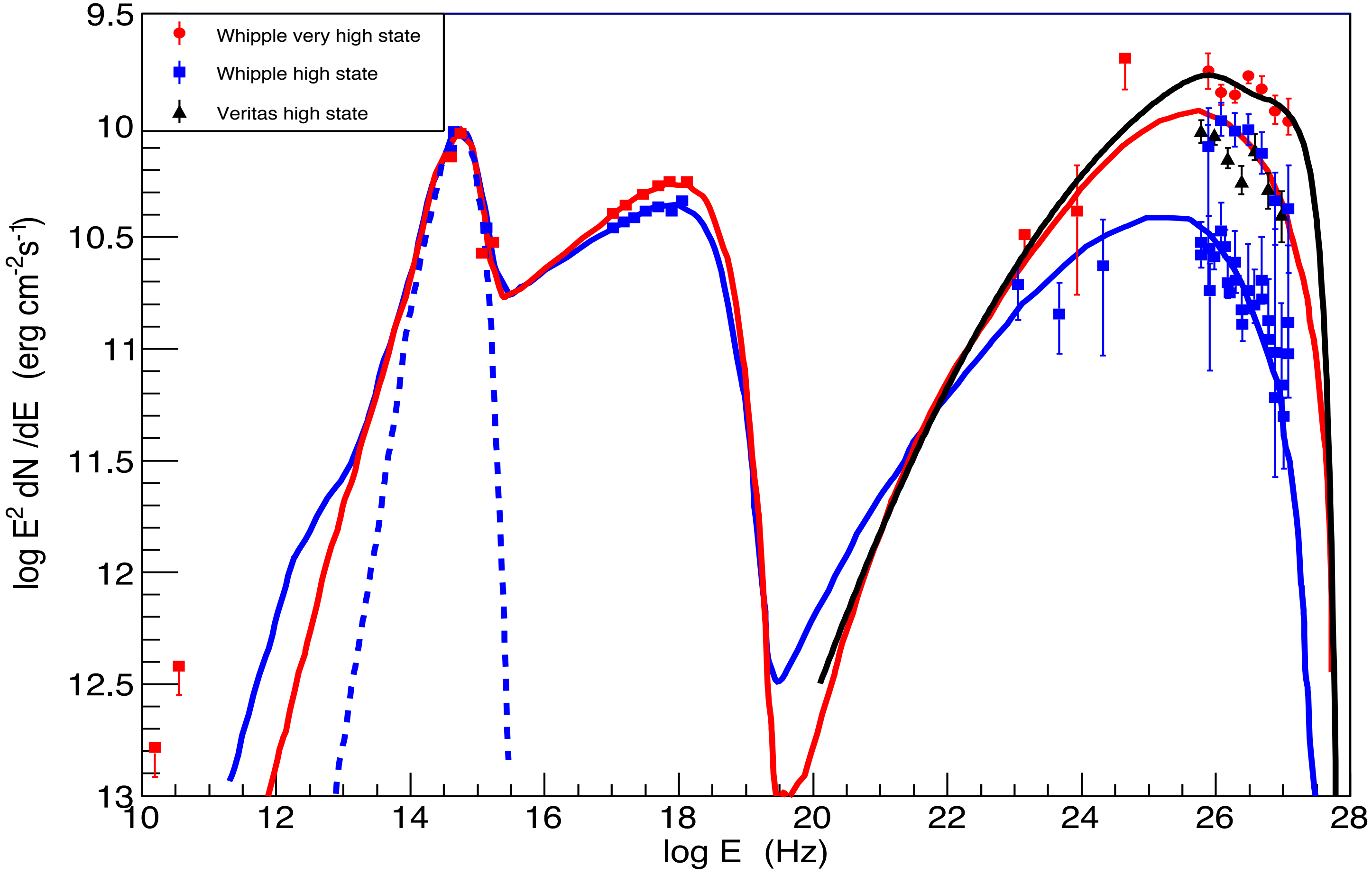


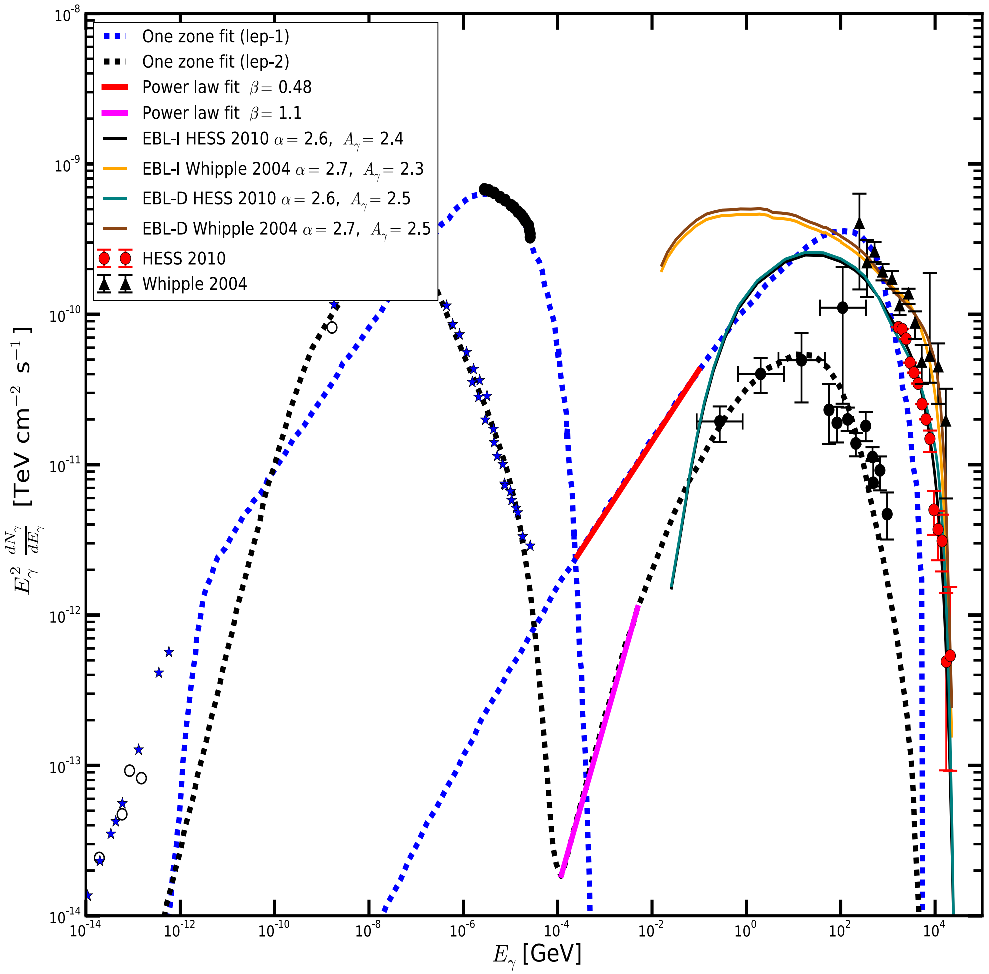






Flaring



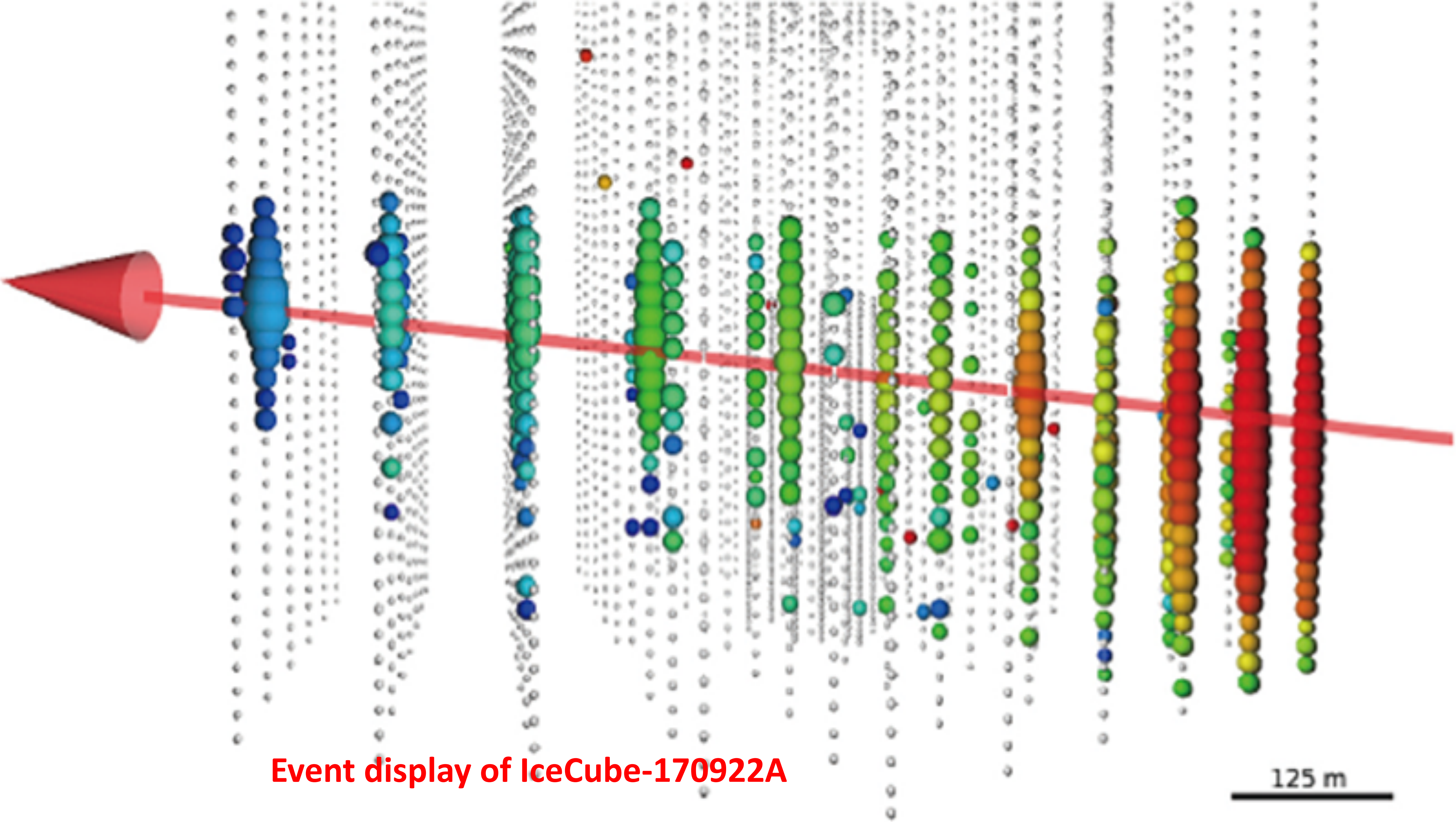


Markarian 501

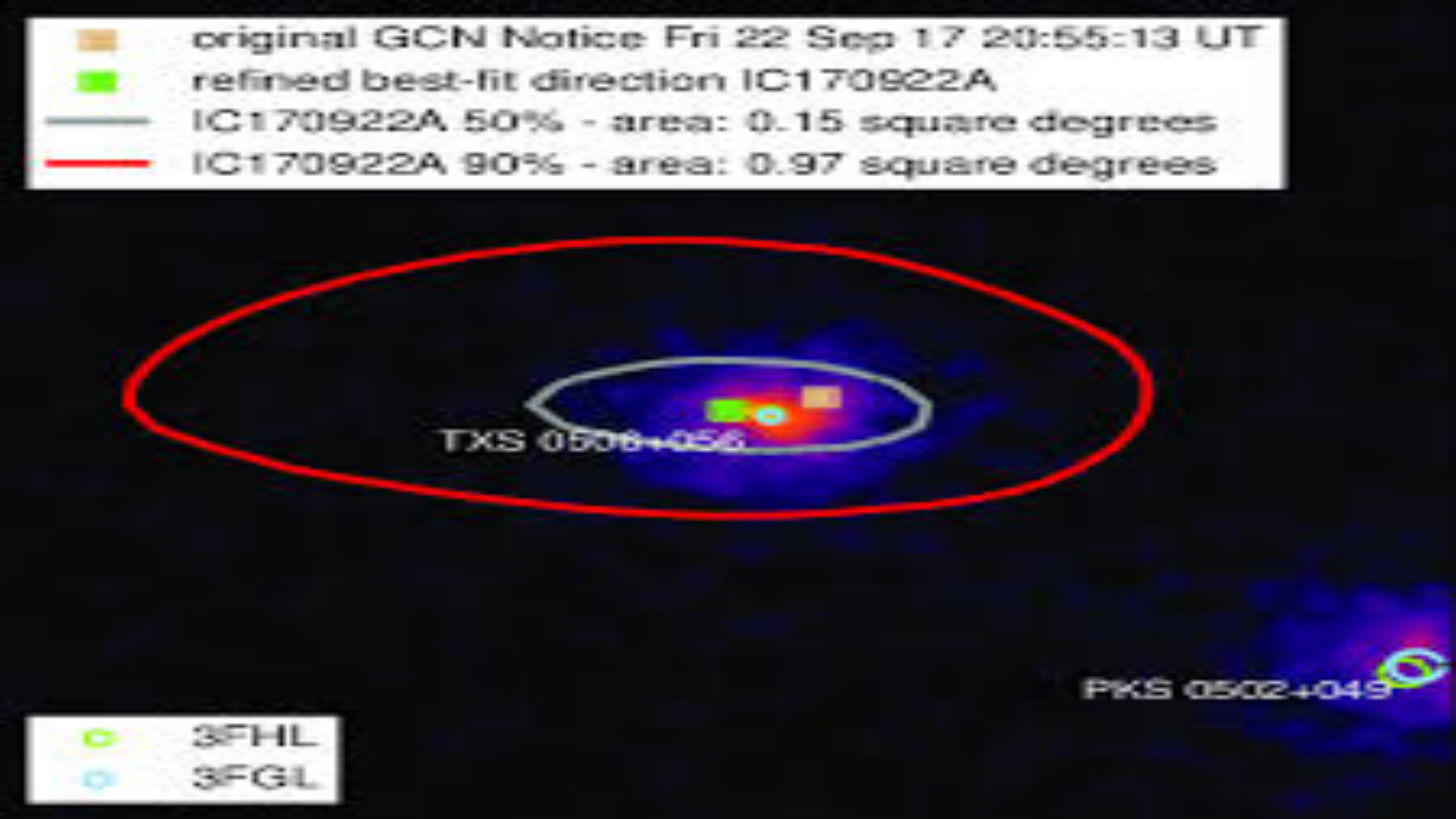
Markarian 421

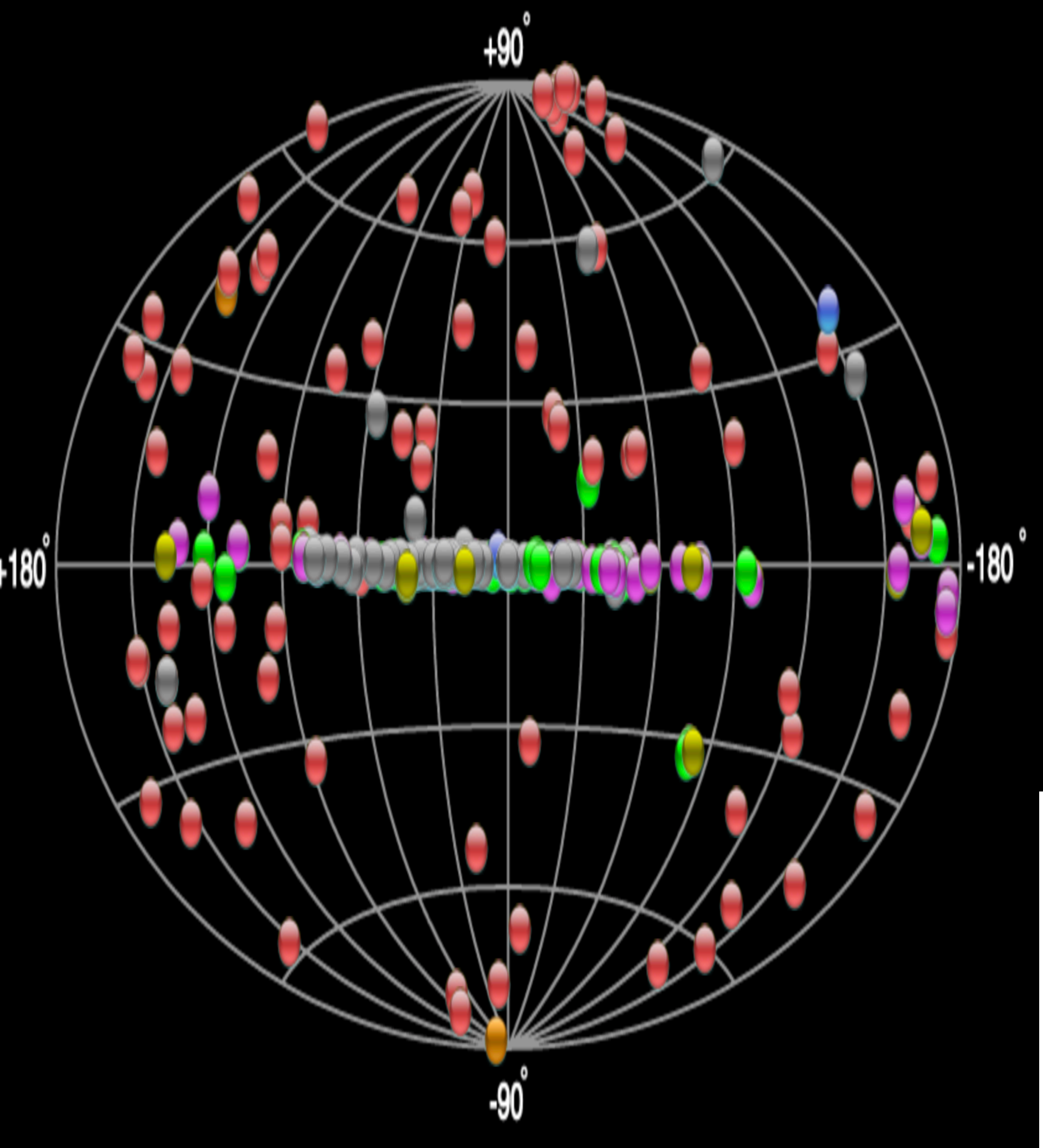
Observations

Neutrino in IceCube-170922A



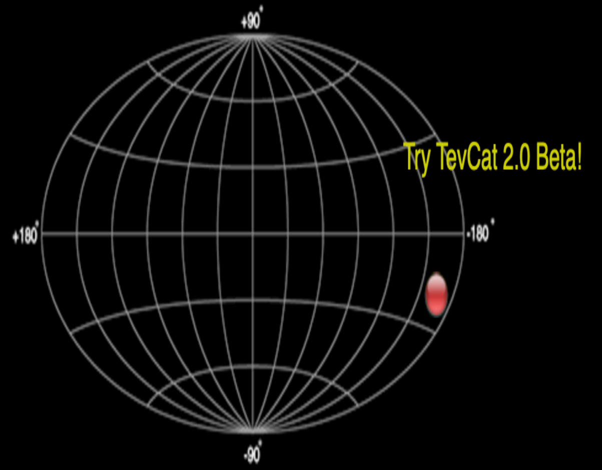
Event display of IceCube-170922A


original GCN Notice Fri 22 Sep 17 20:55:13 UT
refined best-fit direction IC170922A
IC170922A 50% - area: 0.15 square degrees
IC170922A 90% - area: 0.97 square degrees
TXS 0506+056
PKS 0502+049
3FHL
3FGL



TXS 0506+056

Canonical Name:	TXS 0506+056
TeVCat Name:	TeV J0509+056
Other Names:	EHE 170922A 3FGL J0509.4+0541 3FHL J0509.4+0542 VER J0509+057
Source Type:	Blazar
R.A.:	05 09 25 (hh mm ss)
Dec.:	+05 42 09 (dd mm ss)
Gal Long:	195.39 (deg)
Gal Lat:	-19.63 (deg)
Distance:	z=0.3365
Flux:	0.016 (Crab Units)
Energy Threshold:	110 GeV
Spectral Index:	4.8
Extended:	No
Discovery Date:	2017-10
Discovered By:	MAGIC
TeVCat SubCat:	Default Catalog
Source Notes:	



Observation Date (UT) 7-5-2019

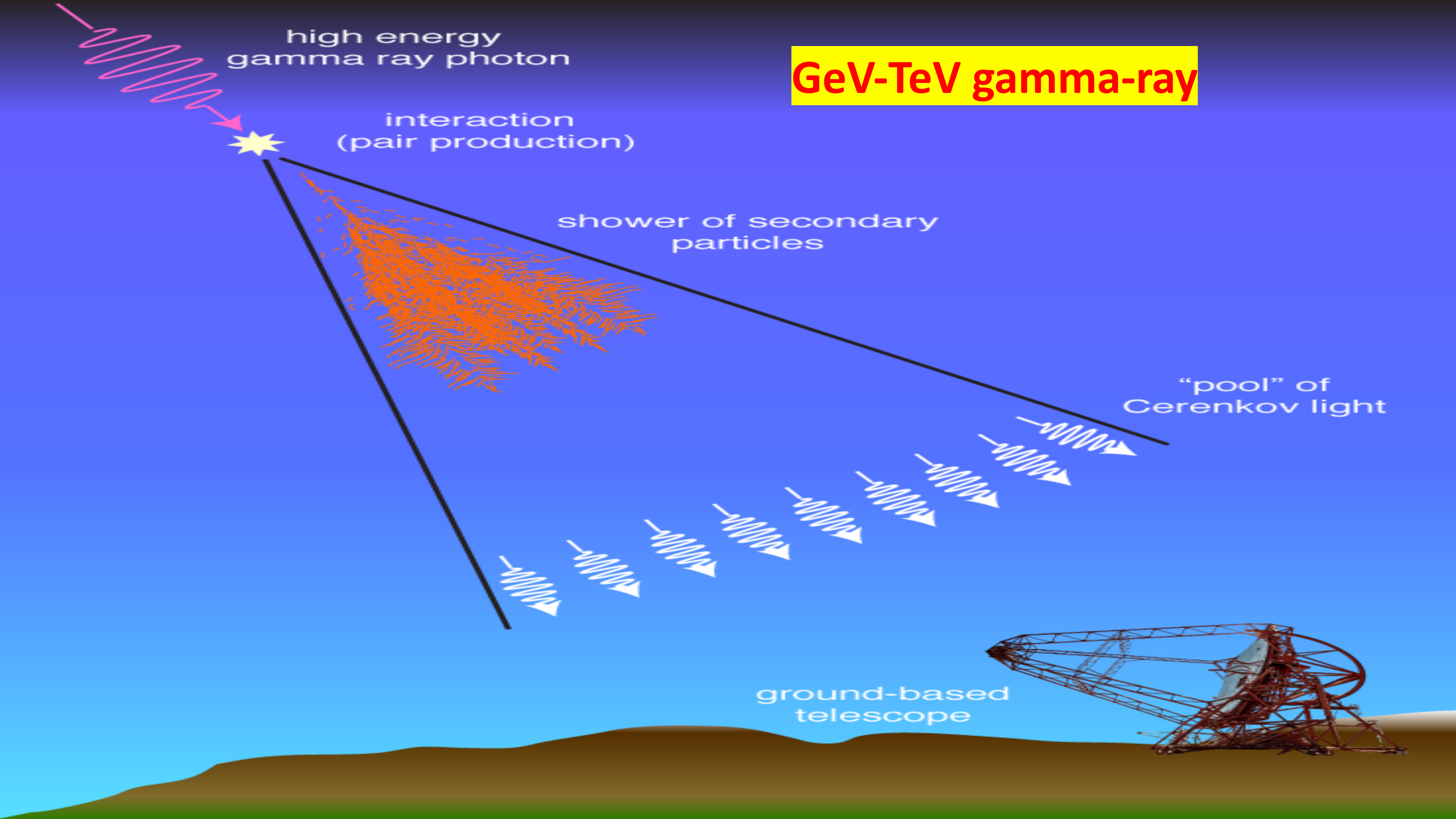
Observation Lat ARGO-YBJ (30.11)

Vis-Plot this Source!

Vis-Plot Full Year

RA 77.3582^{0}, Dec. +5.69314^{0}

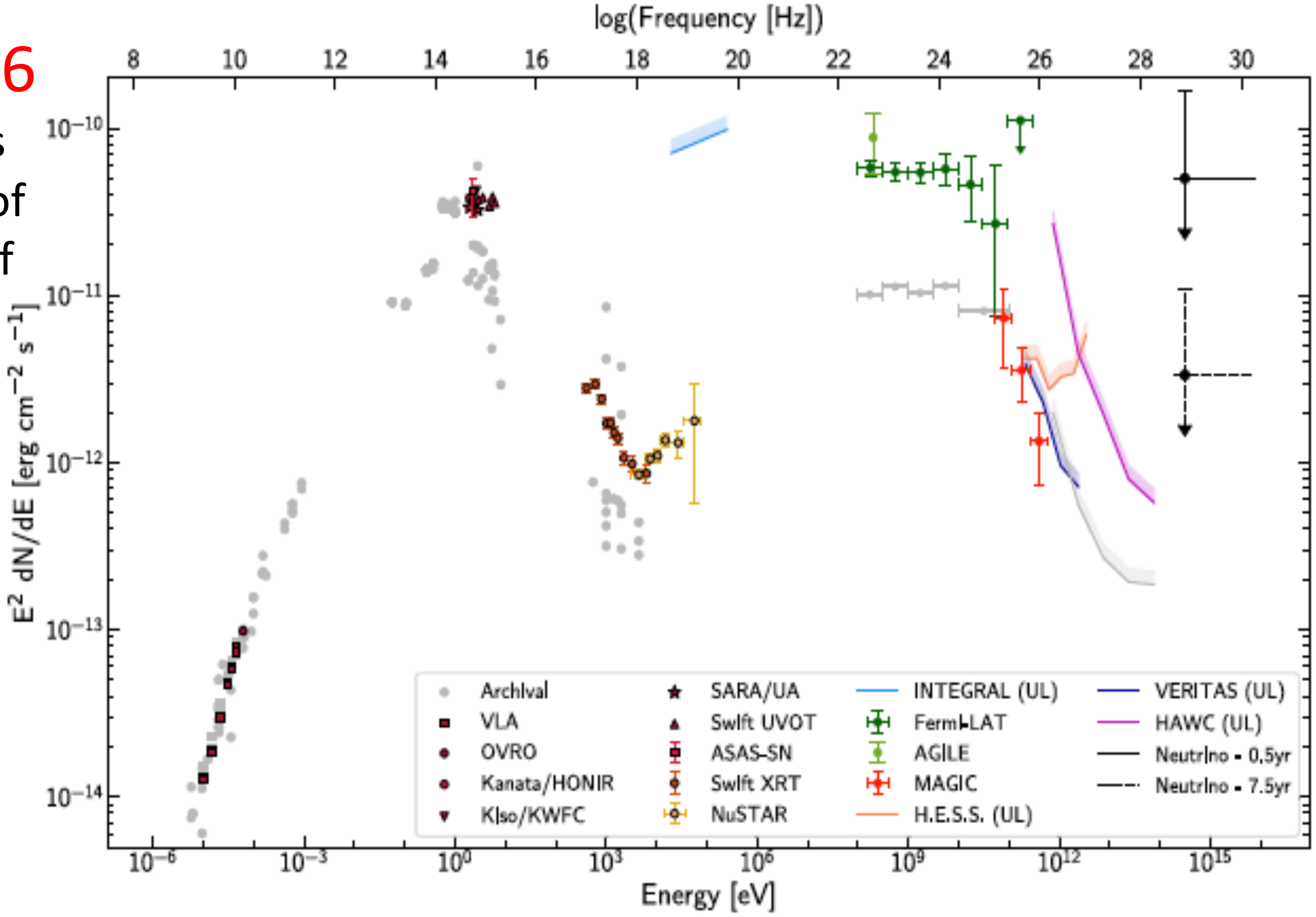
GeV-TeV gamma-ray



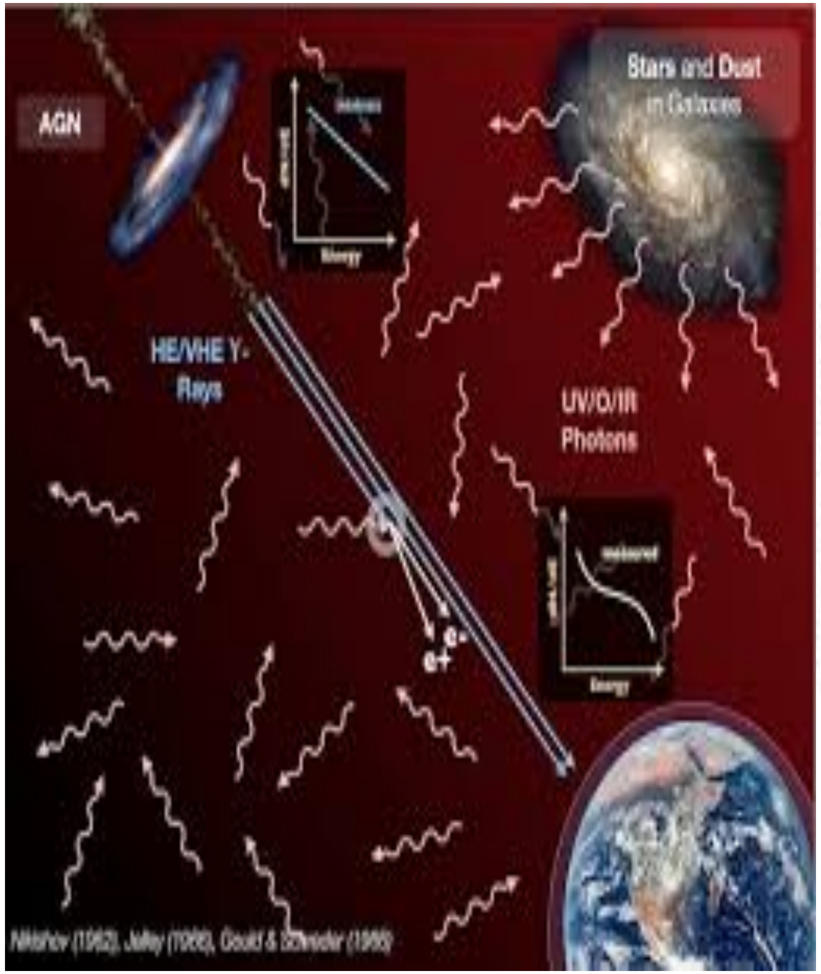
TXS056+056

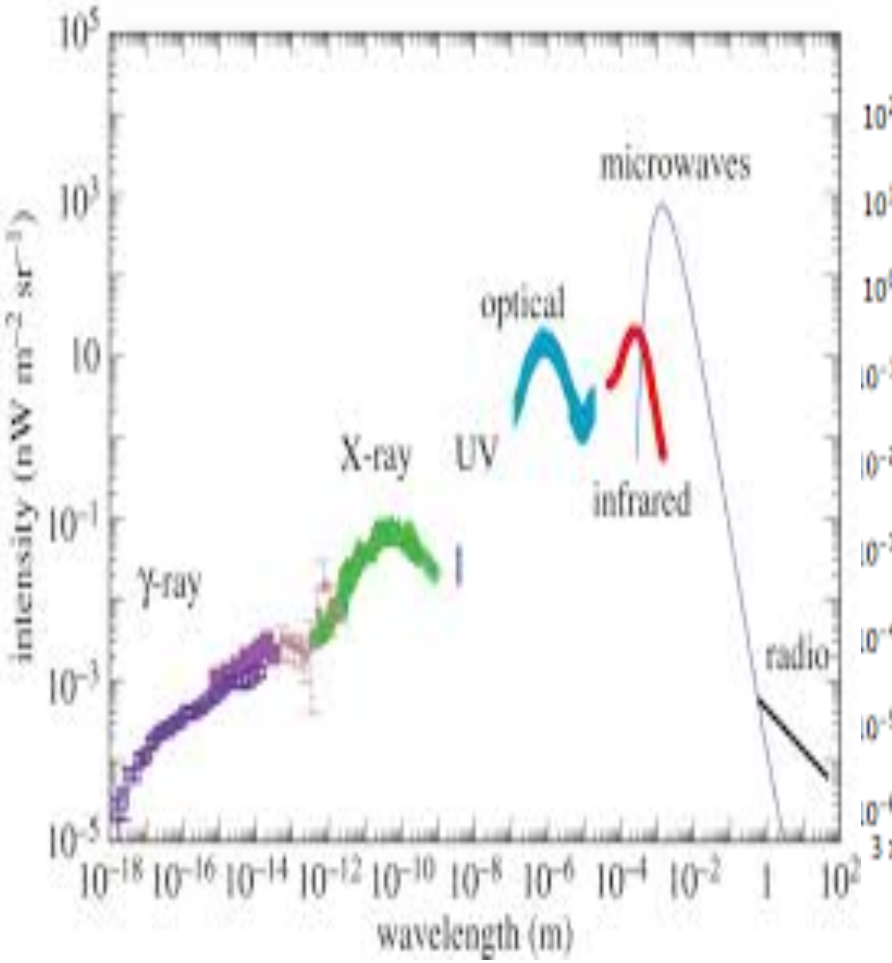
Broad Band Obs within 14 days of The detection of IceCube -170922A

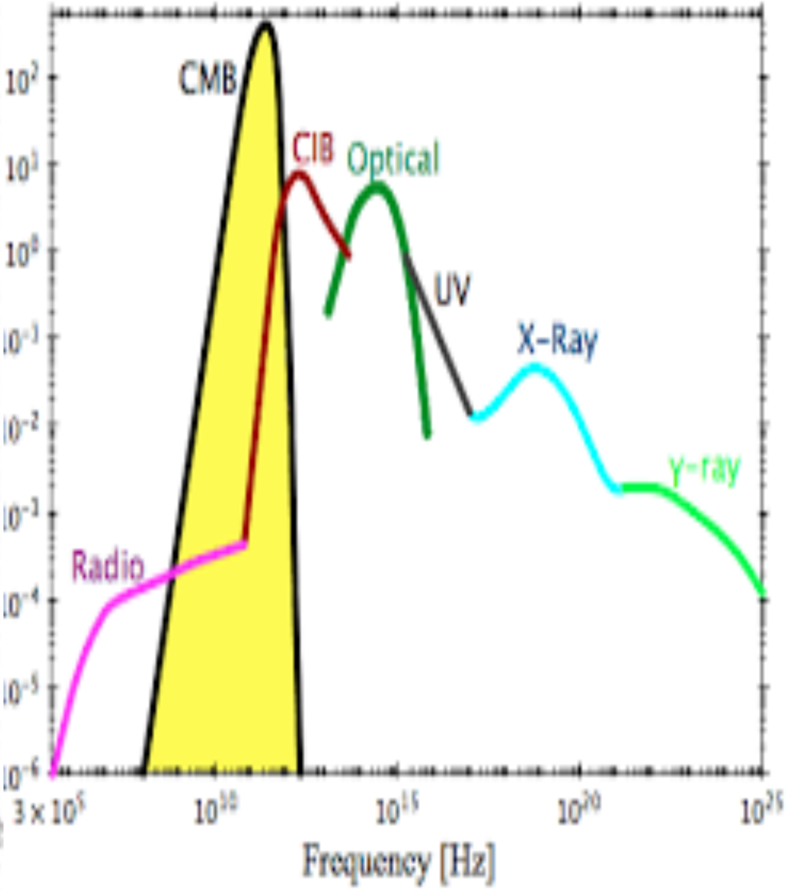
MAGIC
75 GeV < E_g < 366 GeV



Extragalactic Background Light (EBL)





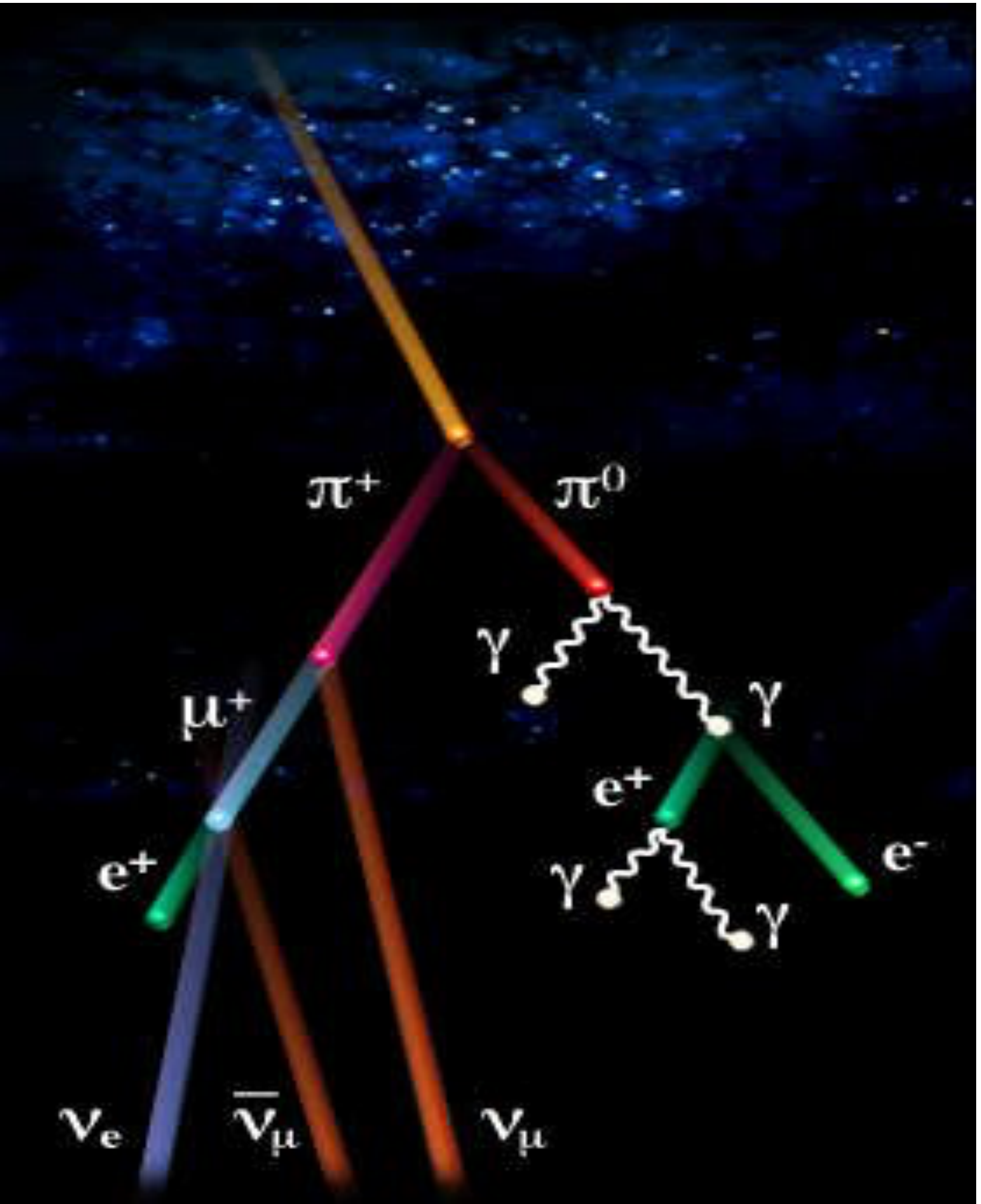


0.1-100 μm wavelength range emitted by stars, galaxies, from nucleosynthesis in AGN, reprocessed by dust.

This diffuse background is called EBL

MAGIC data can be explained using photohadronic scenario and this model is very successful in explaining the flaring from many high energy blazars.

Photohadronic Model



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

Photohadronic scenario

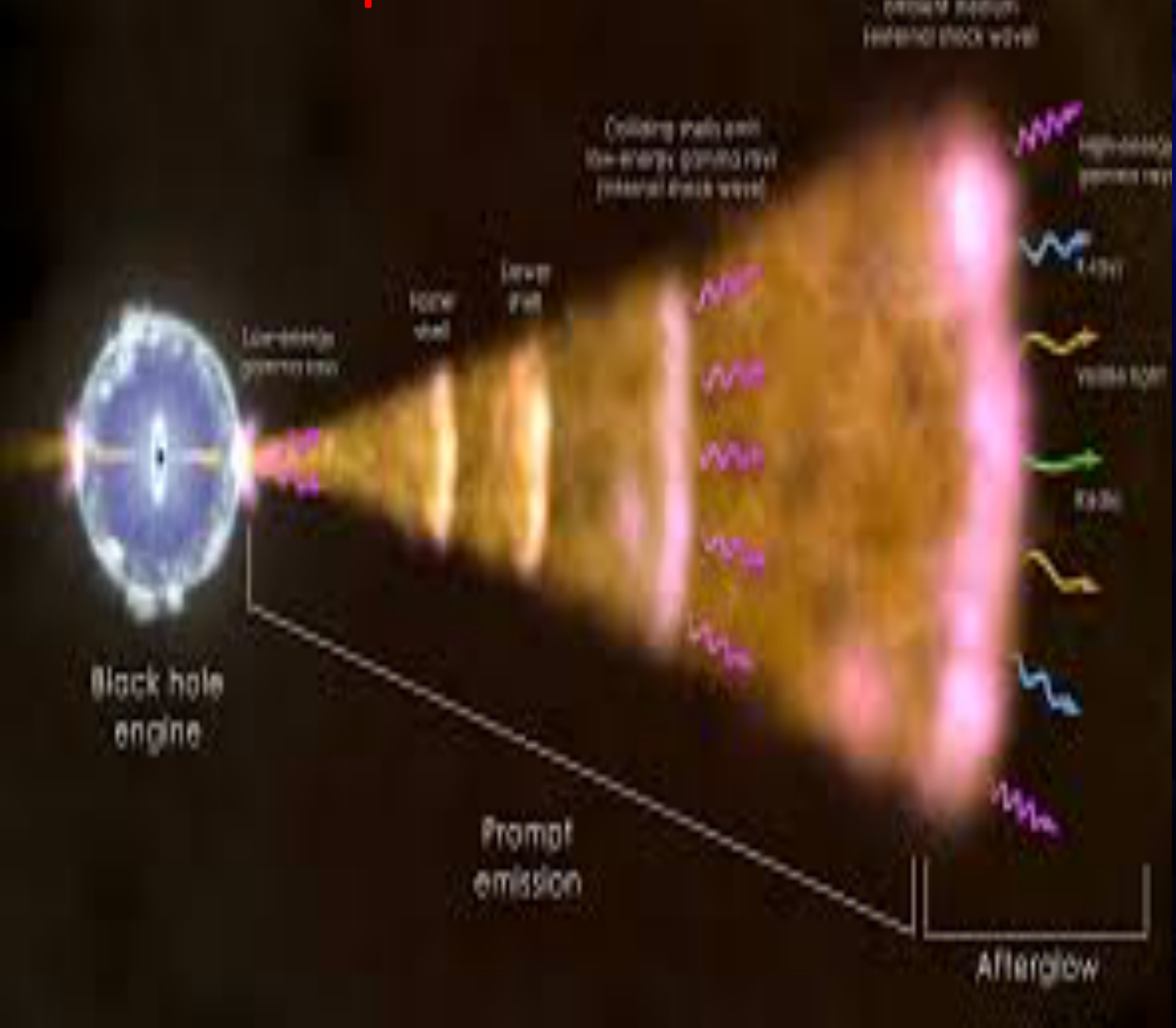
To produce pions through Δ-resonance

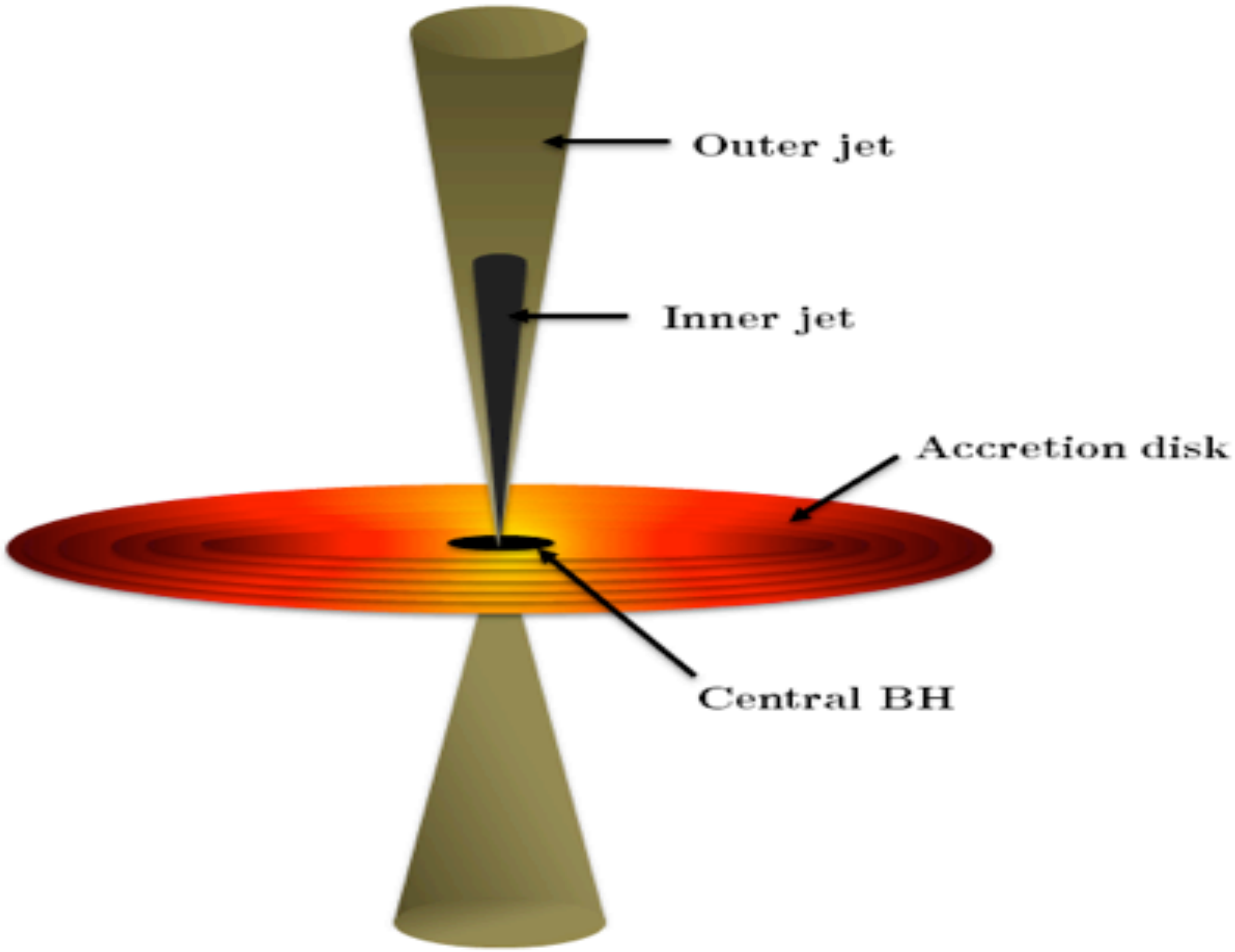
$$p+\gamma \rightarrow \Delta^{+} \rightarrow \begin{cases} p\pi^{0} \rightarrow p\gamma\gamma & \text{fraction } 2/3 \\ n\pi^{+} \rightarrow ne^{+}\nu_{e}\nu_{\mu}\bar{\nu}_{\mu}, & \text{fraction } 1/3. \end{cases}$$

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

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

Where to produce neutrinos : Jets is Astrophysics !!!




Outer jet
Inner jet
Accretion disk
Central BH

Kinematical Condition

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

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

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

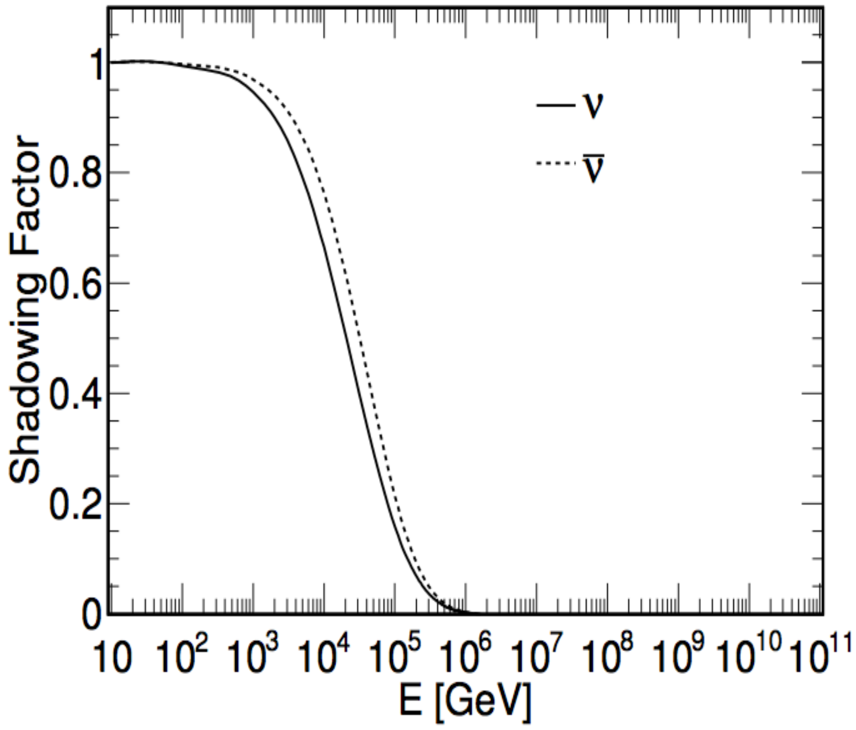


Fig. 5 The shadowing factor P_{shad} as a function of neutrino energy for a zenith angle $\theta = 180°$.

- **Each π carries ~0.2 of the proton energy**
- **Each ν carries ¼ of pion energy**
- **Each γ carries ½ of pion energy.**

What do we assume & Propose ?

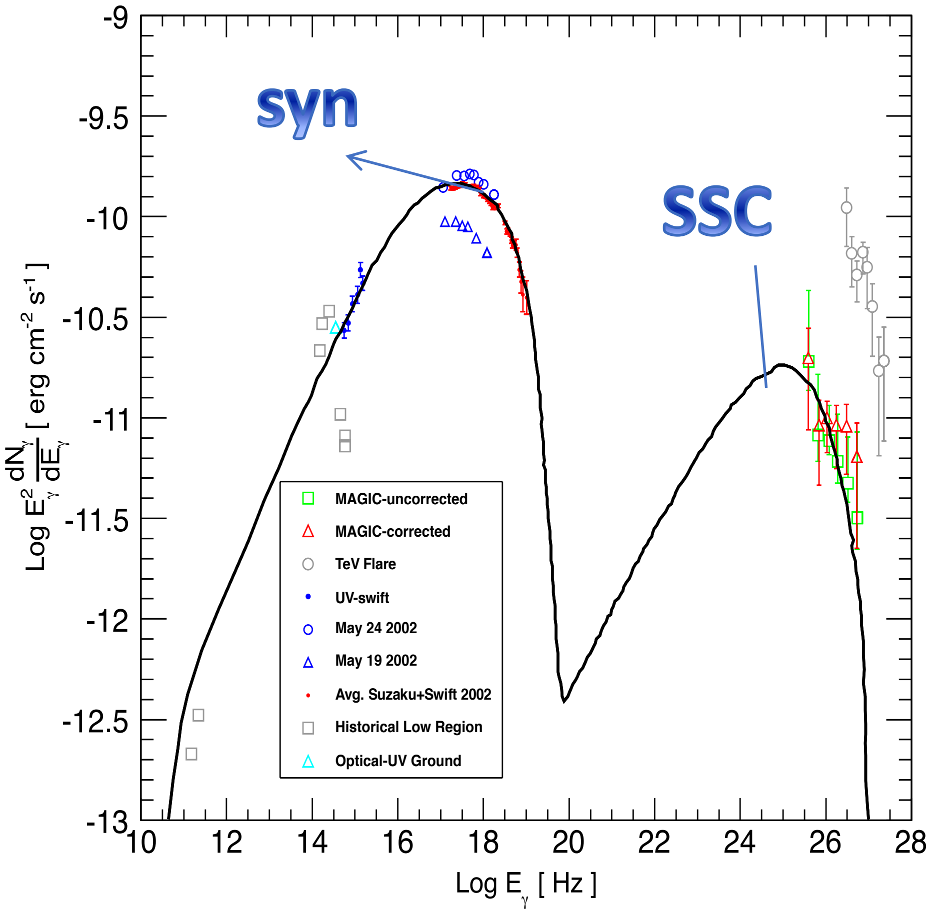
Assume:

Standard Leptonic model which explains both low and high energy peaks by

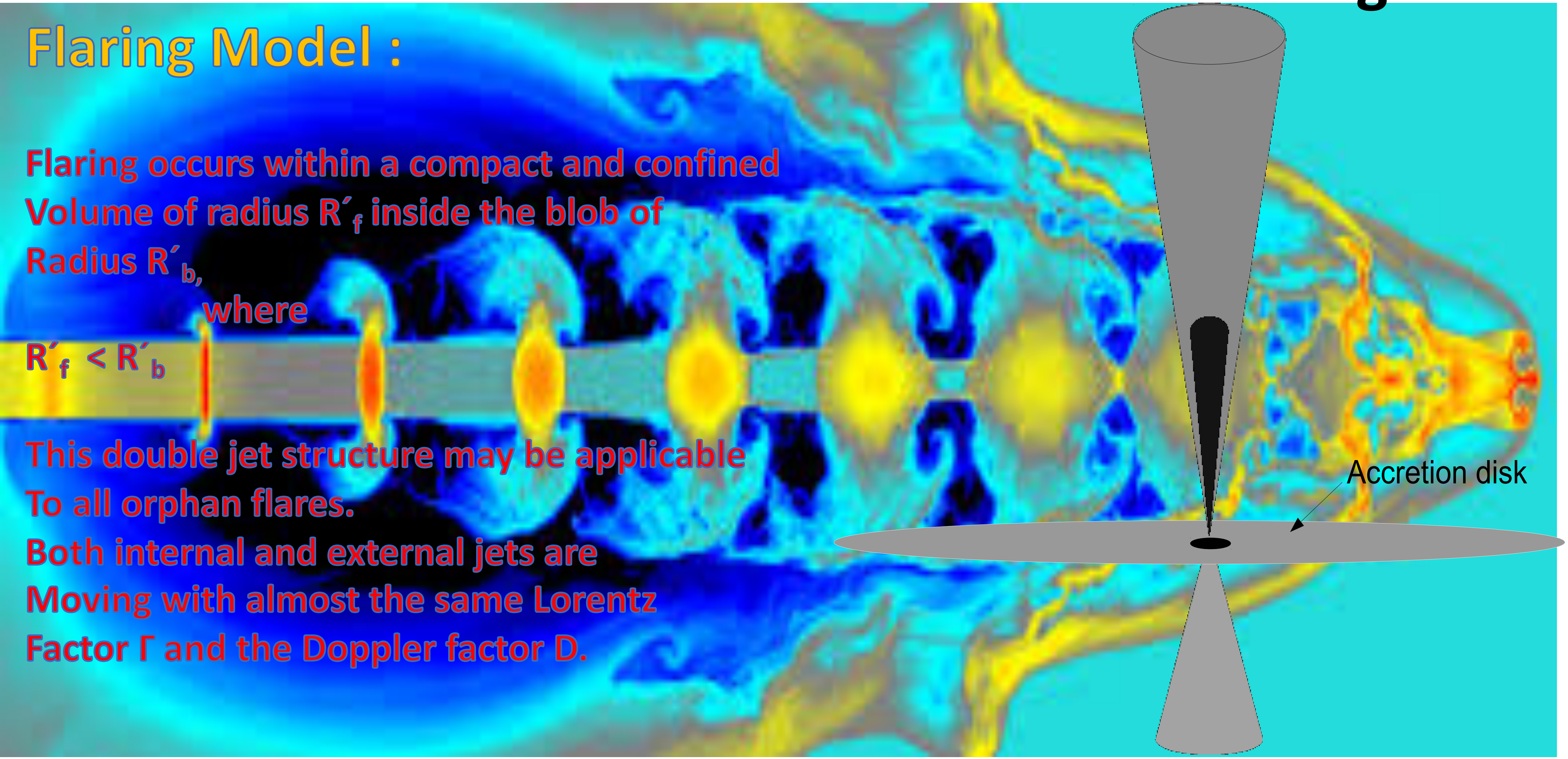
Synchrotron,
SSC photons as in the case of Centaurus A

We propose:

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



Internal– External Jet Structure & Flaring



Flaring Model :

Flaring occurs within a compact and confined
Volume of radius R'_f inside the blob of
Radius R'_b, where

$R'_f < R'_b$

This double jet structure may be applicable
To all orphan flares.
Both internal and external jets are
Moving with almost the same Lorentz
Factor Γ and the Doppler factor D.

$$E_\gamma \epsilon_\gamma = 0.032 \frac{D^2}{(1+z)^2} GeV^2$$

$$\frac{dN_p}{dE_p} \propto E_p^{-\alpha} \begin{cases} 1, & non-flaring \\ e^{-\frac{E_p}{E_{pc}}}, & flaring \end{cases}$$

Optical depth of the Δ resonance is

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

Comoving photon density within the large jet is

κ~(0-1) continuous / discrete.

$$n'_{\gamma,f} = \eta \frac{L_\gamma}{D^{2+\kappa}} \frac{(1+z)}{4\pi R'^2_f \varepsilon_\gamma}$$

In the flaring region, at a given energy

The number of π^0 decay photons depend on the number of high energy protons and the background photons.

$$N(E_\gamma) \propto N(E_p) n'_{\gamma,f}$$

Within the confined volume, the injected spectrum of the Fermi-accelerated charged particles have a power-law with an exponential cutoff.

For proton it is,

$$\frac{dN_p}{dE_p} \propto E_p^{-\alpha} e^{-E_p/E_{pc}}$$

Photon number densities in flaring and non-flaring regions are $n'_{\gamma,f}$ n'_{γ}

$$n'_{\gamma,f} >> n'_{\gamma} \qquad n'_{\gamma,f} = \lambda n'_{\gamma}, \lambda >> 1$$

Can be due to copious annihilation of e+e- pair in the confined volume.

Indise the photons density is unknown.

$$\frac{n'_{\gamma,f}(\varepsilon_{\gamma 1})}{n'_{\gamma,f}(\varepsilon_{\gamma 2})} \approx \frac{n'_{\gamma}(\varepsilon_{\gamma 1})}{n'_{\gamma}(\varepsilon_{\gamma 2})}$$

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

The γ-ray flux due to pion decay will be

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

TeV photon and the HE protons are related through

Neutrino

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

20%   2/3 prob.

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

Using the relations we get

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

and

$$\frac{n'_\gamma(\varepsilon\gamma_{1})}{n'_\gamma(\varepsilon\gamma_{2})} = \frac{\Phi_{SSC(\epsilon_{\gamma1})}}{\Phi_{SSC(\epsilon_{\gamma2})}} \frac{E_{\gamma1}}{E_{\gamma2}}$$

Finally this gives

$$\frac{F_\gamma(E_{\gamma1})}{F_\gamma(E_{\gamma2})} = \frac{\Phi_{SSC(\epsilon_{\gamma1})}}{\Phi_{SSC(\epsilon_{\gamma2})}} \left(\frac{E_{\gamma1}}{E_{\gamma2}}\right)^{-\alpha+3} e^{-(E_{\gamma1}-E_{\gamma2})/Ec}$$

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

$\tau_{\gamma\gamma}$ is the optical depth which depends on both energy and the redshift of the object. The cut-off energy E_c is an extra parameter here which depends on NEW mechanism. However, the optical depth is NATURAL in attenuating the High Energy Flux from the object.

$$\frac{F_\gamma(E_{\gamma 1})}{F_\gamma(E_{\gamma 2})}=\frac{\Phi_{SSC(\epsilon_{\gamma 1})}}{\Phi_{SSC(\epsilon_{\gamma 2})}}\left(\frac{E_{\gamma 1}}{E_{\gamma 2}}\right)^{-\alpha+3} e^{-\tau_{\gamma\gamma}(E_{\gamma 1},z)+\tau_{\gamma\gamma}(E_{\gamma 2},z)}$$

$$F_{\gamma,in}=A_{\gamma}\Phi_{SSC}(\epsilon_{\gamma})\left(\frac{E_{\gamma}}{TeV}\right)^{-\alpha+3}$$

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

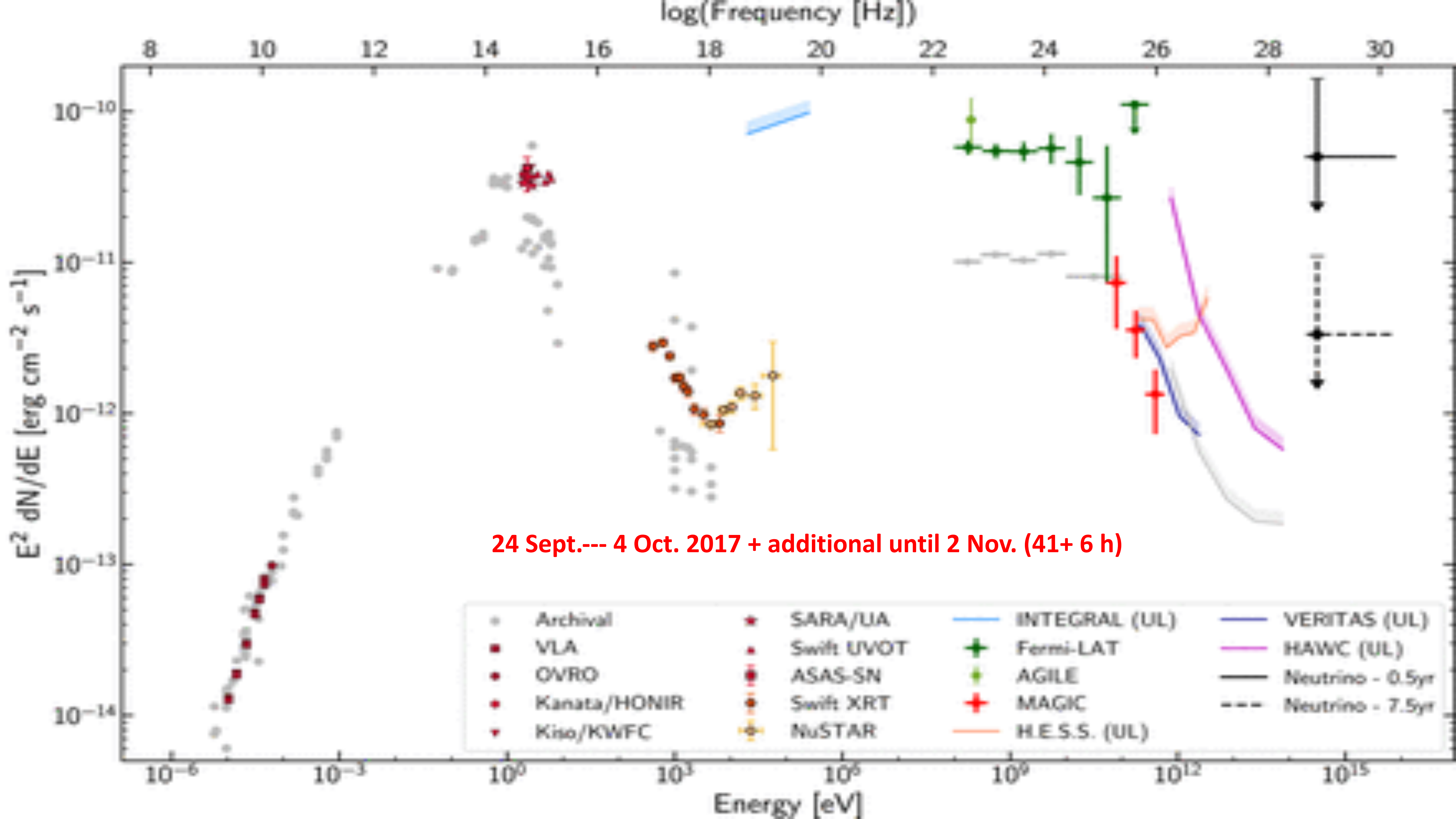
We can see that here $\boldsymbol{\alpha}$ *is the only parameter*.

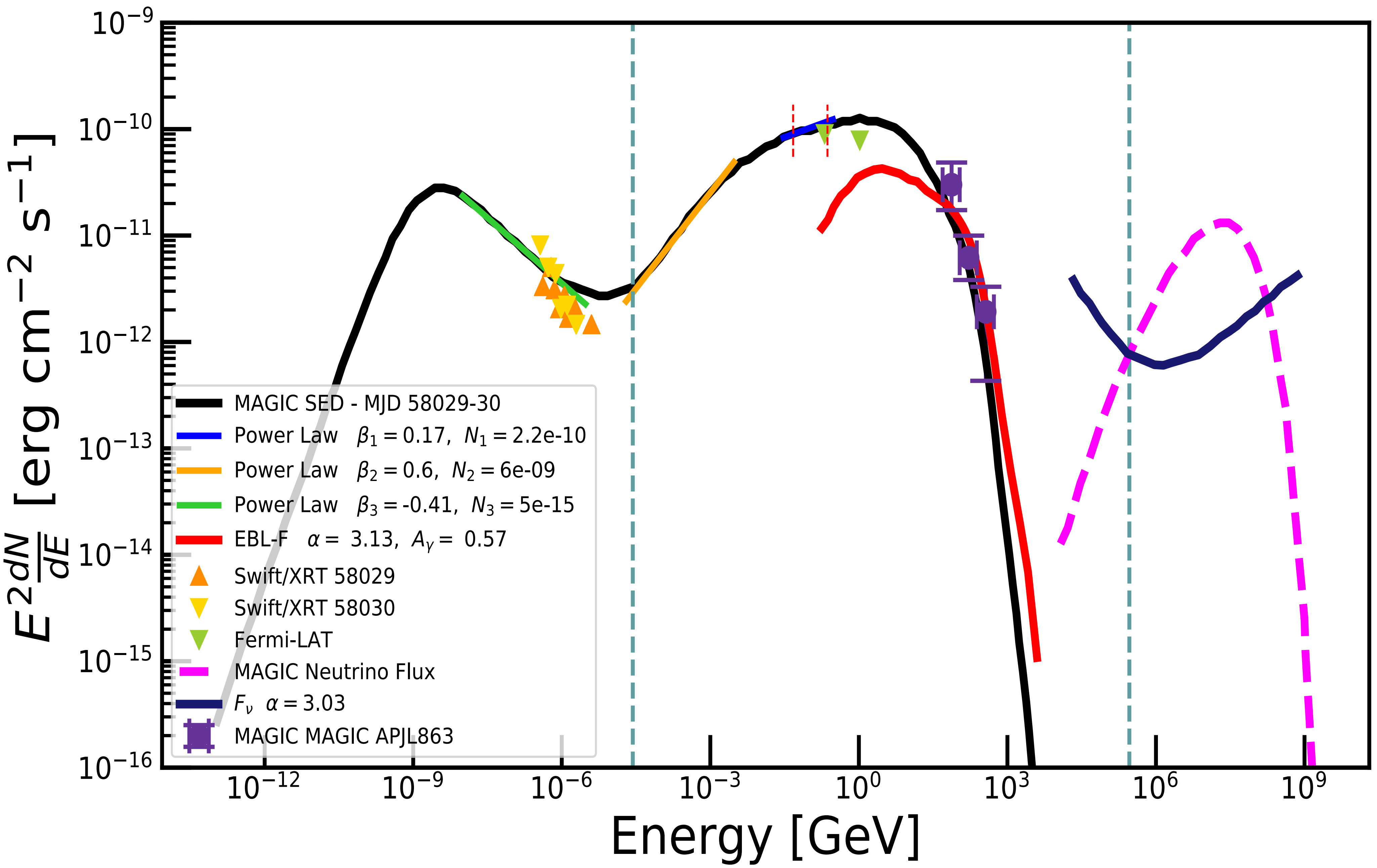
Results

- On 24th Sept 2017 Magic observed TXS056+056
  For 2 h under nonoptimal weather, did not obs gamma-rays.

- 28 sept-4 oct obs 13 h under good weather conditions and observed significant excess in 80-400 GeV band.

- VERITAs, HESS, HAWC did not obs.


log(Frequency [Hz])
E² dN/dE [erg cm⁻² s⁻¹]
Energy [eV]
24 Sept.--- 4 Oct. 2017 + additional until 2 Nov. (41+ 6 h)
Archival
VLA
OVRO
Kanata/HONIR
Kiso/KWFC
SARA/UA
Swift UVOT
ASAS-SN
Swift XRT
NuSTAR
INTEGRAL (UL)
Fermi-LAT
AGILE
MAGIC
H.E.S.S. (UL)
VERITAS (UL)
HAWC (UL)
Neutrino - 0.5yr
Neutrino - 7.5yr



MAGIC SED - MJD 58029-30
Power Law $\beta_1 = 0.17$, $N_1 = 2.2e\text{-}10$
Power Law $\beta_2 = 0.6$, $N_2 = 6e\text{-}09$
Power Law $\beta_3 = \text{-}0.41$, $N_3 = 5e\text{-}15$
EBL-F $\alpha = 3.13$, $A_\gamma = 0.57$
Swift/XRT 58029
Swift/XRT 58030
Fermi-LAT
MAGIC Neutrino Flux
F_ν $\alpha = 3.03$
MAGIC MAGIC APJL863
$E^2\frac{dN}{dE}$ [erg cm^{-2} s^{-1}]
Energy [GeV]

$75\ GeV \leq E_\gamma \leq 366\ GeV$ *observed gamma-ray*

$750\ GeV \leq E_p \leq 3.7\ TeV$ cosmic ray proton

43 MeV$\leq \varepsilon_\gamma \leq 211\ MeV\ background\ photon\ (SSC)$

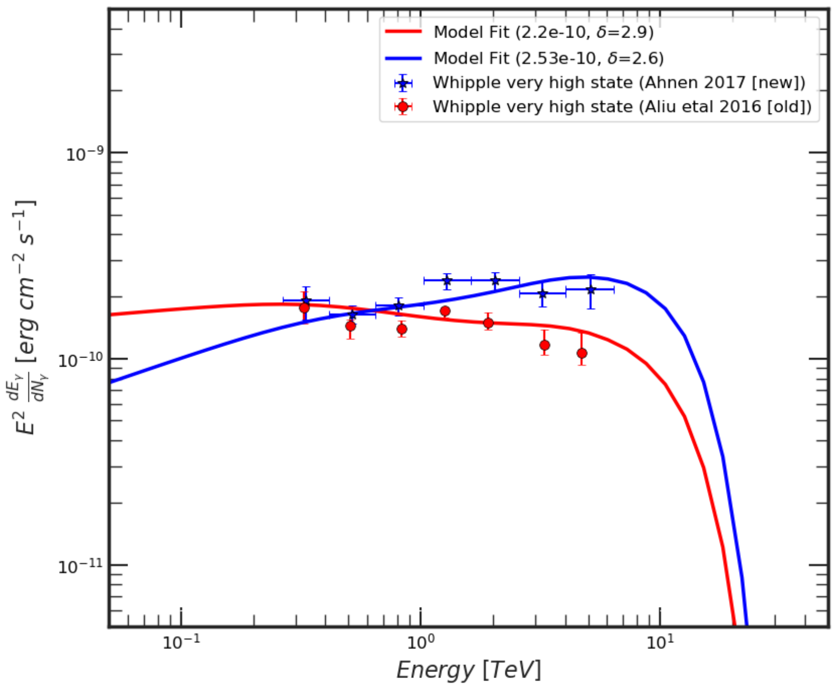
The observed spectrum is a power-law
The SSC photon is a power-law (SSC)
We assume the very high energy protons are also power-law
(290 TeV neutrino implies 6 PeV CR proton)

But

In Future observations

More events and also simultaneous observation in multiwavelength is essential to find the correlation between the Neutrino and the high-energy gamma-ray events.

Example: Markarian 501
Observed on May 1st 2009 , very high flare took place for 0.5 h (Whipple telescope)



Thank You