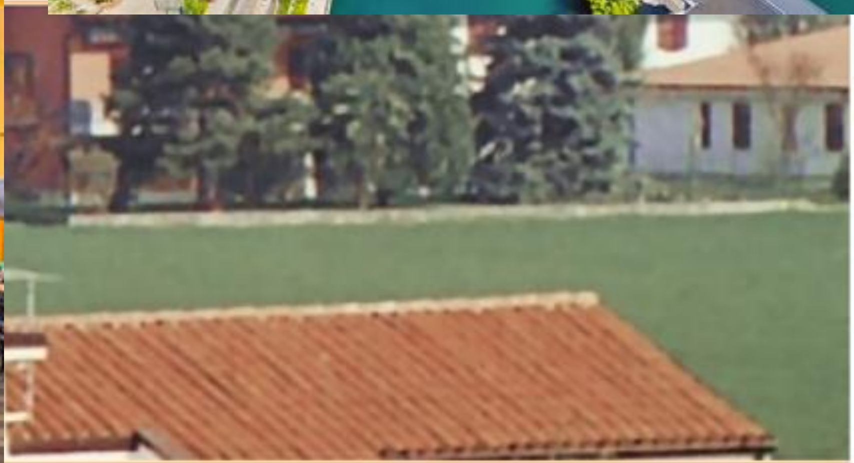
EXTREME TEV BLAZARS: IDEAL PROBES FOR IGMF?

ELISA PRANDINI (PADOVA U.) - 12.02.2025

TRIESTE ‘IFPU FOCUS WEEK - INTERGALACTIC MAGNETIC FIELD: A NEW PROBE OF THE EARLY UNIVERSE’

FEW WORDS ABOUT MYSELF



MY TEAM & COLLABORATIONS

- **Padova U.:**
  Member of the HEAP (high energy astroparticle) group

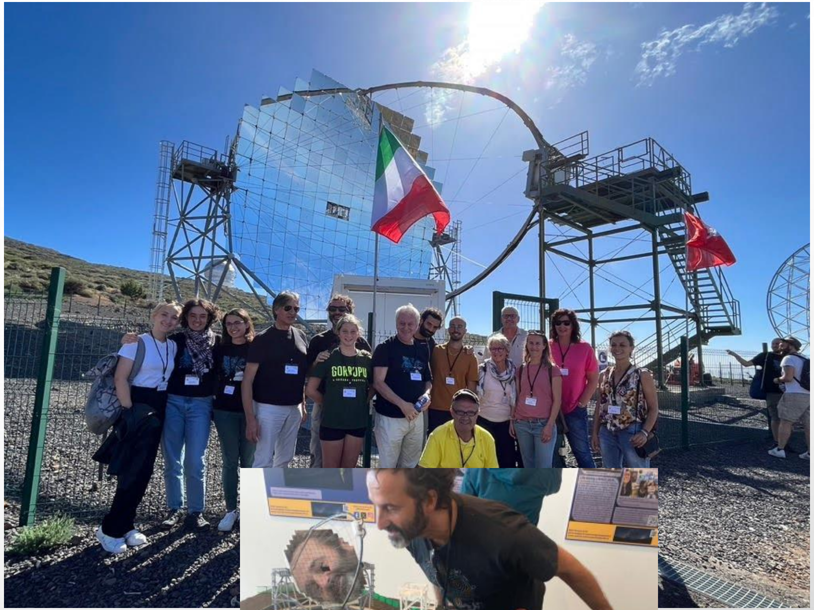
- **MAGIC** member since 2005
  - Extragalactic WG convener
  - MWL coordinator
  - TAC member

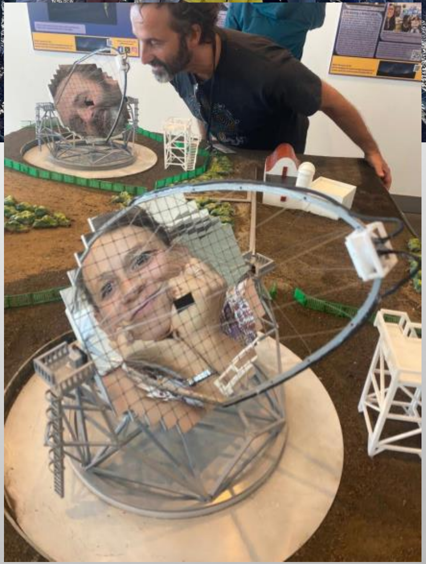
- **CTAC/CTAO** member since 2008
  - Extragalactic WG convener

COLLABORATORS: Antonio Stamerra, Talvikki HovattaCornelia Arcaro, Luca Foffano, Giacomo Bonnoli, Paolo Da Vela, Davide Miceli, Michele Doro, , Stefano Marchesi **MWL**: Claudia Raiteri, Yannis Liodakis, Ivan Agudo, Filippo D'ammando + many

FIELDS OF RESEARCH:

- Search for TeV-emitting blazars
- Characterization of the multiwavelength emission from blazars
- Quest for extreme blazars





… AND OUTREACH ACTIVITIES

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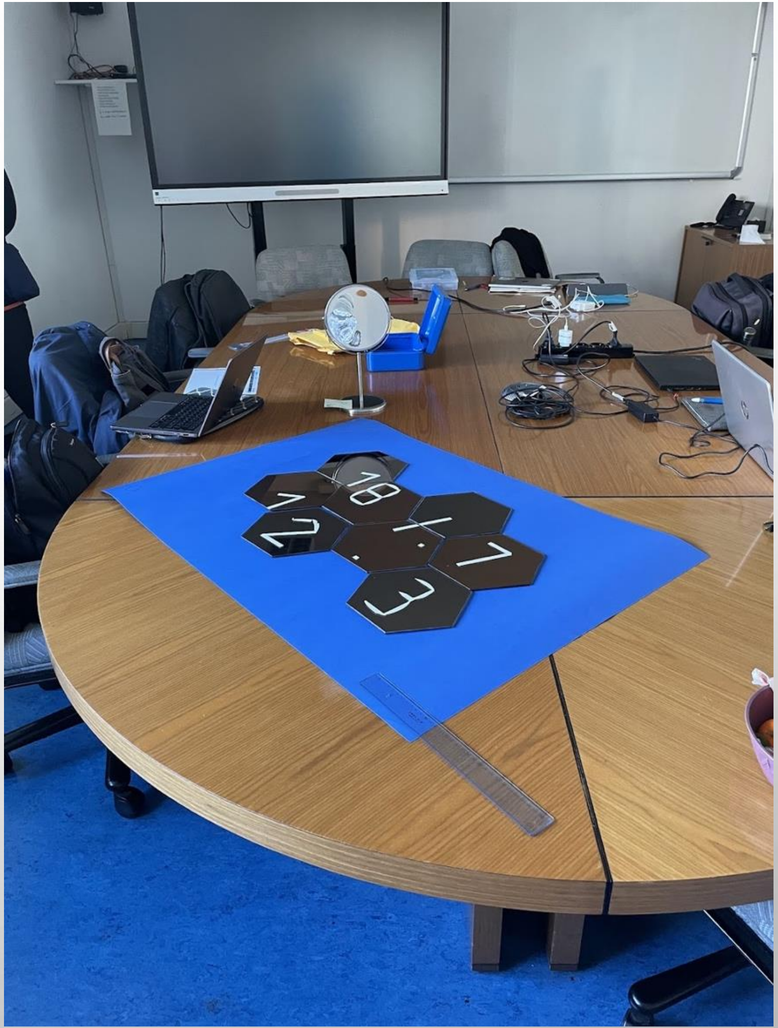
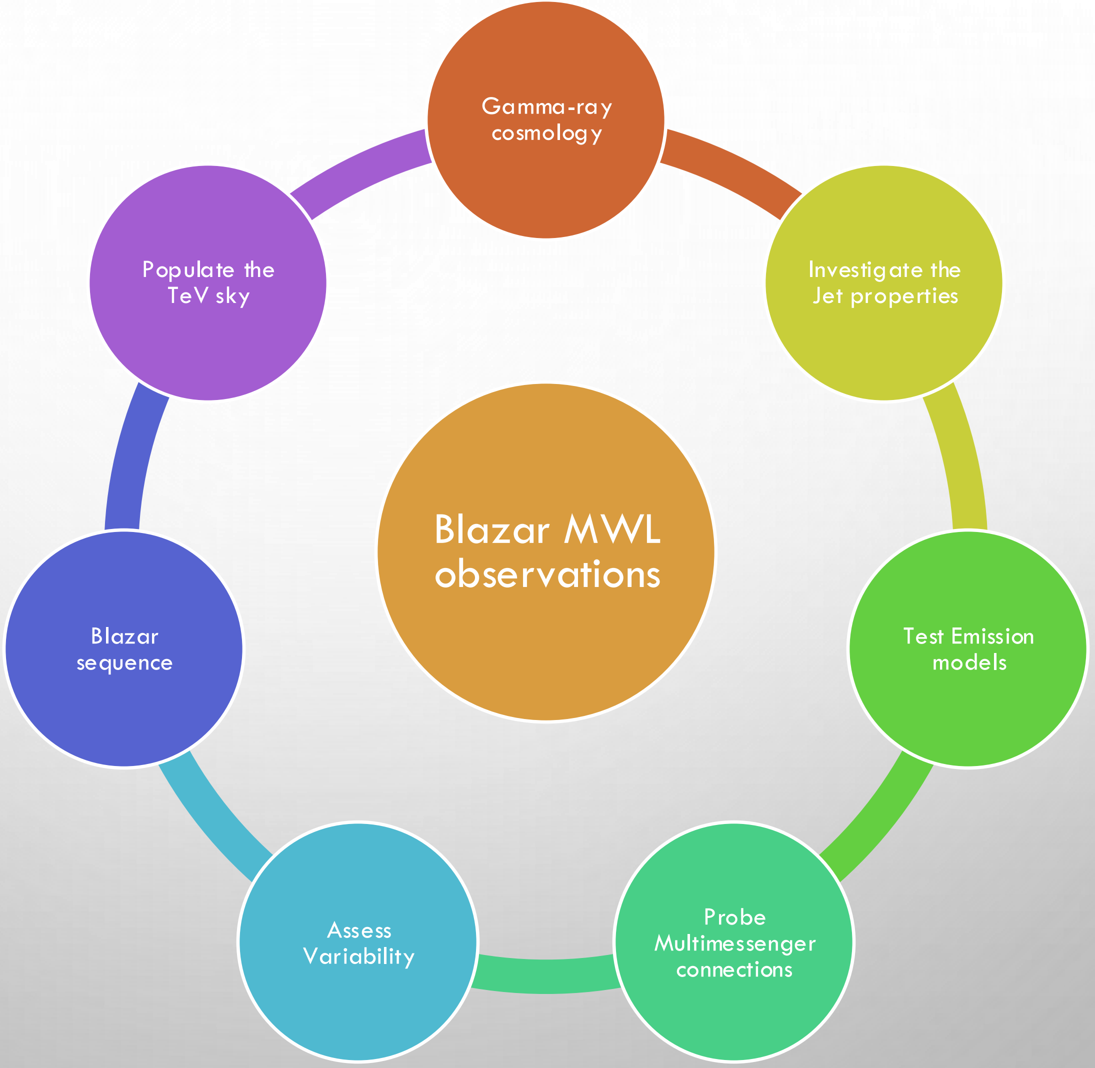
My last effort: I am designing an **escape room** themed experimental astro-particle physics

→ Auger
→ MAGIC
→ KM3NET

Prototype will be presented at the ICRC25

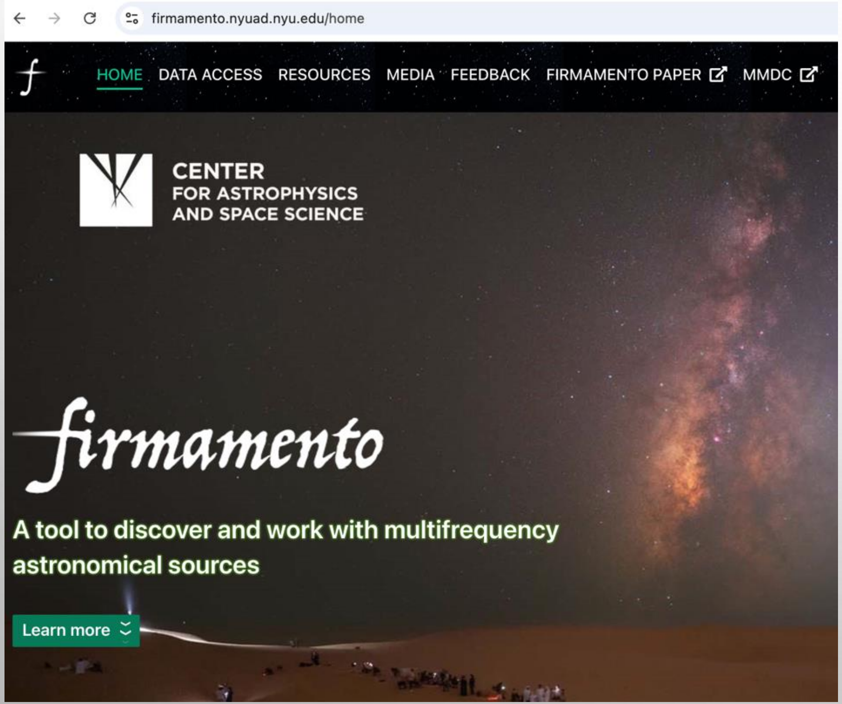


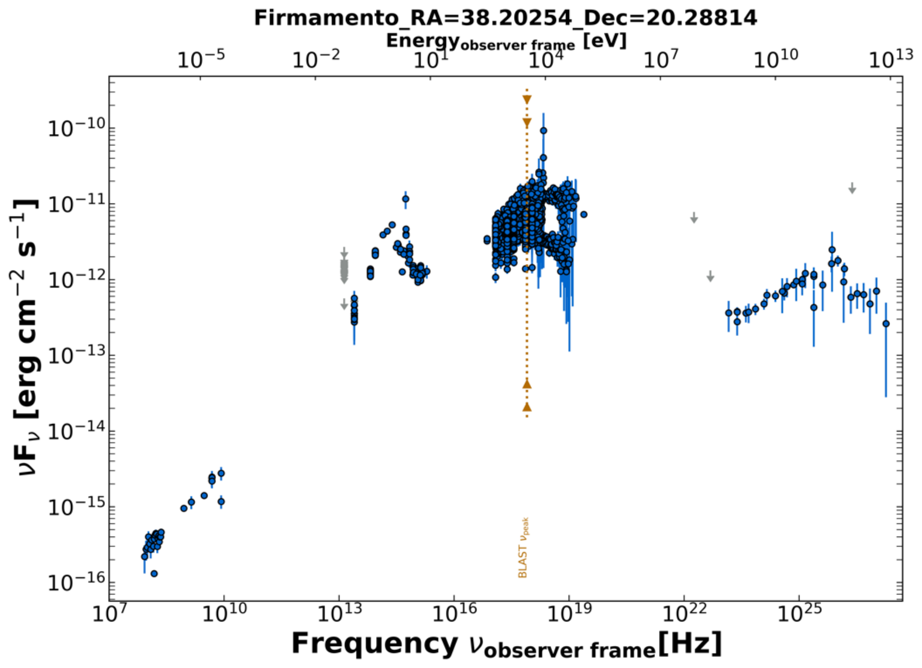
MY RESEARCH ACTIVITY



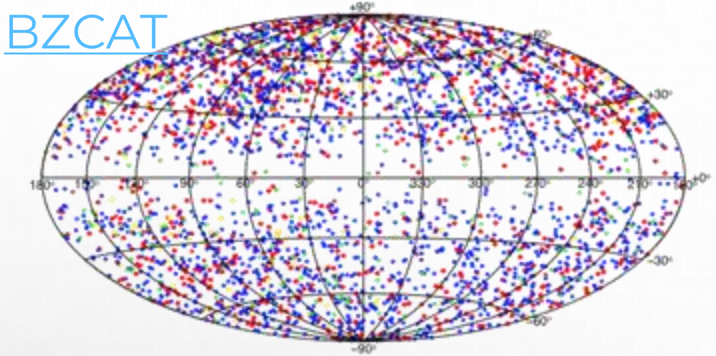
BLAZAR DATA: A (POWERFUL) PORTAL

HTTPS://FIRMAMENTO.NYUAD.NYU.EDU/HOME



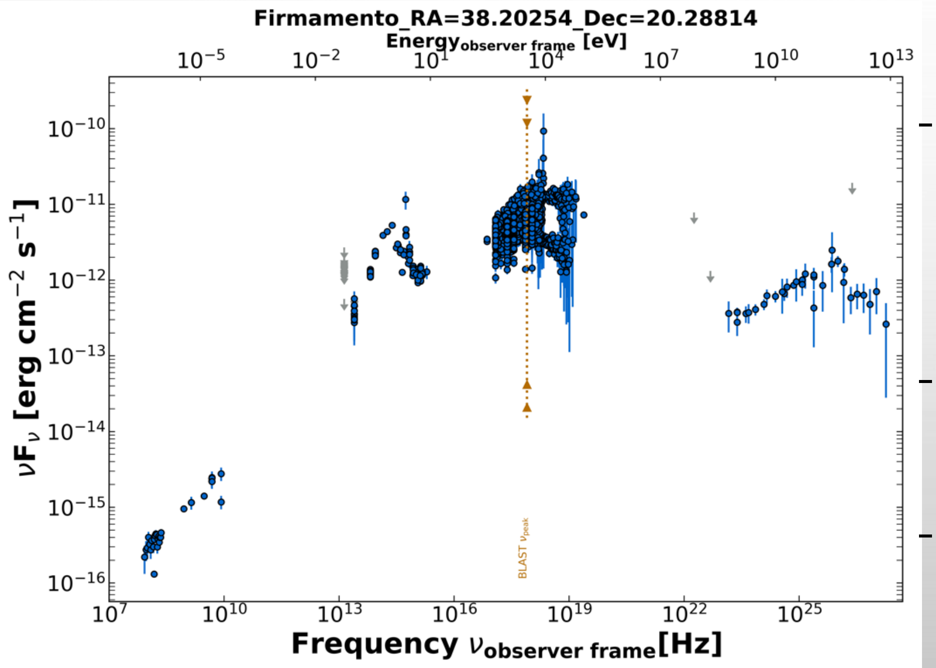


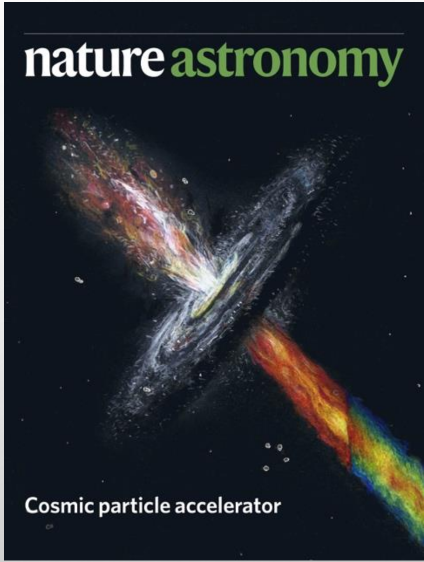
BZCAT



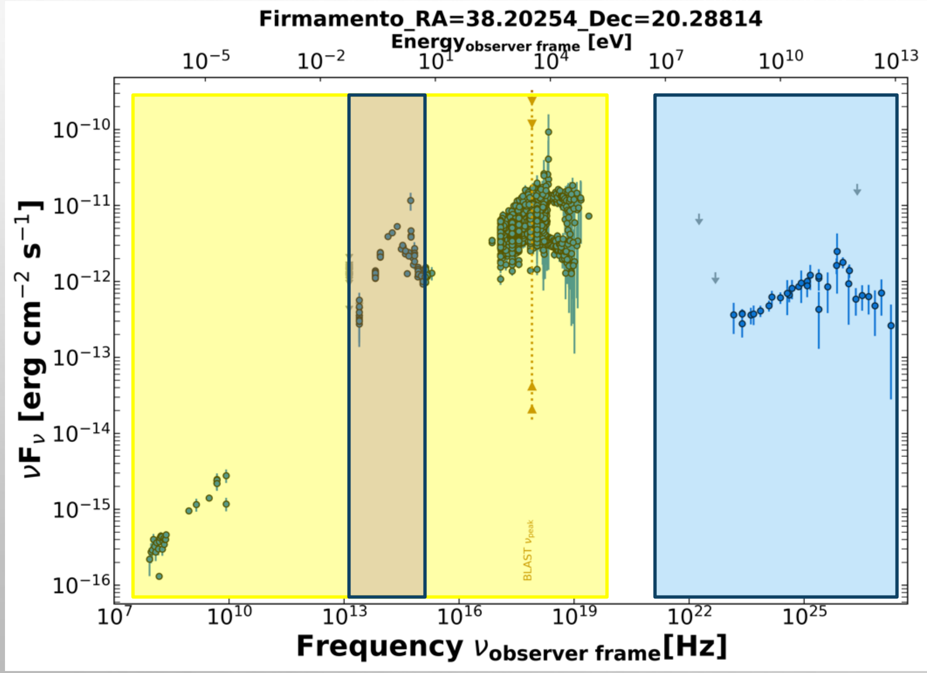
BLAZARS IN A NUTSHELL

- Jetted AGNs with a **jet closely aligned** with the line of sight (counterparts of radiogalaxies)
- Only **~50% with known distance** (lack of measurements + difficulty in detecting the host galaxy)
- SED spans ~20 orders of magnitude in frequency
- Mostly **non-thermal** emission



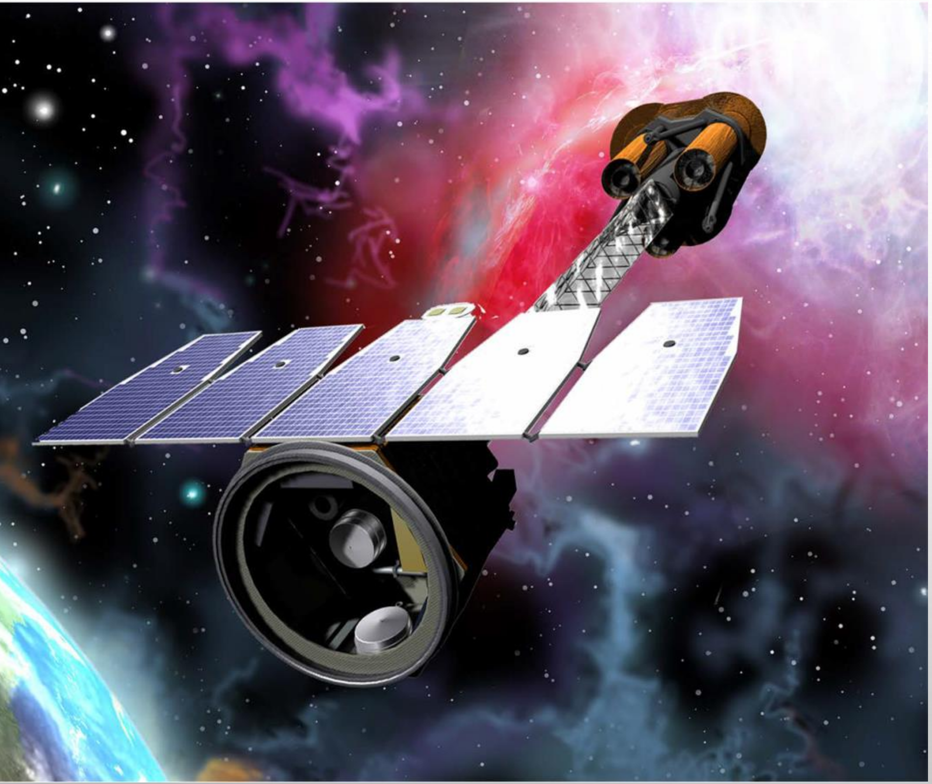


BLAZAR'S SPECTRAL ENERGY DISTRIBUTION (SED)

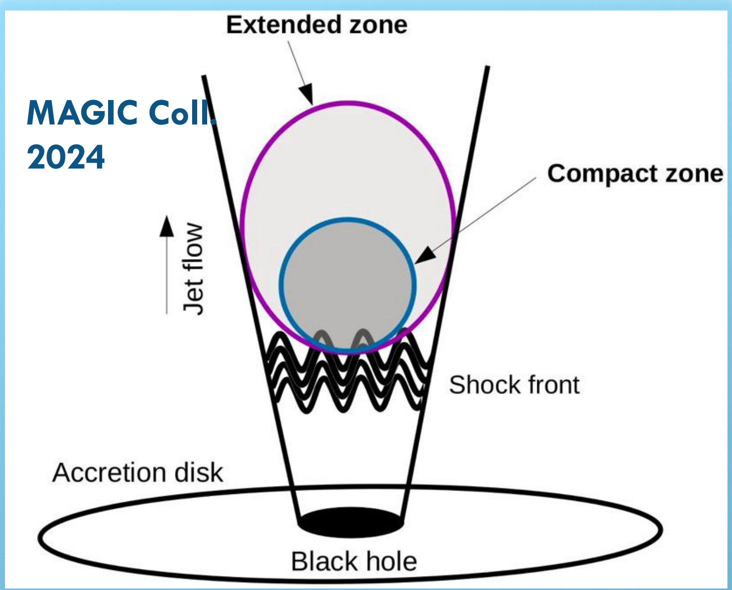


- FIRST PEAK: SYNCHROTRON EMISSION
- SECOND PEAK: INVERSE COMPTON EMISSION + HADRONIC COMPONENT(S)
- HOST GALAXY: EMERGES AT OPTICAL FREQUENCIES

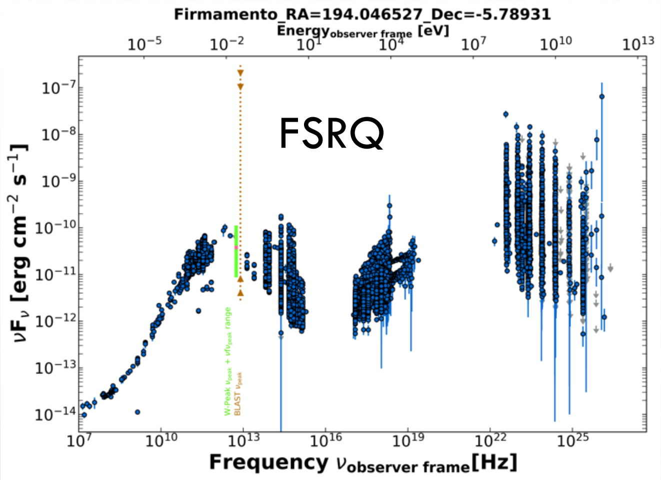
RECENT HIGHLIGHTS FROM BLAZAR STUDIES

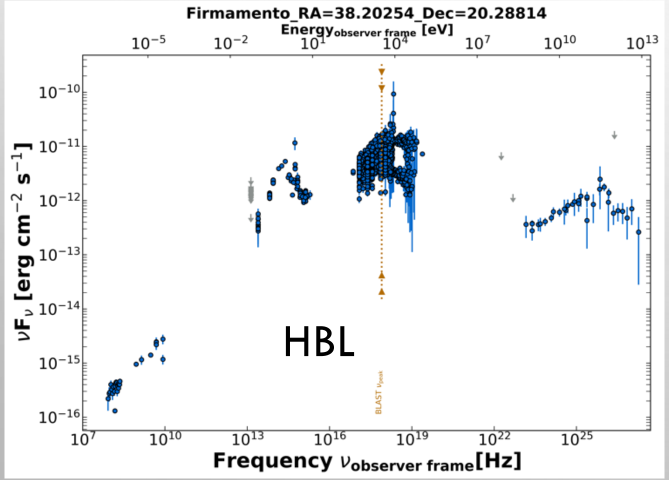


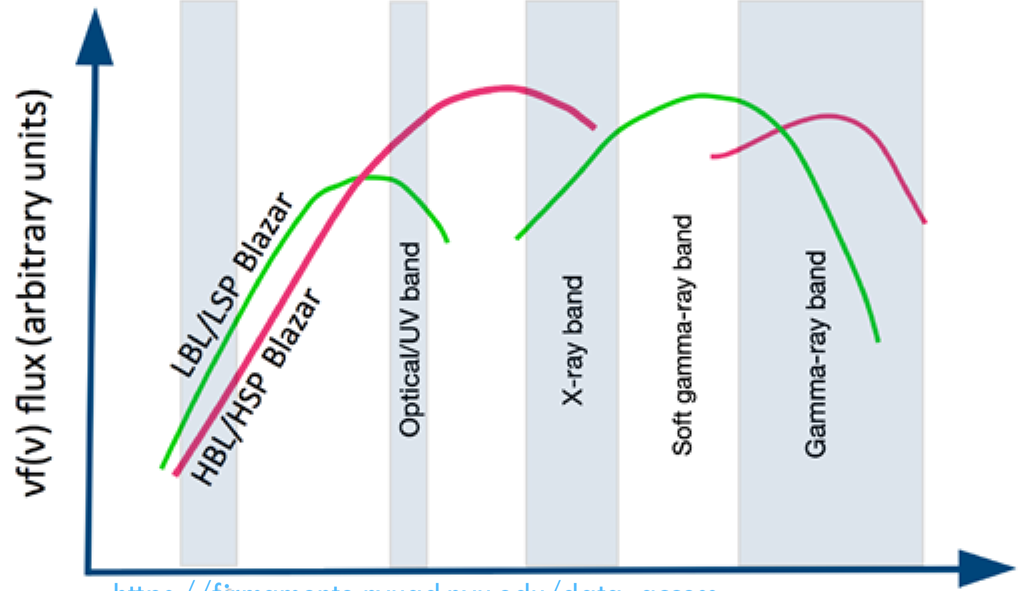
- IXPE: X-ray polarimetry
- High polarization level in blazar's jet suggest a stratified jet



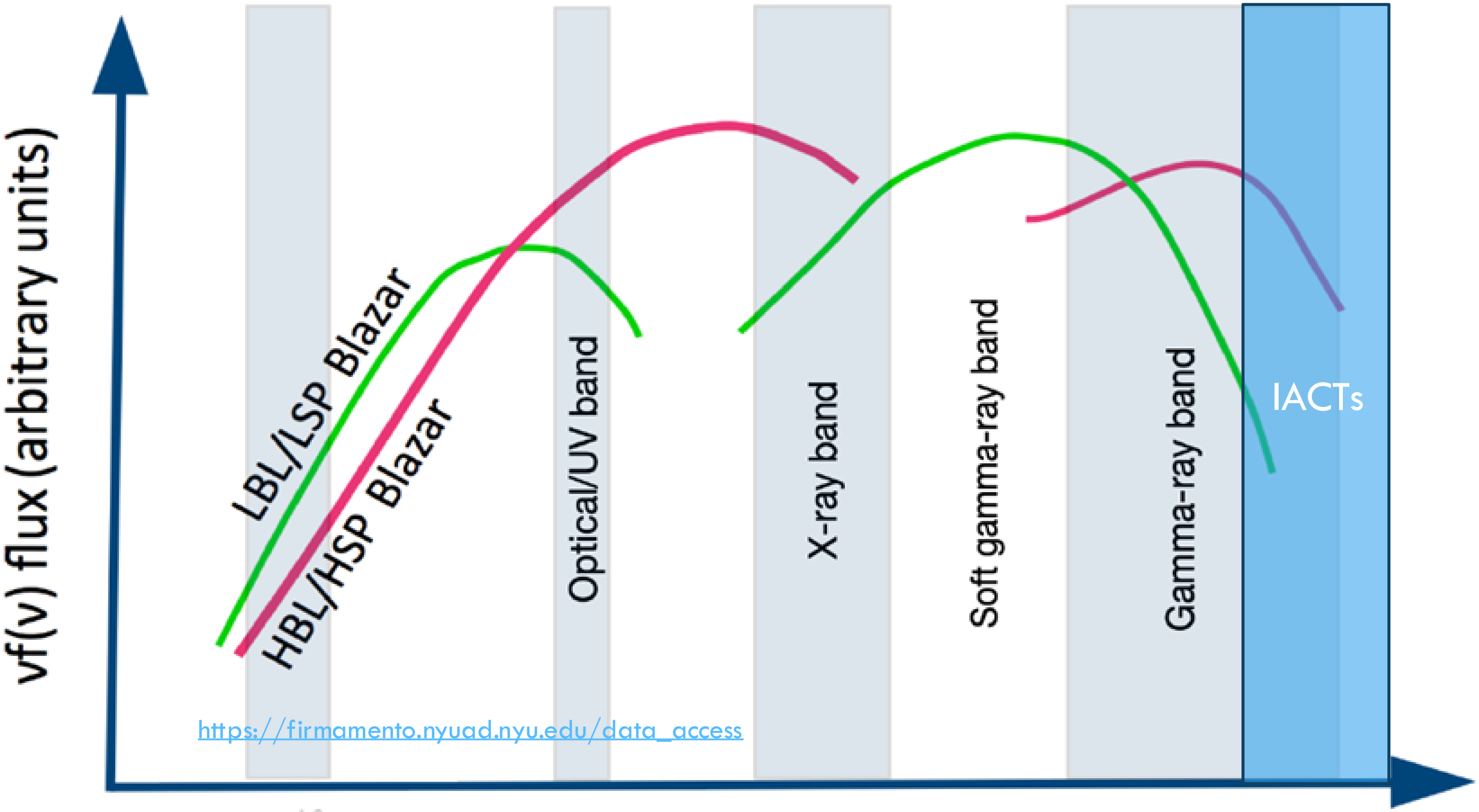
THE SED CAN BE DIFFERENT!







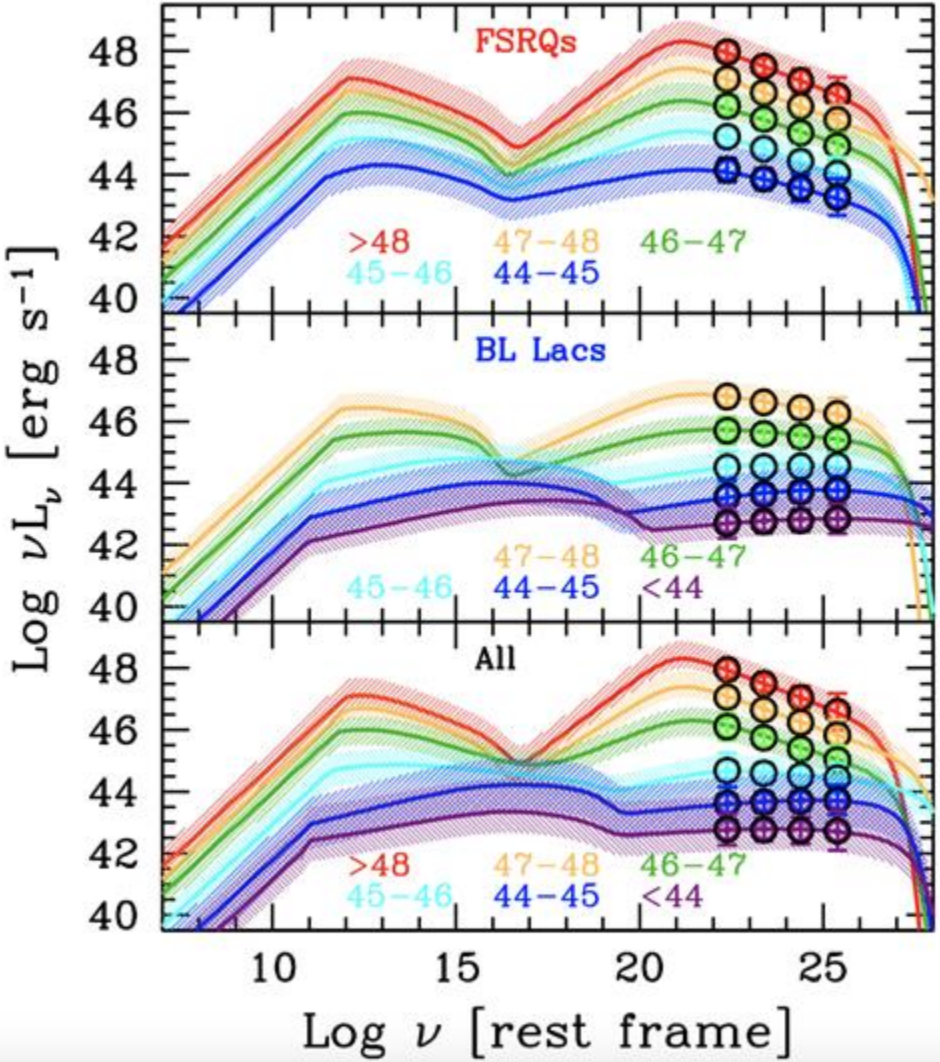
https://firmamento.nyuad.nyu.edu/data_access



https://firmamento.nyuad.nyu.edu/data_access

THE BLAZAR SEQUENCE

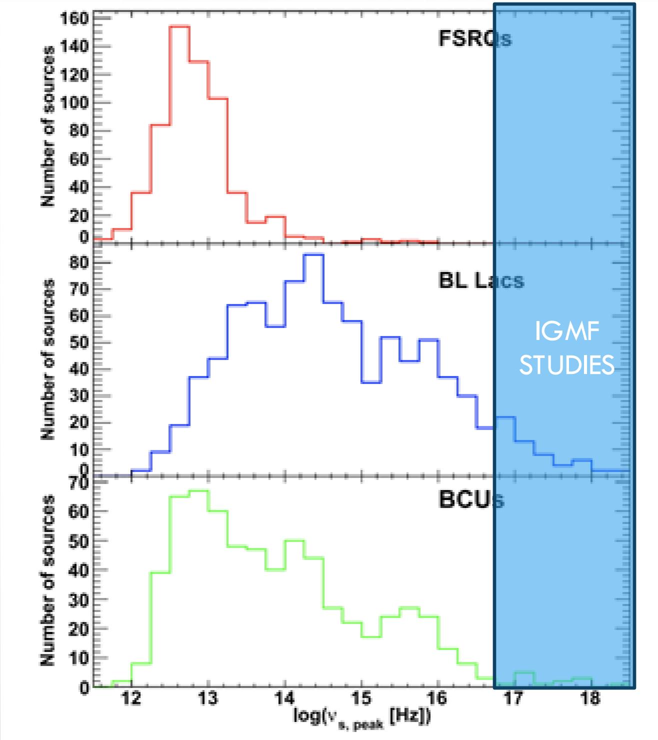
- Data classified according to the *Fermi*-LAT luminosity
- **Anti-correlation** between the **synchro peak** position and the **luminosity** (BL Lacs)
- Trend in Compton dominance

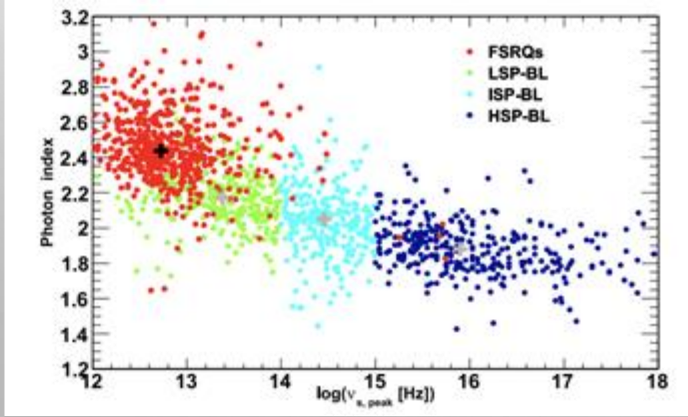


Ghisellini+ 2016, review: EP & Ghisellini 2022, 4LAC, Fermi Coll. 2020

HOW MANY GAMMA-RAY BLAZARS?

- 4LAC CATALOG ON AGN DETECTED BY *FERMI*-LAT: 2560 BLAZARS
- SYNCHROTRON PEAK DISTRIBUTION: SPANS 6 ORDERS OF MAGNITUDE IN FREQUENCY



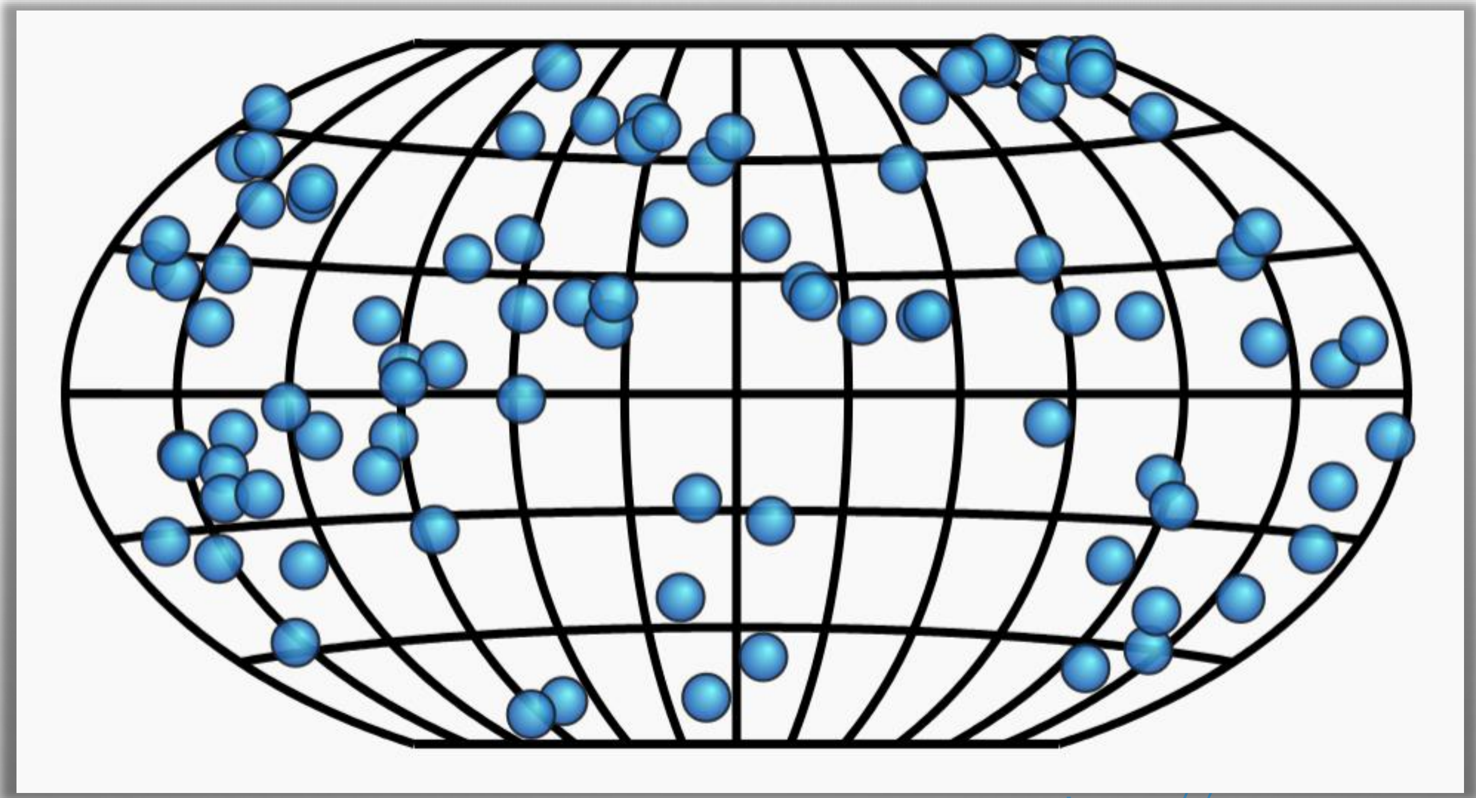


Photon index shows a trend with synchro peak (large dispersion)

HOW MANY TEV BLAZARS?

→ LESS THAN 100 SOURCES!

WHY?

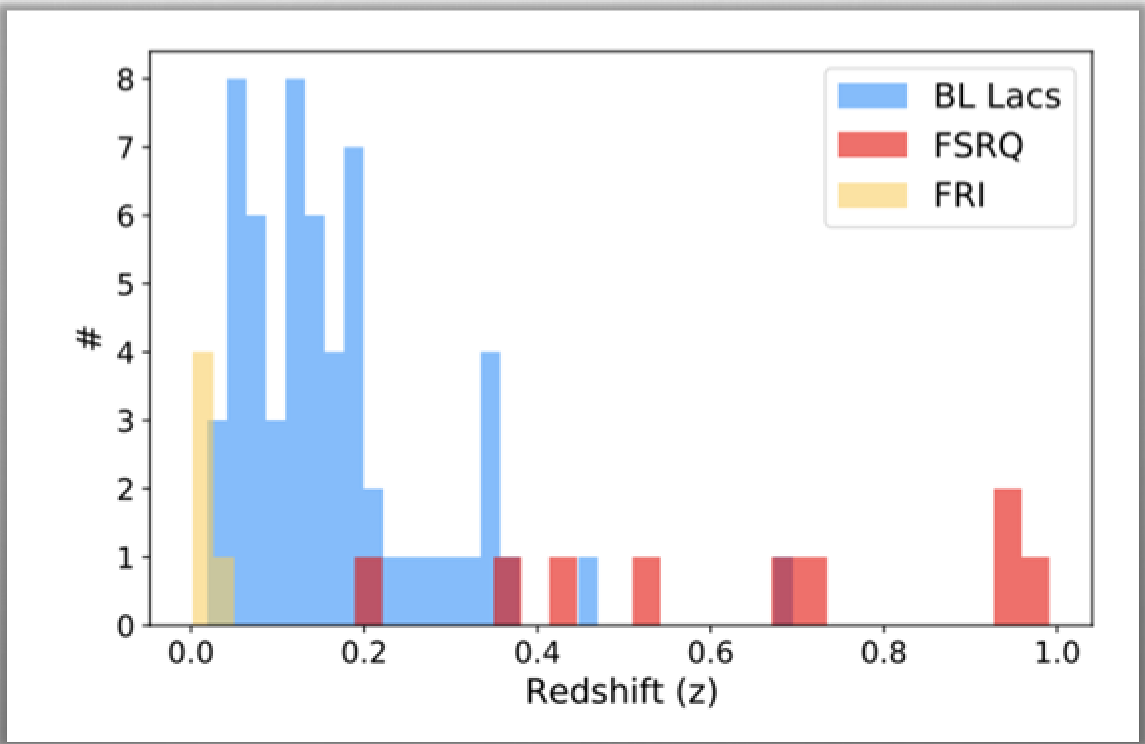


https://www.tevcat.org/

1. THE DISTANCE EFFECT (EBL)

- Distant sources are attenuated by EBL

- Note: distant sources are all FSRQs
  - Many BL Lacs have **unknown redshift**!

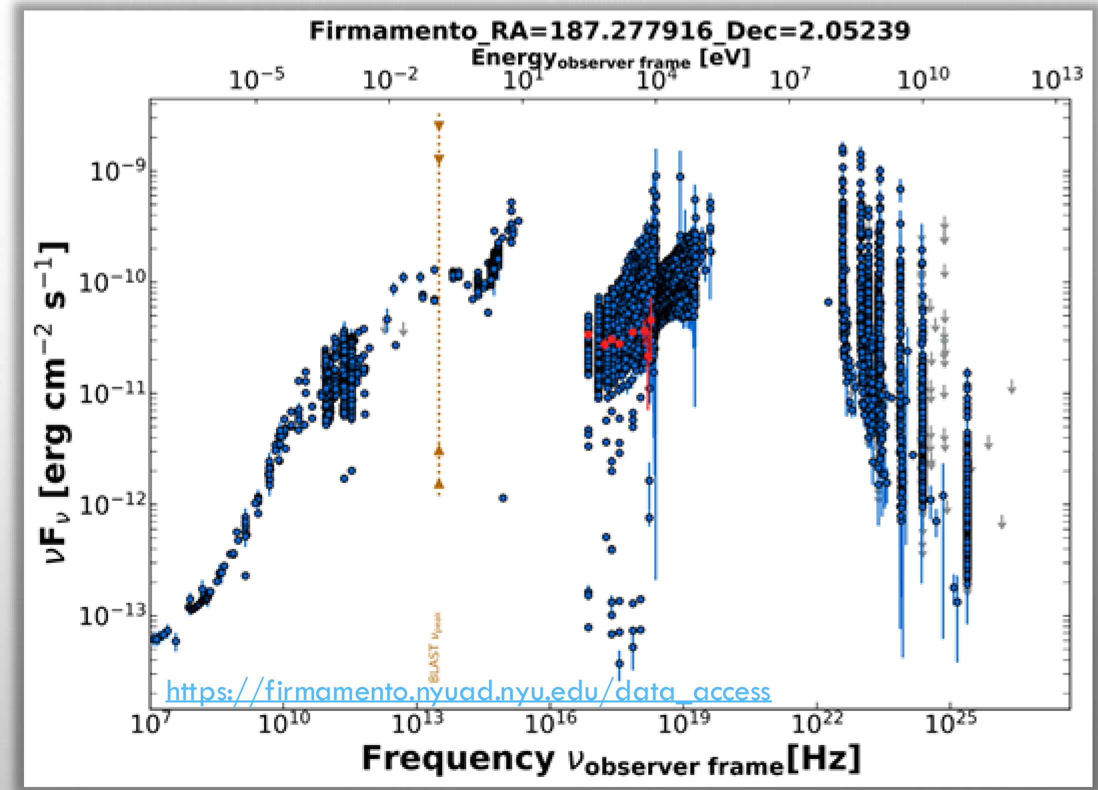


Advances in very high energy astrophysics, Zanin & Mukherjee

2. NOT ALL BLAZARS REACH TEV ENERGIES

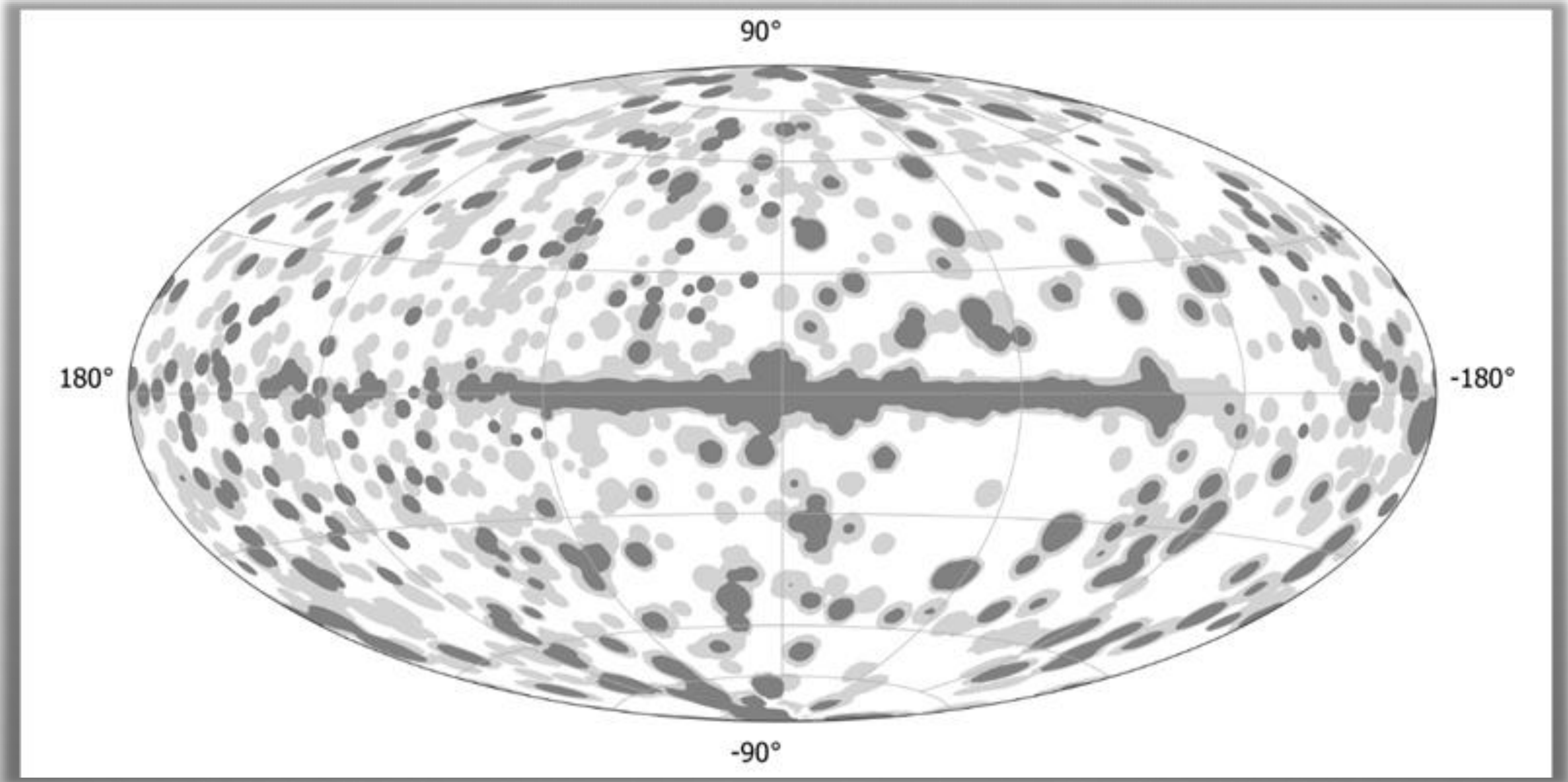
SED OF THE BLAZAR 3C 273

→ IACT NEVER DETECTED IT!



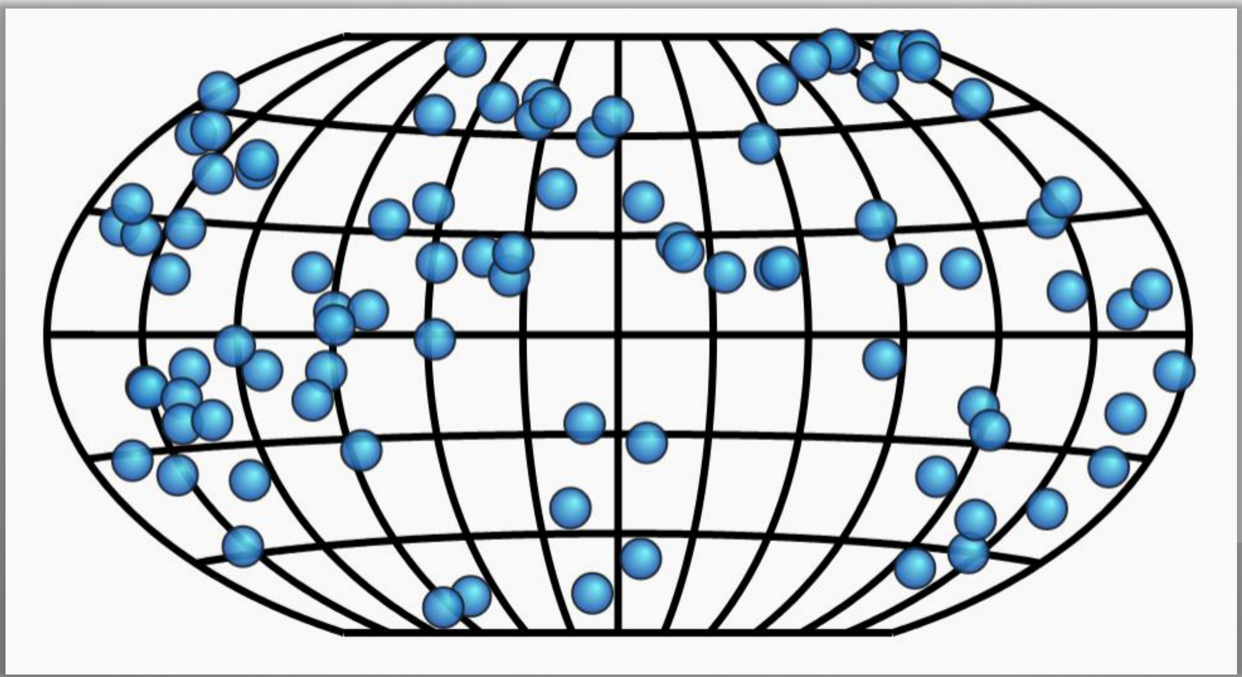
3. TEV SKY EXPOSURE (IACT)

- The FoV of IACTs is limited
- Time available ~hundred hours per year
- Time granted through competitive proposals

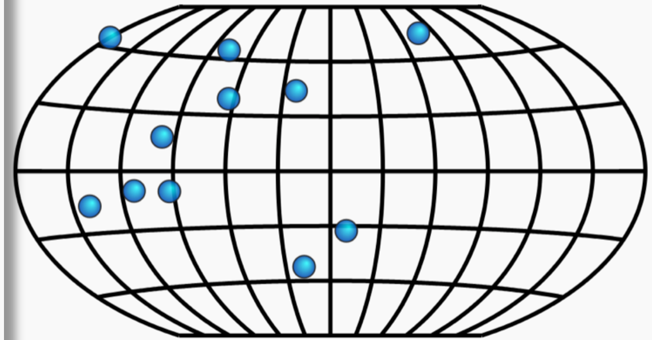


Advances in very high energy astrophysics, Zanin & Mukherjee

TEV-BLAZARS NOW (2025) AND IN 2005!

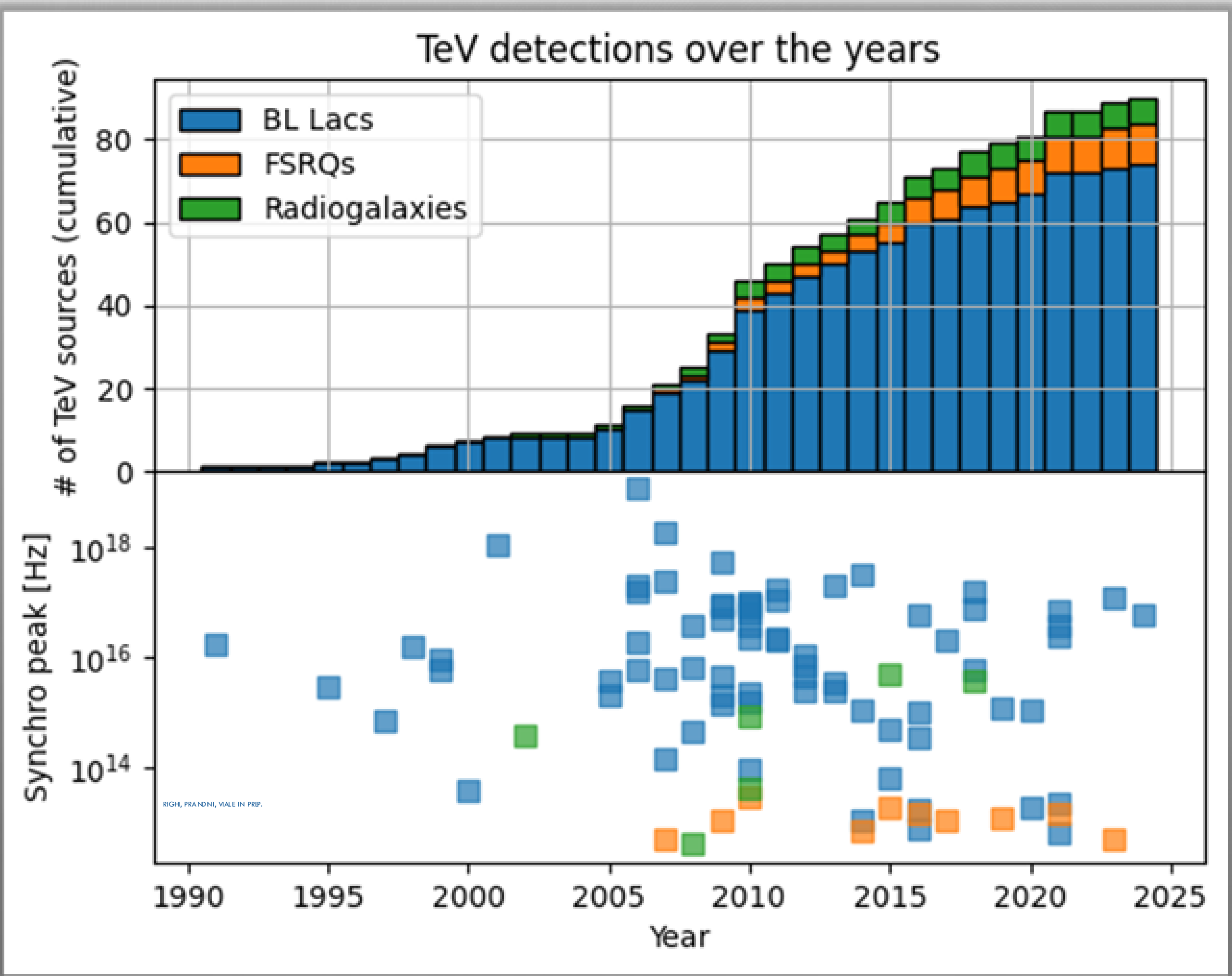


IN 2005: ONLY 11 SOURCES KNOWN!



https://www.tevcat.org/

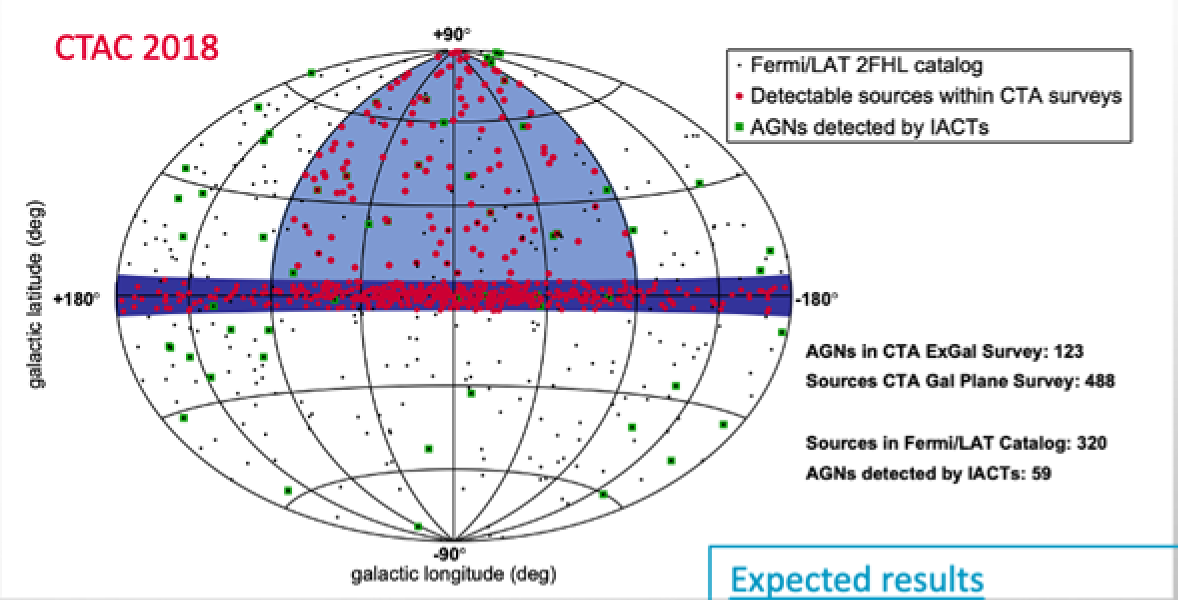
OBSERVATIONS STRATEGY OF IACTS



Biased towards the extremes of the blazar sequence

EGAL SURVEY - CTAO

- Consists of a **survey** with uniform exposure of a contiguous portion of the extragalactic sky
- From the '*Science with CTA*' book:
  - ¼ of the sky
  - **6 mCrab** of integral sensitivity E>125 GeV
- These values and observation strategy could be revised by the CTAC team



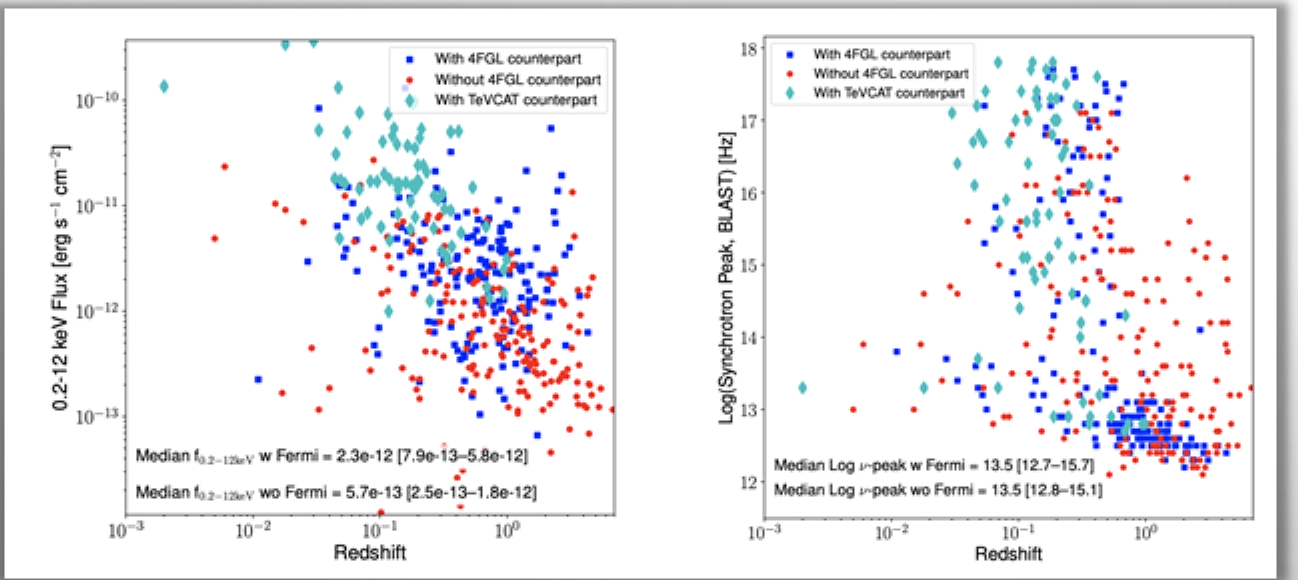
Expected results

- 1^{st} unbiased VHE catalog
- LogN/LogS
- Serendipitous discoveries
- Variable sources

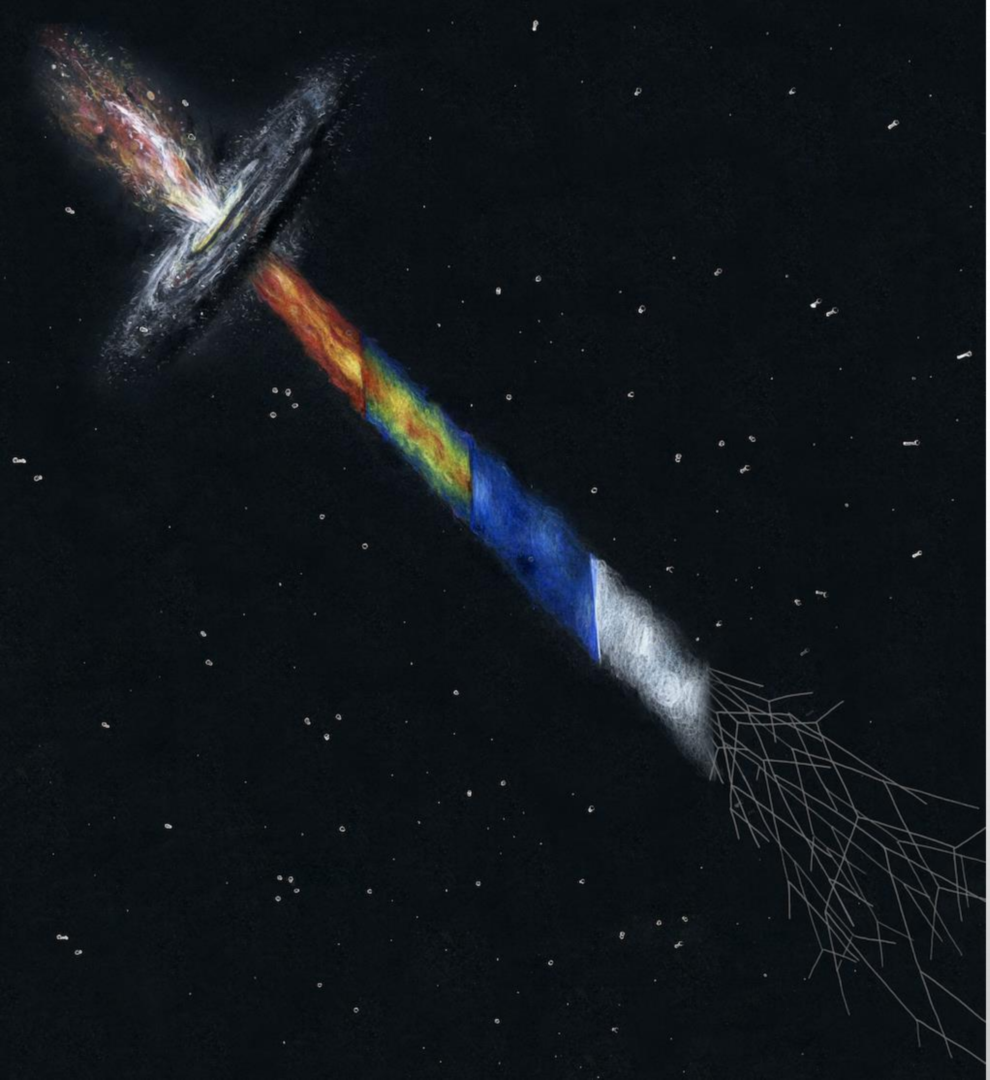
NOT ONLY *FERMI*-LAT

Marchesi, Iuliano, EP + 2025

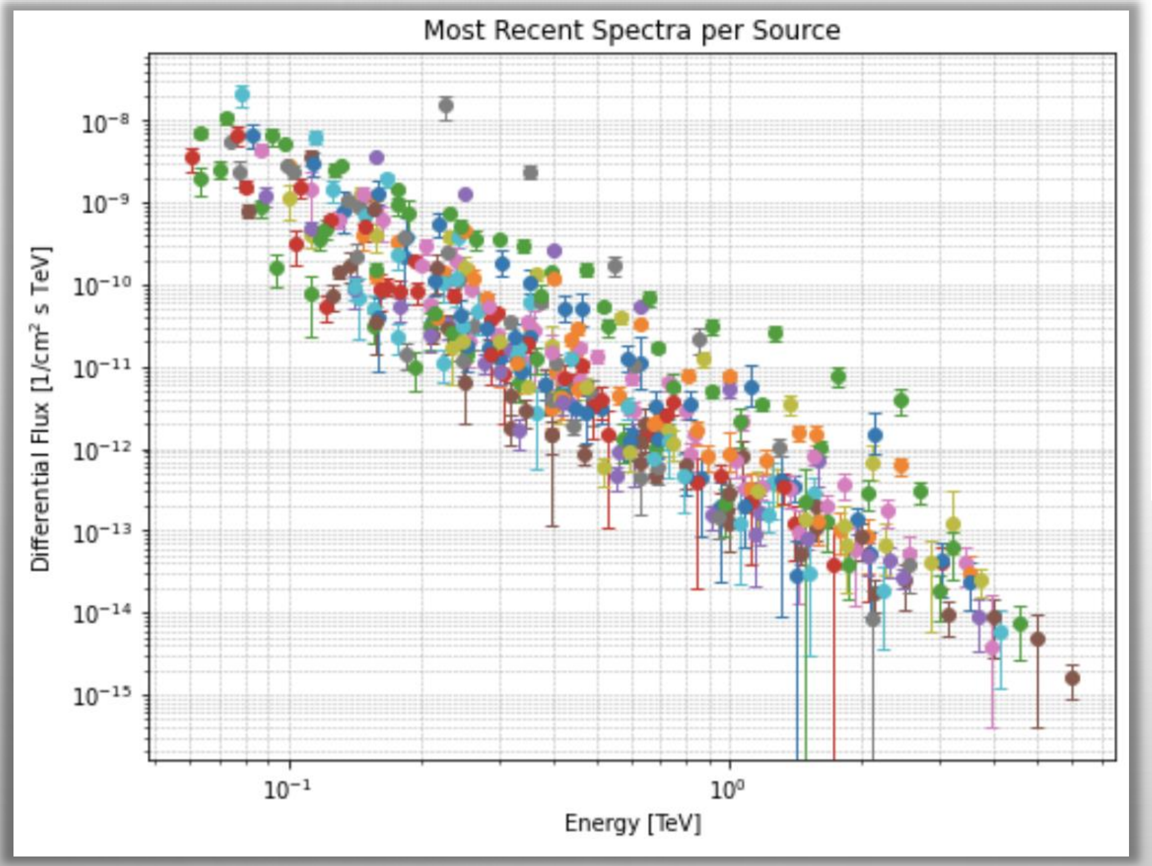
Fermi-LAT observations are flux limited: dedicated studies on ***Fermi* non-detected** sources provide complementary sources to be considered for IACTs

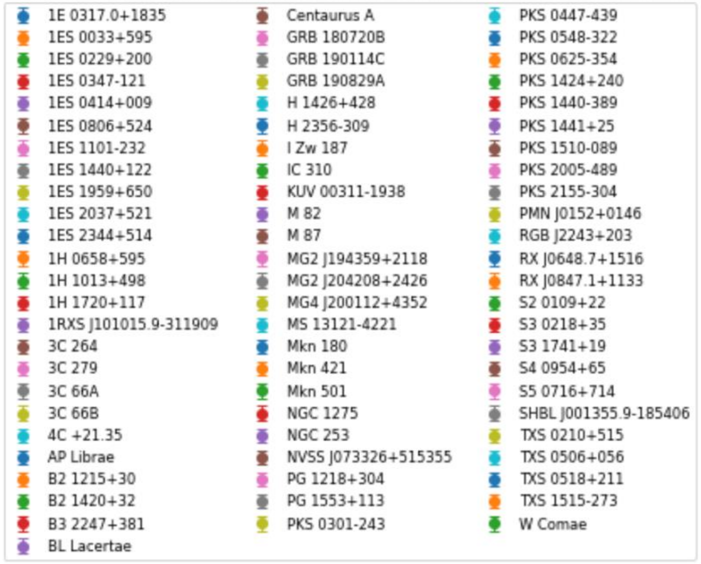


- BZCAT + X-ray detection (XMM/Swift/Chandra or eROSITA): 2435 sources
- 1007 sources non detected in gamma rays
- Fainter in X-ray thanthe gamma-ray detected
- Synchrotron peak covers the different classed of blazars



(EXTREME) BLAZAR SPECTRA

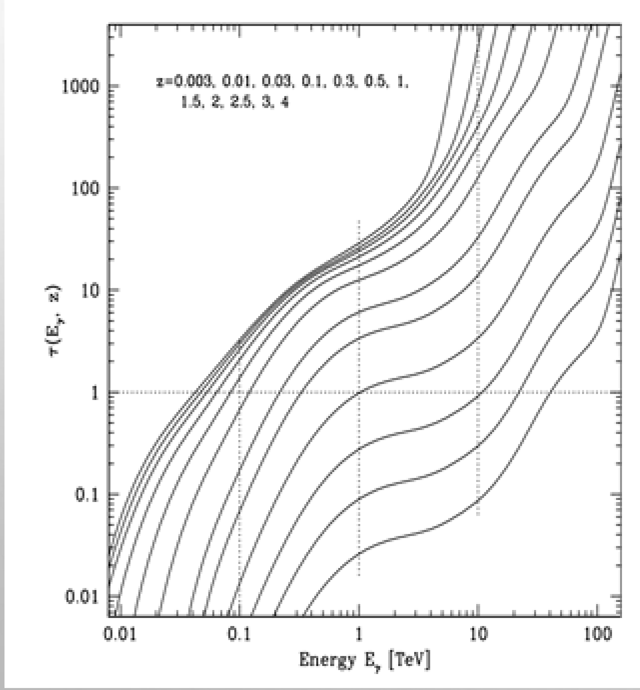




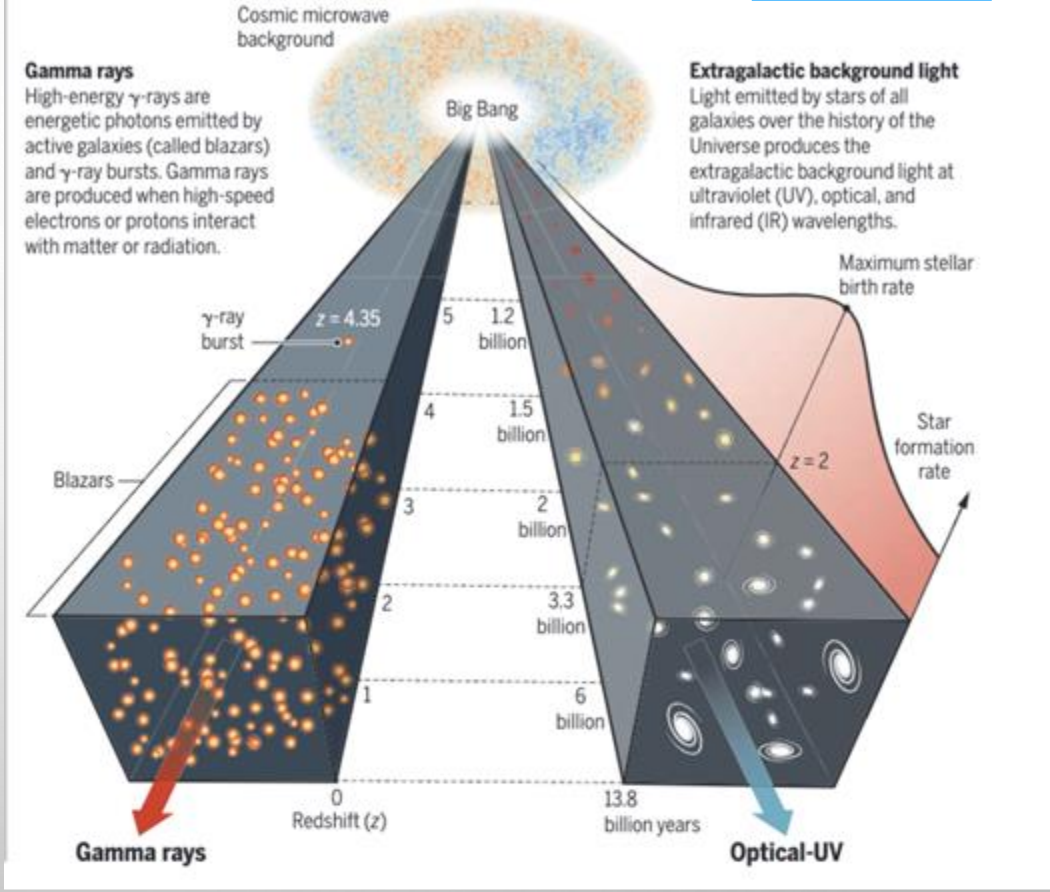
Spectra from STeVeCAT (Greaux+)

GAMMA-RAY OPACITY

FRANCESCHINI & RODIGHIERO 2008

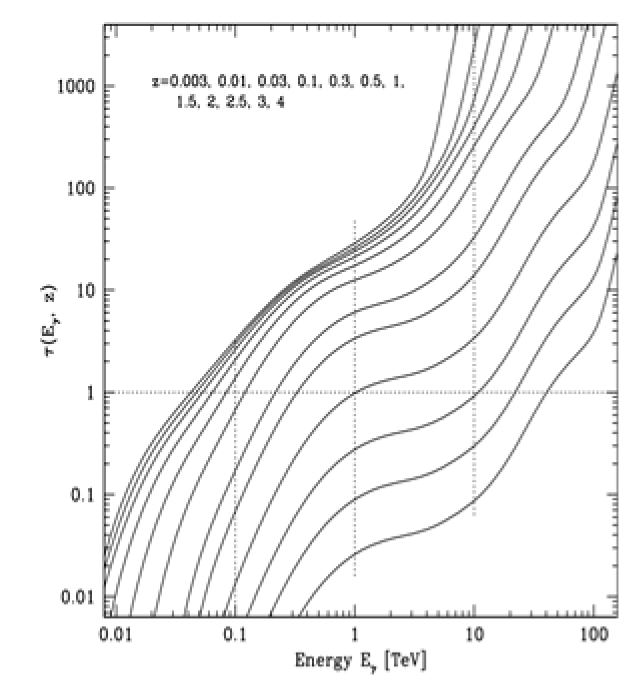


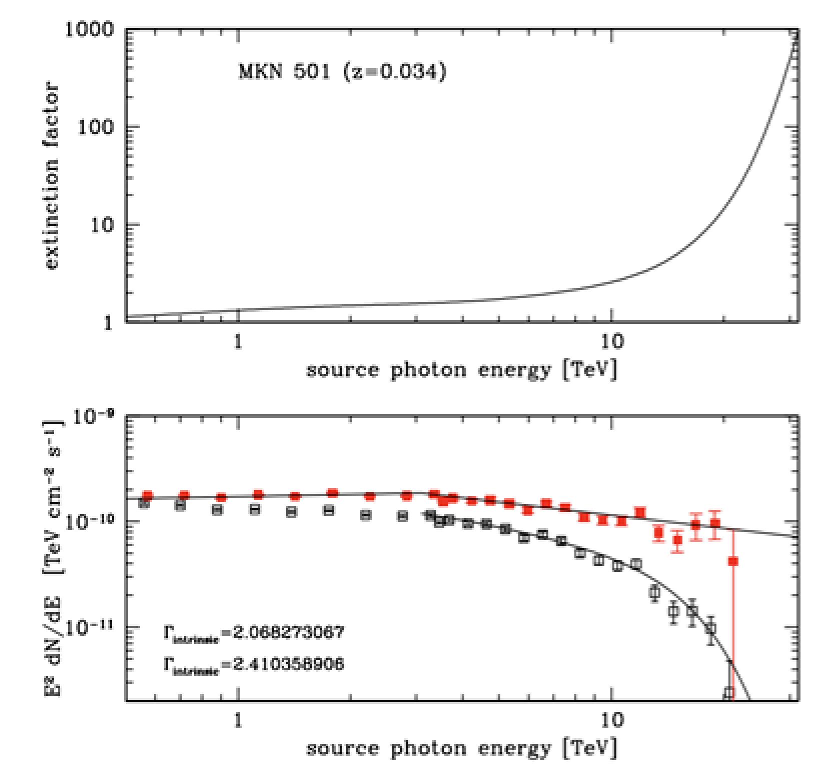
EP Science 2019



OPACITY: EFFECT ON VHE BLAZAR'S SPECTRA

FRANCESCHINI & RODIGHIERO 2008





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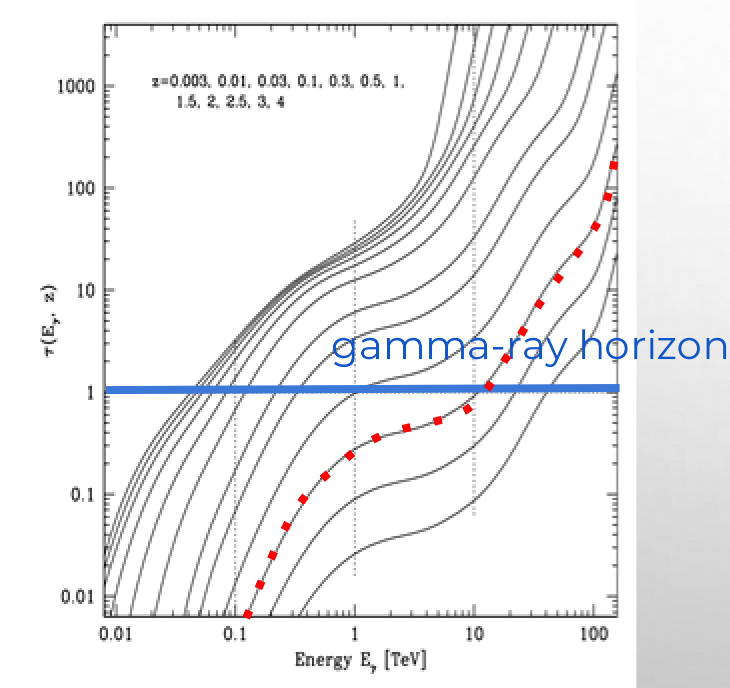

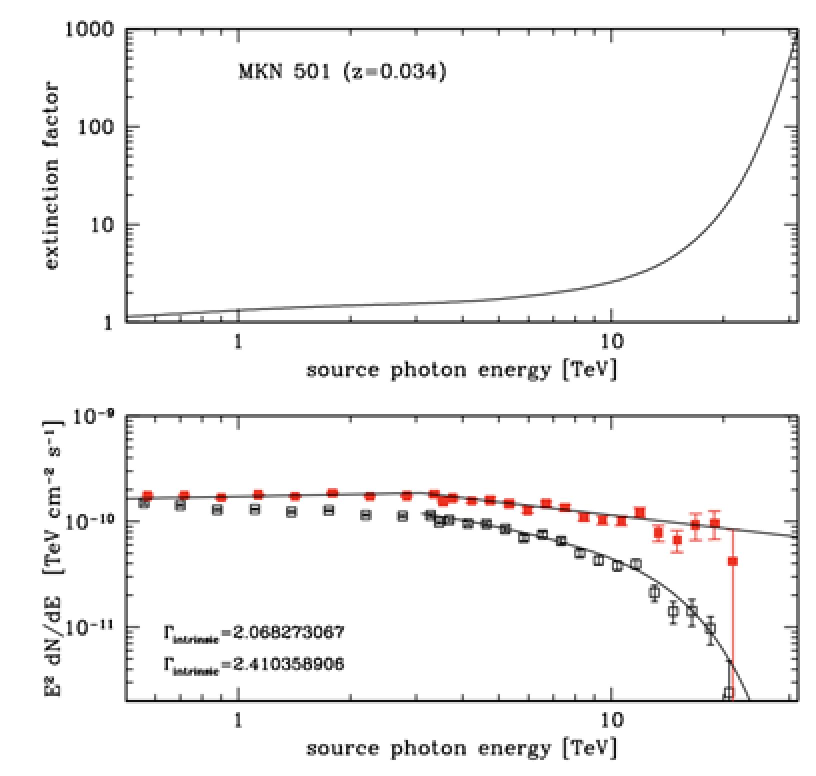

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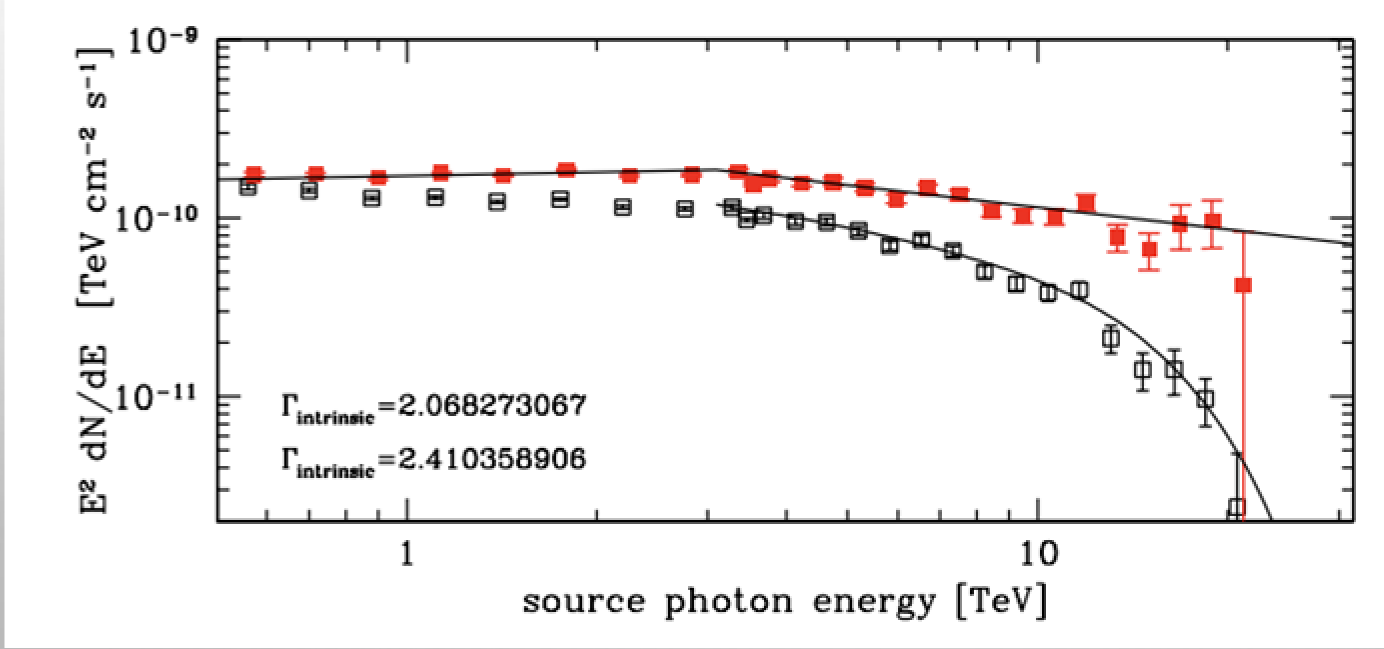
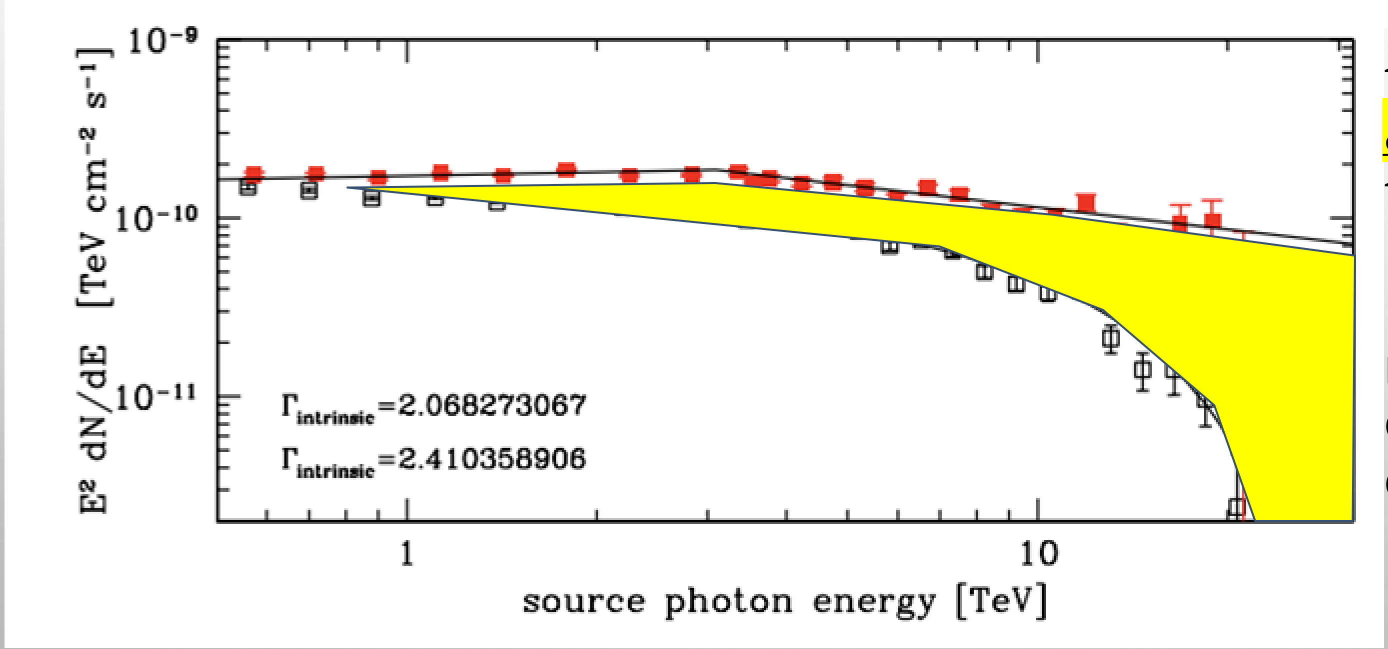


OPACITY: EFFECT ON VHE BLAZAR'S SPECTRA

FRANCESCHINI & RODIGHIERO 2008

$$F(E_{\gamma_0}) = F_0(E'_{\gamma_0}(z_E))e^{-\tau(E_{\gamma_0}, z_E)},$$



these are the **absorbed photons** that convert into pairs and possibly reappears as **reprocessed emission at low energy**

OPACITY: EFFECT ON VHE BLAZAR'S SPECTRA

FRANCESCHINI & RODIGHIERO 2008

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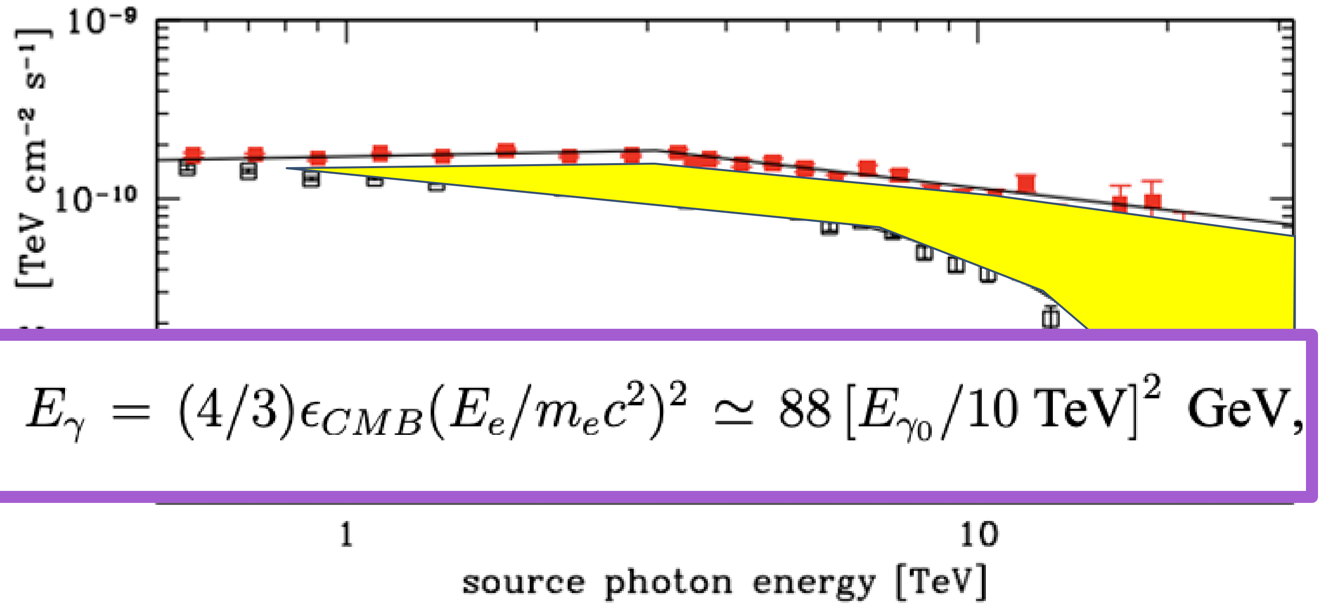
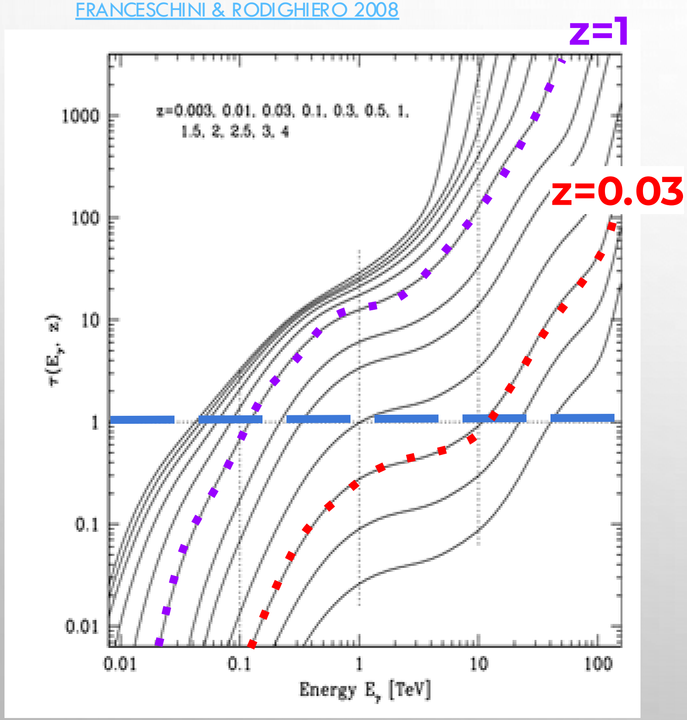


$$E_\gamma = (4/3)\epsilon_{CMB}(E_e/m_ec^2)^2 \simeq 88\,[E_{\gamma_0}/10\ \text{TeV}]^2\ \text{GeV},$$

these are the **absorbed photons** that convert into pairs and possibly reappears as **reprocessed emission at low energy**

OPACITY: EFFECT ON BLAZAR'S SPECTRA

FRANCESCHINI & RODIGHIERO 2008

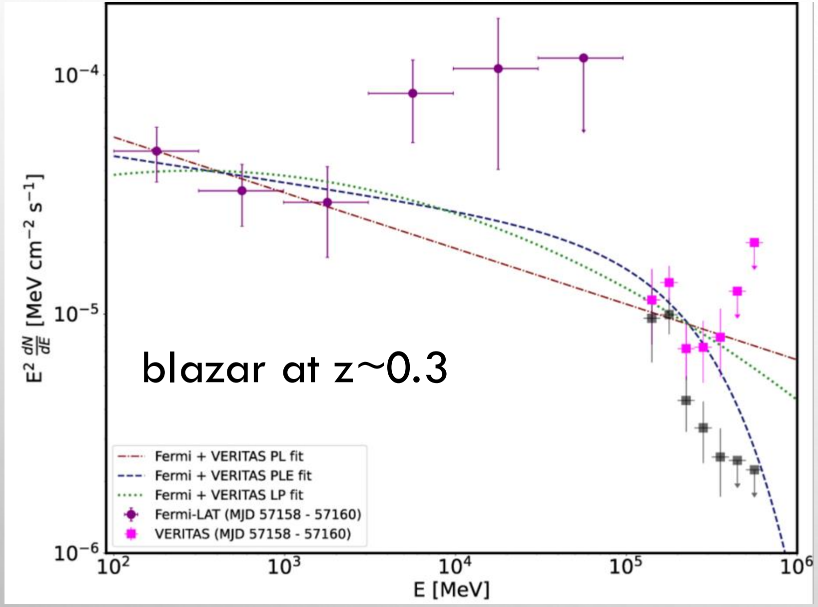


gamma-ray horizon

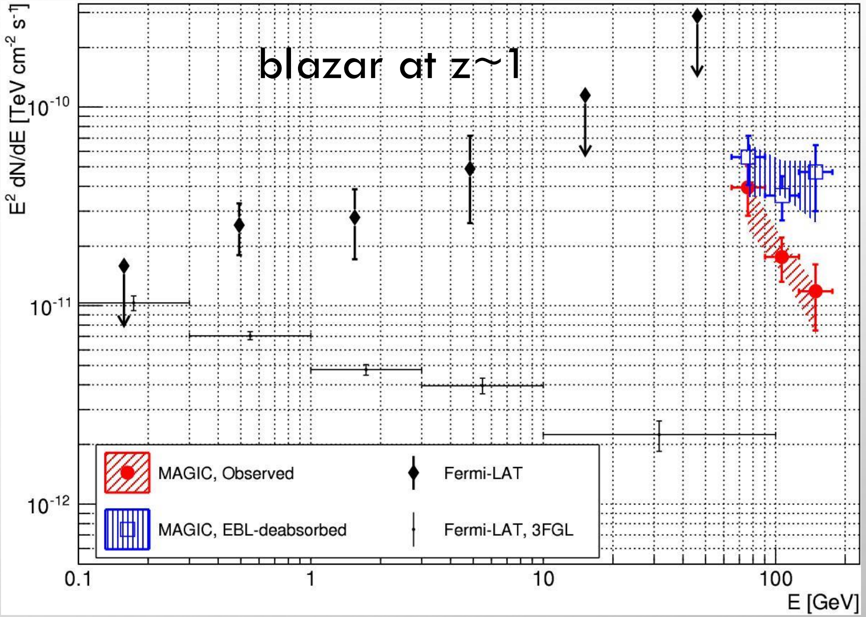
- the EBL induced cutoff is strongly z-dependent
- For sources at z=1, 100 GeV gamma rays are already attenuated by a factor 1/e
- at z=0.03, the same attenuation is for gammas at 10 TeV

EXAMPLES:

VERITAS Coll. 2023

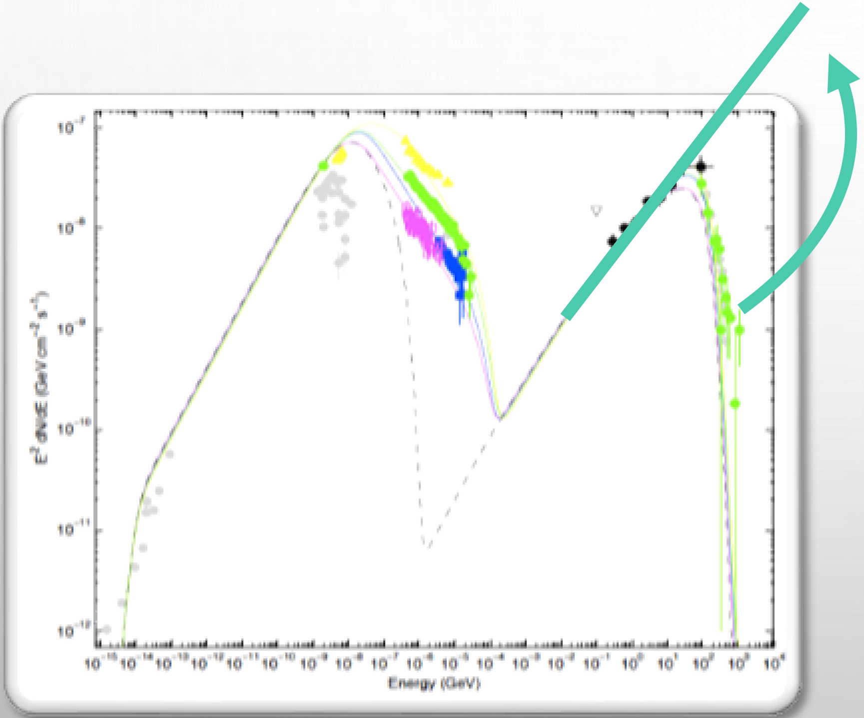


MAGIC Coll. 2016

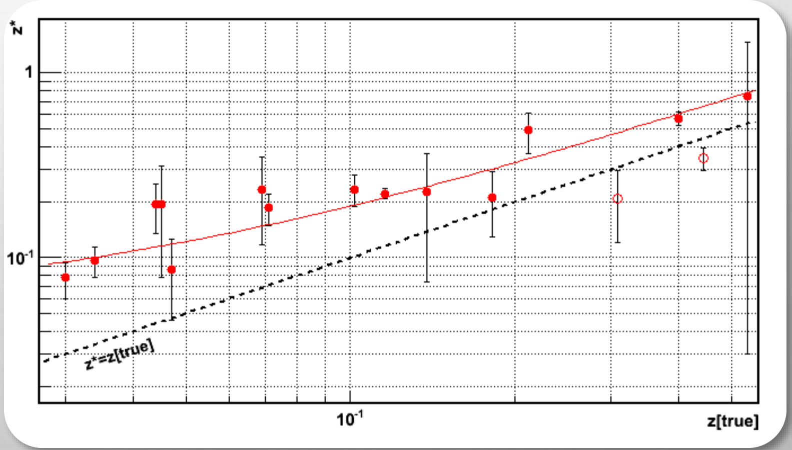


Main message: Our ability of reconstructing **TeV spectra** is strongly **redshift dependent**

CURIOSITY: CONSTRAINING BLAZARS DISTANCE



Maximum Distance can be inferred from TeV+ *Fermi*-LAT data

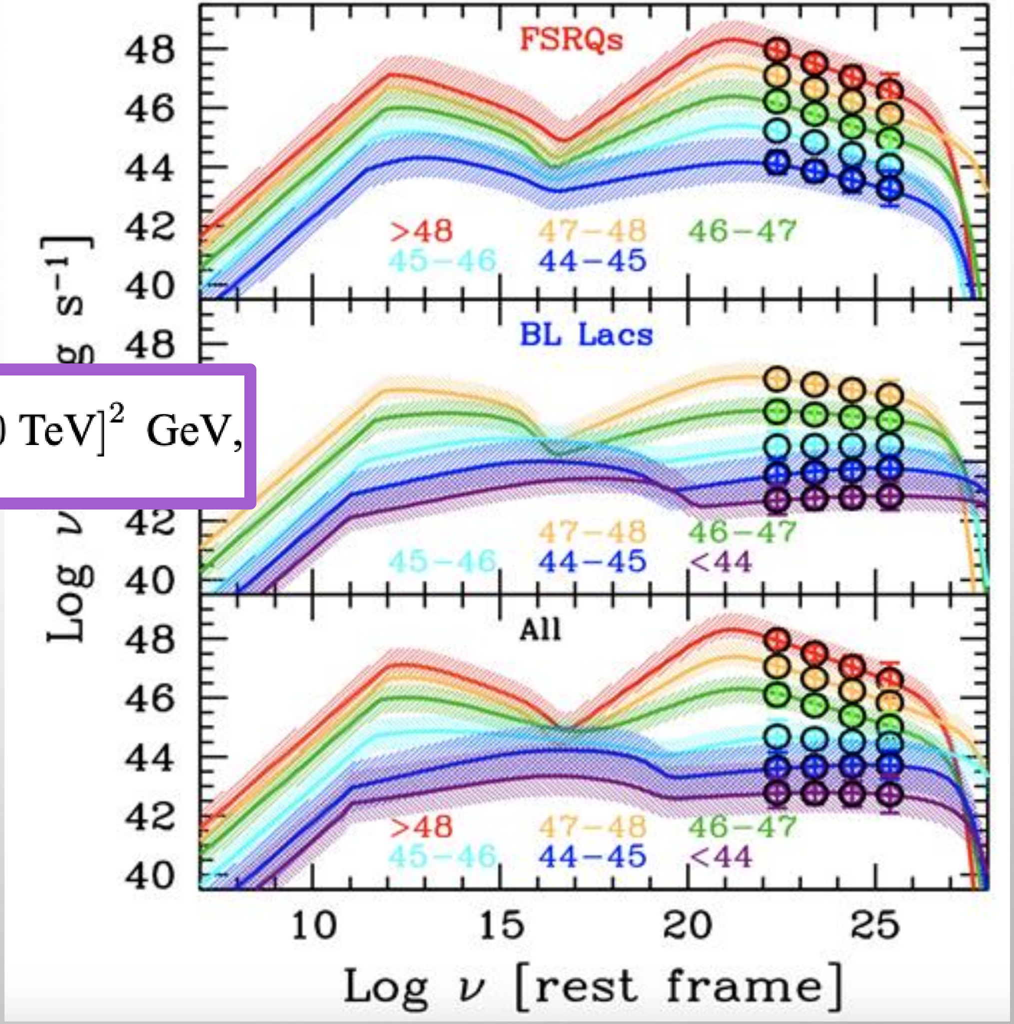


[EP+ MNRAS 2010](#)

TEV-BLAZARS PROMISING FOR IGMF STUDIES

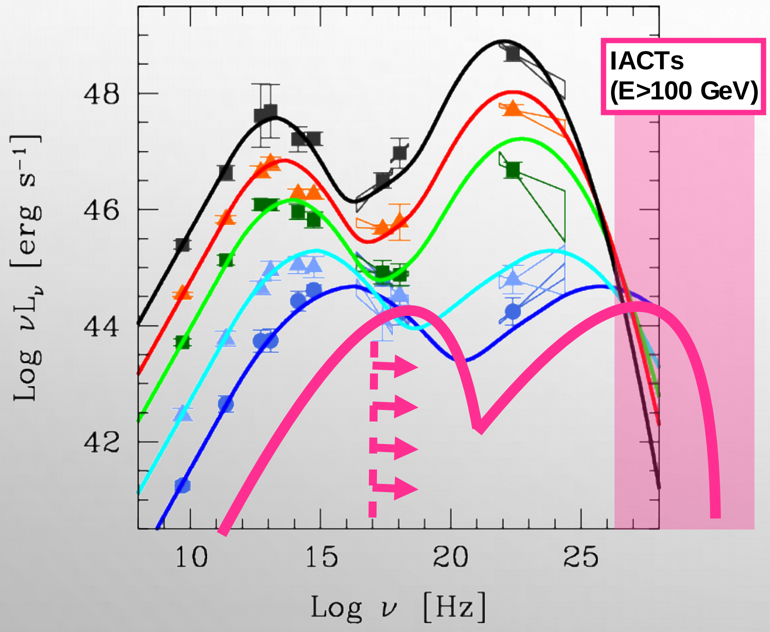
$$E_\gamma = (4/3)\epsilon_{CMB}(E_e/m_e c^2)^2 \simeq 88\,[E_{\gamma_0}/10\ \mathrm{TeV}]^2\ \mathrm{GeV},$$

→ Sources with a **hard TeV spectrum** extending to several TeV, are responsible for cascade emission at 1-100 GeV (*Fermi*-LAT has a good spectral res)



EXTREME BLAZARS - A CLASSICAL DEFINITION

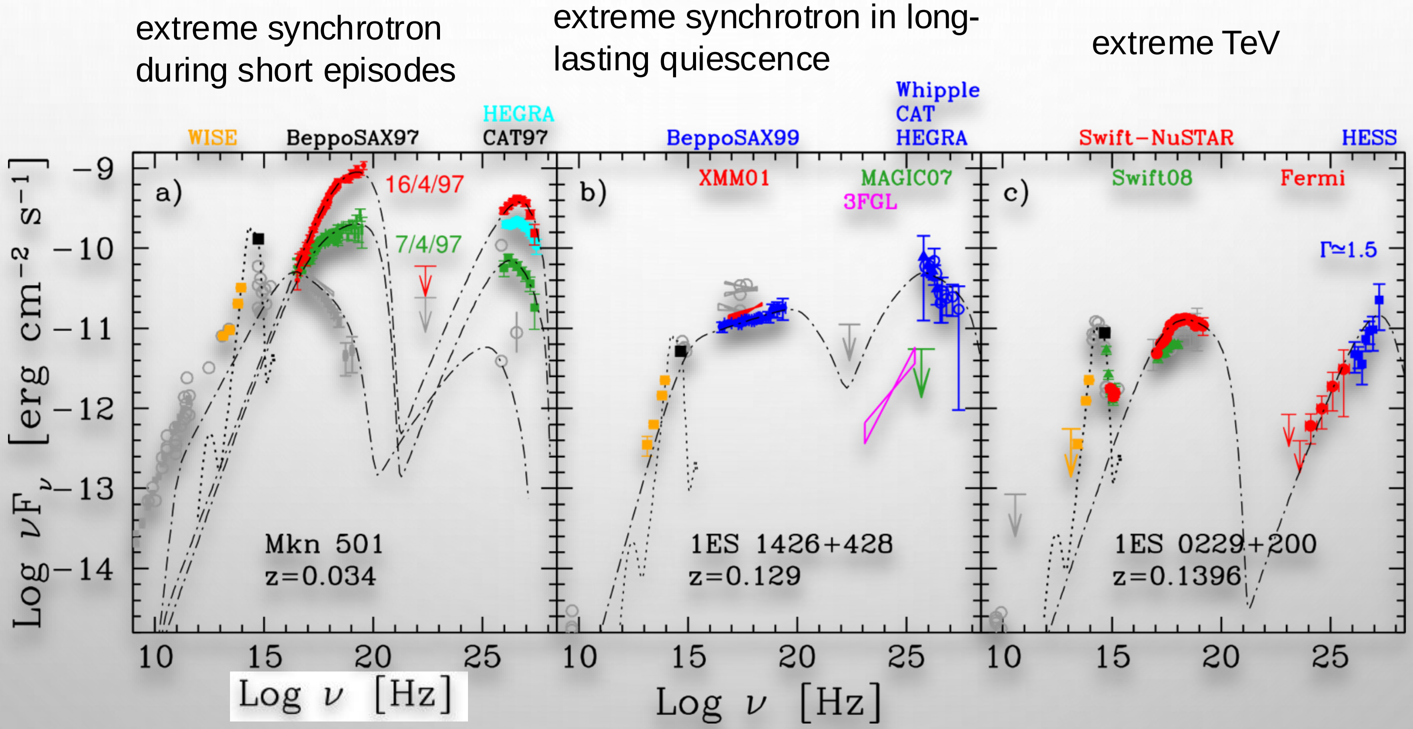
adapted from Fossati et al. MNRAS 1998



The classical definition of extreme blazar is based on the synchrotron peak location (> 1 keV)

- Extreme (synchro) blazars are ideal targets for IACTs
- Standard blazar models constraint the high-energy SED peak below 1 TeV

SPECTRAL SIGNATURES OF EXTREMENESS



Unlike other BL Lac object classes, the host galaxy is well visible in extreme blazars!

Biteau, EP, et al. Nature Astronomy 2020

SPECTRAL SIGNATURES OF EXTREMENESS: EXTREME TEV

- Challenge for blazar modeling

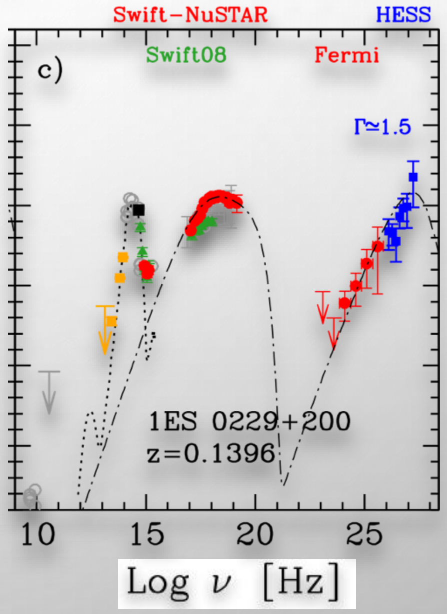
  Hardness of the 0.1 - 1 TeV spectrum $\Gamma_{\gamma}<2$

  Implies a hard accelerated particle spectrum (competition between energy gain and loss, usually spectra indices ~ 2)

  Many scenarios: shock acceleration, turbulent acceleration, shear acceleration, reconnection

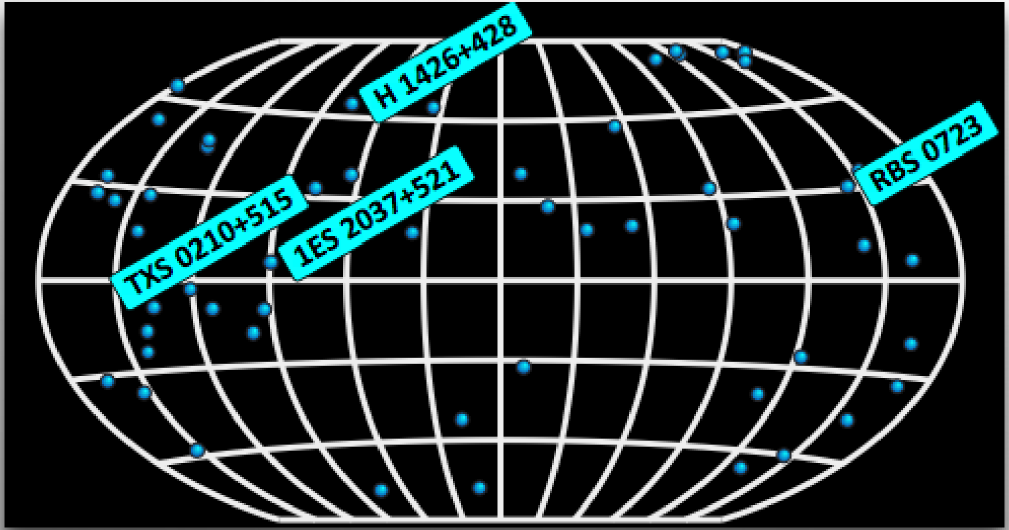
  Peak of radiation at energies > 1 TeV

- **Extremely promising for propagation studies (gamma ray cosmology)**



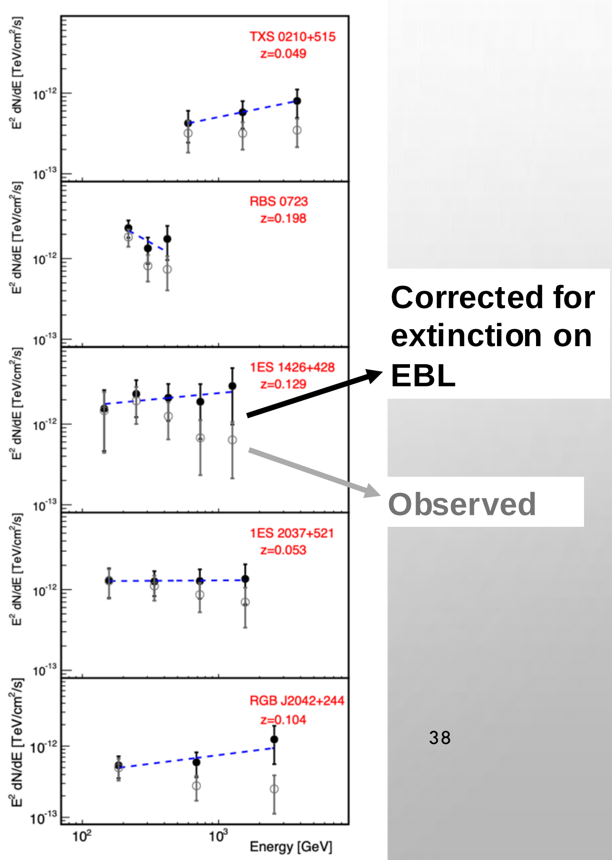
SEARCH FOR EXTREME TEV BLAZARS WITH MAGIC

- 260 hours devoted to this program from 2010 to 2017, 10 sources observed.
- **Four sources firmly detected** and one hint-of-signal

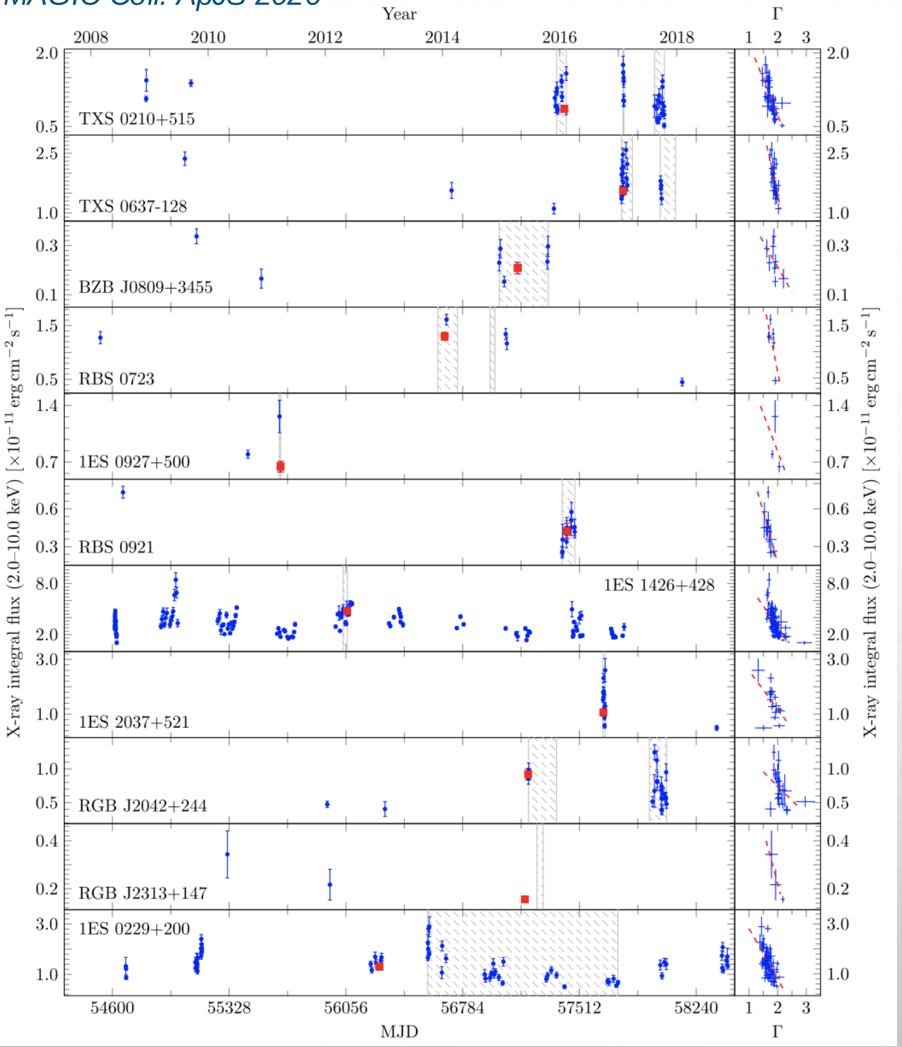


AT LEAST TWO NEW SOURCES WITH HARD-TEV SPECTRUM

MAGIC Coll. ApJS 2020

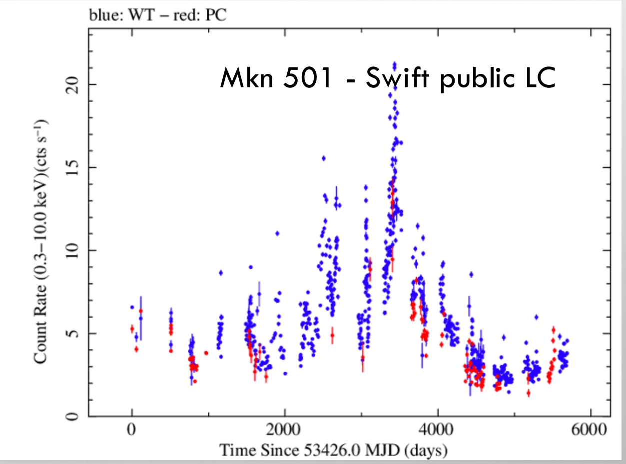


MAGIC Coll. ApJS 2020



X-RAY VIEW OF A SAMPLE OF EXTREME BLAZARS

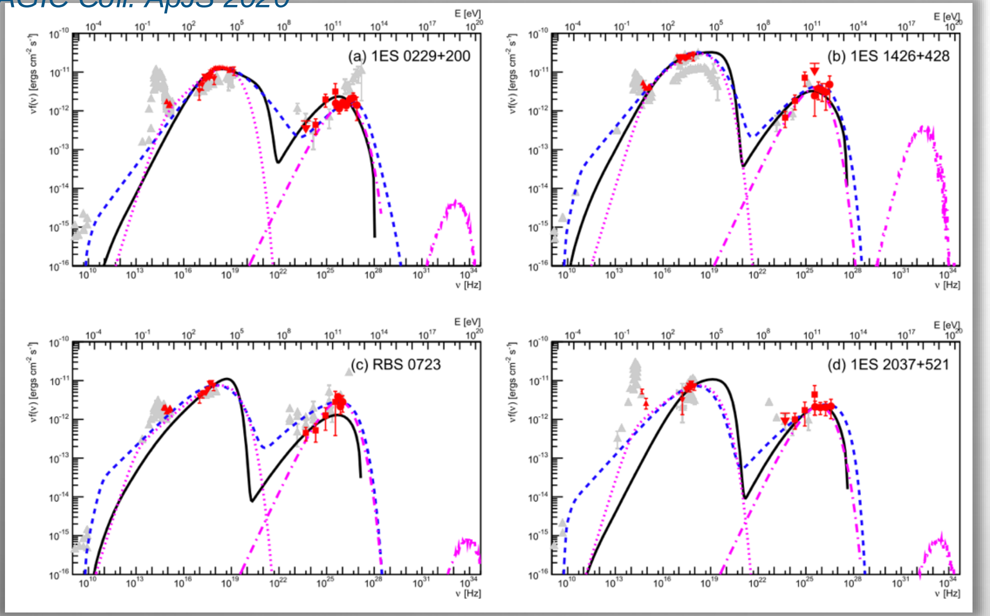
MODERATE (FACTOR OF A FEW) VARIABILITY IN X-RAY



https://www.swift.psu.edu/monitoring/

MODELING THE MAGIC SAMPLE

MAGIC Coll. ApJS 2020



- ✓ 3 models tested an none is favored
- ✓ More data needed in particular in both the hard X-ray and VHE gamma-ray regimes

magenta line: proton-synchrotron model
Blue line: SSC model
Black line: alternative leptonic model (spine-layer)

New IGMF limits from TeV observations

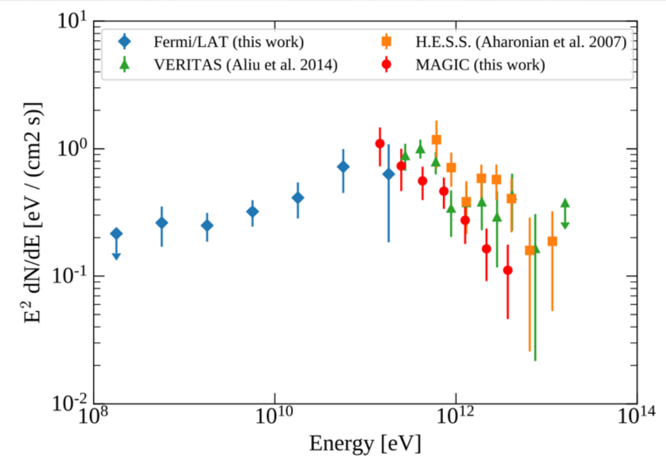
Hard TeV source: 1ES 0229+200

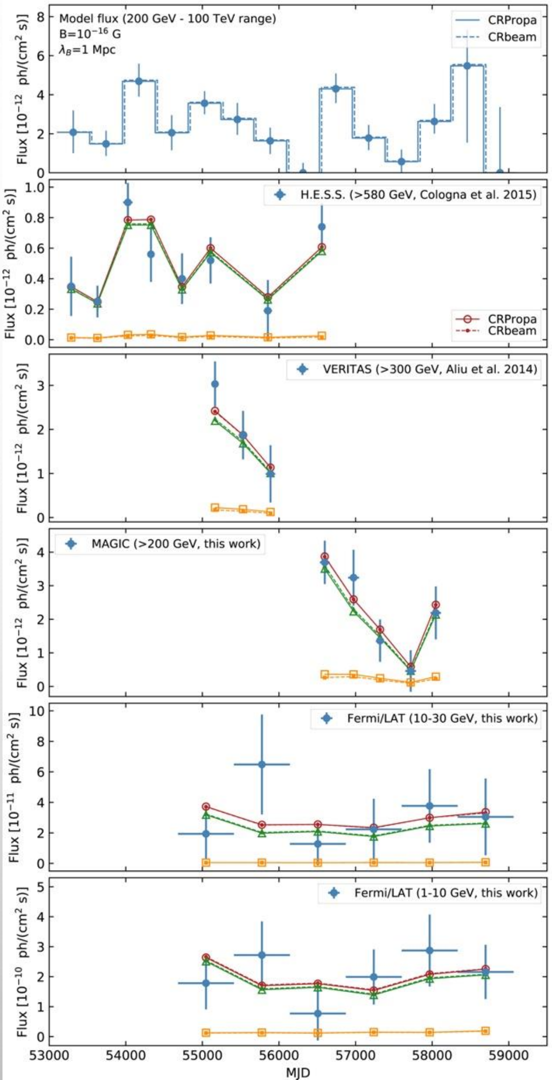
Input: gamma-ray spectrum and variability pattern

Comparison with simulations

No evidence for delayed emission at lower energies

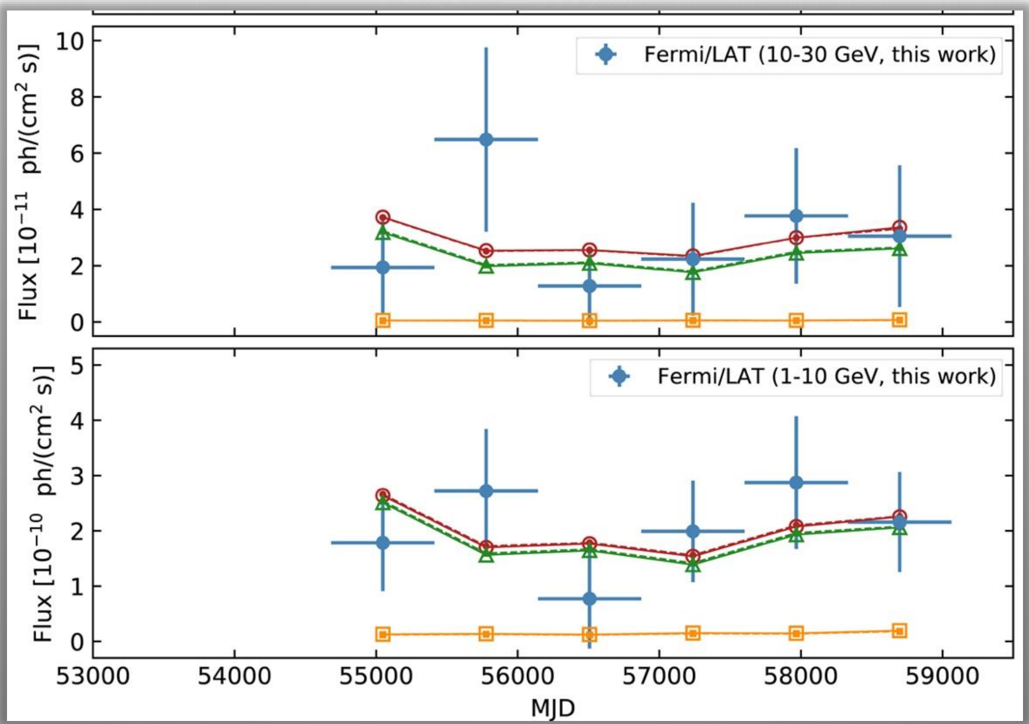
The non-detection of variability at low gamma-ray energies imposes a **lower bound of B > 1.8 × 10^{-17} G**
(B > 10–14 G assuming a short correlation length)





MAGIC Coll. 2022

Faintness of the flux severely limits the ability to properly assess the source variability

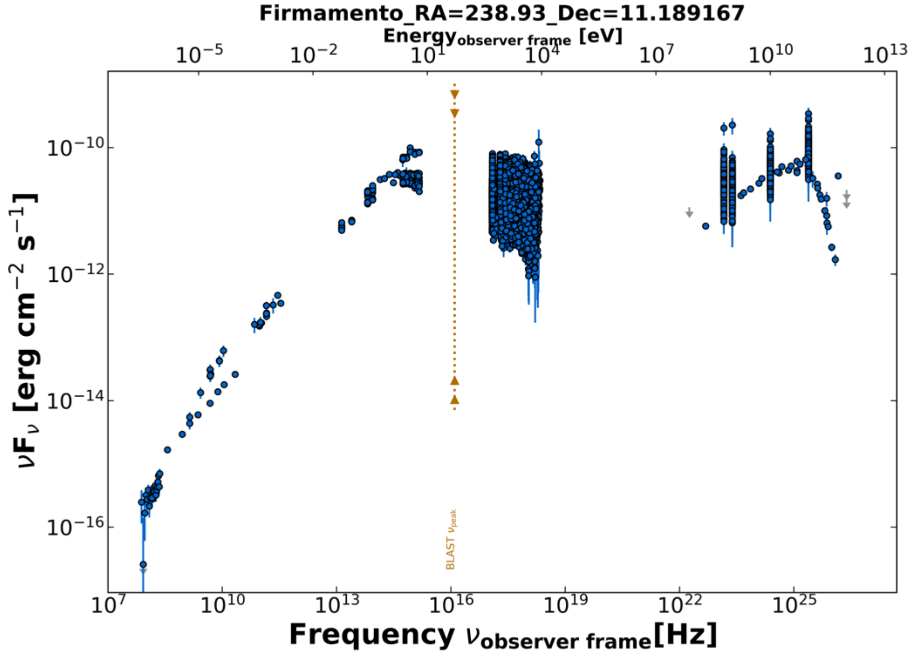


MAGIC Coll. 2022

COMING BACK TO THE MAGIC HARD TEV SOURCES STUDY:

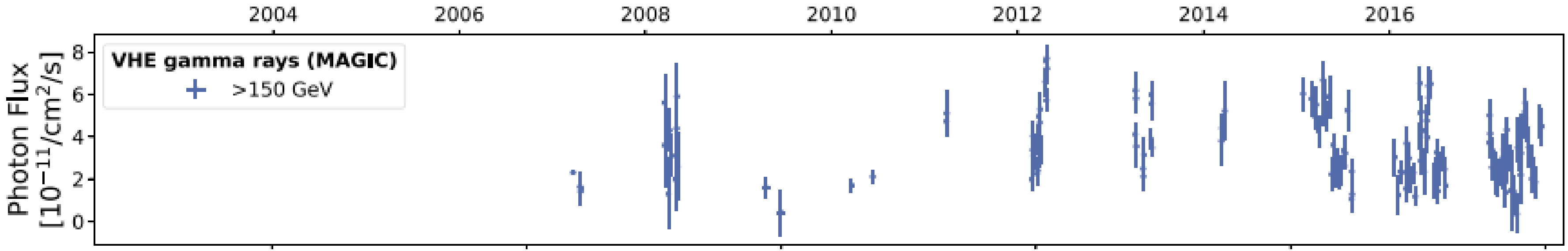
Source	Observation Periods	Time (hr)
TXS 0210+515	2015, 2016, 2017	28.6
TXS 0637–128	2017	16.4
BZB J0809+3455	2015	21.8
RBS 0723	2013, 2014	45.3
1ES 0927+500	2012, 2013	26.2
RBS 0921	2016	13.9
1ES 1426+428	2010	6.5
	2012	8.7
	2013	5.9
1ES 2037+521	2016	28.1
RGB J2042+244	2015	52.5
RGB J2313+147	2015	11.5
1ES 0229+200	2013–2017	117.5

- Observation campaigns are "slow"
- Extreme blazars are **faint sources**!



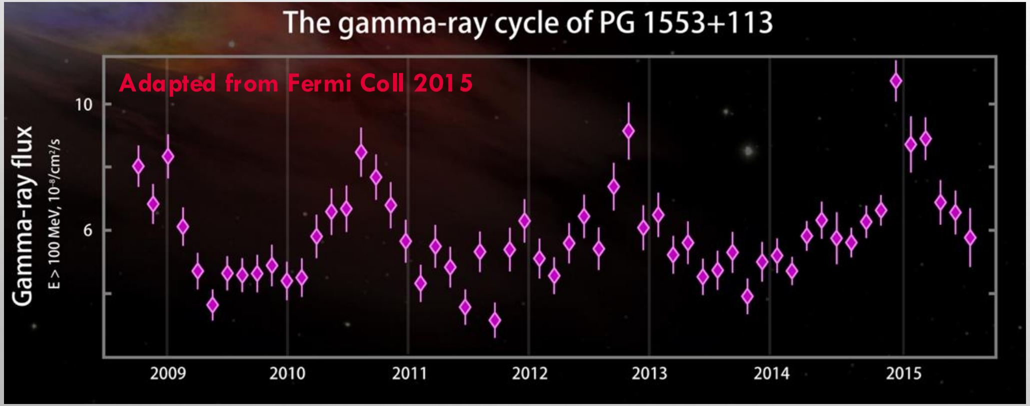
PG1553+113

- z = 0.43
- Bright HBL
- Observed with MAGIC + MWL [(MAGIC coll. 2024)]
- High variability (factor ~6)
- Timescale: down to daily
- Non-uniform coverage (due to visibility and monitoring strategy)

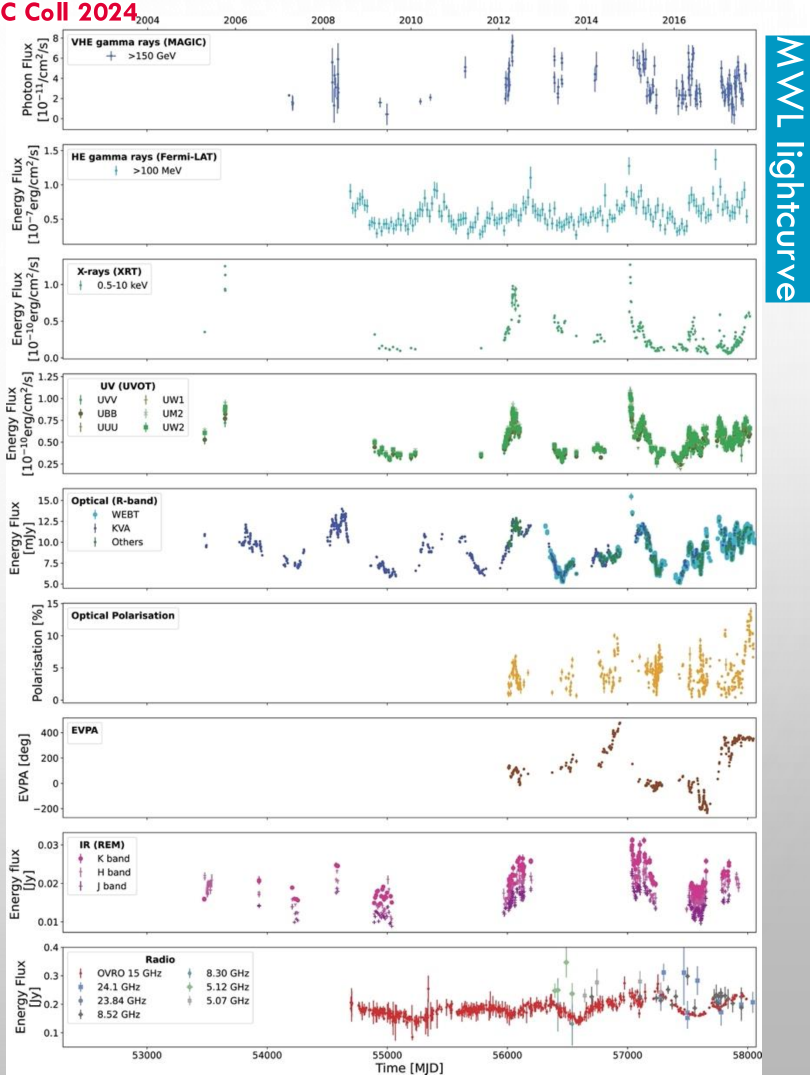


PERIODICITY IN PG 1553+113 WITH MAGIC

- **2.2y periodicity** in *Fermi*-LAT and, possibly, in optical
- Monitored regularly with MAGIC since 2015



MAGIC Coll 2024



PERIODICITY MODELS

GEOMETRICAL MODELS

e.g. Danai et al. 2018;
Sobacchi 2017
Raiteri et al. 2015

jet precession or helical jet

change in Doppler factor: simplest models foresee an achromatic variability

ACCRETION MODULATION

accretion is modulated

e.g. Gracia et al. 2003

Double/multiple **peak sub-structure** expected in the light curve

DYNAMICAL MODELS

Instabilities in the jet due to stresses induced by a secondary (jetted?) black hole orbiting around the jetted black hole

Double/multiple **peak sub-structure** expected in the light curve

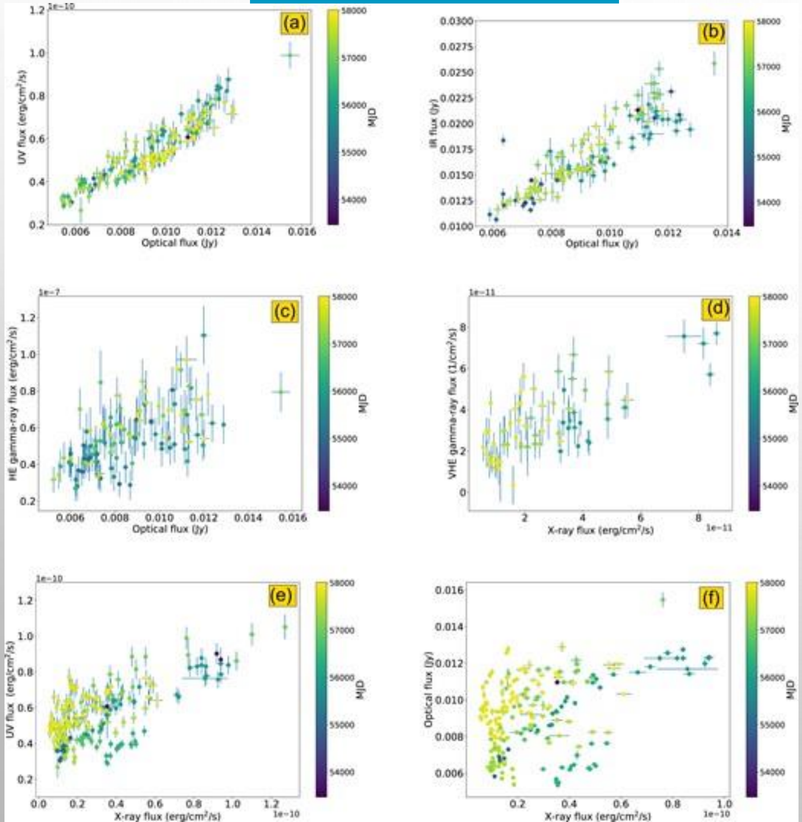
e.g. Tavani et al. 2018

VARIABILITY AND CORRELATION STUDIES

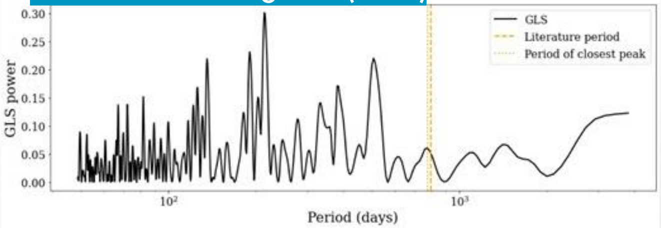
MWL folded lightcurve

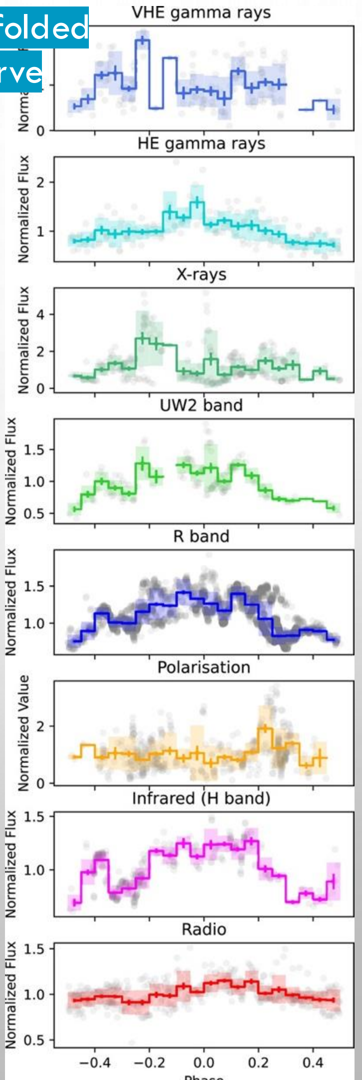
MAGIC Coll 2024

Intra-band correlations



MAGIC Periodgram (GLS)

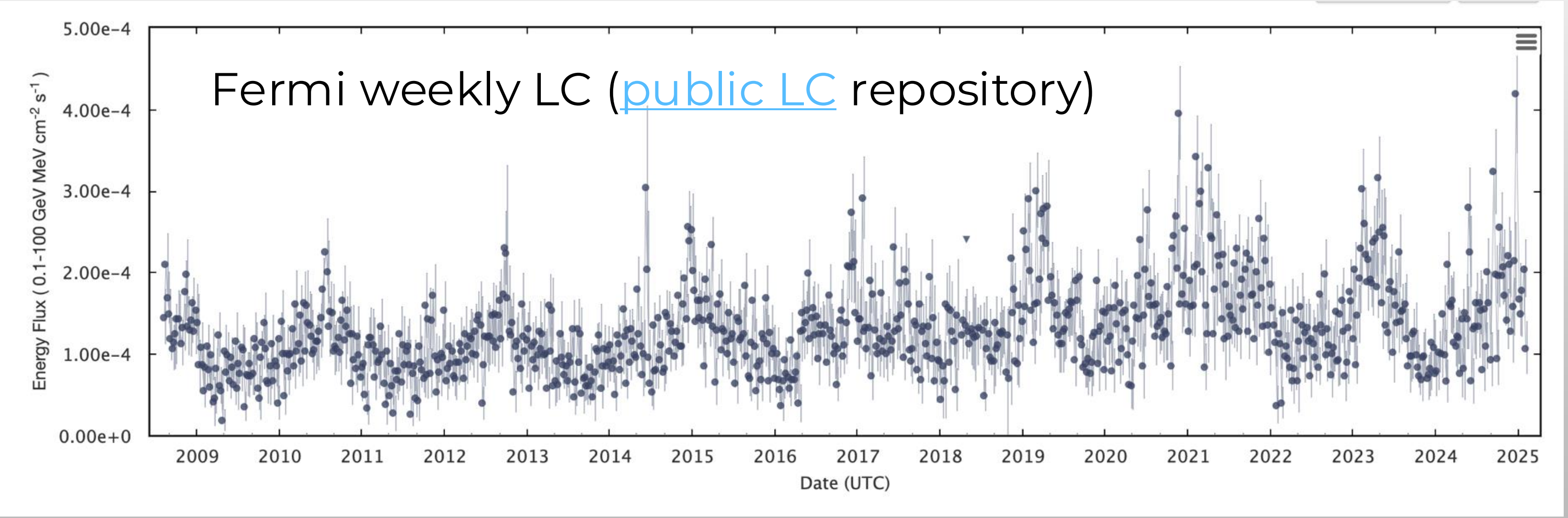




- **No periodicity** in VHE gamma rays and x-rays, confirmed periodicity in HE gamma rays
- Intra-band correlations: complex interplay between bands
  - Multiple zone emission model

PG1553+113

DATATAKING IS ONGOING!

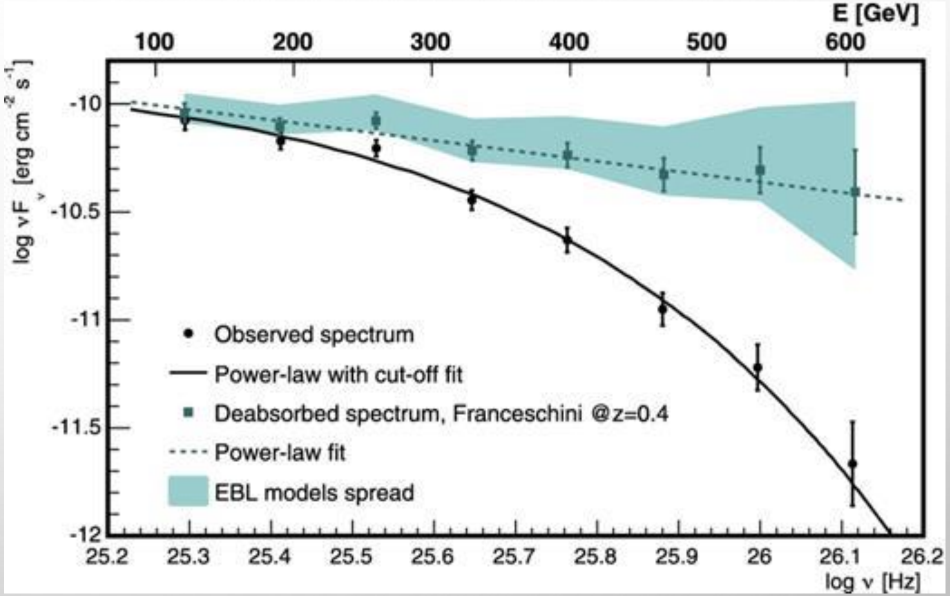


AN UNEXPLORED (?) POSSIBILITY:
NON EXTREME, RELATIVELY DISTANT BLAZAR (HBL) FOR IGMF

- Are extreme blazars the ‘ideal targets’?

- Should we consider other source classes (apart from GRBs?)

→ EP, Paolo DV, Davide M – work in progress!



thank you!

BACKUP

MKN 421: MAGIC-IXPE CONNECTIONS

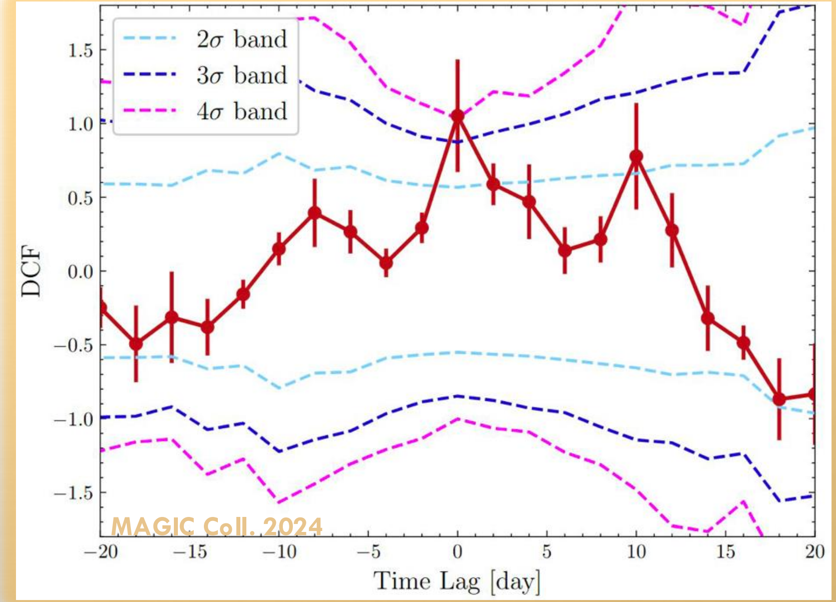
X-RAY (SWIFT) –VHE: STRONG HINT OF CORRELATION

→ TIME INTERVAL: MAY-JUNE 2022

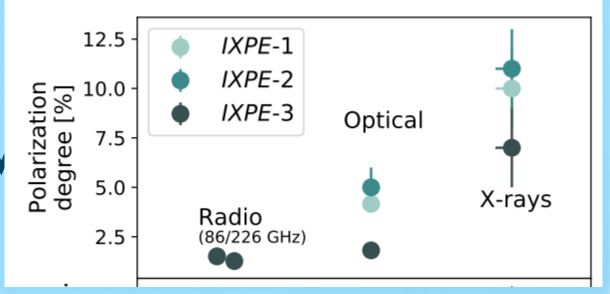
→VHE CO-SPATIAL WITH X-RAY

Strong connection between X-ray and VHE, pointing to a common origin (typical for HSPs)
→ Simultaneous coverage is crucial to probe the physics of the emitting region

Discrete correlation function
Mkn 421 (X-ray – VHE)



RECENT HIGHLIGHTS: M



PAPER ON MAGIC+IXPE SIMULTANOUS OBSERVATIONS IN 2022 (MAGIC+ 2024)

- 3 IXPE POINTINGS (LIODAKIS+ 2022, LISALDS+ 2024)

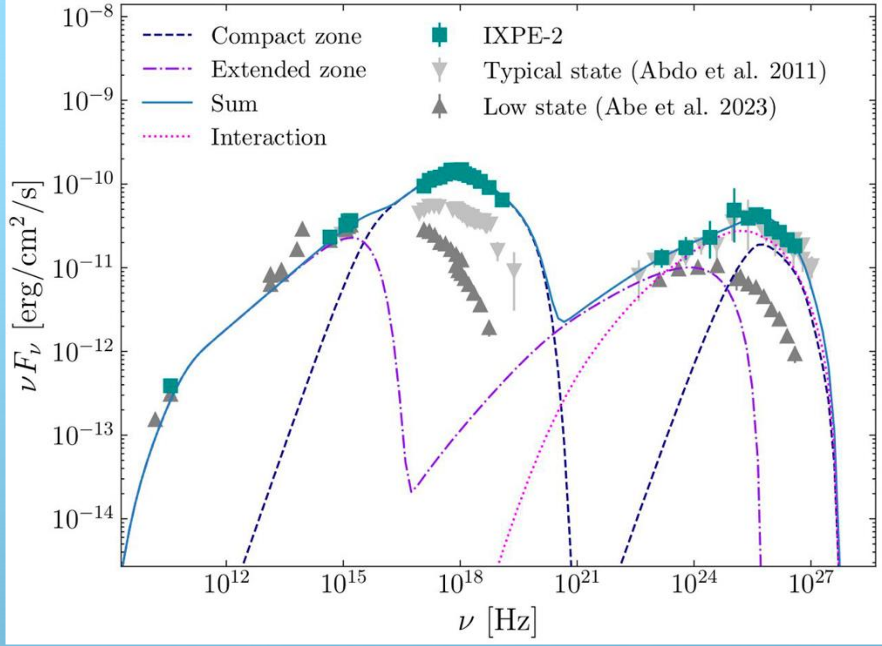
<u>POLARIZATION DEGREE</u>

- X-RAY ~FACTOR 2 HIGHER THAN IN OPTICAL
- DROP IN POLARIZATION FOR IXPE-3

<u>X-RAY POLARIZATION ANGLE</u>

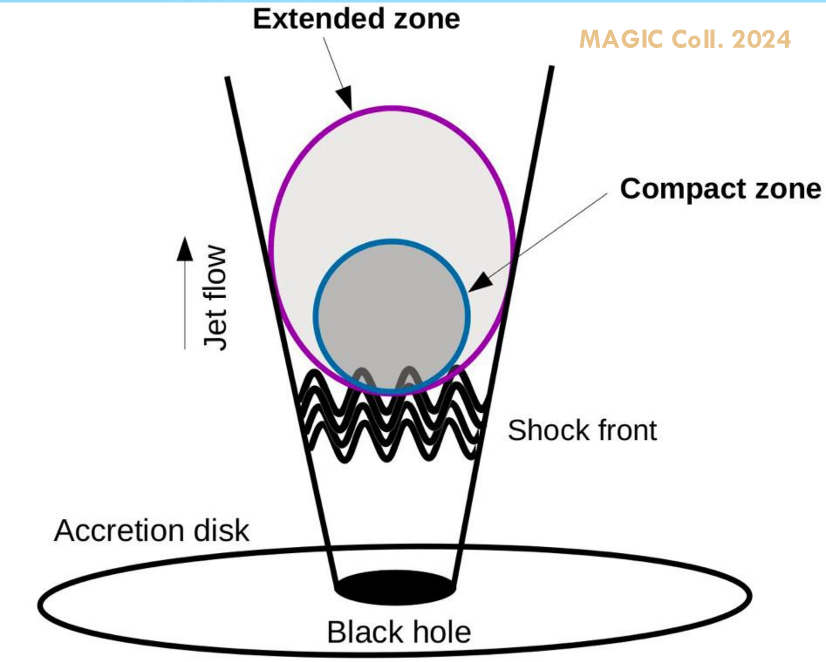
- IN LINE WITH OPTICAL
- PARALLEL TO RADIO JET ORIENTATION

→ Shock acceleration in an energy stratified jet

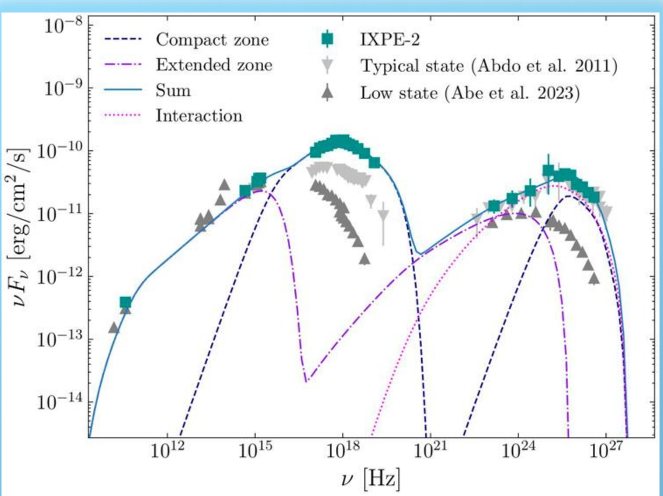


RECENT HIGHLIGHTS: MKN 501

Emission model

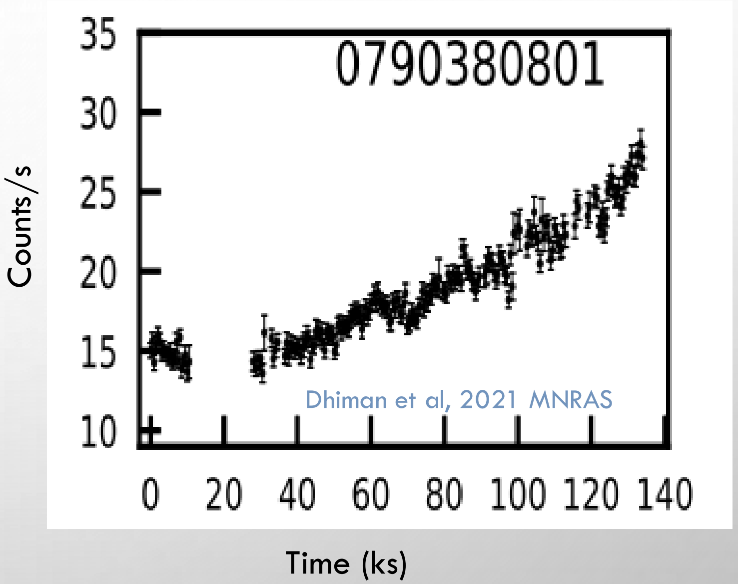


- **ROLE OF MAGIC**: CONSTRAIN THE SECOND ZONE PROPERTIES, THE SAME RESPONSIBLE FOR X-RAY EMISSION.



SHORTEST VARIABILITY TIMESCALE IN PG 1553+113

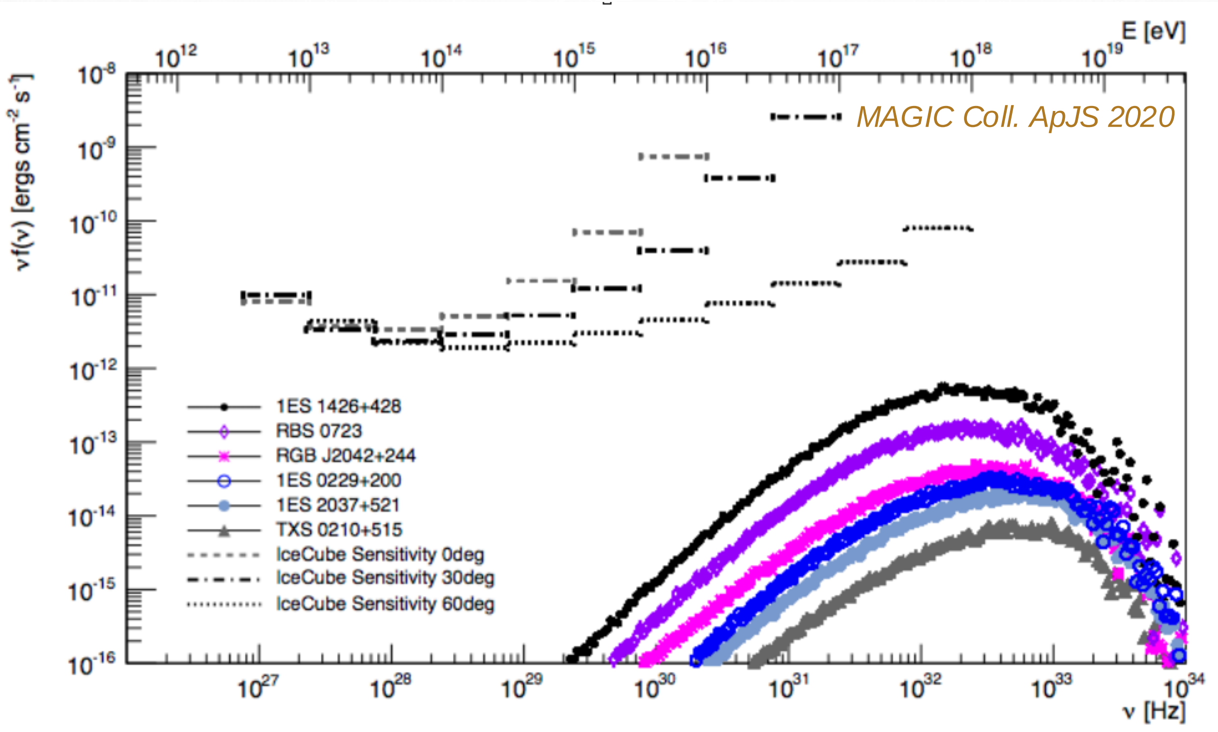
- **STUDY BASED ON XMM OBSERVATIONS**
- CHARACTERIZATION OF VARIABILITY AT DIFFERENT SCALES
- SHORT (INTRA-NIGHT) VARIABILITY: VERY USEFUL TO CONSTRAIN THE EMISSING REGION FOR CAUSALITY REASONS



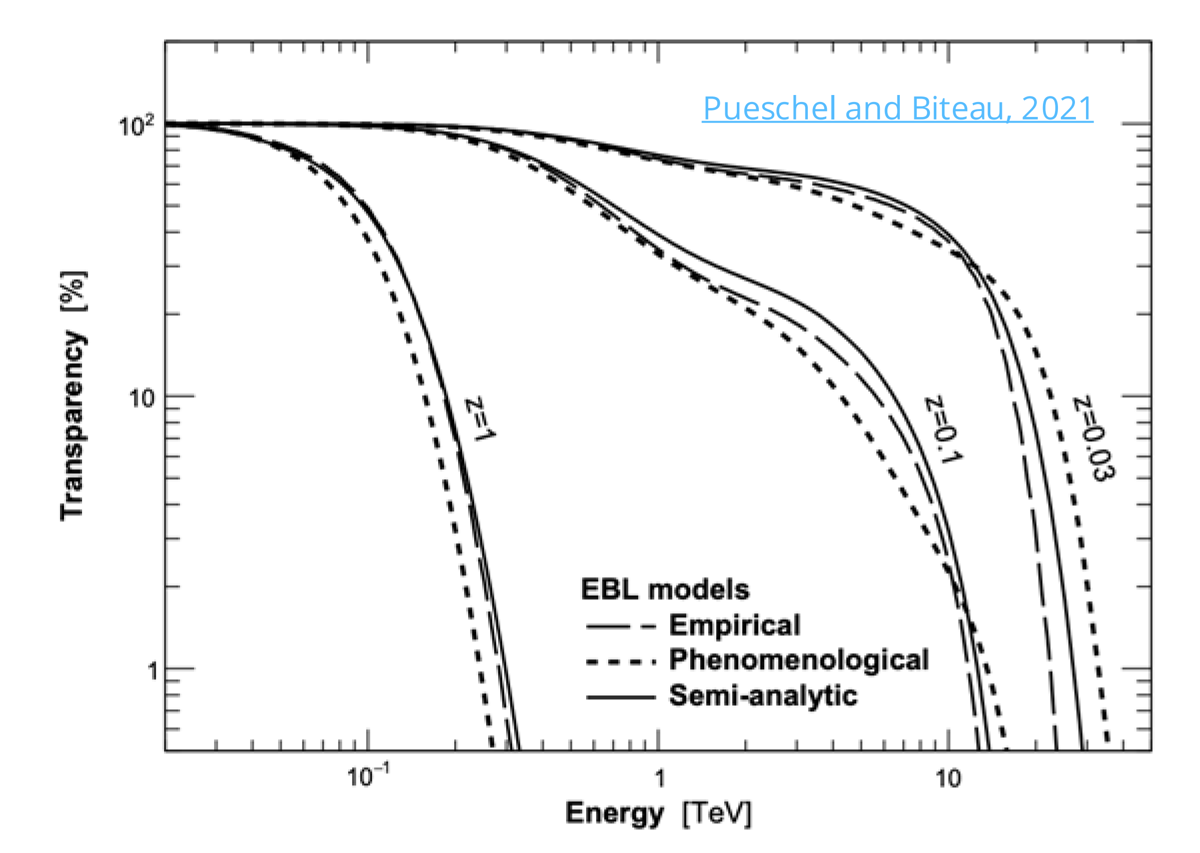
$$R \leqslant \frac{c\, t_{var}\, \delta}{1+z},$$

T_var assumed as the **doubling flux time → 2.4 ks**

NEUTRINOS FROM EXTREME BLAZARS?



The hadronic model tested (proton synchrotron) does not foresee a detectable neutrino output

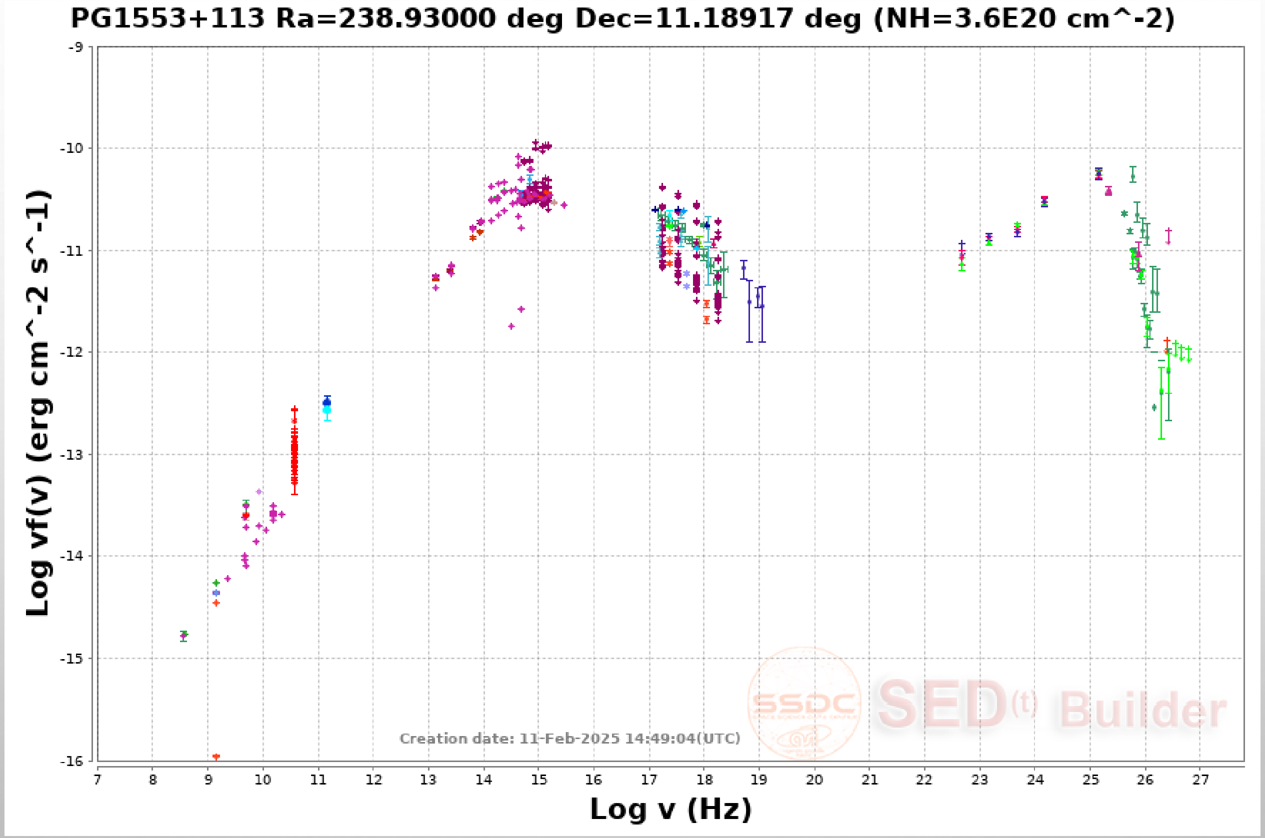


Pueschel and Biteau, 2021
Transparency [%]
Energy [TeV]
z=1
z=0.1
z=0.03
EBL models
Empirical
Phenomenological
Semi-analytic

The cascade electrons loose their energy via IC scattering of the CMB photons within the distance

$$D_e = \frac{3m_e^2c^3}{4\sigma_T U'_{\rm CMB} E'_e} \simeq 10^{23}(1 + z_{\gamma\gamma})^{-4}\left[\frac{E'_e}{10\ {\rm TeV}}\right]^{-1}\ {\rm cm}.$$

SED


PG1553+113 Ra=238.93000 deg Dec=11.18917 deg (NH=3.6E20 cm^-2)
Log νf(ν) (erg cm^-2 s^-1)
-9
-10
-11
-12
-13
-14
-15
-16
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
Log ν (Hz)
Creation date: 11-Feb-2025 14:49:04(UTC)
SED(t) Builder