All the MAGIC of extreme blazars

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Extreme blazar at VHE gamma rays

Why?

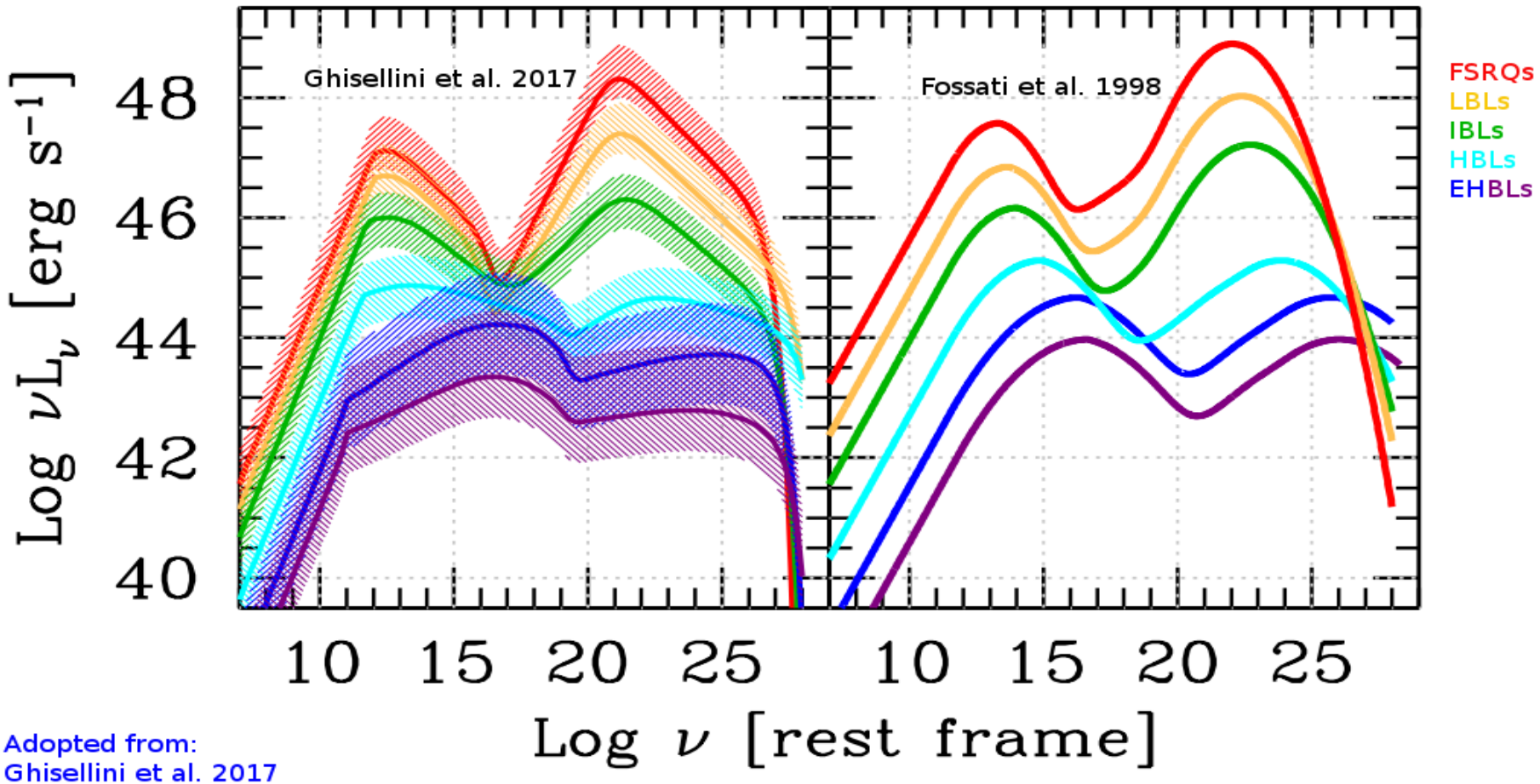
- They are under-represented by Fermi (too faint)
- Showing (sometimes extremely) **hard TeV spectra**
- VHE gamma rays make the difference
- Excellent probes for many science cases:
  EBL, IGMF, Blazar Sequence, Cosmic ray physics and ...
- Before 2010, only 4 sources were detected in VHE gamma rays

Aims?

- Extremeness, is a property or behaviour?
- Search systematically for new EHBLs
- Characterizing broadband SEDs of EHBLs
- Search for common behaviour

Challenges?

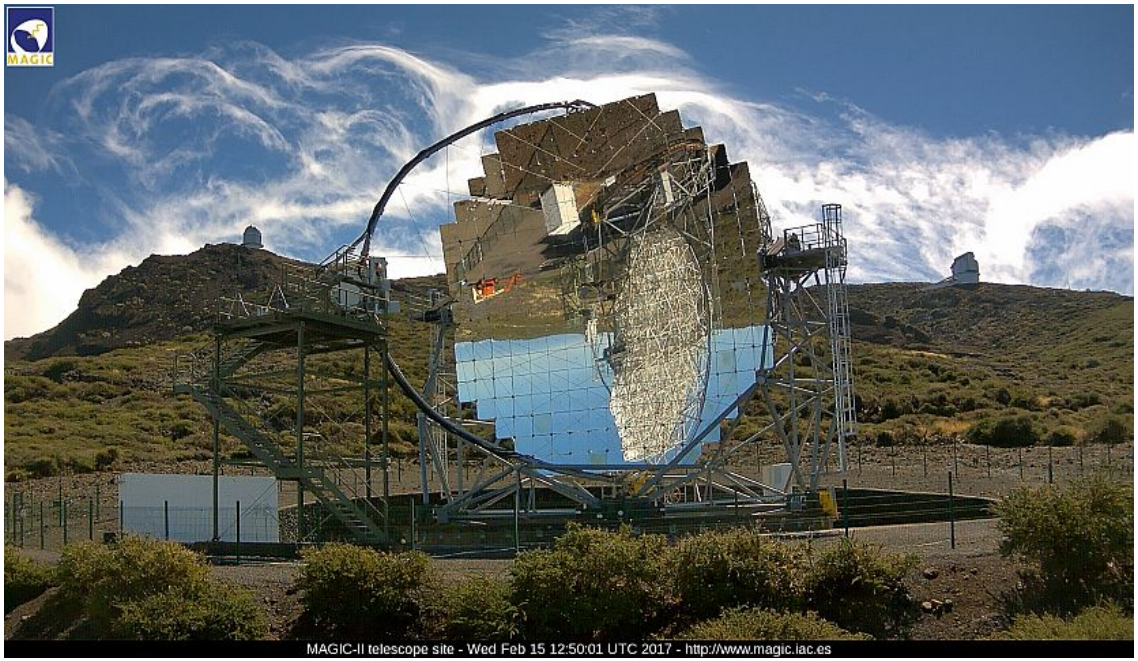
- The need of VHE γ-ray spectrum $\Longrightarrow$ Sensitivity of the instrument
- Study variability $\Longrightarrow$ Observing time



Adopted from:
Ghisellini et al. 2017

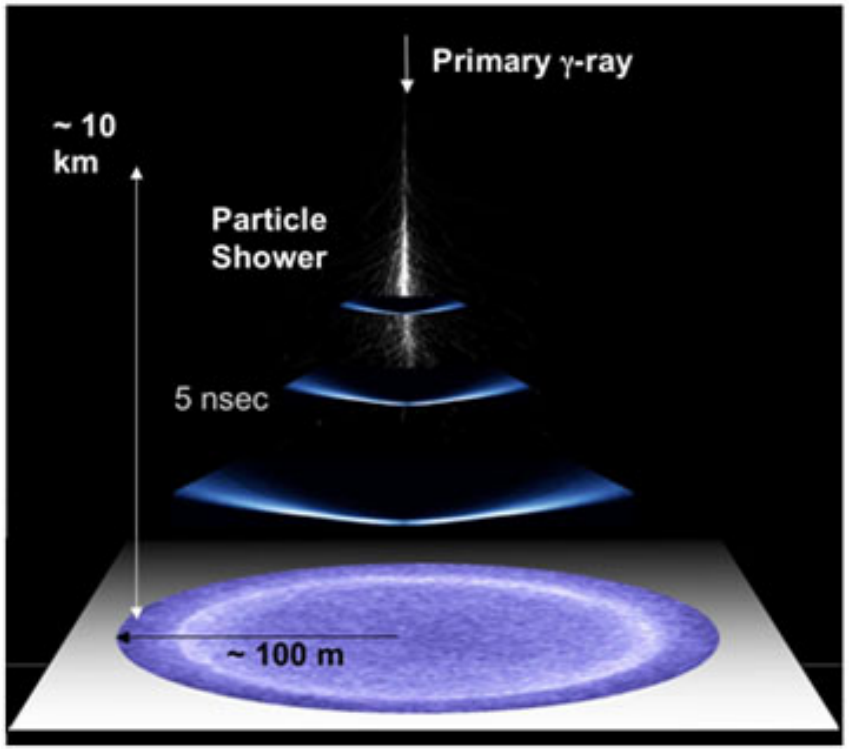
MAGIC view

MAGIC Telescopes



- La Palma, Canary Islands
  28°N, 18°W, Altitude 2200 m a.s.l.
- Energy range: 30 GeV to 100 TeV
- Integral sensitivity (> 220 GeV):
  $(0.66 \pm 0.03)\%$ of Crab Nebula flux
  (50 h exposure)

- FoV: 3.5°
- Angular resolution: $\leq 0.07°$
- Energy resolution: 16%



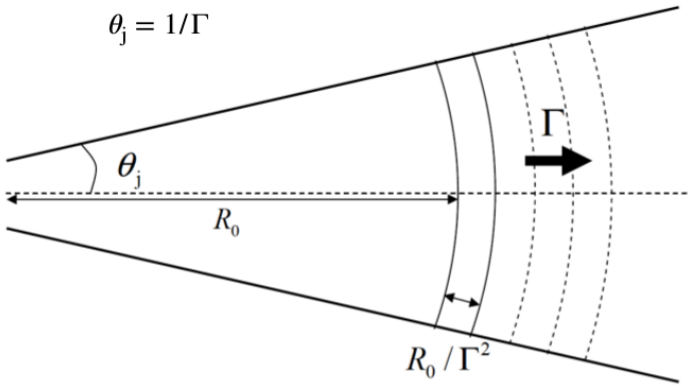
Credits: Cherenkov Telescope Array in Argentina

▸ Aleksić, J. et al., 2016 , Astroparticle Physics, Volume 72, p. 76-94

MAGIC ingredients

- MAGIC telescopes have been observing EHBLs since 2004
- A dedicated program for hunting new EHBLs was launched in 2011
- Candidate selection methods:
  - Empirical MWL prediction method ▸ Fallah Ramazani, V. et al., 2017 , A&A, 608A, 68F
  - X-ray and gamma-ray spectral behaviour ▸ Foffano, L. et al., MNRAS, Submitted
  - X-ray-to-radio flux ratio ▸ Bonnoli, G. et al., 2015 , MNRAS, 451, 611B
- MWL data during MAGIC campaigns for SED modelling

Leptonic model (SSC)



$$B' = B_0\left(\frac{R}{R_0}\right)^{-1}$$

▸ Asano, K. et al., 2014, ApJ, 780, 64A

Physical Processes:

- Electron injection during the dynamical time-scale
- Synchrotron emission and cooling
- Inverse Compton and cooling
- Adiabatic cooling
- Photon escape
- No electron escape!

MAGIC observation log

From January 2011 to April 2018:

- ∼180 h of on new sources
- ∼120 h of on 1ES 0229+200
- 12 sources were observed
- 4 new TeV emitters
- 1 prototype
- 1 known TeV emitter
- 1 hint of signal
- 5 no signal

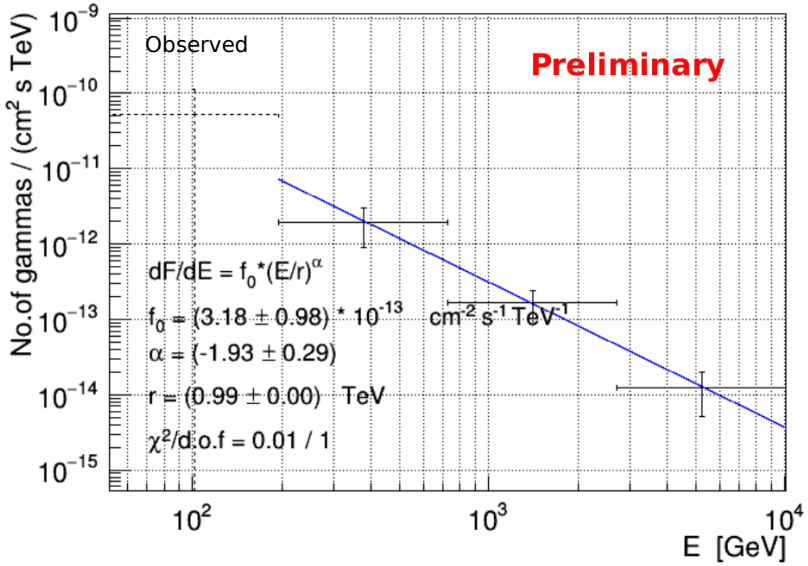
Source	z	FoM	
TXS 0210+515	0.049	1.3	a
1ES 0229+200	0.139	2.0	
PGC 2402248	0.065	1.0	a,b
TXS 0637-128	---	2.5	
BZB J0809+3455	0.083	0.3	
RBS 0723	0.198	1.3	a
1ES 0927+500	0.187	1.0	
RBS 0921	0.236	0.6	
1ES 1426+428	0.129	4.0	
1ES 2037+521	0.053	0.5	a
RGB J2042+244	0.104	0.8	
RGB J2313+147	0.163	0.3	

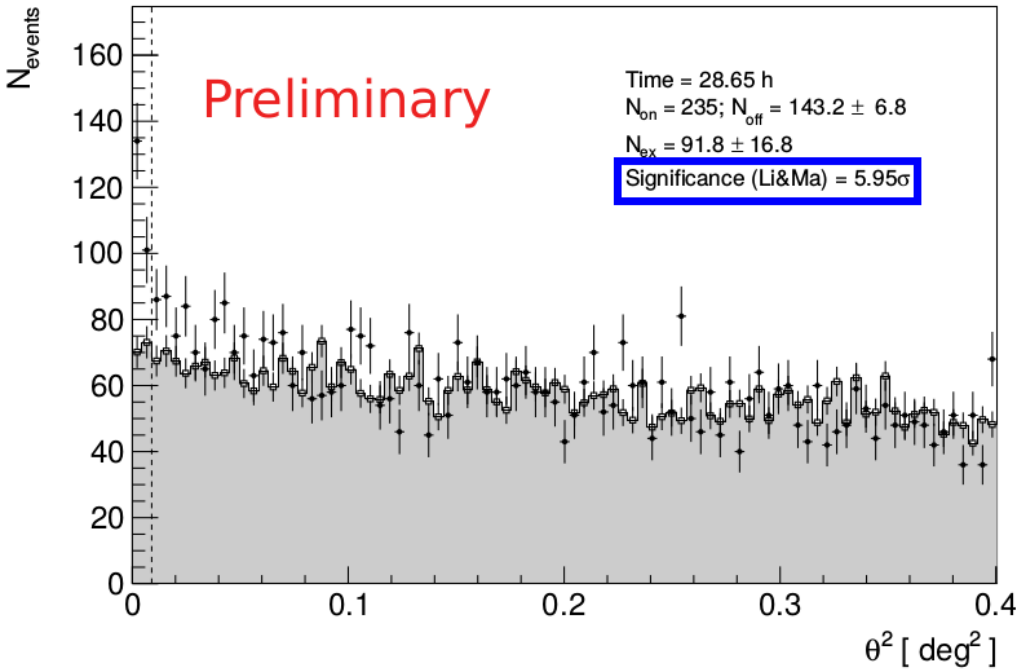
a) New TeV emitter

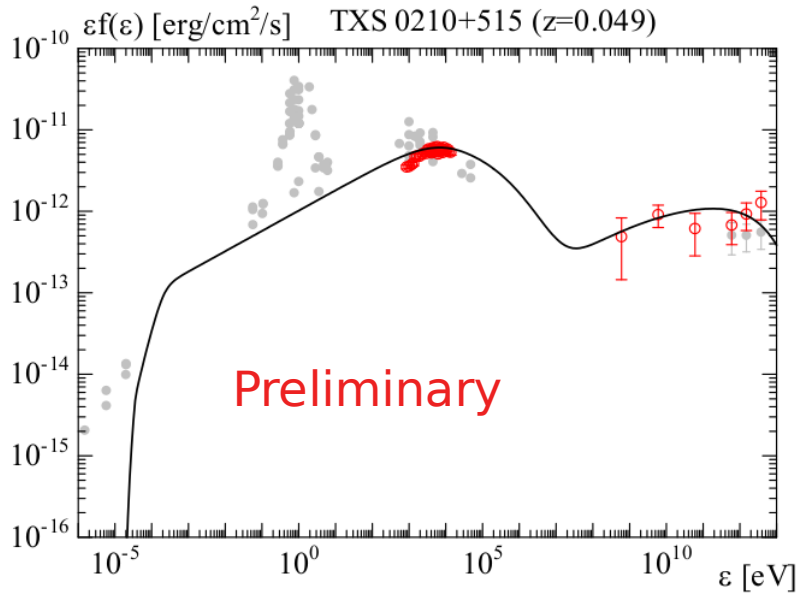
b) Not included in population study

TXS 0210+515 (New announcement)

- $\Gamma_X = 1.75 \pm 0.02$
- $\Gamma_{3FGL} = 2.04 \pm 0.17$
- $F_{1-100\,GeV} = (4.2 \pm 0.9) \times 10^{-10}{}_{[\mathrm{ph/cm^2/s}]}$
- $\Gamma_{VHE,obs} = 1.90 \pm 0.29$
- $F_{>300\,GeV} = (5.1 \pm 2.0) \times 10^{-12}{}_{[\mathrm{ph/cm^2/s}]}$





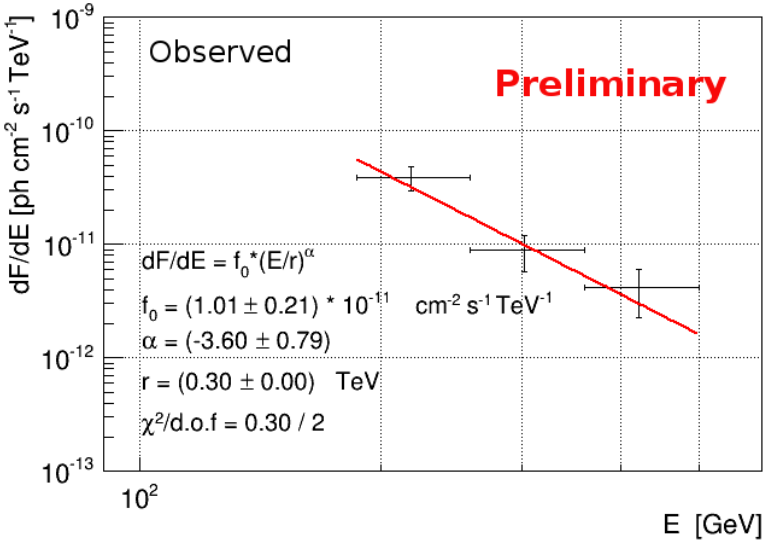


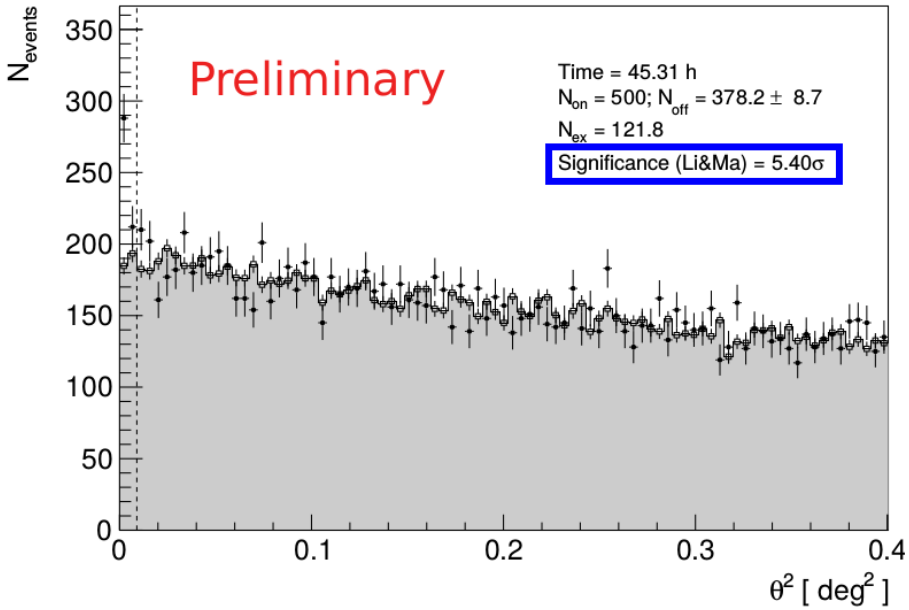
RBS 0723 (a.k.a. RGB J0847+115)

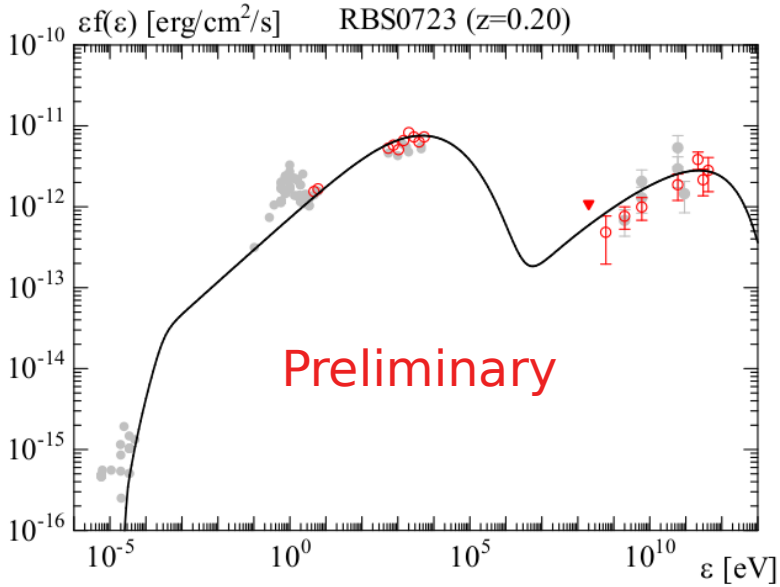
MAGIC detection on 15.01.2014

▸ Mirzoyan, R., 2014, ATel #5768

- $\Gamma_X = 1.79 \pm 0.03$
- $\Gamma_{3FGL} = 1.74 \pm 0.11$
- $F_{1-100GeV} = (5.1 \pm 0.9) \times 10^{-10}{}_{[\mathrm{ph/cm^2/s}]}$
- $\Gamma_{VHE,obs} = 3.6 \pm 0.79$
- $F_{>300GeV} = (1.2 \pm 0.6) \times 10^{-12}{}_{[\mathrm{ph/cm^2/s}]}$







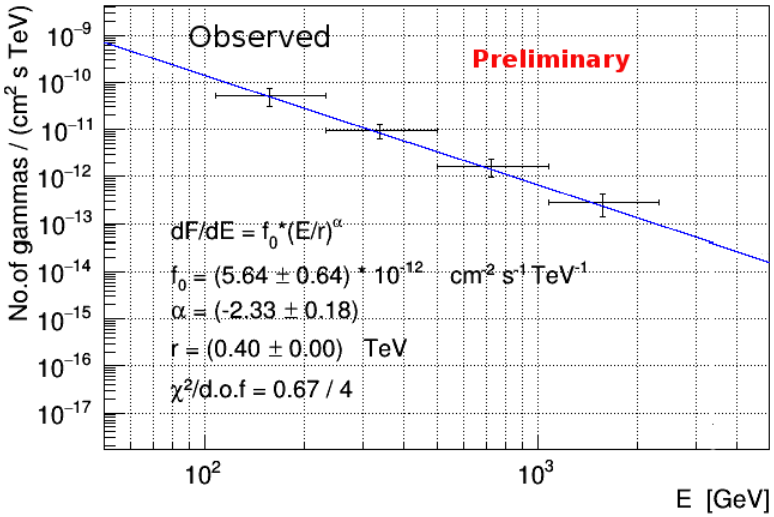
▸ Carosi, A. et al., 2017, AIP Proceedings, 1792, 1, 050036

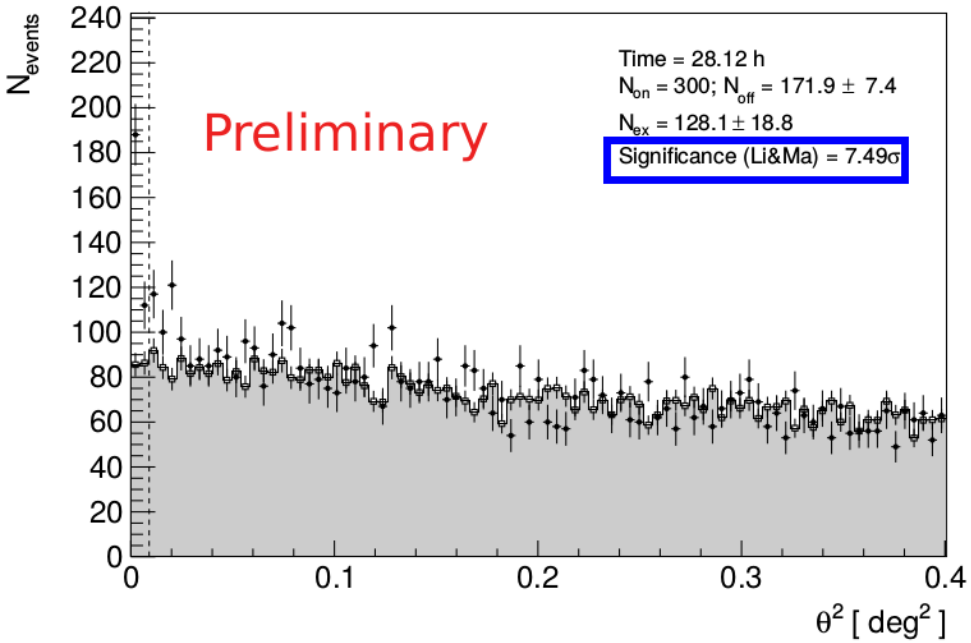
1ES 2037+521

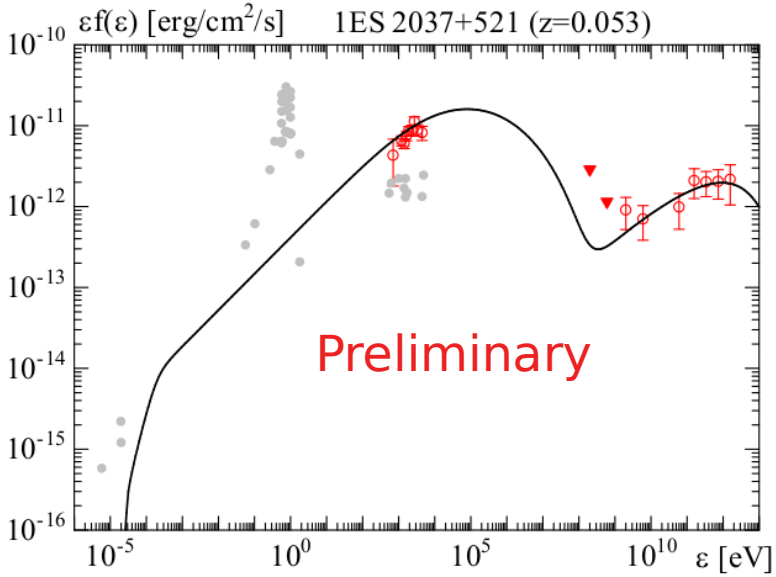
MAGIC detection on 01.10.2016

▸ Mirzoyan, R., 2016, ATel #9582

- $\Gamma_X = 1.72 \pm 0.05$
- $\Gamma_{3FGL} = 1.89 \pm 0.21$
- $F_{1-100GeV} = (3.9 \pm 0.1) \times 10^{-10}{}_{[\mathrm{ph/cm^2/s}]}$
- $\Gamma_{VHE,obs} = 2.33 \pm 0.18$
- $F_{>300GeV} = (2.5 \pm 0.5) \times 10^{-12}{}_{[\mathrm{ph/cm^2/s}]}$

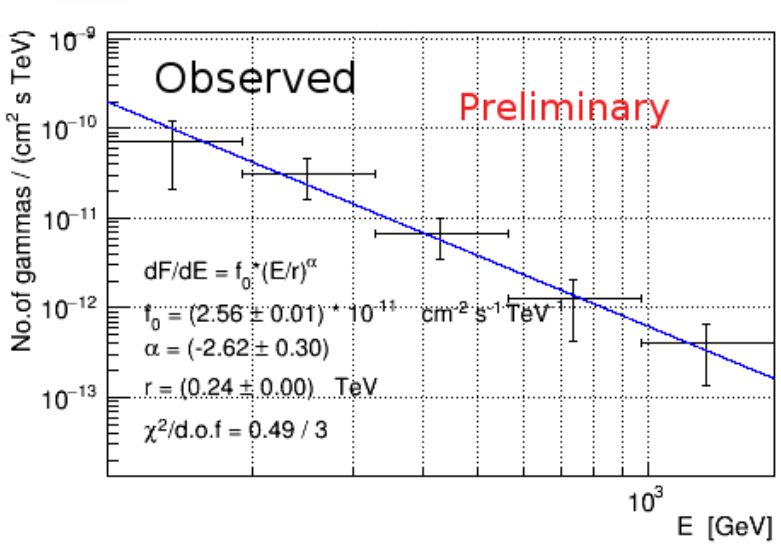


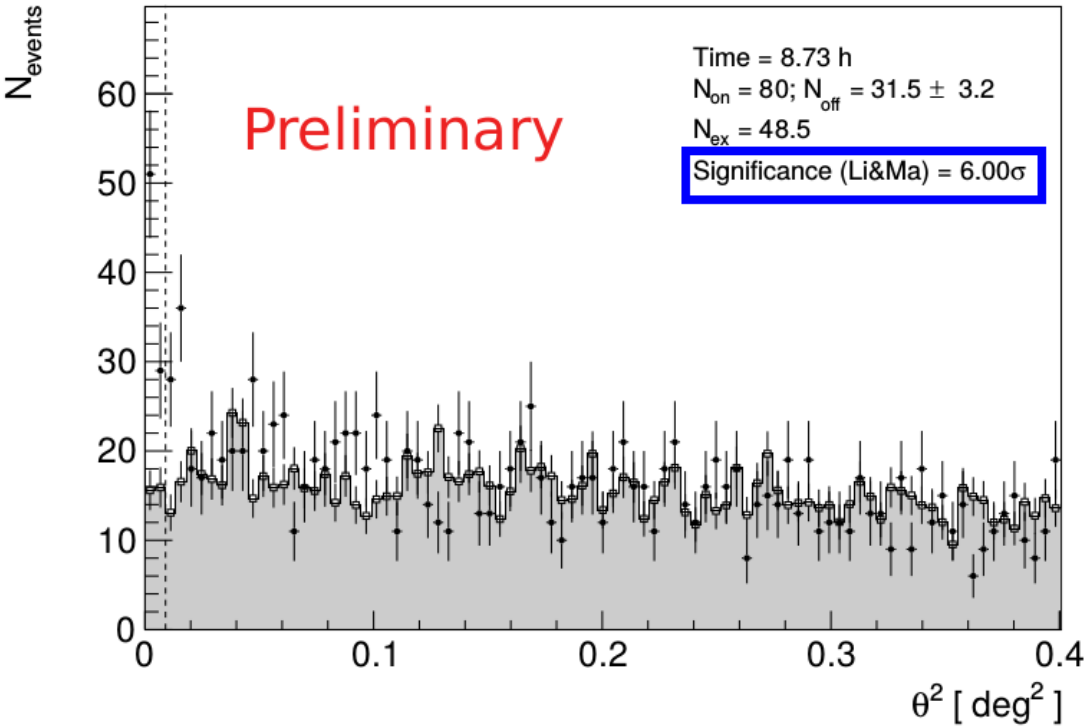


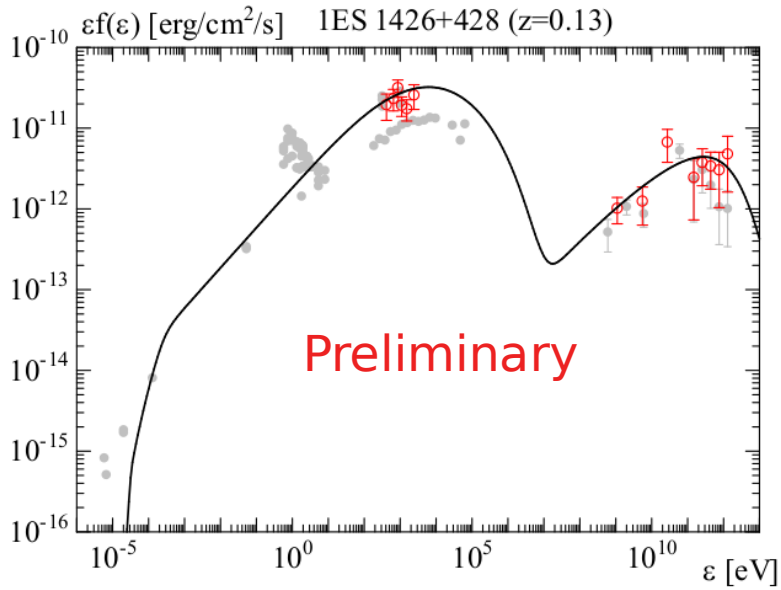


1ES 1426+428 (Known TeV emitter)

- $\Gamma_X = 1.91 \pm 0.01$
- $\Gamma_{3FGL} = 1.57 \pm 0.08$
- $F_{1-100GeV} = (6.6 \pm 0.8) \times 10^{-10}{}_{[\mathrm{ph/cm^2/s}]}$
- $\Gamma_{VHE,obs} = 2.62 \pm 0.30$
- $F_{>300GeV} = (2.7 \pm 0.7) \times 10^{-12}{}_{[\mathrm{ph/cm^2/s}]}$

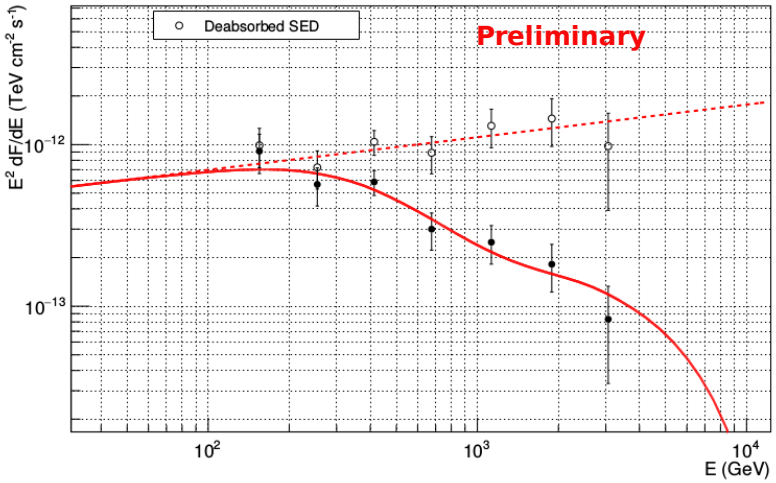


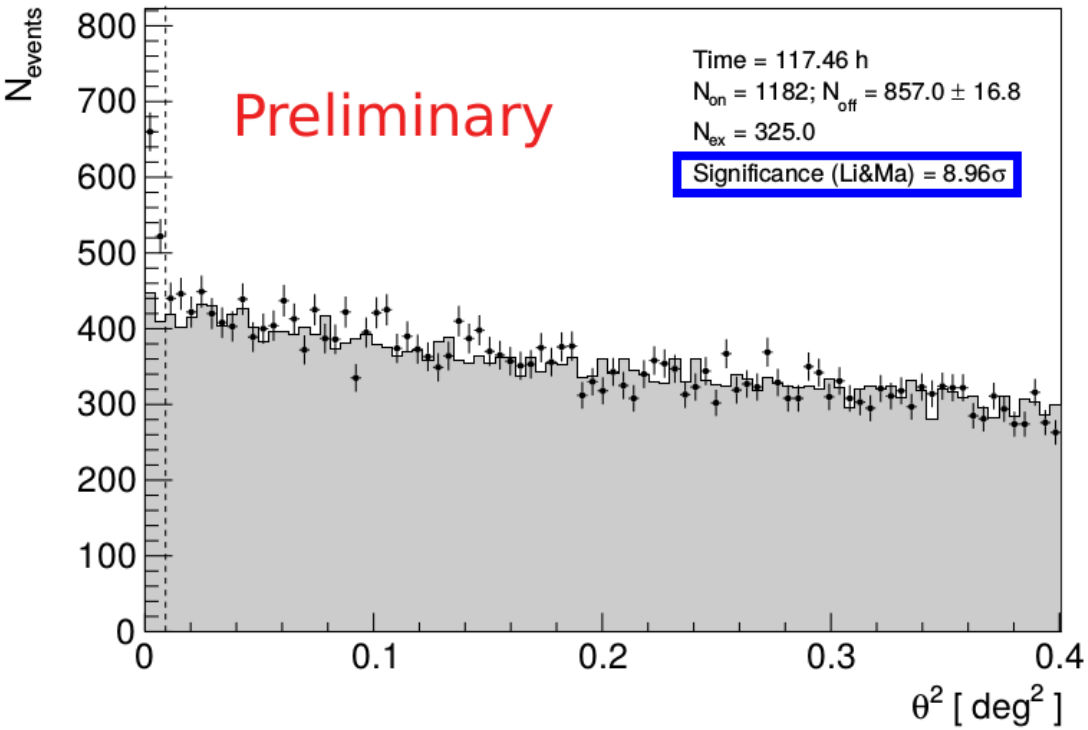


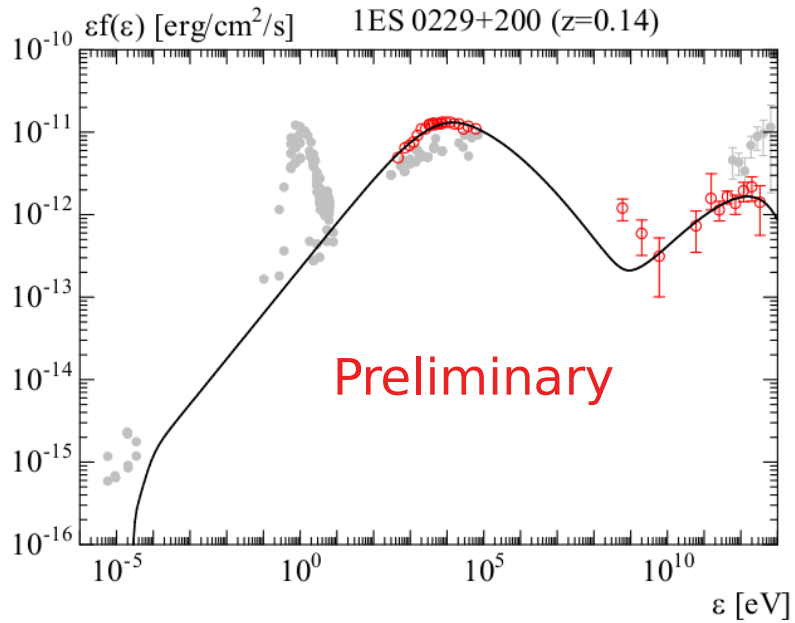


1ES 0229+200 (Prototype)

- $\Gamma_X = 1.68 \pm 0.01$
- $\Gamma_{3FGL} = 2.02 \pm 0.15$
- $F_{1-100GeV} = (4.9 \pm 0.9) \times 10^{-10}{}_{[\mathrm{ph/cm^2/s}]}$
- $\Gamma_{VHE,obs} = 1.80 \pm 0.12$
- $F_{>300GeV} = (3.6 \pm 0.6) \times 10^{-12}{}_{[\mathrm{ph/cm^2/s}]}$







SED modelling results

- No firm VHE γ-ray $\Rightarrow$ Upper limits of the VHE γ-ray spectra
- Quasi-simultaneous MWL data were used for modelling

	Γ	B_0 G	L_e erg s^{-1}	γ_{br}	γ_{max}	p_1	p_2	$\varepsilon_{syn,pk}$ log eV	$\varepsilon_{IC,pk}$ TeV	CD*	$U_B/U_e^{\star\star}$
1ES 0229+200	20	0.06	1.1×10^{44}	10^6	3×10^8	1.9	3.0	4.2	1.585	0.13	2.5×10^{-3}
1ES 1426+428	20	0.20	1.3×10^{44}	—	2×10^6	2.0	—	3.8	0.251	0.14	2.6×10^{-2}
RBS 0723	20	0.11	4.9×10^{44}	—	2×10^6	2.2	—	3.7	0.251	0.37	1.9×10^{-3}
1ES 2037+521	20	0.10	2.1×10^{44}	—	2×10^7	2.1	—	4.9	1.000	0.12	3.9×10^{-3}
RGB J2042+244	20	0.073	1.8×10^{44}	—	3×10^5	2.0	—	2.7	0.158	0.36	2.3×10^{-3}
1ES 0927+500	10	0.13	7.1×10^{43}	3×10^5	3×10^6	1.5	2.5	3.2	0.316	0.25	2.3×10^{-2}
BZB J0809+3455	10	0.04	8.9×10^{43}	10^5	3×10^6	1.8	3.0	2.0	0.100	0.84	1.4×10^{-3}
RGB J2313+147	20	0.09	1.6×10^{44}	8×10^4	2×10^7	2.0	3.5	2.1	0.079	0.37	3.9×10^{-3}
TXS 0210+515	20	0.04	6.5×10^{44}	10^6	2×10^7	2.5	3.0	3.9	0.199	0.18	1.9×10^{-4}
TXS 0637-128	10	0.25	8.0×10^{43}	5×10^5	2×10^7	1.8	3.0	3.3	0.100	0.20	8.1×10^{-2}

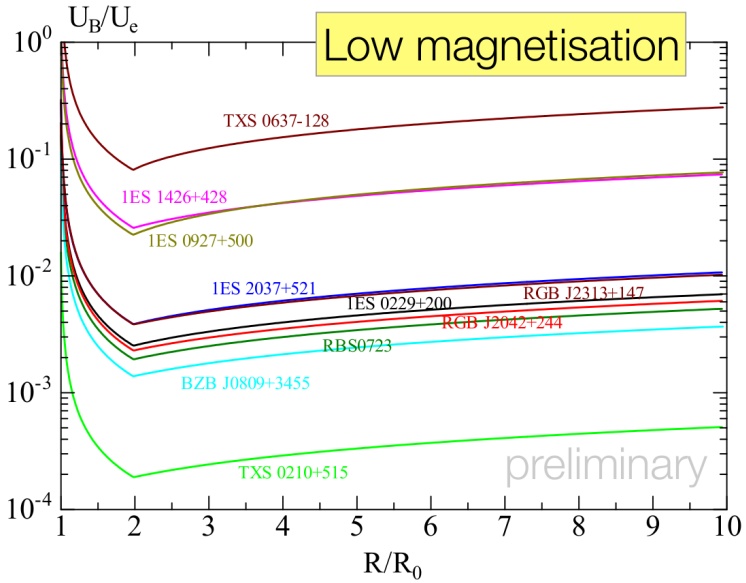
* Ratio of νL_ν at the IC peak to that at the synchrotron peak.

** Value evaluated at the radius where the electron injection shuts down.

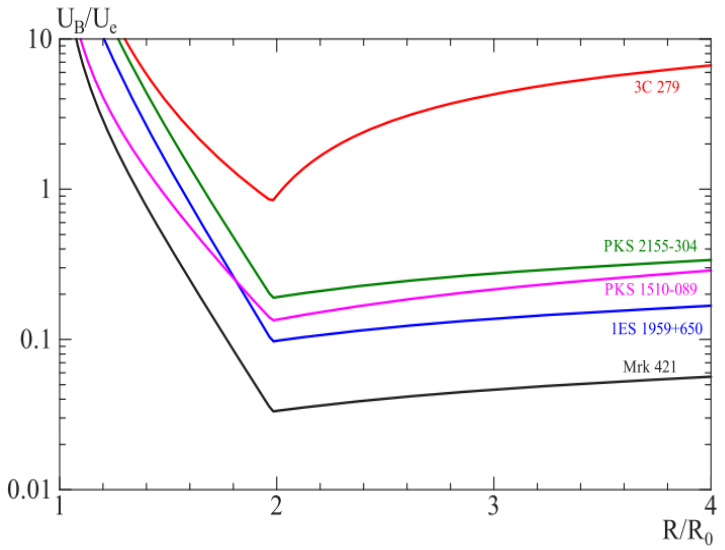
- Minimum IC peak of sample $\simeq$79 GeV
- Minimum synchrotron peak of sample $\simeq 2.42 \times 10^{16}$ Hz

Common properties: Magnetization

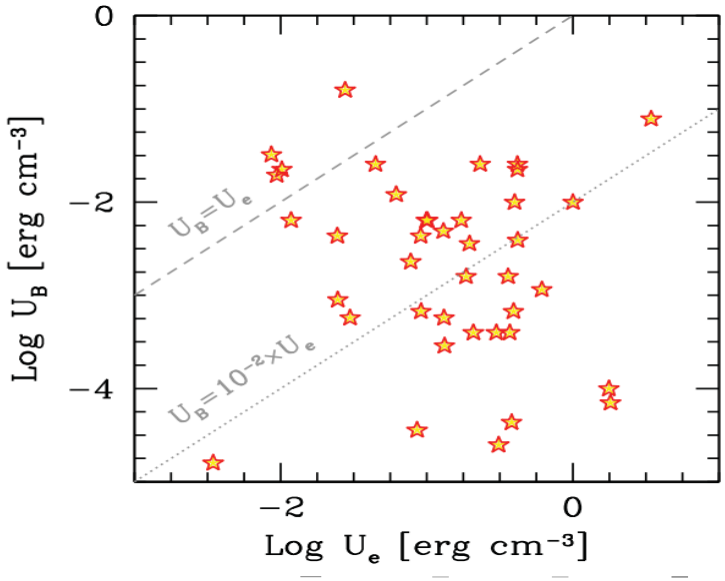
▸ Extreme blazars (This work)



▸ Asano, K. & Hayashida, M., 2018, ApJ, 8611, 31A

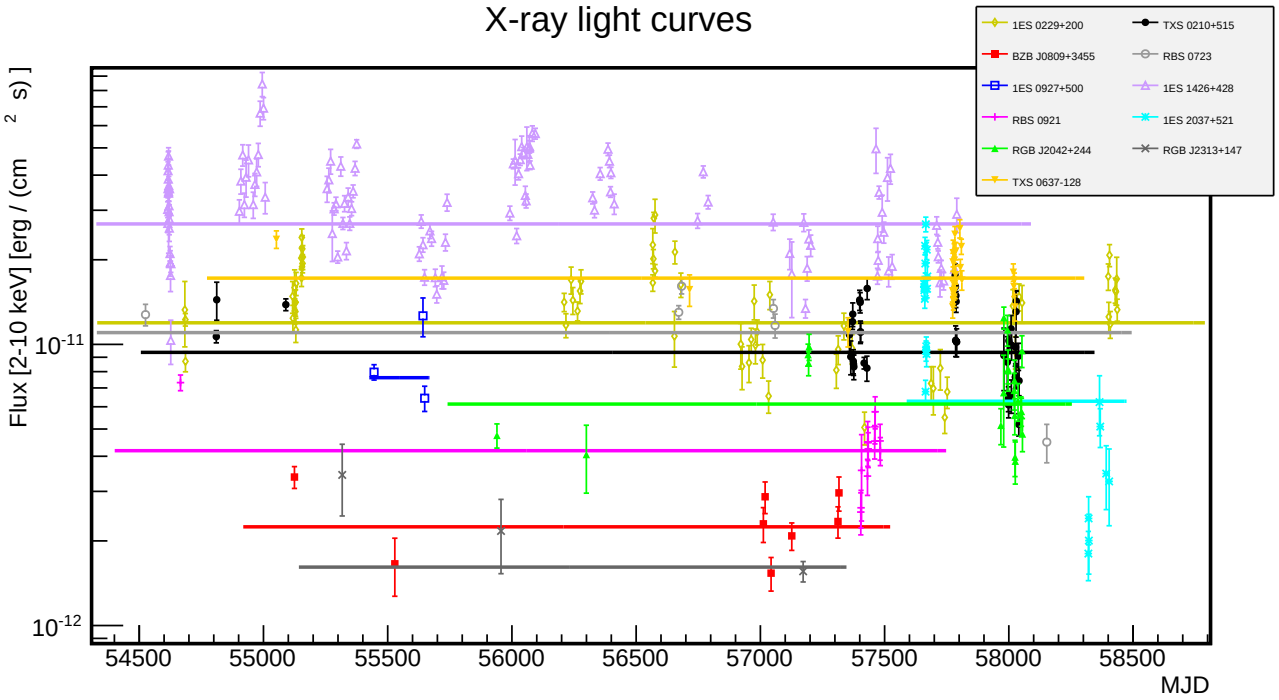


▸ Tavecchio, F. & Ghisellini, G., 2016, MNRAS, 456, 2374T



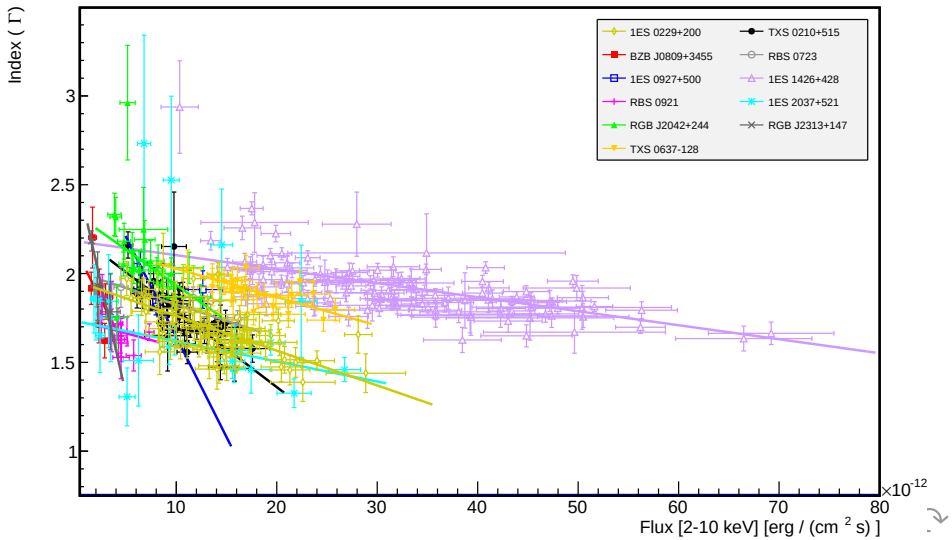
- Low magnetization is common in BL Lacs
- But EHBLs show much lower than average U_B/U_e (<10% of average)

Common properties: X-ray



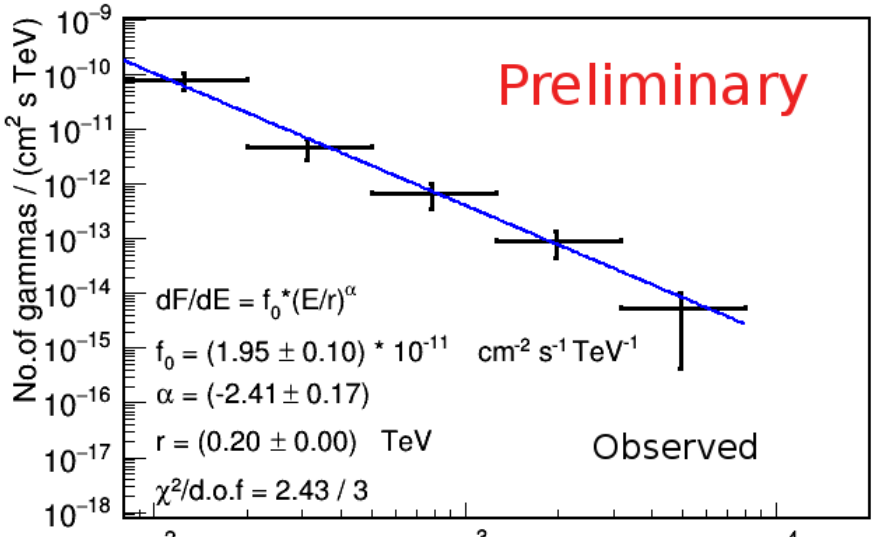
- Variability amplitude < 0.5 for all sources
- Largest F_{var} is for 1ES 0229+200
- For some sources F_{var} is affected by low statics

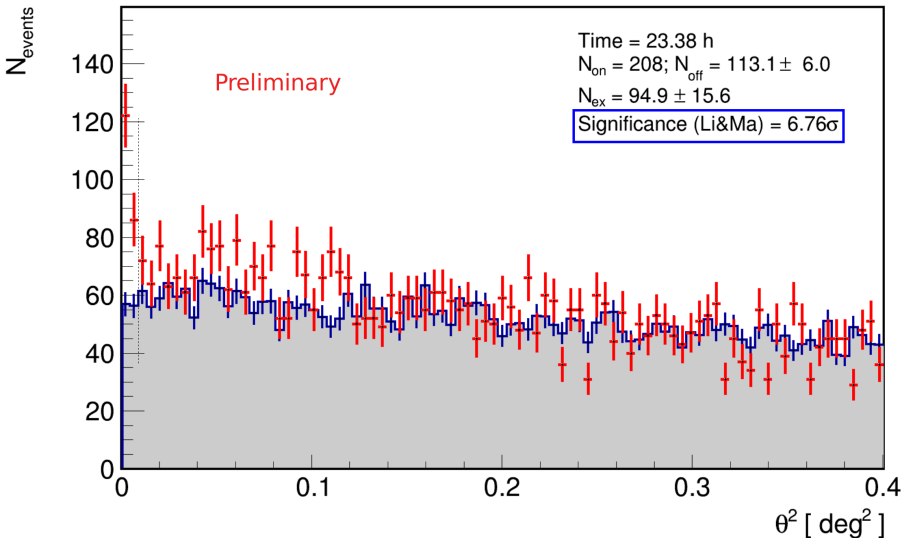
- Strong anti-correlation between spectral index and flux
  $\Rightarrow$ Pearson coefficient in range of -0.93 and -1.00
- Harder-when-brighter behaviour

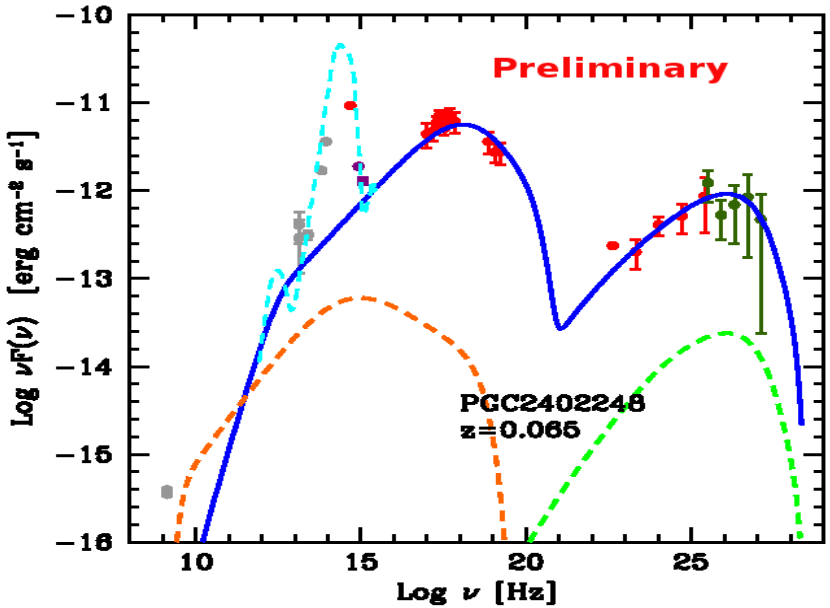


MAGIC news (PGC 2402248)

- The source was proposed by
  - Foffano, L. et al., MNRAS, Submitted
- PGC 2402248 is detected in VHE γ-ray band on 19.04.2018
  - Mirzoyan, R., 2018, ATel #11548







Conclusions

- MAGIC doubled the size of EHBL TeV emitters sample
- When modelled with SSC:
  - EHBLs show high value for γ_{break}, γ_{max}, and synchrotron photon energy
  - In comparison with other blazars, they have weaker magnetic field
- EHBLs show moderate variability in X-ray with $F_{var} \leq 0.5$
- 1ES 2037+521 is the most similar one to the prototype when comparing the shape of SEDs
- TXS 0210+515 is the most extreme source in our sample when comparing GeV-TeV spectra
- Except for the prototype, which have a very long exposure, no variability was detected in VHE γ-ray from our sample

Take home message:
The VHE γ-ray variability of EHBLs should be investigated
(CTA will help see Ulisses talk)

Thank You!!

Image credits: Alice Donini (Universitá di Udine)