Optical spectroscopy of extragalactic γ-ray sources:

Identification, classification & redshifts

Collaborators:

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M. Landoni – INAF OABrera

A. Franceschini – UNIPD

Speaker:

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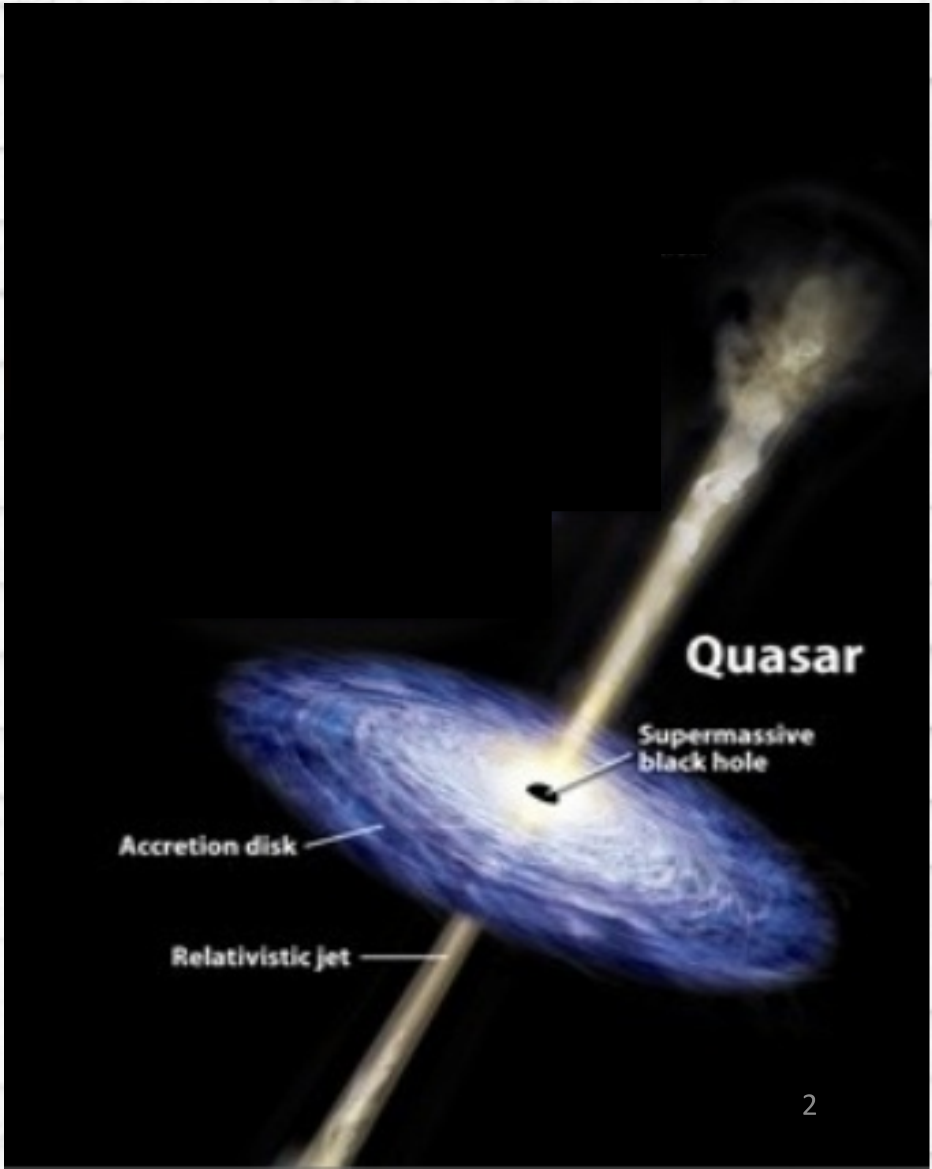
Madrid – 17 December 2019

BLAZARs

Class of jetted AGN...



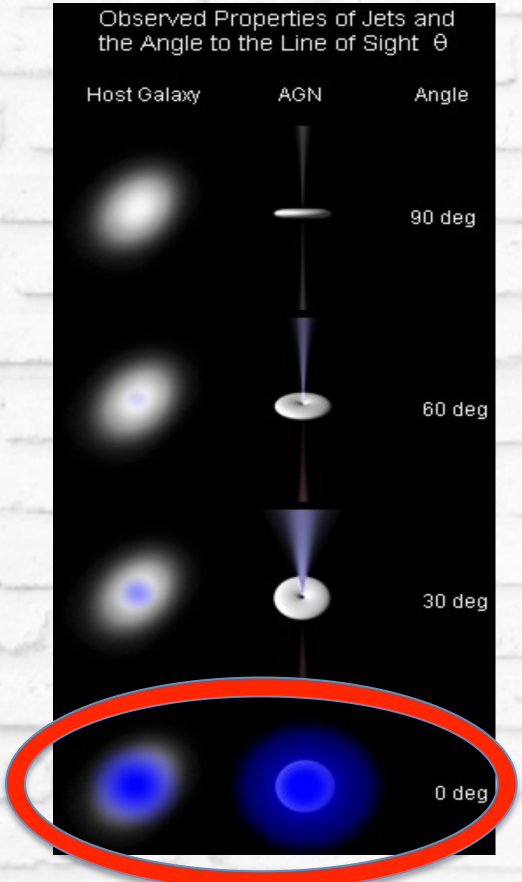
BLAZARs

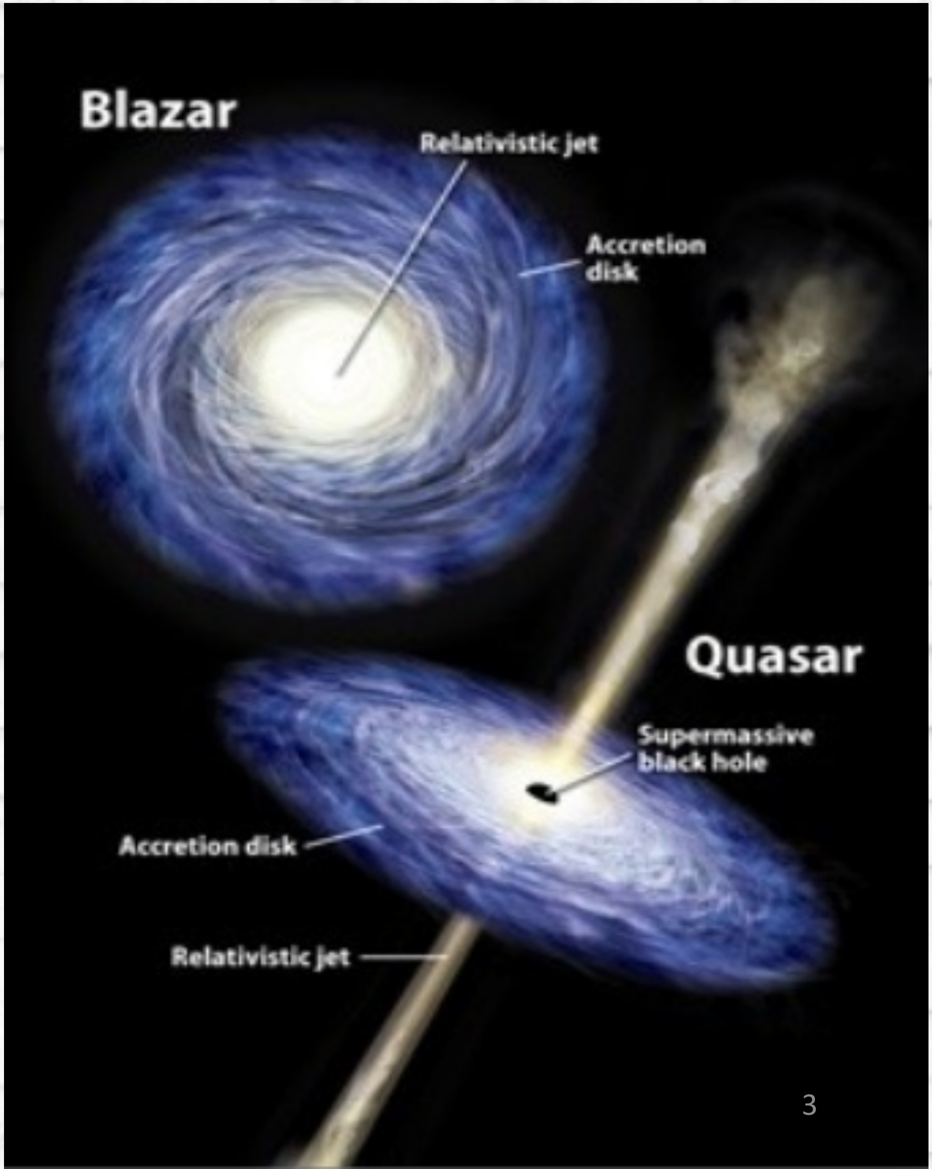
Class of jetted AGN with jet pointing towards the observer

-> The most powerful emitters from radio up to TeV;

-> Highly polarized;

-> Highly variable in amplitude and at all wavelength.





BLAZARs

Class of jetted AGN with jet pointing towards the observer

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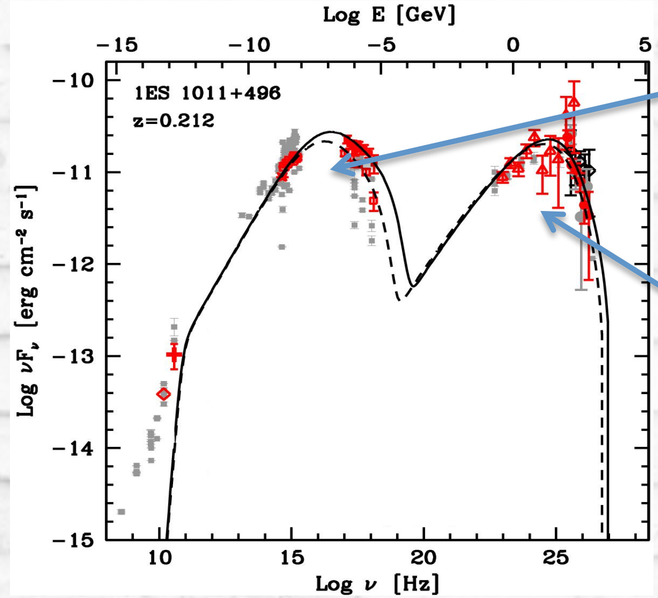
Typical MWL double-bump SED shape



Synchrotron emission (Radio-> X-ray)

Inverse Compton emission (X-ray -> TeV)

Adapted from Aleksic+2016

BLAZARs

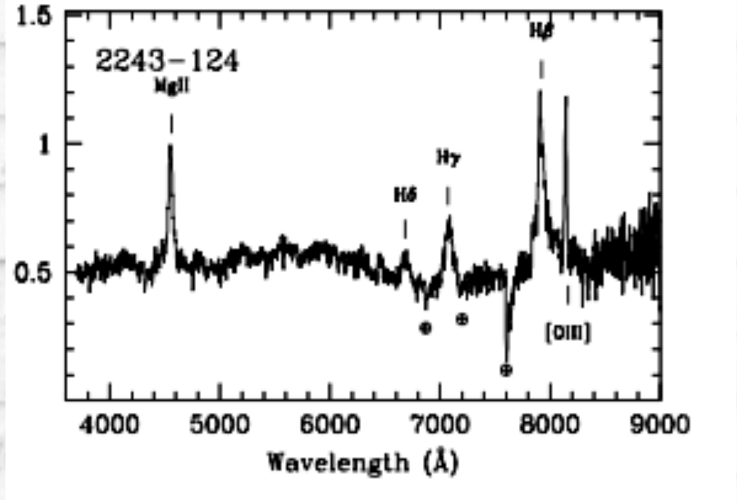
≈ 3500 blazars in the BZCAT (Massaro+2015):

-> sources detected at the radio frequencies
-> 70% detected in the X-ray band

A significant difference is based on the optical spectrum and they are divided in two classes:

FSRQs

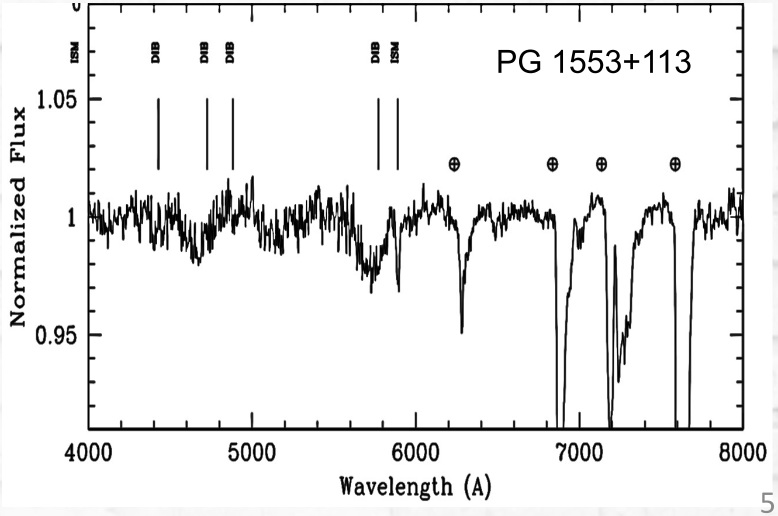
dominated by broad emission lines and thermal blue bump



Scarpa+1998

BLLac objects

emission lines weak or absent



Sbarufatti+2006

BLAZARs

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Blazars represent the most abundant Extragalactic population at GeV-TeV energies

The EXTRAGALACTIC γ-RAY SKY

Blazars represent the most abundant
Extragalactic population at GeV-TeV energies

The γ-ray electromagnetic spectrum:

-> High Energy (HE; >20 MeV)
detected by satellites
(as Fermi, Agile)

-> Very High Energy (VHE; >100GeV)
studied by Imaging Atmospheric
Cherenkov telescopes
(MAGIC, VERITAS, HESS, ... CTA)

THE FERMI SATELLITE & CATALOGS

- Launched in June 2008
  Two instruments on board:
  -> LAT (20MeV-300GeV) - all-sky map every 3 hr
  -> GBM for GRB monitoring
- Several catalogs:
  4FGL > 3FHL > 3FGL > 2FHL > 1FHL >2FGL > 1FGL > 0FGL
  3LAC, 2LAC, 1LAC, 2PC, 1PC, GRBCat....

4FGL catalog reports 5525 γ-ray emitters:

-> 50% are blazars (the most numerous class)
- -> ~ 681 FSRQs
- -> ~ 1102 BLLs
- -> ~ 1155 blazars of uncertain type (BCU)

-> 30% Unassociated Fermi Objects
(most of them probably blazars)

THE TeV BAND & TeV BLAZARS

A sub-sample of the GeV blazars are also emitters at the TeV

-> There is 1 TeV blazar for ~ 25 GeV blazars

In the TeVcat* -> 59 + (2) BLLs
-> 7 FSRQs
-> 4 blazars

TeV band observed with the IACT telescopes:

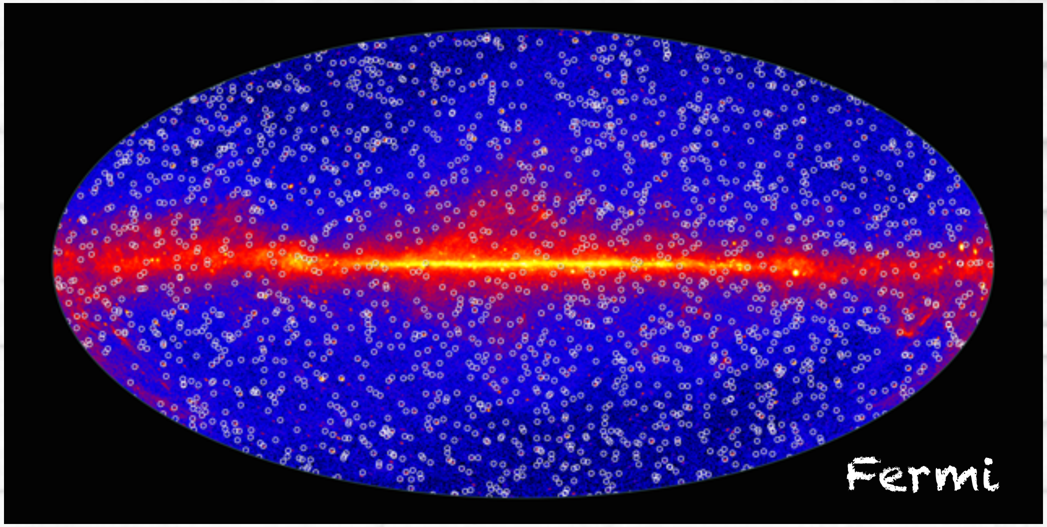
MAGIC telescopes:

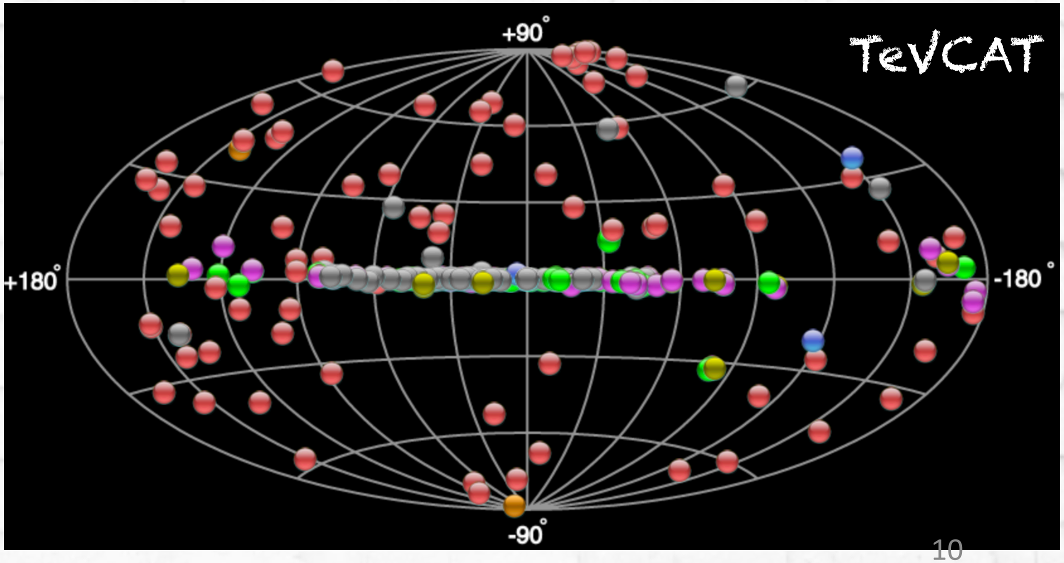
- -> 2 x 17m diameter parabolic surface
- -> Energy threshold: 50 GeV
- -> Energy resolution: 16-17% (>300GeV)
- -> Angular resolution < 0.1 (>100GeV)
- -> Sensitivity(E>100GeV): 1.5% CU/50hr

(*) tevcat.uchicago.edu

THE TeV BAND & TeV BLAZARS

BL Lac objects dominate the extragalactic TeV sky:





THE TeV BAND & TeV BLAZARS

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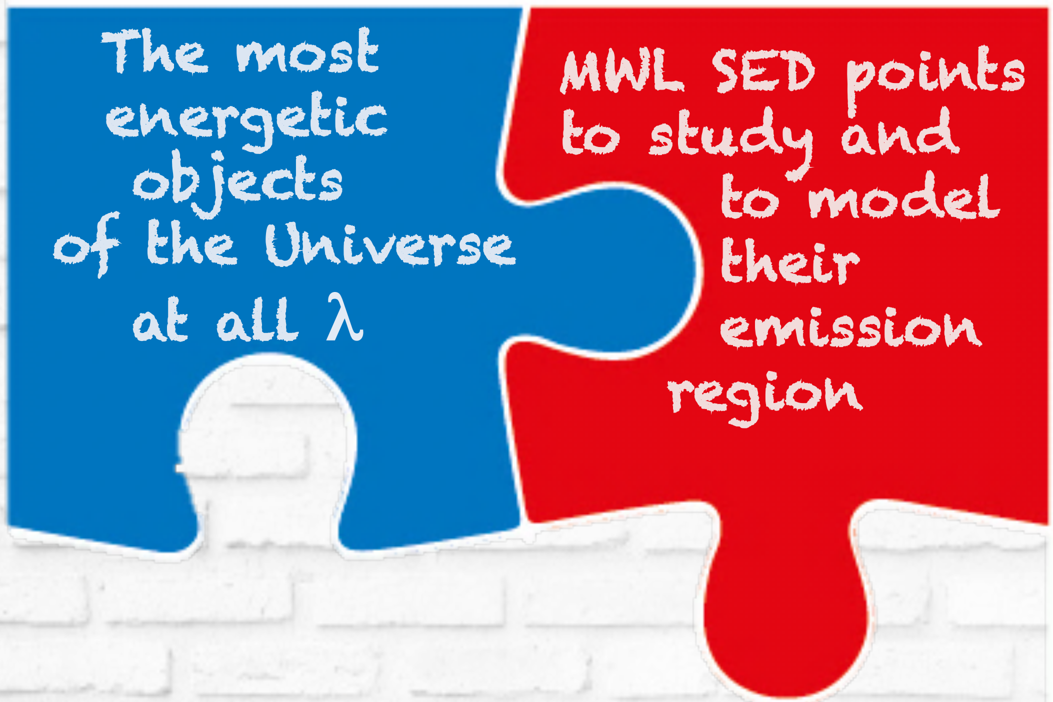
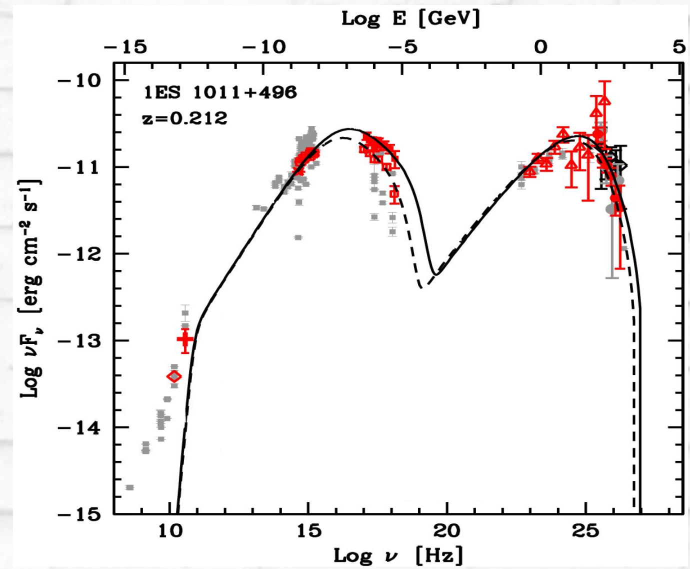


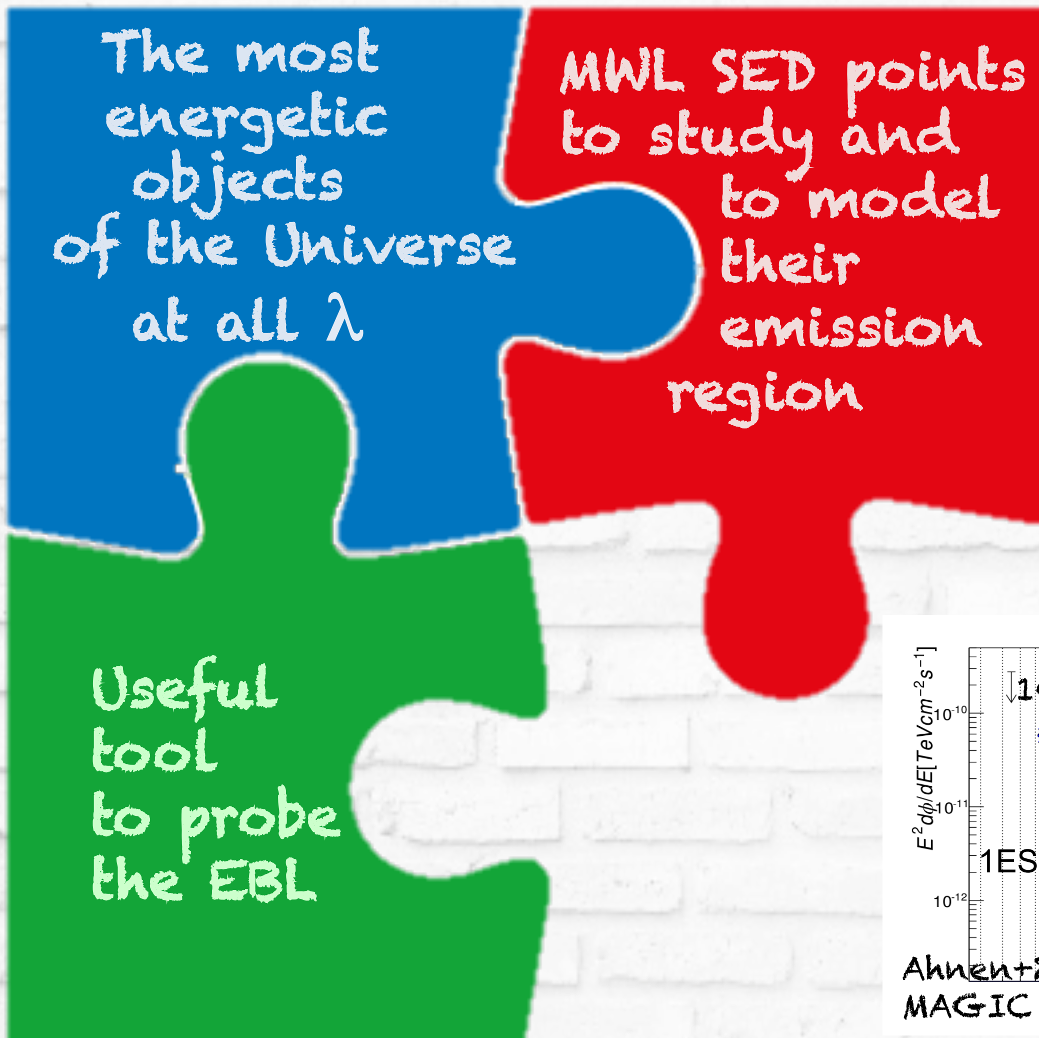


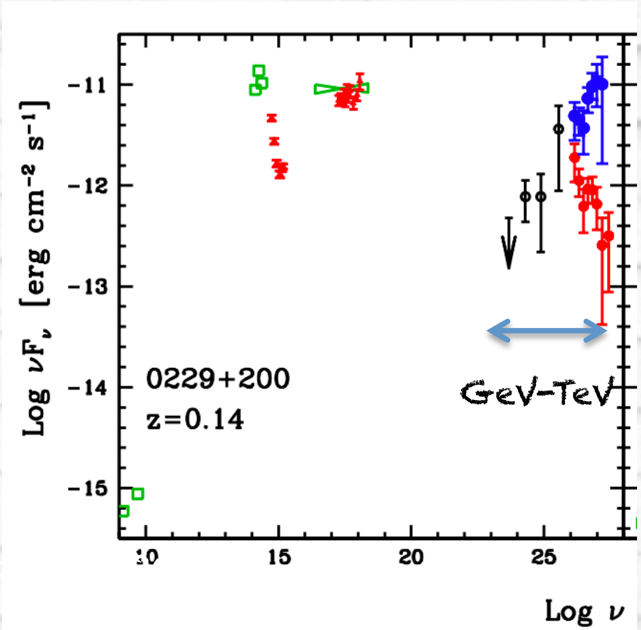
Aleksic+2016

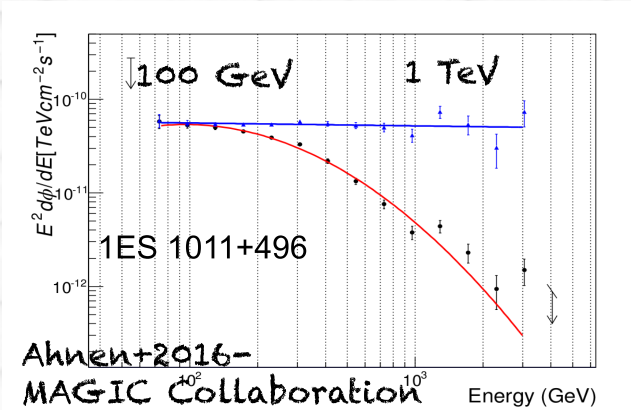
Year	γ_{min} $[10^3]$	γ_b $[10^4]$	γ_{max} $[10^5]$	n_1	n_2	B [G]	K $[10^3\ cm^{-3}]$	R $[10^{16}\ cm]$	δ
2007[a]	3.0	5.0	200	2.0	5.0	0.15	20	1.0	20
2008[b]	7.0	3.4	8.0	1.9	3.3 (3.5)	0.048	0.7 (0.8)	3.25	26
2011/2012[I]	10.0	4.0	7.0	2.0	3.7	0.19	10.0	1.0	20
2011/2012[II]	10.0	3.3	4.0	2.0	3.8	0.19	13.4	0.9	20

THE TeV BAND & TeV BLAZARS

BL Lac objects dominate the extragalactic TeV sky:

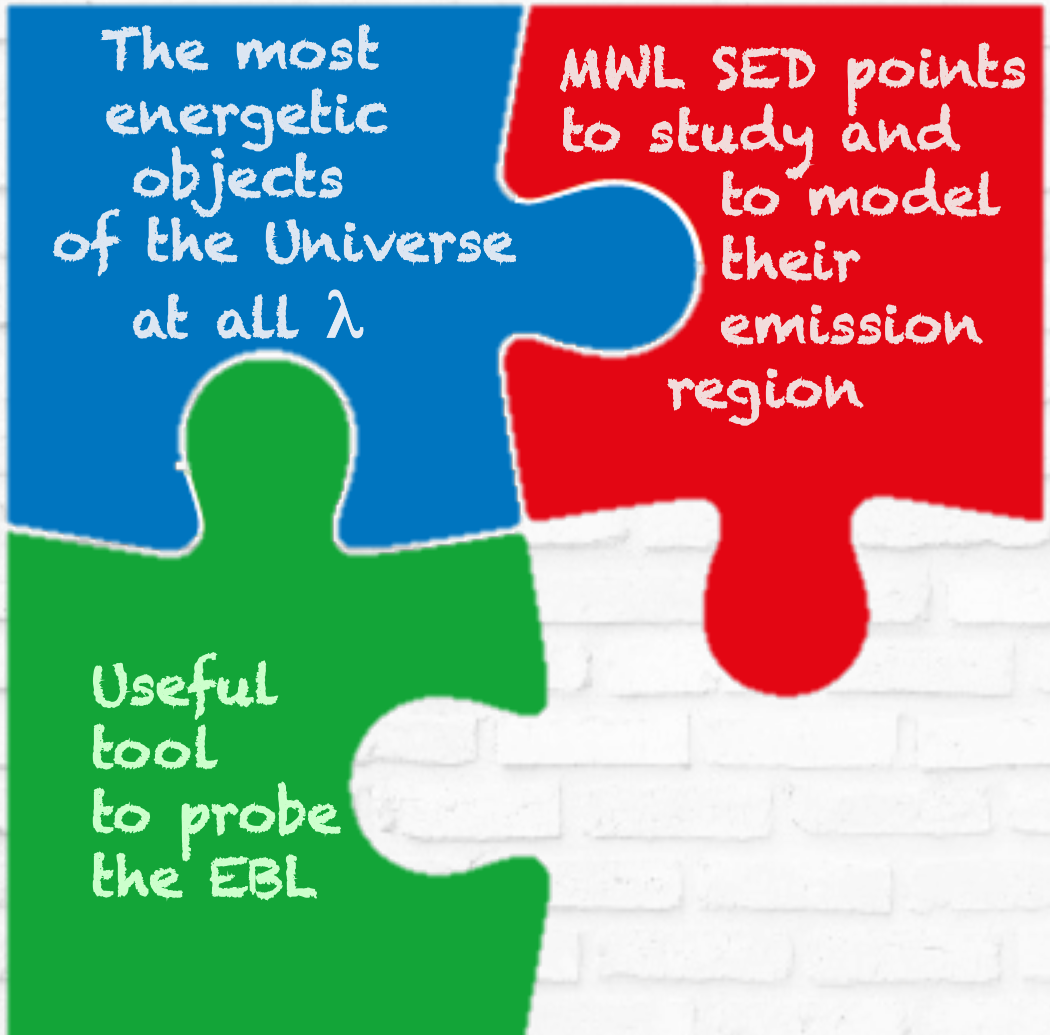






THE TeV BAND & TeV BLAZARS

BL Lac objects dominate the extragalactic TeV sky:



THE TeV BAND & TeV BLAZARS

BL Lac objects dominate the extragalactic TeV sky:

The most energetic objects of the Universe at all λ

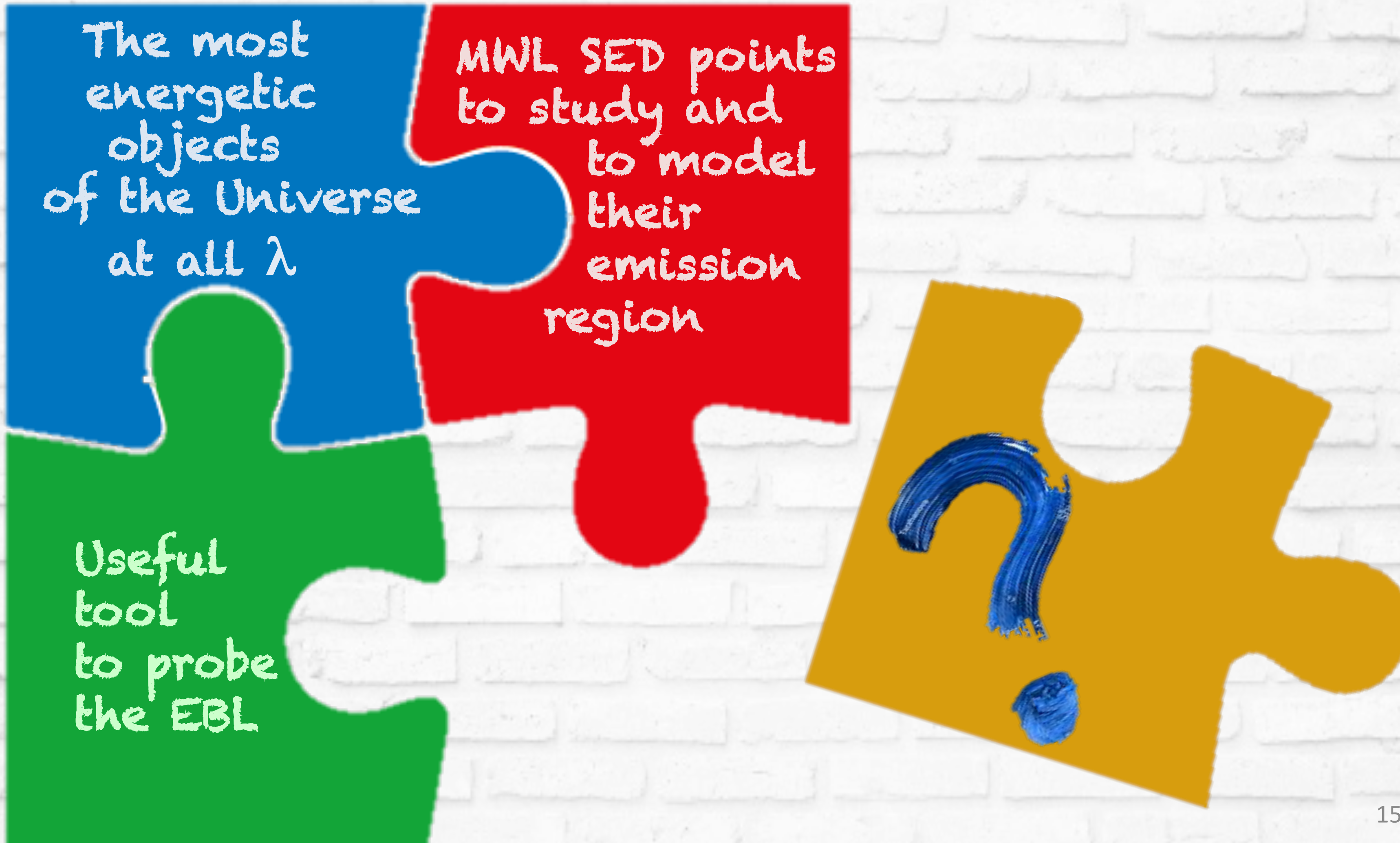
MWL SED points to study and to model their emission region

Useful tool to probe the EBL

Redshift

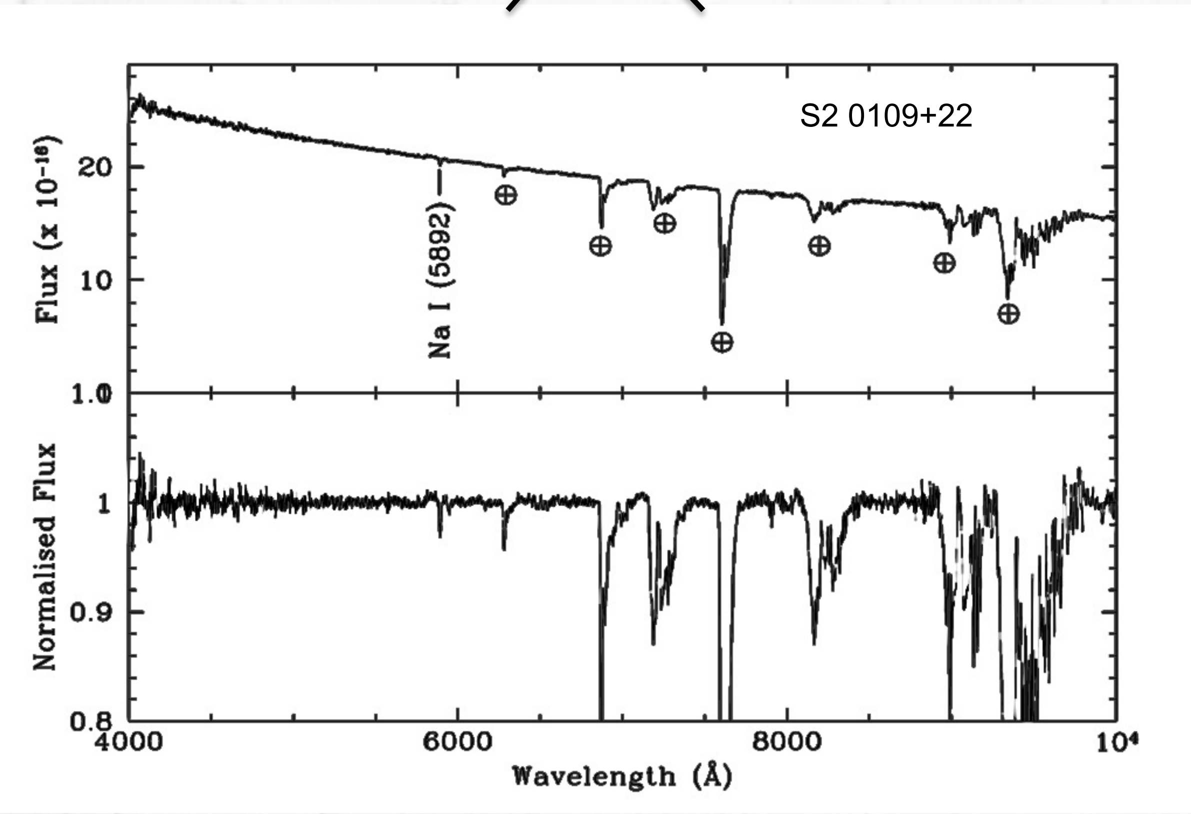
THE TeV BAND & TeV BLAZARS

BL Lac objects dominate the extragalactic TeV sky:



ON THE REDSHIFT OF BLLs

The (quasi) featureless optical spectra is the main characteristic in the optical of the BLL class



Paiano+2016

The determination of their redshift results extremely difficult

≈ 50% of GeV BLLs has unknown or highly uncertain redshift

GTC SPECTROSCOPY CAMPAIGN

It needs to have optical spectra of
high S/N and high resolution

We are carrying out an extensive campaign of spectroscopy with OSIRIS @GTC (10.4 m) of different samples of γ-ray blazars

-> > 200 spectra obtained till now
-> Spectral Range: 4000-10000 A
-> grisms: R500B, R1000B and R1000R
-> Spectral resolution = 1000
-> S/N = 50 - 500 (depending on the source mag)

GTC SPECTROSCOPY CAMPAIGN

LIST OF SUB-SAMPLES:

-> 22 TeV and TeV candidate BLLs with unknown/uncertain redshift
-> Paiano et al. (2016), Paiano et al. (2017a) Landoni et al. (2016), Falomo et al. (2017)

-> 10 high-z GeV BLLs
-> Paiano et al. (2017b)

-> 47 Unassociated Fermi Objects
-> Paiano et al. (2017c), Paiano et al. (2019)

-> 16 Optically selected high redshift BLL candidates
-> Landoni et al. (2018)

-> 60 3FHL blazars (TeV candidates) with unknown redshift
-> Paiano et al. (2020, in prep)

-> 15 high redshift BLL candidates
-> Paiano et al. (2020, in prep)

-> 10 neutrino BLL candidates
-> Paiano et al. (2018a), Paiano et al (Atel#12269,#12802,#13202) Paiano et al. (2020, in prep)

All published Spectra (≈300) are available at the website

http://www.oapd.inaf.it/zbllac/

You can include your spectra of BLLs in our database
See the website for info or ask me!!

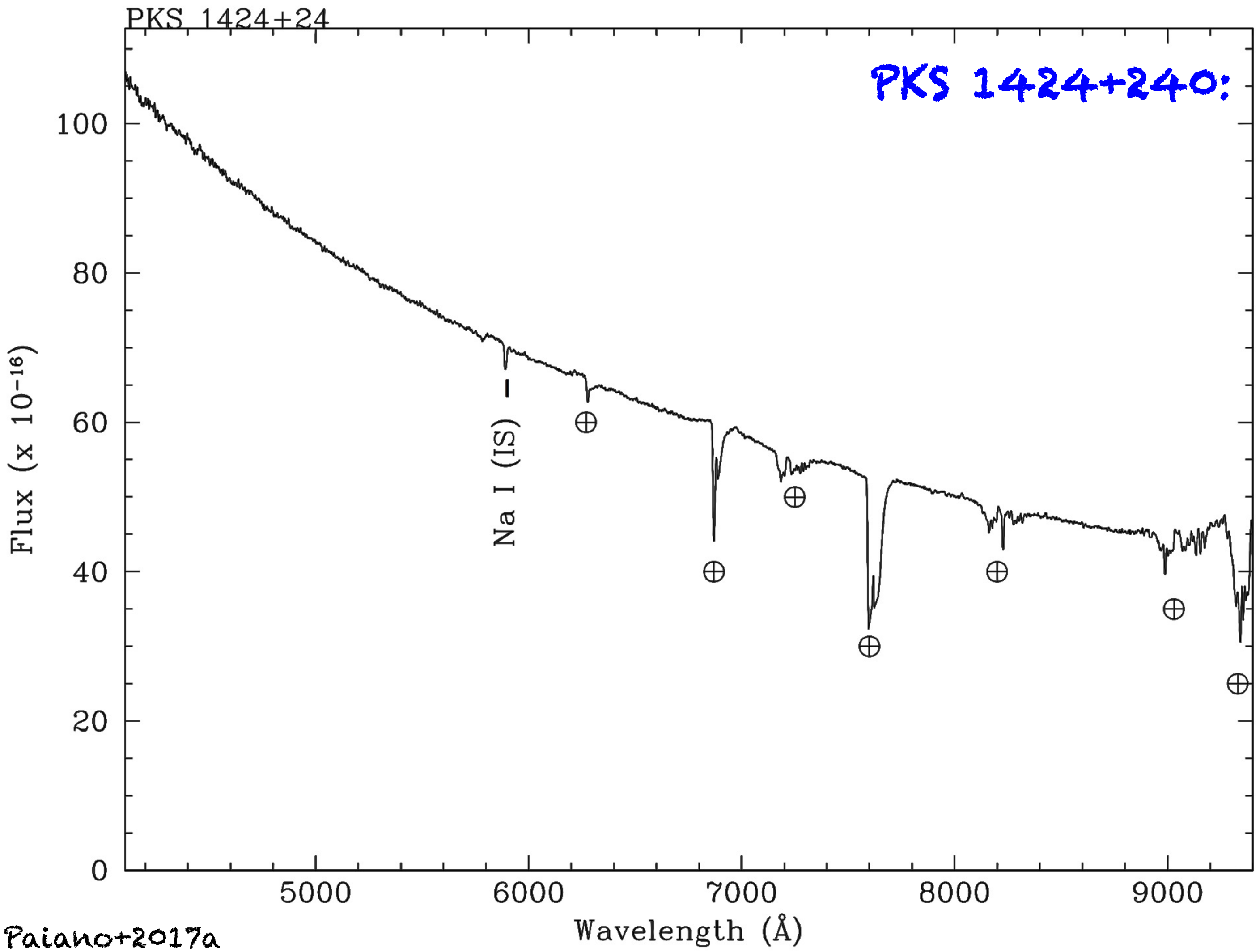
RESULTS

Based on the properties of the optical spectra,
the objects can be grouped into 4 spectrum types :

1. Emission lines characteristic of low-density gas
2. Absorption lines of stars from the host galaxy
3. Intervening absorption lines from cold gas
4. Featureless spectrum

RESULTS (Some examples...)

Emission lines characteristic of low-density gas

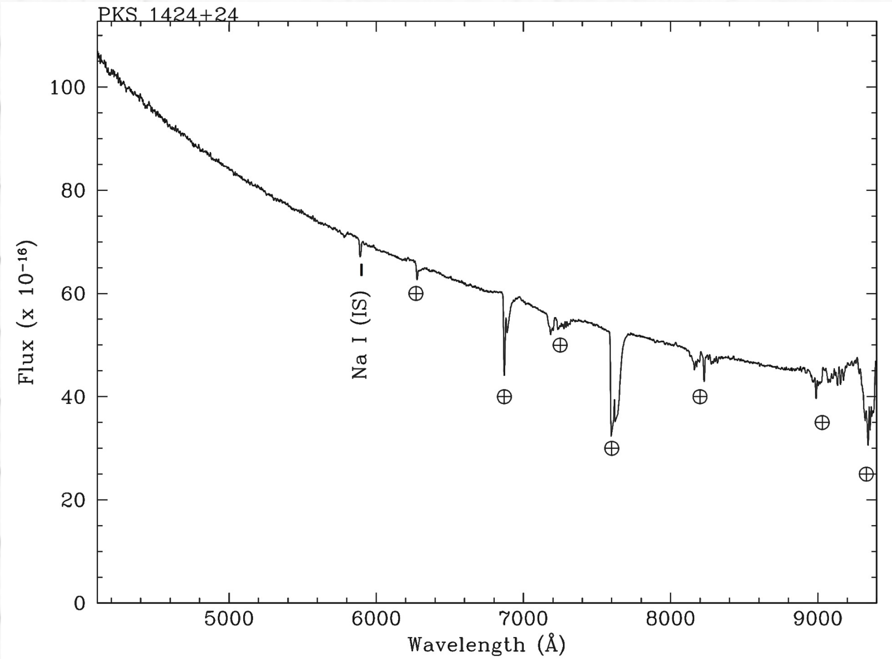


Paiano+2017a

PKS 1424+240: TeV HBL source

RESULTS

Emission lines characteristic of low-density gas



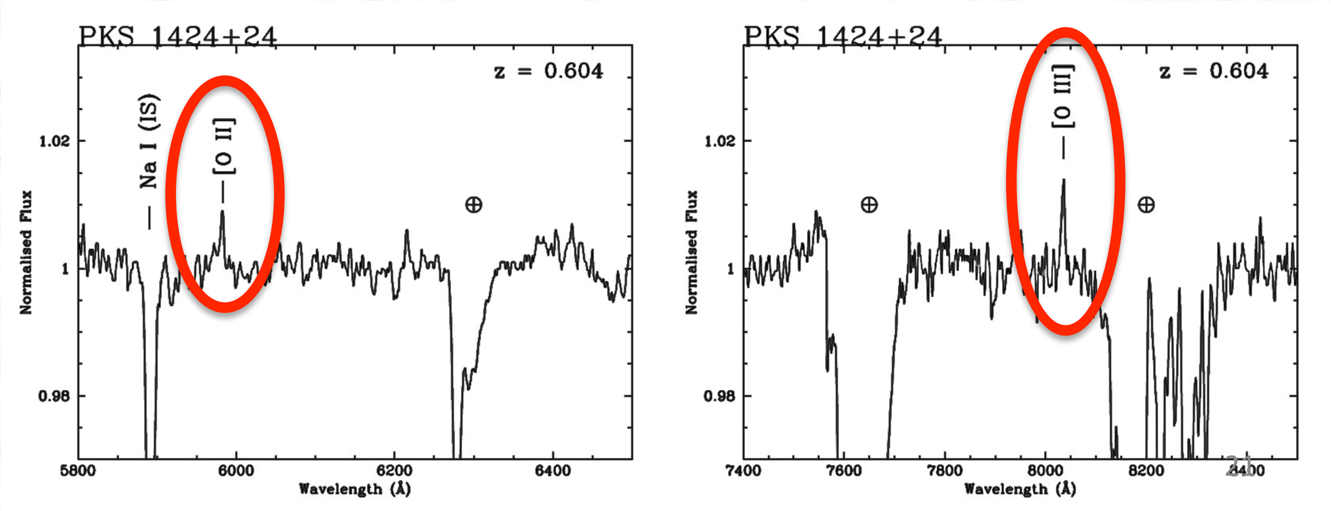
Paiano+2017a

PKS 1424+240: TeV HBL source

[OII](3727) -> EW = 0.05A

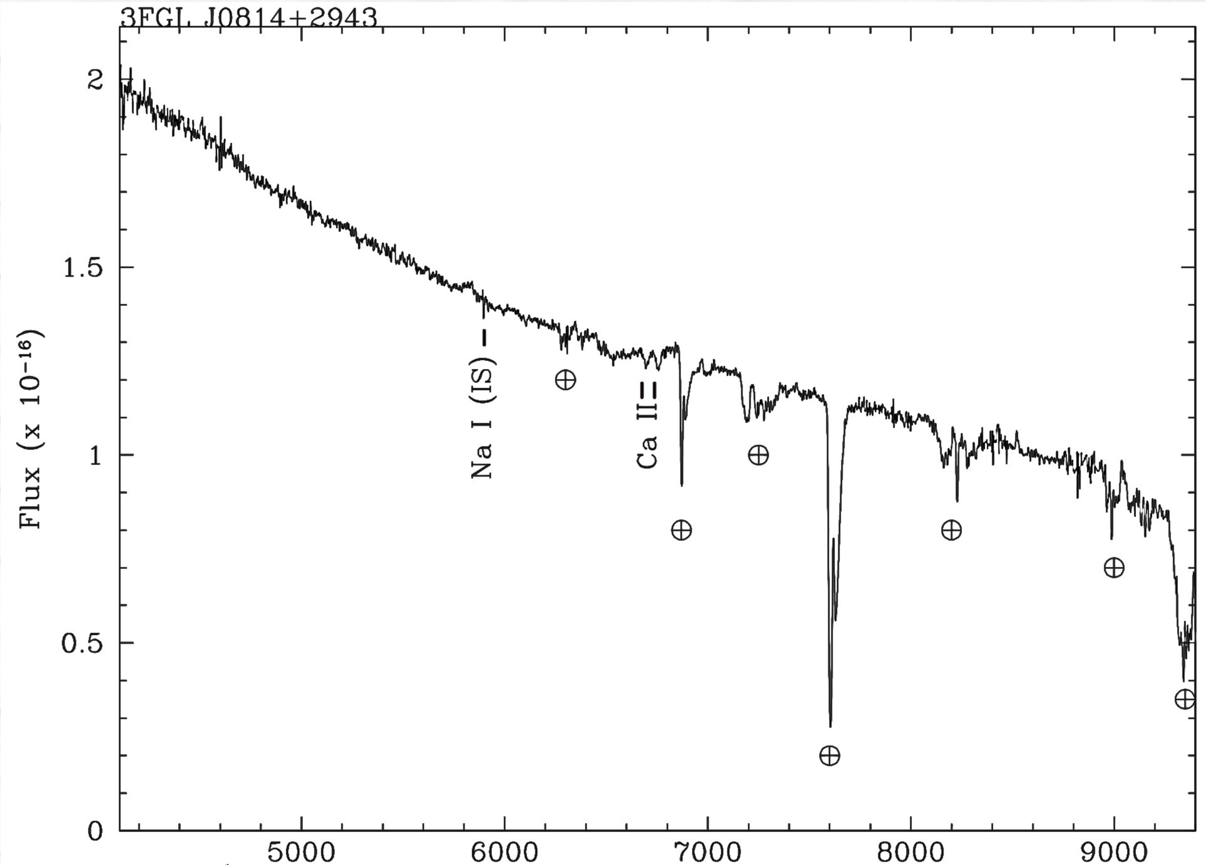
[OIII](5007) -> EW = 0.10A

z = 0.604



RESULTS

Absorption lines of stars from the host galaxy



Paiano+2017b

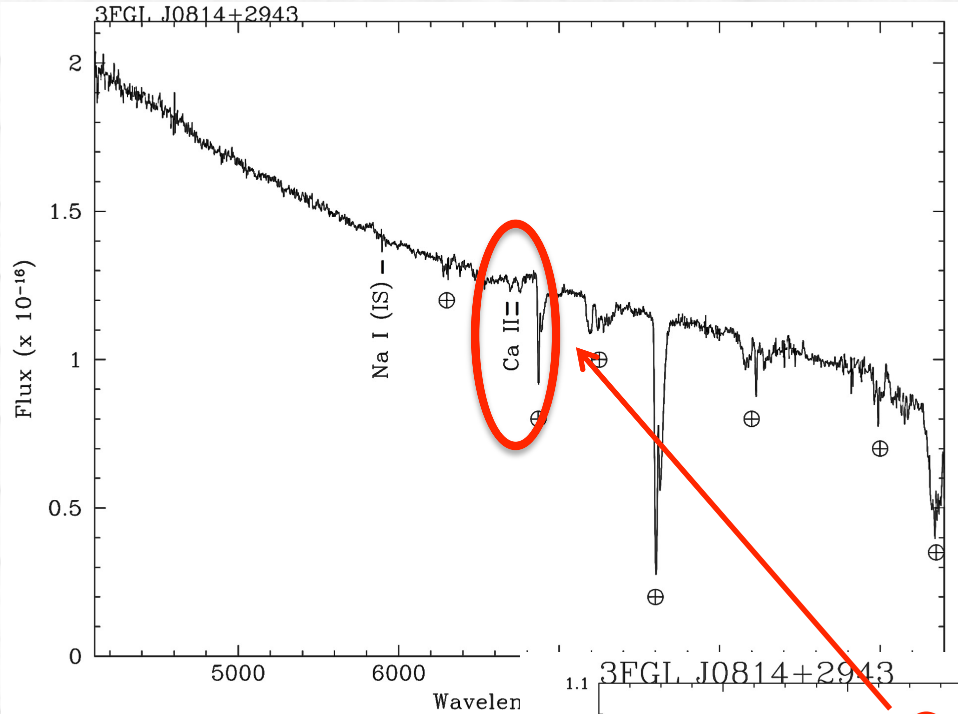
3FGLJ0814+2943

High-z BLL of 3FGL

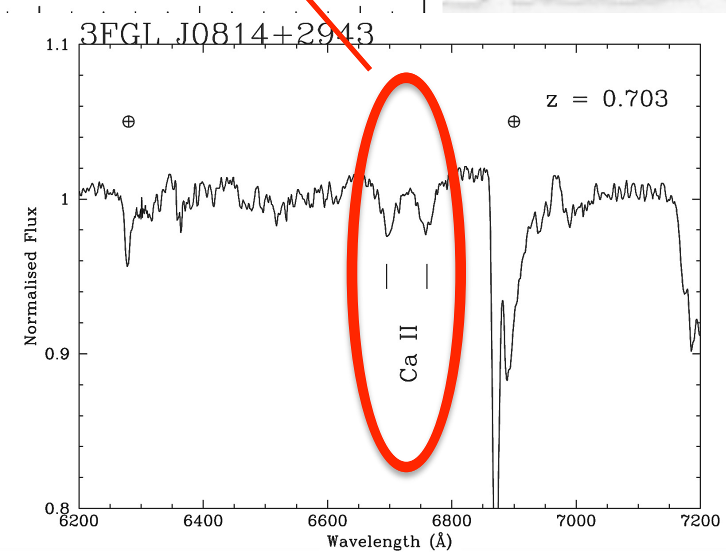
(literature z = 1.08)

RESULTS

Absorption lines of stars from the host galaxy



Paiano+2017b



3FGLJ0814+2943

High-z BLL of 3FGL

(literature ~~z = 1.08~~)

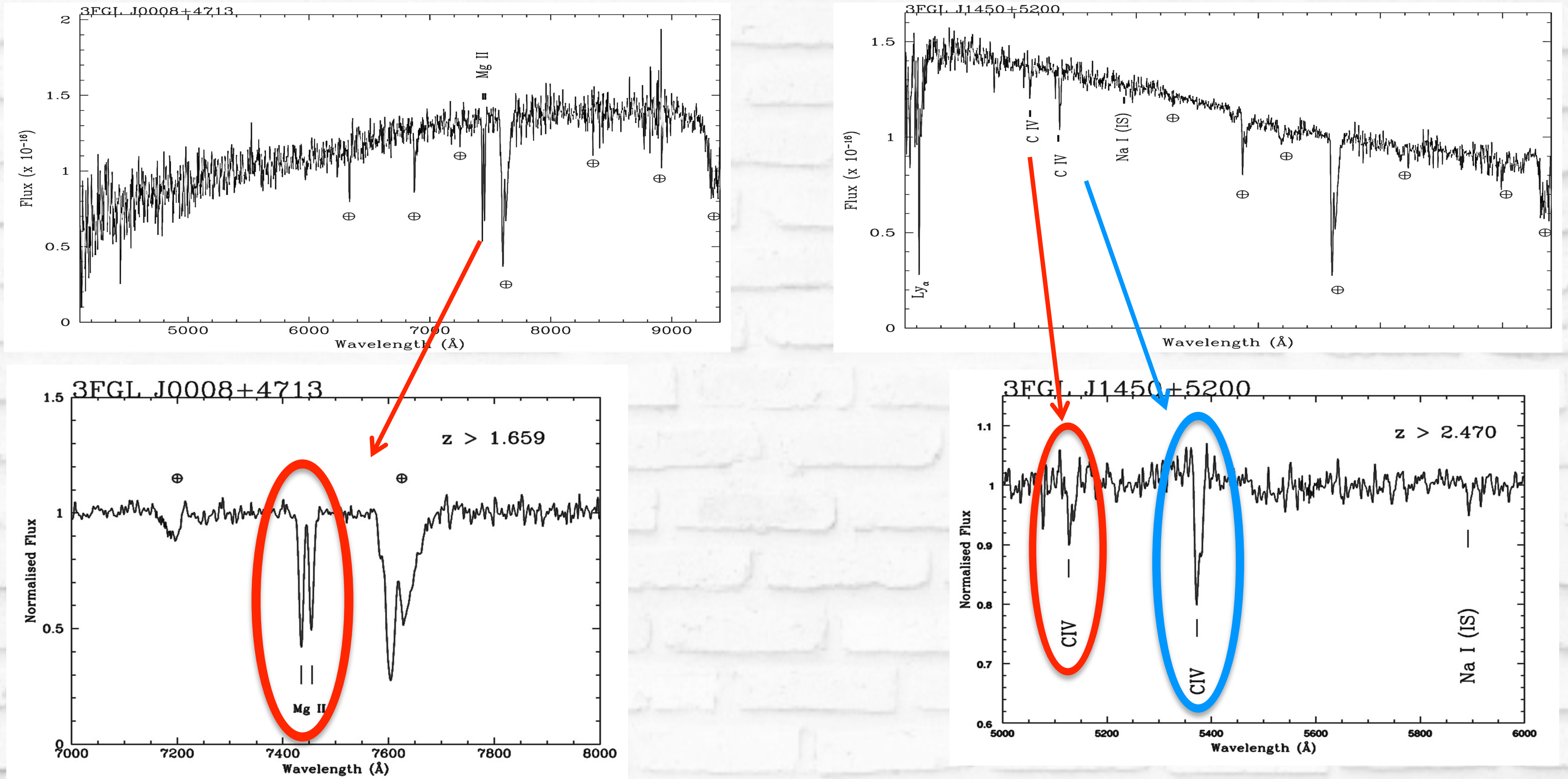
CaII(3934) -> EW = 0.6A

CaII(3968) -> EW = 0.5A

z = 0.703

RESULTS

Intervening absorption lines from cold gas -> Redshift Lower Limits



3FGLJ0008+4713
High-z BLL of 3FGL
MgII (2008)
-> z > 1.659

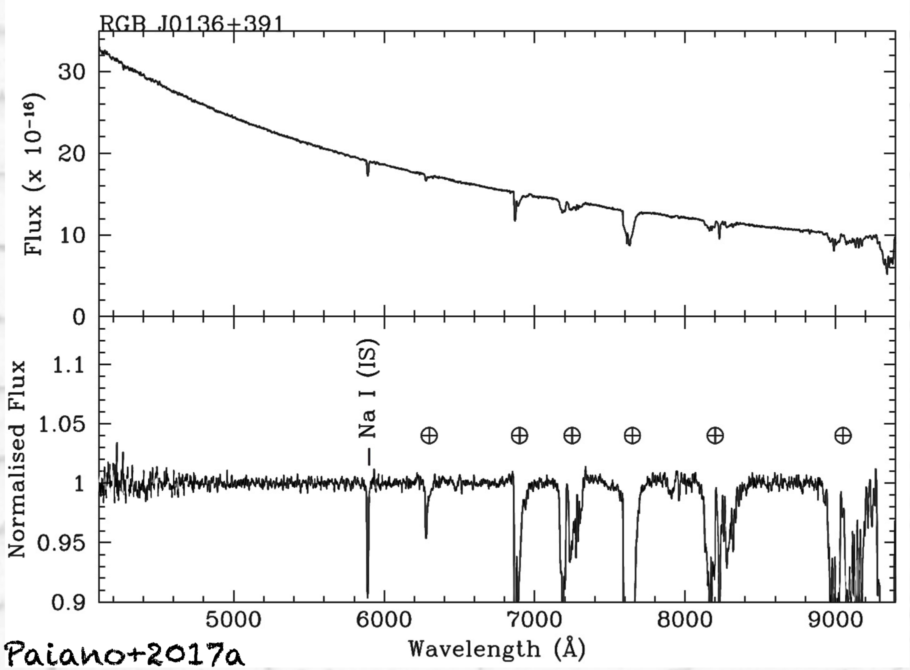
z > 2.470 <-
z > 2.312 <-

3FGLJ1450+5200
High-z BLL of 3FGL
CIV (1548) - Ly-α(1216)
CIV (1548)

Two of the farthest BLLs known!!!

RESULTS

Featureless spectrum

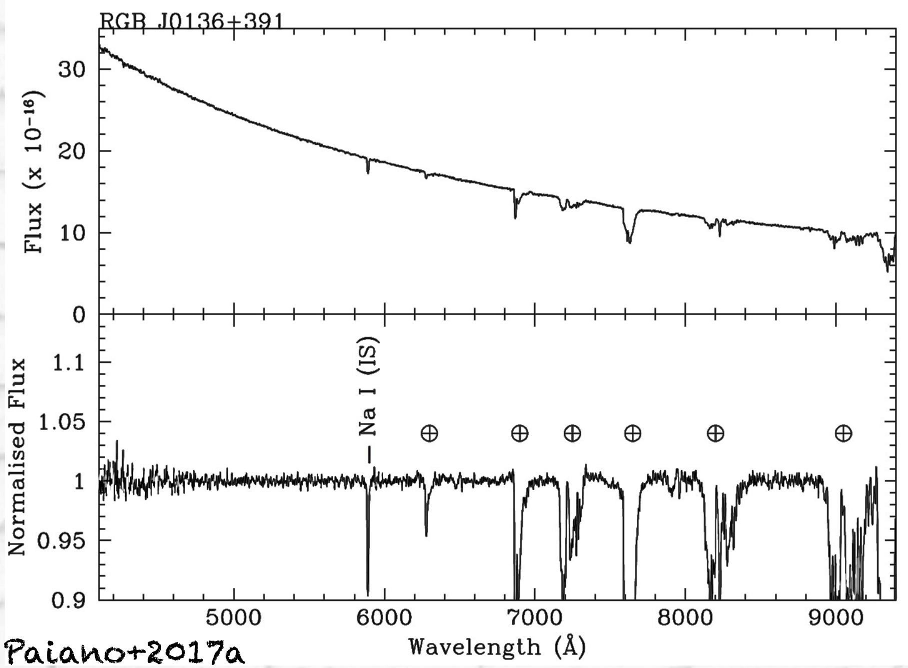


Paiano+2017a

RGB J0136+391
TeV HBL
S/N = 500
r = 15.80

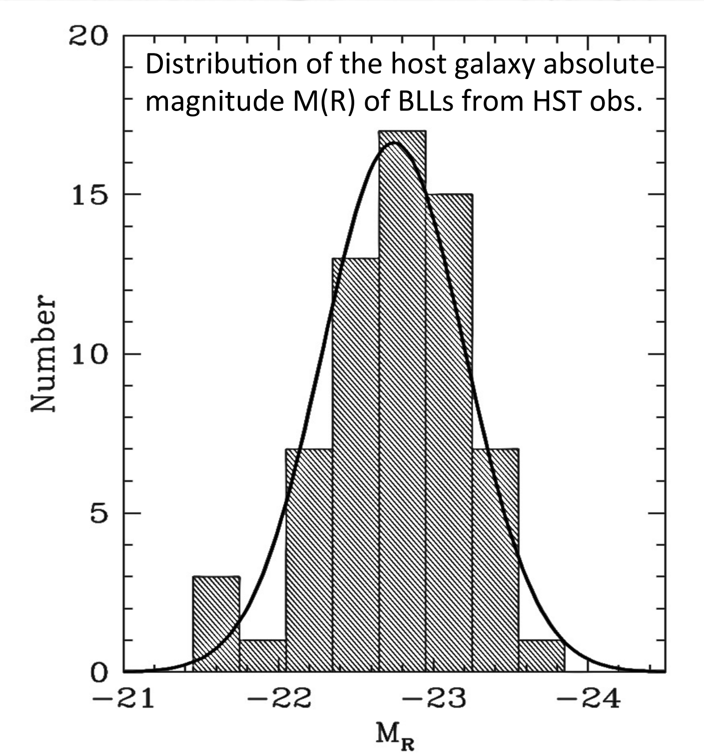
RESULTS: Lower limit of the redshift

Featureless spectrum



Paiano+2017a

Non-thermal Nucleus
+
Elliptical host galaxy
[M(R) = -22.9]
=
Observed spectrum



Sbarufatti+2005

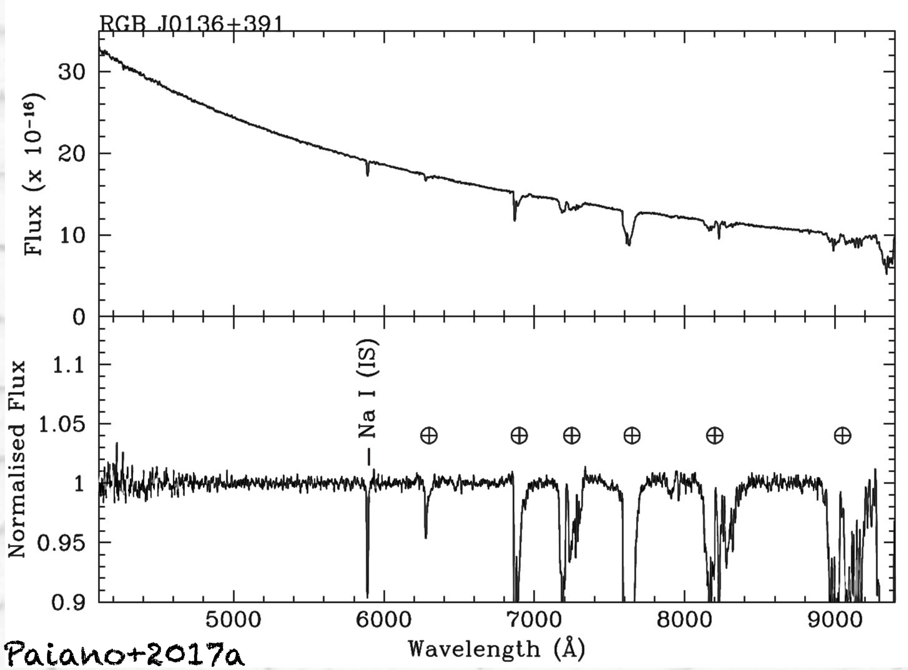
RGB J0136+391

TeV HBL

S/N = 500

RESULTS: Lower limit of the redshift

Featureless spectrum



Paiano+2017a

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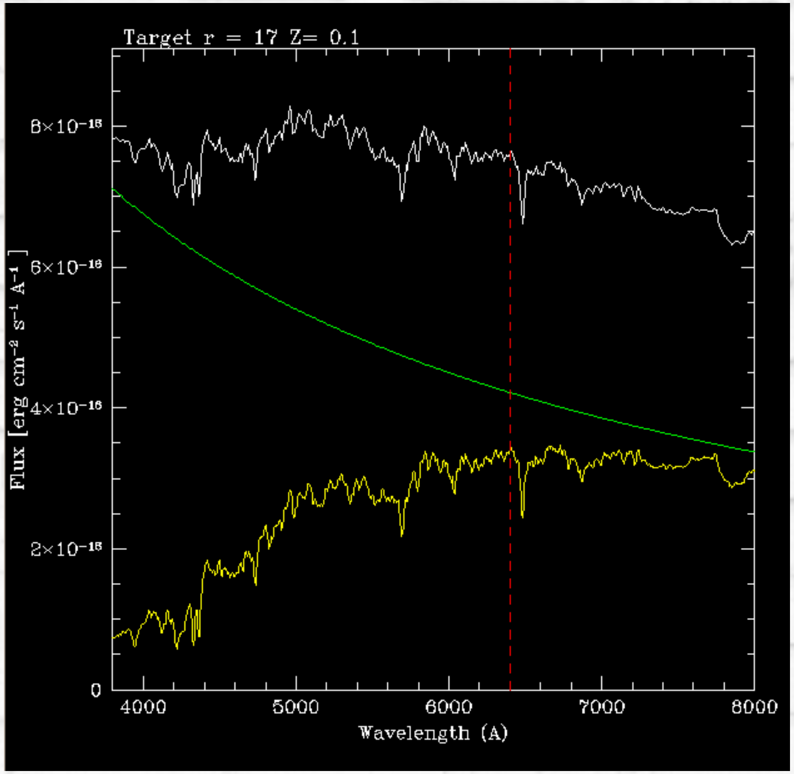


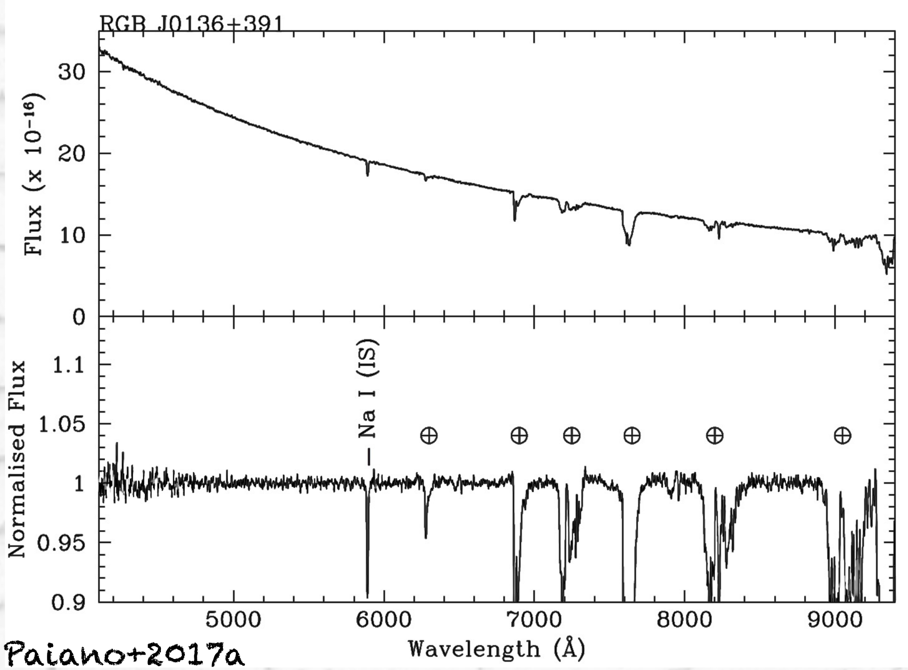
RGB J0136+391
TeV HBL
S/N = 500

Low N/H

Mag=17, z=0.10, Diluited EW=1.6A

RESULTS: Lower limit of the redshift

Featureless spectrum



Paiano+2017a

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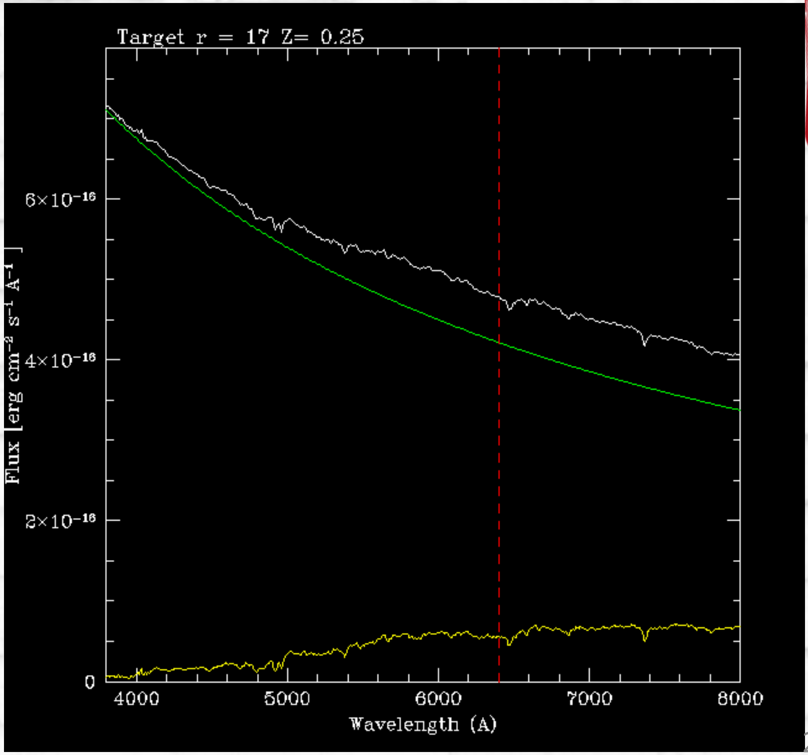


RGB J0136+391

TeV HBL

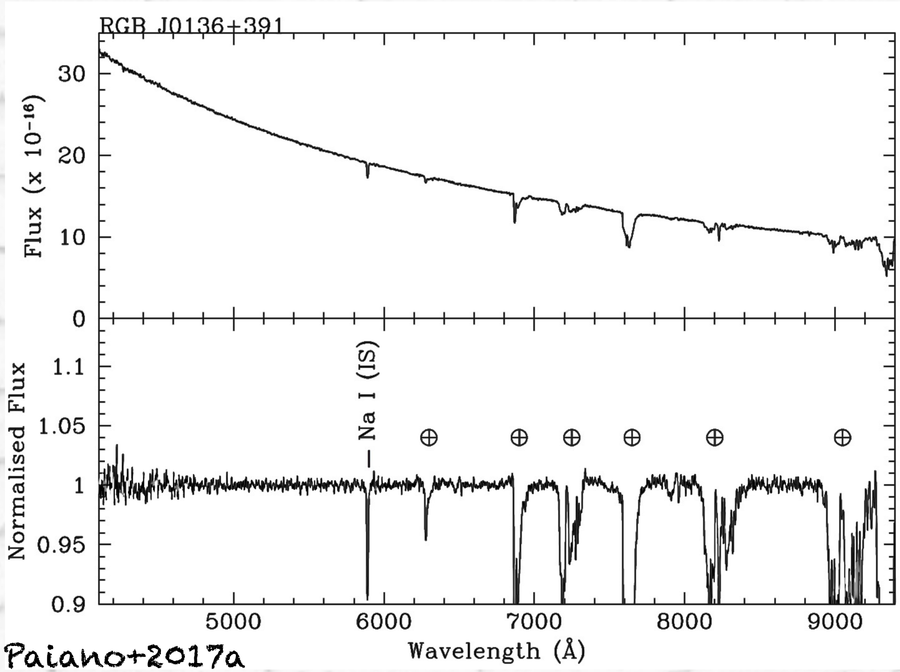
S/N = 500

Higher N/H

Mag=17, z=0.25, Diluited EW=0.5A

RESULTS: Lower limit of the redshift

Featureless spectrum



Paiano+2017a

Non-thermal Nucleus
+
Elliptical host galaxy
[M(R) = -22.9]
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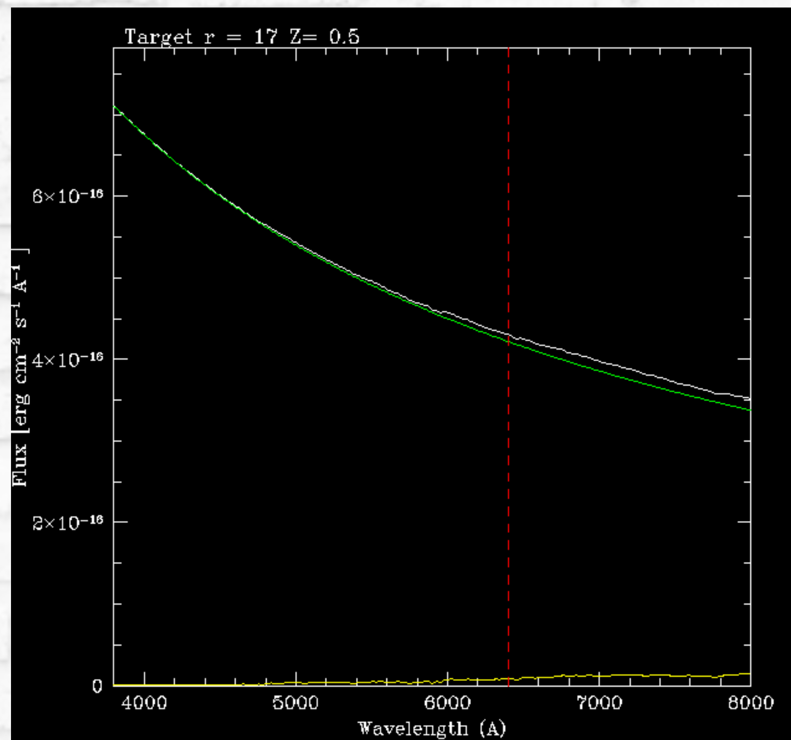
Observed spectrum



RGB J0136+391

TeV HBL

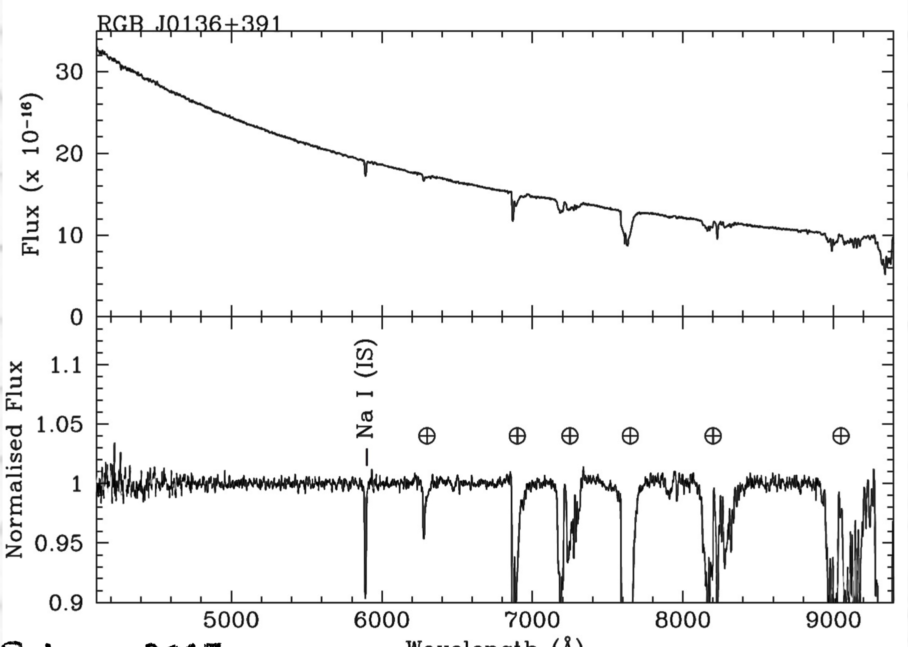
S/N = 500

Higher++ N/H

Mag=17, z=0.50, Diluited EW=0.15A

RESULTS: Lower limit of the redshift

Featureless spectrum

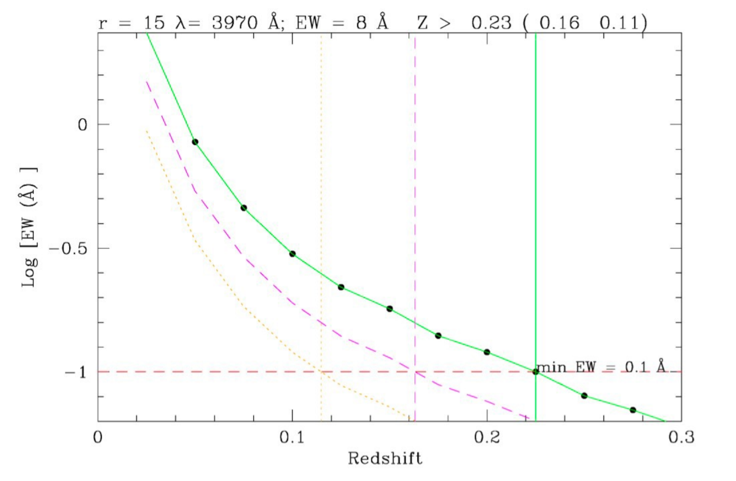


Paiano+2017a

Non-thermal Nucleus
+
Elliptical host galaxy
[M(R) = -22.9]
=
Observed spectrum

We can derive EW UL = minimum detectable EW

$$\mathrm{EW_{obs}} = \frac{(1+z)\mathrm{EW_0}}{1+\rho A(z)}.$$



RGB J0136+391

TeV HBL

S/N = 500

minEW = 0.08

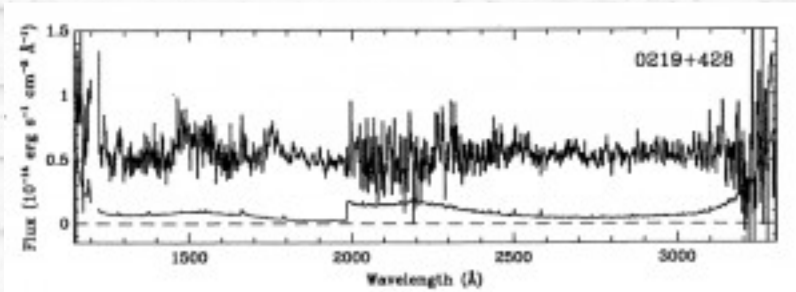
$z_{Lim} > 0.27$

. . . and a lower limit on the redshift

RESULTS: Lower limit of the redshift

For several cases, we disprove the previous published redshift

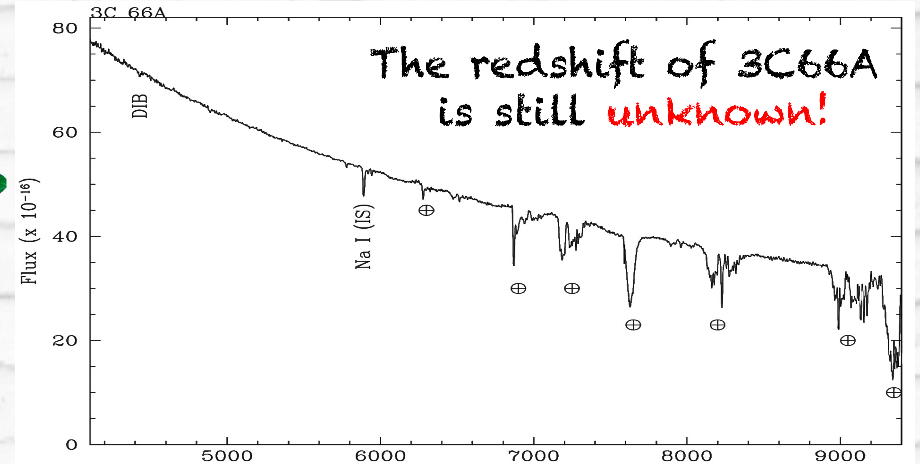
CASE OF 3C66A



One of the first BLLs studied !!

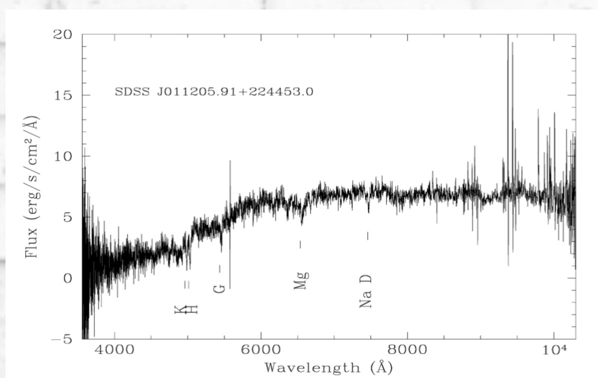
$z = 0.444$

(Miller+78 , Lanzetta+1993)

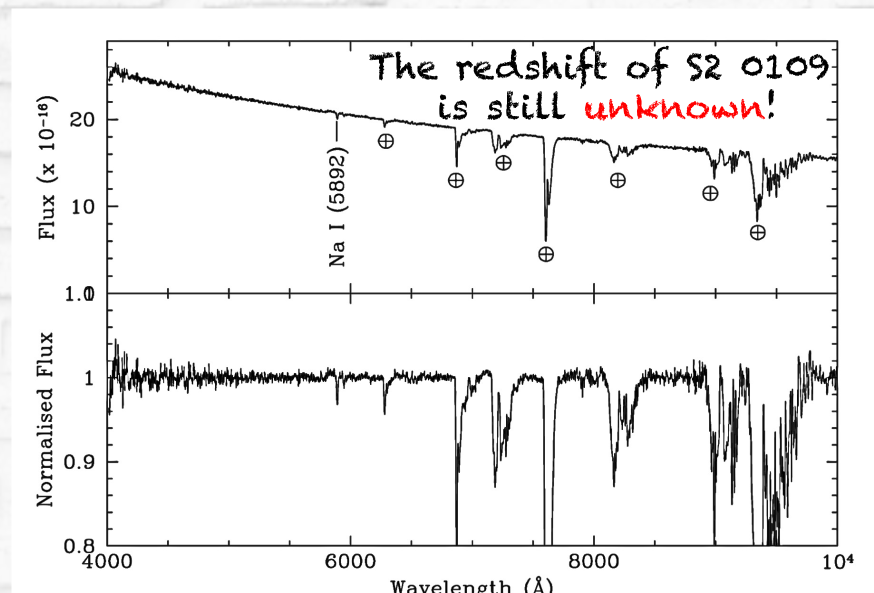


Paiano+2017a

CASE OF S2 0109+22

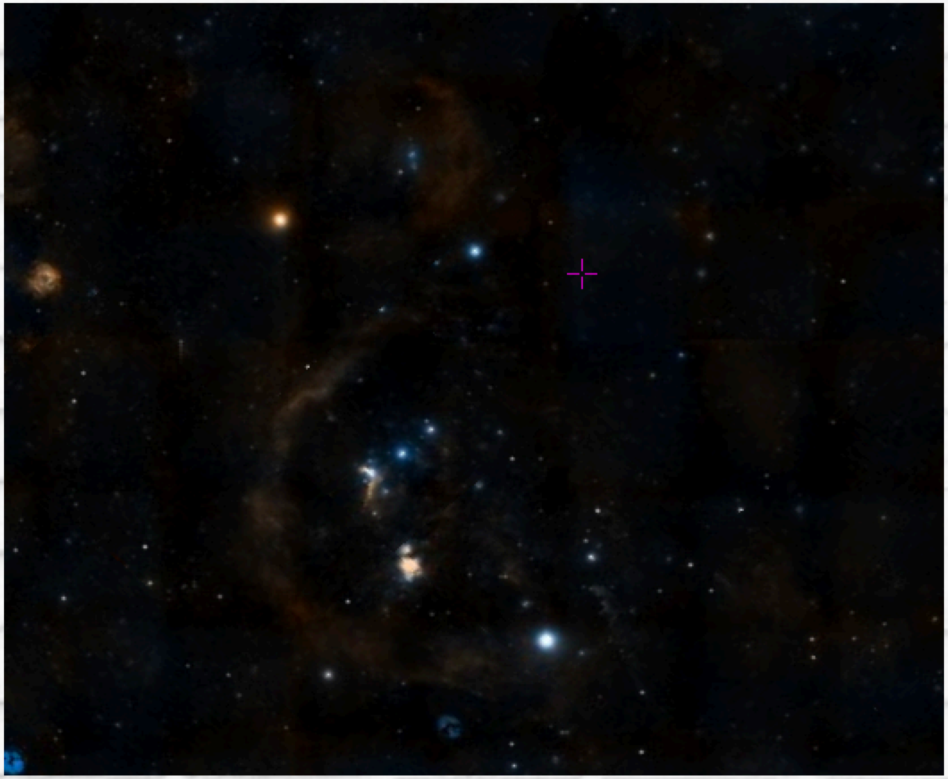


$z = 0.26$, but this is the redshift of a close galaxy!



Paiano+2016

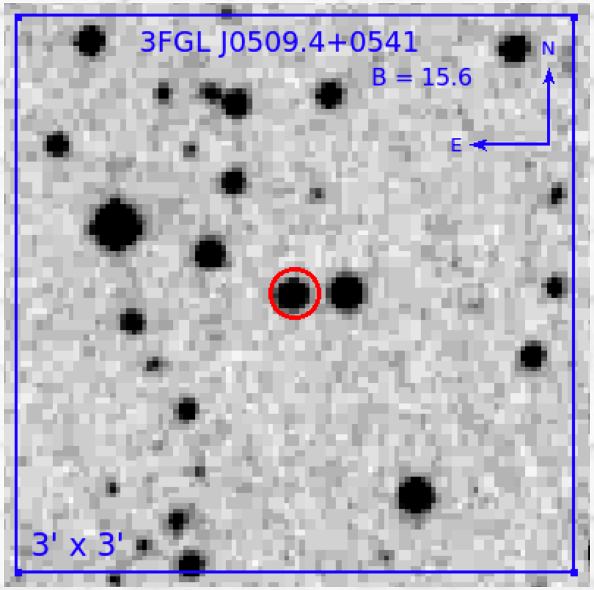
THE REDSHIFT OF THE NEUTRINO BL LAC OBJECT TXS0506+056



TXS 0506+056
(3FGLJ0509+0542)

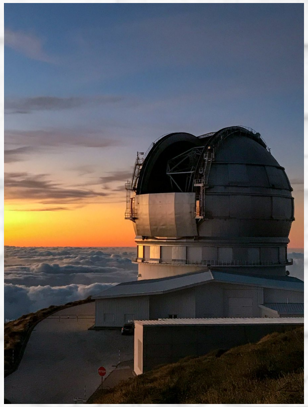
First extragalactic source associated to
Icecube neutrino event

z = ? until 4 feb. 2018



GTC SPECTROSCOPY CAMPAIGN

Motivated by the neutrino detection and
by the high state in the GeV and TeV bands,
in the framework of our observational campaign
of BLLac, we obtained spectroscopic observation
of TXS0506+056 with OSIRIS@GTC (10.4m)



It needs to have optical spectra of
VERY high S/N and high resolution

Table 1. LOG OF THE OBSERVATIONS

Grism	Date	Total exp. time (s)	N
R1000B	23-11-2017	3600	5
	05-12-2017	4200	6
R1000R	02-01-2018	4000	6
	14-01-2018	4000	6
R2500V	14-01-2018	4800	3
	14-01-2018	4800	3
R2500R	15-01-2018	4500	3
	20-01-2018	4800	6
R2500I	10-01-2018	4500	3
	13-01-2018	4500	2
	20-01-2018	4800	6

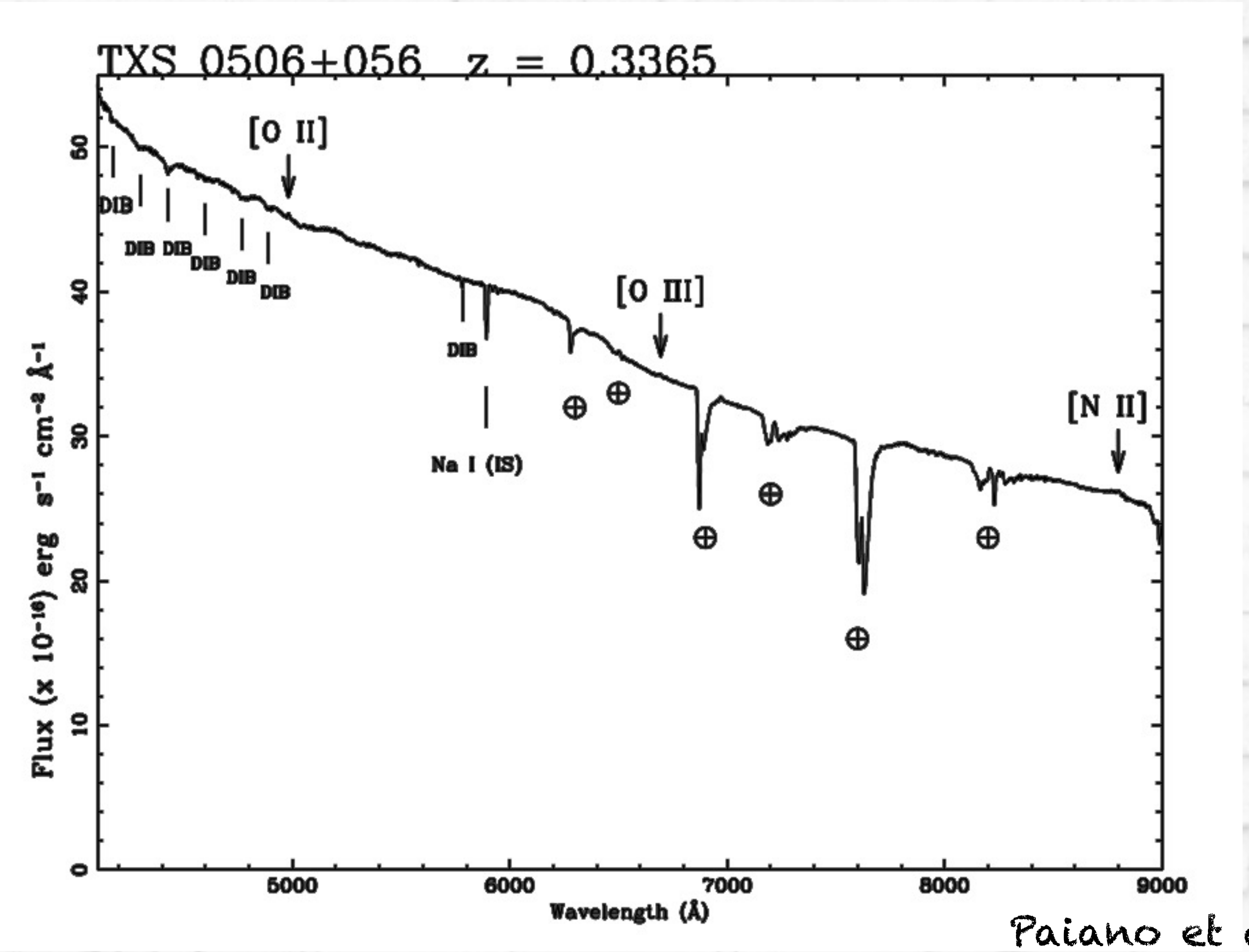
Col.1: Grism name (slit width = 1.0" for R1000 and slit width = 1.2" for R2500); Col.2: Date of the observation, Col.3: Total exposure time, Col.4: Number of individual exposures.

-> 49 individual spectra

-> 5 combined spectra (one for each grism)

-> Each of 5 combinaed spectrum was:
* abs - flux calibrated (g=15.4)
* correct for dereddening
* normalized
(to emphasize the spectral features)
* studied carefully to search to
absorption/emission lines

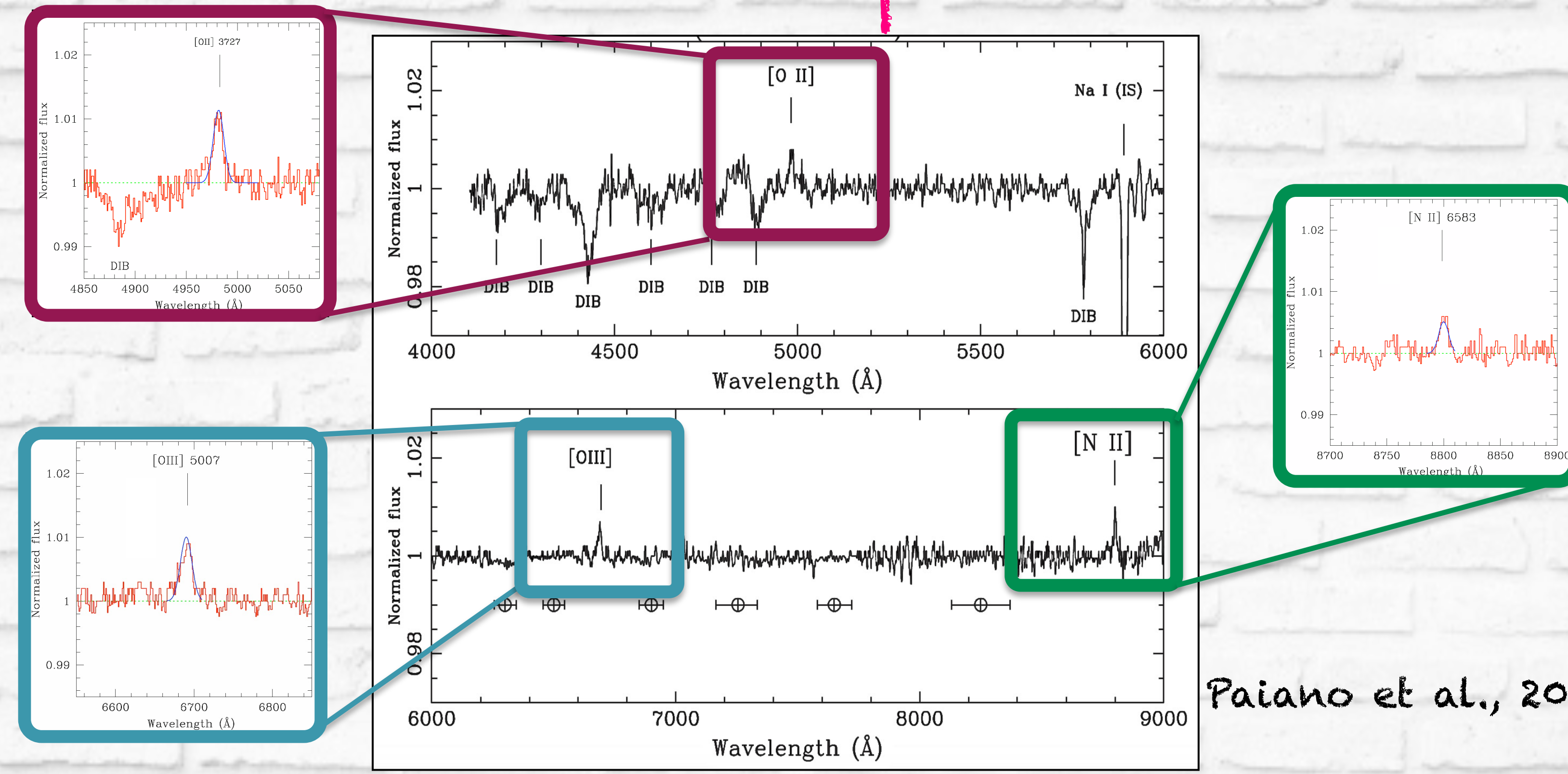
TXS0506+056 spectrum



Paiano et al., 2018

R1000B (4100-7400) + R1000R (5300-9000)
SNR = 600 -1200
Non thermal emission -> PL with slope = -1

TXS0506+056 spectrum



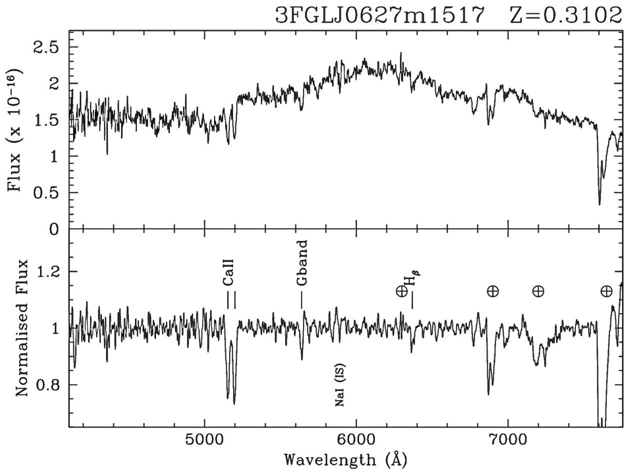
Paiano et al., 2018

We found **three faint and narrow emission lines** at:

- 4981.5 Å identified as [OII] 3727 Å (EW = 0.12 Å),
- 6693.6 Å identified as [OIII] 5007 Å (EW = 0.17 Å),
- 8800.5 Å identified as [NII] 6583 Å (EW = 0.05 Å).

The redshift of this source is: $z = 0.3365 \pm 0.0010$

Spectra of neutrino candidate BLLs

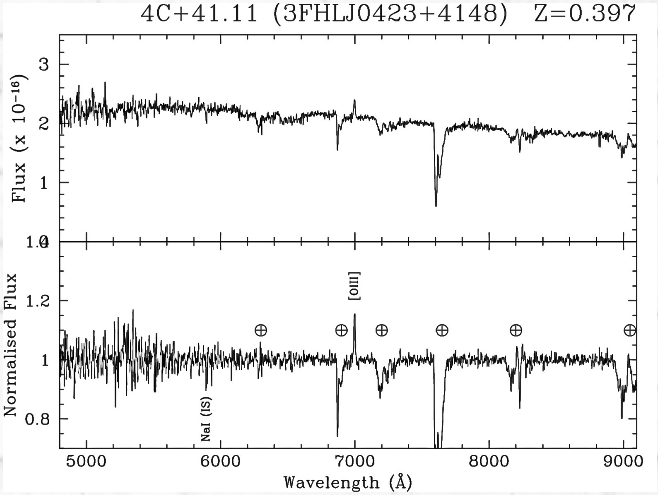


Paiano et al., 2018 - 05 Dec 2018 - Atel#12269

The redshift of 3FGLJ0627.9-1517: a possible counterpart of the Icecube neutrino event IC-170321

$z = 0.3102$

$L_\gamma = 2 \times 10^{46}$ erg/s

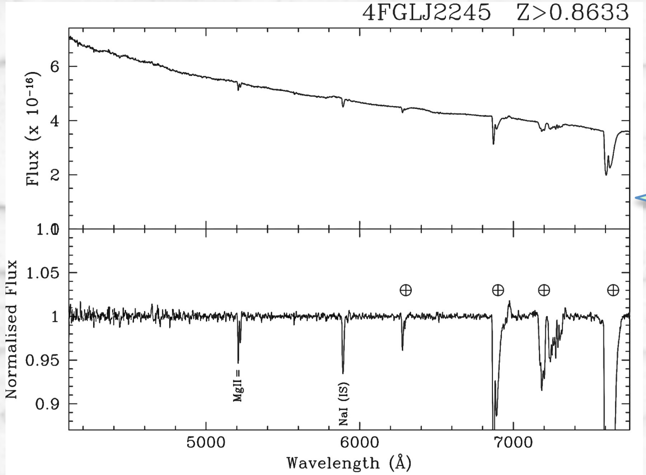


Paiano et al., 2019 - 24 May 2019 - Atel#12802

On the redshift of the BL Lac neutrino candidate 4C+41.11 (3FHLJ0423.8+4149)

$z = 0.397$

$L_\gamma = 1.5 \times 10^{46}$ erg/s



Paiano et al., 2019 - 19 Oct 2019 - Atel#13202

Spectroscopic lower limit to the redshift ($z > 0.863$) of the BL Lac object 4FGL J2255.1+2411, a possible neutrino source

$z > 0.863$

$L_\gamma > 4 \times 10^{46}$ erg/s

SPECTROSCOPY OF HARD FERMI (3FHL) SOURCES

3FHL CATALOG:

1556 sources detected by Fermi at $E > 10$ GeV

246 objects are TeV candidates ($E > 50$ GeV)

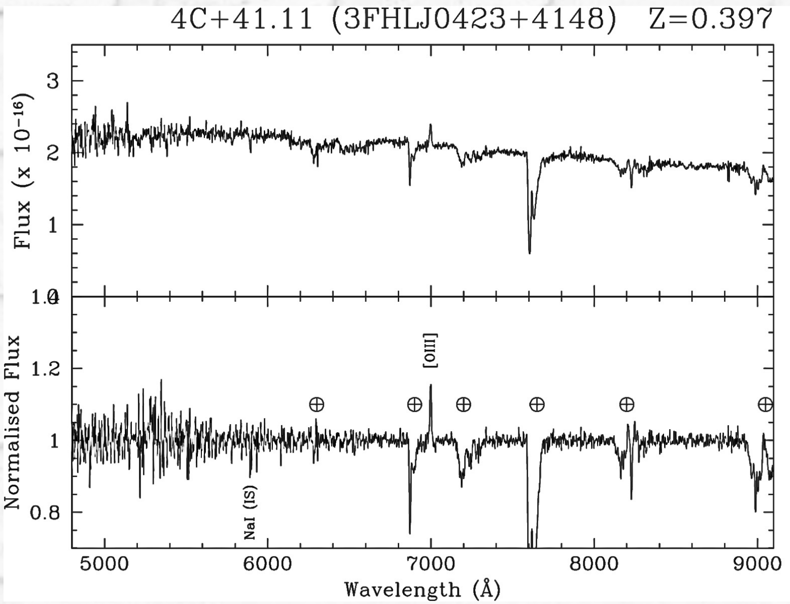
180 BLL (147 with $z = ?$)

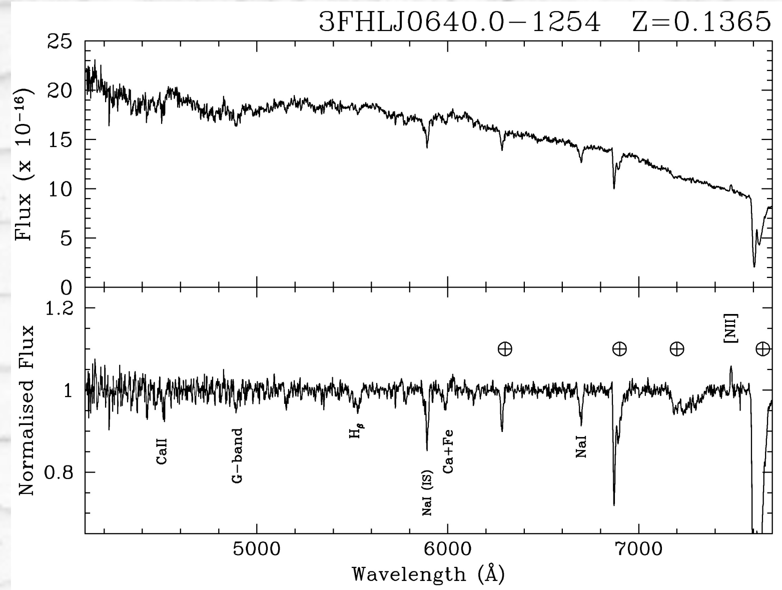
44 BCU (no class & $z = ?$)

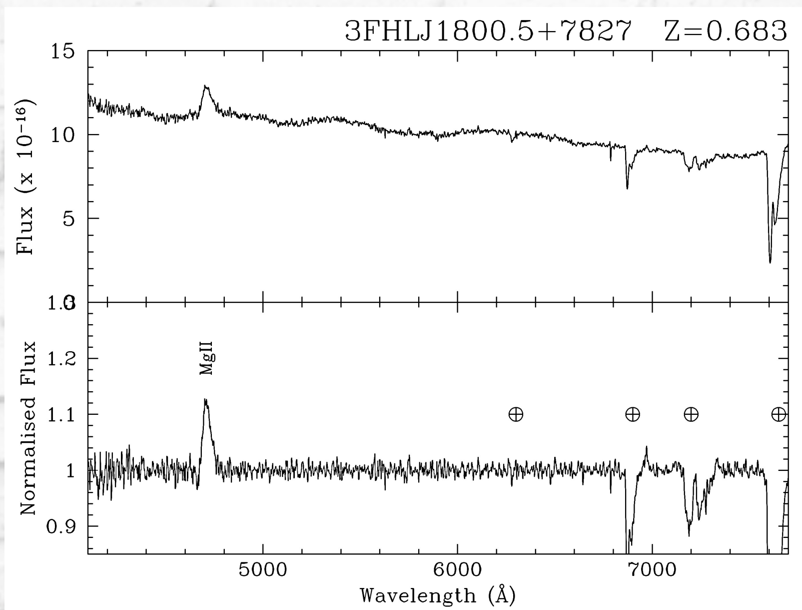
Spectroscopic campaign of a sample of

60 3FHL sources

3FHL SOURCES OBSERVED WITH GTC







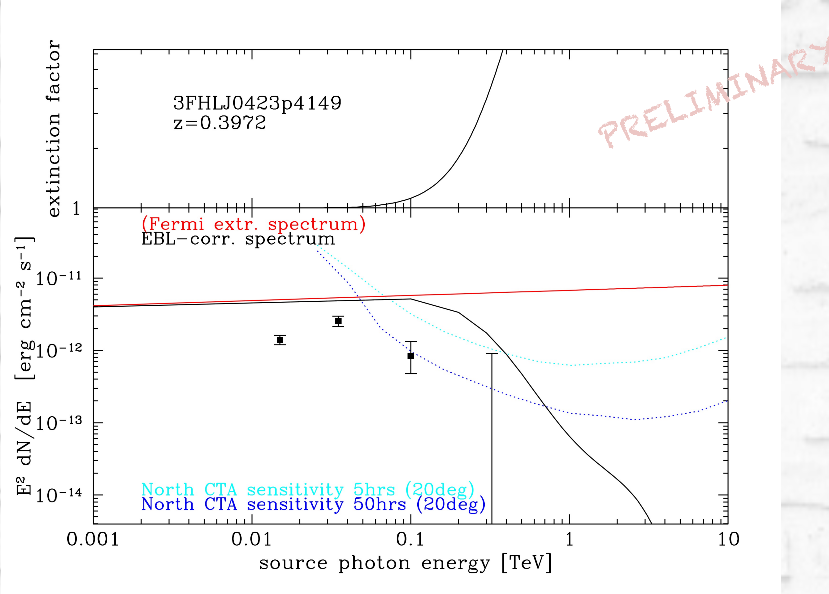
≈ 50% objects exhibit absorption/emission lines in their spectra and we can determine the redshift

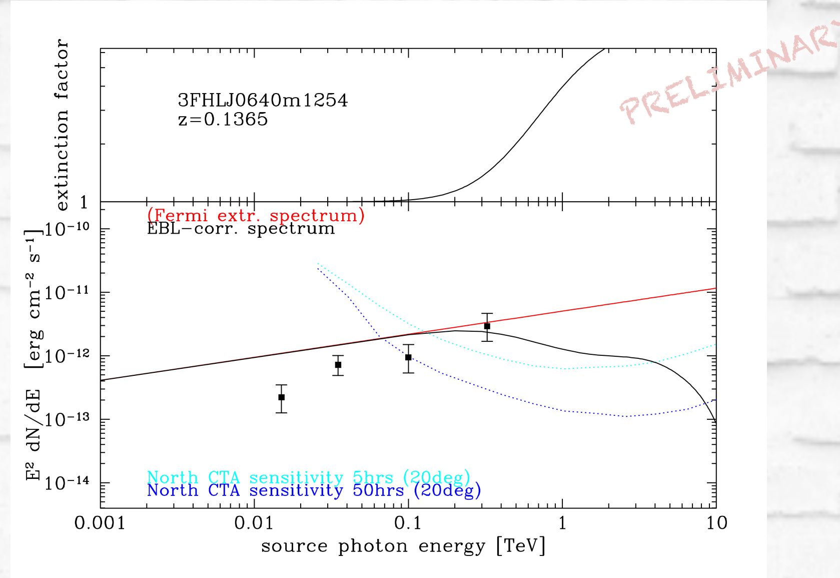
z = 0.05 - >1.1

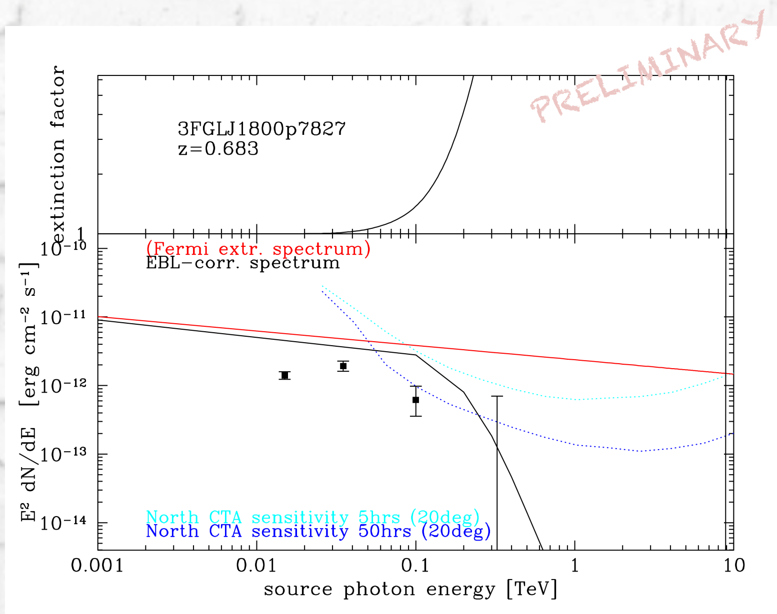
$\langle z \rangle \approx 0.3$

Paiano et al., 2020a, in prep.

3FHL SOURCES OBSERVED WITH CTA







Fermi PL spectrum
extrapolated to VHE
+
EBL absorption as function of z , E
(Franceschini+2017)

≈ 80% (50%)
can be detected with CTA
in 50hs (5hs)

Paiano et al., 2020b, in prep.

(*,*)https://www.cta-observatory.org/science/cta-performance/

SPECTROSCOPY OF UNASSOCIATED γ-RAY SOURCES (UGSs).

On-going spectroscopic campaign of a sample of optical counterparts of UGSs selected using X-ray data covering the 3FGL region and searching for the possible MWL counterparts

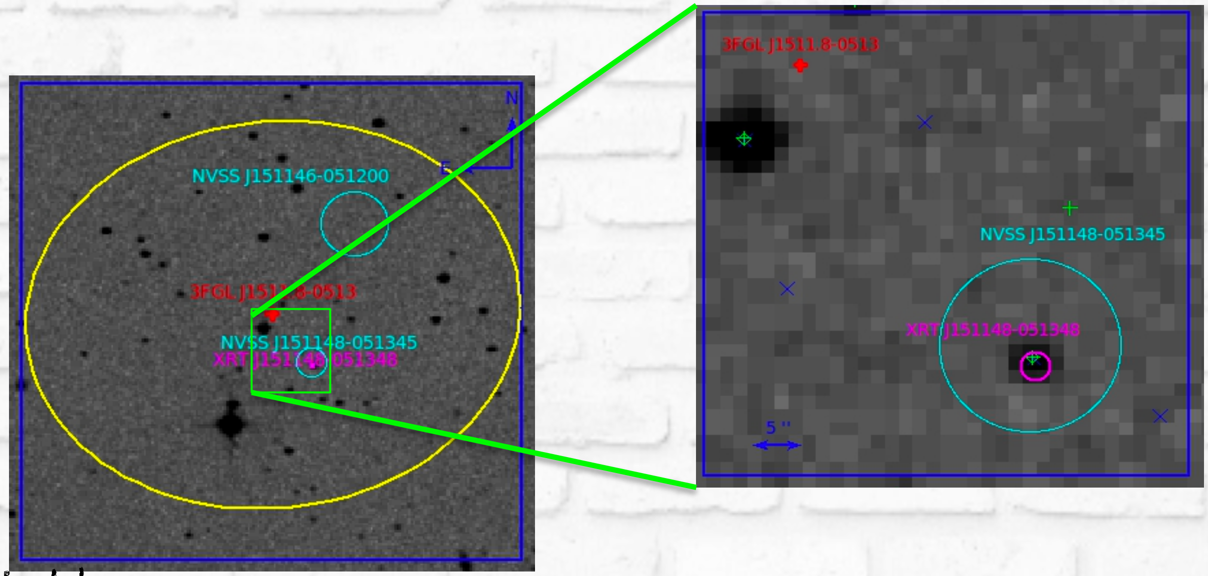
SELECTION CRITERIA:

- Sources are not associated in the 2FGL and 3FGL and other gamma-ray catalogs.
- Target coordinates outside the galactic plane (|b|>20)
- Objects well observable by La Palma
- Presence of at least one X-ray source detected within the UGS error box.
  (two exceptions with only radio counterparts)

180 UGSs observed by Swift -> 60 UGSs with a X-ray detection inside the UGS error box

SPECTROSCOPY OF UNASSOCIATED γ-RAY SOURCES (UGSs).

On-going spectroscopic campaign of a sample of optical counterparts of UGSs selected using X-ray data covering the 3FGL region and searching for the possible MWL counterparts



Adapted by Paiano,Franceschini+2017

180 UGSs observed by Swift -> 60 UGSs with a X-ray detection inside the UGS error box

47 UGS counterparts observed at GTC

SPECTROSCOPY OF UNASSOCIATED γ-RAY SOURCES (UGSs).

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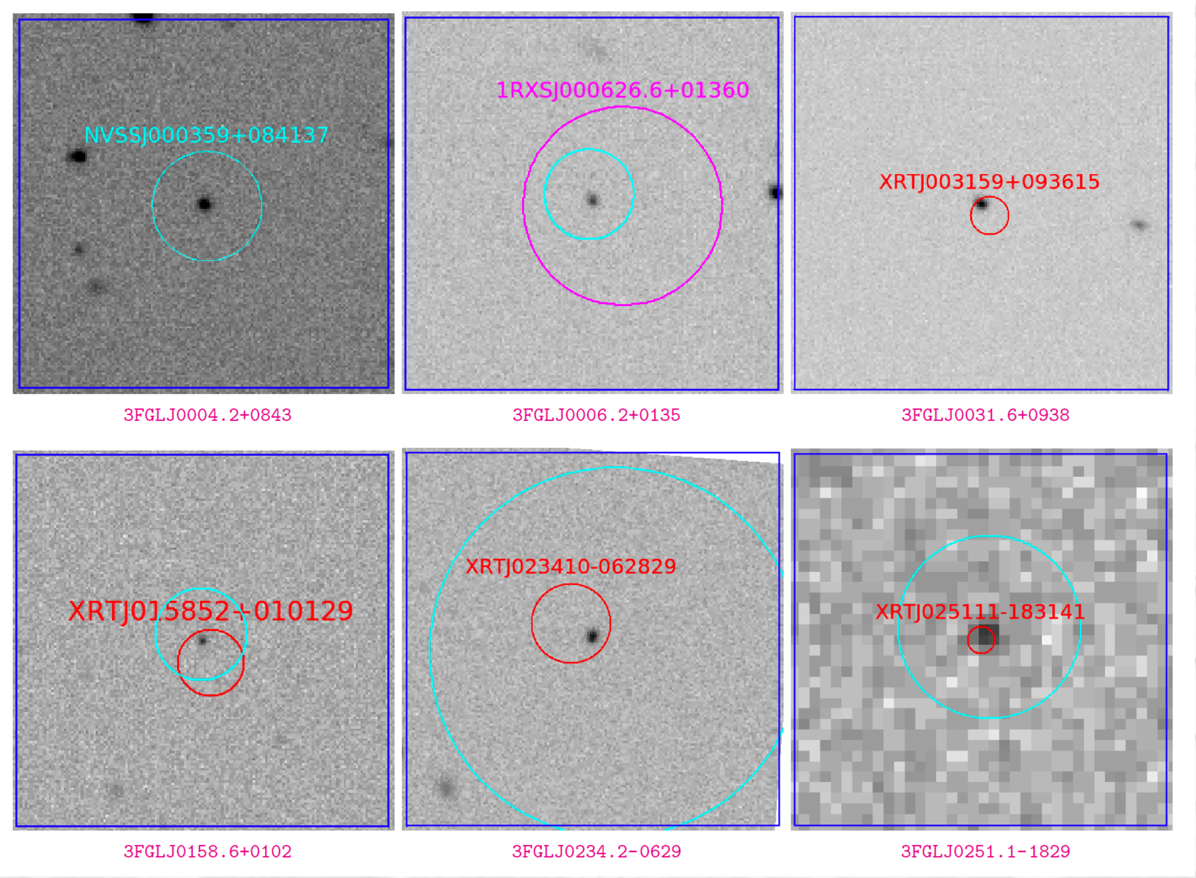
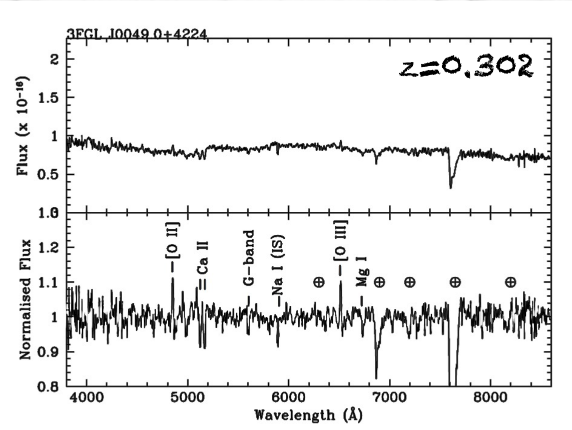
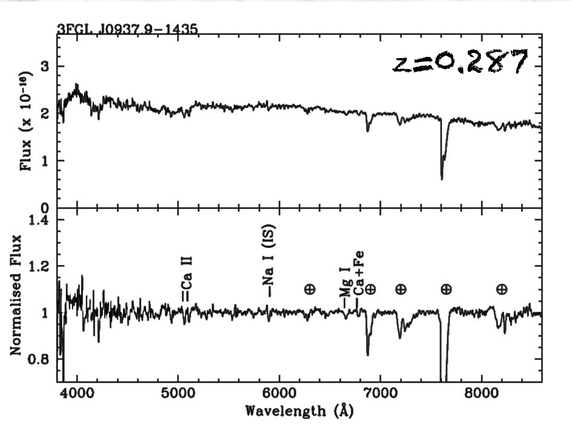


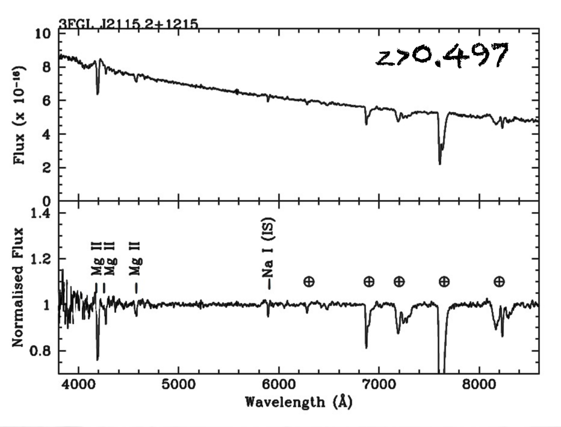
47 UGS counterparts observed at GTC

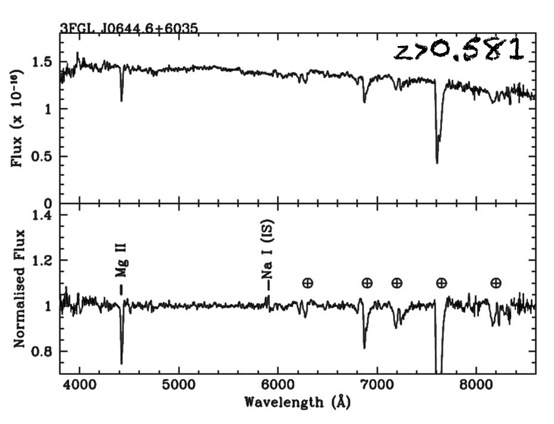
SPECTROSCOPY OF UNASSOCIATED γ-RAY SOURCES (UGSs).

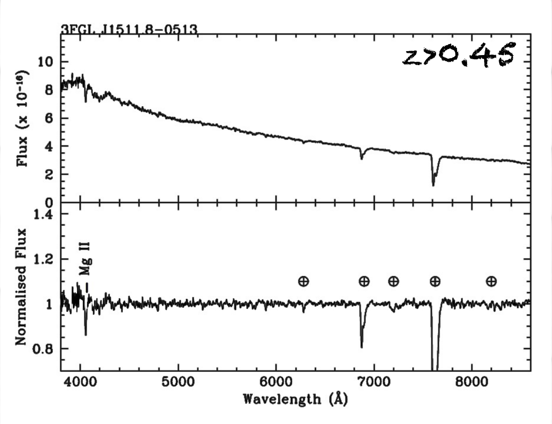
Some examples:

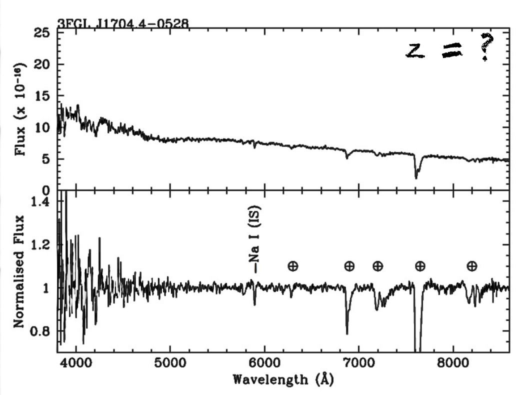










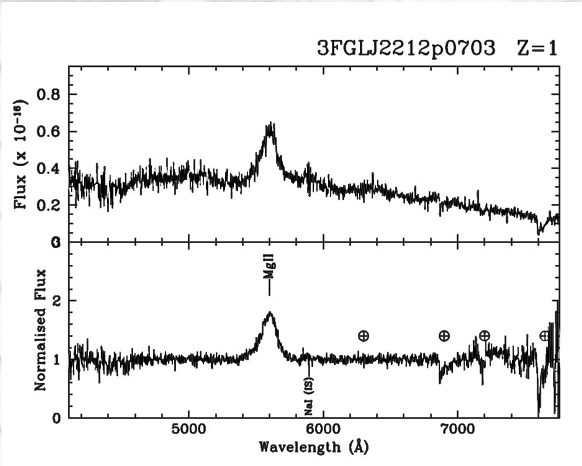


Paiano+2017c

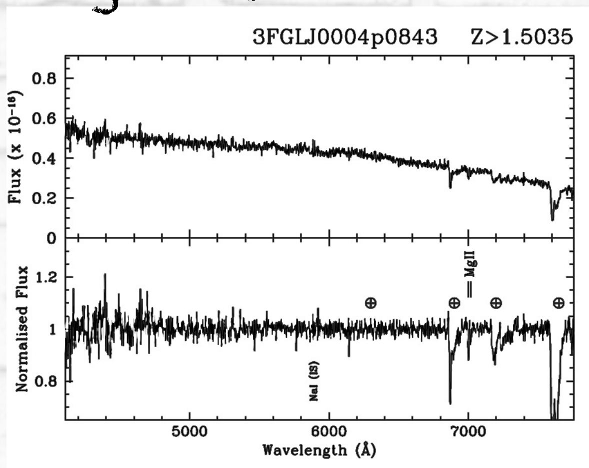
SPECTROSCOPY OF UNASSOCIATED γ-RAY SOURCES (UGSs).

Peculiar cases:

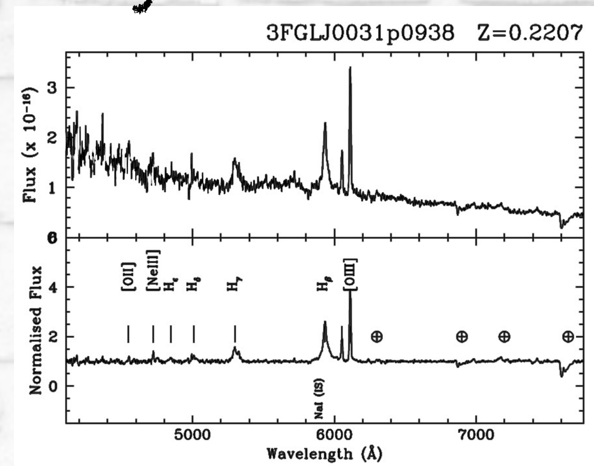
QSO



High-z BLL

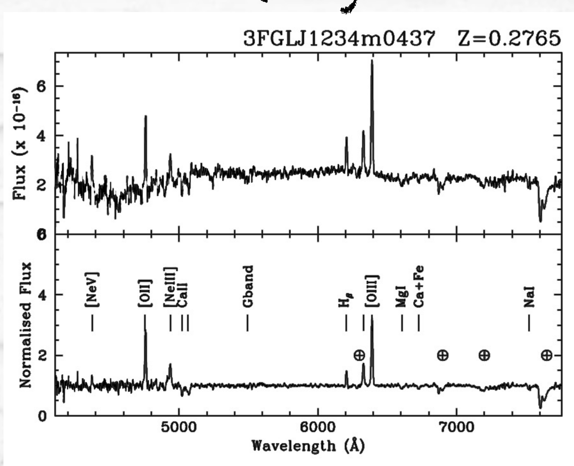


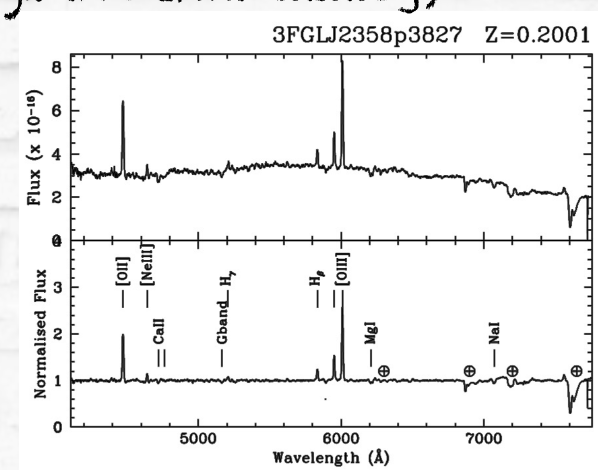
NLSy1



Seyfert 2-Like

(only other two Sy2 in Fermi catalog)





Paiano+2019

CONCLUSIONS

-> High S/N GTC spectra of γ-BLLs allowed us to obtained new redshift or sound lower limits.
Our spectra can be accessed at the website : http://www.oapd.inaf.it/zbllac/

-> Redshift is important and crucial ingredient for several astrophysical topics :

- -> SED modelling and study of intrinsic GeV-TeV spectrum
- -> EBL study
- -> neutrino and photon production
- -> Luminosity Functions (no solid conclusion for BLLs)
- -> Environment study and search for parent populations

-> Redshift of TXS0506+056, the first extragalactic source associated to an extremely high energy neutrino detected by ICECUBE

-> 25% of BLLs at significant high z (>0.5) - (10% with z>1)

-> Spectroscopy of 3FHL-TeV candidate BLLs and UGSs blazar candidates
We confirmed the blazar/AGN nature and for most of them we can derive the redshift

-> Search for BLLs as candidates for CTA observations

LARGE-SIZED TELESCOPE (LST-1) y GRAN TELESCOPIO CANARIAS (GTC) - La Palma / España