The optical view of Extragalactic γ-ray emitters:

Identification, classification and Redshift

Speaker

Simona Paiano – INAF OAPD

Collaborators:

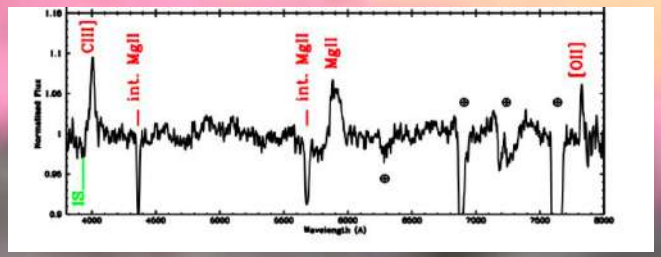
R. Falomo – INAF OAPD

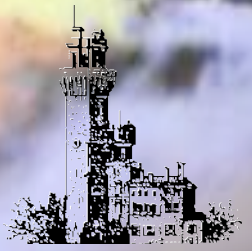
A. Treves – Univ. Insubria

M. Landoni – INAF OABrera

R. Scarpa – IAC/GTC

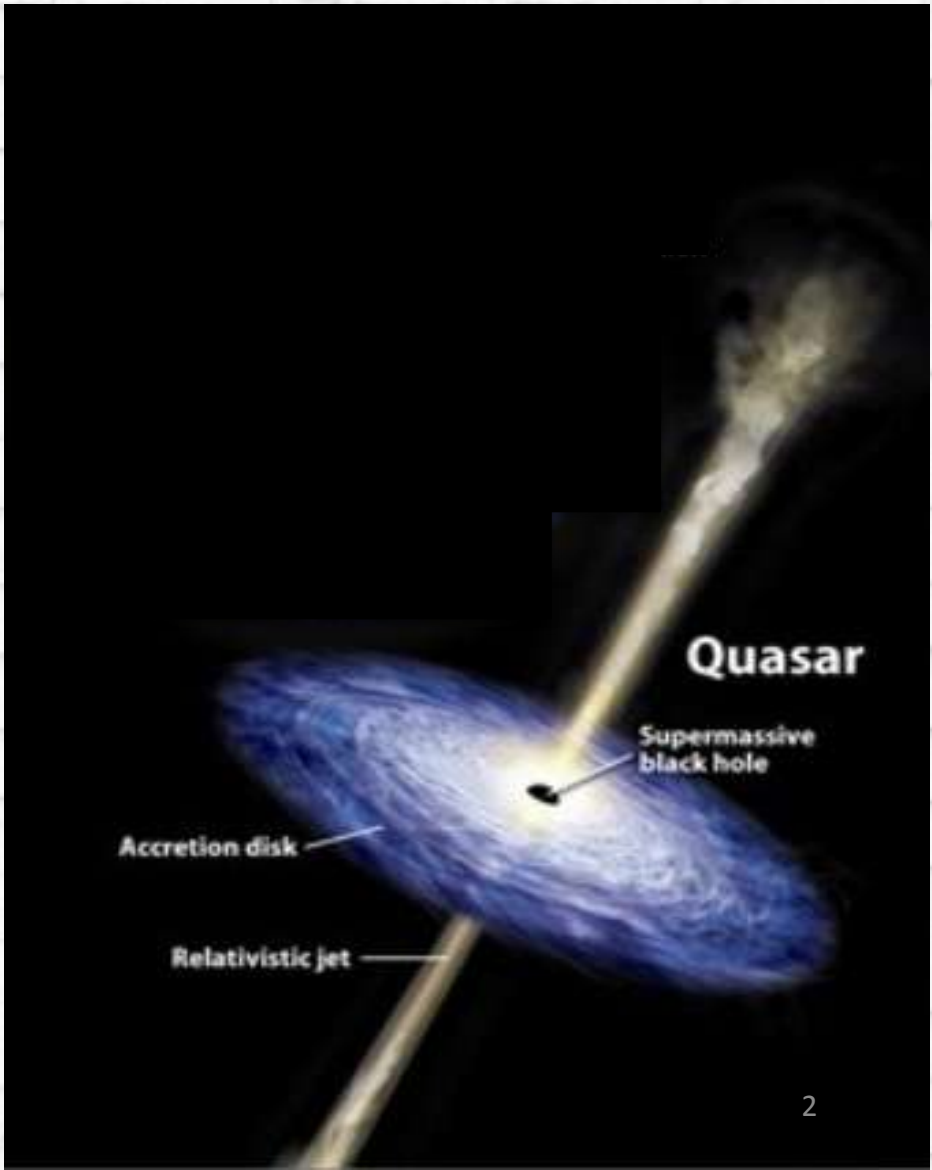
A. Franceschini – UNIPD





BLAZARs

Class of jetted AGNs...



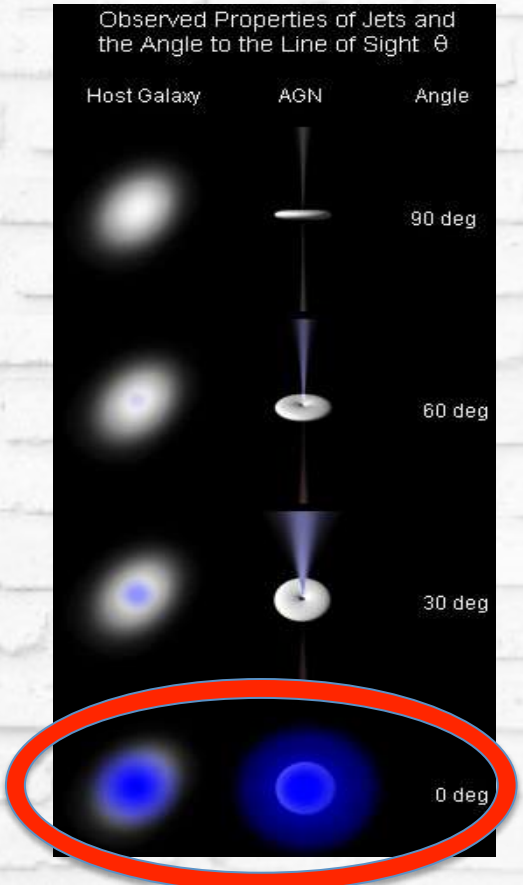
BLAZARs

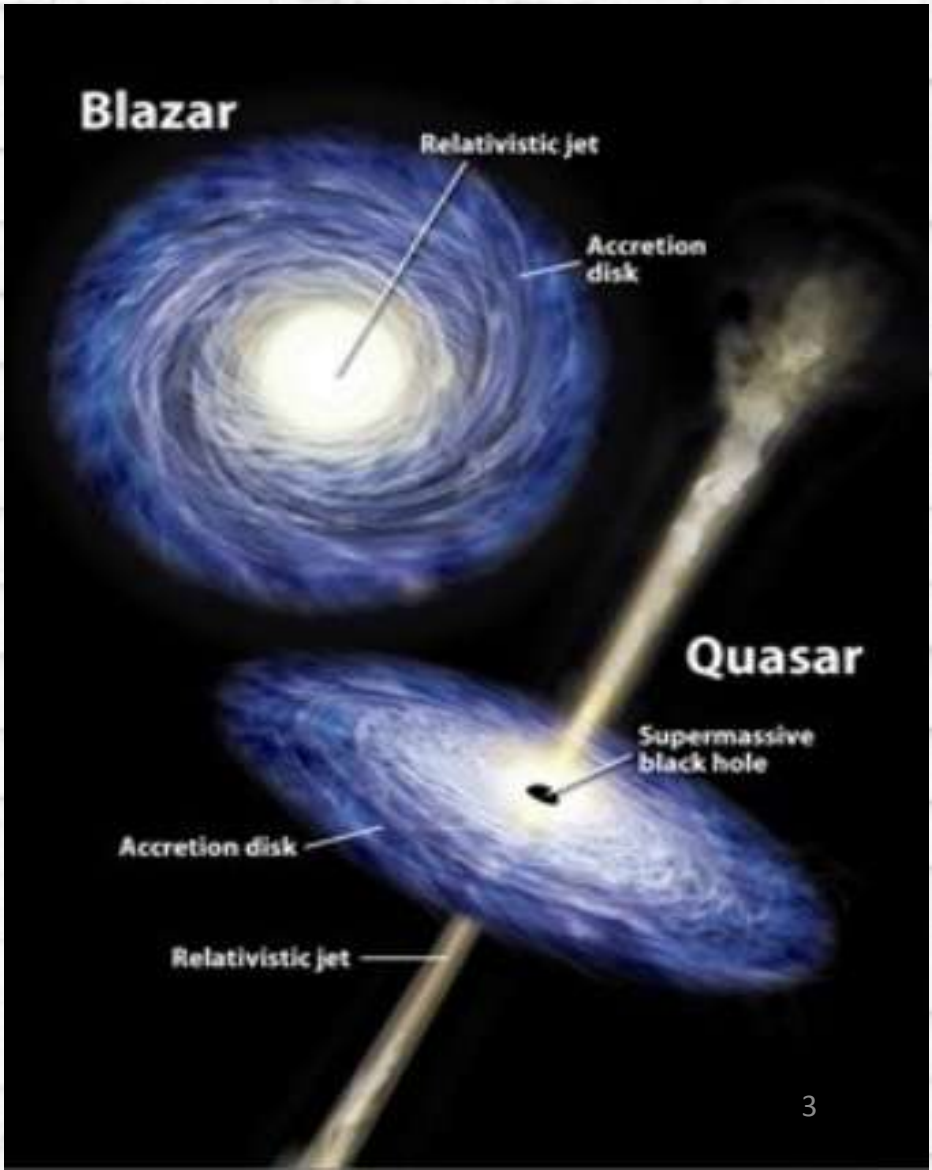
Class of jetted AGNs with jet pointing toward the observer

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

-> Highly polarized;

-> Highly variable in amplitude and at all wavelength.





BLAZARs

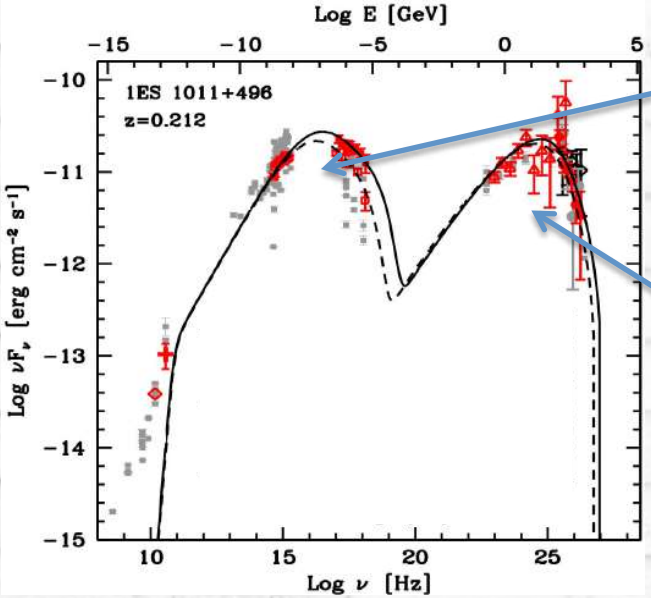
Class of jetted AGNs with jet pointing toward the observer

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

-> Highly polarized;

-> Highly variable in amplitude and at all wavelength.

Typical MWL double-bump SED shape



Synchrotron emission (Radio-> X-ray)

Inverse Compton emission (X-ray -> TeV)

Adapted from Aleksic+2016

BLAZARs

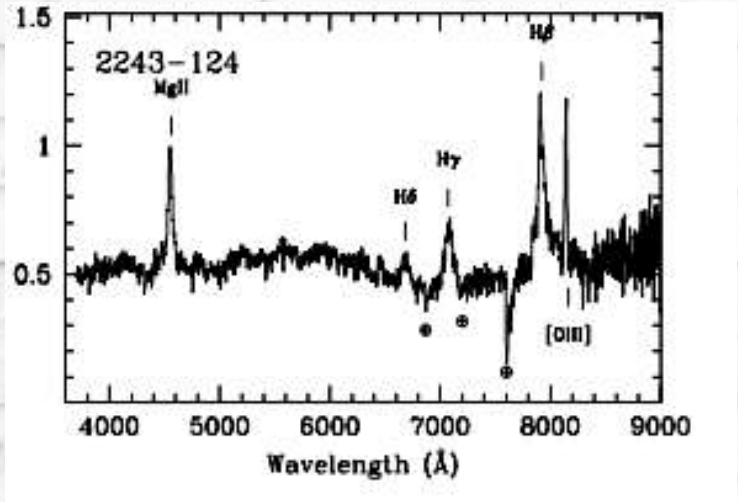
≈ 3500 blazars in the BZCAT (Massaro+2015):

-> 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

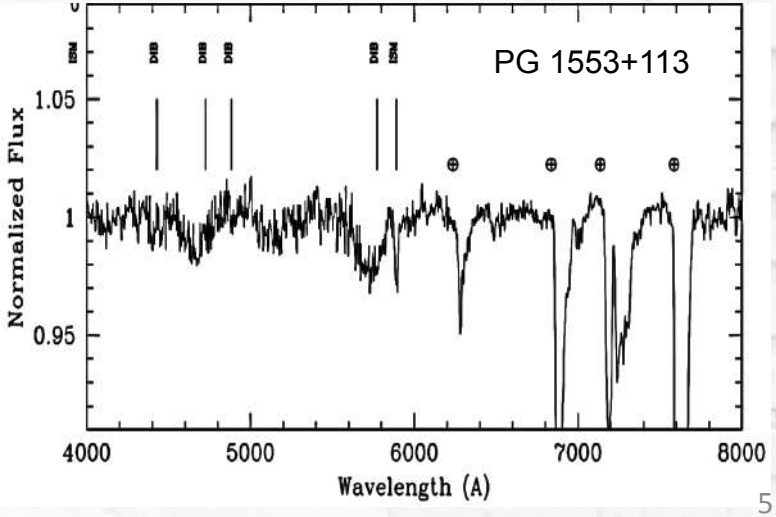
dominated by broad emission lines and thermal blue bump



Scarpa+1998

BLLac objects

emission lines weak or absent



Sbarufatti+2006

BLAZARs

≈ 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

BLLac objects

emission lines weak or absent

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....

3FGL (4FGL) catalog reports 3033 (5525) γ-ray emitters:

-> 40% (50%) are blazars (the most numerous class)
  -> ~ 500 (681) FSRQs
  -> ~ 650 (1102) BLLs
  -> ~ 600 (1155) blazars of uncertain type (BCU)

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

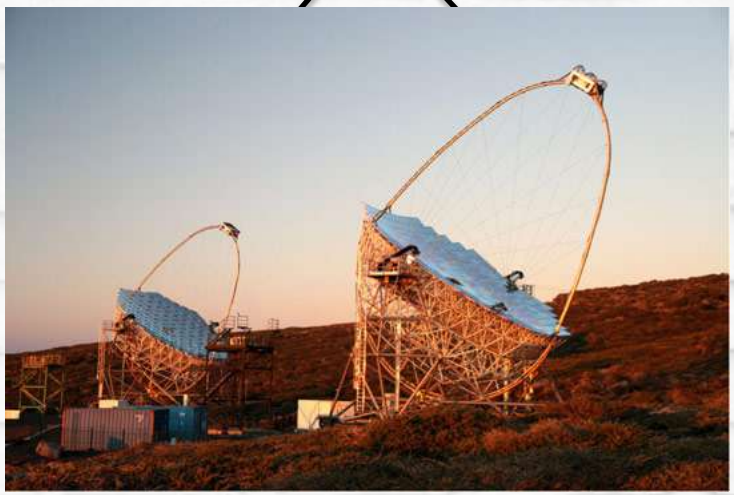
THE TeV BAND & TeV BLAZARS

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:



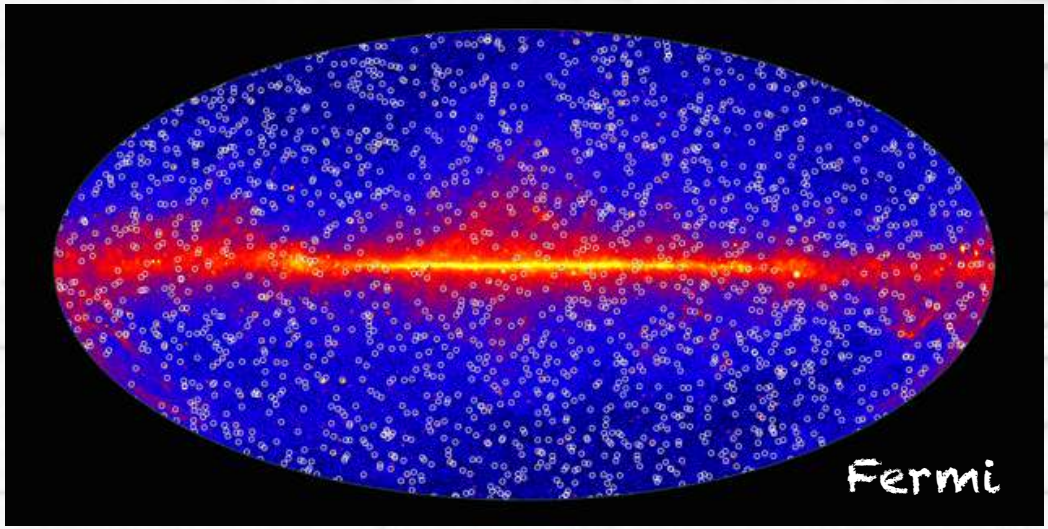
MAGIC telescopes:

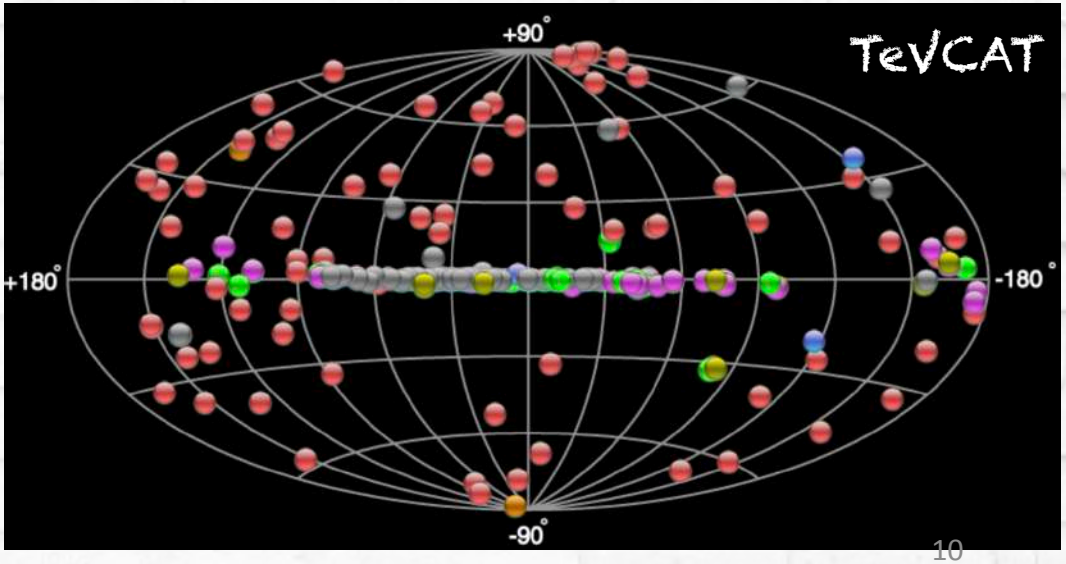
-> 2 x 17m diameter parabolic surface
-> Energy threshold: 50 GeV
-> Energy resolution: 16-17% (>300GeV)
-> Angular resolution < 0.1 (>100GeV)
-> Sensitivity(E>100GeV): 1.5% CU/50hr

THE TeV BAND & TeV BLAZARS

BL Lac objects dominate the extragalactic TeV sky:

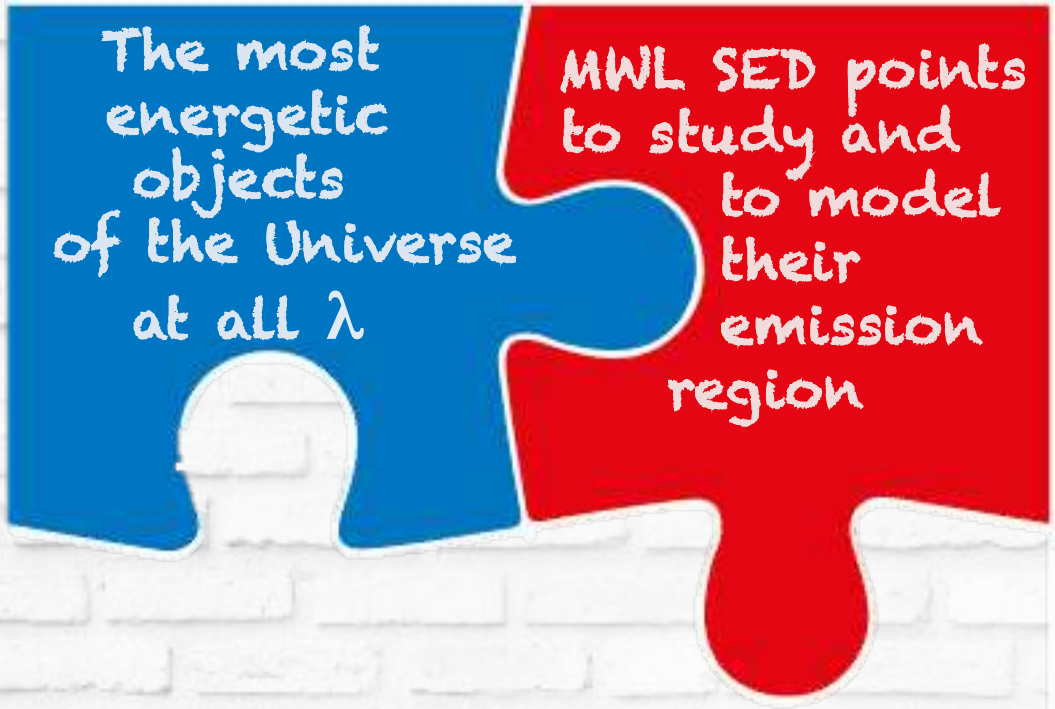
The most energetic objects of the Universe at all λ

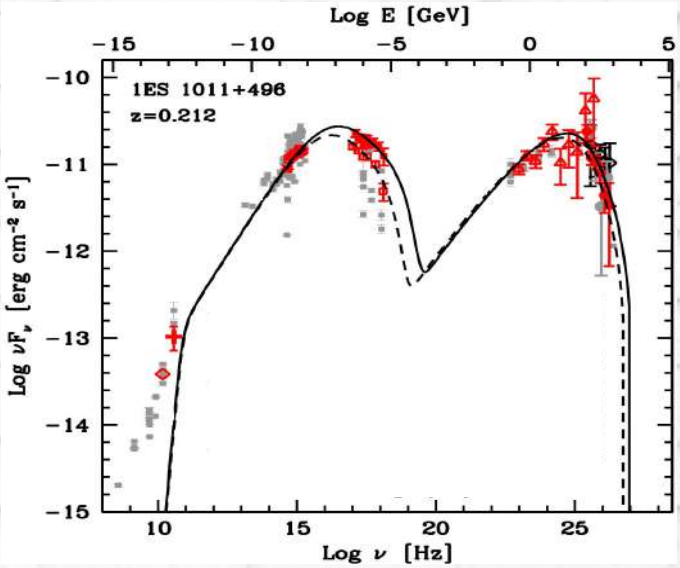




THE TeV BAND & TeV BLAZARS

BL Lac objects dominate the extragalactic TeV sky:



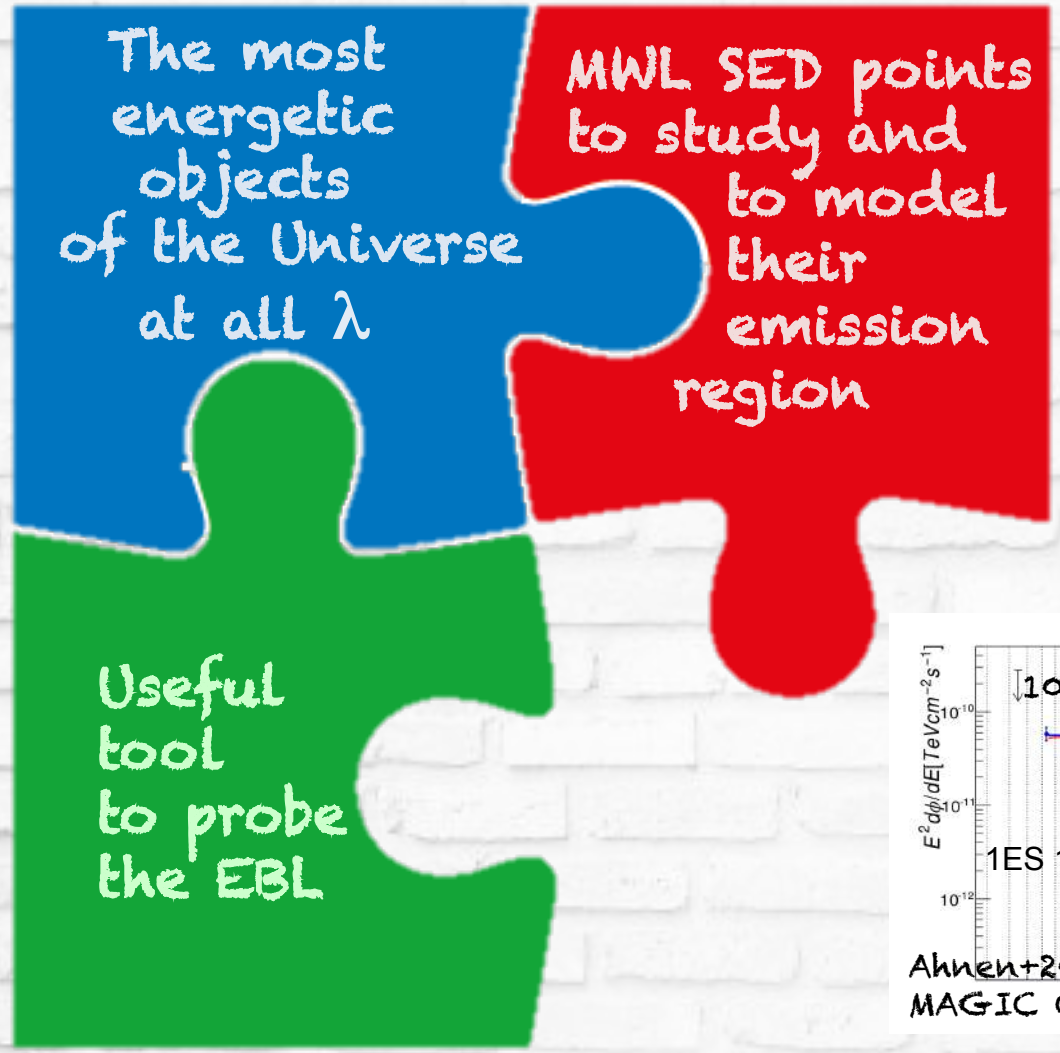


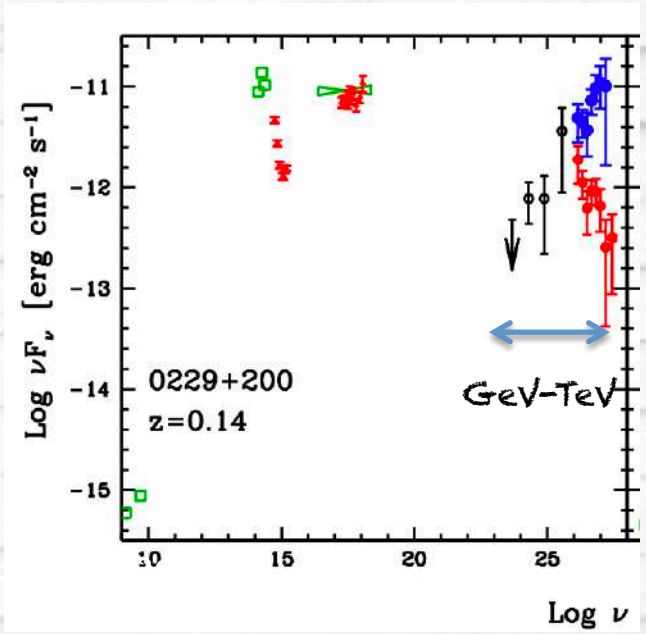
Aleksic+2016

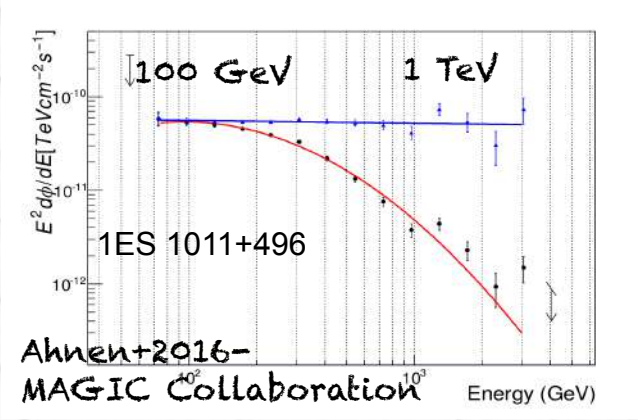
Year	γ_{min} [10^3]	γ_b [10^4]	γ_{max} [10^5]	n_1	n_2	B [G]	K [10^3 cm^{-3}]	R [10^{16} cm]	δ
2007[a]	3.0	5.0	200	2.0	5.0	0.15	20	1.0	20
2008[b]	7.0	3.4	8.0	1.9	3.3 (3.5)	0.048	0.7 (0.8)	3.25	26
2011/2012[I]	10.0	4.0	7.0	2.0	3.7	0.19	10.0	1.0	20
2011/2012[II]	10.0	3.3	4.0	2.0	3.8	0.19	13.4	0.9	20

THE TeV BAND & TeV BLAZARS

BL Lac objects dominate the extragalactic TeV sky:

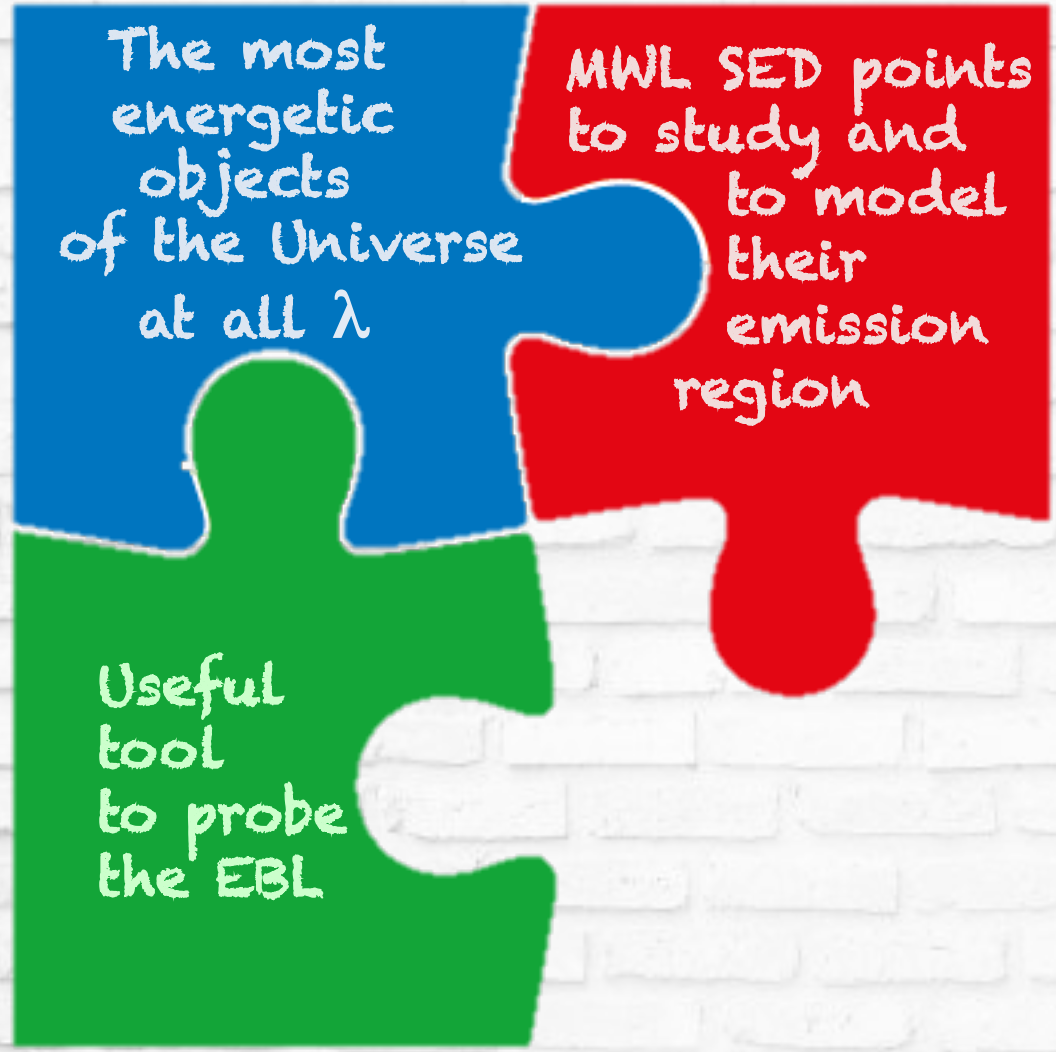






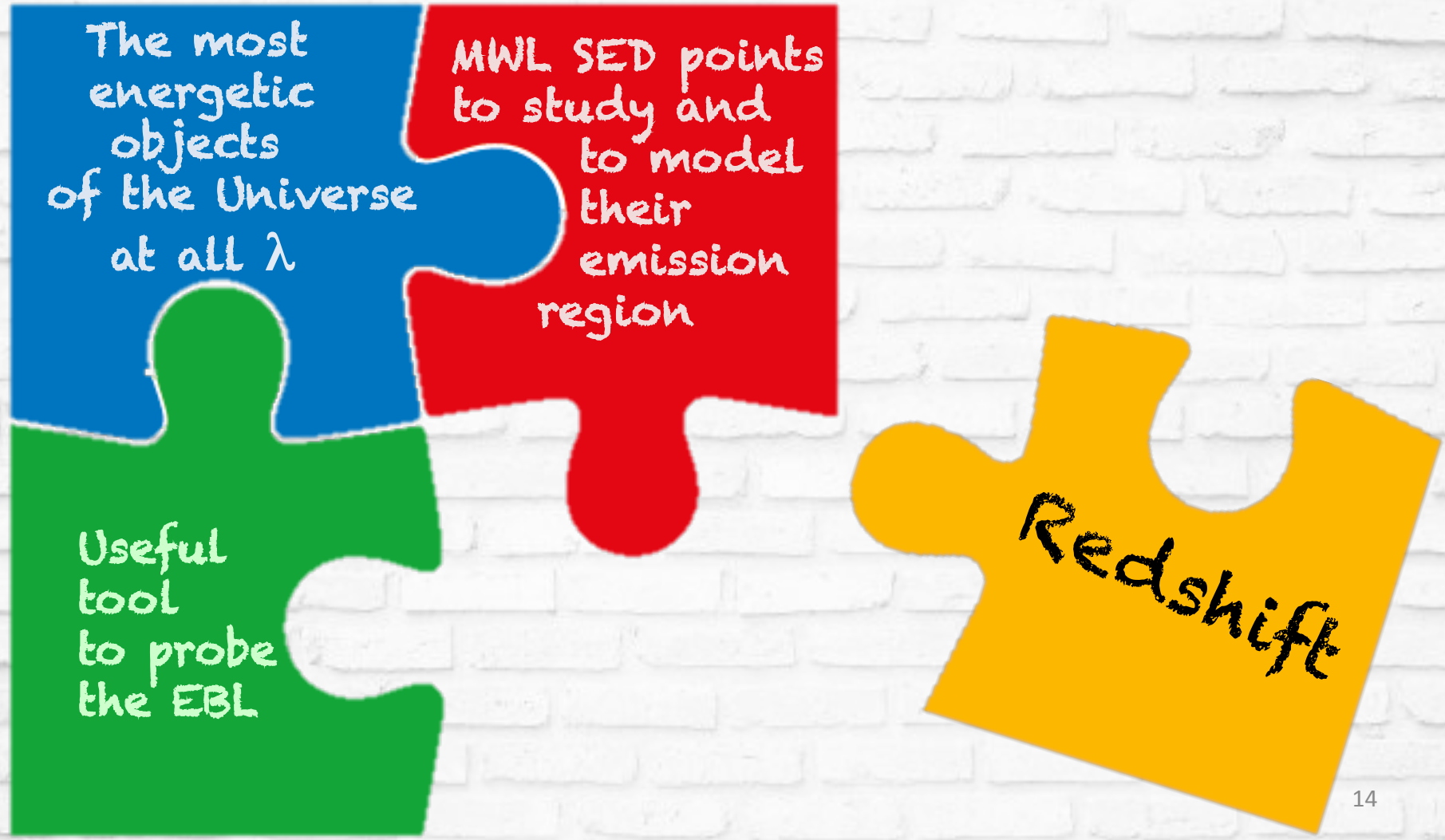
THE TeV BAND & TeV BLAZARS

BL Lac objects dominate the extragalactic TeV sky:



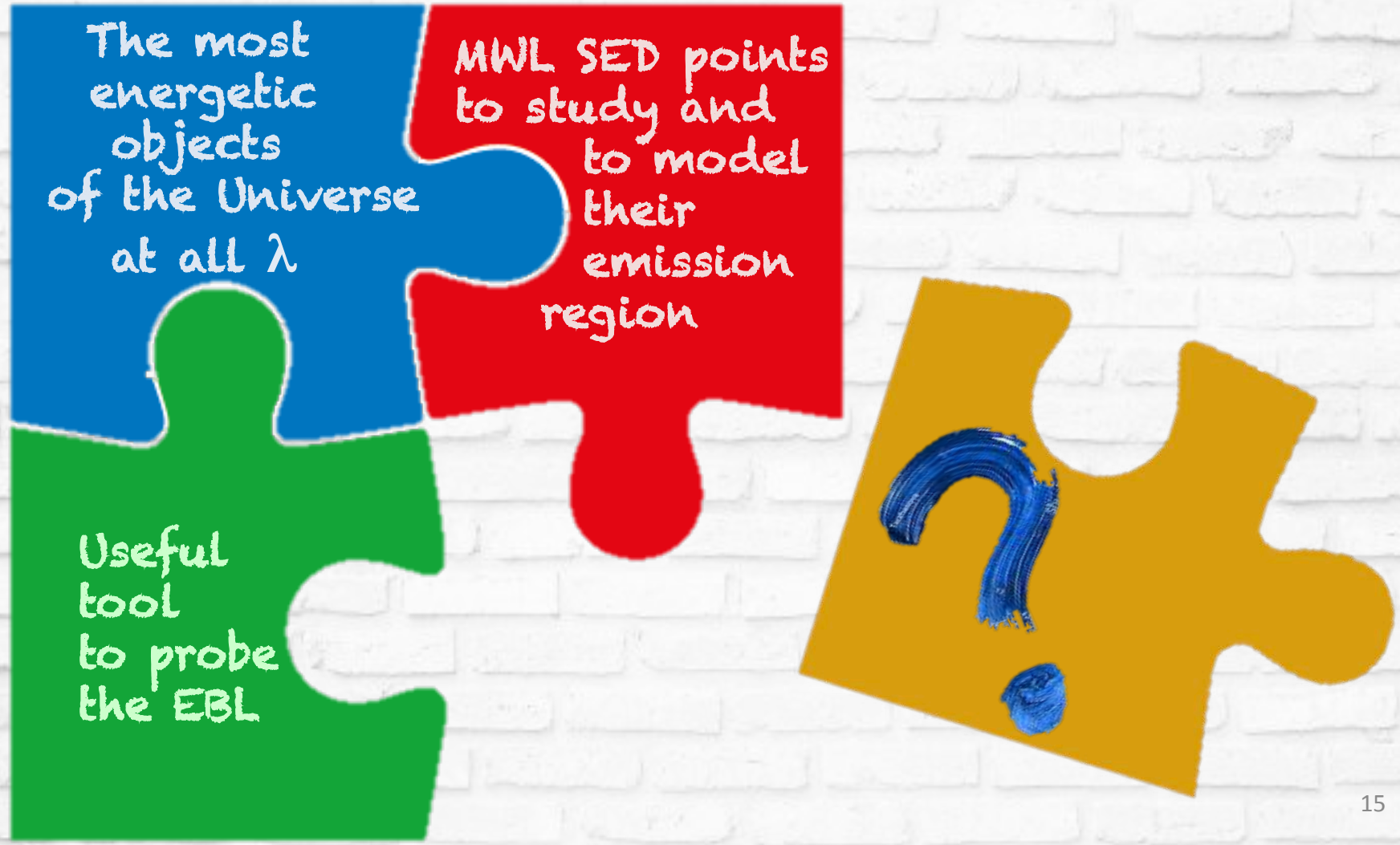
THE TeV BAND & TeV BLAZARS

BL Lac objects dominate the extragalactic TeV sky:



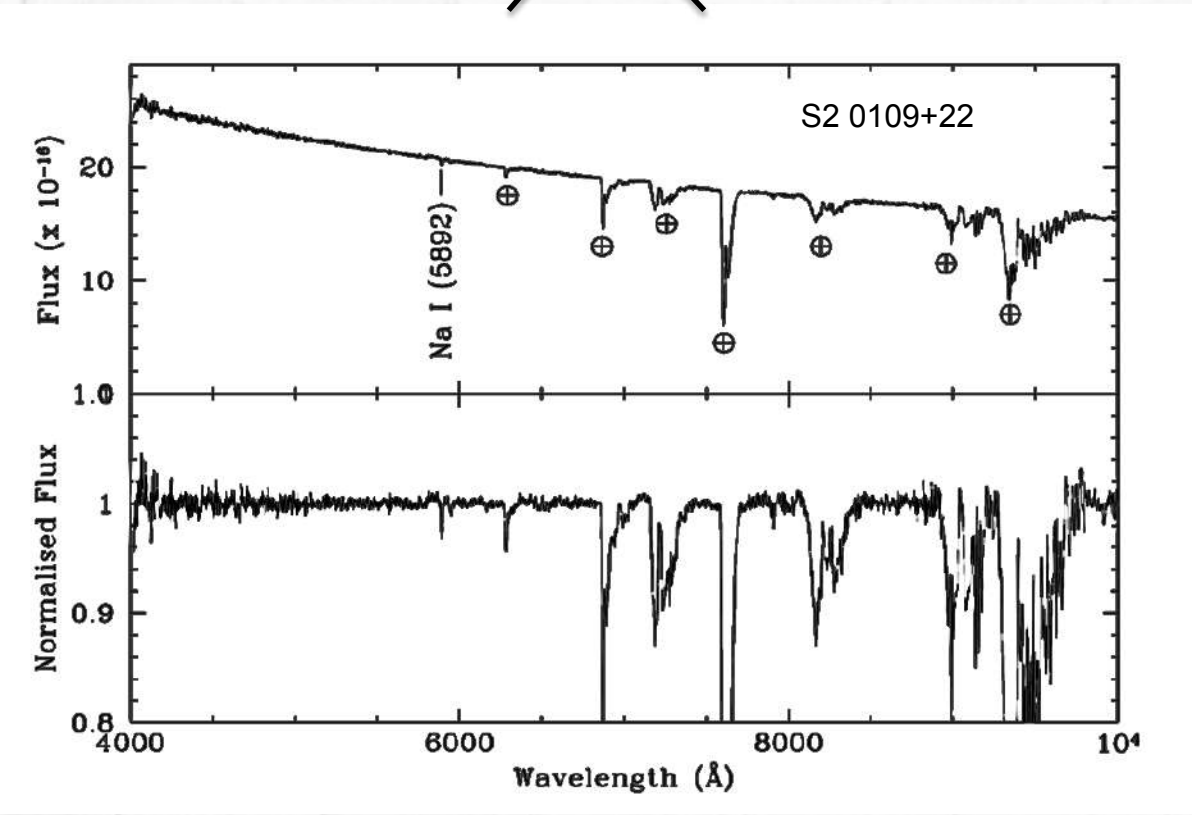
THE TeV BAND & TeV BLAZARS

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 (10m) 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)

-> 20 3FHL blazars with unknown redshift -> Paiano et al. (2019b, in prep)

-> 15 high redshift BLL candidates

-> Paiano et al. (2019c, in prep)

-> 10 neutrino BLL candidates

-> Paiano et al. (2018a),
Paiano et al. (2019b, in prep)

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)

-> 55 Unassociated Fermi Objects
   -> Paiano et al. (2017c),
   Paiano et al. (2019)

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

-> 20 3FHL blazars with unknown redshift
   -> Paiano et al. (2019b, in prep)

-> 15 high redshift BLL candidates
   -> Paiano et al. (2019c, in prep)

-> 10 neutrino BLL candidates
   -> Paiano et al. (2018a),
   Paiano et al. (2019b, in prep)

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

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

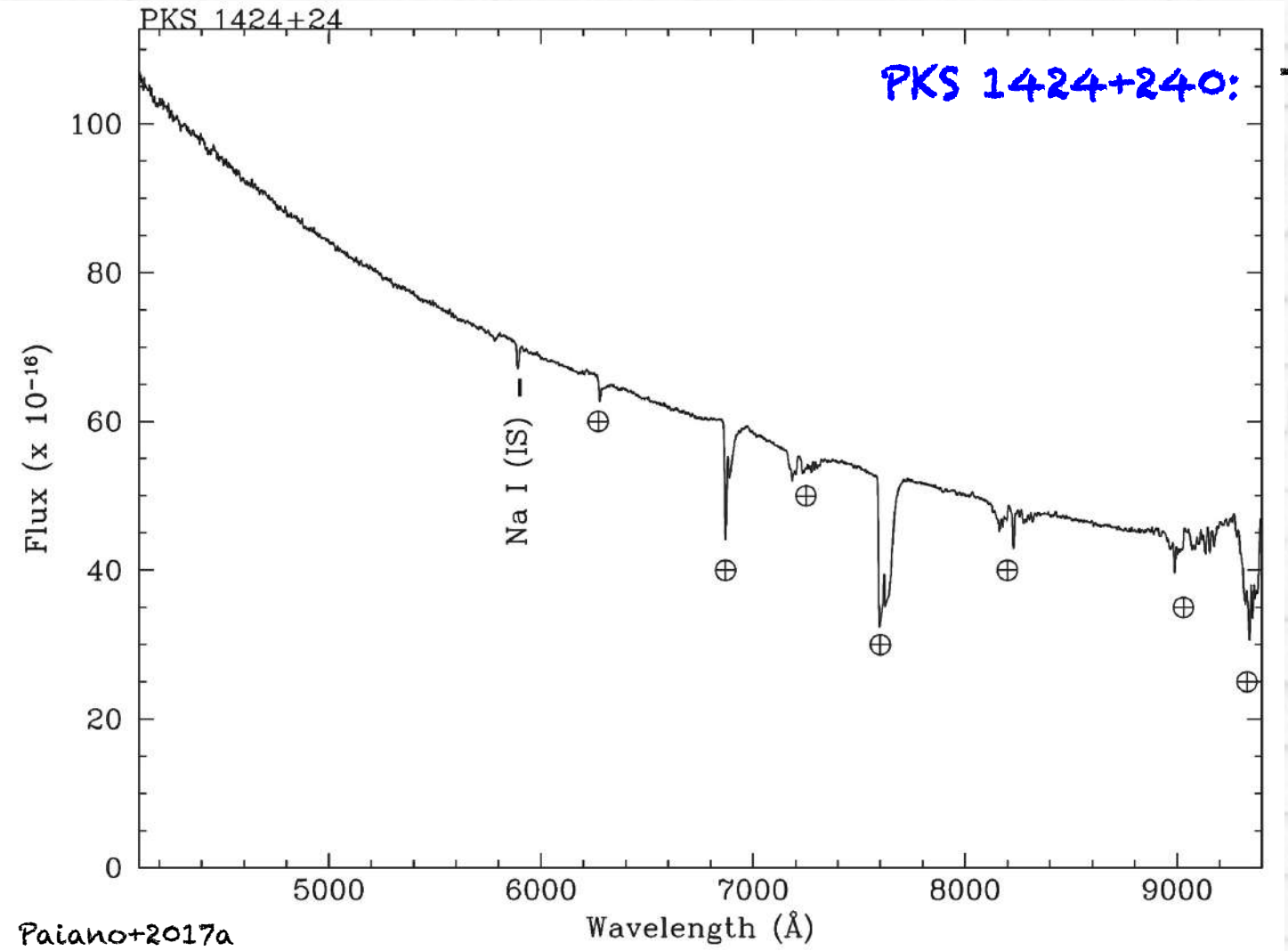
RESULTS

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

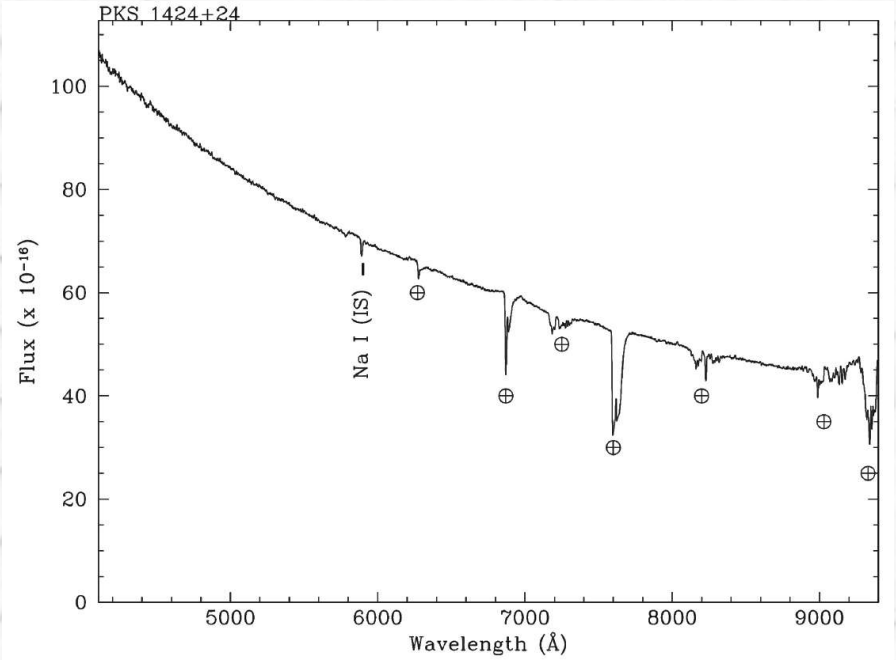


Paiano+2017a

PKS 1424+240: TeV HBL source

RESULTS

Emission lines characteristic of low-density gas



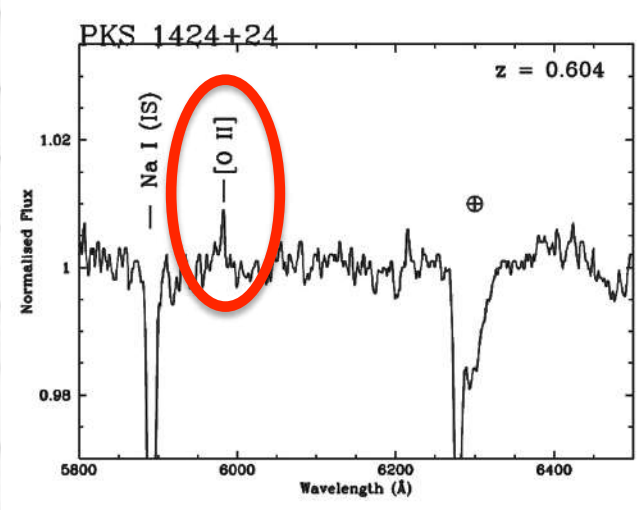
Paiano+2017a

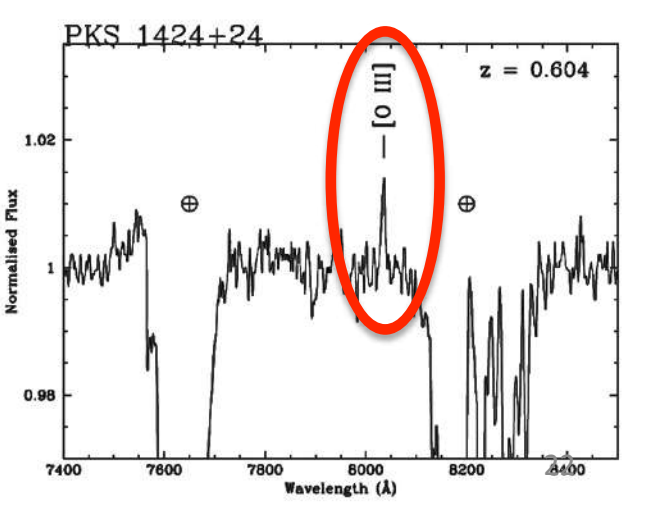
PKS 1424+240: TeV HBL source

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

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

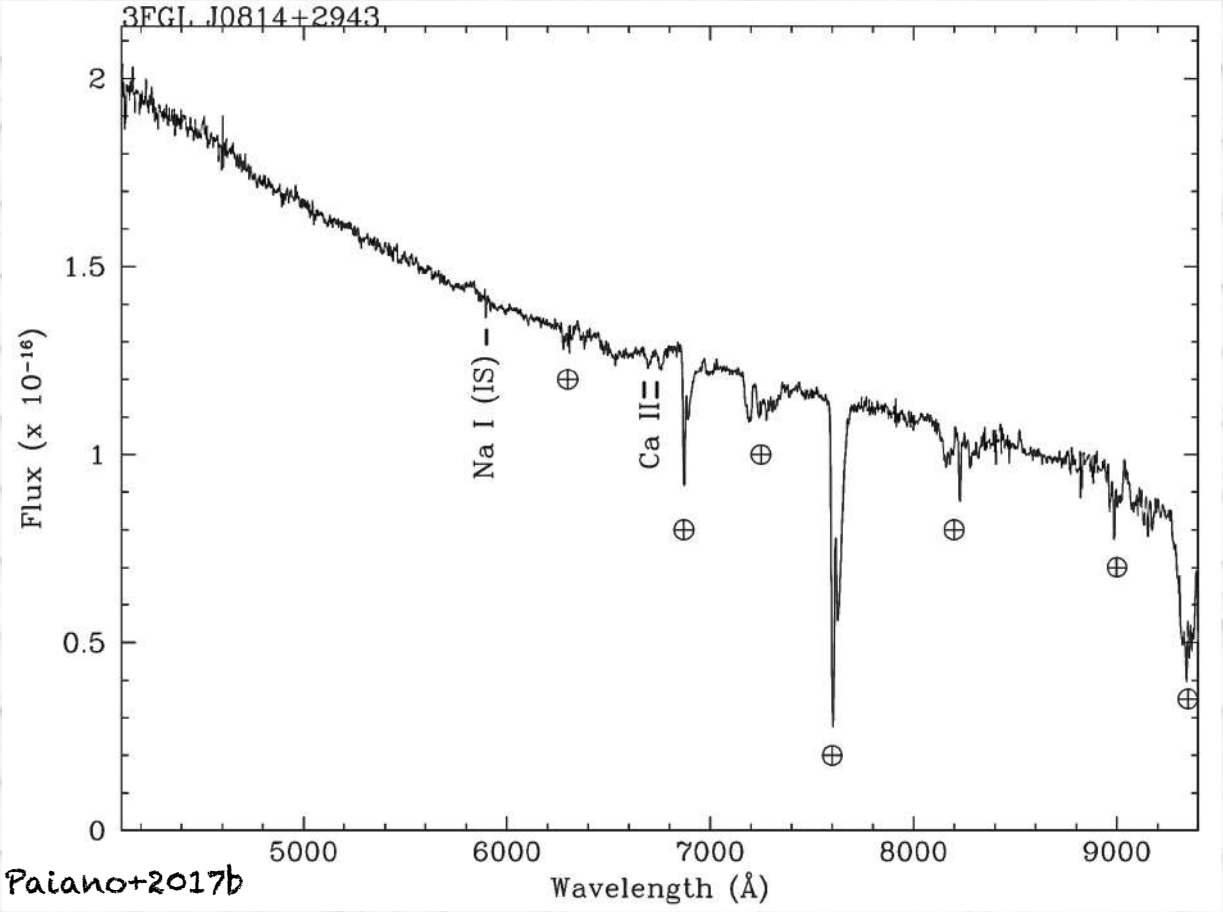
z = 0.604





RESULTS

Absorption lines of stars from the host galaxy



Paiano+2017b

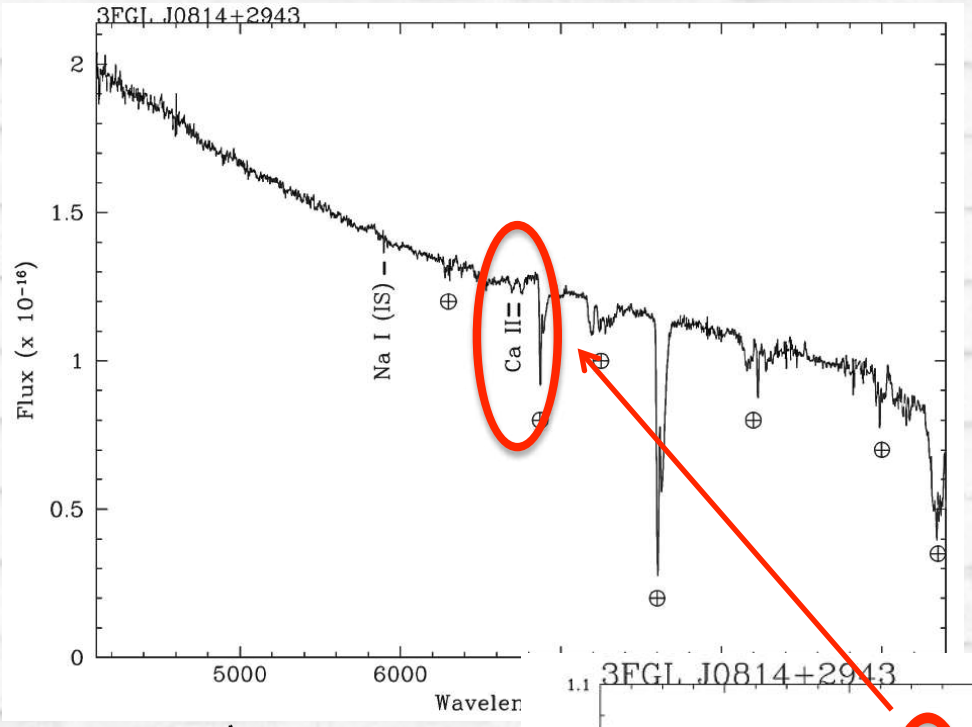
3FGLJ0814+2943

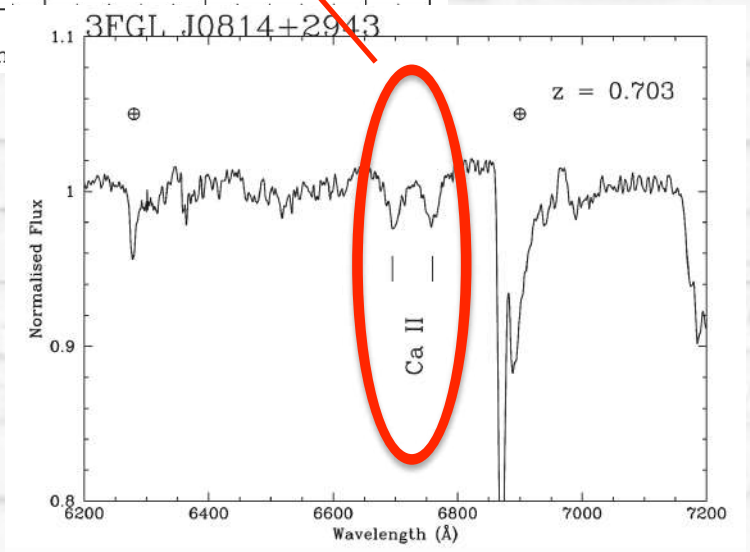
High-z BLL of 3FGL

(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~~)

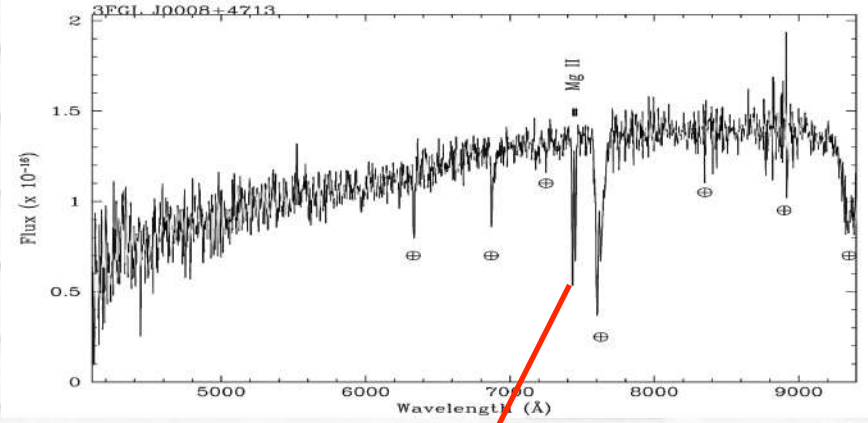
CaII(3934) -> EW = 0.6A

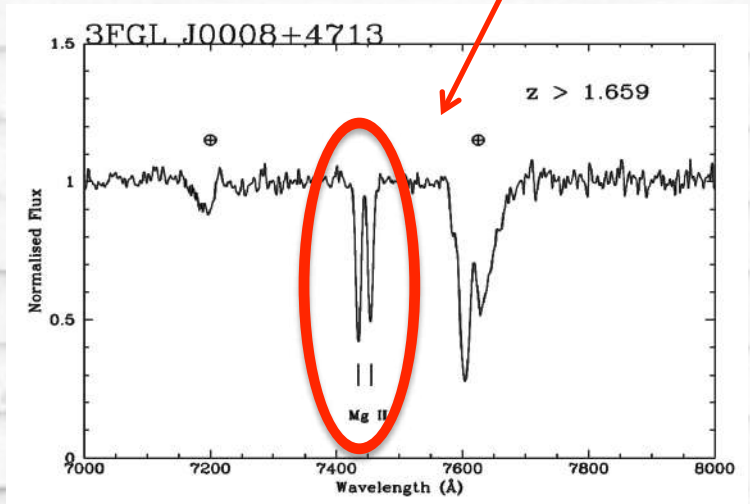
CaII(3968) -> EW = 0.5A

z = 0.703

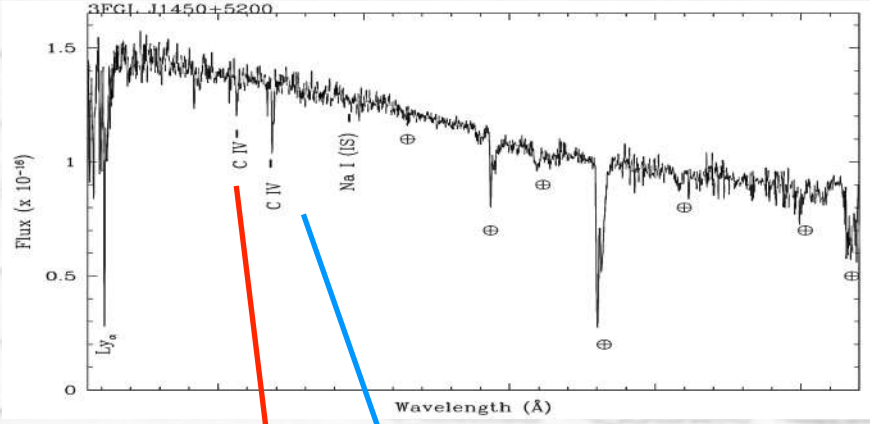
RESULTS

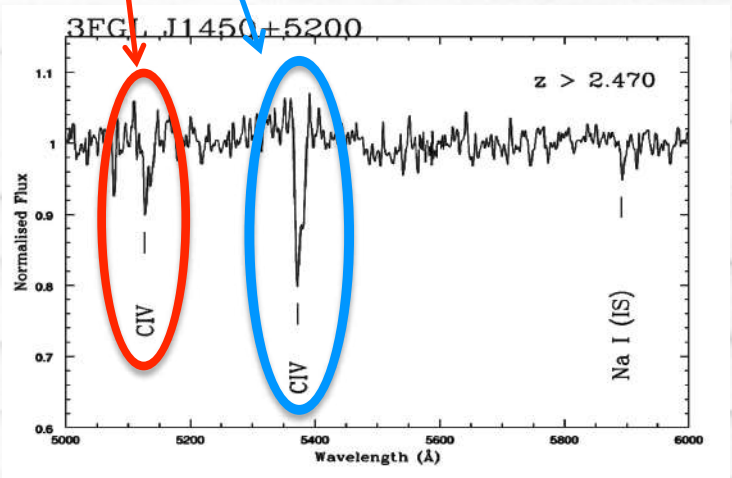
Intervening absorption lines from cold gas -> Redshift Lower Limits





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



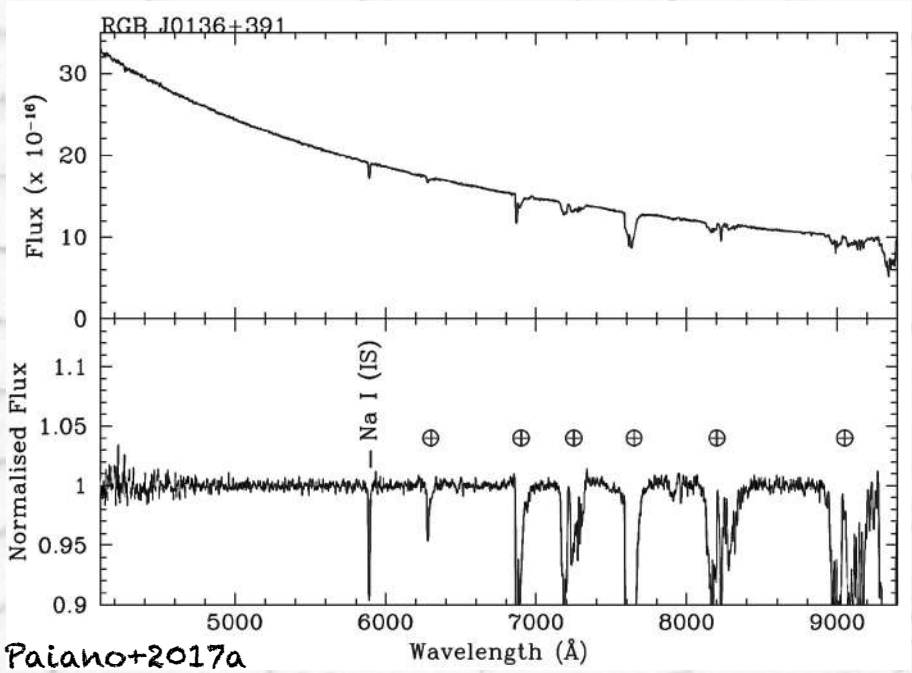


3FGLJ1450+5200
High-z BLL of 3FGL
z > 2.470 <-
z > 2.312 <-
CIV (1548) - Ly-α(1216)
CIV (1548)

Two of the farthest BLLs known!!!

RESULTS

Featureless spectrum



Paiano+2017a

RGB J0136+391

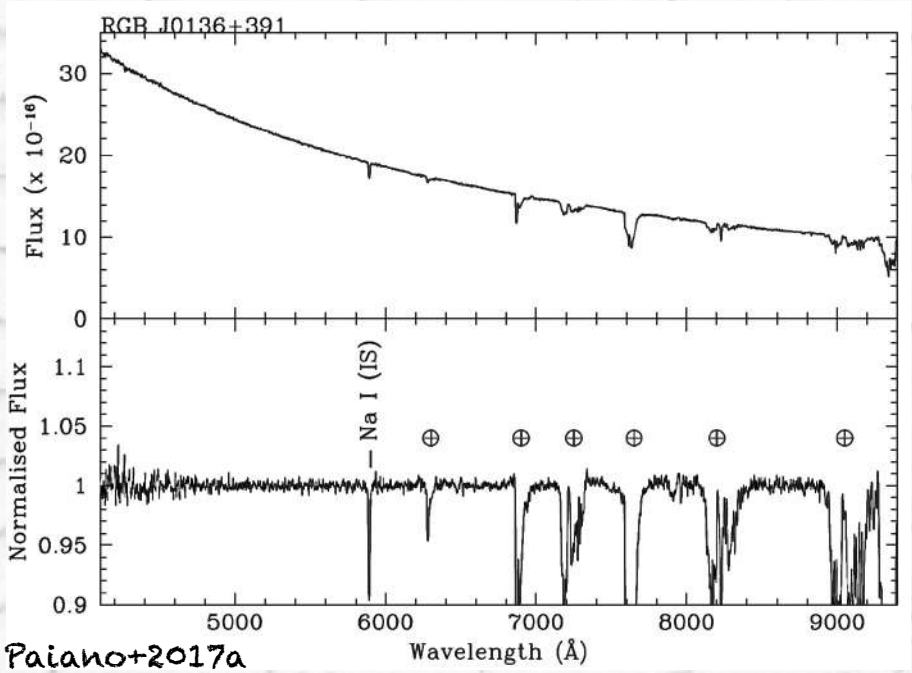
TeV HBL

S/N = 500

r = 15.80

RESULTS

Featureless spectrum

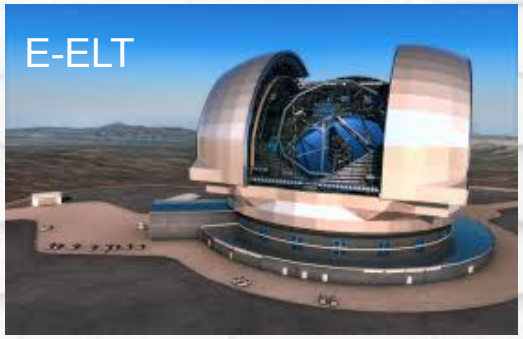


Paiano+2017a

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

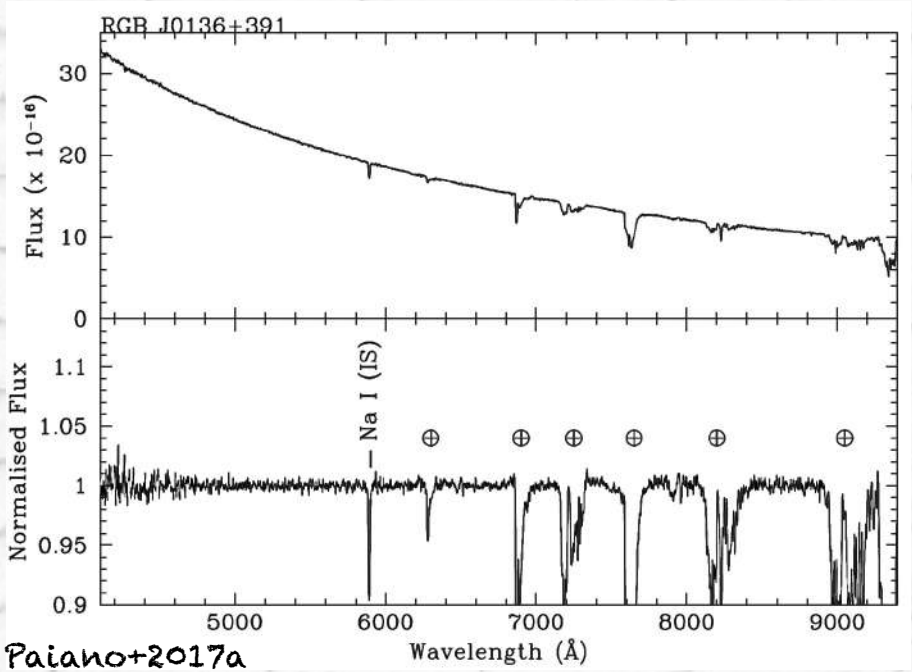
Despite the very high S/N, no absorption/emission lines are detected

Redshift measurement likely possible only with future facilities as ELT



RESULTS: Lower limit of the redshift

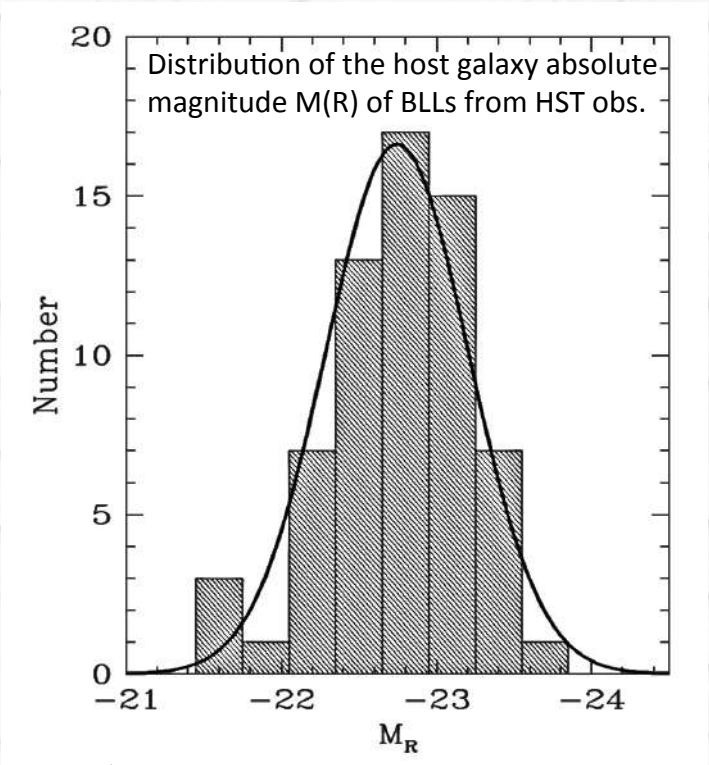
Featureless spectrum



Paiano+2017a

RGB J0136+391
TeV HBL
S/N = 500

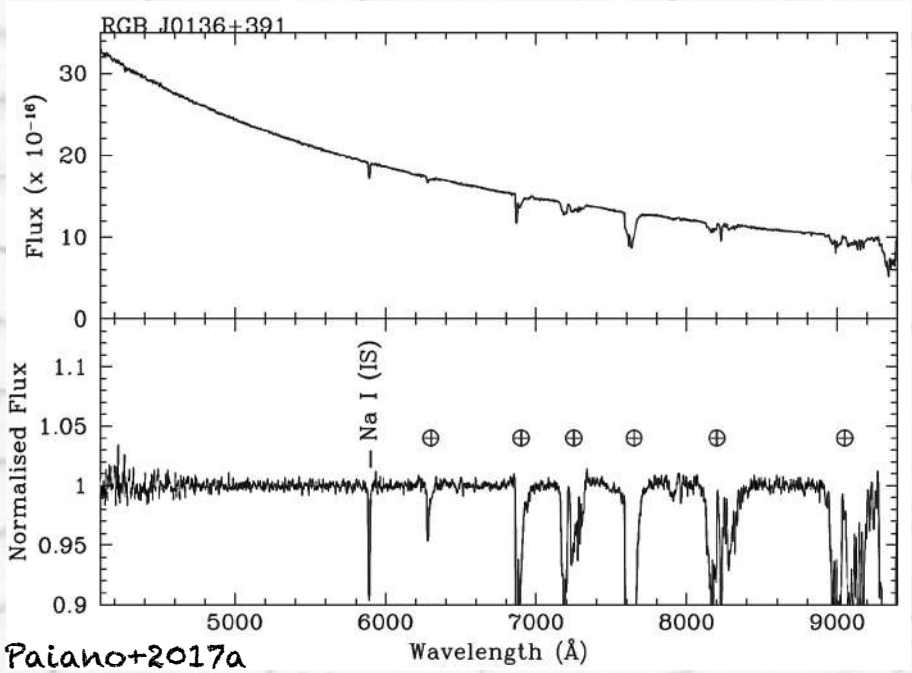
Non-thermal Nucleus
+
Elliptical host galaxy
[M(R) = -22.9]
=
Observed spectrum



Sbarufatti+2005

RESULTS: Lower limit of the redshift

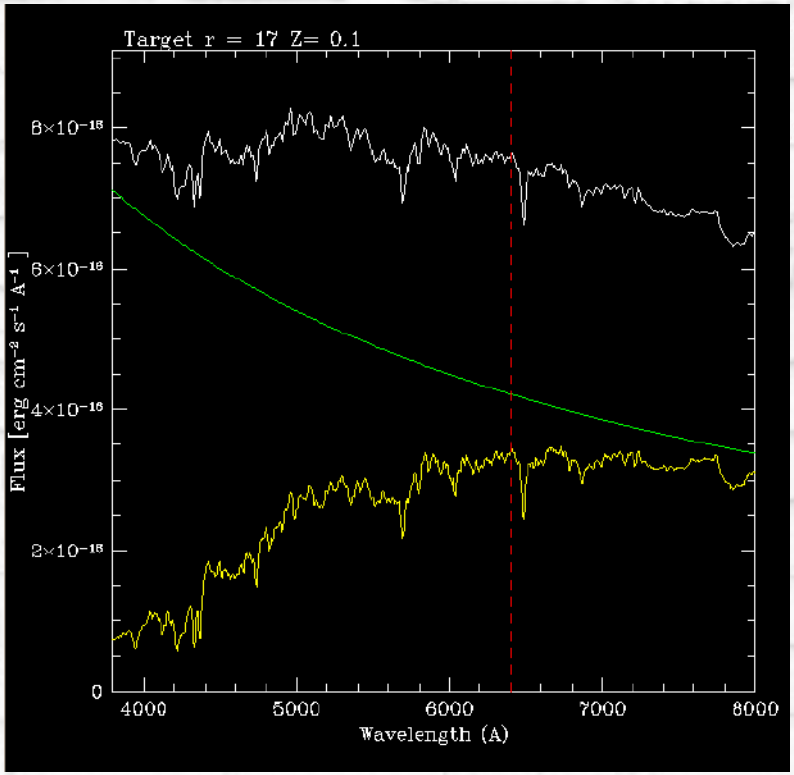
Featureless spectrum



Paiano+2017a

RGB J0136+391
TeV HBL
S/N = 500

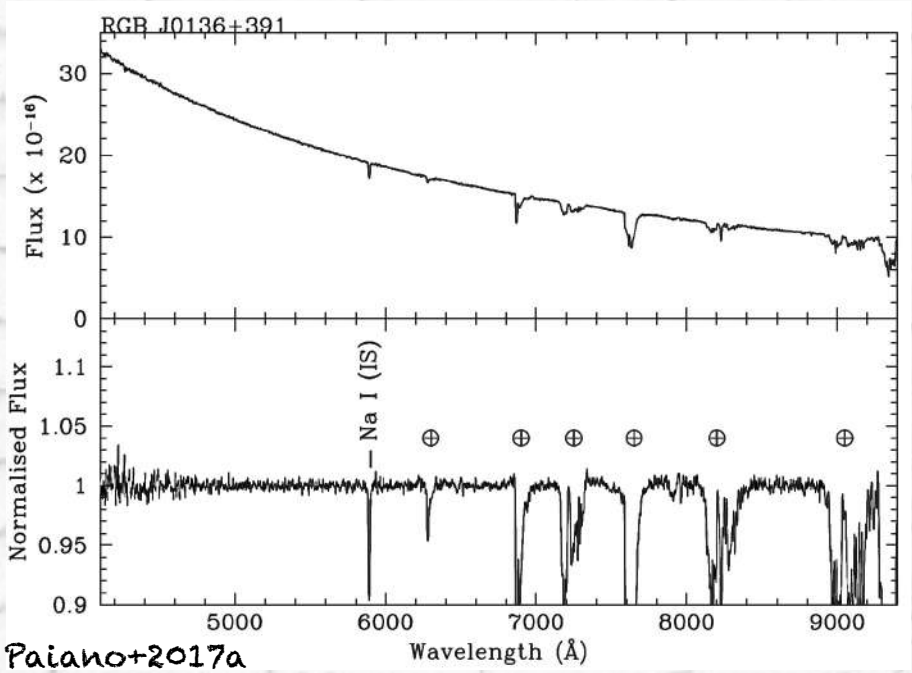
Non-thermal Nucleus
+
Elliptical host galaxy
[M(R) = -22.9]
=
Observed spectrum



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

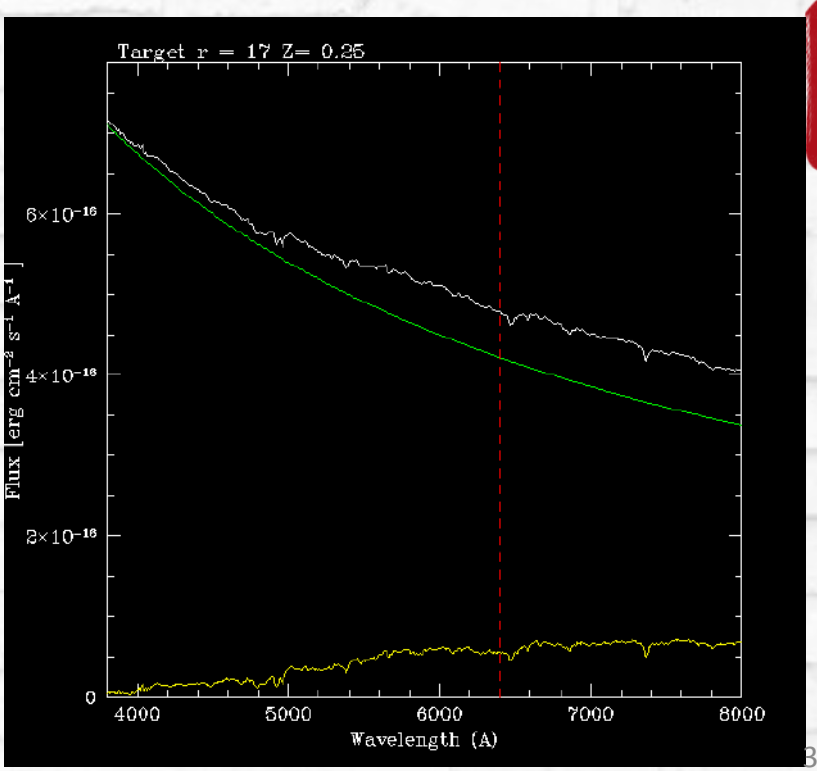
RESULTS: Lower limit of the redshift

Featureless spectrum



Paiano+2017a

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

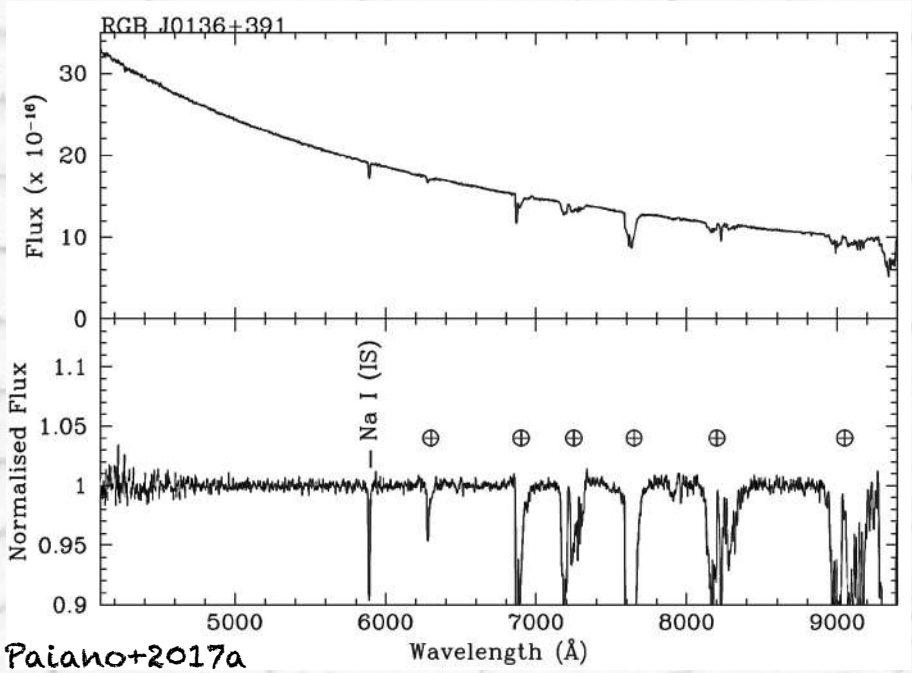


RGB J0136+391
TeV HBL
S/N = 500

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

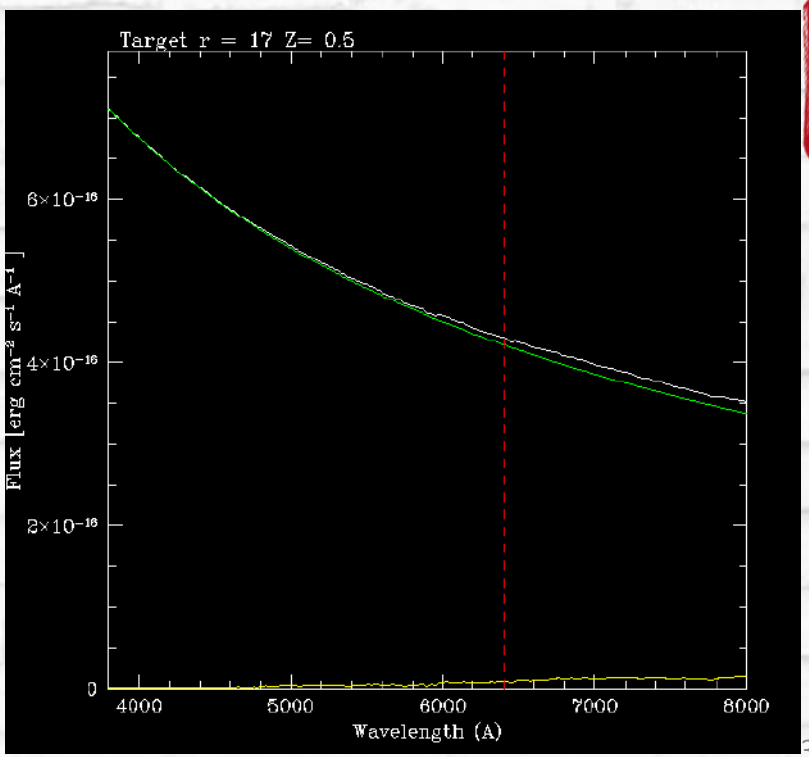
RESULTS: Lower limit of the redshift

Featureless spectrum



Paiano+2017a

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

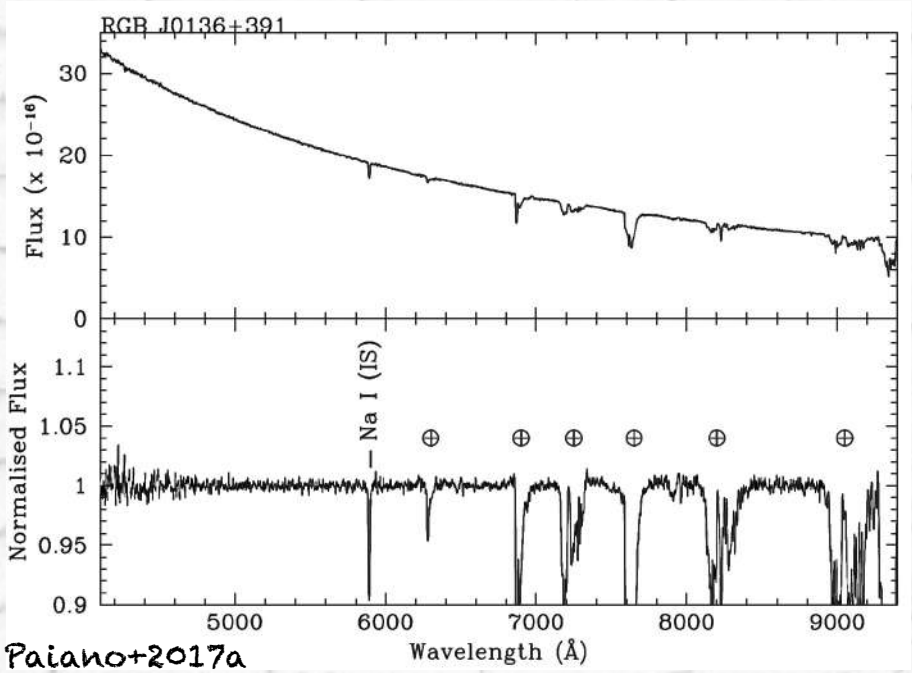


RGB J0136+391
TeV HBL
S/N = 500

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

RESULTS: Lower limit of the redshift

Featureless spectrum

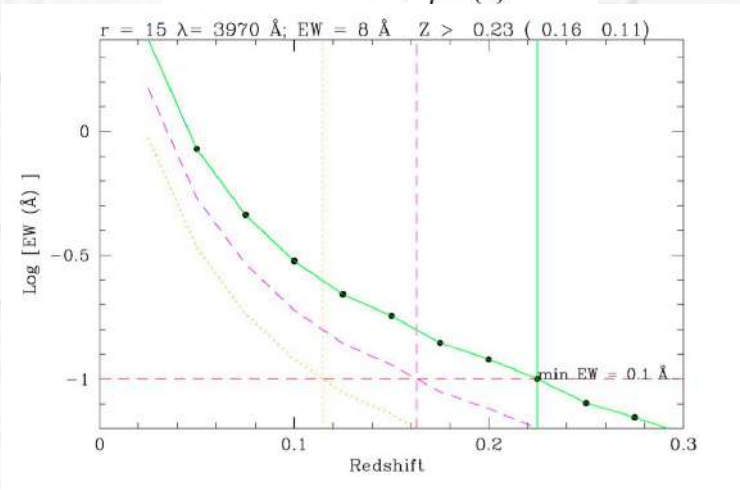


Paiano+2017a

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

We can derive EW UL = minimum detectable EW

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



RGB J0136+391
TeV HBL
S/N = 500
minEW = 0.08

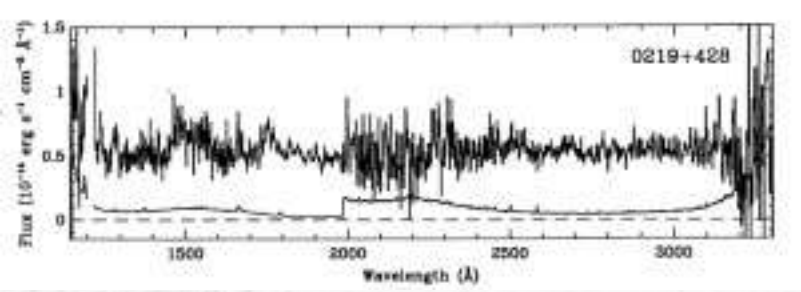
$z_{Lim} > 0.27$

. . . and a Lower Limit on the redshift

RESULTS: Lower limit of the redshift

For several cases, we disprove the previous published redshift

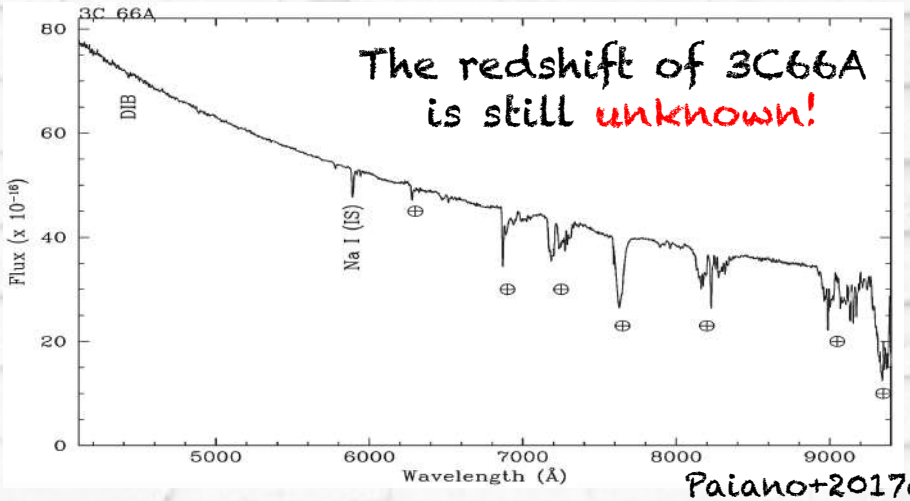
CASE OF 3C66A



One of the first BLLs studied !!

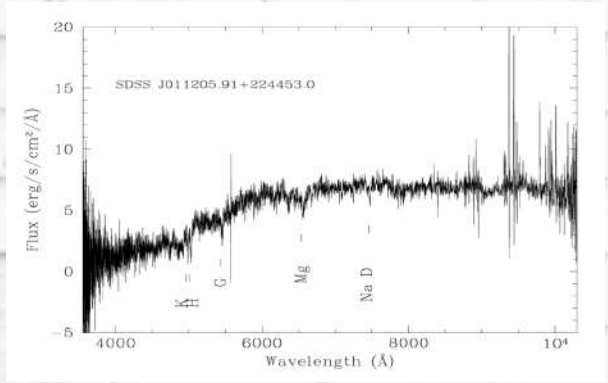
$z = 0.444$

(Miller+78 , Lanzetta+1993)

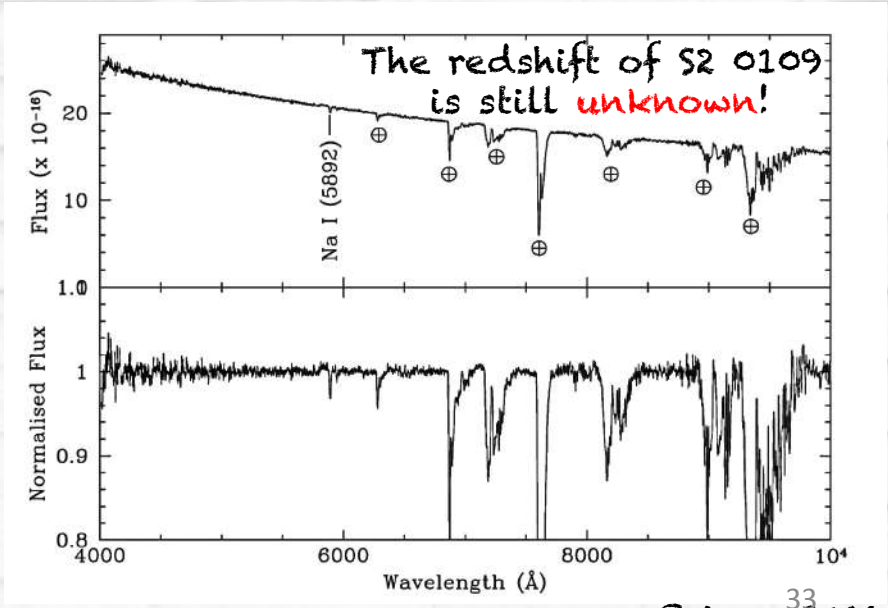


Paiano+2017a

CASE OF S2 0109+22



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



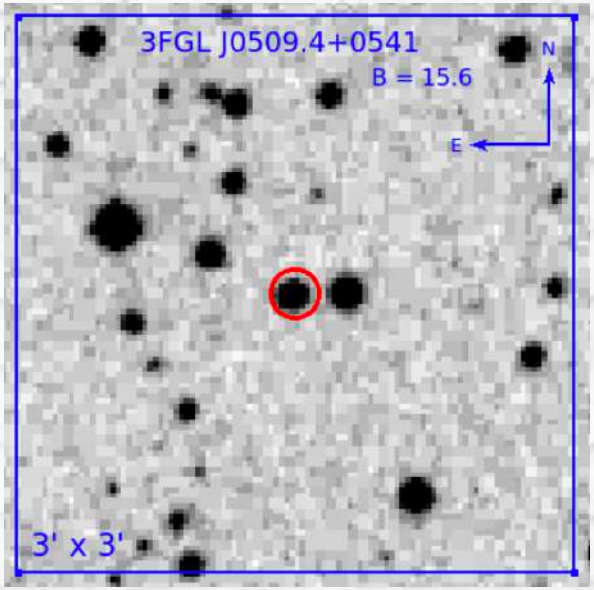
Paiano+2016

THE REDSHIFT OF THE NEUTRINO BL LAC OBJECT TXS0506+056

TXS 0506+056
(3FGLJ0509+0542)

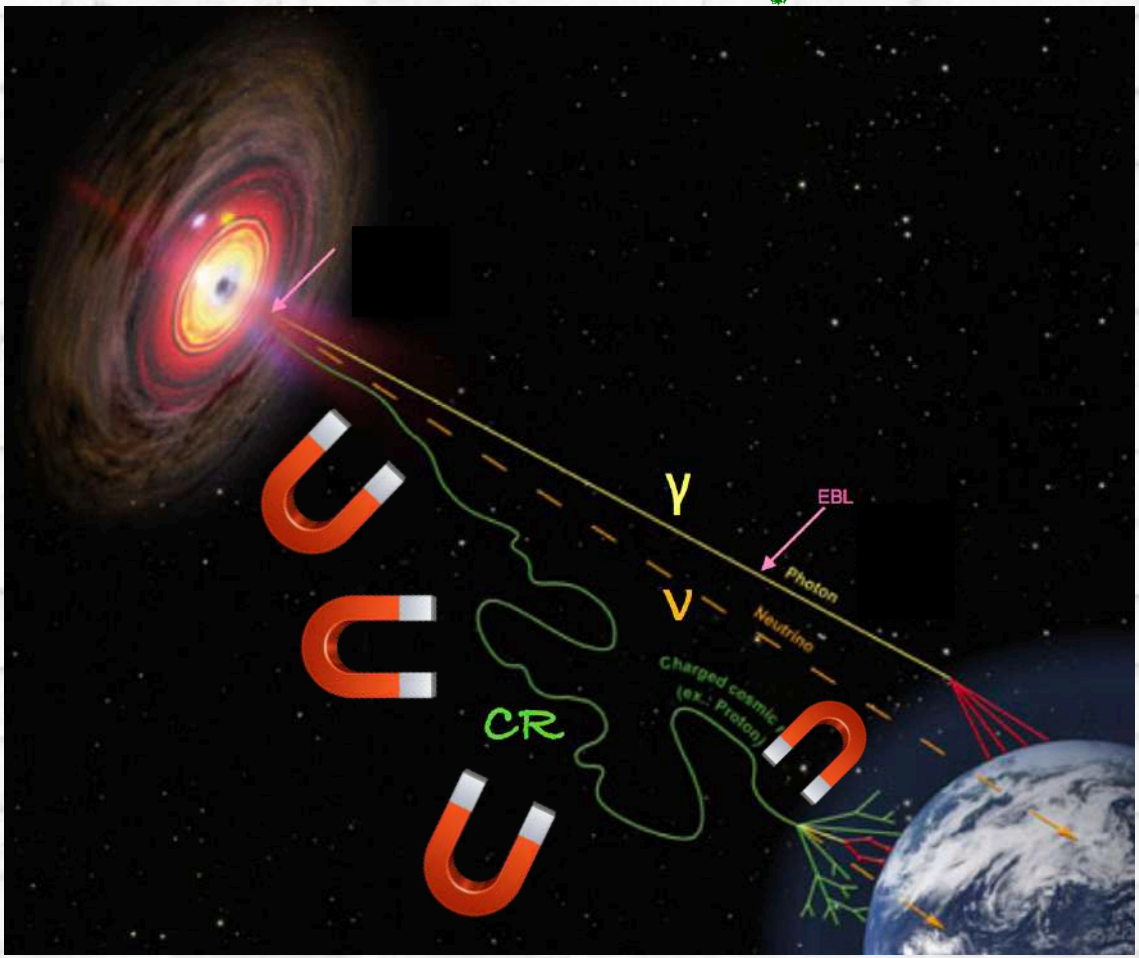
First extragalactic source associated to
Icecube neutrino event

z = ? until 4 feb. 2018



BLAZARS AS NEUTRINO EMITTERS

Blazars are supposed to be the most powerful cosmic accelerators of particles (p, nuclei) and hence sources of cosmic rays (CR)



BLAZARS AS NEUTRINO EMITTERS

Blazars are supposed to be the most powerful cosmic accelerators of particles (p, nuclei) and hence sources of cosmic rays (CR)

High energy protons + matter/photons

proton-proton (pp)

$$p + p \rightarrow \pi + X$$

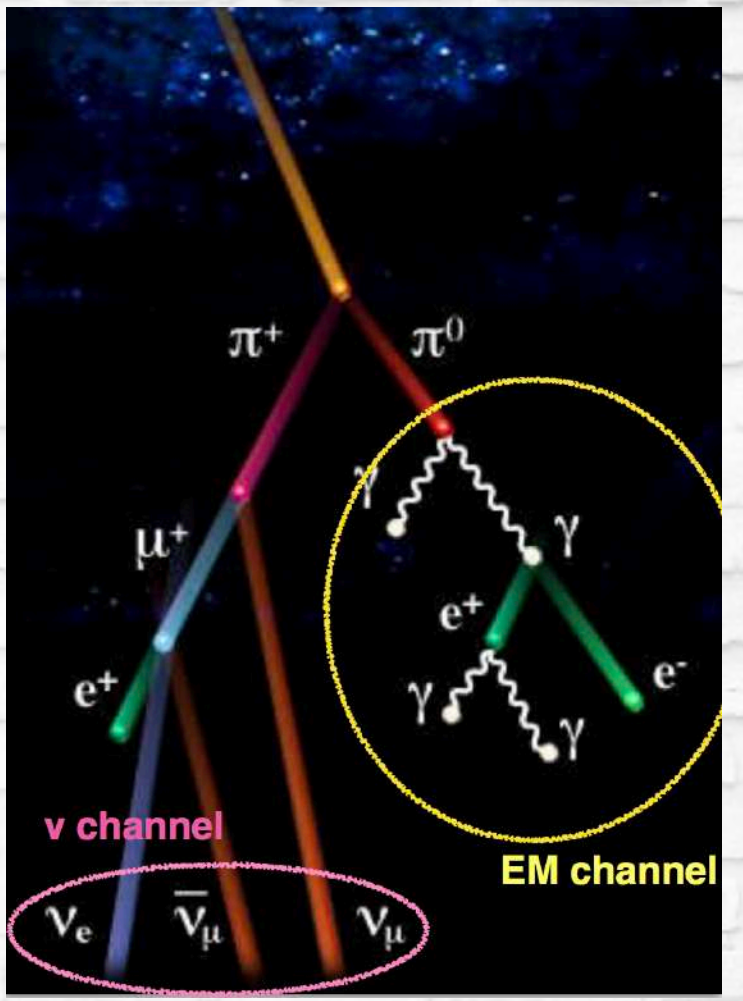
proton-photon (pγ)

$$p + \gamma \rightarrow n + \pi^+$$

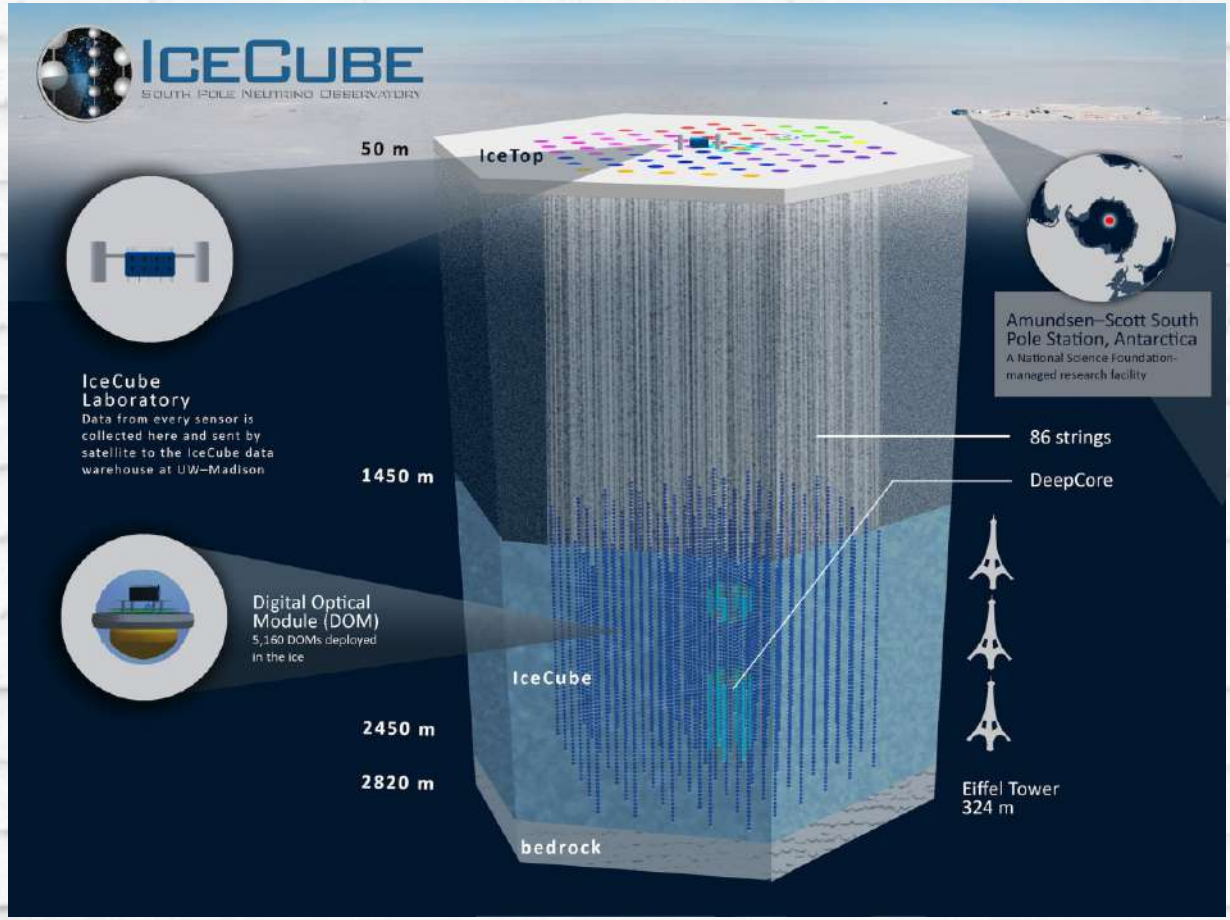
$$p + \gamma \rightarrow p + \pi^0$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \bar{\nu}_e + \bar{\nu}_\mu + \nu_\mu$$

$$\pi^0 \rightarrow 2\gamma$$



THE NEUTRINO OBSERVATORY ICECUBE



http://icecube.wisc.edu/

- Operative since 2010 and located at @South Pole
- 300 physicists of 49 institutions
- 5000 sensors placed under the Antartide ice (1.4-2.5 km)

THE NEUTRINO ASTRONOMY BEGINS...

2017 september 22

ICECUBE detects EHE170922A, a very high energy neutrino (~300TeV)

NEUTRINO ALERT

Inside the ICECUBE neutrino error box (~30'), the Fermi satellite detects the source 3FGLJ0509+0542 (TXS0506+056) in an high flux state

The Cherenkov telescope MAGIC observes TXS0506+056 and confirms its high state at the gamma-ray energies

IT'S NEEDED TO DETERMINE ITS REDSHIFT

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 requested 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

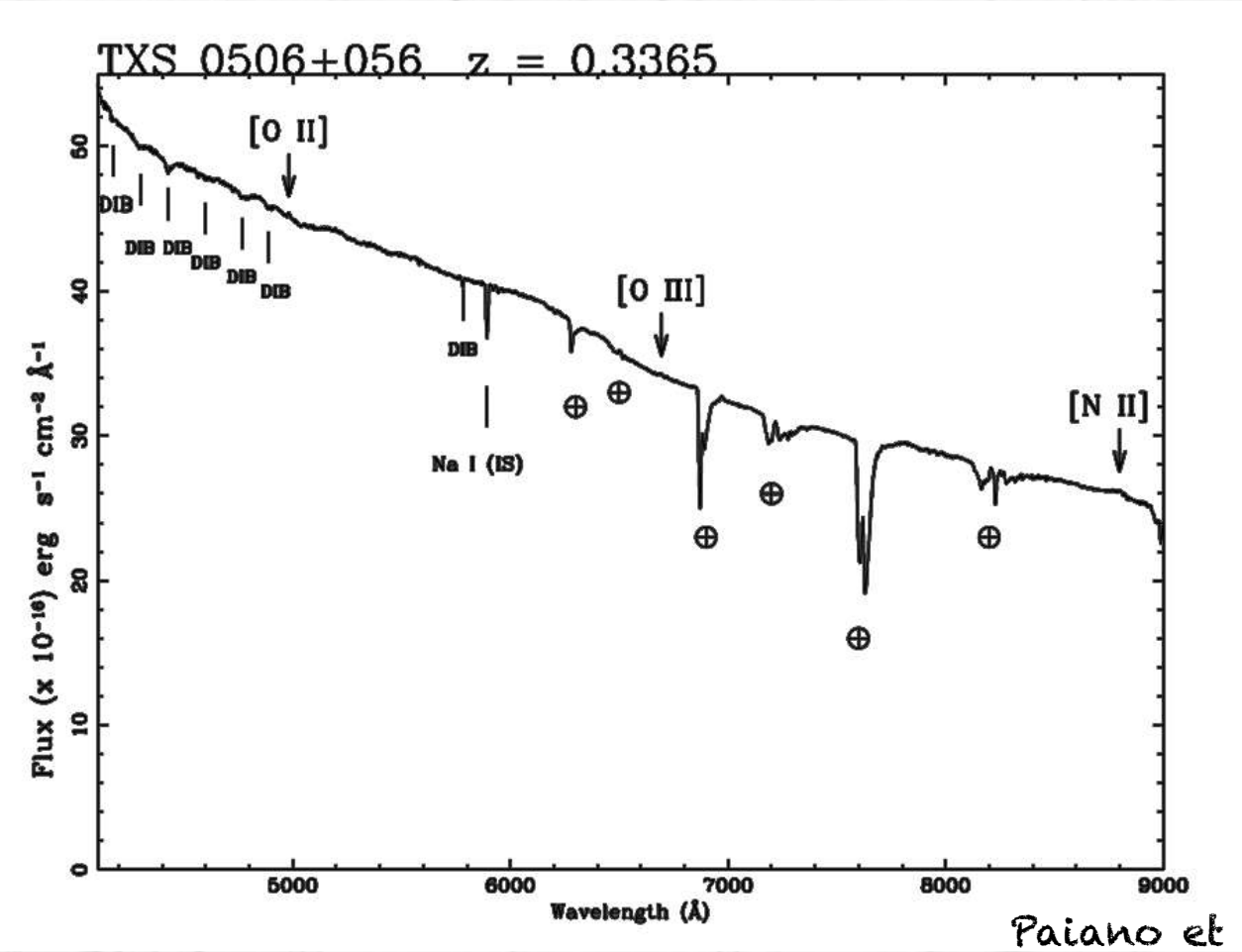
`Col.1`: Grism name (slit width = 1.0" for R1000 and slit width = 1.2" for R2500); `Col.2`: Date of the observation, `Col.3`: Total exposure time, `Col.4`: Number of individual exposures.

-> 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

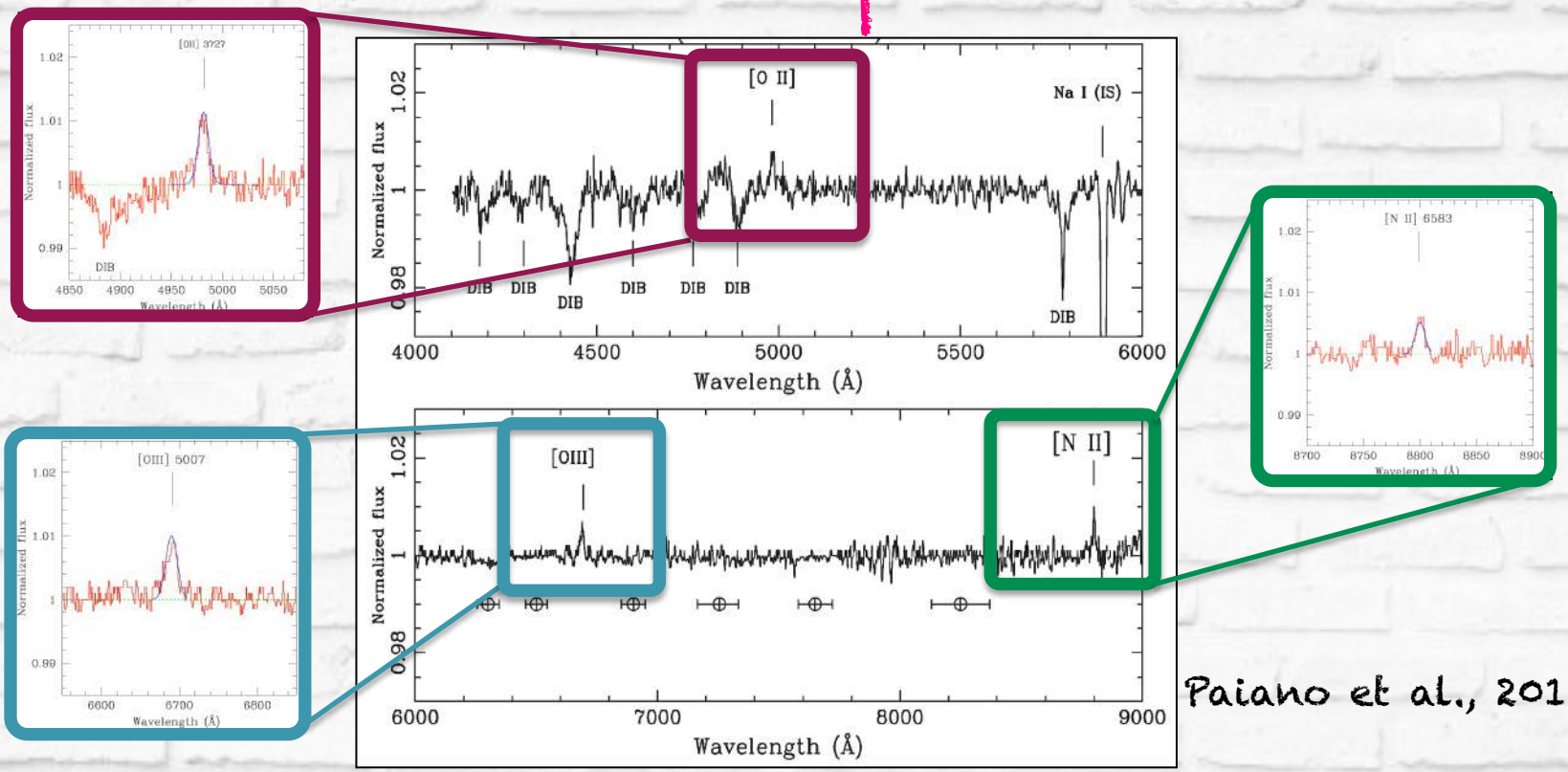
TXS0506+056 spectrum



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:

$z = 0.3365 \pm 0.0010$

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

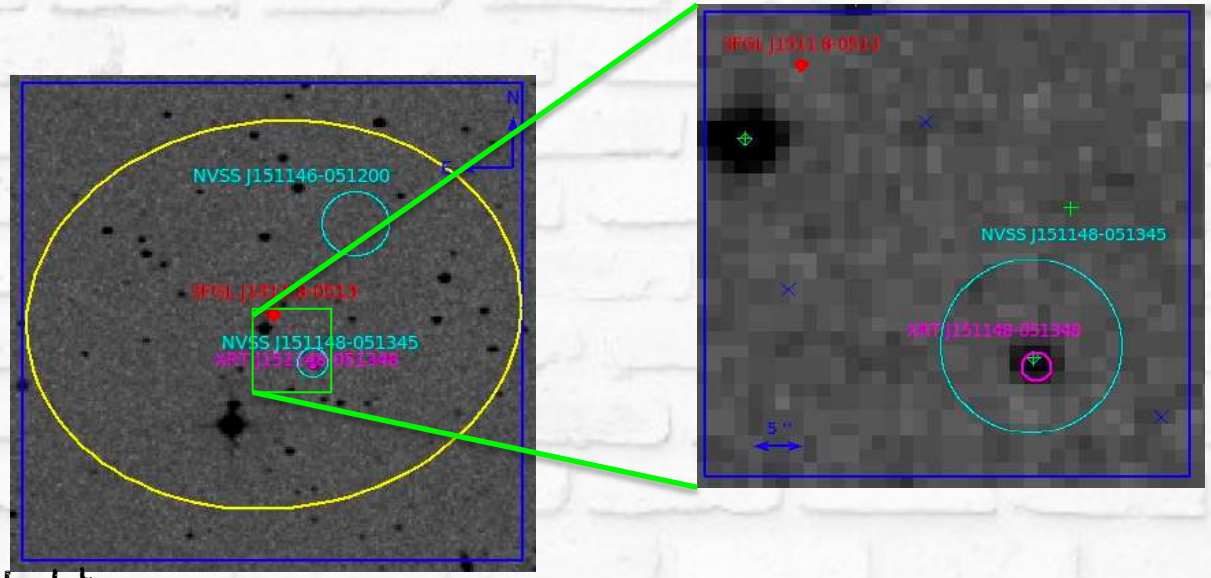
SELECTION CRITERIA:

- 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



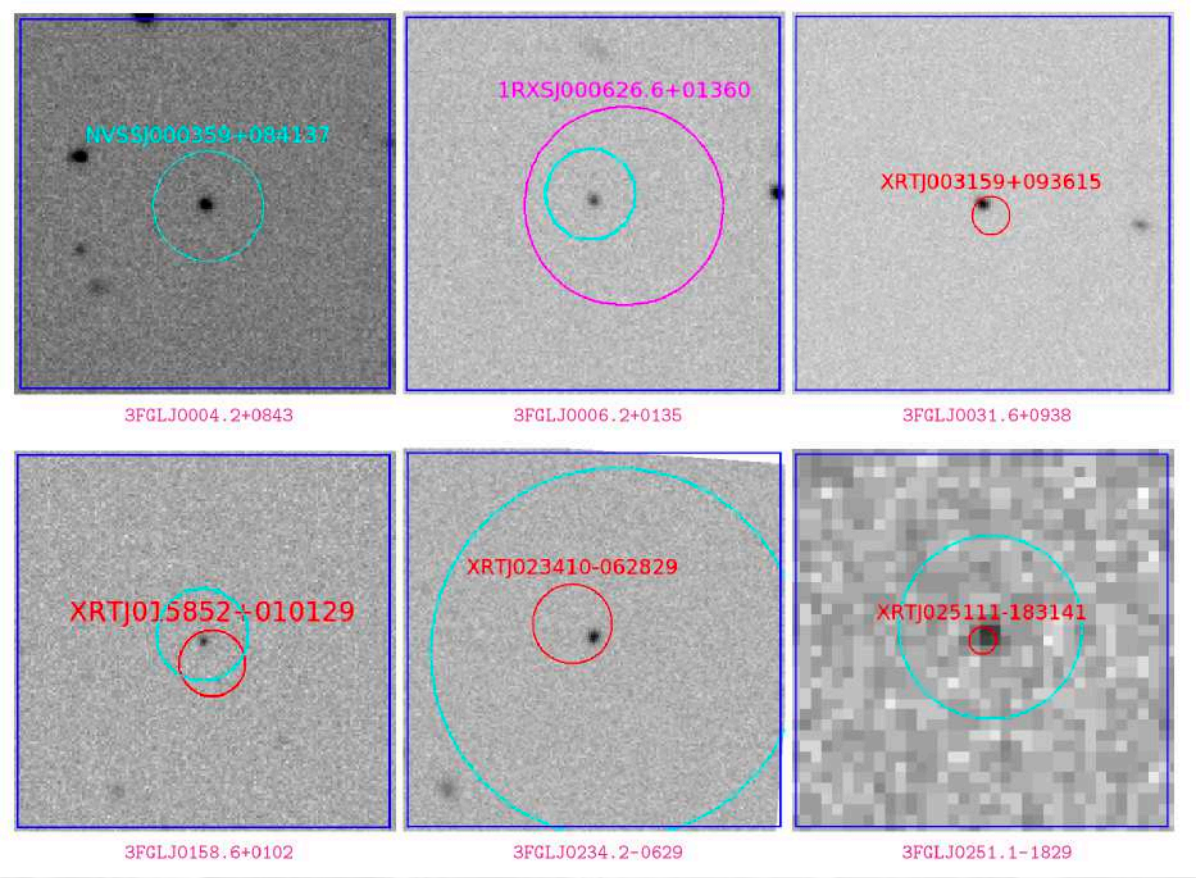
Adapted by Paiano,Franceschini+2017

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).

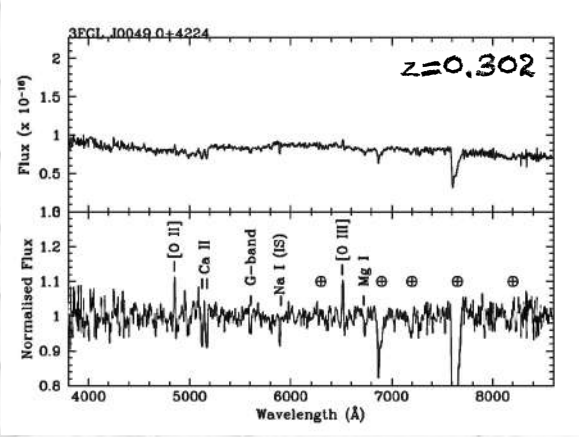
On-going spectroscopic campaign of a sample of optical counterparts of UGSs selected using X-ray data covering the 3FGL region and searching for the possible MWL counterparts

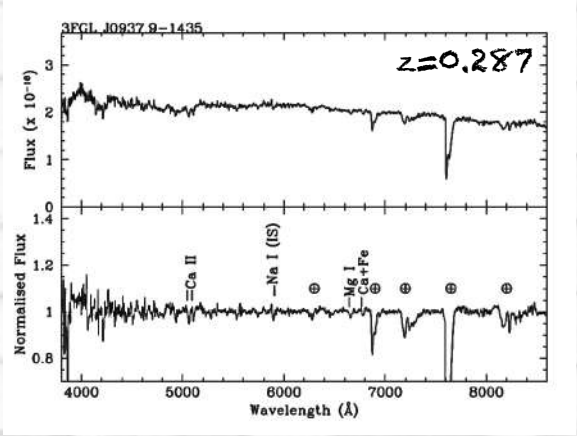


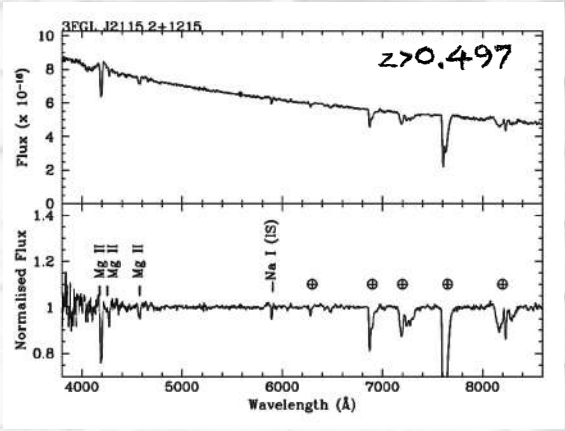
47 UGS counterparts observed at GTC

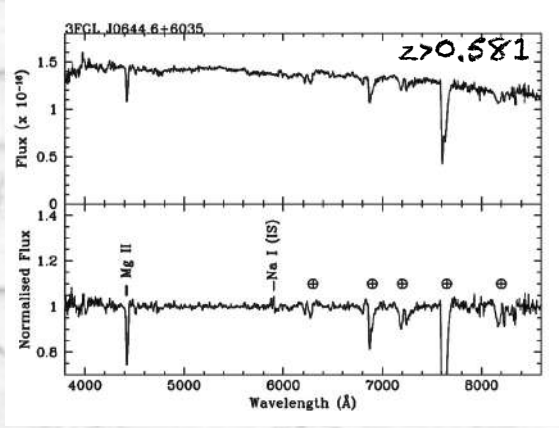
SPECTROSCOPY OF UNASSOCIATED γ-RAY SOURCES (UGSs).

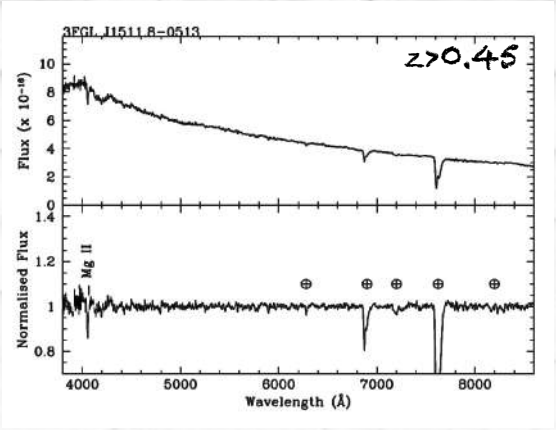
Some examples:

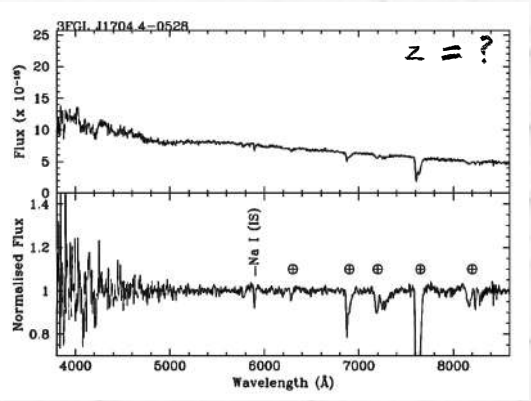










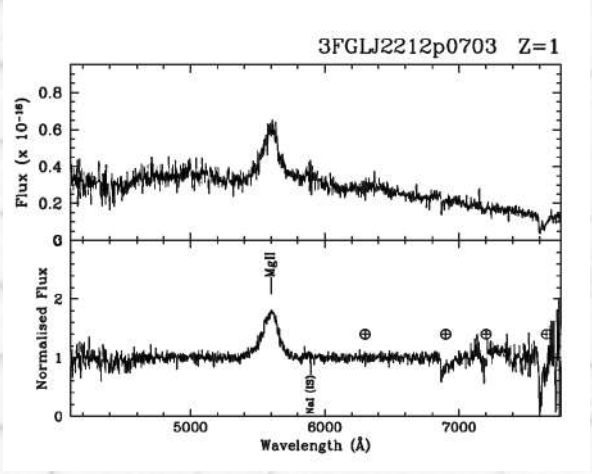


Paiano+2017c

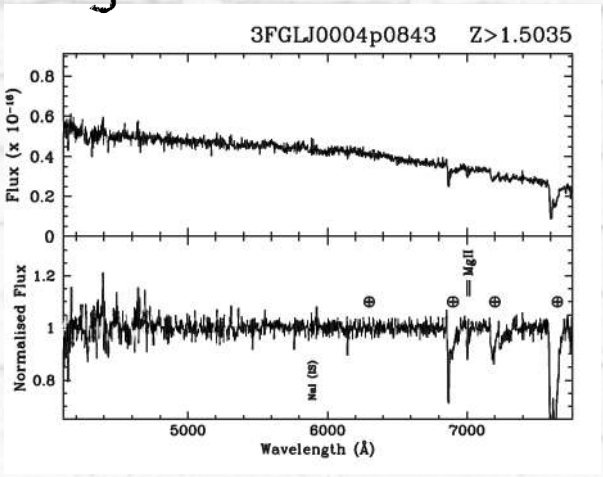
SPECTROSCOPY OF UNASSOCIATED γ-RAY SOURCES (UGSs).

Peculiar cases:

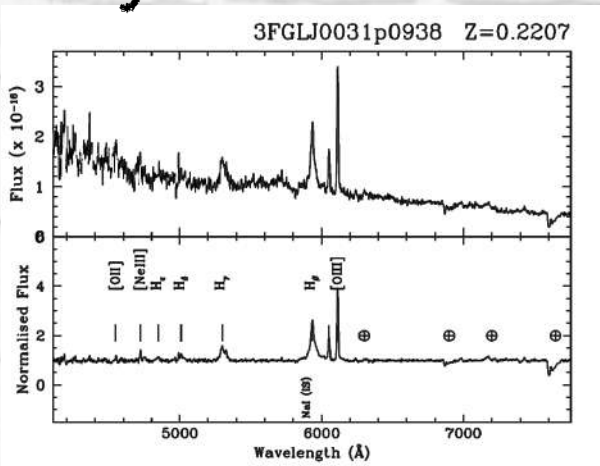
QSO



High-z BLL

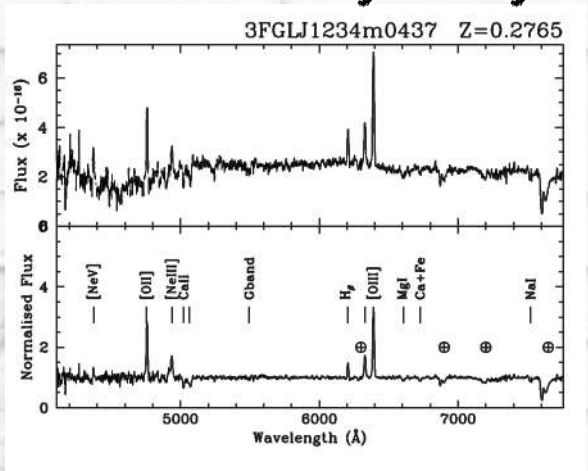


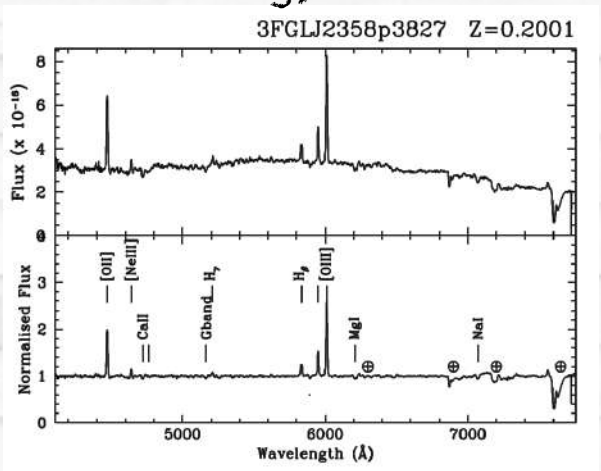
NLSy1



Seyfert 2-like

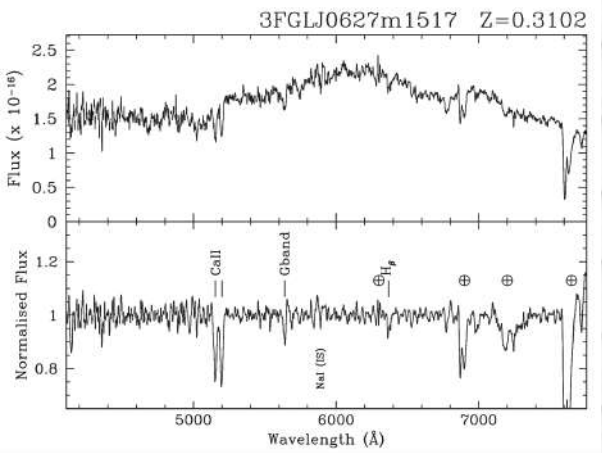
(ony two Sy2 in Fermi catalog)





Neutrino candidate

(see Lucarelli+2018)



Paiano+2019

CONCLUSIONS

-> High S/N GTC spectra of γ-BLLs allowed to obtained
new redshift or sound lower limits
important and crucial ingredient for several astrophysical topics
(SED modelling, EBL, neutrino production, LF, environment study...)

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

-> Revision of previous published redshift for many BLLs

-> Our spectra can be accessed at the website : http://www.oapd.inaf.it/zbllac/

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

-> Spectroscopy of unassociated fermi object,
selected as blazar candidates confirmed the blazar/AGN nature
and for many cases we can derive the redshift

-> Search for high z BLLs as candidates for CTA observations

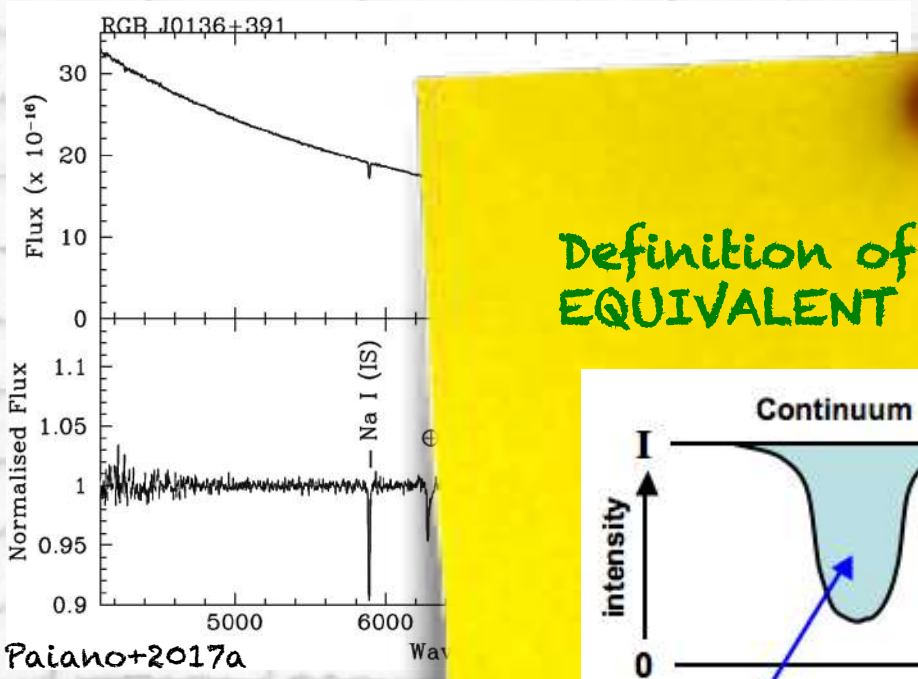
-> Waiting for the EELT (39m) to determine the redshift of
BLL with high nucleus-host ratio


THANK YOU


THANK
YOU

RESULTS: Lower limit of the redshift

Featureless spectrum



Paiano+2017a

RGB J0136+391
TeV HBL
S/N = 500
minEW = 0.08

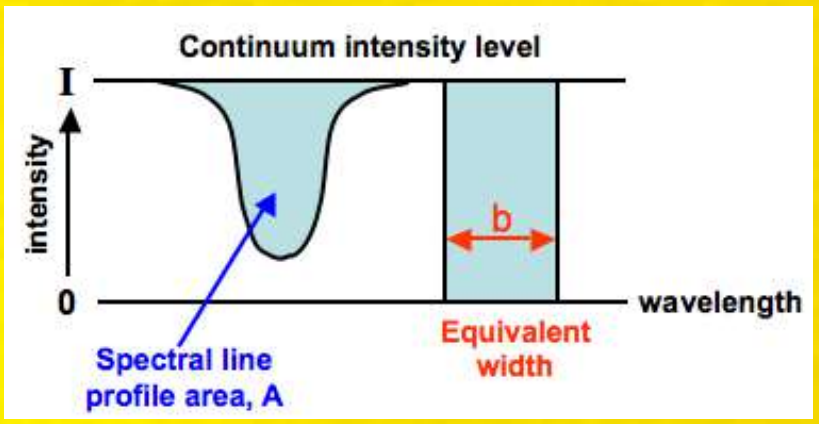
$z_{Lim} > 0.27$

...on-thermal Nucleus

...galaxy

...trum

Definition of
EQUIVALENT WIDTH



$A = I \times b$

B = Equivalent Width