Resolving the mystery of unclassified extragalactic Fermi-LAT blazar-like sources

— Lizelke Klindt

DEX XIII

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Prof. D. Alexander & Dr. D. Rosario
CEA, Durham University, UK

Dr. B. Van Soelen & Prof P.J. Meintjes
University of the Free State, South Africa

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Fisika ~ Physics

The aim is to...

- ➟ Classify selected Active Galactic Nuclei of unknown type (AGU) with blazar characteristics in the Fermi-2LAC catalogue.
- ➟ We identified our sample based on a certain selection criteria for which we carried out a multi-wavelength campaign to establish Spectral Energy Distributions (SEDs) and to
- ➟ Study a variety of properties: variability, optical spectral features and establishing z-measurements.
- ➟ Classify these active galaxies: BL Lacs or Flat Spectrum Radio Quasars (FSRQs)
- ➟ Search for potential TeV emitting sources.

Outline

1. Fermi-LAT
2. AGN & Blazars
3. Fermi-2LAC & Fermi-3LAC catalogues
4. Sample selection criteria
5. Observational campaign: telescopes, data reductions and analysis
6. *Results: optical spectra and SEDs (variability)*
7. Conclusive remarks & Future studies

"For a long time I wanted to become a theologian. Now however, behold, how through my efforts God is being glorified through astronomy." - Johannes Kepler

Fermi Gamma-ray Space Telescope

- successor of EGRET (onboard CGRO)

11 June 2008

NEO: 565 km

Large Area Telescope (LAT)
20 MeV - 300 GeV

Gamma-ray Burst Monitor (GBM)
8 keV - 40 MeV

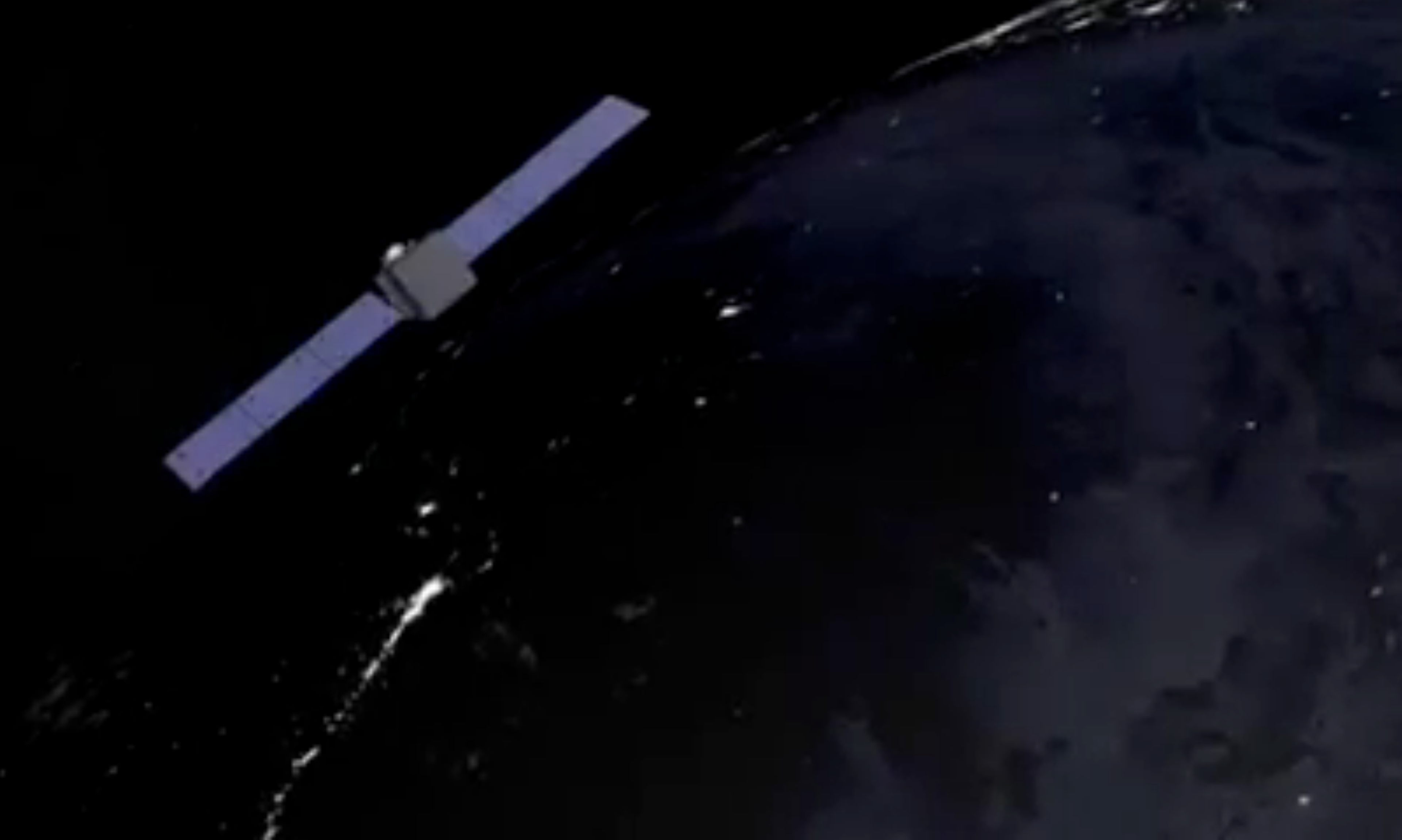
Detected 6378 γ-ray sources since 2008

55% AGN

KEY FEATURE

Large FoV:

- LAT: 2.4 sr; 20% of the sky at any instant.
- observes entire sky every 3 hours.
- FoV 5x larger than EGRET onboard CGRO



Abdo et al., 2010, ApJS, 188, 405

Active Galactic Nuclei

What makes AGN special?

Active nucleus that can outshine the host galaxy

Extremely luminous ~ 10^{47} erg/s

Multi-frequency emission: radio - γ-rays

Strong variability across EM spectrum at different time scales

RADIO LOUD AGN: RELATIVISTIC JETS

In order to correctly understand and model the dynamics of AGN, and in particular blazars, it is imperative to increase the number of well classified AGN and obtain multi-wavelength Spectral Energy Distributions (SEDs) from radio to γ-ray energies.

Active Galactic Nuclei

unification

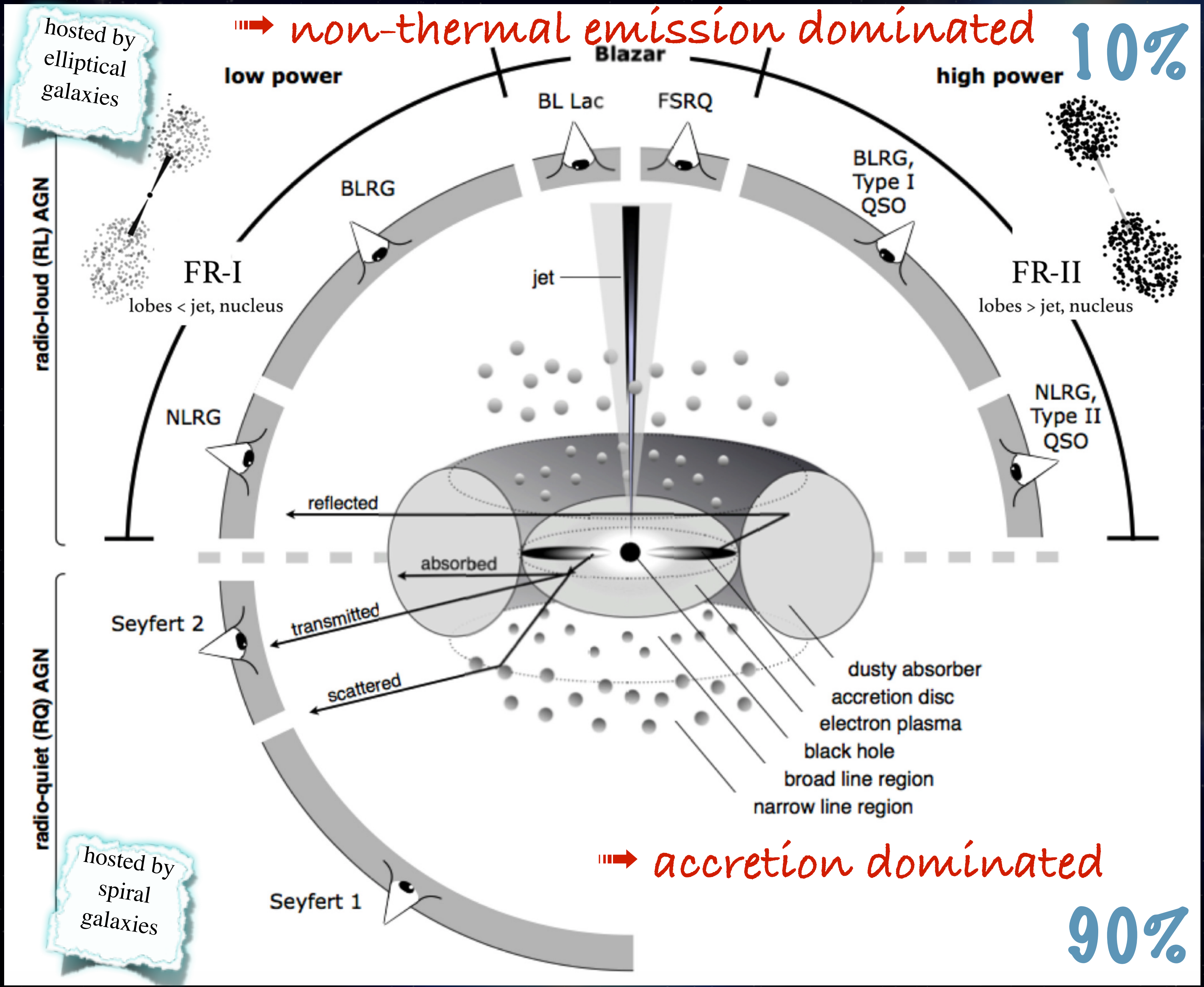


Figure: Illustrative diagram of the nomenclature of AGN in the unified model (adapted from Beckmann and Shrader, 2012, p.132, Fig. 4.16). The classification strongly depends on the viewing angle.

Different manifestations underlying the same phenomenon!

- AGN are divided into subclasses based on the emission we receive from the source.
- The type is dependent on the viewing angle, as well as the presence and morphology of relativistic jets.
- Blazars are jet-dominated AGN which are powered by accretion onto a SMBH at the centre of a host elliptical galaxy, from which a relativistic jet emerges.

adapted from Beckmann & Shrader, 2012, p.132, fig.4.16.

Blazars

Fundamental differences between FSRQs and BL Lacs ??

- the jet power ➟ P_{jet} (erg s^{-1})
- magnetic field strength ➟ B (G)
- Eddington ratio ➟ $\lambda_{Edd} = L_{bol}/L_{Edd}$
- the inferred L_{acc} and L_{Edd}

	log M_{BH} ($M_\odot$)	R_{diss}/R_S	Γ	B (G)	log L_{disc} (erg s^{-1})	λ_{Edd}	log P_e (erg s^{-1})	log P_{jet} (erg s^{-1})
BL Lacs	8–9	300–1000	10–20	0.1–2	42–44	< 0.01	41–43	43.5–45
FSRQs	8–9.5	300–3000	10–16	1–10	44–46.5	> 0.01	42.5–44	45–48

(Ghisellini, 2012, International Journal of Modern Physics, 8, 1)

Classification schemes of blazars

Today the nomenclature depends strongly on the emission-line strengths in the optical spectra and the SED characteristics

1. **Optical Spectra**

   ➟ provides invaluable tool to distinguish between FSRQs & BL Lacs.

2. *Redshift measurements*

   ➟ Observationally challenging for BL Lacs due to featureless spectra ($z < 0.5$).

3. **Spectral Energy Distributions**

   ➟ Depending on frequency @ which synchrotron emission peaks, blazars are subdivided into LSP, ISP or HSP blazars.

4. **Flux variability**

   ➟ Blazars show flux variability over the entire EM spectrum over various time-scales: IDV, STV and LTV.

Stocke et al., 1991, ApJS, 76, 813; Urry and Padovani, 1995, PASP, 107, 803; Marcha et al., 1996, MNRAS, 281, 425

Spectral “fingerprints”

“A picture paints a thousand words, a spectrum paints a thousand pictures” - Liz Bartlett

diluted 4000 Å break

K_{4000} < 0.4: DOMINATING NON-THERMAL EMISSION OF THE JET CONTINUUM TO THE HOST GALAXY’S THERMAL SPECTRUM

Stocke et al., 1991
Marcha et al., 1996

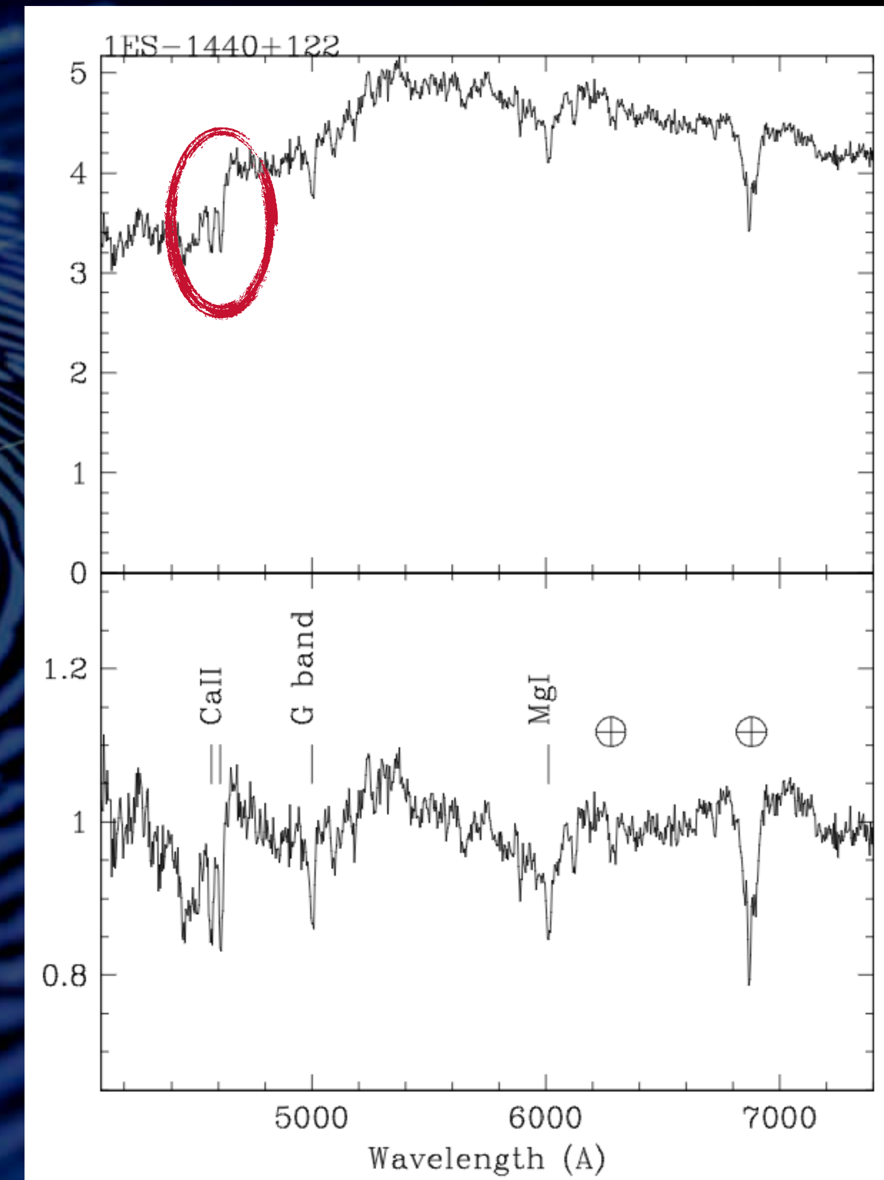


Figure: Spectra of the BL Lacs observed with the ESO 3.6 m and the NOT 2.5 m telescopes (Sbarufatti et al., 2006, A&A, 457, 35).

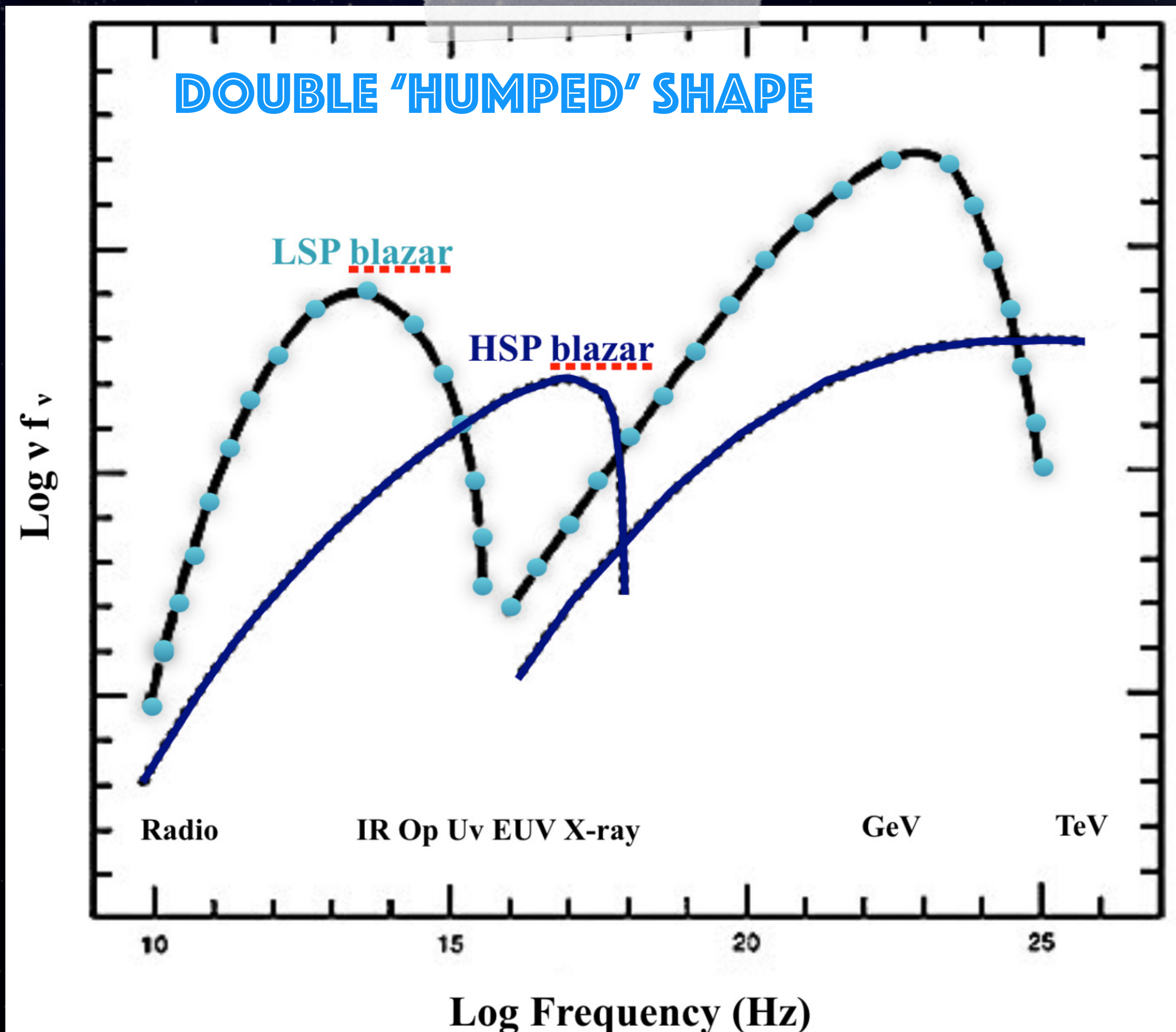
BL LAC OBJECTS

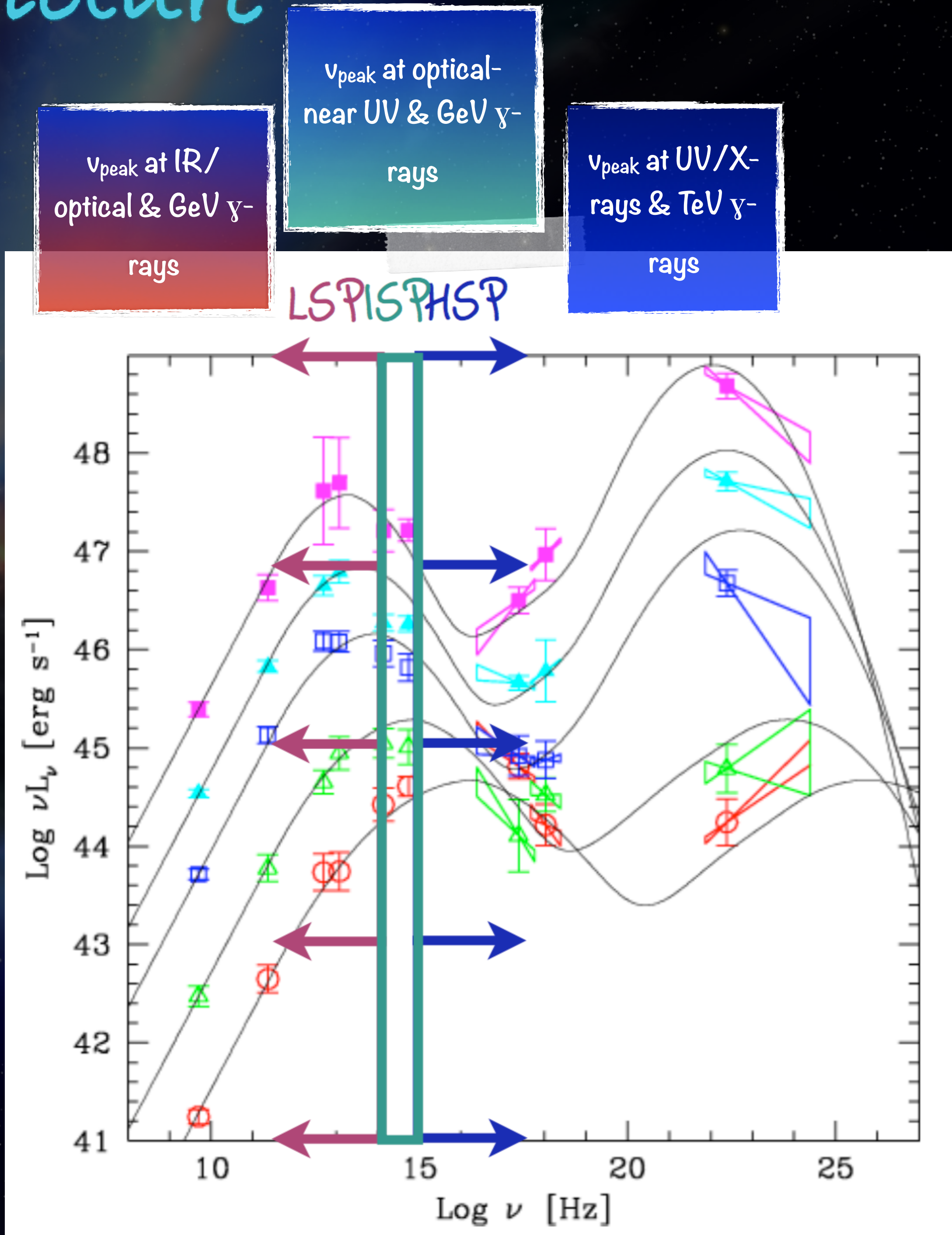
Weak (low state) or absent emission lines.
In some cases narrow/broad emission lines have been detected.
∴ mainly featureless spectra.
Absorption lines ➟ signatures of the host galaxy.
➟ Ca II H&K, G-band, Mg I, Na I-D.
$|W\lambda| < 5$ Å

Sbarufatti B. et al. 2005, ApJ, 129, 559-566; XMM-Newton spectroscopy of an X-ray selected sample of RL AGNs, A&A, 430, 927-940, Landt et al. 2002

SEDs of blazars

The bigger picture





Low-energy peak: synchrotron emission from relativistic electrons in jet

High-energy peak: Source of origin still under debate **LEPTONIC** or **HADRONIC**

IC scattering: SSC or EC — photo-pion/secondary pions

Urry, 1998, AdSpR, 21, 89; Böttcher M, Reimer A, Sweeney K and Prakash A 2013 ApJ 768 54;Mannheim K and Biermann PL 1992 A&A 253 L21; Aharonian FA 2000 NewA 5 377; Mücke A and Protheroe RJ 2001 APh 15 121; Mücke A, Protheroe RJ, Engel R, Rachen JP and Stanev T 2003 APh 18 593

SED modelling

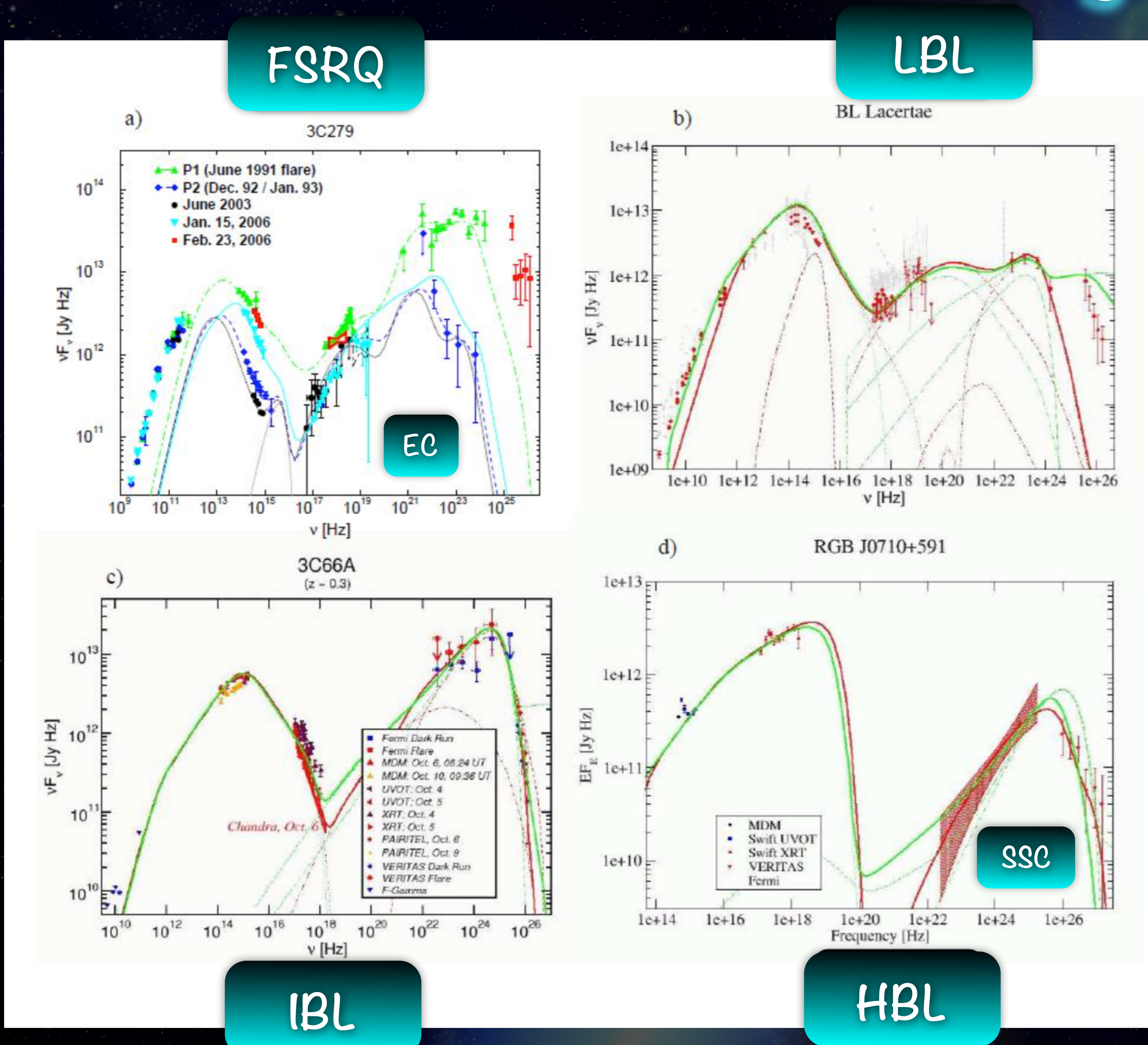


Figure: Spectral Energy Distributions of the subclasses of blazars (Figure adapted from Böttcher, 2010). (a) 3C 279 (FSRQ) (from Collmar et al., 2010), (b) BL Lacertae (LBL) (data from Abdo et al., 2010a), (c) 3C 66A (IBL) (Böttcher et al., 2013), and (d) RGB J0710+591 (HBL) (data from Acciari et al., 2010).

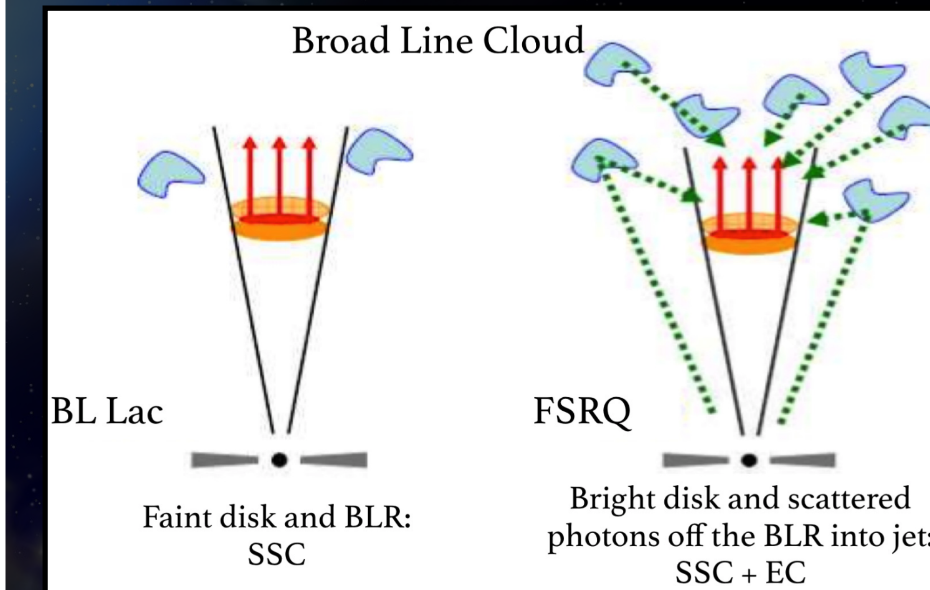


Figure: Illustration of different contributions of radiation in BL Lacs and FSRQs (Nkundabakura, 2010, fig.2.17).

FSRQ

➡ γ-ray dominated

BL LAC

➡ synchrotron dominated

Acciari et al., 2009; Acciari et al., 2010; Abdo et al 2011; Böttcher, 2012, Fermi & Janksy proceedings; Böttcher, 2013, ApJ, 768, 54

Fermi-LAT catalogues

Photon fluxes reported in 5 energy bands: 100 - 300 MeV, 300 MeV - 1 GeV, 1 - 3 GeV, 3 - 10 GeV, 10 - 100 GeV

Fermi-LAT First/Second/Third Source Catalog

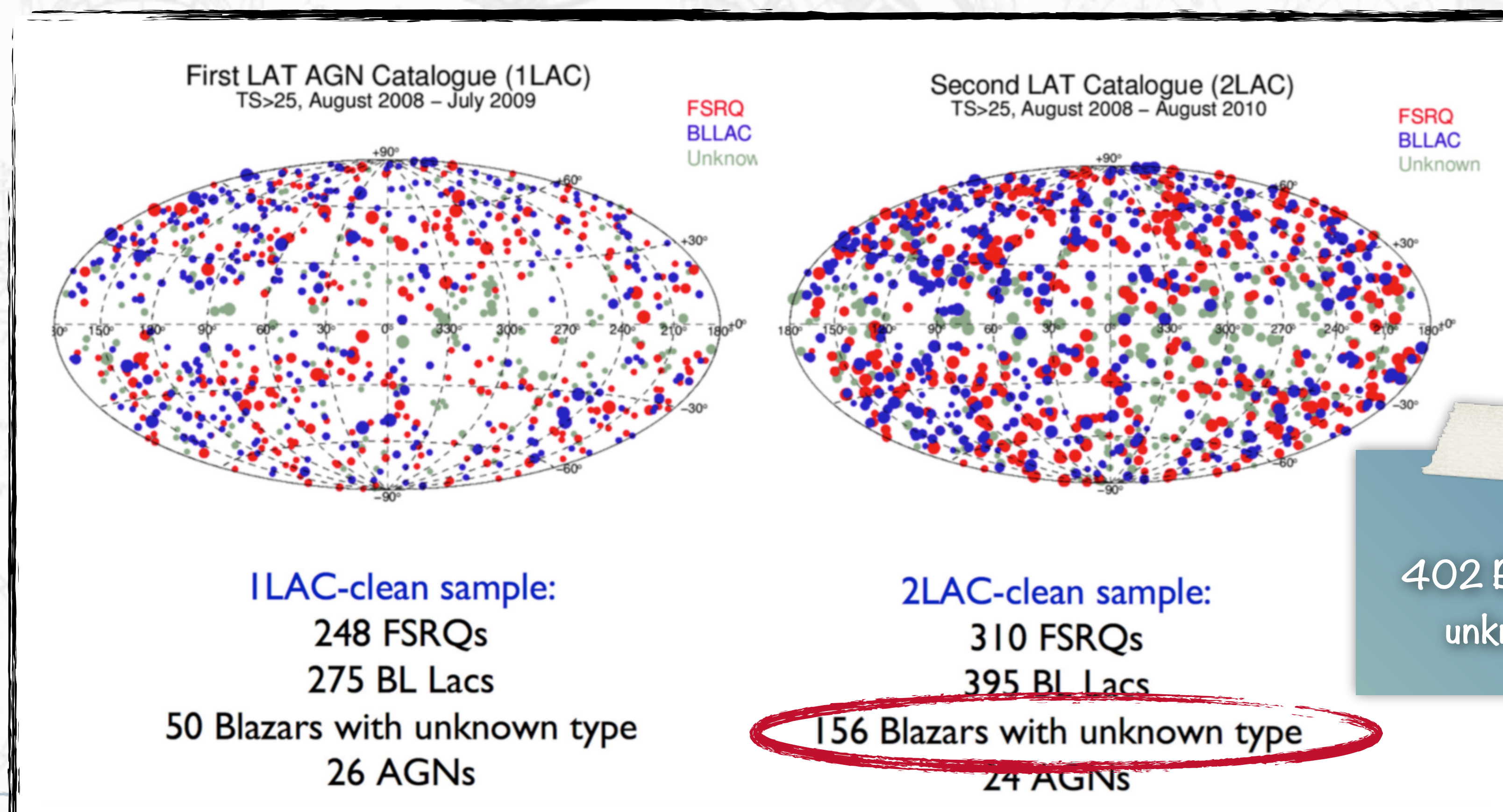
1FGL (Abdo et al., 2010), 2FGL (Nolan et al., 2012), 3FGL (Acero et al., 2015)

1451 → 1873 → 3033

The First/Second/Third Catalog of Active Galactic Nuclei detected by *Fermi*-LAT

1LAC (Abdo et al., 2010), 2LAC (Ackermann et al., 2011), 3LAC (Ackermann et al., 2015)

All AGN @ high galactic latitude (|b| > 10°)



3LAC:
402 Blazar candidates of unknown type (BCU)

Selection Criteria

Based on criteria employed by Nkundabakura & Meintjes (Nkundabakura, 2011, PhD theses) in a study of 13 unidentified sources listed in the Energetic Gamma Ray Experiment Telescope (EGRET) catalogue (3EG catalogue).

(1) High galactic latitude sources

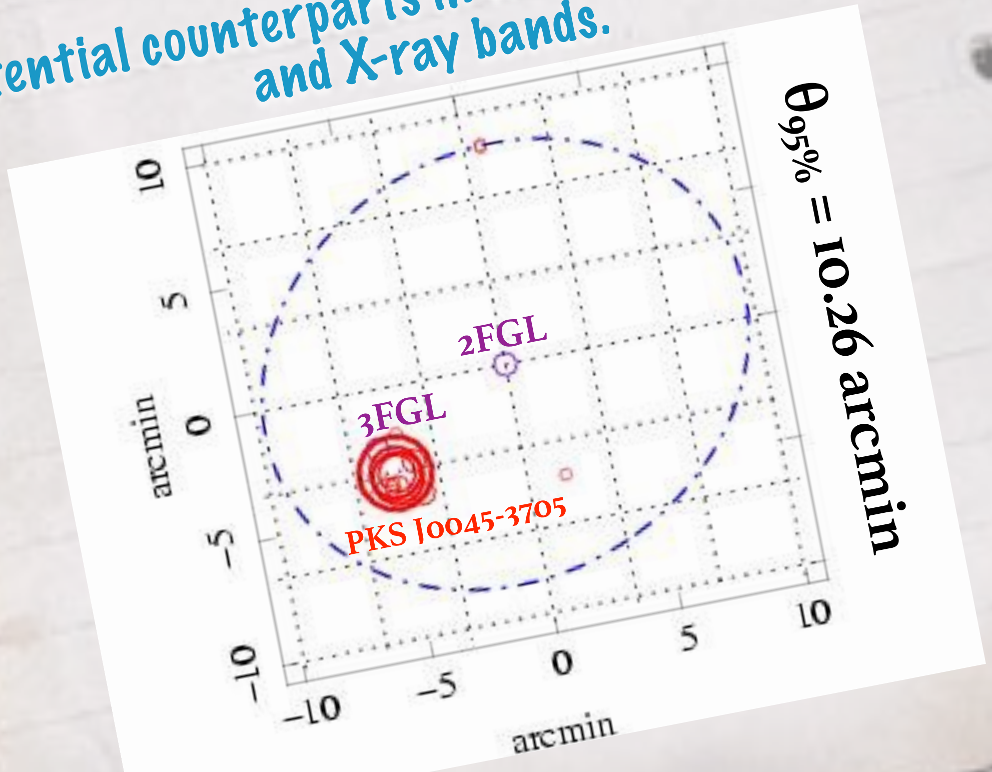
$|b| > 10^\circ$:

near galactic centre source confusion is high and diffuse emission is present.

(2) The 2FGL 95% error radius

Counterparts within 95% error circle of Fermi-2LAC:

potential counterparts in the radio, IR, optical and X-ray bands.



(3) Observability from South Africa

$-90^\circ < \delta < +35^\circ$; Vmag < 21.

(4) Radio brightness

$F_{radio} > 100$ mJy @ 4.85 GHz (detectable with HartRAO 26-m).

(5) Gamma-ray photon index

Power-law spectral function $dN/dE \propto E^{-\Gamma}$; $1.2 < \Gamma < 3$.

(6) Gamma-ray variability

Sources with $TS_{var} > 41.6$ have a 99% chance to be variable over the two year observation period.

(7) Redshift measurements

No available spectra; excluded sources classified by Shaw et al., 2012, ApJS, 199, 31.

For 7 sources redshifts have been obtained ∴ classified.

Multi-wavelength campaign

Investigate optical variability of blazars

- **Intra-day variability (IDV)**
  - probe inner vicinity of BH - upper limit on the BH mass.
- **Short-term variability (STV)**
  - Study structure of jet and accretion disc, and their interactions. Search for colour variations.
- **Long-term variability (LTV)**
  - Broadband correlations to study emission mechanisms.

Photometric obs: SHOC

Sutherland High-Speed Optical Cameras

POETS: Portable Occultation, Eclipse and Transit Systems

9 targets

Observing runs: 1 week August 2014, 3 weeks December 2014 and 2 weeks May 2015.

Spectroscopic observations

(1) Grating Spectrograph mounted @ Cassegrain focus on the SAAO 1.9-m telescope.

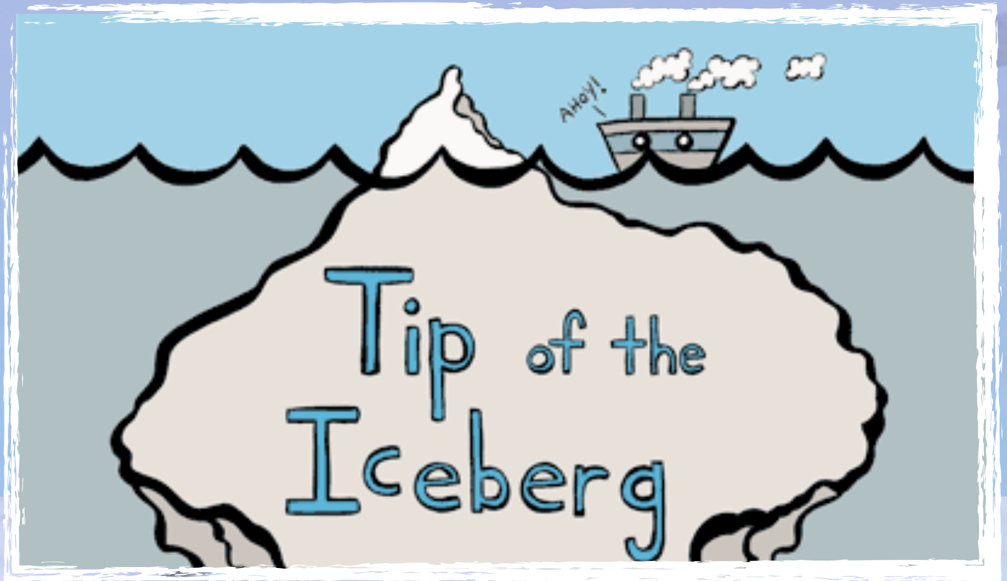
(2) Robert Stobie Spectrograph (RSS) mounted @ prime focus of SALT

= 12 targets

(1) redshift solutions

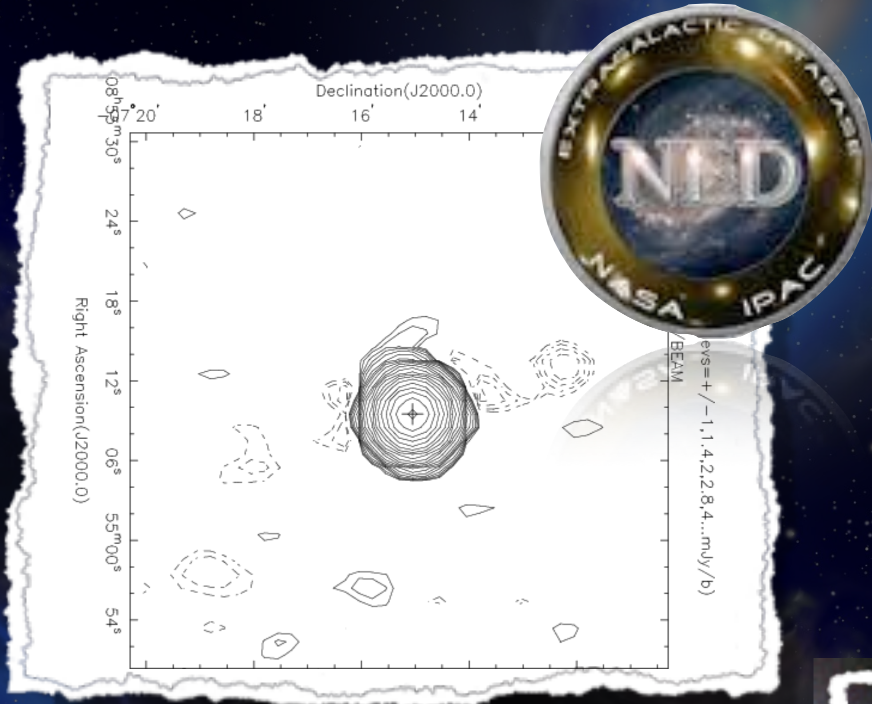
(2) Wλ

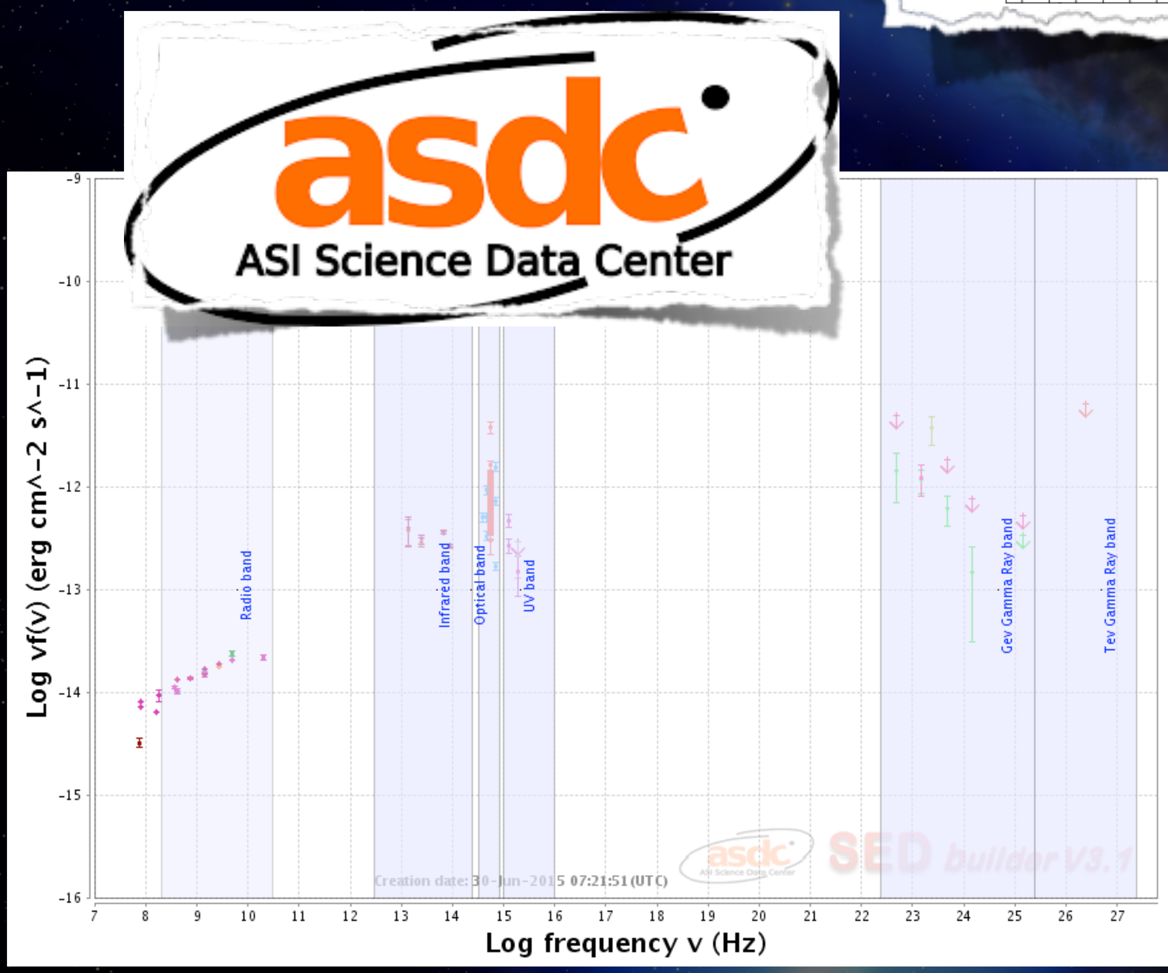
(3) FWHM (km/s)

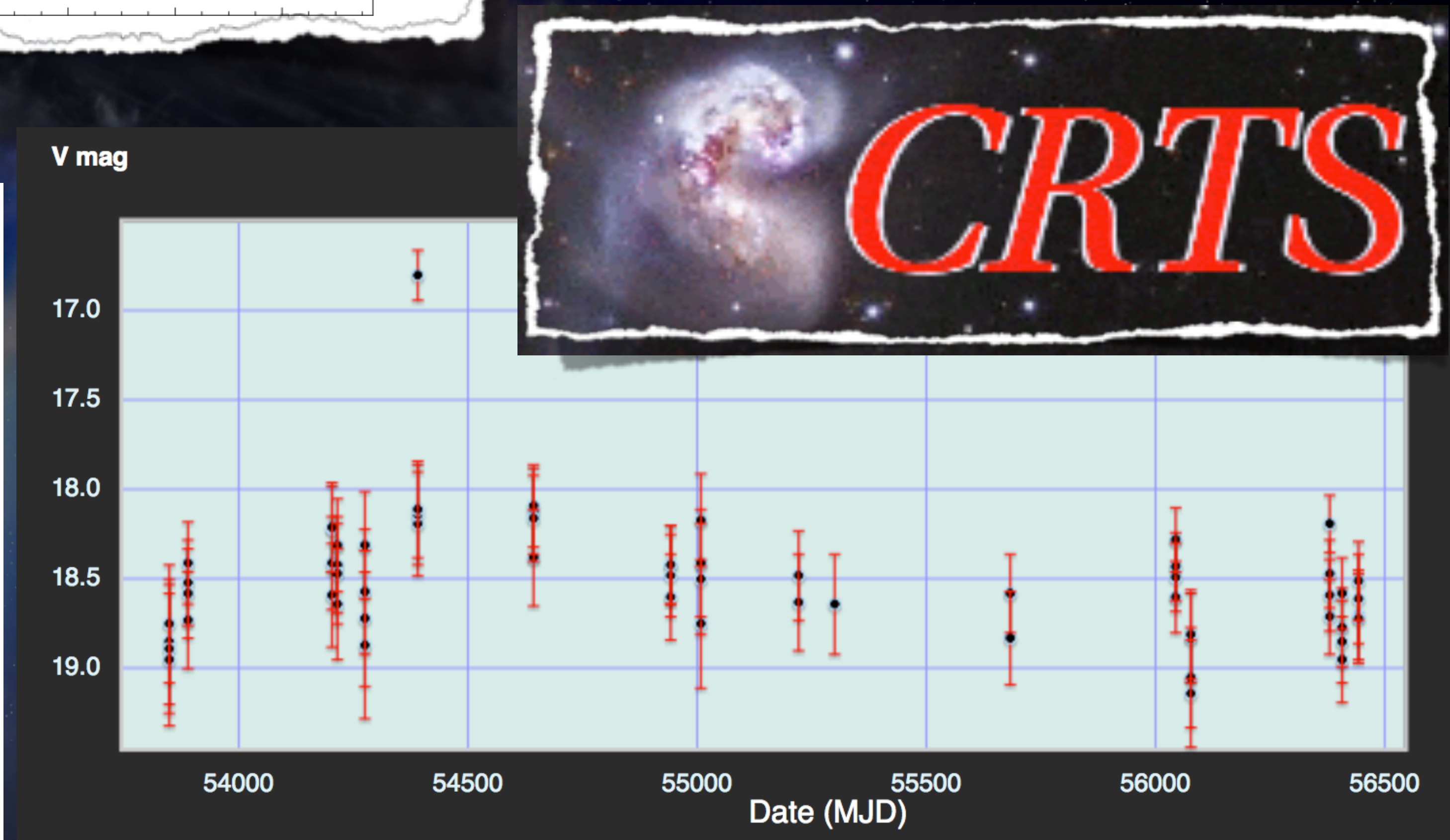


Multi-wavelength data

Archival data...

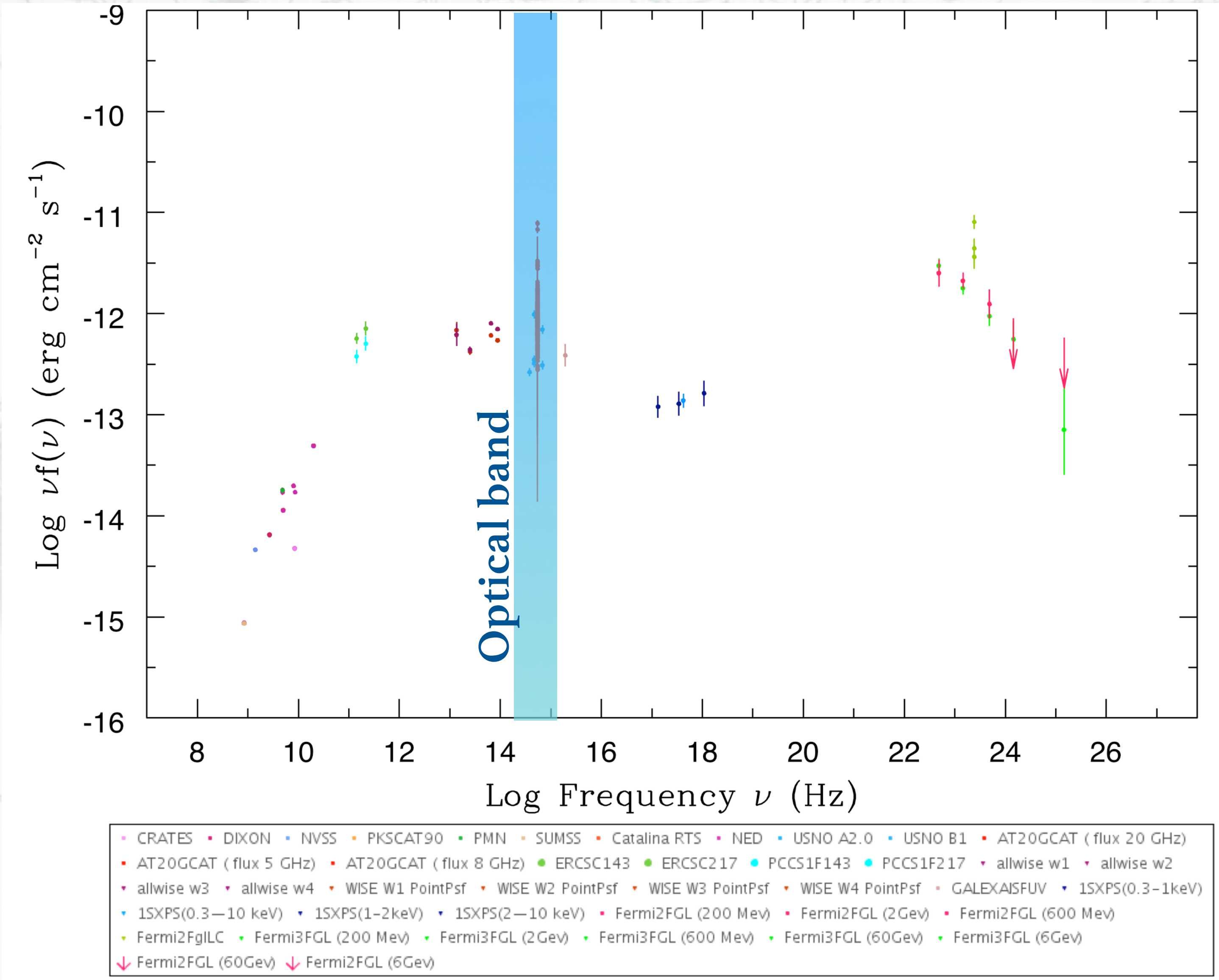






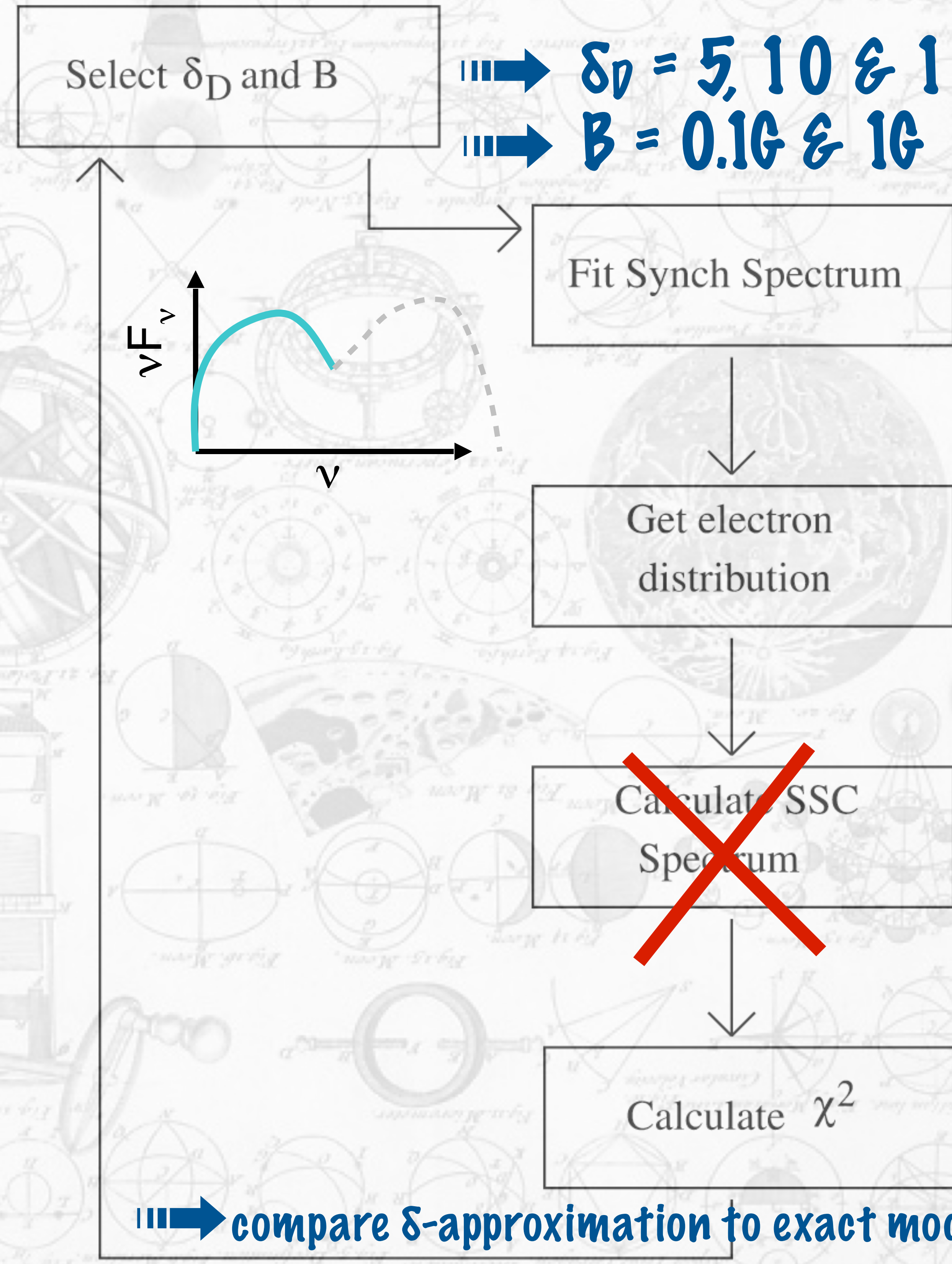
The CRTS survey is funded by the National Aeronautics and Space Administration under Grant No. NNG05GF22G issued through the Science Mission Directorate Near-Earth Objects Observations Program.

Broadband SEDs



δ-approximation

— fit a broken power-law to synchrotron emission in order to determine the ν_{peak}: LSP, ISP or HSP blazar



compare δ-approximation to exact model

δ-approximation

$$f_\epsilon^{\rm syn} = \nu F_\nu = \frac{\delta_{\rm D}^4}{6\pi d_{\rm L}^2} c\sigma_{\rm T} U'_{\rm B} \gamma_{\rm s}'^3 \, N'_{\rm e}(\gamma'_{\rm s})$$

exact synchrotron emission model

$$\nu F_\nu^{\rm syn} = f_\epsilon^{\rm syn} = \frac{\sqrt{3}\delta_{\rm D}^4 \epsilon' e^3 B}{4\pi h d_{\rm L}^2} \int_1^\infty N'_{\rm e}(\gamma') R(x) d\gamma'$$

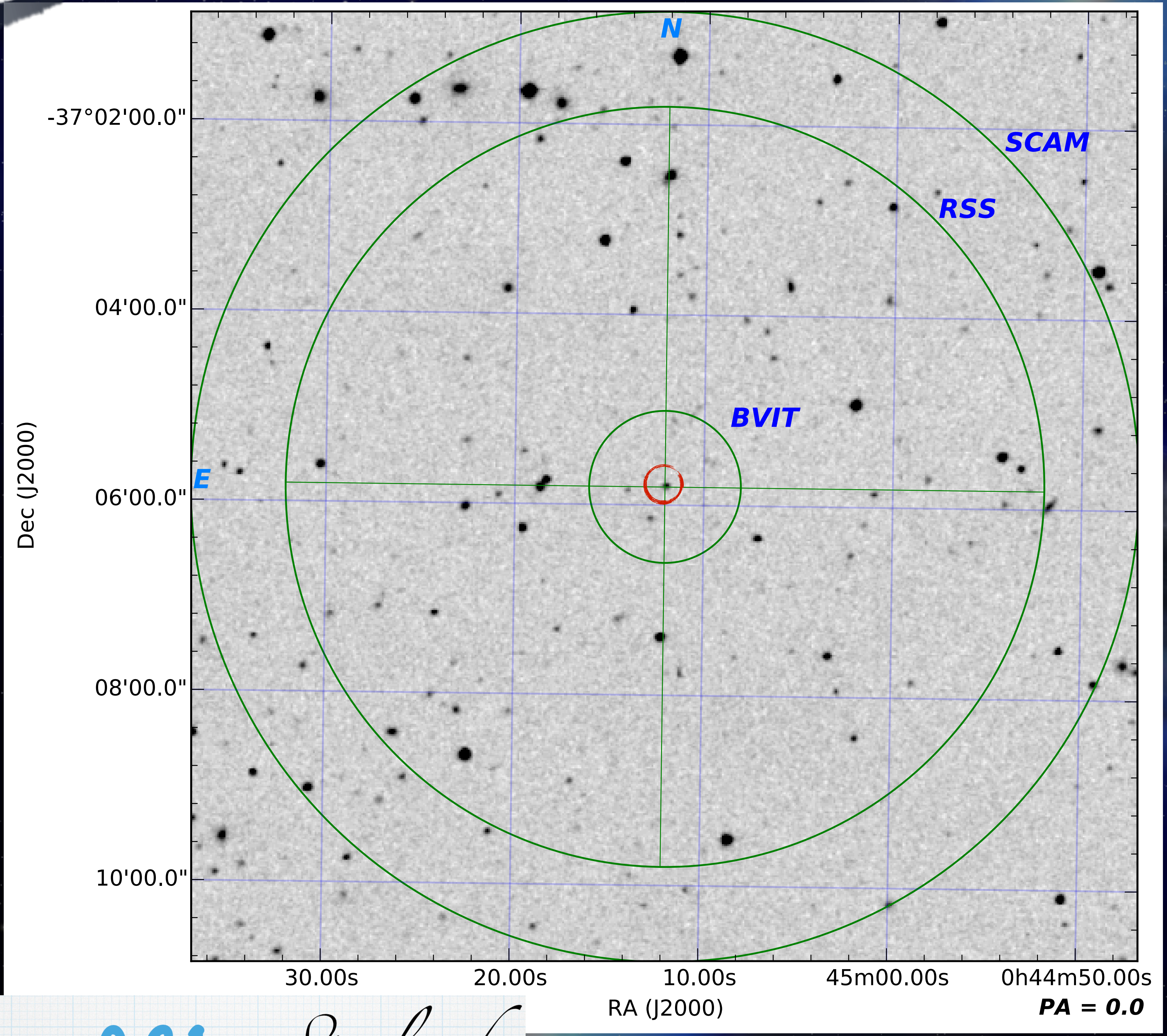
Finke, Dermer, and Böttcher., 2008, ApJ, 686:181 & Dermer, Finke, Krug, and Böttcher, 2009, ApJ, 692:32.

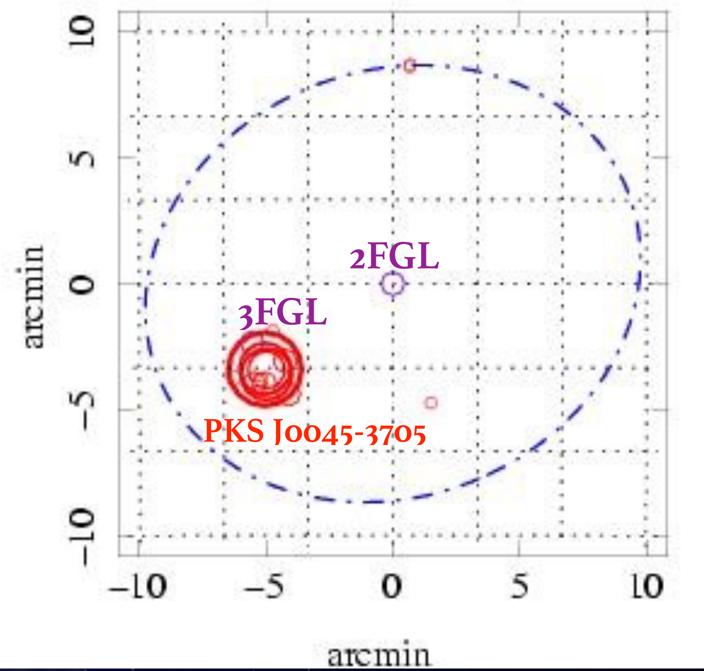
Results

3FGL J0045.2-3704

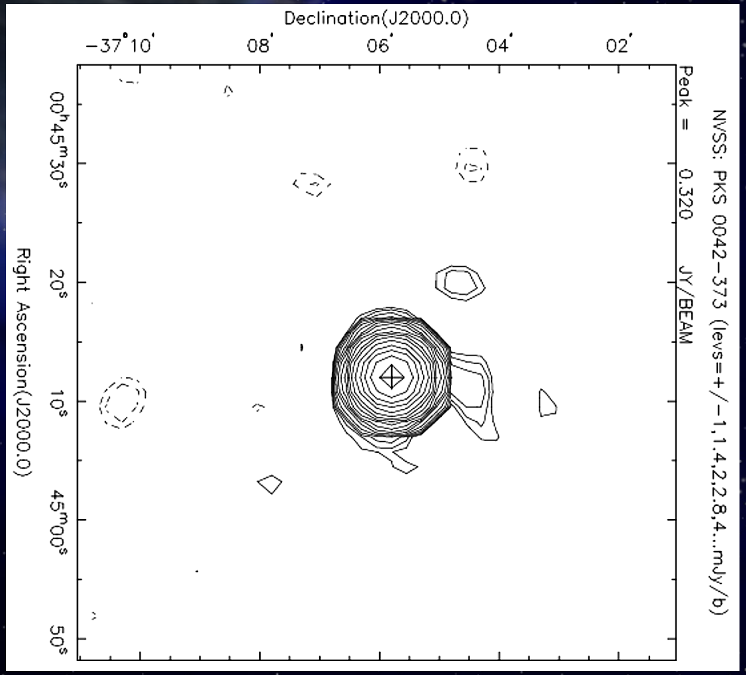
Class prediction by Hassan et al. (2013) : bzq

PKS 0042-373
Vmag = 19.6





$\theta_{95\%}$ = 9.18 arcmin



$S_{4.85}$ = 330 mJy

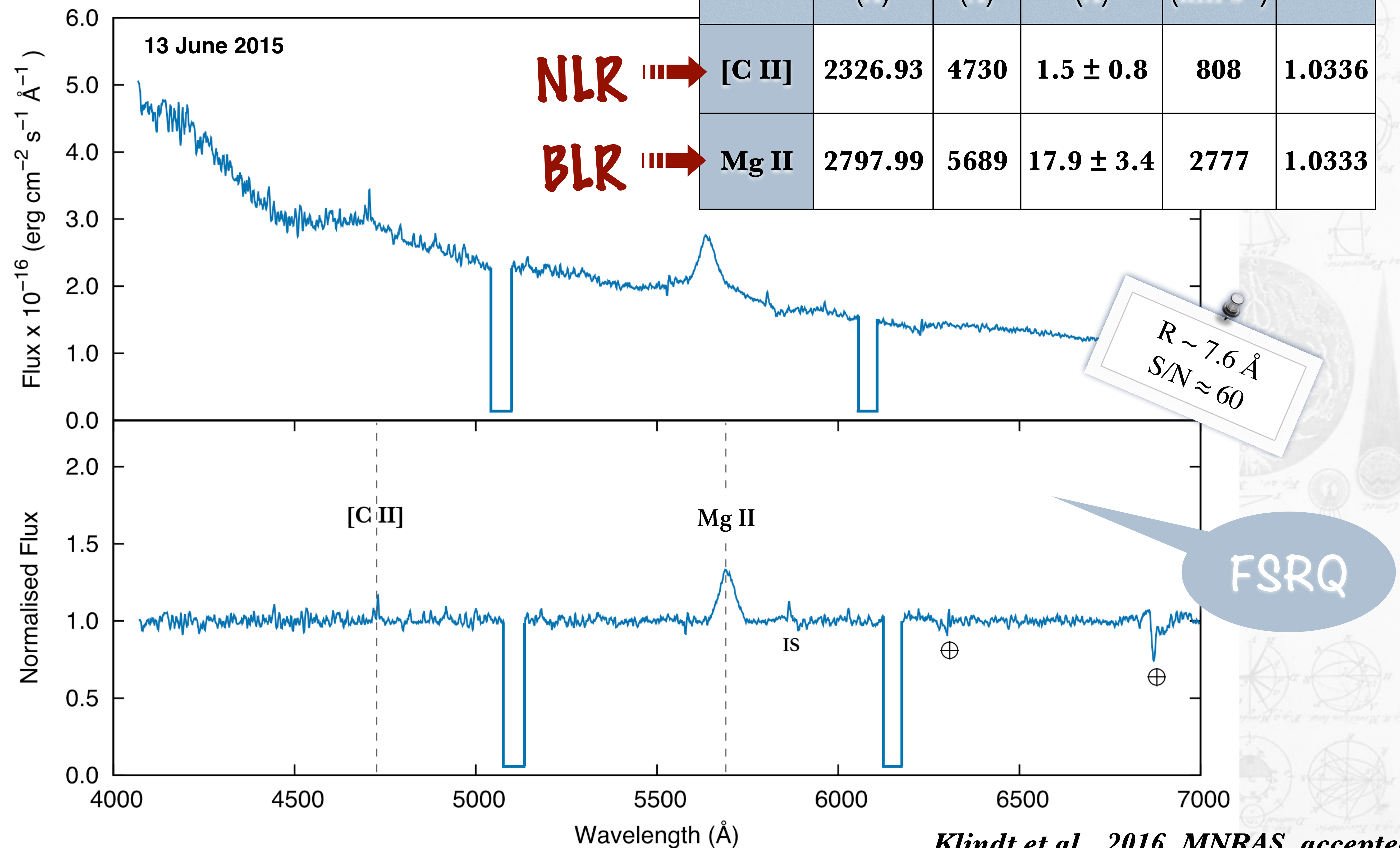
α_{ro} = 0.81 radio loud

#1 3FGL J0045.2-3704 Optical spectra

Vmag = 19.6

Emission lines @ z = 1.0331 ± 0.0004

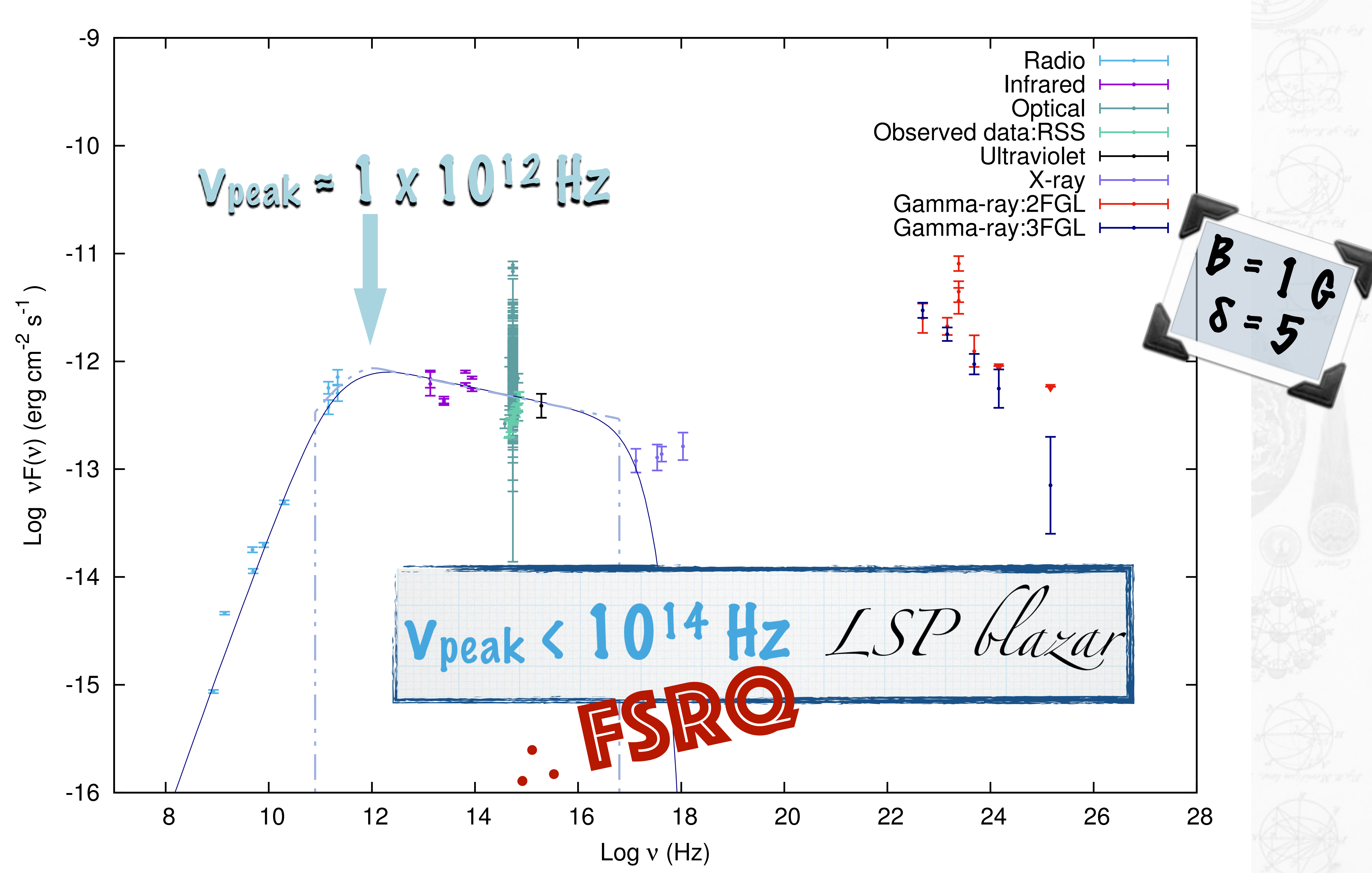
Line	λ_{rest} (Å)	λ_{obs} (Å)	$\lvert W_\lambda \rvert$ (Å)	FWHM (km s^{-1})	z
[C II]	2326.93	4730	1.5 ± 0.8	808	1.0336
Mg II	2797.99	5689	17.9 ± 3.4	2777	1.0333



Klindt et al., 2016, MNRAS, accepted

#1 3FGL J0045.2-3704

Broadband SED: classification

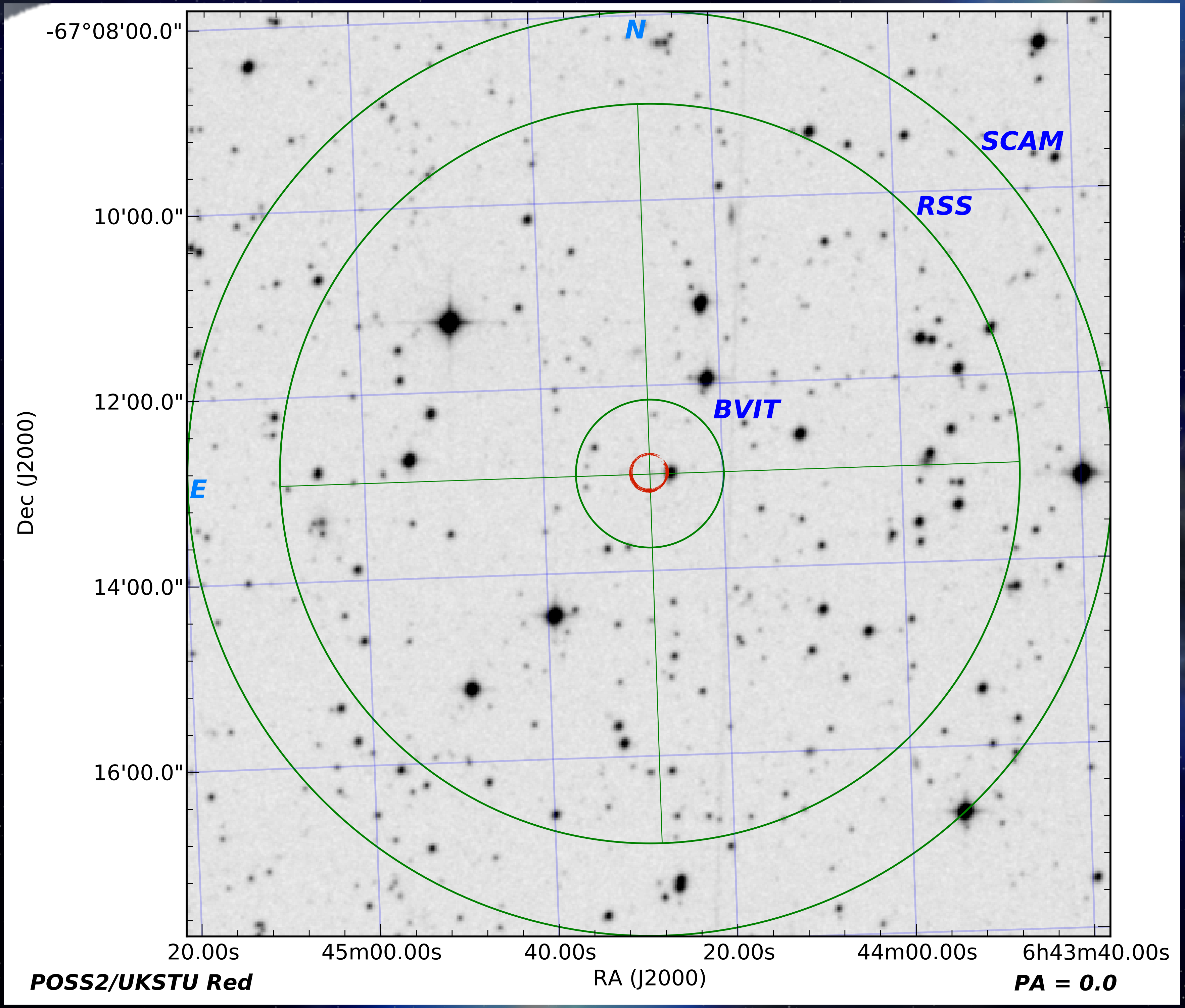


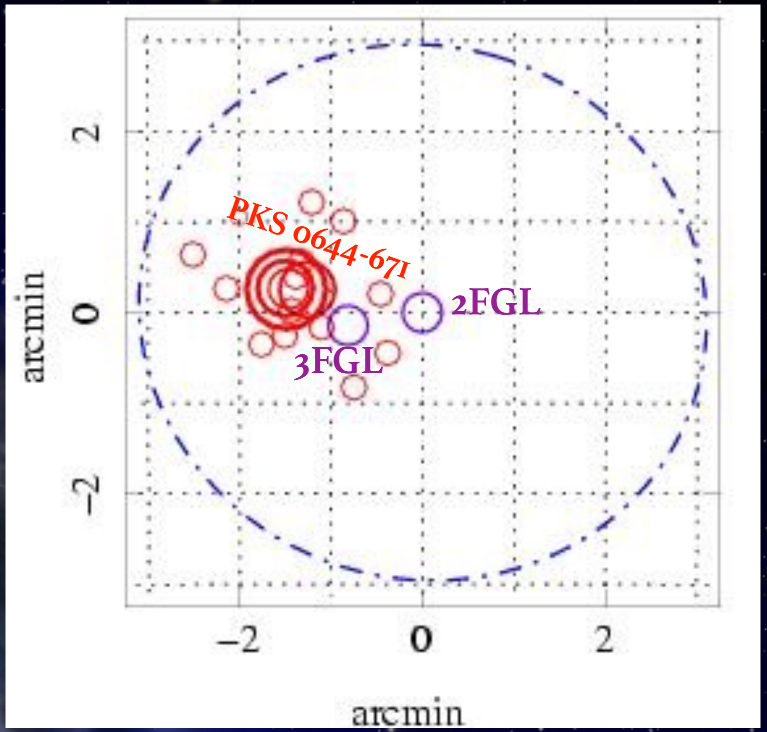
Results

3FGL J0644.3-6713

PKS 0644-671
Vmag = 20.69

$S_{4.85}$ = 218 mJy





$\theta_{95\%}$ = 3.00 arcmin

#3 3FGL J0644.3-6713

Optical spectra

FSRQ

Vmag = 20.69

Table: Observed lines in 2FGL J0644.2-6713. Listed is the equivalent width, $|W_\lambda|$, and the FWHM of each line.

Line	λ_{rest} (Å)	λ_{obs} (Å)	$\lvert W_\lambda \rvert$ (Å)	FWHM (km s^{-1})	z
C IV	1548.19	4539	24 ± 13	7446.3	1.9323
C III]	1908.73	5586	-	-	1.9271

☆ Emission lines @ z = z = 1.930 ± 0.004

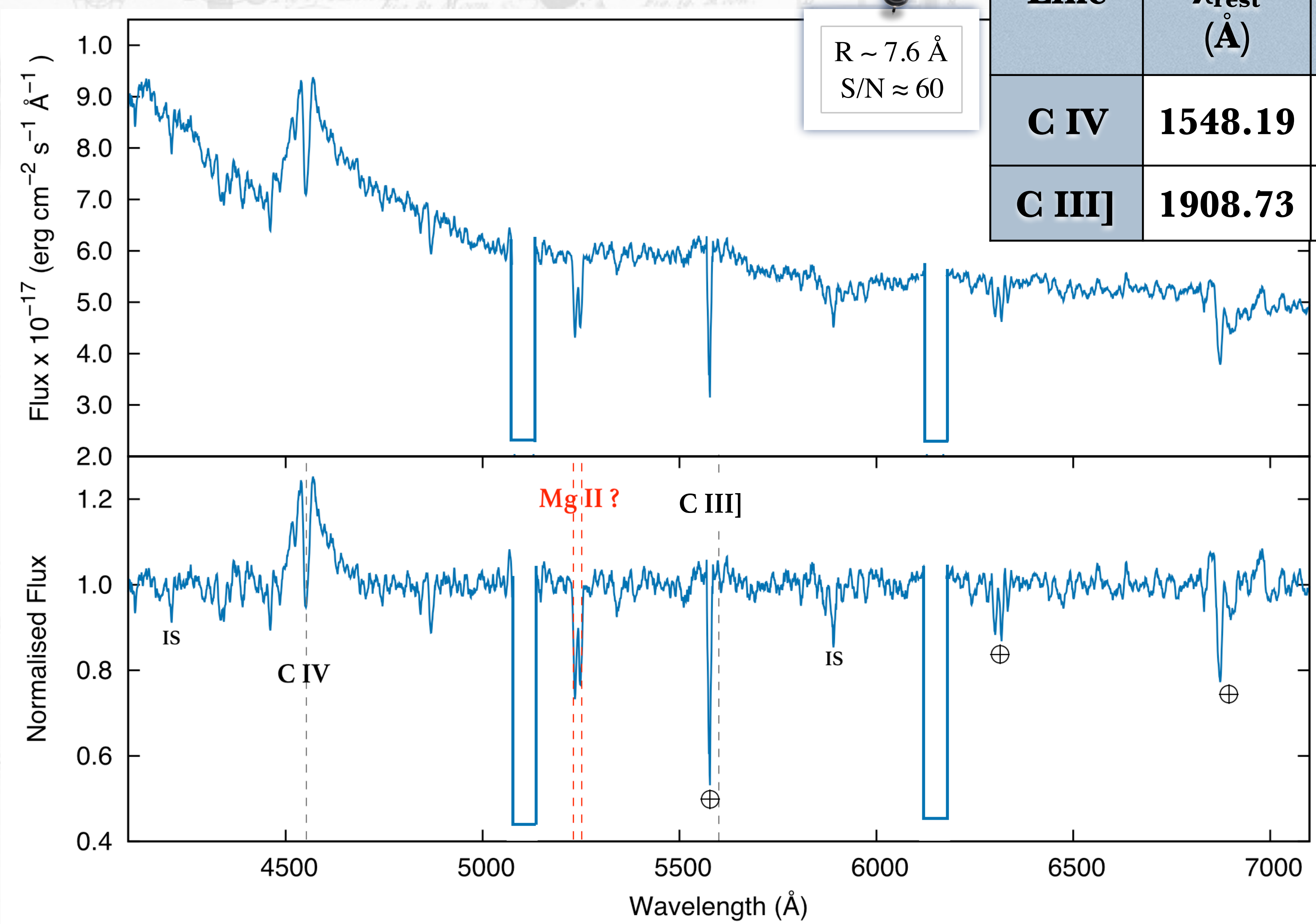


Figure: The average 2FGL J0644.2-6713 spectra obtained with RSS mounted on SALT with setup C.

Narrow double absorption line @ 5240.20 Å: potentially Mg II from an intervening galaxy at z = 0.87.

For an example see VLT spectrum of AO 0235+164 (Raiteri et al., 2007).

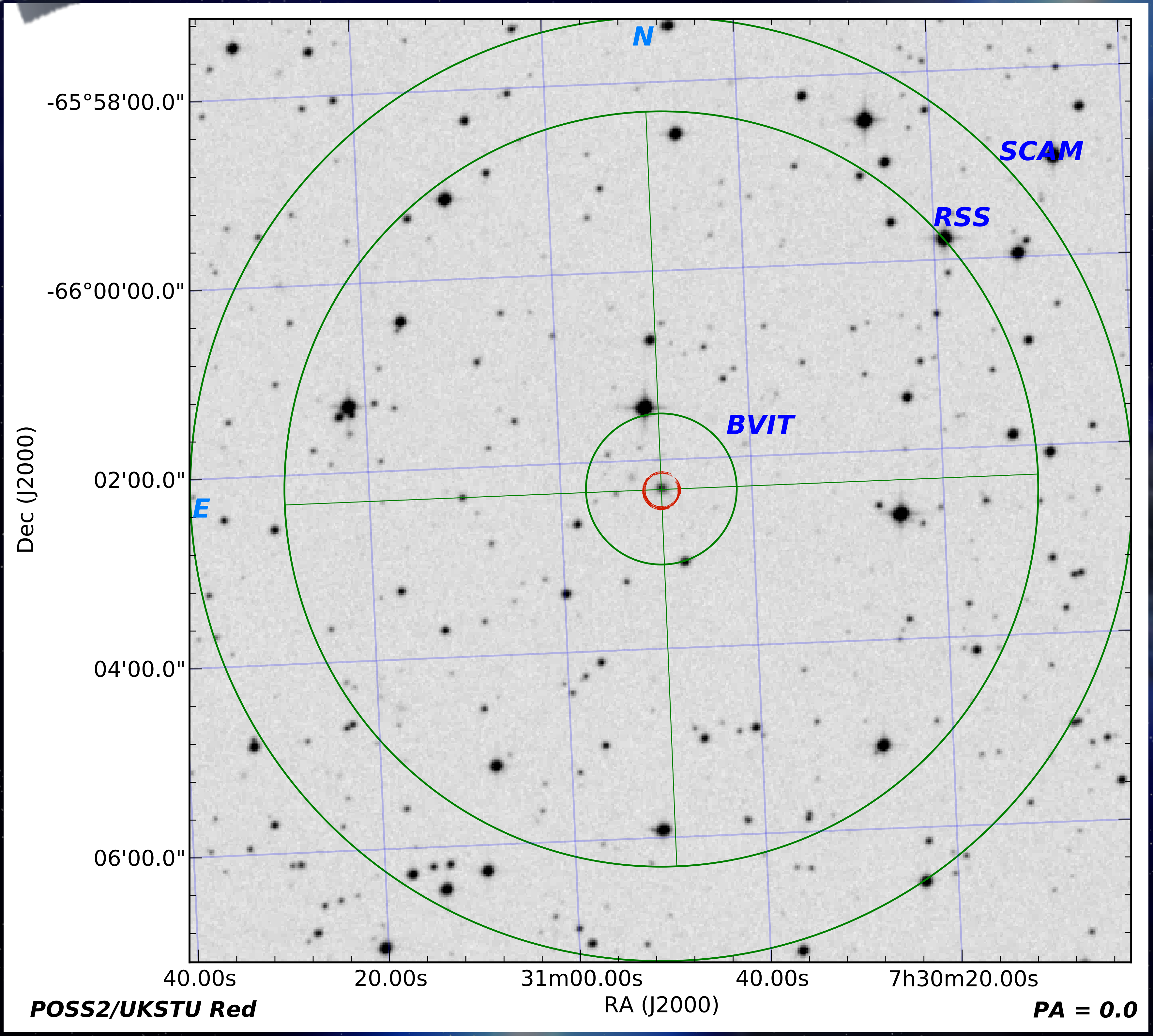
Klindt et al., 2016, MNRAS, accepted

Candidate for VHE studies with IACT
e.g. H.E.S.S.

Results

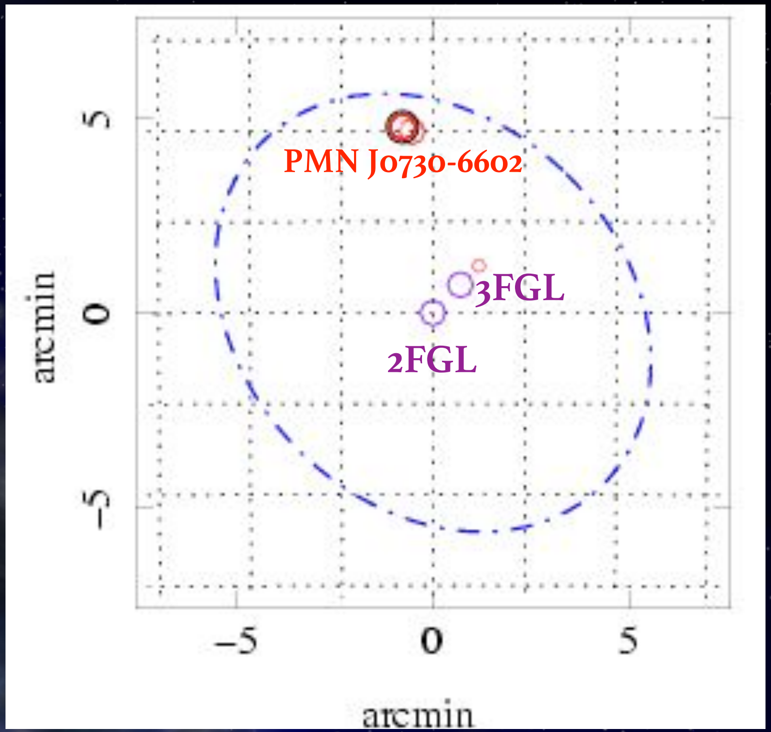
3FGL J0730.5-6606

Class prediction by Hassan et al. (2013) : bzb



PMN J0730-6602
Vmag = 15.13

$S_{4.85}$ = 82 mJy



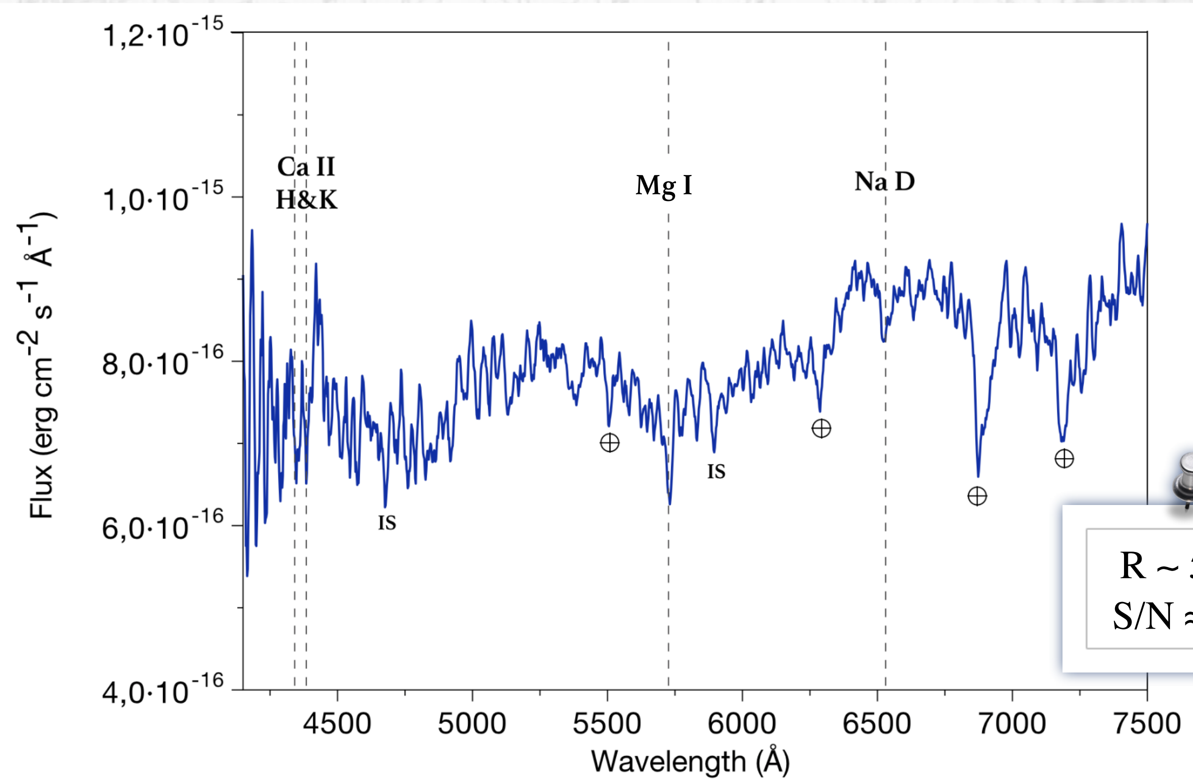
$\theta_{95\%}$ = 5.52 arcmin

α_{ro} = 0.52 radio loud

#4 3FGL J0730.5-6606

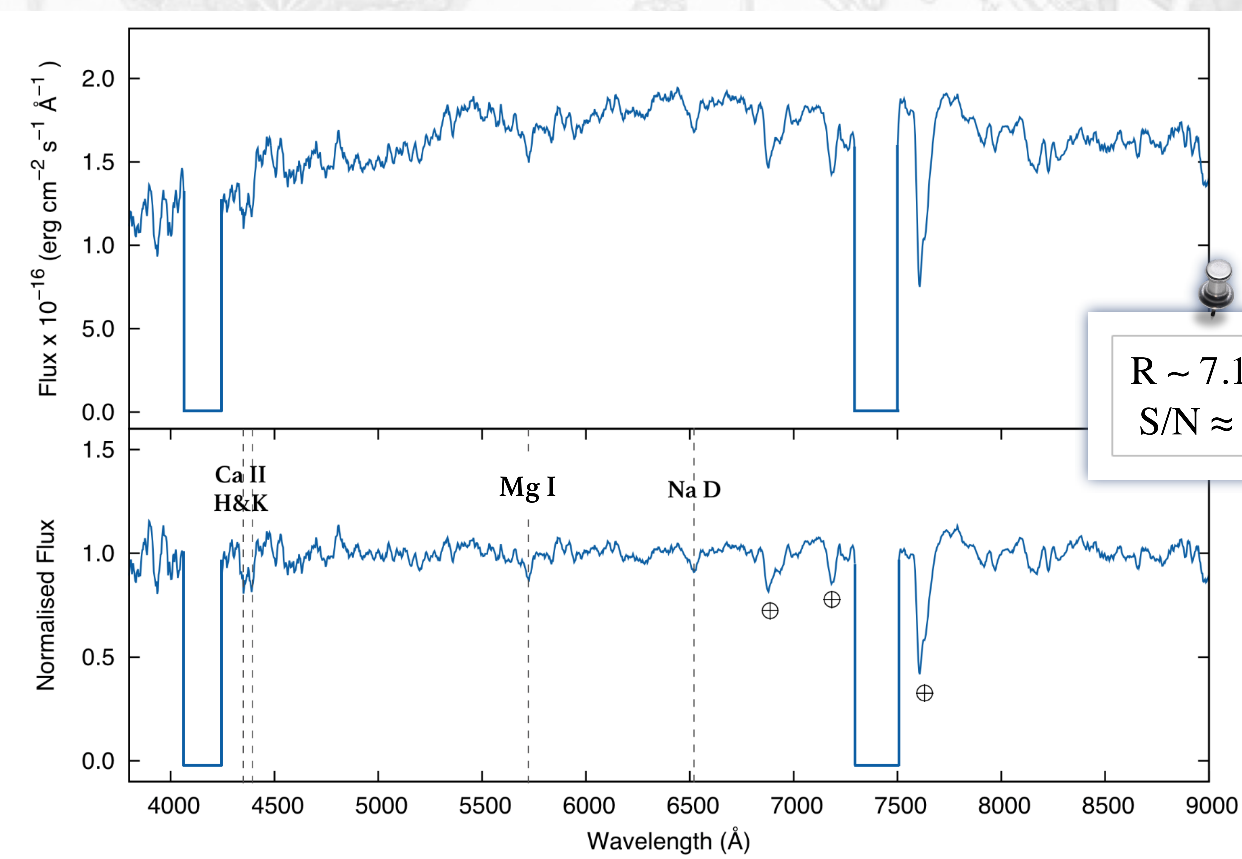
Optical spectra

Vmag = 15.13



R ~ 5 Å
S/N ≈ 15

Figure: The average 2FGL J0730.6-6607 spectrum obtained with the Grating Spectrograph mounted on the SAAO 1.9-m telescope.



R ~ 7.1 Å
S/N ≈ 27

Figure: The average 2FGL J0730.6-6607 spectrum obtained with RSS mounted at prime focus of SALT with setup A and B.

☆ Absorption lines @ $z = 0.1063 \pm 0.0009$

Table: Observed absorption lines in 2FGL J0730.6-6607.

Line	λ_{rest} (Å)	λ_{obs} (Å)	z
Ca II H&K SpCCD	3933.66 3968.47	4349 4387	0.1052 0.1051
Mg I SpCCD	5172.68	5730	0.1076
NaD SpCCD	5895.92	6529	0.1079
Ca II H&K RSS	3933.66 3968.47	4349 4389	0.1052 0.1057
Mg I RSS	5172.68	5724	0.1063
NaD RSS	5895.92	6514	0.1054

BL Lac

$K_{4000} = 0.16 < 0.4$

Klindt et al., 2016, MNRAS, accepted

Candidate for VHE studies with IACT
e.g. H.E.S.S.

Summary of optical results

3FGL name	Instrument	Spectral Line	λ_{rest} (Å)	λ_{obs} (Å)	z	IDV	STV	LTV
J0045.2-3704	RSS	[C II]	2326.93	4730	1.0336	Yes	No	Potential
	RSS	Mg II	2797.99	5689	1.0333			
					$z = 1.0331 \pm 0.0004$			
J0200.9-6635	RSS	C III]	1908.73	4329	1.2677	Yes	Yes	–
	RSS	Mg II	2797.99	6392	1.2846			
	SpCCD	Mg II	2797.99	6398	1.2869			
					$z = 1.28 \pm 0.01$			
J0644.3-6713 *Intervening galaxy*	RSS	Mg II?	2797.99	5240	0.8728	Yes	Yes	Potential
J0644.3-6713	RSS	C IV	1548.19	4539	1.9323			
	RSS	C III]	1908.73	5586	1.9271			
					$z = 1.930 \pm 0.004$			
J0730.5-6606	SpCCD	Ca II H	3933.66	4349	0.1052	Yes	Yes	–
	SpCCD	Ca II K	3968.47	4387	0.1051			
	SpCCD	Mg I	5172.68	5730	0.1076			
	SpCCD	NaD	5895.92	6529	0.1079			
	RSS	Ca II H	3933.66	4349	0.1052			
	RSS	Ca II K	3968.47	4389	0.1057			
	RSS	Mg I	5172.68	5724	0.1063			
	RSS	NaD	5895.92	6514	0.1054			
					$z = 0.106 \pm 0.001$			
J1218.8-4827*	RSS	Ca II H ?	3933.66	4495	0.1425	Yes	–	–
	RSS	Ca II K ?	3938.47	4536	0.1428			
	RSS	G-band ?	4306	4971	0.1544			
					$z = 0.150 \pm 0.006$			
J1407.7-4256*	SpCCD	G-band ?	4306	4863	0.1295	–	–	–
	RSS	G-band ?	4306	4858	0.1284			
	RSS	?	?	5417	?			
	RSS	NaD ?	5895.92	6561	0.1133			
					$z = 0.124 \pm 0.009$			
J2049.7+1002*	SpCCD	Ca II H ?	3933.66	4825	0.2262	–	–	–
	SpCCD	Ca II K ?	3968.47	4860	0.2243			
					$z = 0.226 \pm 0.001$			

Klindt et al., 2016, Optical spectroscopic classification of a selection of Southern Hemisphere Fermi-LAT unclassified blazars , MNRAS, accepted

Summary

Classification of AGUs

3FGL name	Counterpart	Hassan et al. (2013)	Spectral features	*z* obtained from optical spectra	Source Classification
J0045.2-3704	PKS 0042-373	bzq	[C II], Mg II	1.0331 ± 0.0004	FSRQ
J0200.9-6635	PMN J0201-6638	—	C III], Mg II	1.28 ± 0.01	FSRQ
J0644.3-6713	PKS 0644-671	—	C IV, C III]	1.930 ± 0.004	FSRQ
J0730.5-6606	PMN J0730-6602	bzb	Ca II H&K, Mg I , Na I-D	0.106 ± 0.001	HBL
J1218.8-4827	PMN J1219-4826	—	Ca II H&K, G-band ??	0.150 ± 0.006	IBL
J1407.7-4256	CGRaBS J1407-4302	bzb	G-band, Na I-D ??	0.124 ± 0.009	LBL
J2049.7+1002	PKS 2047+098	bzb	Ca II H&K ??	0.226 ± 0.001	LBL

To conclude ...

Multi-wavelength investigation

We have identified **19 blazar candidates** among the 156 AGU sources listed in the Fermi-2LAC catalogue. Of these,

- 13 selected candidate sources are still identified as AGU in the recently released 3FGL catalogue (Acero et al., 2015)
- 3 sources have no classification, but have corresponding source locations
- 3 sources are not listed, which serves as strong motivation for excluding these sources from our analysis.

We have obtained SAAO 1.9-m and SALT spectra for 12 targets listed in our sample, of which we have confirmed redshift measurements for 7 sources in the range:

$0.1 < Z < 1.9$

We have obtained differential LCs for 9 AGU targets to detect IDV and STV. Most sources resembled no IDV, however, 3 sources showed variability of the order of ~0.5 mag over a timescale of a week.

7 sources classified

- 3FGL J0045.2-3704: FSRQ $z = 1.0331 \pm 0.0004$
- 3FGL J0200.9-6635: FSRQ $z = 1.280 \pm 0.010$
- 3FGL J0644.3-6713: FSRQ $z = 1.930 \pm 0.004$
- 3FGL J0730.5-6606: HBL $z = 0.1063 \pm 0.0009$
- 3FGL J1218.8-4827: IBL $z = 0.150 \pm 0.006$
- 3FGL J1407.7-4256: LBL $z = 0.124 \pm 0.009$
- 3FGL J2049.7+1002: LBL $z = 0.2257 \pm 0.0014$

Require more spectra to claim classification

- 3FGL J1154.0-3243: BL Lac ??
- 3FGL J1617.3-2519: BL Lac ??
- 3FGL J1954.9-5640: BL Lac ??

Future studies

Yet to come.

Although AGN have been observed and studied quite extensively since their discovery, there still remains a number of open questions:

- whether the high energy component of non-thermal emission in blazars is formed through hadronic or leptonic processes.

(1) Radio

We have obtained radio flux measurements @ 5 and 8.4 GHz with the HartRAO 26-m telescope for 15 sources.

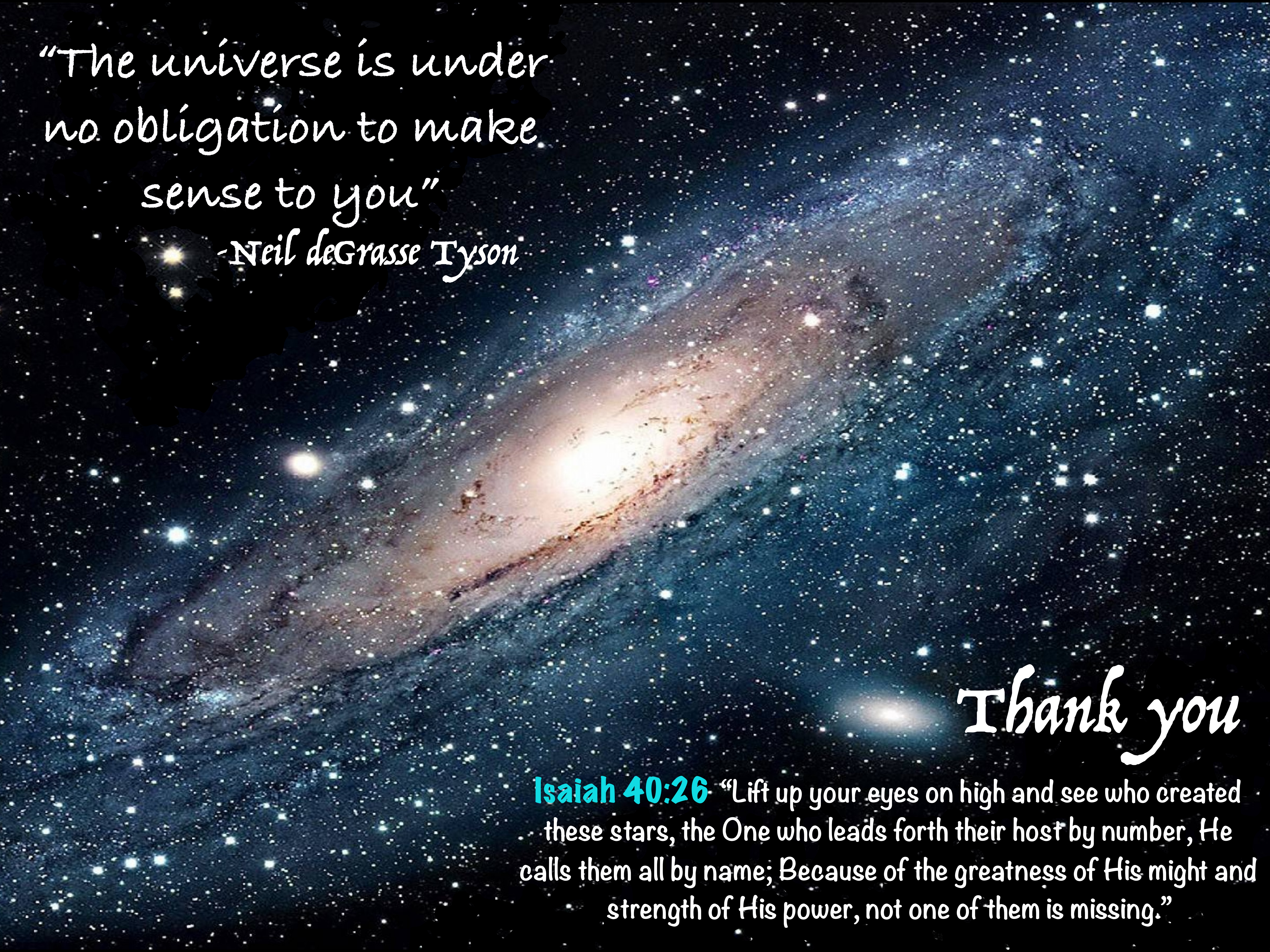
- Based on these results a long term monitoring project can be proposed in order to measure radio flux densities at different frequencies to:
  - firstly, determine the variability and whether it is consistent with blazars.
  - secondly, to establish/verify the flux density at radio wavelengths in order to contribute towards the construction of SEDs for these sources.
- Future works may also include proposing for the Karoo Array Telescope (MeerKAT) observations of the fainter radio sources.

(2) Spectroscopic Follow-ups

RSS follow-up observations for unobserved sources in our sample of 19 targets, as well as acquire higher S/N spectra for sources for which spectral features have been detected and redshift measurements have been established.

(3) Flux variability

Use other statistical test such as Bayesian method to analyse intra-day variability. Propose for long-term simultaneous observations at multi-frequencies to investigate the broadband LTV nature of the targets.


"The universe is under no obligation to make sense to you"
-Neil deGrasse Tyson
Thank you
Isaiah 40:26 "Lift up your eyes on high and see who created these stars, the One who leads forth their host by number, He calls them all by name; Because of the greatness of His might and strength of His power, not one of them is missing."

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