Gamma-ray emission from young radio galaxies and quasars

Principe Giacomo*[1,2,3],

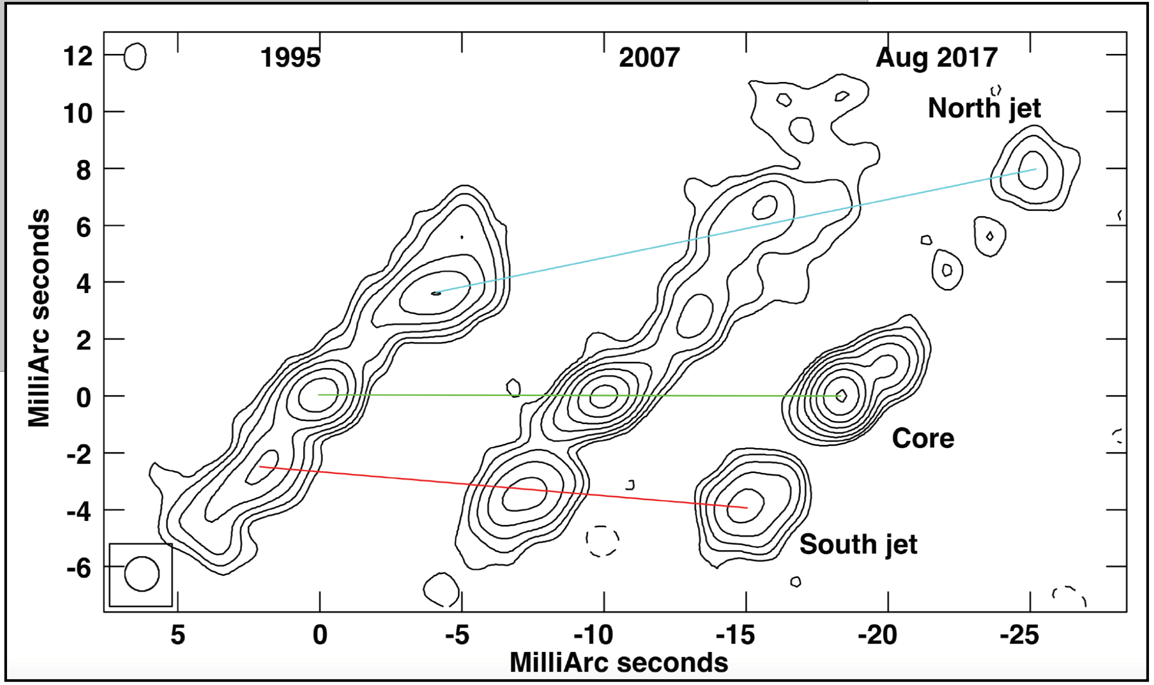
L. Di Venere[4,5], M. Orienti[3], G. Migliori[3], F. D'Ammando[3], M. N. Mazziotta[5], and M. Giroletti[3]

on behalf of the Fermi-LAT collaboration,

[1]Dipartimento di Fisica, Università di Trieste, Trieste, Italy
[2]Istituto Nazionale di Fisica Nucleare, Trieste, Italy
[3]INAF - Istituto di Radioastronomia, Bologna, Italy
[4]Dipartimento di Fisica, Università e Politecnico di Bari, Bari, Italy
[5]Istituto Nazionale di Fisica Nucleare, Bari, Italy

Content

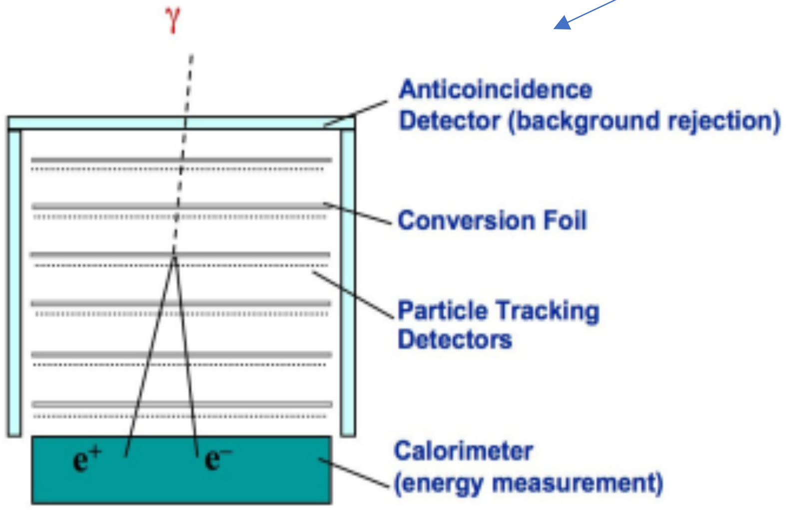
1. Introduction on Fermi-LAT and gamma-ray expectations for young radio sources
2. Sample of young radio sources
3. Fermi-LAT: Data selection and analysis description
4. Fermi-LAT results:
   - individual sources
   - stacking analysis
5. Discussion
   Investigating the origin of the gamma-ray emission
6. Conclusion

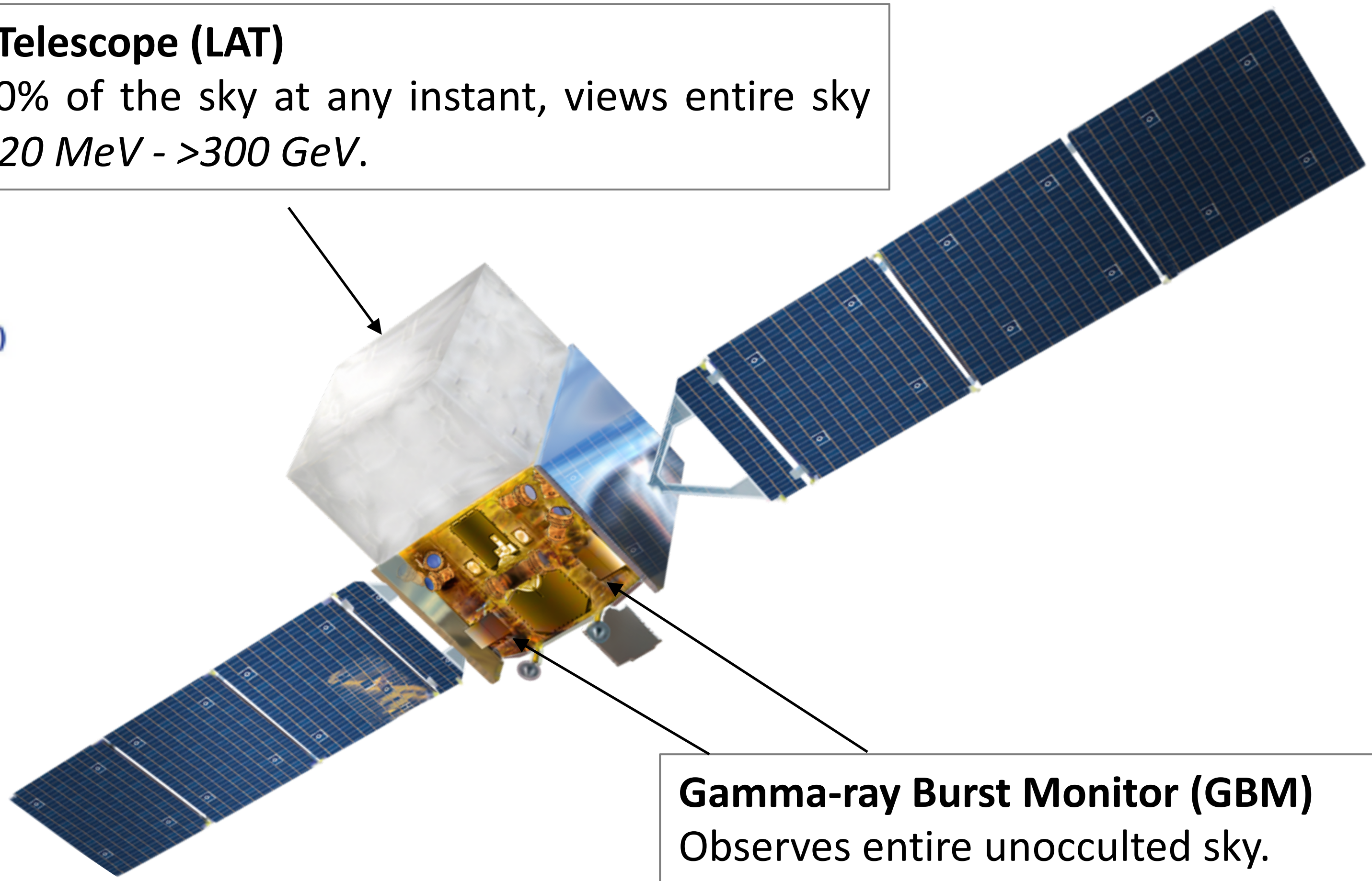


NGC 3894, Principe et al. (2020)

The Fermi observatory

Large Area Telescope (LAT)
Observes 20% of the sky at any instant, views entire sky every 3 hrs *20 MeV - >300 GeV*.





Gamma-ray Burst Monitor (GBM)
Observes entire unocculted sky.
Detects transients from 8 keV - 40 MeV

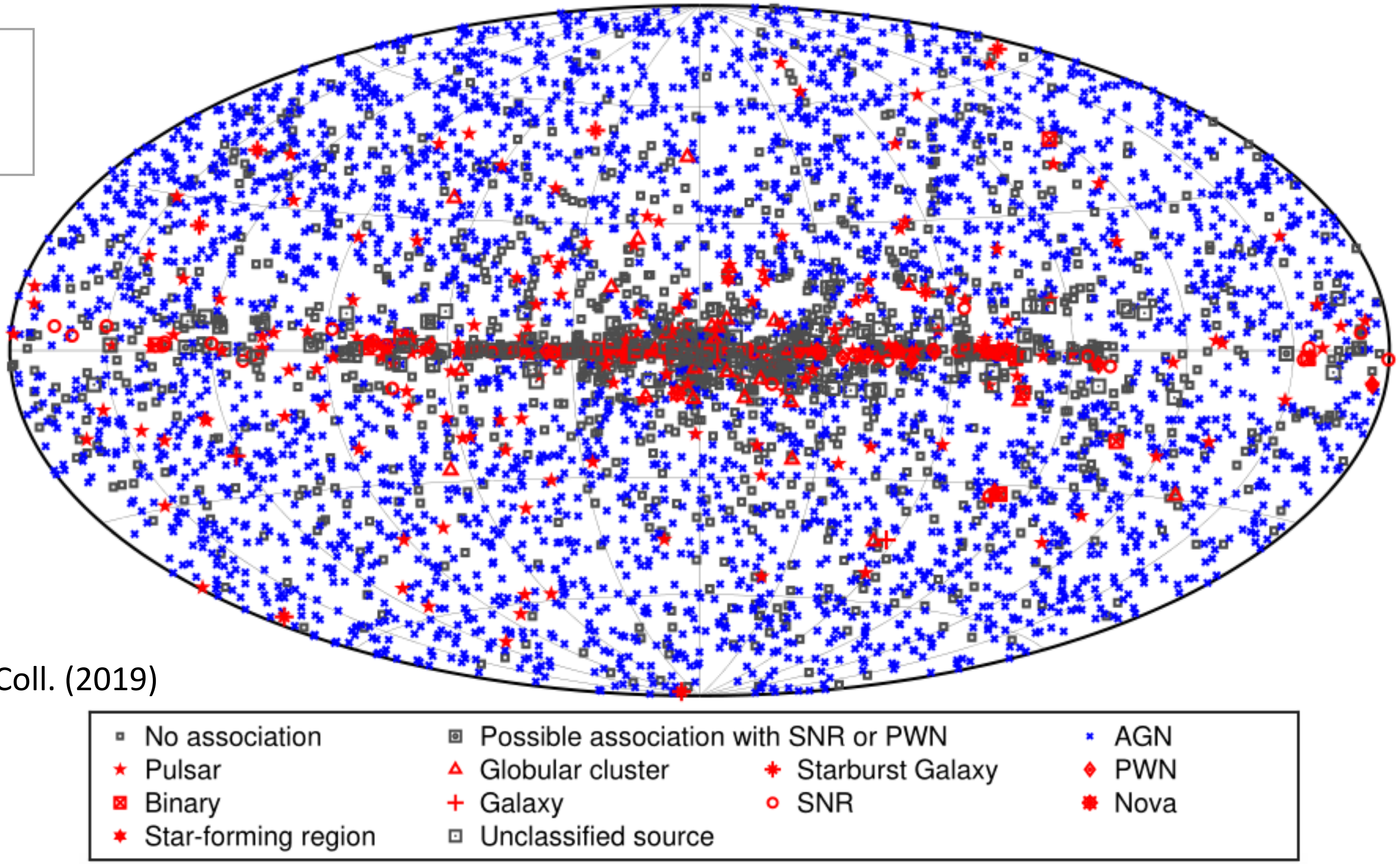
International collaboration between NASA and DOE in the US and agencies in France, Germany, Italy, Japan and Sweden

Fermi-LAT sources

Gamma-ray sky dominated by blazars. Only 2% are radio galaxies (or misaligned AGN), larger jet inclination angles (>10°) and smaller Doppler factor δ≤2−3 (*4LAC*, Fermi-LAT coll. 2019)

42 radio galaxies
5 CSS
(>3000 AGNs)

4FGL catalog
(5065 sources)



4FGL, Fermi-LAT Coll. (2019)

Gamma-ray expectation for young radio sources

Evolutionary scenario (*Fanti et al. 1995; Readhead et al. 1996; Snellen et al. 2000*):

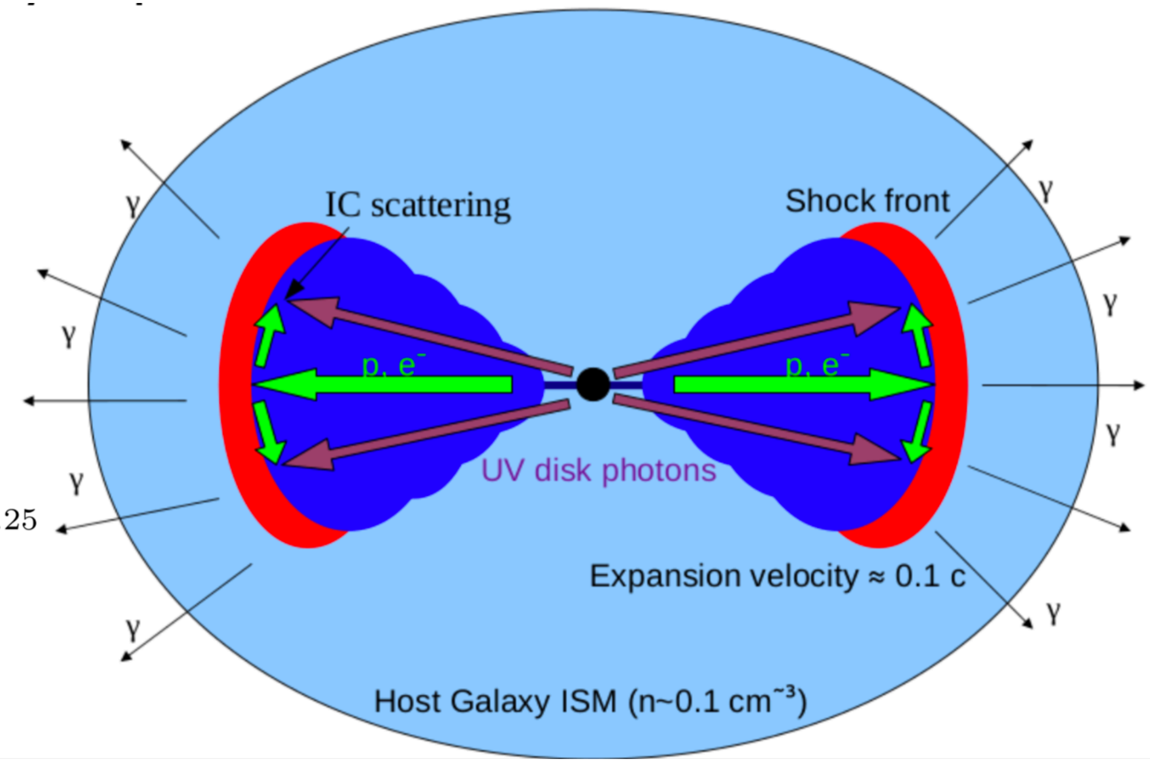
- the size of a radio source is strictly related to its age,
- given their intrinsically compact size, the population of GHz-peaked spectrum (GPS, size<1kpc) and compact steep-spectrum (CSS, size>1kpc) radio sources were proposed as the progenitors of classical radio galaxies.

Gamma-ray emission is expected: mainly due to Inverse Compton of the UV photons from the disk upscattered by the lobes' electrons [*Stawarz et. al. (2008)*].

The high-energy luminosity strictly depends on: linear size, jet power, UV photons, energy range, equipartition condition

$$\frac{\epsilon L_\epsilon}{10^{42}\mathrm{erg/s}} \sim 2\frac{\eta_e}{\eta_B}\left(\frac{L_{\rm jet}}{10^{45}\mathrm{erg/s}}\right)^{0.5}\left(\frac{LS}{100\mathrm{pc}}\right)^{-1}\frac{L_{UV}}{10^{46}\mathrm{erg/s}}\left(\frac{\epsilon}{1\mathrm{Gev}}\right)^{-0.25}$$

$$\frac{(\epsilon S_\epsilon)_{\rm IC/UV}}{10^{-12}\ \mathrm{erg\ cm^{-2}\ s^{-1}}} \sim 1.6\left[\frac{(\epsilon L_\epsilon)_{\rm IC/UV}}{10^{42}\ \mathrm{erg\ s^{-1}}}\right]\left(\frac{d_L}{100\ \mathrm{Mpc}}\right)^{-2}$$

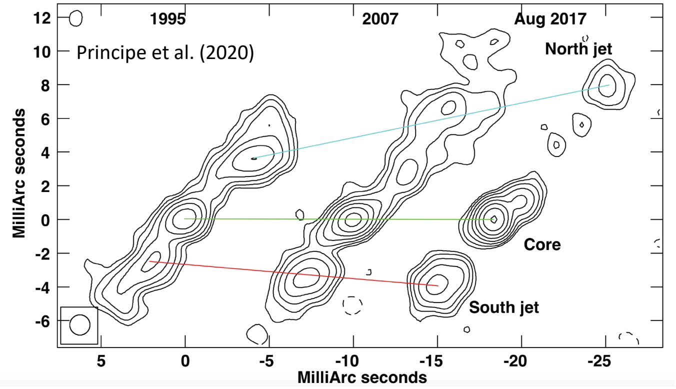


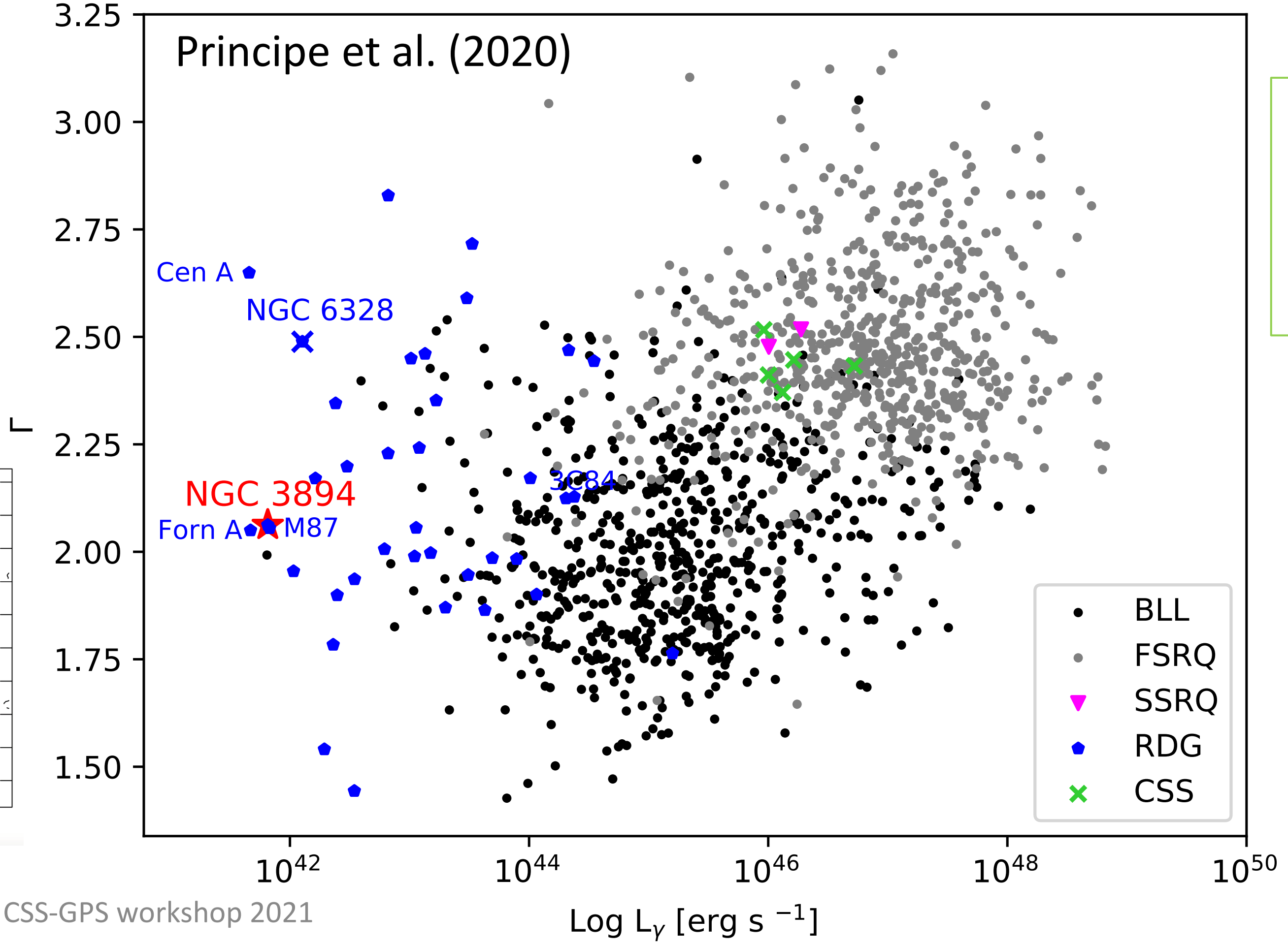
Stawarz et. al (2008)

So far …

Systematic searches for young radio sources in gamma-rays have so far been unsuccessful (D'Ammando et al. 2016), while dedicated studies have reported a handful of detections: the young radio galaxies **NGC 6328** (a.k.a. PKS 1718-649, Migliori et al., 2016) and **NGC 3894** (Principe et al., 2020). The 4FGL source **TXS 0128+554** (BCU*, in 4FGL-DR2) has been recently reclassified as young radio galaxy by Lister et al. (2020).

NGC 3894 (Principe et al. 2020)
est. age: 58 ± 5 years, (LS~4 pc)
viewing angle: 10°< θ< 21°, δ~1.6





*BCU: blazar candidate of unknown type

4FGL contains also 6 CSS-quasars: 3C 138, 3C 216, 3C 286, 3C 309.1, 3C 380, PKS B1413+135; while quasar PKS 0056-00, first reported in 4FGL-DR2.

Association of a 4FGL source to the (possible) young radio source ***PMN J1603-4904.*** *However this source present a typical blazar emission with high gamma-ray variability.*

Sample of young radio sources

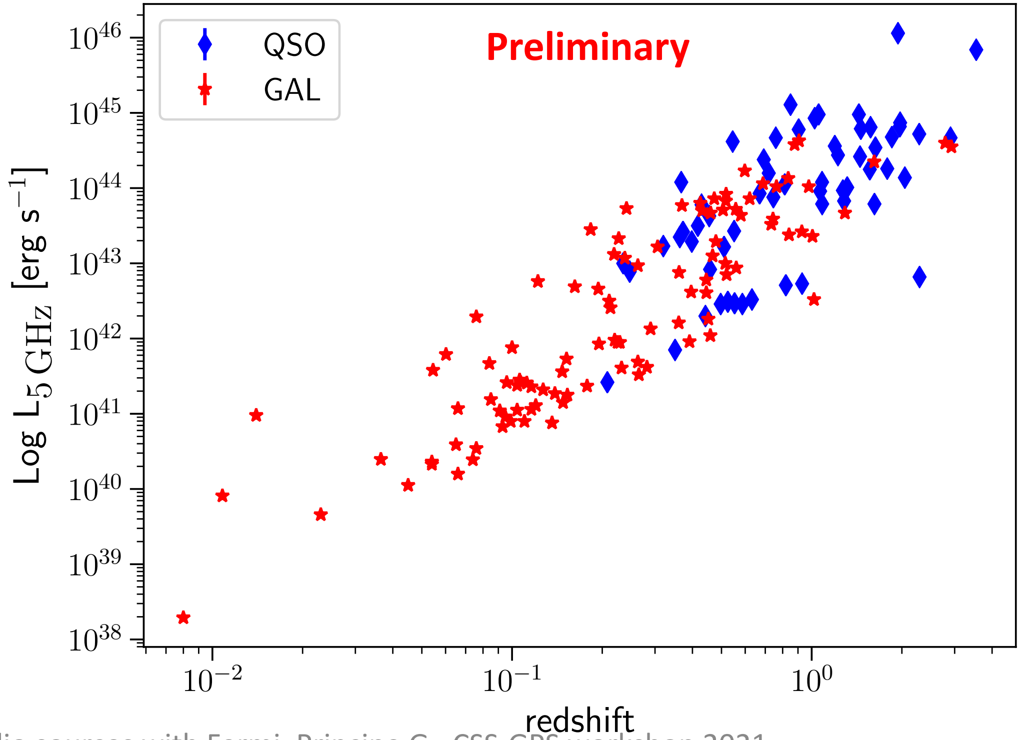
For this work we used 162 young radio sources (103 galaxies, 59 quasars), selected from the following resources:

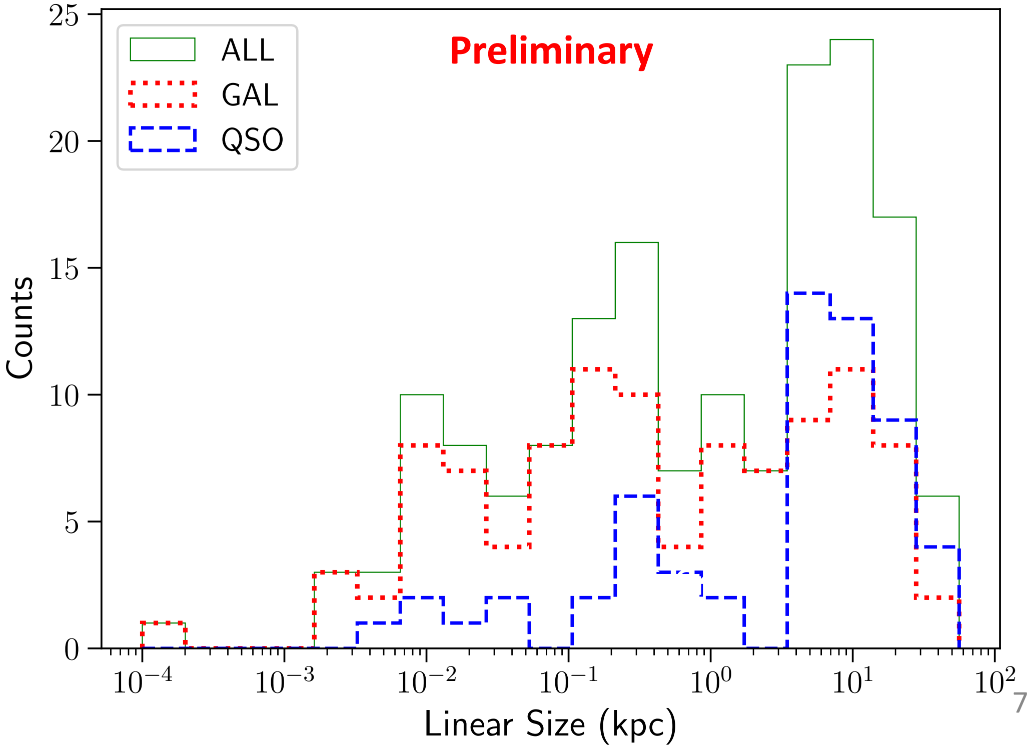
- bona fide radio sources selected using VLBA observations by *Orienti & Dallacasa (2014) [51]*
- nearby (z<0.25) and compact (<2”) radio galaxies contained in the CORALZ sample (Snellen et al. 2004) [25]
- young radio AGNs selected based on SDSS spectroscopy by Liao & Gu (2020) [126]
- GPS and/or CSOs with measured redshifts below 1 and linear sizes below 1 kpc, realized by Wójtowicz et al. (2020), [29]

Final sample

Linear size (LS): 79 CSOs (LS < 1 kpc), 46 MSO (LS: 1 - 10 kpc), 37 sources 10 < LS < 50 kpc.

Radio turnover frequency (f_p): 52 GPS (f_p > 0.5 GHz), 110 CSS (f_p < 0.5 GHz).





Analysis description

Analysis:
1. Likelihood analysis on each single source
optimization, fit, localization(TS>10),SED, lightcurve (1yr bin)
2. Stacked analysis on the undetected (TS<25) sources

We performed the analysis using Fermipy (v. 0.17.4)

Diffuse models:
- galdiff: gll_iem_v07.fits
- isodiff: iso_P8R3_SOURCE_V2_v1.txt

Model for the Fermi-LAT extend sources:
- LAT_extended_sources_8years.fits

Catalog:
We use one of the latest version of the **4FGL**:
- gll_psc_v21.fit

For a comparison of the results we also used the *4FGL-DR2*

Data Selection	Values
IRFs	P8R3_SOURCE_v2
PSF Classes	All [PSF0 and PSF1 excluded, E < 300 MeV] [PSF0 excluded, 300 MeV < E < 1 GeV]
Time Intervals	**11.3 years**
Energy Range	100 MeV – 1 TeV
Zenith angle	< 105° [< 85°, E < 300 MeV] [< 95°, 300 MeV < E < 1 GeV]
Pixel Size	0.1°

Results on single sources

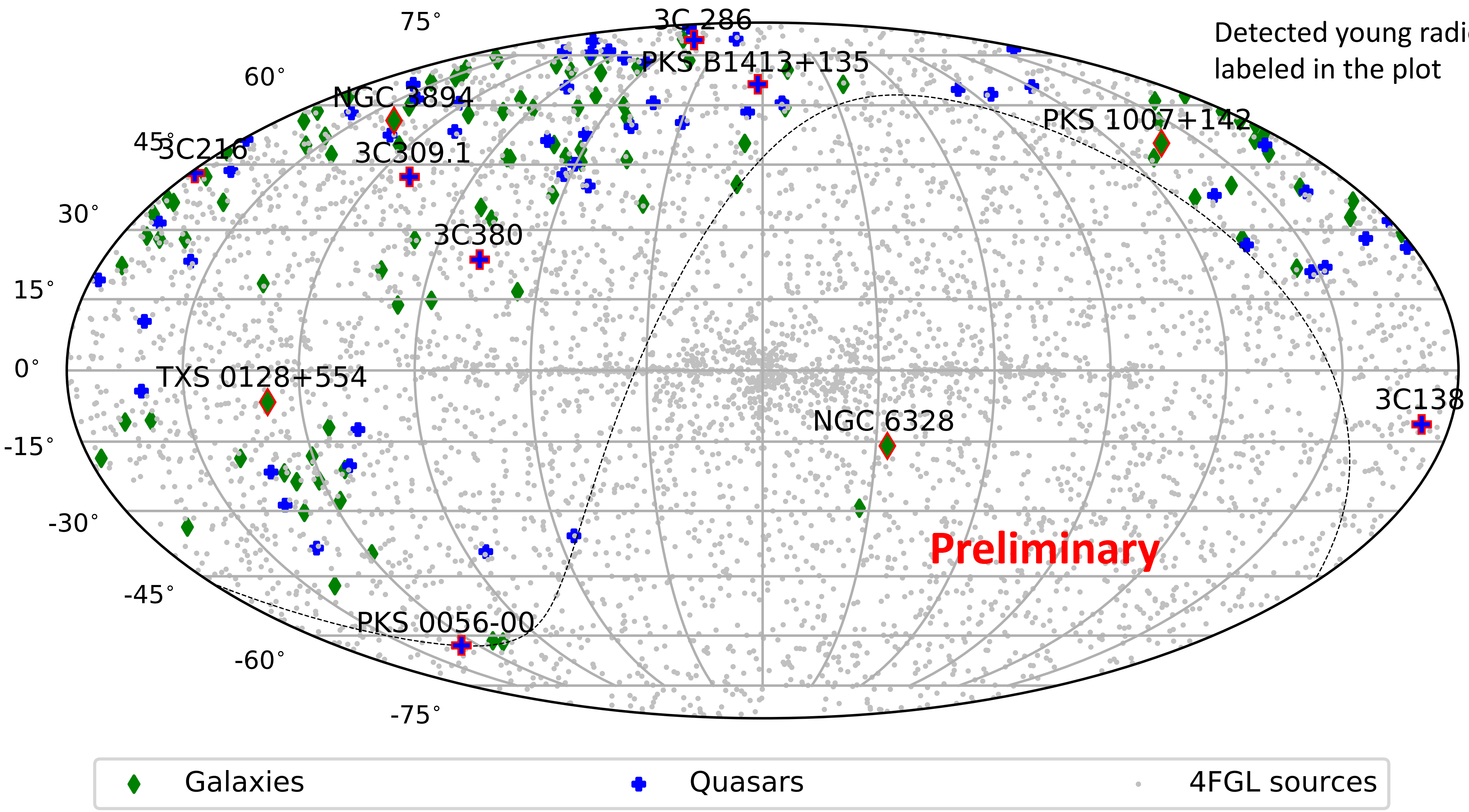
In our analysis we detected 11 sources (4 galaxies and 7 quasars):

* we report the discovery of gamma-ray emission from a compact radio galaxy: PKS 1007+142.
+ 5 quasars present significant gamma-ray variability.

	Name	type	z	LS kpc	ν_p GHz	log $L_{5\,GHz}$ W Hz^{-1}	TS	F_γ 10^{-9} cm^{-2} s^{-1}	Γ	L_γ 10^{44} erg s^{-1}	TS_{var}
						Galaxies					
GALAXIES	NGC 6328	CSO/GPS	0.014	0.002	4	24.28	36	5.30±1.45	2.60±0.14	0.011	5
	NGC 3894	CSO/GPS	0.0108	0.010	5	24.60	95	2.03±0.48	2.05±0.09	0.006	11
	TXS 0128+554	CSO/GPS	0.0365	0.012	0.66	23.69	178	8.03±1.46	2.20±0.07	0.19	9
	PKS 1007+142*	MSO/GPS	0.213	3.3	0.5-2	25.71	31	4.65±1.55	2.55±0.18	2.8	4
						Quasars					
QUASAR	3C 138†	MSO/CSS	0.759	5.9	0.176	27.97	34	2.09±0.89	2.05±0.12	64	68
	3C 216†	LSO/CSS	0.6702	56	0.066	27.23	153	7.78±0.98	2.60±0.09	97	24
	3C 286	LSO/CSS	0.85	25	<0.05	28.41	67	5.60±1.10	2.52±0.12	110	8
	3C 309.1†	MSO/CSS	0.905	17	<0.076	28.08	207	6.33±0.74	2.47±0.07	180	215
	3C 380†	MSO/CSS	0.692	11	<0.05	27.68	2274	36.44±1.48	2.41±0.03	510	68
	PKS 0056-00	MSO/CSS	0.719	15	<0.14	27.50	52	5.21±1.48	2.30±0.15	74	11
	PKS B1413+135†	CSO/GPS	0.247	0.03	8.4-15	26.19	1198	14.72±1.02	2.10±0.03	28	321

Results on single sources

Detected young radio sources are labeled in the plot



PKS 1007+142

PKS 1007+142 (MSO/GPS, z=0.213, LS=3.29 kpc)

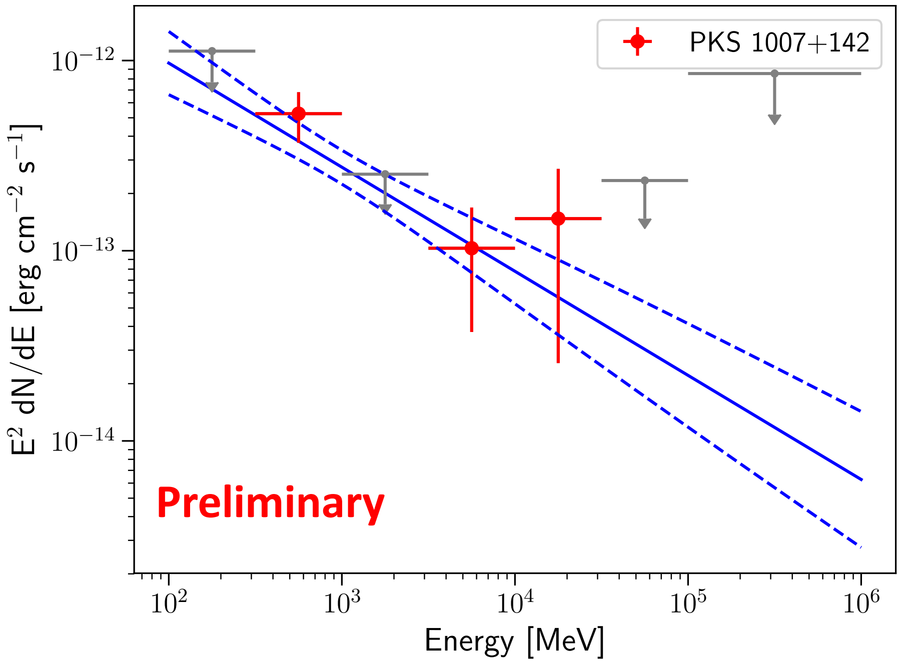
Fermi results

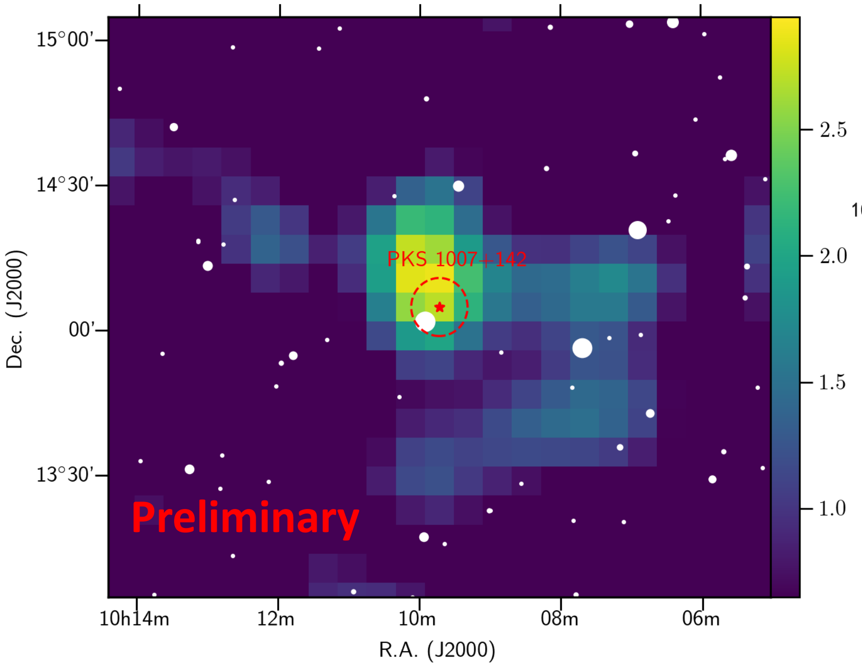
Sign.: TS=31

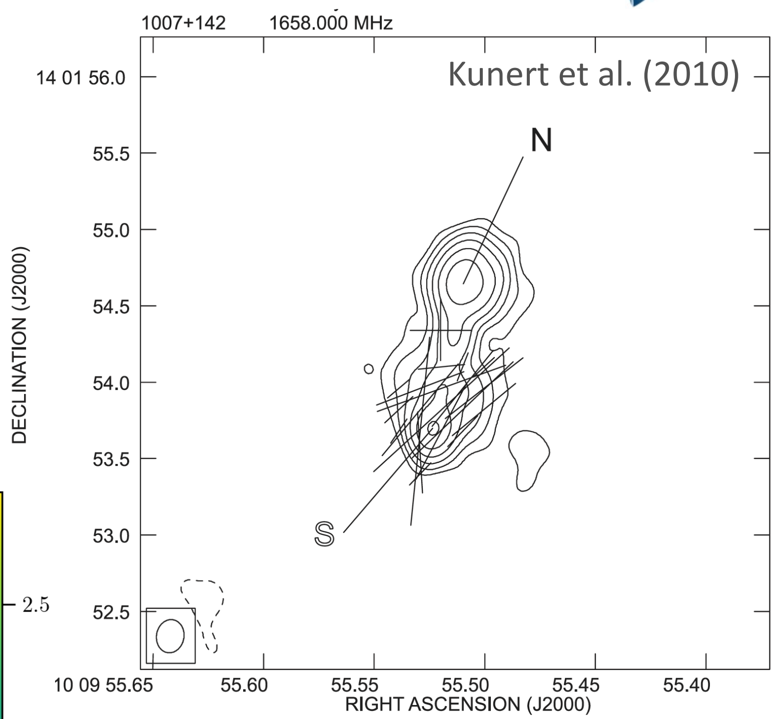
Loc.: (R.A.,decl.(J2000)) = (152.43°$\pm$ 0:07°, 14.08°$\pm$ 0.06°) -> ass. prob. P=0.92

SED – PL: Γ= 2.55$\pm$0.18 , N_0=(1.72$\pm$0.39)x10^{-13} MeV cm^{-2} s^{-1}

Lightcurve: No significant gamma-ray variability observed (TS_{var}= 8)





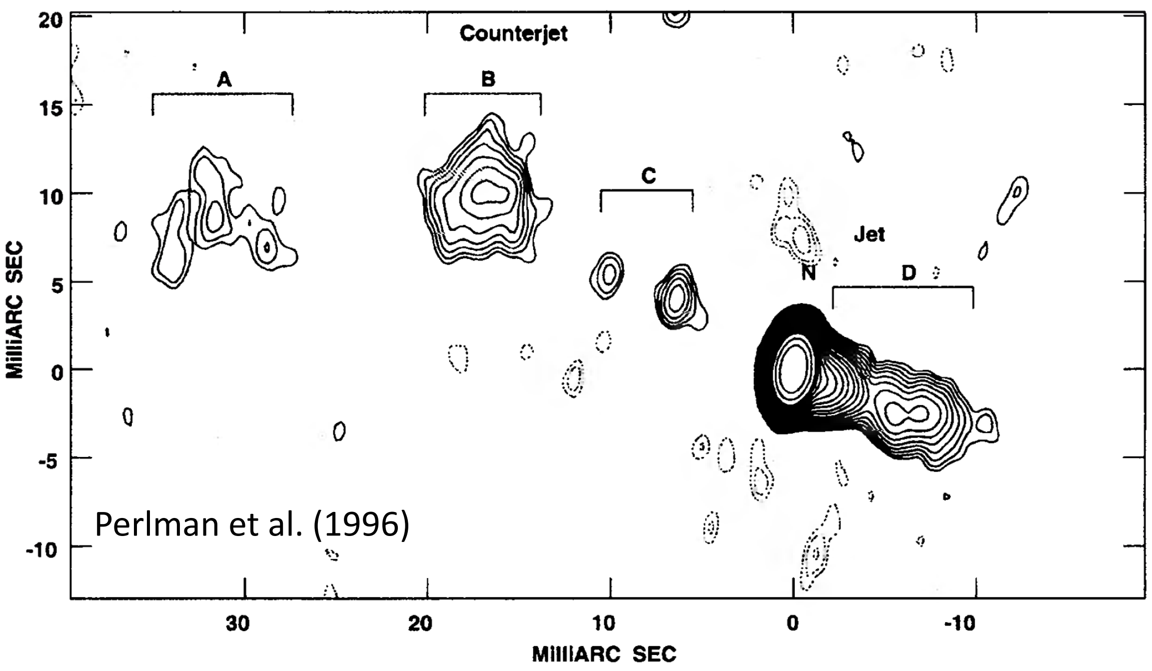


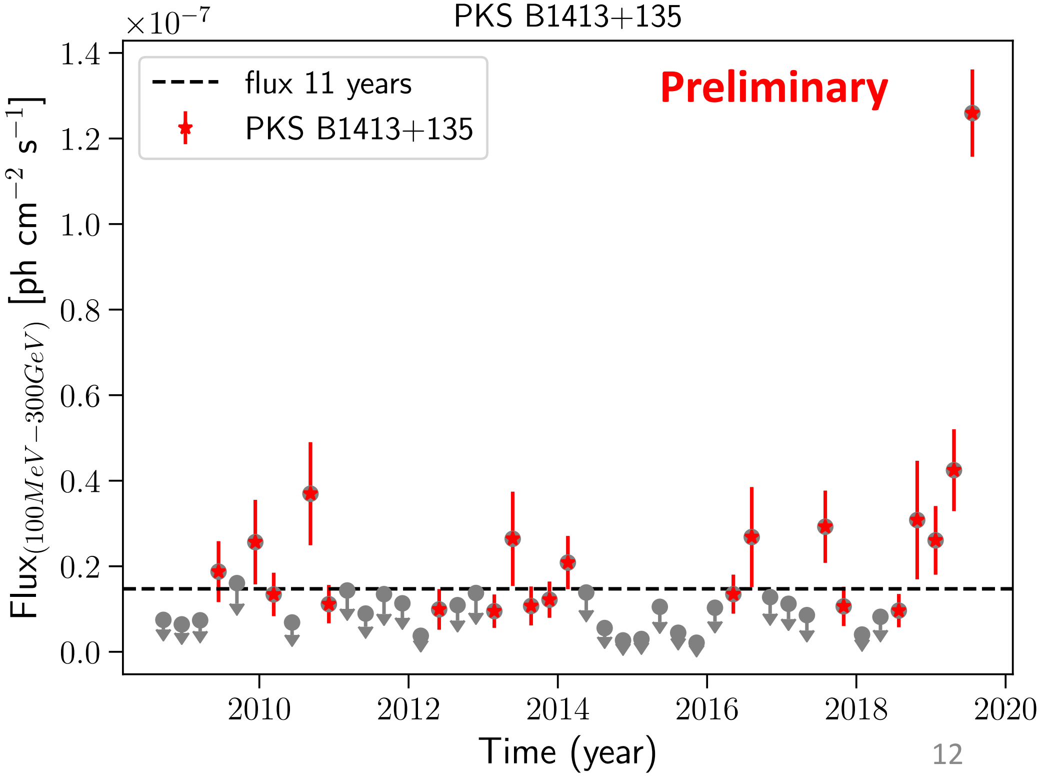
Fermi-LAT TS (in sigma unit).
White circles: radio sources (NVSS catalog). Dimensions are proportional to the flux (arbitrary scale).

The unusual quasar PKS B1413+135

Its classification has been debated for a long time (see also recent paper, Readhead et al. 2020), initially classified as BL Lac, then VLBA obs. showed: (1) a compact radio core, (2) a jet–like structure on a parsec scale, (3) and a counter–jet. The presence of a counter–jet disagrees with the blazar scenario.

Our detection of a bright gamma-ray flare on August - November 2019 supports the idea that the gamma-ray emission is beamed and produced by a relativistic jet at relatively small viewing angle.
Maximum daily-flux on Aug. 29th, F = $(5.4 \pm 1.9)\ 10^{-7}$ ph $cm^{-2}\ s^{-1}$, in agreement with the results in ATel 13049.

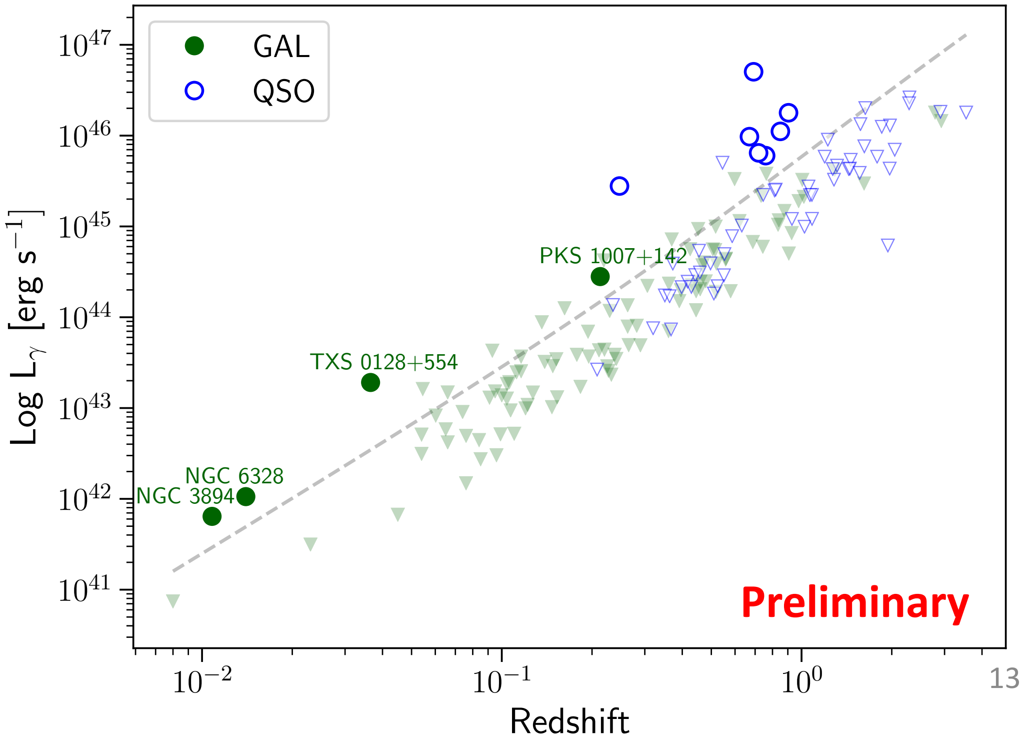




Gamma-ray luminosity and Fermi-LAT sensitivity

	Name	type	z	LS kpc	ν_p GHz	log $L_{5\,\mathrm{GHz}}$ W Hz^{-1}	TS	Flux$_\gamma$ 10^{-9} cm^{-2} s^{-1}	Γ	Lum$_\gamma$ 10^{44} erg s^{-1}
GALAXIES	0404+768	CSO/GPS	0.598	0.866	0.55	27.53	12	2.70±0.81	2.61±0.29	22.2
	1323+321	CSO/GPS	0.369	0.305	0.68	27.07	19	1.36±0.41	2.15±0.23	4.0
	3C346	LSO/CSS	0.162	22.056	<0.045	25.99	13	1.23±0.43	2.07±0.20	0.82
	1843+356	CSO/GPS	0.763	0.022	2	27.32	11	0.59±0.24	1.93±0.24	22.6
	J140051+521606	CSO/CSS	0.116	0.32	<0.15	24.36	17	0.12±0.05	1.64±0.32	0.20
	J083411.09+580321.4	CSO/CSS	0.093	0.0086	<0.4	24.13	15	3.53±0.96	2.66±0.20	0.30
	J092405.30+141021.4	CSO/CSS	0.136	0.74	<0.4	24.18	13	2.15±0.69	2.33±0.24	0.58
	J155235.38+441905.9	MSO/CSS	0.452	6.93	<0.4	25.56	17	0.78±0.26	2.07±0.19	6.0
QSO	3C147	MSO/CSS	0.545	4.454	0.231	27.92	22	6.89±1.51	2.69±0.16	47.120

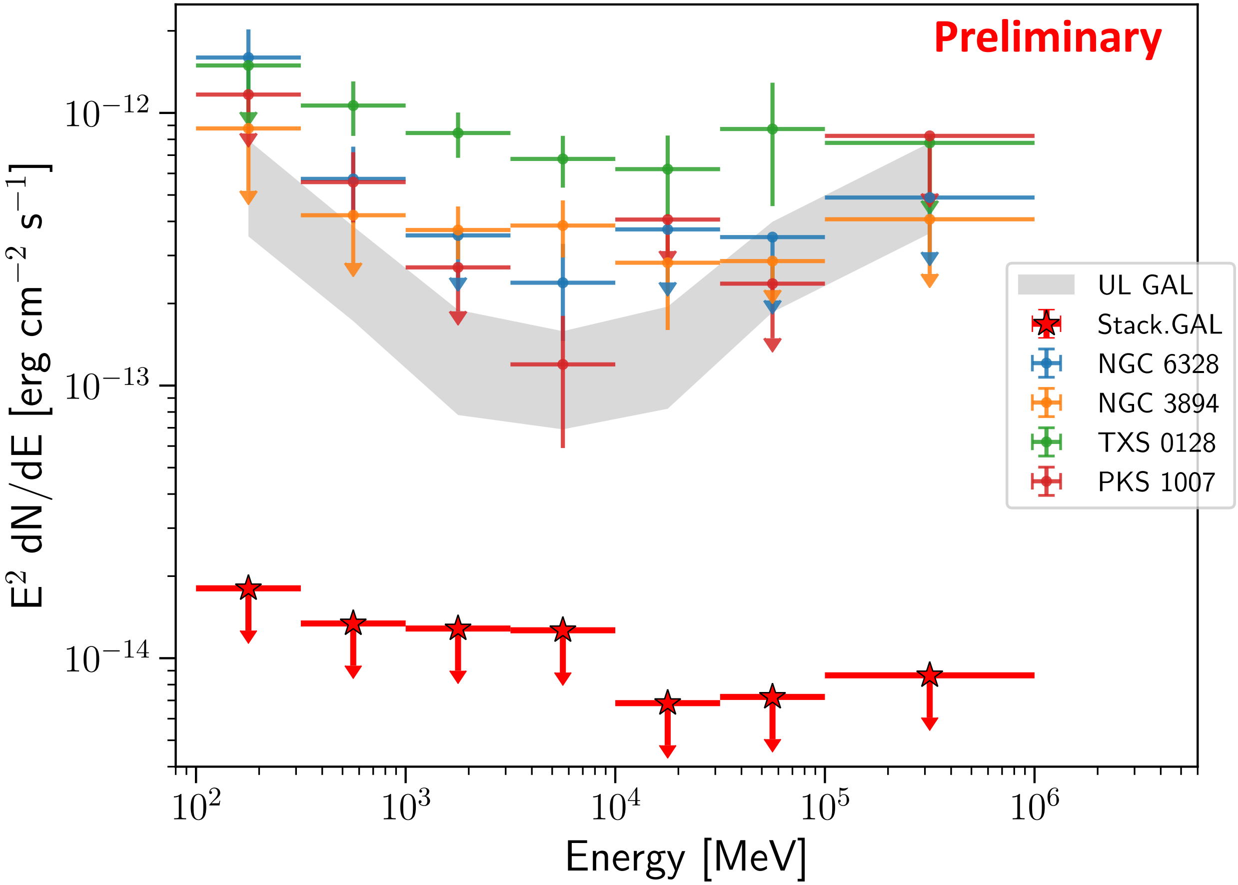
Nine sources present a not negligible gamma-ray emission (TS>10, corresponding to a signif.$>3\sigma$), making them *promising gamma-ray candidates* for being possibly detected in the future.

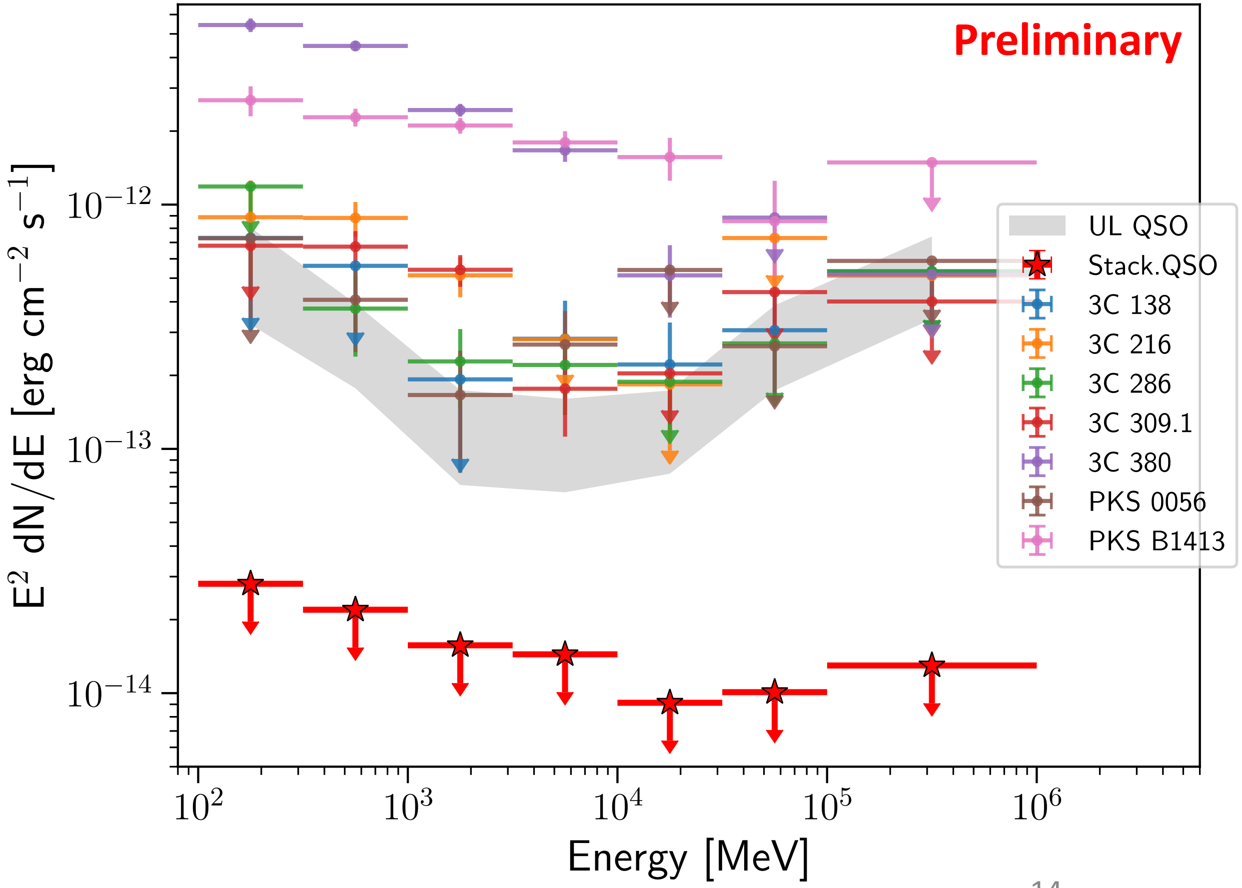


Stacking of young radio sources

We perform the first stacking analysis of the undetected young radio sources (galaxies and quasars). No significant emission has been detected. We repeated the stacking analysis for seven separate energy bands and we compared them with the averaged upper-limits of the undetected radio sources (grey band).

Select.	N	TS	F_γ^*	Γ
All	151	0.3	3.29	2.53
Galaxies	99	0.1	4.62	2.40
Quasars	52	0.2	10.09	2.64



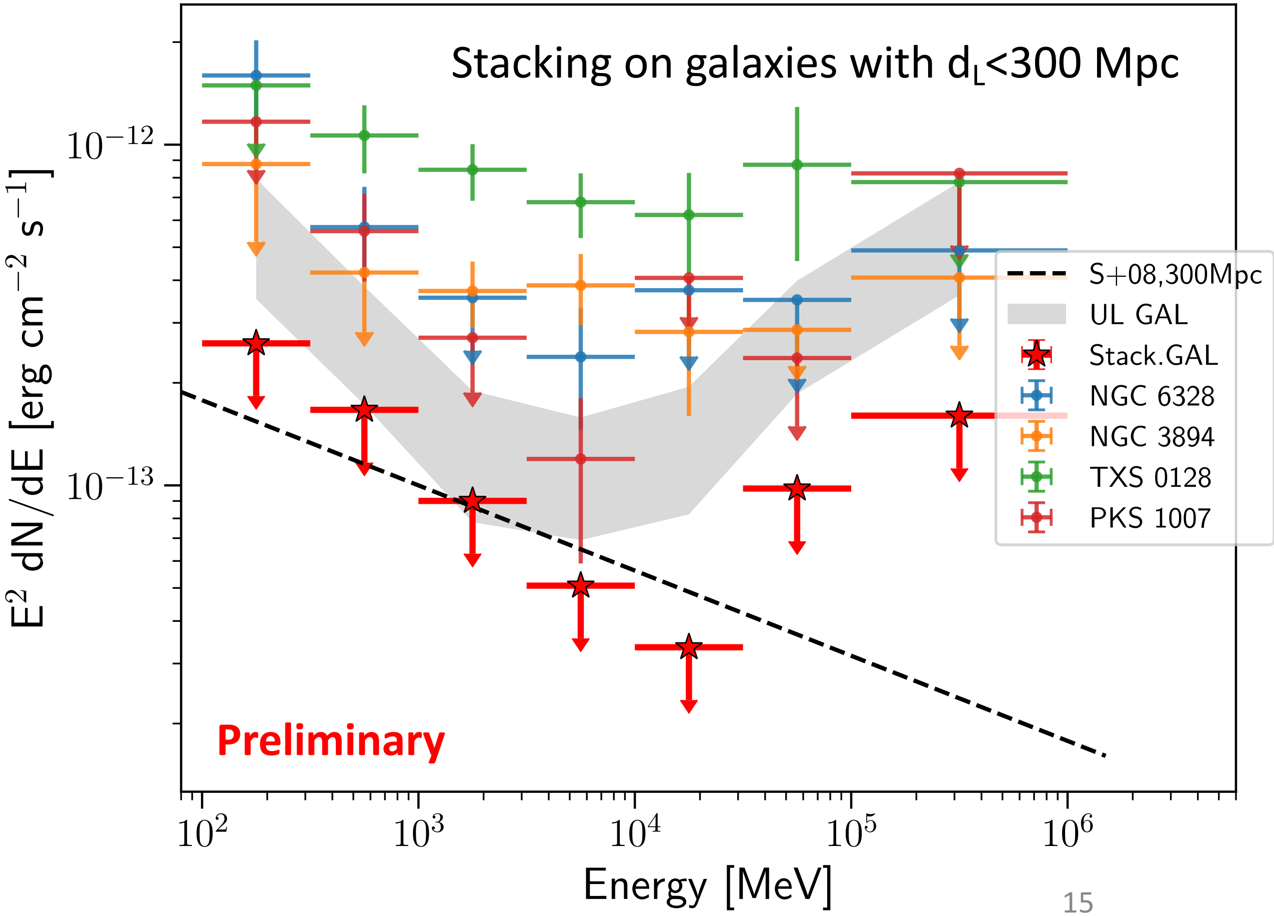


Stacking of selected subsamples

We performed the stacking analysis using different sub-samples defined by selections of the physical properties: nearby (z < 0.07, 0.15, 0.4, and 1) and compact (LS < 0.35, 0.5 and 1 kpc) sources, because they have been indicated as most promising candidates for gamma-ray emission in Stawarz et al. (2008). We found no detection. This allow us to say that the parameters assumed in the model were too optimistic for the sources in our local Universe (d_L<300 Mpc, z<0.07).

F*: UL in unit [10^{-11} ph cm^{-2} s^{-1}]

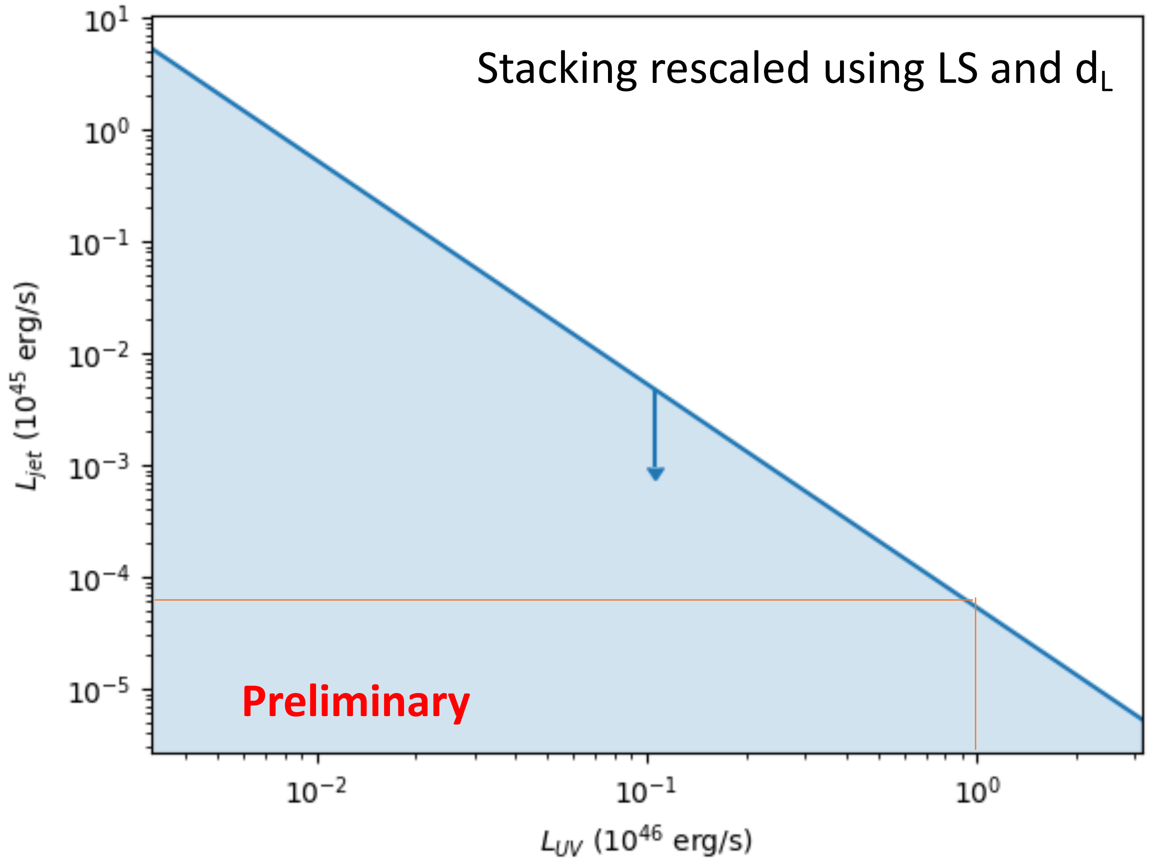
	Galaxies				Quasars			
Select.	N	TS	F^*_γ	Γ	N	TS	F^*_γ	Γ
LS<0.35	48	0.1	7.2	2.36	9	0.0	58.6	2.62
LS<0.5	52	0.1	9.4	2.38	13	0.1	46.1	2.58
LS<1	58	0.1	11.3	2.36	17	0.1	68.7	2.68
z<0.07	10	0.5	108	2.66	0	-	-	-
z<0.15	36	0.1	58.7	2.60	0	-	-	-
z<0.4	63	0.1	10.4	2.54	4	0.0	23.7	2.48
z<1	93	0.1	5.5	2.38	25	0.1	21.3	2.54
z<0.07 LS<0.15	8	0.8	172.9	2.78	0	-	-	-
z<0.15 LS<0.35	27	0.1	31.2	2.52	0	-	-	-
z<0.4 LS<0.5	39	0.1	15.4	2.50	1	0.0	297.5	2.76
O14	37	0.1	4.6	2.50	15	0.1	44.8	2.80



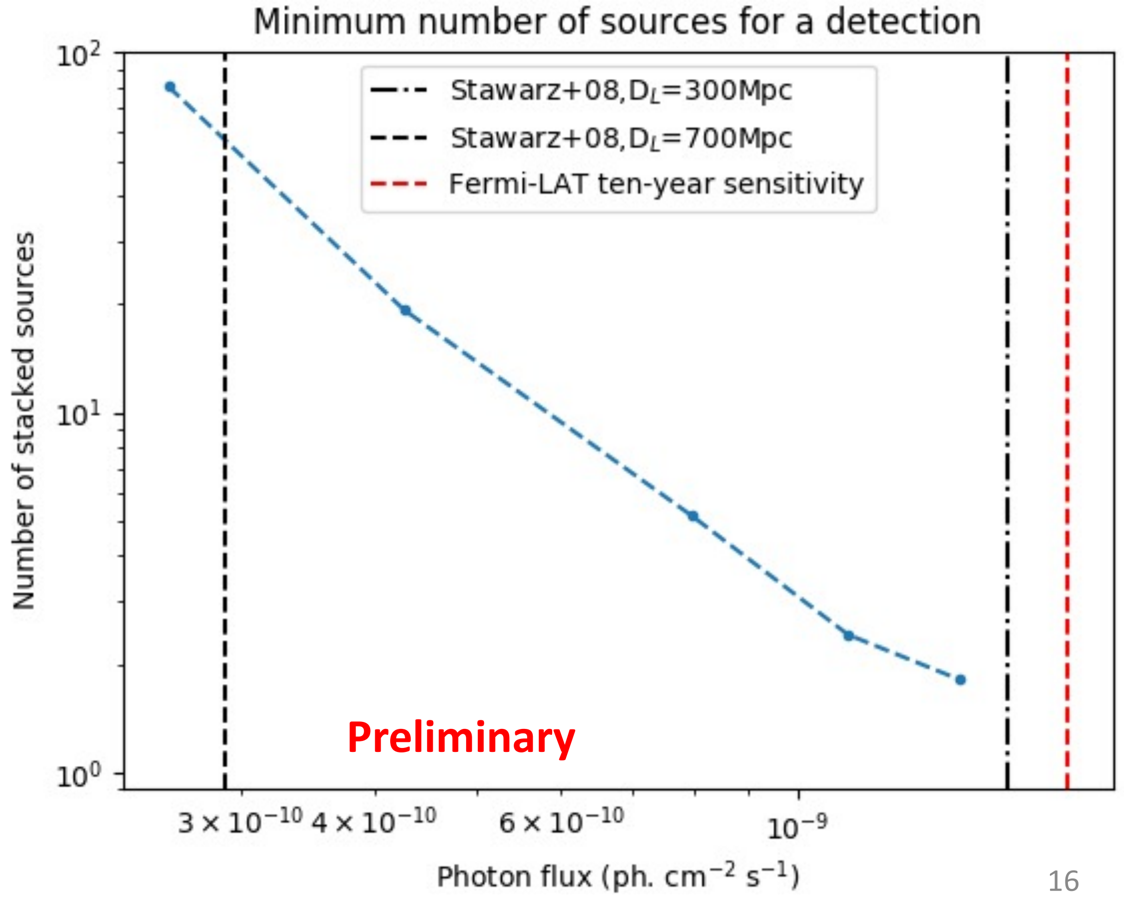
Comparison with gamma-ray expectations from galaxies

1. We repeated the stacking procedure by converting the gamma-ray flux UL into *constraints on the UV and jet luminosity*, using the information on LS and d_L of each individual source.

$$\frac{\epsilon L_\epsilon}{10^{42}\mathrm{erg/s}} \sim 2\frac{\eta_e}{\eta_B}\left(\frac{L_{\mathrm{jet}}}{10^{45}\mathrm{erg/s}}\right)^{0.5}\left(\frac{LS}{100\mathrm{pc}}\right)^{-1}\frac{L_{UV}}{10^{46}\mathrm{erg/s}}\left(\frac{\epsilon}{1\mathrm{Gev}}\right)^{-0.25}$$



2. We estimated the number of sources needed to detect (reject) γ-ray emission assuming the prediction of Stawarz *et al. (2008)*, comparing the γ-ray expectations with the stacking analysis sensitivity (we performed the stacking analysis on 5 simulated dataset varying the simulated flux). *E.g.: at a d_L=300 (700) Mpc ≥2 (60) sources needed*



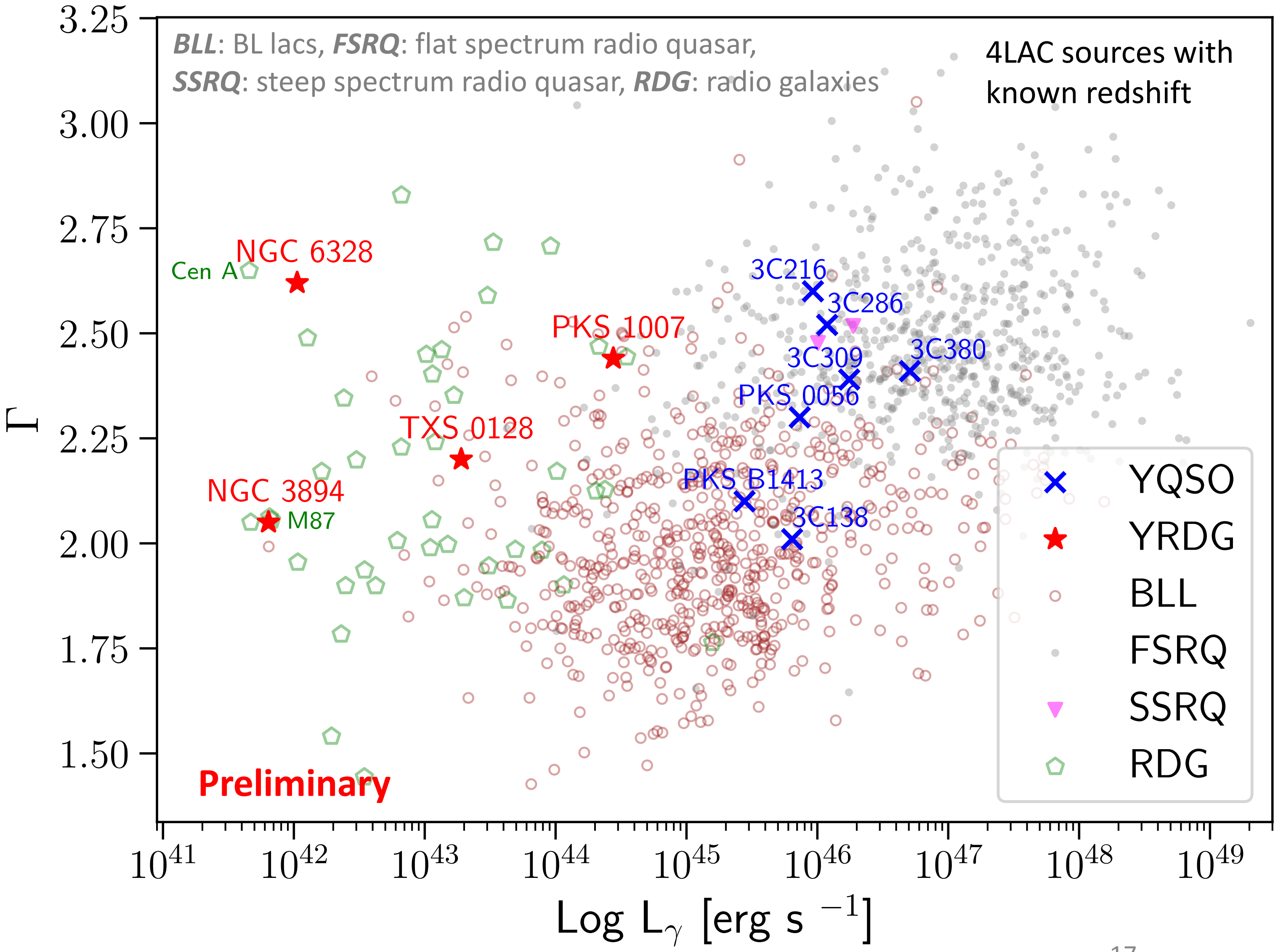
Origin of the gamma-ray emission

YRDG appear to share same γ-ray properties as other misaligned AGN in 4LAC

YQSO present a high gamma-ray luminosity, similar to FSRQ, suggesting that relativistic boosting is likely to play a role in their GeV detection.

Gamma rays in **YQSO** and **YRDG** may have a different origin: **jet** vs **radio lobes**.

PKS 1007+142 lies between the YQSOs and other YRDGs. While the other YRDGs are very nearby (z∼0.1) and compact (LS∼10 pc), it presents a more evolved structure (∼kpc) and it is located much further away (z∼0.2).



Conclusion

We perform the largest and deepest systematic search of gamma-ray emission from young radio galaxies and quasars using a sample of 162 sources and 11.3 years of Fermi-LAT data.

- we detect 11 young radio sources (4 galaxies and 7 quasars)
- we report the first LAT detection of the compact radio galaxy PKS 1007+128 (z=0.213)

We performed for the first time a stacking analysis on a sample of (undetected) young radio sources

- no significant emission found: resulting ULs are 10 times smaller than those on single sources.
- This allows us to say that the parameters assumed in the model of Stawarz+(08) were too optimistic for the sources in our local Universe (d_L=300 Mpc), while more sources are needed for a robust test of the model at larger distances. We constrain the UV and jet luminosity in Stawarz prediction, excluding gamma-ray emission from the brightest and most powerful sources.

Our results suggest that only the closest sources may be detected by Fermi-LAT, while considering objects at higher and higher redshift, boosting effects are necessary for their detection.

The paper has been submitted to MNRAS (stay tuned!!)

Thanks for your attention!