Introduction – Globular Clusters

Local globular clusters have the following characteristics:

- The 155 known [1] globular clusters are bound, spherical stellar systems.
- They are old (~ 10^{10} years), dust-free satellites of the Milky Way galaxy, characterised by dense cores of 100 to 1000 stars per cubic parsec and consequently high stellar encounter rates.
- Some GCs are noted for hosting populations of millisecond pulsars (MSPs) which arise from binary interactions. GCs may also contain central intermediate mass black holes or reside within dark matter halos.
- MSPs are strong gamma sources emitting gamma rays through curvature radiation and electron / positron pair production cascades in their magnetospheres.

25 GCs are significant gamma ray sources and a re-survey with the most up to date pass 8 *Fermi*-LAT data is likely to refine spectra further due to 1 - 7 years of further photon statistics since the last publications.

In addition the latest Pass 8 data release and tools of the *Fermi*-LAT now allow spectral analysis in the 60- 100 MeV range, for which no determinations have been made for any GC.

Globular Cluster Selection

We select 30 local GC for analysis (Table 1) based on the following criteria:

- All GCs to have a well defined absolute visual magnitude. central surface brightness and a known mass.
- Heliocentric distance for 25 of these GC are < 12.5 Kpc and < 19.3 Kpc for the rest.
- $|b| > 15^{o}$ to mitigate Galactic disc background uncertainties.

Name	Helio Distance/kpc	lii	bii	Absolute vmag	Core radius	Central surface brightness	Mass x 10^5 $M_\odot$	MSP Count
47 TUC	4.5	305.89	-44.89	-9.42	0.36	14.38	7	25
E 3	8.1	292.27	-19.02	-4.12	1.87	23.1	0.14	
IC 4499	18.8	307.35	-20.47	-7.32	0.84	20.9	0.09	
NGC 288	8.9	151.28	-89.38	-6.75	1.35	20.05	0.48	
NGC 362	8.6	301.53	-46.25	-8.43	0.18	14.8	2.5	
NGC 1261	16.3	270.54	-52.12	-7.8	0.35	17.73	2.2	
NGC 1851	12.1	244.51	-35.04	-8.33	0.09	14.25	5.5	1
NGC 1904	12.9	227.23	-29.35	-7.86	0.16	16.02	2.2	
NGC 2298	10.8	245.63	-16.01	-6.31	0.31	18.9	0.56	
NGC 4147	19.3	252.85	77.19	-6.17	0.09	17.38	0.53	
NGC 4590	10.3	299.63	36.05	-7.37	0.58	18.81	2.2	
NGC 5024	17.9	332.96	79.76	-8.71	0.35	17.38	3.83	
NGC 5053	17.4	335.7	78.95	-6.76	2.08	22.03	0.87	
NGC 5272	10.2	42.22	78.71	-8.88	0.37	16.64	9.5	1
NGC 5466	16	42.15	73.59	-6.98	1.43	21.61	1.04	
NGC 5897	12.5	342.95	30.29	-7.23	1.4	20.53	2.1	
NGC 6093	10	352.67	19.46	-8.23	0.15	15.11	1	
NGC 6121	2.2	350.97	15.97	-7.19	1.16	17.95	0.67	1
NGC 6171	6.4	3.37	23.01	-7.12	0.56	18.94	0.96	
NGC 6205	7.1	59.01	40.91	-8.55	0.62	16.59	7.5	1
NGC 6218	4.8	15.72	26.31	-7.31	0.79	18.1	1.44	
NGC 6254	4.4	15.14	23.08	-7.48	0.77	17.7	1	
NGC 6341	8.3	68.34	34.86	-8.21	0.26	15.47	2	
NGC 6362	7.6	325.55	-17.57	-6.95	1.13	19.31	0.5	
NGC 6723	8.7	0.07	-17.3	-7.83	0.83	18.13	1.96	
NGC 6752	4	336.49	-25.63	-7.73	0.17	14.88	3.1	5
NGC 6809	5.4	8.79	-23.27	-7.57	1.8	19.36	2.6	
NGC 7078	10.4	65.01	-27.31	-9.19	0.14	14.21	5.6	8
NGC 7089	11.5	53.37	-35.77	-9.03	0.32	15.78	1	
NGC 7099	8.1	27.18	-46.84	-7.45	0.06	15.35	1	2

Table 1: GC Selection for analysis, Core Radius in arc mins, central surface brightness in V magnitudes/square arc sec

Analysis Method

Our standard analysis uses 8.5 years of *Fermi* Pass 8 data from 4th Aug 2008 to 28th Dec 2016 with source class photons and valid front and back converting events. A zenith angle 90° cut excludes photons from the Earth limb.

For reasons of processing speed, an initial cut down analysis method is used to determine significant gamma ray emitters using the Fermipy package with energy selection 100 MeV to 300 GeV and a 15° radius of Interest (ROI). Two iterations of the Fermipy GTAnalysis 'find sources' method is used to identify new power law sources with significance of at least 3σ . The 'optimize' method of the GTAnalysis object is then run. This loops over all model sources in the ROI and fits their normalization and spectral shape parameters and computes the test statistic (TS) of all sources in the ROI. Gamma ray sources within the tidal radius of the cluster are then analysed further to produce a spectral energy distribution.

Detected globular clusters are re-analysed between 60 MeV to 300 GeV with a 25° Radius of Interest (ROI) and 40° source region width using the following steps and methods of the Fermipy GTAnalysis object:

- After an initial Fermipy 'setup' and optimize step, the fit method is run. This is a likelihood optimisation method which executes a fit of all parameters that are currently free in the the model and updates the TS and predicted count (npred) values of all sources.
- The normalisation of all sources within 10° of the GC is freed and the source nearest to the GC center has default model parameters freed.
- The shape and normalisation parameters of all sources with TS>25 (5σ significance) are individually fit using the GTAnalysis 'optimize' method.
- The fit method is run twice with an intervening 'find sources' step and a spectral energy distribution is generated using the GTAnalysis 'sed' method.

Analysis Results

We detect 6 globular clusters (Table 2) and show their best fit SED (Fig 1 – 6). NGC 6254 is a new detection.

Name	Offset (°)	TS	Energy Flux erg cm^{-2} s^{-1}	Photon Flux cm^{-2} s^{-1}
47 Tuc Ref [2]	0.021 0.028	5229 603	$(2.54 \pm 0.08) \times 10^{-11}$ $(2.5 \pm 0.2) \times 10^{-11}$	$(2.17 \pm 0.14) \times 10^{-8}$ $(2.9 \pm 0.14) \times 10^{-8}$
NGC 6093 Ref [7]	0.051 0.06	94 27	$(0.71 \pm 0.10) \times 10^{-11}$ $(0.66 \pm 0.42) \times 10^{-11}$	$(1.28 \pm 0.30) \times 10^{-8}$ $(0.55 \pm 0.36) \times 10^{-8}$
NGC 6218 Ref [6]	0.007 0.061	42 36	$(0.39 \pm 0.08) \times 10^{-11}$ $(0.35 \pm 0.07) \times 10^{-11}$	$(8.92 \pm 3.61) \times 10^{-9}$ $(5.28 \pm 2.44) \times 10^{-9}$
NGC 6254 (New)	0.186 -	40 -	$(0.38 \pm 0.08) \times 10^{-11}$ -	$(6.33 \pm 2.23) \times 10^{-9}$ -
NGC 6752 Ref [7]	0.019 0.078	126 49	$(0.57 \pm 0.06) \times 10^{-11}$ $(0.60 \pm 0.28) \times 10^{-11}$	$(1.23 \pm 0.23) \times 10^{-8}$ $(0.60 \pm 0.28) \times 10^{-8}$
NGC 7078 Ref [6]	0.266 0.062	56 49	$(0.50 \pm 0.08) \times 10^{-11}$ $(0.42 \pm 0.06) \times 10^{-11}$	$(1.94 \pm 0.40) \times 10^{-8}$ $(1.2 \pm 0.25) \times 10^{-8}$

Table 2: Detected globular clusters with angular offset from ROI centre. ROI centre defined as GC RA and DEC from [1], Test Statistic (TS), Energy Flux and Photon Flux (Top in row) compared to previous determinations (bottom)

Sub 100 MeV emission is detected in NGC 6752 at a minimum of 2.8 σ significance but is not reliably detected in the other GCs examined.

Selected Results – Spectral Energy Distributions and Spectral Models

NGC 6218

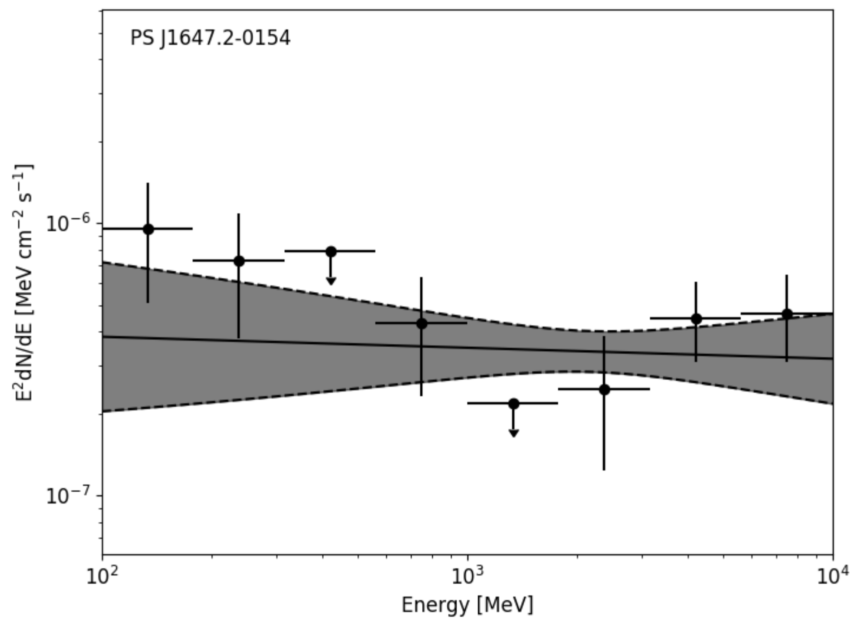

Fig 1 NGC 6218 Power law with prefactor (3.3 ± 1.1) x 10^{-13}, index -1.99 ± 0.32, scale 1000.

NGC 6093

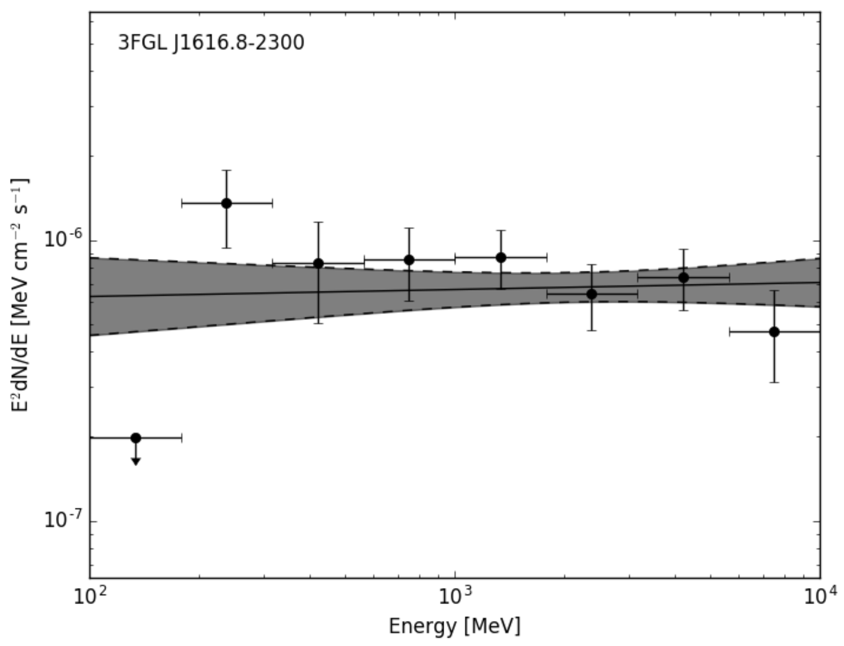

Fig 2 NGC 6093 Power law with prefactor (9.4 ± 1.2) x 10^{-14}, index -(1.99 ± 0.11), scale 2686.

We show SEDs for 4 GCs along with their spectral model parameters (Fig 1 – 4). These GCs are binned at 4 bins per decade of energy within a restricted energy range so that only significant points are fitted.

The flux bin upper limits for the SEDs in Fig 1 – 4 (shown as points with a downward pointing arrow) are determined at a confidence level of 5σ.

The range of TS values for the individual flux bins of each GC SED are listed (Table 3):

GC	Lowest TS	Highest TS
NGC 6218	4.5	19.3
NGC 6093	6.6	30.1
NGC 6254	10.7	23.3
NGC 6752	24.6	76.2

Table 3: TS value range for binned flux points in each GC SED.

NGC 6254 (New Detection)

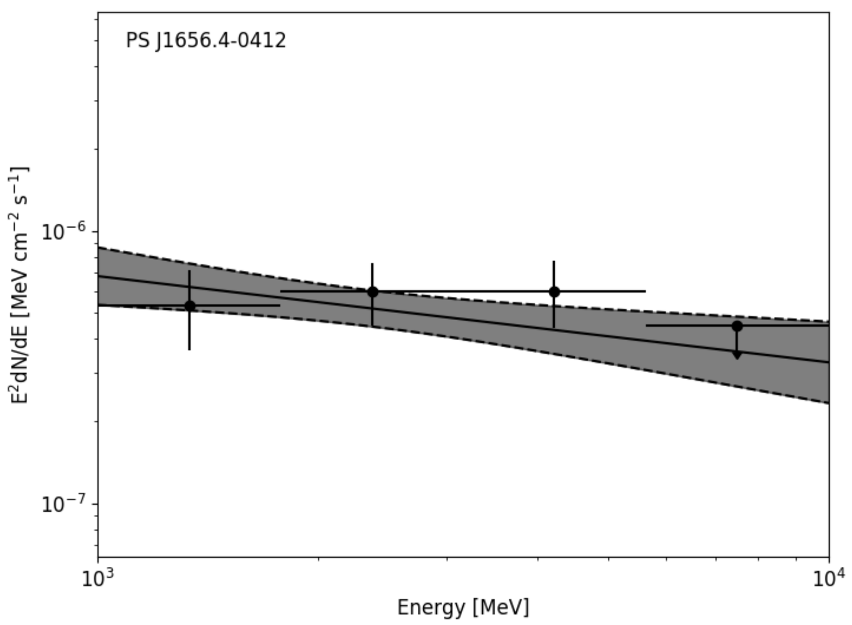

Fig 3 NGC 6254 Power law with prefactor (6.7 ± 1.4) x 10^{-13}, index -2.3 ± 0.18, scale 1000.

NGC 6752

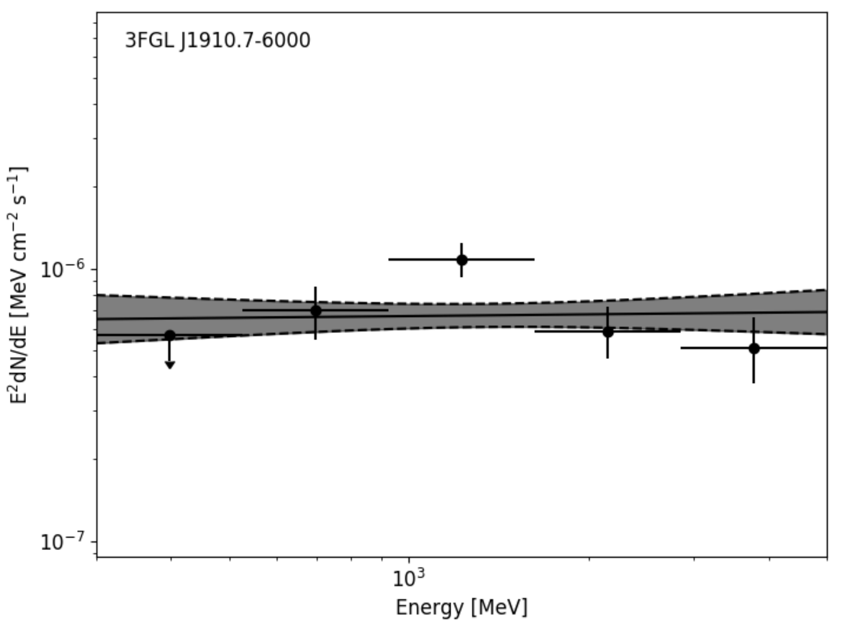

Fig 4 NGC 6752 Power law with prefactor (4.0 ± 0.4) x 10^{-13}, index -1.97 ± 0.13, scale 1272.

The luminosity for each GC in the energy range 60 MeV to 300 GeV is also calculated (Table 4):

GC	$L_{gamma\ 0.06-300\ GeV}$ (erg / s)
NGC 6218	(1.09 ± 0.21) x 10^{34}
NGC 6093	(8.50 ± 1.14) x 10^{34}
NGC 6254	(0.89 ± 0.18) x 10^{34}
NGC 6752	(1.10 ± 0.19) x 10^{34}

Table 4: Luminosities of each GC plotted as a SED.

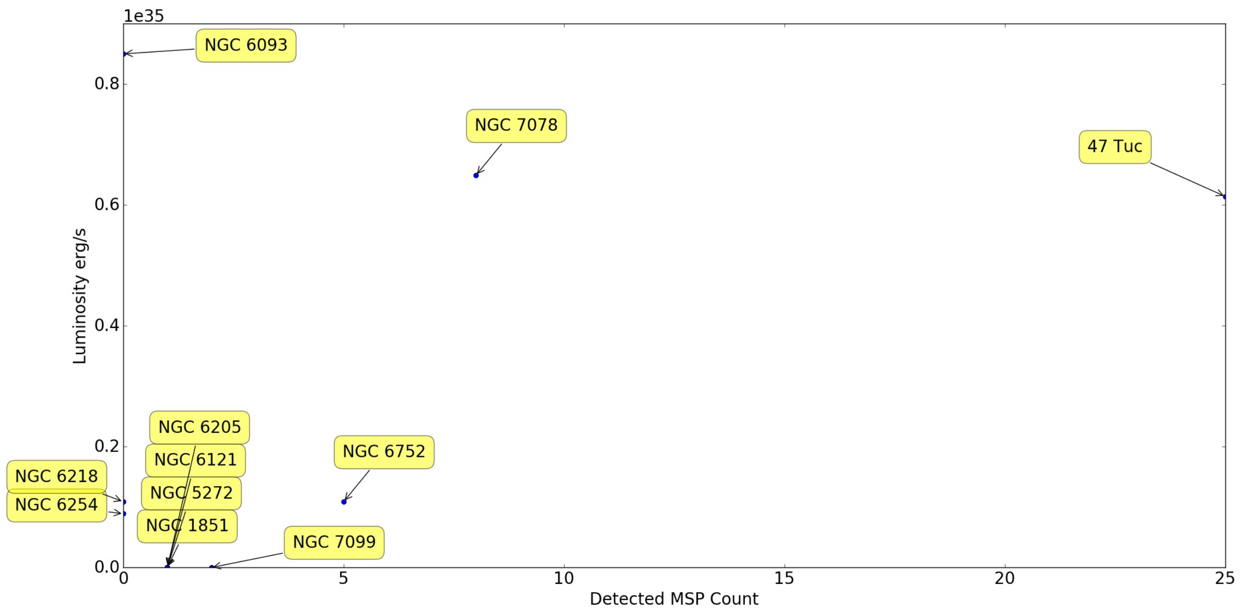

Fig 5 Plot of luminosity vs number of MSPs in each GC. Clusters which are undetected and have no MSPs are omitted.

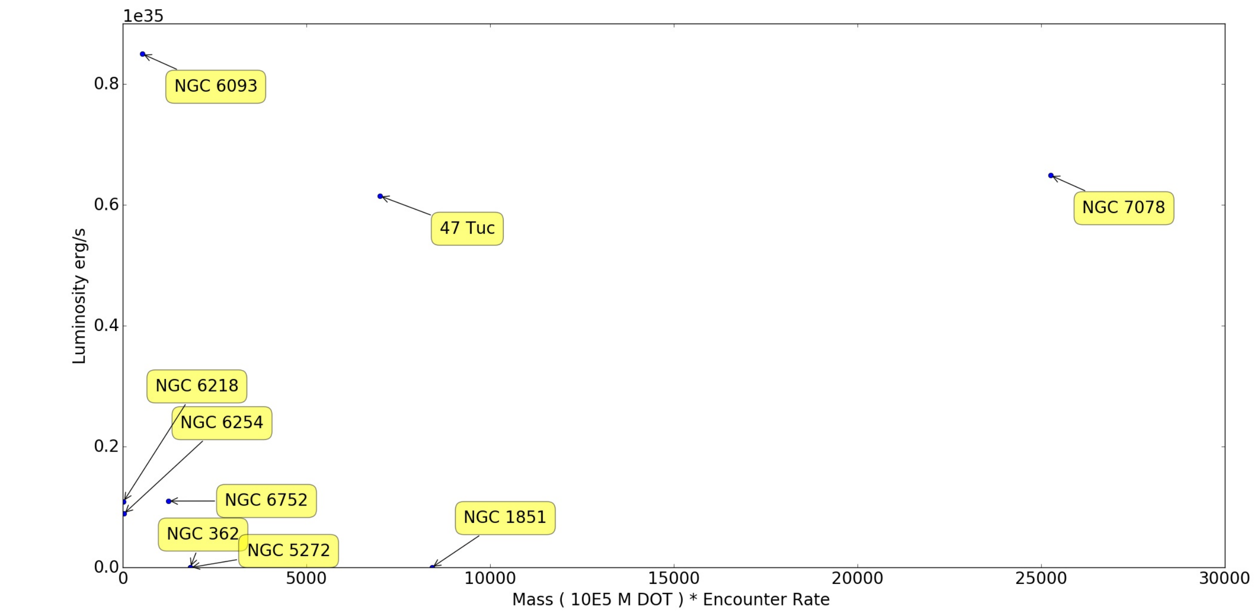

Fig 6 Plot of luminosity vs product of cluster mass and a normalised encounter rate from reference [5]. The encounter rate of 47 Tuc is set at 1000.

Discussion

NGC 6093 and 6218 exhibit flat, hard spectra (Fig 1 - 2) in the range 1 - 10 GeV. This is unlike typical MSP spectra whose binned flux tends to fall markedly between 1 - 10 GeV [4] and have spectral models fit by a power law with super exponential cut off or a power law [3]. These GCs have no known MSPs (Fig 5) and a corresponding low mass encounter rate product (Fig 6) which can be taken as a proxy for the prevalence of binary system creation and MSP recycling. This suggests a predominantly non MSP origin for the gamma ray emission in these clusters.

NGC 6254 (Fig 3) is a new detection with an angular offset within the ROI of 0.18º from the GC co-ordinates (RA=254.28º ,DEC=-4.10º), placing this source inside the GC tidal radius of 0.29º. Like NGC 6093 and NGC 6218, this GC has no known MSP and a low mass encounter rate product. However the upper limit at above 5 GeV means that a high energy spectral cut-off, characteristic of MSPs, cannot be discounted.

NGC 6752 has a hard, flat spectrum when binned in the range 300 MeV - 4 GeV (Fig 4). The source of the sub 100 MeV emission is not known but work is ongoing to characterise the SED of objects in the ROI within the point spread function of the LAT to see if they are contributors in this low energy regime.

References

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[4] Cholis, I, Hooper, D, Linden,T A New Determination of the Spectra and Luminosity Function of Gamma-RayMillisecond Pulsars https://arxiv.org/pdf/1407.5583.pdf Fermilab publication

[5] Bahramian, A., et al., Stellar Encounter Rate In Galactic Globular Clusters. Astrophysical Journal, 2013. 766(2).

[6] Zhang, P.F., et al., Detection of gamma-ray emission from globular clusters M15, NGC 6397, 5904, 6218 and 6139 with Fermi-LAT. Monthly Notices of the Royal Astronomical Society, 2016. 459(1): p. 99-107.

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Contact Details

E-mail:sheridan.j.lloyd@durham.ac.uk