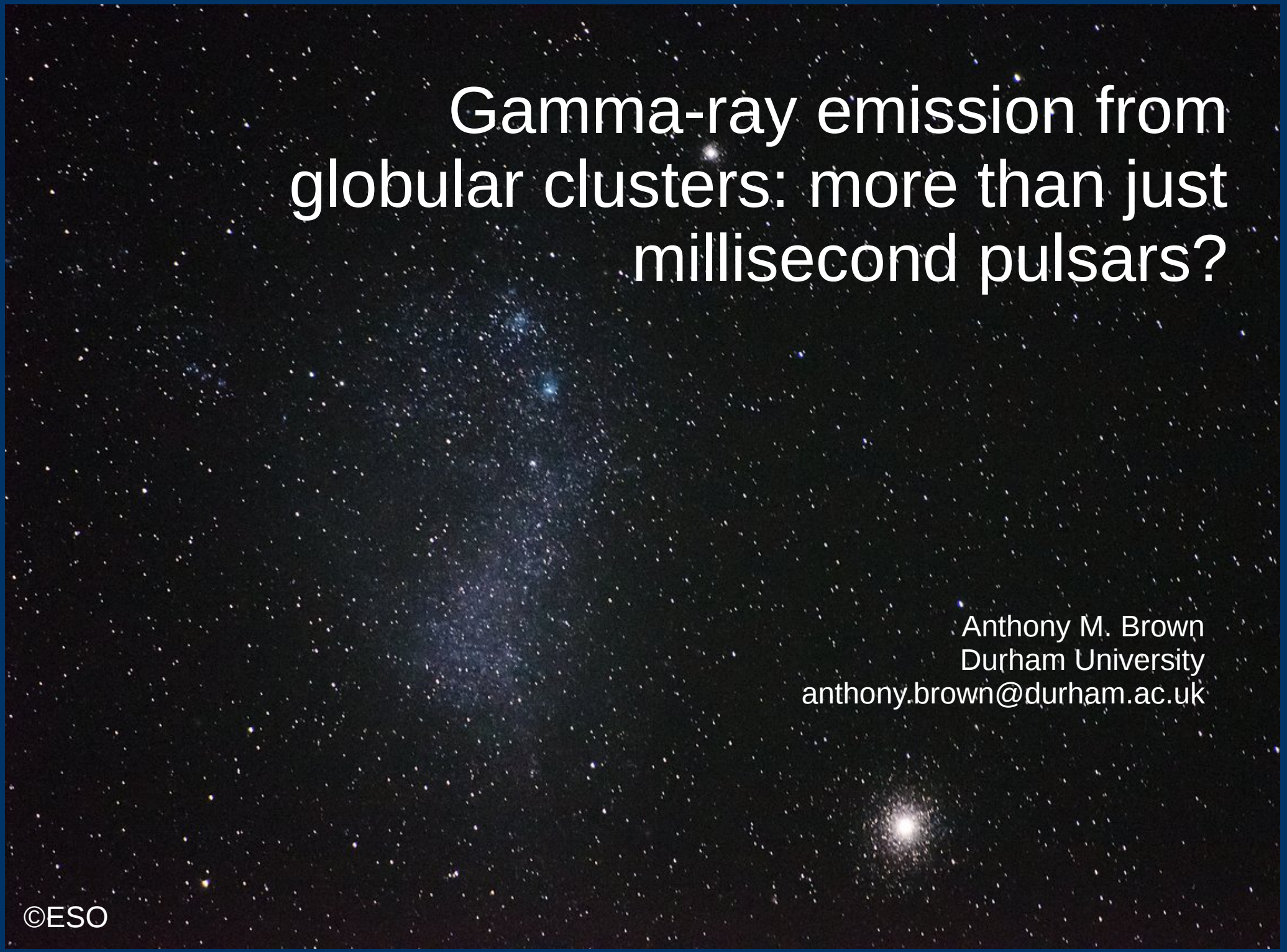

Gamma-ray emission from globular clusters: more than just millisecond pulsars?

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For the next 15 minutes

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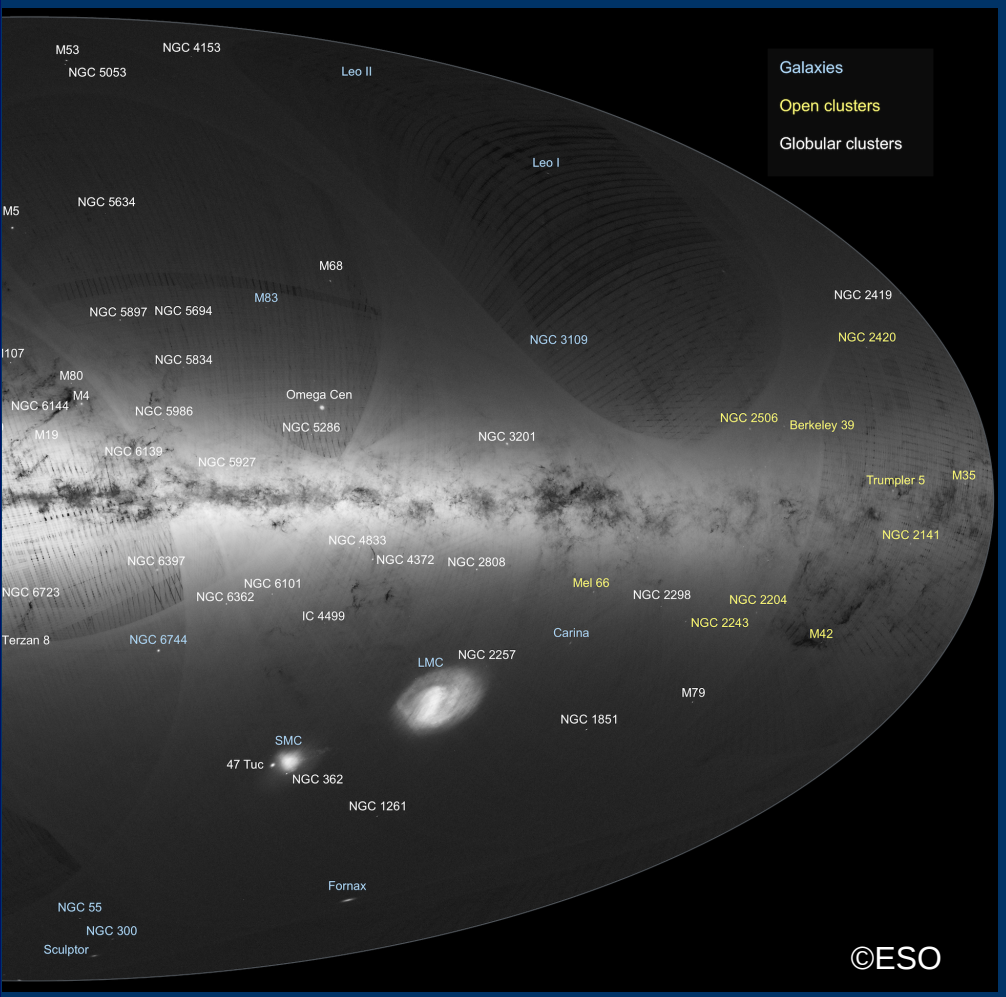
- The where, what, how and why for globular clusters
- 47 Tuc: the case for a DM contribution

(Brown, Lacroix, Lloyd, Boehm & Chadwick, 2018, PRD, 98, 041301)

- Phenomenological approach to search for further evidence for non-MSP emission

(Lloyd, Chadwick & Brown, 2018, MNRAS, 480, 4782)

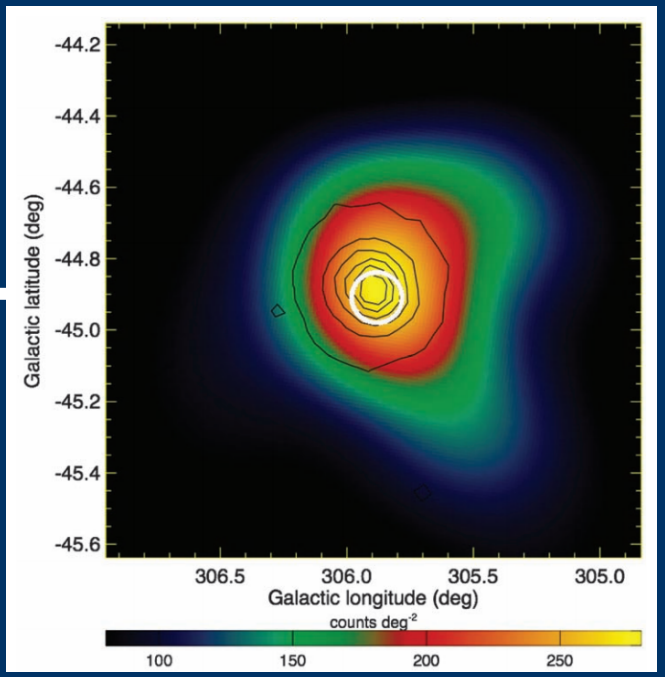
Globular clusters

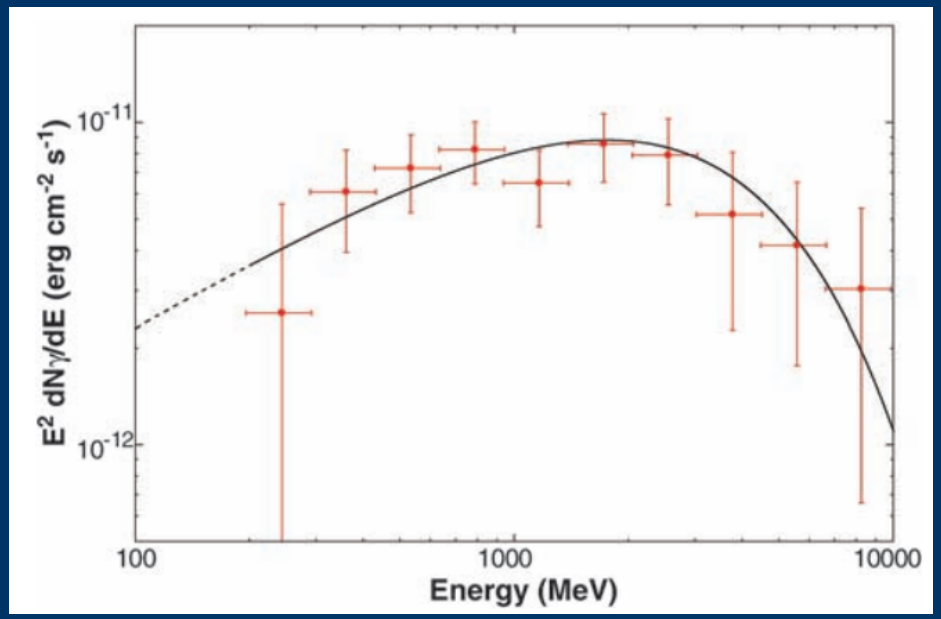


- Oldest components of our galaxy (~10^{10} years)
- >10^5 stars within 50 pc^3
- High stellar encounter rate leading to high low-mass X-ray binary formation rate
- Leads to a large millisecond pulsars (MSP) population
- *Fermi*-LAT found local MSPs to be gamma-ray bright (Abdo et al. Science 2009).

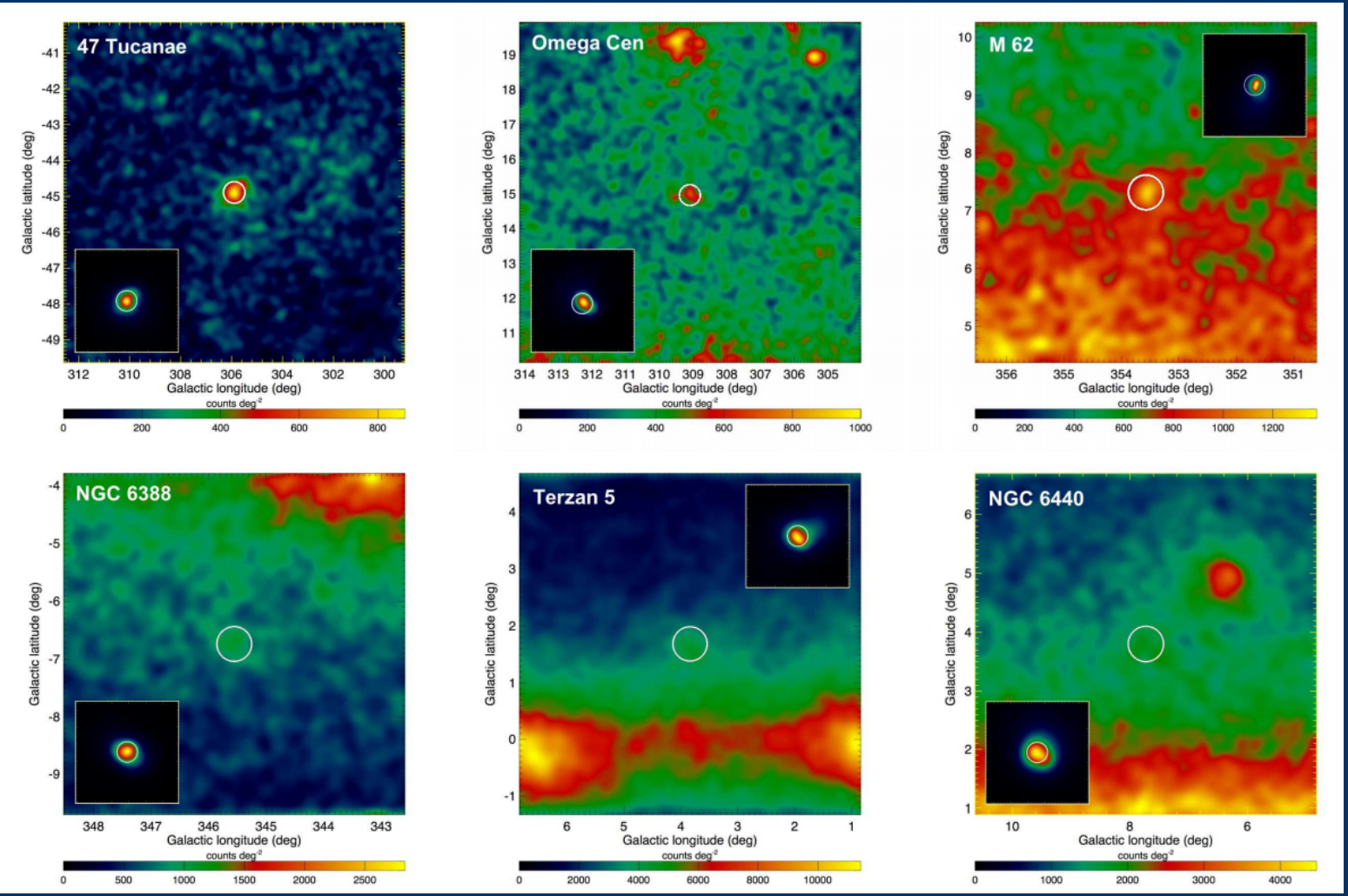
47 Tuc

- 47 Tuc is a prominent, nearby globular cluster with 25 known MSPs
- 8 month of LAT data found 47 Tuc to be gamma-ray bright (Abdo et al. 2009, Science, 325,845)
- 200 MeV to 10 GeV spectra best-fit with an index 1.3 ± 0.3, with a cut-off $2.5_{-0.8}^{+1.6}$ GeV
- Spectrum was found to be consistent with a MSP population.





Gamma-ray bright globular clusters



1.5 years of LAT data

8 globular clusters found to be gamma-ray bright

Abdo et al., 2010 A&A, 524, A75

Back to 47 Tuc

- The spatial distribution/motion of stars within 47 Tuc, combined with detailed N-body simulations, suggest an intermediate-mass black hole (IMBH) within 47 Tuc (Kiziltan et al. Nature 2017)
- Prompts us to consider an enhanced DM density ('spike') around the IMBH (Gondolo & Silk, 1999; Horiuchi & Ando, 2006), which would enhance a possible signal of gamma-rays from DM annihilation

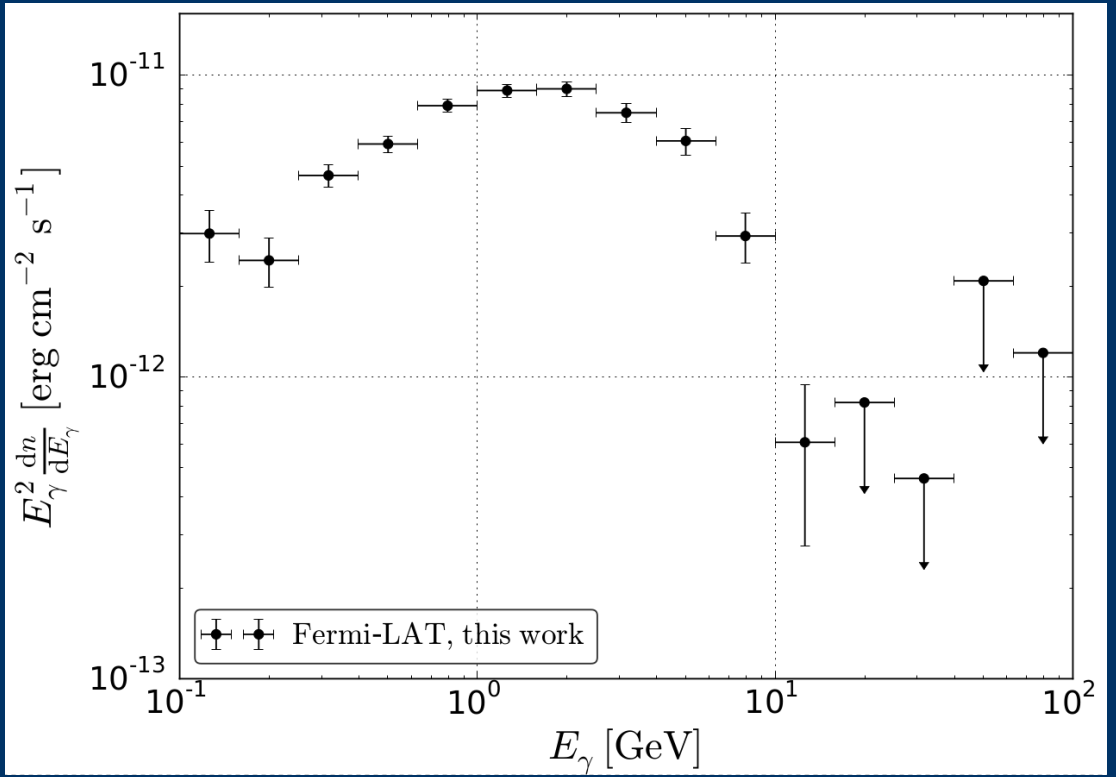
47 Tuc: 9 years of LAT observations

- 9 years of pass8 front+back LAT data
- 0.1 - 100 GeV
- standard zenith cut and GTI criterion

TS=5719

(6.45 ± 0.19) x 10^{34} ergs/s

- Significant emission below 200 MeV was found.



Brown et al. 2018, PRD, 98, 041301 (R)

Millisecond pulsars

- 25 resolved MSPs within 47 Tuc (which have radio & X-ray properties compatible with our local MSPs).
- Use Xing & Wang, 2016, MSP spectral description, who analysed and averaged 39/40 MSPs within the 2PC (Abdo et al. 2013).
  - Using the average gamma-ray spectra from our local MSPs, aligns with the fact that the resolved MSPs in 47 Tuc are compatible with local ones.
- The normalisation set by the number of MSPs in 47 Tuc: we use two approaches
  - Use the X-ray flux from the 25 resolved MSPs, and convert using the X-ray to gamma-ray flux ratio from the 2PC.
  - Leave the normalisation as a free parameter to account for potential unresolved MSPs.

Millisecond pulsars

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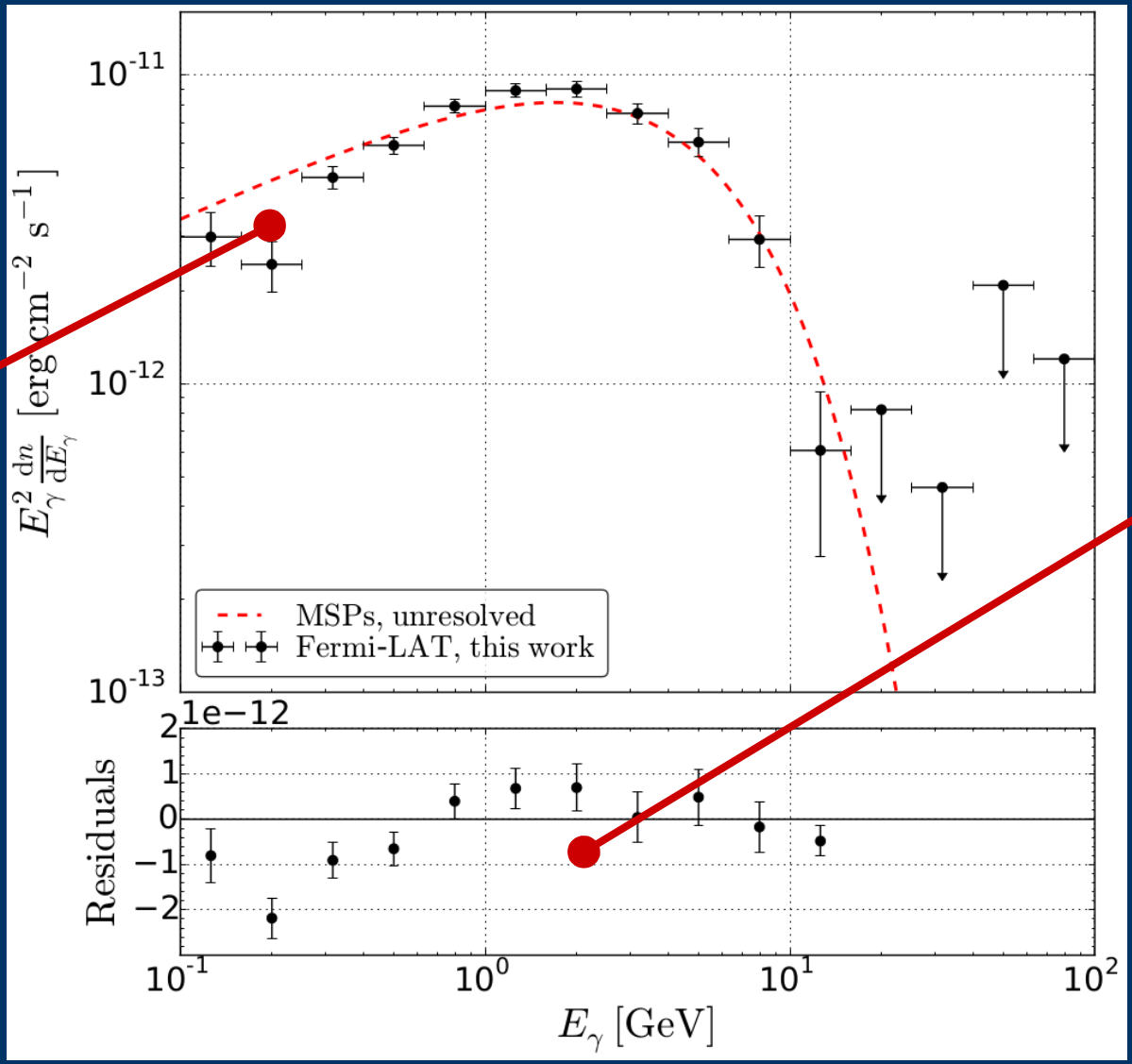
Average MSP spectra over-predicts the <200 MeV emission



Residuals of the fit is not consistent with random fluctuations and clearly shows a trend.

Dark Matter

- Consider a spike around 47 Tuc's IMBH

$$\rho(r) = \begin{cases} 0 & r < 2R_S, \\ \dfrac{\rho_{sp}(r)\rho_{sat}}{\rho_{sp}(r) + \rho_{sat}} & 2R_S \leq r < R_{sp}, \\ \rho_0 \left(\dfrac{r}{R_{sp}}\right)^{-5} & r \geq R_{sp}, \end{cases}$$

Relates to DM particles being captured by the IMBH

Keeps a low DM content outside of cluster, possibly due to tidal stripping.

$$\rho_{sp}(r) = \rho_0 \left(\frac{r}{R_{sp}}\right)^{-3/2}$$

Effects of DM dynamical relaxing with stars

- DM mass 4,000 solar masses: 1% of total 47 Tuc mass, consistent with it's velocity dispersion profile and allowed by uncertainty in IMBH mass).

Dark Matter

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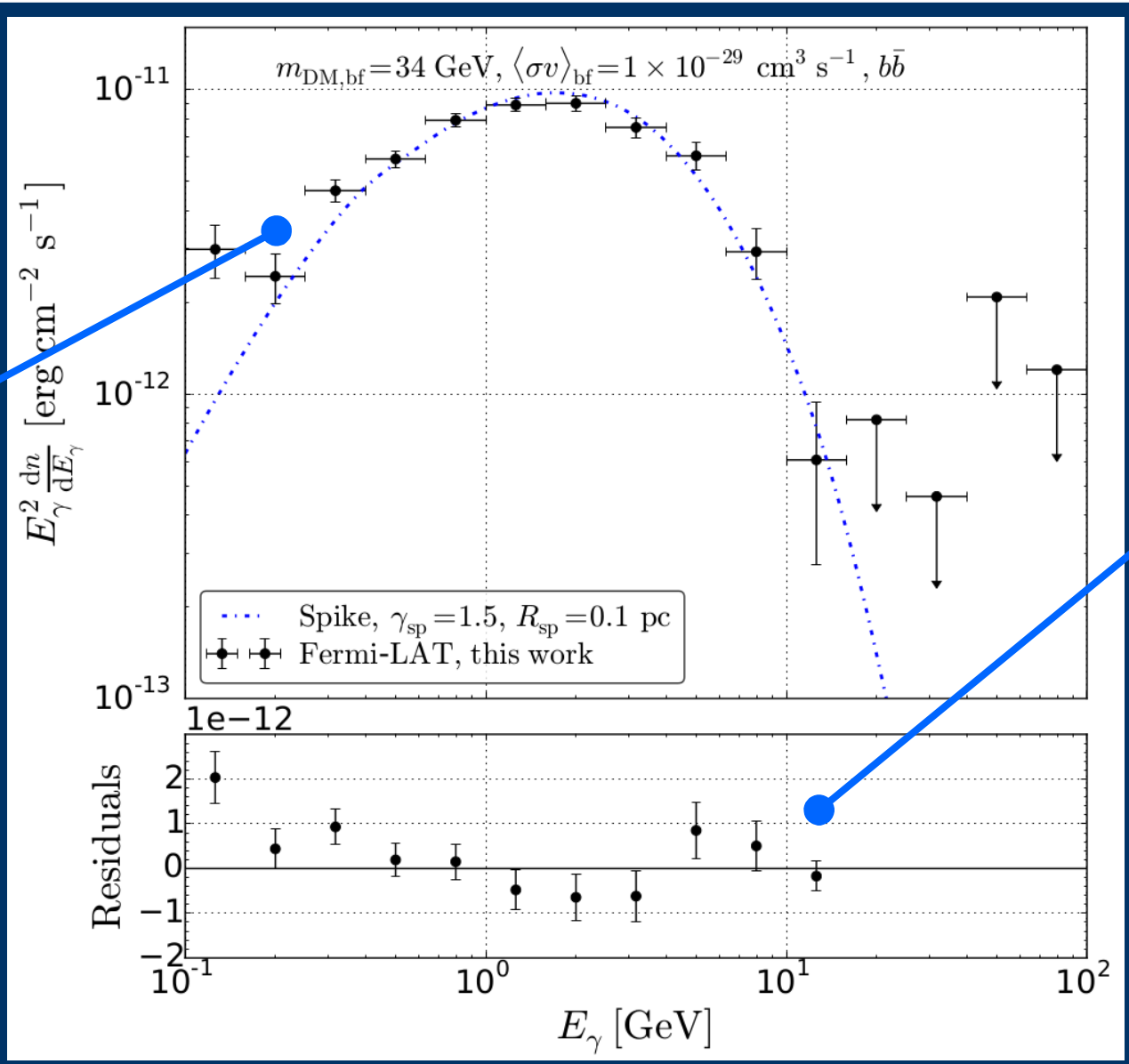
DM spectrum under-predicts the <200 MeV emission

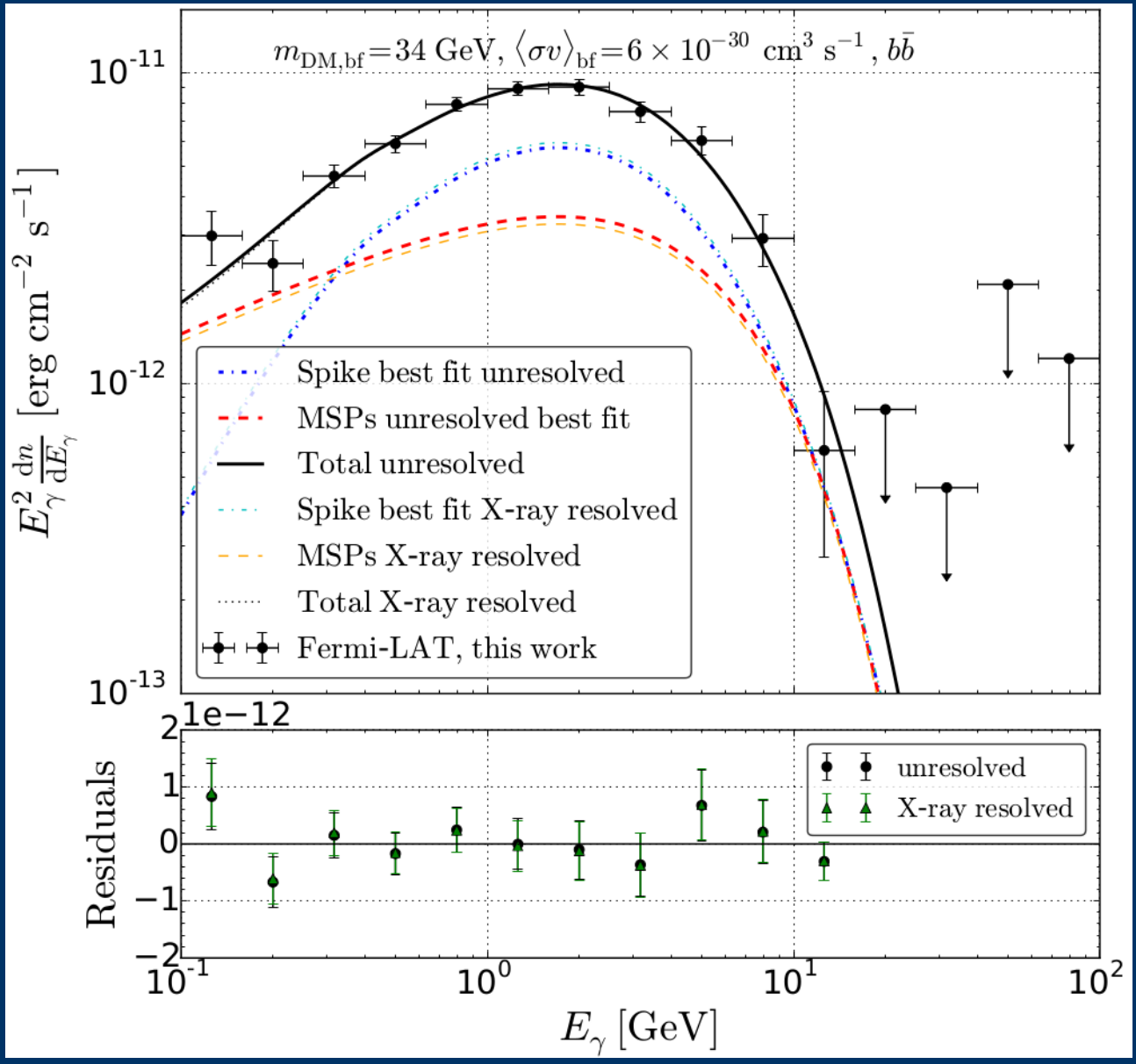


Still shows a trend to the residuals distribution

MSPs + DM

Consider a mixed model, with the normalisation of the DM & MSP components left free.

Likelihood fit finds that the DM+MSP model is preferred with a TS=40 when compared to the MSP only fit.



Possible alternative explanations

- Magnetospheric from IMBH, LMXBs, CVs: all of have critical limitations that rules them out.
- Our assumption about the MSP is not ideal
  - Dominated by a few (usual) MSPs?
    - No evidence of pulsed gamma-ray emission using known MSP ephemerides
  - MSP pop. within 47 Tuc is drastically different from our local MSPs?
    - Global radio & x-ray properties of resolved MSPs are consistent with those in our local neighbourhood, so its hard to imagine the distribution of the gamma-ray properties being vastly different.

Phenomenological studies

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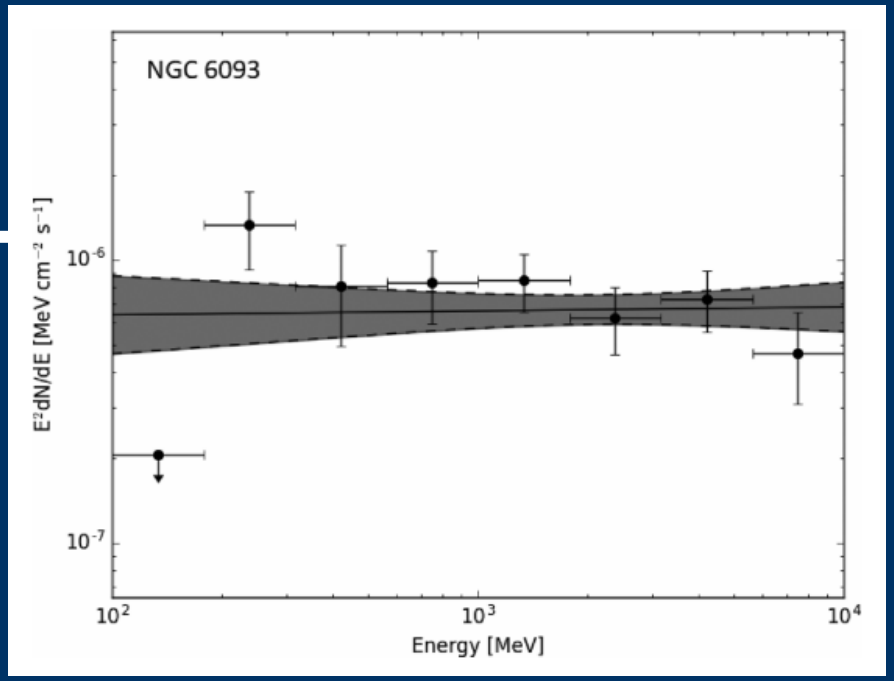
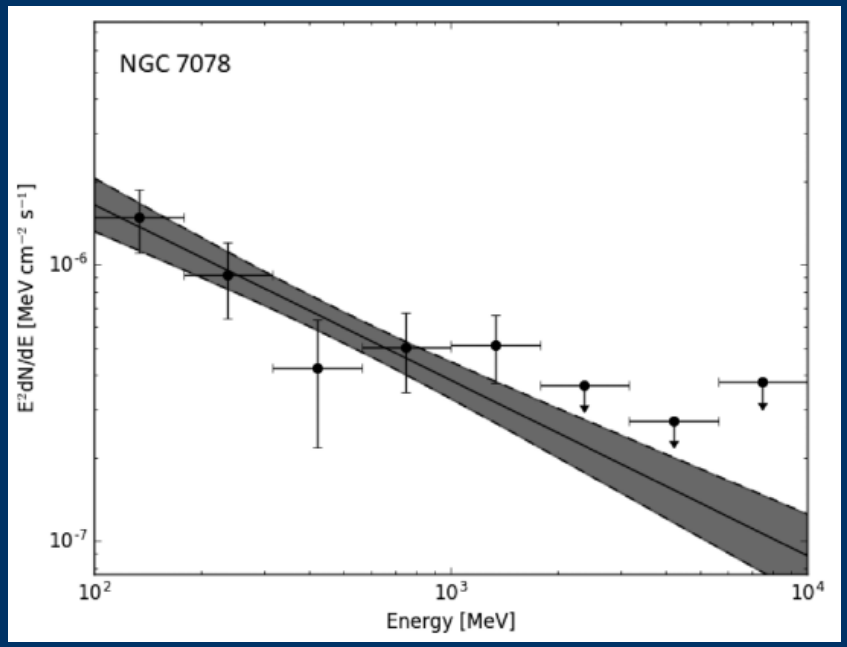
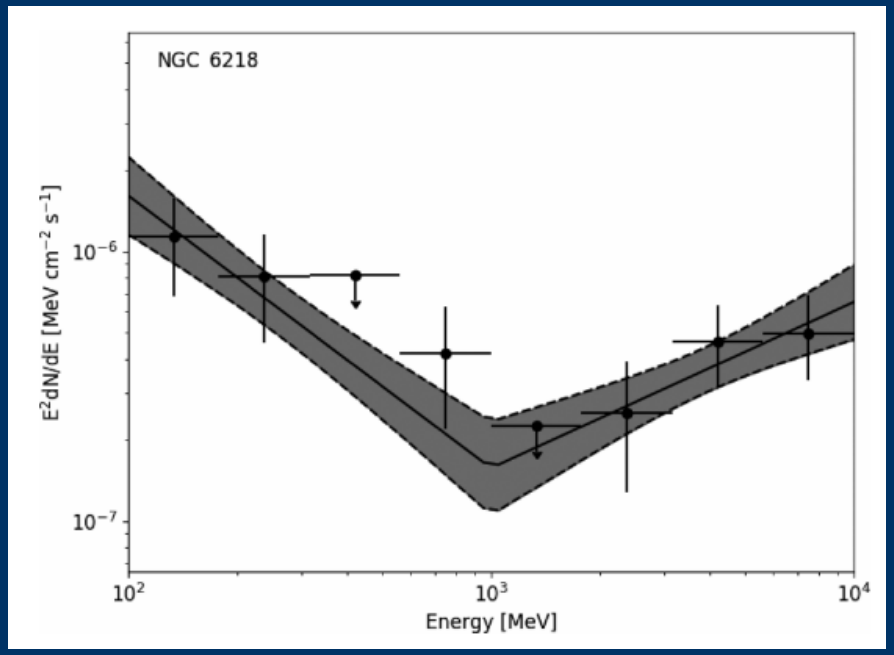
- Study a large sample of nearby, high galactic latitude globular clusters
- Use 8 years of LAT data (0.06-300 GeV) to study nearby globular clusters off the galactic plane, with known masses.
- Investigate spectra/flux/variability for each glob. cluster, in their own right, and as a function of physical characteristics.

Spectra

- Large variety in the spectral forms
- No apparent trend with physical quantity
- Examples of spectra shapes that are inconsistent with current MSP emission models

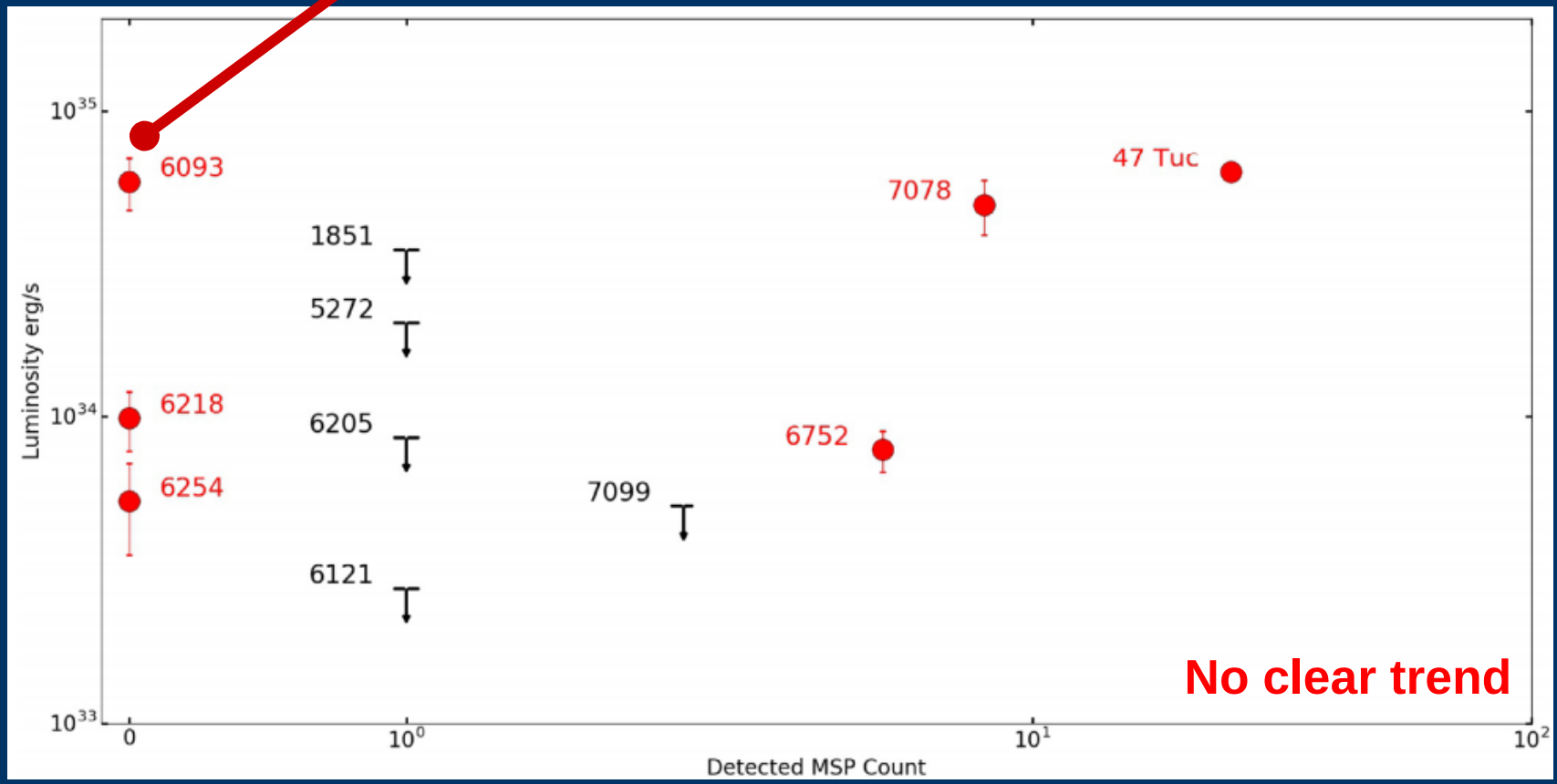






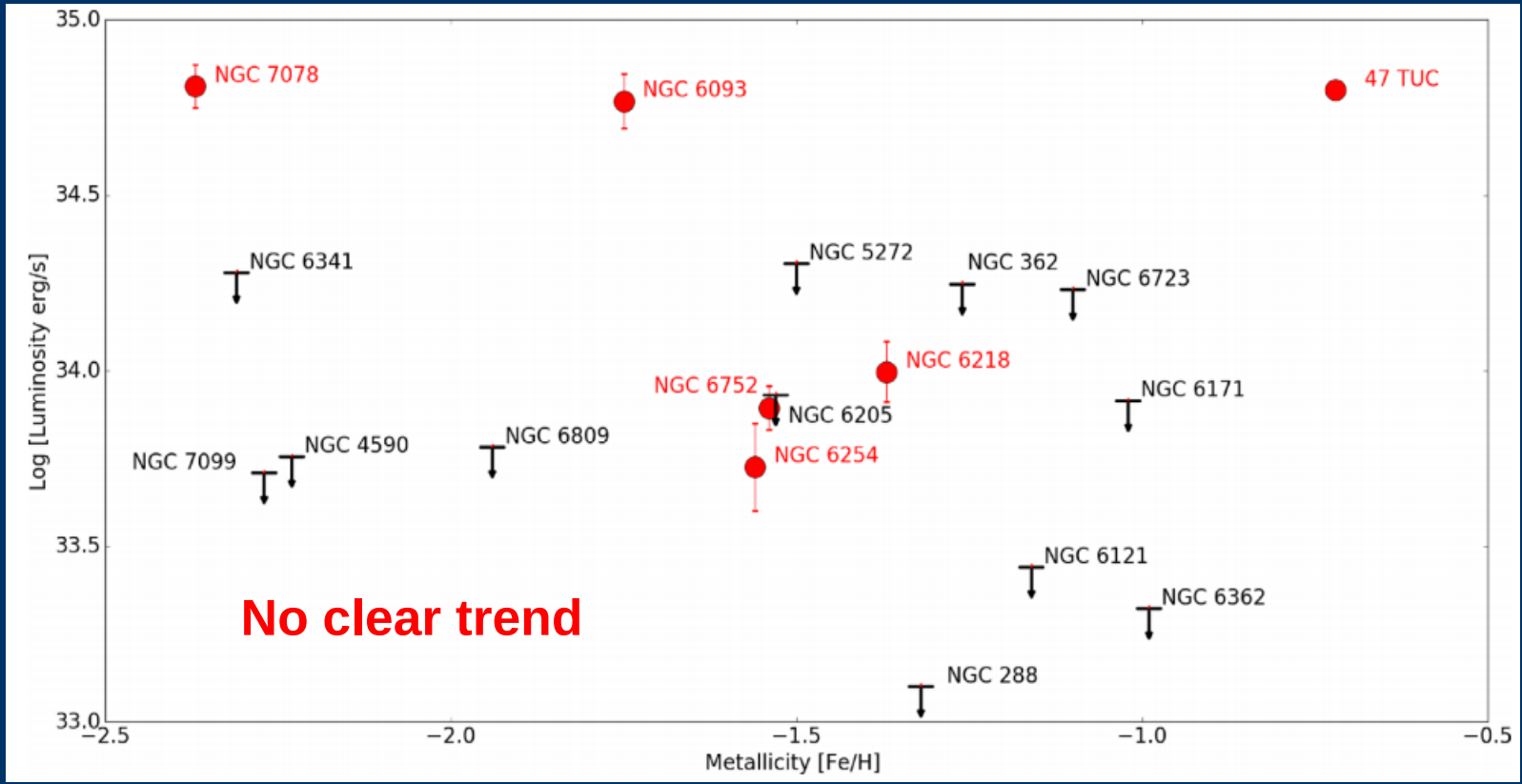
Number of MSPs...

No detected MSPs and yet have a similar gamma-ray luminosity to some of the most MSP populated globular clusters



Metallicity

- Another proxi for MSP production: high metallic systems are more likely to undergo magnetic breaking and thus form MSPs (Hui et al. 2011).



Take home points

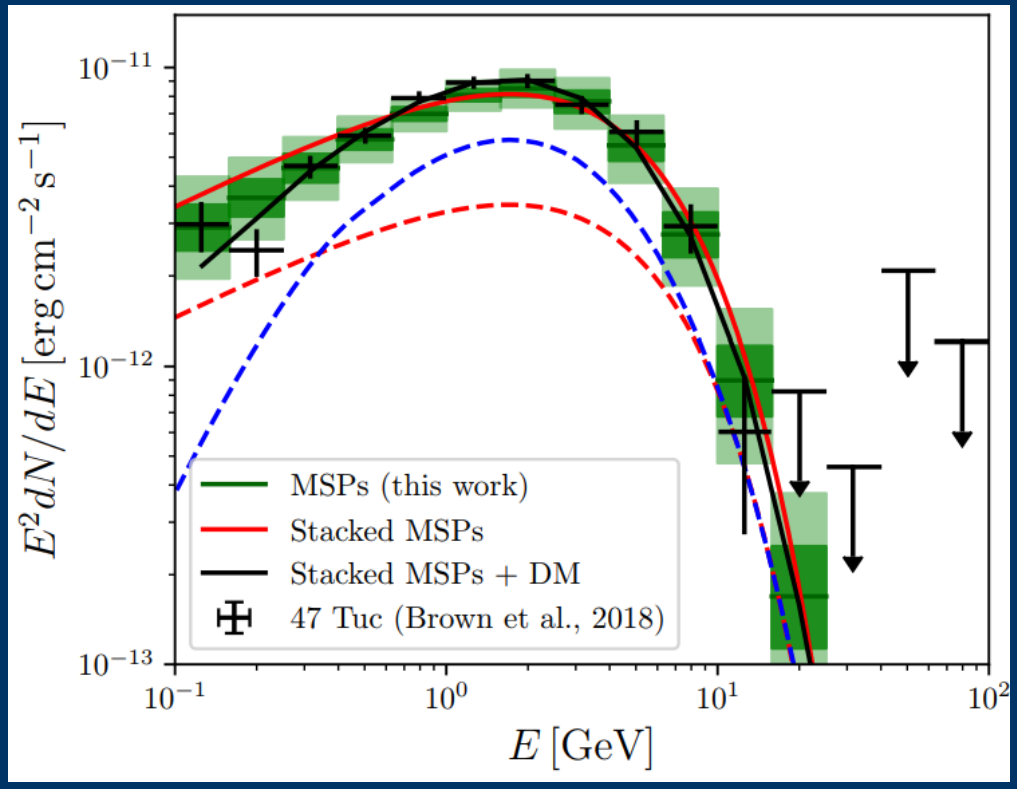
- *Fermi*-LAT observations of globular clusters are affording us the ability to consider/test models beyond the standard MSPs.
- Detailed modelling of the prominent globular cluster 47 Tuc suggests a two source, DM+MSP, model.
- Phenomenological studies revealing a variety of spectral models not consistent with MSP models.
- Growing evidence of DM within globular clusters? Or do we really not understand the MSPs population within them?

Backup

Bartel & Edwards' comment

(I) There is a discrepancy between their MSP model derived from the 2PC and the Xing&Wang model also from the 2PC.

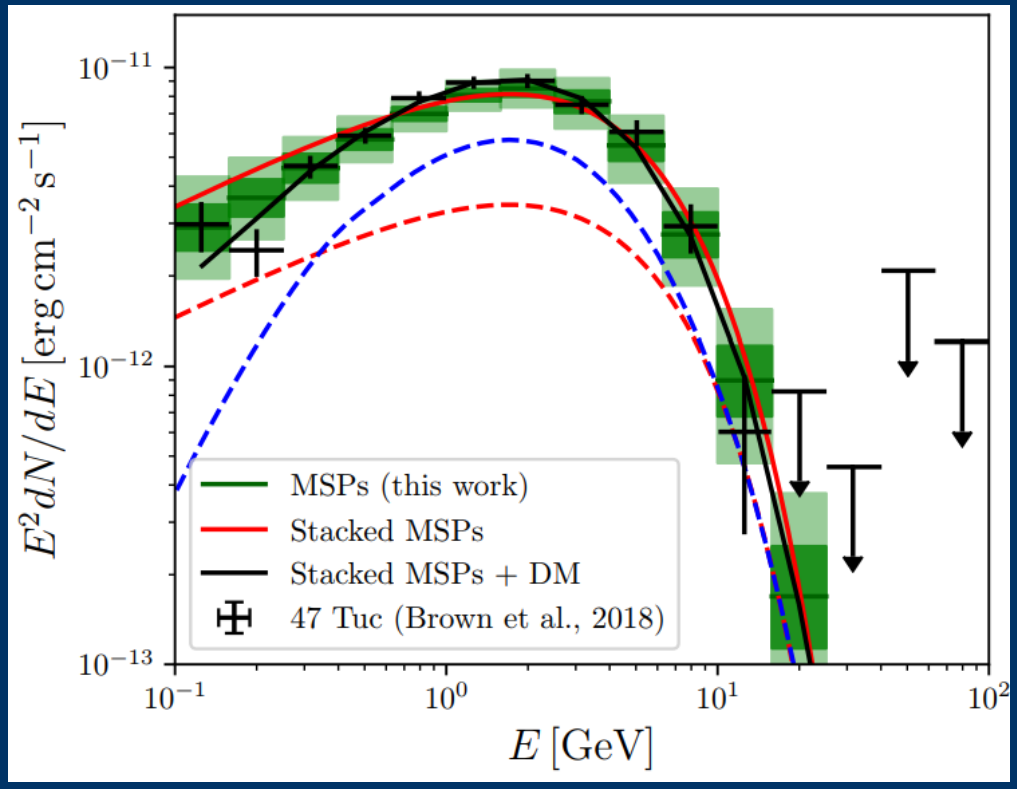
=> due to both curves are derived from the 2PC, they should be the same, irrespective of how you add them up...



Bartel & Edwards' comment

(ii) It is not clear how they derive their spectra: it appears that they randomly assign shapes irrespective of the brightness

=> the 2PC showed that you dont get bright, hard MSPs.



Bartel & Edwards' comment

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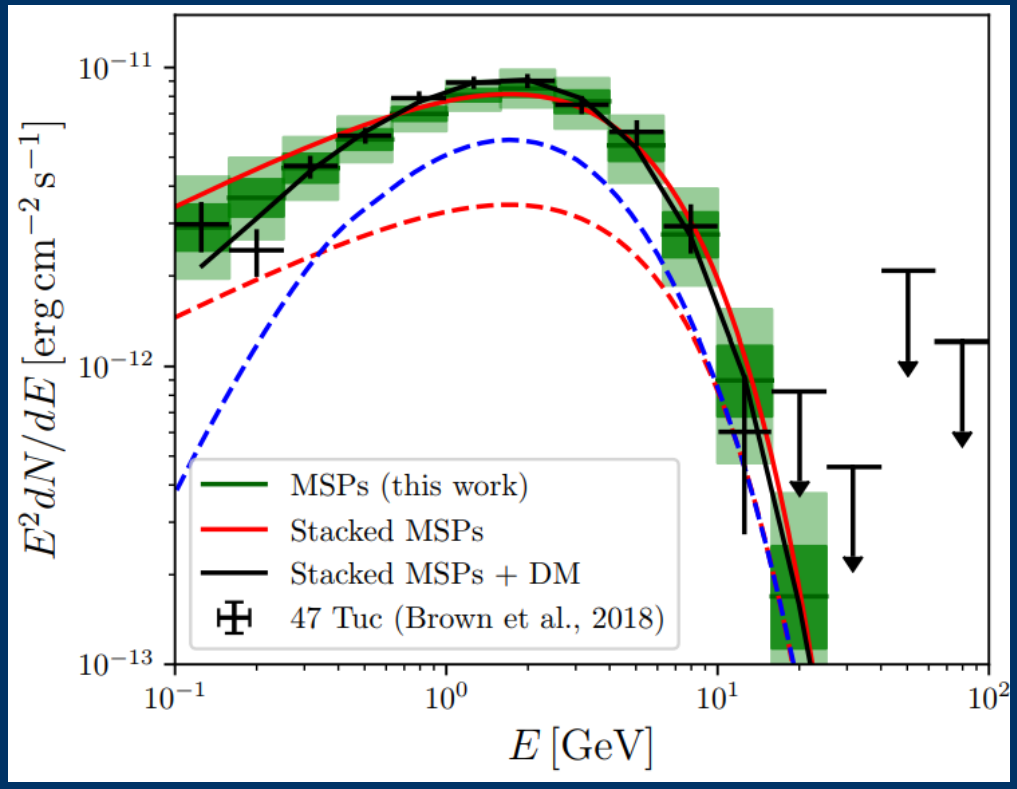
(iii) They still claim that the emission is dominated by a few bright MSPs

=> there is no evidence for this at all in a phased analysis using known ephemerides



Encounter rate?

- Use encounter rate as a proxi for the MSP population
- Some glob. clusters with low encounter rates are actually gamma-ray bright.