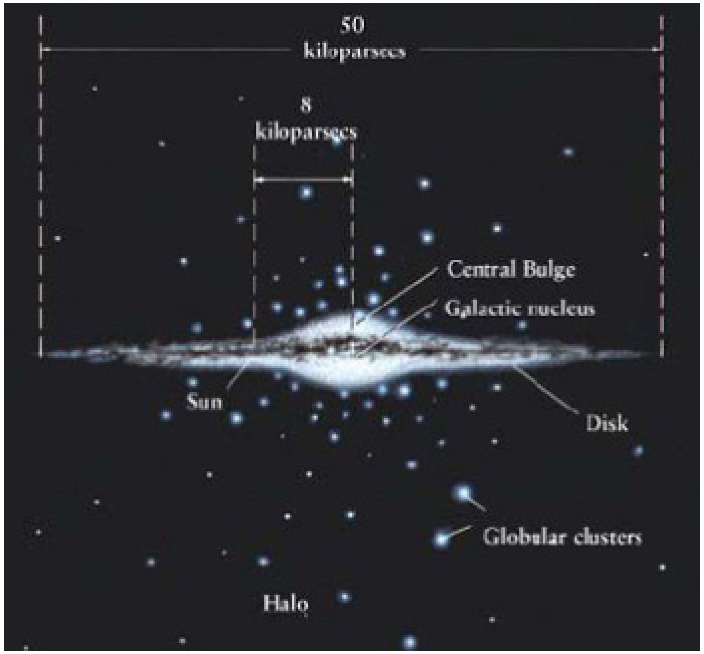
Modelling uncertainties in GeV - TeV flux predictions of Galactic globular clusters

Christo Venter[*,a] Hambeleleni Davids[a,b], Andreas Kopp[a] and Michael Backes[c,a]

[a]*Centre for Space Research, North-West University*
[b]*Department of Science Foundation, School of Science, University of Namibia*
[c]*University of Namibia, Department of Physics, Chemistry & Material Science, Windhoek Campus*

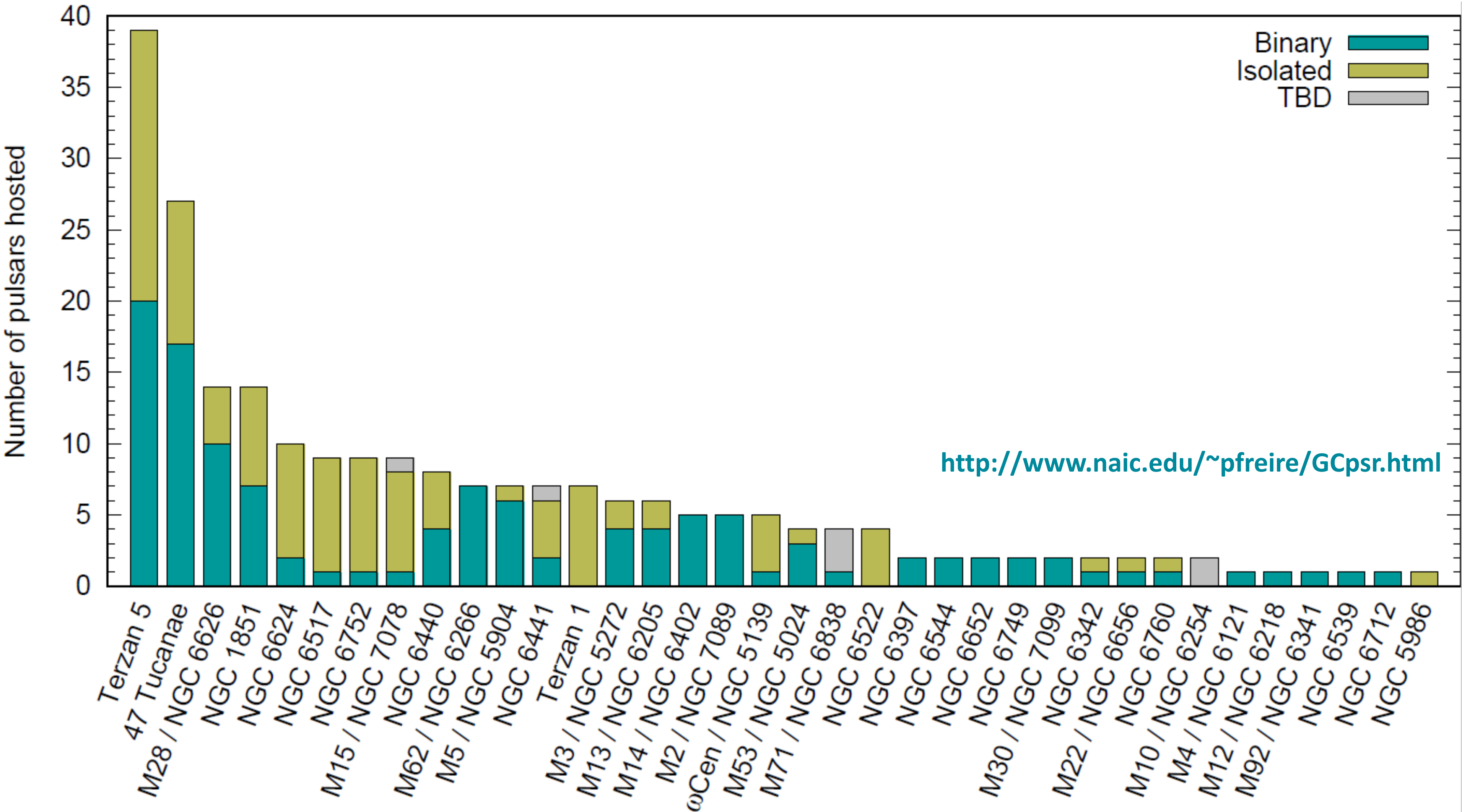
Globular Clusters

- ~160 Galactic globular clusters (GCs)in our Galaxy (Harris 1996).
- <r> ~10 kpc.
- GCs contain ~10^6 old and low-mass stars
- High-density cores: large stellar interaction rate
- Millisecond pulsars (MSPs), cataclysmic variables, low-mass X-ray binaries



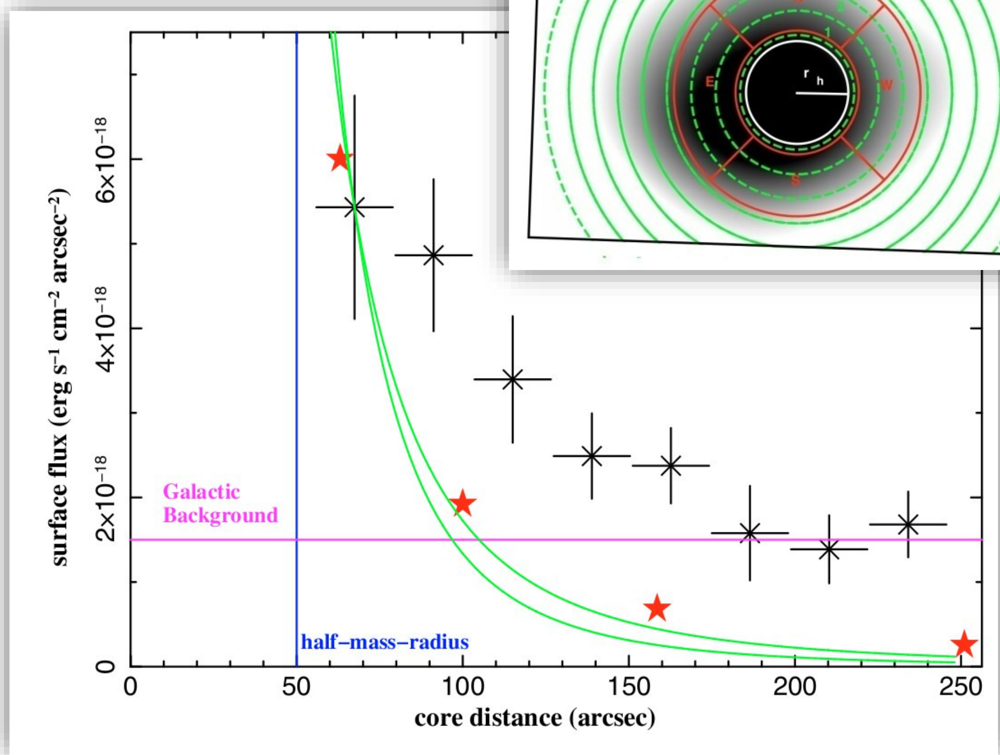
MSPs in Globular Clusters

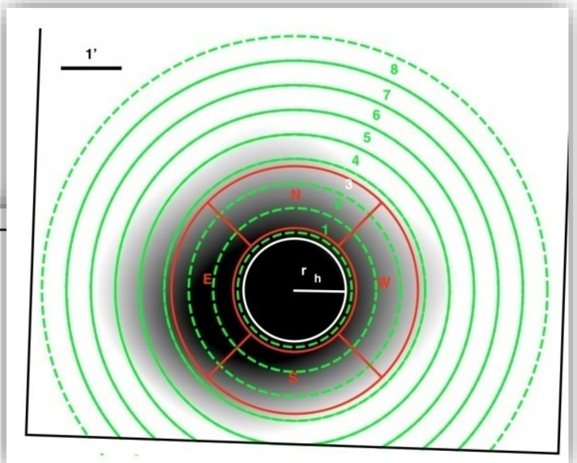
230 MSPs in 36 GCs



Diffuse Radio & X-rays

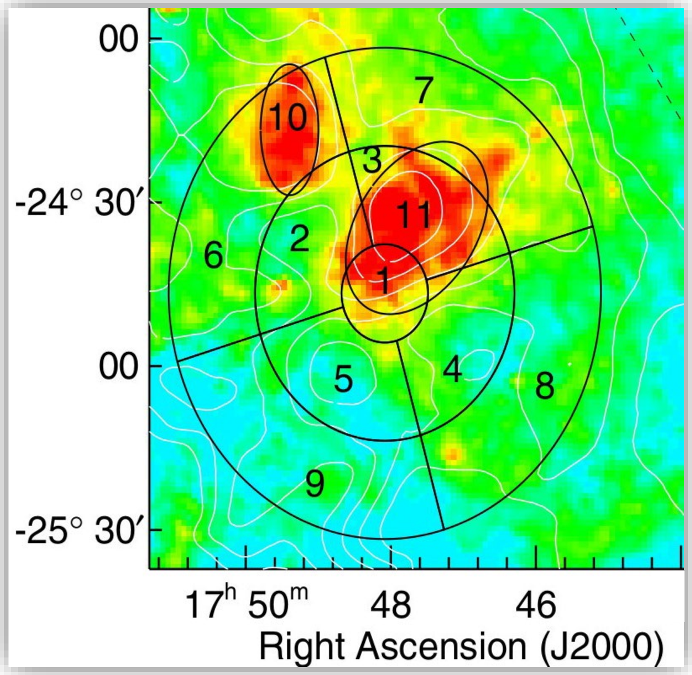
Diffuse X-ray emission





(Eger et al. 2010, 2012)

Terzan 5



Diffuse radio emission

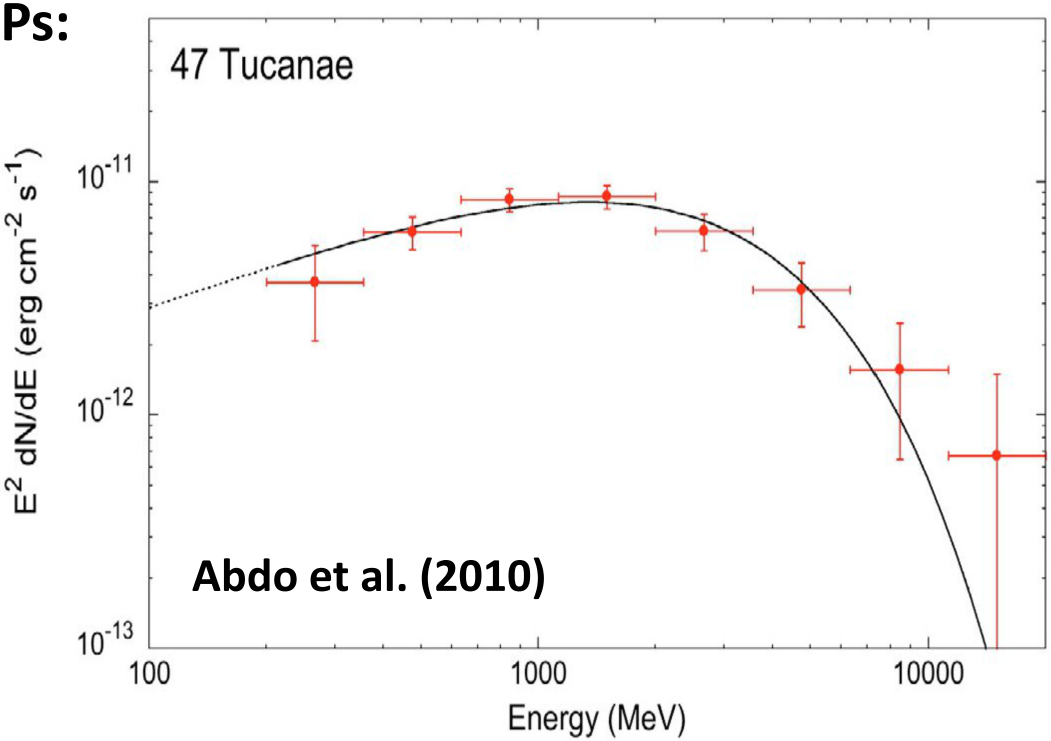
(Clapson et al. 2011)

NWU®

23 *Fermi* Detections

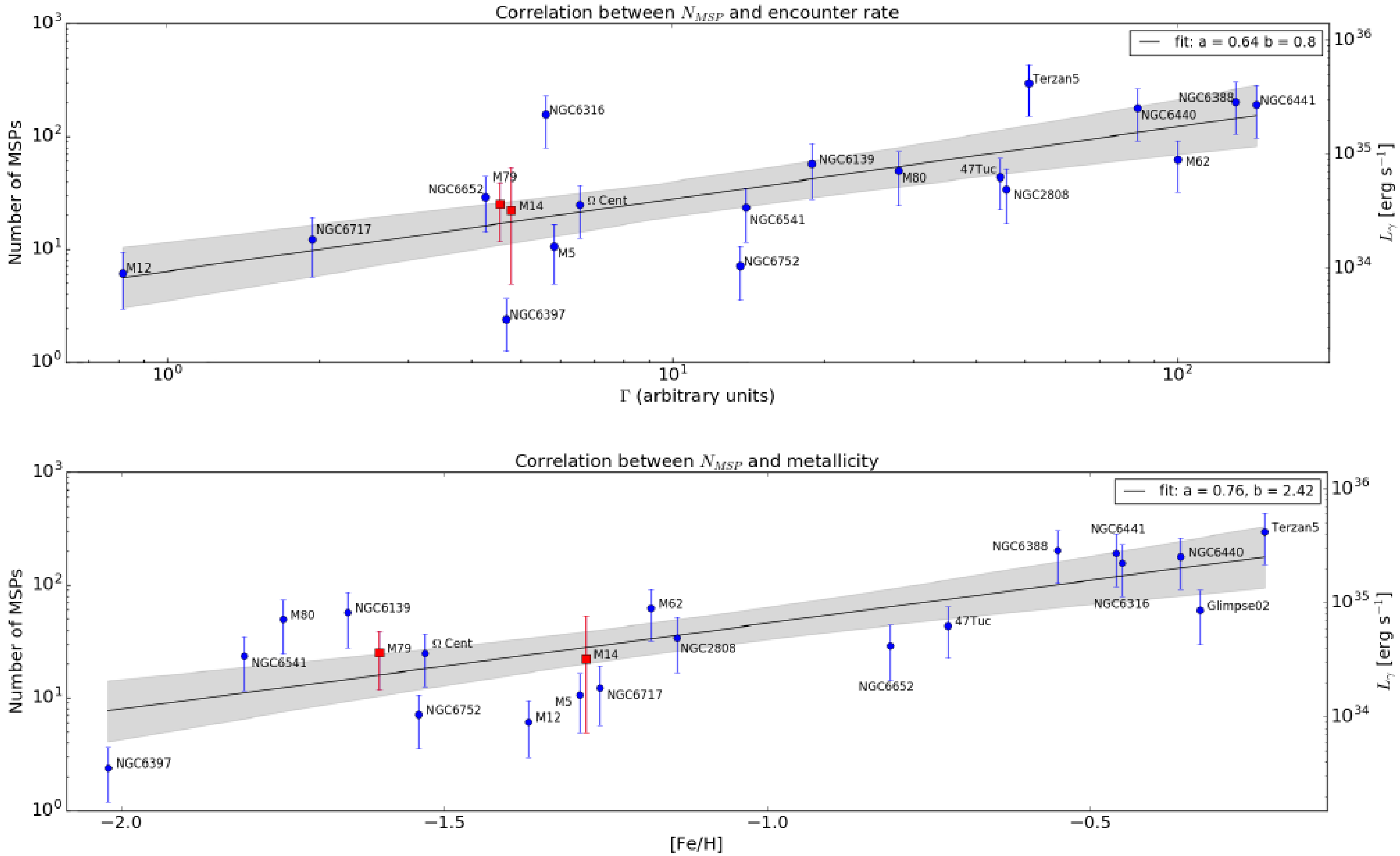
- **23 GCs identified with *Fermi* point-like sources** (Abdo et al. 2009, 2010; Kong et al. 2010; Tam et al. 2011; Zhang et al. 2016, de Menezes et al. 2019).
- **M28 & NGC 6624 contain energetic MSPs: B1821-24 & J1823-3021A, with GeV emission modulated at their spin periods** (Freire et al. 2011; Johnson et al. 2013).
- **Spectra very similar to MSPs: cumulative emission from MSP population** (Chen 1991, Harding et al. 2005, Venter et al. 2008).

$$N_{\rm MSP} = \frac{L_\gamma}{\langle \dot{E} \rangle \langle \eta_\gamma \rangle}$$



23 *Fermi* Detections

- Correlation: $L_\gamma \sim \Gamma$ and $L_\gamma \sim$ [Fe/H] (de Menezes et al. 2019).
- High interaction rate – many MSPs
- High number of SNe – high metallicity



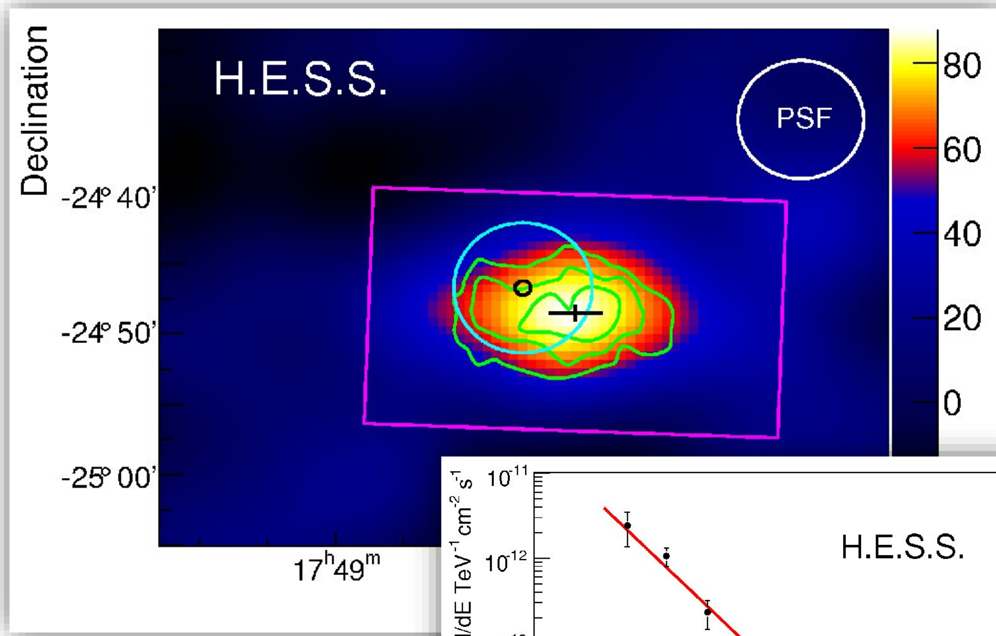
Terzan 5 – the only VHE GC

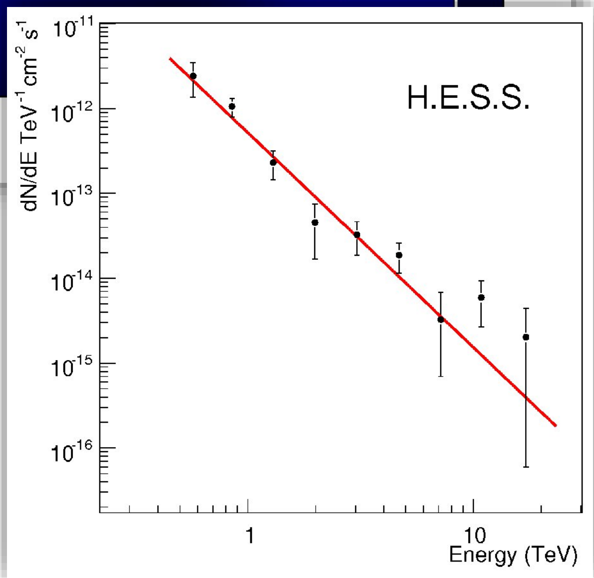
H.E.S.S. detection (Abramowski et al. 2010):

- Terzan 5

H.E.S.S. upper limits
(Aharonian et al. 2009,
Abramowski et al. 2011):

- 47 Tucanae
- NGC 6388
- M 15





MAGIC upper limits
(Anderhub et al. 2009):

- M 13

VERITAS upper limits
(McCutcheon et al. 2009):

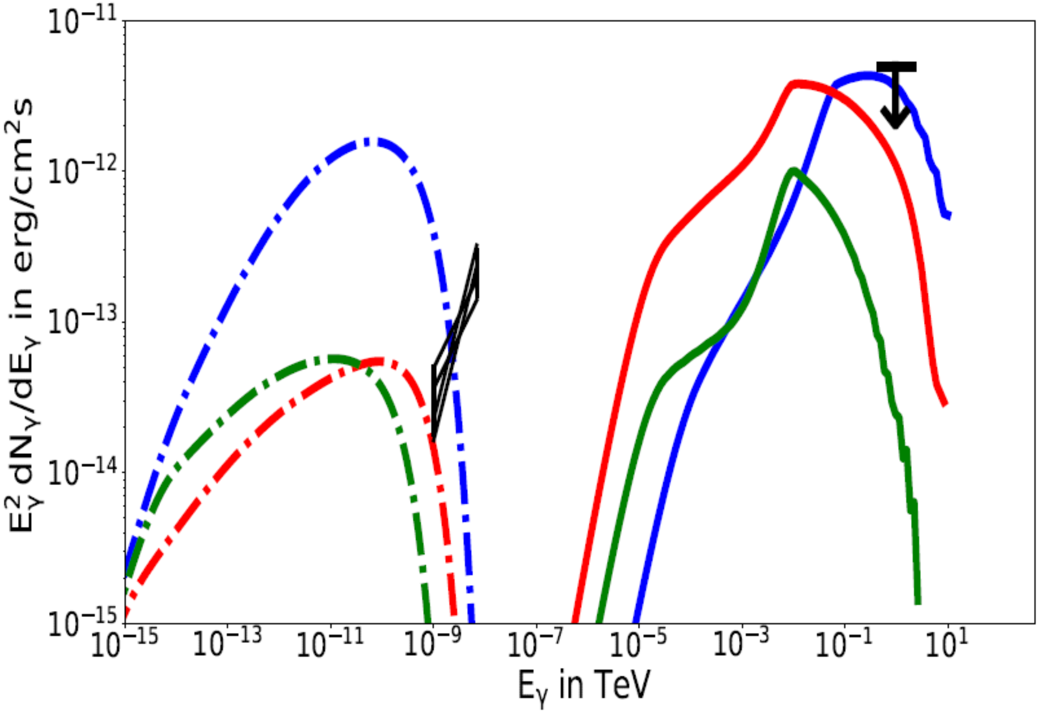
- M 5, M 13, M 15

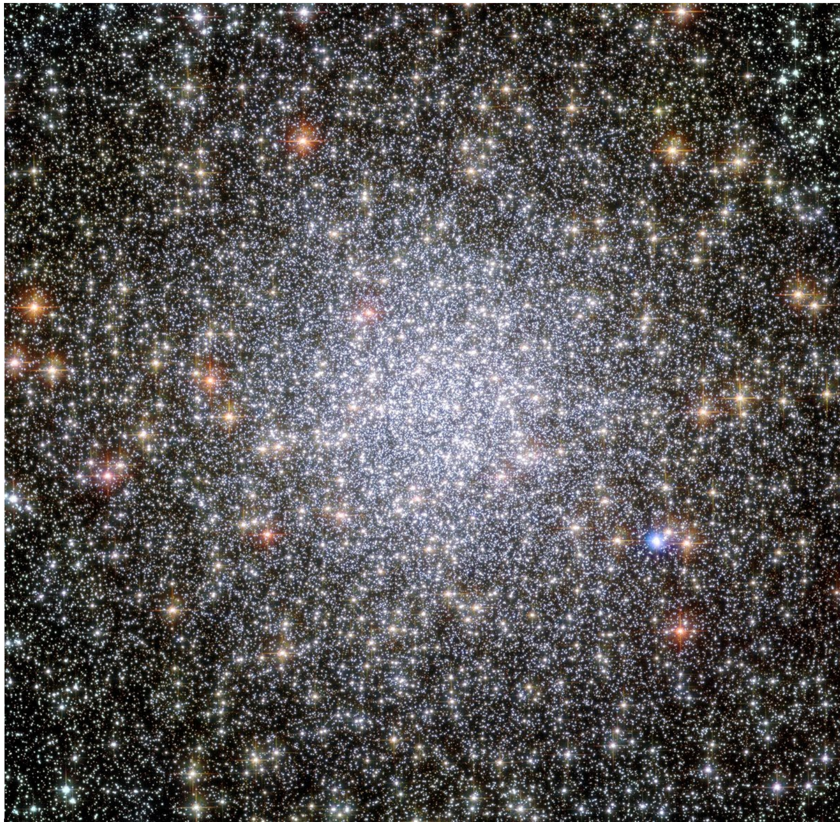
Cf. Non-spherical propagation model of TeV leptons around Terzan 5 (Bednarek & Sobczak 2014).

47 Tucanae

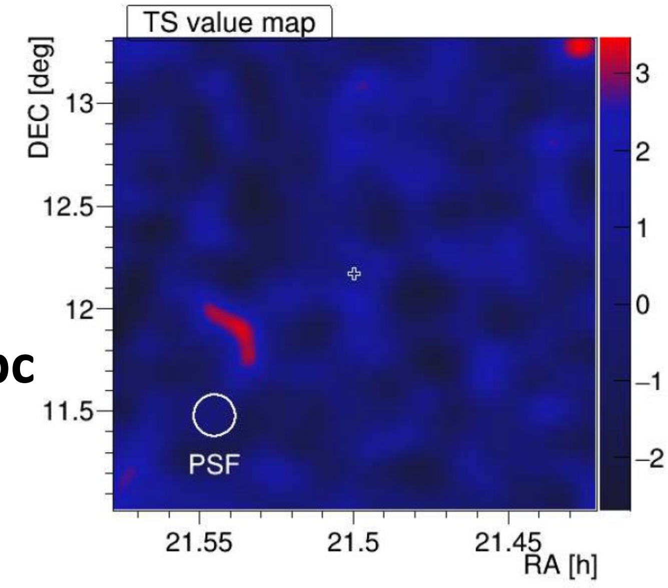
- Distance: 4 kpc, mass: 7 x 10^5 M_{sun}, age: 13 Gyr
- May host intermediate-mass black hole
- Second brightest after Omega Cen
- Contains 27 radio pulsars
- Detected in X-rays, gamma rays

Ndiyavala et al. (2018)

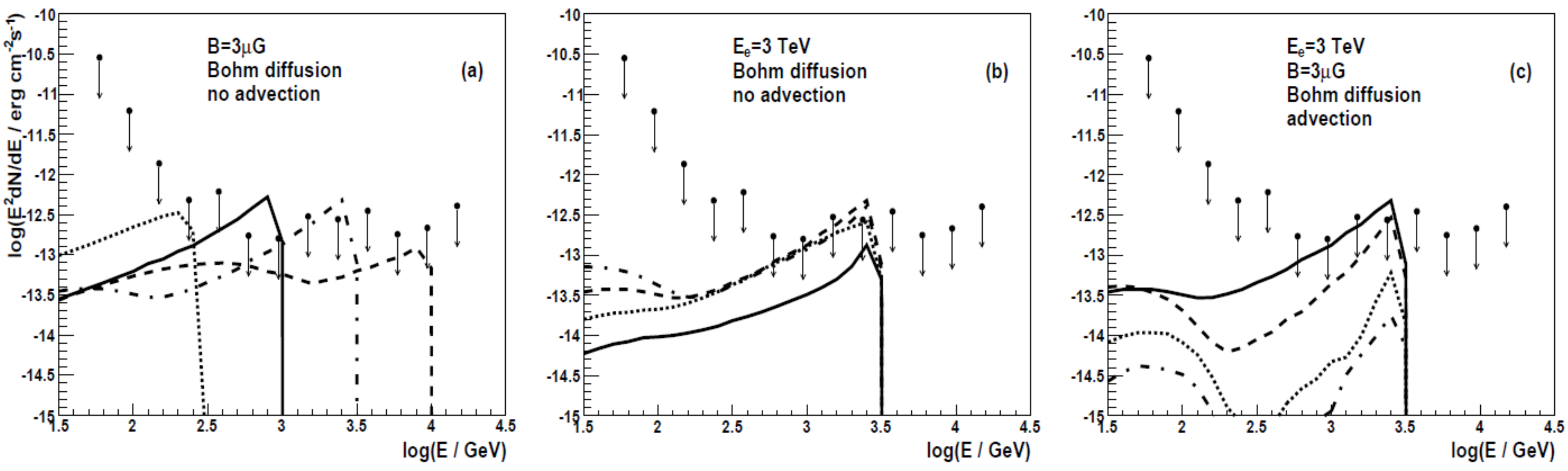




M 15

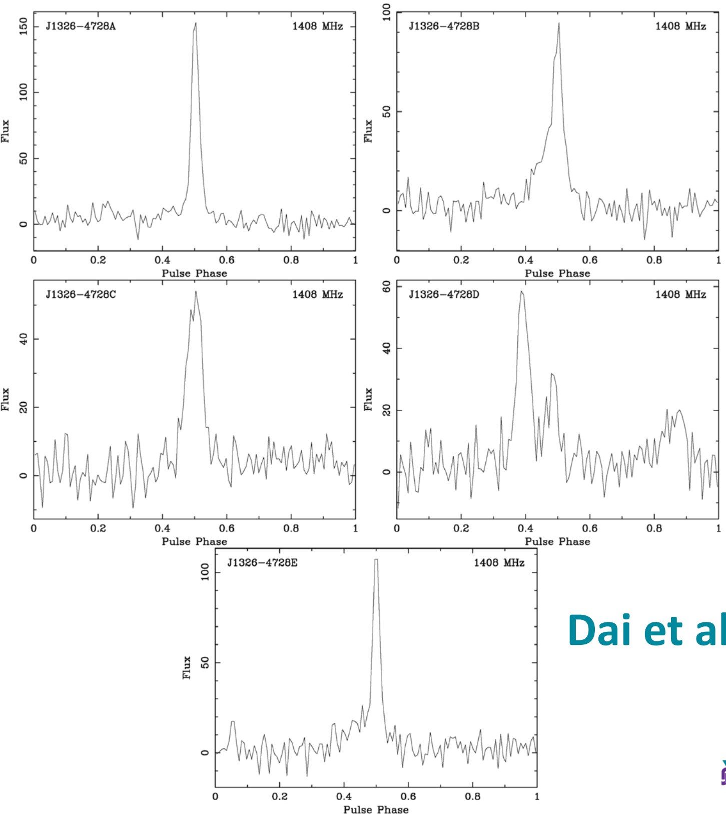


- Total stellar luminosity $7 \times 10^5\ L_{sun}$
- Core radius 0.43 pc, half-mass radius 3.04 pc
- Distance 10.4 kpc (Harris 1996).
- Eight MSPs (Freire et al. 2015).
- MAGIC observations: 165 h
- Deep limit $F(>300\ GeV) < 3.2 \times 10^{-13} cm^{-2} s^{-1}$
- < 0.26% of the Crab Nebula flux
- Constraint on acceleration efficiency of leptons: $\eta \sim 0.01$



Omega Cen

- Distance: 5 kpc, mass: 4 x 10^6 M_{sun}, age: 11.5 Gyr
- Brightest GC, visible to naked eye
- Most massive GC in Milky Way, may contain black hole
- May be the core remnant of disrupted dwarf galaxy
- 5 new radio pulsars detected!



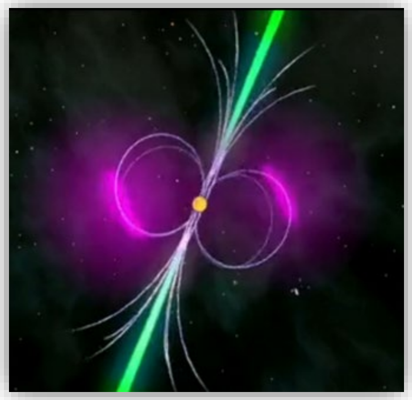
Dai et al. (2020)

Various Models

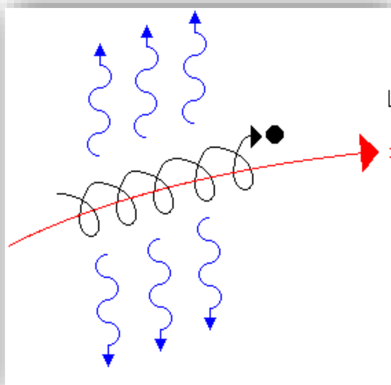
- Pulsars
  - Magnetospheric leptonic (pulsed emission)
    (e.g., Bednarek & Sitarek 2007; Venter et al. 2008, 2009; Cheng et al. 2010; Zajczyk et al. 2013; Bednarek et al. 2016)
  - Cluster leptonic (unpulsed emission)
    (Bednarek & Sitarek 2007; Kopp et al. 2013; Bednarek et al. 2016; Ndiyavala et al. 2018, 2019, 2021)
- White dwarfs (Bednarek 2012)
- Hadronic (Domainko 2011)
- Dark Matter (Brown et al. 2018)

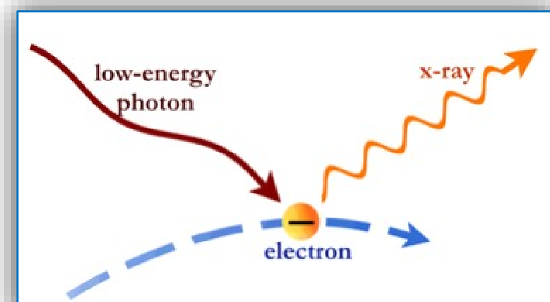
Large spread in the predicted HE / VHE flux

Spectral Components Expected from GC MSPs

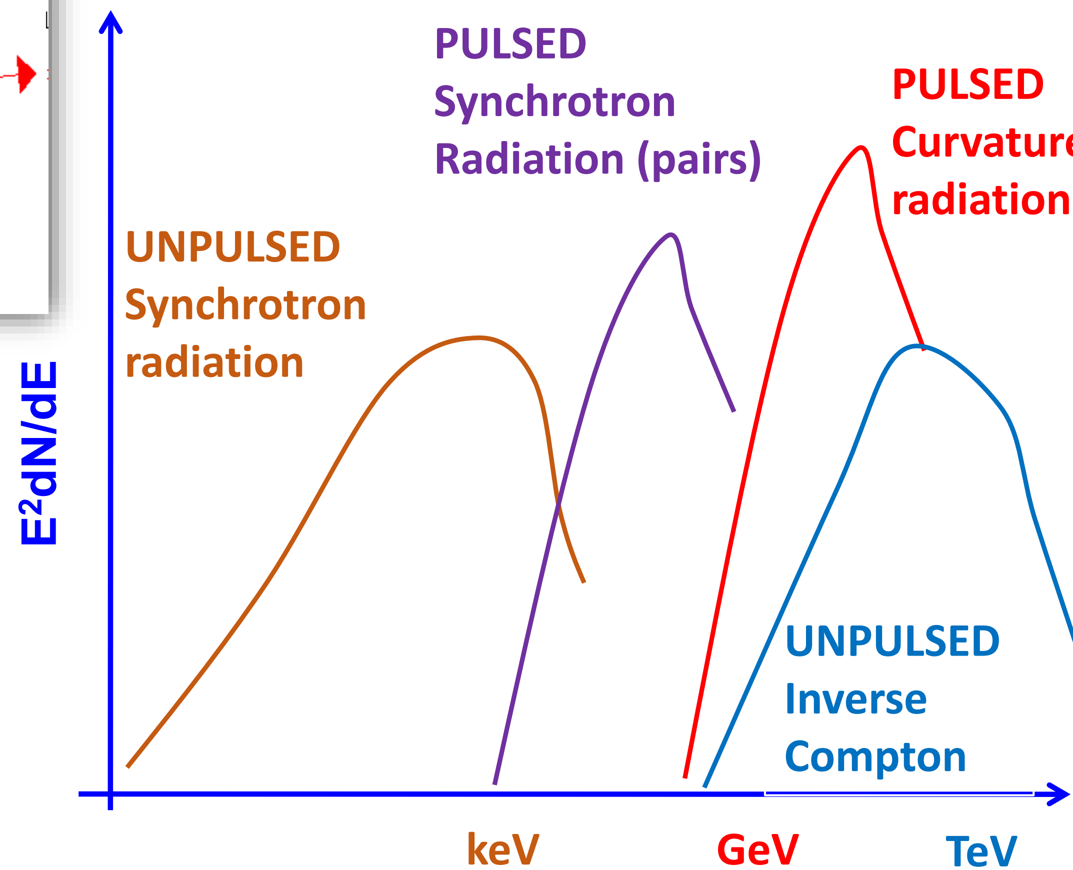


http://i.space.com/images/i/000/013/110/i02/nasa-fermi-pulsar-J1823-2021a.jpg?1320348068

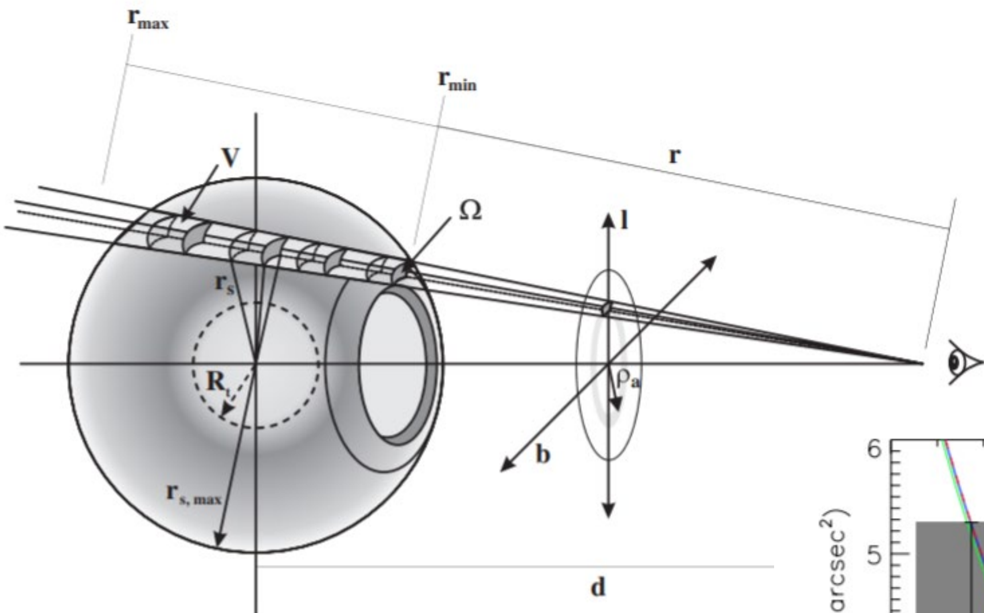




http://www.astro.wisc.edu/~bank/img/inversecompton.jpg



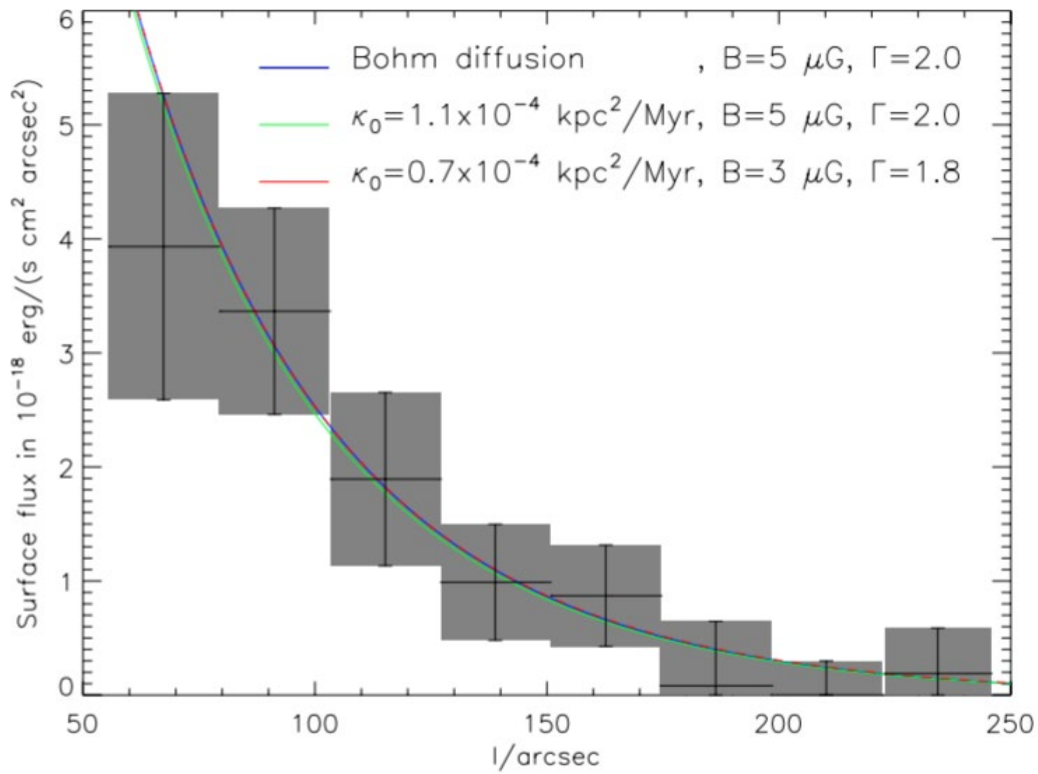
Emission Model



Kopp et al. (2013)

Ndiyavala et al. (2018, 2019, 2021)

- Soft-photon field set up by stellar members
- Particle injection and transport
- Emission and line-of-sight calculation



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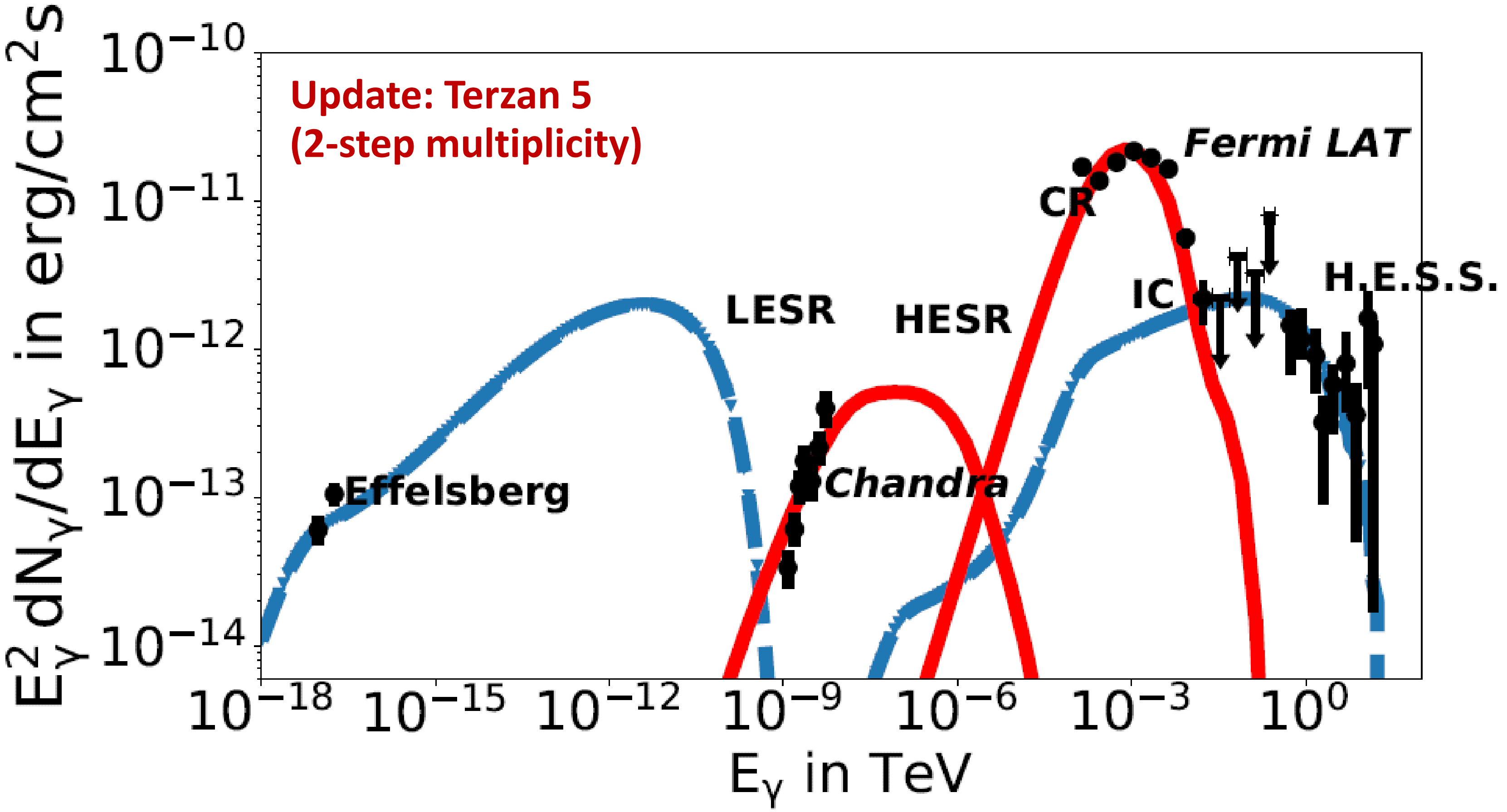
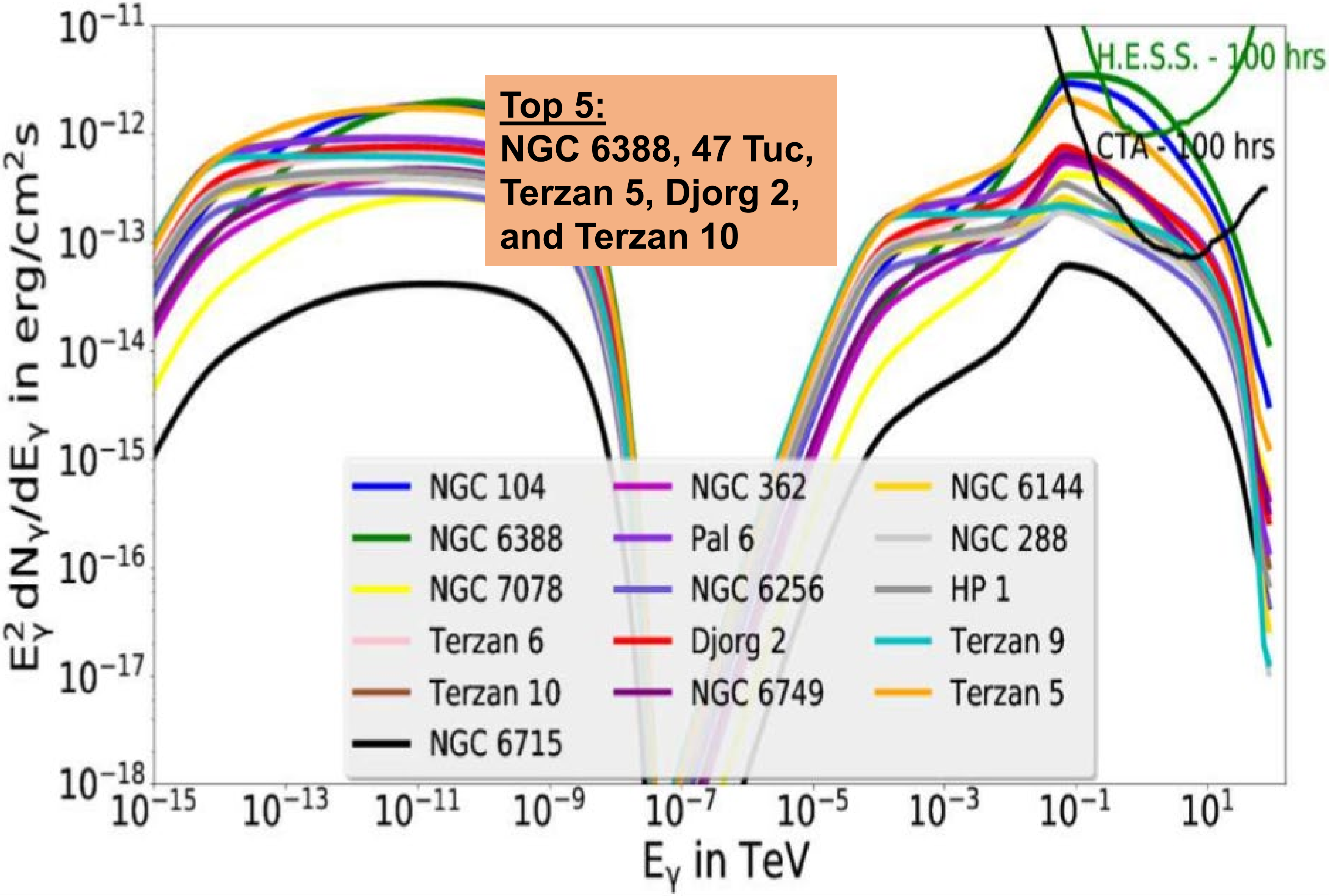


Most Promising VHE GCs

Ndiyavala et al. (2018)



Top 5:
NGC 6388, 47 Tuc, Terzan 5, Djorg 2, and Terzan 10

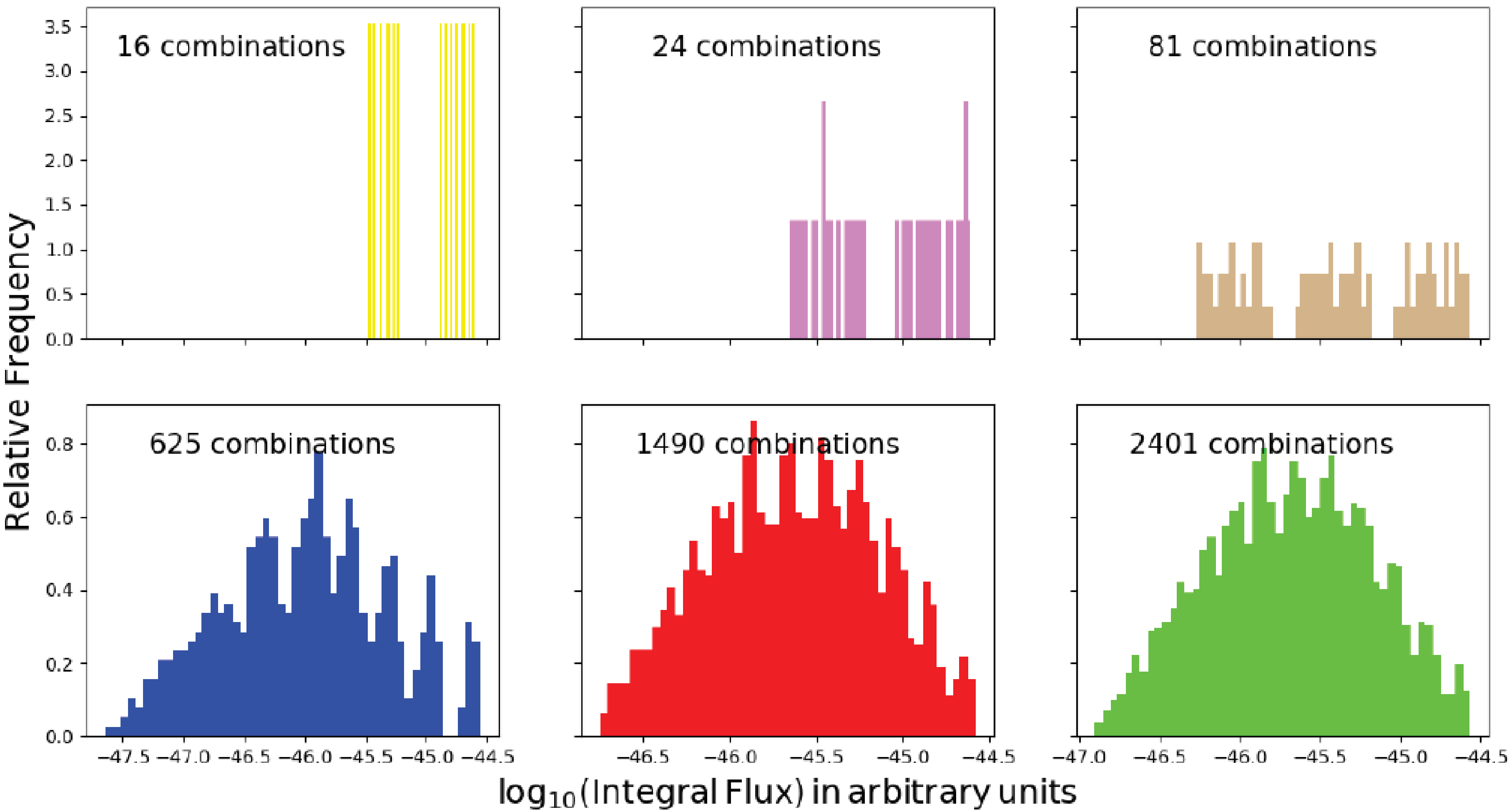
Motivation

- Uncertainty in model parameters leads to a large spread in the predicted flux.
- Can we satisfy upper limits?
- Three case studies:
  - Population of Galactic GCs (H.E.S.S. upper limits)
  - M 15 (deep MAGIC upper limits)
  - Omega Cen (five radio pulsars recently detected)
- Guide the observational strategy of CTA

Convergence

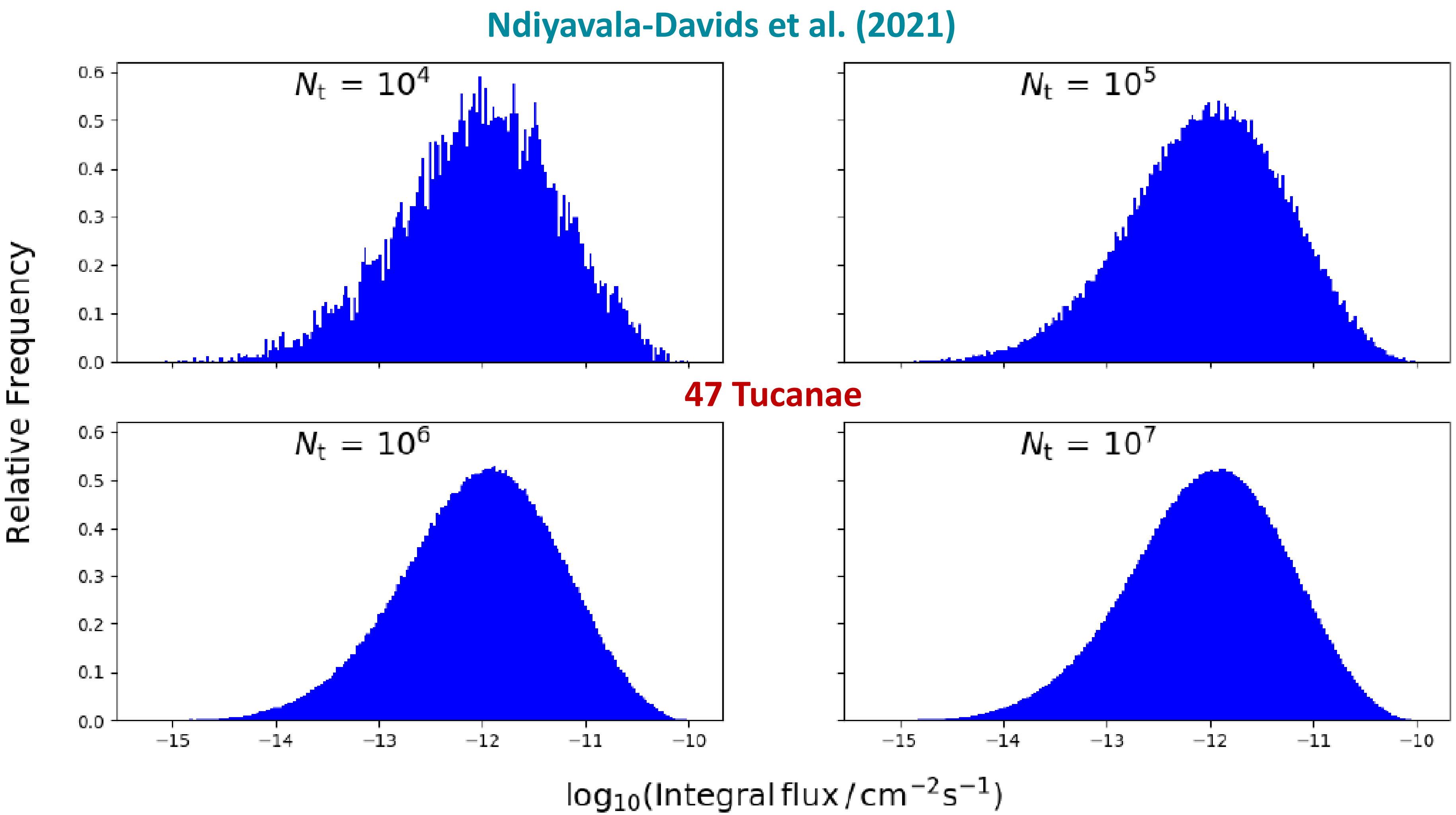
- **Finer sampling of parameter space**

Ndiyavala-Davids et al. (2021)



Convergence

- **More trials (parameter combinations)**



1. GC Population

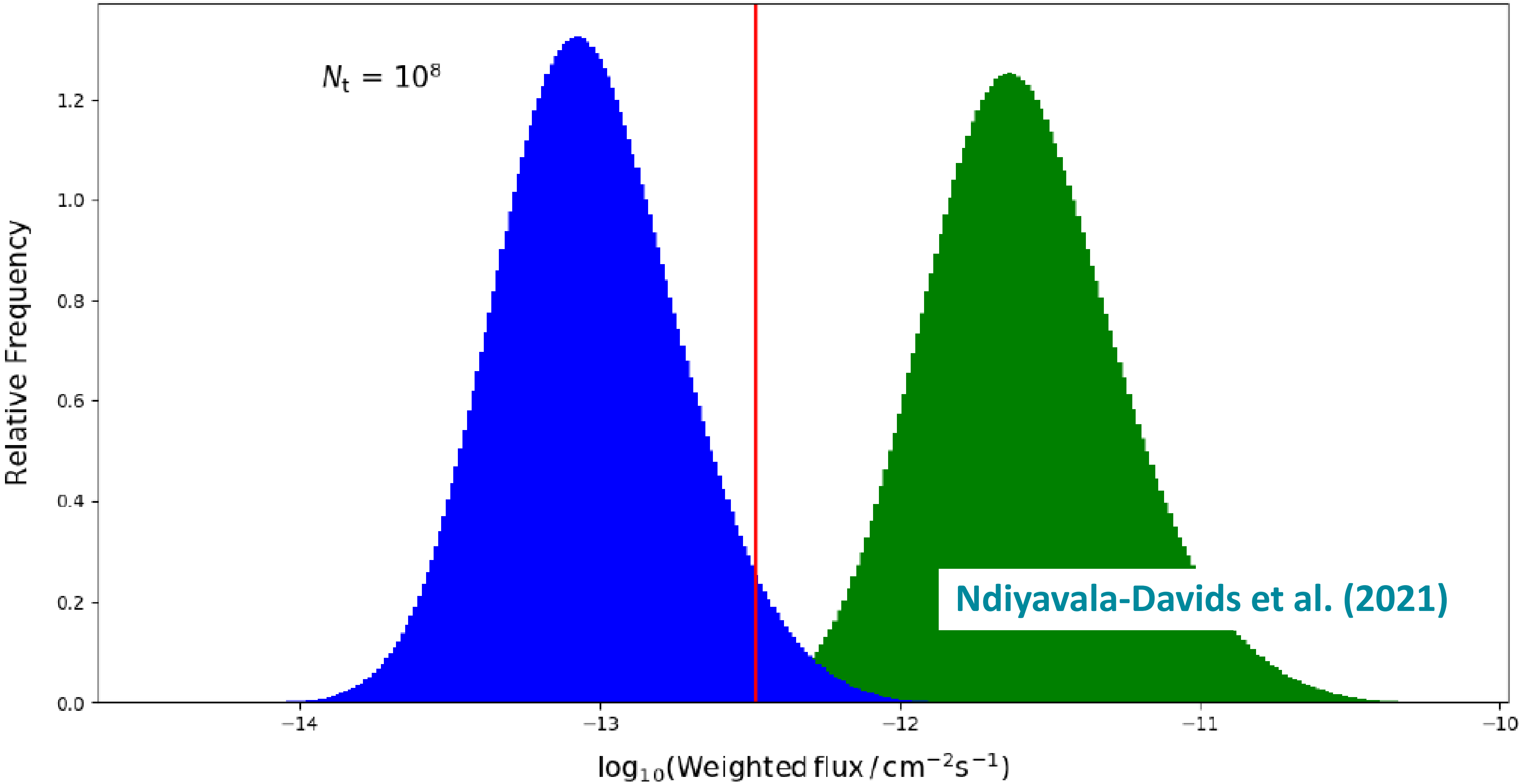
- **First parameter range combination**

Ndiyavala-Davids et al. (2021)

GC name	E_{th} (TeV)	$F_{UL}(E > E_{th})$ $\times10^{-13}$ (ph cm^{-2}s^{-1})	F_μ $\times10^{-13}$ (ph cm^{-2}s^{-1})	σ_{16}/F_μ (%)	σ_{84}/F_μ (%)	F_μ/F_{UL}	$\bar{F}_G$ $\times10^{-13}$ (ph cm^{-2} s^{-1})	σ/F_μ (%)	$\bar{F}_G/F_\mu$
NGC 104	0.72	19	10.0	84	427	0.53	9.4	611	0.92
NGC 6388	0.28	15	5.9	85	461	0.39	5.5	706	0.93
NGC 7078	0.40	7.2	1.7	84	465	0.24	1.5	673	0.94
Terzan 6	0.28	21	6.9	86	518	0.33	6.3	890	0.91
Terzan 10	0.23	29	11.0	87	530	0.38	10.0	903	0.91
NGC 6715	0.19	9.3	1.2	85	478	0.13	1.1	722	0.92
NGC 362	0.59	24	1.5	88	572	0.06	1.4	1081	0.93
Pal 6	0.23	12	11.0	87	534	0.92	9.9	919	0.90
NGC 6256	0.23	32	3.2	87	534	0.10	2.9	941	0.91
Djorg 2	0.28	8.4	10.0	86	508	1.19	9.2	831	0.92
NGC 6749	0.19	14	6.9	87	534	0.49	6.3	913	0.91
NGC 6144	0.23	14	4.3	87	554	0.31	3.9	972	0.91
NGC 288	0.16	5.3	6.1	87	553	1.15	5.6	945	0.92
HP 1	0.23	15	5.4	87	539	0.36	5.0	925	0.93
Terzan 9	0.33	45	2.8	89	644	0.06	2.6	1341	0.93
Stacking analysis	0.23	3.3	25	50	119	7.6	26.0	135	1.04

1. GC Population

- **Two parameter range combinations (second: lower source term)**



1. GC Population

- **Second parameter range combination**

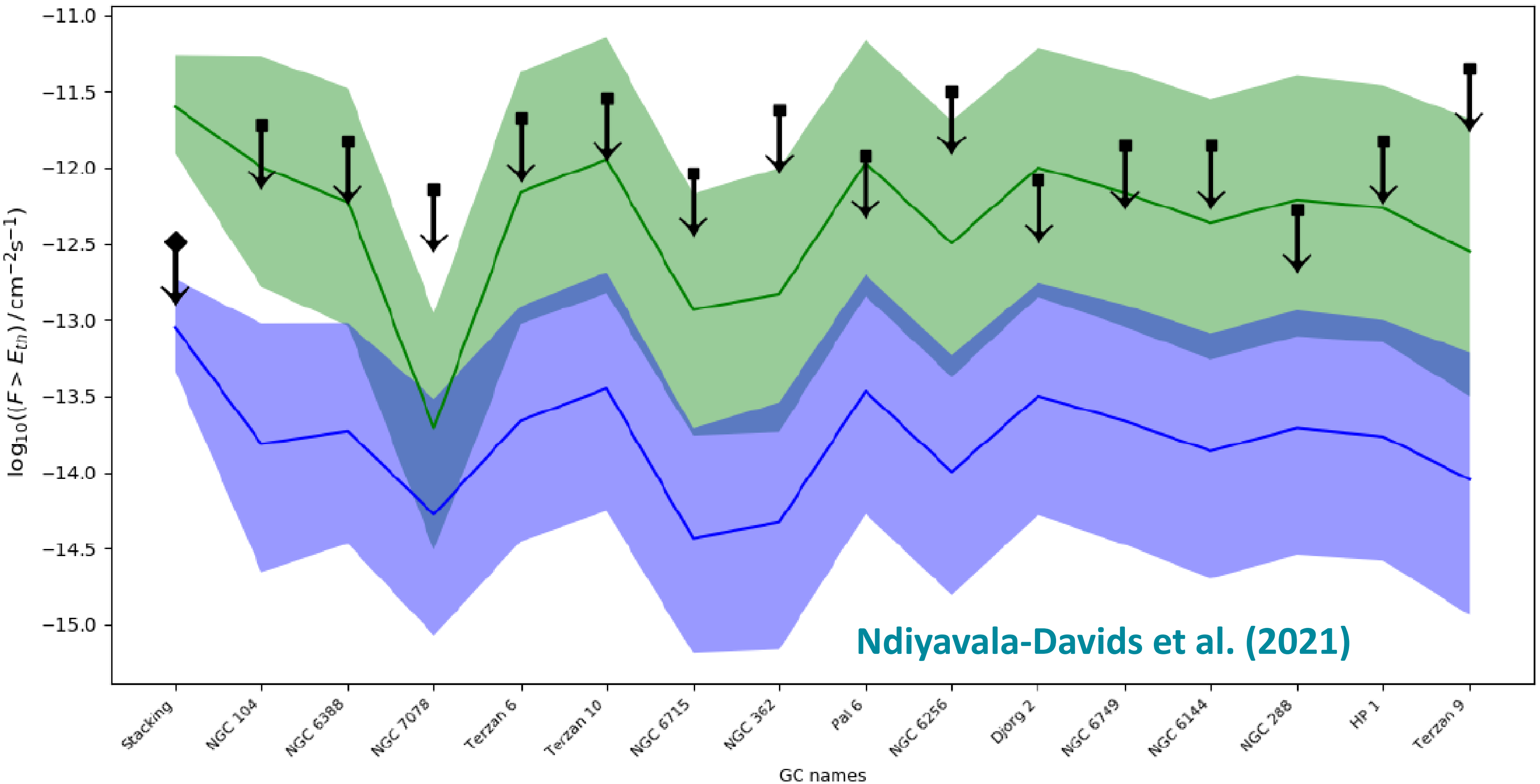
Ndiyavala-Davids et al. (2021)

Table 2. H.E.S.S. flux upper limits and model predictions for the second parameter combination, associated with the blue histograms in Figure 7.

GC name	E_{th} (TeV)	$F_{\mathrm{UL}}(E > E_{\mathrm{th}})$ $\times 10^{-13}$ (ph cm^{-2}s^{-1})	F_μ $\times 10^{-13}$ (ph cm^{-2}s^{-1})	σ_{16}/F_μ (%)	σ_{84}/F_μ (%)	F_μ/F_{UL}	$\bar{F}_G$ $\times 10^{-13}$ (ph cm^{-2} s^{-1})	σ/F_μ (%)	$\bar{F}_G/F_\mu$
NGC 104	0.72	19	0.154	86	614	0.0081	0.145	929	0.94
NGC 6388	0.28	15	0.187	82	410	0.0125	0.179	610	0.96
NGC 7078	0.40	7.2	0.053	84	573	0.0074	0.051	737	0.95
Terzan 6	0.28	21	0.218	84	463	0.0104	0.208	766	0.92
Terzan 10	0.23	29	0.356	84	475	0.0123	0.337	778	0.95
NGC 6715	0.19	9.3	0.037	82	429	0.0040	0.035	622	0.96
NGC 362	0.59	24	0.047	85	513	0.0020	0.044	923	0.94
Pal 6	0.23	12	0.343	85	578	0.0286	0.324	787	0.94
NGC 6256	0.23	32	0.101	84	482	0.0032	0.096	810	0.95
Djorg 2	0.28	8.4	0.317	84	451	0.0377	0.302	713	0.95
NGC 6749	0.19	14	0.218	84	577	0.0156	0.205	780	0.94
NGC 6144	0.23	14	0.138	86	492	0.0097	0.129	819	0.93
NGC 288	0.16	5.3	0.196	85	492	0.0370	0.183	806	0.93
HP 1	0.23	15	0.172	85	481	0.0115	0.162	797	0.95
Terzan 9	0.33	45	0.090	87	580	0.0020	0.084	1147	0.93
Stacking analysis	0.23	3.3	0.895	48	108	0.271	0.923	113	1.03

1. GC Population

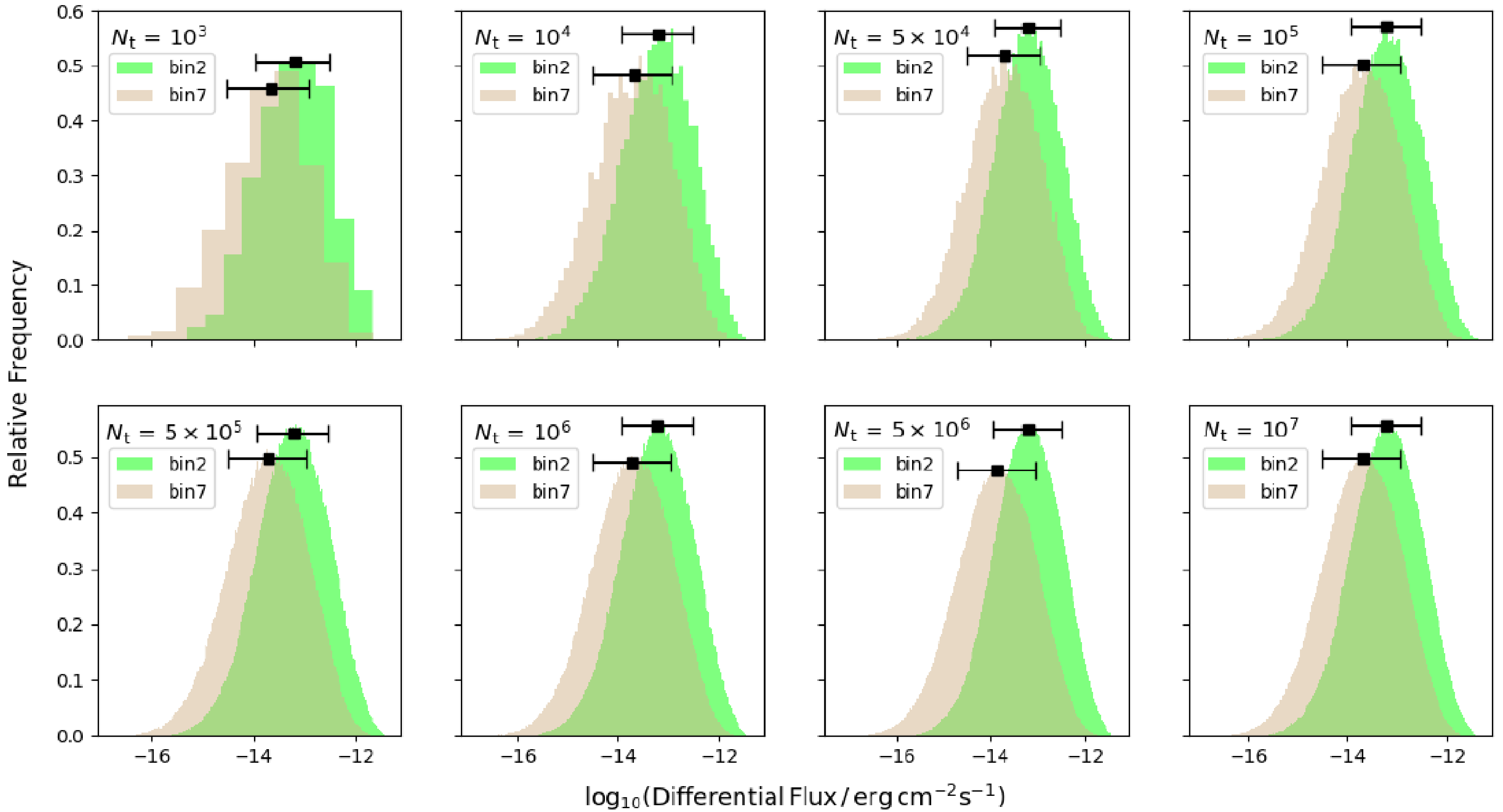
- **Two parameter range combinations (second: lower source term)**



2. M 15

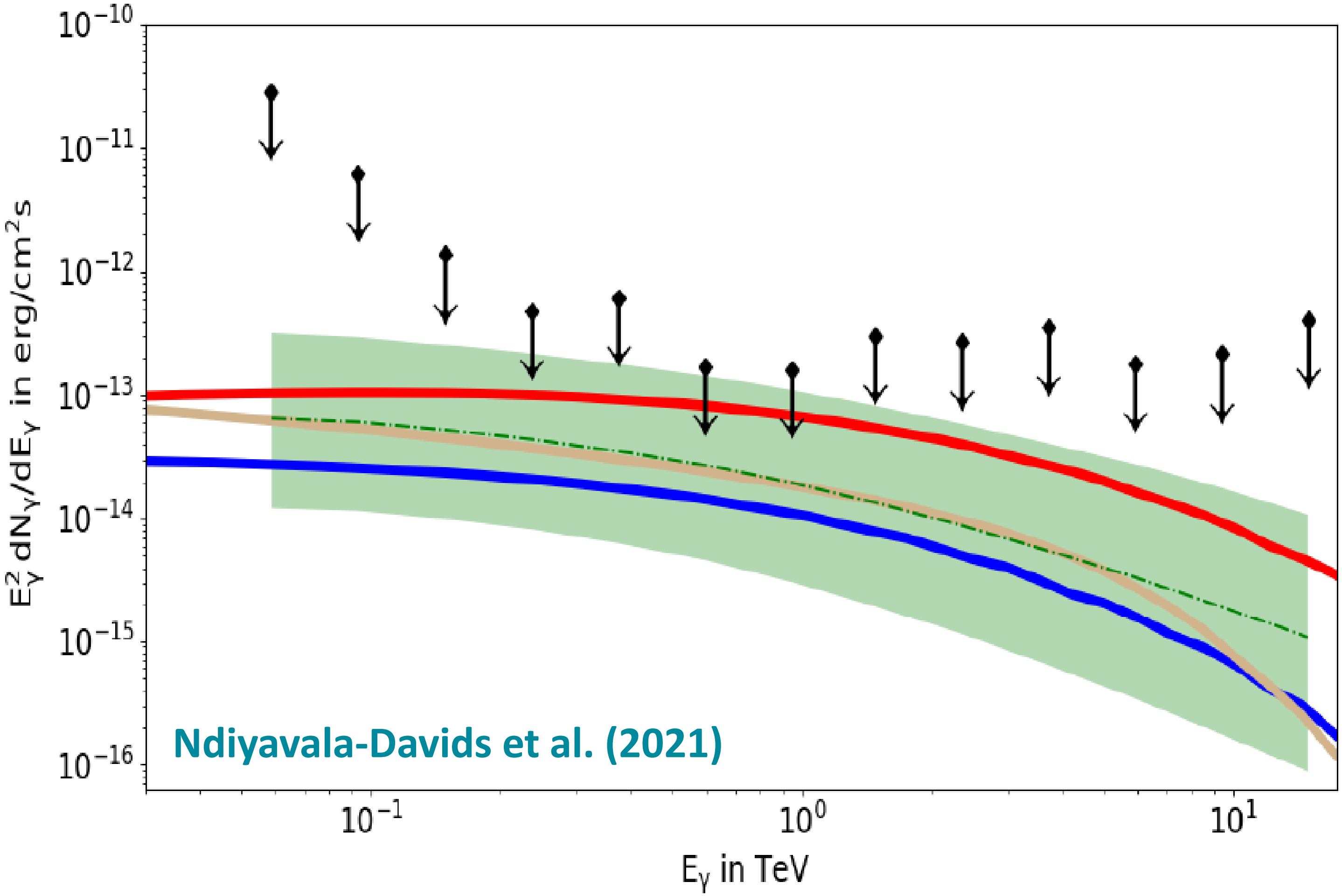
- **MAGIC differential flux upper limits: 7 energy bins**

Ndiyavala-Davids et al. (2021)



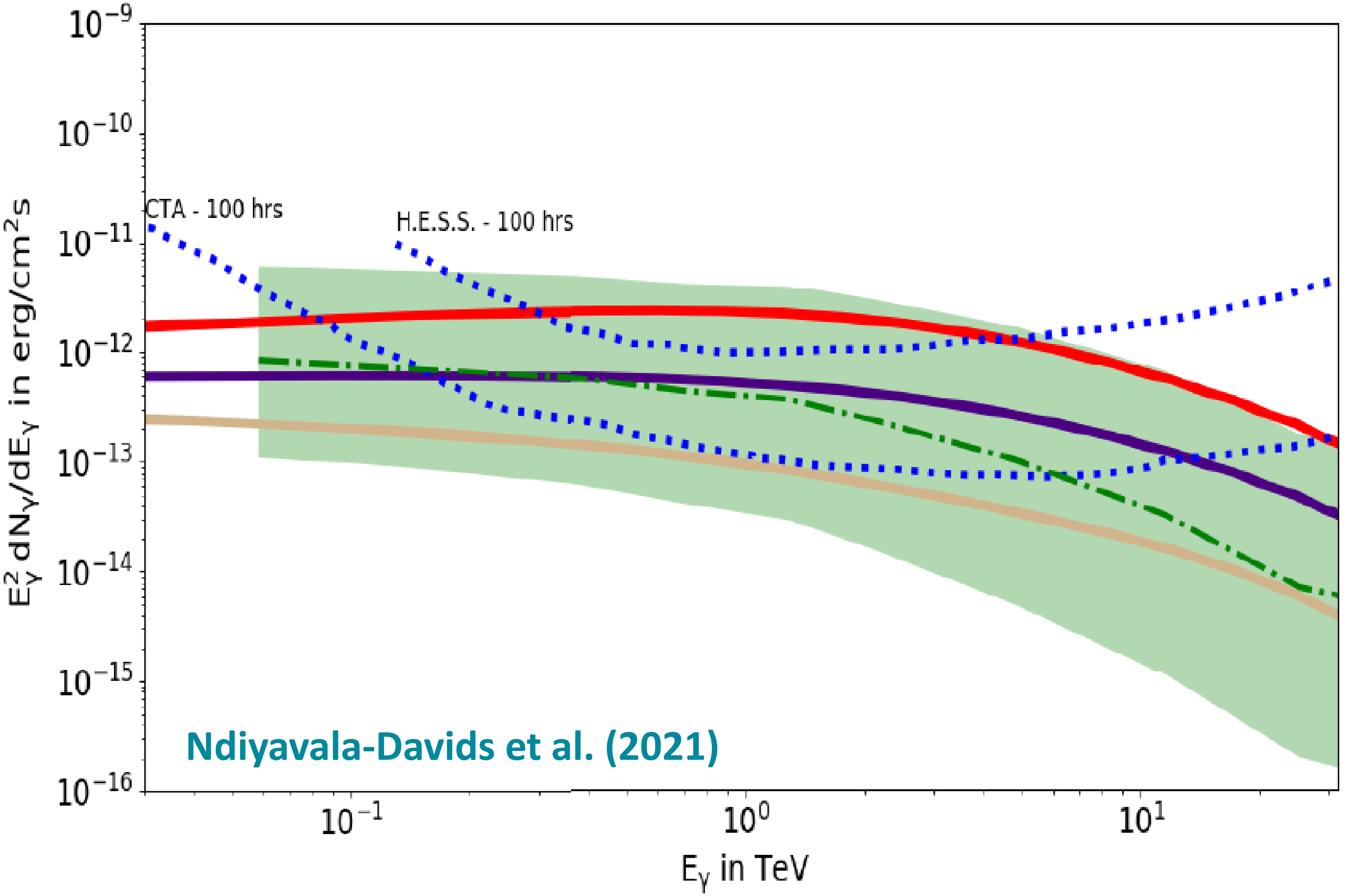
2. M 15

- Median + uncertainty band: due to uncertain model parameters
- Example model predictions



3. Omega Cen

- **Median + uncertainty band: due to uncertain model parameters**
- **Example model predictions**



Conclusions

- Parameter uncertainties: quite a large spread in model flux predictions
- Finer grid, finer sampling → smoother distribution
- Distribution depends on parameter range, number of free parameters
- Stacking: relative errors smaller by 1 order of magnitude, reducing model uncertainty
- Non-unique population-averaged constraints derived from H.E.S.S. stacking upper limits; reasonable parameters
- Need increased accuracy in model parameters

THANK YOU!

"Who has measured the waters in the hollow of His Hand,
or with the breadth of His Hand marked off the heavens?" **(Is. 40:12a).**