HIGH ENERGY RADIATION FROM GLOBULAR CLUSTERS

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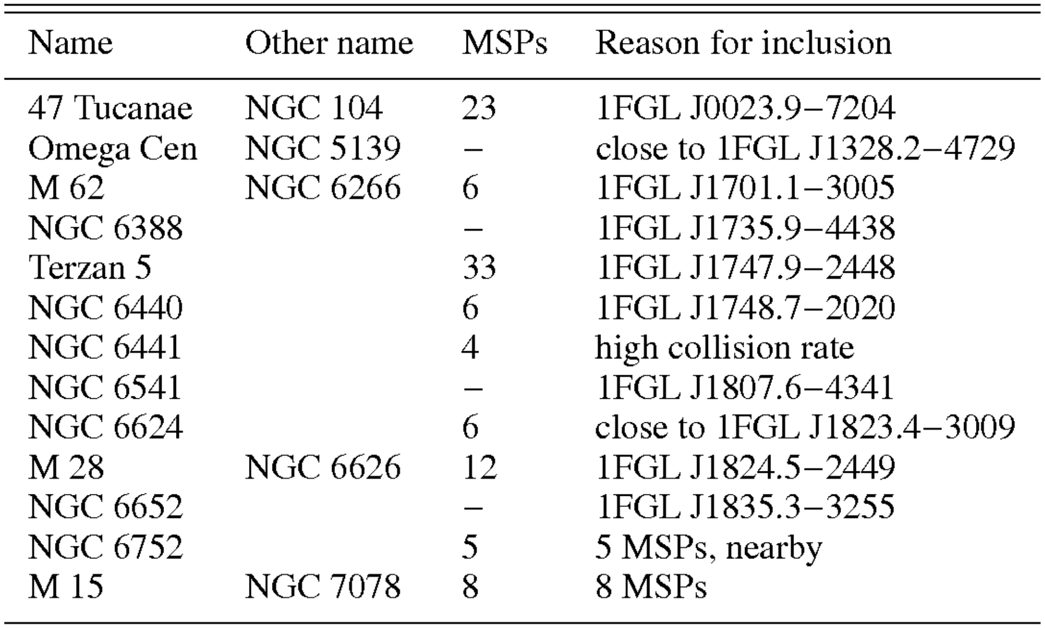
- Why the topic is interesting ?
- What we observe ?
- What seems to be obvious ?
- What should be observed from GCs ?

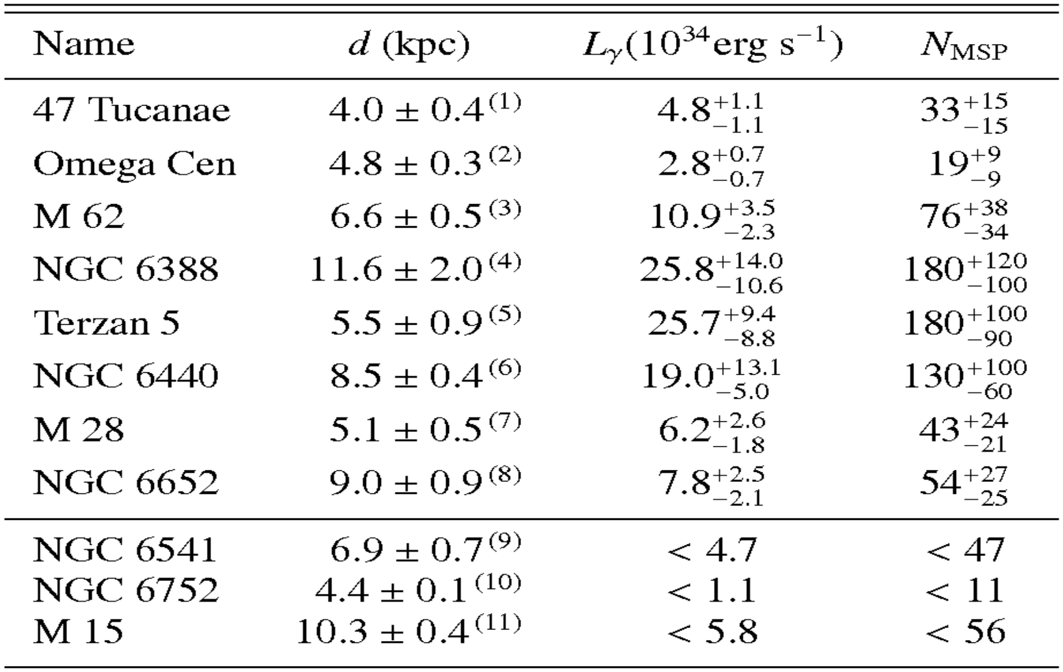
Why high energy processes within GCs ?

- GCs contain many MSPs
- GCs create strong (well defined) rad. field
- GCs related to Fermi GeV sources
- GCs contain many other interesting sources
  (WDs, LMXBs, IMBHs ?)
  (maybe also remnants of SN Ia, Novae ?)

Globular Clusters - MSP - Gamma Rays (Abdo et al. 2010)

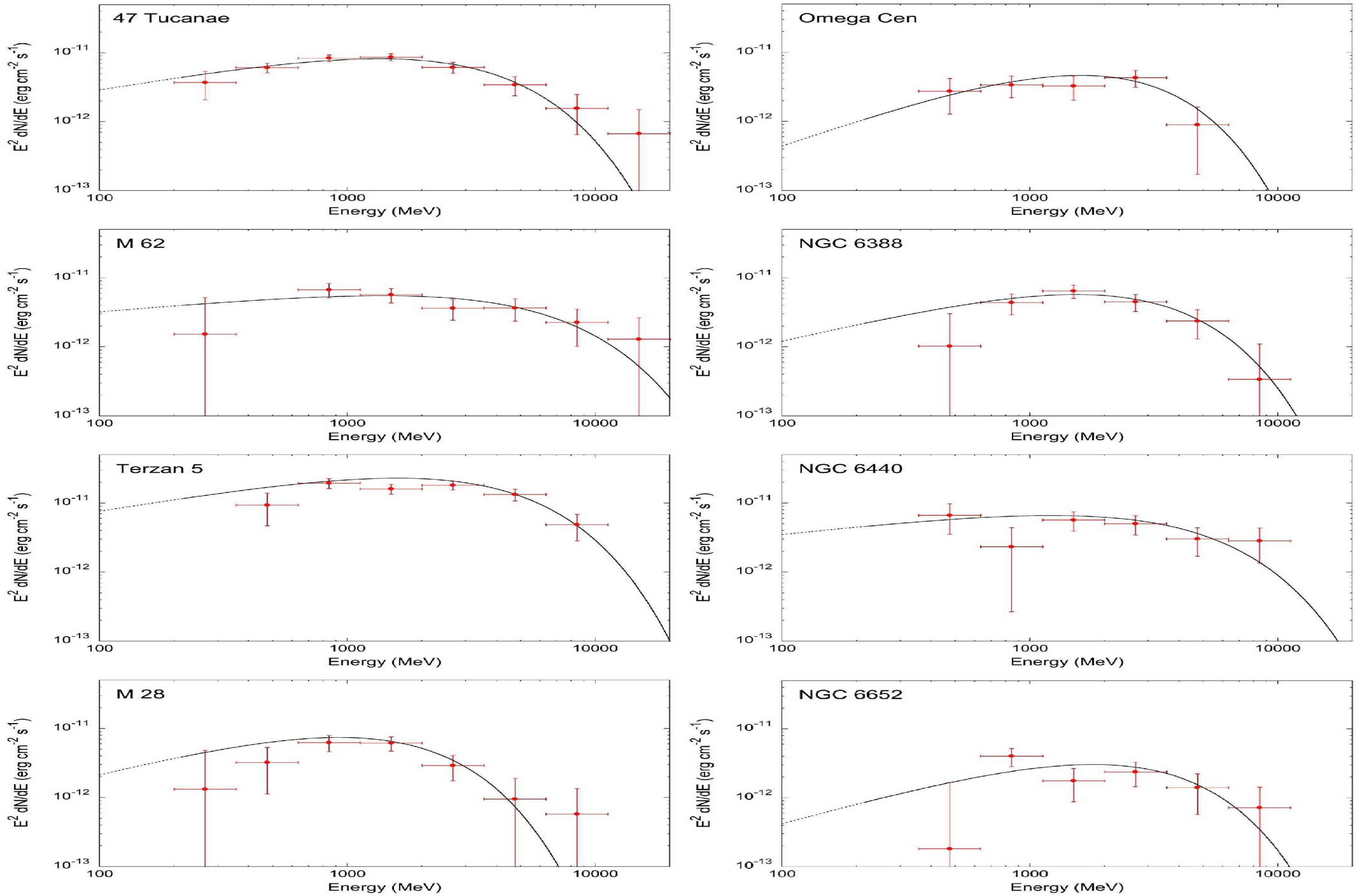


Name	Other name	MSPs	Reason for inclusion
47 Tucanae	NGC 104	23	1FGL J0023.9−7204
Omega Cen	NGC 5139	–	close to 1FGL J1328.2−4729
M 62	NGC 6266	6	1FGL J1701.1−3005
NGC 6388		–	1FGL J1735.9−4438
Terzan 5		33	1FGL J1747.9−2448
NGC 6440		6	1FGL J1748.7−2020
NGC 6441		4	high collision rate
NGC 6541		–	1FGL J1807.6−4341
NGC 6624		6	close to 1FGL J1823.4−3009
M 28	NGC 6626	12	1FGL J1824.5−2449
NGC 6652		–	1FGL J1835.3−3255
NGC 6752		5	5 MSPs, nearby
M 15	NGC 7078	8	8 MSPs



Name	d (kpc)	$L_\gamma (10^{34} \mathrm{erg\ s^{-1}})$	N_{MSP}
47 Tucanae	4.0 ± 0.4 (1)	$4.8^{+1.1}_{-1.1}$	33^{+15}_{-15}
Omega Cen	4.8 ± 0.3 (2)	$2.8^{+0.7}_{-0.7}$	19^{+9}_{-9}
M 62	6.6 ± 0.5 (3)	$10.9^{+3.5}_{-2.3}$	76^{+38}_{-34}
NGC 6388	11.6 ± 2.0 (4)	$25.8^{+14.0}_{-10.6}$	180^{+120}_{-100}
Terzan 5	5.5 ± 0.9 (5)	$25.7^{+9.4}_{-8.8}$	180^{+100}_{-90}
NGC 6440	8.5 ± 0.4 (6)	$19.0^{+13.1}_{-5.0}$	130^{+100}_{-60}
M 28	5.1 ± 0.5 (7)	$6.2^{+2.6}_{-1.8}$	43^{+24}_{-21}
NGC 6652	9.0 ± 0.9 (8)	$7.8^{+2.5}_{-2.1}$	54^{+27}_{-25}
NGC 6541	6.9 ± 0.7 (9)	< 4.7	< 47
NGC 6752	4.4 ± 0.1 (10)	< 1.1	< 11
M 15	10.3 ± 0.4 (11)	< 5.8	< 56

GC spectra (Abdo et al. 2010)



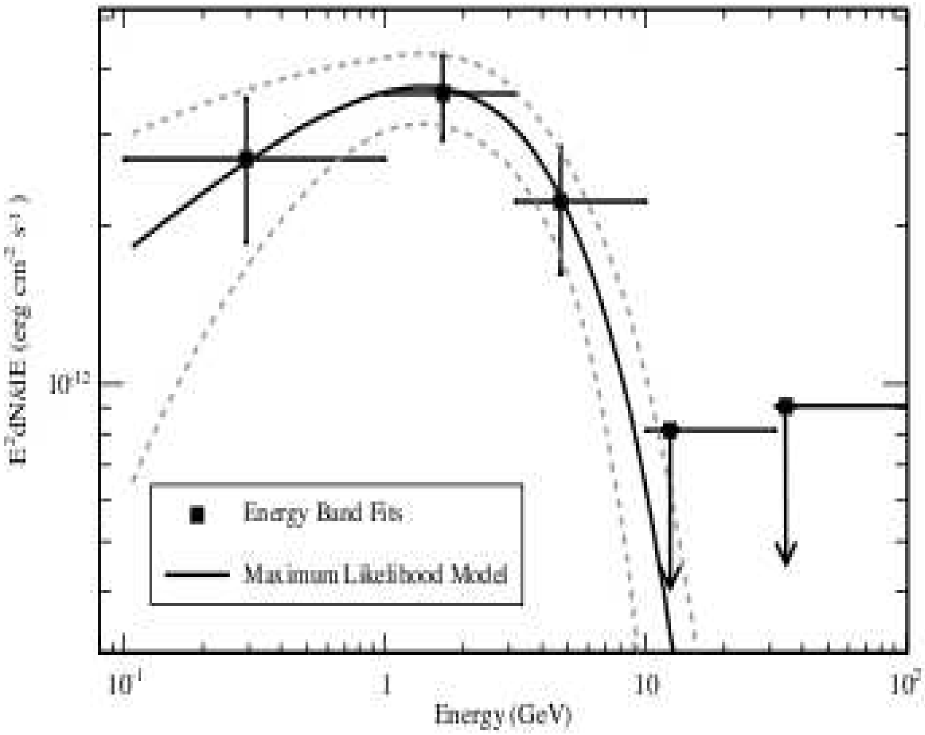
Two luminous MSPs in two GCs

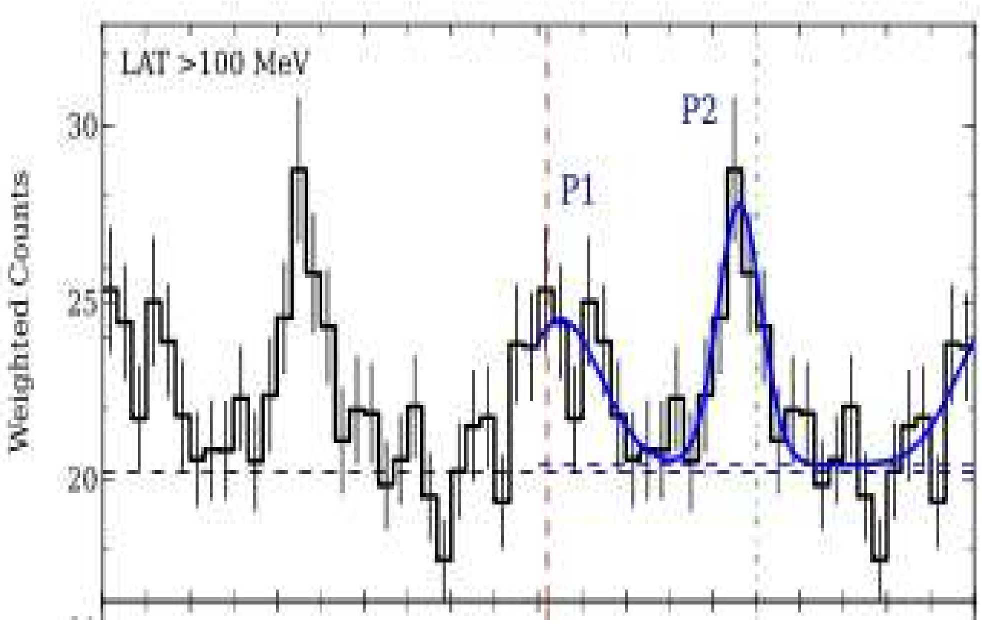
- J1823-3021A in NGC 6624 (Freire et al. 2011)

  (P = 5.44 ms, $L_{\mathrm{SD}} \approx \times 8 \times 10^{35}$ erg/s, $L_\gamma = 8.4 \times 10^{34}$ erg/s)

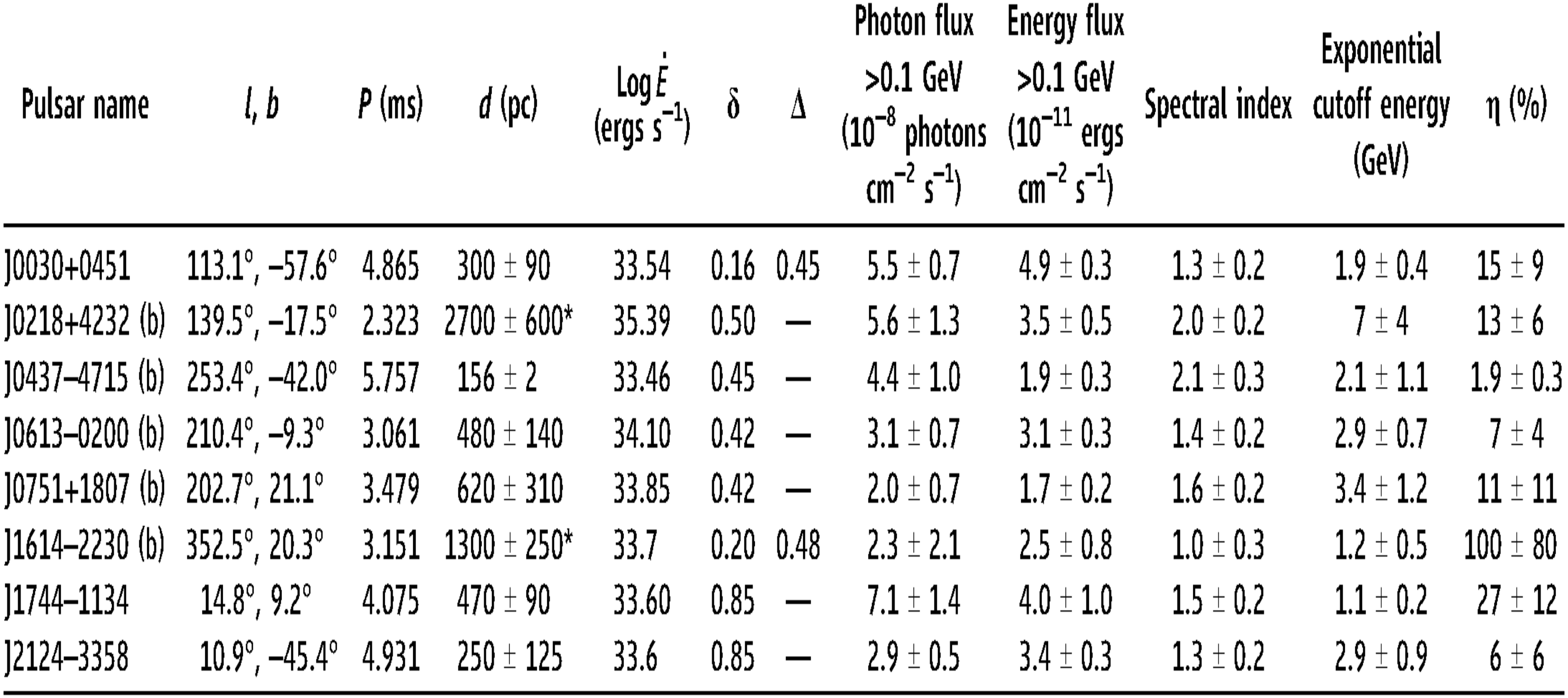
- B1821-24 in M28 (Johnson et al. 2013, Wu et al. 2013)

  (P = 3.05 ms, $L_{\mathrm{SD}} = 2.2 \times 10^{36}$ erg/s, $L_\gamma \approx 4 \times 10^{34}$ erg/s)





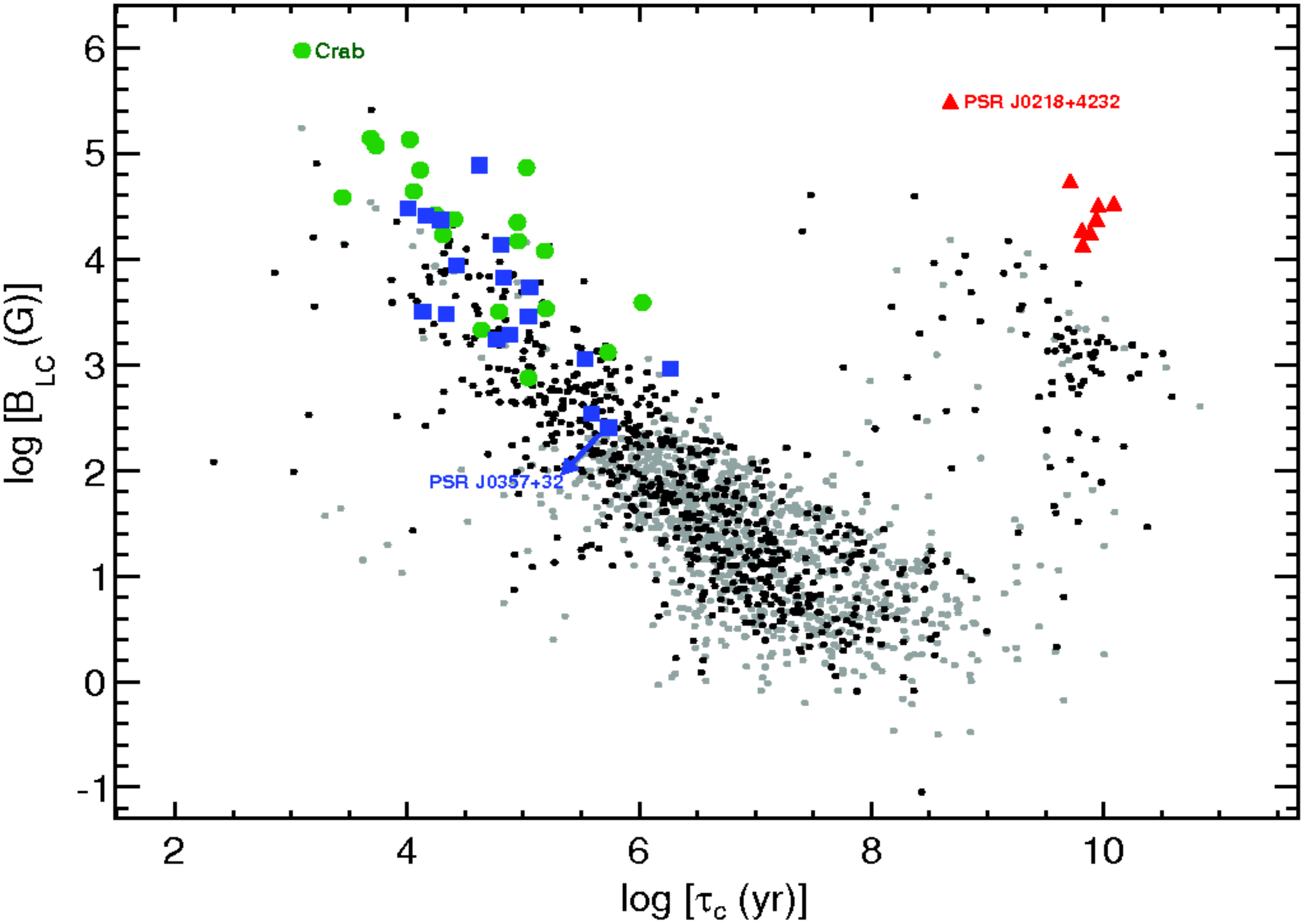
Millisecond pulsars in the field (Abdo et al. 2009) (1)



Pulsar name	*l*, *b*	*P* (ms)	*d* (pc)	Log $\dot{E}$ (ergs s^{-1})	δ	Δ	Photon flux >0.1 GeV (10^{-8} photons cm^{-2} s^{-1})	Energy flux >0.1 GeV (10^{-11} ergs cm^{-2} s^{-1})	Spectral index	Exponential cutoff energy (GeV)	η (%)
J0030+0451	113.1°, –57.6°	4.865	300 ± 90	33.54	0.16	0.45	5.5 ± 0.7	4.9 ± 0.3	1.3 ± 0.2	1.9 ± 0.4	15 ± 9
J0218+4232 (b)	139.5°, –17.5°	2.323	2700 ± 600*	35.39	0.50	—	5.6 ± 1.3	3.5 ± 0.5	2.0 ± 0.2	7 ± 4	13 ± 6
J0437–4715 (b)	253.4°, –42.0°	5.757	156 ± 2	33.46	0.45	—	4.4 ± 1.0	1.9 ± 0.3	2.1 ± 0.3	2.1 ± 1.1	1.9 ± 0.3
J0613–0200 (b)	210.4°, –9.3°	3.061	480 ± 140	34.10	0.42	—	3.1 ± 0.7	3.1 ± 0.3	1.4 ± 0.2	2.9 ± 0.7	7 ± 4
J0751+1807 (b)	202.7°, 21.1°	3.479	620 ± 310	33.85	0.42	—	2.0 ± 0.7	1.7 ± 0.2	1.6 ± 0.2	3.4 ± 1.2	11 ± 11
J1614–2230 (b)	352.5°, 20.3°	3.151	1300 ± 250*	33.7	0.20	0.48	2.3 ± 2.1	2.5 ± 0.8	1.0 ± 0.3	1.2 ± 0.5	100 ± 80
J1744–1134	14.8°, 9.2°	4.075	470 ± 90	33.60	0.85	—	7.1 ± 1.4	4.0 ± 1.0	1.5 ± 0.2	1.1 ± 0.2	27 ± 12
J2124–3358	10.9°, –45.4°	4.931	250 ± 125	33.6	0.85	—	2.9 ± 0.5	3.4 ± 0.3	1.3 ± 0.2	2.9 ± 0.9	6 ± 6

$$\eta = L_\gamma / L_{\rm SD} \approx 10\%$$

Millisecond pulsars (Abdo et al. 2010) (2)



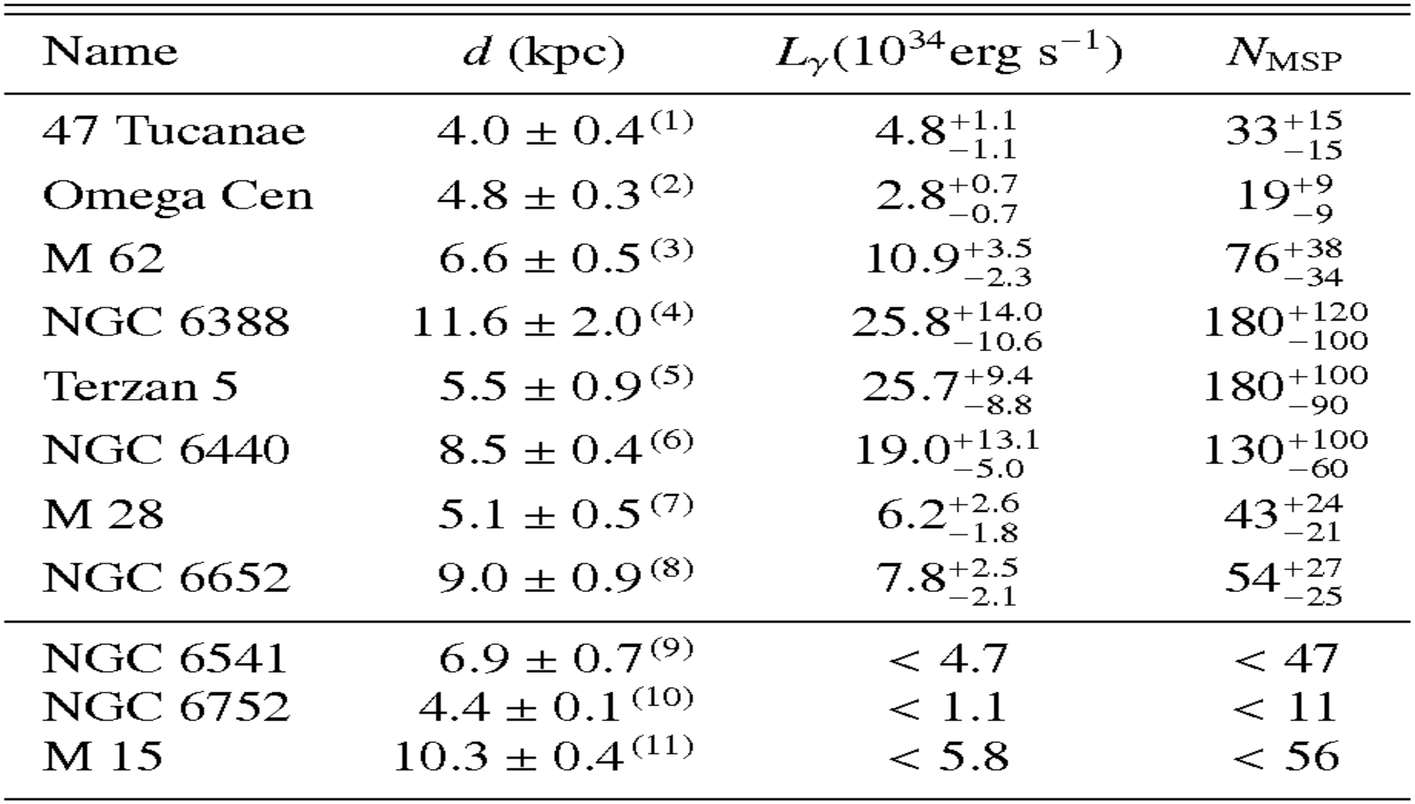
WHAT SEEMS TO BE OBVIOUS ?

GeV γ-rays cumulative emission from MSPs magnetospheres

(Venter & de Jager 2005)

Number of MSPs in specific GC (Abdo et al. 2010)

$$N_{\rm MSP} = L_{\gamma}^{\rm GC} / (\eta_{\gamma} \times < L_{rot,MSP}^{\rm Tuc47} >)$$



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WHAT ELSE MIGHT BE ?

$\Downarrow$

TEV γ-rays produced by leptons escaping from MSPs

(Bednarek & Sitarek 2007)

- Leptons accelerated in the MSP magnetospheres and winds.
- Leptons propagate through globular cluster.
- Leptons comptonize well defined radiation field within GC.
- TeV γ-rays are produced.
- Leptons lose also energy on synchrotron process.
- Non-thermal emission determined by injection rate of leptons.
- TeV obs. → constraints on pulsar physics.

(see also others: Venter et al. 2009, Cheng et al. 2010)

What are their energies ?

Simple scaling from the Crab Nebula

$$E_e^{\max} \sim 3 \times 10^{15} \star (\frac{3 \times 10^8 G}{4 \times 10^{12} G}) \star (\frac{4ms}{33ms})^{-2} eV \sim 15\ TeV. \qquad (1)$$

Advection along the MSP wind shocks within GCs (Bednarek & Sitarek 2007)

$$E_{\text{max}} \approx 4 - 40 \text{ TeV}$$

Stellar radiation field inside GC (Bednarek & Sitarek 2007)

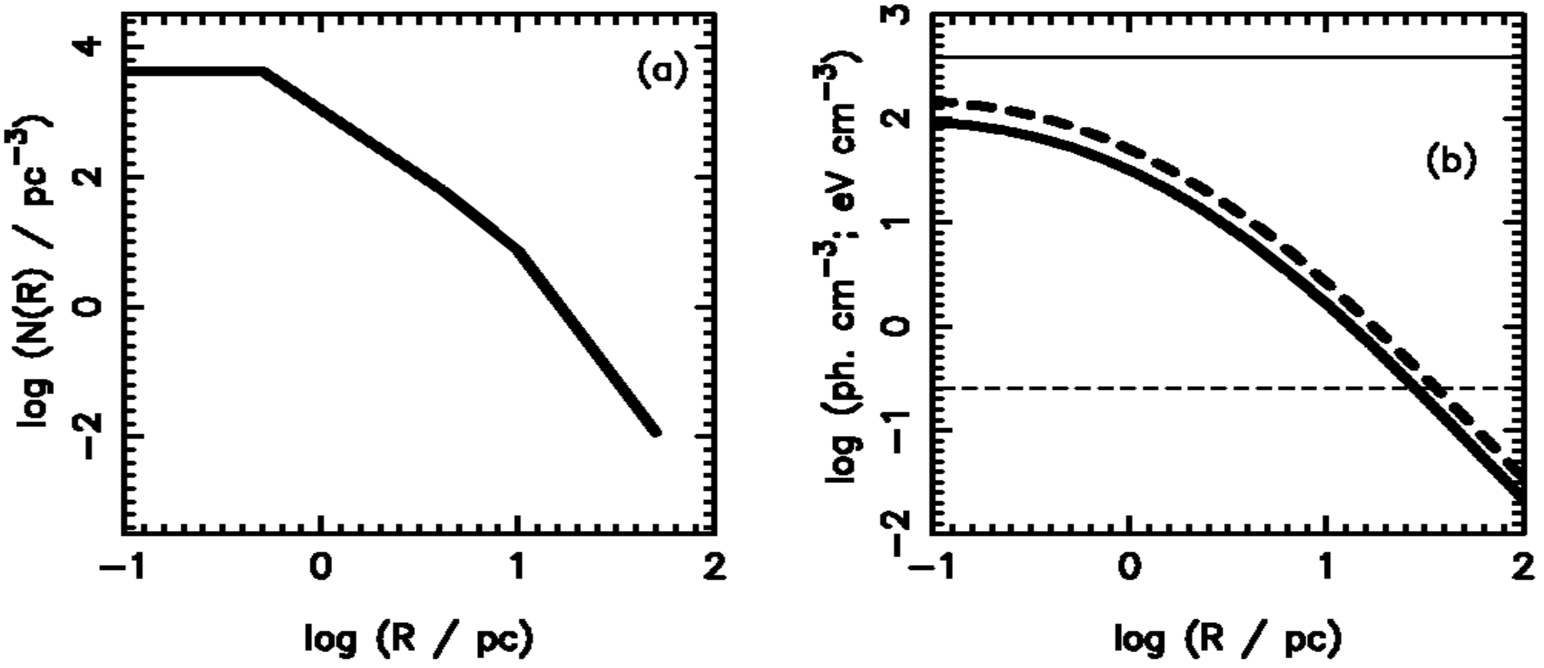


Figure 1. The density of stars (a), and density and energy density of stellar photons (b) as a function of distance R from the centre of a typical GC with the mass $10^5\,M_\odot$, the core radius $R_c = 0.5$ pc, the half-mass radius $R_h = 4$ pc, the tidal radius $R_t = 50$ pc. The stellar density profile is defined by equation (4). The photon densities and energy densities of stellar photons are shown by the thick solid and dashed curves and the corresponding values for the MBR are shown by the thin horizontal lines.

Gamma-ray spectra (Bednarek & Sitarek 2007)

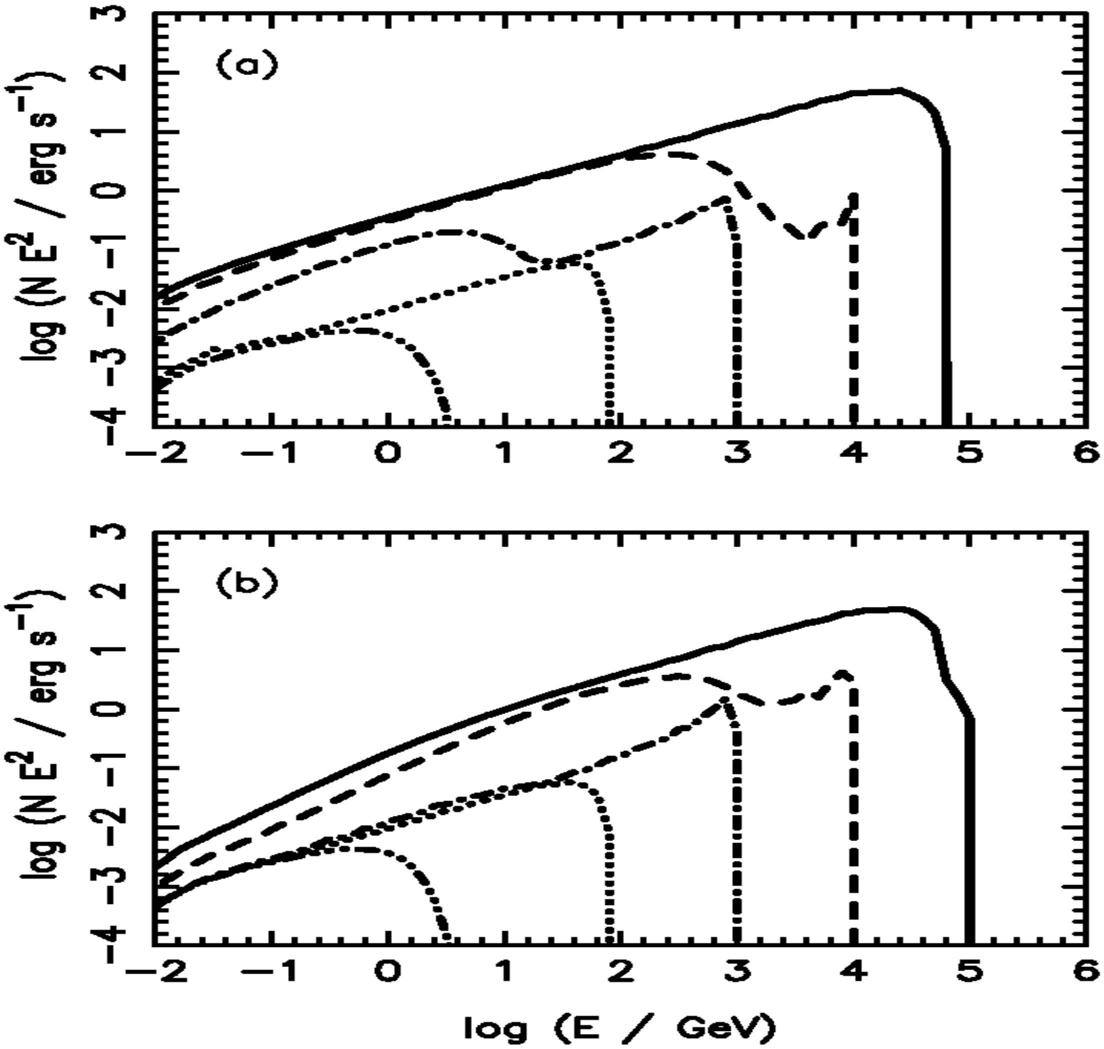
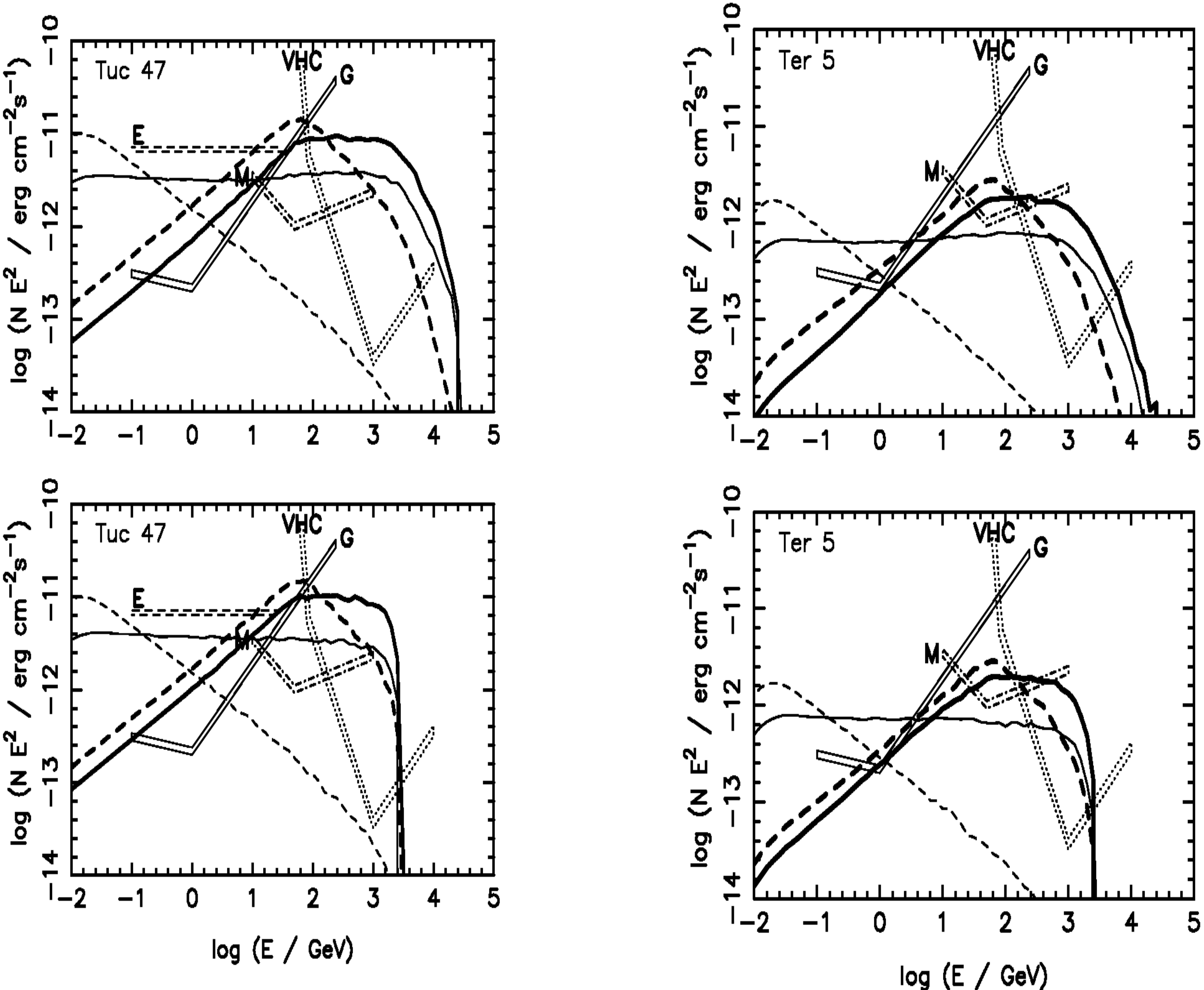


Figure 2. Differential γ-ray spectra (multiplied by the energy squared) produced in the IC scattering of the stellar and MBR radiation by mono-energetic leptons with energies E = 10 GeV (triple-dot–dashed curve), 10^2 GeV (dotted curve), 10^3 GeV (dot–dashed curve), 10^4 GeV (dashed curve) and 10^5 GeV (solid curve), after normalization to a single lepton per second. Leptons are injected by the millisecond pulsars in the core of GC and diffuse in the outward direction in the magnetic and radiation field created by the

Gamma-ray spectra from Tuc 47 and Ter 5 (Bednarek & Sitarek 2007)



Tuc 47 - TeV Gamma (Aharonian et al. 2009)

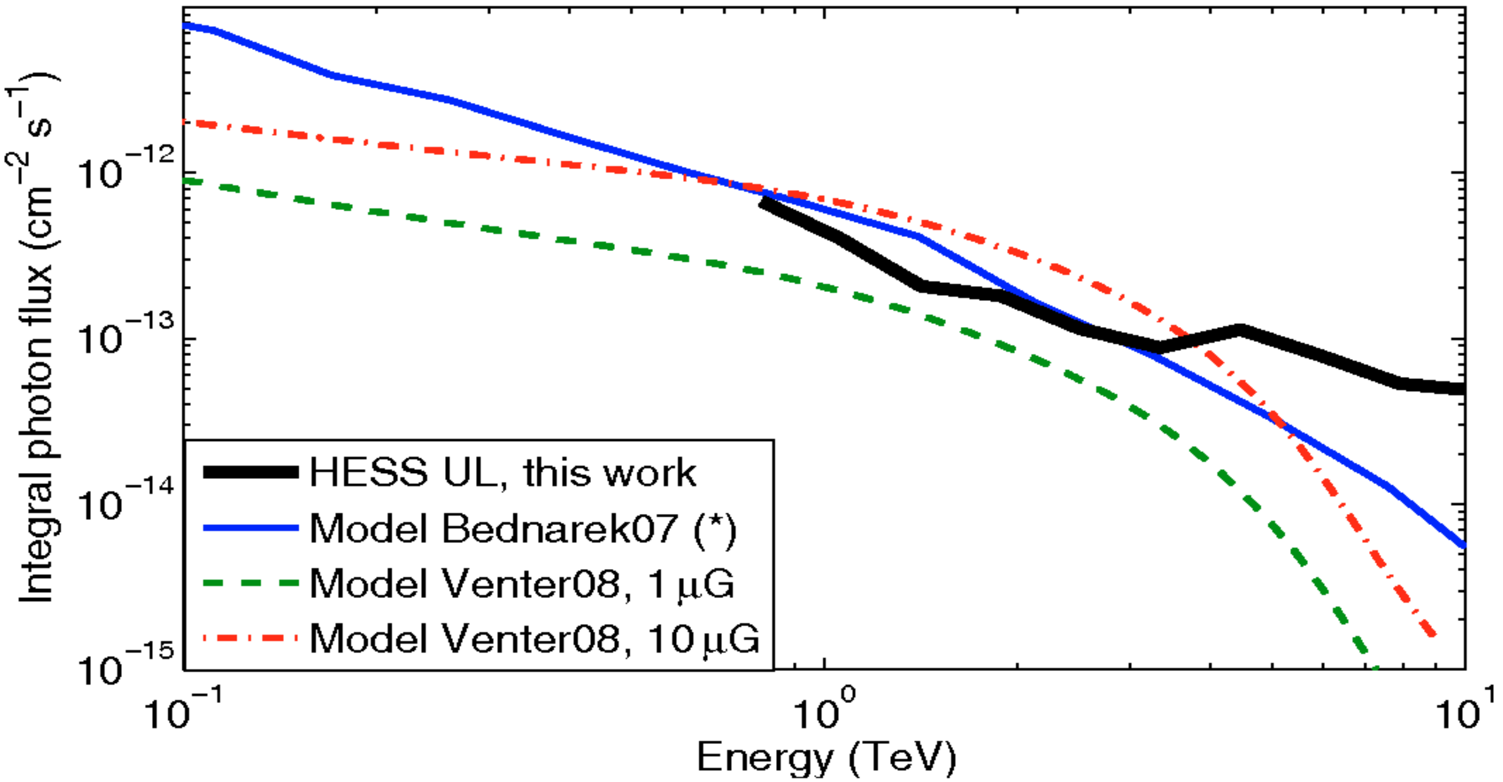
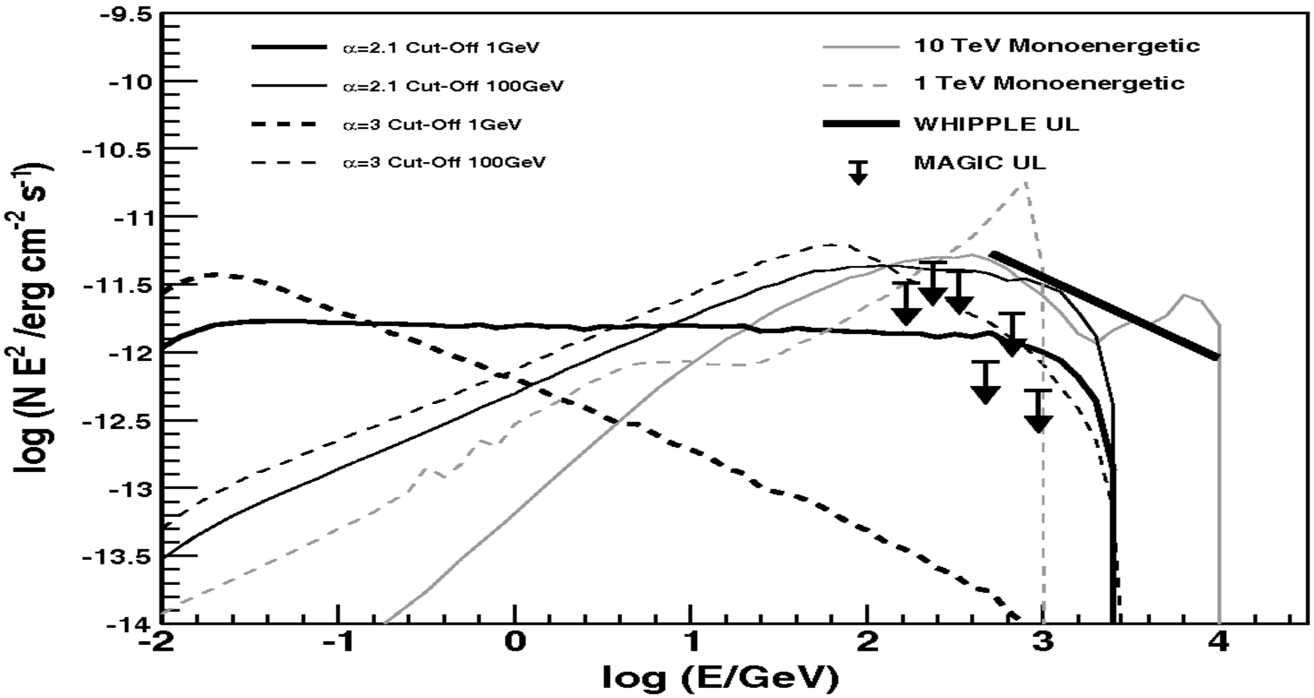


Fig. 1. Upper limit integral flux curve derived from the HESS observations of 47 Tucanae (assuming a photon index of $\alpha = 2$), for "standard" cuts, at the 99% confidence level. Predicted fluxes for 100 msPSRs were added for comparison, rescaled for a distance of 4 kpc. (*) Curve adapted from Bednarek & Sitarek (2007), for $\epsilon_e = 0.01$, $E_{\rm min} =$ 100 GeV and $\alpha = 2$, rescaled to $L_{\rm sd} = 10^{34}$ erg s^{-1} (see Sect. 3 for details).

M13 - MAGIC (Anderhub et al. 2009)



M13, M15, M5 - VERITAS (McCutchen et al. 2009)

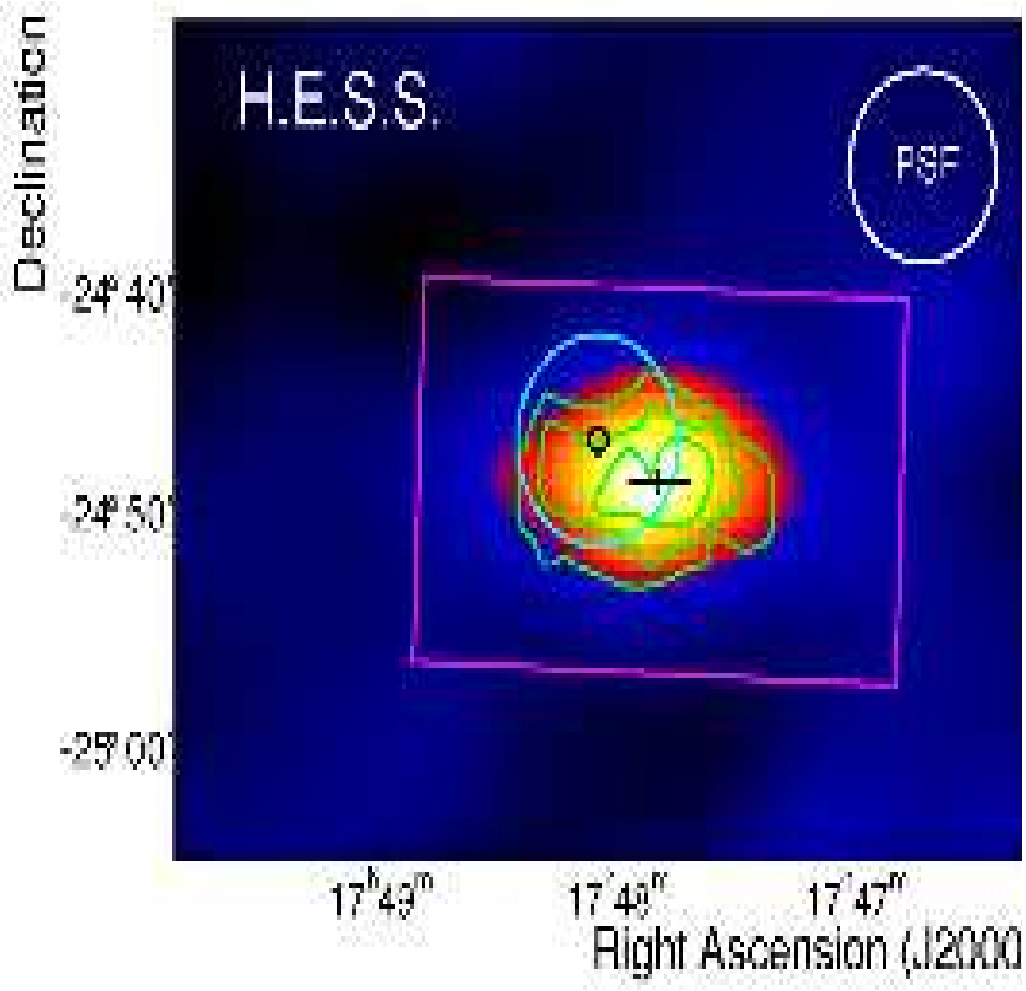
TABLE II

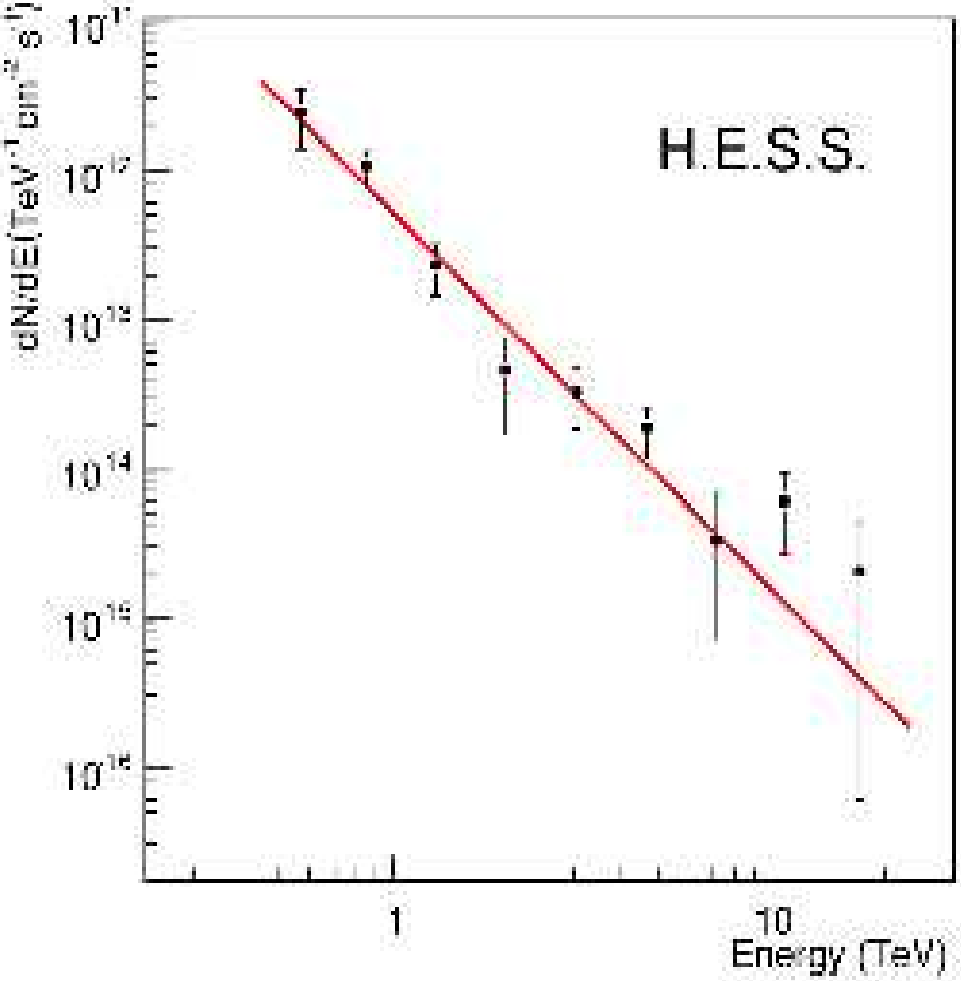
COUNT RATES AND FLUX UPPER LIMITS FROM VERITAS DATA.

Object	# Telescopes	Exposure (min)	N_{ON}	N_{OFF}	α	Significance (σ)	Flux Upper Limit ($E > 600$ GeV) (10^{-12} erg/s/cm^2)	(% Crab)
M15	2	393	10	61	0.25	-1.3	1.1	1.6
M13	3-4	397	12	87	0.10	1.0	1.5	2.2
M5	4	900	25	251	0.11	-0.3	0.4	0.6

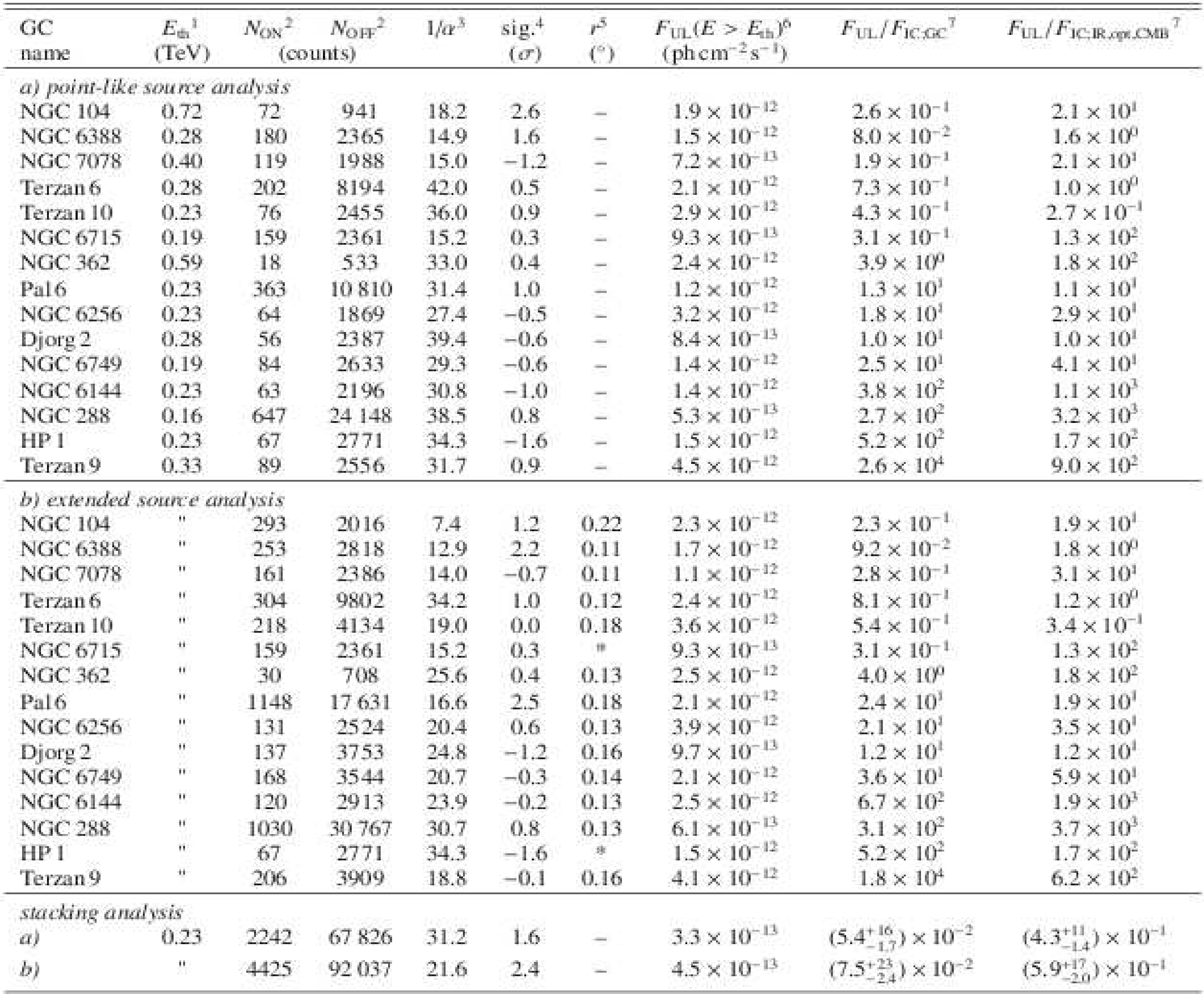
Ter 5 displaced TeV Gamma source ? (Abramowski et al. 2011)

HESS: TeV γ source shifted from centre of Ter 5 or not related ?





Search for TeV sources towards GCs (Abramowski et al. 2013)



GC name	$E_{\rm th}$[1] (TeV)	$N_{\rm ON}$[2] (counts)	$N_{\rm OFF}$[2]	$1/\alpha$[3]	sig.[4] (σ)	r[5] (°)	$F_{\rm UL}(E > E_{\rm th})$[6] (ph cm^{-2} s^{-1})	$F_{\rm UL}/F_{\rm IC;GC}$[7]	$F_{\rm UL}/F_{\rm IC;IR,opt,CMB}$[7]
a) point-like source analysis									
NGC 104	0.72	72	941	18.2	2.6	–	1.9×10^{-12}	2.6×10^{-1}	2.1×10^{1}
NGC 6388	0.28	180	2365	14.9	1.6	–	1.5×10^{-12}	8.0×10^{-2}	1.6×10^{0}
NGC 7078	0.40	119	1988	15.0	−1.2	–	7.2×10^{-13}	1.9×10^{-1}	2.1×10^{1}
Terzan 6	0.28	202	8194	42.0	0.5	–	2.1×10^{-12}	7.3×10^{-1}	1.0×10^{0}
Terzan 10	0.23	76	2455	36.0	0.9	–	2.9×10^{-12}	4.3×10^{-1}	2.7×10^{-1}
NGC 6715	0.19	159	2361	15.2	0.3	–	9.3×10^{-13}	3.1×10^{-1}	1.3×10^{2}
NGC 362	0.59	18	533	33.0	0.4	–	2.4×10^{-12}	3.9×10^{0}	1.8×10^{2}
Pal 6	0.23	363	10 810	31.4	1.0	–	1.2×10^{-12}	1.3×10^{1}	1.1×10^{1}
NGC 6256	0.23	64	1869	27.4	−0.5	–	3.2×10^{-12}	1.8×10^{1}	2.9×10^{1}
Djorg 2	0.28	56	2387	39.4	−0.6	–	8.4×10^{-13}	1.0×10^{1}	1.0×10^{1}
NGC 6749	0.19	84	2633	29.3	−0.6	–	1.4×10^{-12}	2.5×10^{1}	4.1×10^{1}
NGC 6144	0.23	63	2196	30.8	−1.0	–	1.4×10^{-12}	3.8×10^{2}	1.1×10^{3}
NGC 288	0.16	647	24 148	38.5	0.8	–	5.3×10^{-13}	2.7×10^{2}	3.2×10^{3}
HP 1	0.23	67	2771	34.3	−1.6	–	1.5×10^{-12}	5.2×10^{2}	1.7×10^{2}
Terzan 9	0.33	89	2556	31.7	0.9	–	4.5×10^{-12}	2.6×10^{4}	9.0×10^{2}
b) extended source analysis									
NGC 104	"	293	2016	7.4	1.2	0.22	2.3×10^{-12}	2.3×10^{-1}	1.9×10^{1}
NGC 6388	"	253	2818	12.9	2.2	0.11	1.7×10^{-12}	9.2×10^{-2}	1.8×10^{0}
NGC 7078	"	161	2386	14.0	−0.7	0.11	1.1×10^{-12}	2.8×10^{-1}	3.1×10^{1}
Terzan 6	"	304	9802	34.2	1.0	0.12	2.4×10^{-12}	8.1×10^{-1}	1.2×10^{0}
Terzan 10	"	218	4134	19.0	0.0	0.18	3.6×10^{-12}	5.4×10^{-1}	3.4×10^{-1}
NGC 6715	"	159	2361	15.2	0.3	*	9.3×10^{-13}	3.1×10^{-1}	1.3×10^{2}
NGC 362	"	30	708	25.6	0.4	0.13	2.5×10^{-12}	4.0×10^{0}	1.8×10^{2}
Pal 6	"	1148	17 631	16.6	2.5	0.18	2.1×10^{-12}	2.4×10^{1}	1.9×10^{1}
NGC 6256	"	131	2524	20.4	0.6	0.13	3.9×10^{-12}	2.1×10^{1}	3.5×10^{1}
Djorg 2	"	137	3753	24.8	−1.2	0.16	9.7×10^{-13}	1.2×10^{1}	1.2×10^{1}
NGC 6749	"	168	3544	20.7	−0.3	0.14	2.1×10^{-12}	3.6×10^{1}	5.9×10^{1}
NGC 6144	"	120	2913	23.9	−0.2	0.13	2.5×10^{-12}	6.7×10^{2}	1.9×10^{3}
NGC 288	"	1030	30 767	30.7	0.8	0.13	6.1×10^{-13}	3.1×10^{2}	3.7×10^{3}
HP 1	"	67	2771	34.3	−1.6	*	1.5×10^{-12}	5.2×10^{2}	1.7×10^{2}
Terzan 9	"	206	3909	18.8	−0.1	0.16	4.1×10^{-12}	1.8×10^{4}	6.2×10^{2}
stacking analysis									
a)	0.23	2242	67 826	31.2	1.6	–	3.3×10^{-13}	$(5.4^{+16}_{-1.7}) \times 10^{-2}$	$(4.3^{+11}_{-1.4}) \times 10^{-1}$
b)	"	4425	92 037	21.6	2.4	–	4.5×10^{-13}	$(7.5^{+23}_{-2.4}) \times 10^{-2}$	$(5.9^{+17}_{-2.0}) \times 10^{-1}$

M13 - MAGIC (Anderhub et al. 2009)

(Emission model by Bednarek & Sitarek 2007)

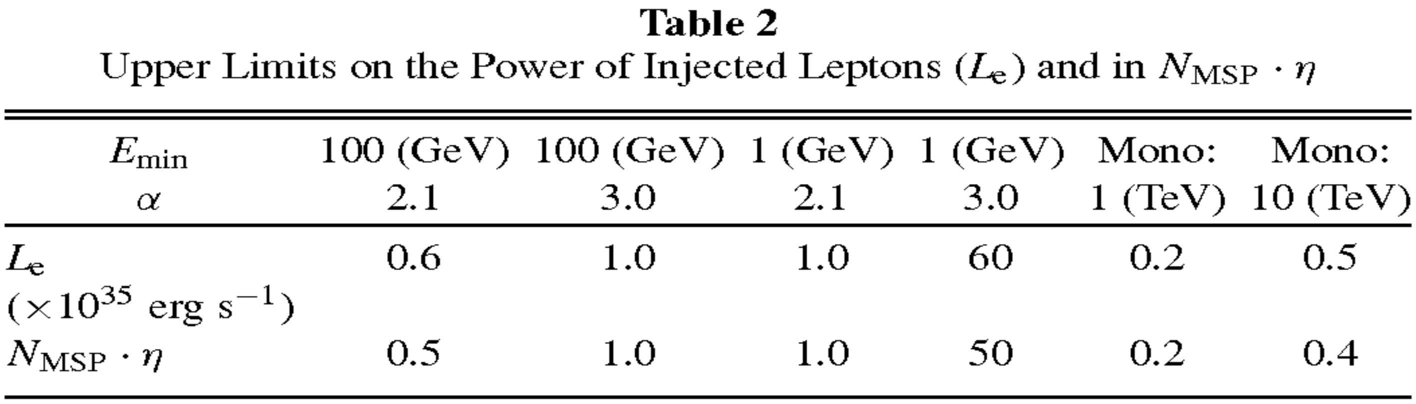


Table 2

Upper Limits on the Power of Injected Leptons (L_e) and in $N_{\rm MSP} \cdot \eta$

$E_{\rm min}$ α	100 (GeV) 2.1	100 (GeV) 3.0	1 (GeV) 2.1	1 (GeV) 3.0	Mono: 1 (TeV)	Mono: 10 (TeV)
L_e ($\times 10^{35}$ erg s^{-1})	0.6	1.0	1.0	60	0.2	0.5
$N_{\rm MSP} \cdot \eta$	0.5	1.0	1.0	50	0.2	0.4

M13, M15, M5 - VERITAS (McCutchen et al. 2009)

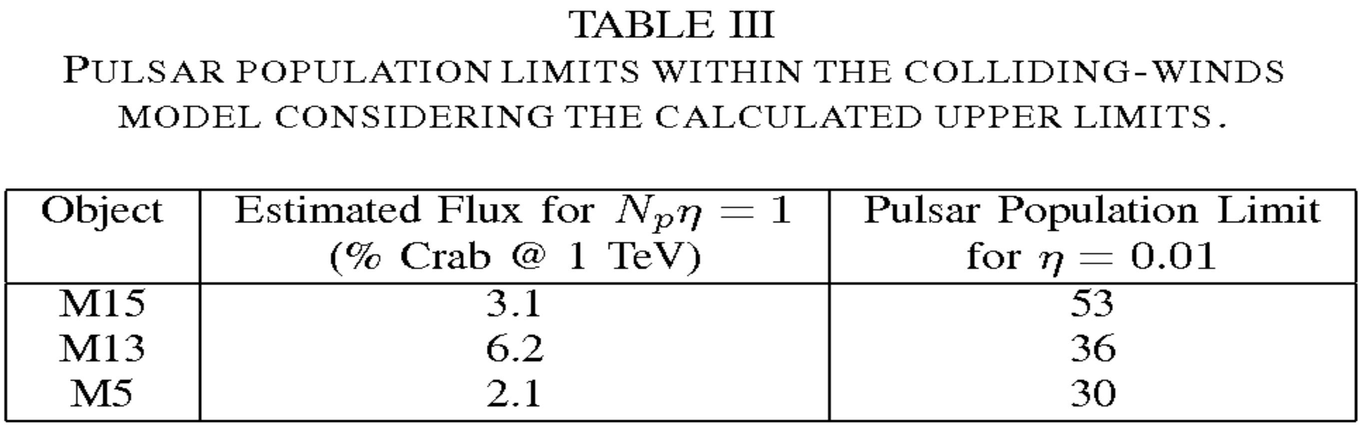


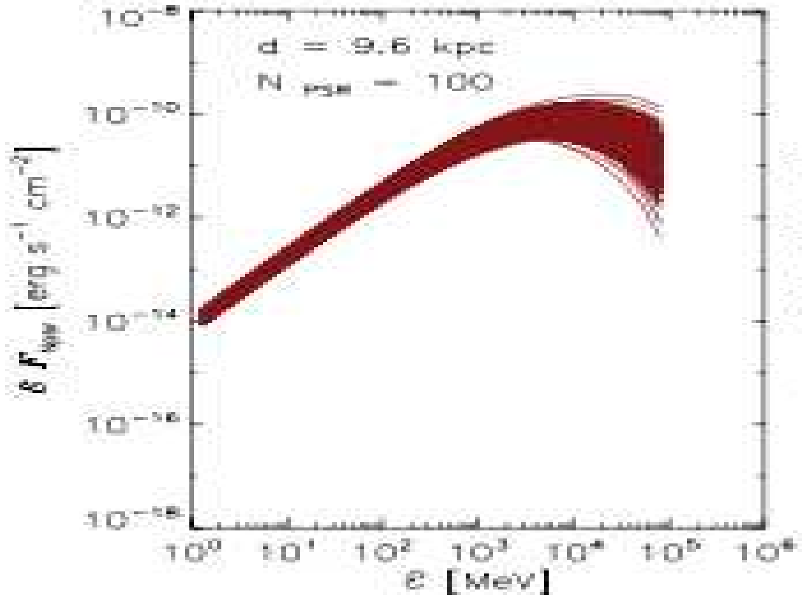
TABLE III

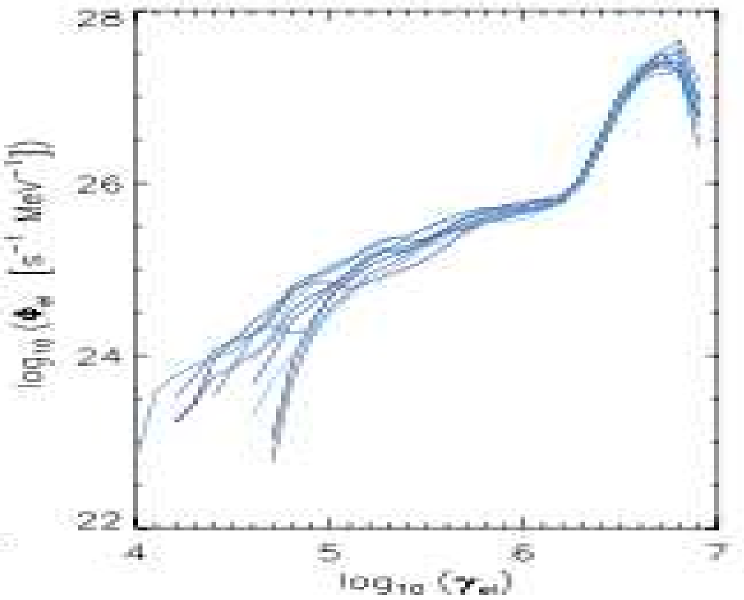
PULSAR POPULATION LIMITS WITHIN THE COLLIDING-WINDS MODEL CONSIDERING THE CALCULATED UPPER LIMITS.

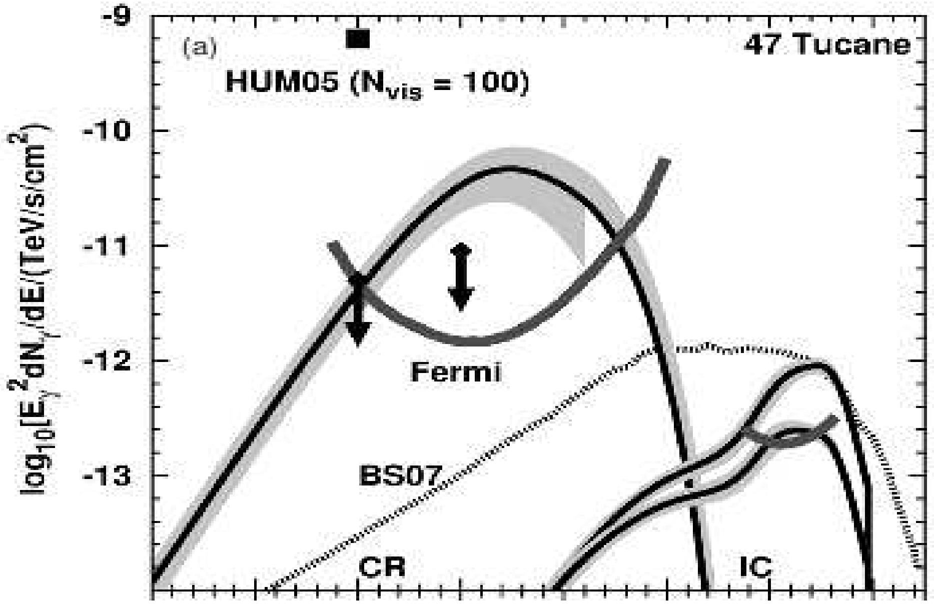
Object	Estimated Flux for $N_p\eta = 1$ (% Crab @ 1 TeV)	Pulsar Population Limit for $\eta = 0.01$
M15	3.1	53
M13	6.2	36
M5	2.1	30

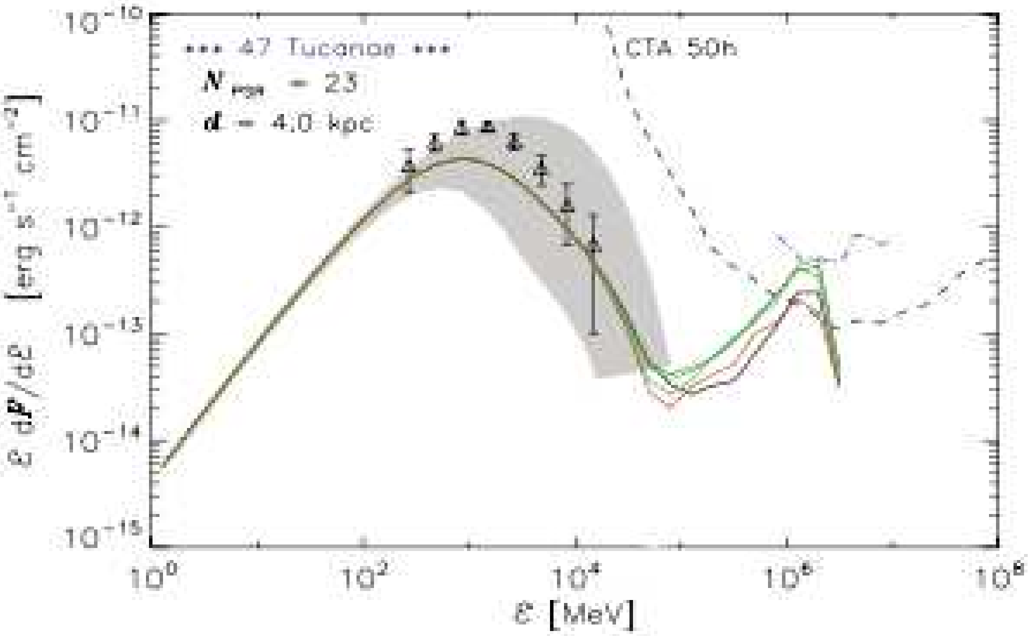
TeV gamma produced by leptons directly from MSPs

(Venter et al. 2009, Zajczyk et al. 2013)



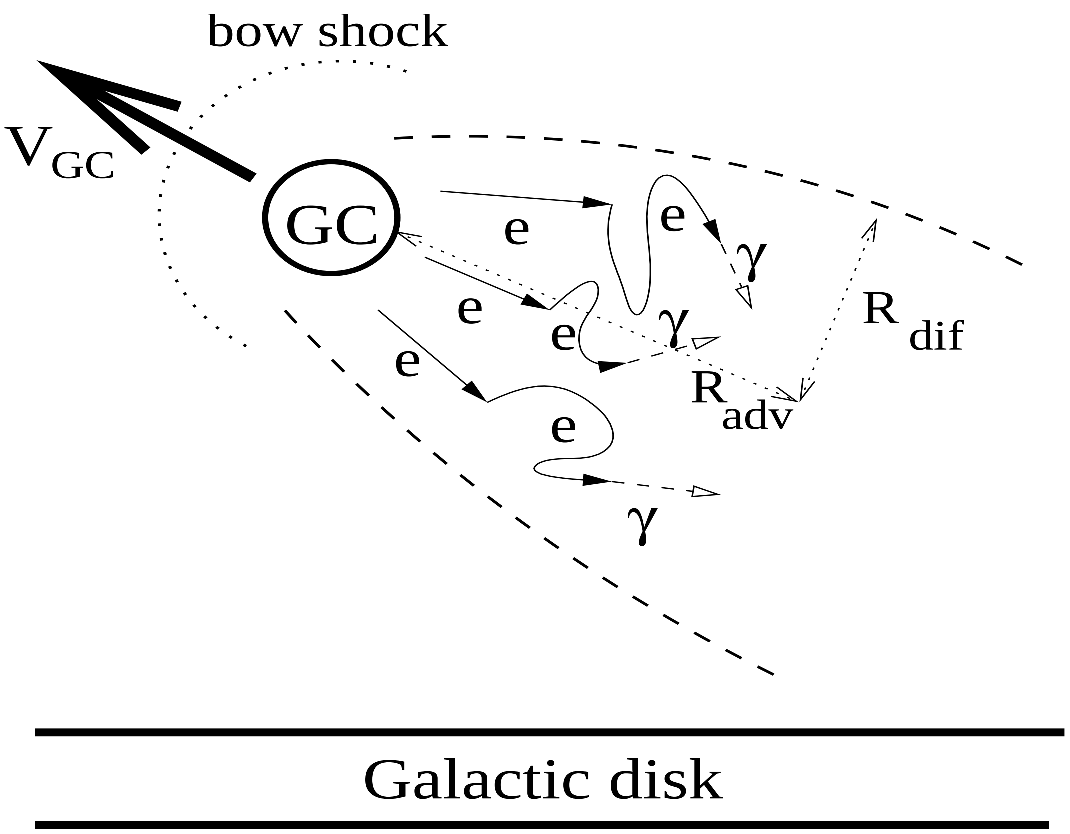






Asymmetric TeV source in vicinity of Ter 5

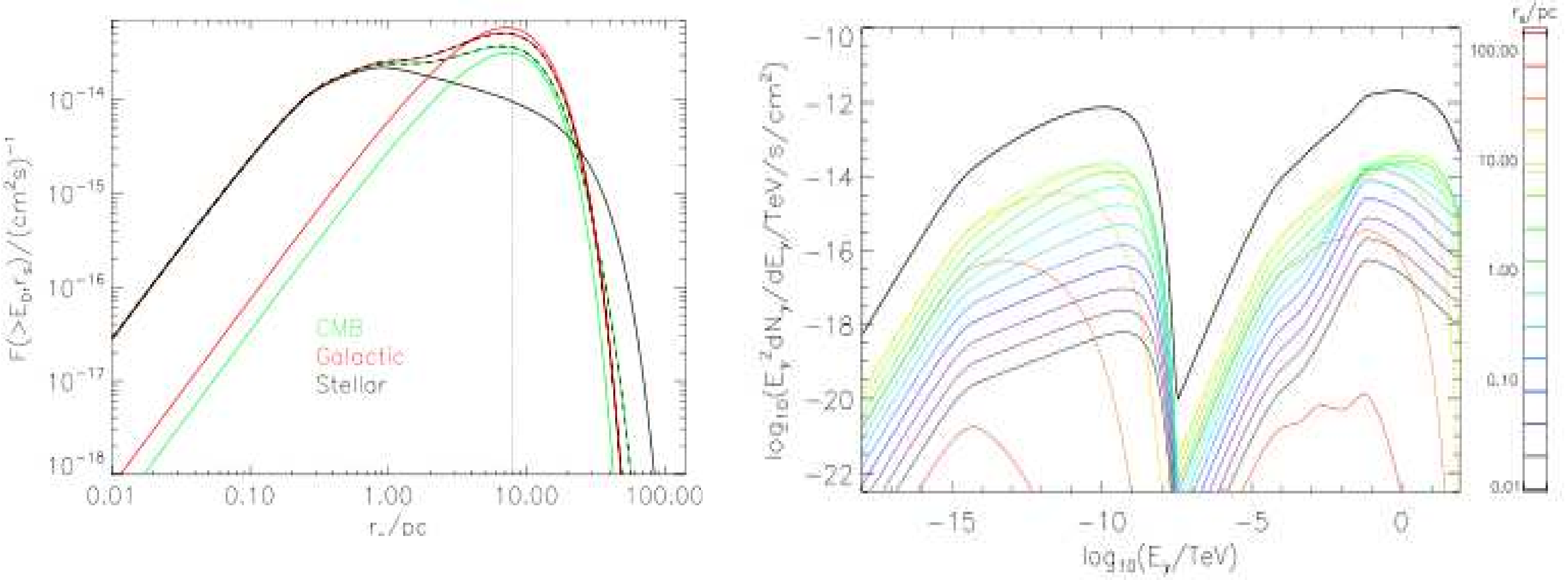
(Bednarek & Sobczak 2014)



- Red giant winds mix with pulsar winds (Globular Cluster wind).
- GC wind interacts with surrounding medium → bow shock.
- Bow shock focuses the GC wind flow opposite the the GC motion.
- Leptons in GC wind produce displaced TeV γ-source.

Recent developments by Kopp et al. (2013)

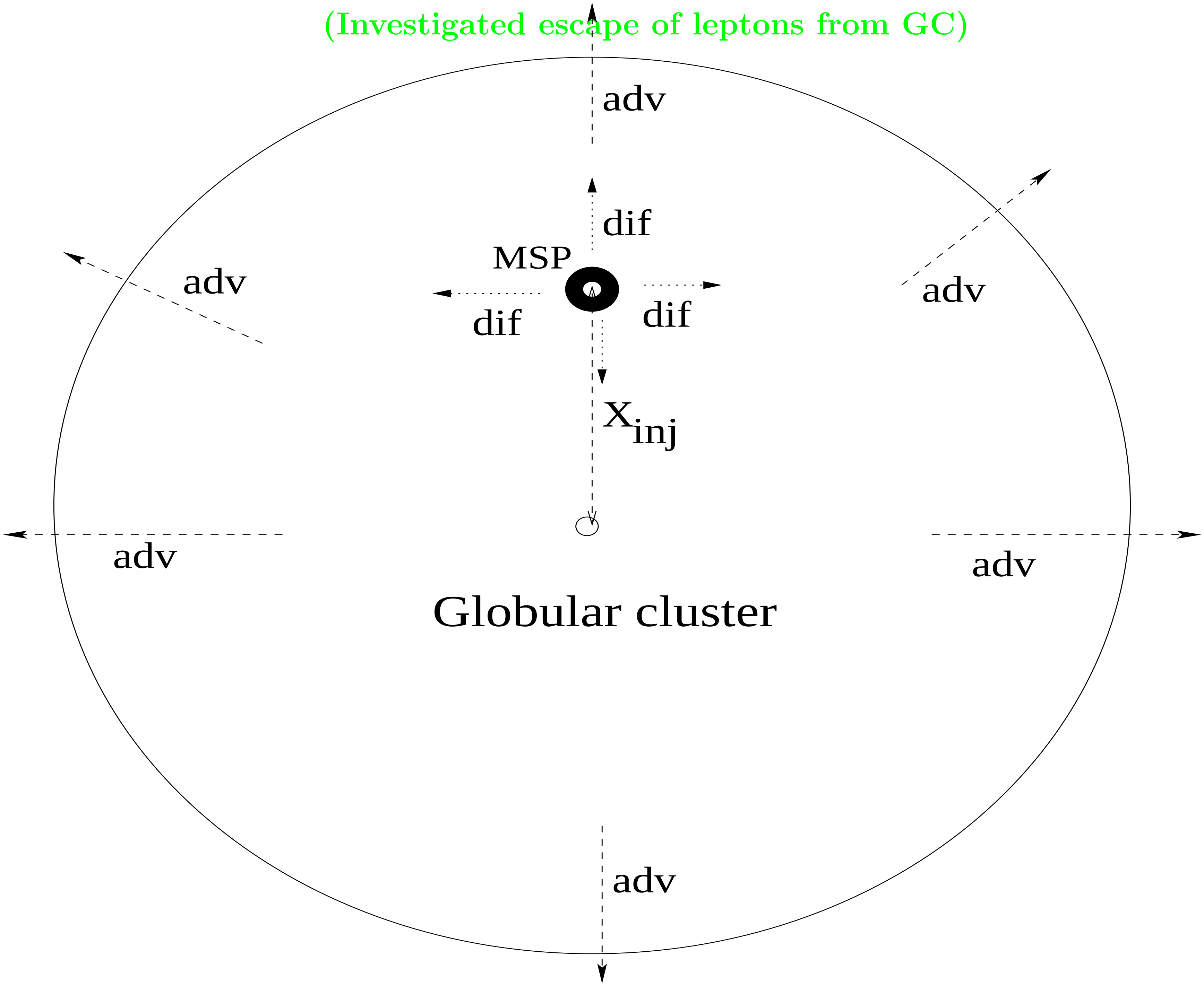
(Investigated morphology of non-thermal source towards GC)



- TeV source slightly extended ($\sim$ 7 arc min for 5 kpc.).
- TeV emission peaks at $\sim$ 10 pc → dominated by IC of CMB and galactic
- TeV γ from inside and outside dominated by IC of stellar radiation

Recent developments by Bednarek et al. (2015)

(Investigated escape of leptons from GC)



Injection of leptons into GC

(Investigated escape of leptons from GC)

- Spectra of leptons.

  Mono-energetic (close to) leptons from inner MSP magnetospheres.

  Leptons with power law spectrum from terminated MSP wind.

- Source of leptons.

  Injection from population of MSPs within GC.

  Injection from dominating, energetic, single MSP.

- Power in leptons normalized to power in GeV (pulsed) γ-rays of MSP(s).

$$\chi = L_{\pm}/L_{\gamma}^{\rm MSP}$$

$$\Downarrow$$

χ should be predicted by accel./rad. models of MSPs

$$\Downarrow$$

χ can be constrained by obs. of TeV γ-rays from GCs.

Expected spectra from mono-energetic leptons

(injected from the MSP J1823-3021A in NGC 6624)

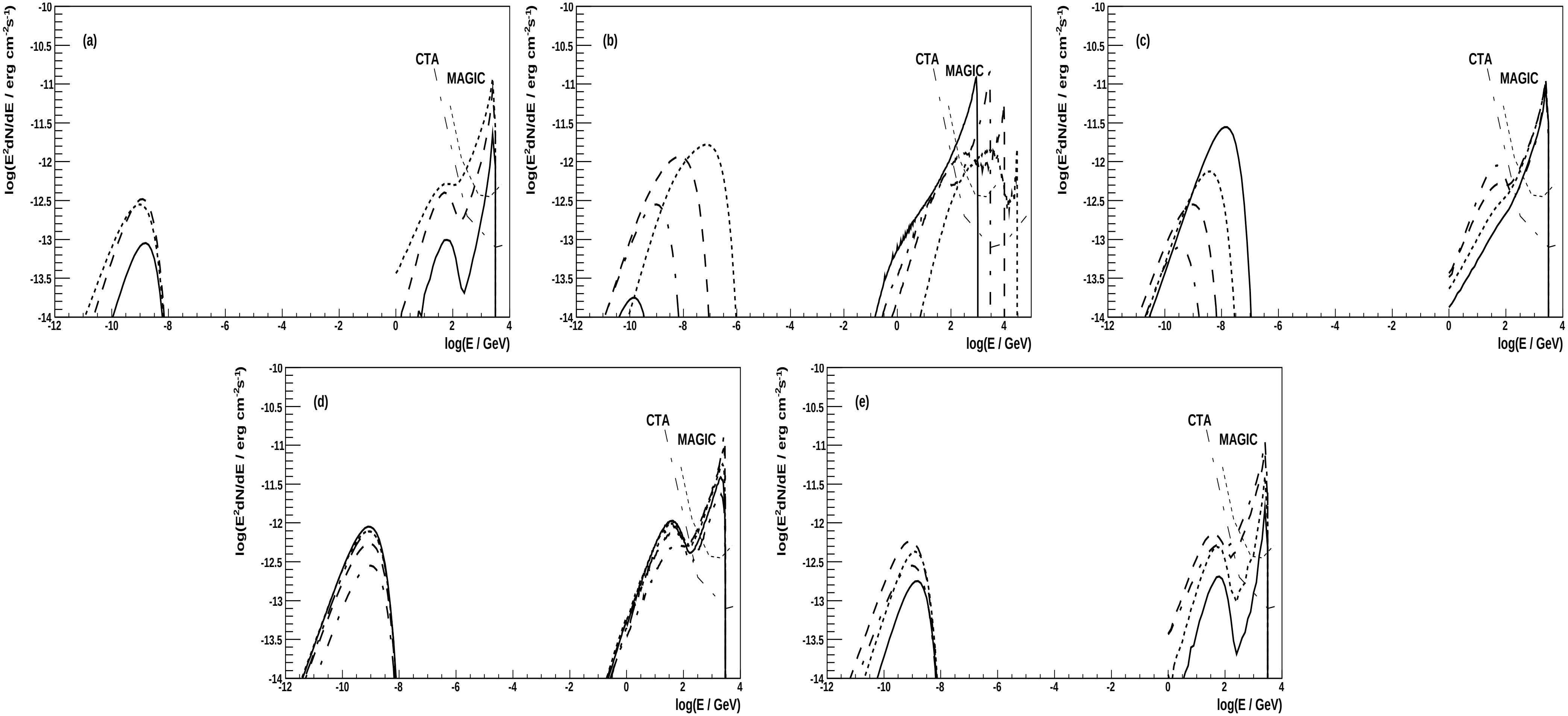


Figure 1: SED by leptons from J1823-3021A in NGC 6624. The spectra as a function of the velocity of the GC wind for $v_{\rm adv} = 0$ cm s^{-1} (dotted), 10^7 cm s^{-1} (dashed), and 10^8 cm s^{-1} (solid) (figure (a)). Other parameters of the model are the following, distance from the core $d = 0.12$ pc, magnetic field strength at the core $B = 3\mu$G, and the energy of leptons 30 TeV. Dependence on energies of leptons are shown for $E_{\rm e} = 1$ TeV (solid), 3 TeV dot-dashed), 10 TeV (dashed), and 30 TeV (dotted). Dependence on the magnetic field strength is shown for $B_{\rm c} = 1\mu$G (dot-dashed), 3μG (dashed), 10μG (dotted), and 30μG (solid) for other parameters as above and the distance of MSP from the core 0.12 pc (c). Dependence on the real distance from the core of GC for $d = 0.12$ pc (dot-dashed), 2 pc (dashed), 4 pc (dotted), 6 pc (solid), and 8 pc (dot-dot-dashed) assuming other parameters as above and the GC wind velocity equal to zero (d). Dependence on the value of the diffusion coefficient equal to the Bohm diffusion coefficient $D_{\rm B}$ (dot-dashed), $3 \times D_{\rm B}$ (dashed), $10 \times D_{\rm B}$ (dotted), and $30 \times D_{\rm B}$ (solid) (e). The MAGIC and CTA 50 hr sensitivities are marked by thin dashed and dot-dashed curves.

Expected spectra from leptons with the power law spectra

(injected from the MSP J1823-3021A in NGC 6624)

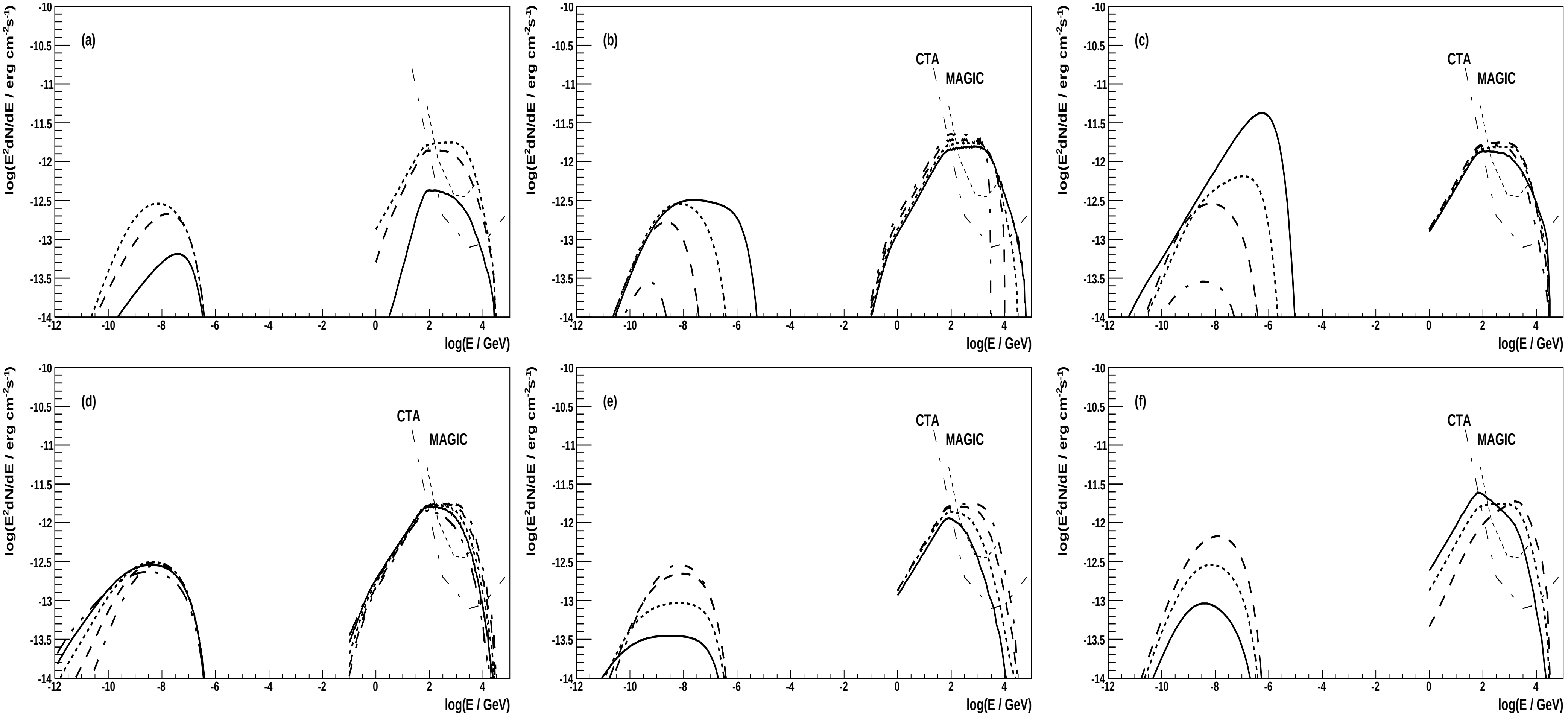


Figure 2: As in Fig. 8 but for leptons with the power law spectrum and the spectral index equal to 2 between 100 GeV and 30 TeV. The dependence of the spectra on the advection velocity of the GC wind (figure (a)), on the maximum energy of injected leptons (b) for 3 TeV (dot-dashed), on the magnetic field strength (c), on the injection distance from the centre of GC (d) on the diffusion coefficient (e), and on the spectral index equal to 1.5 (solid), 2.05 (dotted), and 2.5 (dashed) (f).

Possible limits on lepton injection rate (parameter χ, σ)

(from comparison with sensitivities of present Cherenkov telescopes - 50 hrs)

Mono-energetic leptons:

$v_{\rm adv}$ (cm/s)	0	10^6	10^7	10^8
χ (σ)	0.04 (250)	0.04 (250)	0.05 (200)	0.17 (58)
$E_\pm$ (TeV)	1	3	10	30
χ (σ)	0.14 (70)	0.04 (250)	0.23 (42)	0.26 (37)
$D/D_{\rm B}$	1	3	10	30
χ (σ)	0.04 (250)	0.05 (200)	0.09 (110)	0.23 (42)

Relation of parameters σ and χ

$$\Downarrow$$

$$\sigma \approx (L_{\rm SD} - L_\pm)/L_\pm \approx 10L_\gamma^{\rm MSP}/L_\pm - 1 \approx (10/\chi) - 1$$

[assumed $L_\gamma^{\rm MSP} \approx 10\% L_{\rm SD}$ (Abdo et al. 2010)]

Note: in terms of 3D general, relativistic polar cap model estimate of $\chi \sim 0.3 - 0.5$ (Venter & de Jager 2005,2008).

Possible limits on lepton injection rate (parameter χ, σ)

Power law spectrum of leptons:

$v_{\rm adv}$ (cm/s)	0	10^6	10^7	10^8
χ (σ)	0.17 (58)	0.17 (58)	0.34 (28)	1. (9)
$D/D_{\rm B}$	1	3	10	30
χ (σ)	0.17 (58)	0.26 (37)	0.56 (17)	0.9 (10)

Acceleration region in the parts of MSP wind with $\sigma >> 1$.

Note: $\sigma_{\rm Crab} << 1$ (**Kennel & Coroniti 1984**),
$\sigma_{\rm Vela} \sim 0.1$ (Sefako & de Jager 2003).

Conclusion

- GeV γ-rays from GCs produced in MSP magnetospheres
- $\sim$TeV γ-rays are expected if leptons acceler. by MSP leptons
- First obs. with CTs do not provide enough constraints
- But, CTs can provide important constraints on pulsar physics
- Deep obs. with CTs can constrain χ (σ) below theoretical expectations