



TeV scale dark matter at the galactic center and cosmic ray electrons

Alexander Belikov

Institut d'Astrophysique de Paris

GDR Terascale, LPNHE 2012

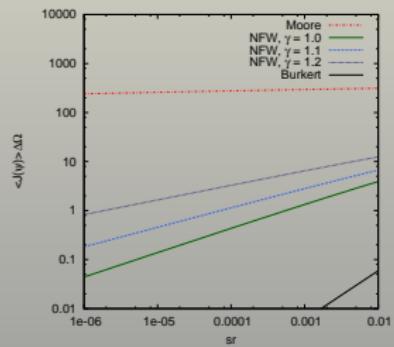
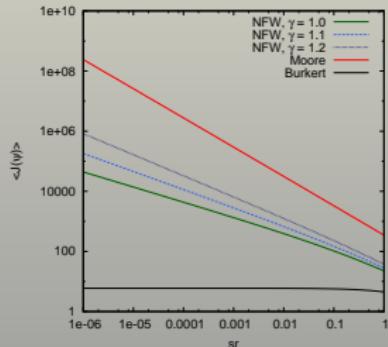
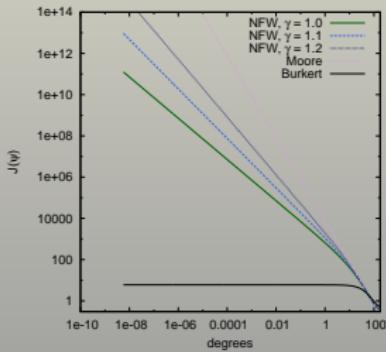
Flux from a single source. J-factor.

$$\Phi_\chi(E, \psi) = \frac{dN}{dE_\gamma}(E) \frac{\langle \sigma v \rangle}{8\pi M_\chi^2} \int_{los} \rho^2(r) dl$$

$$J(\psi) = (0.3 \text{GeV/cm}^{-3})^{-2} (8.5 \text{Kpc})^{-1} \int_{los} \rho^2(r) dl$$

$$J(\Delta\Omega) = \langle J(\psi) \rangle \Delta\Omega = \int_{\Delta\Omega} J(\psi) d\Omega$$

$$\phi_\chi(E) = \int_{\Delta\Omega} d\Omega \Phi_\chi(E, \psi) = \frac{dN}{dE_\gamma}(E) \frac{\langle \sigma v \rangle}{8\pi M_\chi^2} \times \int_{\Delta\Omega} \Omega \int_{los} \rho^2(r) dl d\Omega = \Phi_\chi(E) \times J$$



H.E.S.S. and Fermi-LAT

HESS



100 GeV - 30 TeV
 $10^5 - 10^6 \text{ m}^2$ effective area

Fermi-LAT



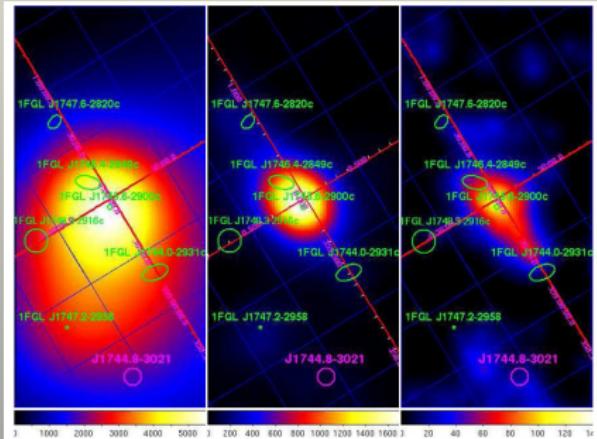
30(100) MeV-100GeV
1.8 m^2 effective area
1 orbit is 96 minutes
full sky coverage in 2 orbits

Data: γ -rays from Galactic center

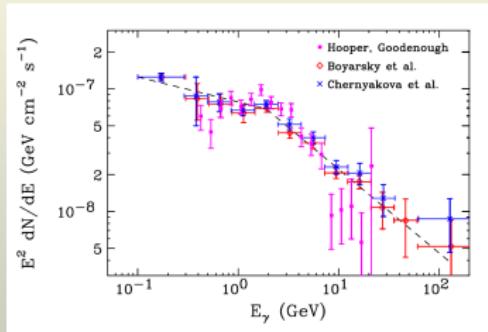
source 1FGL J1745.6-2900 or HESS

J1745-290:

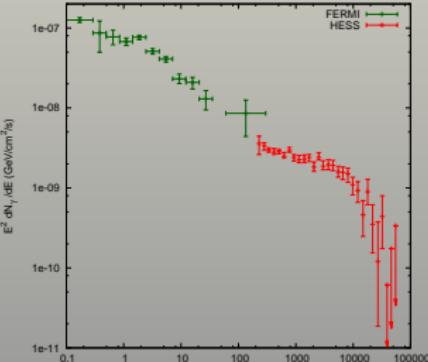
- Fermi-LAT: range 100 MeV-100GeV (no official analysis), 3 year data starting from 2008
- Hess: 200 GeV - 30 TeV, from data from 2004-2006, analysis (2009)



Chernyakova et al., *Astrophys.J.* 726 (2011) 60

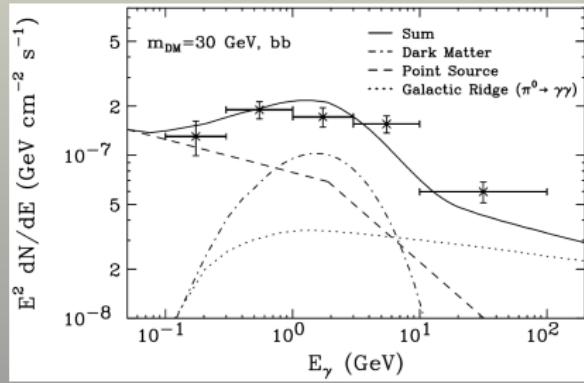
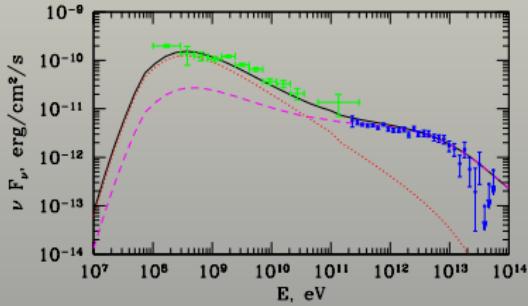


D.Hooper et al. PRD84 (2011) 123005



Previous interpretations of Galactic center gamma-rays

- broken power law: $\Gamma = 2.196 \pm 0.001$ in 300 MeV-5 GeV energy range, and $\Gamma = 2.681 \pm 0.003$ in 5-100 GeV energy range (Fermi); 2.10 ± 0.04 (stat) ± 0.10 (syst) and a cut-off energy at 15.7 ± 3.4 (stat) ± 2.5 (syst) TeV (HESS)
- M.Chernyakova et al. APJ, 726:60, 2011 :
proton flare of duration 10 years 300 years ago + constant source that switched on 300 years ago; in 10 pc region protons accelerated near the black hole may enter the surrounding gaseous environment and initiate VHE gamma-ray emission through neutral pion production and subsequent decay
- D.Hooper et al PRD84 (2011) 123005:
broken power law + galactic ridge + 30 GeV $b\bar{b}$
- S. Profumo, PRD 72 (2005) 103521
best fit for HESS data ≈ 15 TeV DM



Galactic center Fermi and HESS. PL and PL + DM.

Fermi+HESS:

$$AE^{-\Gamma}$$

$$\Gamma = 2.48$$

$$A = 6.45 \times 10^{-8}$$

$$\chi^2/dof = 5.48$$

Fermi+HESS

$$AE^{-\Gamma} + \phi_\chi(E)$$

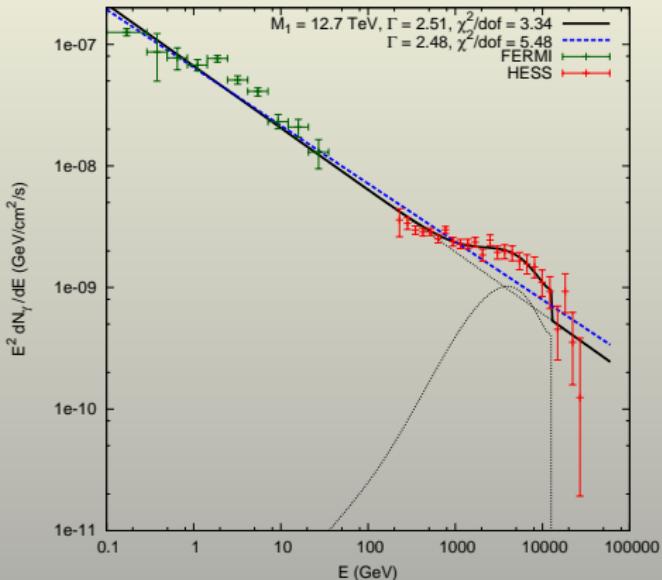
$$\Gamma = 2.51$$

$$A = 6.63 \times 10^{-8}$$

$$M = 12.7 \text{ TeV}$$

$$BF = 390$$

$$\chi^2/dof = 3.34$$



AB, G. Zaharijas, J. Silk, arXiv:1207.2412

Galactic center Fermi and HESS. LogParabola+DM and PL+ExpCutoff+DM.

Fermi+HESS:

$$(E/4.2)^{-2.54 - 0.07 \log(E/4.2)}$$

$$A = 0.25 \times 10^{-8}$$

$$M = 15.5 \text{ TeV}$$

$$(B_{\tau^+\tau^-}; B_{b\bar{b}}) = (0.45; 0.55)$$

$$\text{BF} = 1600$$

$$\chi^2/\text{dof} = 1.4$$

Fermi+HESS:

$$\Gamma = 2.48$$

$$A = 4.8 \times 10^{-8}$$

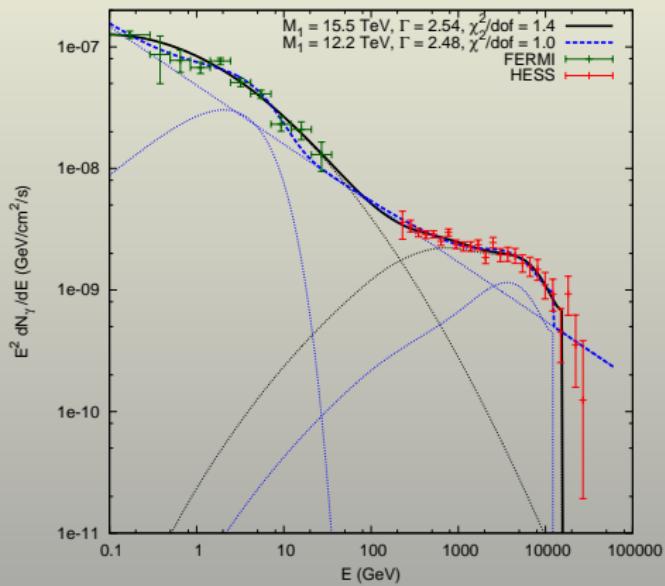
$$E^{-1.5} e^{-E/3.4}$$

$$M = 12.2 \text{ TeV}$$

$$(B_{\tau^+\tau^-}; B_{b\bar{b}}) = (0.8; 0.2)$$

$$\text{BF} = 500$$

$$\chi^2/\text{dof} = 1.0$$



PL + 2DM (Fermi and HESS). PL + DM (HESS)

Fermi+HESS:

$$\Gamma = 2.55$$

$$A = 4.4 \times 10^{-8}$$

$$M_2 = 28 \text{ GeV}, B_{NFW}^{(2)} = 62$$
$$(B_{\tau^+\tau^-}; B_{b\bar{b}}) = (0.48; 0.52)$$

$$\text{BF} = 1400$$

$$\chi^2/\text{dof} = 0.9$$

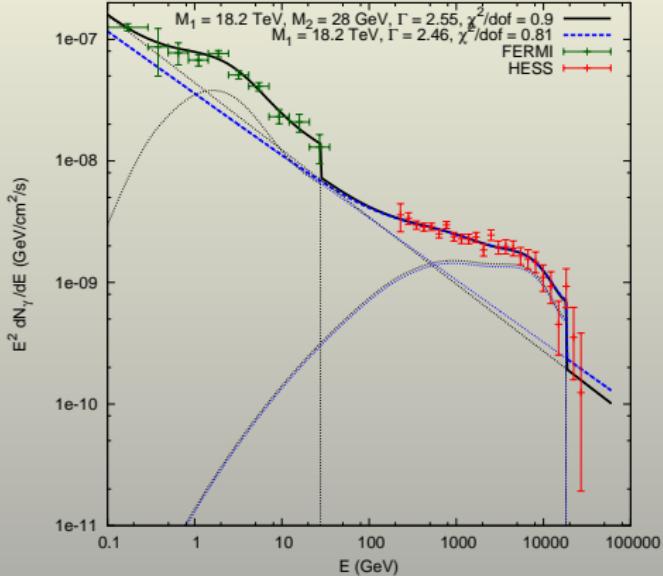
$$\Gamma = 2.46$$

$$A = 3.21 \times 10^{-8}$$

$$(B_{\tau^+\tau^-}; B_{b\bar{b}}) = (0.53; 0.47)$$

$$\text{BF} = 1100$$

$$\chi^2/\text{dof} = 0.81$$



Galactic center Fermi and HESS (full). PL+ExpCutoff+DM and PL + 2DM.

Fermi+HESS(full): $\Gamma = 2.59$

$$A = 4.06 \times 10^{-8}$$

$$E^{-1.44} e^{-E/3.8}$$

$$M = 14.9 \text{ TeV}$$

$$(B_{\tau^+\tau^-}; B_{b\bar{b}}) = (0.47; 0.53)$$

$$\text{BF} = 1300$$

$$\chi^2/\text{dof} = 1.42$$

Fermi+HESS(full):

$$\Gamma = 2.61$$

$$A = 3.98 \times 10^{-8}$$

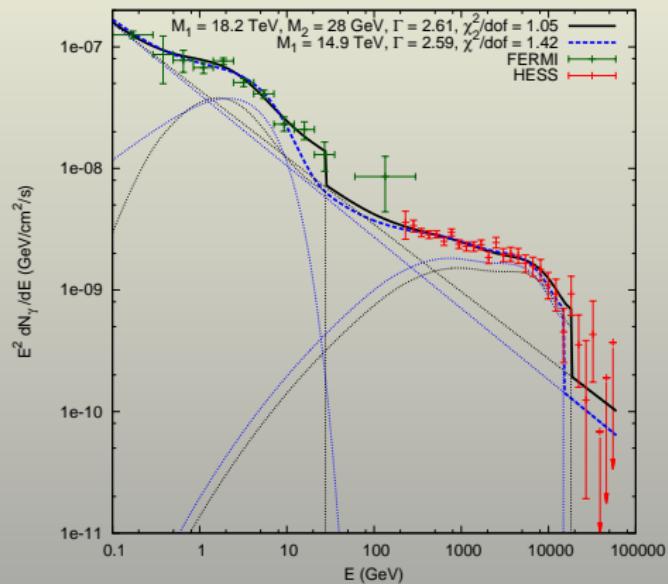
$$m_\chi = 28, B_F = 75$$

$$M = 18.2 \text{ TeV}$$

$$(B_{\tau^+\tau^-}, B_{b\bar{b}}) = (0.42; 0.58)$$

$$\text{BF} = 1700$$

$$\chi^2/\text{dof} = 1.05$$



Galactic center HESS data. PL, PL + DM, PL+ExpCutoff.

HESS:

$$\Gamma = 2.51$$

$$A = 3.21 \times 10^{-8}$$

$$M = 18.2 \text{ TeV}$$

$$(B_{\tau^+\tau^-}; B_{b\bar{b}}) = (0.53; 0.47)$$

$$\text{BF} = 1075; \chi^2/dof = 0.81$$

HESS:

$$\Gamma = 2.29$$

$$A = 1.76 \times 10^{-8}$$

$$\chi^2/dof = 1.96$$

HESS:

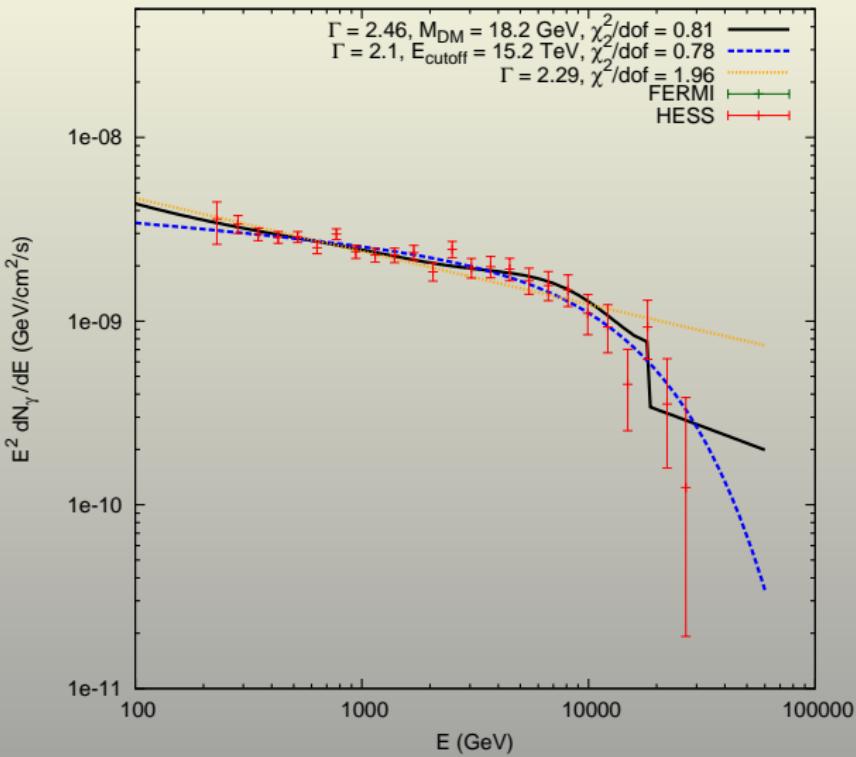
$$\Gamma = 2.1$$

$$AE^{-\Gamma} e^{-E/E_{cut}}$$

$$A = 0.56 \times 10^{-8}$$

$$M_{cut} = 15.2 \text{ TeV}$$

$$\chi^2/dof = 0.78$$



Galactic center Fermi and HESS data. The summary table of best-fits.

case	datasets	Γ	$10^8 \times A$	GeV range fit	M_1 [TeV]	$(B_{\tau^+\tau^-}; B_{b\bar{b}})$	$10^{-3} \times B_{NFW}^{(1)}$	$\chi^2 / \text{d.o.f.}$
G.1	<i>Fermi</i> +HESS	2.48	6.45	-	-	-	-	5.48
G.2	<i>Fermi</i> +HESS	2.51	6.63	-	12.7	(1.0;0.0)	0.39	3.34
G.3	<i>Fermi</i> +HESS	-	0.25	log-parabola ¹	15.5	(0.45;0.55)	1.6	1.4
G.4	<i>Fermi</i> +HESS	2.48	4.8	$E^{-1.5} e^{-E/3.4}$	12.2	(0.8;0.2)	0.5	1.0
G.5	<i>Fermi</i> +HESS	2.55	4.4	light DM ²	18.2	(0.48;0.52)	1.4	0.9
G.6	HESS	2.51	3.21	-	18.2	(0.53;0.47)	1075	0.81
G.7	HESS	2.29	1.76	-	-	-	-	1.96
G.8	HESS	2.1	0.56	-	15.2 ³	-	-	0.78
G.9	<i>Fermi</i> +HESS(full)	2.59	4.06	$E^{-1.44} e^{-E/3.8}$	14.9	(0.47;0.53)	1.3	1.42
G.10	<i>Fermi</i> +HESS(full)	2.61	3.98	light DM ⁴	18.2	(0.42;0.58)	1.7	1.05

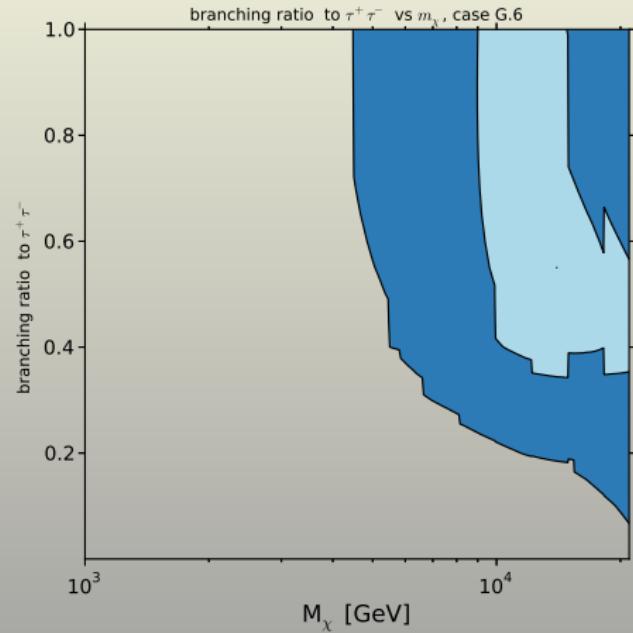
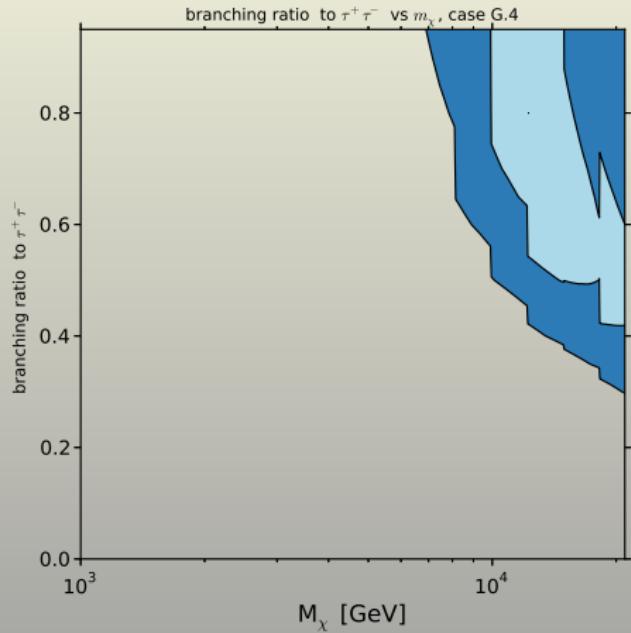
¹ log-parabola is set by $(E/4.2)^{-2.54 - 0.07 \log(E/4.2)}$

² $M_2 = 28 \text{ GeV}$, $B_{NFW}^{(2)} = 62$

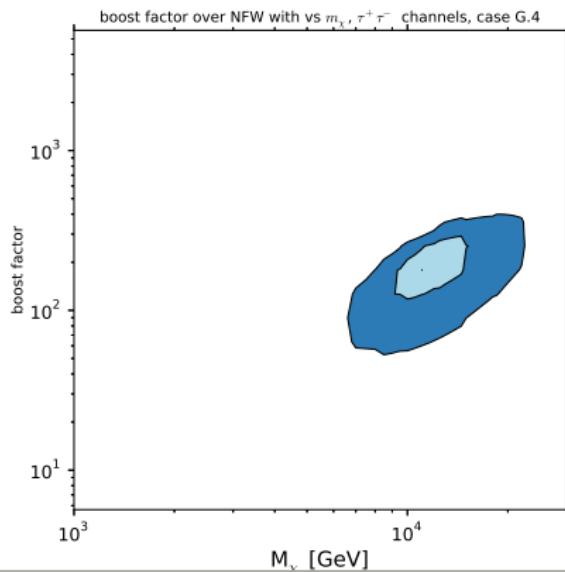
³ the value refers to the energy cutoff, $A E^{-\Gamma} e^{-E/E_{cut}}$

⁴ $M_2 = 28 \text{ GeV}$, $B_{NFW}^{(1)} = 75$

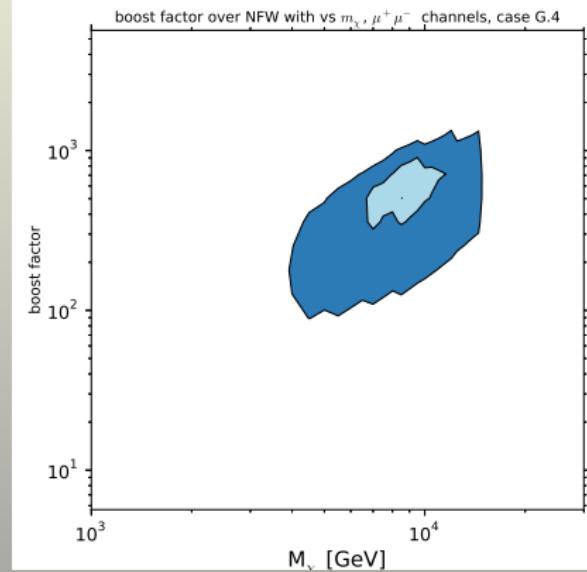
Branching ratio constraints to the gamma rays from the galactic center



Boost factor constraints to the gamma rays from the galactic center

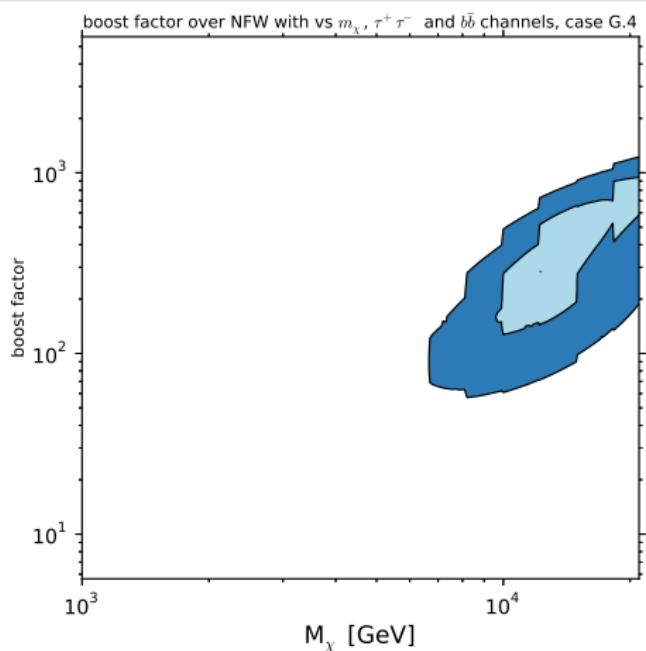


GC, HESS + Fermi (reduced), allowed regions of parameter space m_χ -*BF*, Fermi bump modeled by pulsar, $\tau^+ \tau^-$

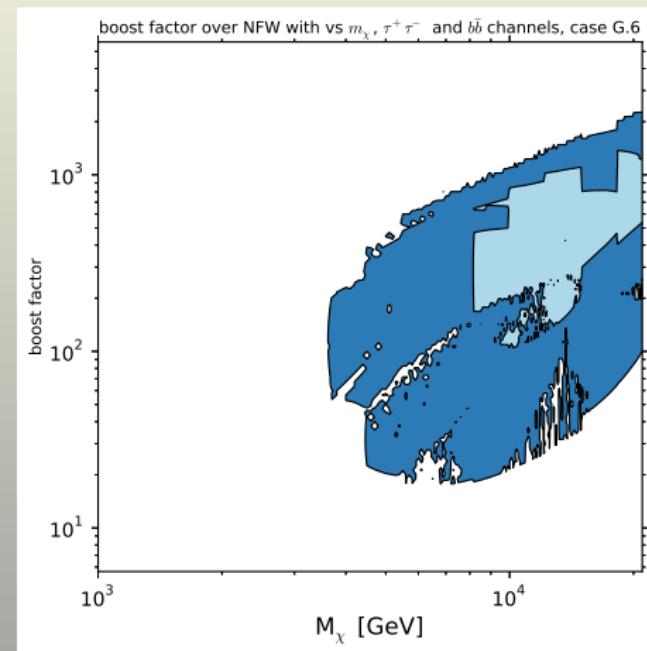


GC, HESS + Fermi (reduced), allowed regions of parameter space m_χ -*BF*, Fermi bump modeled by pulsar, $\mu^+ \mu^-$

Boost factor constraints to the gamma rays from the galactic center



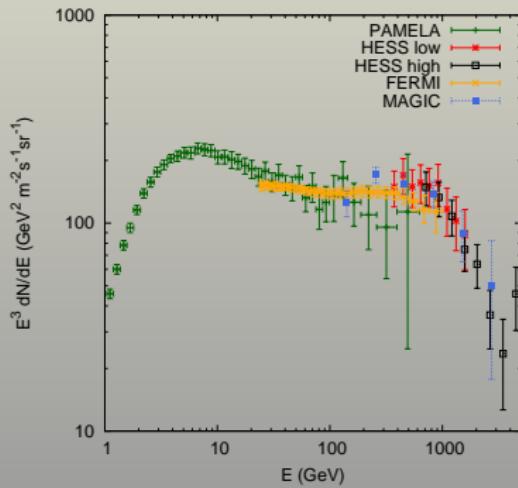
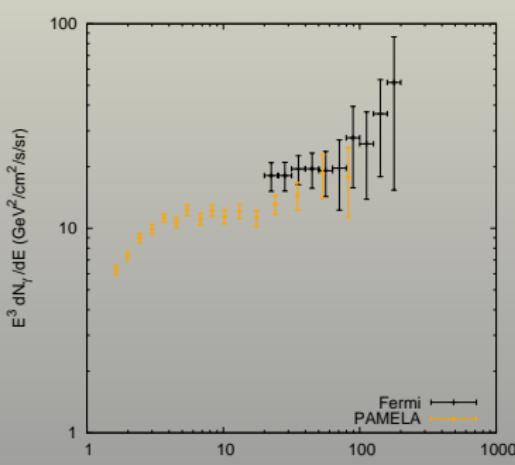
GC, HESS + Fermi (reduced), allowed regions of parameter space m_χ - BF , Fermi bump modeled by pulsar



GC, HESS (reduced), allowed regions of parameter space m_χ - BF

Data: charged particles

- electron+positron flux:
 - PAMELA: 1-625 GeV, 2011
 - Fermi-LAT: range 20 MeV-1 TeV, 2009
 - Hess: 370 GeV - 4.5 TeV, 2010
 - MAGIC: 140 GeV - 2.7 TeV, 2011
- positron flux:
 - PAMELA: 1.5-100 GeV, 2008
 - Fermi-LAT: range 20 MeV-200 GeV, 2009



Cosmic ray electron fits to PAMELA+*Fermi*+HESS data.

PAMELA+*Fermi*+HESS:

$$\Gamma = 3.72; A = 1940; M = 3$$

TeV;

$$(Br_{\tau^+\tau^-}; Br_{b\bar{b}}; Br_{\mu^+\mu^-})$$

$$= (0.9997; 0; 0); \text{BF} =$$

$$12,800; \phi = 980 \text{ MV},$$

$$\chi^2/\text{dof} = 0.3$$

PAMELA+*Fermi*+HESS:

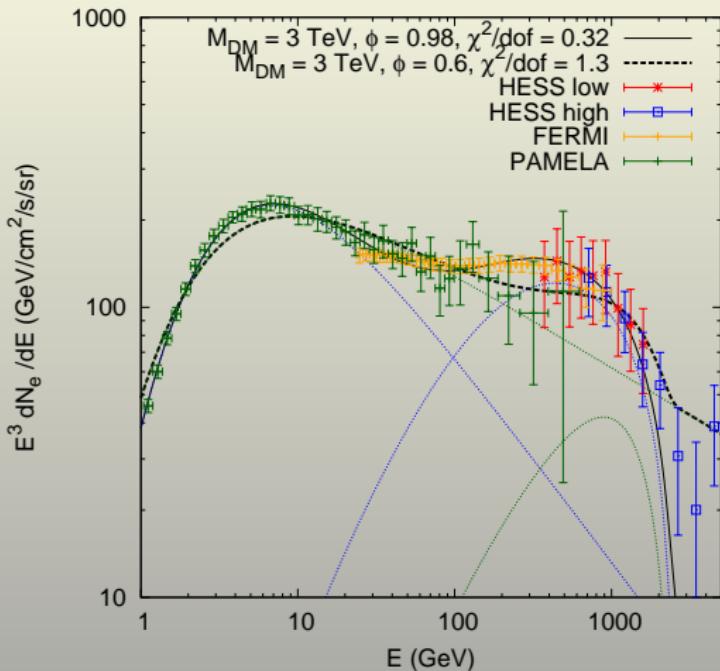
$$\Gamma = 3.33; A = 595; M = 3$$

TeV;

$$(Br_{\tau^+\tau^-}; Br_{b\bar{b}}; Br_{\mu^+\mu^-})$$

$$= (0; 0; 0.9996); \text{BF} = 1,400;$$

$$\phi = 600 \text{ MV}, \chi^2/\text{dof} = 1.3$$



$$J_{TOA}(E) = \frac{E^2 - m^2}{(E + |Z|e\phi)^2 - m^2} J_{IS}(E + |Z|e\phi)$$

Cosmic ray electron (and positron) fits to *Fermi*+HESS data.

Fermi+HESS (+*Fermi* e^+) :

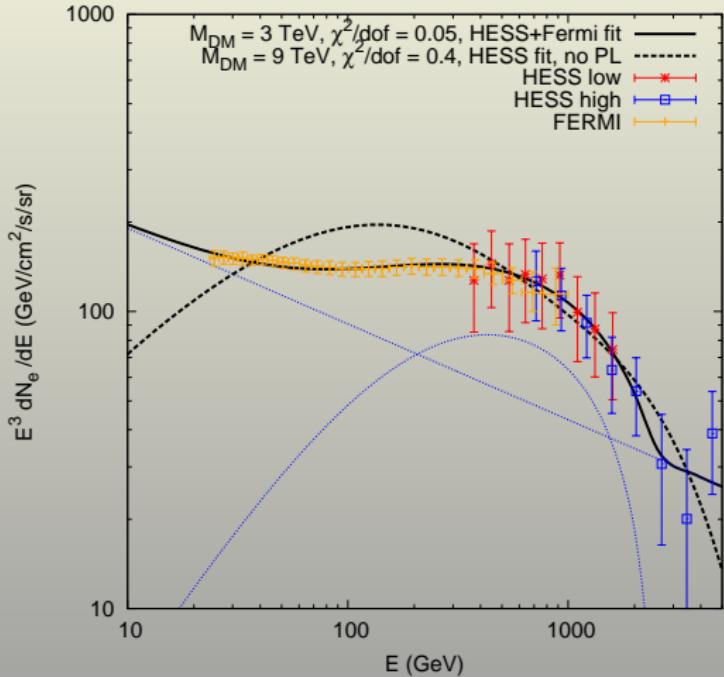
$\Gamma = 3.32$; $A = 400$; $M = 3$ TeV;

$(Br_{\tau^+\tau^-}; Br_{b\bar{b}}; Br_{\mu^+\mu^-})$
= $(0.9997; 0; 0)$; BF = 8,700;
 $\chi^2/dof = 0.05$

HESS:

$\Gamma = 3.33$; $M = 9$ TeV;

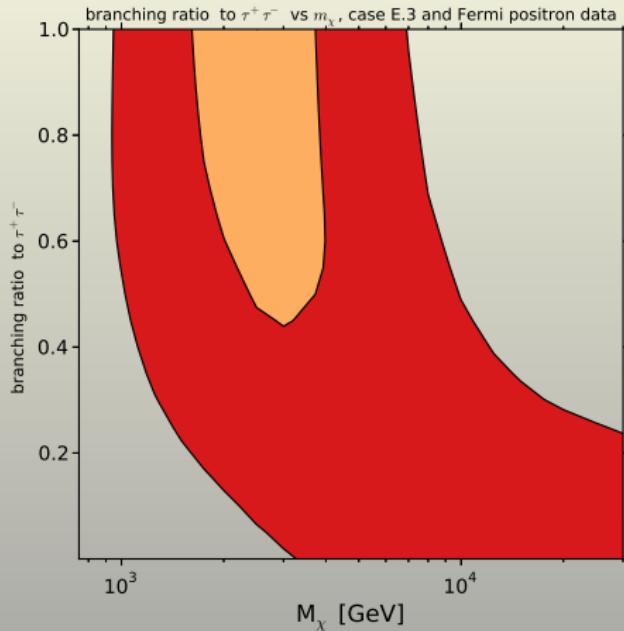
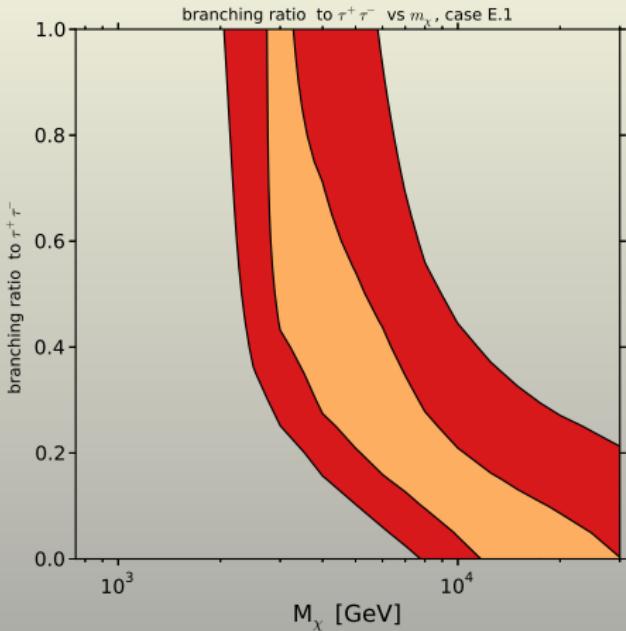
$(Br_{\tau^+\tau^-}; Br_{b\bar{b}}; Br_{\mu^+\mu^-})$
= $(0.035; 0.965; 0.0)$; BF = 95,000; $\chi^2/dof = 0.4$



CREs and cosmic ray positrons. The summary table of best-fits.

datasets	mass[TeV]	$(Br_{\tau^+\tau^-}; Br_{b\bar{b}}; Br_{\mu^+\mu^-}) \times B_{NFW}$	Γ	A	ϕ [MV]	$\chi^2 /d.o.f.$
PAMELA+ <i>Fermi</i> +HESS	3	(0.9997;0;0)	12.8	3.72	1943	986
PAMELA+ <i>Fermi</i> +HESS	3	(0;0;0.9996)	1.38	3.33	595	600
<i>Fermi</i> +HESS (+ <i>Fermi e⁺</i>)	3	(0.9997;0;0)	8.7	3.32	400	-
HESS	9	(0.035;0.965;0)	94.9	-	-	0.4

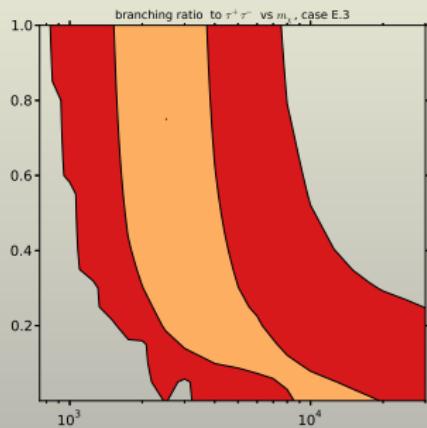
Branching ratio constraints to electrons and positrons



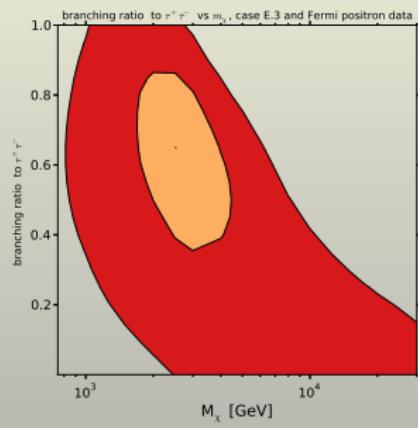
total electron plus positrons and positrons, PAMELA + Fermi + HESS, minimized over values of solar modulation ϕ , allowed regions of parameter space $m_\chi - Br_{\tau^+ \tau^-}$

total electron plus positrons and positrons, HESS + Fermi, allowed regions of parameter space $m_\chi - Br_{\tau^+ \tau^-}$

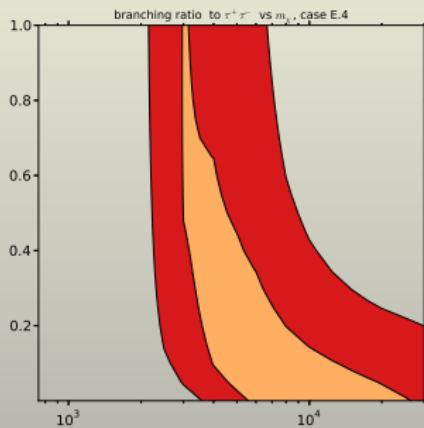
Branching ratio constraints to electrons and positrons



total electron plus positrons, PAMELA +
HESS + Fermi

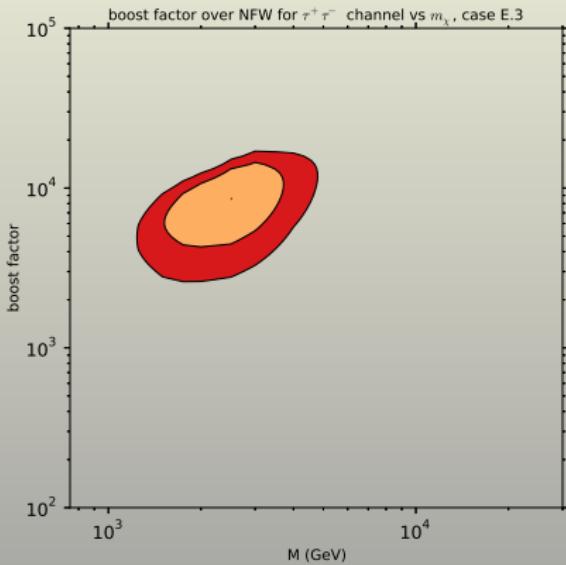


total electron plus positrons, PAMELA +
HESS + Fermi, just DM for positrons

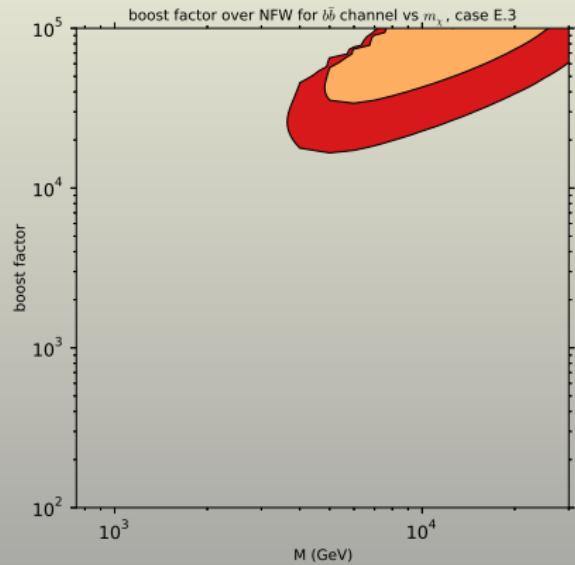


total electron plus positrons and
positrons, HESS, allowed regions of
parameter space m_χ - $Br_{\tau^+ \tau^-}$

Boost factor constraints to the total electron + positron and positron flux

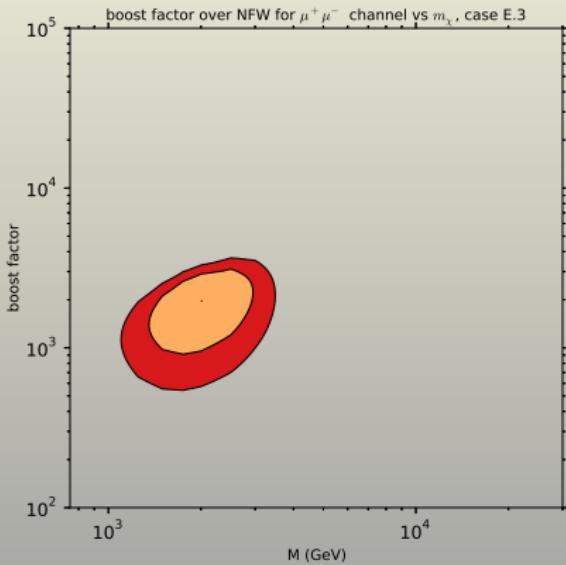


total electron plus positrons and positrons, HESS + Fermi,
allowed regions of parameter space m_χ -BF, $\tau^+\tau^-$ channel

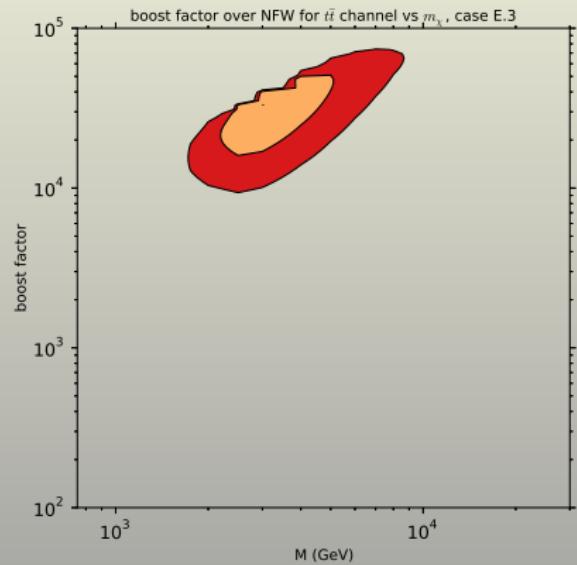


total electron plus positrons and positrons, HESS + Fermi,
allowed regions of parameter space m_χ -BF, $b\bar{b}$ channel

Boost factor constraints to the total electron + positron and positron flux



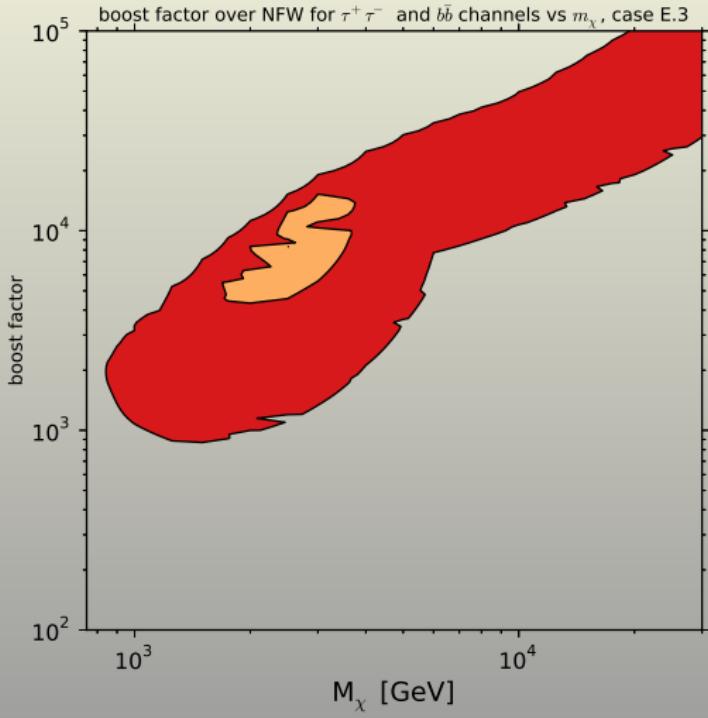
total electron plus positrons and positrons, HESS + Fermi,
allowed regions of parameter space m_χ -BF, $\mu^+ \mu^-$ channel



total electron plus positrons and positrons, HESS + Fermi,
allowed regions of parameter space m_χ -BF, $t\bar{t}$ channel

Boost factor constraints to the total electron + positron and positron flux

Fermi+HESS (+Fermi e⁺) :
the boost factor plots over standard NFW profile, each point is marginalized over the branching ratios to $\tau^+\tau^-$, $b\bar{b}$ and $\mu^+\mu^-$ and the parameters of the power law

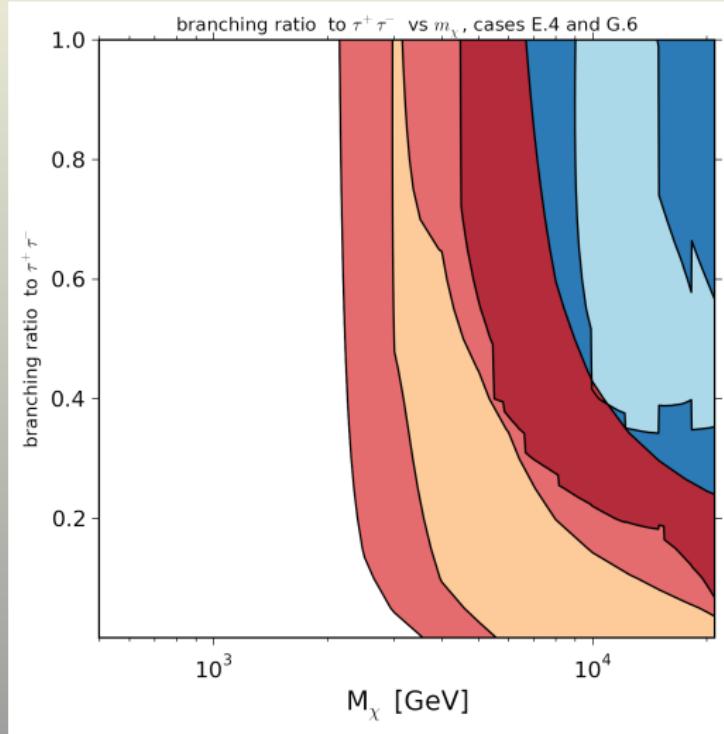


The overlapping regions between gamma rays and cosmic ray electron

HESS data, fit by electrons annihilating to dark matter at fixed branching ratio

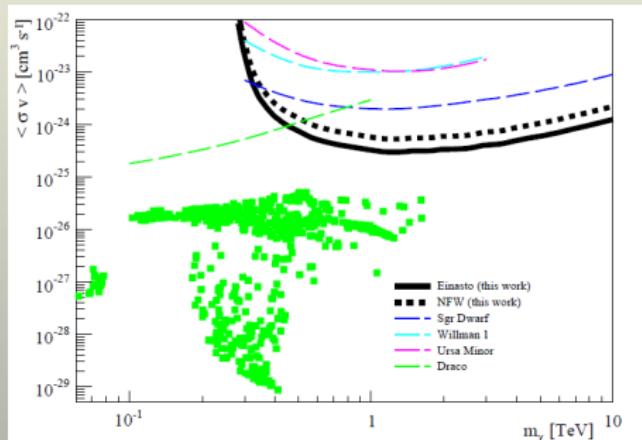
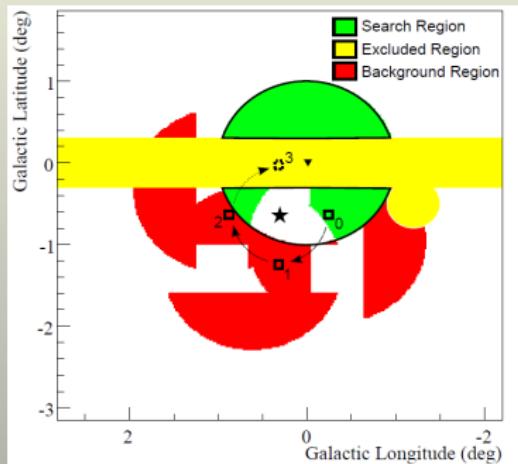
$Br_{\tau^+\tau^-}$ and

$Br_{b\bar{b}} = 1 - Br_{\tau^+\tau^-}$



HESS GC halo

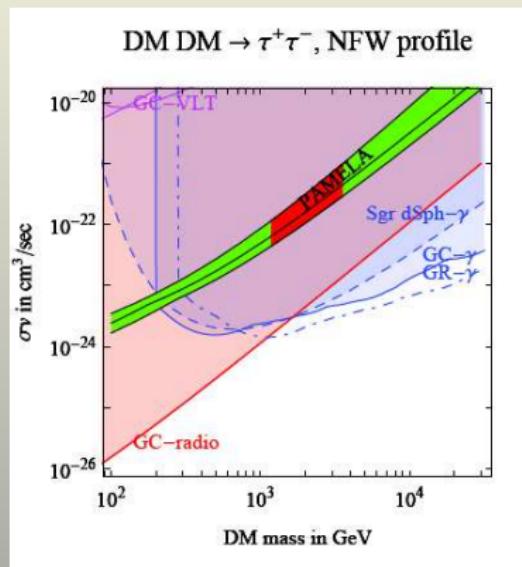
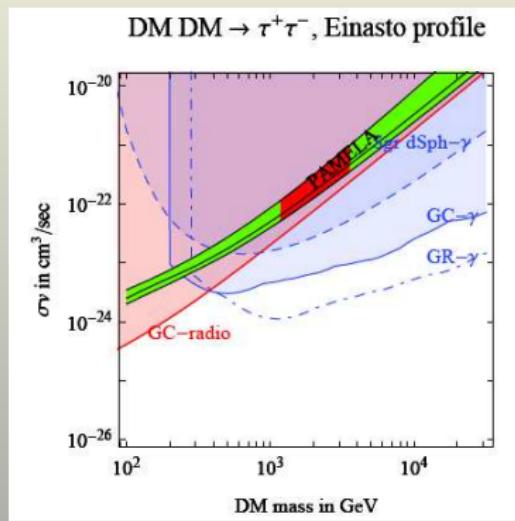
a boost factor of about 140 at 10 TeV



A. Abramowski, Phys.Rev.Lett., 106:161301, 2011

HESS galactic ridge

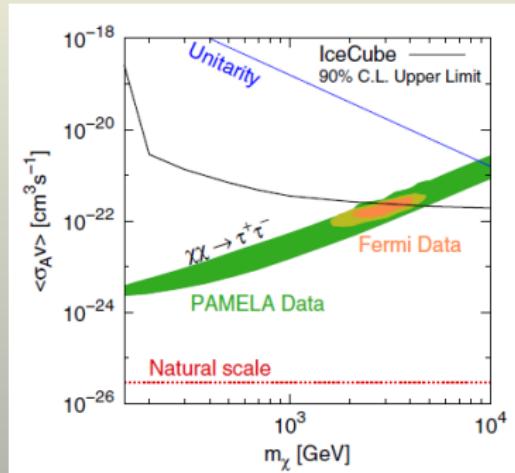
a boost factor of about 700 at 10 TeV



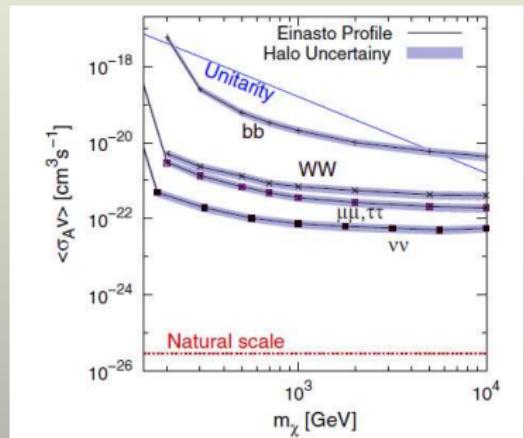
G. Bertone, JCAP 0903:009 (2009)

Galactic center as seen by IceCube

best constraints are at level of $\langle \sigma v \rangle = 10^{-22} \text{ cm}^3 \text{s}^{-1}$



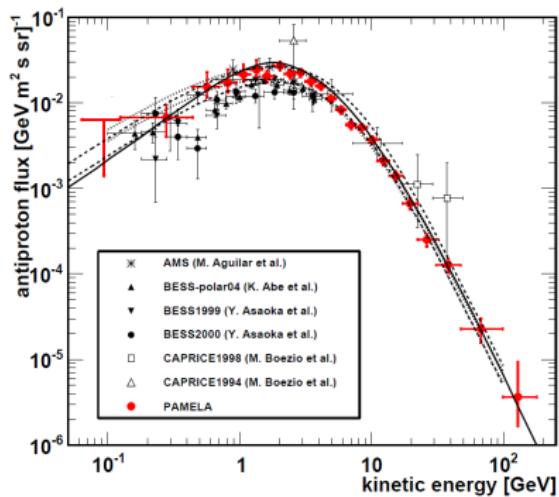
IceCube, R. Abbasi et al., PRD 84, 022004 (2011)



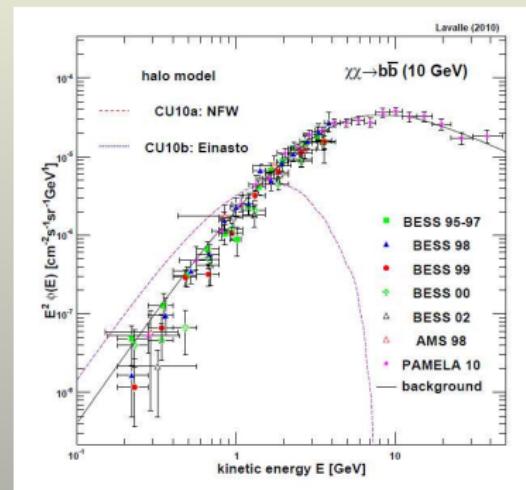
Unitarity bounds: $\langle \sigma v \rangle_{max} \approx 10^{-22} \text{ cm}^3 \text{s}^{-1} \left(\frac{m_\chi}{1 \text{ TeV}} \right)^2$
unitarity bounds:

Antiproton constraints on TeV DM

antiproton flux: PAMELA: 0.09-128 GeV



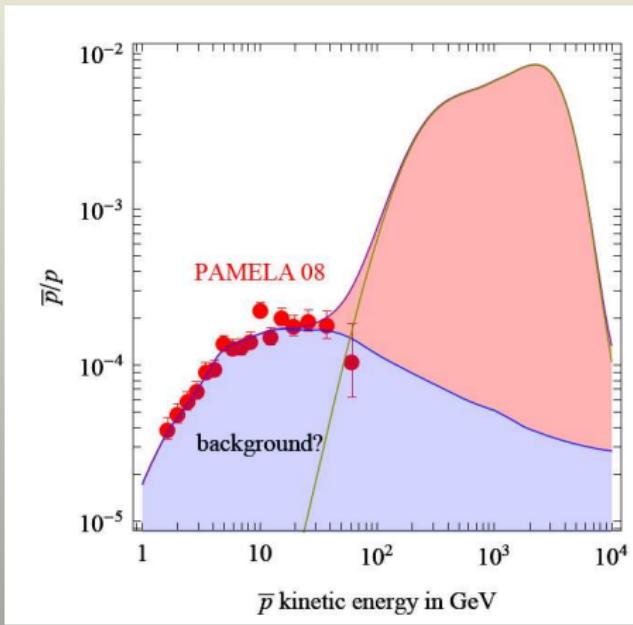
Adriani et al., Phys.Rev.Lett. 105 (2010) 121101



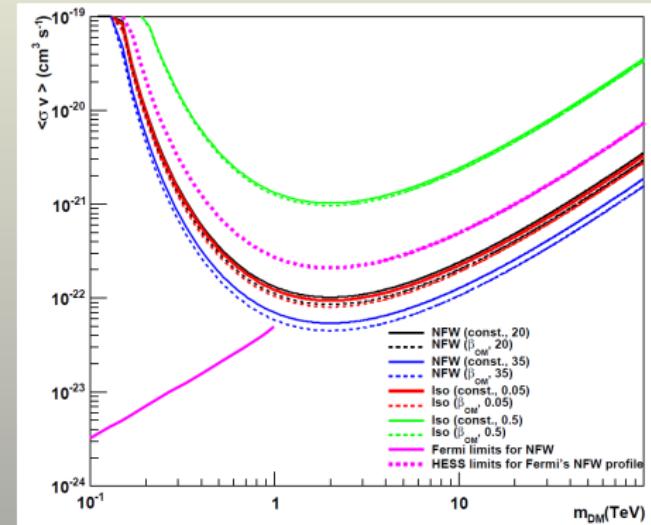
J.Lavalle, arXiv:1007.5253

Constraints from positron and antiproton data Dwarf galaxies from HESS

higher energies or other channels?



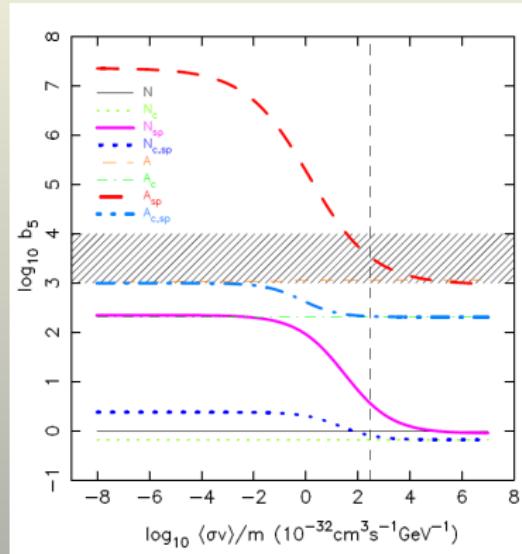
10 TeV, W^+W^- Cirelli et al., Nucl.Phys.B813:1-21,2009



HESS collab., Astropart.Phys. 34 (2011) 608-616

Adiabatic contraction of dark matter density around a massive black hole

	γ_c	γ_{sp}	r_c	$\rho(R_\odot)$	$\log_{10} \bar{J}_3 (\bar{J}_5)$	$\tau = 0$	$\tau = 10$	$\tau = 100$
N	1.0	—	—	0.3	2.56 (3.51)	2.56 (3.50)	2.56 (3.50)	
N_c	1.0	—	10	0.3	2.54 (3.33)	2.54 (3.33)	2.54 (3.33)	
N_{sp}	1.0	2.33	—	0.3	9.21 (11.2)	3.86 (5.84)	2.56 (3.52)	
$N_{c,sp}$	1.0	2.29	10	0.3	6.98 (8.98)	2.61 (3.88)	2.54 (3.33)	
A	1.5	—	—	0.5	5.80 (7.75)	5.26 (7.03)	5.23 (6.98)	
A_c	1.5	—	10	0.5	4.96 (6.27)	4.96 (6.27)	4.96 (6.27)	
A_{sp}	1.5	2.40	—	0.5	14.8 (16.8)	9.25 (11.3)	5.25 (7.02)	
$A_{c,sp}$	1.5	2.29	10	0.5	9.99 (12.0)	5.21 (6.96)	4.96 (6.27)	



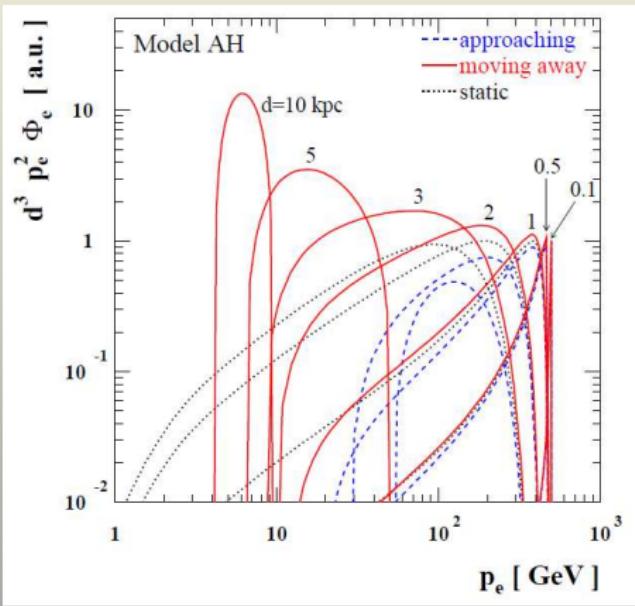
$$\gamma_{sp} = \frac{9 - 2\gamma}{4 - \gamma}$$

G. Bertone, PRD, 72, 103502 (2005)

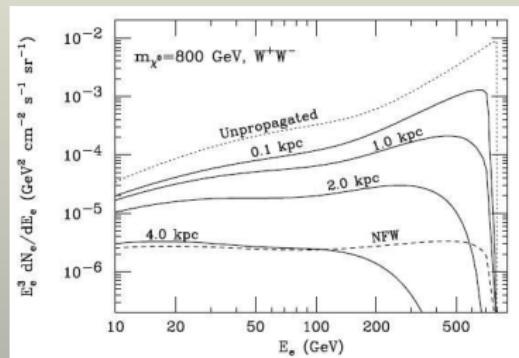
P. Gondolo et al., Phys.Rev.Lett., 83, 1719 (1999)

Electrons propagating from a DM clump

$$l \sim \text{few kPc} \left(\frac{E}{1 \text{ TeV}} \right)^{-1} \left(\left(\frac{B}{5 \mu \text{G}} \right) + 1.6 \left(\frac{w}{1 \text{ eV cm}^{-3}} \right) \right)^{-1}$$



M. Regis et al. ArXiv:0907.5093



D. Hooper et al, Phys.Rev.D79 (2009) 103513

Conclusions

- the gamma ray spectrum from the galactic center (Fermi+HESS) can be fit over 5 orders of magnitude by a combination of spectrum of unresolved pulsars and TeV-scale dark matter
- good fits of the galactic center gamma-ray spectrum are achieved for the slope of the power law $\Gamma = 2.5 - 2.6$ and $\gtrsim 10$ TeV DM annihilating to a combination of $\tau^+\tau^-$ and $b\bar{b}$; log-parabola also provides a good fit
- we performed the analysis of HESS data alone and found that the DM parameter space is less constrained
- we identified the best fits for cosmic ray electron and positron for a combination of PAMELA, Fermi and HESS data sets as a power-law + dark matter of few TeV annihilating to a combination of $\tau^+\tau^-$ and $b\bar{b}$
- we studied the overlap between gamma-ray data from the galactic center and cosmic ray electrons and positron data in the parameter space branching ratio to $\tau^+\tau^- - M_\chi$ and found overlap between 99.999% C.L. regions