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

Alexander Belikov

Institut d'Astrophysique de Paris

Aspen Center for Physics
Winter Conference
Closing in on Dark Matter

Flux from a single source. J-factor.

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

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

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

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

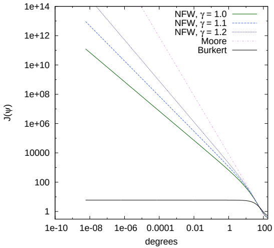
for $\Delta\Omega$ = 1e-5, $J(\Delta\Omega)\Delta\Omega$ is

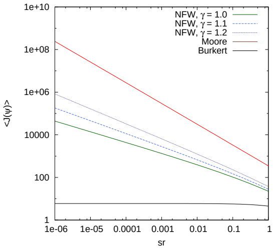
NFW : 0.145

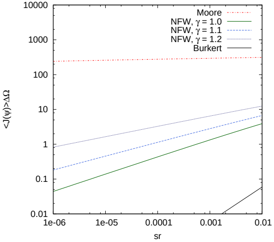
NFW $\gamma = 1.1$: 0.45

NFW $\gamma = 1.2$: 1.73

Moore : 260

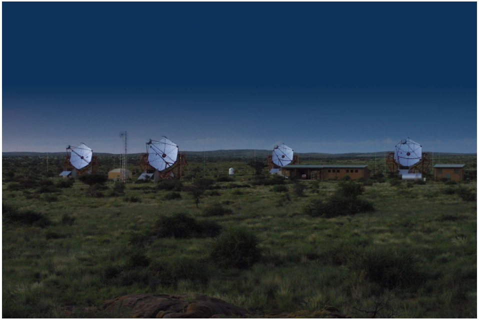






H.E.S.S. and Fermi-LAT

HESS



100 GeV - 30 TeV
$10^5 - 10^6$ m^2 effective area

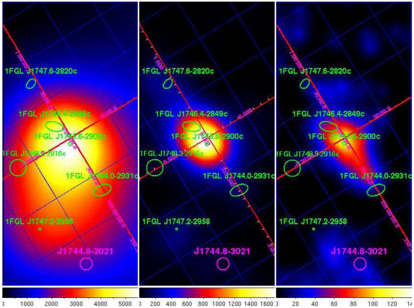
Fermi-LAT

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

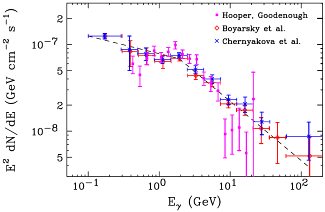
Data: γ-rays from Galactic center

source 1FGL J1745.6-2900 or HESS J1745-290:

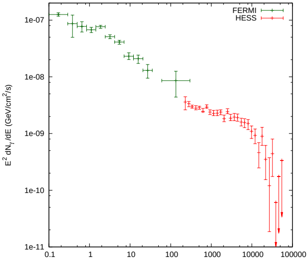
- Fermi-LAT: range 100 MeV-100GeV (no official analysis), 3 year data starting from 2008
- Hess: 200 GeV - 30 TeV, from data from 2004-2006, analysis (2009)



Chernykova et al., Astrophys.J. 726 (2011) 60

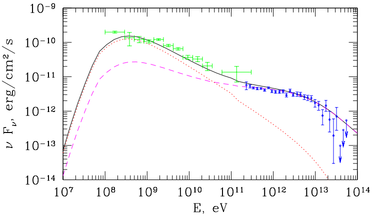


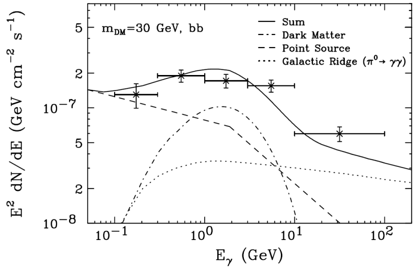
D.Hooper et al. PRD84 (2011) 123005



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); $2.10 \pm 0.04\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst})$ and a cut-off energy at $15.7 \pm 3.4\,(\mathrm{stat}) \pm 2.5\,(\mathrm{syst})$ 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 $\approx$ 15 TeV DM

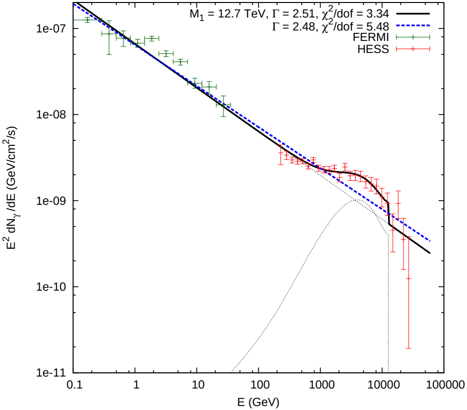




Galactic center Fermi and HESS. PL and PL + DM.

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 TeV
BF = 390
$\chi^2/dof = 3.34$

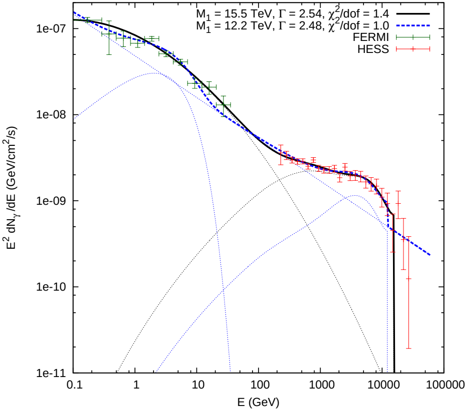


AB, G. Zaharijas, J. Silk, PRD86 (2012) 083516

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 TeV
$(B_{\tau^+\tau^-}; B_{b\bar{b}})$ = (0.45;0.55)
BF = 1600
$\chi^2/dof = 1.4$

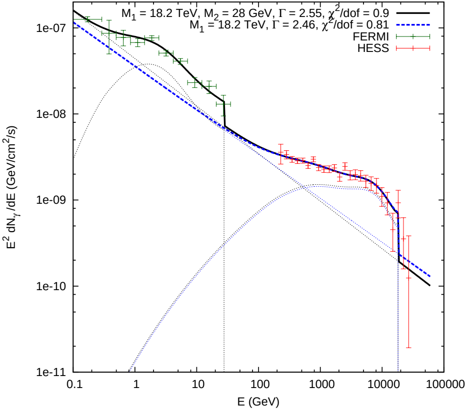
Fermi+HESS:
Γ = 2.48
A $= 4.8 \times 10^{-8}$
$E^{-1.5}\mathrm{e}^{-E/3.4}$
M = 12.2 TeV
$(B_{\tau^+\tau^-}; B_{b\bar{b}})$ = (0.8;0.2)
BF = 500
$\chi^2/dof = 1.0$



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

Fermi+HESS:
$\Gamma = 2.55$
$A = 4.4 \times 10^{-8}$
$M_2 = 28\,\text{GeV},\ B^{(2)}_{NFW} = 62$
$(B_{\tau^+\tau^-};\, B_{b\bar{b}}) = (0.48;0.52)$
BF $= 1400$
$\chi^2/dof = 0.9$

$\Gamma = 2.46$
$A = 3.21 \times 10^{-8}$
$(B_{\tau^+\tau^-};\, B_{b\bar{b}}) = (0.53;0.47)$
BF $= 1100$
$\chi^2/dof = 0.81$

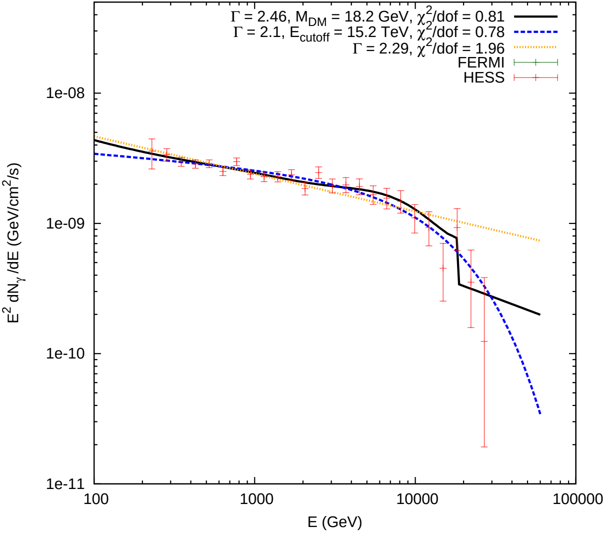


Galactic center HESS data. PL, PL + DM, PL+ExpCutoff.

HESS:
$\Gamma = 2.51$
$A = 3.21 \times 10^{-8}$
$M = 18.2$ TeV
$(B_{\tau^+\tau^-}; B_{b\bar{b}}) = (0.53;0.47)$
$BF = 1075$; $\chi^2/dof = 0.81$

HESS:
$\Gamma = 2.29$
$A = 1.76 \times 10^{-8}$
$\chi^2/dof = 1.96$

HESS:
$\Gamma = 2.1$
$AE^{-\Gamma}e^{-E/E_{cut}}$
$A = 0.56 \times 10^{-8}$
$M_{cut} = 15.2$ 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]	$(B_{\tau^+\tau^-};B_{b\bar{b}})$	$10^{-3}\times B^{(1)}_{NFW}$	χ^2 /d.o.f.
G.1	*Fermi*+HESS	2.48	6.45	-	-	-	-	5.48
G.2	*Fermi*+HESS	2.51	6.63	-	12.7	(1.0;0.0)	0.39	3.34
G.3	*Fermi*+HESS	-	0.25	log-parabola[1]	15.5	(0.45;0.55)	1.6	1.4
G.4	*Fermi*+HESS	2.48	4.8	$E^{-1.5}\mathrm{e}^{-E/3.4}$	12.2	(0.8;0.2)	0.5	1.0
G.5	*Fermi*+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	*Fermi*+HESS(full)	2.59	4.06	$E^{-1.44}\mathrm{e}^{-E/3.8}$	14.9	(0.47;0.53)	1.3	1.42
G.10	*Fermi*+HESS(full)	2.61	3.98	light DM[4]	18.2	(0.42;0.58)	1.7	1.05

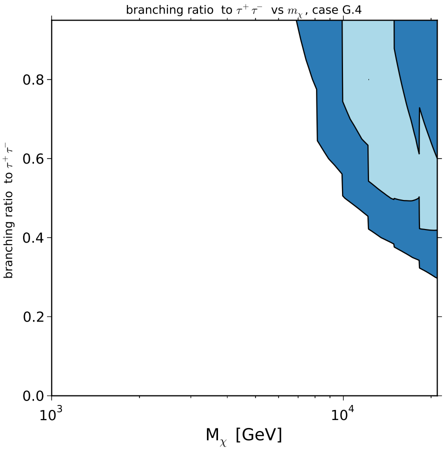
[1] log-parabola is set by $(E/4.2)^{-2.54-0.07\log(E/4.2)}$

[2] $M_2 = 28\,\text{GeV},\ B^{(2)}_{NFW} = 62$

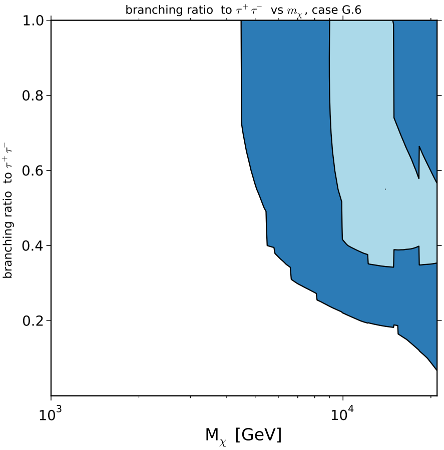
[3] the value refers to the energy cutoff, $AE^{-\Gamma}e^{-E/E_{cut}}$

[4] $M_2 = 28\,\text{GeV},\ B^{(1)}_{NFW} = 75$

Branching ratio constraints to the gamma rays from the galactic center

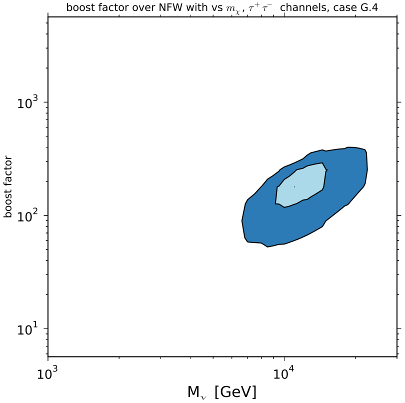


GC, HESS + Fermi (reduced), allowed regions of parameter space m_χ-$Br_{\tau^+\tau^-}$, Fermi bump modeled by exponential cutoff

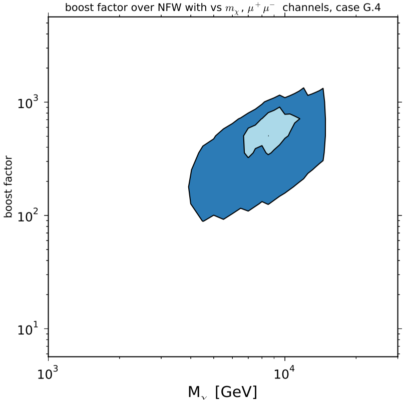


GC, HESS (reduced), allowed regions of parameter space m_χ-$Br_{\tau^+\tau^-}$

Boost factor constraints to the gamma rays from the galactic center



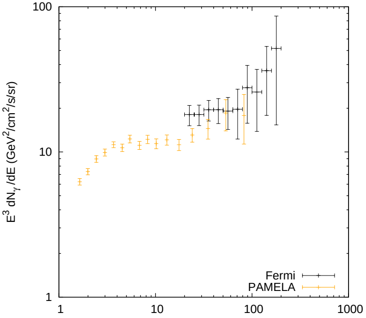
GC, HESS + Fermi (reduced), allowed regions of parameter space m_χ-BF, Fermi bump modeled by pulsar, $\tau^+\tau^-$

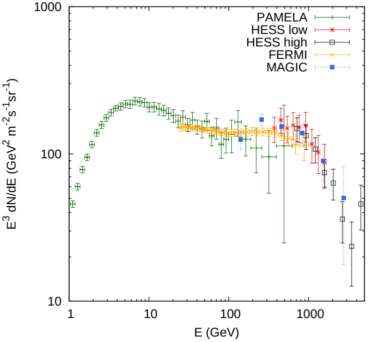


GC, HESS + Fermi (reduced), allowed regions of parameter space m_χ-BF, Fermi bump modeled by pulsar, $\mu^+\mu^-$

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

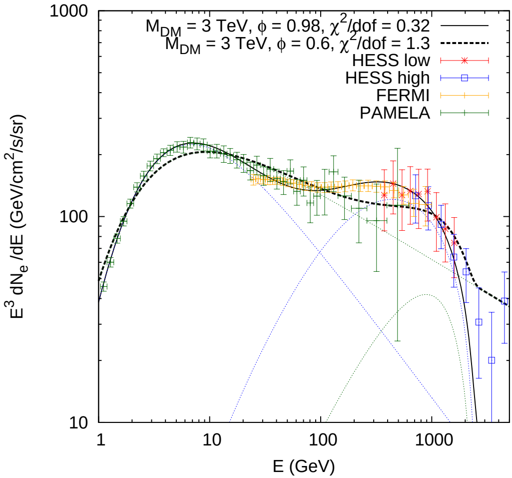




Cosmic ray electron fits to PAMELA+*Fermi*+HESS data.

PAMELA+*Fermi*+HESS:
Γ = 3.72; A = 1940; M = 3 TeV;
$(Br_{\tau^+\tau^-};\ Br_{b\bar{b}};\ Br_{\mu^+\mu^-})$ = (0.9997;0;0); BF = 12,800; ϕ = 980 MV, $\chi^2/dof = 0.3$

PAMELA+*Fermi*+HESS:
Γ = 3.33; A = 595; M = 3 TeV;
$(Br_{\tau^+\tau^-};\ Br_{b\bar{b}};\ Br_{\mu^+\mu^-})$ = (0;0;0.9996); BF = 1,400; ϕ = 600 MV, $\chi^2/dof = 1.3$

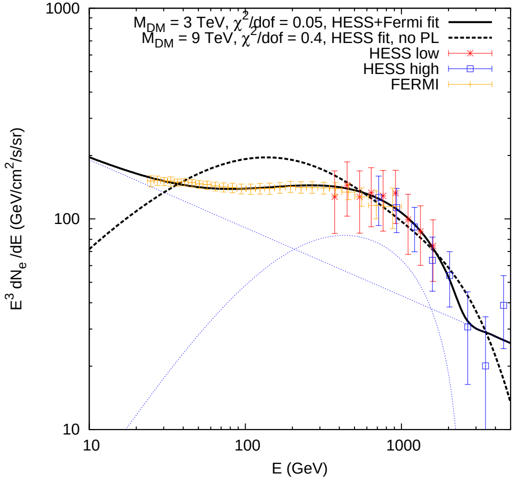


$$J_{TOA}(E) = \frac{E^2 - m^2}{(E+|Z|e\phi)^2 - m^2} J_{IS}(E + |Z|e\phi)$$

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;
$\chi^2/dof = 0.05$

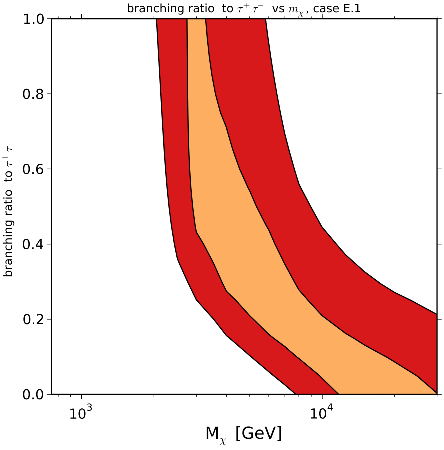
HESS:
$\Gamma = 3.33$; M $= 9$ TeV;
$(Br_{\tau^+\tau^-};\ Br_{b\bar{b}};\ Br_{\mu^+\mu^-})$ $=$ (0.035;0.965;0.0); BF $=$ 95,000; $\chi^2/dof = 0.4$



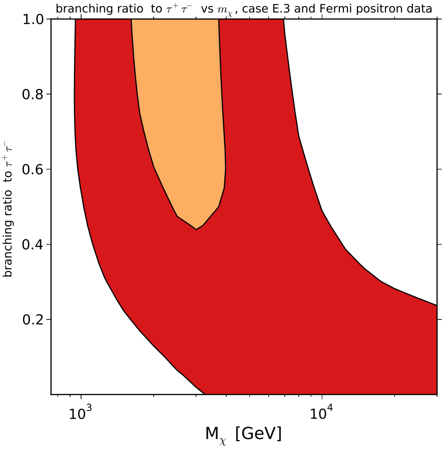
CREs and cosmic ray positrons. The summary table of best-fits.

datasets	mass[TeV]	$(Br_{\tau^+\tau^-}; Br_{b\bar{b}}; Br_{\mu^+\mu^-})$	$10^{-3} \times B_{NFW}$	Γ	A	ϕ [MV]	χ^2 /d.o.f.
PAMELA+*Fermi*+HESS	3	(0.9997;0;0)	12.8	3.72	1943	986	0.3
PAMELA+*Fermi*+HESS	3	(0;0;0.9996)	1.38	3.33	595	600	1.3
Fermi+HESS (+*Fermi* e^+)	3	(0.9997;0;0)	8.7	3.32	400	-	0.05
HESS	9	(0.035;0.965;0)	94.9	-	-	-	0.4

Branching ratio constraints to electrons and positrons

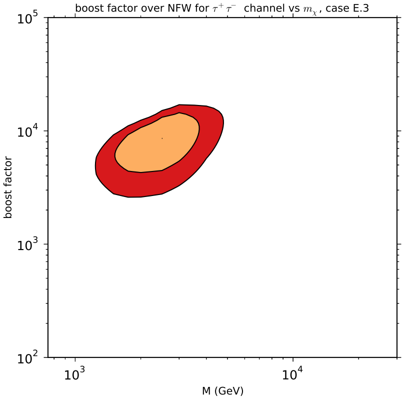


total electron plus positrons and positrons, PAMELA + Fermi + HESS, minimized over values of solar modulation ϕ, allowed regions of parameter space m_χ-$Br_{\tau^+\tau^-}$

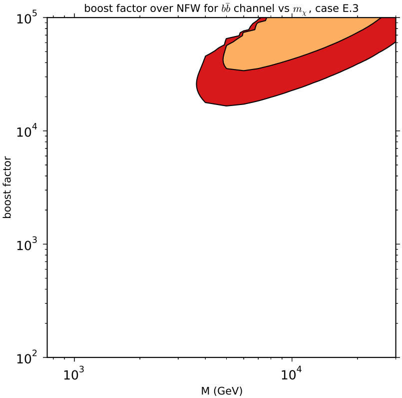


total electron plus positrons and positrons, HESS + Fermi, allowed regions of parameter space m_χ-$Br_{\tau^+\tau^-}$

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

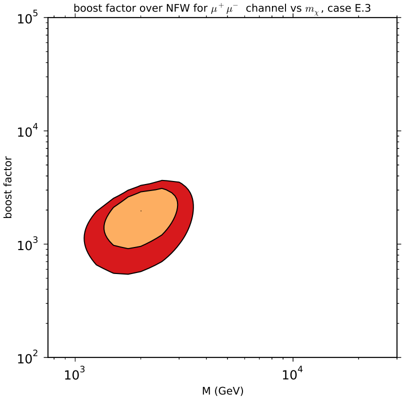


total electron plus positrons and positrons, HESS + Fermi, allowed regions of parameter space m_χ-BF, $\tau^+\tau^-$ channel

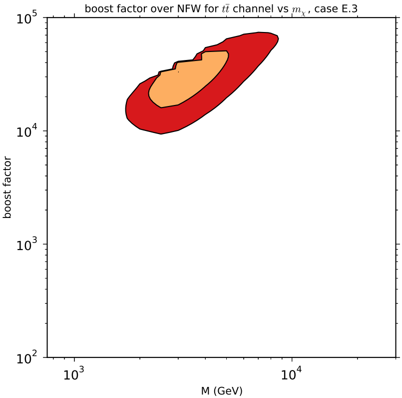


total electron plus positrons and positrons, HESS + Fermi, allowed regions of parameter space m_χ-BF, $b\bar{b}$ channel

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



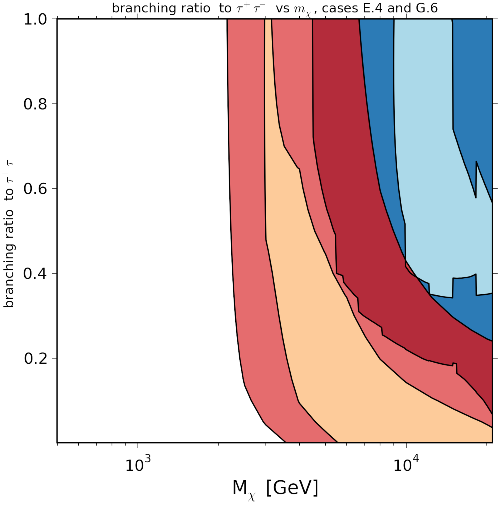
total electron plus positrons and positrons, HESS + Fermi, allowed regions of parameter space m_χ-BF, $\mu^+\mu^-$ channel



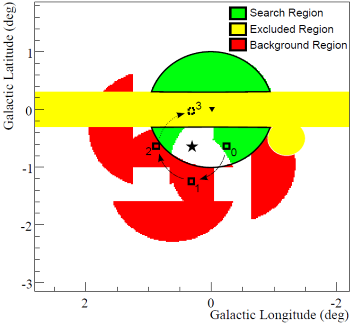
total electron plus positrons and positrons, HESS + Fermi, allowed regions of parameter space m_χ-BF, $t\bar{t}$ channel

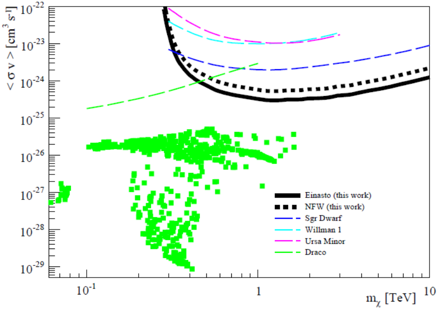
The overlapping regions between gamma rays and cosmic ray electron

HESS data, fit by electrons annihilating to dark matter at fixed branching ratio $Br_{\tau^+\tau^-}$ and $Br_{b\bar{b}} = 1 - Br_{\tau^+\tau^-}$



a boost factor of about 140 at 10 TeV

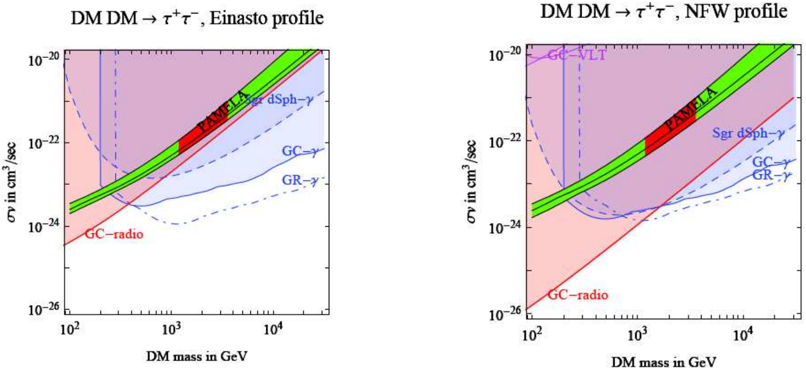




A. Abramowski, Phys.Rev.Lett., 106:161301, 2011

HESS galactic ridge

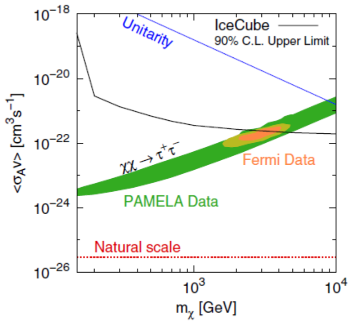
a boost factor of about 700 at 10 TeV



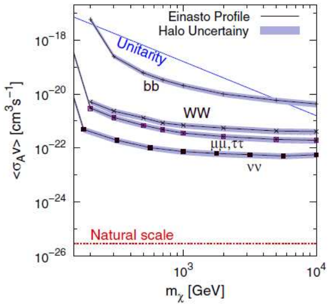
G. Bertone, JCAP 0903:009 (2009)

Galactic center as seen by IceCube

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



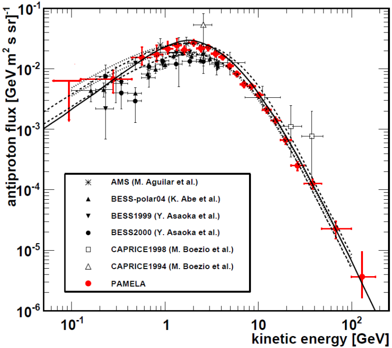
IceCube, R. Abbasi et al., PRD 84, 022004 (2011)



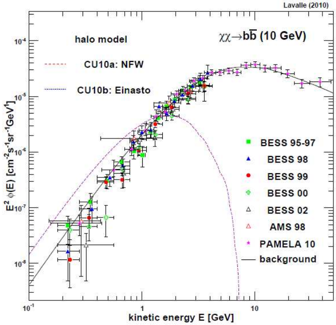
Unitarity bounds: $\langle \sigma v \rangle_{max} \approx 10^{-22} cm^3 s^{-1} \left(\frac{m_\chi}{1TeV}\right)^2$
unitarity bounds:

Antiproton constraints on TeV DM

antiproton flux: PAMELA: 0.09-128 GeV



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

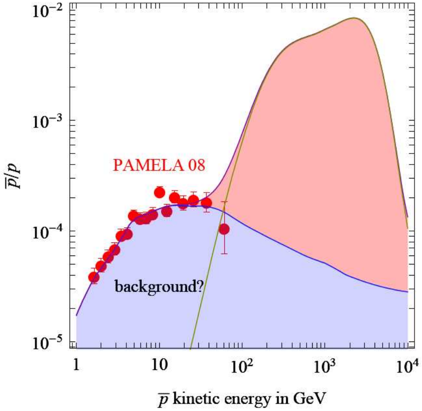


J.Lavalle, arXiv:1007.5253

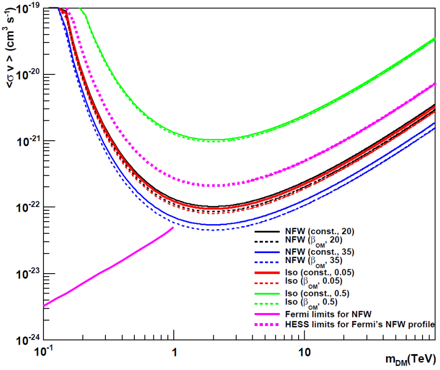
AMS-02?

Constraints from positron and antiproton data
Dwarf galaxies from HESS

higher energies or other channels?



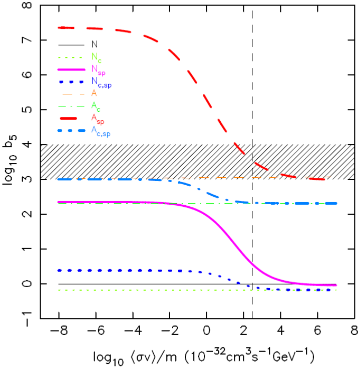
10 TeV, W^+W^- Cirelli et al., Nucl.Phys.B813:1-21,2009



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	$\rho(R_\odot)$	$\log_{10} \overline{J}_3$ $(\overline{J}_5)$ $\tau = 0$	$\tau = 10$	$\tau = 10$
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)



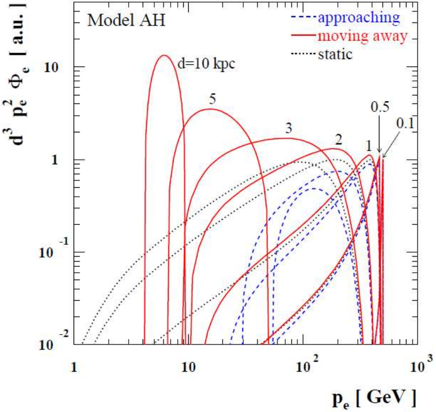
$$\gamma_{sp} = \frac{9 - 2\gamma}{4 - \gamma}$$

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

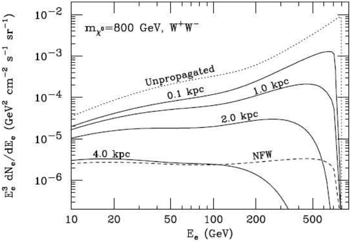
P. Gondolo et al., Phys.Rev.Lett., 83, 1719 (1999)

Electrons propagating from a DM clump

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

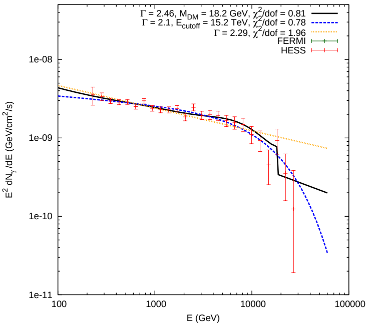


M. Regis et al. ArXiv:0907.5093



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

Spectral feature: cutoff

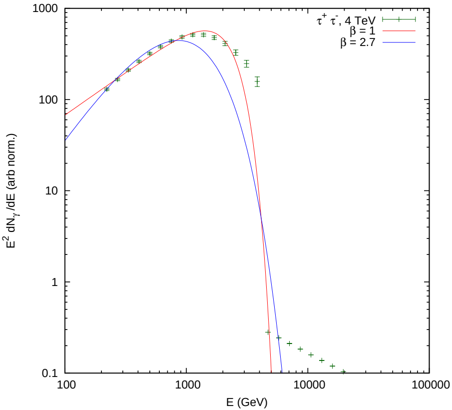


$$\phi(E) = Ae^{-(E/E_{cut})}$$

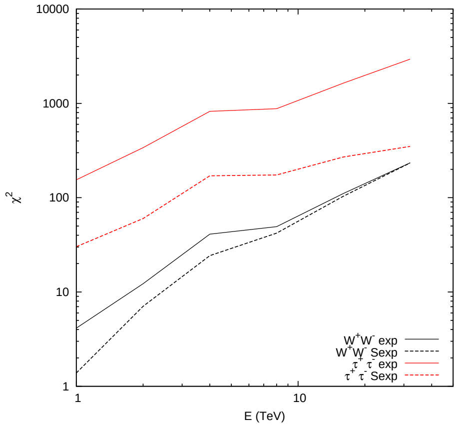
vs

$$\phi(E) = Ae^{-(E/E_{cut})^{\beta}}?$$

Exponential vs Super Exponential cutoff



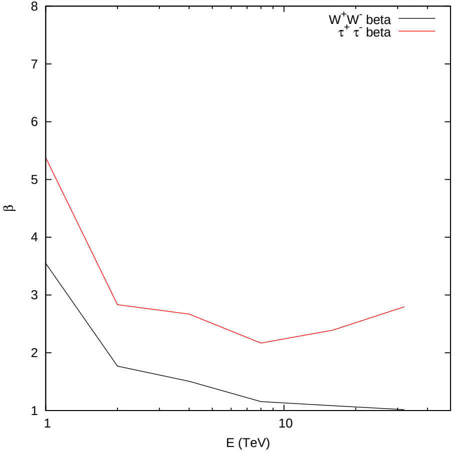
The simulated data for HESS fit by an exponential cutoff and a super exponential cutoff. The flux from $M_\chi = 4$ TeV annihilating to $\tau^+\tau^-$ and the background $\simeq E^{-2.7}$.



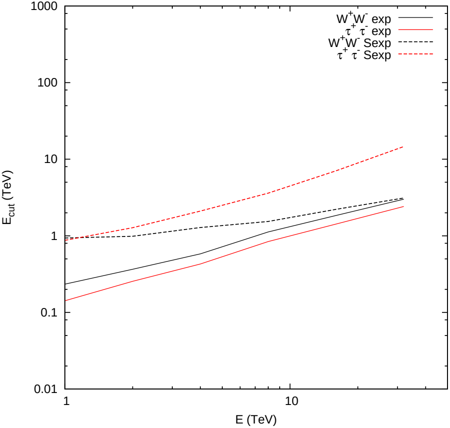
χ^2 values for $\tau^+\tau^-$ and W^+W^- channels, $N_{bins} = 28$

AB, J. Silk, in preparation

E_{cut} and β of best fits as functions of M_χ



β for best fits for $\tau^+\tau^-$ and W^+W^- channels



E_{cut} for best fits for $\tau^+\tau^-$ and W^+W^- channels

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
- there is a marginal 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_χ and found overlap between 99.999% C.L. regions
- it might be possible to rule out the dark matter explanation of some observed spectra based on best fits with the "super" exponential index β