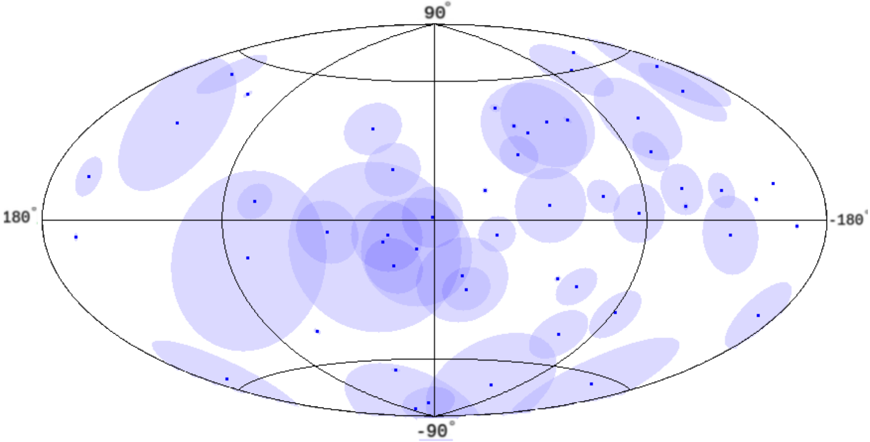
IceCube HESE neutrinos from Dark matter in Dwarf Galaxies & Galactic Ridge

Reetanjali Moharana[1]
with
Danny Marfatia[2], **Soebur Razzaque**[1]

[1] *University of Johannesburg*
&
[2] *University of Hawaii*

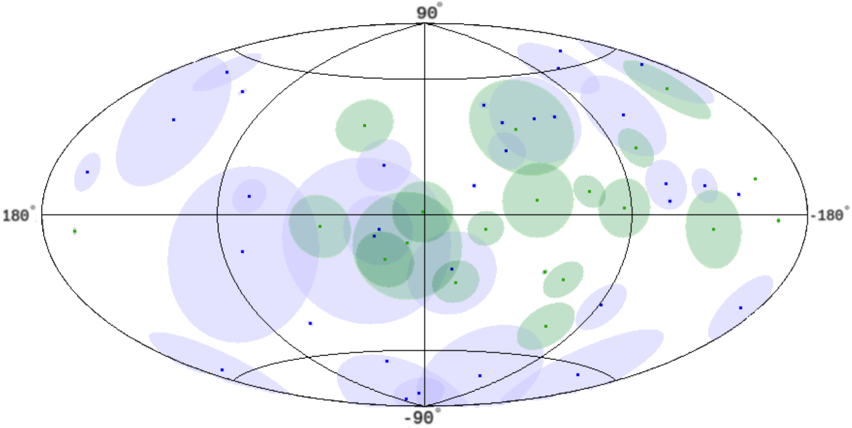
5 May 2016 ICTP, Italy

- 53 Neutrino events including the 2.6 PeV



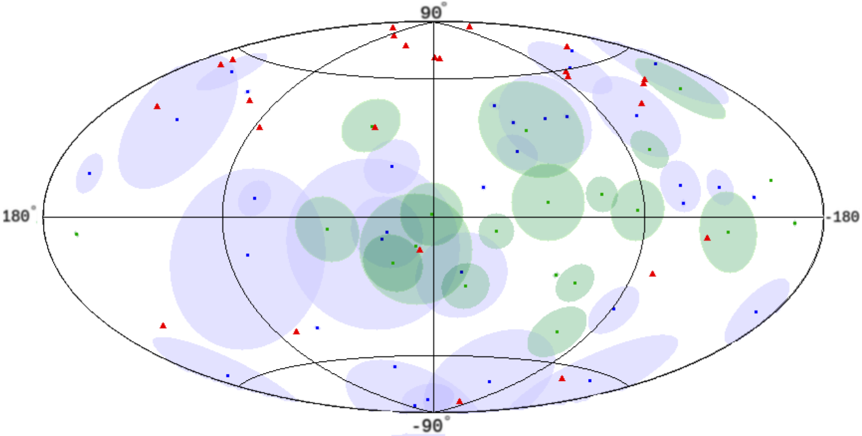
Galactic Coordinate

- 53 Neutrino events including the 2.6 PeV
- 20 above $E_\nu > 100\text{TeV}$



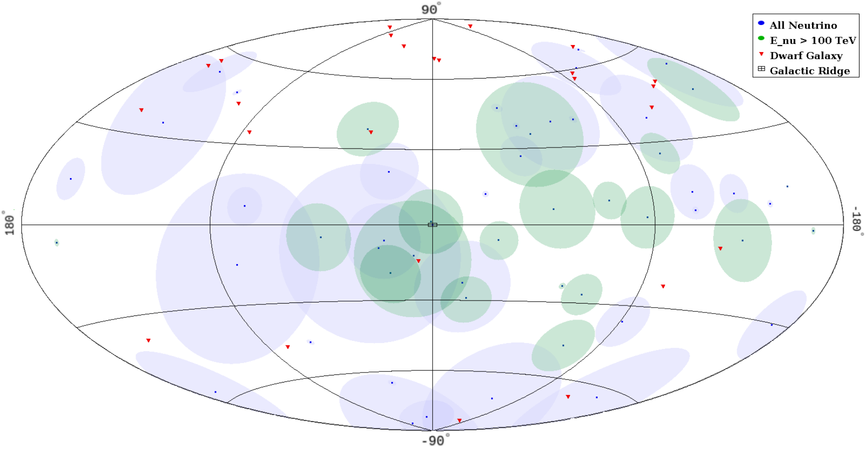
Galactic Coordinate

- 53 Neutrino events including the 2.6 PeV
- 20 above $E_\nu > 100$TeV
- 25 Dwarf spheroid galaxies



Galactic Coordinate

- 53 Neutrino events including the 2.6 PeV
- 20 above $E_\nu > 100$TeV
- 25 Dwarf spheroid galaxies
- Galactic ridge, $0 < |b| < 0.3$, $0 < l < 0.8$ and $359.2 < l < 360$



Galactic Coordinate

Statistical method for analyzing correlation

A. Virmani et al., Astropart. Phys., 2002, Moharana, SR 2015

$$\hat{x} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)^T,$$

where $\phi = RA$ and $\theta = \pi/2 - Dec$.
Angle between neutrino and source vectors $(\hat{x}_{\rm neutrino}, \hat{x}_{\rm source})$

$$\gamma = \cos^{-1}(\hat{x}_{\rm neutrino} \cdot \hat{x}_{\rm source}),$$

For each neutrino direction $\hat{x}_i$ and source direction $\hat{x}_j$ pair as

$$\delta\chi_i^2 = {\rm min}_j(\gamma_{ij}^2/\delta\gamma_i^2),$$

which is minimized for all j.
The distribution with observed data giving a number of "hits" or $N_{\rm hits}$ with $\delta\chi^2 \leq 1$ therefore forms a basis to claim correlation.
Statistical significance of correlation in real data or p-value can be calculated, using frequentists' approach, by counting the number of times we get $N_{\rm hits}$ or more with $\delta\chi^2 \leq 1$ in simulated events divided by the number of realizations.

Statistical method for analyzing correlation

A. Virmani et al., Astropart. Phys., 2002, Moharana, SR 2015

$$\hat{x} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)^T,$$

where $\phi = RA$ and $\theta = \pi/2 - Dec$.
Angle between neutrino and source vectors $(\hat{x}_{\rm neutrino}, \hat{x}_{\rm source})$

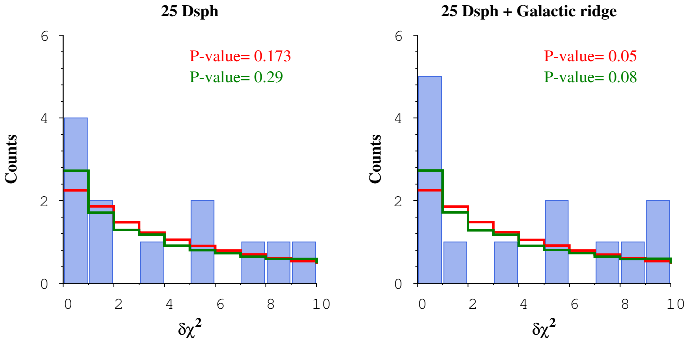
$$\gamma = \cos^{-1}(\hat{x}_{\rm neutrino} \cdot \hat{x}_{\rm source}),$$

For each neutrino direction $\hat{x}_i$ and source direction $\hat{x}_j$ pair as

$$\delta\chi_i^2 = \min_j(\gamma_{ij}^2/\delta\gamma_i^2),$$

which is minimized for all j.
The distribution with observed data giving a number of "hits" or $N_{\rm hits}$ with $\delta\chi^2 \leq 1$ therefore forms a basis to claim correlation.
Statistical significance of correlation in real data or p-value can be calculated, using frequentists' approach, by counting the number of times we get $N_{\rm hits}$ or more with $\delta\chi^2 \leq 1$ in simulated events divided by the number of realizations.

Results



Segue 1, Sagittarius, Hercules and Canis Major. Galactic Ridge

A. Geringer-Sameth et. al., 2014, & HESS Collaboration 2007

Dwarf Galaxy	$E_\nu[TeV]$	$\log_{10} J_a(\theta_{max})$ [Gev^2 cm^{-5}]	$\log_{10}$ (J_d) [Gev cm^{-2}]
Sagittarius	117^{15}_{-15}	19.1	-
Hercules	200^{+27}_{-27}	$16.86^{+0.74}_{-0.68}$	$16.66^{+0.42}_{-0.40}$
Segue 1	210^{+29}_{-26}	$19.36^{+0.32}_{-0.35}$	$17.99^{+0.20}_{-0.31}$
Canis Major	$101.3^{+13.3}_{-11.6}$	19.77	-

M. Cirelli et. al., 2012

Source	$E_\nu[TeV]$	$\delta\Omega$	$\bar{J}_a$	$\bar{J}_d$	$\rho_\odot$	$r_\odot$
Galactic Ridge	117^{15}_{-15}, 1041^{132}_{-144}	0.29×10^{-3}	1904	19.6	0.3 GeV/cm^3	8.33 kpc

Differential neutrino flux from DM annihilation in Dsph,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\langle \sigma_A v \rangle}{2} \frac{1}{4\pi m_\chi^2} J_a \frac{dN_\nu}{dE_\nu}$$

$< \sigma_A v >$, averaged product of annihilation cross section and DM velocity.

J_a is the DM abundance profile for annihilation along the *l.o.s.*

Differential neutrino flux from DM annihilation in Galactic Ridge,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{r_\odot}{4\pi} \frac{\langle \sigma_A v \rangle}{2} \frac{\rho_\odot^2}{m_\chi^2} \bar{J}_a \Delta\Omega \frac{dN_\nu}{dE_\nu}$$

Approximated maximum neutrino flux from DM annihilation,

$$\frac{dN_\nu}{dE_\nu} = \delta(E_\nu - m_\chi)$$

Differential neutrino flux from DM decay in Dsph and Galactic Ridge,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma}{4\pi m_\chi} J_d \frac{dN_\nu}{dE_\nu}$$

$$\frac{d\phi_\nu}{dE_\nu} = \frac{r_\odot}{4\pi} \Gamma \frac{\rho_\odot}{m_\chi} \bar{J}_a \Delta\Omega \frac{dN_\nu}{dE_\nu}$$

Γ, decay width of DM.

$\frac{dN_\nu}{dE_\nu} = \delta(E_\nu - m_\chi/2)$; LA. Anchordoqui et.al., PRD Rapid 2015.

Differential neutrino flux from DM annihilation in Dsph,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\langle \sigma_A v \rangle}{2} \frac{1}{4\pi m_\chi^2} J_a \frac{dN_\nu}{dE_\nu}$$

$< \sigma_A v >$, averaged product of annihilation cross section and DM velocity.
J_a is the DM abundance profile for annihilation along the $l.o.s$.
Differential neutrino flux from DM annihilation in Galactic Ridge,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{r_\odot}{4\pi} \frac{\langle \sigma_A v \rangle}{2} \frac{\rho_\odot^2}{m_\chi^2} \bar{J}_a \Delta\Omega \frac{dN_\nu}{dE_\nu}$$

Approximated maximum neutrino flux from DM annihilation,

$$\frac{dN_\nu}{dE_\nu} = \delta(E_\nu - m_\chi)$$

Differential neutrino flux from DM decay in Dsph and Galactic Ridge,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma}{4\pi m_\chi} J_d \frac{dN_\nu}{dE_\nu}$$

$$\frac{d\phi_\nu}{dE_\nu} = \frac{r_\odot}{4\pi} \Gamma \frac{\rho_\odot}{m_\chi} \bar{J}_a \Delta\Omega \frac{dN_\nu}{dE_\nu}$$

Γ, decay width of DM.

$\frac{dN_\nu}{dE_\nu} = \delta(E_\nu - m_\chi/2)$; LA. Anchordoqui et.al., PRD Rapid 2015.

Differential neutrino flux from DM annihilation in Dsph,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\langle \sigma_A v \rangle}{2} \frac{1}{4\pi m_\chi^2} J_a \frac{dN_\nu}{dE_\nu}$$

$< \sigma_A v >$, averaged product of annihilation cross section and DM velocity.
J_a is the DM abundance profile for annihilation along the $l.o.s$.
Differential neutrino flux from DM annihilation in Galactic Ridge,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{r_\odot}{4\pi} \frac{\langle \sigma_A v \rangle}{2} \frac{\rho_\odot^2}{m_\chi^2} \bar{J}_a \Delta\Omega \frac{dN_\nu}{dE_\nu}$$

Approximated maximum neutrino flux from DM annihilation,

$$\frac{dN_\nu}{dE_\nu} = \delta(E_\nu - m_\chi)$$

Differential neutrino flux from DM decay in Dsph and Galactic Ridge,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma}{4\pi m_\chi} J_d \frac{dN_\nu}{dE_\nu}$$

$$\frac{d\phi_\nu}{dE_\nu} = \frac{r_\odot}{4\pi} \Gamma \frac{\rho_\odot}{m_\chi} \bar{J}_a \Delta\Omega \frac{dN_\nu}{dE_\nu}$$

Γ, decay width of DM.

$\frac{dN_\nu}{dE_\nu} = \delta(E_\nu - m_\chi/2)$; LA. Anchordoqui et.al., PRD Rapid 2015.

Differential neutrino flux from DM annihilation in Dsph,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\langle \sigma_A v \rangle}{2} \frac{1}{4\pi m_\chi^2} J_a \frac{dN_\nu}{dE_\nu}$$

$< \sigma_A v >$, averaged product of annihilation cross section and DM velocity.
J_a is the DM abundance profile for annihilation along the $l.o.s$.
Differential neutrino flux from DM annihilation in Galactic Ridge,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{r_\odot}{4\pi} \frac{\langle \sigma_A v \rangle}{2} \frac{\rho_\odot^2}{m_\chi^2} \bar{J}_a \Delta\Omega \frac{dN_\nu}{dE_\nu}$$

Approximated maximum neutrino flux from DM annihilation,

$$\frac{dN_\nu}{dE_\nu} = \delta(E_\nu - m_\chi)$$

Differential neutrino flux from DM decay in Dsph and Galactic Ridge,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma}{4\pi m_\chi} J_d \frac{dN_\nu}{dE_\nu}$$

$$\frac{d\phi_\nu}{dE_\nu} = \frac{r_\odot}{4\pi} \Gamma \frac{\rho_\odot}{m_\chi} \bar{J}_a \Delta\Omega \frac{dN_\nu}{dE_\nu}$$

Γ, decay width of DM.

$\frac{dN_\nu}{dE_\nu} = \delta(E_\nu - m_\chi/2)$; LA. Anchordoqui et.al., PRD Rapid 2015.

Differential neutrino flux from DM annihilation in Dsph,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\langle\sigma_A v\rangle}{2}\,\frac{1}{4\pi m_\chi^2}\,J_a\,\frac{dN_\nu}{dE_\nu}$$

$< \sigma_A v >$, averaged product of annihilation cross section and DM velocity.

J_a is the DM abundance profile for annihilation along the $l.o.s.$

Differential neutrino flux from DM annihilation in Galactic Ridge,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{r_\odot}{4\pi}\frac{\langle\sigma_A v\rangle}{2}\,\frac{\rho_\odot^2}{m_\chi^2}\,\bar{J}_a\Delta\Omega\,\frac{dN_\nu}{dE_\nu}$$

Approximated maximum neutrino flux from DM annihilation,

$$\frac{dN_\nu}{dE_\nu} = \delta(E_\nu - m_\chi)$$

Differential neutrino flux from DM decay in Dsph and Galactic Ridge,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma}{4\pi m_\chi}\,J_d\,\frac{dN_\nu}{dE_\nu}$$

$$\frac{d\phi_\nu}{dE_\nu} = \frac{r_\odot}{4\pi}\,\Gamma\,\frac{\rho_\odot}{m_\chi}\,\bar{J}_a\Delta\Omega\,\frac{dN_\nu}{dE_\nu}$$

Γ, decay width of DM.

$\frac{dN_\nu}{dE_\nu} = \delta(E_\nu - m_\chi/2)$; LA. Anchordoqui et.al., PRD Rapid 2015.

Differential neutrino flux from DM annihilation in Dsph,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\langle \sigma_A v \rangle}{2} \frac{1}{4\pi m_\chi^2} J_a \frac{dN_\nu}{dE_\nu}$$

$< \sigma_A v >$, averaged product of annihilation cross section and DM velocity. J_a is the DM abundance profile for annihilation along the $l.o.s.$
Differential neutrino flux from DM annihilation in Galactic Ridge,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{r_\odot}{4\pi} \frac{\langle \sigma_A v \rangle}{2} \frac{\rho_\odot^2}{m_\chi^2} \bar{J}_a \Delta\Omega \frac{dN_\nu}{dE_\nu}$$

Approximated maximum neutrino flux from DM annihilation,

$$\frac{dN_\nu}{dE_\nu} = \delta(E_\nu - m_\chi)$$

Differential neutrino flux from DM decay in Dsph and Galactic Ridge,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma}{4\pi m_\chi} J_d \frac{dN_\nu}{dE_\nu}$$

$$\frac{d\phi_\nu}{dE_\nu} = \frac{r_\odot}{4\pi} \Gamma \frac{\rho_\odot}{m_\chi} \bar{J}_a \Delta\Omega \frac{dN_\nu}{dE_\nu}$$

Γ, decay width of DM.

$\frac{dN_\nu}{dE_\nu} = \delta(E_\nu - m_\chi/2)$; LA. Anchordoqui et.al., PRD Rapid 2015.

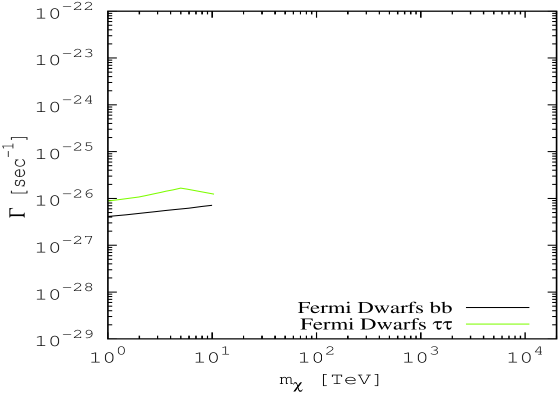
Neutrino events

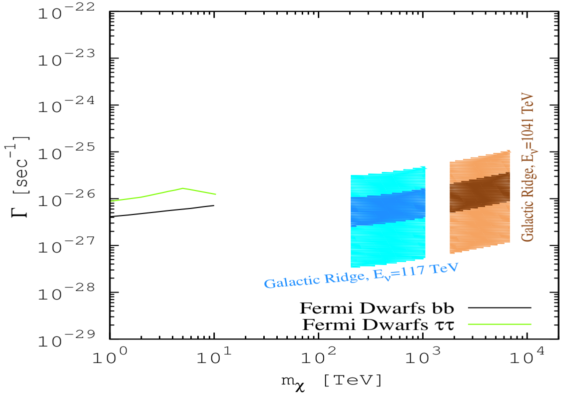
Neutrino events by IceCube,

$$N_\nu = T \int_{E_\nu^{min}}^{E_\nu^{max}} \frac{d\phi_\nu}{dE_\nu} A_{eff}(E_\nu)\, dE_\nu$$

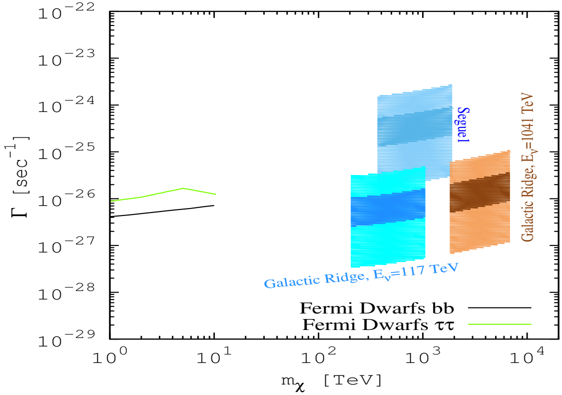
T, 1137 days.

Limits on Decay width

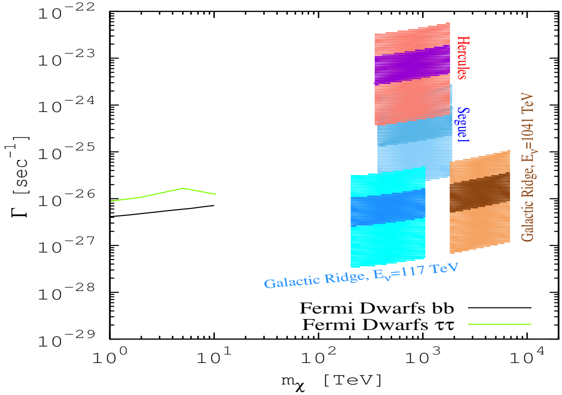




Galactic Ridge, Eν=1041 TeV
Galactic Ridge, Eν=117 TeV
Fermi Dwarfs bb
Fermi Dwarfs ττ
Γ [sec⁻¹]
mχ [TeV]

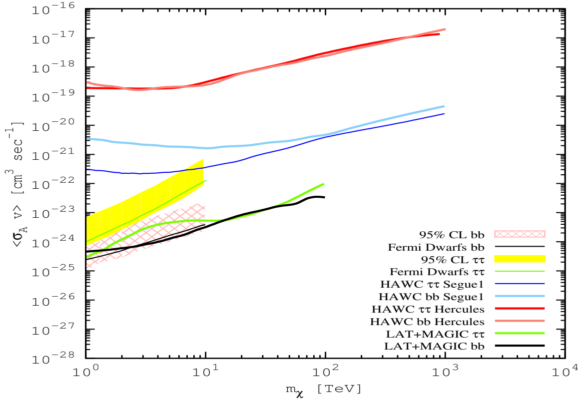


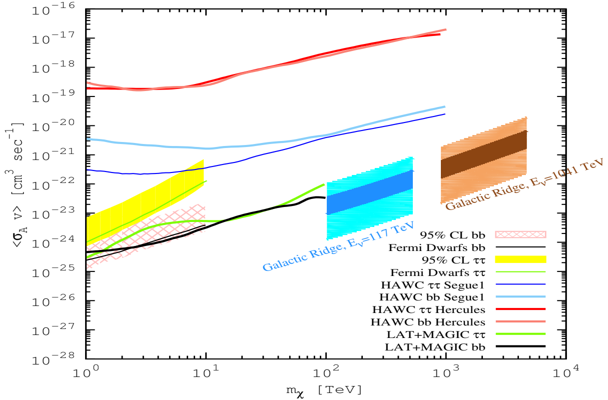
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
Γ [sec^{-1}]
10^0
10^1
10^2
10^3
10^4
m_χ [TeV]
Segue1
Galactic Ridge, E_ν=1041 TeV
Galactic Ridge, E_ν=117 TeV
Fermi Dwarfs bb
Fermi Dwarfs ττ



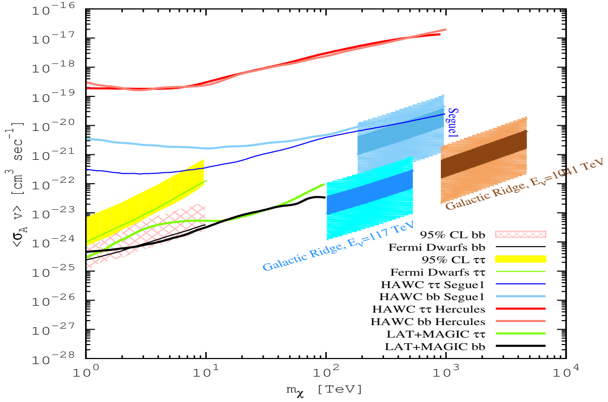
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
Γ [sec^{-1}]
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
m_χ [TeV]
Hercules
Segue1
Galactic Ridge, E_ν=1041 TeV
Galactic Ridge, E_ν=117 TeV
Fermi Dwarfs bb
Fermi Dwarfs $\tau\tau$

Limits on annihilation cross section

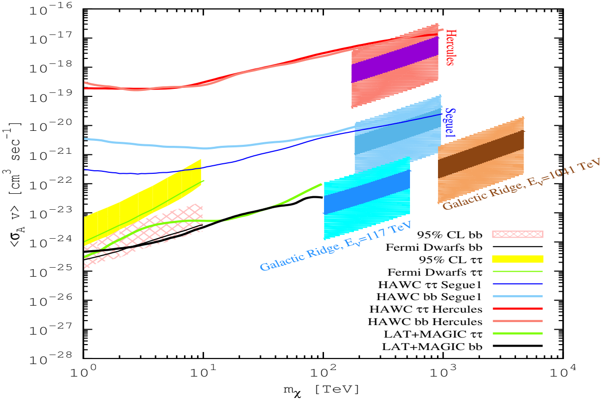




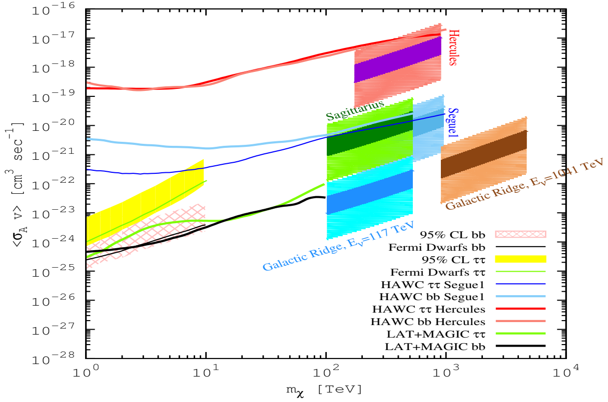
$\langle\sigma_A v\rangle$ [cm^3 sec^{-1}]
m_χ [TeV]
Galactic Ridge, E_ν=117 TeV
Galactic Ridge, E_ν=1041 TeV
95% CL bb
Fermi Dwarfs bb
95% CL ττ
Fermi Dwarfs ττ
HAWC ττ Segue1
HAWC bb Segue1
HAWC ττ Hercules
HAWC bb Hercules
LAT+MAGIC ττ
LAT+MAGIC bb



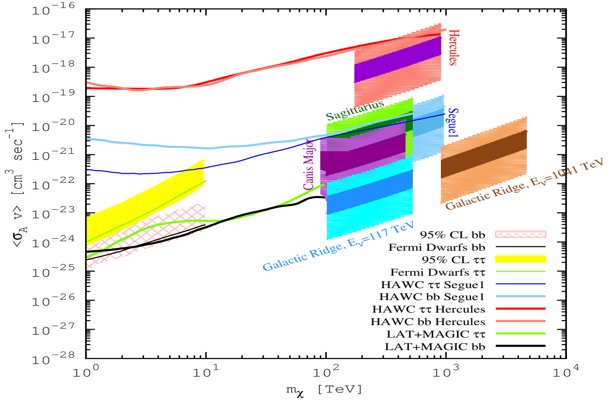
$\langle\sigma_A v\rangle$ [cm^3 sec^{-1}]
m_χ [TeV]
Segue1
Galactic Ridge, E_ν=117 TeV
Galactic Ridge, E_ν=1041 TeV
95% CL bb
Fermi Dwarfs bb
95% CL ττ
Fermi Dwarfs ττ
HAWC ττ Segue1
HAWC bb Segue1
HAWC ττ Hercules
HAWC bb Hercules
LAT+MAGIC ττ
LAT+MAGIC bb



10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$<\sigma_A v>$ [cm^3 sec^{-1}]
10^0
10^1
10^2
10^3
10^4
m_χ [TeV]
Hercules
Segue1
Galactic Ridge, E_ν=1041 TeV
Galactic Ridge, E_ν=117 TeV
95% CL bb
Fermi Dwarfs bb
95% CL ττ
Fermi Dwarfs ττ
HAWC ττ Segue1
HAWC bb Segue1
HAWC ττ Hercules
HAWC bb Hercules
LAT+MAGIC ττ
LAT+MAGIC bb



Hercules
Sagittarius
Segue1
Galactic Ridge, E_ν=1041 TeV
Galactic Ridge, E_ν=117 TeV
95% CL bb
Fermi Dwarfs bb
95% CL ττ
Fermi Dwarfs ττ
HAWC ττ Segue1
HAWC bb Segue1
HAWC ττ Hercules
HAWC bb Hercules
LAT+MAGIC ττ
LAT+MAGIC bb
$\langle\sigma_A v\rangle$ [cm^3 sec^{-1}]
m_χ [TeV]



Hercules
Sagittarius
Segue1
Canis Major
Galactic Ridge, Eν=1041 TeV
Galactic Ridge, Eν=117 TeV
95% CL bb
Fermi Dwarfs bb
95% CL ττ
Fermi Dwarfs ττ
HAWC ττ Segue1
HAWC bb Segue1
HAWC ττ Hercules
HAWC bb Hercules
LAT+MAGIC ττ
LAT+MAGIC bb
<σA v> [cm3 sec−1]
mχ [TeV]

Summary

- The 25 dwarf galaxy correlated with the IceCube neutrino events above energy 100 TeV with nearly 90% CL while for the dwarf galaxy and Galactic Ridge, it has increased to 95 % CL.
- 4 Dwarf galaxies and the Galactic ridge correlated with IceCube neutrino events, assuming they have come from dark matter decay and annihilation we have calculated the limits on the average decay width and velocity cross section respectively.
- Our result is consistence with public constraints.

Summary

- The 25 dwarf galaxy correlated with the IceCube neutrino events above energy 100 TeV with nearly 90% CL while for the dwarf galaxy and Galactic Ridge, it has increased to 95 % CL.
- 4 Dwarf galaxies and the Galactic ridge correlated with IceCube neutrino events, assuming they have come from dark matter decay and annihilation we have calculated the limits on the average decay width and velocity cross section respectively.
- Our result is consistence with public constraints.

Summary

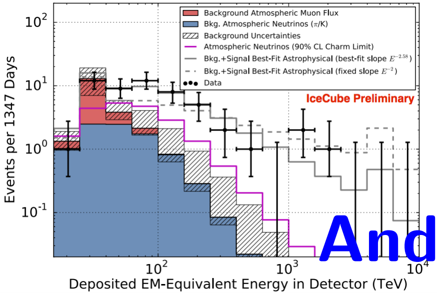
- The 25 dwarf galaxy correlated with the IceCube neutrino events above energy 100 TeV with nearly 90% CL while for the dwarf galaxy and Galactic Ridge, it has increased to 95 % CL.
- 4 Dwarf galaxies and the Galactic ridge correlated with IceCube neutrino events, assuming they have come from dark matter decay and annihilation we have calculated the limits on the average decay width and velocity cross section respectively.
- Our result is consistence with public constraints.

Thank you

IceCube results

ICRC proceeding, 2015, M.G. Aartsen et. al., 2014, Aya Ishihara,TeVPA 2015

- Total 54 events, adding 6 tracks, and 11 cascades.
- Background expectation nearly 21.6. Rejecting only background with 6.5σ.



And

ICRC proceeding, 2015

- Deposited energy 2.6 ± 0.3 PeV.
- Direction: 11.48° dec, 110.34° RA.