Bounds on neutrino-DM interaction from blazar TXS 0506+056 neutrino outburst

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IceCube has detected ν's from blazars, AGN's, and TDE's.

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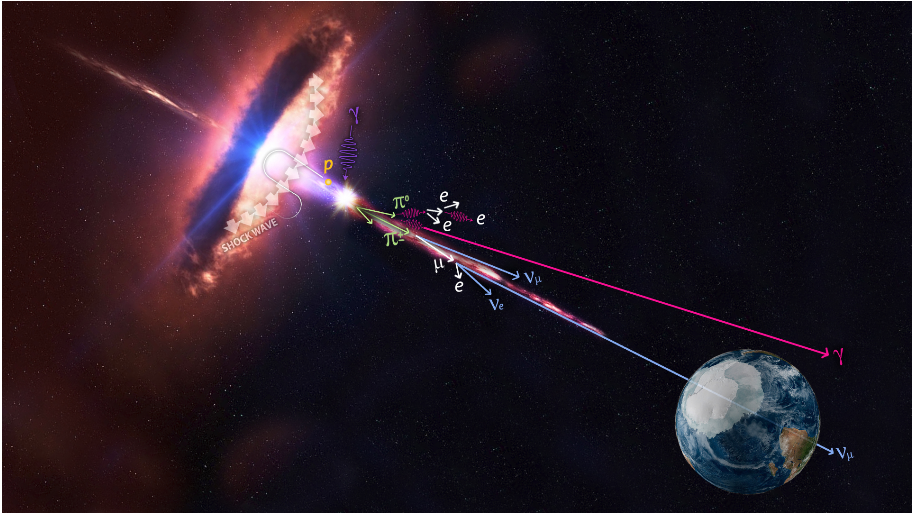
- The jets are composed of **hadrons and leptons**, which interact and generate high-energy emissions.
- Through hadronic processes, blazars can produce **neutrinos** in proton-proton (pp) or proton-photon (pγ) collisions.

Blazars as neutrino sources



[Credit: IceCube/NASA]

IceCube-170922A event

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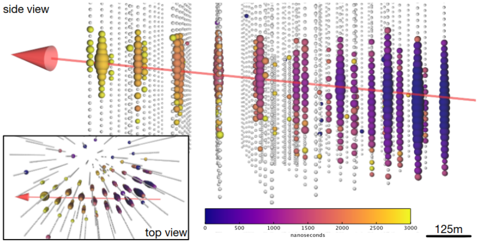

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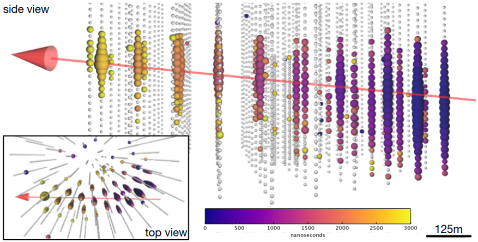

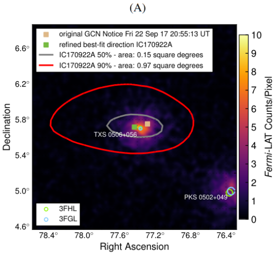

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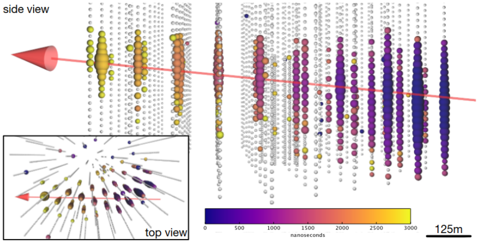
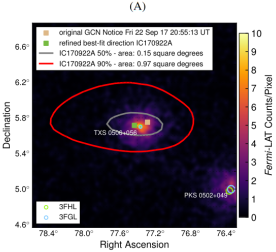
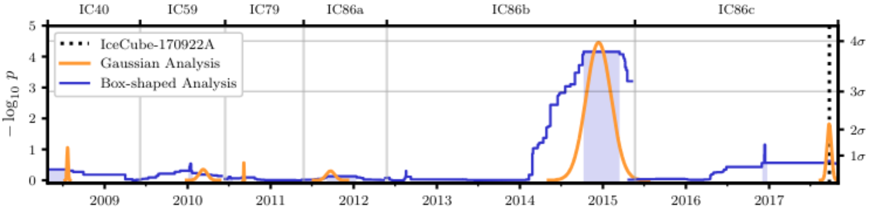




Constrains on $\sigma_{\nu DM}$ from IC170922A: [J.Cline et al., arXiv:2209.02713, F.Ferrer et al., arXiv:2209.06339]

ν emission prior to IC-170922A event

In a posterior analysis, IceCube found an excess of 13 ± 5 neutrinos form the direction of TXS 0506+056 between September 2014 and March 2015. [IceCube et al., Science 361 (2018) 6398]

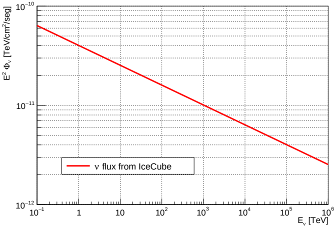


2014-2015 neutrino outburst

Neutrino flux estimated by IceCube as

$$\Phi_{\nu_\mu+\bar{\nu}_\mu}(E_\nu) = \Phi_{ref}\left(\frac{E_\nu}{100\ TeV}\right)^{-\gamma},$$

with $\gamma = 2.2$ and $\Phi_{ref} = 1.6 \times 10^{-15}$ TeV^{-1} cm^{-2} s^{-1}.



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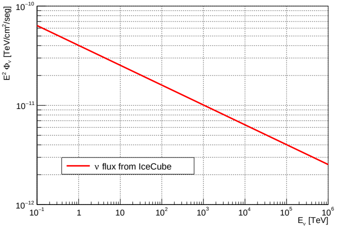
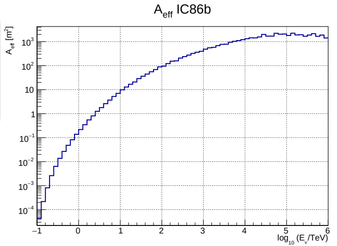
$$N_{pred} = t_{obs}\int dE_\nu \Phi_\nu(E_\nu)A_{eff}(E_\nu)$$

$t_{obs} = 158$ days $\Rightarrow N_{pred} \approx 15$ events.





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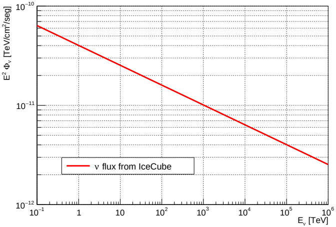

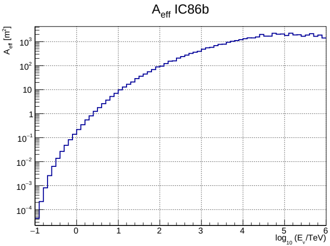

DM spike around TXS 0506+056

Adiabatic growing of a black hole makes the DM density profile steeper in the inner halo [P.Gondolo & J.Silk, PRL 83 (1999) 1719-1722]

$$\rho \propto r^{-\gamma} \Rightarrow \rho'(r) \propto r^{-\gamma_{sp}}, \quad \gamma_{sp} = \frac{9-2\gamma}{4-\gamma}$$

where we consider $\gamma = 1 \Rightarrow \gamma_{sp} = 7/3$.

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We can normalize $\rho'(r)$ via [P.Ullio et al., PRD 64 (2001) 043504]

$$\int_{r_{min}}^{r_{max}} 4\pi\rho'(r)r^2 dr \approx M_{BH}$$

with $r_{min} = 4R_S$ and $r_{max} = 10^5 R_S$, the radius of influence of the black hole. $(R_S = 2GM)$

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Outside of the spike radius, the density of dark matter halo continues to be determined by the pre-existing NFW density profile [J.F.Navarro & C.S.Frenk & S.D.M.White, The Astrophysical Journal 462 (1996) 563]

$$\rho_{DM}(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma} \left(1 + \frac{r}{r_0}\right)^{(\gamma-3)} \quad if \quad r \geq R_{sp}$$

DM spike around TXS 0506+056

If DM annihilation occurs, the spike profile becomes more cored

$$\rho'(r) \propto r^{\gamma_{sp}} \Rightarrow \rho_{DM} = \frac{\rho'(r)\rho_{max}}{\rho'(r) + \rho_{max}}, \quad \rho_{max} = \frac{m_{DM}}{\langle \sigma v \rangle \, t_{BH}}$$

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Model	γ_{sp}	$\langle \sigma v \rangle$ $[cm^3/s]$
BM1	7/3	0
BM2	7/3	10^{-28}
BM3	7/3	3×10^{-26}
BM1'	3/2	0
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Table: $t_{obs} \sim 10^9$ years.

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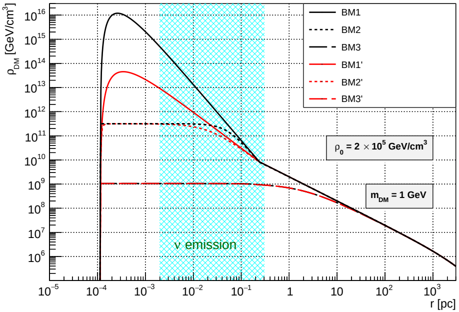

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Model	BM1	BM2	BM3	BM1'	BM2'	BM3'
γ_{sp}	7/3	7/3	7/3	3/2	3/2	3/2
$\langle\sigma v\rangle$ $[10^{-26}\ cm^3/s]$	0	0.01	3	0	0.01	3
Σ_{DM} $[10^{28}\ GeV/cm^2]$	16.07	10.14	3.78	8.70	8.09	3.78

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The cosmological and Milky-Way galactic contributions to Σ_{DM} are negligible compared to that of the DM spike.

Flux attenuation: Cascade equation

The neutrino flux attenuation due the scatter with DM along their journey to the detector can be described by [C. A. Argüelles et al., PRL 119, 201801 (2017)]

$$\frac{d\Phi}{d\tau} = -\sigma_{\nu DM}\Phi + \int_{E_\nu}^{\infty} dE'_\nu \frac{d\sigma_{\nu DM}}{dE_\nu}(E'_\nu \to E_\nu)\Phi(E'_\nu)$$

where $\tau = \Sigma(r)/m_{DM}$ is the accumulated column density.

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A first estimate: Neglecting the second term

$$\frac{\phi_{obs}}{\phi_{em}} \sim e^{-\sigma_{\nu DM}\Sigma_{DM}/m_{DM}} \Rightarrow \sigma \lesssim \mathcal{O}(1) m_{DM}/\Sigma_{DM}$$

to get at least $\sim 60\%$ suppression of the emitted ν flux.

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$$\frac{\phi_{obs}}{\phi_{em}} \sim e^{-\sigma_{\nu DM}\Sigma_{DM}/m_{DM}} \Rightarrow \sigma \lesssim \mathcal{O}(1) m_{DM}/\Sigma_{DM}$$

$$\Rightarrow \sigma \lesssim 6.2 \times 10^{-30} cm^2 \frac{m_{DM}}{GeV} \quad (BM1)$$

Assumption: $\sigma \propto E_\nu^n$

We consider a cross section $\sigma_{\nu DM}$ with a power-law dependence with neutrino energy

$$\sigma_{\nu DM}(E_\nu) = \sigma_0 \left(\frac{E_\nu}{E_0}\right)^n ,$$

with the energy reference $E_0 = 100$ TeV, and $n = 1, 0, -1, -2$.

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For the differential cross section, we can consider a scattering isotropic in the center of mass frame and approximate

$$\frac{d\sigma}{dE_\nu}(E'_\nu \to E_\nu) \approx \frac{\sigma(E'_\nu)}{E'_\nu} = \frac{\sigma_0}{E_0}\left(\frac{E'_\nu}{E_0}\right)^{n-1} . \quad (1)$$

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with the energy reference $E_0 = 100$ TeV, and $n = 1, 0, -1, -2$.
We demand that $N_{obs} \gtrsim 6.55$ events. (90% C.L. lower limit on the number 13 ± 5) , with

$$N_{obs} = t_{obs} \int dE_\nu \Phi_{obs}(E_\nu) A_{eff}(E_\nu)$$

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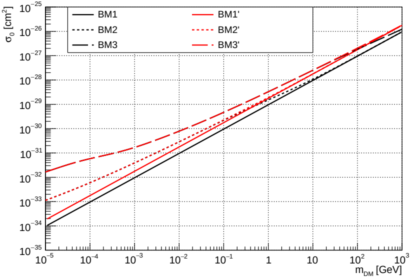
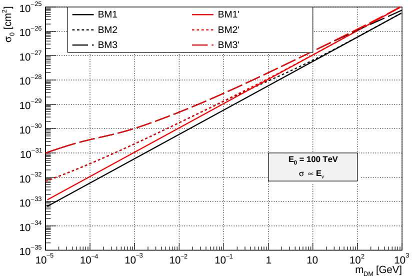
Limits on ν-DM scattering



(a) $\sigma = const.\ \sigma_0 < 1.54 \frac{m_{DM}}{\Sigma_{DM}}$.



(b) $\sigma \propto E_\nu.\ \sigma_0 < 9.32 \frac{m_{DM}}{\Sigma_{DM}}$.

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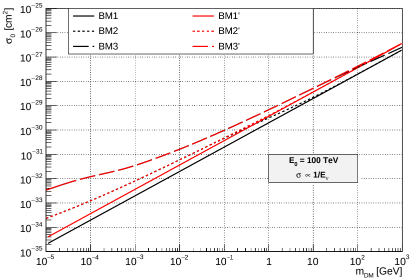
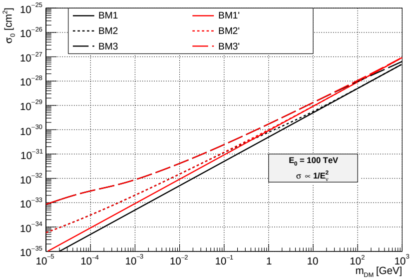


(a) $\sigma \propto \frac{1}{E_\nu}$. $\sigma_0 < 0.32 \frac{m_{DM}}{\Sigma_{DM}}$.



(b) $\sigma \propto \frac{1}{E_\nu^2}$. $\sigma_0 < 0.08 \frac{m_{DM}}{\Sigma_{DM}}$.

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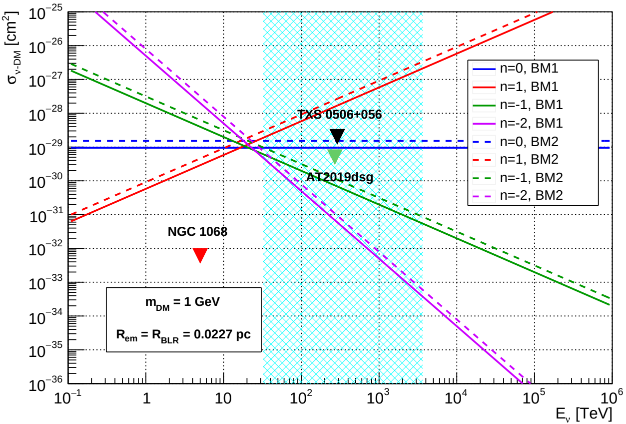
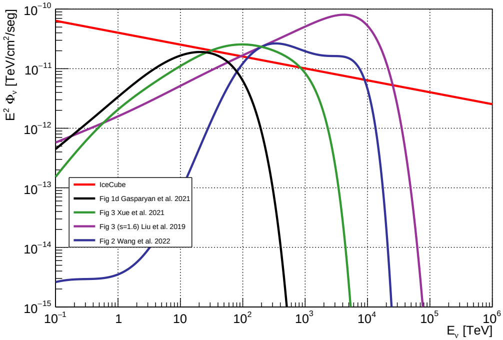
Bounds obtained on DM-neutrino cross section, with $\sigma = \sigma_0(E_\nu/E_0)^n$, where $E_0 = 100$ TeV.

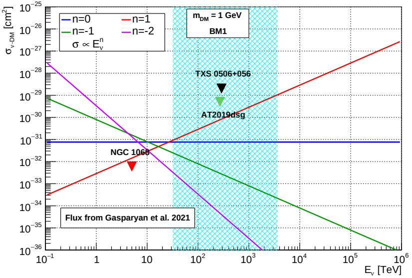


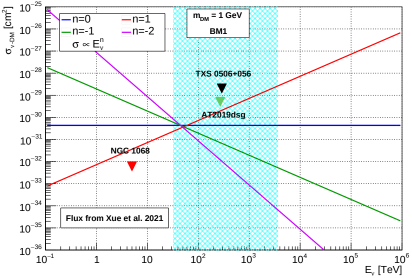
Alternative neutrino fluxes

Flux Φ_ν reference	Color	N_{pred}	R_{em} [pc]	Σ_{DM} [10^{28} GeV/cm^2]
IceCube	Red	15	0.0227	16.07
Fig 1d of Gasparyan et al 2021	Black	6.8	4.86×10^{-3}	84.6
Fig 3 of Xue et al 2021	Green	11.5	1.94×10^{-3}	261
Fig 3 of Liu et al 2019 $s = 1.6$	Purple	15.7	9.72×10^{-3}	37.85
Fig 2 of Wang et al 2022 caso 2	Blue	6.83	0.0324	12.08



Bounds on other fluxes





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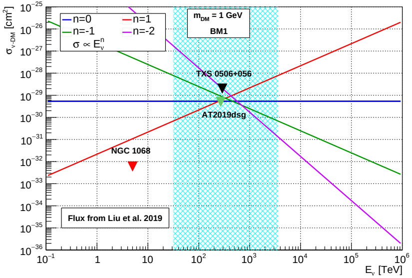

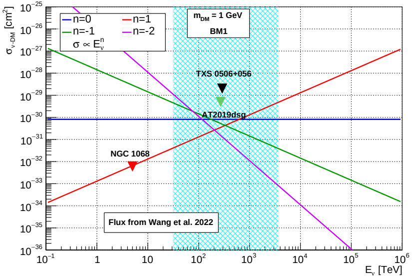

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Summary

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Main results

- We put competitive model-independent bounds for $\sigma_{\nu DM} \propto E_\nu$ and $\sigma_{\nu DM} \sim const$.
- We extend the neutrino energy range of these bounds to $0.1 - 10^6$ TeV.
- We introduce new bounds for $\sigma_{\nu DM} \propto E_\nu^{-1}$ and $\sigma_{\nu DM} \propto E_\nu^{-2}$ (motivated by models with ligth scalar mediators)
- For one particular ν-flux model, we set the strongest bounds.

Summary

We use the 2014-2015 neutrino outburst form TXS 0506+056 to constrain $\sigma_{\nu DM}$, testing different energy dependence and neutrino fluxes.

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Uncertainties on: DM-spike details, DM self-annihilation, location of the neutrino production region and initial ν-fluxes.

Summary

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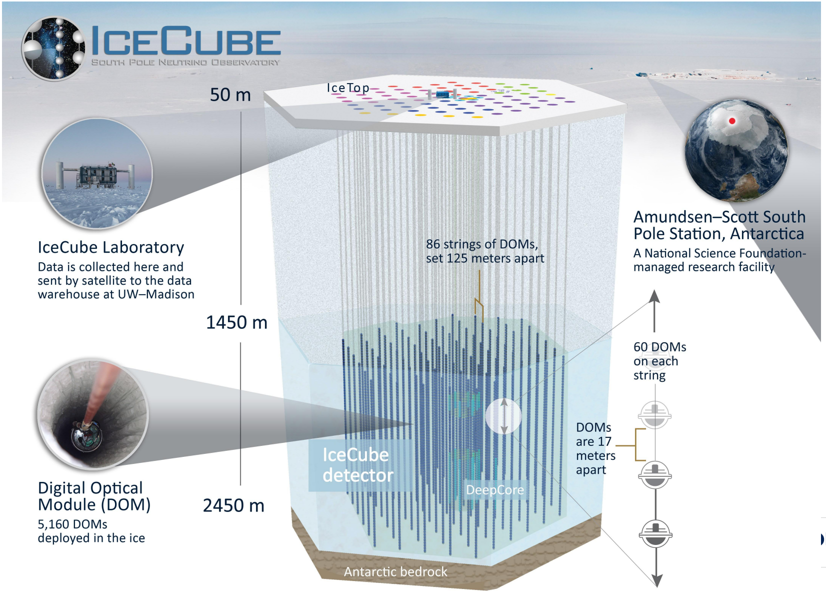
- For one particular ν-flux model, we set the strongest bounds.

Baikal-GVD and KM3NeT are starting to get new HEν's events alongside IceCube.
It's an exciting time for neutrino astronomy!

Thank you for your attention!

Backup slides

IceCube



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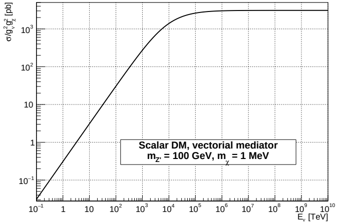
Scalar DM with vectorial mediator

If we consider DM-ν scattering involving the exchange of a vector boson Z' between a complex scalar DM χ and neutrinos: In the limit $m_\chi \ll m_{Z'}$ and $m_\chi \ll E_\nu$, the cross section is

$$\sigma_{\nu\chi} \approx \frac{g_\nu^2 g_\chi^2}{4\pi m_{Z'}^2}\left[1 - \frac{m_{Z'}^2}{s}\ln\left(1 + \frac{s}{m_{Z'}^2}\right)\right]$$

where $s \approx 2m_\chi E_\nu$.
This
cross section has the limiting behaviours

$$\sigma_{\nu\chi} \approx \frac{g_\nu^2 g_\chi^2}{4\pi m_{Z'}^2}\begin{cases} 1, & E_\nu \gg m_{Z'}^2/m_\chi \\ \frac{E_\nu m_\chi}{m_{Z'}^2}, & E_\nu \ll m_{Z'}^2/m_\chi \end{cases}$$



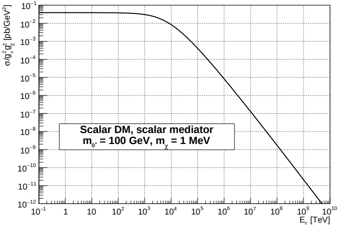
Scalar DM with scalar mediator

For the case with scalar DM χ and a scalar mediator ϕ the cross section in the limit $m_\chi \ll m_{Z'}$ and $m_\chi \ll E_\nu$ is

$$\sigma_{\nu\chi} \approx \frac{g_\nu^2 g_\chi^2}{16\pi} \left[\frac{1}{s^2} \ln\left(1 + \frac{s}{m_\phi^2}\right) - \frac{1}{s(s+m_\phi^2)} \right]$$

This
cross section has the limiting behaviors

$$\sigma_{\nu\chi} \approx \frac{g_\nu^2 g_\chi^2}{16\pi m_\phi^4} \begin{cases} \frac{m_\phi^4}{4 m_\chi^2 E_\nu^2}, & E_\nu \gg m_\phi^2/m_\chi \\ \frac{1}{2}, & E_\nu \ll m_\phi^2/m_\chi \end{cases}$$



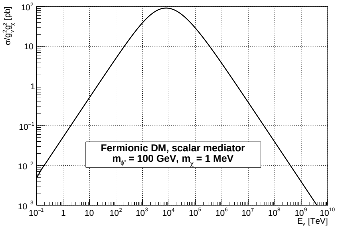
Fermionic DM with scalar mediator

For fermionic DM and scalar mediator ϕ the cross section in the limit $m_\chi \ll m_{Z'}$ and $m_\chi \ll E_\nu$ is

$$\sigma_{\nu\chi} \approx \frac{g_\nu^2 g_\chi^2}{16\pi}\left[\frac{2}{s} - \frac{1}{s+m_\phi^2} - \frac{2m_\phi^2}{s^2}\ln\left(1+\frac{s}{m_\phi^2}\right)\right]$$

This
cross section has the limiting behaviors

$$\sigma_{\nu\chi} \approx \frac{g_\nu^2 g_\chi^2}{16\pi}\begin{cases} \frac{1}{2m_\chi E_\nu}, & E_\nu \gg m_\phi^2/m_\chi \\ \frac{2m_\chi E_\nu}{m_\phi^4}, & E_\nu \ll m_\phi^2/m_\chi \end{cases}$$



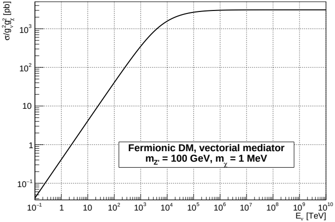
Fermionic DM with vectorial mediator

If we considered fermionic DM and a vector mediator Z' the cross section in the limit $m_\chi \ll m_{Z'}$ and $m_\chi \ll E_\nu$ is

$$\sigma_{\nu\chi} \approx \frac{g_\nu^2 g_\chi^2}{4\pi m_{Z'}^2}\left[\frac{2m_{Z'}^4 + 3m_{Z'}^2 s + 2s^2}{2s(s+m_{Z'}^2)} - \frac{m_{Z'}^2(s+m_{Z'}^2)}{s^2}\ln\left(1+\frac{s}{m_{Z'}^2}\right)\right]$$

This
cross section has the limiting behaviors

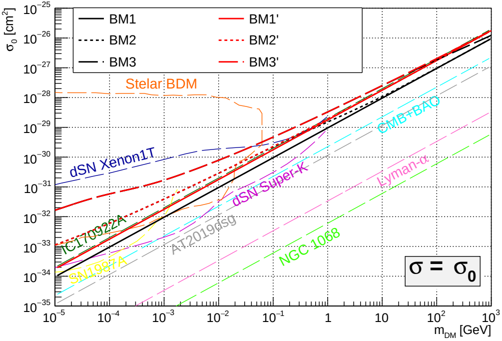
$$\sigma_{\nu\chi} \approx \frac{g_\nu^2 g_\chi^2}{4\pi m_{Z'}^2}\begin{cases} 1, & E_\nu \gg m_{Z'}^2/m_\chi \\ \frac{2E_\nu m_\chi}{m_{Z'}^2}, & E_\nu \ll m_{Z'}^2/m_\chi \end{cases}$$



Comparison with other limits

Bounds on $\sigma_{\nu DM}$ from:

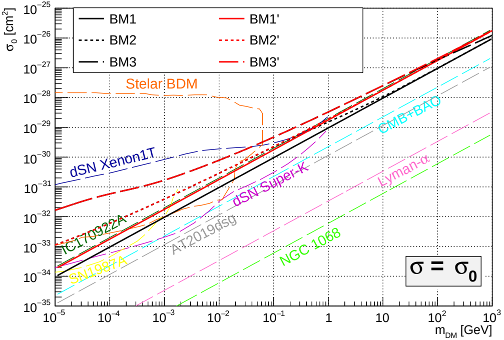
- suppression in primordial density fluctuations affecting CMB and matter power spectra,



Comparison with other limits

Bounds on $\sigma_{\nu DM}$ from:

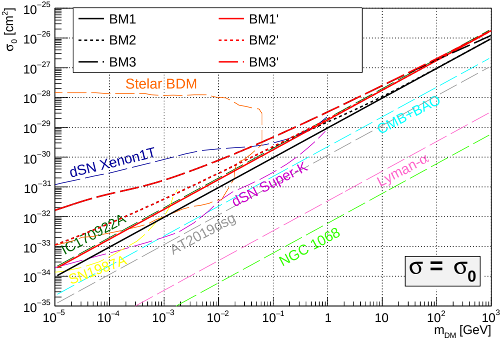
- suppression in primordial density fluctuations affecting CMB and matter power spectra,
- boosting DM by neutrinos from stars, diffuse supernovae, SN1987a,



Comparison with other limits

Bounds on $\sigma_{\nu DM}$ from:

- suppression in primordial density fluctuations affecting CMB and matter power spectra,
- boosting DM by neutrinos from stars, diffuse supernovae, SN1987a,
- attenuation of neutrino flux from supernovae, galactic centre, AGN's, blazars and TDE's.

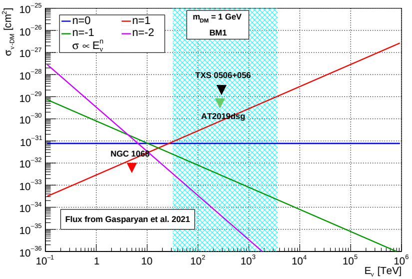


Highlighting text

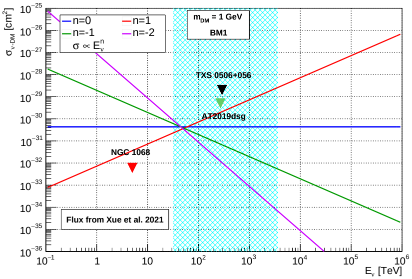
n	1	0	-1	-2
μ	9.3237	1.5369	0.3184	0.0801

Table: Summary of values of μ for the different values of n considered.

Bounds on other fluxes

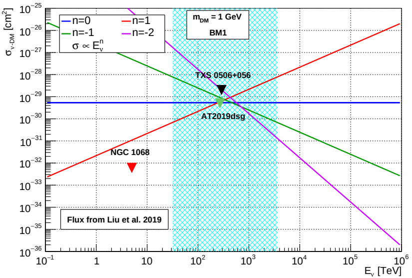


(a)

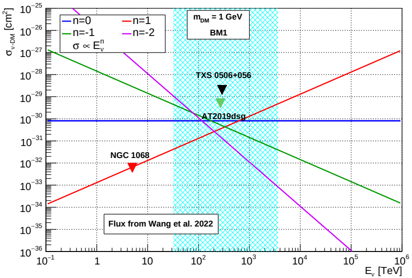


(b)

Bounds on other fluxes



(a)



(b)

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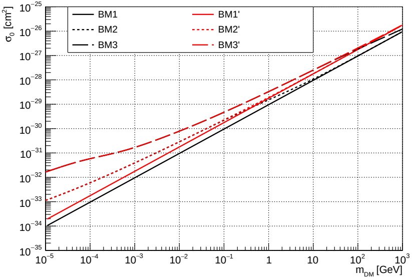
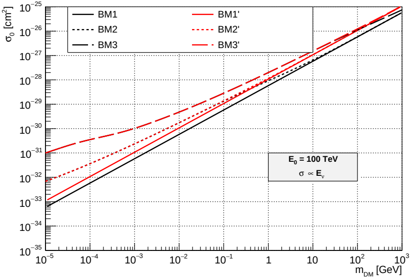
Results

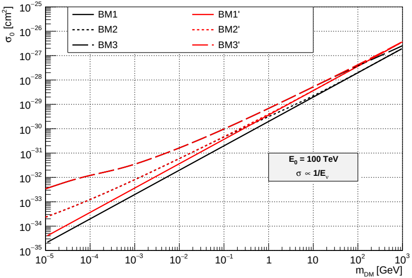


(a) $\sigma = const.\ \sigma_0 < 1.54 m_{DM}/\Sigma_{DM}$.

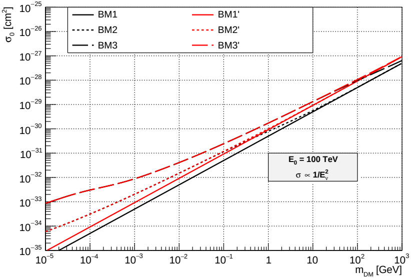


(b) $\sigma \propto E_\nu.\ \sigma_0 < 9.32 m_{DM}/\Sigma_{DM}$.

Results



(a) $\sigma \propto 1/E_\nu$. $\sigma_0 < 0.32 m_{DM}/\Sigma_{DM}$.



(b) $\sigma \propto 1/E_\nu^2$. $\sigma_0 < 0.08 m_{DM}/\Sigma_{DM}$.

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