New constraints on the dark matter-neutrino/photon scatterings

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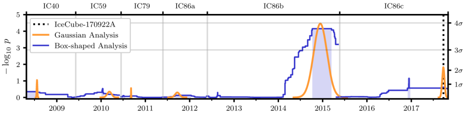
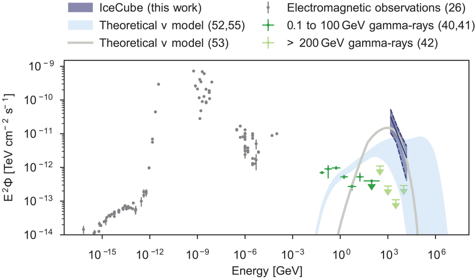
Extragalactic ν sources: TXS 0506+056 and NGC 1068





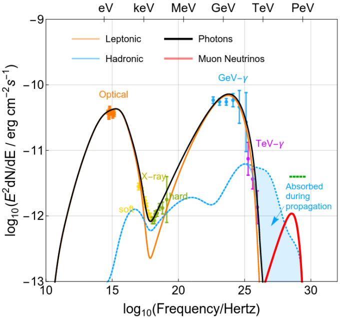
IceCube, 18' , 22'

- IC-170922A: A ~ 290 TeV muon neutrino, identified with the blazar TXS 0506+056 in flaring state at origin direction.
- Subsequent analysis by IceCube with 9.5 years of data finds ~ 10 events above the atmospheric neutrino background, at 3.5 σ.
- IceCube observed ~ 80 neutrinos from the galaxy NGC 1068, at 4.2 σ.
- Electromagnetic emission from both sources was observed, but covering different wavelength ranges.

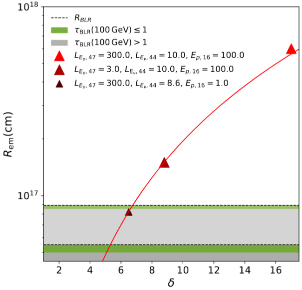
Neutrino and photon emission from TXS 0506+056

- Leptohadronic models are statistically compatible with the observed fluxes
- The emitting region is likely to be located near, or beyond the Broad Line Region (BLR), $R_{em} \approx R_{BLR} \approx 0.023$ pc
- An emitting region closer to the black hole is disfavoured, since stronger internal absorption of ~ 100 GeV gamma-rays by the BLR would have been expected.

Gao, Fedynitch, Winter, Pohl, 19'

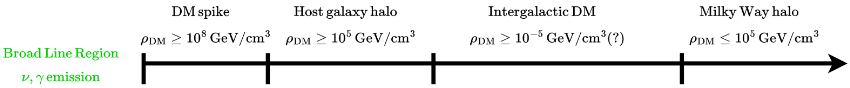


Padovani, Oikonomou, Petropoulou, Giommi, Resconi, 19'



Flux attenuation from TXS 0506+056 to the Earth

- Gamma-rays and neutrinos are subject to attenuation during propagation to the Earth due to SM processes.
- They may also be attenuated due to scatterings with dark matter particles on their path to the Earth.



- The dark matter density in the vicinity of TXS 0506+056 is expected to be significantly larger than in the intergalactic medium and the Milky Way halo.

The dark matter profile around TXS 0506+056

The dark matter in the vicinity of a black hole that grows adiabatically forms a dense spike with profile:

$$\rho_{\rm sp}(r) = \rho_R \, g_\gamma(r) \left(\frac{R_{sp}}{r}\right)^{\gamma_{\rm sp}}$$

(**Peebles, 72' Quinlan, Hernquist, Sigurdsson, 95' Gondolo, Silk, 99'**)

- $R_{\rm sp} \longrightarrow$ Size of the spike
- $g_\gamma(r) \longrightarrow$ Captured particles by the BH
- $\gamma_{\rm sp} = \frac{9-2\gamma}{4-\gamma} \longrightarrow$ Cuspiness of the spike ($\gamma = 1$ for an NFW)
- $M_{\rm BH} \approx 3 \times 10^8 M_\odot$, and $\rho_R \simeq 10^4$ GeV/cm^3 is a normalization used to match the outer profile, and determined by the uncertainty in $M_{\rm BH}$ (**Gorchtein, Profumo, Ubaldi, 10'**).

Only valid for $r \leq R_{\rm sp}$, and in scenarios where the dark matter does not self-annihilate (e.g asymmetric dark matter or axions).

The dark matter profile around TXS 0506+056

When the dark matter particles annihilate, the maximal density in the spike is saturated to $\rho_{\rm sat} = m_{\rm DM}/(\langle\sigma v\rangle t_{\rm BH})$

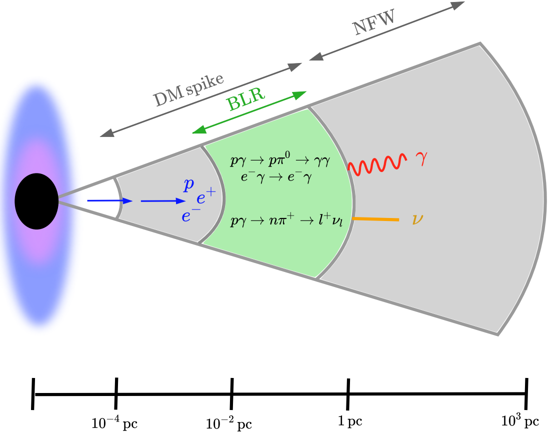
- $t_{\rm BH} \simeq 10^9$yr $\rightarrow$ Time elapsed since the black hole formation.
- $\langle\sigma v\rangle \rightarrow$ Velocity averaged dark matter annihilation cross section.
- Beyond $R_{\rm sp}$, we assume that the dark matter profile follows an NFW.

$$\rho(r) = \begin{cases} 0 & r \leq 4R_S \\ \frac{\rho_{\rm sp}(r)\rho_{\rm sat}}{\rho_{\rm sp}(r)+\rho_{\rm sat}} & 4R_S \leq r \leq R_{sp} \\ \rho_0\left(\frac{r}{r_0}\right)^{-\gamma}\left(1+\frac{r}{r_0}\right)^{-2} & r \geq R_{sp}. \end{cases}$$

- With relativistic effects and/or rotating BH's, the spike vanishes at $2R_S$ and the density of DM particles is enhanced near the core (**Sadeghian, Ferrer, Will, 13'** **Ferrer, Medeiros da Rosa, Will, 17'**).

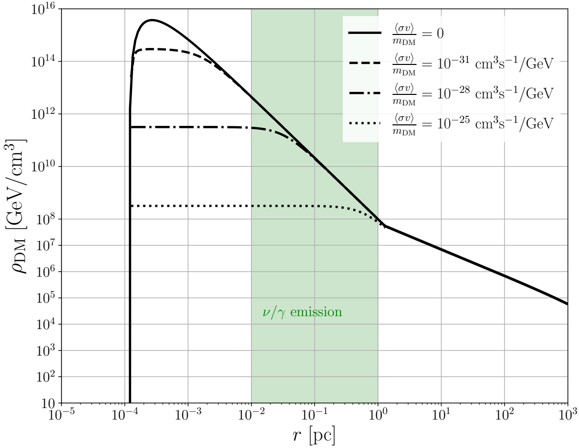
However, these effects do not change the profile in the region of the jet where neutrinos and gamma-rays are produced.

The dark matter profile around TXS 0506+056



✓ High-energy neutrinos and gamma-rays are likely to be produced within the dark matter spike of TXS 0506+056.

The dark matter profile around TXS 0506+056



✓ High-energy neutrinos and gamma-rays are likely to be produced within the dark matter spike of TXS 0506+056.

A criteria for the flux atttenuation

The attenuation of the neutrino and photon fluxes produced at the distance $R_{\rm em}$ from the BH can be described by

$$\frac{\Phi_i^{\rm obs}}{\Phi_i^{\rm em}} = e^{-\mu_i}$$

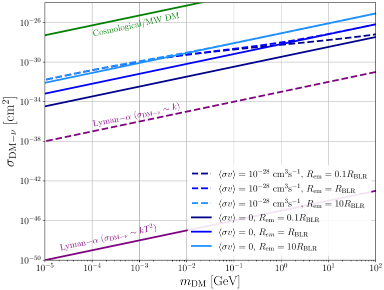
- $\Phi_i^{\rm obs}$,$\Phi_i^{\rm em}$ $\rightarrow$ observed and emitted fluxes of the particle i ($i = \nu$ or γ).
- $\mu_i\big|_{\rm DM} = \sigma_{\rm DM-i}\Sigma_{\rm DM}$.
- $\sigma_{\rm DM-i}$ is the scattering cross section of dark matter with the particle i
- $\Sigma_{\rm DM} \simeq \int_{\rm path} dr\rho(r) \simeq \int_{R_{\rm em}}^{R_{\rm sp}} dr\rho(r) + \int_{R_{\rm sp}}^{\infty} dr\rho(r)$

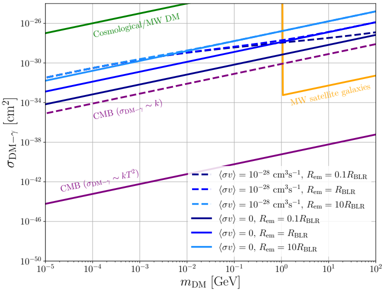
We impose that the attenuation of the neutrino flux due to DM-neutrino scatterings is less than 90%, and less than 99% for DM-photon scatterings

$$\frac{\sigma_{\rm DM-\nu}}{m_{\rm DM}} \lesssim \frac{2.3}{\Sigma_{\rm DM}} \quad , \frac{\sigma_{\rm DM-\gamma}}{m_{\rm DM}} \lesssim \frac{4.6}{\Sigma_{\rm DM}}$$

Constraints on constant cross sections

Ferrer, Herrera, Ibarra, 22'
Cline et al, 22'





- The constraints obtained from the flux attenuation in the vicinity of TXS 0506+056 are at least $\sim$ 5 orders of magnitude stronger than those obtained from the intergalactic medium and the MW.
- For DM-neutrino scatterings, the constraints are $\sim$ 5 orders of magnitude weaker than the constraints from the Lyman-α forest.
- For DM-photon scatterings, the constraints are only $\sim$ 2 orders of magnitude weaker than the constraints from the CMB.

Constraints on energy-dependent cross sections

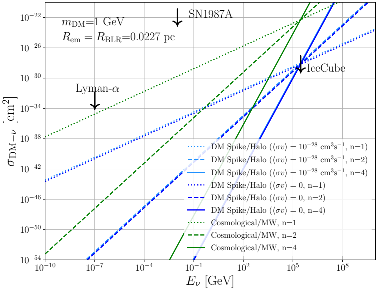
In any realistic model, the DM-neutrino and DM-photon scattering cross sections will depend non-trivially on the incoming particle energy, e.g:

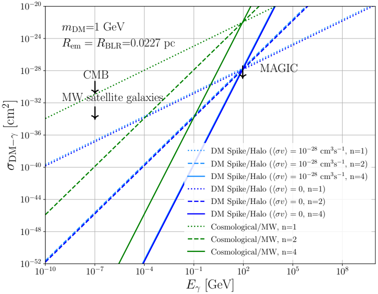
- DM-neutrino scattering via a Z' mediator
  $\rightarrow \sigma_{\mathrm{DM}-\nu} \propto E_\nu$.
- Scalar DM-neutrino scattering via a fermion mediator
  $\rightarrow \sigma_{\mathrm{DM}-\nu} \propto E_\nu^2$.
- DM-photon scattering via higher dimension ≥ 5 operators
  $\rightarrow \sigma_{\mathrm{DM}-\gamma} \propto E_\gamma^2$ or E_γ^4 .

A proper comparison between upper limits requires a rescaling for the energy at which every limit applies.

Constraints on energy-dependent cross sections

Ferrer, Herrera, Ibarra, 22'





- If the cross section scales linearly with the energy of the neutrino, our constraints are $\sim$ 7 orders of magnitude stronger than those from Lyman-α.
- For DM-photon scattering, our constraints are at least $\sim$ 4 orders of magnitude stronger than those from MW satellite galaxies counts.

Conclusions

- The observation of neutrinos and gamma-rays from TXS 0506+056 can be used to constrain the dark matter scattering cross section with neutrinos and photons, since these need to traverse the dark matter spike around the black hole and the halo of the host galaxy.

- The constraints are orders of magnitude stronger than those obtained from the attenuation in the intergalactic medium and the Milky Way.

- When the cross section rises with energy, the constraints are stronger than cosmological ones.

- Still, the constraints are subject to uncertainties from the flux modelling, from the emitting region of neutrinos and gamma-rays, and from the dark matter profile.

More work needed!

Thanks for your attention

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Derivation of the spike profile

Adiabatic growth: A substantial increase in M_{BH} takes place after its initial formation, and the mass is accreted slowly to the pre-existing seed. Mathematically:

$$\rho'(r) = \int_{E_{m'}}^{0} dE' \int_{L'_c}^{L'_m} dL' \frac{4\pi L'}{r^2 v_r} f'(E', L')$$

$$v_r = [2(E' + \frac{GM}{r} - \frac{L'}{2r^2})]^{1/2}$$

$$E'_m = -\frac{GM}{r}(1 - \frac{4R_S}{R})$$

$$L'_c = 2cR_S,\ L'_m = [2r^2(E' + \frac{GM}{r})]^{1/2}$$

Adiabatic conditions :

$$f'(E', L') = f(E, L)$$

$$L' = L \longrightarrow \text{Angular momentum conservation}$$

$$I'(E', L') = I(E, L) \longrightarrow \text{Radial action conservation}$$

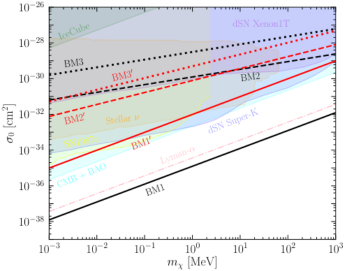
The cascade equation for the flux attenuation

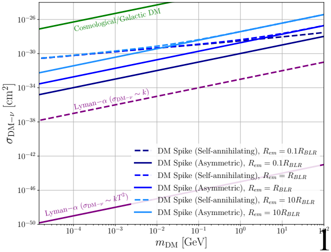
The evolution of the neutrino and photon fluxes Φ_i due to scatterings can be described by a Boltzmann equation

$$\frac{d\Phi}{d\tau}(E_i) = -\sigma_{\rm DM-i}\Phi_i + \int_{E_\nu}^{\infty} dE_i' \frac{d\sigma}{dE_i}(E_i' \rightarrow E_i)\Phi(E_i')$$

with $\tau = \Sigma_{\rm DM}/m_{\rm DM}$, and the second term capturing the effect of the neutrino/photon energy being redistributed.

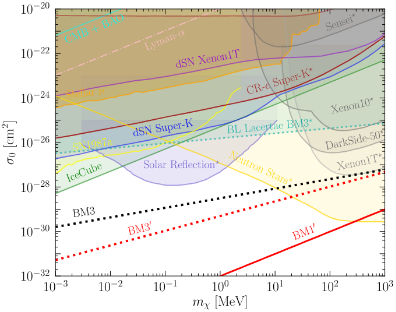
- Our criteria assumes implicitely that $\frac{\Phi_{\rm obs}}{\Phi_{\rm em}} \leq 1$, and the second term can be neglected.
- This was considered in **Cline et al, 22'**, finding more aggressive results, also due to different choices of $R_{\rm em}$.





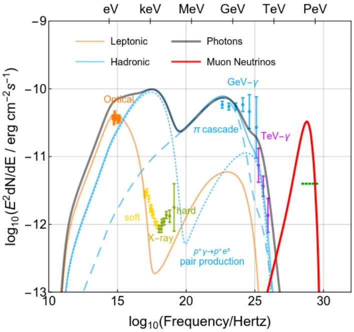
Complementary constraints on the DM-ν cross section

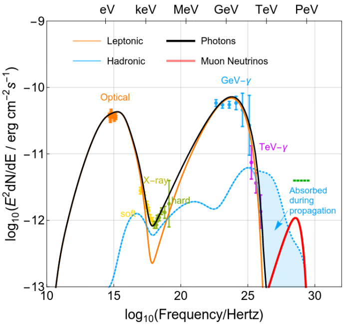
- Complementary constraints (aside from cosmological ones) can be derived under the assumption that dark matter also couples to electrons with similar strength.
- However, these are model dependent (e.g in the Inert Doublet Model the dark matter only couples to neutrinos)



Models of the Spectral Energy Distribution (SED)

Gao, Fedynitch, Winter, Pohl, 19'





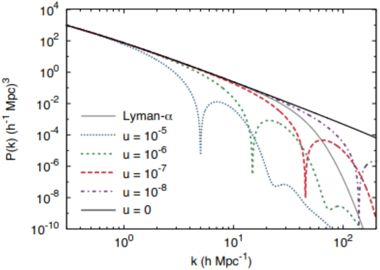
Leptohadronic single-zone models are statistically compatible with the observed fluxes, although it predicts a significantly smaller neutrino flux than observed, otherwise it overshoots X-ray observations.

Alternatives: Multi-zone and multi-epoch models (e.g **Xue, Liu et al, 19'**, **Petropoulou, Murase et al, 19'**)

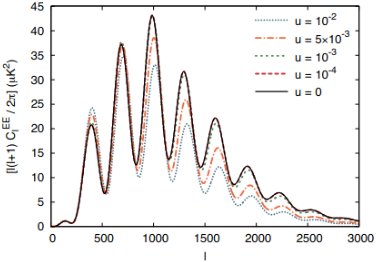
Cosmological constraints

Dark matter interactions with neutrinos and photons suppress small-scales due to damped oscillations in the matter power spectrum.

Wilkinson, Boehm, Lesgourges, 14’



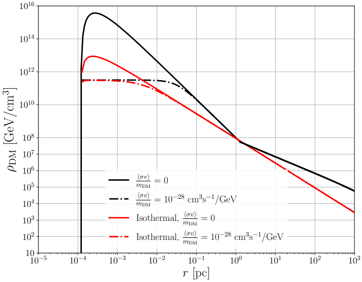
Wilkinson, Boehm, Lesgourges, 13’

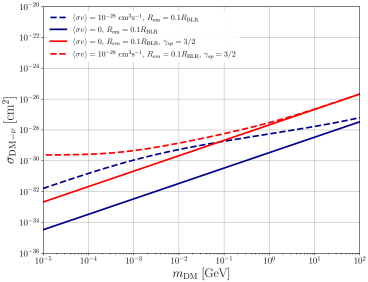


- The height of the peaks is changed due to collisional damping and delayed photon decoupling.

- The position of the peaks is shifted due to drag forces induced by the DM.

- In models with finite cores (e.g the isothermal sphere), the density slope is $\gamma_{\rm sp} = 3/2$
- Depending on $R_{\rm em}$, the upper limits are relaxed up to 2 orders of magnitude.





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$$\rho_{\rm sp}(r) = \rho_R \, g_\gamma(r) \left(\frac{R_{sp}}{r}\right)^{\gamma_{\rm sp}}$$

- $R_{\rm sp} = \alpha_\gamma r_0 (M_{\rm BH}/(\rho_0 r_0^3))^{\frac{1}{3-\gamma}}$ $\longrightarrow$ Size of the spike
- $r_0 \simeq 10$ kpc $\longrightarrow$ Scale radius of the host galaxy
- $g_\gamma(r) \simeq (1 - \frac{4R_S}{r})$ $\longrightarrow$ Captured particles by the BH
- $\gamma_{\rm sp} = \frac{9-2\gamma}{4-\gamma}$ $\longrightarrow$ Cuspiness of the spike ($\gamma = 1$ for an NFW)
- $M_{\rm BH} \approx 3 \times 10^8 M_\odot$, and $\rho_0 \simeq 10^4$ GeV/cm^3 is a normalization used to match the outer profile, and determined by the uncertainty in $M_{\rm BH}$ (**Gorchtein, Profumo, Ubaldi, 10'**).

Only valid for $r \leq R_{\rm sp}$, and in scenarios where the dark matter does not self-annihilate (e.g Asymmetric dark matter or axions).

The dark matter column density around TXS 0506+056

The column density on the spike from $R_{\rm em}$ reads

$$\text{Small } \langle \sigma v \rangle \rightarrow \; \Sigma_{\rm DM}\Big|_{\rm spike} \simeq \frac{\rho_{\rm sp}(R_{\rm em}) R_{\rm em}}{(\gamma_{\rm sp}-1)} \left[1 - \left(\frac{R_{\rm sp}}{R_{\rm em}} \right)^{1-\gamma_{\rm sp}} \right]$$

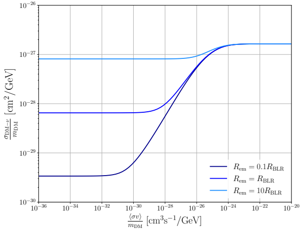
$$\text{Large } \langle \sigma v \rangle \rightarrow \; \Sigma_{\rm DM}\Big|_{\rm spike} \simeq \rho_{\rm sat} R_{\rm sp} \left[1 - \frac{R_{\rm em}}{R_{\rm sp}} \right] \propto m_{\rm DM}/\langle \sigma v \rangle$$

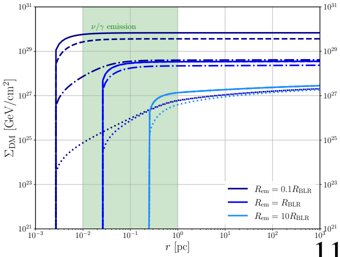
And the contribution from the the halo of the host galaxy reads

$$\Sigma_{\rm DM}\Big|_{\rm host} \simeq \rho_0 r_0 \left[\log\left(\frac{r_0}{R_{\rm sp}} \right) - 1 \right]$$

In general not negligible when compared to the contribution from the spike

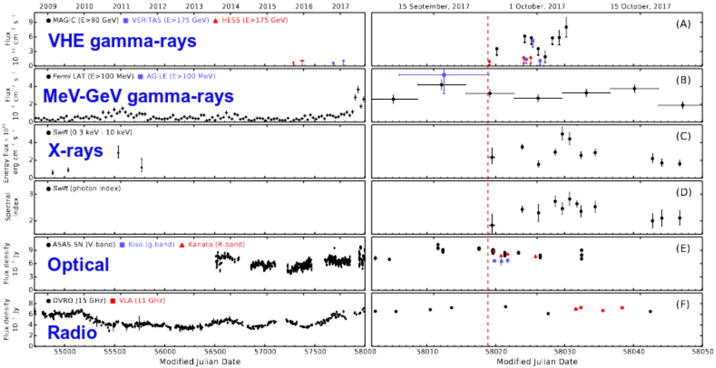
Ferrer, Herrera, Ibarra, 22'





Electromagnetic emission from TXS 0506+056

IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams, 18’

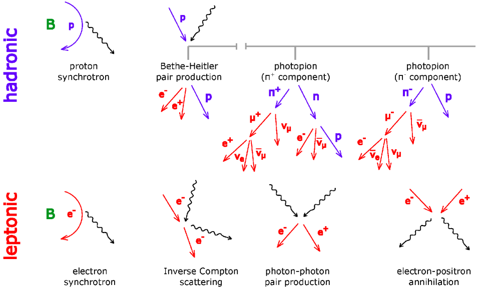


- Multi-wavelength photon observations show an excess compatible with IC-170922A.
- Chance coincidence between the neutrino and gamma-ray events is rejected at 3σ.

High-energy neutrino and gamma-ray production

- Hadronic models: Protons interact with ambient photons, producing neutral and charged pions decaying into both photons and neutrinos.

- Leptonic models: Low-energy photons arising from synchrotron radiation of accelerated electrons, and high-energy photons from inverse compton scattering of electrons with ambient photons.



Gao, Fedynitch, Winter, Pohl, 19'