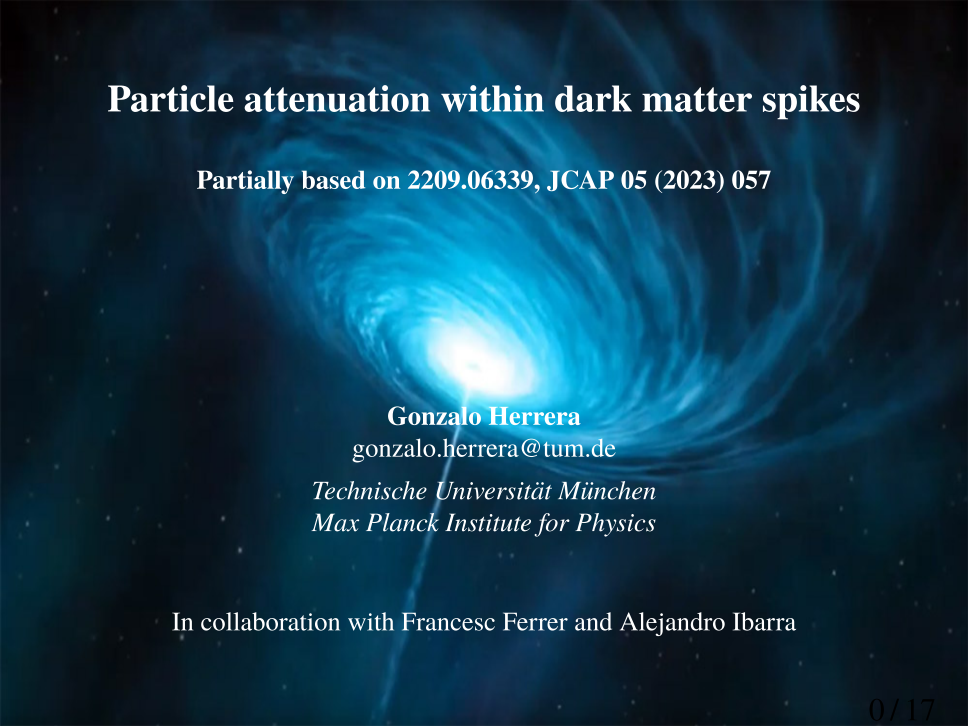

Particle attenuation within dark matter spikes

Partially based on 2209.06339, JCAP 05 (2023) 057

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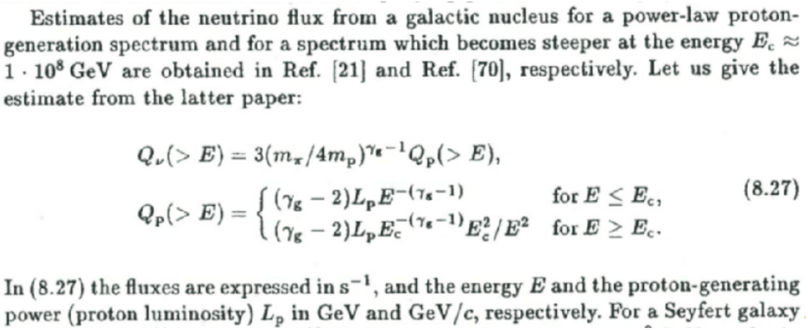
In collaboration with Francesc Ferrer and Alejandro Ibarra

Berezinsky, 77’



Estimates of the neutrino flux from a galactic nucleus for a power-law proton-generation spectrum and for a spectrum which becomes steeper at the energy $E_c \approx 1 \cdot 10^8$ GeV are obtained in Ref. [21] and Ref. [70], respectively. Let us give the estimate from the latter paper:

$$Q_\nu(>E) = 3(m_\pi/4m_p)^{\gamma_g-1}Q_p(>E),$$

$$Q_p(>E) = \begin{cases} (\gamma_g-2)L_p E^{-(\gamma_g-1)} & \text{for } E \leq E_c, \\ (\gamma_g-2)L_p E_c^{-(\gamma_g-1)} E_c^2/E^2 & \text{for } E \geq E_c. \end{cases} \qquad (8.27)$$

In (8.27) the fluxes are expressed in s^{-1}, and the energy E and the proton-generating power (proton luminosity) L_p in GeV and GeV/c, respectively. For a Seyfert galaxy

- In an Active Galactic Nucleus, the emitted neutrino flux is proportional to the injected proton flux from the accretion disk

- $p + \gamma \longrightarrow n + \pi^+$
  $\pi^+ \longrightarrow e^+ + \nu_\mu + \nu_e$
  $p + \gamma \longrightarrow p + \pi^0$
  $\pi^0 \longrightarrow \gamma + \gamma$

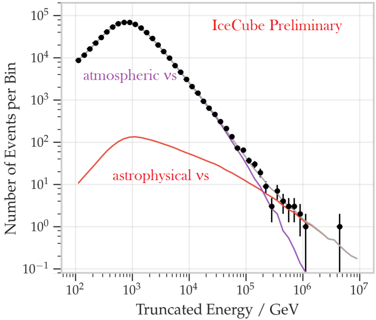
Both processes occur with equal probability:

Comparable neutrino and gamma-ray fluxes!

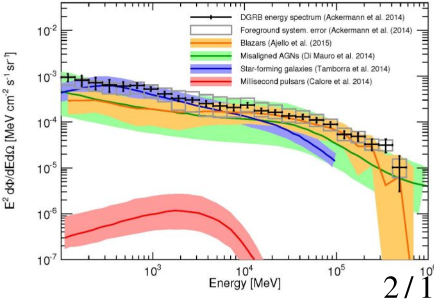
High-energy multi-messenger astronomy

- Photons: Extragalactic sources of high-energy gamma-rays have been identified for several years.
  (e.g Active galactic nuclei, Gamma-ray bursts, Starbust galaxies)
- Neutrinos: Not long ago, the only well known astrophysical sources were the Sun and Supernova 1987A, whereas the origin of the diffuse flux of high-energy cosmic neutrinos remained unclear.

IceCube, 13’

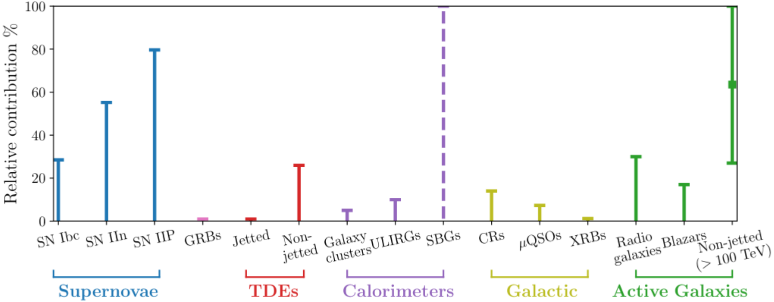


Fermi LAT, 14’



Astrophysical neutrino sources

Oikonomou, 22'



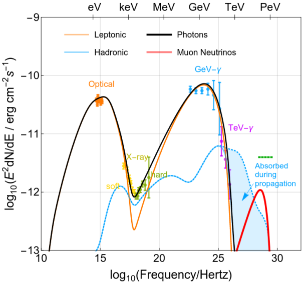
- Blazars: A ~ 290 TeV muon neutrino, identified with the blazar TXS 0506+056 in flaring state at origin direction. Subsequent analysis by IceCube with 9.5 yr data found additional ~ 13 events at 3.5 σ.

- Non-jetted active galaxies: IceCube observed ~ 80 neutrinos from the galaxy NGC 1068, at 4.2 σ.

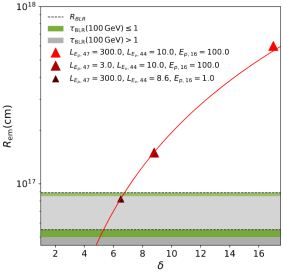
- Tidal disruption events (TDEs): Hints of three events (AT2019dsg, AT2019fdr, AT2019aalc) at 3.7 σ.

Emitting region in TXS 0506+056

Gao, Fedynitch, Winter, Pohl, 19'



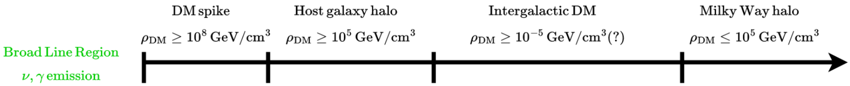
Padovani, Oikonomou, Petropoulou, Giommi, Resconi, 19'



- Single-zone leptohadronic models can accommodate observations to some significance
- The emitting region is likely to be located near, or beyond the Broad Line Region (BLR), $R_{\rm em} \approx R_{\rm BLR} \approx 0.023$ 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.

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.



Broad Line Region
ν, γ emission

DM spike
$\rho_{\rm DM} \geq 10^{8}\ \mathrm{GeV/cm^3}$

Host galaxy halo
$\rho_{\rm DM} \geq 10^{5}\ \mathrm{GeV/cm^3}$

Intergalactic DM
$\rho_{\rm DM} \geq 10^{-5}\ \mathrm{GeV/cm^3}(?)$

Milky Way halo
$\rho_{\rm DM} \leq 10^{5}\ \mathrm{GeV/cm^3}$

- Previous works considered solely the attenuation of neutrinos in the intergalactic medium and Milky Way halo

  Argüelles, Kheirandish, Vincent 17'
  Choi, Kim, Rott 19'

- However, the dark matter density in the vicinity of TXS 0506+056 is expected to be significantly larger

Dark matter spike formation

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

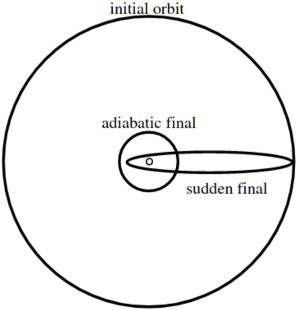
Peebles, 72'
Quinlan, Hernquist, Sigurdsson, 95'

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

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

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

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



Adiabatic conditions :

$f'(E', L') = f(E, L)$ → Phase-space distribution conservation

$L' = L$ → Angular momentum conservation

$I'(E', L') = I(E, L)$ → Radial action conservation

The dark matter spike around TXS 0506+056

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

Gondolo, Silk, 99'

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

- $R_{\rm sp} = \alpha_\gamma r_0 (M_{\rm BH}/(\rho_0 r_0^3))^{\frac{1}{3-\gamma}} \longrightarrow$ 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 profile)
- $M_{\rm BH} \approx 3 \times 10^8 M_\odot$, and $\rho_0 \simeq 10^4$ GeV/cm^3 is a normalization used to match the outer profile

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

- $\frac{dn_{\rm DM}(t,r)}{dt} = \langle\sigma v\rangle n_{\rm DM}^2(t,r) \rightarrow n_{\rm DM}(t,r) \simeq \frac{n_{\rm DM}(t_f,r)}{1+n_{\rm DM}(t_f,r)\langle\sigma v\rangle(t-t_f)}$

$$\rho_{\rm sat} = m_{\rm DM}/(\langle\sigma v\rangle t_{\rm BH})$$

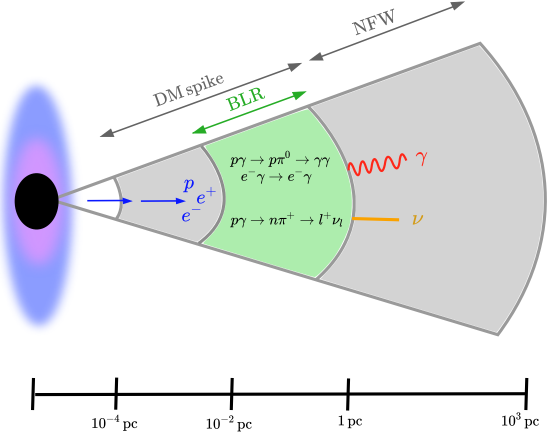
- $t_{\rm BH} \simeq 10^9$yr → Time elapsed since the black hole formation.
- $\langle\sigma v\rangle$ → Velocity averaged dark matter annihilation cross section.

$$\rho(r) = \begin{cases} 0 & r \le 4R_S \\ \frac{\rho_{\rm sp}(r)\rho_{\rm sat}}{\rho_{\rm sp}(r)+\rho_{\rm sat}} & 4R_S \le r \le R_{sp} \\ \rho_0\left(\frac{r}{r_0}\right)^{-\gamma}\left(1+\frac{r}{r_0}\right)^{-3-\gamma} & r \ge R_{sp}\,. \end{cases}$$

- 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'**).

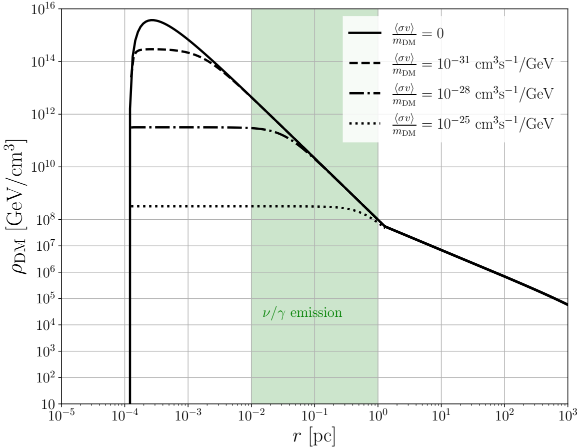
However, these effects do not change the profile in the region of the jet where neutrinos and gamma-rays are produced.

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_{em} from the BH can be described by

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

- $\Phi_i^{\mathrm{obs}}, \Phi_i^{\mathrm{em}}$ → observed and emitted fluxes of the particle i ($i = \nu$ or γ).
- $\mu_i\big|_{\mathrm{DM}} = \sigma_{\mathrm{DM-i}} \Sigma_{\mathrm{DM}}$.
- $\Sigma_{\mathrm{DM}} \simeq \int_{\mathrm{path}} dr\,\rho(r) \simeq \int_{R_{\mathrm{em}}}^{R_{\mathrm{sp}}} dr\,\rho(r) + \int_{R_{\mathrm{sp}}}^{\infty} dr\,\rho(r)$

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

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

The dark matter column density around TXS 0506+056

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

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

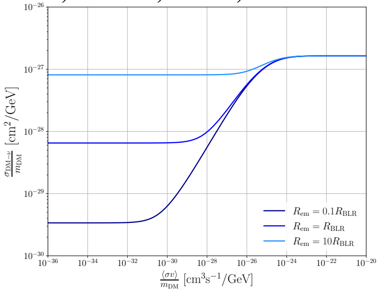
$$\text{Large } \langle\sigma v\rangle \rightarrow \; \Sigma_{\rm DM}\Big|_{\rm spike} \simeq \rho_{\rm sat} R_{\rm sp}\left[1-\frac{R_{\rm em}}{R_{\rm sp}}\right] \propto m_{\rm DM}/\langle\sigma v\rangle$$

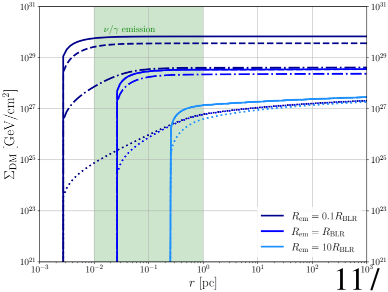
And the contribution from the the halo of the host galaxy reads

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

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

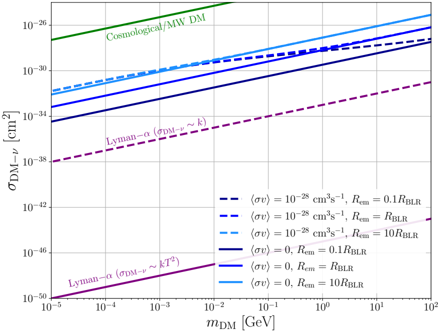
Ferrer, Herrera, Ibarra, 22'

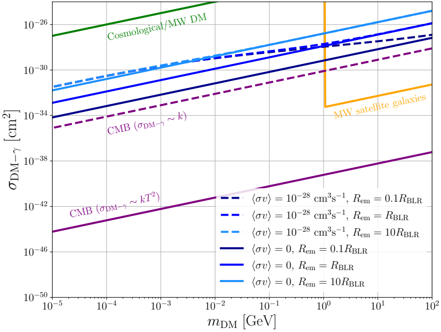




Constraints on constant cross sections

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





- The constraints are $\sim$ 5 orders of magnitude stronger than those obtained from the intergalactic medium and the MW.
- The constraints are $\sim$ 2-5 orders of magnitude weaker than the constraints from the CMB, Lyman-α forest and MW satellite galaxy counts.

Constraints on energy-dependent cross sections

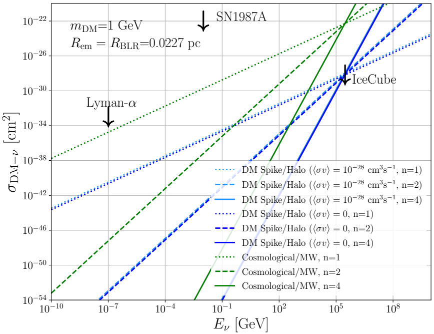
In any realistic model, the DM-neutrino and DM-photon scattering cross sections will depend non-trivially on the incoming particle energy, e.g:

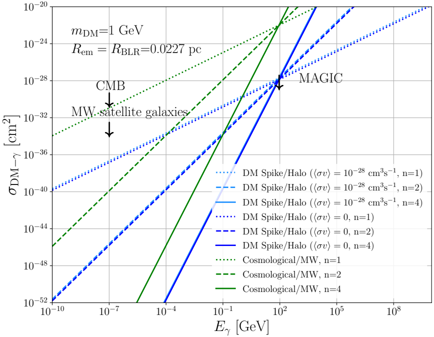
- Fermion DM-neutrino scattering via a Z' mediator $\rightarrow \sigma_{\mathrm{DM}-\nu} \propto E_\nu$.
- Scalar DM-neutrino scattering via a fermion mediator $\rightarrow \sigma_{\mathrm{DM}-\nu} \propto E_\nu^2$
- Fermion DM-photon scattering via higher dimension ≥ 5 operators $\rightarrow \sigma_{\mathrm{DM}-\gamma} \propto E_\gamma^2$ 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 $\sim$ 4-7 orders of magnitude stronger than those from cosmology.

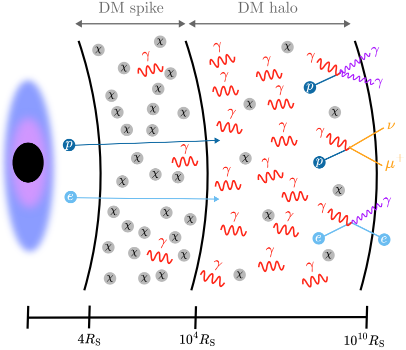
Proton and electron attenuation in the DM spike

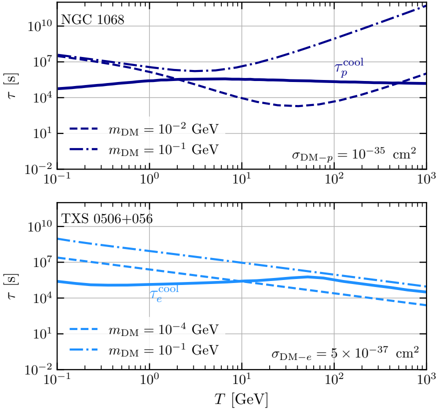
The timescale of elastic dark matter-proton/electron scattering can be compared with the cooling timescales ($\tau^{\rm cool} \lesssim 10^5$s)

$$\tau^{\rm el}_{{\rm DM}-i} = \left[-\frac{1}{E}\left(\frac{dE}{dt}\right)_{{\rm DM}-i} \right]^{-1} \qquad \left(\frac{dE}{dt}\right)_{{\rm DM}-i} = \frac{\rho_{\rm DM}}{m_{\rm DM}} \int_0^{T_{\rm DM}^{\max}} dT_{\rm DM}\, T_{\rm DM} \frac{d\sigma_{\rm el}}{dT_{\rm DM}}$$

Herrera, *In progress*

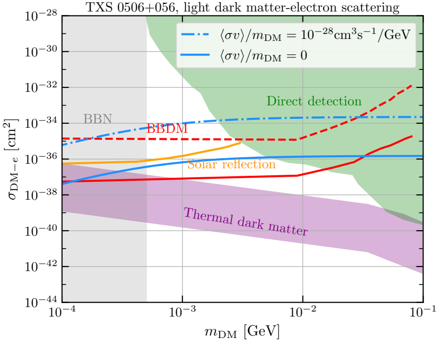
$$\tau^{\rm el}_{{\rm DM}-i} \geq \tau_i^{\rm cool}$$

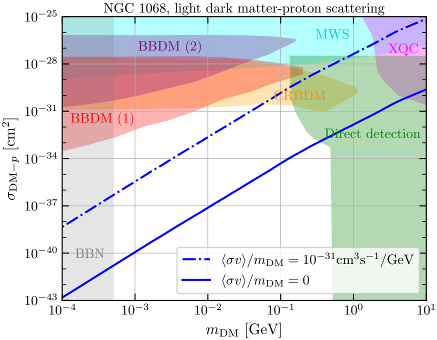




Proton and electron attenuation in the DM spike

Herrera, *In progress*





- Strongest constraint to date on sub-GeV dark matter coupling to protons.
- Competitive bound for asymmetric sub-GeV dark matter coupling to electrons.

Conclusions

- **Neutrinos, photons, electrons and protons may scatter off dark matter particles within AGNs**

- The constraints for ν,γ are orders of magnitude stronger than those obtained from the attenuation in the intergalactic medium and the Milky Way, and stronger than cosmological ones in some models.

- The constraints for p are the strongest to date for light dark matter, and the constraints for e are competitive with other bounds.

- Still, these are subject to uncertainties from the proton and electron luminosities, 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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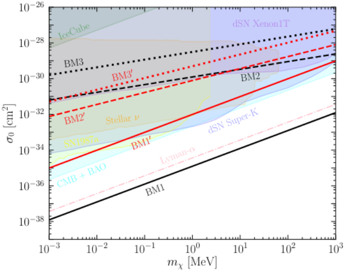
The cascade equation for the flux attenuation

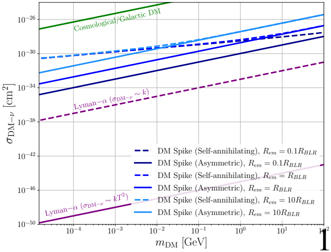
The evolution of the neutrino and photon fluxes Φ_i due to scatterings can be described by a Boltzmann equation

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

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

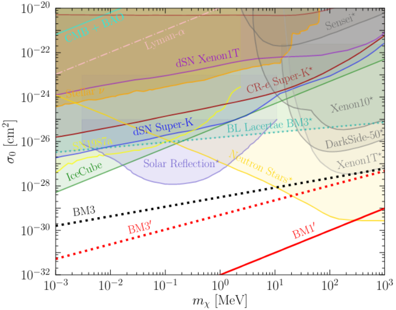
- Our criteria assumes implicitely that $\frac{\Phi_{\mathrm{obs}}}{\Phi_{\mathrm{em}}} \leq 1$, and the second term can be neglected.
- This was considered in **Cline et al, 22'**, finding more aggressive results, also due to different choices of R_{em}.





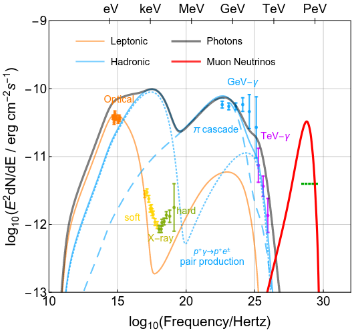
Complementary constraints on the DM-ν cross section

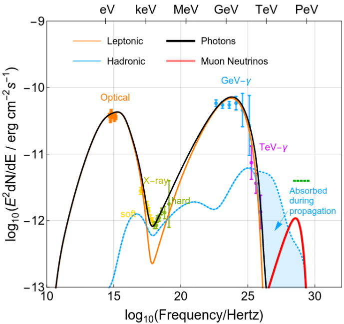
- Complementary constraints (aside from cosmological ones) can be derived under the assumption that dark matter also couples to electrons with similar strength.
- However, these are model dependent (e.g in the Inert Doublet Model the dark matter only couples to neutrinos)



Models of the Spectral Energy Distribution (SED)

Gao, Fedynitch, Winter, Pohl, 19’





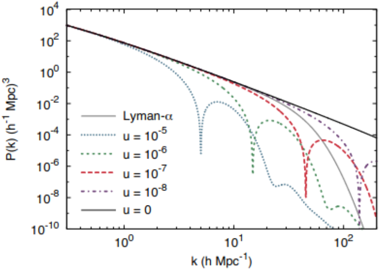
Leptohadronic single-zone models are statistically compatible with the observed fluxes, although it predicts a significantly smaller neutrino flux than observed, otherwise it overshoots X-ray observations.

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

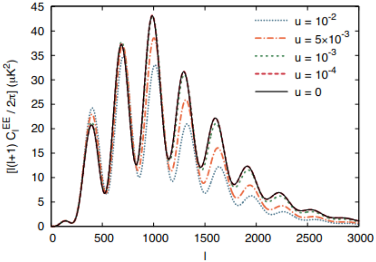
Cosmological constraints

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

Wilkinson, Boehm, Lesgourges, 14’



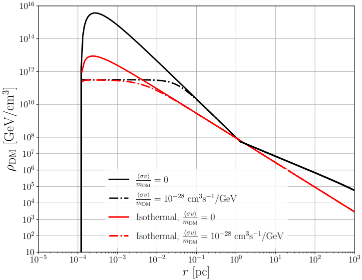
Wilkinson, Boehm, Lesgourges, 13’

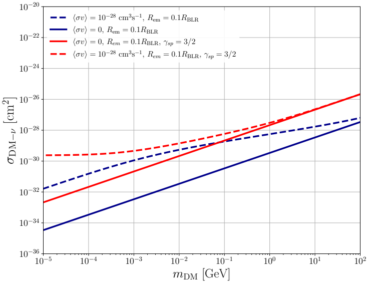


- The height of the peaks is changed due to collisional damping and delayed photon decoupling.
- The position of the peaks is shifted due to drag forces induced by the DM.

Constraints for ν with initial cored profiles

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

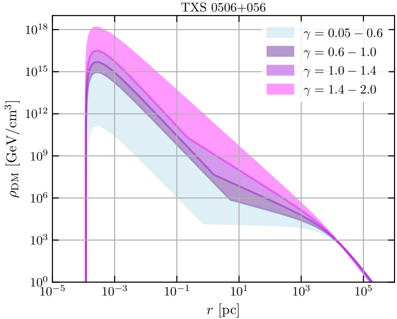


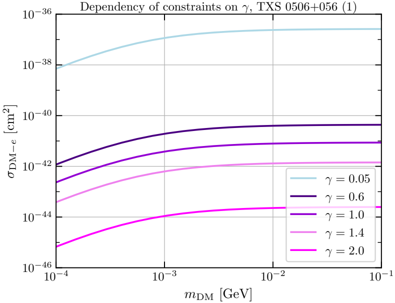


Dependency of constraints on *e* with profile index

- Simulations favor values in the range $\gamma \sim 0.6 - 1.4$
  Dutton, Maccio, 14'

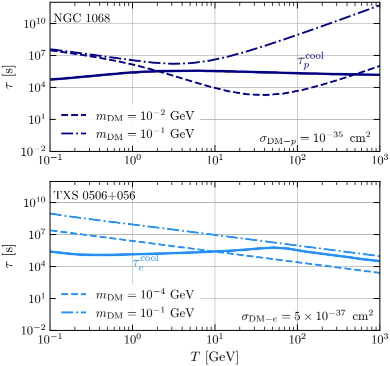
- Constraints for $\gamma = 0$ are still stronger than complementary bounds, but wouldn't probe the thermal production range

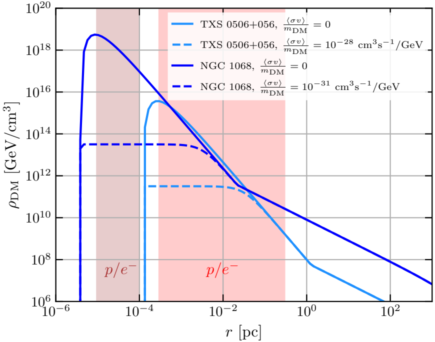




Assumptions for p, e bounds

Eichmann, Oikonomou, Salvatore, Dettmar, Becker 14’
Xue, Liu, Petropoulou, Oikonomou, Wang, 19’





$$T^{\rm max}_{\rm DM} = \frac{2T^2+2m_iT}{m_{\rm DM}}\left[\left(1+\frac{m_i}{m_{\rm DM}}\right)^2+\frac{2T}{m_{\rm DM}}\right]^{-1}$$

$$\frac{d\sigma}{dT} = \frac{\sigma_{{\rm DM}-i}}{T^{\rm max}_{\rm DM}}\,\frac{F_i^2(q^2)}{16\,\mu^2_{{\rm DM}-i}\,s}\,(q^2+4m_i^2)(q^2+4m^2_{\rm DM})$$

$$\tau^{\rm el}_{{\rm DM}-i} = \left[-\frac{1}{E}\left(\frac{dE}{dt}\right)_{{\rm DM}-i}\right]^{-1}$$

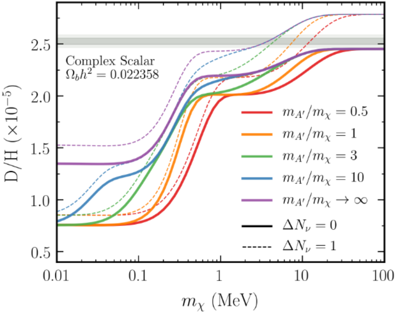
$$\left(\frac{dE}{dt}\right)_{{\rm DM}-i} = \frac{\rho_{\rm DM}}{m_{\rm DM}}\int_0^{T^{\rm max}_{\rm DM}} dT_{\rm DM}\,T_{\rm DM}\,\frac{d\sigma}{dT_{\rm DM}}$$

Fermionic DM and a heavy scalar mediator

BBN constraints on light dark matter

- Light dark matter affects the expansion rate of the Universe, as well as the temperature of Standard Model particles, leaving signatures on primordial abundances and N_{eff}

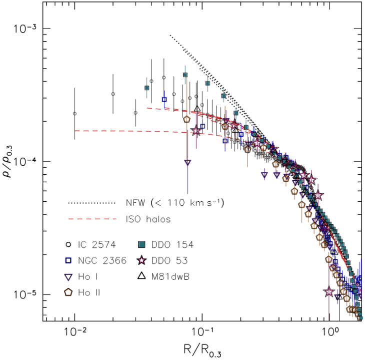
$$N_{\text{eff}} = 3\left[\frac{11}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3_0\right]^{4/3}\left(1+\frac{\Delta N_\nu}{3}\right)$$



Dark matter halos

- Early ΛCDM simulations predicted cuspy dark matter halos scaling as $\rho \propto r^{-1}$ in the inner regions of the galaxy
- Current observational data suggests dark matter cores in the inner regions of galaxies, and simulations including baryonic physics are still inconclusive

Oh et al, 11'



We adopt the generalized NFW profile

$$\rho(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma} \left(1 + \frac{r}{r_0}\right)^{-3+\gamma}$$

with $\gamma \in [0, 2]$

Dark matter distribution in the local universe

Böhringer, Chon, Collins ’19

Karachentsev, Telikova ’18

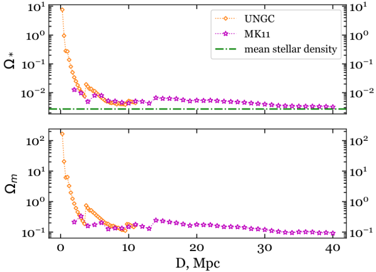
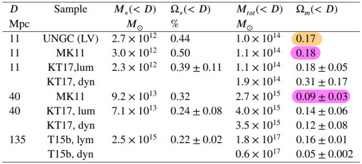


TABLE 2 Mean densities and total masses of the stellar and dark matter within spheres with radii D.



D Mpc	Sample	$M_*(< D)$ $M_\odot$	$\Omega_*(< D)$ %	$M_{tot}(< D)$ $M_\odot$	$\Omega_m(< D)$
11	UNGC (LV)	2.7×10^{12}	0.44	1.0×10^{14}	0.17
11	MK11	3.0×10^{12}	0.50	1.1×10^{14}	0.18
11	KT17,lum	2.3×10^{12}	0.39 ± 0.11	1.1×10^{14}	0.18 ± 0.05
	KT17, dyn			1.9×10^{14}	0.31 ± 0.17
40	MK11	9.2×10^{13}	0.32	2.7×10^{15}	0.09 ± 0.03
40	KT17, lum	7.1×10^{13}	0.24 ± 0.08	4.0×10^{15}	0.14 ± 0.06
	KT17, dyn			3.5×10^{15}	0.12 ± 0.08
135	T15b, lym	2.5×10^{15}	0.22 ± 0.02	1.8×10^{17}	0.16 ± 0.01
	T15b, dyn			0.6×10^{17}	0.05 ± 0.002

- Observational measurements of the average DM density $\Omega_m \approx 0.09 - 0.18$ are systematically lower than the cosmic value $\Omega_m = 0.31$

- The discrepancy might point towards a significant fraction of the DM being distributed homogeneously within clusters of galaxies.

- We are lacking simulations of the dark matter distribution in the Local Universe, but dedicated studies are on the way (e.g CLUES, Hestia).