McGill

Constraining neutrino-dark matter scattering with blazar TXS 0506+056

J. M. Cline, S. Gao, F. Guo, Z. Lin, S. Liu, **MP**, P. Todd, and T. Xiao,
arXiv:2209.02713

Matteo Puel

Physics Department, McGill University

DM+nu Forum @ TDLI/SJTU

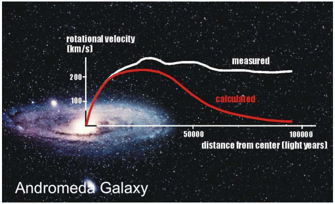
October 12, 2022

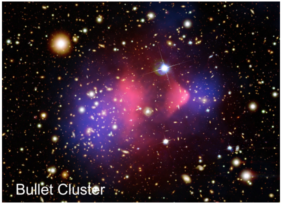
McGill Space Institute
Institut Spatial de McGill

Outline

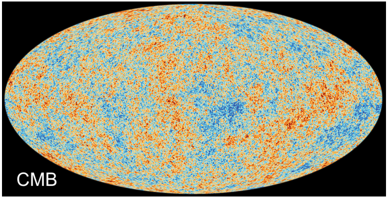
Existence of dark matter

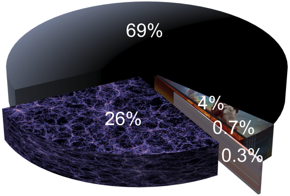
A variety of different astrophysical and cosmological observations provides strong evidence that **Dark Matter (DM)** should be out there!

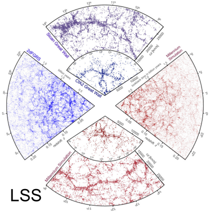




[Credits: NASA, ESA, and Hubble (STScI/AURA); Queen's Univ.; D.Clowe et al., ApJ 648, L109 (2006)]







[Credits: ESA/Planck Collaboration; V.Springel et al., Nature 440, 1137 (2006)]

DM interactions: with neutrinos?

Intensive studies have been undertaken to understand and probe additional interactions between DM and ordinary matter besides gravity.

Hardest interaction to constrain: DM-neutrino interaction, because of the weakly interacting nature of the neutrino (ν).

Popular strategy: Use high-energetic neutrinos emitted by astrophysical sources (e.g. supernovae, stars, etc.) to accelerate light DM particles and make them detectable by DM and neutrino experiments (e.g. [D.Ghosh et al., PRD 105 (2022) 10, 103029] [Y.Jho et al., arXiv:2101.11262] [Y.-H.Lin et al., arXiv:2206.06864]).

Downside: It requires additional interactions between DM and Standard Model (SM) particles, such as with protons or electrons.

Question: Is there a more model-independent way to constrain just ν-DM interaction?

DM interactions: with neutrinos?

Intensive studies have been undertaken to understand and probe additional interactions between DM and ordinary matter besides gravity.

Hardest interaction to constrain: DM-neutrino interaction, because of the weakly interacting nature of the neutrino (ν).

Popular strategy: Use high-energetic neutrinos emitted by astrophysical sources (e.g. supernovae, stars, etc.) to accelerate light DM particles and make them detectable by DM and neutrino experiments (e.g. [D.Ghosh et al., PRD 105 (2022) 10, 103029] [Y.Jho et al., arXiv:2101.11262] [Y.-H.Lin et al., arXiv:2206.06864]).

Downside: It requires additional interactions between DM and Standard Model (SM) particles, such as with protons or electrons.

Question: Is there a more model-independent way to constrain just ν-DM interaction?

DM interactions: with neutrinos?

Intensive studies have been undertaken to understand and probe additional interactions between DM and ordinary matter besides gravity.

Hardest interaction to constrain: DM-neutrino interaction, because of the weakly interacting nature of the neutrino (ν).

Popular strategy: Use high-energetic neutrinos emitted by astrophysical sources (e.g. supernovae, stars, etc.) to accelerate light DM particles and make them detectable by DM and neutrino experiments (e.g. [D.Ghosh et al., PRD 105 (2022) 10, 103029] [Y.Jho et al., arXiv:2101.11262] [Y.-H.Lin et al., arXiv:2206.06864]).

Downside: It requires additional interactions between DM and Standard Model (SM) particles, such as with protons or electrons.

Question: Is there a more model-independent way to constrain just ν-DM interaction?

DM interactions: with neutrinos?

Intensive studies have been undertaken to understand and probe additional interactions between DM and ordinary matter besides gravity.

Hardest interaction to constrain: DM-neutrino interaction, because of the weakly interacting nature of the neutrino (ν).

Popular strategy: Use high-energetic neutrinos emitted by astrophysical sources (e.g. supernovae, stars, etc.) to accelerate light DM particles and make them detectable by DM and neutrino experiments (e.g. [D.Ghosh et al., PRD 105 (2022) 10, 103029] [Y.Jho et al., arXiv:2101.11262] [Y.-H.Lin et al., arXiv:2206.06864]).

Downside: It requires additional interactions between DM and Standard Model (SM) particles, such as with protons or electrons.

Question: Is there a more model-independent way to constrain just ν-DM interaction?

DM interactions: with neutrinos?

Intensive studies have been undertaken to understand and probe additional interactions between DM and ordinary matter besides gravity.

Hardest interaction to constrain: DM-neutrino interaction, because of the weakly interacting nature of the neutrino (ν).

Popular strategy: Use high-energetic neutrinos emitted by astrophysical sources (e.g. supernovae, stars, etc.) to accelerate light DM particles and make them detectable by DM and neutrino experiments (e.g. [D.Ghosh et al., PRD 105 (2022) 10, 103029] [Y.Jho et al., arXiv:2101.11262] [Y.-H.Lin et al., arXiv:2206.06864]).

Downside: It requires additional interactions between DM and Standard Model (SM) particles, such as with protons or electrons.

Question: Is there a more model-independent way to constrain just ν-DM interaction?

Basic idea: look at the neutrinos!

The answer is **Yes!** Instead of looking at boosted DM in the detector, we can focus on the arriving neutrinos.

Idea

Infer ν-DM scattering properties by studying how the neutrino flux from a source gets attenuated along its journey to the detector on Earth (e.g. [K.-Y.Choi et al., PRD 99 (2019) 8, 083018] [J.-W. Wang et al., PRL 128 (2022) 22, 221104] [A.Granelli et al., JCAP 07 (2022) 07, 013])

Minimal requirements:

1. Find a high-energy ν source, whose ν's have already been detected;
2. Have a good theoretical understanding of the possible initial ν spectrum at the source location;
3. Know the DM distribution along the neutrino journey to the detector.

Event: IceCube detected a neutrino from a known blazar!

Basic idea: look at the neutrinos!

The answer is **Yes!** Instead of looking at boosted DM in the detector, we can focus on the arriving neutrinos.

Idea

Infer ν-DM scattering properties by studying how the neutrino flux from a source gets attenuated along its journey to the detector on Earth (e.g. [K.-Y.Choi et al., PRD 99 (2019) 8, 083018] [J.-W. Wang et al., PRL 128 (2022) 22, 221104] [A.Granelli et al., JCAP 07 (2022) 07, 013])

Minimal requirements:

1. Find a high-energy ν source, whose ν's have already been detected;
2. Have a good theoretical understanding of the possible initial ν spectrum at the source location;
3. Know the DM distribution along the neutrino journey to the detector.

Event: IceCube detected a neutrino from a known blazar!

Basic idea: look at the neutrinos!

The answer is **Yes!** Instead of looking at boosted DM in the detector, we can focus on the arriving neutrinos.

Idea

Infer ν-DM scattering properties by studying how the neutrino flux from a source gets attenuated along its journey to the detector on Earth (e.g. [K.-Y.Choi et al., PRD 99 (2019) 8, 083018] [J.-W. Wang et al., PRL 128 (2022) 22, 221104] [A.Granelli et al., JCAP 07 (2022) 07, 013])

Minimal requirements:

1. Find a high-energy ν source, whose ν's have already been detected;
2. Have a good theoretical understanding of the possible initial ν spectrum at the source location;
3. Know the DM distribution along the neutrino journey to the detector.

Event: IceCube detected a neutrino from a known blazar!

Basic idea: look at the neutrinos!

The answer is **Yes!** Instead of looking at boosted DM in the detector, we can focus on the arriving neutrinos.

Idea

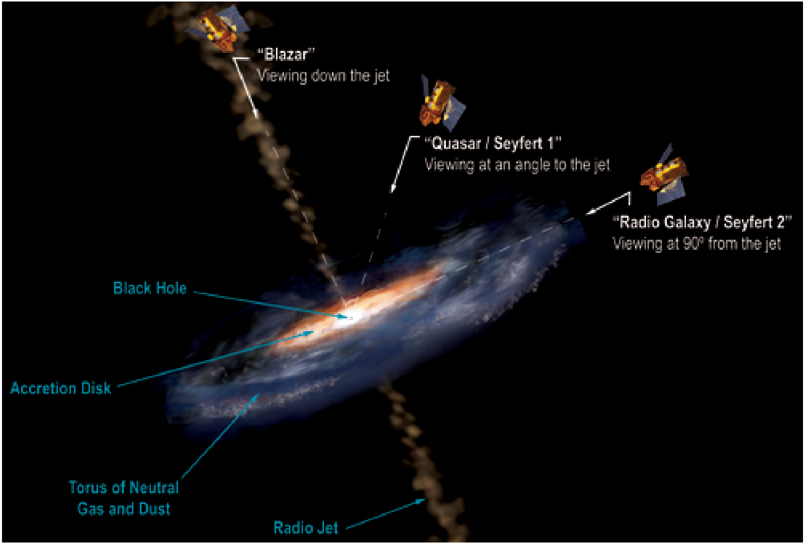
Infer ν-DM scattering properties by studying how the neutrino flux from a source gets attenuated along its journey to the detector on Earth (e.g. [K.-Y.Choi et al., PRD 99 (2019) 8, 083018] [J.-W. Wang et al., PRL 128 (2022) 22, 221104] [A.Granelli et al., JCAP 07 (2022) 07, 013])

Minimal requirements:

1. Find a high-energy ν source, whose ν's have already been detected;
2. Have a good theoretical understanding of the possible initial ν spectrum at the source location;
3. Know the DM distribution along the neutrino journey to the detector.

Event: IceCube detected a neutrino from a known blazar!

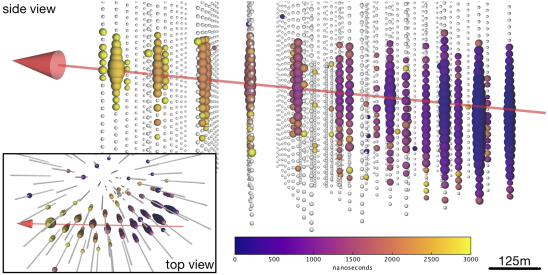
What's a blazar?



[Credit: Aurore Simonnet, Sonoma State University]

On September 22 2017, a neutrino with energy of ∼ 290 TeV was detected by IceCube from the known blazar TXS 0506+056.

The flaring stage of the source was observed simultaneously by several telescopes, e.g. Fermi-LAT, MAGIC, etc. [IceCube et al., Science 361 (2018) 6398]

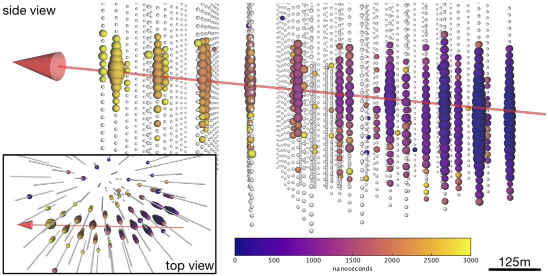


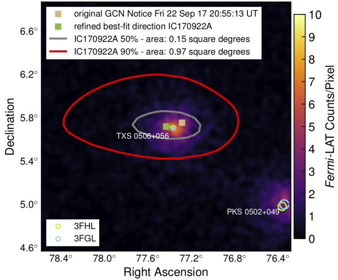
Recent news! Baikal-GVD claims the detection of a 224 ± 75 TeV neutrino from TXS 0506+056 on April 18 2021, followed by a radio flare observed by RATAN-600. [Baikal-GVD, arXiv:2210.01650]

IceCube-170922A event

On September 22 2017, a neutrino with energy of ~ 290 TeV was detected by IceCube from the known blazar TXS 0506+056.

The flaring stage of the source was observed simultaneously by several telescopes, e.g. Fermi-LAT, MAGIC, etc. [IceCube et al., Science 361 (2018) 6398]



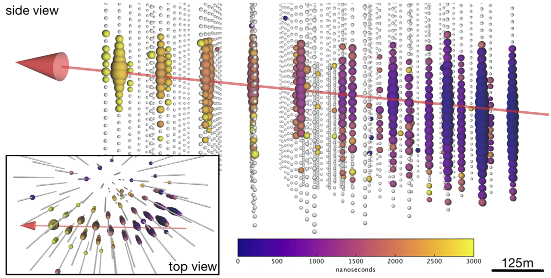


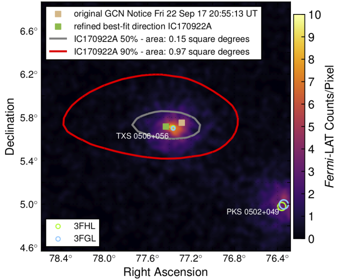
Recent news! Baikal-GVD claims the detection of a 224 ± 75 TeV neutrino from TXS 0506+056 on April 18 2021, followed by a radio flare observed by RATAN-600. [Baikal-GVD, arXiv:2210.01650]

IceCube-170922A event

On September 22 2017, a neutrino with energy of ~ 290 TeV was detected by IceCube from the known blazar TXS 0506+056.

The flaring stage of the source was observed simultaneously by several telescopes, e.g. Fermi-LAT, MAGIC, etc. [IceCube et al., Science 361 (2018) 6398]





Recent news! Baikal-GVD claims the detection of a 224 ± 75 TeV neutrino from TXS 0506+056 on April 18 2021, followed by a radio flare observed by RATAN-600. [Baikal-GVD, arXiv:2210.01650]

How do ν and γ get produced in blazars?

Electrons and protons in the relativistic jet emit synchrotron radiation.

The UV / X-ray emission is caused by electrons. We can have three different scenarios depending on what is the dominant process producing the γ-ray part of the spectrum: [M.Cerruti, Galaxies 8 (2020) 4, 72]

- *Leptonic models* – γ-rays are produced by inverse-Compton scattering;
- *Hadronic models* – γ-rays are produced by proton synchrotron emission;
- *Lepto-Hadronic models* – γ-rays are generated by secondary leptons produced in proton-photon interactions.

Neutrinos are produced **only** in proton-photon interactions:

$$p + \gamma \rightarrow p + \pi^0 \qquad \pi^0 \rightarrow 2\gamma$$

$$\left.\begin{array}{l} p + \gamma \rightarrow n + \pi^+ \\ p + \gamma \rightarrow p + \pi^+ + \pi^- \end{array}\right\} \quad \begin{array}{l} \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \boldsymbol{\nu_e} + \boldsymbol{\bar{\nu}_\mu} + \boldsymbol{\nu_\mu} \\ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \boldsymbol{\bar{\nu}_e} + \boldsymbol{\nu_\mu} + \boldsymbol{\bar{\nu}_\mu} \end{array}$$

How do ν and γ get produced in blazars?

Electrons and protons in the relativistic jet emit synchrotron radiation.

The UV / X-ray emission is caused by electrons. We can have three different scenarios depending on what is the dominant process producing the γ-ray part of the spectrum: [M.Cerruti, Galaxies 8 (2020) 4, 72]

- *Leptonic models* – γ-rays are produced by inverse-Compton scattering;
- *Hadronic models* – γ-rays are produced by proton synchrotron emission;
- *Lepto-Hadronic models* – γ-rays are generated by secondary leptons produced in proton-photon interactions.

Neutrinos are produced **only** in proton-photon interactions:

$$p + \gamma \to p + \pi^0 \qquad \pi^0 \to 2\gamma$$

$$\left.\begin{array}{l} p + \gamma \to n + \pi^+ \\ p + \gamma \to p + \pi^+ + \pi^- \end{array}\right\} \quad \begin{array}{l} \pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\ \pi^- \to \mu^- + \bar{\nu}_\mu \to e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu \end{array}$$

How do ν and γ get produced in blazars?

Electrons and protons in the relativistic jet emit synchrotron radiation.

The UV / X-ray emission is caused by electrons. We can have three different scenarios depending on what is the dominant process producing the γ-ray part of the spectrum: [M.Cerruti, Galaxies 8 (2020) 4, 72]

- *Leptonic models* – γ-rays are produced by inverse-Compton scattering;
- *Hadronic models* – γ-rays are produced by proton synchrotron emission;
- *Lepto-Hadronic models* – γ-rays are generated by secondary leptons produced in proton-photon interactions.

Neutrinos are produced **only** in proton-photon interactions:

$$p + \gamma \rightarrow p + \pi^0 \qquad \pi^0 \rightarrow 2\gamma$$

$$\left.\begin{array}{l} p + \gamma \rightarrow n + \pi^+ \\ p + \gamma \rightarrow p + \pi^+ + \pi^- \end{array}\right\} \qquad \begin{array}{l} \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \boldsymbol{\nu_e} + \boldsymbol{\bar{\nu}_\mu} + \boldsymbol{\nu_\mu} \\ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \boldsymbol{\bar{\nu}_e} + \boldsymbol{\nu_\mu} + \boldsymbol{\bar{\nu}_\mu} \end{array}$$

How do ν and γ get produced in blazars?

Electrons and protons in the relativistic jet emit synchrotron radiation.

The UV / X-ray emission is caused by electrons. We can have three different scenarios depending on what is the dominant process producing the γ-ray part of the spectrum: [M.Cerruti, Galaxies 8 (2020) 4, 72]

- *Leptonic models* – γ-rays are produced by inverse-Compton scattering;
- *Hadronic models* – γ-rays are produced by proton synchrotron emission;
- *Lepto-Hadronic models* – γ-rays are generated by secondary leptons produced in proton-photon interactions.

Neutrinos are produced **only** in proton-photon interactions:

$$p + \gamma \rightarrow p + \pi^0 \qquad \pi^0 \rightarrow 2\gamma$$

$$\left.\begin{array}{l} p + \gamma \rightarrow n + \pi^+ \\ p + \gamma \rightarrow p + \pi^+ + \pi^- \end{array}\right\} \qquad \begin{array}{l} \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu \end{array}$$

How do ν and γ get produced in blazars?

Electrons and protons in the relativistic jet emit synchrotron radiation.

The UV / X-ray emission is caused by electrons. We can have three different scenarios depending on what is the dominant process producing the γ-ray part of the spectrum: [M.Cerruti, Galaxies 8 (2020) 4, 72]

- *Leptonic models* – γ-rays are produced by inverse-Compton scattering;
- *Hadronic models* – γ-rays are produced by proton synchrotron emission;
- *Lepto-Hadronic models* – γ-rays are generated by secondary leptons produced in proton-photon interactions.

Neutrinos are produced **only** in proton-photon interactions:

$$p + \gamma \rightarrow p + \pi^0 \qquad \pi^0 \rightarrow 2\gamma$$

$$\left.\begin{array}{l} p + \gamma \rightarrow n + \pi^+ \\ p + \gamma \rightarrow p + \pi^+ + \pi^- \end{array}\right\} \quad \begin{array}{l} \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \boldsymbol{\nu_e} + \bar{\boldsymbol{\nu}}_{\boldsymbol{\mu}} + \boldsymbol{\nu_\mu} \\ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\boldsymbol{\nu}}_{\boldsymbol{e}} + \boldsymbol{\nu_\mu} + \bar{\boldsymbol{\nu}}_{\boldsymbol{\mu}} \end{array}$$

How do ν and γ get produced in blazars?

Electrons and protons in the relativistic jet emit synchrotron radiation.

The UV / X-ray emission is caused by electrons. We can have three different scenarios depending on what is the dominant process producing the γ-ray part of the spectrum: [M.Cerruti, Galaxies 8 (2020) 4, 72]

- *Leptonic models* – γ-rays are produced by inverse-Compton scattering;
- *Hadronic models* – γ-rays are produced by proton synchrotron emission;
- *Lepto-Hadronic models* – γ-rays are generated by secondary leptons produced in proton-photon interactions.

Neutrinos are produced **only** in proton-photon interactions:

$$p + \gamma \to p + \pi^0 \qquad \pi^0 \to 2\gamma$$

$$\left.\begin{array}{l} p + \gamma \to n + \pi^+ \\ p + \gamma \to p + \pi^+ + \pi^- \end{array}\right\} \quad \begin{array}{l} \pi^+ \to \mu^+ + \nu_\mu \to e^+ + \boldsymbol{\nu_e} + \boldsymbol{\bar{\nu}_\mu} + \boldsymbol{\nu_\mu} \\ \pi^- \to \mu^- + \bar{\nu}_\mu \to e^- + \boldsymbol{\bar{\nu}_e} + \boldsymbol{\nu_\mu} + \boldsymbol{\bar{\nu}_\mu} \end{array}$$

How do ν and γ get produced in blazars?

Electrons and protons in the relativistic jet emit synchrotron radiation.

The UV / X-ray emission is caused by electrons. We can have three different scenarios depending on what is the dominant process producing the γ-ray part of the spectrum: [M.Cerruti, Galaxies 8 (2020) 4, 72]

- ~~*Leptonic models* – γ-rays are produced by inverse-Compton scattering~~;
- *Hadronic models* – γ-rays are produced by proton synchrotron emission;
- *Lepto-Hadronic models* – γ-rays are generated by secondary leptons produced in proton-photon interactions.

Neutrinos are produced **only** in proton-photon interactions:

$$p + \gamma \to p + \pi^0 \qquad \pi^0 \to 2\gamma$$

$$\left.\begin{array}{l} p + \gamma \to n + \pi^+ \\ p + \gamma \to p + \pi^+ + \pi^- \end{array}\right\} \qquad \begin{array}{l} \pi^+ \to \mu^+ + \nu_\mu \to e^+ + \boldsymbol{\nu_e} + \boldsymbol{\bar{\nu}_\mu} + \boldsymbol{\nu_\mu} \\ \pi^- \to \mu^- + \bar{\nu}_\mu \to e^- + \boldsymbol{\bar{\nu}_e} + \boldsymbol{\nu_\mu} + \boldsymbol{\bar{\nu}_\mu} \end{array}$$

How do ν and γ get produced in blazars?

Electrons and protons in the relativistic jet emit synchrotron radiation.

The UV / X-ray emission is caused by electrons. We can have three different scenarios depending on what is the dominant process producing the γ-ray part of the spectrum: [M.Cerruti, Galaxies 8 (2020) 4, 72]

- ~~*Leptonic models* – γ-rays are produced by inverse-Compton scattering~~;
- *Hadronic models* – γ-rays are produced by proton synchrotron emission;
- *Lepto-Hadronic models* – γ-rays are generated by secondary leptons produced in proton-photon interactions.

To fit the spectrum data, (pure) hadronic models

- require extremely high proton density, giving $L_p \gg L_{\text{Edd}}$;
- require very strong magnetic field;
- give generally a low ν production.

How do ν and γ get produced in blazars?

Electrons and protons in the relativistic jet emit synchrotron radiation.

The UV / X-ray emission is caused by electrons. We can have three different scenarios depending on what is the dominant process producing the γ-ray part of the spectrum: [M.Cerruti, Galaxies 8 (2020) 4, 72]

- ~~*Leptonic models* – γ-rays are produced by inverse-Compton scattering~~;
- *Hadronic models* – γ-rays are produced by proton synchrotron emission;
- *Lepto-Hadronic models* – γ-rays are generated by secondary leptons produced in proton-photon interactions. $\Longrightarrow$ **favored!**

To fit the spectrum data, (pure) hadronic models

- require extremely high proton density, giving $L_p \gg L_{\text{Edd}}$;
- require very strong magnetic field;
- give generally a low ν production.

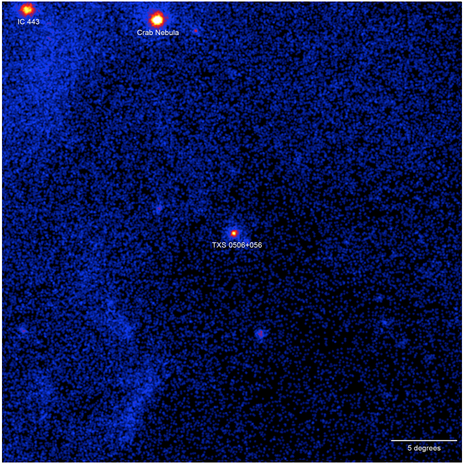
Blazar TXS 0506+056

Parameter	Value
z	0.3365
D_L	1835.4 Mpc
$M_{\rm BH}$	$3.09 \times 10^8 \ M_\odot$
R_S	$\sim 10^{14}$ cm

Table: 1 pc $\sim 3 \times 10^{18}$ cm $\sim 3 \times 10^4$ $\rm R_S$.

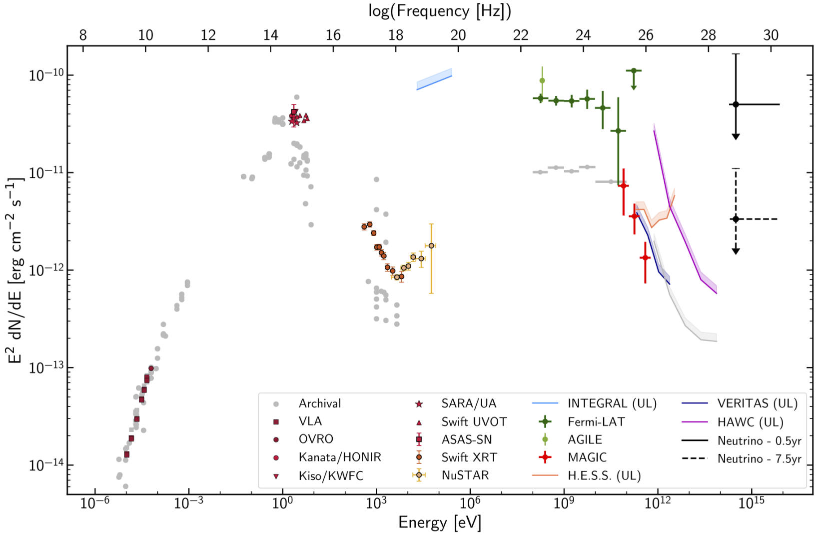
[P.Padovani et al., MNRAS 484 (2019) 1, L104-L108]

[S.Paiano et al., ApJL 854 (2018) 2, L32]



[Credit: NASA/DOE/Fermi LAT Collaboration]

Blazar TXS 0506+056 during 2017 flare



[IceCube et al., Science 361 (2018) 6398]

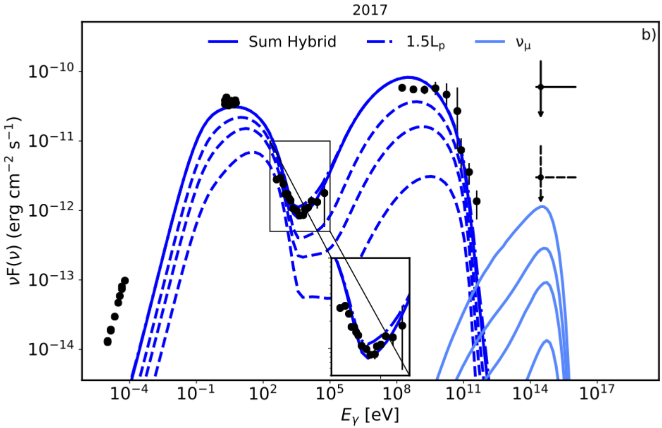
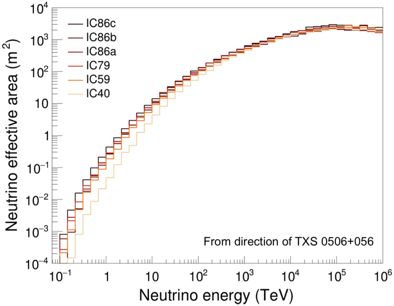


Figure: SOPRANO simulation result. Dashed lines are intermediate solutions during the time-evolution of the system. [S.Gasparyan et al., MNRAS 509 (2021) 2, 2102-2121]

The neutrino spectrum is consistent with the result of other simulations (e.g. [S.Gao et al., Nature Astron. 3 (2019) 1, 88-92]).

Number of ν expected by IceCube (w/o DM interaction)

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



During the entire campaign where the event occurred

$t_{\text{obs}} \sim 900$ days $\Rightarrow$ $N_{\text{pred}} \simeq 2.6$ evts

Sample	Start	End
IC40	2008 Apr 5	2009 May 20
IC59	2009 May 20	2010 May 31
IC79	2010 May 31	2011 May 13
IC86a	2011 May 13	2012 May 16
IC86b	2012 May 16	2015 May 18
IC86c	2015 May 18	2017 Oct 31

During the $\sim$ 6-month flare

$t_{\text{obs}} \sim 180$ days $\Rightarrow$ $N_{\text{pred}} \simeq 0.5$ evts

consistent with observations!

[S.Gasparyan et al., MNRAS 509 (2021) 2, 2102-2121]

[IceCube, Science 361 (2018) 6398, 147-151]

Number of ν expected by IceCube (w/o DM interaction)

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

During the entire campaign where the event occurred

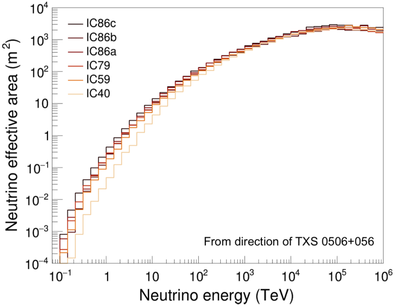
$t_{\rm obs} \sim 900$ days $\Rightarrow$ $\mathrm{N_{pred}} \simeq 2.6$ evts

During the $\sim$ 6-month flare

$t_{\rm obs} \sim 180$ days $\Rightarrow$ $\mathrm{N_{pred}} \simeq 0.5$ evts

consistent with observations!

[S.Gasparyan et al., MNRAS 509 (2021) 2, 2102-2121]



Sample	Start	End
IC40	2008 Apr 5	2009 May 20
IC59	2009 May 20	2010 May 31
IC79	2010 May 31	2011 May 13
IC86a	2011 May 13	2012 May 16
IC86b	2012 May 16	2015 May 18
IC86c	2015 May 18	2017 Oct 31

[IceCube, Science 361 (2018) 6398, 147-151]

DM distribution around blazars:

DM spike

DM distribution around blazars: DM spike

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

$$\rho(r) \propto r^{-\gamma} \qquad \Longrightarrow \qquad \rho'(r) \propto r^{-\alpha}\,, \qquad \alpha = \frac{9-2\gamma}{4-\gamma}$$

where $0 \leq \gamma \leq 2$ $(\gamma_{\mathrm{NFW}} = 1)$ and hence $2.25 \leq \alpha \leq 2.5$ $(\alpha_{\mathrm{NFW}} = 7/3)$.

Gravitational scattering between DM and stars can dynamically relax the DM spike profile to $\alpha = 3/2$. [O.Y.Gnedin & J.R.Primack, PRL 93 (2004) 061302]

The normalization of $\rho'(r)$ can be determined via [P.Ullio et al., PRD 64 (2001) 043504]

$$4\pi \int_{4R_S}^{r_0} dr\, r^2 \rho'(r) \simeq M_{\mathrm{BH}}$$

where $R_S = 2GM_{\mathrm{BH}}$ is the Schwarzschild radius and $r_0 \simeq 10^5 R_S$ is the typical size of the spike. [M.Gorchtein et al., PRD 82 (2010) 083514]

DM distribution around blazars: DM spike

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

$$\rho(r) \propto r^{-\gamma} \qquad \Longrightarrow \qquad \rho'(r) \propto r^{-\alpha}\,, \qquad \alpha = \frac{9-2\gamma}{4-\gamma}$$

where $0 \leq \gamma \leq 2$ $(\gamma_{\mathrm{NFW}} = 1)$ and hence $2.25 \leq \alpha \leq 2.5$ $(\alpha_{\mathrm{NFW}} = 7/3)$.

Gravitational scattering between DM and stars can dynamically relax the DM spike profile to $\alpha = 3/2$. [O.Y.Gnedin & J.R.Primack, PRL 93 (2004) 061302]

The normalization of $\rho'(r)$ can be determined via [P.Ullio et al., PRD 64 (2001) 043504]

$$4\pi \int_{4R_S}^{r_0} dr\, r^2 \rho'(r) \simeq M_{\mathrm{BH}}$$

where $R_S = 2GM_{\mathrm{BH}}$ is the Schwarzschild radius and $r_0 \simeq 10^5 R_S$ is the typical size of the spike. [M.Gorchtein et al., PRD 82 (2010) 083514]

DM distribution around blazars: DM spike

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

$$\rho(r) \propto r^{-\gamma} \qquad \Longrightarrow \qquad \rho'(r) \propto r^{-\alpha}\,, \qquad \alpha = \frac{9-2\gamma}{4-\gamma}$$

where $0 \leq \gamma \leq 2$ $(\gamma_{\rm NFW} = 1)$ and hence $2.25 \leq \alpha \leq 2.5$ $(\alpha_{\rm NFW} = 7/3)$.

Gravitational scattering between DM and stars can dynamically relax the DM spike profile to $\alpha = 3/2$. [O.Y.Gnedin & J.R.Primack, PRL 93 (2004) 061302]

The normalization of $\rho'(r)$ can be determined via [P.Ullio et al., PRD 64 (2001) 043504]

$$4\pi \int_{4R_S}^{r_0} dr\, r^2 \rho'(r) \simeq M_{\rm BH}$$

where $R_S = 2GM_{\rm BH}$ is the Schwarzschild radius and $r_0 \simeq 10^5 R_S$ is the typical size of the spike. [M.Gorchtein et al., PRD 82 (2010) 083514]

DM distribution around blazars: DM spike

If DM annihilation occurs, the spike profile becomes more cored

$$\rho'(r) \propto r^{-\alpha} \qquad \Longrightarrow \qquad \rho_\chi(r) \simeq \frac{\rho'(r)\,\rho_c}{\rho'(r)+\rho_c}\,, \qquad \rho_c \simeq \frac{m_\chi}{\langle\sigma_a v\rangle\, t_{\rm BH}}$$

where $\langle\sigma_a v\rangle$ is the "effective" velocity-averaged annihilation cross section and $t_{\rm BH}$ is the age of the BH.

Model	α	$\langle\sigma_a v\rangle$ [cm^3/s]
BM1	7/3	0
BM2	7/3	10^{-28}
BM3	7/3	3×10^{-26}
BM1′	3/2	0
BM2′	3/2	10^{-28}
BM3′	3/2	3×10^{-26}

Table: $t_{\rm BH} \sim 10^9$ yrs.

DM distribution around blazars: DM spike

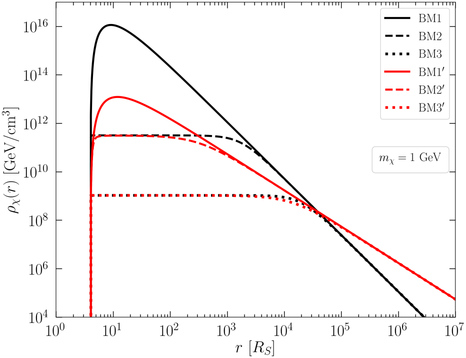
If DM annihilation occurs, the spike profile becomes more cored

$$\rho'(r) \propto r^{-\alpha} \qquad \Longrightarrow \qquad \rho_\chi(r) \simeq \frac{\rho'(r)\,\rho_c}{\rho'(r)+\rho_c}, \qquad \rho_c \simeq \frac{m_\chi}{\langle\sigma_a v\rangle\, t_{\rm BH}}$$

where $\langle\sigma_a v\rangle$ is the "effective" velocity-averaged annihilation cross section and $t_{\rm BH}$ is the age of the BH.

Model	α	$\langle\sigma_a v\rangle$ [cm^3/s]
BM1	7/3	0
BM2	7/3	10^{-28}
BM3	7/3	3×10^{-26}
BM1′	3/2	0
BM2′	3/2	10^{-28}
BM3′	3/2	3×10^{-26}

Table: $t_{\rm BH}\sim10^9$ yrs.

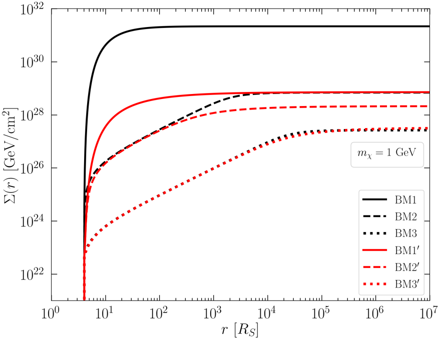


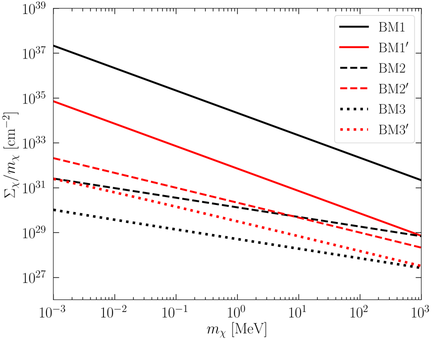
DM distribution around blazars: DM spike

The important quantity for ν-DM scattering is the **DM column density**

[J.-W. Wang et al., PRL 128 (2022) 22, 221104] [A.Granelli et al., JCAP 07 (2022) 07, 013]

$$\Sigma(r) = \int_{4R_S}^{r} dr' \, \rho_\chi(r') \qquad \longrightarrow \qquad \Sigma_\chi \equiv \Sigma(r \gtrsim 10^6 R_S \sim \mathcal{O}(10 \text{ pc}))$$





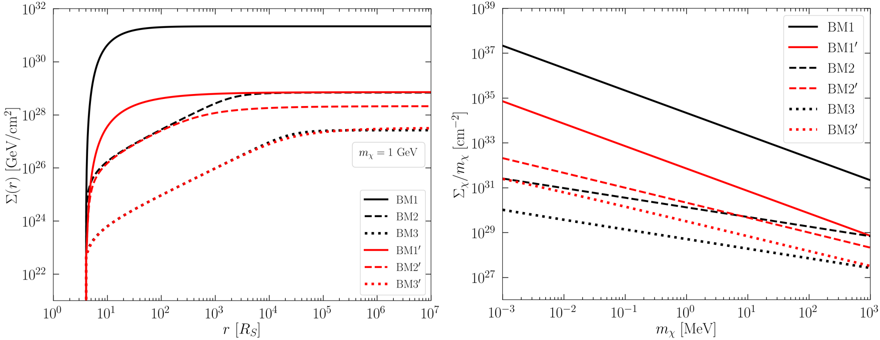
Note: The cosmological and Milky-Way galactic contributions to Σ_χ are negligible compared to that of the DM spike. Possible to include the effect of the outer halo of the host galaxy (see [F.Ferrer et al., arXiv:2209.06339]).

DM distribution around blazars: DM spike

The important quantity for ν-DM scattering is the **DM column density**

[J.-W. Wang et al., PRL 128 (2022) 22, 221104] [A.Granelli et al., JCAP 07 (2022) 07, 013]

$$\Sigma(r) = \int_{4R_S}^{r} dr' \, \rho_\chi(r') \quad \longrightarrow \quad \Sigma_\chi \equiv \Sigma(r \gtrsim 10^6 R_S \sim \mathcal{O}(10 \text{ pc}))$$



Note: The cosmological and Milky-Way galactic contributions to Σ_χ are negligible compared to that of the DM spike. Possible to include the effect of the outer halo of the host galaxy (see [F.Ferrer et al., arXiv:2209.06339]).

Flux attenuation: Cascade equation

The neutrino flux from the source gets attenuated while passing through the DM density along the l.o.s. according to [C. A. Argüelles et al., PRL 119, 201801 (2017)]

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

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

- First term: energy loss due to ν-DM scatterings;
- Second term: redistribution of ν energy from high to low energies.

Naive estimate: Neglecting the second term

$$\frac{\Phi_\nu^{\rm obs}}{\Phi_\nu^{\rm em}} \sim e^{-\sigma_{\nu\chi}\,\Sigma_\chi/m_\chi} \qquad \Longrightarrow \qquad \sigma_{\nu\chi} \lesssim \mathcal{O}(1)\, m_\chi/\Sigma_\chi$$

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

Flux attenuation: Cascade equation

The neutrino flux from the source gets attenuated while passing through the DM density along the l.o.s. according to [C. A. Argüelles et al., PRL 119, 201801 (2017)]

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

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

- First term: energy loss due to ν-DM scatterings;
- Second term: redistribution of ν energy from high to low energies.

Naive estimate: Neglecting the second term

$$\frac{\Phi_\nu^{\rm obs}}{\Phi_\nu^{\rm em}} \sim e^{-\sigma_{\nu\chi}\Sigma_\chi/m_\chi} \qquad \Longrightarrow \qquad \sigma_{\nu\chi} \lesssim \mathcal{O}(1)\, m_\chi/\Sigma_\chi$$

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

Flux attenuation: Cascade equation

The neutrino flux from the source gets attenuated while passing through the DM density along the l.o.s. according to [C. A. Argüelles et al., PRL 119, 201801 (2017)]

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

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

- First term: energy loss due to ν-DM scatterings;
- Second term: redistribution of ν energy from high to low energies.

Naive estimate: Neglecting the second term

$$\frac{\Phi_\nu^{\rm obs}}{\Phi_\nu^{\rm em}} \sim e^{-\sigma_{\nu\chi}\,\Sigma_\chi/m_\chi} \qquad \Longrightarrow \qquad \sigma_{\nu\chi} \lesssim \mathcal{O}(1)\, m_\chi/\Sigma_\chi$$

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

Assumption: linear energy-dependent $\sigma_{\nu\chi}$

A simple and well-motivated choice for $\sigma_{\nu\chi}(E_\nu)$ is

$$\sigma_{\nu\chi} = \sigma_0 \frac{E_\nu}{E_0}\,, \qquad E_0 = 290\ \text{TeV}$$

and, for isotropic scattering in the CoM frame, $d\sigma_{\nu\chi}/dE_\nu = \sigma_0/E_0$.

Solving the cascade equation numerically and demanding that

$$N_{\text{pred}} = t_{\text{obs}} \int_{E_\nu \geq E_0} dE_\nu\, \Phi_\nu(E_\nu)\, A_{\text{eff}}(E_\nu) \geq 0.1$$

we get

$$\sigma_0 = \sigma_{\nu\chi}(E_0) < 1.6\, m_\chi/\Sigma_\chi$$

in agreement with the naive estimate!

Assumption: linear energy-dependent $\sigma_{\nu\chi}$

A simple and well-motivated choice for $\sigma_{\nu\chi}(E_\nu)$ is

$$\sigma_{\nu\chi} = \sigma_0 \frac{E_\nu}{E_0}\,, \qquad\qquad E_0 = 290\text{ TeV}$$

and, for isotropic scattering in the CoM frame, $d\sigma_{\nu\chi}/dE_\nu = \sigma_0/E_0$.

Solving the cascade equation numerically and demanding that

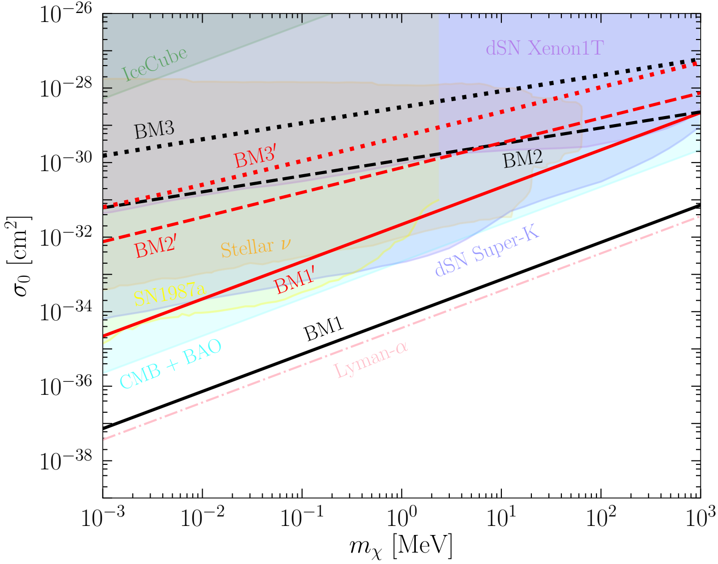
$$N_{\text{pred}} = t_{\text{obs}} \int_{E_\nu \geq E_0} dE_\nu \, \Phi_\nu(E_\nu)\, A_{\text{eff}}(E_\nu) \geq 0.1$$

we get

$$\sigma_0 = \sigma_{\nu\chi}(E_0) < 1.6\, m_\chi/\Sigma_\chi$$

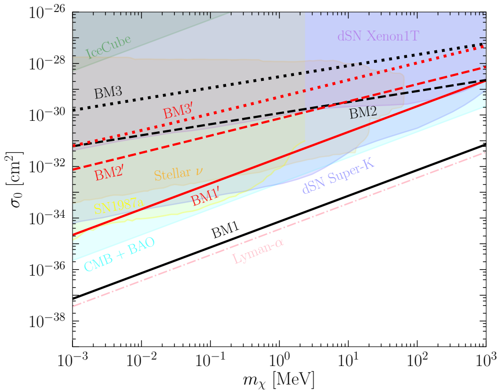
in agreement with the naive estimate!

Our upper limits on σ_0



Note: Other limits shown assume **energy-independent** $\sigma_{\nu\chi}$!

Our upper limits on σ_0



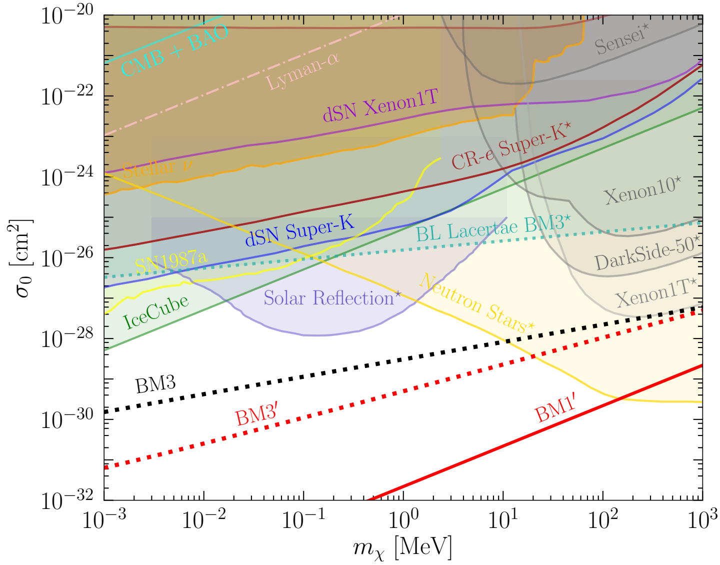
Note: Other limits shown assume **energy-independent** $\sigma_{\nu\chi}$!

Existing bounds on $\boldsymbol{\sigma_{\nu\chi}}$ from:

- suppression in primordial density fluctuations affecting CMB and matter power spectra (cyan, pink$^{(*)}$);
- boosting DM by neutrinos from stars (orange), diffuse supernovae (dark violet, blue), SN1987a (yellow);
- attenuation of neutrino flux from supernovae, galactic centre;
- delayed neutrino propagation;
- effects in the extragalactic distribution and spectra of PeV neutrinos.

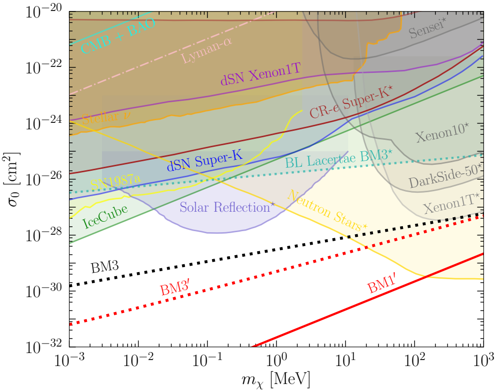
(for references, see [J.Cline et al., arXiv:2209.02713])

Comparison to previous limits (those for $\sigma_{e\chi}$ with *)



Note: Re-scaled existing limits to $E_0 = 290$ TeV !

Comparison to previous limits (those for $\sigma_{e\chi}$ with *)



Note: **Re-scaled** existing limits to $E_0 = 290$ TeV !

(for references, see [J.Cline et al., arXiv:2209.02713])

Existing bounds on $\boldsymbol{\sigma_{e\chi}}$ from:

- alteration of CMB anisotropies, shape of matter power spectrum and abundance of Milky-Way satellites;
- CMB spectral distortions;
- heating/cooling the gas in dwarf galaxies;
- boosting DM by cosmic rays (brown), particle in solar interior (slateblue) or in blazar jets (turquoise);
- direct detection on light DM (gray);
- alteration of cosmic-ray spectrum;
- heating neutron stars (gold) and white dwarfs.

How can we get $\sigma_{\nu\chi} \sim E_\nu$ physically?

Consider a simple model with scattering between DM particle χ (e.g. complex scalar) and SM lepton doublet L_i mediated by a new boson Z'.
Assume flavor universal coupling g.

At high energies $(E_\nu \gg m_\chi)$

$$\sigma_{\nu\chi} \simeq \frac{g^4}{4\pi\, m_{Z'}^2}\left[1 - \frac{m_{Z'}^2}{2m_\chi E_\nu}\ \ln\left(1 + \frac{2m_\chi E_\nu}{m_{Z'}^2}\right)\right]$$

Two regimes:

- $\boxed{\sigma_{\nu\chi} \propto E_\nu}$ *(heavy mediator)*
  for $m_{Z'}^2 > m_\chi E_\nu \gtrsim 1\ \mathrm{GeV}^2$
- $\boxed{\sigma_{\nu\chi} \sim \mathrm{const}}$ *(light mediator)*
  for $E_\nu \gg m_{Z'}^2/m_\chi$

How can we get $\sigma_{\nu\chi} \sim E_\nu$ physically?

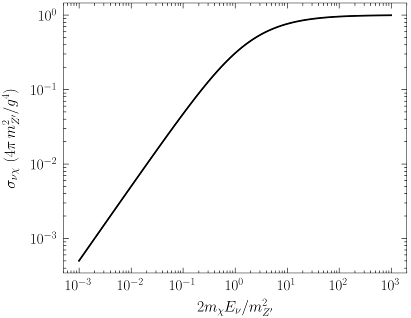
Consider a simple model with scattering between DM particle χ (e.g. complex scalar) and SM lepton doublet L_i mediated by a new boson Z'.
Assume flavor universal coupling g.

At high energies $(E_\nu \gg m_\chi)$

$$\sigma_{\nu\chi} \simeq \frac{g^4}{4\pi\, m_{Z'}^2}\left[1 - \frac{m_{Z'}^2}{2m_\chi E_\nu}\ \ln\left(1 + \frac{2m_\chi E_\nu}{m_{Z'}^2}\right)\right]$$

Two regimes:

- $\boxed{\sigma_{\nu\chi} \propto E_\nu}$ *(heavy mediator)*
  for $m_{Z'}^2 > m_\chi E_\nu \gtrsim 1\ \mathrm{GeV}^2$
- $\boxed{\sigma_{\nu\chi} \sim \mathrm{const}}$ *(light mediator)*
  for $E_\nu \gg m_{Z'}^2/m_\chi$



How can we get $\sigma_{\nu\chi} \sim E_\nu$ physically?

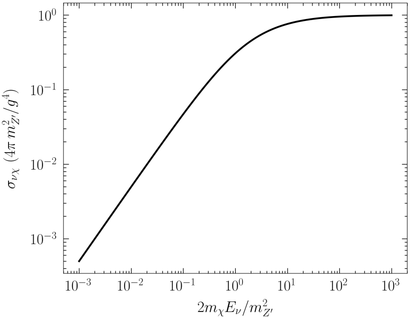
Consider a simple model with scattering between DM particle χ (e.g. complex scalar) and SM lepton doublet L_i mediated by a new boson Z'.
Assume flavor universal coupling g.

At high energies ($E_\nu \gg m_\chi$)

$$\sigma_{\nu\chi} \simeq \frac{g^4}{4\pi\, m_{Z'}^2}\left[1 - \frac{m_{Z'}^2}{2m_\chi E_\nu} \ln\left(1 + \frac{2m_\chi E_\nu}{m_{Z'}^2}\right)\right]$$

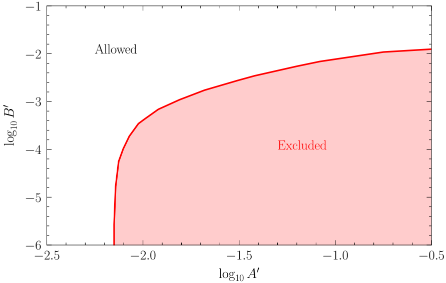
Two regimes:

- $\boxed{\sigma_{\nu\chi} \propto E_\nu}$ *(heavy mediator)*
  for $m_{Z'}^2 > m_\chi E_\nu \gtrsim 1\ \mathrm{GeV}^2$
- $\boxed{\sigma_{\nu\chi} \sim \mathrm{const}}$ *(light mediator)*
  for $E_\nu \gg m_{Z'}^2/m_\chi$



How can we get $\sigma_{\nu\chi} \sim E_\nu$ physically?

$$A' \equiv \frac{g^4\,\Sigma_\chi \cdot (1\,\mathrm{TeV})}{4\pi\, m_{Z'}^4}, \qquad B' \equiv \frac{m_\chi \cdot (1\,\mathrm{TeV})}{m_{Z'}^2}$$

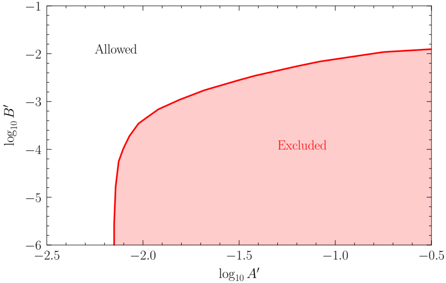


Observations:

- $\sigma_{\nu\chi} \propto E_\nu$ for $B' \lesssim 0.1$ and hence $A' \lesssim 7.2 \times 10^{-3}$
- $\sigma_{\nu\chi} \sim$ const as B' increases and bound on A' relaxes

How can we get $\sigma_{\nu\chi} \sim E_\nu$ physically?

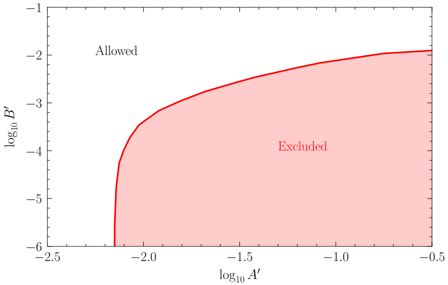
$$A' \equiv \frac{g^4\,\Sigma_\chi \cdot (1\,\text{TeV})}{4\pi\, m_{Z'}^4}, \qquad B' \equiv \frac{m_\chi \cdot (1\,\text{TeV})}{m_{Z'}^2}$$

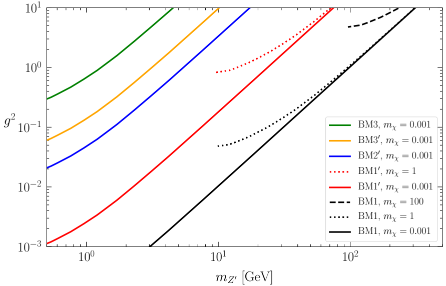


Observations:

- $\sigma_{\nu\chi} \propto E_\nu$ for $B' \lesssim 0.1$ and hence $A' \lesssim 7.2 \times 10^{-3}$
- $\sigma_{\nu\chi} \sim$ const as B' increases and bound on A' relaxes

$$A' \equiv \frac{g^4\,\Sigma_\chi \cdot (1\,\text{TeV})}{4\pi\, m_{Z'}^4}, \qquad B' \equiv \frac{m_\chi \cdot (1\,\text{TeV})}{m_{Z'}^2}$$





Observations:

- $\sigma_{\nu\chi} \propto E_\nu$ for $B' \lesssim 0.1$ and hence $A' \lesssim 7.2 \times 10^{-3}$
- $\sigma_{\nu\chi} \sim$ const as B' increases and bound on A' relaxes

Summary & Outlook

We used the attenuation of the neutrino flux from TXS 0506+056 to constrain $\sigma_{\nu\chi}$, based on the assumption that IceCube-170922A came indeed from this blazar.

Main Results

- If $\sigma_{\nu\chi} \propto E_\nu$ (e.g. heavy mediator), we set the **strongest** limits in the literature for sub-GeV DM at energies of ~ 300 TeV, independently of the DM-spike profile;
- Same conclusion for $\sigma_{e\chi}$ if DM has the same coupling with charged leptons and neutrinos;
- If $\sigma_{\nu\chi} \sim$ const (e.g. light mediator), we set *competitive* and independent bounds.

Uncertainties on: DM-spike profile around the BH powering TXS 0506+056, value of $\langle \sigma_a v \rangle$, location of neutrino emitting region, ...

Summary & Outlook

We used the attenuation of the neutrino flux from TXS 0506+056 to constrain $\sigma_{\nu\chi}$, based on the assumption that IceCube-170922A came indeed from this blazar.

Main Results

- If $\sigma_{\nu\chi} \propto E_\nu$ (e.g. heavy mediator), we set the **strongest** limits in the literature for sub-GeV DM at energies of $\sim$ 300 TeV, independently of the DM-spike profile;
- Same conclusion for $\sigma_{e\chi}$ if DM has the same coupling with charged leptons and neutrinos;
- If $\sigma_{\nu\chi} \sim$ const (e.g. light mediator), we set *competitive* and independent bounds.

Uncertainties on: DM-spike profile around the BH powering TXS 0506+056, value of $\langle \sigma_a v \rangle$, location of neutrino emitting region, ...

Summary & Outlook

We used the attenuation of the neutrino flux from TXS 0506+056 to constrain $\sigma_{\nu\chi}$, based on the assumption that IceCube-170922A came indeed from this blazar.

Main Results

- If $\sigma_{\nu\chi} \propto E_\nu$ (e.g. heavy mediator), we set the **strongest** limits in the literature for sub-GeV DM at energies of ~ 300 TeV, independently of the DM-spike profile;
- Same conclusion for $\sigma_{e\chi}$ if DM has the same coupling with charged leptons and neutrinos;
- If $\sigma_{\nu\chi} \sim$ const (e.g. light mediator), we set *competitive* and independent bounds.

Uncertainties on: DM-spike profile around the BH powering TXS 0506+056, value of $\langle \sigma_a v \rangle$, location of neutrino emitting region, . . .

Summary & Outlook

- If $\sigma_{\nu\chi} \propto E_\nu$ (e.g. heavy mediator), we set the **strongest** limits in the literature so far for sub-GeV DM at energies of ~ 300 TeV, independently of the DM-spike profile;
- Same conclusion for $\sigma_{e\chi}$ if DM has the same coupling with charged leptons and neutrinos;
- If $\sigma_{\nu\chi} \sim$ const (e.g. light mediator), we set *competitive* and independent bounds.

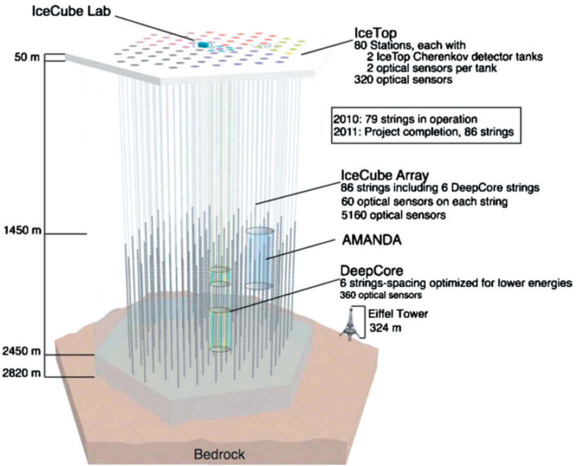
Exciting time! New possible neutrino-blazar associations have been done after IceCube-170922A with TXS 0506+056

(e.g. IceCube-190730A with PKS 1502+106 [X.Rodrigues et al., ApJ 912 (2021) 1, 54]; IceCube-200107A with 3HSP J095507.9+355101 [P.Giommi et al., A&A 640 (2020) L4]; IceCube-141209A with GB6 J1040+0617 [FermiLAT et al., ApJ 880 (2019) 2, 880-103]; IceCube-35 with PKS B1424-418 [M.Kadler et al., Nature Phys. 12 (2016) 8, 807-814]; IceCube-211208A with PKS 0735+178 [N.Sahakyan et al., arXiv:2204.05060]; IceCube events with PKS 1424+240 and GB6 J1542+6129 [IceCube Coll., ApJL 920 (2021) 2, L45]; others [P.Giommi, MNRAS 497 (2020) 1, 865-878] [A.Franckowiak, ApJ 893 (2020) 2, 162])

Thank you for your attention!

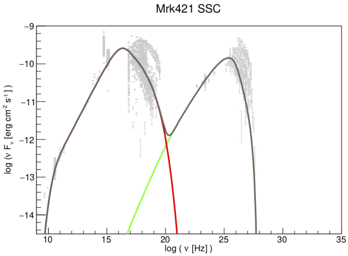
Backup slides

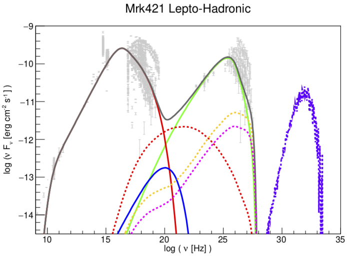
IceCube observatory

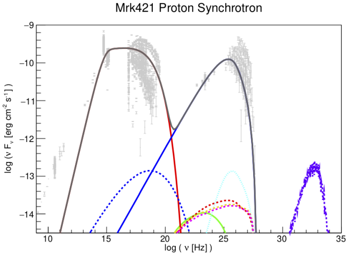


[Credit: IceCube Science Team - Francis Halzen (UoW)]

Blazar jet models







[M.Cerruti, Galaxies 8 (2020) 4, 72]

Legend:

solid red – electron synchrotron;
solid green – inverse-Compton;
solid blue – proton synchrotron;
dotted blue – synchrotron emission by secondary pairs from proton–synchrotron;
dotted red – synchrotron emission by $p + \gamma \rightarrow p + e^- + e^+$ (*Bethe-Heitler* cascade);
dotted yellow – synchrotron emission by π^0 cascade;
dotted pink – synchrotron emission by $\pi^{\pm}$;
violet – neutrino emission.

Z' boson mediated $\nu - \chi$ scattering

Simple model with boson Z', DM particle χ (complex scalar), SM lepton doublet L_i and assuming universal coupling g

$$\mathcal{L} \supset g^2 Z'_\mu Z'^{\mu} \chi^* \chi - i g Z'_\mu [\chi^* (\partial^\mu \chi) - (\partial^\mu \chi^*) \chi] - g Z_\mu \bar{L} \gamma^\mu L$$

The square of the matrix element is (t-*channel*)

$$|\mathcal{M}|^2 = \frac{4g^4}{(t - m_{Z'}^2)} [(s - m_\chi^2)^2 + s\, t]$$

The full cross section is

$$\sigma = \frac{g^4}{4\pi m_{Z'}^2} \left[1 - \frac{m_{Z'}^2 (2E_\nu + m_\chi)}{4 m_\chi E_\nu^2} \ln \left(1 + \frac{4 m_\chi E_\nu^2}{m_{Z'}^2 (2E_\nu + m_\chi)} \right) \right]$$

Note: To cancel gauge anomalies, the Z' should also couple to right-handed leptons and neutrinos. A scalar-mediated interaction would require insertions of the Higgs field to satisfy $SU(2)_L$ gauge invariance, which could lead to inelastic scattering involving Higgs bosons at high energy.

Z' boson mediated $\nu - \chi$ scattering

Simple model with boson Z', DM particle χ (complex scalar), SM lepton doublet L_i and assuming universal coupling g

$$\mathcal{L} \supset g^2 Z'_\mu Z'^\mu \chi^* \chi - ig Z'_\mu [\chi^* (\partial^\mu \chi) - (\partial^\mu \chi^*)\chi] - g Z_\mu \bar{L} \gamma^\mu L$$

At high energies ($E_\nu \gg m_\chi$)

$$\sigma_{\nu\chi} \simeq \frac{g^4}{4\pi\, m_{Z'}^2} \left[1 - \frac{m_{Z'}^2}{2 m_\chi E_\nu} \ln\left(1 + \frac{2 m_\chi E_\nu}{m_{Z'}^2} \right) \right]$$

The corresponding differential cross section is

$$\frac{d\sigma_{\nu\chi}}{dE_\nu} (E'_\nu \to E_\nu) \simeq \frac{(g^4/4\pi)(m_\chi\, E_\nu / E'_\nu)}{(m_{Z'}^2 + 2 m_\chi (E'_\nu - E_\nu))^2}$$

Note: To cancel gauge anomalies, the Z' should also couple to right-handed leptons and neutrinos. A scalar-mediated interaction would require insertions of the Higgs field to satisfy $SU(2)_L$ gauge invariance, which could lead to inelastic scattering involving Higgs bosons at high energy.