Blazar-Boosted Dark Matter

Jin-Wei Wang
Astroparticle Physics, SISSA

JW Wang, A. Granelli, P. Ullio; PRL, arXiv:2111.13644
A. Granelli, P. Ullio, JW Wang; JCAP, arXiv:2202.07598

Taipei, Jun 30th, 2022
Outline

• Introduction and motivation
• Spectrum of the relativistic blazar jet
• Dark matter density profile
• Dark matter flux from blazars
• Experimental constraints
• Summary
Dark matter in the Universe

• The astrophysical and cosmological observations have provided compelling evidences of the existence of **dark matter (DM)**.

\[
\Omega_c h^2 = 0.11933 \pm 0.00091 \\
\Omega_b h^2 = 0.02242 \pm 0.00014 \\
\Omega_\Lambda = 0.6889 \pm 0.0056
\]
DM direct detection

(XENON Collaboration)
Phys. Rev. Lett. 121, 111302
DM direct detection

(1XON Collaboration)
Phys. Rev. Lett. 121, 111302

DM number density
$\sigma_{SI} \sim m_\chi$
DM direct detection

Kinetic energy

$E_R \in [4.9, 40.9] \text{ keV}$

DM number density

$\sigma_{SI} \sim m_\chi$
DM direct detection

(XENON Collaboration)
Phys. Rev. Lett. 121, 111302

Kinetic energy

\[ E_R \in [4.9, 40.9] \text{ keV} \]

- **Improve DM kinetic energy:** scattering between cosmic-ray particles and DM (CRDM); [1810.10543]
- **Reduce** \( E_{th} \): Migdal effects; [1907.11485, 1707.07258]

DM number density
\[ \sigma_{SI} \sim m_\chi \]
Why Blazars?
Why Blazars?

- The extremely powerful jet, which implies high proton and/or electron flux;
- Large DM density;
The blazar jet model

- **The leptonic (synchrotron-self-Compton) model**: the radio through X-ray emission is produced by electron-synchrotron radiation, while the $\gamma$-rays are produced by inverse Compton scattering;
The blazar jet model

- **Pure hadronic (proton–synchrotron) model**: high-energy emission is produced by proton–synchrotron emission.
The blazar jet model

- **Lepto-Hadronic model**: high-energy emission is produced by secondary leptons produced in p-\(\gamma\) interactions are usually referred to as lepto-hadronic models.
The blazar jet model

- **The leptonic (synchrotron-self-Compton) model**: the radio through X-ray emission is produced by synchrotron radiation, while the $\gamma$-rays are produced by inverse Compton scattering;

- **Pure hadronic (proton–synchrotron) model**: high-energy emission is produced by proton–synchrotron emission.

- **Lepto-Hadronic model**: high-energy emission is produced by secondary leptons produced in $p-\gamma$ interactions are usually referred to as lepto-hadronic models.

### Photo-Meson Production

\[
P + \gamma \rightarrow p' + \pi^0 \\
P + \gamma \rightarrow n + \pi^+ \\
P + \gamma \rightarrow p' + \pi^+ + \pi^-
\]

Neutrinos as smoking gun of hadronic processes
The blazar jet model

- **The leptonic (synchrotron-self-Compton) model**: the radio through X-ray emission is produced by synchrotron radiation, while the $\gamma$-rays are produced by inverse Compton scattering;

- **Pure hadronic (proton–synchrotron) model**: high-energy emission is produced by proton–synchrotron emission.

In July 2018, the IceCube Neutrino Observatory announced that they have traced an extremely-high-energy neutrino back to its point of origin in the blazar TXS 0506 +056

Photo-Meson Production

Neutrinos as smoking gun of hadronic processes

\[
\begin{align*}
    p + \gamma &\rightarrow p' + \pi^0 \\
    p + \gamma &\rightarrow n + \pi^+ \\
    p + \gamma &\rightarrow p' + \pi^+ + \pi^-
\end{align*}
\]
The blazar jet model

- **The leptonic (synchrotron-self-Compton) model**: the radio through X-ray emission is produced by synchrotron radiation, while the $\gamma$-rays are produced by inverse Compton scattering;

- **Pure hadronic (proton–synchrotron) model**: high-energy emission is produced by proton–synchrotron emission.

- **Lepto-Hadronic model**: high-energy emission is produced by secondary leptons produced in $p-\gamma$ interactions are usually referred to as lepto-hadronic models.

- **TXS 0506+056 lepto-hadronic model** & **BL Lacerta pure hadronic model**

- Consider the **proton/electron-DM** interaction.
Spectrum of the relativistic blazar jet

\[ \frac{d\Gamma'_j}{dE'_j d\Omega'} \]

Blob frame

\[ \Gamma_B \equiv (1 - \beta_B^2)^{-1/2} \]

Lorentz boost

\[ \frac{d\Gamma_j}{dE_j d\Omega} \]

Black hole (BH) frame
Spectrum of the relativistic blazar jet

- Single power-law distribution:
  \[
  \frac{d\Gamma_j'}{dE_j'd\Omega'} = \frac{1}{4\pi c_j} \left( \frac{E_j'}{m_j} \right)^{-\alpha_j}
  \]

\[\Gamma_B \equiv (1 - \beta_B^2)^{-1/2}\]

Blob frame\hspace{1cm} Lorentz boost\hspace{1cm} Black hole (BH) frame
Spectrum of the relativistic blazar jet

- Single power-law distribution:

\[
\frac{d\Gamma_j'}{dE_j'd\Omega'} = \frac{1}{4\pi} c_j \left( \frac{E_j'}{m_j} \right)^{-\alpha_j}
\]

- Lorentz boost:

\[
\gamma'(\gamma, \mu) = (1 - \beta_B \beta \mu) \gamma \Gamma_B, \quad \mu'(\gamma, \mu) = \frac{\beta \mu - \beta_B}{\sqrt{(1 - \beta_B \beta \mu)^2 - (1 - \beta^2)(1 - \beta_B^2)}}
\]

with \( \beta = \sqrt{1 - 1/\gamma^2} \) is the particle velocity
Spectrum of the relativistic blazar jet

- The spectrum of blazar jet in black hole frame can be expressed as:

\[
\frac{d\Gamma}{dE \, d\Omega} = \Gamma_B \left| \frac{d\Gamma'}{dE' \, d\Omega'} \right| \det \begin{pmatrix}
\frac{\partial \gamma'}{\partial \gamma} & \frac{\partial \gamma'}{\partial \mu'} \\
\frac{\partial \mu'}{\partial \gamma} & \frac{\partial \mu'}{\partial \mu}
\end{pmatrix} = \frac{d\Gamma'}{dE' \, d\Omega'} \sqrt{1 - \beta \beta_B \mu^2} - (1 - \beta^2) (1 - \beta_B^2) \frac{\beta}{(1 - \beta_B^2)}.\]

- Using the jet power to fix normalization factor \( c_j \)

\[
L_j = \int d\Omega \int dT_j (T_j + m_j) \frac{d\Gamma_j}{dT_j \, d\Omega} = c_j m_j^2 \Gamma_B^2 \int_{\gamma'_{\min, j}}^{\gamma'_{\max, j}} d\gamma' (\gamma')^{1 - \alpha_j}.
\]

\[
c_j = \frac{L_j}{m_j^2 \Gamma_B^2} \times \begin{cases} 
(2 - \alpha_j) / \left[ (\gamma'_{\max, j})^{2 - \alpha_j} - (\gamma'_{\min, j})^{2 - \alpha_j} \right] & \text{if } \alpha_j \neq 2 \\
1 / \log \left( \frac{\gamma'_{\max, j}}{\gamma'_{\min, j}} \right) & \text{if } \alpha_j = 2
\end{cases}
\]
Spectrum of the relativistic blazar jet

<table>
<thead>
<tr>
<th>Parameter (unit)</th>
<th>TXS 0506+056</th>
<th>BL Lacertae</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z$</td>
<td>0.337</td>
<td>0.069</td>
</tr>
<tr>
<td>$d_L$ (Mpc)</td>
<td>1835.4</td>
<td>322.7</td>
</tr>
<tr>
<td>$M_{BH}$ ($M_\odot$)</td>
<td>$3.09 \times 10^8$</td>
<td>$8.65 \times 10^7$</td>
</tr>
<tr>
<td>$\mathcal{D}$</td>
<td>40*</td>
<td>15</td>
</tr>
<tr>
<td>$\Gamma_B$</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>$\theta_{LOS}$ ($^\circ$)</td>
<td>0</td>
<td>3.82</td>
</tr>
<tr>
<td>$\alpha_p$</td>
<td>2.0</td>
<td>2.4</td>
</tr>
<tr>
<td>$\alpha_e$</td>
<td>2.0</td>
<td>3.5</td>
</tr>
<tr>
<td>$\gamma'_{min, p}$</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$\gamma'_{max, p}$</td>
<td>$5.5 \times 10^7^*$</td>
<td>$1.9 \times 10^9$</td>
</tr>
<tr>
<td>$\gamma'_{min, e}$</td>
<td>500</td>
<td>700</td>
</tr>
<tr>
<td>$\gamma'_{max, e}$</td>
<td>$1.3 \times 10^4^*$</td>
<td>$1.5 \times 10^4$</td>
</tr>
<tr>
<td>$L_p$ (erg/s)</td>
<td>$2.55 \times 10^{48}^*$</td>
<td>$9.8 \times 10^{48}$</td>
</tr>
<tr>
<td>$L_e$ (erg/s)</td>
<td>$1.32 \times 10^{44}^*$</td>
<td>$8.7 \times 10^{42}$</td>
</tr>
<tr>
<td>$c_p$ ($s^{-1} \text{sr}^{-1} \text{GeV}^{-1}$)</td>
<td>2.54 $\times 10^{47}$</td>
<td>1.24 $\times 10^{49}$</td>
</tr>
<tr>
<td>$c_e$ ($s^{-1} \text{sr}^{-1} \text{GeV}^{-1}$)</td>
<td>2.42 $\times 10^{50}$</td>
<td>2.59 $\times 10^{54}$</td>
</tr>
</tbody>
</table>

$\mathcal{D} = 2\Gamma_B$

$\theta_{LOS} \simeq 1/\mathcal{D}$
Spectrum of the relativistic blazar jet

- Spectrum in BH frame:

\[
\frac{d\Gamma_j}{dT_j d\Omega} = \frac{1}{4\pi} c_j \left(1 + \frac{T_j}{m_j}\right)^{-\alpha_j} \frac{\beta_j (1 - \beta_j \beta_B \mu)^{-\alpha_j} \Gamma_B^{-\alpha_j}}{\sqrt{(1 - \beta_j \beta_B \mu)^2 - (1 - \beta_j^2)(1 - \beta_B^2)}}
\]
Dark matter density profile

- The DM distribution depends on the properties of central supermassive black hole;

\[ \rho(r) \propto r^{-\gamma} \]

Adiabatic growth

\[ \rho'(r) \propto r^{-\frac{9-2\gamma}{4-\gamma}} \]

Set \( \gamma = 1 \), which corresponds to the NFW profile
Dark matter density profile

- The DM distribution depends on the properties of central supermassive black hole:
  \[ \rho(r) \propto r^{-\gamma} \]
  
  Set \( \gamma = 1 \), which corresponds to the NFW profile

- The possible DM annihilations could flatten the DM profile in the inner region
  \[ \rho_{\text{DM}}(r) = \frac{\rho'(r)\rho_{\text{core}}}{\rho'(r) + \rho_{\text{core}}} \]

- Adiabatic growth
  \[ \rho'(r) \propto r^{-\frac{9-2\gamma}{4-\gamma}} \]
Dark matter density profile

- The DM distribution depends on the properties of central supermassive black hole;

\[ \rho(r) \propto r^{-\gamma} \]

Adiabatic growth

\[ \rho'(r) \propto r^{-\frac{9-2\gamma}{4-\gamma}} \]

Set \( \gamma = 1 \), which corresponds to the NFW profile

- The possible DM annihilations could flatten the DM profile in the inner region

\[ \rho_{\text{core}} \approx \frac{m_\chi}{(\langle \sigma v \rangle_0 t_{\text{BH}})} \]

Annihilation

\[ \rho_{\text{DM}}(r) = \frac{\rho'(r)\rho_{\text{core}}}{\rho'(r) + \rho_{\text{core}}} \]

- The normalization condition to fix the DM profile

\[ \int_{4R_S}^{10^5 R_S} 4\pi r^2 \rho'(r) dr \approx M_{\text{BH}} \]

Where \( R_S \) is Schwarzschild radius
Dark matter density profile

- Consider two benchmark points

  BMP1) \( \langle \sigma v \rangle_0 = 0 \), so that \( \rho_{\text{core}} \to +\infty \) and \( \rho_{\text{DM}} = \rho' \);
  
  BMP2) \( \langle \sigma v \rangle_0 = 10^{-28} \text{ cm}^3 \text{ s}^{-1} \) and \( t_{\text{BH}} = 10^9 \text{ yr} \);

- DM profile

- The line-of-sight integral of DM density

  \[
  \Sigma_{\text{DM}}(r) \equiv \int_{r_{\min}}^{r} \rho_{\text{DM}}(r') \, dr'
  \]
Dark matter flux from blazars

• The BBDM flux can be expressed as

\[
\frac{d\Phi_{\chi}}{dT_{\chi}} = \frac{\sum_{\text{DM}}^\text{tot} \tilde{\sigma}_{\chi p}}{2\pi m_{\chi} d_L^2} \int_0^{2\pi} d\phi_s \int_{T_p\text{min}(T_{\chi})}^{T_p\text{max}(T_{\chi})} \frac{dT_p}{T_{\chi}(T_p)} \frac{d\Gamma_p}{dT_p d\Omega}
\]
Direct detection constraints

- The BBDM-induced target nucleus (electron) recoil rate can be expressed as

\[
\Gamma_j^{DM} \simeq \int_{T_{\text{exp}}^{\text{min}}}^{T_{\text{exp}}^{\text{max}}} dT_j \tilde{\sigma}_j \int_{T_j^{\text{min}}(T_j)}^{+\infty} \frac{dT_\chi}{T_j^{\text{max}}(T_\chi)} \frac{d\Phi_\chi}{dT_\chi} \quad (\text{with } j = e, N)
\]

- For Xenon1T (SI):

\[
\Gamma_N(4.9 \text{ keV} \leq T_{Xe} \leq 40.9 \text{ keV}) < 2.41 \times 10^{-34} \text{ s}^{-1}
\]

For Borexino (SD):

\[
\Gamma_p(T_P > 25 \text{ MeV}) < 2 \times 10^{-39} \text{ s}^{-1}
\]
Constraints from Super-K

- Due to the large volume (22.5 kt in fiducial volume) and long exposure time (2628.1 days), Super-K is an ideal detector to search for DM-electron scattering signals.

- Three energy bins are considered, and the spatial distribution of the events are also given.

\[ P \left( \mu_e > \cos \delta; T_{\chi}^{\text{min}} (T_e = T_i^{\text{min}}) \right) \gtrsim 0.95 \]

\[ 0.1 < \frac{T_e}{\text{GeV}} < 1.33 \quad 1.33 < \frac{T_e}{\text{GeV}} < 20 \quad 20 < \frac{T_e}{\text{GeV}} < 10^3 \]
Constraints from Super-K

- After doing a Poisson analysis, we derive the 95% C.L. upper limits.

<table>
<thead>
<tr>
<th>Sensitivity of Super-Kamiokande</th>
<th>Bin1</th>
<th>Bin2</th>
<th>Bin3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_e$ (GeV)</td>
<td>(0.1, 1.33)</td>
<td>(1.33, 20)</td>
<td>(20, $10^3$)</td>
</tr>
<tr>
<td>$N_{\text{Data}}$</td>
<td>4042</td>
<td>658</td>
<td>3</td>
</tr>
<tr>
<td>$N_{\text{Bkg}}$</td>
<td>3992.9</td>
<td>772.6</td>
<td>7.4</td>
</tr>
<tr>
<td>$\epsilon_{\text{sig}}$</td>
<td>93.0%</td>
<td>91.3%</td>
<td>81.1%</td>
</tr>
<tr>
<td>$\delta$</td>
<td>24°</td>
<td>7°</td>
<td>5°</td>
</tr>
<tr>
<td>$N_{\delta \text{T XS}}$</td>
<td>169</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>$N_{\delta \text{BL}}$</td>
<td>167</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>$N_{\delta \text{Bkg}}$</td>
<td>172.6</td>
<td>2.88</td>
<td>0.014</td>
</tr>
<tr>
<td>$N_{\text{T XS}}$ (95% C.L.)</td>
<td>19.39</td>
<td>3.42</td>
<td>2.98</td>
</tr>
<tr>
<td>$N_{\text{BL}}$ (95% C.L.)</td>
<td>17.27</td>
<td>6.27</td>
<td>2.98</td>
</tr>
</tbody>
</table>

- The number of BBDM-induced electron recoil events at Super-K:

\[
N_e^{\text{DM}} \approx N_e \sigma_{\chi e} t_{\text{obs}} \int_{T_{\text{min}}^{\text{exp}}}^{T_{\text{max}}^{\text{exp}}} dT_e \int_{T_{\text{min}}(T_e)}^{+\infty} dT_{\chi} \frac{dT_{\chi}}{T_{e}^{\text{max}}(T_{\chi})} \frac{d\Phi^z}{dT_{\chi}}
\]

\[
N_e^{\text{DM}} \times \epsilon_{\text{sig}} < N_{\text{T XS}} \ (N_{\text{BL}})
\]
Constraints from Super-K

- Combing three bins, we derive the 95% C.L. upper limits on $\sigma_{\chi e}$

- Left: fix $\sigma_{\chi p}$ with XENON1 T constraints; Right: for various $\sigma_{\chi p}$. 
Summary

- A novel astrophysical mechanism for DM acceleration;
- Due to the powerful jets and large DM densities, the blazars are ideal DM boosters and can induce a stronger DM flux than that from CRs;
- The strong constraints on $\sigma_{\chi p}$ and $\sigma_{\chi e}$ are derived by using the results of XENON1T and Super-K;
- It not only unveils a novel fascinating possibility to explore the nature of DM but also provides astrophysicists with a new way to better understand the characteristics of blazar jets.
Summary

- A novel astrophysical mechanism for DM acceleration;
- Due to the powerful jets and large DM densities, the blazars are ideal DM boosters and can induce a stronger DM flux than that from CRs;
- The strong constraints on $\sigma_{\chi p}$ and $\sigma_{\chi e}$ are derived by using the results of XENON1T and Super-K;
- It not only unveils a novel fascinating possibility to explore the nature of DM but also provides astrophysicists with a new way to better understand the characteristics of blazar jets.