Dark Matter Annihilation in the Late Universe

Nicole Bell
The University of Melbourne

Collaborators:
John Beacom (Ohio State), Gregory Mack (Ohio State), Hasan Yuksel (Ohio State), Thomas Jacques (Melbourne), Gianfranco Bertone (Paris), James Dent (Vanderbilt) and Tom Weiler (Vanderbilt).
Dark Matter

• Evidence for dark matter arises from a wide range of astrophysical observations which are each sensitive to dark matter’s gravitational influence.

• As yet, very little information on the particle properties of dark matter.
Dark Matter Candidate Zoo

Axions, Neutralinos, Gravitinos, Axinos, Sneutrinos, Kaluza-Klein particles, Heavy Fourth Generation Neutrinos, Mirror particles, superWIMPs, WIMPzillas, Sterile Neutrinos, Light Scalars, Q-Balls, Brane World Dark Matter, Primordial Black Holes, …. things we haven’t thought of ….

It’s clear that any model-dependent approach to searching for dark matter has shortcomings.
**Dark Matter Annihilation**

- Self-annihilation cross-section is a fundamental property of dark matter.

- For thermal relics it is specified by the DM relic density:
  
  e.g. $\Omega_{DM} \sim 0.3$ implies $\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm$^3$ s$^{-1}$

- More generally, it controls the DM annihilation rate in galaxies today → can affect galaxy halo density profiles.

There exist two general constraints on the rate of dark matter annihilation/disappearance:
Constraint 1. - Unitarity Bound

- Unitarity sets a general upper bound on the cross-section:
  \[
  \langle \sigma_A v \rangle \leq \frac{4\pi}{m^2} \frac{1}{v}
  \]
  (in the low-velocity limit, where the cross-section is s-wave dominated)

- In galaxies today:
  \[
  \langle \sigma_A v \rangle \leq 1.5 \times 10^{-13} \, \frac{\text{cm}^3}{\text{s}} \left[ \frac{\text{GeV}}{m_\chi} \right]^2 \left[ \frac{300 \, \text{km/s}}{v_{\text{rms}}} \right] .
  \]

- Most restrictive for high masses.

L. Hui
Constraint 2. - Kaplinghat-Knox-Turner Model

- Large dark matter annihilation rate flattens galaxy cores invoked to resolve conflict between predicted (sharp cusps) and observed (flat cores) halo density profiles.

- KKT model requires cross-sections \( \sim 10^7 \) times larger than the natural scale for a thermal relic: 

\[
\langle \sigma_A v \rangle_{KKT} \simeq 3 \times 10^{-19} \frac{\text{cm}^3}{\text{s}} \left[ \frac{m_\chi}{\text{GeV}} \right]
\]

- Reinterpret this type of model as upper bound on \( \langle \sigma_A v \rangle \)
Search for fluxes of DM annihilation or decay products:

- Annihilation in our Galaxy
  - look for flux coming from Galactic center

- Annihilations in galaxies throughout the universe
  - cosmic diffuse flux

- Despite being harder to detect than gamma rays, neutrinos provide important information and **strong, model independent bounds.**
If the dark matter is the lightest new particle:

- All final states except neutrinos produce gamma rays,

→ Bound the total cross-section with the neutrino signal limit i.e. Assume $\text{Br}(\text{“invisible”}) = 100\%$
Annihilation to neutrinos:

\[ \chi \chi \rightarrow \bar{\nu} \nu \]

Diffuse flux (Ullio, et al.):

\[
\frac{d\Phi_\nu}{dE} = \frac{\langle \sigma_A \nu \rangle}{2} \frac{c}{4\pi H_0} \frac{\Omega_{DM}^2 \rho_{\text{crit}}^2}{m_\chi^2} \int_0^{z_{\text{up}}} \frac{\Delta^2(z) dN_\nu(E')}{h(z) dE'}
\]

The factor \( \Delta \) accounts for the increase in density due to the clustering of dark matter in halos. (\( \Delta = 1 \) corresponds to all matter being at the average density in the Universe today)

Atmospheric neutrinos are the background

Conservative detection criteria: Signal 100% as large as angle averaged atmospheric neutrino background.
Upper panel: –
Annihilation flux superimposed on atmospheric neutrino background

Lower panel:
(Signal+Background)/Background
Upper bounds on the dark matter total annihilation cross-section


Also:


Kachelriess and Serpico, PRD 76, 063516 (2007).

Bell, Dent, Jacques, & Weiler, arXiv:0805.3423
Annihilation effect in Galaxy Halos?

- Annihilation flattens halo cusps to a core density of:
  \[ \rho_A \sim \frac{m_\chi}{\langle \sigma_A v \rangle H_0^{-1}} \]

- Our bound implies that for all \( m > 0.1 \) GeV:
  \[ \rho_A \gtrsim 5 \times 10^3 \text{ GeV/cm}^3 \]

Only affects the very inner region of typical galaxies. e.g. In the Milky Way, this density occurs only at radii < 1 pc for an NFW profile (and maybe not at all for less steep profiles).

Dark matter annihilation cannot have a macroscopic effect on galactic halos.
Dark matter annihilation – MeV mass

90% C.L. Super-Kamiokande bound

\( \langle \sigma v \rangle_{90} \) [cm\(^3\)/s]

\( m_\chi \) [MeV]


\( \leftarrow \) cross-section for thermal relic DM
Dark Matter Lifetime

Photons $X \rightarrow X' \gamma$
... strong limit

Neutrinos $X \rightarrow \nu\nu$
... model-independent limit

Yuksel & Kistler

Palomares-Ruiz

Nicole Bell, The University of Melbourne
TeVPA, Beijing, 24th September 2008
Radiative corrections $\rightarrow$ photons

$\chi \chi \rightarrow \nu \bar{\nu}$ is accompanied by: $\chi \chi \rightarrow \nu \bar{\nu} Z \rightarrow$ gamma rays

- Z decays to hadrons $\sim 70\%$ of the time.
- On average, 20 neutral pions per Z decay, which in turn decay as $\pi \rightarrow \gamma \gamma$

- For $E \gg M_Z$: ratio of the cross-sections $\sim \alpha$
Radiative corrections to neutrino processes give photons

But direct neutrino limits are comparable/stronger!

Kachelriess and Serpico, PRD 76, 063516 (2007).

Bell, Dent, Jacques, & Weiler, arXiv:0805.3423
Direct Annihilation to gamma rays \( \chi\chi \rightarrow \gamma\gamma \)

- The process \( \chi\chi \rightarrow \gamma\gamma \) is present in most dark matter models, though with a model-dependent rate. (Usually occurs at loop order.)

- It’s detection would be a “smoking gun” signature of dark matter.

- Monocromatic line at \( E_\gamma = M_\chi \) would measure DM mass.
Annihilation signals & γ-ray background

Mack, Jacques, Beacom, Bell, Yuksel
arXiv:0803.0157
DM halo density vs radius

Cross-section limits for $XX \rightarrow \gamma\gamma$

Mack, Jacques, Beacom, Bell, Yuksel
arXiv:0803.0157
Comparison of neutrino and photon limits on dark matter annihilation

\[
\langle \sigma v \rangle_{\text{total}} \quad \text{[cm}^3\text{s}^{-1}] \\
10^{-16} \quad 10^{-18} \quad 10^{-20} \quad 10^{-22} \quad 10^{-24} \\
10^{-26} \quad 10^{-28} \quad 10^{-30} \\
10^{-5} \quad 10^{-3} \quad 10^{-1} \quad 10^{1} \quad 10^{3} \quad 10^{5} \\
\text{m}_\chi \quad \text{[GeV]} \\
\]

Gamma Rays \( \text{Br}(\gamma\gamma) = 10^{-4} \)
Neutrinos \( \text{Br}(\nu\nu) = 1 \)
KKT
Unitarity Bound
Natural Scale

Mack, Jacques, Beacom, Bell, Yuksel
arXiv:0803.0157
Summary – DM Annihilation

- Dark matter total annihilation cross-section can be bounded using the least detectable annihilation products (i.e. neutrino appearance rate.)

- Neutrino bound much stronger than Unitarity for \( m < 10 \) TeV.

- For large mass, neutrinos bounds are comparable to those for \( \gamma \gamma \)

- Dark Matter halos cannot be significantly modified by annihilation.