Towards Constraining Dark Sectors with 21-cm Cosmology

A detailed analysis of the global 21-cm signal in dark cooling scenarios

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Nov. 2022

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Plan

• Basics of 21-cm Cosmology
• Dark Cooling - Valid Models
• Predictions
After \((z \sim 1100)\) neutral Hydrogen is the most abundant component of the baryonic matter.

Most hydrogen is at its \(1s\) ground state

The hyperfine splitting of the ground state corresponds to 21-cm \((6 \times 10^{-6} eV)\)
Introduction to 21-cm Cosmology

- CMB photons transverse through dense Hydrogen clouds before reaching us

Redshift to $21(1 + z)\, \text{cm}$  \[ \bar{I}(\lambda = 21\, \text{cm}) \]

$I(\lambda = 21\, \text{cm})$

$z, \frac{n_1}{n_0}$

SARAS 3 Antenna
Introduction to 21-cm Cosmology

- CMB photons transverse through dense Hydrogen clouds before reaching us
- Photons at the black body tail interact with the hyperfine levels of Hydrogen

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SARAS 3 Antenna
Introduction to 21-cm Cosmology

- CMB photons transverse through dense Hydrogen clouds before reaching us.
- Photons at the black body tail interact with the hyperfine levels of Hydrogen.
- The measured intensity at $21(1 + z)cm$ depends on the relative occupancy of the Hyperfine levels at redshift $z$.
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• The measured intensity at $21(1 + z)\, cm$ depends on the relative occupancy of the Hyperfine levels at redshift $z$

\[
\bar{I}(\lambda = 21\, cm) = F
\]

Absorption

Redshift to $21(1 + z)\, cm$
Introduction to 21-cm Cosmology

• The signal is determined by the hyperfine occupancy ratio
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• Once formed, stars emit Lyα photons
• Lyα photons cause spin flips (W.F.) relating between $T_{21}$ and $T_K$
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Absorption signal at cosmic dawn
Dark Cooling – Enhanced Absorption

Elastic DM-SM interactions cool the baryonic gas
Dark Cooling – Enhanced Absorption

Elastic DM-SM interactions cool the baryonic gas

Impact on 21-cm Enhanced absorption at cosmic dawn

![Graph showing frequency vs. temperature and redshift](image)
Dark Cooling – Enhanced Absorption

Elastic DM-SM interactions cool the baryonic gas

Impact on 21-cm Enhanced absorption at cosmic dawn

Anomalous absorption signal

Constrain over cooling?
Dark Cooling – Viable Models

• mDM is the only viable model that can lead to an $\mathcal{O}(1)$ cooling at cosmic dawn

• CMB constraints imply $f_m < 0.4\%$

[K. K. Boddy et al, 2018]

[Barkana, Outmezguine, Redigolo, Volansky, 2018]
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Dark Cooling – Viable Models

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No cooling because $f_m < 0.4\%$ implies a small heat capacity
Dark Cooling – Viable Models

• \( g_m g_c = 0 \) is arbitrary

• General scenario allows \( g_m g_c \neq 0 \)

[Liu, Outmezguine, Redigolo, Volansky, 2019]
Dark Cooling – Viable Models

• $g_m g_C = 0$ is arbitrary

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• mDM-CDM interactions effectively increase the heat capacity of mDM

[Liu, Outmezguine, Redigolo, Volansky, 2019]
Dark Cooling – Viable Models

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How Much Can we Cool?
How Much Can we Cool?

Park et al. 2019

\[ \min\{T_{21}^{SM}\} = -80mK \]
How Much Can we Cool?

Cohen et al. 2017

\[ \min \{T_{21}^{SM}\} = -120 \text{mK} \]

Park et al. 2019

\[ \min \{T_{21}^{SM}\} = -80 \text{mK} \]
Summary

• $T_{21}$ is strongly related to $T_K$ at cosmic dawn

• DM-SM elastic interactions cool the baryons, therefore enhancing the absorption signal

• mDM is the only viable DM model that can generate and $\mathcal{O}(1)$ cooling

• mDM can generally also interact with CDM

• Current measurements can lead to strong constraints from overcooling
Backup
Astrophysical Modeling
Astrophysical Modeling

Fiducial scenarios of leading models

Star formation efficiency

[Munouz et al. 2022]
Astrophysical Parameters
Pumped X-rays
Worst Case Scenario
no mDM - CDM Interactions
21-cm Basics
Introduction to 21-cm Cosmology

- Define the spin temperature

\[ \frac{n_1}{n_0} = 3e^{\frac{E_{21}}{T_s}} \]

- Differential brightness temperature

\[ T_{21} \propto T_s(z) - T_\gamma(z) \]
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\[ T_s = T_\gamma \Rightarrow \text{null signal} \]

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\[ T_s < T_\gamma \Rightarrow \text{absorption} \]
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• Differential brightness temperature

\[ T_{21} \propto T_s(z) - T_\gamma(z) \]

\[ T_s > T_\gamma \Rightarrow \text{emission plot} \]
W.F. Coupling

- Lyα photons emitted by the first luminous cause spin flips (W.F.)
- Energy transfer by recoil couple $T_s$ and $T_K$
Counter Dark Cooling Effects
Dark Cooling Suppression

Heating effects counter cooling

Ly\(\alpha\) photons couple \(T_s \rightarrow T_{c^{eff}} \rightarrow T_K\)

\[X-rays \times 10\]

\[x_\alpha \times 0.1\]
Dark Cooling Suppression
Inefficient Lyα Coupling

Photons around line center lose energy due to recoil with H

Intensity drops around line center

Inefficient Lyα coupling

\[ x_\alpha = \frac{8\pi \lambda_{\text{Ly}\alpha}^2 \gamma T_\star}{9A_{10} T_\gamma} S_\alpha J_\alpha \]
Dark Cooling Suppression
Inefficient $Ly\alpha$ Coupling

- Eventually enough $Ly\alpha$ photons are emitted
- Heating effects ⇒ moderate temperatures
Dark Cooling Suppression

Heating

\[
\frac{dT_K}{d \log(a)} = -2T_K + \frac{1}{H} (\dot{Q}_{\text{Dark Cooling}} + \dot{Q}_{\text{Comp}} + \dot{Q}_{\text{Xrays}} + \dot{Q}_{\text{CMB}} + \dot{Q}_{\text{Lyα}})
\]

Enhanced at low $T_K$

[Venumadhav et al. 2018, Chen & Miralda 2003]
Dark cooling – Standard scenario

Long range interactions $m_\phi < \mu_1 v_{rel} \approx 1 \text{KeV} \frac{\mu_I}{1 \text{GeV}}$ \hspace{1cm} $m_\phi < 1/r_{Bohr}$

**Screened or unscreened?**

- Hidden photon
- Millicharged DM

Interactions do not probe the constituents of atoms

- Yukawa coupling scalar mediator
- B-L coupling scalar or vector mediator
Dark cooling – Standard scenario

Cooling is dominated by the small ionized fraction

[Barkana, Outmezguine, Redigolo, Volansky, 2018]
The mediator must be either the SM’s photon or a Hidden photon.

\[
\frac{d\sigma}{d\Omega} = \frac{\bar{\sigma}}{4\pi} |F(q^2)|^2 = \frac{\bar{\sigma}}{4\pi} |f_{DM}(q^2)|^2 \left| f_{SM}(q^2) \right|^2
\]
• EDGES collaboration – anomalous absorption at cosmic dawn