CMB CONSTRAINTS ON DARK MATTER INTERACTIONS

New Physics from Galaxy Clustering
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Cosmic History

Dark matter interactions in 3 parts

(1) Small-scale suppression

(2) Energy injection

(3) IGM cooling

Dark Ages

Cosmic Dawn

Reionization

Halo Abundance

\[ z = \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}} \]
Dark matter scattering suppresses small-scale structure formation
Cosmic Microwave Background

\[ T_0 = 2.7255 \pm 0.0006 \text{ K} \]

Dark matter in $\Lambda$CDM:
- cold, collisionless
- $\sim 6x$ more abundant than baryons

"baryons" = protons + helium + electrons


ESA and Planck Collaboration
Dark Matter Scattering

\[ \sigma_{MT}(v) = \int (1 - \cos \theta) \frac{d\sigma}{d\Omega} \, d\Omega = \sigma_0 v^n \]

**Heavy mediator**

- \( n = 0 \quad \mathcal{L} \sim \bar{\chi} \chi \bar{f} f \)
- \( n = 2 \quad \mathcal{L} \sim i \bar{\chi} \chi \bar{f} \gamma^5 f, \quad i \bar{\chi} \gamma^5 \chi \bar{f} f \)
- \( n = 4 \quad \mathcal{L} \sim \bar{\chi} \gamma^5 \chi \bar{f} \gamma^5 f \)

**Light mediator**

- \( n = -2 \) (electric dipole)
- \( n = -4 \) (Coulomb)

To be as model-independent as possible, decouple effects of annihilation and scattering

\( f \) in early Universe: \( e^-, p, \) He

see Boddy and Gluscevic (PRD 2018) for application of nonrelativistic EFT operator formalism
Modify Boltzmann Equations

\[ \dot{b} = -\theta_b - \frac{\dot{h}}{2}, \quad \dot{\chi} = -\theta_\chi - \frac{\dot{h}}{2} \]
\[ \dot{\theta}_b = -\frac{\dot{a}}{a} \theta_b + c_b^2 k^2 \delta_b + R_\gamma (\theta_\gamma - \theta_b) + \frac{\rho_\chi}{\rho_b} R_\chi (\theta_\chi - \theta_b) \]
\[ \dot{\theta}_\chi = -\frac{\dot{a}}{a} \theta_\chi + c_\chi^2 k^2 \delta_\chi + R_\chi (\theta_b - \theta_\chi) \]

✦ Momentum-transfer rate

\[ R_{\chi,f} \sim a n_f \left( \frac{\sigma_0}{m_\chi + m_f} \right) \left( \frac{T_b}{m_f} + \frac{T_\chi}{m_\chi} \right)^{(n+1)/2} \]

✦ Heat-transfer rate

\[ R'_{\chi,f} = \frac{m_\chi}{m_\chi + m_f} R_{\chi,f} \]

✦ Assume Maxwell-Boltzmann distribution for dark matter

\[ \dot{T}_b + 2 \frac{\dot{a}}{a} T_b = 2 \frac{\mu_b}{m_e} R_\gamma (T_\gamma - T_b) + 2 \frac{\mu_b}{m_\chi} R'_{\chi} (T_\chi - T_b) \]
\[ \dot{T}_\chi + 2 \frac{\dot{a}}{a} T_\chi = 2 R'_{\chi} (T_b - T_\chi) \]

✦ Nonlinearities arise if relative bulk velocity > thermal velocity; relevant for \( n = -2, -4 \)

Modified CLASS: [https://github.com/kboddy/class_public/tree/dmeff](https://github.com/kboddy/class_public/tree/dmeff)
see also CLASS v3.2 and Becker, Hooper, Kahlhoefer, Lesgourgues, Schöneberg (JCAP 2021)
Effects of Dark Matter Scattering

Chen+ (2002); Sigurdson+ (2004); Dvorkin+ (2014); Gluscevic and KB (2018); KB and Gluscevic (2018); Xu+ (2018); Slatyer+ (2018); KB+ (2018)

$D_\ell [\mu K^2]$ vs. multipole $\ell$

- with interactions
- no interactions ($\Lambda$CDM)

Enhancement
Peaks shift
Small-scale suppression

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Momentum Transfer

\[ \sigma_{MT}(v) = \sigma_0 v^n \]

with \( \sigma_0 \) at 95% C.L. upper limit

efficient scattering

\[ \sigma_{MT}(v) = \sigma_0 v^n \]

for \( n \geq 0 \): KB, Gluscevic (PRD 2018); Gluscevic, KB (PRL 2018)

for \( n < 0 \): KB, Gluscevic, Poulin, Kovetz, Kamionkowski, Barkana (PRD 2018)
CMB Constraints

Scattering with Protons

Scattering with Electrons

DM mass $m_\chi$ [MeV]

DM-electron cross section $\sigma_0$ [cm$^2$]

DM-proton cross section $\sigma_0$ [cm$^2$]

Limits from CMB anisotropies using Planck 2018 temperature, polarization, lensing varying 6 standard $\Lambda$CDM parameters + $\sigma_0$ @ fixed $m_\chi$

Nguyen, Sarnaik, KB, Nadler, Gluscevic (PRD 2021)
Incorporating helium scattering is model-dependent, but important for large DM mass and $n \geq 0$.

DM may preferentially interact with neutrons, rather than protons $\Rightarrow$ scattering with He, not H.
CMB Projections: Scattering with Protons (n=0)

Li, Gluscevic, KB, Madhavacheril (PRD 2018)
WIP with Gluscevic to make projections for other values of n

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Matter Power Spectrum

\[ P(k) \text{ [Mpc}^3] \]

\[ \Lambda CDM \]

\[ \sigma_{MT} \sim v^0 \text{ (1 MeV)} \]
\[ \sigma_{MT} \sim v^0 \text{ (1 GeV)} \]
\[ \sigma_{MT} \sim v^2 \text{ (1 MeV)} \]
\[ \sigma_{MT} \sim v^2 \text{ (1 GeV)} \]

\[ k \text{ [1/Mpc]} \]

\[ P_m(k) \text{ [Mpc}^3h^3] \]

- Planck 2018 TT
- Planck 2018 EE
- Planck 2018 PhD
- DES Y1 cosmic shear
- SDSS DR7 LRG
- eBOSS DR14 Ly-\( \alpha \) forest
Milky Way Satellites

Classic dwarfs
SDSS-identified dwarfs

DES and Pan-STARRS1 identified dwarfs
Suppression of (Linear) Matter Power Spectrum

\[ n = 0 \]

\[ P_{\text{collisional}} / P_{\text{CDM}} \]

- \( m_{\text{WDM}} = 0.3 \text{ keV} \)
- \( m_{\text{WDM}} = 1.2 \text{ keV} \)
- \( m_{\text{WDM}} = 4.7 \text{ keV} \)
- \( \sigma_0 = 10^{-27} \text{ cm}^2 \)
- \( \sigma_0 = 10^{-28} \text{ cm}^2 \)
- \( \sigma_0 = 10^{-29} \text{ cm}^2 \)

Nadler, Gluscevic, KB, Wechsler (ApJL 2019)

Maamari, Gluscevic, KB, Nadler, Wechsler (ApJL 2021)
Constraints: Scattering with Protons (n=0)

see also Rogers+ (PRL 2021) and Hooper+ (JCAP 2022) using Ly-alpha forest and Ali-Haimoud (PRD 2021) using spectral distortions
Constraints: Scattering with Electrons

DM-electron cross section $\sigma_e$ [cm$^2$]

DM mass $m_\chi$ [MeV]

$n = 0$

Planck CMB

Milky Way satellites

$n = -4$

Planck CMB

Constraints: Scattering with Electrons

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Nguyen, Sarnaik, KB, Nadler, Gluscevic (PRD 2021)

see also Buen-Abad+ (2021)
Dark matter annihilation injects energy
Assume thermal relic, freeze-out DM

- DM annihilation (or decay) transfers energy and entropy into SM sector, which affects radiation content of Universe (parameterized by $N_{\text{eff}}$)
- Light DM itself affects expansion rate, modifying proton-neutron conversion freeze out (affects primordial element abundances)
- Consider joint constraint for DM scattering and thermal relic DM by adjusting $Y_p$, $\Delta N_{\nu}$, and DM mass $m_\chi$
Combined Constraints from CMB and BBN

\[ \sigma_0 \text{ [cm}^2\text{]} \]

- **DM mass** $m_\chi$ [MeV]
- **CMB**
- **BBN**

\[ n = -2 \]
\[ n = 0 \]
\[ n = 2 \]
\[ n = 4 \]
\[ n = 6 \]

\[ \sigma_0 \text{ [cm}^2\text{]} \]

An, KB, Gluscevic (to appear)
Effect of Energy Injection on CMB

Example: s-wave annihilation from Padmanabhan and Finkbeiner (2005) see also Slatyer+ (2009); Galli+ (2009,2013); Finkbeiner (2011); Slatyer (2016)

DM annihilation
- suppression across (mostly) all scales
CMB Annihilation and Decay Constraints

s-wave annihilation

\[ \langle \sigma v \rangle = \frac{G_F m_X^2}{4 \pi} \]

- Excluded by CMB
- Thermal cross-section
- Fermi/HESS $e^+ e^-$
- AMS/PAMELA positron fraction
- AMS Galactic anti-proton excess
- Fermi Galactic center excess

Planck Collaboration (2018)

Anisotropies most sensitive at $z \sim 600$ (annihilation)
$z \sim 300$ (decay)

decay

\[ \tau = \frac{1}{\lambda m_X^2} \]

- $\langle \sigma v \rangle = 10^{-27}$
- $m_X$ [GeV]

Planck Collaboration (2018)

decaying fraction

- $\tau_{\text{AMS}}$
- $\tau_{\text{Planck}}$
- $\tau_{\text{BBN}}$

Slatyer and Wu (PRD 2017)

Poulin, Lesgourgues, Serpico (JCAP 2017)
Annihilation Constraints from BBN and CMB

\[ f_{\text{eff}} \langle \sigma v \rangle \] [cm$^{-1}$s$^{-1}$]

\[ m_\chi \] [MeV]

No kinetic equilibrium

preliminary

An, KB, Gluscevic (to appear)
Dark matter scattering can cool intergalactic medium during cosmic dawn (and dark ages)
21-cm Global Signal: Schematic Overview

CMB photons

Excite 21cm hyperfine transition

CMB serves as backlight

Observe brightness temperature contrast

Bowman+ (Nature 2018)
EDGES Absorption Signal

Experiment to Detect the Global Epoch of Reionization Signature

\[ \sigma \sim \nu^{-4} \]

DM-baryon scattering cools gas

Barkana (Nature 2018)
see also Tashiro, Kadota, Silk (PRD 2014); Muñoz, Kovetz, Ali-Haïmoud (PRD 2015)

Bowman+ (Nature 2018)
CMB constraints

- $T_{21}$ lines assume all DM interacts, but neglects suppression of matter power spectrum
  
  Driskell, Mirocha, Morton, Gluscevic, KB, Benson, Nadler (2209.04499)

- DM-H vs DM-ion scattering?
  - DM-H scattering highly constrained
  - DM-ion scattering suffers from low $x_{ei}$
  - so need larger $\sigma_0$ than allowed by CMB

- Allow only fraction of DM to interact

Muñoz, Loeb (2018)
Berlin, Hooper, Krnjaic, McDermott (2018)
Barkana, Outmezguine, Redigolo, Volansky (2018)

KB, Gluscevic, Poulin, Kovetz, Kamionkowski, Barkana (PRD 2018)
Kovetz, Poulin, Gluscevic, KB, Barkana, Kamionkowski (PRD 2018)

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Millicharged Dark Matter

Planck loses sensitivity to small fractions of millicharged DM

Planck excluded

\[ f_\chi \lesssim 0.4\% \]

DM Millicharge: Viable Parameter Space

KB, Gluscevic, Poulin, Kovetz, Kamionkowski, Barkana (PRD 2018)
see also de Putter+ (PRL 2018)

Kovetz, Poulin, Gluscevic, KB, Barkana, Kamionkowski (PRD 2018)
Complementarity

Snowmass 2021 Theory Frontier: Astrophysical and Cosmological Probes of Dark Matter (2203.06380)
Recap

1. Dark matter scattering suppresses small-scale structure formation

2. Dark matter annihilation injects energy

3. Dark matter scattering can cool intergalactic medium during cosmic dawn (and dark ages)

Exciting times for cosmo/astro probes of dark matter!
KitP 2024 Program Plug

Dark Matter Theory, Simulation, and Analysis in the Era of Large Surveys

✦ Coordinators:
  KB, Vera Gluscevic, Ferah Munshi, Annika Peter
✦ Scientific advisors:
  Jo Dunkley, Tim Tait, Risa Wechsler
✦ May 20 – July 12, 2024
  [Application deadline: February 12, 2023]

Cosmic Signals of Dark Matter Physics: New Synergies

✦ Coordinators:
  KB, Ferah Munshi, Ethan Nadler, Annika Peter
✦ June 3 – 6, 2024
  [Registration deadline: May 5, 2024]