Joint CMB and BBN Constraints for Light Dark Sectors

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Pheno 2021
May 25th, 2021

With Mariangela Lisanti, Hongwan Liu, and Joshua Ruderman
Interest in Sub-GeV Dark Matter

WIMPs
(10s of GeV – TeV)

Sub-GeV Dark Matter
(∼MeV – GeV)

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Dark Photon + Dark Matter

Dark Sector

\[ m_{A'} = 3m_\chi \]

Standard Model

Dark matter couples to Standard Model through new dark photon mediator

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Current Constraints

Dark Photon + $\chi$, $m_{A'} = 3m_\chi$

XENON10 Collaboration, 1104.3088
deNiverville et al., 1107.4580
Essig et al., 1509.01598
NA64 Collaboration, 1610.02988
BaBar Collaboration, 1702.03327
Essig et al., 1703.00910
XENON Collaboration, 1907.11485
SENSEI Collaboration, 2004.11378
PandaX-II Collaboration, 2101.07479

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Additional Constraints from Cosmology

Current Constraints

Dark Photon + \( \chi \), \( m_{A'} = 3m_\chi \)

Additional image credit:
NASA/WMAP 2010
Roen Kelly for Astronomy Magazine

Additional Constraints?

\( \bar{\sigma}_e (\text{cm}^2) \)

\( m_\chi (\text{MeV}) \)

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Additional Constraints from Cosmology

Cosmic evolution sensitive to photon temperature ($T_\gamma$) and radiation density ($\rho_R$)

Universe temperature

Recombination and Cosmic Microwave Background (CMB) formation

Big Bang Nucleosynthesis (BBN)
Additional Constraints from Cosmology

Cosmic Microwave Background (CMB) and Big Bang Nucleosynthesis (BBN) can constrain light dark matter changes.

Cosmic evolution sensitive to photon temperature ($T_\gamma$) and radiation density ($\rho_R$).

P. Serpico and G. Raffelt, astro-ph/0403417
Boehm et al., 1207.0497
C. M. Ho and R. J. Scherrer, 1208.4347
Boehm et al., 1303.6270
K. M. Nollet and G. Steigman, 1312.5725
K. M. Nollet and G. Steigman, 1411.6005
Wilkinson et al., 1602.01114
M. Escudero, 1812.05605
Depta et al., 1901.06944
Sabti et al., 1910.01649

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CMB Constraints

\[ N_{\text{eff}} \sim \left( \frac{T_\nu}{T_\gamma} \right)^3 \left( 1 + \frac{\rho_\xi}{\rho_\nu} \right) \]

*\(N_{\text{eff}}\) parametrizes anomalous heating to photons and presence of additional light species*

- \(\chi\) increases \(T_\gamma\)
- \(T_\nu\) is decreased relative to \(T_\gamma\)
- \(N_{\text{eff}}\) decreases in a dark matter scenario

Entropy transfer from dark sector to photon sector
CMB Constraints

\[ N_{\text{eff}} \sim \left( \frac{T_\nu}{T_\gamma} \right)^3 \left( 1 + \frac{\rho_\xi}{\rho_\nu} \right) \]

\( \chi \) increases \( T_\gamma \)

\( T_\nu \) is decreased relative to \( T_\gamma \)

\[ N_{\text{eff}} \text{ decreases in a dark matter scenario} \]

Observation \[ N_{\text{eff}} = 2.92^{+0.37}_{-0.37} \]

Planck Collaboration, 1807.06209

Prediction \[ N_{\text{eff}} = 1.46 \]

\[ N_{\text{eff}} = 2.92 \]

\[ m_\chi = 1 \text{ MeV} \]
\[ m_{\Lambda'} = 3m_\chi \]

+ equivalent neutrinos \([\xi]\)

Workaround: adding additional degrees of freedom can restore \( N_{\text{eff}} \) to its measured value

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BBN Constraints

Expansion rate is proportional to $\rho_R$

If the expansion rate is too fast, heavy elements can’t form

Light element abundances change in a dark matter scenario

$\chi$ impacts $\rho_R, T_\gamma$

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BBN Constraints

\[ N_{\text{eff}} \sim \left( \frac{T_\nu}{T_\gamma} \right)^3 \left( 1 + \frac{\rho_\xi}{\rho_\nu} \right) \]

\( \chi \) impacts \( \rho_R, T_\gamma \)

- Light element abundances change in a dark matter scenario
- Equivalent neutrinos increase \( \rho_R \)
- Light element abundances are difficult to tune

Observation \( Y_P = 0.245 \pm 0.008 \)
(Helium-4 mass fraction)

Prediction \( Y_P = 0.249 \)

\[ m_\chi = 1 \text{ MeV} \]
\[ m_{\chi'} = 3m_\chi \]

- \( (N_{\text{eff}} = 1.46) \times \)
- \( (N_{\text{eff}} = 2.92) \checkmark \)

+ equivalent neutrinos

Particle Data Group, Prog. Theor. Exp. Phys. 2020, 083C01

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New Constraints

Improvements upon previous work:

• Updated constraint framework to accommodate dark sector

• Combined and improved upon state-of-the-art computational tools (PRIMAT, nudec_BSM) to make precise CMB and BBN predictions
  • Expanded temperature/abundance calculation routines for a dark sector
  • Included possibility of additional inert states in dark sector
  • Updated reaction network (BBN)
  • Improved treatment of neutrino decoupling

• Implemented uncertainty calculation routines (BBN)
Results

Existing Constraints

Joint CMB+BBN constraint (includes possibility of inert states)

*Dark matter is assumed to be thermal (verified)
Summary

• CMB and BBN can constrain light dark sectors, even in the presence of additional degrees of freedom

• A hidden sector with a complex scalar $\chi$ and dark photon with $m_{A'} = 3m_{\chi}$ is constrained to have $m_{\chi} \gtrsim 5\text{ MeV}$

• Future work
  • Accommodate more exotic dark sectors
  • Address additional proposals to model build around these constraints