Probing Dark Matter Interactions with Cosmological Observables

Arnab Paul
Department of Physics
IIT Madras, Chennai

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Based on - AP, A. Chatterjee, A. Ghoshal, S. Pal, JCAP 2021;
A. Dey, AP, S. Pal, MNRAS 2023.

Outline

- Dark Matter (DM)
  - Missing mass in Astrophysical and Cosmological observations (Gravitational evidence)
  - Other searches (non-gravitational interaction possibilities)
- Effect of DM in Cosmological evolution
  - History and composition of Universe
  - Brief tour of Cosmological Evolution in early universe: Background and Linear Perturbations
  - Observables: Cosmic Microwave Background (CMB), Matter Power spectrum
- DM-neutrino (ν) interaction and Early Universe
  - Effect in perturbations from non-gravitational interactions
  - Constraints
  - Viable microscopic scenario (example)
- Effects of DM-ν scattering in Late Universe
  - Effect on reionisation and Constraints
- Conclusion

Dark Matter: Evidence

Presence of Dark Matter (DM) is well-established from observations suggesting missing mass at all scales - Astrophysical to Cosmological

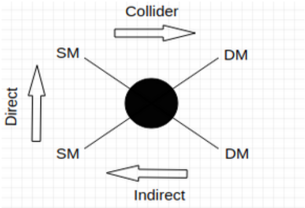
- Motion of neighbouring stars in the Milky Way ... Jan Oort (1932)
- Motion of galaxies in COMA cluster ... Fritz Zwicky (1932)
- Galaxy rotation curve ... Vera Rubin (1960's)
- Lensing observation of Bullet Cluster ... D. Clowe et.al. (2004)
- CMB acoustic peaks ... Wilkinson Microwave Anisotropy Probe (WMAP)

Note: Evidences are gravitational only.

Dark Matter: Our knowledge so far

- Known so far (from gravitational evidences without much additional assumptions):
  - DM relic abundance: $\rho_{\rm DM}/\rho_{SM} = 5.3$ at current epoch
  - Must be non-relativistic from a very early epoch

- Particle nature of DM yet to be known:
  - Production mechanism ... Thermal mechanisms like freeze-out require SM-DM interactions ... No such hint till now from direct or in-direct searches ... May also be Non-thermal mechanisms
  - Possible interactions with SM or Dark particles ... Difficult to observe in terrestrial experiments ... Interesting to look for in Cosmological observations (?)



Basics of standard (ΛCDM) Cosmological evolution

The framework cosmological evolution depends on mainly four points:

- The theory of Gravity:
  General Relativity
- The composition of Universe:
  photon, neutrino, baryons (electron, H and He); dark matter, dark energy. (The evolution we are interested in, starts from well after BBN, so the other SM particles are not relevant. The mode corresponding to $k \sim 10\ \mathrm{Mpc}^{-1}$ enters during $T \sim \mathrm{keV}$, much after BBN at $T \sim \mathrm{MeV}$)
- The initial conditions of perturbations:
  Assumed nearly scale invariant with small tilt along with adiabatic initial conditions
- Model of interactions between the components of the Universe:
  Following Standard model (and optionally non-standard interactions).

Metric and Energy-momentum tensor

- FLRW Metric (assuming flat) with scalar perturbation (ignoring vector and tensor fluctuations) in Newtonian gauge:

$$ds^2 = a^2(\eta)\left\{-(1+2\psi)d\tau^2 + (1-2\phi)dx^i dx_i\right\}$$

- Perturbation in energy-momentum tensor (of some species, in fluid description):

$$\begin{aligned} T^0{}_0 &= -(\bar{\rho}+\delta\rho)\,, \\ T^0{}_i &= (\bar{\rho}+\bar{P})v_i = -T^i{}_0\,, \\ T^i{}_j &= (\bar{P}+\delta P)\delta^i{}_j + \Sigma^i{}_j\,, \end{aligned}$$

total T^μ_ν requires sum over all species.

Einstein's equations

$$G^{\mu\nu} = 8\pi\mathcal{G}T^{\mu\nu}$$

- 0th order - Friedmann equations

$$\left(\frac{a'}{a}\right)^2 = \frac{8\pi}{3}Ga^2\bar{\rho}\,,$$

$$\frac{d}{d\eta}\left(\frac{a'}{a}\right) = -\frac{4\pi}{3}Ga^2(\bar{\rho}+3\bar{P})\,,$$

- 1st order in perturbation - Linearised Einstein's equations - describes evolution of metric perturbations

$$k^2\phi + 3\frac{a'}{a}\left(\phi' + \frac{a'}{a}\psi\right) = 4\pi Ga^2\delta T^0{}_0\,,$$

$$k^2\left(\phi' + \frac{a'}{a}\psi\right) = 4\pi Ga^2(\bar{\rho}+\bar{p})\theta\,,$$

$$\phi'' + \frac{a'}{a}(\psi' + 2\phi') + \left(2\frac{a''}{a} - \frac{a'^2}{a^2}\right)\psi + \frac{k^2}{3}(\phi-\psi) = \frac{4\pi}{3}Ga^2\delta T^i{}_i\,,$$

$$k^2(\phi-\psi) = 12\pi Ga^2(\bar{\rho}+\bar{p})\sigma\,,$$

where $\theta = ik^j v_j$, $\Sigma_{ij} = -(\hat{k}_i\hat{k}_j - \frac{1}{3}\delta_{ij})\sigma$.

Energy-momentum conservation (fluid)

$$T^{\mu\nu}{}_{;\mu} = \partial_\mu T^{\mu\nu} + \Gamma^{\nu}{}_{\alpha\beta} T^{\alpha\beta} + \Gamma^{\alpha}{}_{\alpha\beta} T^{\nu\beta} = 0$$

For n-th free (non-interacting) species:

- 0th order - Evolution of energy density of n-th species

$$\bar{\rho}_n' = -3\mathcal{H}(\bar{\rho}_n + \bar{P}_n)$$

- 1st order in perturbation - Evolution of over-density ($\delta_n = \frac{\delta\rho_n}{\bar{\rho}_n}$) and velocity divergence ($\theta_n = ik_j v^j_{(n)}$) in Fourier space:

$$\begin{aligned} \delta_n' &= -(1+w_n)\left(\theta_n - 3\phi'\right) - 3\frac{a'}{a}\left(\frac{\delta P_n}{\delta\rho_n} - w_n\right)\delta_n \,, \\ \theta_n' &= -\frac{a'}{a}(1-3w_n)\theta_n - \frac{w_n'}{1+w_n}\theta_n + \frac{\delta P_n/\delta\rho_n}{1+w_n}\,k^2\delta_n - k^2\sigma_n + k^2\psi \,. \end{aligned}$$

where $w_n = \frac{\bar{P}_n}{\bar{\rho}_n}$.

- In fluid picture, for each species we get a pair $(\delta',\ \theta')$ of evolution equations.

Distribution description (massless species)

When interactions between species are present, it is convenient to use distribution functions $f(x^i, P_j, \eta)$ and perturb around thermal distribution f_0,

$$f(x^i, P_j, \eta) = f_0(q)\left[1 + \Psi(x^i, q, n_j, \eta)\right].$$

Using Boltzmann and geodesic equations,

$$\frac{\partial \Psi}{\partial \eta} + i\,\frac{q}{\epsilon}\,(\vec{k}\cdot\hat{n})\,\Psi + \frac{d\ln f_0}{d\ln q}\left[\dot{\phi} - i\,\frac{\epsilon}{q}(\vec{k}\cdot\hat{n})\,\psi\right] = \frac{1}{f_0}\left(\frac{\partial f}{\partial \eta}\right)_{Collision}.$$

Integrating out the q-dependence in the distribution function and expanding the directional dependence as sum of Legendre polynomials $P_l(\hat{k}\cdot\hat{n})$, defining,

$$F(\vec{k}, \hat{n}, \eta) \equiv \frac{\int q^2 dq\, q f_0(q)\Psi}{\int q^2 dq\, q f_0(q)} \equiv \sum_{l=0}^{\infty} (-i)^l (2l+1) F_l(\vec{k}, \eta) P_l(\hat{k}\cdot\hat{n}).$$

$$
\begin{aligned}
\delta &= \frac{1}{4\pi}\int d\Omega F(\vec{k},\hat{n},\eta) = F_0\,,\\
\theta &= \frac{3i}{16\pi}\int d\Omega\,(\vec{k}\cdot\hat{n})F(\vec{k},\hat{n},\eta) = \frac{3}{4}kF_1\,,\\
\sigma &= -\frac{3}{16\pi}\int d\Omega\left[(\hat{k}\cdot\hat{n})^2-\frac{1}{3}\right]F(\vec{k},\hat{n},\eta) = \frac{1}{2}F_2\,,
\end{aligned}
$$

We get a hierarchy of equations (for free species),

$$
\begin{aligned}
\delta' &= -\frac{4}{3}\theta + 4\phi'\,,\\
\theta' &= k^2\left(\frac{1}{4}\delta-\sigma\right)+k^2\psi\,,\\
F_l' &= \frac{k}{2l+1}\left[lF_{(l-1)}-(l+1)F_{(l+1)}\right]\,,\quad l\geq 2\,.
\end{aligned}
$$

Perturbation equations for different species

- CDM

$$\delta'_{\rm cdm} = -\theta_{\rm cdm} + 3\phi',$$
$$\theta'_{\rm cdm} = k^2\psi - \mathcal{H}\theta_{\rm cdm}.$$

- Neutrinos

$$\delta'_\nu = -\frac{4}{3}\theta_\nu + 4\phi',$$
$$\theta'_\nu = k^2\psi + k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right).$$

- Photons

$$\delta'_\gamma = -\frac{4}{3}\theta_\gamma + 4\phi',$$
$$\theta'_\gamma = k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) + k^2\psi + an_e\sigma_T(\theta_b - \theta_\gamma).$$

- Baryons

$$\delta'_b = -\theta_b + 3\phi',$$
$$\theta'_b = -\mathcal{H}\theta_b + c_s^2 k^2\delta_b + \frac{4\bar{\rho}_\gamma}{3\bar{\rho}_b} an_e\sigma_T(\theta_\gamma - \theta_b) + k^2\psi.$$

- Initial conditions are chosen as $\delta_{cdm} = \delta_b = \frac{3}{4}\delta_\gamma = \frac{3}{4}\delta_\nu$, $\delta_\gamma = -2\phi$, $\phi = \frac{2}{3}\mathcal{R}$ with power spectrum of $\mathcal{R}$ given by $\mathcal{P}_s = A_s\left(\frac{k}{k_*}\right)^{n_s-1}$

Imprint in CMB and Matter Power Spectrum

- Observable CMB PS:
  Line-of-sight integral (in real space in one direction):

$$(\Theta_\gamma + \psi)|_{obs} = \int_{\eta_{ini}}^{\eta_0} d\eta \, [g(\Theta_{\gamma,0} + \psi + n.v_b) + e^{-\tau}(\phi' + \psi')]$$

  - Temperature fluctuation at last scattering surface + Energy loss for getting out of potential well
  - Doppler effect
  - Sachs-Wolfe effect (Early and Late)

- Observable Matter PS:

$$P(k) \propto \delta_{cdm}(k)^2$$

  - Dark Matter density fluctuation

Constraining DM-ν interaction from cosmological observations (AP et.al., JCAP 2021)

- Vanilla ΛCDM model of cosmology has so far been well established in the light of cosmological observables ... Apart from some tensions like Hubble tension
  - DM is assumed to be non-relativistic and non-interacting with other species
  - 6 parameters in simplest scenario

$$\{\underbrace{\omega_b, \omega_{cdm}, 100 * \theta_s}_{\text{composition}}, \underbrace{\ln(10^{10} A_s), n_s}_{\text{ini. cond.}}, \underbrace{\tau_{reio}}_{\text{blur}}\} \qquad (2)$$

(where $\omega_i = \Omega_i^0 h^2$ with $H_0 = 100\, h\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\theta_s = \frac{d_s(\eta_{LS})}{d_A(\eta_{LS})}$, $\tau_{reio} = \int_{\eta_{reio}}^{\eta_0} d\eta\, \Gamma(\eta)$ with $\Gamma(\eta) = a(\eta)(n_e(\eta)x_e(\eta))\sigma_{Thomson}c$)

- However particle models of DM often require DM to interact with SM particles ... For example DM-baryon interaction in freeze-out mechanism

- Another interesting possibility is DM-ν interaction
  - Useful for thermal production of MeV scale DM (Berlin & Blinov, 2017)
  - Difficult to probe such interactions with terrestrial experiments
  - Cosmological perturbations may have imprint of such interactions ... Possibility to constrain such interaction via CMB PS and Matter PS

Extensive study have been done in scenarios with DM-ν scattering by groups of Melchiorri,Lesgourgues, Mena, Boehm.
On the other hand DM annihilation have been studied by Kahlhoefer, Picon separately.

Our Work

- Find effect of such DM-ν interaction term, i.e. DM-ν scattering and DM annihilation in the equations of evolution of cosmological perturbations
  - Couple the conservation equations of DM and ν fluids
  - Find modifications in first order perturbations due to this coupling
- Modify publicly available code `CLASS` (Blas, Lesgourgues, Tram, 2011) to incorporate those changes
- Study effect of these modifications in CMB TT PS and Matter PS
- Constrain such effects using MCMC analysis using `MontePython` (Brinckman, Lesgourgues)
- Map those constraints in parameter space of viable particle model

Modified Background equations due to annihilation

We start with,

$$T_{\nu}^{\mu(\nu)} = P_{\nu} g^{\mu}{}_{\nu} + (\rho_{\nu} + P_{\nu}) U^{\mu(\nu)} U_{\nu}^{(\nu)} ,$$
$$T_{\nu}^{\mu(cdm)} = \rho_{cdm} U^{\mu(cdm)} U_{\nu}^{(cdm)} ,$$

where $U^{\mu(i)} = dx^{\mu}/\sqrt{-ds^2}$ is the fluid's four-velocity.
The energy flow from DM (Ψ with mass M_{Ψ}) due to DM annihilation is,

$$T_{\mu}^{(cdm)\,\nu}{}_{;\nu} = -\frac{\langle \sigma v \rangle}{M_{\Psi}} \rho_{cdm}^{2} U_{\mu}^{(cdm)} .$$

where $\langle \sigma v \rangle$ is the average dark matter annihilation cross section times relative velocity, along with,

$$T_{\mu}^{(\nu)\,\nu}{}_{;\nu} = +\frac{\langle \sigma v \rangle}{M_{\Psi}} \rho_{cdm}^{2} U_{\mu}^{(cdm)} .$$

At 0th order, four velocities of dark matter and ν are taken to be $u^{\mu} = \delta^{\mu}{}_{0}/a$,

$$\bar{\rho}'_{cdm} + 3\mathcal{H}\bar{\rho}_{cdm} = -\frac{\langle \sigma v \rangle}{M_{\Psi}} \bar{\rho}_{cdm}^{2} a,$$
$$\bar{\rho}'_{\nu} + 4\mathcal{H}\bar{\rho}_{\nu} = +\frac{\langle \sigma v \rangle}{M_{\Psi}} \bar{\rho}_{cdm}^{2} a.$$

Modified Perturbation equations

Evolution of density contrast and velocity divergence of DM and ν perturbations are modified as,

$$
\begin{aligned}
\delta'_{\rm cdm} &= -\theta_{\rm cdm} + 3\phi' - \frac{\delta\langle\sigma v\rangle}{M_\Psi}\rho_{\rm cdm} a - \frac{\langle\sigma v\rangle}{M_\Psi}\rho_{\rm cdm}\delta_{\rm DM} a - \frac{\langle\sigma v\rangle}{M_\Psi}\rho_{\rm cdm} a\psi \ , \\
\theta'_{\rm cdm} &= k^2\psi - \mathcal{H}\theta_{\rm cdm} - S^{-1}\mu'(\theta_{\rm cdm} - \theta_\nu) + 2\frac{\langle\sigma v\rangle}{M_\Psi}\rho_{\rm cdm}\theta_{\rm cdm} a \ , \\
\delta'_\nu &= -\frac{4}{3}\theta_\nu + 4\phi' + \frac{\delta\langle\sigma v\rangle}{M_\Psi}\frac{\rho^2_{\rm cdm}}{\rho_\nu} a + \frac{\langle\sigma v\rangle}{M_\Psi}\frac{\rho^2_{\rm cdm}}{\rho_\nu}(2\delta_{\rm DM} - \delta_\nu)\, a + \frac{\langle\sigma v\rangle}{M_\Psi}\frac{\rho^2_{\rm cdm}}{\rho_\nu} a\psi, \\
\theta'_\nu &= k^2\psi + k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) - \mu'(\theta_\nu - \theta_{\rm cdm}) - a\frac{\langle\sigma v\rangle}{M_\Psi}\frac{\rho^2_{\rm cdm}}{\rho_\nu}\left(\frac{3}{4}\theta_{\rm cdm} + \theta_\nu\right)
\end{aligned}
$$

where $\mu' \equiv a\,\sigma_{\Psi-\nu}\,c\,n_{\rm cdm}$, $S = \frac{3}{4}(\rho_{\rm cdm}/\rho_\nu)$.
The effect of DM-ν scattering is quantified by,

$$
u \equiv \left[\frac{\sigma_{\Psi-\nu}}{\sigma_{\rm Th}}\right]\left[\frac{M_\Psi}{100\ {\rm GeV}}\right]^{-1} \ ,
$$

The velocity averaged annihilation cross-section of DM particles $\langle\sigma v\rangle$ is parametrised as,

$$
\left[\frac{\langle\sigma v\rangle}{\langle\sigma v\rangle_w}\right]\left[\frac{M_\Psi}{100\ {\rm GeV}}\right]^{-1} \equiv \frac{\Gamma a}{3\times 10^{-12}} \ ,
$$

the proportionality factor of a comes due to Sommerfeld enhancement.

Effect on CMB TT PS and Matter PS

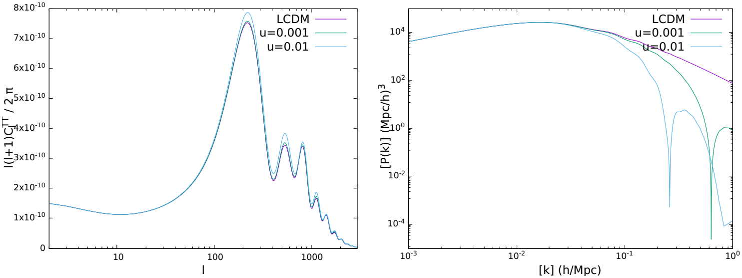


Figure: The effect of DM-ν scattering on the CMB TT PS and on Matter PS.

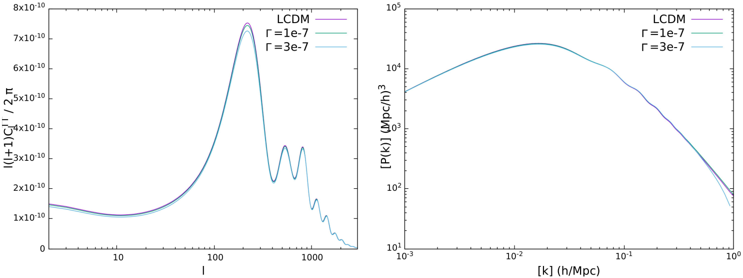
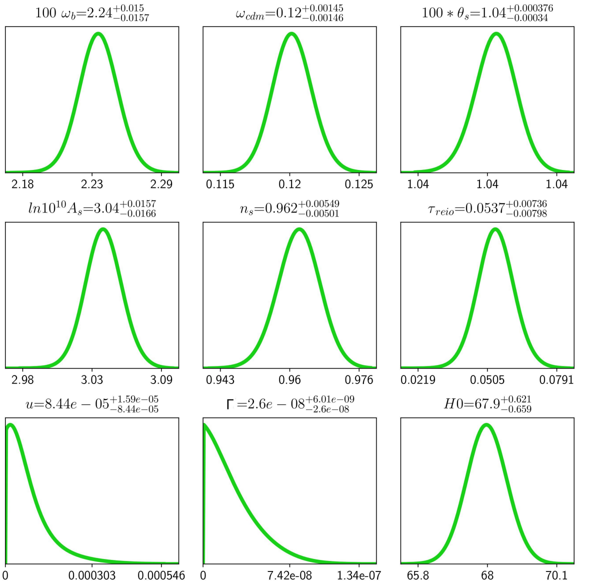


Figure: The effect of DM annihilation on the CMB TT PS and on Matter PS.

Posterior distribution of ΛCDM+u+Γ using Planck 2018 high-l TT+TE+EE, low-l TT, low-L EE data-set



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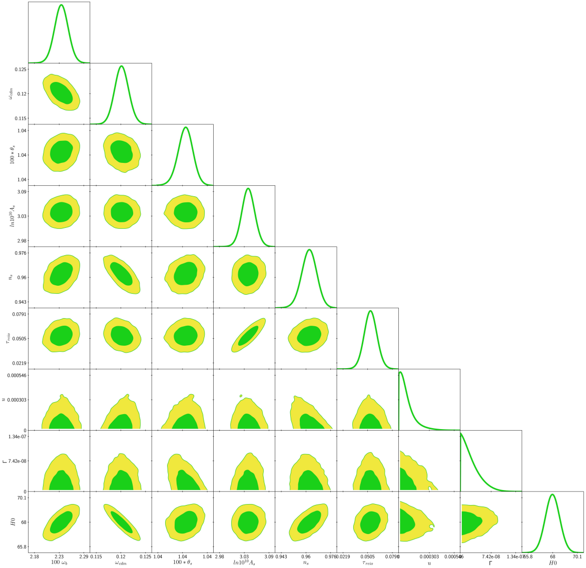
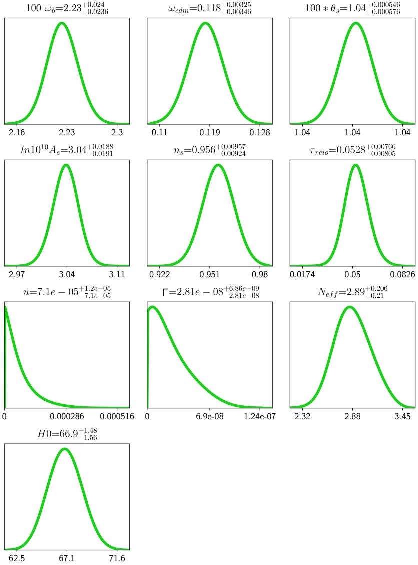


Table of posteriors

Parameter	best-fit	mean$\pm\sigma$	95% lower	95% upper
$100~\omega_b$	2.239	$2.239^{+0.015}_{-0.016}$	2.21	2.269
ω_{cdm}	0.1201	$0.1204^{+0.0014}_{-0.0015}$	0.1176	0.1233
$100 * \theta_s$	1.042	$1.042^{+0.00038}_{-0.00034}$	1.041	1.042
$ln10^{10}A_s$	3.04	$3.045^{+0.016}_{-0.017}$	3.013	3.077
n_s	0.9638	$0.9618^{+0.0055}_{-0.005}$	0.9514	0.9721
τ_{reio}	0.05354	$0.05373^{+0.0074}_{-0.008}$	0.03856	0.06937
u	–	.0001003 $(1-\sigma$ upper)	–	0.0002373
Γ	–	3.204×10^{-8} $(1-\sigma$ upper)	–	6.821×10^{-8}
$H0$	67.96	$67.95^{+0.62}_{-0.66}$	66.7	69.22

Table: *Statistical results of 6+2 parameter model with parameters* $\{\omega_{\rm b},\ \omega_{\rm cdm},\ \theta_{\rm s},\ A_{\rm s},\ n_{\rm s},\ \tau_{\rm reio},\ u,\ \Gamma\}$ *using* `Planck` *2018 dataset (high-l TT+TE+EE, low-l TT, low-l EE).*

Posterior distribution of ΛCDM+u+Γ + $N_{\rm eff}$ using Planck 2018 high-l TT+TE+EE, low-l TT, low-L EE data-set



Posterior distribution of ΛCDM$+u+\Gamma+N_{\rm eff}$ using `Planck 2018 high-l TT+TE+EE, low-l TT, low-L EE` data-set

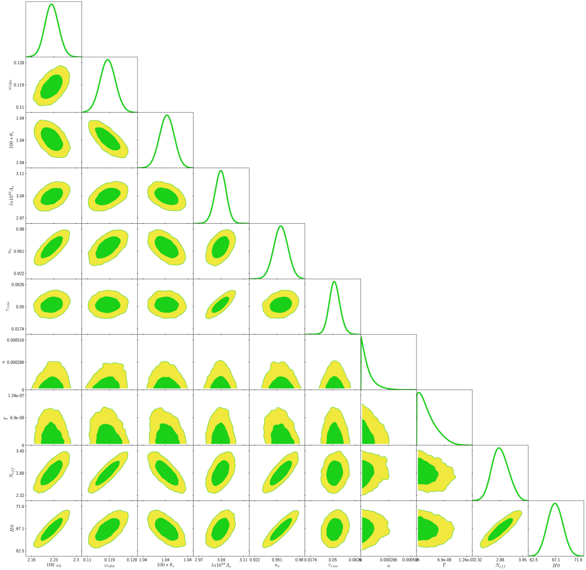


Table of posteriors

Parameter	best-fit	mean$\pm\sigma$	95% lower	95% upper
$100~\omega_b$	2.24	$2.225^{+0.024}_{-0.024}$	2.179	2.271
ω_{cdm}	0.1189	$0.1181^{+0.0033}_{-0.0035}$	0.1116	0.1247
$100*\theta_s$	1.042	$1.042^{+0.00055}_{-0.00058}$	1.041	1.043
$ln10^{10}A_s$	3.04	$3.037^{+0.019}_{-0.019}$	2.999	3.075
n_s	0.9633	$0.956^{+0.0096}_{-0.0092}$	0.9374	0.9742
τ_{reio}	0.05145	$0.05275^{+0.0077}_{-0.0081}$	0.03678	0.06908
u	–	8.296×10^{-5} $(1-\sigma$ upper$)$	–	0.0002123
Γ	–	3.502×10^{-8} $(1-\sigma$ upper$)$	–	7.192×10^{-8}
N_{eff}	3.001	$2.888^{+0.21}_{-0.21}$	2.484	3.303
$H0$	67.98	$66.88^{+1.5}_{-1.6}$	63.86	69.9

Table: *Statistical results of 6+2 parameter model with parameters* $\{\omega_{\rm b},\ \omega_{\rm cdm},\ \theta_{\rm s},\ A_{\rm s},\ n_{\rm s},\ \tau_{\rm reio},\ u,\ \Gamma,\ N_{\rm eff}\}$ *using* `Planck` *2018 dataset (high-l TT+TE+EE, low-l TT, low-l EE).*

Example model

- We consider a model,

$$-\mathcal{L} \supset g_s \bar{\nu}_s \gamma_5 \nu_s \phi + g_\Psi \bar{\Psi} \gamma_5 \Psi \phi$$

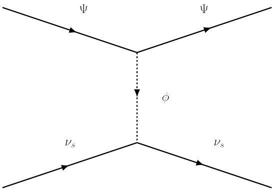
- The DM-ν scattering cross-section is given by,

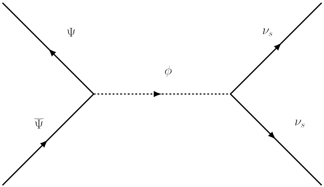
$$\sigma_{\Psi-\nu} = \frac{g_s^2 g_\Psi^2}{64\pi M_\Psi^2} \sin^4(\theta_{\rm m}).$$

- The DM annihilation rate into ν_s or ϕ is given by,

$$\langle \sigma v \rangle = \langle S \sigma v \rangle_{\rm tree} = \langle S \rangle \langle \sigma v \rangle_{\rm tree},$$

where $\langle S \rangle = \langle \frac{g_\Psi^2}{4v} \rangle = \frac{g_\Psi^2}{\sqrt{8\pi}} \sqrt{\frac{M_\Psi}{T_\Psi}}$, $\langle \sigma v \rangle_{\rm tree} = \frac{g_\Psi^2 g_s^2}{64 M_\Psi^2}$ or $\frac{g_\Psi^4}{64 M_\Psi^2}$





Constraints on parameter space

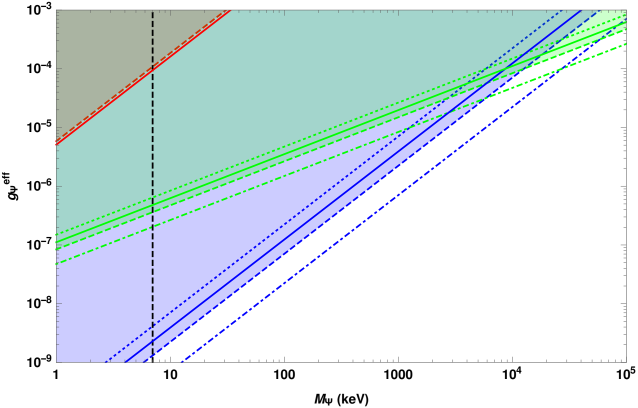


Figure: We have used $g_\Psi^{\text{eff}} = g_\Psi \sin^2(\theta_{\text{m}})$ for the scattering process and $g_\Psi^{\text{eff}} = g_\Psi$ for the annihilation processes to keep them on the same footing, as during scattering the DM particles scatter to the active neutrinos through mixing with ν_s, whereas during annihilation, the more stringent bound comes from annihilation of DM into ν_s. The red, blue and green lines correspond to bounds from scattering and annihilation of DM into sterile neutrinos and pseudoscalars respectively. We have used $g_s = 10^{-4}$ and $\theta_{\text{m}} = 0.1$ for these plots. The vertical dashed line at $M_\Psi \sim 7$ keV corresponds to the lower mass bound of fermionic DM from Lyman-α observations.

Mini-conclusion

Importance:

- DM-ν interaction is hard to probe in terrestrial experiments $\rightarrow$ Explore effect on cosmological perturbations

Our Findings

- Find first order cosmological perturbation equations with DM-ν interaction $\rightarrow$ Implement modifications in publicly available code CLASS
- DM$-\nu$ scattering enhances the CMB acoustic peaks, thereas DM annihilation suppresses them
- Both DM$-\nu$ scattering and DM annihilation suppresses power of Matter PS at small scales
- MCMC analysis shows no preference of DM-ν interaction over vanilla ΛCDM, however gives upper limits on DM$-\nu$ scattering and DM annihilation strength, which can be used for particular particle models ($\sigma_{\Psi-\nu} < 6.75 \times 10^{-29}\ \mathrm{cm}^2$, $\langle \sigma v \rangle < 2.91 \times 10^{-25}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$ at last scattering surface for $M_\Psi = 100\ \mathrm{GeV}$)

Dynamics of universe after recombination

- After the DM fluctuations grow significantly (and the perturbation theory breaks down), they start to form DM haloes
- Baryons tend to fall into DM haloes, become cool and dense, form stars
- High energy photons from the stars in the haloes begin to ionize the H atoms around it, starting the reionization process, ionized bubbles are formed
- If there is some signature in the linear power spectra itself, that property propagates to the nonlinear evolution and hence to the reionization process

Steps to reionization

Formation of dark matter haloes

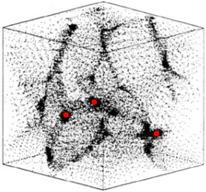
- Analytic (spherical/elliptical collapse)
- N-body simulation

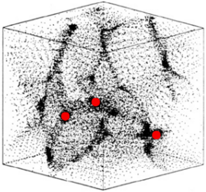
Production of ionizing photons

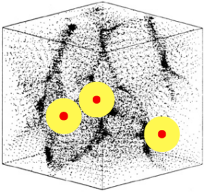
- Star/Galaxy formation
- Escape of high energy photons into IGM

Radiative transfer in the IGM

- Simulations
- Semi-numerical







(Base picture taken from Davis et.al., 1985)

Our Work

1. Generate linear Matter PS for different values of u at $z \sim 100$ (we only consider DM-ν scattering for this work, not DM annihilation)
2. Use linear Matter PS as initial condition of the nonlinear N-body simulation
3. Find DM haloes using Friend-of-Friend (FoF)
4. Study reionization history using Reion-Yuga code
5. Constrain u

Tools and Constraints used

N-body Simulation: Particle Mesh Code
(Bharadwaj and Srikant 2004, Mondal et al. 2015)

- Grid= 2144^3, Volume= 150.0 Mpc^3, Resolution= 0.07 Mpc, Particle number= 1072^3

Halo finder: Friends of Friends algorithm (Mondal et al. 2015)

- M_{min}=$1.9 \times 10^9 M_\odot$

Reionization: ReionYuga code
(Choudhury et al. 2009, Majumdar et al. 2014, Mondal et al. 2017)

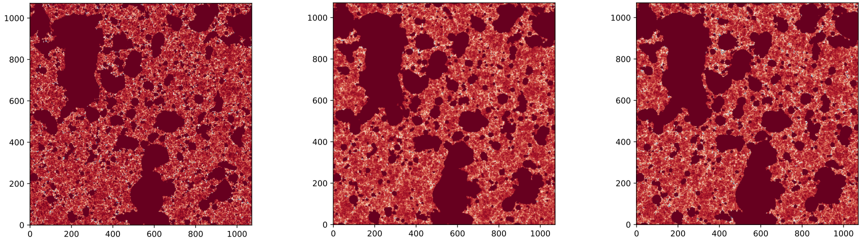
- N_{ion}=23.21 for ΛCDM
- R_{mfp}=20 Mpc

Linear Matter PS is used as initial condition of the N-body simulation

Constraints used from other studies:

- Ionization Criteria: $x_{HI} = 0.5$ at z=8.0
- N_{ion} for Population-II stars: $N_{ion} < 500$ (Conservative limit)
  $N_{ion} = 8 \frac{N^b_{ion}}{4000} \frac{M_b/M_{halo}}{1/5} \frac{f_*}{10\%} \frac{f_{esc}}{10\%}$, where N^b_{ion} is number of ionizing photons per baryon, f_* and f_{esc} are uncertian parameters related to metalicity, initial mass function (MNRAS. 459 (July, 2016), 2342-2353)

HI map at $z = 8.0$ and constraints



$u = 0$ (ΛCDM), $N_{ion} = 24$

$u = 8.8 \times 10^{-8}$, $N_{ion} = 300$

$u = 6.6 \times 10^{-7}$, $N_{ion} = 500$

- Higher $u \rightarrow$ suppression in power at small scales $\rightarrow$ less small scale structures $\rightarrow$ higher N_{ion} required to attain same amount of reionization
- Constraint on upper limit of $N_{ion} \rightarrow$ Constraint on upper limit of u
- $x_{HI} = 0.5$ at $z = 8 \rightarrow u < 6.6 \times 10^{-7}$ (in comparison to $u \lesssim 10^{-4}$ from CMB)

Conclusion

- DM-ν interaction is hard to probe in terrestrial experiments $\rightarrow$ Explore effect on cosmological perturbations
- DM$-\nu$ scattering enhances the CMB acoustic peaks, thereas DM annihilation suppresses them
- Both DM$-\nu$ scattering and DM annihilation suppresses power of Matter PS at small scales
- MCMC analysis shows no preference of DM-ν interaction over vanilla ΛCDM, however gives upper limits on DM$-\nu$ scattering and DM annihilation strength, which can be used for particular particle models
- Even a small suppression of Matter power spectrum at small scales can considerably change the halo formation history
- A increase in the ionisation efficiency (via N_{ion}) of each halo can keep the reionization redshift z_{reio} unchanged (taking $z_{reio} \sim 8$ at face value)
- Limit on N_{ion} can then constrain DM-ν interaction strength, which is 4 orders of magnitude stronger than CMB constraints

Thank You