Constraints on Dark Matter - Neutrino interaction from 21 cm Cosmology

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in collaboration with Dr. Arnab Paul and Prof. Supratik Pal)
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Contents

Introduction

- 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
- 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 terrestial experiments
    - Cosmological perturbations may have imprint of such interactions .. Possibility to constrain such interaction via CMB PS and Matter PS

DM - massless ν interaction model

- **Modified Perturbation equation**:
  Evolution of density contrast and velocity divergence of DM and ν,
  $\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu + 4\dot{\phi}$
  $\dot{\theta_\nu} = k^2\Psi + k^2(\frac{1}{4}\delta_\nu - \sigma_\nu) - \dot{\mu}(\theta_\nu - \theta_{DM})$
  $\dot{\delta}_{DM} = -\theta_{DM} + 3\dot{\phi}$
  $\dot{\theta}_{DM} = k^2\Psi - \mathcal{H}\theta_{DM} - S^{-1}\dot{\mu}(\theta_{DM} - \theta_\nu)$
  where $\dot{\mu} \equiv a\sigma_{DM-\nu} c n_{DM}$, $S \equiv 3/4\rho_{DM}/\rho_\nu$
- **Interaction parameter**:

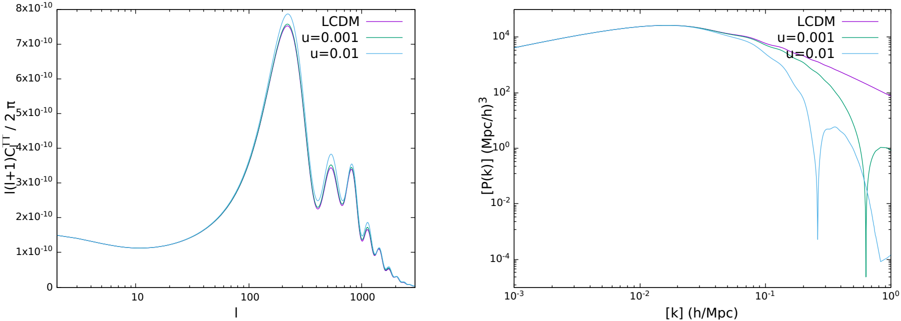
$$u \equiv \frac{\sigma_{DM-\nu}}{\sigma_{TH}}[\frac{m_{DM}}{100 Gev}]^{-1}$$

- δ_ν, θ_ν and δ_{DM}, θ_{DM} are coupled through Drag terms alongside gravity (θ, ϕ)

Model Parameters

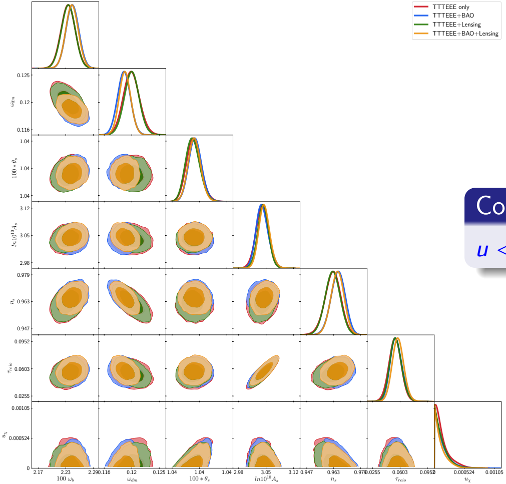
$\omega_b, \omega_{cdm}, 100 * \theta_s, ln10^{10}A_s, n_s, \tau_{reion}, u, M_{tot} = 0$

Effect on CMB TT PS and Matter PS



The effect of DM-ν scattering on CMB TT PS and Matter PS. (**Generated from modified version of CLASS)**

Posterior distribution of ΛCDM + u using Planck 2018 high-l TTTEEE, low-l TT, low-l EE, lensing data set (Mosbech et al. 2021, JCAP03(2021)066, Paul et al. 2021)



Constrain on u from Planck

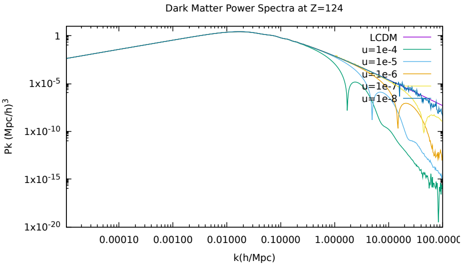
$u < 3.55 \times 10^{-4}$ from Planck 2018 data

Constraints on Dark Matter -ν interaction model from Reionization Epoch (MNRAS 524, 100-107, (2023))

Semi-numerical Simulation

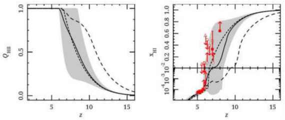
1. **N-body Simulation**: Particle Mesh Code (Bharadwaj and Srikant 2004, Mondal et al. 2015)
    - Grid= 2144^3
    - Volume= 150.0 Mpc^3
    - Resolution= 0.07 Mpc
    - Number of Particles= 1072^3
2. **Halo finder**: Friends of Friends algorithm (Mondal et al. 2015)
    - $\boxed{M_{min}=1.9 \times 10^9\ M_\odot}$
3. **Reionization**: ReionYuga code (Choudhury et al. 2009, Majumdar et al. 2014, Mondal et al. 2017)
    - $\boxed{N_{ion}=\textbf{23.21 for } \Lambda CDM}$
    - $\boxed{R_{mfp}=\textbf{20 Mpc}}$

- **Linear Matter PS for different values of u is input to the Simulation**


Dark Matter Power Spectra at Z=124

Constraints

1. Ionization Criteria



J. Astrophys. Astr. (2016) 37:29

- mean and 2σ limits on Q_{HII} and x_{HI} from Planck data
- Models with x_{HI} lying in shaded region will satisfy Reionization condition

$x_{HI} = 0.5$ at z=8.0: 50% Ionization Criteria

2. N_{ion} for Pop II stars

$$N_{ion} = 8\frac{N^b_{ion}}{4000}\frac{M_b/M_{halo}}{1/5}\frac{f_*}{10\%}\frac{f_{esc}}{10\%}$$

- N^b_{ion}: number of ionizing photons per baryons, M_b/M_{halo}: baryonic mass fraction
- f_*,f_{esc}: metalicity, initial mass function: uncertain parameters

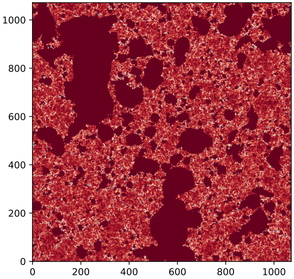
Pop II stars $N_{ion} < 500$ (Conservative limit) MNRAS. 459 (July, 2016), 2342-2353

Our Workplan

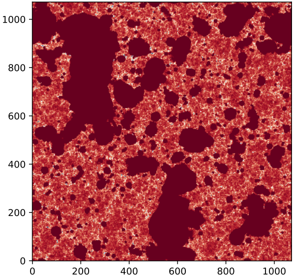
1. Generate linear Matter PS for different interaction strength u
2. Put linear Matter PS as input to the N-body code
3. Run N-body, FoF, Reion-Yuga code and varies N_{ion} from 23 to 500 to achieve $x_{HI} = 0.5$ at z=8.0

Results (MNRAS 524, 100-107, (2023))

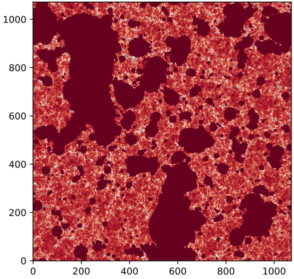
1. HI map at z=8.0



$u = 0.0$ **(ΛCDM), N_{ion} = 24**



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

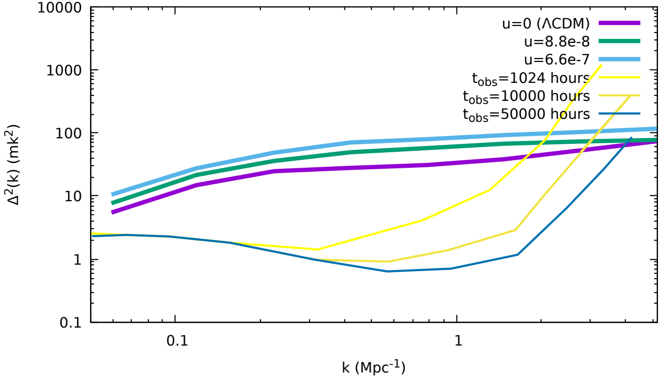


$u = 6.6 \times 10^{-7}$**, N_{ion} = 500**

- Increasing 'u' delays ionization
- To achieve $x_{HI} = 0.5$, N_{ion} must be increased

From Reionization physics we get more tighter constrain on u; $u < 6.6 \times 10^{-7}$

2. Comparison of Signal with Noise PS for SKA1-LOW Telescope



- **Signal to Noise Ratio**: $\boxed{SNR \approx 5}$
- Signal is much higher than the Noise Power Spectra for $0.1 < k < 2.0$
- Possibility to detect the Signal from the SKA1-LOW observation

Mini Summary

1. **21 cm observation improves the constrain on DM- ν interaction by few orders of magnitude in Conservative limit**.
2. ***HI* map confirms the presence of non-trivial interaction.**
3. **High SNR implies a possibility to detect the signal.**

Constraints on Dark Matter - Massive ν interaction from Post-Reionization Epoch (MNRAS 527, 790-802, (2024))

- Perturbation equations for Dark Matter is same for DM-massless ν case.
- It solves the **full Boltzmann hierarchy for massive neutrinos**.
- We consider **degenerate case of massive neutrinos**.
- **Interaction parameter**:

$$u \equiv \frac{\sigma_{DM-\nu}}{\sigma_{TH}}\left[\frac{m_{DM}}{100\,Gev}\right]^{-1}$$

- Planck 2018 data $u < 3.97 \times 10^{-4}$ (Mosbech et al. 2021, JCAP03(2021)066)

Model Parameters

$\omega_b, \omega_{cdm}, 100 * \theta_s, ln10^{10}A_s, n_s, \tau_{reion}$, u, M_{total}

Our Workplan

1. Generate the Mock Catalogues for upcoming 21 missions SKA-Mid in Post-reionization era, future Galaxy Surveys and Cosmic Shear Surveys Euclid and DESI
2. Run the Fisher matrix forecast Analysis for $6 + 2$ model parameters using upcoming missions
3. Perform the MCMC analysis using the mock data for the future missions and check the possible 1σ bounds on the model parameters

Observations

1. 21-cm Intensity Mapping Observations

21-cm intensity power spectrum $P_{21}(k, \mu, z)$

$$P_{21,\mathrm{obs}}(k,\mu,z) =$$

$$\underbrace{\left[\frac{D_{\mathrm{A}}(z)}{D_{\mathrm{A,t}}(z)}\right]^2 \frac{H_{\mathrm{t}}(z)}{H(z)}}_{\text{Alcock-Paczynski Effect}} \times \underbrace{e^{-k^2\left[\mu^2\cdot\left(\sigma_{\parallel}^2(z)-\sigma_{\perp}^2(z)\right)+\sigma_{\perp}^2(z)\right]}}_{\text{Resolution Effect}} \times \underbrace{\overbrace{\left(1+\beta(k_{\mathrm{t}},z)\,\mu_{\mathrm{t}}^2\right)^2}^{\text{Kaiser Effect}}\overbrace{e^{-k_{\mathrm{t}}^2\mu_{\mathrm{t}}^2\sigma_{\mathrm{nl}}^2}}^{\text{FoG Effect}}}_{\text{Redshift Space Distortions}}$$

$$\times\, b_{21}^2(z) \times P_{\mathrm{m}}(k_{\mathrm{t}},z) + P_{\mathrm{N}}(z)$$

Noise Power Spectrum

$$\boxed{P_{\mathrm{N}}^2 = T_{\mathrm{sys}}^2 \frac{4\pi f_{\mathrm{sky}}\, r^2(z)(1+z)^2}{2H(z)\, t_{\mathrm{tot}}\, \nu_0 N_{\mathrm{dish}}}}$$

Bias Parameter

$$\boxed{b_{21}(z) = b_0^{IM}\left(0.904 + 0.135(1+z)^{1.696 b_1^{IM}}\right)}$$

SKA Intensity Mapping specifications

Parameter	$\nu_{\mathrm{min}}(\mathrm{MHz})$	$\nu_{\mathrm{max}}(\mathrm{MHz})$	z_{min}	z_{max}	$\delta_\nu(\mathrm{kHz})$	$T_{\mathrm{inst}}(\mathrm{K})$
SKA1 Band 1	400 (350)	1000 (1050)	0.45	2.65	10.9	23
SKA1 Band 2	1000 (950)	1421 (1760)	0.05	0.45	12.7	15.5

2. Galaxy Clustering Observations

Galaxy Power Spectrum

$$P_{\rm g}(k,\mu,z) =$$

$$\underbrace{\left[\frac{D_{\rm A}(z)}{D_{\rm A,t}(z)}\right]^2 \frac{H_{\rm t}(z)}{H(z)}}_{\text{Alcock-Paczynski Effect}} \times \underbrace{e^{-k^2\left[\mu^2\cdot\left(\sigma_{\shortparallel}^2(z)-\sigma_{\perp}^2(z)\right)+\sigma_{\perp}^2(z)\right]}}_{\text{Resolution Effect}} \times \underbrace{\overbrace{\left(1+\beta(k_{\rm t},z)\,\mu_{\rm t}^2\right)^2}^{\text{Kaiser Effect}}\overbrace{e^{-k_{\rm t}^2\mu_{\rm t}^2\sigma_{\rm nl}^2}}^{\text{FoG Effect}}}_{\text{Redshift Space Distortions}}$$

$$\times\, b_{\rm g}^2(z) \times P_{\rm m}(k_{\rm t},z)$$

Bias Parameter

$$\boxed{b_g(z) = b_0(1+z)^{0.5b_1}}$$

SKA Galaxy Clustering specifications

Parameter	$\nu_{\rm min}[\rm MHz]$	$\nu_{\rm max}[\rm MHz]$	$z_{\rm min}$	$z_{\rm max}$	$S_{\rm area}[\rm deg^2]$	$\delta_\nu\,[\rm KHz]$	$B[\rm km]$
SKA1	950	1760	0.00	0.5	5000	12.7	150 (5)
SKA2	470	1290	0.10	2.0	30,000	12.8	3000 (5

3.Cosmic Shear Observations

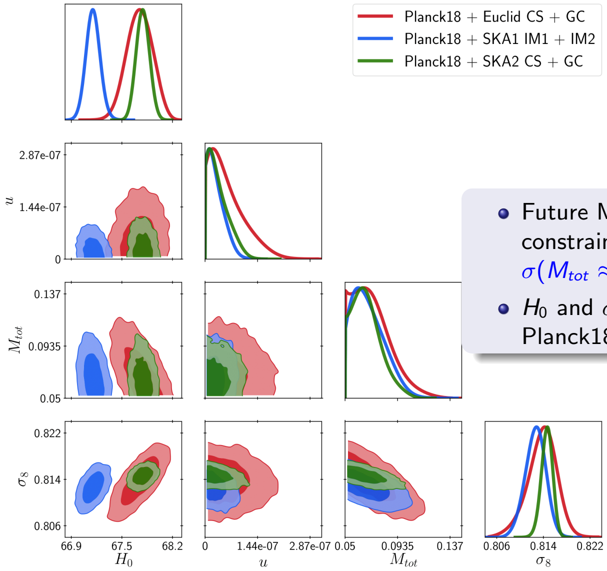
Cosmic shear power spectrum of multipole l at redshift bins $\{i,\ j\}$

$$C^{l}_{\mathrm{ij}} = \frac{9}{16}\Omega_m^2 H_0^4 \int_0^\infty \frac{\mathrm{dr}}{r^2} g_i(r) g_j(r) P\left(k = \frac{l}{r}, z(r)\right)$$

Cosmic Shear specifications for SKA and Euclid

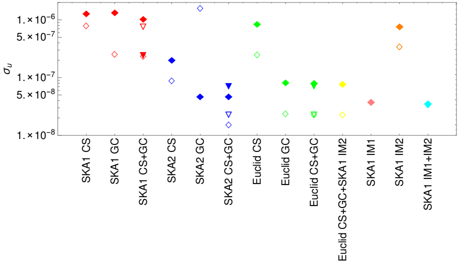
Experiments	f_{sky}	$n_{\mathrm{gal}}(\mathrm{arcmin}^{-2})$	z_m	α	β	γ	$f_{\mathrm{spec-z}}$	$Z_{\mathrm{spec-max}}$
SKA1	0.1212	2.7	1.1	$\sqrt{2}$	2	1.25	0.15	0.6
SKA2	0.7272	10	1.3	$\sqrt{2}$	2	1.25	0.5	2.0
Euclid	0.3636	30	0.9	$\sqrt{2}$	2	1.5	0.0	0.0

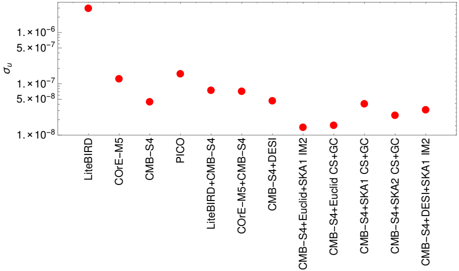
Results (MNRAS 527, 790-802, (2024))



- Future Missions SKA2 will put tighter constraints on $\sigma(u) < 10^{-8}$ and $\sigma(M_{tot} \approx 0.009eV)$
- H_0 and σ_8 values are consistent with Planck18 data

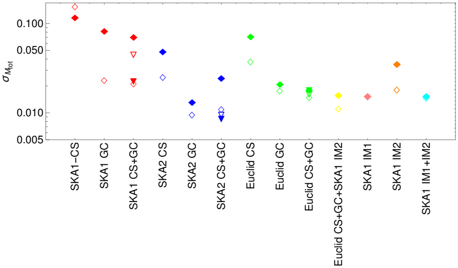
1σ uncertainties on the DM-Massive ν interaction parameter u

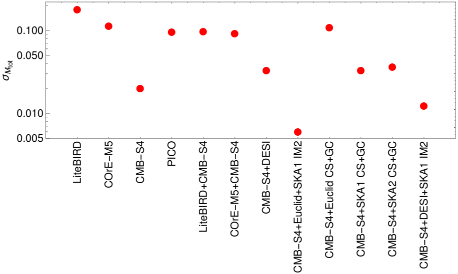




Future Missions SKA2, CMB-S4 + Euclid + SKA Intensity Mapping 2 will put tighter constraints on $\sigma(u) < 10^{-8}$

1σ uncertainties on mass of neutrinos M_{tot}





Future Missions SKA2, CMB-S4 + Euclid + SKA Intensity Mapping 2 will put tighter constraints on $\sigma(M_{tot}) \approx 0.006eV$

Mini Summary

1. Forthcoming missions **SKA2, Euclid, next generation CMB missions CMB-S4** will put **tighter constraints on the DM-ν interaction parameter u.**
2. **Future missions** will also measure **sum of neutrino mass M_{tot} more robustly.**
3. Next generation missions may put **some light on the H_0, σ_8 tensions.**

Conclusions and Future Directions

1. Future 21 cm missions hold important promise in improving the constraints on DM-ν interaction parameter by few orders of magnitude in Reionization era as well as in Post-Reionization era.
2. Upcoming missions will precisely determine the sum of neutrino mass.
3. High SNR implies a possibility to detect the signal in the Reionization Epoch using SKA1-Low telescope.
4. In the upcoming decade, future missions like SKA, Euclid, CMB-S4 will provide significant insight into the cosmological history.
5. More realistic foreground models and noise elimination techniques can be incorporated in order to detect the signal.

Thank You

Basics of Cosmological Perturbation Theory (Theory behind CMB and Matter PS)

- Perturbed energy-momentum conservation equation (for free species):

$$\dot{\delta} = -(1+w)(\theta - 3\dot{\phi}) - 3\frac{\dot{a}}{a}(\frac{\delta P}{\delta \rho} - w)\delta,$$
$$\dot{\theta} = \frac{\dot{a}}{a}(1+w)\theta - \frac{\dot{w}}{1+w}\theta + \frac{\delta P/\delta \rho}{1+w}k^2\delta - k^2\sigma + k^2\psi.$$

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

$$(\Theta + \psi)|_{obs} = \int_{\eta_{ini}}^{\eta_0} \mathrm{d}\eta g[(\theta_0 + \psi + n.v_B) + exp^{-\tau}(\dot{\phi} + \dot{\psi})]$$

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

- Observable Matter PS:

$$P(k) \propto \delta(k)^2$$

  - Dark Matter density fluctuation

Features in CMB TT, EE, TE PS and Matter PS

1. An **increase in the magnitude of the peaks** and a **slight shift to larger l** with respect to vanilla ΛCDM model
2. **Suppression of Power** at small scales (large k)
3. **Oscillatory behaviour** in non-linear regime k$\geq$0.2
4. In standard ΛCDM,

$$\boxed{\delta_{DM} = C_1 log(k\eta) + C_2}$$

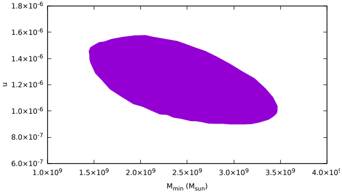
whereas for interacting DM-ν,

$$\boxed{\delta_{DM} \sim \frac{S_{-1}\dot{\mu}}{H}\frac{sin(k\eta)/\sqrt{3}}{k\eta/\sqrt{3}} exp\frac{-2k^2\eta}{15\dot{\mu}}}$$

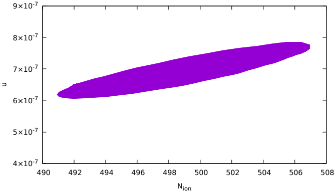
5. The term $exp\frac{-2k^2\eta}{15\dot{\mu}}$ leads to **suppression** at **large k**
6. The term $\frac{sin(k\eta)/\sqrt{3}}{k\eta/\sqrt{3}}$ leads to **oscilatory behaviour**

Fisher Forecast Analysis

Fisher Matrix analysis: $$\boxed{F_{\alpha\beta} = \sum_{ij} \left(\frac{\partial \bar{P}(k_i)}{\partial q_\alpha} [C^{-1}]_{ij} \frac{\partial \bar{P}(k_j)}{\partial q_\beta} \right)}$$



1σ error ellipse of u and M_{min}



1σ error ellipse of u and N_{ion}

- Negative correlation between u and M_{min}
- Positive correlation between u and N_{ion}
- No correlation between u and R_{mfp}