Cosmological observables and the nature of dark matter

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1. How dark matter entered cosmology

- `Hot vis-a-vis Cold dark matter`: Bottom-up formation of structures (CDM) or up-bottom formation of structures (HDM), .e.g. massive standard model neutrinos of mass 10–30 eV.
- Improved detection of galaxy clustering, e.g. two-point correlation function, power spectrum, in 1980s, culminating in the APM survey.
- Clustering signal at large scales $r \geq 10\,\mathrm{Mpc}$ or $k \leq 0.1\,\mathrm{Mpc}^{-1}$ allows theoretical prediction from linear perturbation theory to be directly compared to data. Such data became available after late 1980s, e.g. APM, Las Campanas, 2dF, SDSS surveys.
- CMB data: post-WMAP (2003)

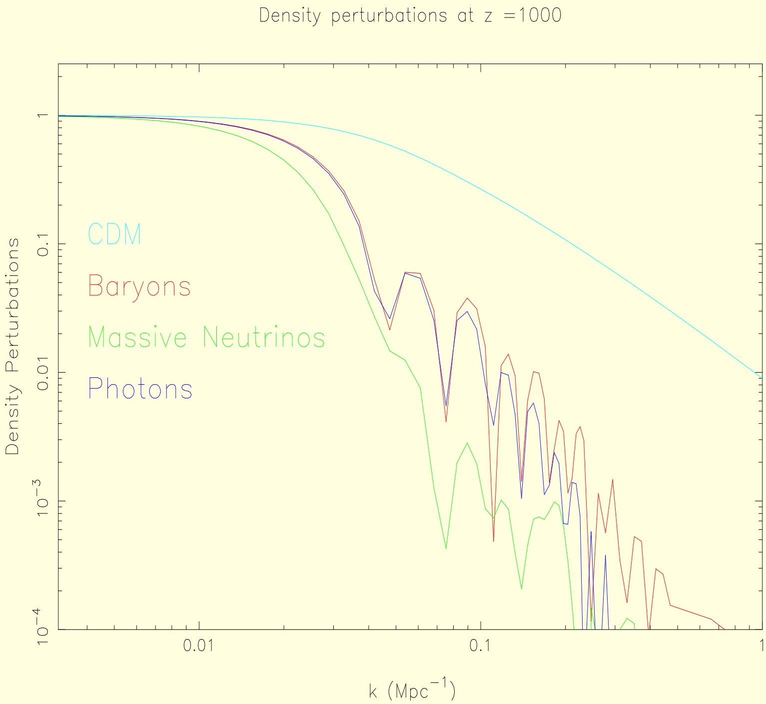
2. Matter power spectrum

- $P(k,t) = P(k,t_i)T^2(k,t_i,t)$
- $P(k,t_i) = Ak^{n_s}$: initial power spectrum—generated at the time of inflation, super-horizon scales; $n_s \simeq 1$ from inflationary theory.
- $T(k,t_i,t)$: transfer function—growth of perturbations, sub-horizon physics
- $T(k,t_i,t) \equiv T(k,t)D_+(t_i,t)$

$$T(k,t) = \frac{\sum_i \delta_i(k,t)\bar{\rho}_i}{\sum_i \bar{\rho}_i} \tag{1}$$

$i =$
$\{\mathrm{CDM}, \mathrm{Baryons}, \mathrm{neutrinos(massive, massless)}, \mathrm{photons}\}$

3. Evolution of Density perturbations: $z = 1000$



4. Scales in the problem

- `Matter-radiation equality`:

$$k_{\rm eq} \simeq 0.2\,\Omega_{\rm m} h^2\,{\rm Mpc}^{-1} \qquad (2)$$

Determines the shape of CDM perturbations

- `Sound velocity of baryon-photon fluid`: $c_s \simeq c/\sqrt{3}$. At $z \simeq 1000$:

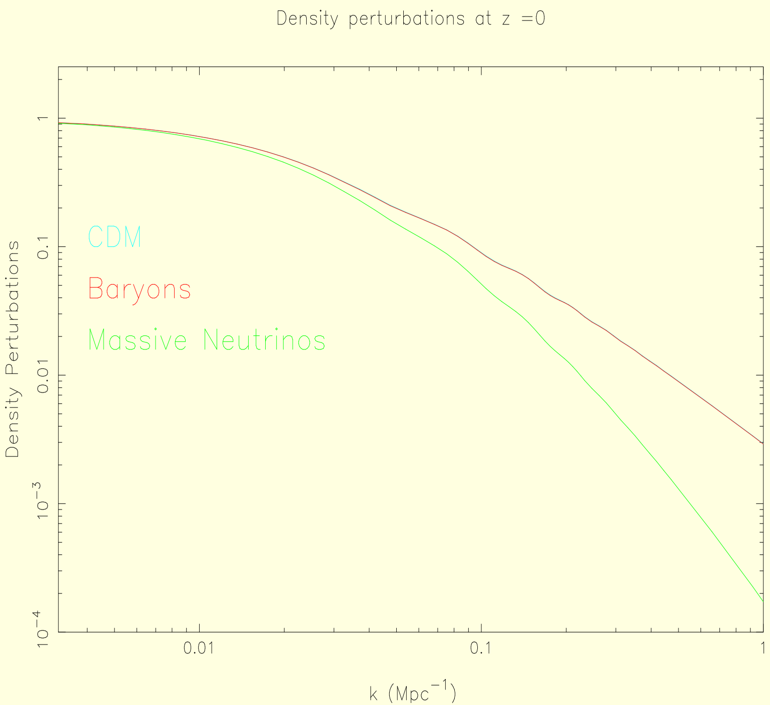
$$k_{\rm sound} \simeq \sqrt{3} H(z) \simeq 0.02 (\Omega_m h^2)^{1/2}\,{\rm Mpc}^{-1} \qquad (3)$$

- `Silk damping`: The damping scale of baryon-photon fluid owing to viscosity. $l_s^2 \simeq H^{-1} l_{\rm mf}$:

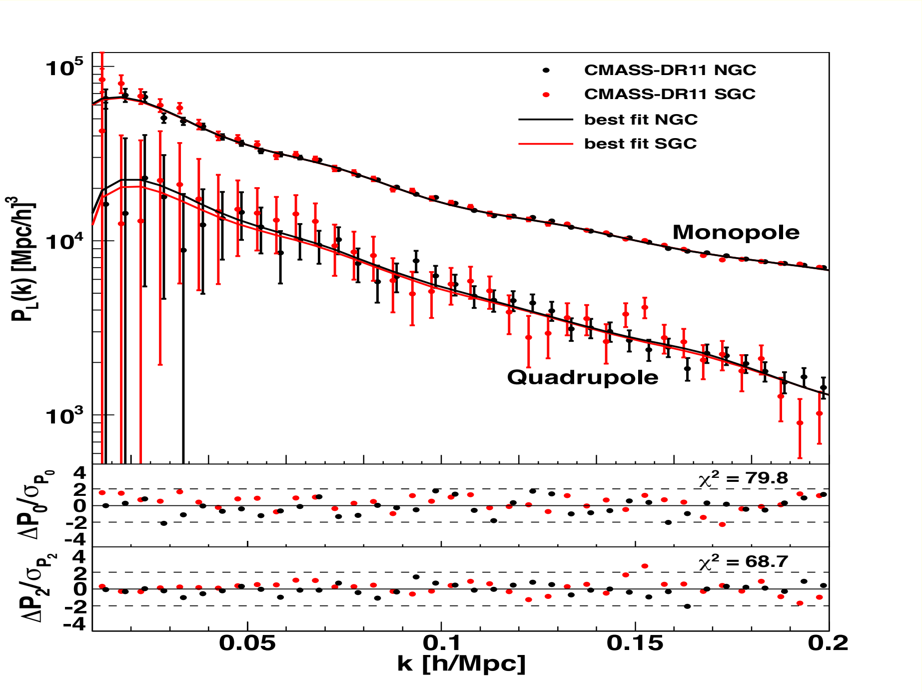
$$k_s \simeq 0.5 \left(\frac{\Omega_b h^2}{0.022}\right)^{1/2} (\Omega_m h^2)^{1/4}\,{\rm Mpc}^{-1} \qquad (4)$$

- `Free streaming of massive neutrino`: Roughly H^{-1} at $T \simeq m_\nu$, e.g. for $m_\nu \simeq 0.2\,{\rm eV}$, $k_{\rm fs} \simeq 0.01\,{\rm Mpc}^{-1}$

5. Evolution of Density perturbations: $z = 0$



6. SDSS results: power spectrum



(Beutler et al. 2013)

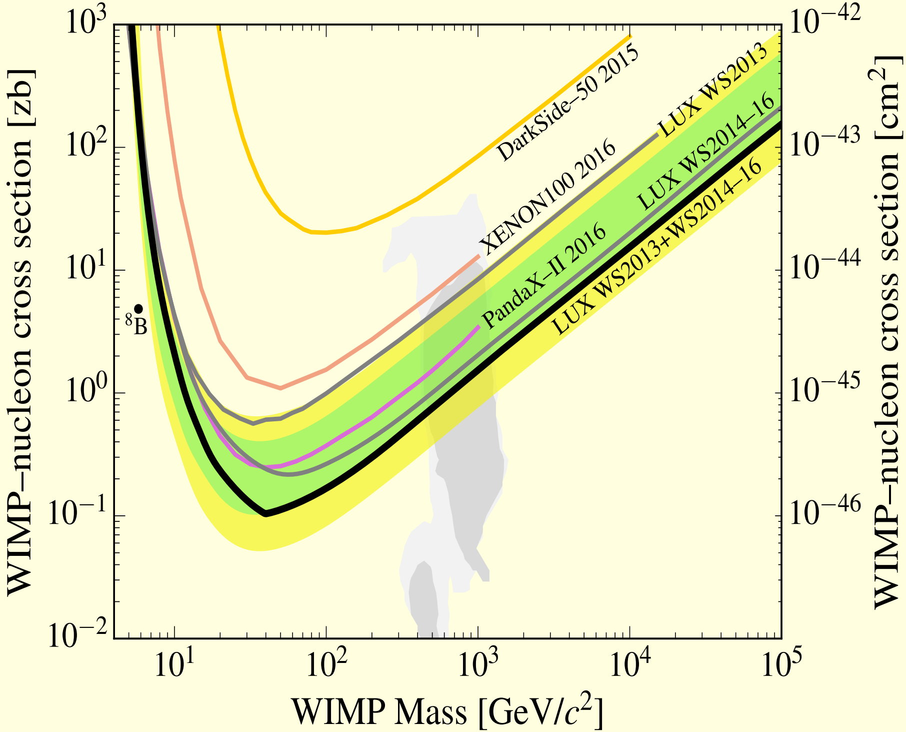
7. Determining the nature of Dark matter: Planck results

- `Primordial perturbations`: scalar spectral index, $n_s = 0.9652 \pm 0.0062$
- `Baryons`: $\Omega_B h^2 = 0.022 \pm 0.00023$
- `Nonrelativistic component of the dark matter`: $\Omega_{cdm} h^2 = 0.1199 \pm 0.0022$
- `Hubble's constant`: $H_0 = 67.26 \pm 0.98$, the most precise measurement of Hubble's constant
- `Massive neutrinos`: $\sum m_\nu < 0.23\,\mathrm{eV}, \Rightarrow \Omega_\nu < 0.005$ (particle physics data gives: $\Omega_\nu > 0.001$)
- `Massless neutrinos`: $N_{\rm eff} = 3.15 \pm 0.23$
- `Total matter content`: Consistent with spatially flat universe $\Omega_{\rm total} = 1 \pm 0.005$

8. Does CDM work at sub-galactic scales?

- *Missing sub-haloes of Milky Way*: Simulation reproduce adequately substructures of clusters but predict up to 25 times more dwarf spheroidals than detectable in Milky Way (Klypen et al. 1999, Moore et al. 1999). Less power at small scales?
- *Cuspy profiles*: Simulations suggest cuspy profiles in the center of galaxies, yet observations suggest flat profiles (e.g. Blok 2010). Interacting dark matter?
- *Too big to fail conundrum*: Simulations suggest substructures of Milky Way are too big or they should have hosted baryonic structures (Boylan-Kolchin et al. 2011).

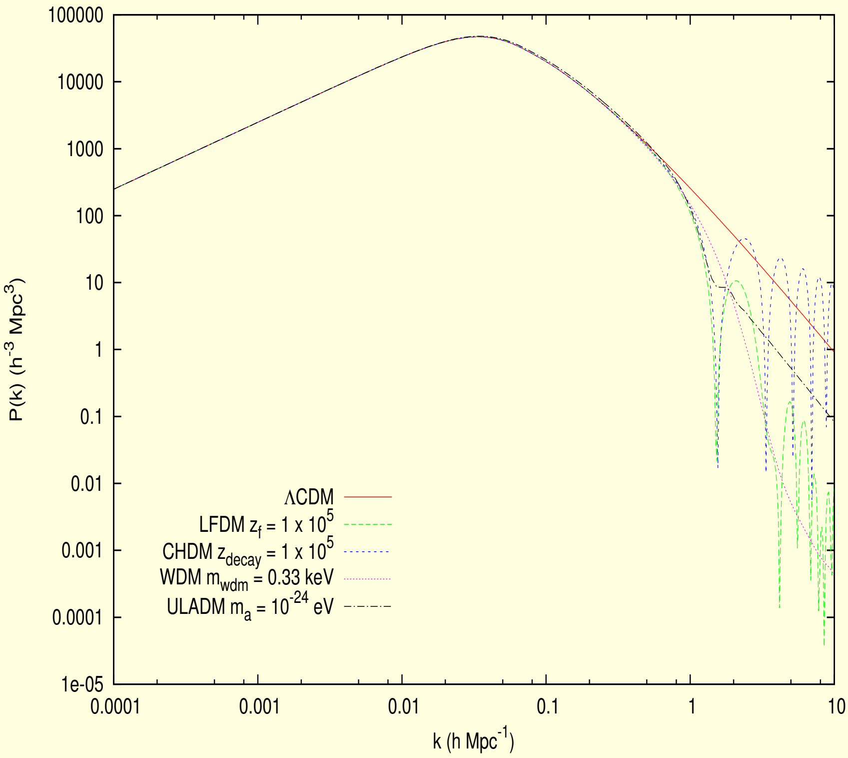
9. Dark matter detection experiments



10. Alternative dark matter models

- `Warm Dark Matter`: massive particle of $m_{\rm wdm} \simeq$ keV free streams and suppresses density perturbations at cosmological scales.
- `Late Forming Dark matter`: The dark matter forms due to a phase transition at $z = z_f$, inheriting the initial conditions of massless neutrinos. Power suppressed at scales inside the horizon for $z < z_f$.
- `Ultra-Light Axion`: Dark matter is a scalar field with non-zero effective mass, m_a, and sound velocity. Density perturbations at scales smaller than the sound horizon cannot grow.
- `Decaying Charged particle`: A charged particle decays into a neutral particle and an electron at $z = z_{\rm decay}$, impacting scales below horizon for $z < z_{\rm decay}$.

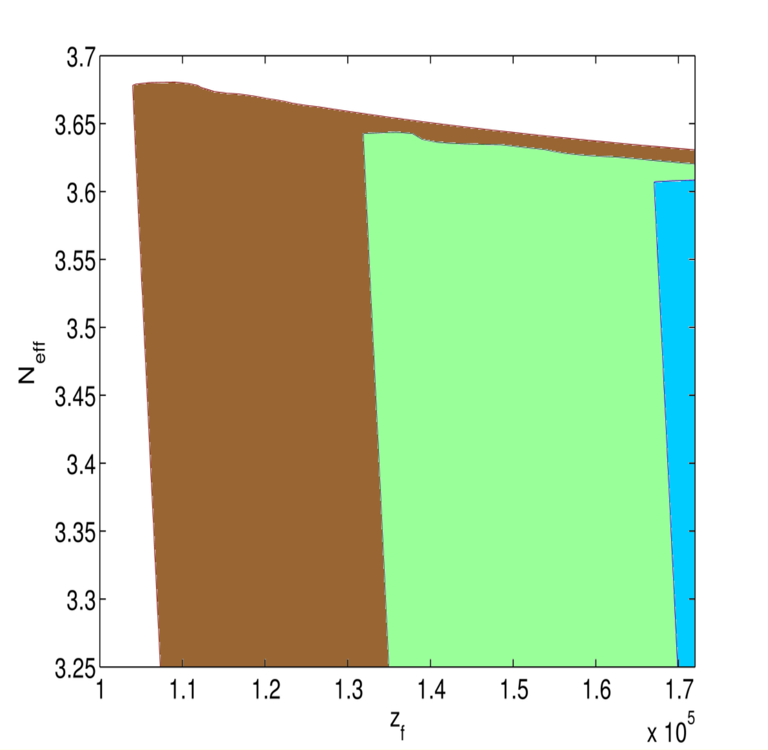
11. Matter power spectra



12. Cosmological observables at small scales

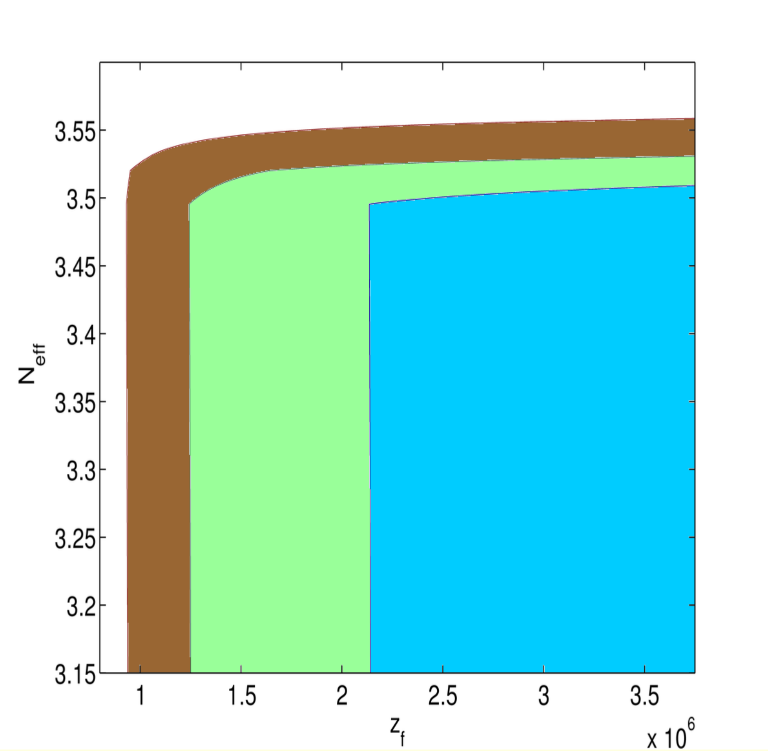
- *Lyman-α clustering*: Probes nearly non-linear density perturbations at scales up to $k \simeq 4\,\mathrm{Mpc}^{-1}$
- *Epoch of reionization*: Halo population decreases for alternative dark matter models, leading to different reionization histories and the neutral hydrogen (HI) signal. Scales $k \simeq 5$–$25\,\mathrm{Mpc}^{-1}$.
- *Collapsed fraction of matter at high redshifts*: Average HI mass density upto $z \simeq 5$ is known from damped Lyman-α studies. This can be linked to the collapsed fraction of matter which is extremely sensitive to the matter power spectrum at scales $k \simeq 5\,\mathrm{Mpc}^{-1}$.
- *CMB spectral distortion from Silk damping*: Viscous damping damps scales in the range $0.3 < k < 10^4\,\mathrm{Mpc}$ in pre-recombination era. This is the only linear probe of such range of scales.

13. LFDM: SDSS data



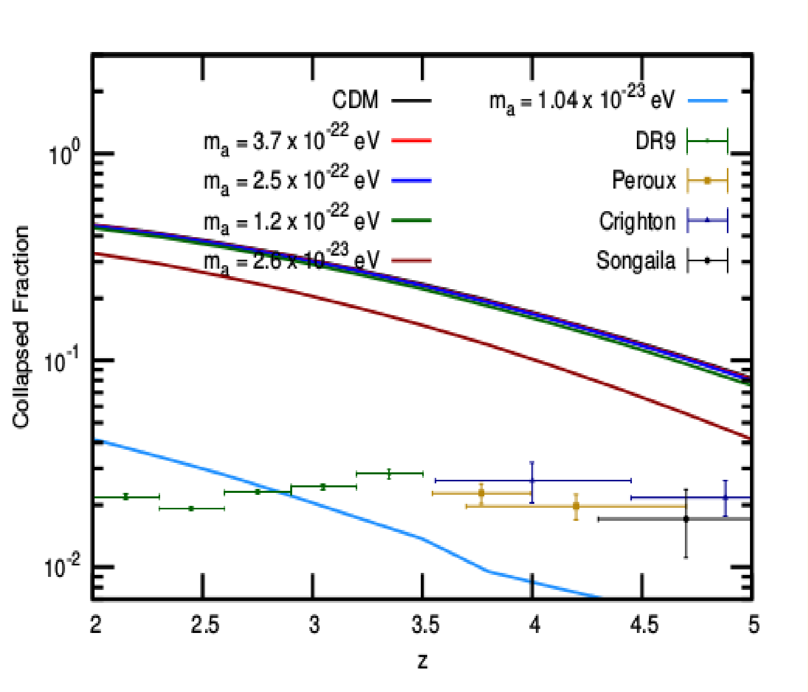
(Sarkar et al. 2015)

14. LFDM: Lyman alpha data



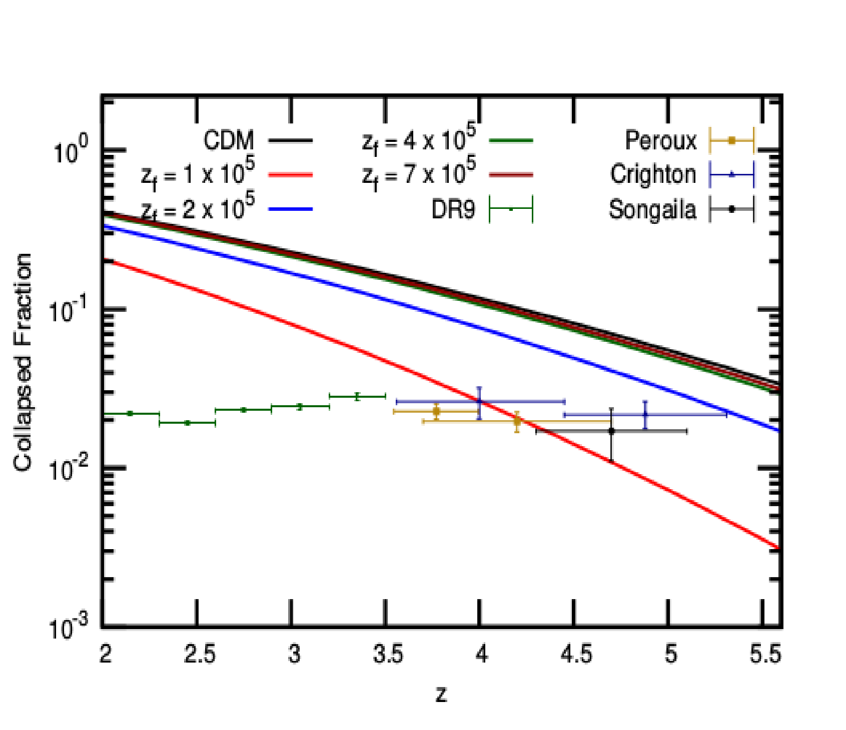
(Sarkar et al. 2015)

15. Collapsed fraction of HI: ULA



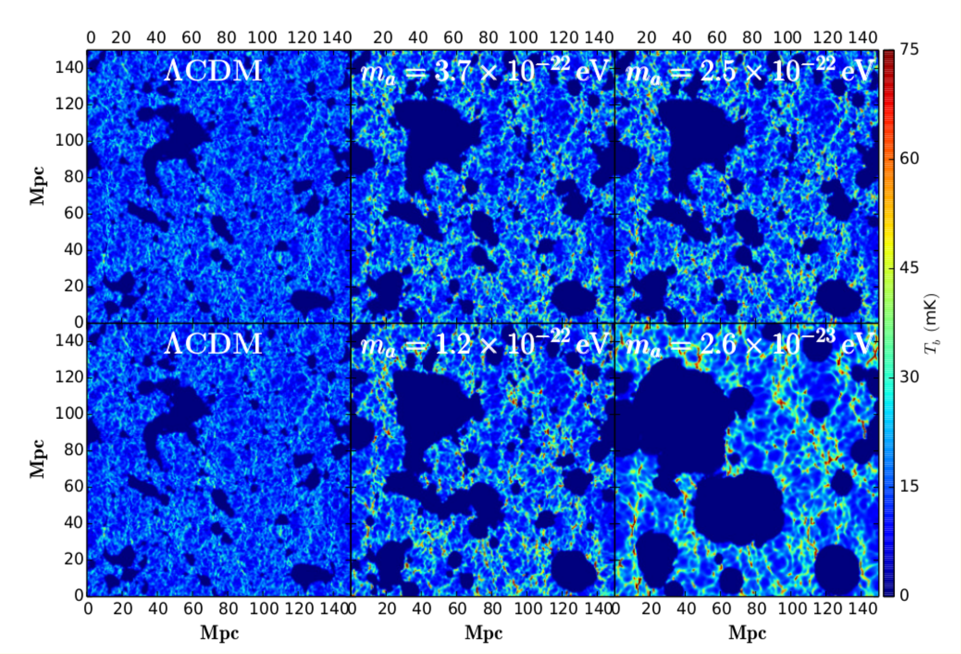
(Sarkar et al. 2016)

16. Collapsed fraction of HI: LFDM



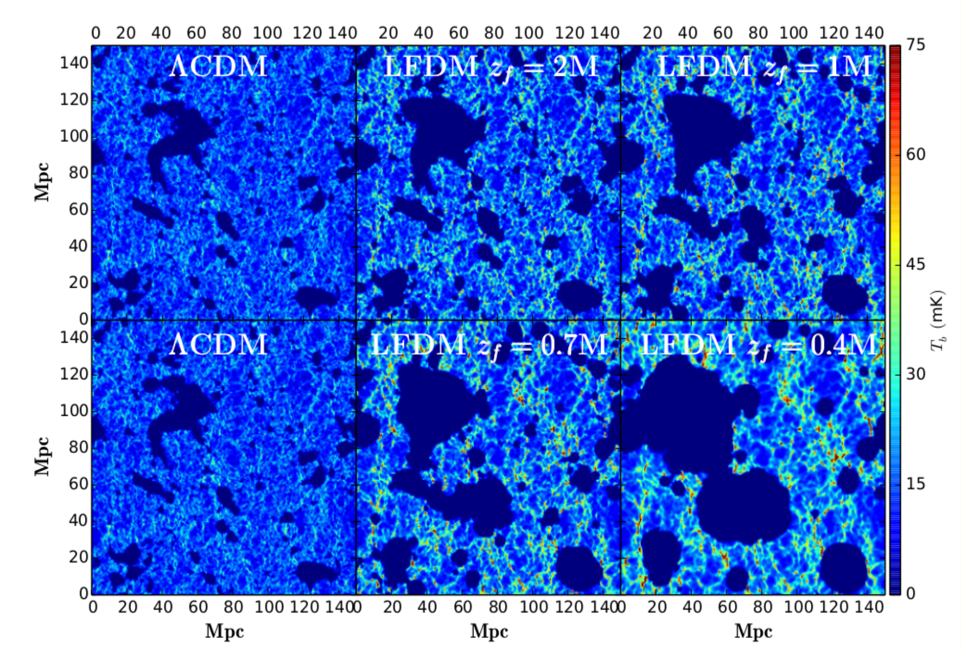
(Sarkar et al. 2016)

17. HI signal from the epoch of reionization: ULA



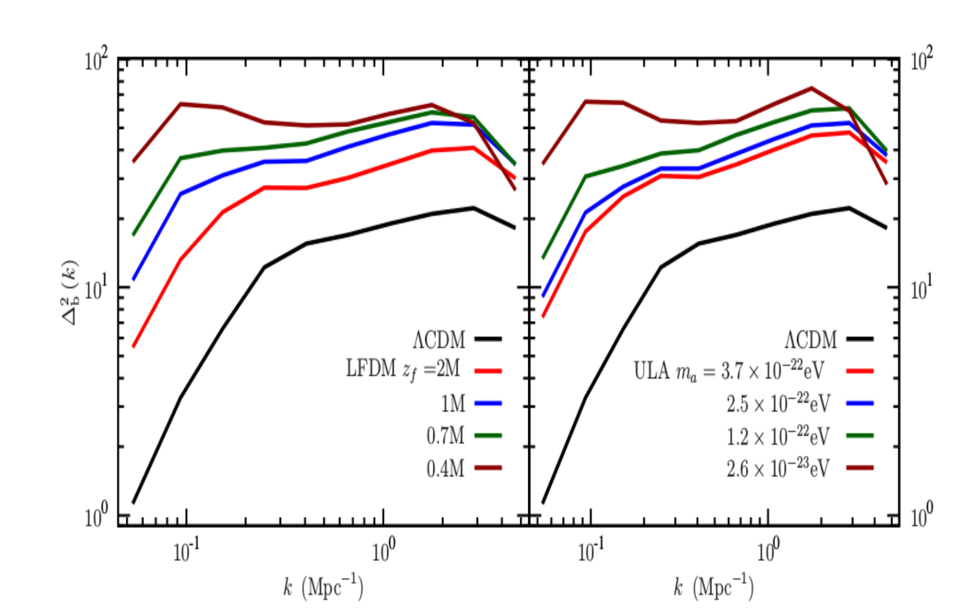
(Sarkar et al. 2016)

18. HI signal from the epoch of reionization: LFDM



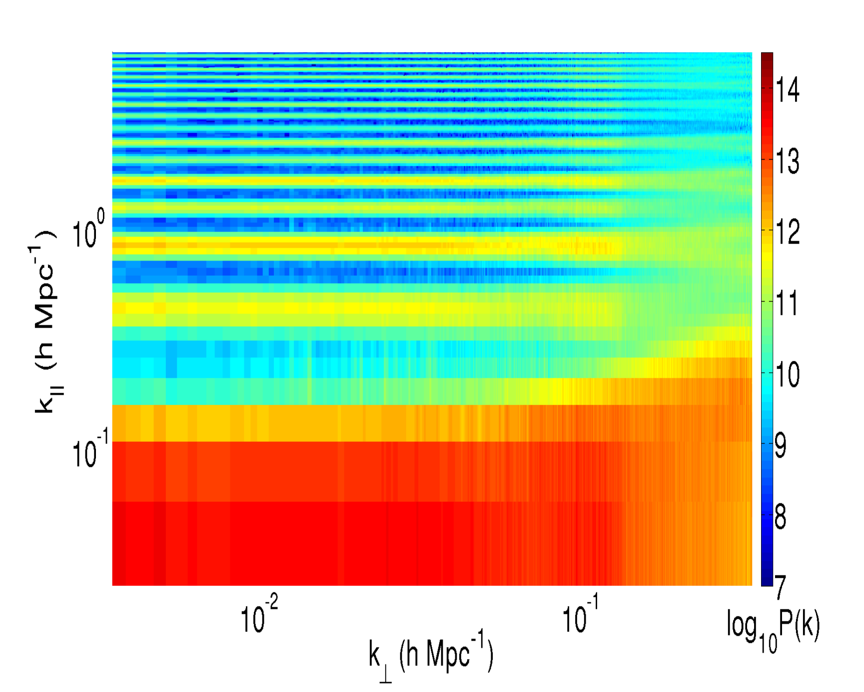
(Sarkar et al. 2016)

19. HI power spectrum from the epoch of reionization



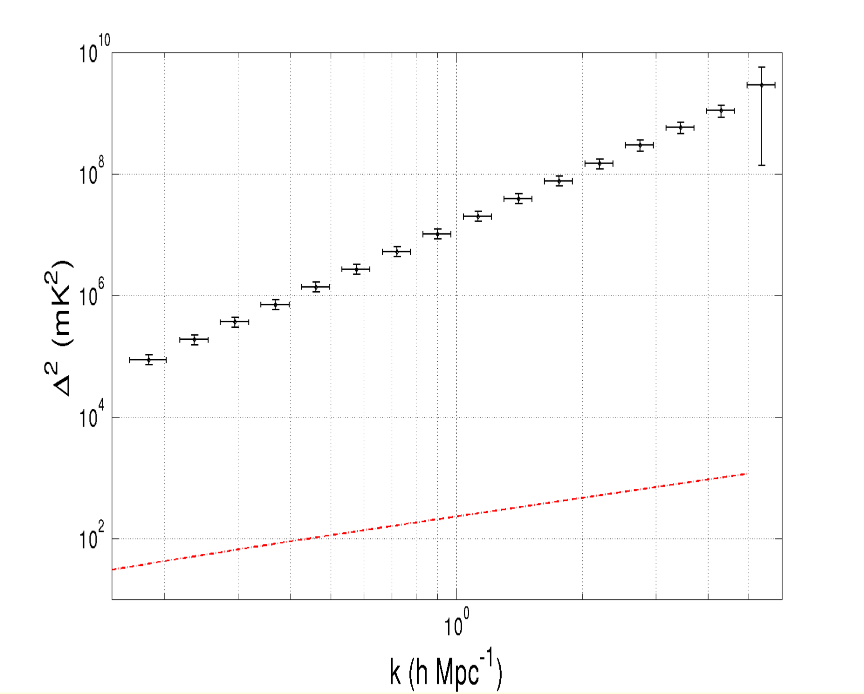
(Sarkar et al. 2016)

20. Signal from the epoch of reionization: MWA



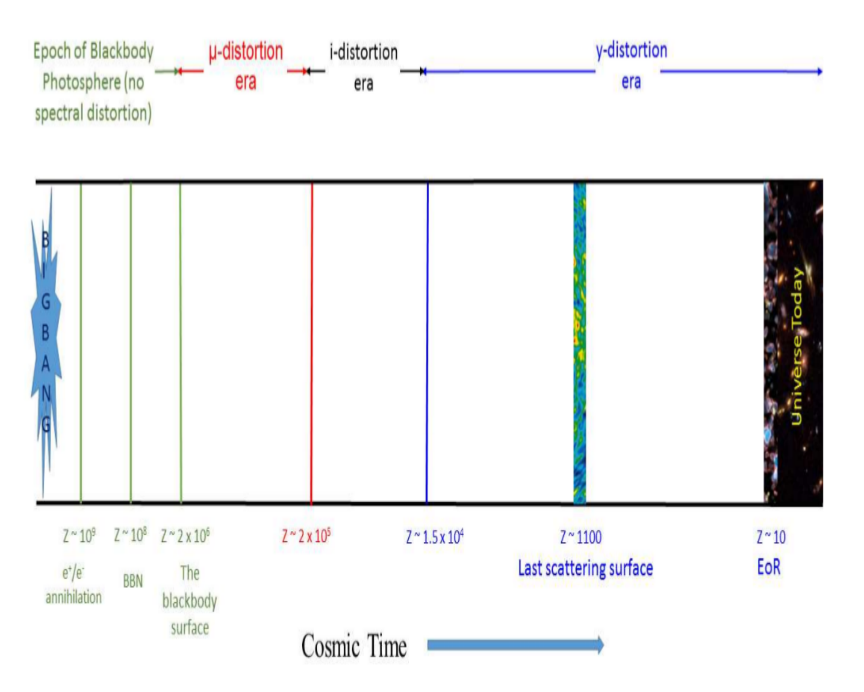
(Paul et al. 2016)

21. HI signal from the epoch of reionization: MWA

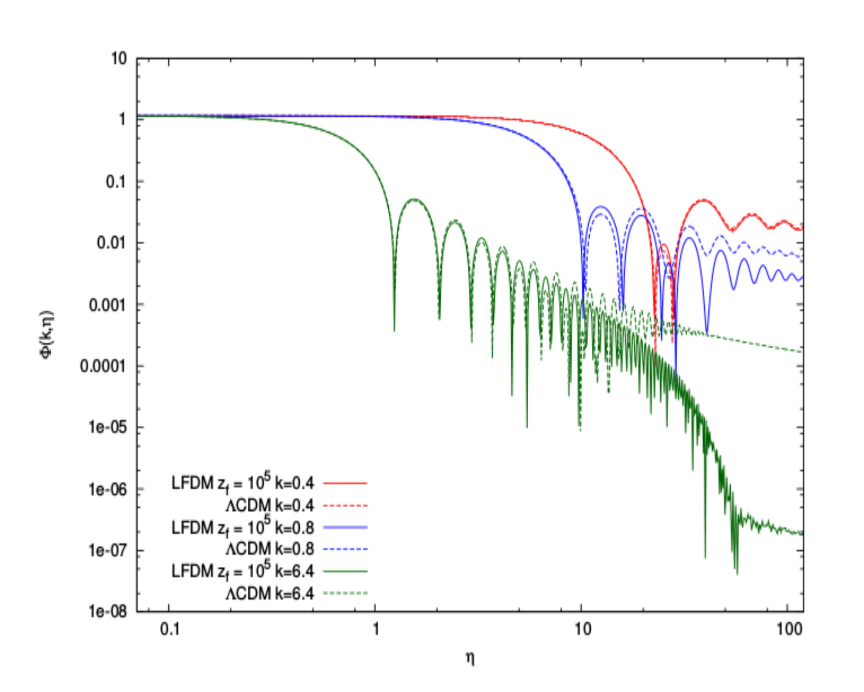


(Paul et al. 2016)

22. CMB spectral distortion

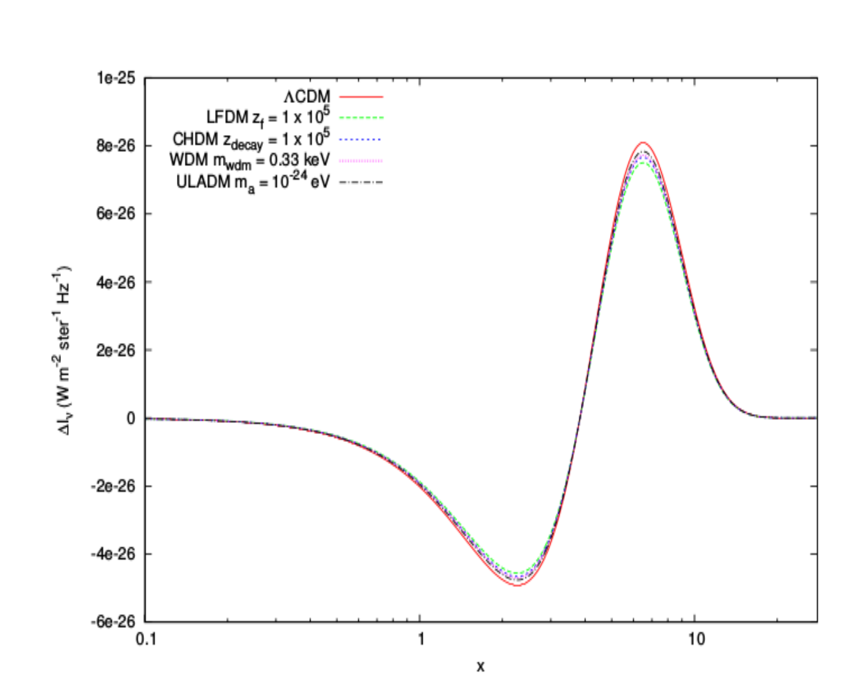


23. Evolution of gravitational potential: LFDM



(Sarkar et al. 2017)

24. Spectral distortion as a probe of dark matter models



(Sarkar et al. 2017)

25. Spectral distortion as a probe of dark matter models

Model	Parameter	$y \times 10^9$	% difference of y from ΛCDM
CDM	[1]	4.4180	0.0
LFDM	$z_f = 5 \times 10^4$	3.8561	14.57
	$z_f = 1 \times 10^5$	4.1001	7.75
	$z_f = 2 \times 10^5$	4.3037	2.65
	$z_f = 5 \times 10^5$	4.3959	0.50
WDM	$m_{\rm wdm} = 0.33$ keV	4.2178	4.74
	$m_{\rm wdm} = 0.70$ keV	4.3105	2.49
	$m_{\rm wdm} = 1.00$ keV	4.3398	1.80
	$m_{\rm wdm} = 2.00$ keV	4.3680	1.14
	$m_{\rm wdm} = 5.00$ keV	4.3798	0.87
Charged Particle Decay	$z_{\rm decay} = 5 \times 10^4$	3.8913	13.53
	$z_{\rm decay} = 1 \times 10^5$	4.1884	5.48
	$z_{\rm decay} = 2 \times 10^5$	4.2945	2.87
	$z_{\rm decay} = 5 \times 10^5$	4.4002	0.4
ULA DM	$m_a = 2.8 \times 10^{-25}$ eV	3.8840	13.74
	$m_a = 1.0 \times 10^{-24}$ eV	4.2812	3.19
	$m_a = 2.8 \times 10^{-23}$ eV	4.3990	0.43
	$m_a = 1.0 \times 10^{-21}$ eV	4.4177	6.8×10^{-3}

(Sarkar et al. 2017)

26. Summary and future prospects

- The nature of dark matter is still unknown, in spite of the success of ΛCDM model. Experimental searches have failed so far and there are issues with the model at small scales.
- Many cosmological observables at small scales constrain alternative dark matter models, e.g. Lyman-α data, collapsed fraction of HI at high redshifts.
- HI signal from the epoch of reionization might reveal the nature of dark matter; interferometers such as MWA, LOFAR, HERA and SKA.
- CMB spectral distortion owing to Silk damping remains the only linear probe at small scales. Upcoming telescope PIXIE with sensitivity $y \simeq 10^{-9}$.