Cosmological observables and the nature of dark matter

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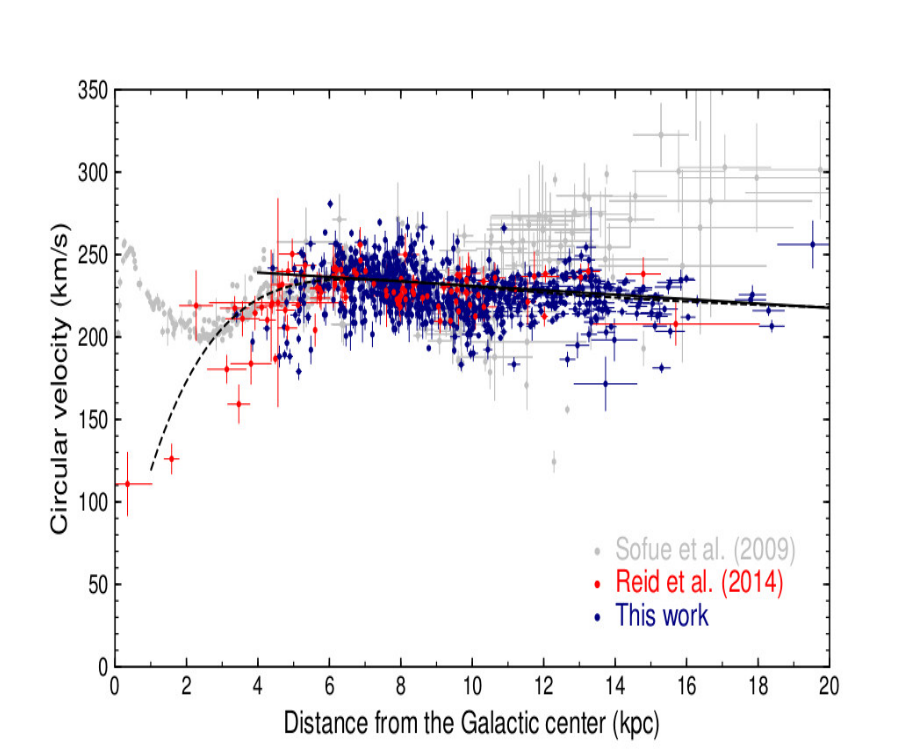
January 23, 2020

1. What is dark matter?

- *Galaxy rotation curves for spiral galaxies*: These galaxies show rotation of stars and gas in spiral arms. Most of the luminous mass is in the center. This would suggest, rotational velocity, $v \propto 1/r$ but $v \simeq$ const far away from the center. This implies there is matter in galactic halo that doesn't shine through star formation. The total mass of Milky way is around $10^{12}\,\mathrm{M}_\odot$, nearly 10 times the mass in gas and stars on scales around 50 kpc (total mass around $10^{12}\ M_\odot$) . For other spiral and elliptical galaxies, the number could be similar or even larger.

- *Clusters of galaxies*: Orbits of galaxies, intra-cluster medium, and gravitational lensing show similar trend (Zwicky 1930s), e.g. for Coma cluster the ratio is close to 10 for scales close to 3 Mpc (total mass around $7 \times 10^{14}\,\mathrm{M}_\odot$).

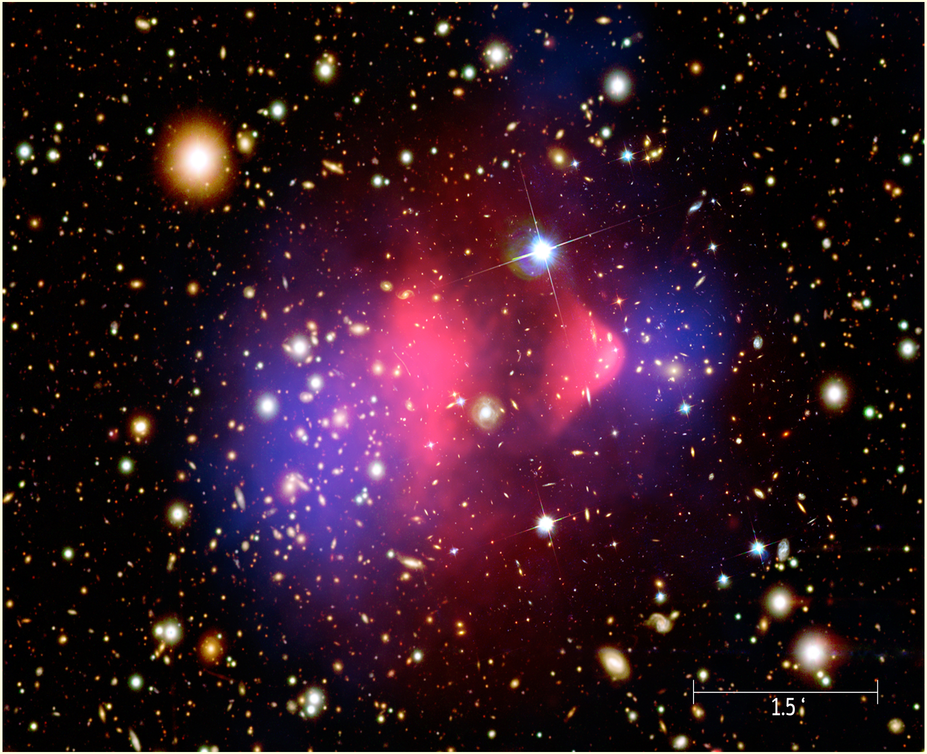
2. Milky way rotation curve



3. What the dark matter could be?

- *Planets, proto-stars, or dead stars?*: Planets such as Jupiter or cold White dwarves are undetectable at galactic distances. Their contribution to total dark matter is constrained by micro-lensing experiments (e.g. MACHO project which constrained the total mass of such objects to be $\leq 10^{11}\,\mathrm{M}_\odot$ for mass range 0.2–0.9 solar mass).
- *Exotic objects from early universe, e.g PBH*: No evidence and is also constrained by micro-lensing (e.g. recent Subaru results).
- *Elementary particles: Gunn-Tremaine bound*: If DM is fermionic, then the potential well should be deep enough to counter Fermi pressure, which gives: $m_{\mathrm{dm}}^4 > h^3/(G^{3/2}M^{1/2}R^{3/2})$. For dwarf spheroidals, this gives $m_{\mathrm{dm}} \geq 0.4\,\mathrm{keV}$.

4. Direct evidence: Bullet cluster



5. Dark matter in cosmology: Large scale behaviour of dark matter

- *Background cosmology—equation of state*: relativistic vs non-relativistic particle at early times. Cosmological constant vs dark energy, etc. This plays a role in determining the neutrino degrees of freedom from CMB data.

- *Clustering in linear perturbation theory*: Generalizes Jeans analysis to multiple component interacting fluids. The nature of dark matter is determined by: (a) its initial velocity dispersion, (b) its interaction with other matter, neutrinos, baryons, etc, and (c) its interaction with itself, e.g. zero initial velocity dispersion implies cold dark matter, etc.

6. 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)

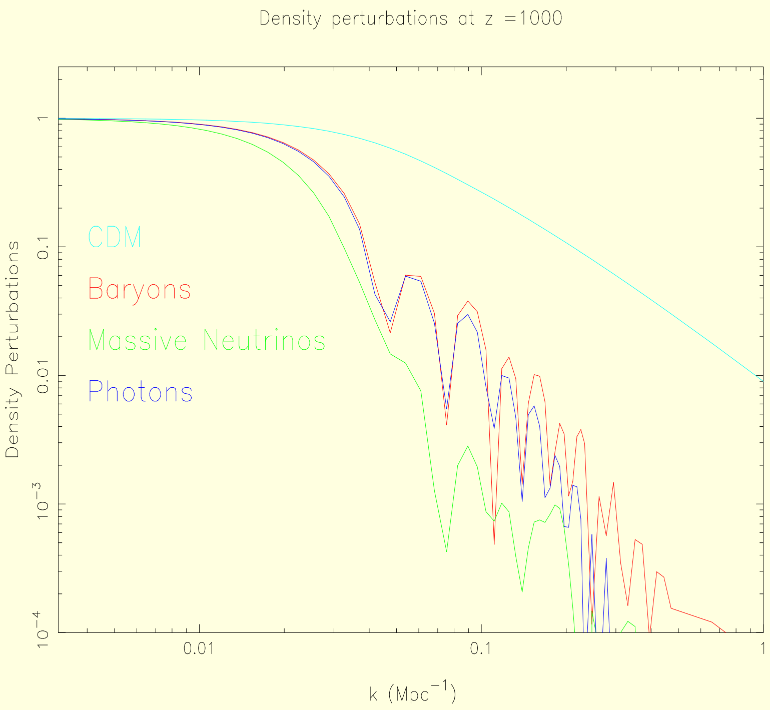
7. Matter power spectrum

- $P(k,t) = P(k,t_i)T^2(k,t_i,t)$
- $P(k,t_i) = Ak^{n_s}$: 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
- $T(k,t_i,t) \equiv T(k,t)D_+(t_i,t)$

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

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

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



9. Scales in the problem

- Matter-radiation equality:

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

  Determines the shape of CDM perturbations

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

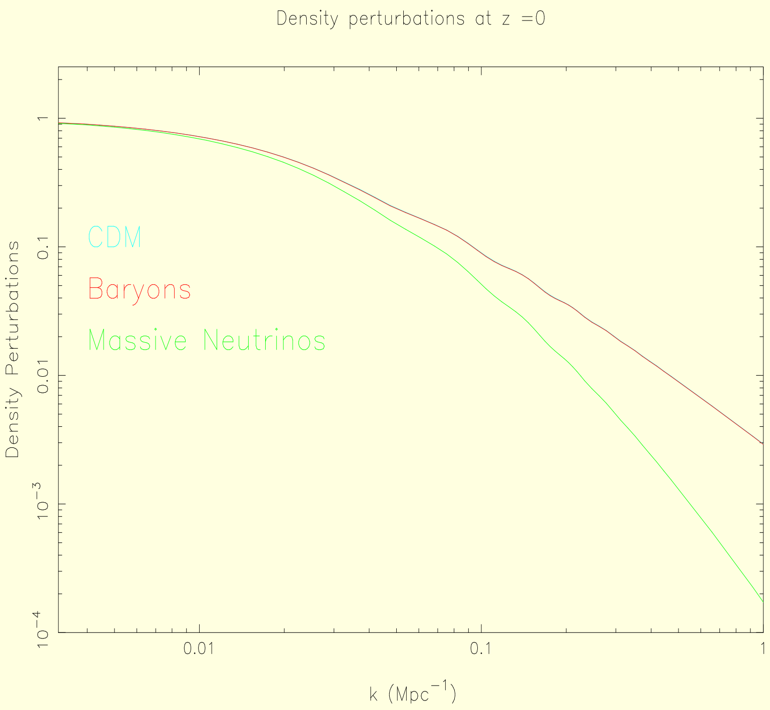
$$k_{\rm sound} \simeq \sqrt{3}H(z) \simeq 0.02(\Omega_m h^2)^{1/2}\,{\rm Mpc}^{-1} \tag{3}$$

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

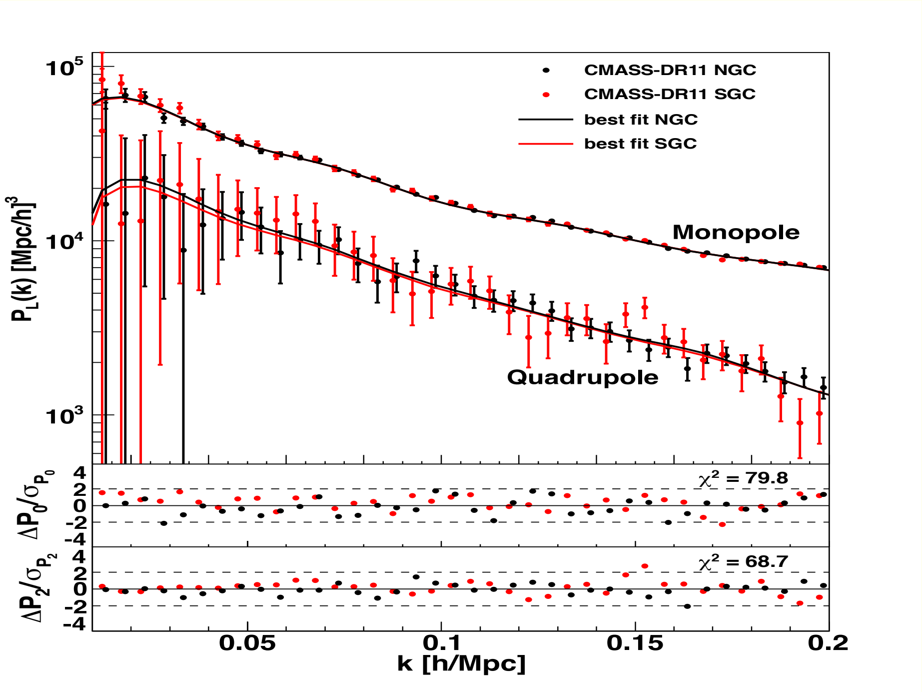
$$k_s \simeq 0.5\left(\frac{\Omega_b h^2}{0.022}\right)^{1/2}(\Omega_m h^2)^{1/4}\,{\rm Mpc}^{-1} \tag{4}$$

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

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



11. SDSS results: power spectrum



(Beutler et al. 2013)

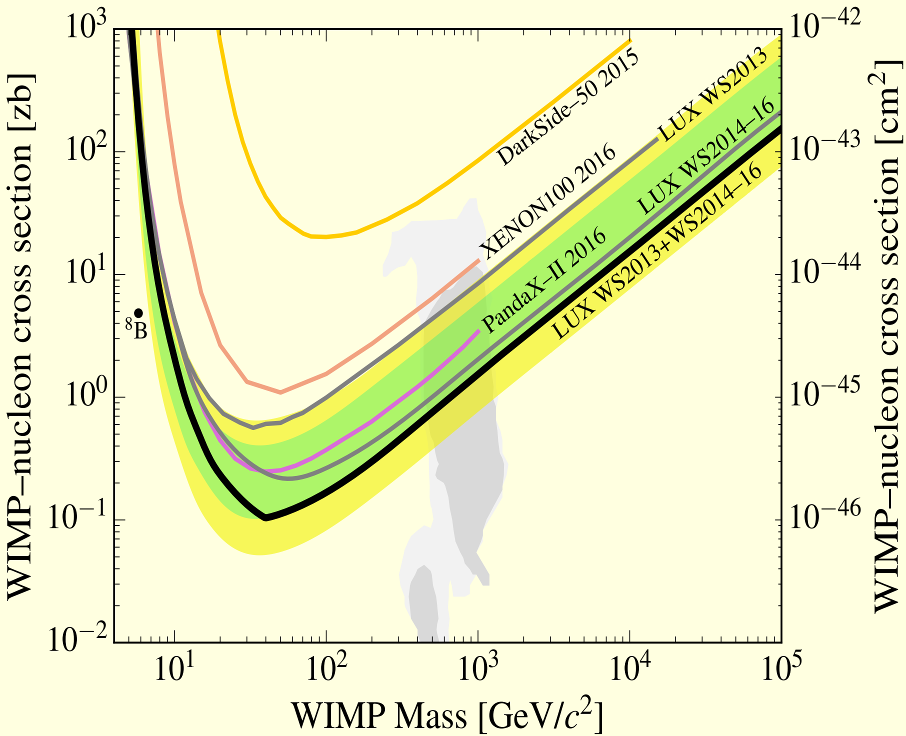
12. Determining the nature of Dark matter: Planck results

- **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**: $N_{\mathrm{eff}} = 3.15 \pm 0.23$
- **Total matter content**: Consistent with spatially flat universe $\Omega_{\mathrm{total}} = 1 \pm 0.005$

13. 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).

14. Dark matter detection experiments



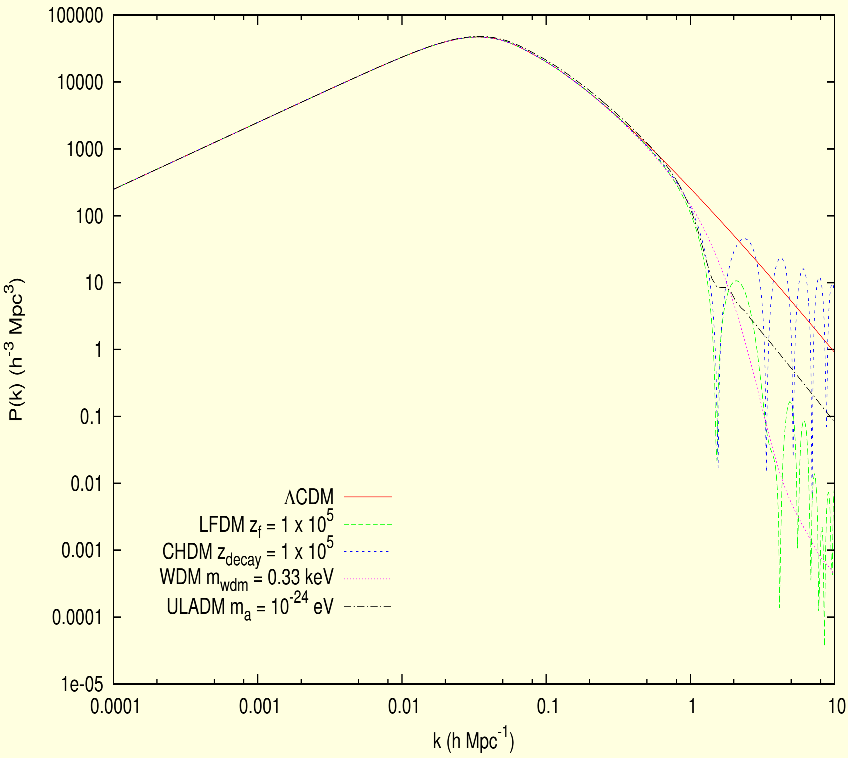
15. Alternative dark matter models

- `Warm Dark Matter`: massive particle of $m_{\rm wdm} \simeq$ keV free streams and suppresses density perturbations at cosmological scales.
- `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.
- `Stable dark matter with electromagnetic interactions`: If dark matter is charged its mass exceeds 10^8 GeV. If it forms an atom with electron or proton the atom is unstable. Viable models: Milli-charged particles, neutral atoms formed off two heavy charged particles of atomic charge, or neutral atoms formed off a heavy doubly charged dark matter and Helium nucleus (Gautham and Sethi 2019).

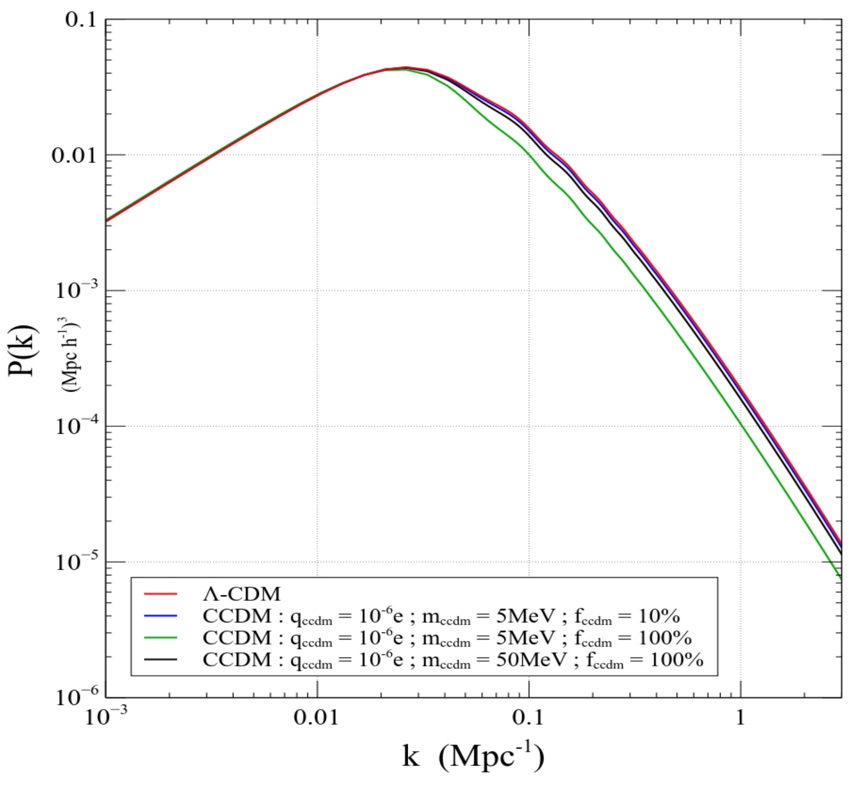
16. How to construct an atom with dark matter

- If DM has a unit negative charge then it can recombine with proton to make a neutral atom, PD. If the rate of interaction of this atom exceeds expansion rate, as it does for $z > 10^4$ or so, it can turn into a more stable atom, HeD, which is charged (charge exchange reaction).
- One way around this issue is to construct an atom which is more stable atom than HeD. This can happen if there are two oppositely charged particles much heavier than helium nucleus. This yields a neutral atom, DD.
- Another way is to consider a doubly (negatively) charged heavy particle. Many atoms are possible with it: pd, ppd, HeD. pd is charged, ppd is unstable to charge-exchange reaction (it can form Hepd). HeD is the most stable form before ppd.

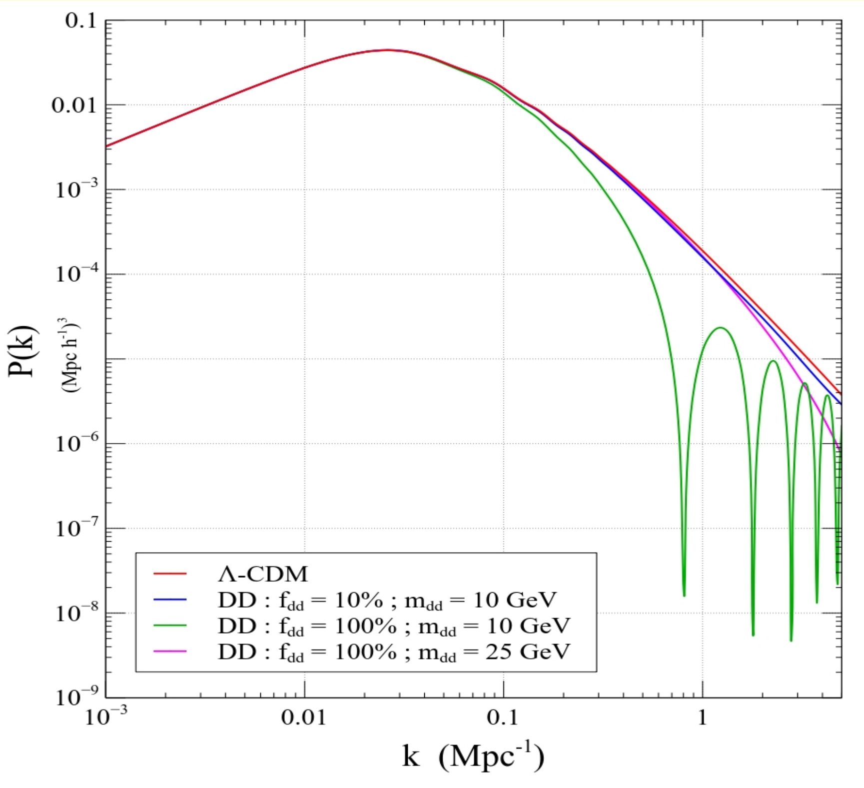
17. Matter power spectra



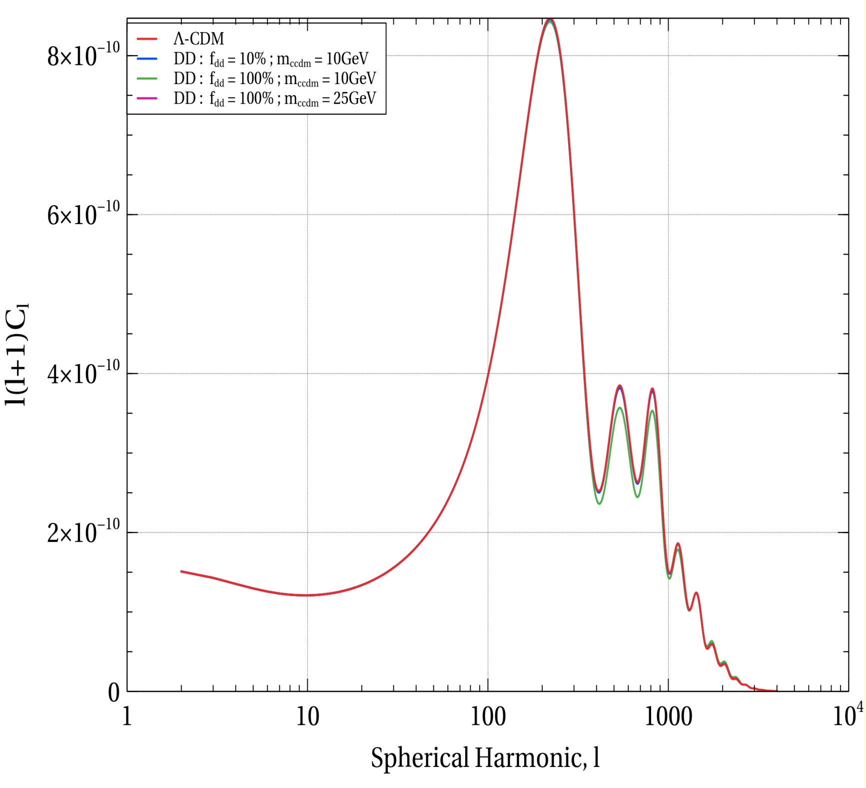
18. Matter power spectra: milli-charged particles



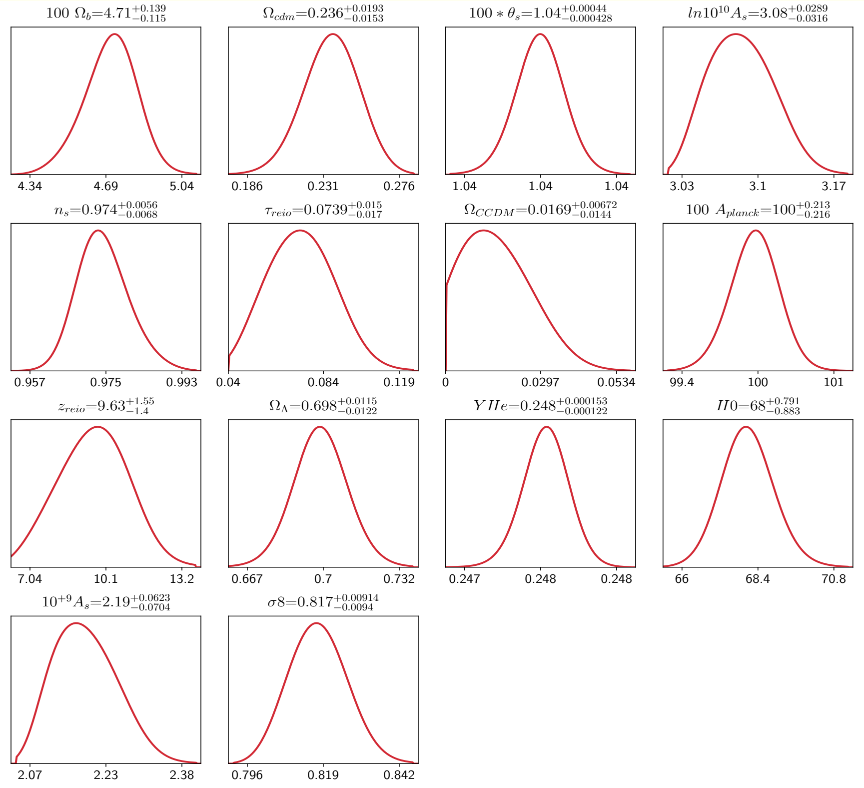
19. Matter power spectra: DD atom



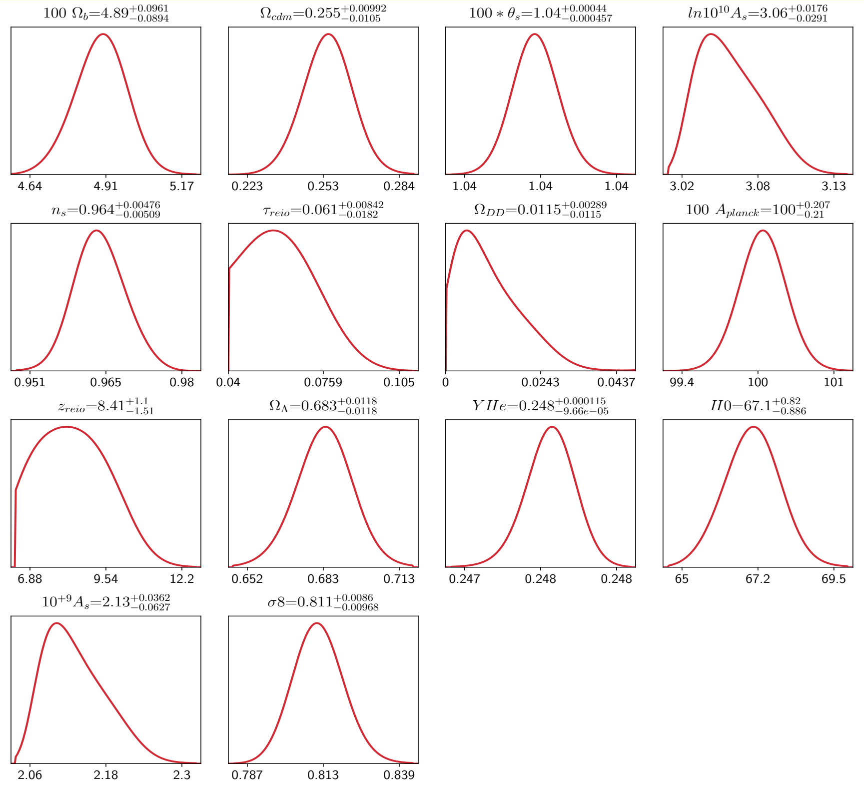
20. CMB power spectrum



21. Comparison with Planck data:CCDM model



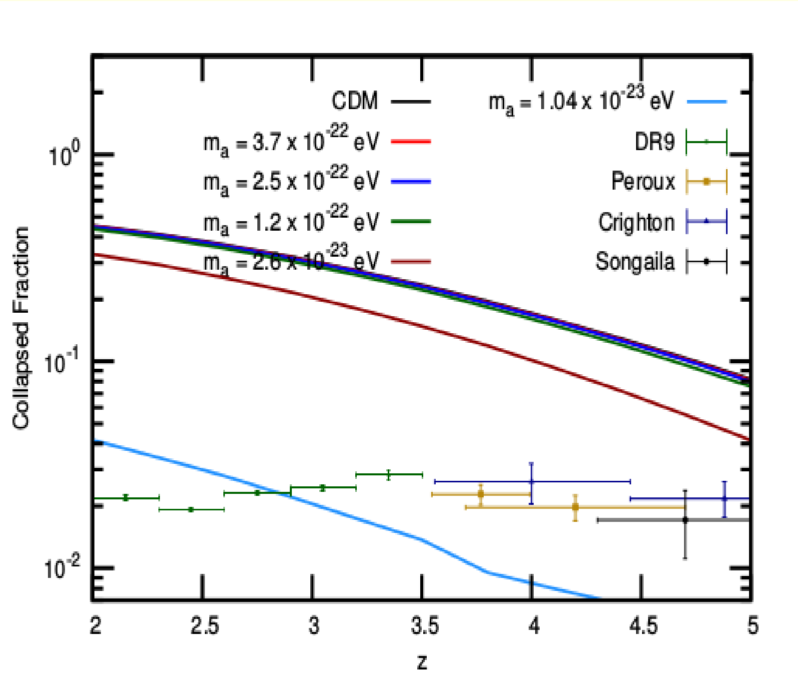
22. Comparison with Planck data: DD model



23. Cosmological observables at small scales

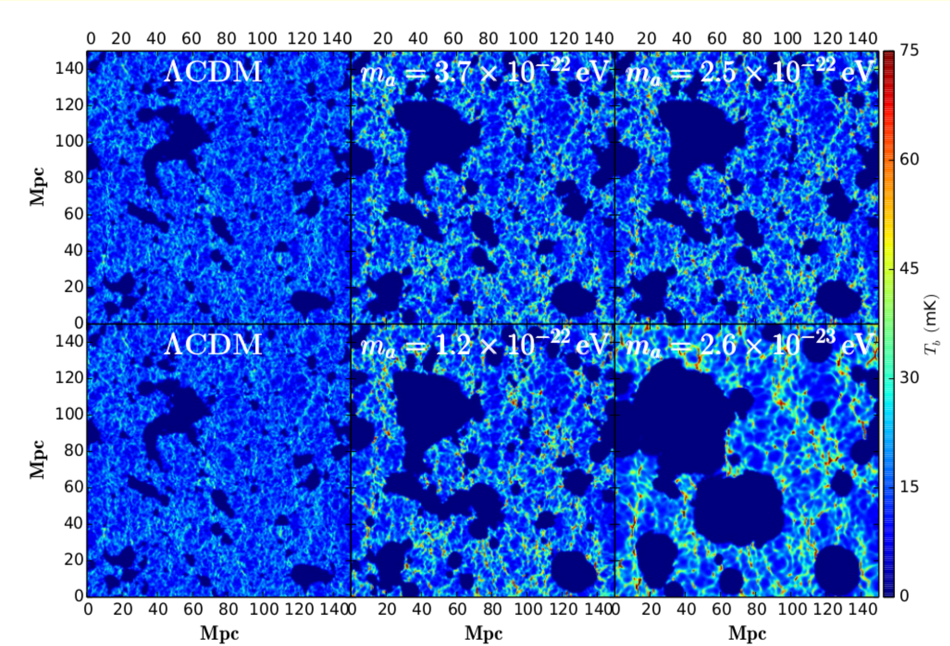
- *Lyman-α clustering*: Probes nearly non-linear density perturbations at scales up to $k \simeq 4\,\mathrm{Mpc}^{-1}$
- *Epoch of reionization*: Halo population decreases for alternative dark matter models, leading to different reionization histories and the neutral hydrogen (HI) signal. Scales $k \simeq 5$–$25\,\mathrm{Mpc}^{-1}$.
- *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.

24. Collapsed fraction of HI: ULA



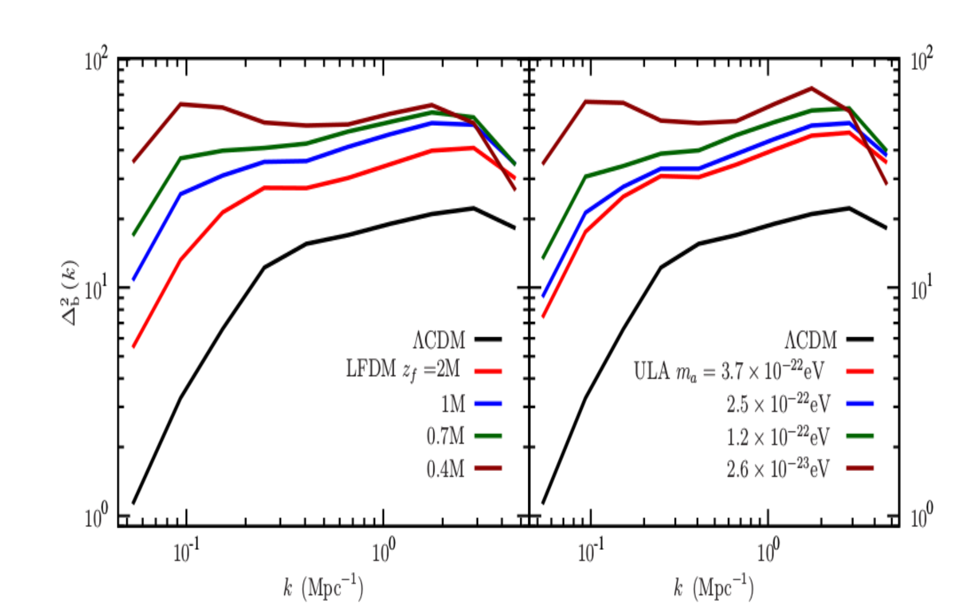
(Sarkar et al. 2016)

25. HI signal from the epoch of reionization: ULA



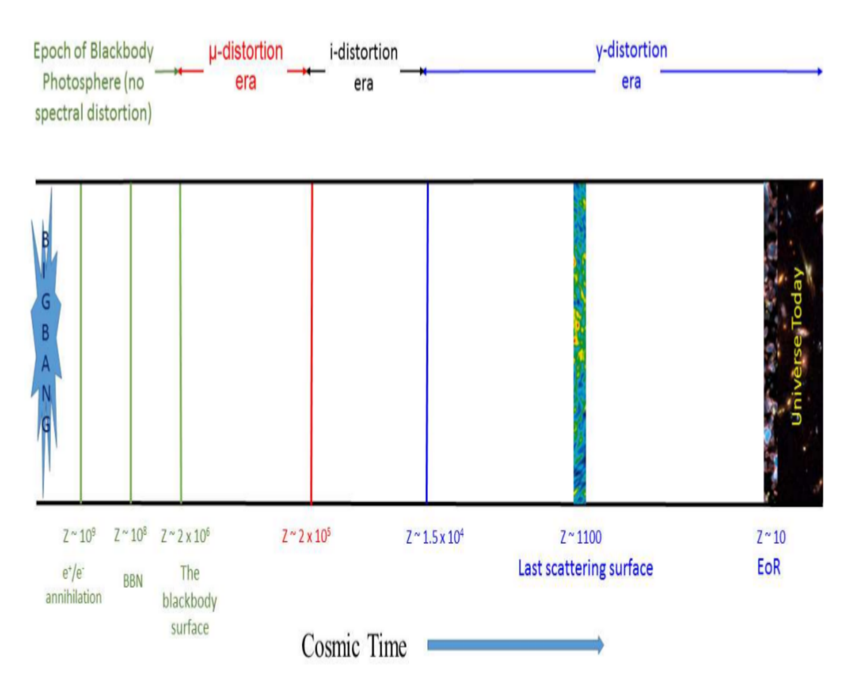
(Sarkar et al. 2016)

26. HI power spectrum from the epoch of reionization



(Sarkar et al. 2016)

27. CMB spectral distortion



Does CDM work at . . .
Dark matter detection . . .
Alternative dark . . .
Matter power spectra
Cosmological . . .
LFDM: SDSS data
LFDM: Lyman alpha data
Collapsed fraction of . . .
Collapsed fraction of . . .
HI signal from the . . .
HI signal from the . . .
HI power spectrum . . .
Signal from the epoch . . .
HI signal from the . . .
CMB spectral distortion
Evolution of . . .
Spectral distortion as . . .
Spectral distortion as . . .
Summary and future . . .
Title Page
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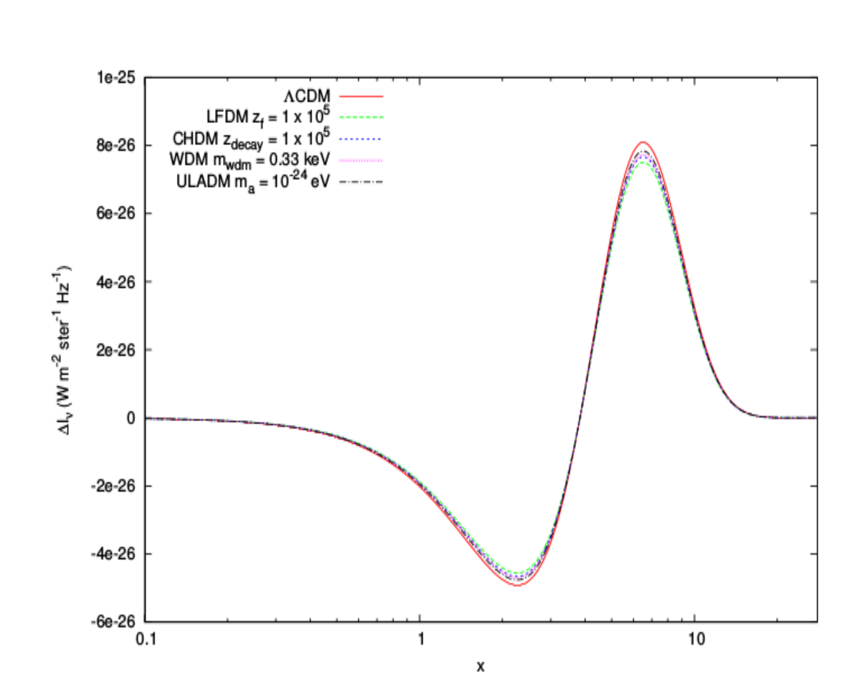
28. Spectral distortion as a probe of dark matter models



(Sarkar et al. 2017)

29. 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 $y \simeq 10^{-9}$.