Reionization and 21cm absorption in WDM and sterile neutrino DM cosmologies
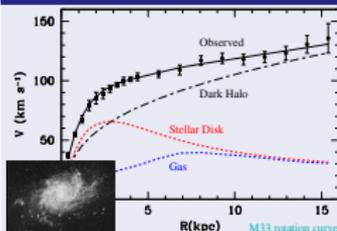
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OAC, Crete, July 9, 2018

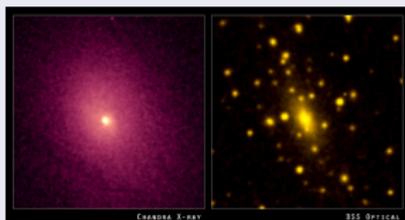# Dark Matter in the Universe

Astrophysical evidence:

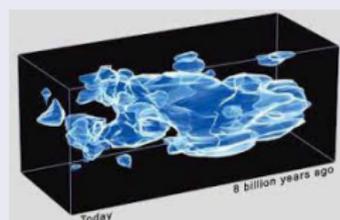**Expected:**
$v(R) \propto \frac{1}{\sqrt{R}}$
Observed:
$v(R) \approx \text{const}$

Expected:
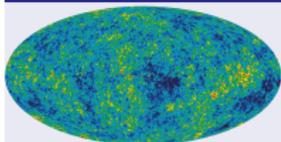$\text{mass}_{\text{cluster}} = \sum \text{mass}_{\text{gals}}$
Observed: 10^2 times more
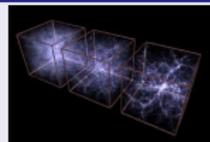mass confining ionized gas

Lensing signal (direct
mass measurement)
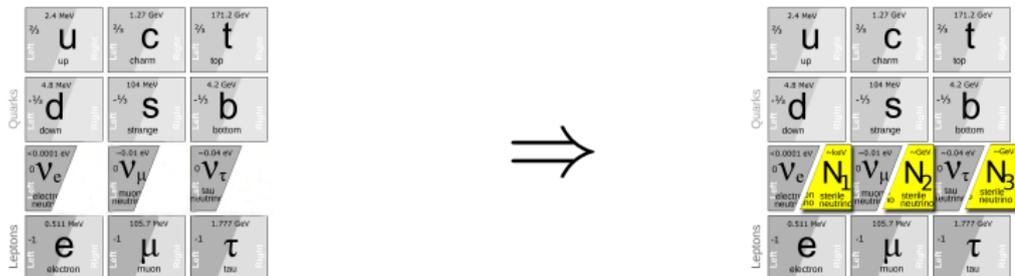**confirms** other
observations

Cosmological evidence:

Jeans instability turned tiny density
fluctuations into visible structures

νMSM: SM extension with 3 sterile neutrinos

Asaka & Shaposhnikov'05. Review: Boyarsky+'09

- Neutrino masses: **Bilenky & Pontecorvo'76; Minkowski'77; Yanagida'79; Gell-Mann et al.'79; Mohapatra & Senjanovic'80; Schechter & Valle'80**
- Baryon asymmetry: **Fukugita & Yanagida'86; Akhmedov, Smirnov & Rubakov'98; Pilaftsis & Underwood'04-05**;
- Dark matter: **Dodelson & Widrow'93; Shi & Fuller'99; Dolgov & Hansen'00**
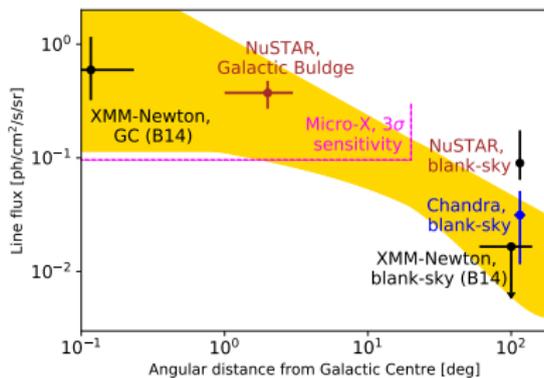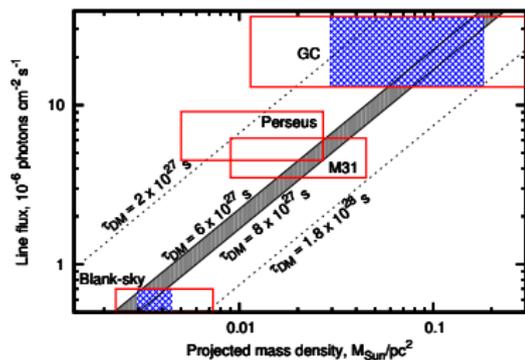

A **unified SM** of particle physics and cosmology

Sharing success of the Standard Model at accelerators and resolving major BSM problems:
Neutrino masses and oscillations; Baryon asymmetry of the Universe; Dark matter

Sterile neutrino: decaying dark matter

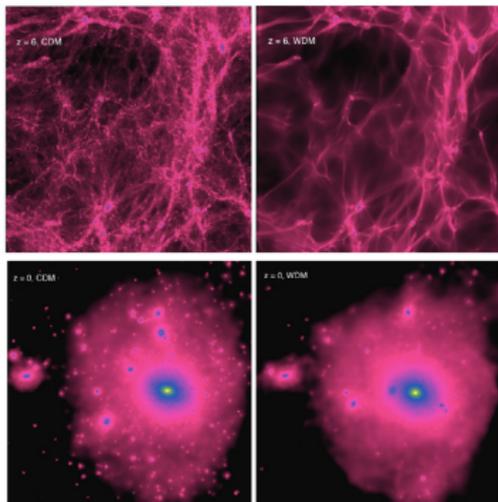3.5 keV line, first reports: **Bulbul+, ApJ'14; Boyarsky, Ruchayskiy, DI, Franse, PRL'14**

- Observations point to $\tau_{\mathrm{DM}} = (6-8) \times 10^{27}$ s **[1408.2503, 1508.05186]**;
- More evidence since 2014 **[1607.04487, 1607.07328, 1701.07932]**;
- No common explanation for every detection and non-detection
- . . . apart from decaying dark matter signal

Sterile neutrino: warm dark matter
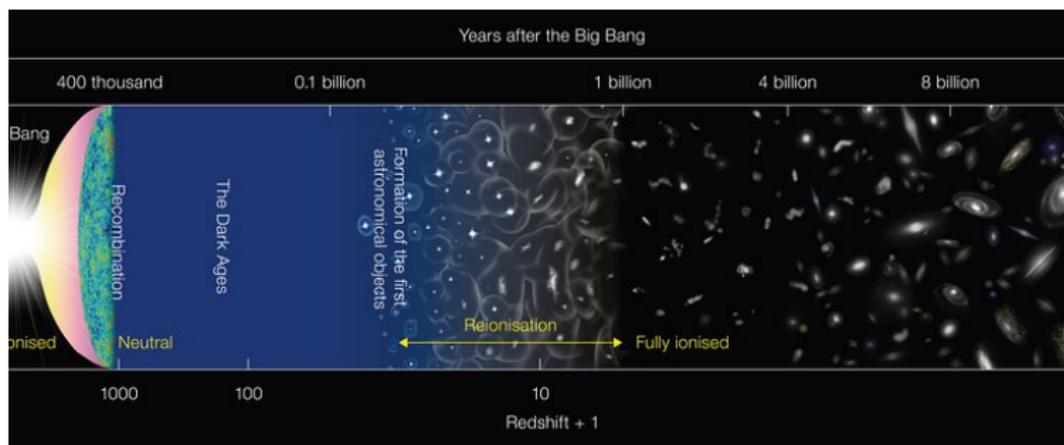
COCO Warm simulation Bose+'15. Sterile neutrino dark matter:

- Same structures as in **CDM** Universe at Mpc scales and above $\rightarrow$ no signatures in CMB/galaxy counts
- Decreasing number of small galaxies around Milky Way
- Decreasing number of small satellite galaxies **within** Milky Way halo
- **Can help** with "too big to fail" or "missing satellites" problems

Reionization of the intergalactic medium

- After recombination (at $z \lesssim 1300$), Universe becomes **neutral**;
- Observations of distant quasars (**Gunn-Peterson trough**) show that Universe was again **ionized** before $z \simeq 6$;
- It is now well established that the starlight from first galaxies and quasars **reionized** the Universe around $z \sim 7 - 20$
  [astro-ph/0010468,0905.0929,1102.4638,1404.7146,1409.4946];

Reionization and WDM/sterile neutrino DM

WDM and sterile neutrino DM can influence structure formation in a number of ways:

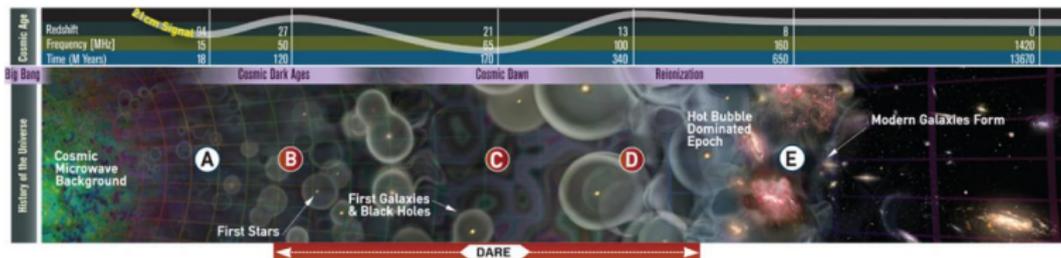- less galaxy-sized haloes $\rightarrow$ less **ionizing sources**;
- less subhaloes $\rightarrow$ less amount of **recombinations** in the densest subhaloes (working as **sinks** of ionizing photons because the photons coming from recombination **cannot** ionize hydrogen again);
- different **morphology** of structure formation (star-forming **filaments**, see e.g. Gao, Theuns & Springel **1403.2475**).

We need to model these effects in details

Modeling of reionization

Two approaches:
- Detailed N-body + gas simulations:
- ... have to properly describe **very different** scales (from star formation regions to observable part of the Universe);
- Semi-analytical models:
- ... much less precise but computationally cheaper alternatives.

'Bubble' model of reionization

- Originally proposed by Furlanetto, Zaldarriaga & Hernquist
  [astro-ph/0403697]
- According to this model, the mass of gas ionized by early stars m_{ion}, the mass of recombined hydrogen m_{rec} and the mass of baryons collapsed into galaxies m_{gal} are related with the simple **linear** expression

$$\zeta m_{\text{gal}} = m_{\text{ion}} + m_{\text{rec}},$$

  ζ is the number of ionizing photons per baryon released due to star formation during the process of halo collapse.
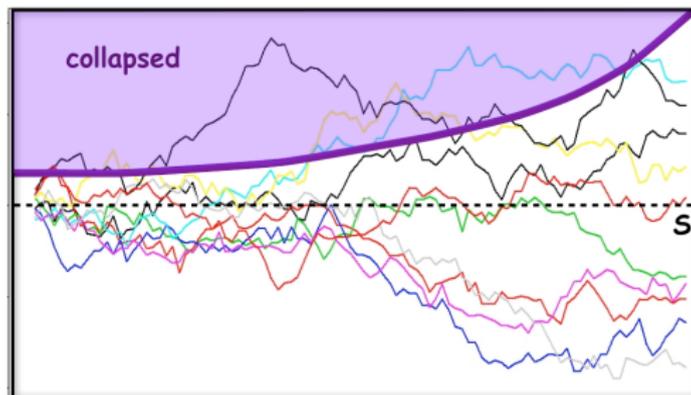- To collapse, a 'bubble' region is assumed to contain mass in stars enough to ionize **all** of its hydrogen atoms, so that the collapsed fraction f_{coll} should not be smaller than the ratio of $m_{\text{gal}}/(m_{\text{ion}} + m_{\text{rec}})$:

$$\zeta f_{\text{coll}} \geq 1 + \xi f_{\text{rec}},$$

  where $f_{\text{rec}} = m_{\text{rec}}/(\xi \, m_{\text{ion}})$, ξ is the average number of recombinations per atom in collapsed mini-haloes during the whole epoch of reionization.

Calculation of f_{coll} and f_{rec}

- To calculate f_{coll} and f_{rec}, we again followed Furlanetto, Zaldarriaga & Hernquist who used **extended Press-Schechter** formalism;
- Nice recap of EPS formalism: `http://phys.huji.ac.il/~joaw/winterschool/vandenBosch_lecture2.pdf`
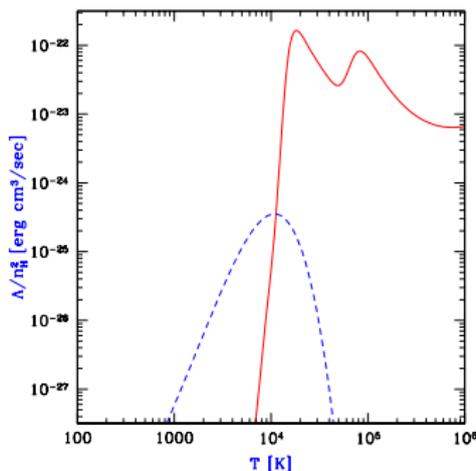
Calculation of f_{coll}

- f_{coll} is the fraction of halos larger than the minimal mass of haloes with collapsed hydrogen

$$m_{\mathsf{min}} = 3.59 \times 10^7 \ h^{-1} \ \mathrm{M}_\odot \left(\frac{0.6}{\mu} \right)^{3/2} \left(\frac{10}{1+z} \right)^{3/2}$$

(assuming $T_{vir} \simeq 10^4$ K that corresponds to **atomic** H cooling):

Calculation of f_{rec}

- f_{rec} is the fraction of **mini-haloes** used as "recombination sinks": haloes smaller than m_{min} but larger than the Jeans mass:
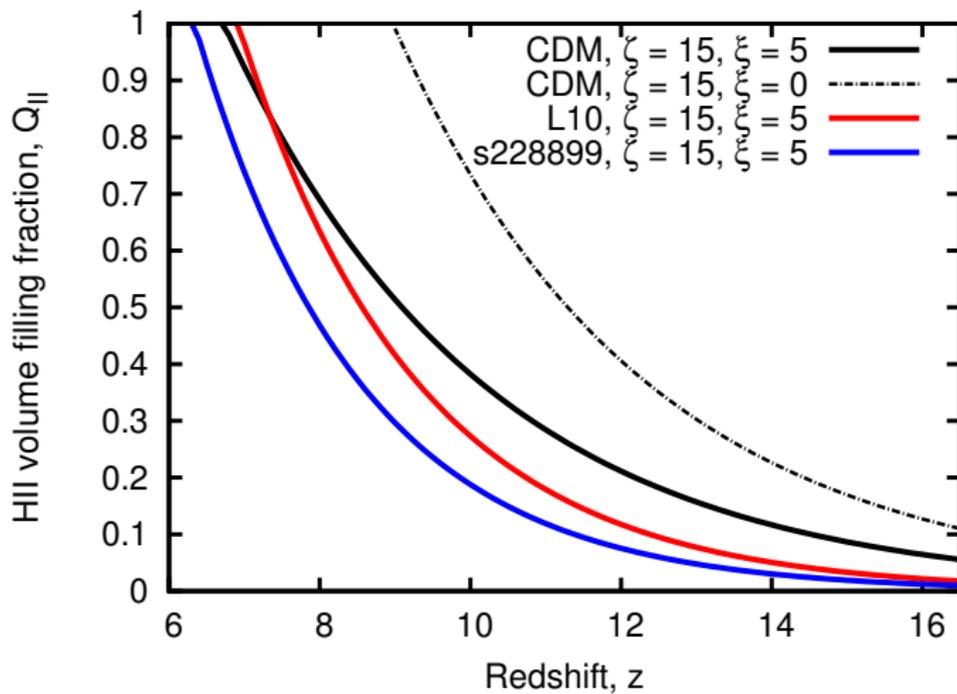
$$m_{\text{J}} = 3.96 \times 10^3 \ h^{-1} \ \text{M}_\odot \left(\frac{0.307}{\Omega_0} \right)^{1/2} \left(\frac{0.0222}{\Omega_b h^2} \right)^{3/5} \left(\frac{1+z}{10} \right)^{3/2}$$

- If minihalo formation is not suppressed, up to 80-90% of the emitted ionizing photons are absorbed by them, see e.g. [astro-ph/0511623]
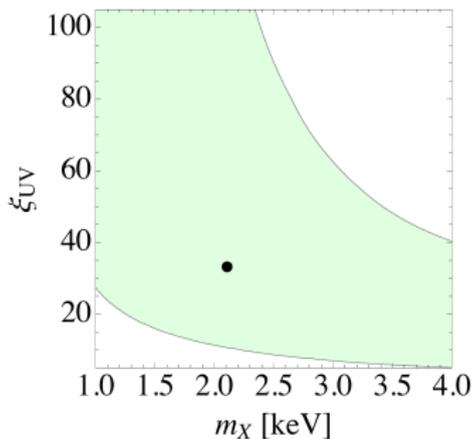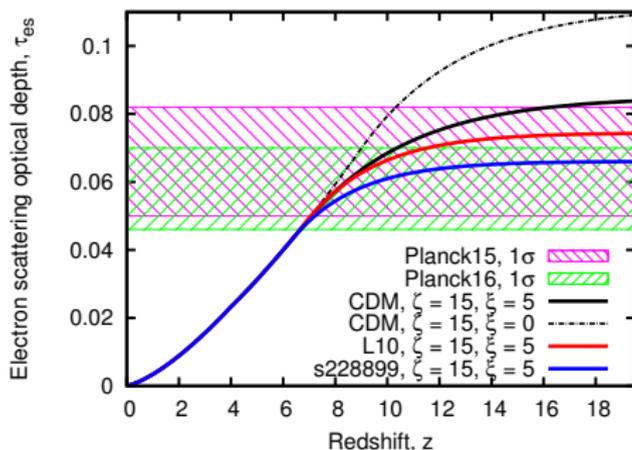
Results [1604.01341]

- We study a set of 2-parametric models (ζ, ξ) for a number of DM models (CDM, resonantly produced 7 keV sterile neutrinos with different lepton asymmetries, including those consistent with observed properties of 3.5 keV line);

- for sterile neutrino models with realistic values of ξ, the effect from decreasing ionization sinks in mini-haloes is comparable or even larger than the effect from decreasing ionization sources – reproducing [1201.3686] for WDM;

- For sterile neutrino models, reionization is much narrower than for CDM – reproducing [1201.3686, 1604.07409] – and produce smaller value of electron scattering optical depth (better consistent with the latest **Planck** measurement than with CDM).
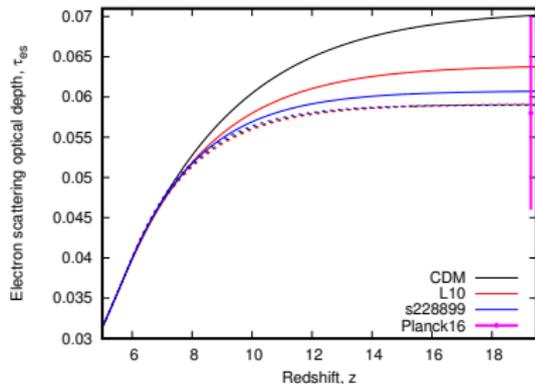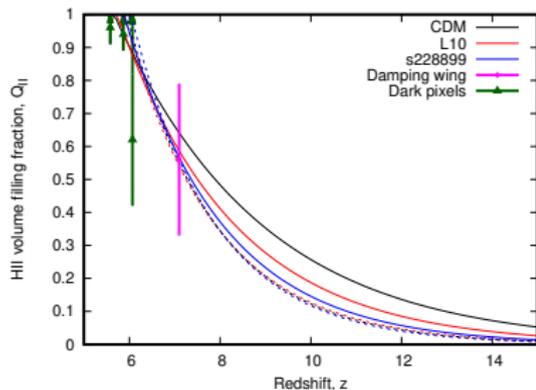
Results [1604.01341, 1703.02302]

- WDM/sterile neutrino DM fits data **better**;
- Best-fit parameters is surpisingly close to WDM mass 2.3 keV (roughly equivalent to 7 keV sterile neutrino DM) although the errors are huge;

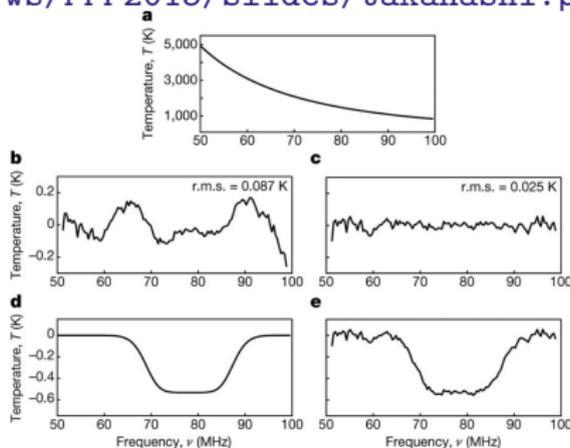# Results [D.I. et al., in progress]

7 keV sterile neutrino DM fits **better** reionization data than CDM (but the effect drops to $\lesssim 1\sigma$ when taking astrophysical uncertainties into account)
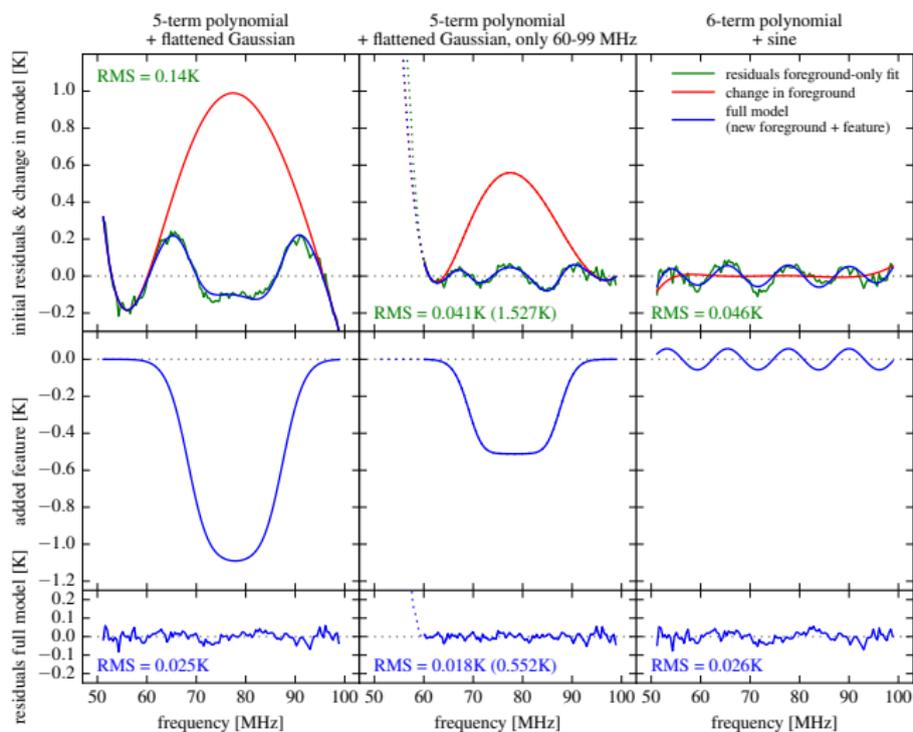
Summary of EDGES detection
21 cm absorption feature

- Bowman et al. (2018) reports detection of **21 cm absorption feature** at $\nu \simeq 72 - 85$ MHz (corresponding to redshifts $1420\text{ MHz}/\nu - 1 \simeq 14 - 19$;
- **99% ranges** of model parameters: best-fit maximum position 78±1 MHz; FWHM 19^{+4}_{-2} MHz; amplitude $\delta T_b = -0.5^{+0.2}_{-0.5}$ K.
- Nice recap of 21 cm line physics http://www2.yukawa.kyoto-u.ac.jp/~ppp.ws/PPP2015/slides/takahashi.pdf
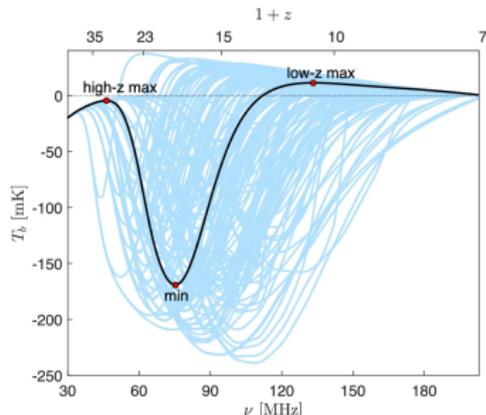
Refitting of EDGES data in 1805.01421

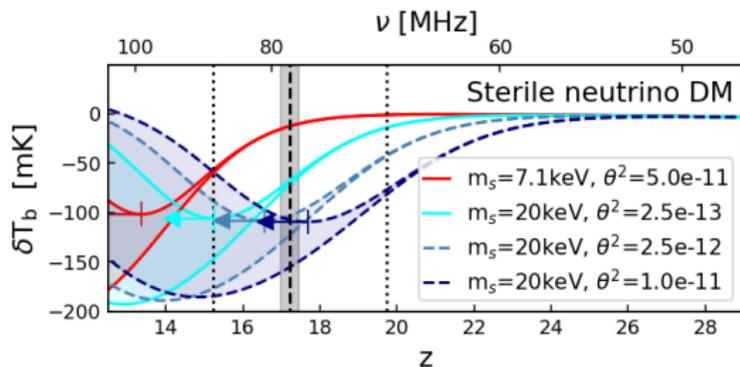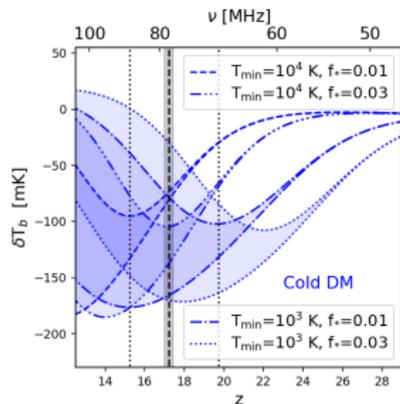Found large ambiguity in results assuming different foregrounds:

LCDM predictions from 1609.02312

- **Before** EDGES paper, an extensive study of expected LCDM signal was performed (193 different combinations of astrophysical parameters);
- Reported EDGES signal strength ($\delta T_b = -0.5^{+0.2}_{-0.5}$ K) is **in odds** with these predictions.

- However, the position of EDGES dip maximum ($\nu_{max} = 78 \pm 1$ MHz) is consistent with LCDM expectations.

3 key assumptions of 1805.00021:

* use **ONLY** ν_{max} (but not δT_b) to constrain LCDM alternatives;
* restrict the range of astrophysical parameters (wrt to 1609.02312) by comparing with detailed **LCDM-based** simulations (e.g., 1604.07842 and 1801.07259);
* WDM etc. halo mass functions are derived from k-**sharp filter**.

  - In both 1609.02312 and 1805.00021, authors used three main astrophysics parameters:
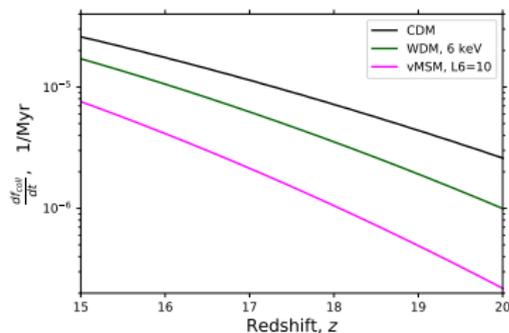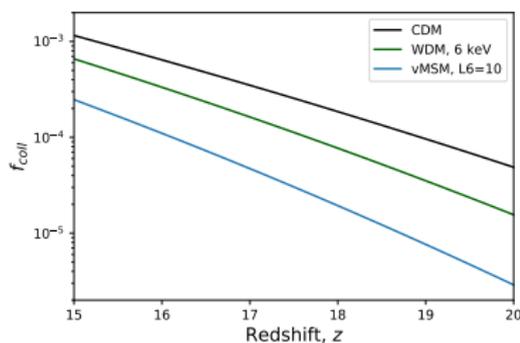   - f_* - stellar to baryonic mass ratio in collapsed haloes;
    - T_{vir} - minimal 'virial' temperature of collapsed haloes;
    - f_X - X-ray efficiency parameter.

    There are **some tensions** for the parameter choice. For example, 1805.00021 assumes maximal $f_* = 0.03$ (stating that "it is in agreement with radiation-hydrodynamics simulations of high-redshift galaxies in a neutral medium"), but 1609.02312 uses much wider range of f_* (0.005-0.5 with mean 0.05) which **changes the conclusions of 1805.00021**.

Adjusting star formation efficiency:

- Position of 21-cm absorption feature is determined by the moment, when ionizing luminosity is large enough;
- In 1805.00021, is it tightly related with time derivative of collapsed halo fraction $f_{\rm coll}(z)$:

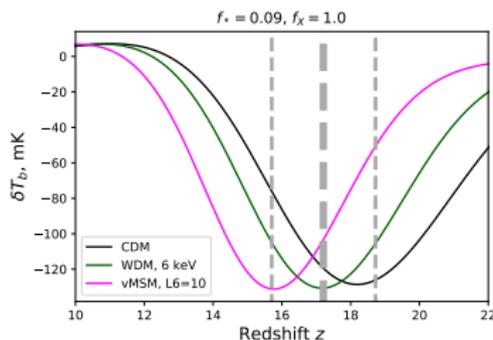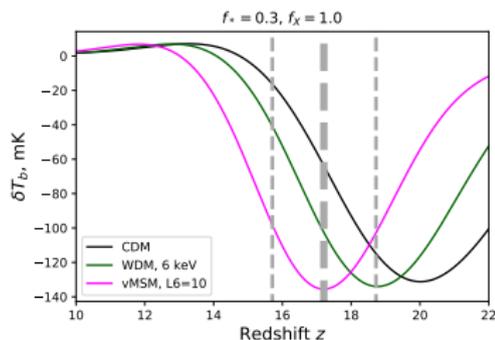$$\dot{\rho}_*(z) = f_* \bar{\rho}_{\rm b,0} \dot{f}_{\rm coll}(z).$$
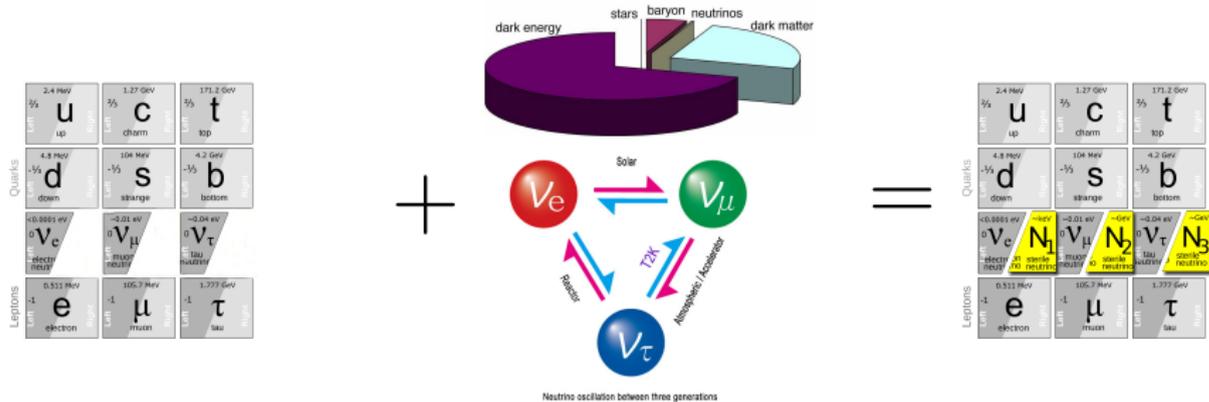
Adjusting star formation efficiency:

- However, as we discussed before, in WDM stars form **differently** (e.g. in **filaments**);
- Moreover, f_* is measured **only** from comparison with galaxy luminosity functions at $z \simeq 6 - 10$;
- Clearly, for WDM/sterile neutrino DM expected values of f_* are several times higher than for CDM;

21-cm absorption with adjusted f_*:

- We reproduced analysis of 1805.00021 with adjusted values of f_*;
- Both for WDM and sterile neutrino model, we reproduced timing (but **not** amplitude) expected from EDGES measurement;
- Both models reproduce the EDGES timing as good as CDM: **no constraints** can be obtained.

Conclusions

Thank you for your attention!