Reionization

and the

High-Redshift Galaxy UV Luminosity Function

with

Axion Dark Matter

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Galaxy-scale Challenges for ΛCDM

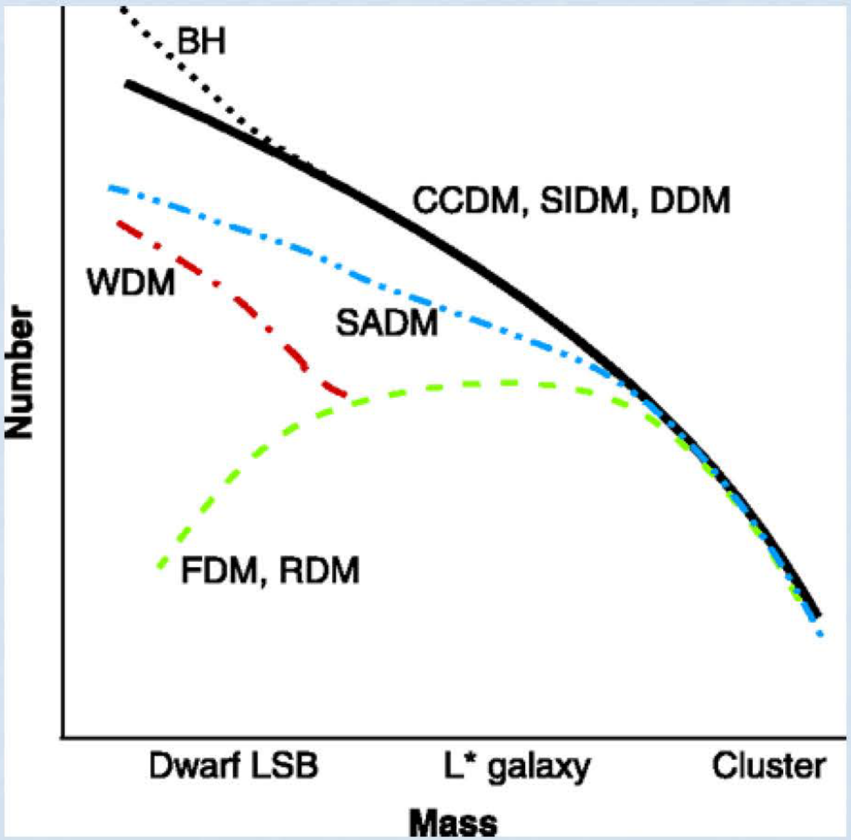
- ΛCDM extremely successful on large scales
- Challenges on smaller scales
  - \`Missing satellites' – theoretical predictions of many more low-mass dark haloes than visible satellite dwarf galaxies around the Milky Way (Moore et al 1999; Klypin et al 1999)
  - \`Too Big to Fail' – predictions of massive dark sub-haloes of Milky Way mass dark haloes that should form stars but are not visible (Boylan-Kolchin et al 2011, 2012)
  - \`Core vs Cusp' – predictions of rising density profile to central regions of dark haloes whereas cores are favoured (e.g. Gilmore, Wilkinson, RW et al 2007; Walker & Penarrubia 2011; Oh et al 2015)
  - Bulgeless disk galaxies and old thick disks – predictions of active merger histories lead to massive bulges and young thick disks (e.g. Toth & Ostriker 1992; Wyse 2001)

Baryonic Physics or Dark Matter Physics?

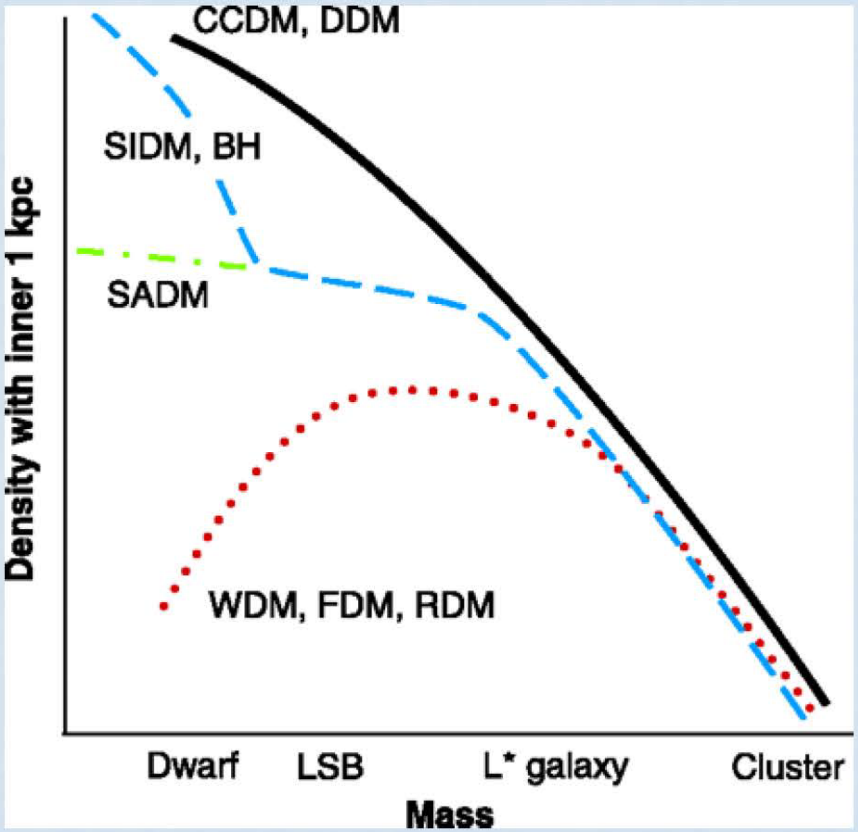
- Much ongoing effort to craft baryonic solutions
  - Star formation efficiency, feedback
  - Constrained by stellar populations e.g. bursty star-formation to erase cusps (e.g. Onorbe et al 2015)
- Challenges point to too much small-scale power
  - Modify dark matter power spectrum to suppress small scale power
  - Need to be careful not to erase too much power and delay galaxy formation too much e.g. very old stars in dwarf satellites, observed high-redshift galaxies, limits from reionization redshift and optical depth

Small Scales Reveal Nature of Dark Matter

Ostriker & Steinhardt 2003



Galaxy mass function depends on DM type



Inner DM mass density depends on the type(s) of DM

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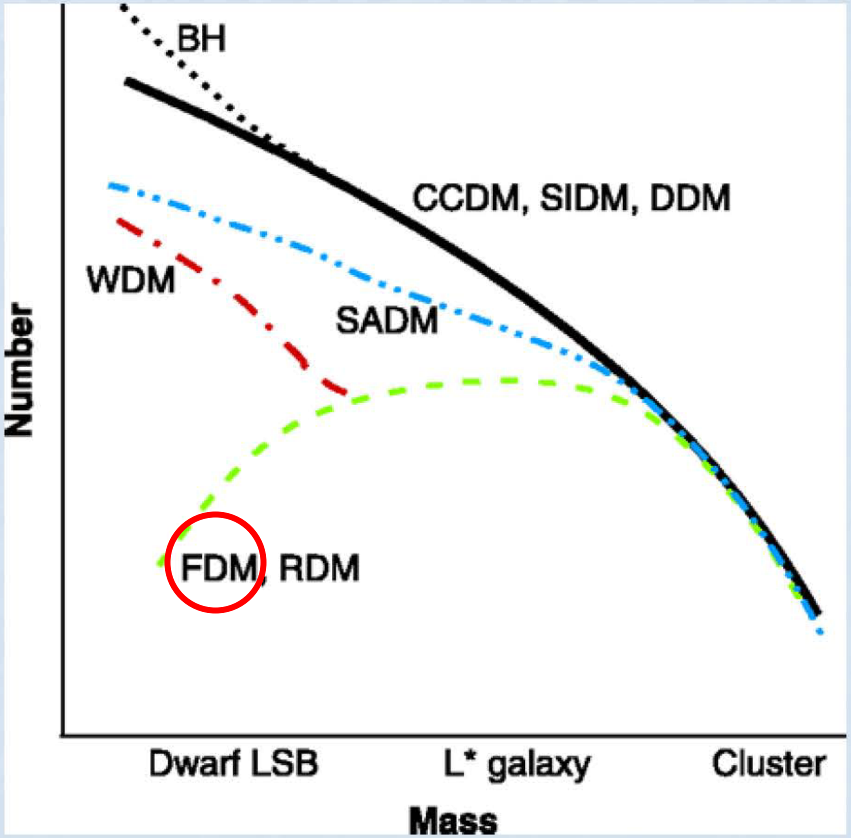
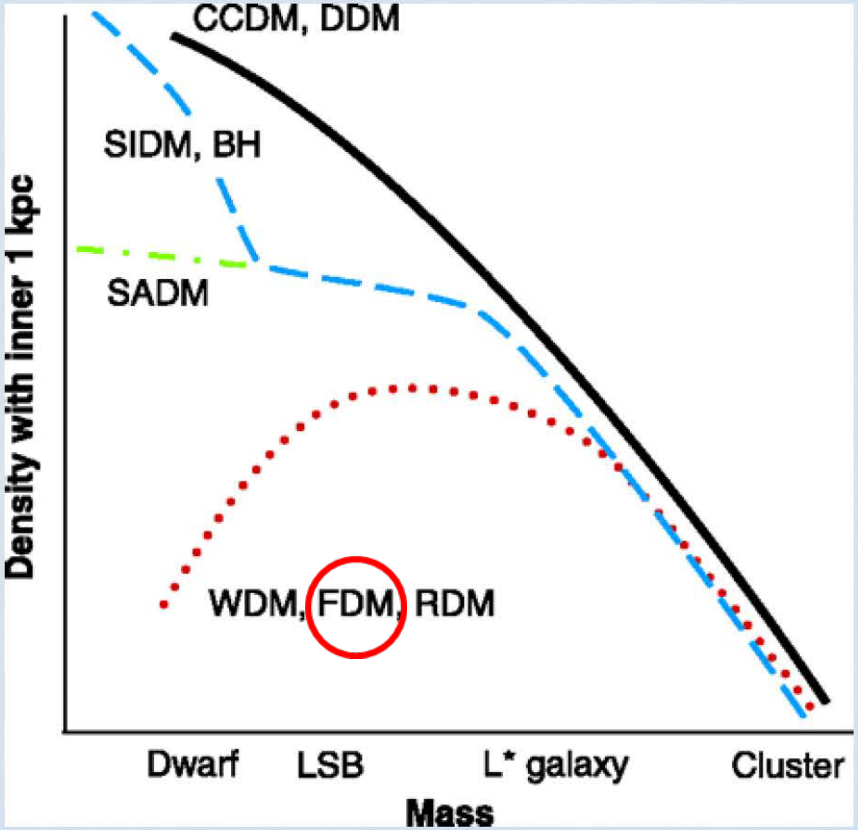


Galaxy mass function depends on DM type



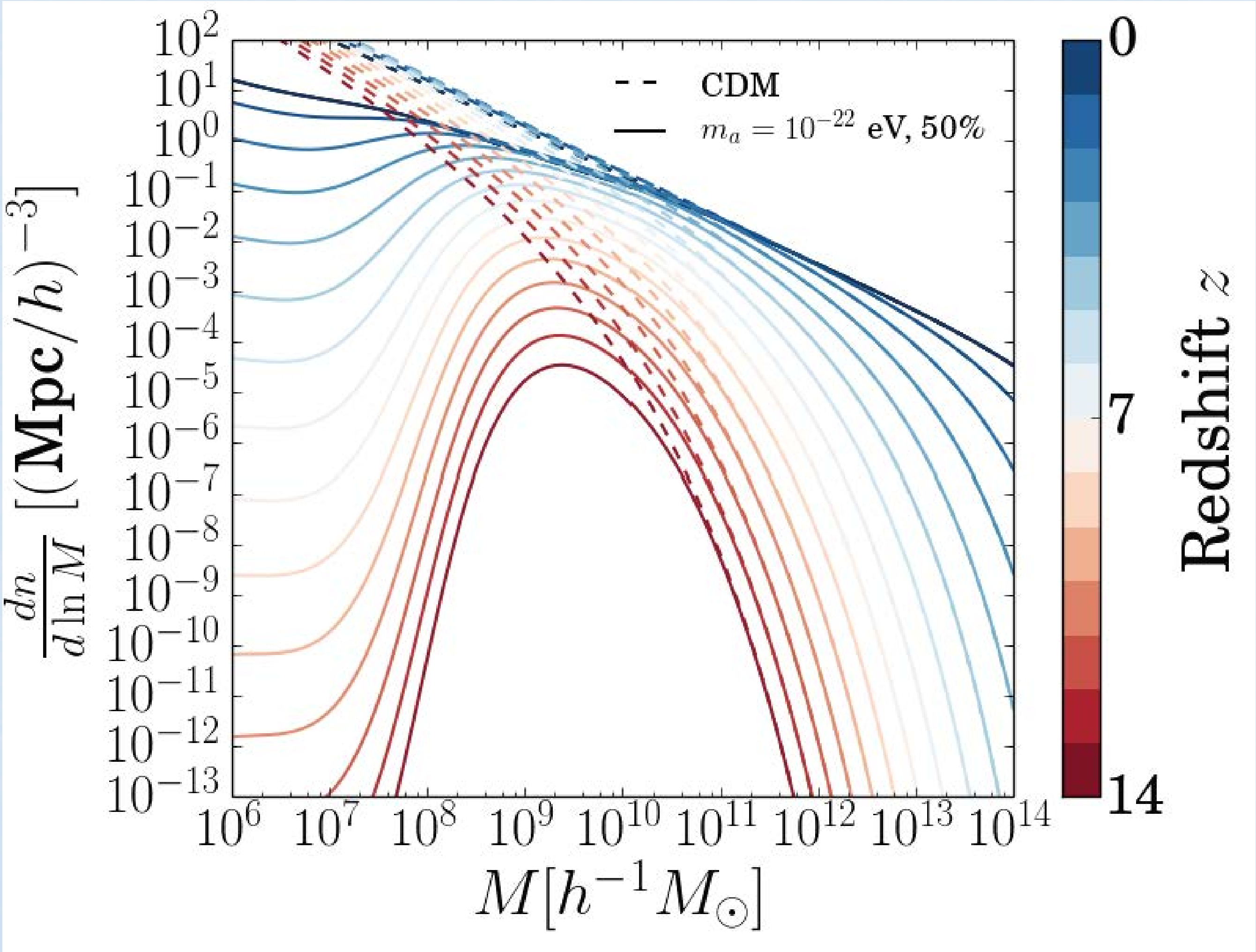
Inner DM mass density depends on the type(s) of DM

Fuzzy Dark Matter

- Low enough mass particle that quantum physics wave-nature is manifest on scales of astrophysical interest: $\lambda = h/(mv)$
- Virial Theorem for dark matter halo : $v^2 \sim GM/R$, get minimum radius $R_{min} \sim \lambda \sim 1\text{kpc}\,(10^9 M_\odot/M)(10^{-22}\text{eV}/m)^2$
- Scaling M ~1/R plus critical density for collapse ➔ minimum mass increases with redshift, suppress small scales earlier
- Redshift-dependent effective sound speed ➔ Jeans length, $\ell_J \sim (1+z)^{1/4}$, growth suppressed on smaller scales
- Matches CDM on larger scales
- Ultra-low-mass axion m ~ 10^{-22}eV is fuzzy DM that can create cores in dwarf galaxies ➔ what about other constraints?

Hu, Barkana & Gruzinov 00; Ostriker 15; Marsh & Silk 15; Marsh & Pop 15

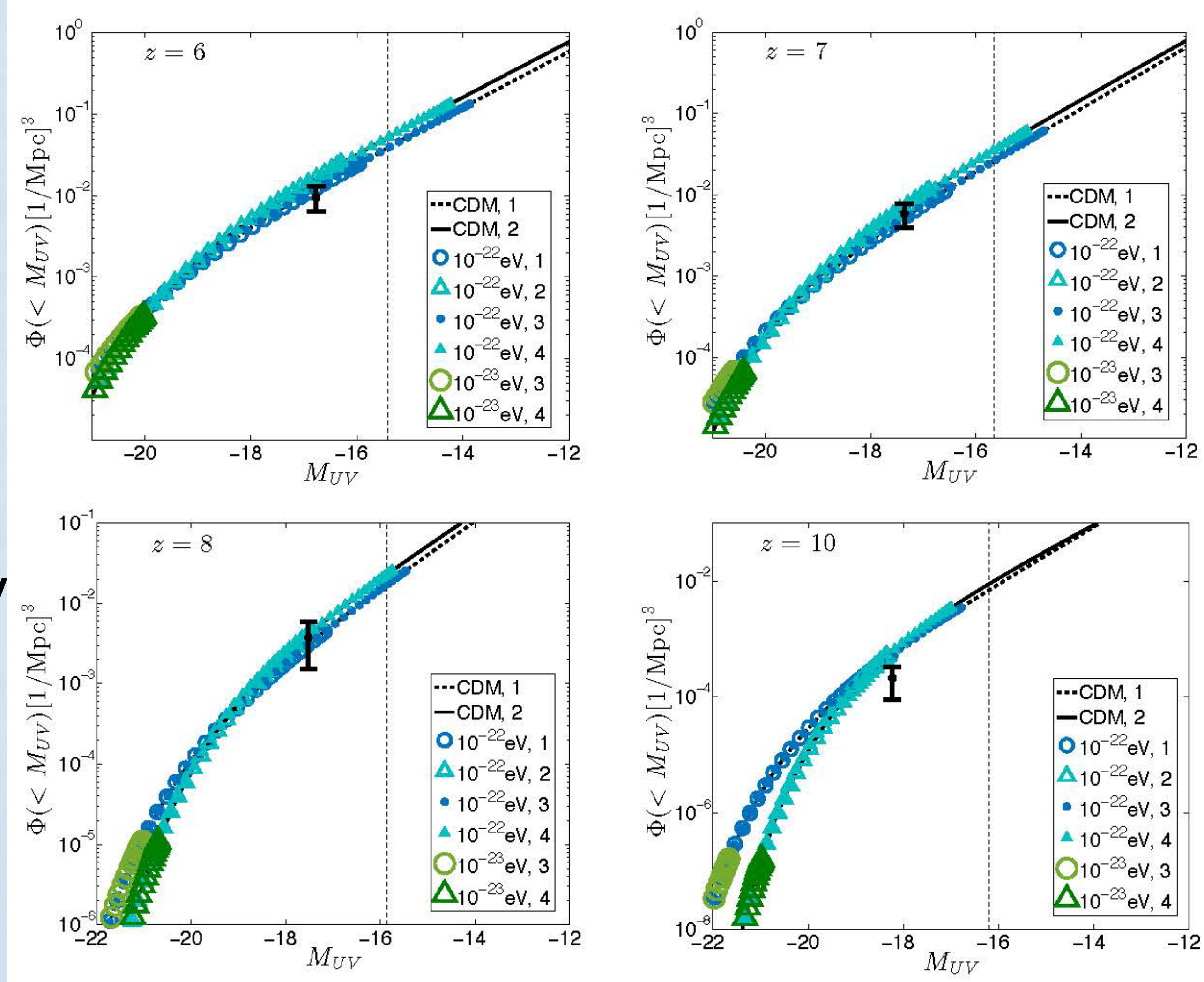
Halo mass function as a function of redshift, 50% dark matter in ultra-low-mass axions, m=10^{-22}eV, 50% CDM: Suppression of small-scale structure compared to 100% CDM



Bozek, Marsh, Silk & RW 2015

High Redshift UV Luminosity Function

- Abundance matching to go from halo mass function to UV luminosity
- Cumulative luminosity function
- Data point from Bouwens et al 15
- Exclude axion masses < 10^{-23}eV from contributing more than 50% of dark matter ➔ too few faint galaxies

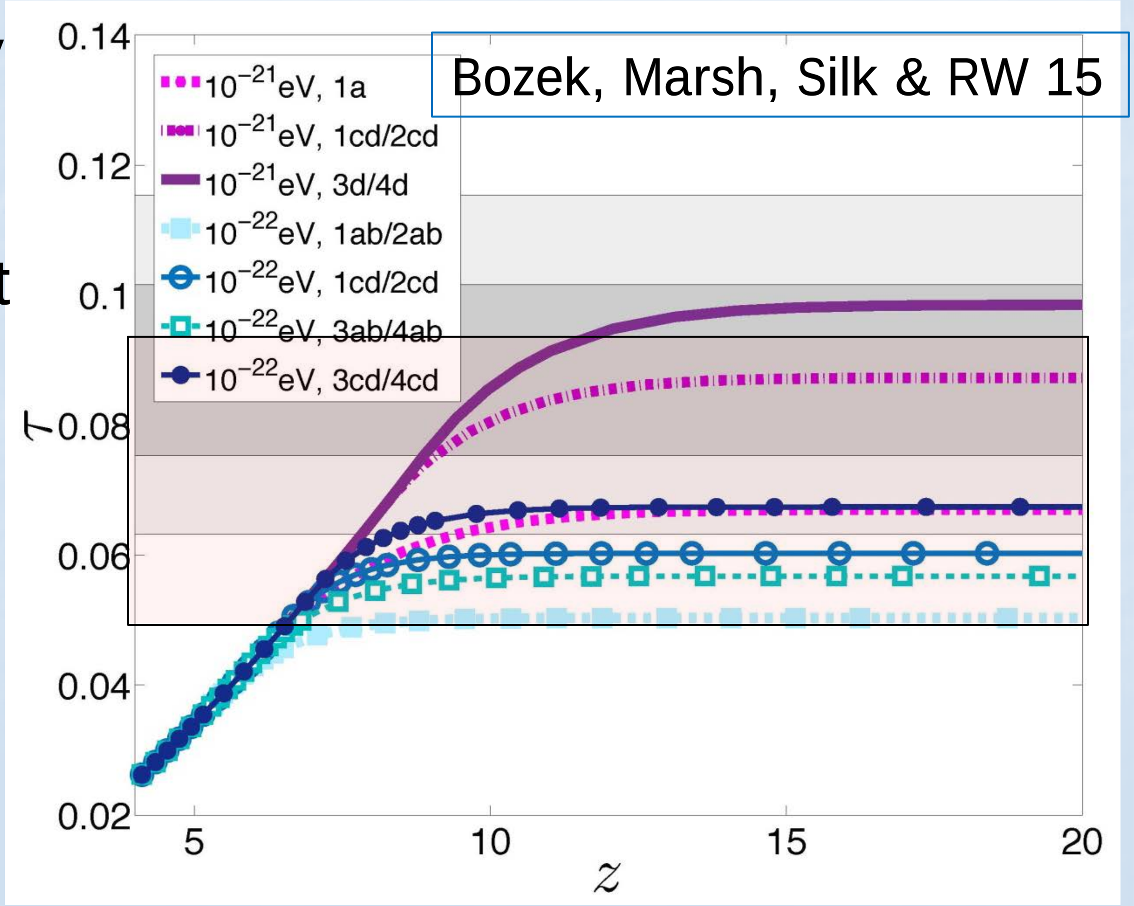


Bozek, Marsh, Silk & RW 2015

Reionization Constraints: Optical Depth to Thomson Scattering

- Estimate ionizing photon flux from UV luminosity function following e.g. Kuehlen & Faucher-Giguere 2012

- Escape fraction typically 20%
- $m_a \sim 10^{-23}$ eV excluded
- $m_a \sim 10^{-22}$ eV consistent with Planck limits
- $m_a \sim 10^{-21}$ eV also consistent

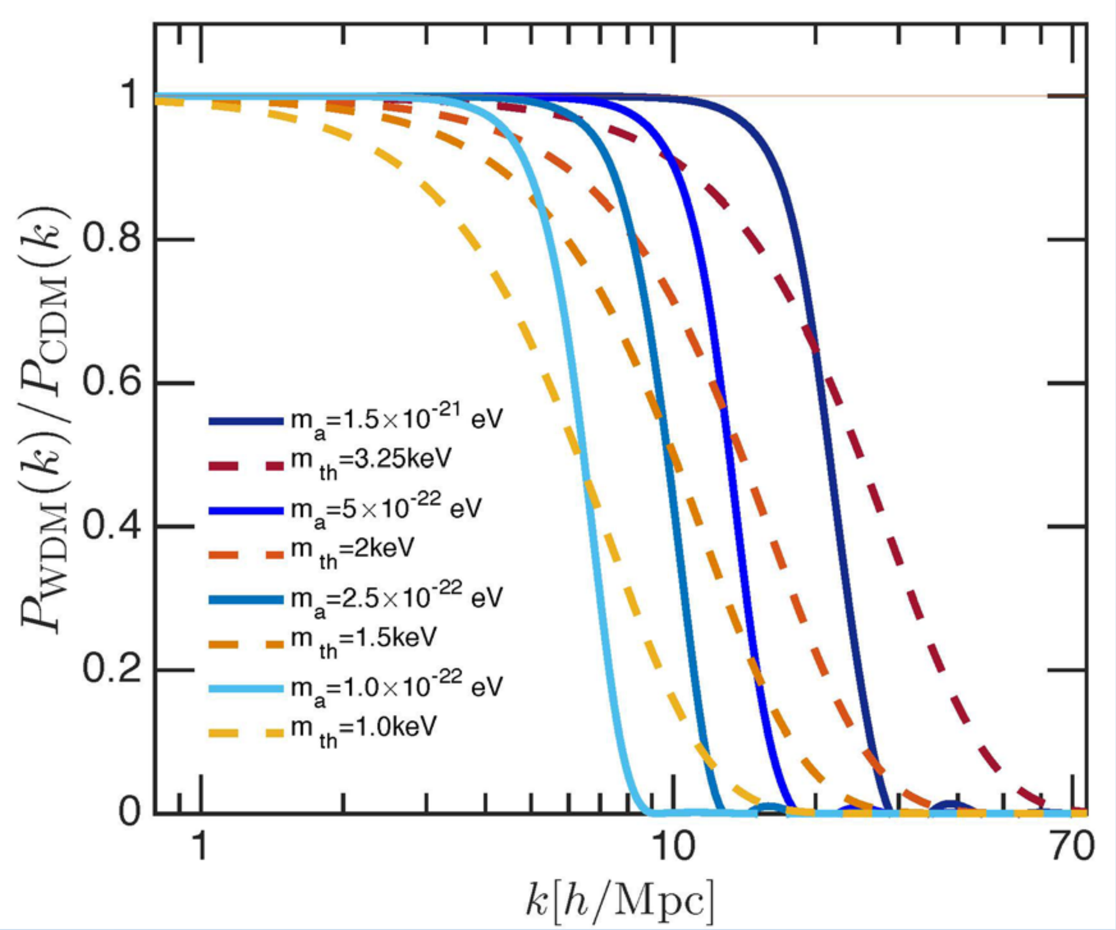


Conclusions

- Ultra-low-mass axions of mass ~ 10^{-22} eV consistent with high-redshift galaxy luminosity function – need to push fainter!
- Also consistent with Thomson optical depth
- Reionization completed more rapidly than WIMP CDM – $\Delta z \sim 2$ compared to $\Delta z \sim 2.7$, for very similar median redshift ~ 9.5 – may be testable with e.g. AdvACT
- Same mass of axion DM produces cores in dwarf galaxies, as observed (Schive et al 14, Marsh & Pop 15)
- Large-scale successes of WIMP CDM retained, answers (these) small-scale challenges

What about the Lyman Alpha Forest?

- Proposed suppression of small-scales by (thermal) Warm Dark Matter constrained by Lyman-alpha forest data to masses > 3.3 keV (Viel et al 2013)
- Matching scale at which suppression is 50% would imply axion mass of > $10^{-20.5}$ eV
- But Fuzzy Axion Dark Matter has different (steeper) small-scale cut-off than WDM



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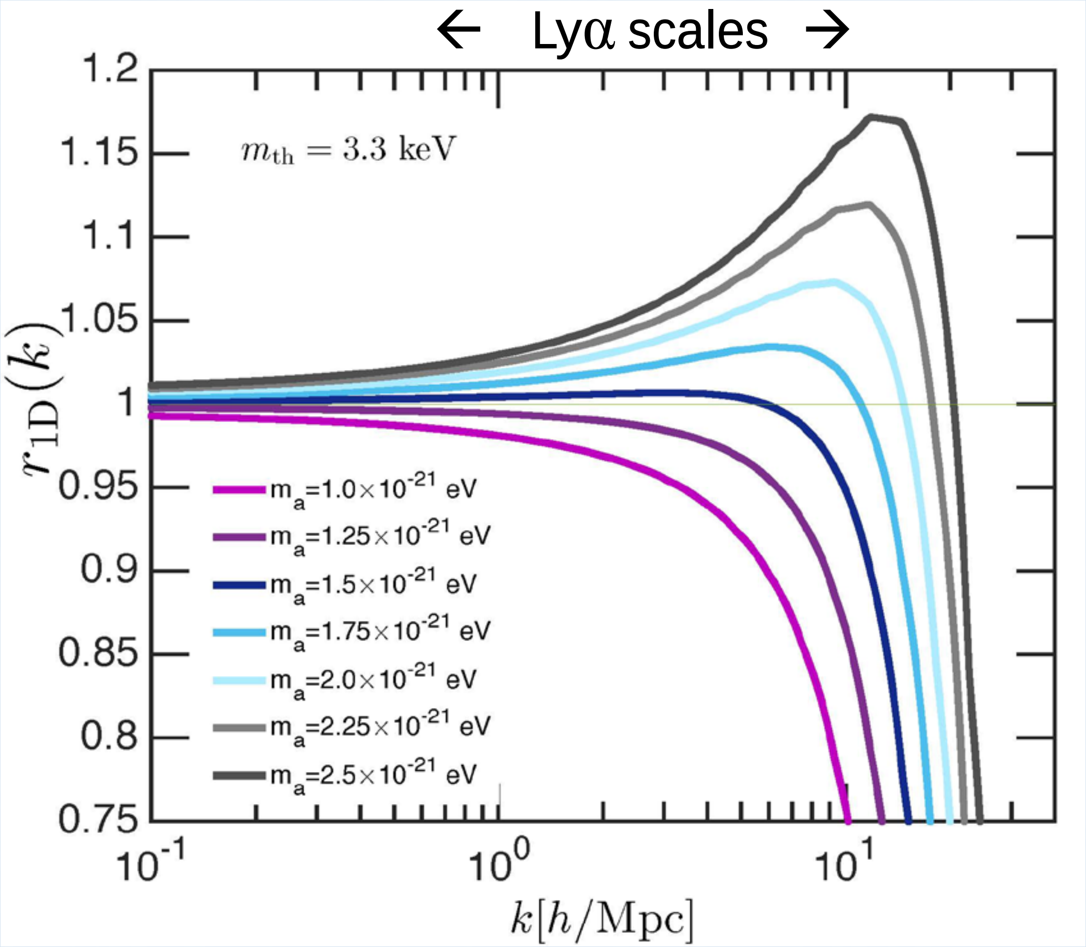
Lyman-alpha: linear power matching

- Ratio of power on given scale for axion DM relative to thermal WDM that meets Ly α constraints
- Ratio greater than unity on scales of interest implies that axion DM also meets constraints
  ➔ $1.5\text{x}10^{-21}$eV
- $5\text{x}10^{-22}$eV axion matches WDM of 2keV
- Next step: non-linear evolution



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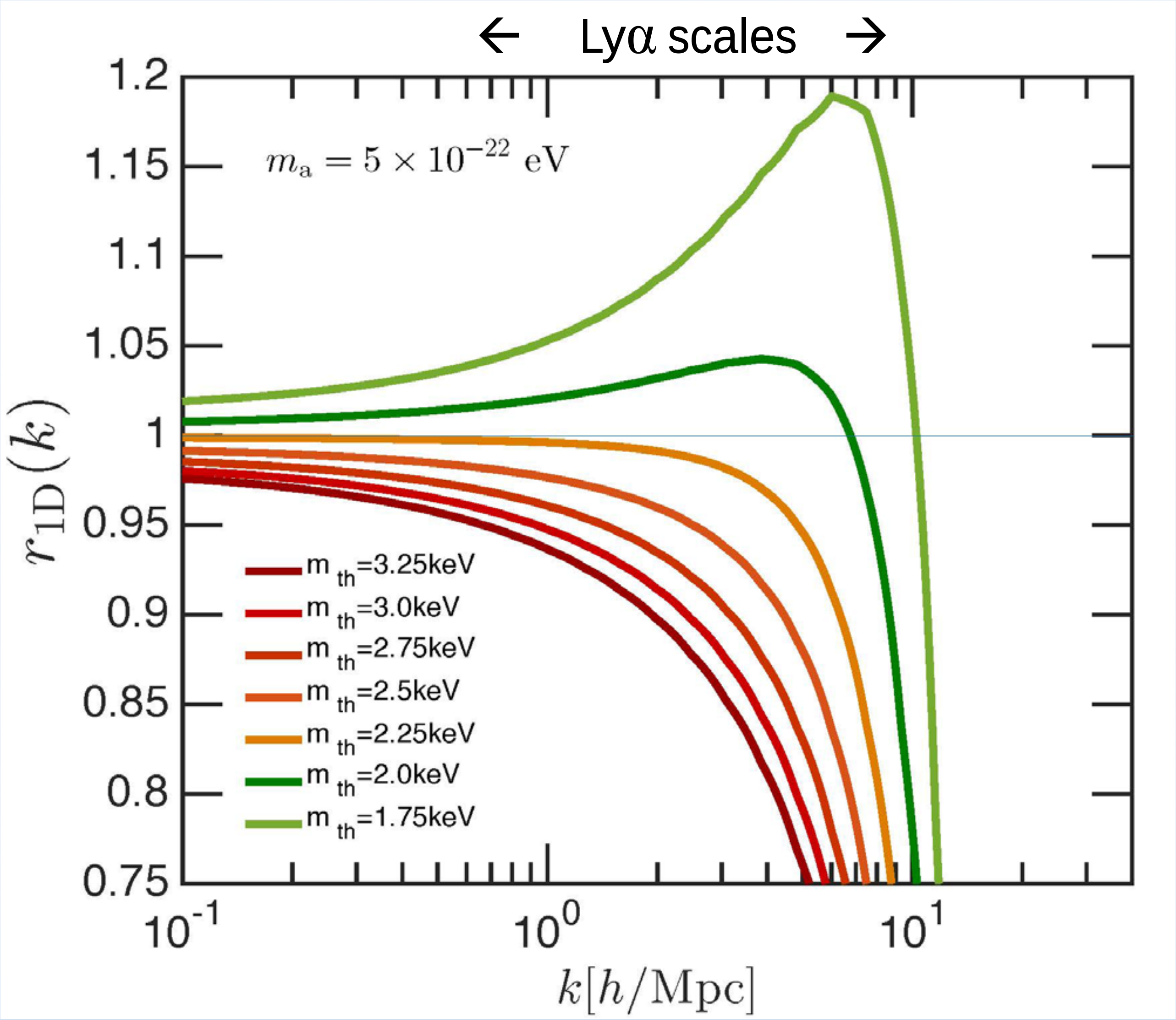
- $5x10^{-22}$eV axion matches WDM of 2.25keV



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