Title: Impact of alternative dark matter (altDM) models on galaxies during the Epoch of Reionization (EoR)

Speakers: Rahul Kannan

Collection: Dark Matter, First Light

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Abstract: Current and upcoming James Webb Space Telescope (JWST) imaging surveys hold enormous potential for uncovering the faint low-mass galaxy population, which could provide constraints on alternative DM (altDM) models. In this talk I will investigate the impact of altDM models that exhibit small-scale suppression of the matter power spectrum, namely warm dark matter (WDM), fuzzy dark matter (FDM), and interacting dark matter (IDM) with strong dark acoustic oscillations (sDAO) on the properties of galaxies in the EoR. In altDM scenarios, both the halo mass functions and the ultraviolet luminosity functions at z ? 6 are suppressed at the low-mass/faint end, leading to delayed global star formation and reionization histories. However, strong non-linear effects enable altDM models to 'catch up' with cold dark matter (CDM) in terms of star formation and reionization. The specific star formation rates are enhanced in halos below the half-power mass in altDM models. This enhancement coincides with increased gas abundance, reduced gas depletion times, more compact galaxy sizes, and steeper metallicity gradients at the outskirts of the galaxies. These changes in galaxy properties can help disentangle altDM signatures from a range of astrophysical uncertainties. However, we uncover significant systematic uncertainties in reionization assumptions on the faint-end luminosity function. This underscores the necessity of accurately modeling the small-scale morphology of reionization in making predictions for the low-mass galaxy population.

THESAN

Impact of alternative dark matter models on galaxies during the Epoch of Reionization

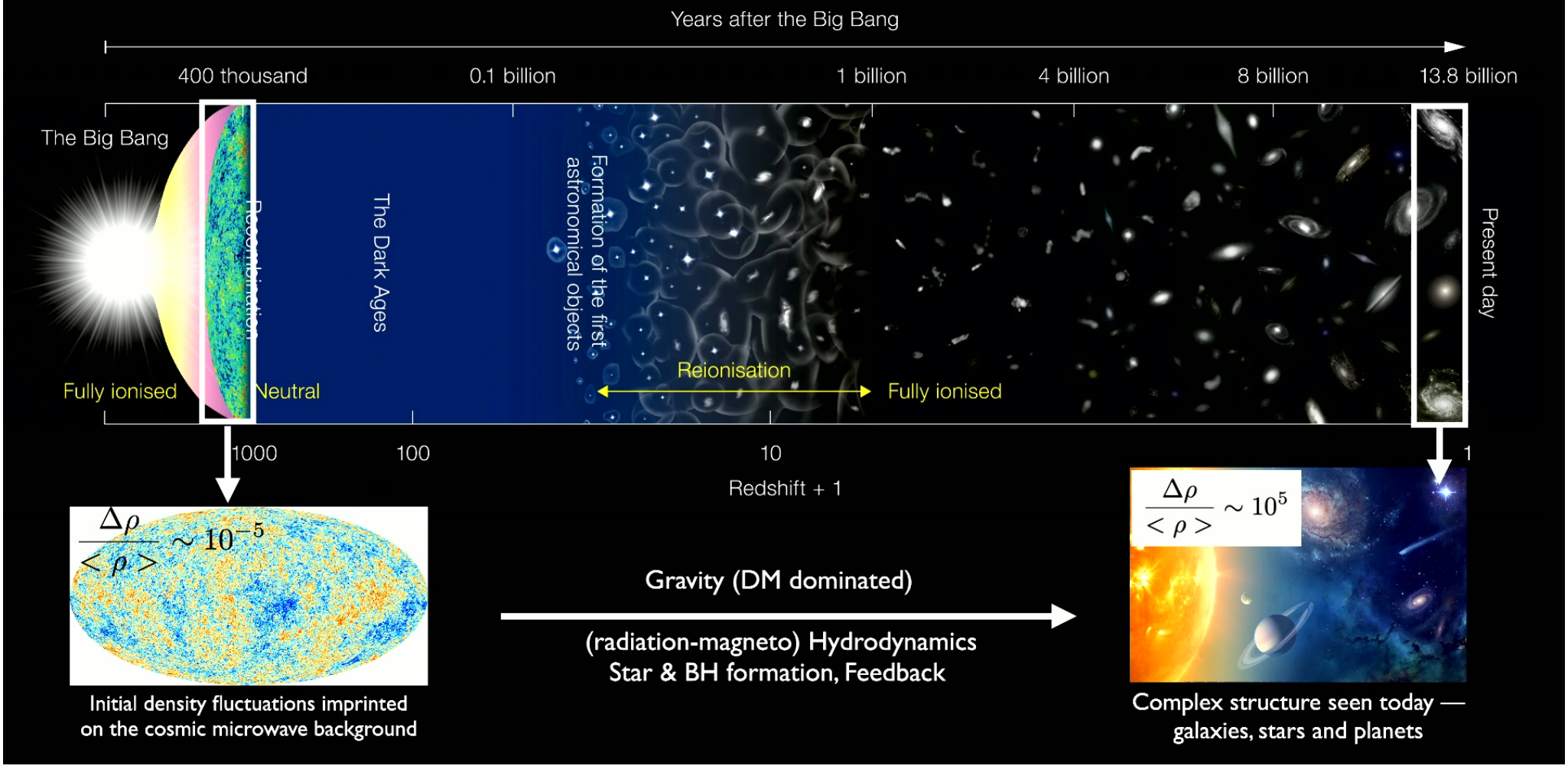
Dark Matter, First Light Workshop
Perimeter Institute for Theoretical Physics
February 28, 2024

Kannan+2022a,b
Borrow,Kannan+2023
Shen+2024 (incl. Kannan)

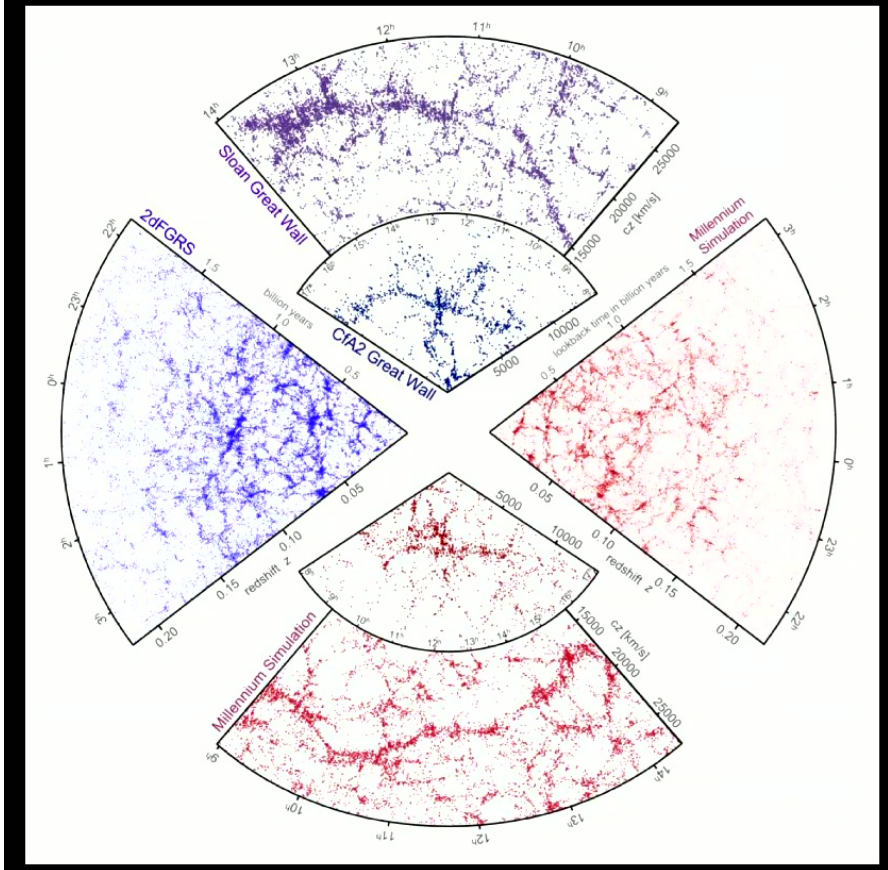
Rahul Kannan
York University

YORK UNIVERSITÉ UNIVERSITY

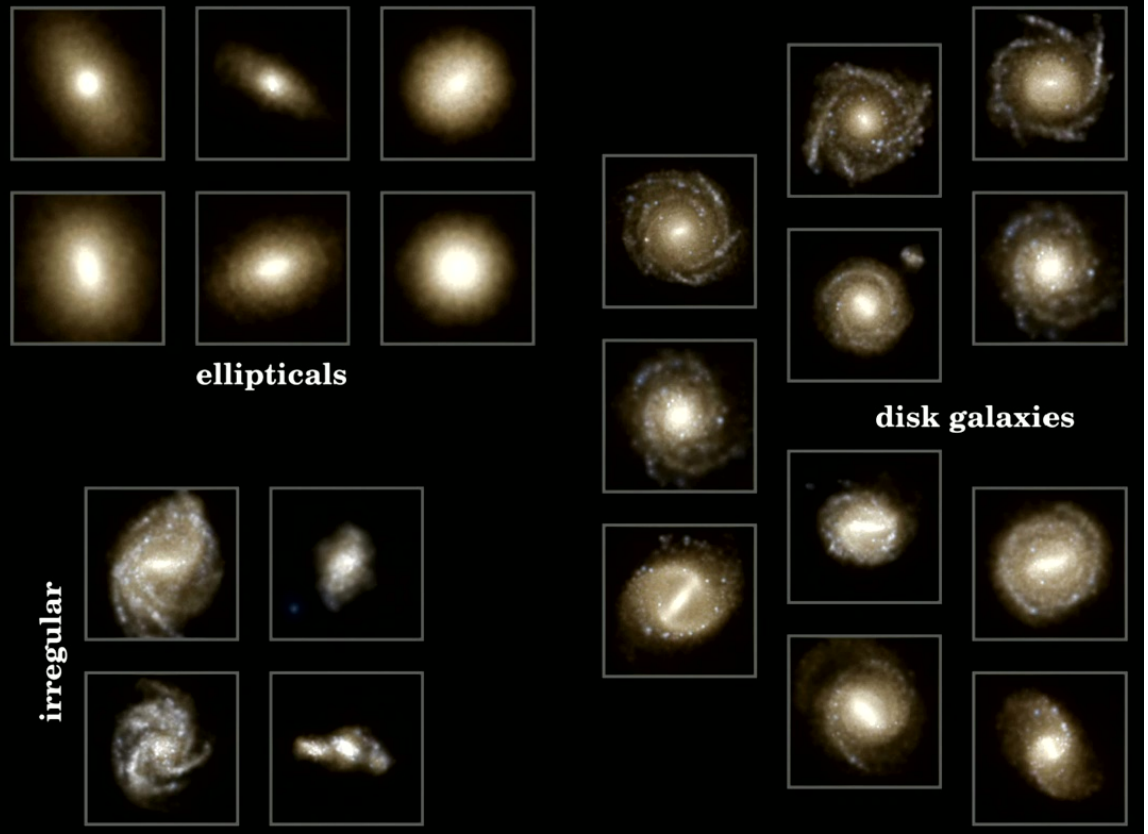
Cosmological structure formation



CDM is successful in explaining large scale cosmic structure

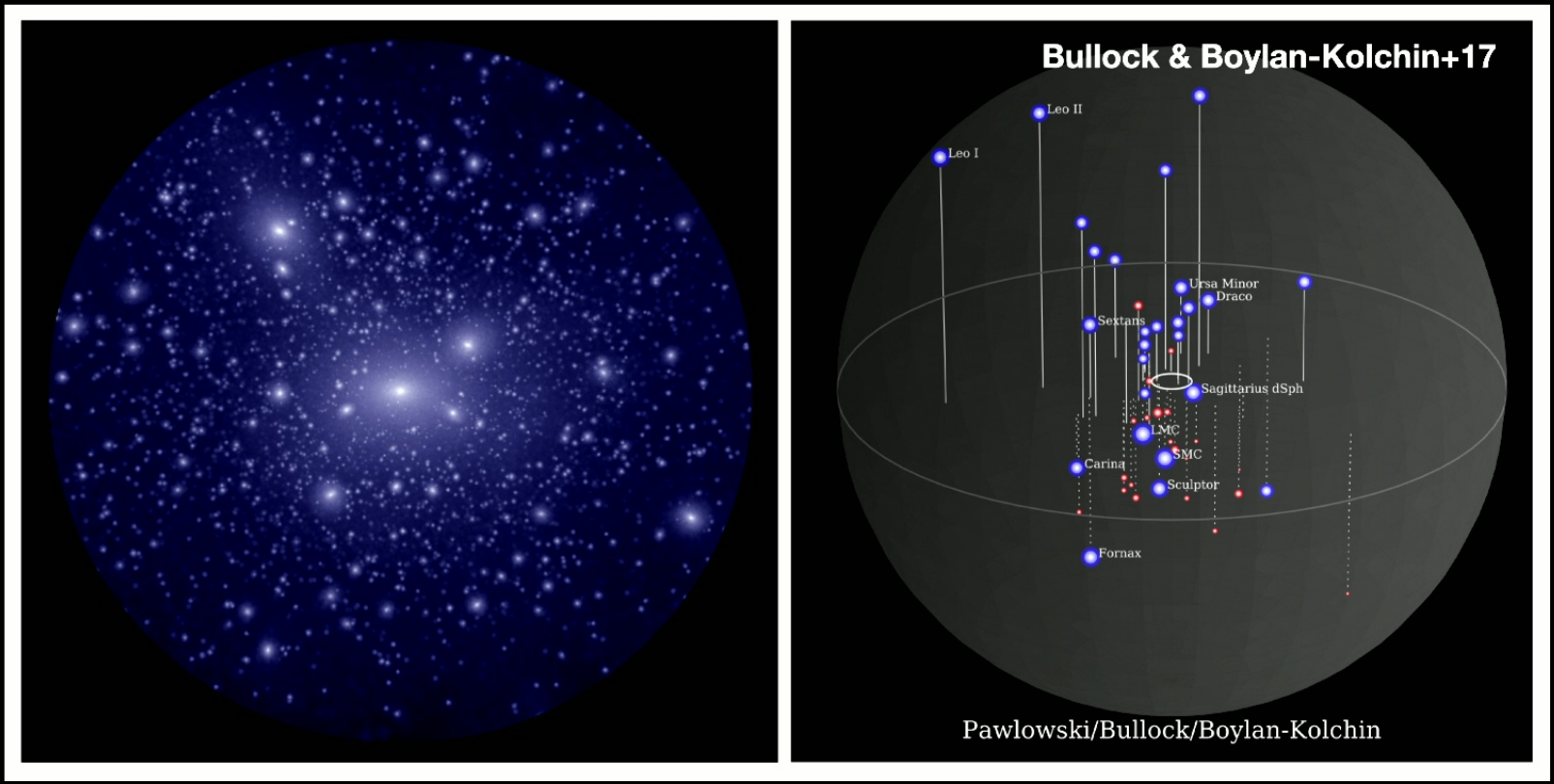


Springel+06



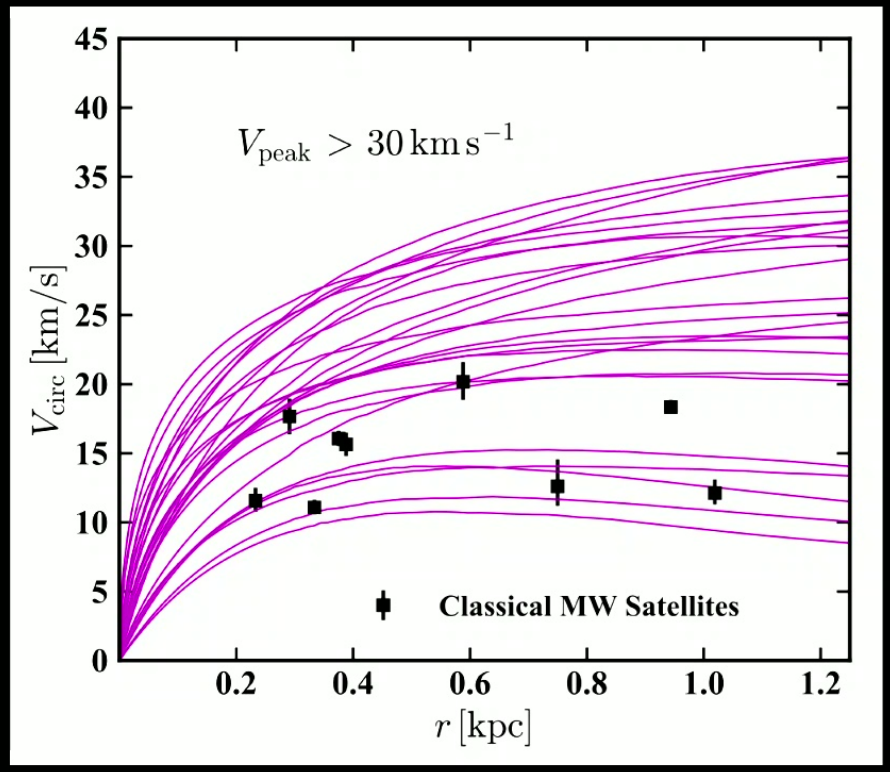
Vogelsberger+14

Problems on small scales - missing satellites problem

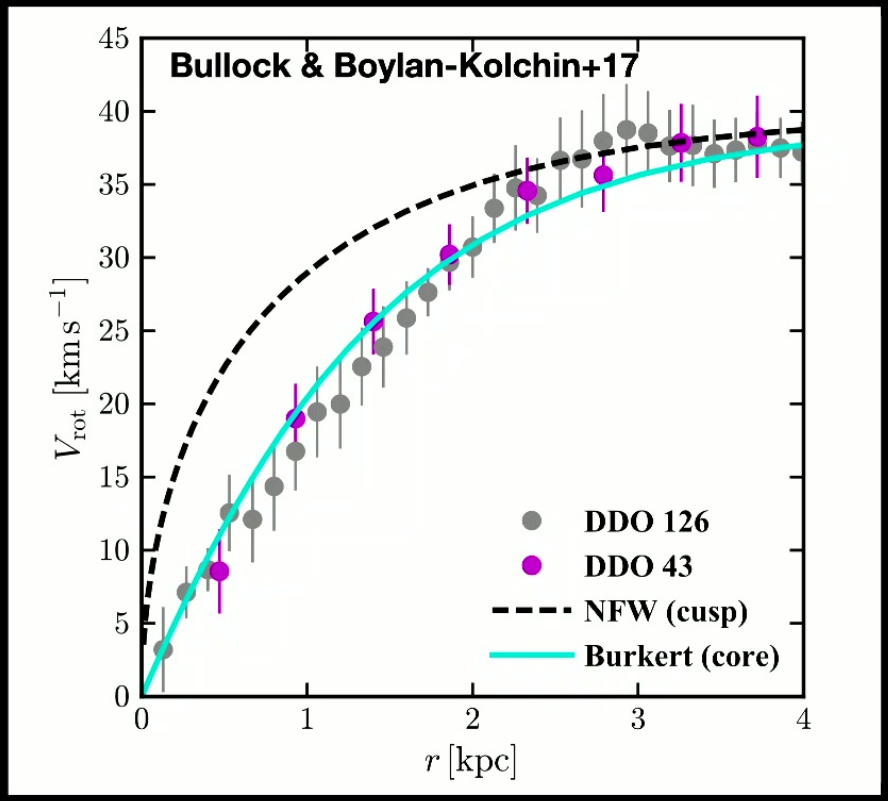


- ~50 satellite galaxies in MW compared to thousands in simulations

Problems on small scales - to big to fail & cusp core problem

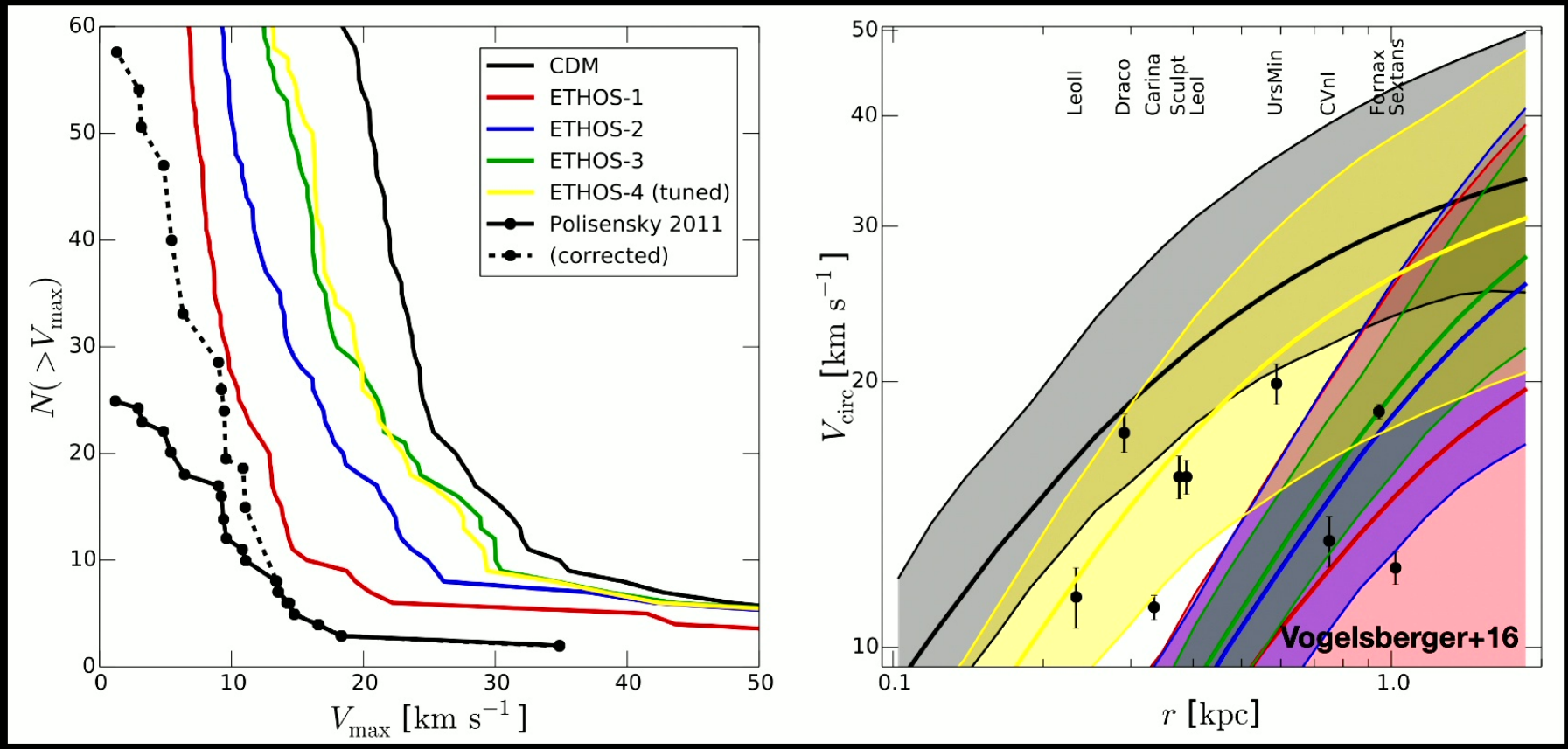


- Halos with Vmax > 30 km/s are resistant to star formation suppression by reionization and thus too big to have failed to form stars



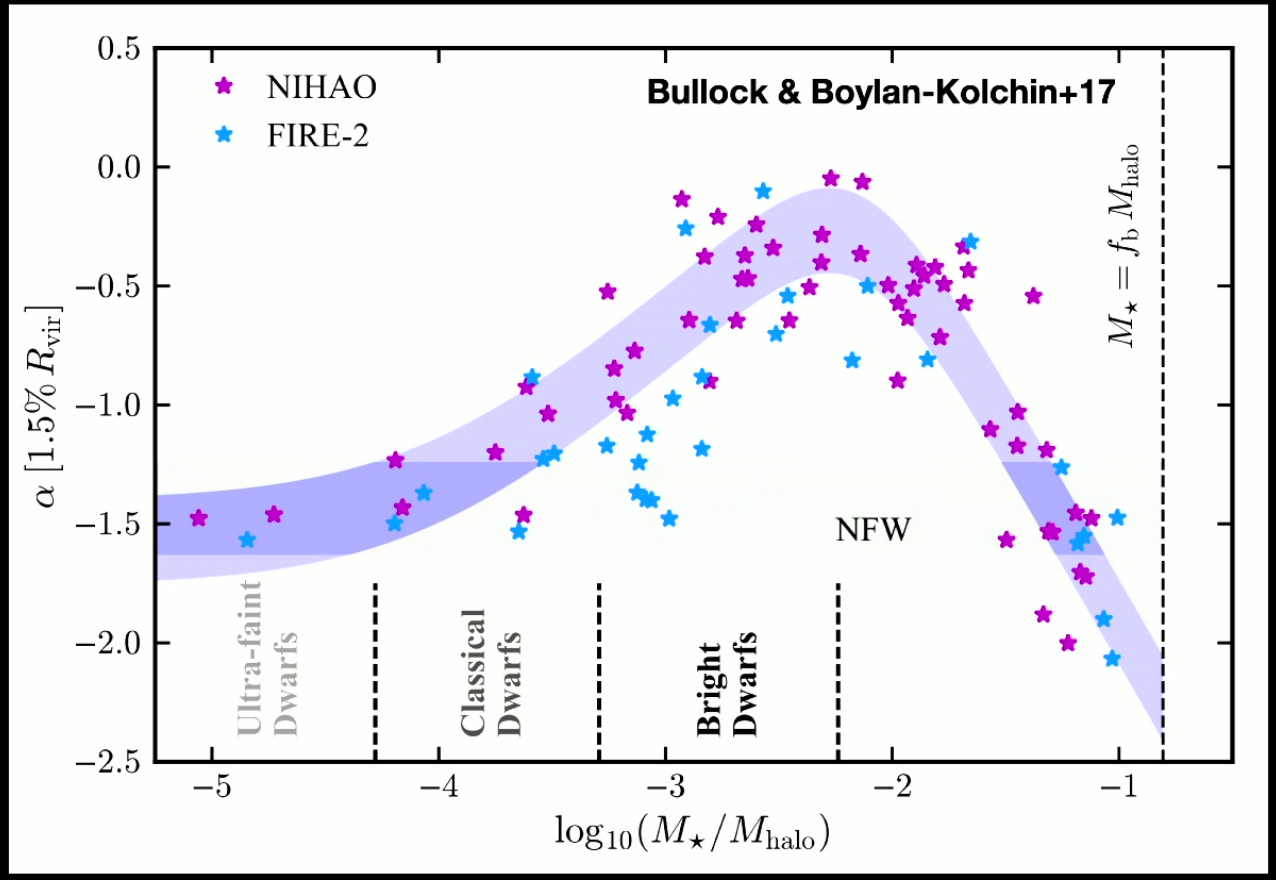
- The NFW profile predicts a ρ ~1/r which gives rise to steeply rising rotation curves while observations of satellites prefer a density profile with a constant density core

altDM models ease this tension



- Suppression of structure formation on small scales eases too big to fail and cusp/core problem

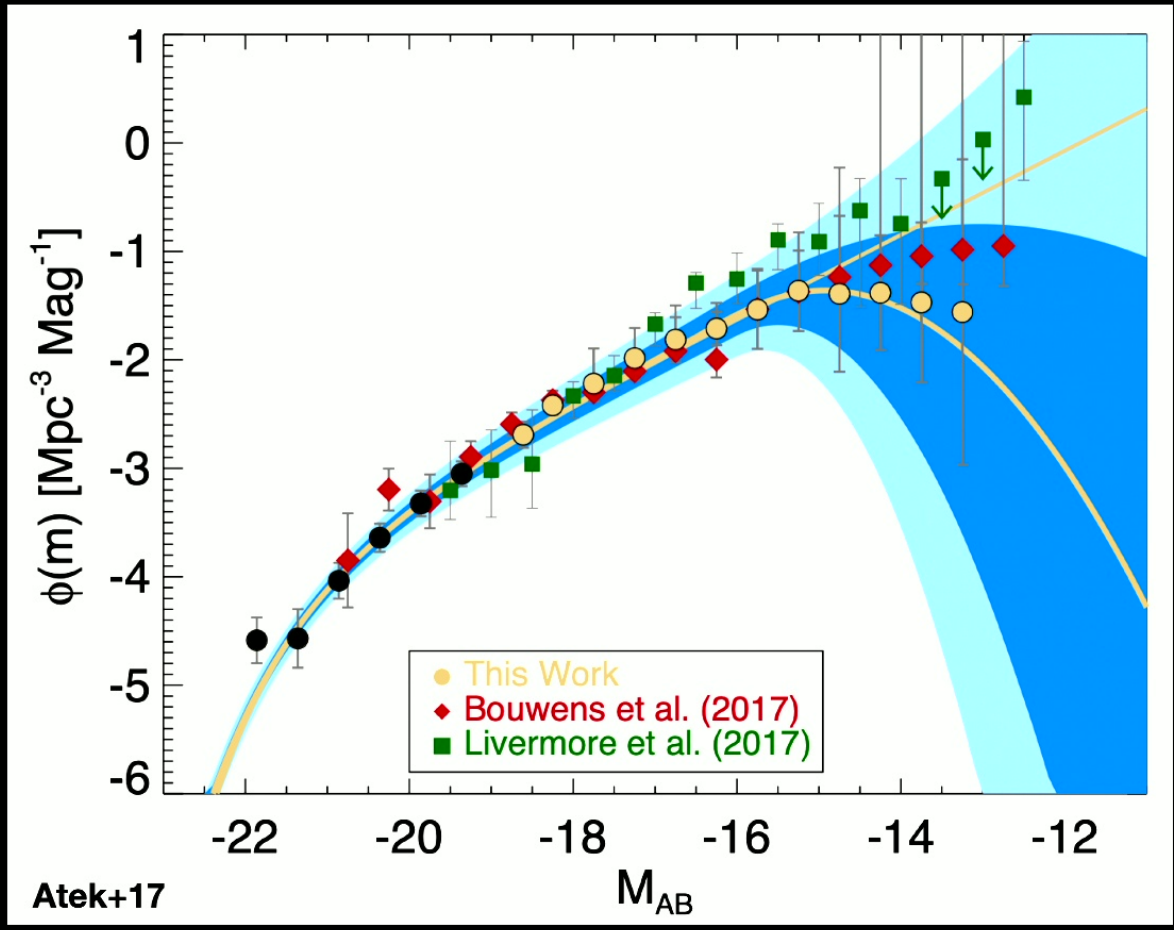
But so does baryonic physics



- Strong Sne feedback (strongly varying central potential) can perturb the DM distribution turning cusps to cores in certain halos

Can we constrain altDM models using high-z observations?

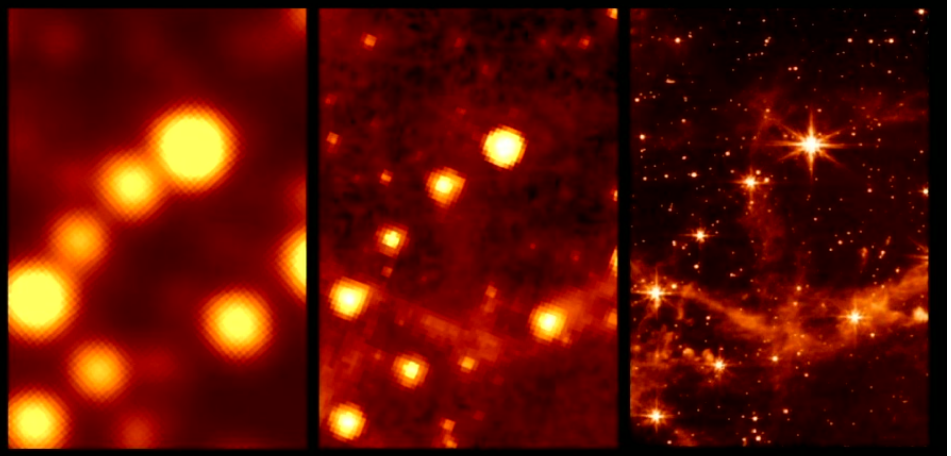
- Suppression on small scales can cause a reduction in the number of low-mass low-luminosity galaxies
- They can also imprint their signatures on the 21cm and Line intensity mapping signals
- However, until recently, obtaining accurate measurements was very difficult (e.g. UV luminosity function)

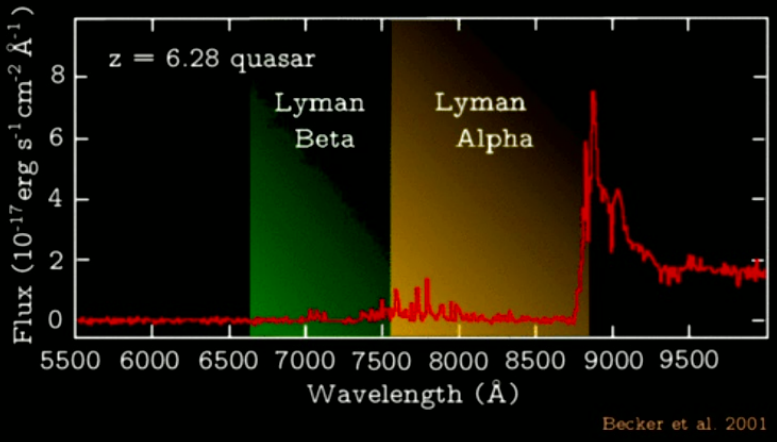


High-z observations - new high precision era

JWST

ALMA

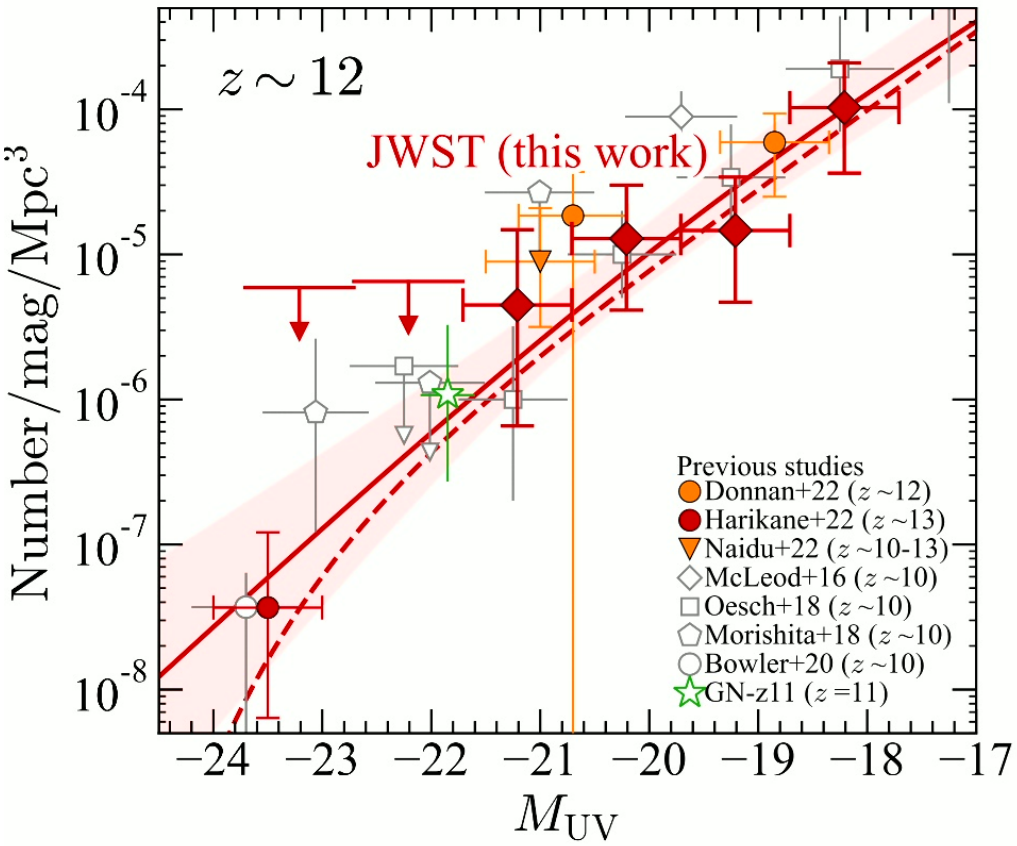


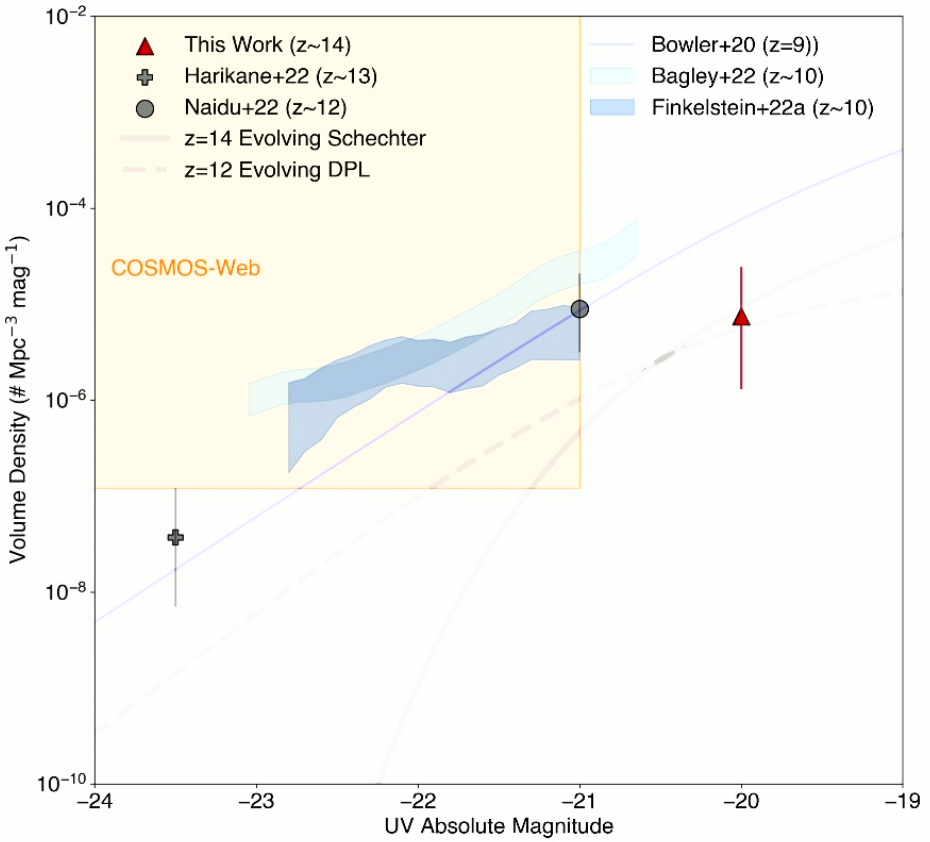


Intensity mapping

21cm & Nebular lines

Galaxy detections at z>10

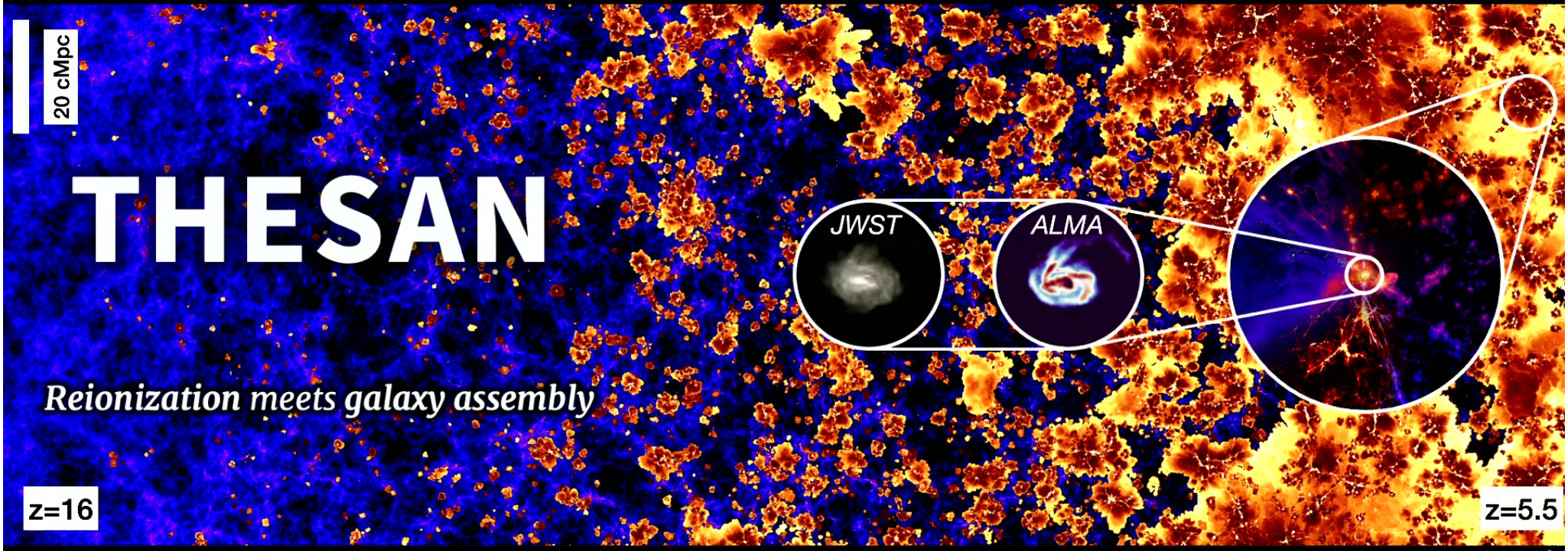




Harikane+22

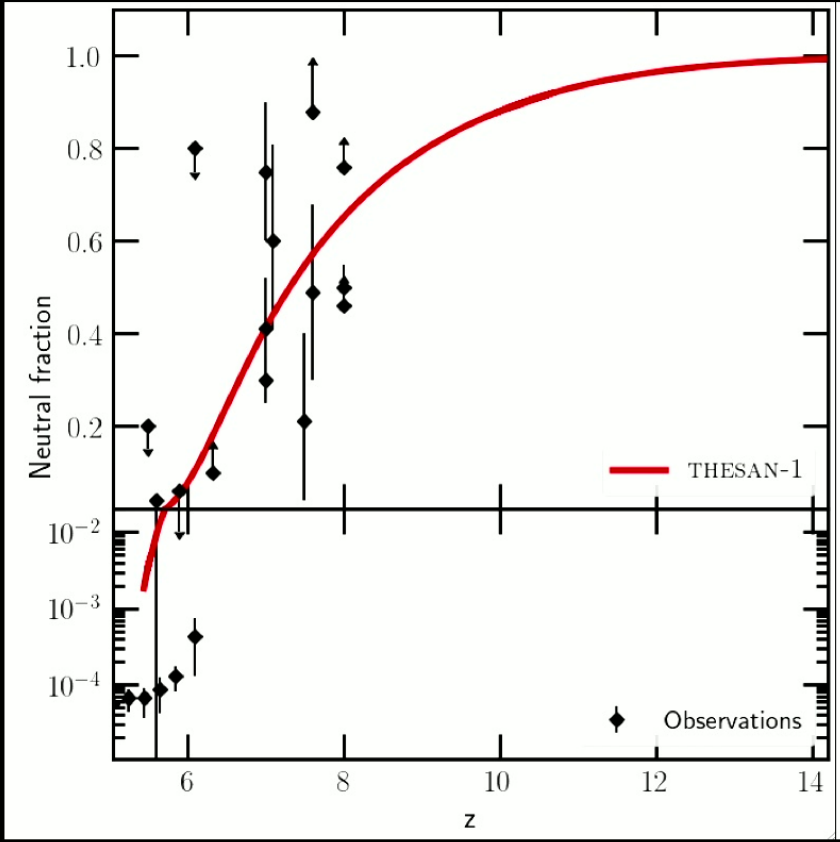
Finkelstein+22

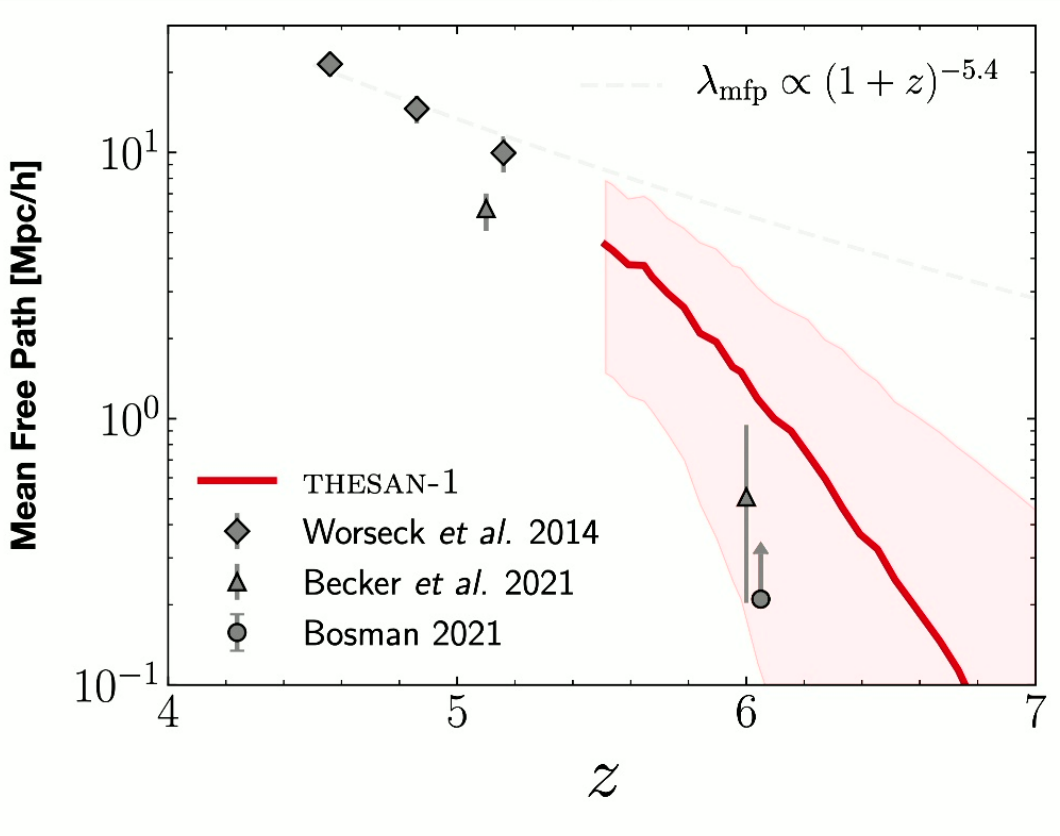
The THESAN Project



Galaxy formation in an evolving radiation field

Accurate Reionization History





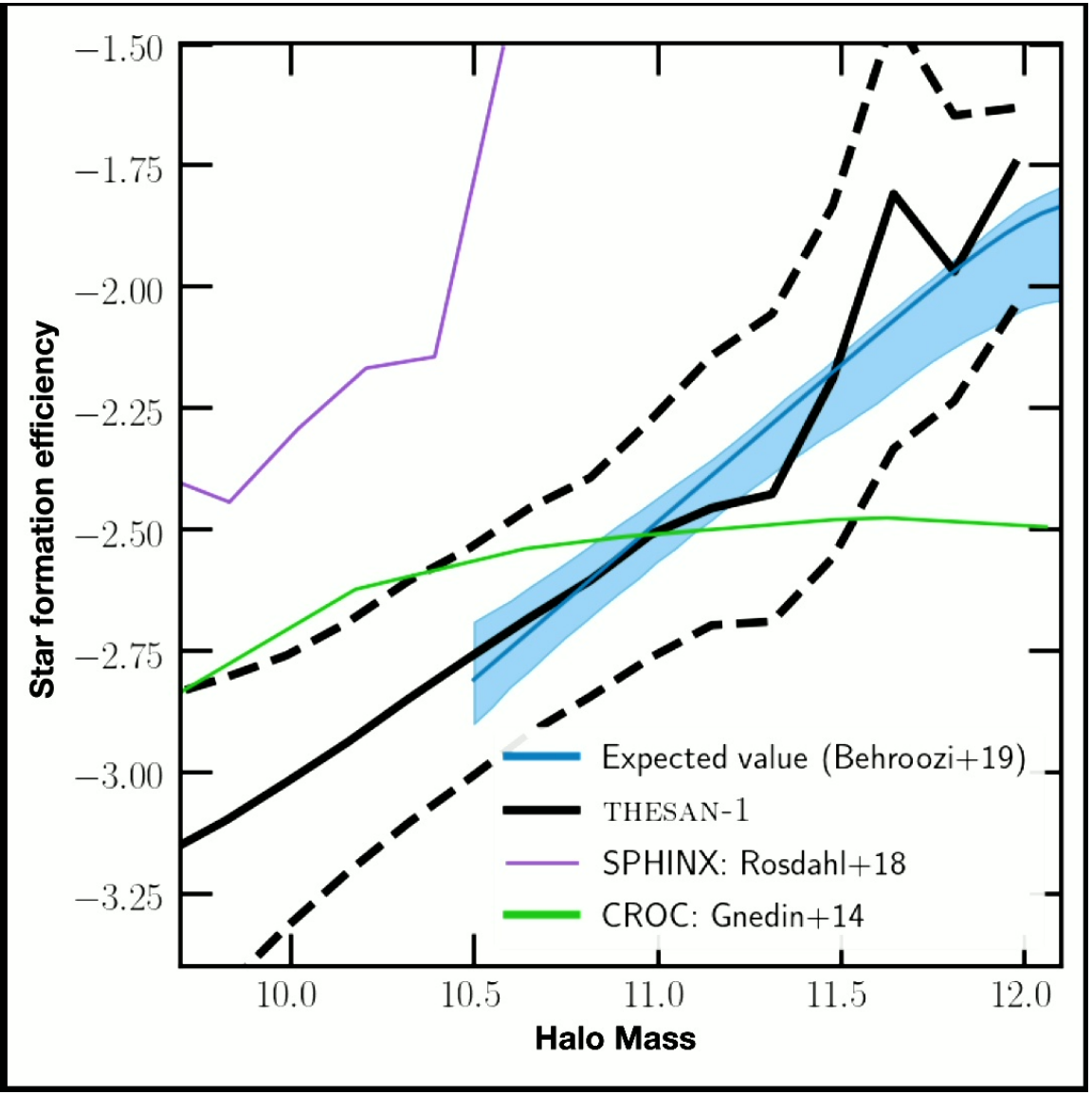
Kannan+22; Garaldi, Kannan+22

- Matches ionization history
- Can model rapid mean free path evolution without resorting to sub-grid sink models (Cain+21, Davies+21)

Accurate Galaxy Properties

- The amount of stars formed within a halo is an important quantity to match
- Most galaxy formation models strive to get this correct
- THESAN simulations do a good job of reproducing this relation -> accurate galaxy properties
- Other simulations have too high star formation rates (eg. SPHINX: Rosdahl+18) or too low (eg. CROC: Gnedin+14)

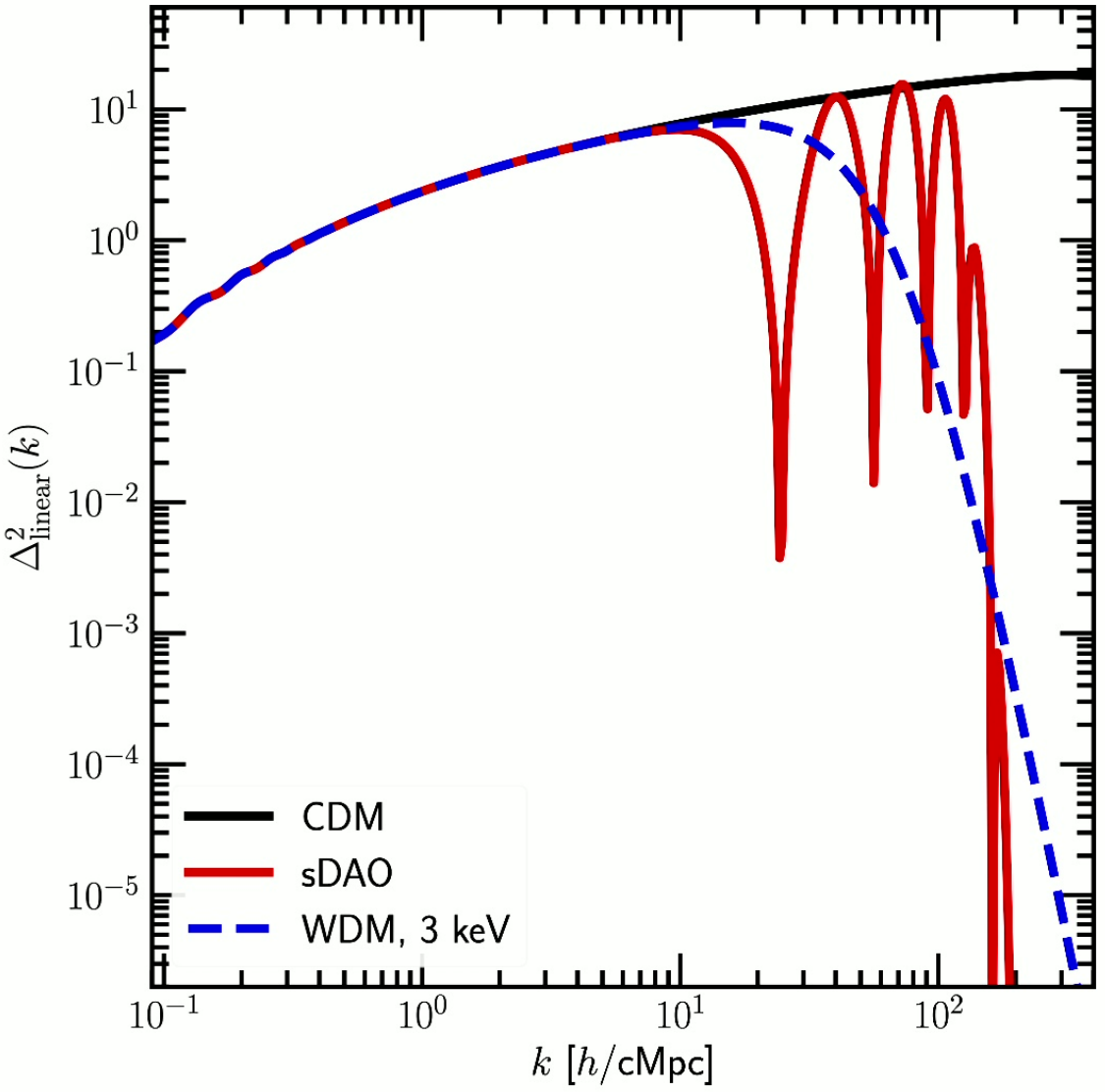
Kannan+22



AltDM models & Reionization

- In addition to CDM, we also ran an additional simulation with a sDAO model.
- Included as a cutoff of the matter power spectrum at small scales due to collisional damping caused by interactions between DM and relativistic particles in the early universe

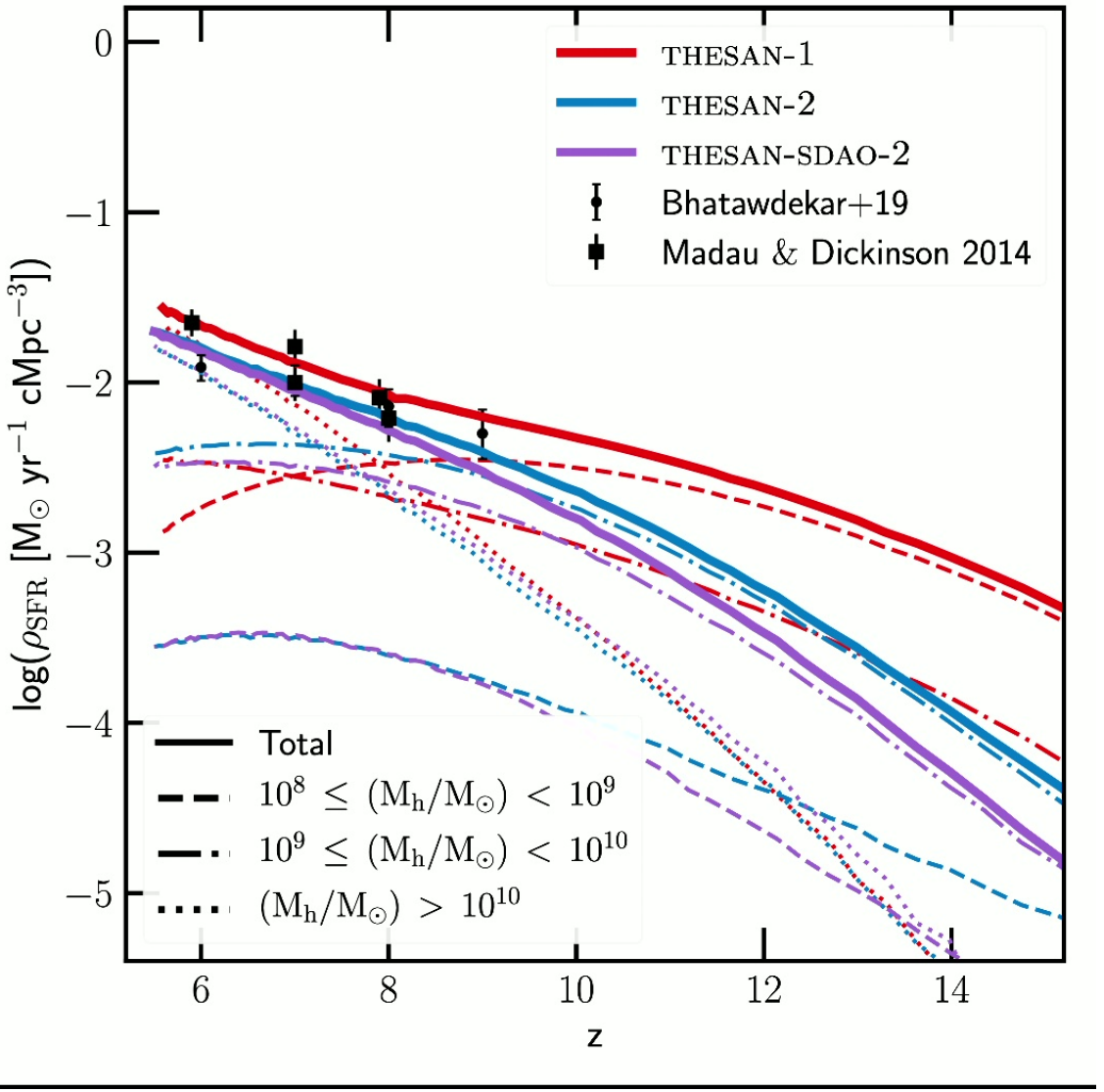
Kannan+22



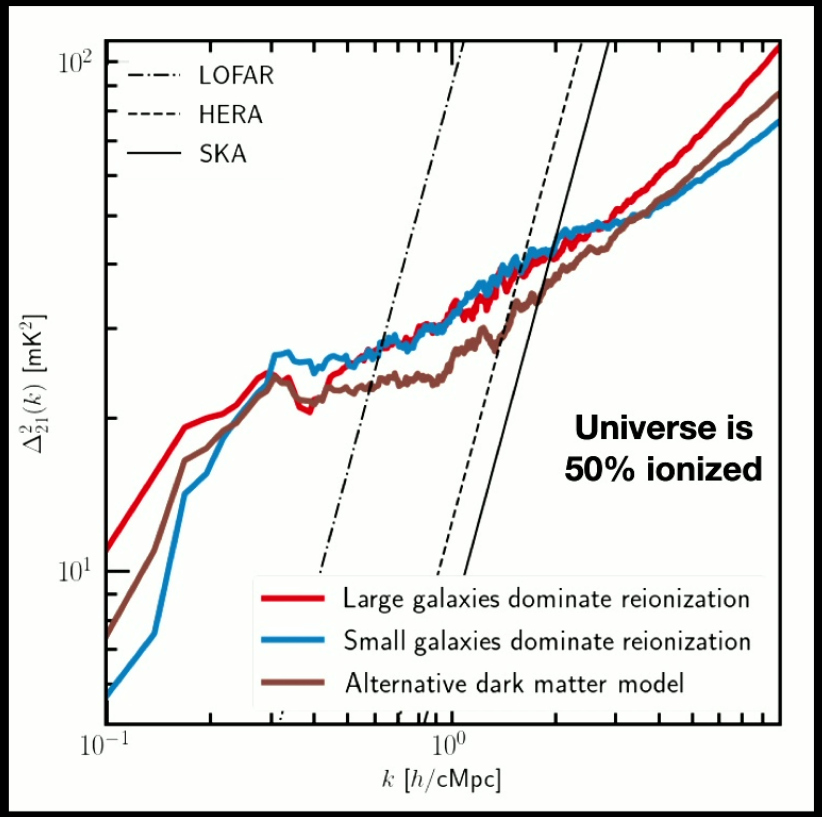
AltDM models and SFRD

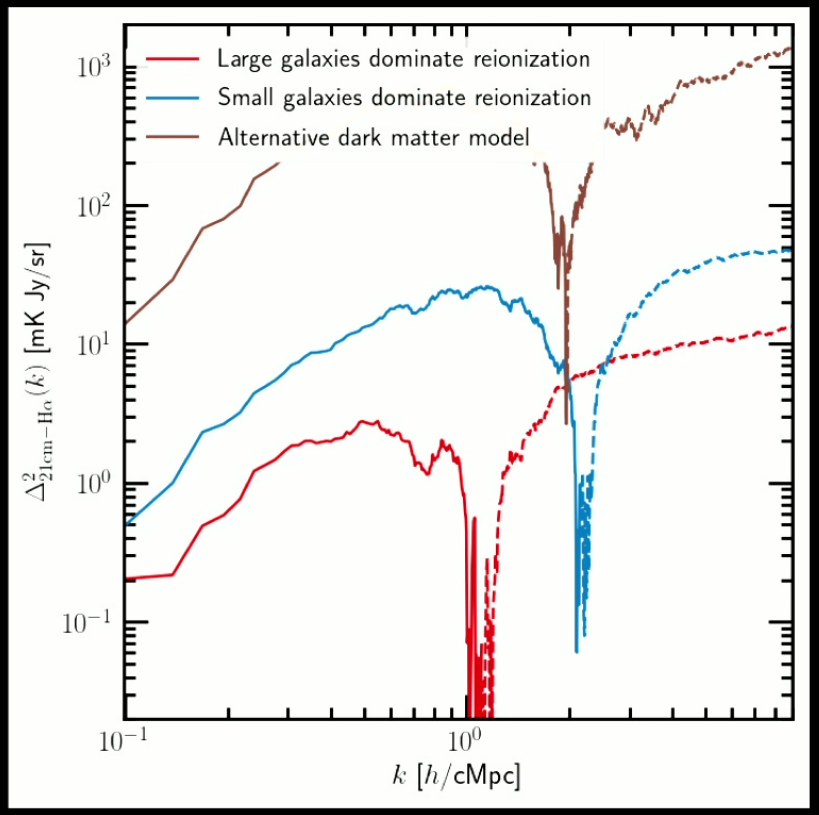
- sDAO models have lower star formation at higher redshift
- Due to delayed low-mass structure formation
- However, star formation catches up at later times

Kannan+22



Can 21cm and LIM differentiate between different DM models?



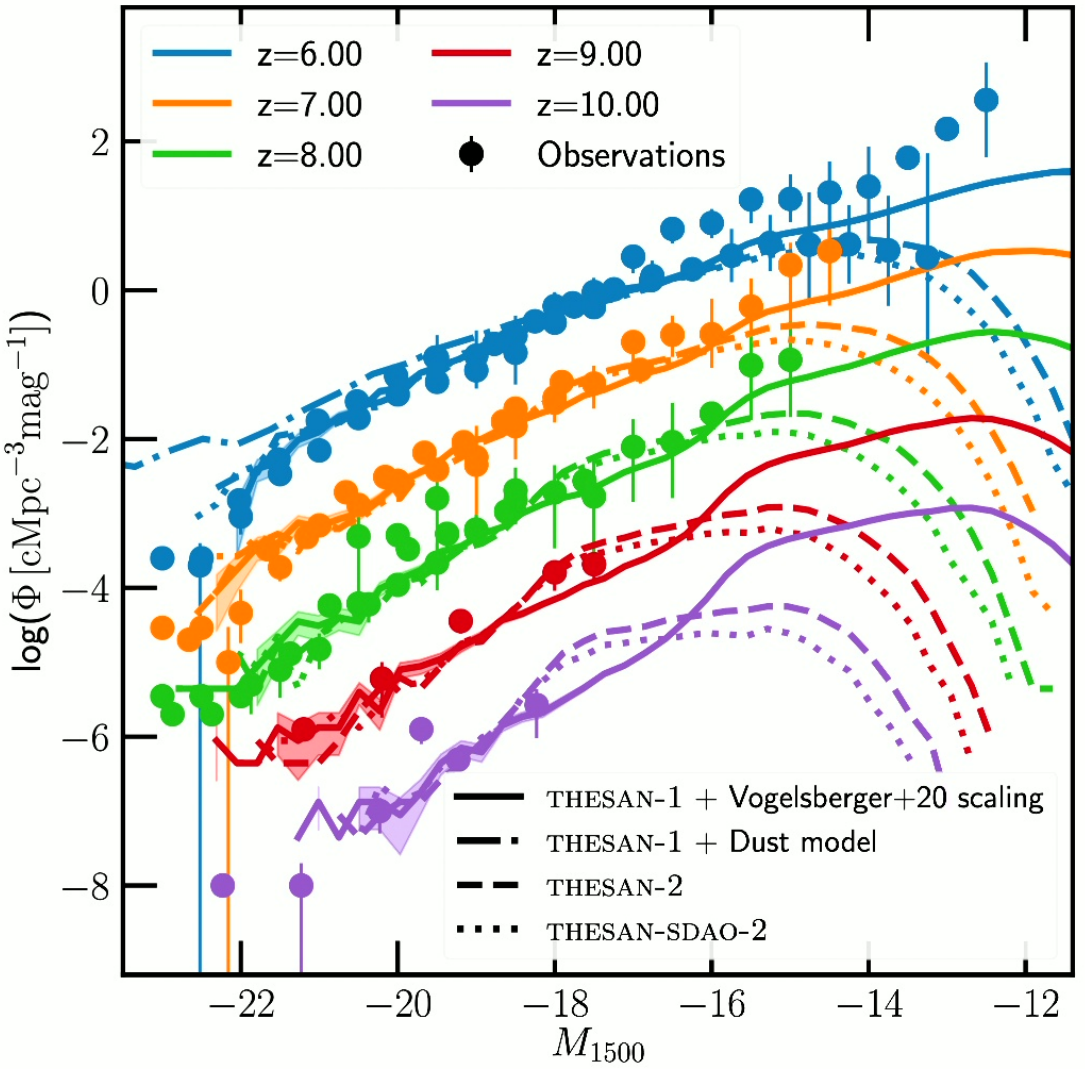


- Signature of altDM degenerate with baryonic physics

Kannan+22a,b

Impact of AltDM models -

- sDAO reduces the abundance of faint galaxies
- However, the reduction in the UVLF due to resolution is much larger than the cutoff due to altDM
- Need much higher resolutions to gauge this impact

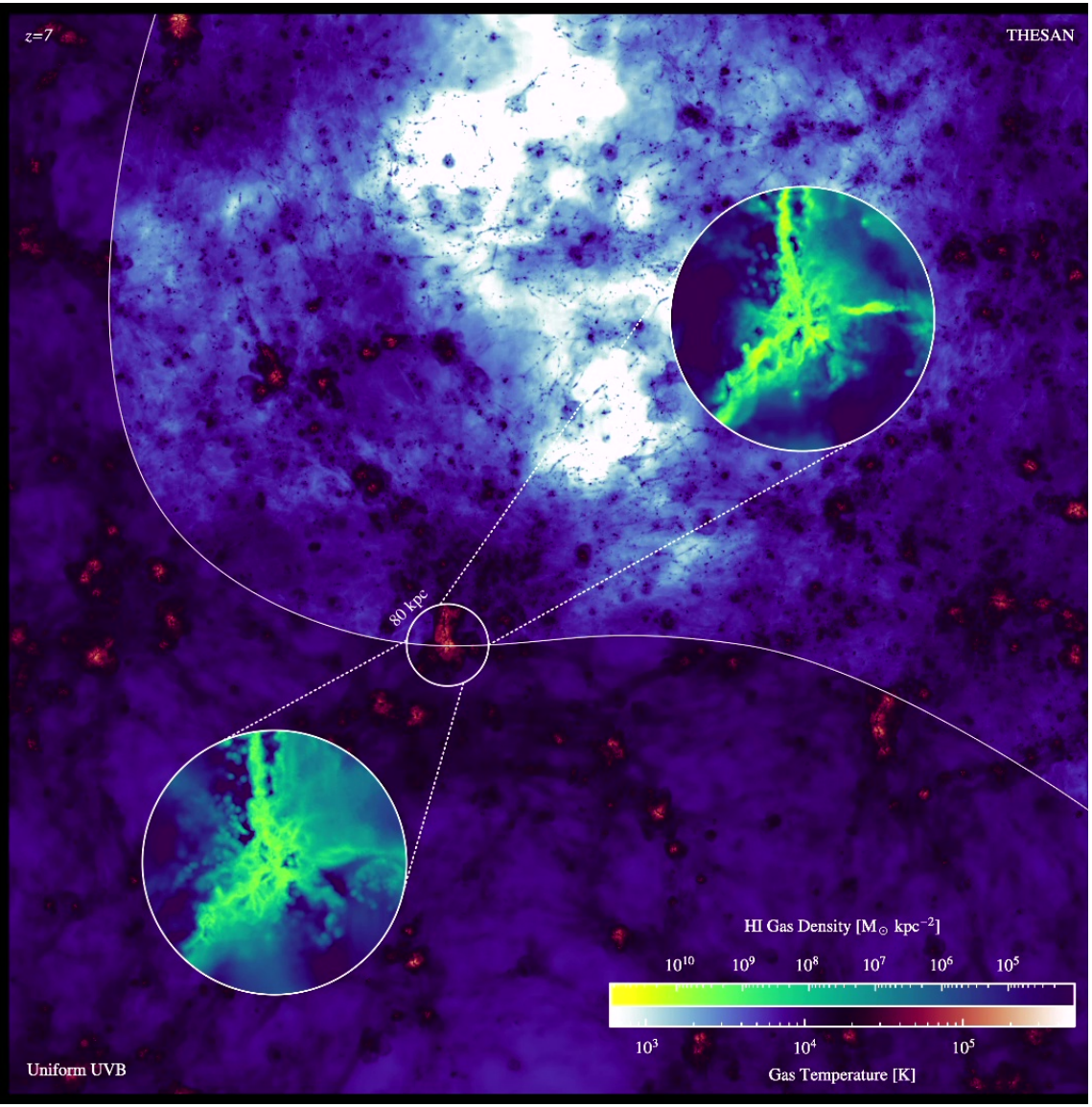


Kannan+22

THESAN-HR - high resolution galaxy formation + reionization simulations

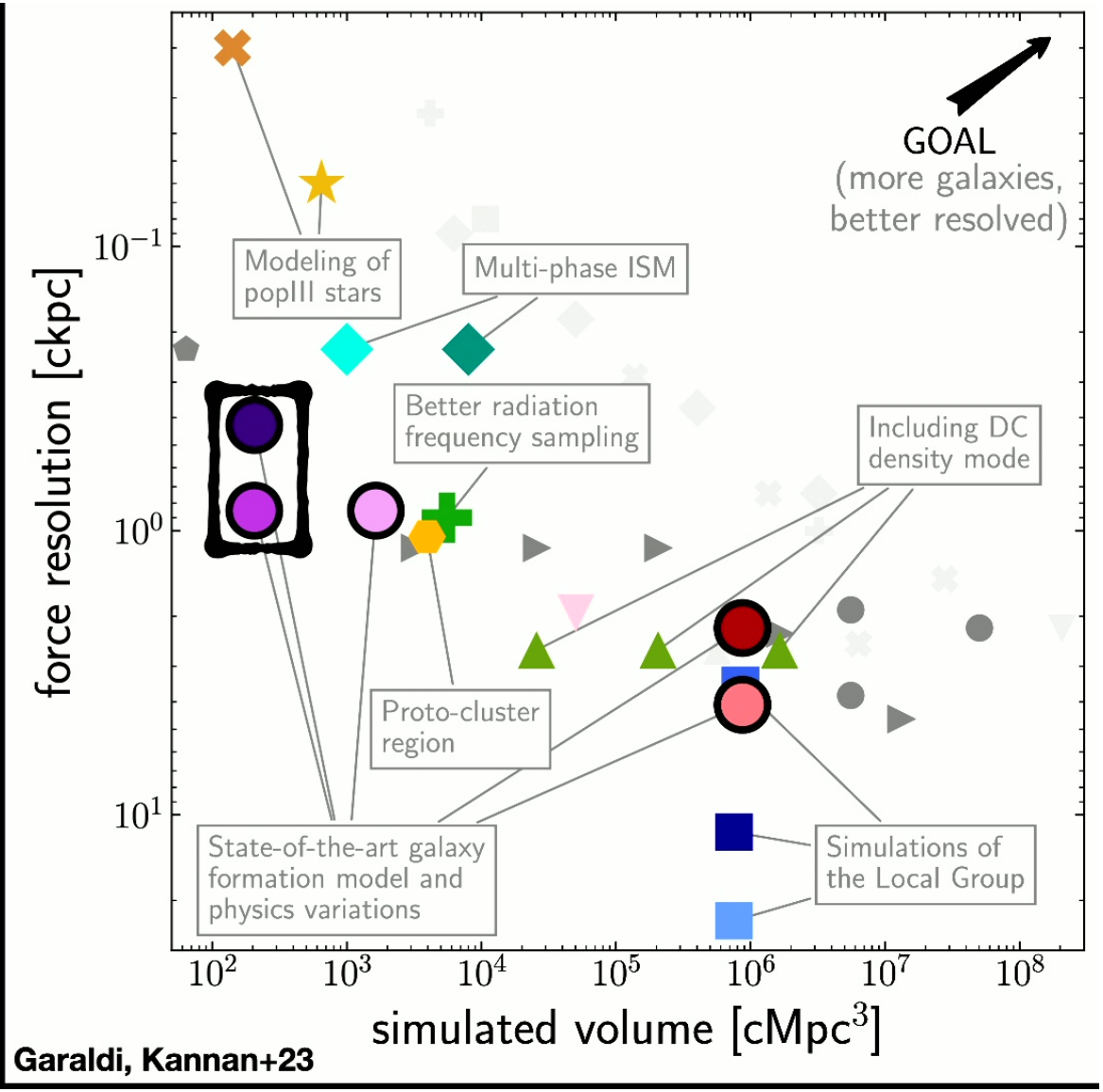
- Focused on impact of reionization and altDM models on early galaxy formation

Borrow, Kannan+23, Shen,..,Kannan+24



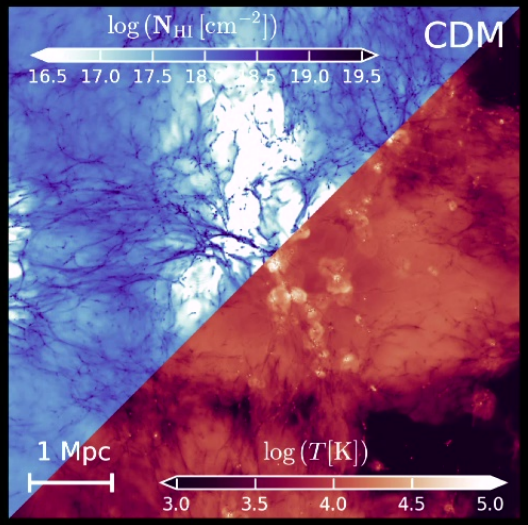
The THESAN-HR Project

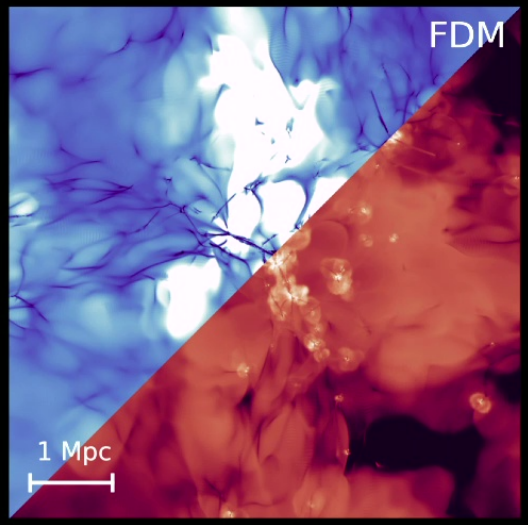
- Small volume simulations (6 cMpc)^3
- Mass resolutuon of ~ 10^4 Msun
- Spatial resolution of ~400 pc
- Includes Full-RT and multiple altDM models like Warm DM, sDAO and Fuzzy dark matter

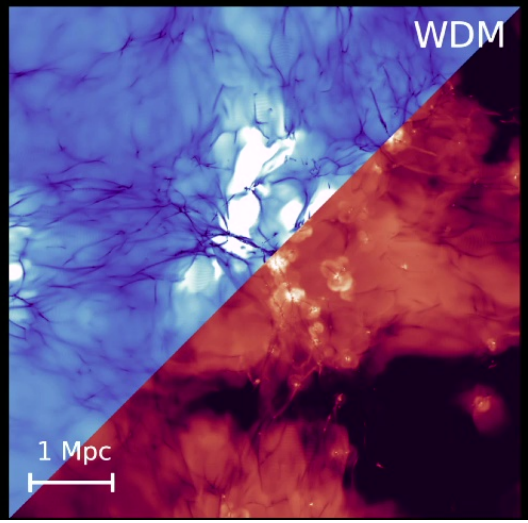


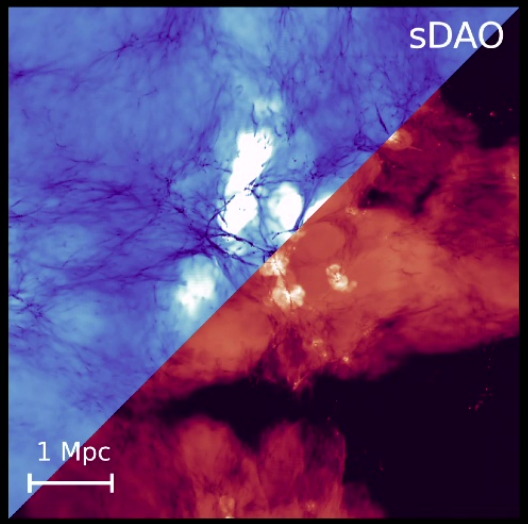
Garaldi, Kannan+23

Reionization + altDM models







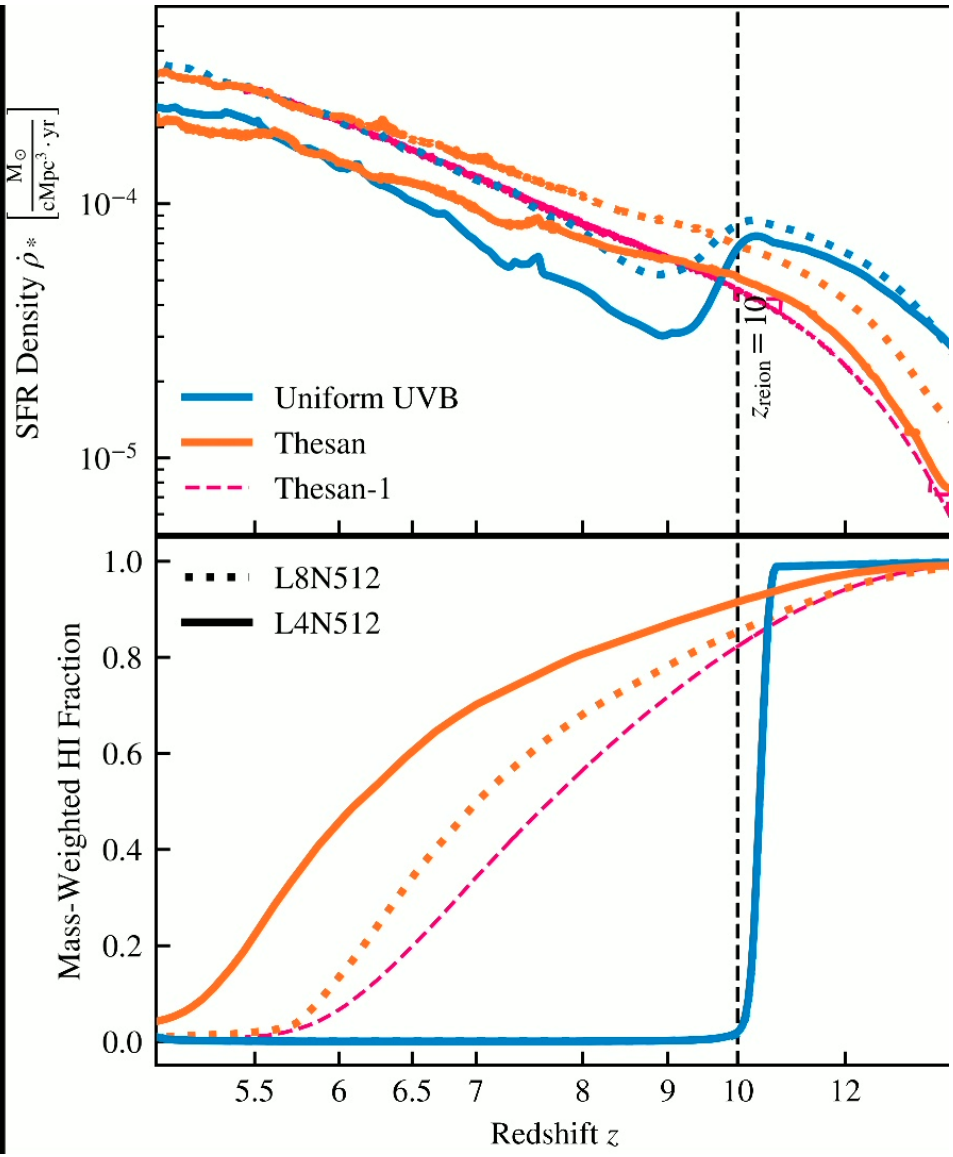


Shen+24 (incl. Kannan)

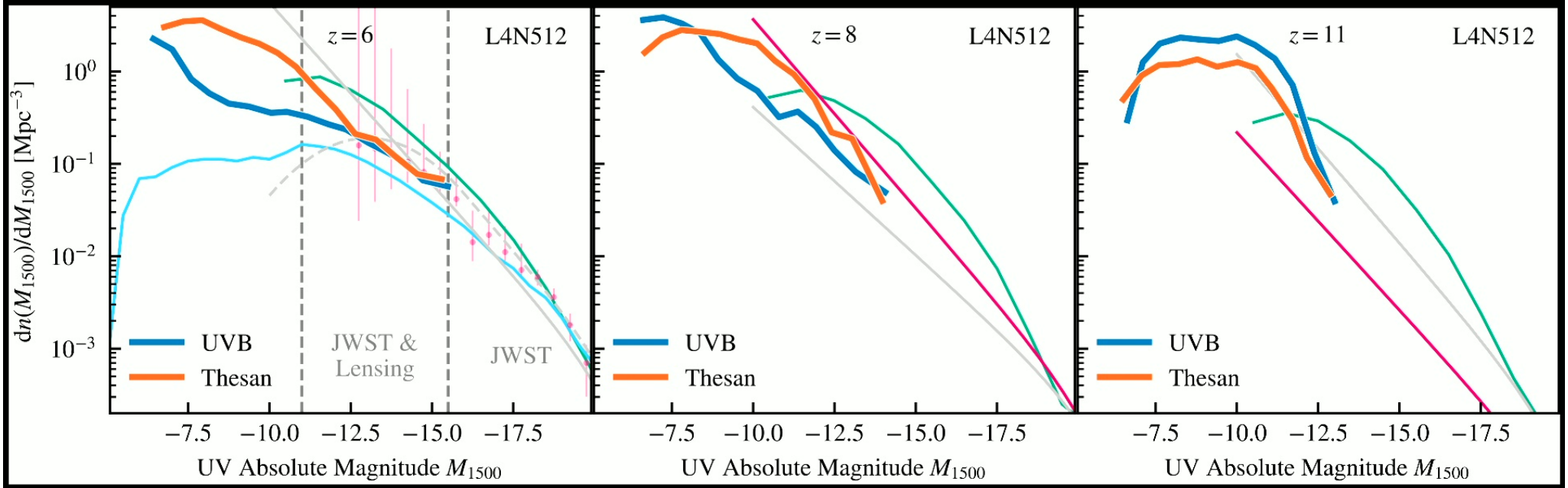
The need for accurate radiation fields

- The galaxies that are impacted in altDM models are also the most susceptible to external ionizing radiation fields
- The uniform UVB assumption is not accurate
- The radiation field seen by the galaxies is a function of their star formation rate and the overdensity it resides in
- Spatially constant UVB artificially reduces star formation rates in low-mass galaxies
- Topology of reionization matters!!!!

Borrow, Kannan+23



The need for accurate radiation fields



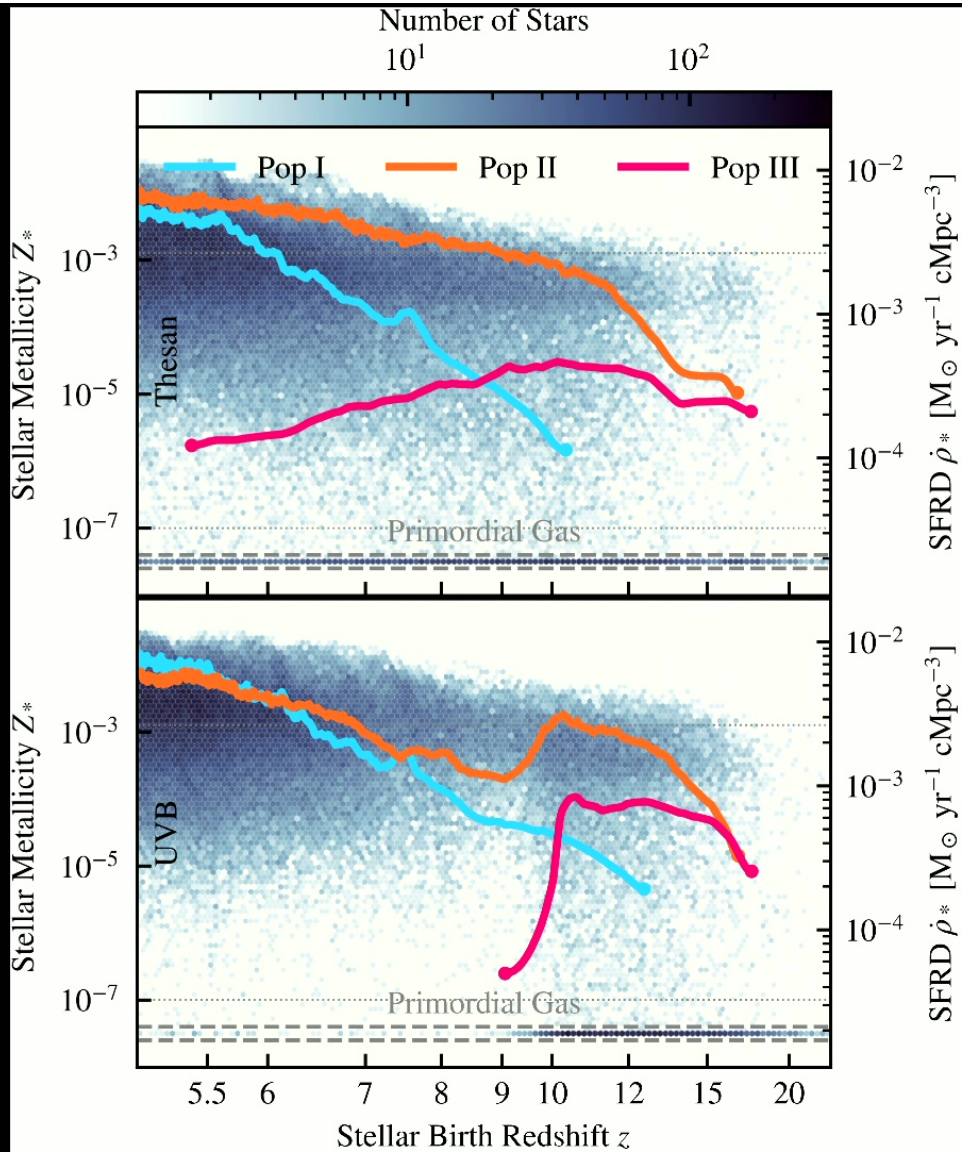
Borrow, Kannan+23

- The radiation fields modulate the UVLF, especially at the low luminosity end

Implications for Pop III star formation

- If you have a uniform UVB, it photo heats the gas in all low mass (low metallicity) galaxies, ending their star formation
- While realistic reionization simulations allow these low-mass galaxies to persist and they continue to form low metallicity stars deep into the reionization epoch

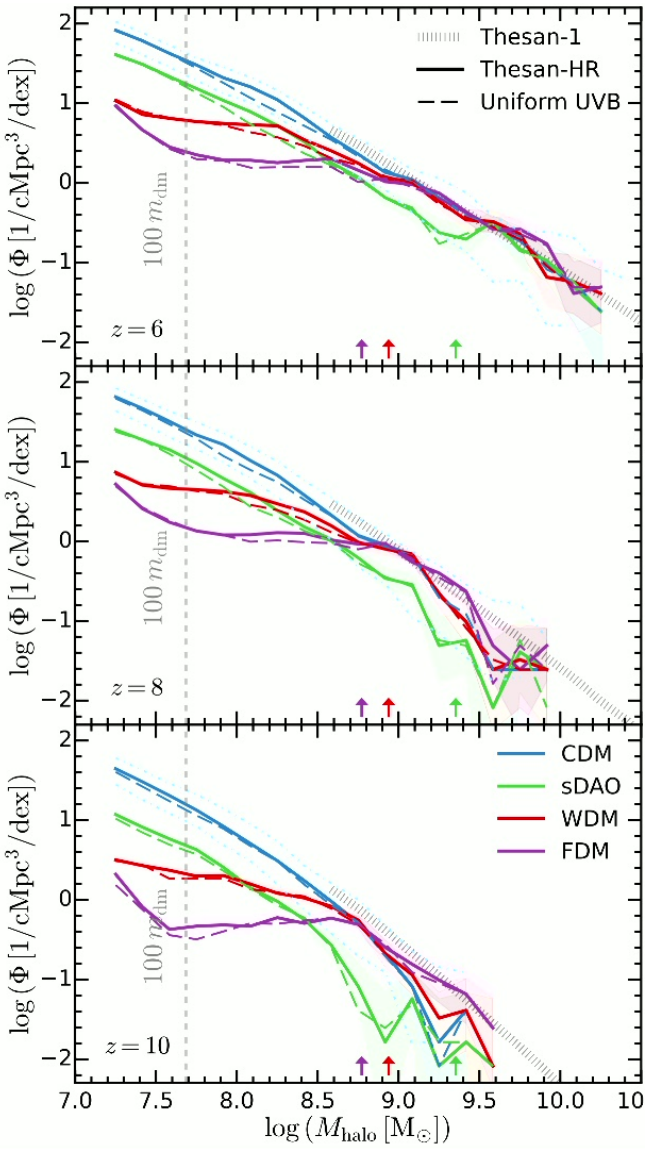
Borrow, Kannan+23



Galaxy formation in altDM models

- Halo mass functions of altDM models show a suppression below the half-power mass
- The exact shape of the mass function is dependent on the shape of the transfer function

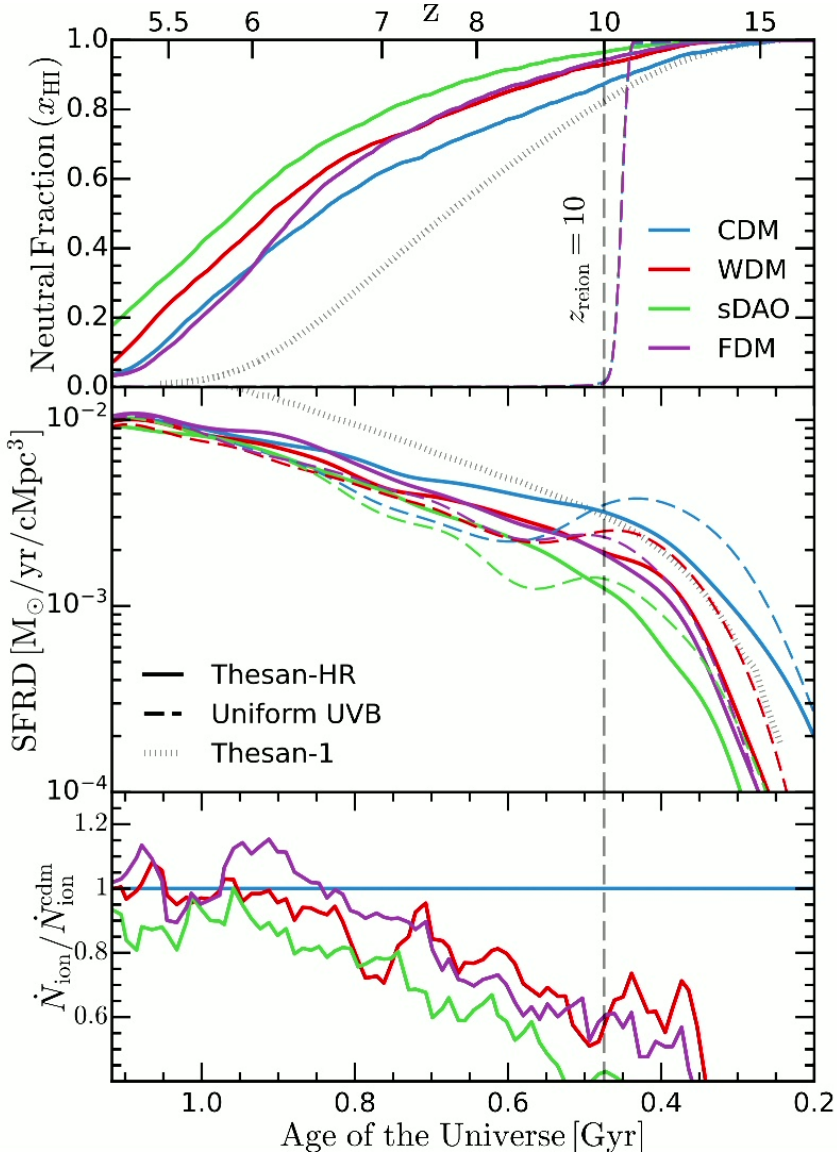
Shen+24 (incl. Kannan)



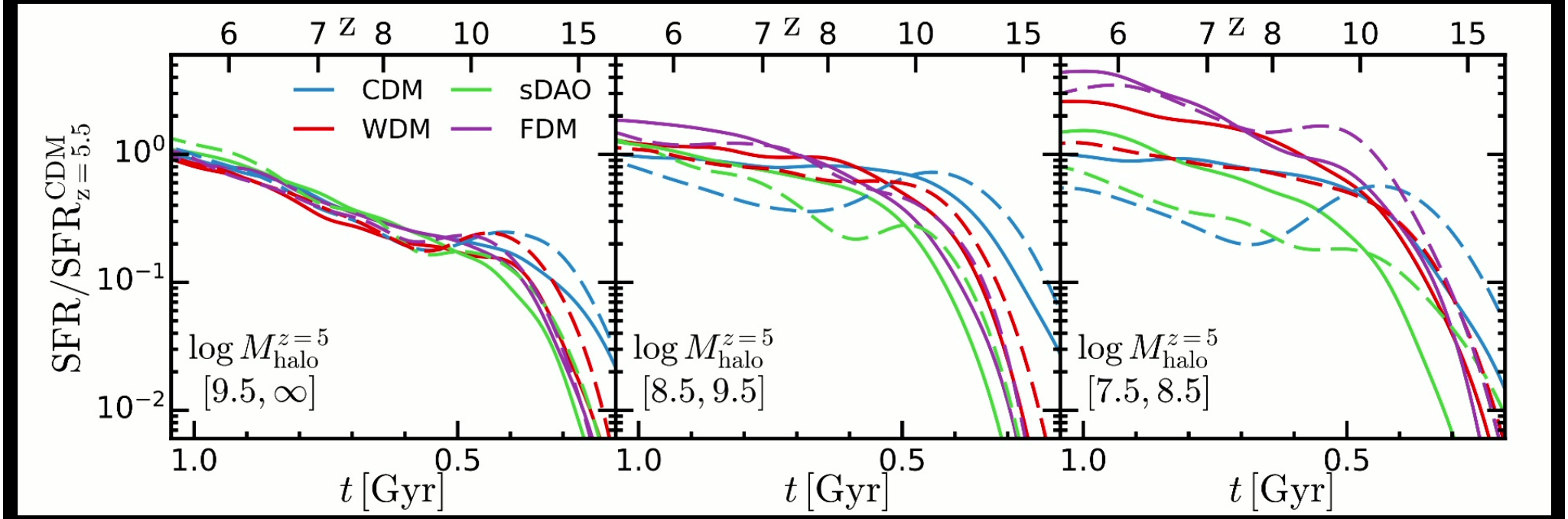
Reionization in altDM models

- Only minor changes to the reionization history
- The SFR is initially delayed in altDM models due to suppression of structure formation at small scales
- However, the star formation rates catch at later times
- For example, a late starburst in the FDM model increases ionizing output and accelerates reionization

Shen+24 (incl. Kannan)



Star formation in altDM models



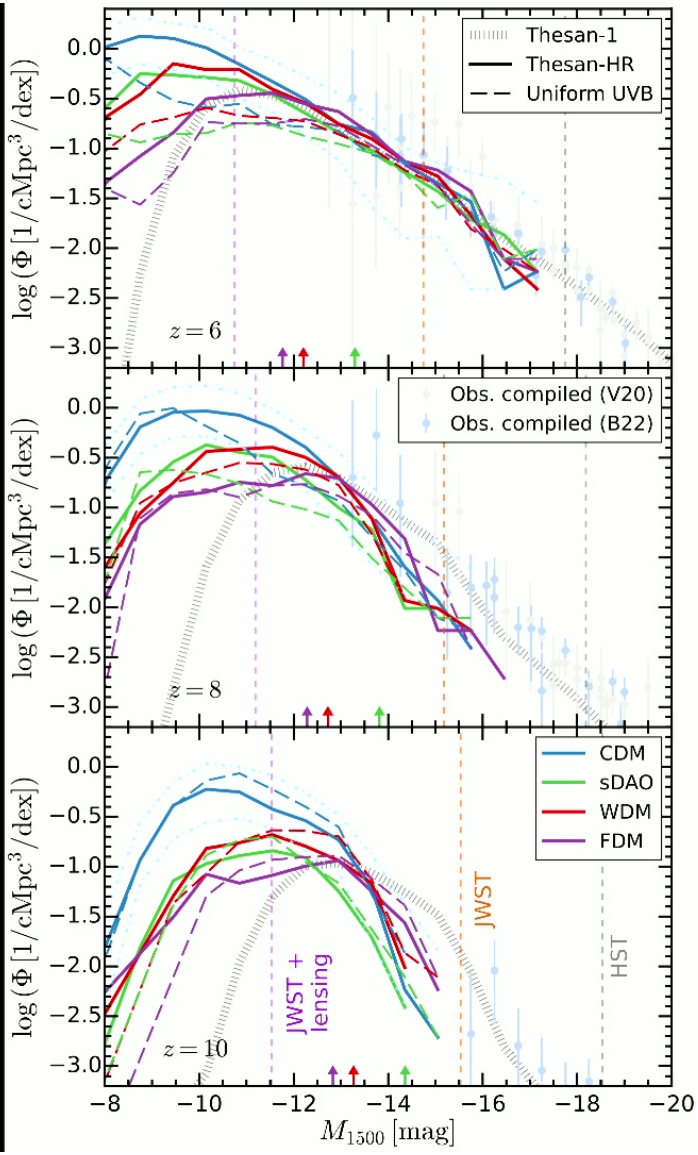
- The SFR is initially delayed in altDM models due to suppression of structure formation at small scales (log (Mhalo) = [7.5-8.5])]
- At later times there is an increase in star formation, especially in low-mass haloes

Shen+24 (incl. Kannan)

UV luminosity functions

- The UV luminosity function is substantially suppressed at z=10 in altDM models
- But the late burst in star formation allows the altDM models to catch up by z=6
- JWST measurement of lense-magnified systems can potentially detect the impact of altDM models

Shen+24 (incl. Kannan)



Conclusions

- **Galaxy abundance**: altDM models suppress small-scale power (below half power scale), which can be seen in the stellar and UV luminosity functions. JWST+lensing is a promising avenue to detect signatures of altDM
- **Complexities from reionization modelling**: Important astrophysical uncertainty is the topology and timing of reionization. If a uniform UVB is used (like almost all other simulations), photoheating can mimic suppression from altDM.
- **Non-linear effects**: altDM models produce positive feedback at late times, which manifests in higher UVLFs and sSFR.
- **Ways to disentangle DM and baryonic physics**: Feedback from stars and the radiation field can also suppress star formation in halos, which can mimic altDM. However, increased star formation at late times seems to be a feature of DM physics

Future Work

- Investigate baryonic physics in more controlled settings — higher resolution and better galaxy physics (multi-phase ISM, Sne feedback and radiation feedback)
- This will help us understand baryonic physics better - which will allow us to place better constraints on altDM models
- Larger - more representative volumes to predict altDM's impact on reionization observables like 21cm and LIM