Cosmic mysteries and the hydrogen 21-cm line & Cosmic Structures in FDM

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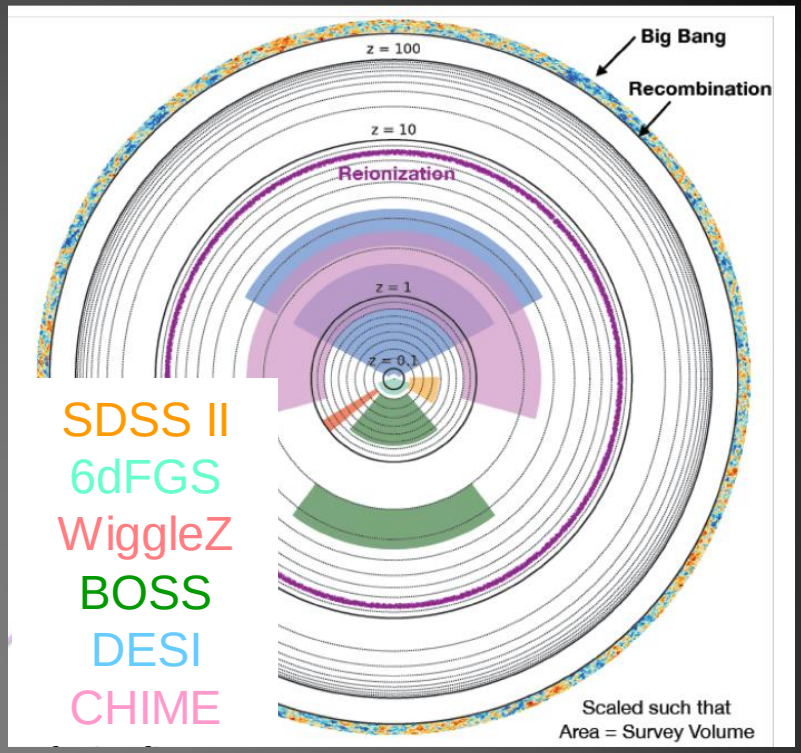
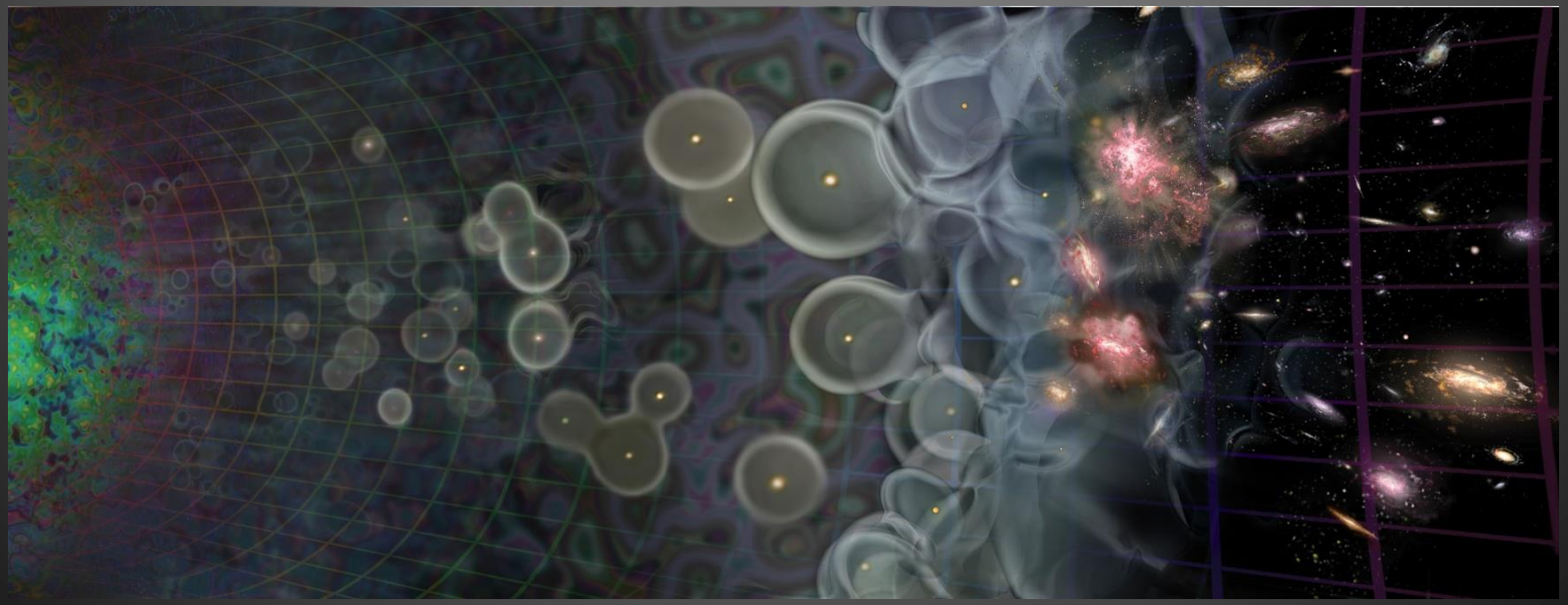
The Observed Universe

Existing surveys:
Last scattering surface CMB (z=1000)
Local Universe (z < 3)

Handful of bright galaxies out to z ~ 13 (JWST, HST & ALMA)
Bright quasars out to z ~ 7.5



Credit: Seth Siegel



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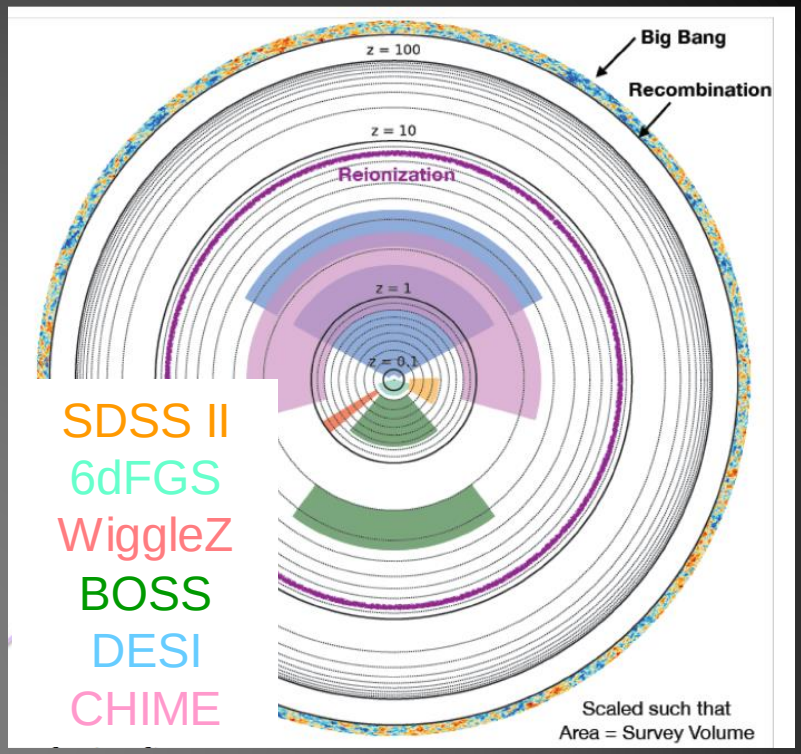

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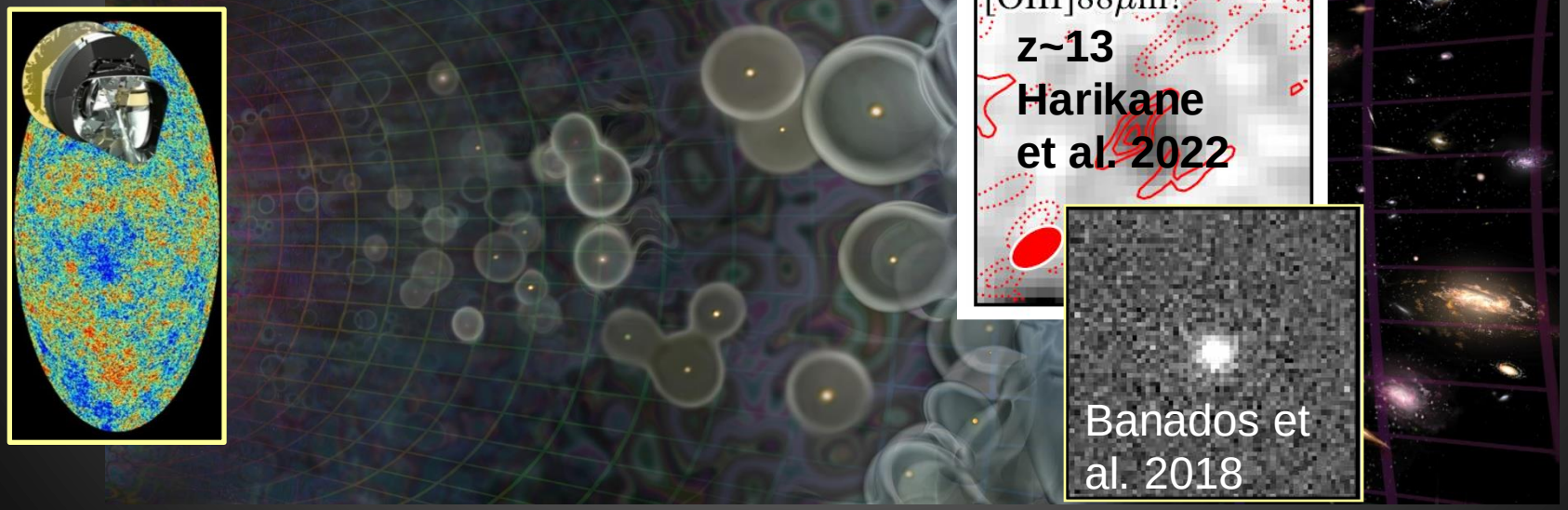
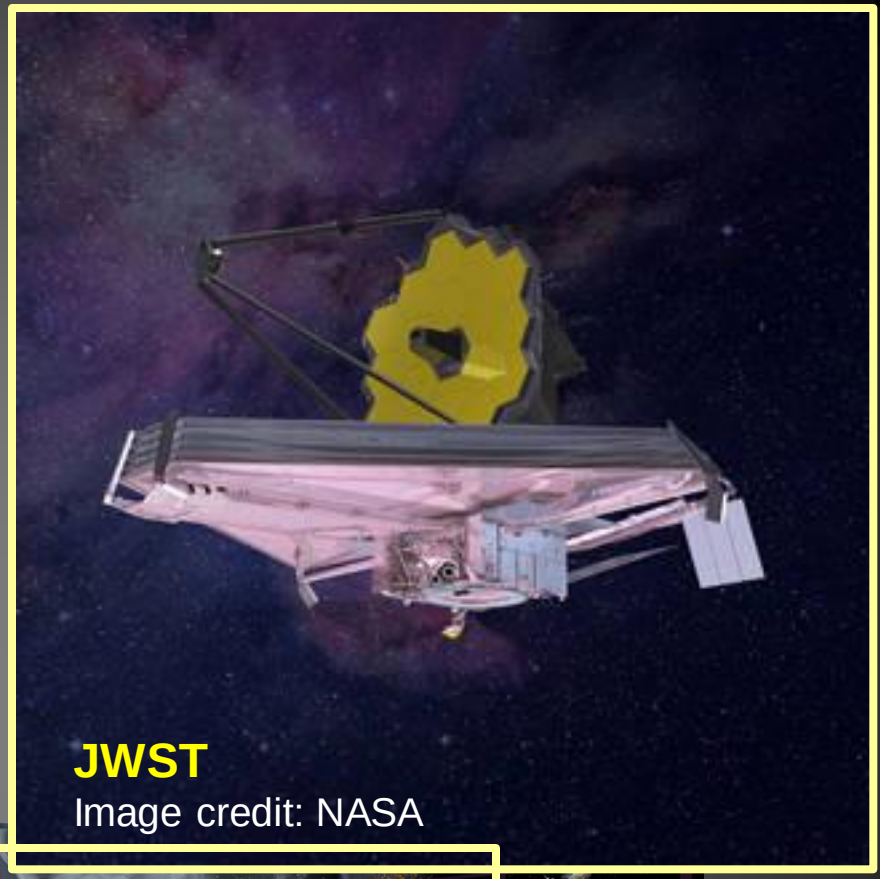
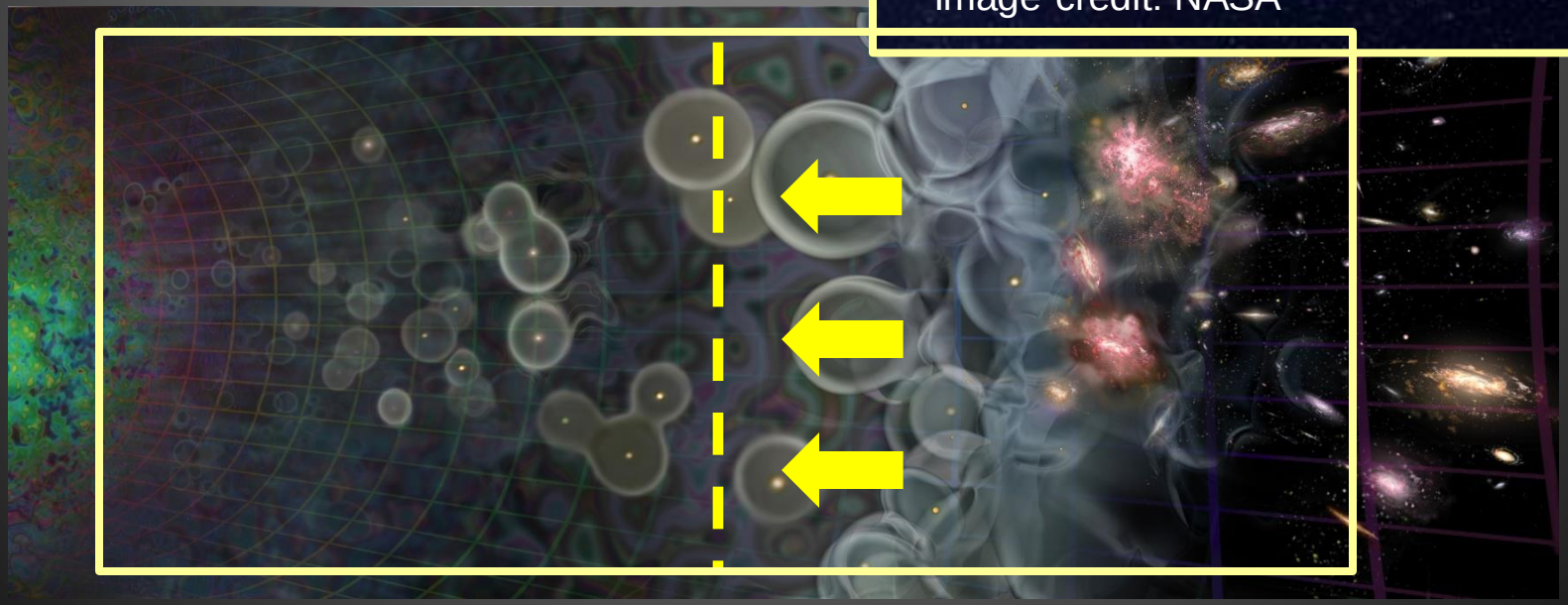


The Unobserved Universe

JWST will push the frontier and explore bright galaxies out to z~20, in the Epoch of Reionization (EoR)!

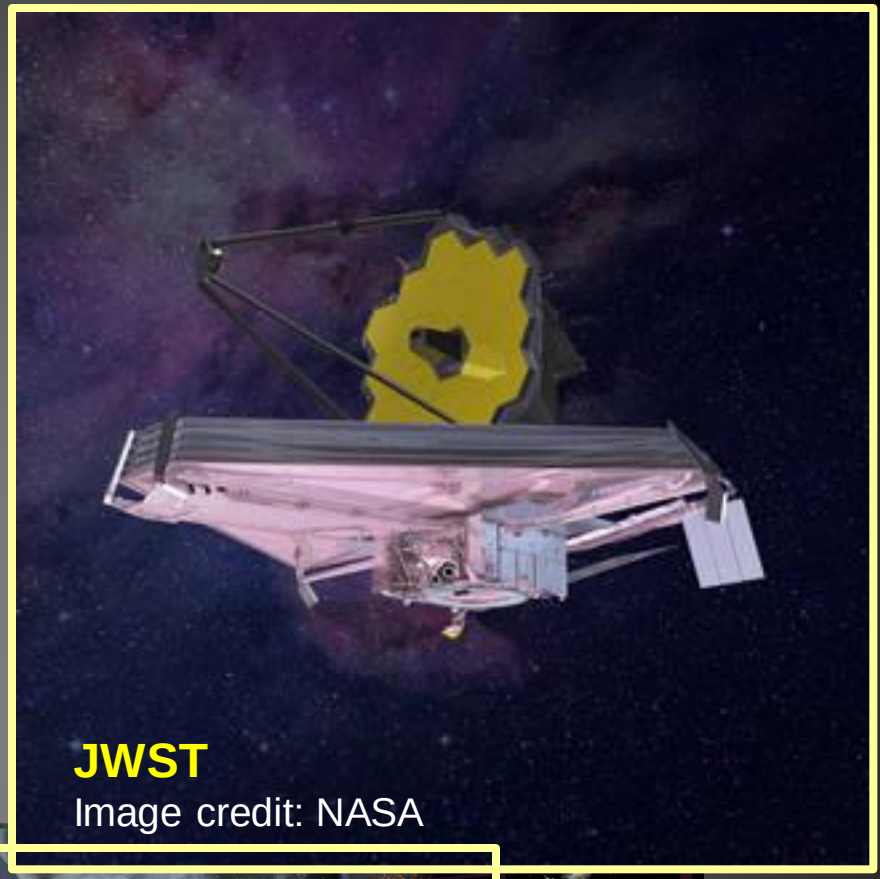


JWST
Image credit: NASA

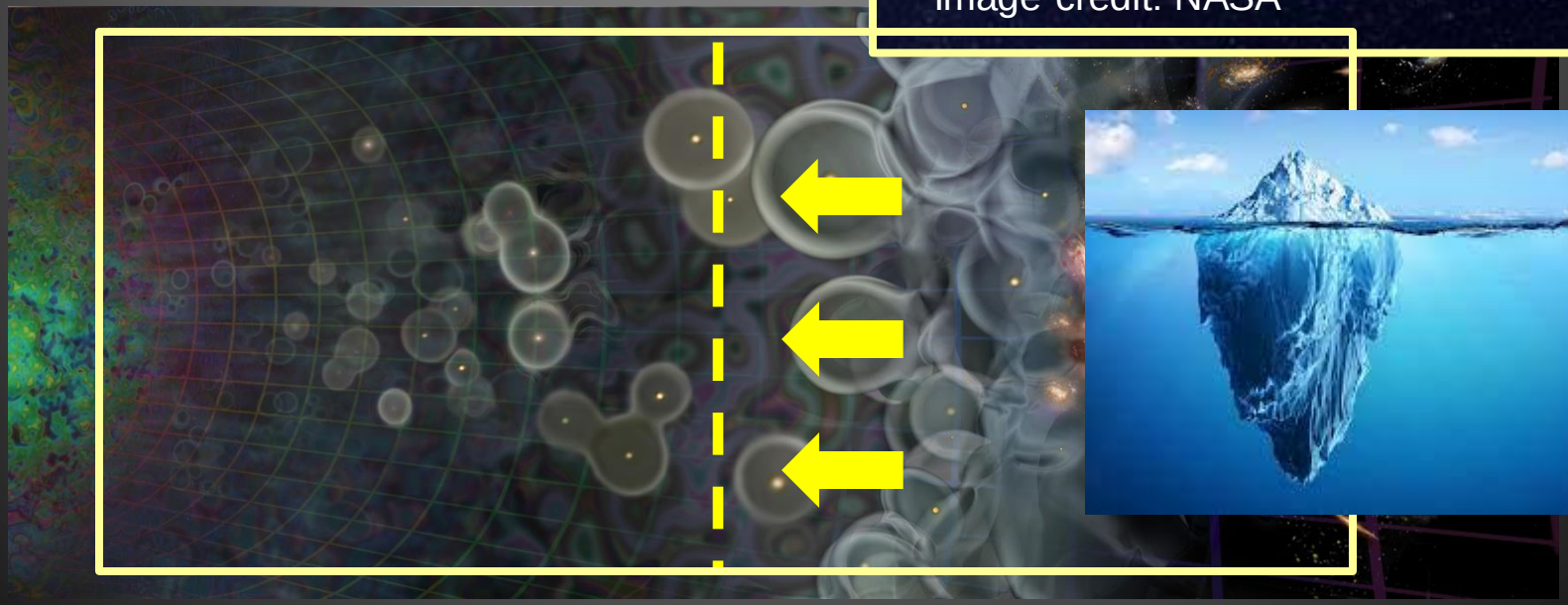


JWST will also push the frontier and explore bright galaxies out to z~20, in the Epoch of Reionization (EoR).

21-cm is a probe of the typical population.

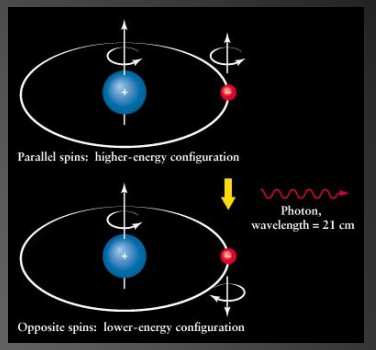


JWST
Image credit: NASA



21-cm Discovery Space: Dark Ages, Cosmic Dawn and the EoR

Hyperfine transition of hydrogen atom



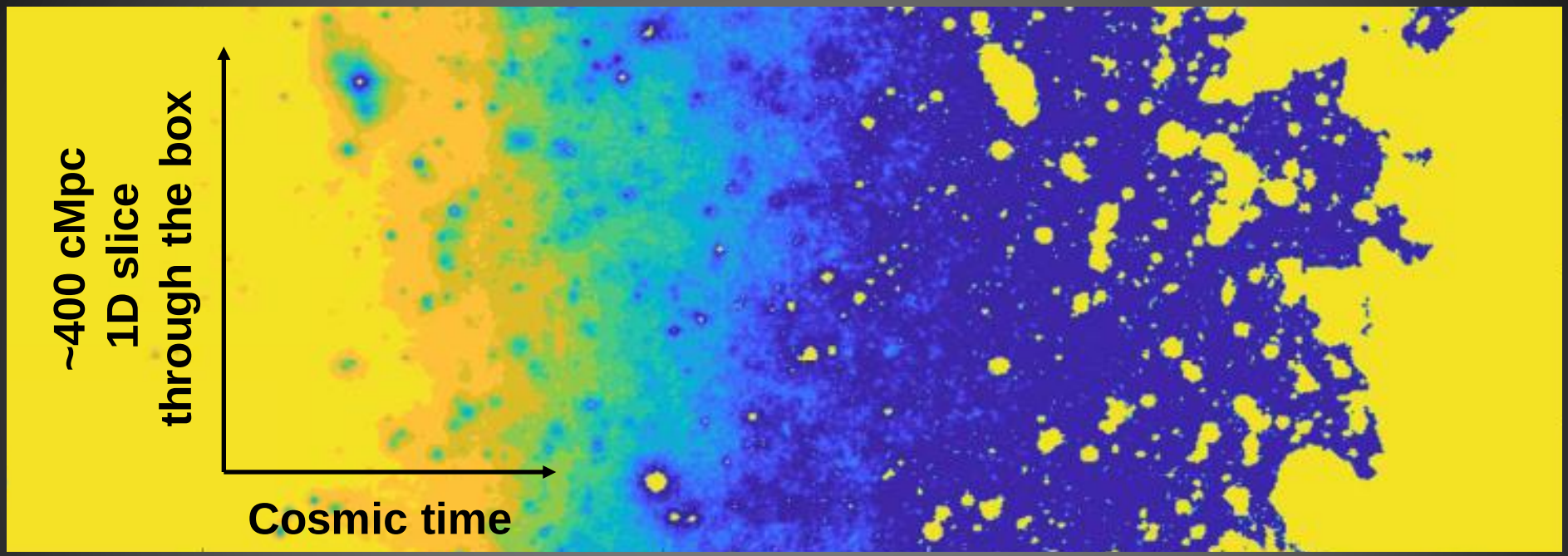
- Signal of hydrogen in the intergalactic medium
- 3D probe of astrophysics and cosmology between recombination and reionzation (z~6-1000-> ~1-200 MHz)

Space or Moon

Accessible from Earth

Precision Modelling of the 21cm Signal

21-cm is rich in astrophysics and cosmology, tracer of dark matter physics



Dark Ages

Dark matter and cosmology

Cosmic Dawn

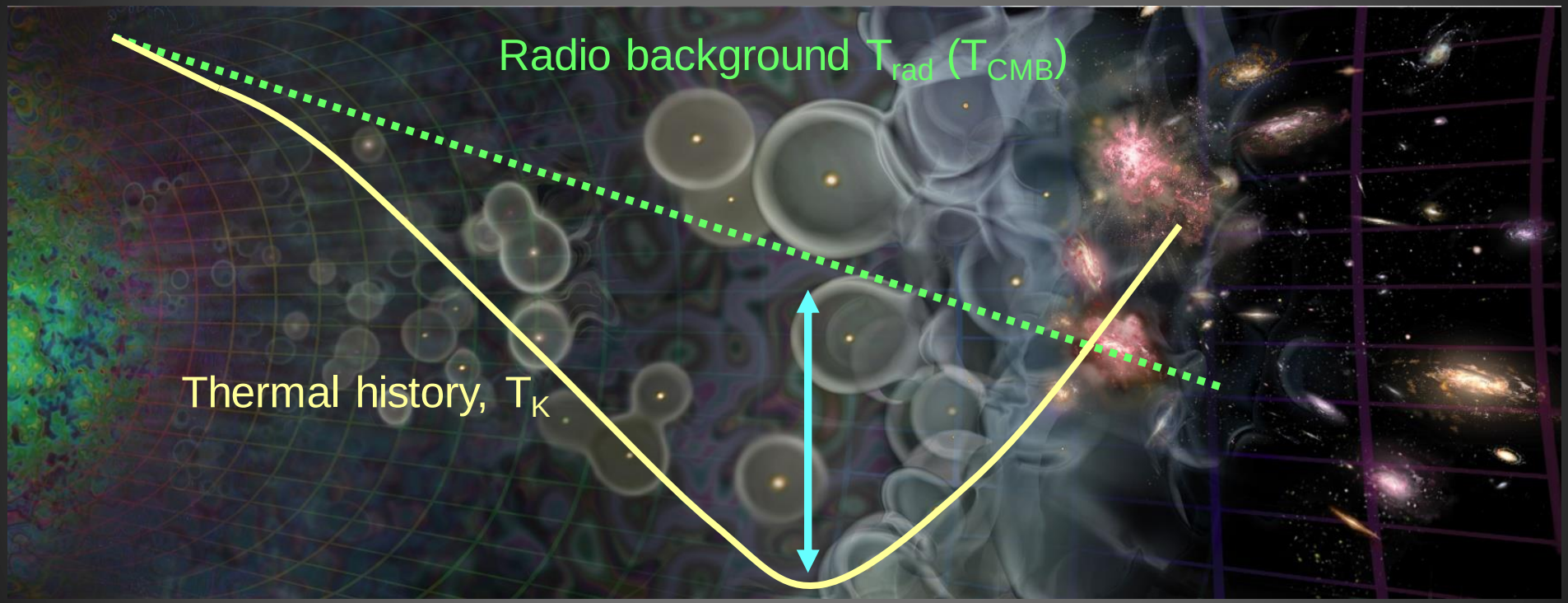
First stars and black holes

Epoch of Reionization

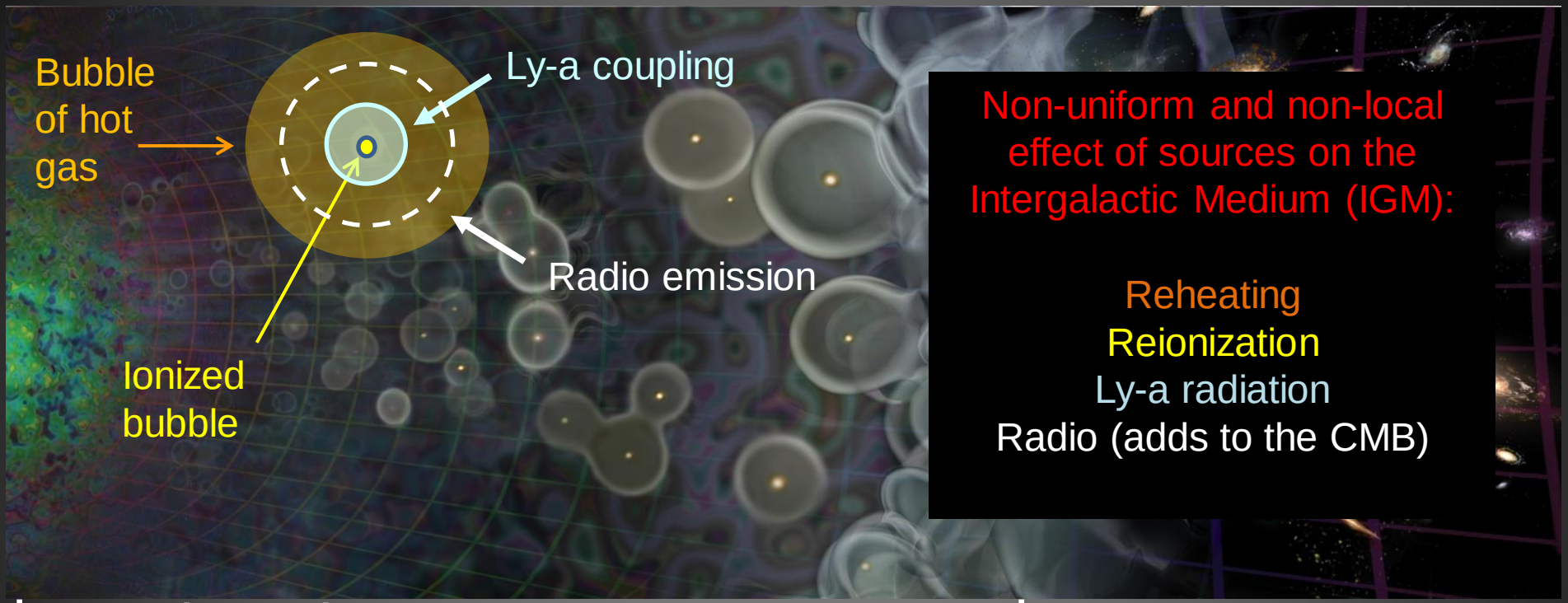
Massive galaxies and quasars

$$T_{21} \propto x_{HI}\left(1 - {}^{T_{rad}}/_{T_S(T_K, Lya)}\right)$$

The Absorption Trough



21-cm is Rich in Astrophysics and Cosmology
Tracer of Dark Matter Physics



Non-uniform and non-local effect of sources on the Intergalactic Medium (IGM):

Reheating
Reionization
Ly-a radiation
Radio (adds to the CMB)

Epoch of Reionization

Cosmic Dawn: First Stars and Galaxies

Dark Ages

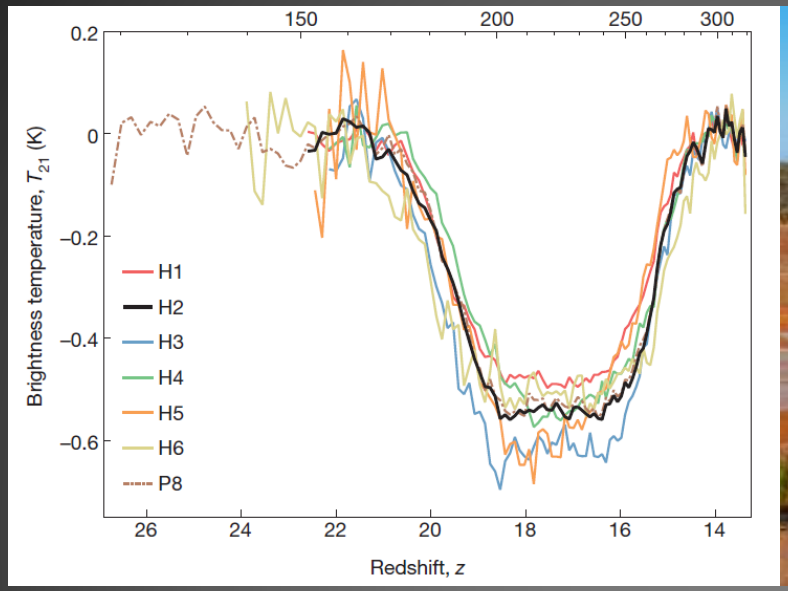
CMB

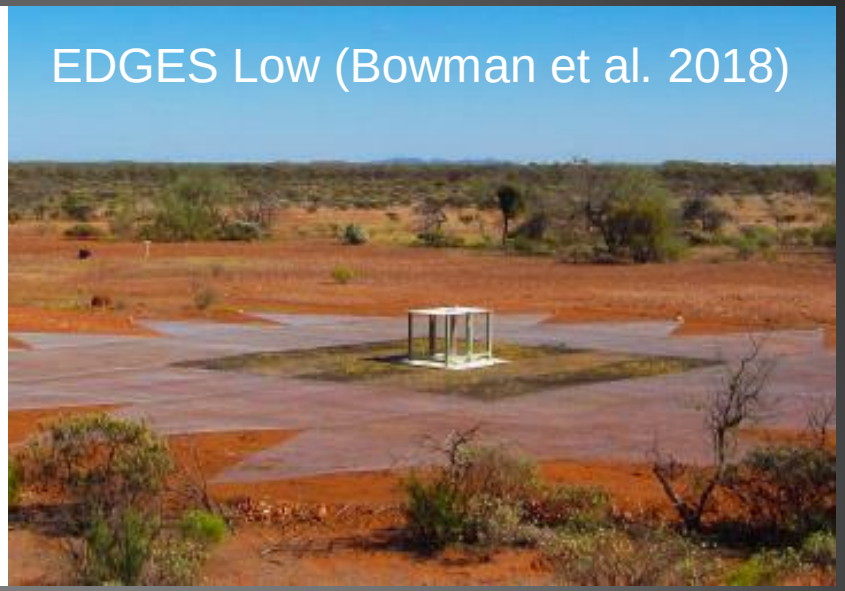
Ongoing Observational Effort

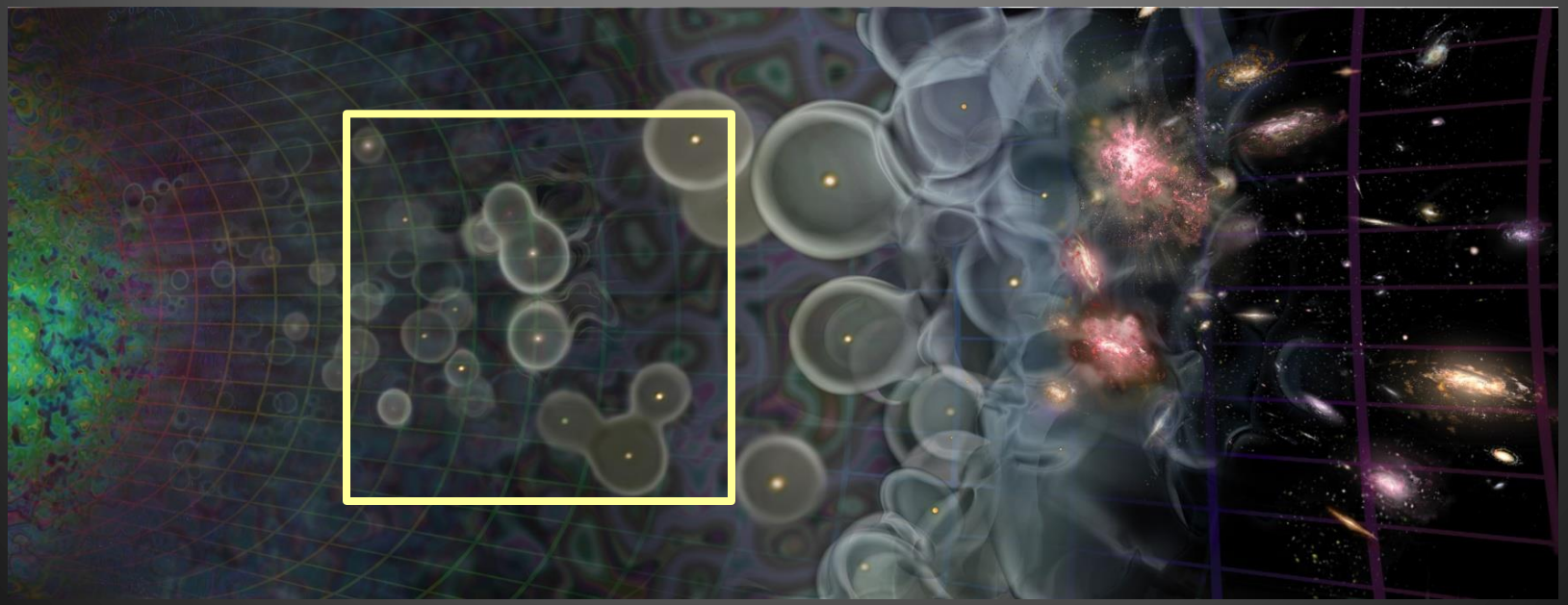
Global signal
and
power spectra
experiments

Koopmans et al. 2021

First Claimed Detection of the 21-cm from Cosmic Dawn Still a Mystery!







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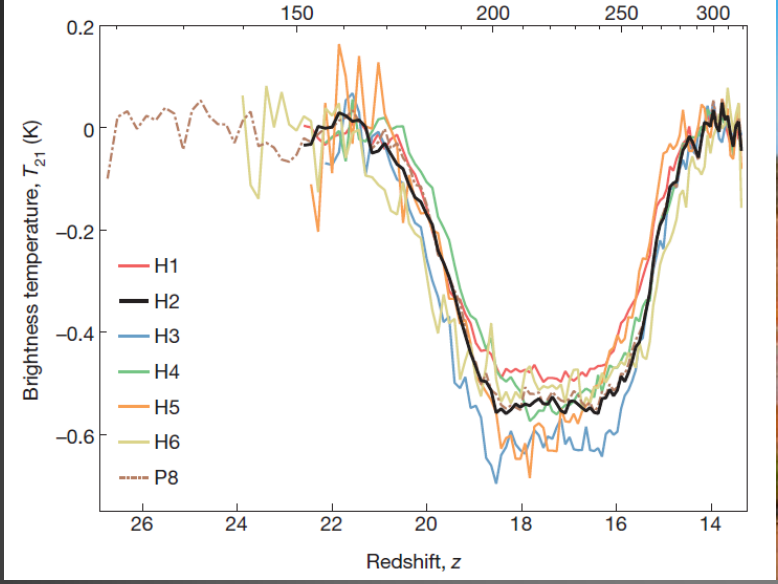
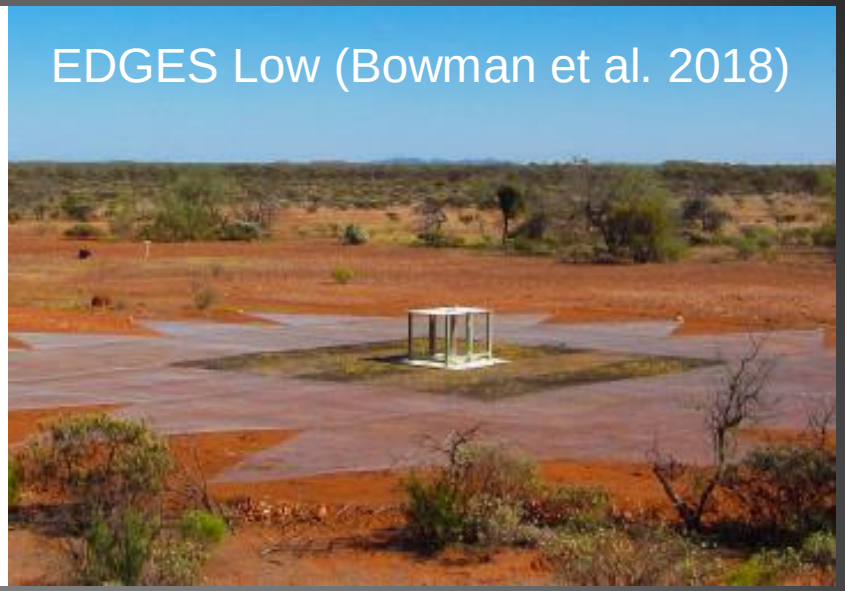
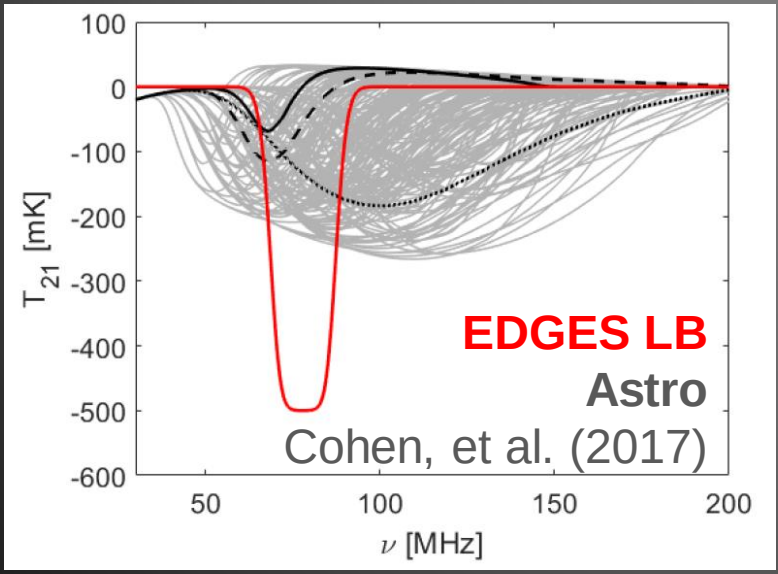






Inconsistent with standard astro

Proposed solutions:

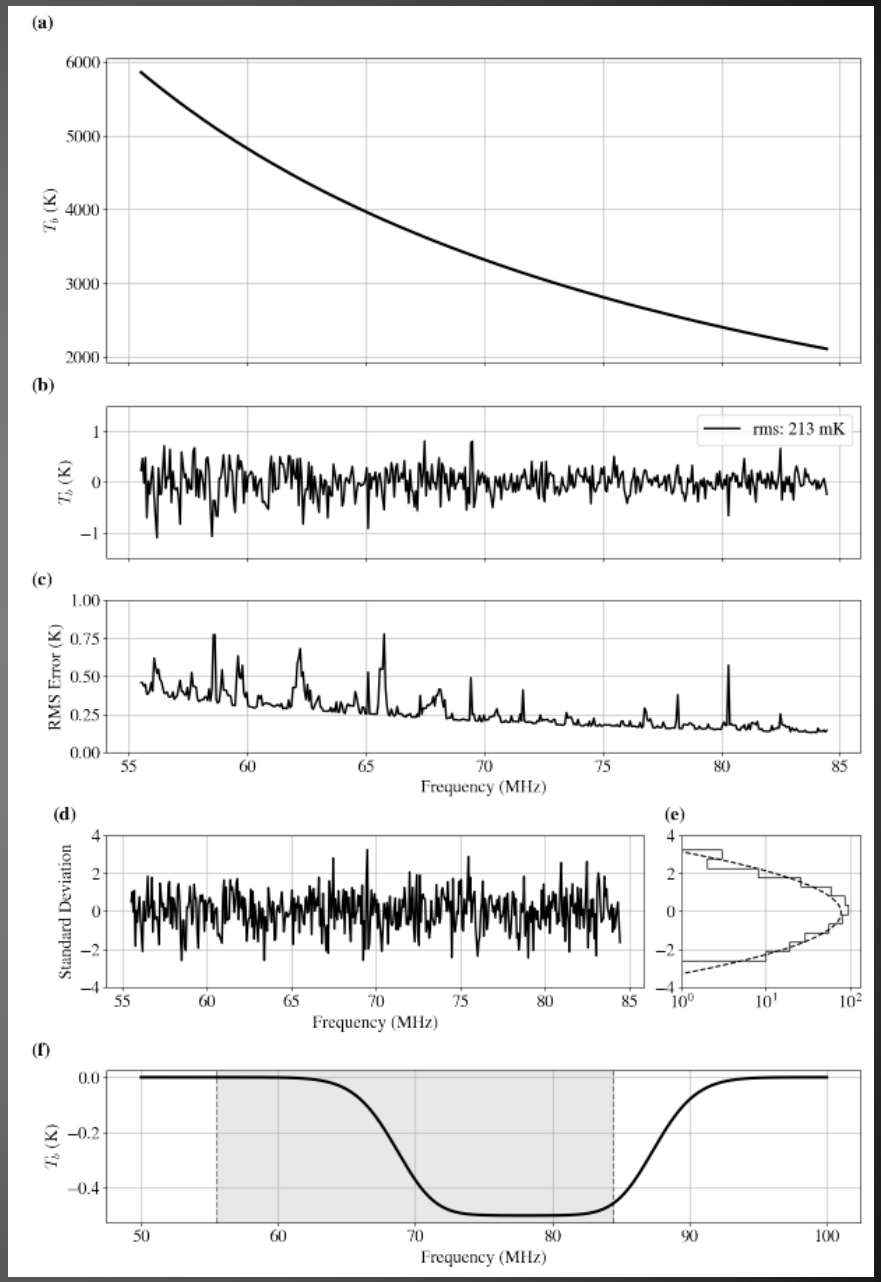
- dark matter interactions (fine-tuned)
- extra-radio background (extreme)

Verification Attempts

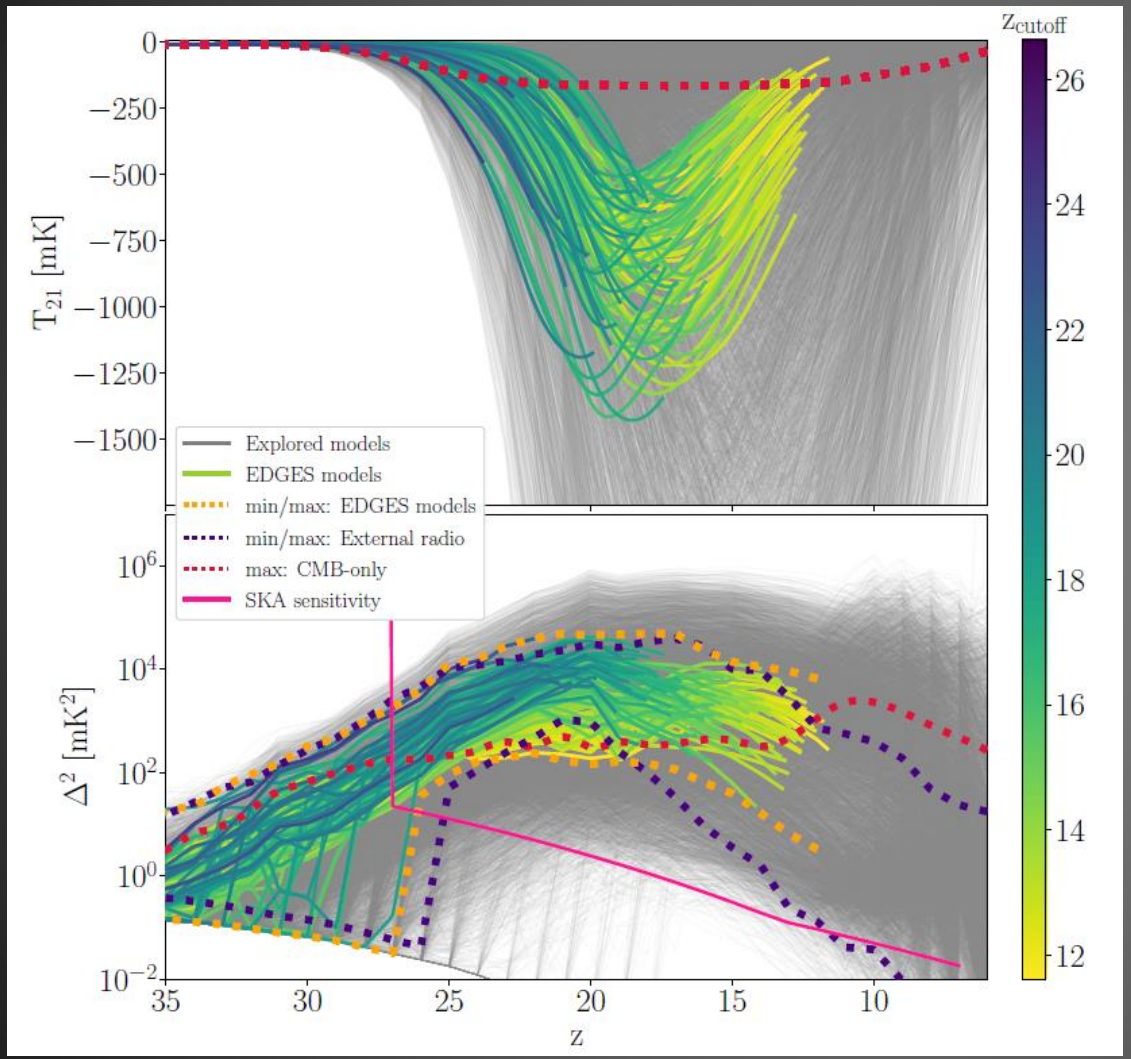
Global signal
and
power spectra
experiments

SARAS3 rejects EDGES-Low Profile at 95.3%

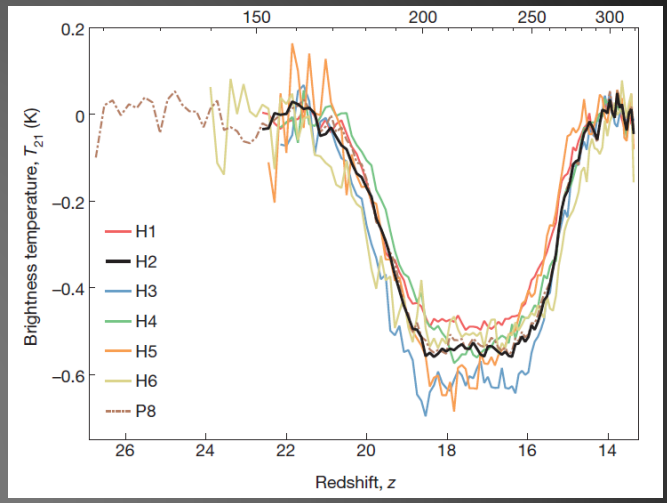
Singh et al. 2022



Theoretical Explanations: Extra Radio Background



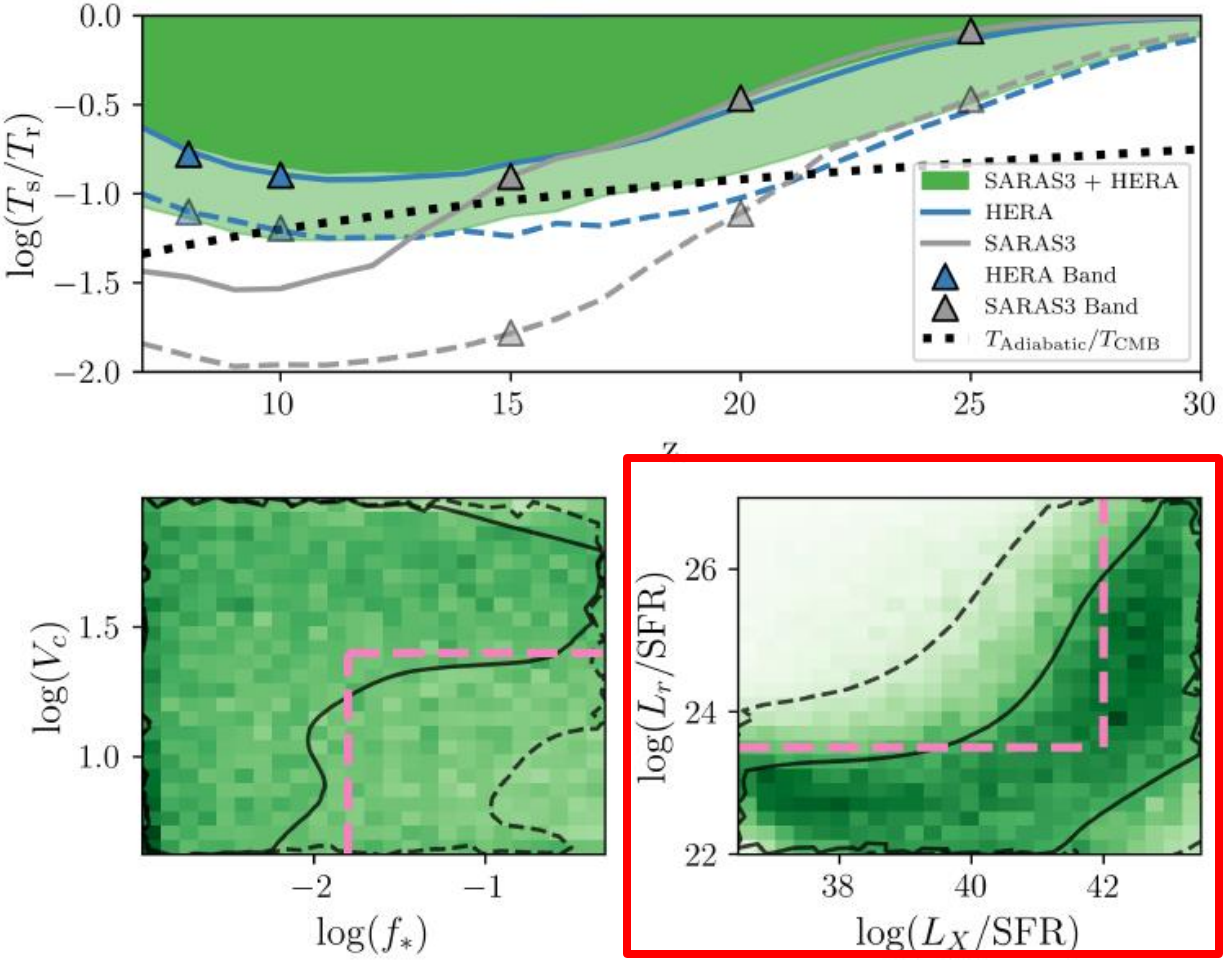
Reis, **Fialkov**, Barkana (2020)



Bowman, et al. (2018)

Testable prediction:
enhanced power spectrum

First Synergetic Constraints from a Global Signal Experiment and an Interferometer: SARAS3 + HERA

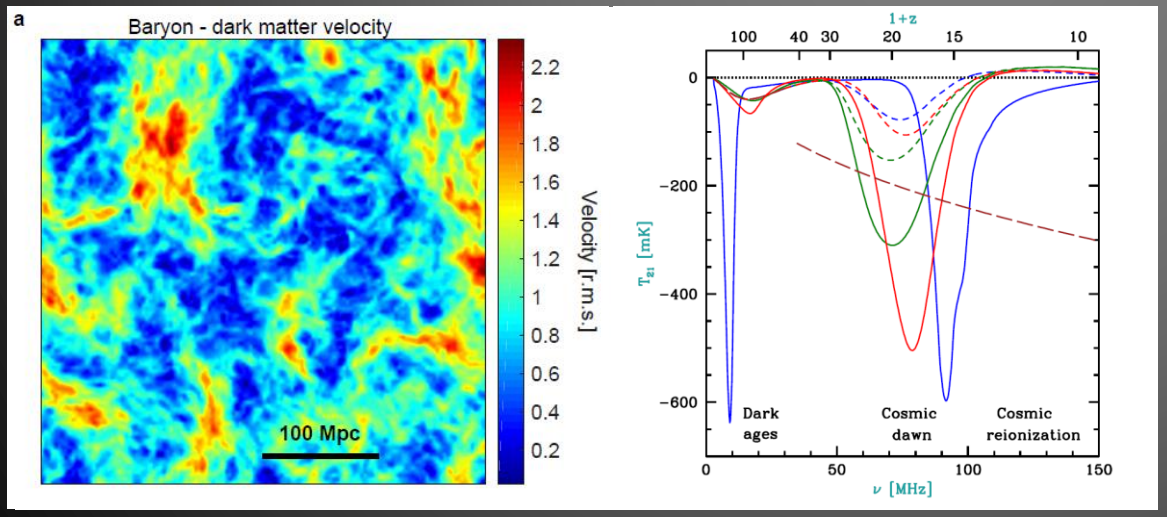


Bevins, Heimersheim, Abril-Cabezas et al. 2023

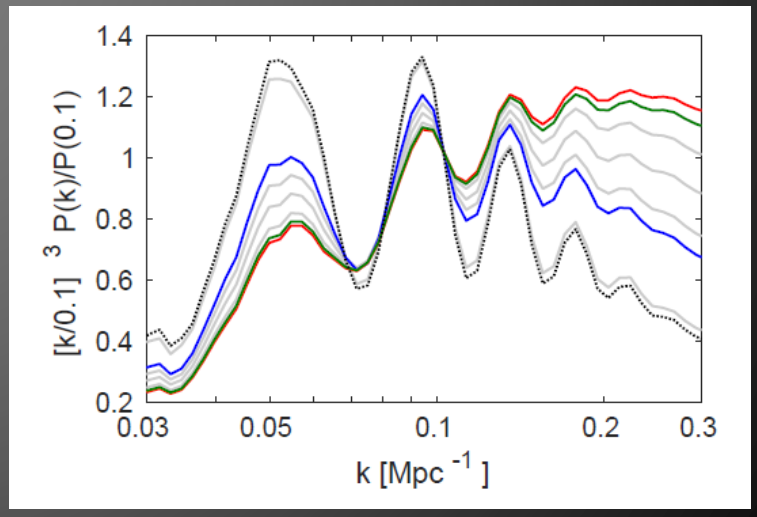
Theoretical Explanations: Cooling of Gas by Dark Matter

- Two-fluid dark sector: dominant CDM and subdominant millicharged DM (mDM) component interacting with baryons via Rutherford/Coulomb scattering
- DM-baryon scattering enhances the signal (EDGES range)
- mDM-b interaction weakens rapidly with velocity -> signature of vel fields
- Produces a 21-cm power spectrum signal with acoustic oscillations

$$\sigma(v) = \sigma_c \left(\frac{v}{c}\right)^{-4}$$



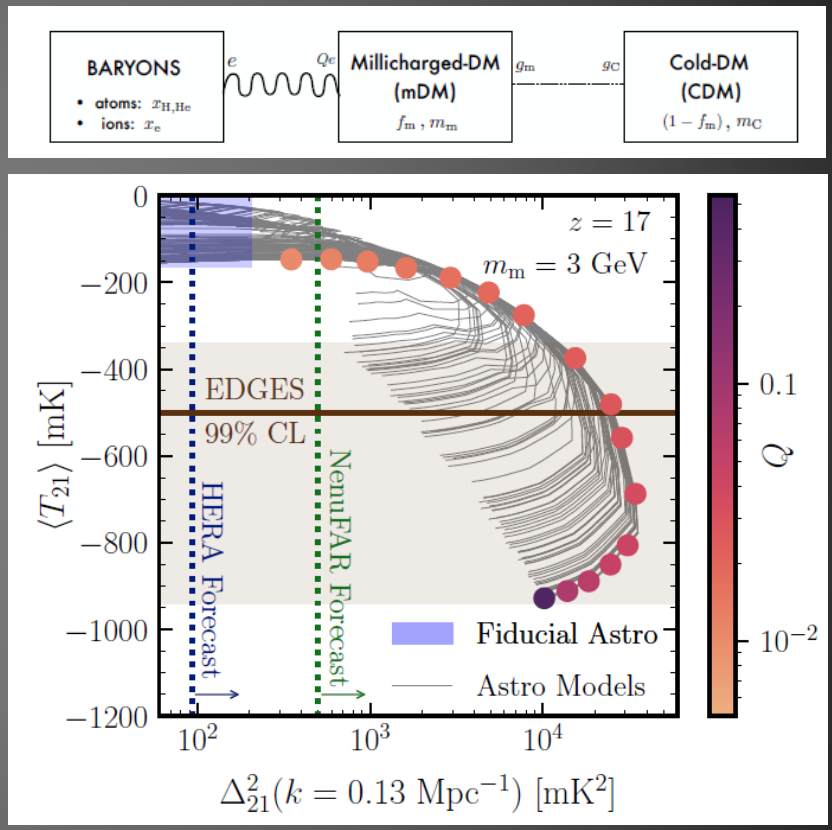
Barkana 2018



Fialkov et al. 2019

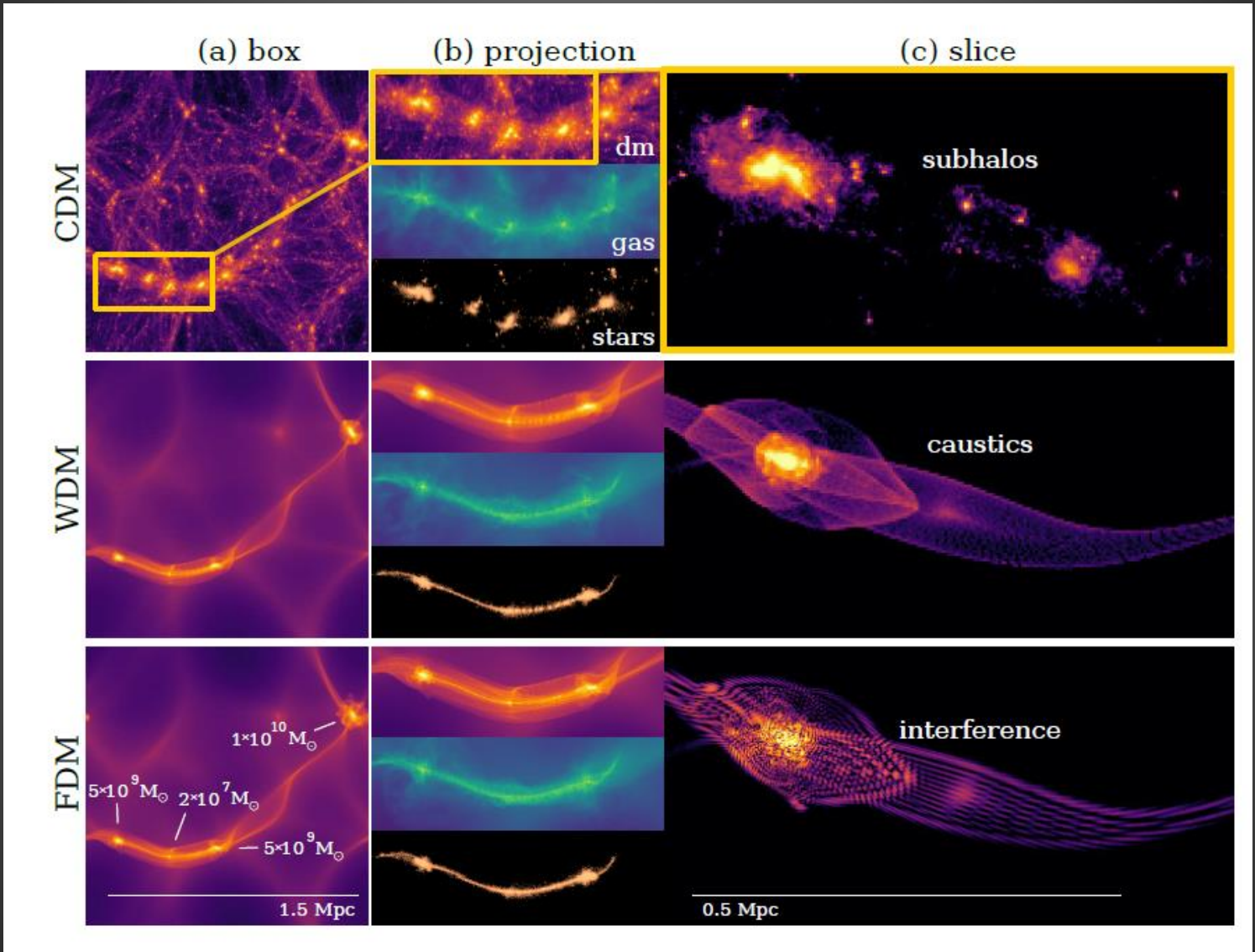
Theoretical Explanations: Cooling of Gas by Dark Matter

- Two-fluid dark sector: dominant CDM and subdominant millicharged DM (mDM) component interacting with baryons via light mediator.
- Before recombination baryons couple to mDM, after recombination mDM-b interactions transfer heat between baryons and DM bath (cold!).
- DM-baryon scattering enhances the signal (EDGES range) while avoiding stringent CMB constraints on momentum transfer between baryons and DM



Barkana et al. 2022

Structures in Fuzzy Dark Matter (FDM) Cosmology

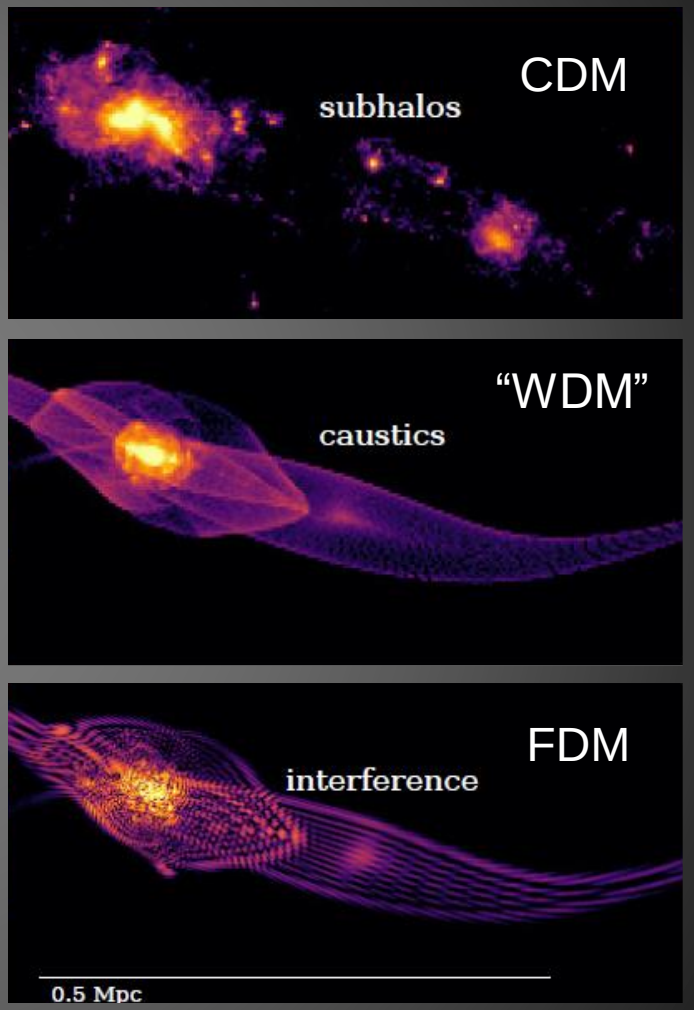


Mocz, Fialkov et al. 2019

Axion Dark Matter (FDM)

- Ultralight axion-like DM 10^{-22} -10^{-5} eV
- Solve Schrodinger-Poisson Equations
- Impact on clustering and large-scale structure

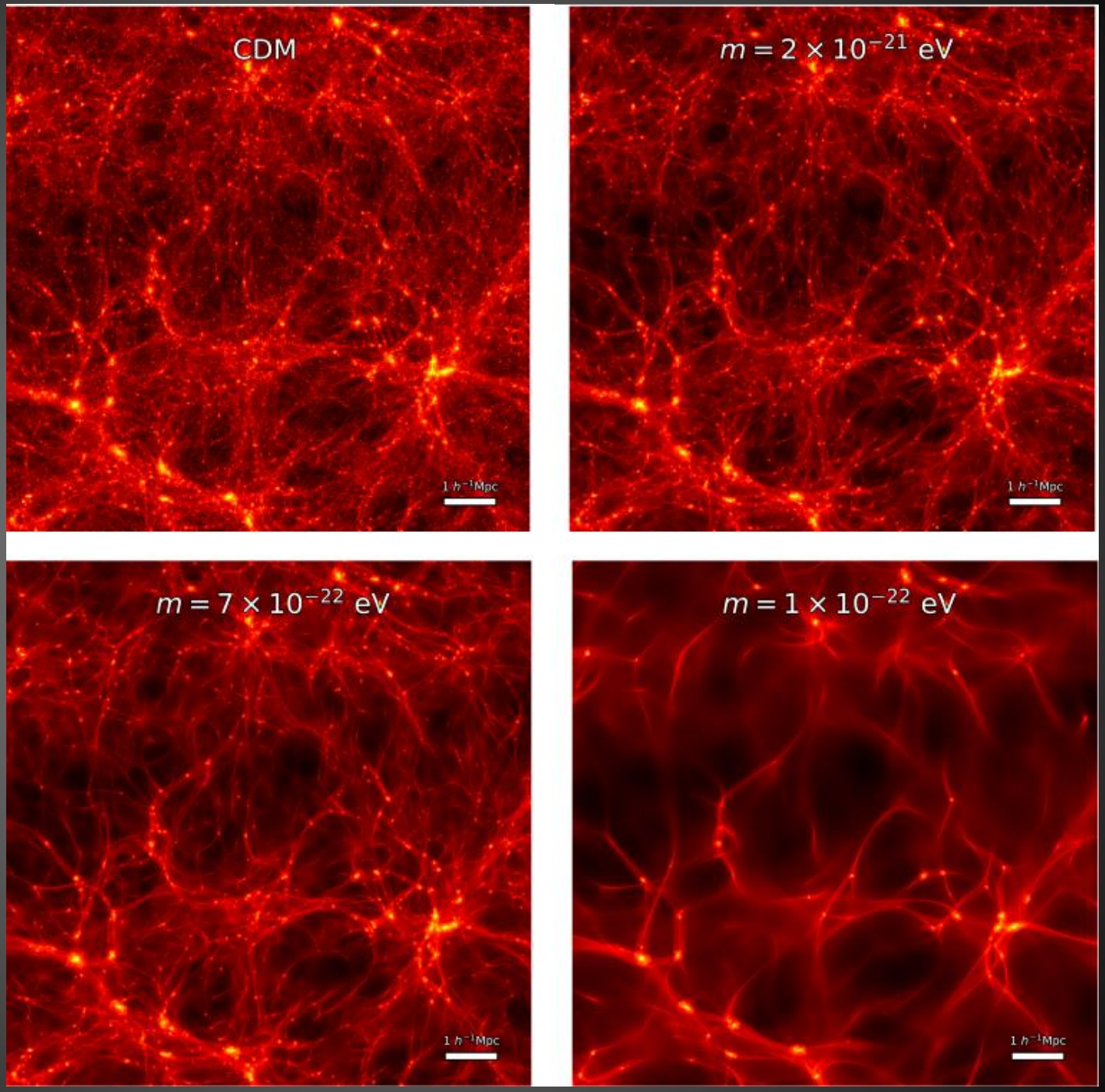
$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + mV\psi, \quad \nabla^2 V = 4\pi G(\rho - \overline{\rho}), \quad \rho = |\psi|^2$$



Mocz, Fialkov et al. 2019

Large scale structure

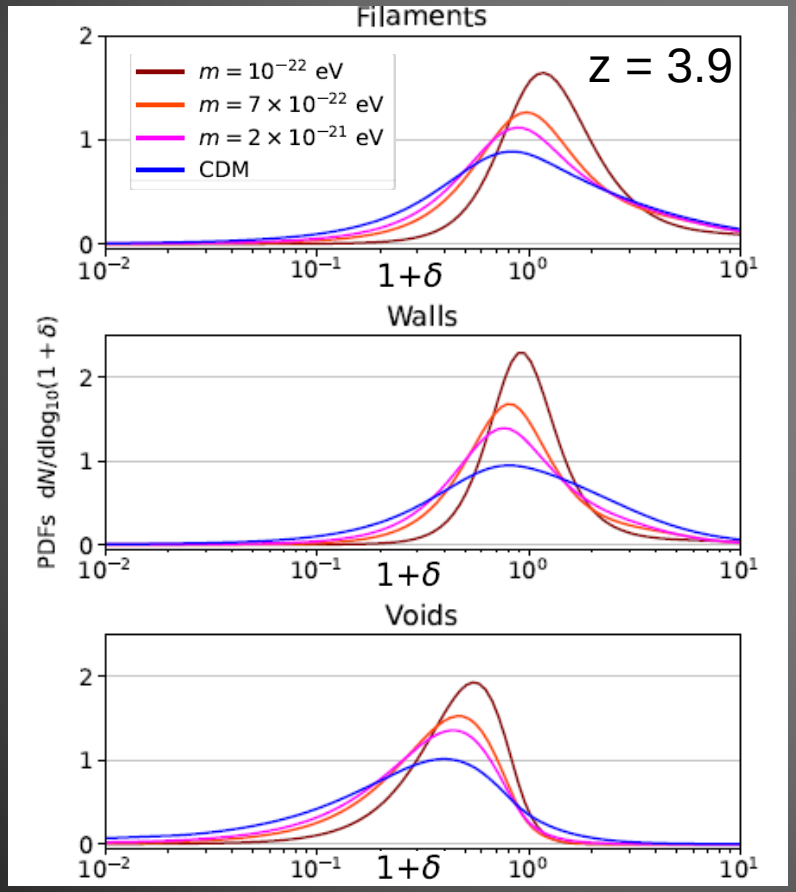
Lack of small scale power



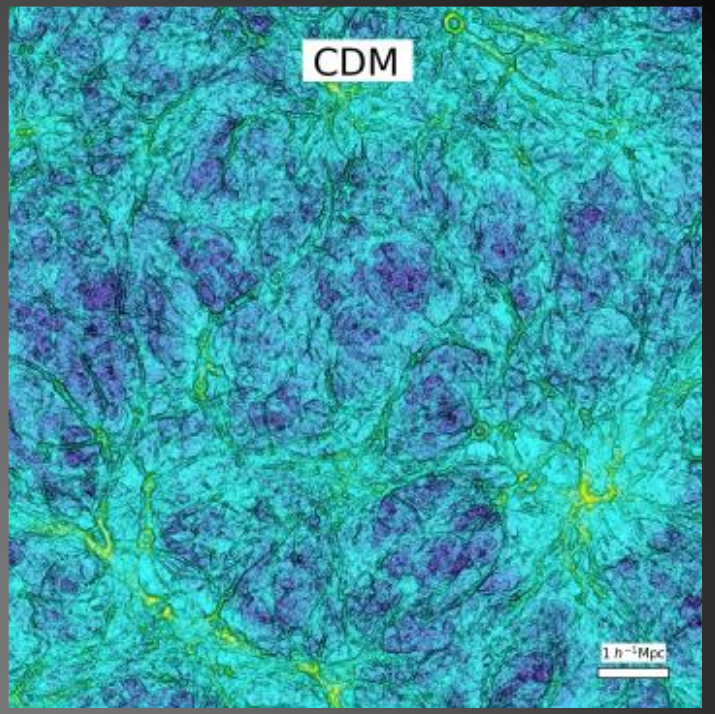
Dome et al 2023

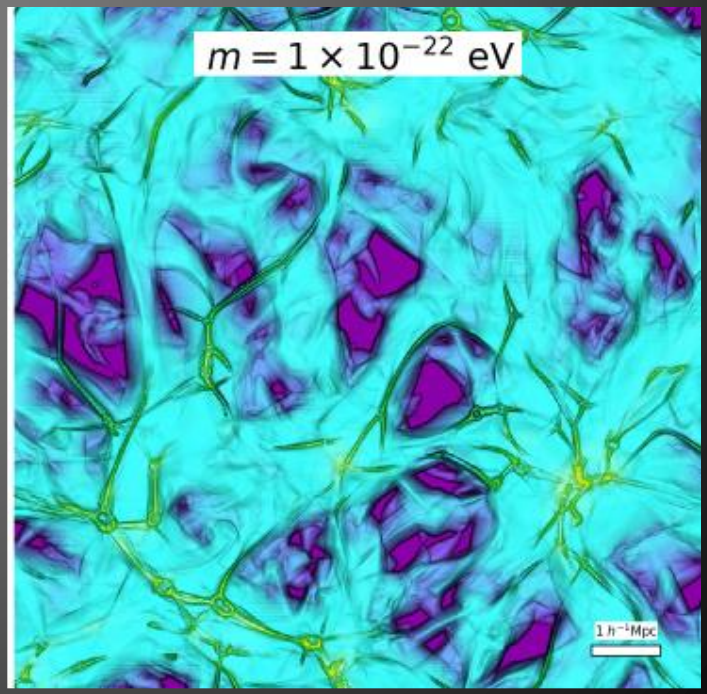
Cosmic Web Decomposition

Statistics of nodes, voids, filaments and walls depends on cosmology



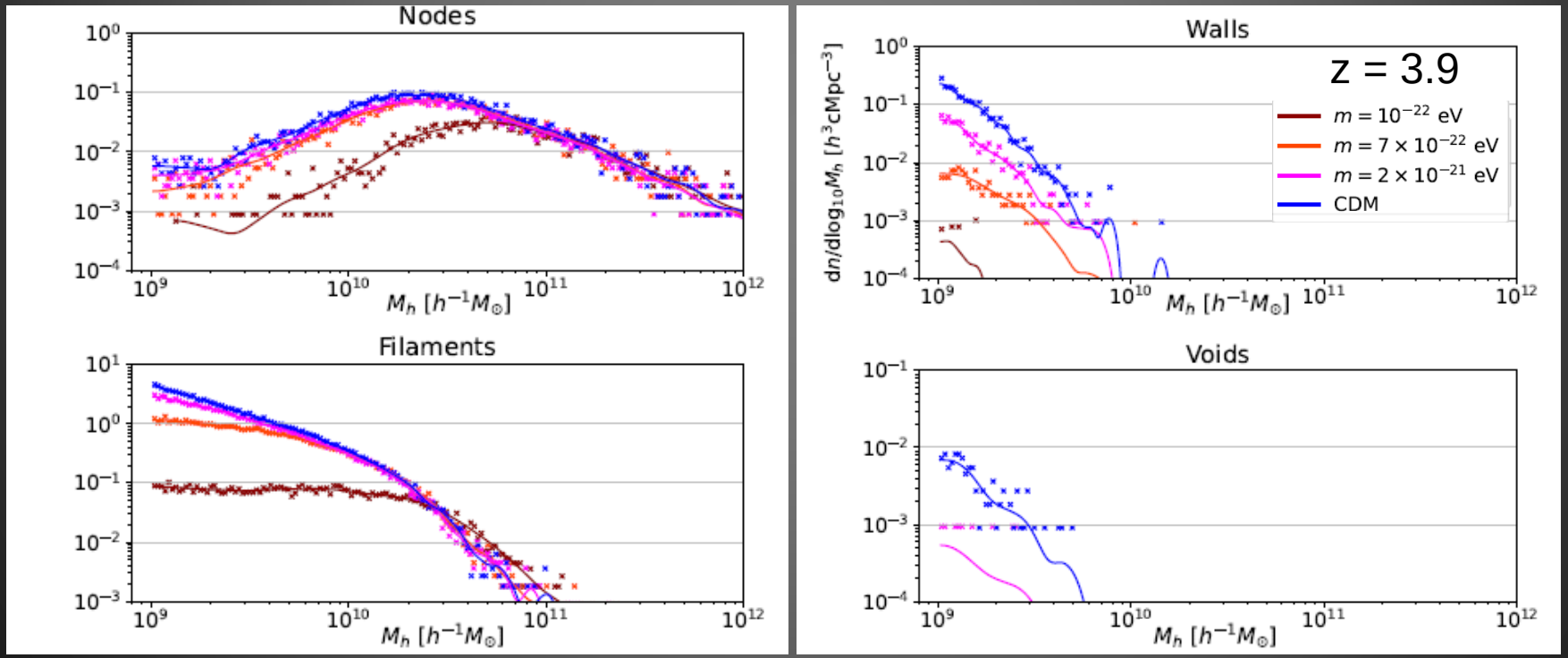
Dome et al 2023





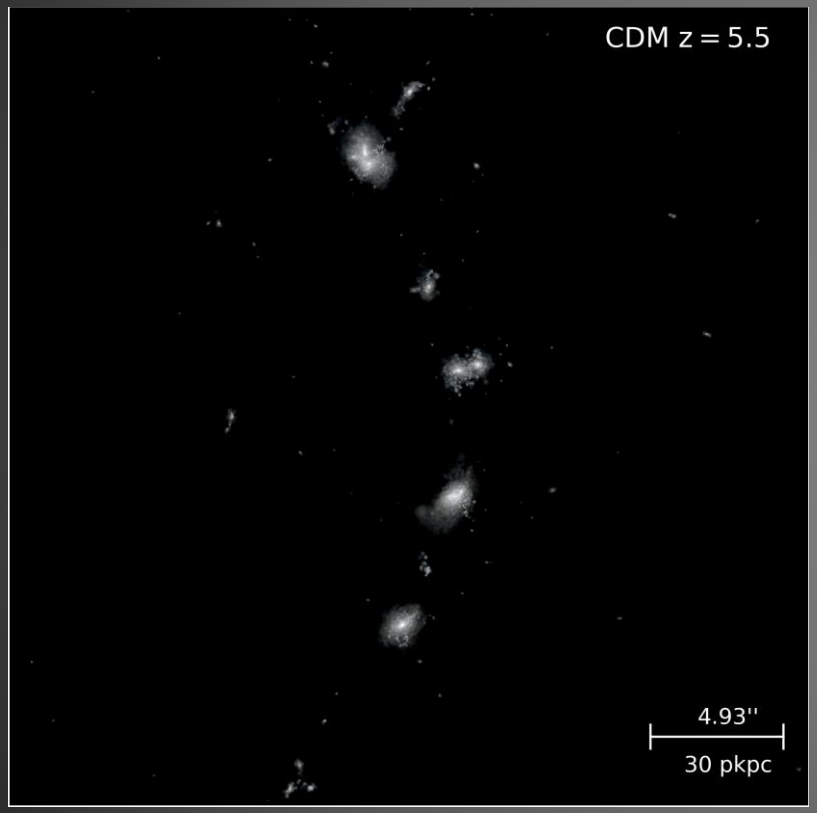
Halo Mass Functions in Different Environments

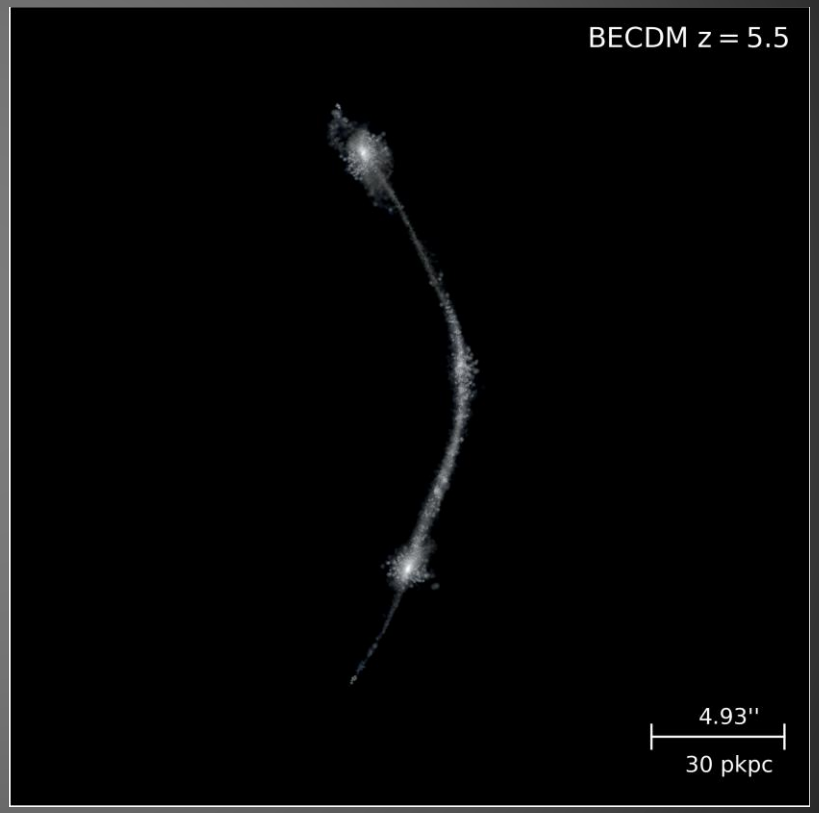
Halo abundance depends on environment and cosmology



Dome et al 2023

Galaxies

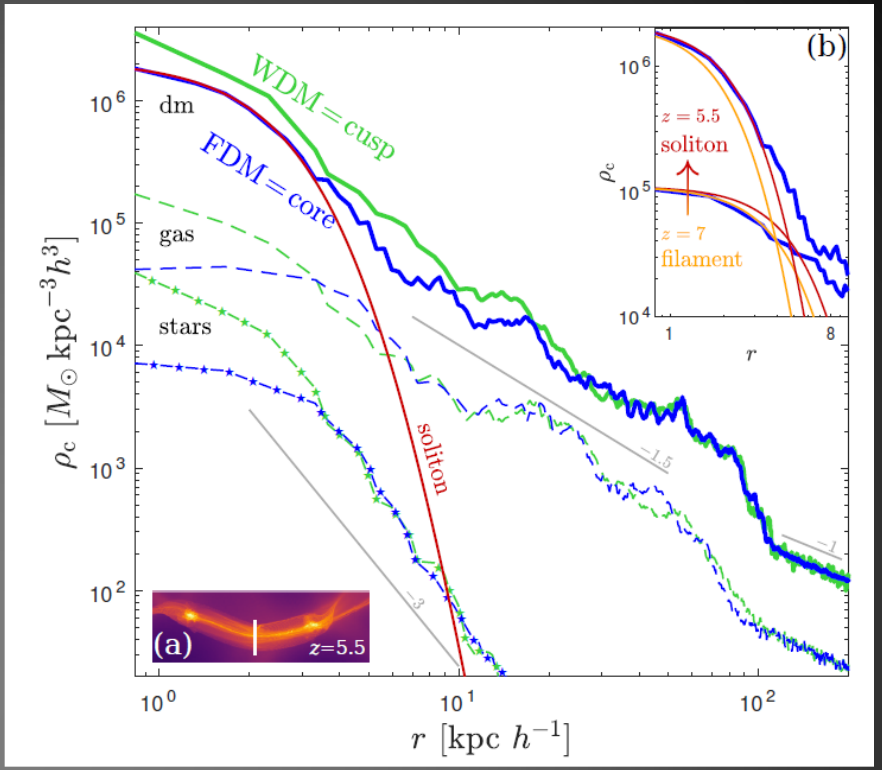


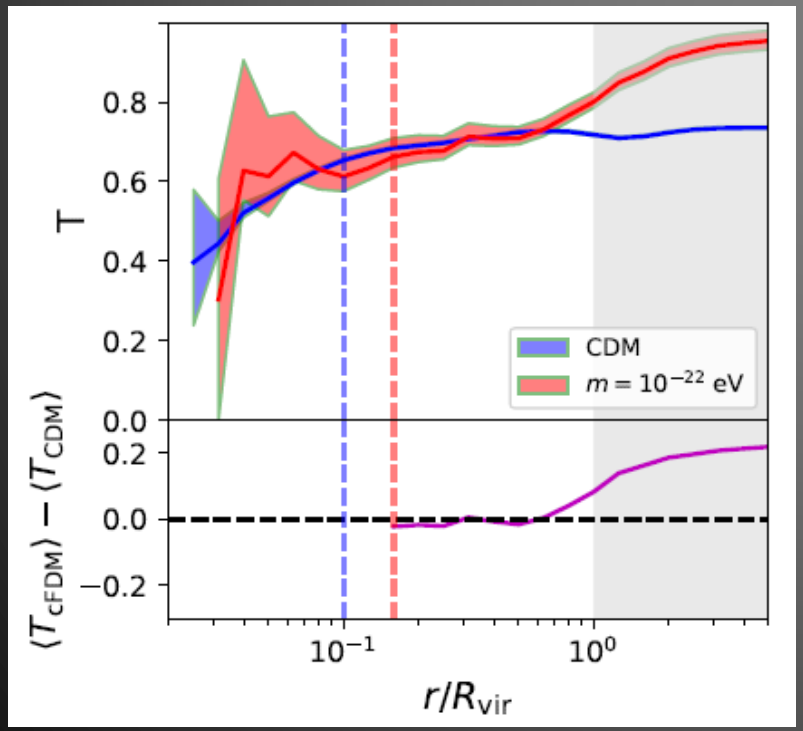


Mocz et al. 2020

Shapes and Profiles

Solitonic cores in halos and filaments
Mocz et al. 2019

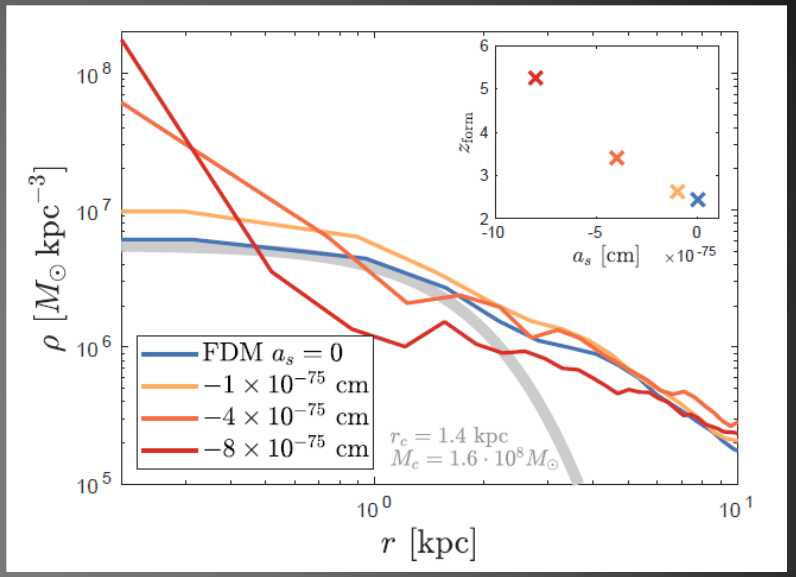


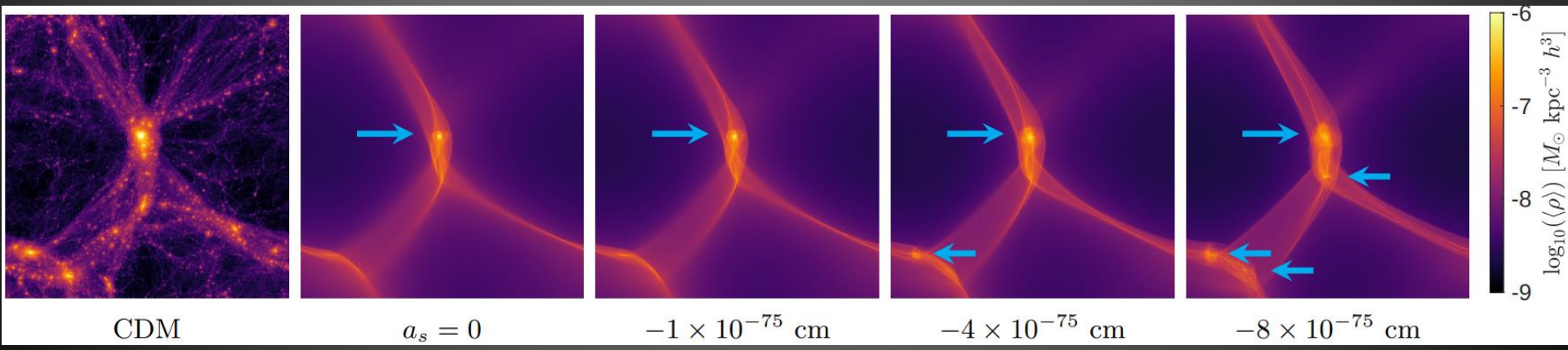


Halos are less concentrated and more triaxial in FDM
Dome et al 2023

Structures in Self-Interacting Dark Matter

- SI arises if FDM are ultralight axion (strong CP symmetry-breaking scale/decay constant).
- Weak **attractive SI** may be strong enough to alter structure formation.
- Enhanced small-scale structures, soliton cores above a critical mass undergo a phase transition, transforming **from dilute to dense solitons**.





Mocz et al. 2023

Conclusions:

1) 21-cm cosmology is exciting: first experimental constraints on the nature of DM and star formation at cosmic dawn.

2) Structure formation and shapes of objects are sensitive tracers of the nature of DM. Future observations of first galaxies with JWST and 21-cm line will constrain light ultra-light particle DM, as well as decaying and annihilating DM scenarios.