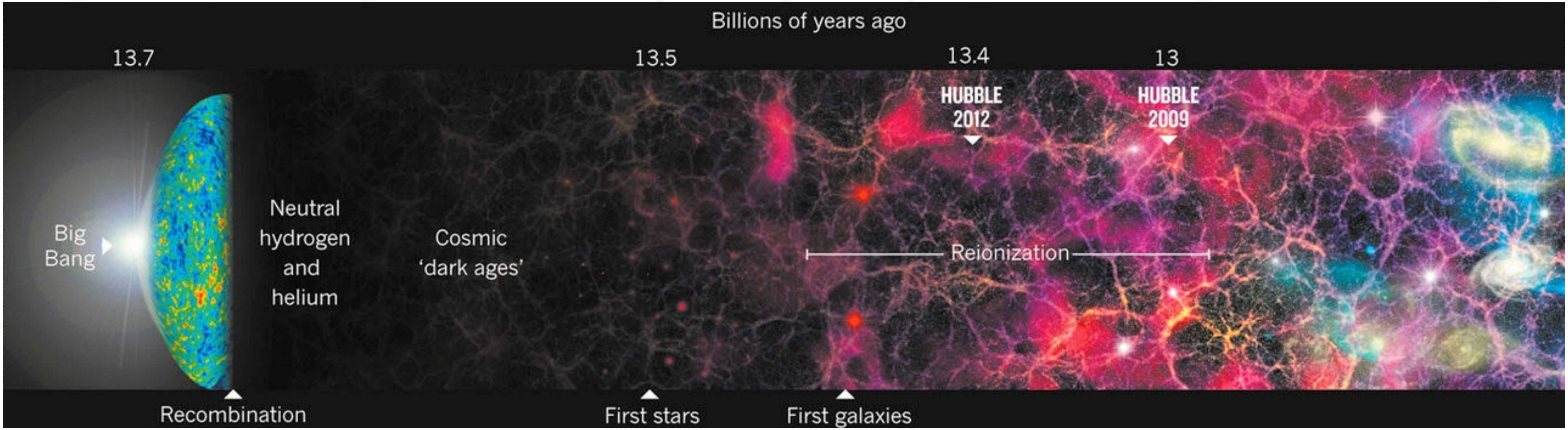
Constraints on Dark Matter scenarios from Reionization

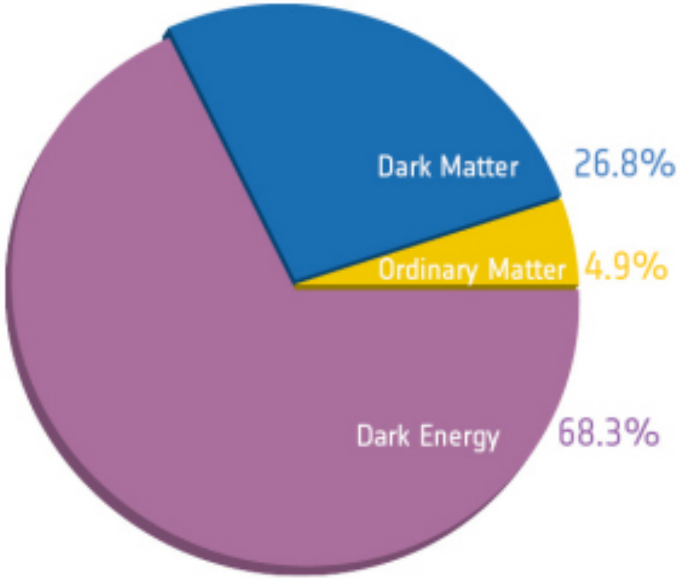
Marco Castellano

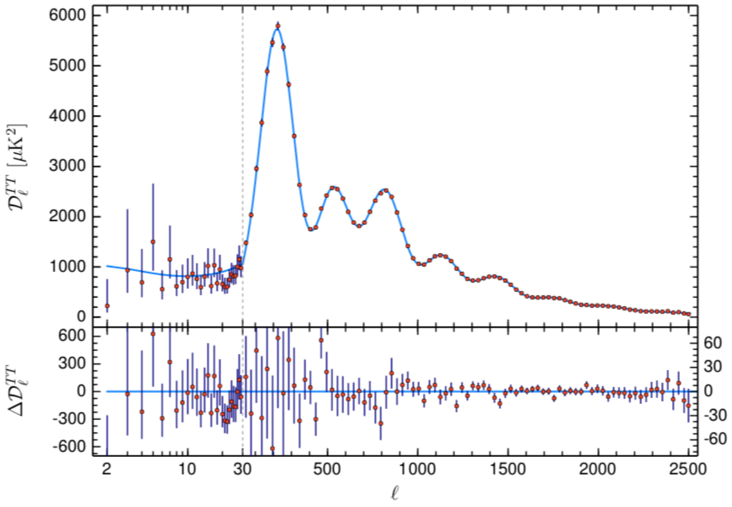
N. Menci, M. Romanello, P. Santini

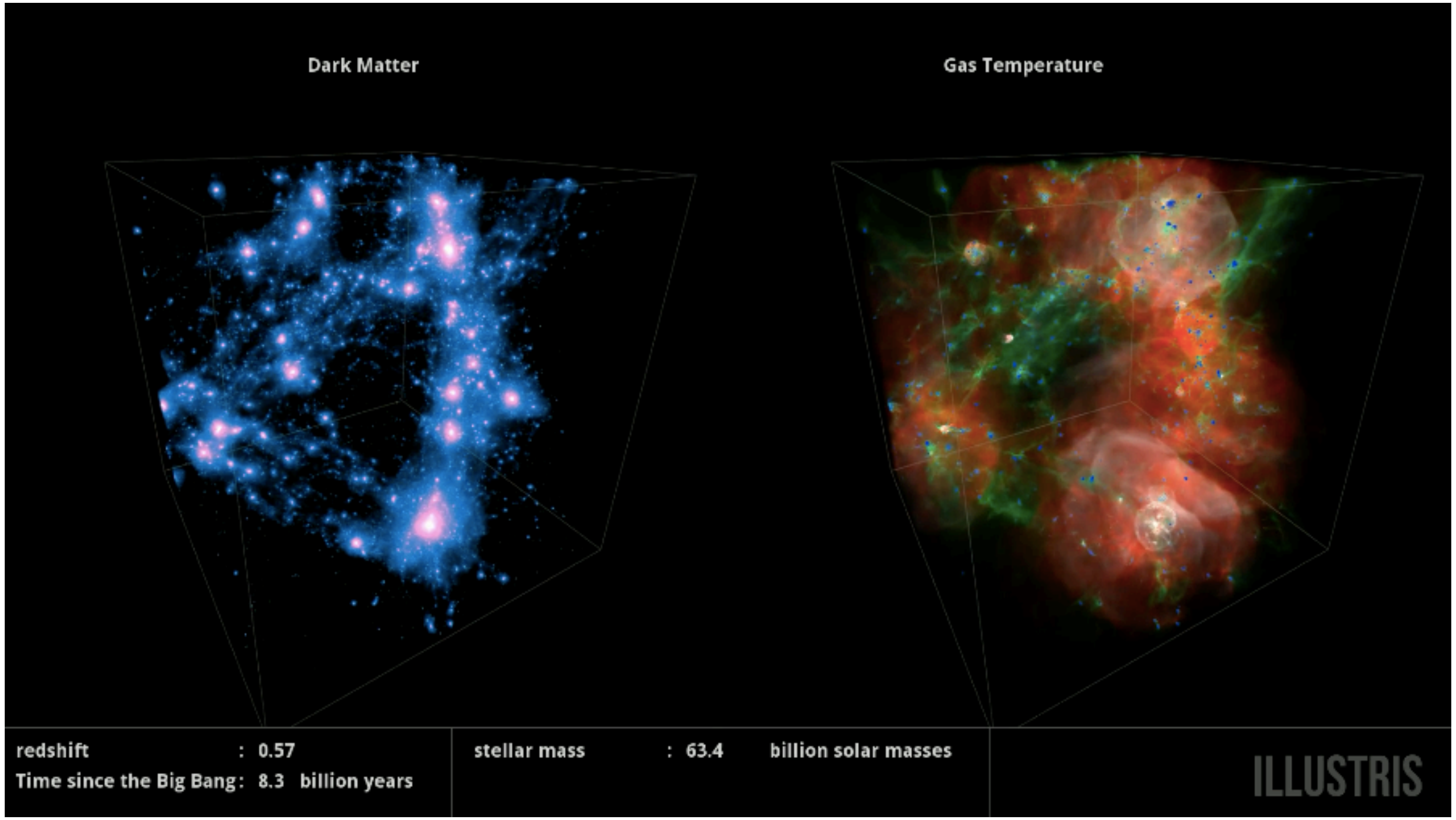
29/09/2022



ΛCDM model







Initial power spectrum yields to a hierarchical growth of matter perturbation

Planck 2018

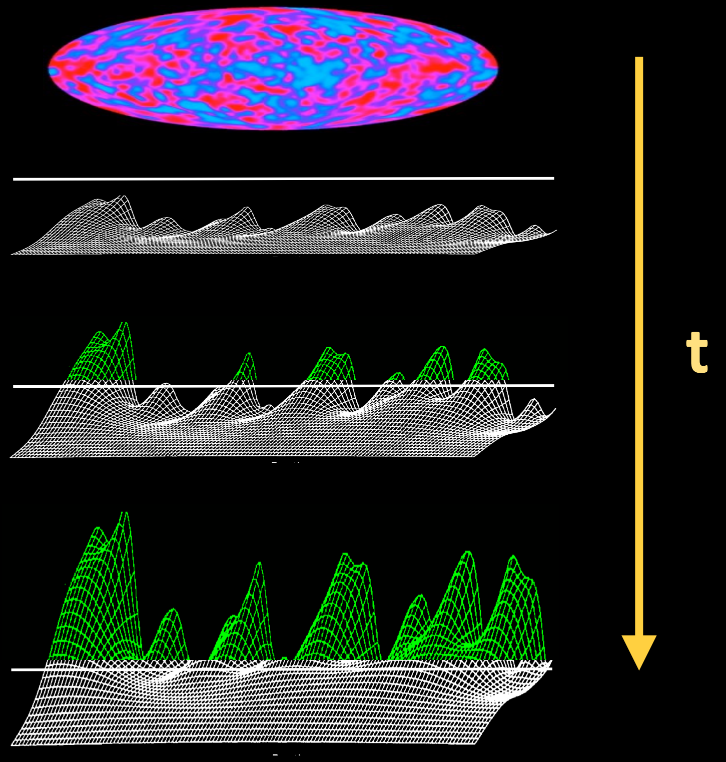
The Nature of DM determines the shape of the power spectrum P(k) and hence of the variance $\sigma^2(M)$

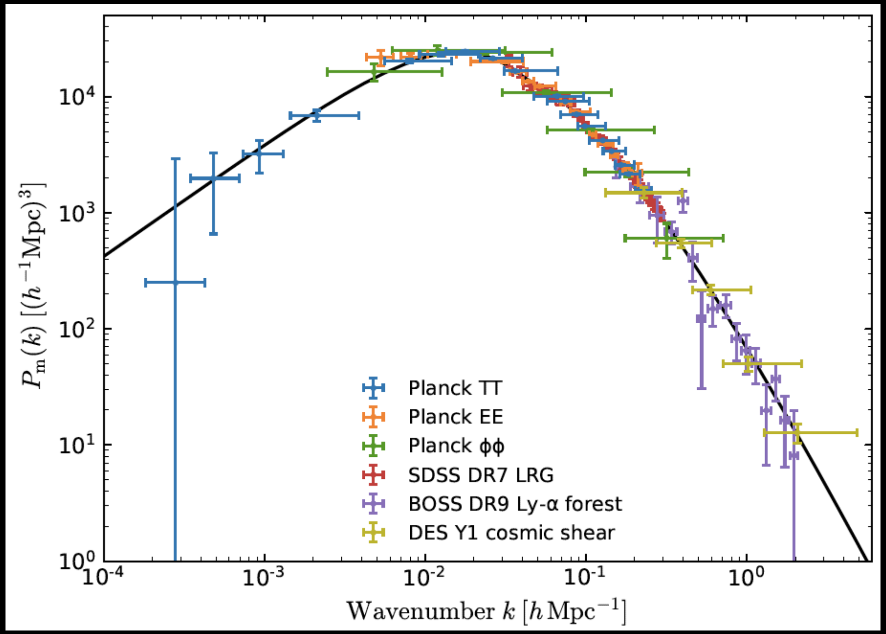
Mean (square) value of perturbations of size R(~1/k) enclosing a mass M

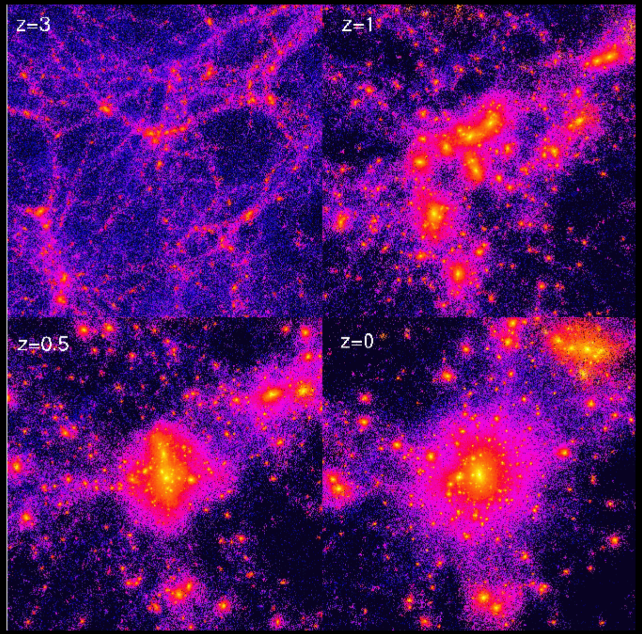
$$P(k) = \frac{1}{V}\,\langle|\delta_k|^2\rangle$$

$$\sigma_M^2 = \frac{1}{(2\pi)^3\,V}\int^{M\leftrightarrow k} dk\,k^2\,P(k)$$

$$\sigma_M^2 \leftrightarrow P(k)$$



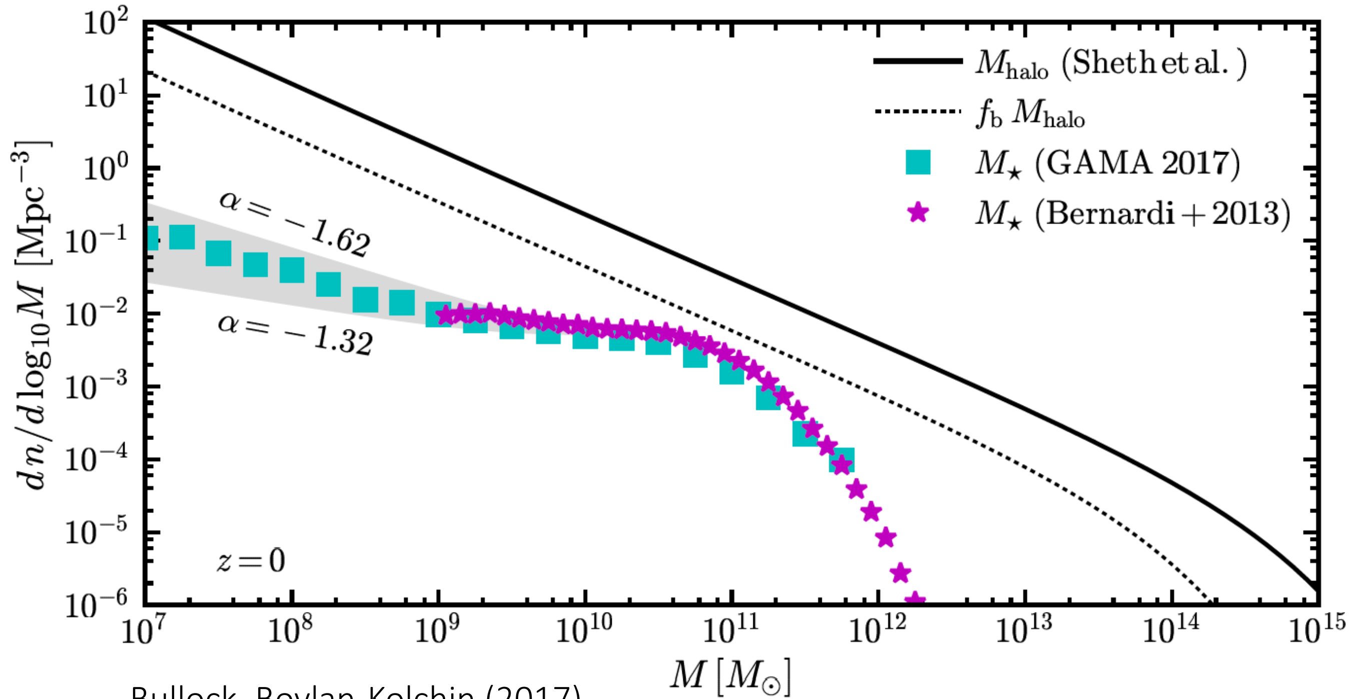




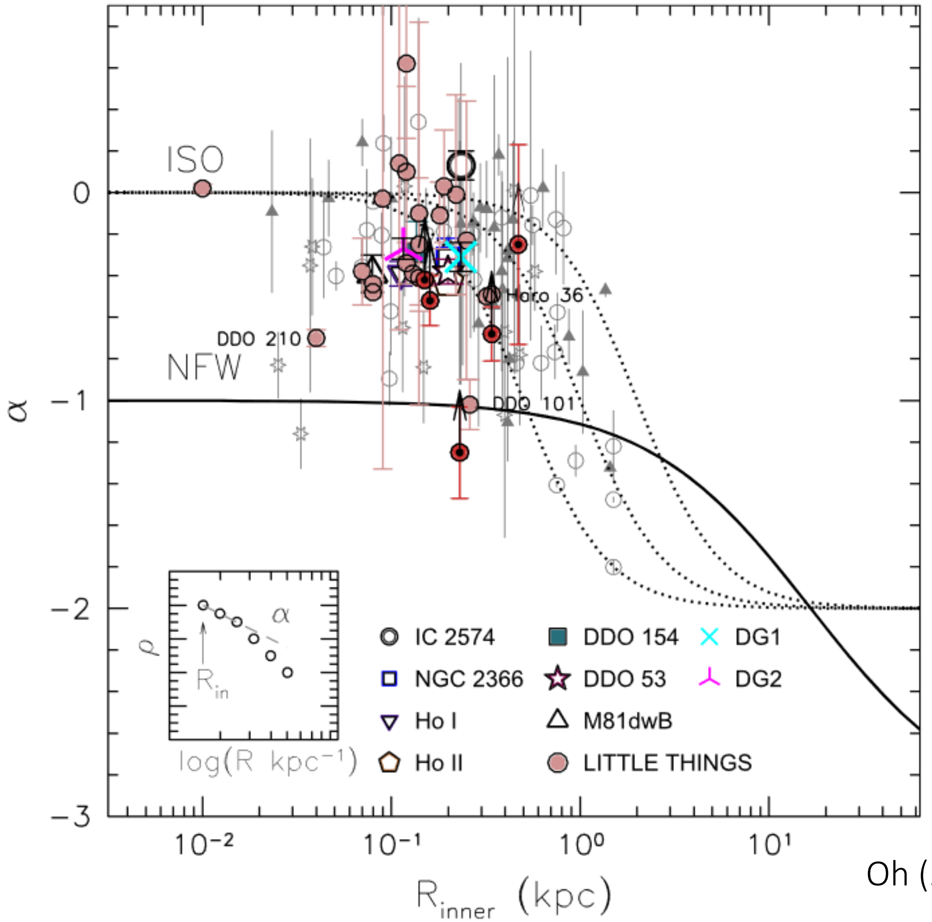
Issues with the ΛCDM model

Missing satellites and "too big to fail" debate

Cusp/core debate

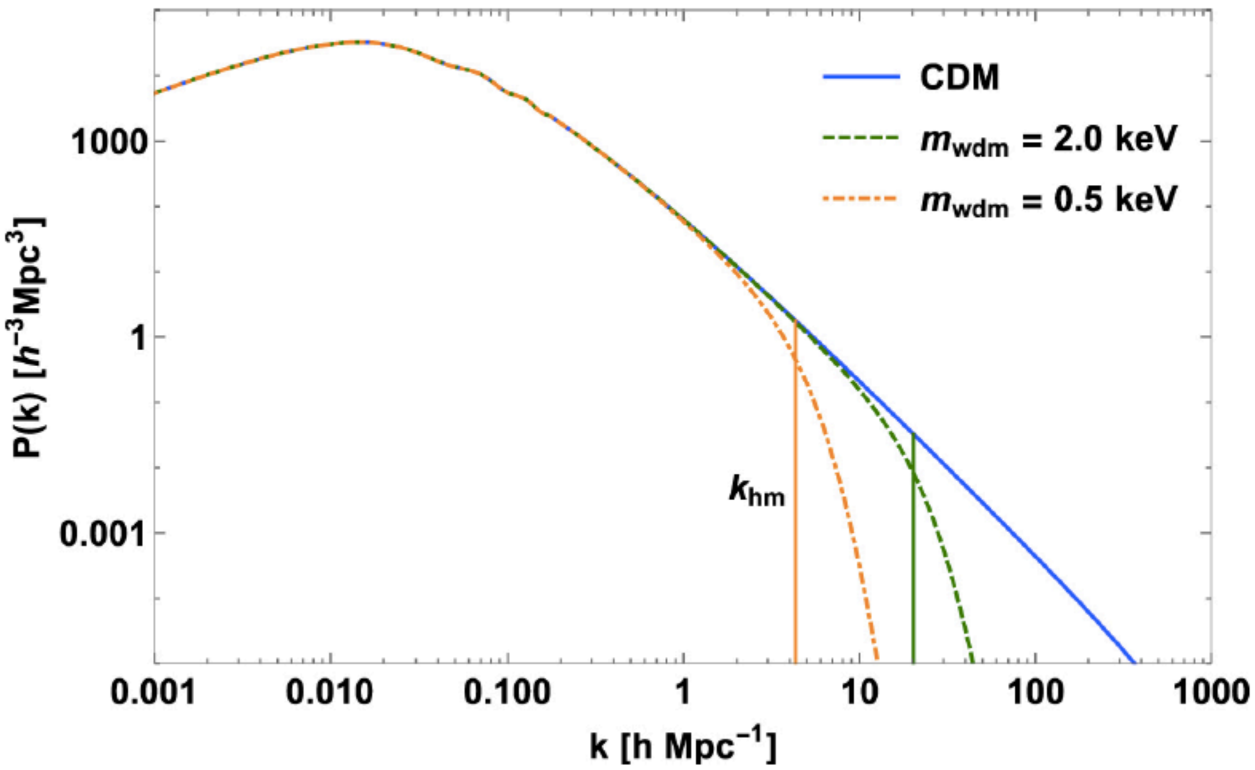


Bullock, Boylan-Kolchin (2017)



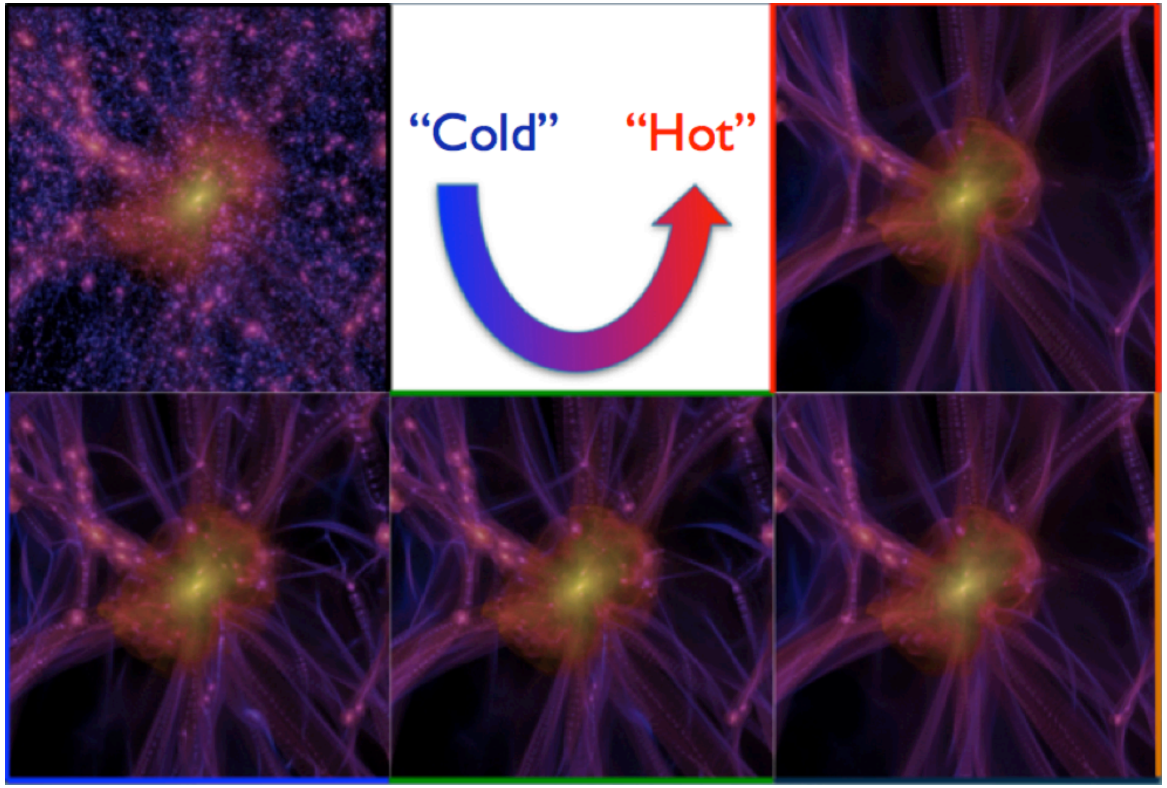
Oh (2015)

Possible alternative: WDM cosmologies



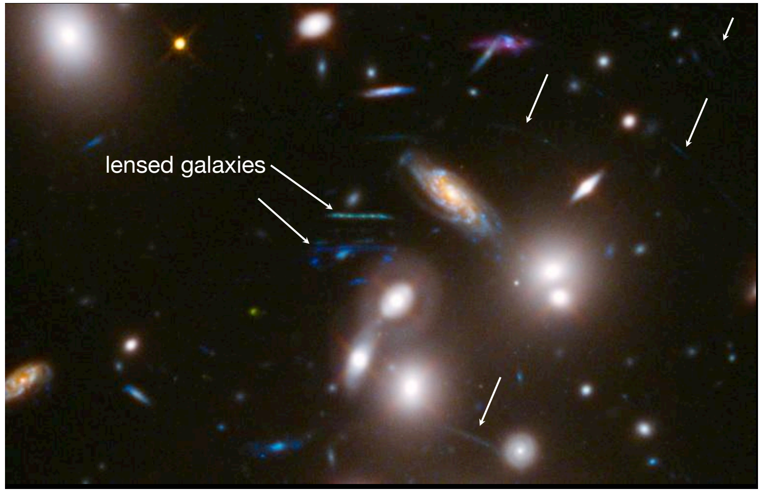
Fairbairn+21

Free-streaming of DM particles determines a suppression in low mass halos.

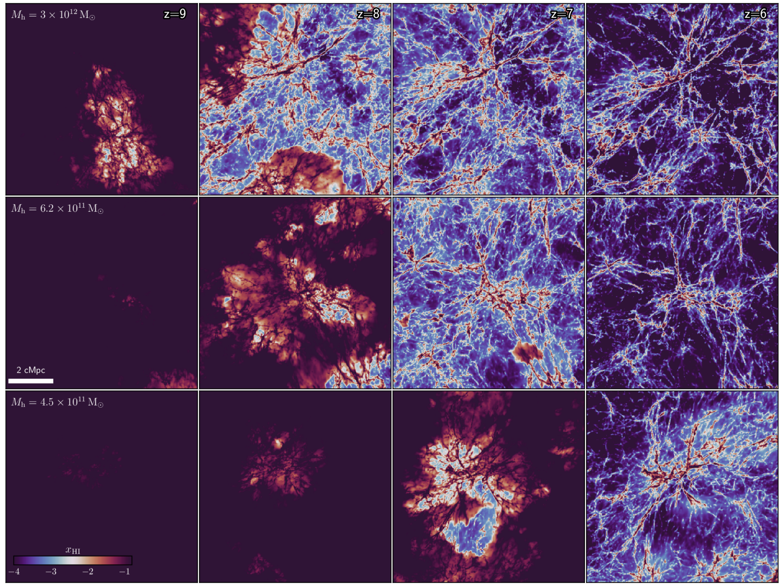


Outline of the talk

1) Constraints on WDM models from the number density of high-redshift galaxies



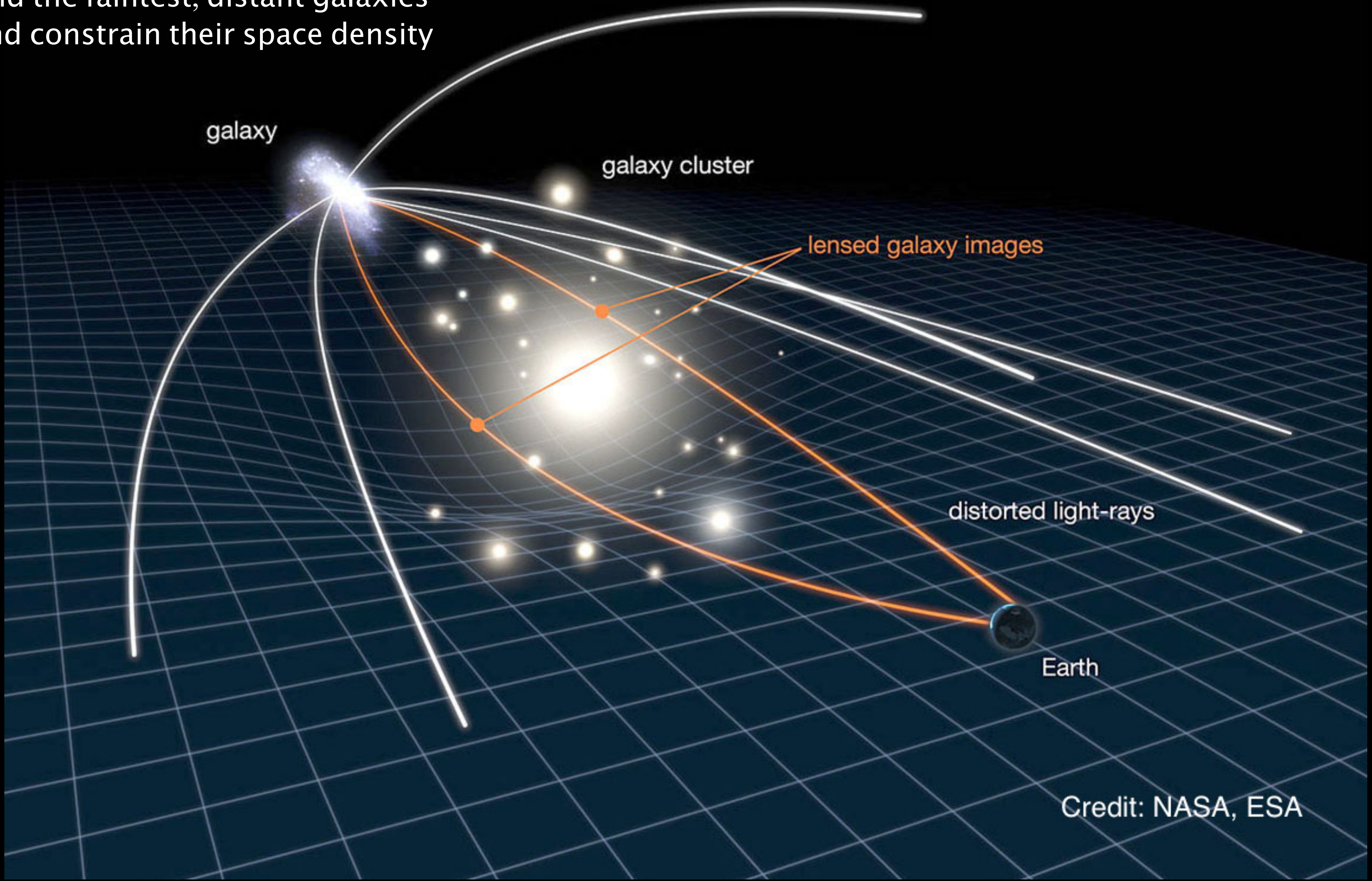
2) The epoch of reionization in WDM models

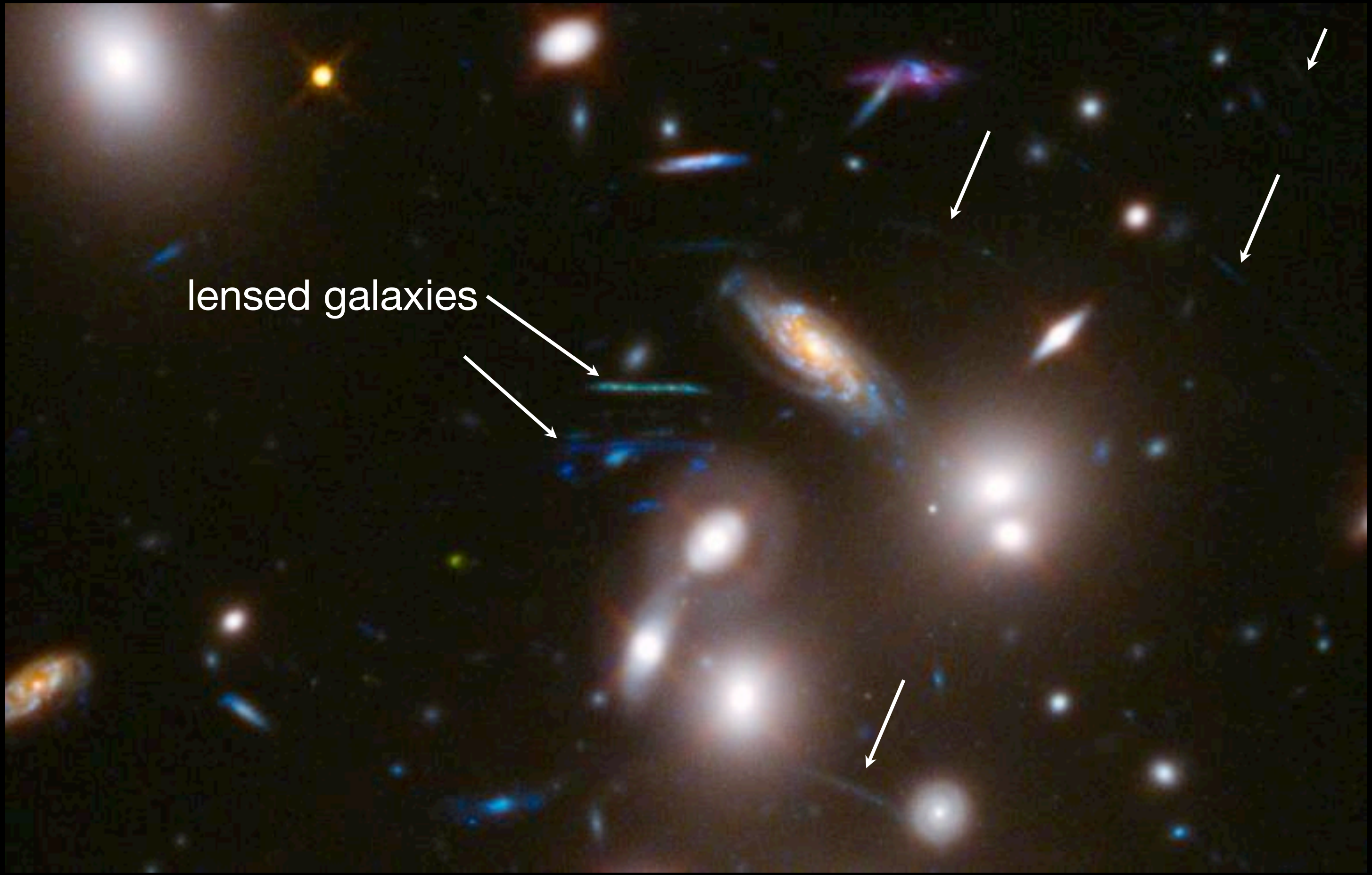


1- Constraints on WDM models from the number density of high-redshift galaxies

Finding the faintest galaxies

Gravitational lensing is the tool we need to
find the faintest, distant galaxies
and constrain their space density

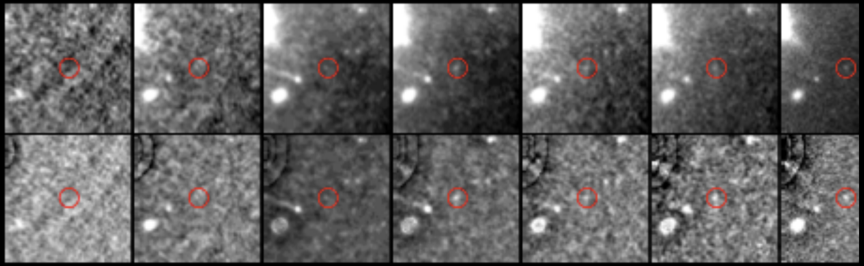




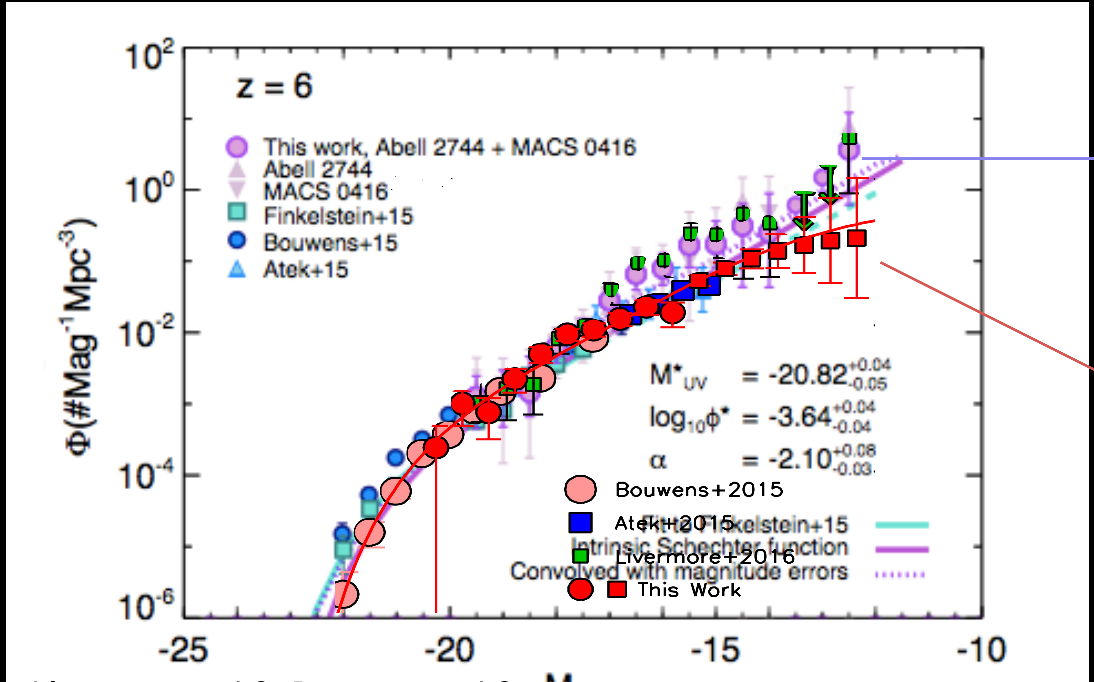
background galaxies are magnified by factors up to ~10-20,
providing the deepest yet view of the universe

slide by Jennifer Lotz

Luminosity Functions of z=6 Galaxies in the Hubble Frontier Fields:
Based on 2 HFF lensing clusters 164 galaxies at z=6



Postage stamp image of a2744 z6 3341, from the z ~ 6 sample detected in the Abell 2744 cluster field. The circle shows a 0.4" aperture. This galaxy is magnified by a factor ~ 20×, giving it an intrinsic UV magnitude of MUV = −14.54, but was not detected in previous studies due to the bright foreground object close to the line of sight (top row). It is easily detected in the wavelet-subtracted images (lower row



Livermore+16, Bouwens+16

Integrated number densities of galaxies (#/Mpc^3) down to the faints magnitude: correspond to

Livermore et al. 2017

Best fit	log Φ_{obs}=0.54
1σ	log Φ_{obs}=0.26
2σ	log Φ_{obs}=0.01
3σ	log Φ_{obs}=—0.36

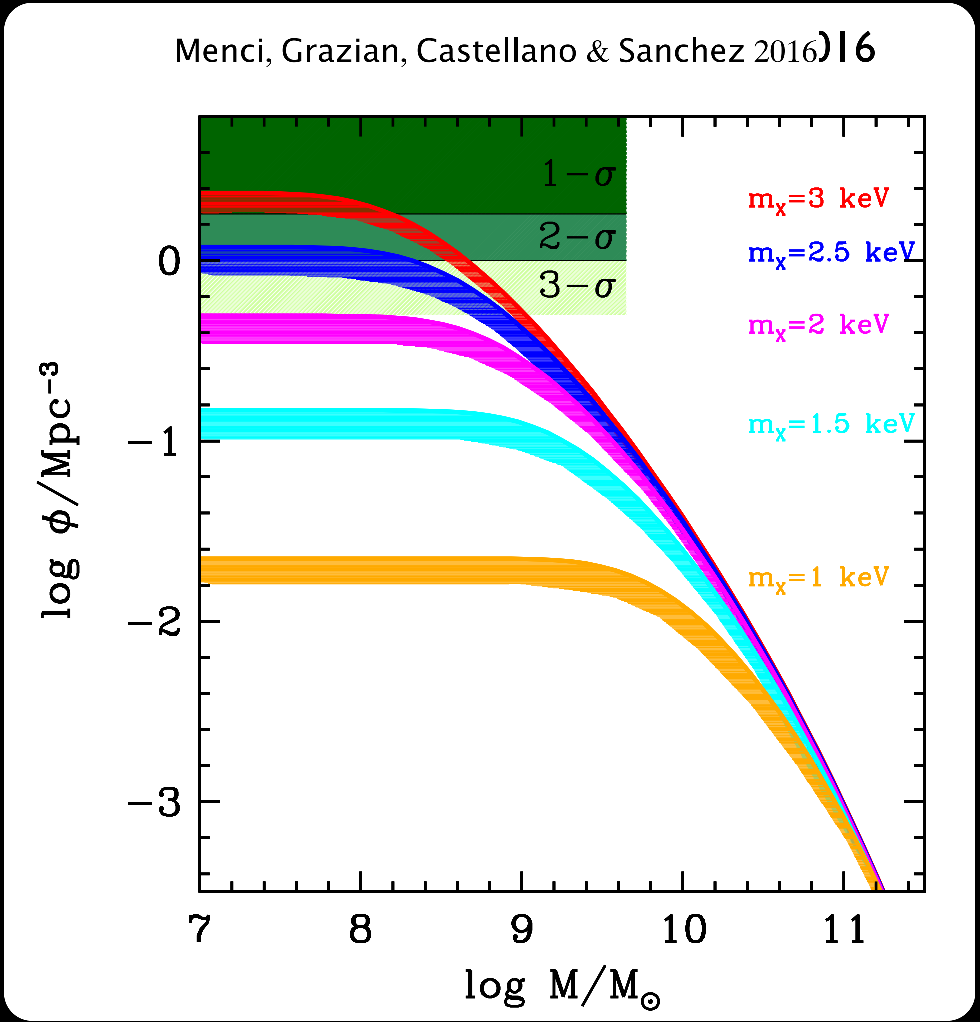
Bouwens et al. 2017

Best fit	log Φ_{obs}=-0.25
1σ	log Φ_{obs}=-0.47
2σ	log Φ_{obs}=-0.62
3σ	log Φ_{obs}=-0.9

HFF constraints on thermal WDM models

Based on 2 HFF lensing clusters Abell 2744 and MACS 0416

thermal relics



Menci, Grazian, Castellano & Sanchez 2016

1. Starting from observed luminosity function, we run 10^7 Monte Carlo extractions of galaxies according to the observed distribution and with an uncertainty provided by the observed error bars.

2. Compute the total nuber density of galaxies down to the faintest magn bin: # of galaxies/Mpc^3 at different confidence levels:

3. Assume a Power Spectrum $P(m_X$, production model)

4. Compute the associated WDM cumulative mass function and the corresponding maximum number density $\tilde{\Phi}$ (m_X, production model)

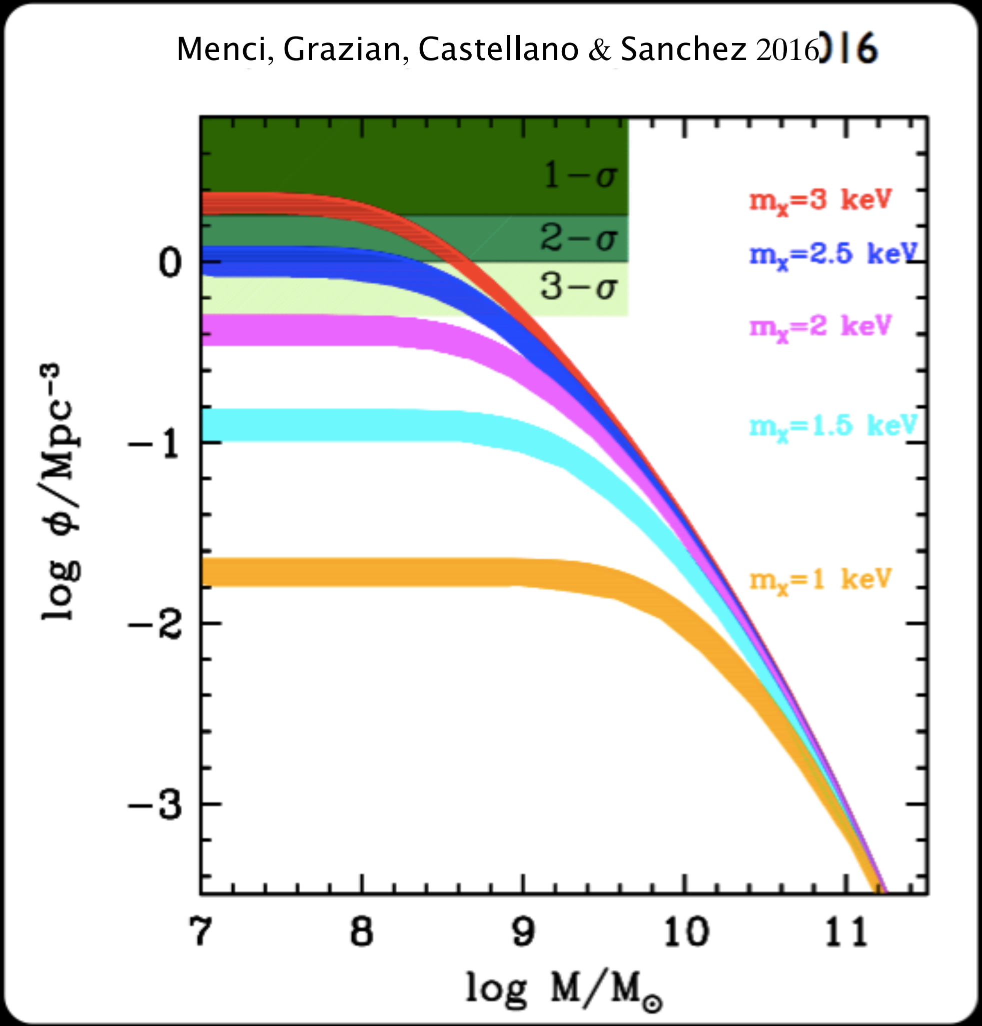
5. Allowed WDM models are those with $\Phi_{obs} \leq \tilde{\Phi}$ (m_X, production model)
observed galaxies cannot outnumber the DM halos

HFF constraints on thermal WDM models

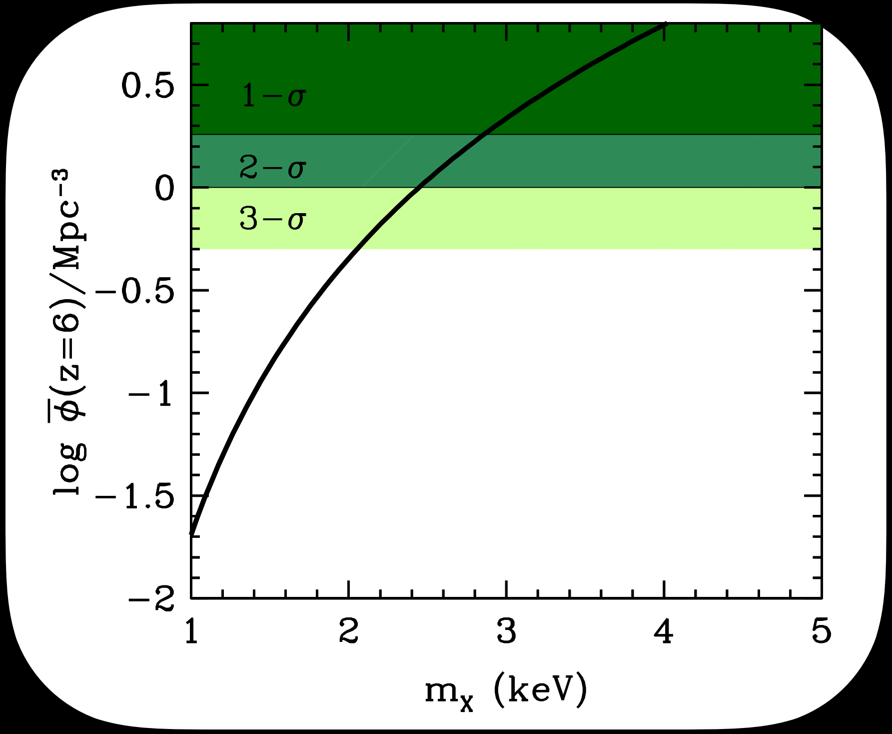
$m_X > 3$ keV (1σ) $m_X > 2.4$ keV (2σ)
(comparing with Livermore et al)

$m_X > 2.5$ keV (1σ) $m_X > 2.$ keV (2σ)
(comparing with Bouwens et al)

The tighter limits derived so far independently of baryon physics visible galaxies cannot outnumber their host DM halos



Very Conservative: The observed galaxies cannot outnumber their host DM halo, whose density saturates to a max. value depending on m_X



Sterile Neutrino WDM

Production from Active-Sterile Transitions

Exploring the Parameter Space of
Sterile Neutrino Models
based on resonant production

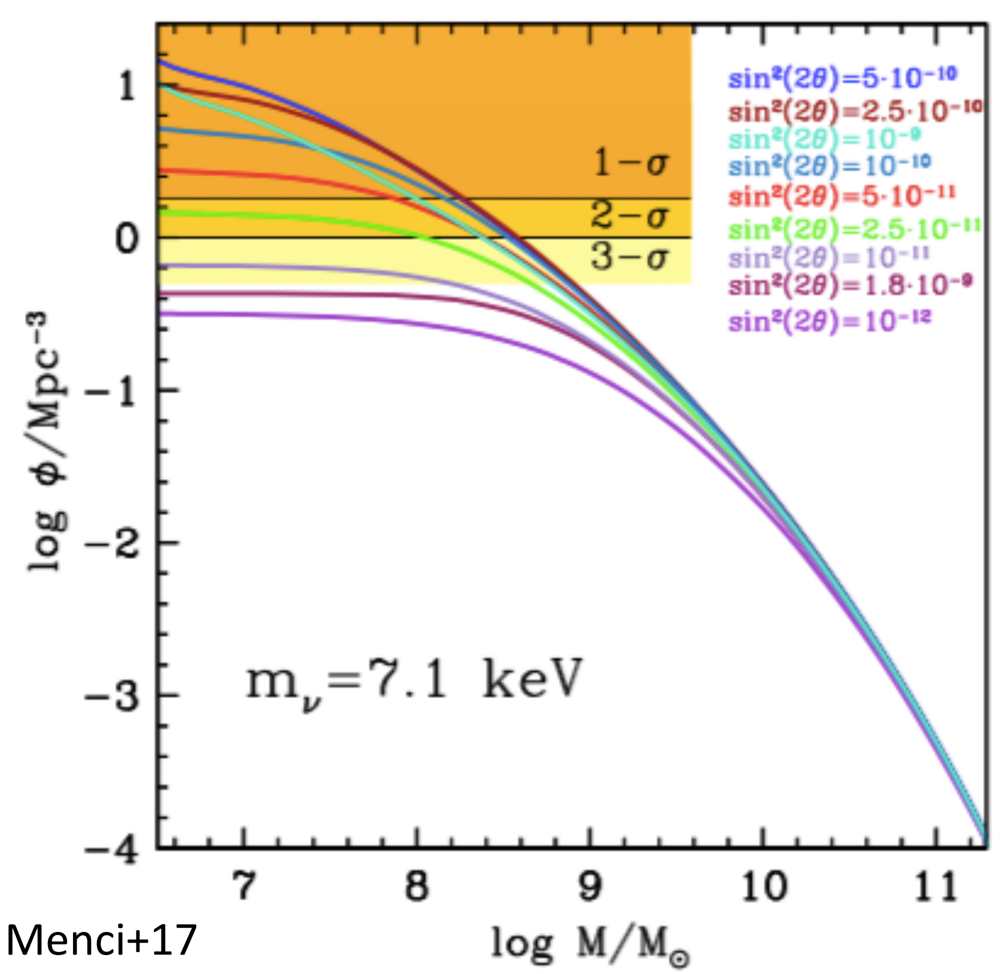
Grid of Values for
m_ν $sin^2(2\theta)$

For each point in the grid
of parameter space

Compute Power Spectrum $P(k)$
(solve Boltzmann equation)

Compute $\overline{\phi}$

Compare with HFF number
density of galaxies at z=6
Allowed region: $\overline{\phi} \geq \phi_{obs}$



Menci+17

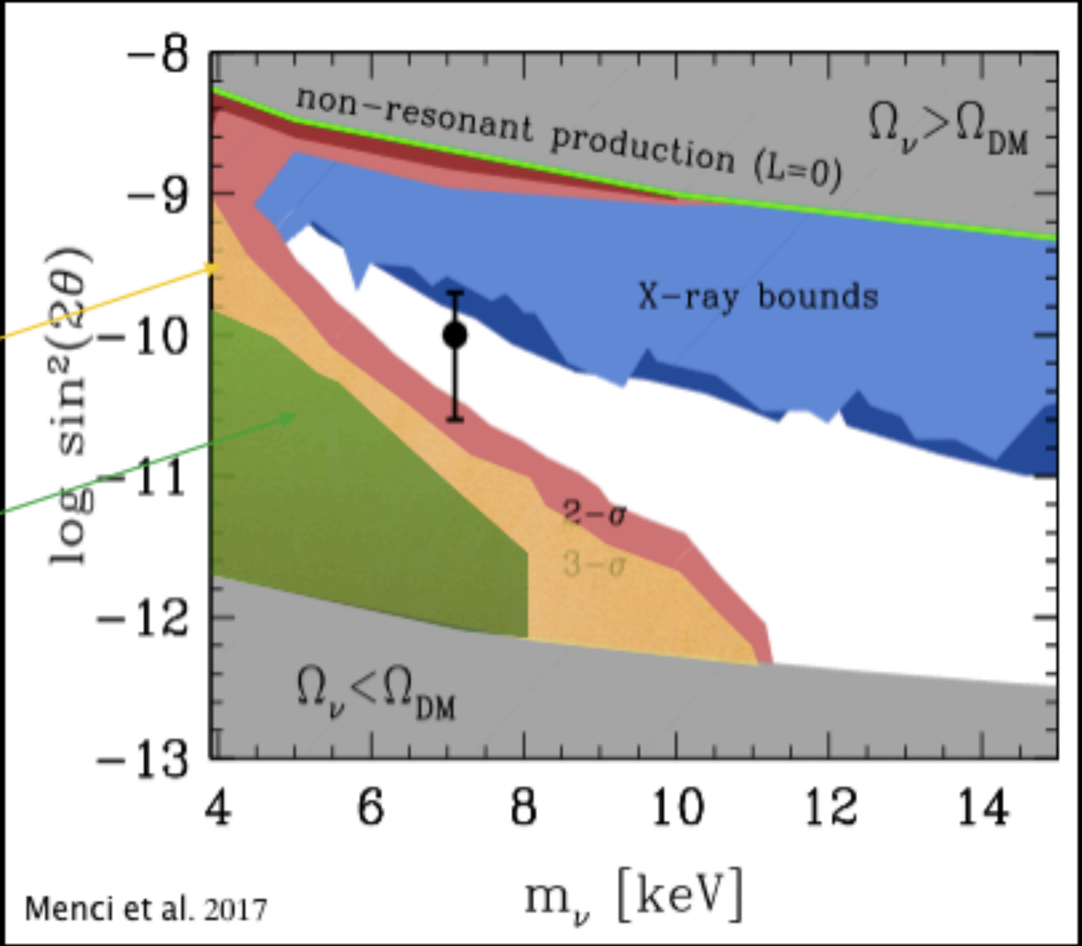
Sterile Neutrino WDM

Production from Active-Sterile Transitions

Exploring the Parameter Space of
Sterile Neutrino Models
based on resonant production

Schneider et al. 2016

Lovell et al. 2015



Limits from Milky Way satellites:

Depend on

assumed upper limit for MW mass

assumed lower limit for satellite masses (based on estimated L/M ratio or stellar velocity dispersion depending on assumed density profile)

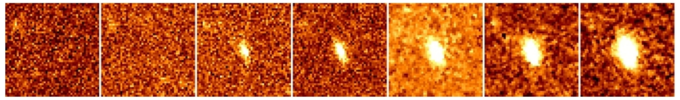
assumed isotropic distribution to correct SDSS observations for limited sky coverage

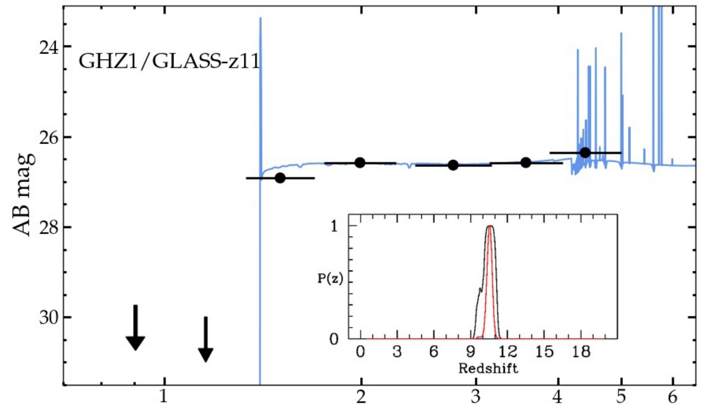
assumed halo-to-halo variance

Sets lower bounds for mixing angle which are Independent of baryon physics (L/M ratio) and of the assumed density profile.

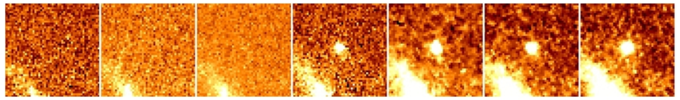
Unprecedented constraints on parameter space of such models

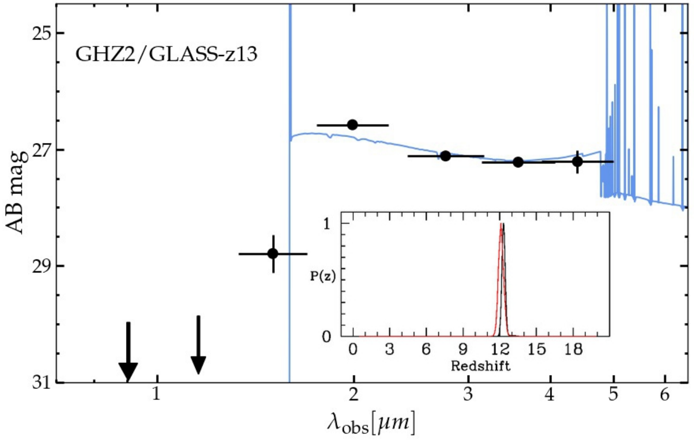
The future: constraints at cosmic dawn with JWST

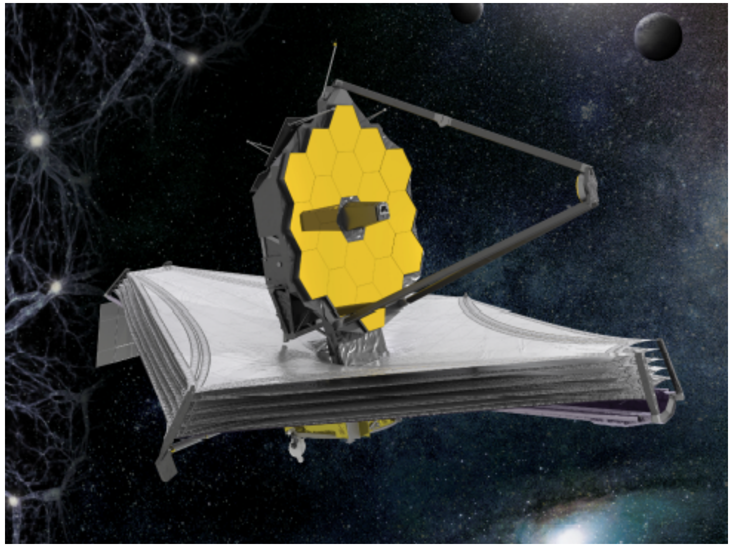


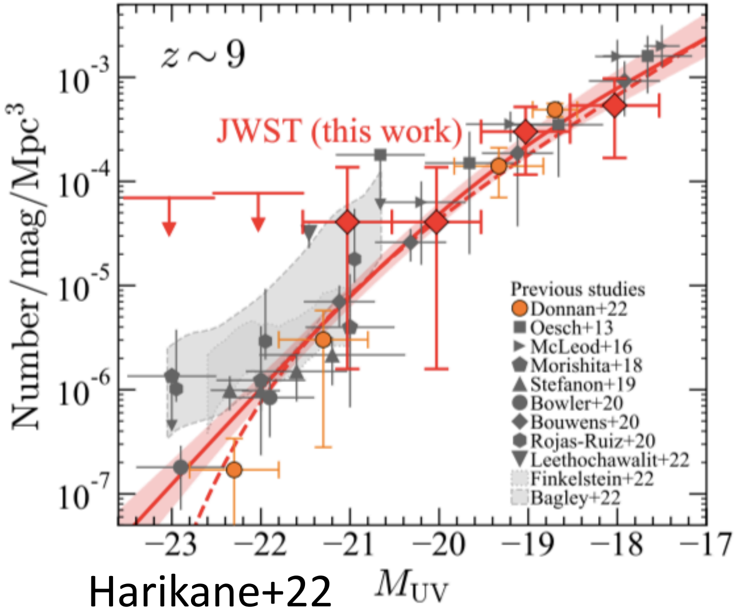


MC+22b ApJL

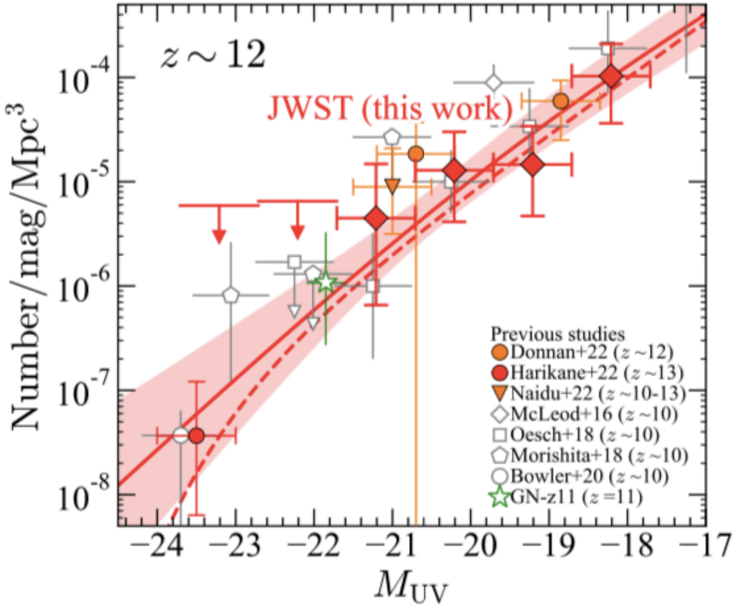




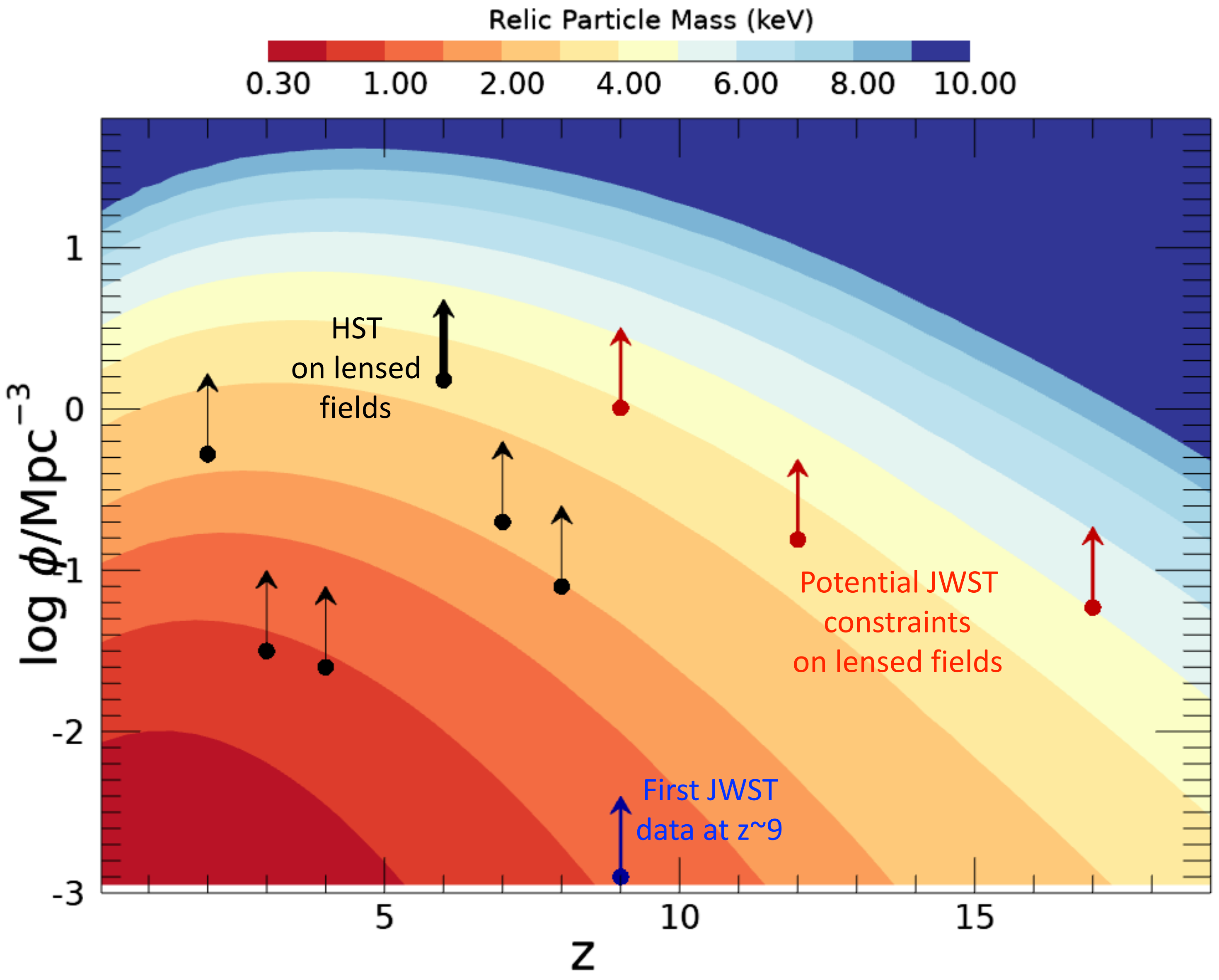




Harikane+22



The future: constraints at cosmic dawn with JWST



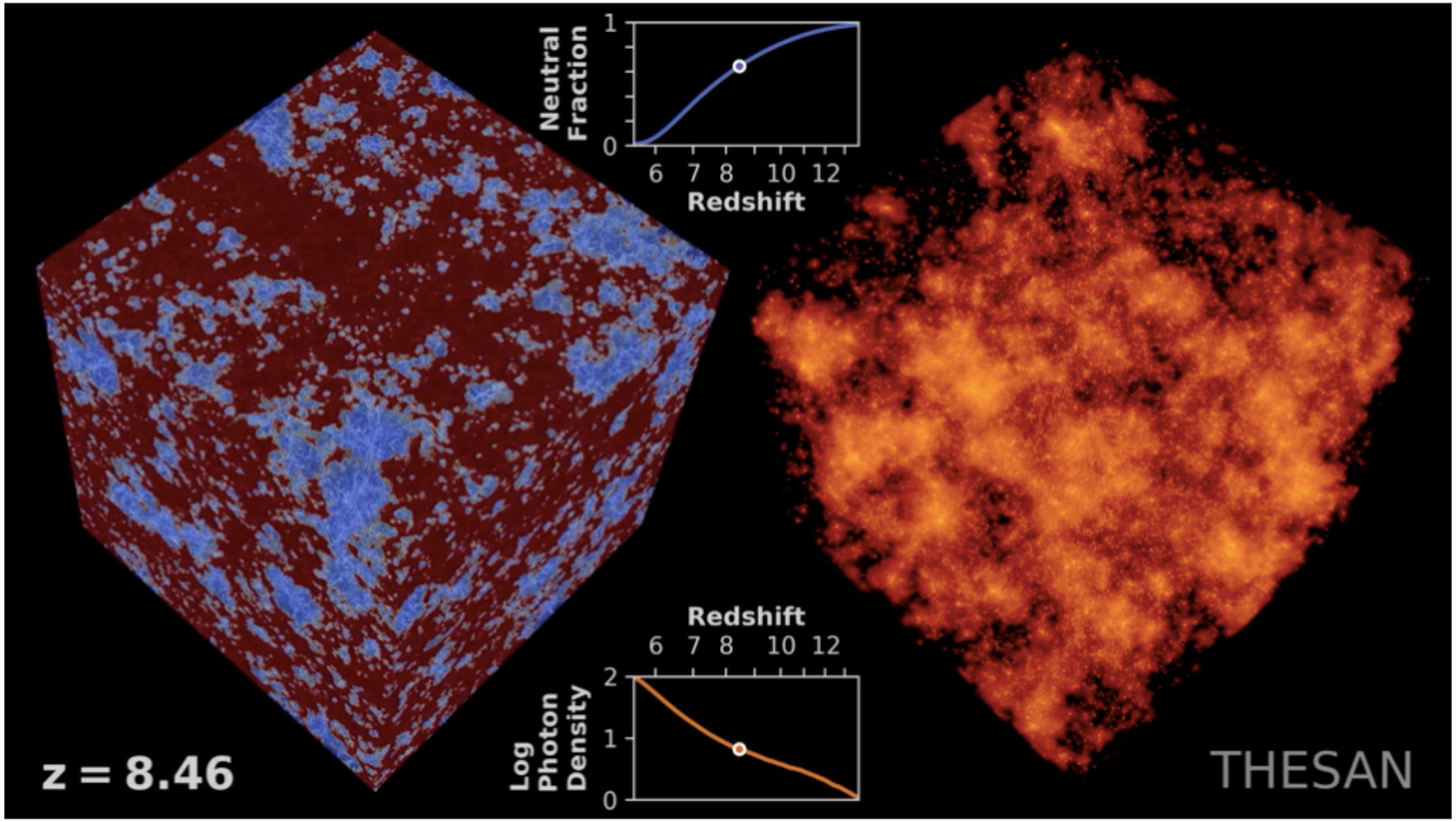
Galaxy number density becomes **more powerful as a probe of WDM at increasing redshift**

New JWST data probe z=9 and beyond, but not deep enough yet (**blue point**)

HST-based estimates (up to z~6, **black points**) are more constraining still

But: similar JWST observations on deep lensed fields (red points) may improve constraints and potentially exclude m_x<4-5 keV

2- The epoch of reionization in WDM models



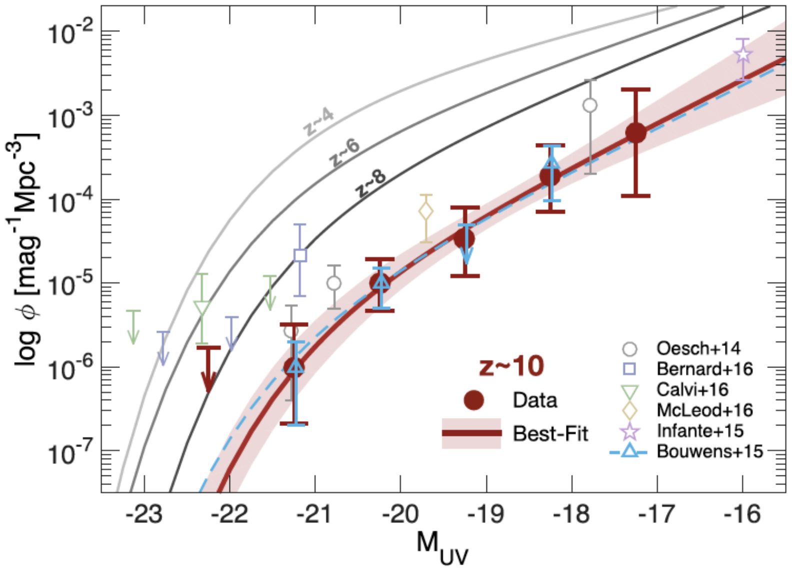
THESAN Project
https://www.thesan-project.com

Kannan+22,
Garaldi+22
Smith+22

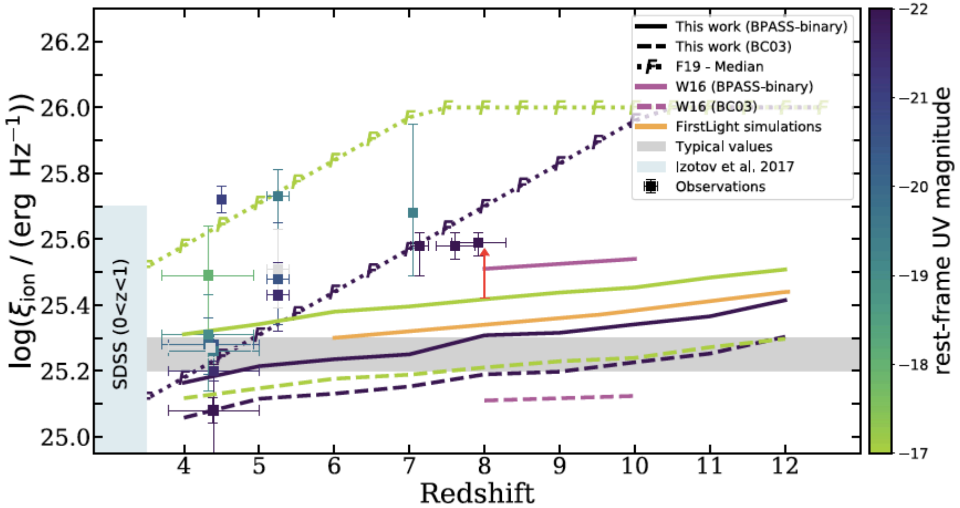
The Epoch of Reionization (EoR) marked a fundamental phase transition in the history of the Universe, during which the Intergalactic Medium (IGM) became transparent to UV photons.

The sources of reionization

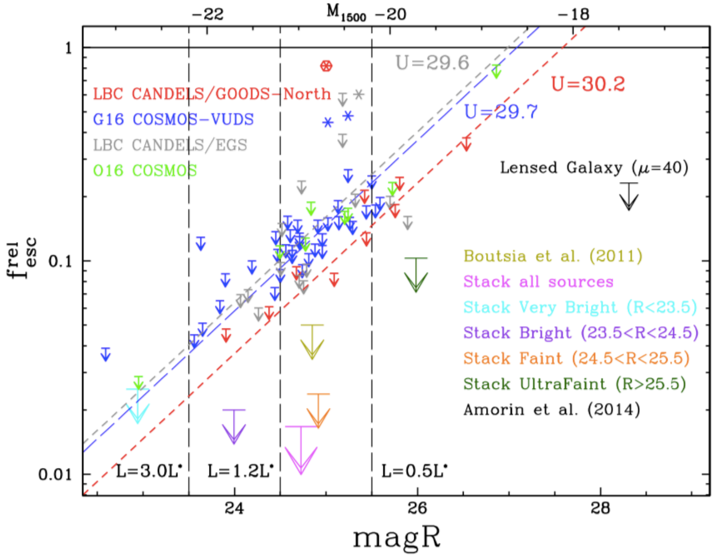
UV Luminosity Density



Ionizing photon production



Escape fraction of ionizing photons



$$\dot{N}_{ion} = \rho_{UV}\xi^*_{ion} f_{esc}$$

$$\dot{Q}_{HII} = \frac{\dot{N}_{ion}}{\bar{n}_H} - \frac{Q_{HII}}{t_{rec}}$$

$\bar{n}_H \approx 2 \times 10^{-7}(\Omega_b h^2/0.022)\ \mathrm{cm}^{-3}$ $\qquad t_{rec} \approx 3.2\ \mathrm{Gyr}\ [(1+z)/7]^{-3} C_{HII}^{-1}$

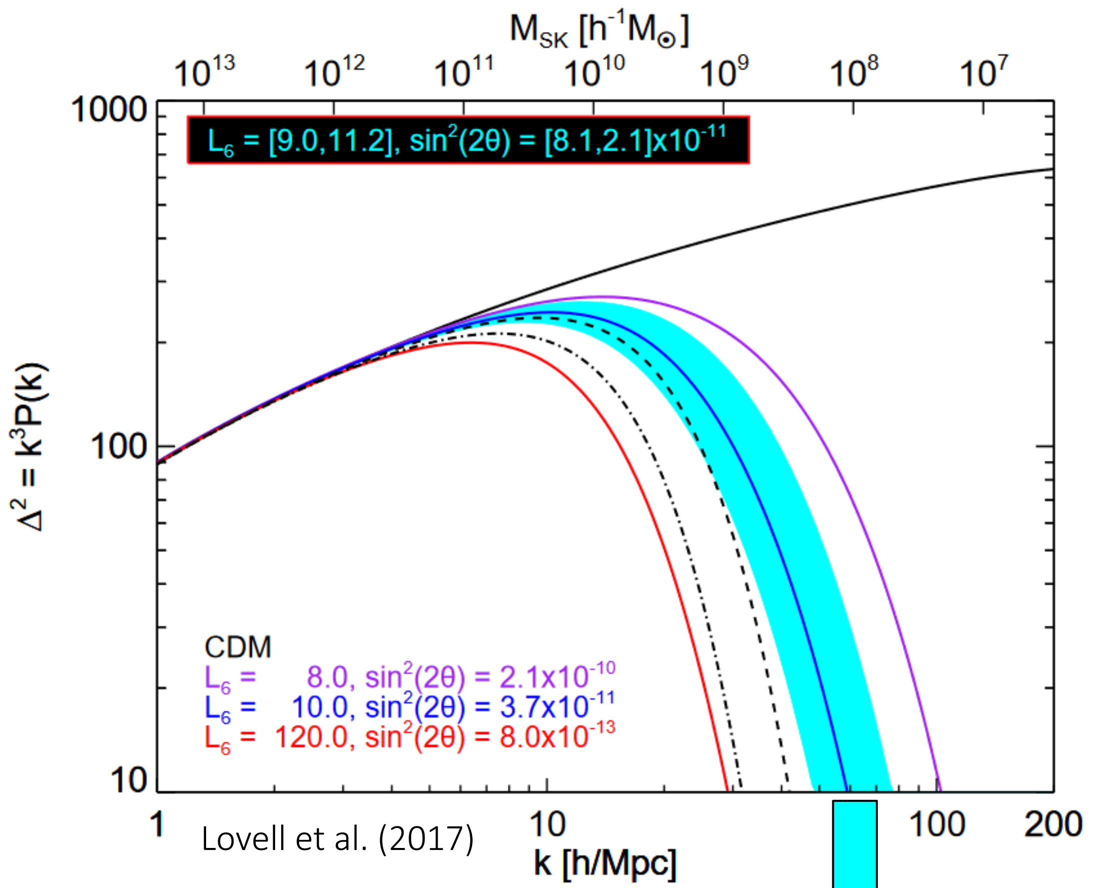
The evolution of the ionized fraction depends on several factors

Dependence on UV luminosity density implies a dependence on the power spectrum, i.e. on DM models

WDM power spectrum

DM model	M_{hm} ($M_\odot$)
LA8	1.3×10^8
LA9	2.6×10^8
LA10	5.3×10^8
LA11	9.2×10^8
LA120	3.1×10^9
WDM 2	1.6×10^9
WDM 3	4.1×10^8
WDM 4	1.6×10^8

From Lovell et al. (2020)



Lovell et al. (2017)

LA9-LA10-LA11 are compatible with 3.5 keV emission line observed towards galaxy-clusters.

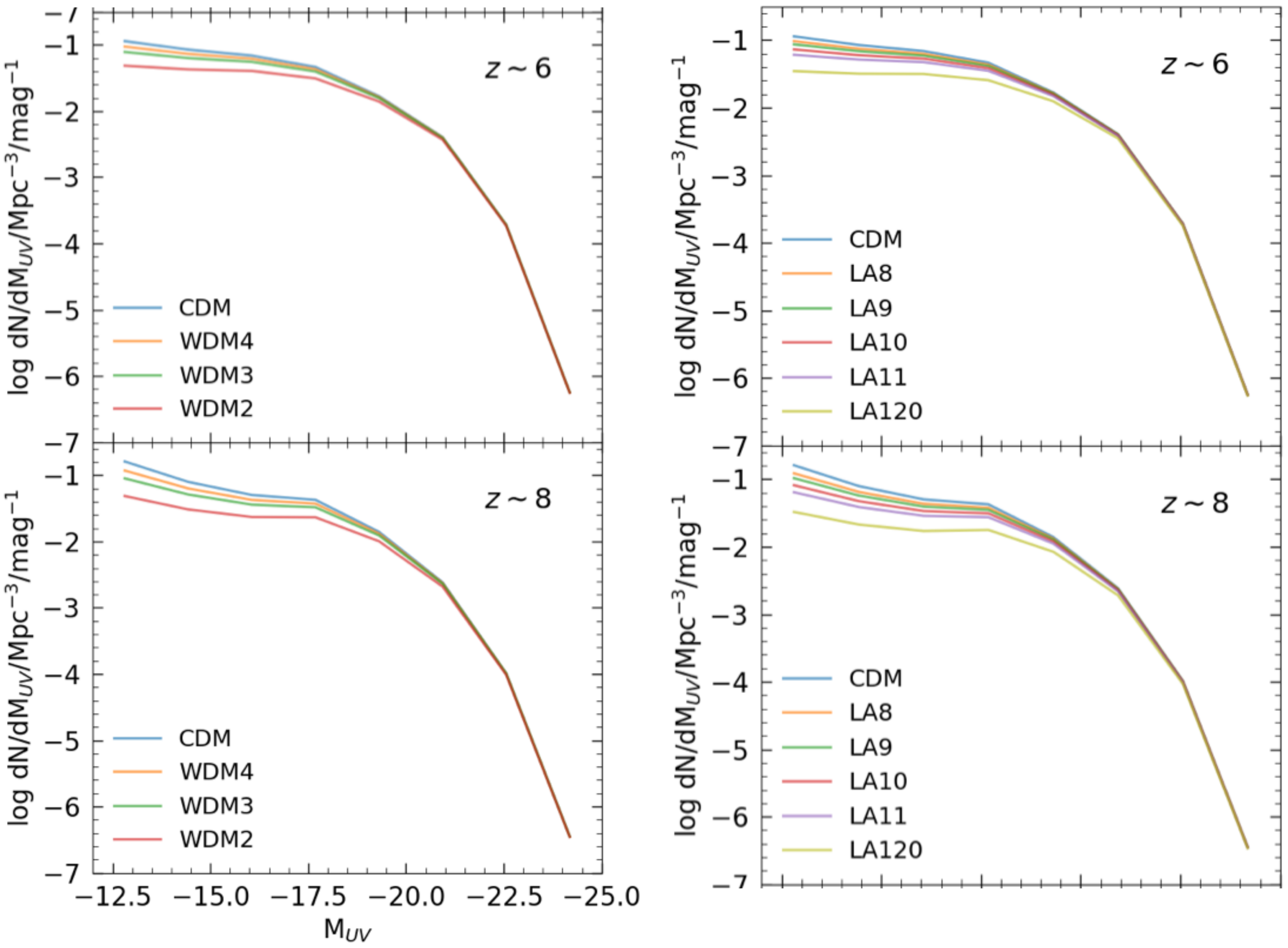
In thermal WDM case the half-mode mass:

$$M_{hm} \approx 3 \times 10^8 \left(\frac{m_X}{3.3\mathrm{keV}}\right)^{-3.33} \mathrm{M}_\odot$$

The UV Luminosity Function

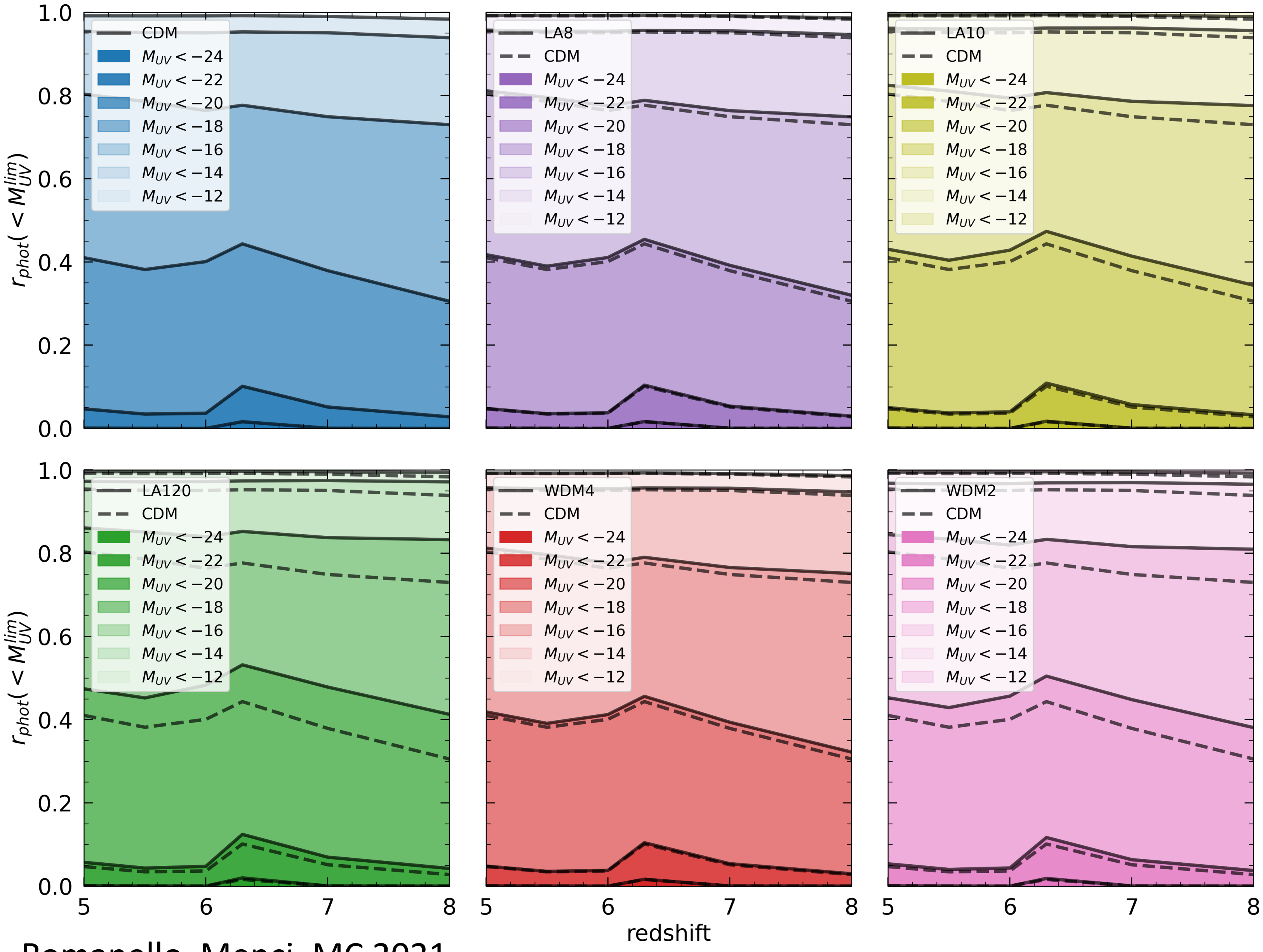
We use the PANDA semi-analytic model (Menci+18) to compute UV LF with CDM and WDM power spectra under several assumptions on galaxy properties

DM model	M_{hm} ($M_\odot$)
LA8	1.3×10^8
LA9	2.6×10^8
LA10	5.3×10^8
LA11	9.2×10^8
LA120	3.1×10^9
WDM 2	1.6×10^9
WDM 3	4.1×10^8
WDM 4	1.6×10^8



Romanello, Menci, MC 2021

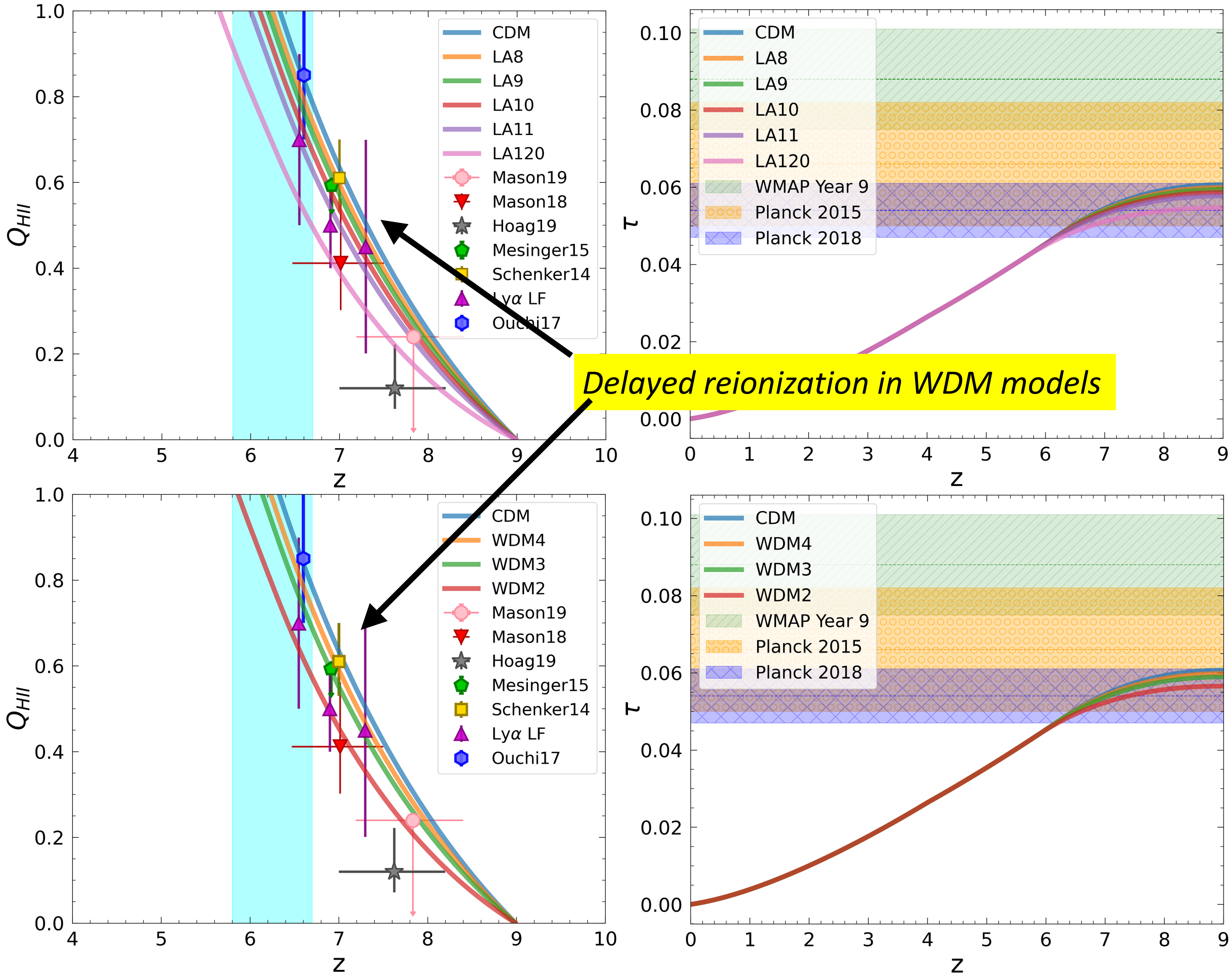
Reionization and UV magnitude



Romanello, Menci, MC 2021

$$r_{phot}(< M_{lim}^{UV}) = \frac{\dot{N}_{ion}(M_{UV} < M_{UV}^{lim})}{\dot{N}_{ion,tot}}$$

1. Role of bright galaxies increases with time.
2. Faint galaxies are suppressed in WDM cosmologies.



Different DM models yield to different reionization histories

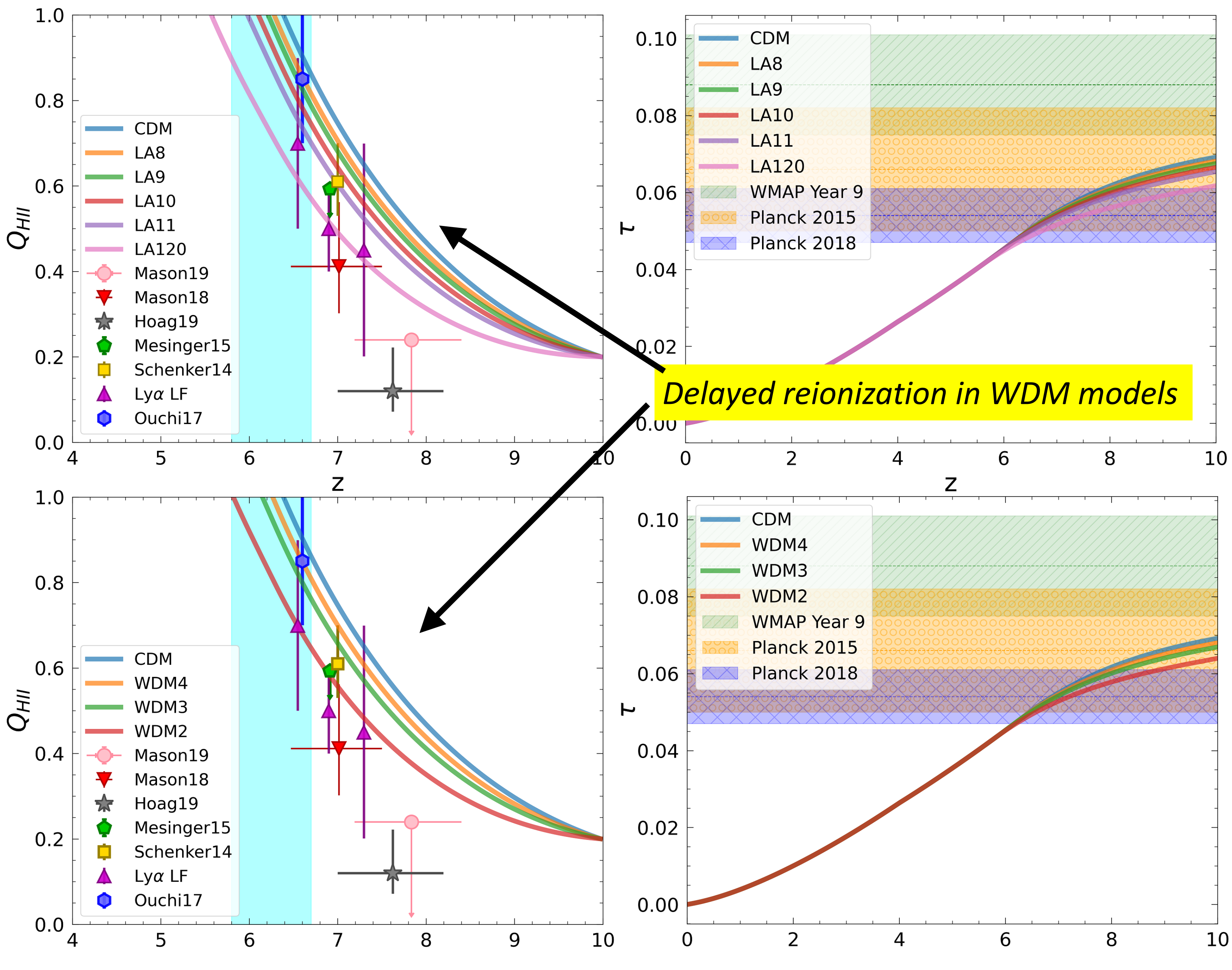
Current constraints are not strong enough to discriminate DM models, due also to degeneracies with galaxy properties (ionizing budget and escape fraction).

Probing highest redshifts with JWST will be fundamental.

$$Q_{HII}(z=9) = 0.0$$

$f_{esc} = 6\%$

Romanello, Menci, MC 2021



Different DM models yield to different reionization histories

Current constraints are not strong enough to discriminate DM models, due also to degeneracies with galaxy properties (ionizing budget and escape fraction).

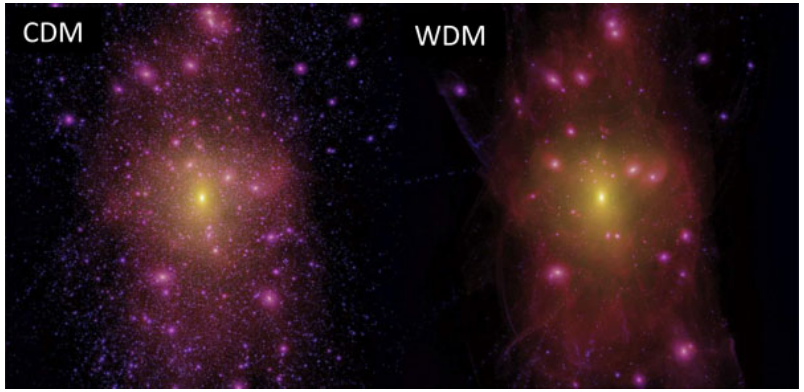
Probing highest redshifts with JWST will be fundamental.

$$Q_{HII}(z=10) = 0.2$$

$f_{esc} = 6\%$

Romanello, Menci, MC 2021

Summary and conclusion



- The abundance of faint galaxies at z~5-7 yields strong constraints on DM models
- m_X>2.4 keV for thermal relics at 2-σ level
- Sterile neutrinos from resonant production: unprecedented lower limits for $\sin^2(2\vartheta)$ as a function of $m_{sterile}$. E.g., for $m_{sterile}$=7 keV we obtain $-10.4 < \log \sin^2(2\vartheta) < -9.8$ at at 2-σ level

- The impact of faint-galaxies ($M_{UV} > -20$ or $M_{halo} < 10^{10.5} M_{sun}$) is dominant during the EoR (z>6)
- WDM scenarios yield to an overall reduction of the ionizing photons and to a delay in Reionization process with respect to CDM
- Future JWST observation will be fundamental to constrain WDM models with very high-redshift galaxies