A Review: Signatures of Warm Dark Matter in Reionization, 21-cm, First Galaxies

Anastasia Fialkov
Harvard

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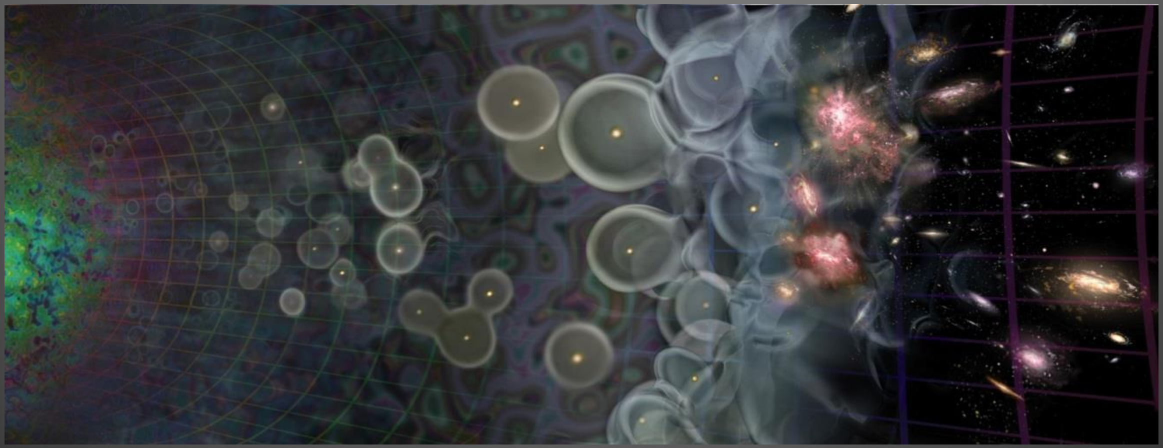
Outline

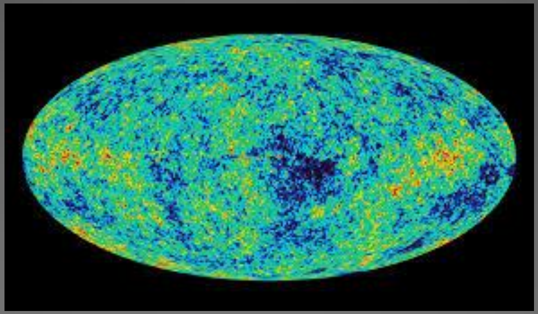
- The early Universe (overview)
- Effect of WDM on:
  1. Number Counts
  2. Star formation
  3. Thermal history and Reionization
  4. 21-cm signal



Today: Golden Age of Astronomy, Cosmology and Astrophysics

The Universe

Unobservable
Universe
(optically thick)



Observable
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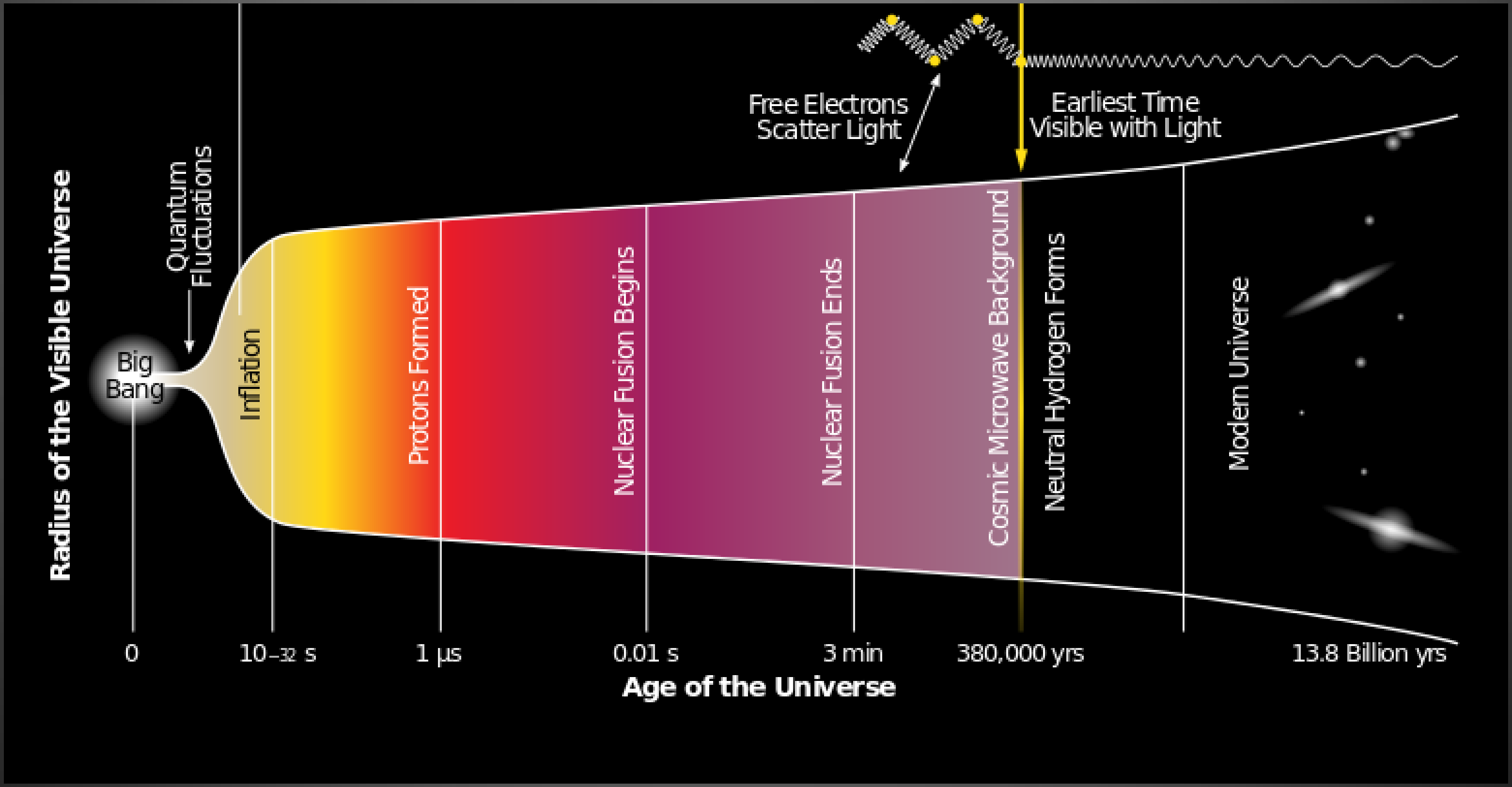
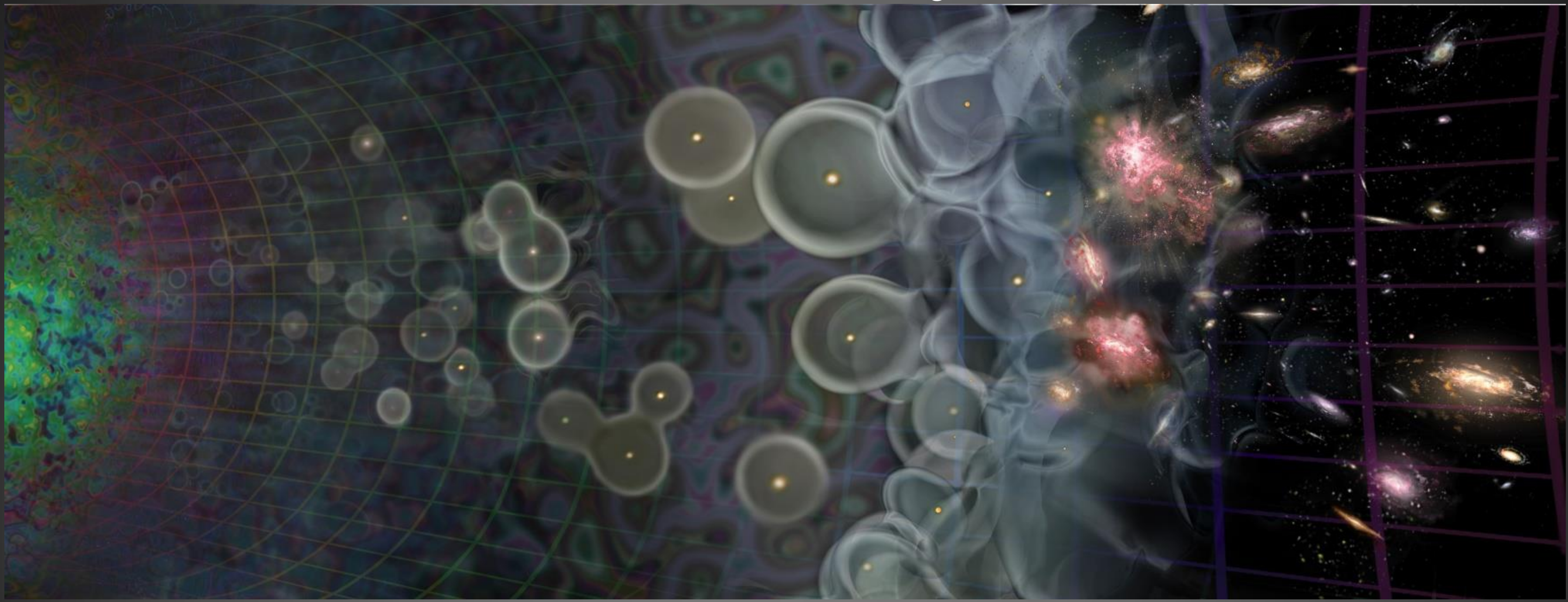


The Observable Universe

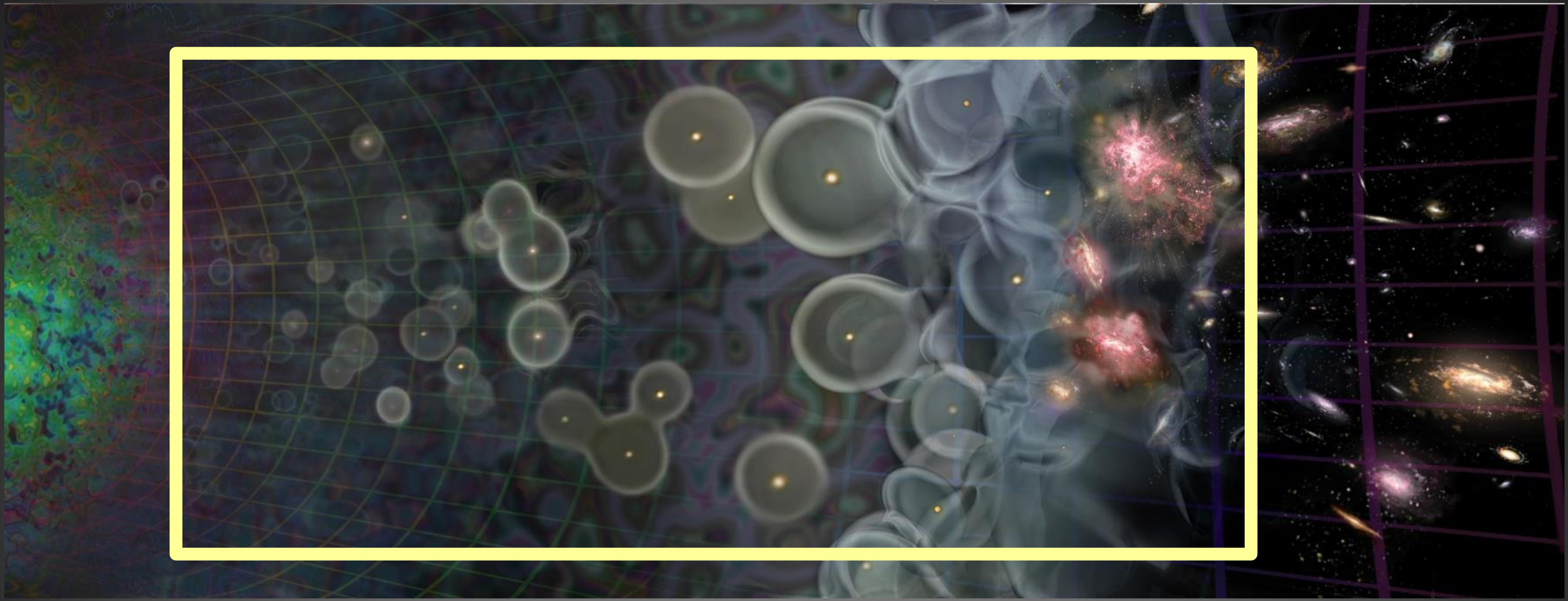
Image: Loeb, Scientific American 2006



CMB
Dark Ages
First stars & galaxies
Reionization
Large Scale Structure

Unobserved Part of the Observable Universe

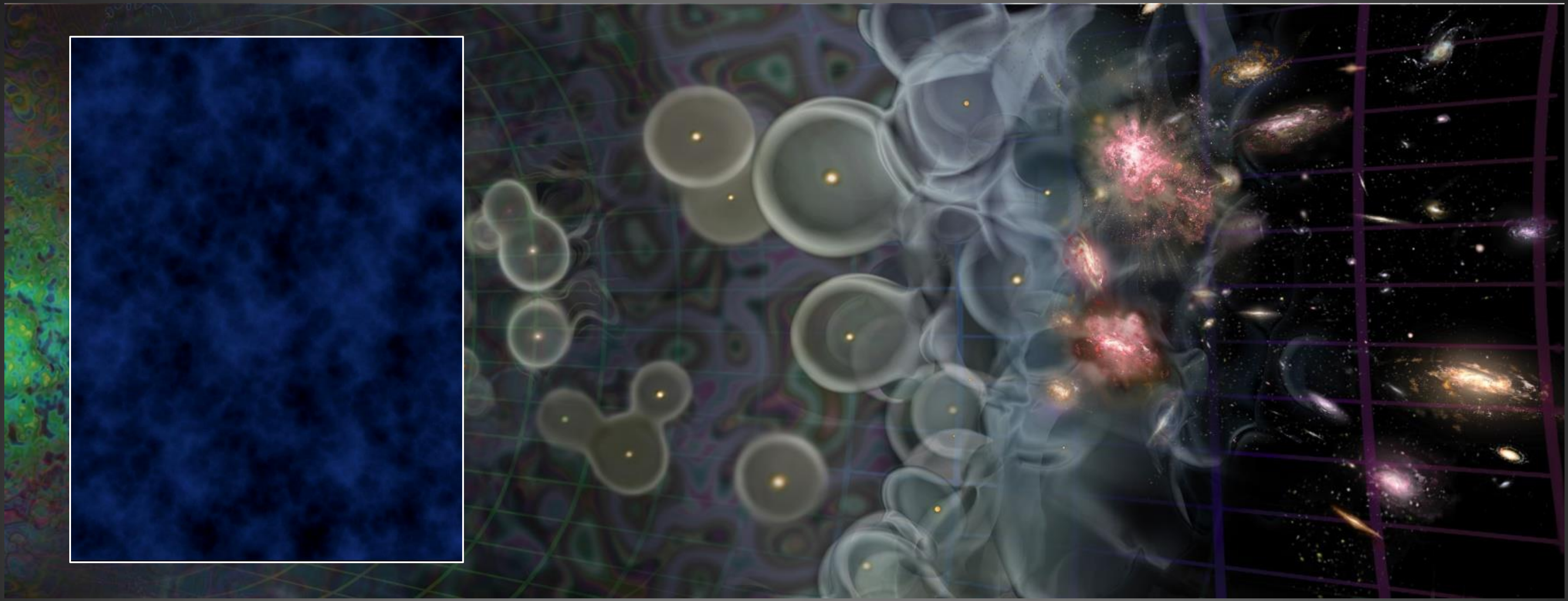
Image: Loeb, Scientific American 2006



Dark ages First stars & galaxies Reionization

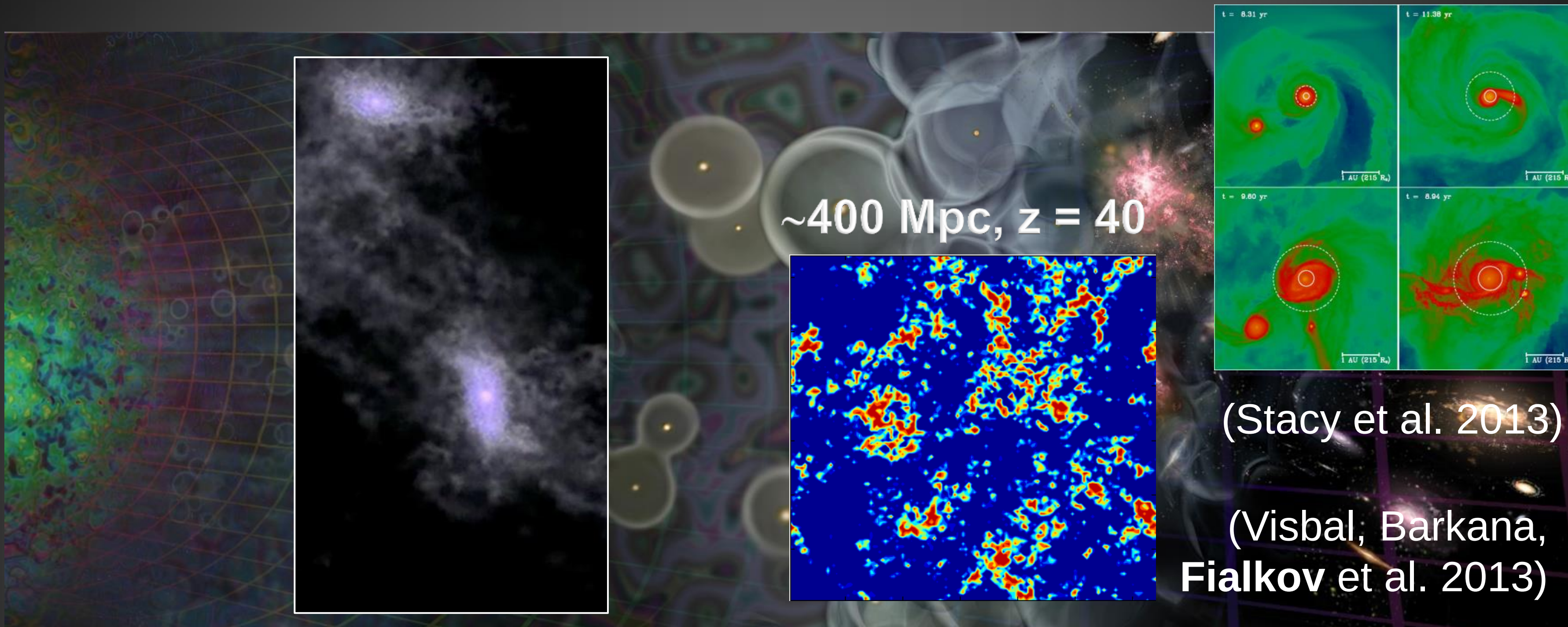
What can we learn about Dark Matter from Future Observations at Higher Redshifts?

Dark Ages



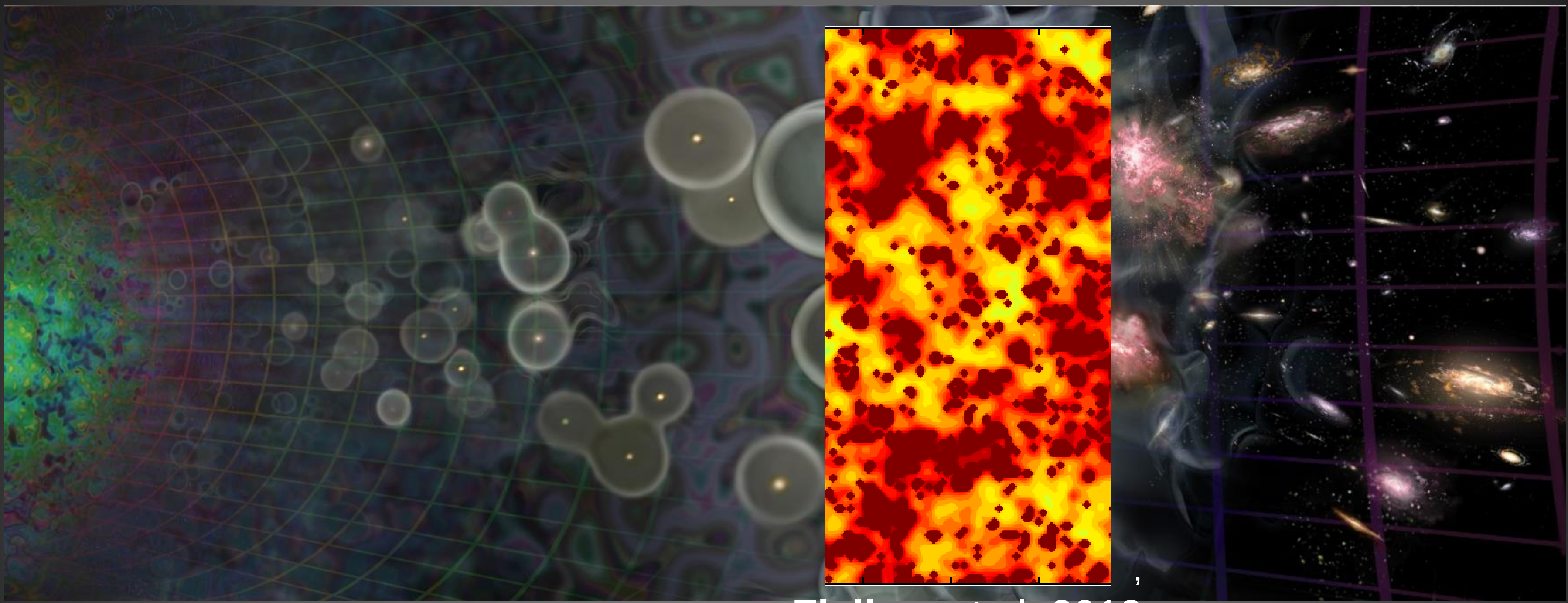
- Universe expands and cools
- Large scale density fluctuations grow linearly
- No stars

Cosmic Dawn: First Stars and Galaxies



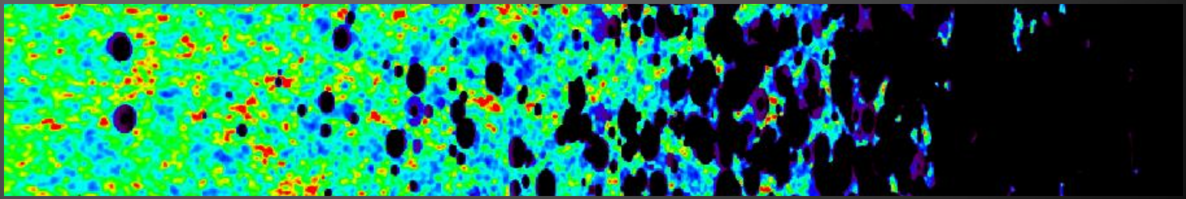
- First halos collapse, star formation starts at z ~ 65 (majority form at z < 30)
- Primordial star formation in minihalos : H or H_2 cooling
- Stars are rare at high redshifts (biased by δ_{LS} and v_{bc})

Reionization



,
Fialkov et al. 2013

- Radiation from stars and quasars gradually (re-) heats and (re-) ionizes intergalactic gas
- Ionization bubbles



Plethora of Open Questions

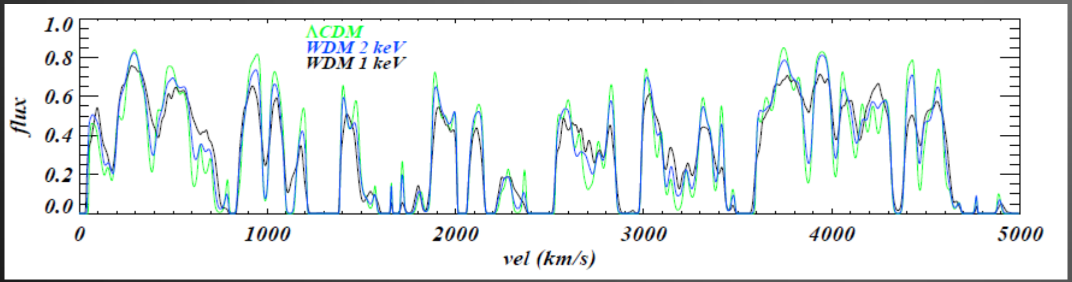
Some of the unknowns:

- What were the masses of first stars and star forming halos?
- How efficient was star formation?
- How first stars ended their lives?
- What was the dominating heating mechanism?
- How efficient were the stars in ionizing the gas?
- How efficient were radiative and mechanical feedbacks?
- How metal enrichment proceeded?
- Were there any exotic processes (e.g., dark matter annihilation)?
- What is the nature of ~ 85 % of matter??

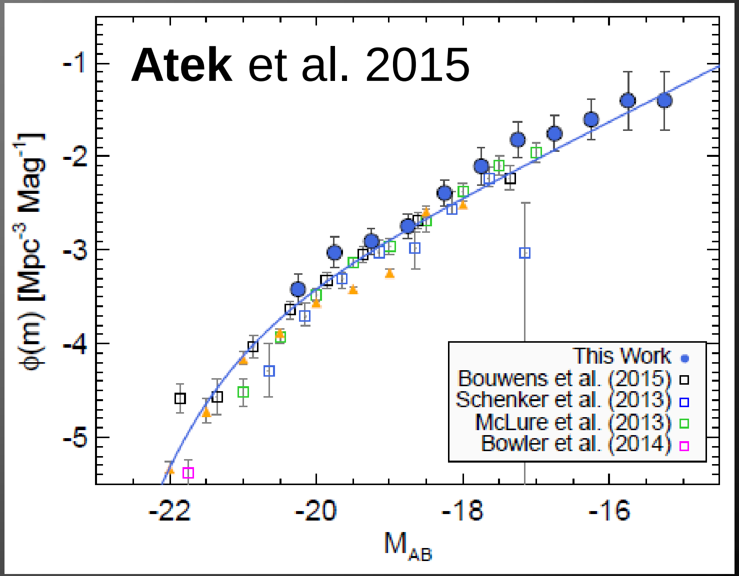
Current WDM Constraints

- Abundance of observed ultra-faint satellites: $m_X > 1.5 - 2.3$ keV (Polisensky & Ricotti 2011, Lovell et al. 2012, Horiuch et al. 2014, Kennedy et al. 2013)
- UV LFs of faint galaxies at $z{\sim}6$: $m_X > 1$ keV (Schultz et al. 2014) & $m_X > 2.9$ keV (Menci et al. 2016)
- Lyman-a forest of z > 4 quasar spectra: $m_X > 3$ keV (Viel et al. 2013).
- Number density of high-z galaxies: $m_X > 0.9 - 1.5$ keV (Pacucci et al. 2013, Lapi & Danese 2015).

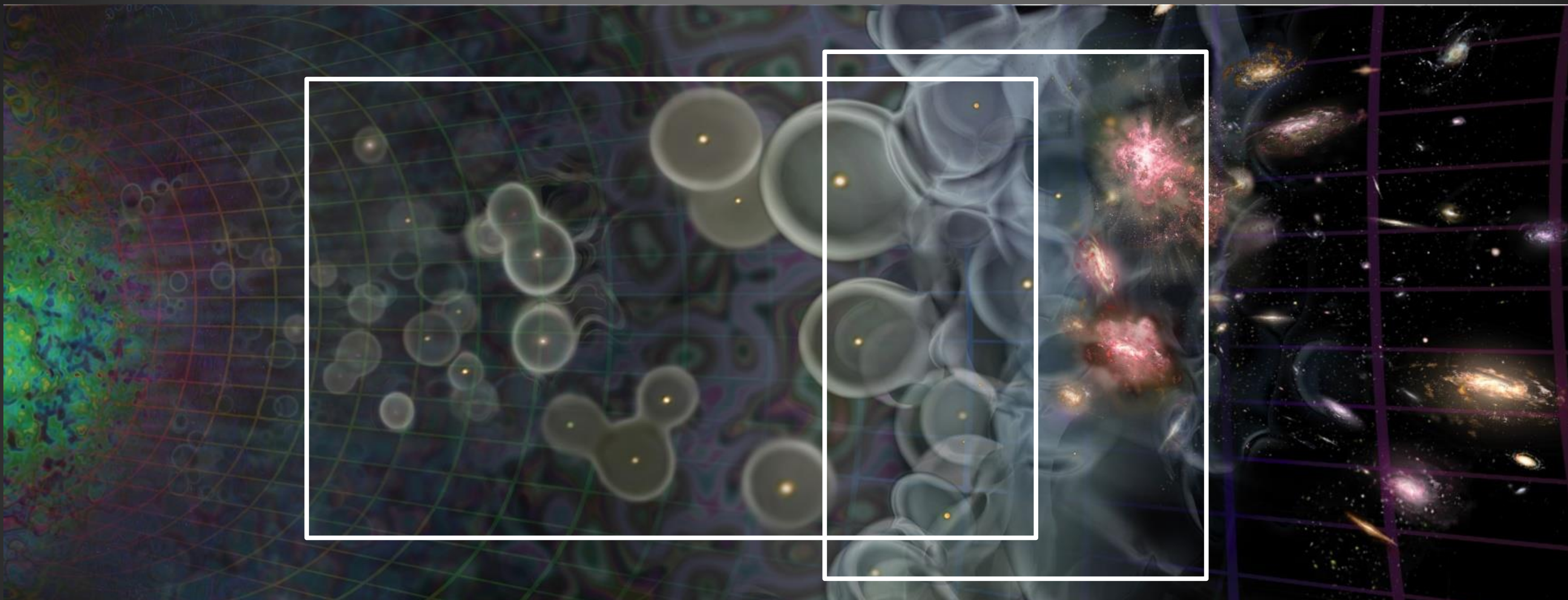
Transmitted flux along a set of random LOSs for models at z = 4.6.



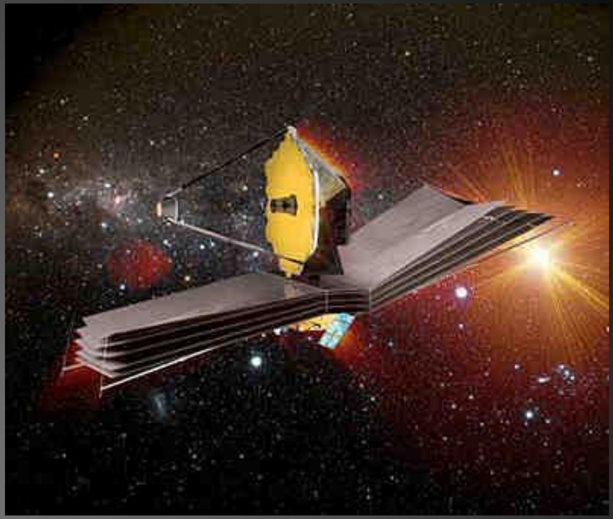
Viel et al. 2013



Future observations of the early Universe could answer some of these questions

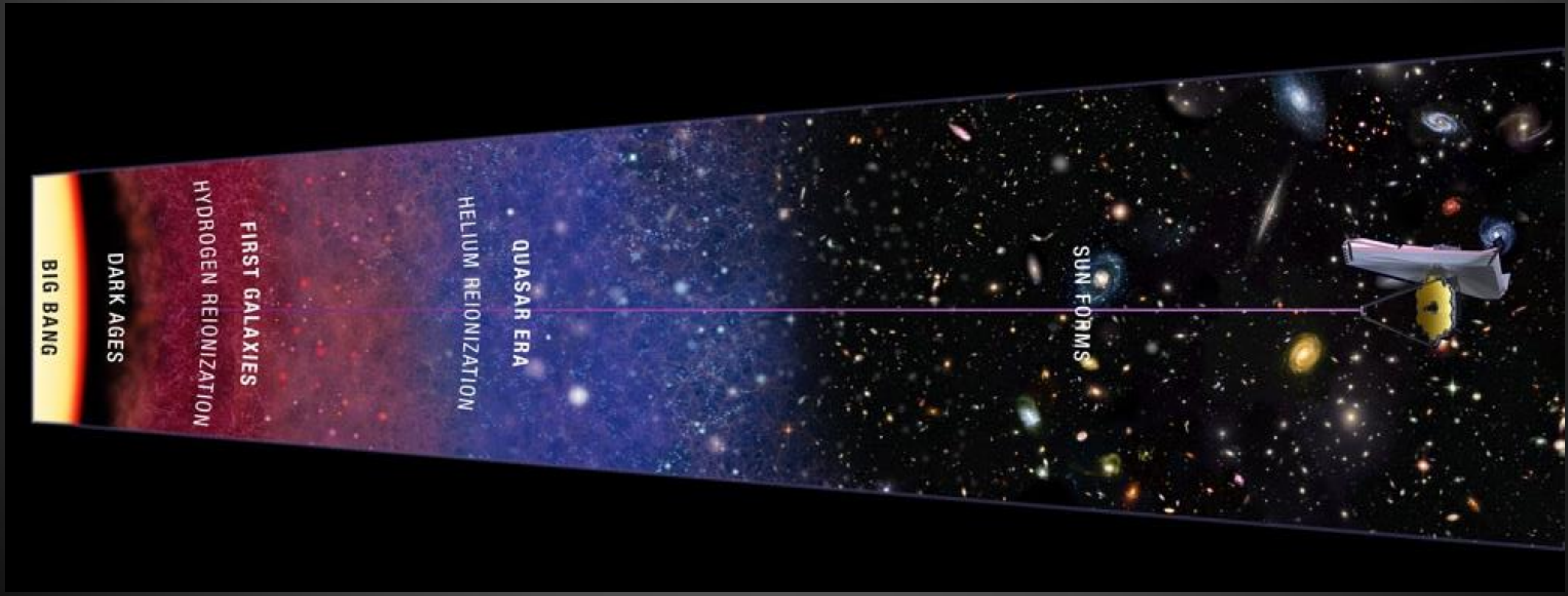


Seeing the First Galaxies



JWST - a powerful time machine (IR) that will peer back over 13.5 billion years to see the first stars and galaxies forming out of the darkness of the early universe.

Probe galaxies during reionization

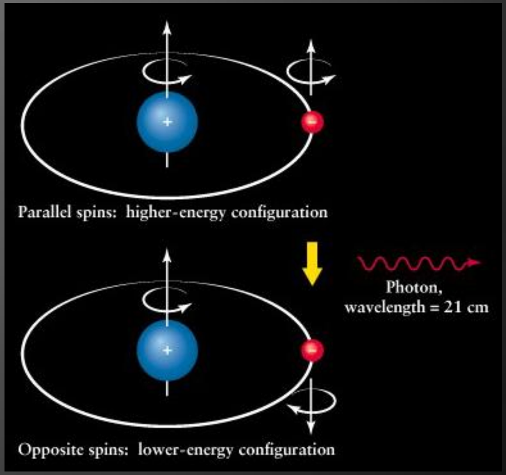


21-cm Signal of HI

Image: Loeb, Scientific American 2006

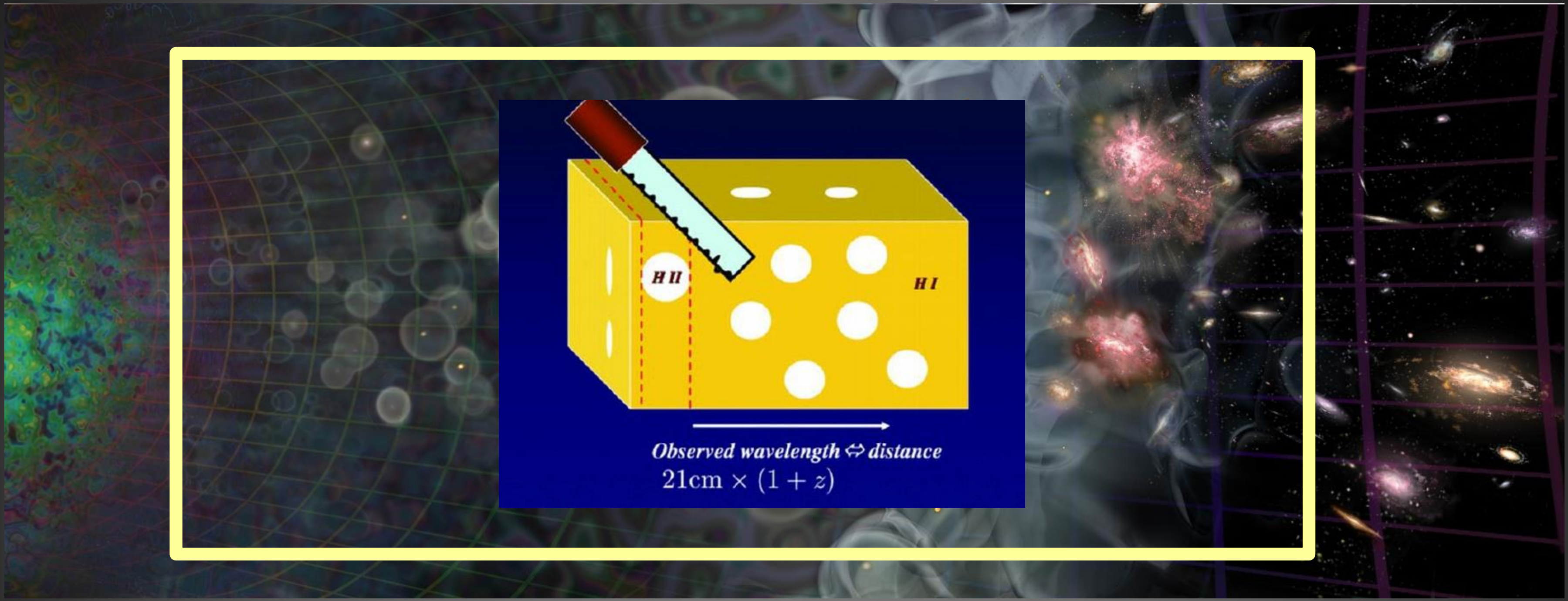
High-z Universe is mostly filled with HI
HI emits 21-cm signal, probe of

- Dark Ages
- Cosmic Dawn
- Reionization



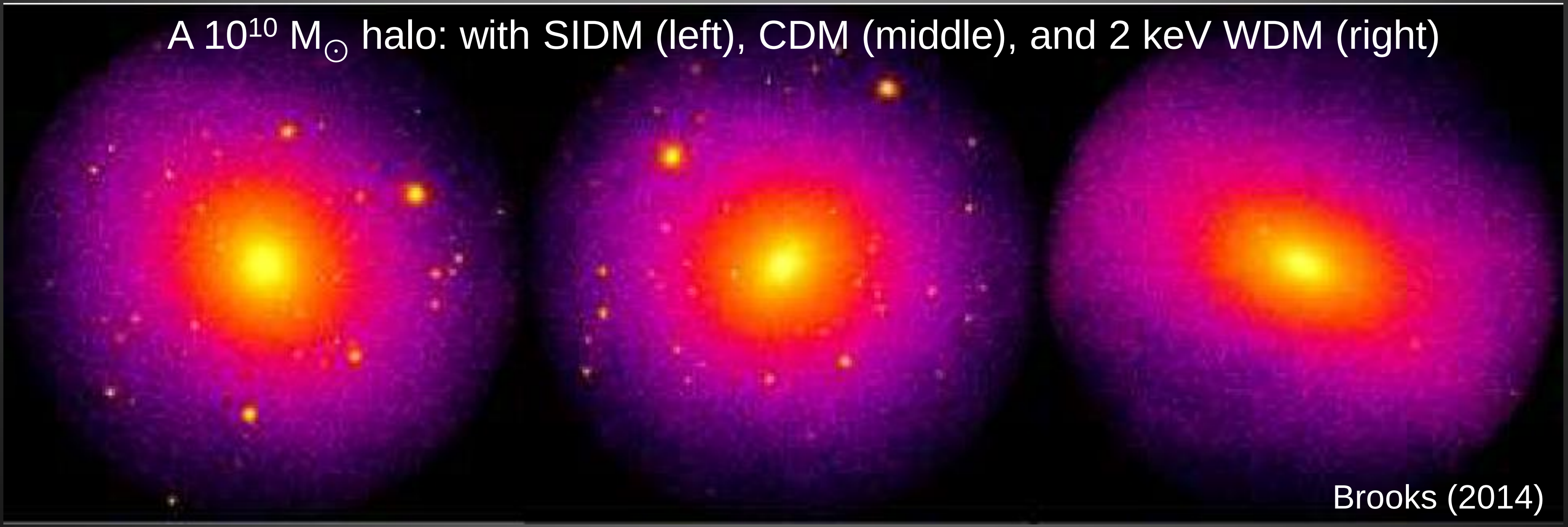
Promising tools

Image: Loeb, Scientific American 2006



- 3D picture of the Universe
- Probe of small scale structure (no Silk damping)

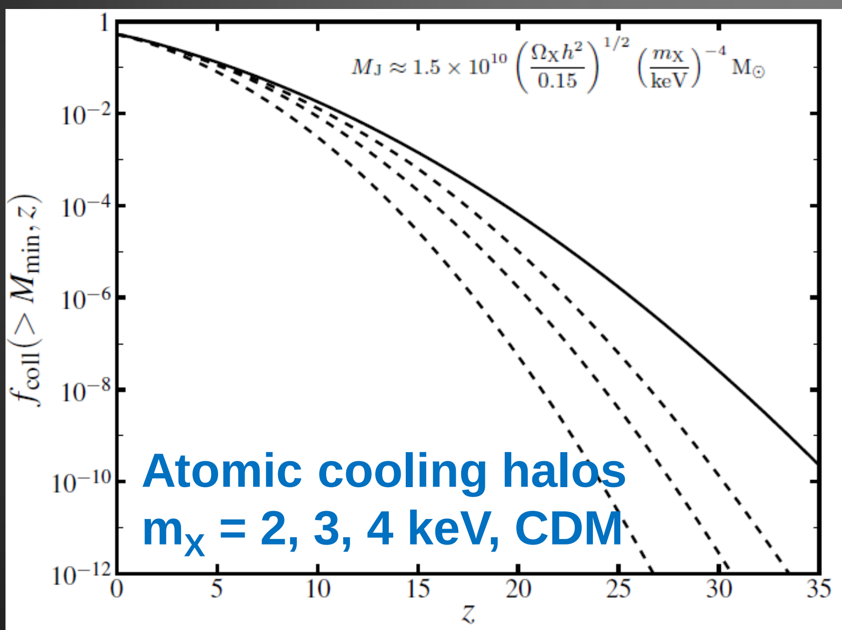
Probes of Warm Dark Matter in the Early Universe



Abundance of Dark Matter Halos

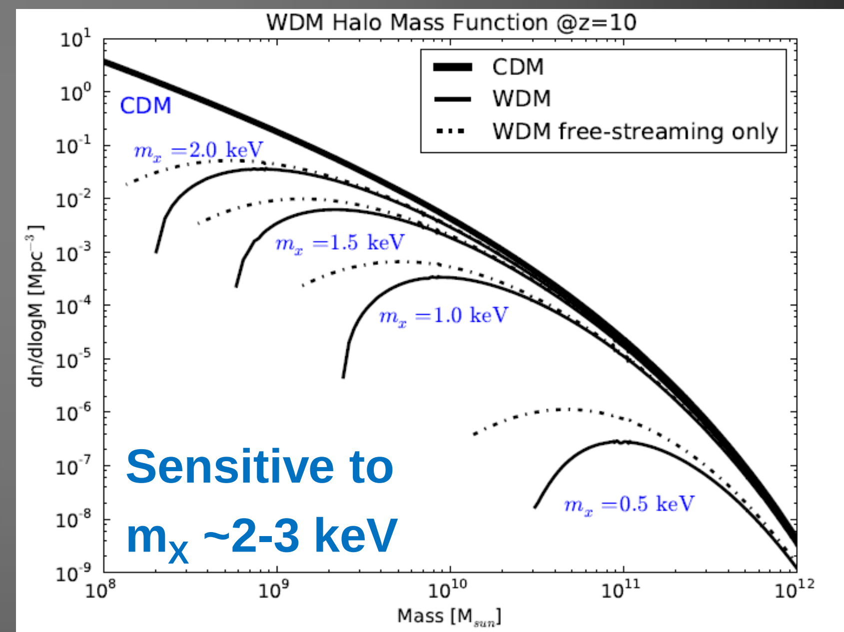
- WDM: Decrease in the number density, no small galaxies.

Collapsed fraction



Sitwell, Mesinger, Ma, Sigurdson 2014

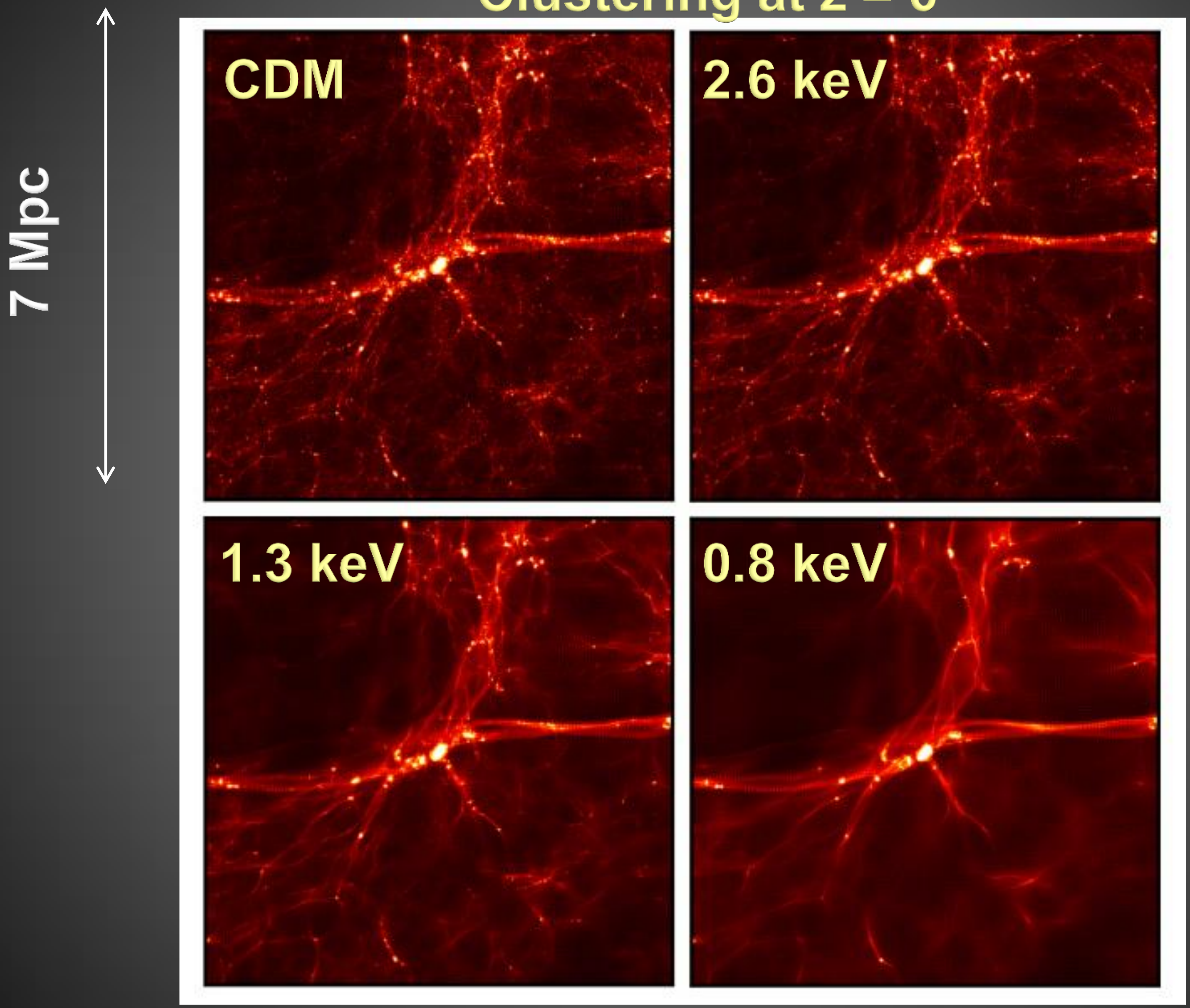
Number counts at z = 10



Pacucci, Mesinger, Haiman 2013

WDM: Structure formation on small scales is suppressed

Clustering at z = 6



Schultz et al. 2014

First Stars

The First Billion Years of a Warm Dark Matter Universe

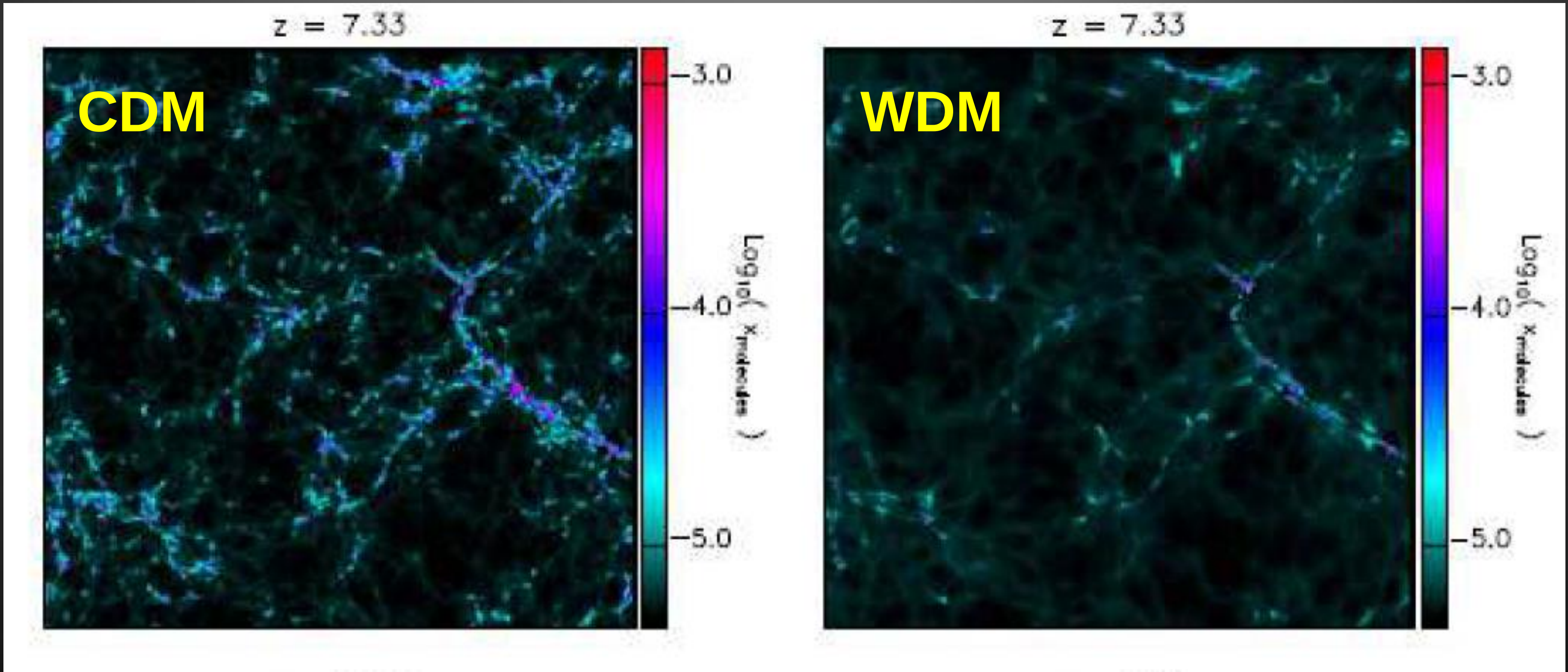
Umberto Maio[1,2⋆], Matteo Viel[1,3]

"The most striking effect of WDM results to be a
dramatic drop of star formation activity
in the whole first billion years.
$\Delta z = 6$ (0.1 Gyr) delay in collapse and star formation"

First Stars

- WDM: no minihalos, H_2 cooling in WDM haloes (> 3 keV) is inhibited
- CDM: more intense star formation activity, more advanced stages of collapsing material (effects of shocks, winds and thermal heating)

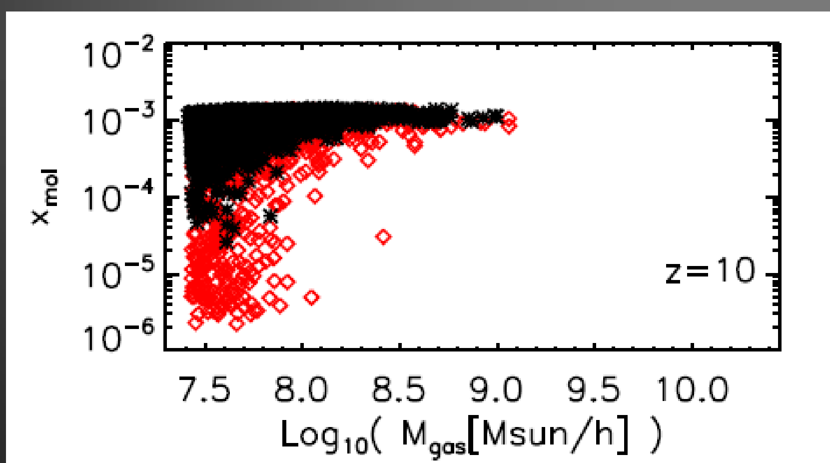
Molecular Fractions, >3 keV

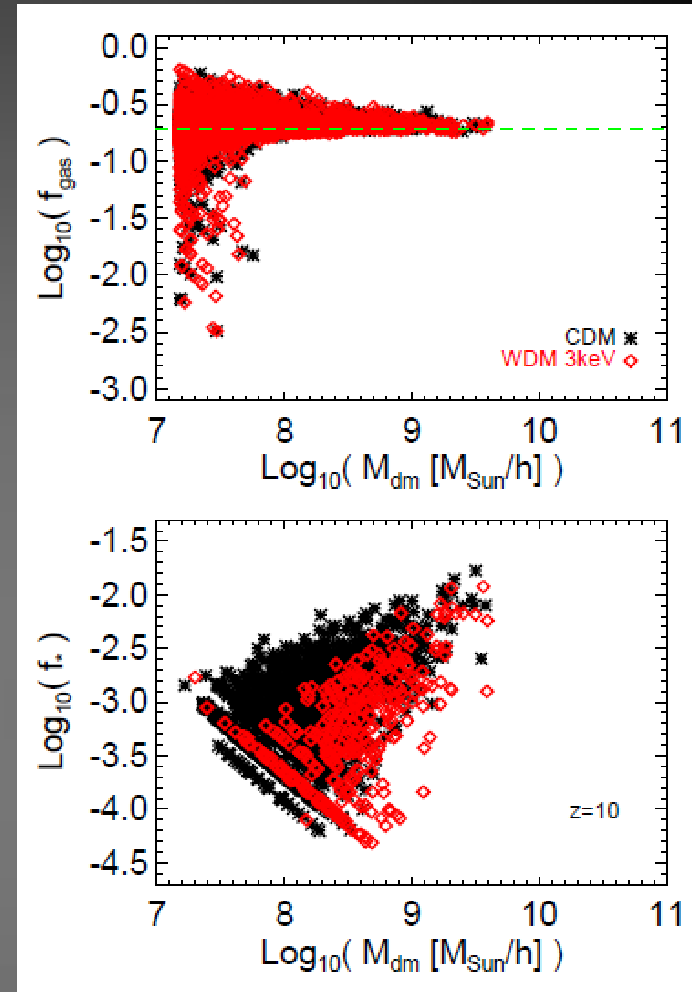


Maio & Viel (2014)

First Stars : WDM vs CDM

- Luminous objects in WDM are very rare at z > 10
- Less halos exist, more halos form stars
- Gas fraction is more sensitive to local baryon physics than to the nature of the hosting dark matter structure.
- Star production, molecules in CDM is enhanced with respect to WDM





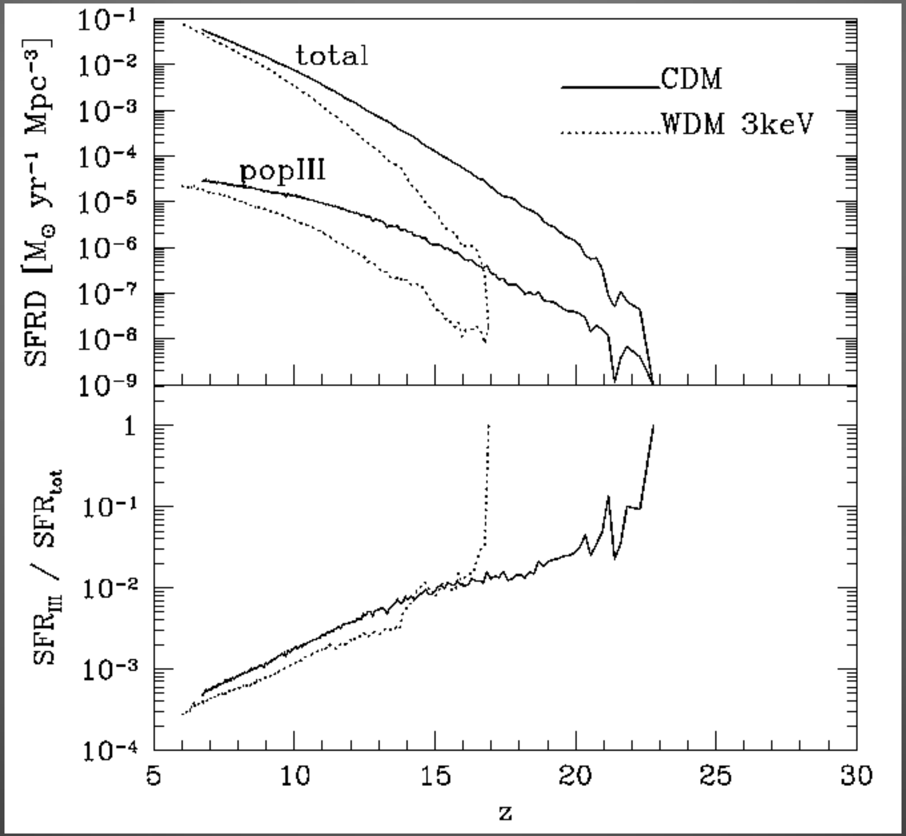
Fraction of star hosting haloes in CDM and WDM models.

Redshift	CDM	WDM
$z = 7$	67 %	70 %
$z = 10$	43 %	55 %
$z = 15$	17 %	40 %

Maio & Viel (2014)

Pop III, SFR is suppressed in WDM

CDM : metal pollution starts earlier, host halos are small.
WDM : larger halos, more gas turns into stars and can experience more chemical feedback. Enrichment takes place suddenly. PopIII contribution drops down fast.

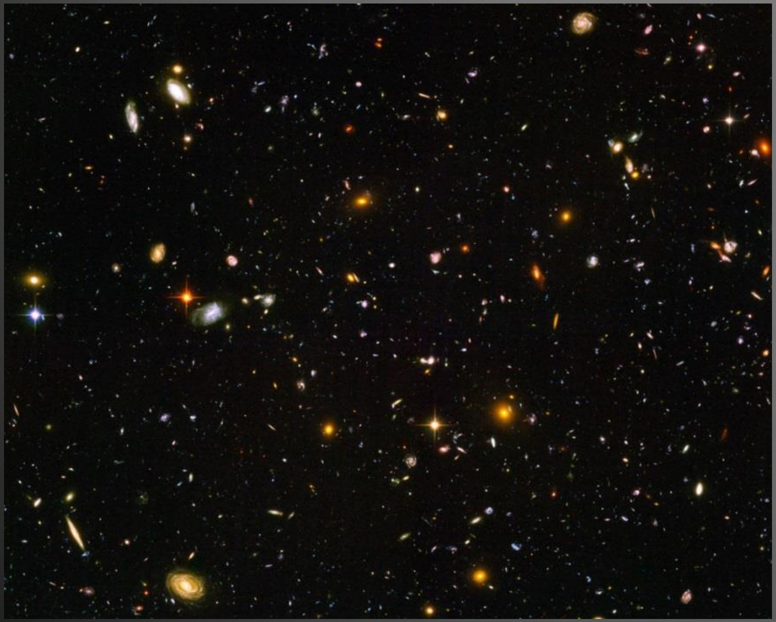


Maio & Viel (2014)

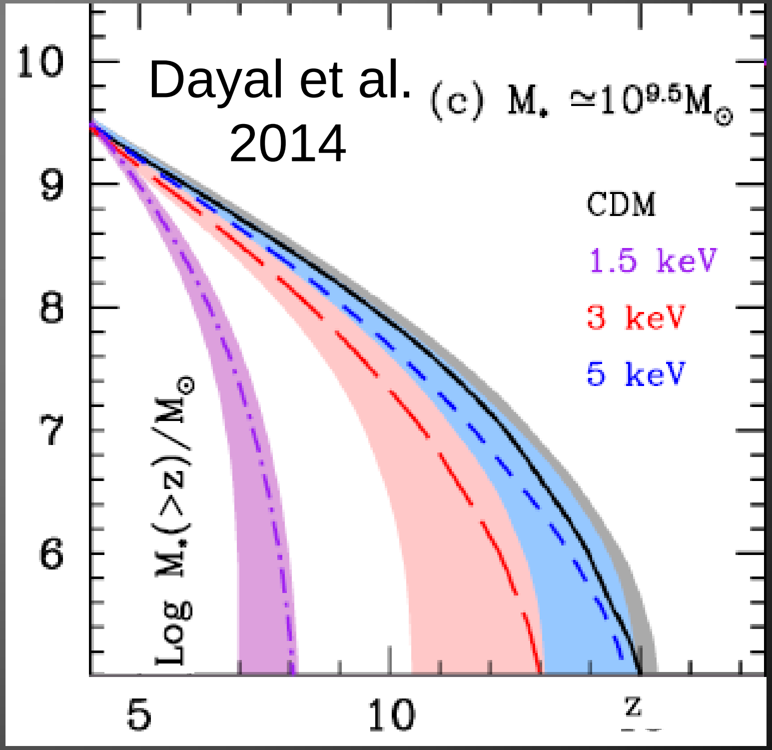
Stellar Mass in the Universe

- Galaxies in WDM models form later.
- Assemble their stars more rapidly compared to CDM.
- Younger, more UV luminous stellar population.
- Sudden star formation activity in massive halos

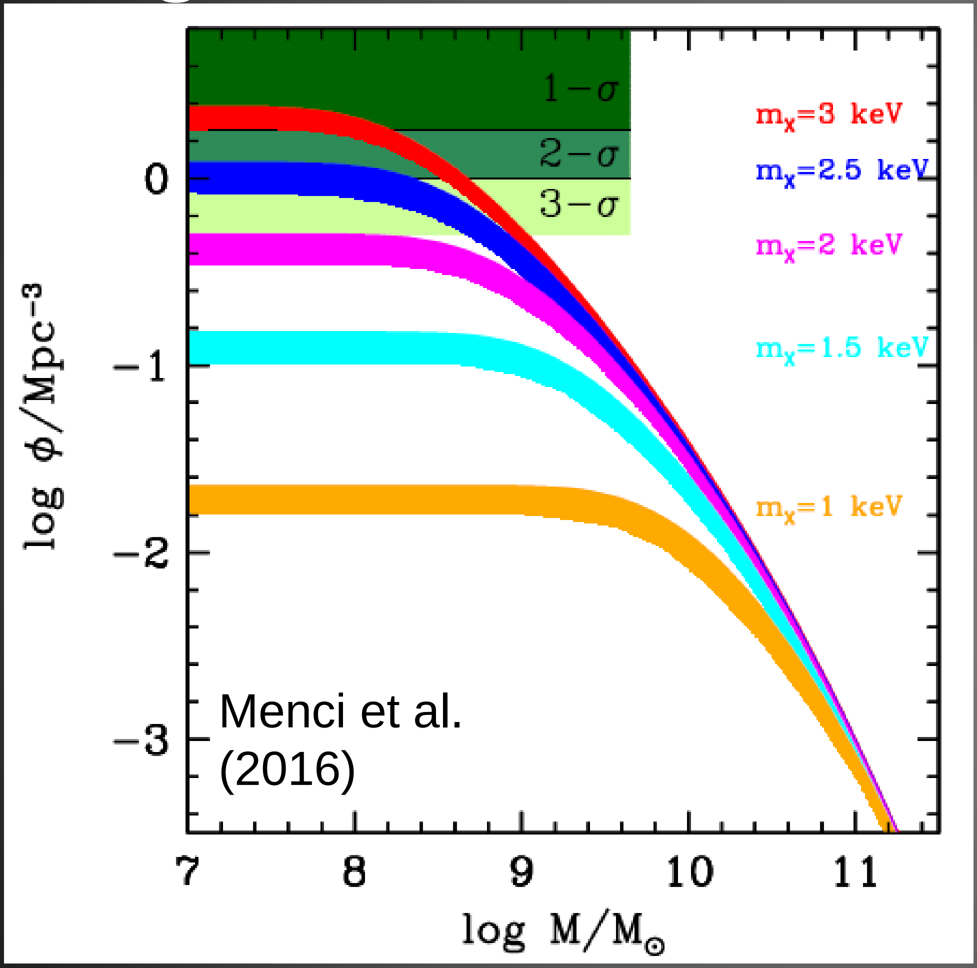
Average stellar mass assembly of galaxies as a function of z

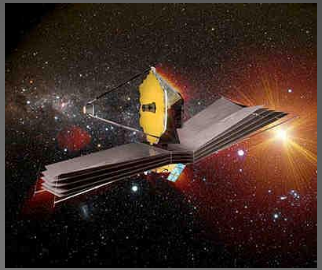


HUDF

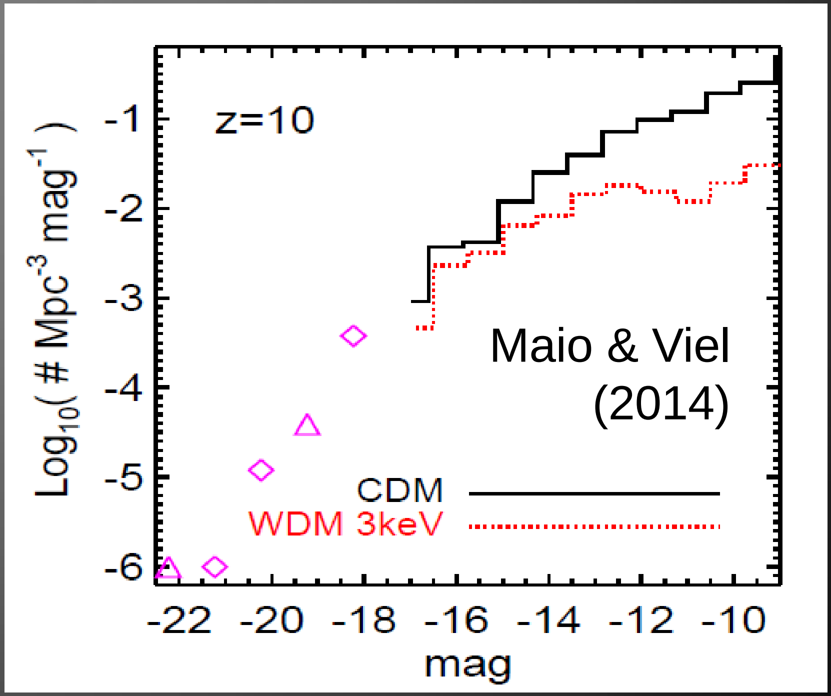


Effect on the Luminosity Function at High Redshfts





Faint galaxy counts at higher redshift are sensitive to WDM scenario



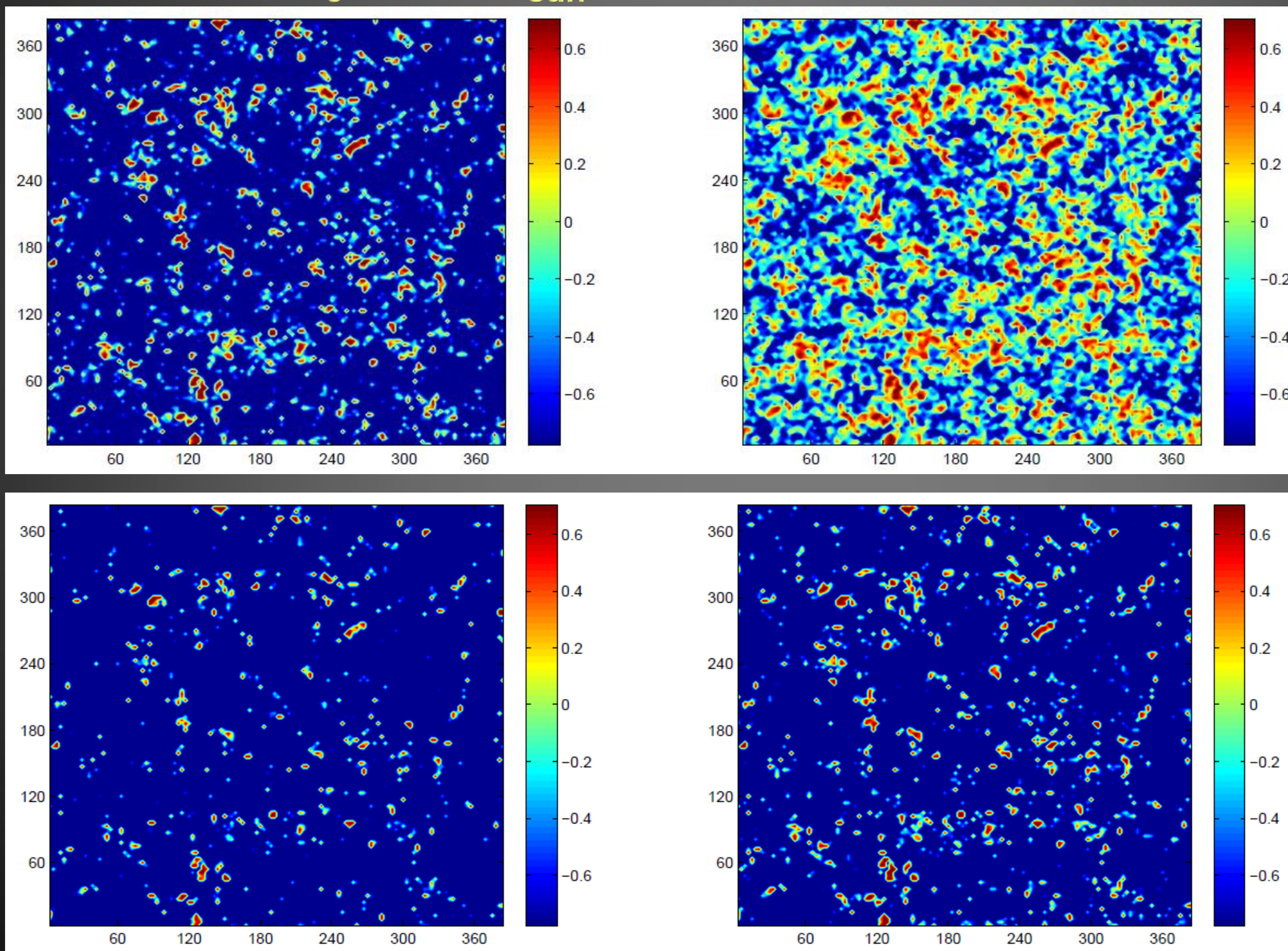
Predicted number density of galaxies brighter than $M_{AB} < -12.5$, z~6

Feedback + CDM is similar to WDM

Collapsed Fraction at z = 10, Fluctuations

WDM, 3 keV, $M_J \sim 10^9\ M_{sun}$

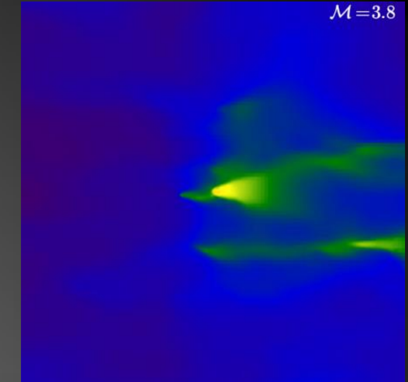
CDM



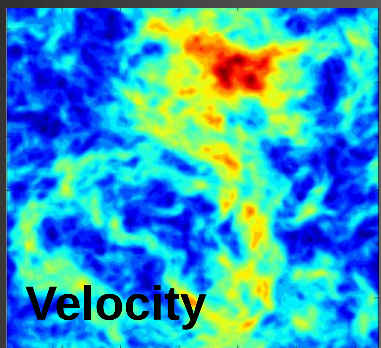
Atomic cooling
$M > 10^7\ M_{sun}$

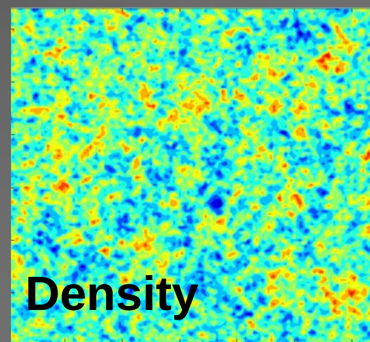
Star formation
in heavy halos
$M > 10^{10}\ M_{sun}$

Sources of Astrophysical Uncertainties



Initial conditions



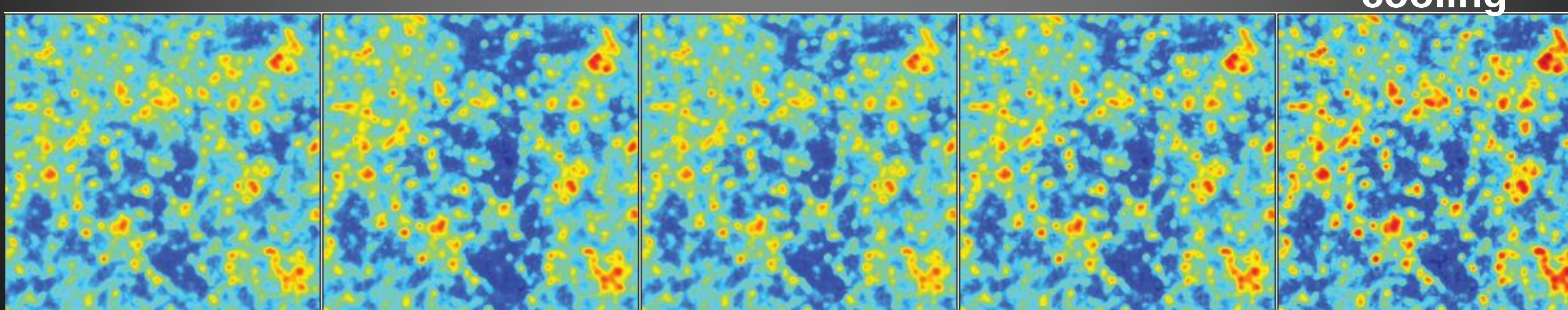


- Density
- Velocity
- Radiative backgrounds
  - X-rays
  - Ly-α
  - Lyman-Werner
  - Ionizing

21-cm brightness temperature

← **Molecular cooling** →

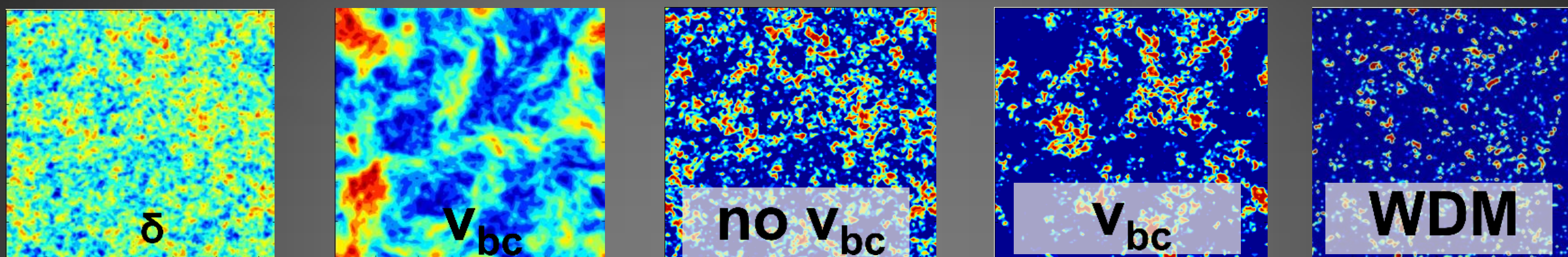
Atomic cooling



No feedback, No vbc | **No feedback** | **Weak feedback** | **Strong feedback** | **Saturated feedbback**

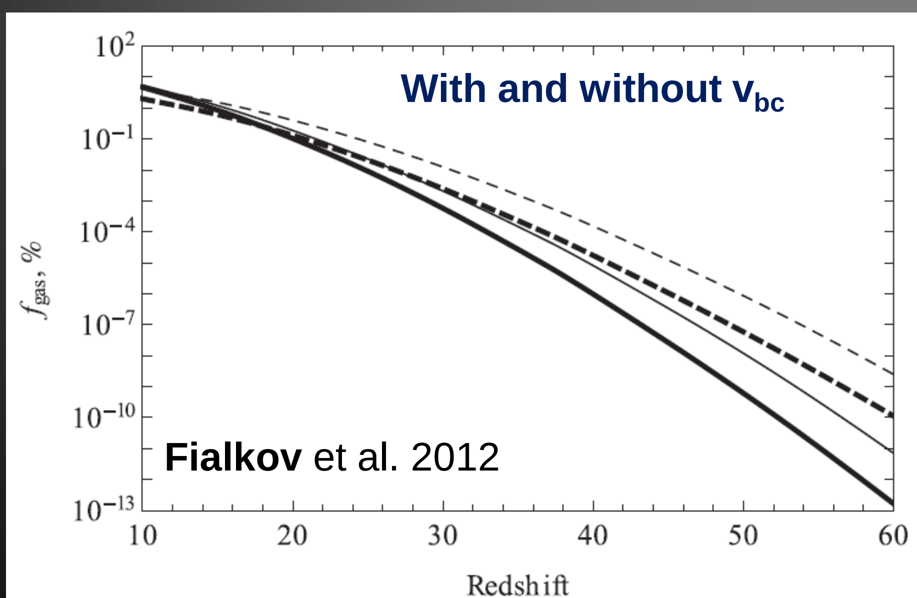
Fialkov, Barkana, Visbal, Tseliakhovich, Hirata (2013)

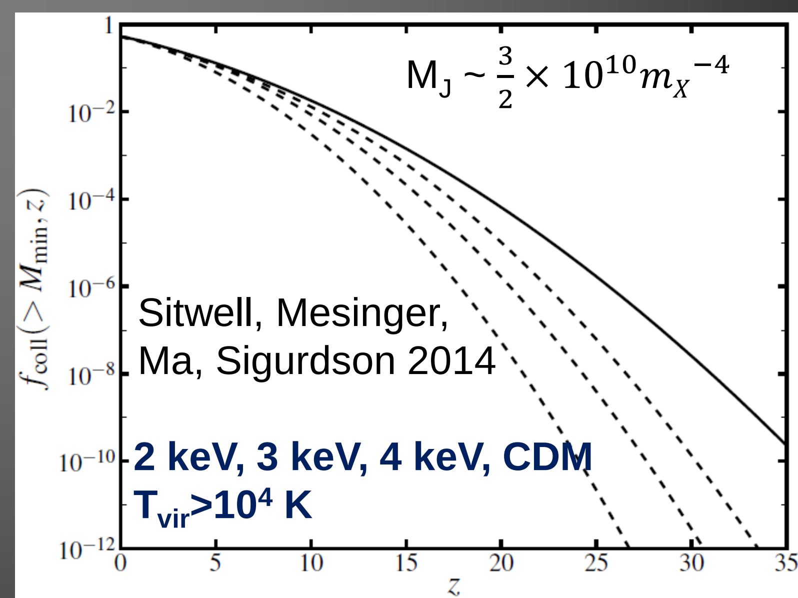
Abundance of Dark Matter Halos
Astrophysical Uncertainties



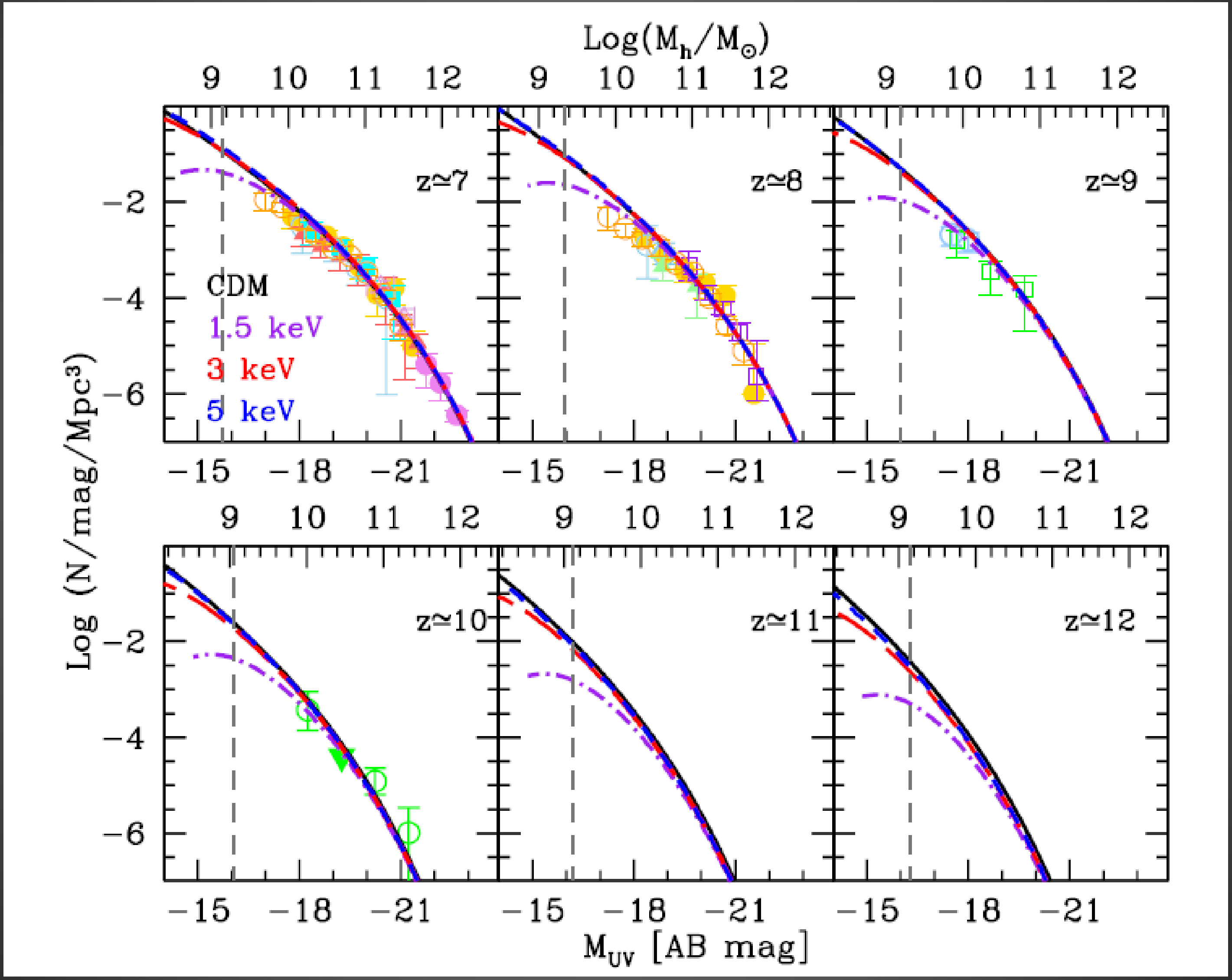
Star formation in 10^5-10^7 M_{sun} halos:

Interplay between WDM (~ 10 keV), astrophysics and v_{bc}.



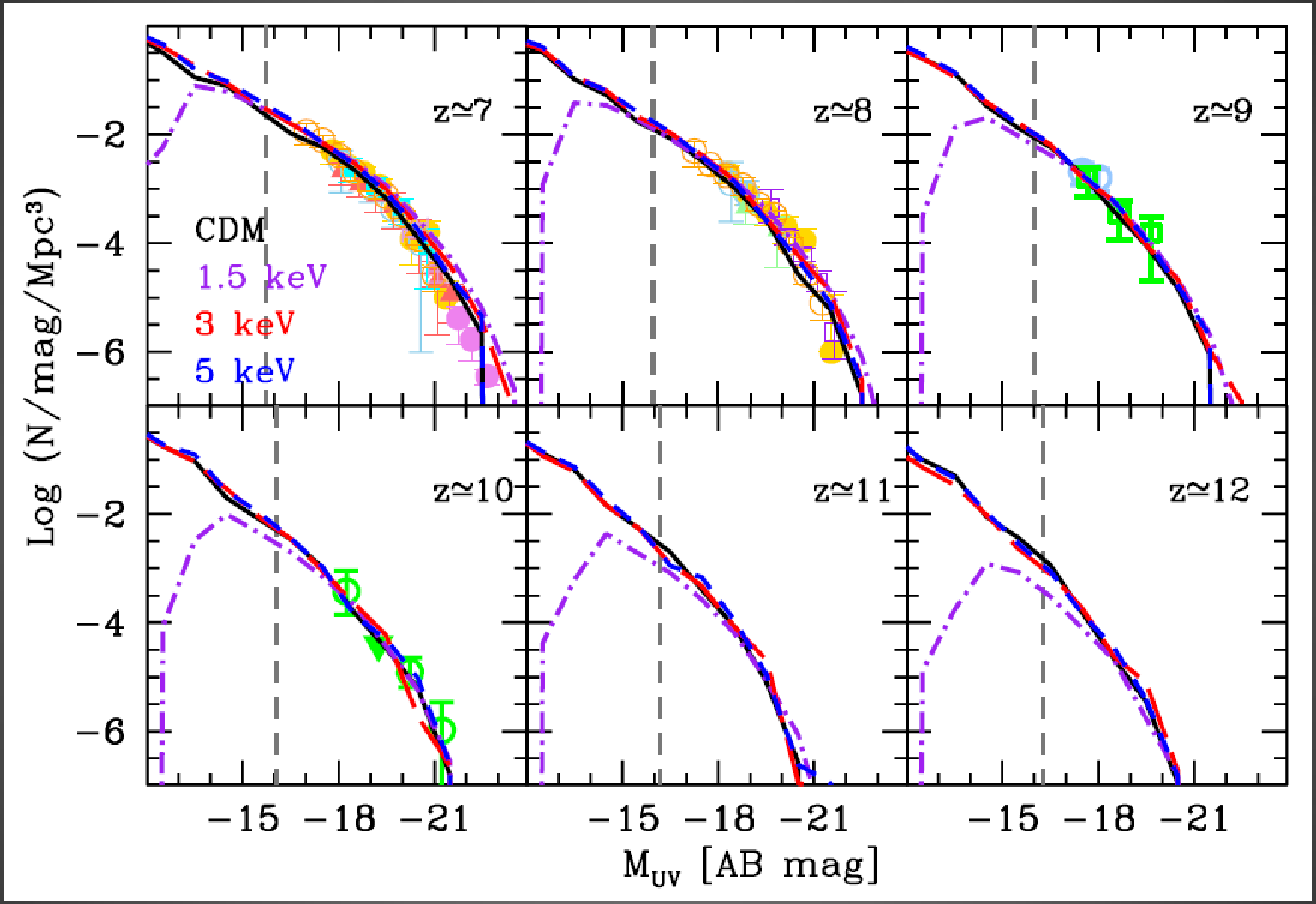


Luminosity Function in WDM



Dayal et al. 2015

Luminosity Function with UV Feedback



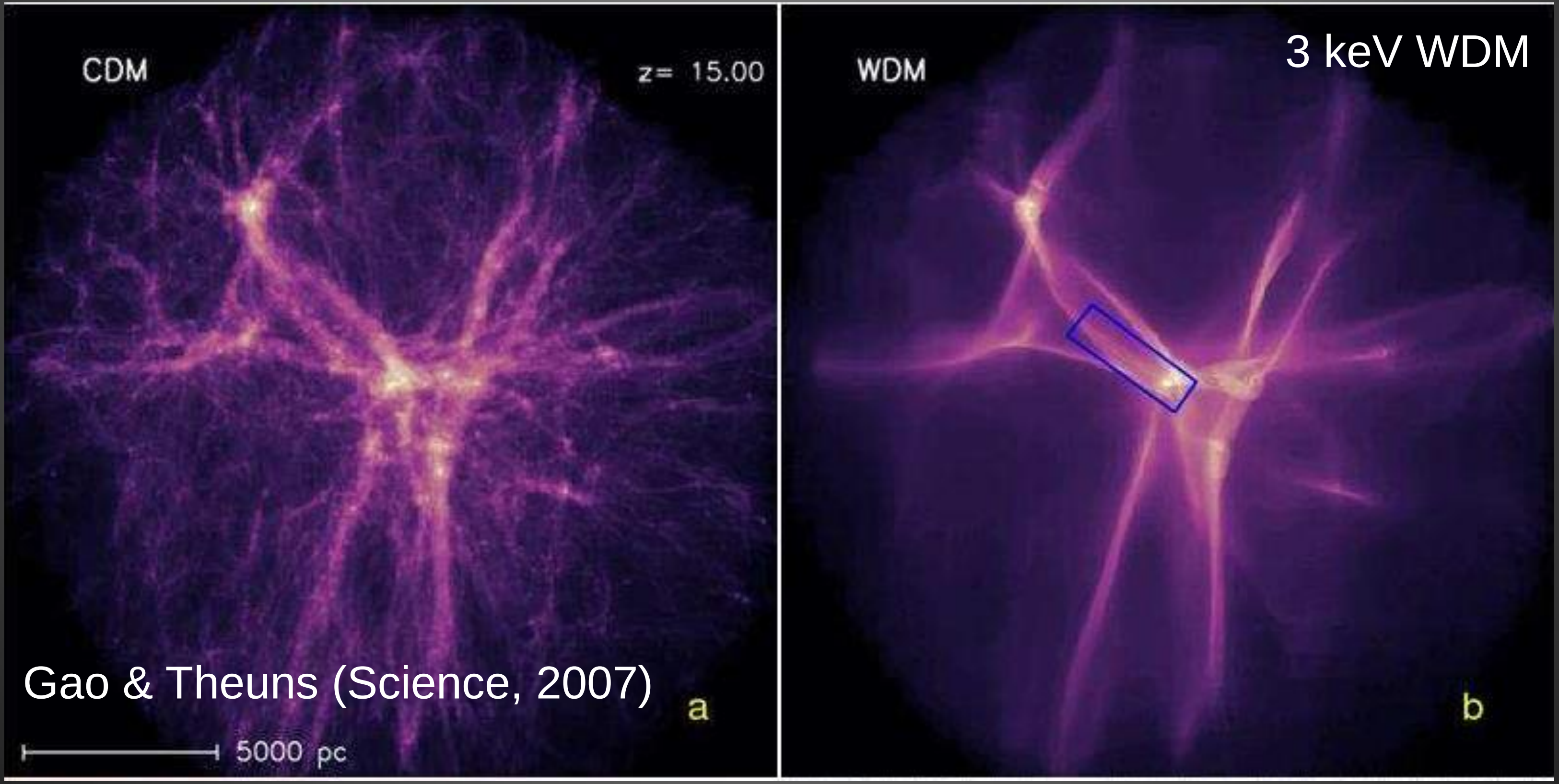
Dayal et al. 2015

Feedback: Even JWST (probes UVLF M_{UV}~16) will be hard pressed to obtain constraints on m_x ~ 2 keV

Filaments

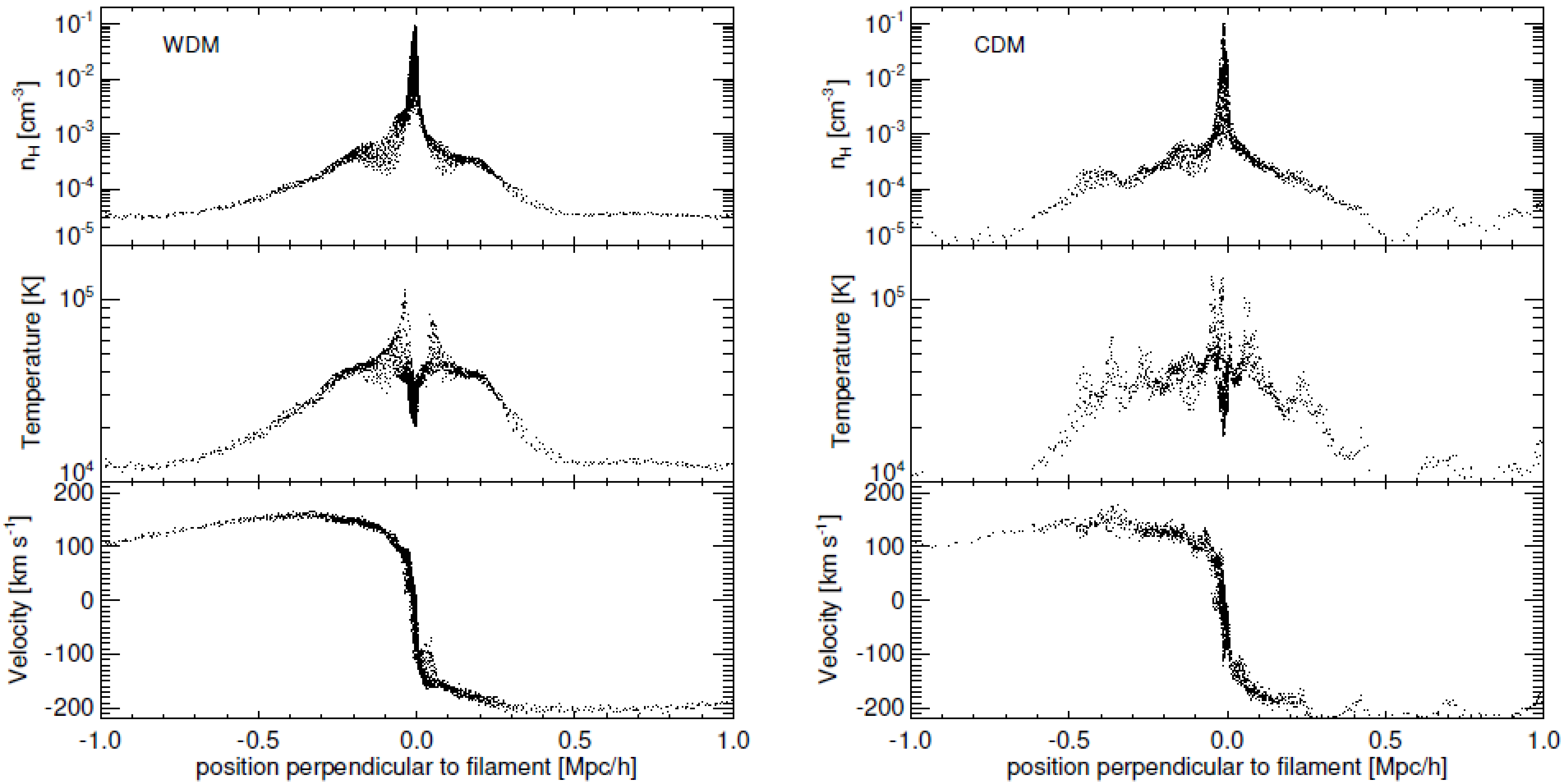
The structure of the filaments is very different:

- CDM filaments fragment into numerous nearly spherical high density regions ('halos')
- No feedbacks included



See also Paduroiu et al 2015

Filaments: CDM vs WDM

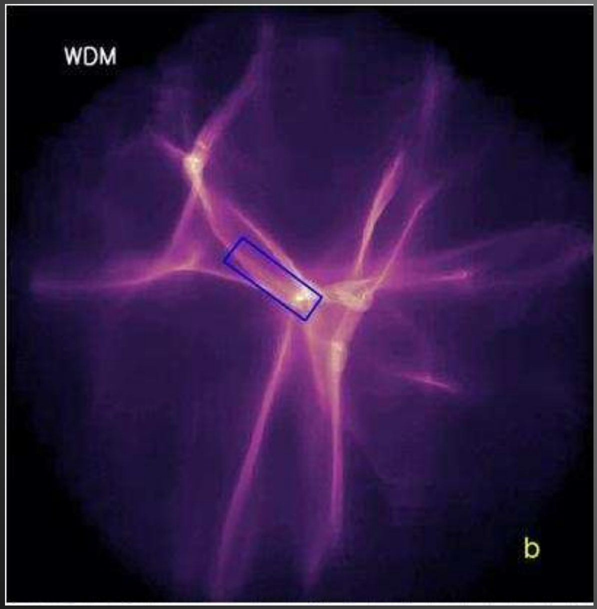


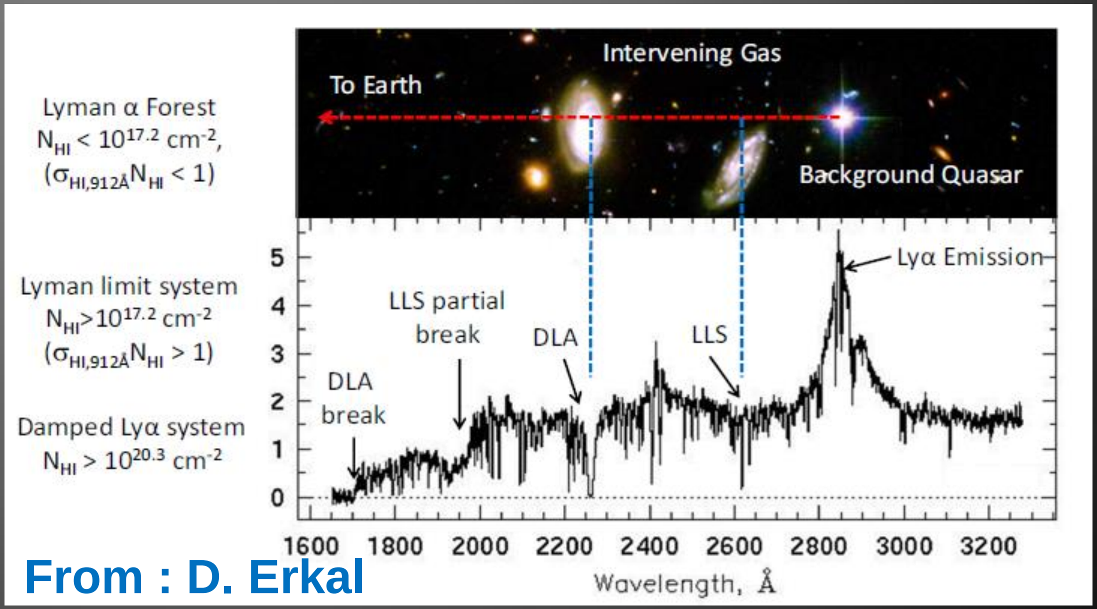
- WDM: more particles in filaments, high density regime, no fragmentation.

Gao, Theuns, Springel 2015

Observational Prospects: LLSs & DLAs

- WDM: Atomic line cooling allows gas in the centers of filaments to cool, resulting in a very striking pattern of extended Lyman-limit systems (LLSs).
- Column density of gas through the WDM filaments is very high (> 10^{18} cm^{-2})
- LLS correlation function is different in CDM vs WDM

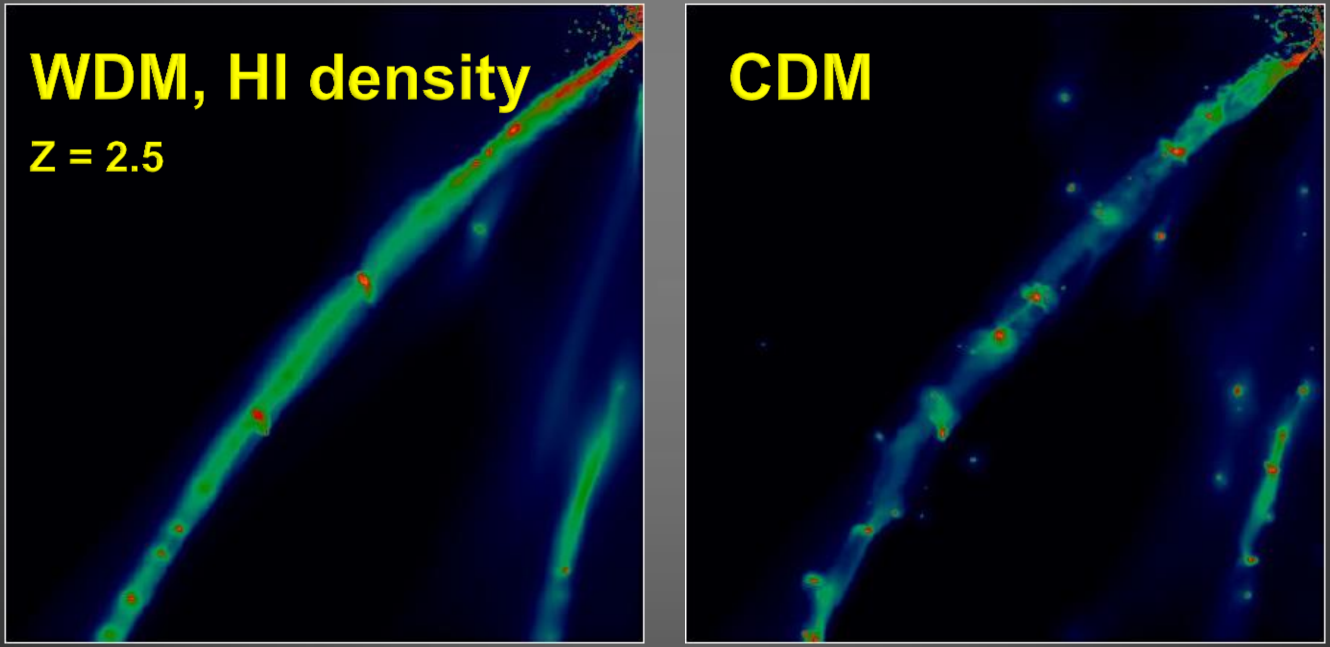




From : D. Erkal

Stars in WDM can form in Filaments!

- For $m_x \sim 1.5$ keV → SF in filaments dominates at $z > 6$!
- Reionization → gas density in filaments decreases (photoheating), star formation in haloes dominates at $z < 6$
- By $z = 0$, 15 % of stars in a simulated galaxy formed in filaments.
- However: “No theory” for star formation in filaments yet.

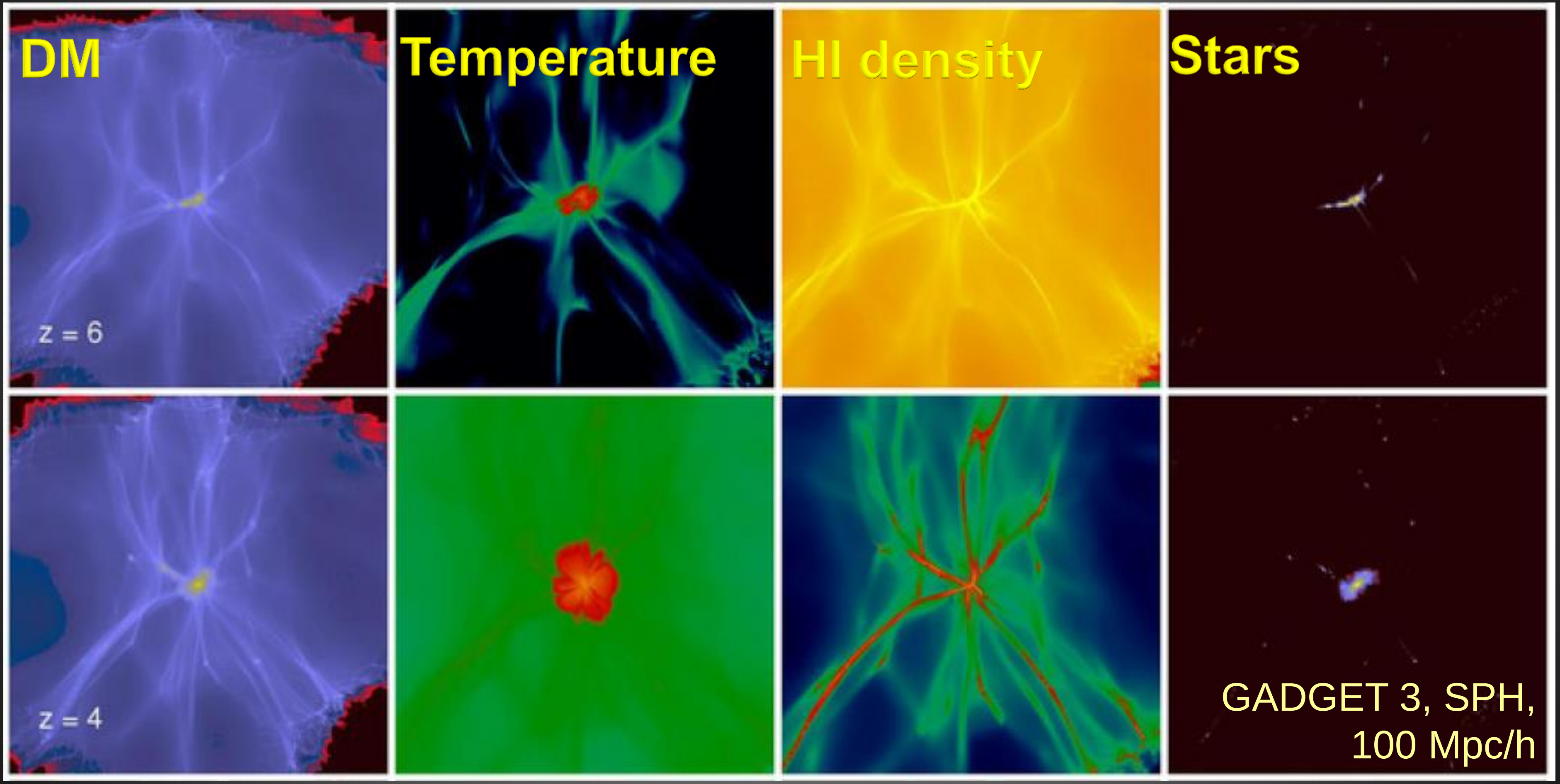


WDM: Filaments do not fragment

(Gao & Theuns, 2007; Gao, Theuns, Springel 2015)

Effect of WDM on First Stars

Example: Star Formation in Filaments for 1.5 keV WDM, atomic cooling

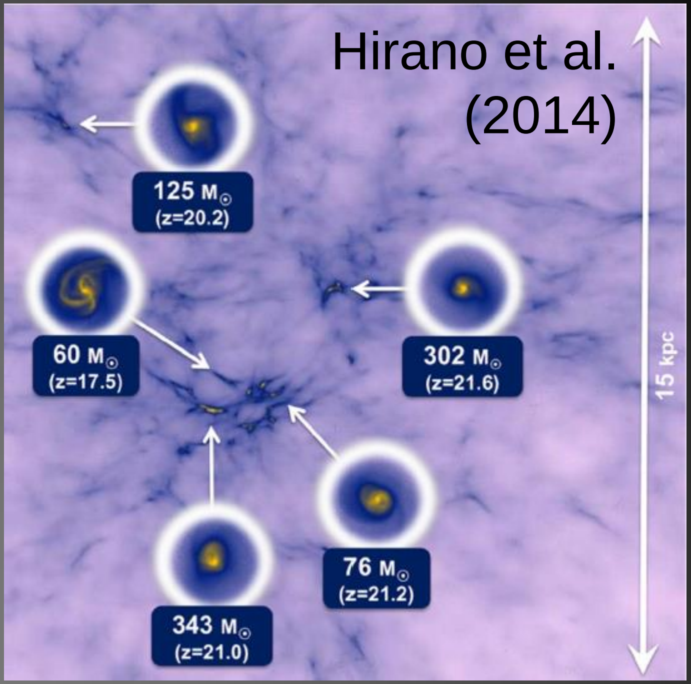


Gao, Theuns, Springel (2014)

Results from zoomed cosmological hydrodynamical simulations. Formation of a Milky Way-like galaxy in WDM.

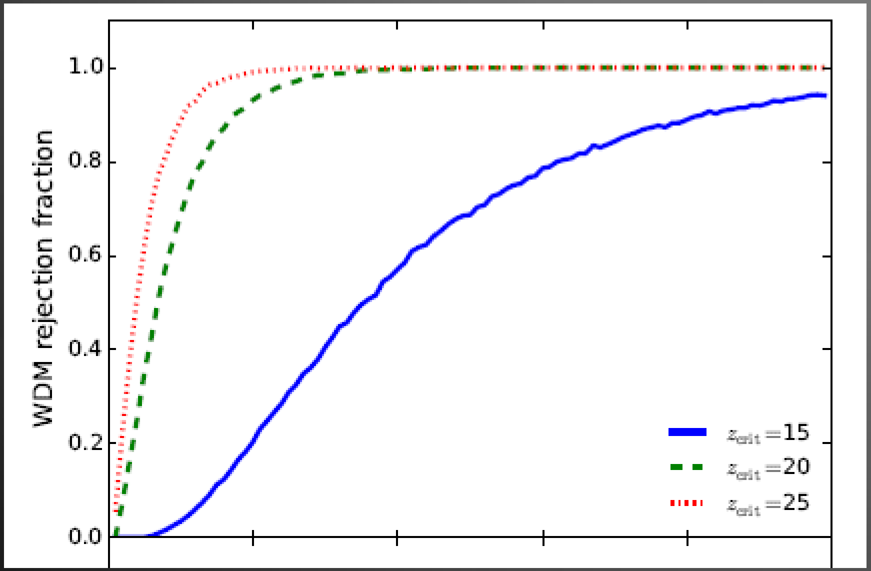
High Redshift SNe

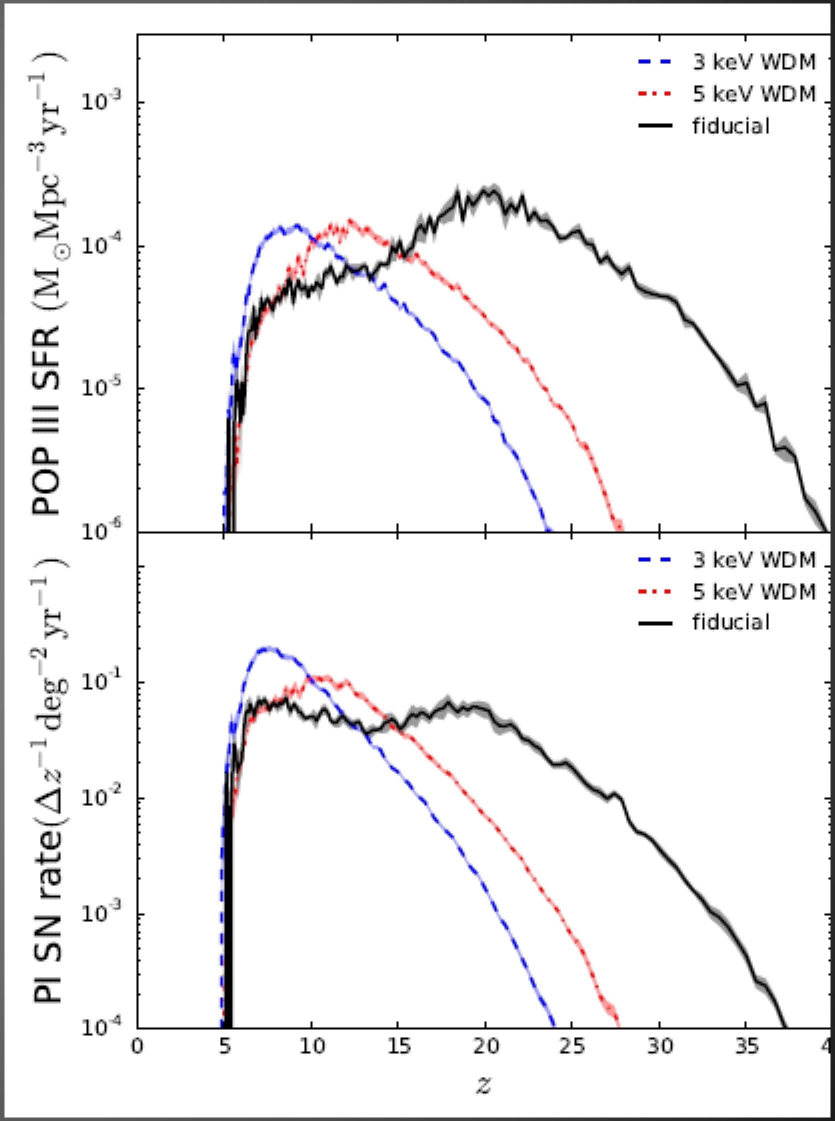
- PopIII SF is poorly studied, no feedback from previous SF
- $M_S = 10 - 1000$ solar masses
- The final fates of the first stars depend on their masses and rotation rates
  - $M_S = 8 - 40$ solar die as core-collapse (CC) SNe
  - $M_S = 40 - 90$ solar directly collapse to a black hole
  - $M_S > 90$ solar Pop III stars can encounter the pair instability. $M_S = 140 - 260$ PI SNe will be visible to JWST and the E-ELT up to $z = 30$ and to Euclid and WFIRST at $z = 10 - 20$.



WDM and SNe as Probes of Structure Formation

- No feedback from previous SF, SN rate curve is unique to each cosmology
- WDM suppresses early Pop III SF and SN rates. Detections of PI SNe at high z rule out WDM.



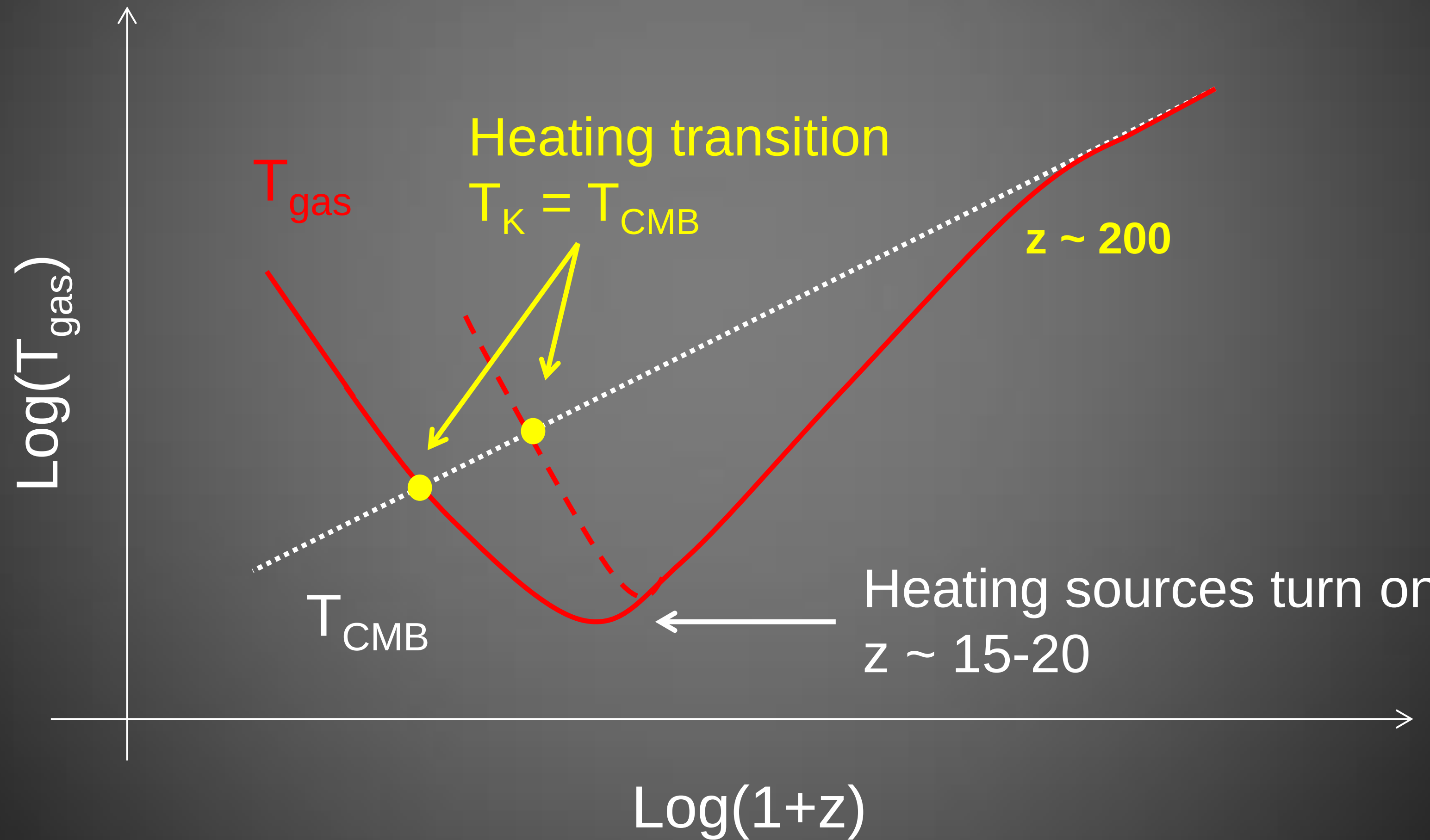


Magg et al. (2016)

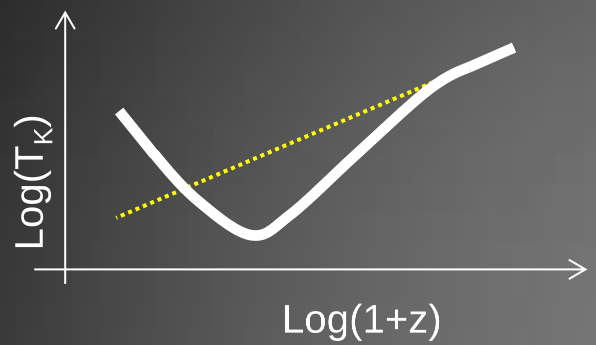
Thermal history, reionization and 21-cm signal as a probe of WDM

High-z Thermal History is Unknown

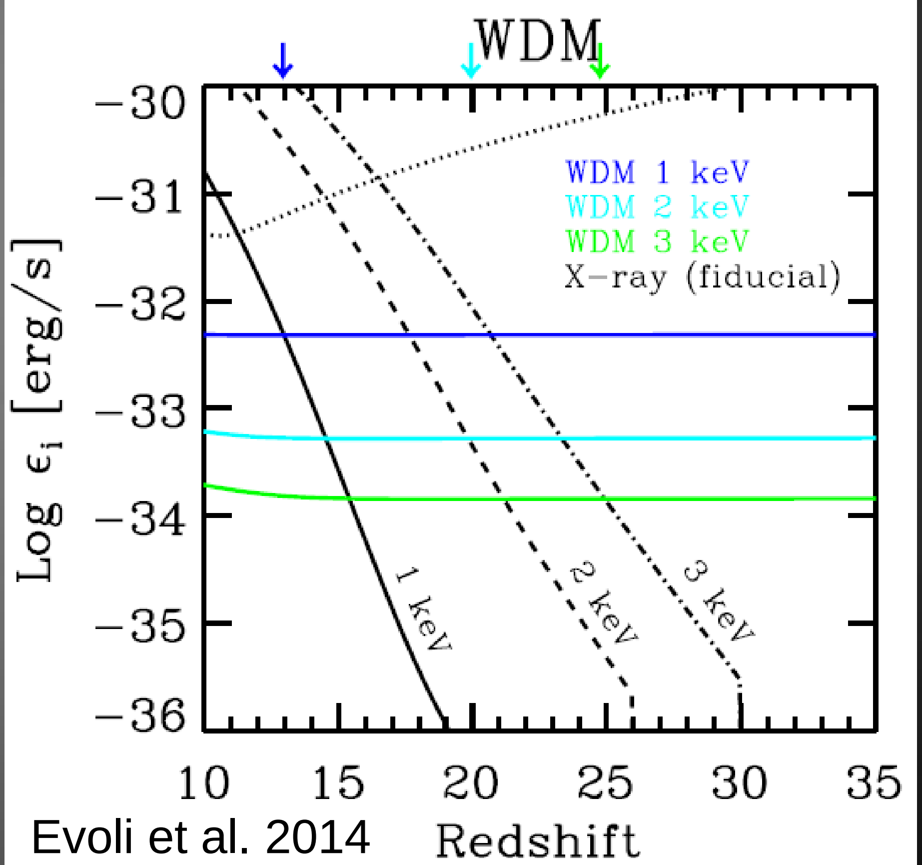
Different types of heating sources → different thermal histories



Thermal History WDM vs CDM



Heating from WDM decay, astrophysical heating (X-rays), and adiabatic cooling rates



Evoli et al. 2014

Effects of WDM on Heating:

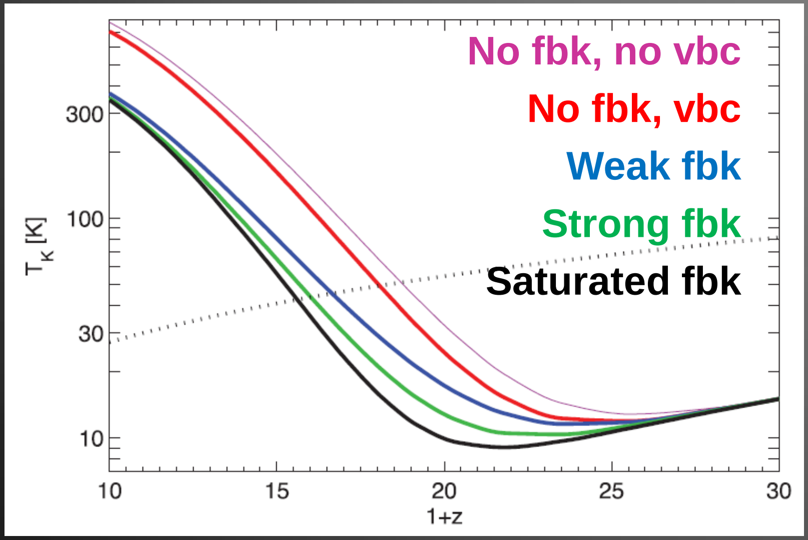
- Suppressed structure formation, delay in heating and reionization
- Heat transfer to gas from WDM decay (insignificant)

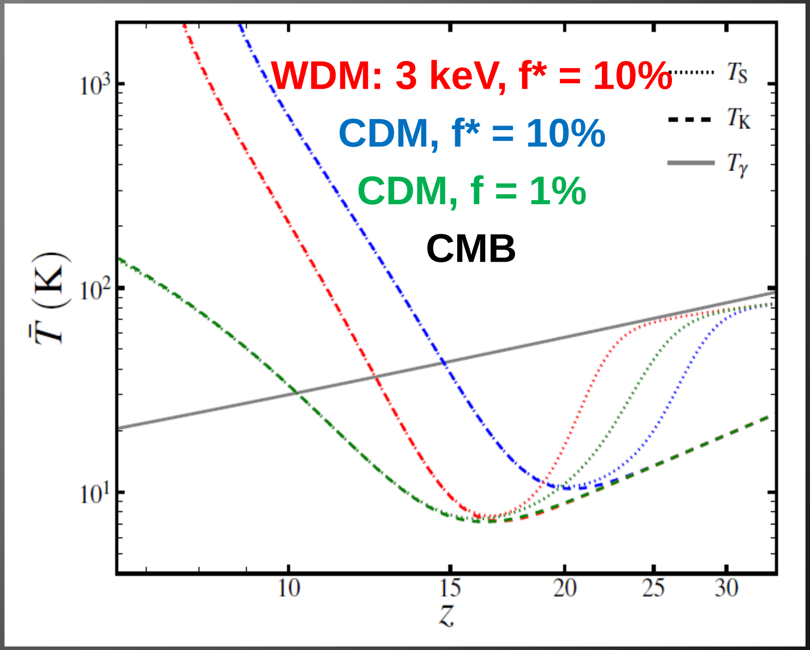
Thermal History WDM vs CDM
Astrophysical Uncertainties

- Heating efficiencies Δz ~ few
- Star formation scenario Δz ~ 0.8
- Radiative feedbacks: Δz ~ 2.5
- v_{bc} : Δz < 1

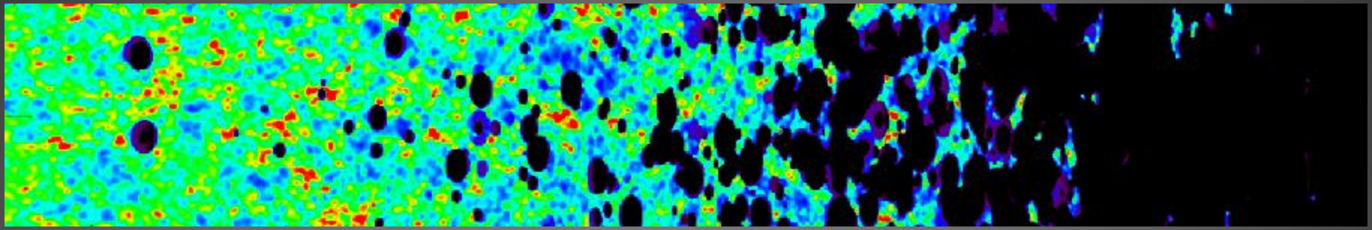
Sitwell, Mesinger, Ma, Sigurdson (2014)

Fialkov et al. (2013)





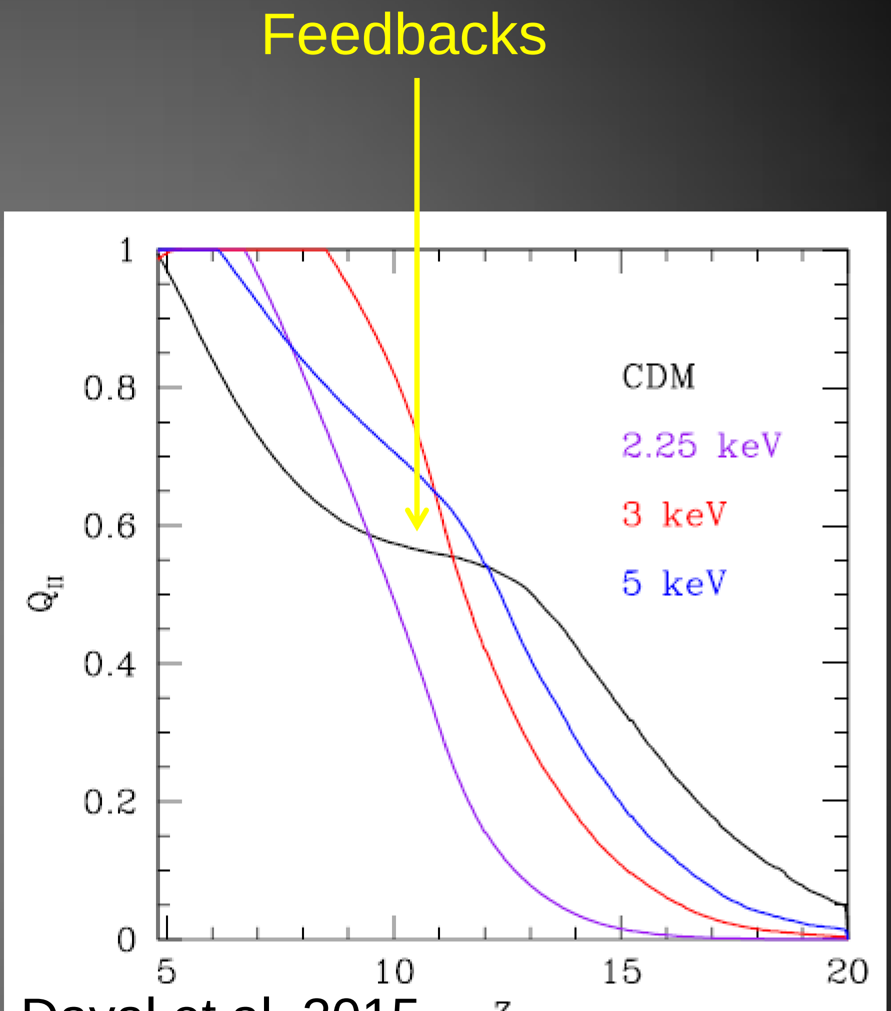
Reionization WDM vs CDM



- Not well understood
- Delayed: fewer stars at high redshifts (Mesinger, Ewall-Wice, Hewitt 2014; Yue, Chen 2012).
- Enhanced: less sinks (minihalos), lower recombination rate (e.g., Haiman et al. 2001, Benson et al. 2001; Barkana & Loeb 2002).
- In CDM the bulk of the reionization photons come from $M_h < 10^9 M_{sun}$ WDM : shift in the reionization population to larger masses (Dayal et al. 2015)
- Astrophysical uncertainties: star formation efficiency; escape fraction, feedbacks.

Ionized Volume

- CDM: suppression of star formation in small halos due to numerous feedbacks. Stalling of reionization.
- WDM catches up quickly larger number of ionizing photons. No stalling (no mini-halos), quicker end to EoR
- Shift in the reionization population to larger (halo and stellar) masses.



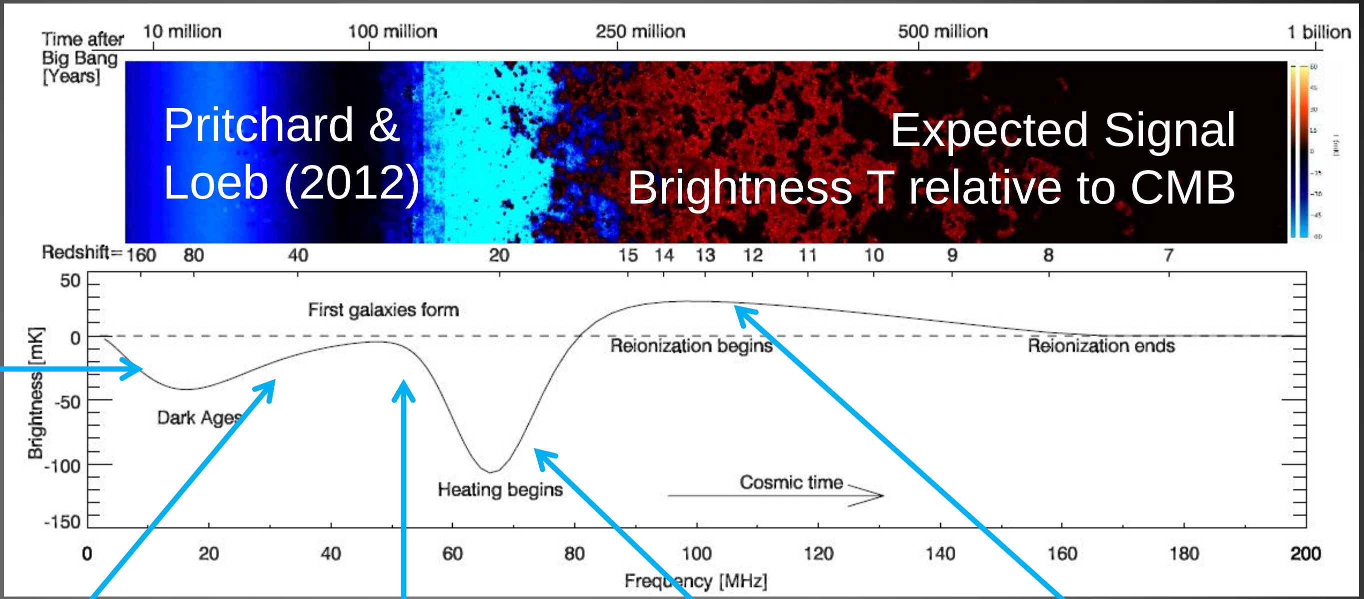
Dayal et al. 2015

21-cm Signal
3D Picture of the Universe

Golden Mine for astrophysics and cosmology!

- Dark Ages
- First Stars and Galaxies
- Reionization

Global 21-cm Signal



Dark ages, Collisional coupling, $T_S \rightarrow T_K$

Universe expands collisions are inefficient $T_S \rightarrow T_{CMB}$

Stars appear Ly-a coupling $T_S \rightarrow T_C \sim T_K$

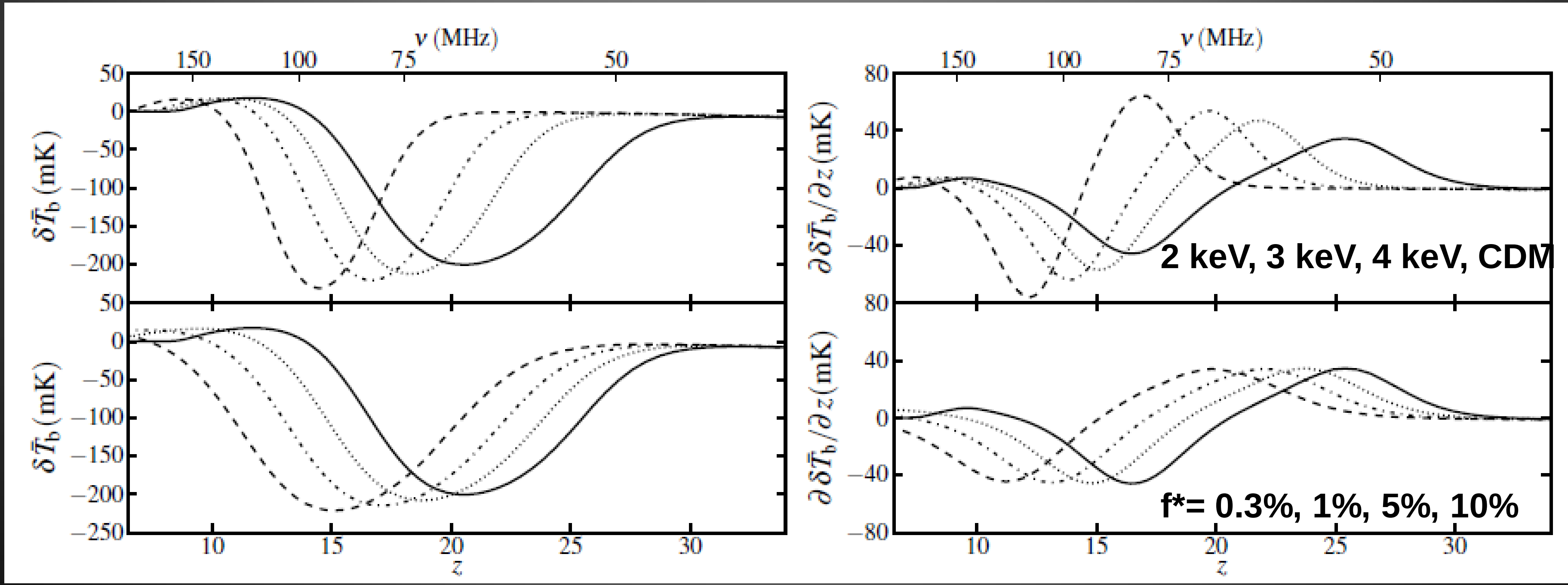
Heating, $T_S \sim T_K > T_{CMB}$

Ionization

$$\delta T_b \propto x_{HI}(1+\delta)(1+z)^{1/2}\left[1-\frac{T_{CMB}}{T_S}\right]\left[\frac{H(z)/(1+z)}{dv_{||}/dr_{||}}\right]$$

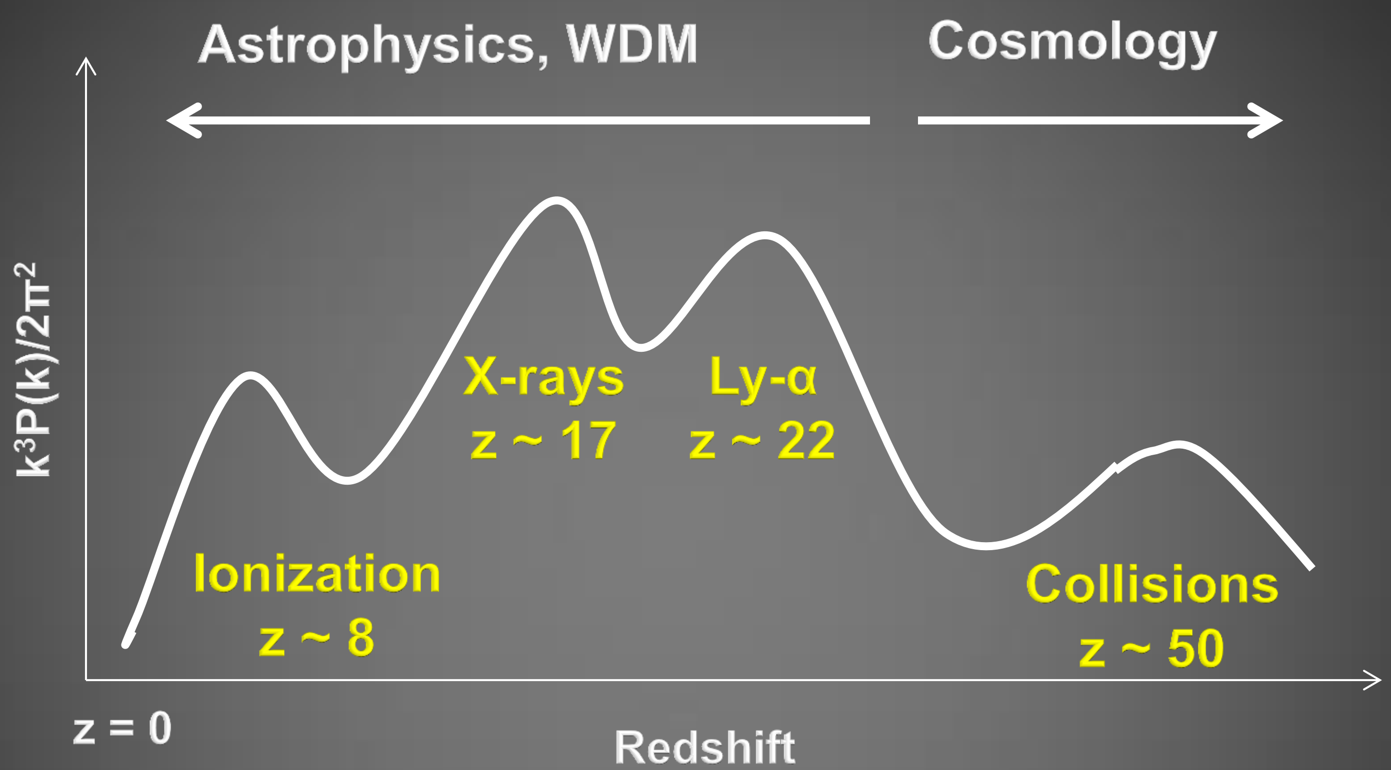
WDM Fingerprints in the 21-cm Signal Degenerated with Star Formation

- Absorption trough is deeper by ~25 % than in CDM (cools longer)
- Shift of the trough Δz ~ 5
- Larger derivatives at higher freq. Easier to observe (e.g., LEDA)
- Astrophysical uncertainties: feedback, X-ray heating, v_{bc} …

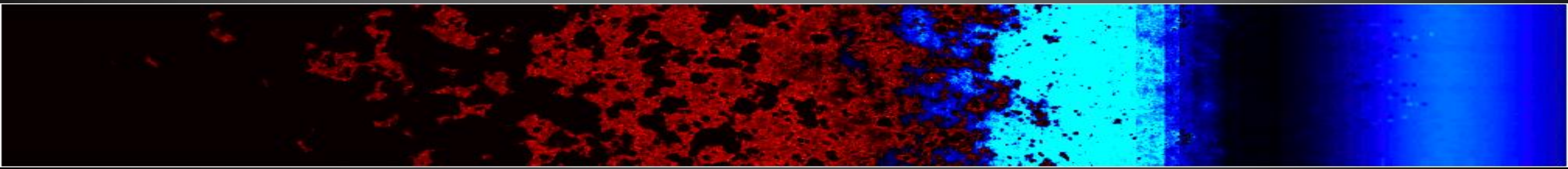


Sitwell, Mesinger, Ma, Sigurdson (2014)

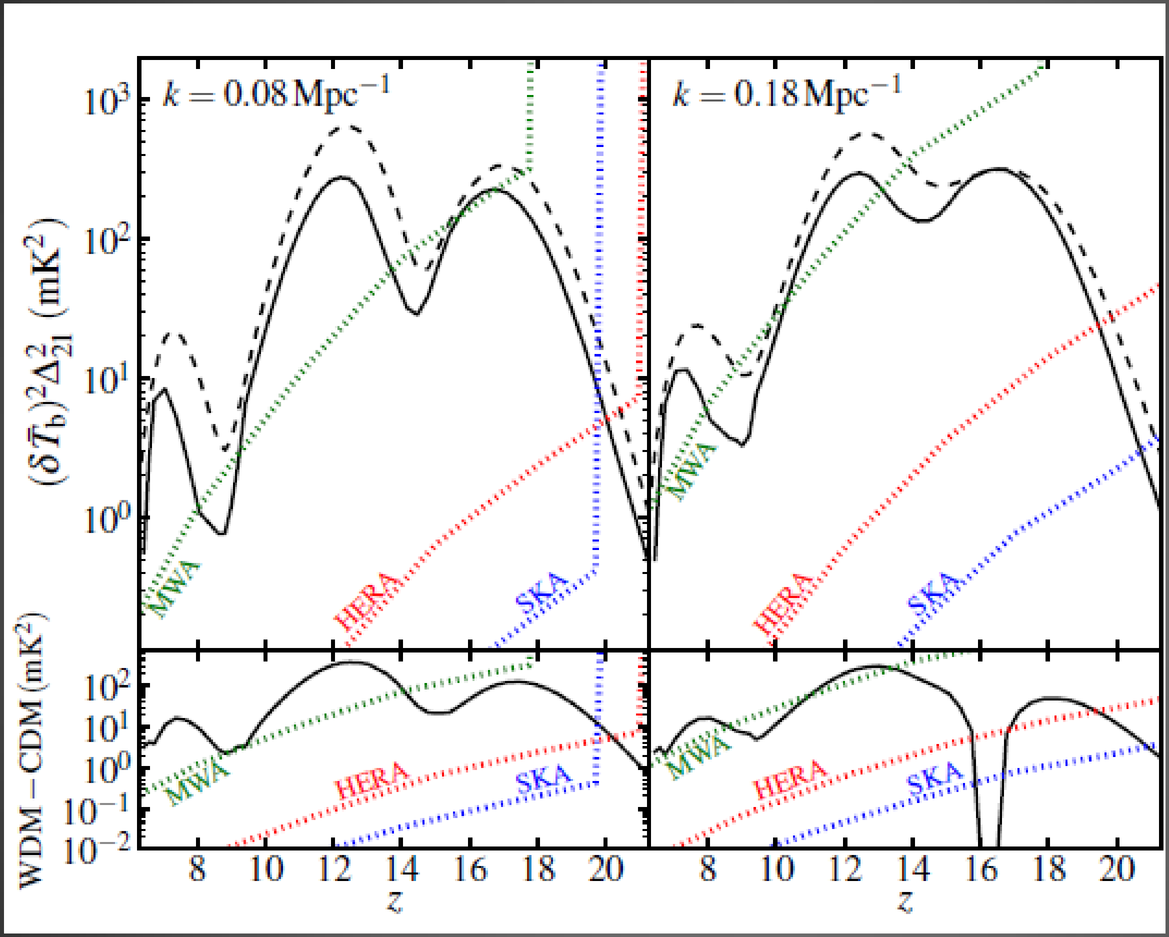
Inhomogeneous Signal. Fluctuations

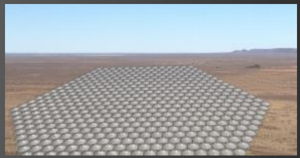


- Generic dependence of power spectrum on z for a given k
- Each source of fluctuations contributes at different epoch



21-cm Power Spectrum





Dotted curves show forecasts for the 1σ power spectrum thermal noise with 2000h of observation time.

Summary: WDM in the Early Universe

WDM

- CDM + feedbacks ~ WDM
- Stars could form in filaments!

Astrophysical processes can have similar effect

- v_{bc}, feedbacks, X-ray heating, SF efficiency, escape fraction,…

Future probes:

- High-z galaxies, 21-cm signal, transients