Signatures and constraints on Warm Dark Matter scenarios from reionization, 21-cm, first galaxies

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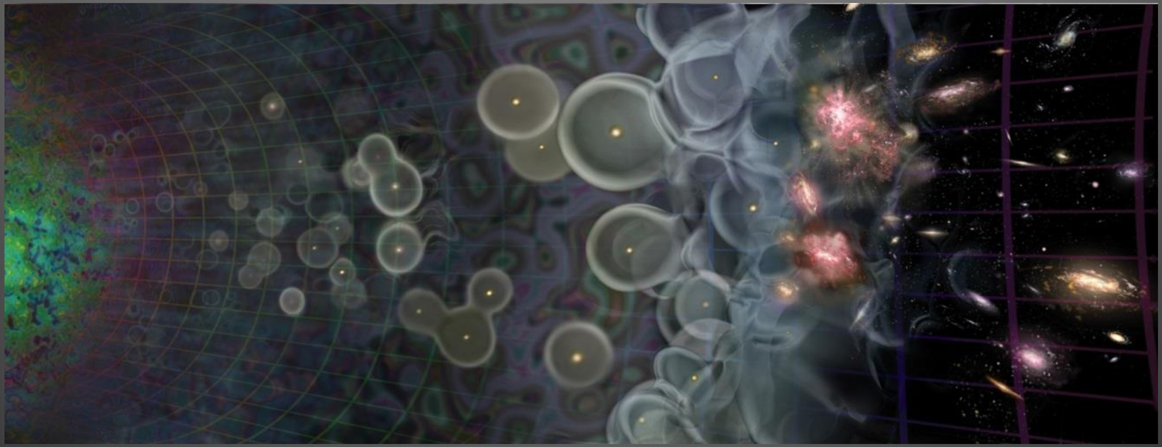
Outline

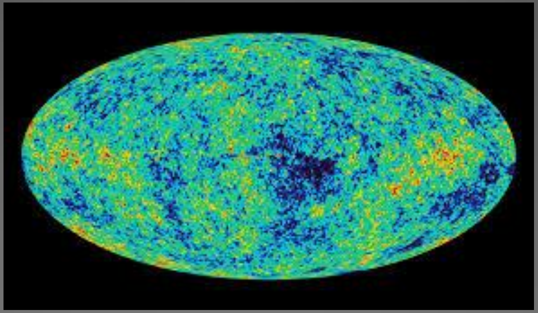
- The early Universe (overview)
- Effect of WDM on:
  1. Number Counts
  2. Thermal history and Reionization
  3. 21-cm signal
  4. Star formation



Today: Golden Age of Astronomy, Cosmology and Astrophysics

The Universe

Unobservable
Universe
(optically thick)



Observable
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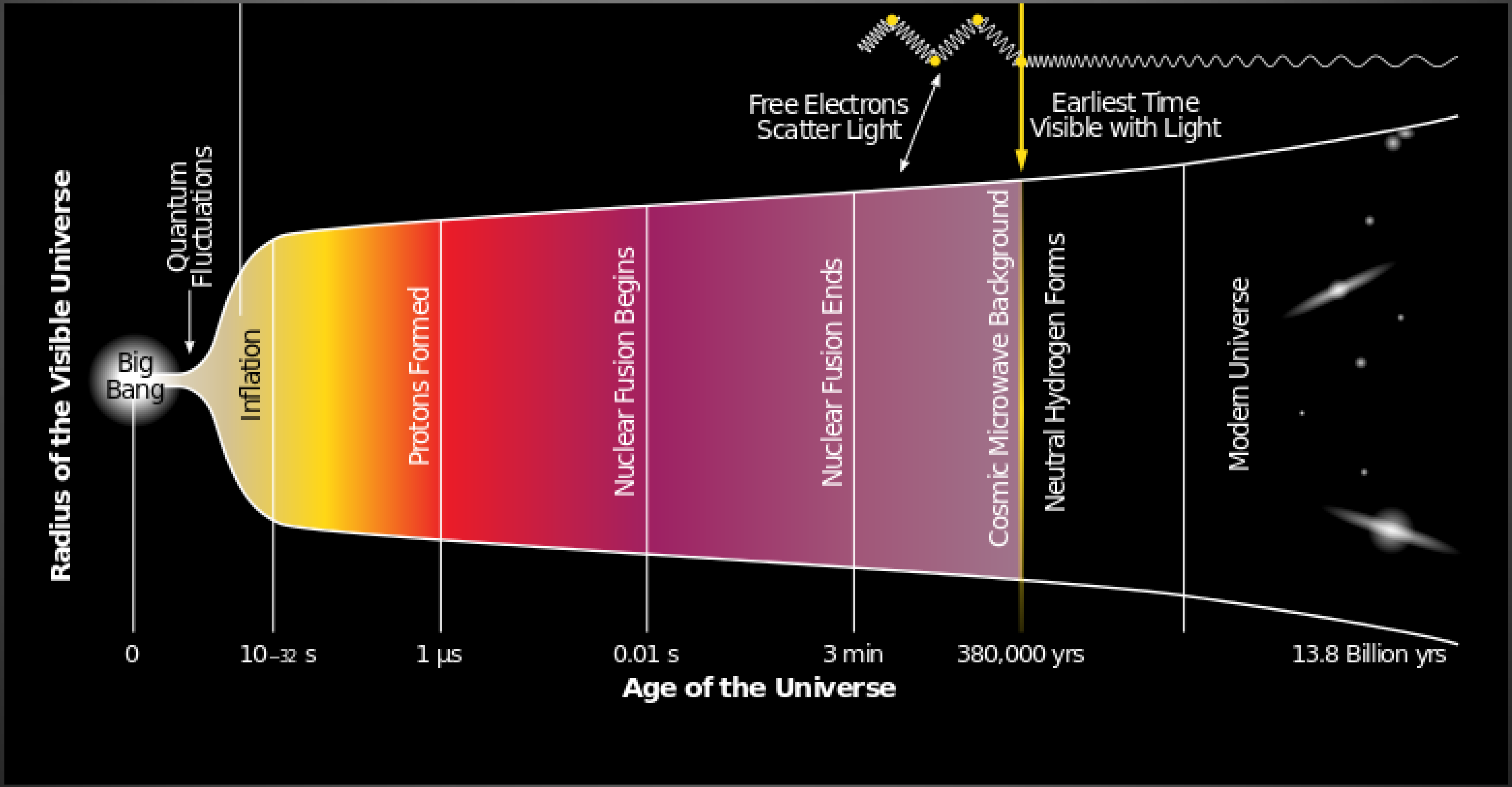
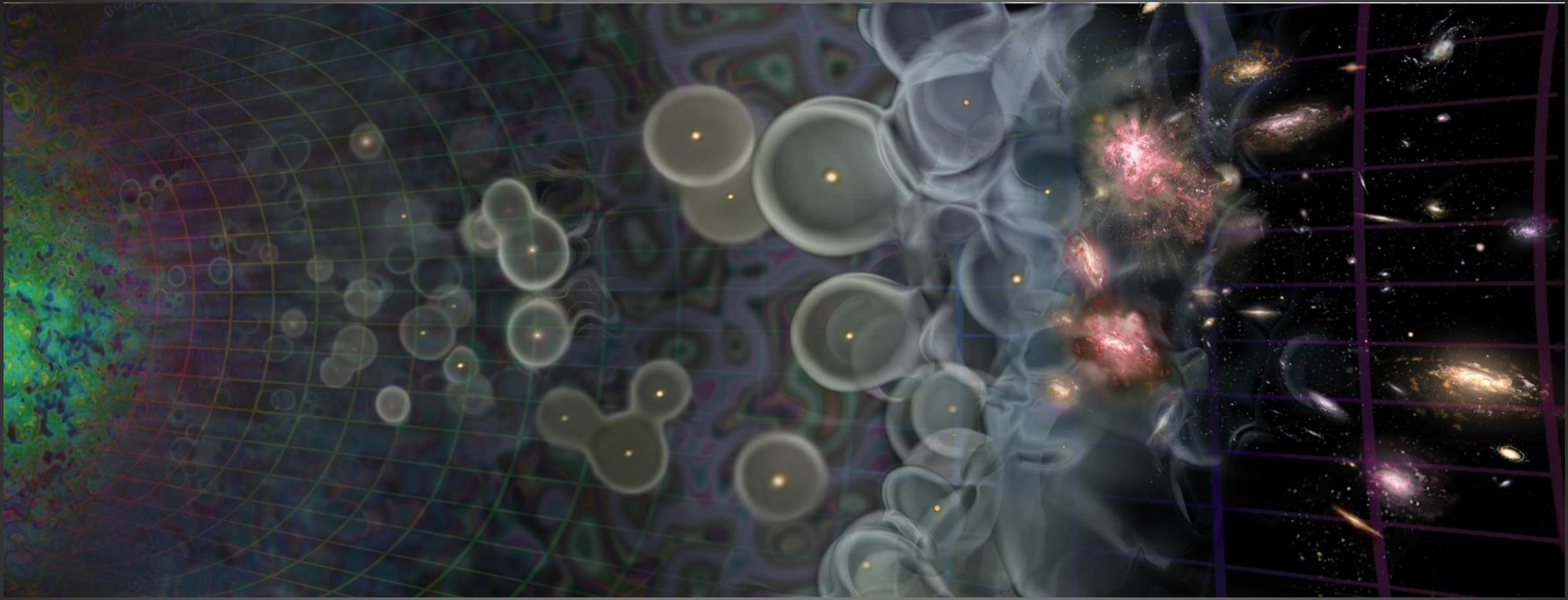


The Observable Universe

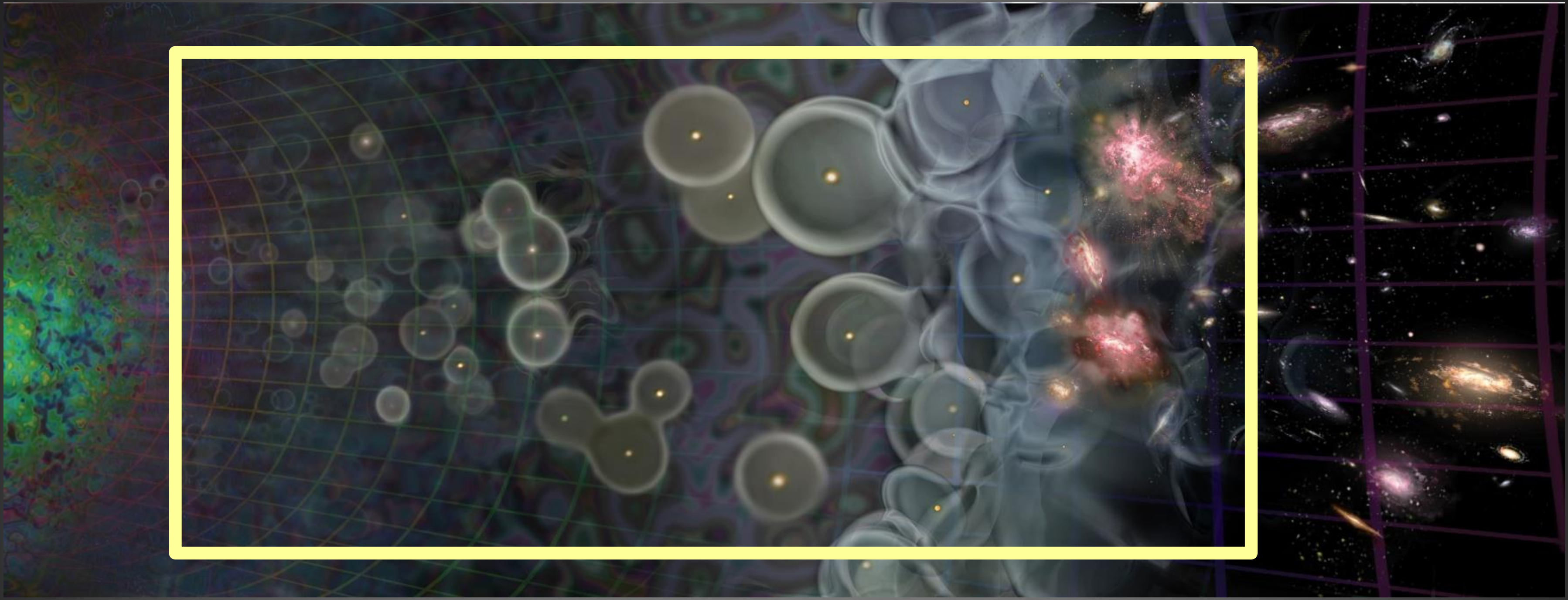
Image: Loeb, Scientific American 2006



CMB
Dark Ages
First stars & galaxies
Reionization
Large Scale Structure

Unobserved Part of the Observable Universe

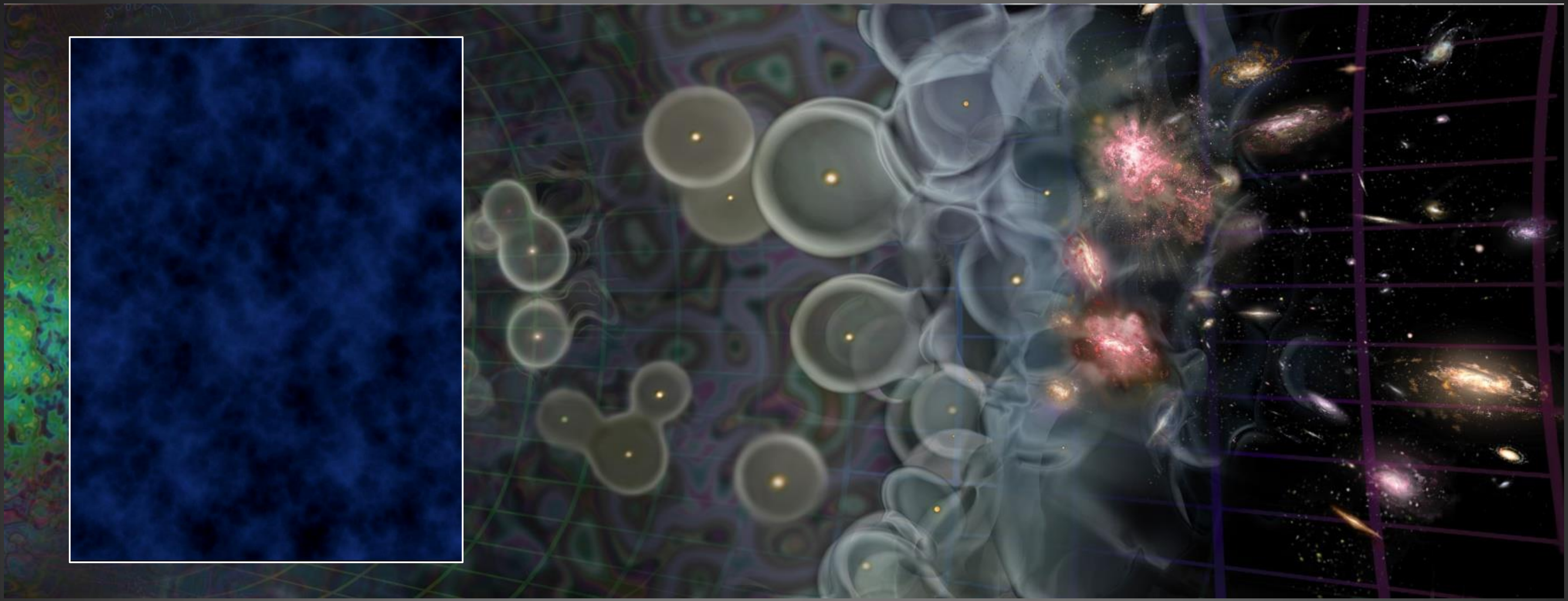
Image: Loeb, Scientific American 2006



Dark ages First stars & galaxies Reionization

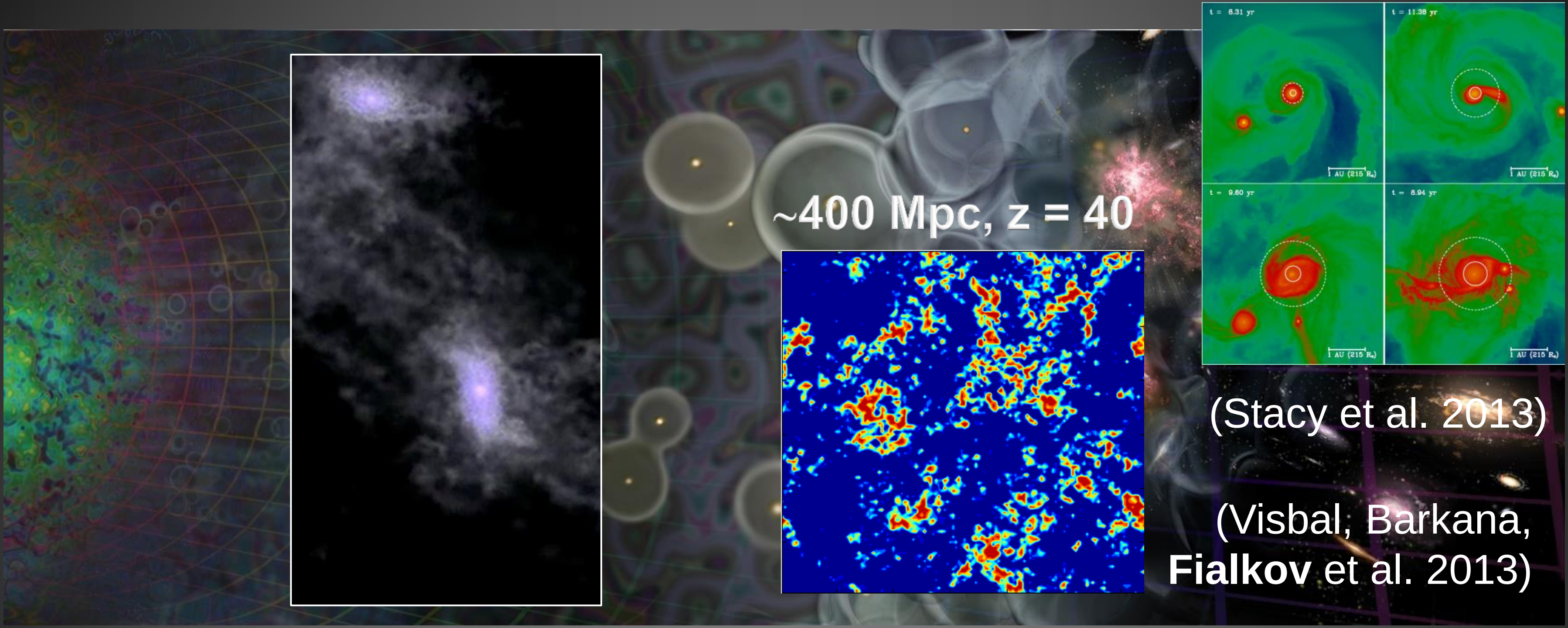
What can we learn about Dark Matter from Future Observations at Higher Redshifts?

Dark Ages



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

Cosmic Dawn: First Stars and Galaxies

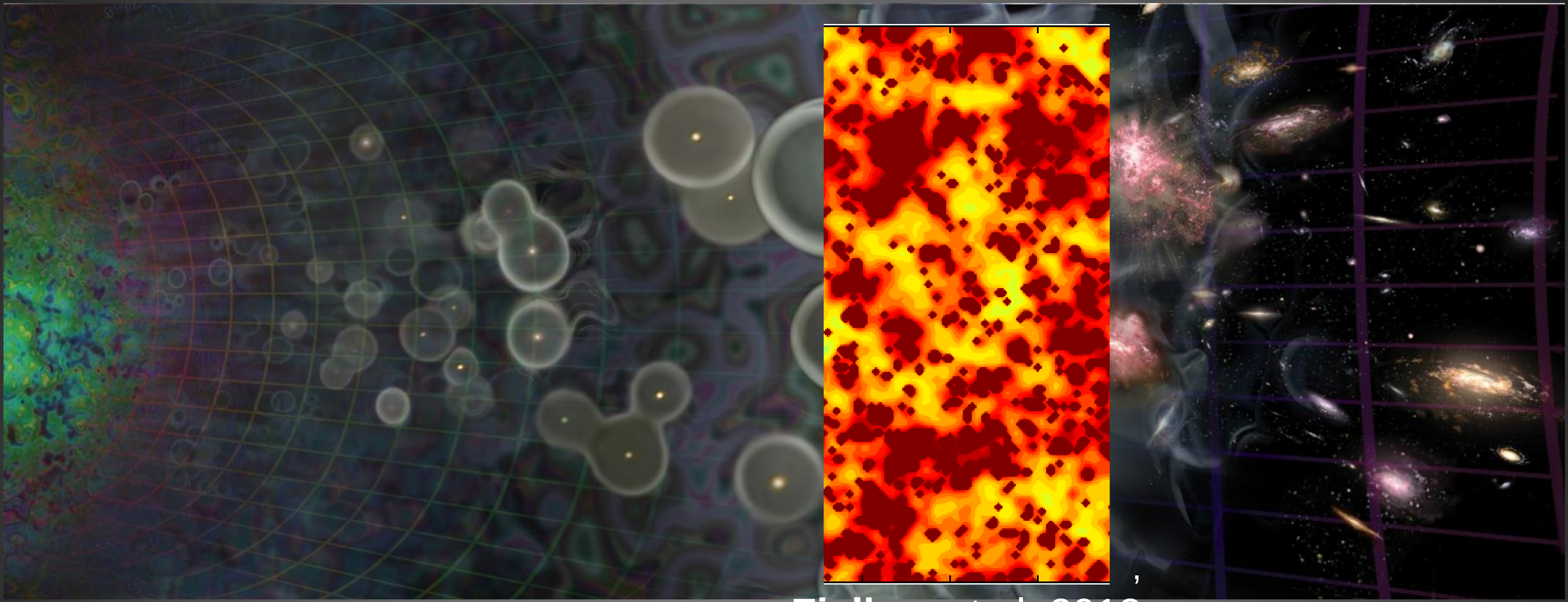


(Stacy et al. 2013)

(Visbal, Barkana, **Fialkov** et al. 2013)

- First halos collapse, start 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})

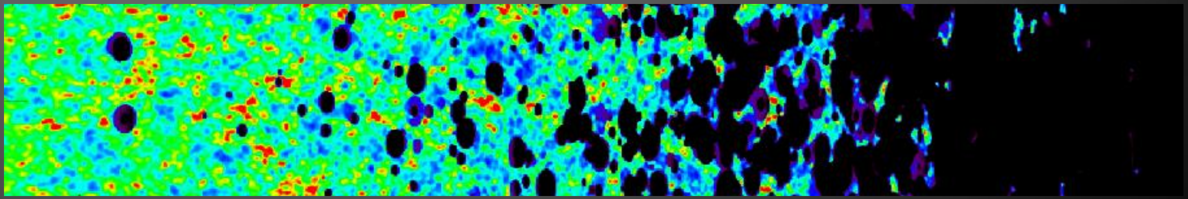
Reionization



Fialkov et al. 2013

- Radiation from stars and other sources 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)?

…

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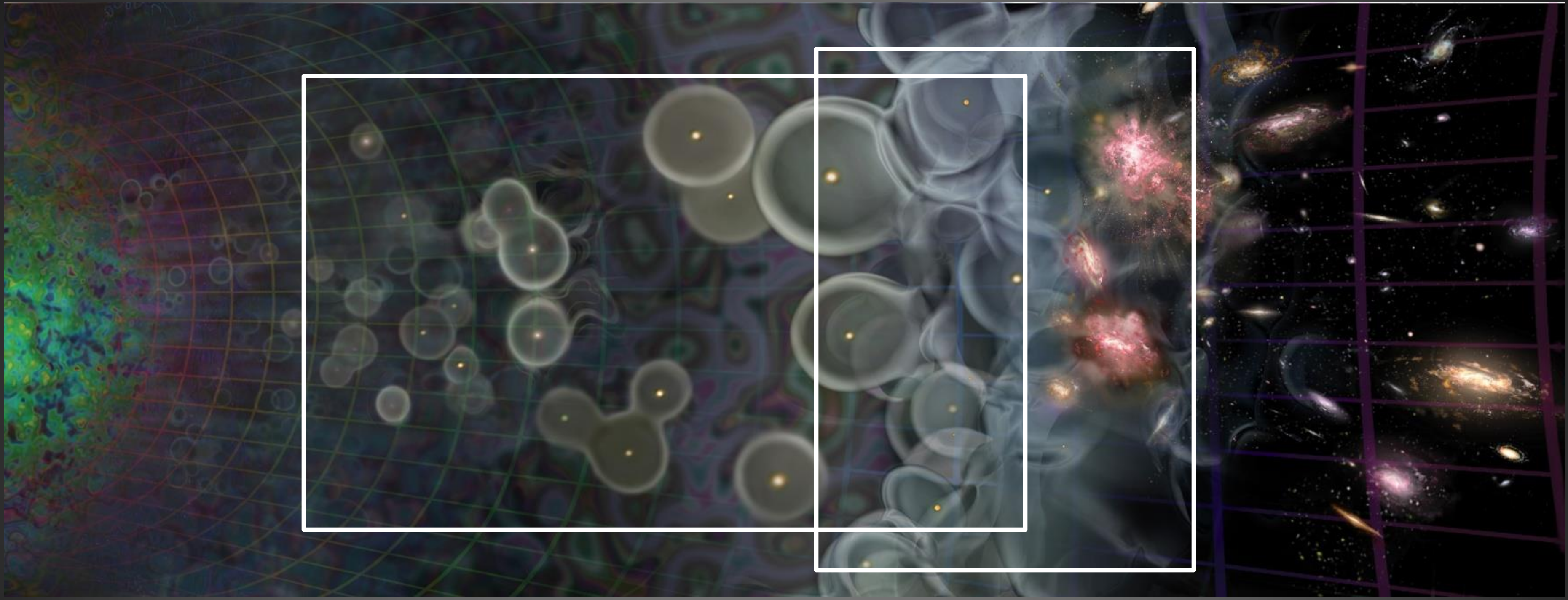
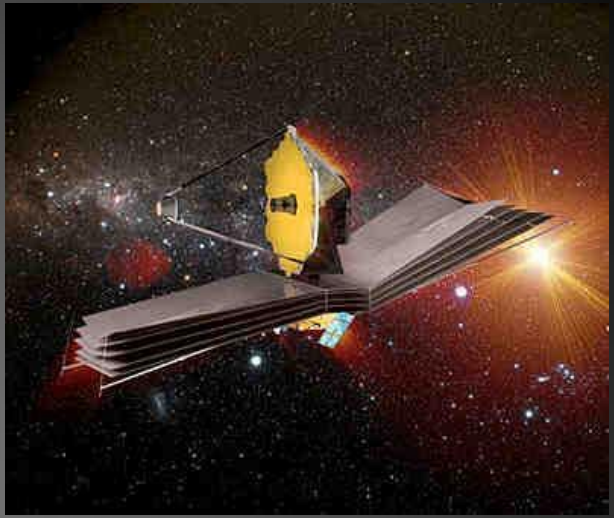
…

What is the nature of ~ 85 % of matter??

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

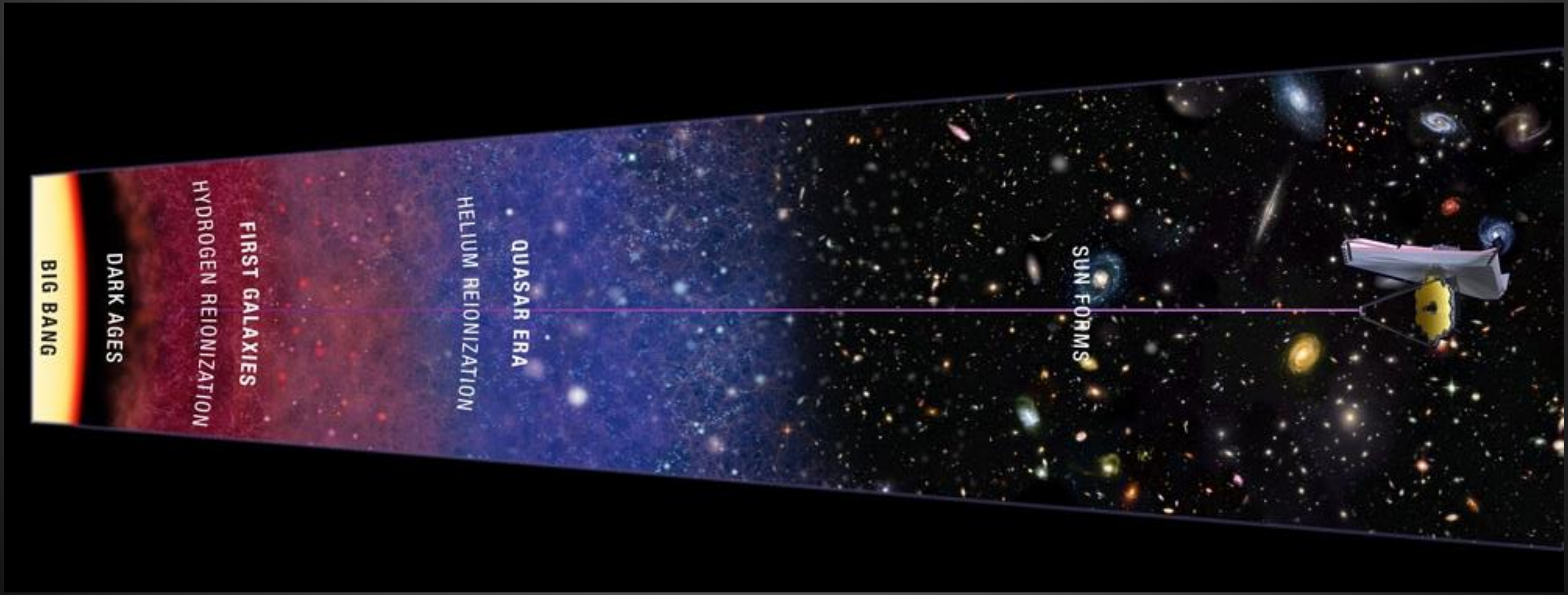


Seeing the First Galaxies



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



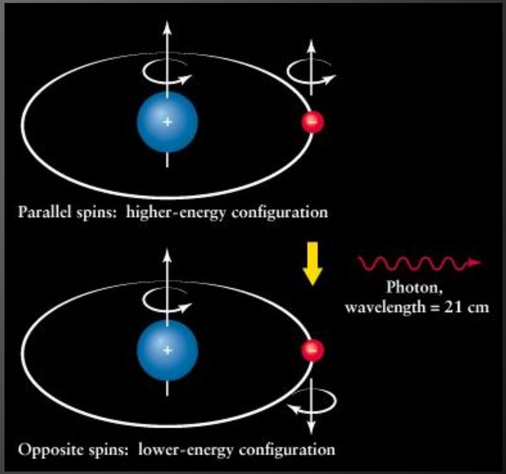
21-cm Signal of HI

Image: Loeb, Scientific American 2006

High-z Universe is mostly filled with HI

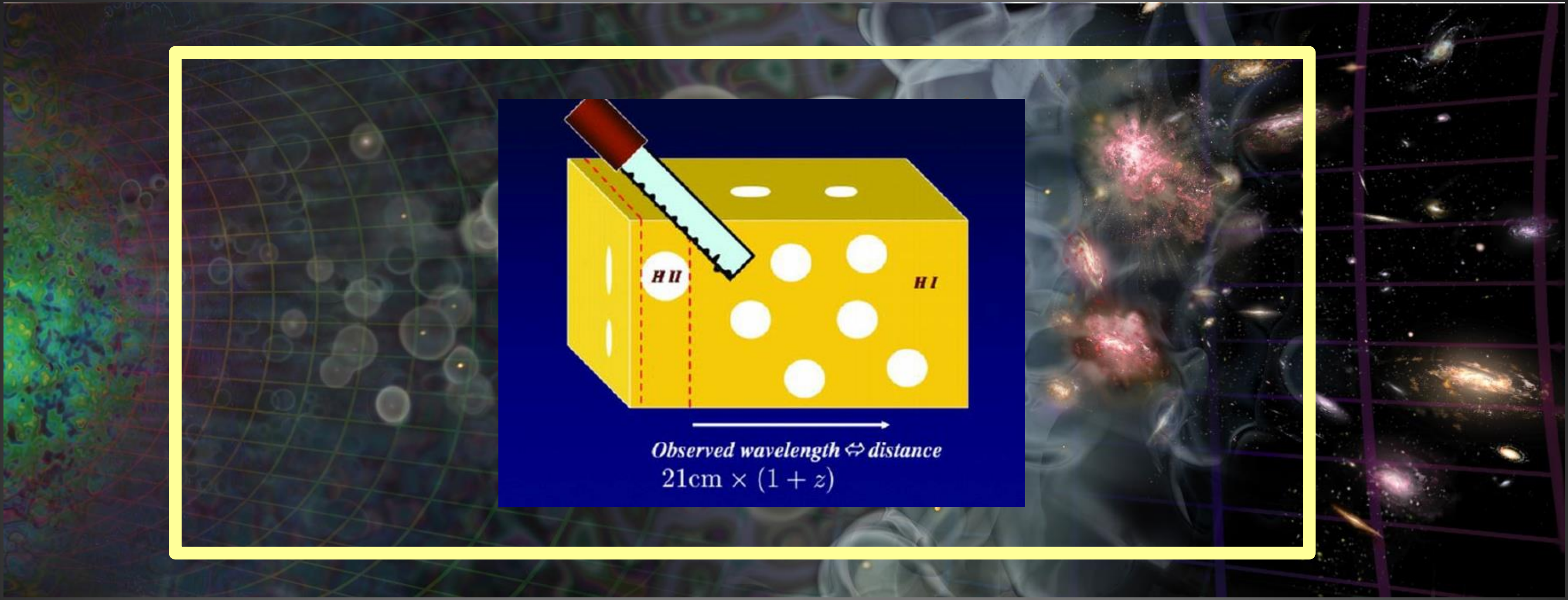
HI emits 21-cm signal, probe of

- Dark Ages
- Cosmic Dawn
- Reionization



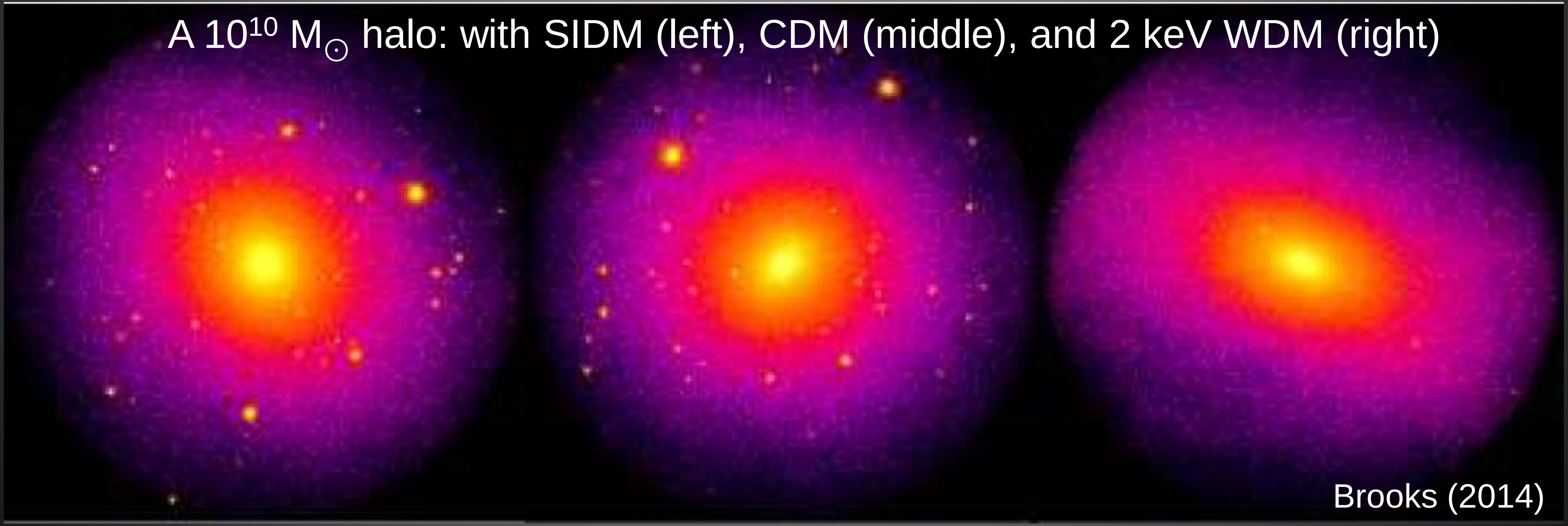
Promising tools

Image: Loeb, Scientific American 2006



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

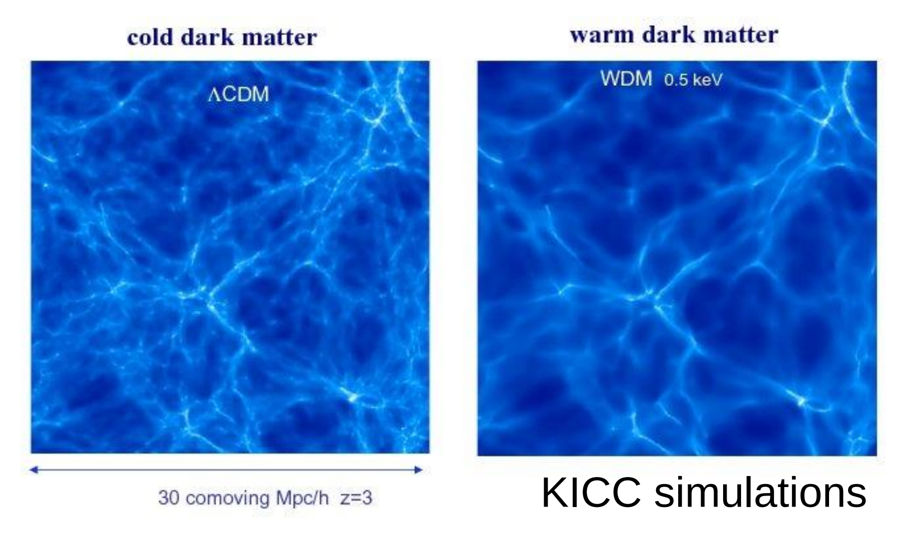
Probes of Warm Dark Matter in the Early Universe



A 10^{10} $M_\odot$ halo: with SIDM (left), CDM (middle), and 2 keV WDM (right)

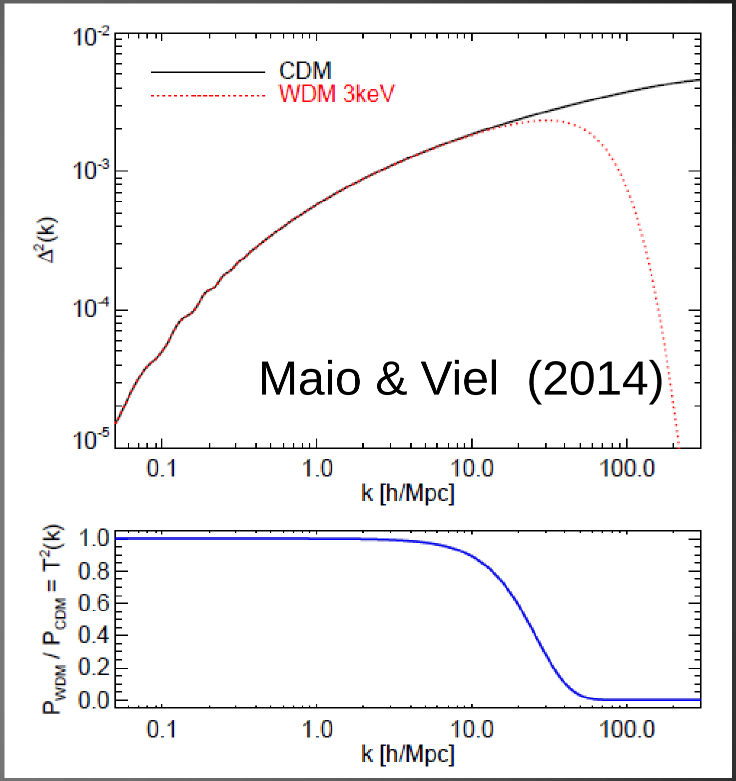
Brooks (2014)

Large Scale Structure



KICC simulations

Matter power spectra for 3 keV WDM

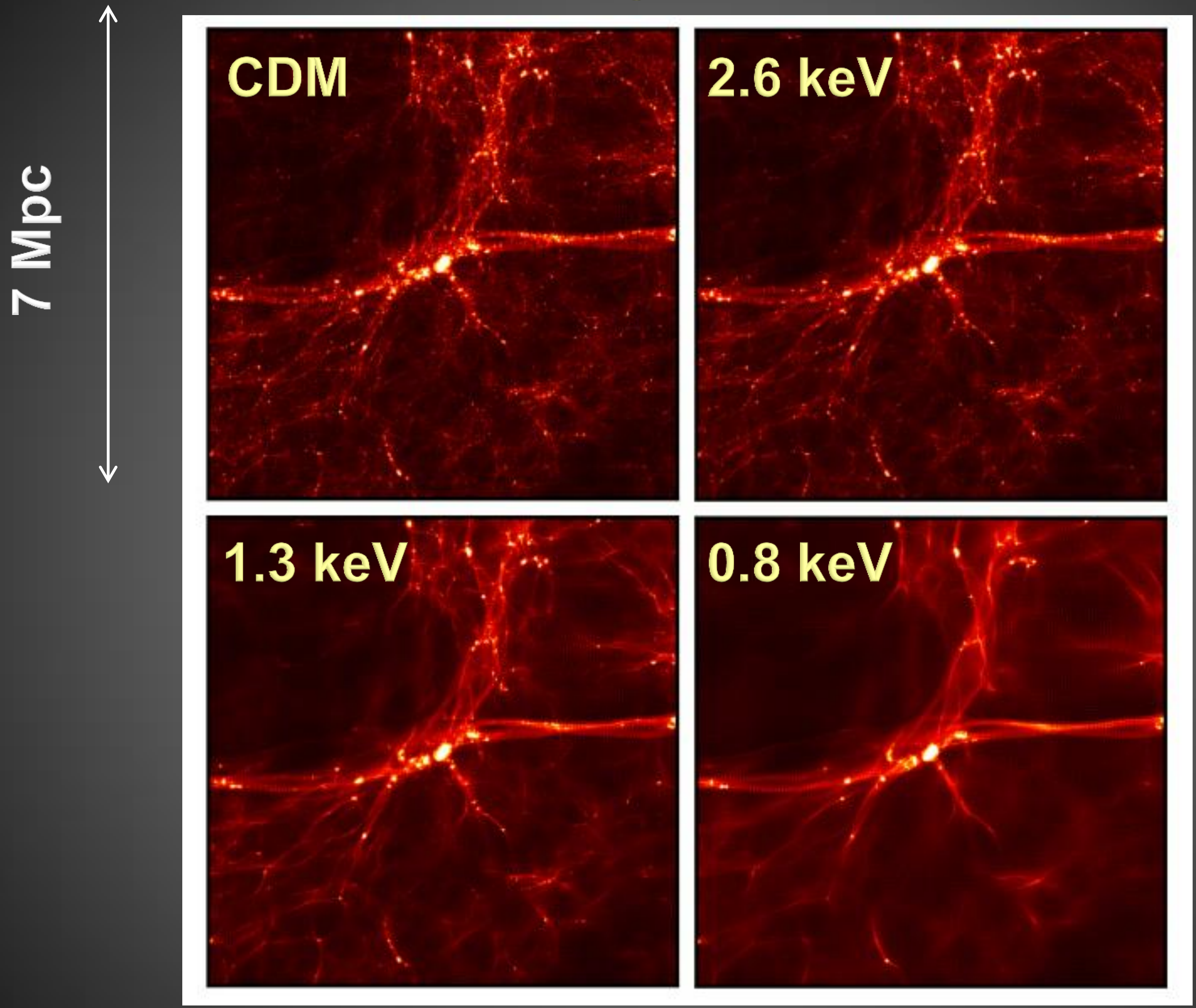


Maio & Viel (2014)

Structure formation on small scales is suppressed:

- Particle free streaming (Bode P., Ostriker J. P., Turok N., 2001)
- Residual velocity dispersion of the WDM delays gravitational collapse (e.g., Barkana R., Haiman Z., Ostriker J. P., 2001)

Clustering at z = 6

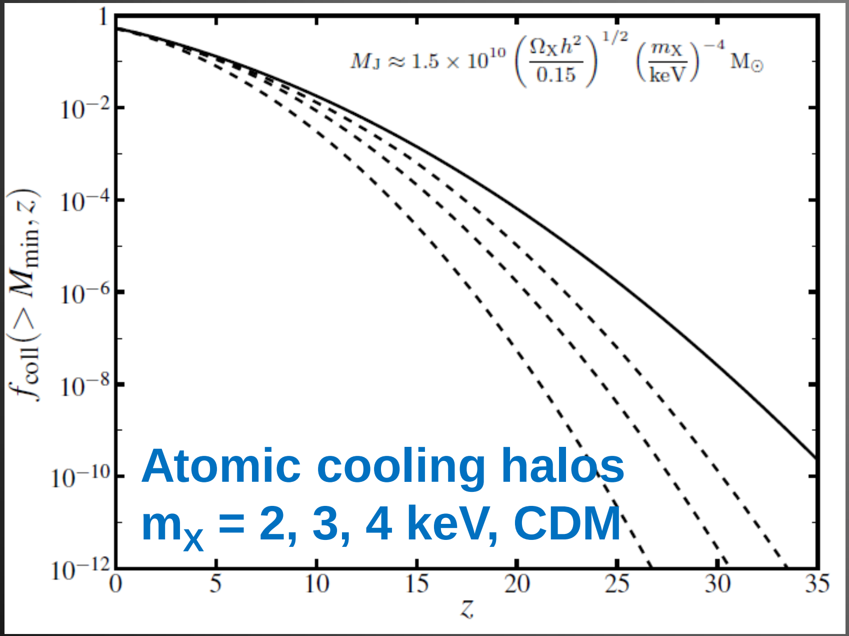


Schultz et al. 2014

Abundance of Dark Matter Halos

- Decrease in the number density
- Change in the mass build up of the smallest galaxies at the highest redshifts, WDM – no light galaxies

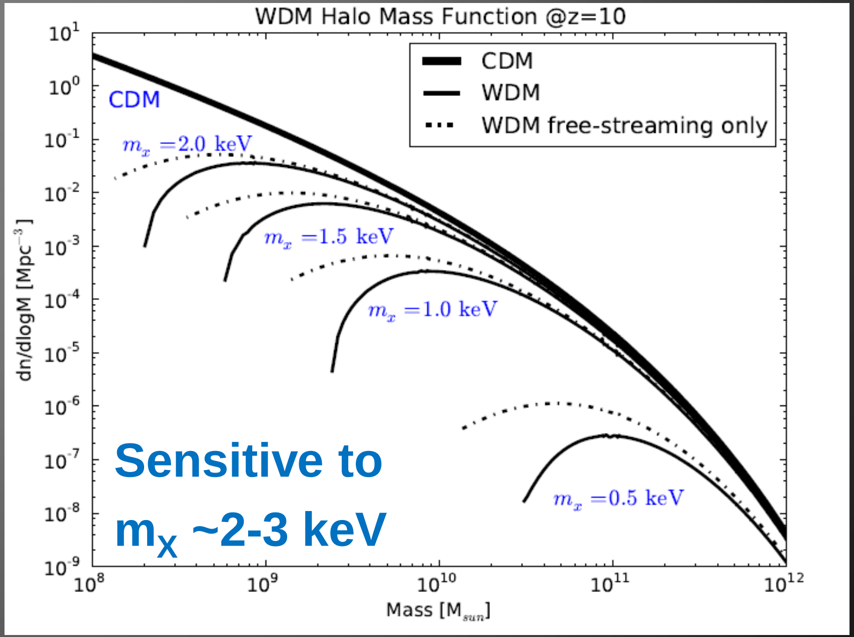
Collapsed fraction



Atomic cooling halos
m_X = 2, 3, 4 keV, CDM

Sitwell, Mesinger, Ma, Sigurdson 2014

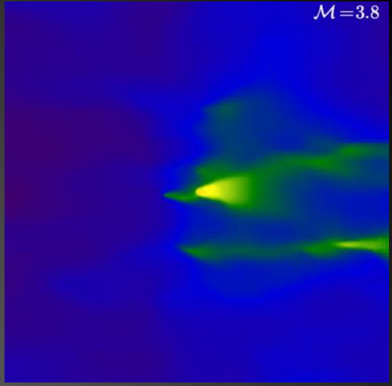
Number counts at z = 10



Sensitive to
m_X ~2-3 keV

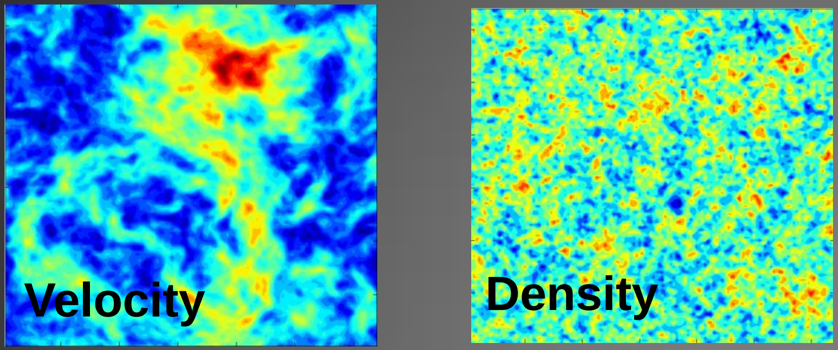
Pacucci, Mesinger, Haiman 2013

Sources of Astrophysical Uncertainties



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

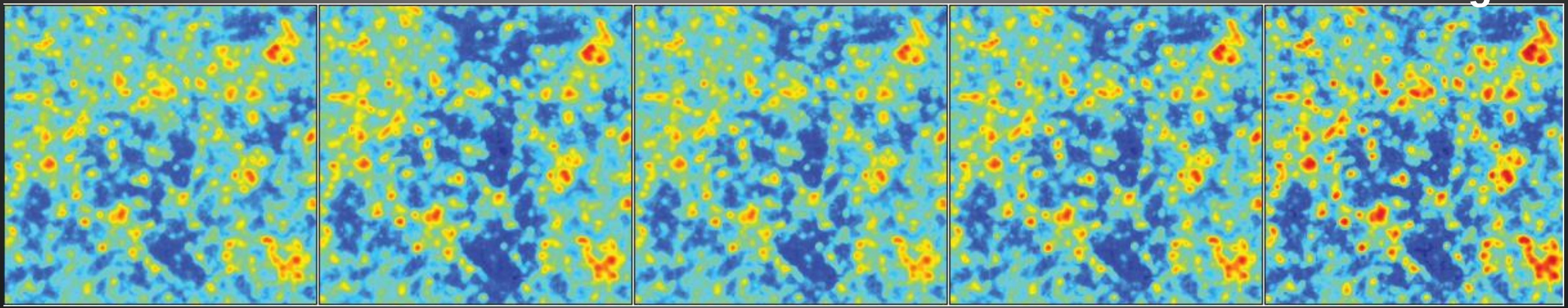
Initial conditions



21-cm brightness temperature

← **Molecular cooling** →

Atomic cooling



No feedback, No vbc

No feedback

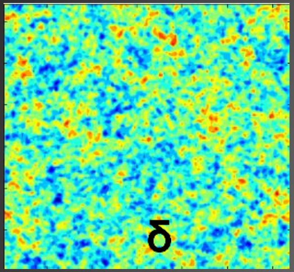
Weak feedback

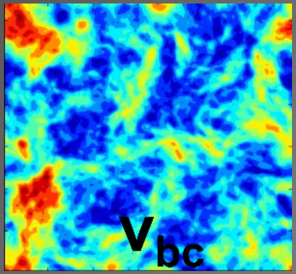
Strong feedback

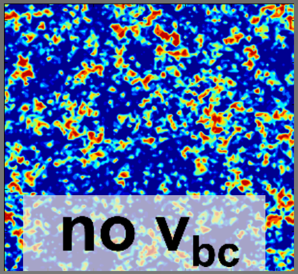
Saturated feedbback

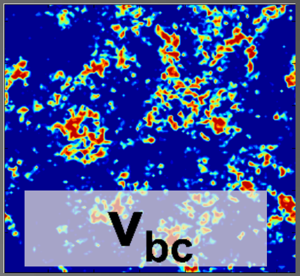
Fialkov, Barkana, Visbal, Tseliakhovich, Hirata (2013)

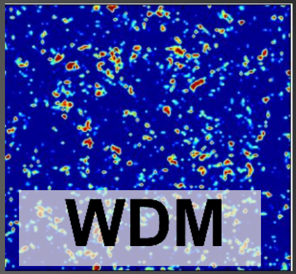
Abundance of Dark Matter Halos Astrophysical Uncertainties





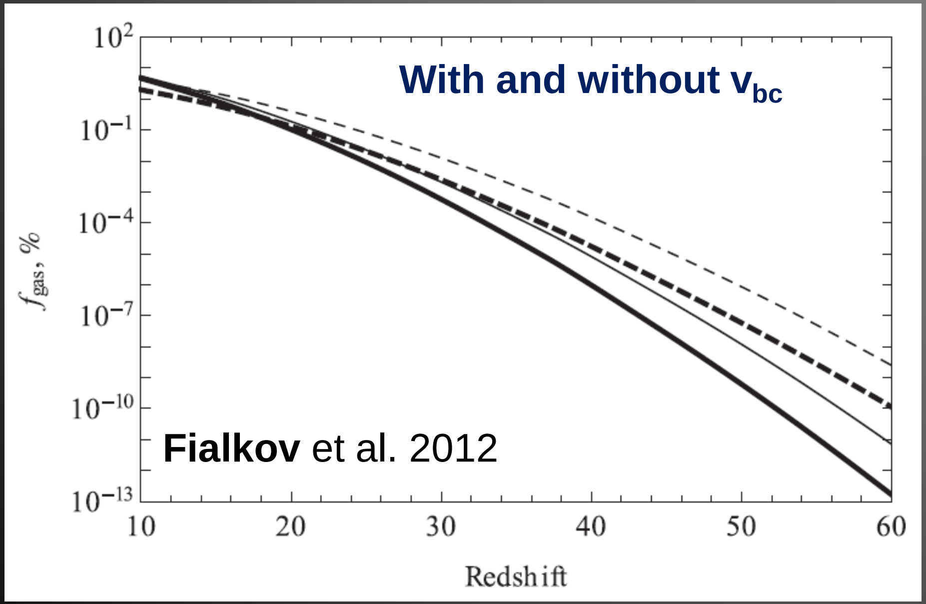






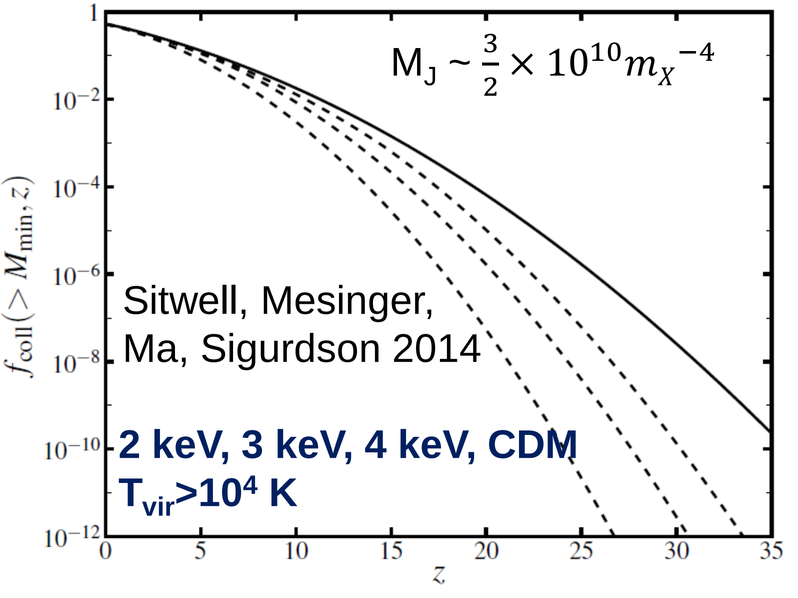
Star formation in 10^5-10^7 M_{sun} halos:

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



With and without v_{bc}

Fialkov et al. 2012



$M_J \sim \frac{3}{2} \times 10^{10} m_X{}^{-4}$

Sitwell, Mesinger, Ma, Sigurdson 2014

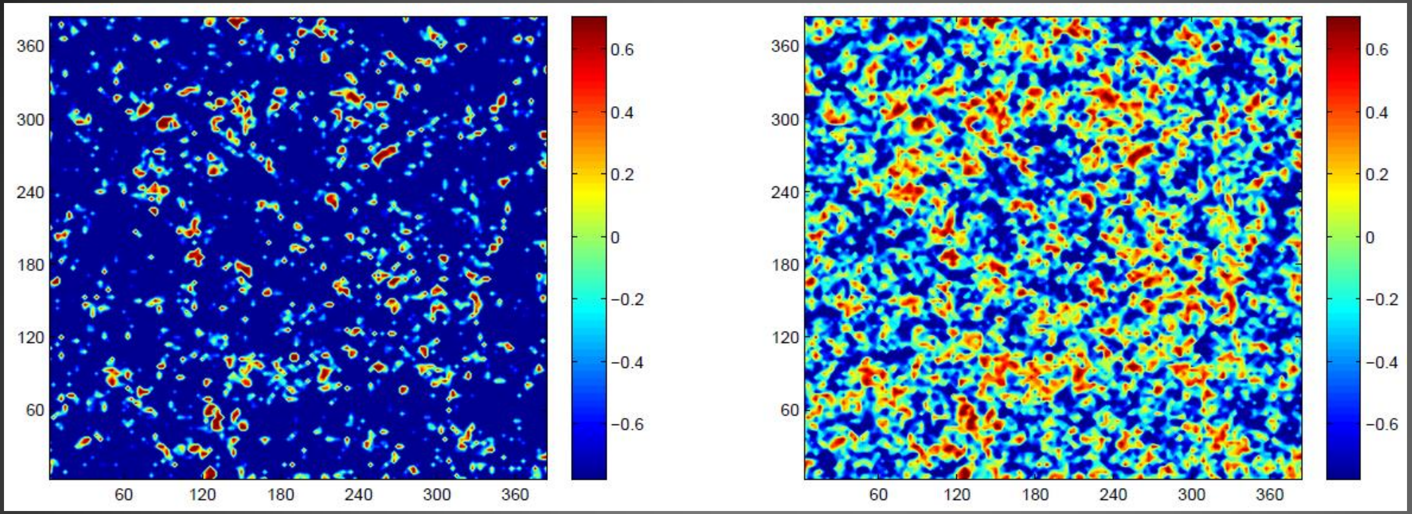
2 keV, 3 keV, 4 keV, CDM

T_{vir}>10^4 K

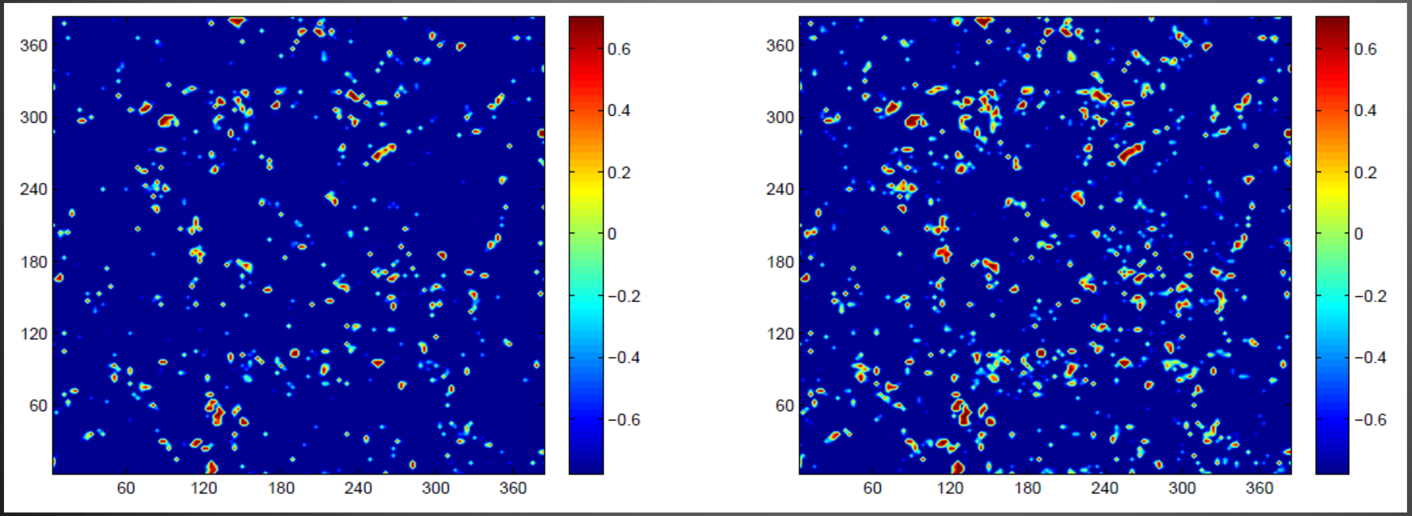
Collapsed Fraction at z = 10, Fluctuations

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

CDM



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



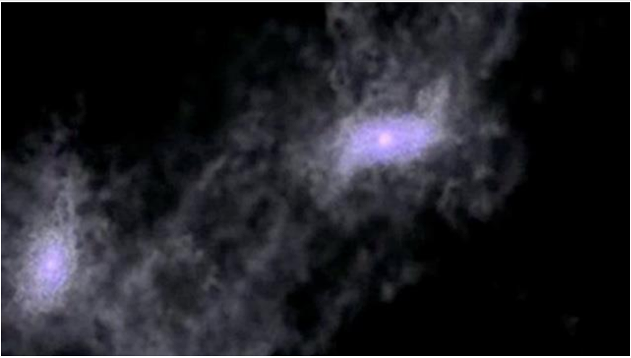
Star formation
in heavy halos
$M>10^{10}\ M_{sun}$

First Stars

The First Billion Years of a Warm Dark Matter Universe

Umberto Maio[1,2⋆], Matteo Viel[1,3]

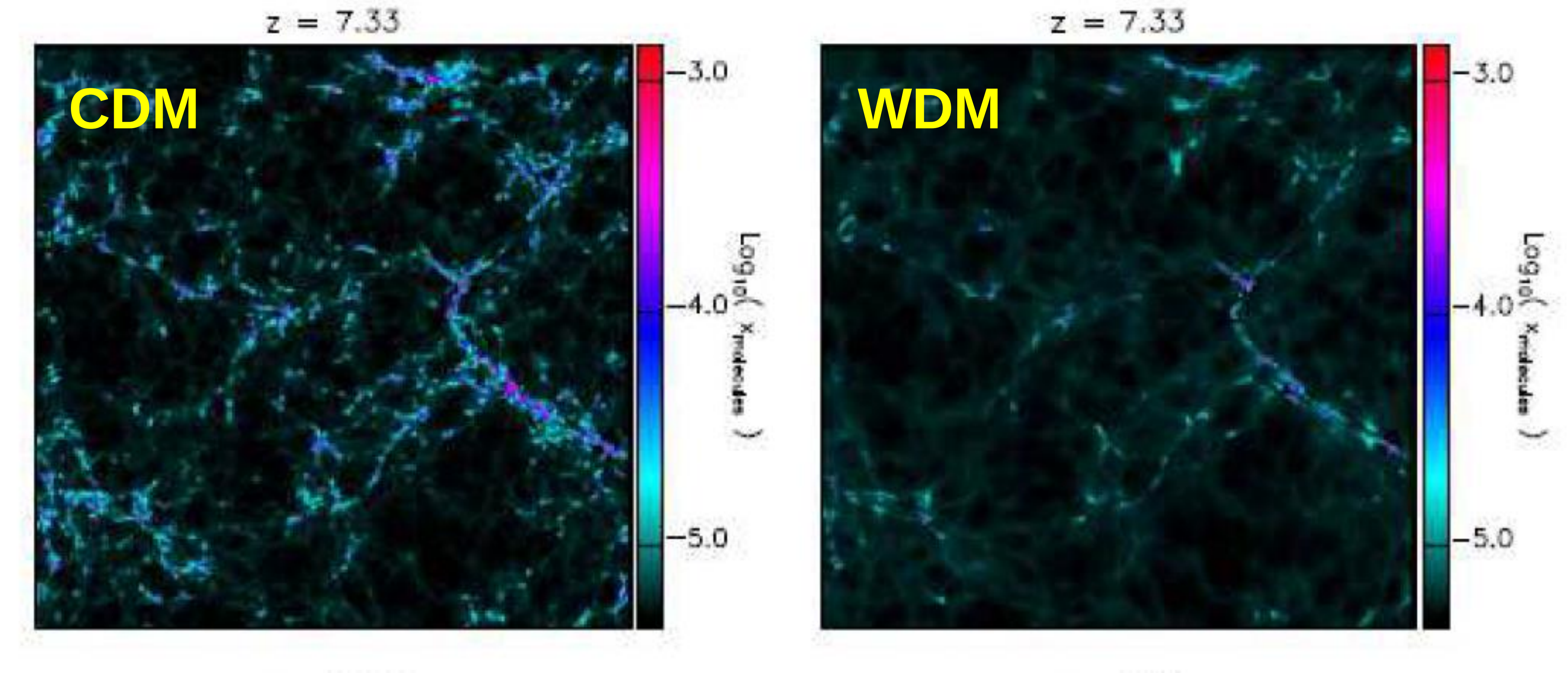
“The most striking effect of WDM results to be a
dramatic drop of star formation activity
in the whole first billion years.
Δz = 6 (0.1 Gyr) delay in collapse and star formation”



First Stars

- Primordial stars form via H_2 or HI cooling
- WDM: no minihalos, H_2 cooling in WDM haloes (> 3 keV) is inhibited

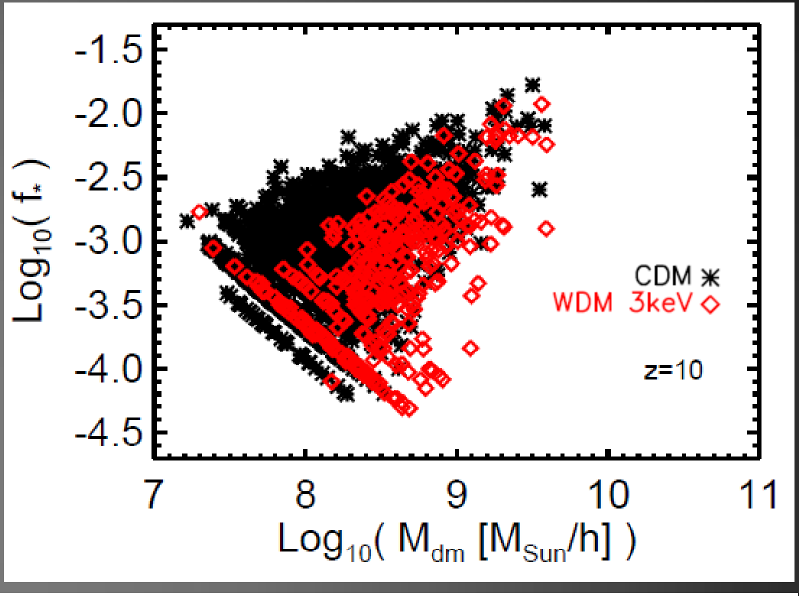
Molecular Fractions, >3 keV

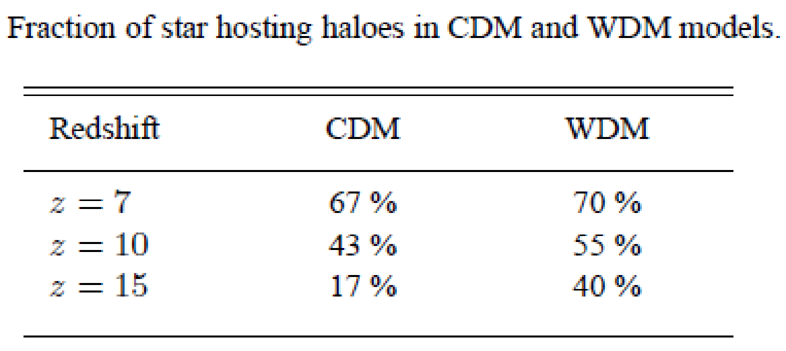


Maio & Viel (2014)

First Stars : WDM vs CDM

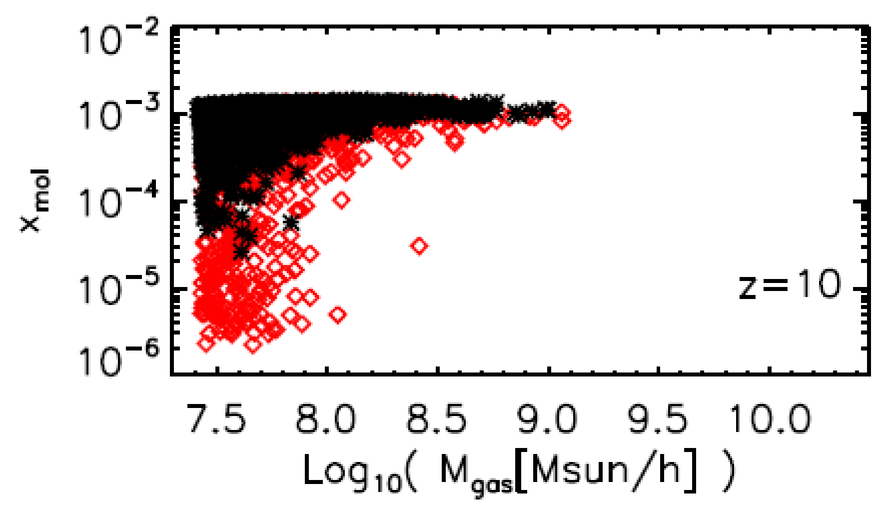
- Luminous objects in WDM are very rare at z > 10
- In WDM star formation via HI and metal line cooling
- Less halos exist
- More halos form stars





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 %

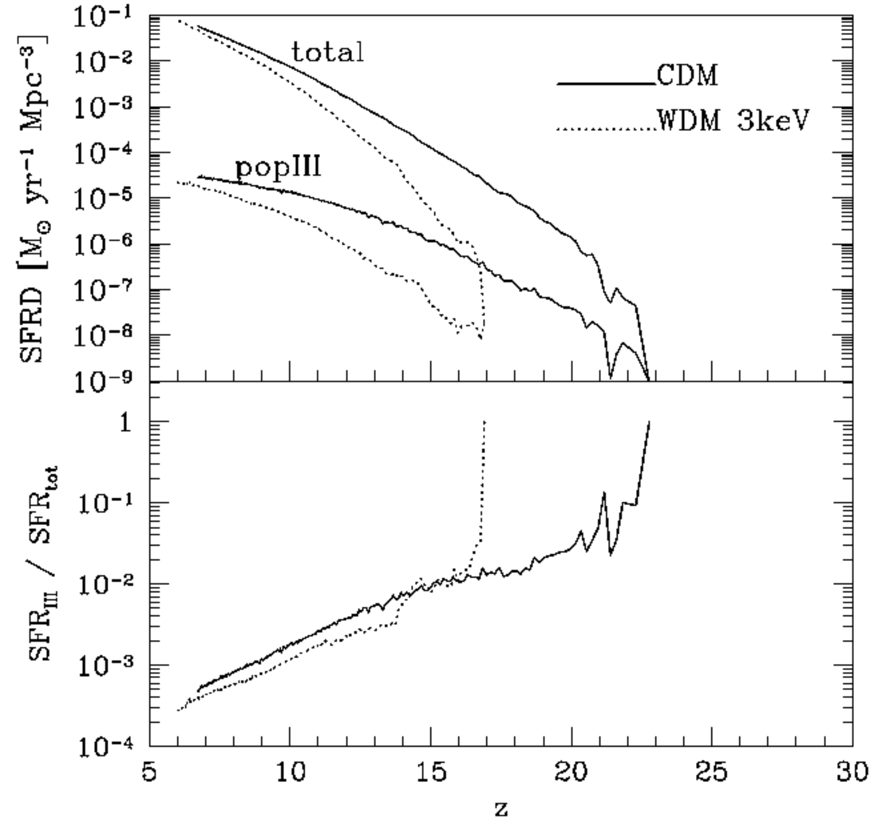


Maio & Viel (2014)

Pop III, SFR is suppressed in WDM

CDM : metal pollution starts earlier.

WDM : PopIII contribution drops down fast (enrichment takes place suddenly). More gas turns into stars and can experience more chemical feedback.

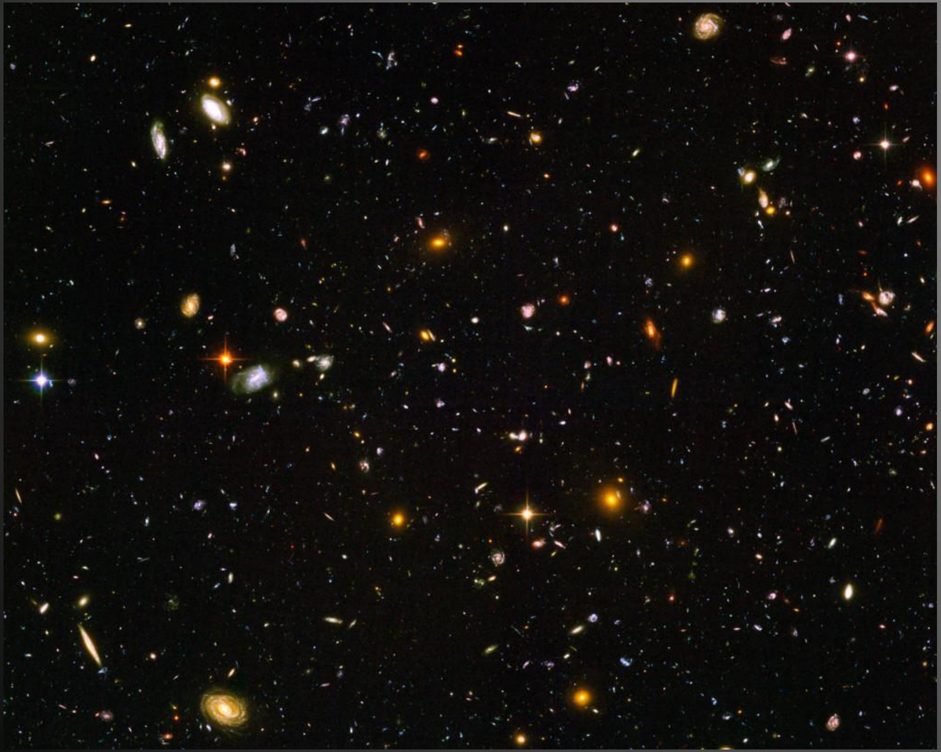


Maio & Viel (2014)

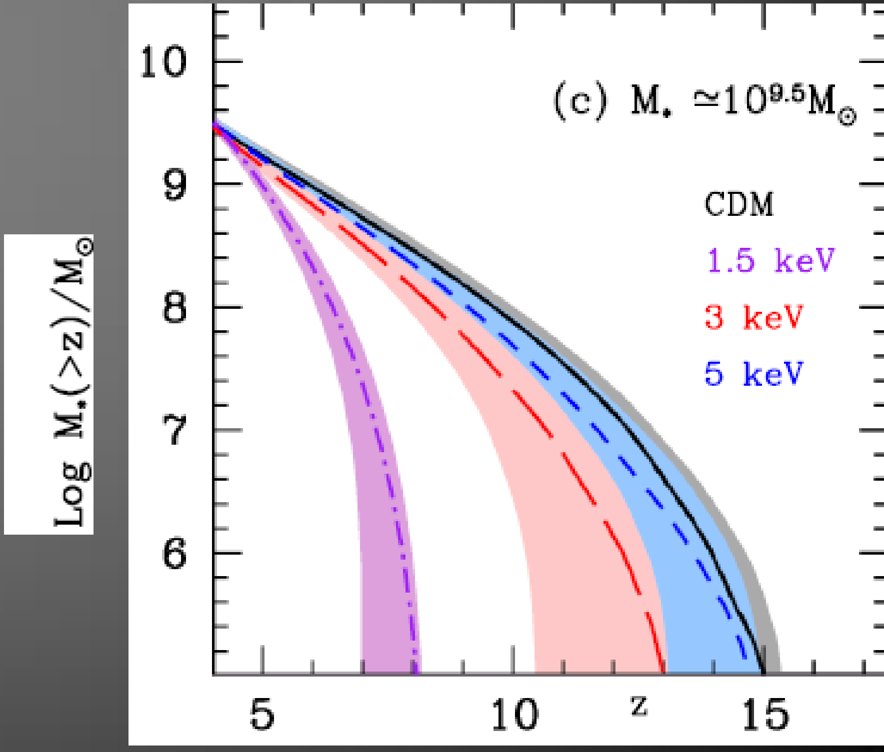
Stellar Mass in the Universe

- Galaxies in WDM models form later
- Assemble their stars more rapidly compared to CDM.
- Younger, more UV luminous stellar population.

HUDF

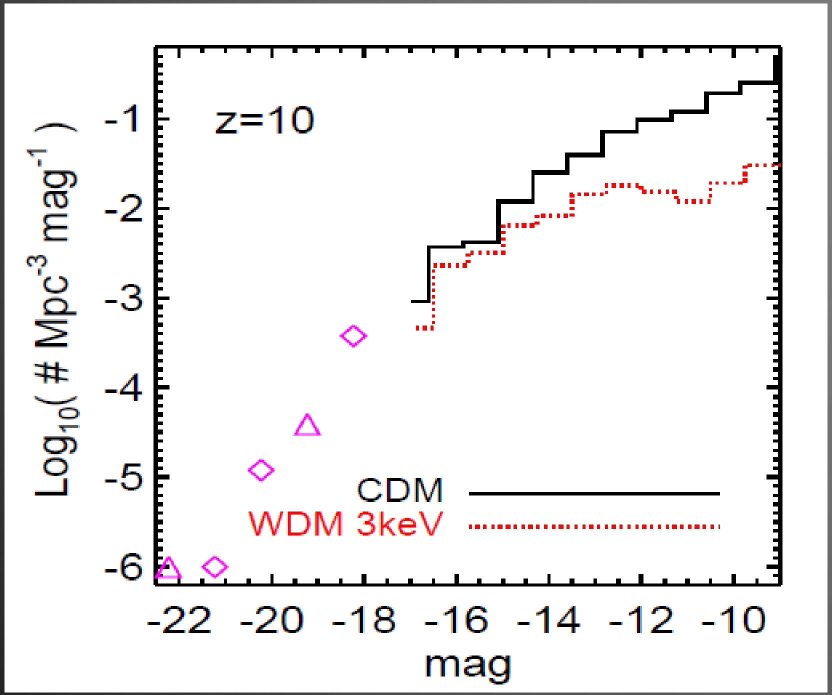


Average stellar mass assembly of galaxies as a function of z, Dayal et al. 2014

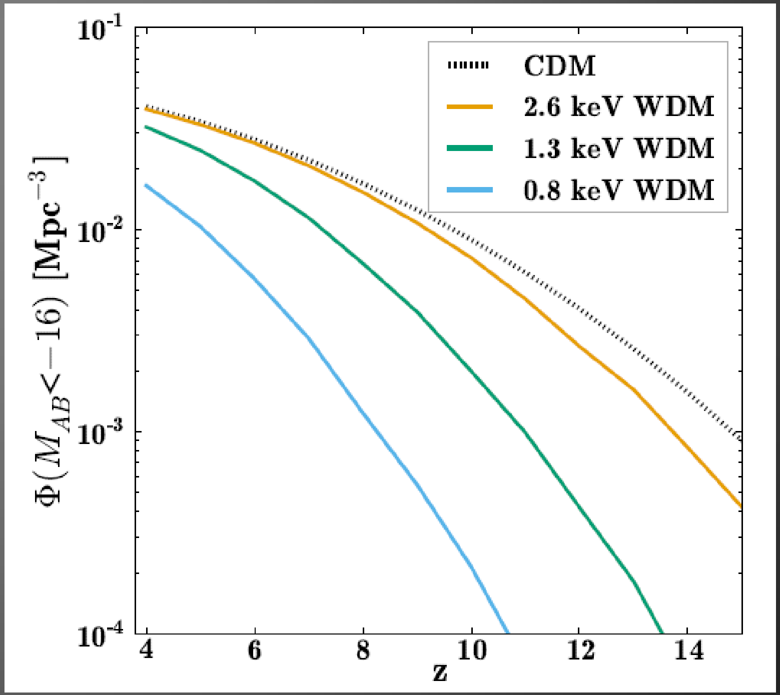


Effect on the Luminosity Function at High Redshfts

Faint galaxy counts at higher redshift will be sensitive to WDM scenario

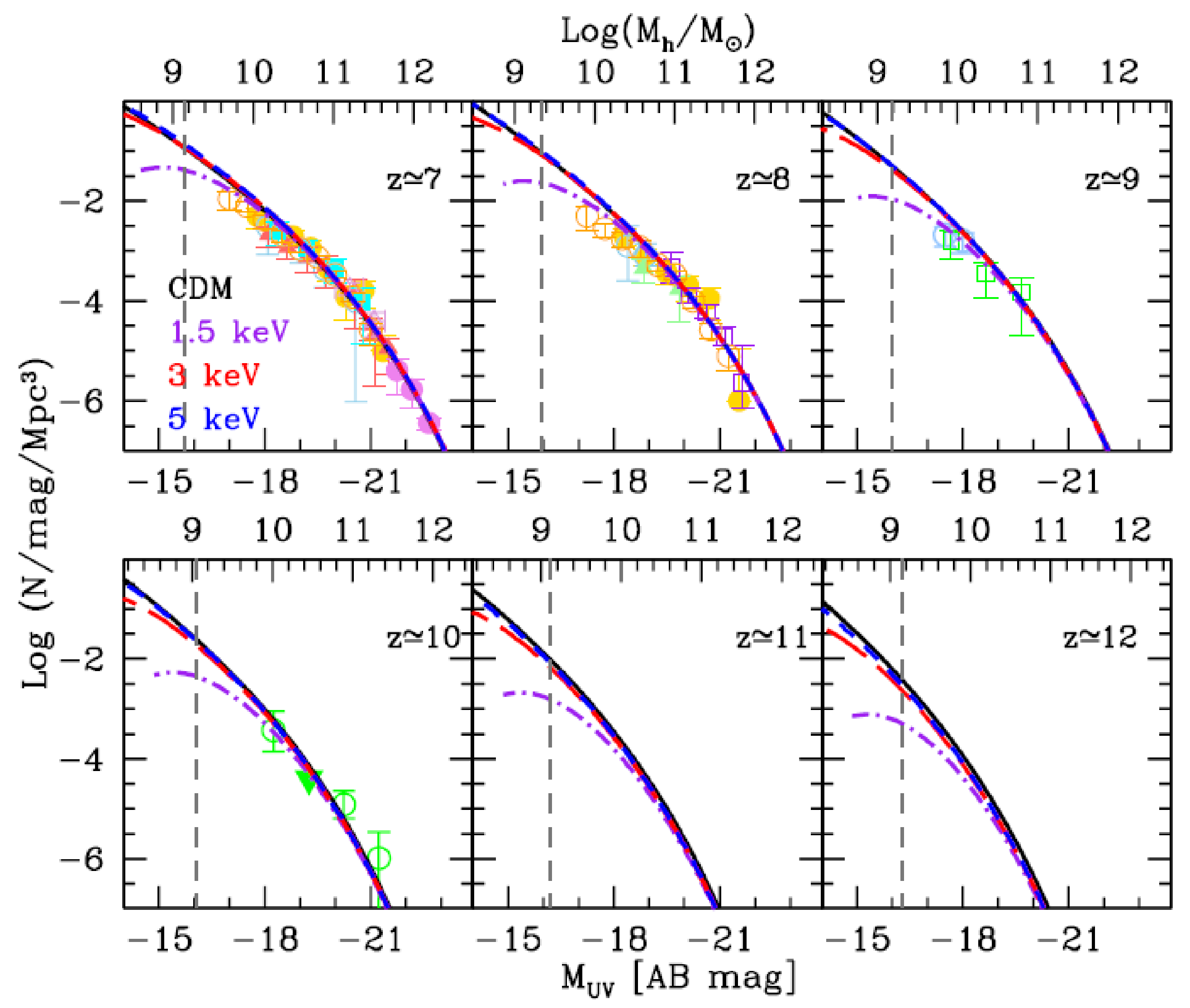


Maio & Viel (2014)



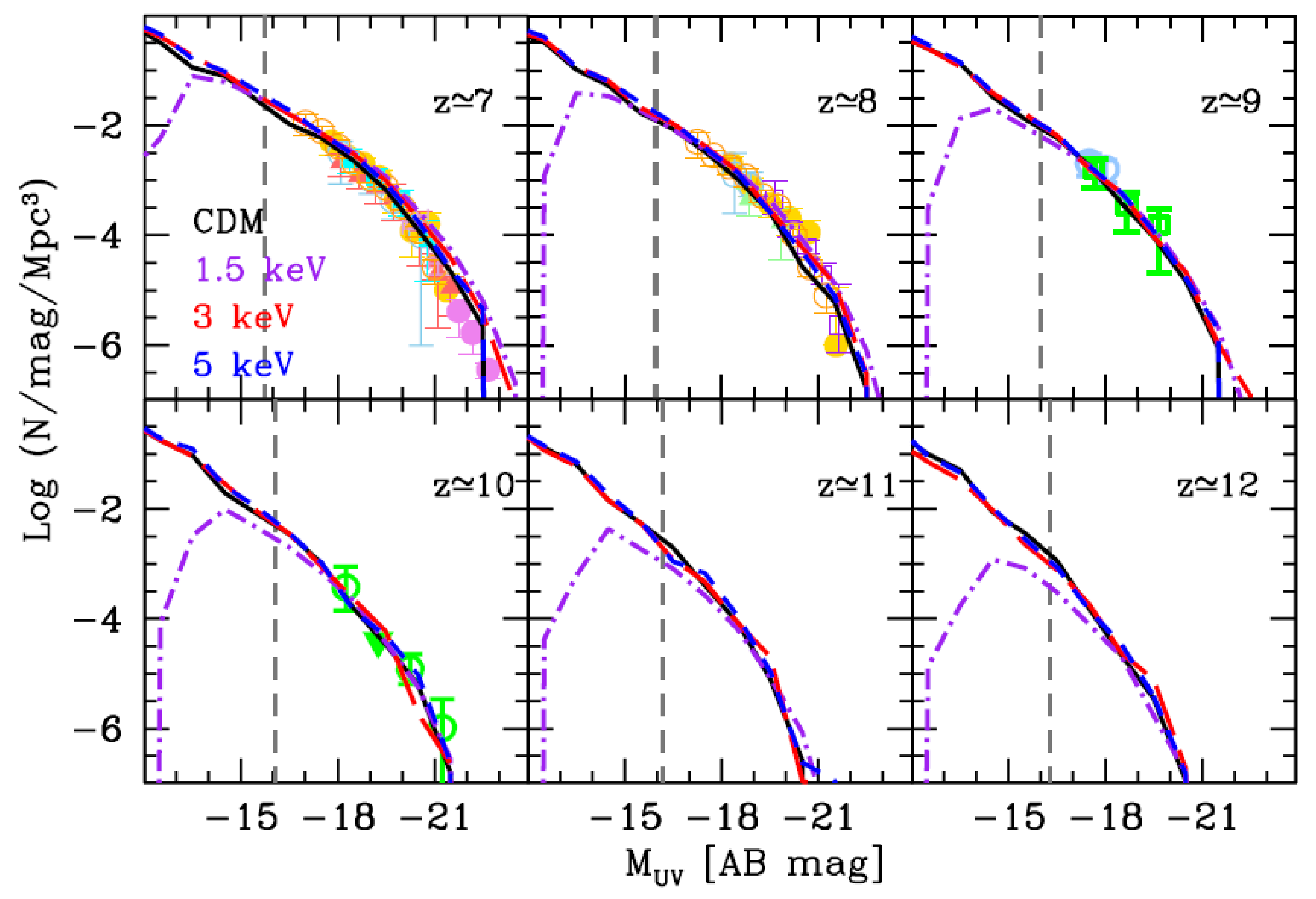
Predicted number density of galaxies brighter than M_{AB} = -16 (Schultz et al. 2014)

Luminosity Function in WDM



Dayal et al. 2015

Luminosity Function with UV Feedback



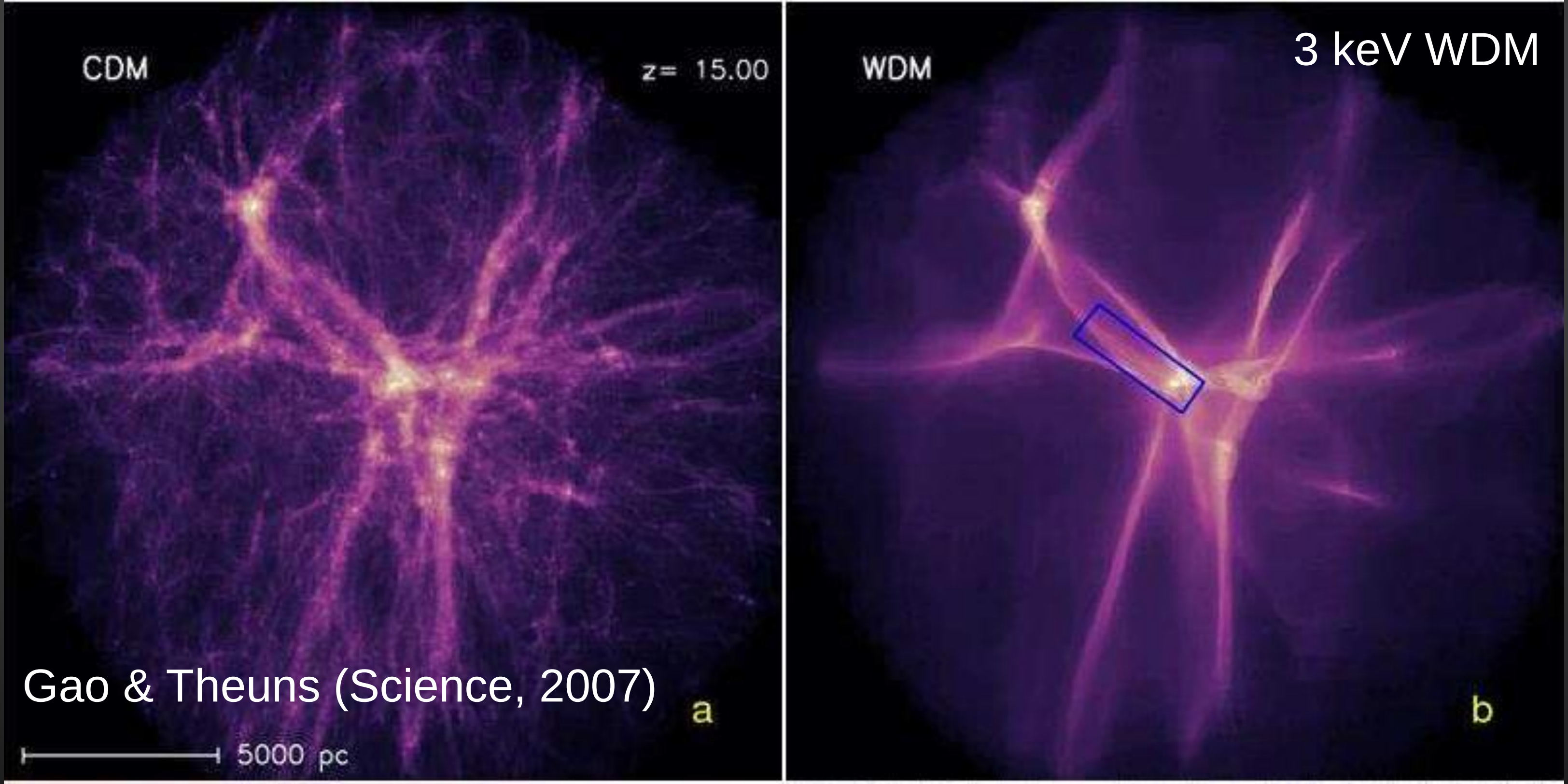
Dayal et al. 2015

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:

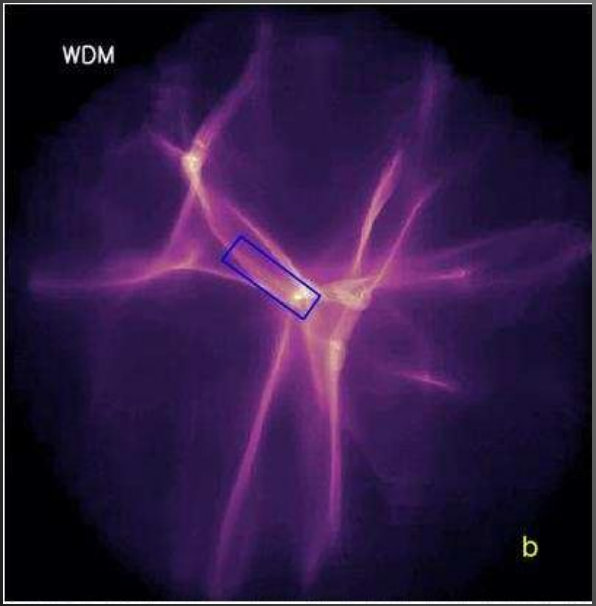
- CDM filaments fragment into numerous nearly spherical high density regions (‘halos’)
- WDM filaments are mostly devoid of such substructure

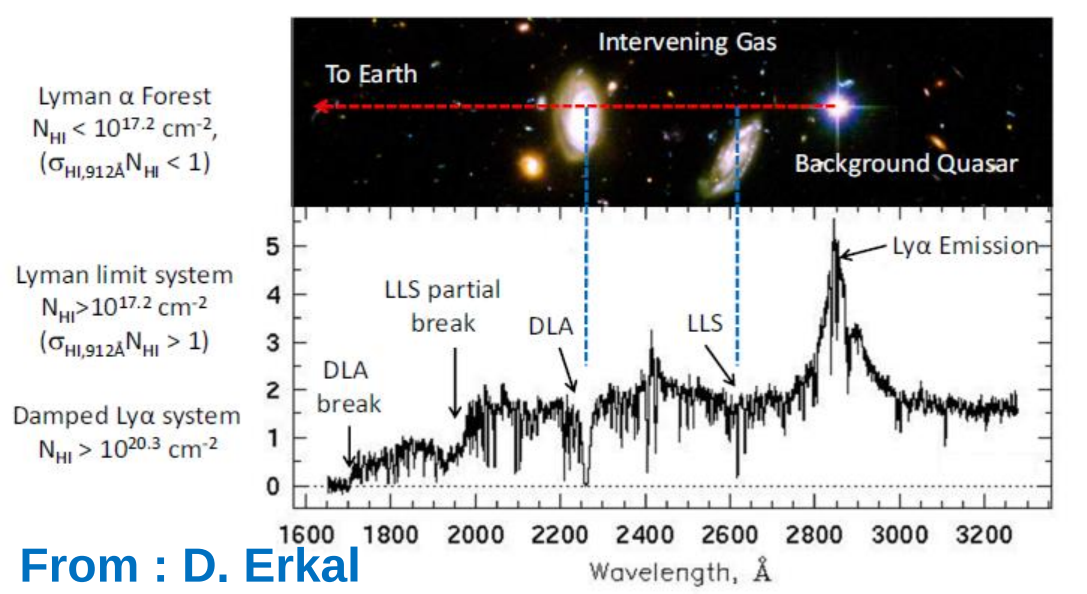


Gao & Theuns (Science, 2007)

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

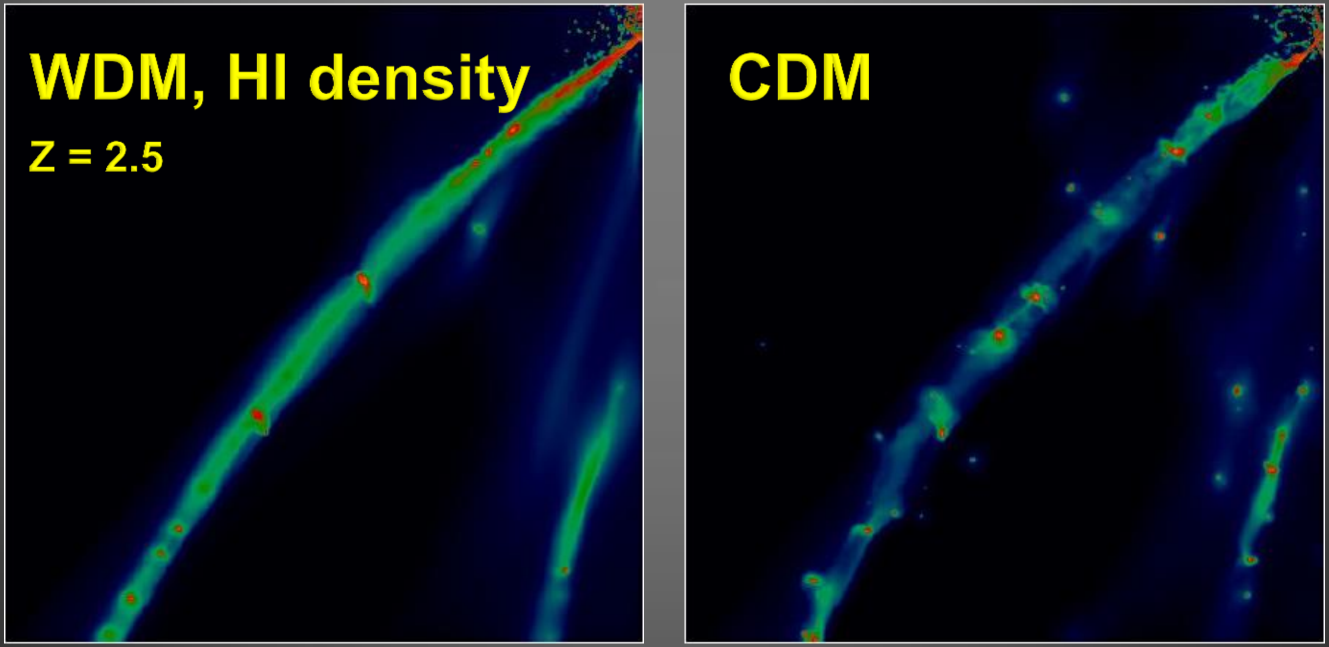




From : D. Erkal

Stars in WDM can form in Filaments!

- For m_x ~ 1.5 keV → SF in filaments dominates at $z > 6$!
- Reionisation → 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.

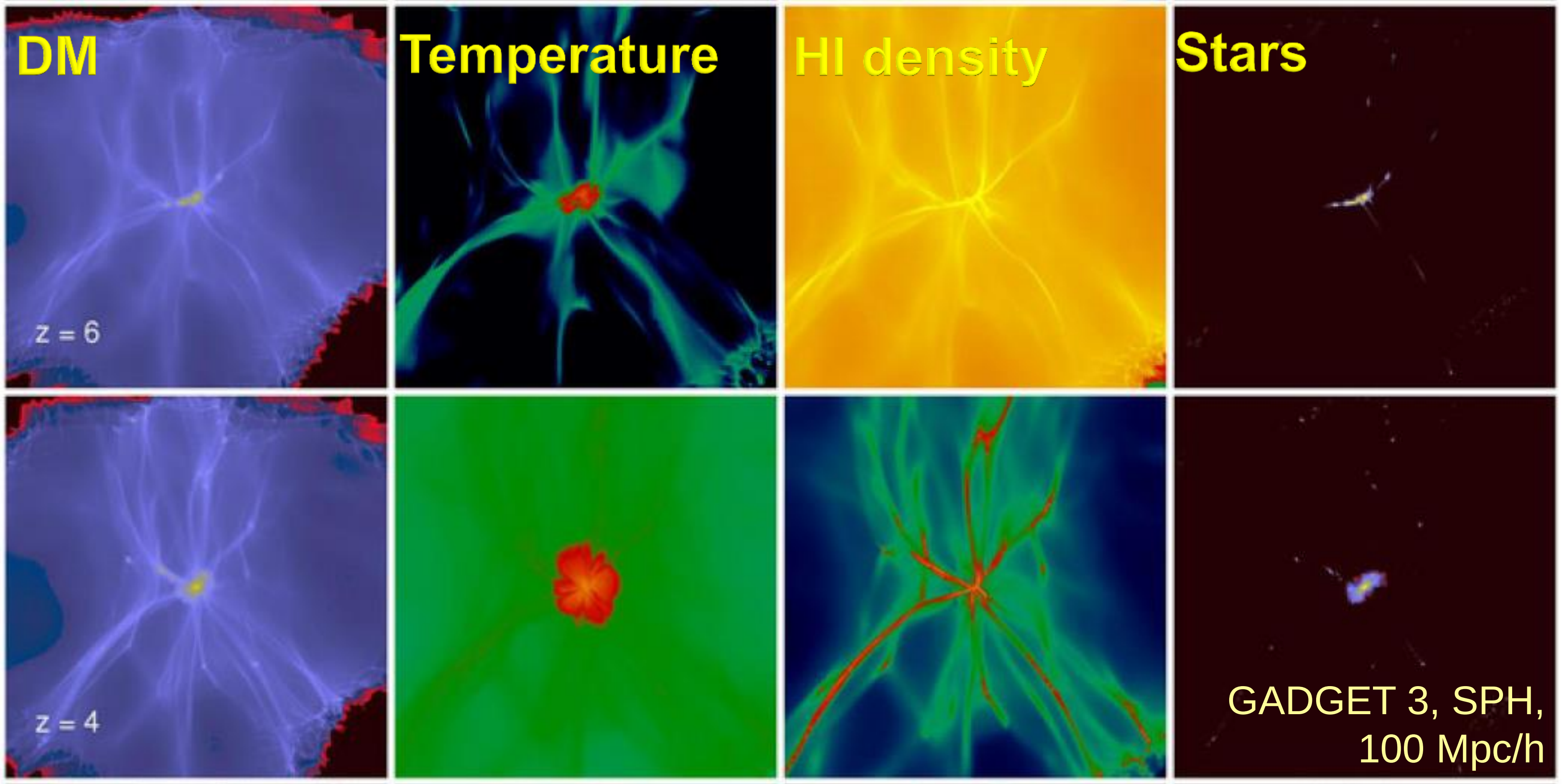


WDM: Filaments do not fragment

(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

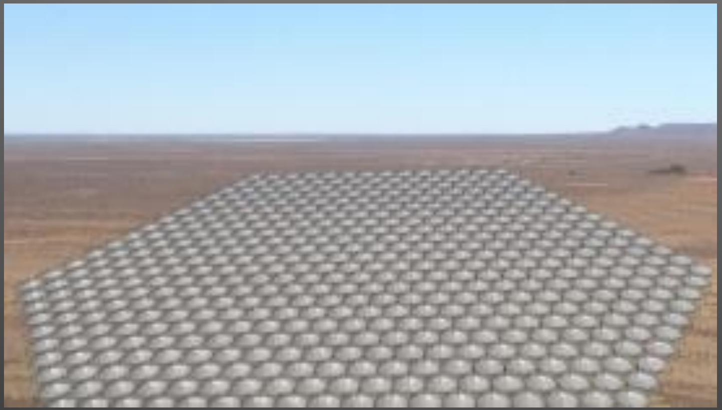


GADGET 3, SPH,
100 Mpc/h

Gao, Theuns, Springel (2014)

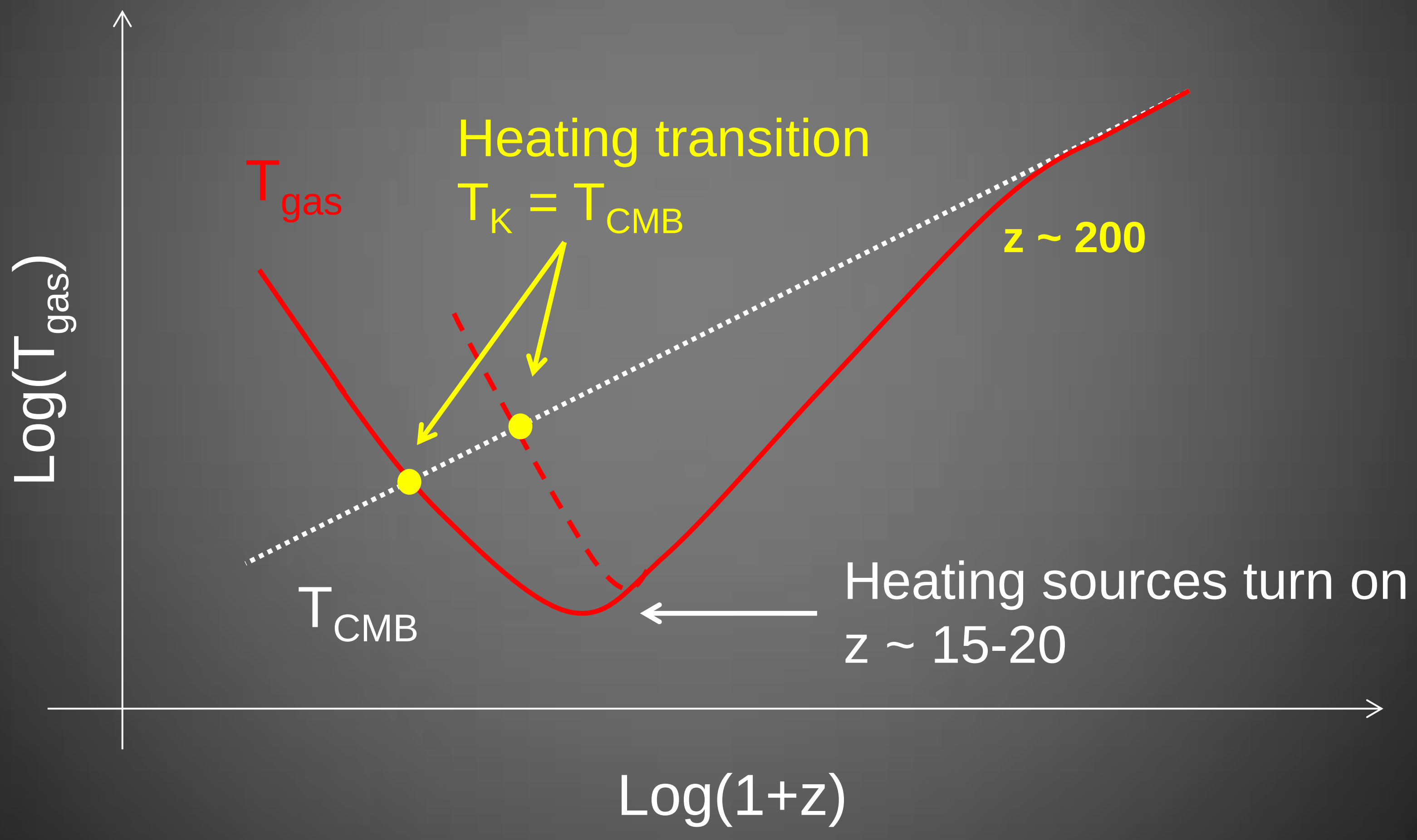
Results from zoomed cosmological hydrodynamical simulations. Formation of a Milky Way-like galaxy in WDM.

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



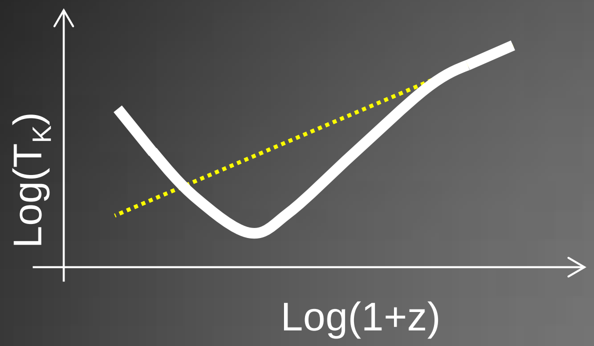
High-z Thermal History is Unknown

Different types of heating sources → different thermal histories



Heating sources turn on z ~ 15-20

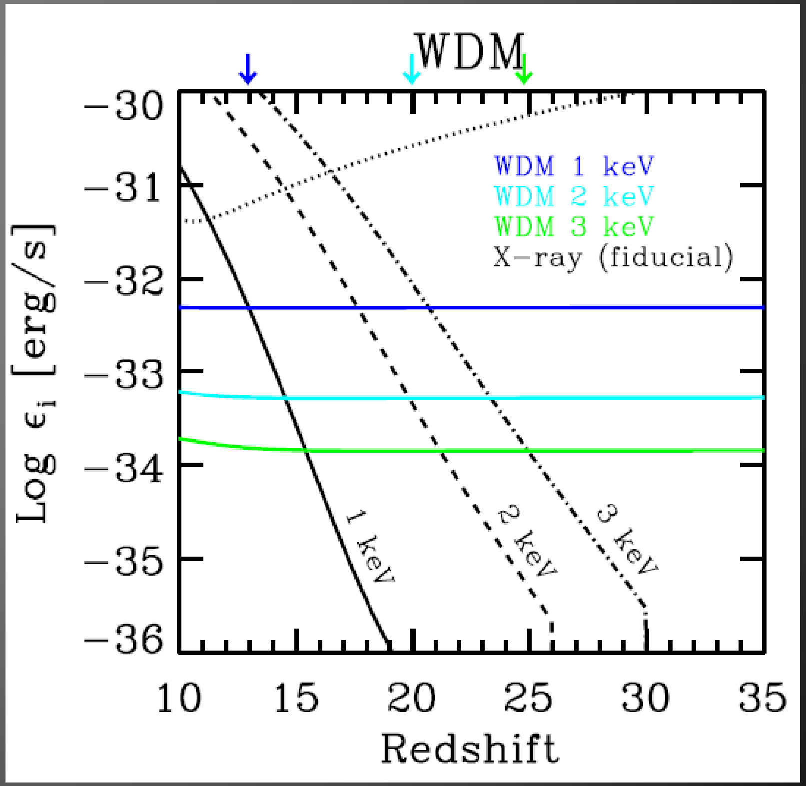
Thermal History WDM vs CDM



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

Effects of WDM on Heating:

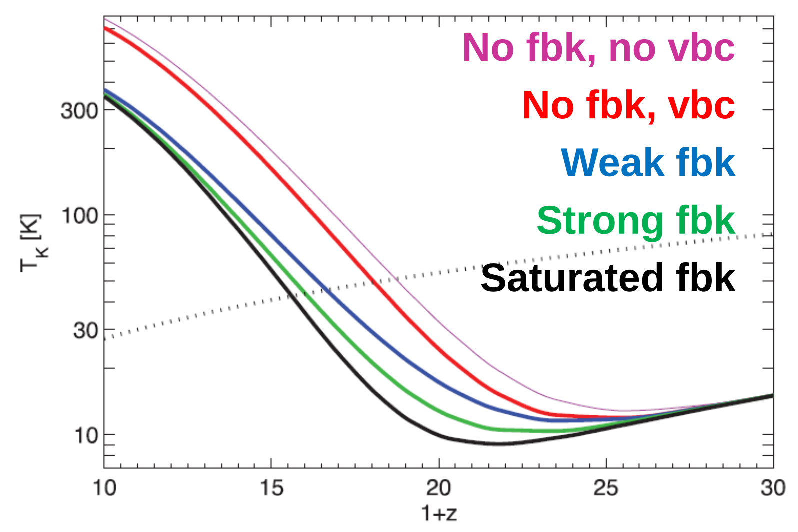
- Suppressed structure formation, delay in heating and reionization
- Heat transfer to gas from WDM decay (insignificant)



Evoli et al. 2014

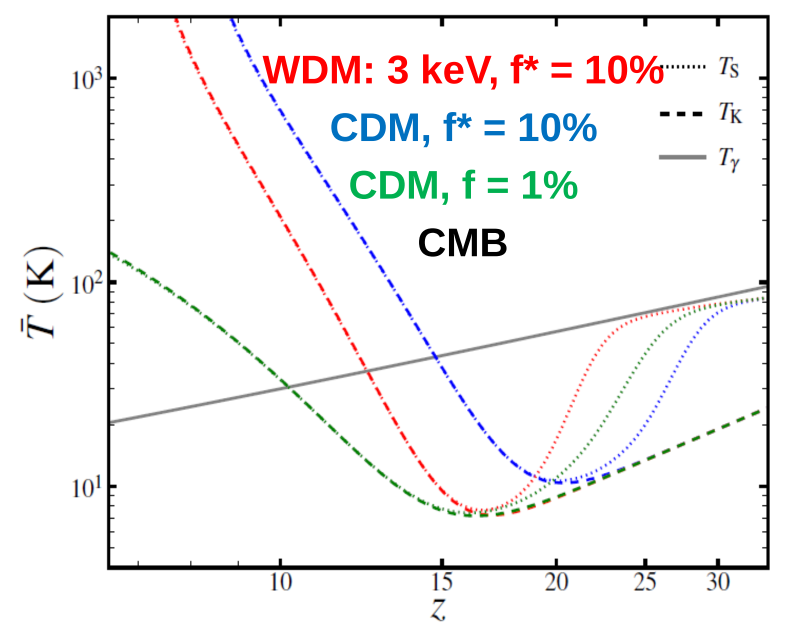
Thermal History WDM vs CDM
Astrophysical Uncertainties

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

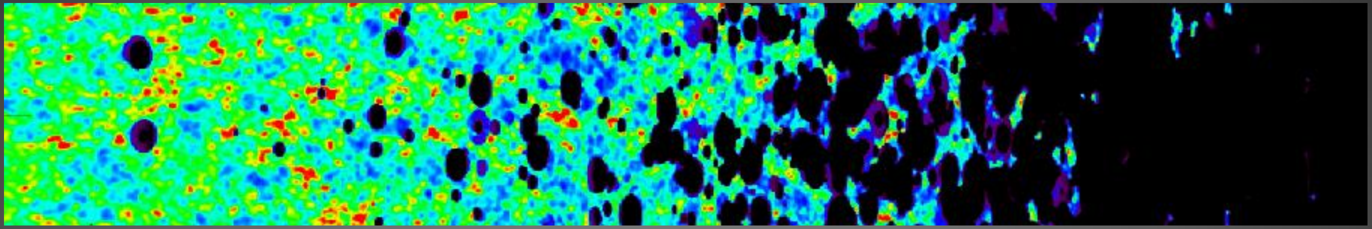


Fialkov et al. (2013)

Sitwell, Mesinger, Ma, Sigurdson (2014)

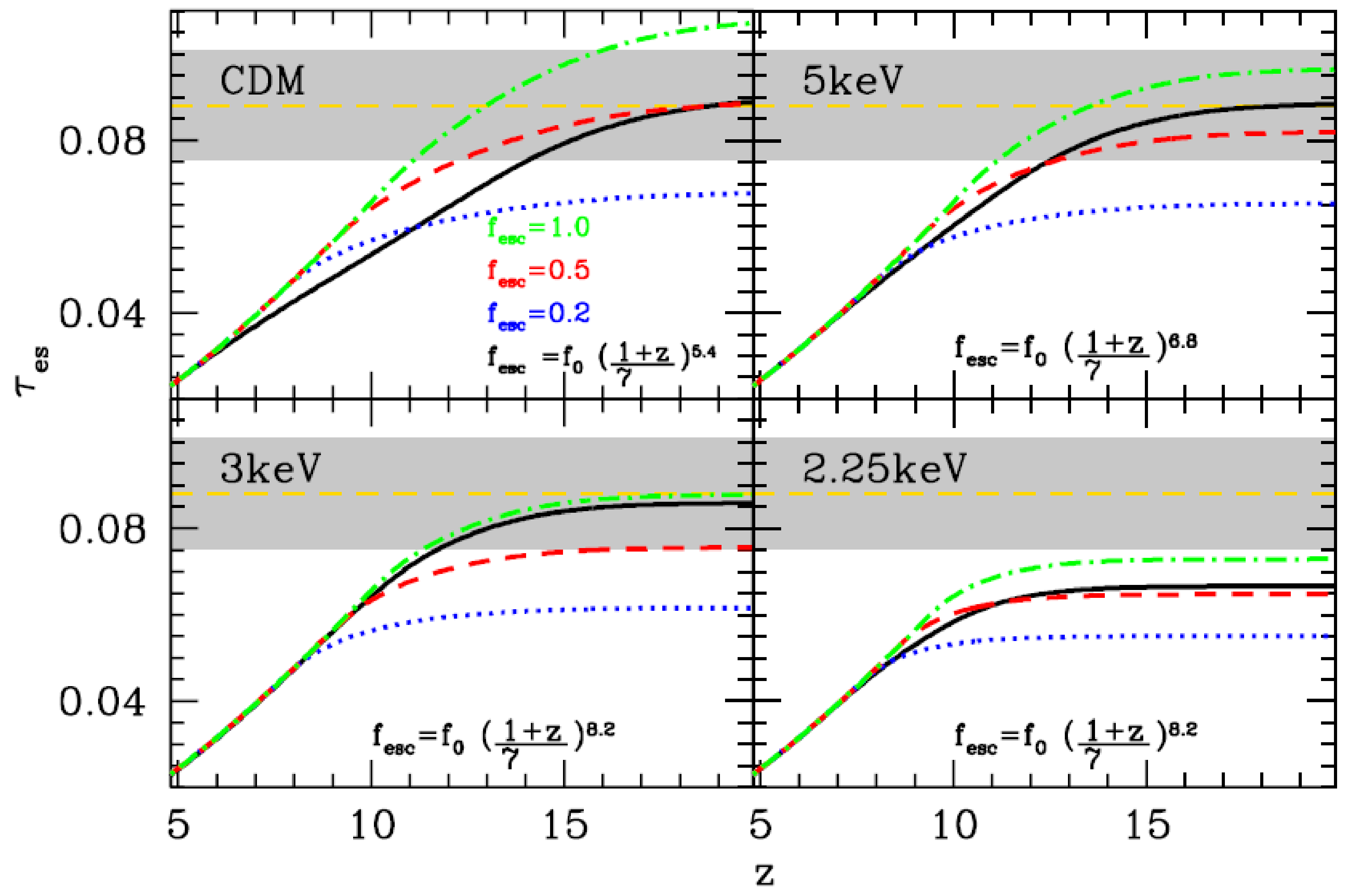


Reionization WDM vs CDM



- 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.

m_x < 2.5 keV is ruled out by Planck



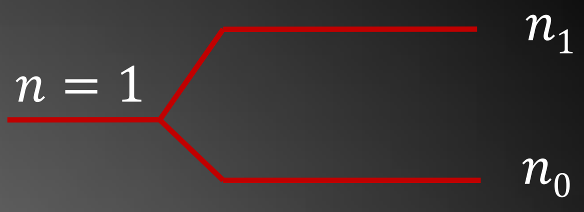
Dayal et al. 2015

21-cm Signal
3D Picture of the Universe

Golden Mine for astrophysics and cosmology!

- Dark Ages
- First Stars and Galaxies
- Reionization

21-cm Signal
Spin-flip Transition of HI



- Allows to map distribution of neutral hydrogen
- Probe Dark Ages, Cosmic Dawn and Reionization

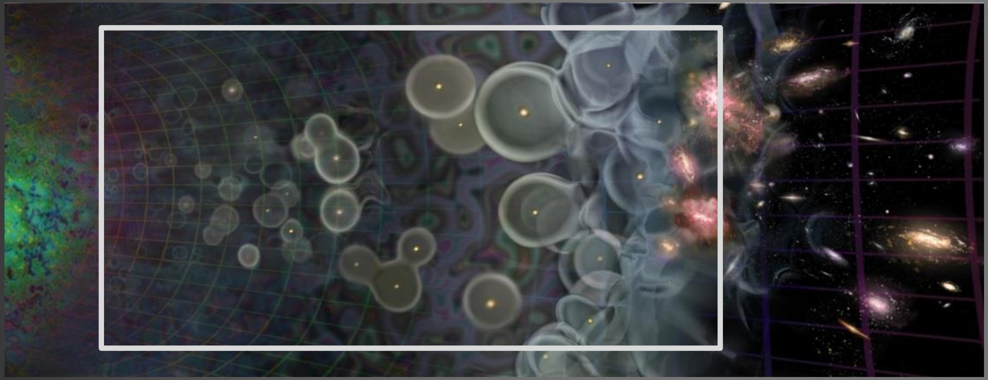
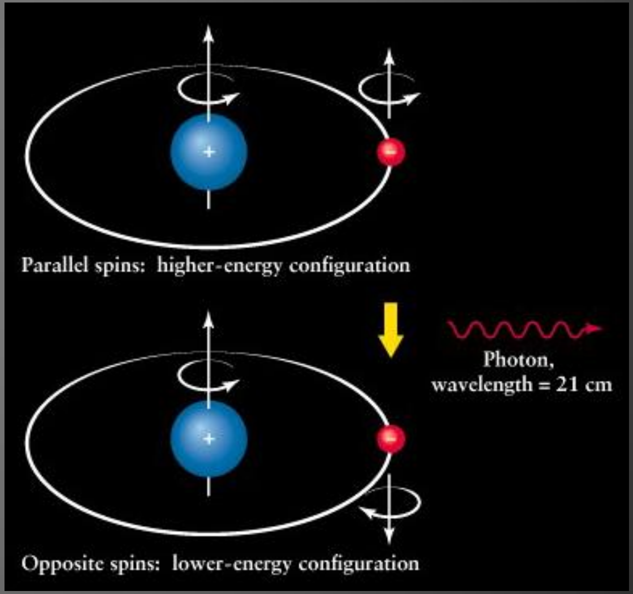


Image: Loeb, Scientific American 2006



Spin Temperature

$n_1/n_0 \equiv 3\exp(-T_*/T_S)$,

$T_* = 0.068$ K

λ = 21 cm

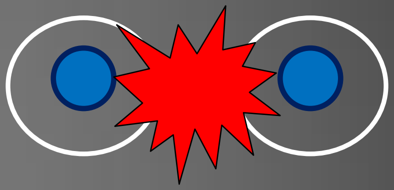
ν = 1420 MHz (Radio)

T_S is Determined by 3 Processes

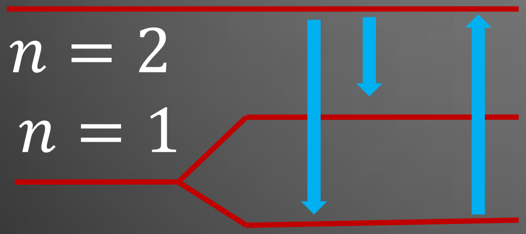
- Absorption of CMB: $T_S \rightarrow T_{CMB}$

$$\frac{1}{T_s} = \frac{T_{\rm CMB}^{-1} + x_C T_K^{-1} + x_\alpha T_C^{-1}}{1 + x_C + x_\alpha}$$

- Collisions with other HI: x_C, $T_S \rightarrow T_{gas}$



- Absorption and reemission of Lyα: x_α, $T_S \rightarrow T_c \sim T_{gas}$ (Wouthuysen 1952, Field 1958)

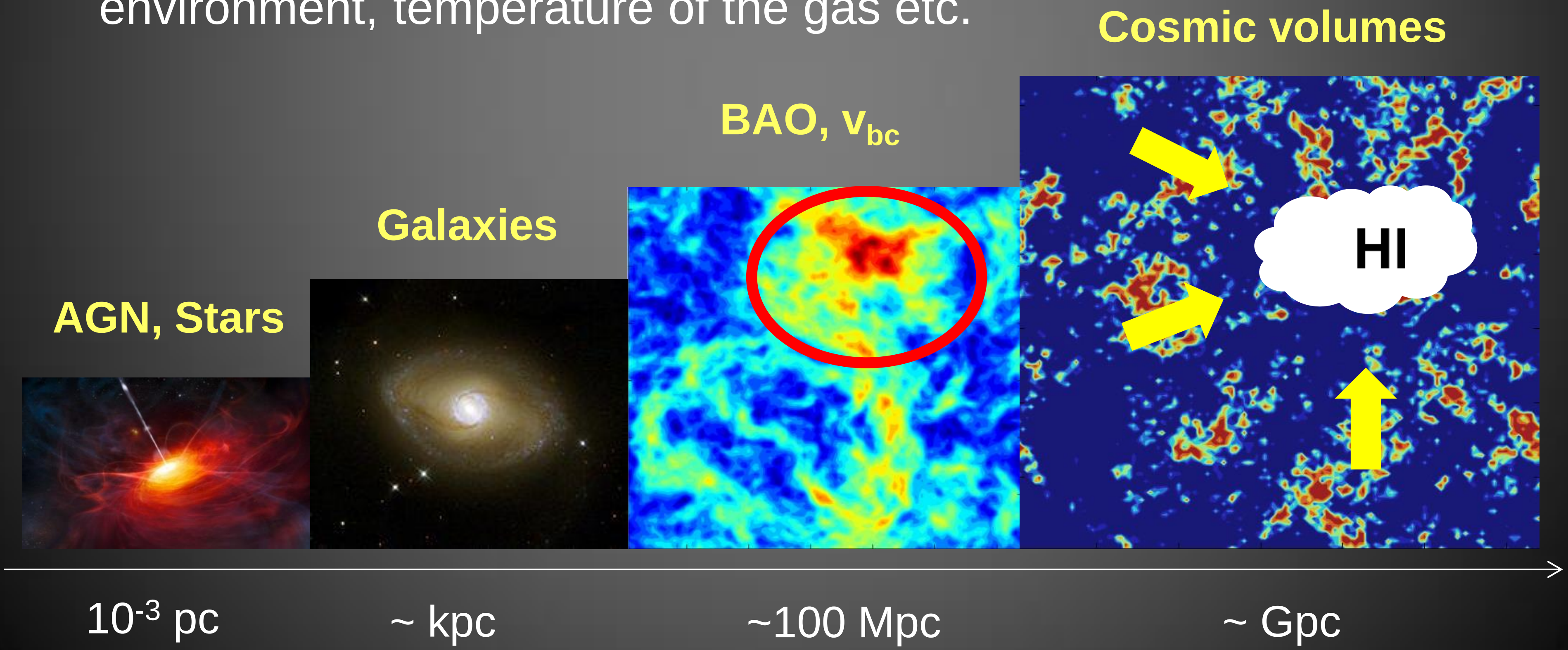


T_S depends on many astrophysical and cosmological parameters

21-cm Signal is Science-rich but Hard to Model

Simulate both small scales (stars) and large cosmological scales (size of the Universe)

Include many parameters: IC, first stars, their radiation, environment, temperature of the gas etc.



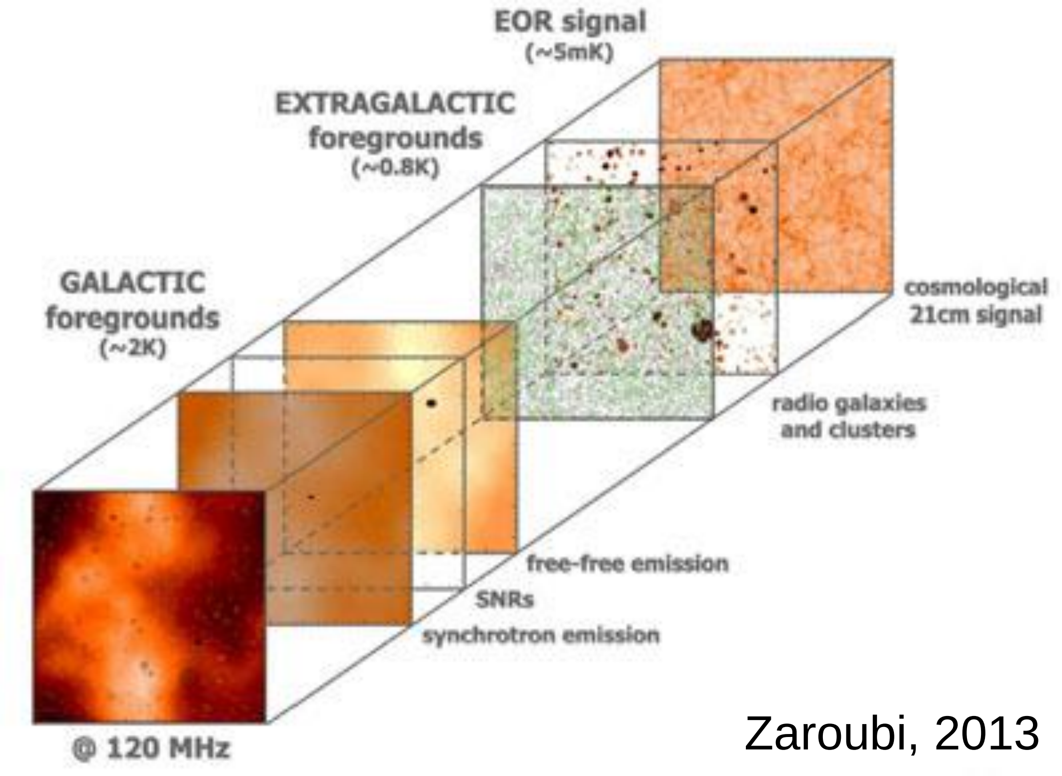
21-cm Signal is Science-rich but Hard to Measure

Astrophysical Foregrounds

- Galactic Synchrotron Emission
- Extragalactic Radio Sources

Terrestrial

- Radio Frequency Interference
- Ionosphere Distortions



Zaroubi, 2013

Current and Future Observational Effort:


NenuFAR

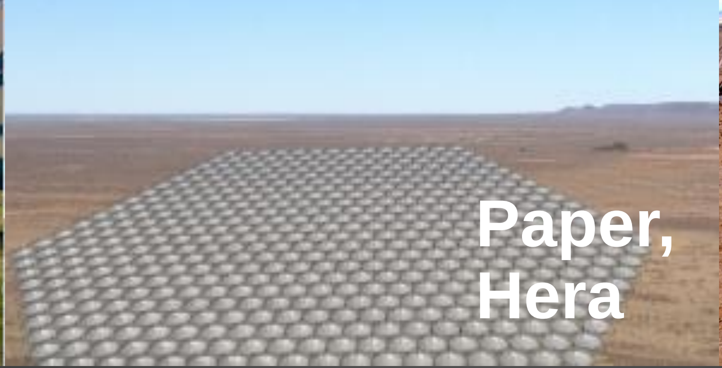

GMRT


LOFAR


MWA

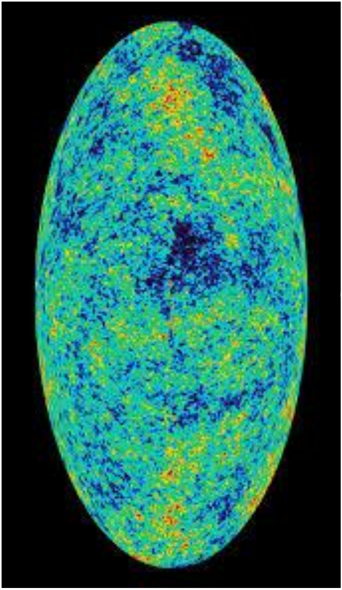

SKA

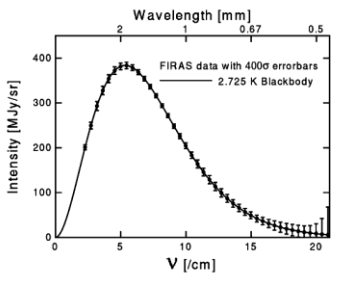

21-CMA

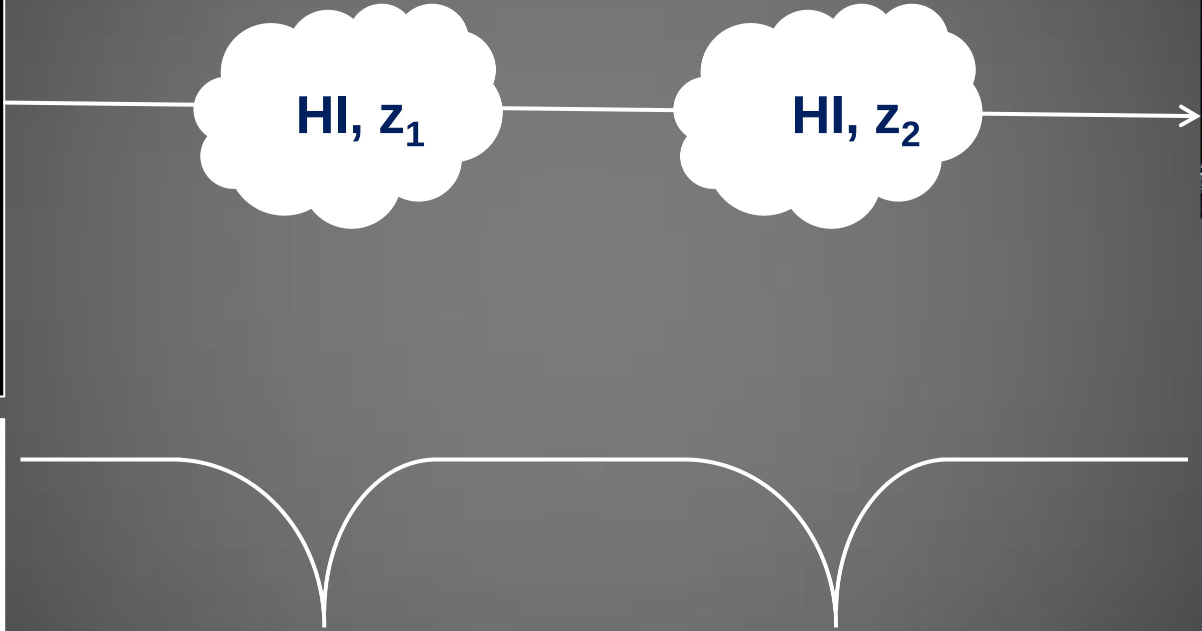

Paper, Hera


LEDA

What do We Actually Observe?





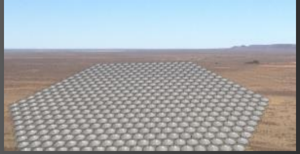


HI, z_1

HI, z_2

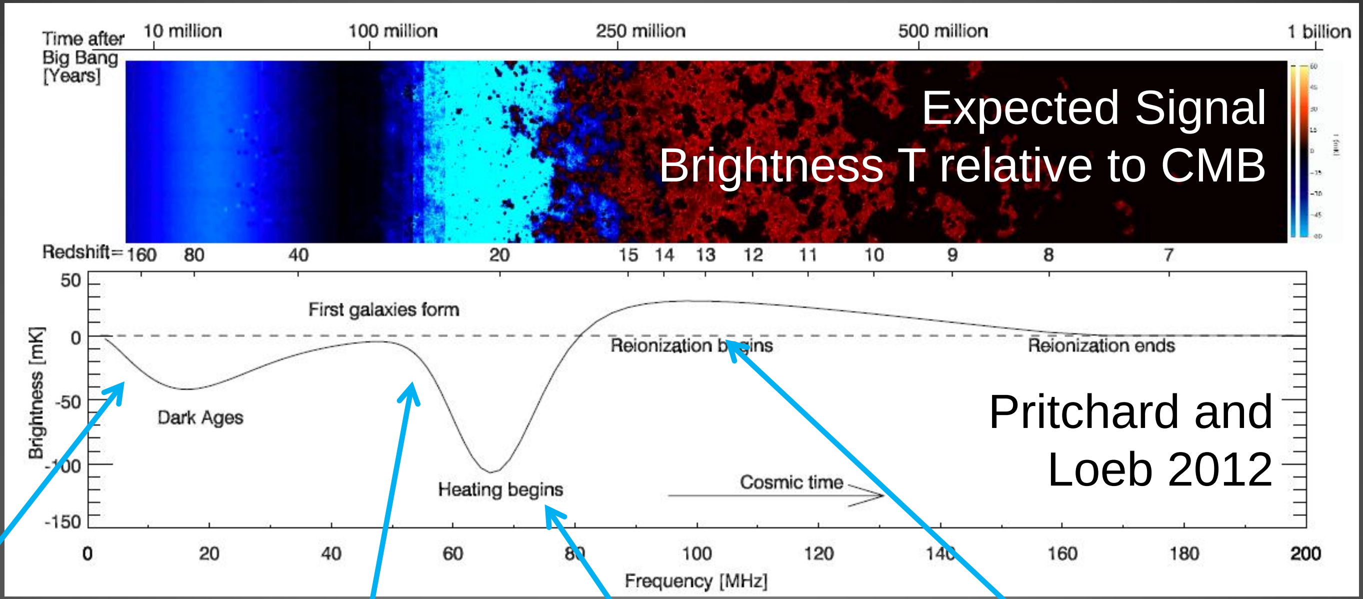
λ_{obs} = 21(1+z_1) cm

λ_{obs} = 21(1+z_2) cm



The redshifted 21-cm line probes 3D distribution and properties of HI

Predicted Global 21-cm Signal



Expected Signal
Brightness T relative to CMB

Pritchard and
Loeb 2012

**Dark ages,
Collisional
coupling**

**Stars appear
Ly-a coupling**

Heating

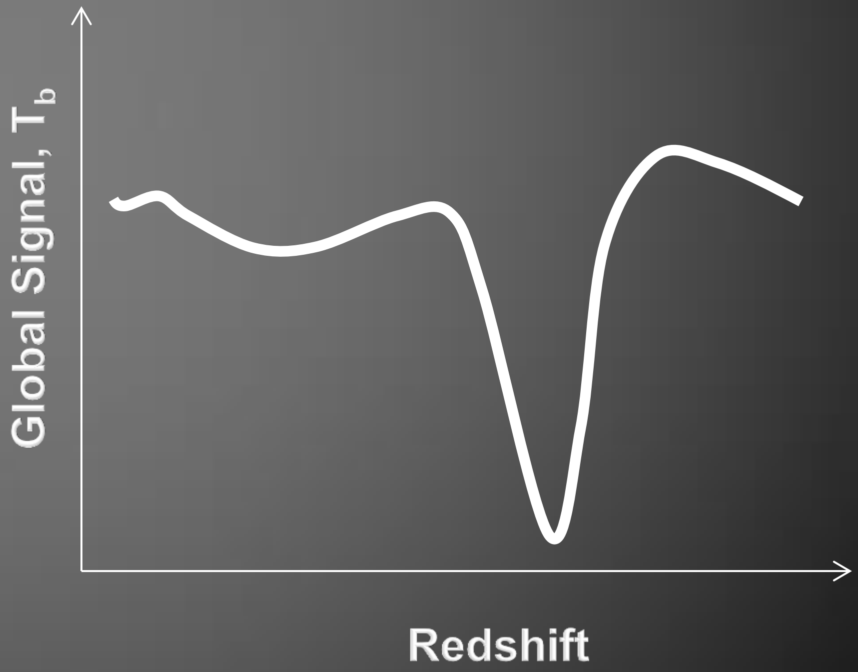
Ionization

$$\delta T_b(\nu) = \frac{T_S - T_\gamma(z)}{1+z}\left(1-e^{-\tau_{\nu 0}}\right) \approx \frac{T_S - T_\gamma(z)}{1+z}\,\tau_{\nu 0}$$

$$\approx 9\, x_{\mathrm{HI}}(1+\delta)\,(1+z)^{1/2}\left[1-\frac{T_\gamma(z)}{T_S}\right]\left[\frac{H(z)/(1+z)}{\mathrm{d}v_\parallel/\mathrm{d}r_\parallel}\right]\ \mathrm{mK}$$

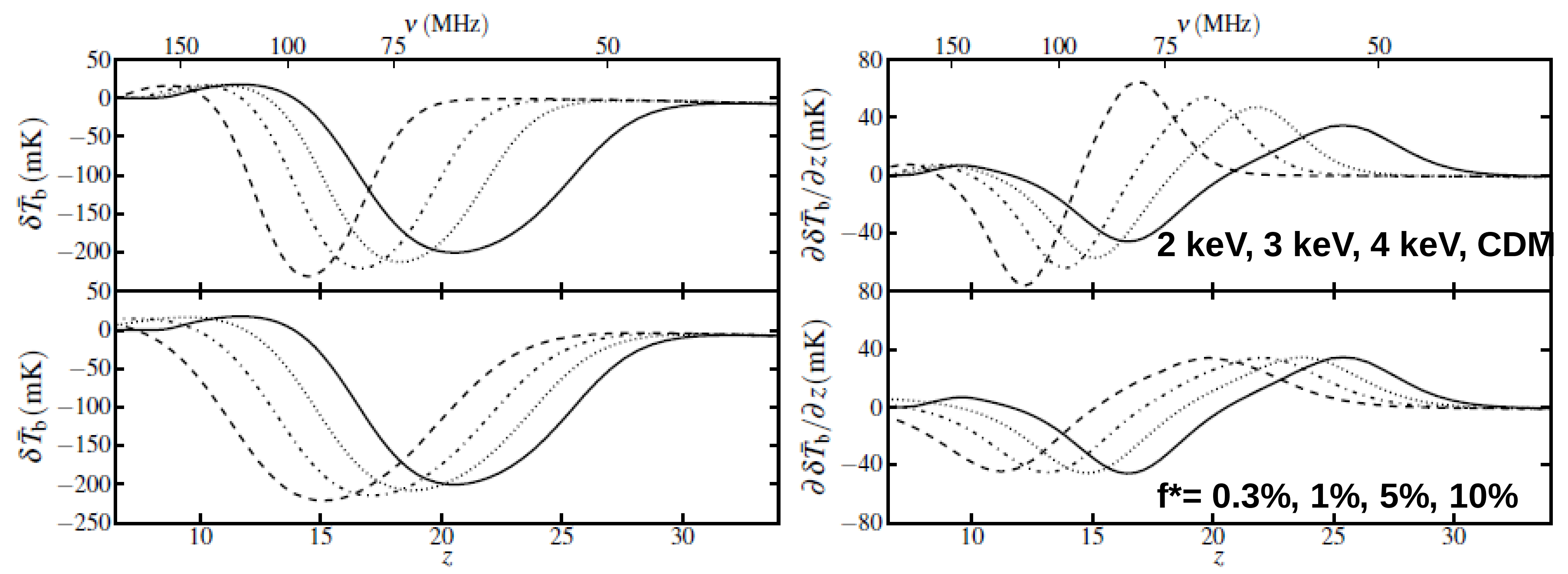
WDM Fingerprints in the 21-cm Signal

- Delayed stellar evolution
- Deeper absorption trough
- “Accelerated” heating (later start)



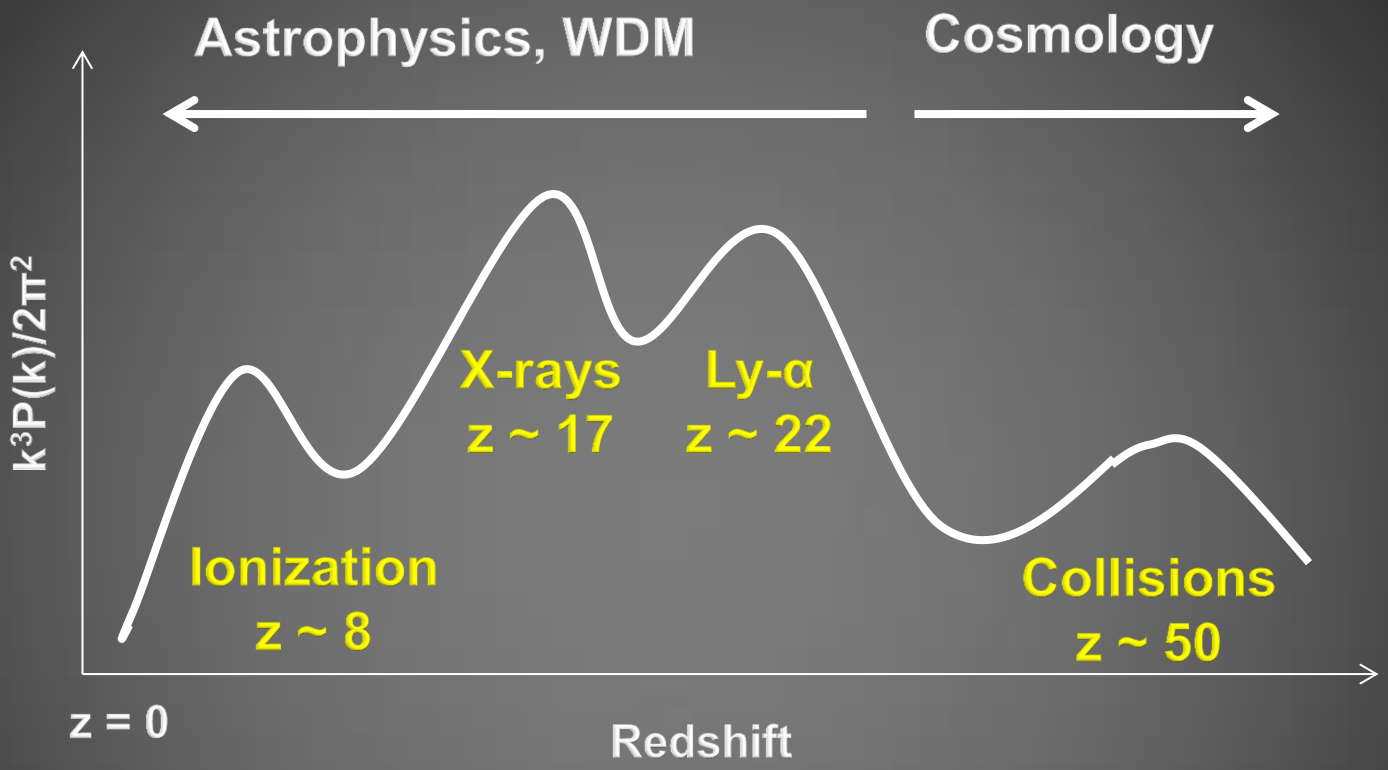
WDM Fingerprints in the 21-cm Signal
Degenerated with Star Formation

- 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} …

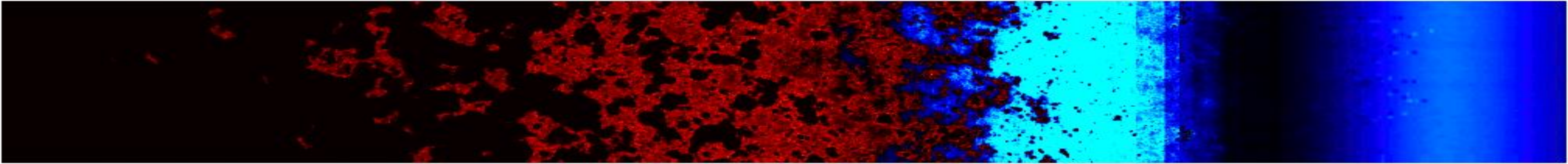


Sitwell, Mesinger, Ma, Sigurdson (2014)

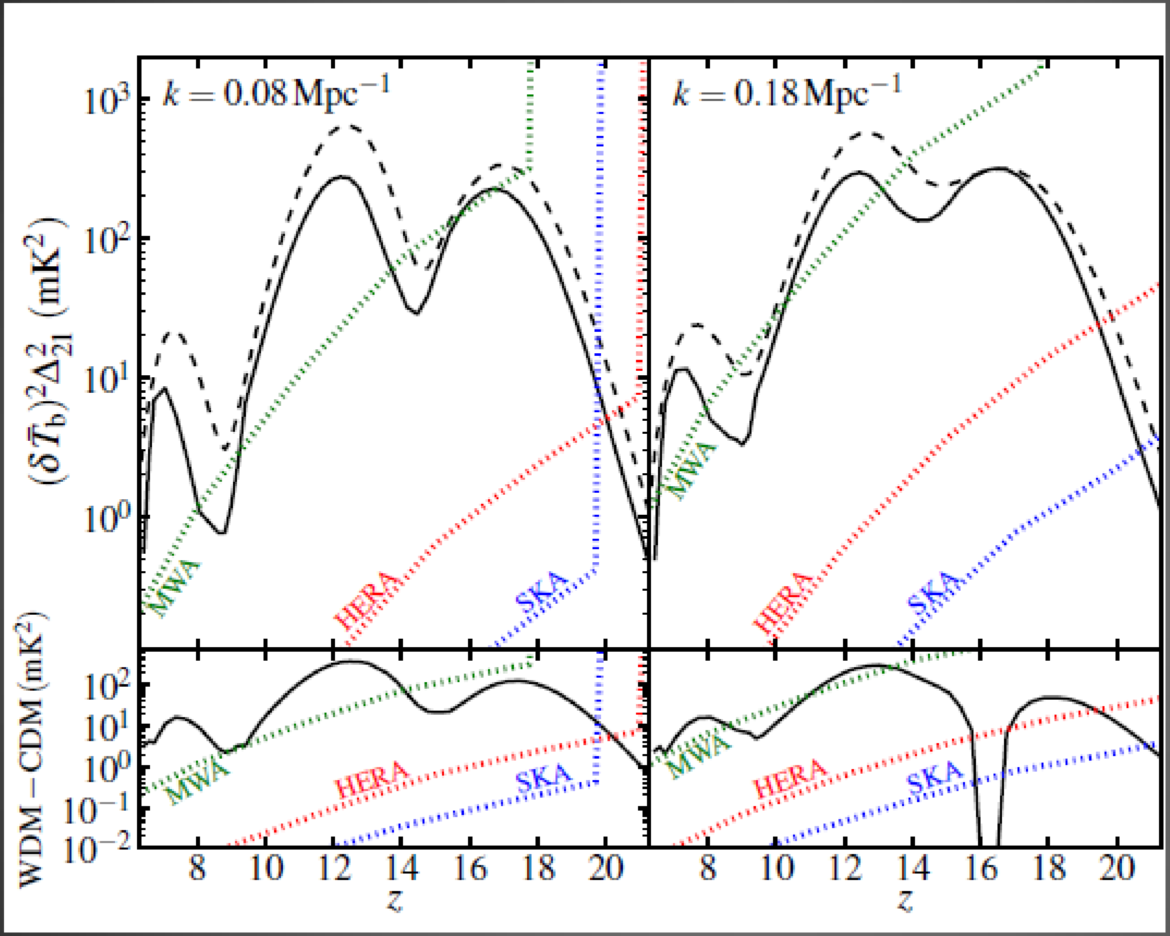
Inhomogeneous Signal. Fluctuations

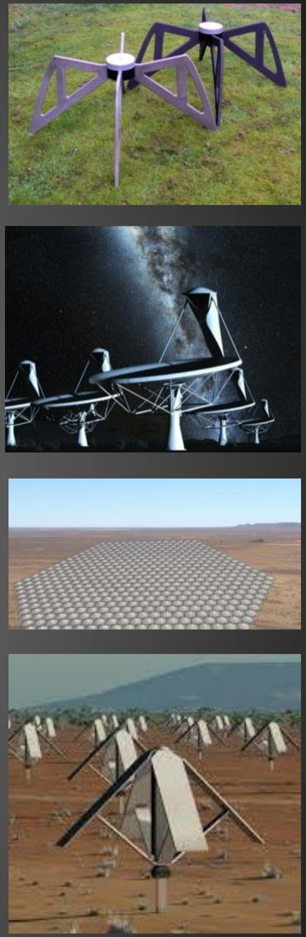


- Generic dependence of power spectrum on z for a given k
- Each source of fluctuations contributes at different epoch



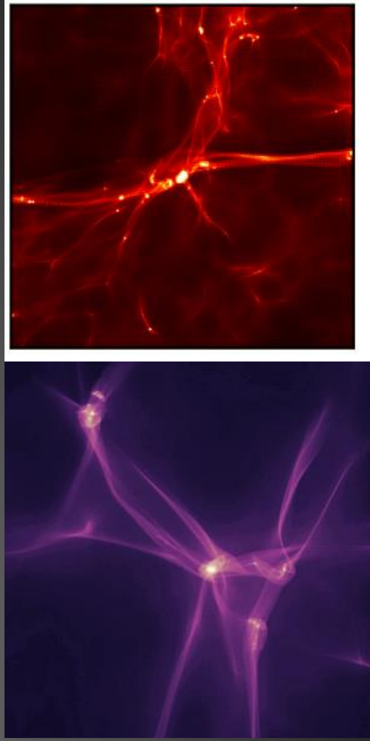
21-cm Power Spectrum





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

Summary:
WDM in the Early Universe



WDM

- Suppresses fluctuations at small scales
- Delays stellar evolution
- Delays build-up of radiative feedbacks
- Affects reionization
- 21-cm signal from $z \lesssim 30$
- **Stars could form in filaments**

Astrophysical processes can have similar effect

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