Warm Dark Matter, the Temperature of the IGM, and the Ly-α Forest

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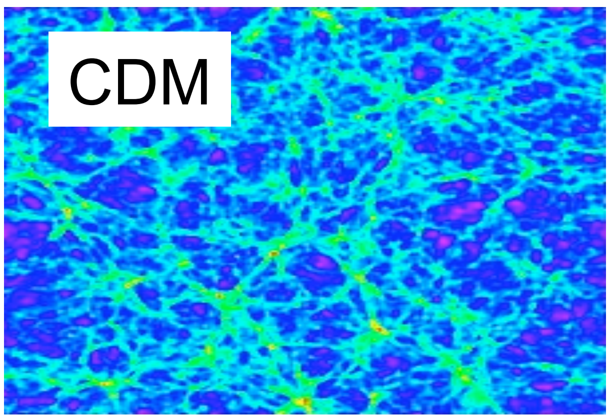
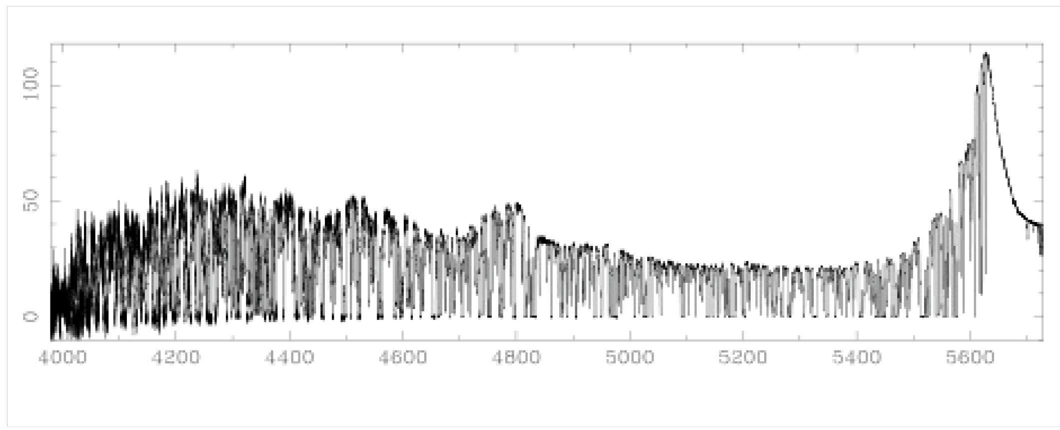
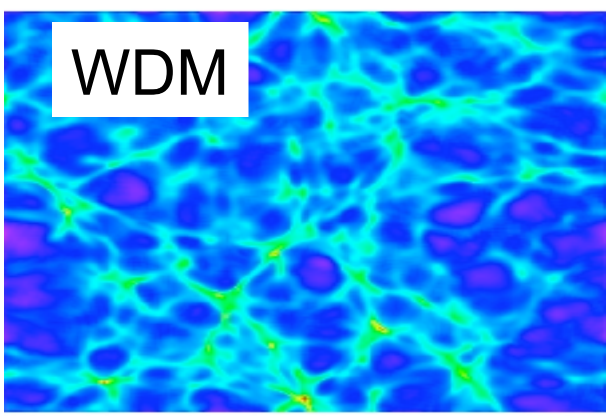
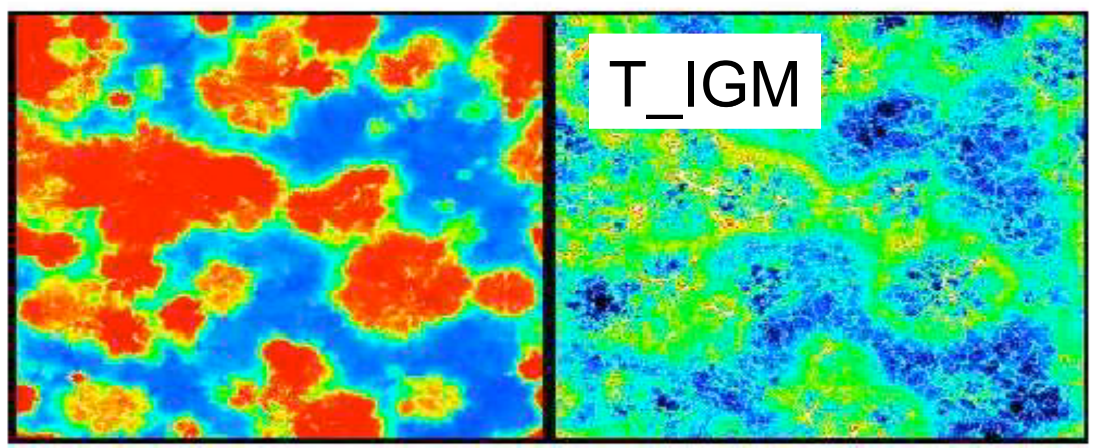
DM_MCFP: April 2, 2009









Outline

- Update on modeling of z~3 IGM.
- Explain Ly-a forest constraint on WDM.
- DM w/ significant free streaming erases small-scale structure in the Ly-a forest. Increasing T of IGM also suppresses small scale structure in the forest.
- Can we distinguish CDM + hot IGM and WDM + colder IGM?

Work in Progress!

Collaborators

WDM:

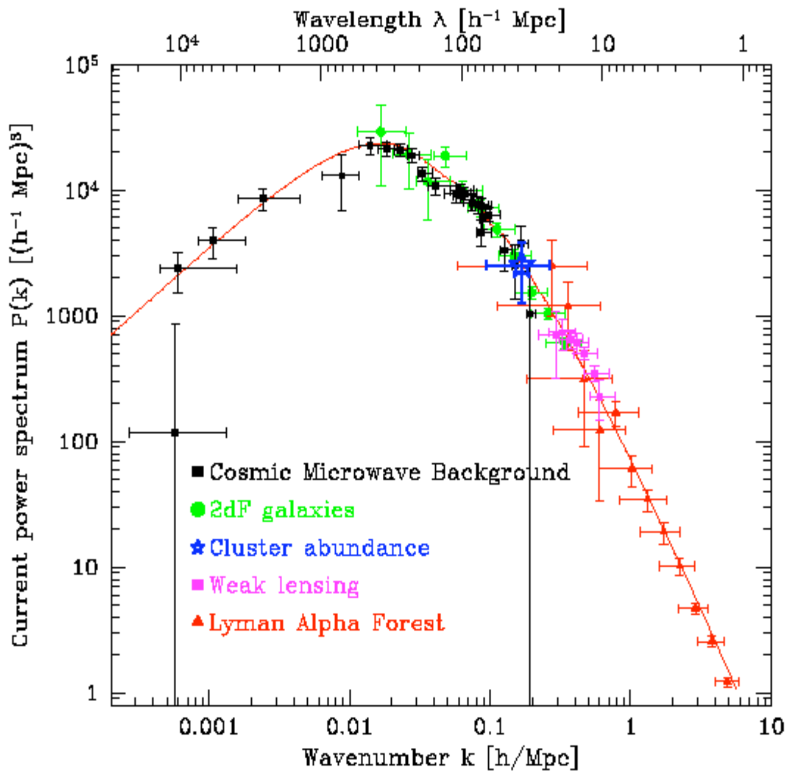
- Kev Abazajian (Maryland)
- Neal Dalal (CITA)
- Massimo Ricotti (Maryland)

T of IGM:

- Aldo Dall'Aglio (Potsdam)
- Claude-Andre Faucher-Giguere (CfA)
- Cora Fechner (Potsdam)
- Lars Hernquist (CfA)
- Matt McQuinn (CfA)
- Matias Zaldarriaga (CfA)

Large Scale Structure

- Clustering studies of many varieties: strong support of CDM.
- So far, not so much direct support on small scales. <~ 1 Mpc
- Best probe of small-scales in quasi-linear regime so far is Ly-a forest.



Tegmark & Zaldarriaga (2002)

WDM: Who Ordered That?

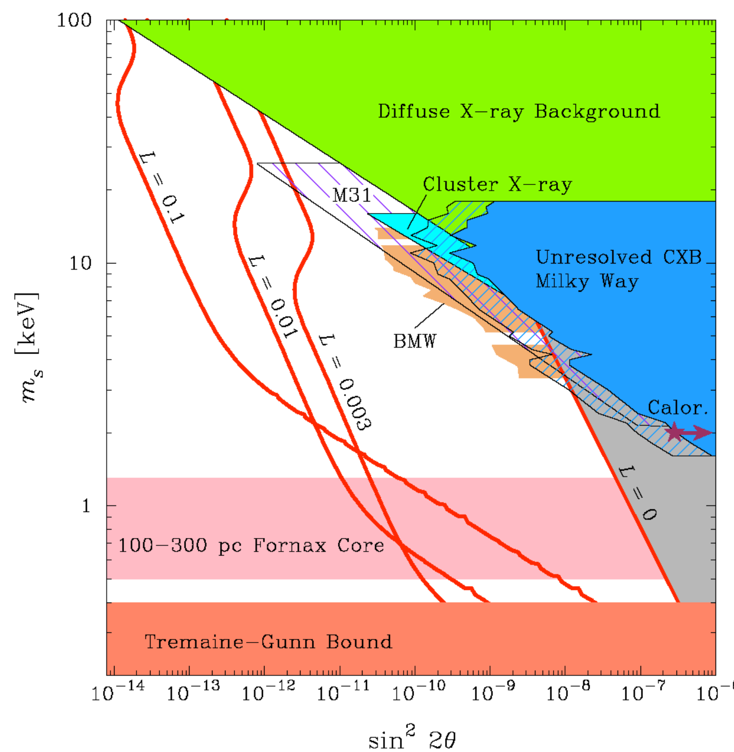
- Test basic feature of CDM, negligible free-streaming.
- Particle physics explanation for missing satellite problem, lack of cusps?
- Sterile neutrino can be warm dark matter and is a well-motivated particle DM candidate!

Sterile Neutrinos

- One piece of beyond SM physics we *know about is neutrino mass.* Likely want right-handed neutrinos that interact only by mixing with active neutrinos and gravitationally. (“Sterile neutrinos”).
- Want 2 heavy sterile neutrinos to explain atmospheric/solar oscillation data.
- 3rd lightest one could be the dark matter! Want > keV mass, small mixing angle: never thermalized.
- Properties depend on production mechanism. Most constraints assume only produced through mixing. Can get enhancement from initial lepton asymmetry, MSW-like effect.

Sterile Neutrinos: Parameter Space

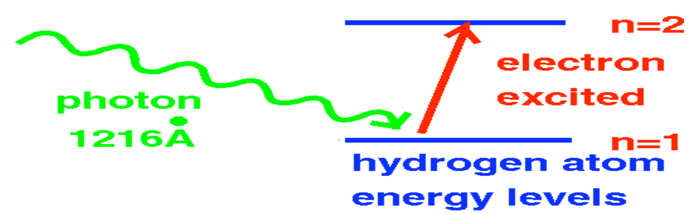
- X-ray constraints: sterile neutrino decays producing X-ray line with E~m_s/2, which is not observed (so far)!
- Seljak et al. m_s>14 keV, Viel et al. m_s > 9 keV, 28 keV from HIRES data.
  assuming non resonant production of sterile nus.
- If so, much of parameter space ruled out!

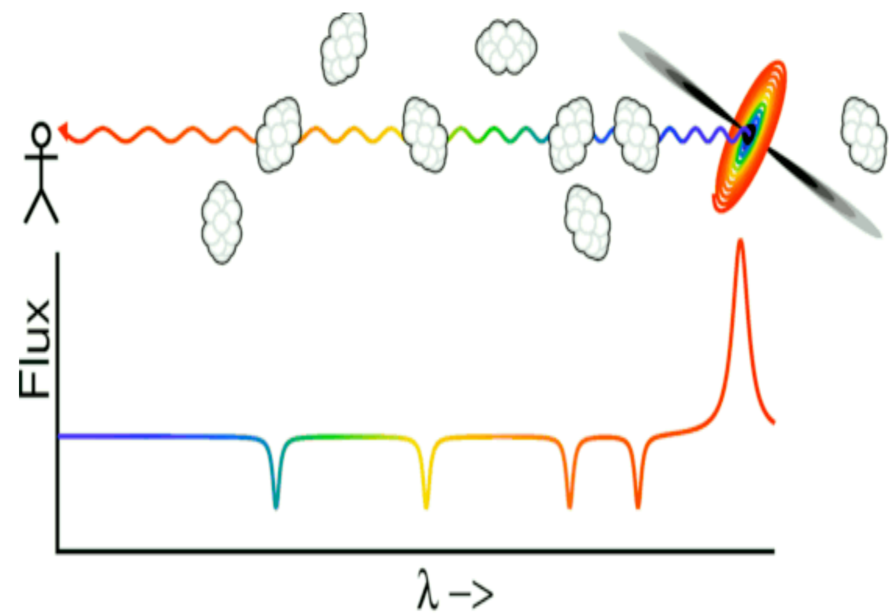


Abazajian et al. (2007)

The Ly-a Forest: Cartoon Version

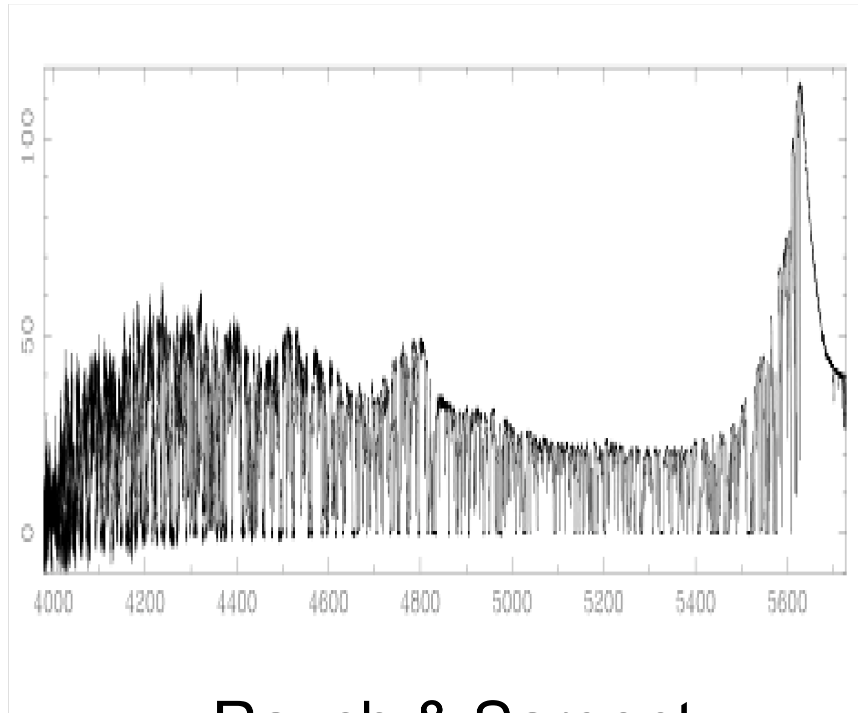
- Quasar source light redshifts.
- Neutral hydrogen atoms interact with whatever quasar light is at 1216 A when it reaches them.
- Rest of the light keeps traveling to us.





The Ly-a Forest at z~3

- Neutral hydrogen leads to absorption at
  $$\lambda \leq 1216(1+z_q)A$$
- ~70% of quasar flux is transmitted at z~3.

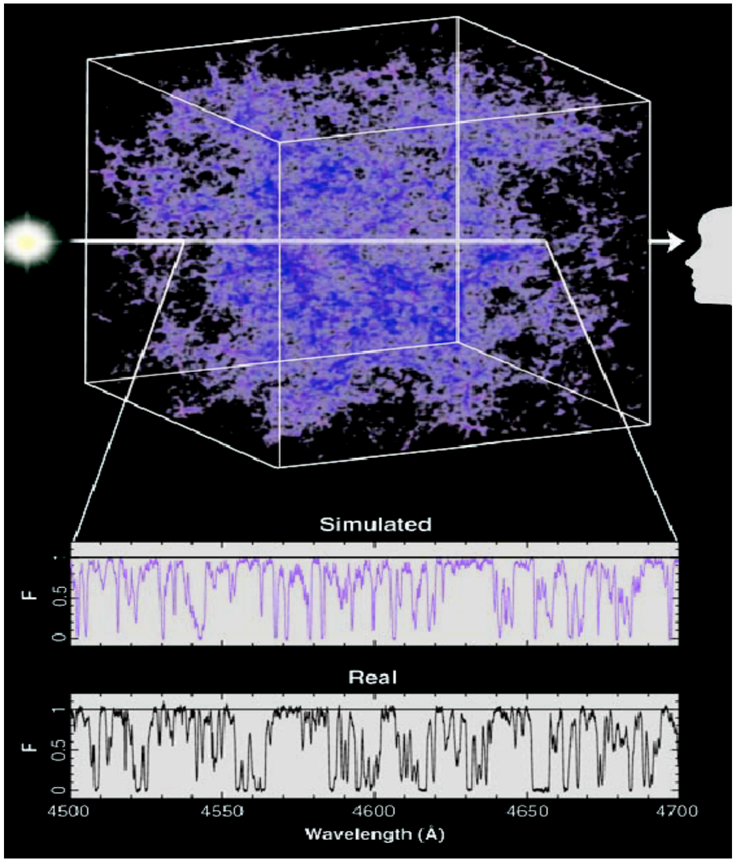


Rauch & Sargent

t~2.2 Gyr

Simulating the Cosmic Web

- First principles simulations predict properties of z~3 forest.
- One of primary success stories beyond linear theory in cosmology!
- Exactly how good is the model? Missing physics? Systematic error budget?



Faucher-Giguere, Lidz, & Hernquist, 2008

Constraining IGM physics and Cosmology w/ Ly-a forest

- Constraints come from ~ 50 VLT/HIRES Keck, and ~3000 quasar spectra. WDM constraints from : McDonald, Seljak et al., Viel, Haehnelt, et al.
- Measure power spectrum of fluctuations in the forest, and mean transmitted flux.
- Run “grid” of simulated models spanning cosmological and IGM parameters and compare with measurements. Full hydro + various approximations.

Ly-a Forest Basic Model

$$\tau_\alpha \propto (1 + \delta_b)^{2-0.7(\gamma-1)}$$

(plus peculiar velocities and thermal broadening)

- IGM gas is photoionized. Photoionization equilibrium w/ UV background from galaxies and/or quasars.

- Temperature-density relation: $T = T_0\,(1 + \delta_b)^{\gamma-1}$

- Gas-pressure smoothing: neutral hydrogen traces dark matter dist on large scales but is smoothed out on small scales. (k_F)

Ly-a Forest Basic Model II

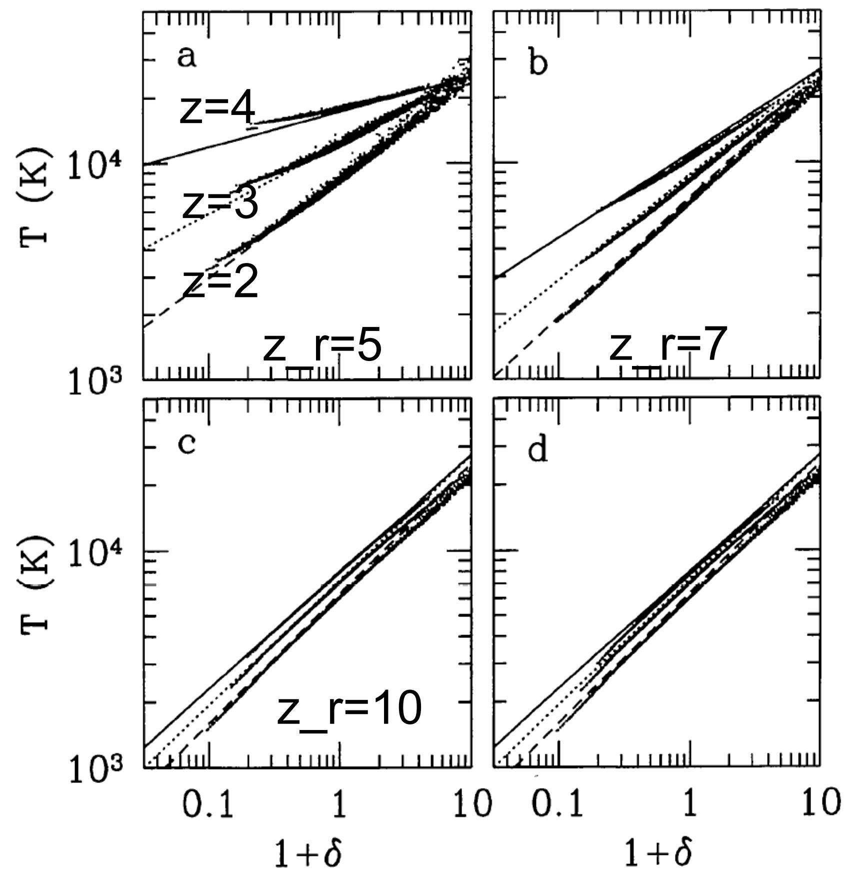
- $1 + \delta_b$: amplitude of density flucs, slope of density power spectrum at k~1 h/Mpc, Jeans-smoothing scale. *Cosmology/ thermodynamics.*

- T_0, γ : *thermal state of gas.*

- Γ_{HI} : *intensity of UV background* from galaxies/quasars that keep gas ionized.

Temperature-Density Relation

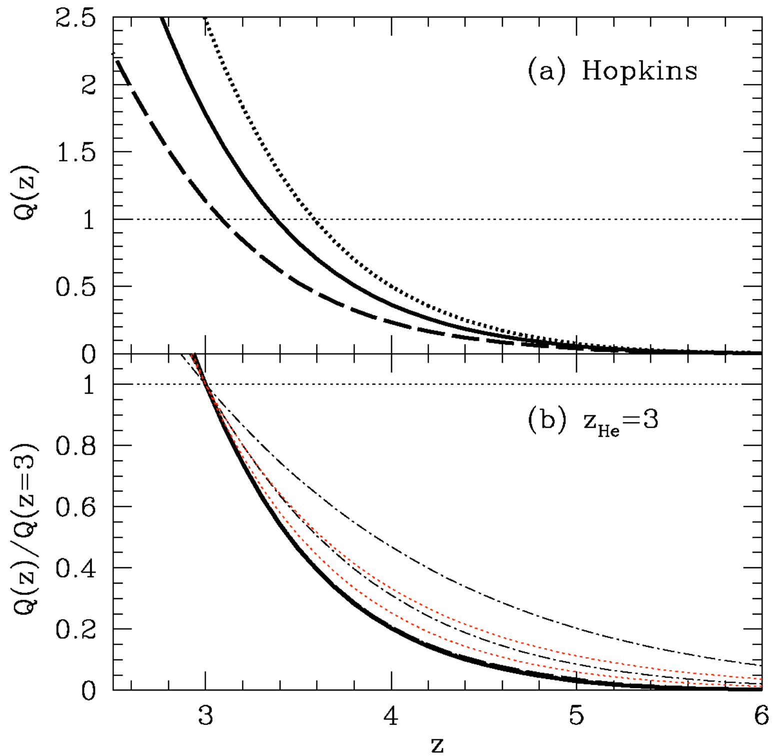
- T_0, γ depend on when and how gas is reionized! Gas contains "memory" of when it was reionized.
- Existing calcs assume a uniform, homogenous reionization process. Not realistic!
- How bad is it?



Hui & Gnedin (97)

Best Guess Reionization History

- HI (13.6eV),
  HeI (24.4eV) reionized by star-forming galaxies at z>~6.
- HeII (54.4eV) reionized by quasars at z?=3
- Assumption of uniform T-δ relation particularly bad if HeII reionization finishes at z~3.



Furlanetto & Oh (2007)

Reionization and T_IGM?

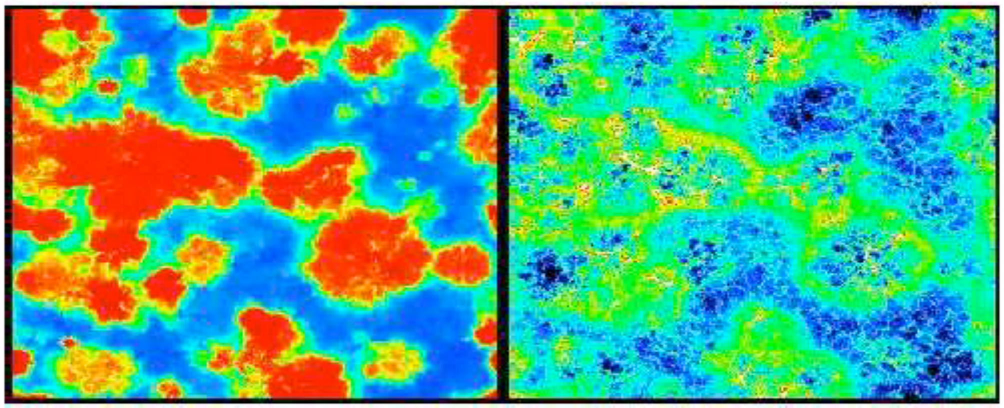
- During *HeII reionization* : expect absorbing gas to be hot, and the temperature to fluctuate from place to place across the IGM. (Can we detect this?) How does it impact the forest?

- *HI reionization :* extended process, with reionization finishing last in large-scale underdense regions. These regions will have less time to cool, and be hotter than other regions. Impacts T-δ relation if this scatter is not overwhelmed by scatter from HeII heating.

HeII reionization heats IGM

- $He^+ + \gamma \longrightarrow He^{++} + e^-$
- Photon with energy > 54.4 eV
- Excess energy goes into k.e. of outgoing electron. Electron scatters through IGM and heats it up.

Simulating HeII Reionization

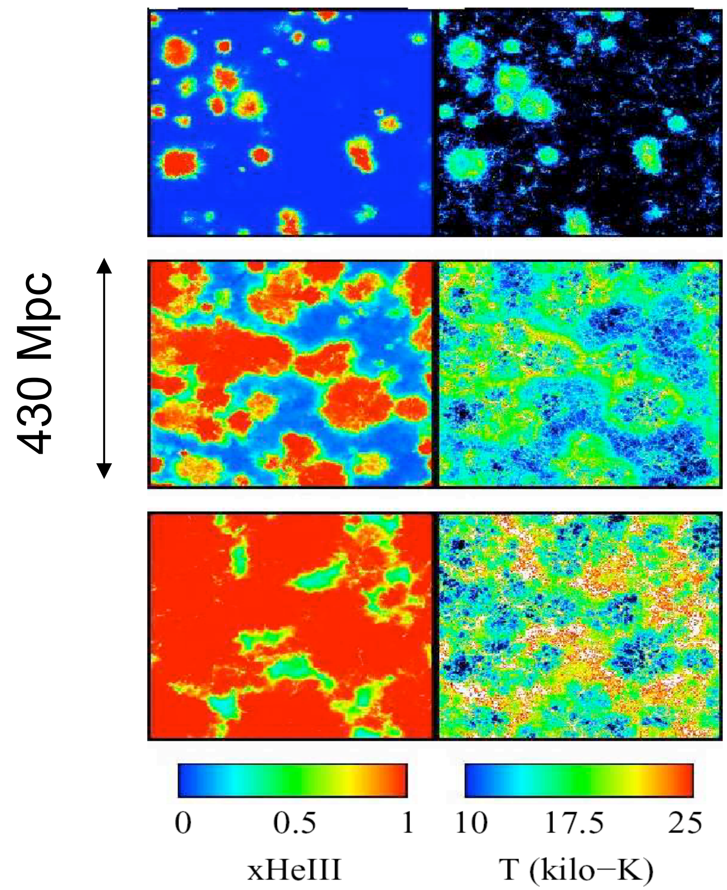


- 190 Mpc, 430 Mpc, N=1024^3 dm simulations.
- Quasar sources w/ appropriate abundance/clustering.
- Explore: quasar lifetime, beaming, HeII Lyman-limit systems.
- Radiative transfer in post-processing. Track T.

McQuinn, AL, et al. (2008)

Inhomogeneous HeII Reionization

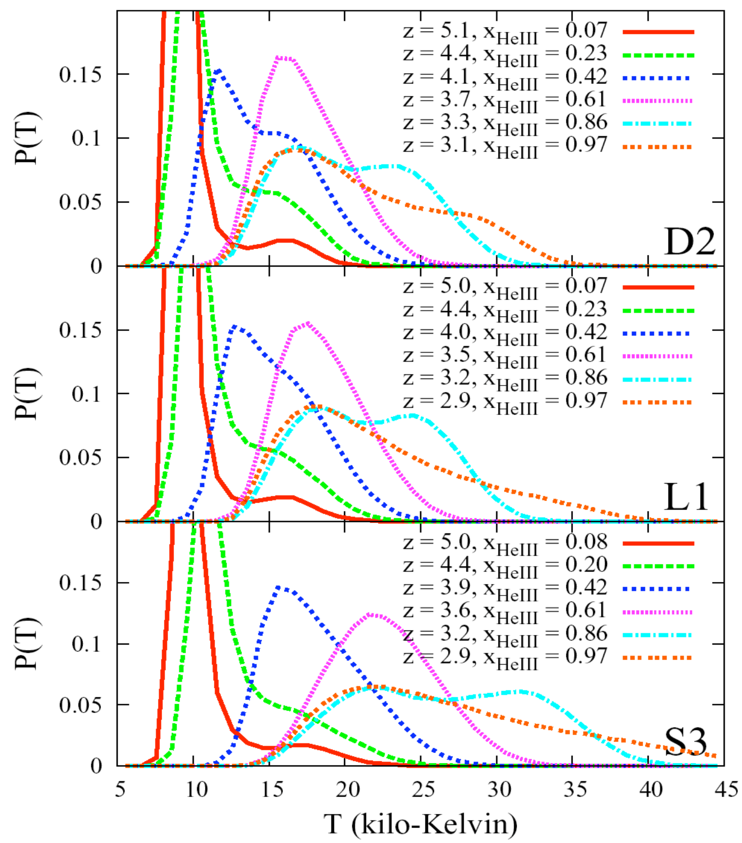
- Extended, inhomogeneous process.
- Hot regions where Helium is doubly ionized.
- Cooler regions where Hydrogen is ionized and Helium only singly ionized.
- High energy quasar photons important for heating: not sharp 'bubbles'.



McQuinn, AL, et al. 2008

Complex T-δ relation during/after HeII Reionization

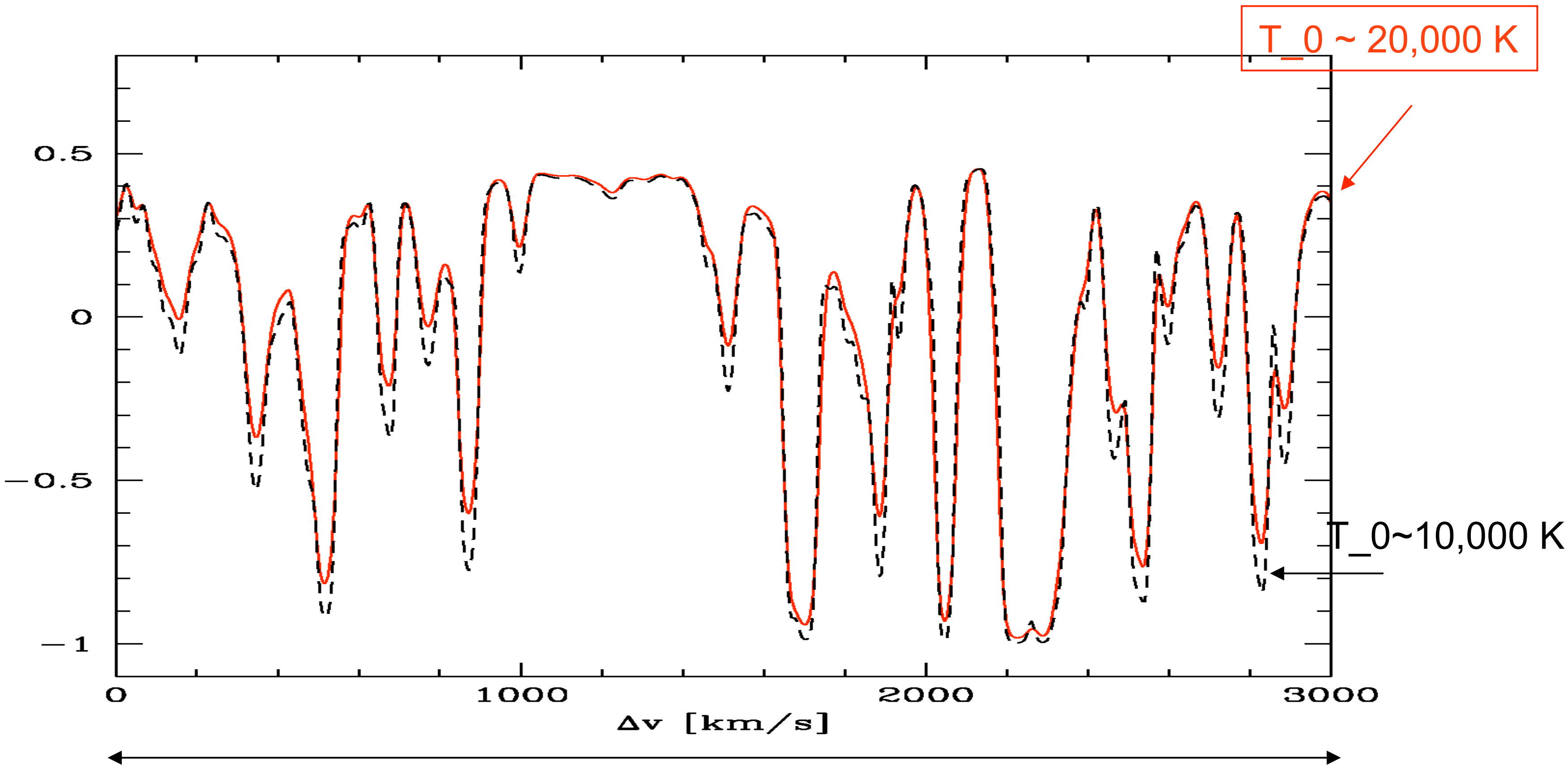
- PDF of T_0 from HeII reionization simulation
- Significant scatter in T_0, unlike usual assumption of perfect T-δ relation.



McQuinn, AL, et al. 2008

T impacts structure of HI Ly-a Forest

Doppler broadening and Jeans-smoothing….



~ 30 mpc/h co-moving

T Measurements High

- Attempts to measure T_IGM from Ly-a forest, generally find high T_0 values, *assuming CDM.* T_0~20,000 K (e.g. Ricotti, Gnedin, & Shull 2000, McDonald et al. 2001, Zaldarriaga et al. 2001, Lidz et al. in prep).
- Expected from z~3-4 HeII reionization.
- But could we be fooling ourselves?

T-δ Recap

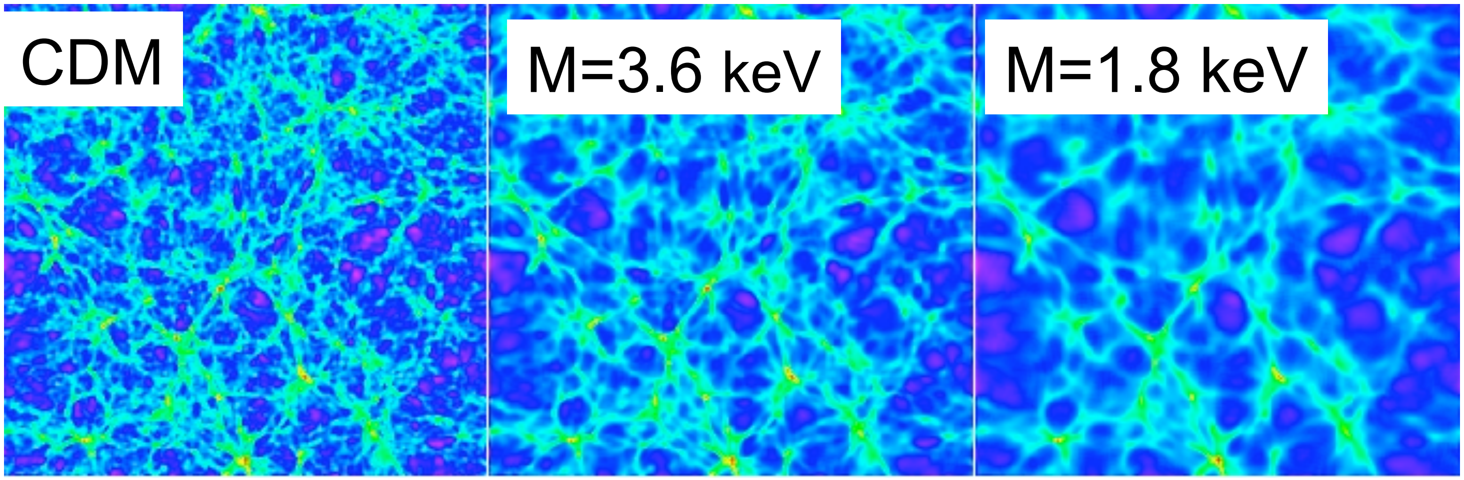
Modeling Issue:

- High, inhomogeneous T during/right after HeII reionization. Complex T-δ neglected in Ly-a forest modeling so far. Impact unclear.

Degeneracies?: (Beware of priors on IGM params!)

- High T acts to smooth out structure in Ly-a forest. As we will see, WDM does something similar.
- Alternative is to complete HI/HeI/HeII reionization at z >6 (e.g. by faint quasars) ---> cooler IGM.
- Can we accommodate a cooler IGM with forest measurements by making dark matter warm?

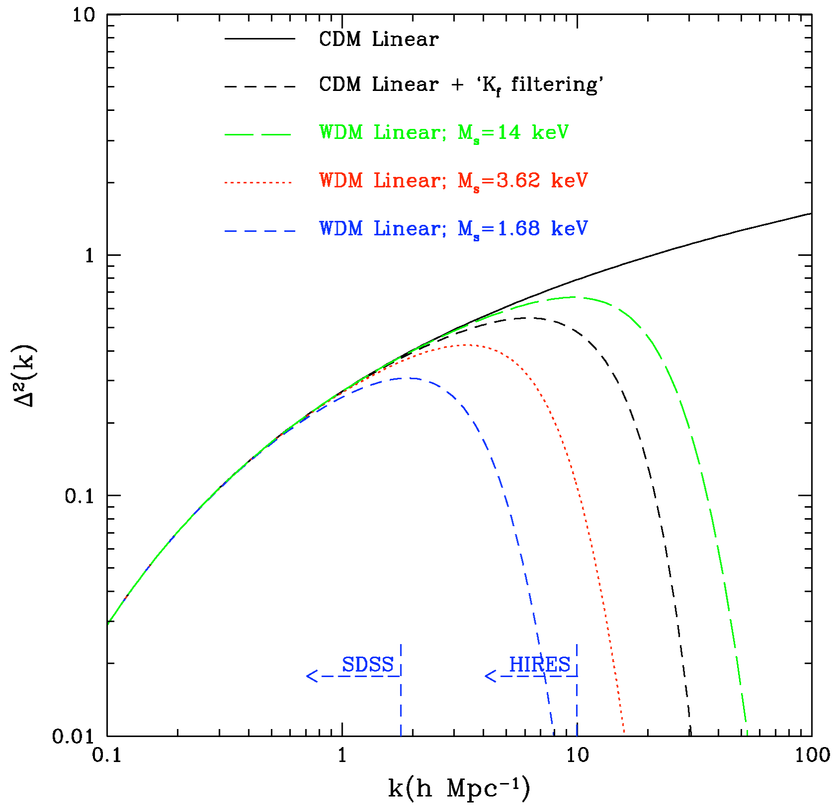
Let’s Check T Degeneracy!



- N. Dalal sims 512^3/32 Mpc/h, dark matter only.
- Smooth dm field to approximate gas pressure smoothing.
- Generate mock spectra for a large range of T_0, γ for CDM/WDM and check degeneracy with thermal state of IGM gas.

Linear Density Power CDM/WDM

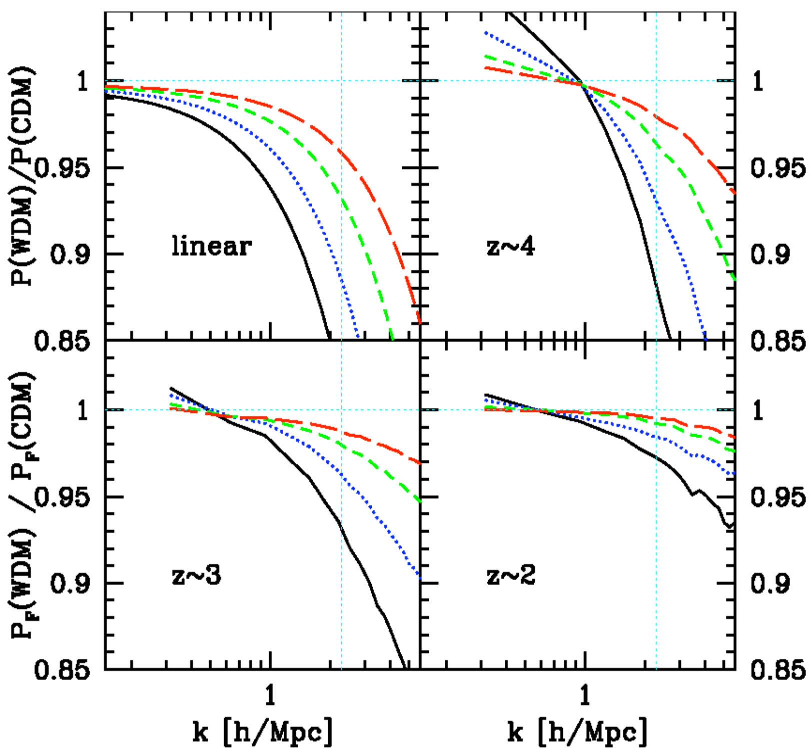
- Probing highest k possible obviously best!
- Free-streaming scale is comparable to Jeans smoothing scale for m_s >~ 10 keV. Hard to constrain these m_s w/ Ly-a?



How is SDSS useful for WDM?

- Interesting free streaming lengths smaller than SDSS spectral resolution.
- Aliasing from 1d skewers, a blessing and a curse:

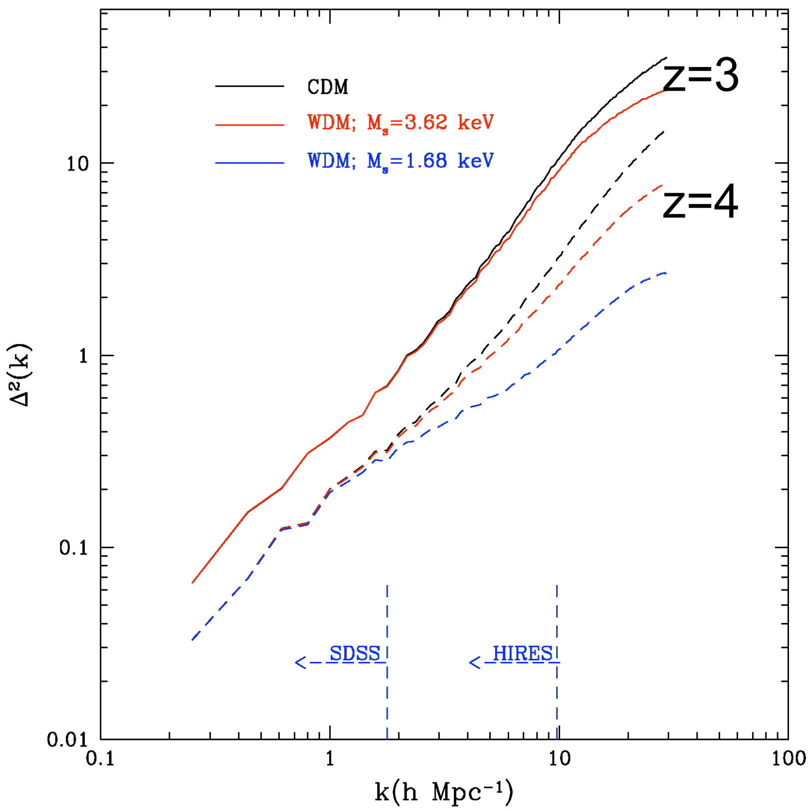
$$P_{1\mathrm{d}}(k_{\|}) = \int_{k_{\|}}^{\infty} \frac{dk}{2\pi} k P_{3\mathrm{d}}(k).$$



Seljak et al. 2006

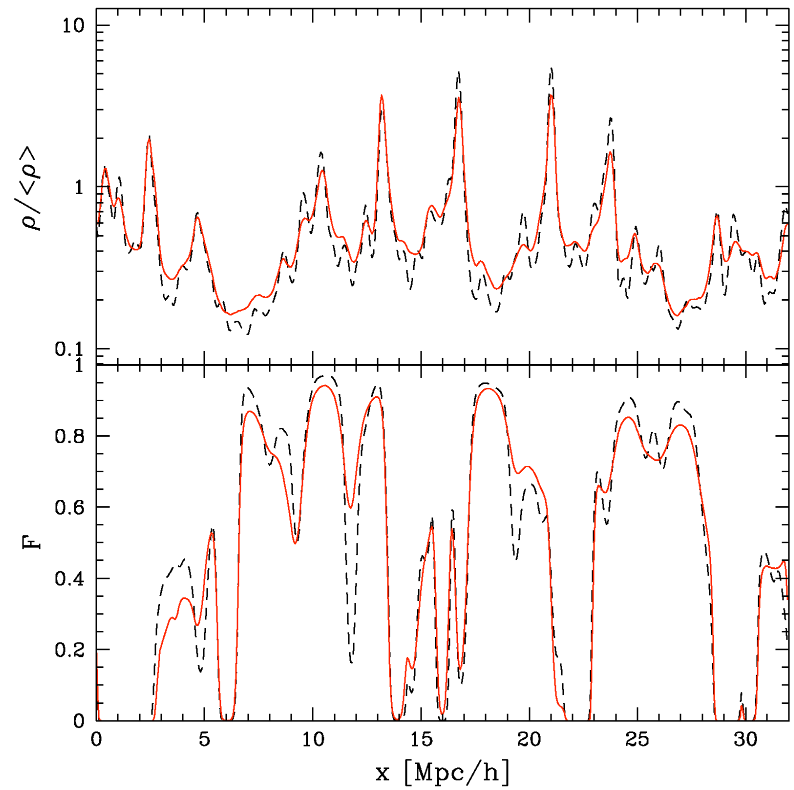
Non-linear Matter Power Spectrum

- Even by z~3 non-linear evolution wipes out much of difference between models.
- Highest possible z clearly best!



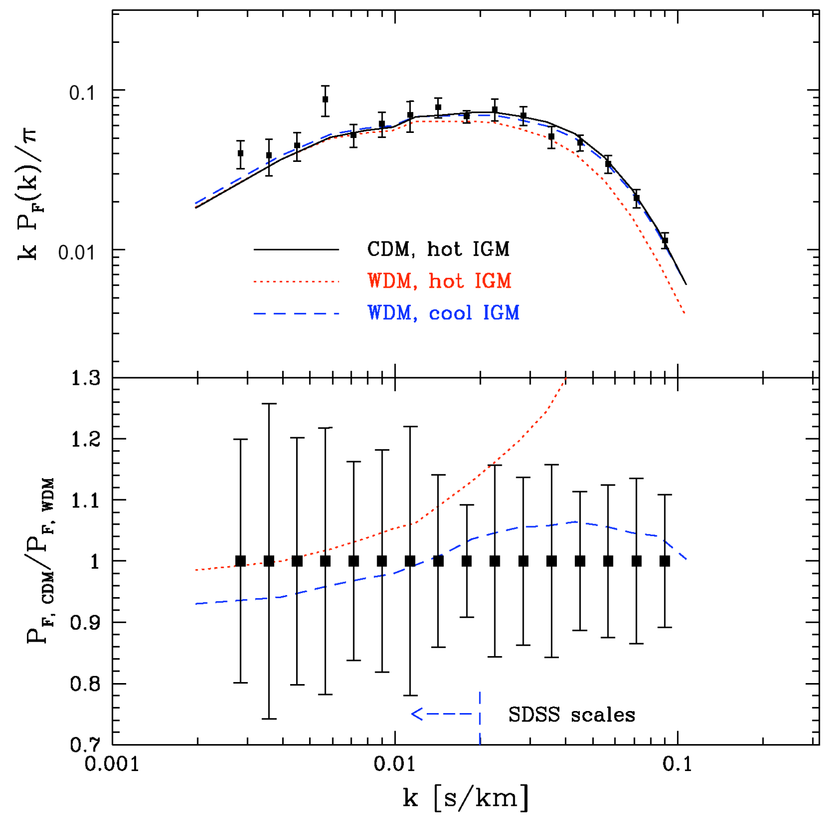
WDM and Ly-a at z~3

- Simulated spectra.
- Black dashed CDM.
- Red solid WDM w/ m_s = 3.62 keV.
- Identical `nuisance parameters'.
- Less small scale structure in WDM.



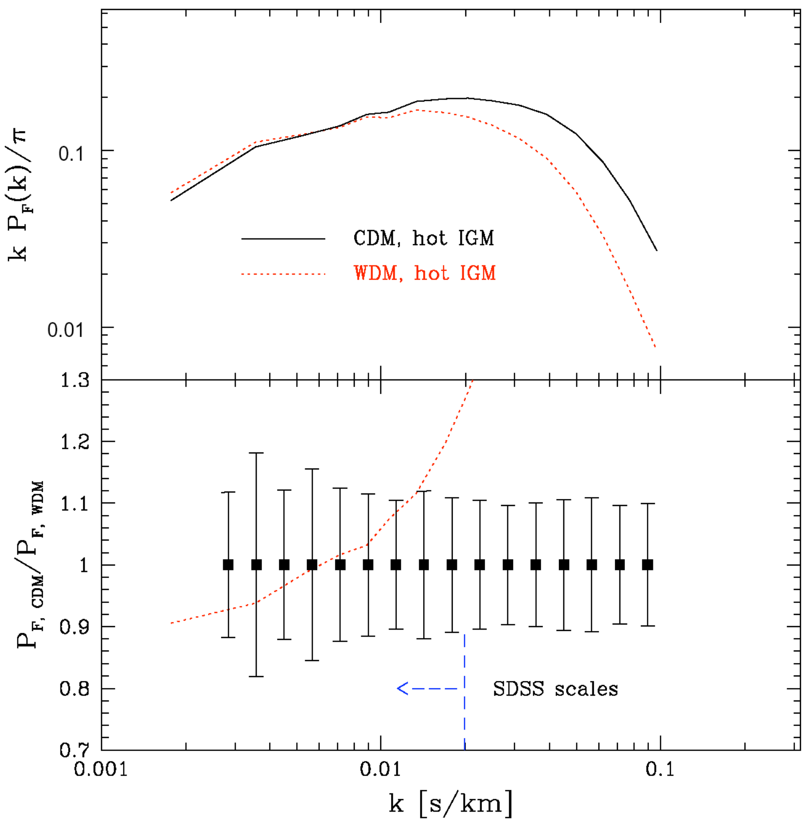
CDM+hot IGM vs. WDM+cold IGM

- At z~3, there is a degeneracy between hot IGM + CDM and cold IGM + WDM!
- Both have T_0~20,000 K
  WDM has γ -1~0.0
  CDM has γ -1~0.34
  very modest changes in other nuisance params.



Degeneracy at z~4?

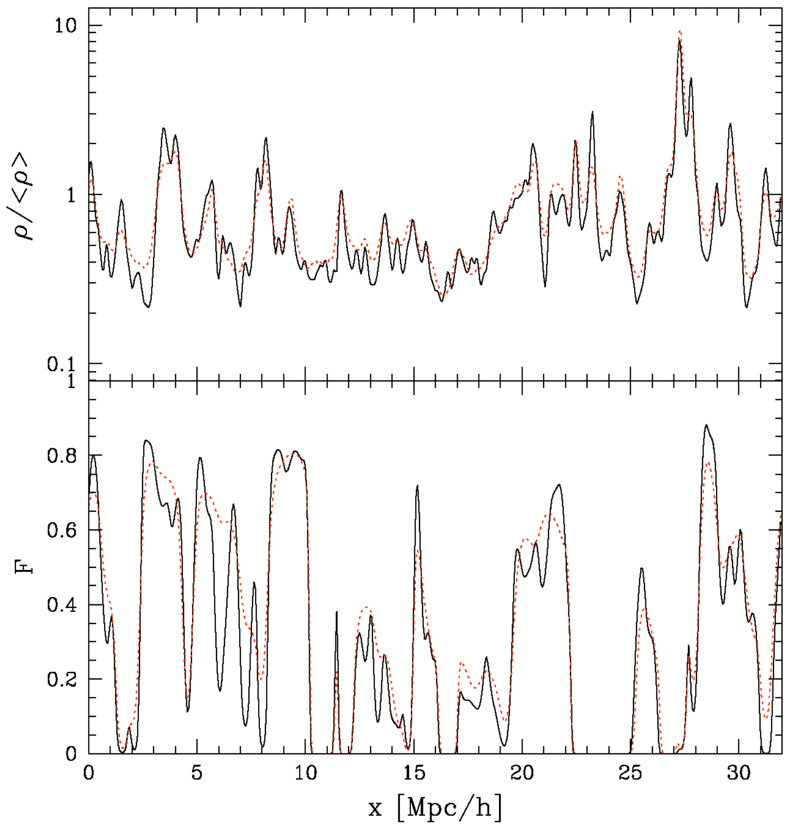
- Note larger suppression!
- Can not match m_s=3.6 keV with cooler IGM to hotter CDM model. Checked for large range in T_0, k_F, γ -1.
- z~4 is better! More linear, more absorption, and `lines' in the forest.
- This is m_s = 3.6. Recall quoted bounds are m_s > 10-30 keV.



Sightlines at z~4

- More absorption at z~4: every little density `wiggle' in CDM gives a `line' or flux fluctuation, which are absent in WDM.

- Reducing the thermal smoothing is not enough! (for m_s=3.6 keV)



Conclusions

- Both T and WDM smooth-out structure in Ly-a forest.
- Thermal state of IGM likely more complex than previously assumed. Especially if HeII reionization at z~3.
- Degeneracy between T_IGM and m_s at z~3, but mostly broken at z~4.
- *Suggests* existing constraints mostly robust to T_IGM modeling issues and uncertainties.