

“Thermal Evolution of the primordial clouds in warm dark matter models with keV sterile neutrinos.”

Jaroslaw Stasielak, Peter L. Biermann, Alexander Kusenko

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“Relic keV sterile neutrinos and reionization.”

Peter L. Biermann & Alexander Kusenko

PRL. 96 091301 (2006), astro-ph/0601004

Astronomy Journal Club 10/26/07

Daniel Grin

# Outline:

- Why WDM (Warm Dark Matter)?
- Sterile Neutrinos:
  - Basic physics, cosmological behavior, radiation backgrounds
- Existing constraints
- Sterile Neutrinos and reionization
- Sterile Neutrinos and reionization:  $H_2$  and ‘star formation’
- The model: Tegmark and friends (1996) + sterile neutrinos
- Results
- Caveats



# Who's afraid of Cold Dark Matter?



- Missing satellites problem
- Central density cusp vs flat core controversy

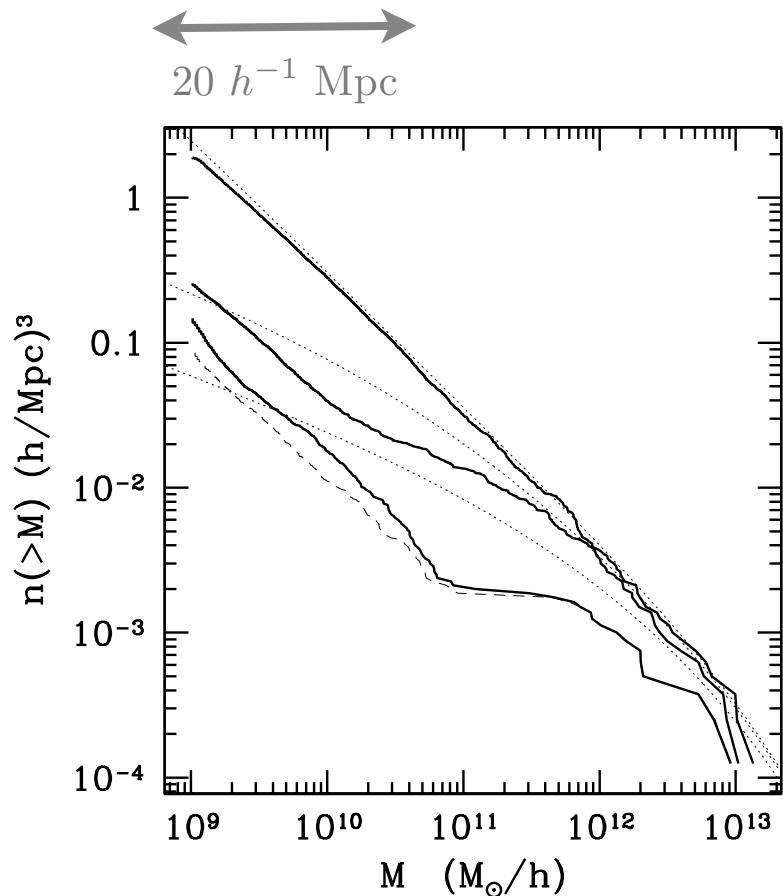
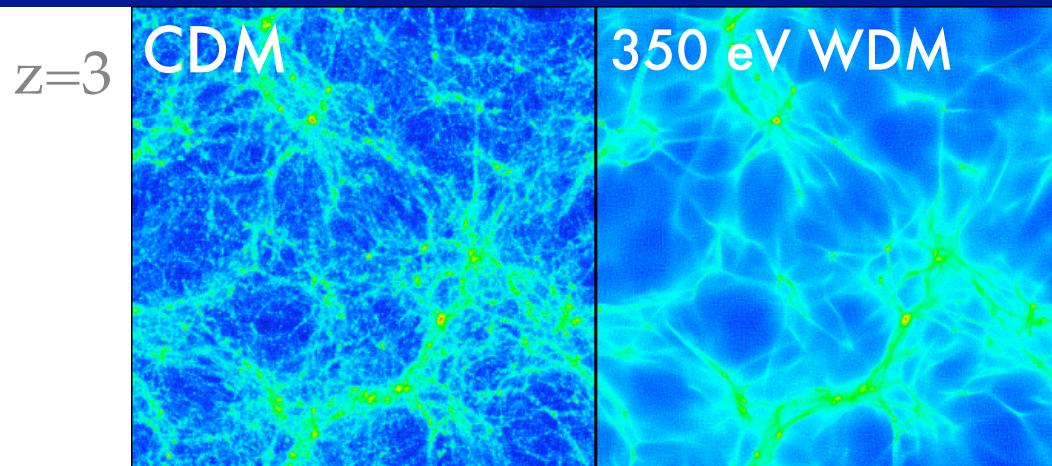
# WDM patches up small-scale structure

- Thermal streaming of WDM erases structure on smallest scales

- King (cored) profile + phase-space bounds

$$m_s \gtrsim \left( \frac{32 \text{ pc}}{r_c} \right)^{1/2} \left( \frac{10 \text{ km s}^{-1}}{\sigma} \right)^{1/4} \text{ keV}$$

- WDM seems to suppress number of small halos
- WDM still produces cuspy cores!
- WDM upends hierarchical structure formation



# Sterile Neutrinos: A ‘natural’ keV WDM particle

- Standard model has no  $\nu$  masses
- Can add Dirac mass  $\mathcal{L}_{\nu,\text{mass}} = m_D \bar{\nu}_R \nu_L$
- Adding heavy  $\nu$  can explain observed masses.

$$\mathcal{L}_{\nu,\text{mass}} = m_D \bar{\nu}_R \nu_L + m_R \nu_R \bar{\nu}_R$$

$$m_1 \simeq m_D^2/m_R \quad m_2 \simeq m_R$$

- Lighter (keV) Majorana  $\nu$  can still explain  $\nu$  masses
- ‘Sterile’  $\nu_R$  does not directly interact with SM particles
- Sterile  $\nu$  mixes with active  $\nu$

$$P_{a \rightarrow s} \propto \sin^2 2\theta \quad \theta \sim m_D/m_R$$



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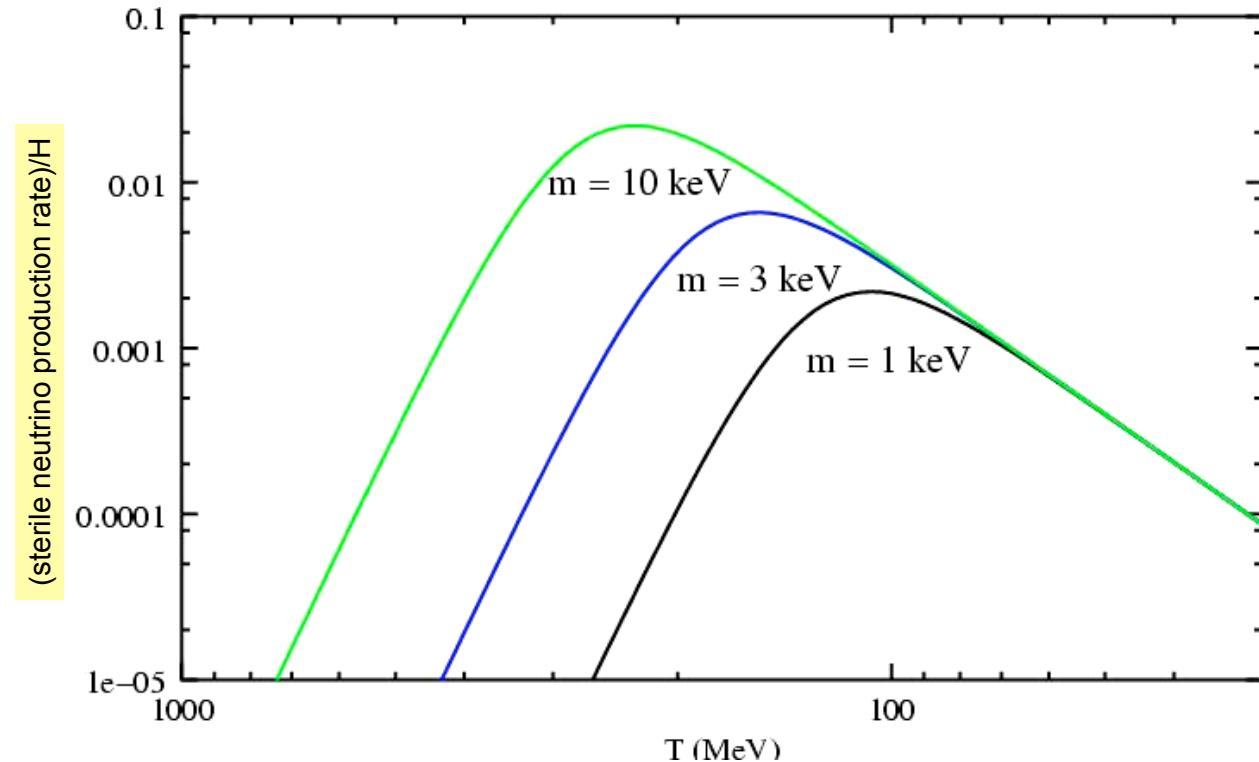
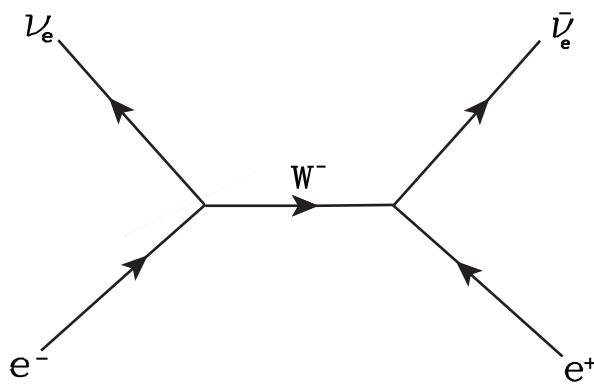
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See-Saw!

# Making sterile neutrinos in the primordial fireball

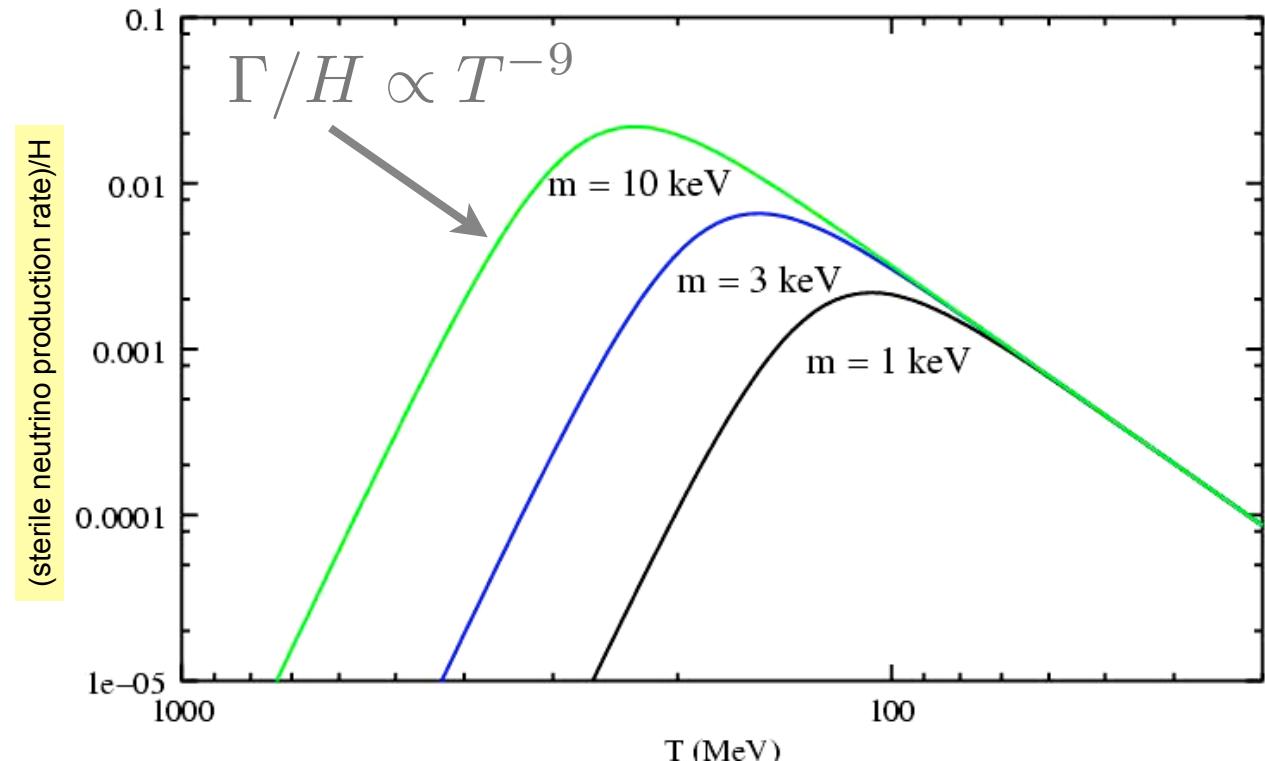
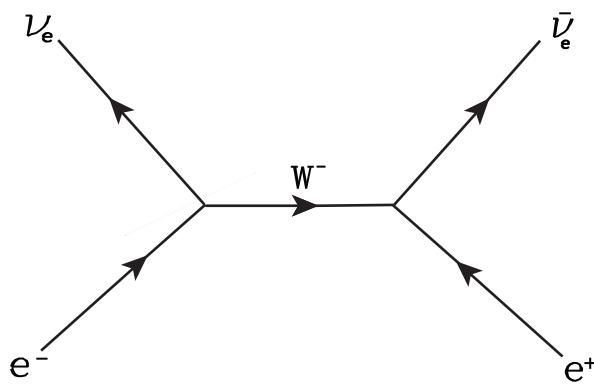
- Out of equilibrium!
- Ordinary Neutrinos thermally produced



- Sterile neutrinos produced by oscillation from SM neutrinos
$$\Gamma \sim G_F^2 T^5 \sin^2 [\theta_0] / 2$$
- Real mixing suppressed by leptons/hadrons in plasma
- Full Boltzmann treatment yields:

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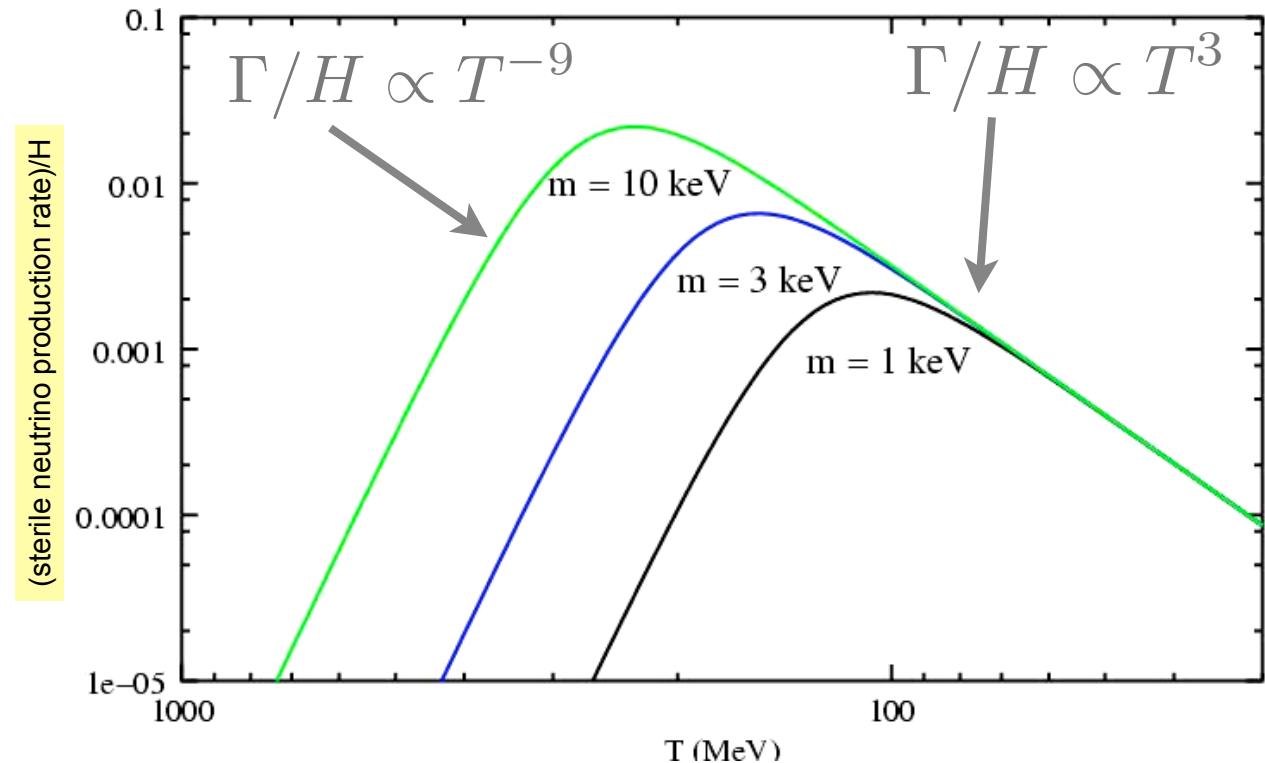
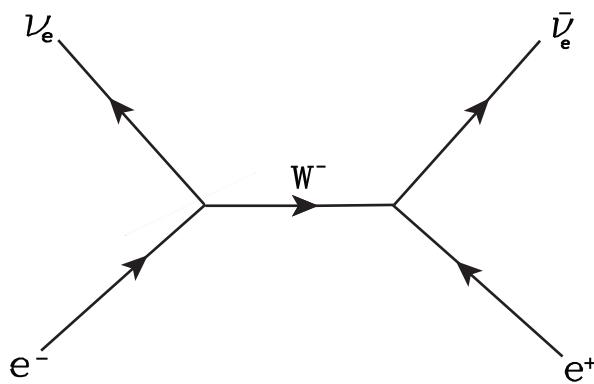
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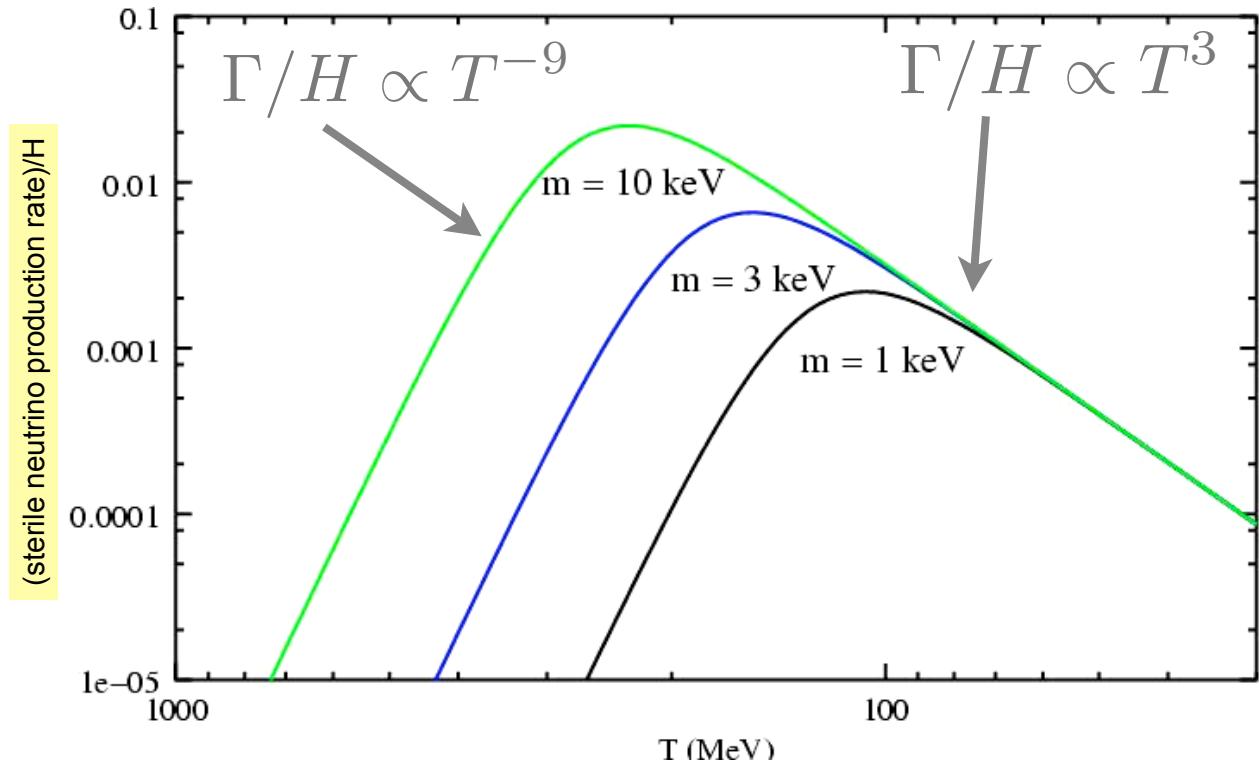
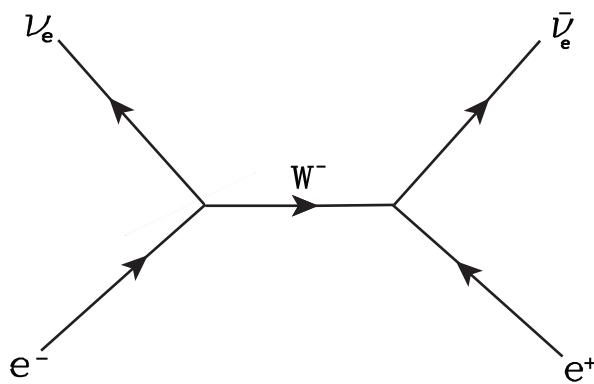
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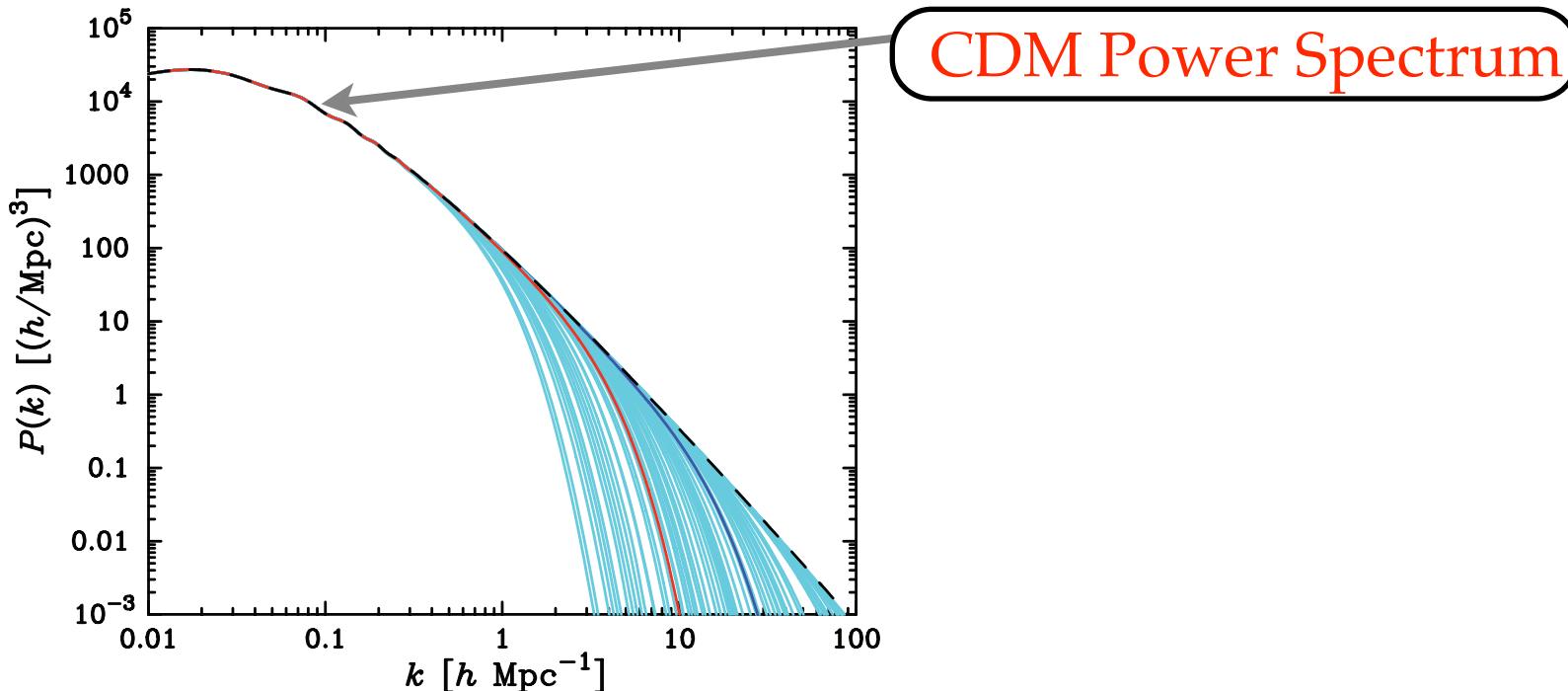
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$$\Omega_s h^2 \simeq 0.13 \left[ \frac{\sin^2 (2\theta_0)}{10^{-8}} \right] m_{s,10 \text{ keV}}^2$$

# Sterile neutrinos and small-scale large-scale structure

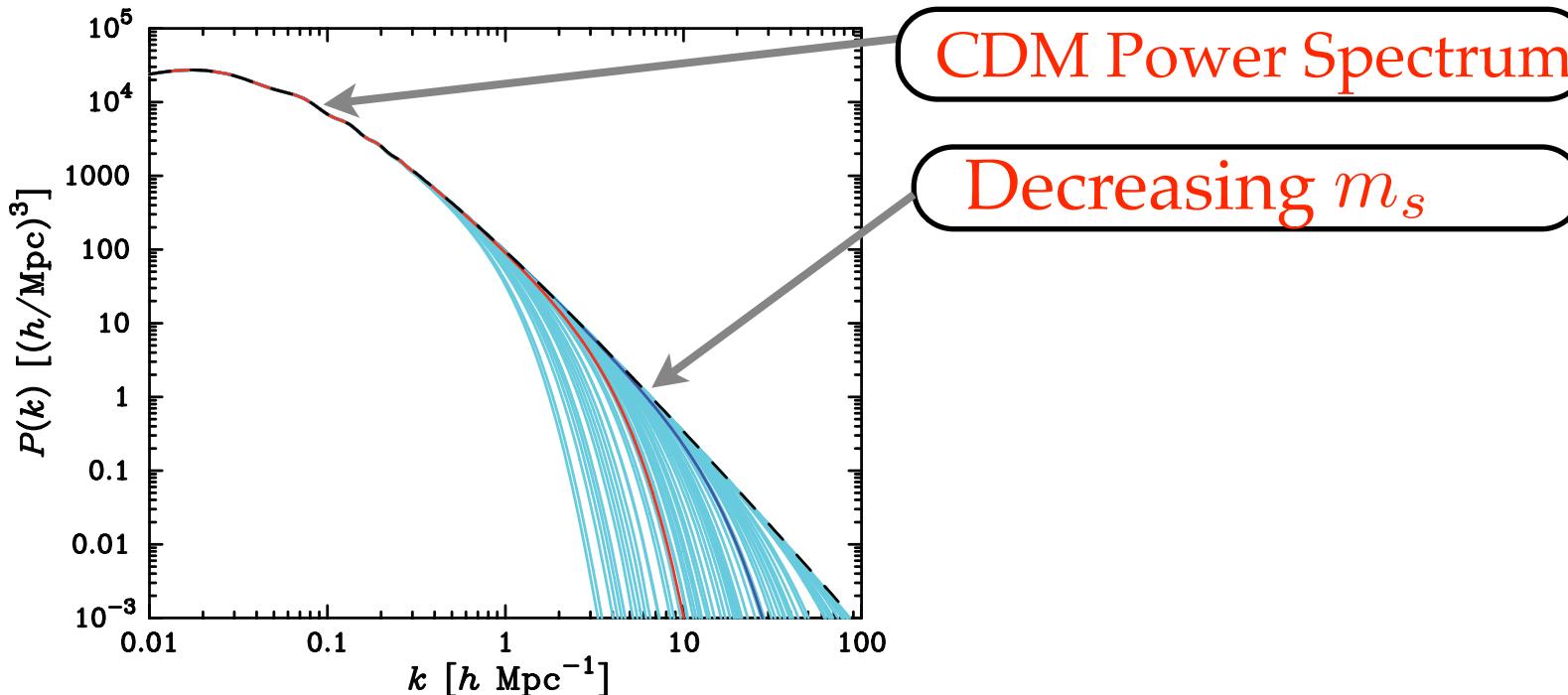


CDM Power Spectrum

- Predictions of CDM recovered on Large Scales
- Relativistic streaming erases structure on small length scales

$$\lambda_{\text{fs}} \simeq 1.2 \text{ Mpc} \left[ \frac{\text{keV}}{m_s} \right]$$

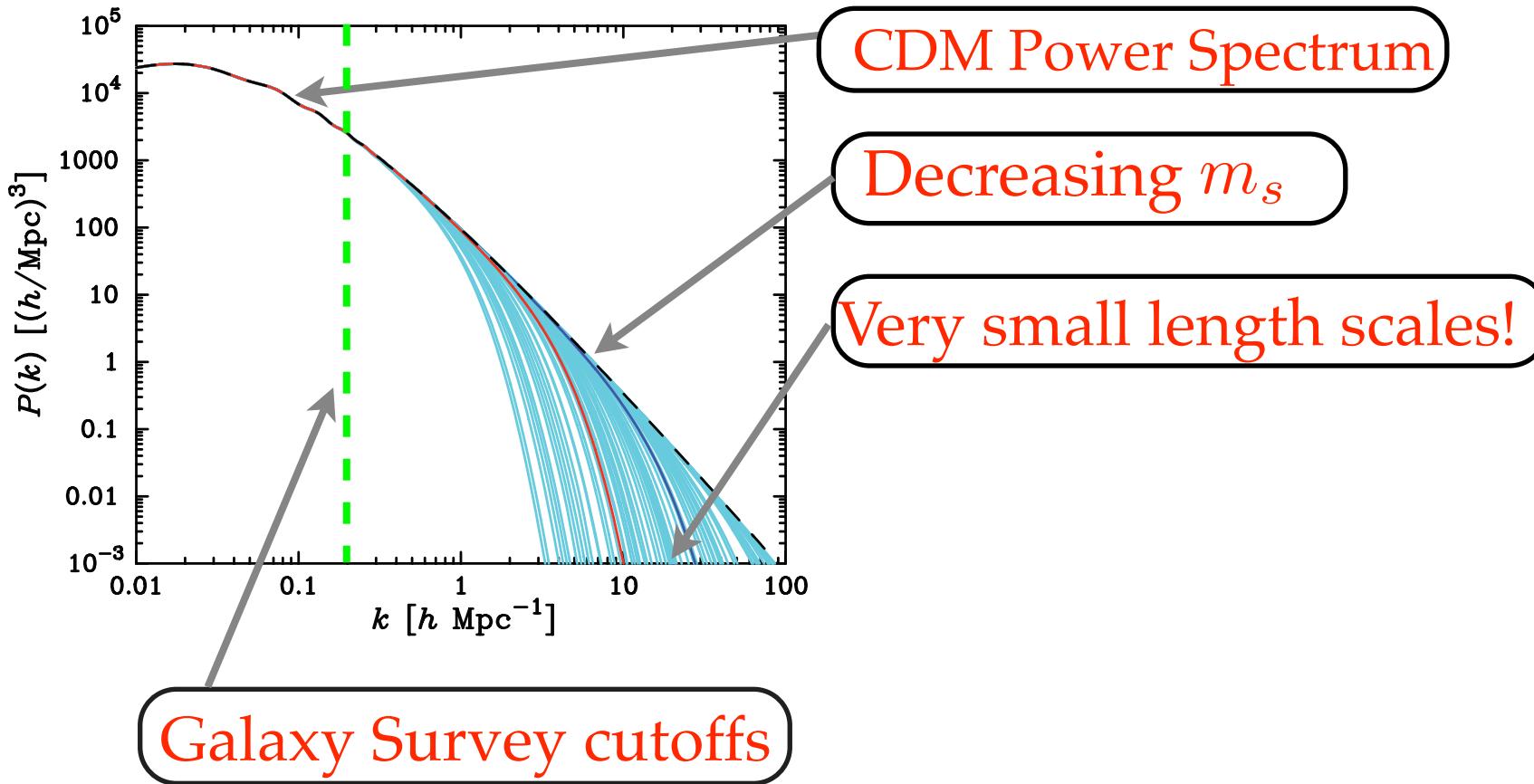
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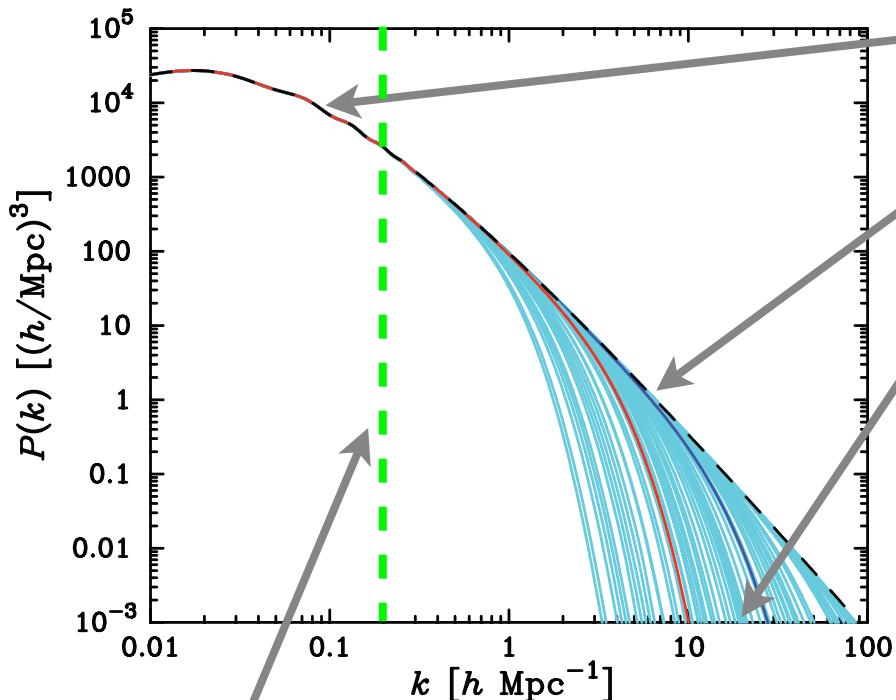
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# Sterile neutrinos and small-scale large-scale structure



CDM Power Spectrum

Decreasing  $m_s$

Very small length scales!

- Constraints from Ly- $\alpha$  forest

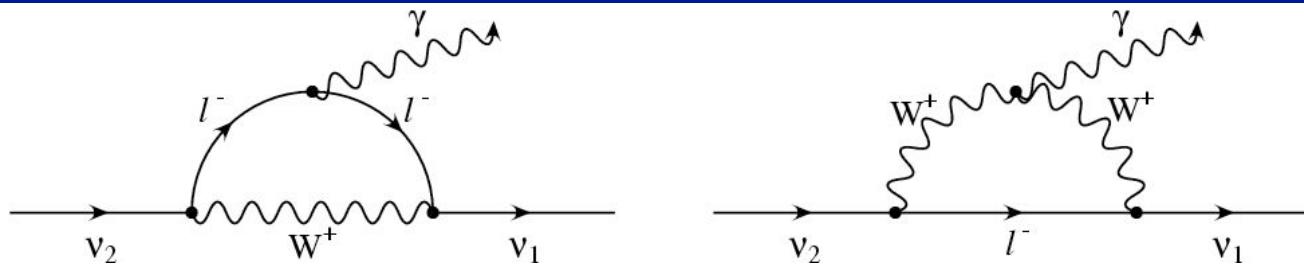
$$m_s \gtrsim 2 - 10 \text{ keV}$$

Galaxy Survey cutoffs

- Predictions of CDM recovered on Large Scales
- Relativistic streaming erases structure on small length scales

$$\lambda_{\text{fs}} \simeq 1.2 \text{ Mpc} \left[ \frac{\text{keV}}{m_s} \right]$$

# Sterile Neutrino decays



- X-rays! (keV photons)

$$\tau = 10^{26} \text{ s} \left( \frac{7 \text{ keV}}{m_s} \right)^5 \left( \frac{10^{-9}}{\sin^2 \theta} \right)$$

- X-ray background constraint  
(XMM)  $\sin^2 2\theta \lesssim 1.15 \times 10^{-4} m_{s,\text{keV}}^{-5}$
- Coma-Virgo Constraints

$$\sin^2 2\theta \lesssim 8 \times 10^{-5} m_{s,\text{keV}}^{-5.43}$$

# Sterile neutrinos and reionization

- Generic WDM scenario suppresses low mass halos (Yoshida/Sokasian 2003)  $\tau_{\max} \simeq 0.05$
- Decaying WDM (a sterile neutrino) would produce additional XRB
- This could hasten reionization (Mapelli and Ferrara 2005) but doesn't cut it!
- An additional ionizing background changes star formation!

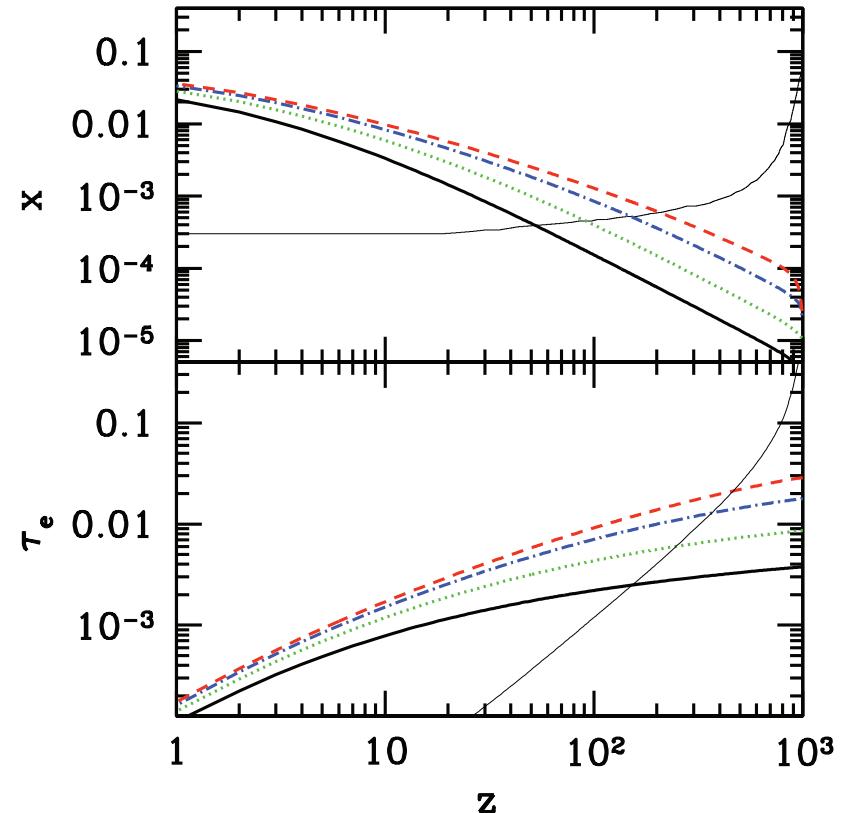


Figure 8. Ionization fraction (top panel) and Thomson optical depth (bottom panel) due to radiatively decaying neutrinos of masses 2 (solid line), 4 (dotted line), 8 (dot-dashed line) and 14 keV (dashed line). The solid thin line indicates: in the top panel the relic ionization fraction (Tegmark et al. 1997); in the bottom panel the Thomson optical depth due to relics.

# The temperature evolution of a molecular cloud

$$\frac{dT}{dz} = (\gamma - 1) \frac{T}{n_p} \frac{dn_p}{dz} + \gamma \frac{T}{\mu} \frac{d\mu}{dz} + \frac{T}{\gamma - 1} \frac{d\gamma}{Dz} + \frac{(\gamma - 1) \Lambda}{n_p k H_0 (1 + z) \sqrt{\Omega_\Lambda + \Omega_m (1 + z)^3}}$$

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PdV work



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PdV work

Ionization/Composition

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PdV work

Ionization/Composition

Heating/Cooling

Heating

- Photo-ionization by CMB
- Collisional ionization by electrons

Cooling

- Compton Cooling
- Recombination Cooling
- Collisional excitation of H lines
- Collisional excitation of  $H_2$  transitions
- Bremsstrahlung
- Heat of formation of  $H_2$

# The temperature evolution of a molecular cloud with sterile neutrinos

$$\frac{dT}{dz} = (\gamma - 1) \frac{T}{n_p} \frac{dn_p}{dz} + \gamma \frac{T}{\mu} \frac{d\mu}{dz} + \frac{T}{\gamma - 1} \frac{d\gamma}{Dz} + \frac{(\gamma - 1) \Lambda}{n_p k H_0 (1 + z) \sqrt{\Omega_\Lambda + \Omega_m (1 + z)^3}}$$

PdV work

Ionization/Composition

Heating/Cooling

Heating

- Photo-ionization by CMB
- Collisional ionization by electron
- Photo-ionization of H by neutrino produced photons
- Collisional ionization by secondaries

Cooling  
Compton Cooling

Recombination Cooling

Collisional excitation of H lines

Collisional excitation of  $H_2$  transitions

Bremsstrahlung

Heat of formation of  $H_2$

# The (crude) chemistry of molecular clouds

- Two formation chains for molecular hydrogen  $e^- + H \rightarrow H^- + \gamma$      $H^+ + H \rightarrow H_2^+ + \gamma$   
 $H^- + H \rightarrow H_2 + e^-$      $H_2^+ + H \rightarrow H_2 + H^+$
- Photo and collisional dissociation of  $H_2$
- Photo and collisional ionization of H, recombination

# The (crude) chemistry of molecular clouds with sterile neutrinos

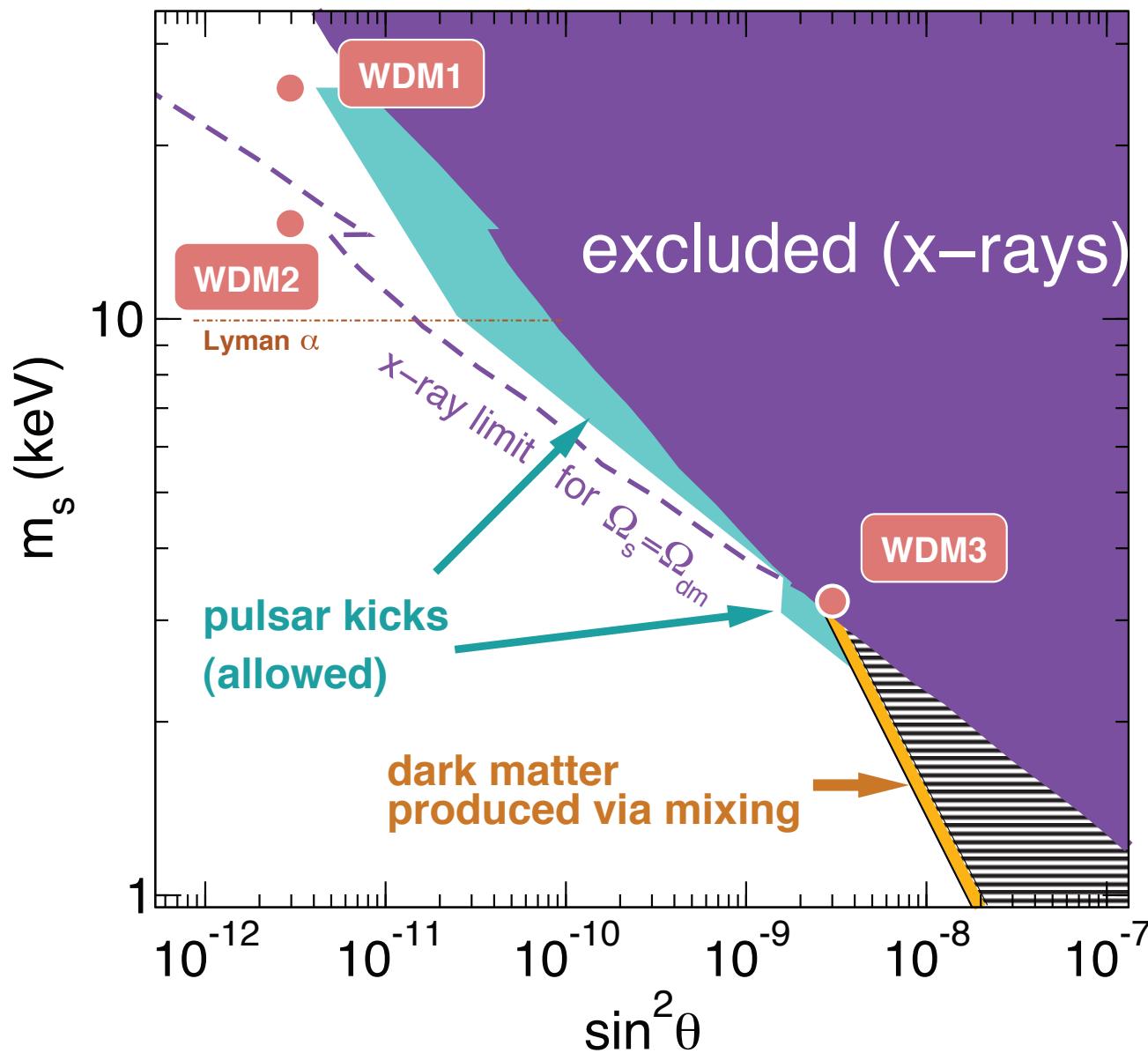
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Neutrino decay products included in photoionizing background

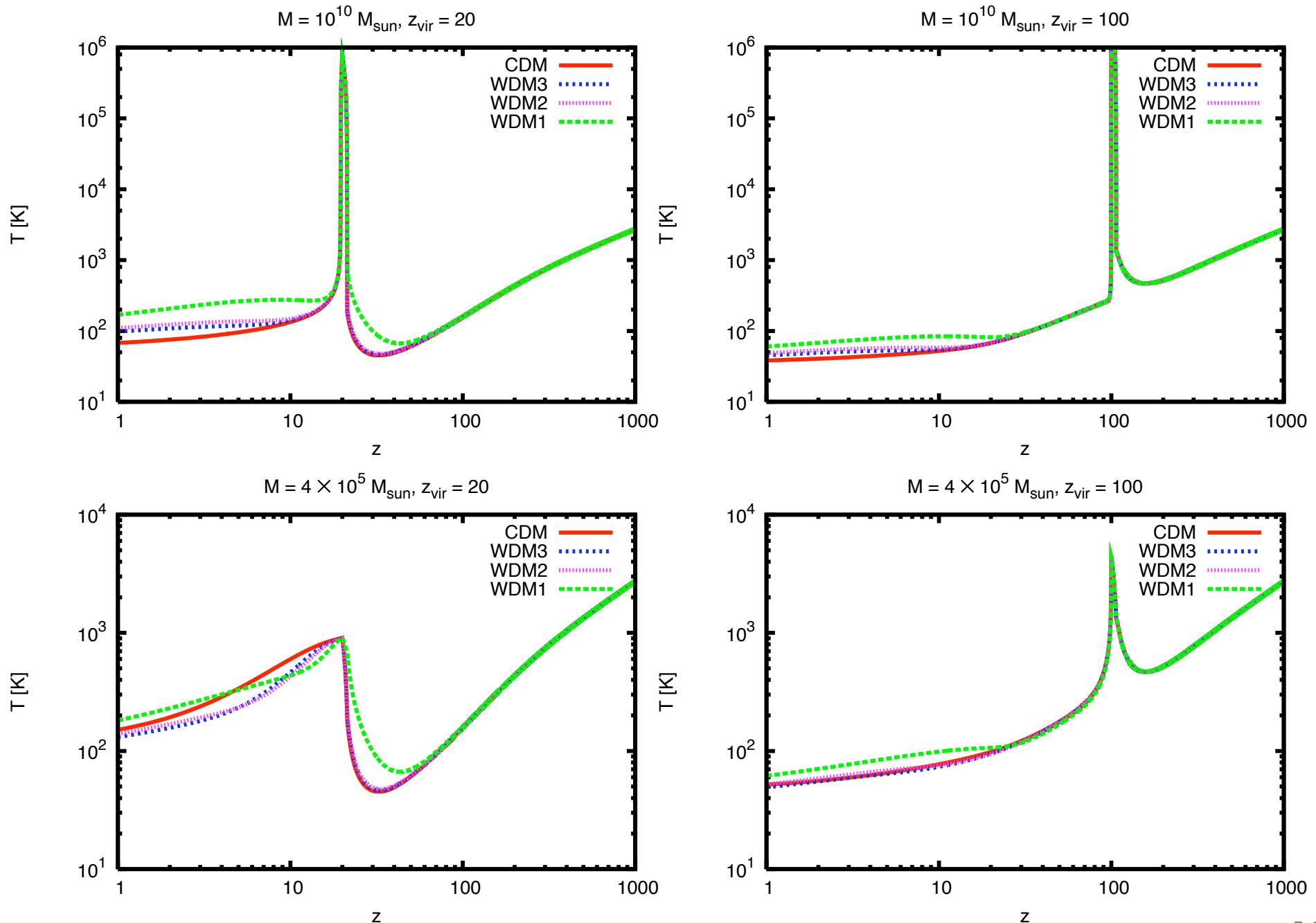
# Other ingredients

- Model ~~stolen~~ adapted from Tegmark, Silk, Rees 1997
- Spherical top-hat collapse until shortly before  $z_{\text{vir}}$
- Temperature rapidly ramped up to  $T_{\text{vir}}$
- $4 \times 10^5 M_{\odot}$  &  $10^{10} M_{\odot}$  halos
- $z_{\text{vir}} = 100$  &  $z_{\text{vir}} = 20$
- Halo ‘fragments if’  $T(0.75z_{\text{vir}}) \leq 0.75T(z_{\text{vir}})$

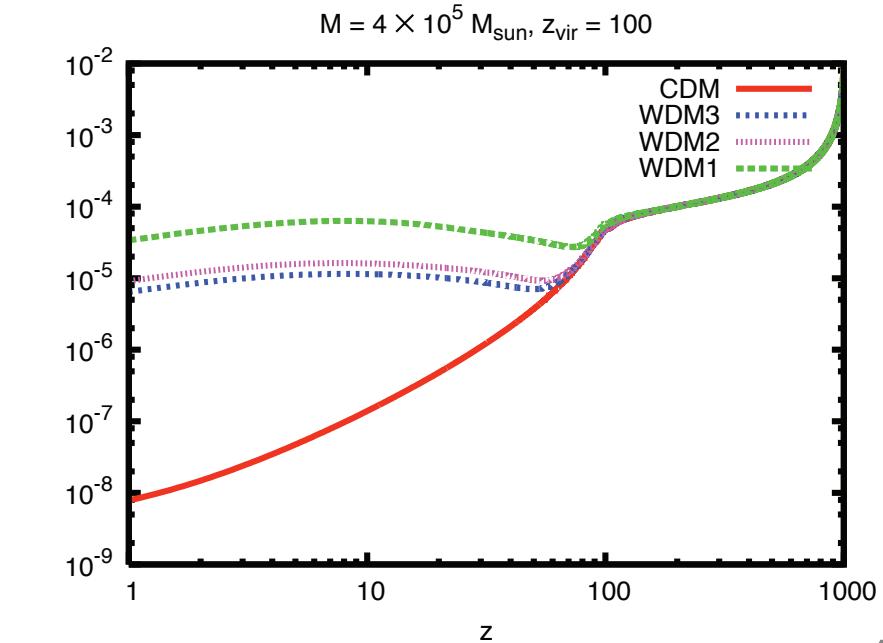
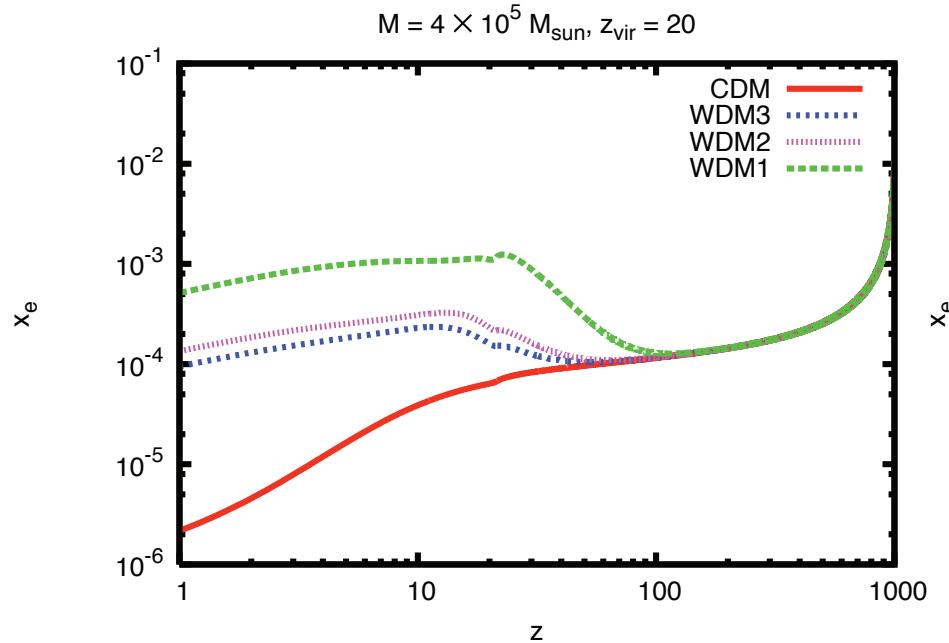
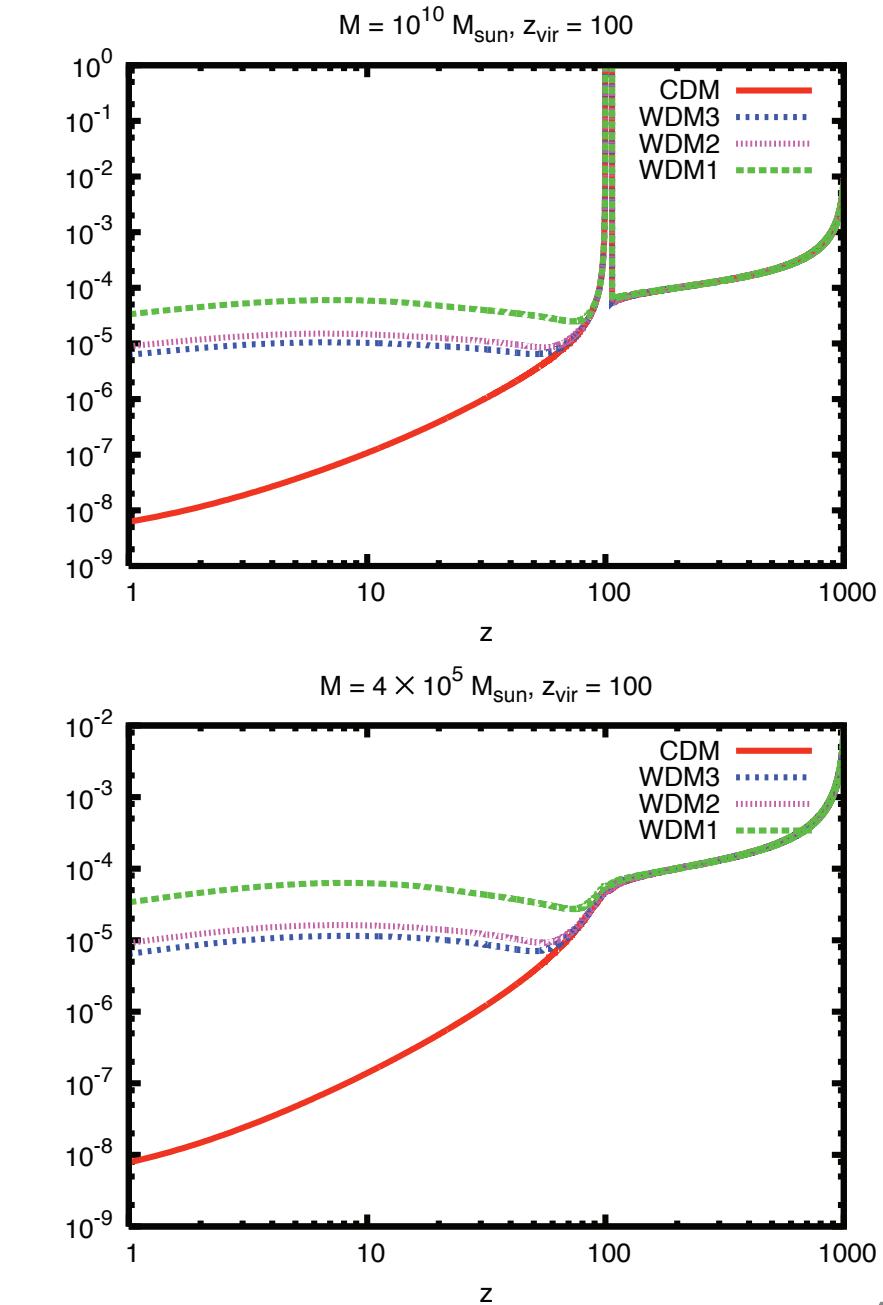
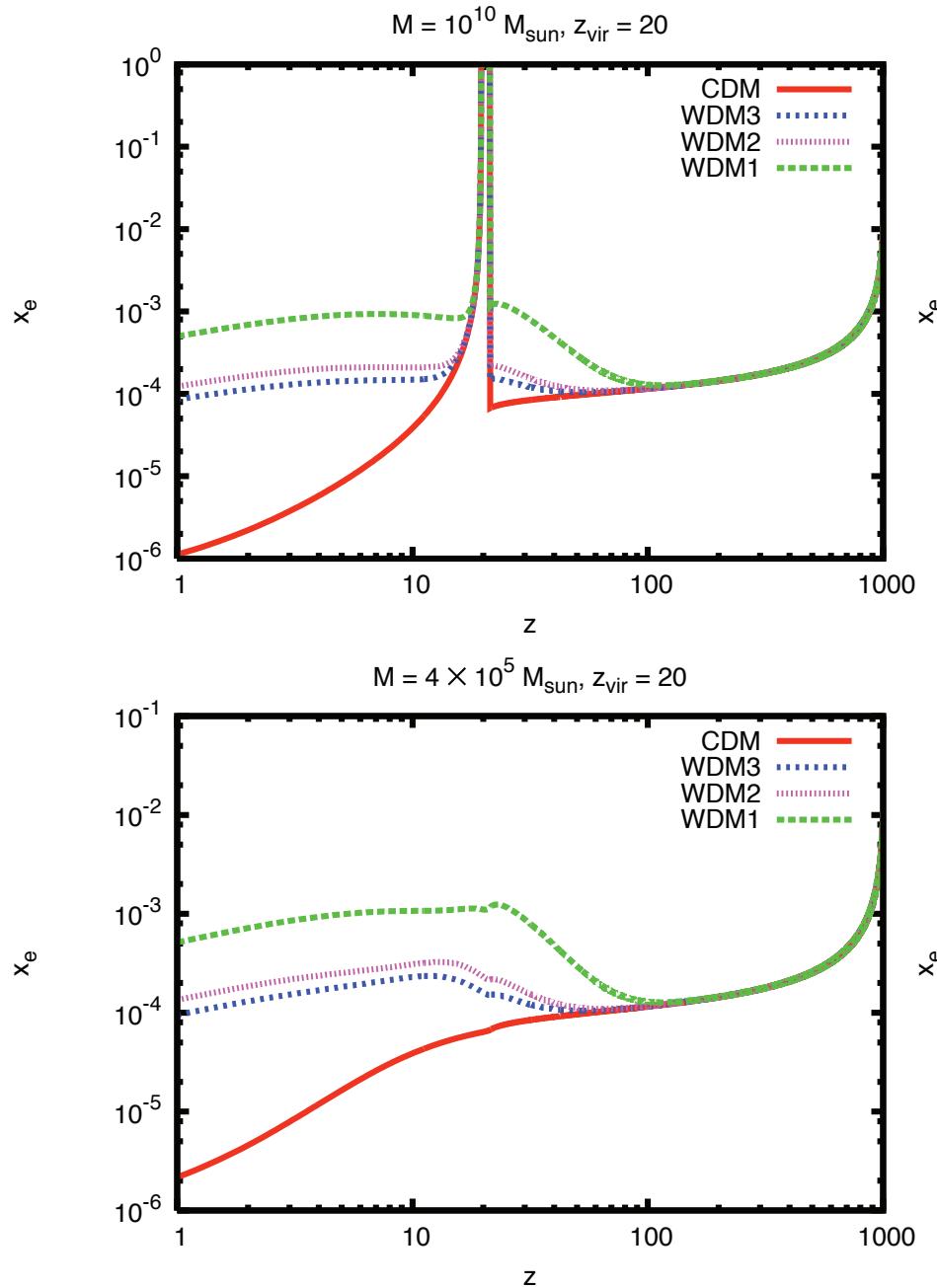
# The big picture



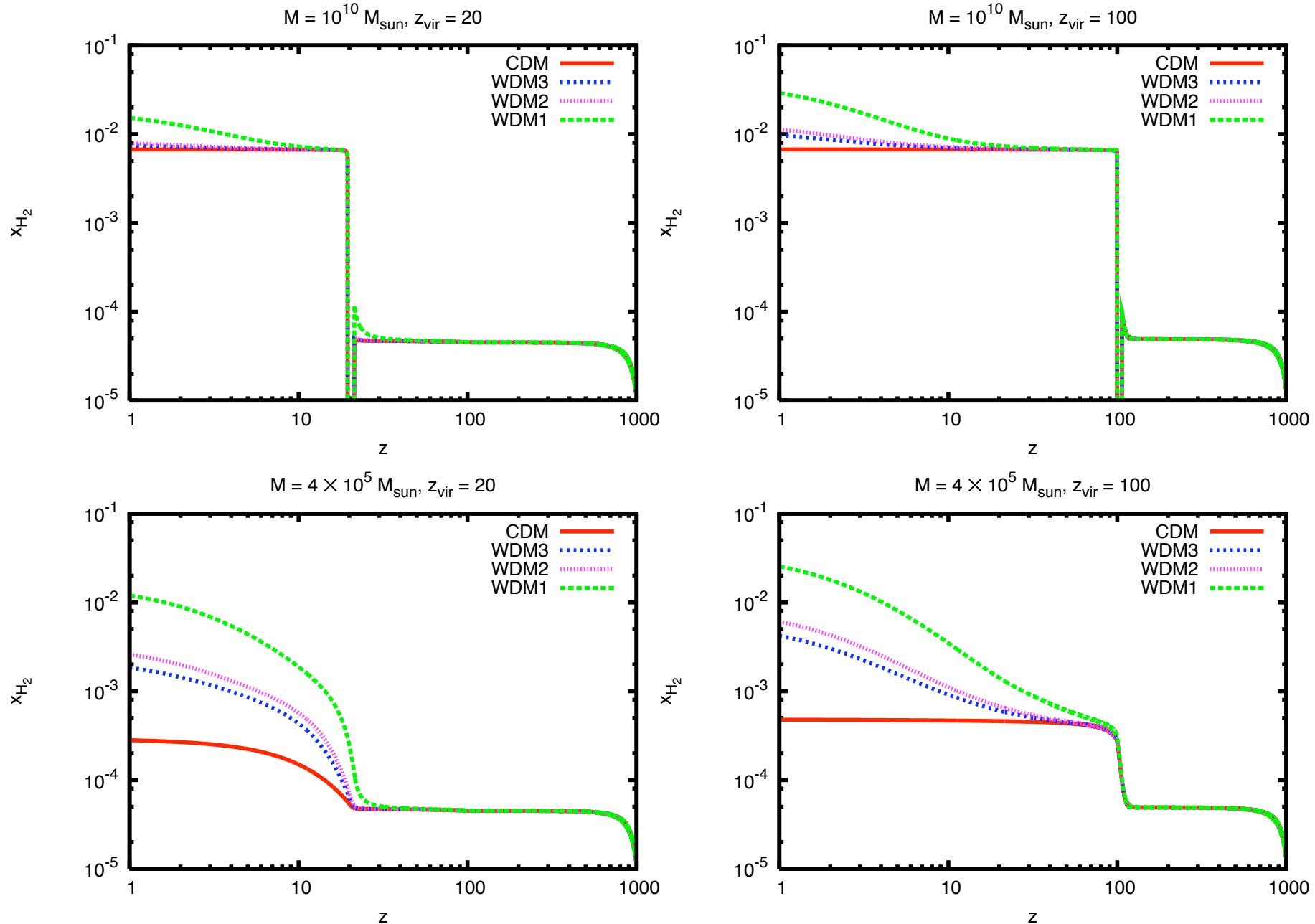
# Results: Gas temperature



# Results: Ionization Fraction

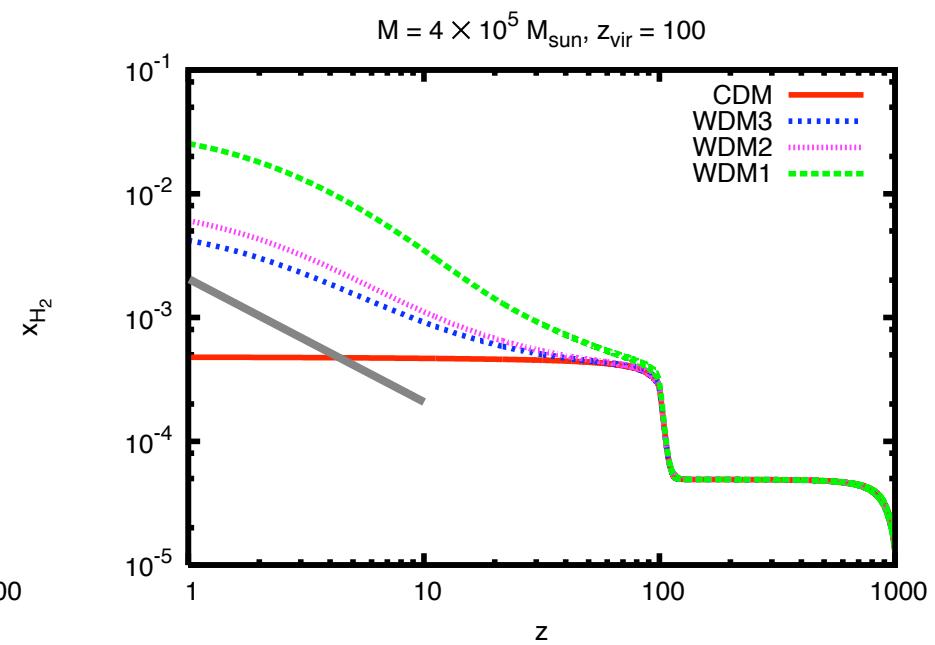
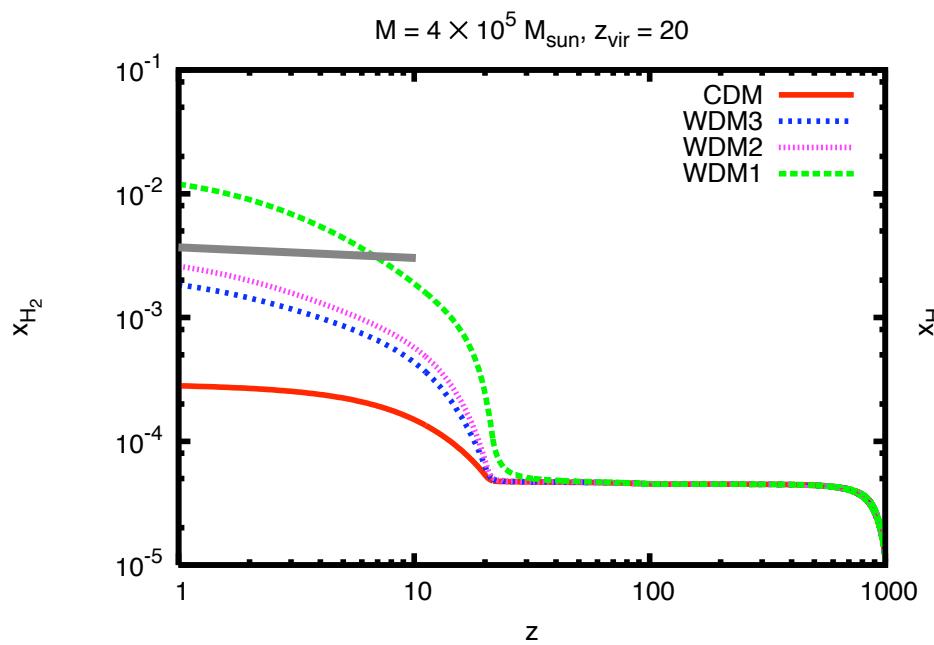


# Results: $H_2$ abundance



# Results: $H_2$ abundance

PUNCHLINE: DECAYING STERILE NEUTRINOS  
ENABLE LOW MASS HALOS TO COOL



# but.....

- No modeling of actual star formation and ionizing background from stars
- No realistic assessment of how this changes ionization history of universe
- Actual halo population/effect of free-streaming not modeled
- Unrealistic modeling of virialization (shock-heating/cooling ignored)
- Enhanced local radiation field not included

# Closing thoughts

- Be afraid, be very afraid of sterile neutrino participation in reionization, and enjoy the Halloween party