Warm Dark Matter and Epoch of Reionization

Laura Lopez Honorez

FREEDOM TO RESEARCH

partially based on `arXiv:1703.02302`
in collaboration with O. Mena, A. Moline, S. Palomares-Ruiz,
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SIDM workshop - Copenhagen

ΛCDM problems?

Problems of Cold Dark Matter (CDM) on galactic and sub galactic scales

- Missing sattelite: [Kyplin'99, Moore'99] CDM fails to reproduce abundance and properties of low mass galaxies $M < 5 \times 10^9 M_\odot$ [Zavala'09, Papastergis'11, Kyplin'11]
- Core-Cusp problem: [DeBlock'97, Oh'11, Walker'11] CDM inner density of Galaxies have cusp $\propto r^{-\alpha}$ with $\alpha \simeq 1$ [NFW'96 etc]
- Too big to fail: [Boylan'11, Papastergis'15] host of dwarf galaxies are too massive to account for the galactic rotation curves ($V_{rot}(r)$ too large)

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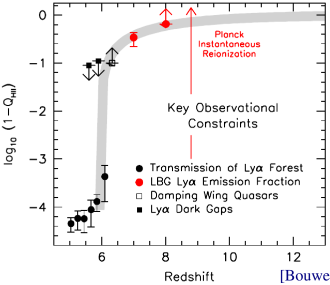
Solutions?

- within ΛCDM: baryonic physics (SN feedback, etc) see Pontzen's talk!
- Beyond ΛCDM $\rightsquigarrow$ suppress structure formation at small scales:
  - (S)IDM? see [Boehm'00+, Cyr-Racine'12+,Bringman'12+,Buckley'14,etc] and also Yo, Valli,... talk!
  - WDM?

Epoch of Reionization and WDM

IN THIS TALK:

- WDM free streeming
  $\rightsquigarrow$ effect on EoR?
- constraints from Lyα emmission,
  Gunn Peterson effect,
  and Planck optical depth



[Bouwens'15]

Epoch of Reionization and WDM

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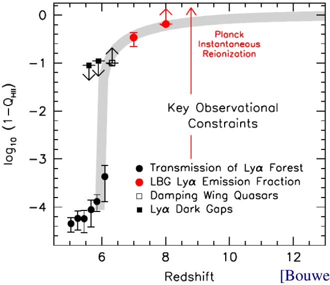
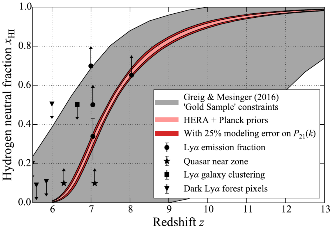
Notice that understanding of EoR is expected to improve with (near) future cosmo probe $\equiv$ 21cm signal



[Bouwens'15]



HERA 2020 set-up [DeBoer'16]

WDM description

WDM free-streaming: linear regime

At early time collisionless particles can stream out of overdense to underdense regions

- smooth out inhomogeneities for $\lambda < \lambda_{FS} = \int_0^{t_0} \frac{v}{a} dt$
  $\rightsquigarrow$ particles relativistic at the time of decoupling can give substancial λ_{FS}

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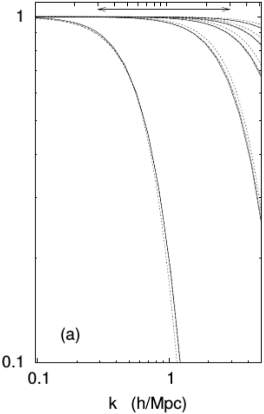
- Assuming thermal WDM [Viel'05]

$$\begin{aligned} T_{\rm WDM}(k) &= (P_{\rm WDM}(k)/P_{\rm CDM}(k))^{1/2} \\ &= (1+(\alpha k)^{2\nu})^{-5/\nu} \end{aligned}$$

with $\nu = 1.12$ and the breaking scale:



[Viel'05]

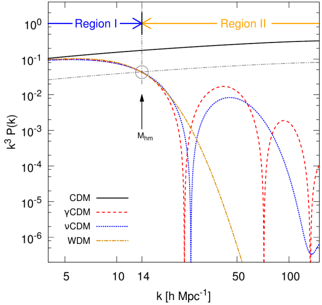
$$\alpha = 0.049 \left(\frac{\rm keV}{m_X}\right)^{1.11} \left(\frac{\Omega_X}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22} {\rm Mpc}/h$$

$\rightsquigarrow$ WDM suppress power at small scales (large k)

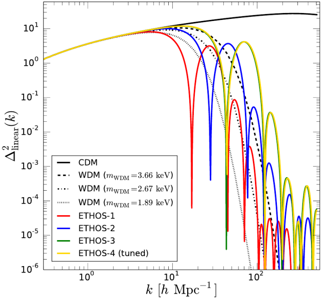
(S)IDM collisional Damping: linear regime

For dark matter interacting with (dark) relativistic degrees of freedom:

see also Zavala, Cyr-Racine, etc talks



[Schewtschenko'14]



[VogelsBerger'15]

Towards generalized fit to non-CDM (SIDM included)? [Murgia'17]

$T(k) = (1 + (\alpha k)^{\beta})^{\gamma}$ → might be usefull enough to derive

Lyα forest and MW satelite count constraints

WDM: non linear regime

At low redshifts, DM pertubations in the non linear regime
⇝ use Press-Schechter (PS) formalism [PS'74, Bond'91] to match N-body simu.:

$$\frac{dn(M,z)}{dM} = \frac{\rho_{m,0}}{M^2} \frac{d \ln \sigma^{-1}}{d \ln M} f(\sigma)$$

- $f(\sigma)$ represents the fraction of mass collapsed into halos.
  For WDM we use Sheth & Tormen [ST'99+].
- $\sigma^2 = \sigma^2(P_{lin}(k), W(kR))$ is the variance of linear perturb. smoothed over the radius $R(\leftrightarrow M)$ using a window fn. W.

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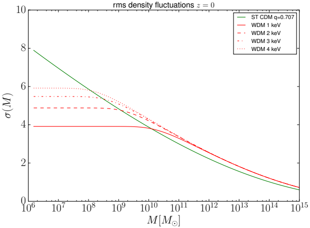
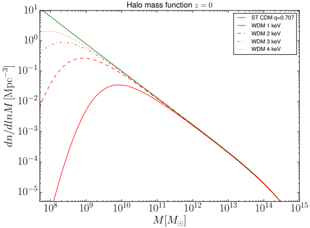
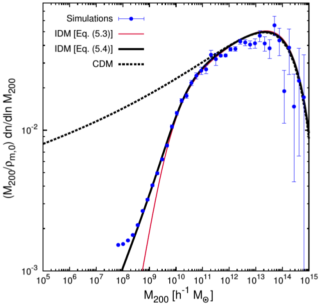
- for WDM, $\sigma(M)$ cst. at low mass accounts for free-streeming effects [Benson'13, Schneider'13]



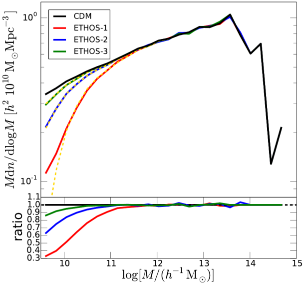


⇝ suppression of the halo mass function at low masses for WDM

(S)IDM: non-linear regime



[Moline'16]



[VogelsBerger'15]

WDM solution to CDM problems?

- WDM can potentially provide partial solutions but strongly challenged by Lyα forest constr. $\rightsquigarrow m_X > 4.65$ keV (at 95%CL)

  [Yèche 17] see also [Viel'13, Baur'15, Irsik 17]

all constraints from SDSS Ly-α QSO spectra BUT depends on T_{IGM} description!
HiRes $\rightsquigarrow$ good fit $m_X \simeq$ 2-3 keV [Garzilli'13], max lik. $m^{rp}_{\nu_s} \simeq$ 8 keV [Baur'17]

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- Similar effects/constraints for Mixed DM, sterile neutrinos (non) resonantly produced, etc

  Some Ly-α forest constraints [Baur 17] :

  $m_X > 3.2$ keV for $F_{wdm} > 80\%$ (at 95%CL)

  $m^{rp}_{\nu_s} > 3.5$ keV (3σ)

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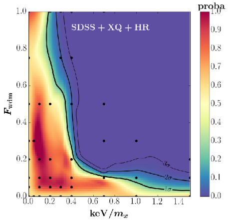

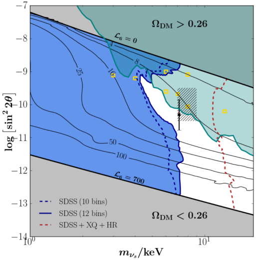

[Baur'17]

WDM and reionization

WDM imprint on Reionization

similar to [Sitwell'14, Bose'16] and for different approach [Yue'12,Barkana'01, Somerville'03,Yoshida'03, Schultz'14, Dayal '14+, Rudakovskyi'16]

- Ionization level at $z \sim z_{reio}$:

$$\bar{x}_i \approx \zeta_{UV} f_{\rm coll} \text{ with } f_{\rm coll} = f_{\rm coll}(> M_{\rm vir}^{\rm min}) = \int_{M_{\rm vir}^{\rm min}} \frac{M}{\rho_{m,0}} \frac{dn}{dM}\, dM \; .$$

- Optical depth to reionization:

$$\tau = \sigma_T \int \bar{x}_i\, n_b\, dl \text{ and Planck: } \tau = 0.055 \pm 0.009 \text{ [Aghanim'16]}$$

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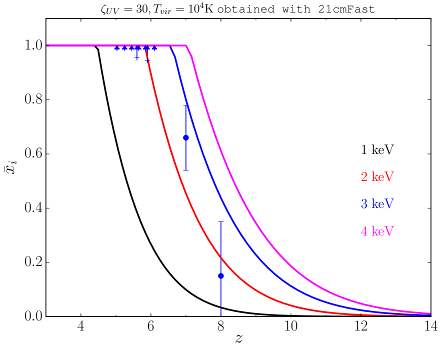
Within our framework:

low m_X suppress structure formation at small scales

⇝ reduces $\bar{x}_i$

⇝ WDM can delay reionization



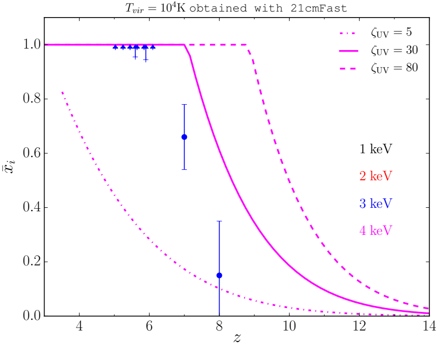
Astro parameters and Reionization

- Ionization efficiency:
  $\zeta_{UV} \propto f_{esc} N_{\gamma/b} f_\star$
  Regions ionized when

  $$\zeta_{UV} f_{\rm coll} > 1$$

  $\rightsquigarrow$ lower ζ_{UV} has similar effect than lower m_X similar to [Sitwell'14]

$T_{vir} = 10^4$K obtained with 21cmFast



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- Threshold for halos hosting star-forming galaxies:

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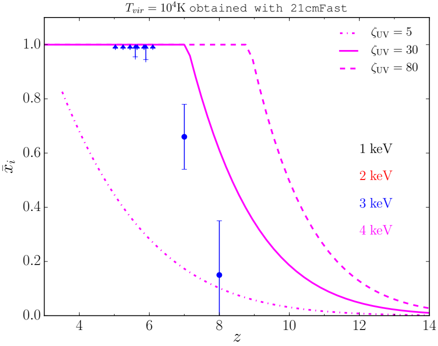

$$M_{\rm vir}^{\rm min}(z) \simeq 10^8 \left(\frac{T_{\rm vir}^{\rm min}}{2\times 10^4\ {\rm K}}\right)^{3/2} \left(\frac{1+z}{10}\right)^{-3/2} M_\odot \rightsquigarrow \text{larger } T_{\rm vir}^{\rm min} \text{ delays the reionization}$$

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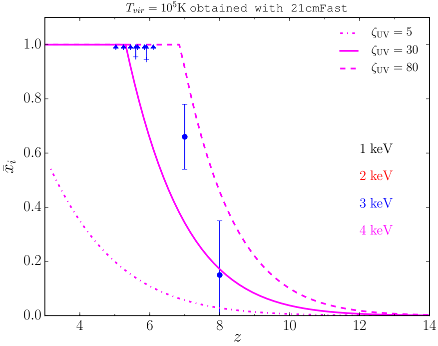

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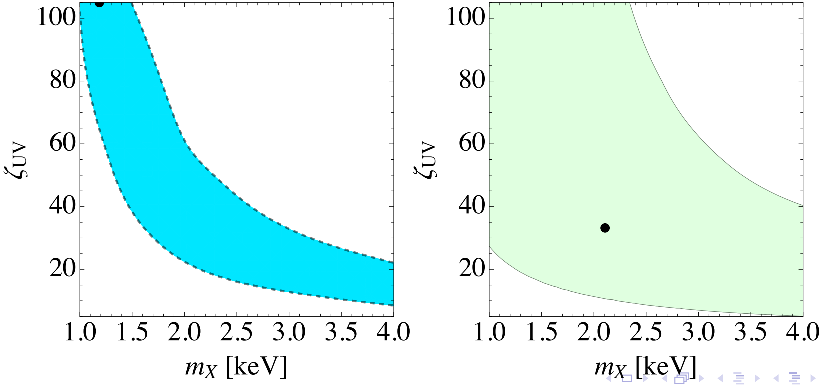
Important degeneracies between astro $\{\zeta_{UV}, T_{\rm vir}^{\rm min}\}$ and WDM effects

Degeneracies

Allowed regions at 90% CL for $\bar{x}_i$ and τ data:

- One can compensate larger ζ_{UV} with smaller m_X

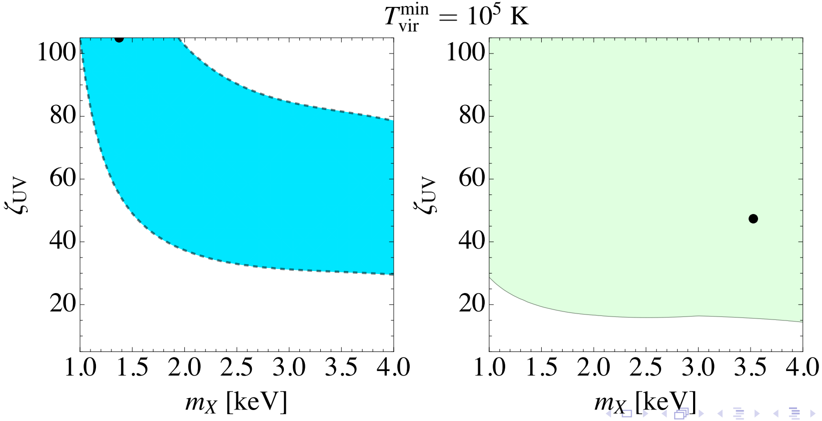
$T_{\rm vir}^{\rm min} = 10^4$ K



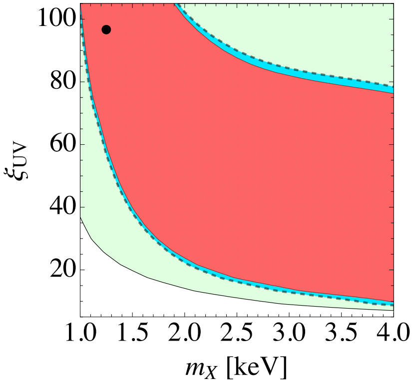
Degeneracies

Allowed regions at 90% CL for $\bar{x}_i$ and τ data:

- One can compensate larger ζ_{UV} with smaller m_X
- Larger $T_{\rm vir}^{\rm min}$ shifts contours to larger ζ_{UV}



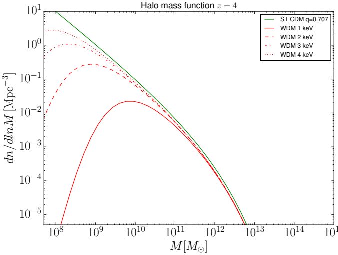
Final contours



BUT constraints on T_{IGM} should provide a lower bound on m_X

Caveats

- HMF considered validated until $z = 5$ only see e.g. [Schneider'14] $\rightsquigarrow$ needs Hydro-simu to larger z
- What about if $\zeta = \zeta_{UV}(z)$?
  $\rightsquigarrow$ even $\zeta_{UV}(z)$ such that $x_i(z)^{WDM} = x_i(z)^{CDM}$ might be discriminated but needs good knowledge of ζ_{UV} using e.g. P_{21} [Sitwell'13]
- SN feedback $\rightsquigarrow$ eject cold gas from galaxies, can inihibit ionizing γ production
  see e.g. for WDM+SNfb [Bose'16]
- We assume $\zeta_{UV} \propto 1/(1 + n_{rec})$ BUT the lack of minihaloes in WDM could suppress the average number of recombination/H atom
  $\rightsquigarrow$ some WDM could even get earlier reionization than CDM
  see e.g. [Barkana'01, Somerville'03,Yoshida'03, Yue'12, Schultz'14, Dayal '14+, Rudakovskyi'16]



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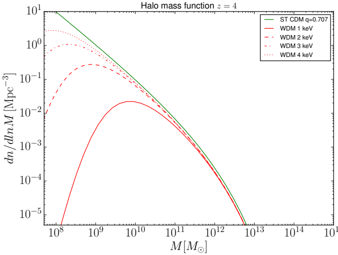
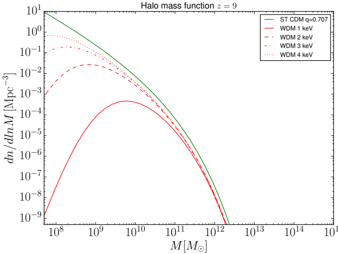
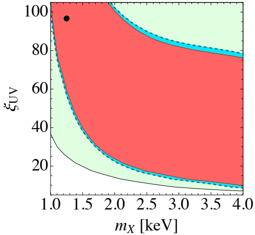




Conclusion: WDM and EoR?



- Non-cold dark matter can supress small scale structure formation $\rightsquigarrow$ can delay reionization
- Parametrizing reionization as a function of a reduced set of parameters mainly $\zeta_{UV}, T_{vir}^{min}, m_X$, we observed strong degeneracies to agree with the data$\rightsquigarrow$ smaller $m_X \Leftrightarrow$ larger ζ_{UV} and smaller T_{vir}.

Within this framework the entire range of tested m_X is compatible with reionization and Planck data if one is allowed to consider ζ_{UV} up to 100.

Thank you for your attention

Backup

Top hat versus sharp k cutoff scale for γCDM

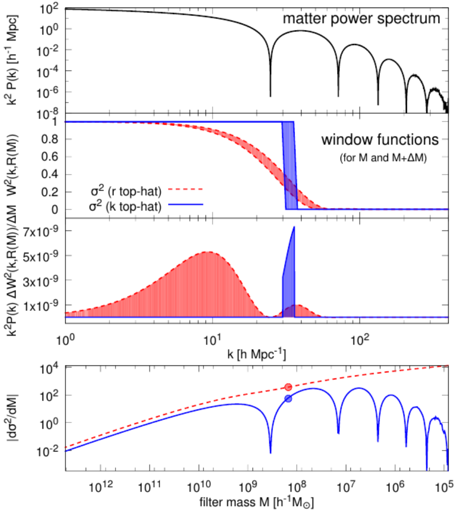


Figure 4. Real-space and k-space top-hat window functions in Press-Schechter HMF predictions for γCDM. The upper panel shows the matter power spectrum, while the second panel shows the Fourier transform of the two window functions (r top-hat and k top-hat). Each window function is evaluated for two filter masses, M and $M + \Delta M$. The difference between the two filter masses is highlighted by the shaded region in each case. The third panel shows the result of applying this differential filter to the matter distribution. Finally, the lower panel shows the integrated result for both window functions. The red and blue points are the results for the specific filter mass M used in the middle two panels.

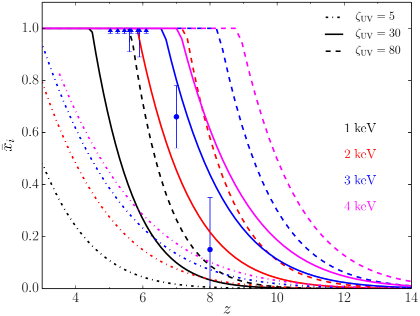
$\rightsquigarrow$ with r-top hat filter (TH) a large number of un-suppressed small k scales contribute to $\sigma(M)$

$\rightsquigarrow$ not good to describe $\sigma(M)$ for suppressed $P(k)$ including WDM

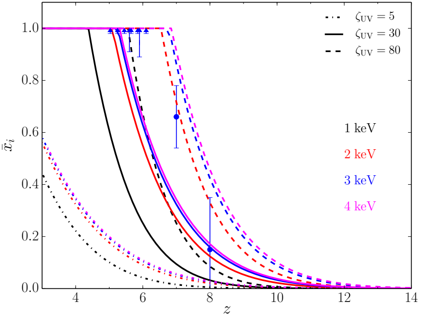
[Schewtschenko'14]

WDM imprint on ionized fraction

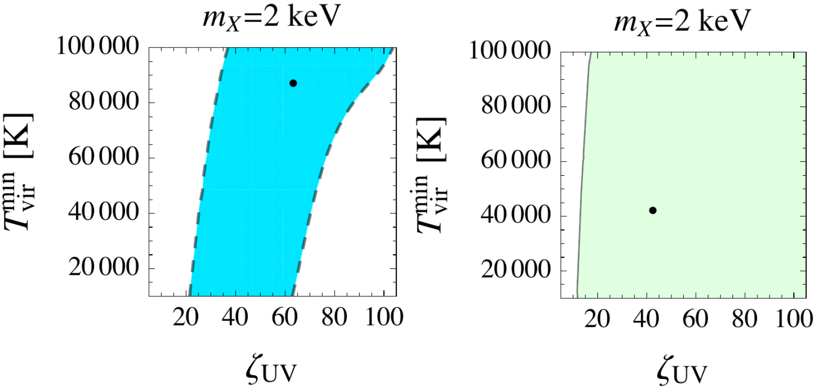
$$T_{vir}^{min} = 10^4\mathrm{K}$$



$$T_{vir}^{min} = 10^5\mathrm{K}$$



Fixed WDM mass and full contours



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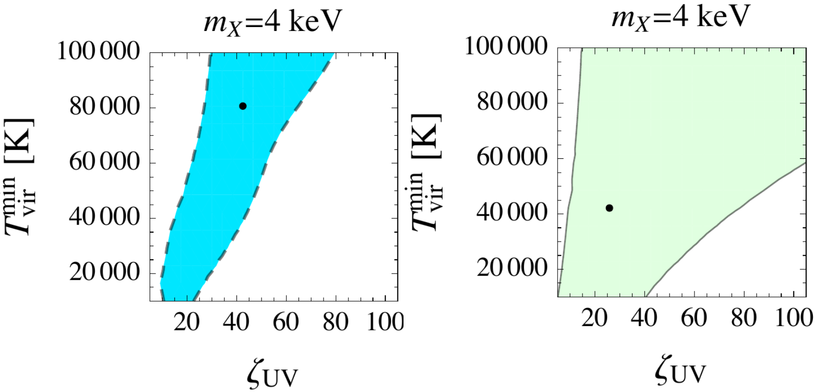
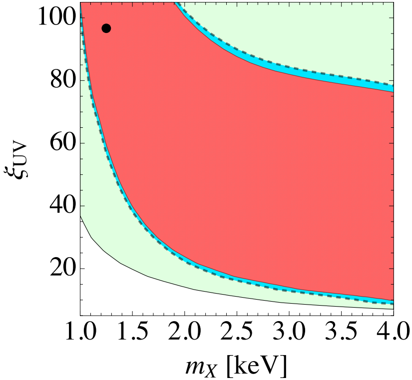


Fixed WDM mass and full contours

- All together best fit at 1.25 keV, $\zeta_{UV} = 96.6$



BUT constraints on T_{IGM} should provide a lower bound on m_X

Characterization of the 21cm signal

The observed brightness of a patch of HI relative to the CMB at $\nu = \nu_0/(1+z)$ is associated to the differential brightness temperature δT_b:

$$\delta T_b(\nu) \simeq 27\, x_{\rm HI}\,(1+\delta_b)\left(1-\frac{T_{\rm CMB}}{T_S}\right)\left(\frac{1}{1+H^{-1}\partial v_r/\partial r}\right)\left(\frac{1+z}{10}\right)^{1/2}\left(\frac{0.15}{\Omega_m h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\ \mathrm{mK}$$

Fraction of neutral H

Spin temperature= excitation T of 21cm line

T_S characterises the relative occupancy of the 2 HI ground state energy levels: $n_1/n_0 = 3\exp[-h\nu_0/(k_B T_S)]$ and is driven by

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- Scattering of CMB photons

  if CMB alone $\rightsquigarrow$ thermalisation $T_S = T_{CMB}$ $\rightsquigarrow$ IGM unobservable

Characterization of the 21cm signal

The observed brightness of a patch of HI relative to the CMB at $\nu = \nu_0/(1+z)$ is associated to the differential brightness temperature δT_b:

$$\delta T_b(\nu) \simeq 27\, x_{\rm HI}\,(1+\delta_b)\left(1-\frac{T_{\rm CMB}}{T_S}\right)\left(\frac{1}{1+H^{-1}\partial v_r/\partial r}\right)\left(\frac{1+z}{10}\right)^{1/2}\left(\frac{0.15}{\Omega_m h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\ \mathrm{mK}$$

Fraction of neutral H

Spin temperature= excitation T of 21cm line

T_S characterises the relative occupancy of the 2 HI ground state energy levels: $n_1/n_0 = 3\exp[-h\nu_0/(k_B T_S)]$ and is driven by

- Scattering of CMB photons

  if CMB alone $\leadsto$ thermalisation $T_S = T_{CMB}$ $\leadsto$ IGM unobservable
- Atomic collisions with H, p or e^- (when IGM is dense, dark ages)
- Scattering of Lyα photons $\equiv$ Wouthuysen-Field (WF) effect (once early radiation sources light on)

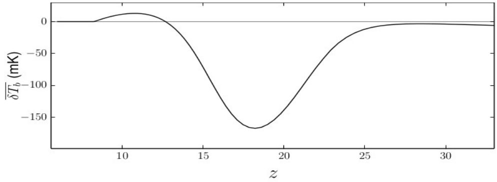
  $\leadsto$ IGM is seen in absorption or emission compared to CMB

  i.e. when $T_K \neq T_{CMB}$ and some mechanism couples T_K to T_S

$$\delta T_b(\nu) \simeq 27\, x_{\rm HI}\, (1+\delta_b) \left(1 - \frac{T_{\rm CMB}}{T_S}\right) \left(\frac{1}{1+H^{-1}\partial v_r/\partial r}\right) \left(\frac{1+z}{10}\right)^{1/2} \left(\frac{0.15}{\Omega_m h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \,\mathrm{mK}$$

Fraction of neutral H

Spin temperature= excitation T of 21cm line



δT_b and Δ_{21} obtained using `21cm Fast` [Mesinger'10]

$$\delta T_b(\nu) \simeq 27\, x_{\rm HI}\,(1+\delta_b)\left(1-\frac{T_{\rm CMB}}{T_S}\right)\left(\frac{1}{1+H^{-1}\partial v_r/\partial r}\right)\left(\frac{1+z}{10}\right)^{1/2}\left(\frac{0.15}{\Omega_m h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\ \mathrm{mK}$$

Fraction of neutral H

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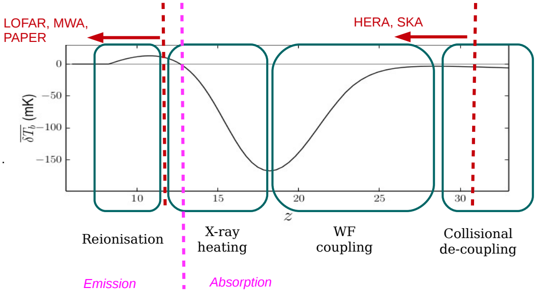

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Fraction of neutral H

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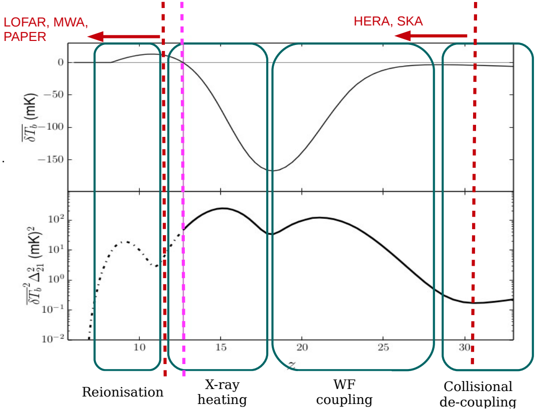
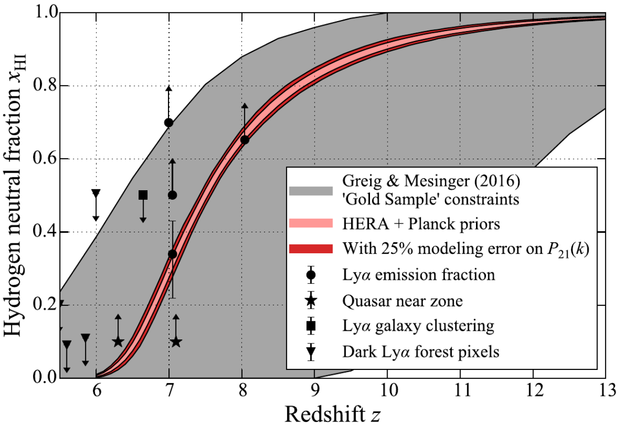


$$\langle\widetilde{\delta}_{21}(\mathbf{k},z)\widetilde{\delta}^*_{21}(\mathbf{k}',z)\rangle \equiv (2\pi)^3\delta^D(\mathbf{k}-\mathbf{k}')P_{21}(k,z) \qquad \Delta^2_{21}(k,z) = \frac{k^3}{2\pi^2}P_{21}(k,z)$$

$$\delta_{21}(\mathbf{x},z) = \delta T_b(\mathbf{x},z)/\overline{\delta T_b}(z) - 1$$

δT_b and Δ_{21} obtained using `21cm Fast` [Mesinger'10]

HERA reach on x_{HI}



[De Boer'16]

Current constraints on EoR $\delta T_b^2 \Delta_{21}$

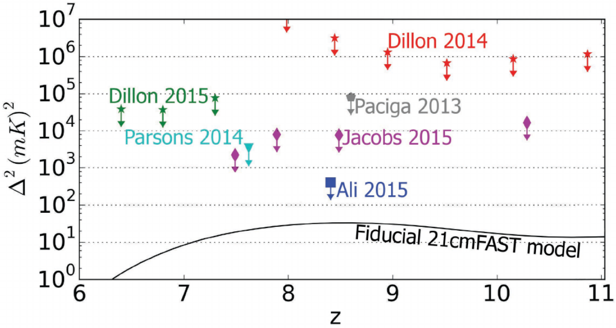


Figure 9. The current best published 2σ upper limits on the 21cm power spectrum, $\Delta^2(k)$, compared to a 21cmFAST-generated model at $k = 0.2\,h\,\mathrm{Mpc}^{-1}$. Analysis is still underway on PAPER and MWA observations that approach their projected full sensitivities; HERA can deliver sub-mK^2 sensitivities.

[De Boer'16]

Current and future reach on $\delta T_b^2 \Delta_{21}$

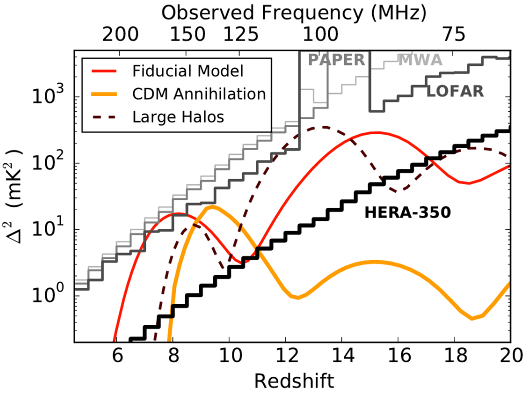


Figure 4. 1σ thermal noise errors on $\Delta^2(k)$, the 21 cm power spectrum, at $k = 0.2\,h\,\mathrm{Mpc}^{-1}$ (the dominant error at that k) with 1080 hours of integration (black) compared with various heating and reionization models (colored). Sensitiv-

[De Boer'16]

Resonant scattering of Lyα photons

Cause spin flip transitions

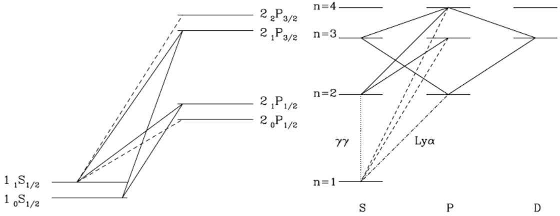


Figure 2. *Left panel:* Hyperfine structure of the hydrogen atom and the transitions relevant for the Wouthuysen-Field effect [24]. Solid line transitions allow spin flips, while dashed transitions are allowed but do not contribute to spin flips. *Right panel:* Illustration of how atomic cascades convert Lyn photons into Lyα photons.

[Pritchard'11]

title

This is really the end