A fresh look into Interacting Dark Matter Scenarios

IDM collisional damping imprint on N_{sat}, EoR and 21cm

Laura Lopez Honorez

mainly based on **JCAP 1806 (2018) no.06, 007**
in collaboration with M. Escudero, O. Mena, S. Palomares-Ruiz
& P. Villanueva Domingo

Dark Side of the Universe Annecy - 25-29/06

ΛCDM problems?

Some Problems of Cold Dark Matter on galactic and sub galactic scales

- Missing satellite: [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)

ΛCDM problems?

Some Problems of Cold Dark Matter on galactic and sub galactic scales

- Missing satellite: [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)

Solutions?

- within ΛCDM: baryonic physics (SN feedback, etc)
- Beyond ΛCDM $\rightsquigarrow$ suppress structure formation at small scales: "Non-Cold" DM Scenarios ? [Murgia'17]
  - Warm Dark matter (WDM)
  - DM interacting with light degrees of freedom (IDM)

    see [Boehm'00+, Cyr-Racine'12+,Bringman'12+,Buckley'14,etc]
  - also fuzzy DM, sterile neutrinos, mixed DM, freeze-in DM

    see e.g. [Murgia'17,8], [Boulebnane'17, Calibbi'17]

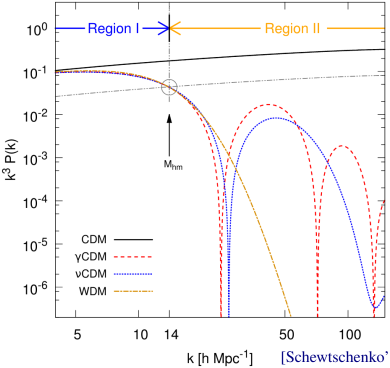
see also talks of F. Cyr Racine, Y. Wong, A. Aoki today, and D. Hooper tomorrow!

IDM description

IDM linear regime: suppressed power at small scale

■ WDM: free-streeming (collision-less damping): collisionless particles can stream out of overdense to underdense regions

■ IDM: collisional damping (Silk damping): damping length associated to diffusion processes and propto distance traveled by coll. particles during random walk



[Schewtschenko'14

IDM linear regime: suppressed power at small scale

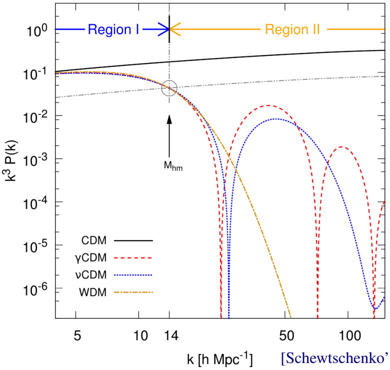
■ WDM: free-streeming (collision-less damping): collisionless particles can stream out of overdense to underdense regions

■ IDM: collisional damping (Silk damping): damping length associated to diffusion processes and propto distance traveled by coll. particles during random walk

$$T_X(k) = (P_X(k)/P_{CDM}(k))^{1/2} = (1 + (\alpha_X k)^{2\nu})^{-5/\nu}$$

with $\nu = 1.2$ and define the scales

- $\alpha_{\gamma CDM} \propto 0.073 \left(10^8 \left(\sigma_{\gamma DM}/\sigma_T\right)\right)^{0.48}$ Mpc$/h$ for IDM with γ induced damping [Bhoem'01]
- half mode mass : $T_X(k_{hm}) = 1/2$ $\rightsquigarrow M_{hm} = M_{hm}(\sigma_{\gamma DM}, \nu)$



[Schewtschenko'14]

$\rightsquigarrow$ IDM & WDM suppress power at small scales (large k) characterized by α_X or equiv M_{hm} functions of $\sigma_{\gamma DM}$ or m_{WDM} see also [Murgia'17-18]

IDM non linear regime: less low mass haloes

At low redshifts, DM pertubations in the non linear regime
$\rightsquigarrow$ 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. We use Sheth & Tormen [ST'99+].
- $\sigma^2 = \sigma^2(P_{lin}(k), W(kR))$ is the variance of linear perturb. smoothed over $R(\leftrightarrow M)$

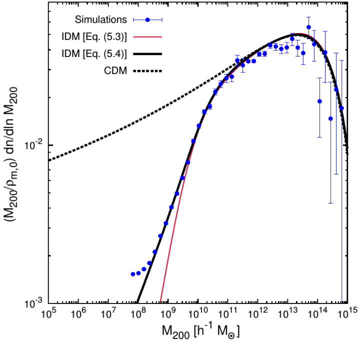
IDM non linear regime: less low mass haloes

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. We use Sheth & Tormen [ST'99+].
- $\sigma^2 = \sigma^2(P_{lin}(k), W(kR))$ is the variance of linear perturb. smoothed over $R(\leftrightarrow M)$
- from CDM to Non-Cold DM [Schneider'12, Bhoem'14, Moline'16]

$$\left.\frac{dn(M,z)}{dM}\right|_{\rm IDM} = F_{\rm IDM}(M_{hm}) \times \left.\frac{dn(M,z)}{dM}\right|_{\rm CDM}$$



[Moline'16]

⇝ suppression of the halo mass function for WDM, IDM can be described as fn. of $M_{hm}(m_{\rm WDM})$ or $M_{hm}(\sigma_{\gamma \rm CDM})$ BUT more low mass haloes in IDM than WDM at fixed M_{hm} see also [VogelsBerger'15]

IDM reionization, satellites and 21cm Cosmology

Number of MW Satellites

Current number of discovered MW satellites galaxies: $N_{\rm gal}^{\rm obs} = 54$ (11 class., 17 DES, 17 SDSS, 9 others). Extrapolation to the entire sky: $N_{\rm gal} > 85$ at 95% CL [Newton'17] and [Bechtol'15, Drlica-Wagner'15,Ahn'12, Koposov'09]. From [Kim'17]

Number of MW Satellites

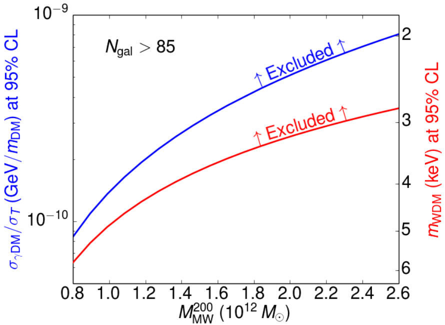
Current number of discovered MW satellites galaxies: $N_{\rm gal}^{\rm obs} = 54$ (11 class., 17 DES, 17 SDSS, 9 others). Extrapolation to the entire sky: $N_{\rm gal} > 85$ at 95% CL [Newton'17] and [Bechtol'15, Drlica-Wagner'15,Ahn'12, Koposov'09]. From [Kim'17]

$$N_{\rm gal} = \int_{M_{\rm min}}^{M_{\rm host}} \frac{dN_{sub}}{dM} f_{\rm lum}(M)\, dM$$

- dN/dM is the *subhalo* mass funtion,

$$\frac{dN_{sub}^{\rm IDM}}{dM} = F_{\rm IDM}(M_{hm}) \frac{dN_{sub}^{\rm CDM}}{dM} \; ,$$

- $dN_{sub}^{\rm CDM}/dM$ is function of $M_{\rm MW}$ and $f_{\rm lum}(M)$ account for the probability that a subhalo of a given mass hosts a luminous galaxy. We use [Dooley'16].



$$(\sigma_{\gamma\rm DM}/\sigma_T) < 8 \times 10^{-10} \; (m_{\rm DM}/\rm GeV)$$

Improves on previous limits by a factor ~ 10 previous limits [Bhoem'14].

IDM cosmo. imprint: delay reionization

imprint similar to [Sitwell'14, Bose'16, Safarzadeh'18, Lidz'18, Schneider'18] and
for different approach [Barkana'01, Somerville'03,Yoshida'03, Yue'12, Schultz'14, Dayal '14+, Rudakovskyi'16, Lovell'17]

- 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:

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

IDM cosmo. imprint: delay reionization

imprint similar to [Sitwell'14, Bose'16, Safarzadeh'18, Lidz'18, Schneider'18] and
for different approach [Barkana'01, Somerville'03,Yoshida'03, Yue'12, Schultz'14, Dayal '14+, Rudakovskyi'16, Lovell'17]

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

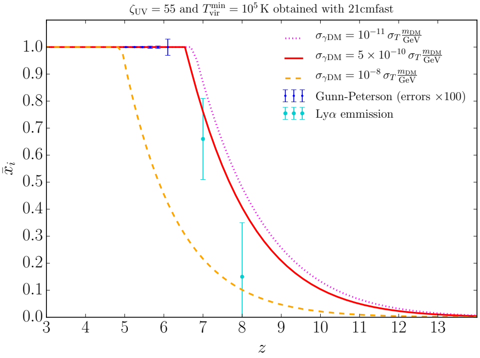
$$\bar{x}_i \approx \zeta_{UV} f_{\rm coll} \text{ with } f_{\rm coll} = f_{\rm coll}(> M_{\rm vir}^{\rm min}) = \int_{M_{\rm vir}^{\rm min}} \frac{M}{\rho_{m,0}} \frac{dn}{dM}\, dM\ .$$

- Optical depth to reionization:

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

Within our framework:

large $\sigma_{\gamma CDM}$ suppress structure formation at small scales
$\rightsquigarrow$ reduces $\bar{x}_i$
$\rightsquigarrow$ IDM can delay reionization
$\leftrightarrow$ low WDM m_X

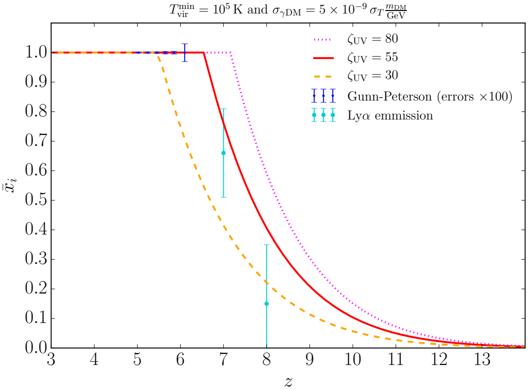


Astro degeneracies: Lower ζ_{UV} allow for higher $\sigma_{\gamma \mathrm{CDM}}$

The ionization efficiency ζ_{UV} parametrizes the number of ionizing photons per atom to be ionized. In the 21cmFast code, regions are ionized when $\zeta_{UV} f_{\mathrm{coll}} > 1$.

Astro degeneracies: Lower ζ_{UV} allow for higher $\sigma_{\gamma\mathrm{CDM}}$

The ionization efficiency ζ_{UV} parametrizes the number of ionizing photons per atom to be ionized. In the 21cmFast code, regions are ionized when $\zeta_{UV} f_{\mathrm{coll}} > 1$.



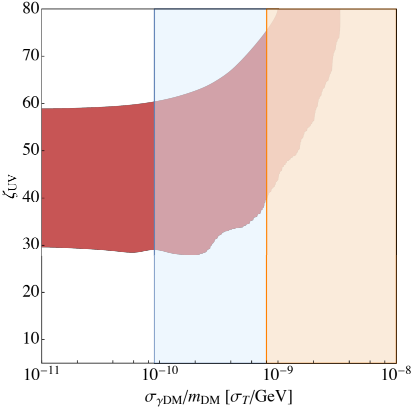
Important degeneracies between astro ζ_{UV} and IDM effects.

$\rightsquigarrow$ you can compensate higher $\sigma_{\gamma\mathrm{CDM}}$ effect with higher ζ_{UV}

see also [Sitwell'14, LLH'17] for WDM

Constraints from Reionization and N_{sat}

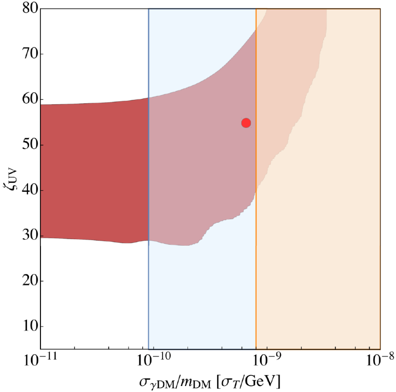
Final contour profiling over T_{vir} in red while vertical lines are the MW satellites constraints



Satellite nb count put the strongest constraints

Constraints from Reionization and N_{sat}

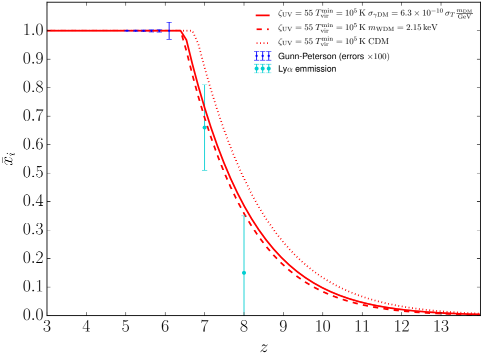
Final contour profiling over T_{vir} in red while vertical lines are the MW satellites constraints



Satellite nb count put the strongest constraints

Constraints from Reionization and N_{sat}

Final contour profiling over T_{vir} in red while vertical lines are the MW satellites constraints



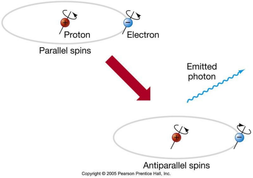
Satellite nb count put the strongest constraints

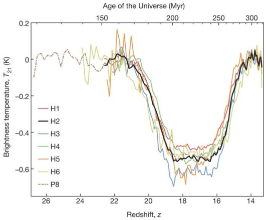
21cm Brightness temperature

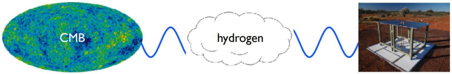
$$\delta T_b(\nu) \simeq 27\, x_{\rm HI}\,(1+\delta_b)\left(1-\frac{T_{\rm CMB}}{T_S}\right)\left(\frac{1}{1+H^{-1}\partial v_r/\partial r}\right)\left(\frac{1+z}{10}\right)^{1/2}\left(\frac{0.15}{\Omega_m h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\,\mathrm{mK}$$

Fraction of neutral H

Spin temperature= excitation T of 21cm line







Adapted from J. Pritchard

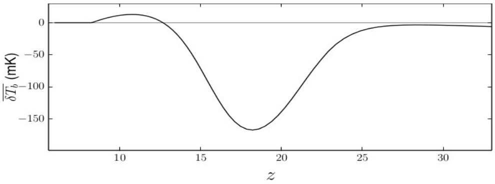
e.g., EDGES

21cm Brightness temperature

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

Fraction of neutral H

Spin temperature= excitation T of 21cm line

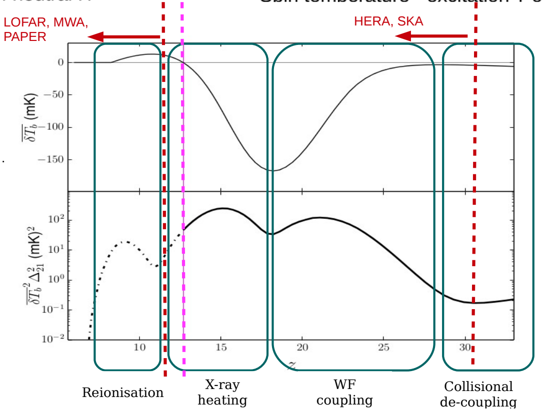


21cm Brightness temperature

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

Fraction of neutral H

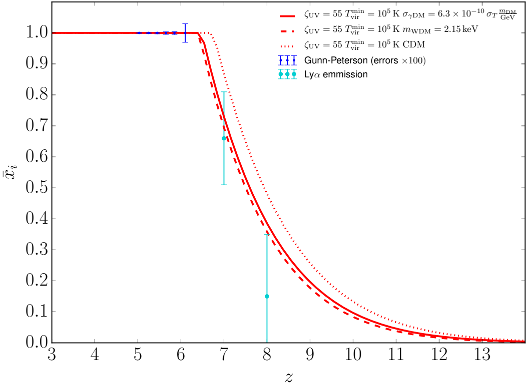
Spin temperature= excitation T of 21cm line



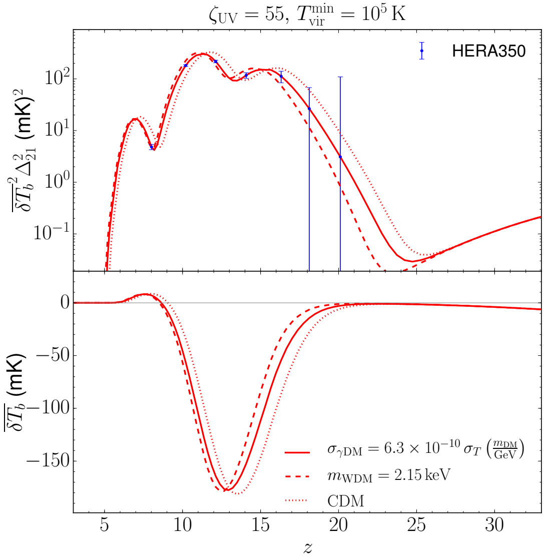
$$\langle\widetilde{\delta}_{21}(\mathbf{k},z)\widetilde{\delta}^*_{21}(\mathbf{k}',z)\rangle \equiv (2\pi)^3\delta^D(\mathbf{k}-\mathbf{k}')P_{21}(k,z) \qquad \Delta^2_{21}(k,z) = \frac{k^3}{2\pi^2}P_{21}(k,z)$$

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

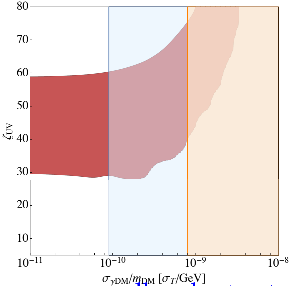
21cm could help to discriminate between Non-CDM



21cm could help to discriminate between Non-CDM

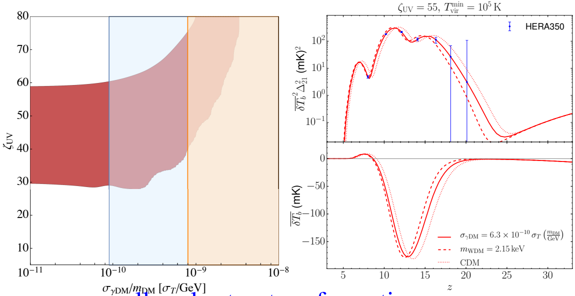


Conclusion: constraints on IDM as a NCDM scenario



- IDM can suppress small scale structure formation
  $\rightsquigarrow$ can affect sattelite nb. count, can delay reionization and 21cm signal
- Updated constraints from sattelite number count:
  $(\sigma_{\gamma DM}/\sigma_T) < 8 \times 10^{-10}\ (m_{DM}/\text{GeV})$. Similar constraints for $\sigma_{\nu DM}$ expected.

Conclusion: constraints on IDM as a NCDM scenario

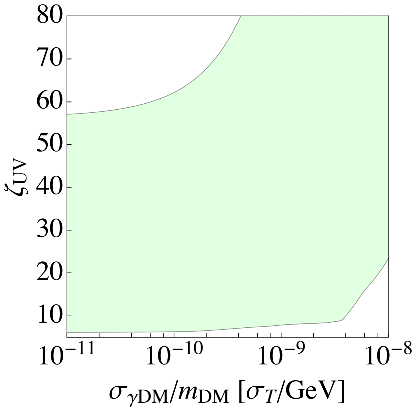


- IDM can suppress small scale structure formation
  ⇝ can affect sattelite nb. count, can delay reionization and 21cm signal
- Updated constraints from sattelite number count:
  $(\sigma_{\gamma DM}/\sigma_T) < 8 \times 10^{-10}\ (m_{DM}/\text{GeV})$. Similar constraints for $\sigma_{\nu DM}$ expected.
- Reionization parametrized as a function of a reduced set of astro parameters
  $\zeta_{UV}, T_{vir}^{min}$ give strong degeneracies with $\sigma_{\gamma DM}$
  ⇝ only a more modest bound on $\sigma_{\gamma DM}$ can be obtained.
- Same degeneracies to be expected for 21cm signal can provide the possibility to discriminate between the different NCDM models.

Thank you for your attention

Backup

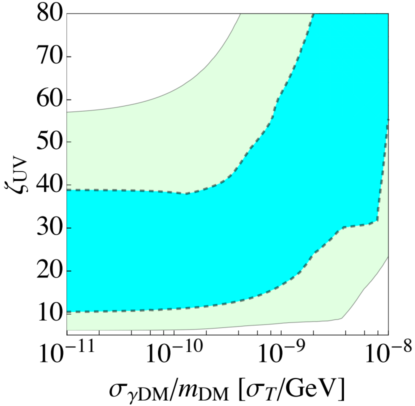
Reionisation Constraints at fixed T_{vir}^{min}



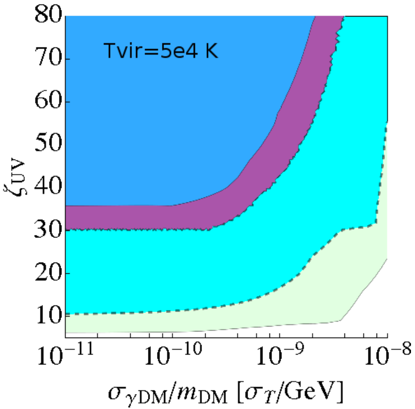
$T_{vir}^{min} = 5 \times 10^4 K$

Reionisation Constraints at fixed T_{vir}^{min}

$T_{vir}^{min} = 5 \times 10^4 K$



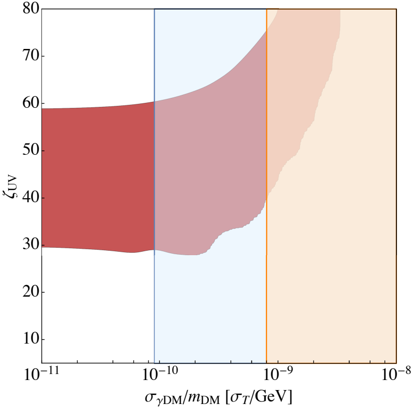
Reionisation Constraints at fixed T_{vir}^{min}



$T_{vir}^{min} = 5 \times 10^4 K$

Constraints from Reionization and N_{sat}

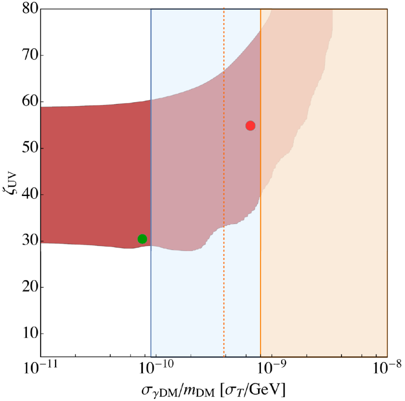
Final contour profiling over T_{vir} in red while vertical lines are the MW satellites constraints



Satellite nb count put the strongest constraints

Constraints from Reionization and N_{sat}

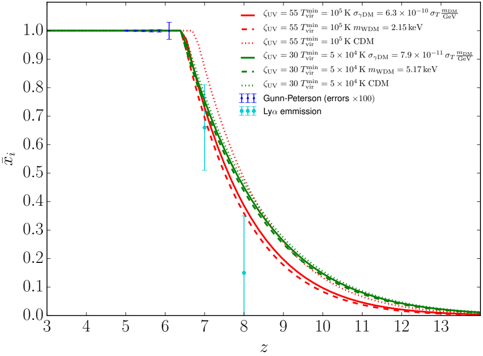
Final contour profiling over T_{vir} in red while vertical lines are the MW satellites constraints



Satellite nb count put the strongest constraints

Constraints from Reionization and N_{sat}

Final contour profiling over T_{vir} in red while vertical lines are the MW satellites constraints

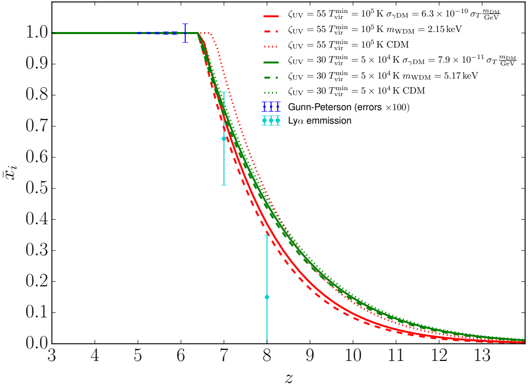


Satellite nb count put the strongest constraints

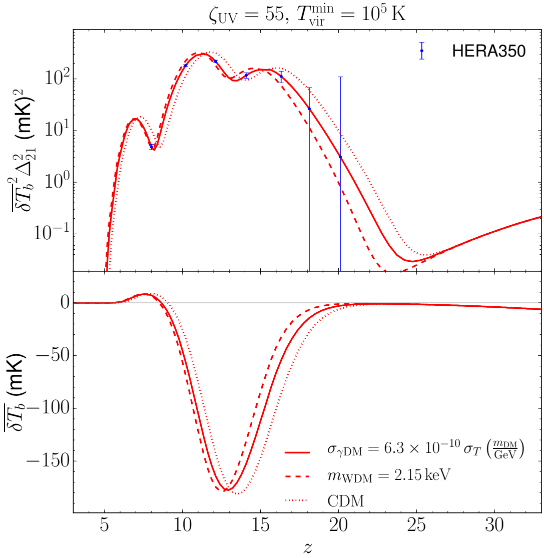
Benchmark models

	α_X [Mpc/h]	$M_{\rm hm}$ [$M_\odot$]	$\zeta_{\rm UV}$	$T_{\rm vir}^{\rm min}$ [K]	τ
$\sigma_{\gamma\rm DM} = 6.3 \times 10^{-10}(\sigma_T \times m_{\rm DM}/{\rm GeV})$ $m_{\rm WDM} = 2.15$ keV	0.0071	6.9×10^8	55	10^5	0.061 0.059
$\sigma_{\gamma\rm DM} = 7.9 \times 10^{-11}(\sigma_T \times m_{\rm DM}/{\rm GeV})$ $m_{\rm WDM} = 5.17$ keV	0.0020	3.5×10^7	30	5×10^4	0.064 0.063

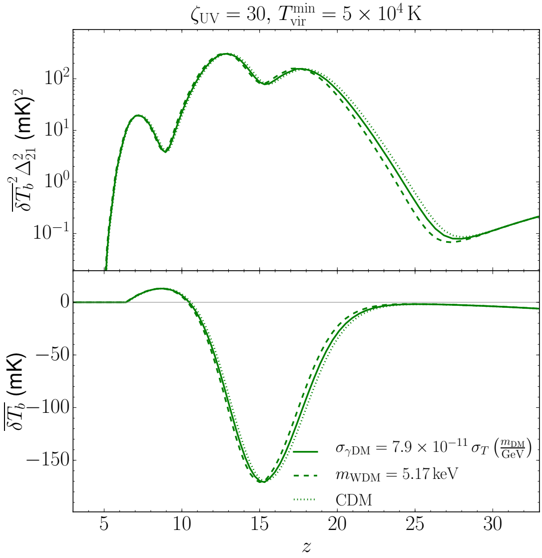
21cm could help to discriminate between Non-CDM



21cm could help to discriminate between Non-CDM

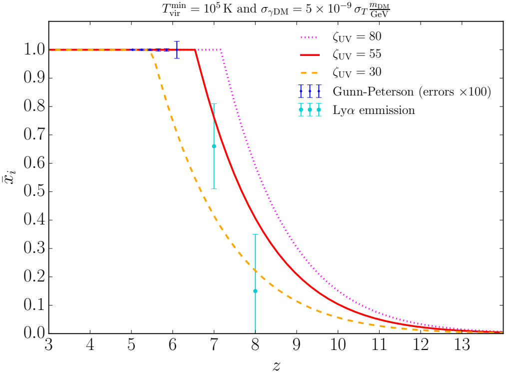


21cm could help to discriminate between Non-CDM



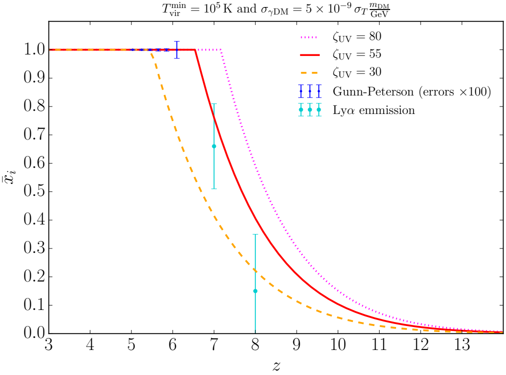
Astro degeneracies: Lower ζ_{UV} allow for higher $\sigma_{\gamma\mathrm{CDM}}$

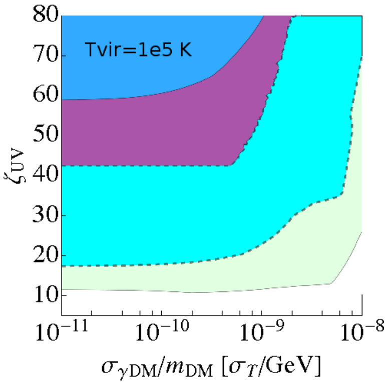
The ionization efficiency ζ_{UV} parametrizes the number of ionizing photons per baryons. In the 21cmFast code, regions are ionized when $\zeta_{UV} f_{\mathrm{coll}} > 1$.



Astro degeneracies: Lower ζ_{UV} allow for higher $\sigma_{\gamma\mathrm{CDM}}$

The ionization efficiency ζ_{UV} parametrizes the number of ionizing photons per baryons. In the 21cmFast code, regions are ionized when $\zeta_{UV} f_{\mathrm{coll}} > 1$.





Important degeneracies between astro ζ_{UV} and IDM effects.

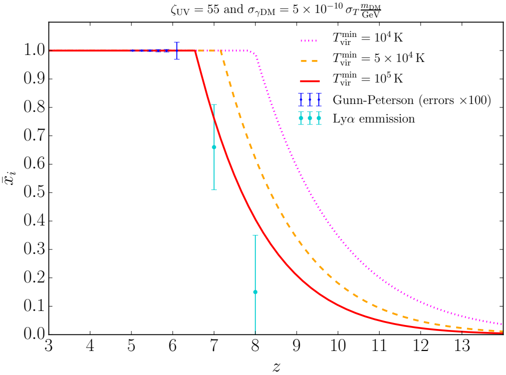
$\rightsquigarrow$ lower ζ_{UV} has similar effect than higher $\sigma_{\gamma\mathrm{CDM}}$

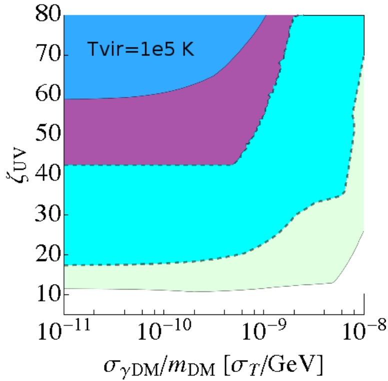
see also [Sitwell'14, LLH'17] for WDM

Astro degeneracies: Larger $T_{\rm vir}^{\rm min}$ allow for higher $\sigma_{\gamma\rm CDM}$

Threshold for halos hosting star-forming galaxies: $f_{\rm coll}(> M_{\rm vir}^{\rm min}) = \int_{M_{\rm vir}^{\rm min}} \frac{M}{\rho_{m,0}} \frac{dn}{dM}\, dM$

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

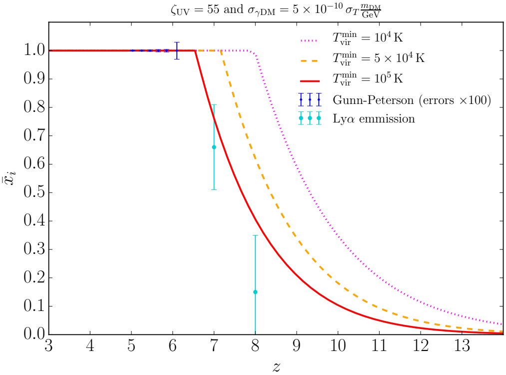


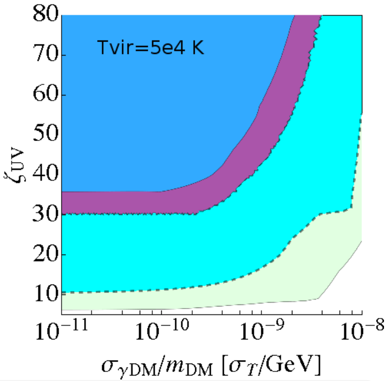


Astro degeneracies: Larger $T_{\rm vir}^{\rm min}$ allow for higher $\sigma_{\gamma{\rm CDM}}$

Threshold for halos hosting star-forming galaxies: $f_{\rm coll}(> M_{\rm vir}^{\rm min}) = \int_{M_{\rm vir}^{\rm min}} \frac{M}{\rho_{m,0}} \frac{dn}{dM}\, dM$

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





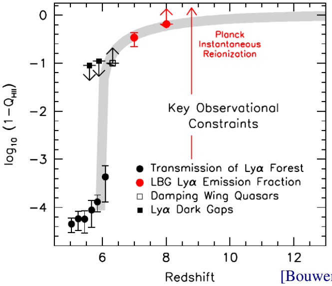
lower $T_{\rm vir}^{\rm min}$ ⇝ earlier reionization

⇝ shifts 95% CL contours to lower ζ_{UV}

IDM collisional damping imprint on N_{sat}, EoR and 21cm

IN THIS TALK:

- IDM collisional damping
  $\rightsquigarrow$ effect on
  Epoch of Reionization (EoR)
  and the number of satellites?
- Satellites: $N_{\rm gal} > 85$ at 95% CL across the entire sky [Newton'17]
- EoR: constraints from Lyα emmission, Gunn Peterson effect, and Planck optical depth



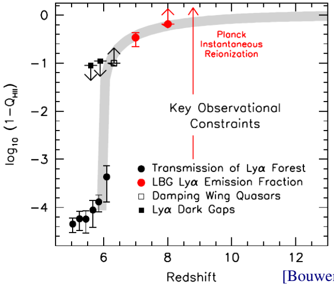
[Bouwens'15]

IDM collisional damping imprint on N_{sat}, EoR and 21cm

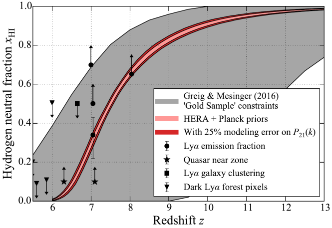
IN THIS TALK:

- IDM collisional damping
  ⇝ effect on
  Epoch of Reionization (EoR)
  and the number of satellites?
- Satellites: $N_{\rm gal} > 85$ at 95% CL across the entire sky [Newton'17]
- EoR: constraints from Lyα emmission, Gunn Peterson effect, and Planck optical depth

Notice that understanding of EoR is expected to improve with (near) future cosmo probe ≡ 21cm signal
⇝ imprint on 21cm Cosmology?



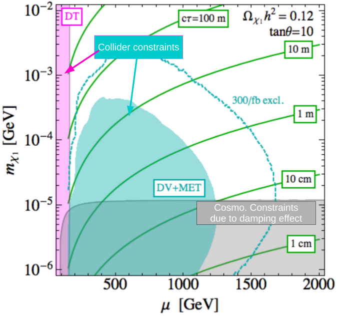
[Bouwens'15]



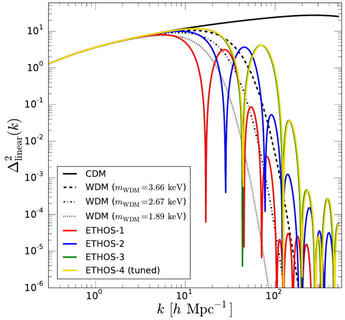
HERA 2020 set-up [DeBoer'16]

other "Non-CDM" models with damping effect

Also for non thermal DM with non-negligible velocity dispersion or DM interacting dark relativistic degrees of freedom:



Freeze-in [Calibbi'18], see also Goudelis talk



DM- dark radiation [VogelsBerger'15], see also D. Hooper talk

Towards generalized fit to non-CDM (IDM included)? [Murgia'17,18]

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

Lyα forest and MW satellite count constraints

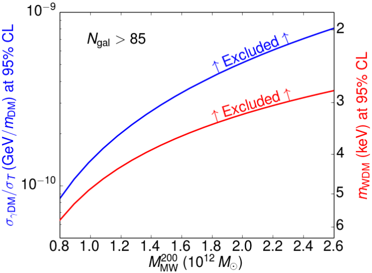
Caveats

- HMF considered validated at $z = 0$ only see e.g. [Moline'16] $\rightsquigarrow$ needs simu to larger z.
- What 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]
- Lack of minihaloes in WDM could suppress the average number of recombination/H atom $\rightsquigarrow$ WDM get earlier/similar reionization than CDM [Barkana'01, Somerville'03,Yoshida'03, Yue'12, Schultz'14, Dayal '14+, Rudakovskyi'16].
- 1st galaxies to form more massive& more gaz rich in NCDM $\rightsquigarrow$ larger nb. of ioniz. γ compensate the halo suppressed formation see [Lovell'17, Bose'16-17, Dayal'17]
- etc

Number of MW Satellites

Number of discovered MW satellites extrapolated to the entire sky $N_{\rm gal} > 85$ at 95% CL [Newton'17] $N_{\rm gal} = \int_{M_{\rm min}}^{M_{\rm host}} \frac{dN}{dM} f_{\rm lum}(M)\, dM$

- $\frac{dN^{\rm CDM}}{dM^{\rm peak}} = K_0 \left(\frac{M^{\rm peak}}{M_\odot}\right)^{-\chi} \frac{M_{\rm host}}{M_\odot}$ [Dooley'16]. with $K_0 = 1.88 \times 10^{-3}\, M_\odot^{-1}$ and $\chi = 1.87$.
- $\frac{dN}{dM}^{\rm IDM} = \left(1 + \frac{M_{\rm hm}}{b\,M}\right)^a \left(1 + \frac{M_{\rm hm}}{g\,M}\right)^c \frac{dN}{dM}^{\rm CDM}$, with $a = -1$, $b = 0.33$, $g = 1$, $c = 0.6$ and $M = M(z=0)$ and $(M/M_\odot) = (M^{\rm peak}/M_\odot)^{0.965}$ [Garrison-Kimmel'13].
- $\frac{dN}{dM}^{\rm WDM} = \left(1 + g_s \frac{M_{\rm hm}}{M}\right)^{-b_s} \frac{dN}{dM}^{\rm CDM}$, where $g_s = 2.7$, $b_s = 0.99$. [Lovell'13].



Suppression of power at small scale: 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}

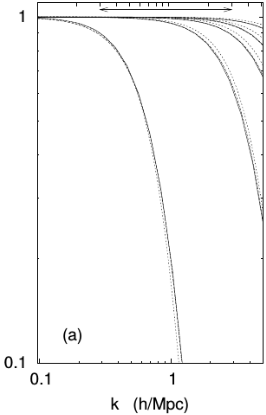
Suppression of power at small scale: linear regime

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}
- Assuming thermal WDM [Viel'05]

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

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

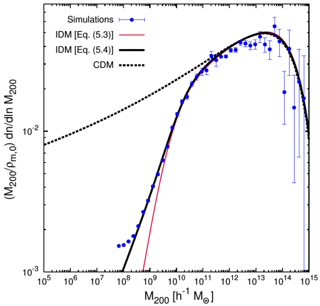


[Viel'05]

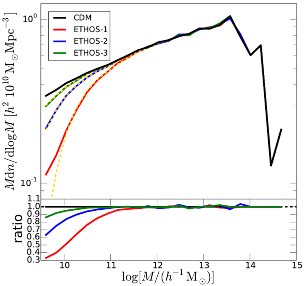
$$\alpha = 0.049 \left(\frac{\rm keV}{m_X}\right)^{1.11} \left(\frac{\Omega_X}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22} \ {\rm Mpc}/h$$

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

(S)IDM: 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]

[Baur'17]

WDM solution to CDM problems?

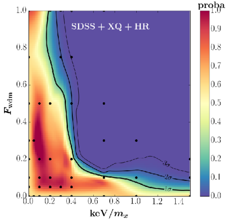
- WDM can potentially provide partial solutions but strongly challenged by Lyα forest constr. $\rightsquigarrow m_X > 4.65$ keV (at 95%CL)

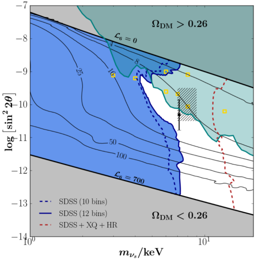
  [Yèche 17] see also [Viel'13, Baur'15, Irsik 17]

- 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)

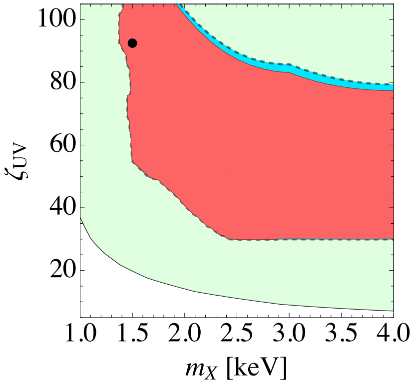
all constraints from SDSS Ly-α QSO spectra BUT depends on T_{IGM} description!
HiRes $\rightsquigarrow$ good fit $m_X \simeq$ 2-3 keV [Garzilli'13], max lik. $m^{rp}_{\nu_s} \simeq 8$ keV [Baur'17]





[Baur'17]

Final contours WDM



⇝ modest lower bound: $m_X > 1.4$ keV at 90% CL

constraints on T_{IGM} could provide extra constraints on m_X

Top hat versus sharp k cutoff scale for γCDM

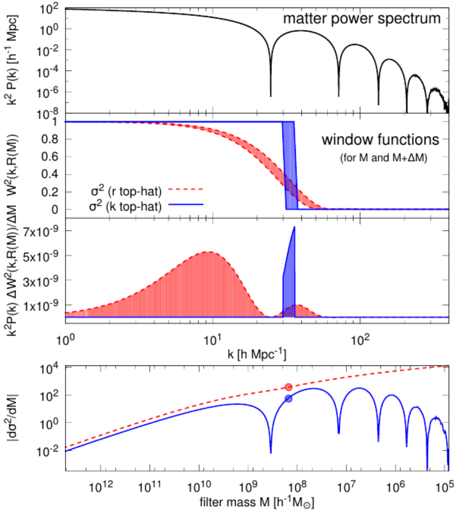


Figure 4. Real-space and k-space top-hat window functions in Press-Schechter HMF predictions for γCDM. The upper panel shows the matter power spectrum, while the second panel shows the Fourier transform of the two window functions (r top-hat and k top-hat). Each window function is evaluated for two filter 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.

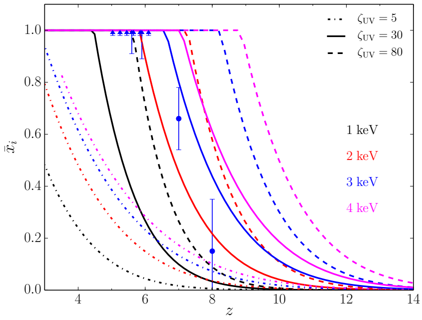
$\rightsquigarrow$ with r-top hat filter (TH) a large number of un-suppressed small k scales contribute to $\sigma(M)$

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

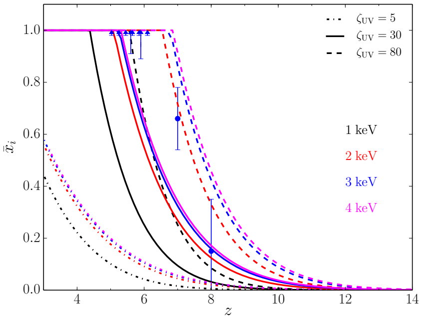
[Schewtschenko'14]

WDM imprint on ionized fraction

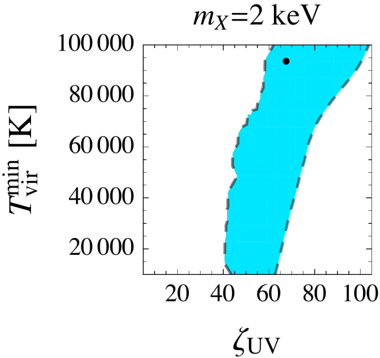
$T_{vir}^{min} = 10^4$K

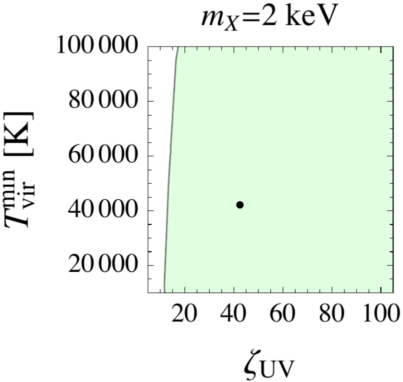


$T_{vir}^{min} = 10^5$K

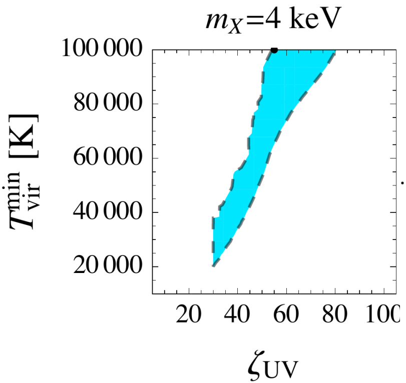


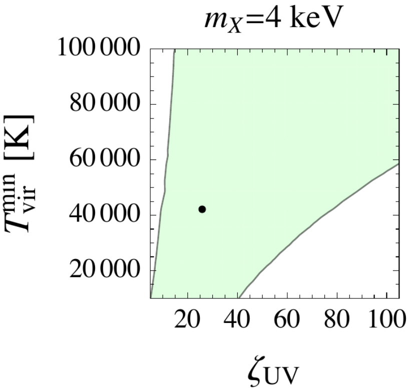
Fixed WDM mass and full contours





Fixed WDM mass and full contours





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

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 $\rightsquigarrow$ 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

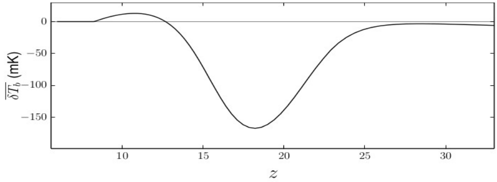
- Scattering of CMB photons
  if CMB alone $\rightsquigarrow$ thermalisation $T_S = T_{CMB}$ $\rightsquigarrow$ IGM unobservable
- Atomic collisions with H, p or e^- (when IGM is dense, dark ages)
- Scattering of Lyα photons $\equiv$ Wouthuysen-Field (WF) effect (once early radiation sources light on)

  $\rightsquigarrow$ 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

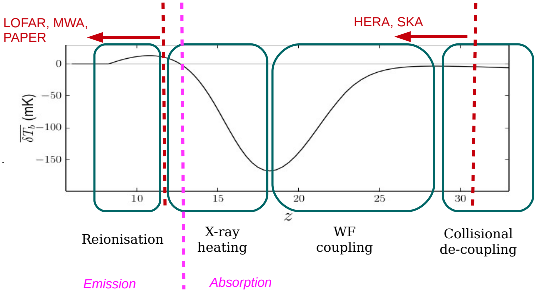


δT_b and Δ_{21} obtained using 21cm Fast [Mesinger'10]

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

Fraction of neutral H

Spin temperature= excitation T of 21cm line

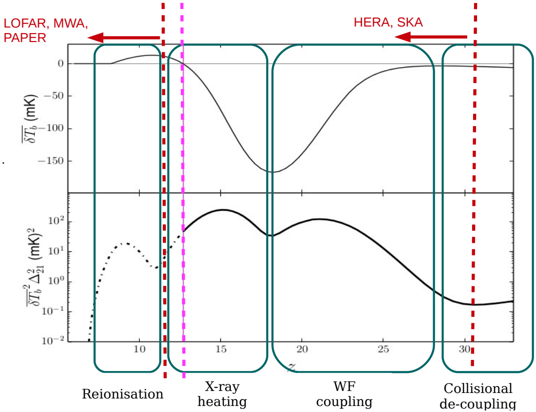


δT_b and Δ_{21} obtained using `21cm Fast` [Mesinger'10]

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

Fraction of neutral H

Spin temperature= excitation T of 21cm line

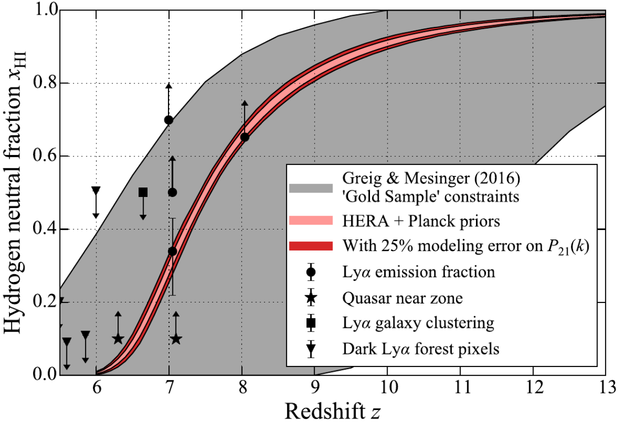


$$\langle\widetilde{\delta}_{21}(\mathbf{k},z)\widetilde{\delta}^*_{21}(\mathbf{k}',z)\rangle \equiv (2\pi)^3\delta^D(\mathbf{k}-\mathbf{k}')P_{21}(k,z) \qquad \Delta^2_{21}(k,z) = \frac{k^3}{2\pi^2}P_{21}(k,z)$$

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

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

HERA reach on x_{HI}



[De Boer'16]

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

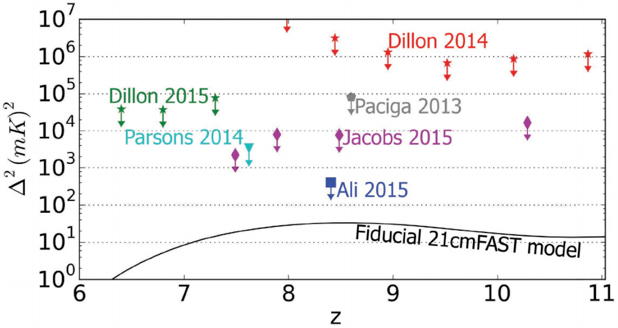


Figure 9. The current best published 2σ upper limits on the 21cm power spectrum, $\Delta^2(k)$, compared to a 21cmFAST-generated model at $k = 0.2\, h\, \mathrm{Mpc}^{-1}$. Analysis is still underway on PAPER and MWA observations that approach their projected full sensitivities; HERA can deliver sub-mK^2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

[De Boer'16]

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

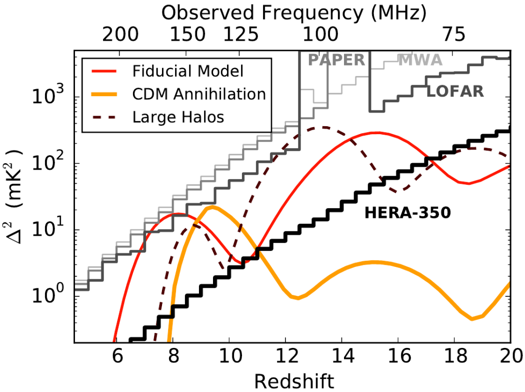


Figure 4. 1σ thermal noise errors on $\Delta^2(k)$, the 21 cm power spectrum, at $k = 0.2\, h\,\mathrm{Mpc}^{-1}$ (the dominant error at that k) with 1080 hours of integration (black) compared with various heating and reionization models (colored). Sensitiv-

[De Boer'16]

Resonant scattering of Lyα photons

Cause spin flip transitions

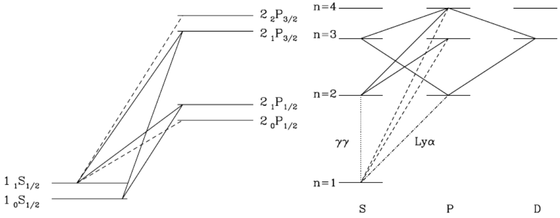


Figure 2. *Left panel:* Hyperfine structure of the hydrogen atom and the transitions relevant for the Wouthuysen-Field effect [24]. Solid line transitions allow spin flips, while dashed transitions are allowed but do not contribute to spin flips. *Right panel:* Illustration of how atomic cascades convert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

[Pritchard'11]

title

This is really the end