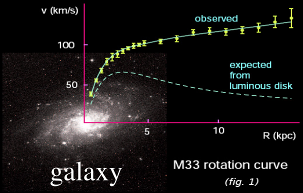
Interacting dark matter vs Warm Dark matter

...or collisional damping vs free streaming

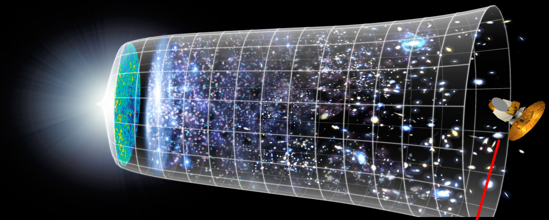
Laura Lopez Honorez

based on **JCAP 1806 (2018) no.06, 007 and Phys. Rev. D 99, 023522 (2019)**
in collaboration with M. Escudero, O. Mena, S. Palomares-Ruiz
& P. Villanueva Domingo

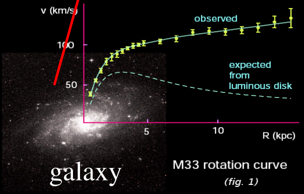
Seminar at IPPP Durham



The Quest to determine the Composition of our Universe



Dark matter



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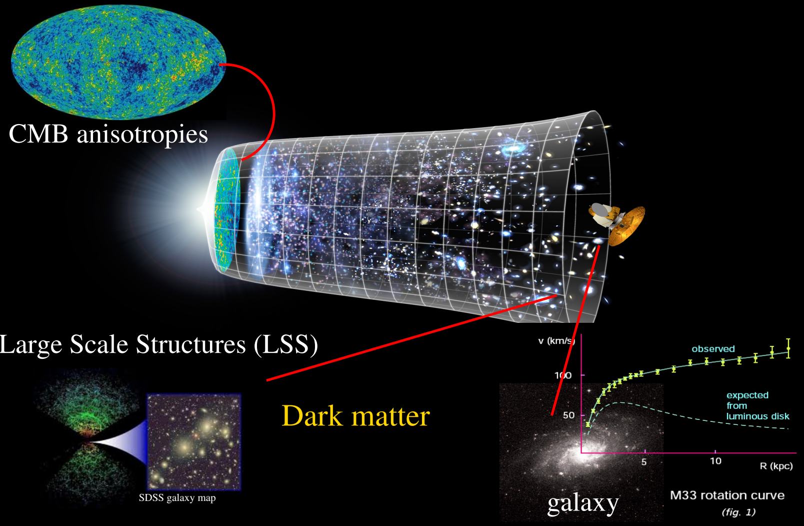

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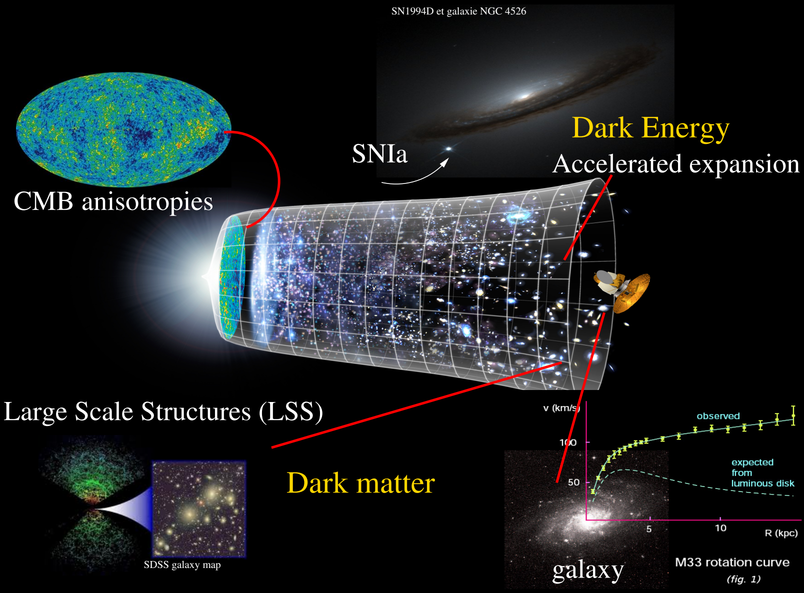

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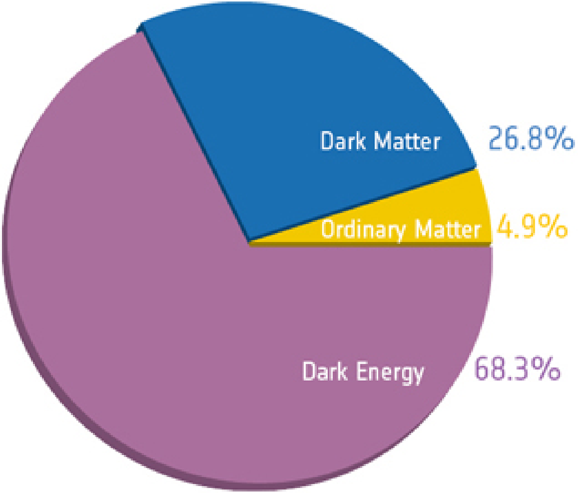

80% of the matter content is made of Dark Matter

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]
- Too big to fail: [Boylan'11, Papastergis'15] subaloes hosting dwarf galaxies are too massive to account for the galactic rotation curves ($V_{circ}(r)$ too large)
- 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]
- Diversity of (inner) rotation curves [Oman'15] $V_{circ}(R)$ is not fixed by V_{max}

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Proposed (partial) 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)

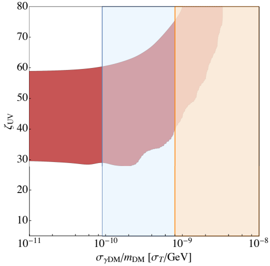
    see [Boehm'00+, Cyr-Racine'12+,Bringman'12+,Buckley'14,etc]
  - also SIDM, fuzzy DM, sterile neutrinos, mixed DM, freeze-in DM

    see e.g. [Murgia'17,18]

Non Cold Dark Matter: imprint and constraints/prospects

IN THIS TALK:

- Satellites, Reionization and NCDM
  - Non Cold DM suppress power on small scales
    $\rightsquigarrow$ delay reionization + MSP



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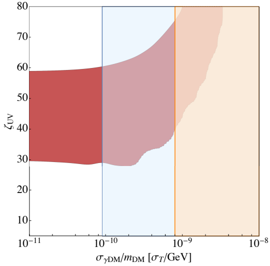
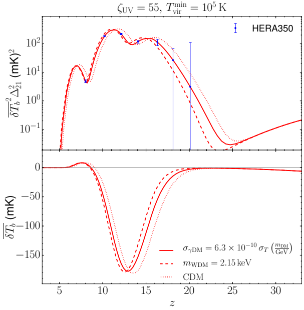
- 21cm and NCDM
  - NCDM also delay in 21cm features
  - Can help to disentangle WDM from IDM

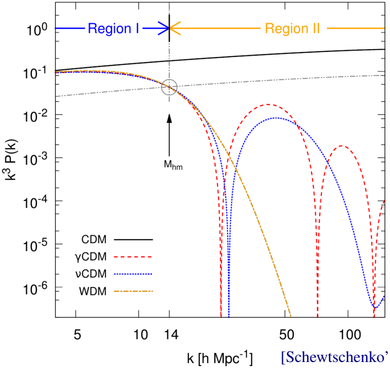




NCDM description

NCDM 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 (depend distance traveled by coll. particles during random walk)



[Schewtschenko'14

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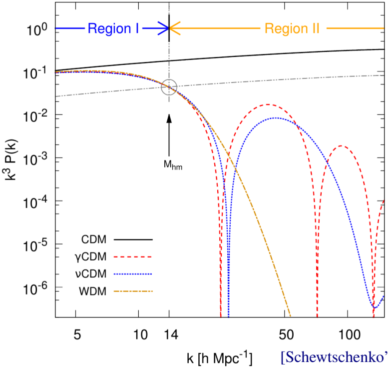
$$\begin{aligned} T_X(k) &= (P_X(k)/P_{CDM}(k))^{1/2} \\ &= (1 + (\alpha_X k)^{2\nu})^{-5/\nu} \end{aligned}$$

with $\nu = 1.2$ and define the scales

- $\alpha_{IDM} \propto (\sigma_{IDM}/m_{DM})^{0.48}$ [Bhoem'01]
  for IDM with γ induced damping
  $\alpha_{WDM} \propto (1/m_{WDM})^{1.15}$ [Bode'00]
- half mode mass : $T_X(k_{hm}) = 1/2$
  $\rightsquigarrow M_{hm} = M_{hm}(\sigma_{IDM}/m_{DM})$ or $M_{hm}(m_{WDM})$



[Schewtschenko'14]

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

NCDM 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.:

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

- We use the first crossing distribution $f(\sigma)$ of Sheth & Tormen [ST'99+].
- $\sigma^2 = \sigma^2(P_{lin}(k), W(kR))$ is the variance of linear perturb. smoothed over $R(\leftrightarrow M)$

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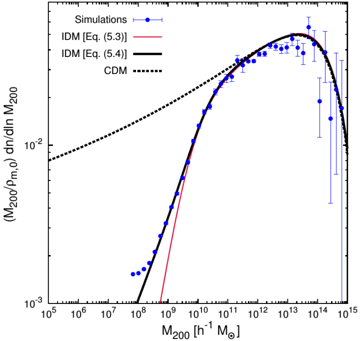
- from CDM to Non-Cold DM [Schneider'12, Bhoem'14, Moline'16]

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



[Moline'16]

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

IDM (and WDM) reionization and satellites constraints

Number of MW Satellites

we worked with a number of 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]

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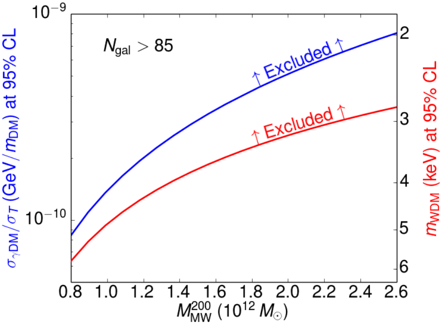
$$N_{\rm gal} = \int_{M_{\rm min}}^{M_{\rm host}} \frac{dN_{sub}}{dM} f_{\rm lum}(M)\, dM$$

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

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

- $f_{\rm lum}(M)$ fraction of subhalo of a given mass hosts a luminous galaxy. We use [Dooley'16].



$$(\sigma_{\rm IDM}/m_{\rm DM}) < 8 \times 10^{-10}\; (\sigma_T/{\rm GeV})$$
$$m_{WDM} < 2.8\ {\rm keV}$$

Improves on $\sigma_{\rm IDM}$ previous limits by a factor ~ 10 [Bhoem'14].

NCDM 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:

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

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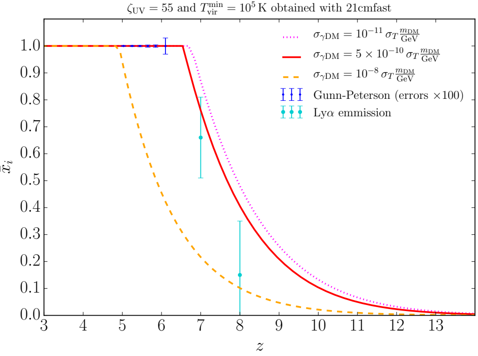
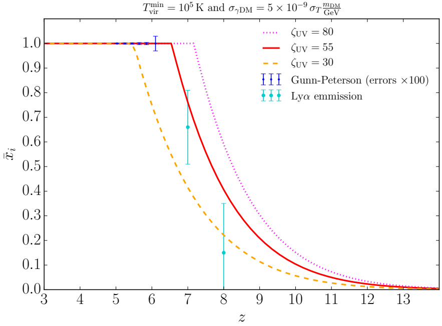
Within our framework:

NCDM can suppress structure formation at small scales
⇝ reduces $\bar{x}_i$
⇝ can delay reionization
for low WDM $m_{\rm WDM}$ or large $\sigma_{\rm IDM}$



Astro degeneracies: $\zeta_{UV}, T_{vir}^{min}$ allow for higher/lower $\sigma_{\gamma\mathrm{CDM}}$

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



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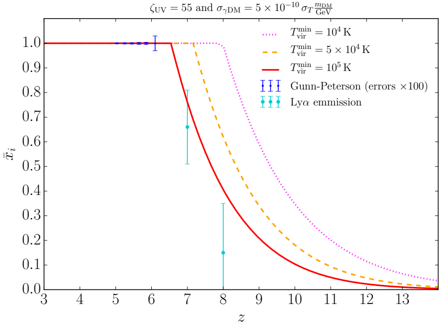
Threshold for halos hosting star-forming galaxies:

$$f_{\mathrm{coll}}(> M_{\mathrm{vir}}^{\mathrm{min}}) = \int_{M_{\mathrm{vir}}^{\mathrm{min}}} \frac{M}{\rho_{m,0}} \frac{dn}{dM}\, dM \text{ and } M_{\mathrm{vir}}^{\mathrm{min}}(z) \simeq 10^8 \left(\frac{T_{\mathrm{vir}}^{\mathrm{min}}}{2\times 10^4\ \mathrm{K}}\right)^{3/2} \left(\frac{1+z}{10}\right)^{-3/2} M_\odot$$

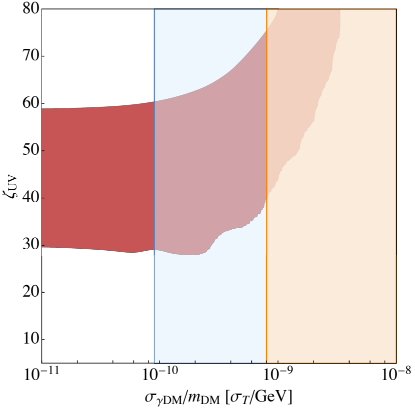


Important degeneracies between astro $\zeta_{UV}, T_{\mathrm{vir}}^{\mathrm{min}}$ and IDM effects.

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

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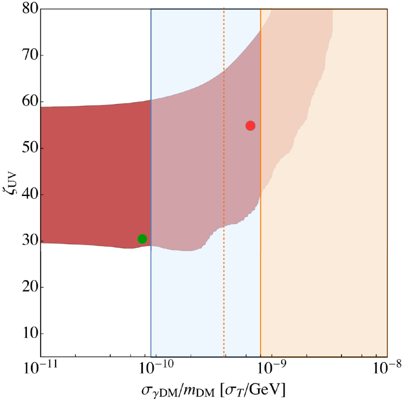

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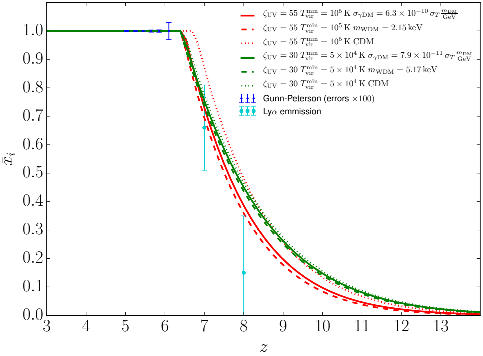

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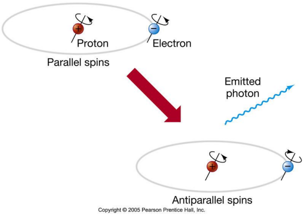
IDM (and WDM) imprint on 21cm signal

21 cm signal?



- Transitions between the two ground state energy levels of neutral hydrogen HI $\rightsquigarrow$ 21 cm photon ($\nu_0 = 1420$ MHz)

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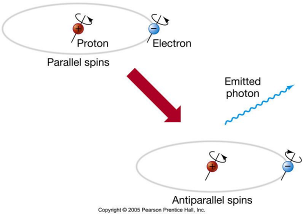
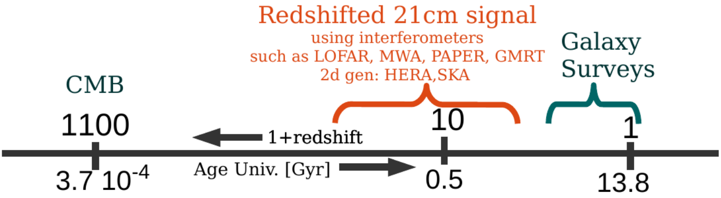
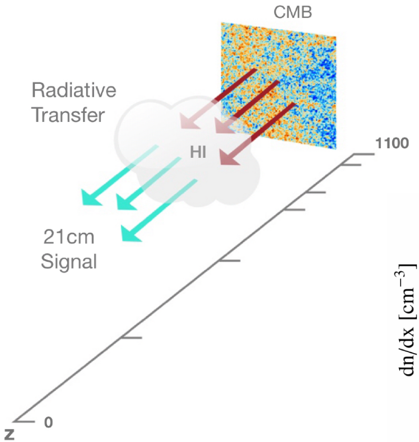


- Transitions between the two ground state energy levels of neutral hydrogen HI $\rightsquigarrow$ 21 cm photon ($\nu_0 = 1420$ MHz)
- 21 cm photon from HI clouds during dark ages & EoR redshifted to $\nu \sim 100$ MHz $\rightsquigarrow$ new cosmology probe

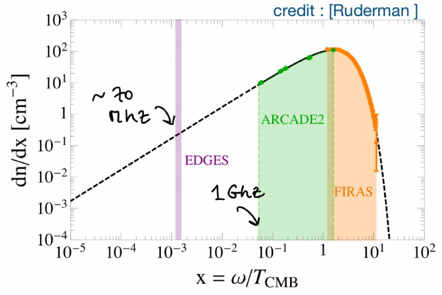


21 cm in practice



credit : [Kovetz]

- 21cm signal observed as CMB spectral distortions



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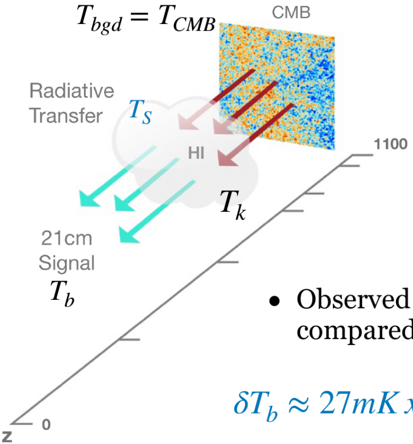

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- 21cm signal observed as CMB spectral distortions
- The spin temperature (= excitation T of HI) charaterises the relative occupancy of HI gnd state

$$n_1/n_0 = 3\exp(-h\nu_0/k_B T_S)$$

- Observed brightness of a patch of HI compared to CMB at $\nu = \nu_0/(1+z)$

$$\delta T_b \approx 27mK\, x_{HI}(1+\delta)\sqrt{\frac{1+z}{10}}\left(1 - \frac{T_{CMB}}{T_S}\right)$$

The spin temperature

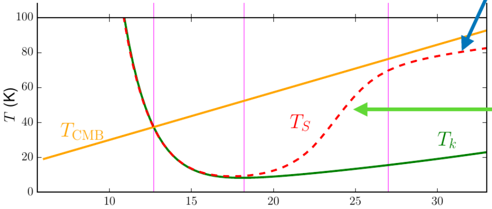
$$T_S^{-1} = \frac{T_{CMB}^{-1} + x_c T_k^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha}$$

Emmission/ absorption of CMB photons

$T_S \rightarrow T_{CMB}$

- Collisions with H, e
- Scattering of Ly-α photons (Wouthuysen-Field effect)

$T_S \rightarrow T_k$



$T(K)$ and δT_b obtained using `21cm Fast` [Mesinger'10]

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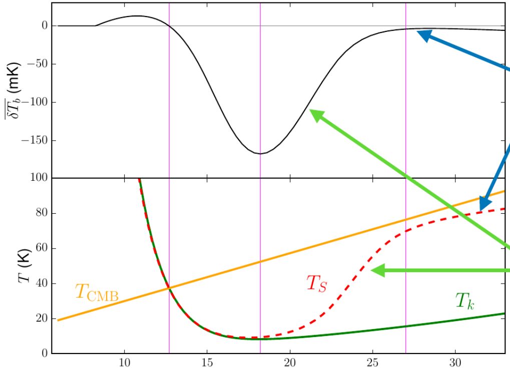

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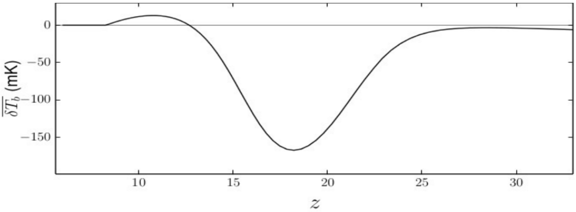

δT_b and Δ_{21} obtained using `21cm Fast` [Mesinger'10]

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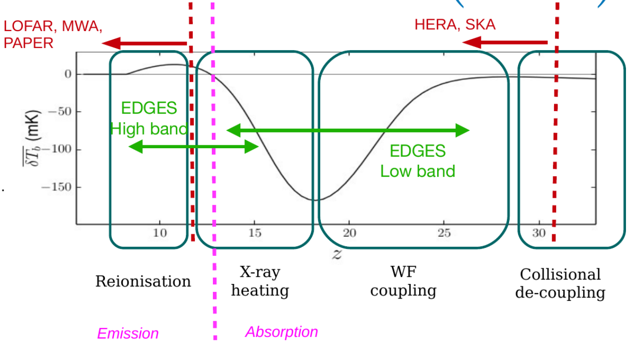

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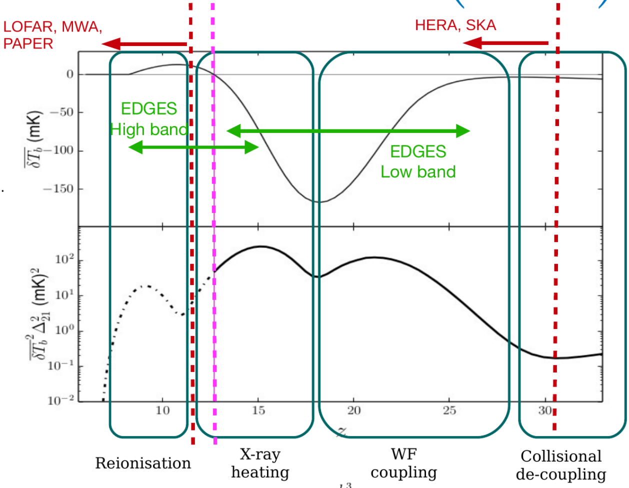


$$\langle \widetilde{\delta}_{21}(\mathbf{k},z)\widetilde{\delta}^*_{21}(\mathbf{k}',z)\rangle \equiv (2\pi)^3\delta^D(\mathbf{k}-\mathbf{k}')P_{21}(k,z) \qquad \Delta^2_{21}(k,z) = \frac{k^3}{2\pi^2}P_{21}(k,z)$$

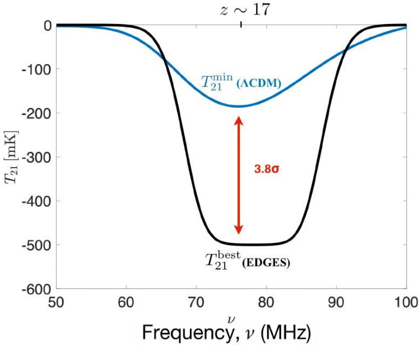
δT_b and Δ_{21} obtained using `21cm Fast` [Mesinger'10]

EDGES and compatibility with NCDM

EDGES result of observation

- First detection of an absorption trough at 78+/-1 Mhz (z~17) with amplitude $0.5^{+0.2}_{-0.5}$K at 99% CL
- Stronger absorption than predicted

  $T_{CMB}/T_S > 15$ instead of 7
- Needs a larger bgd radiation temperature or a lower gas temperature as $T_S^{min} \sim T_K$



[credit: Kovetz] see also [Bowman18, Barkana18]

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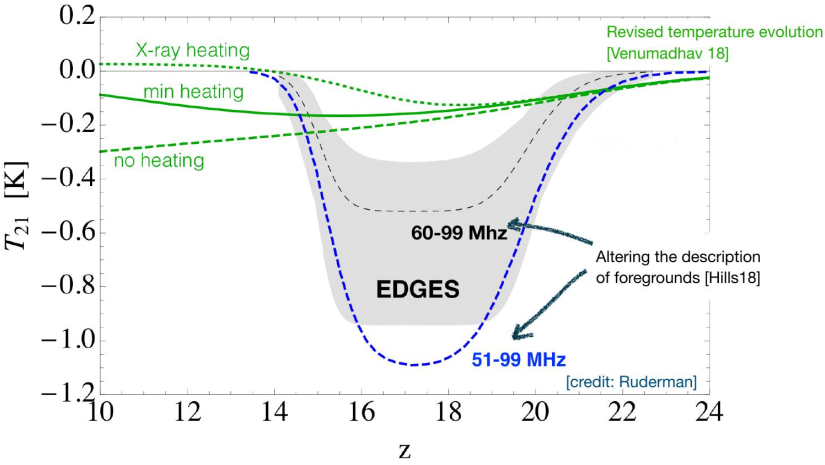


Imprint of NCDM

Halo suppression leads to delayed astro processes giving rise to 21cm features. Can be constrained by:

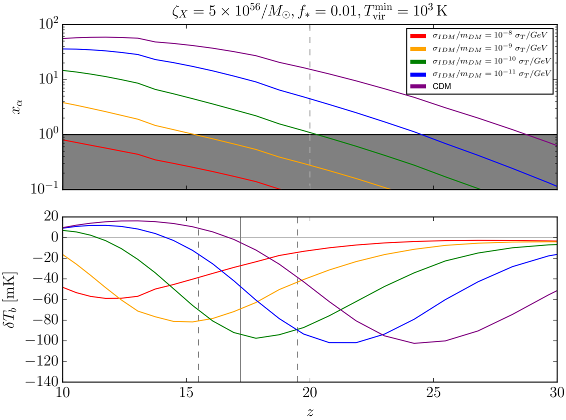
- imposing large enough Ly-α coulping [Lidz'18]

$$x_\alpha(z=20) \gtrsim 1$$

$$\delta T_b \propto \left(1-\frac{T_{\rm CMB}}{T_{\rm S}}\right) = \frac{x_{tot}}{1+x_{tot}}\left(1-\frac{T_{\rm CMB}}{T_k}\right)$$

- imposing early enough absorption [Schneider'18]

$$z(\delta T_b^{min}) > 17.2$$



Beware important degeneracies with T_{vir}^{min},f_* and ζ_X

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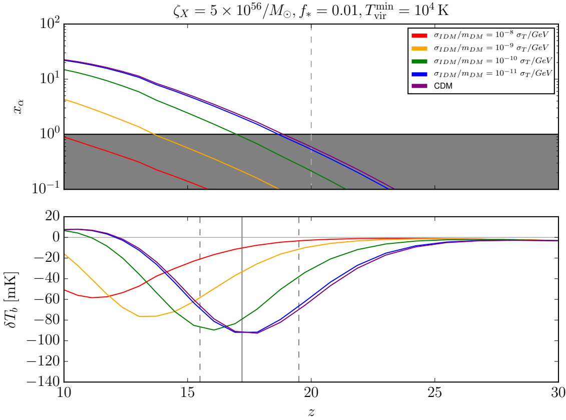

Beware important degeneracies with T_{vir}^{min}, f_* and ζ_X

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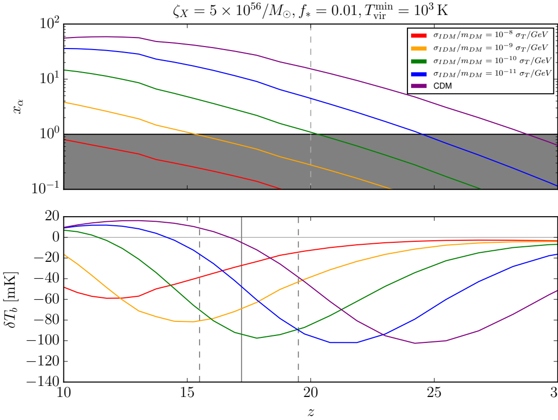

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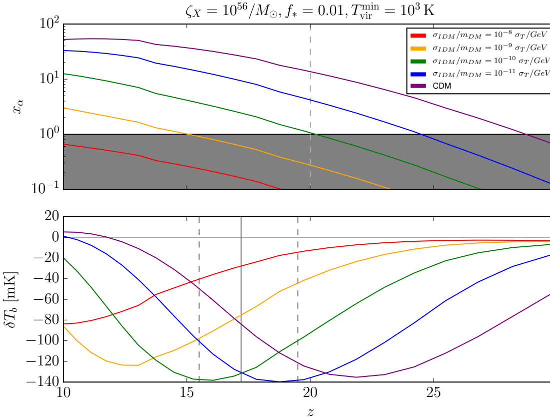

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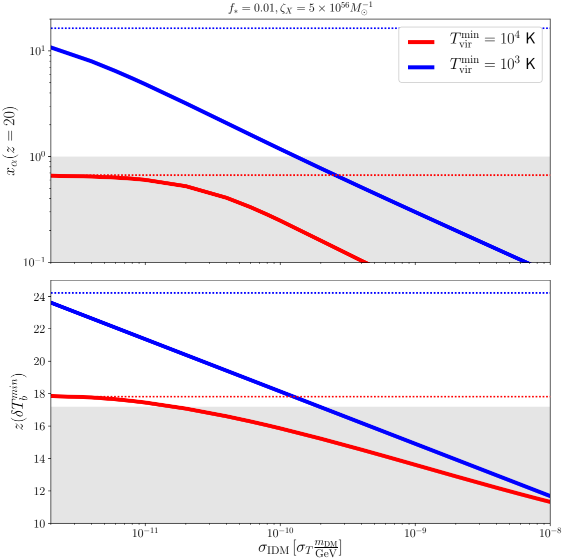
Constraints on NCDM from EDGES

- If the EDGES signal is confirmed for a fixed astro setup 21 cm can provide stringent constraints on NCDM [see also Safarzadeh'18, Lidz'18, Schneider'18]
- To be compared with existing limits from Lyα forest [Yeche 17]

$$m_{WDM} > 4.65\,\mathrm{keV}$$

and Satellite number count:

$$\sigma_{IDM} < 8\times10^{-10}(m_{DM}/GeV)$$



Can be relaxed for larger f_* !

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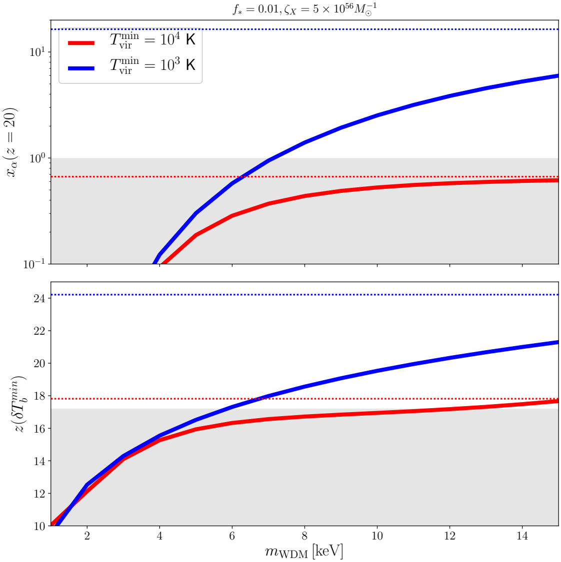
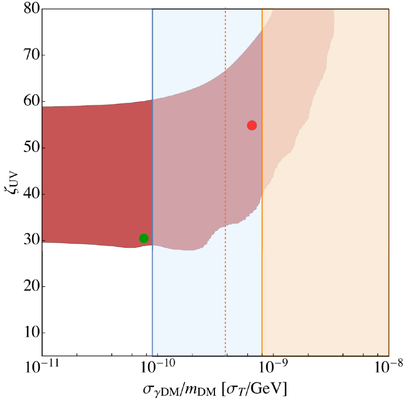


Future prospects for 21cm cosmology

21cm could help to discriminate between Non-CDM



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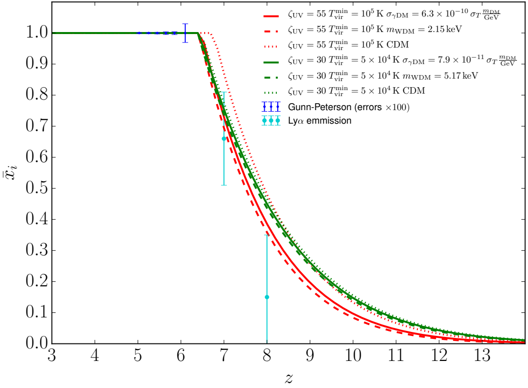

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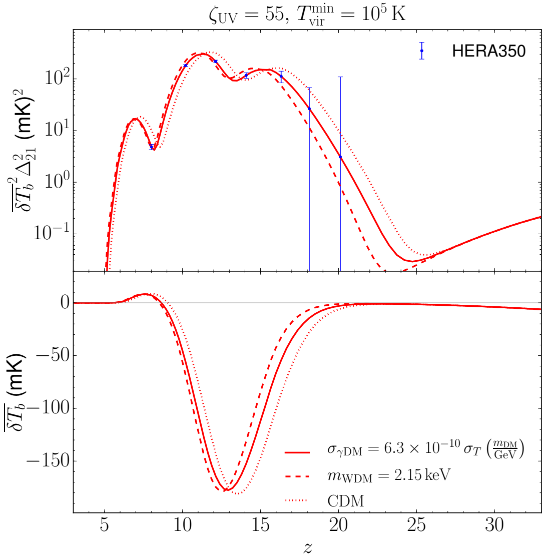

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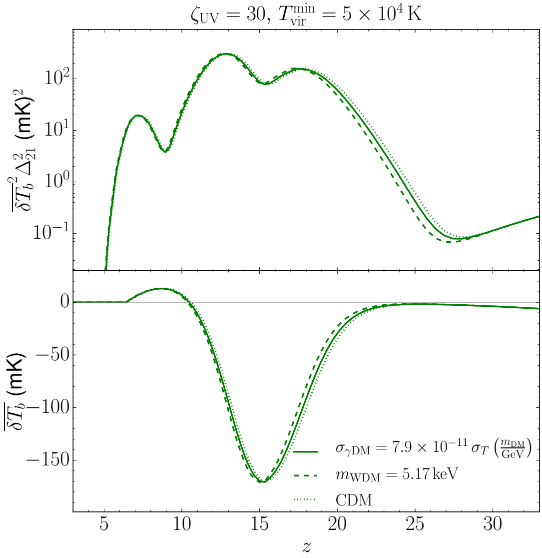
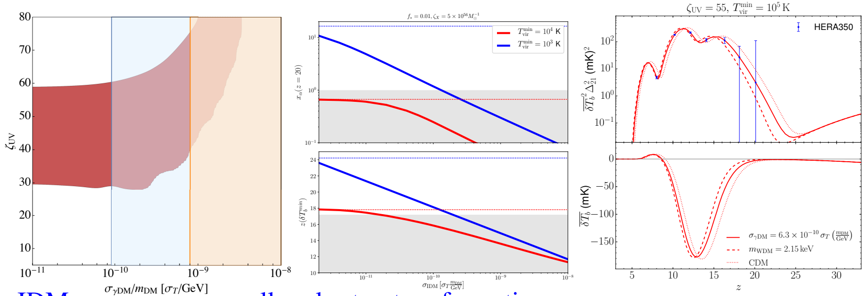


Caveats

- HMF considered validated at $z = 0$ only see e.g. [Moline'16] $\rightsquigarrow$ needs simu to larger z. See however [Schneider'18] for $z > 0$.
- 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

Conclusion: constraints on NCDM scenario



- IDM can suppress small scale structure formation
  $\rightsquigarrow$ can affect satellite nb. count, can delay reionization and 21cm signal
- Updated constraints from satellite number count:
  $(\sigma_{IDM}/\sigma_T) < 8\times10^{-10}\ (m_{DM}/\mathrm{GeV})$. Similar constraints for $\sigma_{\nu DM}$ expected.
- Reionization: $\zeta_{UV}, T_{vir}^{min}$ give strong degeneracies with σ_{IDM}
  $\rightsquigarrow$ only a more modest bound on σ_{IDM} can be obtained.
- 21cm: degeneracies with $\zeta_X, T_{vir}^{min}, f_*$.
  21cm signal can provide the possibility to discriminate between the different NCDM models and potentially lead to stringent constraints on NCDM.

Thank you for your attention

Backup

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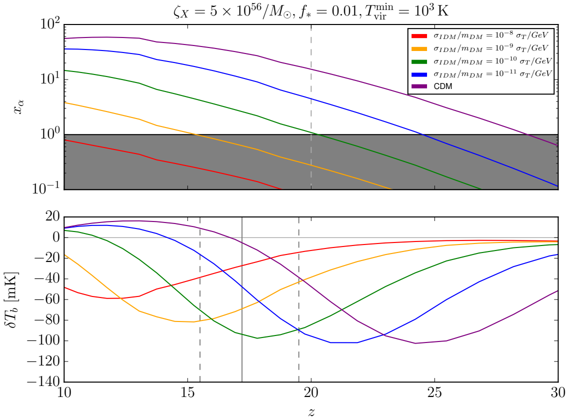

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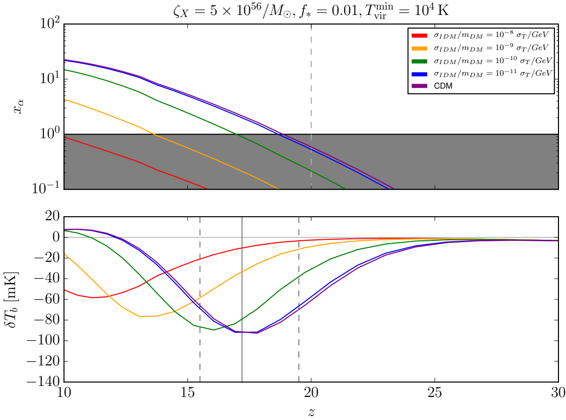

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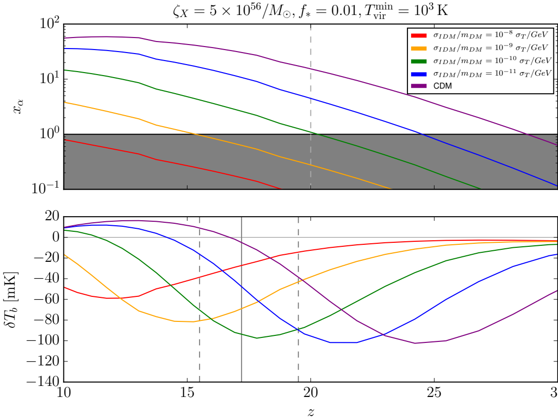

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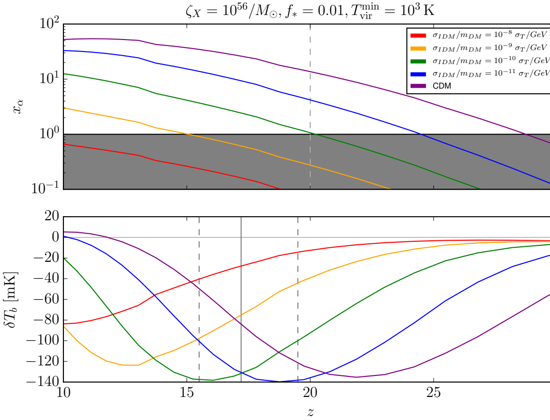

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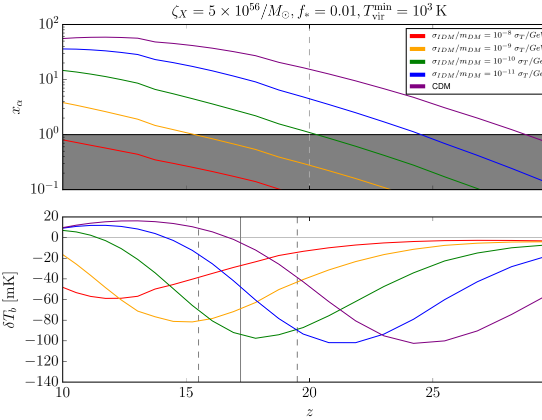

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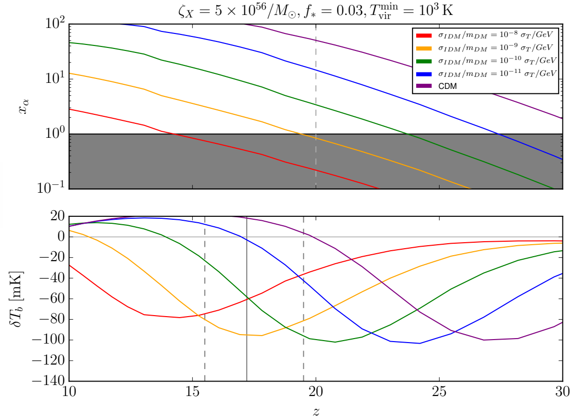
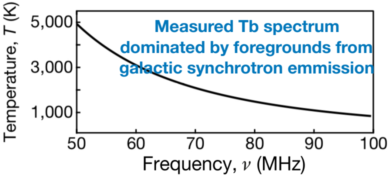
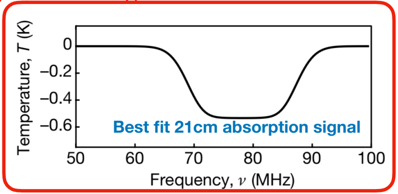


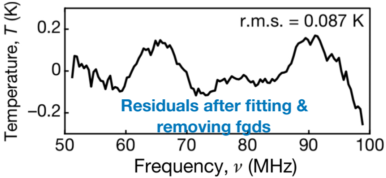
Beware important degeneracies with T_{vir}^{min}, f_* and ζ_X

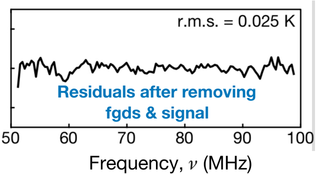
EDGES

Experiment to detect the global EoR signatures









[Bowman18]

Boltzmann equations and effect on CMB

arXiv:1811.11408

DM-X scattering rate: $\dot{\mu}_X = a\sigma_{\mathrm{DM}-X} n_{\mathrm{DM}}$

$$\dot{\mu}_X \simeq 1.0537 \times 10^{-5}\ a^{-2}\ \Omega_c h^2\ \frac{\sigma_{\mathrm{DM}-X}}{m_{\mathrm{DM}}}\ \mathrm{GeV\ cm}^{-3}$$

$$\dot{\delta}_\gamma = -\frac{4}{3}\theta_\gamma + 4\dot{\phi},$$
$$\dot{\theta}_\gamma = k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \dot{\kappa}\left(\theta_\gamma - \theta_b\right) - \dot{\mu}_\gamma\left(\theta_\gamma - \theta_{\mathrm{DM}}\right),$$

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu + 4\dot{\phi},$$
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$$\dot{\delta}_{\mathrm{DM}} = -\theta_{\mathrm{DM}} + 3\dot{\phi},$$
$$\dot{\theta}_{\mathrm{DM}} = k^2\psi - \mathcal{H}\theta_{\mathrm{DM}} - S_\gamma^{-1}\dot{\mu}_\gamma\left(\theta_{\mathrm{DM}} - \theta_\gamma\right)$$

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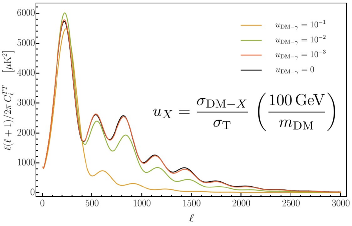
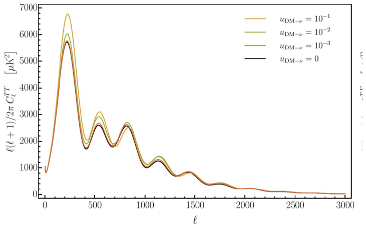
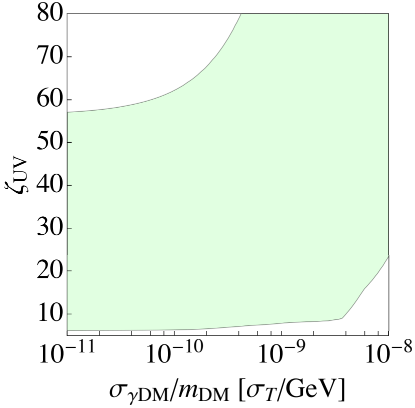




Reionisation Constraints at fixed T_{vir}^{min}



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

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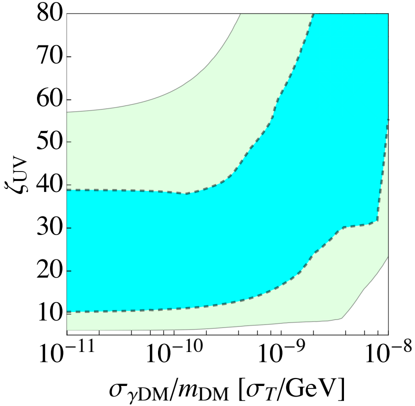

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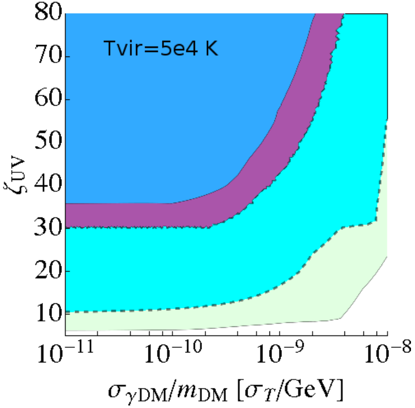

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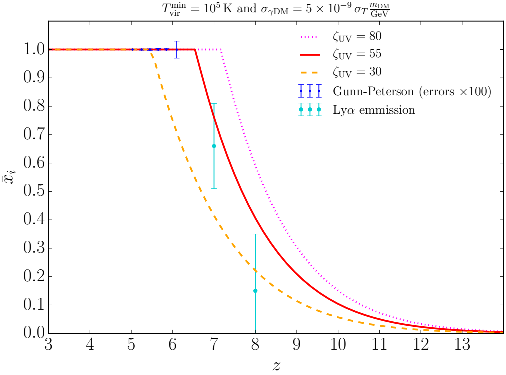
Astro degeneracies: Lower ζ_{UV} allow for higher $\sigma_{\rm IDM}$

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



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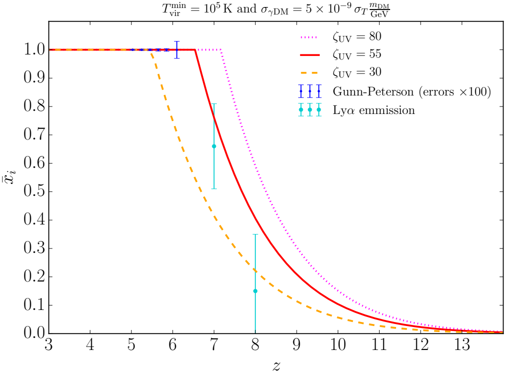
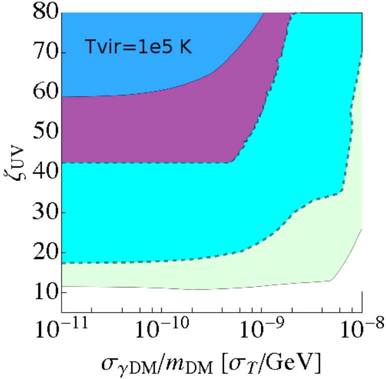




Important degeneracies between astro ζ_{UV} and IDM effects.

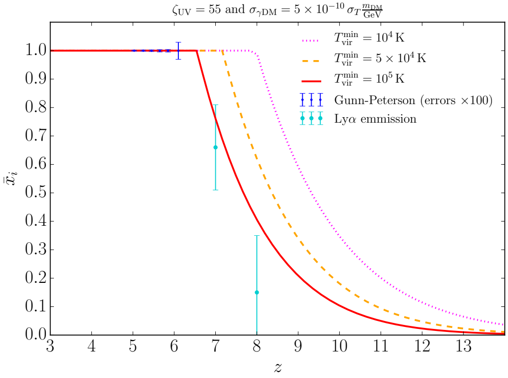
$\rightsquigarrow$ lower ζ_{UV} has similar effect than higher $\sigma_{\rm IDM}$

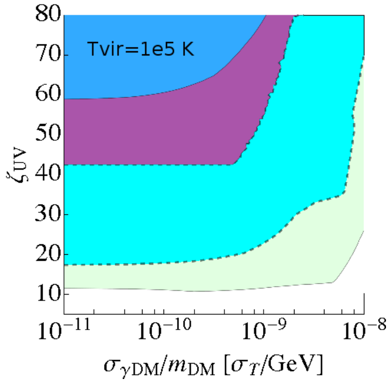
see also [Sitwell'14, LLH'17] for WDM

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

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

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





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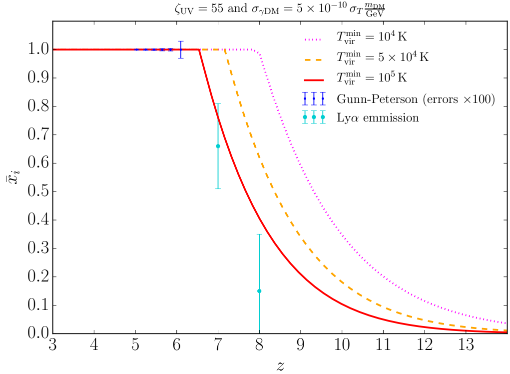
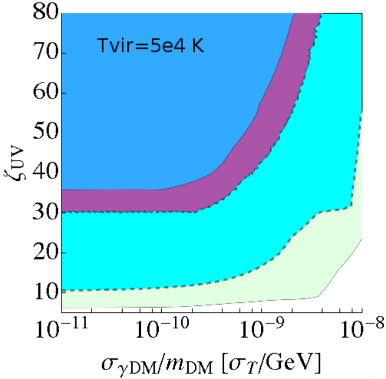
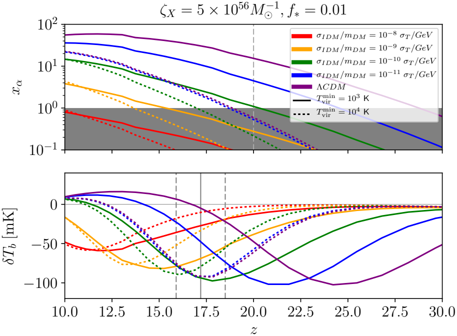


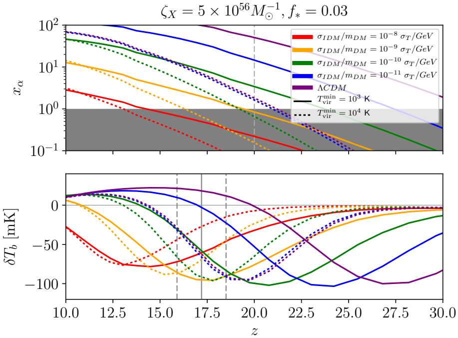


lower $T_{\rm vir}^{\rm min}$ ⇝ earlier reionization

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

Imprint of NCDM





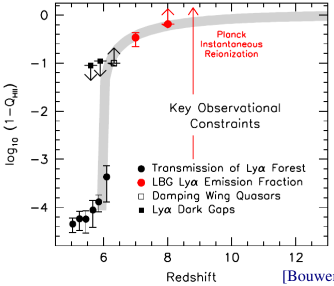
Benchmark models

	α_X [Mpc/h]	$M_{\rm hm}$ [$M_\odot$]	$\zeta_{\rm UV}$	$T_{\rm vir}^{\rm min}$ [K]	τ
$\sigma_{\gamma{\rm DM}} = 6.3\times10^{-10}(\sigma_T \times m_{\rm DM}/{\rm GeV})$ $m_{\rm WDM} = 2.15$ keV	0.0071	6.9×10^8	55	10^5	0.061 0.059
$\sigma_{\gamma{\rm DM}} = 7.9\times10^{-11}(\sigma_T \times m_{\rm DM}/{\rm GeV})$ $m_{\rm WDM} = 5.17$ keV	0.0020	3.5×10^7	30	5×10^4	0.064 0.063

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]

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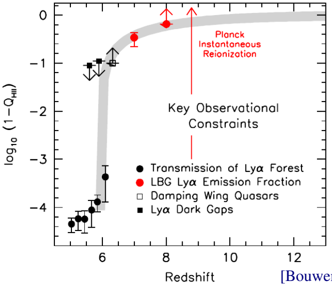
Notice that understanding of EoR is expected to improve with (near) future cosmo probe $\equiv$ 21cm signal
$\rightsquigarrow$ imprint on 21cm Cosmology?



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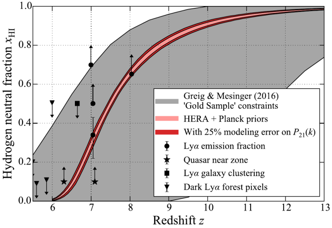
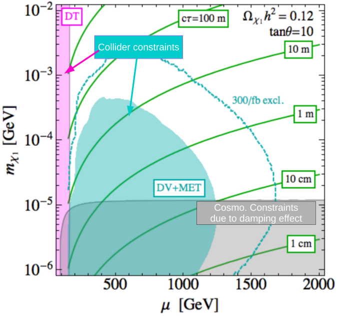


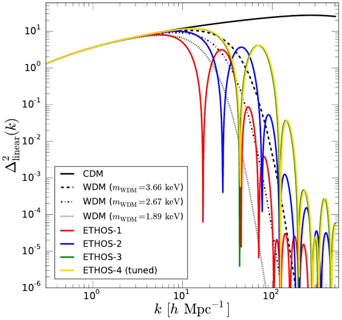
HERA 2020 set-up [DeBoer'16]

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

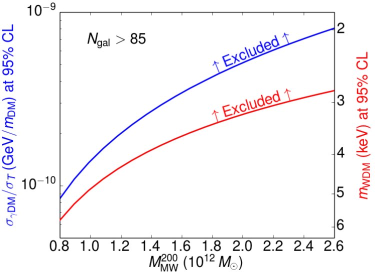
Towards generalized fit to non-CDM (IDM included)? [Murgia’17,18]

$T(k) = (1 + (\alpha k)^\beta)^\gamma \rightarrow$ might be usefull enough to derive Lyα forest and MW satellite count constraints

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}

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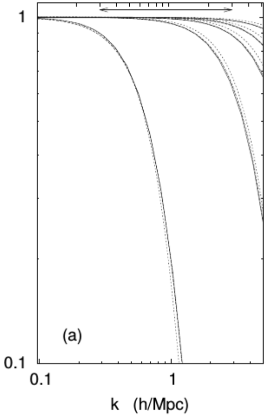
  $\rightsquigarrow$ particles relativistic at the time of decoupling can give substancial λ_{FS}
- Assuming thermal WDM [Viel'05]

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

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

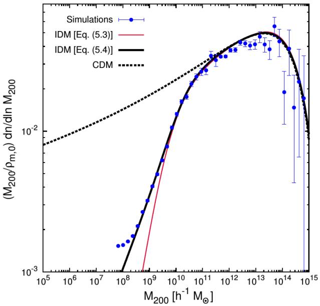


[Viel'05]

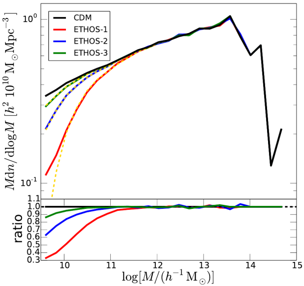
$$\alpha = 0.049 \left(\frac{\rm keV}{m_X}\right)^{1.11} \left(\frac{\Omega_X}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22} \ {\rm Mpc}/h$$

$\rightsquigarrow$ 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]

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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)
  $m_{\nu_s}^{rp} > 3.5$ keV (3σ)

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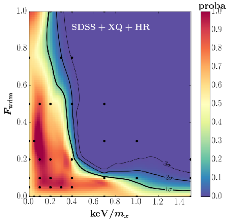
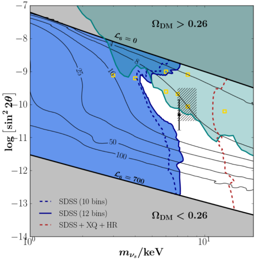
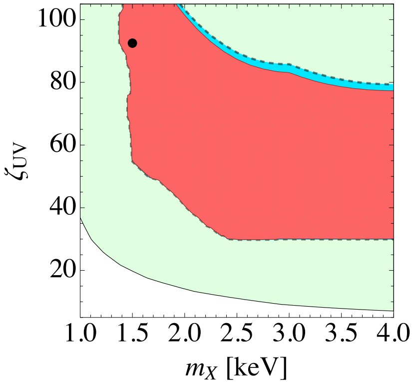




[Baur'17]

Final contours WDM



$\rightsquigarrow$ 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

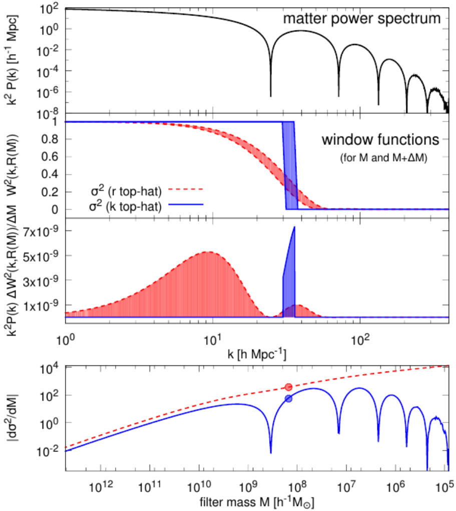


Figure 4. Real-space and k-space top-hat window functions in Press-Schechter HMF predictions for γCDM. The upper panel shows the matter power spectrum, while the second panel shows the Fourier transform of the two window functions (r top-hat and k top-hat). Each window function is evaluated for two filter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

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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- 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

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

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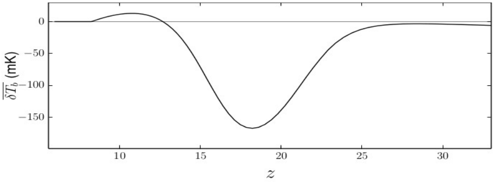

δT_b and Δ_{21} obtained using `21cm Fast` [Mesinger'10]

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

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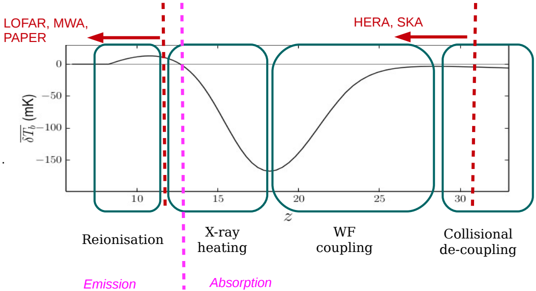

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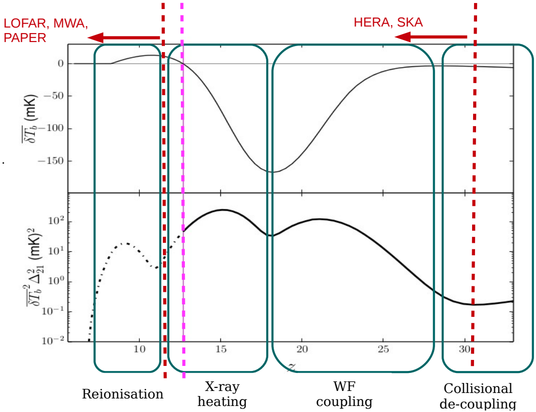
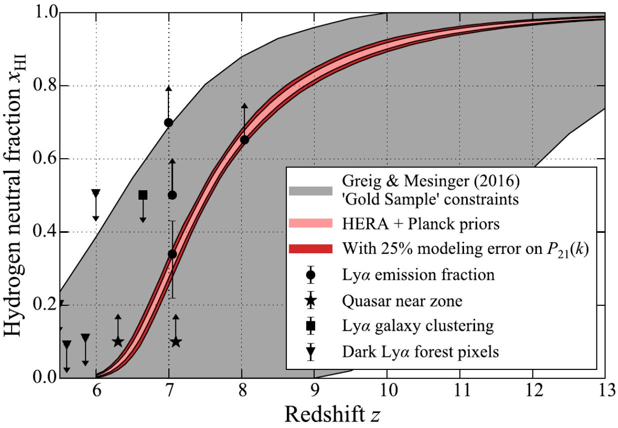


$$\langle \widetilde{\delta}_{21}(\mathbf{k},z)\widetilde{\delta}^*_{21}(\mathbf{k}',z)\rangle \equiv (2\pi)^3\delta^D(\mathbf{k}-\mathbf{k}')P_{21}(k,z) \qquad \Delta^2_{21}(k,z) = \frac{k^3}{2\pi^2}P_{21}(k,z)$$

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

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

HERA reach on x_{HI}



[De Boer'16]

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

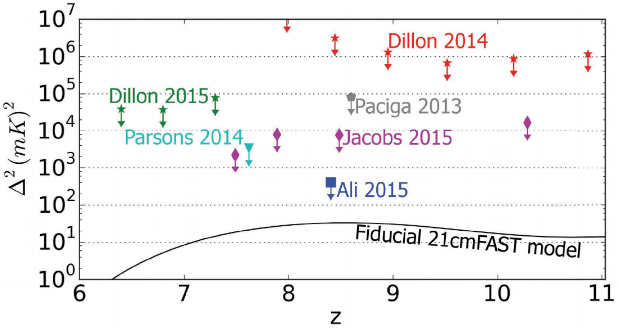


Figure 9. The current best published 2σ upper limits on the 21cm power spectrum, $\Delta^2(k)$, compared to a 21cmFAST-generated model at $k = 0.2\,h\,\mathrm{Mpc}^{-1}$. Analysis is still underway on PAPER and MWA observations that approach their projected full sensitivities; HERA can deliver sub-mK^2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

[De Boer'16]

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

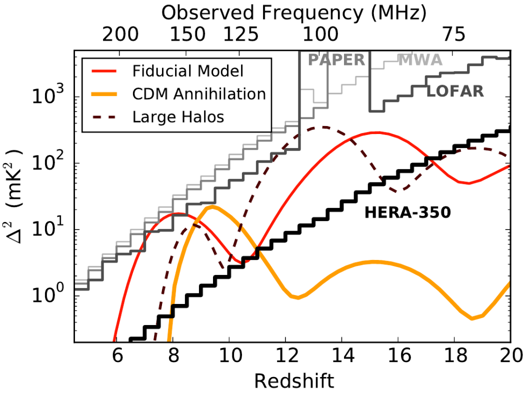


Figure 4. 1σ thermal noise errors on $\Delta^2(k)$, the 21 cm power spectrum, at $k = 0.2\,h\,\mathrm{Mpc}^{-1}$ (the dominant error at that k) with 1080 hours of integration (black) compared with various heating and reionization models (colored). Sensitiv-

[De Boer'16]

Resonant scattering of Lyα photons

Cause spin flip transitions

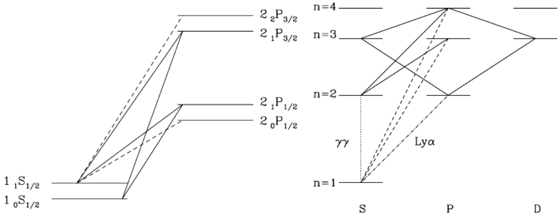


Figure 2. *Left panel:* Hyperfine structure of the hydrogen atom and the transitions relevant for the Wouthuysen-Field effect [24]. Solid line transitions allow spin flips, while dashed transitions are allowed but do not contribute to spin flips. *Right panel:* Illustration of how atomic cascades convert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

[Pritchard'11]

title

This is really the end