Looking for dark matter in the 21 cm sky
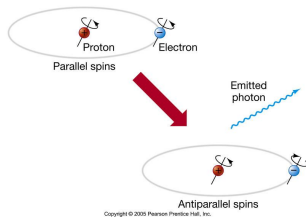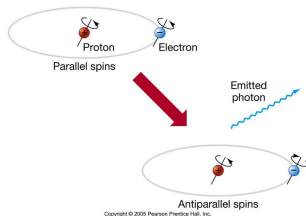
Laura Lopez Honorez

News from the Dark 4 - University of Montpellier - 20-22/05/2019
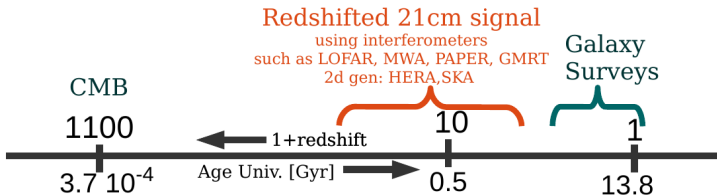
21 cm signal?

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

21 cm signal?

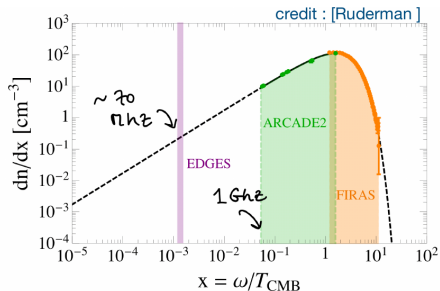- Transitions between the two ground state energy levels of neutral hydrogen HI ⇝ 21 cm photon ($\nu_0 = 1420$ MHz)
- 21 cm photon from HI clouds during dark ages & EoR redshifted to $\nu \sim 100$ MHz ⇝ new cosmology probe
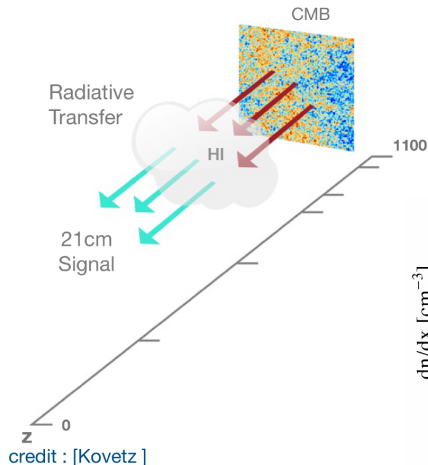
Redshifted 21cm signal
using interferometers
such as LOFAR, MWA, PAPER, GMRT
2d gen: HERA,SKA

Galaxy Surveys

CMB
1100

← 1+redshift

10

1

3.7 10⁻⁴

Age Univ. [Gyr] →

0.5

13.8

21 cm in practice

CMB

Radiative
Transfer

HI

1100

21cm
Signal

z 0

credit : [Kovetz]

- 21cm signal observed as
  CMB spectral distortions

credit : [Ruderman]

dn/dx [cm^{-3}]

~ 70
nhz

EDGES

ARCADE2

1 Ghz

FIRAS

$x = \omega/T_{CMB}$

21 cm in practice

$T_{bgd} = T_{CMB}$

CMB

Radiative Transfer T_S

HI

1100

T_k

21cm Signal T_b

z 0

credit : [Kovetz]
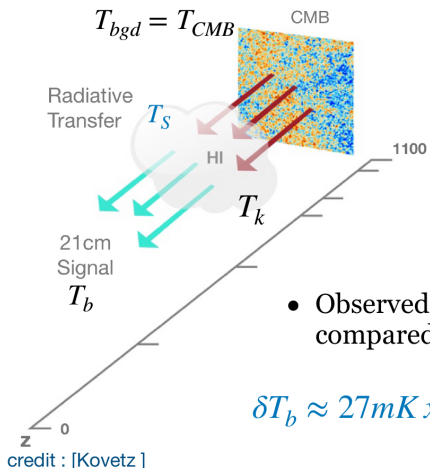
- 21cm signal observed as CMB spectral distortions

- The spin temperature (= excitation T of HI) charaterises the relative occupancy of HI gnd state

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

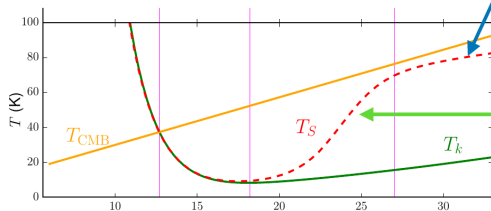- Observed brightness of a patch of HI compared to CMB at $\nu = \nu_0/(1+z)$

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

The spin temperature

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

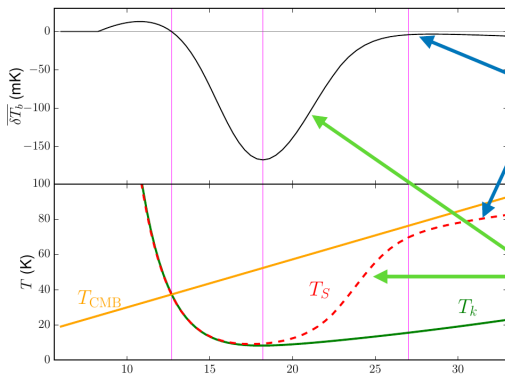Emmission/ absorption of CMB photons
$$T_S \rightarrow T_{CMB}$$

- 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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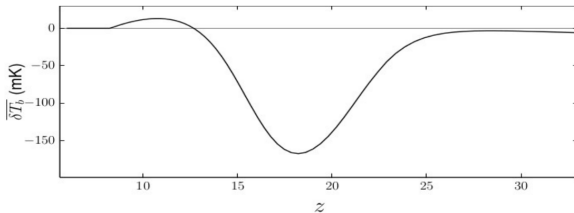 $$T_S \to T_{CMB}$$

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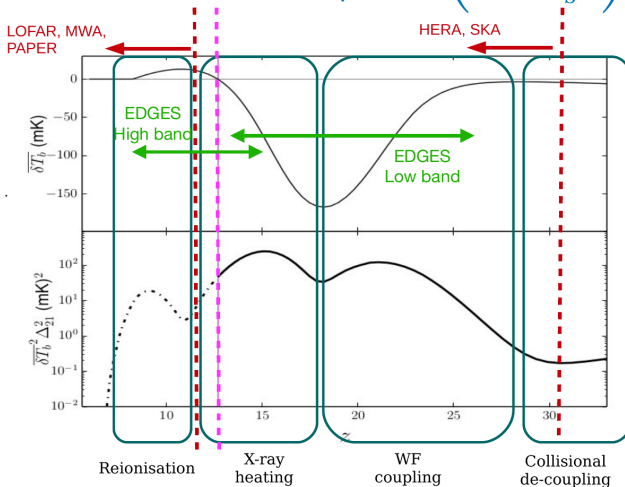LOFAR, MWA, PAPER

HERA, SKA

EDGES High band

EDGES Low band

$\overline{\delta T_b}$ (mK)

$\overline{\delta T_b}^2\, \Delta_{21}^2$ (mK)^2

Reionisation

X-ray heating

WF coupling

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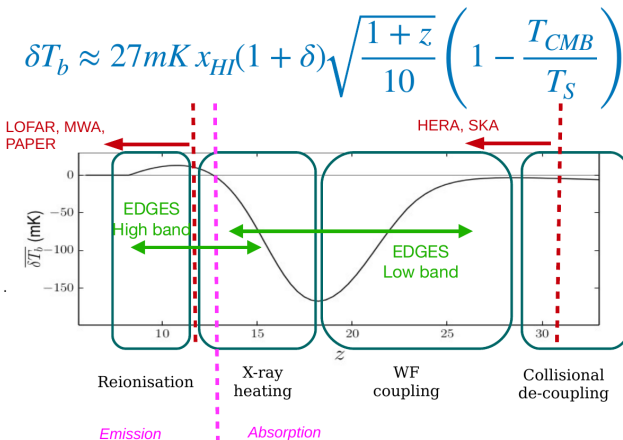
$\langle \widetilde{\delta}_{21}(\mathbf{k}, z)\widetilde{\delta}_{21}^*(\mathbf{k}', z)\rangle \equiv (2\pi)^3 \delta^D(\mathbf{k} - \mathbf{k}') P_{21}(k, z)$ $\Delta_{21}^2(k, z) = \frac{k^3}{2\pi^2} P_{21}(k, z)$

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

Intermezzo: EDGES claim 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 $T_S^{min} \sim T_K$
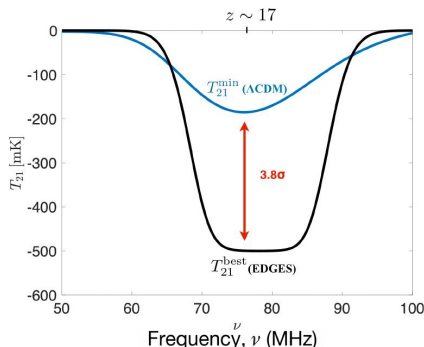
[credit: Kovetz] see also [Bowman18, Barkana18]

Dark Matter?

Dark Matter 26.8%

Ordinary Matter 4.9%

Dark Energy 68.3%
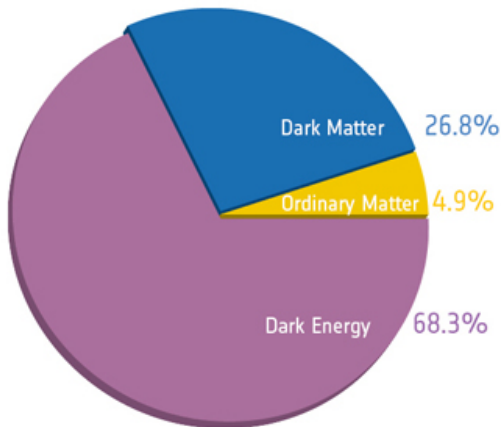
80% of the matter content is made of Dark Matter

In this talk

- Annihilating CDM
  - Energy injection affect CMB
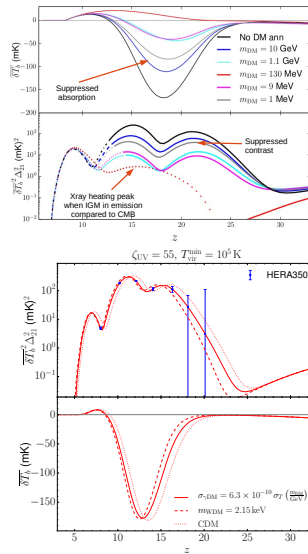 - further constraints from 21cm?
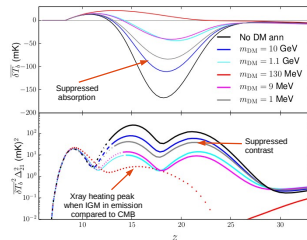
In this talk

- Annihilating CDM
    - Energy injection affect CMB
    - further constraints from 21cm?

- Non Cold Dark Matter:
  WDM vs IDM
    - NCDM delays structure formation
    - also delay in 21cm features
    - can help to disentangle NCDMs?

DM as a WIMP (or a PBH)
Energy injection

The Standard lore of Dark Matter as a WIMP

- WIMP relic abundance is driven by processes:
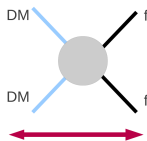
Freeze-out mechanism:

$$\rightsquigarrow \Omega h^2 \propto 1/\langle \sigma v \rangle$$

- Cosmo observations ($\Omega h^2 \sim 0.12$)
  $\Leftrightarrow \langle \sigma v \rangle \sim 2.2 \, 10^{-26}$ cm^3/s

$\rightsquigarrow$ target value for detection experiments looking for annihilation products
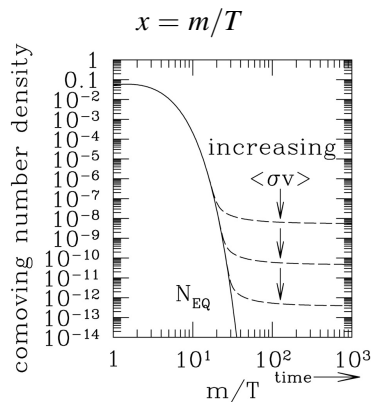
Plumbing equivalent
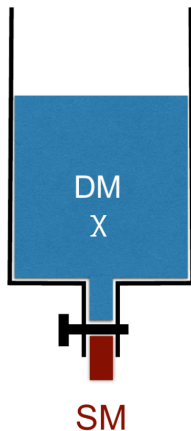
Freeze-out
DM annihilation driven

$$\Omega h^2 \propto 1/\langle \sigma v \rangle_{\chi\chi}$$

Testing WIMPs: the "simple" picture
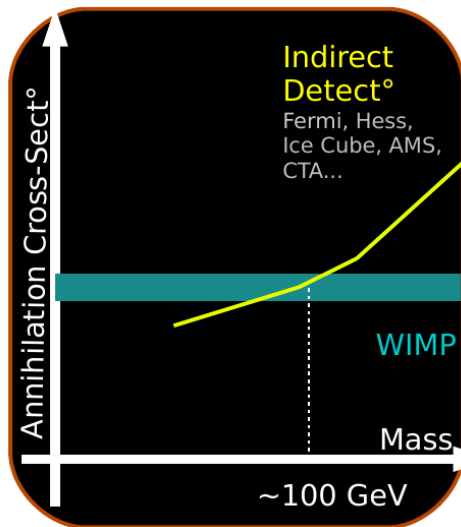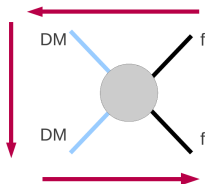
Testing WIMPs: the "simple" picture
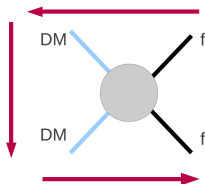
⤳ WIMPs at the verge of discovery/exclusion
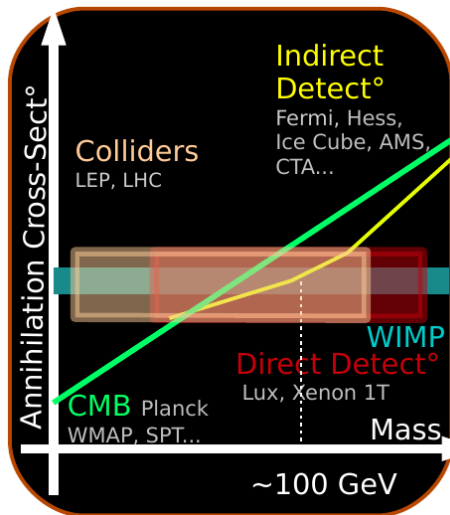
A word of Caution: beyond simple plumbing

see also T. Lacroix talk with p-wave annihilation
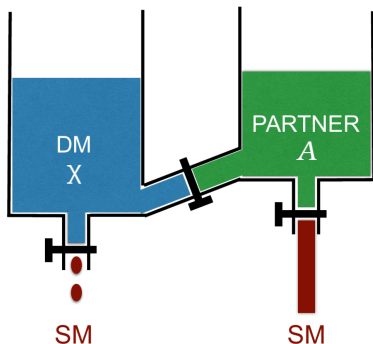
Freeze-out
Partner annihilation driven

$$\Omega h^2 \propto 1/\langle \sigma v \rangle_{eff}$$

$$\langle \sigma v \rangle_{eff} \propto e^{-2x_f \frac{\Delta m}{m_\chi}} \langle \sigma v \rangle_{AA}$$

$$\Delta m = m_A - m_\chi$$

Energy *deposition* from DM annihilations

see previous work [Shchekinov'06, Furlanetto'06, Valdes'07, Chuzhoy'07, Cumberbatch'08, Natarajan'09, Yuan'09, Valdes'12, Evoli'14],
see also [Adams'98,Chen'03, Hansen'03, Pierpaoli'03, Padmanabhan'05] for CMB

- What does DM annihilate into?:
  - $f, \gamma, W, Z, ... \rightsquigarrow e^+, e^-, \gamma$ using e.g. [Pythia, Mardon'09, PPPC4DMID]
  - neutrinos $\rightsquigarrow$ suppressed but possible via EW corrections

Energy *deposition* from DM annihilations

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- Dark matter annihilation inject energy within the dark ages
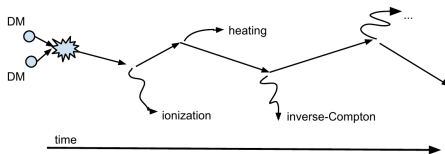
[image from A. Vincent]

Rate of energy injection/deposition into $c =$ heat, ionization, excitation

$$\left(\frac{dE_c(\mathbf{x},z)}{dtdV}\right)^{\text{smooth}}_{\text{deposited}} \equiv f_c(z) \left(\frac{dE(\mathbf{x},z)}{dtdV}\right)^{\text{smooth}}_{\text{injected}} \equiv f_c(z)\, n_{DM}(z)^2 \frac{\langle\sigma v\rangle}{m_{\text{DM}}}$$

$f_c(z) =$ energy deposition efficiency per channel
(obtained using tabulated transfer fns $T^c(z,z',E)$ [Slatyer '15], new: see also ExoClass)

From Injected to Deposited: clustering can matter

$\sum_c f_c(z)$ for $\chi\chi \to e^+ e^-$ [Slatyer'15]
as fn of E_{inj} of 1 member of $e^+ e^-$ pair and z_{abs}

- Energy deposition efficiency channel ≡ includes contribs. from particles injected at all z'>z

- Boost at late times due to structure formation

$$\left(\frac{dE(z)}{dtdV}\right)_{\text{injected}} = \frac{\langle\sigma v\rangle}{m_{\text{DM}}} n_{\text{DM}}^2(z) \left[1 + \mathcal{B}(z)\right]$$

$$\mathcal{B}(z) \propto \int_{M_{\text{min}}} \frac{dn(M,z)}{dM} dM \int_0^{R_{\text{vir}}} \rho^2(r) 4\pi r^2 dr$$

Relevant window for CMB studies

Relevant window for 21 cm studies

Redshift (1+z)

Energy (eV)

From Injected to Deposited: clustering can matter
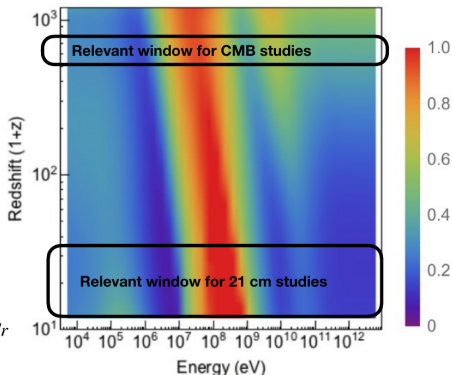
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- astro **uncertainties** for 21cm signal

[LLH, Mena, Moline, Palomares, Vincent 13]

Legend:
$f(z) + g(z)$, $m_{\text{DM}} = 130$ MeV
$f(z) + g(z)$, $m_{\text{DM}} = 10$ GeV
$f(z)(1 + \mathcal{B}_{\text{W13}}(z))$, $m_{\text{DM}} = 130$ MeV
$f(z)(1 + \mathcal{B}_{\text{W13}}(z))$, $m_{\text{DM}} = 10$ GeV
$0.22(1 + \mathcal{B}_{\text{PS}}(z))$, $m_{\text{DM}} = 10$ GeV

$M_{\text{min}} = 10^{-12} M_\odot$
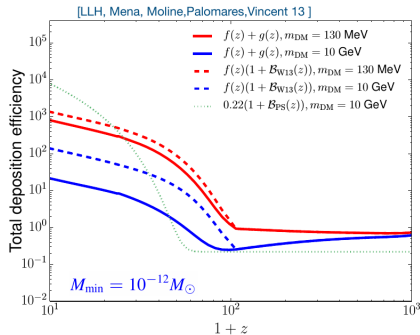
$$\int dz'\,[1 + \mathcal{B}(z')]\,T^c(z, z', E)$$

$$\neq f_c(z)[1 + \mathcal{B}(z)]$$

see e.g. [Slatyer'12]

CMB constraints on DM annihilation

see e.g. [Chen'03, Padmanabhan'05, Cirelli'09, Slatyer'09, Galli'11, Giesen'12, LLH'13, Galli'13, Madhavacheril'13, Poulin'15,...]

- This energy injections can modify the history of recombination and affect CMB temperature and polarisation anisotropies

m_{DM} [GeV]	0.001	0.009	0.13	1.1	10
$\langle \sigma v \rangle$ [cm³/s]	10^{-30}	10^{-29}	10^{-28}	10^{-27}	10^{-26}

$\leadsto$ $p_{ann} = f_{eff} \langle \sigma v \rangle / m_{DM} < 4.1 \, 10^{-28}$ cm³/s/GeV at 95% CL [Planck'15]

similar to new [Planck'18] results

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see e.g. [Chen'03, Padmanabhan'05, Cirelli'09, Slatyer'09, Galli'11, Giesen'12, LLH'13, Galli'13, Madhavacheril'13, Poulin'15,...]

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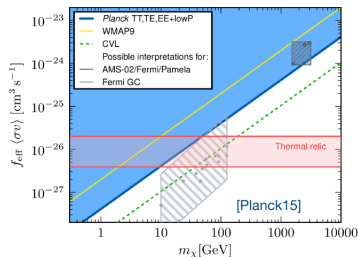
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similar to new [Planck'18] results

- Advantage of CMB compared to other DM annihilation probes: do not suffer astrophysics uncertainties (such as ρ_{DM}) and no contributions from halos for σv independent of v (s-wave annihilation) [LLH'13, Poulin'15, Hongwan'16].

DM energy injection: earlier heating

[Planck15]

see also [Valdes13, Evoli14, D'Amico18,Liu18]

DM energy injection: earlier heating

DM energy injection: earlier heating

[LLH, Mena, Moline, Palomares, Vincent 16]

[Planck15]

- Suppressed absorption
- Imposing some maximal δTb could constrain DM annihilation

see also [Valdes13, Evoli14, D'Amico18, Liu18]

DM energy injection: earlier heating

Beware!
large astrophysics
uncertainties

[LLH, Mena, Moline, Palomares, Vincent 13]

DM energy injection: earlier heating
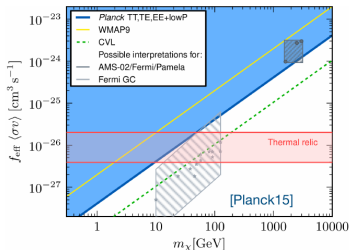
[Planck15]

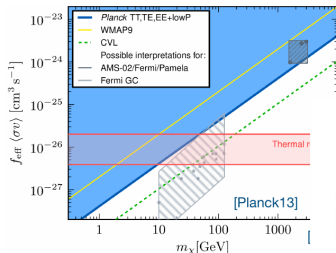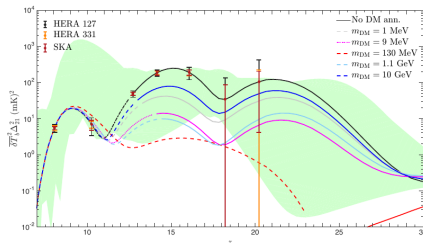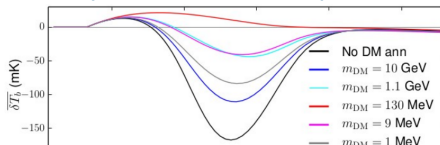- Suppressed absorption
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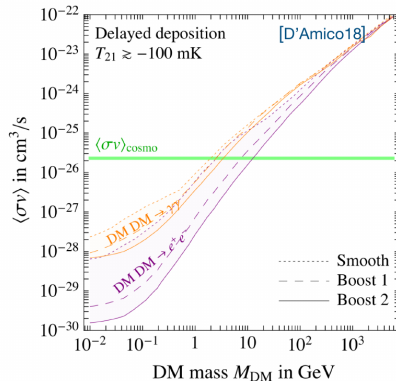
see also [Valdes13, Evoli14,LLH16, Liu18]

PBH energy injection: earlier heating

See also [Ricotti 07, Ali-Haimoud 17, Poulin 17, Ewall-Wice 18, Hektor 18]

- Accreting BH can provide extra radio bgd [Ewall-Wice 18]

- More importantly accretion comes with extra energy injection

- Bondi accretion (spherical) with

$$L_E(z) = L_{\text{Edd}}\, \dot{m}(z) \left(\frac{\dot{m}(z)}{\dot{m}_{\text{crit}}}\right)^{\beta} \times f(E),$$

$$\dot{m}(z) \simeq 8 \times 10^{-7}\lambda \left(\frac{M_{\text{PBH}}}{10 M_\odot}\right) \left(\frac{n_B(z)}{1 \text{cm}^{-3}}\right) \left(\frac{v_{\text{eff}}(z)}{10 \text{km/s}}\right)^{-3}$$

[Hektor 18]

- imposing some maximal T_k, Hektor et al could constrain PBH with mass $\mathcal{O}(10) M_\odot$ to be less than 1-0.001 of the DM
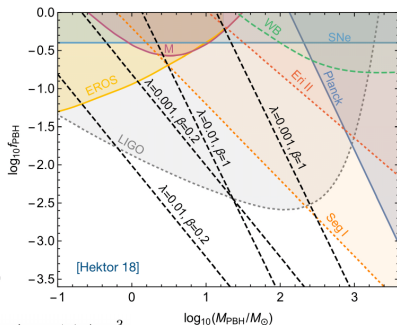
Astro Uncertainties: Halo mass function

For δT_b and Δ_{21}, we make use of 21cmfast. [Mesinger'10]

$\leadsto$ dependence on halo mass function, T_{vir}, ζ_X, N_α. In particular, the ionization, heating and excitation critically depend on the fraction of mass collapsed in halos

$$f_{\text{coll}}(> M_{\text{vir}}) = \int_{M_{\text{vir}}} \frac{M}{\rho_0} \frac{dn(M,z)}{dM} \, dM \;,$$
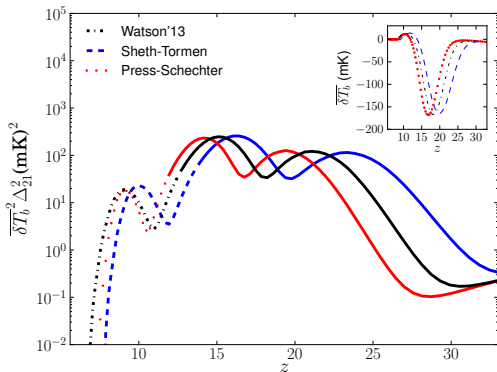
- W13: our default for CDM annihilation analysis

- PS: underpredicts $\frac{dn(M,z)}{dM}$ at large M and z and overpredicts $\frac{dn(M,z)}{dM}$ at low M and z

- ST: default 21cmFast: slight overestimation compared to simu. at large z see e.g. Watson'13

$\leadsto$ PS $\to$ W13 $\to$ ST: astro sources switch on earlier

Astro Uncertainties: Threshold for star formation

$$f_{\text{coll}}(> M_{\text{vir}}) = \int_{M_{\text{vir}}} \frac{M}{\rho_0} \frac{dn(M,z)}{dM}\, dM\;,$$

Threshold for efficient star formation: $T_{\text{vir}} > T_{\text{vir},0} = 10^4$ K

($\equiv M_{\text{vir},0}(z=10) = 3\,10^7\, M_\odot$) [Evrard'90, Blanchard'92, Tegmark'96, Haiman'99, Ciardi'99]

$$M_{\text{vir}} \simeq 10^8 \left(\frac{T_{\text{vir}}}{2\,10^4\text{ K}} \frac{10}{1+z} \right)^{3/2} M_\odot$$
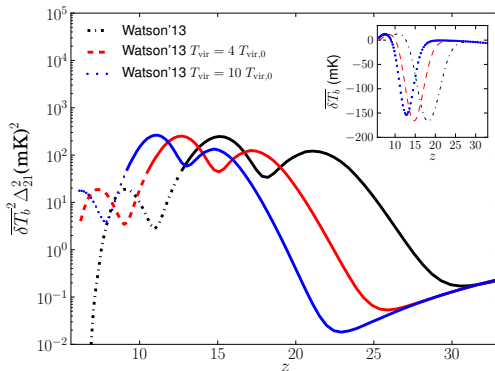
$\rightsquigarrow$ larger M_{vir} threshold implies a delay in the X-ray and UV sources.

Non-Cold Dark Matter and the delay of structure formation

NCDM linear regime: suppressed power at small scale

■ WDM: free-streaming (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]
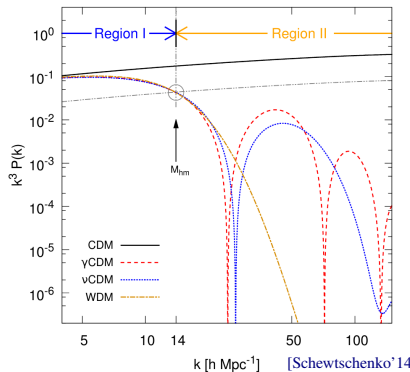
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■ IDM: collisional damping (Silk damping): damping length associated to diffusion processes (depend distance traveled by coll. particles during random walk)

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

with $\nu = 1.2$ and define the scales

- $\alpha_{IDM} \propto (\sigma_{IDM}/m_{DM})^{0.48}$ [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 $M_{hm}(m_{WDM})$

$\rightsquigarrow$ 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]
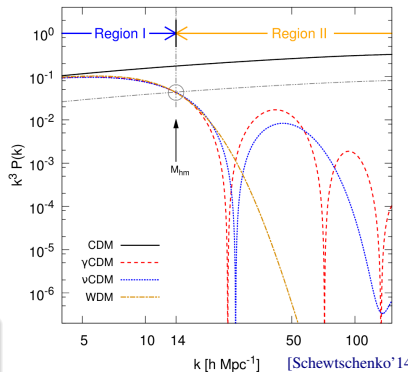
[Schewtschenko'14]

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.:

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- $\sigma^2 = \sigma^2(P_{lin}(k), W(kR))$ is the variance of
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NCDM non linear regime: less low mass haloes

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

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

[Moline'16]
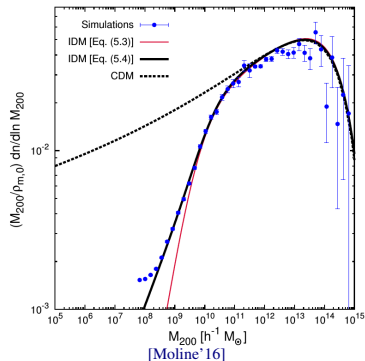
$\rightsquigarrow$ suppression of the halo mass function for WDM, IDM
can be described as fn. of $M_{hm}(m_{\text{WDM}})$ or $M_{hm}(\sigma_{\text{IDM}}/m_{DM})$ BUT
more low mass haloes in IDM than WDM at fixed M_{hm} see also [VogelsBerger'15]

Number of MW Satellites

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

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

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

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

- $f_{lum}(M)$ fraction of subhalo of a given mass hosts a luminous galaxy. We use [Dooley'16].
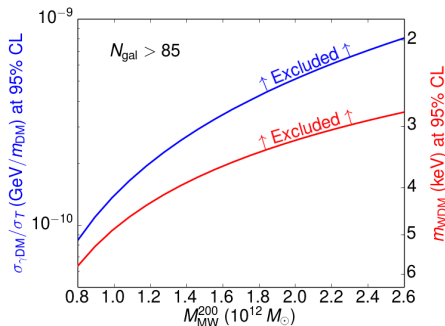
$$(\sigma_{IDM}/m_{DM}) < 8 \times 10^{-10}\, (\sigma_T/\text{GeV})$$
$$m_{WDM} > 2.8\ \text{keV}$$

Improves on σ_{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, Stoychev'19] and
for different approach [Barkana'01, Somerville'03,Yoshida'03, Yue'12, Schultz'14, Dayal '14+, Rudakovskyi'16, Lovell'17]

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

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

- 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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$\zeta_{UV} = 55$ and $T_{vir}^{min} = 10^5 \, \mathrm{K}$ obtained with 21cmfast

Legend:
- $\sigma_{\gamma DM} = 10^{-11} \, \sigma_T \frac{m_{DM}}{GeV}$
- $\sigma_{\gamma DM} = 5 \times 10^{-10} \, \sigma_T \frac{m_{DM}}{GeV}$
- $\sigma_{\gamma DM} = 10^{-8} \, \sigma_T \frac{m_{DM}}{GeV}$
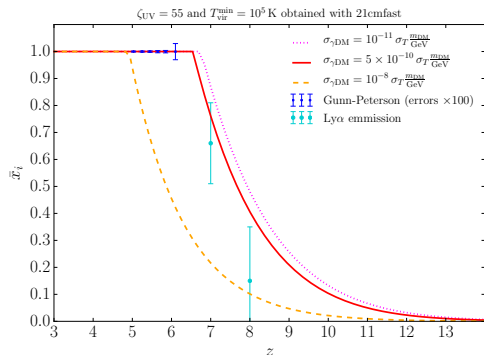- Gunn-Peterson (errors ×100)
- Lyα emmission

Within our framework:

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

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

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

$T_{vir}^{min} = 10^5\,\text{K}$ and $\sigma_{\gamma\text{DM}} = 5 \times 10^{-9}\,\sigma_T \frac{m_{\text{DM}}}{\text{GeV}}$

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

The ionization efficiency ζ_{UV} parametrizes the number of ionizing photons per atom to be ionized. In the 21cmFast code, regions are ionized when $\zeta_{UV} f_{\text{coll}} > 1$.
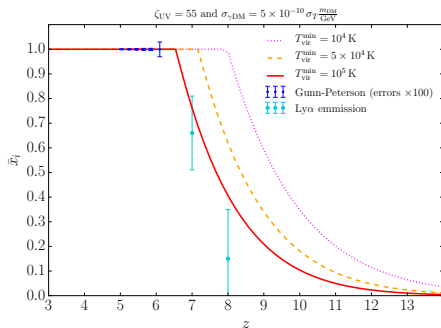Threshold for halos hosting star-forming galaxies:

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

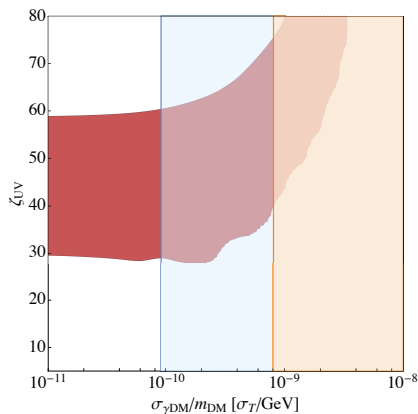$\zeta_{UV} = 55$ and $\sigma_{\gamma\text{DM}} = 5 \times 10^{-10} \sigma_T \frac{m_{\text{DM}}}{\text{GeV}}$

Important degeneracies between astro ζ_{UV}, $T_{\text{vir}}^{\text{min}}$ 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

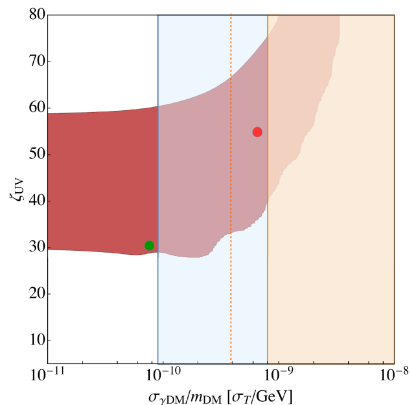# Constraints from Reionization and N_{sat}

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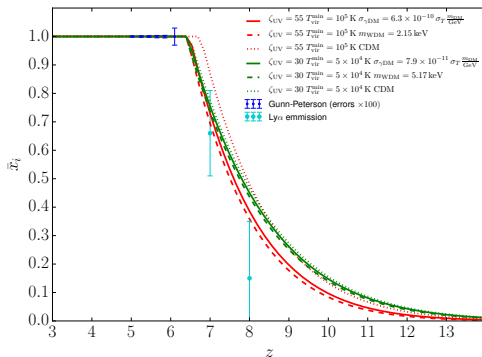

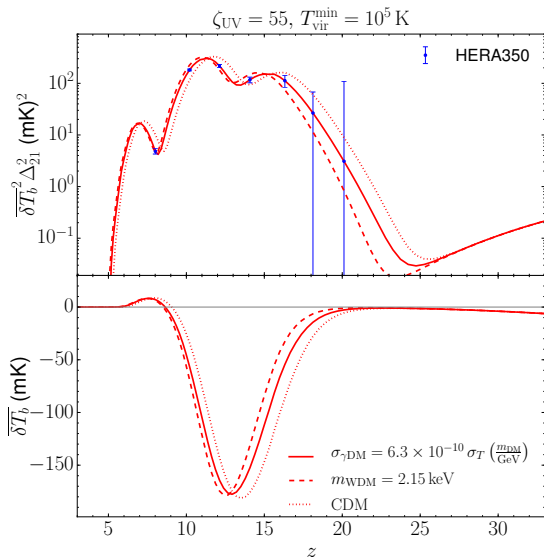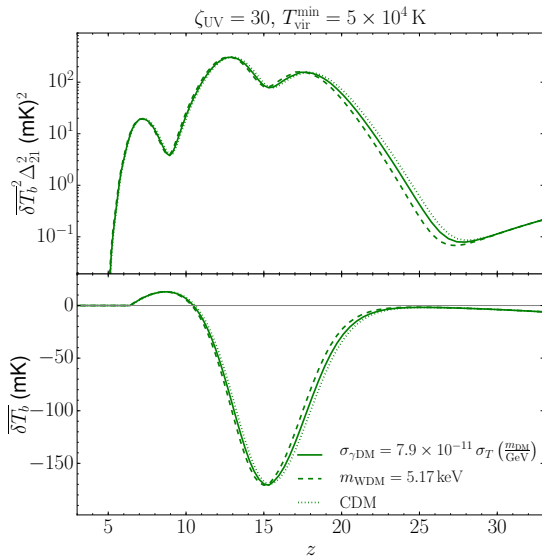Satellite nb count put the strongest constraints

21cm could help to discriminate between Non-CDM

21cm could help to discriminate between Non-CDM

# 21cm could help to discriminate between Non-CDM

$\zeta_{\rm UV} = 30,\ T_{\rm vir}^{\rm min} = 5 \times 10^4\,{\rm K}$

$\sigma_{\gamma\rm DM} = 7.9 \times 10^{-11}\, \sigma_T \left(\frac{m_{\rm DM}}{\rm GeV}\right)$
$m_{\rm WDM} = 5.17\,{\rm keV}$
CDM

Caveats NCDM

- 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
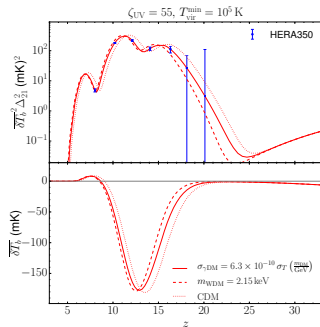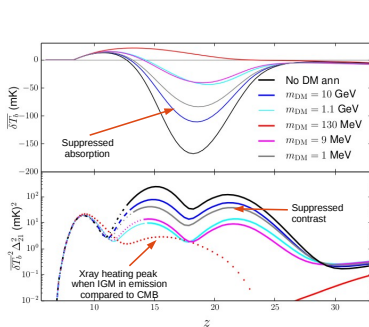
- 21cm cosmology is opening a new window on the early universe
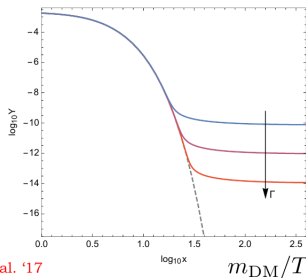
- DM scenarios such as Annihilating DM (PBH) and NCDM can potentially leave a distinctive imprint such as modifying the position and the deepness of the absorption trough/ peaks in the power spectrum.

Thank you for your attention!

Backup

WIMP versus FIMP: Simple picture

DM abundance: Freeze-out   versus   Freeze-in (through decay)

Bernal et al. '17

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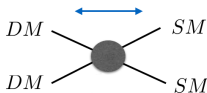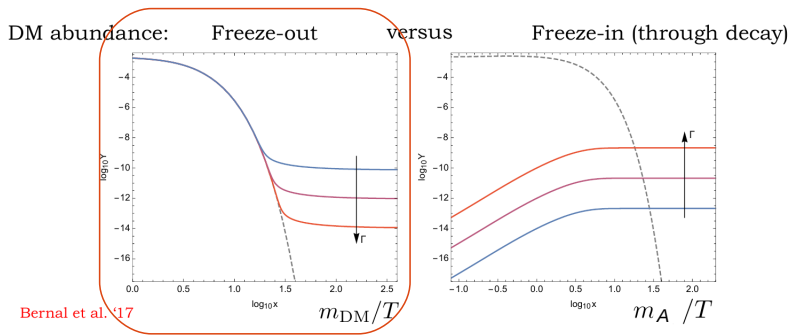
$$\Omega h^2 \sim 0.12 \times \frac{m_{DM}}{100 \text{GeV}} \times \frac{0.2\text{pb}}{\langle \sigma v \rangle}$$

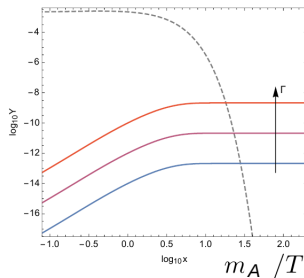Typical cross-section probed by indirect detect° searches or CMB

WIMP versus FIMP: Simple picture

DM abundance: Freeze-out   versus   Freeze-in (through decay)

Bernal et al. '17
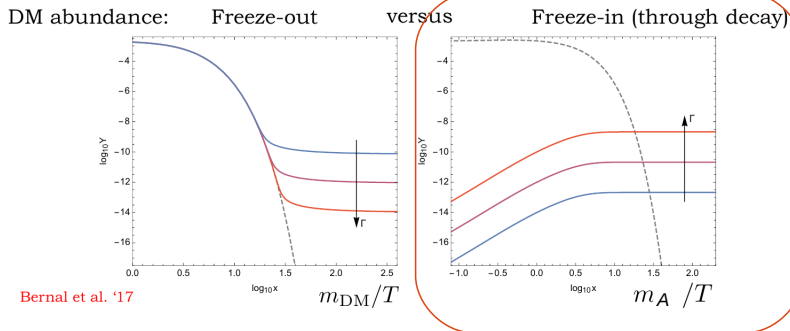
$$\Omega h^2 \sim 0.12 \left(\frac{\Gamma_A}{4 \times 10^{-15} \text{ GeV}} \right) \left(\frac{600 \text{ GeV}}{m_A} \right)^2 \left(\frac{m_{DM}}{10 \text{ keV}} \right)$$

$y \sim 10^{-8}$ for $\Gamma_A \sim \dfrac{y^2}{8\pi} m_A$

A —⬤y— B
                χ
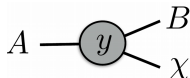
WDM constraints on FIMPs

See Heeck et al '1706 and '1709

- WDM: free-streaming (collision-less damping): collisionless particles can stream out of overdense to underdense regions
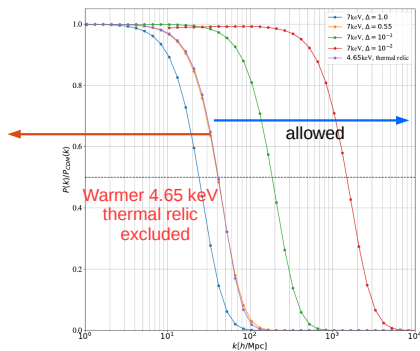
smooth out inhomogeneities for $\lambda < \lambda_{FS} = \int_0^{t_0} \frac{v}{a} dt$
⇝ particles relativistic at the time of decoupling can give substancial λ_{FS}

WDM constraints on FIMPs

See Heeck et al '1706 and '1709
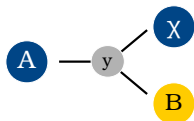
$$\frac{\partial f_{\mathrm{DM}}}{\partial t} - Hp\frac{\partial f_{\mathrm{DM}}}{\partial p} = \mathcal{C}(p)$$

$$\frac{\partial f_{\mathrm{DM}}}{\partial r} = \frac{g_A \, S \, \Gamma \, M_0 \, r^2}{2 \, p_{\mathrm{DM}} \, x \, \sqrt{m_A^2 x^2 + m_{\mathrm{DM}}^2 r^2}} \int_{\xi^-}^{\xi^+} \mathrm{d}\xi \, f_A(\xi)$$

- r=1, ⟨x⟩=0.131
- r=2, ⟨x⟩=0.157
- r=5, ⟨x⟩=0.221
- r=8, ⟨x⟩=0.247
- T_{eff}=0.25/3
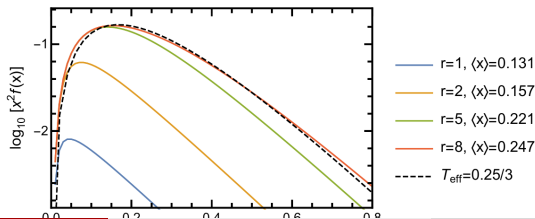
A word of Caution: beyond the simple picture

ways to break $\langle\sigma v\rangle_{\text{fo}}\leftrightarrow\langle\sigma v\rangle_{\text{today}}\leftrightarrow\sigma_{\text{direct,coll}}$??

- Depending on DM properties (odd Z_2 assumed) and on the portal:
  - velocity dependent annihilation
  - richer DM sector with coannihilations [Griest & Seckel '90]
  - annihilation near thresholds and resonances [Griest & Seckel '90]
  - annihilation into light mediators
    (Sommerfeld enhancement [Hisano '04, Cirelli '05], secluded DM [Pospelov '07])

- non WIMP, non "standard" Freeze-out or stability other than Z_2:
  freeze-in , co-annihilation without chemical equilibrium, dark freeze-out,
  reannihilation, semi-annihilating DM, asymmetric dark matter, ALP, SIMP, ...

Why CMB constraints in very Brief

- The CMB arises from the last scattering surface at the epoch when the universe became transparent ($z \sim 1000$).

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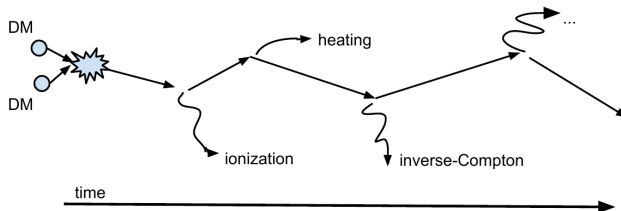
[image from A. Vincent]

- This energy injections can modify the history of recombination and affect CMB temperature and polarisation spectra probed by Planck, SPT, ACT, WMAP,... $\leadsto$ constraints on the DM viable parameter space

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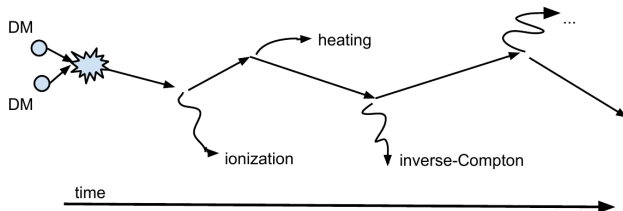

[image from A. Vincent]

- This energy injections can modify the history of recombination and affect CMB temperature and polarisation spectra probed by Planck, SPT, ACT, WMAP,... ⤳ constraints on the DM viable parameter space

- Advantage of CMB compared to other DM annihilation probes: Bgd constraints do not suffer astrophysics uncertainties such as e.g. local ρ_{DM}

From *injected* energy to *deposited*

see e.g. [Ripamonti'06, Slatyer'09, Valdes'10, Evoli'12, Slatyer'12, Galli'13, Weniger'13, **Slatyer'15**, Hongwan'16]

$$\epsilon_c^{\text{DM}}(\mathbf{x}, z) \equiv f_c(z) \left(\frac{dE_c(\mathbf{x}, z)}{dtdV} \right)_{\text{injected}}^{\text{smooth}}$$

$\sum_c f_c(z)$ for $\chi\chi \to e^+ e^-$ [Slatyer'15]
as fn of E_{inj} of 1 member of $e^+ e^-$ pair and z_{abs}

$f_c(z) =$ energy deposition efficiency
per channel $\equiv$ amount of energy
absorbed by the medium at z
including contributions from
particles injected at all $z' > z$

(obtained using tabulated transfer fns
$T^c(z, z', E)$ [Slatyer '15])

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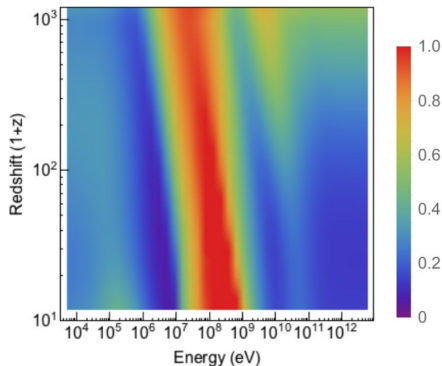
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Recombination history and power spectra modified

$\chi\chi \rightarrow e^+e^-$ $m_\chi = 2$ GeV

Legend:
- $\langle\sigma v\rangle = 10^{-28}$ cm^3/s
- $\langle\sigma v\rangle = 10^{-27}$ cm^3/s
- $\langle\sigma v\rangle = 10^{-26}$ cm^3/s
- $\langle\sigma v\rangle = 10^{-25}$ cm^3/s

y-axis: x_e
x-axis: $1+z$
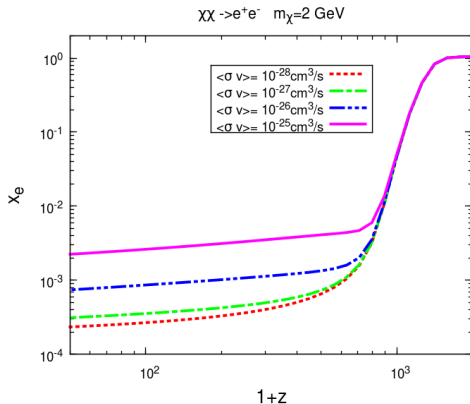
- increased residual ionization

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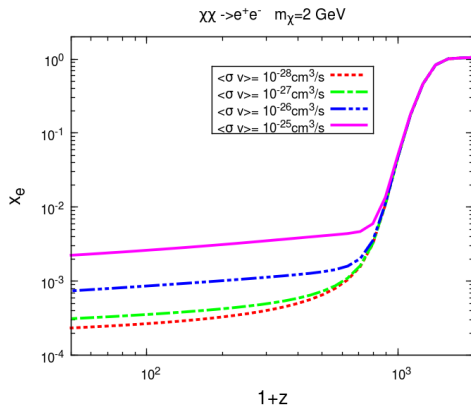
- increased residual ionization
- affects the optical depth τ to recombination with:

$$\dot{\tau} = -\sigma_T n_e a$$

and the visibility function

$$g(z) = -\dot{\tau} exp(-\tau(z))$$

$\equiv$ probability that a γ last scattered at z, very peaked around $z \sim 1000$

$\rightsquigarrow$ broadening of the last scattering surface

Effect on the CMB power spectra
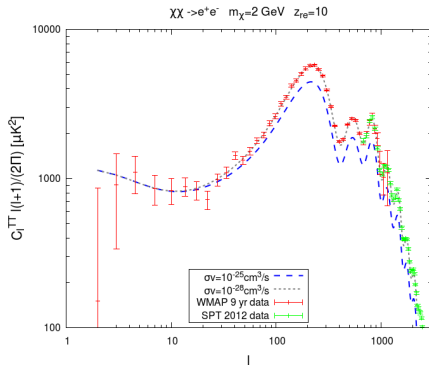
broadening of the last scattering surface :

- attenuates of correlations at small scales (large l) [Padmanabhan'05].

Effect on the CMB power spectra
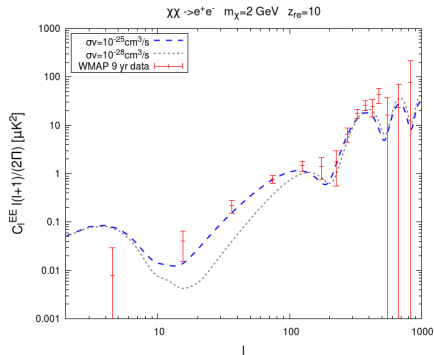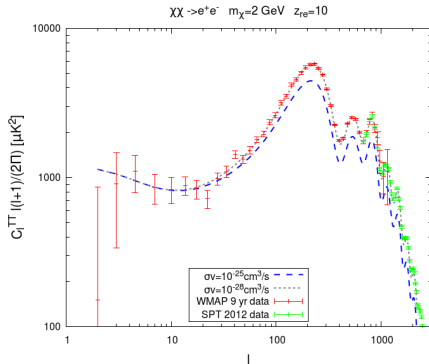
broadening of the last scattering surface :

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- increases the polarisation fluctuations and shift the EE (TE) peaks at large scale
  [Padmanabhan'05].

In practice how to proceed

- What does DM annihilate into?:
  - neutrinos ⤳ escape constraints from CMB
  - $f\bar{f}$, γ, $W^{+}W^{-}$, ... ⤳ e^{+}, e^{-}, γ using e.g. [Pythia, Mardon'09, PPPC4DMID]

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- Rate of heating or ionization depends on see e.g. [Chen'03, Padmanabhan'05, Galli'13]

$$\mathcal{F}(z) = \frac{\chi_i(z)}{H(z)(1+z)n_H(z)} \left(\frac{dE}{dtdV} \right)_{deposit}$$

$\chi_i(z)$ = fraction of injected energy into i = heat, ionization, excitation

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  see e.g. [Ripamonti'06, Slatyer'09, Valdes'10, Evoli'12, Slatyer'12, Galli'13, Weniger'13]

$$\left(\frac{dE}{dtdV}\right)_{deposit} = f(z)\left(\frac{dE}{dtdV}\right)_{inject} \propto f(z) \times \begin{cases} n_{DM}^2 \langle \sigma v \rangle & \text{annihil} \\ n_{DM}/\tau_{DM} e^{-t/\tau_{DM}} & \text{decay} \end{cases}$$

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  see e.g. [Ripamonti'06, Slatyer'09, Valdes'10, Evoli'12, Slatyer'12, Galli'13, Weniger'13]

$$\left(\frac{dE}{dtdV}\right)_{deposit} = f(z)\left(\frac{dE}{dtdV}\right)_{inject} \propto f(z) \times \begin{cases} n_{DM}^2 \langle\sigma v\rangle & \text{annihil} \\ n_{DM}/\tau_{DM} e^{-t/\tau_{DM}} & \text{decay} \end{cases}$$

  $f(z) =$ energy deposition efficiency: amount of energy absorbed by the medium at z
  including contributions from particles injected at all $z' > z$.

Minimum Halo mass

$$\mathcal{B}(z) \propto \int_{M_{\min}} \frac{dn(M,z)}{dM} \, dM \int_0^{R_{\mathrm{vir}}} \rho^2(r) \, 4\pi r^2 dr$$

Even for $M_{\min} = 10^{-3} \, M_\odot$
$\rightsquigarrow$ X-ray heating peak
(partially) in emission for
$m_{\mathrm{DM}} = 130$ MeV
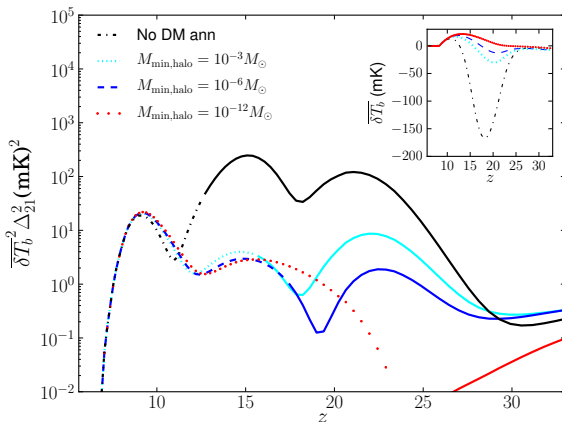
Halo Contributions- Substructures

In practice we have made the substitution:

$$\int_0^{R_{\text{vir}}} \rho^2(r)\, 4\pi r^2\, dr$$

$$\rightarrow \int_0^{R_{\text{vir}}} \rho^2(r)\, 4\pi r^2\, dr + \int_{M_{\min}}^{M} \frac{dn_{\text{sub}}}{dm}\, dm \int_0^{r_{\text{vir}}} \rho_{\text{sub}}^2(r_{\text{sub}})\, 4\pi\, r_{\text{sub}}^2\, dr_{\text{sub}}\,,$$
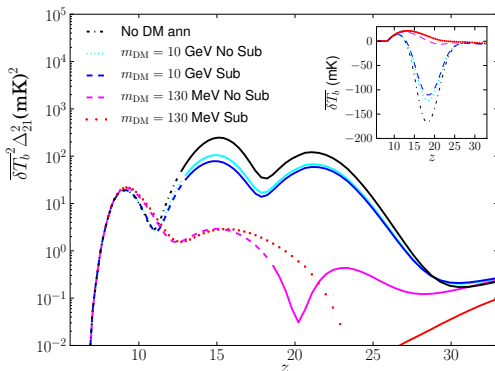
- $dn_{\text{sub}}/dm = A/M\,(m/M)^{-\alpha}$, we set $A = 0.012$ [Sanchez-Conde'13] and $\alpha = 2$ for largest effects
- effect of subhalos more significant for 130 MeV but X-ray heating peak still fully in emission.

Theoretical uncertainties and experimental forecasts

- Large astro uncertainties (green region $\equiv$ varying $N_\alpha, \zeta_X, dn/dM, M_{\rm vir}$).
- Assuming complete foreground removal (using `21cmSense`)
  - promising sensitivity for $z < 16$ for default model
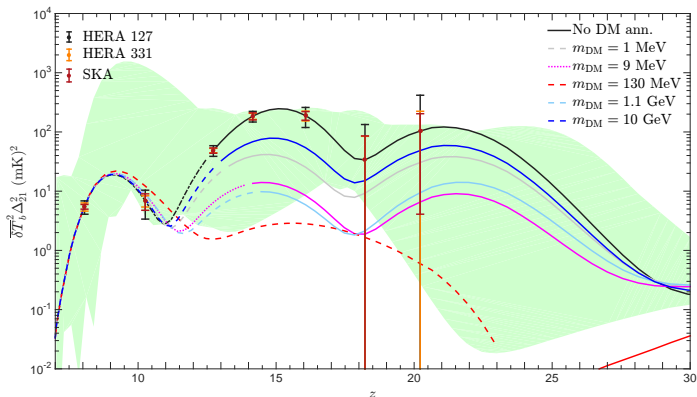
X-ray efficiency

X-ray emission rate is directly proportional to the number of X-ray photons per $M_\odot$ in stars: ζ_X
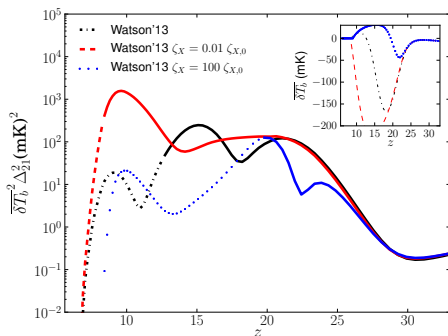
increasing ζ_X
$\rightsquigarrow$ earlier X-ray heating

- less pronounced dip in $\delta\bar{T}_b$
- earlier X-ray peak in P_{21}

$$\zeta_{X,0} = 10^{56}\, M_\odot^{-1} \;\leftrightarrow\; N_X \simeq 0.1$$

Ly$_\alpha$ contribution from stars

The direct stellar emission of photons between Ly$_\alpha$ and the Lyman limit will redshift until they enter a Lyman series resonance and subsequently, may generate Ly$_\alpha$ photons.

Increasing N_α
(driving $J_{\alpha,\star}$):

- deeper trough in $\delta\bar{T}_b$
- earlier Ly$_\alpha$ peak in P_{21}
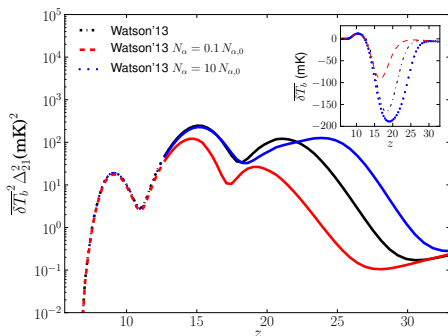
$N_{\alpha,0}$ assumes Pop II stars [Barkana'04],

normalizing their emissivity to $\sim$ 4400 ionizing photons per stellar baryon

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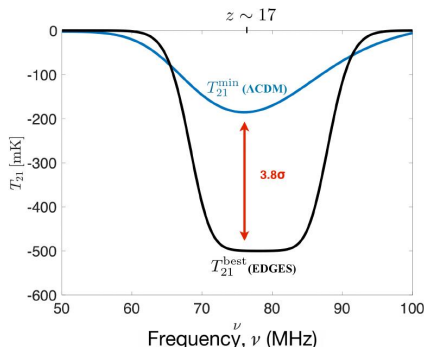
- **First detection** of an absorption trough at 78+/-1 Mhz (z~17) with amplitude 0.5$^{+0.2}$$_{-0.5}$K at 99% CL

- **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]

EDGES result of observation

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]

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

$\zeta_X = 5 \times 10^{56}/M_\odot, f_* = 0.01, T_{\rm vir}^{\rm min} = 10^3\,{\rm K}$

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

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Legend: $\sigma_{IDM}/m_{DM} = 10^{-8}\,\sigma_T/GeV$, $\sigma_{IDM}/m_{DM} = 10^{-9}\,\sigma_T/GeV$, $\sigma_{IDM}/m_{DM} = 10^{-10}\,\sigma_T/GeV$, $\sigma_{IDM}/m_{DM} = 10^{-11}\,\sigma_T/GeV$, CDM

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

Imprint of NCDM

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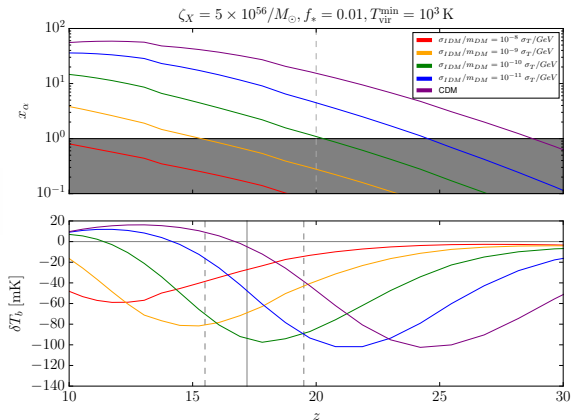
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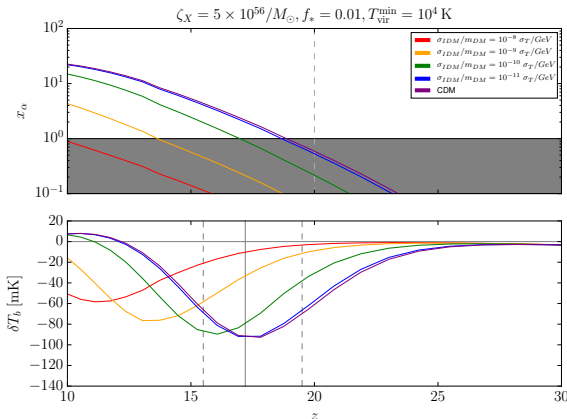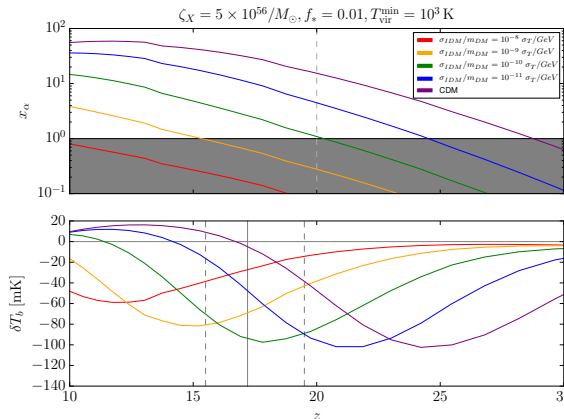 $$x_\alpha(z=20) \gtrsim 1$$

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$\zeta_X = 10^{56}/M_\odot, f_* = 0.01, T_{\mathrm{vir}}^{\mathrm{min}} = 10^3\,\mathrm{K}$

$\sigma_{IDM}/m_{DM} = 10^{-8}\,\sigma_T/GeV$
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$\sigma_{IDM}/m_{DM} = 10^{-11}\,\sigma_T/GeV$
CDM

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

Constraints on NCDM from EDGES

$f_* = 0.01, \zeta_X = 5 \times 10^{56} M_\odot^{-1}$

- 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]

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

and Satellite number count:

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

Can be relaxed for larger f_* !

Constraints on NCDM from EDGES

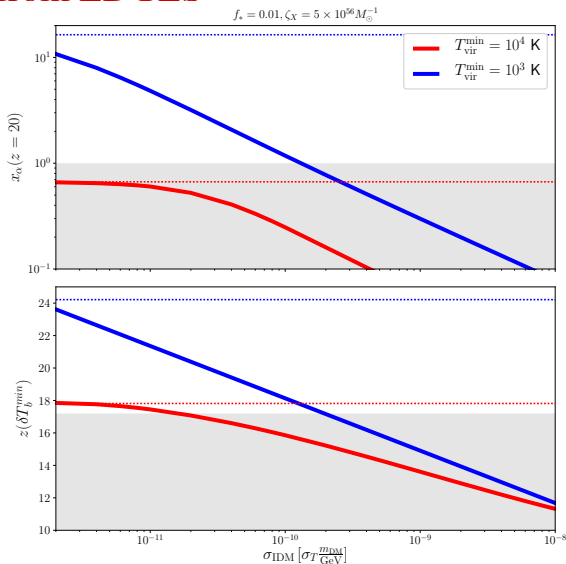$f_* = 0.01, \zeta_X = 5 \times 10^{56} M_\odot^{-1}$
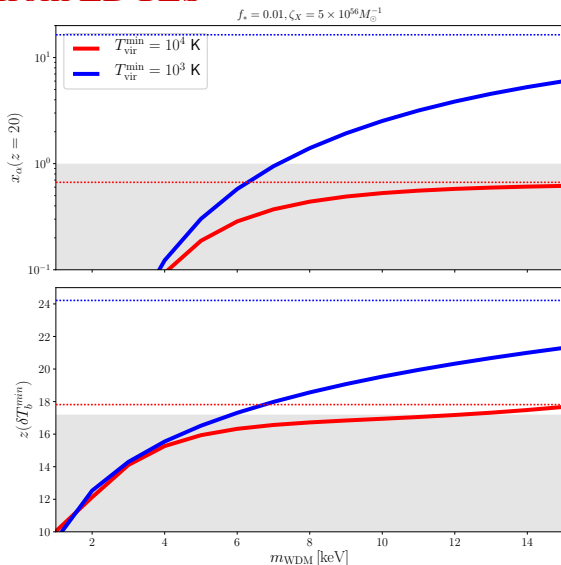
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$f(z)$

- High energy photons (GeV,TeV) or electrons do not deposit directly their energy in the medium.
- Their energy is degraded to ~ 3 keV [Slatyer'13] energy before being possibly absorbed by atomic processes (heat, ionisation, excitation)
- For high energy e^- the main energy loss is Inverse Compton Scattering (ICS) on the CMB $\gamma e \to \gamma e \rightsquigarrow$ effective injected photon spectrum
- For high energy γ we have (per order of increasing E)
    - photoionization
    - Compton scattering
    - pair production off nuclei: $\gamma A \to A e \bar{e}$
    - photon photon scattering
- Photons produced originally or in the cooling cascade can fall into the "transparency window" depending on their energy (typically between 10^6 and 10^{12} eV) or redshift (at low redshift universe more transparent) $\rightsquigarrow$ their energy is possibly never degraded to the atomic scale $\rightsquigarrow$ part of diffuse γ background

Resonant scattering of Lyα photons
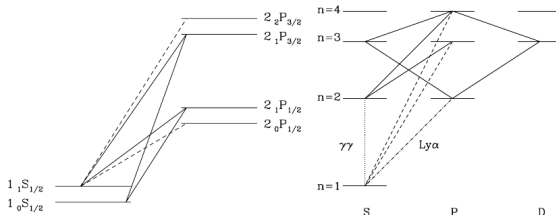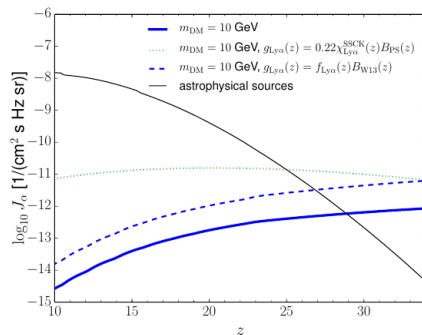
Cause spin flip transitions

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]

Impact of DM with s-wave annihilation

DM imprint $\equiv$ earlier and uniform heating of the IGM, see also [Valdes'13, Evoli'14]

Halo mass function

Ionization, heating and excitation critically depend on the fraction of mass collapsed in halos

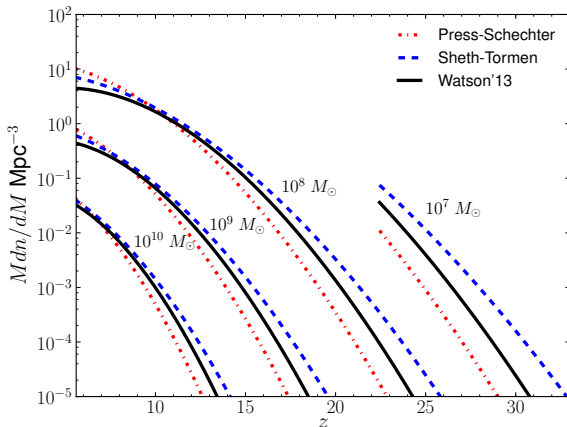$$f_{\text{coll}}(> M_{\text{vir}}) = \int_{M_{\text{vir}}} \frac{M}{\rho_0} \frac{dn(M,z)}{dM} \, dM \, ,$$
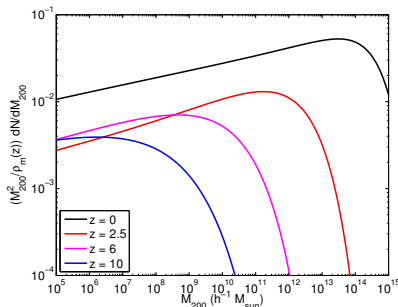
Halo contribution from N-body simulations

$$G(z) \equiv \frac{1}{\left(\Omega_{\text{DM},0}\, \rho_{c,0}\right)^2}\, \frac{1}{(1+z)^6}\, \int_{M_{\min}}^{\infty} \mathrm{d}M\, \frac{\mathrm{d}n(M,z)}{\mathrm{d}M}\, \int_0^{r_\Delta} \mathrm{d}r\, 4\pi r^2\, \rho_{\text{halo}}^2(r)\ .$$

- For NFW profile:
  $\int_0^{r_\Delta} dr\, 4\pi r^2\, \rho_{\text{halo}}^2(r) = \tilde{g}(c_\Delta)\, \frac{M\, \Delta\, \rho_c(z)}{3}$
  The concentration param. c_Δ is obtained
  from MultiDark/BigBolshoi simulations
  [Prada '11] (the fitting function is
  extrapolated outside limited simul. range)

- $\frac{\mathrm{d}n_{\text{halo}}(M,z)}{\mathrm{d}M} = \frac{\rho_{\text{m}}(z)}{M^2}\, \frac{\mathrm{d}\ln \sigma^{-1}}{\mathrm{d}\ln M} f(\sigma, z)\ ,$

The parametrization of the differential mass function $f(\sigma, z)$ is based on the results obtained in
[Watson'12] by using the CubeP^{3}M halofinder (CPMSO) and the Amiga Halo Finder (AHF).
We have used this fit outside the range where it was obtained, $-0.55 \leq \ln \sigma^{-1} \leq 1.35$, with
$\sigma(M, z)$ the rms density fluctuation, across all redshifts There could be differences of up to a
few orders of magnitude with respect to other parametrizations.

For 21 cm signal probes: Halo Contributions- Substructures

$$\int_0^{R_{vir}} \rho^2(r)\, 4\pi r^2\, dr$$

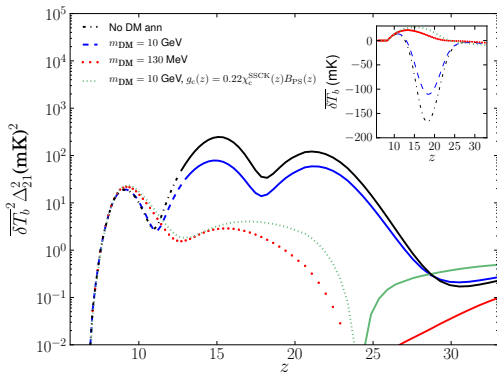$$\rightarrow \int_0^{R_{vir}} \rho^2(r)\, 4\pi r^2\, dr + \int_{M_{min}}^{M} \frac{dn_{sub}}{dm}\, dm \int_0^{r_{vir}} \rho_{sub}^2(r_{sub})\, 4\pi r_{sub}^2\, dr_{sub}\,,$$

- $dn_{sub}/dm = A/M\,(m/M)^{-\alpha}$, ($\alpha$ in the range [1.9, 2] in simu [Diemand'06, Madau'08, Springel'08]) and we set $A = 0.012$ [Sanchez-Conde'13].
- We took $\alpha = 2$ for largest effects Concentrat^o-$\sigma(M)^{-1}$ as for haloes from [Prada'12], with z dependence as $\sigma(M) \propto 1 + z$
- More concentrated sub $\rightsquigarrow$ factor of a few in ann. rate [Moline'16]
- we checked that not overcounting tot+ sub $\rightsquigarrow$ reduction of 10-30% ann. rate

Previous analysis : comparison

- *With DM annihilations the X-ray heating peak in the 21 cm power could be lower than the other two peaks:* not for the case considered in [Evoli'14] but ok for $m_{\text{DM}} = 130$ MeV and $\langle \sigma v \rangle = 10^{-28}$ cm^3/s, even for $M_{\text{min}} = 10^{-3} M_\odot$.

- *Dramatic drop in large-scale power between the Lyα pumping and X-ray heating epochs.* This feature is only seen for the most extreme case we consider.

- *The X-ray heating peak could occur when the IGM is already in emission against the CMB:* we only do reach that conclusion for the most extreme of our cases, $m_{\text{DM}} = 130$ MeV, $\langle \sigma v \rangle = 10^{-28}$ cm^3/s and $M_{\text{min}} = 10^{-12} M_\odot$.

Evolution equations

- Ionized fraction:

$$\frac{dx_e(\mathbf{x}, z)}{dz} = \frac{dt}{dz} \left(\Lambda_{\text{ion}} - \alpha_{\text{A}} \, C \, x_e^2 \, n_b f_{\text{H}} \right)$$

- Gas temperature:

$$\frac{dT_K(\mathbf{x}, z)}{dz} = \frac{2}{3 \, k_B \, (1 + x_e)} \frac{dt}{dz} \sum_{\beta} \epsilon_{\beta} + \frac{2 \, T_K}{3 \, n_b} \frac{dn_b}{dz} - \frac{T_K}{1 + x_e} \frac{dx_e}{dz} \, ,$$

- Lyα background:

$$J_\alpha = J_{\alpha,X} + J_{\alpha,\star} + J_{\alpha,\text{DM}}$$

Evolution equations

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- Lyα background:

$$J_\alpha = J_{\alpha, X} + J_{\alpha, \star} + \boxed{J_{\alpha, \text{DM}}}$$

⤳ we make use of `21cmFast` to generate the 21cm background signal and powerspectrum.

DM contributions

- Ionized fraction and for the kinetic temperature of the gas

$$\Lambda_{\text{ion}}|_{\text{DM}} = \mathfrak{f}_{\text{H}} \frac{\epsilon_{\text{HI}}^{\text{DM}}}{E_{\text{HI}}} + \mathfrak{f}_{\text{He}} \frac{\epsilon_{\text{HeI}}^{\text{DM}}}{E_{\text{HeI}}} \,, \tag{1}$$

$$\left.\frac{dT_K}{dz}\right|_{\text{DM}} = \frac{dt}{dz} \frac{2}{3 \, k_B \, (1 + x_e)} \, \epsilon_{\text{heat}}^{\text{DM}} \,, \tag{2}$$

where $E_{\text{HI,HeI}}$ are the ionization energies for hydrogen and helium and $\mathfrak{f}_{\text{He}} = N_{\text{He}}/N_b$ is the helium number fraction.

- The Lyα flux

$$J_{\alpha,\text{DM}} = \frac{c \, n_b}{4\pi} \frac{\epsilon_{\text{Ly}\alpha}^{\text{DM}}}{h\nu_\alpha} \frac{1}{H(z)\nu_\alpha} \,, \tag{3}$$

where ν_α is the emission frequency of a Lyα photon.

bla

This is really the end