Particle Physics at Cosmic Dawn - Part II

Focus on Dark Matter imprint

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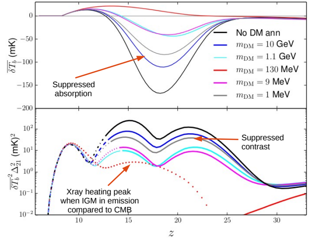
inspired by JCAP 07 (2013) 046, JCAP 02 (2014) 017,and JCAP 08 (2016) 004
in collaboration with R. Diamanti, O. Mena, A. Moline, S. Palomares Riuz, and A. Vincent

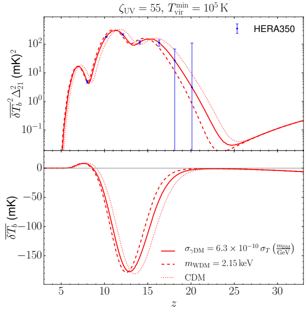
Frontiers of Astrophysics and Cosmology
Scuela Normale (Pisa, Italy)

In these seminar-lectures

- Extra energy injection
  - Annihilating DM
  - Energy injection affect e.g. CMB
  - further constraints from imprint at cosmic dawn?



- Delay of structure formation
  - Non Cold Dark Matter: free-streeming, collisional damping
  - also delay in 21cm features
  - can help to disentangle NCDMs?



Energy injection

Energy injection: Ionization, excitations and Heating

DM energy injection implies extra heating and ionization rates:

$$\begin{aligned} \dot{x}_e &= \Lambda_{ion} - \Lambda_{rec} + \Lambda_{\rm DM} \\ \dot{T}_k &= Q_{adia} + \sum_\alpha Q_\alpha + Q_{\rm DM} \\ J_\alpha &= J_{\alpha,*} + J_{\alpha,X} + J_{\alpha,{\rm DM}} \end{aligned}$$

$Q_{\rm DM}, \Lambda_{\rm DM} \propto \left.\frac{dE}{dtdV}\right|_{\rm inj}$ depend on the DM fundamental properties:

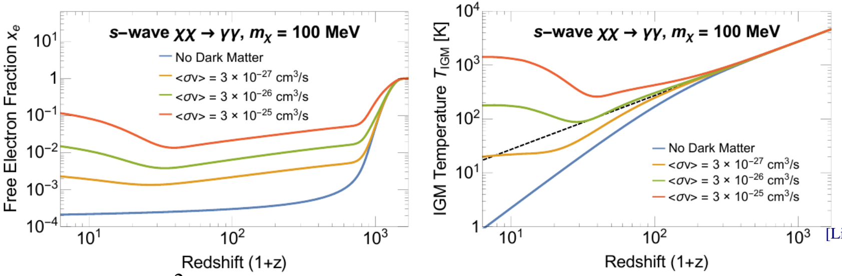
s-wave annihilating DM ($\langle\sigma v\rangle \sim \sigma v_0$)	$\frac{dE}{dtdV} \propto \frac{\rho_\chi^2}{m_\chi} \times \sigma v_0$
accreting Primordial Black Holes (PBH)	$\frac{dE}{dtdV} \propto n_{PBH} \times L_{acc}$
p-wave annihilating DM ($\langle\sigma v\rangle \sim \langle v^2\rangle$)	$\frac{dE}{dtdV} \propto \frac{\rho_\chi^2 \langle v^2\rangle}{m_\chi} \times \frac{\sigma v_0}{v_0^2}$
decaying DM	$\frac{dE}{dtdV} \propto \rho_\chi \times \tau_\chi^{-1} e^{-t/\tau_\chi}$

Each of these depositions give rise to
a different IGM ionization and temperature history.

Early or later energy injection history

Early energy deposition e.g. s-wave annihilating DM (e.g. complex scalar ann to $\bar{f}f$):

$$\frac{dE}{dtdV} \propto (1+z)^6 \frac{\rho^2_{\chi,0}}{m_\chi} \times \sigma v_0$$



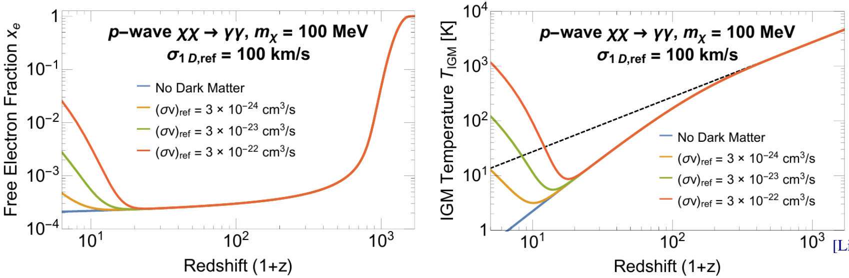
[Liu'16]

+ later Boost of ρ^2_χ from structure formation see e.g. [LLH'13, Liu'16, etc]

Early or later energy injection history

Later energy deposition e.g. p-wave annihilating DM
(e.g. neutralino ann to $\bar{f}f$):

$$\frac{dE}{dtdV} \propto (1+z)^6 \langle v^2 \rangle \frac{\rho^2_{\chi,0}}{m_\chi} \frac{\sigma v_0}{v_0^2}$$



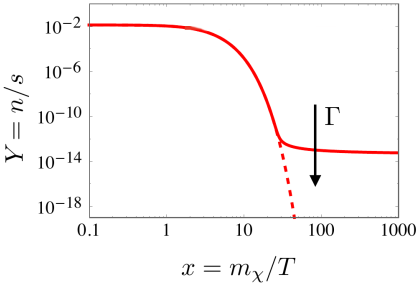
[Liu'16]

very suppressed due to low CDM velo at early times but later Boost of $\langle v^2 \rangle \rho_\chi^2$ from structure formation see e.g. [Diamanti'13, Liu'16,etc]

Here we focus on the illustrative case of
s-wave annihilating DM benchmark

s-wave annihilating DM- Aka vanilla WIMP

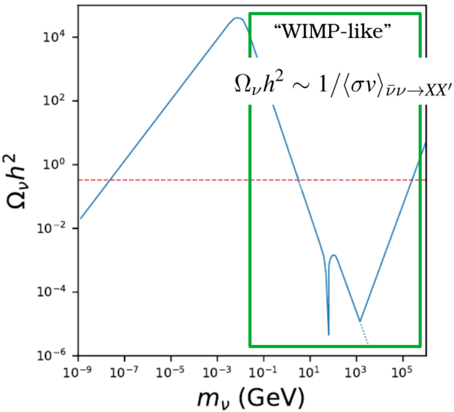
$$\frac{df_\chi}{dt} = \mathcal{C}[f_\chi] \quad \rightsquigarrow \quad \dot{n}_\chi = \sigma v_0 (n_\chi^2 - n_{\chi,eq}^2)$$



- DM annihilation driven freeze-out
- χ chem. & kin. equilibrium
- $\Omega_\chi \propto 1/\sigma v_0$
- $\Omega_\chi h^2 = 0.12$
  $\rightsquigarrow \sigma v_0 = 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$
- $x = m_\chi/T$ and $x_{\mathrm{FO}} \sim 25$

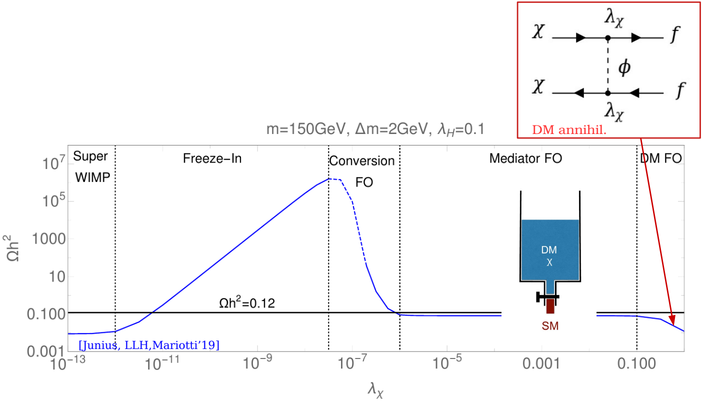
Careful: coannihilations, velocity suppressed $\langle \sigma v \rangle$, potential large contributions from higher order processes, etc, not taken into account in this simple picture.

Some freeze-out/WIMP examples



The SM neutrino

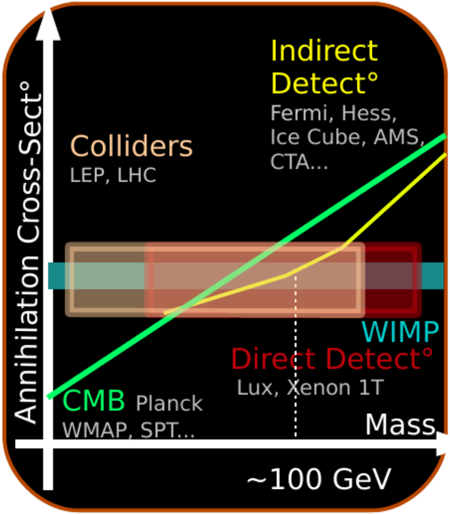
Some freeze-out/WIMP examples



Leptophilic DM: $\mathcal{L} \subset \lambda_\chi \phi \bar{\chi} f_R \; + \; h.c.$

Testing s-wave ann. DM - aka Vanilla WIMP

An annihilation cross-section $\sigma v_0 \sim$ few $\times 10^{-26}\,\mathrm{cm}^3$ is a prime target for DM searches including for cosmology-related experiments.



From energy injection to deposition

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,LLH'16],
see also [Adams'98,Chen'03, Hansen'03, Pierpaoli'03, Padmanabhan'05] for CMB

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

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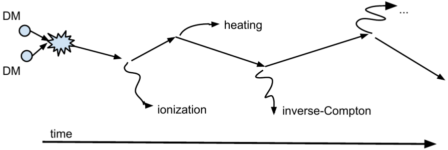
- Dark matter annihilation inject energy within the dark ages



[image from A. Vincent]

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

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

$f_c(z)$ = energy deposition efficiency per channel
(obtained using tabulated transfer fns $T^c(z, z', E)$ [Slatyer '15, Liu'19])

From Injected to Deposited: clustering can matter

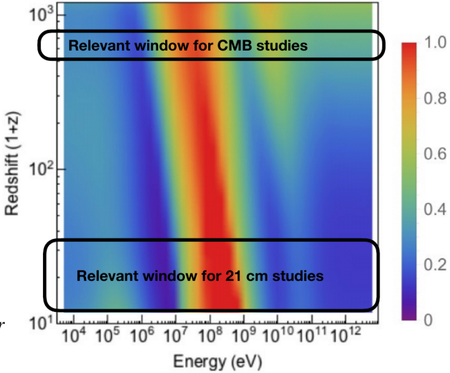
- Energy deposition efficiency channel ≡ includes contribs. from particles injected at all z‘>z

- Boost at late times due to structure formation

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

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

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



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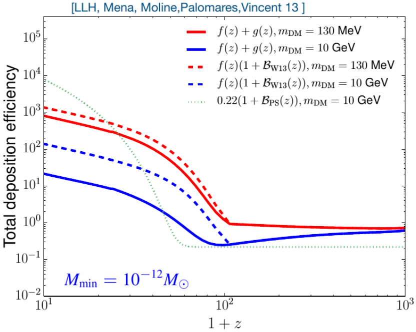
- astro uncertainties for 21cm signal

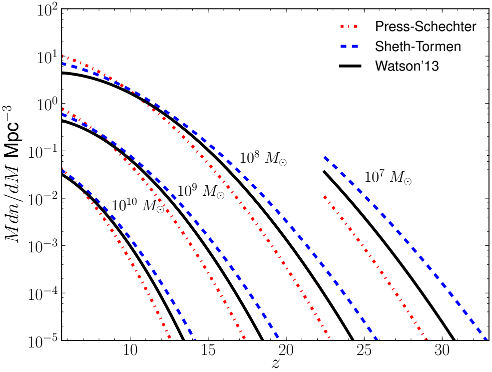


$$\int dz' \,[1+\mathcal{B}(z')]\, T^c(z,z',E)$$

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

see e.g. [Slatyer'12]

CDM halo mass function



- 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
- W13: our default

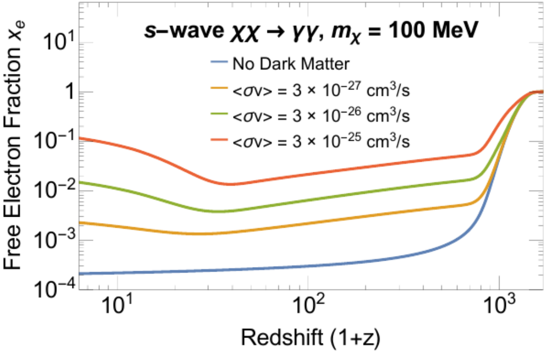
$\rightsquigarrow$ PS $\rightarrow$ W13 $\rightarrow$ ST: larger number of fixed mass halo at fixed z at early time

Notice that the assumed dn/dM not only plays a key role for the DM energy injection efficiency but **also** on ionization, heating and excitation from astro sources when using semi-numerical approaches as 21cmFast code, see later discussion.

DM energy injection imprint on Cosmology Observables

DM annihilation implies higher ionization floor

Extra ionization due to DM annihilation final states:



[Liu'16]

Early energy injection

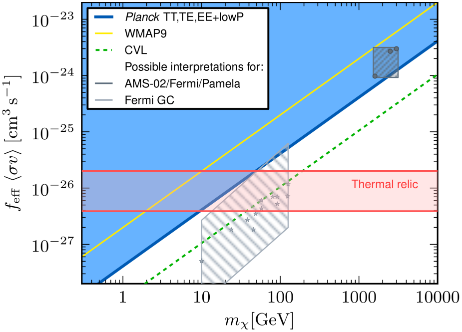
⇝ increased residual ionization right after recombination

⇝ broadening of the last scattering surface

⇝ attenuates correlations at small scales (large ℓ) and increases the polarisation fluctuations in the CMB T and polarisation 2D-power spectra.

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

$m_{\rm DM}$ [GeV]	0.001	0.009	0.13	1.1	10
$\langle\sigma v\rangle$ [cm^3/s]	10^{-30}	10^{-29}	10^{-28}	10^{-27}	10^{-26}

$\rightsquigarrow$ $p_{ann} = f_{eff}\langle\sigma v\rangle / m_{DM} < 4.1\ 10^{-28}$ cm^3/s/GeV at 95% CL [Planck'15]

similar to new [Planck'18] results

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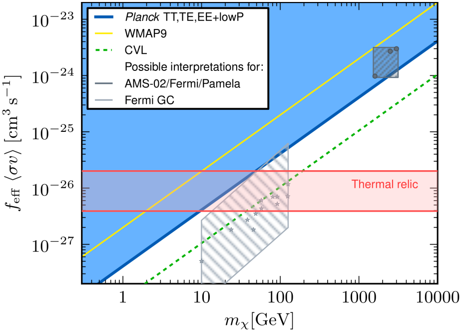

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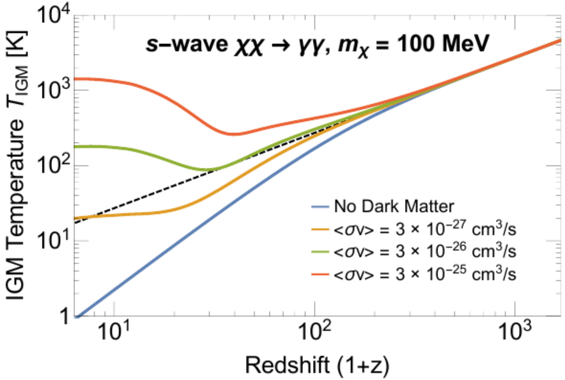
- Advantage of CMB compared to other DM annihilation probes: do not suffer astrophysics uncertainties (such as ρ_{DM}) and no contributions from halos for σv independent of v (s-wave annihilation) [LLH'13, Poulin'15, Hongwan'16].

DM annihilation implies earlier heating

Extra heat due to DM annihilation final states:



[Liu'16]

Early heating of IGM

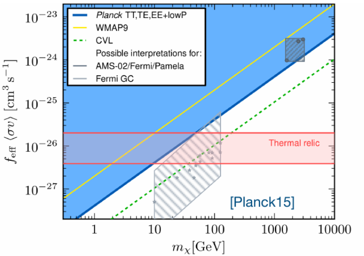
$\rightsquigarrow$ increased T_k when astro sources light-on

$\rightsquigarrow$ When $T_S \sim T_k$ and $T_k < T_{CMB} \rightsquigarrow |\delta T_b| \sim |(1 - T_{CMB}/T_S)|$ is suppressed

$\rightsquigarrow$ suppressed absorption in δT_b at cosmic dawn

DM energy injection: earlier heating

see also [Hansen'04, Pierpaoli'04, Bierman'06, Mapelli'06, Valdes'07, Natarajan'08, Evoli'14, etc]



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

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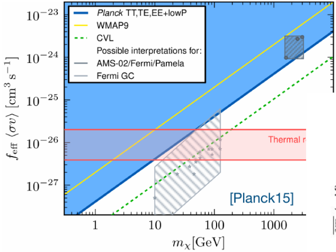
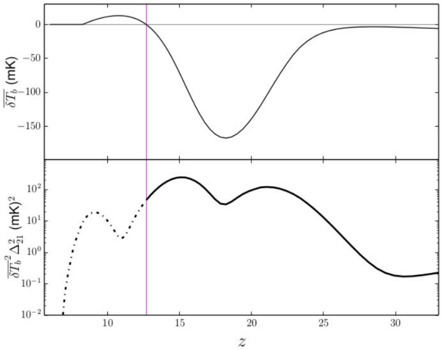


[LLH, Mena, Moline,Palomares,Vincent 16]



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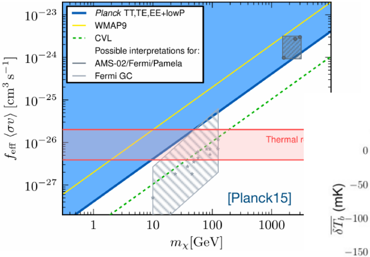

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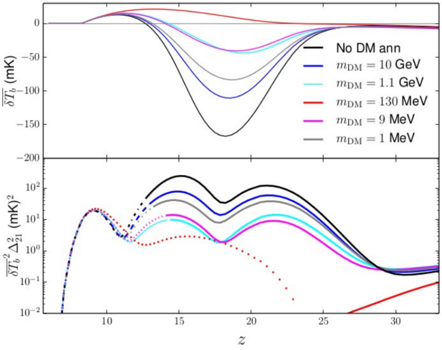

- Suppressed absorption
- Imposing some maximal δTb could constrain DM annihilation

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

DM energy injection: earlier heating

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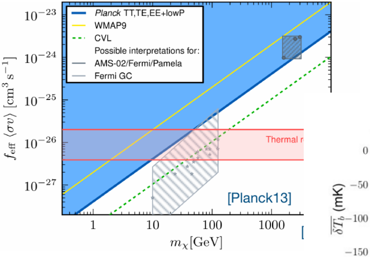
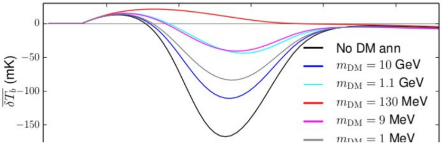
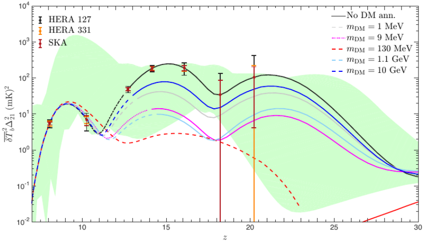


Beware!
large astrophysics
uncertainties

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





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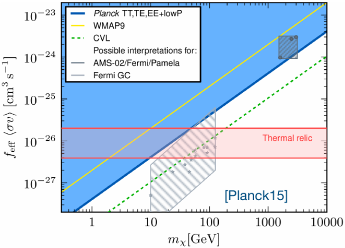

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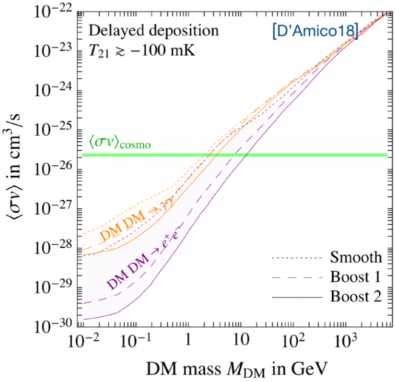


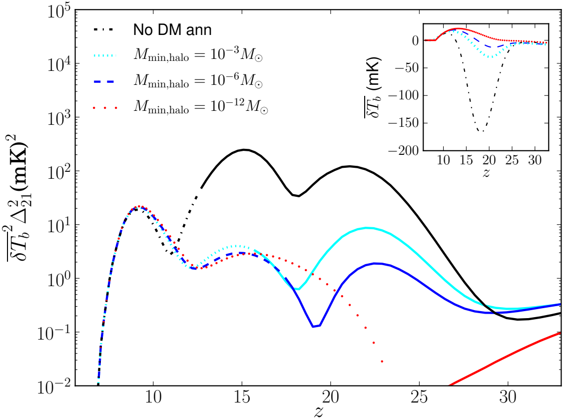
see also [Valdes13, Evoli14,LLH16, Liu18]

Astrophysics/DM parameters (a selection)

Minimum Halo mass

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

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

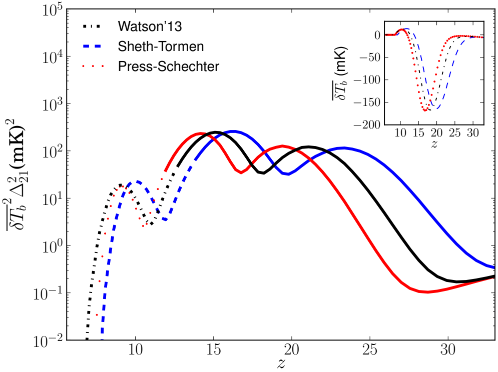


Astrophysics Uncertainties: Halo mass function

Using semi-numerical tools such as 21cmfast [Mesinger'10]: δT_b and Δ_{21}

⇝ depends on halo mass function, T_{vir}, L_X (ζ_X), N_α. In particular, the ionization, heating and excitation critically depend on the fraction of mass collapsed in halos

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



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⇝ PS → W13 → ST: astro sources switch on earlier

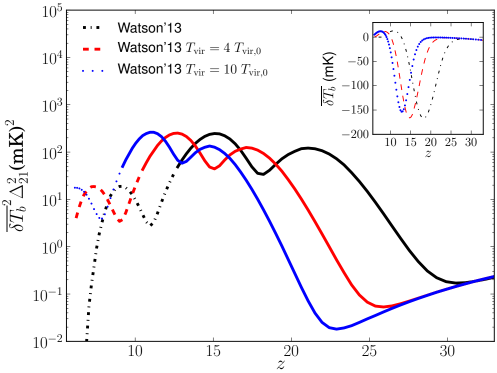
Astro Uncertainties: Threshold for star formation

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

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

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

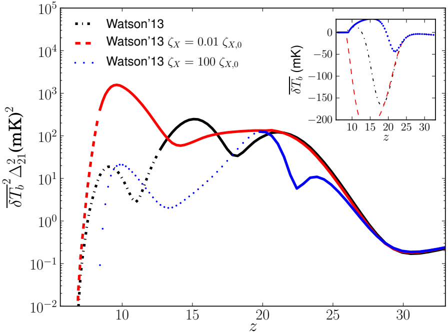
$$M_{\rm vir} \simeq 10^8 \left(\frac{T_{\rm vir}}{2\,10^4\,{\rm K}} \frac{10}{1+z}\right)^{3/2} M_\odot$$



$\rightsquigarrow$ larger $M_{\rm vir}$ threshold implies a delay in the X-ray and UV sources.

Astro Uncertainties: 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}

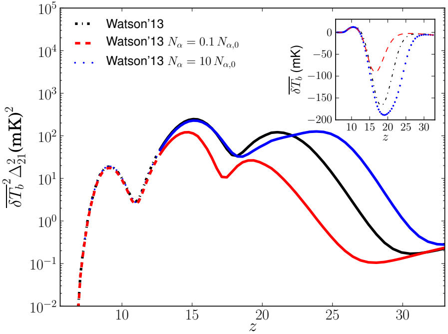
$\zeta_{X,0} = 10^{56}\, M_\odot^{-1} \leftrightarrow \frac{L_{X<2\mathrm{keV}}}{SFR} \sim 10^{39.5} erg/s/(M_\odot/yr)$

Astro-uncertainties: 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 less pronounced dip in $\delta\bar{T}_b$
- earlier Ly$_\alpha$ peak in P_{21}



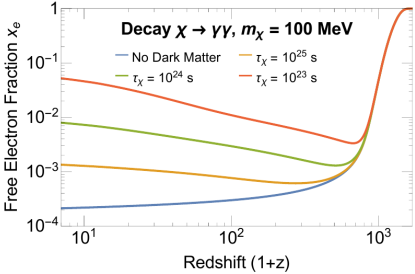
$N_{\alpha,0}$ assumes Pop II stars [Barkana'04],

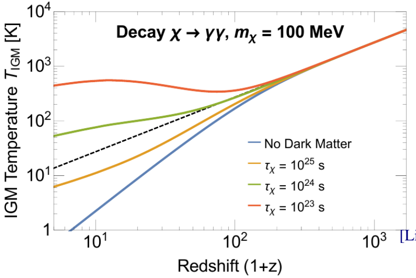
normalizing their emissivity to $\sim$ 4400 ionizing photons per stellar baryon

Other scenarios with energy injection (a selection)

Decaying DM energy injection history

$$\frac{dE}{dtdV} \propto (1+z)^3 \frac{\rho_{\chi,0}}{m_\chi} \times \frac{\exp[-t/\tau]}{\tau}$$



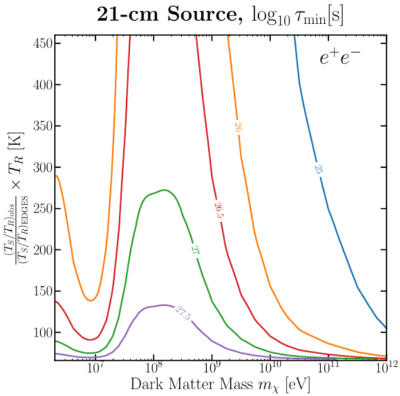


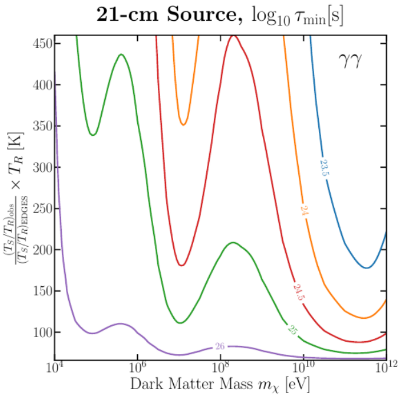
[Liu'16]

Decaying DM: Constraints on τ_{DM} from T_S/T_R

EDGES T_{21} at $z \sim 17.2$ of $\bar{T}_{21} = -500^{+200}_{-500}$ mK

$\frac{T_m}{T_R}(z = 17.2) \lesssim 0.105$

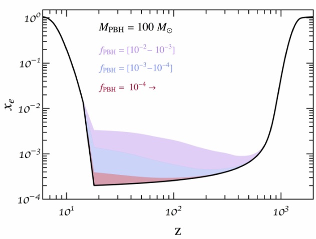


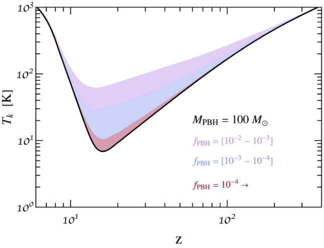


Minimum decay life time Liu 1803.09739

Accreting PBH injection history

$$\frac{dE}{dtdV} \propto (1+z)^3 n_{PBH,0} L_{acc}(z)$$





[Mena'19]

FIG. 1. Free electron fraction, x_e, as a function of redshift, including the contribution of a monochromatic PBH population with mass $M_{\rm PBH} = 100\,M_\odot$, for different PBH dark matter fractions $f_{\rm PBH} = (10^{-2}, 10^{-3}, 10^{-4}, \lesssim 10^{-4})$. The standard scenario with $f_{\rm PBH} = 0$ is denoted by the solid black line. We use fiducial astrophysical parameters: $(\zeta_{\rm UV}, \zeta_{\rm X}, T_{\rm min}, N_\alpha) = (50,\, 2\times 10^{56}\, M_\odot^{-1},\, 5\times 10^4\, K,\, 4000)$; see Section IV.1.

FIG. 2. Kinetic temperature of the gass, T_k, as a function of redshift, including the contribution of a monochromatic PBH population with mass $M_{\rm PBH} = 100\,M_\odot$, for different PBH dark matter fractions $f_{\rm PBH} = (10^{-2}, 10^{-3}, 10^{-4}, \lesssim 10^{-4})$. The standard scenario with $f_{\rm PBH} = 0$ is denoted by the solid black line. We use fiducial astrophysical parameters: $(\zeta_{\rm UV}, \zeta_{\rm X}, T_{\rm min}, N_\alpha) = (50,\, 2\times 10^{56}\, M_\odot^{-1},\, 5\times 10^4\, K,\, 4000)$; see Section IV.1.

$$L_{acc} = \epsilon \dot{M}$$

Carrefull: have to take into account extra poisson noise in the computations, Disk accretion has been assumed here and multiple models for PBH luminosity exists.

PBH accretion: effect on $\delta T_b, \Delta_{21}$

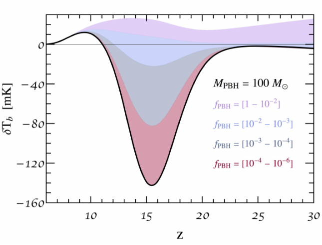
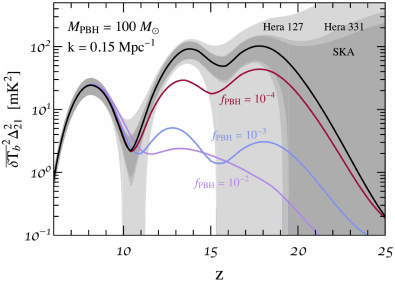
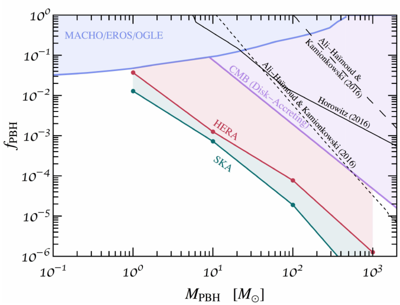


FIG. 3. Global 21cm differential brightness temperature for various values of $f_{\rm PBH}$, assuming $M_{\rm PBH} = 100\,M_\odot$ and different ranges for the PBH dark matter fraction. The standard scenario with $f_{\rm PBH} = 0$ is denoted by the solid black lines. We use fiducial astrophysical parameters: $(\zeta_{\rm UV}, \zeta_{\rm X}, T_{\rm min}, N_\alpha) = (50,\, 2\times 10^{56}\,M_\odot^{-1},\, 5\times 10^4\,K,\, 4000)$; see Section IV.1.



[Mena'19]

PBH accretion: forecasts 21 cm constraints



[Mena'19]

Take home message - Part II

- Multiple DM scenarios give rise to energy injection in the IGM at early time (DM decay, DM annihilation, PBH accretion etc).
- Heating the IGM prior to first stars giving rise to suppressed absorption in δT_b and suppressed power in Δ_{21} at early time.
- 21cm observations at cosmic dawn might help to test the DM properties beyond e.g. CMB or indirect DM detection probes

Thank you for the invitation
and for your attention!!

Backup

Evolution equations in the ionized phase

- Ionized fraction:

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

- 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:

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

Evolution equations

- Ionized fraction:

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

- 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:

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

$\leadsto$ 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

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

$$\frac{dT_K}{dz}\bigg|_{\rm DM} = \frac{dt}{dz}\, \frac{2}{3\, k_B\, (1+x_e)}\, \epsilon^{\rm DM}_{\rm heat}\,, \tag{2}$$

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

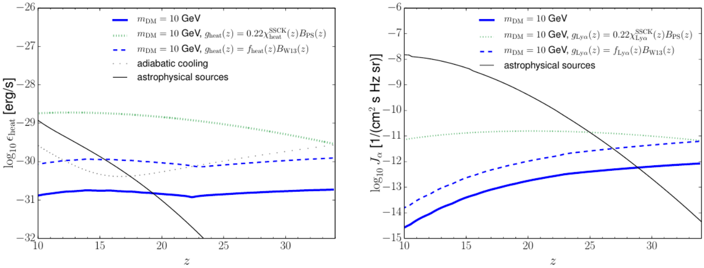
- The Lyα flux

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

where ν_α is the emission frequency of a Lyα photon.

Heating rate and Lyα flux

Comparison with a reproduction of DM energy deposition rate



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

Interactions of photons with IGM

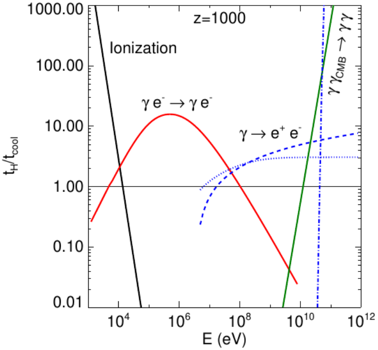
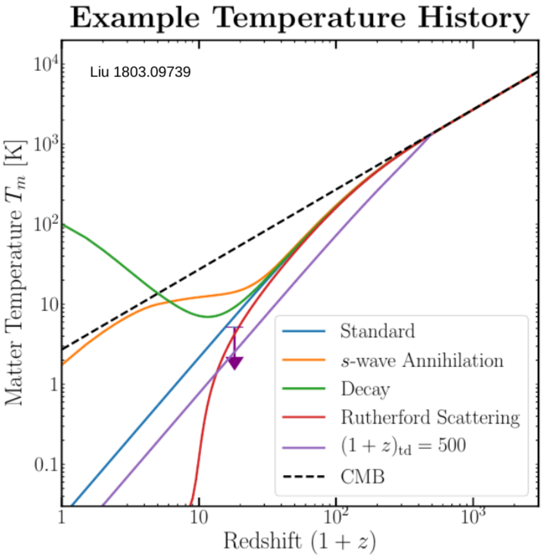


FIG. 1: A comparison of the photon cooling time to the Hubble time at $z = 1000$, for different photon energies. The dominant processes (in order of increasing energy) are ionization, Compton scattering, pair production on the H/He gas, photon-photon scattering, and pair production on the CMB. All the curves assume a He mass fraction of 1/4, with a density of 2.57×10^{-7} amu / cm^3 today. The dotted curve shows pair production on a neutral IGM, the dashed curve shows pair production on a fully ionized IGM, and the dashed-dotted curve represents pair production on the CMB. This figure updates Fig. 1 in [4], which had an error leading to cooling

Example history



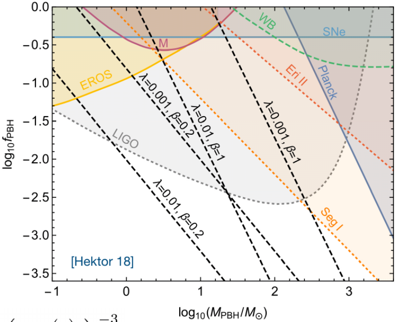
PBH energy injection: earlier heating

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

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



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

- 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

bla

This is really the end