The role of soft photon injection and heating in 21cm cosmology

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21cm Cosmology

- 21 cm ($\approx 1.4GHz$) line arises from hyperfine splitting of ground state of hydrogen
- Observable - 21cm brightness temperature relative to background radiation at that frequency

$$\Delta T_b = \frac{(1-\mathrm{e}^{-\tau_{21}})}{1+z}(T_S - T_R)$$

- Typically, $T_R = T_{\mathrm{CMB}}$ assuming this is the only background but it can have extra non-thermal contribution with $T_R = T_{\mathrm{CMB}} + \Delta T$.

21cm Cosmology

- Spin temperature (T_S) is defined as the ratio of population of upper and lower hyperfine states,

$$\frac{n_1}{n_0} = 3\mathrm{e}^{-\mathrm{T}_*/\mathrm{T}_\mathrm{S}}, T_* = \frac{h\nu_{21}}{k_B}$$

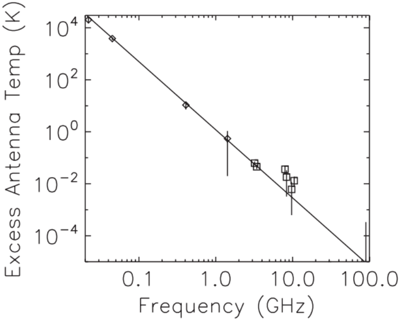
- Spin temperature is determined by processes such as interaction of HI with radiation, collision with other hydrogen atoms, electrons and protons, resonant scattering of Lyman-alpha photons from stars and X-ray heating from energetic photon sources.

Tale of two radio excess
1. EDGES

- Strong 21 cm absorption signal reported by EDGES collaboration (Bowman et al 2018) with $\Delta T_b \approx$ -500 mK at $z \approx 18$. For just CMB as a background, $\Delta T_b \approx -(100 - 150)$ mK.
- Since $\Delta T_b \propto x_{HI}\left(1 - \frac{T_R}{T_S}\right)$,extra radio background on top of CMB can potentially explain the absorption depth given the spin temperature does not get affected by the radio background
- EDGES measurement could not be reproduced by SARAS 3 (Singh et al 2022). We use EDGES as a figure of merit in our work.

Tale of two radio excess
2. ARCADE2/LWA excess

- Detected excess radio background, as seen today, on top of CMB within 20 MHz-10 GHz even after accounting for resolved discrete radio sources with best fit power law with index ≈ 2.6



Fixsen et. al 2011, Dowell and Taylor 2018

Interplay between two excesses

- If the ARCADE2/LWA excess was already present at $z \approx 20$, the absorption depth would have been even deeper than the EDGES detection (Feng and Holder 2018)

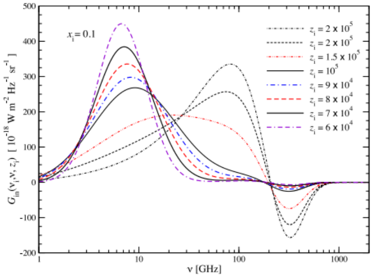
- EDGES detection allows for about 5 percent of radio excess at $z \approx 18$

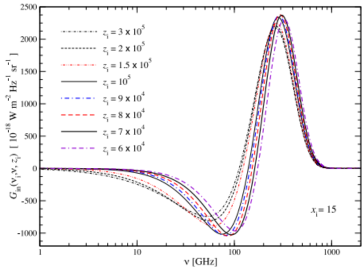
- 21 cm anisotropy measurements puts complementary constraints on allowed radio background at $z \approx 10$ (HERA collaboration 2022) though it does not allow or exclude EDGES measurements currently

- These constraints are derived assuming that the radio photons, once injected, just redshift over time

Impact of photon injection on thermal history of the Universe

- Addition of photons disturbs the equilibrium between CMB photons and the electrons
- CMB photons and the electrons evolve to establish the equilibrium but expansion of universe prohibits that giving rise to distortion from Planck spectrum.





Chluba(2015)

Consistent thermal history evolution with CosmoTherm

- We can consistently solve for evolution of thermal history of the universe using *CosmoTherm* (Chluba and Sunyaev 2012)
- One can compute evolution of injected photon spectrum, temperature evolution, ionization history and 21cm global distortion signal

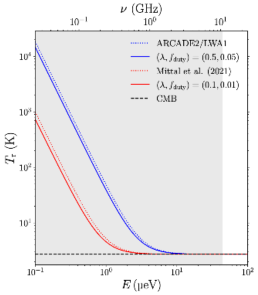
Soft vs hard photons

- Hard photons- photons with energy $>$13.6 eV. Can ionise neutral gas in post-recombination universe which changes ionization history drastically $\rightarrow$ strong CMB anisotropy constraint
- Soft photons- Lower energy photons cant ionise neutral gas directly. Heating due to absorption of these soft photons by electrons $\rightarrow$ rise in gas temperature and moderate change in post-recombination ionization history

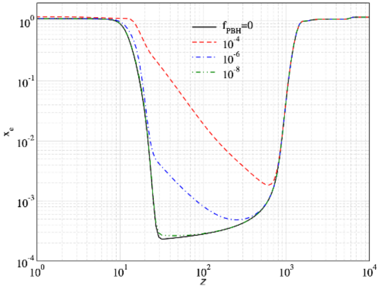
Complementarity of 21cm and CMB observables for astrophysical emission processes

- Typically, astrophysical emissions have broad emission spectrum

- For accreting primordial black holes, UV photon emission is strongly constrained by CMB anisotropies which then constraints amount of radio emission given there is a correlation between radio and UV flux



Mittal and Kulkarni 2022

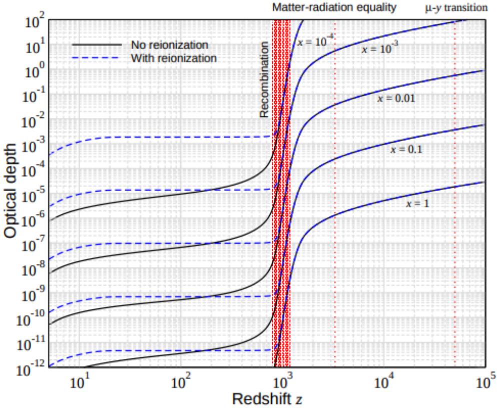


Acharya, Dhandha and Chluba 2022

Heating due to soft photons (SPH) at low redshifts

- Low frequency photons are absorbed by electrons via Bremsstrahlung process which leads to heating

$$x = \frac{E_\gamma}{k_B T_{\rm CMB}}$$



Bolliet et. al. 2022

Equation for photon evolution

$$\left.\frac{\mathrm{d}n(x)}{\mathrm{d}\tau}\right|_{ff} = \frac{\Lambda_{\mathrm{BR}} e^{-x_e}}{x_e^3}\left[1 - n(e^{x_e} - 1)\right]$$

$\tau = \int \sigma_{\mathrm{T}} N_e c dt,\ x_e = x \frac{T_{\mathrm{CMB}}}{T_M}$ (Chluba 2015)

- Energy of absorbed photons heat matter.
- We solve for coupled equations for $n(x)$, T_M and electron ionization fraction.

Phenomenological model for photon injection

- We consider a phenomenological profile for photon injection,

$$\frac{\mathrm{d}\rho_\gamma}{\mathrm{d}t} = f_{dm}\Gamma\rho_{cdm}\mathrm{e}^{-\Gamma \mathrm{t}}$$

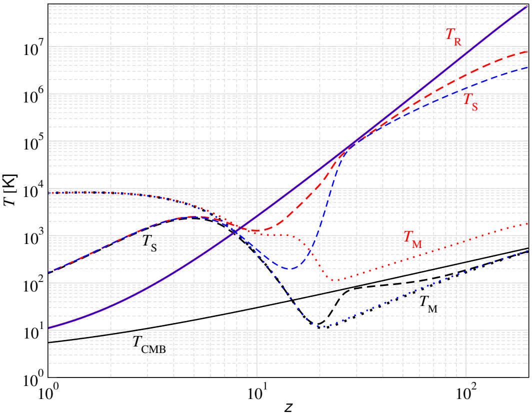
- The injection spectrum is a broad power-law distribution,

$$\Delta I(x) \propto x^{-\gamma}\mathrm{e}^{-\frac{x}{x_{inj,0}}}$$

- We consider two cases with $\gamma = 0$ and 0.6 which are free-free and synchrotron spectrum respectively

Thermal history including SPH

Acharya, Cyr, Chluba 2023

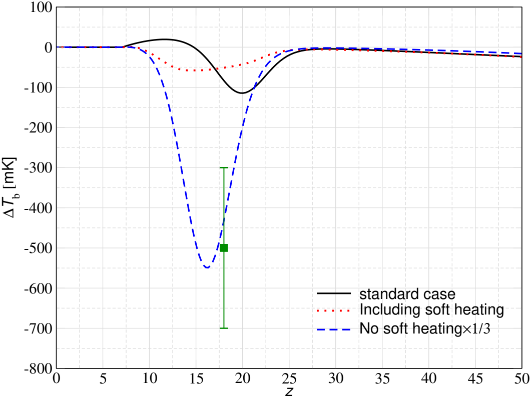


Black-standard cosmology,

Red-with SPH,

Blue-without SPH

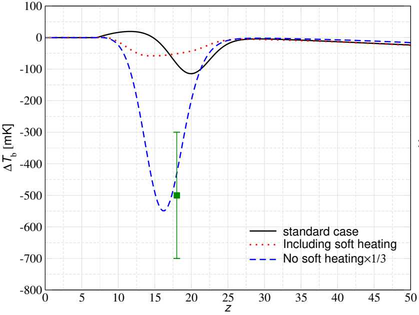
Implication for 21cm signal

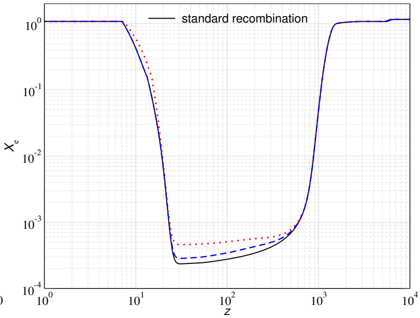


Parmeter combination chosen to have ARCADE excess at $z \approx 20$.

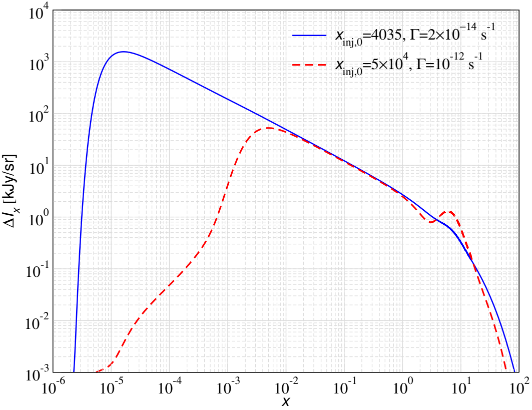
Complementarity with CMB observables

Heated baryons lead to less recombinations which lead to increased residual electron ionization fraction → modification to CMB anisotropies

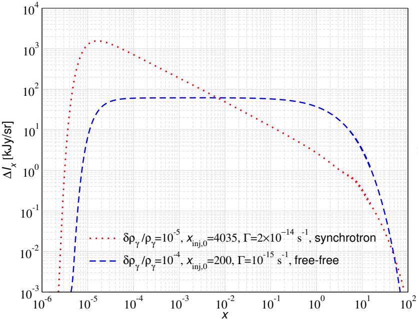


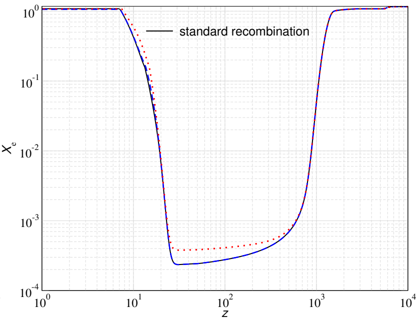


SPH mechanism is only effective in post-recombination Universe



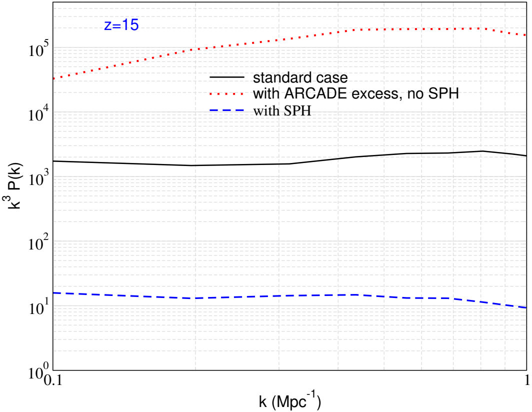
SPH mechanism is dependent on soft photon spectrum





Importance of SPH for 21cm anisotropy

Preliminary work



Conclusions

- We showed the importance of heating due to soft or radio photons for global 21cm signal
- Has implications for 21cm anisotropy signal too
- This effect can be computed using CosmoTherm and also with a simpler analytic prescription