Global 21-cm signal and its implications

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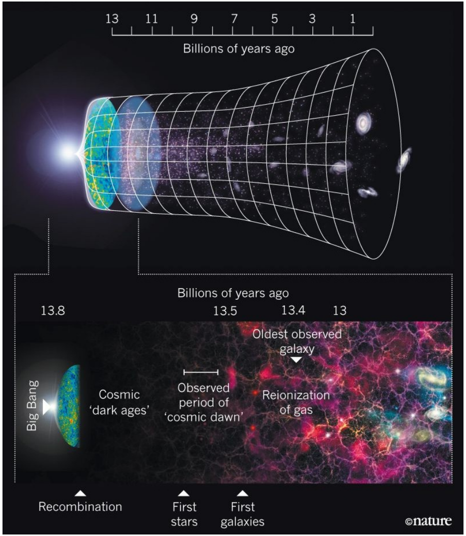
SOTU seminar, TIFR, Dec 2021

Outline

- Time evolution of the Universe
- Basics of the Global 21-cm signal
- Redshift Evolution of the signal
- Observation and Existing theory
- Implications of the signal
    - Constraining mass of the Warm Dark Matter
    - Estimating SFRD of PopIII stars
    - CosmoReionMC: A parameter estimation package to constrain cosmological and astrophysical parameters
- Future outlook
- Summary

Time evolution of the Universe



Basics of the Global 21-cm signal

- The cosmic mean 21-cm differential brightness temperature

$$\delta T_b \propto \left(\frac{T_S - T_\gamma}{T_S} \right) x_{HI}$$

(Field 1958)

- The spin temperature T_S can be written as

$$T_S^{-1} \simeq \frac{T_\gamma^{-1} + x_\alpha T_k^{-1}}{1 + x_\alpha}$$

- T_k is the kinetic temperature of the IGM; x_{HI} is the neutral Hydrogen fraction.
- x_α is the Lyman-α coupling coefficient.

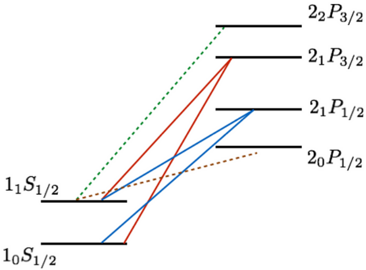
Evolution of kinetic temperature & W-F effect

- The evolution equation of gas kinetic temperature is given by

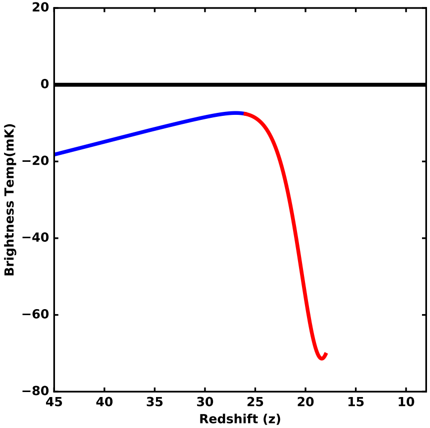
$$\frac{dT_k}{dz} = \frac{2T_k}{1+z} - \frac{2}{3H(z)(1+z)}\frac{\epsilon_X}{k_B n} \qquad [\epsilon_X : \mathrm{X-ray\ \ emissivity}]$$

(Furlanetto et al. 2006)

- Lyman-α coupling (W-F effect)

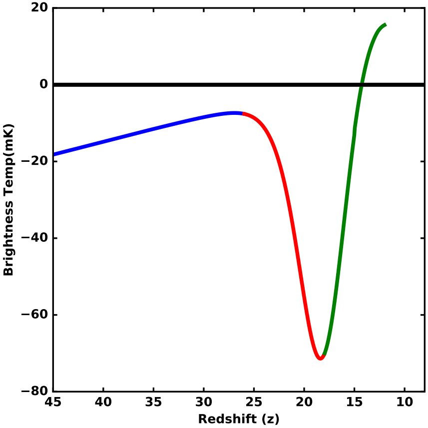


Redshift evolution of the brightness temperature



$x_\alpha >> 1 \qquad T_s \approx T_k \qquad \delta T_b = \left(\frac{T_k - T_\gamma}{T_k}\right) x_{HI}$

Redshift evolution of the brightness temperature



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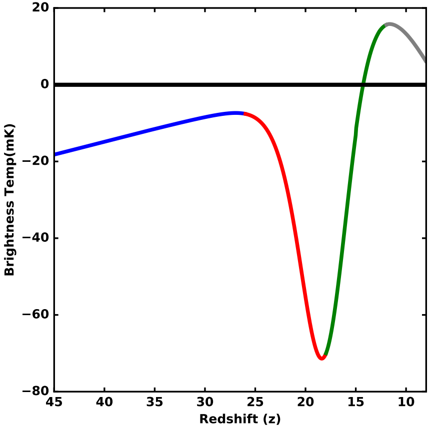

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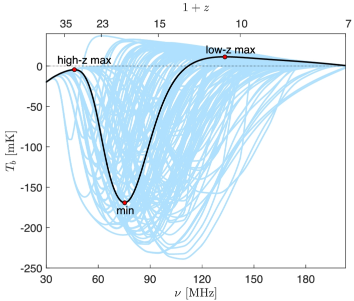
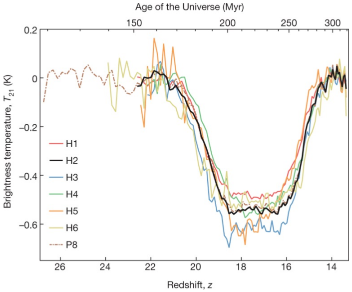
$x_{HI} \rightarrow 0.0 \qquad T_s \approx T_k \qquad \delta T_b = \left(\frac{T_k - T_\gamma}{T_k}\right) x_{HI}$

Observation & Existing theory



Model **(Cohen et al. 2017)**



Observation **(Bowman et al. 2018)**

Existing theory cannot explain the excess dip in the observed signal.

- Debate over cosmological origin of the signal. **(Hills et al. 2018)**
- Global 21-cm signal probes the structure formation.

Ruling out 3 keV warm dark matter using 21 cm-EDGES data

In collaboration with Pratika Dayal, Tirthankar Roy Choudhury & Anne Hutter

ΛCDM and WDM

- Problems with the ΛCDM model
    - Over-predicts the number of satellite and field galaxies compared to the observations. **(Moore et al. 1999)**
    - Predicting cuspy halo profiles as opposed to the observationally preferred constant density cores. **(Navarro et al. 1997)**
    - Predicts massive concentrated Galactic sub-halos inconsistent with observations. **(Boylan-Kolchin et al. 2012)**
    - Limited success with baryonic feedback. **(Boylan-Kolchin et al. 2012)**
- Structure formation is delayed in WDM models.
- Global 21-cm signal probes the structure formation.

X-ray heating & Lyman-α coupling

- The energy density injected into the gas per second through X-ray heating is given by

$$\epsilon_X \propto f_{X,h} \times \left(\frac{\dot{\rho}_*}{\mathrm{M_\odot yr^{-1} Mpc^{-3}}} \right) \ \mathrm{erg/sec/mpc^3}$$

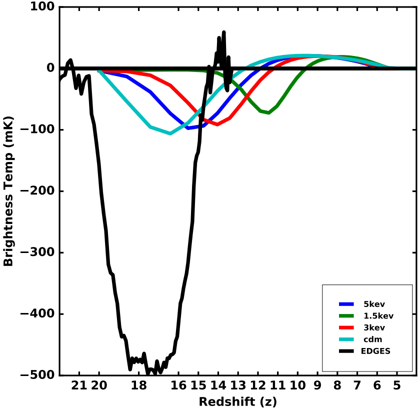
(Ranalli et al. 1992)

- $\dot{\rho}_*$ is the Star Formation Rate Density (SFRD).
- $f_{X,h} = f_X \times f_h$
- The Lyman-α coupling coefficient can be expressed as

$$x_\alpha = 1.81 \times 10^{11} (1+z)^{-1} S_\alpha J_\alpha$$

  J_α is the background $Ly\alpha$ flux.
- The SFRD is taken from a semi-numerical code DELPHI. **(Dayal et al. 2014)**

Global 21-cm signal from different DM models



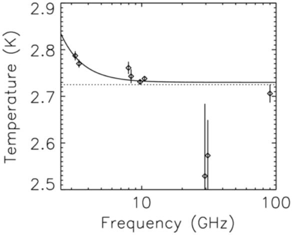
Excess Radio background

- Arcade-2 observed an excess radio background along with the CMB background. (**Fixsen et al. 2011**)
- Possible origin is faint extragalactic sources although Galactic emission origin can not be excluded. **(Seiffert et al. 2011)**
- Radio emissivity ϵ_R is modelled as

$$\epsilon_R \propto f_R \dot{\rho}_*$$

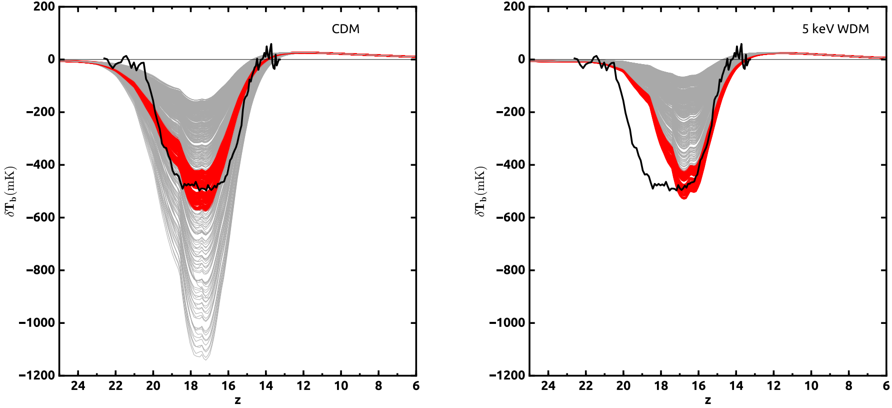
- f_R accounts for any differences between the local and high-z observation.
- Background temperature becomes

$$\boxed{T_\gamma = T_{CMB} + T_R}$$



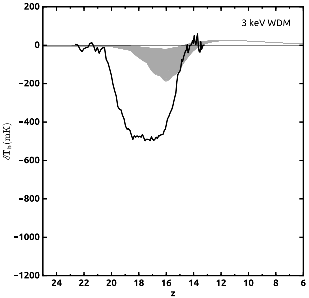
(Fixsen et al. 2011)

CDM and 5 keV WDM



(a) CDM (b) 5 keV WDM

3 keV WDM



3keV WDM

$m_X \leq$ 3 keV is ruled out

(AC, PD, TRC, AH 2019, MNRAS)

Limitation: Only PopII stars no PopIII

A hint on the metal-free star formation rate density from 21-cm-EDGES data

In collaboration with Pratika Dayal, Tirthankar Roy Choudhury & Raffaella Schneider

PopIII Stars

- The first generation of stars are known as Pop III stars.
- Postulated to explain the metallicity-gap from Big Bang Nucleosynthesis to the metal-rich PopII stars in high redshift galaxies.
- Massive, short-lived and yet to be detected from direct observation. **(Tumlinson 2006)**
- 21-cm signal at $z \approx 12 - 21$ probes the epoch when the first stars form.

SFRD model

- The global 21 cm brightness temperature can be computed once SFRD ($\dot{\rho}_*$) is known.

- $\dot{\rho}_*$ is assumed to have contribution from both PopII and PopIII stars

$$\boxed{\dot{\rho}_* = \dot{\rho}_*^{II} + \dot{\rho}_*^{III}}$$

- $\dot{\rho}_*^{III}$ is taken as a fourth degree polynomial

$$\log\left[\frac{\dot{\rho}_*^{III}(z)}{\dot{\rho}_*^{III}(z_{\rm mean})}\right] = a_1(z - z_{\rm mean}) + a_2(z - z_{\rm mean})^2 + a_3(z - z_{\rm mean})^3 + a_4(z - z_{\rm mean})^4$$

- We take PopII contribution from DELPHI. **(Dayal et al. 2014)**

Contribution from both PopII and PopIII

- The X-ray energy density per unit time, ϵ_X, can be written as

$$\epsilon_X \propto \left(f_{X,h}^{II} \dot{\rho}_*^{II} + f_{X,h}^{III} \dot{\rho}_*^{III} \right)$$

- $\dot{n}_\nu$, the production rate of Ly-α photons per unit frequency per unit comoving volume, get contribution from both PopII and PopIII stars

$$\dot{n}_\nu = \dot{n}_\nu^{II} + \dot{n}_\nu^{III}$$

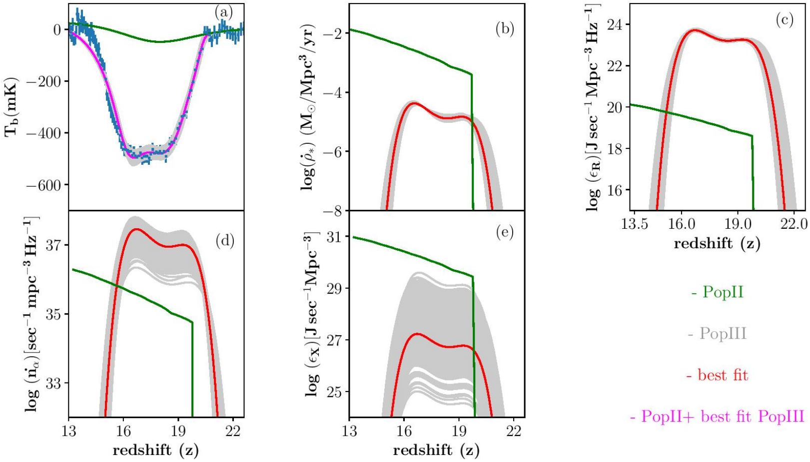
- $\dot{n}_\nu^{III} = f_\alpha^{III} \dot{\rho}_*^{III}(z')$, f_α^{III} being the proportionality factor.

- Radio emissivity ϵ_R can be expressed as

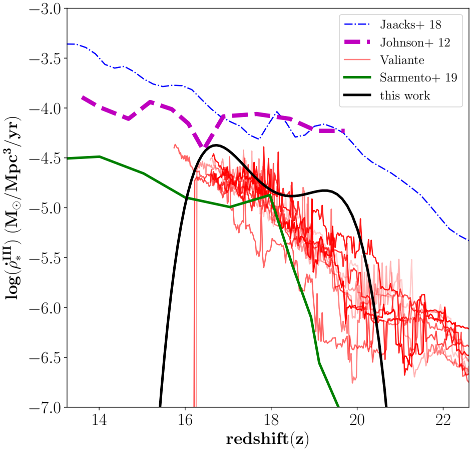
$$\epsilon_R \propto \left(f_R^{II} \dot{\rho}_*^{II} + f_R^{III} \dot{\rho}_*^{III} \right)$$

- PopII parameters are kept fixed.

MCMC analysis



Compare SFRD



CosmoReionMC: A parameter estimation package using Reionization and Cosmic dawn observations

In collaboration with Tirthankar Roy Choudhury & Sourav Mitra

Constraining Reionization model from CMB observations

- Interaction of the CMB photons with the free electrons in the IGM imprinted in the CMB angular power spectrum observations. **(Sunyaev & Zeldovich 1980)**

- This observations along with an assumed reionization history measures the Thomson scattering optical depth τ. **(Planck Collaboration et al. 2016)**

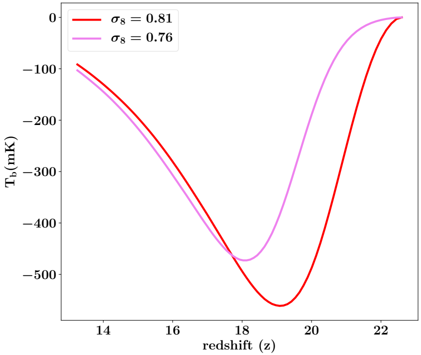
- τ from the observation can then be compared with the prediction from a reionization model to constrain free parameters of the model. **(Pandolfi et al. 2011)**

- Usual approach of comparing observed τ (based on a tanh reionization) with the theoretically estimated τ based on a different reionization model is not a correct approach.

- To overcome this, connect a reionization model with a “CMB anisotropy code” like CAMB or CLASS and constrain cosmological and astrophysical parameters simultaneously. **(Qin et al. 2020)**

Motivation for adding 21-cm signal to constrain parameters

- Modelling of 21-cm signal depends on cosmological parameters.



- Inclusion of observed 21-cm signal (by EDGES) along with CMB and other reionization related observations can jointly put tighter constraint on cosmological parameters.

Reionization Model (**Choudhury & Ferrera 2005,2006**)

- The over-densities in the low density region of the IGM follows a lognormal distribution and change to a power-law distribution in high density region. **(Miralda-Escude 2003)**

- The sources of reionization are QSOs, PopII and PopIII stars.

- The collapse fraction for PopII and PopIII stars are assumed to be

$$f_{\mathrm{coll,II}} = \frac{1}{\rho_m} \int_{M_{\mathrm{min}}(z)}^{\infty} \mathrm{d}M \, [1 - f_{\mathrm{III}}(M,z)] \, M \frac{\partial n(M,z)}{\partial M},$$

$$f_{\mathrm{coll,III}} = \frac{1}{\rho_m} \int_{M_{\mathrm{min}}(z)}^{\infty} \mathrm{d}M [f_{\mathrm{III}}(M,z)] M \frac{\partial n(M,z)}{\partial M},$$

- PopIII → PopII transition essentially determines the form of $f_{\mathrm{III}}(M,z)$.

$$f_{\mathrm{III}}(M,z) = f_{\mathrm{III}}(z) = \frac{1}{2}\left[1 + \tanh\left(\frac{z - z_{\mathrm{trans}}}{\delta z}\right)\right].$$

Photon production from stars

- The photon production rate from stellar sources is

$$\begin{aligned}\dot{n}_\nu(z) &= \dot{n}_\nu^{\mathrm{II}} + \dot{n}_\nu^{\mathrm{III}} \\ &= \rho_b \left[f_*^{\mathrm{II}} f_{\mathrm{esc}}^{\mathrm{II}} \left(\frac{\mathrm{d}N_\nu}{\mathrm{d}M}\right)_{\mathrm{II}} \frac{\mathrm{d}f_{\mathrm{coll,II}}}{\mathrm{d}t} + f_*^{\mathrm{III}} f_{\mathrm{esc}}^{\mathrm{III}} \left(\frac{\mathrm{d}N_\nu}{\mathrm{d}M}\right)_{\mathrm{III}} \frac{\mathrm{d}f_{\mathrm{coll,III}}}{\mathrm{d}t} \right]\end{aligned}$$

- ρ_b: Mean comoving baryon density.
- f_*: Star formation efficiency ; f_{esc}: Escape fraction of the ionizing photons entering IGM
- $\frac{\mathrm{d}N_\nu}{\mathrm{d}M}$: Number of photons emitted per frequency range per unit mass of stars.
- $\frac{\mathrm{d}f_{\mathrm{coll}}}{\mathrm{d}t}$: Rate of collapse fraction

Observable quantities from the Reionization model

- The reionization model can predict the redshift distribution of the Lyman-limit systems $\mathrm{d}N_{\mathrm{LL}}/\mathrm{d}z$.
- The hydrogen photoionization rate (Γ_{PI}) can be obtained from

$$\Gamma_{\mathrm{PI}}(z) = (1+z)^3 \int_{\nu_H}^{\infty} \mathrm{d}\nu \; \lambda_{\mathrm{mfp}}(z) \; \dot{n}_\nu(z) \; \sigma_H(\nu),$$

- $\sigma_H(\nu)$: Hydrogen photoionization cross-section.
- The mean free path of the photons (λ_{mfp}) given by

$$\lambda_{\mathrm{mfp}} = \frac{\lambda_0}{[1 - F_v]^{2/3}}$$

- F_v: Volume fraction of the ionized region; λ_0: Free parameter of the model.
- Global 21-cm signal can also be calculated from this model.

MCMC analysis: Parameter space, Likelihood and Constraints

- Free parameters

$$\Theta = \{\underbrace{H_0, \Omega_b h^2, \Omega_c h^2, A_s, n_s}_{\Theta_{cosmo}}, \underbrace{f_{\rm esc}^{\rm II}, \lambda_0}_{\Theta_{Re}}, \underbrace{f_{Xh}^{\rm II}, f_{*,\rm esc}^{\rm III}, f_{*,\alpha}^{\rm III}, f_{*,R}^{\rm III}, z_{\rm trans}}_{\Theta_{21}}\}$$

- $f_{*,\rm esc}^{\rm III} \equiv f_*^{\rm III}\ f_{\rm esc}^{\rm IIII}$; $\quad f_{*,\alpha}^{\rm III} \equiv f_*^{\rm III}\ f_{\alpha}^{\rm III}$; $\quad f_{*,Xh}^{\rm III} \equiv f_*^{\rm III}\ f_{Xh}^{\rm III}$; $\quad f_{*,R}^{\rm II} \equiv f_*^{\rm III}\ f_R^{\rm III}$
- Fixed parameters

$$f_{\alpha}^{\rm II} = f_R^{\rm II} = 1; \quad f_{Xh}^{\rm III} = 0; \quad f_*^{II} = 0.01$$

- Likelihood: $\mathcal{L} = \mathcal{L}_{\rm Pl} + \mathcal{L}_{\rm Re} + \mathcal{L}_{21}$

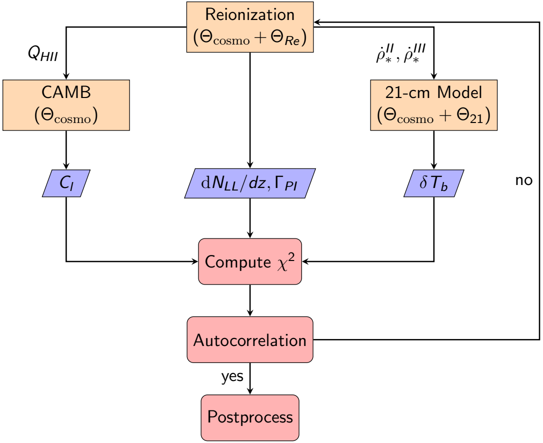
  where

  $$\mathcal{L}_{21} = \sum_i \left[\frac{\delta T_b^{\rm obs}(\nu_i) - \delta T_b^{\rm th}(\nu_i)}{\sigma_i}\right]^2; \ \mathcal{L}_{Re} = \frac{1}{2}\sum_{\alpha=1}^{N_{\rm obs}}\left[\frac{\zeta_\alpha^{\rm obs} - \zeta_\alpha^{\rm th}}{\sigma_\alpha}\right]^2.$$

- Constraint
  - Reionization must be completed at $z >= 5.3$ **(Kulkarni et al. 2019a, Choudhury et al. 2020)**
  - Upper limit on the neutral hydrogen fraction coming from the dark fractions in quasar spectra. **(McGreer et al. 2015)**

CosmoReionMC

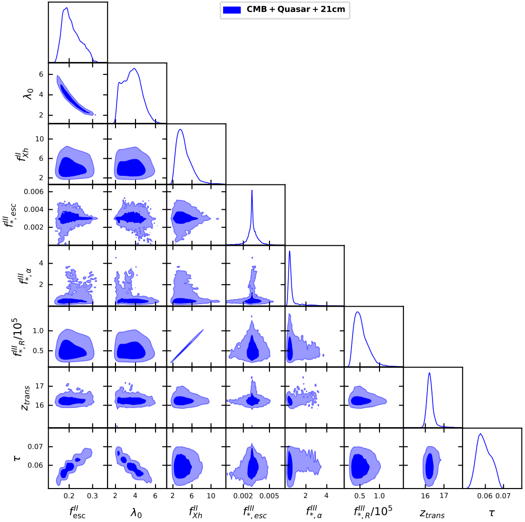
- Written completely in Python.
- Free parameters
  - Cosmological (Θ_{cosmo}) + Reionization (Θ_{Re}) + 21-cm signal (Θ_{21})
- Theoretical model
  - CAMB+ Reionization + 21-cm signal
- Observational data used
  - Planck 2018 + QSO observations + EDGES
- MCMC package used
  - `emcee`



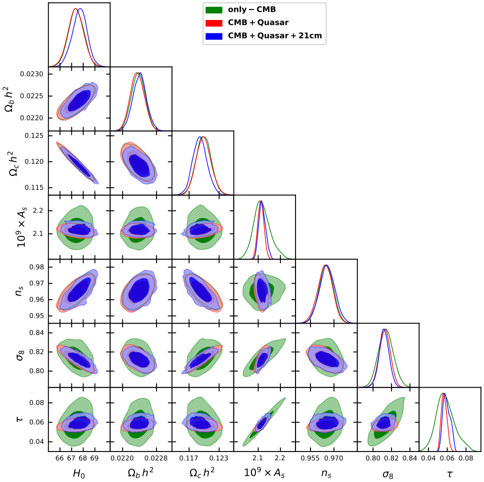
AC, TRC, SM 2021

Constrain on astrophysical parameters

- Strong positive correlation between τ and $f_{\rm esc}^{\rm II}$.
- Increasing the value of $f_{\rm esc}^{\rm II}$ the reionization will take place earlier so τ will increase.
- Efficiency parameters related to the PopIII stars are required to be non-zero to match the data.
- $z_{\rm trans}$ is well constrained between 15.89 and 16.68.
- Strong correlation between $f_{*,R}^{\rm III}$ and $f_{Xh}^{\rm II}$.



Constraints on cosmological parameters from different analysis



Tighter constraints when reionization observations has been used. Chatterjee et al. 2021

Future Outlook

- Updating CosmoReionMC with more observational data and more accurate reionization model.
- Constraining non-standard cosmology with CosmoReionMC.
- Using Neural Network based machine learning approach to make the MCMC run remarakably efficient.

Summary

- Global 21-cm signal is an excellent probe for structure formation in the high redshift Universe.
- EDGES observation of the signal bring renewed interest in this field.
- WDM constraint
  - WDM model with particle mass ≤ 3 keV cannot explain EDGES signal.
- PopIII SFRD
  - We provide for the first time a completely data driven PopIII SFRD using EDGES data.
- CosmoReionMC
  - We introduce an advanced MCMC based parameter estimation package called CosmoReionMC which connects a reionization model (Choudhury & Ferrera 2006) with CAMB and vary both cosmological and model parameters simultaneously to put constraints on them.
  - When reionization observations along with the Planck observation are used, we get tighter constraints on τ and σ_8.
  - Cosmological parameters do not change significantly when EDGES signal is included.