Constraint on PMFs In the Light of ARCADE 2 and EDGES Observations

Based on Eur. Phys. J. C 81, 394 (2021)

Pravin K. Natwariya

THEPH Division,
Physical Research Laboratory, Ahmedabad.

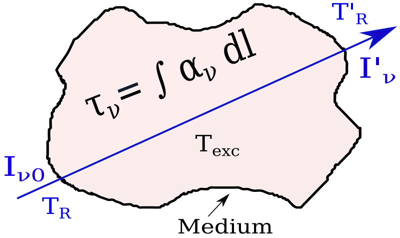
State of the Universe Seminar, TIFR
January 28, 2022

Outline

- 21-cm differential brightness temperature
  - EDGES low band observation
- ARCADE-2 & LWA-1 observations
- IGM gas temperature evolution in presence of PMFs
- Constraint on present-day PMFs strength
- Results and Conclusion

21-cm differential brightness temperature

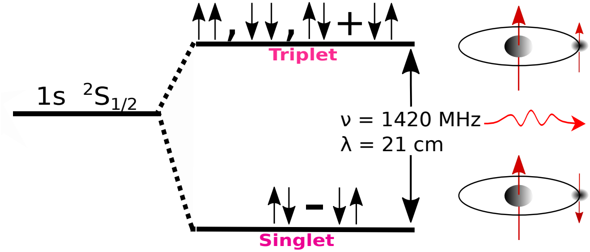
- 21-cm differential brightness temperature appears to be a treasure trove to study physics during cosmic dawn and reionization.
- Differential brightness temperature:



$$\frac{dI_\nu}{dl} = j_\nu - \alpha_\nu I_\nu \quad \xrightarrow[\mathcal{I}_\nu = 2\nu^2 T]{2\pi\nu/T \ll 1} \quad \delta T_B = T'_\mathrm{R} - T_\mathrm{R} = (T_\mathrm{exc} - T_\mathrm{R})(1 - e^{-\tau_\nu})$$

21-cm differential brightness temperature

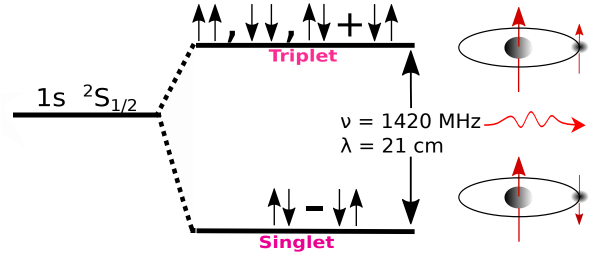
- For the 21-cm line: $T_{\rm exc} = T_S$ (spin temperature),



- characterised by number density ration in the hyperfine states,
  - $\frac{n_{\rm T}}{n_{\rm S}} = \frac{g_{\rm T}}{g_{\rm S}} \times \exp\left[-\frac{2\pi\nu_{\rm TS}}{T_S}\right]$, $\nu_{\rm TS} = 1420\ {\rm MHz} = 1/(21\ {\rm cm})$
- $T_{\rm S}$ in presence of collisions ($P^{\rm C}$), radio ($P^{\rm R}$) & Lyα (P^{α}) radiation:

$$\frac{dn_{\rm S}}{dt} = -n_{\rm S}(P^{\rm C}_{\rm ST} + P^{\rm R}_{\rm ST} + P^{\alpha}_{\rm ST}) + n_{\rm T}(P^{\rm C}_{\rm TS} + P^{\rm R}_{\rm TS} + P^{\alpha}_{\rm TS}),$$ [1]

[1] Field G. B., Proc. IRE, 46, 240 (1958)



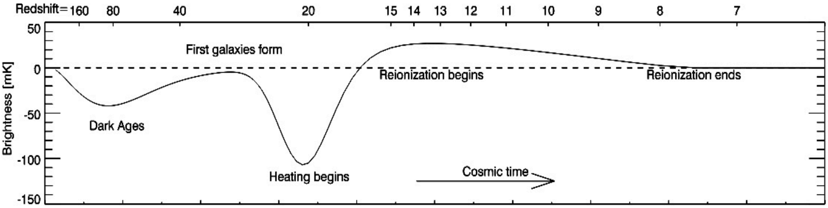
$$T_S^{-1} = \frac{T_R^{-1} + x_c\, T_{\rm gas}^{-1} + x_\alpha\, T_\alpha^{-1}}{1 + x_c + x_\alpha}\,, \qquad x_C = \frac{P_{\rm TS}^{\rm C}}{P_{\rm TS}^{\rm R}},\ x_\alpha = \frac{P_{\rm TS}^{\alpha}}{P_{\rm TS}^{\rm R}}.$$

- For neutral hydrogen medium (expending Universe),

$$\delta T_B \;=\; T_{21} = \frac{T_{\rm S} - T_{\rm R}}{1+z}(1 - e^{-\tau_\nu}), \quad \tau_\nu \approx \frac{3\,A_{10}\,n_{\rm HI}}{16\nu_{\rm TS}^2\,H\,T_{\rm S}}$$

Evolution of the global 21-cm signal

- Absorption/emission in 21 cm line: $T_{21} \propto (1 - T_R/T_S)$.
- Below $z \sim 200$ (ΛCDM): $T_{\rm gas} \propto (1+z)^2$, $T_{\rm CMB} \propto (1+z)$.



Pritchard & Loeb, Rep. Prog. Phys. 75, 086901 (2012)

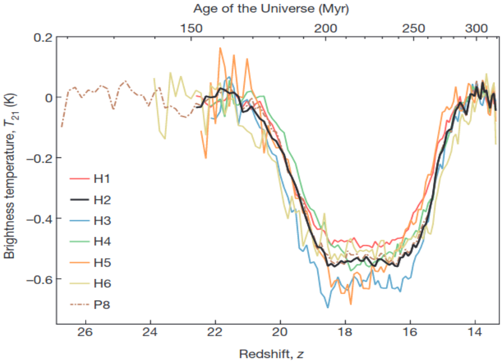
- At $z \sim 17$, $x_\alpha \gg 1$, x_C $\longrightarrow$ $T_{\rm S} \simeq T_{\rm gas}$.

21-cm signal as a probe

- In the standard scenario: $T_{\rm gas} \sim 6.8$ K & $T_{\rm CMB} \sim 48.6$ K at $z = 17$ $\Rightarrow T_{21} \approx -220$ mK.
- Any change in gas temperature will reflect in the absorption amplitude of T_{21}.
- This feature can provide a robust bound on the sources of energy injection into IGM, for e.g. primordial magnetic field, primordial black hole & sterile neutrino dark matter, etc.
- Recently, such an absorption at $z \sim 17$ has been confirmed by EDGES observation.

EDGES low band observation

- EDGES low band observation reported: $T_{21} = -500^{+200}_{-500}$ mK. [2]



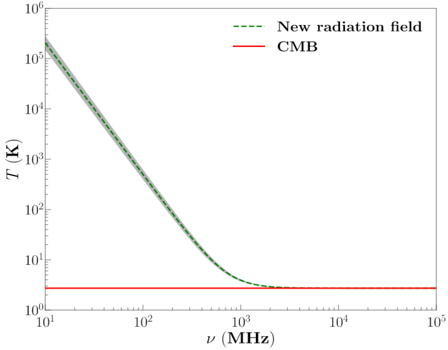
- It is centered at 78 ± 1 MHz or $z = 17.2 \pm 0.2$. Here, $\nu_0 = \frac{\nu}{1+z}$ and $\nu = 1420$ MHz.

[2] Bowman et. al. Nature 555, 67–70 (2018).

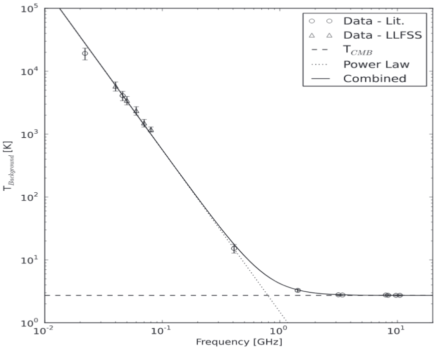
Observation of excess radio radiation

- There are only two ways to explain this absorption signal:
  - By increasing radio background, or
  - cooling the gas in IGM below the standard ΛCDM prediction.
- Any possible explanation requires (at the centre of the 'U' profile):
  - T_R should be grater than 104 K, or
  - T_{gas} should be less than 3.2 K.
- ARCADE 2 observation detected extra-galactic excess radio radiation in the frequency range 3-90 GHz.
- This excess radio radiation can also explain the EDGES anomaly.

ARCADE-2 and LWA-1 observations



ARCADE2 (2011) [Fixsen et al., APJ, 11; Feng et al., APJL, 18]



LWA1 (2018) [Dowell et al., APJL, 18]

- The enhancement in the radio radiation is also supported by the first station of the Long Wavelength Array (LWA1) in the frequency range 40-80 MHz.

ARCADE-2 and LWA-1 observations

- The excess radiation[3]

$$T_R = T_{\rm CMB}\,(1+z)\,\left[1 + A_r\,\left(\frac{\nu_{\rm obs}}{78\ {\rm MHz}}\right)^{\beta}\,\right],$$

  - $T_{\rm CMB} = 2.725$ K, $\beta = -2.6$ & $\nu_{\rm obs} = 1420/(1+z)$ MHz.
  - $1.9 < A_r < 418$ is amplitude of radiation excess–depending on origin.
- ARCADE 2 is modelled by a power law with a spectral index $\beta = -2.62 \pm 0.04$
- while, LWA1 is modelled with $\beta = -2.58 \pm 0.05$.
- There are several theoretical models to explain this excess at CD, for e.g., axion-photon conversion in the presence of IGM MFs, also by radiative decays of relic neutrinos, stimulated emission from Bose stars, etc.

[3]Fialkov & Barkana, MNRAS 486, 1763 (2019)

Excess radio radiation & gas temperature

- The presence of early radiation excess over the CMB can not be completely ruled out.
- Excess radio background at CD can transfer energy to gas mediated by Lyα photons from first stars[4].
- This effect can increase the gas temperature by more than 10%, even in the absence of x-ray heating.
- Increasing the excess radio radiation above a certain value, the gas heating becomes more dramatic.
- Considering the possibilities of having early excess radiation, we believe that it is important to analyse constraints on the PMFs in the presence of such radiation for EDGES.

[4] Venumadhav et al., PRD 98, 103513 (2018).

Decay of primordial magnetic fields & IGM evolution

- PMFs energy density and gas temperature, $E_B = B^2/(8\pi)$,

$$\frac{dE_B}{dz} = 4\,\frac{E_B}{1+z} + \frac{1}{(1+z)\,H}\left[\Gamma_{\rm ambi}(\propto B^4/(X_e)) + \Gamma_{\rm turb}(\propto B^2)\right],$$

$$\frac{dT_{\rm gas}}{dz} = \left.\frac{dT_{\rm gas}}{dz}\right|_{\rm Cool+Com} - \frac{2}{3\,N_{\rm tot}(1+z)\,H}(\Gamma_{\rm ambi} + \Gamma_{\rm turb})\,.$$

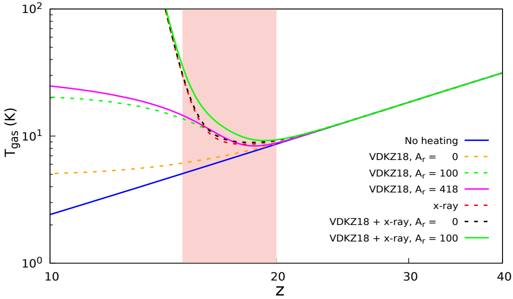
- Inclusion of first stars effect

$$+\left.\frac{dT_{\rm gas}}{dz}\right|_{\rm x-ray} - \frac{\Gamma_R}{(1+z)\,(1+f_{He}+X_e)}\,,^{5}$$

$$\Gamma_R = X_{\rm HI}\,\frac{A_{10}}{2\,H}\,x_R\left[\frac{T_R}{T_S} - 1\right]\,T_{10}\,.$$

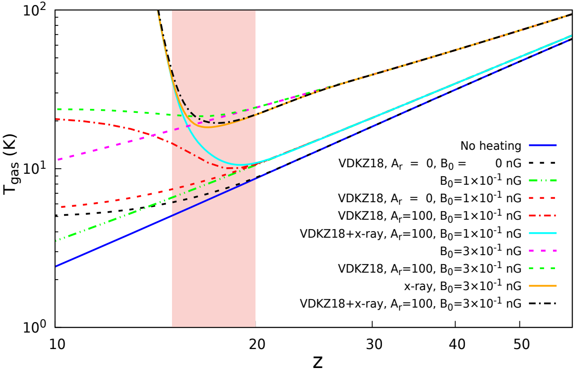
[5] Venumadhav et al., PRD 98, 103513 (2018).

IGM evolution in presence of excess radiation



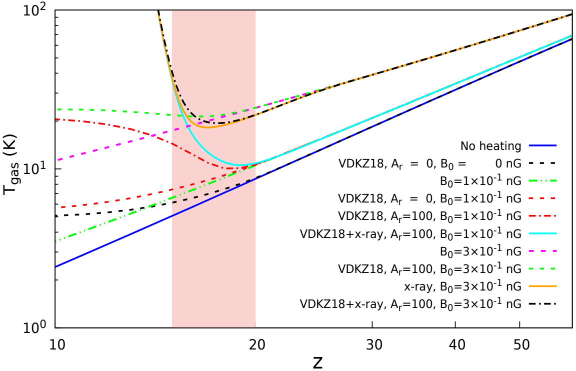
- Pink band corresponds to EDGES absorption signal, $z \to 15$ - 20
- Solid blue line $\to$ no effects of first stars
- Increasing excess radiation fraction (A_r), the gas temperature rises
- Inclusion of X-ray $\to$ increases $T_{\rm gas}$ further in pink band
- Later X-ray dominates & all lines merge

Inclusion of PMFs ($n_B = -2.99$)



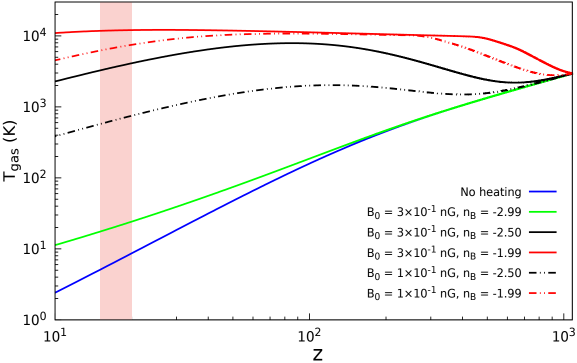
- $T_{\rm gas}$ decreases after the inclusion of the x-ray heating due to first stars.
- It happens because the ionization fraction increases by x-ray radiation.
- Ambipolar diffusion evolves as $\Gamma_{\rm ambi} \propto 1/X_e$.

Inclusion of PMFs ($n_B = -2.99$)



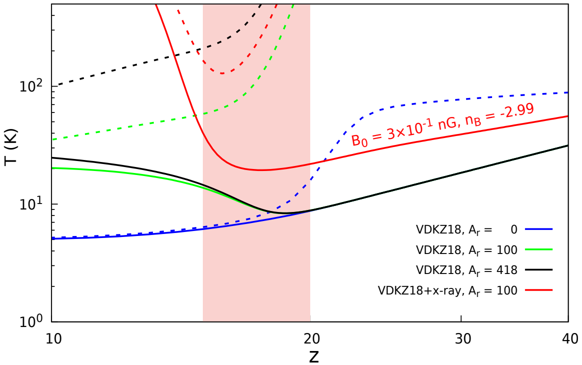
- as X_e increases, ambipolar diffusion of the MFs decreases.
- Thus, heating due to MFs decreases by including x-ray heating.
- Gas temperature also decreases for $B_0 = 1 \times 10^{-1}$ nG, but it can not be clearly seen due to the small strength of B_0.

IGM evolution for different PMFs spectral index (n_B)



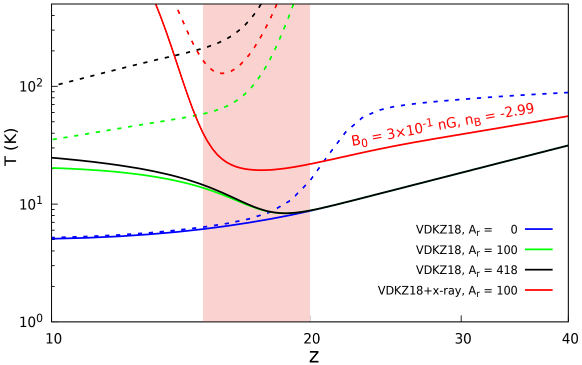
- Increasing n_B, the magnetic heating due to ambipolar diffusion and turbulent decay increases as $\Gamma_{\rm ambi} \propto \left(1/\Gamma[(n_B+3)/2]\right)^2$ and $\Gamma_{\rm turb} \propto 1/\Gamma[(n_B+3)/2]$.
- For example, if one changes n_B from its value -2.99 to -1 then $1/\Gamma[(n_B+3)/2]$ changes from 5×10^{-3} to 1.

Spin & gas temperature evolution for different cases



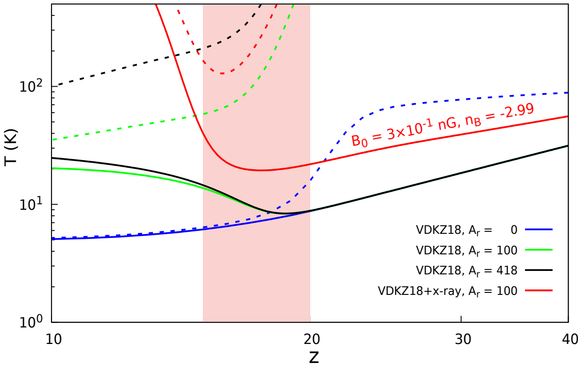
- Increases excess radiation fraction (A_r) above 100, does not significantly change the $T_{\rm gas}$.
- Because $\Gamma_R \propto (T_R/T_S - 1) \sim T_R/T_S$
- Coupling between $T_{\rm gas}$ and T_S are $\propto 1/T_R$.

Spin & gas temperature evolution for different cases



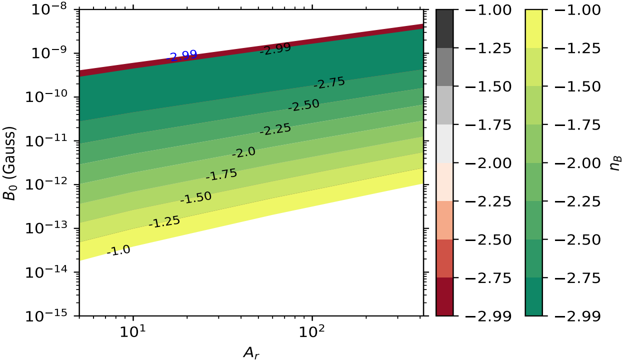
- Therefore, the coupling between $T_{\rm gas}$ and T_S decreases by increasing A_r.
- In this case T_S will be determined by the T_R & the ratio T_R/T_S will become nearly constant

Spin & gas temperature evolution for different cases



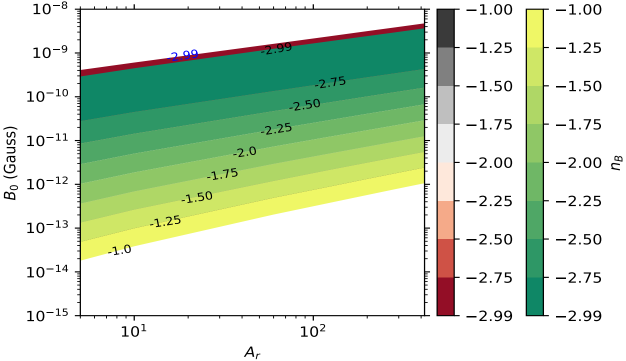
- For example, at $z = 17$, T_R/T_S is 6.5 for $A_r = 0$, 51.4 for $A_r = 100$ and 54.9 for $A_r = 418$.
- Here, we can see that, even increasing A_r to ~ 4 times (100 to 418), T_R/T_S increases by only 6.8 percent.

In the Plane of B_0 & A_r in absence of heating due first stars



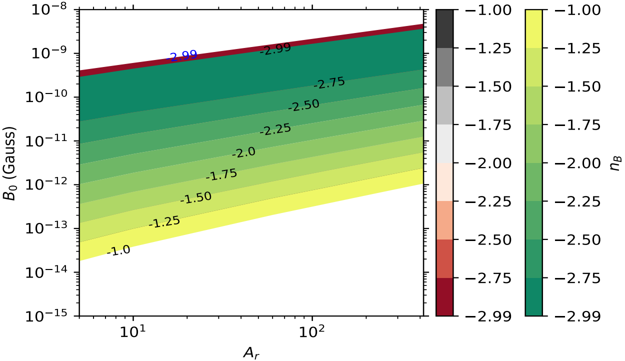
- Here, heating due to x-ray and radio background (mediated by Lyα) is excluded.
- Red-grey color scheme represents the case with $T_{21}|_{z=17.2} \simeq -300$ mK.
- Green-yellow color scheme represents the case with -500 mK.

In the Plane of B_0 & A_r in absence of heating due first stars



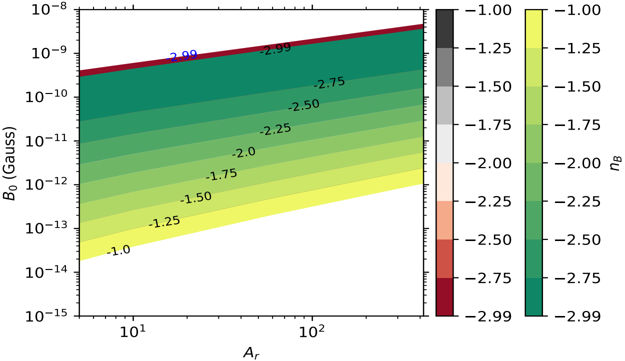
- For this plot, we consider $x_\alpha \gg x_c, 1$ (i.e. $T_S \simeq T_{\rm gas}$).
- When, $x_\alpha \gg x_c, 1 \to T_{21} \propto (1 - T_R/T_{\rm gas})$.
- Increasing A_r, T_R increases $\to$ more window to increase $T_{\rm gas}$.
- Therefore, we can increase B_0 as we increase A_r.

In the Plane of B_0 & A_r in absence of heating due first stars



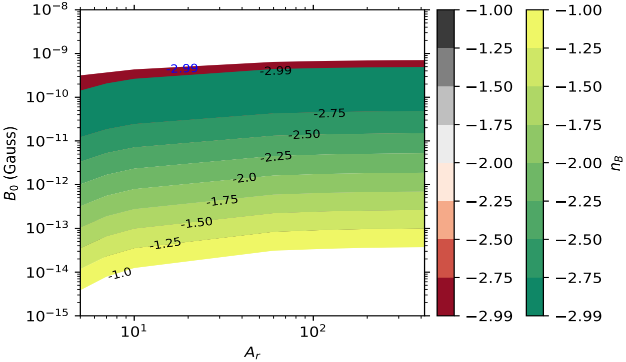
- As discussed earlier, by decreasing n_B, the amplitude of the MF power spectrum also decreases.
- It results in less magnetic energy dissipation into the gas kinetic energy.

In the Plane of B_0 & A_r in absence of heating due first stars



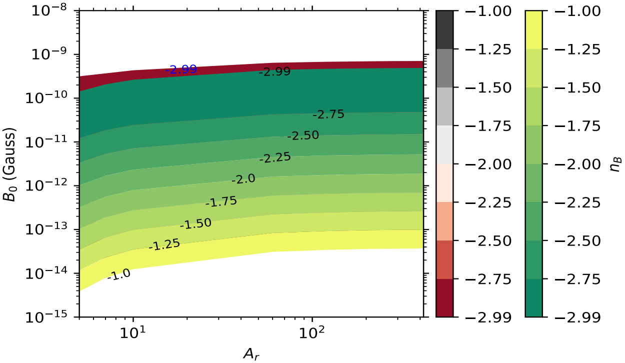
- Thus by reducing values of n_B from -1 to -2.99, we get more window to increase B_0.
- Next, when one increases T_{21} from -500 mK to -300 mK, the allowed value of B_0 increases further (red-grey colour scheme).

In the Plane of B_0 & A_r in presence of heating due first stars



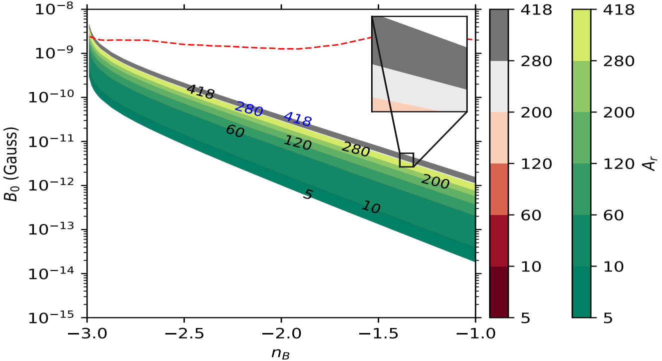
- Here, heating due to x-ray and radio background (mediated by Lyα) is included.
- As discussed before, increasing A_r above ~ 100, T_R/T_S remains nearly constant.

In the Plane of B_0 & A_r in presence of heating due first stars



- This also mean that T_{21} remain unchanged.
- Consequently one can not increase the value of B_0
- and one gets nearly flat profile for B_0 for $A_r \gtrsim 100$.

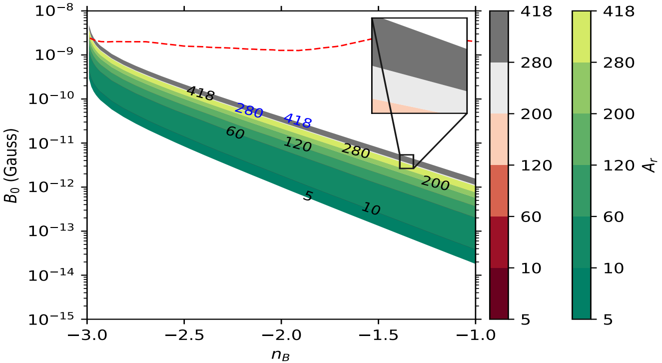
Upper bound on B_0 in absence of heating due first stars



- Here, heating due to x-ray and radio background (mediated by Lyα) is excluded.
- In this plot, we consider $x_\alpha \gg x_c, 1$ (i.e. $T_S \simeq T_{\rm gas}$).
- Red dashed line depicts the Planck 2015 upper bound on B_0[6].

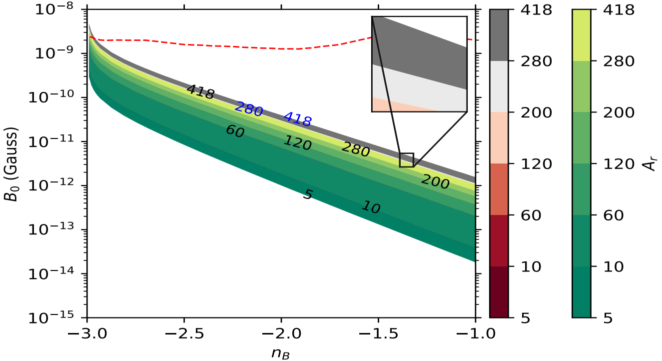
[6] Planck Collaboration, A&A 594, A19 (2016).

Upper bound on B_0 in absence of heating due first stars



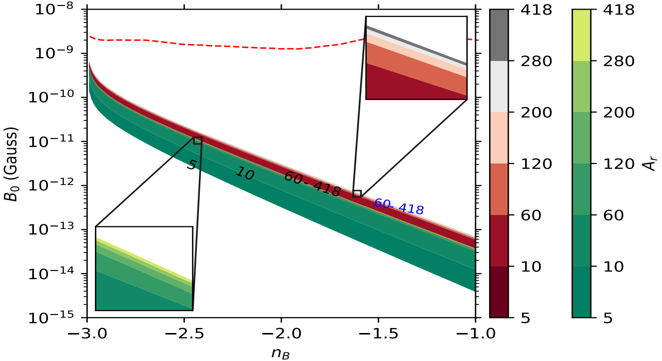
- Color-bars represent the variation in excess radiation fraction, A_r.
- A_r varies from 5 to LWA1 limit ~ 418.
- By decreasing A_r below the LWA1 limit, we get a more stringent bound on B_0 .

Upper bound on B_0 in absence of heating due first stars



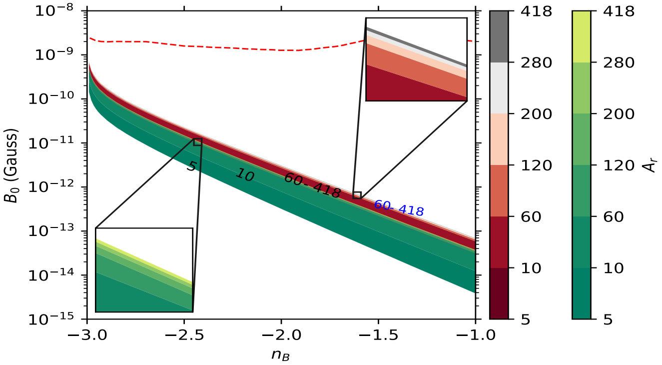
- Using Planck 2015 bounds, we can also rule-out some parameter space for A_r,
- for e.g., Considering $T_{21}|_{z=17.2} \simeq -300$ mK, for $n_B < -2.98$ the $A_r \gtrsim 200$ is excluded.

Upper bound on B_0 in presence of heating due first stars



- Here, heating due to x-ray and radio background (mediated by Lyα) is included.
- As discusses earlier, for $A_r \gtrsim 100$, T_R/T_S ratio remain nearly constant.
- Therefore, the upper bound on B_0 is not changing significantly for $A_r \gtrsim 100$—the plots are merged for $A_r \gtrsim 100$.

Upper bound on B_0 in presence of heating due first stars



- Increasing $n_B \to T_{\rm gas}$ increases $\to$ can erase 21 cm signal
- One needs to lower value of B_0.
- Therefore, we get more stringent upper bounds on B_0 by increasing n_B.

Results and Conclusions

- We have studied the upper constraint on B_0 for different n_B & A_r using the bound of EDGES observation on T_{21}, in the presence of excess radiation reported by ARCADE 2 and LWA1 observations.
- We find stronger bounds on the present-day strength of primordial magnetic fields compared to Planck 2015.
- In conclusion, the presence of excess radio radiation at cosmic dawn can play a significant role in constraining the primordial magnetic field strength for the EDGES signal.
- We also constrain the other sources of energy injection into IGM: primordial black hole DM with non-zero spin & sterile neutrino dark matter.

Thank You!