

21cm線グローバルシグナルを 用いた等曲率揺らぎの制限

第2回：21cm線ミニワークショップ

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Adiabatic and isocurvature perturbations

adiabatic (curvature) perturbations

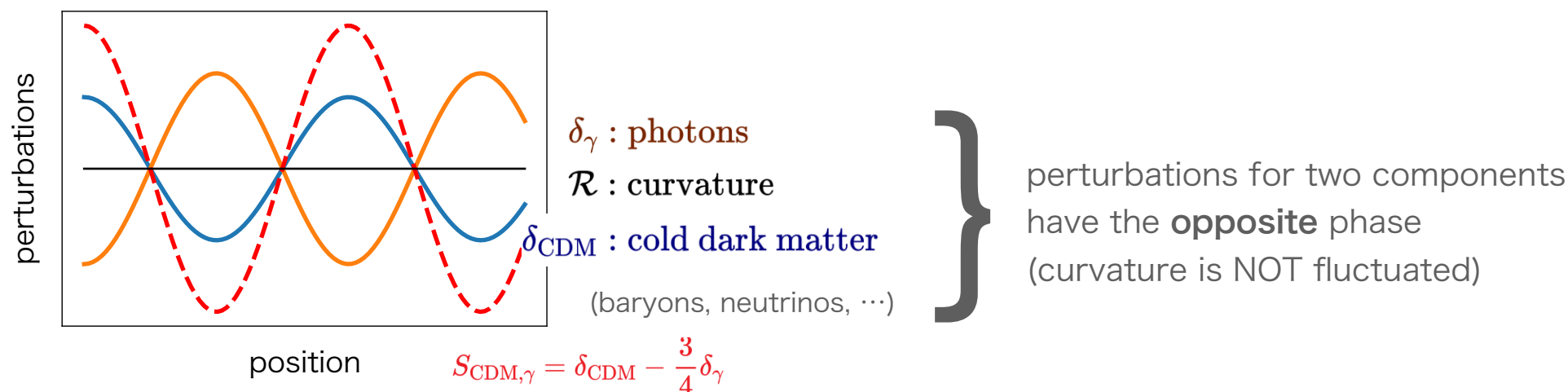


- For the pure adiabatic mode, the entropy is conserved:

$$S_{a,b} \equiv \frac{\delta n_a}{\bar{n}_a} - \frac{\delta n_b}{\bar{n}_b} = 0 \quad (n_a : \text{number density of the particle labeled "a"})$$

Adiabatic and isocurvature perturbations

isocurvature (entropy) perturbations



- For the isocurvature mode, the entropy is perturbed:

$$S_{a,b} \equiv \frac{\delta n_a}{\bar{n}_a} - \frac{\delta n_b}{\bar{n}_b} = \frac{\delta_a}{1+w_a} - \frac{\delta_b}{1+w_b}$$

Adiabatic and isocurvature perturbations

- Power spectra of curvature and isocurvature (entropy) perturbations

$$\mathcal{P}_\zeta(k) = A_s^{\text{adi}} \left(\frac{k}{k_*} \right)^{n_s^{\text{adi}} - 1}$$

$$\mathcal{P}_{S_{\text{CDM}}}(k) = A^{\text{iso}} \left(\frac{k}{k_*} \right)^{n^{\text{iso}} - 1}$$

$$r_{\text{CDM}} = \frac{A^{\text{iso}}}{A_s^{\text{adi}}}$$

Parameters for the curvature power spectrum is fixed by Planck 2018.

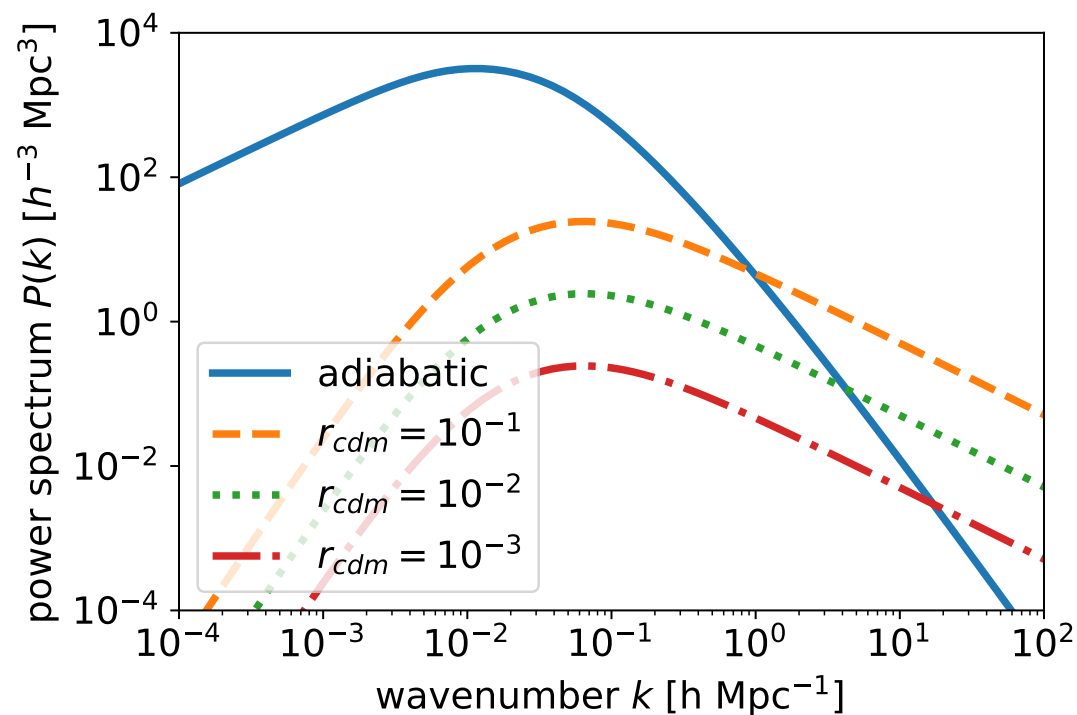
$$A_s^{\text{adi}} = 2.101 \times 10^{-9},$$

$$n_s^{\text{adi}} = 0.965$$

the isocurvature perturbations are parameterized by r_{CDM} and n^{iso}

Matter power spectrum

- The blue-tilted isocurvature perturbations enhance the matter power spectrum on small scales.
- Increasing r_{CDM} , the amplitude of matter power spectrum is larger.
- Blue-tilted isocurvature is naturally explained by the QCD axion (Kasuya and Kawasaki 2009)



We fix $n^{\text{iso}}=3.0$

Astrophysical parameters

A. Mesinger, S. Furlanetto, & R. Cen (2011), MNRAS, 411, 955

- We use galaxy-driven reionization model with “21cmFAST”
- UV luminosity function is written by:

$$\phi(M_{\text{UV}}) = \left(f_{\text{duty}} \frac{dn}{dM_{\text{h}}} \right) \left| \frac{dM_{\text{h}}}{dM_{\text{UV}}} \right|$$

- Duty cycle is parametrized by M_{turn} :

$$f_{\text{duty}} = \exp\left(-\frac{M_{\text{h}}}{M_{\text{turn}}}\right)$$

M_{turn} : the minimum halo mass to host galaxies due to the cooling and/or stellar feedback

Astrophysical parameters

- UV magnitude is determined by the star formation rate

$$\dot{M}_*(M_h, z) = \frac{M_*}{t_* H(z)^{-1}} \quad t_* : \text{the typical star formation timescale normalized by the Hubble time}$$

- The stellar-to-halo mass ratio

$$\frac{M_*}{M_h} = f_{*,10} \left(\frac{M_h}{10^{10} M_\odot} \right)^{\alpha_*} \left(\frac{\Omega_b}{\Omega_m} \right)$$

Astrophysical parameters

- The recent 21-cm observations by HERA give constraints on the astrophysical parameters

The best fitted values for HERA constraint is the model 1 (fiducial)

| | α_* | $M_{\text{turn}} [M_{\odot}]$ | t_* | $\log_{10}(L_{X<2.0\text{keV}}/\text{SFR}/[\text{erg s}^{-1}M_{\odot}^{-1} \text{ yr}])$ |
|---------|------------|-------------------------------|-------|--|
| model 1 | 0.50 | 3.8×10^8 | 0.60 | 40.64 |
| model 2 | 0.41 | 1.6×10^8 | 0.29 | 41.52 |
| model 3 | 0.62 | 1.5×10^9 | 0.86 | 39.47 |

Table 1: Astrophysical parameters for each model adopted in our analysis.

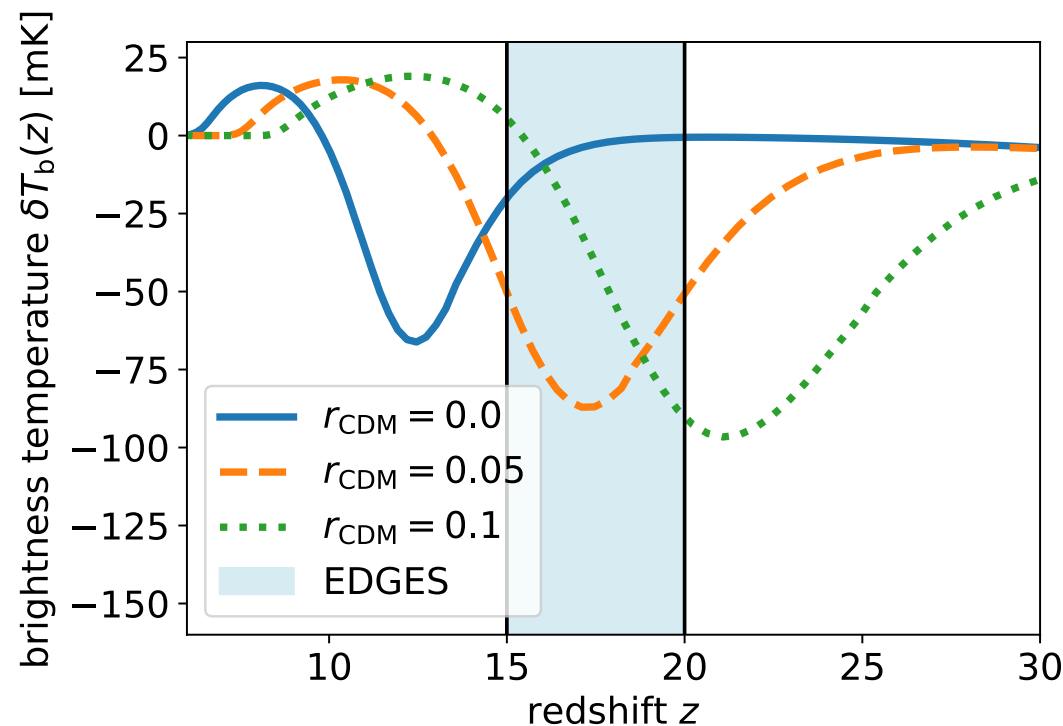
21-cm global signal

Differential brightness temperature:

$$\delta T_b(\nu) \simeq 27 x_{\text{HI}}(z) \left(\frac{1+z}{10} \right)^{1/2} \left(1 - \frac{T_{\text{CMB}}(z)}{T_{\text{spin}}(z)} \right) [\text{mK}]$$

Increasing the isocurvature fraction, the Ly- α coupling and heating starts at higher redshifts.

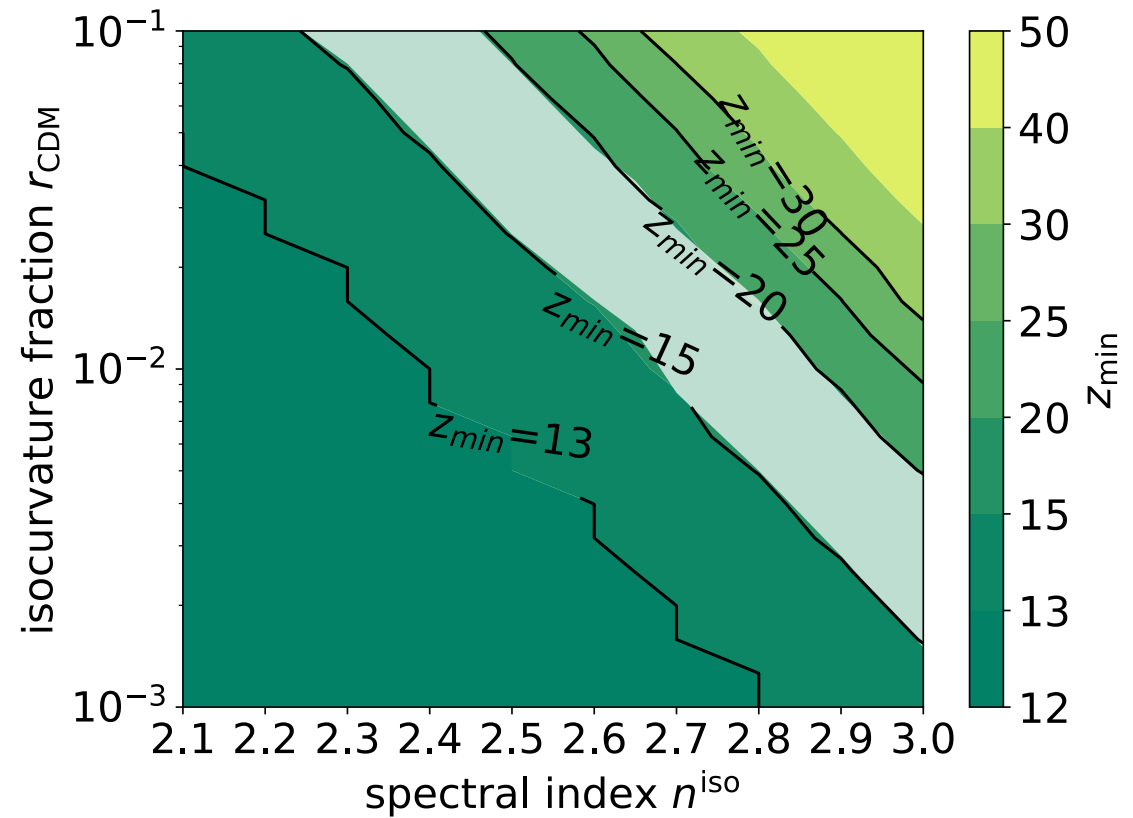
The central redshifts of absorption signal are $z_{\text{min}}=12.46$ ($r_{\text{CDM}}=0.0$), 17.11 ($r_{\text{CDM}}=0.05$), and 21.08 ($r_{\text{CDM}}=0.1$)



We fix $n^{\text{iso}}=2.5$

Constraints in 2-D parameter space

- Once the absorption signal can be observed around some redshift, we can obtain the constraint on the isocurvature perturbations.



Chi^2 analysis in 2-D parameter space

- Calculating chi squared for different param sets,

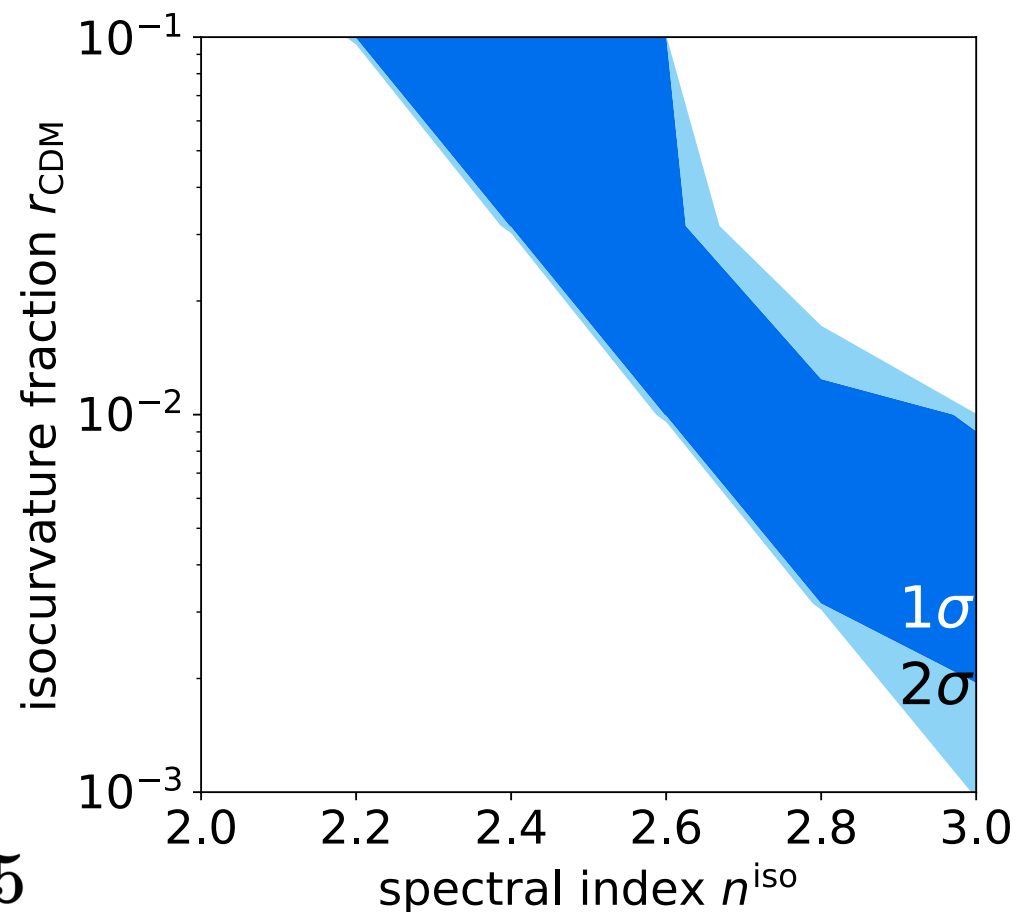
$$\mathbf{p} \equiv (r_{\text{CDM}}, n^{\text{iso}}, M_{\text{turn}}, L_{\text{X} < 2.0\text{keV}}/\text{SFR})$$

$$\chi^2(\mathbf{p}) = \frac{(z_{\text{min,th}}(\mathbf{p}) - z_{\text{min,obs}})^2}{\Delta z_{\text{obs}}^2}$$

$$z_{\text{min,obs}} = 17.2 \text{ and } \Delta z_{\text{obs}} = 0.2$$

- Finally the constraint is

$$4.5 \leq 2.5n^{\text{iso}} + \log_{10} r_{\text{CDM}} \leq 5.5$$



Summary

- We calculate the effects of the isocurvature perturbations on the 21-cm line signal, and give a constraint on isocurvature.
- We also discuss the degeneracy between uncertainty of astrophysical parameters and one of isocurvature parameters.
- For the future prospects, the further severe constraint would be given by the combined analysis of the 21-cm line signal and the other observables (the CMB optical depth, galaxy luminosity function, and so on)
- Related works: running parameters (2304.09474, 2305.11441), dark age global signal (2309.06762, Okamatsu-san's talk)

Matter power spectrum

- Primordial power spectrum is related to the matter power spectrum through the transfer function

$$P_m(k) = \mathcal{P}_\zeta(k) T_{\text{adi}}^2(k) + \mathcal{P}_{S_{\text{CDM}}}(k) T_{\text{iso}}^2(k)$$

- BBKS (1986) and Sugiyama (1995) give transfer functions:

$$T_{\text{adi}}(k) = \frac{\ln(1 + 2.34q)}{2.34q} \times [1 + 3.89q + (16.1q)^2 + (5.46q)^3 + (6.71q)^4]^{-1/4}$$

$$T_{\text{iso}}(k) = \left[1 + \frac{(40q)^2}{1 + 215q + (16q)^2(1 + 0.5q)^{-1}} + (5.6q)^{8/5} \right]^{-5/4}$$

where $q = k / (\Omega_m h^2 \exp(\Omega_b - \Omega_b / \Omega_m) [\text{Mpc}^{-1}])$