

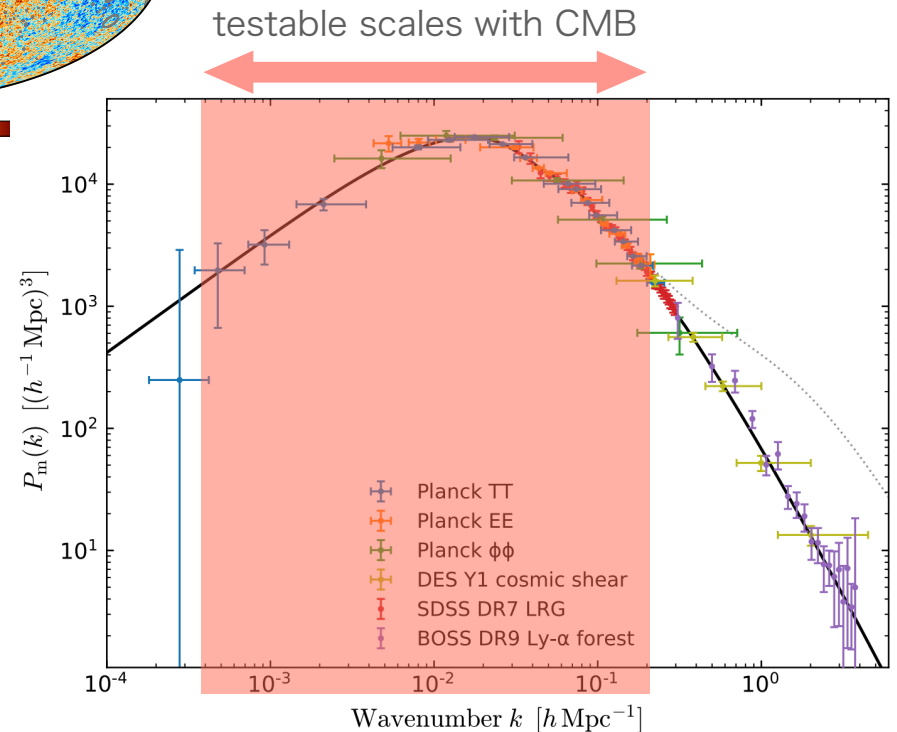
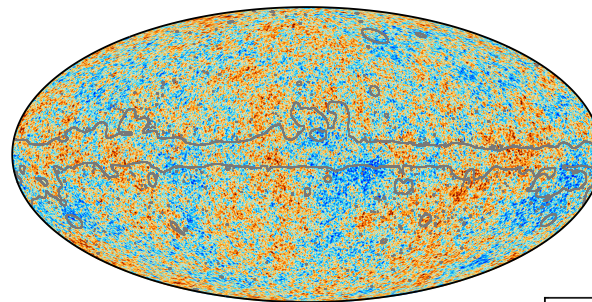
Probing isocurvature perturbations with 21-cm global signal

21 cm Cosmology Workshop 2024 & Tianlai Collaboration Meeting
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Teppei Minoda (Tsinghua University),
Shintaro Yoshiura (NAOJ), Tomo Takahashi (Saga University)
(arXiv:2112.15135, PRD 105 083523)

Primordial curvature perturbations

- CMB anisotropy, galaxy distributions suggest the primordial fluctuations
- Explained very well by adiabatic (curvature) perturbations with a single power-law power spectrum
- Testable scales of primordial fluctuations with CMB are finite
- Larger scales? > Causality limit, GW?



Adiabatic and isocurvature perturbations

adiabatic (curvature) perturbations

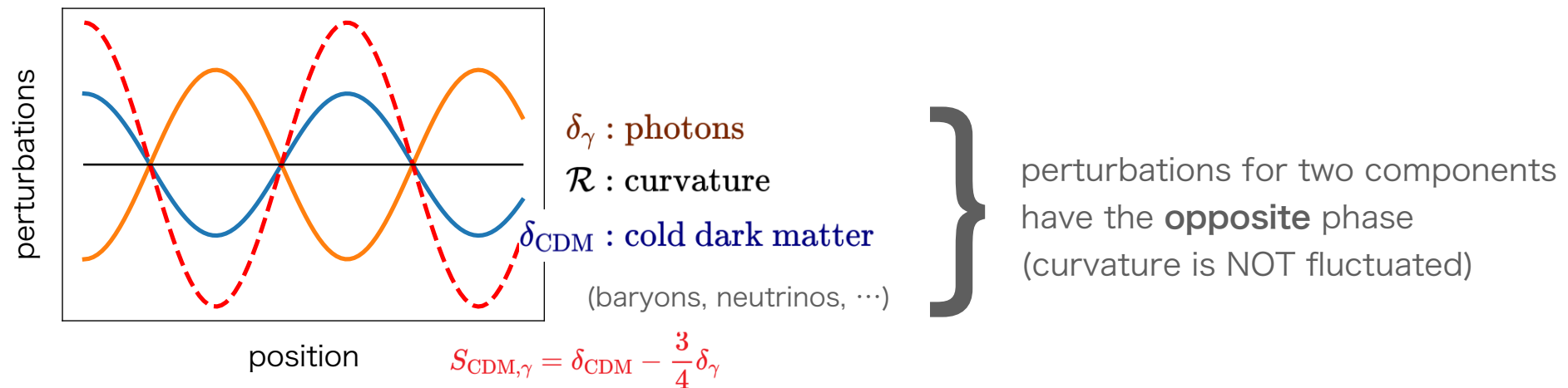


- For the pure adiabatic mode, the entropy is conserved:

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

Adiabatic and isocurvature perturbations

isocurvature (entropy) perturbations



- For the isocurvature mode, the entropy is perturbed:

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

axion or PBH dark matter scenarios
 predict the isocurvature perturbations

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.

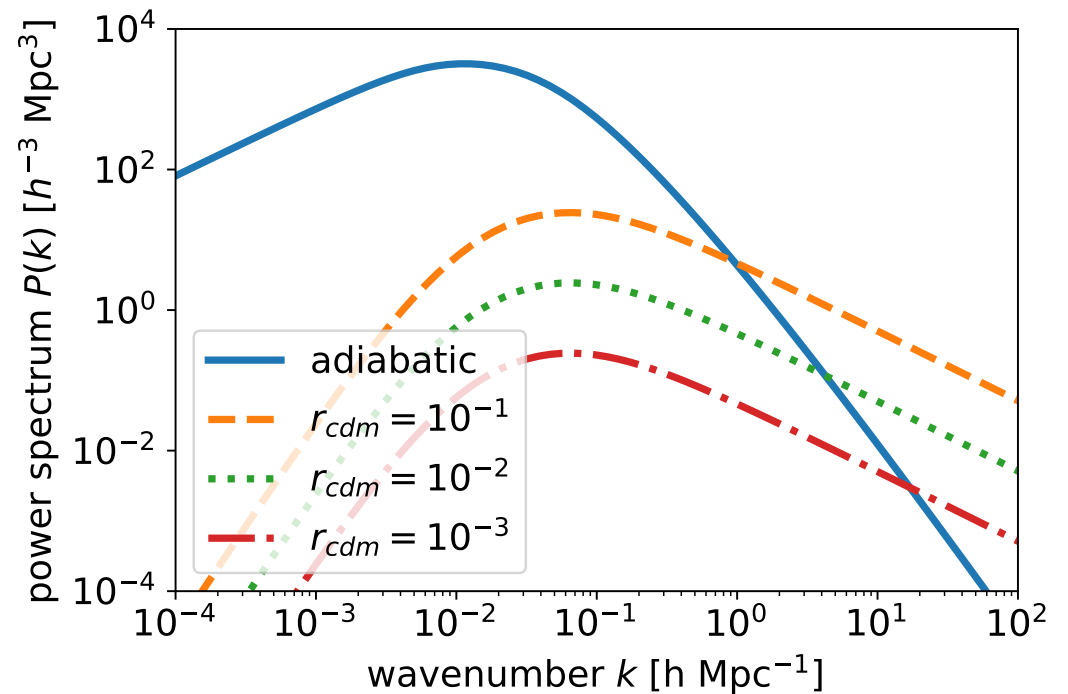
$$A_s^{\text{adi}} = 2.101 \times 10^{-9},$$

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

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 expected by one of the QCD axion scenarios (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} :

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

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

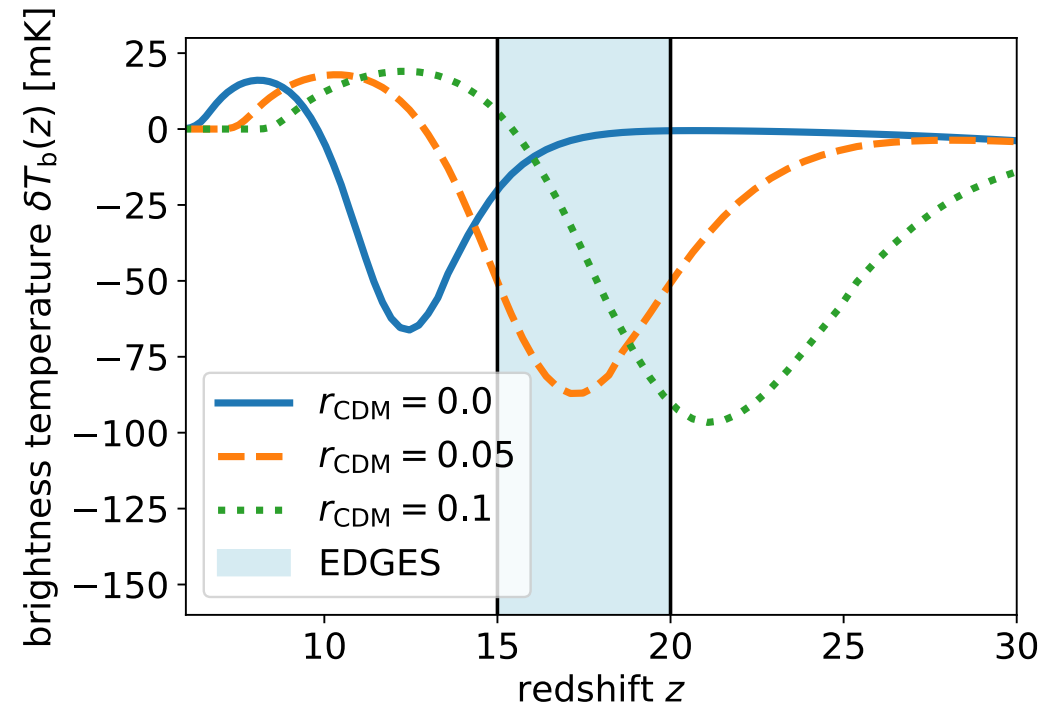
Table 1: Astrophysical parameters for each model adopted in our analysis.

Alternative probe: 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.



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

Alternative probe: 21-cm global signal

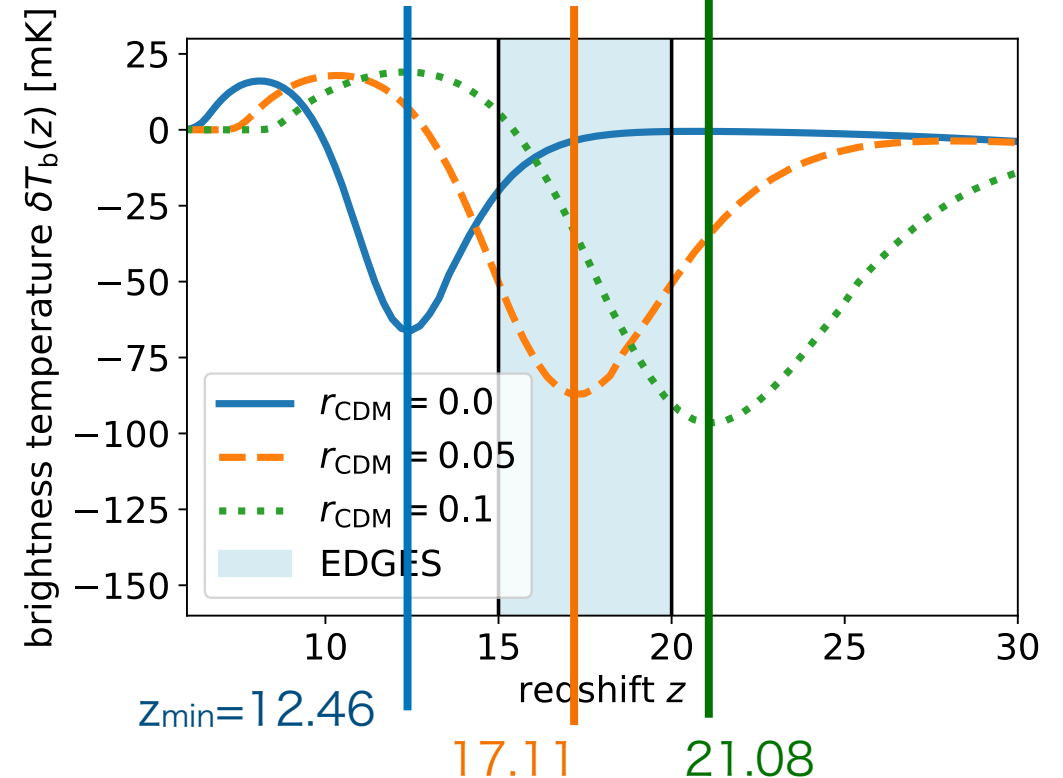
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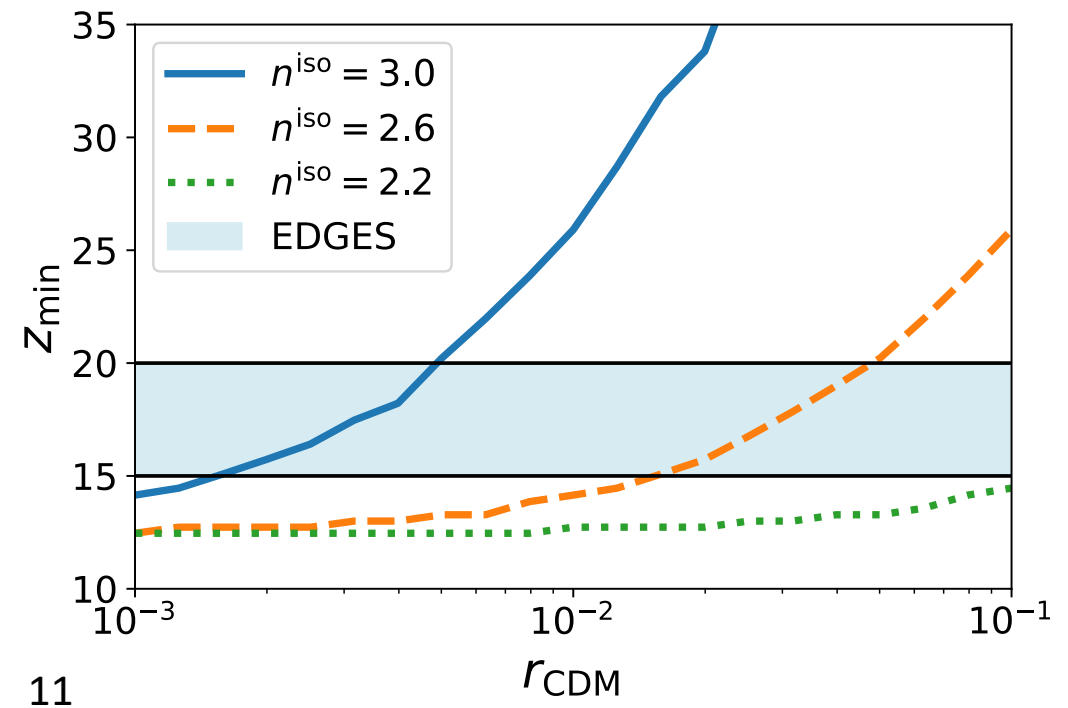
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The central redshifts of absorption signal are $z_{\text{min}}=12.46$ ($r_{\text{CDM}}=0.0$), 17.11 ($r_{\text{CDM}}=0.05$), and 21.08 ($r_{\text{CDM}}=0.1$)



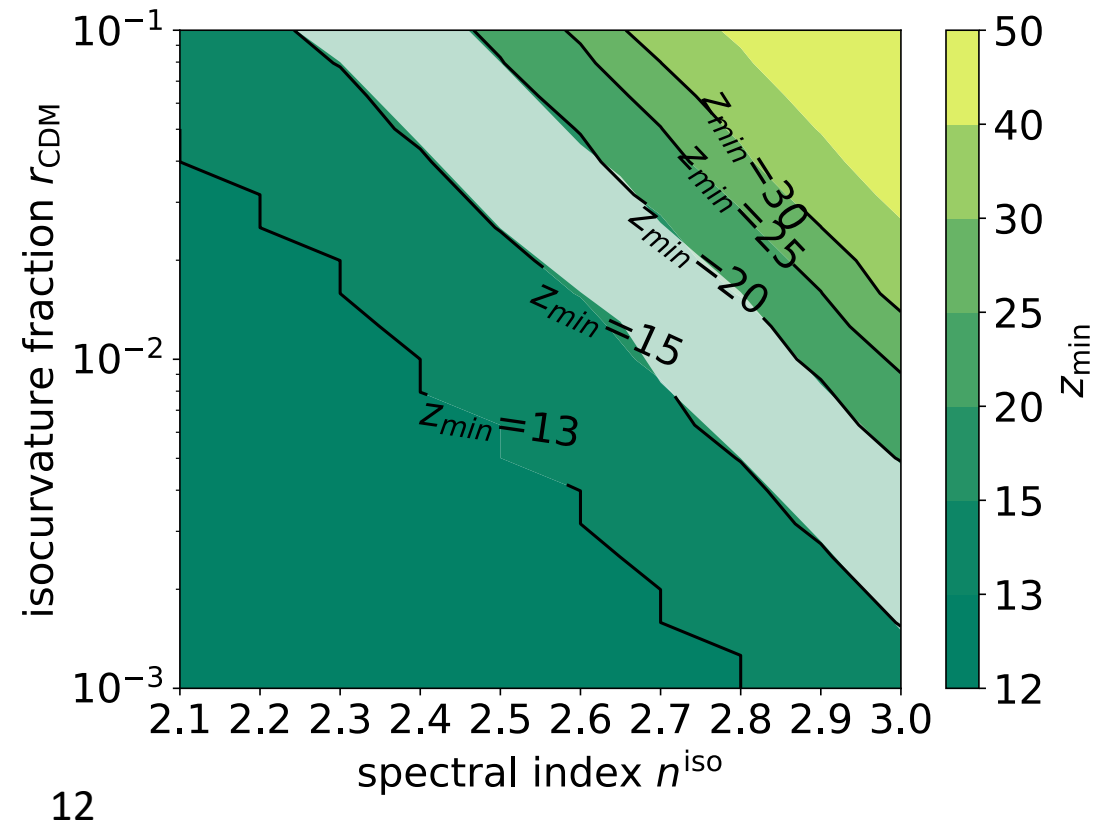
Absorption position with varying r_{CDM}

- Fixing n^{iso} and increasing r_{CDM} , the central redshift of absorption gets higher.
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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,

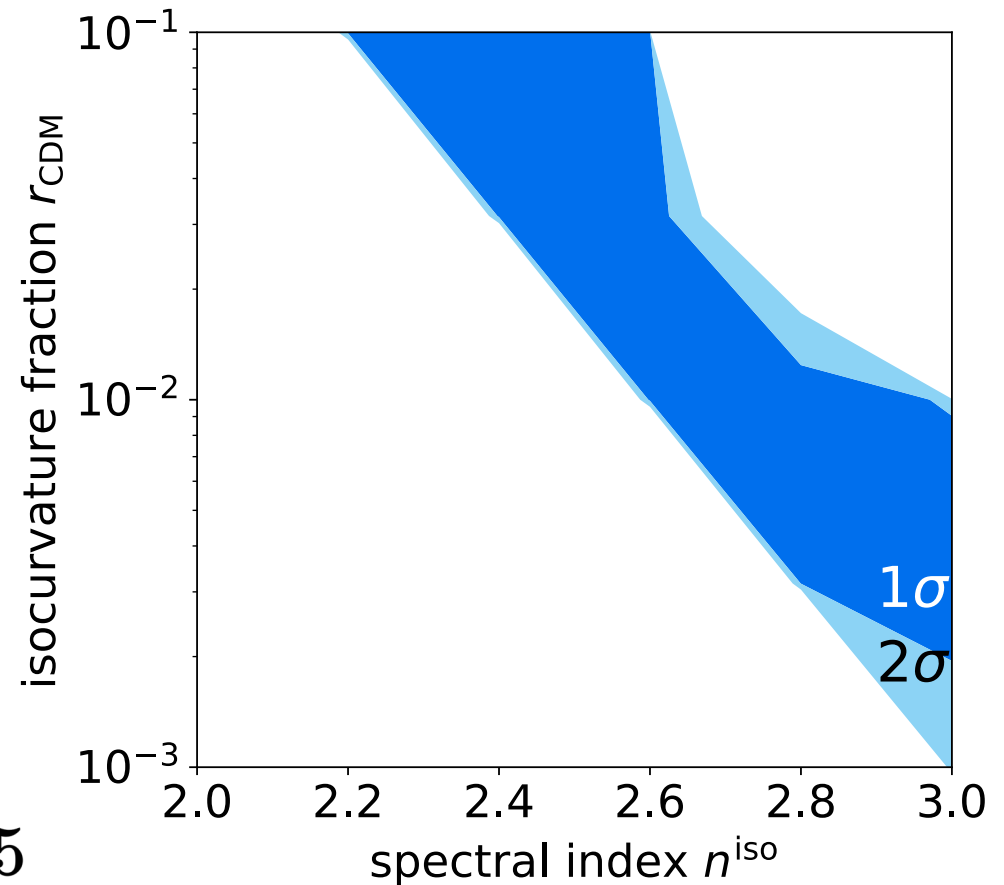
$$\mathbf{p} \equiv (r_{\text{CDM}}, n^{\text{iso}}, M_{\text{turn}}, L_{\text{X} < 2.0 \text{keV}} / \text{SFR})$$

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

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

- Finally the constraint is

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



Summary

- We calculate the effects of the isocurvature perturbations on the 21-cm line signal, and predict 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)
- Please see our paper [arXiv:2112.15135](https://arxiv.org/abs/2112.15135) if you are interested