Probing isocurvature perturbations with 21-cm global signal

21 cm Cosmology Workshop 2024 & Tianlai Collaboration Meeting

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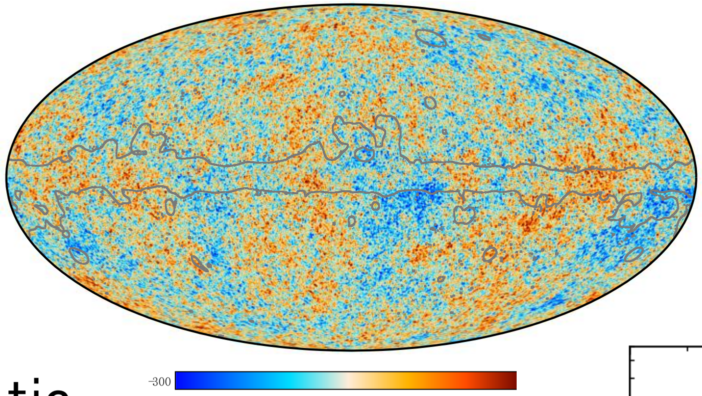
Teppei Minoda (Tsinghua University),

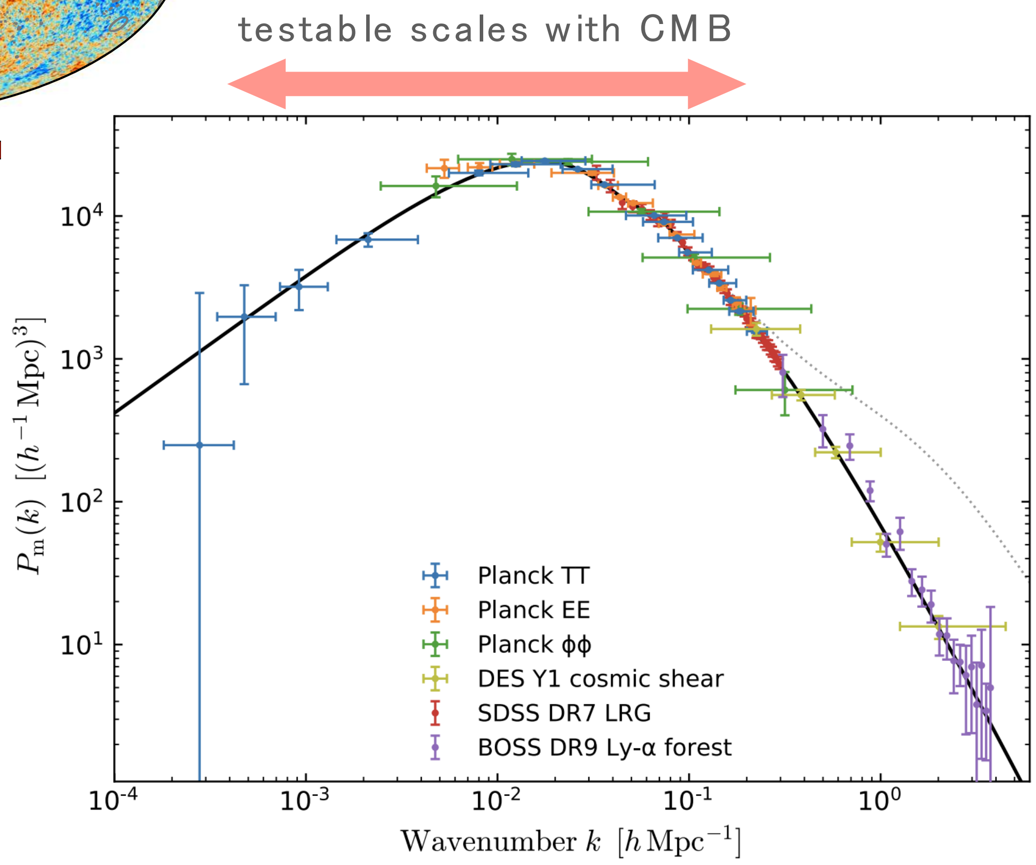
Shintaro Yoshiura (NAOJ), Tomo Takahashi (Saga University)

(arXiv:2112.15135, PRD 105 083523)

Primordial curvature perturbations



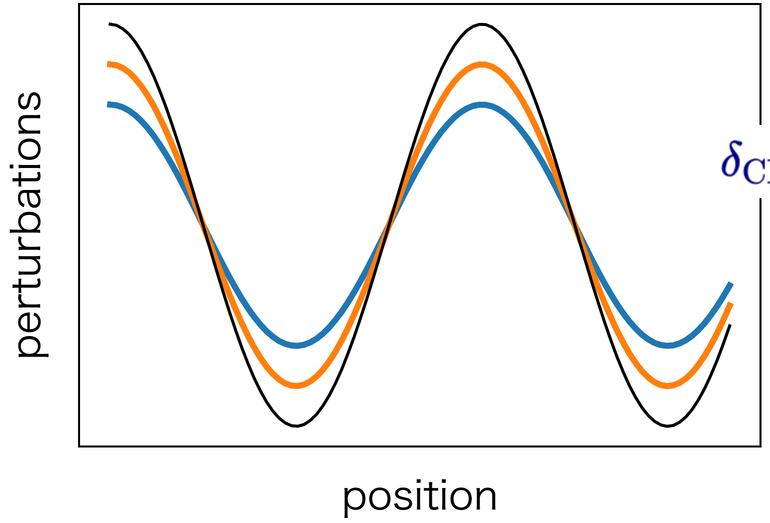
- CMB anisotropy, galaxy distributions suggest the primordial fluctuations
- Explained very well by adiabatic (curvature) perturbations with a single power-law power spectrum
- Testable scales of primordial fluctuations with CMB are finite
- Larger scales? > Causality limit, GW?



Planck 2018 results (2020), A&A, 641, A1

Adiabatic and isocurvature perturbations

adiabatic (curvature) perturbations



δ_{CDM} : cold dark matter

δ_γ : photons

$\mathcal{R}$: curvature

(baryons, neutrinos, ⋯)

perturbations for all components have the **same** phase (and different amplitudes)

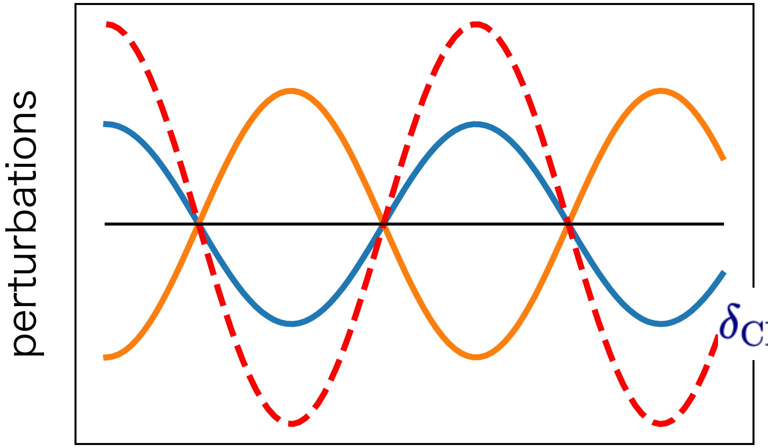
- For the pure adiabatic mode, the entropy is conserved:

$$S_{a,b} \equiv \frac{\delta n_a}{\bar{n}_a} - \frac{\delta n_b}{\bar{n}_b} = 0$$

(n_a : number density of the particle labeled "a")

Adiabatic and isocurvature perturbations

isocurvature (entropy) perturbations



δ_γ : photons

$\mathcal{R}$: curvature

$\delta_{\rm CDM}$: cold dark matter

(baryons, neutrinos, ⋯)

perturbations for two components have the **opposite** phase (curvature is NOT fluctuated)

$$S_{{\rm CDM},\gamma} = \delta_{\rm CDM} - \frac{3}{4}\delta_\gamma$$

- 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

$$\mathcal{P}_\zeta(k) = A_\mathrm{s}^\mathrm{adi}\left(\frac{k}{k_*}\right)^{n_\mathrm{s}^\mathrm{adi}-1}$$

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

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

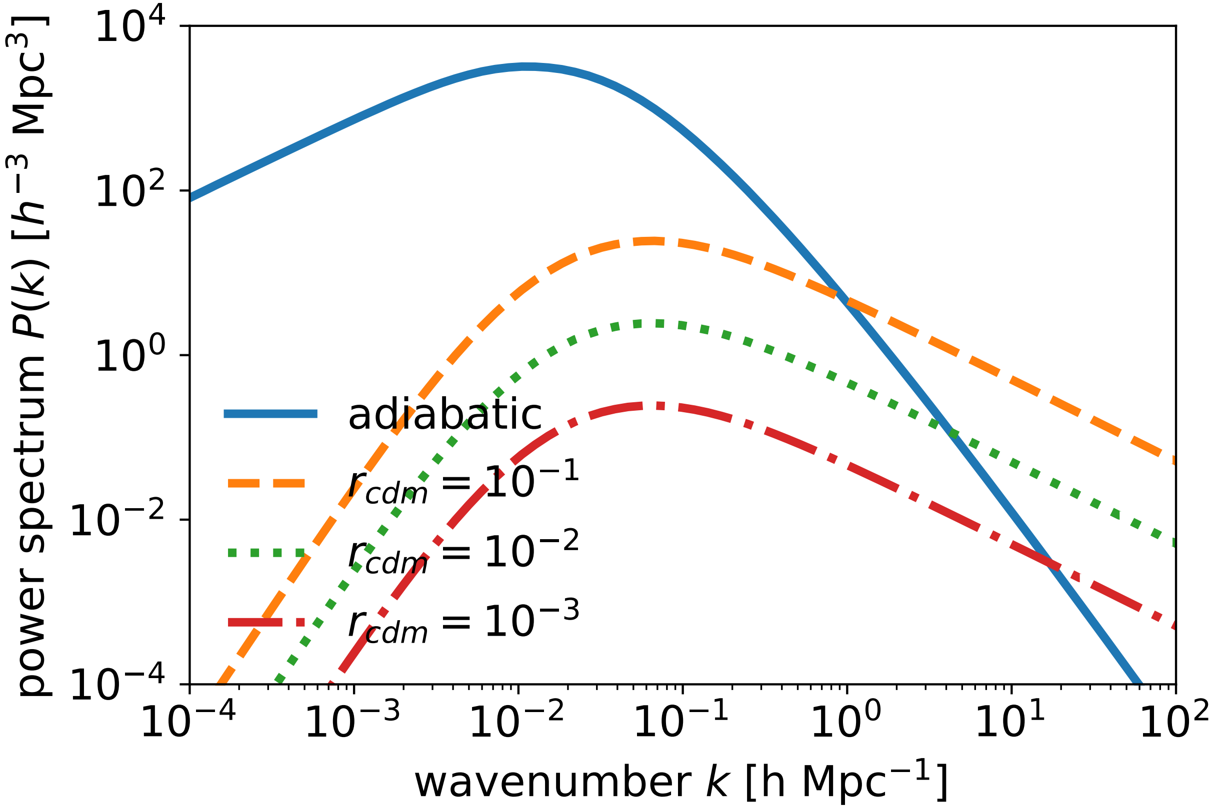
Parameters for the curvature power spectrum is fixed by Planck 2018.

$$A_\mathrm{s}^\mathrm{adi} = 2.101 \times 10^{-9},$$
$$n_\mathrm{s}^\mathrm{adi} = 0.965$$

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 $n^{iso}=3.0$

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:

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

- Duty cycle is parametrized by $M_{\rm turn}$:

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

$M_{\rm turn}$: 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

$$\dot{M}_*(M_\mathrm{h}, z) = \frac{M_*}{t_* H(z)^{-1}}$$

$t_\star$: the typical star formation timescale normalized by the Hubble time

- The stellar-to-halo mass ratio

$$\frac{M_*}{M_\mathrm{h}} = f_{*,10}\left(\frac{M_\mathrm{h}}{10^{10}M_\odot}\right)^{\alpha_*}\left(\frac{\Omega_\mathrm{b}}{\Omega_\mathrm{m}}\right)$$

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_*	$M_{\rm turn}$ $[M_\odot]$	t_*	$\log_{10}(L_{\rm X<2.0keV}/{\rm SFR}/[{\rm erg\ s^{-1}} M_\odot^{-1}\ {\rm yr}])$
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.

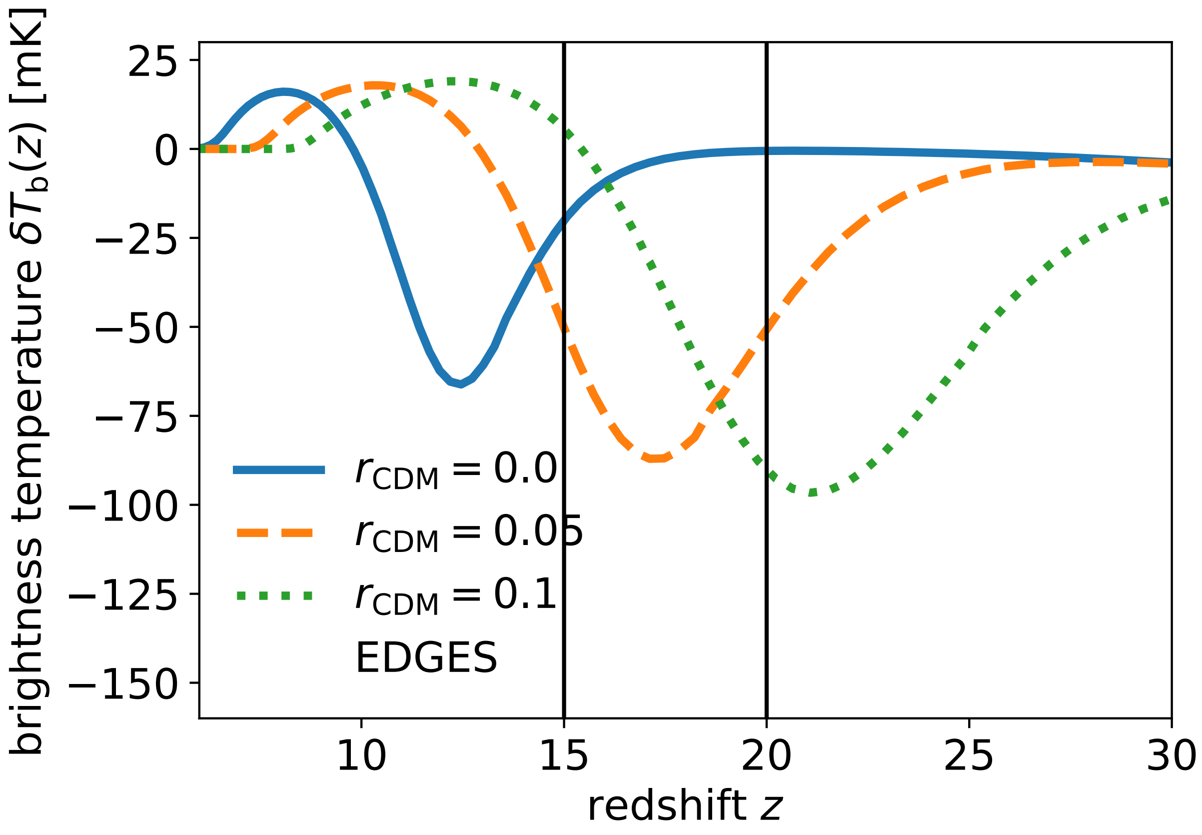
Minoda, Yoshiura, and Takahashi, Phys. Rev. D 105, 083523 (2022)

Alternative probe: 21-cm global signal

Differential brightness temperature:

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

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



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

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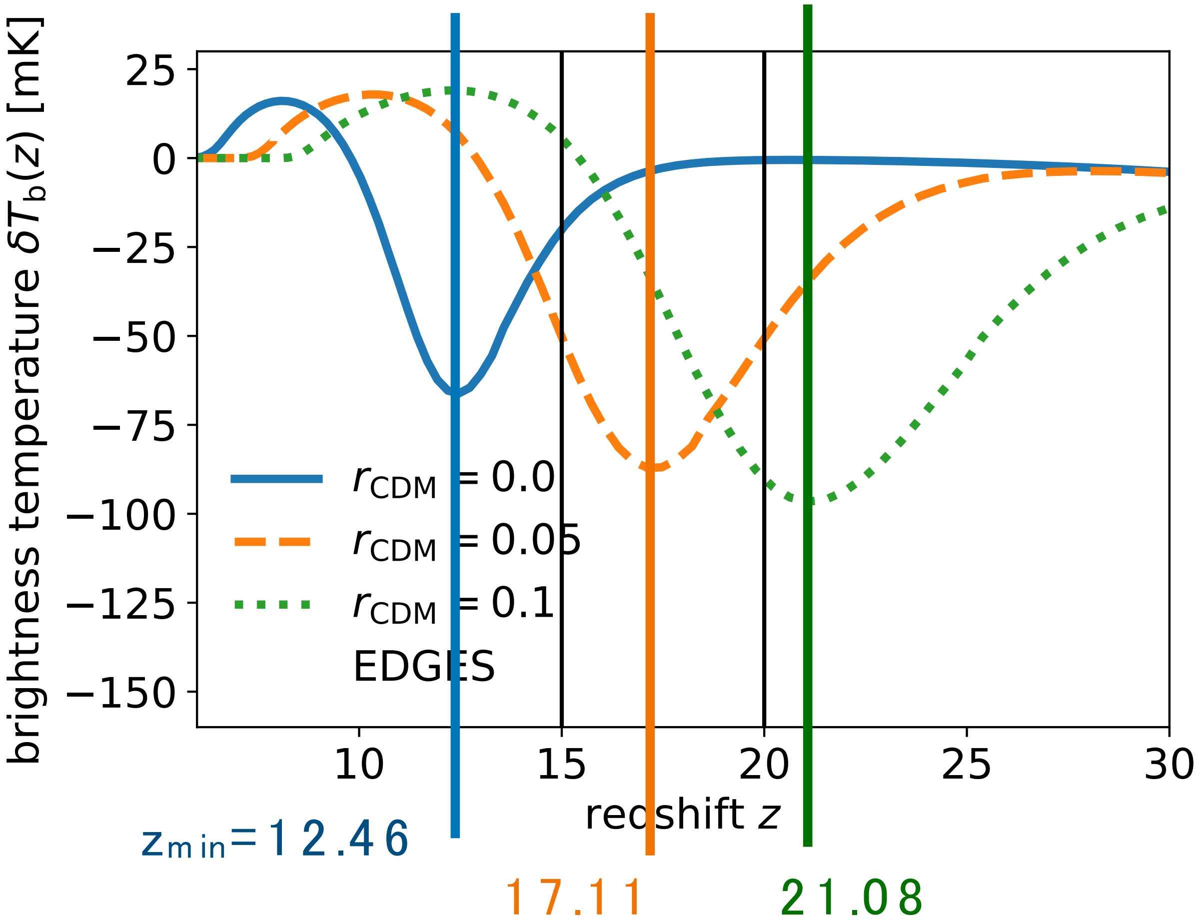
Increasing the isocurvature fraction, the Ly-α coupling and heating starts at higher redshifts.

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

We fix n^{iso}=2.5



Absorption position with varying r_{CDM}

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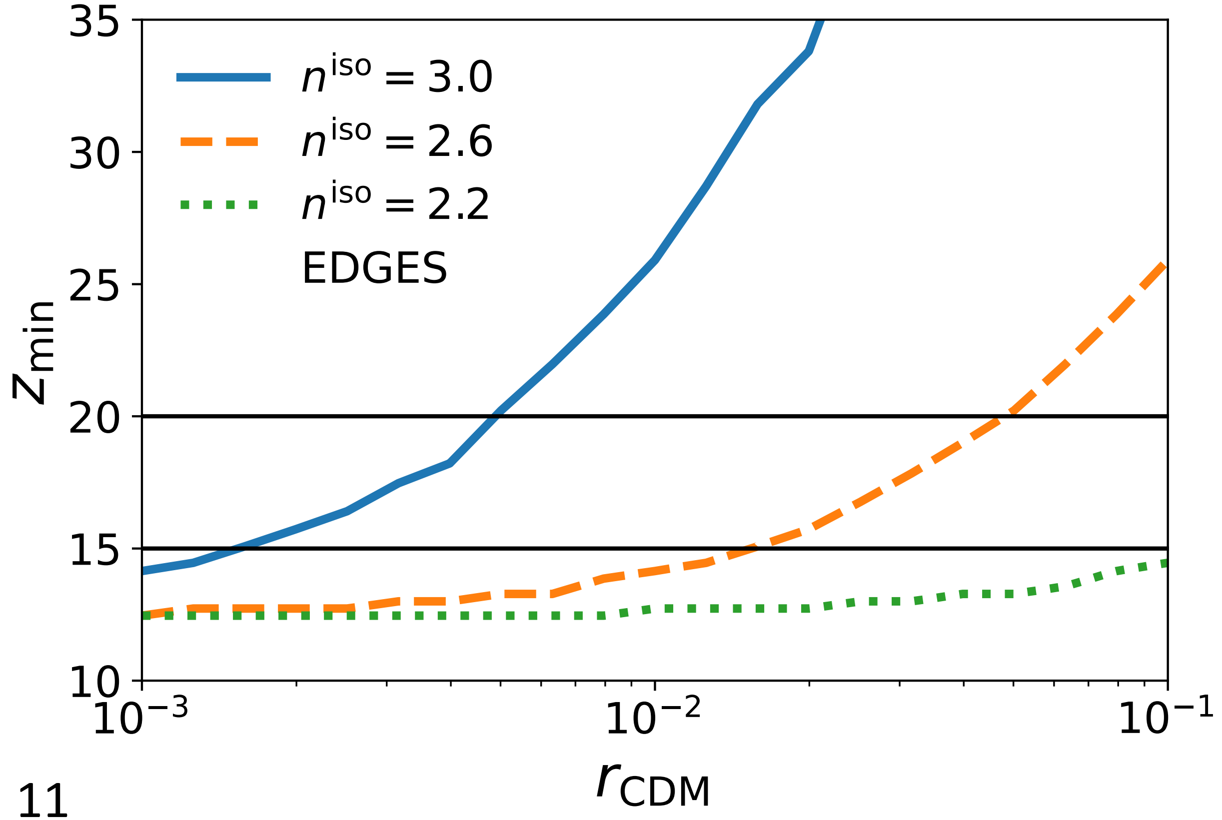
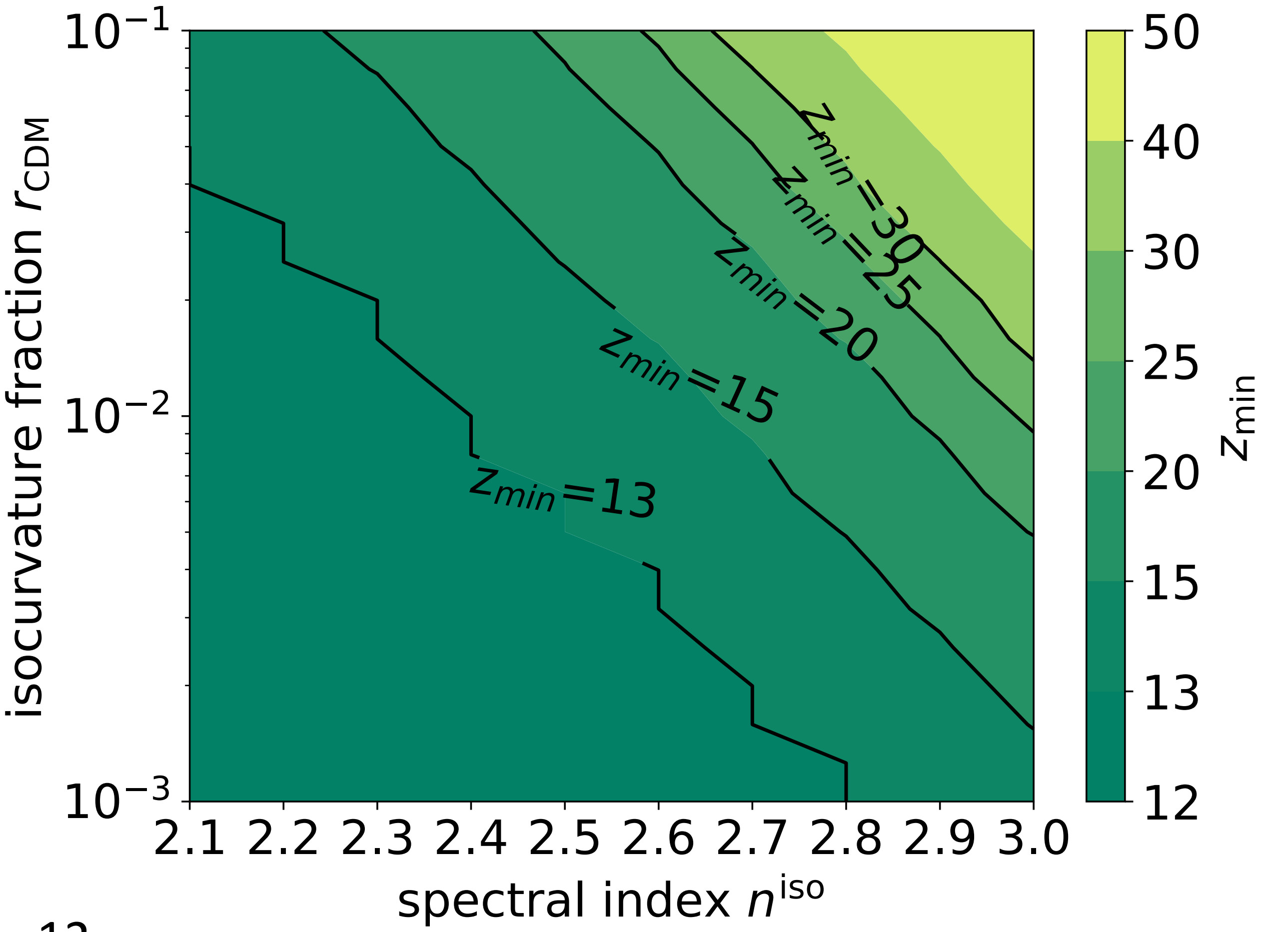


Constraints in 2-D parameter space

- 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,

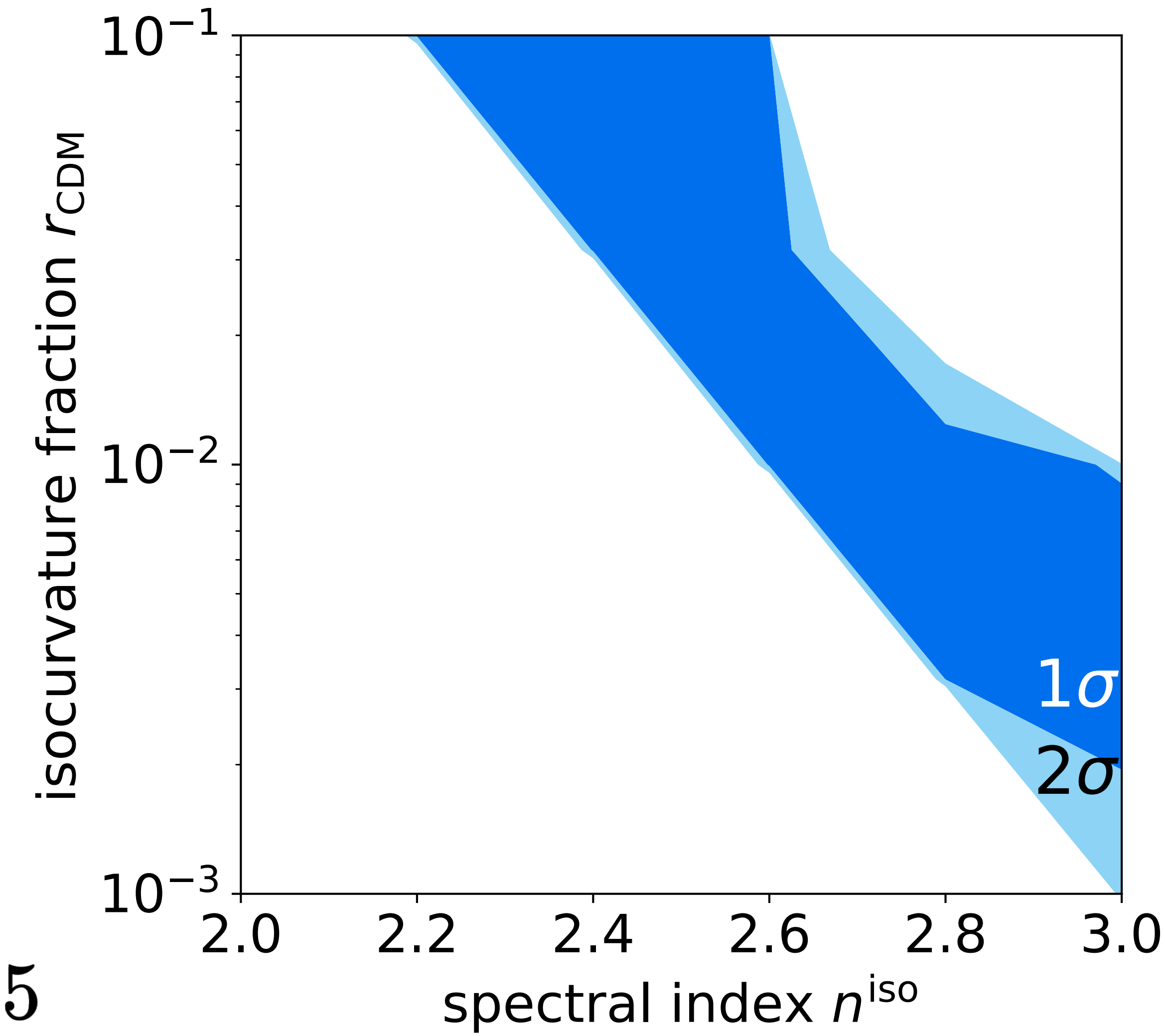
$$\boldsymbol{p} \equiv (r_{\rm CDM}, n^{\rm iso}, M_{\rm turn}, L_{{\rm X}<2.0{\rm keV}}/{\rm SFR})$$

$$\chi^2(\boldsymbol{p}) = \frac{\left(z_{\rm min,th}(\boldsymbol{p}) - z_{\rm min,obs}\right)^2}{\Delta {z_{\rm obs}}^2}$$

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

- Finally the constraint is

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



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 if you are interested