Probing primordial fluctuations with the 21-cm line and reionization history

Nagoya-Melbourne Joint Research Workshop on Cosmology

20th, February, 2024

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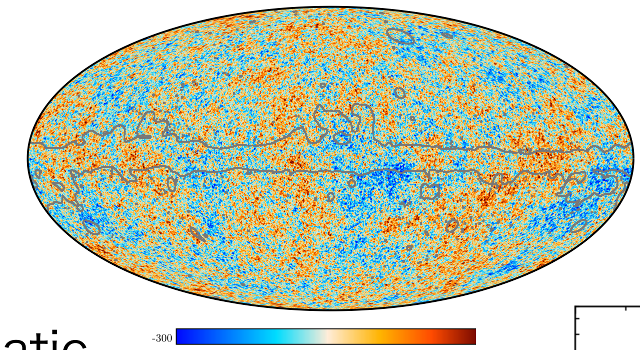
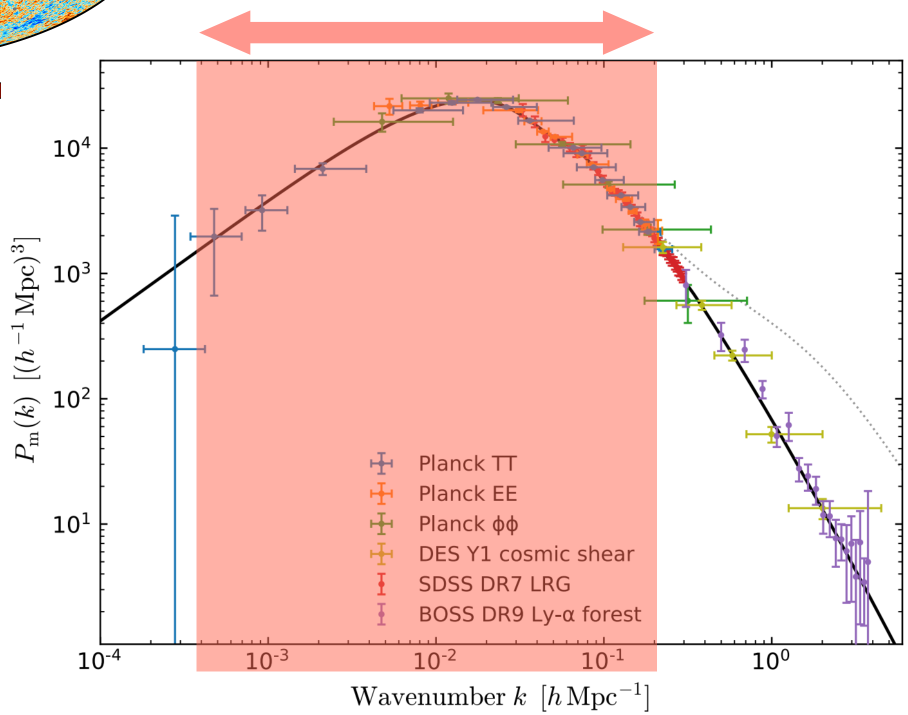
Planck image-gallery (https://www.cosmos.esa.int/web/planck/picture-gallery)

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

Power spectrum of the curvature perturbations

Different inflation models,
different features on primordial spectrum

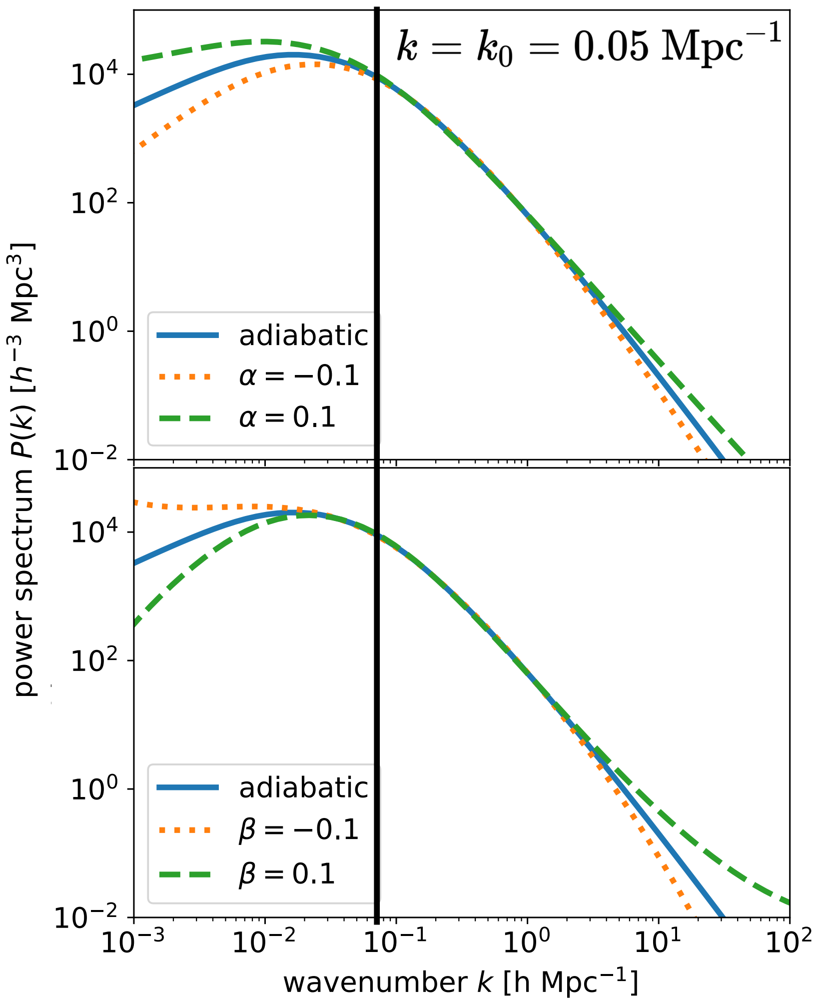
Top-down approaches (physical motivation): Potential of inflaton, slow-roll parameters

Bottom-up approaches (phenomenological):

(1) running indices:

$$\mathcal{P}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1 + \frac{1}{2}\alpha_s \ln\left(\frac{k}{k_0}\right) + \frac{1}{6}\beta_s \left[\ln\left(\frac{k}{k_0}\right)\right]^2}$$

Power spectrum of the adiabatic perturbations



Constraints on running parameters

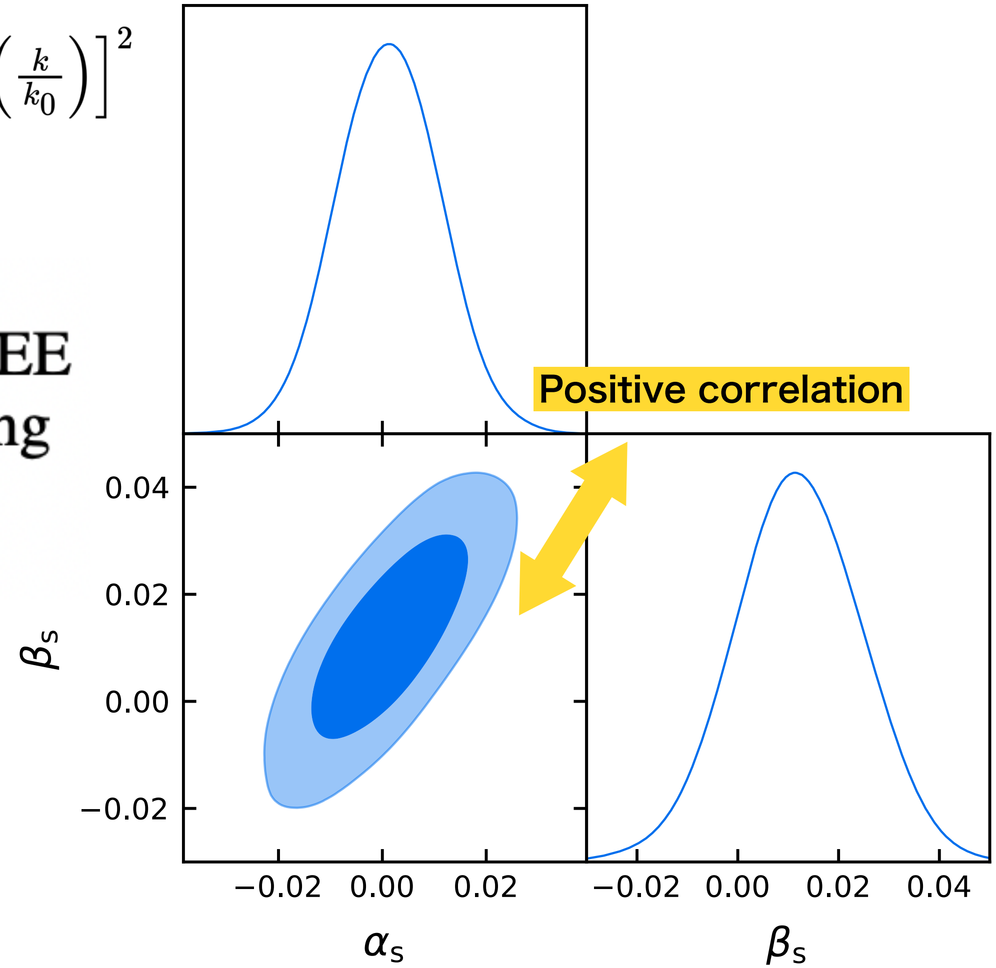
$$\mathcal{P}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1 + \frac{1}{2}\alpha_s \ln\left(\frac{k}{k_0}\right) + \frac{1}{6}\beta_s \left[\ln\left(\frac{k}{k_0}\right)\right]^2}$$

$$\left.\begin{aligned} \beta_s &= 0.009 \pm 0.012, \\ \alpha_s &= 0.0011 \pm 0.0099, \\ n_s &= 0.9647 \pm 0.0043, \end{aligned}\right\} \quad \begin{aligned} &68\,\%, \text{TT,TE,EE} \\ &\text{+lowE+lensing} \\ &\text{+BAO.} \end{aligned}$$

Planck 2018 results :

consistent with a single power-law on

$$0.008\ \mathrm{Mpc}^{-1} \lesssim k \lesssim 0.1\ \mathrm{Mpc}^{-1}$$



Constraints on running parameters

$$\mathcal{P}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1 + \frac{1}{2}\alpha_s \ln\left(\frac{k}{k_0}\right) + \frac{1}{6}\beta_s \left[\ln\left(\frac{k}{k_0}\right)\right]^2}$$

$\beta_s = 0.009 \pm 0.01$

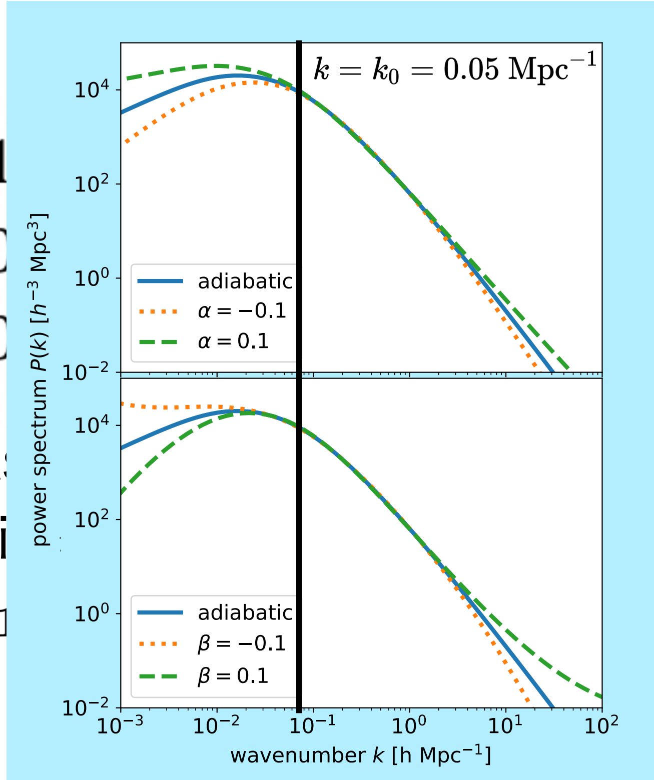
$\alpha_s = 0.0011 \pm 0.0$

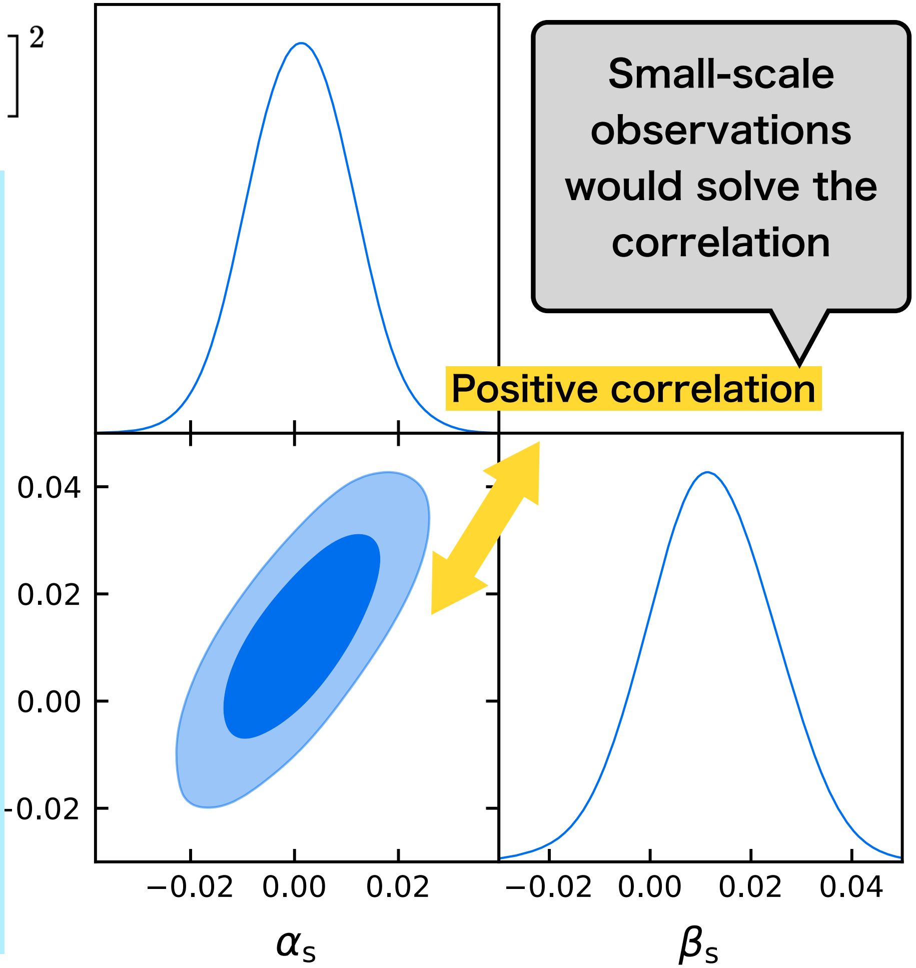
$n_s = 0.9647 \pm 0.0$

Planck 2018 result

consistent with a si

$0.008\ \mathrm{Mpc}^{-1}$



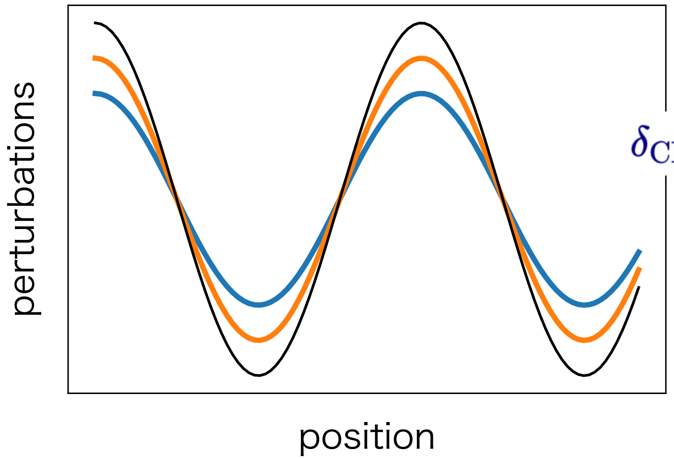


Small-scale observations would solve the correlation

Adiabatic and isocurvature perturbations

(2) isocurvature perturbations:

adiabatic (curvature) perturbations



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

δ_{γ} : photons

$\mathcal{R}$: curvature

(baryons, neutrinos, $\cdots$)

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

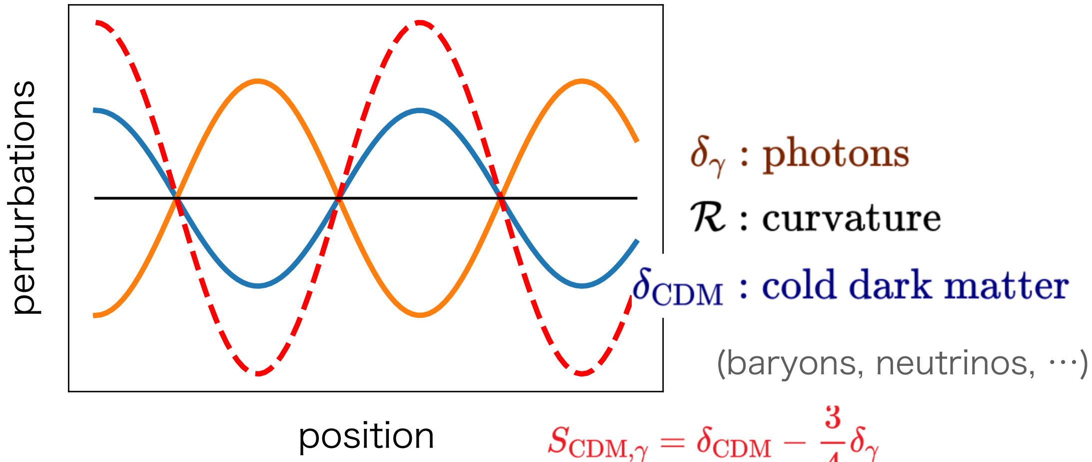
- For the pure adiabatic mode, the entropy is conserved:

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

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

Adiabatic and isocurvature perturbations

isocurvature (entropy) perturbations



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.

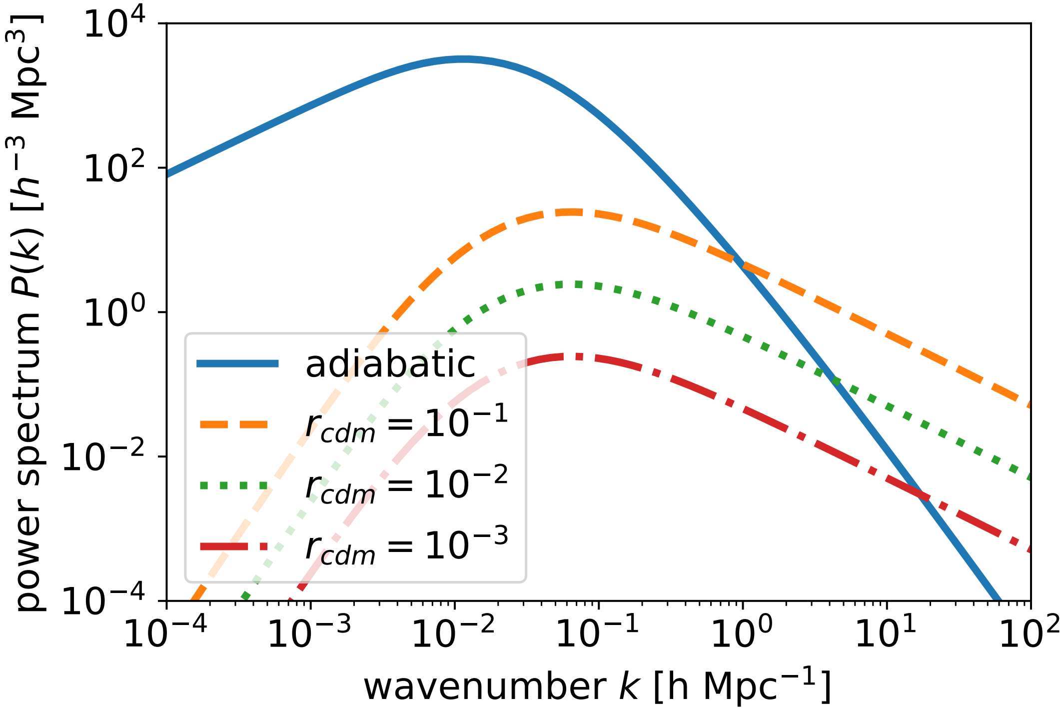
$$A_\mathrm{s}^\mathrm{adi} = 2.101 \times 10^{-9},$$
$$n_\mathrm{s}^\mathrm{adi} = 0.965$$

the isocurvature perturbations are parameterized by r_CDM and n^iso

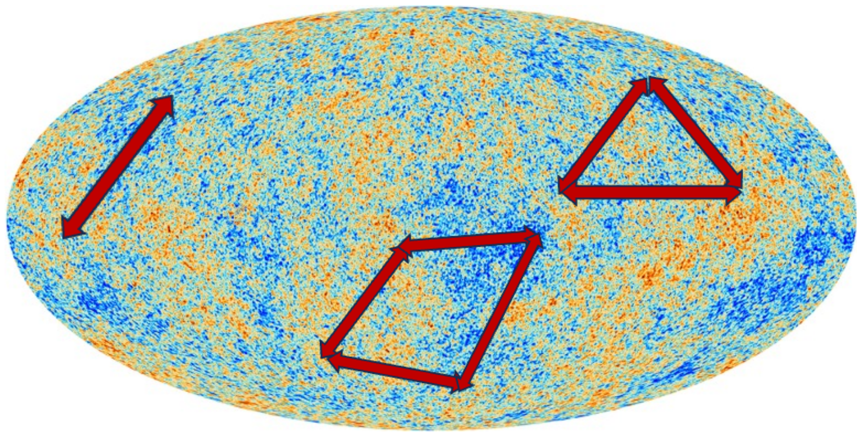
Matter power spectrum

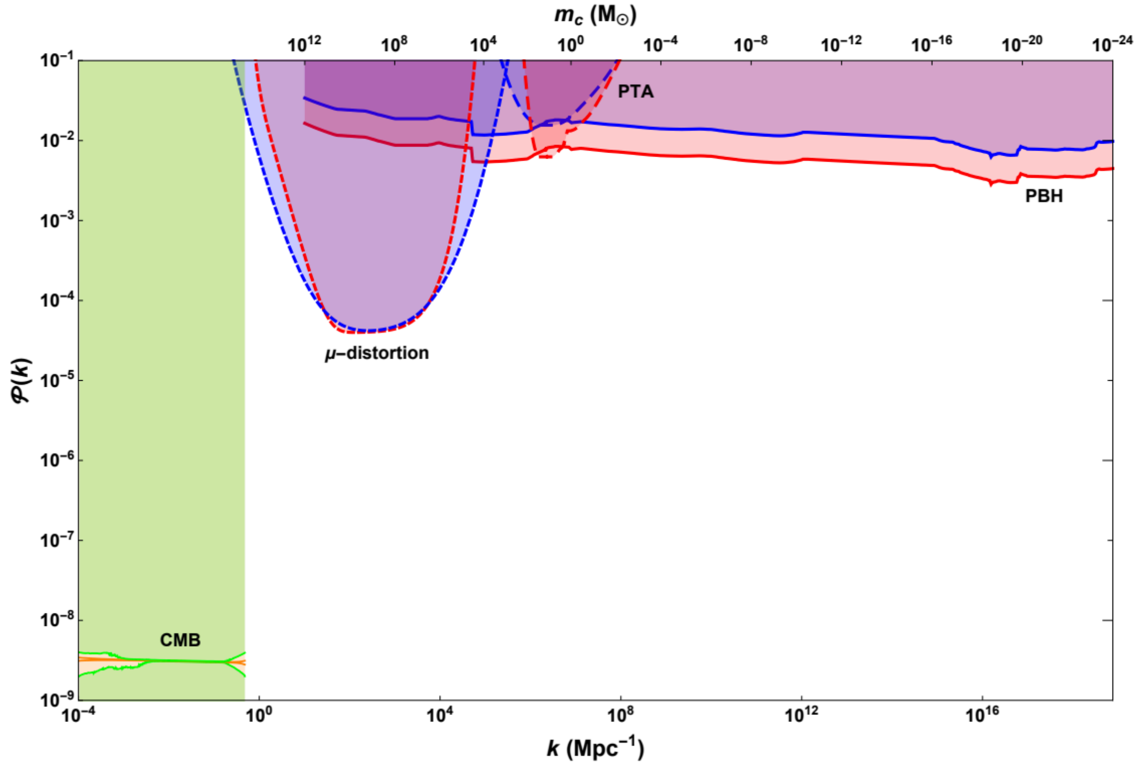
- The blue-tilted isocurvature perturbations enhance the matter power spectrum on small scales.
- Increasing r_{CDM}, the amplitude of matter power spectrum is larger.
- Blue-tilted isocurvature is expected by one of the QCD axion scenarios (Kasuya and Kawasaki 2009)

Fixing n^{iso}=3.0



Other topics related to small-scales





Gaussian fluctuations can be treated by
2-point correlation > power spectrum
Non-gaussian fluctuations:
3-point > bispectrum, $f_{\rm NL}$
4point > trispectrum, $g_{\rm NL}, \tau_{\rm NL}$

Primordial Black Holes, and Pulsar Timing Array can access "really" small scales, ~ > 10^5 Mpc^{-1}

Gow et al. (2021), JCAP, 2021, 002.

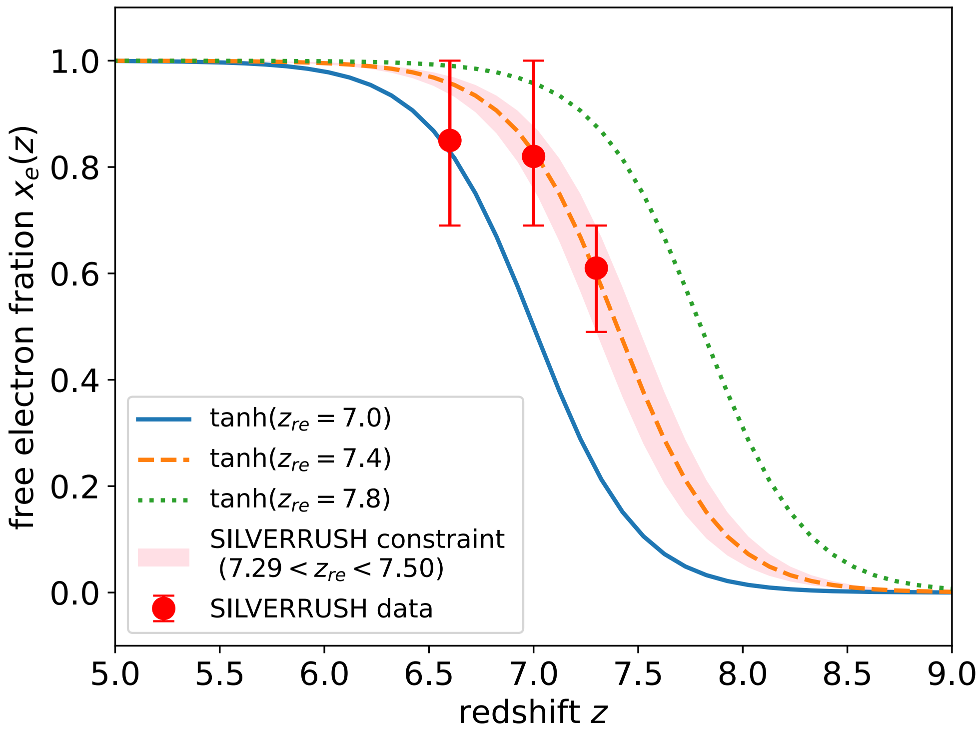
A new probe for the primordial fluctuations: reionization history

$$x_{\rm e}(z, z_{\rm re}) = \frac{1}{2}\left[1 + \tanh\left(\frac{y(z_{\rm re}) - y(z)}{\Delta y}\right)\right],$$

$$y(z) = (1+z)^{2/3},$$

$$\Delta y = 3/2(1+z_{\rm re})^{1/2}\Delta z$$

$$\Delta z = 0.5$$



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SILVERRUSH. XI. Constraints on the Lyα Luminosity Function and Cosmic Reionization at z = 7.3 with Subaru/Hyper Suprime-Cam

Hinako Goto[1], Kazuhiro Shimasaku[1,2], Satoshi Yamanaka[3,4], Rieko Momose[1], Makoto Ando[1], Yuichi Harikane[5,6], Takuya Hashimoto[7], Akio K. Inoue[4,8], and Masami Ouchi[5,9,10]

Published 2021 December 24 • © 2021. The Author(s). Published by the American Astronomical Society.

The Astrophysical Journal, Volume 923, Number 2

Citation Hinako Goto *et al* 2021 *ApJ* **923** 229

DOI 10.3847/1538-4357/ac308b

SILVERRUSH

Systematic **I**dentification of **L**AEs for **V**isible **E**xploration and **R**eionization **R**esearch **U**sing **S**ubaru **H**SC

Calculation of reionization history

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

Using the "21cmFAST" calculation code

Physical parameters for reionization history:

(1) UV luminosity function

Star formation rate

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

halo formation history
curvature perturbations
Cosmological parameters

Duty cycle is parametrized by M_{turn}:

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

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Physical parameters for reionization history:

(1) UV luminosity function

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

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

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

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

Calculation of reionization history

(2) Star formation rate

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

$t_\star$: ratio of the typical star formation time to the Hubble time

(3) Stellar mass - Halo mass relation

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

(4) escape fraction of ionizing photons

$$f_\mathrm{esc}(M_\mathrm{halo}) = f_{\mathrm{esc},10}\left(\frac{M_\mathrm{halo}}{10^{10} M_\odot}\right)^{\alpha_\mathrm{esc}},$$

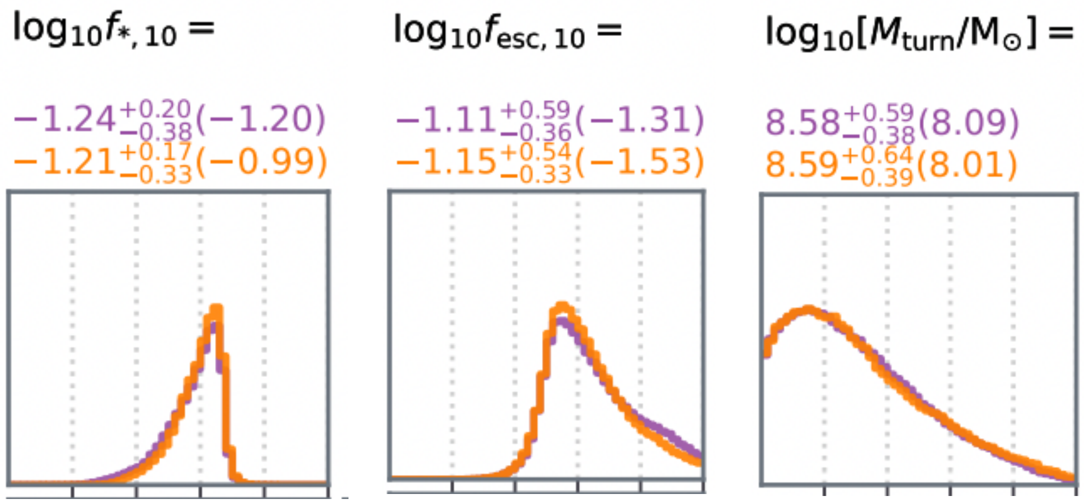
Particularly important parameters:

$M_\mathrm{turn}, f_{\mathrm{esc},10}, f_{*,10}$

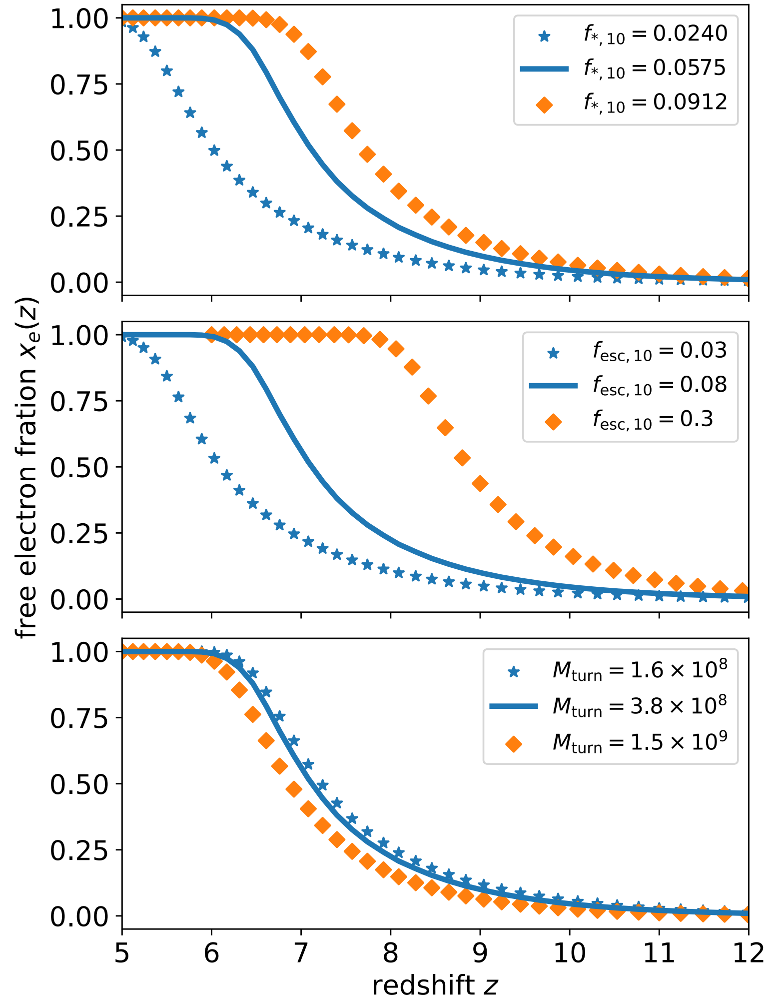
Astrophysical effects on the reionization history

Previous constraints on 21cmFAST parameters

HERA 21cm PS + galaxy UV LFs
+ QSO dark fraction + CMB optical depth



Abdurashidova, Z. et al. 2022, ApJ, 924, 51.



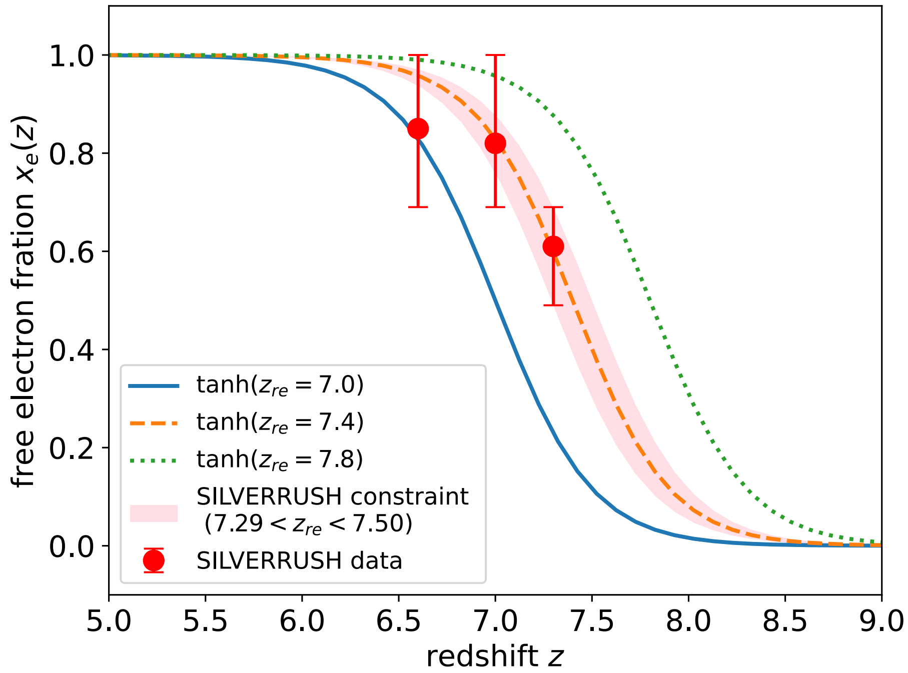
Minoda, Yoshiura, and Takahashi, Phys. Rev. D 108, 123542 (2023)

Fitting function of 21cmFAST results

$$x_{\rm e}(z=7.3) = \min(1.0, \tilde{x}_{\rm e,7.3}),$$

$$\tilde{x}_{\rm e,7.3} = \left\{0.421{\rm e}^{A} + B\left[\left(\frac{f_{*,10}}{0.058}\right)^{C} - 1.0\right] + D\log\left(\frac{M_{\rm turn}}{3.8\times10^{8}M_\odot}\right)\right\}\left(\frac{f_{\rm esc,10}}{0.078}\right)^{E},$$

$$A = 8.43\alpha_s + 11.41\beta_s,$$
$$B = 4.00\alpha_s + 7.75\beta_s + 0.38,$$
$$C = -5.24\alpha_s - 12.04\beta_s + 1.34,$$
$$D = -0.7\alpha_s - 1.20\beta_s - 0.07,$$
$$E = -3.11\beta_s + 1.08.$$



Mean fitting error: ~0.02

Observation error of SILVERRUSH: ~0.2

$$0.49 \le x_{\rm e} \le 0.69 \text{ at } z = 7.3.$$

$$7.29 \le z_{\rm re} \le 7.50$$

Minoda, Yoshiura, and Takahashi, Phys. Rev. D 108, 123542 (2023)

MCMC analysis (only running)

Flat prior:
-0.2 < alpha < 0.2
-0.2 < beta < 0.2

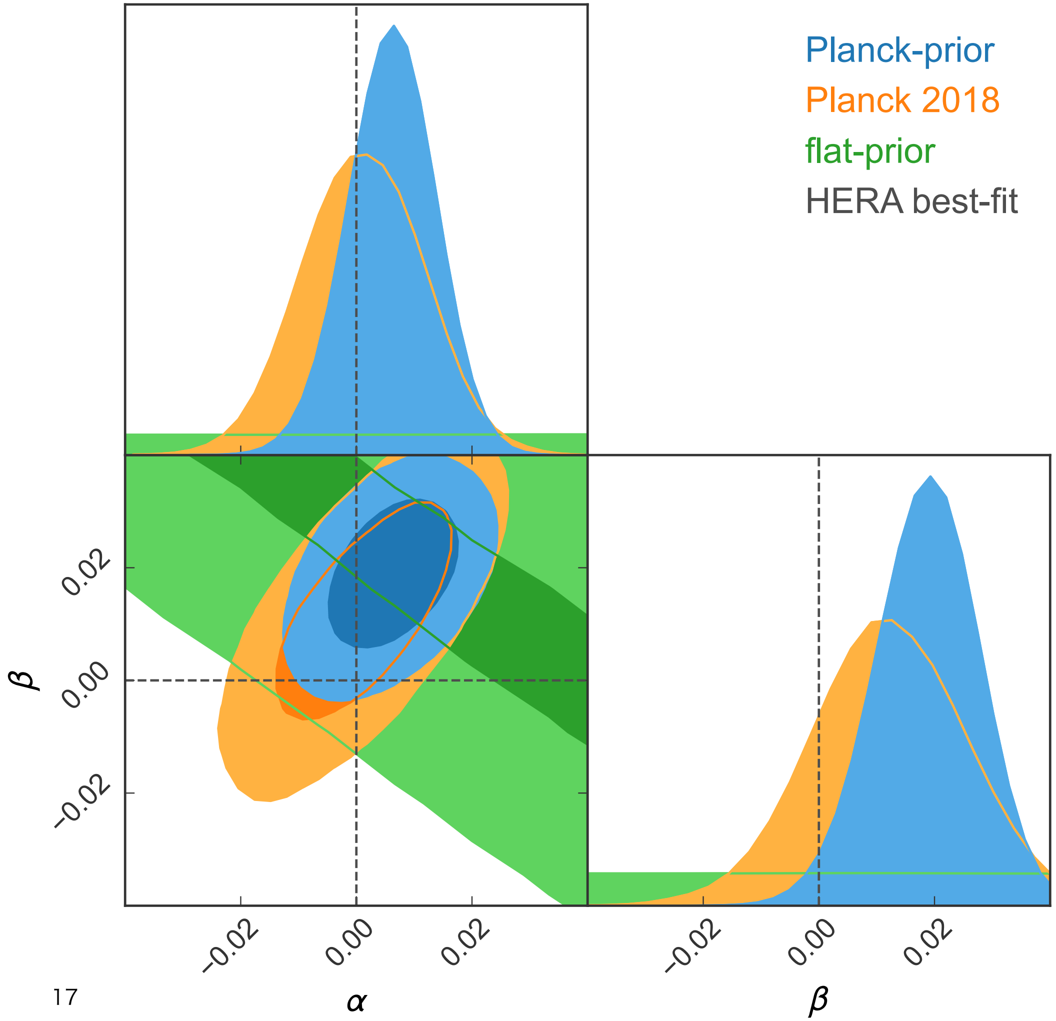
Planck prior:
2D gaussian on alpha and beta,
with Planck 2018 covariance matrix

Planck 2018

$$\alpha_s = 0.0011 \pm 0.0099,$$
$$\beta_s = 0.009 \pm 0.012,$$

Our results

$$\alpha_s = 0.006^{+0.007}_{-0.007}$$
$$\beta_s = 0.019^{+0.008}_{-0.009}$$

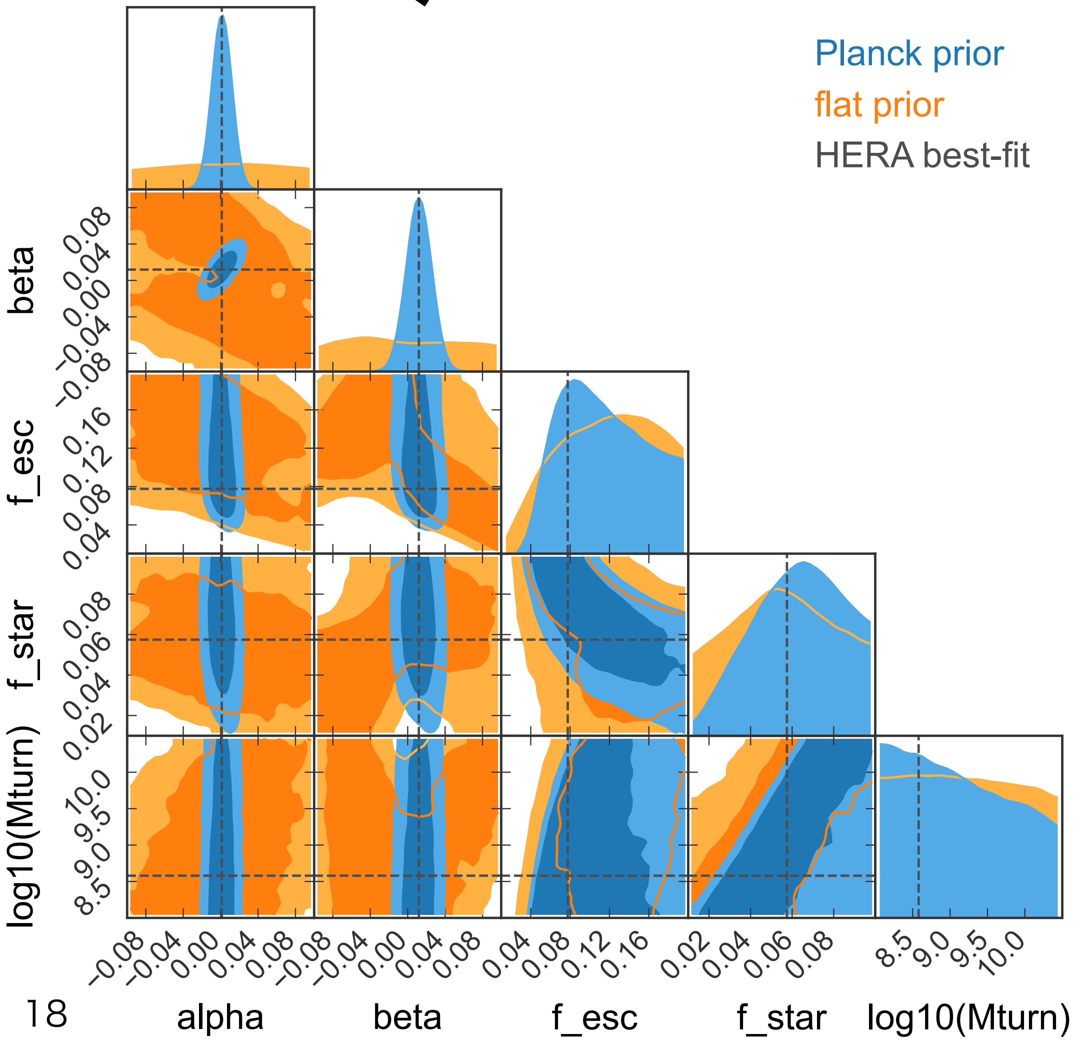


Minoda, Yoshiura, and Takahashi, Phys. Rev. D 108, 123542 (2023)

MCMC analysis (with astro)

Flat prior:
-0.2 < alpha < 0.2
-0.2 < beta < 0.2
0.001 < fesc < 0.4
0.001 < fstar < 0.4
7.0 < logM < 10.5

Planck prior:
2D gaussian on alpha and beta



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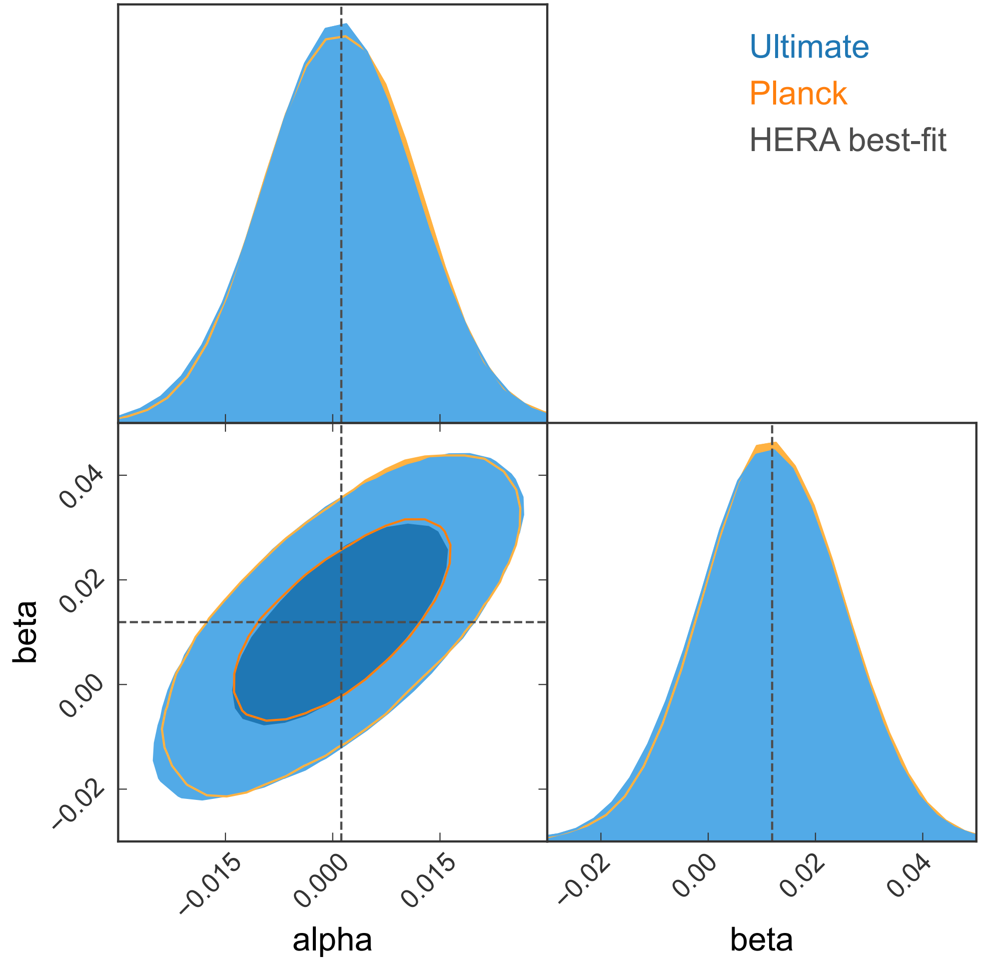
0.001 < fesc < 0.4
0.001 < fstar < 0.4
7.0 < logM < 10.5

Planck prior:
2D gaussian on alpha and beta

- Almost same with the Planck-only constraint



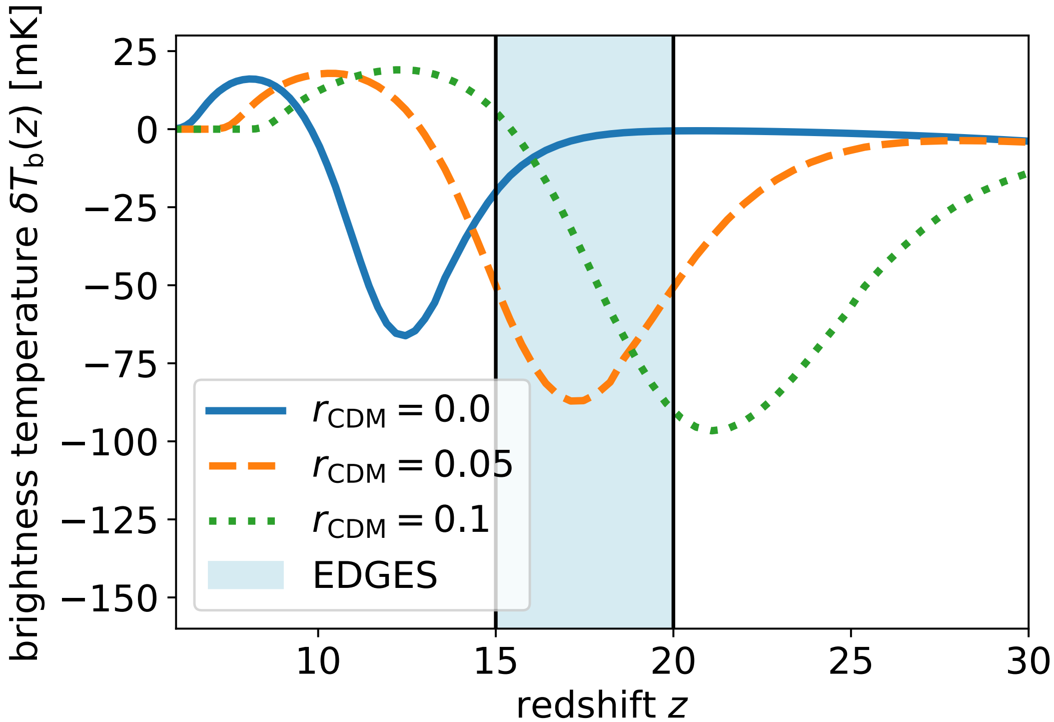
Minoda, Yoshiura, and Takahashi, Phys. Rev. D 105, 083523 (2022)

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

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

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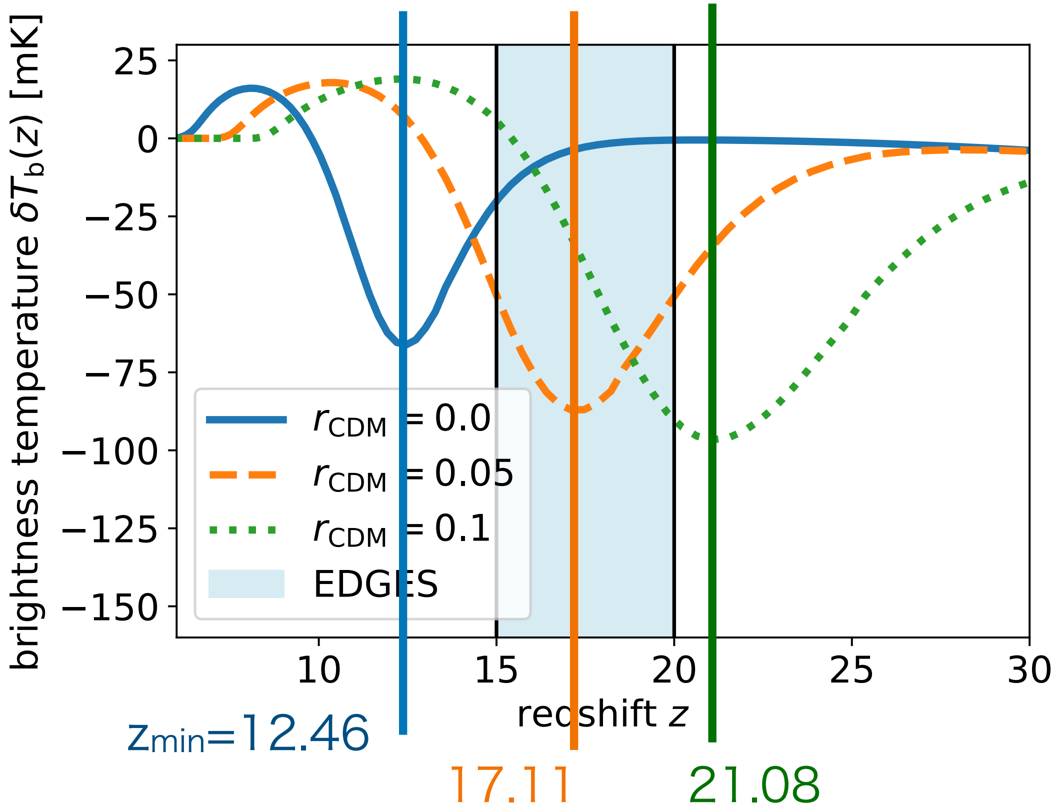
Increasing the isocurvature fraction, the Ly-α coupling and heating starts at higher redshifts.

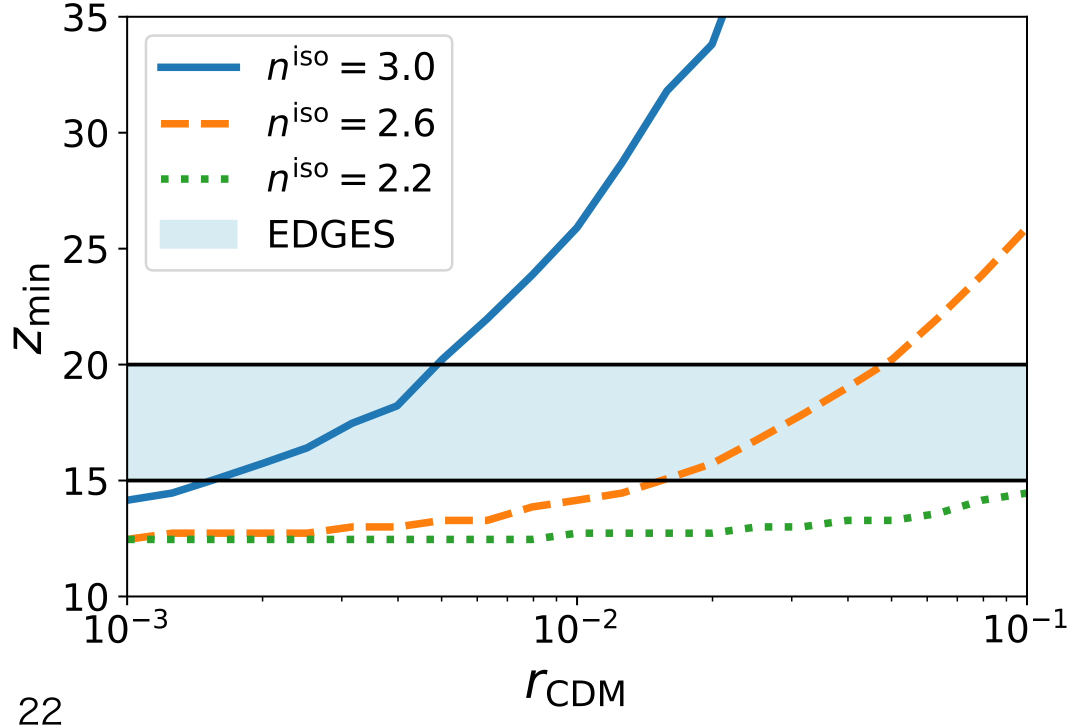
The central redshifts of absorption signal are z_{min}=12.46 (r_{CDM}=0.0), 17.11 (r_{CDM}=0.05), and 21.08 (r_{CDM}=0.1)

We fix n^{iso}=2.5



Absorption position with varying r_{CDM}

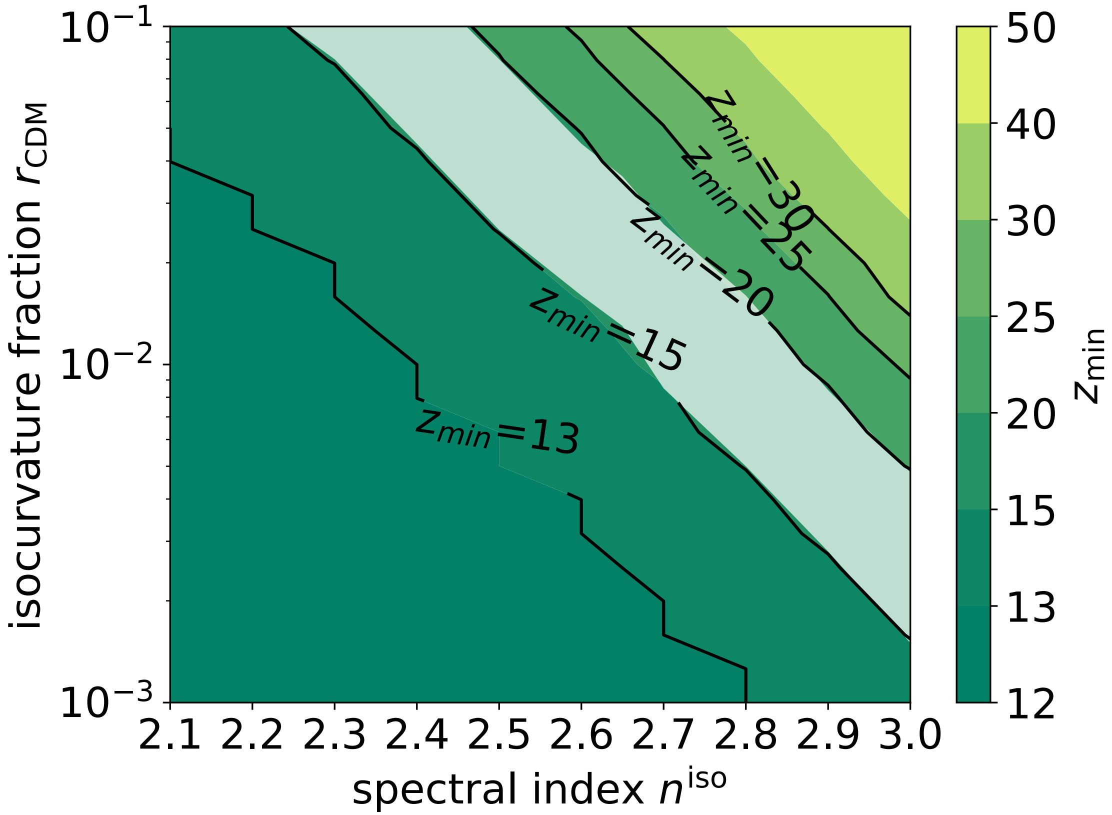
- Fixing n^{iso} and increasing r_{CDM}, the central redshift of absorption gets higher.
- Fixing r_{CDM} and increasing n^{iso}, the central redshift of absorption gets higher.



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

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.



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

Chi^2 analysis in 2-D parameter space

- Calculating chi squared for different param sets,

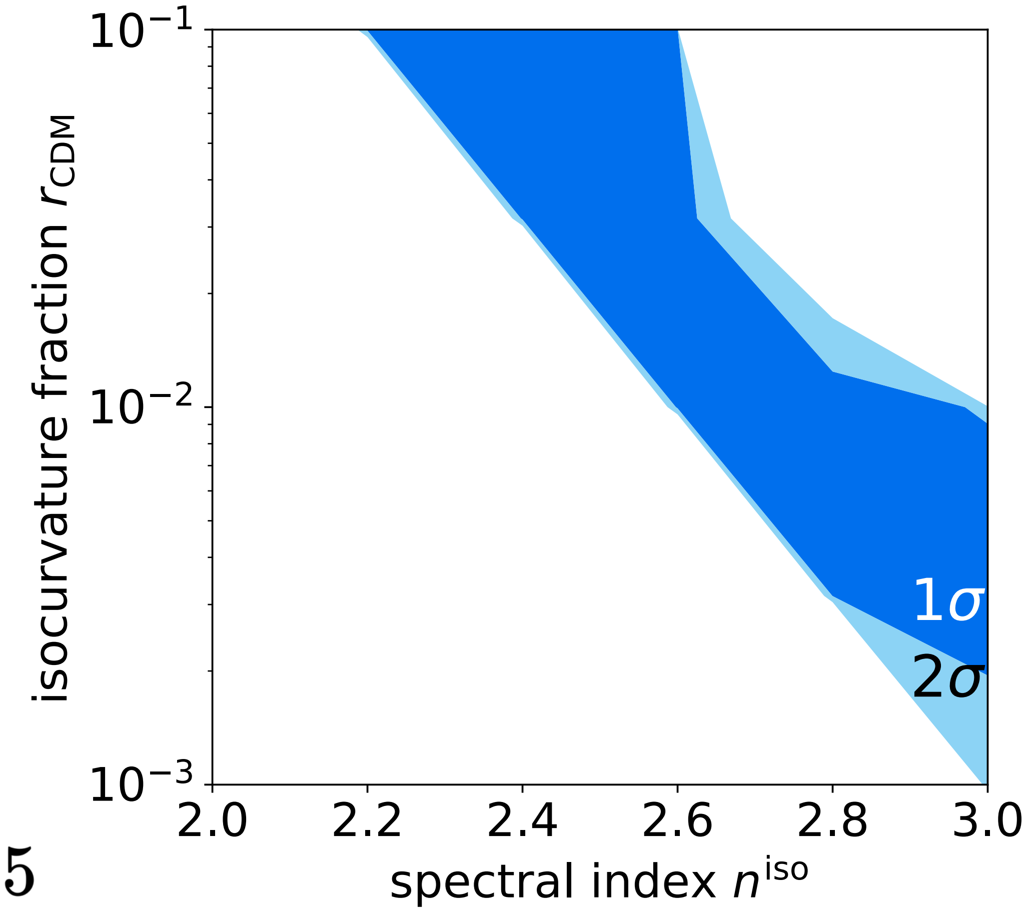
$$\boldsymbol{p} \equiv \left(r_{\rm CDM}, n^{\rm iso}, M_{\rm turn}, L_{\rm X<2.0keV}/{\rm SFR}\right)$$

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

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

- Finally the constraint is

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



Summary

- We calculate the effects of the primordial perturbations on the reionization history and 21-cm line signal.
- We also discuss the degeneracy between uncertainty of astrophysical parameters and primordial perturbations.
- For the future prospects, the further severe constraint would be given by the combined analysis of the 21-cm line signal and the reionization, and/or the other observables (21-cm power spectrum, CMB distortion, Lyman alpha forest, and so on)
- Another idea? Synergy with another observation?