Probing small-scale baryon and dark matter isocurvature perturbations using CMB anisotropies

(arXiv:2108.07798 w/ Yacine Ali-Haïmoud (NYU))

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Cosmology from Home - July 2022

OUTLINE

00 AD

A new recombination code: **HyRec-2** (N. Lee and Y. Ali-Haimoud, Phys. Rev. D 102, 083517 (2020))

01 Motivation

Any way to probe small-scale (k>1/Mpc) initial conditions using CMB anisotropies

02 Method (constraining small-scale power, k>1/Mpc)

Average free electron abundance using Green’s function

03 Results

Constraints on isocurvature perturbations amplitude

The Hubble tension?

Recombination codes before HyRec-2

RECFAST

- Most commonly used for CMB data analysis (ex. Planck)
- Pros : Fast (~20ms)
- Cons : Not physically modeled. Uncertainty is larger than 0.1%

HyRec & CosmoRec

- State-of-the-art codes
- Pros : Theoretical uncertainty is a few times 0.01% (solve radiative transfer equations)
- Cons : Relatively slow (~0.5s)

A new recombination code: HyRec-2

HyRec-2

- The same accuracy as the original HyRec
- The fastest (under 1ms)
- https://github.com/nanoomlee/HYREC-2
- Phys. Rev. D 102, 083517 (arXiv:2007.14114)

Motivation

CMB anisotropy data cannot probe initial conditions on small scales, k > 0.1 /Mpc

Weak indirect constraints from CMB spectral distortion (Chlubar and Grin, 2013)

Any way to use CMB anisotropies to put constraints on such small scales? YES
(See also relevant previous studies, Jedamzik and Abel (2011) and Jedamzik and Pogosian (2020))

→ Non-linear contributions to free-electron abundance from small-scale baryon perturbations

- CMB spectra strongly depends on recombination history.
- Recombination is a non-linear process. $\dot{n}_e\big|_{\rm rec} \propto -n_e n_p \propto -n_H^2$
- Recombination rate depends non-linearly on the local baryon density (and velocity divergence).

- (if any) Small-scale baryon perturbations can modify the average free electron abundance.
- Observed CMB spectra will put a limit on small scales perturbations.

Motivation

Different inflation models give different initial conditions

- Single-field inflation → Adiabatic initial conditions
- Multi-field inflation → Isocurvature initial conditions

Adiabatic (or curvature) initial conditions

$$\frac{1}{3}\delta_{b,i} = \frac{1}{3}\delta_{c,i} = \frac{1}{4}\delta_{\gamma,i} = \frac{1}{4}\delta_{\nu,i}$$

Entropy (or isocurvature) initial conditions

- We can consider these as any deviation from adiabatic initial conditions

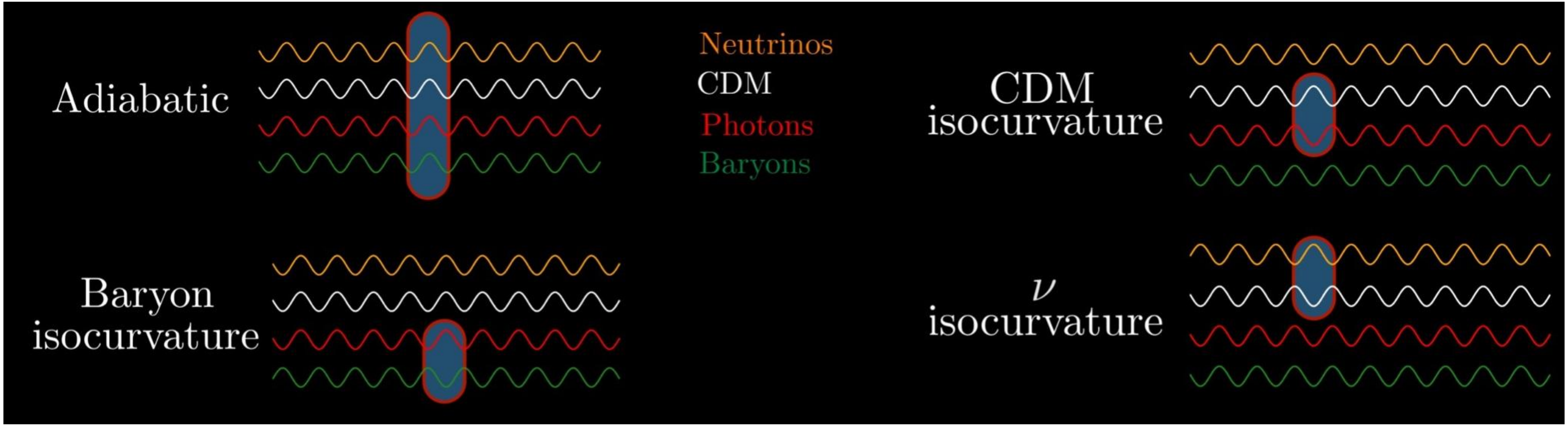
Constraints from CMB (large-scale)

- Adiabatic perturbations : $\Delta^2_{\rm adi} \sim 2 \times 10^{-9}$
- Any isocurvature perturbations cannot take more than 2% of total perturbations.

(Planck 2018 results. X.)

Motivation

Various Isocurvature Perturbations

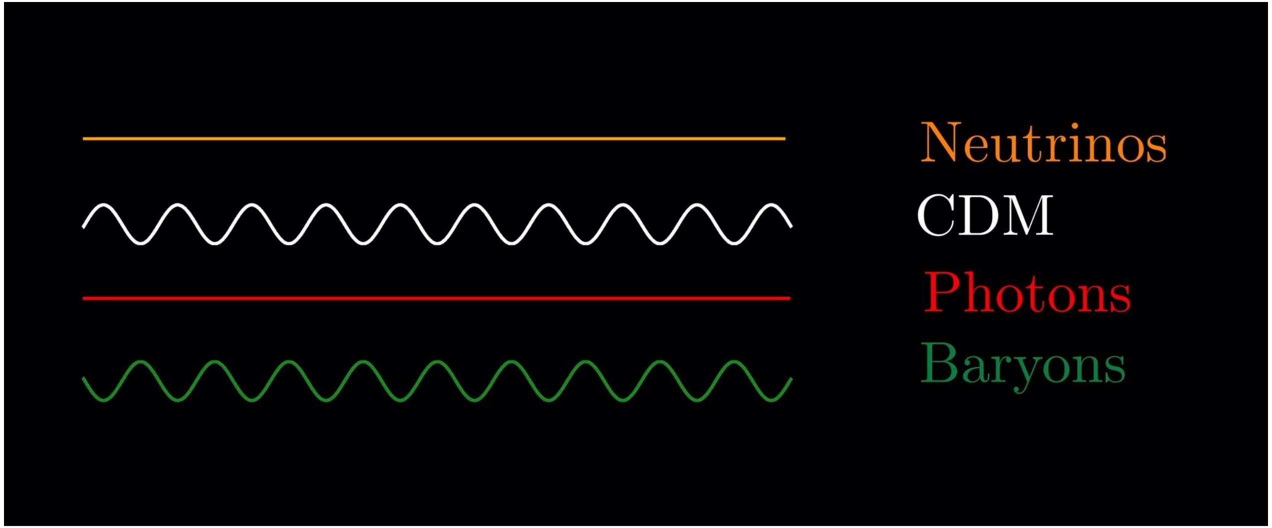


(http://danielgrin.net)

Motivation

Compensated Isocurvature Perturbations

$$\rho_c \delta_{c,i} + \rho_b \delta_{b,i} = 0, \;\; \delta_{\gamma,i} = 0$$



(http://danielgrin.net)

Motivation

We consider four different isocurvature initial conditions.

1. CDM isocurvature perturbations (CI)

2. Baryon isocurvature perturbations (BI)

3. Baryon & CDM isocurvature perturbations (BCI)

4. Compensated isocurvature perturbations (CIP)

Method

Free electron abundance depends non-linearly on initial baryon perturbations.

$$n_e = n_e^{(0)} + n_e^{(1)} * \Delta_i + n_e^{(2)} * \Delta_i * \Delta_i + \mathcal{O}(\Delta_i)^3$$

Taking average,

$$\langle n_e \rangle = n_e^{(0)} + n_e^{(2)} * \langle \Delta_i * \Delta_i \rangle + \mathcal{O}(\Delta_i^4)$$

In general, the symbol * represents convolution.

- **First assumption**
  - We assume the net recombination rate depends on local baryon perturbations (and velocity divergence).
  - This is valid up to k < 10^3 / Mpc. (Venumadhav and Hirata 2015)

→ We consider scales 1/Mpc < k < 10^3/Mpc.

Method

Notation:

$$\delta_b(\eta,\vec{k}) = T_b(\eta,k)\delta_i(\vec{k}), \quad \theta_b(\eta,\vec{k}) = -\dot{T}_b(\eta,\vec{k})\delta_i(\vec{k})$$

$$\vec{B} \equiv (\delta_b,\theta_b), \; \vec{T}(\vec{k}) \equiv (T_b(\vec{k}), -\dot{T}_b(\vec{k}))$$

Then, the average free electron abundance can be written as

$$\langle n_e\rangle(\eta) = n_e^{(0)}(\eta) + \iint^{\eta} d\eta_1 d\eta_2 \; G^{(2)}_{\alpha\beta}(\eta;\eta_1,\eta_2)\langle B_\alpha(\eta_1,\vec{x})B_\beta(\eta_2,\vec{x})\rangle$$

In terms of dimensionless power spectrum of initial perturbations, $\Delta_i^2(k) \equiv \frac{k^3}{2\pi^2}P_{\delta_i}$

We have

$$\langle n_e\rangle(\eta) = n_e^{(0)}(\eta) + \int d\ln k \; n_e^{(2)}(\eta;k)\Delta_i^2(k)$$

$$n_e^{(2)}(\eta;k) \equiv \iint^{\eta} d\eta_1 d\eta_2 \; G^{(2)}_{\alpha\beta}(\eta;\eta_1,\eta_2)T_\alpha(\eta_1,k)T_\beta(\eta_2,k)$$

So, what we need is $n_e^{(2)}(\eta;k)$.

Method

Using

$$n_e(\eta,\vec{x}) = n_e^{(0)}(\eta) + \int^\eta d\eta' G_\alpha^{(1)}(\eta;\eta') B_\alpha(\eta',\vec{x}) + \iint^\eta d\eta_1 d\eta_2\, G_{\alpha\beta}^{(2)}(\eta;\eta_1,\eta_2) B_\alpha(\eta_1,\vec{x}) B_\beta(\eta_2,\vec{x})$$

we can calculate

$$n_e^{(2)}(\eta;k) = \frac{n_e^+(\eta;k) + n_e^-(\eta;k) - 2n_e^{(0)}(\eta)}{2\epsilon^2}$$

where $n_e^\pm(\eta) = n_H^{(0)}(1 \pm \epsilon T_b(\eta,k)) x_e^\pm$.

$x_e^\pm$ are calculated using HyRec-2 with

$$\delta_b = \pm\epsilon T_b(\eta,k), \quad \theta_b = \mp\epsilon \dot{T}_b(\eta,k).$$

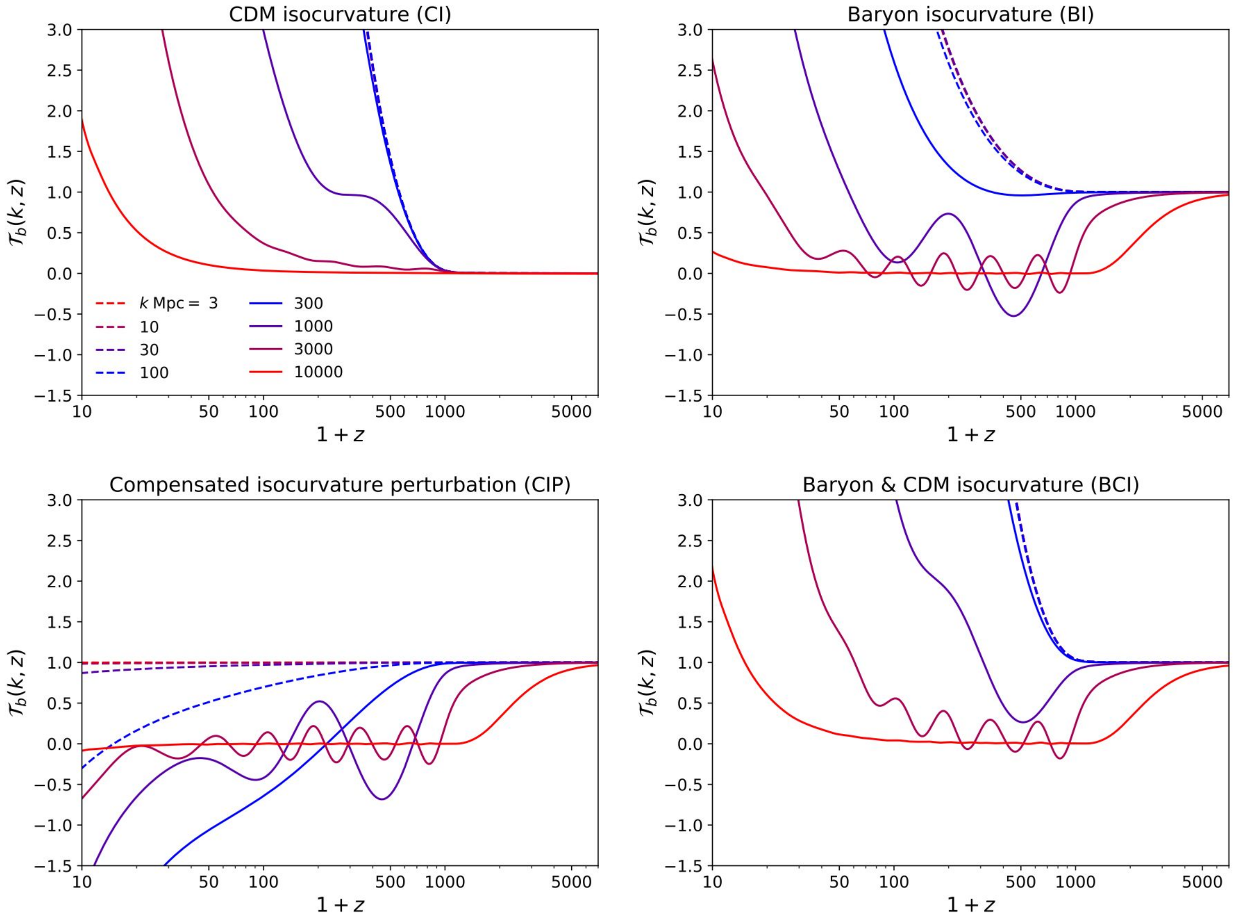
Specifically, with time-varying baryon energy density

$$\Omega_b \;\to\; \Omega_b(1 \pm \epsilon T_b(\eta,k))$$

and with modified local expansion rate in Lyman-alpha escape rate

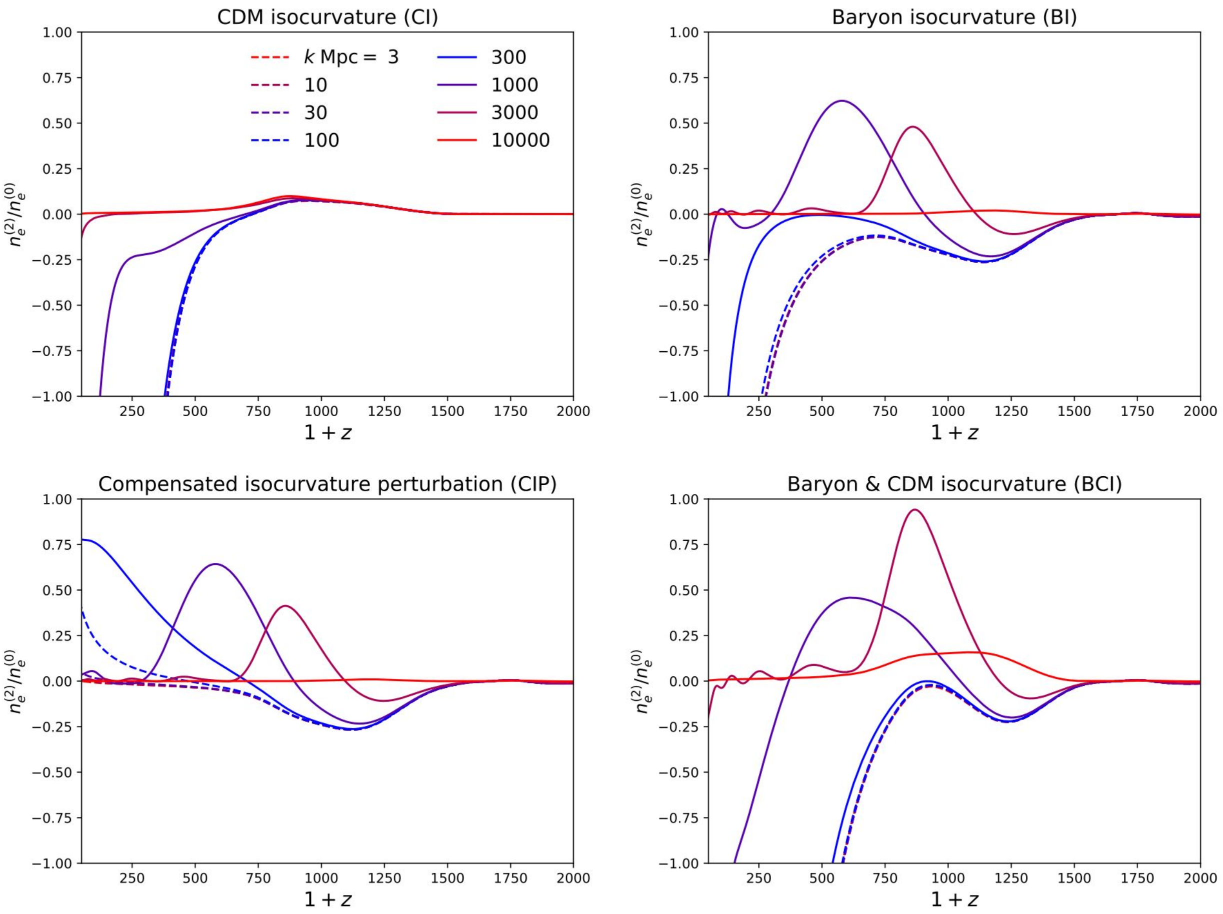
$$H \;\to\; H \mp \frac{1}{3}\epsilon \frac{\dot{T}_b(\eta,k)}{a}.$$

Method



(Obtained using CLASS)

Method



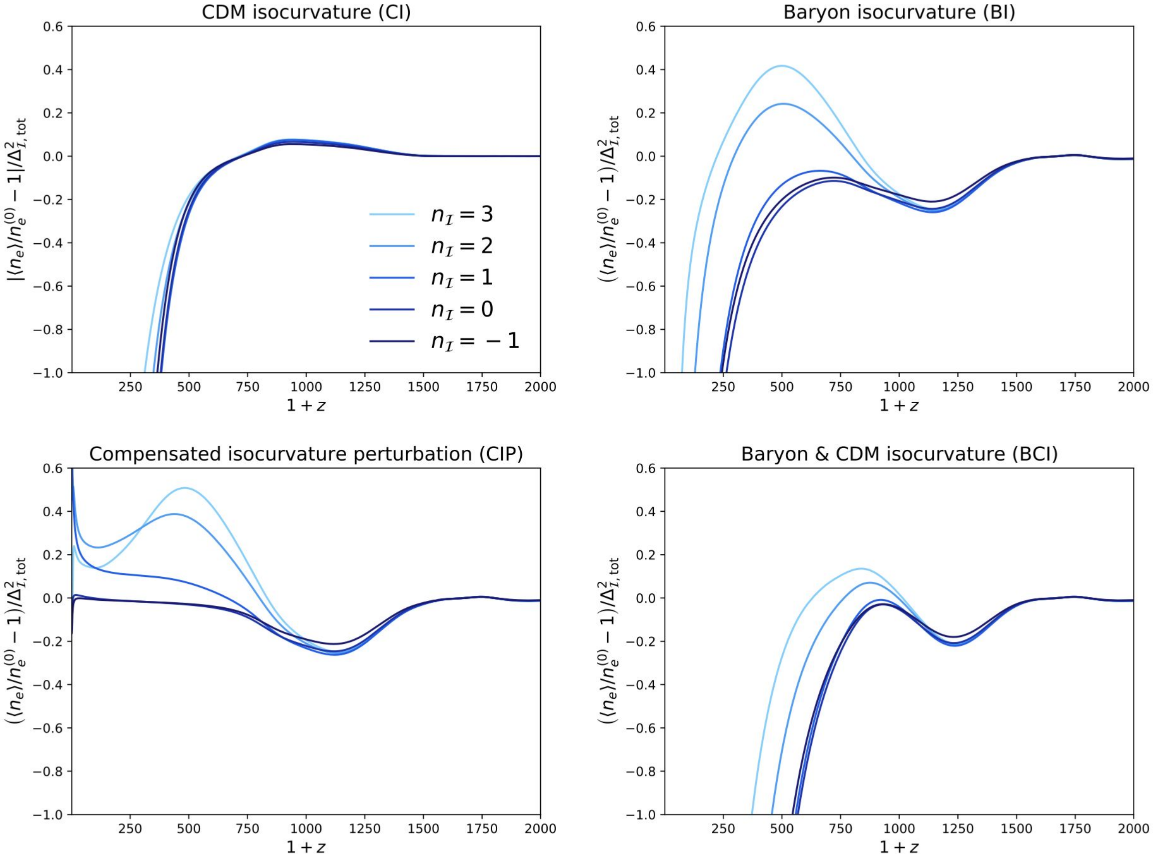
CDM isocurvature (CI)
Baryon isocurvature (BI)
Compensated isocurvature perturbation (CIP)
Baryon & CDM isocurvature (BCI)
k Mpc = 3
10
30
100
300
1000
3000
10000
$n_e^{(2)}/n_e^{(0)}$
1 + z

Method

$$\Delta^2_{\mathcal{I}}(k) = \Delta^2_{\mathcal{I}}(k_p)\left(\frac{k}{k_p}\right)^{n_{\mathcal{I}}-1}, \qquad k_p \equiv 30\ \mathrm{Mpc}^{-1}$$

$$k_{\rm min} \equiv 1\ \mathrm{Mpc}^{-1} \leq k \leq k_{\rm max} \equiv 10^3\ \mathrm{Mpc}^{-1}$$

$$\Delta^2_{\mathcal{I},\rm tot} \equiv \int_{k_{\rm min}}^{k_{\rm max}} d\ln k\ \Delta^2_{\mathcal{I}}(k) = \frac{\Delta^2_{\mathcal{I}}(k_p)}{n_{\mathcal{I}}-1}\left[\left(\frac{k_{\rm max}}{k_p}\right)^{n_{\mathcal{I}}-1} - \left(\frac{k_{\rm min}}{k_p}\right)^{n_{\mathcal{I}}-1}\right]$$



Method

In addition to standard six parameters of $\Lambda\mathrm{CDM}$, we add a new parameter for the amplitude of initial power, and do MCMC analysis

- MontePython v3.0
- Modified HyRec-2
- Planck 2018 TT TE EE + lensing

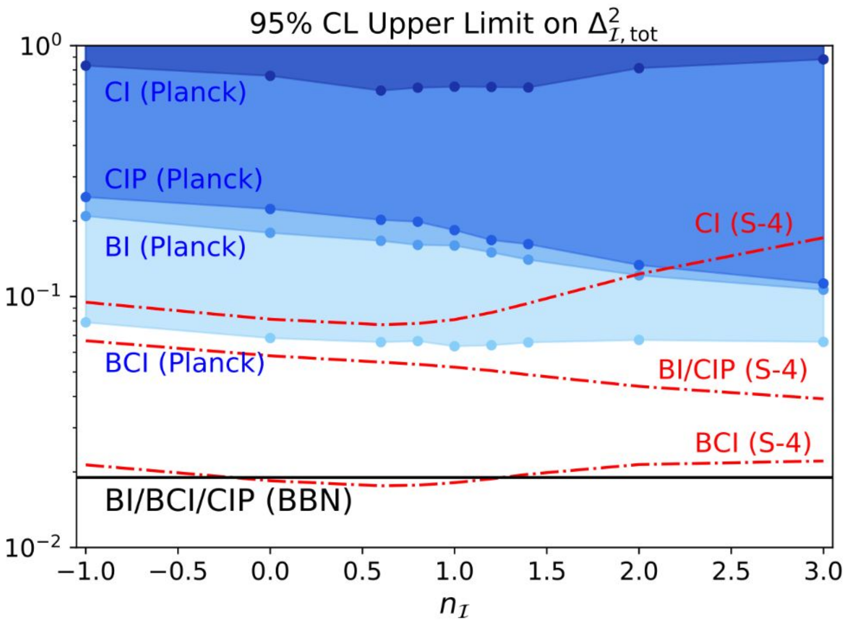
Two parameterizations for initial power spectrum

- Power-law: $\Delta^2_{\mathcal{I}}(k) = \Delta^2_{\mathcal{I}}(k_p)\left(\frac{k}{k_p}\right)^{n_{\mathcal{I}}-1}, \quad k_p \equiv 30\ \mathrm{Mpc}^{-1}$

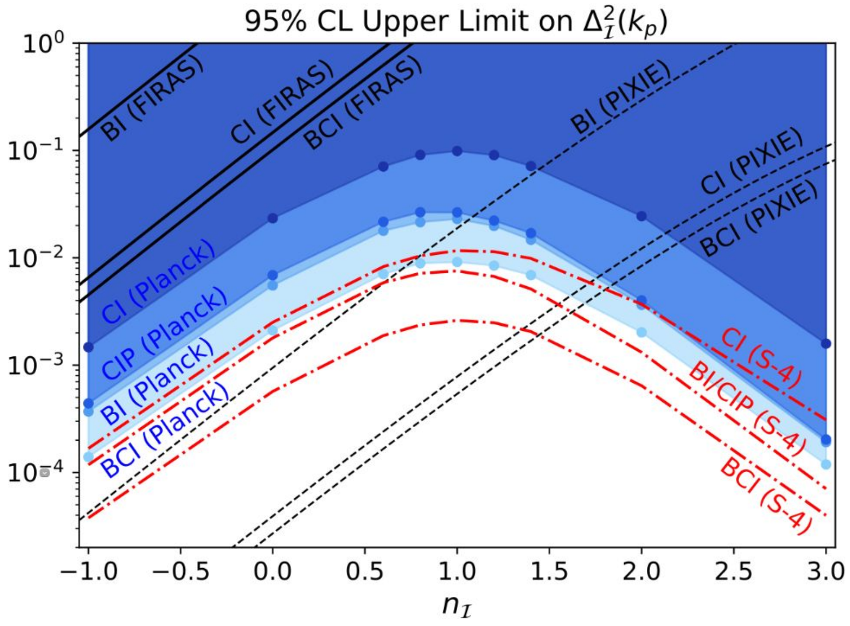
- Dirac-delta spike: $\Delta^2_{\mathcal{I}}(k) = \Delta^2_{\mathcal{I}}(k_0)\delta_{\mathrm{D}}(\ln k - \ln k_0)$

Results (Power-law)

$$\Delta^2_{\mathcal{I}}(k) = \Delta^2_{\mathcal{I}}(k_p)\left(\frac{k}{k_p}\right)^{n_{\mathcal{I}}-1}, \qquad \Delta^2_{\mathcal{I},\mathrm{tot}} \equiv \int_{k_{\min}}^{k_{\max}} d\ln k\, \Delta^2_{\mathcal{I}}(k) = \frac{\Delta^2_{\mathcal{I}}(k_p)}{n_{\mathcal{I}}-1}\left[\left(\frac{k_{\max}}{k_p}\right)^{n_{\mathcal{I}}-1} - \left(\frac{k_{\min}}{k_p}\right)^{n_{\mathcal{I}}-1}\right]$$



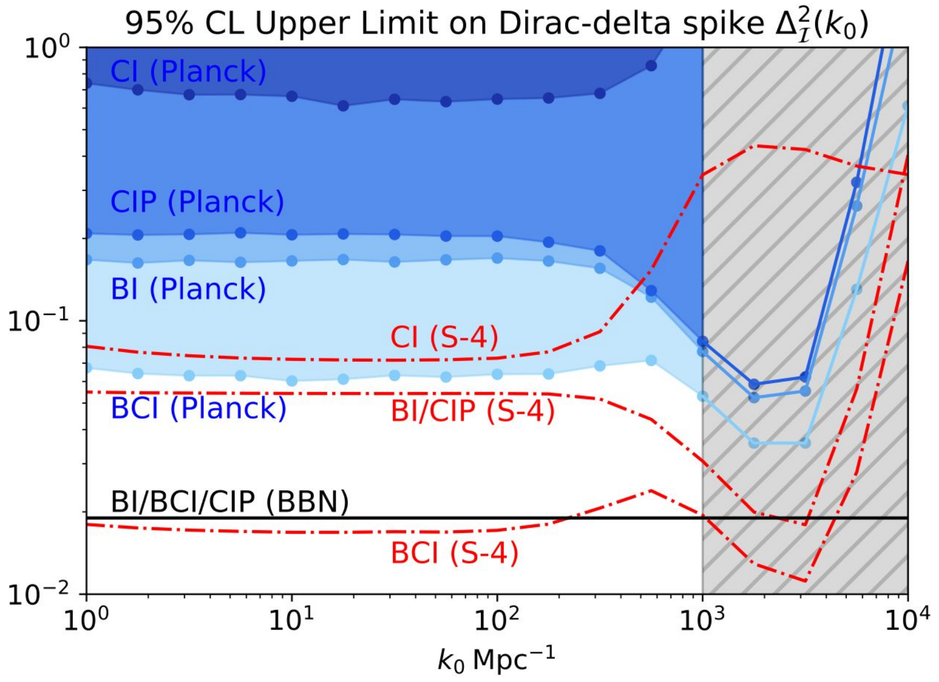
(BBN constraint from Inomata et al. 2018)



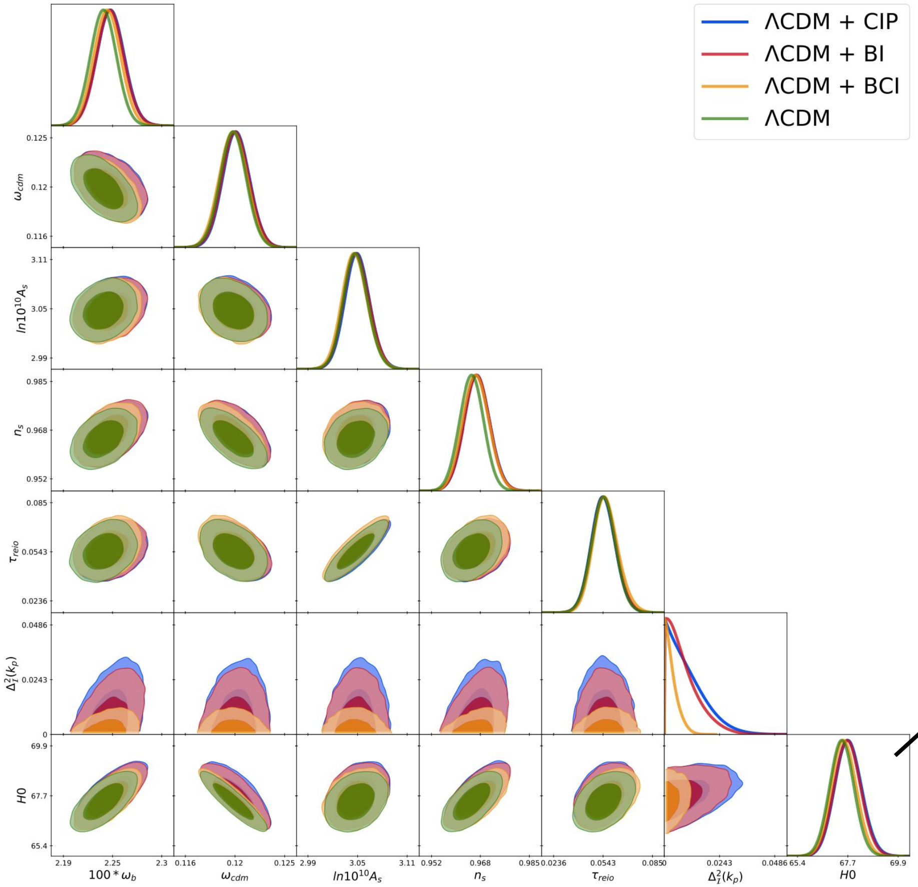
(CMB spectra distortion constraints and forecasts from Chluba and Grin, 2013)

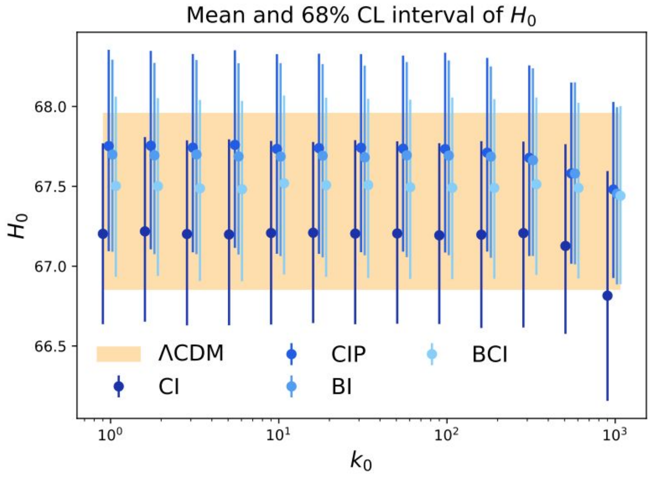
Results (Dirac-delta spike)

$$\Delta^2_{\mathcal{I}}(k) = \Delta^2_{\mathcal{I}}(k_0)\delta_{\rm D}(\ln k - \ln k_0)$$



Results (MCMC)





Not likely to resolve Hubble tension

Summary

- Complementary probes for small-scale initial conditions using CMB
- Better constraints than those from CMB spectral distortion
- Not effective for resolving the Hubble tension

Other things I'm doing

- Probing cosmic birefringence angle using pSZ tomography
- Try to resolve the Hubble tension by modifying recombination (xe itself or time-dependent alpha)
- Redshift-space distortion / DM-baryon scattering
- Interested in many other things in cosmology