Reconstruction of the speed of sound of the inflaton using early and late cosmological data

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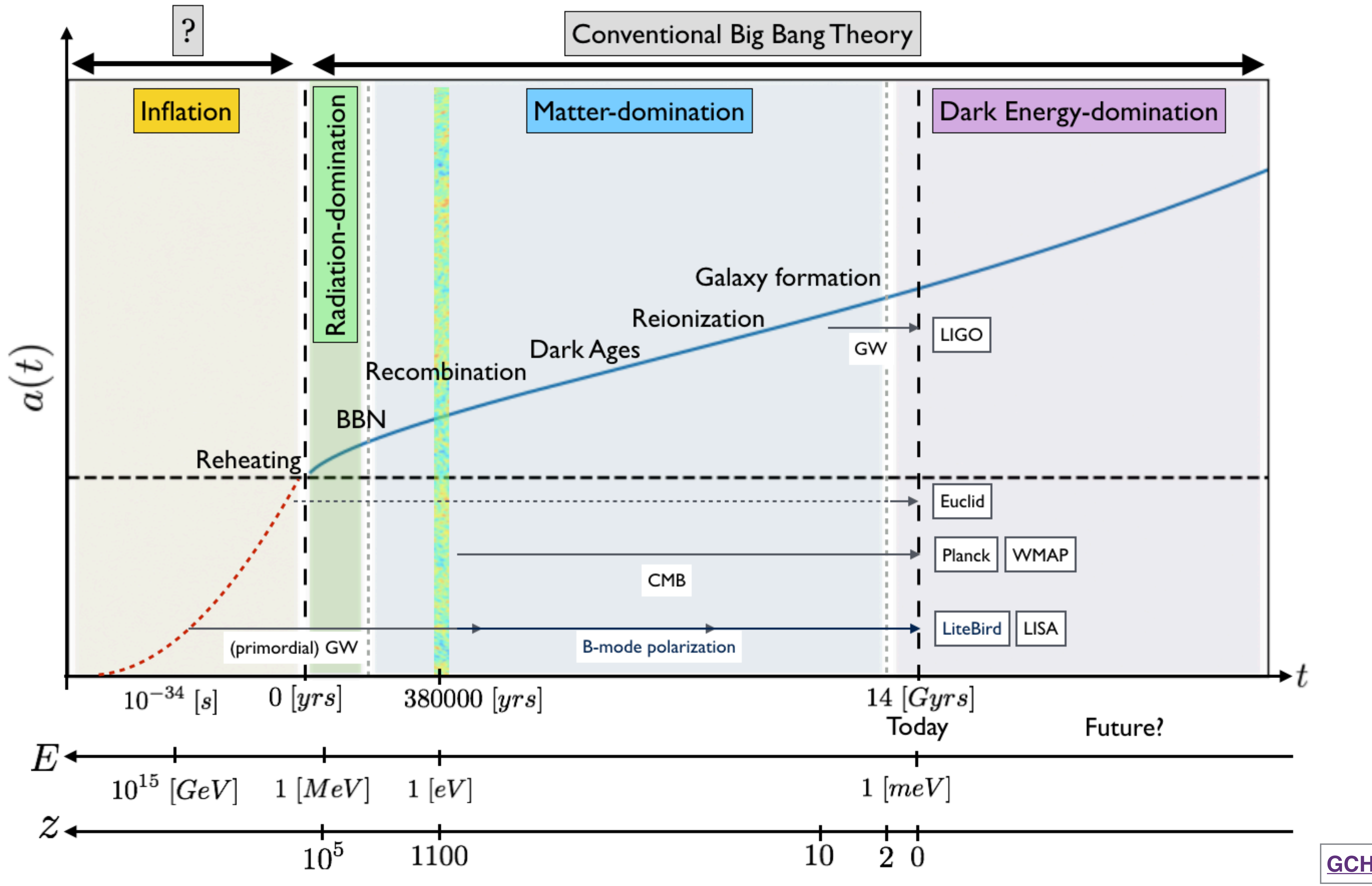
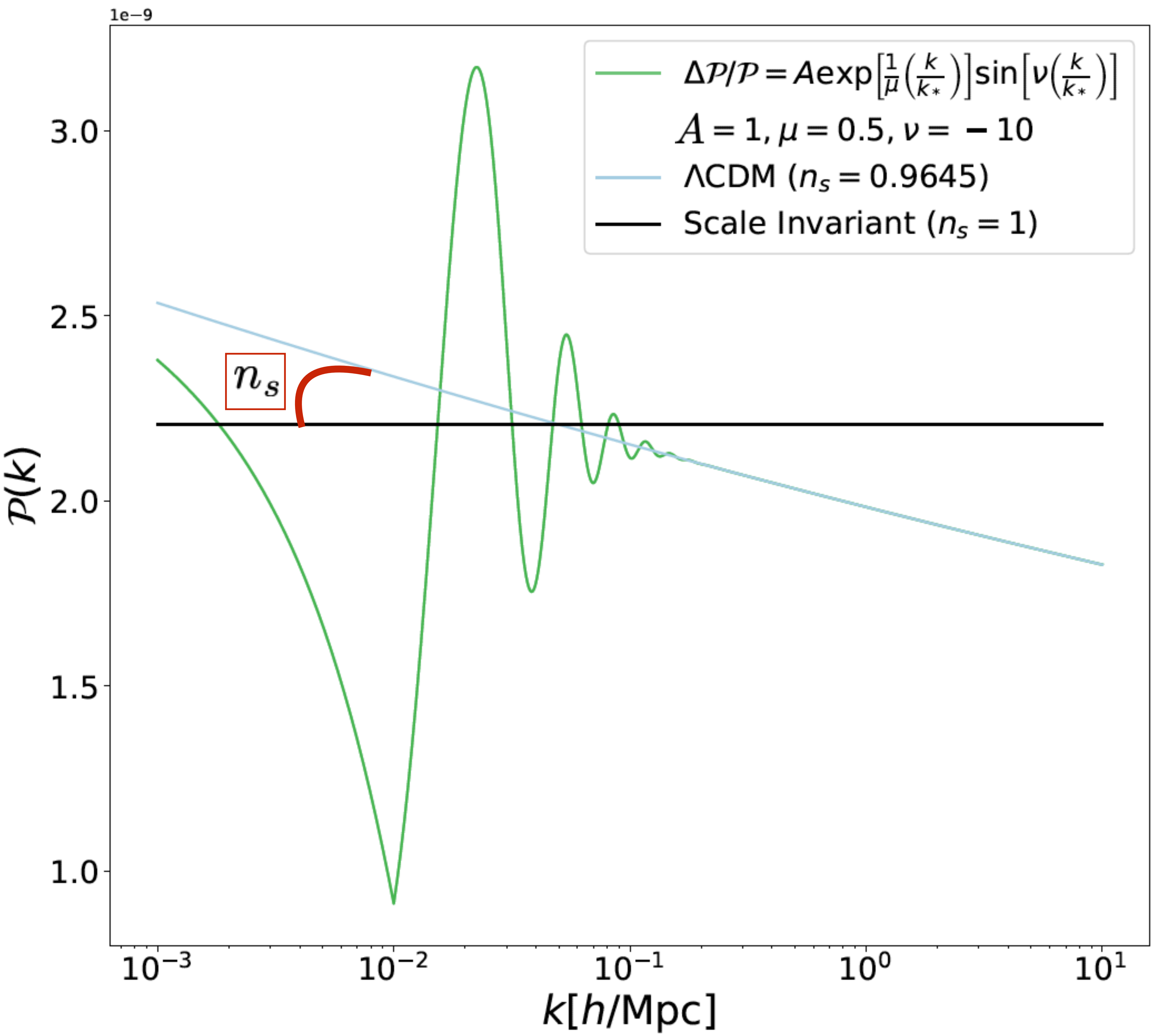
Universe Timeline



Primordial Power Spectrum (PPS)



Dimensionless PPS

Scalar-Amplitude

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

pivot-scale

scalar spectral index

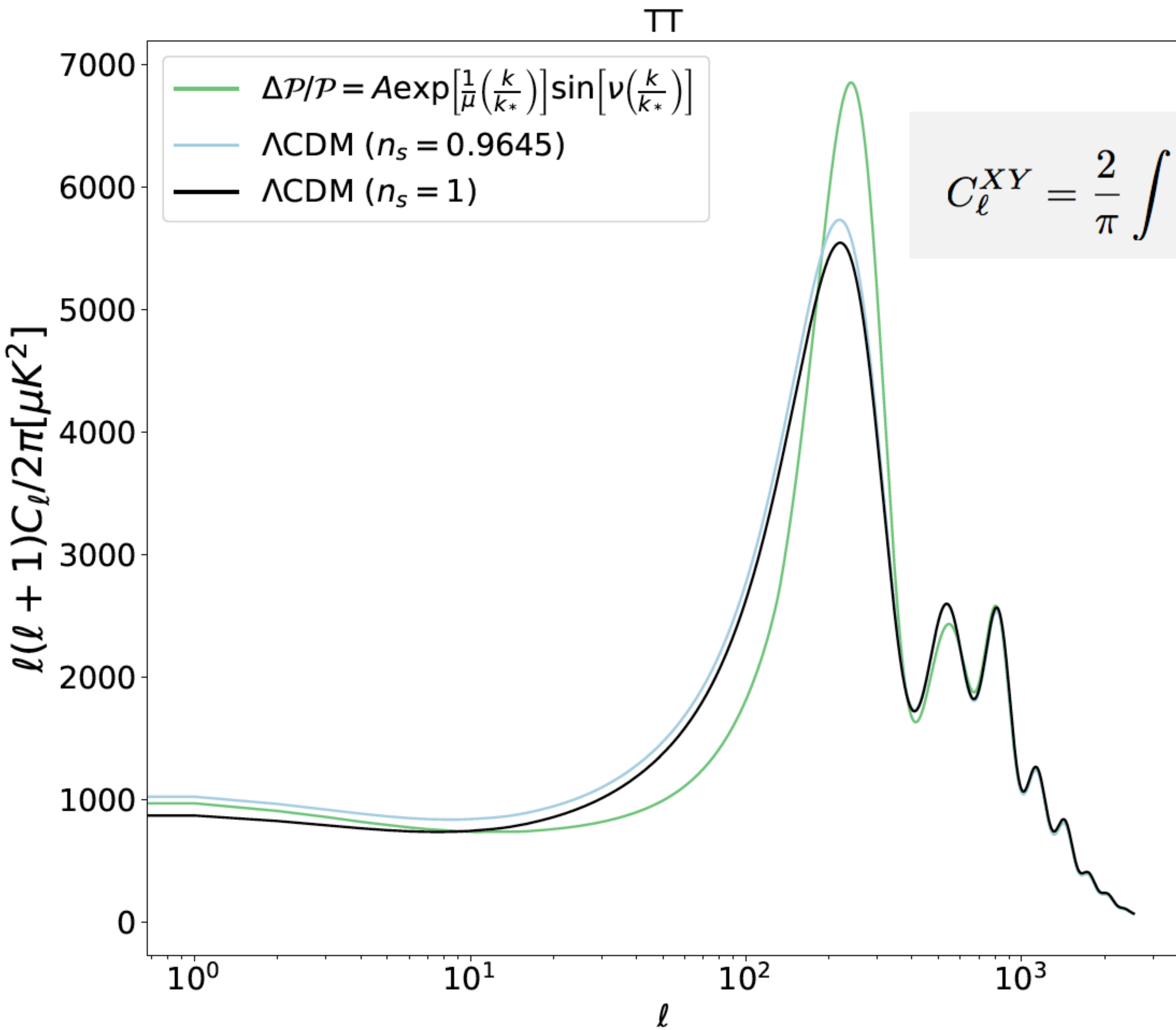
$$n_s = 1 - 2\epsilon_1 - \epsilon_2$$

1st slow-roll param: $\epsilon_1 := -\frac{\dot{H}}{H^2} < 1$

2nd slow-roll param: $\epsilon_2 := \frac{\dot{\epsilon}_1}{H\epsilon_1} < 1$

CAMB / GCH + M. Martinelli

Primordial Power Spectrum (PPS)



$$C_\ell^{XY} = \frac{2}{\pi}\int k^2 dk \mathcal{P}(k)\Delta T_\ell^X(k)\Delta T_\ell^Y(k)$$

CAMB 1.0 / GCH + M. Martinelli

But…

- ΛCDM consistent with Planck 2018

So…

- Many embeddings of inflation predict the existence of extra degrees of freedom during inflation
- Planck's bispectrum suggests the presence of features, which could indicate multi-field inflation
- How do we explore multi-field inflation while still agreeing with the data? Using an EFT approach

EFT of inflation

- Framework: effective field theory of inflationary perturbations:

$$S_2 = \int d^4x a^3 M_P^2 \epsilon_1(t) H^2 \left[-\frac{\dot{\pi}^2}{c_s^2(t)} + \frac{(\partial_i \pi)^2}{a^2} \right]$$

First slow-roll parameter

Variable sound speed not equal to 1

- Features from variable slow-roll parameter

1904.00991/Durakovic et al.

- Features from variable sound speed

1211.5619/Achucarro et al.

1311.2552 /Achucarro et al.

1502.02114/Achucarro et al.

Reductions in the sound speed

- Particular scenario :

$$S_2 = \int d^4x a^3 M_P^2 \epsilon_1 (t) H^2 \left[-\frac{\dot{\pi}^2}{c_s^2(t)} + \frac{(\partial_i \pi)^2}{a^2} \right] + \text{ corrections}$$

small, **mild** and **transient**

- Using Perturbation theory:

$$S_{2,\phi} = S_\phi(single - field) + \delta S(feature)$$

- Second part gives perturbations to the scale-invariant power spectrum:

$$\frac{\Delta \mathcal{P}_\mathcal{R}}{\mathcal{P}_{\mathcal{R}0}} = k \int_{-\infty}^{0} d\tau \left(1 - \frac{1}{c_s^2}\right) \sin(2k\tau)$$

Conformal time

Reduction in the sound speed

1502.02114/Achucarro et al.

Reductions in the sound speed

- Name:

$$u(t) := 1 - \frac{1}{c_s^2(t)}$$

$$\Delta\mathcal{P}_{\mathcal{R}}(k)/\mathcal{P}_{\mathcal{R}}(k) \propto \mathrm{FourierTranform}(u)$$

Feature

- Constraints in this scenario:

$$u(t) \ll 1$$ **small**

$$s(t) := \frac{\dot{c}_s(t)}{Hc_s(t)} \ll 1$$ **mild**

Goal
Constrain with data

- Summary:

Slow-roll condition still apply

$$\epsilon_1, \epsilon_2 \ll \max(u, s) \ll 1$$

Methodology: parameter estimation

- Bayes' theorem:

Goal

Constrain with data

$$u(t) := 1 - \frac{1}{c_s^2(t)}$$

$$s(t) := \frac{\dot{c}_s(t)}{H c_s(t)}$$

Data

Planck 2018

Information

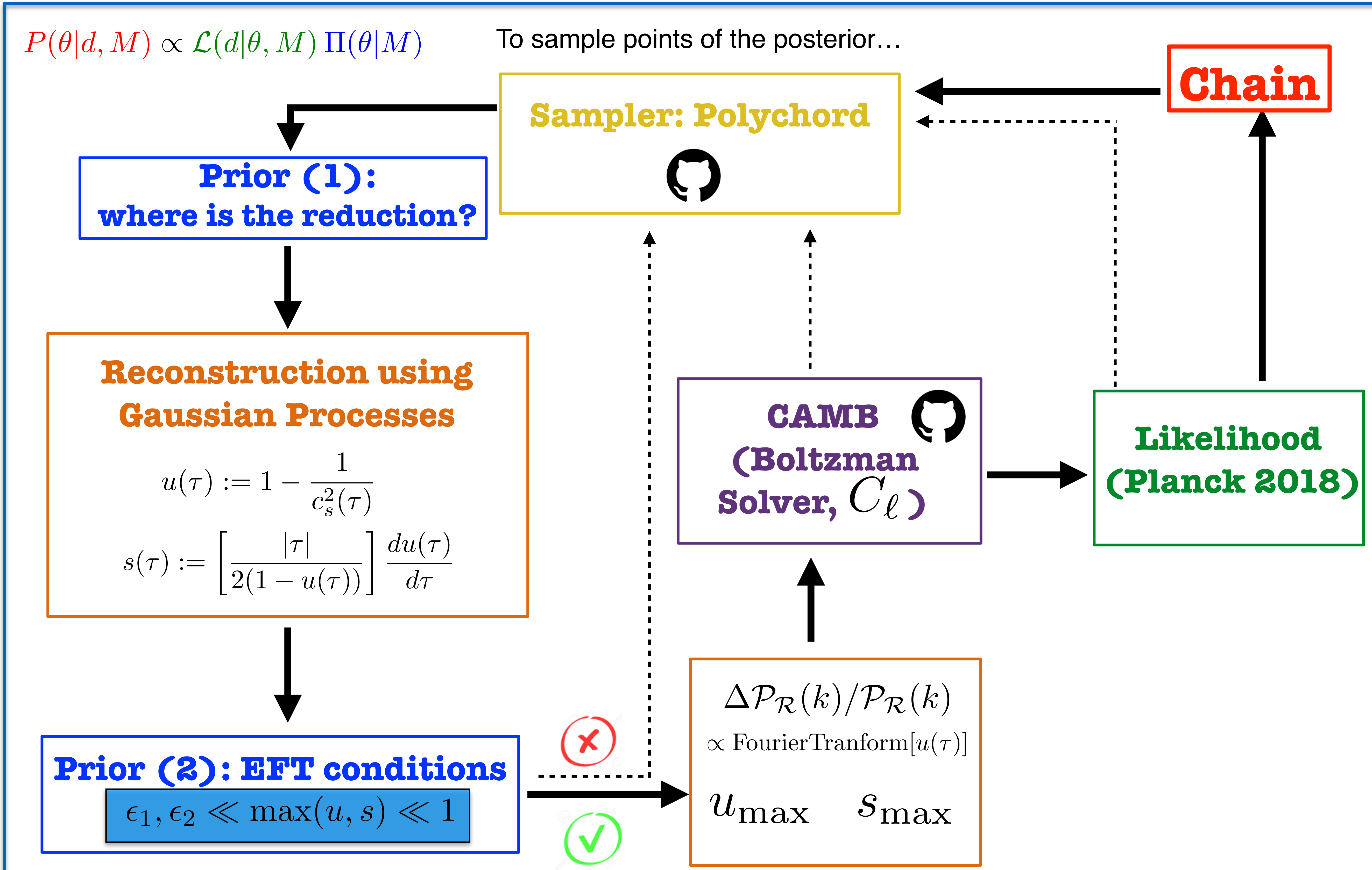
Previous results + Theoretical constraints

$$P(\theta|d, M) \propto \mathcal{L}(d|\theta, M)\, \Pi(\theta|M)$$

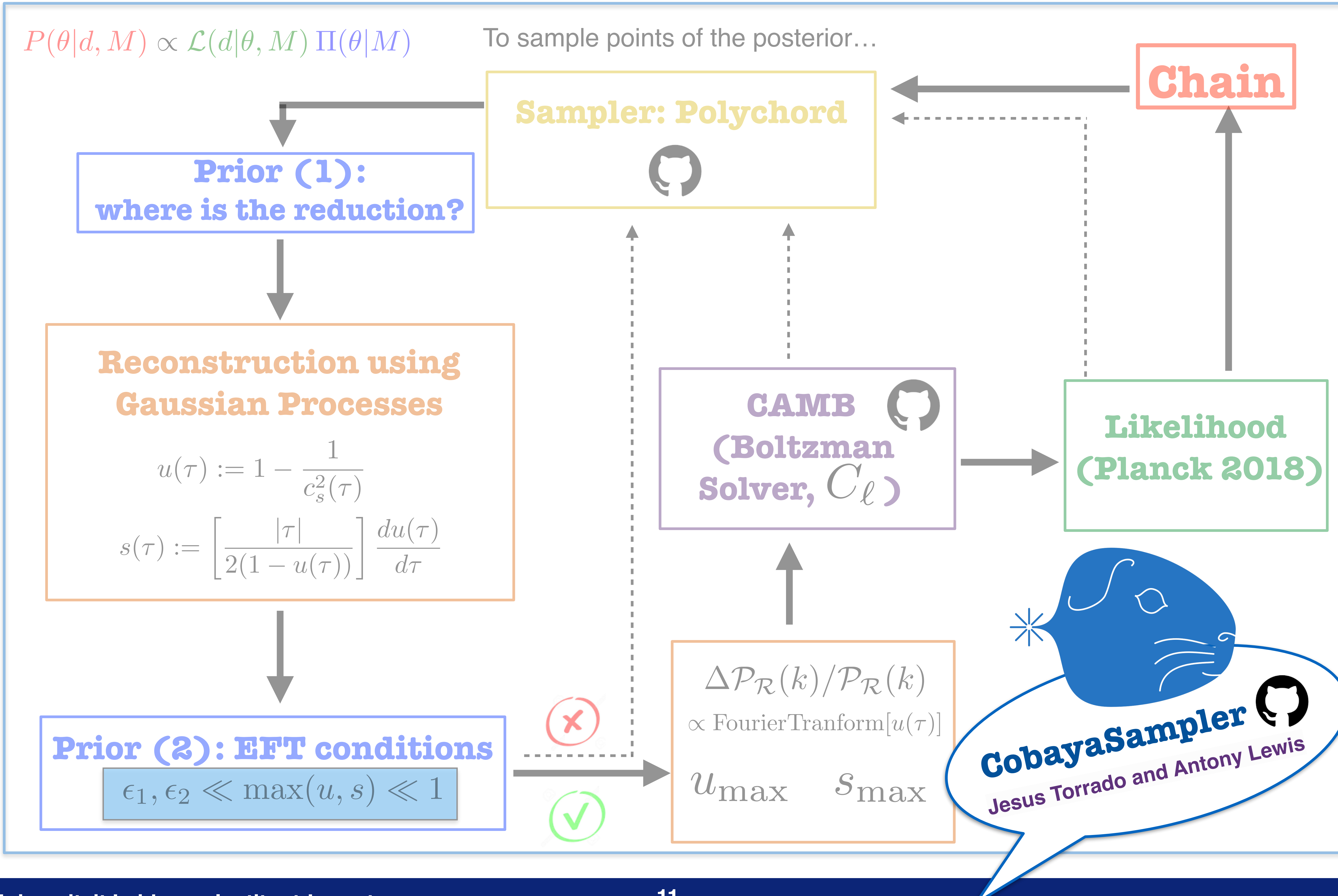
Posterior — Likelihood — Prior

Sampler

Methodology: pipeline



Methodology: pipeline



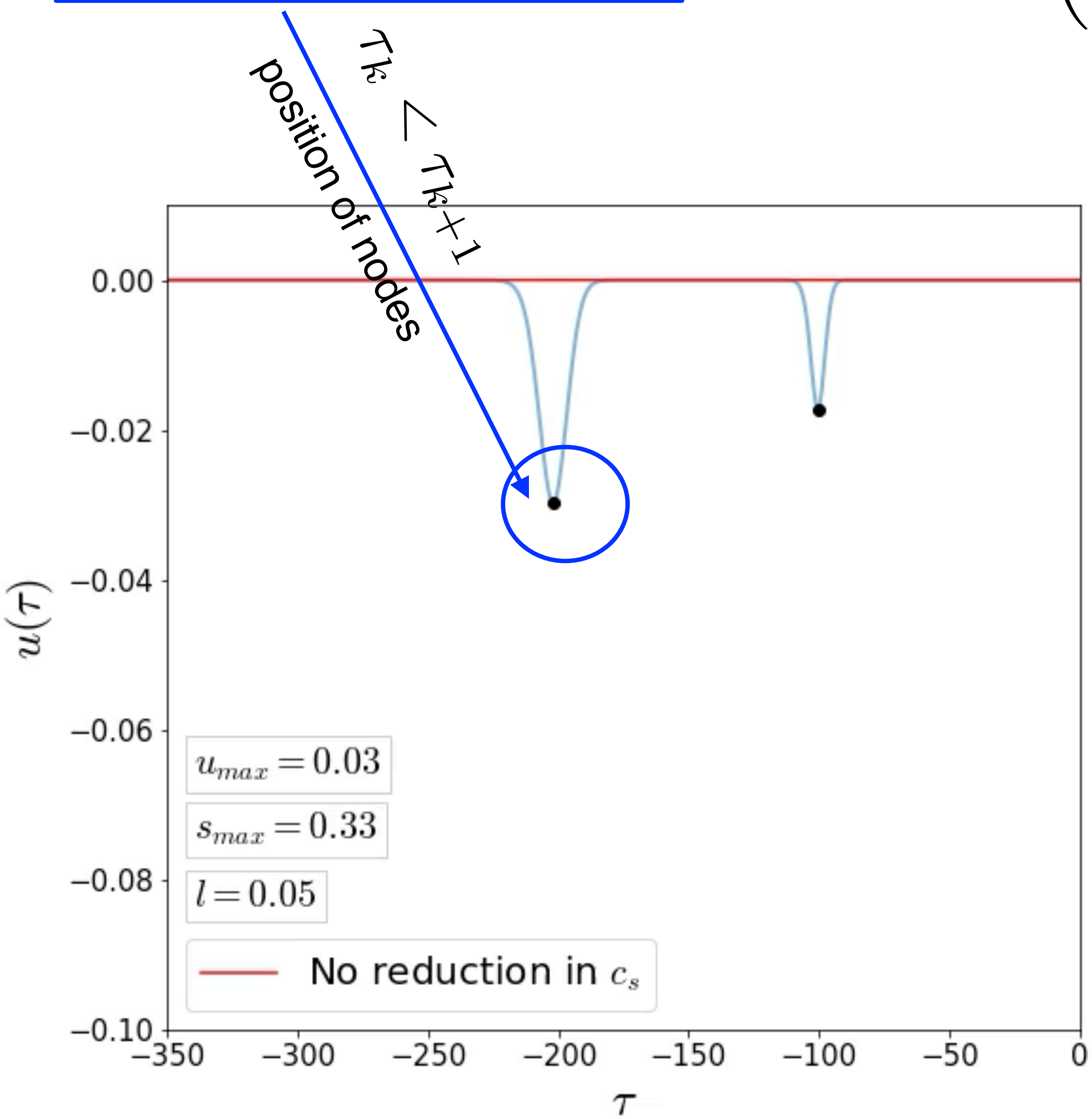
Reconstruction of u(τ)

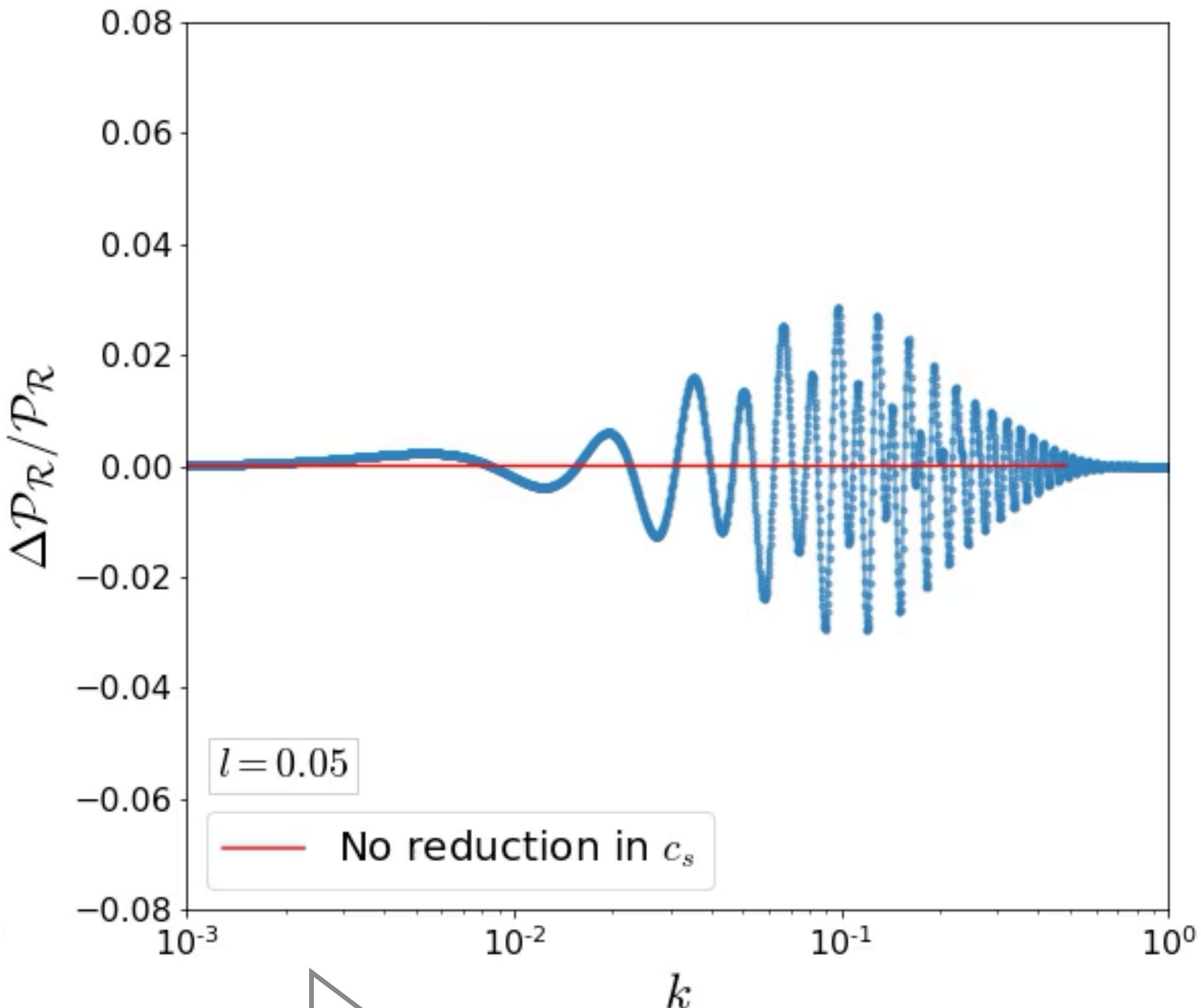
Prior (1): where is the reduction?

$$u(\tau) = \exp\left(-\frac{|\tau_k - \tau_{k+1}|}{2l}\right)$$

correlation length

Reconstruction using Gaussian Processes





Fourier Transform

Reconstruction using GPs/**GCH**

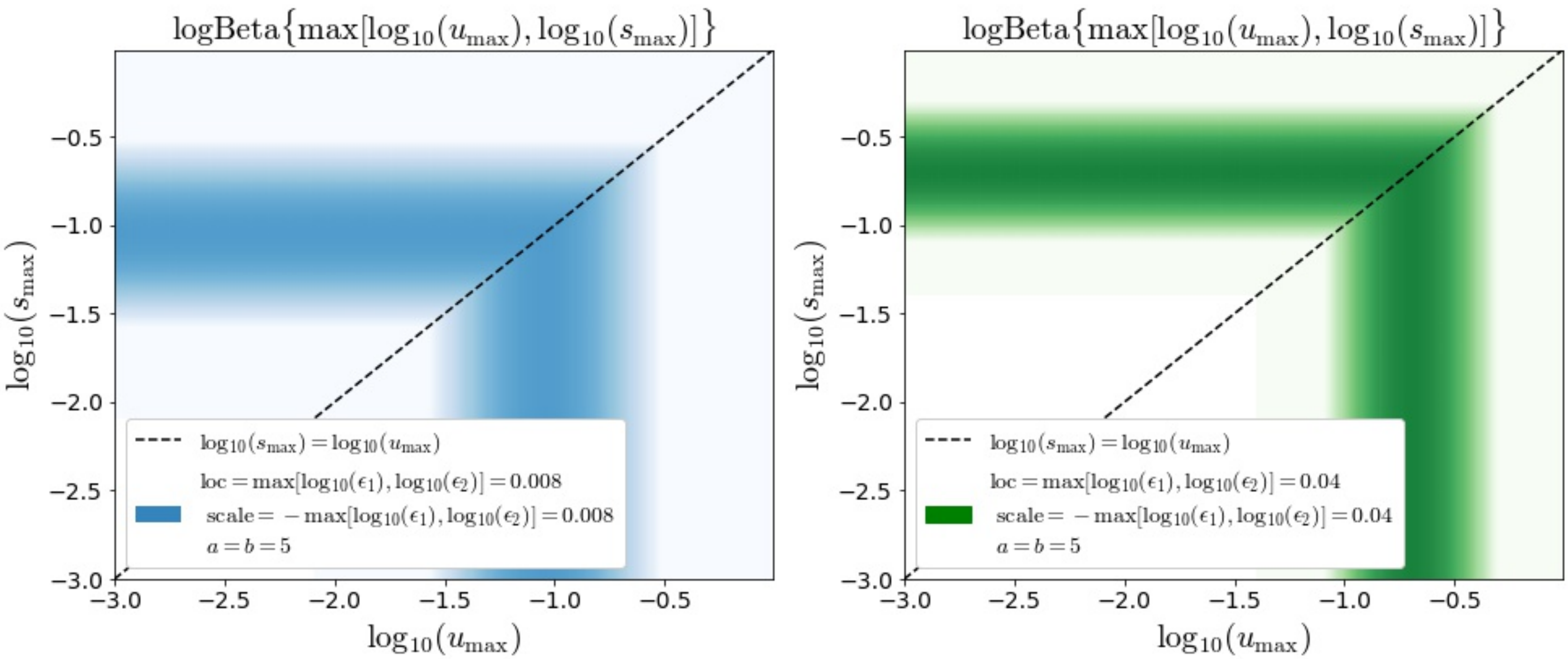
Reconstruction of u(τ)

	Details
Number of parameters	1 (correlation length) + 2 x number of nodes (position of nodes)
Parameters	(l, u_{train}, τ_{train})
Theory parameters? $u_{\max}$ $s_{\max}$	Numerically

Weakly informative prior

Prior (2): EFT condition

$$\epsilon_1, \epsilon_2 \ll \max(u, s) \ll 1$$



1611.10350/Torrado et al.

However… $\tau_k < \tau_{k+1}$

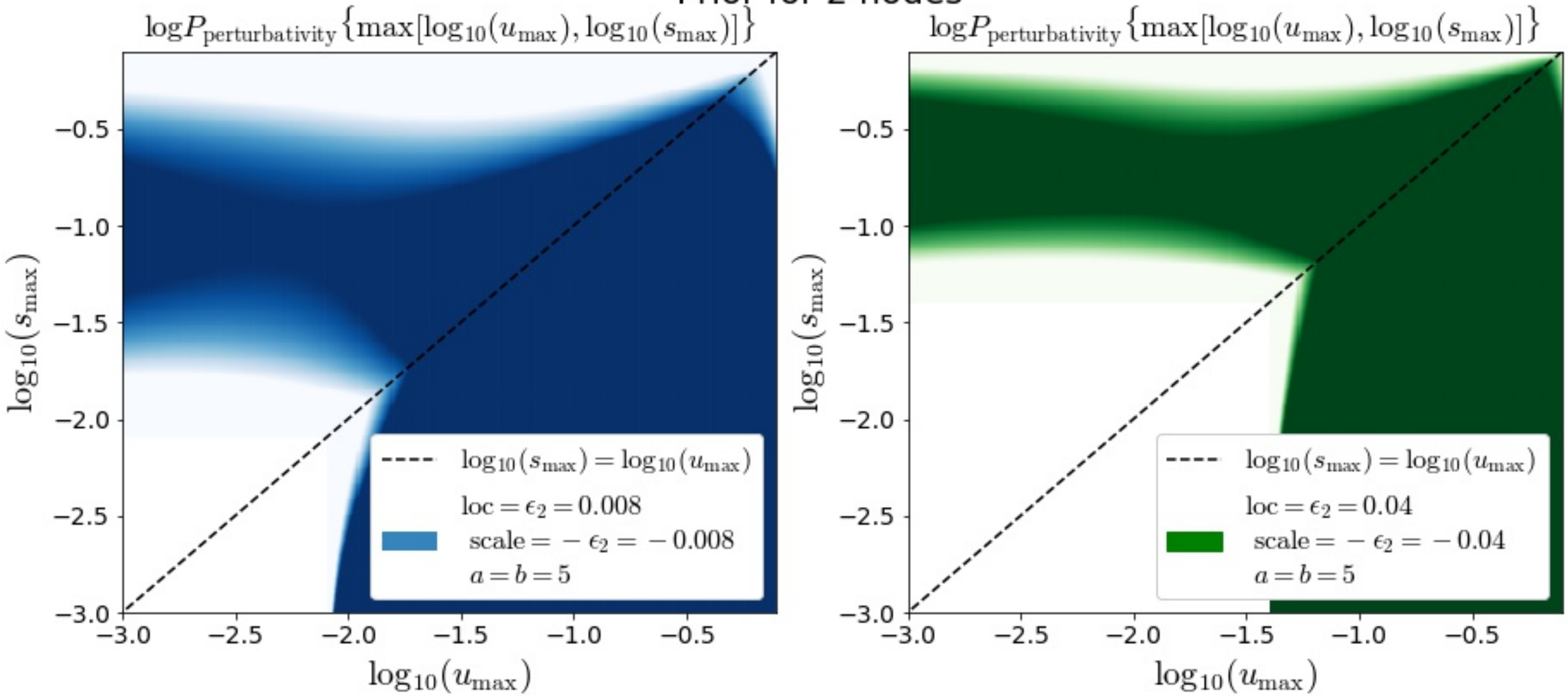
1804.08143/Handley et al.

Maximum Entropy

Prior (2): EFT condition

$$\epsilon_1, \epsilon_2 \ll \max(u, s) \ll 1$$

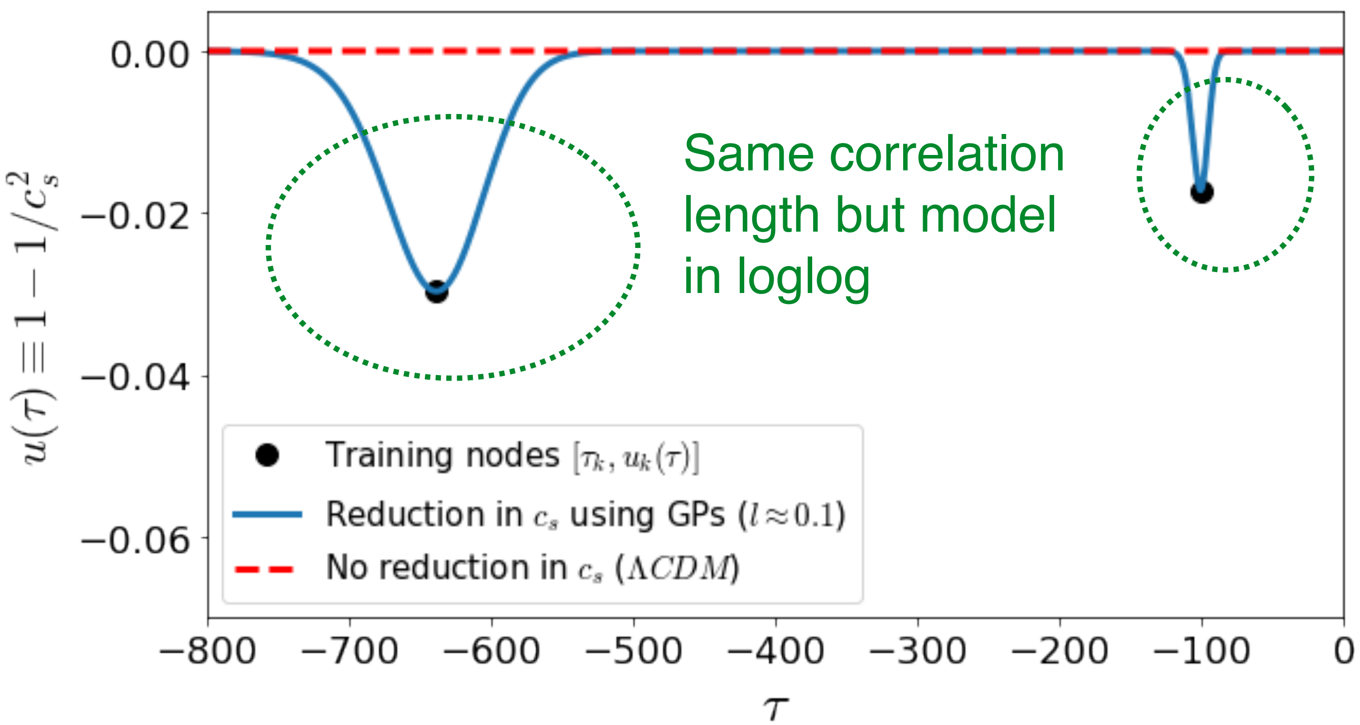
Prior for 2 nodes

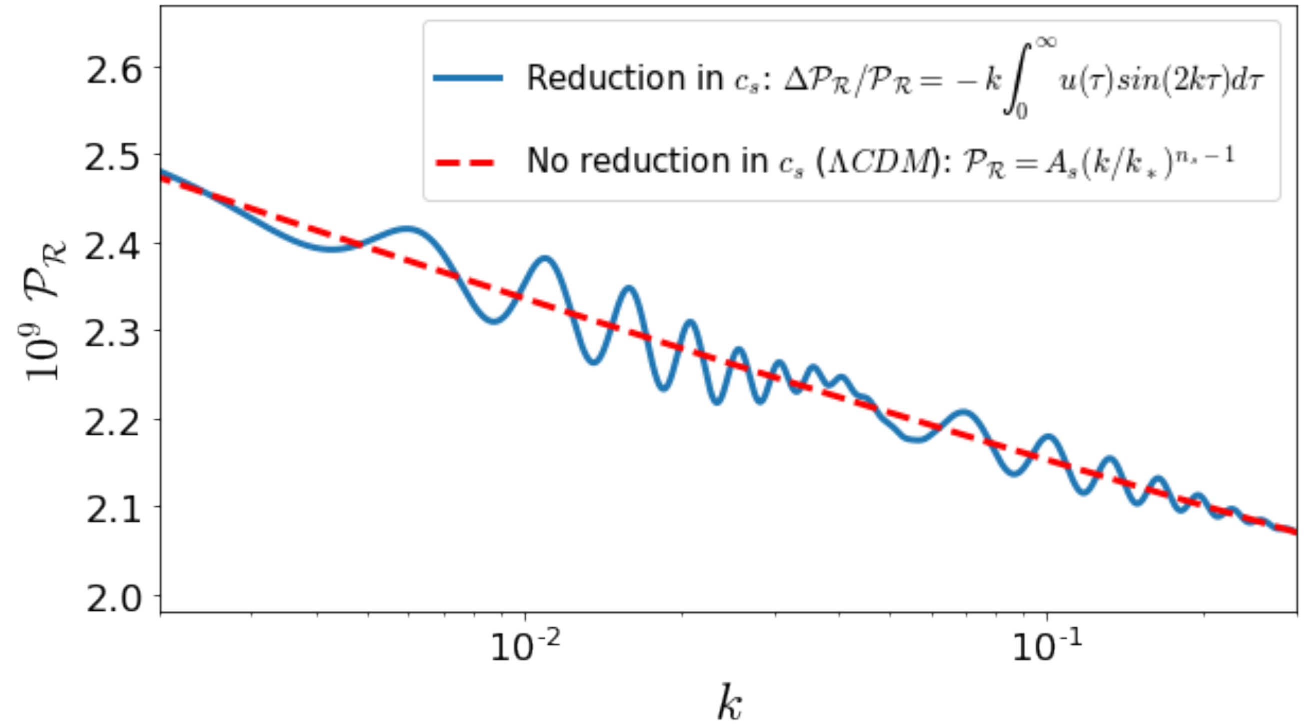


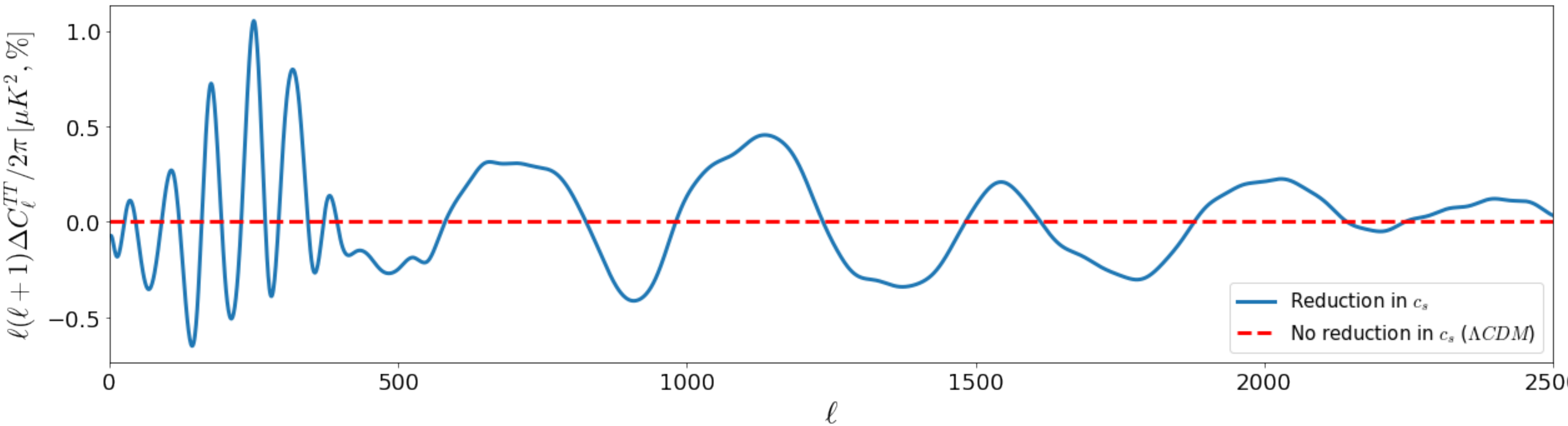
However… $\tau_k < \tau_{k+1}$

$$\log P_{\rm perturbativity} = \log \mathrm{Beta}(a, a) - \log P_{\text{Max-Ent}}$$

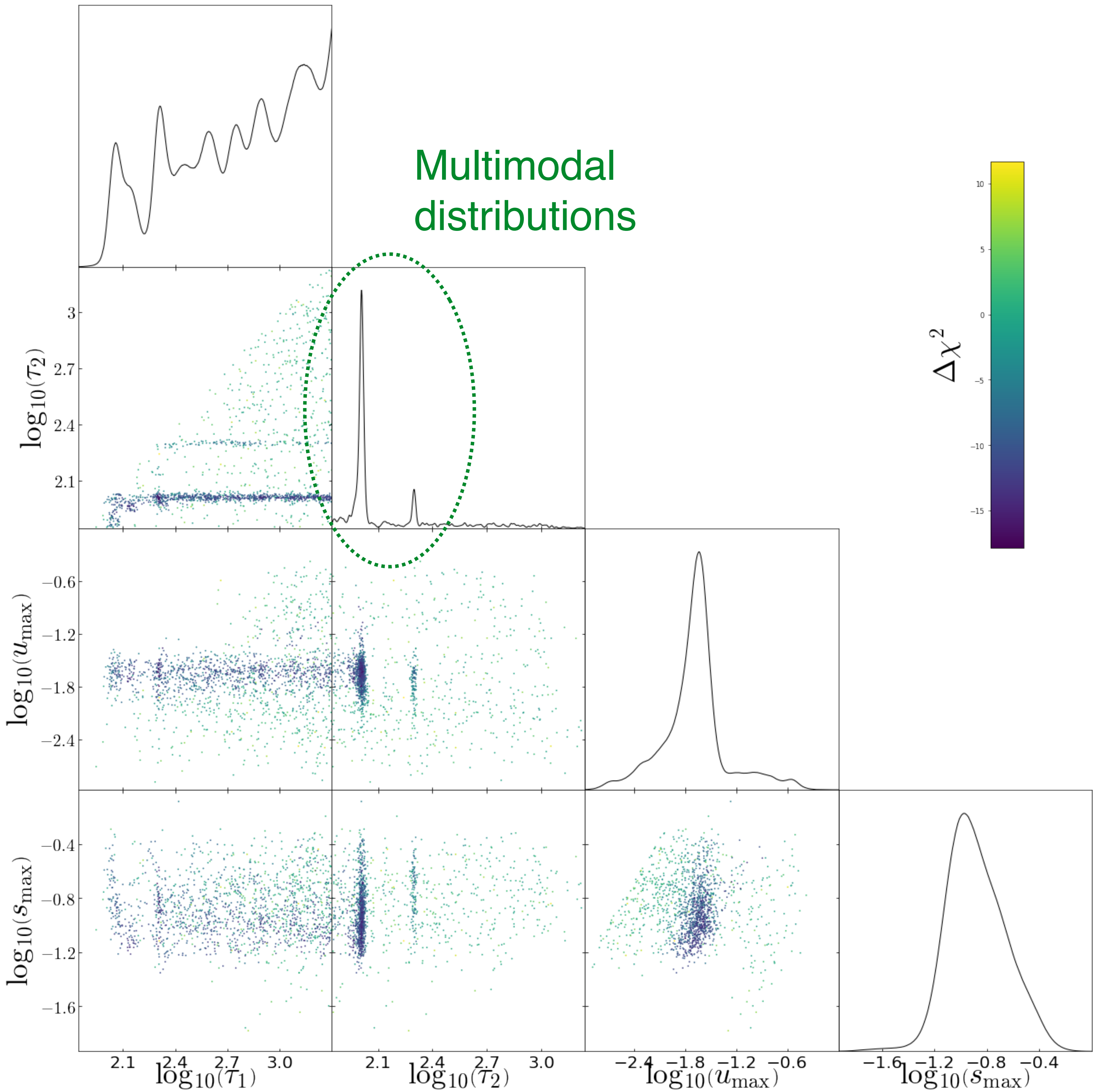
Comparing to data





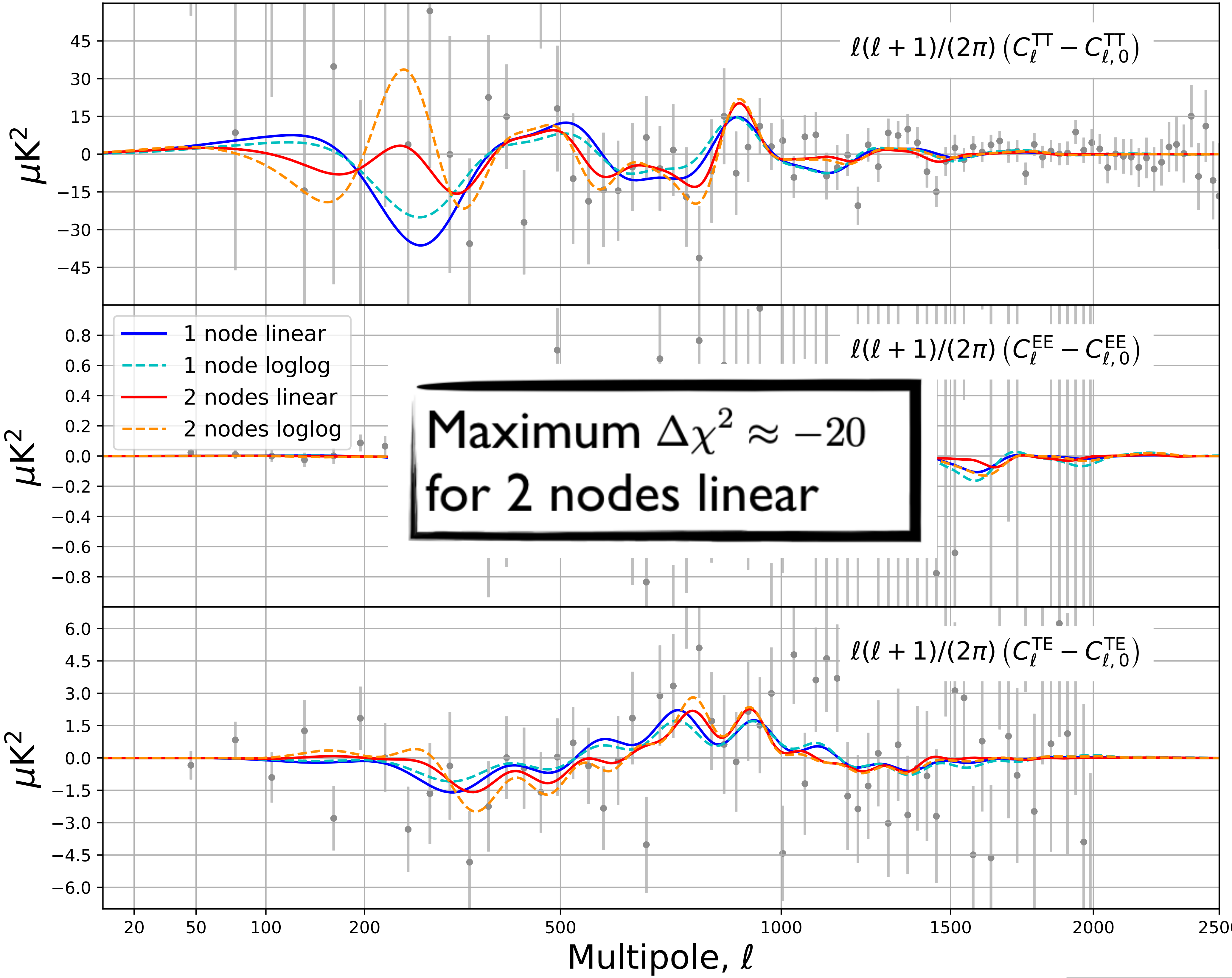


Posterior distributions: 2 nodes



GCH, AA, JT

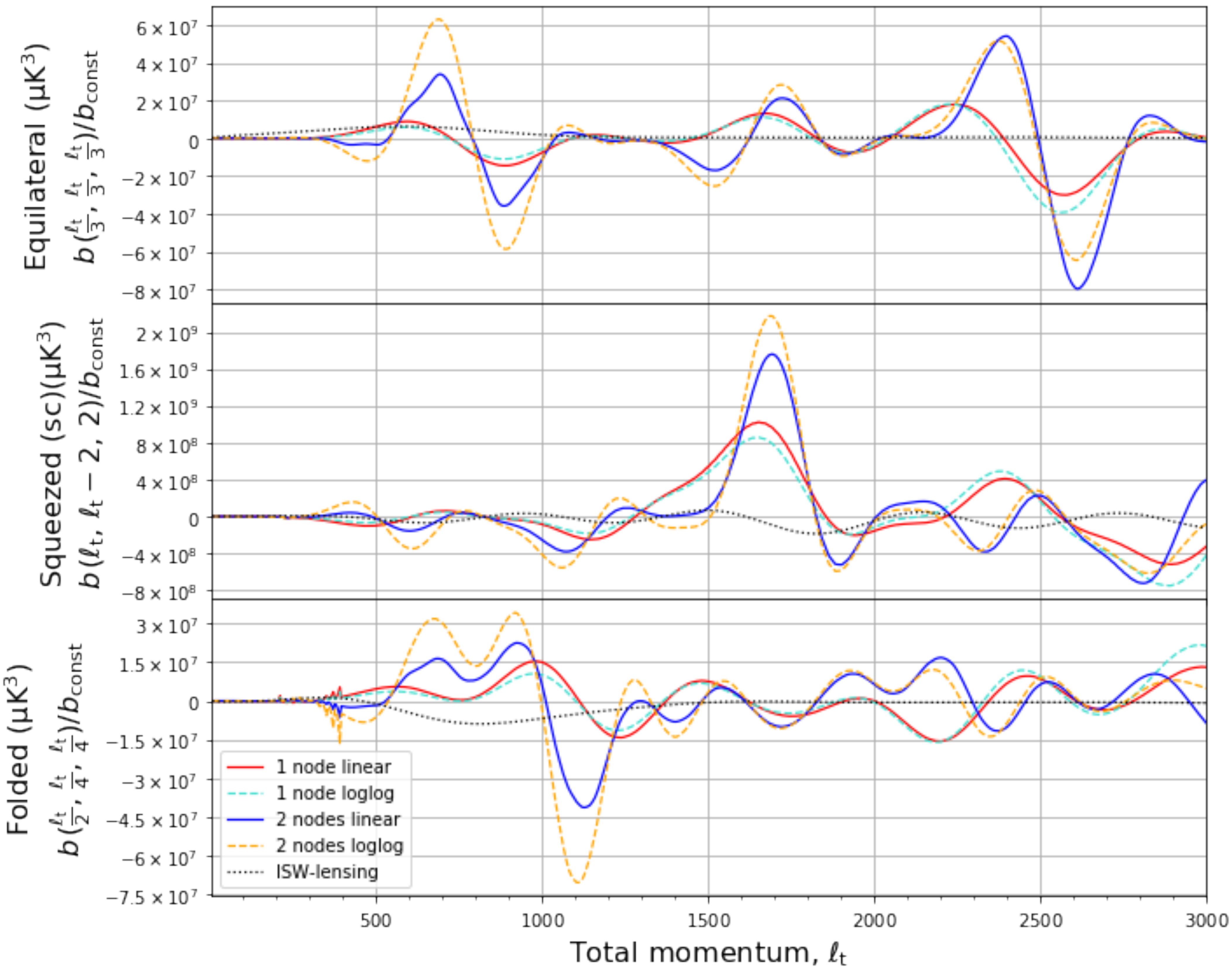
Best fits with Planck 2018



Maximum $\Delta\chi^2 \approx -20$ for 2 nodes linear

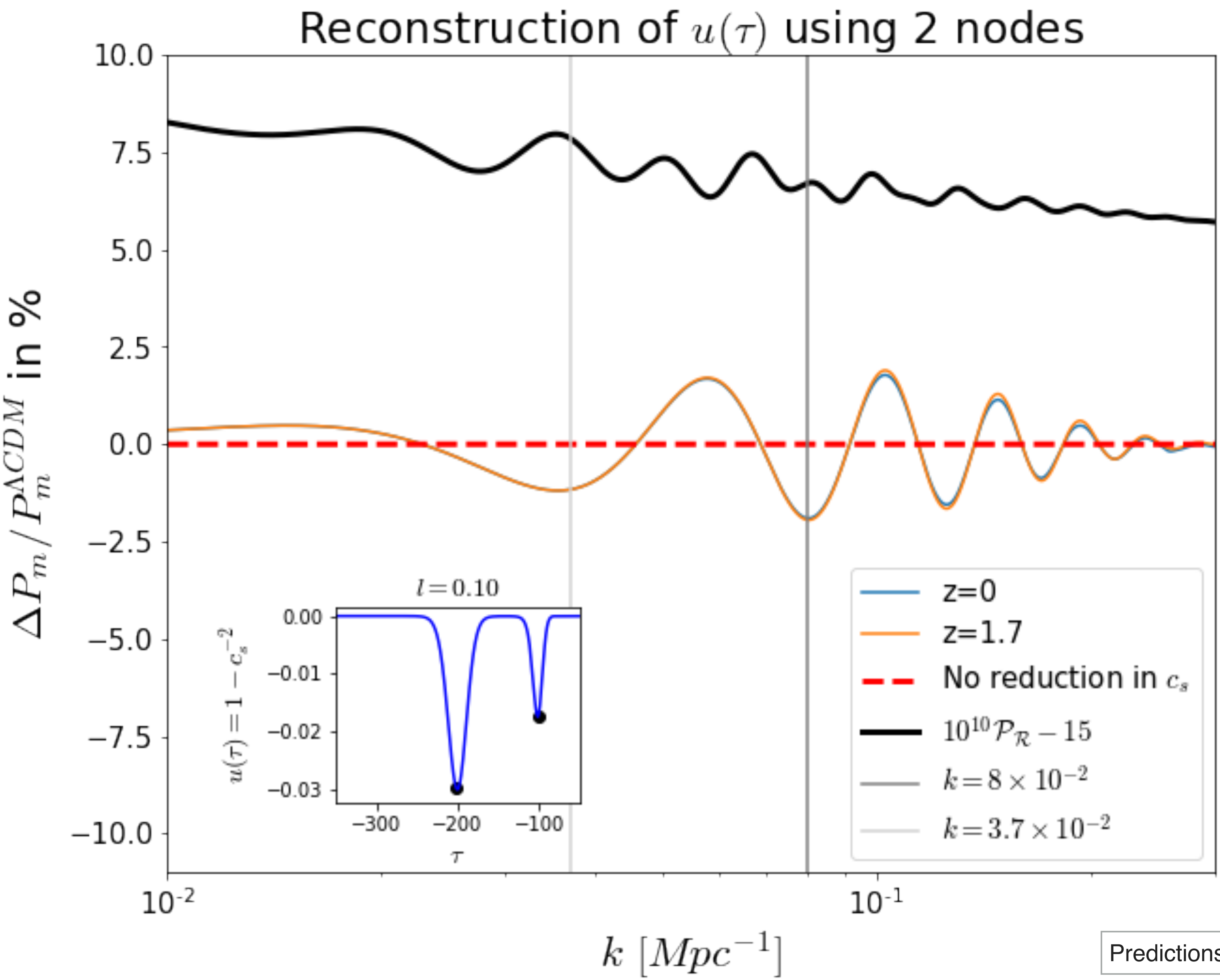
GCH, A. Achúcarro, J. Torrado

Bispectrum



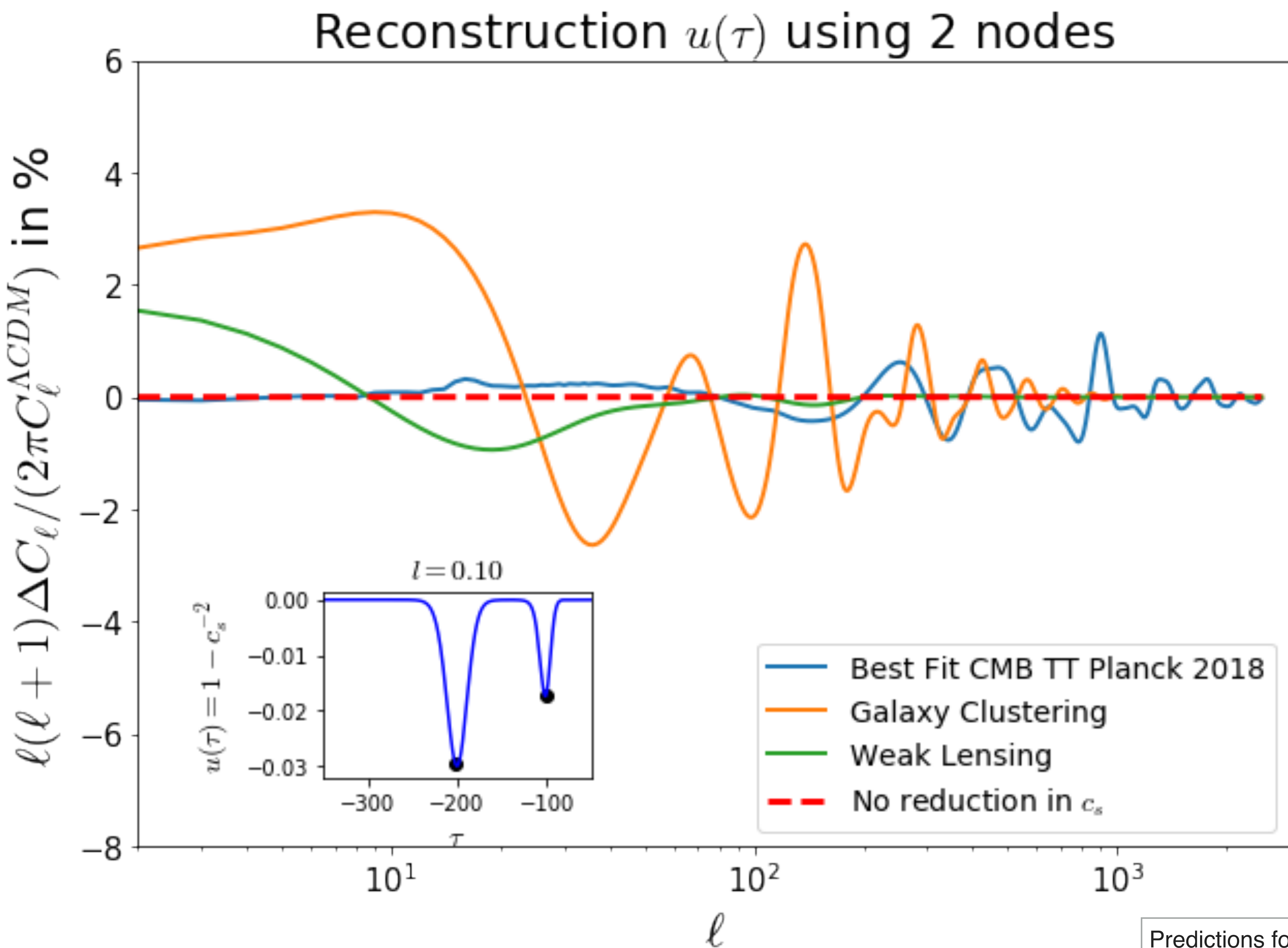
J. Torrado

Predictions for LSS



Predictions for Euclid/**GCH**

Predictions for LSS



Predictions for Euclid/**GCH**

Summary

- **Efficient and flexible pipeline for** the analysis of features from **small, mild and transient reductions in sound speed** in cosmological data
- Bayesian pipeline: proper treatment sound-speed reduction's parameters w.r.t. physical constraints.
- This model has not been tested by **Planck**
- **Features** in primordial power spectrum **correlated to bispectrum**
- Future work: **test** against CMB **bispectrum** and other data sets (**LSS**)

¡Gracias!

Bispectrum

- Multiple Field Inflation — non-gaussianities encoded in:

$$S_3 = \int d^4x a^3 M_P^2 \epsilon H^2 \left[-2Hsc_s^{-2}\pi\dot{\pi}^2 - (1-c_s^{-2})\dot{\pi}\left(\frac{\dot{\pi}^2}{c_s^2} - \frac{(\partial_i\pi)^2}{a^2}\right)\right]$$

$$\downarrow$$

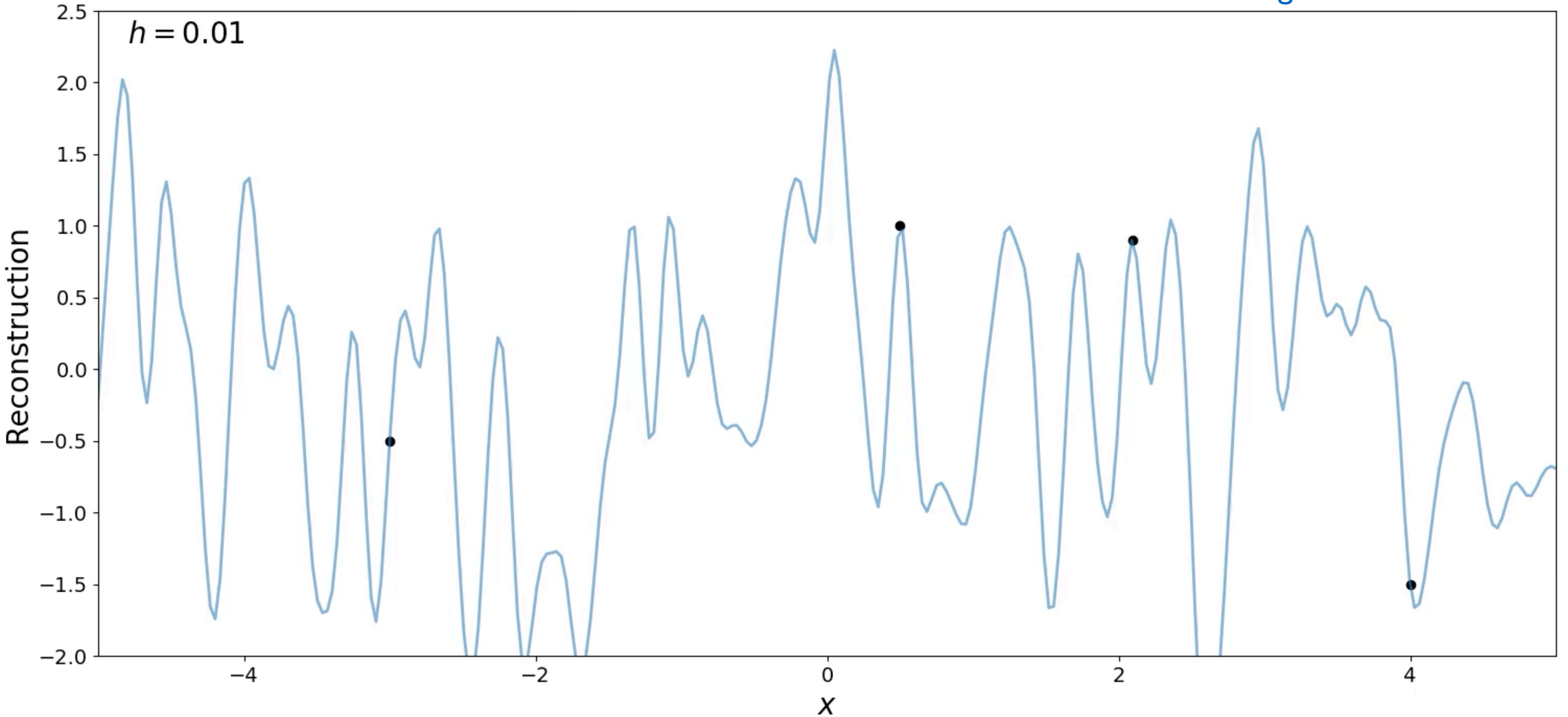
$$\langle \mathcal{R}(\mathbf{k}_1)\mathcal{R}(\mathbf{k}_2)\mathcal{R}(\mathbf{k}_3)\rangle \equiv (2\pi)^3\delta^3(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)B_{\mathcal{R}}(k)$$

- For a transient and mild reduction of the speed of sound:

$$\Delta\mathcal{B}_{\mathcal{R}} = \frac{(2\pi)^4 \mathcal{P}_{\mathcal{R}0}^2}{(k_1k_2k_3)^2}\left\{ -\frac{2}{3}\frac{k_1k_2}{k_3}\left[\frac{1}{2k}\left(1+\frac{k_3}{2k}\right)\frac{\Delta\mathcal{P}_{\mathcal{R}}}{\mathcal{P}_{\mathcal{R}0}} - \frac{k_3}{4k^2}\frac{d}{d\log k}\frac{\Delta\mathcal{P}_{\mathcal{R}}}{\mathcal{P}_{\mathcal{R}0}}\right] + 2\text{ perm} + \right.$$
$$+\frac{1}{4}\frac{k_1^2+k_2^2+k_3^2}{k_1k_2k_3}\left[\frac{1}{2k}\left(4k^2 - k_1k_2 - k_2k_3 - k_3k_1 - \frac{k_1k_2k_3}{2k}\right)\frac{\Delta\mathcal{P}_{\mathcal{R}}}{\mathcal{P}_{\mathcal{R}0}}\right.$$
$$\left.\left. - \frac{k_1k_2+k_2k_3+k_3k_1}{2k}\frac{d}{d\log k}\left(\frac{\Delta\mathcal{P}_{\mathcal{R}}}{\mathcal{P}_{\mathcal{R}0}}\right) + \frac{k_1k_2k_3}{4k^2}\frac{d^2}{d\log k^2}\left(\frac{\Delta\mathcal{P}_{\mathcal{R}}}{\mathcal{P}_{\mathcal{R}0}}\right)\right]\right\}$$

Machine Learning techniques: Gaussian Processes

Kernel $K(x_1 - x_2) = \exp\left(\frac{-|x_1 - x_2|}{2h}\right)$ Correlation length



Course: Data Basis and Data Mining/**Jarle Brinchmann + GCH**

Physics of Inflation

- First condition: a decreasing comoving Hubble radius
- This is analogous to:
  - Accelerated expansion = Negative pressure = Adiabatic condition

$$\frac{d}{dt}\left(\frac{1}{aH}\right) < 0 \longleftrightarrow \frac{d^2a}{dt^2} > 0 \longleftrightarrow \rho + 3p < 0 \longleftrightarrow \omega < -\frac{1}{3}$$

$$\epsilon_1 := -\frac{\dot{H}}{H^2} < 1$$

First slow-roll parameter

$$\epsilon_2 := \frac{\dot{\epsilon}}{H\epsilon} < 1$$

Second slow-roll parameter