Tracing fingerprints of cosmic evolution in the large scale structures of the Universe

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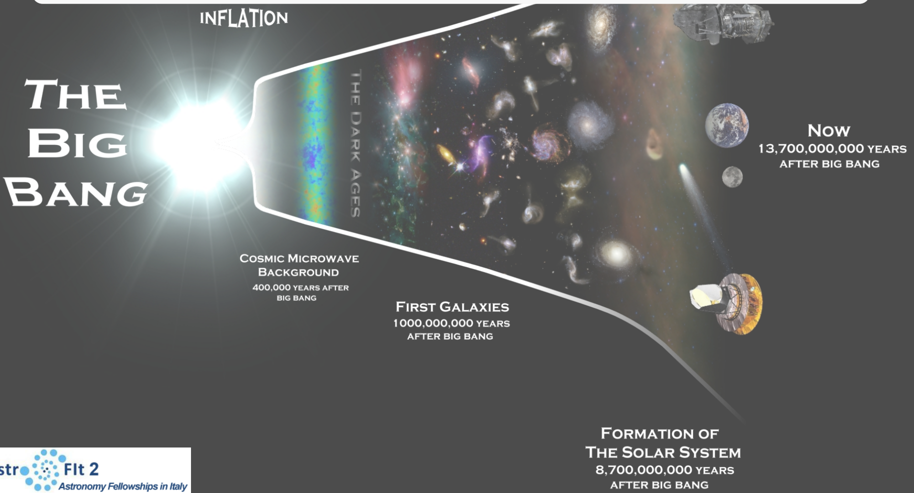
Main epochs of discussion

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement n. 664931

Inflation

Initial rapid expansion of the Universe, generation of primordial fluctuations



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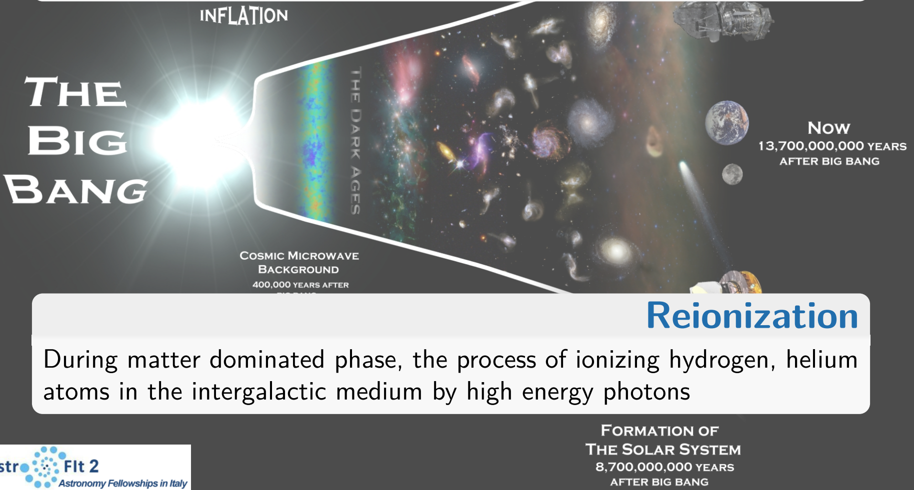

Reionization

During matter dominated phase, the process of ionizing hydrogen, helium atoms in the intergalactic medium by high energy photons

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Reconstructing primordial Universe

CMB anisotropy map $\Longrightarrow$ Angular power spectrum (C_ℓ^{T})

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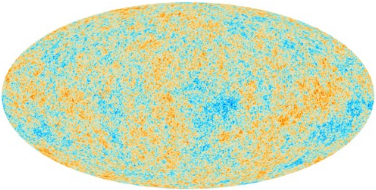
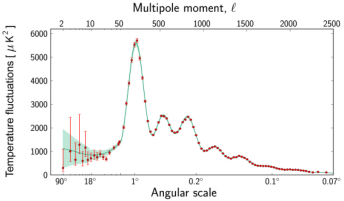
Planck CMB map



Angular power spectrum (Planck)



From the map of temperature anisotropy, we obtain the its power spectrum in angular scales

Primordial power spectrum (P_k) $\Longrightarrow$ Angular power spectrum (C_ℓ^{T})

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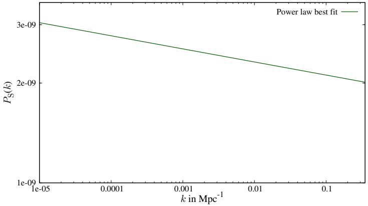
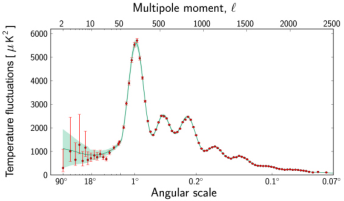
Primordial power spectrum



Angular power spectrum (Planck)



$$C_\ell^{\mathrm{T}} = \sum_i G_{\ell k_i} P_{k_i}$$

$G_{\ell k}$ is the radiative transport kernel.

Transport kernel ($G_{\ell k}$)

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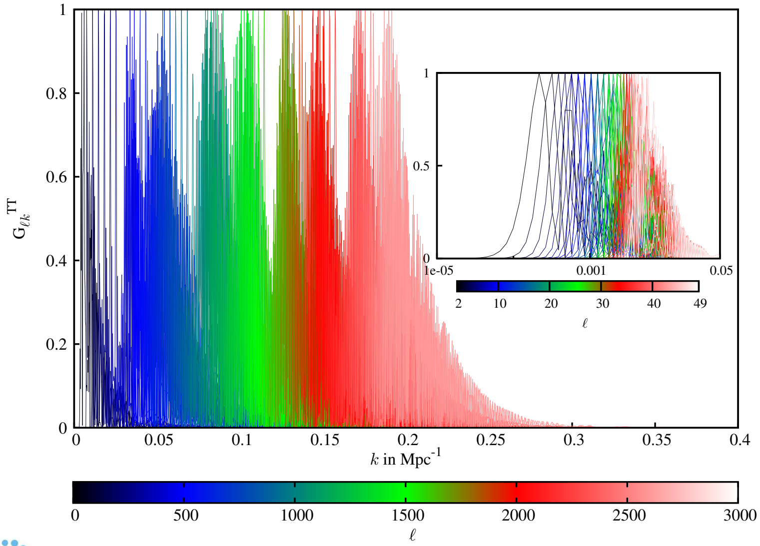
Transport kernel for temperature anisotropy computed using CAMB



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Hazra, Shafieloo and Souradeep, JCAP 2014

Understanding primordial physics from data

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To search for the shape of primordial spectra:

I use 2 approaches:

- The reverse engineering or top down approach:

  Directly from the data (say CMB anisotropy), I use different **deconvolution algorithms** to trace back or reconstruct the primordial signal

- Model building and fitting or bottom up approach:

  Using proper theoretical/phenomenological models of inflation, I confront them with the data

  Both the approaches have to be used efficiently in order **to extract the most out of the data**. Such as, the reconstruction provides the hints for building models in the shape of the data

Richardson-Lucy algorithm : Origin

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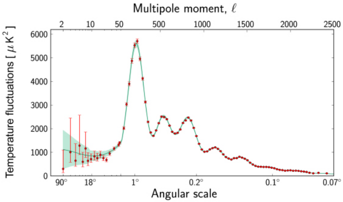
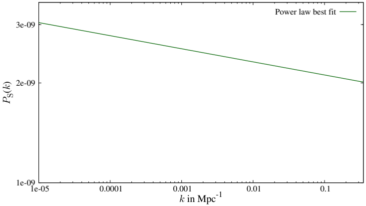
This deconvolution iteratively solves for the PPS:

Richardson (1972) and Lucy (1974)

$$P_k^{(i+1)} - P_k^{(i)} = P_k^{(i)} \times \left[\sum_\ell \widetilde{G}_{\ell k} \left(\frac{C_\ell^{\mathrm{D}} - C_\ell^{\mathrm{T}(i)}}{C_\ell^{\mathrm{T}(i)}} \right) \right]$$

PPS at $i + 1$'th iteration is obtained as a correction factor to the i'th PPS through the deconvolution





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Issues with Planck

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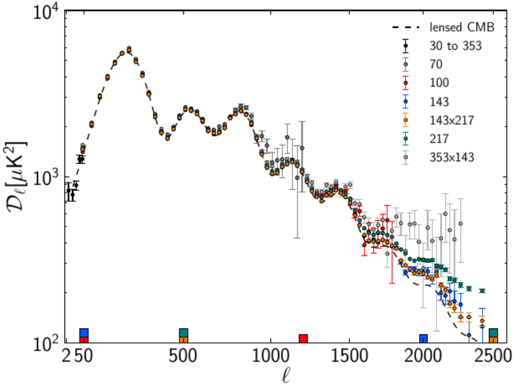
Angular power spectra (in different Planck frequencies)



- 5 different spectra for parameter estimation, calculated from combinations of maps in different frequency channels
- Foreground and calibration effects
- Substantial lensing

Features and error estimation

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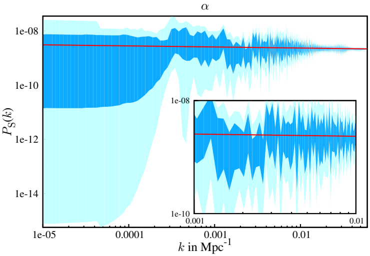
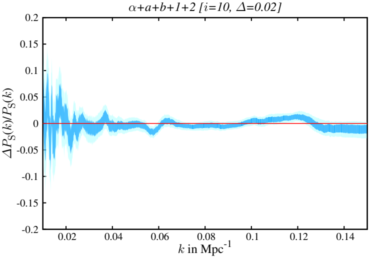
We generate and use 1000 mock angular power spectra in every Planck channels. Using 1000 reconstructed spectra we obtain the 68% and 95% confidence contours





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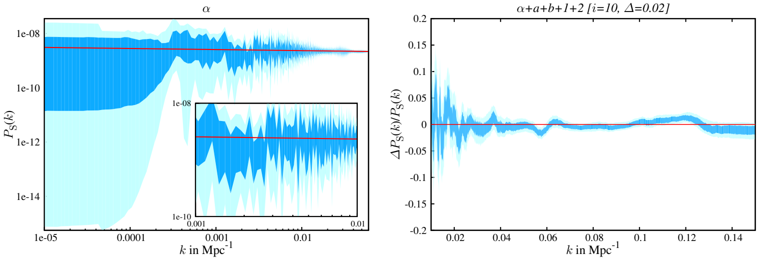

Standard model assumption, power law is consistent at all scales apart from few localized oscillations, near $\ell \simeq 22,\ 200-300,\ 750-850$

Hazra, Shafieloo and Souradeep, JCAP 2014

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Inflation

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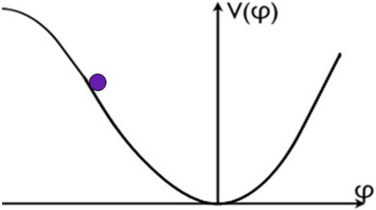
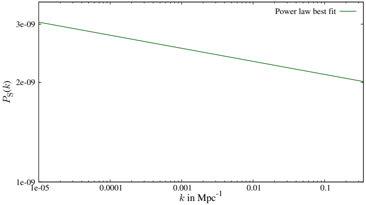
Inflation is rapid expansion of the Universe, driven by presumably a scalar field, rolling slowly down its nearly flat potential





Scalar perturbations generated from the fluctuations in the field does not have strong scale dependence

Towards a theory of features

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In order to generate the features indicated by the reconstruction, we need departure from the strict slow roll inflaton

Start from a **faster roll potential** and **transition to a slow roll potential** or a step in the inflaton potential generates the required features.

Extensive works on feature model have been carried out We are not the only ones : Starobinsky-1992; Linde, Sasaki, Tanaka-1999; Adams, Creswell, Easther-2001; Covi, Hamann, Melchiorri, Slosar, Sorbera-2006; Joy, Sahni, Starobinsky-2008; Jain, Chingangbam, Gong, Sriramkumar, Souradeep-2009; Mortonson, Dvorkin, Peiris, Hu-2009; Hazra, Aich, Jain, Sriramkumar, Souradeep-2010; Flauger, McAllister, Pajer, Westphal and Xu-2010; Aich, Hazra, Sriramkumar, Souradeep-2011; Bousso, Harlow, Senatore-2013; Meerburg, Spergel, Wandelt-2014 ......

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We were the first to generate a wide class of features in a single framework of inflaton potential

Towards a theory - Whipped Inflation

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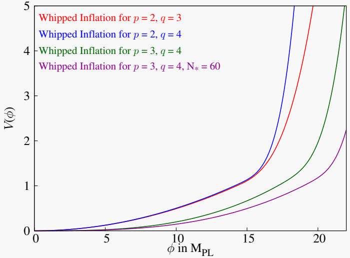
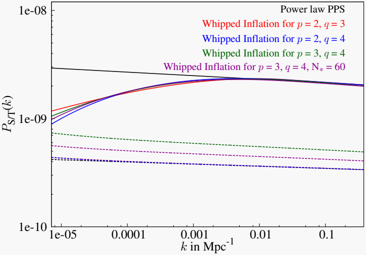
Hazra, Shafieloo, Smoot, Starobinsky, PRL (2014) [Editor's suggestion]

Whipped Inflation potential

$$V(\phi) = V_S(\phi) + \gamma V_R(\phi)$$

Moderate fast-roll $\Longrightarrow$ strict slow-roll





In a continuous potential Whipped Inflation provides **large scale scalar suppression** (without a running like small scale suppression), **low non-Gaussianity**. The tensor amplitude depends on the scale of $V(S)$.

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BINGO: One code to solve them

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Based on **Maldacena 2002** formalism, see **Chen et al. 2006-2010** for initial works on feature model non-Gaussianities

BINGO : BI-spectra and Non-Gaussianity Operator, **Hazra, Sriramkumar and Martin, JCAP 2013; Sreenath, Hazra, Sriramkumar, JCAP 2015**

- BINGO solves the scalar field equation for background and the curvature perturbation equation (Mukhanov-Sasaki equation) for any canonical scalar field driven inflaton
- Calculates the bispectra for arbitrary triangular configurations [**First public code to calculate the bispectrum from inflation**]
- Performs complete numerical calculation without any slow roll approximations (MPI enabled)
- Easy to fuse with CAMB and COSMOMC for parameter estimation

Features : earlier works

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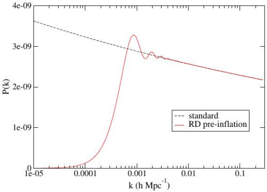
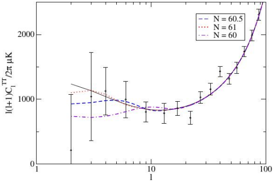
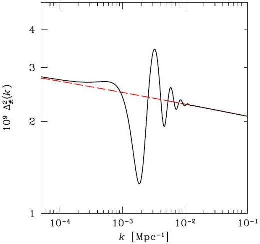
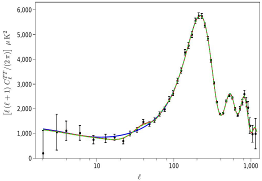
Local features and large scale suppression

Vilenkin, Ford 1982; Powell, Kinney 2006









Mortonson et al. 2009

Hazra, Aich, Jain, Sriramkumar, Souradeep, **JCAP 2010**

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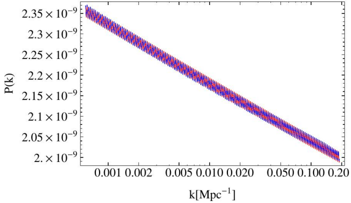
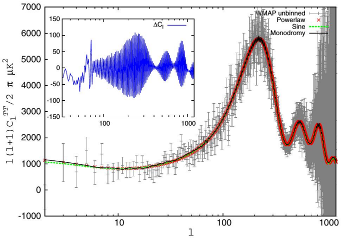
Non-local features : axion monodromy model





Flauger et al. 2009, 2014

Aich, Hazra, Sriramkumar, Souradeep, PRD 2013, Meerburg et. al. 2013 - 2014

Features from WWI

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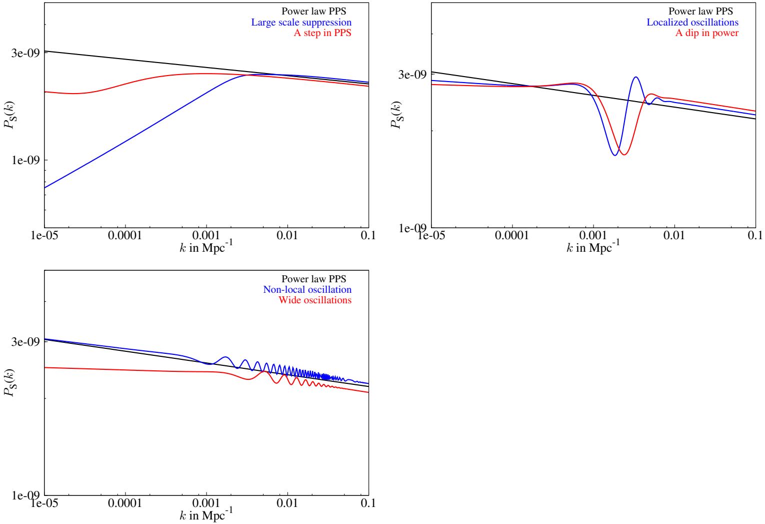
Classes of features in WWI



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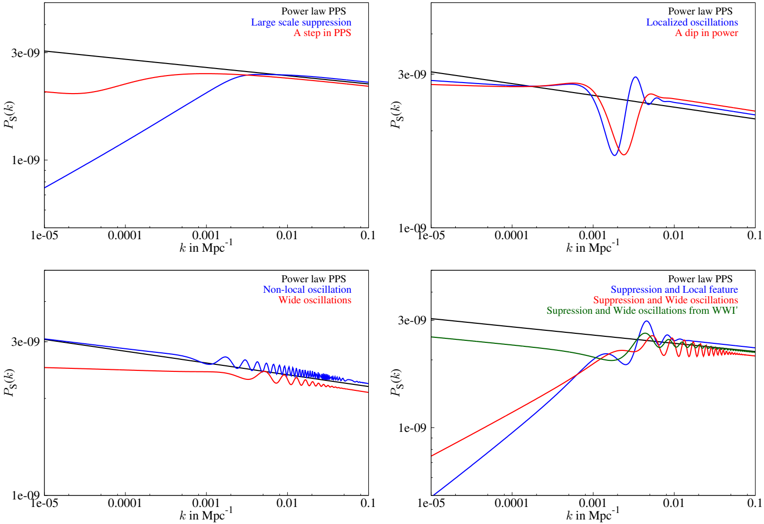

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Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2016

Wiggly Whipped Inflation : Planck 2015

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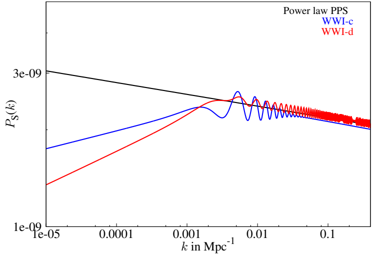

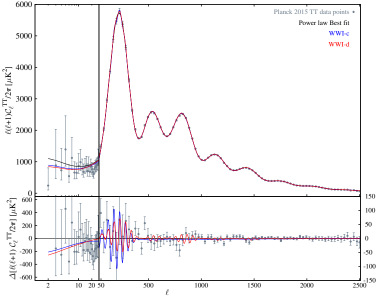

WWI-c provides ~ 10 improvement in χ^2 fit. This improvement comes from low-ℓ TEB and high-ℓ E data.

WWI-d provides $\sim 12 - 14$ improvement while most of the improvement comes owing to the inability of standard model in fitting the temperature and polarization datasets in a combination.

Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2016

Features in the future

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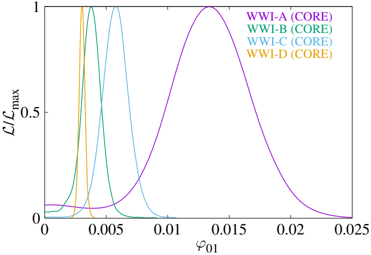
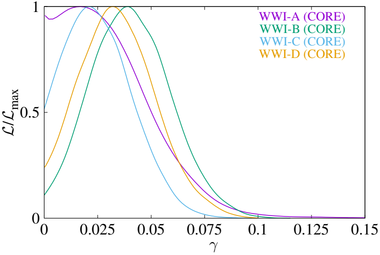
With Cosmic Origins Explorer (CORE)-like survey specification

Wiggles



Suppression



- Large scale suppressions can not be detected with high significance
- Some of the intermediate and small scale oscillations can be detected, if present

Hazra, Paoletti, Ballardini, Finelli, Shafieloo, Smoot, Starobinsky, JCAP 2018

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Reconstructing reionization history

How the Universe got reionized

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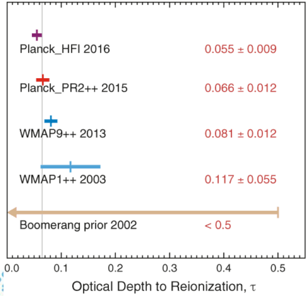
The common practice is to parametrize the ionized hydrogen fraction/free electron fraction as a function of redshift

In CMB study usually a Tanh model of nearly-instantaneous reionization has been used [Planck has used some asymmetric models as well]

Solving the ionization equation by parametrizing ionizing photon emission and recombination time is another way to model the history

The integrated optical depth constraint that we have till now:



Planck 2018 $= 0.054 \pm 0.007$

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Parametrizing ionized hydrogen

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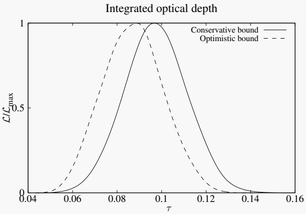
Introduced **Poly-Reion** (a way to construct the history of reionization) and explored possible ways the Universe could have been reionized.

Compared to the conventional nearly instantaneous reionization history we find Planck-2015 prefers an extended history, **higher optical depth**

First free form history of reionization respecting physical bounds on the free electron fraction

Constraints on the optical depth

$$\tau = \int \sigma_{\mathrm{T}} n_e(z) dl$$



Hazra and Smoot, JCAP 2017

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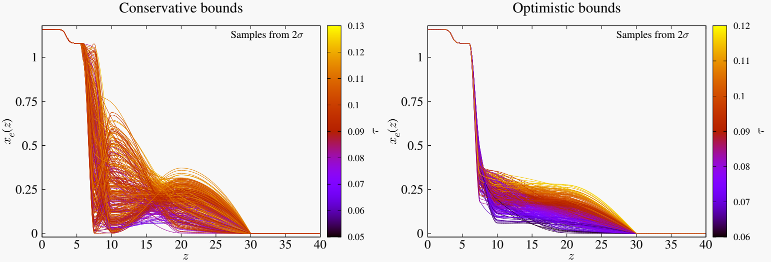
Only CMB | **CMB+low redshift observables**



Hazra and Smoot, JCAP 2017

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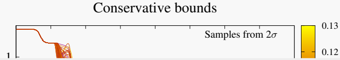
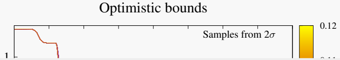
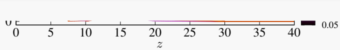
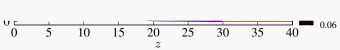




Poly-reion formalism has been used by different groups, Villanueva-Domingo *et. al.* 2018; Millea and Bouchet 2018 (in a modified form) and Planck 2018: cosmological parameters





Hazra and Smoot, JCAP 2017

Free form solution

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- Why free form solution is important:
  - Not biased towards particular phenomenological construct
  - Solving ionization equation provides realistic ionization fractions
  - Constraints are conservative
  - Physical parameters can be obtained in post-process
- Why complete CMB data is needed:
  - Correlations with other parameters are important
  - Use of τ-only constraints can be biased towards the baseline model
  - Analysis with adding other dataset will be robust

Hazra, Paoletti, Finelli, Smoot, arXiv 2019

Free form solution: datasets used

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1. **Planck 2015 angular power spectrum and lensing (P15)**

2. **UV luminosity density from Hubble Frontier Fields (HFF) data (UV)**
   Spanning $z \sim 6 - 11$, we use Bouwens et. al. 2015 and Ishigaki et. al. 2018

3. **Constraints from Lyman-α (QHII)**
   Spanning $z \sim 6 - 8$, we use Fan et. al. 2006, Schroeder et. al. 2013, Schenker et. al. 2014
   Using parmetric form and Planck-2016 τ and UV luminosity density from HFF, recent works are Gorce et. al. 2018, Ishigaki et. al. 2018; a new analysis with free form source function appeared recently Mason et. al. 2019

Hazra, Paoletti, Finelli, Smoot, arXiv 2019

Free form solution: constraints

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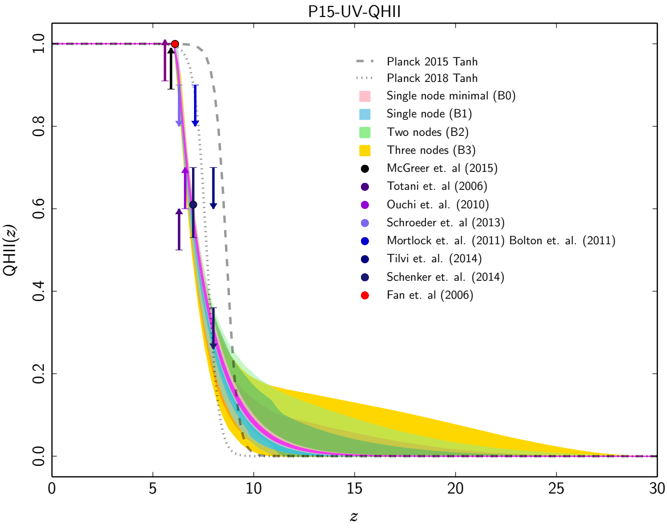

Hazra, Paoletti, Finelli, Smoot, arXiv 2019 see also: Wyithe, Loeb 2003

Degeneracies and how to break them

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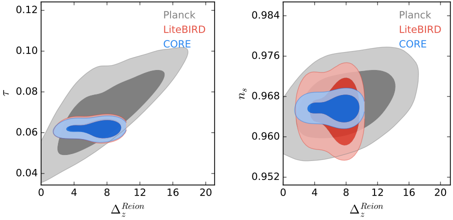
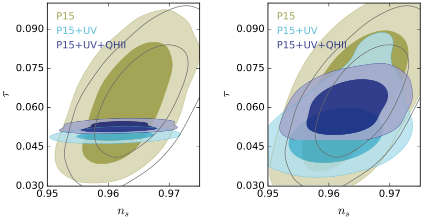
Wait for better data:



Hazra, Paoletti, Finelli, Smoot, JCAP 2018

Use astrophysical observations



Astro Fit 2 Astronomy Fellowships in Italy

Hazra, Paoletti, Finelli, Smoot, arXiv 2019

Upcoming works

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- Analysis of inflation and reionization with Planck 2018 data (released in July 2019)
- Mock reconstruction with Euclid
- Joint forecast of features with Euclid
- Breaking correlations between inflation and reionization, chances with JWST.

Thank you