Joint QSO-CMB Constraints on Reionization

Sourav Mitra[1], T. Roy Choudhury[1] and Andrea Ferrara[2]

[1] *Harish-Chandra Research Institute, India*
[2] *Scuola Normale Superiore, Italy*

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Confronting particle-cosmology with Planck and LHC
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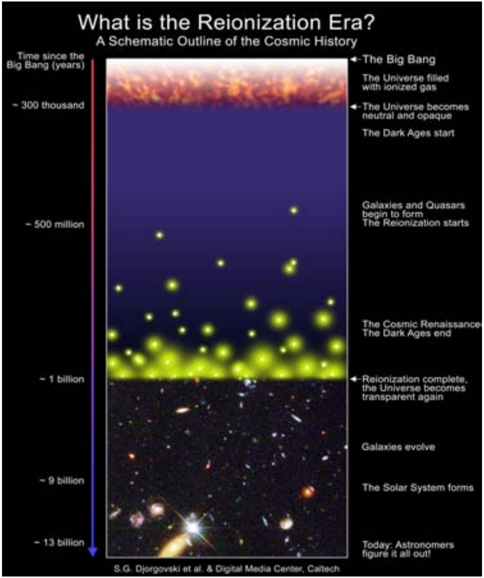
Plan of the Talk

1. Basics of Reionization
2. Features of the semi-analytical model Choudhury & Ferrara (2005,2006)
3. Detailed statistical analysis using principal component analysis
4. Results compare with the WMAP7 and forthcoming PLANCK data

Basics of Reionization



- Recombination epoch
- Dark age
- Reionization
- Post-reionization

Features of the semi-analytical model Choudhury & Ferrara (2005,2006)

- Obtain mass function of collapsed haloes and SFR to calculate total no. of ionizing photons in the IGM

$$\dot{n}_{ph} = N_{ion} n_b \frac{df_{coll}(t)}{dt}$$

- Treat the IGM as multi-phase medium and take into account the inhomogeneities in the IGM.
- Follow ionization and thermal histories of *HI*, *HII* & *HeIII* regions simultaneously and self-consistently.
- Sources of ionizing radiation -
  1. Stars
  2. Quasars (significant sources at $z \lesssim 6$)
- Radiative feedback suppressing star formation in low-mass haloes using a Jeans mass prescription
- Uncertainties (free parameters) - Number of photons per unit collapsed mass $N_{ion}(z)$

Principal Component Analysis - with T. Roy Choudhury and Andrea Ferrara (MNRAS 2011 and arXiv:1106.4034)

- Most likely N_{ion} is a function of halo mass and the redshift : dependences are not well understood $\rightarrow$ taken to be a constant.
- Assume $N_{\rm ion}$ to be an unknown function of z and decompose it into principal components
  – Include only one stellar population
  – No explicit chemical feedback
- These PCs filter out components of the model which are most sensitive to the data
- **Likelihood analysis** using 3 different data sets -
  1. $\Gamma_{\rm PI}$ using Lyα forest Gunn-Peterson optical depth and a large set of hydrodynamical simulations (Bolton & Haehnelt 2007)
  2. $\partial N_{\rm LL}/\partial z$ at $0.36 < z < 6$ using a large sample of QSO spectra (Songaila & Cowie 2010)
  3. C_l for TT, TE and EE modes using WMAP7 (Larson et al. 2010) and forecasted PLANCK data (Lewis 2005; Galli et al. 2010) - **also varying σ_8 and n_s**

Basic theory of PCA

- Consider a set of $n_{\rm obs}$ observational data points $\mathcal{G}_\alpha$

- Construct the **Fisher matrix**

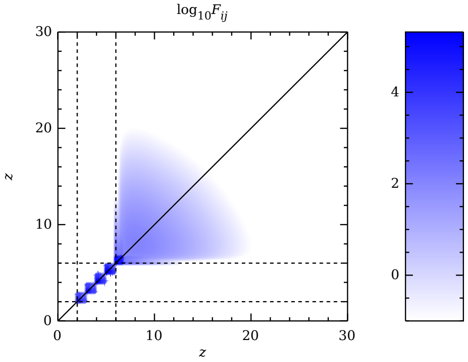
$$F_{ij} = \sum_{\alpha=1}^{n_{\rm obs}} \frac{1}{\sigma_\alpha^2} \frac{\partial \mathcal{G}_\alpha^{\rm th}}{\partial N_{\rm ion}^{\rm fid}(z_i)} \frac{\partial \mathcal{G}_\alpha^{\rm th}}{\partial N_{\rm ion}^{\rm fid}(z_j)} \quad \text{(inclusion of the free parameter } \lambda_0\text{)}$$

- Expand the deviation of $N_{\rm ion}$ from its fiducial model

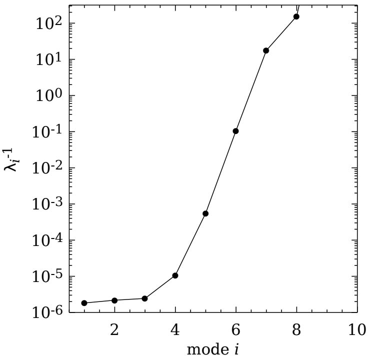
$$\delta N_i \equiv N_{\rm ion}(z_i) - N_{\rm ion}^{\rm fid}(z_i) = \sum_{k=1}^{n_{\rm bin}} m_k S_k(z_i)$$

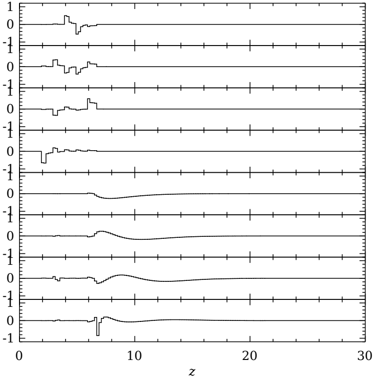
- Largest eigenvalues correspond to minimum variance – possible to reconstruct δN_i using only first $M \leq n_{\rm bin}$ modes

Results Fisher matrix F_{ij} in the $z - z$ plane



Results eigenvalues and eigenmodes





Results Choice of the number of modes

1. Trial-and-error method to fix M

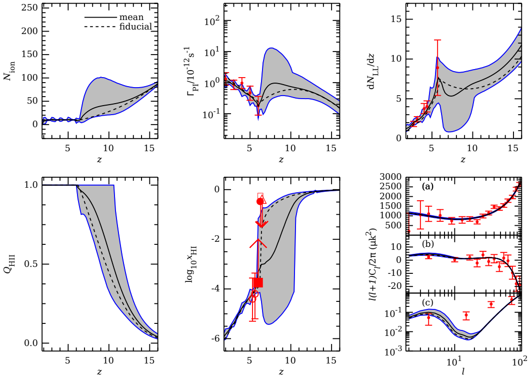
2. Minimizing the quantity Risk (Wasserman et al. 2001)

$$R = \sum_{i=1}^{n_{\rm bin}} \left(\delta N_i^{(M)}\right)^2 + \sum_{i=1}^{n_{\rm bin}} \left\langle \left(\delta N_i^{(M)}\right)^2 \right\rangle$$

– 1st term is the bias contribution (arises from neglecting the higher order terms)
– 2nd term is the error (rises as higher order terms are included)
– Risk is minimum for $M = 8$

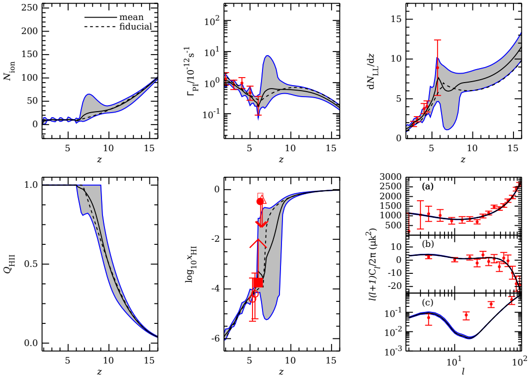
3. **Akaike information criterion** ($\mathrm{AIC} = \chi^2_{\rm min} + 2M$)
$M = 2$ to 8 which satisfy $\mathrm{AIC} < \mathrm{AIC}_{\rm min} + \kappa$ where $\kappa = 10$, produces very solid results.

Results Marginalized posteriori distribution from PCA using AIC criterion for WMAP7 data



Parameters	Mean value	95% confidence limits
τ_{el}	0.093	[0.080, 0.112]
$z(Q_{HII} = 0.5)$	10.206	[8.952, 11.814]
$z(Q_{HII} = 0.99)$	7.791	[5.800, 10.427]

Results Marginalized posteriori distribution from PCA using AIC criterion for forthcoming Planck data



Parameters	2-σ errors	
	WMAP7	PLANCK (forecast)
τ_{el}	0.032	0.009
$z(Q_{\rm HII} = 0.5)$	2.862	1.117
$z(Q_{\rm HII} = 0.99)$	4.627	3.013

CONCLUSIONS

1. It is sufficient to model $N_{\rm ion}(z)$ over the redshift range $2 < z < 14$ using first 8 parameters to extract the maximum information contained within the data

2. All quantities related to reionization can be severely constrained for $z < 6$ because of a large number of data points, whereas constraints at $z > 6$ are relatively loose

3. $N_{\rm ion}(z)$ must increase at $z > 6$ – ruling out reionization by a single stellar population

4. With the forthcoming PLANCK data on large-scale polarization, the $z > 6$ constraints will be improved considerably
   - $2-\sigma$ error on $\tau_{\rm el}$ reduced to 0.009
   - $2-\sigma$ error on $z(Q_{\rm HII} = 0.5)$ and $z(Q_{\rm HII} = 0.99)$ would be ~ 1 and 3