The shape of cosmological fluctuations

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Quantum fluctuations of inflaton field

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Universe with fluctuating energy+matter density.

Φ

Very large scales : space filled with matter or radiation must expand

Intermediate scales : gravitational attraction

Very small scales : Electromagnetic + weak + strong forces

Interactions at different scales modulate the shapes of the primordial Φ.

The shape of Φ

Effect of scattering

Scattering decreases the amplitude of fluctuations. Homogenizes.

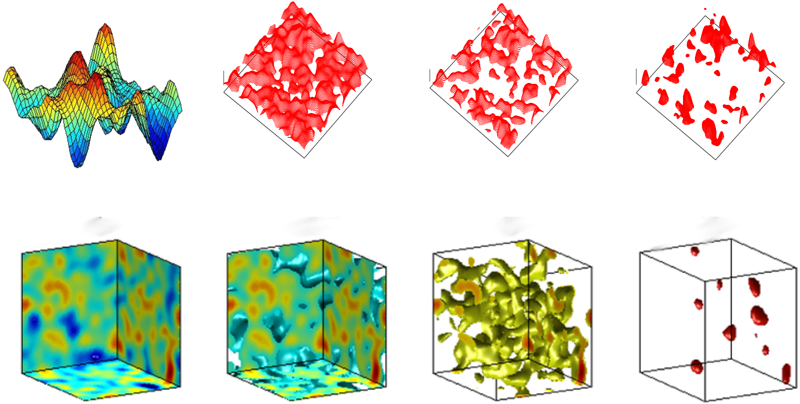
Effect of gravitational attraction

Gravity is isotropic. But the mass distribution on smaller scales is not isotropic. Hence tidal forces will distort the shape of Φ.

Effect of expansion

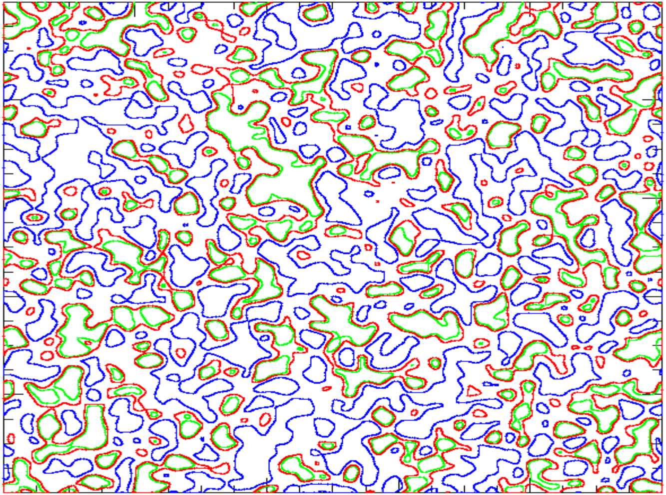
If the expansion is isotropic, the size of structures gets scaled, but shape does not change.

Shapes of random fields - excursion sets



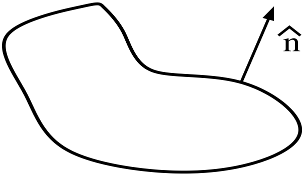
Picture credit: R. Adler

Boundaries - curves/surfaces - of excursion sets



2D fields - Contour Minkowski Tensor

McMullen (1997), Alesker (1999), Hug *et al.* (2008), Schroeder-Turk *et al.* (2009)



$$\mathcal{W}^{(2)} = \int_C \hat{n} \otimes \hat{n} \;\, \mathrm{d}\ell$$

$$\left(\hat{n} \otimes \hat{n} \right)_{ij} \equiv \frac{1}{2} \left(\hat{n}_i \hat{n}_j + \hat{n}_j \hat{n}_i \right)$$

Ellipse $\longrightarrow$ $\mathcal{W}^{(2)} = \begin{bmatrix} f(p,q) & 0 \\ 0 & f(q,p) \end{bmatrix}$

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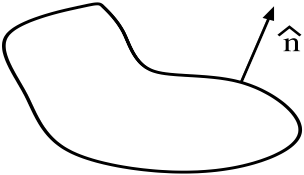

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Shape parameter : $\beta \equiv \lambda_1/\lambda_2$, $\lambda_1 < \lambda_2$

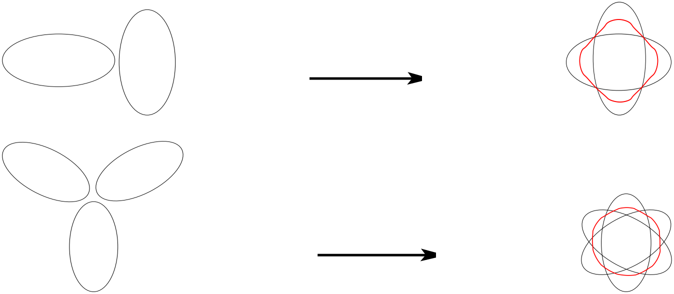
$0 < \beta \leq 1.$ m-fold symmetry, $m \geq 3$ $\rightarrow$ $\beta = 1.$

Alignment of many curves - α

PC, Yogendran, Joby, Ganesan, Appleby & Park 2017

Sum all $\mathcal{W}^{(2)} \quad \longrightarrow \quad \overline{\mathcal{W}}^{(\mathbf{2})} \quad \longrightarrow \quad \mathbf{\Lambda_1}, \mathbf{\Lambda_2}$

Alignment parameter : $\alpha \equiv \frac{\mathbf{\Lambda_1}}{\mathbf{\Lambda_2}}, \quad 0 < \alpha \leq 1$



α **is the shape/anisotropy parameter of the locus curve.**

3D fields - Area Minkowski Tensor

Schroeder-Turk *et al.* (2010)

Single structure : $\mathcal{W}^{(3)} = \int_S \hat{n} \otimes \hat{n} \; \mathrm{d}a$

- Three eigenvalues $\longrightarrow$ $\lambda_{\mathbf{1}}, \lambda_{\mathbf{2}}, \lambda_{\mathbf{3}}, \qquad \lambda_1 < \lambda_2 < \lambda_3$
- **Shape parameters :** $\beta_{\mathbf{1}} \equiv \frac{\lambda_{\mathbf{1}}}{\lambda_{\mathbf{2}}}, \qquad \beta_{\mathbf{2}} \equiv \frac{\lambda_{\mathbf{2}}}{\lambda_{\mathbf{3}}}$

Many structures : $\overline{\mathcal{W}}^{(3)} \longrightarrow \quad \mathbf{\Lambda_1}, \mathbf{\Lambda_2}, \mathbf{\Lambda_3}$

- **Alignment parameters :**

$$\alpha_{\mathbf{1}} \equiv \frac{\mathbf{\Lambda_1}}{\mathbf{\Lambda_2}}, \qquad \alpha_{\mathbf{2}} \equiv \frac{\mathbf{\Lambda_2}}{\mathbf{\Lambda_3}}$$

$\overline{\mathcal{W}}^{(2,3)}$ for Gaussian isotropic fields

PC, Yogendran, Joby, Ganesan, Appleby & Park 2017;

Appleby, PC, Park, Yogendran & Joby 2018

2D fields : $\langle \overline{\mathcal{W}}^{(2)}(\nu) \rangle \quad \propto \quad \frac{1}{r_c} e^{-\nu^2/2} \times I \times \text{Area}$

3D fields : $\langle \overline{\mathcal{W}}^{(3)}(\nu) \rangle \quad \propto \quad \frac{1}{r_c} e^{-\nu^2/2} \times I \times \text{Volume}$

$$r_c \equiv \frac{\sigma_0}{\sigma_1} \qquad \longrightarrow \quad \text{correlation length.}$$

Statistical isotropy :

2D: The locus curve must have $\alpha = 1$.

3D: The locus surface must have $\alpha_1 = \alpha_2 = 1$.

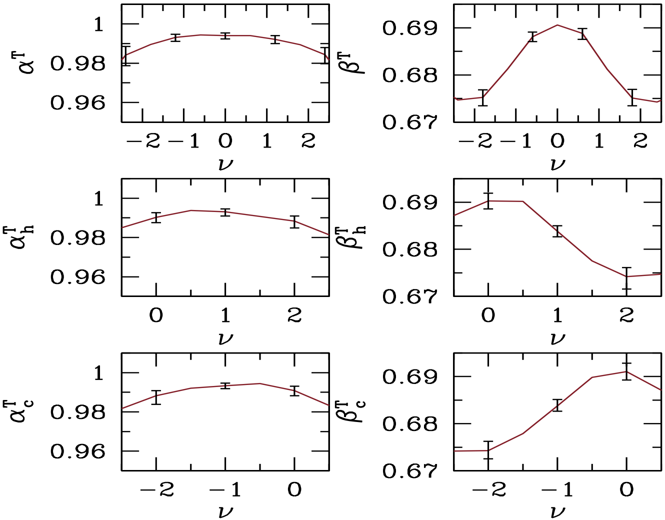
Application to cosmological fields

- **Testing statistical isotropy of the universe using CMB data from PLANCK**

- **Distorsion of CMB fields by lensing**

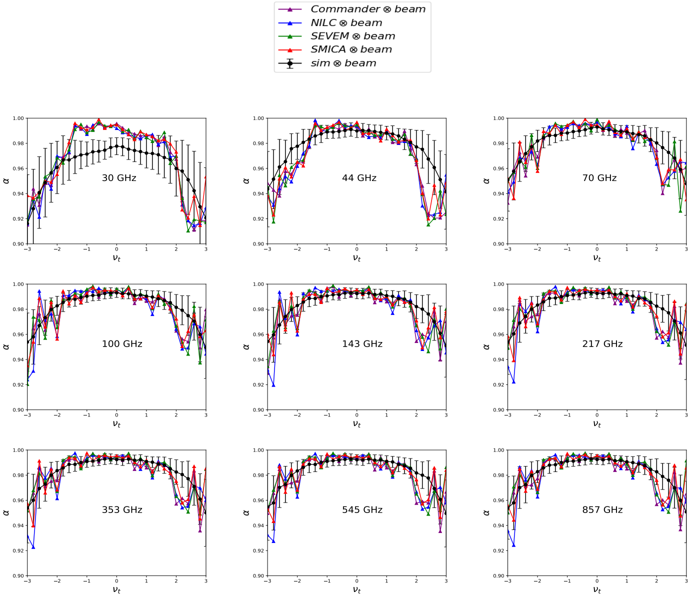
- **Probing length and times scales of the epoch of reionization**

CMB - Gaussian isotropic simulations



Search for statistical anisotropy using 2015 PLANCK data

Joby, PC, T. Ghosh *et al.*, 2018



Search for statistical anisotropy using PLANCK data

Joby, PC, T. Ghosh *et al.*, 2018

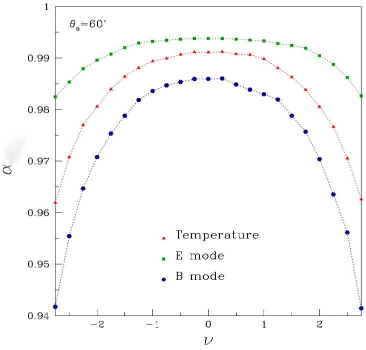
- **Conclusion** : PLANCK 2015 temperature data exhibits no statistically significant deviation from SI.
- 30 GHz data for all cleaning methods show mild decrepancy at $\sim 2\sigma$.
- Small increase of discrepancy when analyzed at higher resolution using $Nside = 1024$.

  $\Rightarrow$ discrepancy is likely due to improper noise estimates for 30 GHz.
- 2015 polarization data for all cleaning methods found to have higher than 3σ deviation from SI. **Vidhya Ganesan & PC 2017**
- Full probe of 2018 PLANCK data for both temperature and polarization ongoing.

Distortions in the CMB induced by lensing

Priya Goyal, PC, Appleby *et al.*, in prep

Simulations of lensed CMB fields : LENSPIX Antony Lewis



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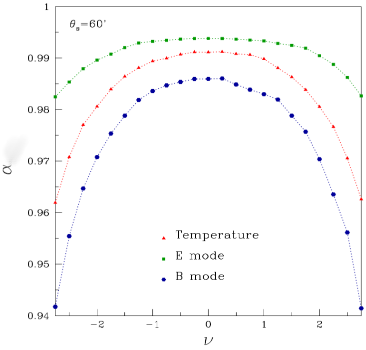

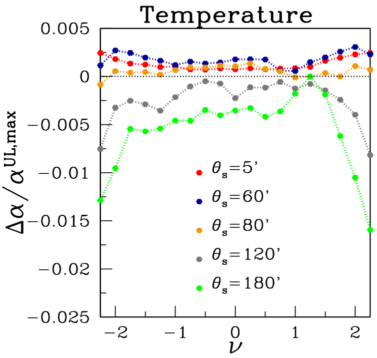

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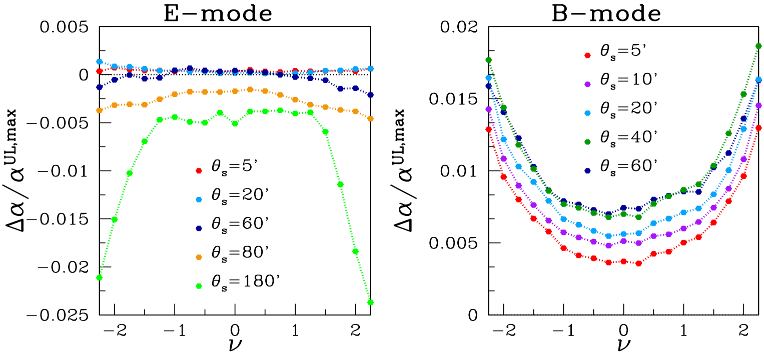
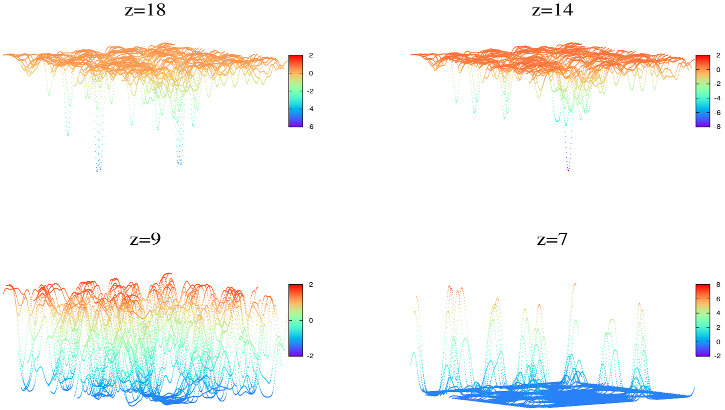


Epoch of Reionization - ionization history

Akanksha Kapahtia, PC, Appleby & Park 2018

21cmFAST simulations **Messinger, Furlanetto & Cen 2010**

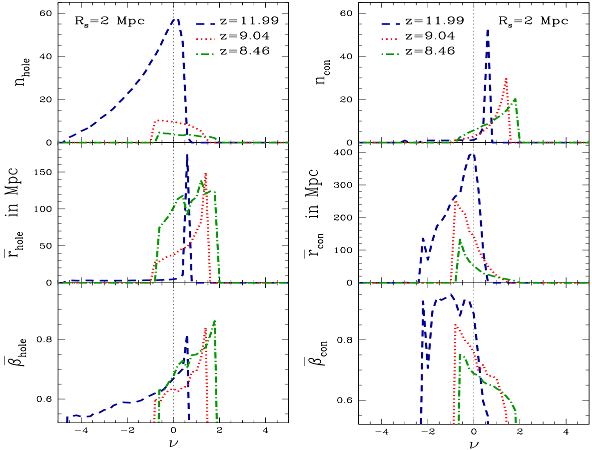


Epoch of Reionization - ionization field

Akanksha Kapahtia, PC, Appleby & Park 2018

Let $r \equiv (\lambda_1 + \lambda_2)/2\pi$.

Calculate $n_{\rm hole}$, $n_{\rm con}$, $r_{\rm hole}$, $r_{\rm con}$, $\beta_{\rm hole}$, $\beta_{\rm con}$.



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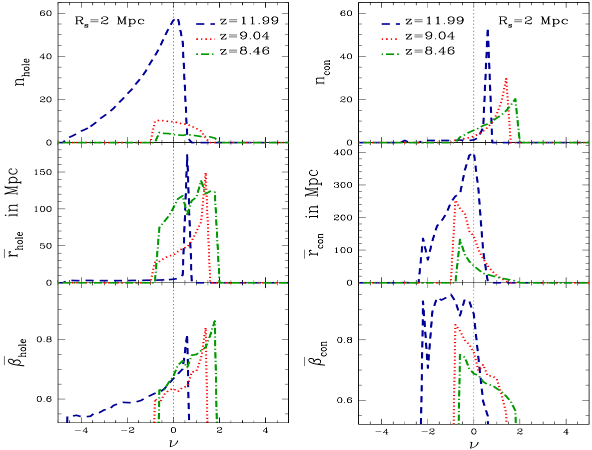


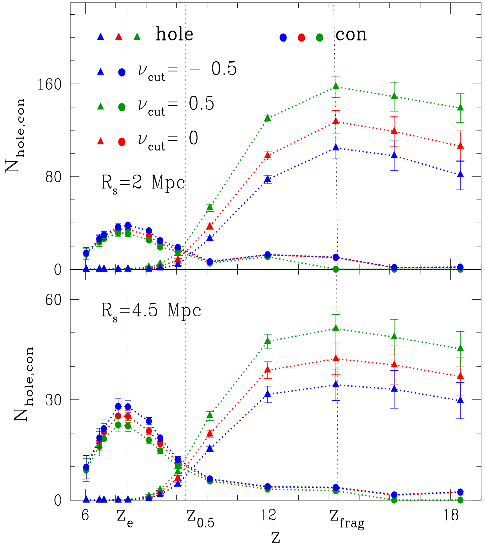
$$N_{\mathrm{x}} \equiv \int n_{\mathrm{x}} \mathrm{d}\nu$$

$$r_{\mathrm{x}}^{\mathrm{ch}} \equiv \frac{1}{N_{\mathrm{x}}} \int n_{\mathrm{x}} r_{\mathrm{x}} \mathrm{d}\nu$$

$$\beta_{\mathrm{x}}^{\mathrm{ch}} \equiv \frac{1}{N_{\mathrm{x}}} \int n_{\mathrm{x}} \beta_{\mathrm{x}} \mathrm{d}\nu$$

EoR - ionization field

Akanksha Kapahtia, PC, Appleby & Park 2018



Important time scales

$$\mathbf{z}_{\mathrm{frag}} \sim 14$$

$$\mathbf{z}_{0.5} \sim 9$$

$$\mathbf{z}_{\mathrm{e}} \sim 7$$

EoR - ionization field

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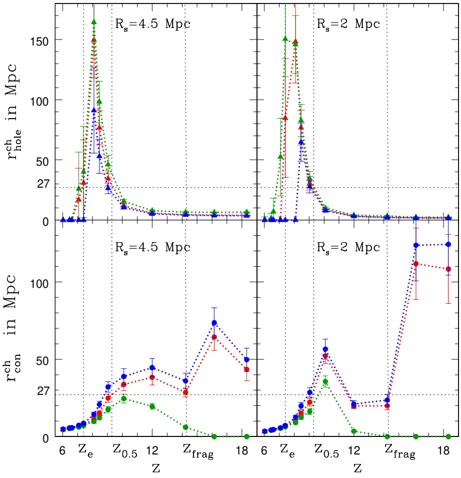
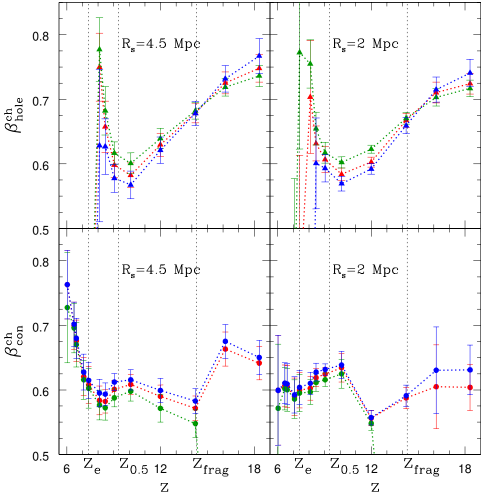


Ionized bubbles grow to size of 27 Mpc by $z_{0.5}$.

EoR - ionization field

Akanksha Kapahtia, PC, Appleby & Park 2018



Maximum merger happens before $z_{0.5}$.

Summary

- Ionized bubble shapes are **not spherical** as often assumed for analytic arguments. Our method quantifies the anisotropy.
- The size and shape information give the important times scales of reionization.
- They are sensitive to different models of reionization. Hence can be used to constrain models.
- Effect of instrumental noise and foregrounds need to be carefully investigated.

Akanksha Kapahtia, PC, Appleby *et al.*, in prep