ミンコフスキー汎関数を用いた背景21cm線への重力レンズ効果の検証

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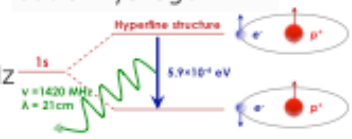
The 21cm signal

- **A forbidden hyperfine transition** between two $1^2s_{1/2}$ ground level state of neutral hydrogen.
  - Energy difference: **λ = 21cm**, ν = 1420 MHz



- **Differential brightness temperature**
  - IGM during EoR (Epoch of Reionization) has measurable signal.

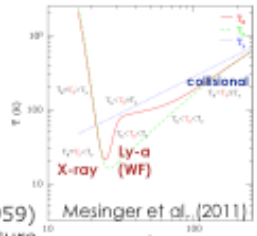
$$\delta T_{\rm b} = \frac{3h_{\rm p}c^3A_{21\rm cm}}{21\pi k_{\rm B}\nu_{21\rm cm}^2}\frac{n_{\rm HI}}{(1+z)H(z)}\left(1-\frac{T_{\rm CMB}(z)}{T_{\rm s}}\right)\left(1+\frac{1}{H(z)}\frac{dv_{\parallel}}{dr_{\parallel}}\right)^{-1}$$

- **Spin temperature**
  - Couplings with T_s
    - **Collisional:** H-H, H-e⁻
    - **Radiative:**
      - CMB, **Ly-a**, **X-ray**, etc...

$$T_{\rm s}^{-1} = \frac{T_{\rm CMB}^{-1} + y_\alpha T_{\rm c}^{-1} + y_{\rm c}T_{\rm k}^{-1}}{1 + y_\alpha + y_{\rm c}}$$

  - T_c: color temperature
    - $T_c \sim T_k$ - Field (1959)
  - T_k: kinematic temperature

- $n_{\rm HI}$: neutral hydrogen density
- T_s : spin temparature
- $v_{\parallel}$: line of sight velocity

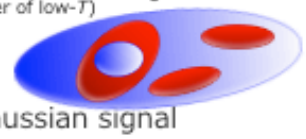


Minkowski Functionals

- Statistical indicator for the morphology related to the isothermal (line)
- Functions of threshold of temperature ν
  - ***For 2D field:***
    - V_0 – **Area** of high-T region
    - V_1 – **Length** of the isothermal
    - V_2 – **Euler number** (Genus)

      (number of high-T) - (number of low-T)

      Ex. V_2 = 3 - 2 = **+1**
  - ***For 3D field:***
    - V_0 - **Volume**
    - V_1 – **Area**
    - V_2 – **Length**
    - V_3 – **Euler num.**



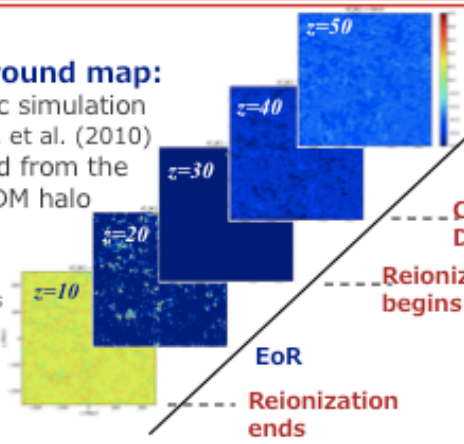
- Analysis for non-Gaussian signal
  - **Higher-order specra:**
    - Bispectrum, Trispectrum, etc... are too hard due to many legs
  - **Optimal estimators:**
    - Skewness, Kurtosis, etc... lose some information

$$\mathcal{S} = \sum_{\ell_1,\ell_2,\ell_3} W_{\ell_1\ell_2\ell_3} B_{\ell_1\ell_2\ell_3} \qquad \mathcal{K} = \sum_{\ell_1,\cdots\ell_4,L} W_{\ell_1\ell_2\ell_3\ell_4 L} T^{\ell_1\ell_2}_{\ell_3\ell_4}(L)$$

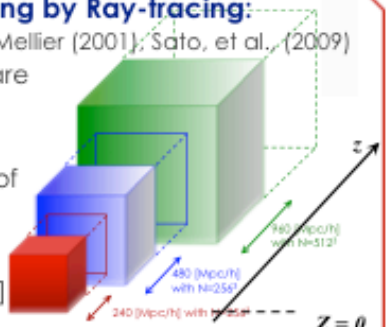
  - **Morphological analysis:**
    - **Minkowski Functionals** include all of higher-order correlations

Simulation

- **21cm background map:**
  - Semi-analytic simulation Santos, et al. (2010)
  - HI is assigned from the distribution of DM halo
  - L=500 [Mpc] (352 [Mpc/h])
  - N_h=1024³ particles
  - N_c=1024³ grids
  - minmum halo mass ~ $10^8 M_{\rm sun}$



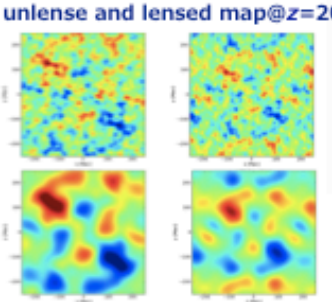
- **Gravitational Lensing by Ray-tracing:** Hamana & Mellier (2001), Sato, et al. (2009)
  - Simulation boxes are made by Gadget-2:
    - Light corns are made from 3 kind of simulation boxes
  - angular resolution => 0.5~1.0 [arcsec]

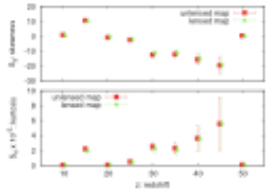


Results

- Simulated 21cm maps smoothed by different smoothing scale θ_s=1′ or 5′.
- Both the deformation of individual peaks and the distortion of the relative positions of the peaks are clearly visible.

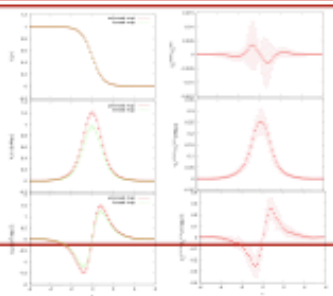
unlense and lensed map@z=20





- Skewness and Kurtosis for each redshift.
  - The deviations of S3 and S4 from unlense map due to lensing effect are small.

- MFs estimated from simulation maps@z=20
  - smoothing scale: θ_s=1′
- Differences between unlensed and lensed map can be seen especially on V_1 and V_2.



Summary

- We estimate the gravitational lensing effect of 21cm-line background map by the semi-analytical 21cm simulation and ray-tracing simulation.
- We measure the lensing effect with three morphological descriptors, a.s.a Minkowski Functionals.
- Minkowski Functionals can measure the lensing effects with the future 21cm survey such like SKA.