2 points statistics for weak lensing and intensity maps

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Work with **David Bacon,**

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Outline

- Introduction to ICG
- Weak Gravitational Lensing
- 21cm cosmology
- HI intensity map
- Spherical Harmonics and Angular Power Spectrum
- Lensing-HI 2-point functions

Introduction to ICG

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Research Groups In ICG

- Very early Universe
- Dark energy
- Testing gravity on cosmological scales
- Large scale structure
- Gravitational lensing
- Supernovae
- Galaxy evolution
- Stellar population modelling
- Gravitational Wave

Basic of Gravitational Lensing

- Small perturbation in flat FLRW

$$ds^2 = a^2(\tau)\left[-(1+2\Psi)d\tau^2 + (1-2\Phi)d\vec{x}^2\right]$$

- Deflection angle

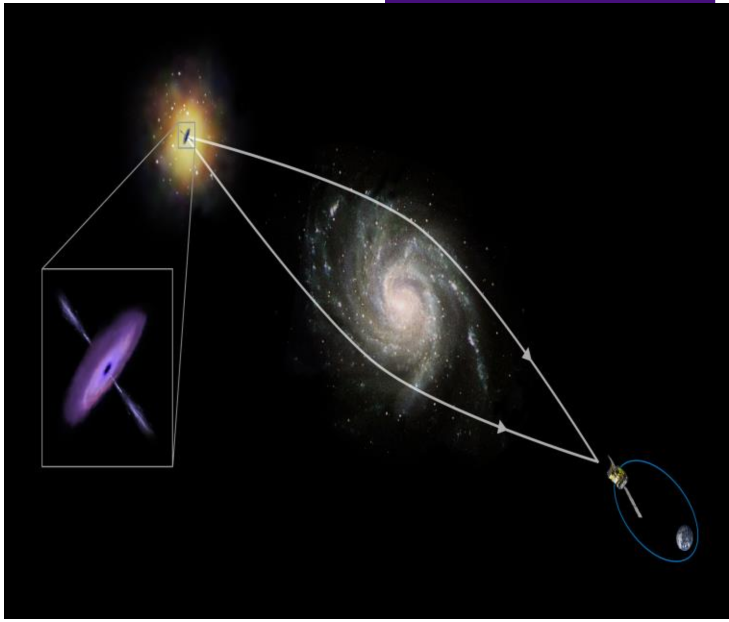
$$\alpha(\hat{n}) = \int_0^{\chi_s} d\chi' q_L(\chi', \chi_s)\nabla_\perp \phi_W(\chi', \chi'\hat{n})$$

- Weyl potential (Growth structure)

$$\phi_W = \frac{1}{2}(\Psi + \Phi)$$

- Lensing weight function (Geometry)

$$q_L(\chi', \chi_s) = \frac{\chi'(\chi_s - \chi')}{\chi_s}$$



Cr : ESA

In LCD

$$\nabla \phi_W \propto \frac{1}{a}\delta_m(\chi, \chi\hat{n})$$

Basic of Gravitation Lensing : continue

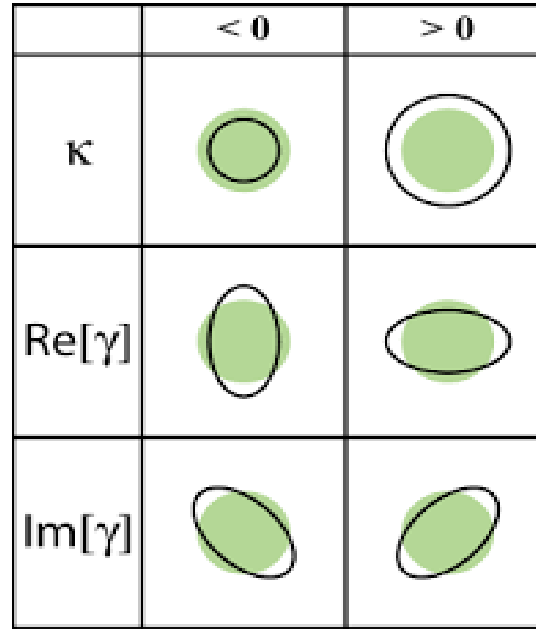
$$\vec{\alpha}(\chi\hat{n}) = \nabla_\theta \psi(\chi\hat{n})$$

- Convergence

$$\kappa(\chi\hat{n}) = \frac{1}{2}\nabla^2_\theta(\chi\hat{n})$$

- Shear

$$\gamma(\chi,\chi\hat{n}) = \frac{1}{2}\eth\eth\psi(\chi,\chi\hat{n})$$

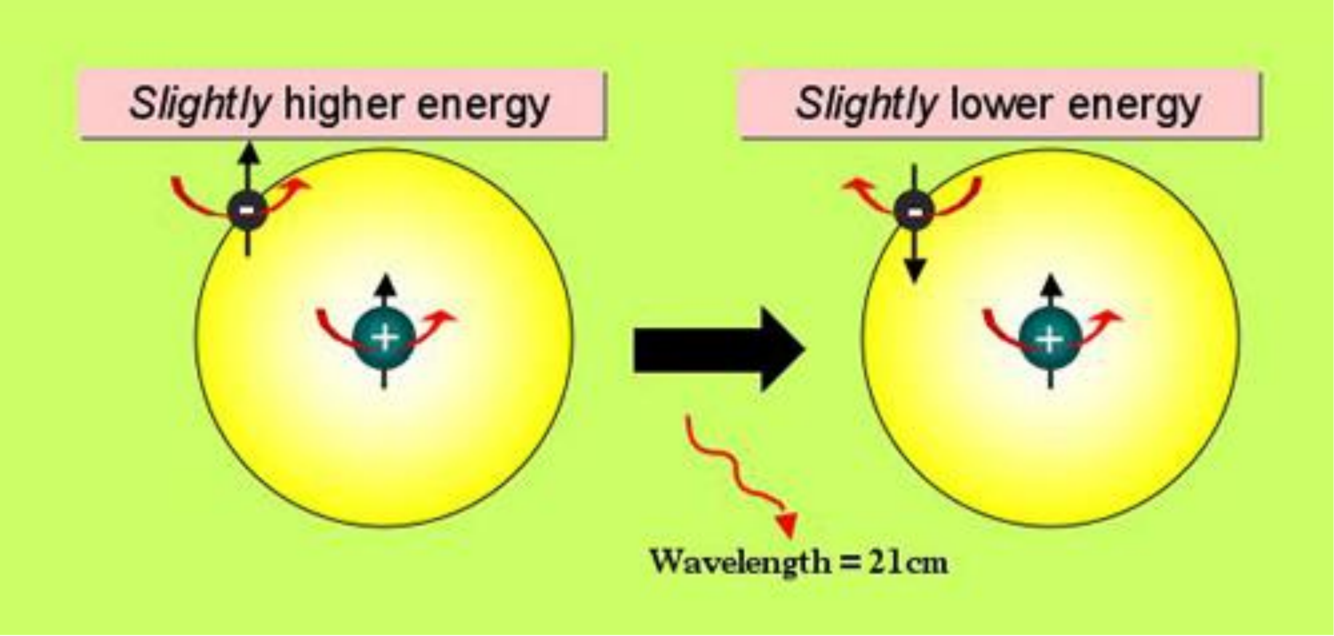


Why is lensing a good cosmological probe ?

- 2 in one : measure both geometry (lensing weight function) and growth structure (Weyl / Gravitational Potential)
- Sensitive to modified gravity (MG) : (Weyl Potential)
- Deflection angle is small > Flat sky approximation > 2D > very powerful when considering joint statistic with other tracers
- 3D weak lensing > growth index > constraint M
- Muti-wavelength phenomena

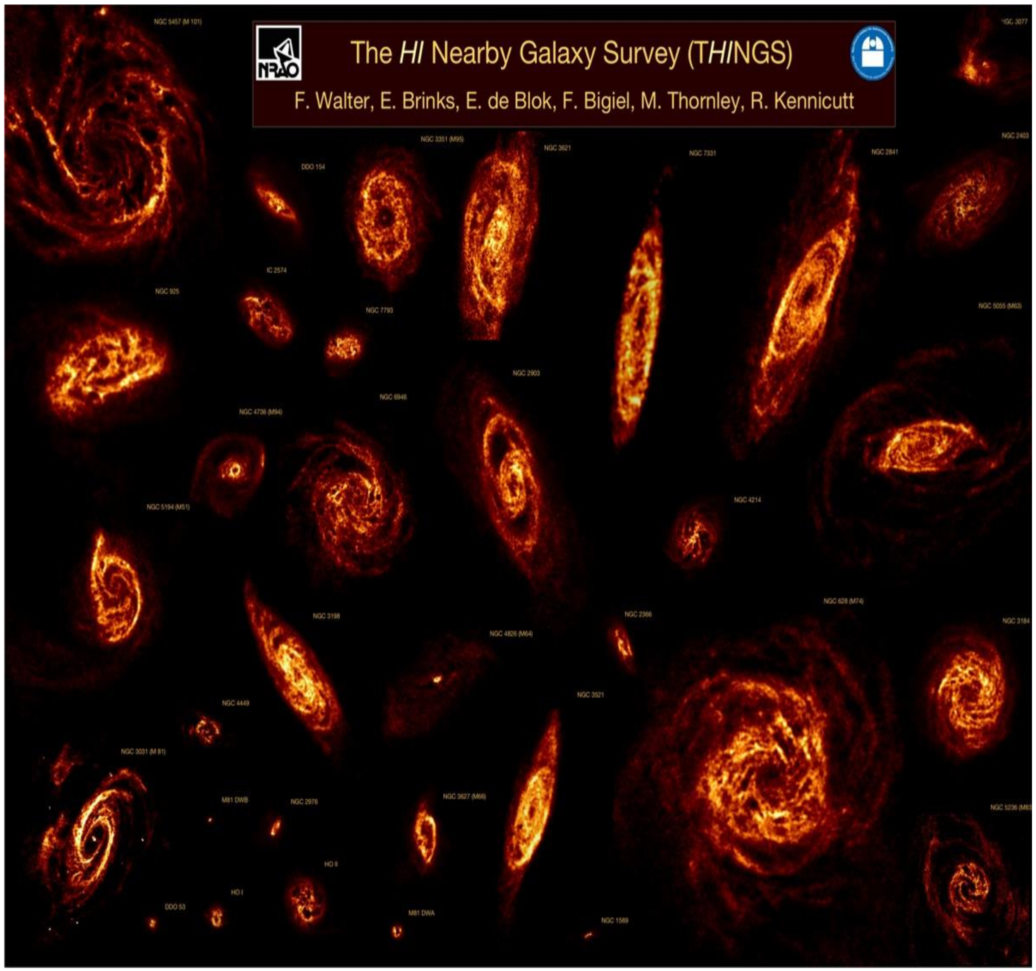
21 CM Cosmology

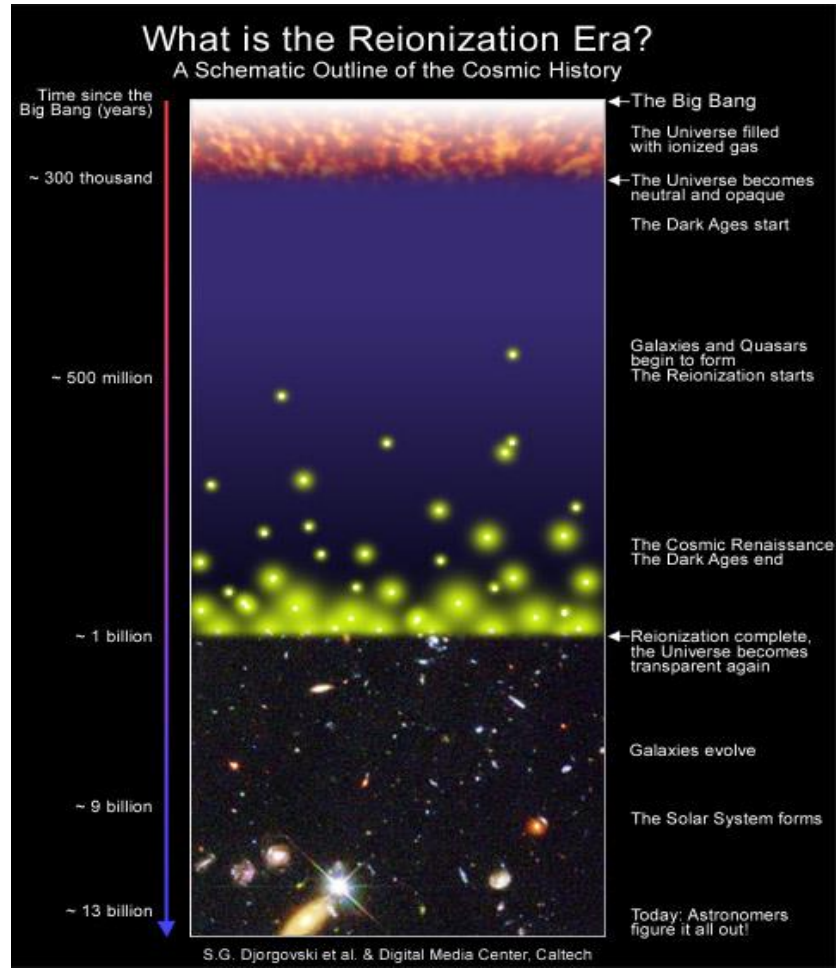
The most abundant element inter galactic medium!!



$$\nu_{10} = \frac{8}{3} g_{\mathrm{I}} \left(\frac{m_{\mathrm{e}}}{m_{\mathrm{p}}}\right) \alpha^2 (R_{\mathrm{M}} c) \approx 1420.405751 \text{ MHz} => \lambda \approx 21 \text{ cm}$$

HI sources


The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt


What is the Reionization Era?
A Schematic Outline of the Cosmic History
Time since the Big Bang (years)
~ 300 thousand
~ 500 million
~ 1 billion
~ 9 billion
~ 13 billion
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
The Cosmic Renaissance
The Dark Ages end
Reionization complete, the Universe becomes transparent again
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
S.G. Djorgovski et al. & Digital Media Center, Caltech

Intensity Map

Lower Resolution but deeper

$$\Delta T_{\rm HI}(z,\hat{n}) = \bar{T}_{\rm HI}(z) b_{\rm HI}(z) \delta(z,\hat{n})$$

$$\bar{T}_{\rm HI}(z) = 180\Omega_{\rm HI}(z) h \frac{(1+z)^2}{H(z)/H_0} [{\rm mK}]$$

Battye et al. (2013)

$$\Omega_{\rm HI}(z) = 0.00048 + 0.00039z - 000065z^2$$

SKA cosmology SWG et. al 2018

2-point functions

- Cosmological Principle = Isotropic + Homogenous
- Imply, any process is randomly in all directions and everywhere
- Central limit theorem > Gaussian process
- 2 point functions contain all statistical properties of Gaussian random fields.

2-point functions (con)

In 2D projection on the spherical surface, 2-point functions can easily measure by the amplitude square of spherical harmonics modes, in which we call “angular power spectrum”

$$f(\theta,\phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta,\phi)$$

Angular power spectra

$$C_\ell^{XY} = < a^X_{\ell m} a^{Y*}_{\ell m} >_m$$

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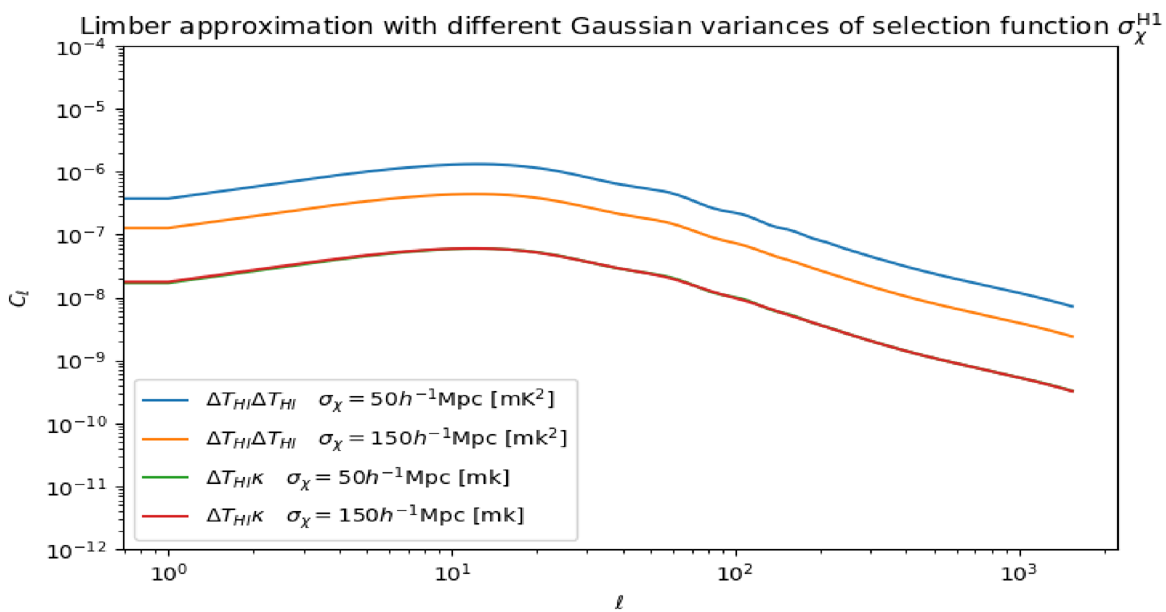
Limber Approximation

- Most of lensing power spectra (and its cross correlations) can be approximated by Limber approximation as if expect small deflection angle => flat sky approximation => Limber approximation

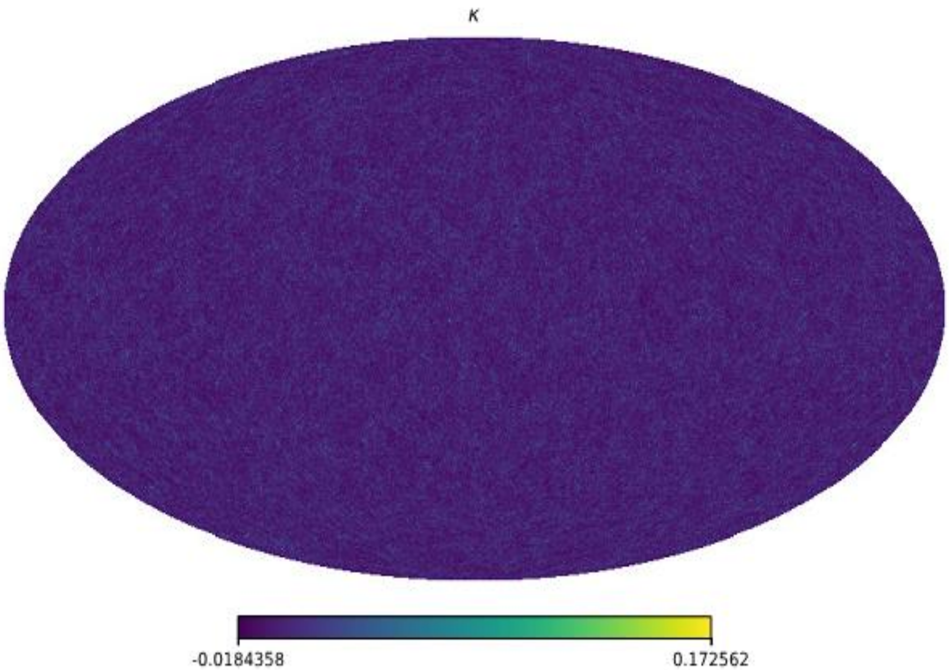
$$C_\ell^{XY} = \int d\chi \, q^X(\chi) q^Y(\chi) P_\delta\left(\frac{\ell + 1/2}{\chi}, z(\chi)\right)$$

$$q^{\rm HI}(\chi) = \bar{T}_{\rm HI}(\chi) b_{\rm HI}(\chi) \frac{n^i_{\rm HI}(z(\chi))}{\bar{n}^i_{\rm HI}} \frac{dz}{d\chi}, \quad q^\kappa(\chi) = \frac{3\Omega_m H_0^2}{2c^2} \frac{\chi}{a(\chi)} \int_\chi^\infty d\chi' \frac{n^i_s(z(\chi')) \frac{dz}{d\chi'}}{\bar{n}^i_s} \frac{\chi' - \chi}{\chi'}$$

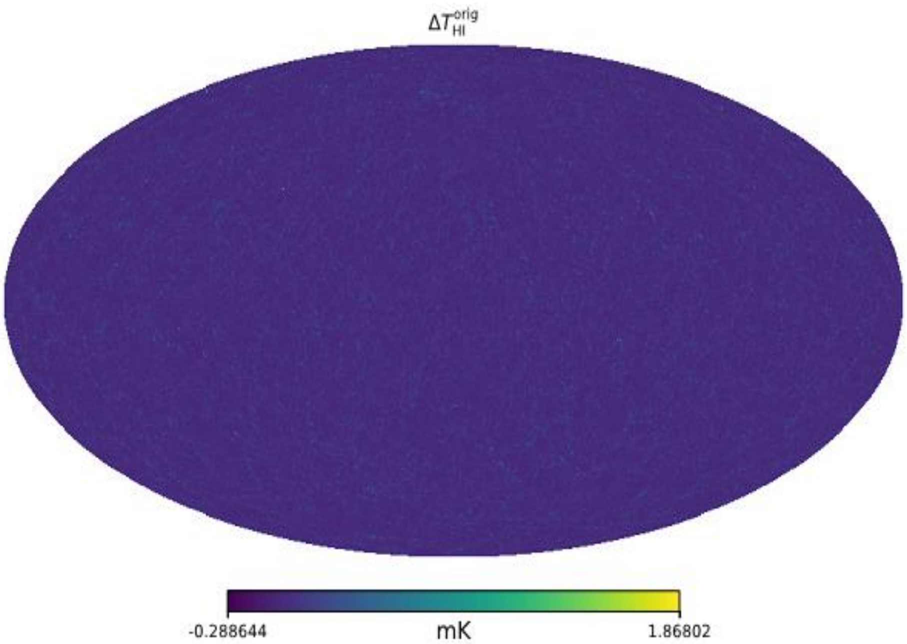


Result from Mock Catalogues

$\kappa(z = 0.78)$



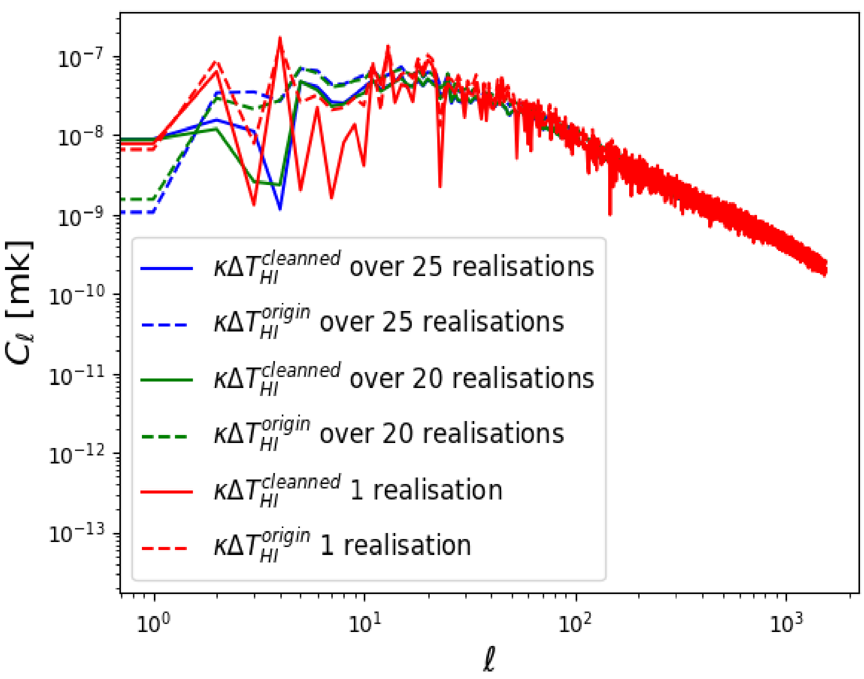
$\Delta T_{\mathrm{HI}}(z = 0.3)$

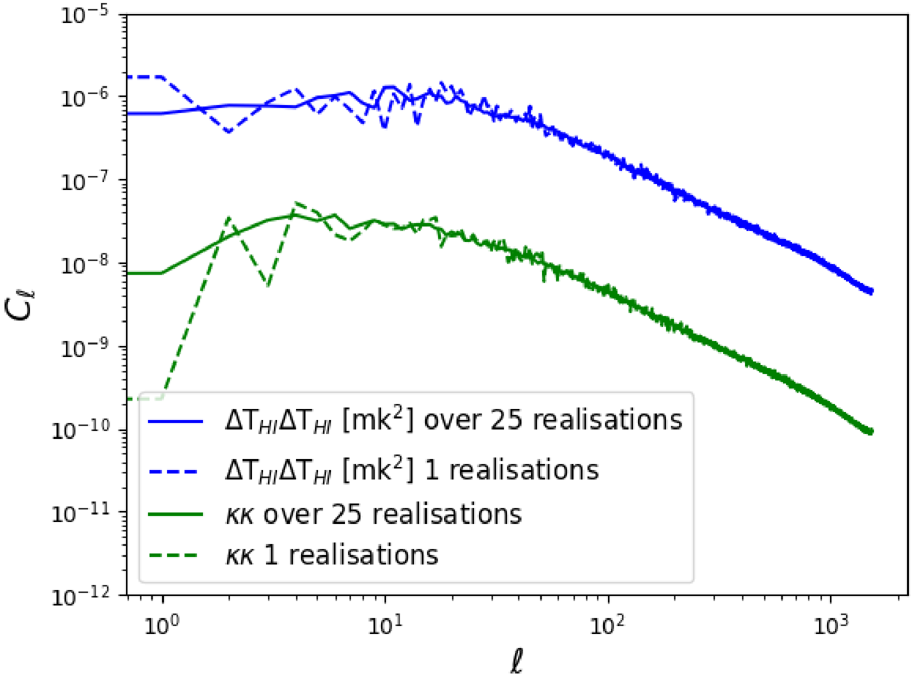


108 realisations of full sky ray tracing code: 0.05 < z < 5.3 + CMB lensing

Takashi et. al 2017
http://cosmo.phys.hirosaki-u.ac.jp/takahasi/allsky_raytracing/

Result from Mock Catalogues (con)





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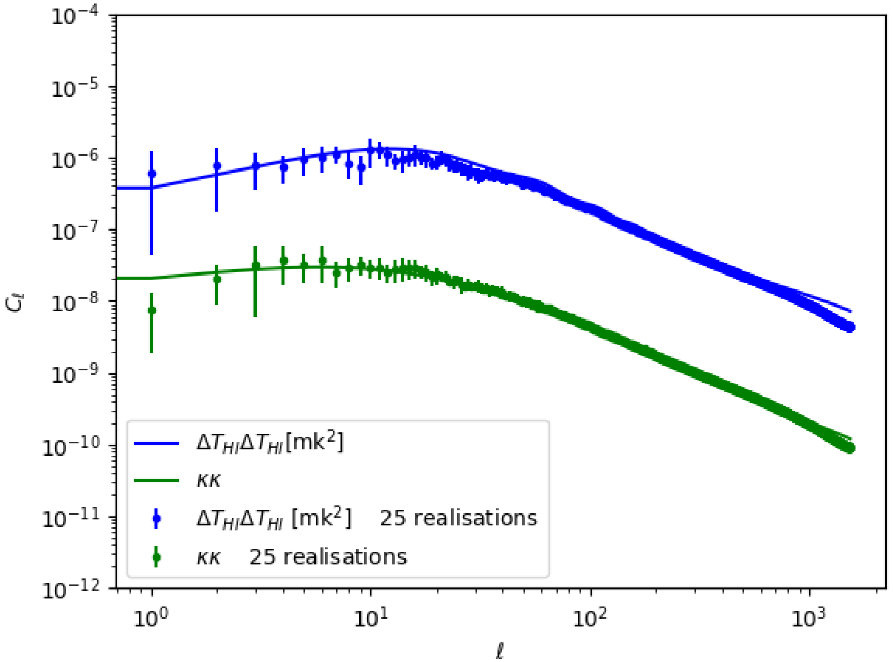
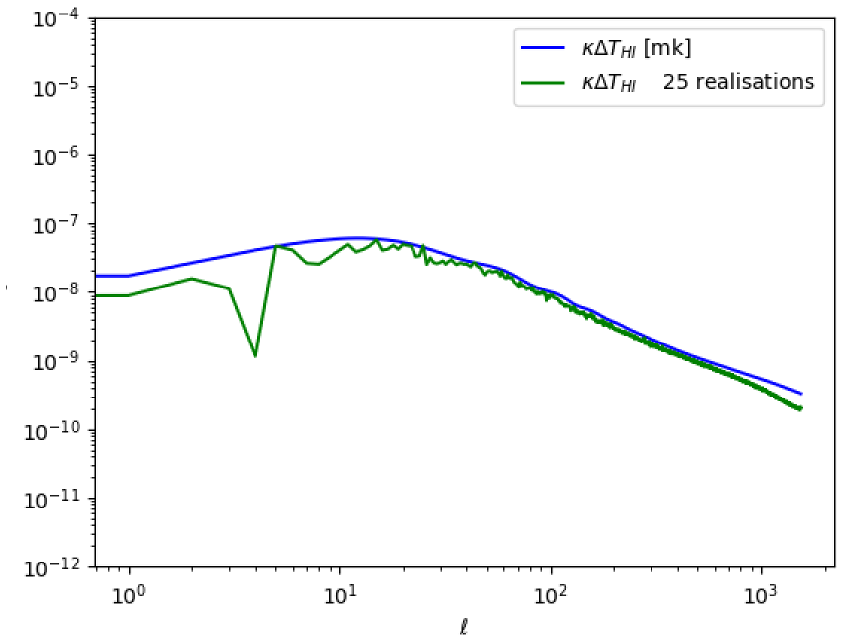
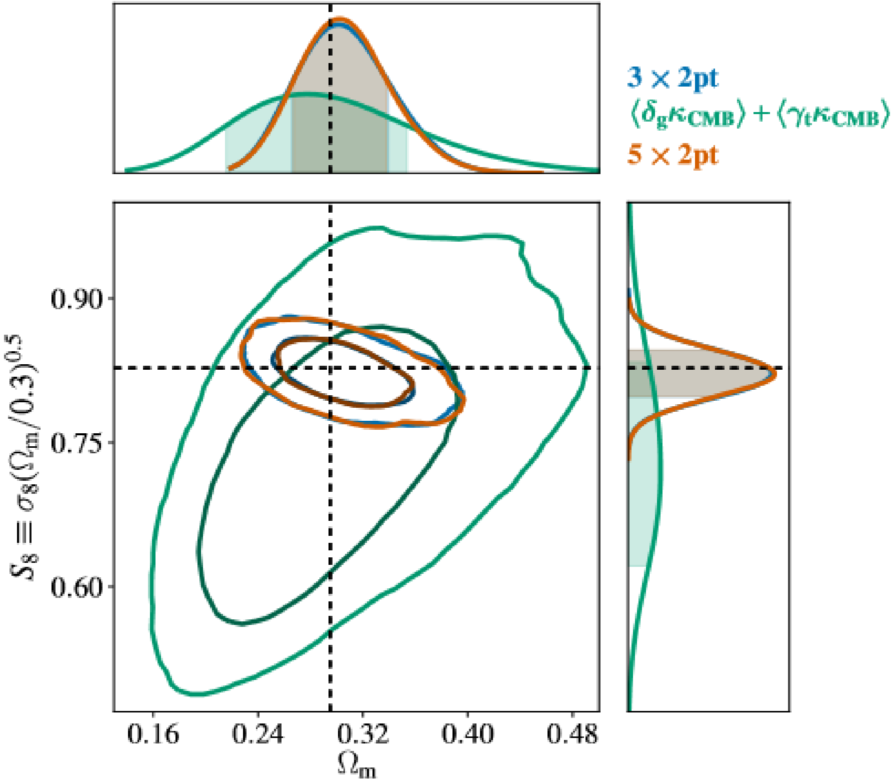




What we would expect (or what will we do) ?



DES Year I : joint analysis of 2-points function : cosmological constrain

- Include, EOR + CMB lensing
- Make fisher forcast