Cross-Correlation of CFHTLenS Galaxy Catalogue and Planck CMB Lensing

A 5-month internship under the direction of Simon Prunet

Adrien Kuntz

Ecole Normale Supérieure, Paris

July 08, 2015

Outline

The Initial Motivation

Cross-Correlation of CFHTLenS Galaxy Number Density and Planck CMB Lensing

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12 February 2015

ABSTRACT
We measure the cross-power spectrum between galaxy density from Canada-France-Hawaii-Telescope Lensing Survey (CFHTLenS) catalogues and gravitational lensing convergence from Planck data release 1 (2013) and 2 (2015). We investigate three main galaxy samples: $18.0 < i_{AB} < 22.0$, $18.0 < i_{AB} < 23.0$, $18.0 < i_{AB} < 24.0$ in the redshift range $0.2 < z < 1.3$ in each of the four CFHTLenS wide fields. By comparing the measured cross-spectrum with model predictions, linear galaxy-dark matter biases of $b = 0.82^{+0.24}_{-0.23}, 0.83^{+0.19}_{-0.18}, 0.82^{+0.16}_{-0.14}$ are inferred at significances of $3.5, 4.5, 5.6\sigma$ using the Planck 2015 release. These measurements are marginally consistent with biases derived from galaxy-galaxy auto-correlations: $b = 1.15^{+0.02}_{-0.01}, 1.08^{+0.01}_{-0.01}$ and $0.96^{+0.01}_{-0.01}$ respectively. Using the 2013 Planck release, we obtain biases of $b = 1.33^{+0.29}_{-0.28}, 1.19^{+0.23}_{-0.23}, 1.16^{+0.19}_{-0.18}$, showing significant differences between the releases.

Aims of my Internship

- Achieve a good comprehension of the cosmological perturbation theory and of the halo model *(1 month1/2)*
- Implement a python program to compute covariances from the halo model *(1 month 1/2)*
- Retrieve data from both the CFHTLenS and the Planck collaboration, format them in a sky map, and perform simulations *(1 month)*
- Use a bayesian analysis to fit galaxy bias from the correlation of the two maps *(1 week)*
- Write an insternship report and a presentation*(2 weeks)*

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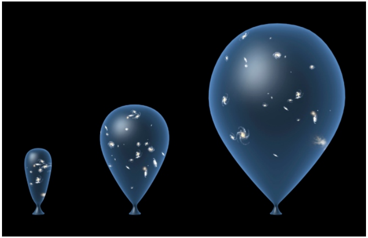
Friedmann-Lemaître Model



- $ds^2 = c^2 dt^2 - a^2(t)\, d\boldsymbol{x}^2$
- Physical coordinates : $\boldsymbol{r} = a(t)\, \boldsymbol{x}$
- Friedmann equations :
$$\begin{cases} \frac{\dot{a}^2 + kc^2}{a^2} = \frac{8\pi G\rho + \Lambda c^2}{3} \\ \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3} \end{cases}$$
- Solution : $p = w\rho c^2 \Rightarrow \rho \propto a^{-3(1+w)}$

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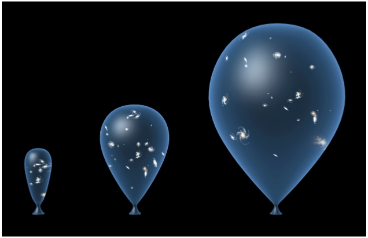

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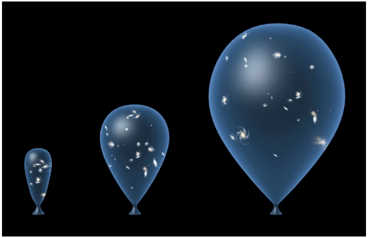

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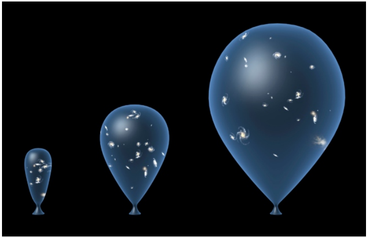

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Perturbation Theory

- $\rho(\boldsymbol{x}, t) \equiv \bar{\rho}(t)(1 + \delta(\boldsymbol{x}, t))$
- Linear solution : $\delta(\boldsymbol{x}, t) = D_1^+(t) A(\boldsymbol{x})$
- Non-linear solution : $\tilde{\delta}(\boldsymbol{k}, t) = \sum_{n=1}^{+\infty} a^n(t) \delta_n(\boldsymbol{k})$

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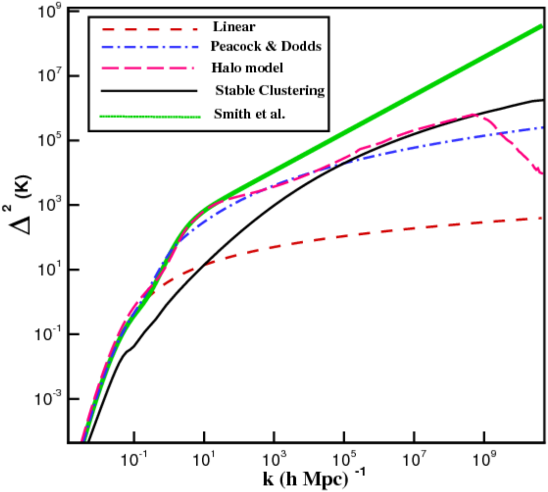
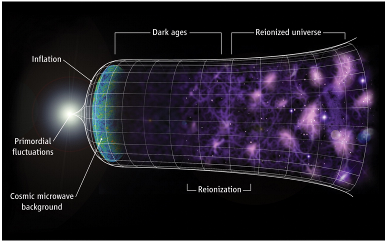
Linear and Non-Linear Scales



Credit : Baghram et al (2011)

Correlation Function and Power Spectrum



- Primordial quantum fluctuations and inflation $\Rightarrow$ Gaussian initial conditions
- Gravitational instability
- $\xi(r) = \langle \delta(\mathbf{x}) \delta(\mathbf{x} + \mathbf{r}) \rangle$
- $\langle \delta(\mathbf{k}) \delta(\mathbf{k'}) \rangle = (2\pi)^3 \delta_D(\mathbf{k} + \mathbf{k'}) P(k)$
- and higher order : B, T...

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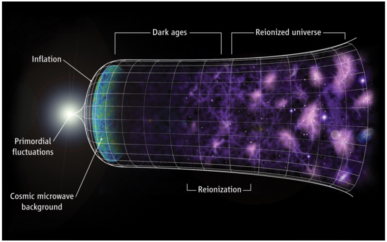

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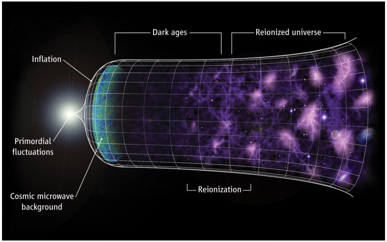

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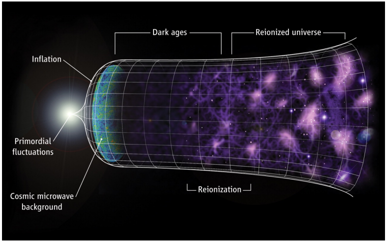

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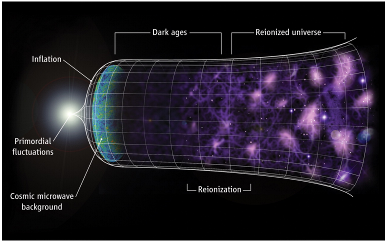

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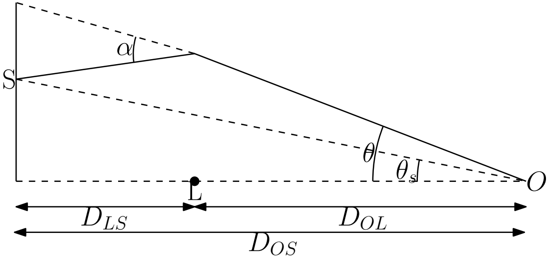
Lens Equation



- α given in General Relativity
- Lens equation :

  $\theta = f\left(\theta_s\right)$

Illustration

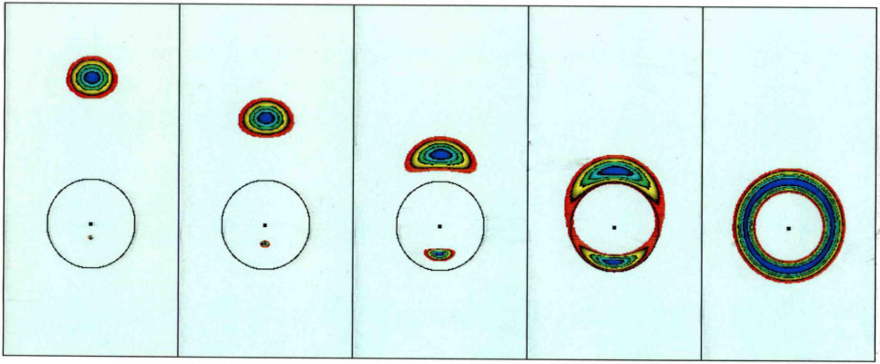
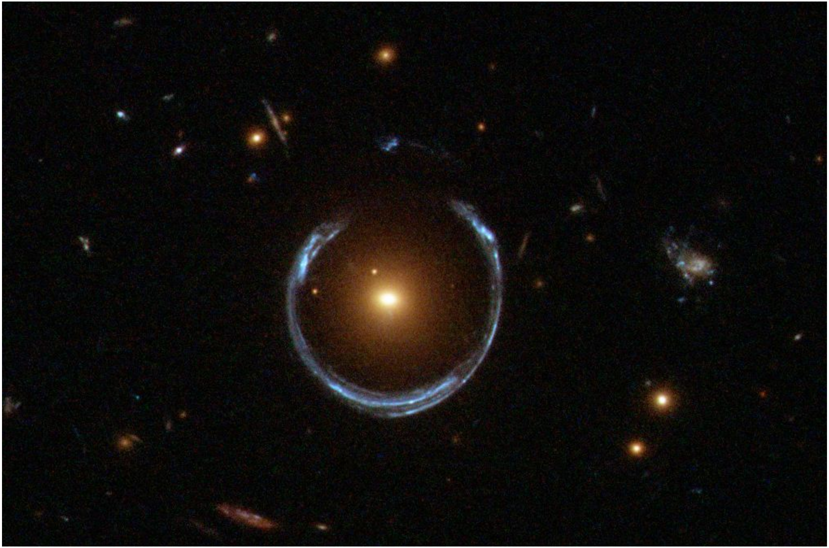


Figure: Distortion of an extended source by a point-like lens

Illustration



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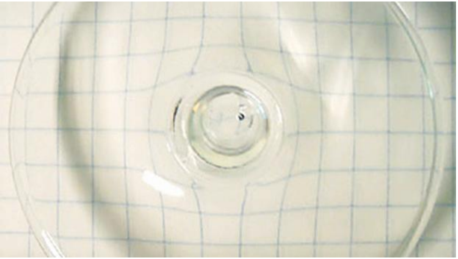
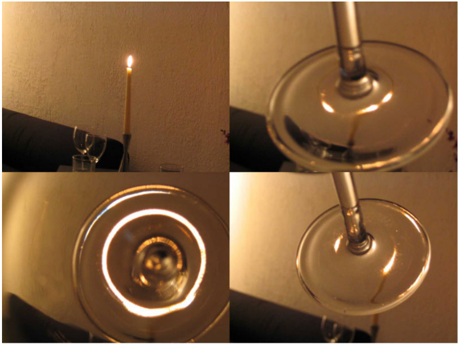
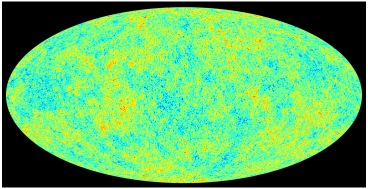




Effect on the CMB



- Deformation of the photon paths
- $\kappa(\boldsymbol{\theta}) = \int_0^{\chi_{CMB}} W^{\kappa}(\chi)\,\delta(\chi\boldsymbol{\theta}, \chi)\, d\chi$

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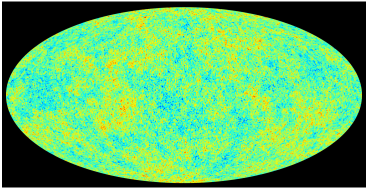

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Galaxy Overdensity

- $\delta^{gal}(\chi\boldsymbol{\theta},\chi) = b(\chi)\,\delta(\chi\boldsymbol{\theta},\chi)$
- $g(\boldsymbol{\theta}) = \int_0^{\chi_{CMB}} W^g(\chi)\,\delta(\chi\boldsymbol{\theta},\chi)\,d\chi$
- $W^g(\chi) \propto b(\chi)$

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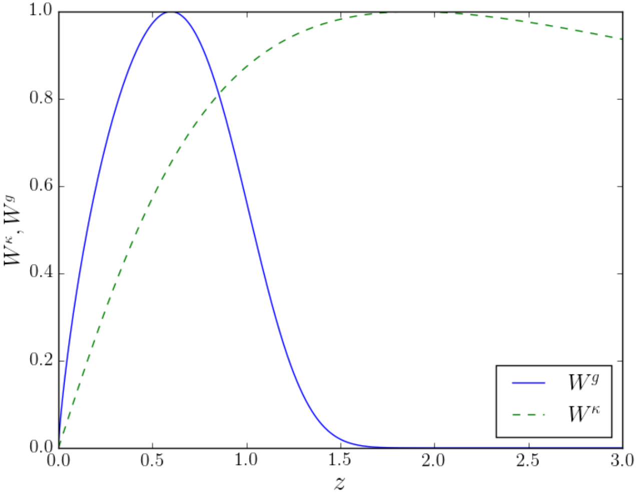
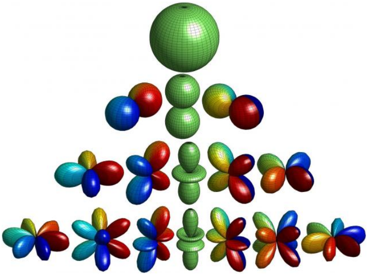
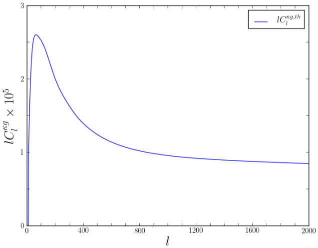
Lensing kernels



Outline

Spherical Harmonics and Correlation





- $\kappa(\boldsymbol{\theta}) \equiv \sum_{lm} \kappa_{lm} Y_l^m(\boldsymbol{\theta})$ and $g(\boldsymbol{\theta}) \equiv \sum_{lm} g_{lm} Y_l^m(\boldsymbol{\theta})$
- $\left\langle \kappa_{lm} g^*_{l'm'} \right\rangle = \delta_{ll'} \delta_{mm'} C_l^{\kappa g}$
- $C_l^{\kappa g} = \int d\chi \frac{W^\kappa(\chi) W^g(\chi)}{\chi^2} P\left(k = \frac{l}{\chi}, z(\chi)\right)$

Covariance

- Covariance : $\Sigma_{ij}^{\kappa g} = \left\langle \tilde{C}_{l_i}^{\kappa g} \tilde{C}_{l_j}^{\kappa g} \right\rangle - \left\langle \tilde{C}_{l_i}^{\kappa g} \right\rangle \left\langle \tilde{C}_{l_j}^{\kappa g} \right\rangle$
- $\Sigma_{ij}^{\kappa g} = \text{Gaussian Term} + \text{Non-Gaussian Term}$
- Non-Gaussian term involves $T = \langle \delta(\mathbf{k}_1) \delta(\mathbf{k}_2) \delta(\mathbf{k}_3) \delta(\mathbf{k}_4) \rangle$

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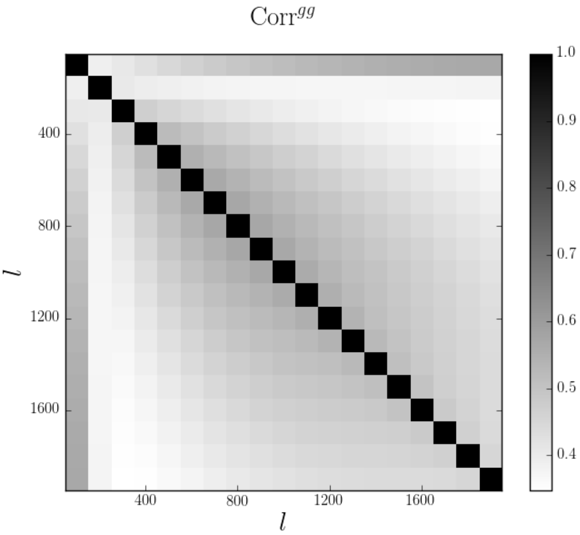
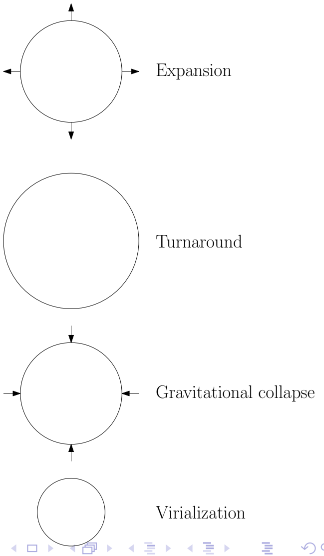
Correlation Matrix



Outline

Spherical Collapse

- $\delta_{sc} = 1.69$
- $\rho_{halo} = \Delta_{sc}\, \rho_{background}$, $\Delta_{sc} \simeq 340$



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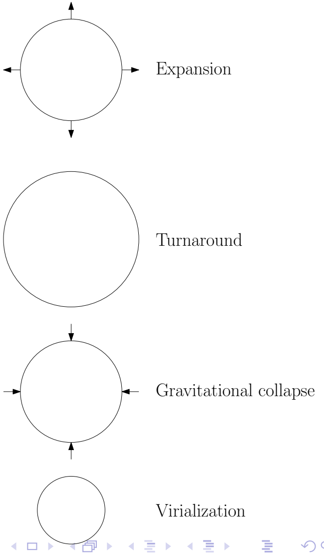

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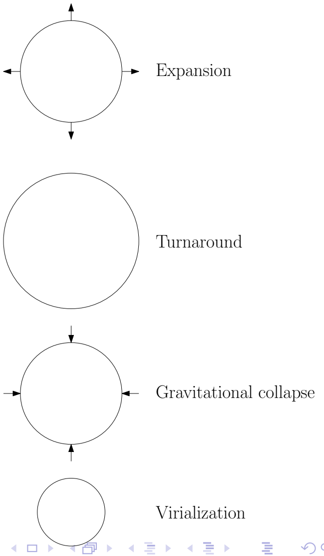
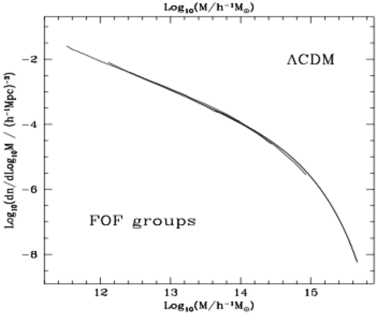
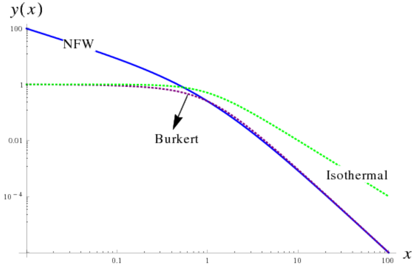


Ingredients



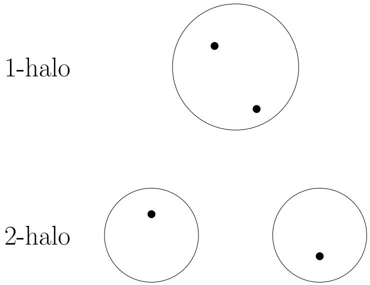


$n\,(m, z)$ Press & Schechter (1974)

$\rho\,(r; m)$ NFW profile (1997)

$\delta_h\,(\boldsymbol{x}, z; m) = \sum_{k>0} b_k\,(m, z)\,\delta\,(\boldsymbol{x})^k\,/k!$ Mo & White (1995)

Correlation Function

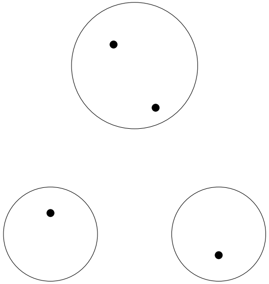


- $\rho_{tot}(\boldsymbol{x}) = \sum_i \rho(\boldsymbol{x} - \boldsymbol{x_i}, m_i)$
- $\xi(r) = \left\langle \frac{\rho(\boldsymbol{x})\rho(\boldsymbol{x}+\boldsymbol{r})}{\bar{\rho}^2} \right\rangle - 1$
- $\langle \rho(\boldsymbol{x}) \rho(\boldsymbol{x}+\boldsymbol{r}) \rangle =$ 1-halo term + 2-halo term

Correlation Function

1-halo

2-halo



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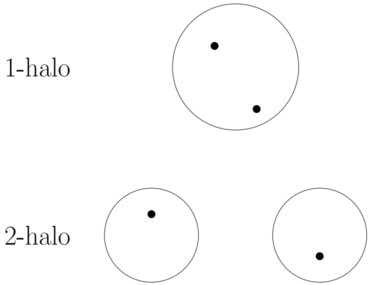
Correlation Function



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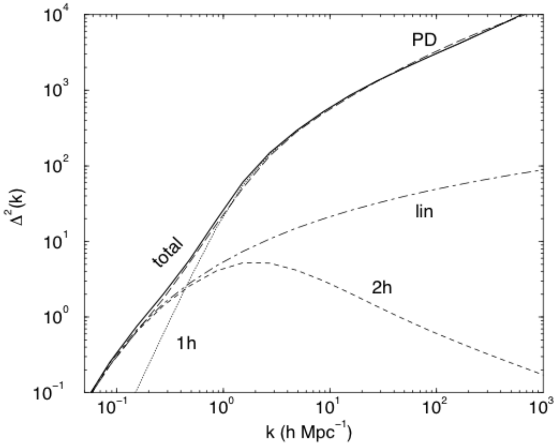
Power Spectrum



Credit :

Cooray &

Sheth (2002)

Trispectrum

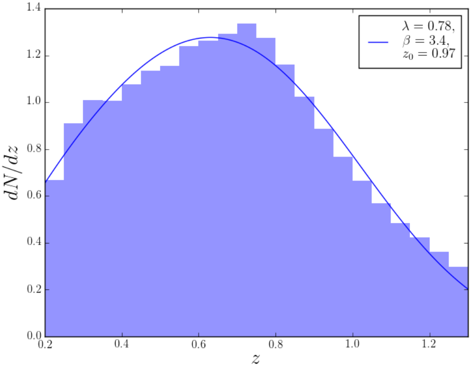
$$T_{hhhh}(\boldsymbol{k}_1, -\boldsymbol{k}_1, \boldsymbol{k}_2, -\boldsymbol{k}_2) = T^{1h} + T^{2h} + T^{3h} + T^{4h}$$

Outline

The CFHTLenS Catalogue

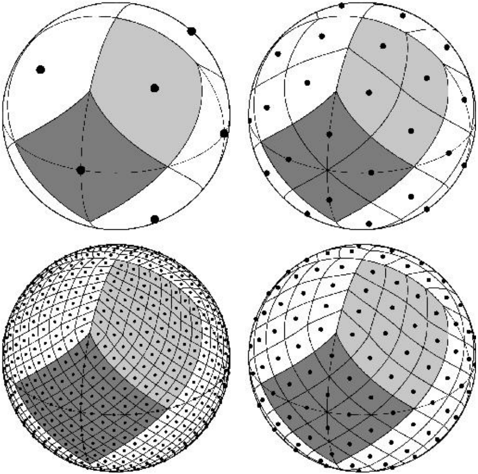
- Analysis of the CFHT Legacy Survey specialized in the production of a galaxy catalogue for lensing measurement
- CFHTLS : 171 MegaCam pointings 2003-2008, more than 2300 hours
- 4 patches, 154 deg^2
- Galaxy catalogue and accurate photometric redshifts : $\sigma \sim 0.04\,(1+z)$
- $0.2 < z < 1.3$ and $18 < i_{AB} < 24$

Redshift Distribution



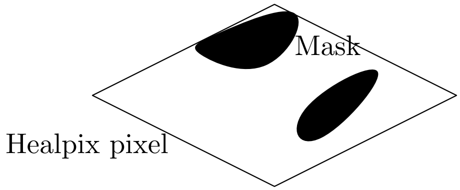
$$\frac{dN}{dz} = \frac{\alpha}{z_0}\left(\frac{z}{z_0}\right)^{\lambda} \exp\left(-\left(\frac{z}{z_0}\right)^{\beta}\right)$$

Healpix



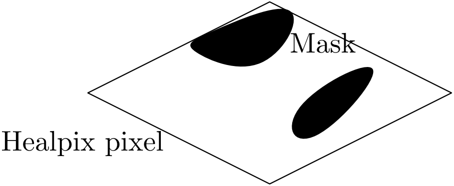
- JPL / NASA
- Pixels of equal area
- Iso-latitude
- Interface in Python
- 1 pixel = 1.7 arcmin

Mask



- Weight : $w_i = \frac{S_{unmasked}}{S_{tot}}$
- Galaxy overdensity : $\delta_i = \frac{N_i/w_i - \langle N \rangle}{\langle N \rangle}$
- $\bar{n} = 15.1$ gal / arcmin^2

Mask



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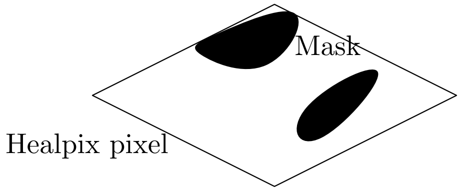

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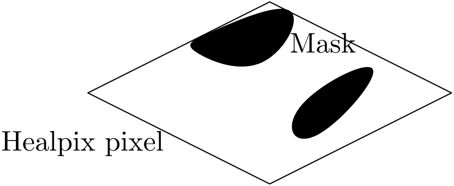

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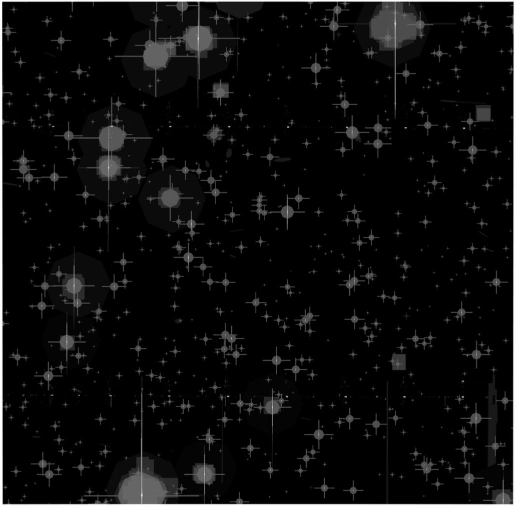
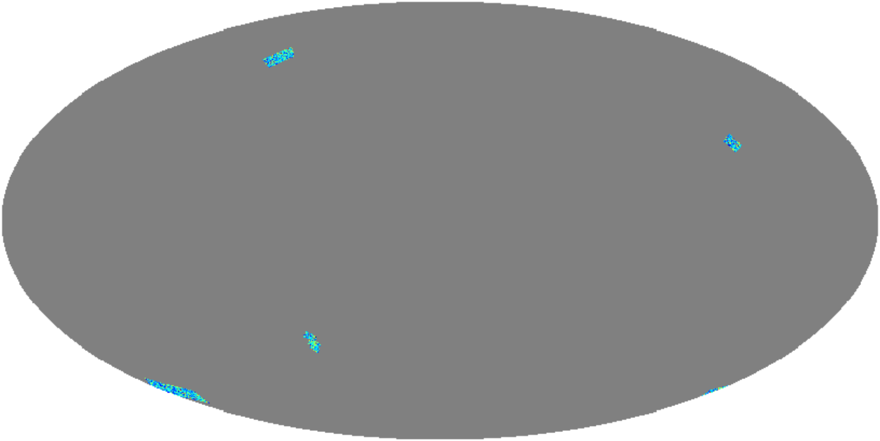


Galaxy Map



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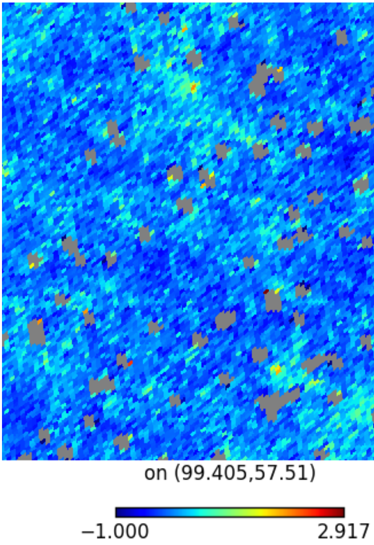
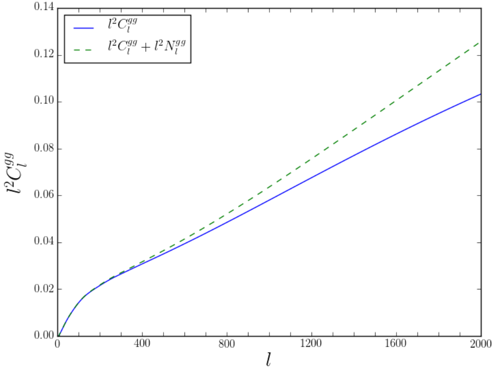


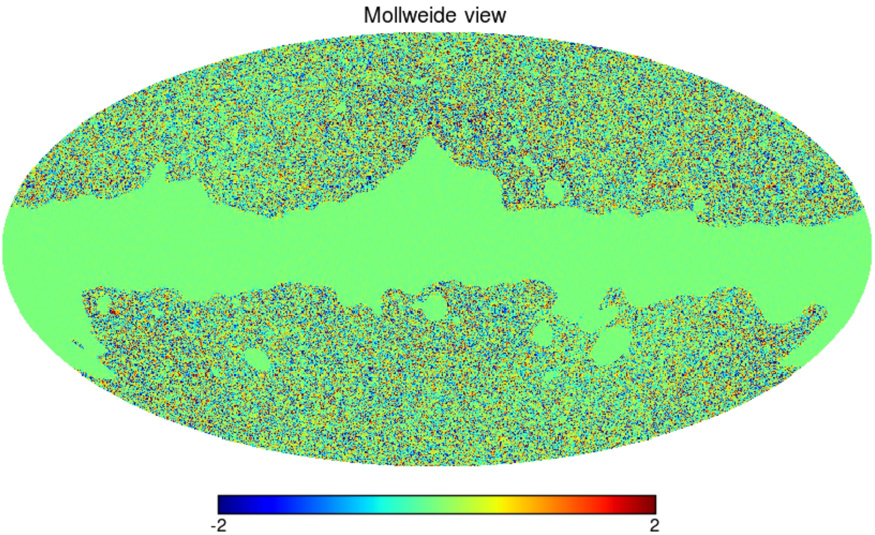
Noise



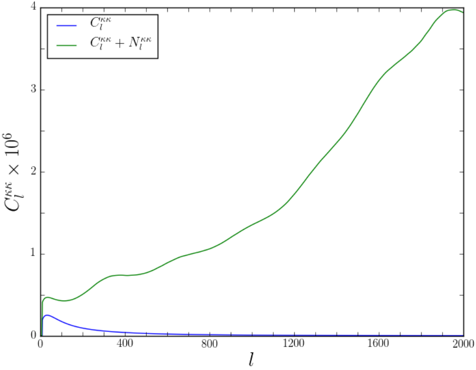
- Poisson process : shot noise
- $C_l^{gg} \to C_l^{gg} + N_l^{gg}$, $N_l^{gg} = 1/\bar{n}$ ($\bar{n}$ in galaxies / steradian !)
- Small effect

Outline

Convergence Map



Noise



- Obtained from the Planck simulations
- Dominant over $C_l^{\kappa\kappa}$!

A Consequence of the High Level of Noise

$$\Sigma_{ij}^{\kappa g} = \frac{1}{4\pi f_{sky}} \left[\frac{(2\pi)^2}{\Omega_i} \delta_{ij}^K \left(\left(C_{l_i}^{\kappa\kappa} + N_{l_i}^{\kappa\kappa} \right) \left(C_{l_j}^{gg} + N_{l_i}^{gg} \right) + \left(C_{l_i}^{\kappa g} \right)^2 \right) + \bar{T}_{ij}^{\kappa g} \right]$$

Outline

Bayes Theorem

- $\begin{cases} \tilde{C}_l^{\kappa g} = A \times b \times C_l^{\kappa g} \\ \tilde{C}_l^{gg} = b^2 \times C_l^{gg} \end{cases}$

- $P\left(A, b \mid \mathbf{C}\right) = \frac{P(A,b)P(\mathbf{C}|A,b)}{P(\mathbf{C})}$

$$P\left(\mathbf{C} \mid A, b\right) = \mathcal{N} \exp\left\{-\frac{1}{2}\left(\tilde{\mathbf{C}} - \mathbf{C}\left(A, b\right)\right) \Sigma^{-1} \left(\tilde{\mathbf{C}} - \mathbf{C}\left(A, b\right)\right)\right\}$$

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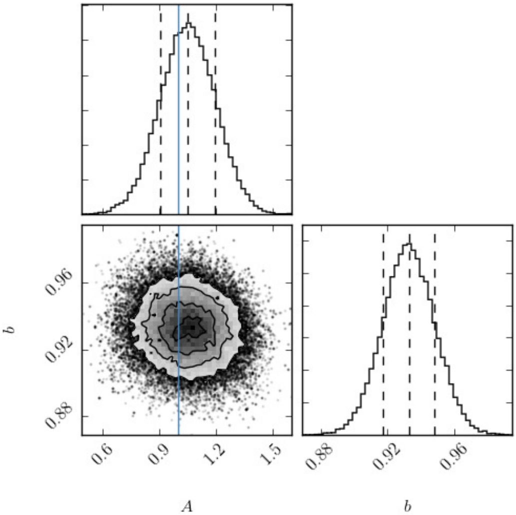
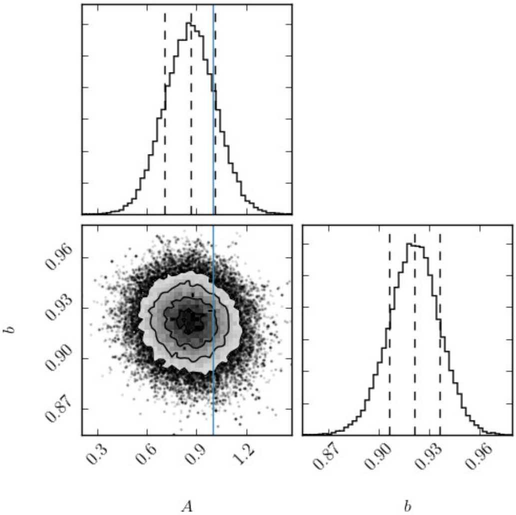
MCMC 2013



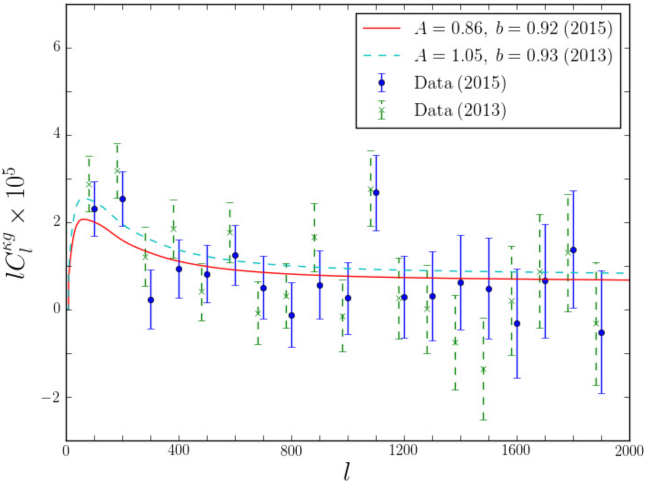
MCMC 2015



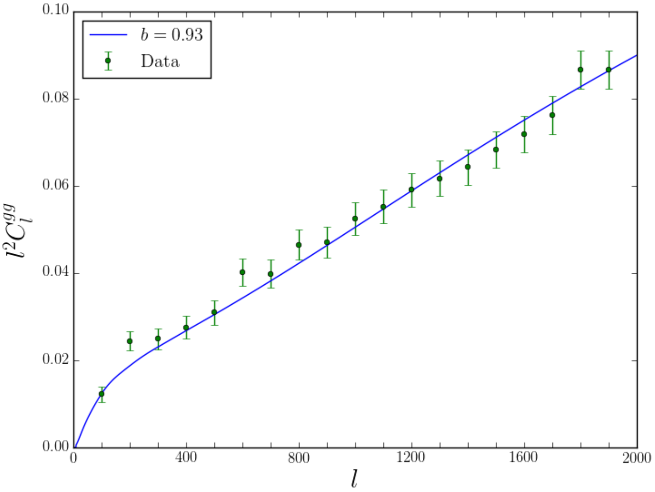
Best-Fit Values

Patch	2013			2015		
	A	b	χ^2/ν	A	b	χ^2/ν
All	$1.05^{+0.15}_{-0.15}$	$0.93^{+0.02}_{-0.02}$	$47.2/36$	$0.86^{+0.15}_{-0.16}$	$0.92^{+0.02}_{-0.02}$	$37.4/36$

$C_l^{\kappa g}$

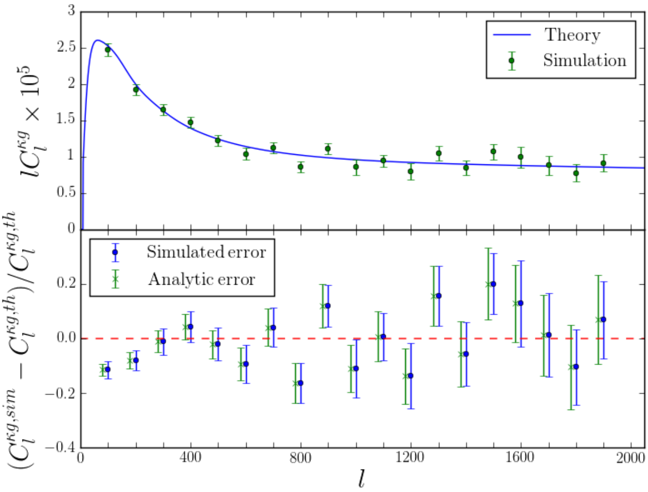

$A = 0.86,\ b = 0.92$ (2015)
$A = 1.05,\ b = 0.93$ (2013)
Data (2015)
Data (2013)
$lC_l^{\kappa g} \times 10^5$
l
6
4
2
0
−2
0
400
800
1200
1600
2000

C_l^{gg}

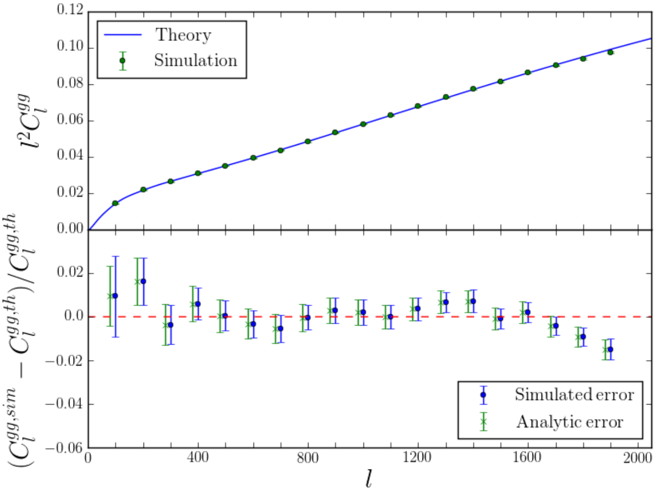

$b = 0.93$
Data
0.10
0.08
0.06
0.04
0.02
0.00
$l^2 C_l^{gg}$
0
400
800
1200
1600
2000
l

Outline

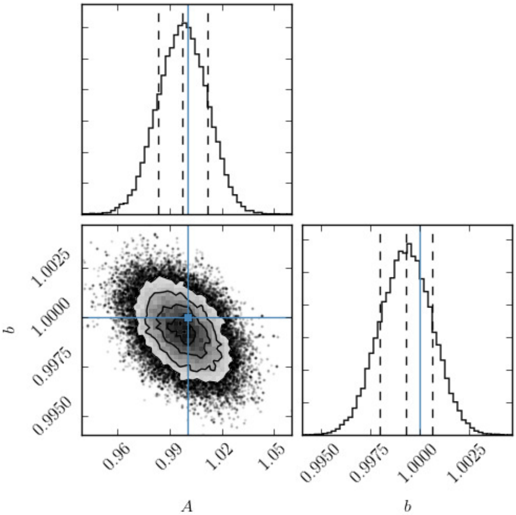
$C_l^{\kappa g}$, simu



C_l^{gg}, simu


Theory
Simulation
Simulated error
Analytic error
$l^2 C_l^{gg}$
$(C_l^{gg,sim} - C_l^{gg,th})/C_l^{gg,th}$
l
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.0
−0.02
−0.04
−0.06
0
400
800
1200
1600
2000

Recovered A and b



Outline

Summary

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- Implemented a Python program to compute the trispectrum in the halo model
- Created a galaxy and convergence map
- Used a Bayesian analysis to fit a galaxy bias
- Performed consistency checks

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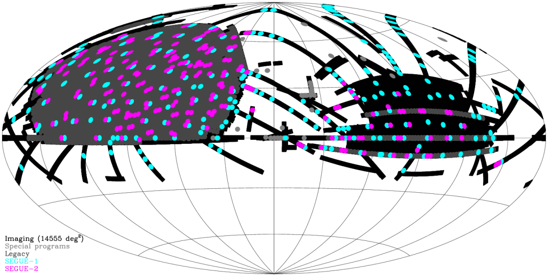
Conclusions

- $b = 0.92^{+0.02}_{-0.02}$: good tracers of matter
- $A^{2013} = 1.05^{+0.15}_{-0.15}$ and $A^{2015} = 0.86^{+0.15}_{-0.15}$: compatible but different
- Partly confirm Omori & Holder (2015)

Forthcoming Work



- SDSS data : much better coverage of the sky
- If still a difference : investigate !

Questions ? Comments ?

Thank You CFHT !