Searching for galaxy clusters through weak lensing

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Abstract

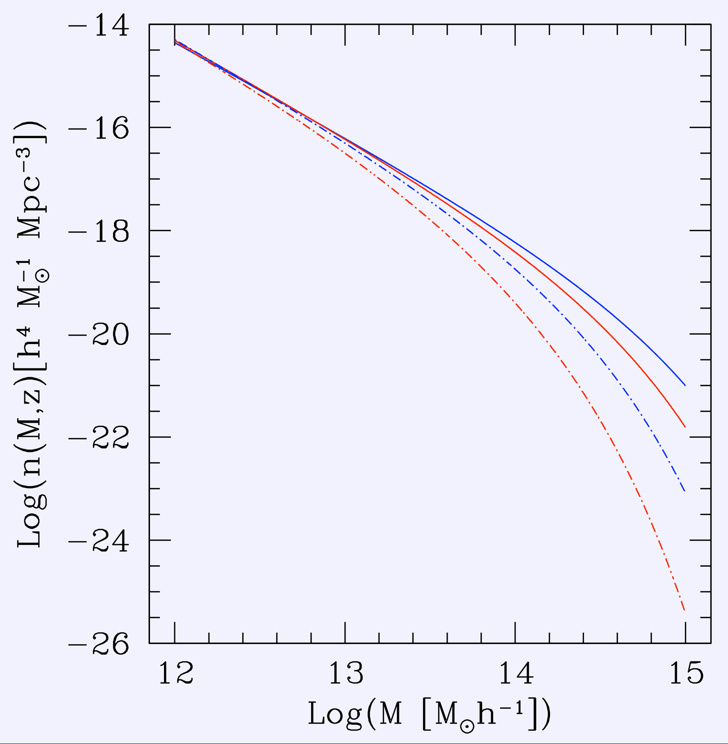
Weak gravitational lensing observations have proven to be extremely successful tools for mapping mass distributions and constraining cosmology. It is the only technique which directly probes mass avoiding any assumption about the physical conditions of the investigated matter. Distortions caused by gravitational lensing are quantified by the projected gravitational tidal field or shear. We constructed a linear filter optimised for detecting dark-matter halos in shear data which has the following advantages over the most used filters:

- Its shape is physically motivated.
- It is optimized for suppressing LSS contamination.
- It is stable in the sense that the results are almost independent of the parameters chosen for its definition.

We used raytracing high resolution hydrodynamical N-body simulations to investigate the performances of the filter and we compared the results with the most used techniques.

The framework

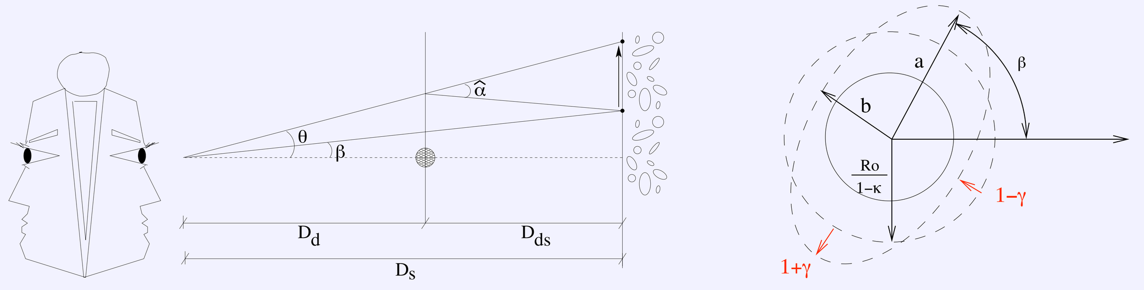
The cluster mass function and dark energy



The study of galaxy clusters provides a unique source of information for cosmology. Their abundance at different redshifts and their matter content allow us to place constraints on the cosmological model and dark energy.
Here we show the mass function of galaxy clusters at redshift $z = 0$ (solid lines) and at redshift $z = 1$ (dashed lines) in cosmology with cosmological constant (red) and with early dark energy (blue).
We studied the possibility of detecting dark matter haloes via weak lensing observations.

The weak lensing observables

Mass concentrations along the line-of-sight distort the images of background sources (in this work we consider far galaxies) via gravitational lensing. When these distortions are small, a linear approximation can be used and the lensing properties of the intervening matter are described by the convergence κ and the shear γ which quantify the isotropic magnification and distortion of the background source image, respectively. In the right figure we show the lensing effect acting on a circular source represented by the solid circle.
In searching for galaxy clusters via weak lensing, we have two main noise contributions, the intrinsic ellipticity of the sources and the contamination given by the LSS along the line-of-sight. Since the latter is not negligible for deep observations, it is necessary to design a filter capable of reducing this contamination.



Detection of galaxy clusters via weak lensing

An optimal matched filter

The measured data $D(\boldsymbol{\theta}) = A\tau(\boldsymbol{\theta}) + N(\boldsymbol{\theta})$ is composed of the signal from the lens $S = A\tau(\boldsymbol{\theta})$ and by the noise N, where A is the total amplitude of the tangential shear and $\tau(\boldsymbol{\theta})$ is its angular shape. In our case, the noise N comprises the contamination due to the LSS along the line-of-sight and to the intrinsic ellipticity dispersion and finite number of the background sources.
By using the linear estimator adopted for the aperture mass statistic (Schneider, 1996)

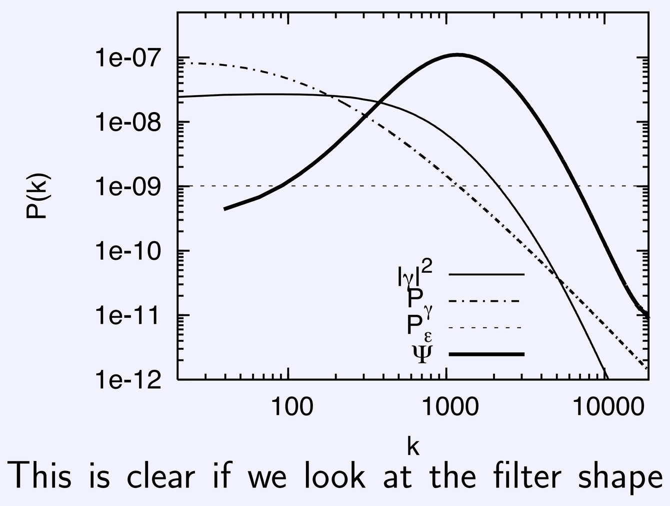
$$A_{\rm est}(\boldsymbol{\theta}) = \int d^2\theta' D(\boldsymbol{\theta}')\Psi(|\boldsymbol{\theta}' - \boldsymbol{\theta}|)\,,$$

we derived the optimal filter Ψ which returns an unbiased estimate of the tangential shear amplitude A, i. e. $b \equiv \langle A_{est} - A\rangle = 0$, and which minimizes the estimate variance $\sigma^2 \equiv \langle (A_{est} - A)^2\rangle$.
In Fourier space, the filter which satisfies both of these conditions is

$$\hat{\Psi}_{OPT}(\boldsymbol{k}) = \lambda \frac{\hat{\tau}(\boldsymbol{k})}{P_N(k)} \qquad \text{where} \qquad \lambda = \frac{1}{(2\pi)^2}\left[\int \frac{|\hat{\tau}(\boldsymbol{k})|^2}{P_N(k)} d^2k\right]^{-1},$$

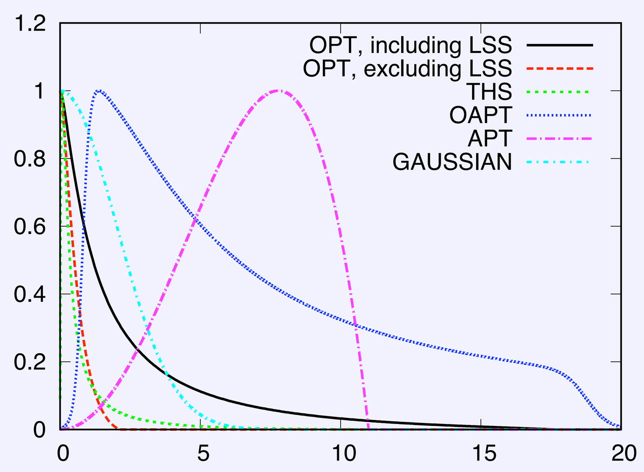
where the hats denote the Fourier transform. The last equation shows that the optimal filter Ψ depends on the model adopted for the shape of the signal, τ, and on the power spectrum of the noise, $P_N = P_\epsilon + P_\gamma$. Here it should be noticed that the suppression of the LSS contamination is due to the presence of the expected power-spectrum of the effective tangential shear P_γ, as given by the linear theory of the growth of structures (Maturi et al., 2005; Maturi et al., 2007).

Why does it suppress the LSS contamination?

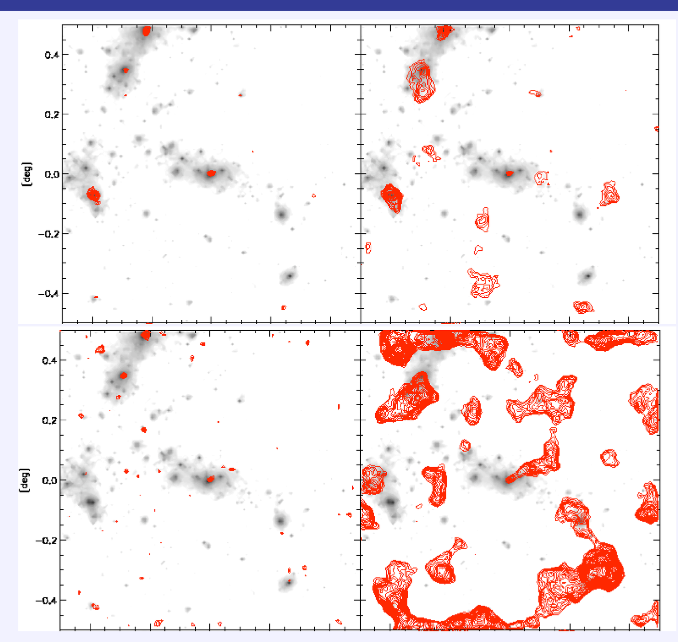


Here we compare the filter Ψ with the expected signal for a NFW halo of $10^{15} M_\odot h^{-1}$ at redshift $z = 0.3$ ($|\gamma|^2$) and the power spectra of the contaminations, such as the intrinsic noise of galaxies (P_ϵ) and the LSS tangential shear (P_γ). The filter minimizes signal contamination by suppressing the large scale modes (small frequencies) where the LSS contribution is larger.

This is clear if we look at the filter shape in the real space. Ignoring the contamination due to the LSS the optimal filter would mimic the expected signal profile (black line), but when the LSS are considered the filter shrinks (red dashed line). It is interesting to note how our filter compares to a Gaussian filter whose size was adjusted with an heuristic approach (THS, Hennawi & Spergel, 2005)
The most used filter profiles adopted in the standard aperture mass are also shown for comparison (APT and OAPT Schneider, 1996; Schirmer et al., 2004).



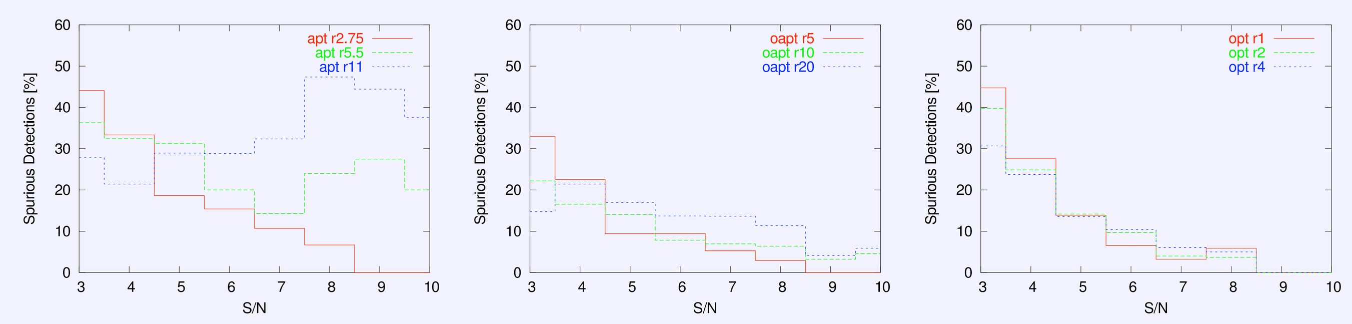
Example from a numerical simulation



In this figure we compare our filter (left panels) and the aperture mass defined by Schneider (1996) (right panels) for sources placed at redshift $z = 1$ (upper panels) and at $z = 2$ (bottom panels). It is clear how our optimal filter suppresses most of the LSS contamination and how its use is of interest especially for very deep observations where the amount of LSS matter along the line-of-sight is larger.

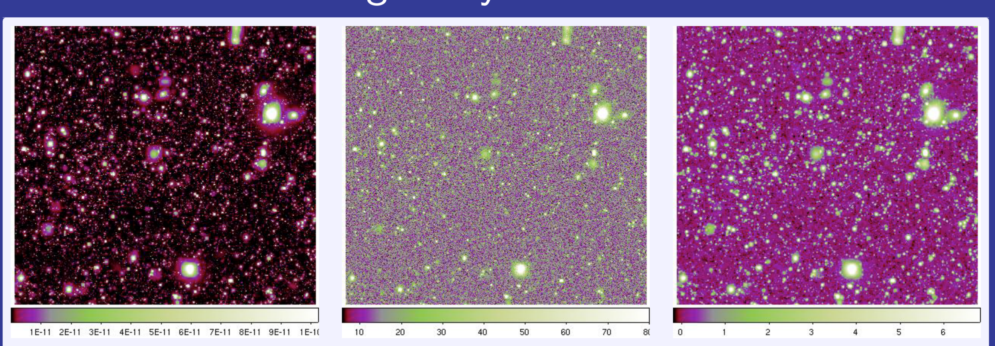
Bench marking different filters

We analyzed ray-tracing in the multiple lens-plane approximation through a large cosmological simulation to quantify the fraction of spurious detections caused by LSS obtained with different filters. In the figure below, we plot the results for the aperture mass defined by Schneider (1996) (left panel), for the aperture mass which mimics the expected shear of a NFW halo (Schirmer et al., 2004) (middle panel) and for our filter (right panel). For all filters we used three different scales showing the stability of our filter outcome (Pace et al., 2007).



Ongoing and future research: extension of the filter to other observables

Filtering X-rays observations

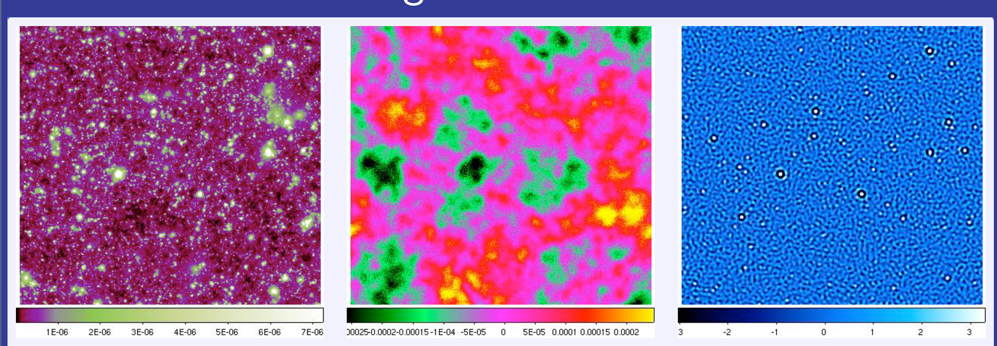


From left to right: soft band X-ray emission, the same with noise (XMM, $100ks$), signal-to-noise map resulting from our filter.

Combining all observables

Galaxy clusters can also be observed through X-rays and Sunyaev Zel'dovich (SZ) observations. We performed numerical simulations for these signals to investigate the possibility of defining a multi-band filter for the optimal combination of these very different data sets. This richness in information together with the optimal noise suppression, ensured by the optimal filter, will allow us to detect high redshift galaxy clusters with the hope to gain new constraints on dark energy models.

Filtering SZ observations



From left to right: SZ effect at $145GHz$, the same with noise (ACT) and CMB, signal-to-noise map resulting from our filter.

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