Detecting substructure in dark matter halos with gravitational lensing flexion

Markus Rexroth, Jean-Paul Kneib, Priyamvada Natarajan, David Goldberg
Contact: markus.rexroth@epfl.ch

Gravitational lensing flexion

Flexion extends the weak gravitational lensing formalism to second order,

$$\beta_i = A_{ij}\,\theta_j + \frac{1}{2} D_{ijk}\,\theta_j\,\theta_k,$$

where β and θ are the two dimensional coordinates in the source plane and the lens plane. The $A_{ij}(\theta) = \frac{\partial \beta_i}{\partial \theta_j}$ matrix describes the first order lensing effects, which are a slight magnification and an elliptical elongation called shear. The $D_{ijk}(\theta) = \frac{\partial A_{ij}(\theta)}{\partial \theta_k}$ terms describe the flexion (Bacon et al. 2006). The combination of shear and flexion gives rise to the arclets which we observe close to strong lenses (Fig. 1).

Flexion comes in two flavors: $\mathcal{F}$-Flexion and $\mathcal{G}$-Flexion. Bacon et al. (2006) showed that the former is the derivative of the convergence κ and thus traces the change in the local projected surface mass density, and that the latter is the derivative of the shear field γ. As a result, for typical shear and convergence dependence $\propto r^{-1}$, flexion drops off as $\propto r^{-2}$. This makes flexion a highly sensitive probe of small scale structures, such as dark matter clumps. Therefore it has many promising applications, such as increasing the resolution of lens mass maps, constraining dark matter properties in colliding clusters, or finding dark matter substructure. A simulation by Leonard et al. (2009) demonstrates this advantage (Fig. 2).

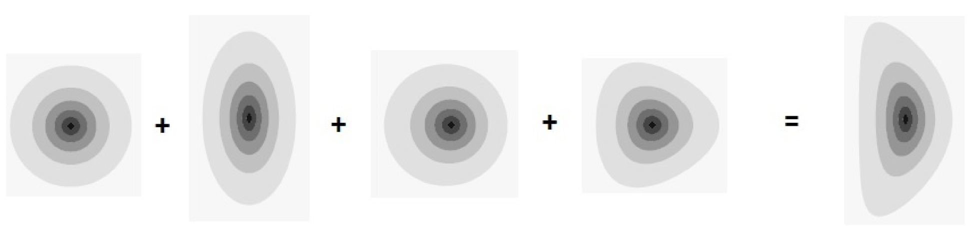

Fig. 1: Unlensed source + shear + $\mathcal{F}$-Flexion + $\mathcal{G}$-Flexion = arclet

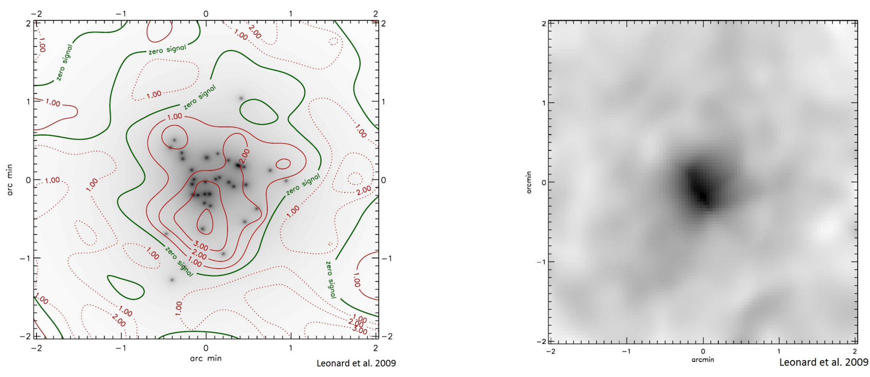

Fig. 2: Simulated dark matter substructure (left, greyscale) is recovered by $\mathcal{F}$-Flexion (left, colored contours) whereas the shear only constrains the total matter content of the clump (right) (Leonard et al. 2009)

A public, automated flexion measurement pipeline for *Hubble* data

Several papers have demonstrated that flexion can in principle be measured in simulated data or in the strong lensing cluster Abell 1689 (Leonard et al. 2007, Okura et al. 2008, Rowe et al. 2013). However, measurements in real data have proved to be very difficult and a publicly available pipeline does currently not exist. We have developed an automated, efficient pipeline for *Hubble Space Telescope* data.

The pipeline uses the Higher Order Lensing Image Characteristics (HOLICs) flexion measurement technique (Okura et al. 2007 and 2008, Goldberg & Leonard 2007). It extends the Kaiser, Squires and Broadhurst technique for shear measurements (Kaiser et al. 1995) by including higher order image moments of the form $Q_{ijkl} = \frac{\int d^2\theta\; q(I(\theta))\Delta\theta_i\Delta\theta_j\Delta\theta_k\Delta\theta_l}{\int d^2\theta\; q(I(\theta))}$, where $q(I(\theta))$ is a weighting function which depends on the surface brightness distribution. This way, relations between the image moments and the flexions can be derived. In their simplest form without Point Spread Function (PSF) or weighting function corrections, these are:

$$\begin{aligned} F &\approx \left\langle \frac{\zeta}{(9/4) - 3(\mathrm{tr}Q)^2/\xi} \right\rangle, \\ G &\approx \frac{4}{3} < \delta >, \end{aligned}$$

where F and G are the reduced flexions, Q is the matrix of quadrupole moments and ξ, ζ and δ are combinations of higher order moments. In our pipeline, we use the full version of these relations, including PSF and weighting function correction terms.

Flexion measurements depend on many variables, such as the flexion strength, the source size and signal-to-noise (Rowe et al. 2013), as well as its morphology, ellipticity and shear (Viola et al. 2012). Thus the measurement error is hard to estimate. In addition, these dependencies can introduce biases into the flexion measurement process. Therefore we have created a simulation of galaxies with a wide range of different properties and flexion values, resulting in more than 2 TB of data. We are using this data to calibrate our measurement pipeline, $\mathcal{F}_{true} = m \cdot \mathcal{F}_{meas} + c$, and analogously for $\mathcal{G}$-Flexion, to account for these biases. In addition, the code will also provide an automated measurement error estimate.

Preliminary results: Flexion in the *Hubble Frontier Fields* cluster MACSJ0416

We applied an early version of our pipeline to the *Hubble Frontier Fields* cluster MACSJ0416. By virtue of the high quality of the *Frontier Fields* data it is very well suited for flexion measurements. The flexion calibration was not yet applied, therefore the measured values are most likely a bit too high and we only investigate the 16 biggest and thus most reliable sources. The final code will measure the flexion of many more objects. The F-Flexion results confirm several substructures predicted by the high precision mass model from strong lensing and shear constraints presented in Jauzac et al. (2015). These are labeled with the blue numbers 1-4. We also find 2 new candidate dark matter clumps, which the previous mass model could not constrain (blue numbers 5 and 6). These will be further investigated with the final version of the code. The G-Flexion has to our knowledge never been measured in real data. We measure a signal that is compatible with the F-Flexion results, but has higher measurement errors. These results show that already this limited flexion sample can greatly improve the mass reconstruction.

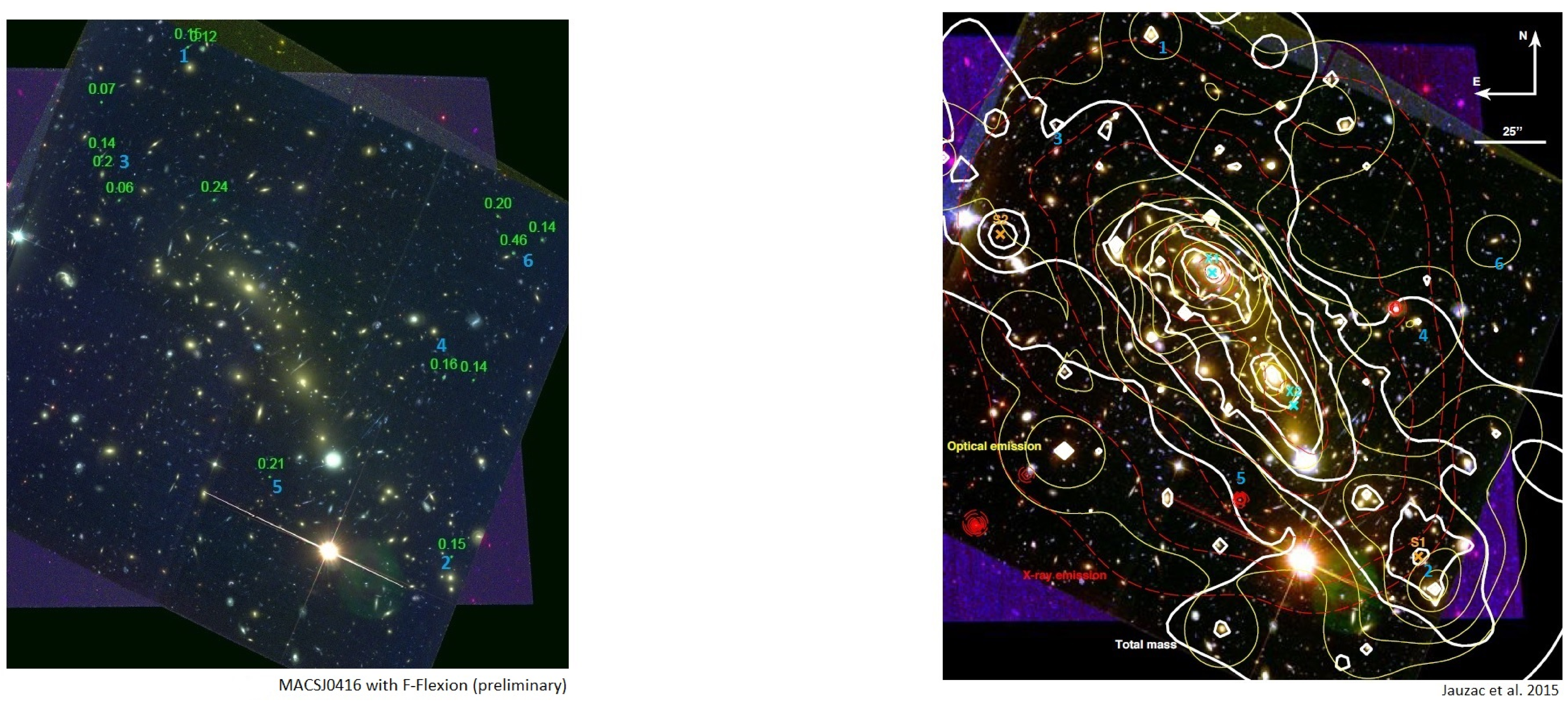

Fig. 3: Preliminary F-Flexion measurements (green, left image) confirm substructures in the mass model from Jauzac et al. (2015) (white contours, right image) and detect 2 new candidate dark matter clumps

Outlook

We will measure the flexion in all 6 *Frontier Fields* clusters and use it to further improve the high-precision mass maps. In particular, we will put tighter constraints on their substructures. Flexion measurements profit tremendously from a small PSF and pixel size, and in the near future the *James Webb Space Telescope* will routinely deliver such high quality data. Flexion will greatly improve dark matter constraints from bullet clusters as well as lens models and the science results derived from them, e.g. studies of the early universe by using strong lenses as "cosmic telescopes".

References

Bacon D., Goldberg D., Rowe B., Taylor A., 2006, *MNRAS*, 365, 414
Jauzac M., Jullo E., Eckert D., *et al.*, 2015, *MNRAS*, 446, 4132
Leonard A., Goldberg D,. Haaga J., Massey R., 2007, *ApJ*, 666, 51
Okura Y., Umetsu K., Futamase T., 2007, *ApJ*, 660, 9950
Rowe B., Bacon D., Massey R., *et al.*, 2013, *MNRAS*, 435, 822
Goldberg D., Leonard A., 2007, *ApJ*, 660, 1003
Kaiser N., Squires G., Broadhurst T., 1995, *ApJ*, 449, 460
Leonard A., King L., Wilkins S., 2009, *MNRAS*, 395, 1438
Okura Y., Umetsu K., Futamase T., 2008, *ApJ*, 680, 1
Viola M., Melchior P., Bartelmann M., 2012, *MNRAS*, 419, 2215