CDM substructure: comparing simulations with observations

Maruša Bradač

T. Baltz, P. Schneider, M. Lombardi, M. Steinmetz, L.V.E. Koopmans, J. Navarro

KIPAC Institute

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Motivation

- According to our simulating friends, the Universe is lumpy. Galaxies and clusters are full of substructure.
- Substructure in galaxies can be probed using strong and possibly weak (higher order lensing).

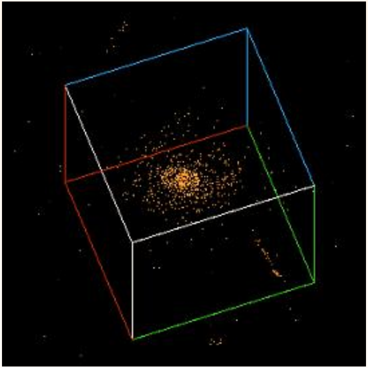
$\Rightarrow$ Agreement between observations and simulations unclear.

$\Rightarrow$ Need to carefully look for evidence of substructure in lens galaxies and compare with predictions from simulations.

$\Rightarrow$ Baryons are crucial here!!!

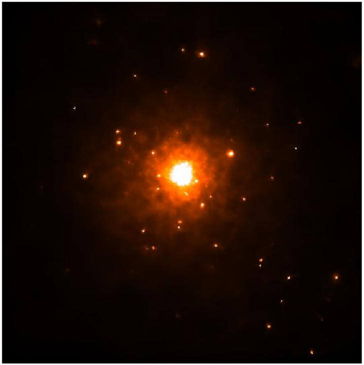
Lensing by a simulated galaxy

- What flux anomalies do we expect from a “typical” galaxy? (Bradač et al. 2004)



Matthias Steinmetz

GRAPESPH ΛCDM



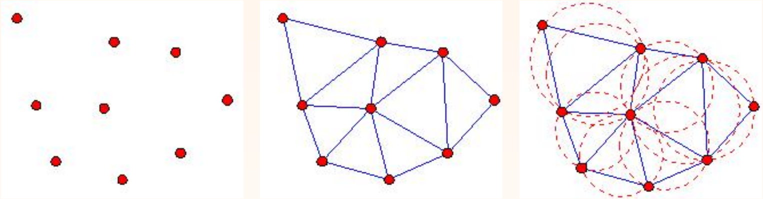
$\kappa(x) = \frac{\Sigma(\xi_0 \vec{x})}{\Sigma_c}$

Smoothing using Delaunay Tesselation

Lens properties using FFT

Dealaunay Tesselation

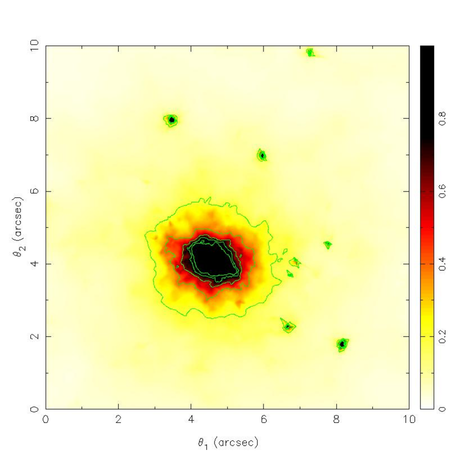
- Fully adaptive and parameter free - neither size nor shape of smoothing "kernel" are considered a parameter.



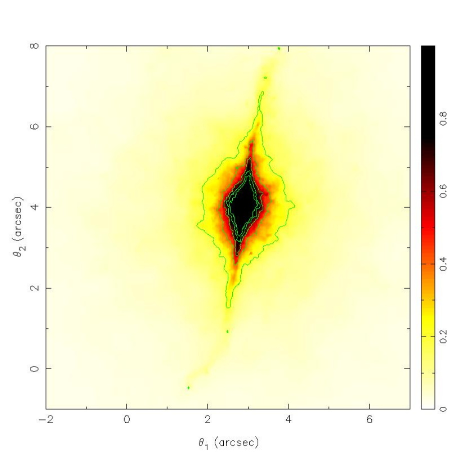
- If we work in M dimensions, each cell consists of $1 + M$ points, W_i is the volume of all cells belonging to point i.
- Density estimate at each point (Schaap and van de Weygaert 2000)

$$\rho(\mathbf{x}_i) = \frac{m\,(1+M)}{W_i}$$

Surface mass density maps

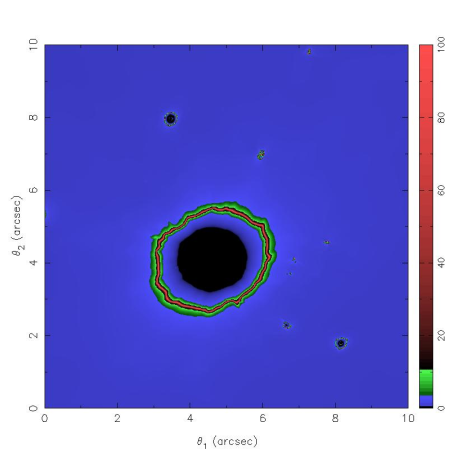


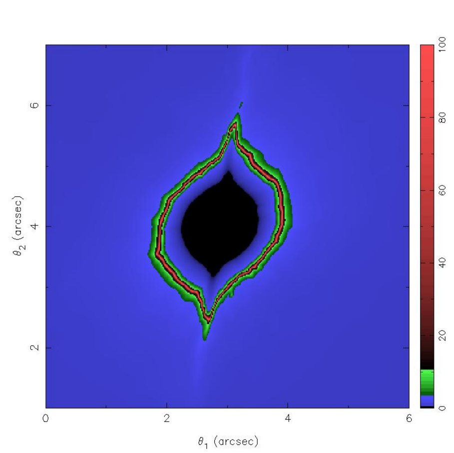
κ



κ

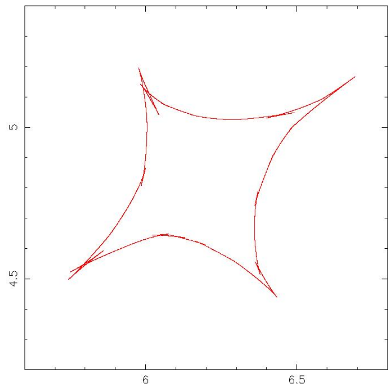
Magnification maps



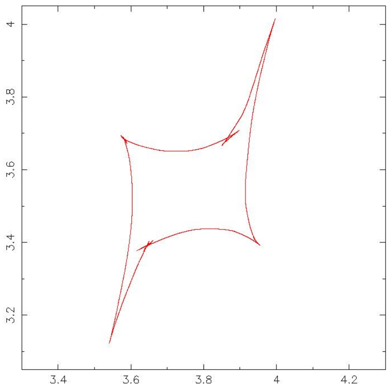


μ μ

Caustics

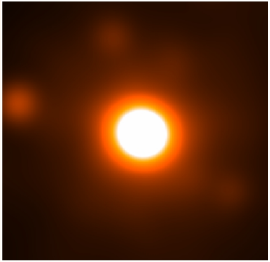


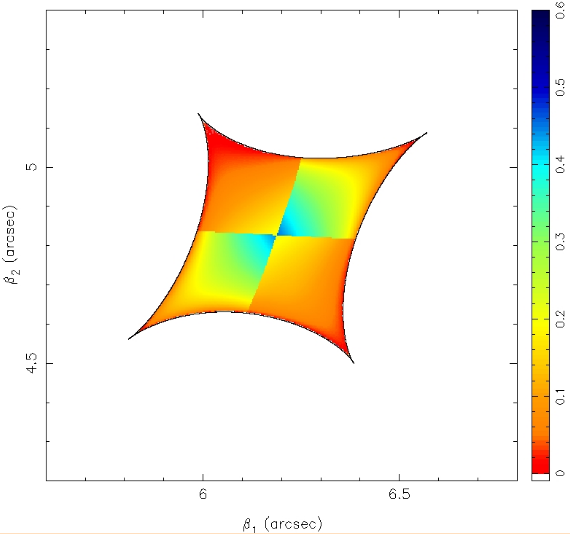
Caustic



Caustic

Cusp Relation

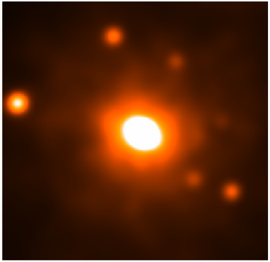




$$R_c = \frac{|A-B+C|}{A+B+C}$$

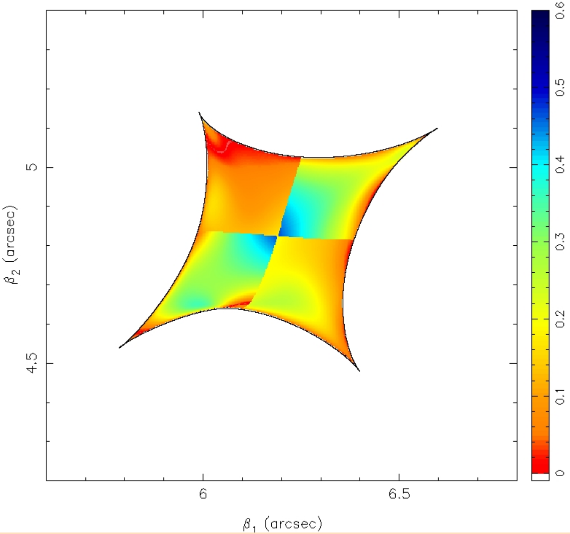
$\sigma \sim 4$ kpc

Cusp Relation

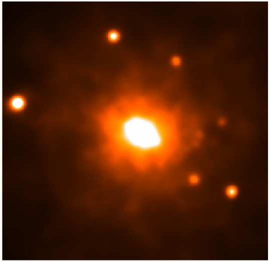


$$R_c = \frac{|A-B+C|}{A+B+C}$$

$\sigma \sim 1.5$ kpc

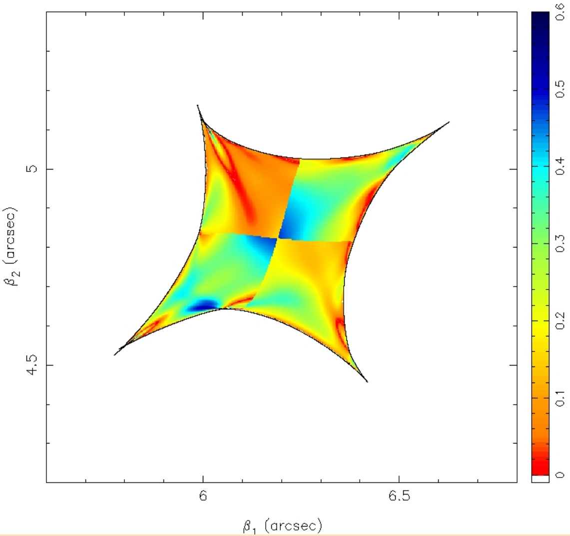


Cusp Relation

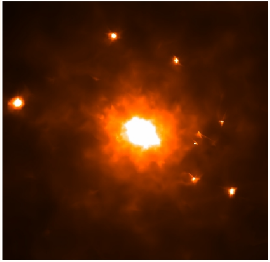


$$R_c = \frac{|A - B + C|}{A + B + C}$$

$\sigma \sim 0.8$ kpc

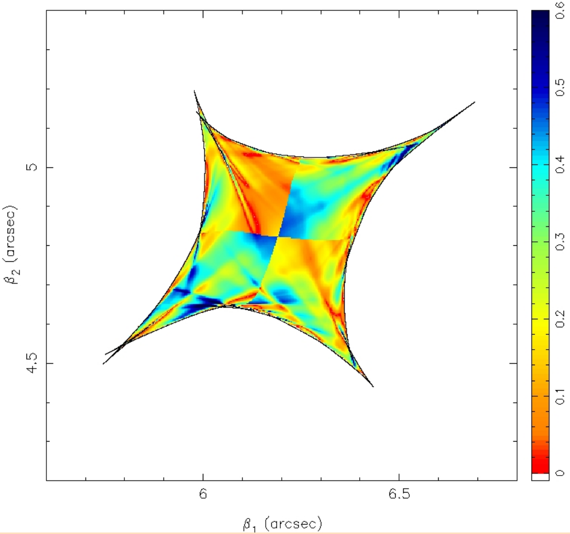


Cusp Relation



$$R_c = \frac{|A-B+C|}{A+B+C}$$

$\sigma \sim 0$ kpc



Are these signatures unique?

- N-body simulations:
  - Mao et al. (2004) Predicted fraction of substructures too high compared with observations (single galaxy)
  - Amara et al. (2006) Lower level of cusp violations and no swallowtails than what we observed.
  - Macciò et al. (2006) Not enough substructure to reproduce the observed high numbers of discrepancies observed in the flux ratios of multiply lensed quasars.
- Analytic models:
  - Chen et al. (2003) Str along the line-of-sight only a minor effect.
  - Oguri (2005) The environmental effects can partly explain the high incidence of anomalous flux ratios.
  - Rozo et al. (2006) The average magnification is lower (higher) than that in smooth models for positive-parity (negative-parity) images.

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- This is a big mess!!!

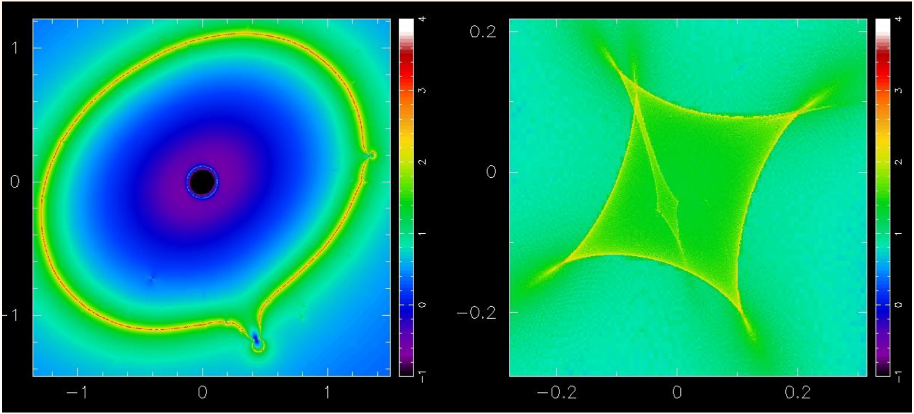
GLAMROC

Gravitational Lens Adaptive Mesh Raytracing of Catastrophes by Edward A. Baltz / KIPAC

- Use tractable lens "atoms" - all derivatives are done analytically
  - Cored isothermal spheres, NFW profiles, point lenses
  - Ellipticity and boxiness in isopotentials (arbitrary quartic in x,y)
- Arbitrary number of lens atoms on arbitrary number of planes
  - Going from 1 to 2 lens planes is a huge mess
  - Going from 2 to N lens planes is simple
- Up to 6th derivative of (potential = time delay) can be calculated
  - Covers all "elementary" catastrophes: critical curve (2nd derivative), cusp (3rd derivative), swallowtail (4th derivative), etc.
  - Convergence, shear (2nd derivative), flexion (3rd derivative)
- Adaptive mesh refinement improves resolution where needed
  - Based on (image plane) magnification to resolve critical curves
  - Based on (source plane) surface brightness for efficient lens modeling

GLAMROC

- Simulated galaxy, based on simulations from Taylor and Babul (2005)



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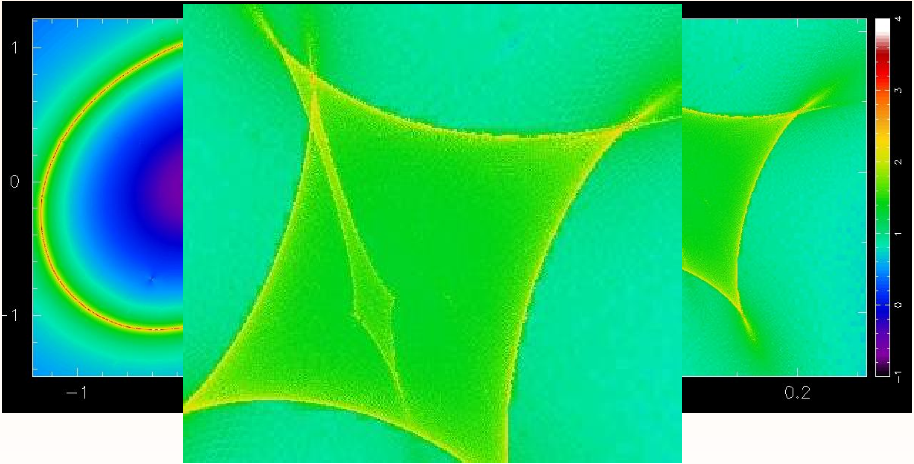

Summary

- CDM substructure does affect flux ratios, causing flux ratio anomalies, however its effects are far more subtle that first thought of.
- Detailed comparisson with simulations have not been performed yet.
- How to proceed:
- Detail analysis of simulated galaxies (remember: baryons are important, and halos are NOT self similar)
- Look for unusual lenses (higher order catastrophes; beyond folds and cusps).
- Higher order "weak" lensing (flexion, etc. Irwin and Shmakova 2005)
- Remember this is important, lensing is a unique tool to study substructure in galaxies at high redshifts!!

Λ-CDM Crises

- Two “crises” challenging the standard picture of galaxy formation and the ΛCDM paradigm...

Λ-CDM Crises

- Two "crises" challenging the standard picture of galaxy formation and the ΛCDM paradigm...
  1. We need better simulations!!
  2. We need more data!!

SWhite in search of dwarfs

- Take seven simulated halos, with the redshifts 0.96, 0.41, 0.31, 0.34, 0.63, 0.76, 0.87 and velocity dispersions $160 \lesssim \sigma \lesssim 220 km\, s^{-1}$
- Don't forget their baryons!
- Determine the properties: flux ratios, cusp relation, saddle point demagnification, etc.
- Compare: MG 0414+0534, B0712+472, PG 1115+080, B1422+231, B1608+656, B1933+503, and B2045+265.
- How well can we measure substructure fraction, Hubble constant, etc.?

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