Simulations of Strong Lensing

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Outline

Introduction

Simulations of Strong Lensing

Simulated Lensed Images

Work in Progress

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Gravitational Lensing

- Gravitational lensing is the phenomenon of light deflecting when light ray passes through a gravitational potential.
- The occurrence and morphological properties of lensed images reflect the properties of the gravitational potential between the source and the observer.
- Lensing effects can be almost observed on all scales, e.g., weak lensing (Mpc), strong lensing (kpc), micro lensing (pc).
- Applications: reconstruct mass distribution of lens, detect galaxies at high redshift, measure the Hubble constant, etc.

Gravitational Lensing

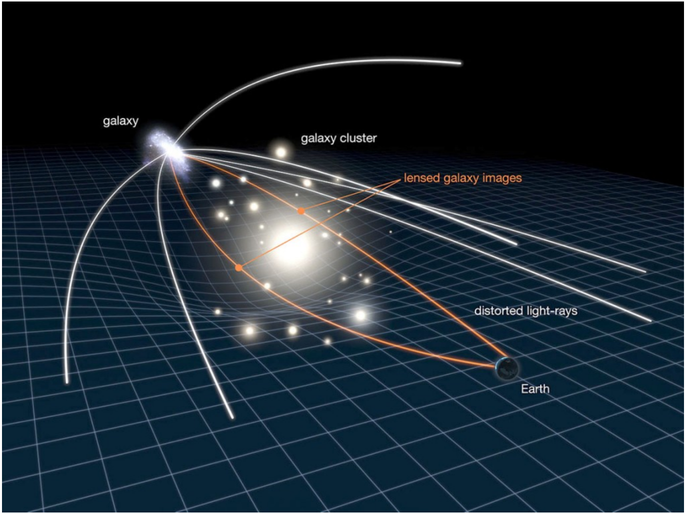


Figure 1 : Illustration of gravitational lensing.

Gravitational Lensing

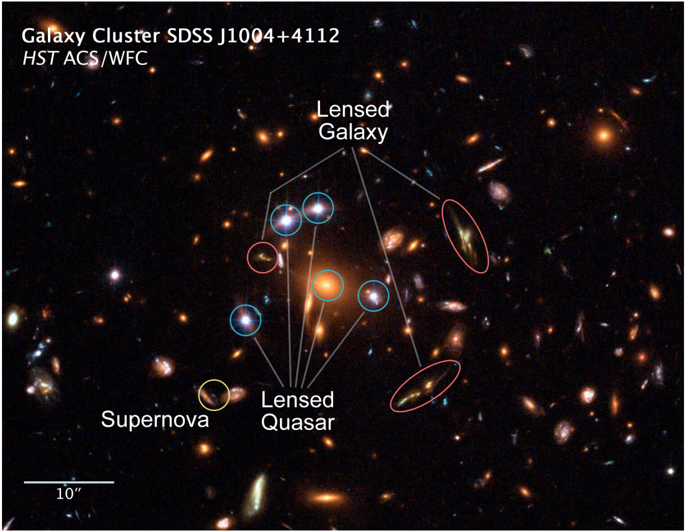
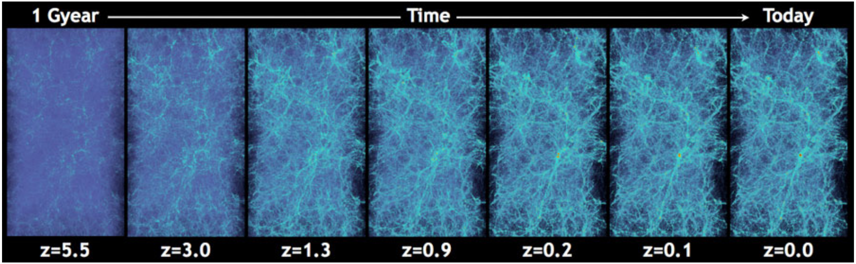


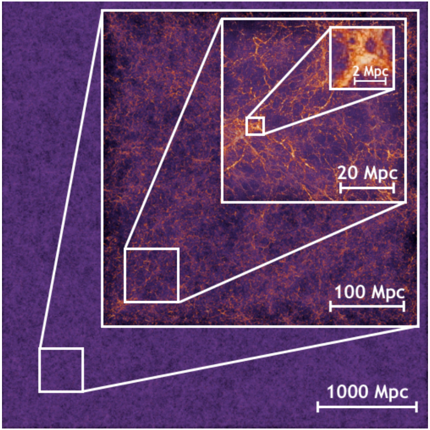
Figure 2 : Typical observation of strong gravitational lensing.

N-body Simulation

- N-body simulation is a simulation of a dynamical system of particles under the influence of gravity.
- In cosmology, it is used to study processes of non-linear structure formation, e.g., halos and filaments.



The Outer Rim Simulation

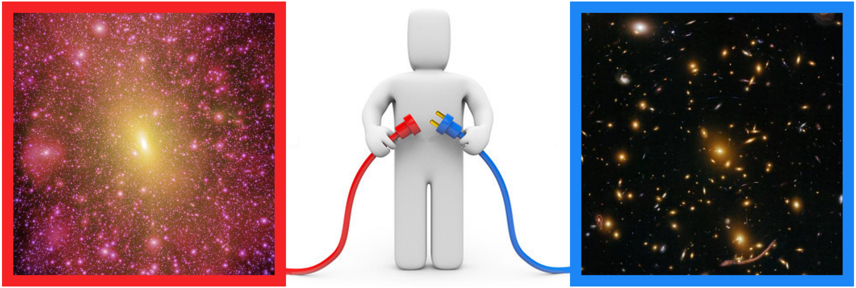


- $V_{\rm box} = (3h^{-1}{\rm Gpc})^3$.
- $M_{\rm p} = 1.85 \times 10^9 h^{-1} M_\odot$.
- $N_{\rm p} = 10240^3$.
- 100 snapshots (10 to 0).
- More than 1000000 clusters.

Katrin Heitmann

Simulations of Strong Lensing

- Simulation of gravitational lensing is an effective connection between N-body simulation and Observations.
- Basic steps : 1) estimate density field; 2) calculate deflection angles; 3) ray-tracing; 4) generate lensed images.
- Comparing the simulated lensed images with the observations, we can study the properties of dark matter particles.



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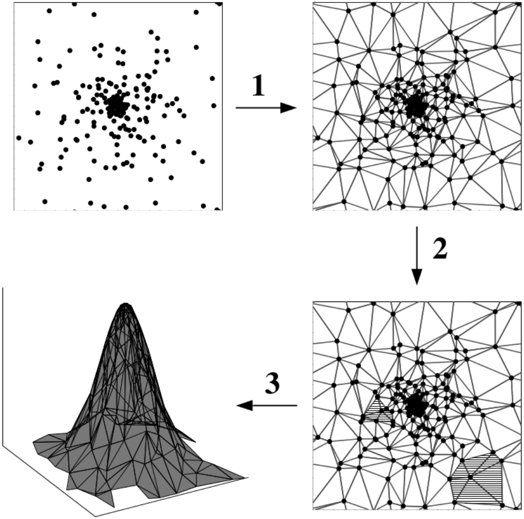
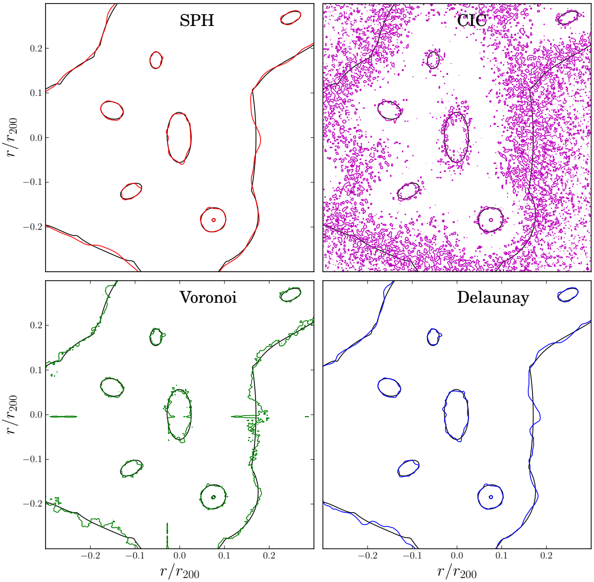
Estimate Density Field

- Estimating densities of the halo from N-body simulations is a critical first step for lensing simulations.
- There are several well known methods to estimate density field: Cloud in Cell (CIC), Triangular Shaped Cloud (TSC), Smoothed Particle Hydrodynamics (SPH) ......
- In our work, we use a different way: Delaunay Tessellation Field Estimator (DTFE). It is fully self-adaptive and more natural than the kernel estimators.

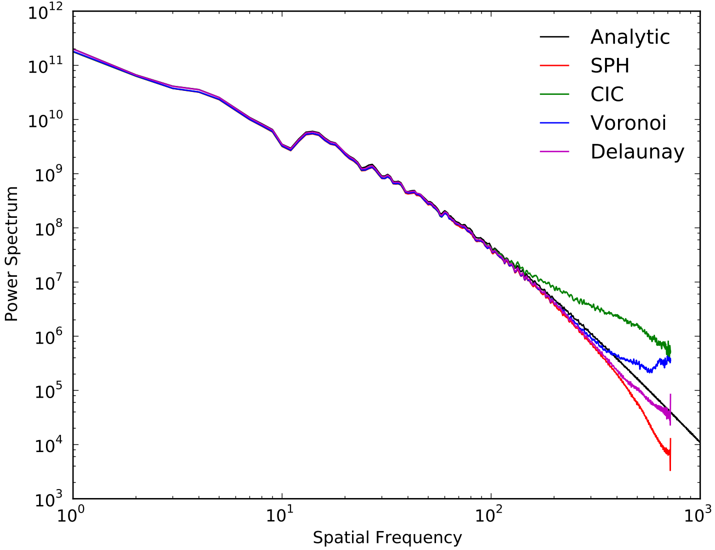
Delaunay Tessellation



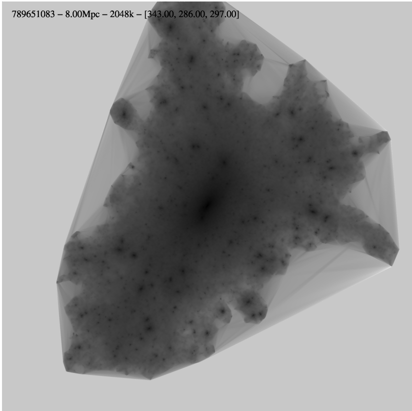
Compare with Other Methods



Compare with Other Methods



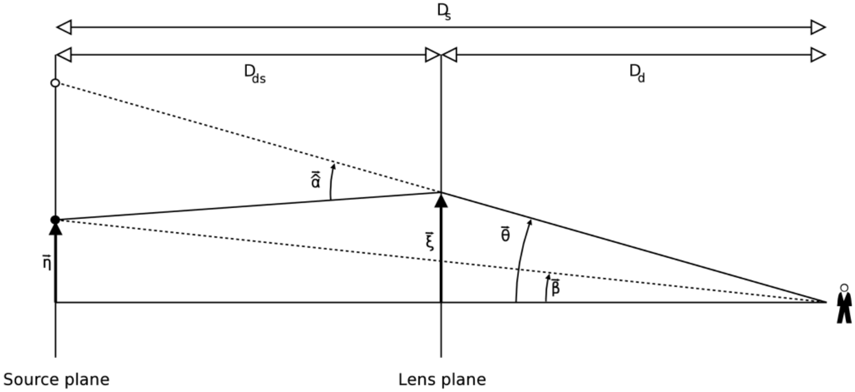
One Example



Steve Rangel

Calculate Deflection Angles

- $\vec{\alpha}(\vec{\theta}) = \frac{1}{\pi} \int \mathrm{d}^2\vec{\theta}' \, \kappa(\vec{\theta}') \, \frac{\vec{\theta} - \vec{\theta}'}{|\vec{\theta} - \vec{\theta}'|^2} \, .$
- $\beta = \theta - \alpha(\theta)$.



Deflection Angles

$$\hat{\vec{\alpha}}(\vec{\xi}) = \frac{4G}{c^2} \int \mathrm{d}^2\xi' \, \Sigma(\vec{\xi'}) \, \frac{\vec{\xi} - \vec{\xi'}}{|\vec{\xi} - \vec{\xi'}|^2} \, . \tag{1}$$

$$\kappa(\vec{\theta}) = \frac{\Sigma(D_\mathrm{d}\vec{\theta})}{\Sigma_\mathrm{crit}}, \; \Sigma_\mathrm{crit} = \frac{c^2}{4\pi G}\frac{D_\mathrm{s}}{D_\mathrm{d} D_\mathrm{ds}}, \; \vec{\alpha}(\vec{\theta}) = \frac{D_\mathrm{ds}}{D_\mathrm{s}}\hat{\vec{\alpha}}(D_\mathrm{d}\vec{\theta}) \, , \tag{2}$$

$$\vec{\alpha}(\vec{\theta}) = \frac{1}{\pi} \int \mathrm{d}^2\vec{\theta'} \, \kappa(\vec{\theta'}) \, \frac{\vec{\theta} - \vec{\theta}'}{|\vec{\theta} - \vec{\theta}'|^2} \, . \tag{3}$$

Convergence and Shear

2D projection of 3D Gravitational potential along LOS.

$$\psi(\vec{\theta}) = \frac{D_{\rm ds}}{D_{\rm d} D_{\rm s}} \frac{2}{c^2} \int \Phi(D_{\rm d}\vec{\theta}, z) dz \tag{4}$$

The first order deraviation:

$$\vec{\nabla}_\theta \psi(\vec{\theta}) = \frac{2}{c^2} \frac{D_{\rm ds}}{D_{\rm s}} \int \vec{\nabla}_\perp \Phi dz = \vec{\alpha} \tag{5}$$

The second order deraviation:

$$\kappa = \frac{1}{2}(\psi_{11} + \psi_{22}) \ , \quad \gamma = \frac{1}{2}(\psi_{11} - \psi_{22}) + {\rm i}\frac{1}{2}(\psi_{12} + \psi_{12}) \tag{6}$$

Magnificagion

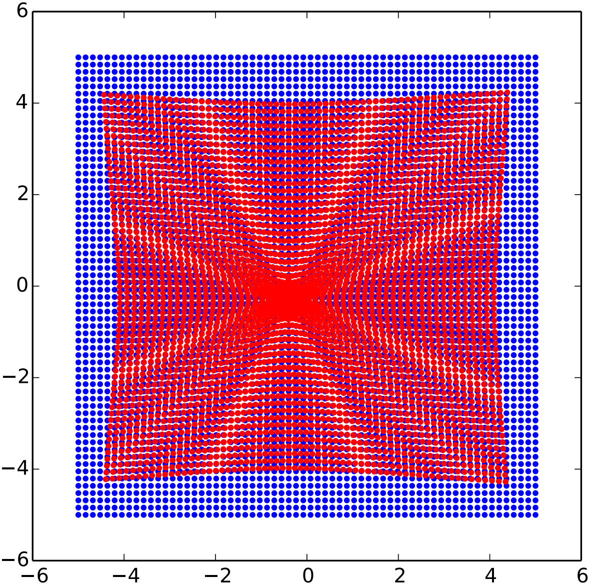
The magnification:

$$\mu = \frac{\theta d\omega d\theta}{\beta d\omega d\beta} = ((1-\kappa)^2 - |\gamma|^2)^{-1} \tag{7}$$

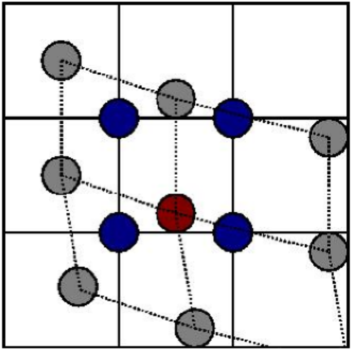
Or:

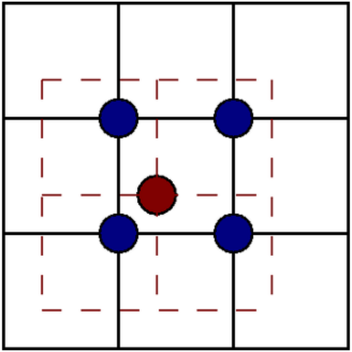
$$\mu = ((1-\psi_{11})(1-\psi_{22}) - \psi_{12}\psi_{21})^{-1} \tag{8}$$

From Lens Plane to Source Plane



From Source Plane to Lens Plane





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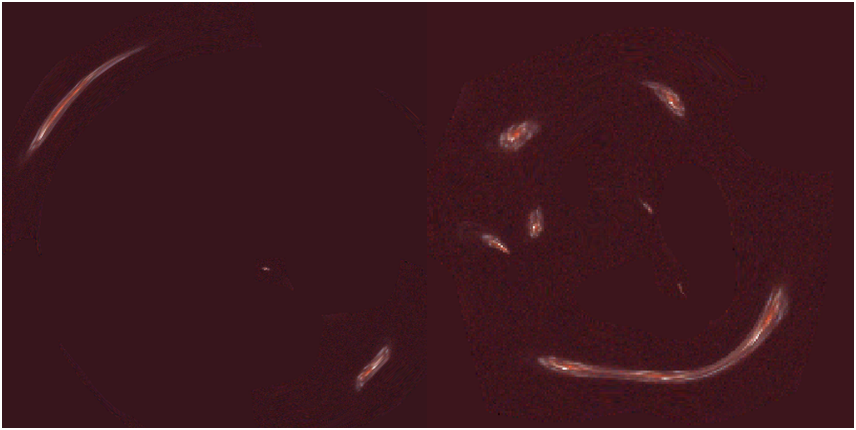
Monte Carlo Halos



Compare with observations

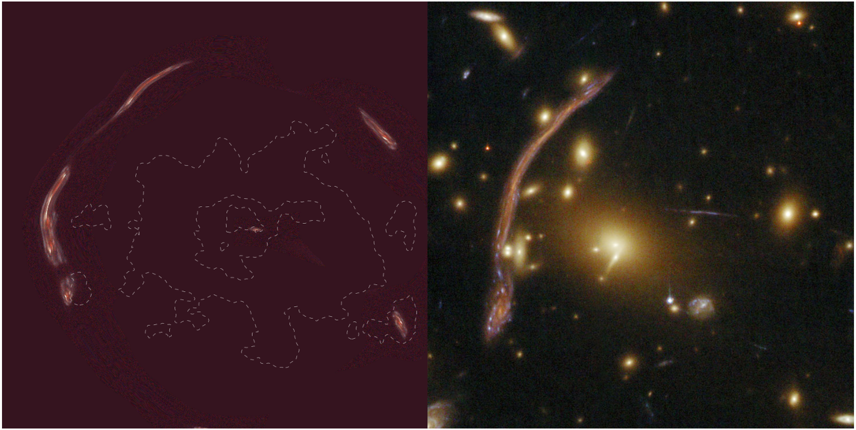


Figure 3 : Comparing a simulated image with a observed lensed image.

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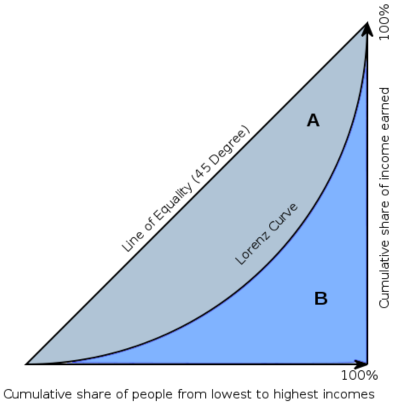
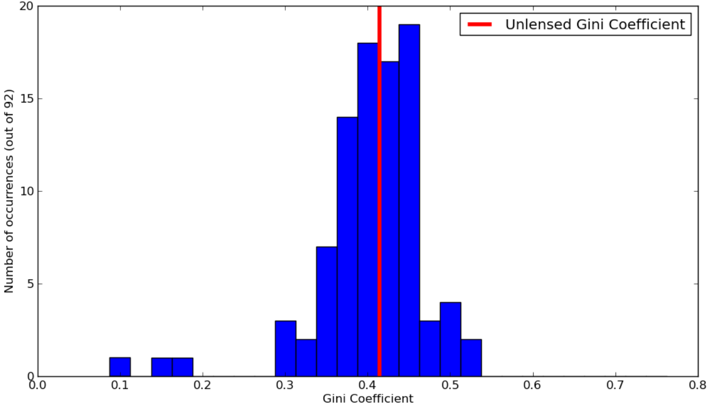
2. Lensing effects on the Gini Coefficient of the background source galaxies. (HST)

Gini Coefficient



- The Gini coefficient is a measure of the inequality of light distribution. ($A/(A+B)$)
- It reflects some information on properties of galaxies statistically, e.g., type, evolution...
- To measure the Gini Coefficient of the galaxies at high redshift more accurately.

Lensing Effects on Gini Coefficient



Michael Florian

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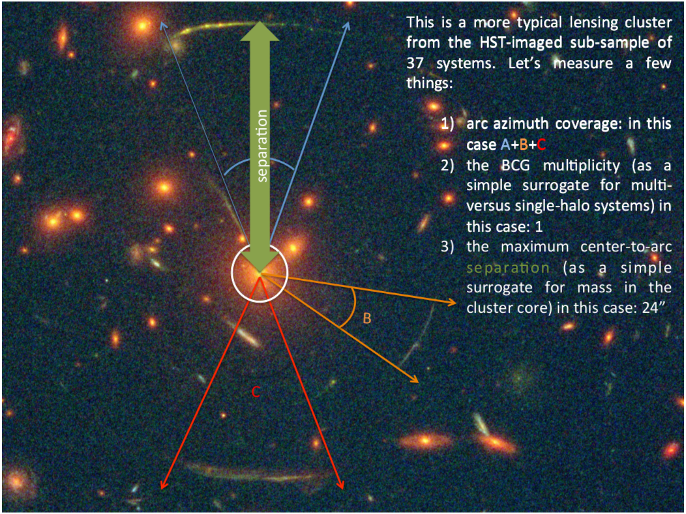
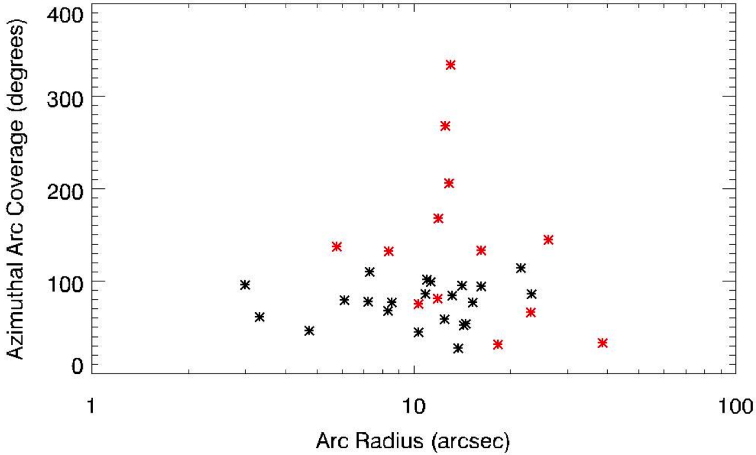
Cluster Merging and Giant Arcs



Mike Gladders

Cluster Merging and Giant Arcs



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4. Prepare to study the statistics of giant lensed arcs in galaxy clusters. (SPT, Gemini).