Galaxy-mass offsets/wobbles in Hubble Frontier Field clusters and isolated galaxies using multiple image lensing

Liliya Williams (U Minnesota)
Kevin Sebesta
Matthew Gomer
Jori Liesenborgs (U Hasselt)

Offsets/wobbles
in
massive galaxies
of Hubble
Frontier Field Clusters

Galaxy-scale mass-light offsets in clusters

Calculations/predictions:
Kahlhoefer+2014, 2015
Kim+2016
Harvey+2016
Taylor+2017

Detections with strong lensing:
Williams & Saha 2011
Mohammed+2015
Massey+2015, 2017 (in prep.)
Harvey+2017

We use Grale to do lens inversion

free-form adaptive grid lens inversion method
solutions found using genetic algorithm;
does not use any information about cluster/galaxy light
(Liesenbogs+2008, 2010, 2012)

We measure mass-light offsets between central galaxies in clusters and the nearest mass peak, ~0-15 kpc, and estimate statistical significance

Mass-light offsets could be due to ***SIDM*** or purely ***Newtonian gravity***

Hubble Frontier Field Clusters

Accuracy of lens mass reconstructions depends on the quality of the input data

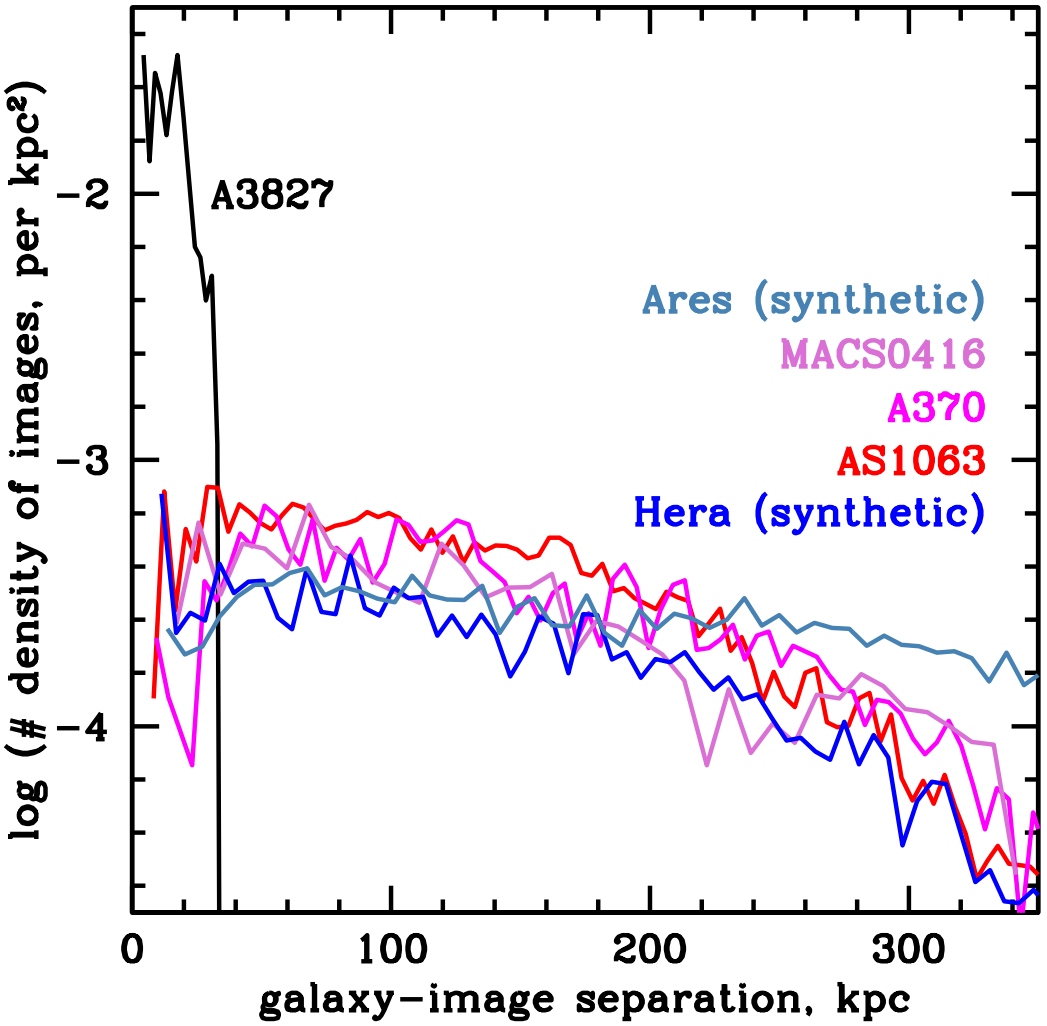
HFF clusters are some of the richest in lensed images, and have the most spectroscopic redshifts

of spec z's:

MACS 1149:	10 sources with	24 ims
MACS 0717:	10 sources with	30 ims
Abell S1063:	22 sources with	58 ims
Abell 2744:	30 sources with	88 ims
MACS 0416:	39 sources with	107 ims
Abell 370:	38 sources with	116 ims

Caminha+2016
Karman+2017
Diego+2016
Lagattuta+2016, 2017

Abell 3827 is tailor-made to detect offsets
How do HFF clusters compare?



To detect galaxy-mass offsets using multiply imaged sources, one needs high image density close to galaxies

Within separations of ~20 kpc, Abell 3827 has nearly ***x100 more images*** than HFF clusters.

A3827 is rather unique!

How we measure offsets and their statistical significance

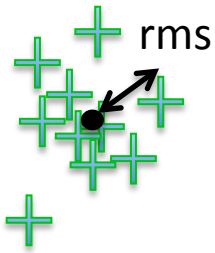
Each Grale reconstruction is an average of $\mathcal{N}$ individual mass maps

We measure offsets from the ensemble average mass map

Offsets in $\mathcal{N}$ individual mass maps are used to estimate uncertainty, in two different ways: [which one is more appropriate ??]

(1) ***Assumption:*** each of the $\mathcal{N}$ maps can be considered a fair representation of reality

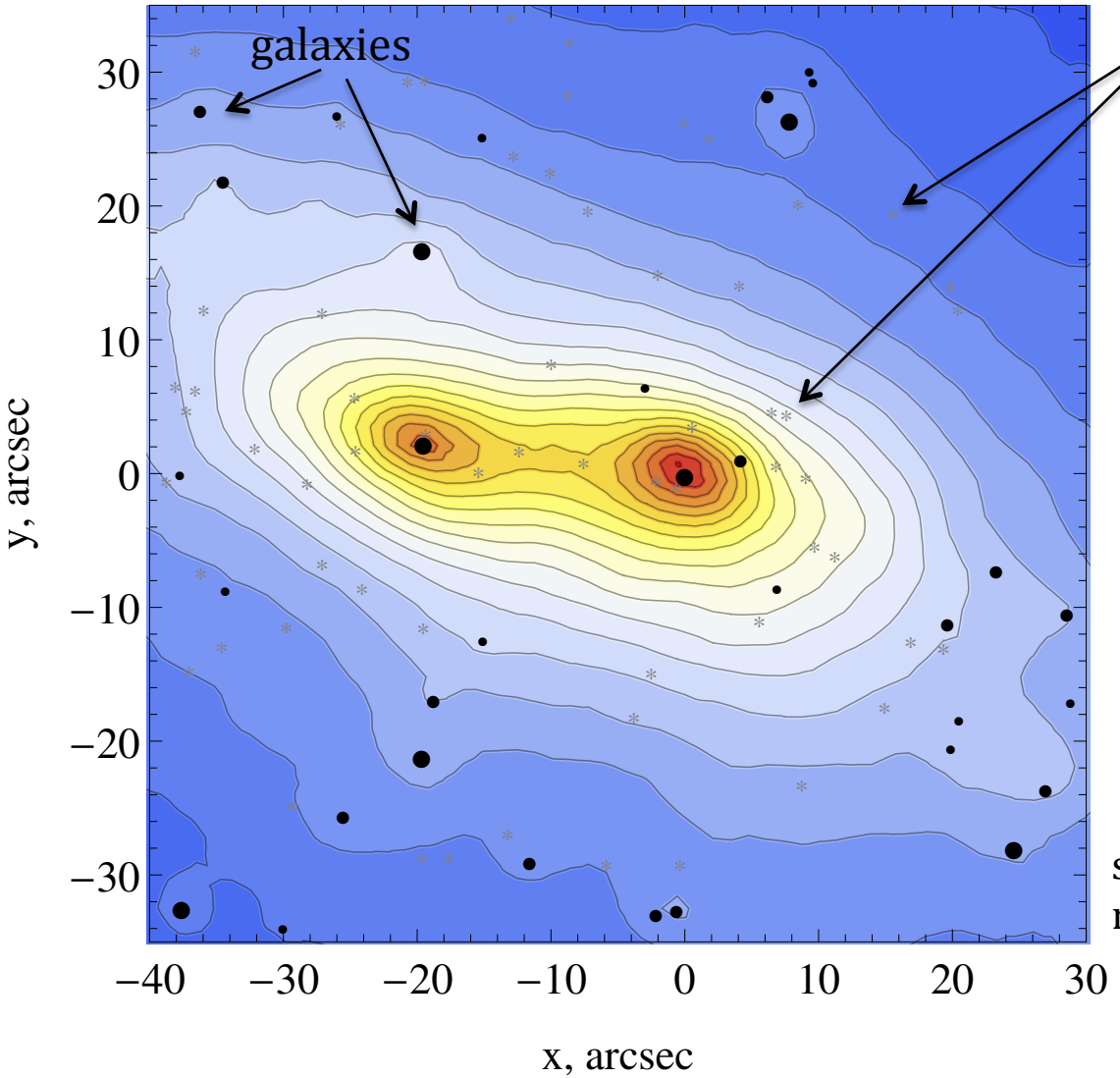
Calculate rms in the spatial distribution of mass peaks from $\mathcal{N}$ individual mass maps → Significance= offset/rms



(2) ***Assumption:*** only the ensemble average of $\mathcal{N}$ maps is a fair representation of reality

Significance = offset/rms/square root($\mathcal{N}$)

Use Hera to calibrate Grale's ability to detect mass-light offsets

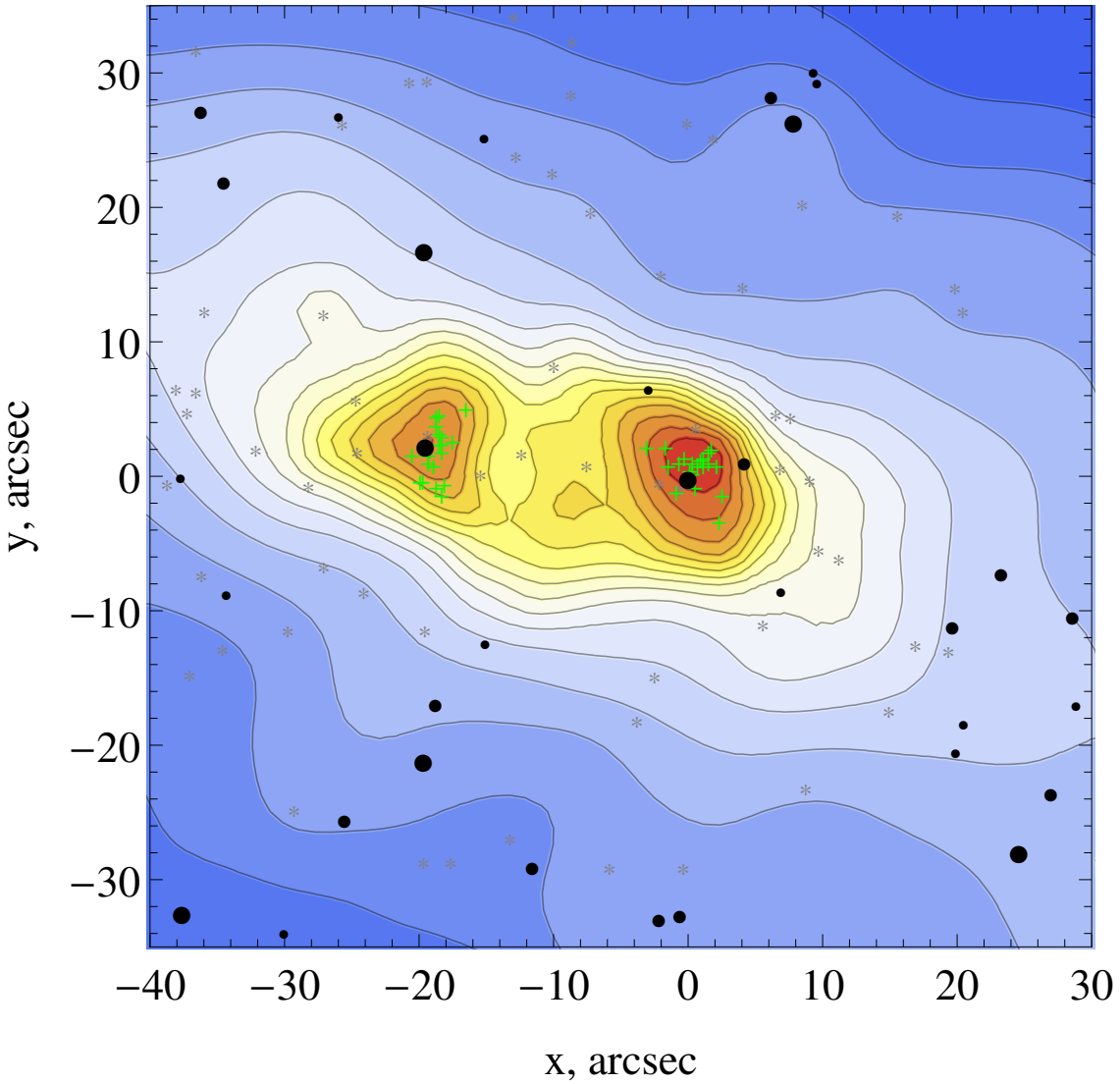


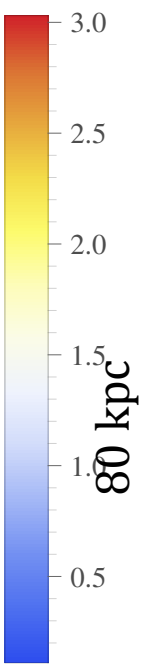
True projected mass distribution of Hera, hydrodynamically simulated cluster (Meneghetti+2016)

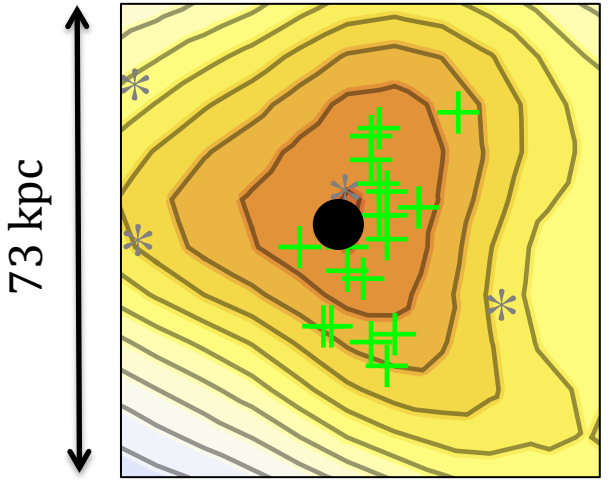
No offset between the two brightest galaxies and the corresponding mass peaks.

Grale map of Hera

simulated cluster



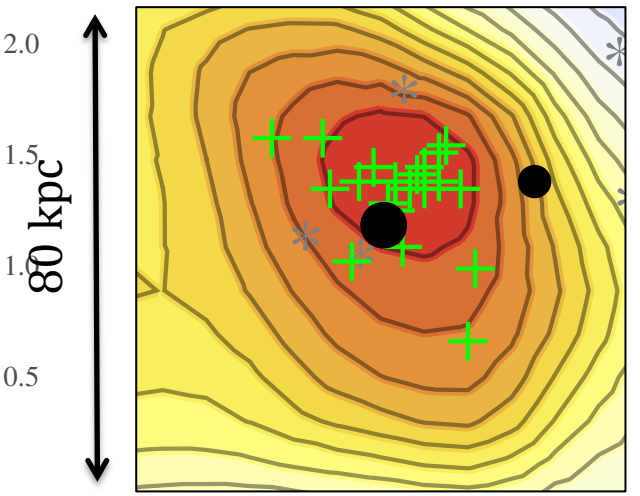




offset = 5.7 *kpc*

offset/rms = 0.46

offset/rms/$\sqrt{N}$ = 2.05

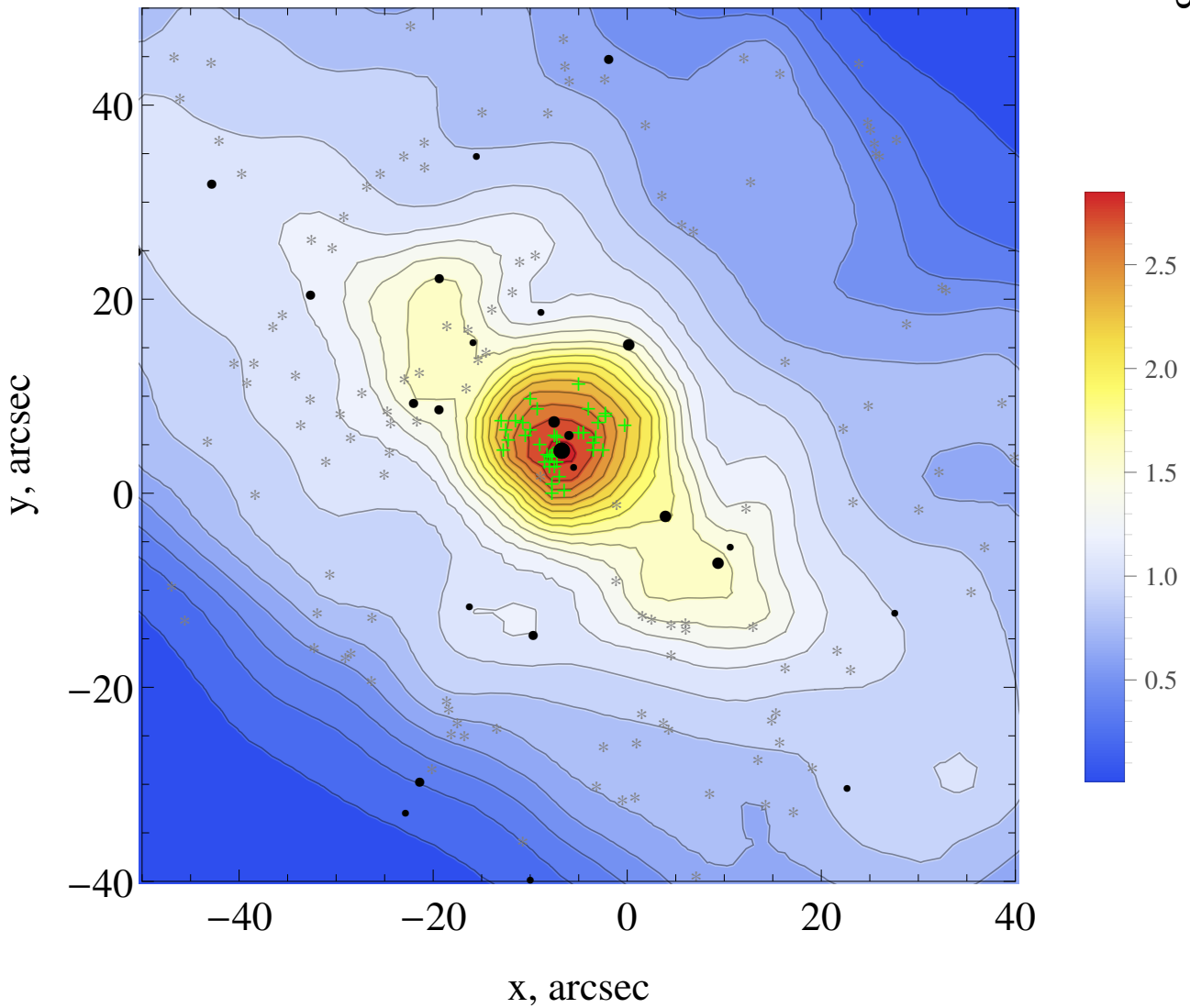


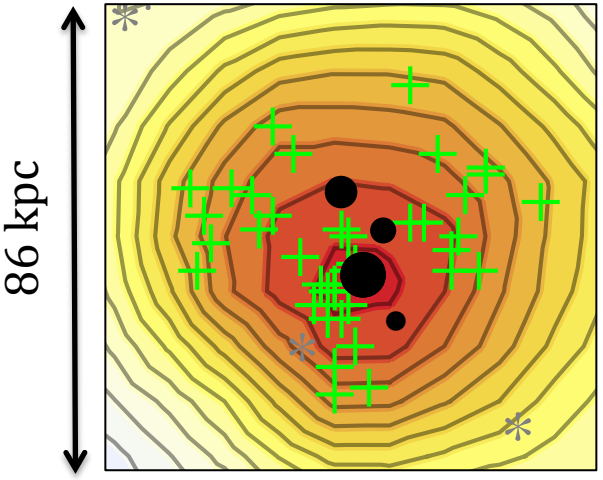
offset = 5.1 *kpc*

offset/rms = 0.43

offset/rms/$\sqrt{N}$ = 1.91

Grale map of Abell S1063



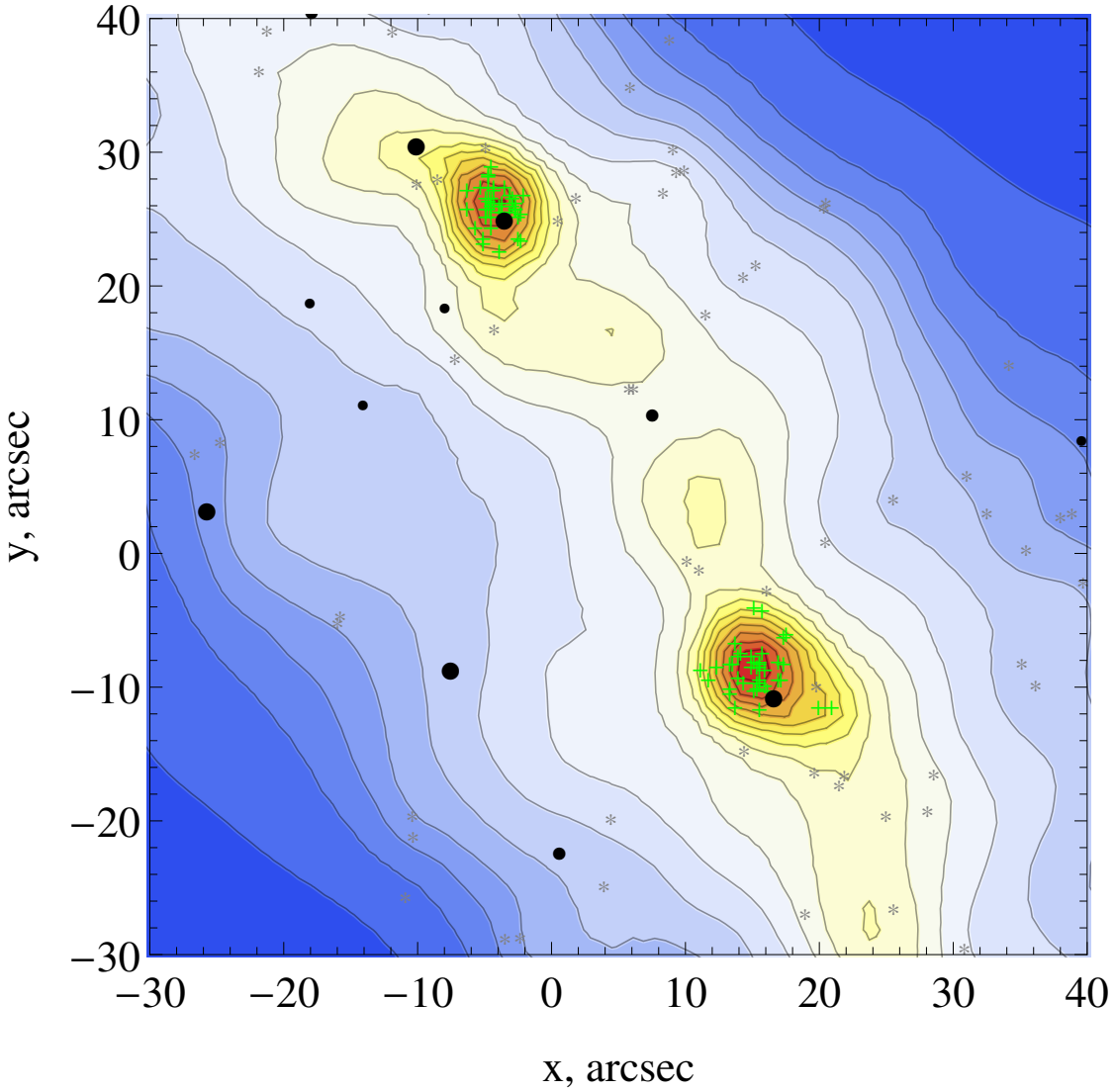


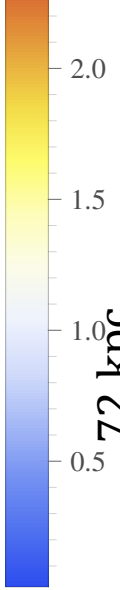
offset = 4.8 *kpc*

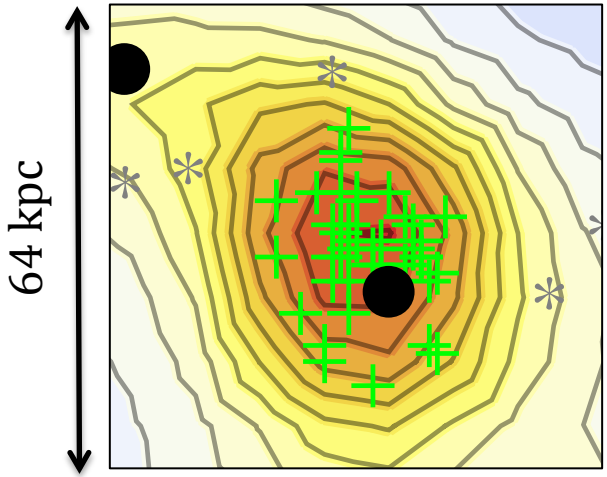
offset/rms = 0.25

offset/rms/$\sqrt{N}$ = 1.56

Grale map of MACS 0416



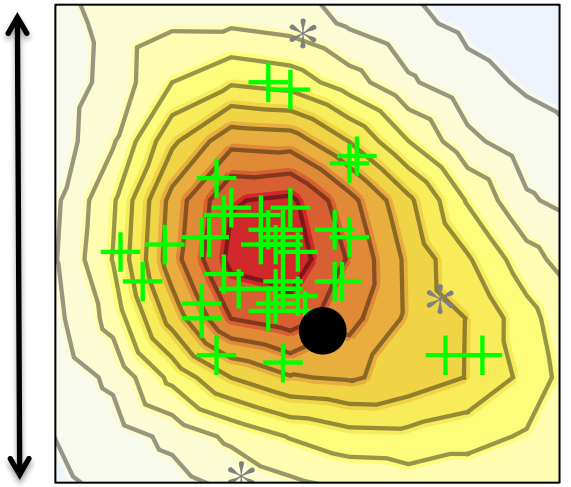




offset = 5.6 *kpc*

offset/rms = 0.59

offset/rms/$\sqrt{N}$ = 3.76

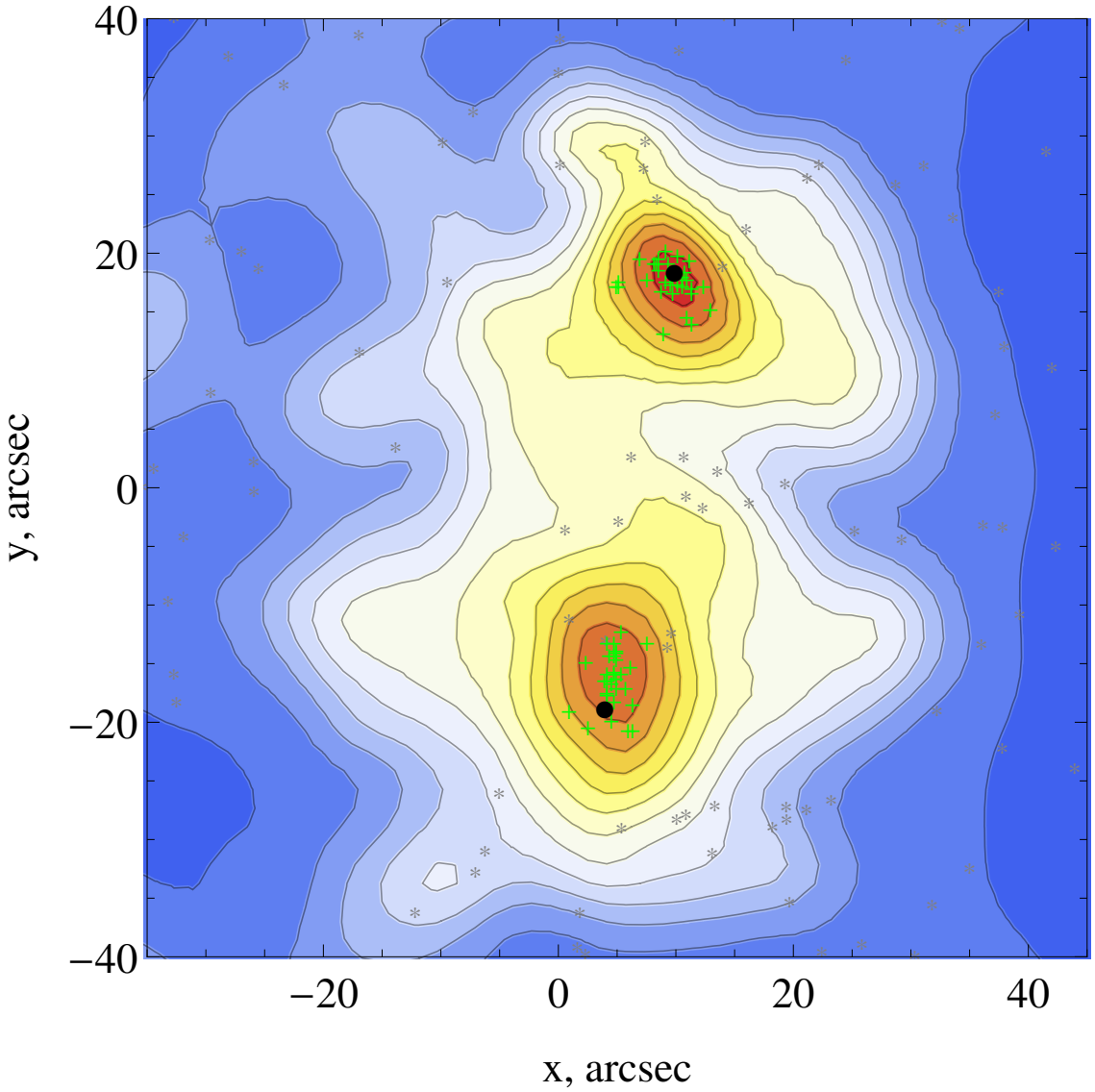


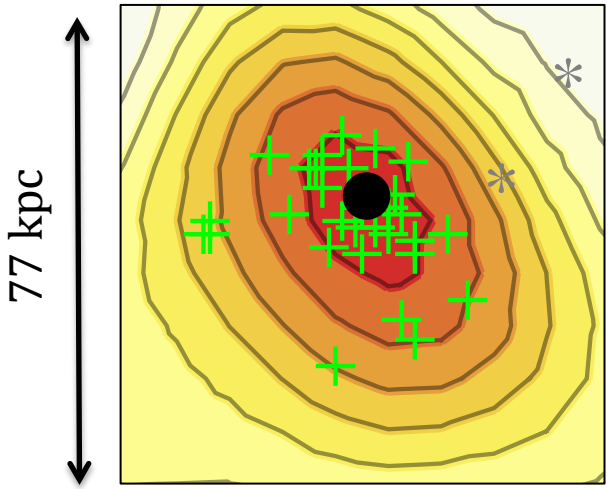
offset = 12.8 *kpc*

offset/rms = 0.94

offset/rms/$\sqrt{N}$ = 5.94

Grale map of Abell 370

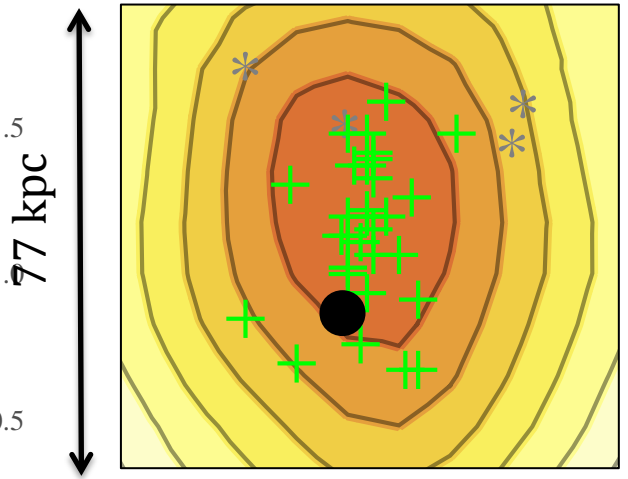




offset = 5.2 *kpc*

offset/rms = 0.39

offset/rms/$\sqrt{N}$ = 2.13

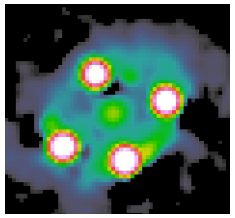


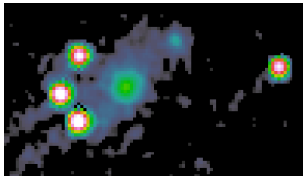
offset = 13.3 *kpc*

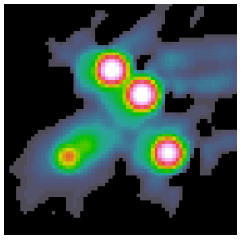
offset/rms = 0.98

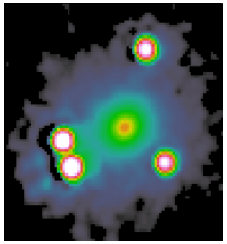
offset/rms/$\sqrt{N}$ = 5.39

Offsets/wobbles
in
isolated galaxies





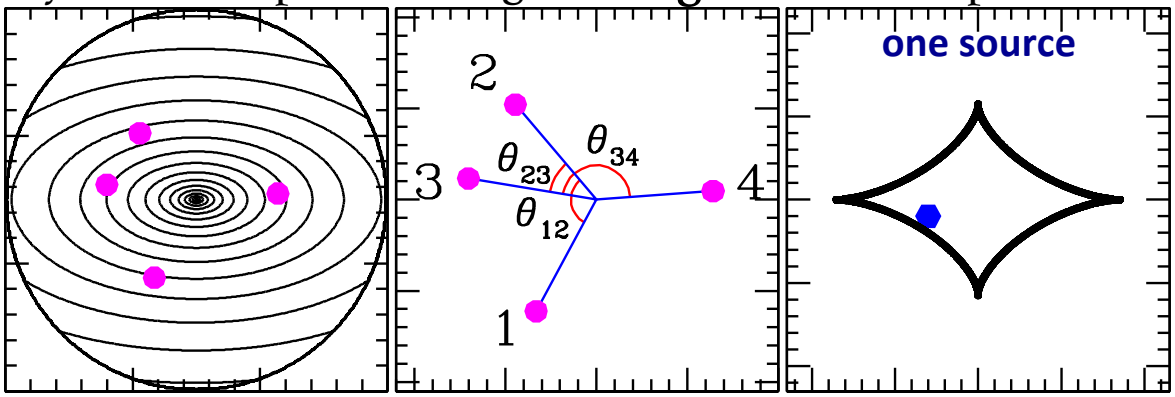




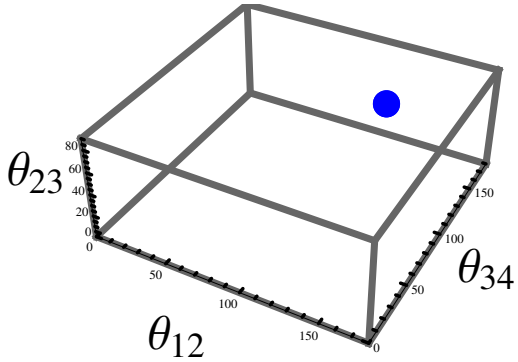
CASTLeS

An interesting property of quad lenses

sky view/lens plane | images & **angles** | source plane



3D angles space



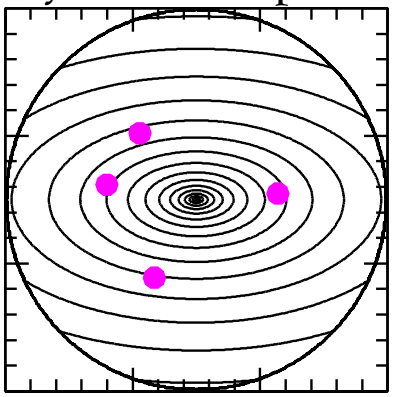
galaxy-lens isodensity contours and 4 quad images

1, 2, 3, 4: time arrival sequence

Woldesenbet+Williams 2012, 2015

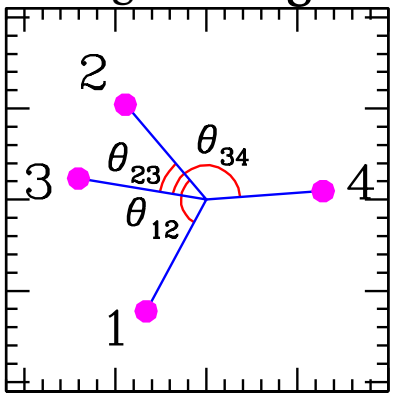
An interesting property of quad lenses

sky view/lens plane



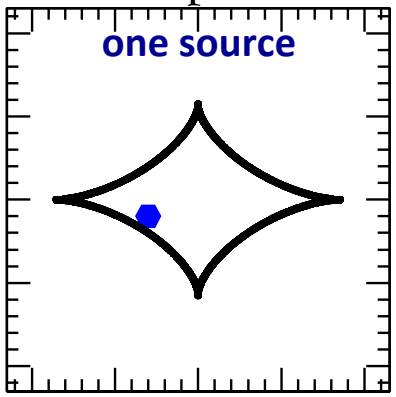
galaxy-lens isodensity contours and 4 quad images

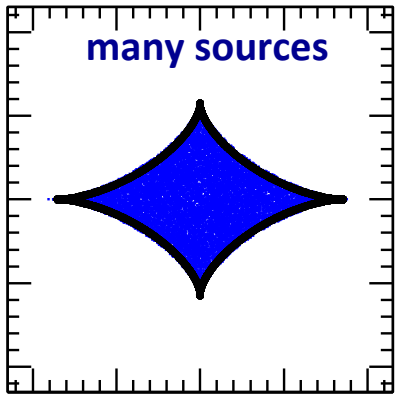
images & **angles**



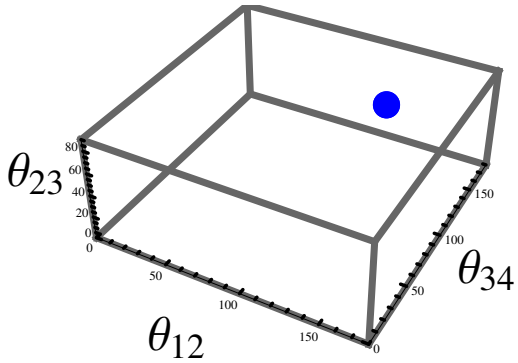
1, 2, 3, 4: time arrival sequence

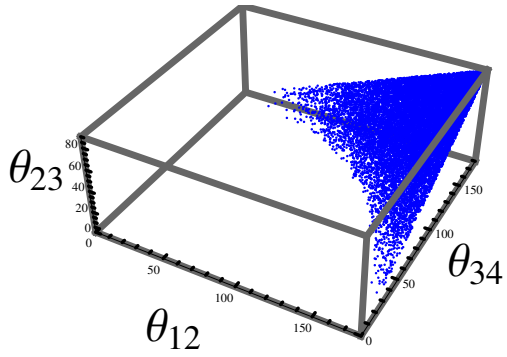
source plane





3D angles space

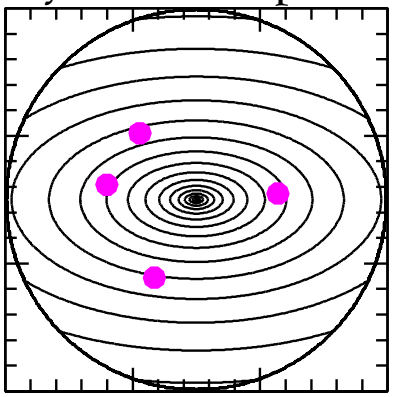




Woldesenbet+Williams 2012, 2015

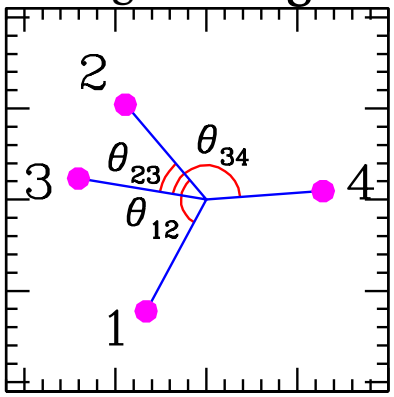
An interesting property of quad lenses

sky view/lens plane



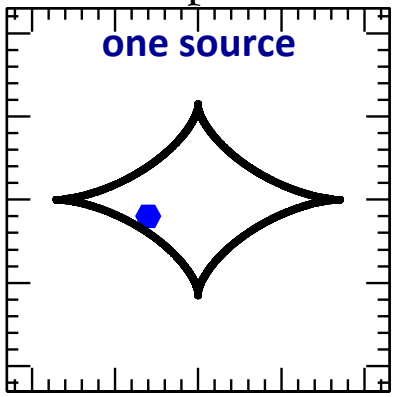
galaxy-lens isodensity contours and 4 quad images

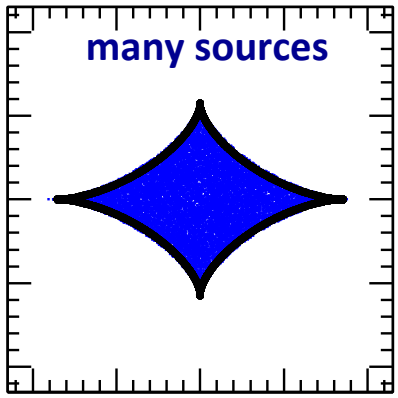
images & **angles**



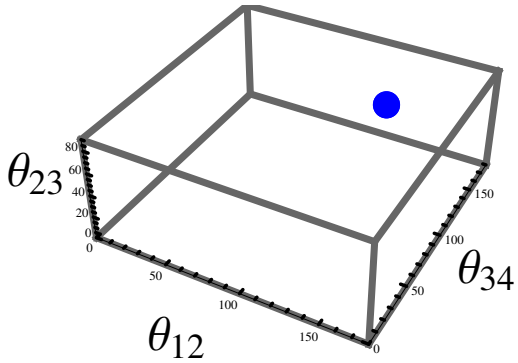
1, 2, 3, 4: time arrival sequence

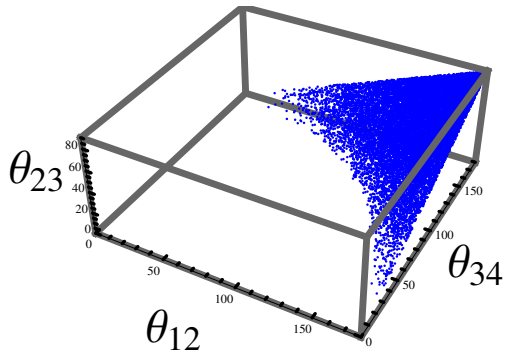
source plane





3D angles space





Woldesenbet+Williams 2012, 2015

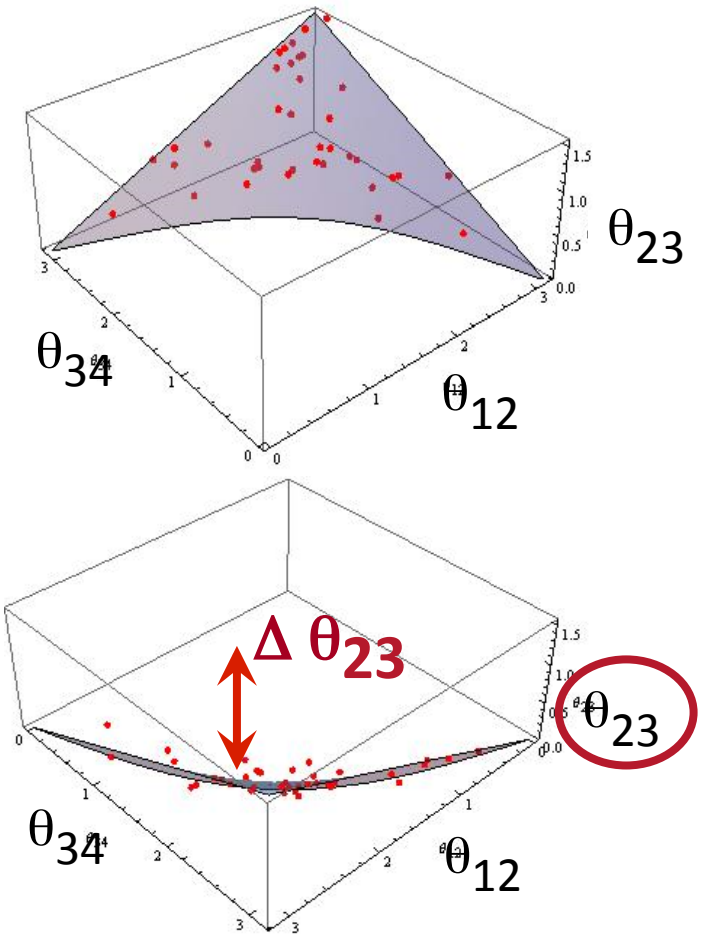
Double-mirror symmetric lenses with different density profile slopes and ellipticities produce *nearly identical* surfaces in 3D angles space

Fundamental Surface of Quads, FSQ

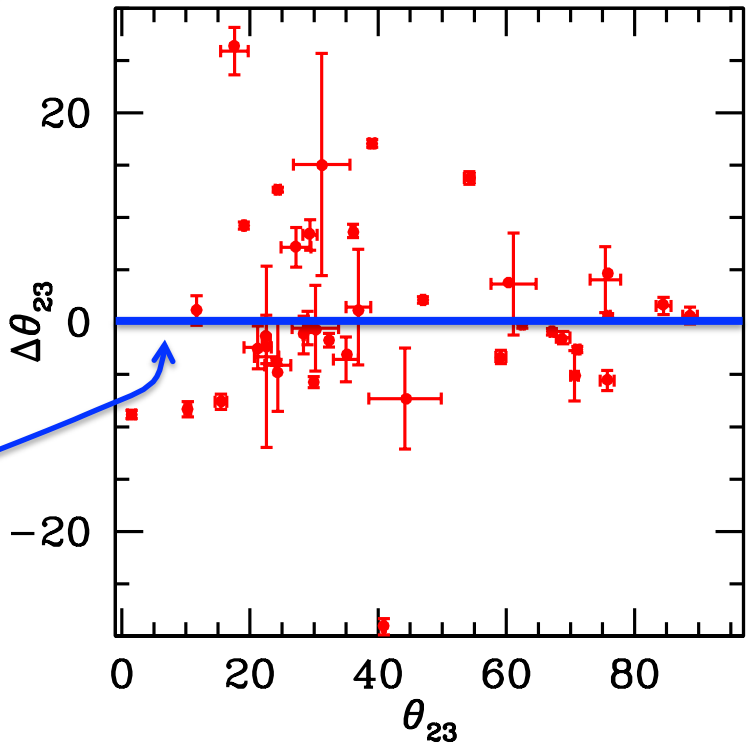
FSQ as a reference surface

Lenses that are not double-mirror symmetric do not lie on FSQ.
Instead, produce different distributions of quads around FSQ.

3D angles space



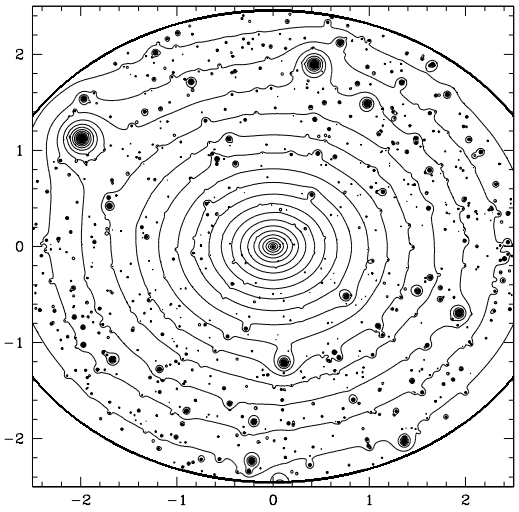
2D projected angles space

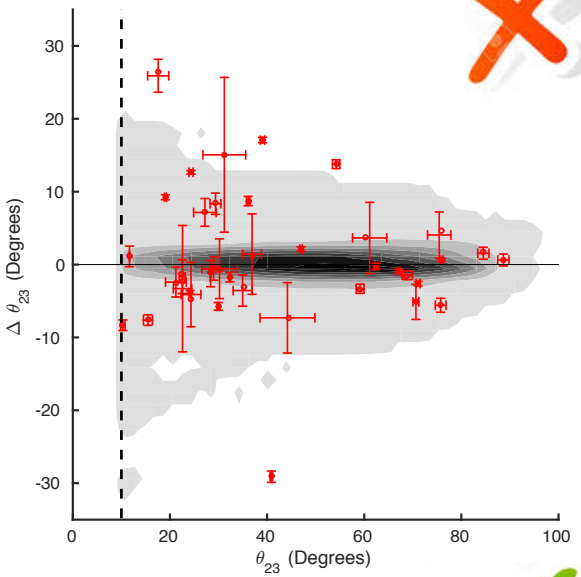


Each general type of lens has its own characteristic distribution, i.e. deviations from FSQ.

What type of substructure can reproduce deviations from the FSQ?

10xLCDM model--
based on Springel+2008 Aquarius sim. results, but each subhalo's mass has been increased by x10

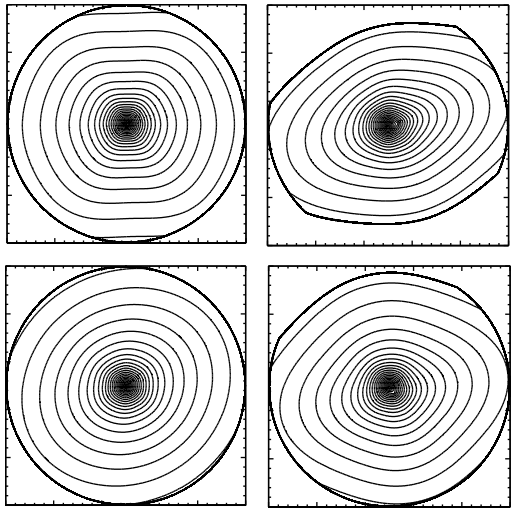


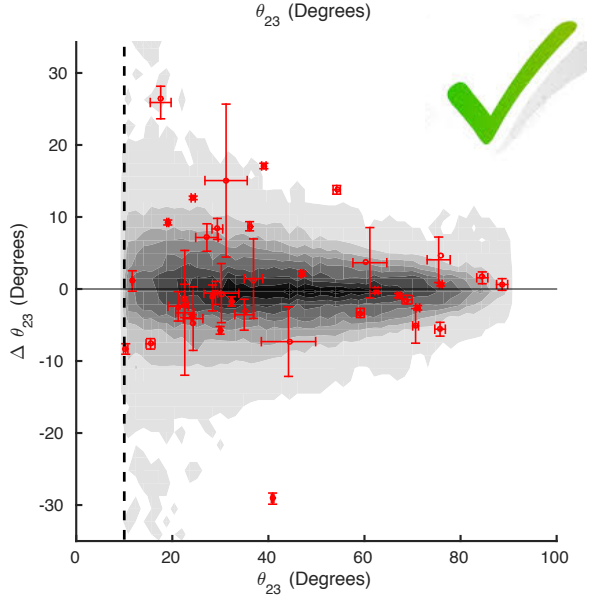


Deviations from elliptical symmetry—
→stars + DM distrib.
→perturbations from elliptical isodens

$$\Delta R = \sum_{k=3}^{6} a_k \cos(k\phi) + b_k \sin(k\phi)$$

→**DM-stars offset, < 1kpc**
→magnification bias





Gomer+Williams 2017

Fundamental Surface of Quads

Advantages of this approach
of extracting information on lens mass distribution, from galaxy quads

* Polar image angles are straightforward to measure
* No fitting of models to individual lenses
  → model free
  → lensing degeneracies not an issue
* Use quad population as a whole

Future surveys, LSST, DES,…, with follow up from HST, JWST, LBT will uncover 100's – 1000's quads, with well defined selection cuts

Summary

Offsets detected in clusters & galaxies,
using two very different techniques

HST Frontier Field Clusters:
offsets between the brightest galaxies and the nearest mass peaks are ~0-15 kpc; statistical significance?
None of the 5 galaxy-mass offsets is larger than ~15 kpc.

Quads hosted by isolated massive galaxies:
distribution of image polar angles of the quad population shows that elliptical+shear and LCDM substructure are not enough to reproduce deviations from the Fundamental Surface of Quads. *Offseting the centers of the stellar and dark matter distribution by <1kpc can reproduce observations.*