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Signatures of Mass-to-light Deviations in Abell 370

A free-form reconstruction using BUFFALO strong lensing data

arXiv:2104.11781

Introduction

We used the strong lensing image data of the merging galaxy cluster Abell 370 from the **Beyond Ultra-deep Frontier Fields and Legacy Observations (BUFFALO)** to obtain a reconstructed lens model using the free-form lens inversion algorithm **GRALE**.

In general mass follows light but we found signatures of **three mass features** which indicates mass-to-light deviation scenarios.

GRALE

GRALE is a **free-form lens inversion algorithm**, based on a genetic algorithm (GA).

An initial coarse uniform grid in the lens plane is populated by the basis set, projected Plummer density spheres.

The GA breeds the best solution for a given grid.

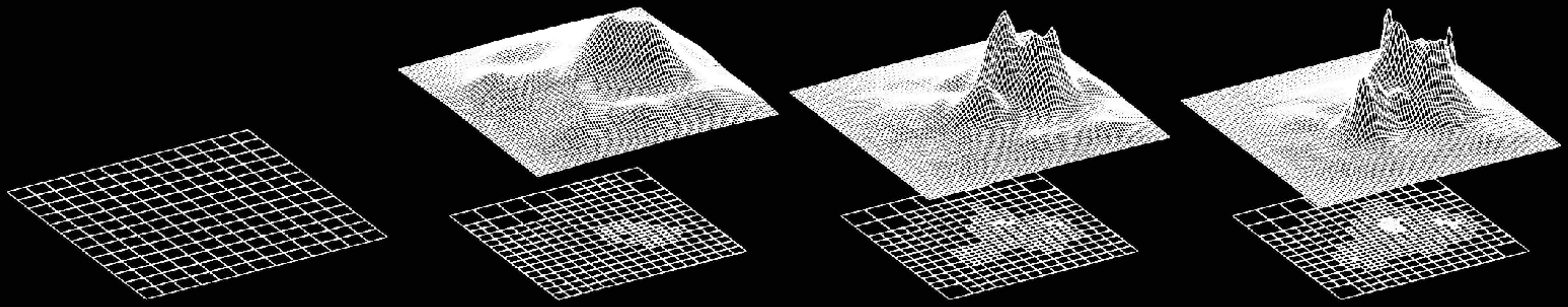
Using dynamic grid, the denser regions are resolved with a finer grid and each cell given a Plummer with a proportional width.

The fitness value is calculated based on fractional overlapping of back-projected images from the same source.

The final map is a superposition of Plummers, each with its own size and weight.

Liesenborgs et al. (2006, 2020)
Ghosh et al. (2020)

We use an average of 40 independent runs.



Abell 370

The BUFFALO mosaic in *HST* **ACS/F814w** filter. Although BUFFALO covers a much wider area, here we are focussing only on the strongly lensed central region.

Center

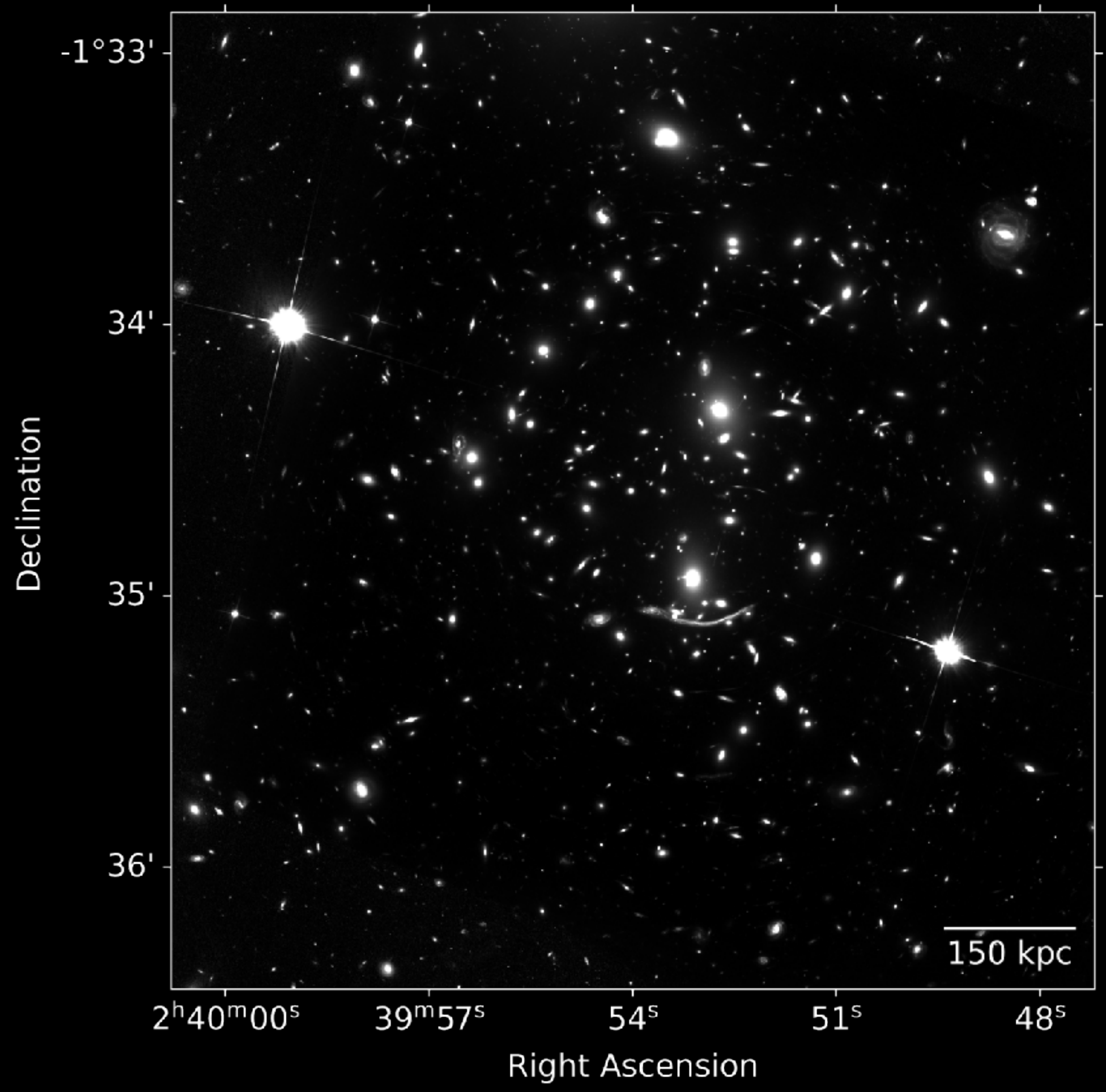
$R.A. = 39.970°$

$dec. = -1.577°$

Cluster Redshift

$z = 0.375$

Steinhardt et al. (2020)



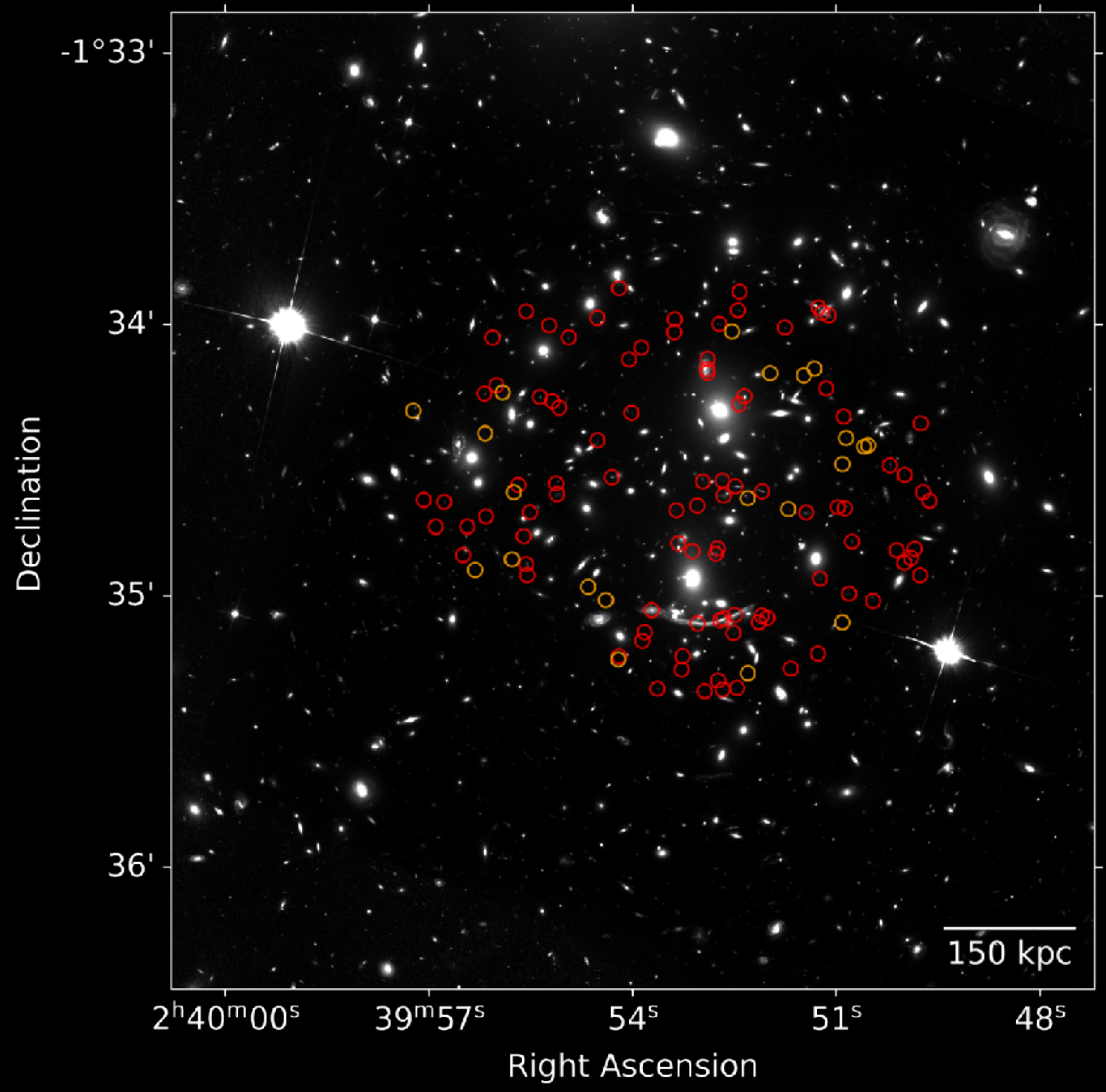
Multiply Lensed Images

GRALE only uses the **multiply lensed images and their redshifts** as input.

We used 39 systems with 114 multiple images from the BUFFALO strong lensing multiple image catalog.

Image **Redshifts**

- 31 systems with spectroscopic redshifts from MUSE (Lagattuta et al. 2019)
- 8 systems with photometric redshifts.



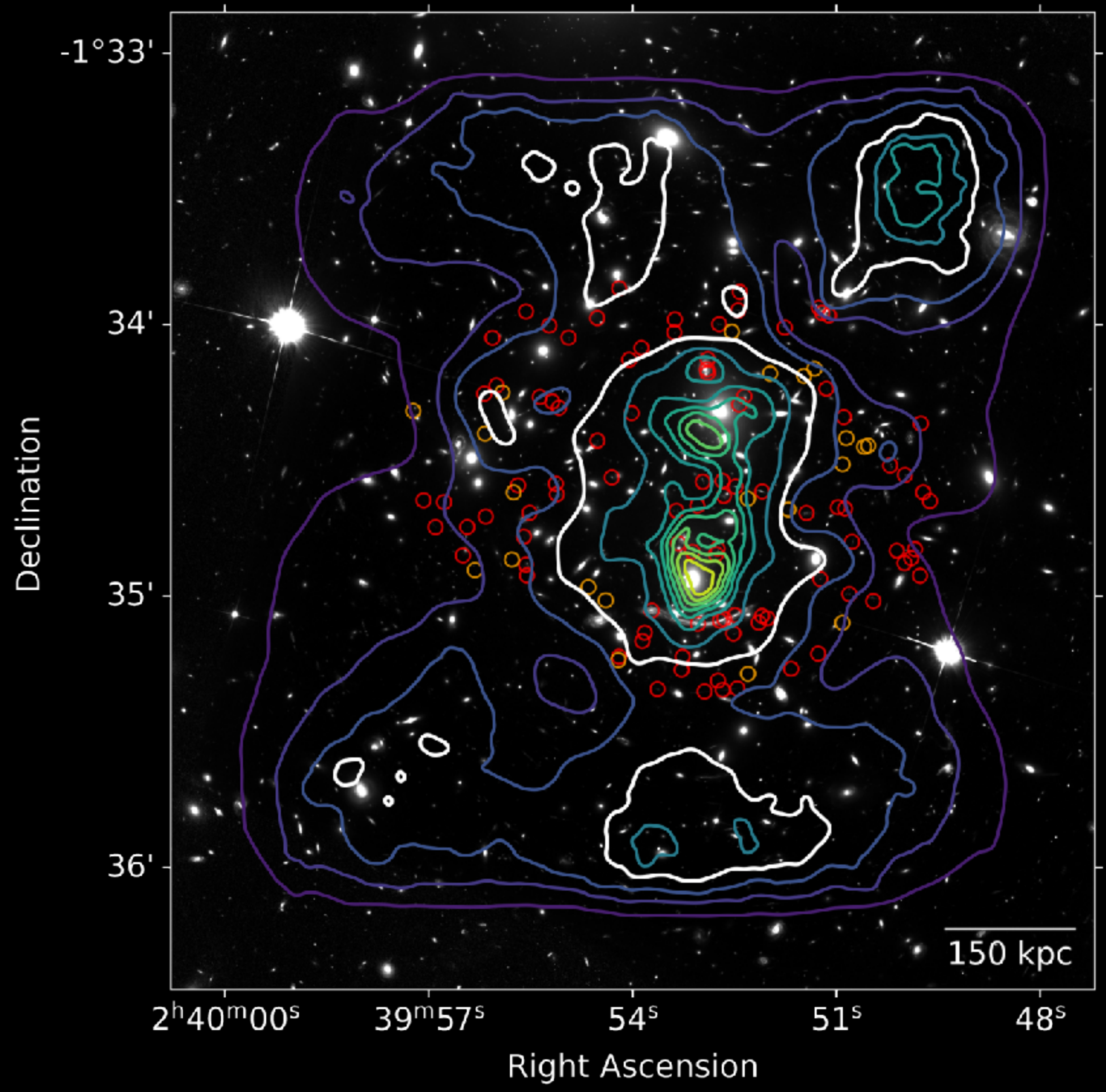
Reconstructed Mass Distribution

The final mass map is an average of 40 individual GRALE runs.

The mass distribution is normalized by the critical surface mass density for sources at infinity, $\Sigma_{crit,0} = c^2/4\pi G D_{ol}$.

White contours: $\kappa = 1$.

The reconstruction confirms **active merging state of the cluster**, as indicated by two large mass peaks separated by ~200 kpc along the N-S direction.



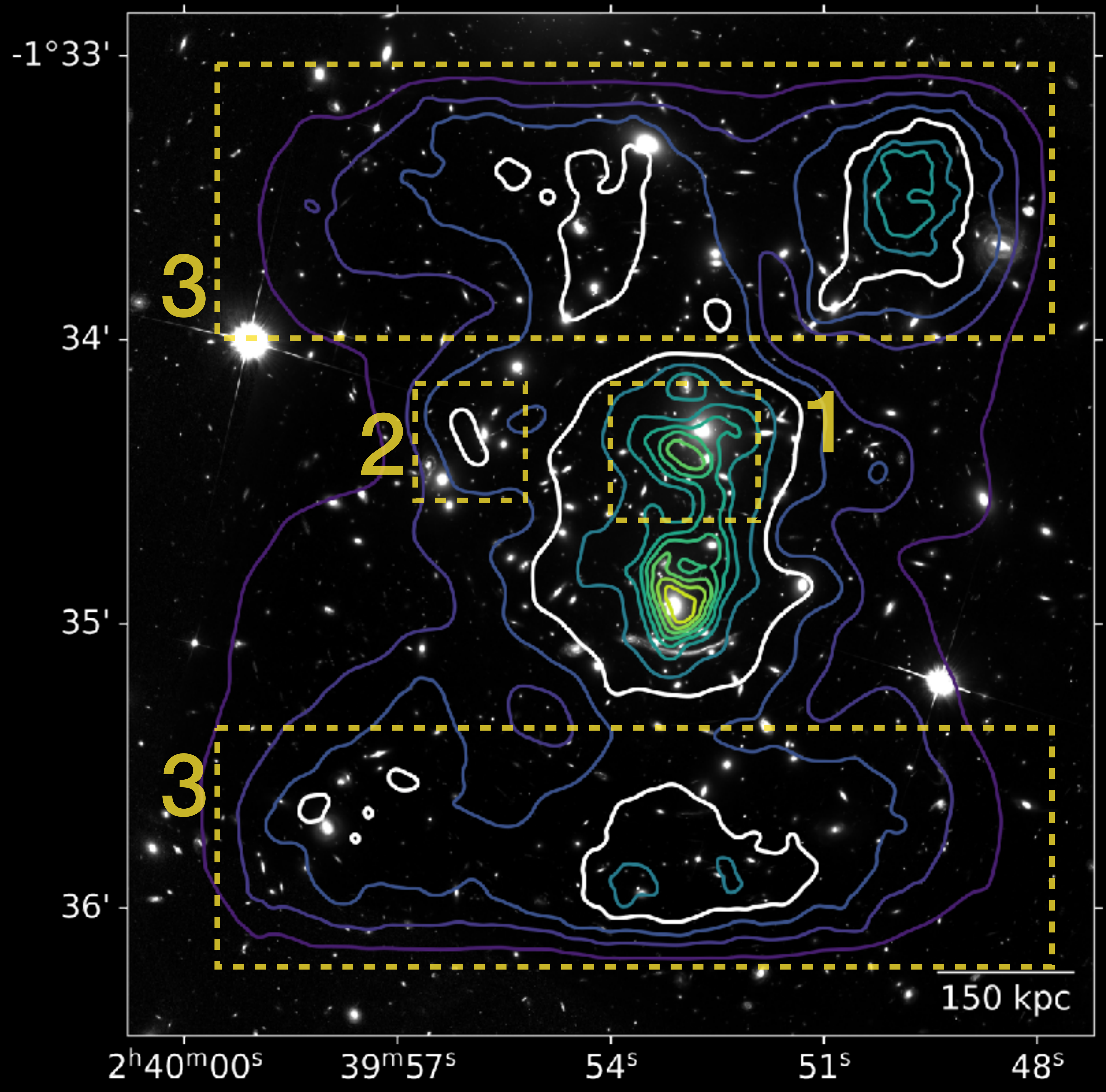
Signatures of Mass-to-Light Deviations

Three possible signatures:

1. The **offset between the northern BCG and the nearest mass peak**.

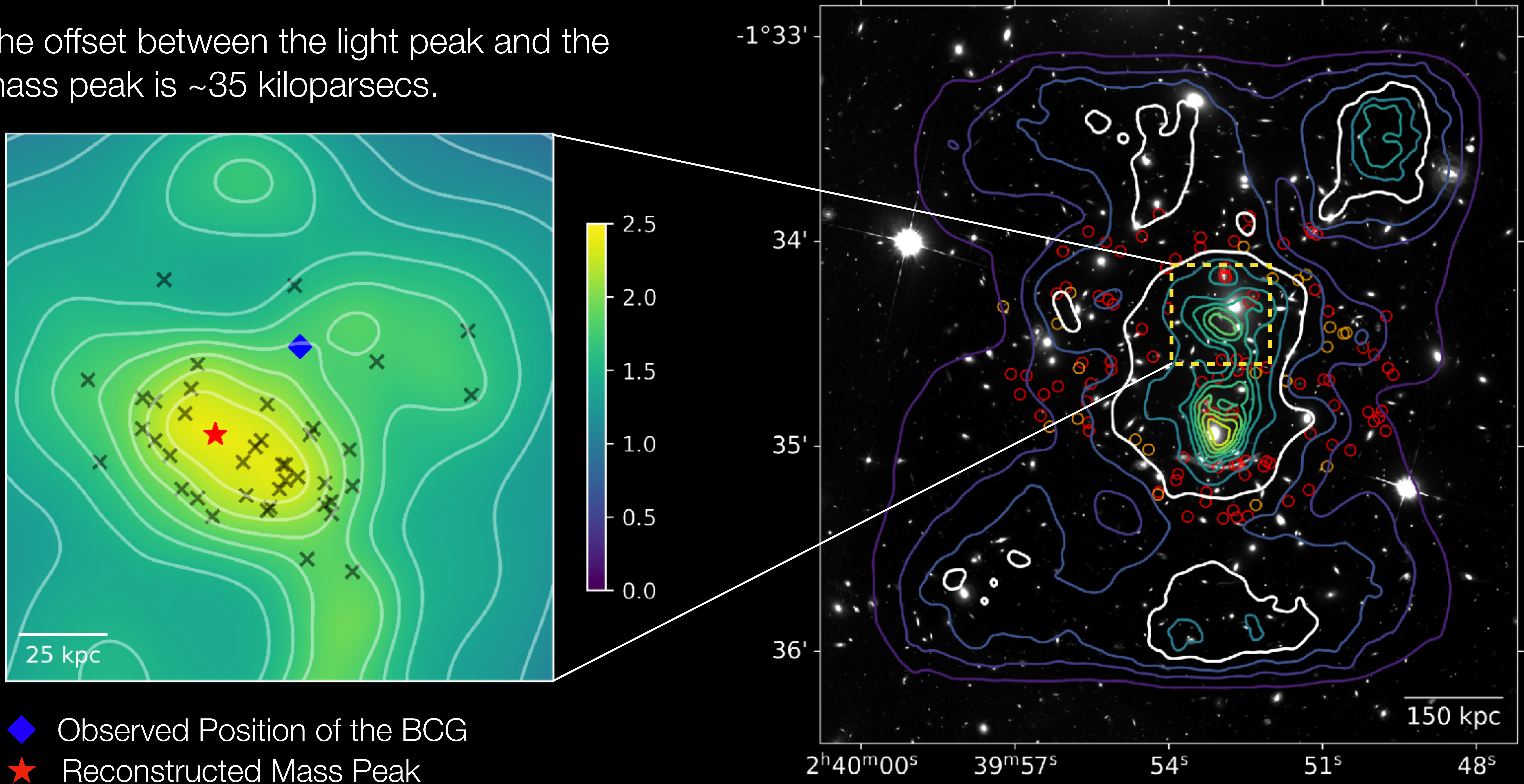
2. The **~100 kpc mass concentration** of super-critical density ~250 kpc east of the main cluster.

3. **A filament-like structure** passing N-S through the cluster.



Offset in the Northern BCG

The offset between the light peak and the mass peak is ~35 kiloparsecs.

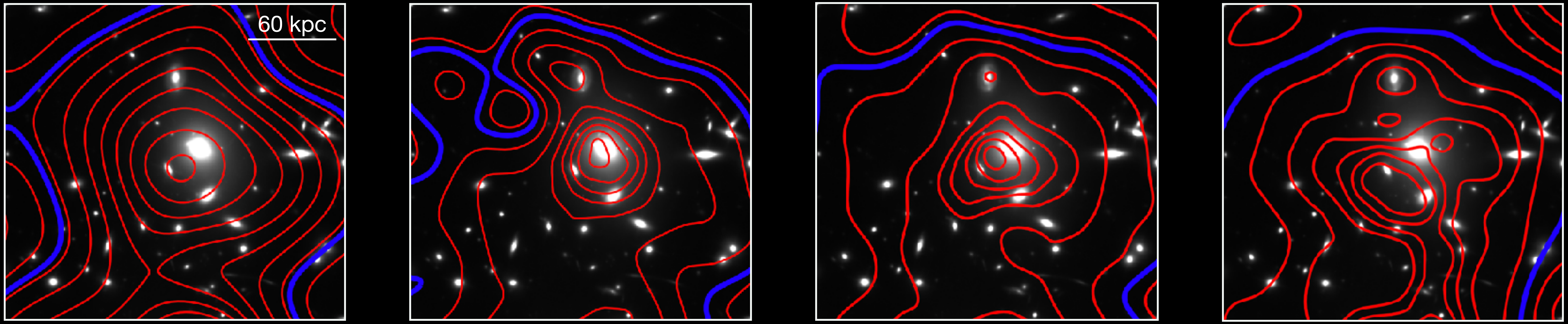


Observed Position of the BCG

Reconstructed Mass Peak

Black crosses: Mass peaks for individual runs

Northern BCG: GRALE Models

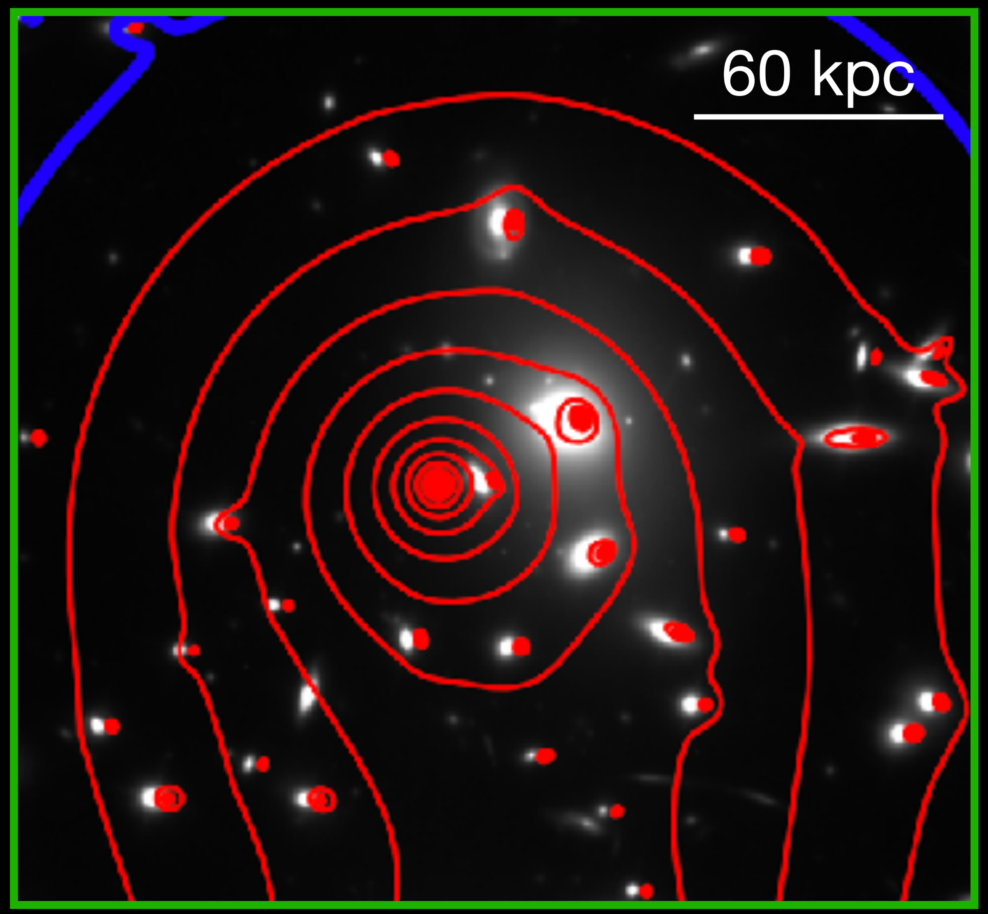


GRALE HFF v1	GRALE HFF v4	GRALE HFFv4.1	GRALE BUFFALOv1 (This Work)
~40 images	124 images	101 images	114 images

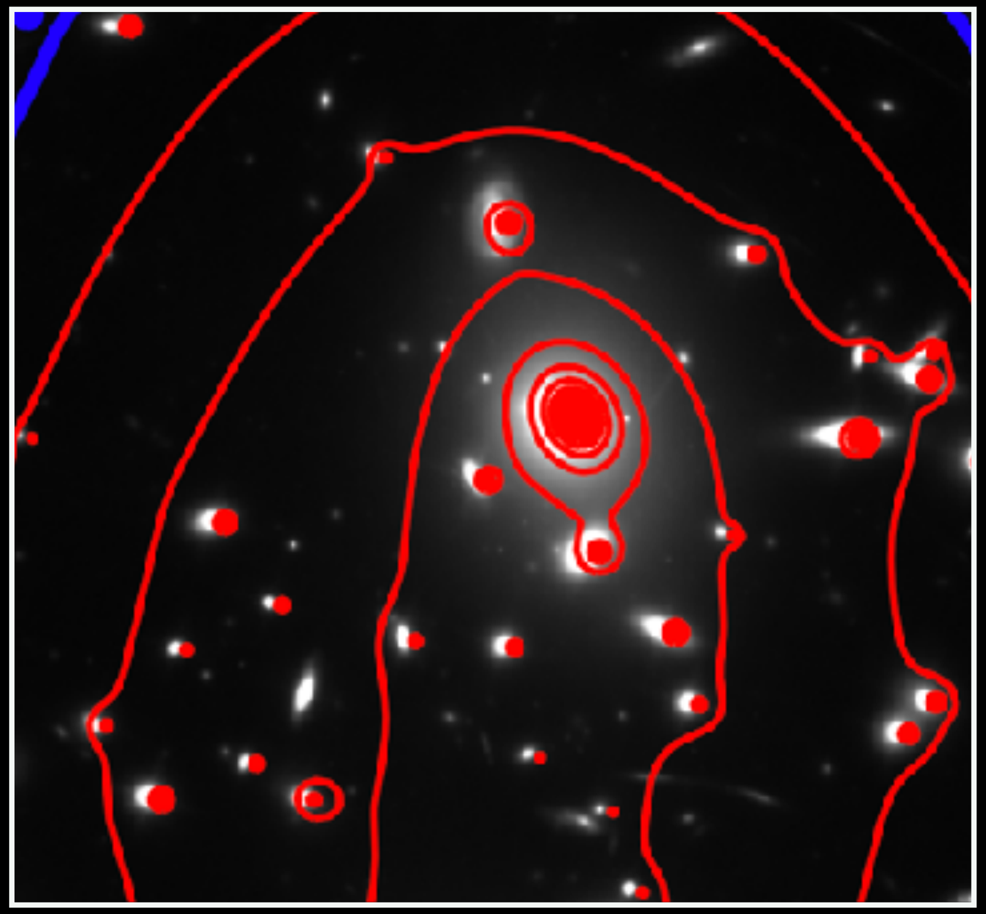
Red contours show the convergence. Blue contours are $\kappa = 1$.
All the GRALE reconstructions since HFFv1 shows the offset between the northern light peak of the BCG and the reconstructed mass peak.

Note: *The contours are not uniformly scaled.*

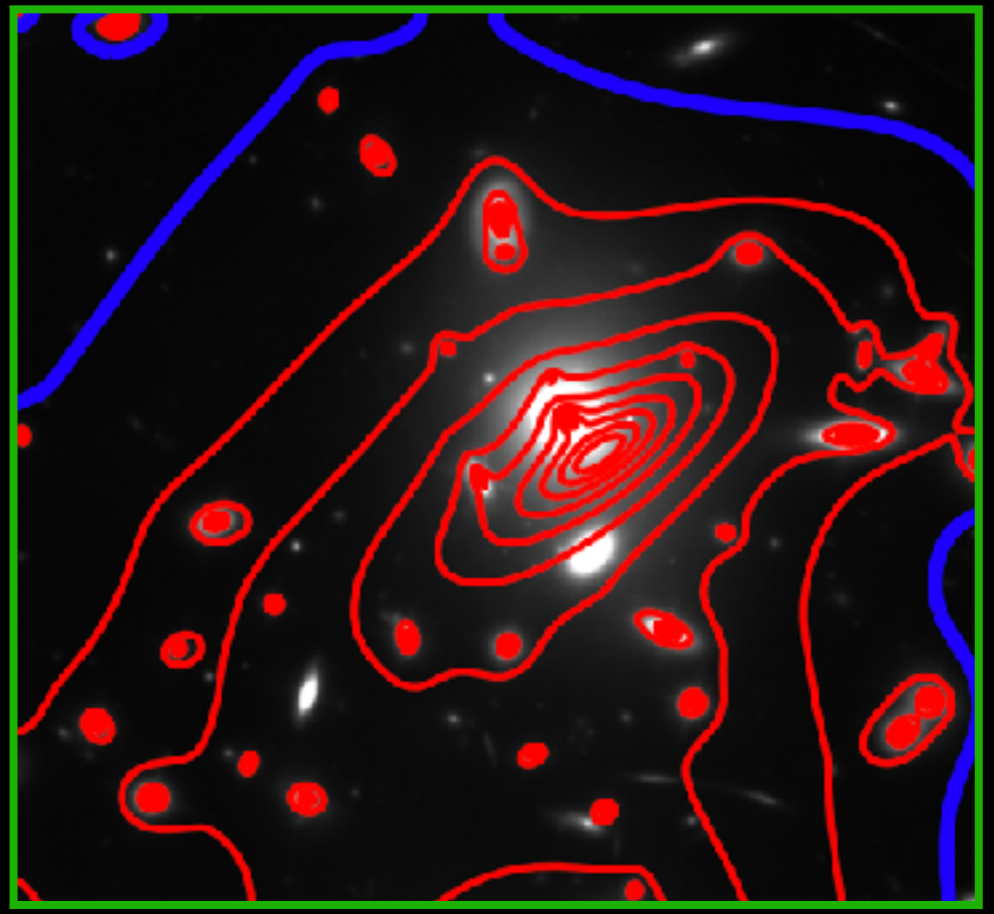
Northern BCG: HFF Models



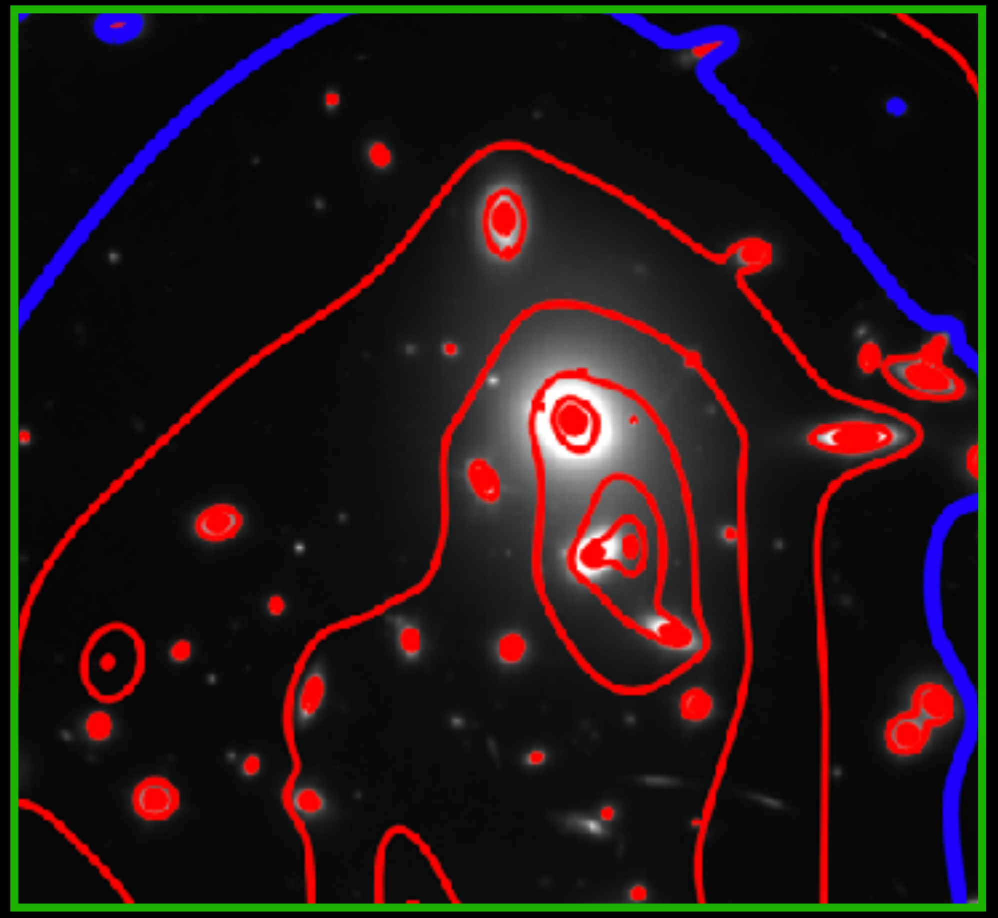
Zitrin NFW v1



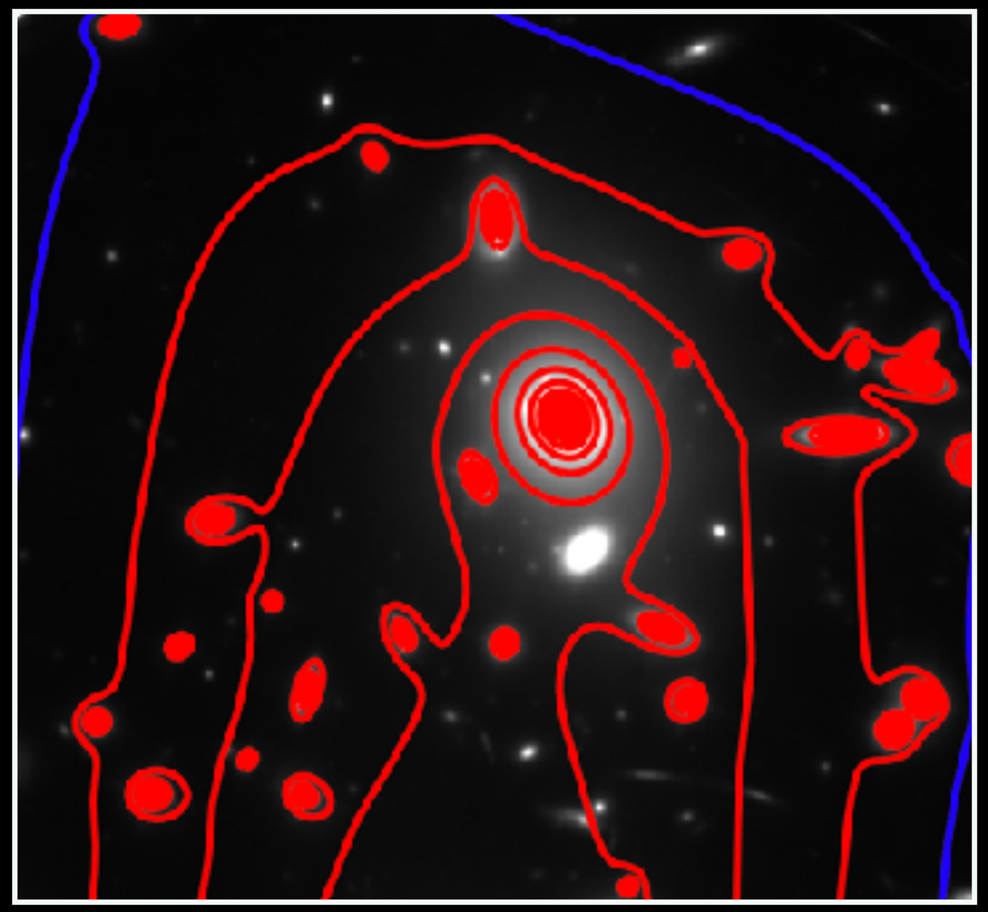
Zitrin LTM v1



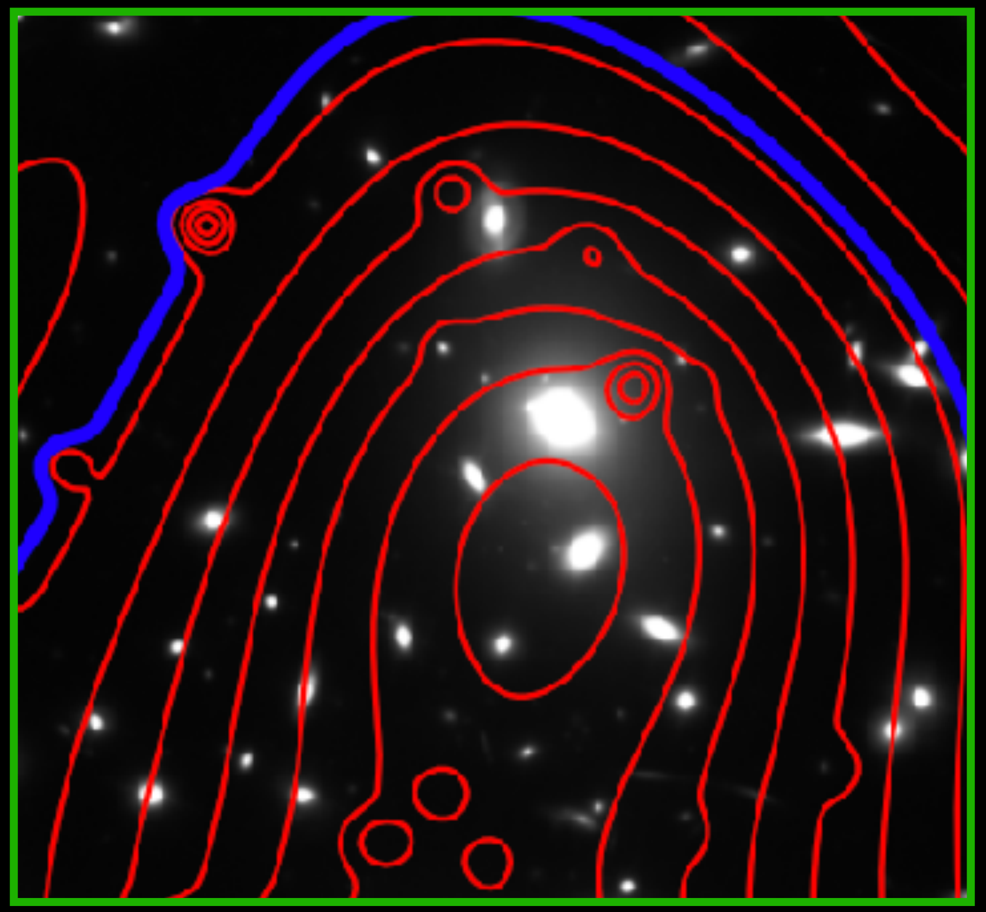
LENSTOOL Sharon v4



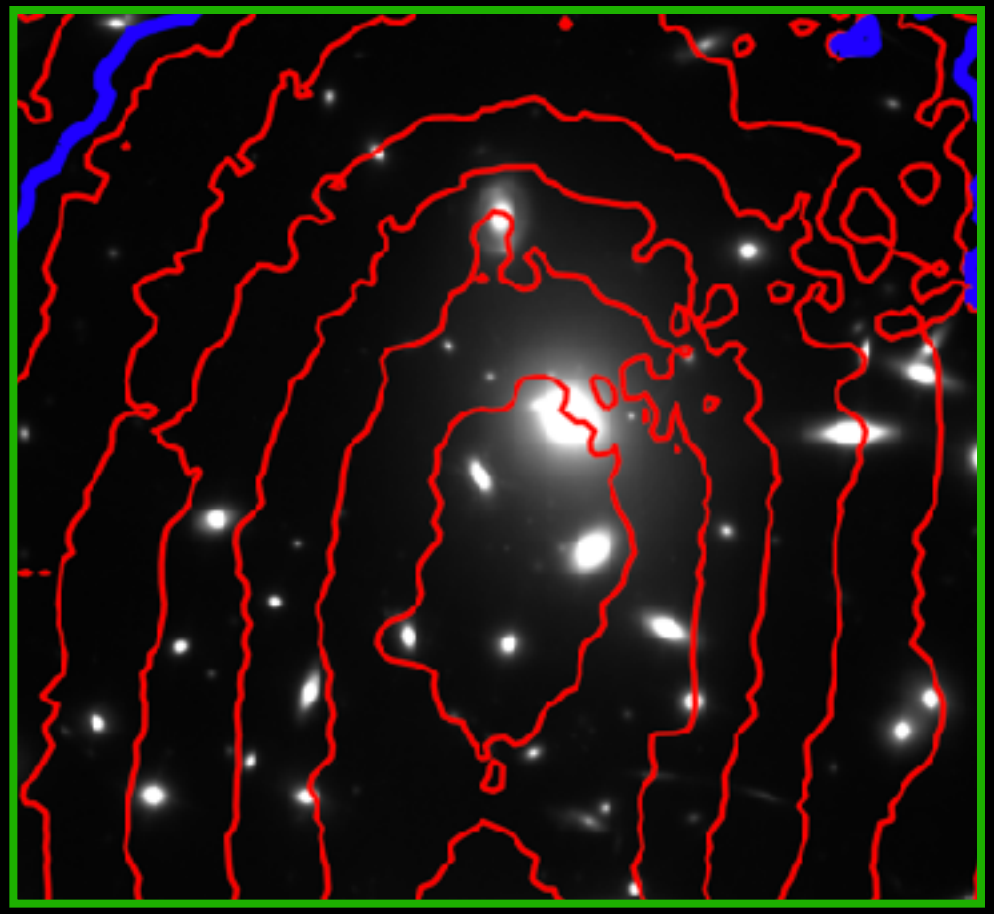
GLAFIC v4



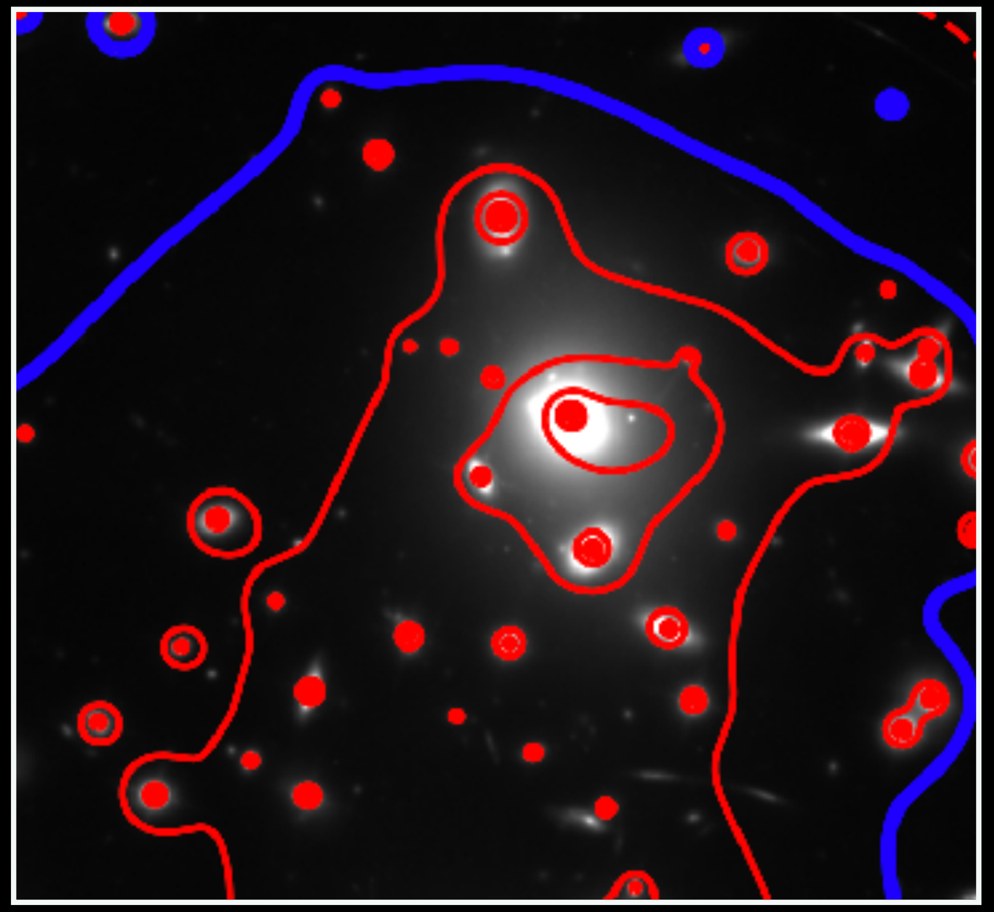
LENSTOOL CATS v4



WSLAP+ v4



SWUnited v4



LENSMODEL v4

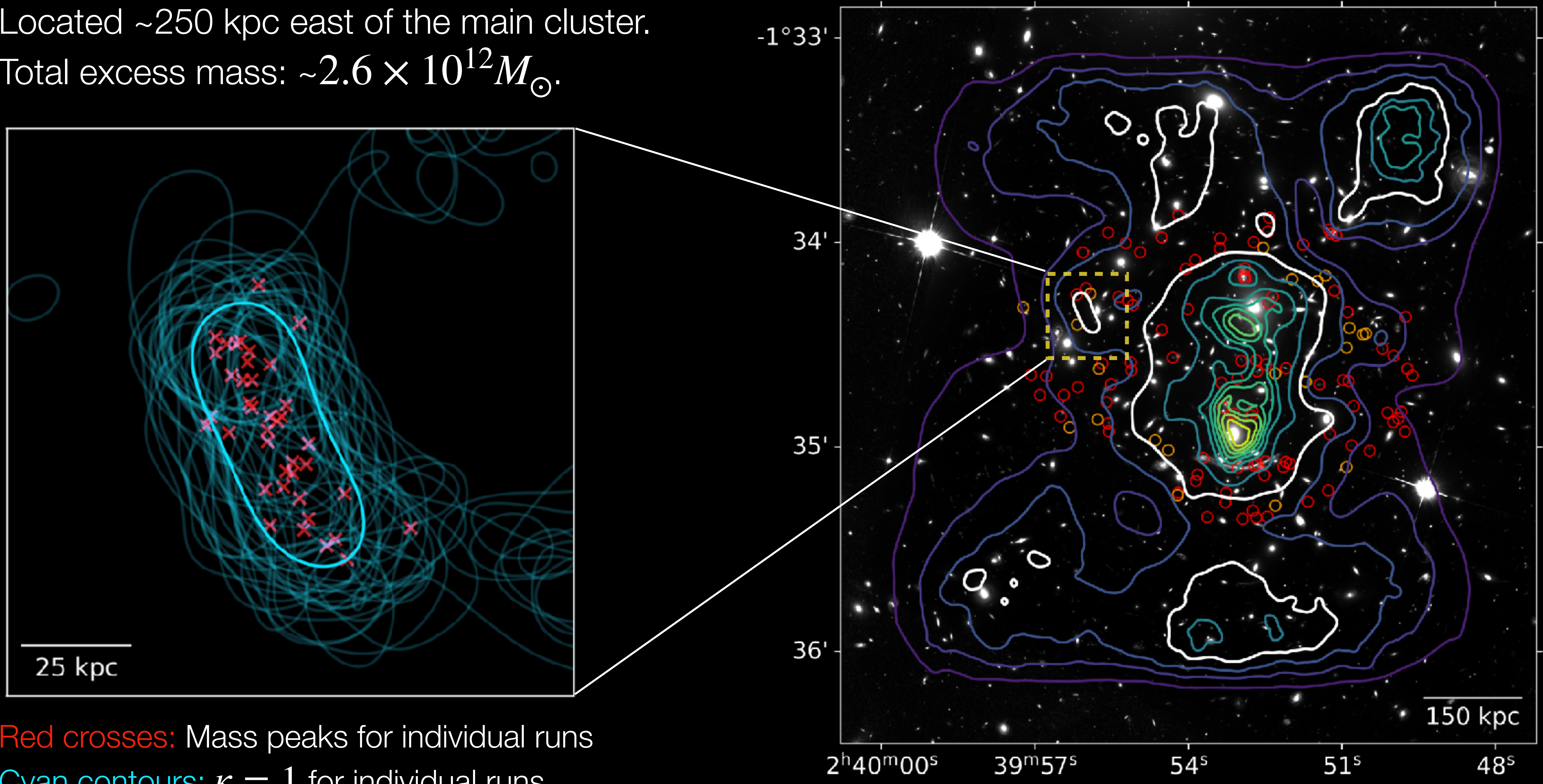
Note: *The contours are not uniformly scaled.*

Source: STScI/MAST

A ~100 kpc substructure

Located ~250 kpc east of the main cluster.

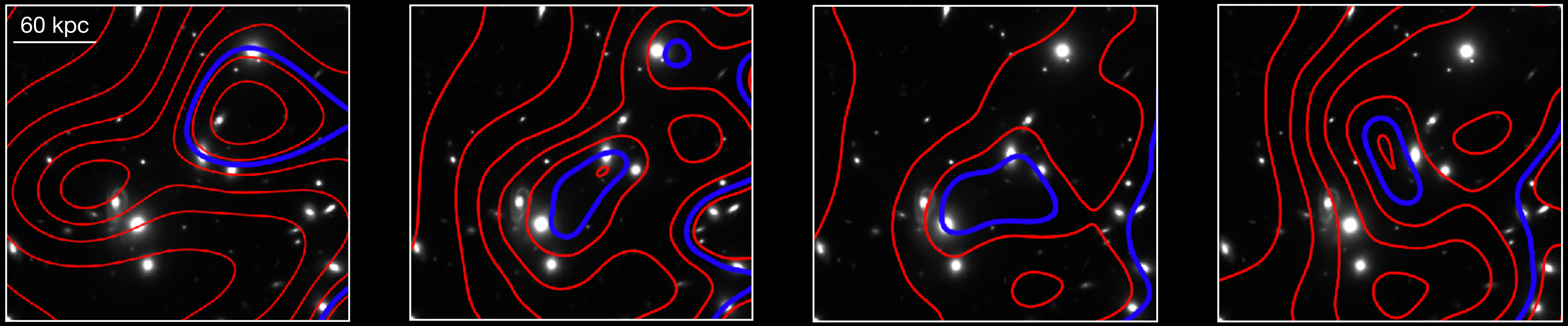
Total excess mass: ~$2.6 \times 10^{12} M_{\odot}$.



Red crosses: Mass peaks for individual runs

Cyan contours: $\kappa = 1$ for individual runs

~100 kpc substructure: GRALE models

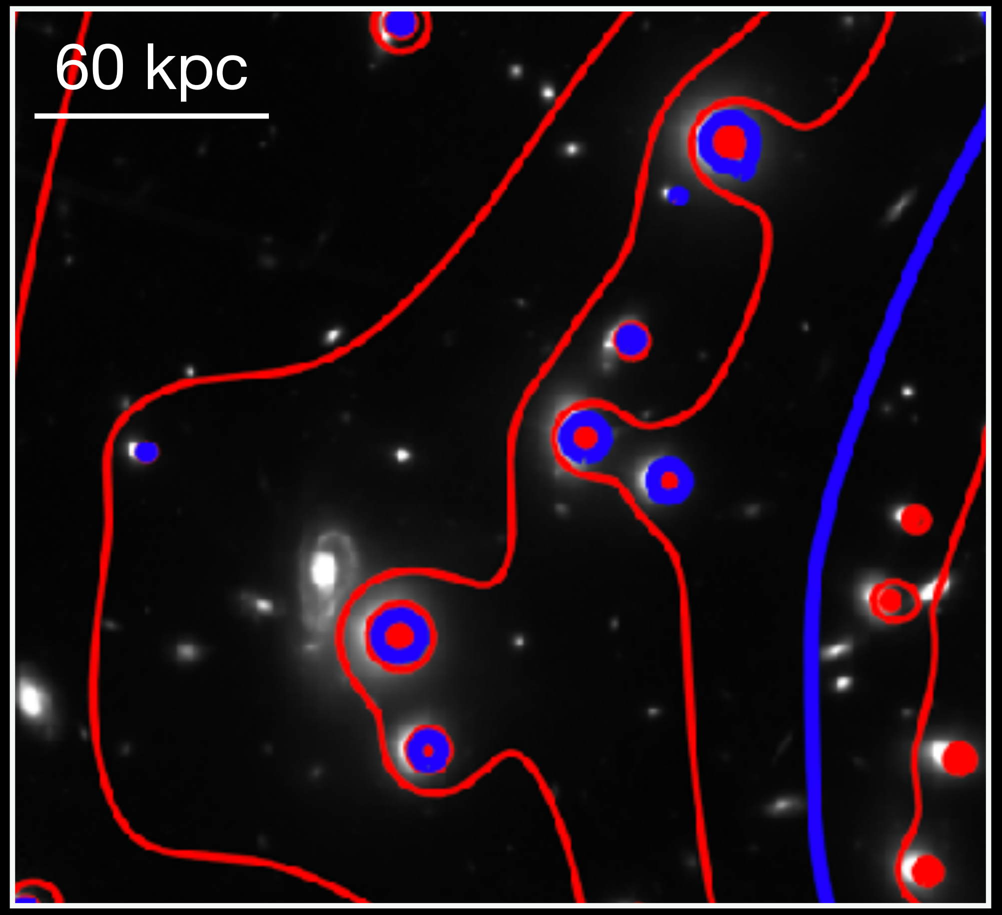


GRALE HFFv1 | **GRALE HFFv4** | **GRALE HFFv4.1** | **GRALE BUFFALOv1 (This Work)**

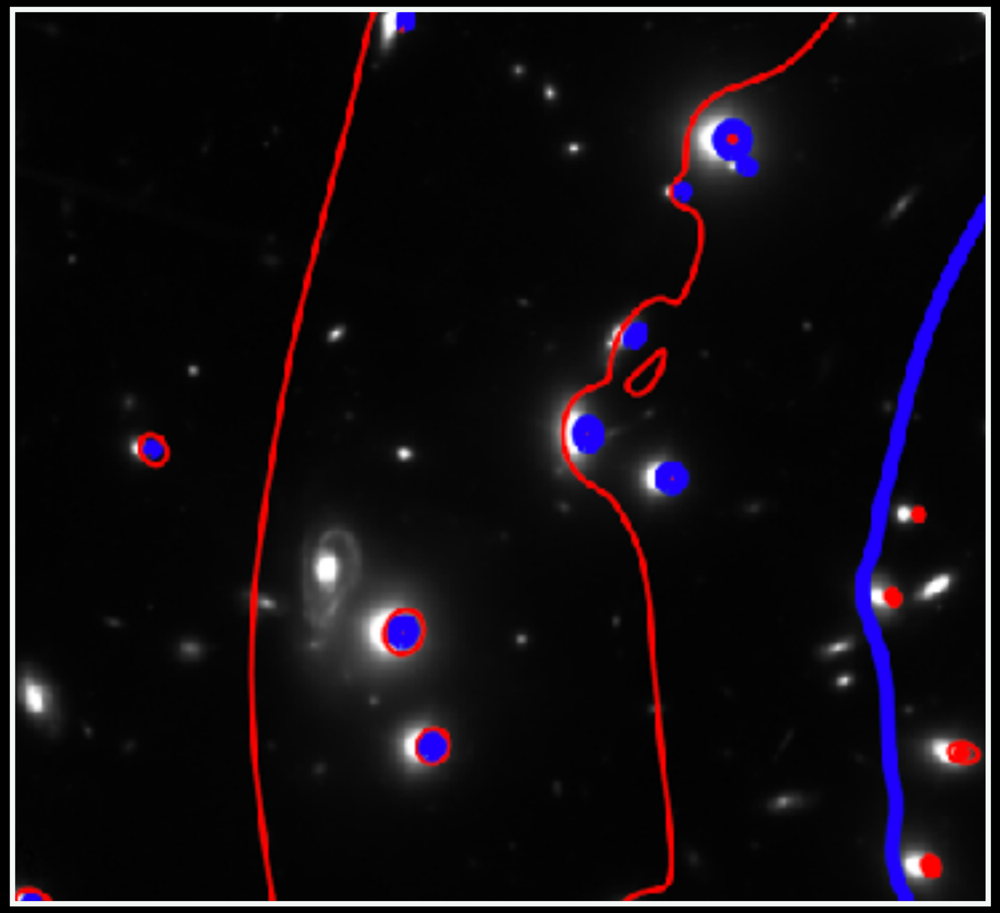
Red contours show the convergence. Blue contours are $\kappa = 1$.
All the GRALE reconstructions have consistently recovered a substructure around the same location since HFFv1.

Note: *The contours are not uniformly scaled.*

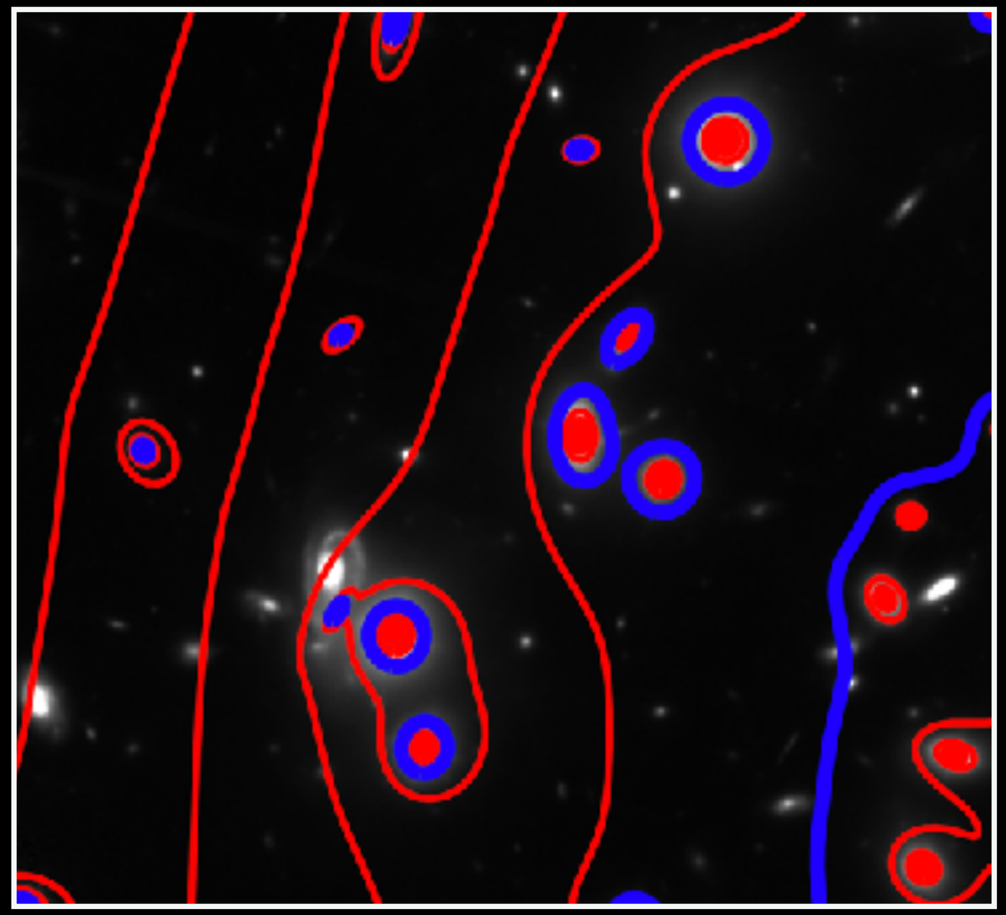
~100 kpc substructure: HFF Models



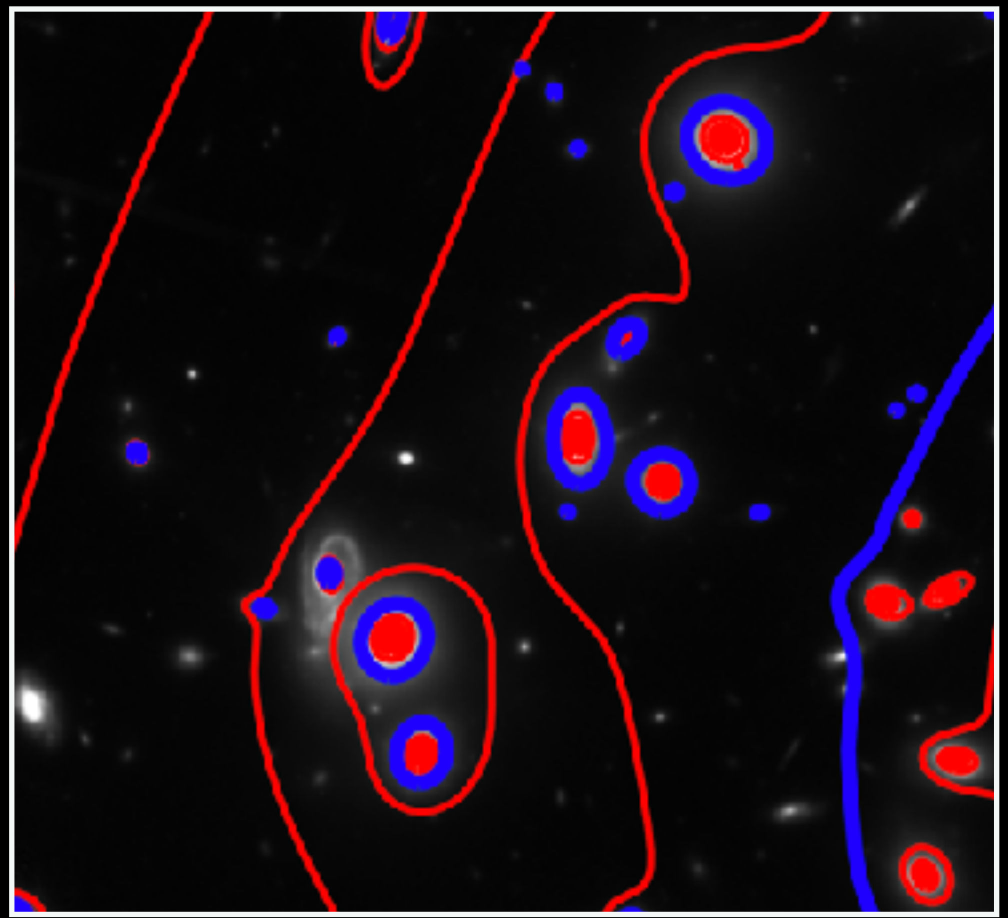
Zitrin LTM v1



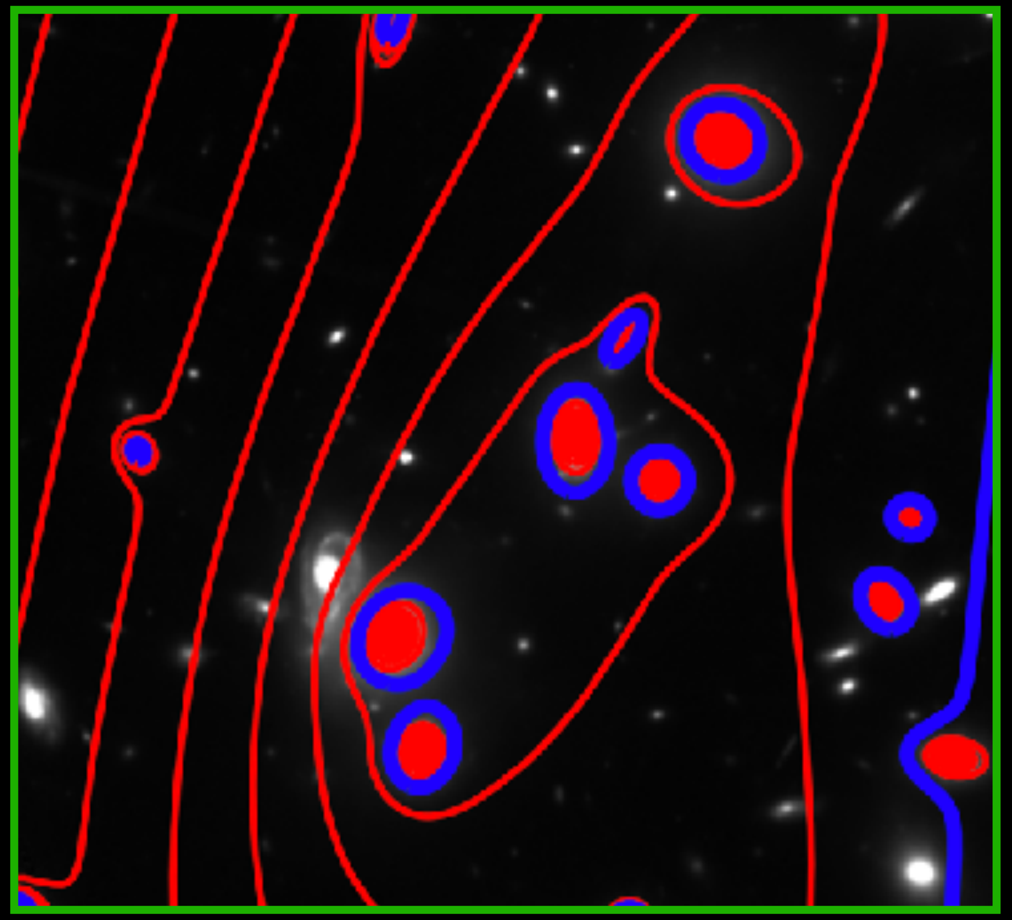
Zitrin NFW v1



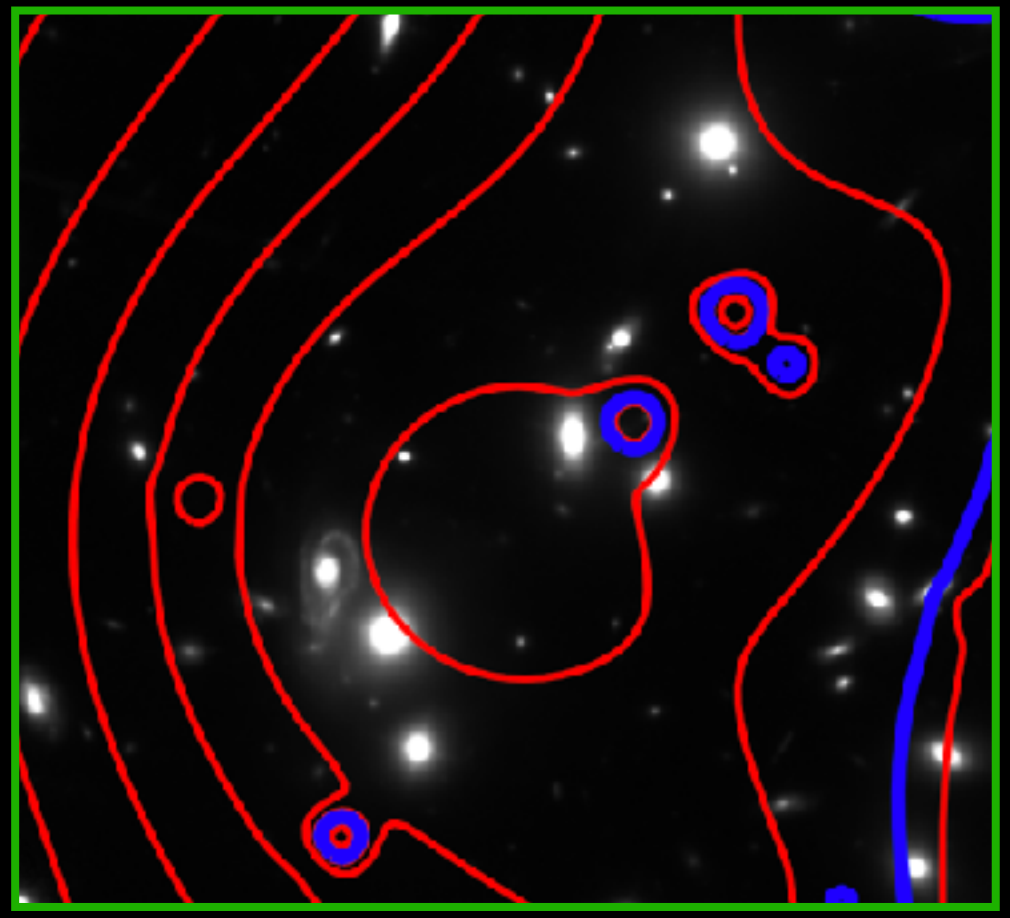
LENSTOOL Sharon v4



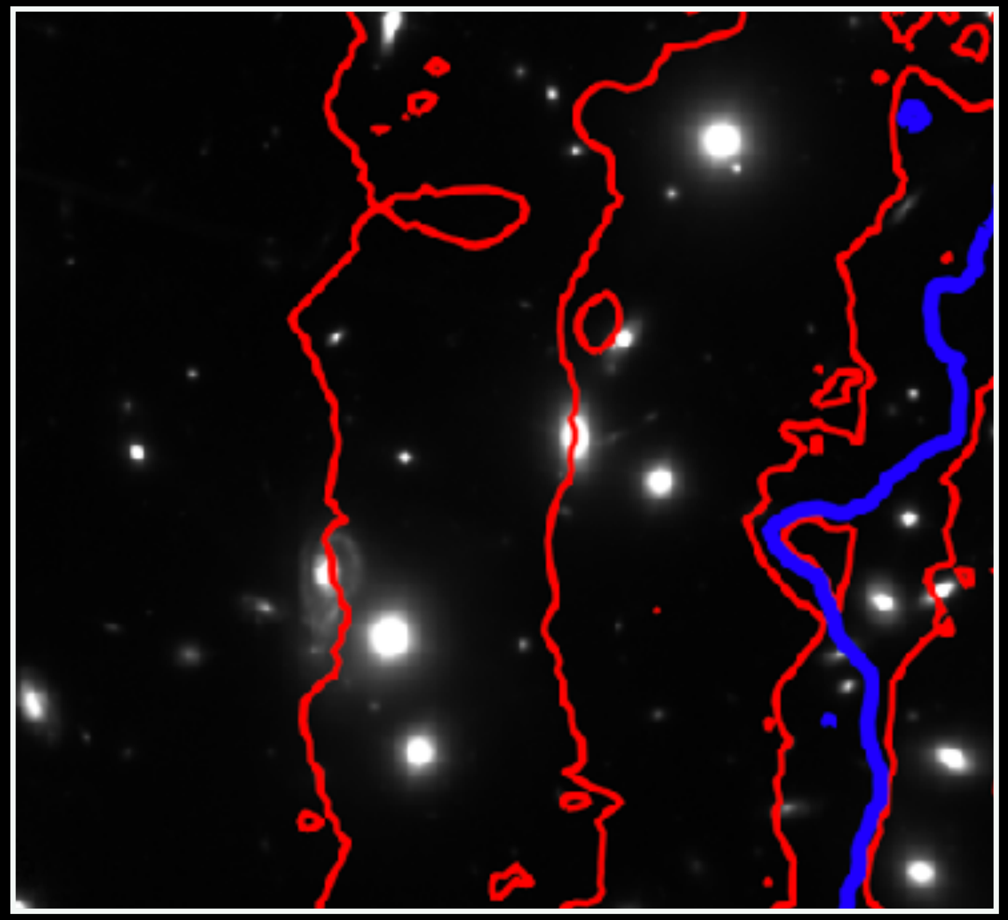
GLAFIC v4



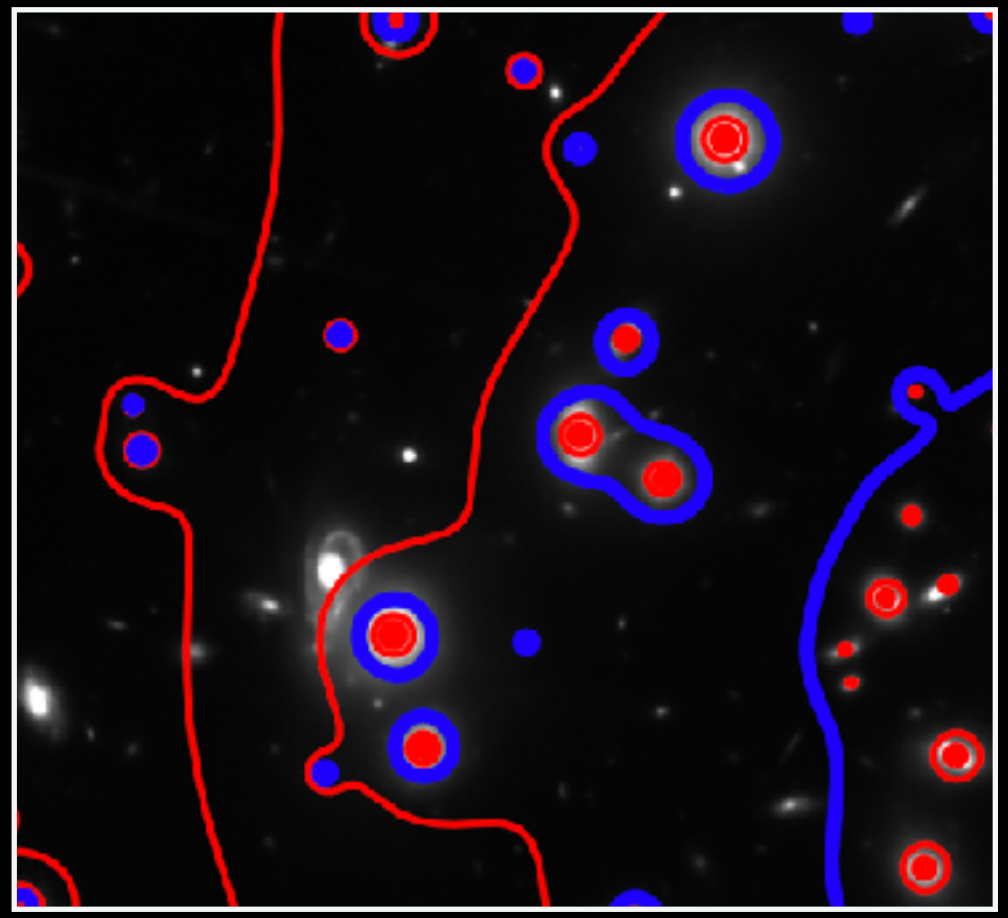
LENSTOOL CATS v4



WSLAP+ v4



SWUnited v4



LENSMODEL v4

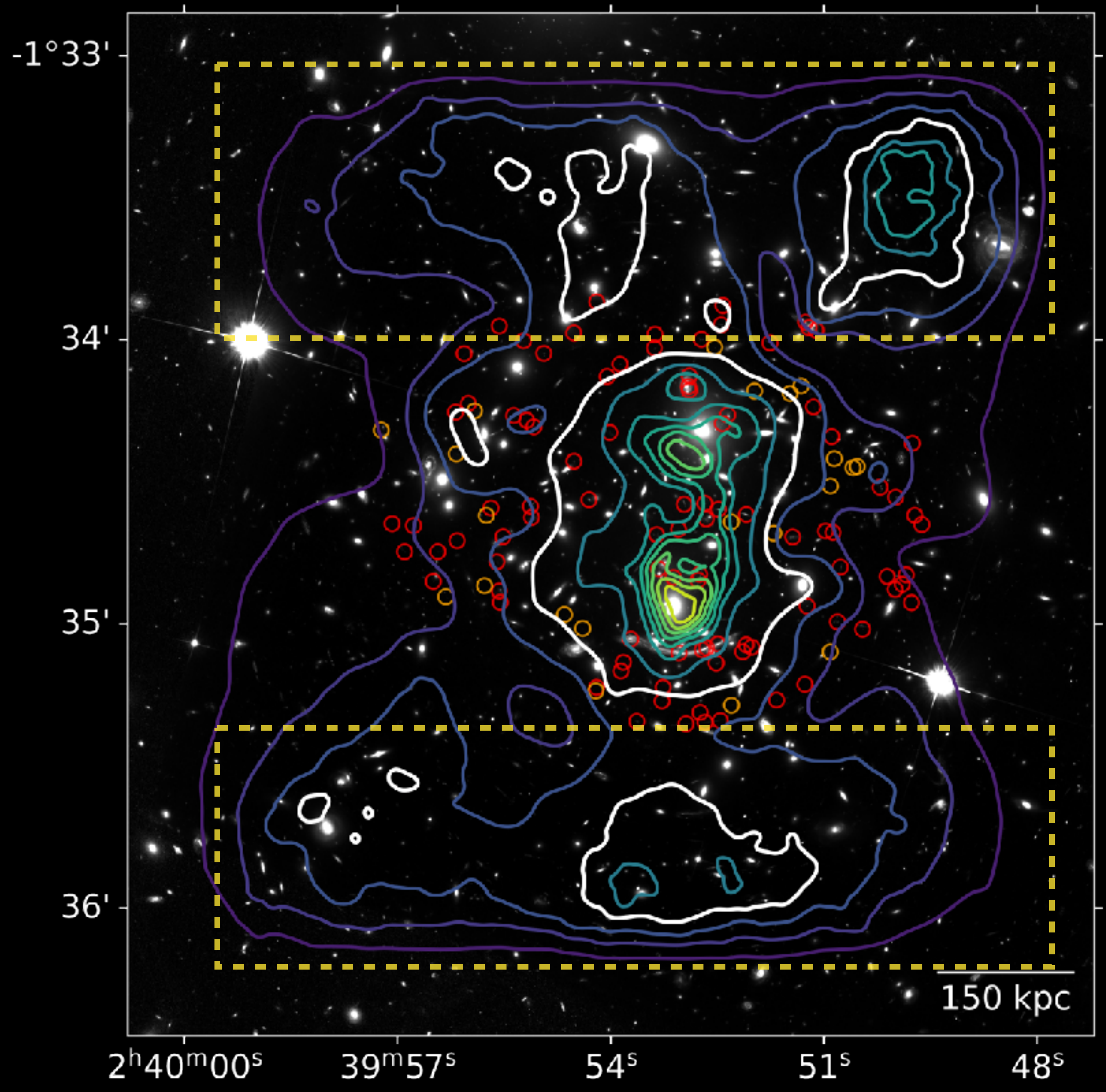
Note: *The contours are not uniformly scaled.*

Source: STScI/MAST

A North-South Filament

Significant fictitious mass clumps,
located about 40 arcseconds
(about 200 kpc)
above and below the central region.

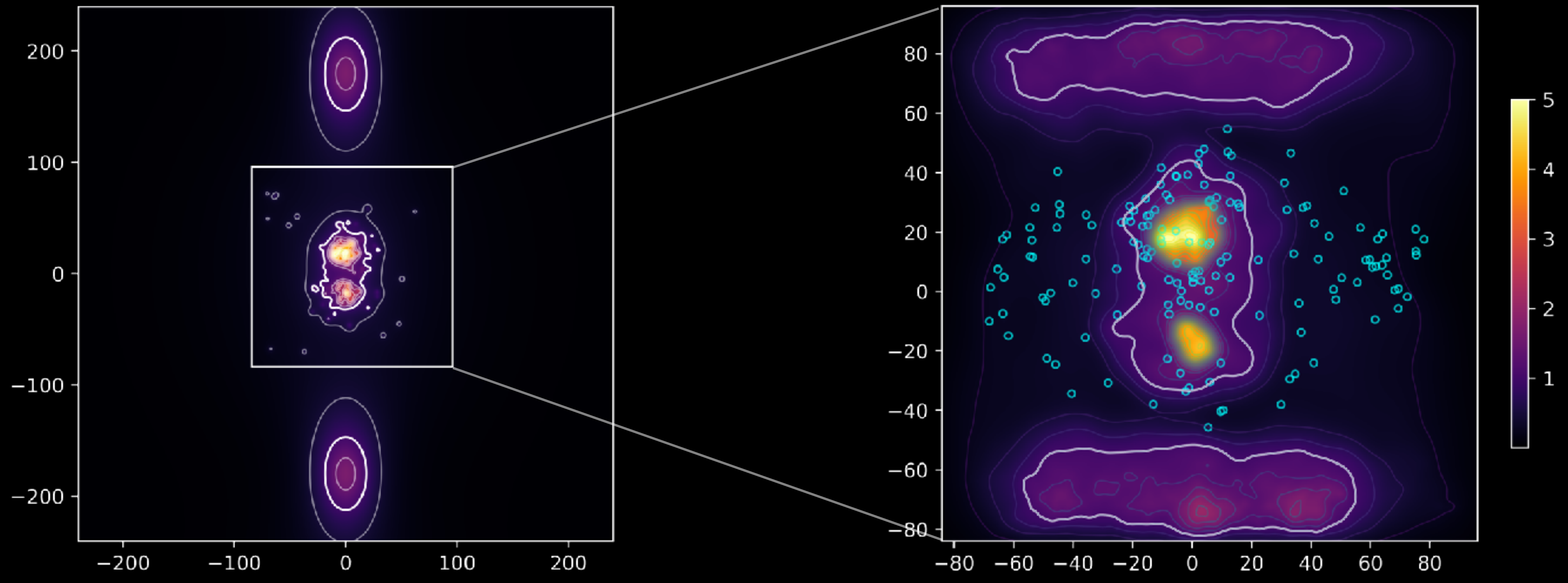
These can be attributed to GRALE trying to **compensate for an otherwise unobserved mass well outside the strong lensing region**, which is consistent with a filament-like structure passing through this cluster.



Modeling a Synthetic Cluster with Filament

We created a synthetic cluster - Irtysh III - following our previous work in Ghosh et al. (2020) with external masses situated far outside the strongly lensed region around the cluster center.

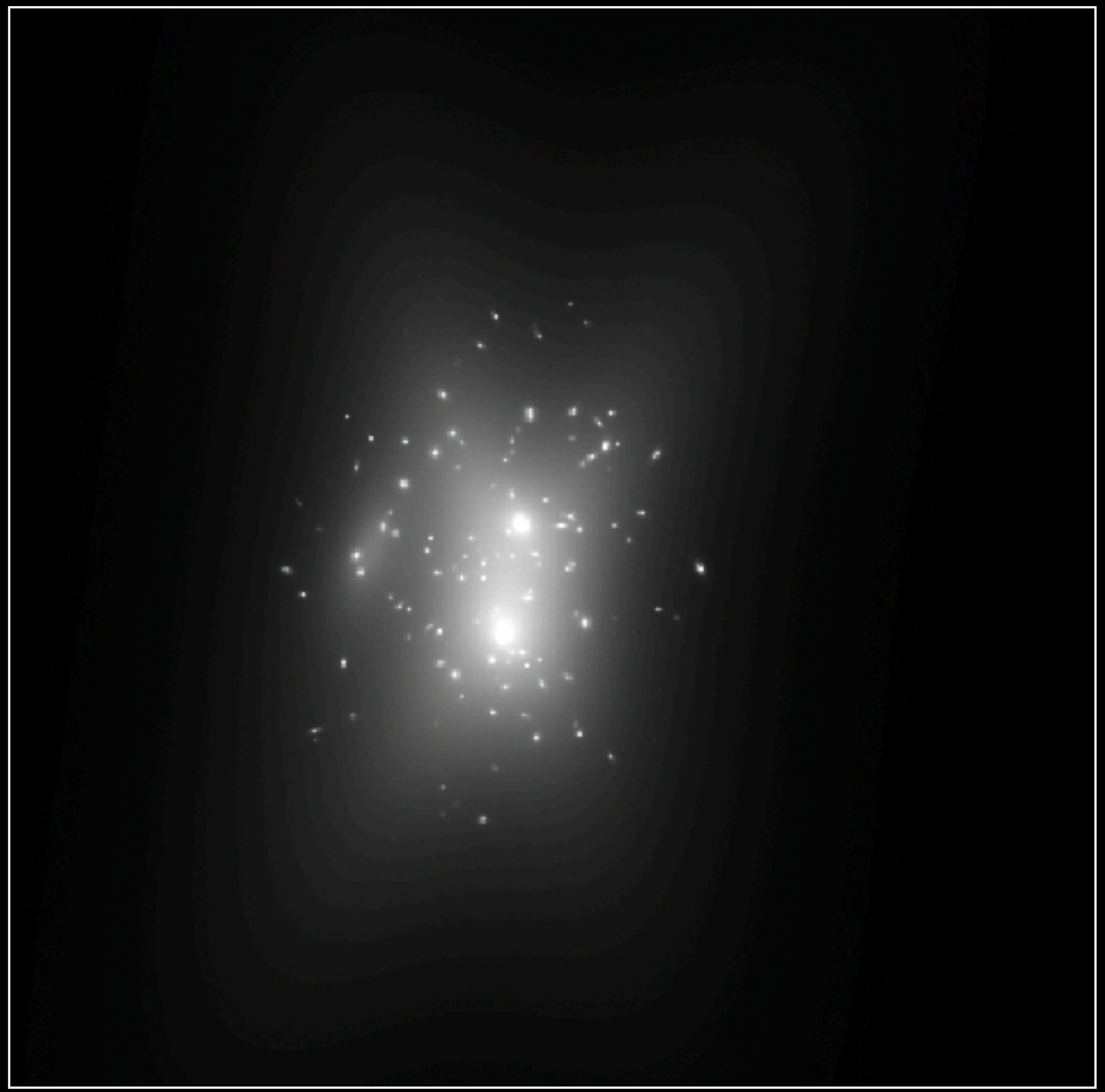
The reconstruction shows that **the fictitious mass clumps can replicate the effect of actual mass structures lying well outside the reconstructed region**.



True

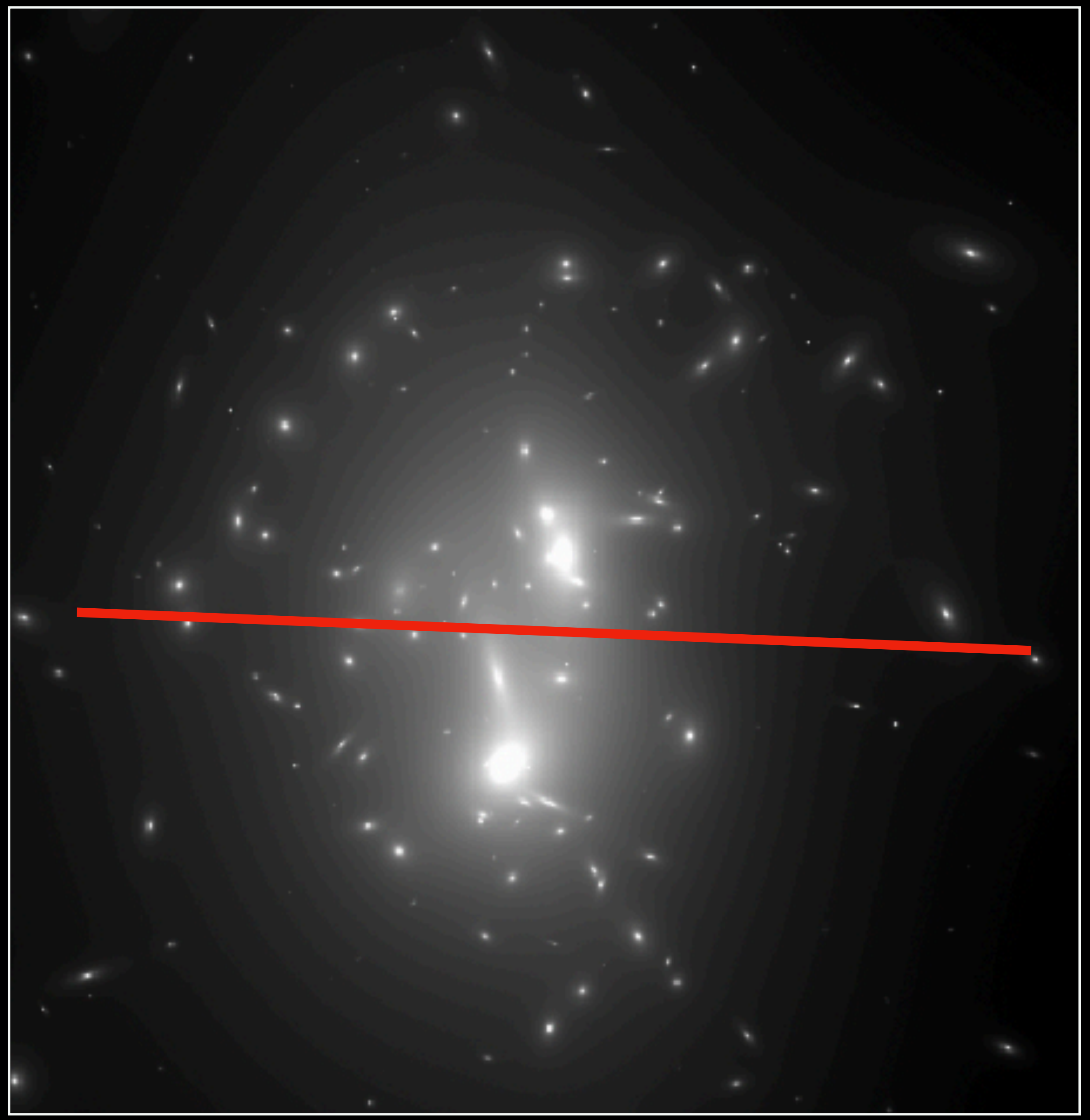
Reconstruction

Further support for a N-S Filament



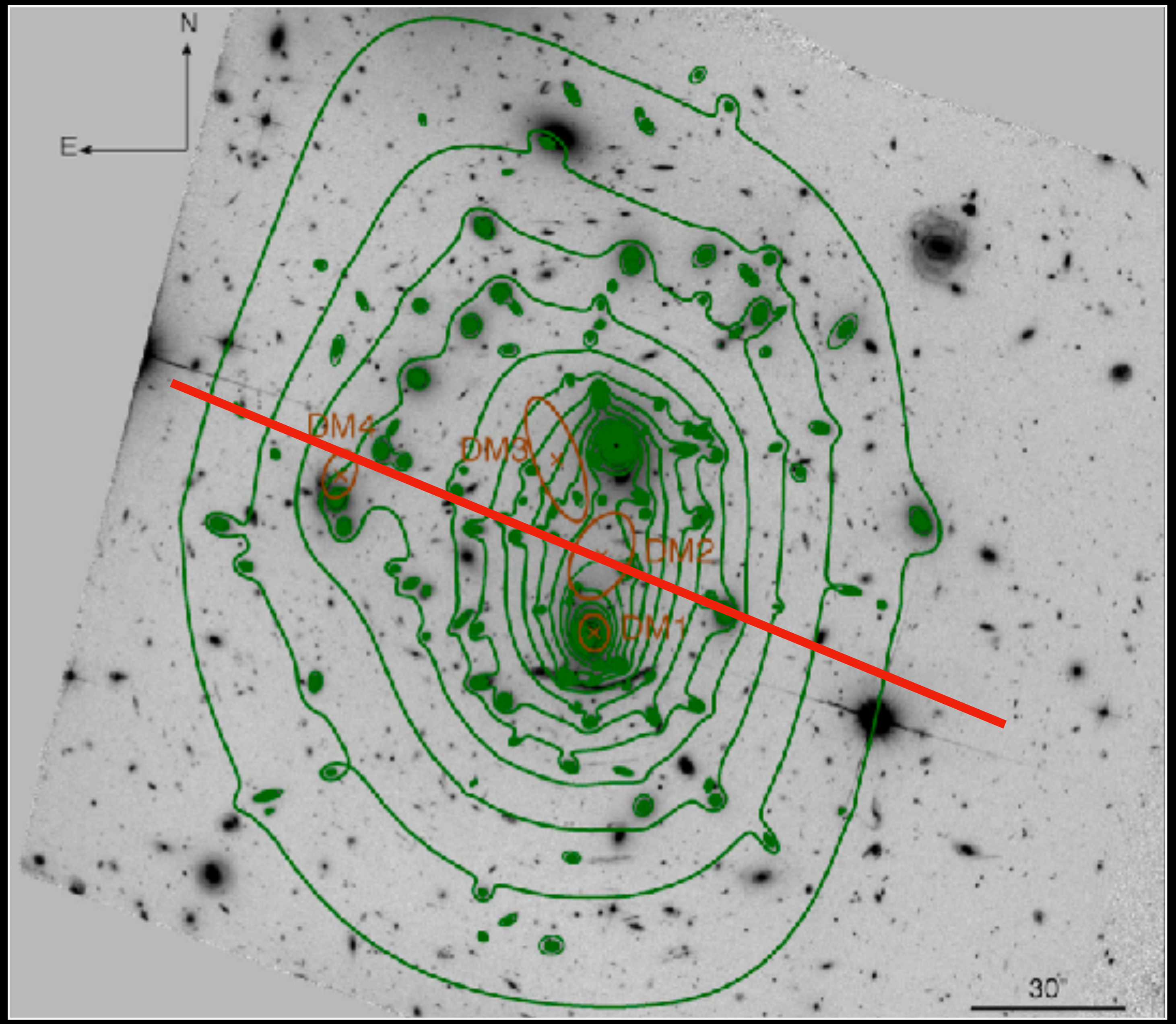
CATS HFFv4 Reconstruction (LENSTOOL)

Shows two elongated, low density mass 'fingers'.



GLAFIC HFF v4 (Kawamata et al. 2018)

External shear present in the model with $\gamma = 6.55 \times 10^{-2}$ and $\theta_\gamma = 177.7$ deg.



Lagattuta et al. (2019) (LENSTOOL)

External shear present in the model $\gamma = 1.28 \times 10^{-2}$ and $\theta_\gamma = -19.7$ deg.

Source: STScI/MAST

Further support for a N-S Filament

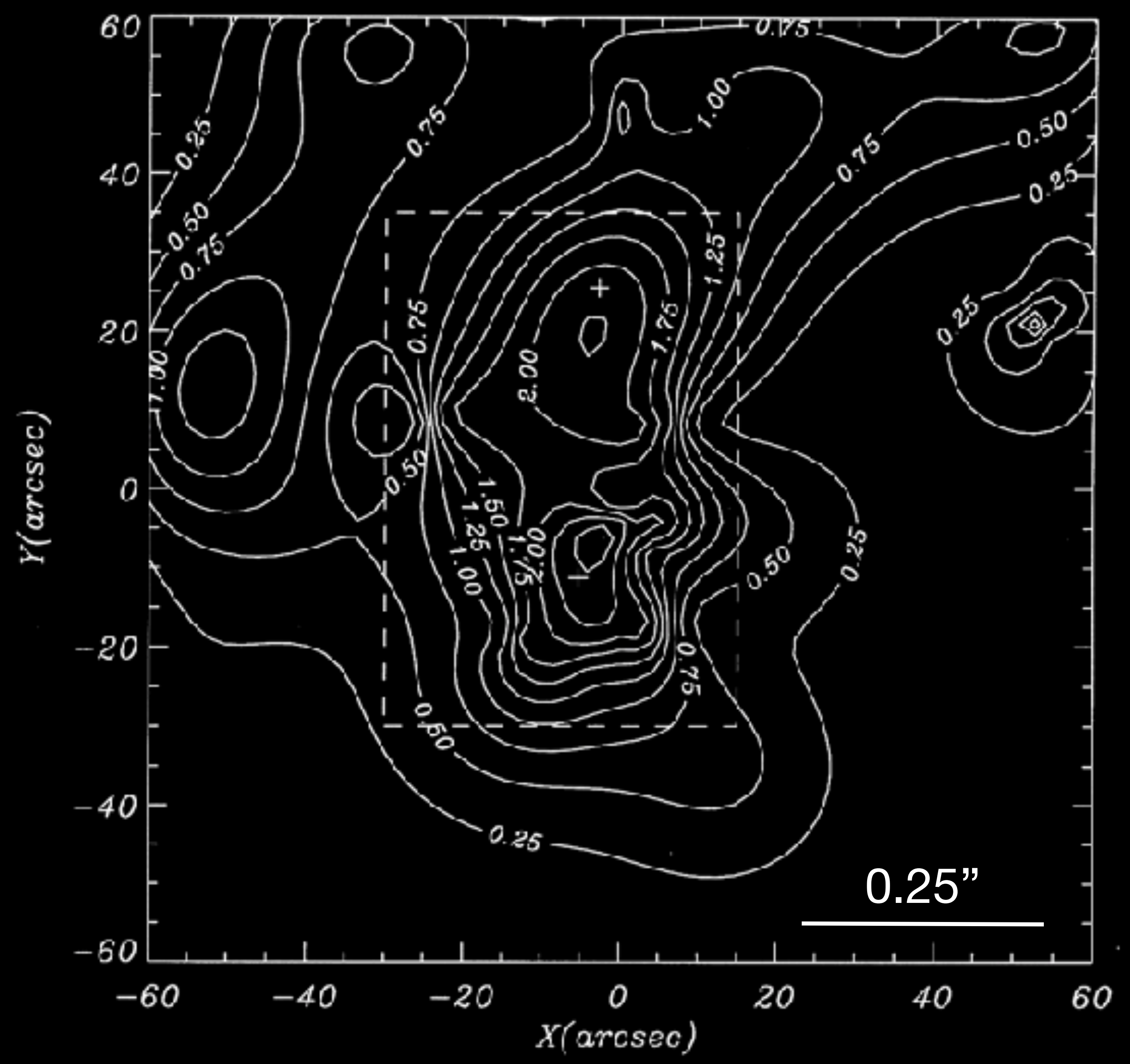


Figure 3 from Abdelsalam et al. (1998)

Shows mass extensions towards NW. Also notice the substructure to the East.

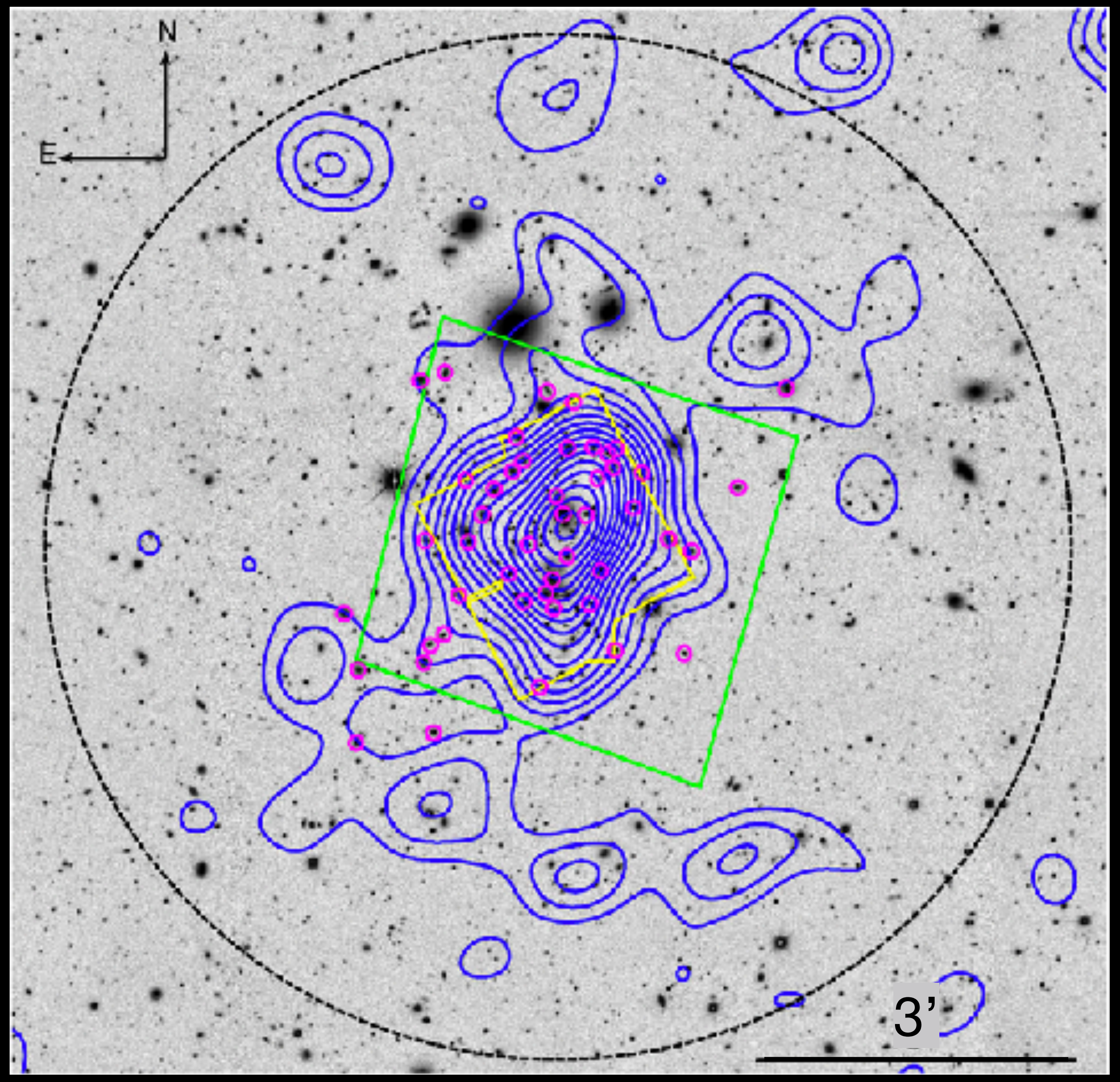


Figure 11 from Lagattuta et al. (2019)

Shows several concentrations of galaxies with similar colors to cluster members, in lower resolution image taken with the CFHT with CHF12K (Hoekstra 2007).
Blue contours show smoothed out light distribution from the cluster red sequence members.

Note mass structures towards NNW and SSE, and within the virial radius, shown by the dashed black circle.

Summary of the Mass Features

Model	Type	Mass peak near northern BCG	Substructure ~250kpc east of center	N-S Filament (or similar external mass)
Abdelsalam et al. (1998)	Free-form	Displaced (~30 kpc)	Present	Mass extension to the NW
LENSTOOL (Richard et al. 2010)	Paramteric	Displaced (~50 kpc)	Absent	None
Zitrin-LTM HFFv1	Paramteric	Not Displaced	Absent	None
Zitrin-NFW HFFv1	Paramteric	Displaced (~35 kpc)	Absent	None
LENSTOOL (Richard et al. 2014)	Paramteric	Not Displaced	Absent	None
LENSTOOL (Johnson et al. 2014)	Parametric	Displaced (~30 kpc)	Absent	None
GRALE HFFv1 (Mohammed et al. 2016)	Free-form	Displaced (~20 kpc)	Present	Mass clumps near N and S boundaries
LENSTOOL (Sharon HFFv4)	Parametric	Displaced (~15 kpc)	Absent	None
LENSTOOL (CATS HFFv4)	Parametric	Not Displaced	Additional DM Halo	Two elongated, low density mass 'fingers'
GLAFIC (Kawamata et al. 2018)	Parametric	Displaced*	Absent	External shear present ($\gamma = 6.55 \times 10^{-2}$)
WSLAP+ (Diego et al. 2018)	Hybrid	Displaced (~40 kpc)	Present	None
GRALE HFFv4	Free-form	Displaced (~15 kpc)	Present	Mass clumps near N and S boundaries
SWUnited (Strait et al. 2018)	Free-form	Diffuse (~15 kpc)	Absent	None
LENSTOOL (Lagattuta et al. 2019)	Parametric	Displaced (~50 kpc)	Additional DM Halo	External shear present ($\gamma = 1.28 \times 10^{-2}$)
LENSMODEL (Raney et al. 2020)	Parametric	Not Displaced	Absent	None
GRALE BUFFALOv1 (This Work)	Free-form	Displaced (~35 kpc)	Present	Mass clumps near N and S boundaries

** There are two nearby halos, one is ~20 kpc away and the other one is ~100 kpc away.*

Conclusions

- We detected three mass features in A370 which are recovered by some of the other reconstruction methods as well. Of the three, offset around the Northern BCG appears most robust.

- Because free-form models enjoy the freedom from fixed parameter spaces of parametric models, it enables them to recover mass features that are elusive for some parametric models.

- With upcoming observational facilities like the *JWST*, which is expected to uncover hundreds of new strongly lensed images, free-form methods will be well positioned to accurately map out cluster mass distribution on scales greater than most individual galaxies.