The Stellar Halos of Massive Ellipticals, Revealed with Strong Gravitational Lensing

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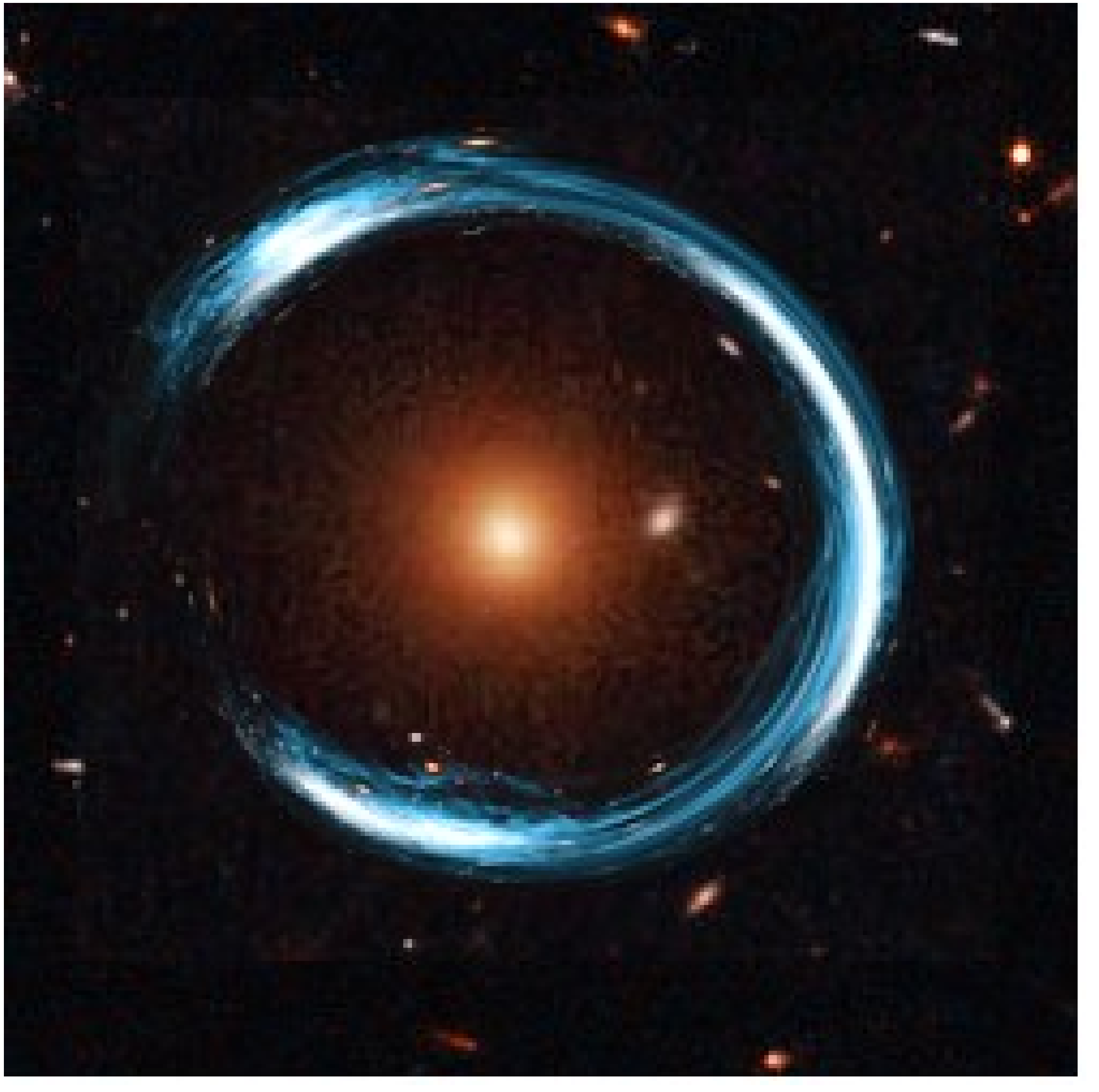
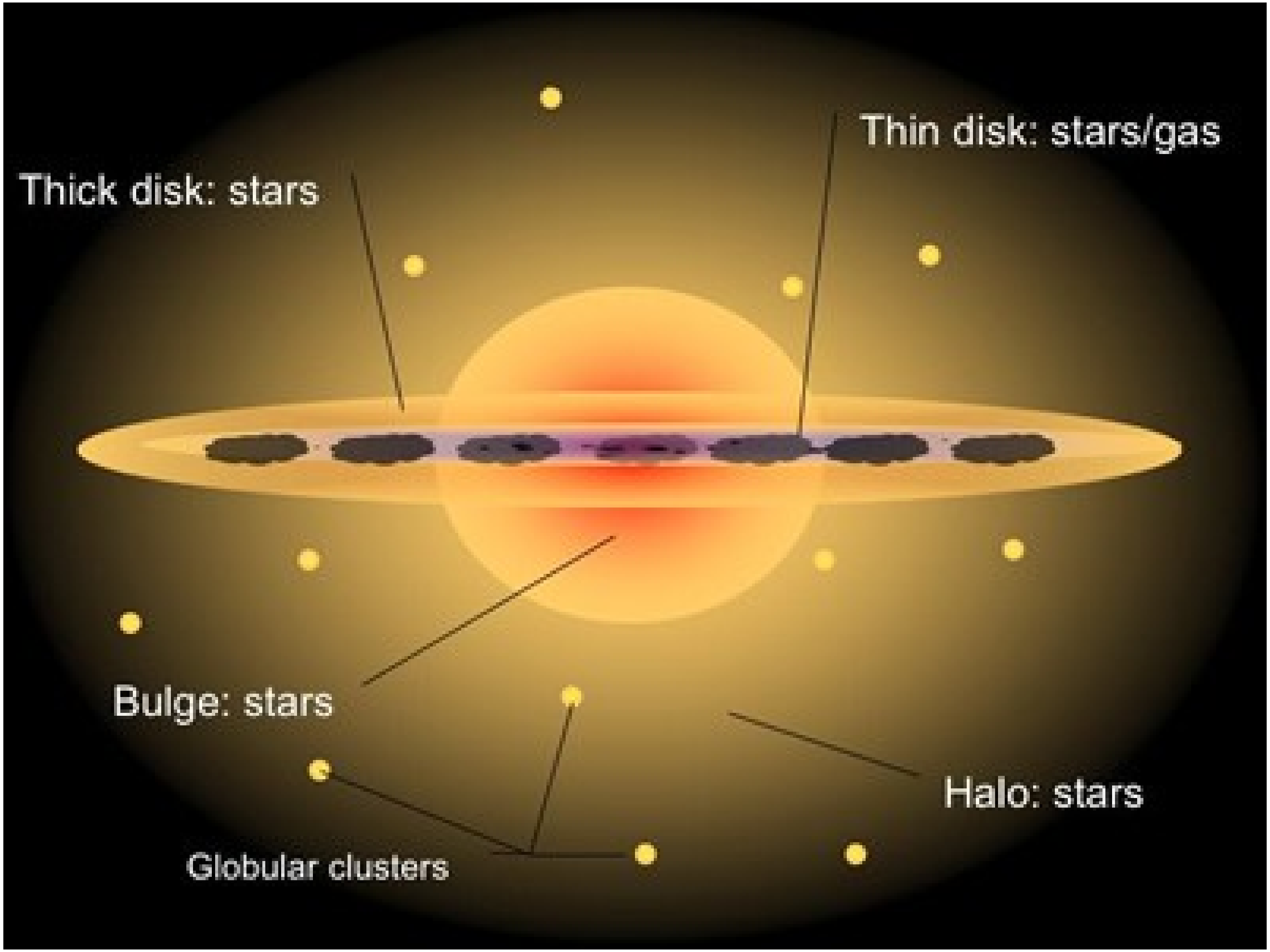


The Milky Way



http://astronomy.swin.edu.au/

The Milky Way Stellar Halo

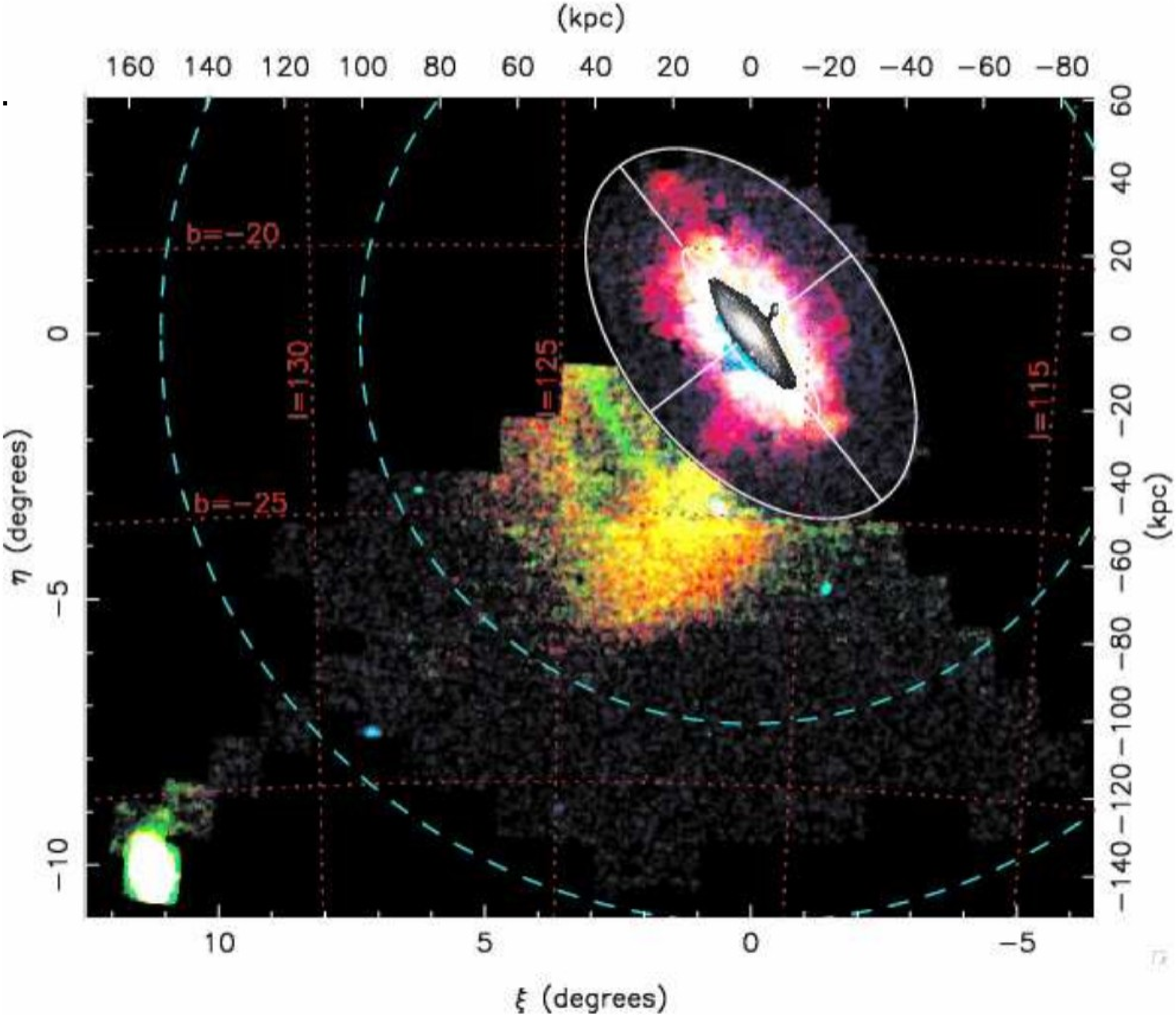
- **Makes up ~ 1% of stellar emission and mass.**
- **Arguably the most interesting component to study:**

  - Low metallicity / mass stars.
- **Stellar halo structure is linked intimately to how the galaxy formed:**

  - Contains an ‘archaeological print’ of the galaxies accretion history.

M31

Ibata et. al 2007



Extragalactic Stellar Halos

- **If stellar halos are ~ 1% of a galaxy's light, surely there's no hope of detecting them outside the local group?**
- **Not quite – in higher mass dark matter halos galaxies undergo many more mergers.**

  - Bigger and brighter stellar halos!

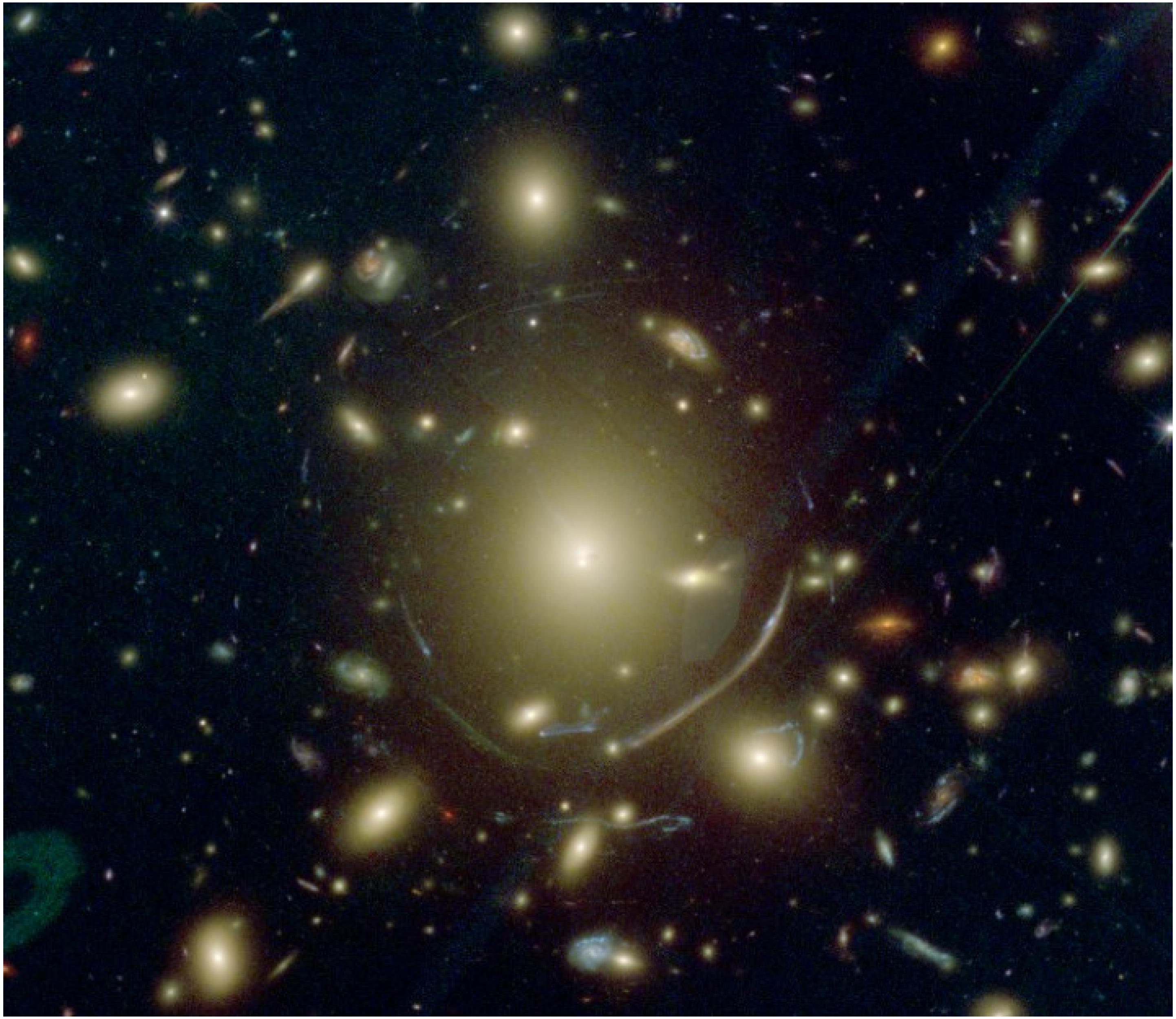
  - Especially in clusters and earlier type galaxies.

NGC3311 (cD Galaxy)

https://www.physics.mcmaster.ca/Fac_Harris/

Abell 383 (Brightest Cluster Galaxy)

NASA / STSCI



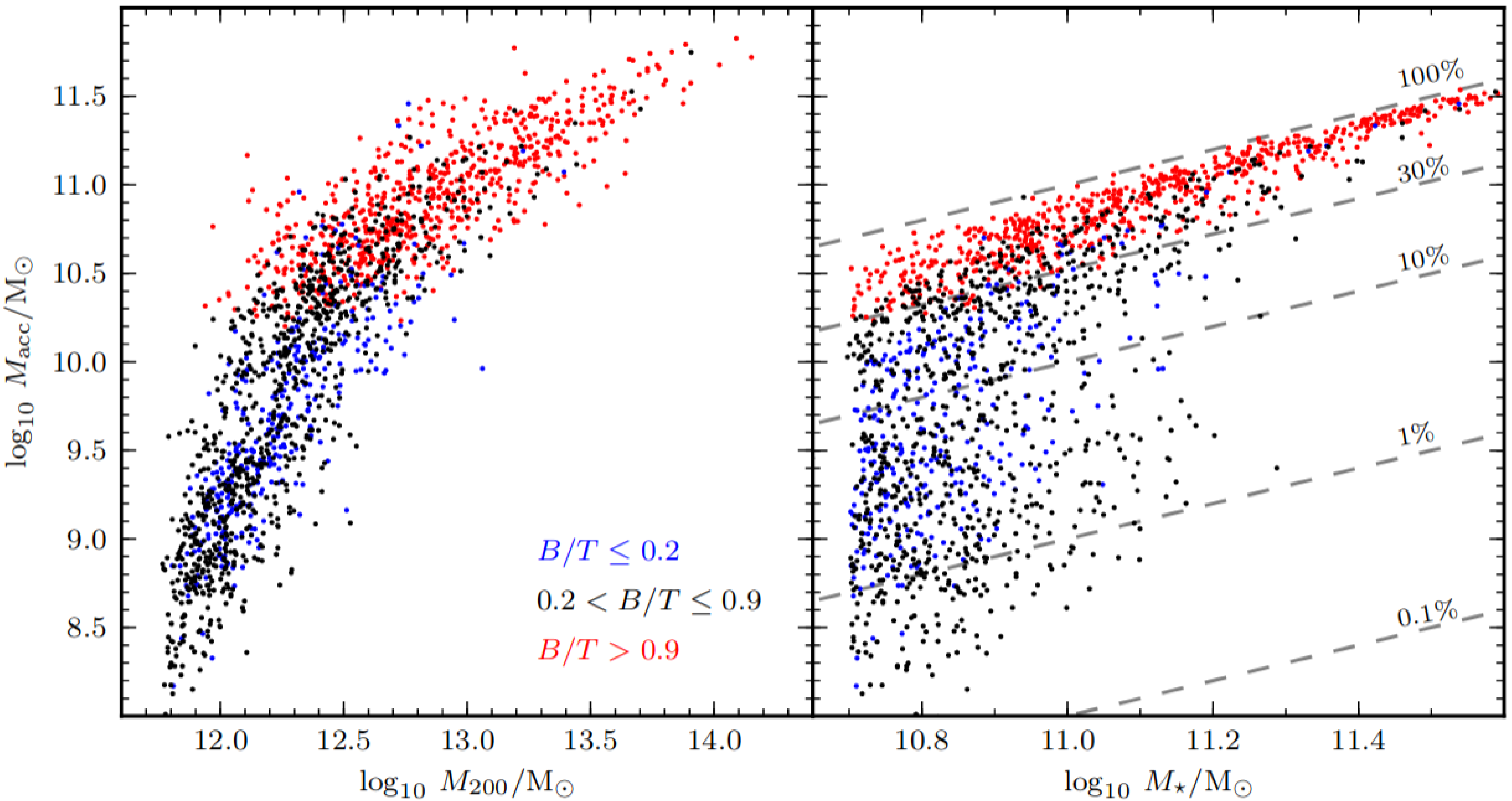
Galaxy Cluster Stellar Halos

- **Great if you're interested in cluster formation and physics.**
- **However, the archaeological value of galaxy-sized halos is somewhat lost.**

  - To many environmental processing going on in clusters!

Everything Else

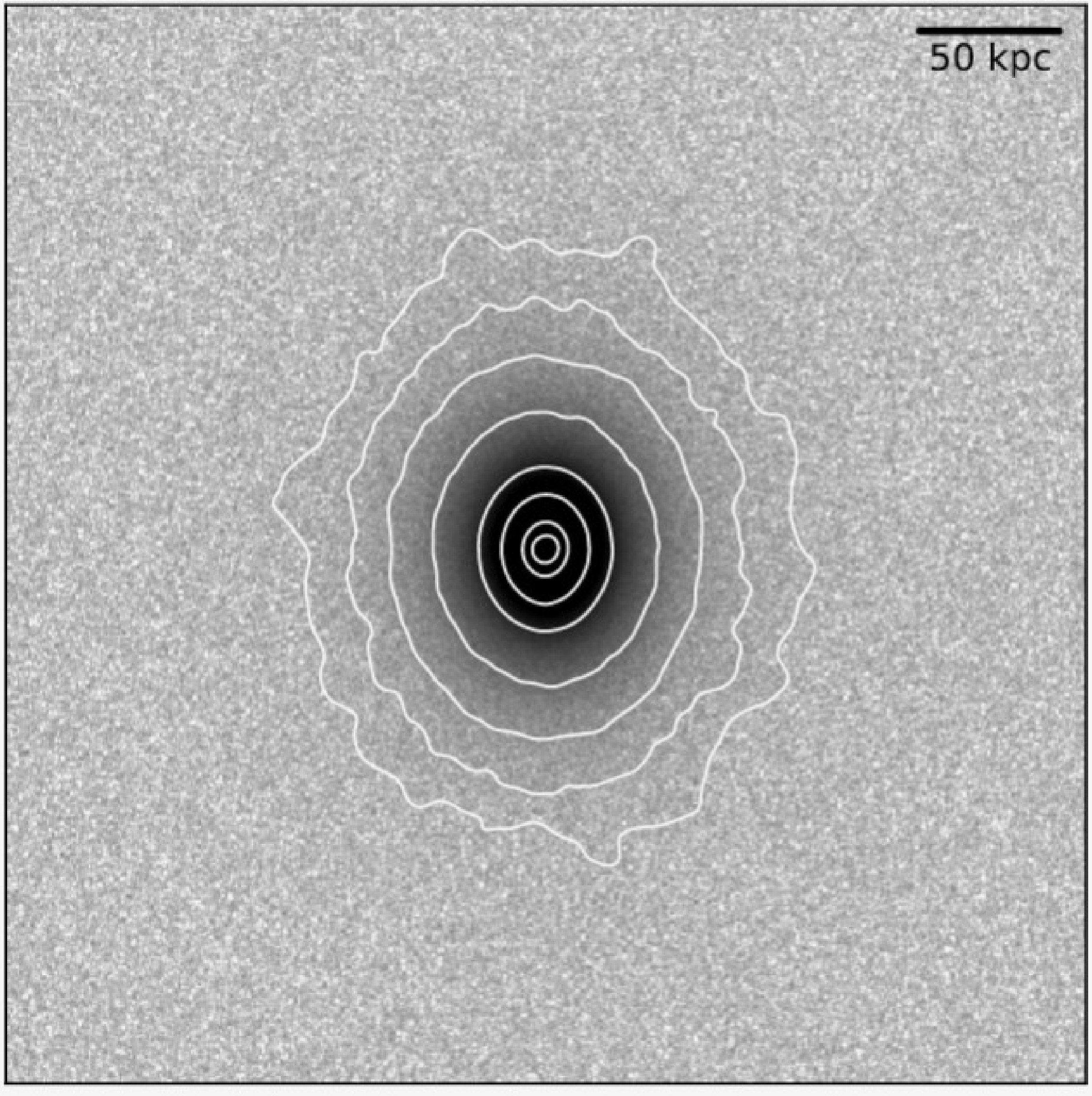
Cooper et. al 2013



Extended Stellar Halos

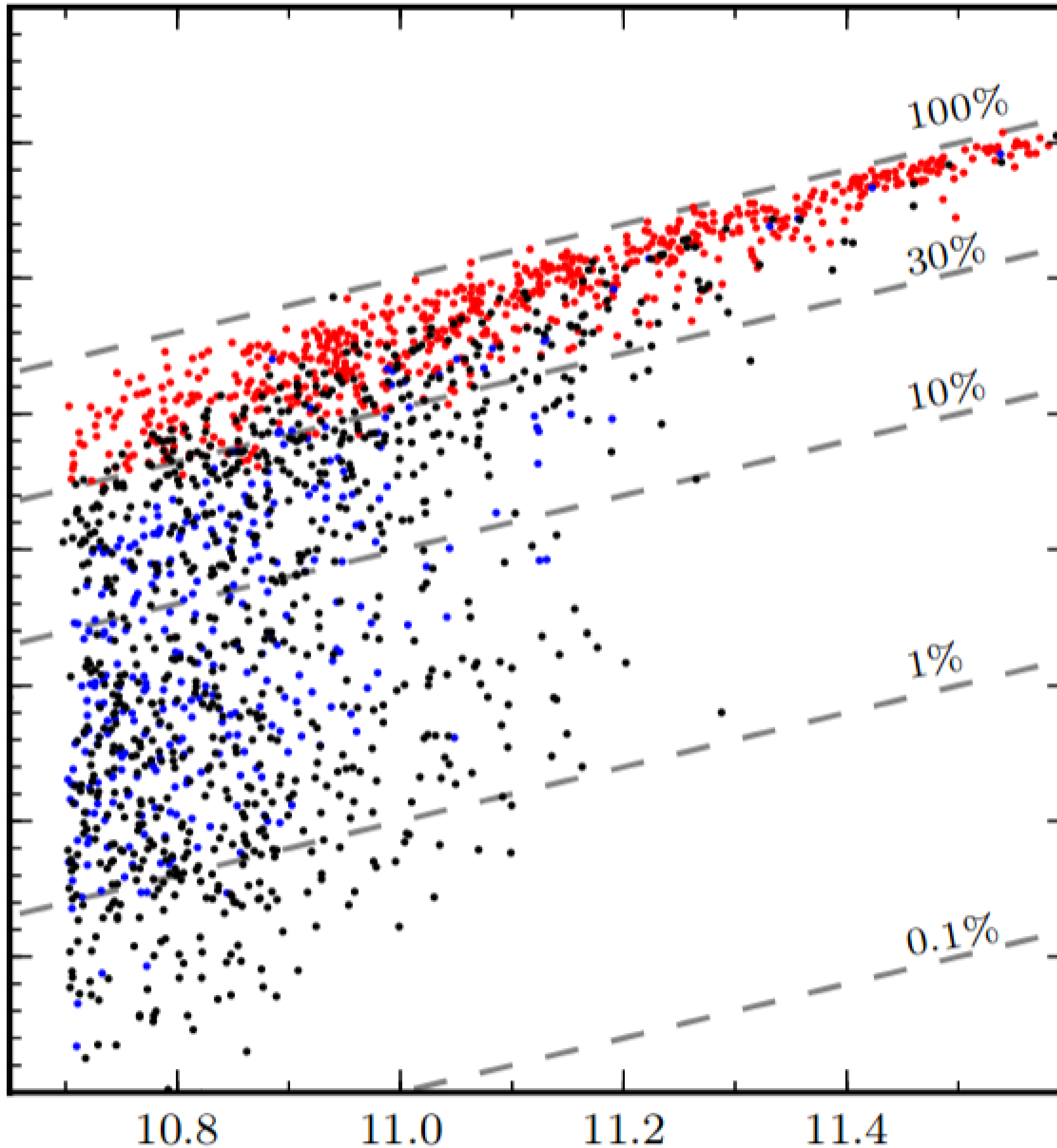
- Stellar halos – extended low surface-brightness emission.
- Seen stacking 10000 SDSS galaxies (assumes geometric alignment).

D'Souza et al 2014



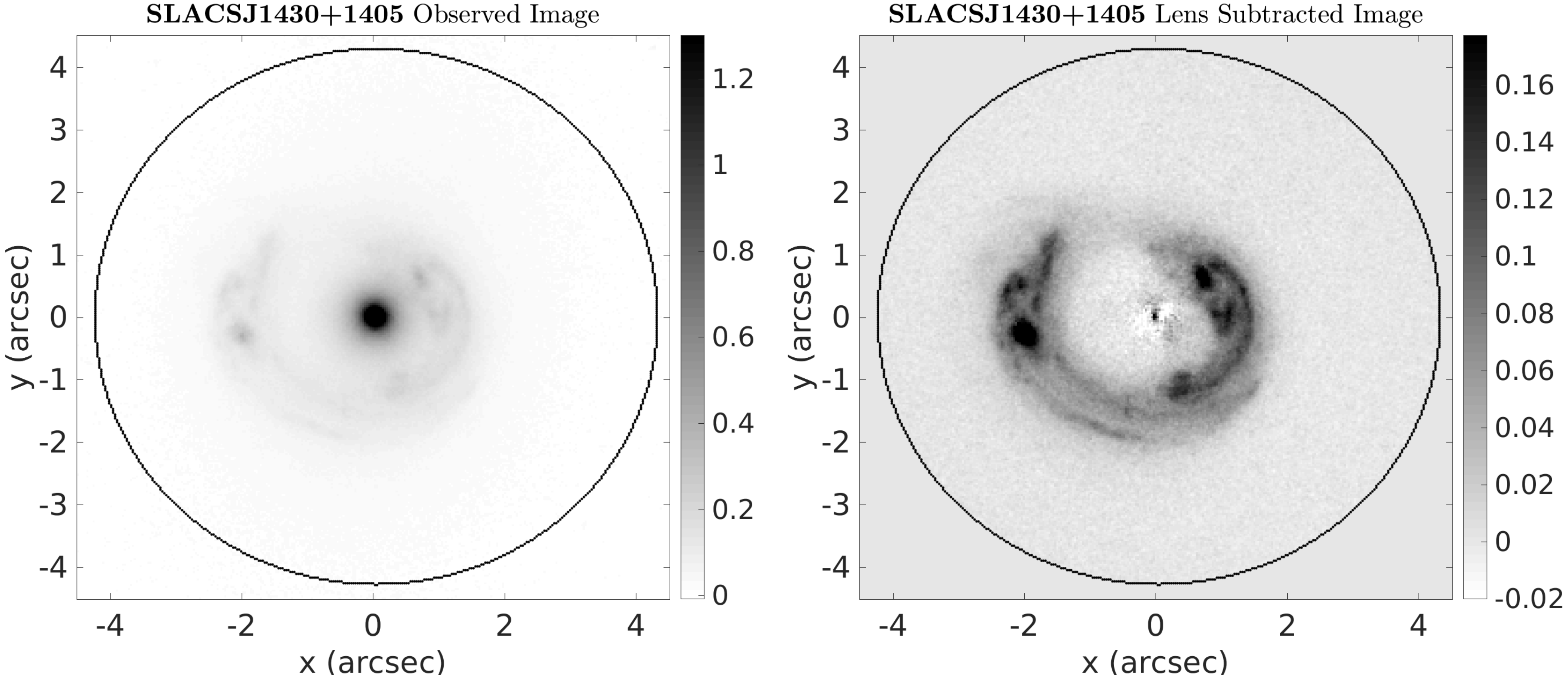
Stellar Halo Mass Fractions

- Many field galaxies whose stellar halo is ~50%, or more, of the galaxy's total mass.
- Very low surface brightness, but **maybe their mass can be detected?**

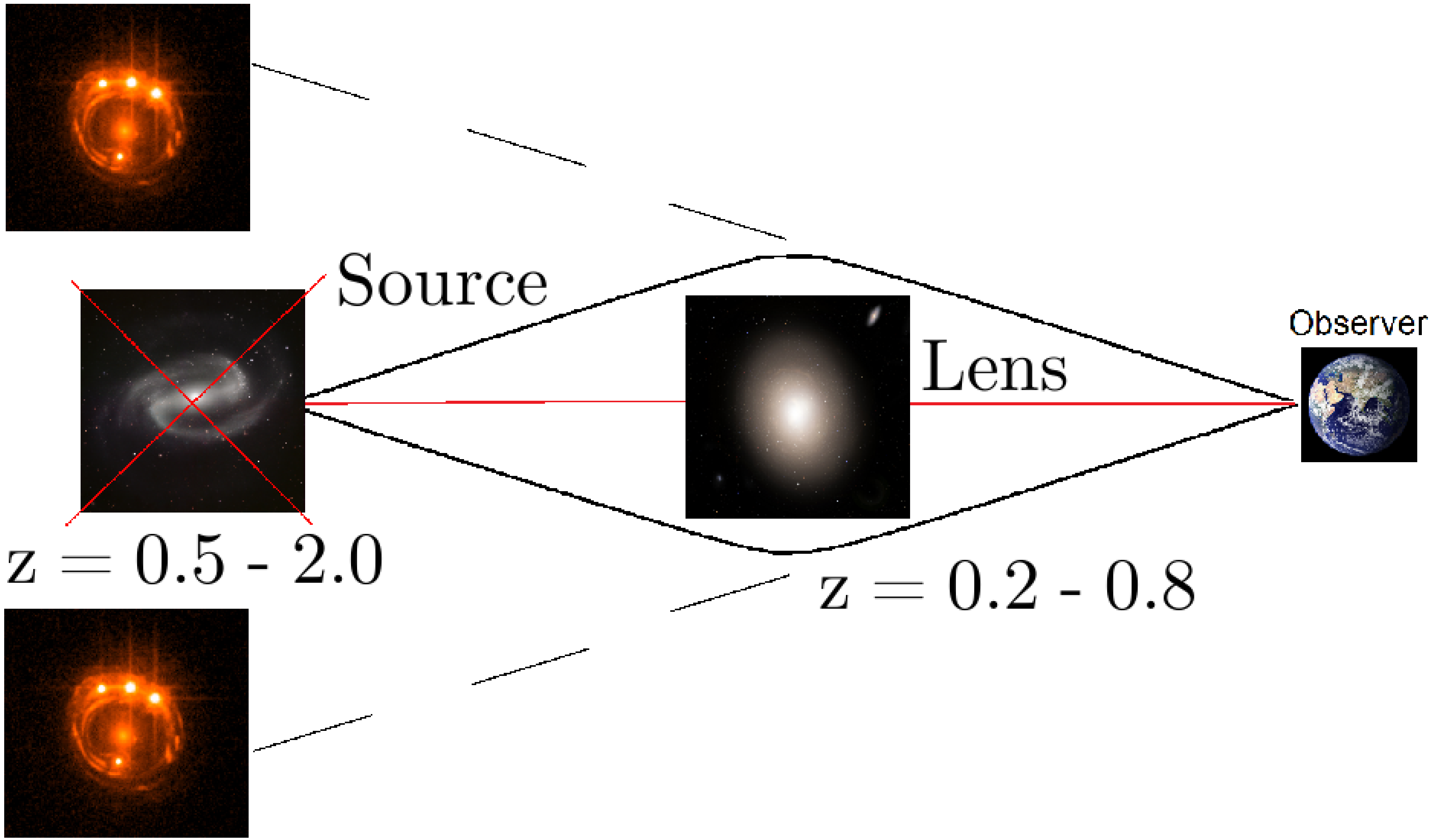


Cooper et. al 2013 $\log_{10} M_\star/\mathrm{M}_\odot$

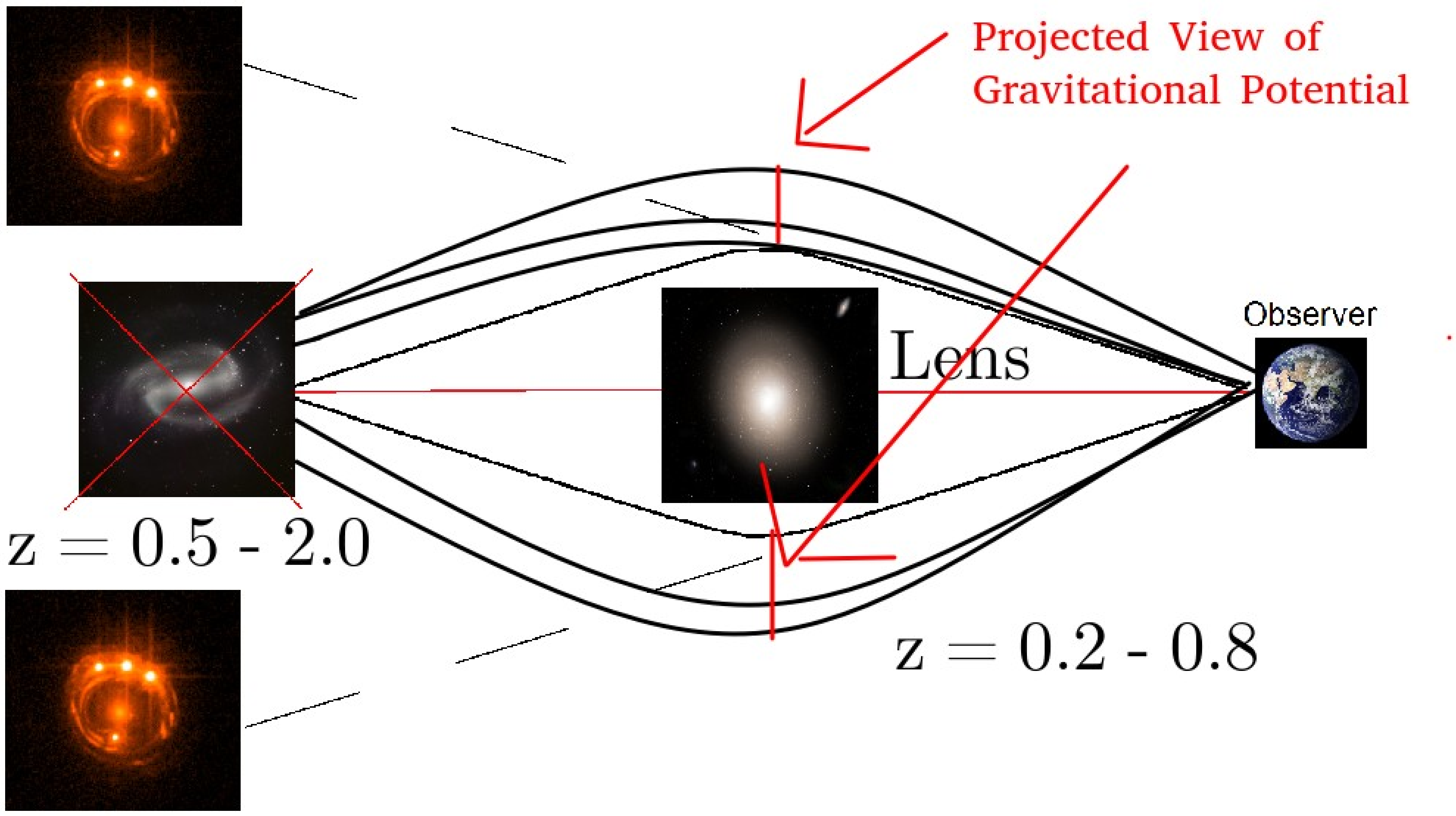
Strong Gravitational Lensing



Strong Lensing

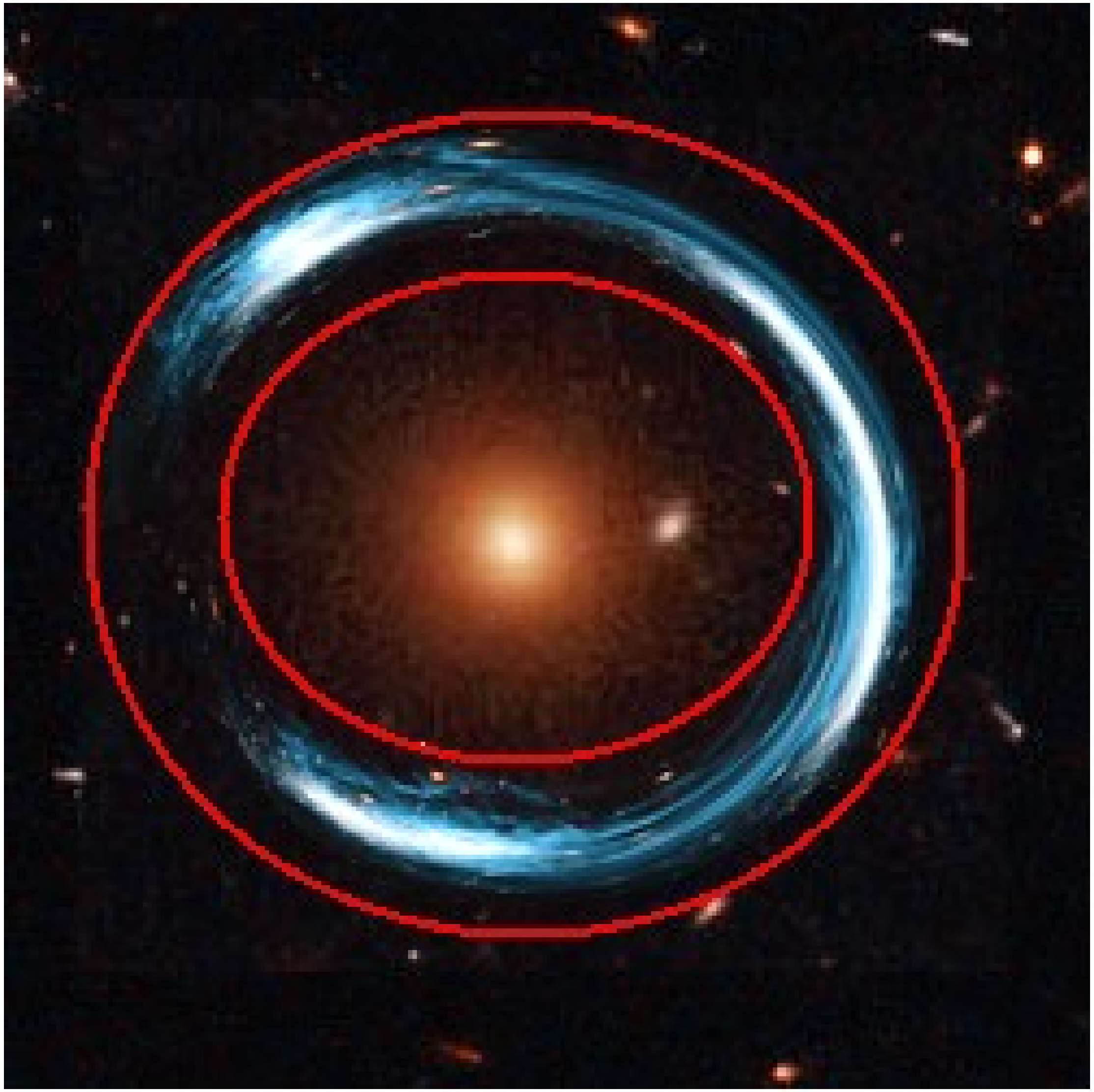


Strong Lensing



Extended source Strong Lensing

- **Extended Surface-brightness modeling:**
- **Uses -** The extended source's light distribution.
- **Measures (direct) –** The lens's mass distribution, at the Einstein Radius, R_{ein}.
- **Measures (indirect) –** The lens's mass distribution around R_{ein}.



Open-Source Modeling

- **Rewriting AutoLens, from scratch, in Python.**

  - Open-source and freely available.

  - Fully documented, tested, object-oriented.

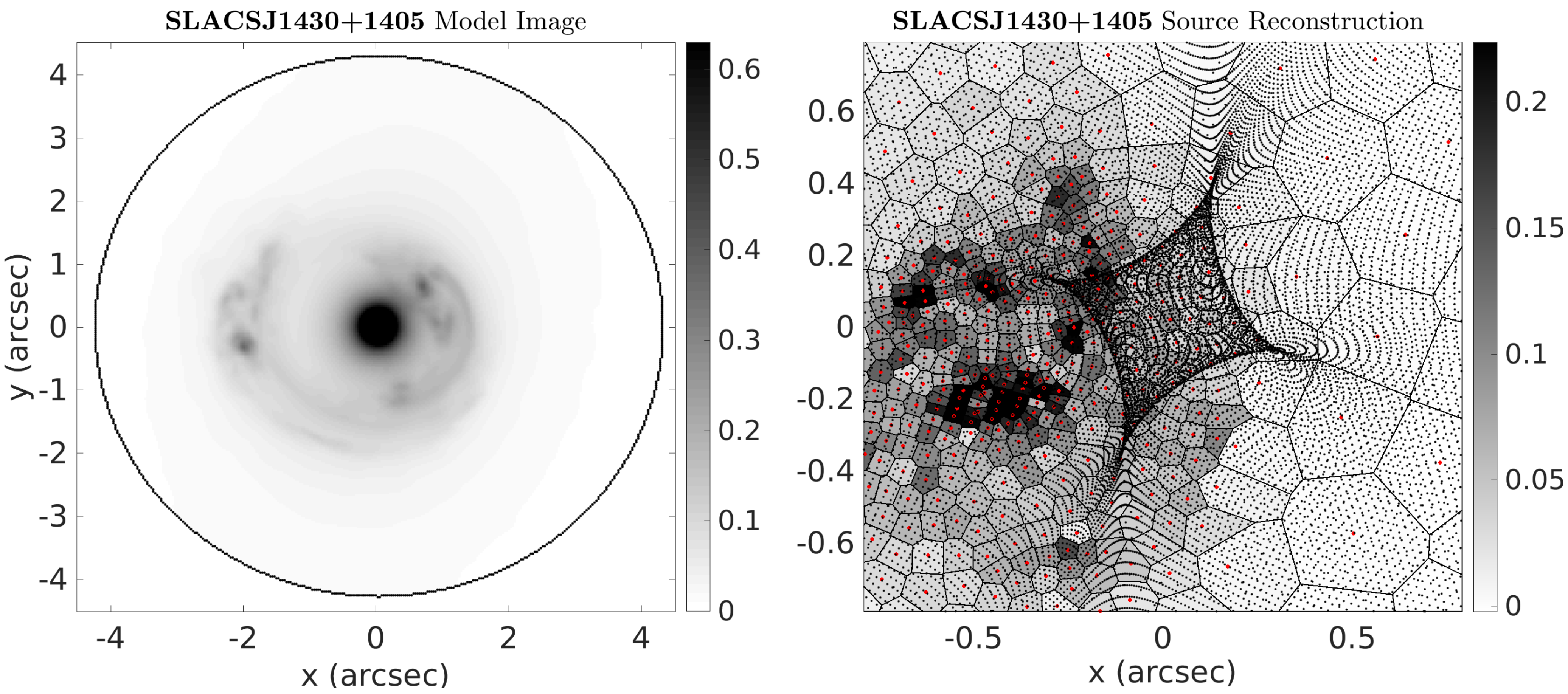
- **Let me know if you want to be a beta tester!**

  https://github.com/Jammy2211/AutoLens

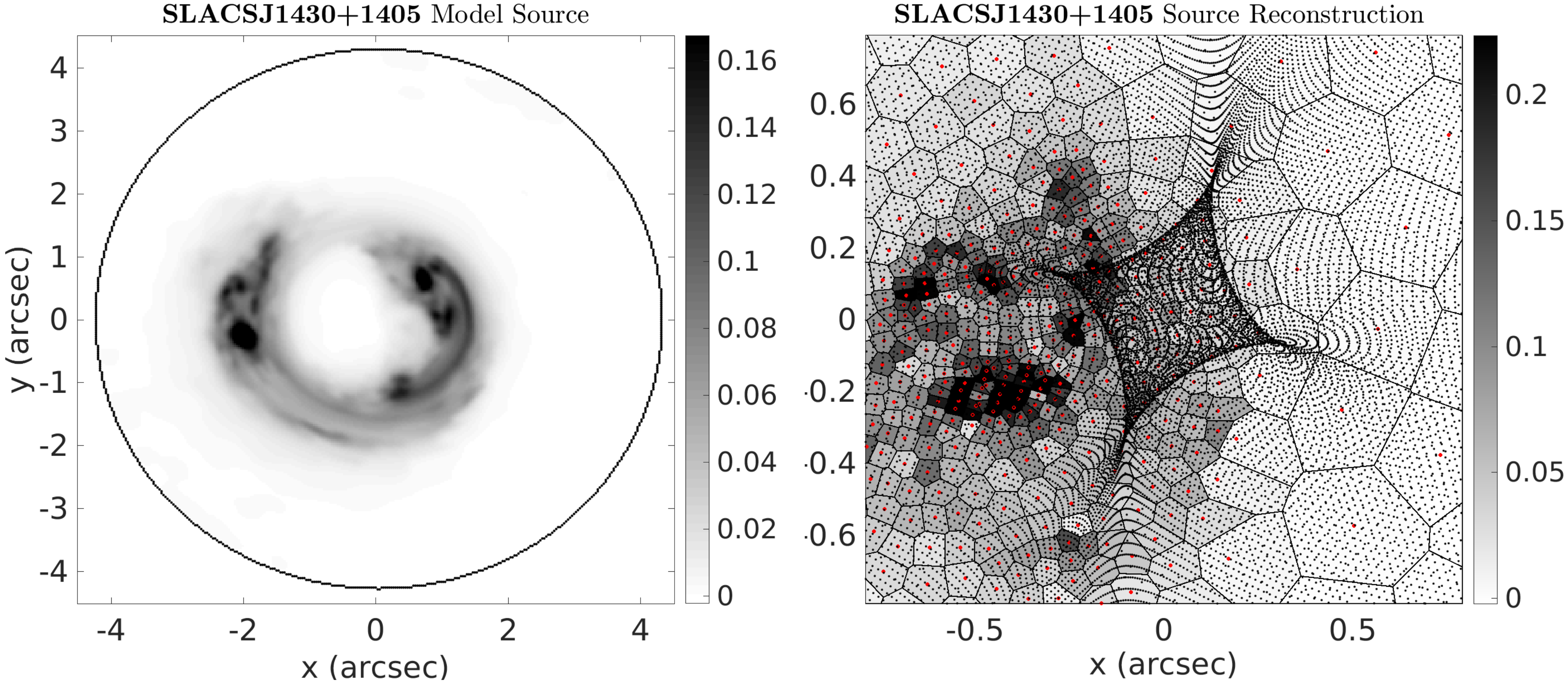
- **The results shown today use my own personal Fortran code.**

  - This isn’t something anyone else is going to want to look at...

SLACS3 (SLACSJ1430+4105)



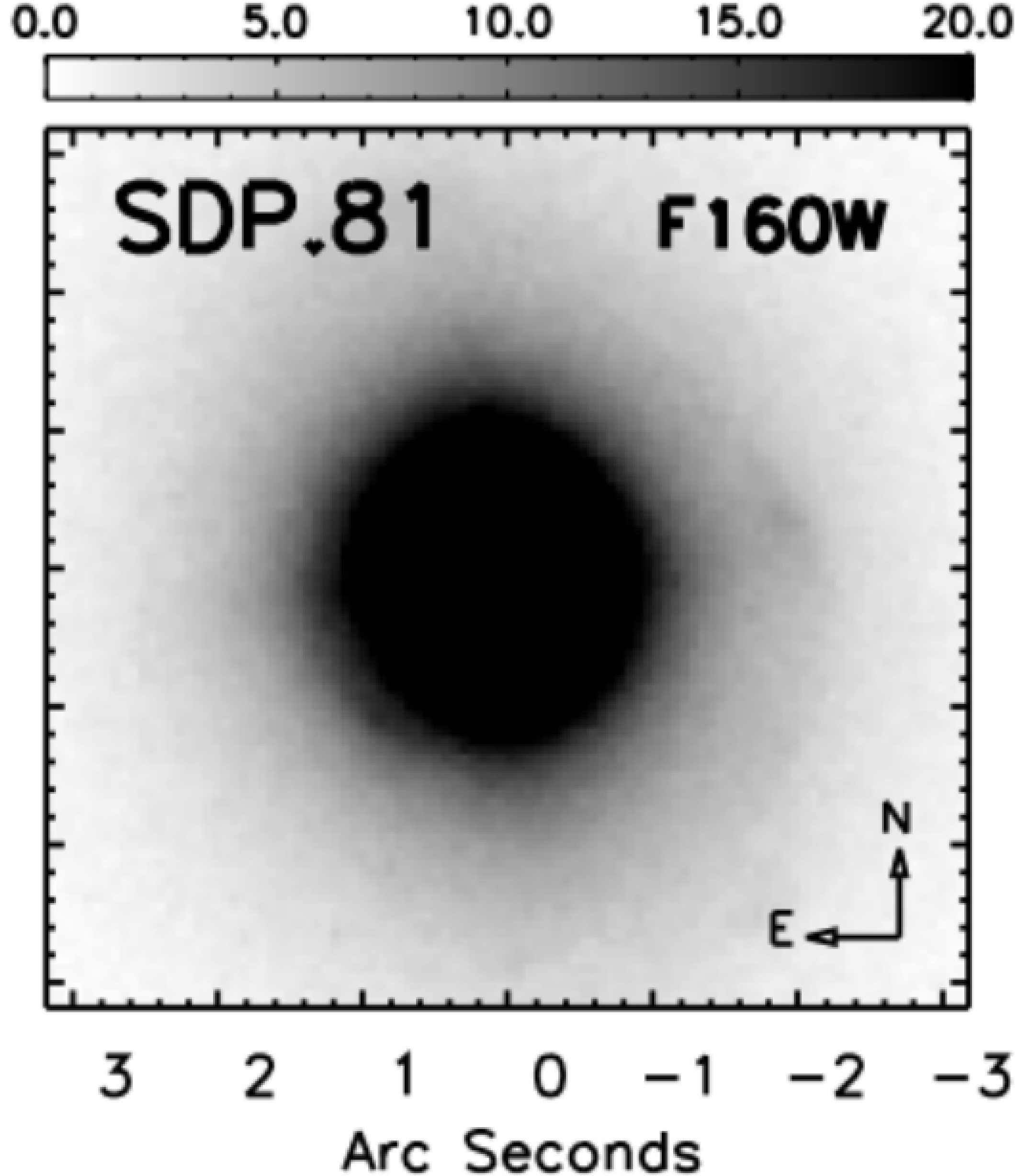
SLACS3 (SLACSJ1430+4105)



Exploiting the Lens Light

Negrello et al. 2014

Dye et al. 2014



Exploiting the Lens Light

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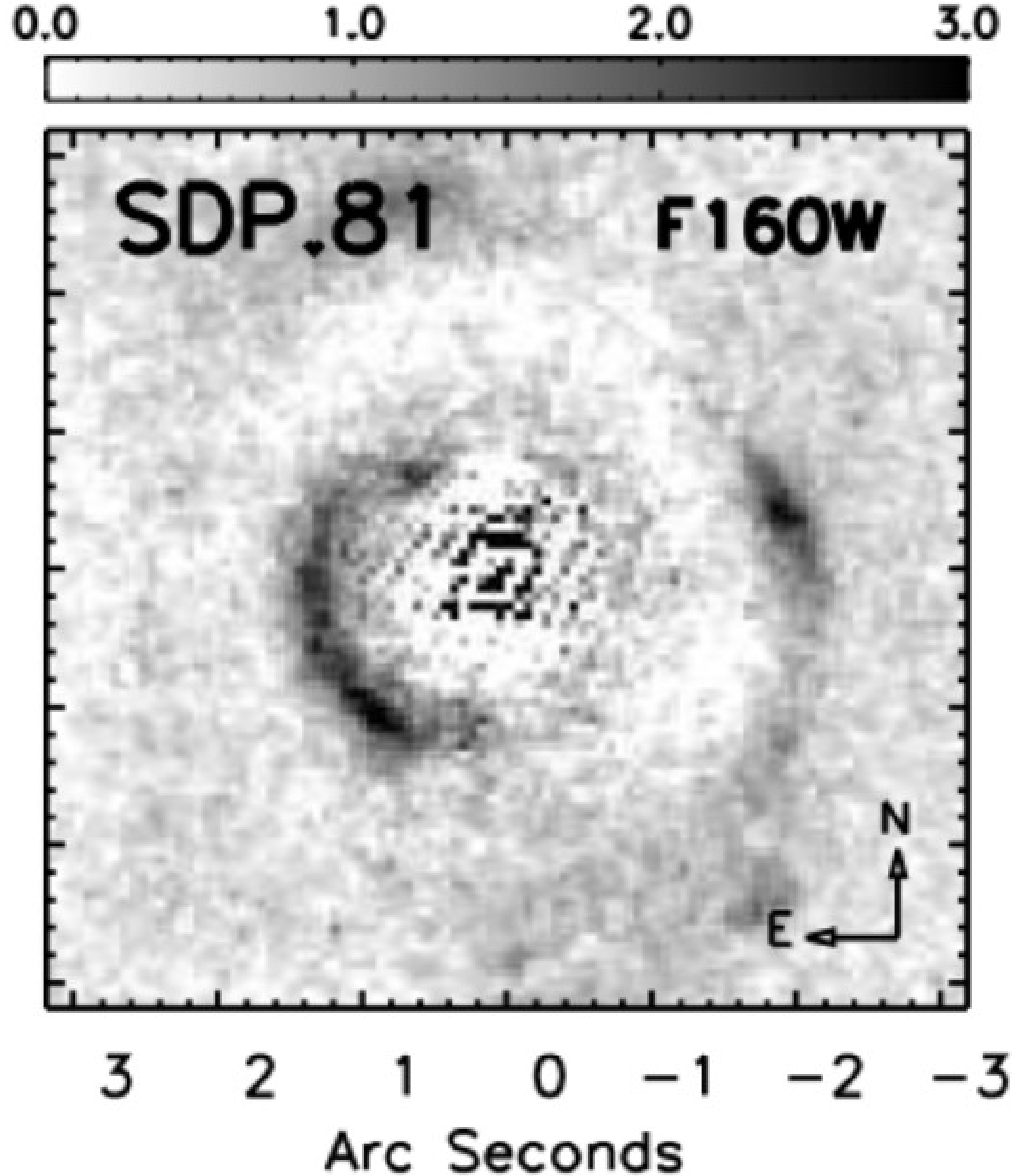


Decomposed Mass Model

- We advocate **decomposed mass modeling** representing the **light** (Multi-Sersic) ...

$$\kappa_{Sersic}(\xi_l) = \Psi_l I_l \exp\left\{ -k_l\left[\left(\frac{\xi_l}{R_l}\right)^{\frac{1}{n_l}} - 1\right]\right\}$$

- ... and **dark** (NFW) matter:

$$\rho = \frac{\rho_s}{(r/r_s)^\gamma (1 + r/r_s)^{3-\gamma}}$$

$r_s = 50$ kpc
(Bullock et al. 2001)

Detecting a Stellar Halo

- **Compare two models:**

  - Model without a stellar halo - single Sersic profile **(bulge)**.

  - Model with a stellar halo – a Sersic + Exponential profile **(bulge + halo).**

- **The detection of a stellar halo is decided via Bayesian Model Comparison.**

Bayesian Model Comparison

- **Analysis gives a model's Bayesian Evidence:**

$$P(d|M) = \int P(m|M)P(d|m,M)dm$$

- **Ratio of two evidences gives the Bayes Factor:**

$$P(d|M_1)/P(d|M_2)$$

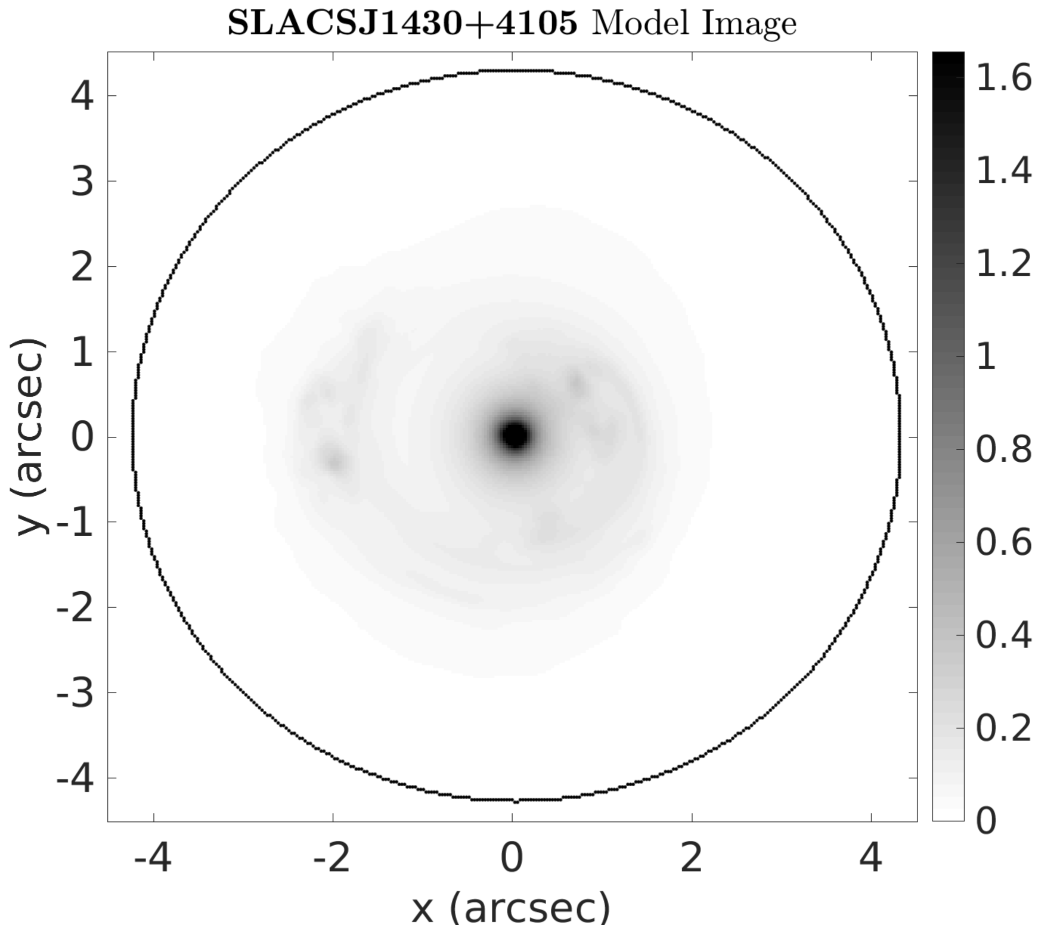
- **Objective criterion for whether a more complex model is favoured by the data.**
- **Accounts for Occam's Razor!**

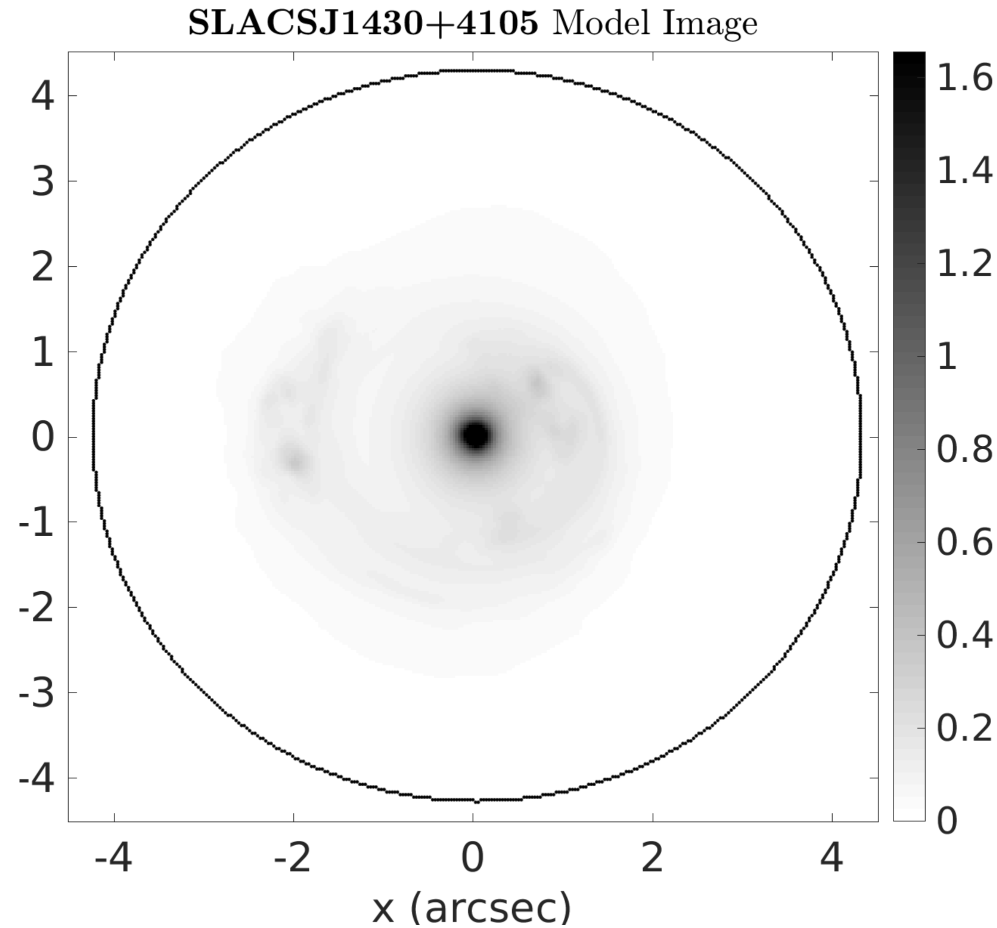
One or Two Sersic's?

$\Delta \ln \varepsilon$ = Two-Component / One-Component

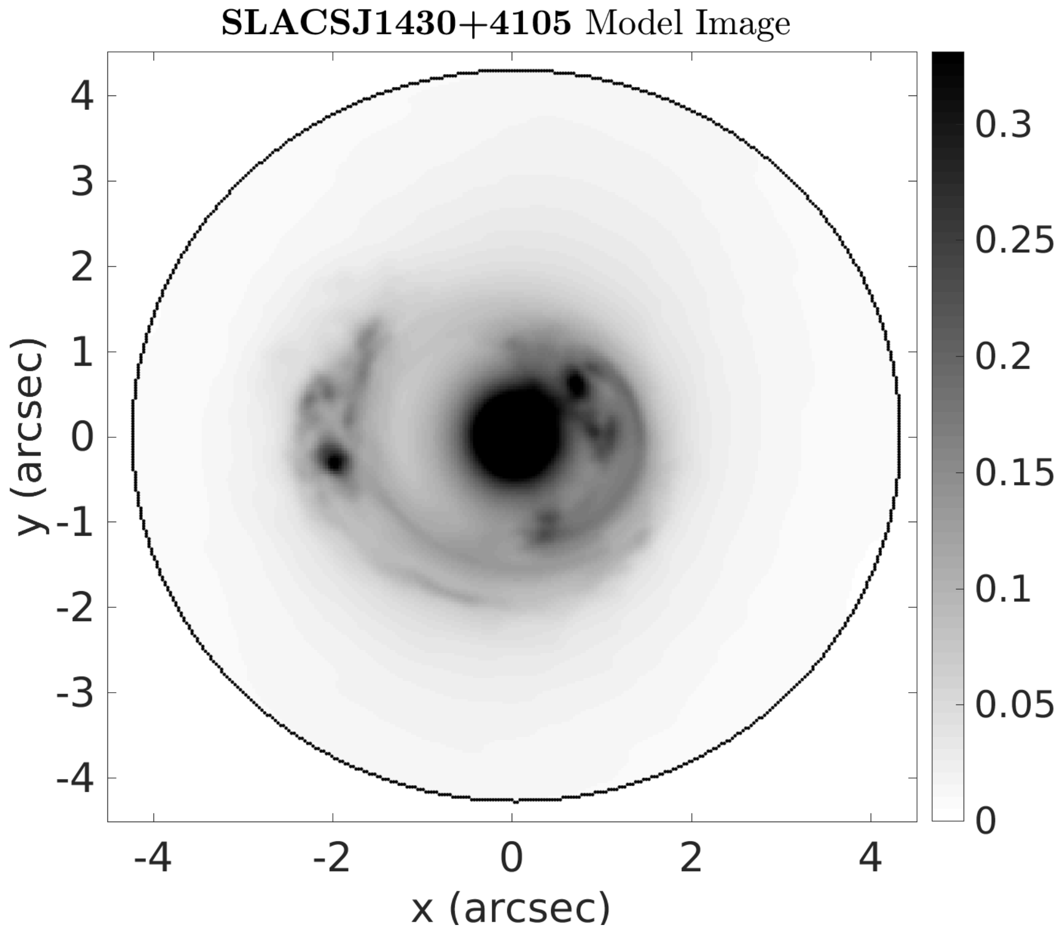
	Bayes Factor
• SLACS1 – $\Delta \ln \varepsilon$ =	**666**
• SLACS2 – $\Delta \ln \varepsilon$ =	**150**
• SLACS3 – $\Delta \ln \varepsilon$ =	**704**
• RX? – $\Delta \ln \varepsilon$ =	**801**

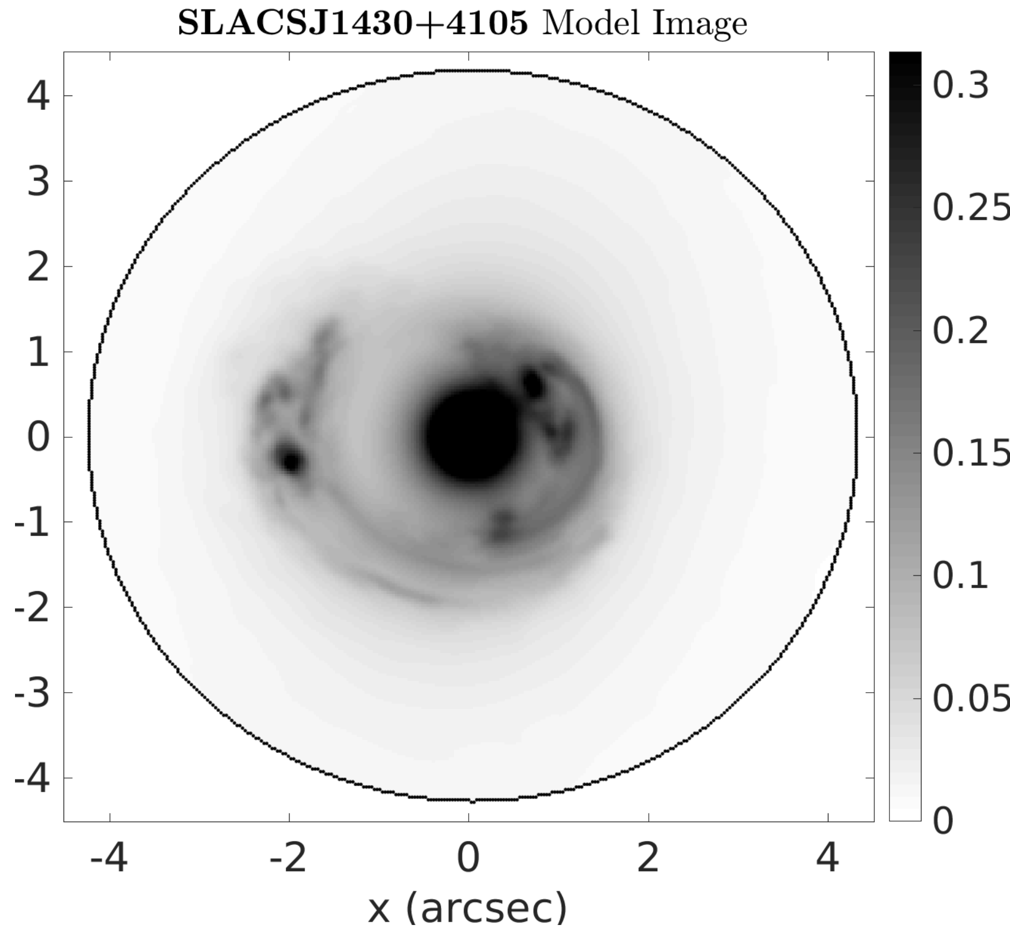
Light Profiles



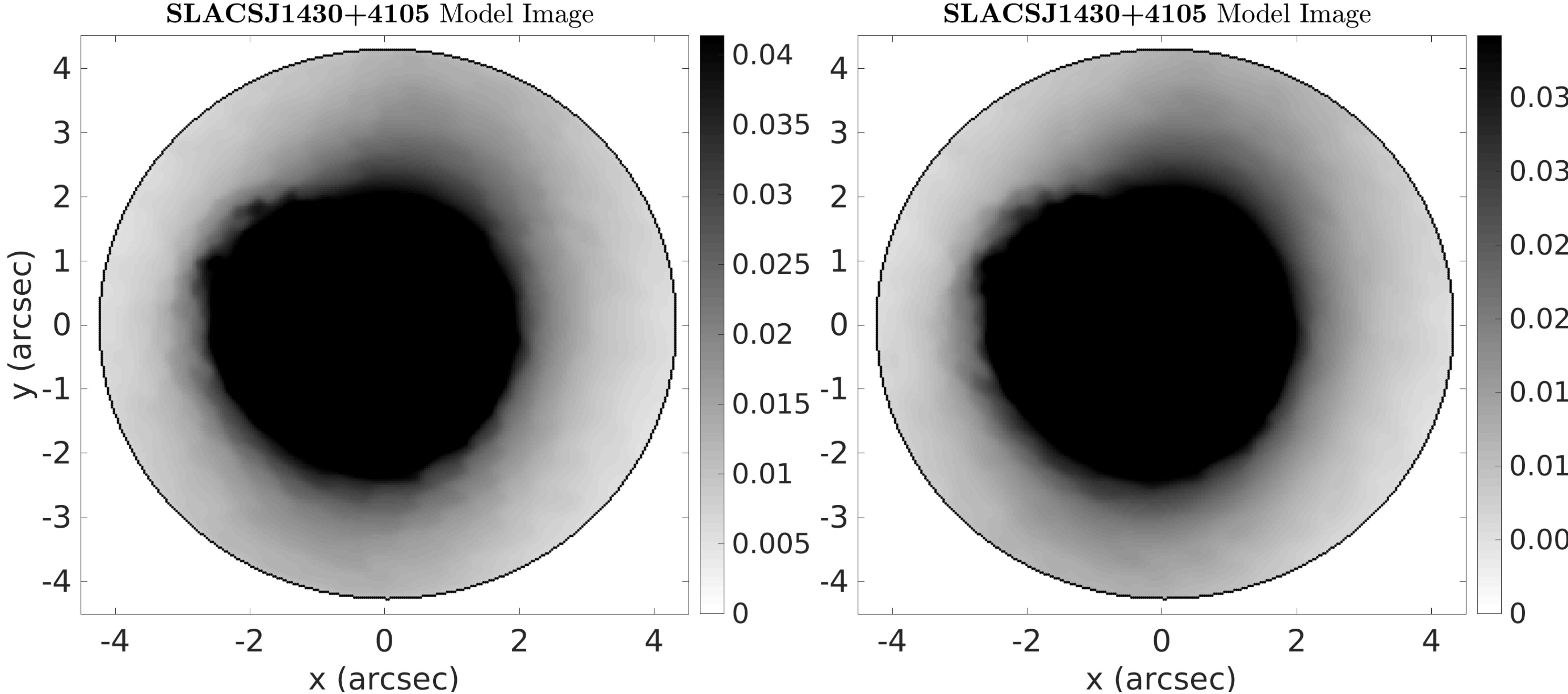


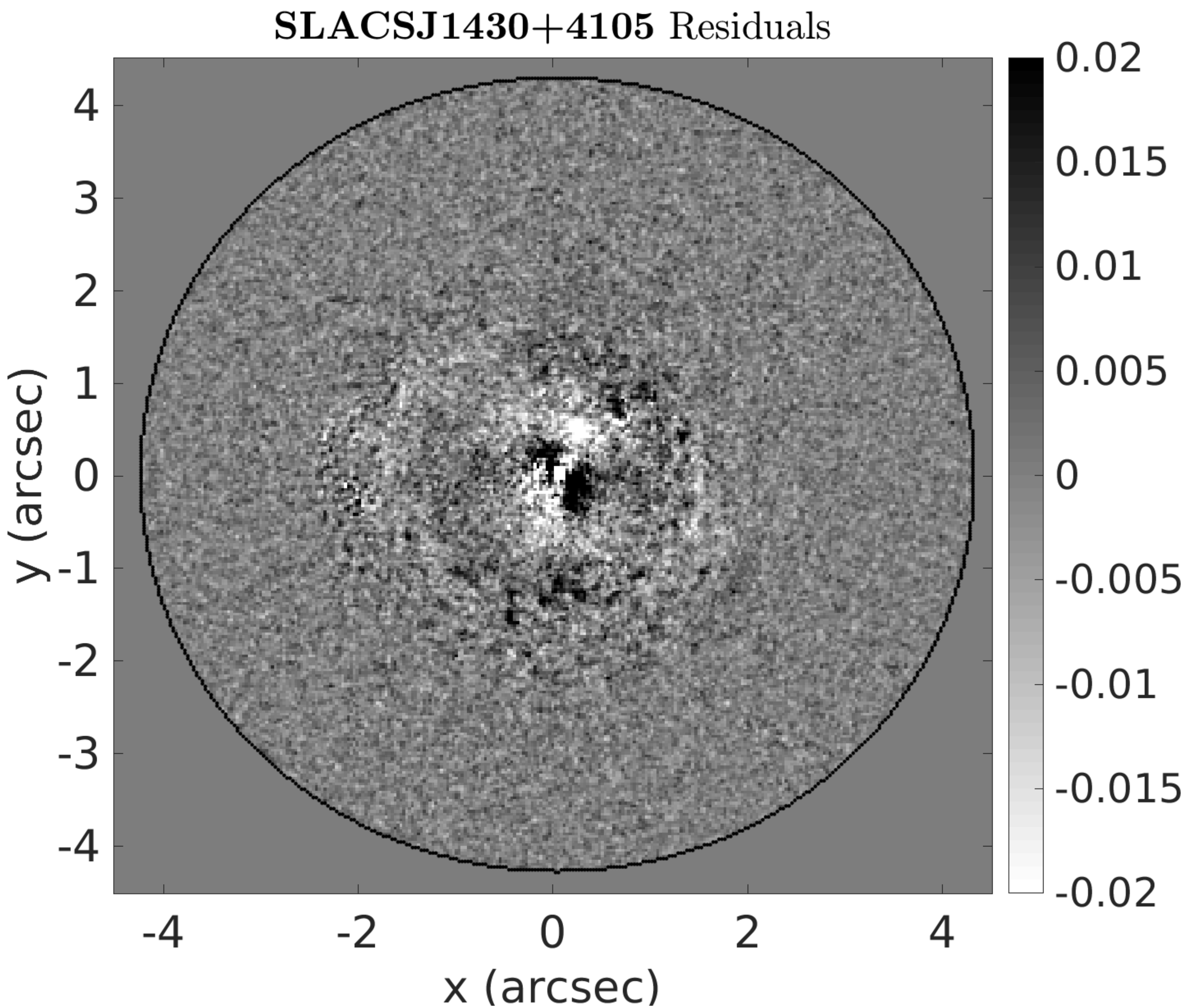
Light Profiles

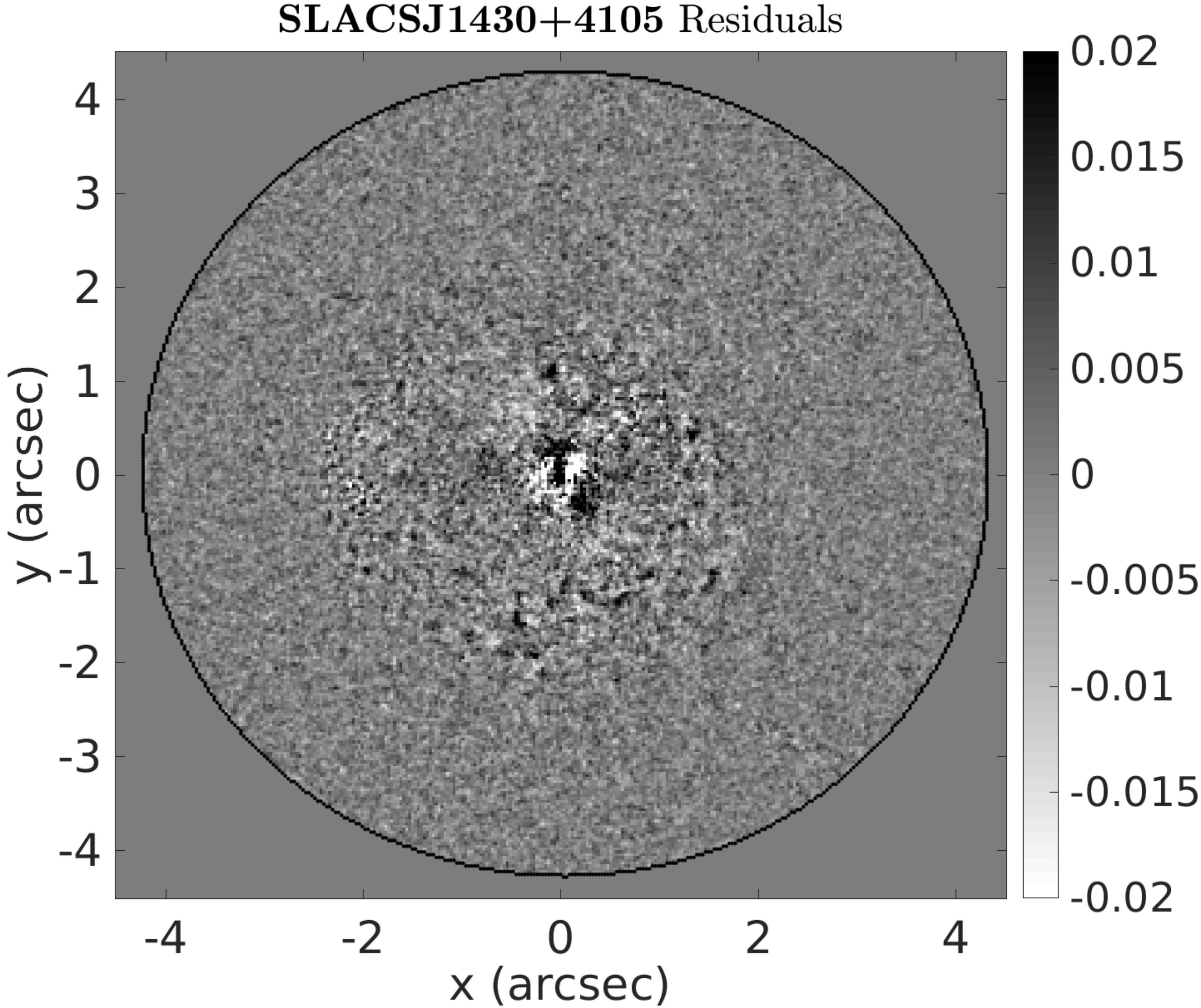




Light Profiles




SLACSJ1430+4105 Residuals
y (arcsec)
x (arcsec)
4
3
2
1
0
-1
-2
-3
-4
-4
-2
0
2
4
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02



SLACSJ1430+4105 Residuals
4
3
2
1
0
-1
-2
-3
-4
y (arcsec)
-4
-2
0
2
4
x (arcsec)
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02

Two component model

- **Component 1:**

  Smaller: Effective Radius = 0.20”, 0.55”, 0.64”

  Concentrated: Sersic Index = 3.6, 3.8, 3.0

  Round: Axis Ratio (b/a) = 0.88, 0.88, 0.92

- **Component 2:**

  Extended: Effective Radius = 0.82”, 2.00”, 3.52”

  Smooth: Sersic Index = 1.0, 1.0, 1.0

  Flat: Axis Ratio (b/a) = 0.79, 0.92, 0.63

- **Note – Axis ratio of SLACS2 Component 2 = 0.92**

Aligned Rotationally?

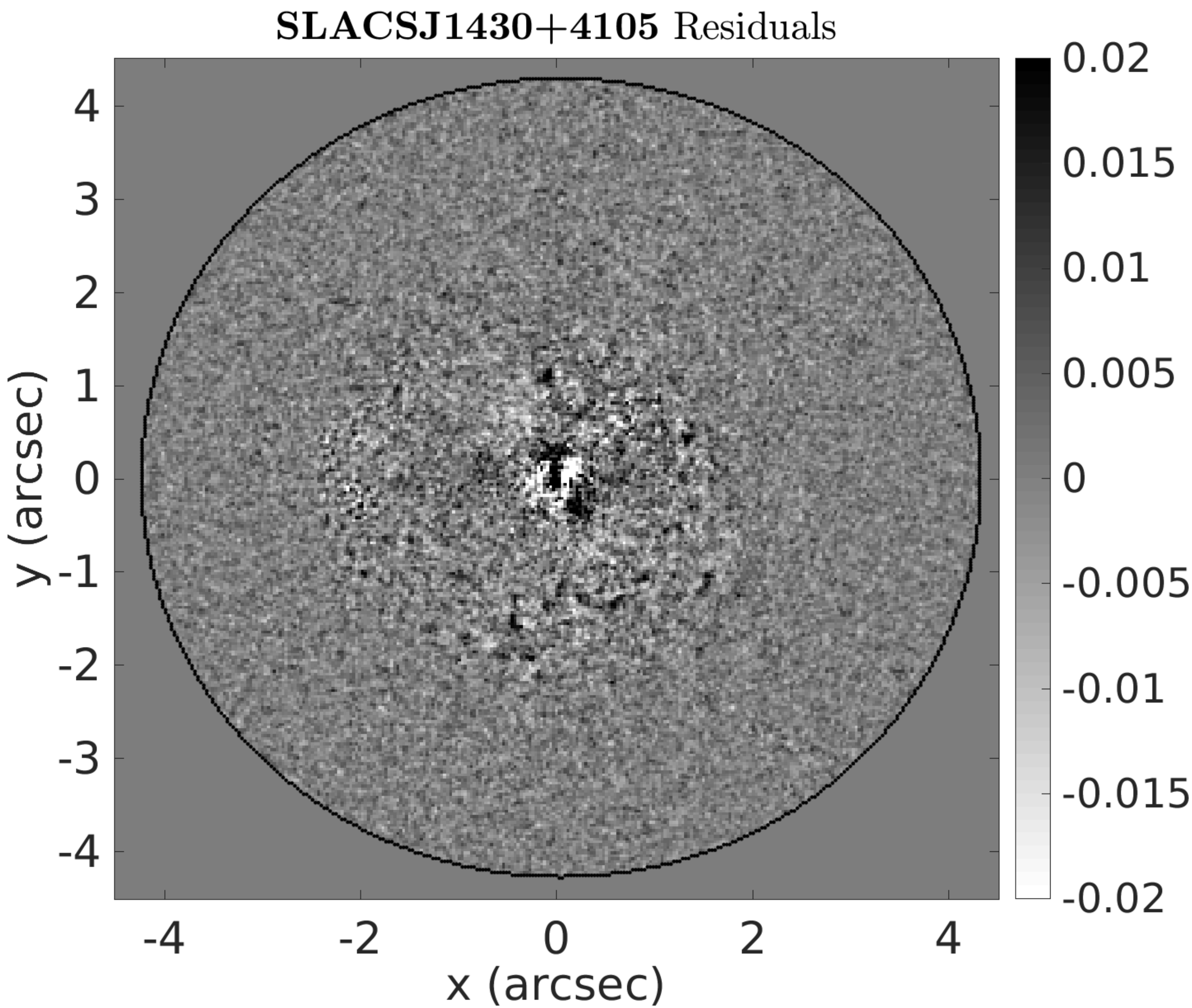
$\Delta \ln \varepsilon$ = Rotationally Offset / Rotationally Aligned

	Bayes Factor
• SLACS1 – $\Delta \ln \varepsilon$ =	**81**
$\Delta\Theta$ = ~ 67-73°	
• SLACS2 – $\Delta \ln \varepsilon$ =	**90**
$\Delta\Theta$ = ~ 77-83°	
• SLACS3 – $\Delta \ln \varepsilon$ =	**135**
$\Delta\Theta$ = ~ 22-24°	
• Abell - $\Delta \ln \varepsilon$ =	**210**
$\Delta\Theta$ = ~ 9-11°	

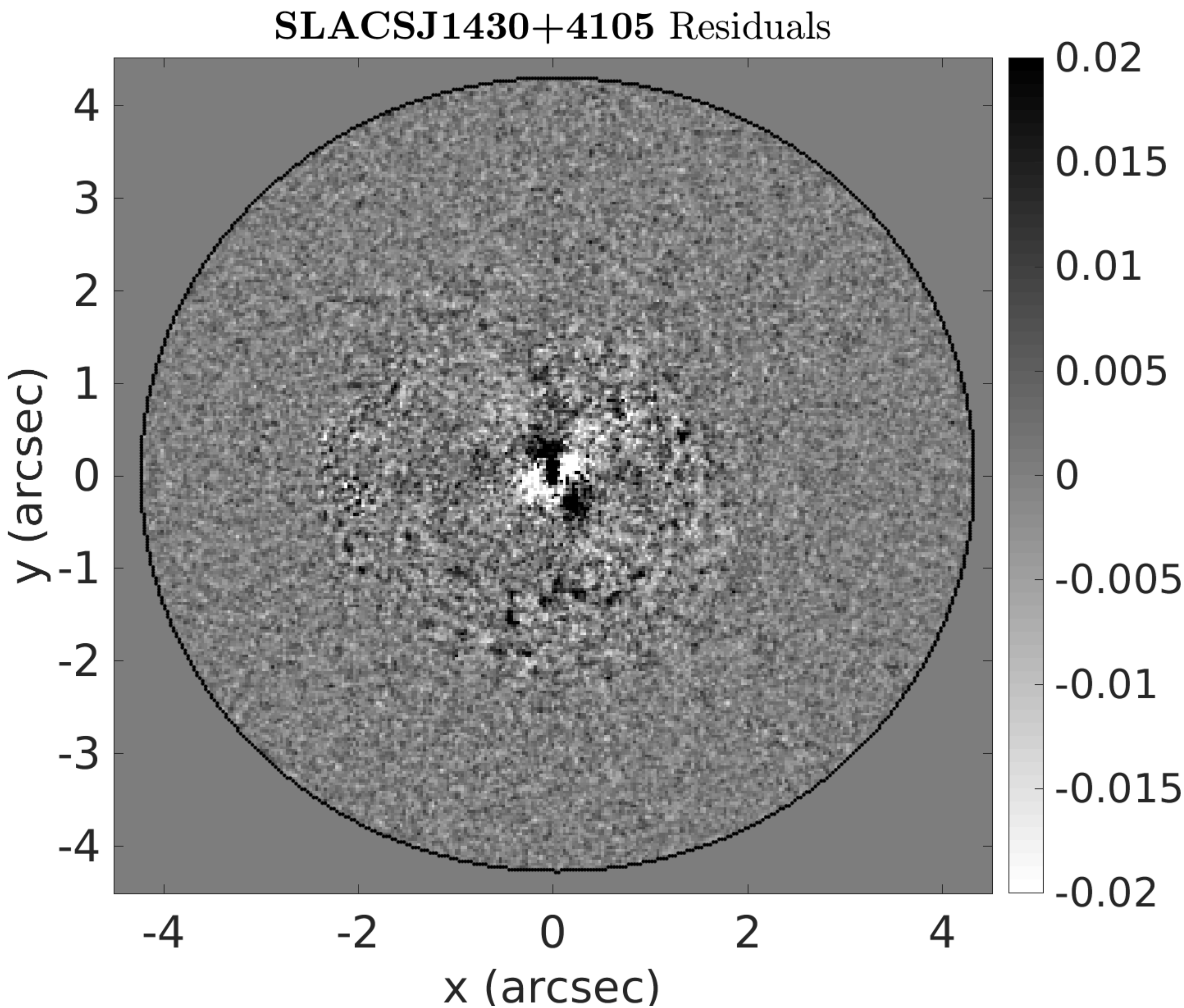
Aligned Centrally?

Δlnε = Centrally Offset / Centrally Aligned

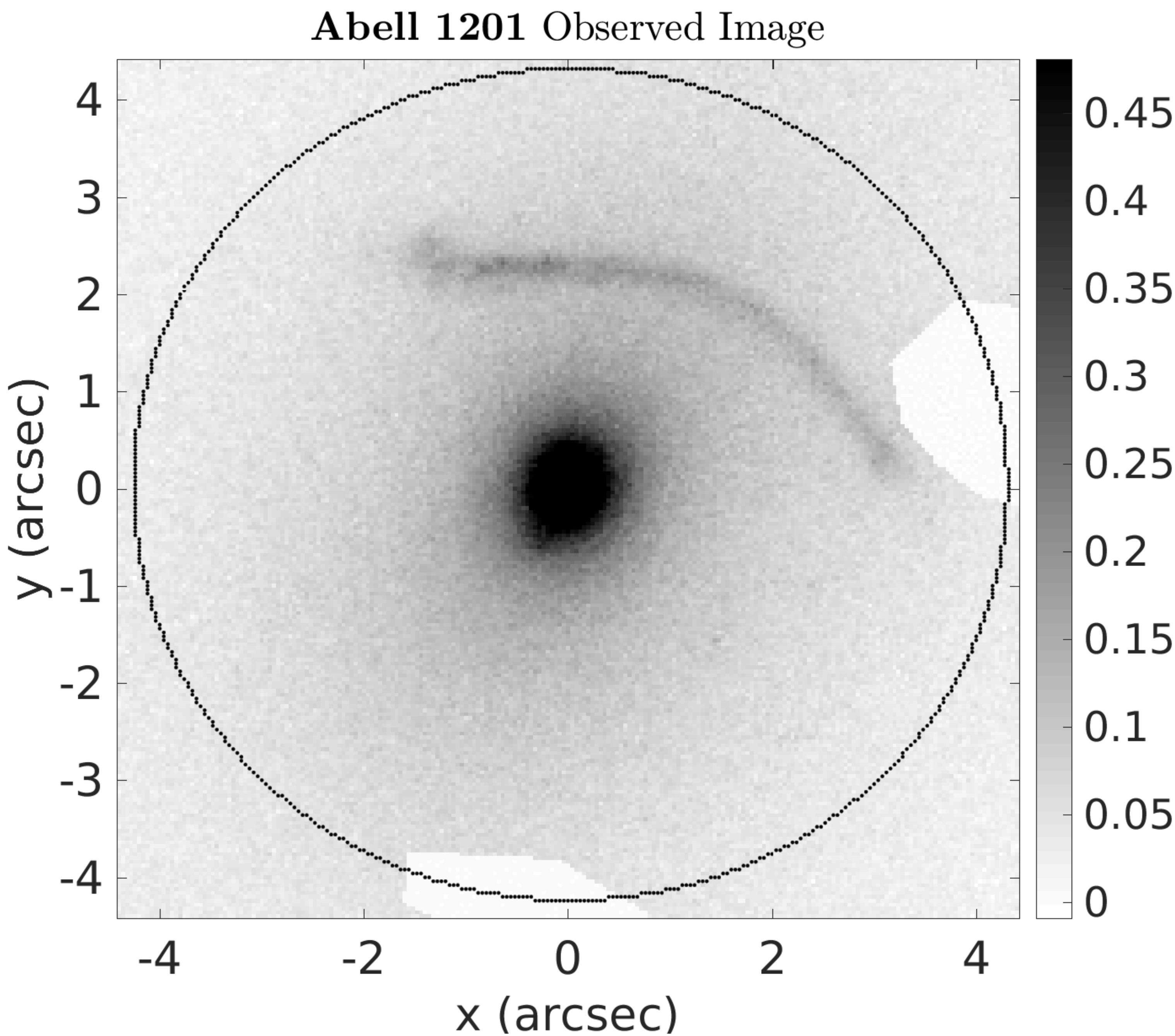
	Bayes Factor
• SLACS1 – Δlnε =	**2**
SLACS2 – Δlnε =	**60**
ΔR = ~ 0.0218” = 0.090 kpc	
• SLACS3 – Δlnε =	**47**
ΔR = ~ 0.0794” = 0.344 kpc	
• **Abell** – Δlnε =	**55**
ΔR = ~ 0.0794” = 0.403 kpc	



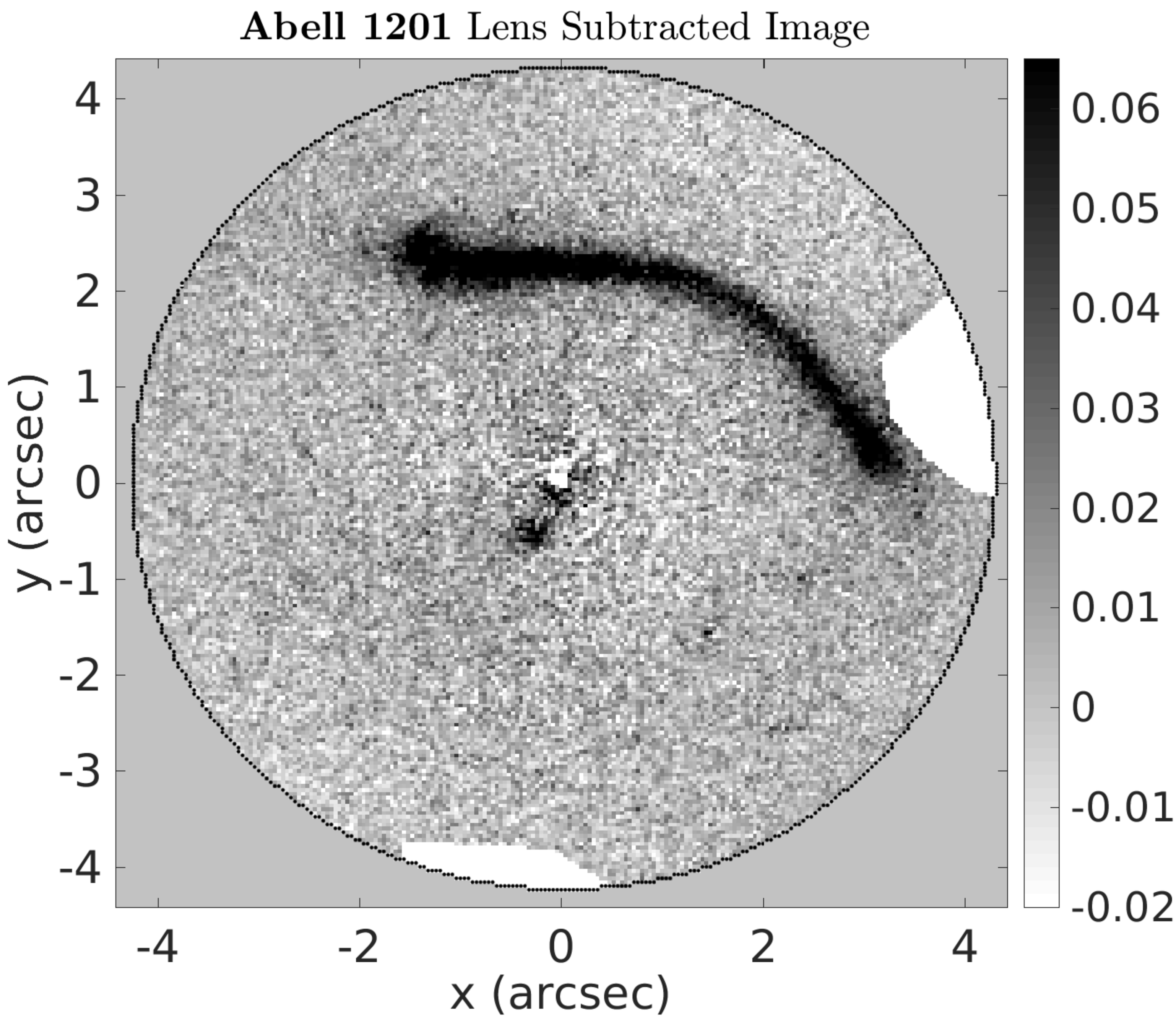
SLACSJ1430+4105 Residuals
y (arcsec)
x (arcsec)
4
3
2
1
0
-1
-2
-3
-4
-4
-2
0
2
4
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02

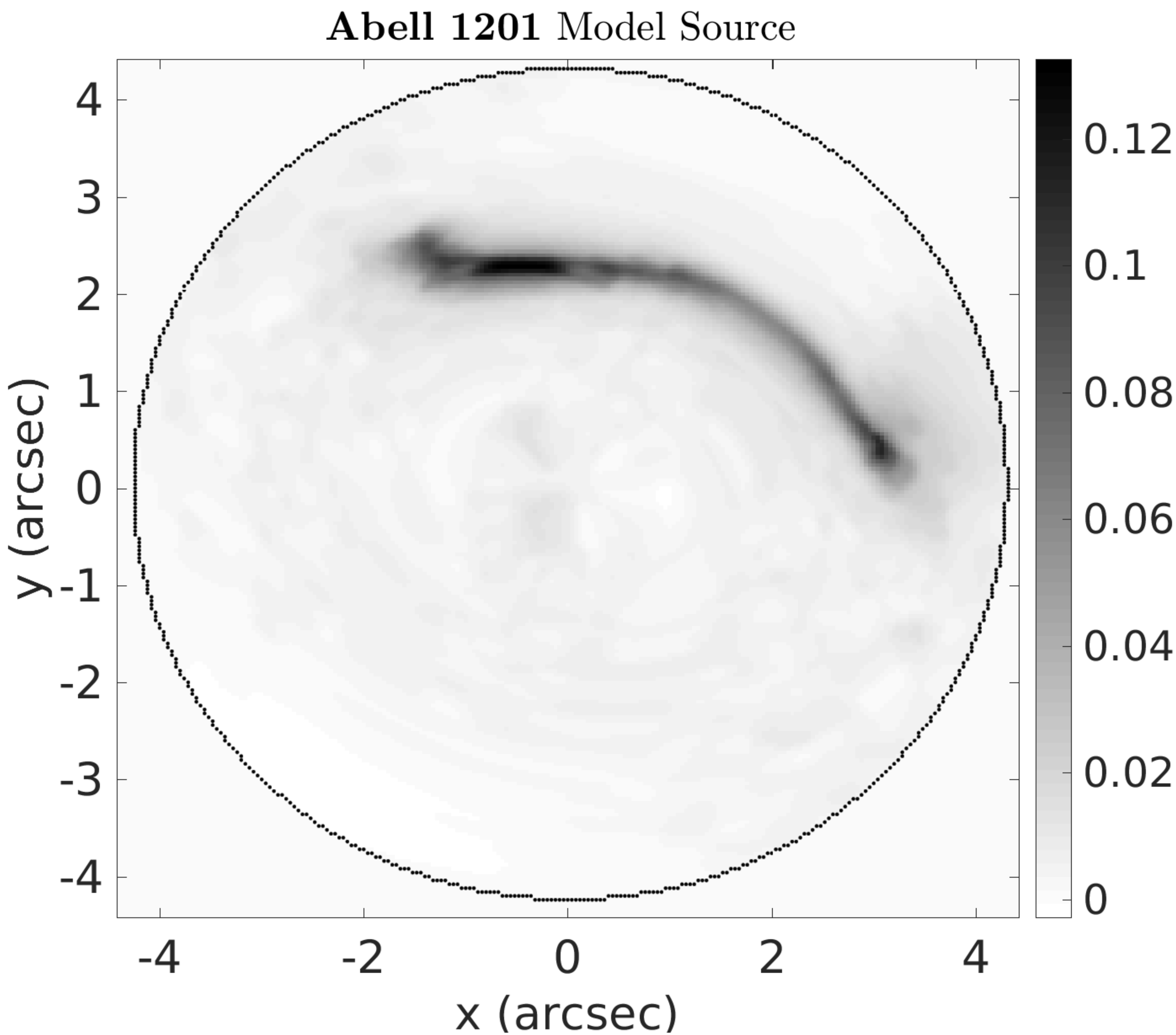


SLACSJ1430+4105 Residuals
4
3
2
1
0
-1
-2
-3
-4
y (arcsec)
-4
-2
0
2
4
x (arcsec)
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02

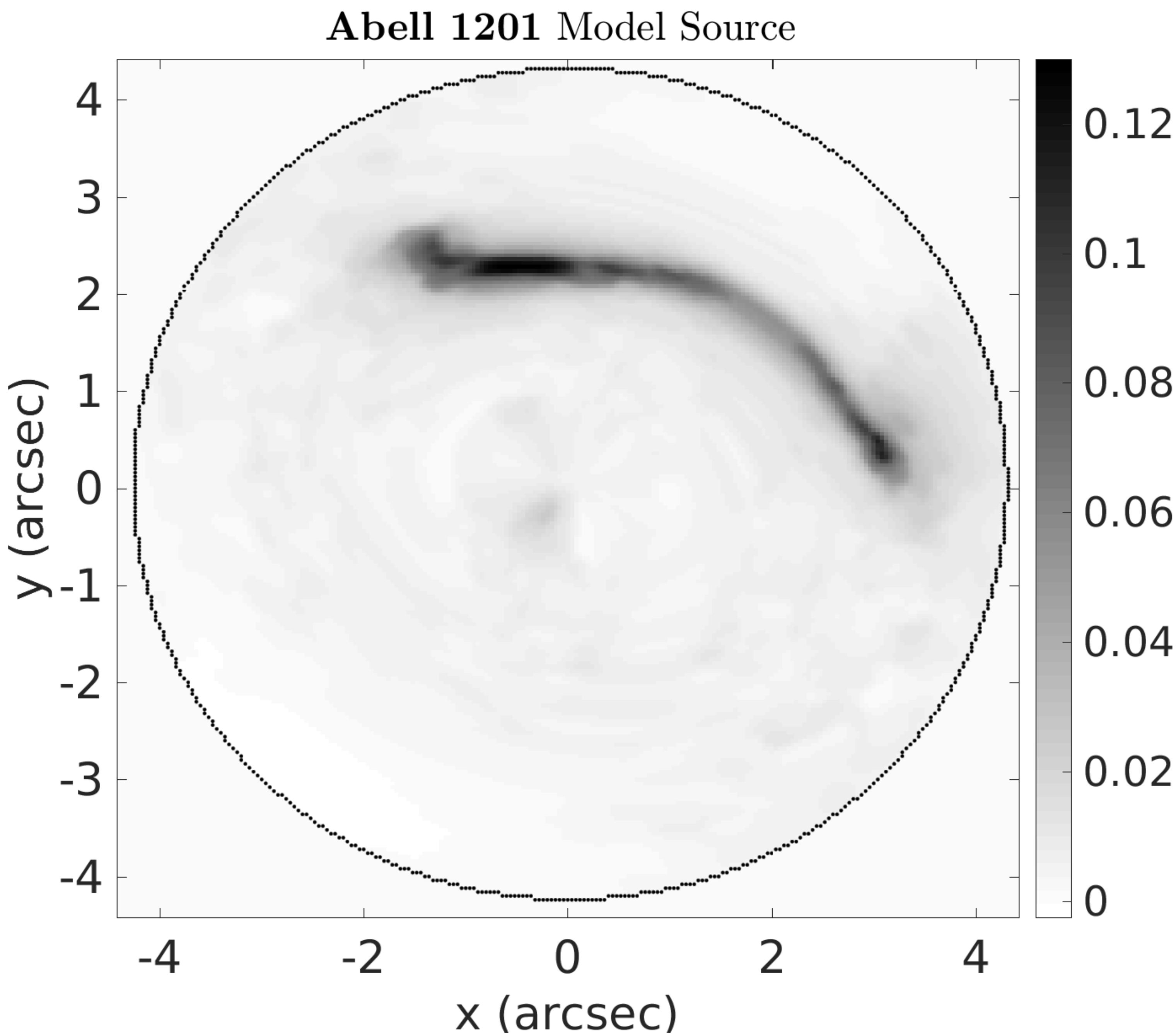


Abell 1201 Observed Image
y (arcsec)
x (arcsec)
4
3
2
1
0
-1
-2
-3
-4
-4
-2
0
2
4
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

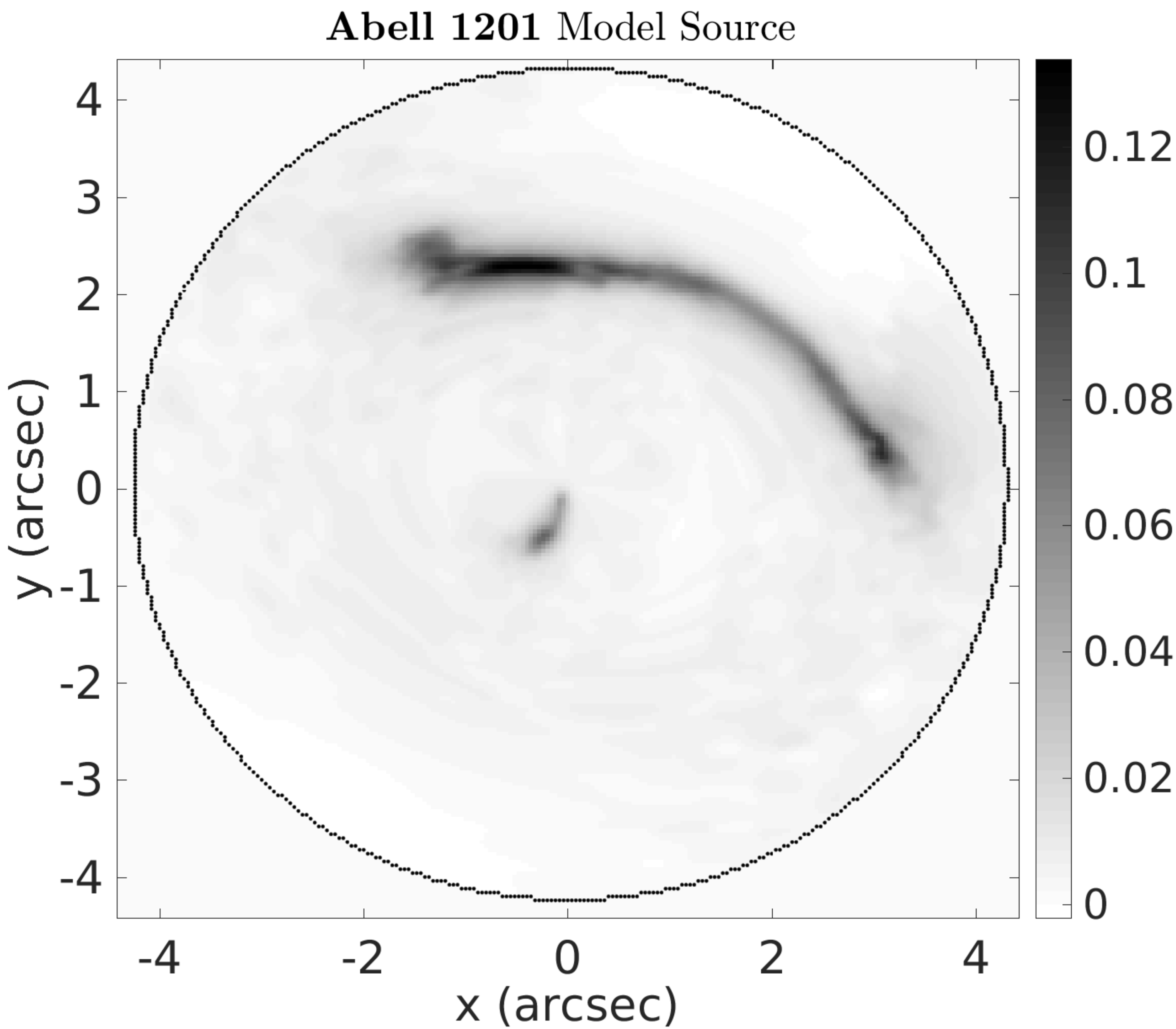

Abell 1201 Lens Subtracted Image
y (arcsec)
x (arcsec)
4
3
2
1
0
-1
-2
-3
-4
-4
-2
0
2
4
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02



Abell 1201 Model Source
y (arcsec)
x (arcsec)
4
3
2
1
0
-1
-2
-3
-4
-4
-2
0
2
4
0.12
0.1
0.08
0.06
0.04
0.02
0



Abell 1201 Model Source
y (arcsec)
x (arcsec)
4
3
2
1
0
-1
-2
-3
-4
-4
-2
0
2
4
0.12
0.1
0.08
0.06
0.04
0.02
0


Abell 1201 Model Source
y (arcsec)
x (arcsec)
4
3
2
1
0
-1
-2
-3
-4
-4
-2
0
2
4
0.12
0.1
0.08
0.06
0.04
0.02
0

What did Lensing Add?

- **We can fit the lens galaxy's independent of the mass model:**

  - 2 component models favoured (lower Bayes Factors).

  - 3 of 4 rotational offsets detected (lower Bayes Factors).

  - 1 of 4 centroid offsets detected (but x / y parameters go to the same values as with lensing on).

- **Thus, we see the same results without lensing, reassuring us this isn't a quirk of mass modeling!**

Lens Galaxy Structure

- In all 4 (Massive Elliptical) lenses studied thus far, **lensing reveals two distinct physical components:**

  Component 1 - High Sersic index, round, compact.

  Component 2 – Low Sersic index, flat, extended.

- **Geometrically independent** (projected rotational offsets as large as **80˚,** centroid offsets up to **~300 pc**).
- **Different mass-to-light ratios** (second component lower mass-to-light ratio).

Stellar Halos

- **The second component is the stellar halo.**

  - Stellar halo oriented w.r.t to local environment where there is preferential accretion (not observed yet).

  - Geometry of the bulge detached from dark matter halo / local environment during formation.

  - The different mass-to-light ratios of each components suggest the stellar halo is younger stellar material.

Beyond Morphology

- Visual morphology is perhaps the oldest study in extragalactic astronomy (Hubble 1926).
- Lensing helps confirm that what we see corresponds to genuine **physical structures in the galaxy.**

  - IFS surveys like ATLAS3D have told us how important this is.
- **As lens samples grow, we can begin to play this game over the entire Hubble diagram.**

Dark Matter

- Lensing also measures the central dark matter halo mass (and potentially ellipticity and orientation).