Free-form lens models of four Hubble Frontier Fields clusters:
Maximum lensing efficiency

J. Vega-Ferrero, J. M. Diego and G. Bernstein

University of Pennsylvania

Instituto de Física de Cantabria

Summary

1. Hubble Frontier Fields (HFF)
2. Free-form gravitational lensing models
3. Results

5. Conclussions

1. Hubble Frontier Fields (HFF)

Motivations

- Unprecedented look into the cosmos with the help of giant cosmic lenses in space
- Gravity of massive **galaxy clusters (GCs)** distorts and magnifies the light of distant galaxies (**10-100 times fainter** than any previously observed)
- **Galaxy evolution** in the early the universe (re-ionization)
- **Dark matter** within massive GCs
- Early glimpse of the work by the **JWST**

HST data

http://www.stsci.edu/hst/campaigns/frontier-fields/

- 560 orbits (**630 hours**) of HST to observe six **CGs**

Abell 2744	*z=0.308*	MACS 1149	*z=0.541*
MACS 0416	*z=0.397*	Abell S1063	*z=0.348*
MACS 0717	*z=0.545*	Abell 370	*z=0.375*

- Drizzled images (**0".03 pixel^{-1}**) provided by **STScI**
- **ACS optical images:** F435W (B435), F606W (V606), F814W (i814) --- **M_{AB} = 28.7 mag**
- **WFC3/IR images:** F105W (Y105), F125W (J125), F140W (JH140), F160W (H160) --- **M_{AB} = 29 mag**

1. Hubble Frontier Fields (HFF)

Frontier Fields Lens Models v4

https://archive.stsci.edu/prepds/frontier/lensmodels/

- Robust and reliable **lens (mass) models** for exploiting the science of HFF
- Mass model accuracy relies on:
  - **number of multiple imaged** background galaxies
  - **spectroscopy** of these multiple images
- **Five teams** contracted by **STScI** to produce GL models
- **Share latest observational constraints** (positions and redshifts) from GLASS, CLASH-VLT, MUSE-VLT
- **GOLD**, SILVER and BRONCE candidates

Gravitational lensing models

Strong lensing constraints ⇒ **lens inversion**

- **WSLAP+** (Weak & Strong Lensing Analysis Package): **free-form** lensing model
- **WSLAP+ team**: G. Bernstein, J. M. Diego, J. Vega-Ferrero, D. Lam, T. Broadhurst

Parametric	Free-form
Mass reconstruction by combining clumps of matter	Cluster subdivided into a mesh to map lensing observables
Clumps described by an ensemble of parameters (density profile)	Mesh transformed into a pixelised mass distribution

WSALP+ lensing model

Diego et al. 2005, 2007; Sendra et al. 2014; Diego et al. 2016

- **No assumptions on the distribution of DM**

Mass distribution

Compact component

cluster members

M/L ratio (N_g)

total mass: NFW or surface brightness

Diffuse component

gaussians on a grid (N_c)

params. ∝ grid points

\+ background sources (N_s)

WSALP+ lensing model

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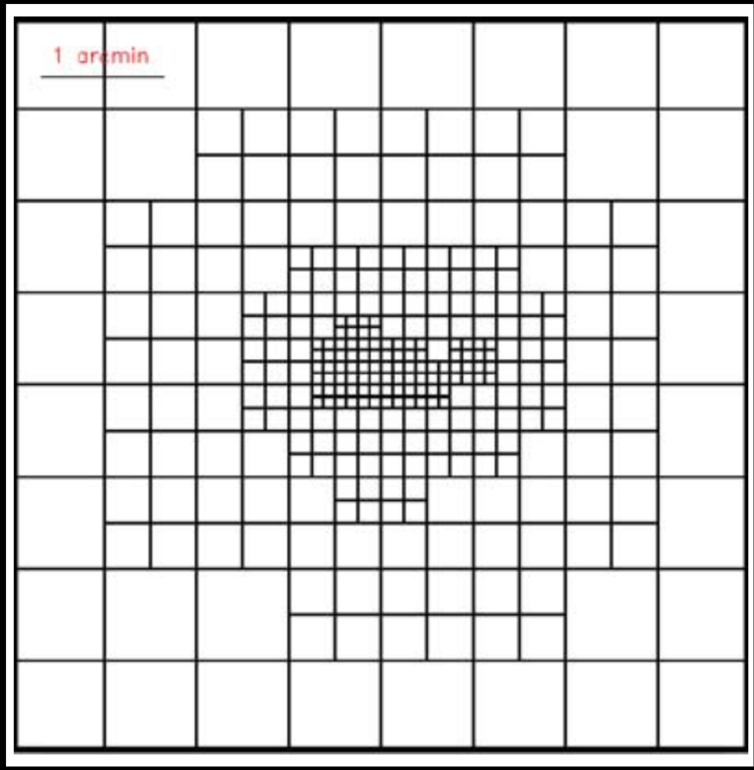
- **No assumptions on the distribution of DM**
- **Fast algorithm** (secs. to mins.): multiple solutions
- Multiresolution code: adaptative grid



2. Free-form gravitational lensing models

WSALP+ lensing model

Diego et al. 2005, 2007; Sendra et al. 2014; Diego et al. 2016

- **No assumptions on the distribution of DM**
- **Fast algorithm** (secs. to mins.): multiple solutions
- Multiresolution code: adaptative grid
- Combine **weak and strong lensing**
- Spatial information about **knots in resolved systems**
- **Multilens plane** (different layers)

The Frontier Fields Lens Modeling Comparison Project

(Meneghetti et al. 2016)

3. Results

Frontier Fields Lens Models v4

https://archive.stsci.edu/prepds/frontier/lensmodels/

HFF	z	Multiple images (systems)	Cluster Members	Members references
MACS1149	0.544	132(9) 154(17)	203	3 layers: 1 x central BCG + 1 x bright galaxy + 1 x cluster members
MACS0416	0.396	113 (35) 158 (54)	249	VIMOS CLASH-VLT (Balestra et al. 2016). VLT/MUSE spectroscopic (Caminha et al. 2016), Zitrin et al. (2013) F814W-F475W color
MACS0717	0.548	54 (9) 72 (17)	338	Richard et al. (2014): colour-colour, two colour-magnitude, spectroscopical calibration
Abell 2744	0.308	76(24) 180(53)	403	AstroDeep (Merlin et al. 2016, Castellano et al. 2016), GLASS (Treu et al. 2015), Owers et al. 2011

FF Lens teams & STCsI

3. Results

Frontier Fields Lens Models v4

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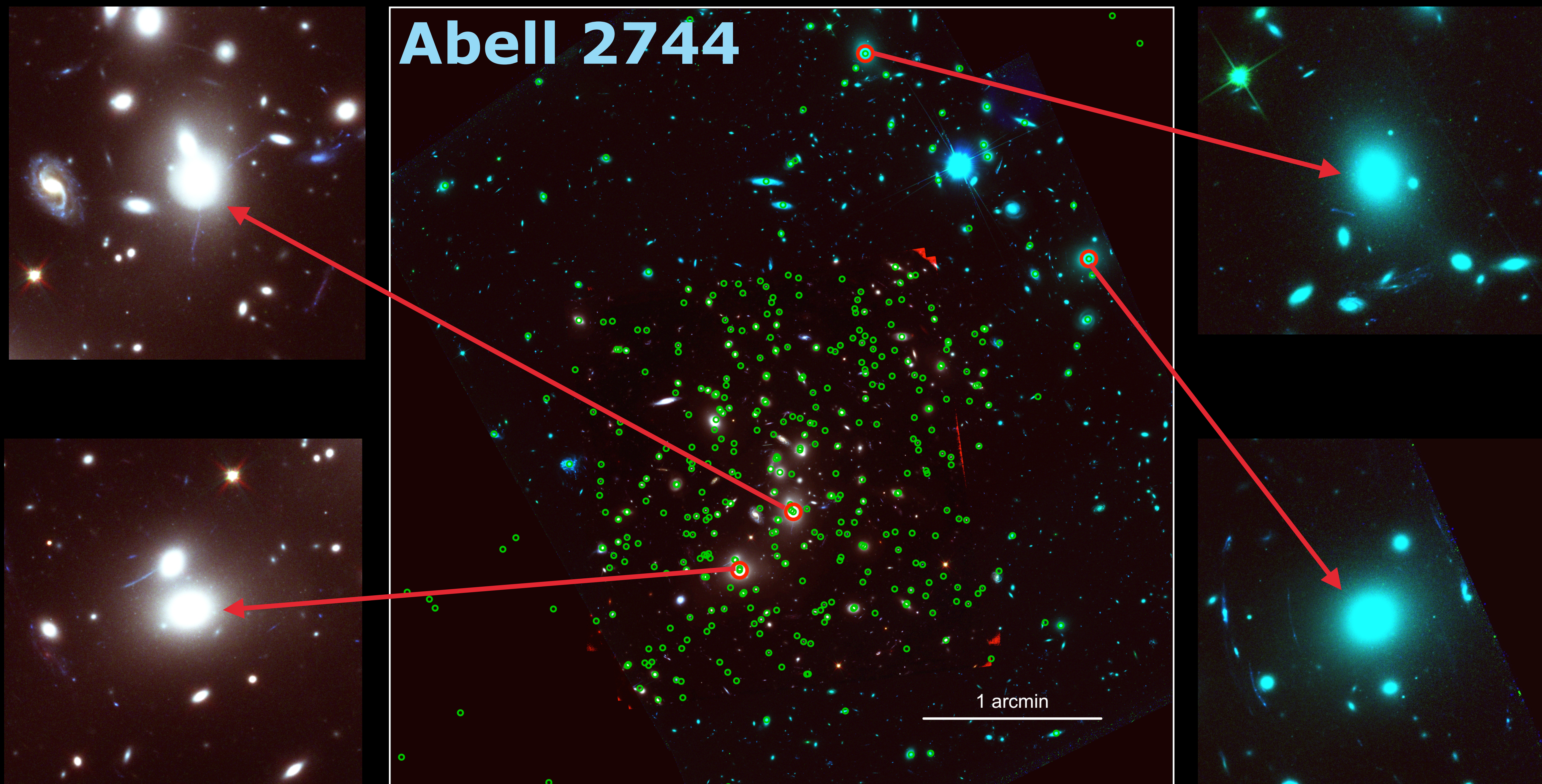
Jauzac et al. 2015: 9 spect. Systems

WSALP+ lensing models

HFF	z	Layers	FOV (arcmin^2)	Leyer description
MACS1149	0.544	3	3.6 x 3.6	1 x central BCG + 1 x bright galaxy + 1 x cluster members
MACS0416	0.396	4	3.6 x 3.6	1 x North BCG + 1 x South BCGs + 1 x foreground (z = 0.112) + 1 x cluster members
MACS0717	0.548	2	3.6 x 3.6	1 x foreground (z = 0.154) + 1 x cluster members
Abell 2744	0.308	1	4.4 x 4.4	1 x Center BCG + 1 x South BCGs + 2 x bright galaxies + 1 x cluster members

3. Results

WSALP+ lensing models



WSALP+ lensing models

- **Two sets of solutions:**

GOLD

ALL = GOLD + SILVER + BRONSE

Confirmed + z-spec | **Confirmed** | **Dubious**

- **Two different models:**

BEST

1 x **300k iter.**

RANGE

100 x **100k iter.**

$\sigma_z = 0.2(1+z)$

Goodness of model

- *root-mean-square:* $$rms = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\theta_i^{obs} - \theta_i^{pred}\right)^2}$$

rms (arcsec)		MACS1149	MACS0416	MACS0717	Abell 2744
BEST	ALL	1.06	0.72	0.68	1.18
BEST	GOLD	0.99	0.74	**0.55**	0.88
RANGE	ALL	1.02	0.88	0.86	1.28
RANGE	GOLD	0.98	0.86	**0.56**	1.07

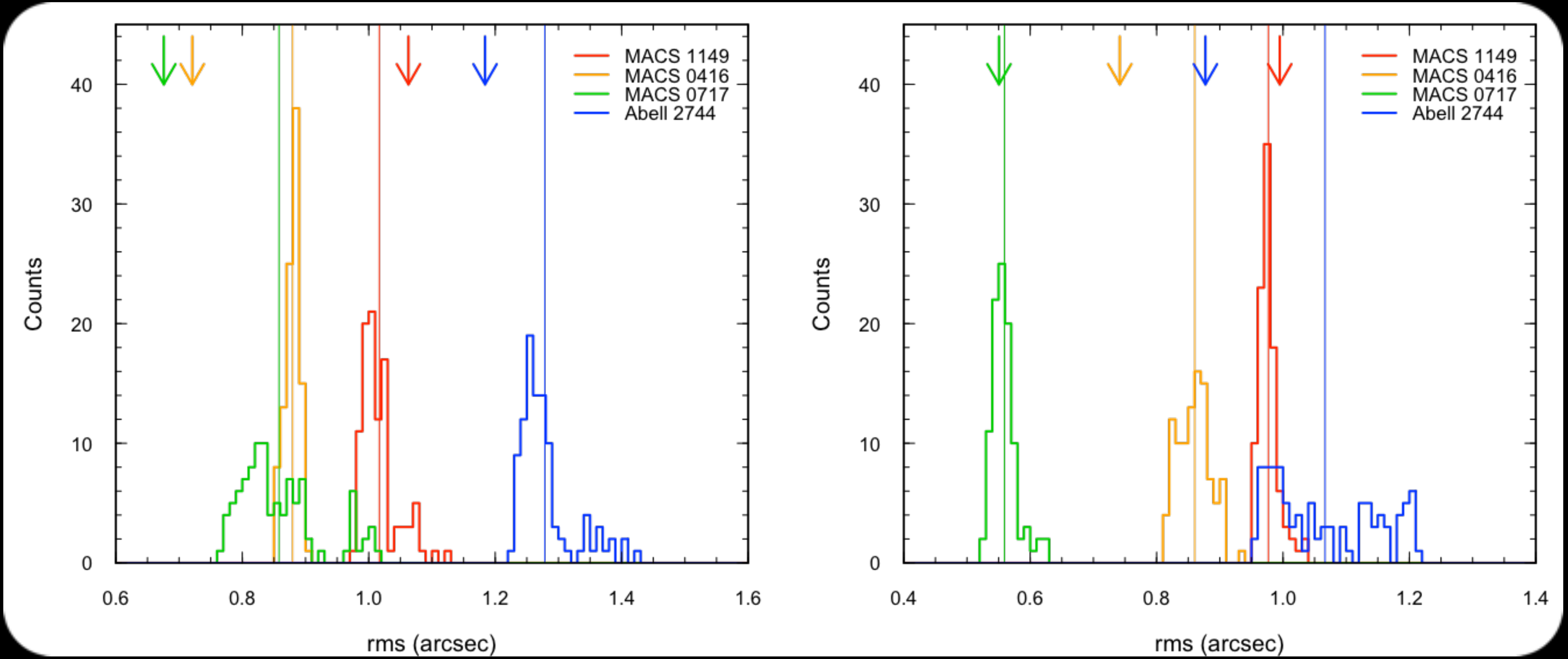
- **z-spect** required for accuracy in the magnification (Johnson & Sharon 2017)

3. Results

Goodness of model

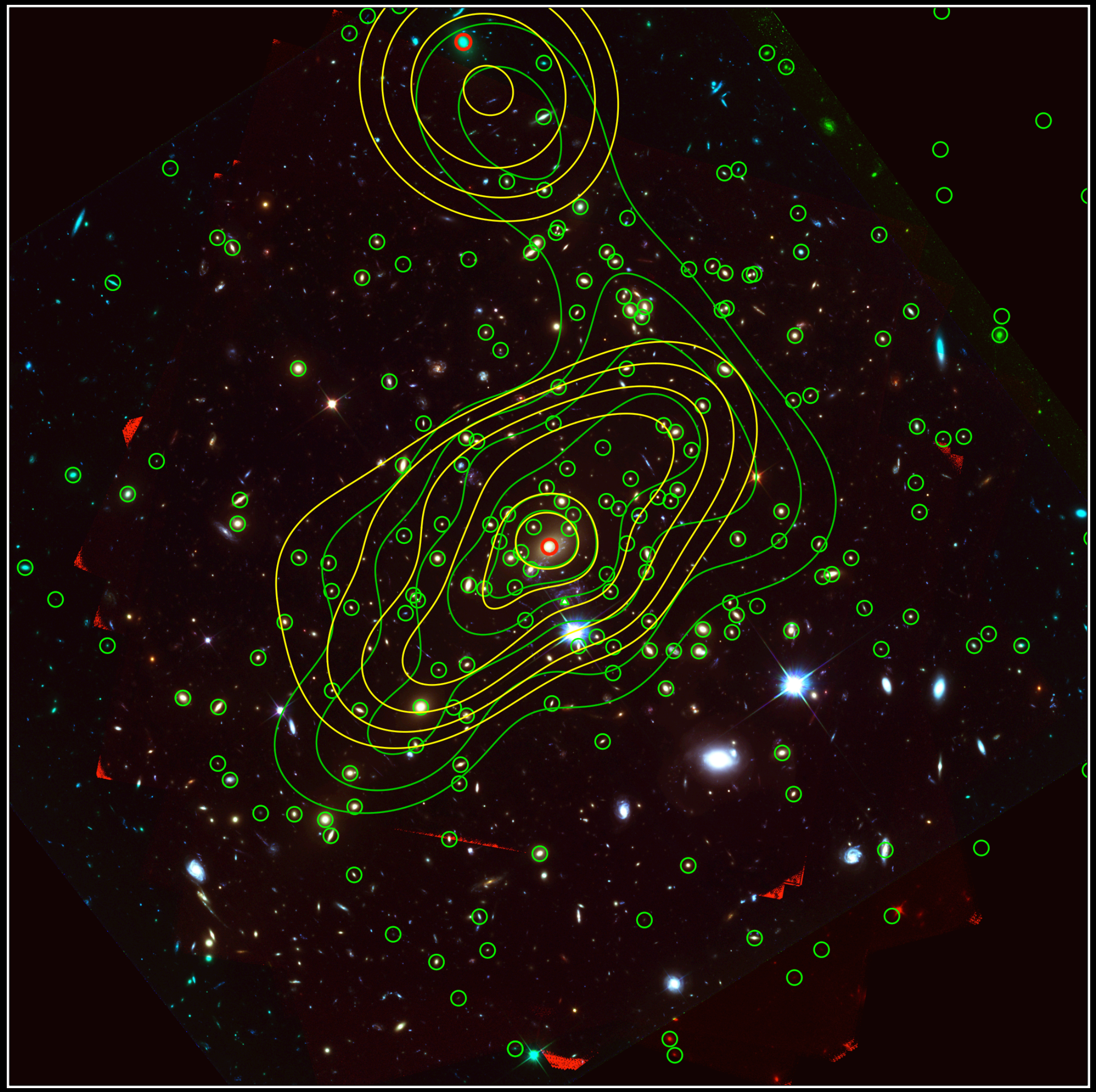
- *root-mean-square:* $$rms = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\theta_i^{obs} - \theta_i^{pred}\right)^2}$$

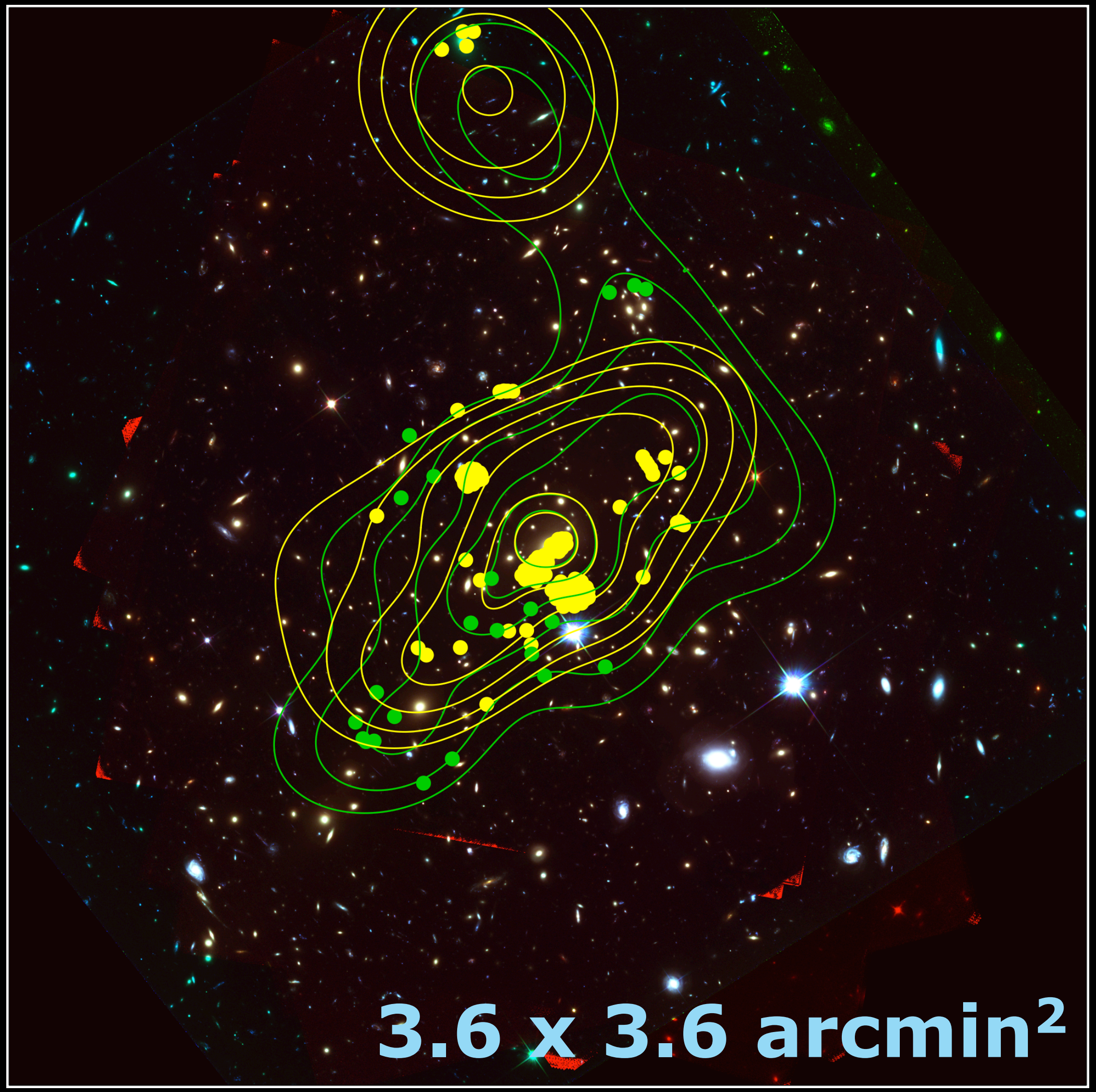
ALL **GOLD**



3. Results

MACS 1149: Mass distribution

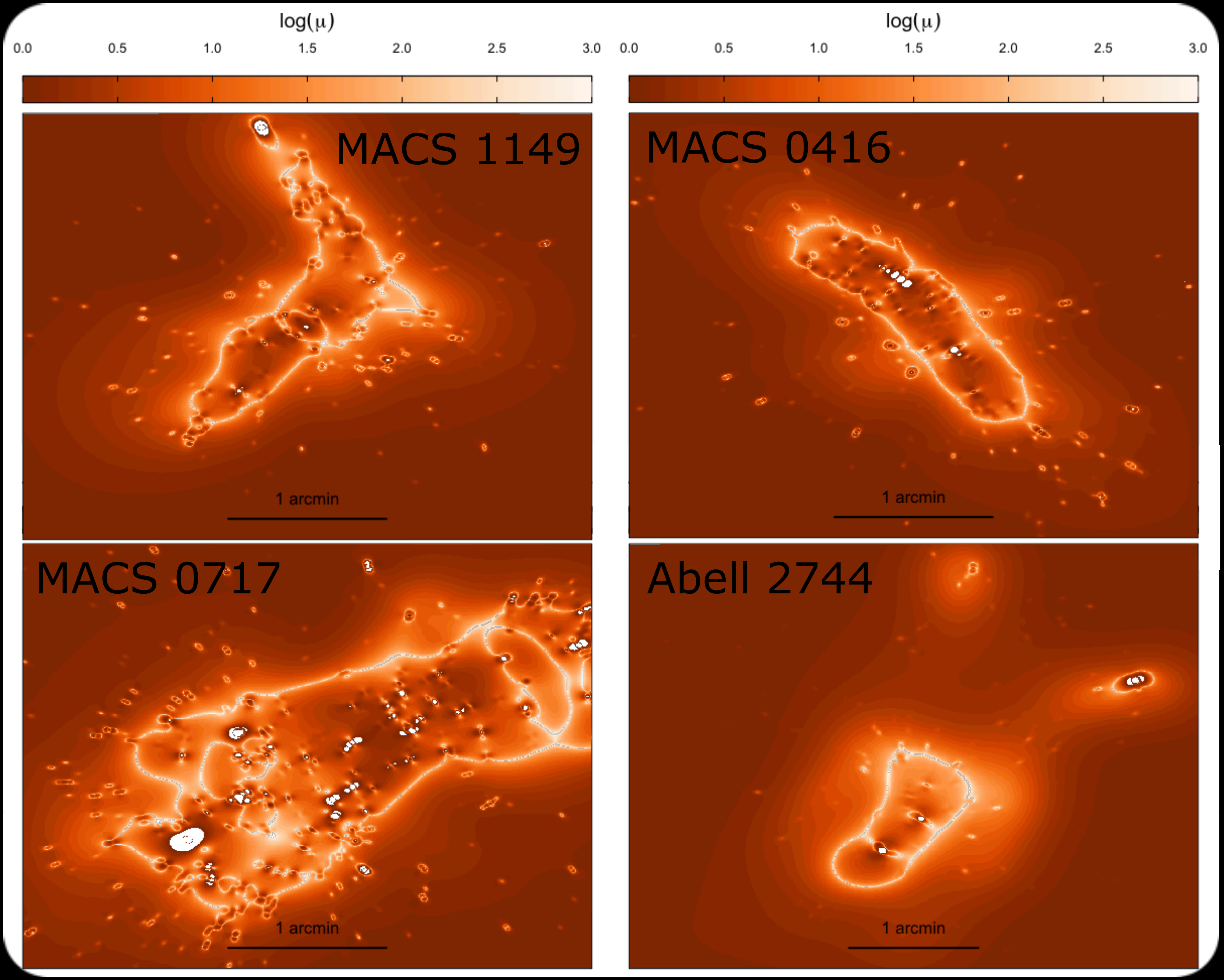




- **Subs. outskirts** significant impact on predicted positions (Acebron et al. 2017) and mass distributions

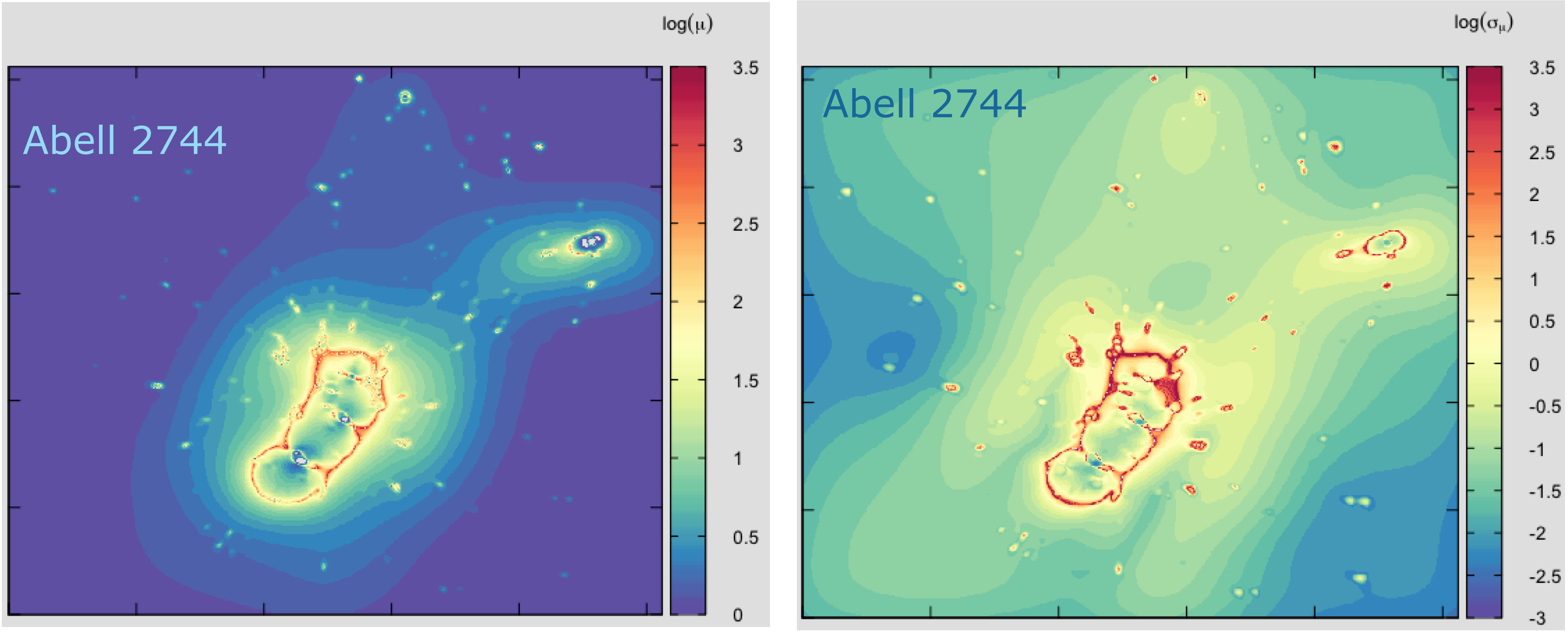
3. Results

Magnification maps (z_s = 9)

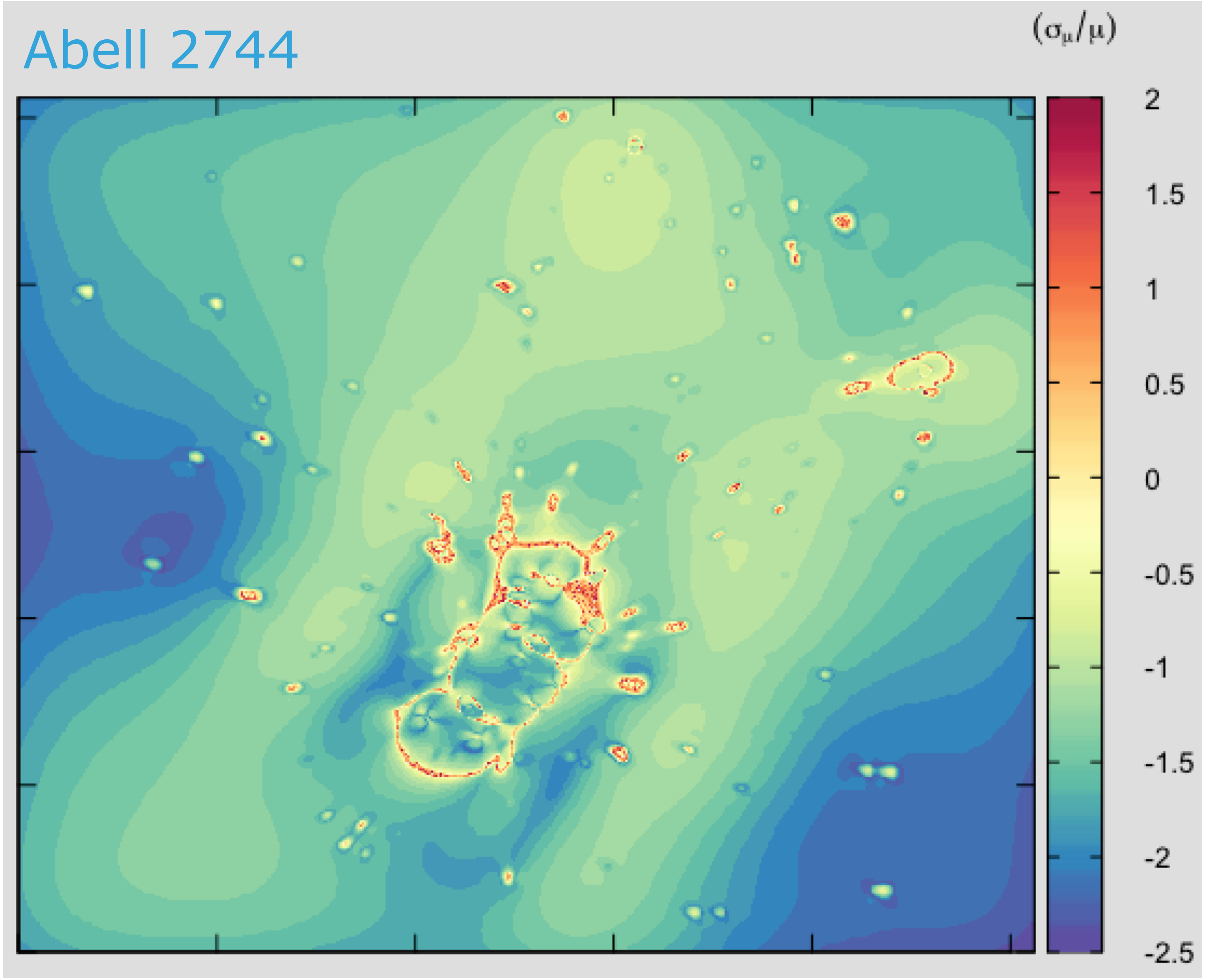


3. Results

Magnification maps (z_s = 9)



Magnification maps (z_s = 9)



Lensing efficiency

- **Lensing efficiency** (Wong et al. 2012): total surface **area in the source plane** above μ = 3
- Caustics from magnification:

$$A_s(\mu) = \frac{1}{\mu} A_l(\mu) \longrightarrow A(>\mu) = \int \frac{dA_s}{d\mu} d\mu$$

$\frac{dA_s}{d\mu} \propto 1/\mu$

$A(>\mu) \propto 1/\mu^2$

Lensing efficiency (z_s = 9)

- Caustics from magnification:

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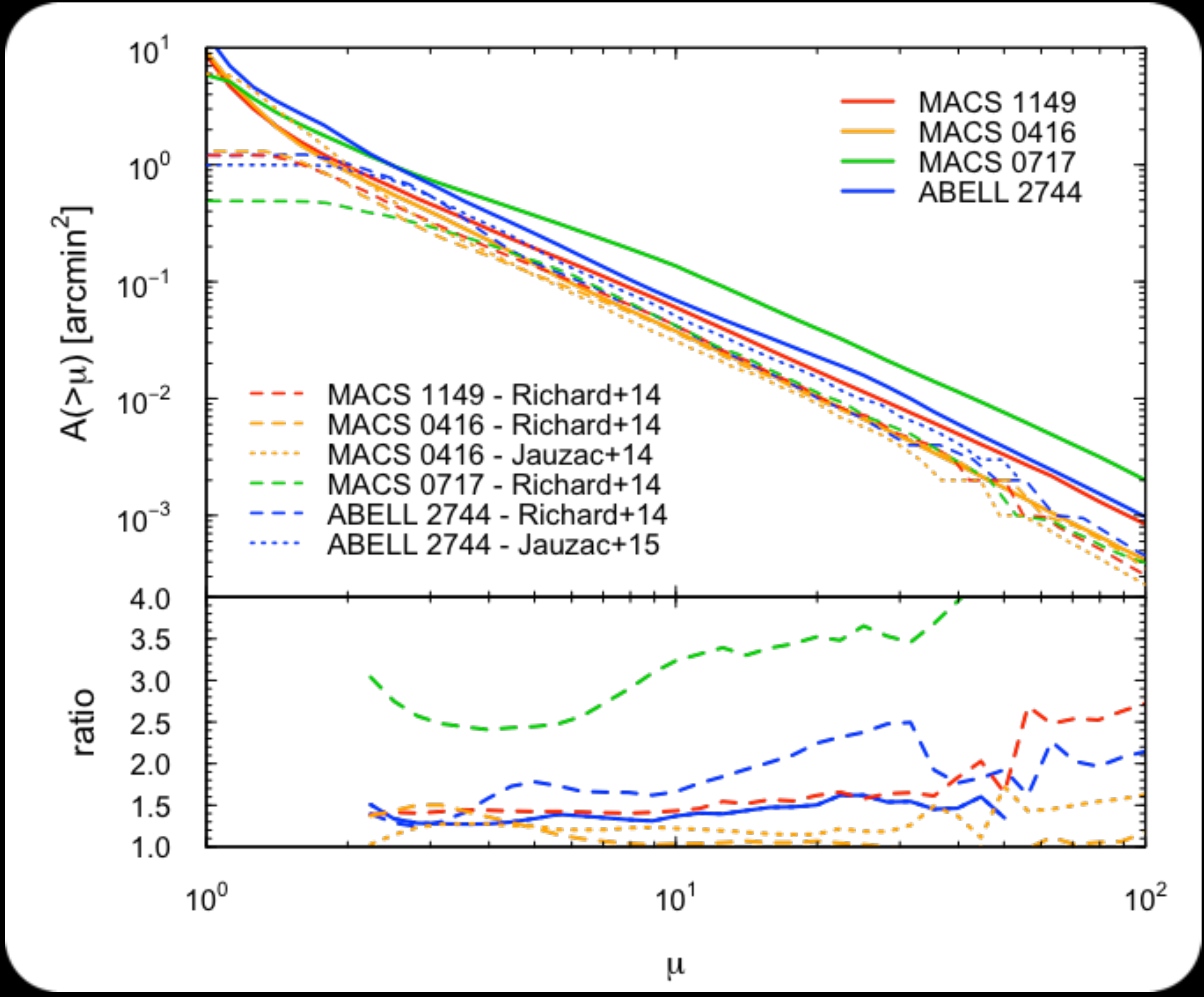


Lensing efficiency ($z_s = 9$)

- **Lensing efficiency $\Longrightarrow$ high-z lensed galaxies and high-z luminosity function**

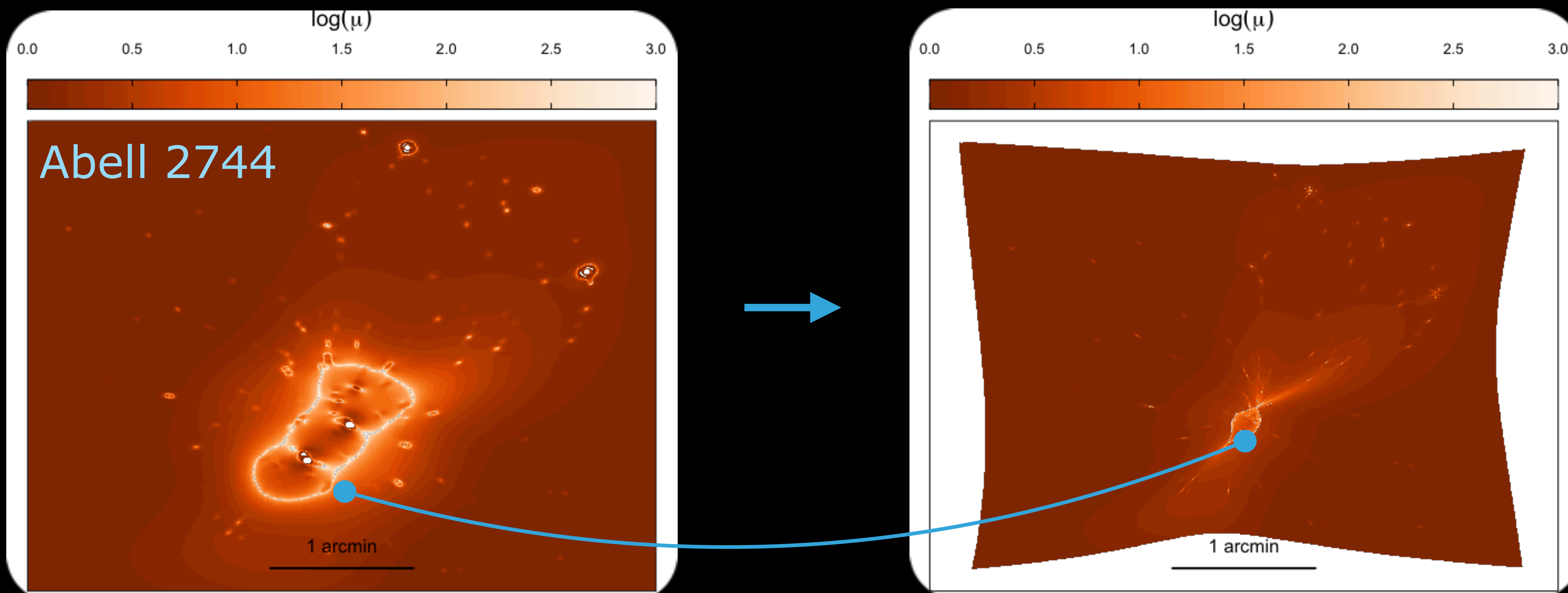
A (arcmin^2)	MACS1149	MACS0416	MACS0717	Abell 2744
A ($\mu > 3$)	0.461	0.396	**0.741**	0.685
A ($\mu > 5$)	0.015	0.011	**0.028**	0.013
A ($\mu > 10$)	0.005	0.003	**0.011**	0.004

~3 x larger than Richard et al. 2014

Lensing efficiency (z_s = 9)

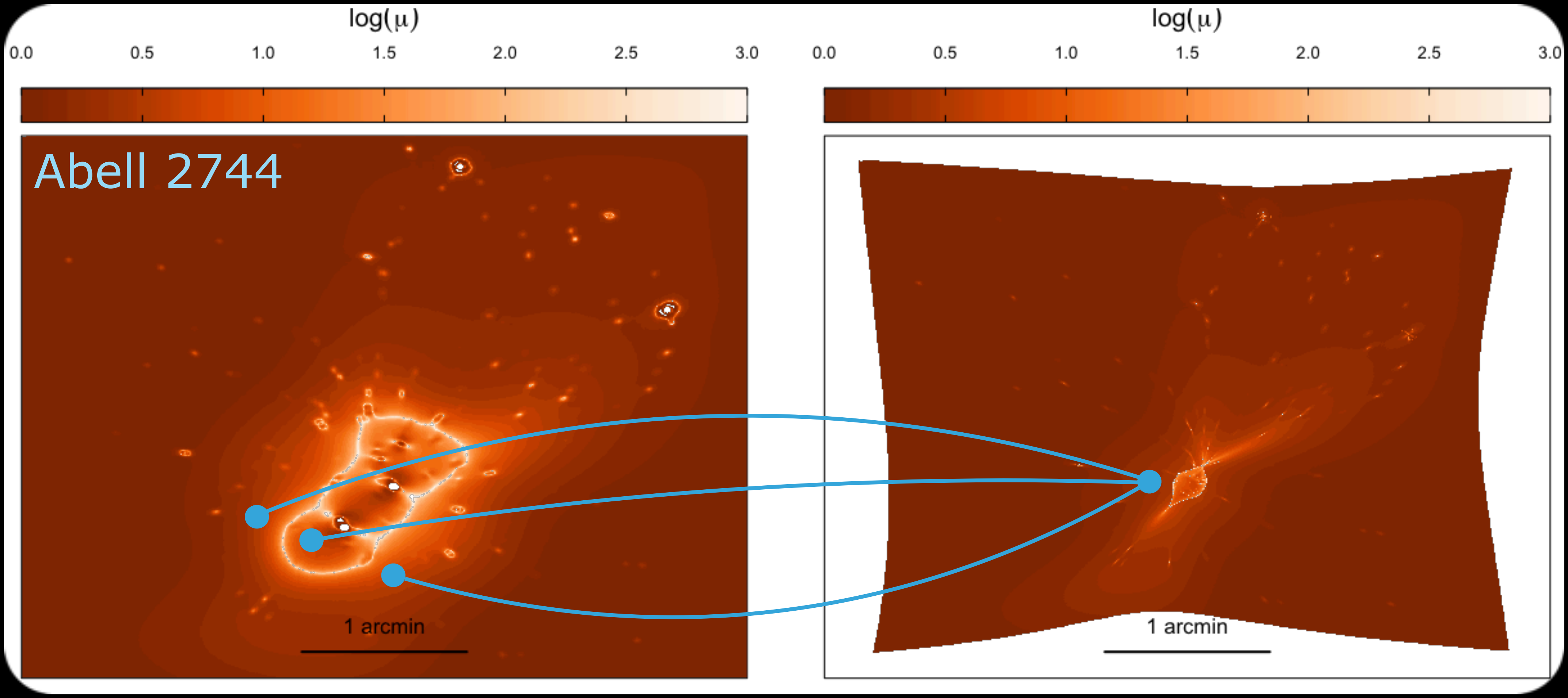
- Caustics maps:

Magnification map (lens plane) → Lens equation $$\beta = \theta - \alpha(\theta)$$ → Caustic map (Source plane)



Maximum lensing efficiency

- Caustics maps:
  - Mean value (A_{mean})
  - Maximum value (A_{max})



Maximum lensing efficiency

- Caustics from magnification:

$$A(> \mu) = \int \frac{dA_s}{d\mu} d\mu$$

$$\propto 1/\mu^2$$

- Caustics maps:
  - Mean value (A_{mean})
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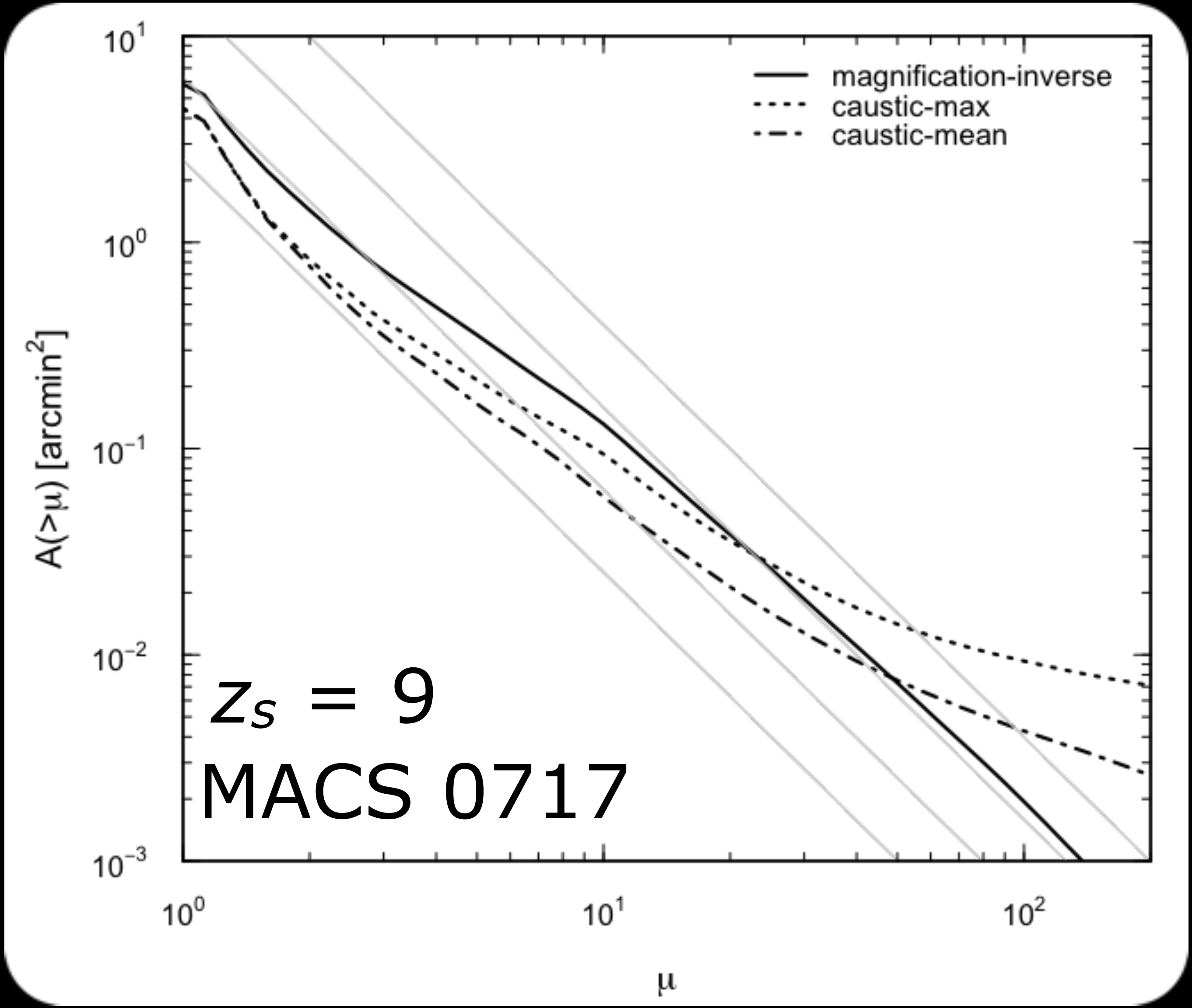


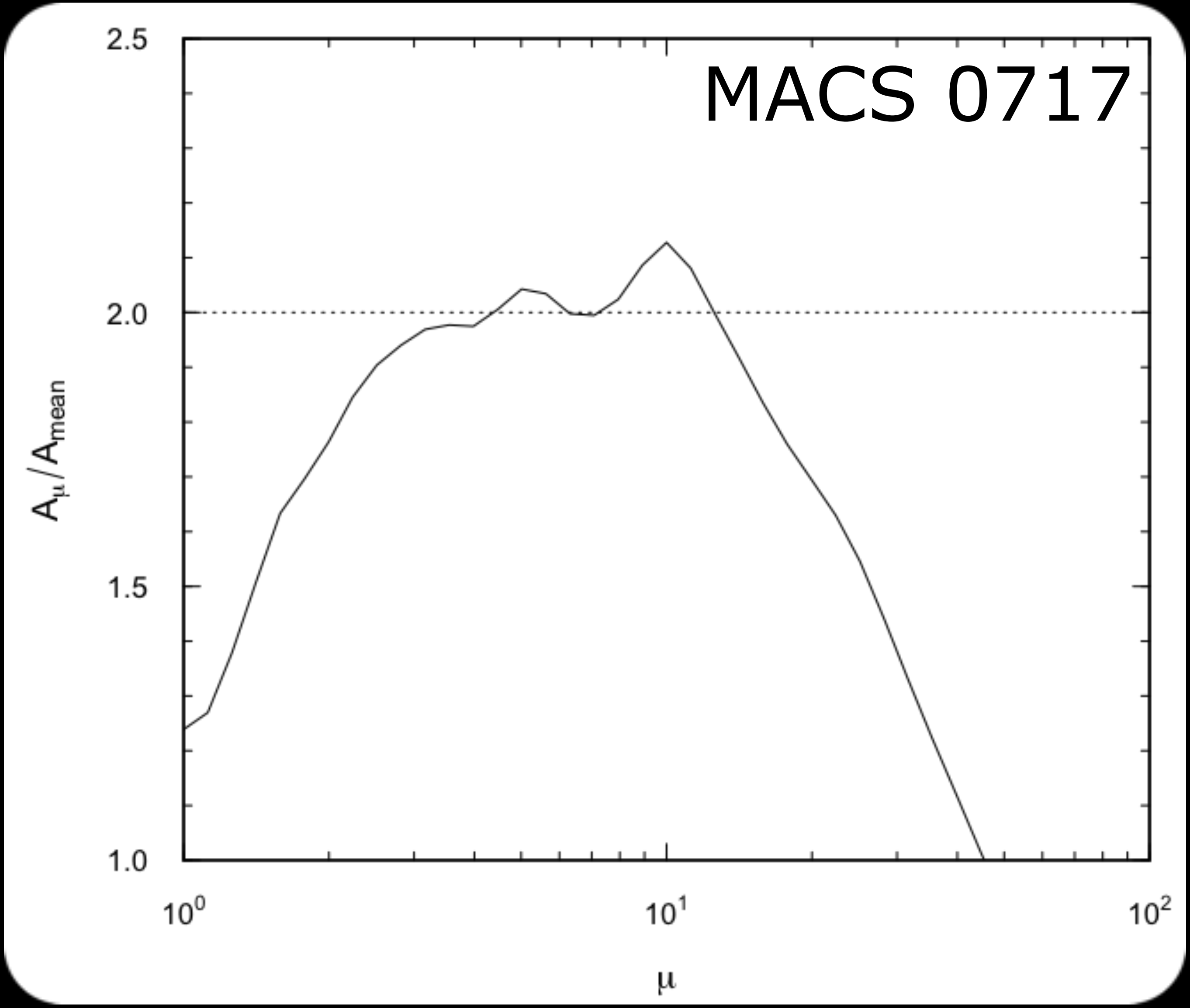
High res. 8192 x 8192 pix.

Maximum lensing efficiency

- Caustics maps:
  - Mean value (A_{mean})
  - Maximum value (A_{max})

$$\frac{A_\mu}{A_{mean}} \approx 2$$

Number of multiple images falling into the same pixel in the source plane

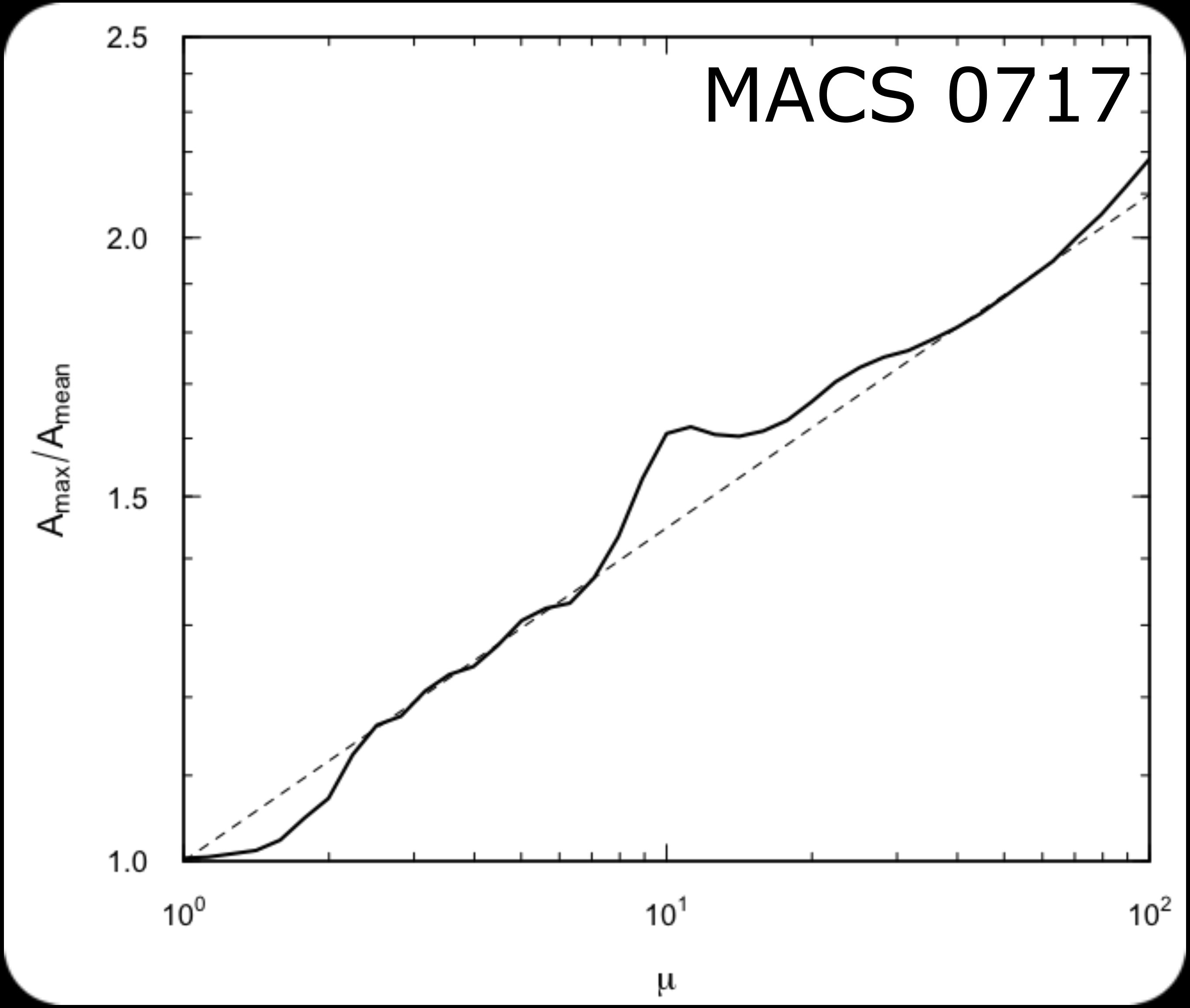


Maximum lensing efficiency

- Caustics maps:
  - Mean value (A_{mean})
  - Maximum value (A_{max})

$$\frac{A_{max}}{A_{mean}} = \mu^{0.161 \pm 0.002}$$

$$A_{max} \approx \frac{A_{\mu}}{2} \mu^{0.161 \pm 0.002}$$



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- Caustics maps:
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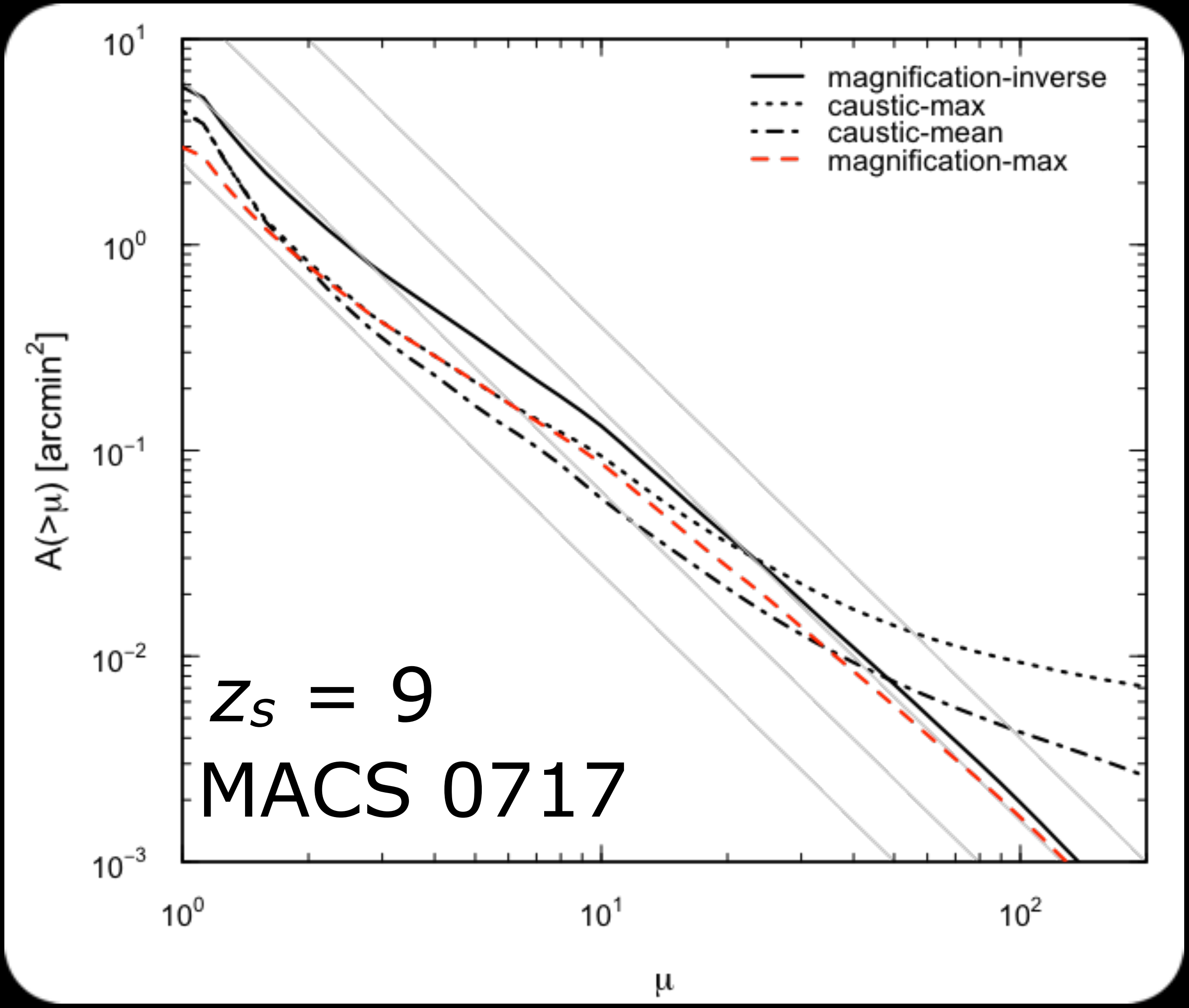

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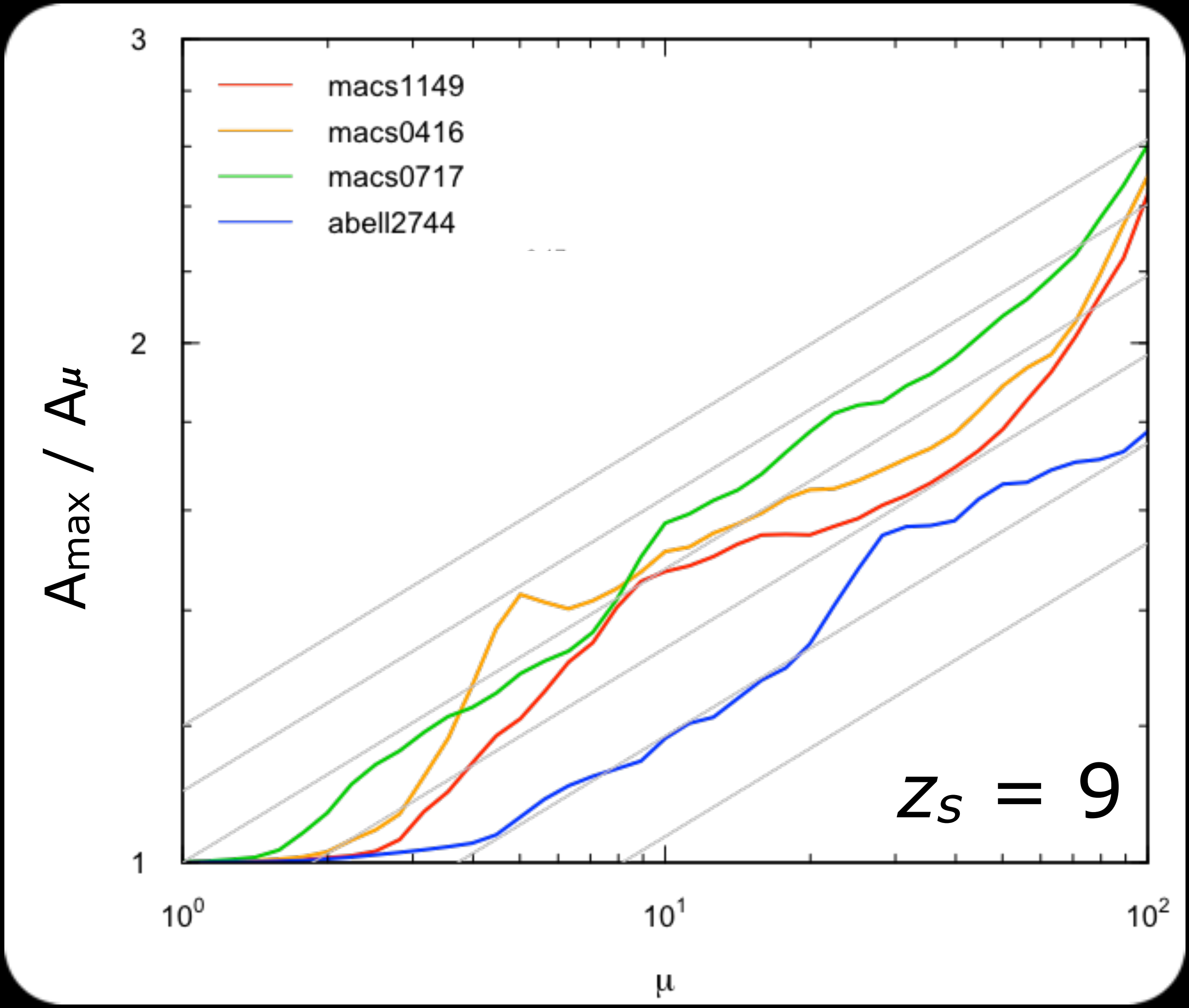

5. Conclussions

- Two models: BEST and RANGE (100 solutions) $\Longrightarrow$ **model variance, stat. errors**
- **Image RMS $\lesssim$1 arcsec. GOLD smaller RMS $\Longrightarrow$ z-spect** for accuracy in the magnification
- **Subs. outskirts** significant impact on predicted positions (Acebron et al. 2017) and mass distributions
- Lensing efficiency **MACS 0717 (0.741 arcmin^2) ~3 x larger** than Richard et al. 2014
- **Maximum lensing efficiency:** high-z galaxies and luminosity function

$$A_{max} \approx \frac{A_\mu}{2}\mu^{0.161\pm0.002}$$

Rest HFF clusters
Comparison sims.