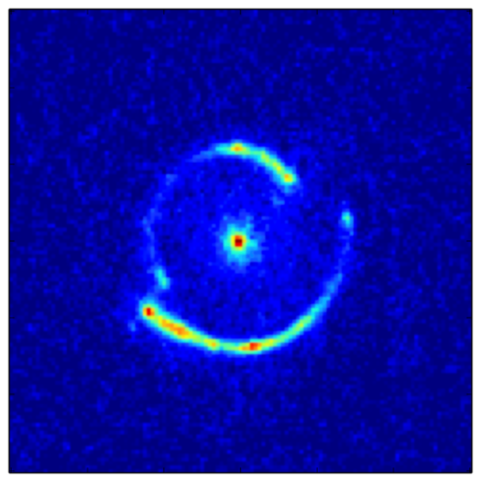
PROBING THE NATURE OF DARK MATTER WITH GALAXY-GALAXY STRONG GRAVITATIONAL LENSING



DOROTA BAYER

SWINBURNE UNIVERSITY OF TECHNOLOGY
ASTRO 3D

MELBOURNE 14 OCTOBER 2020

INTRODUCTION

What is the nature of dark matter?

MACHOs, particle dark matter
or modified gravity?

phenomenological models
based on free-streaming length

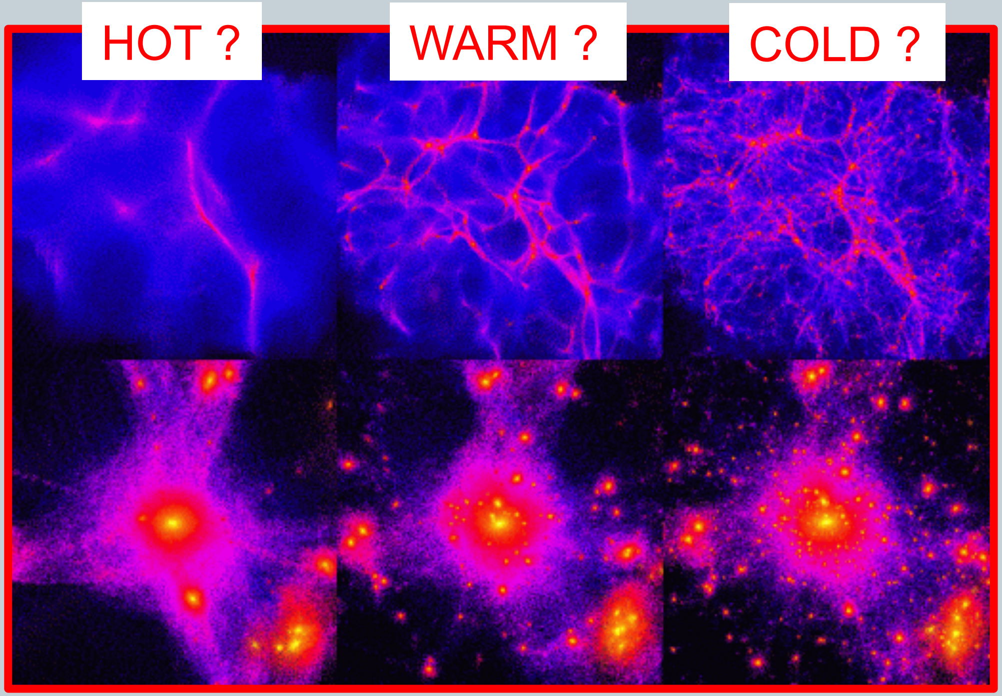
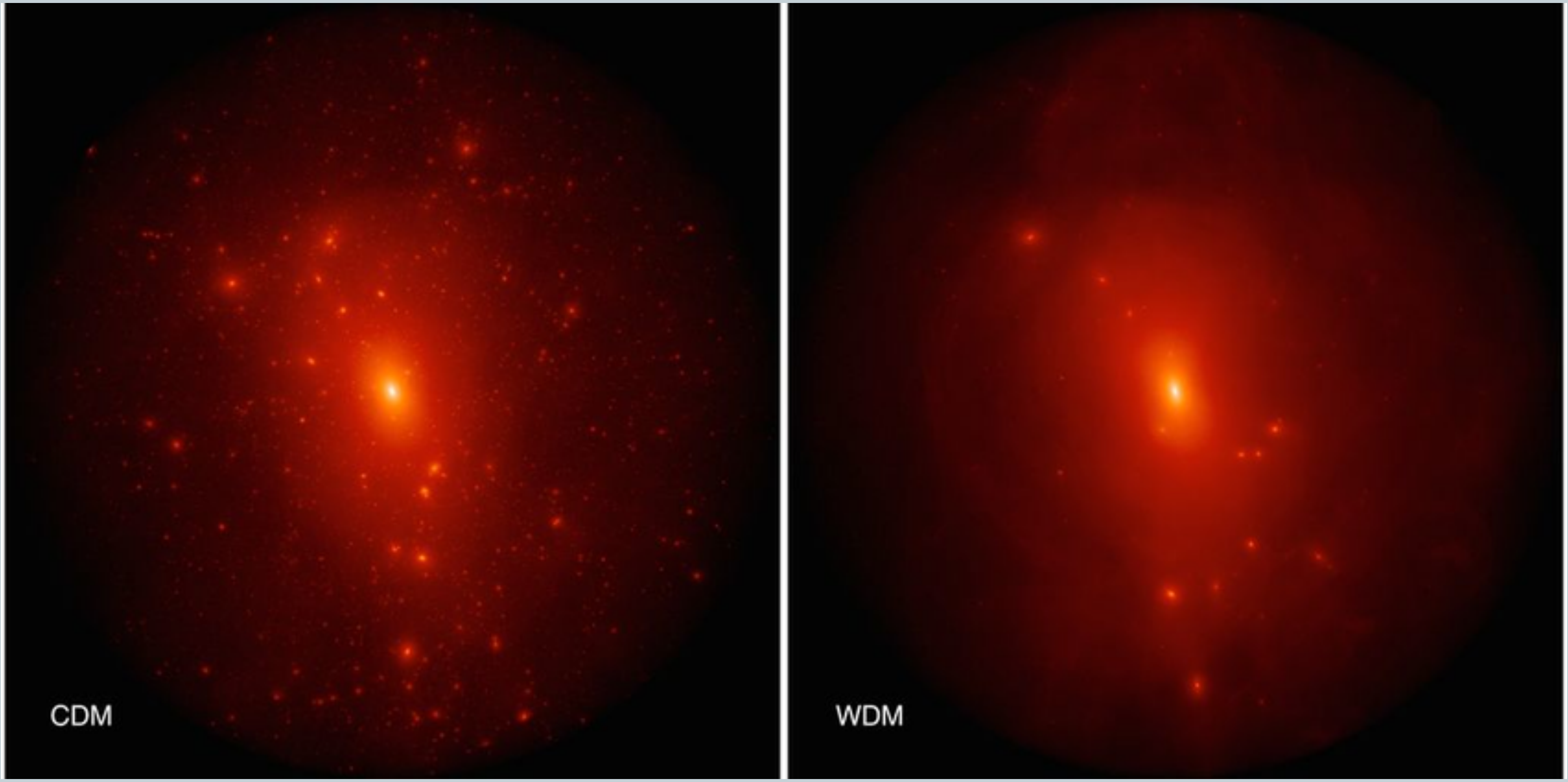


Image credits: Bertone & Tait (2018), Ben Moore (University of Zurich)

Sub-galactic mass structure as a probe of DM



HOW CLUMPY/SMOOTH IS THE MASS DISTRIBUTION IN GALACTIC HALOES ?

Image credit: Lovell et al. (2014)

Sub-halo mass function

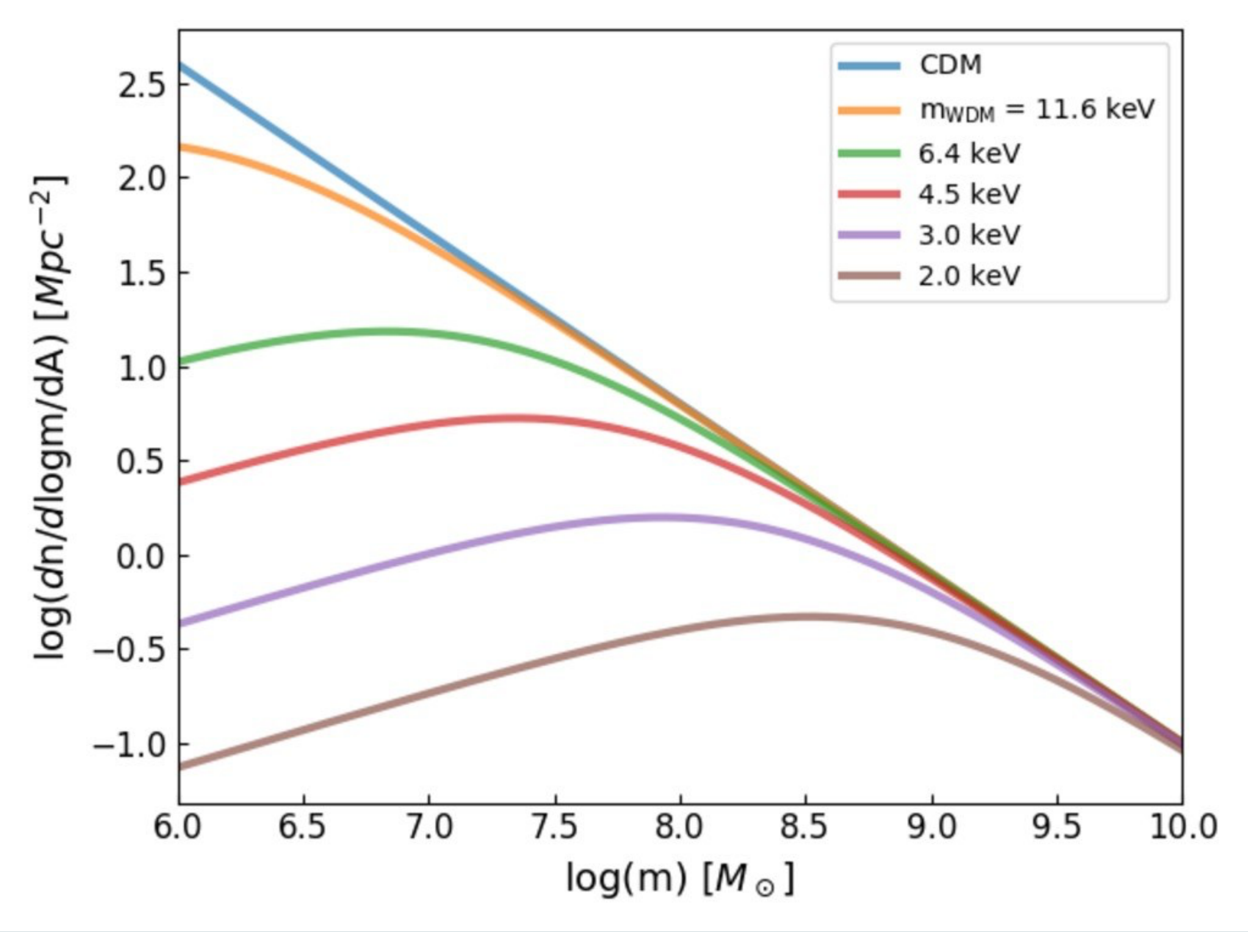


Image credit: Hsueh et al. (2020)

Sub-halo mass function

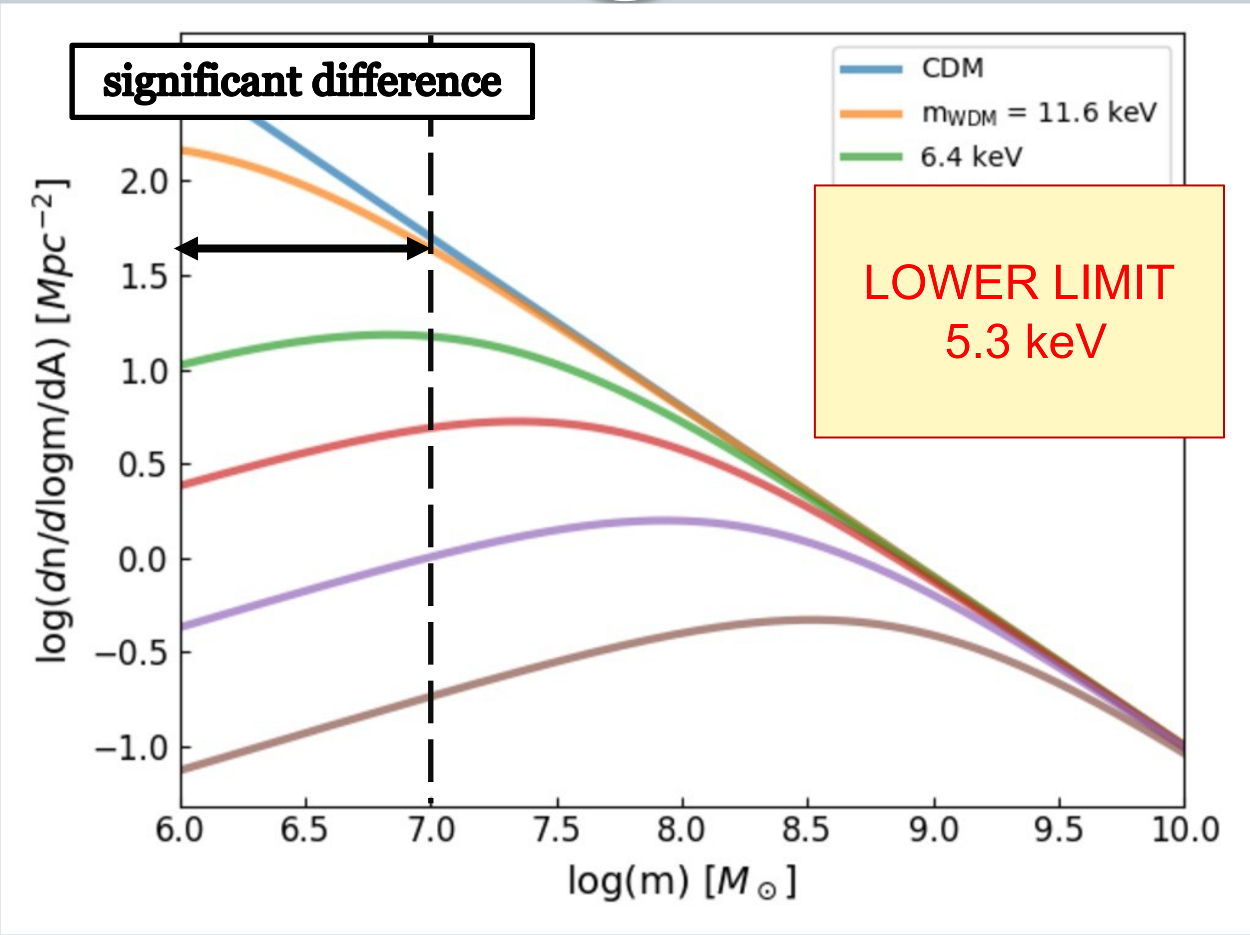


Image credit: Hsueh et al. (2020)

Galaxy-galaxy strong gravitational lensing

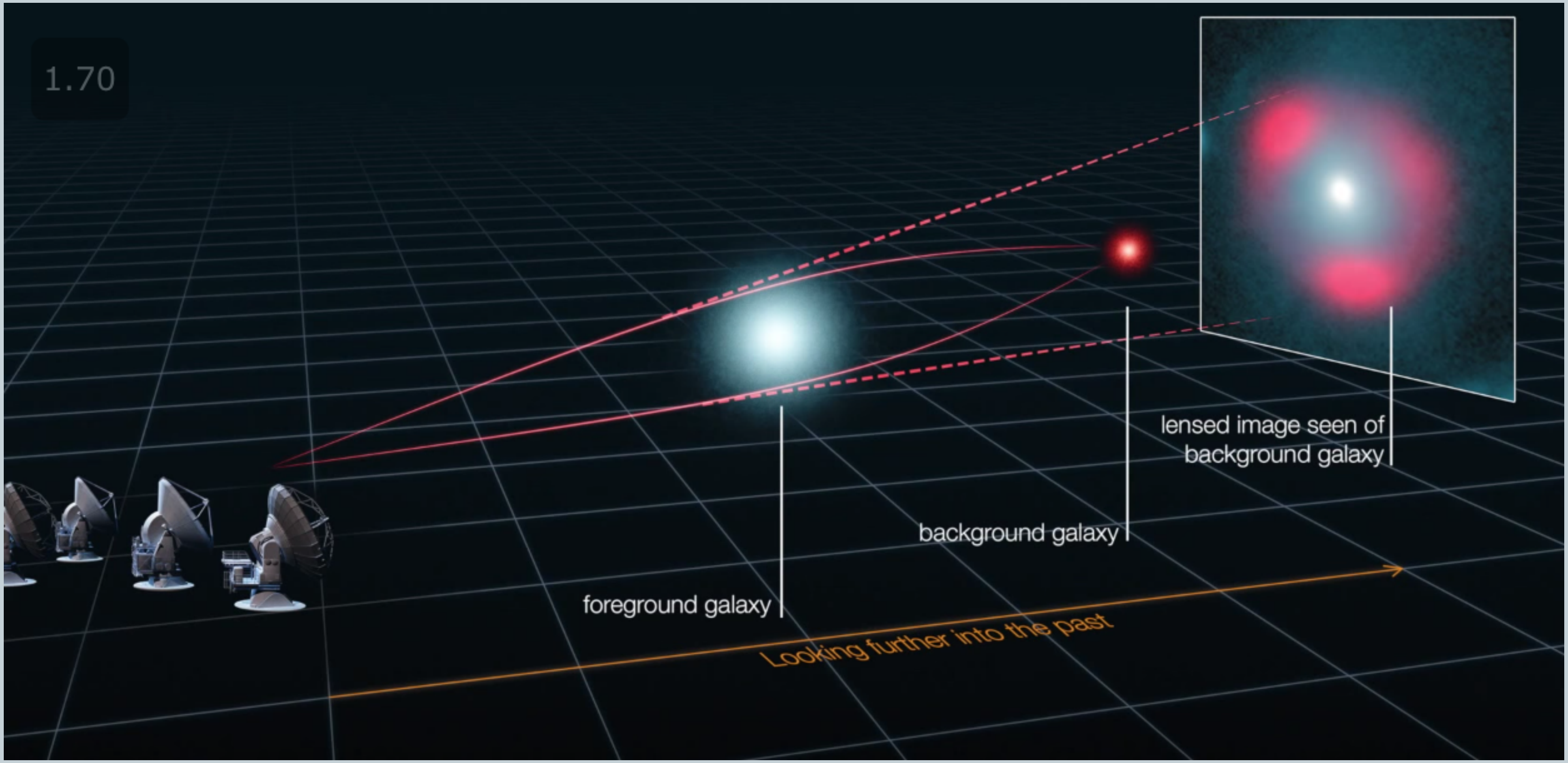


Image credit: ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al.

Substructure lensing

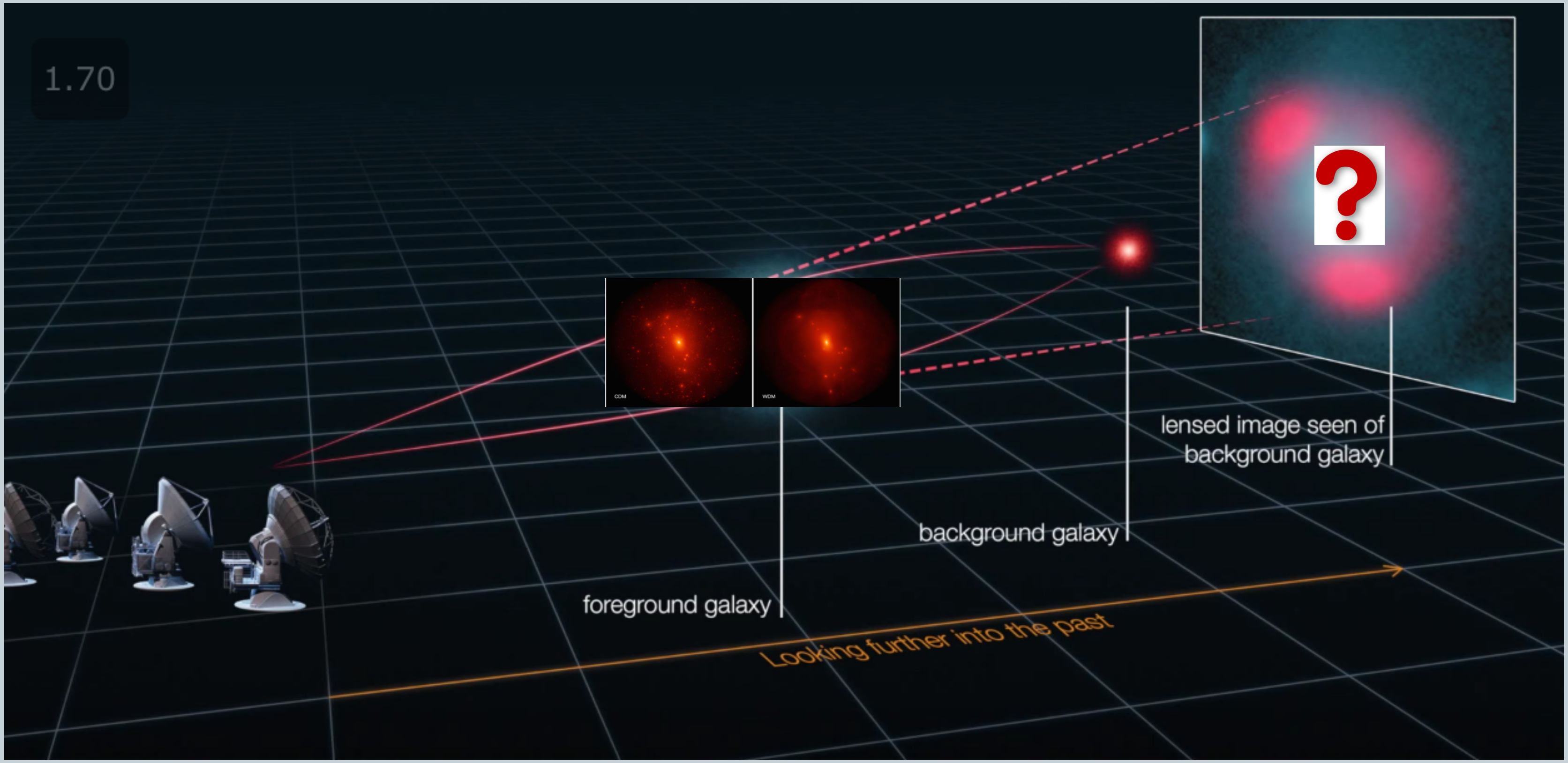


Image credit: ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al.

Gravitational imaging of galactic substructure

Substructure in Lens Galaxy

↓

Perturbations to Smooth Lensing Potential

↓

Surface-Brightness Anomalies
in Lensed Images

Koopmans (2005), Vegetti & Koopmans (2009)

Gravitational imaging of galactic substructure

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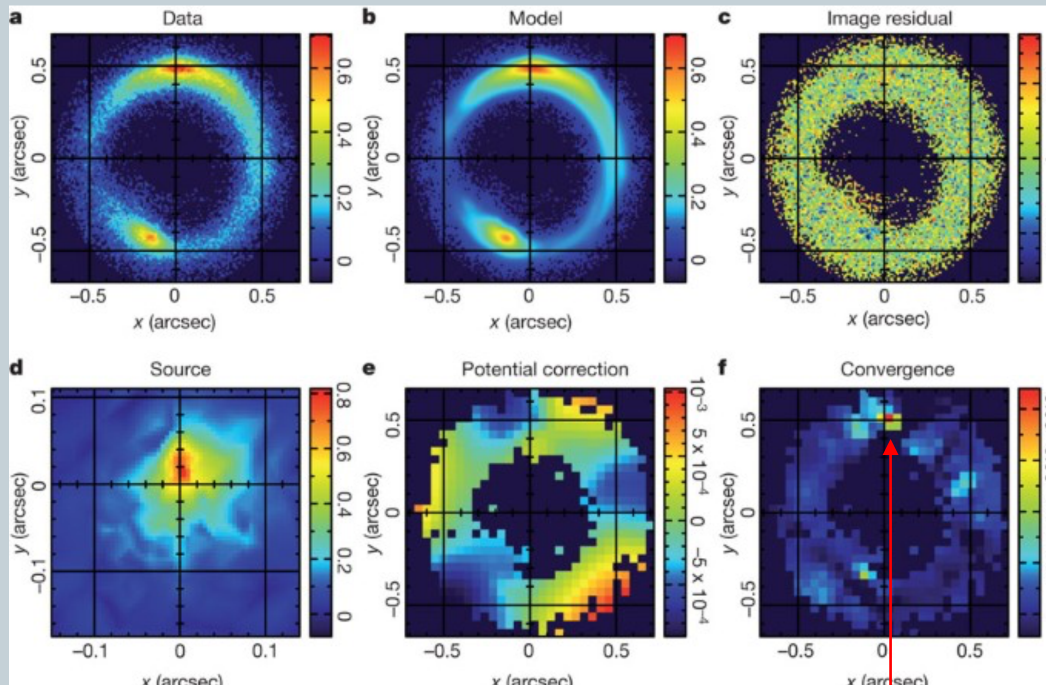
Gravitational imaging of galactic substructure

SDSS J120602.09+514229.5

SDSS J0946+1006



sub-halo mass = 2.75 * 10^10 $M_{\odot}$
redshift = 0.422

sub-halo mass = 1.9 * 10^8 $M_{\odot}$
redshift = 0.881

Image credits: Vegetti et al. (2010b, 2012)

Sub-halo mass function

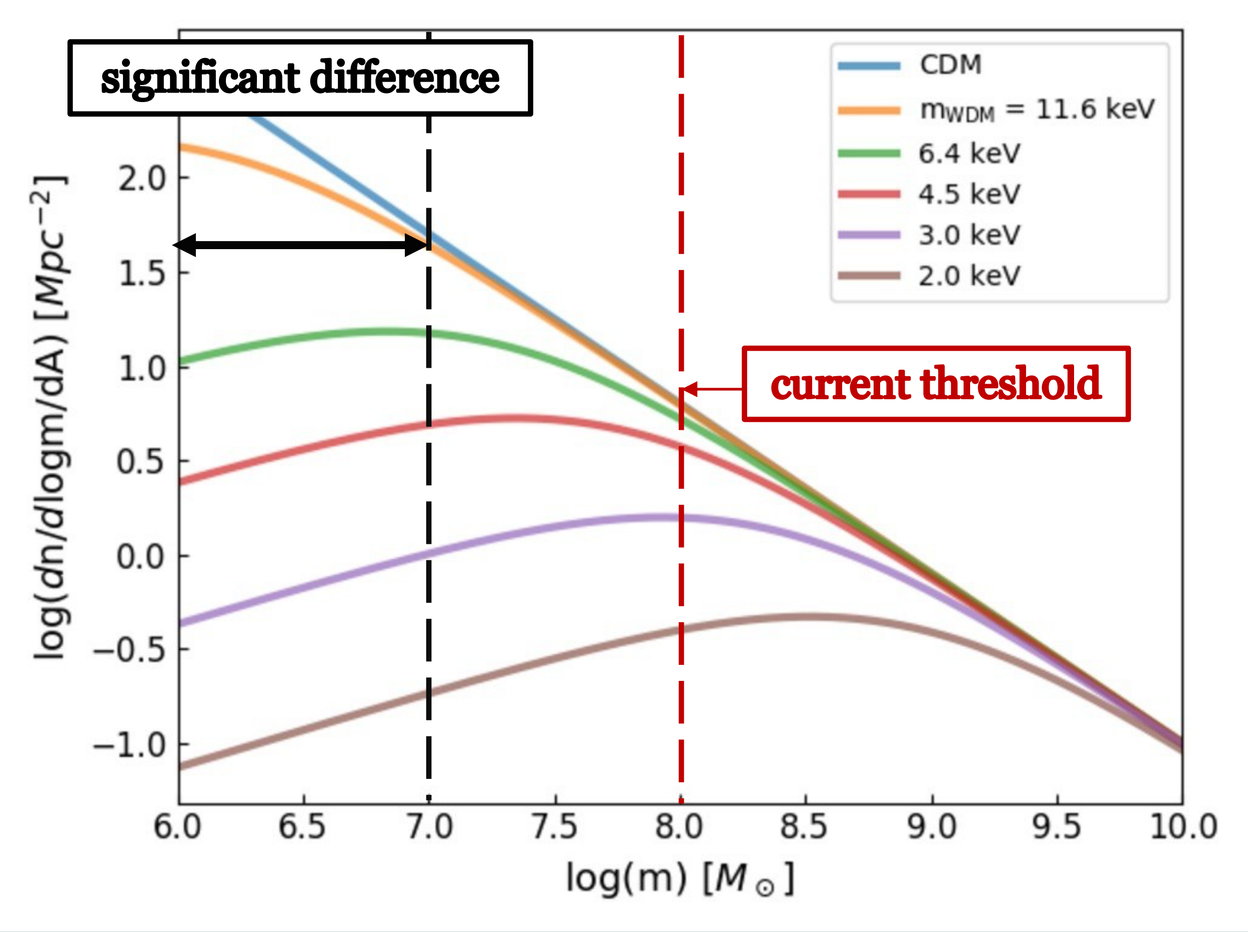


Image credit: Hsueh et al. (2020)

NOVEL STATISTICAL APPROACH

Our approach

Density Fluctuations in the Lens Galaxy

↓

Perturbations to Smooth Lensing Potential

↓

Surface-Brightness Anomalies
in the Lensed Images

Chatterjee & Koopmans (2018), Bayer et al. (submitted to MNRAS)

Our approach

Density Fluctuations in the Lens Galaxy

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GRF Perturbations to Smooth Lensing Potential

↓

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in the Lensed Images

POWER SPECTRUM

Chatterjee & Koopmans (2018), Bayer et al. (submitted to MNRAS)

Our approach

Density Fluctuations in the Lens Galaxy

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GRF Perturbations to Smooth Lensing Potential

↑

Surface-Brightness Anomalies
in the Lensed Images

POWER SPECTRUM

Analysis overview

- Observed surface-brightness anomalies
- GRF potential perturbations & mock power spectra
- Statistical comparison

↓

Upper-limit constraints on
sub-galactic mass structure
(1-10 kpc scales)

SURFACE-BRIGHTNESS ANOMALIES

SLACS lenses

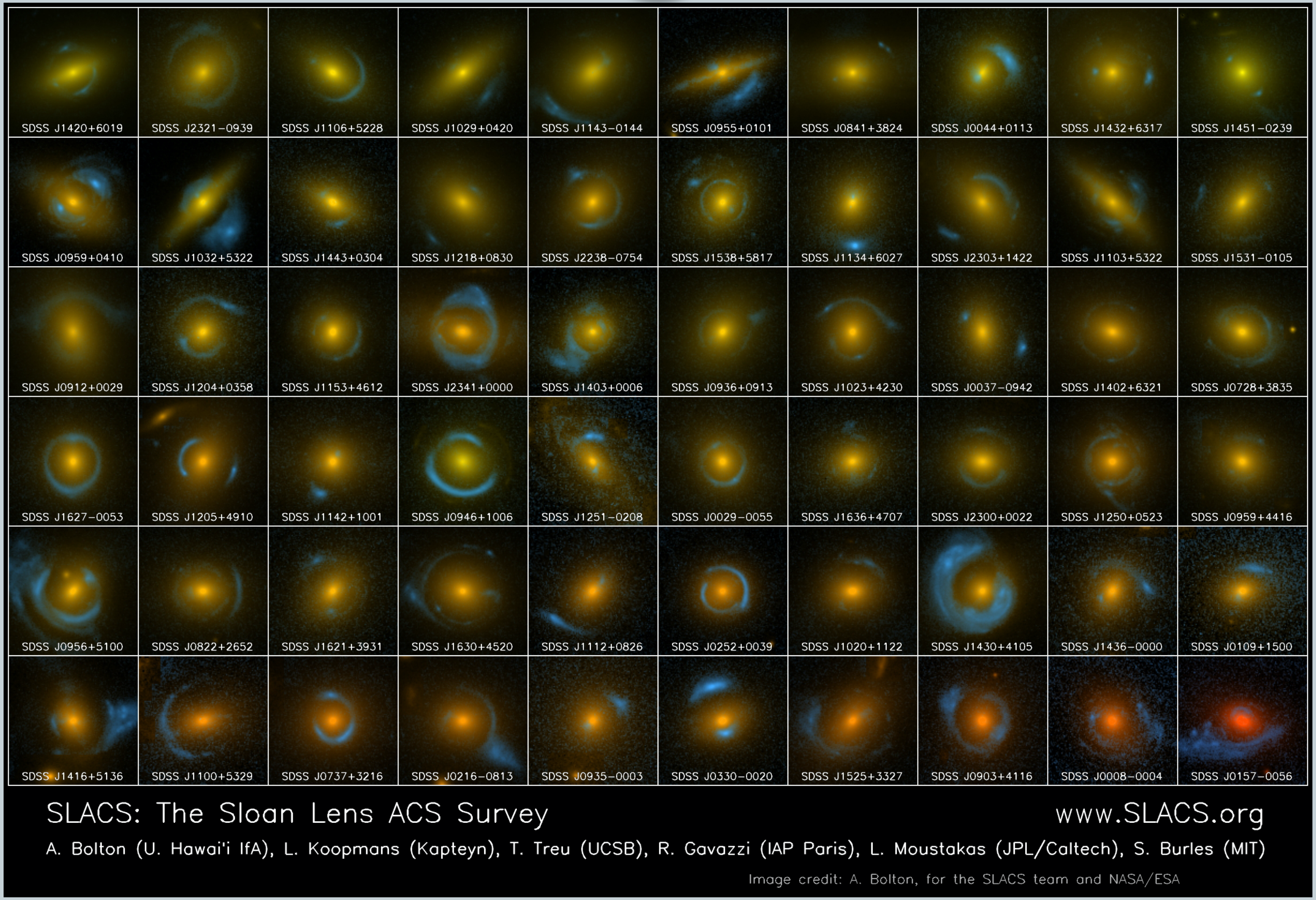


Image credit: A. Bolton, SLACS team

SLACS lens systems

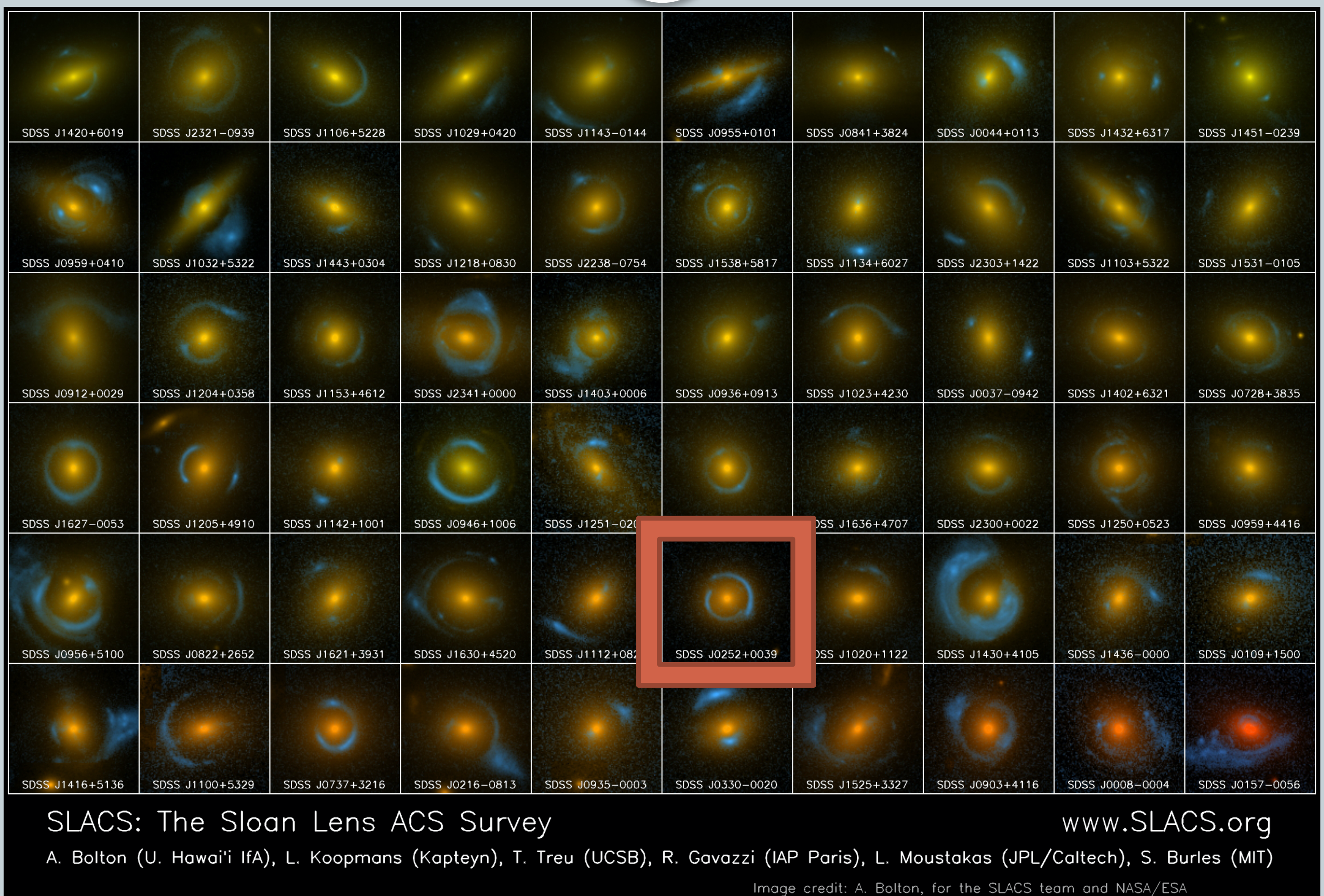
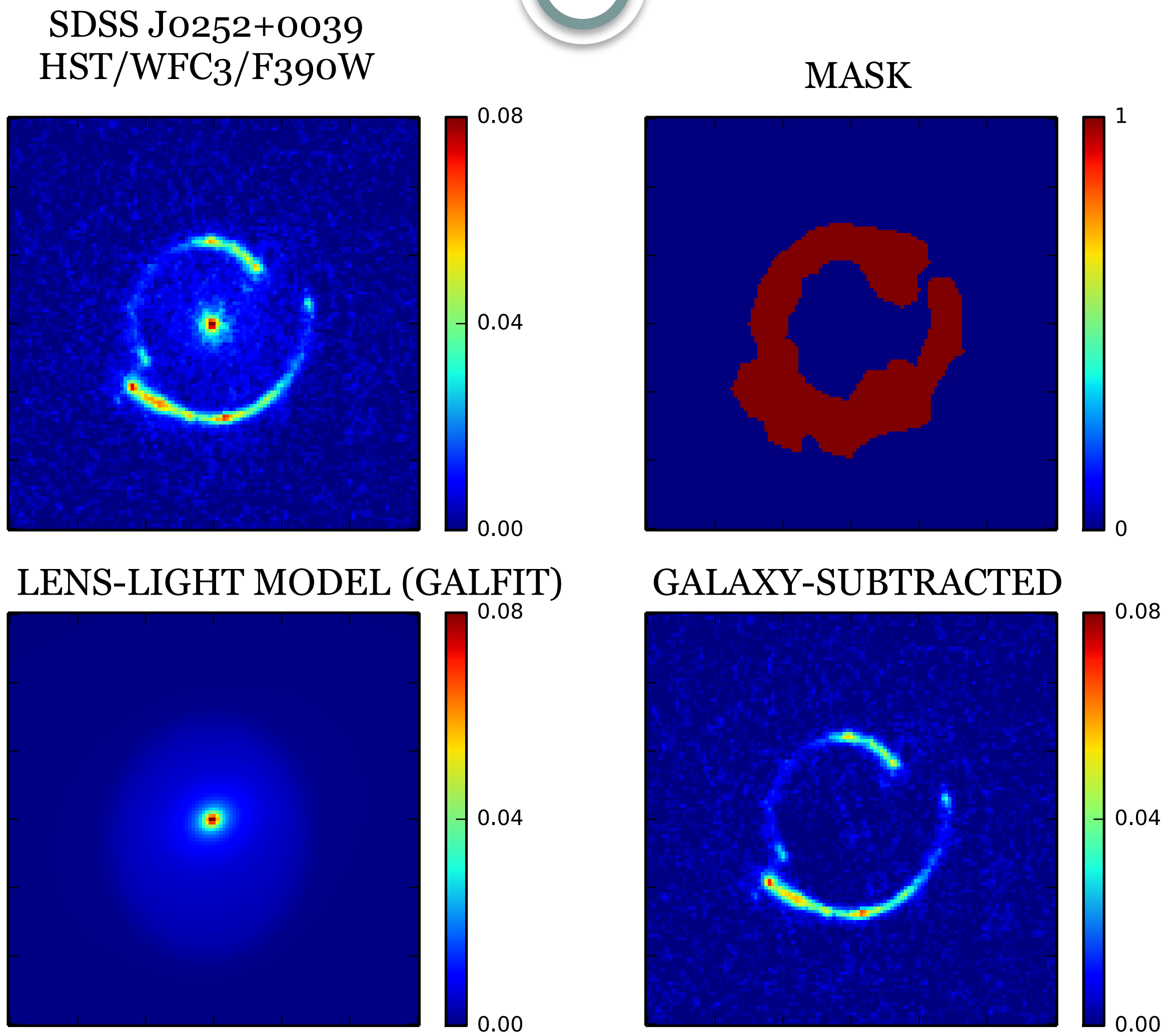


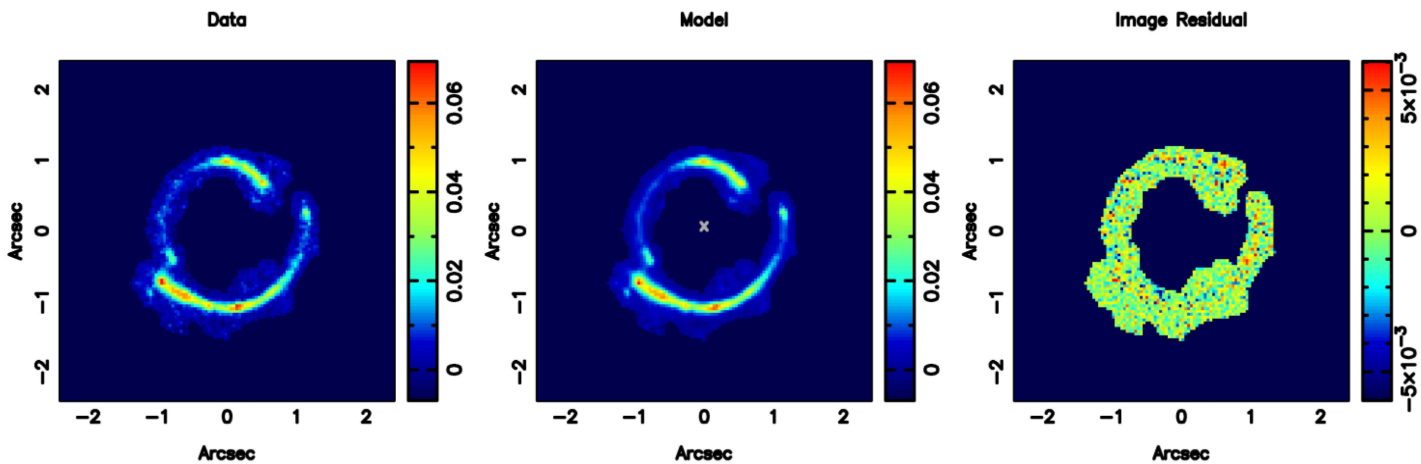
Image credit: A. Bolton, SLACS team

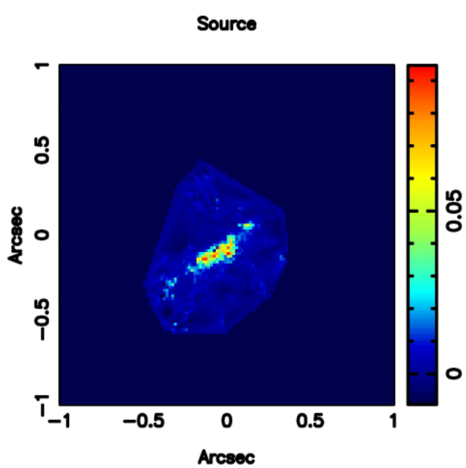
Step 1: Subtraction of lens-galaxy light



Bayer et al. (submitted to MNRAS)

Step 2: Smooth lens modeling



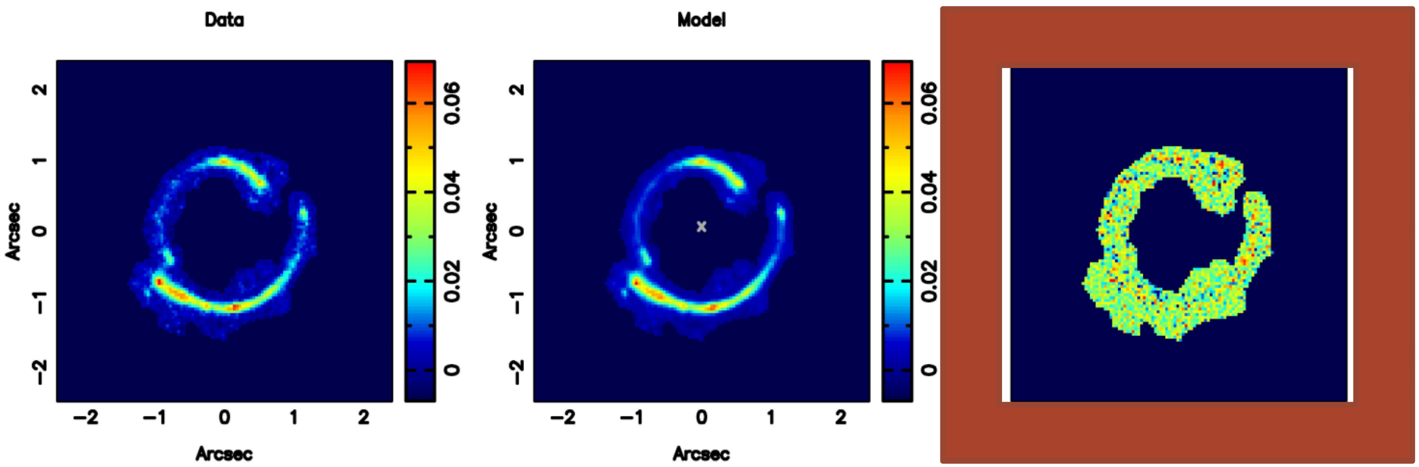


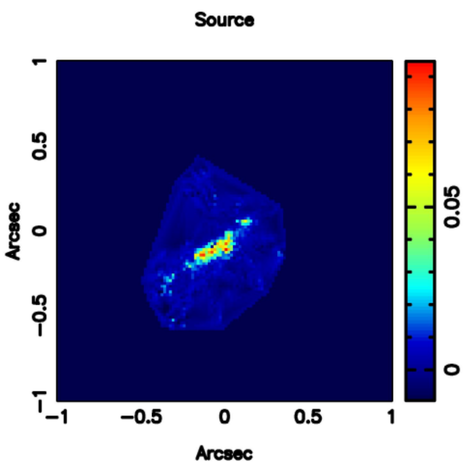
SMOOTH LENS MODEL:
POWER-LAW ELLIPTICAL MASS DISTRIBUTION

- Einstein radius
- center of mass
- position angle
- axis ratio
- mass-density slope
- external shear strength & position angle

Adaptive, grid-based, Bayesian lens modeling technique by Vegetti & Koopmans (2009)

Step 3: Residuals





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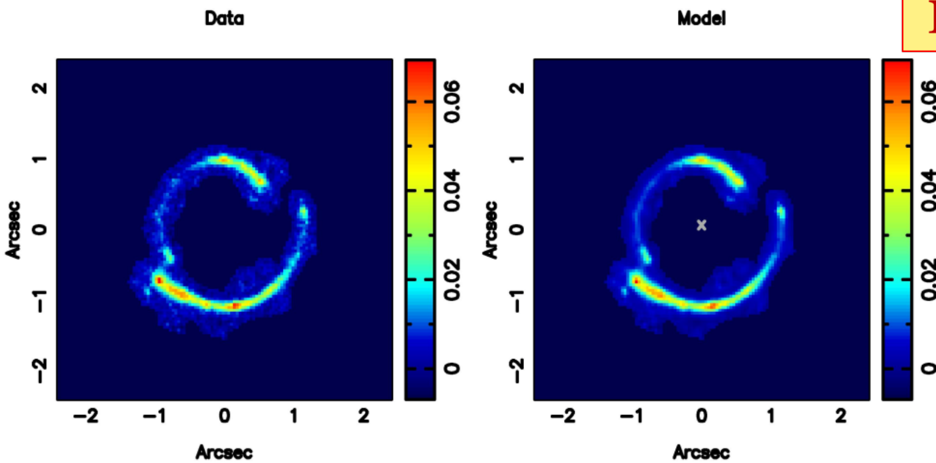
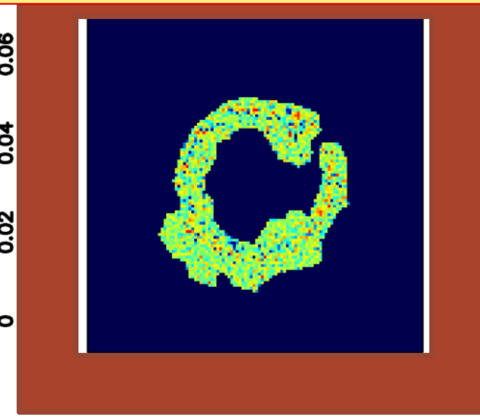
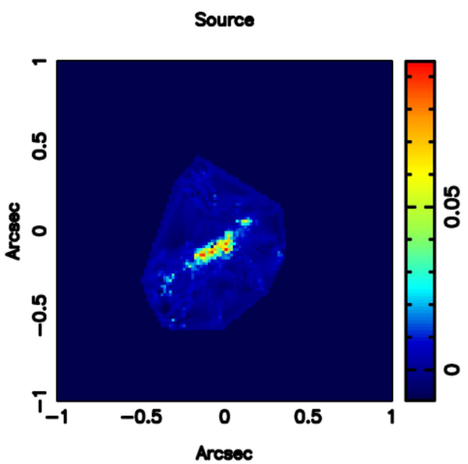
Adaptive, grid-based, Bayesian lens modeling technique by Vegetti & Koopmans (2009)

Step 4: Residual power spectrum



POWER SPECTRUM

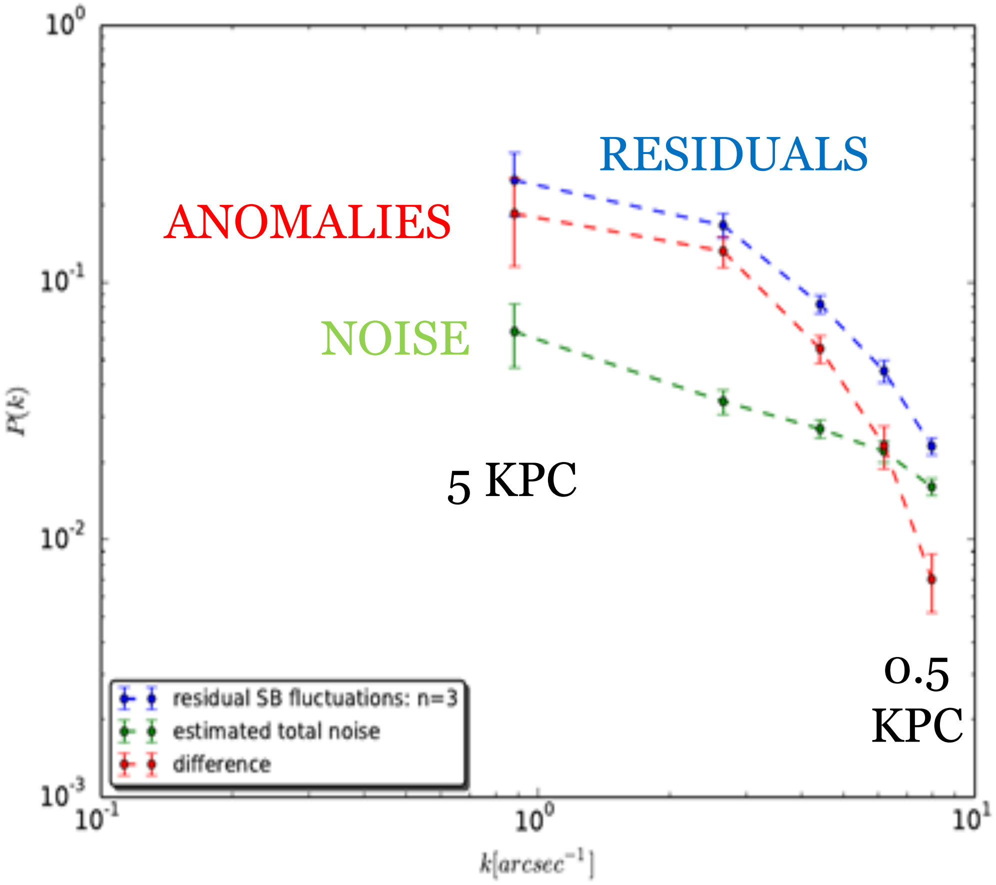




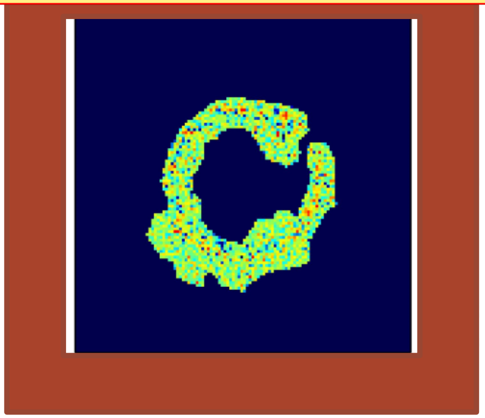
SMOOTH LENS MODEL:
POWER-LAW ELLIPTICAL MASS DISTRIBUTION

- Einstein radius
- center of mass
- position angle
- axis ratio
- mass-density slope
- external shear strength & position angle

Step 4: Surface-brightness anomalies



POWER SPECTRUM

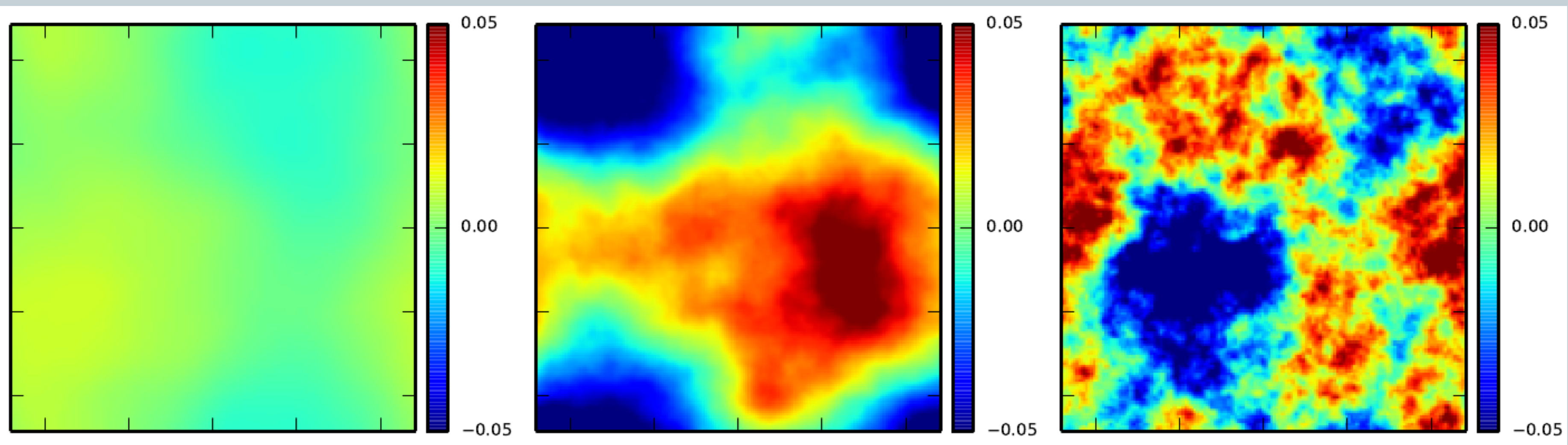


Adaptive, grid-based, Bayesian lens modeling technique by Vegetti & Koopmans (2009)

UNDERLYING MASS STRUCTURE

GRF potential perturbations

$$P_{\delta\psi}(k) = \frac{N_{\mathrm{pix}}}{2\sum_k k^{-\beta}} \times \sigma^2_{\delta\psi} \times k^{-\beta}$$



$\beta = 5.5$ $\beta = 4.25$ $\beta = 3$

Bayer et al. (submitted to MNRAS)

Best-fitting smooth lens model

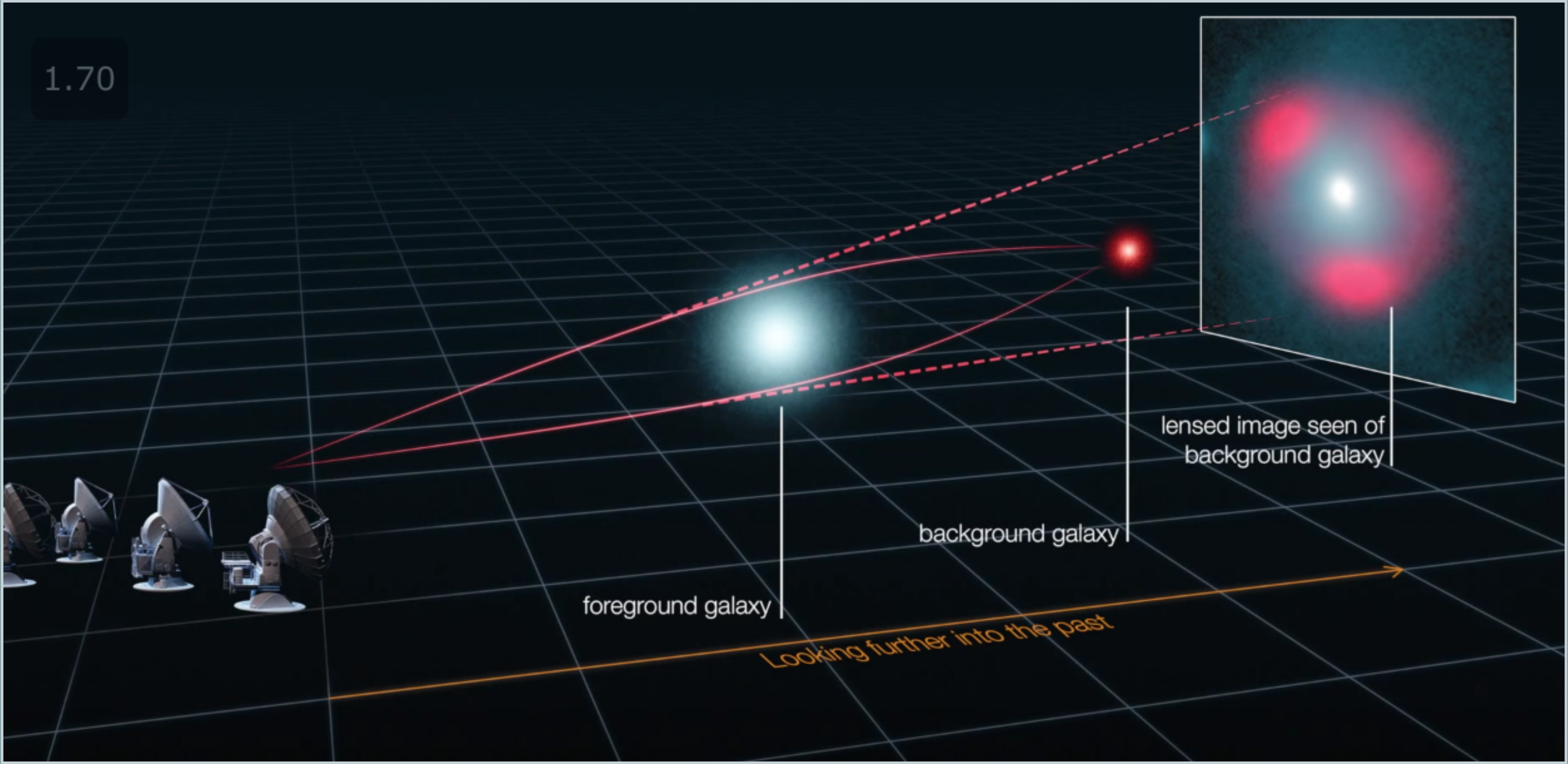


Image credit: ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al.

Effect of GRF potential perturbations

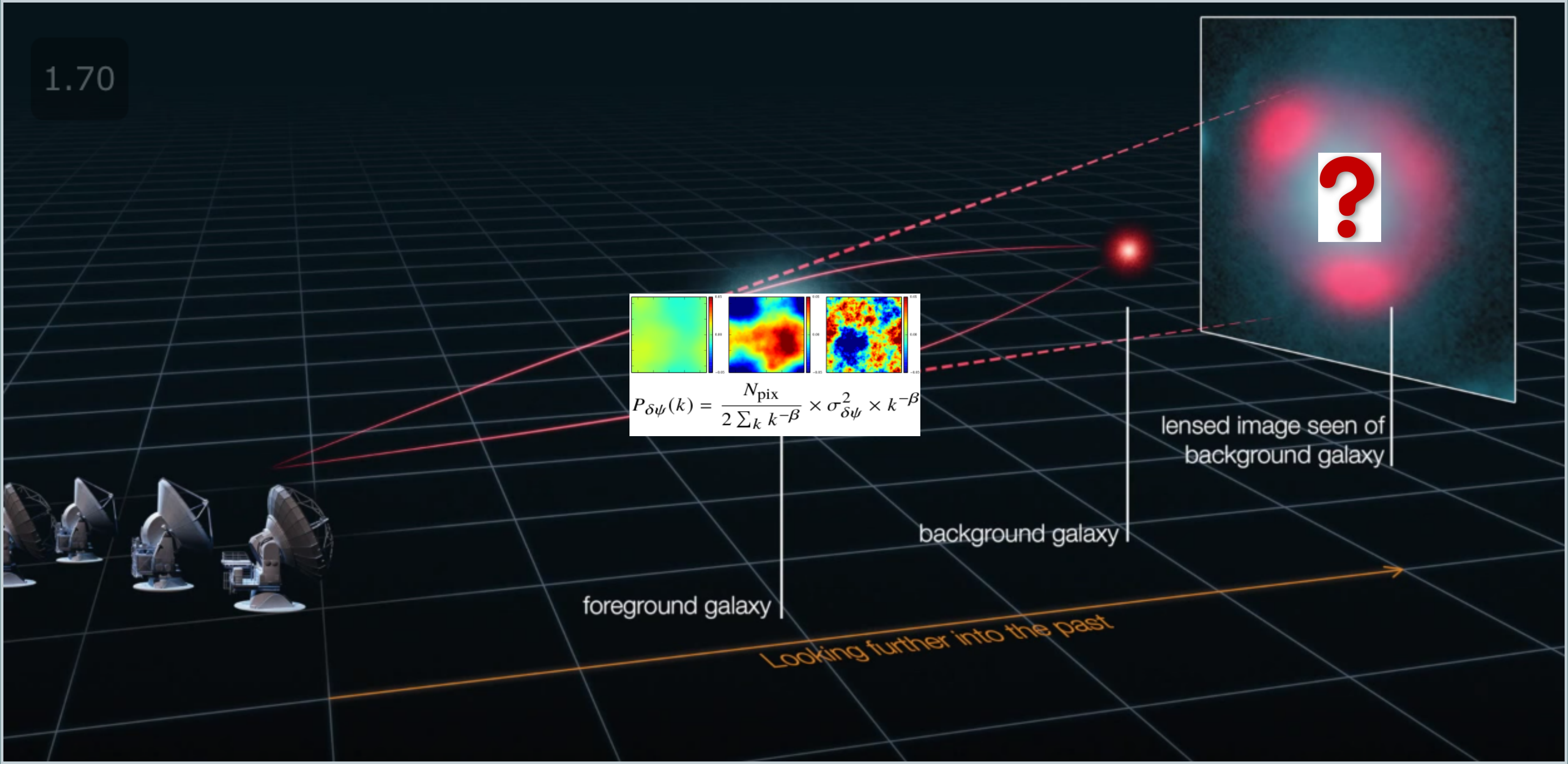
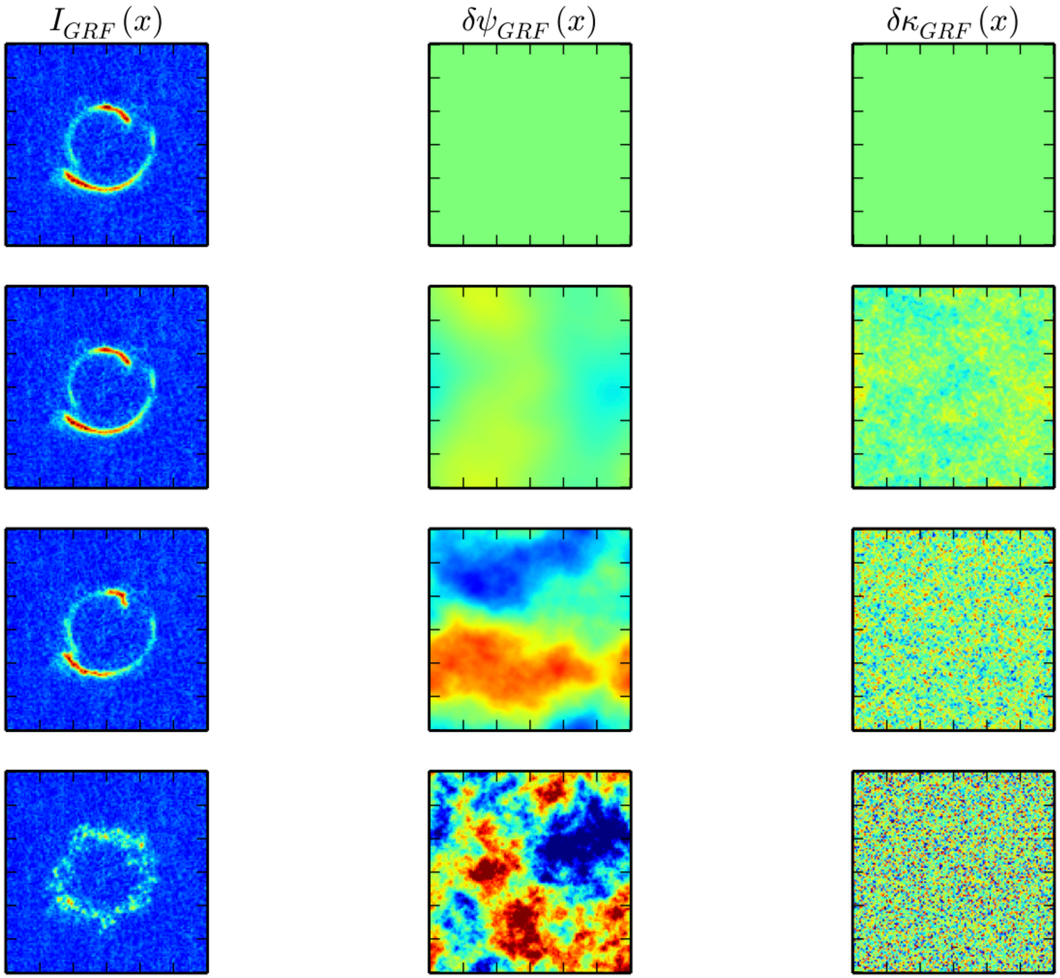


Image credit: ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al.

Mock perturbed lens systems

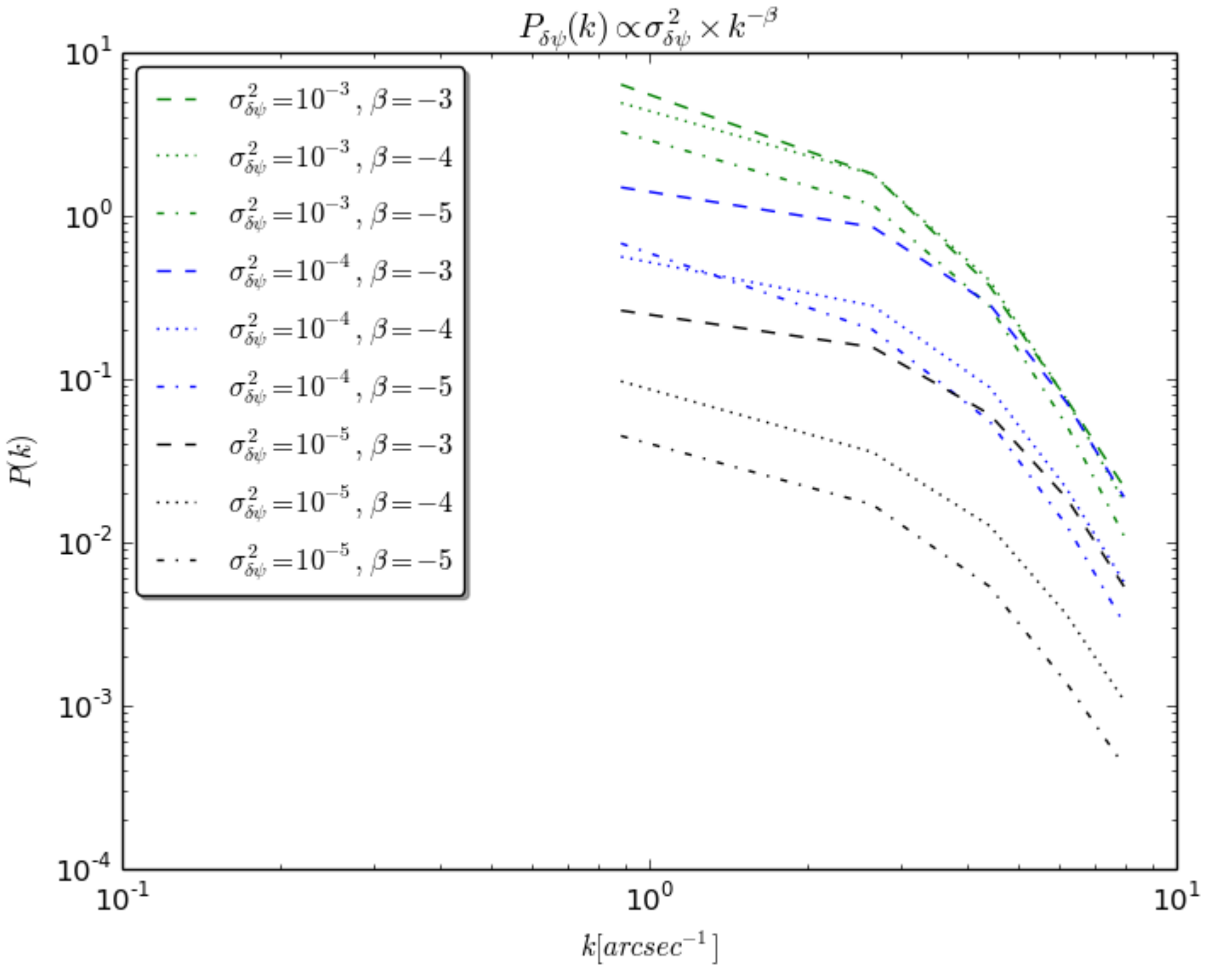
$$\nabla^2 \delta\psi_{\mathrm{GRF}}(\boldsymbol{x}) = 2 \times \delta\kappa_{\mathrm{GRF}}(\boldsymbol{x})$$

$$P_{\delta\kappa}(k) = 4\pi^4 k^4 P_{\delta\psi}(k)$$



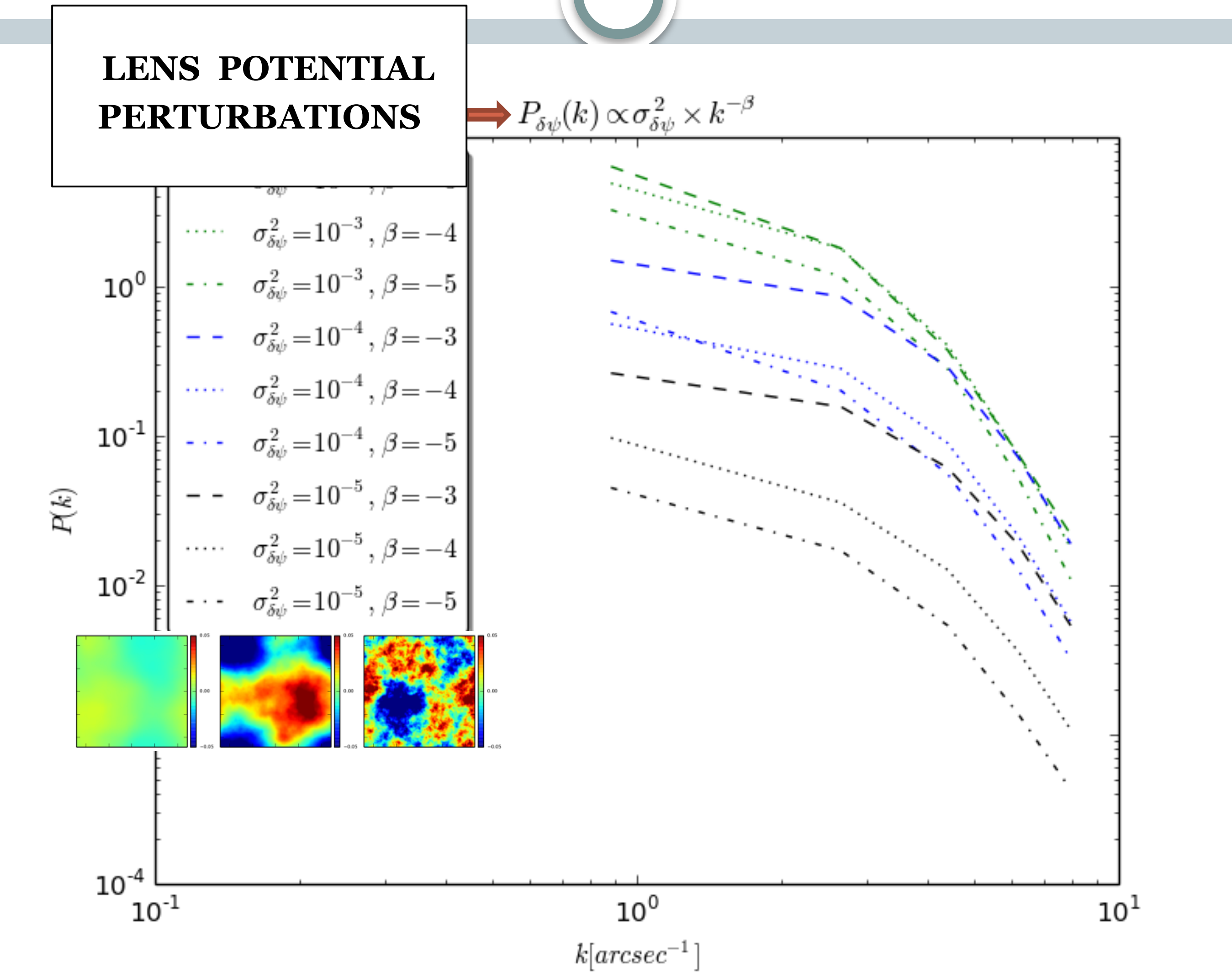
Bayer et al. (submitted to MNRAS)

Template of mock power spectra



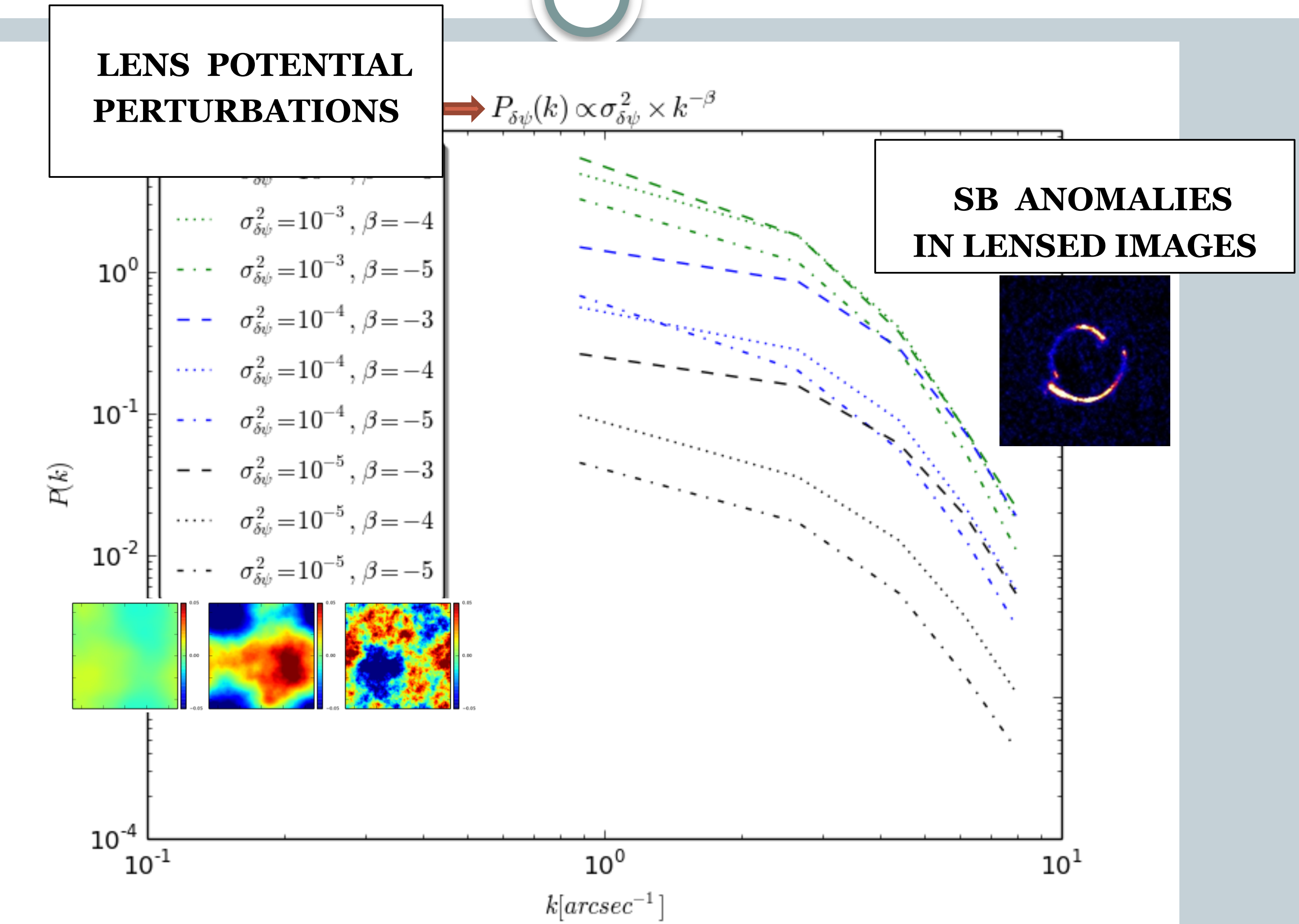
Bayer et al. (submitted to MNRAS)

Template of mock power spectra



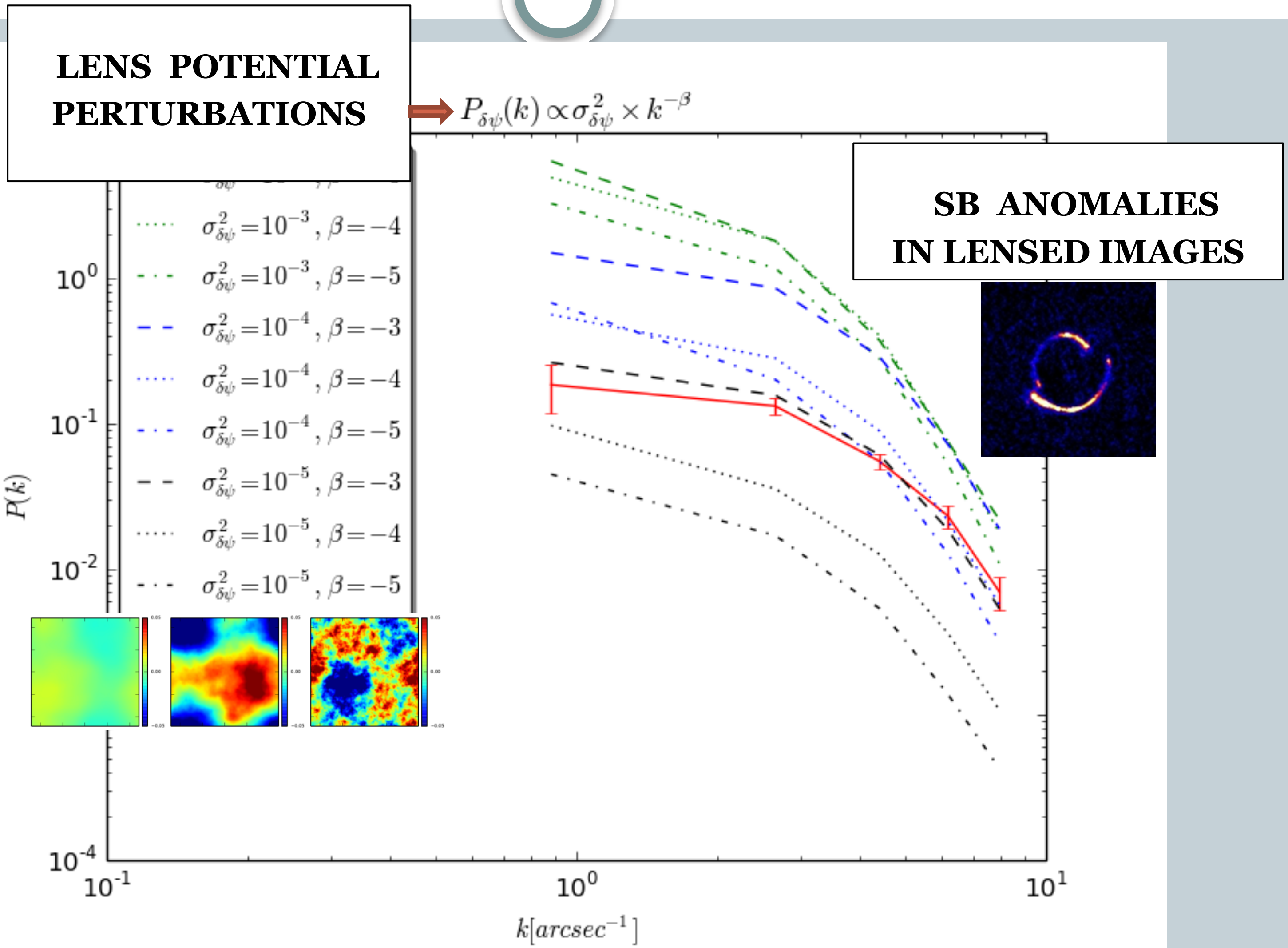
Bayer et al. (submitted to MNRAS)

Template of mock power spectra



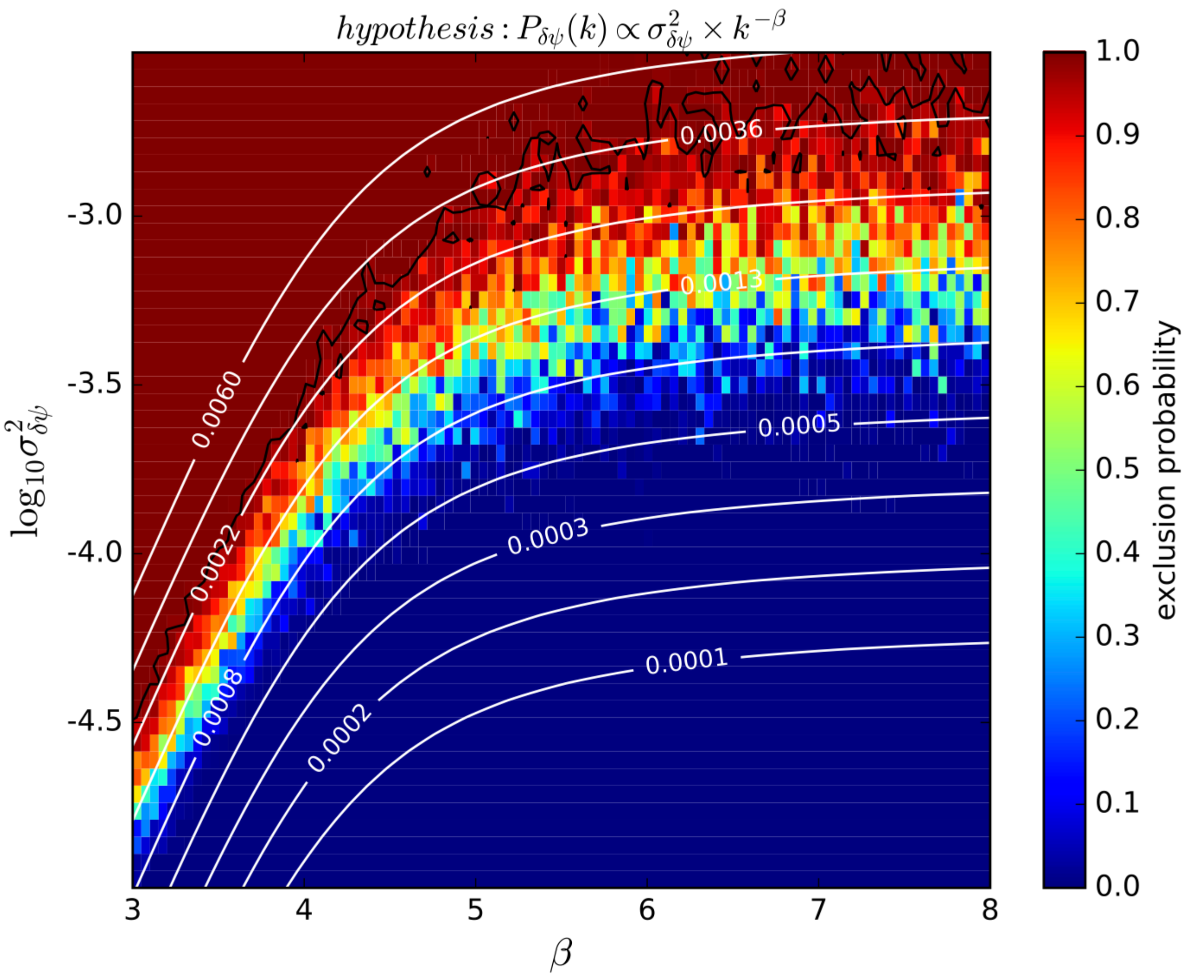
Bayer et al. (submitted to MNRAS)

Comparison with data



Bayer et al. (submitted to MNRAS)

Exclusion probability

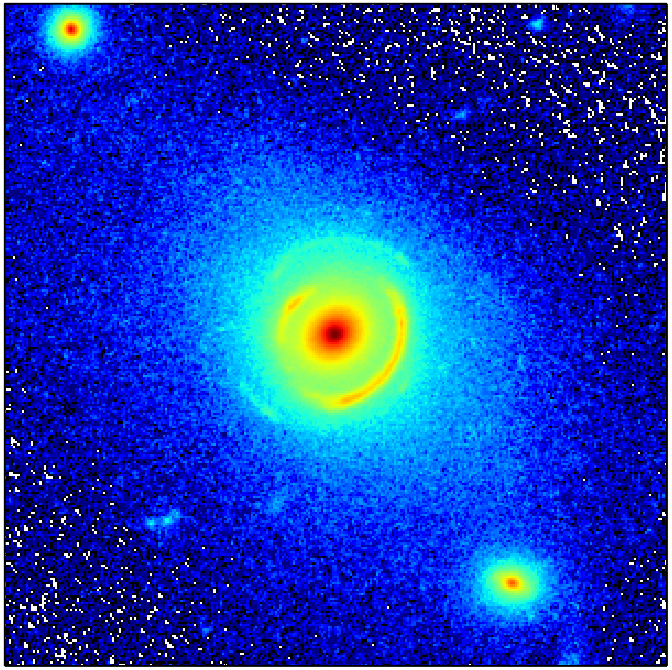


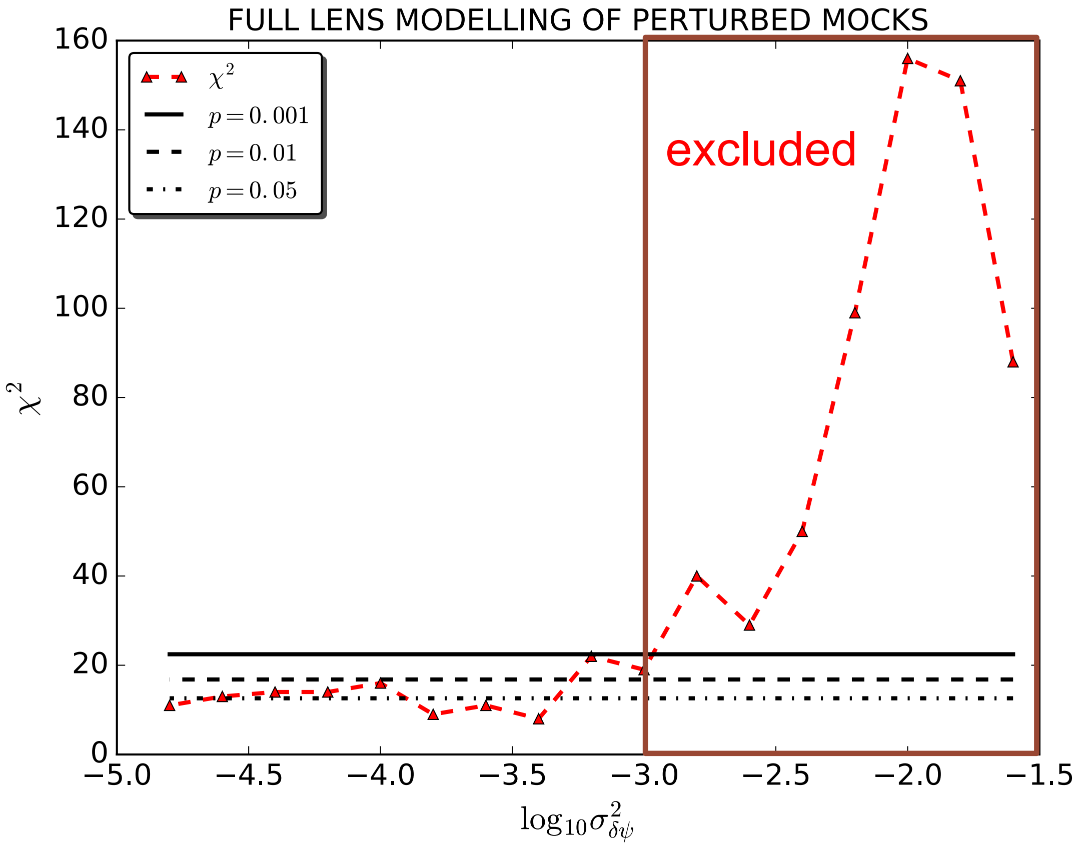
Bayer et al. (submitted to MNRAS)

DOUBLE RING LENS SYSTEM

Constraints from the Double Ring system

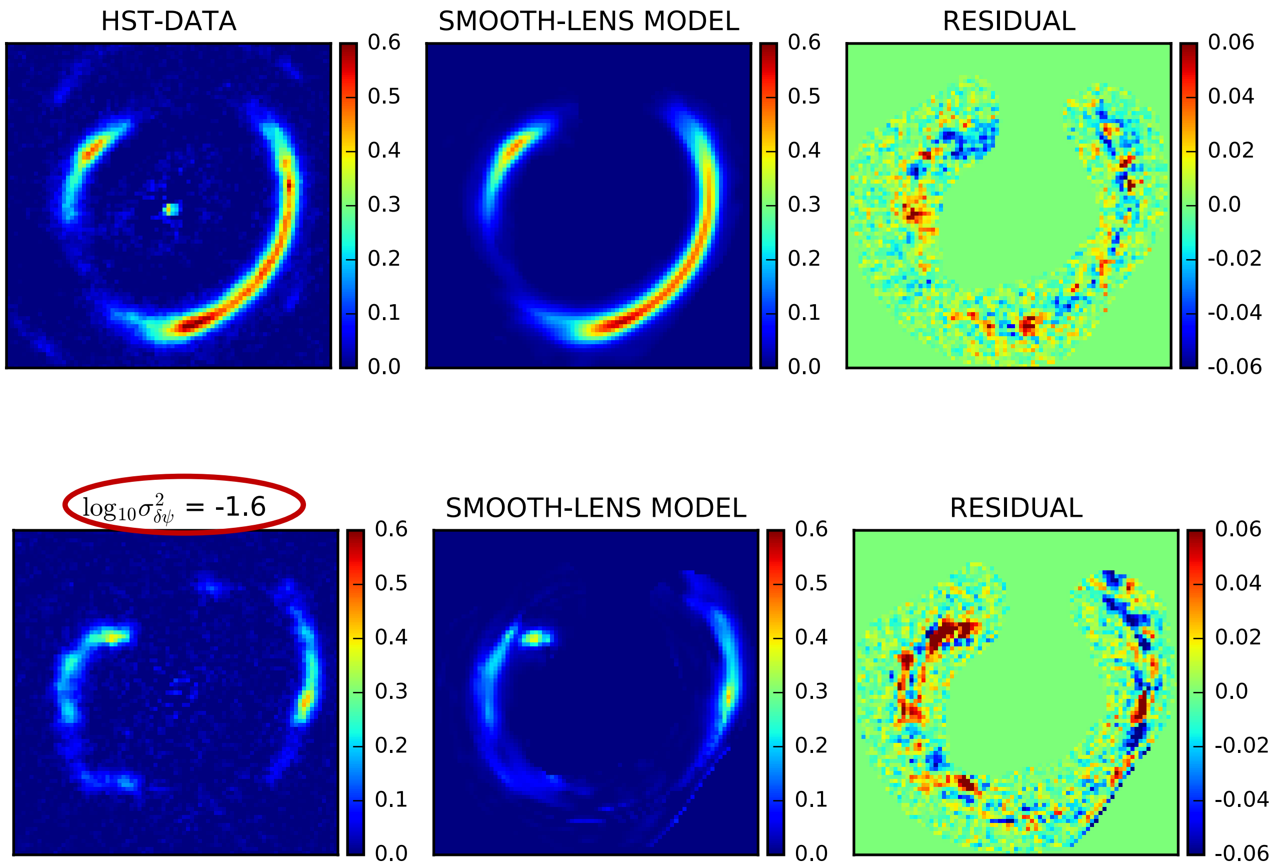
SDSS J0946+1006
HST/ACS/814W





Constraints from the Double Ring system

EXCLUDED



Bayer et al. (in prep)

Constraints from the Double Ring system

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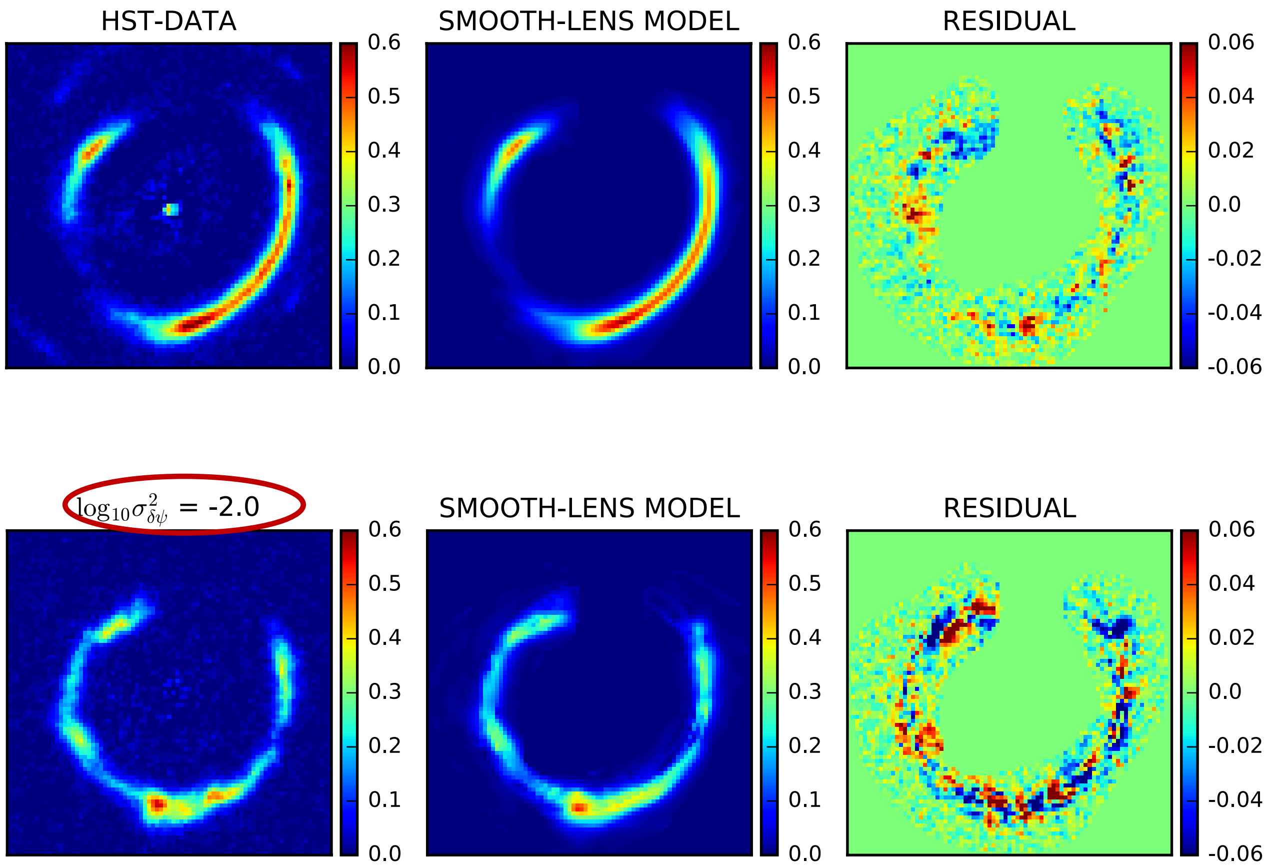

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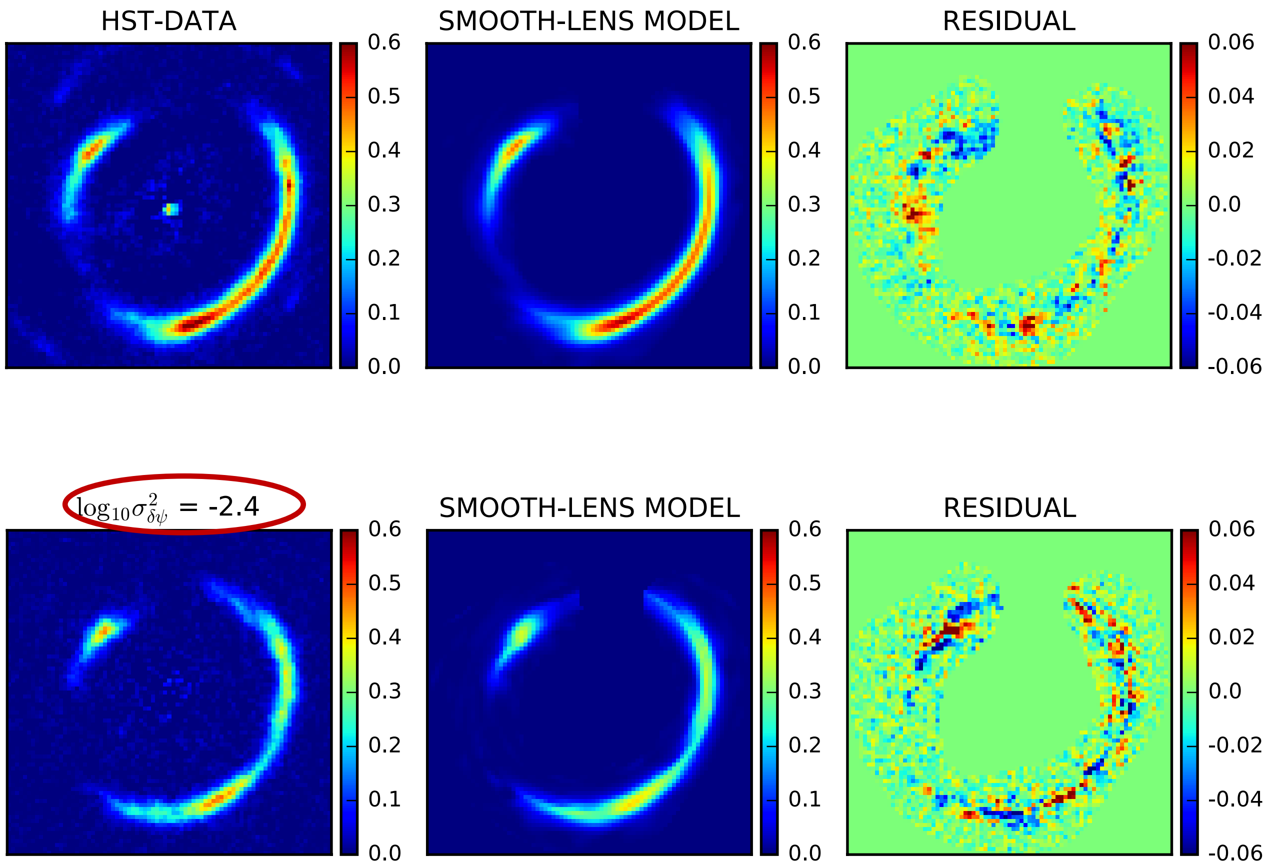

Bayer et al. (in prep)

Constraints from the Double Ring system

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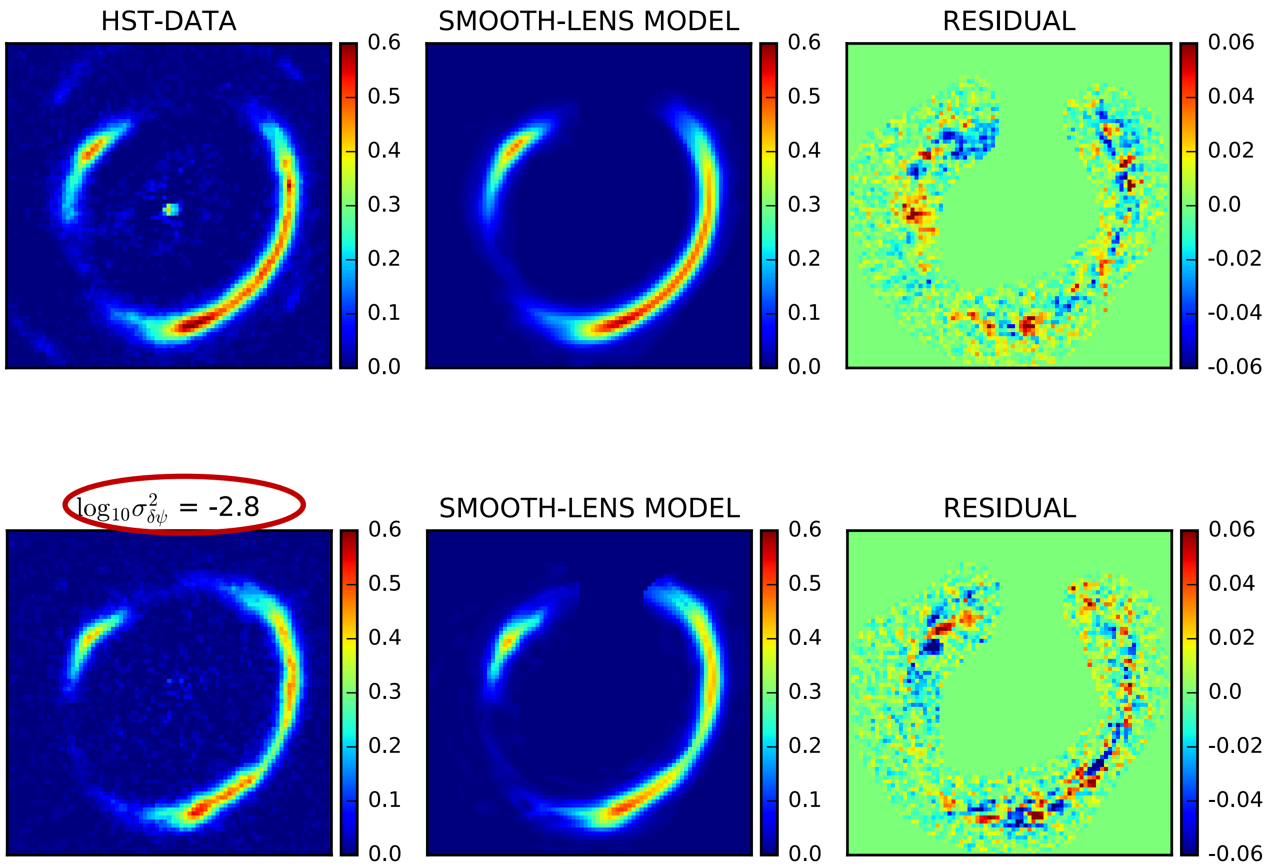
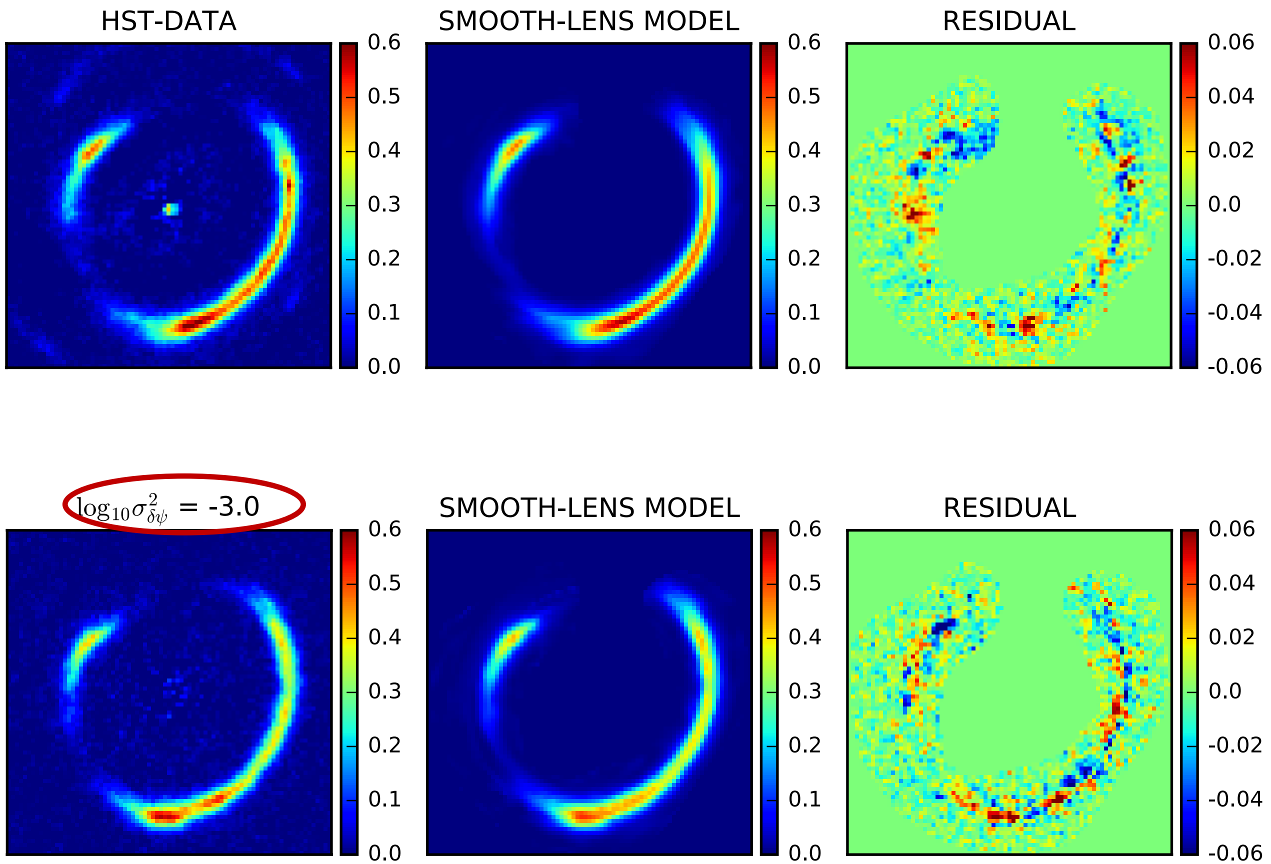


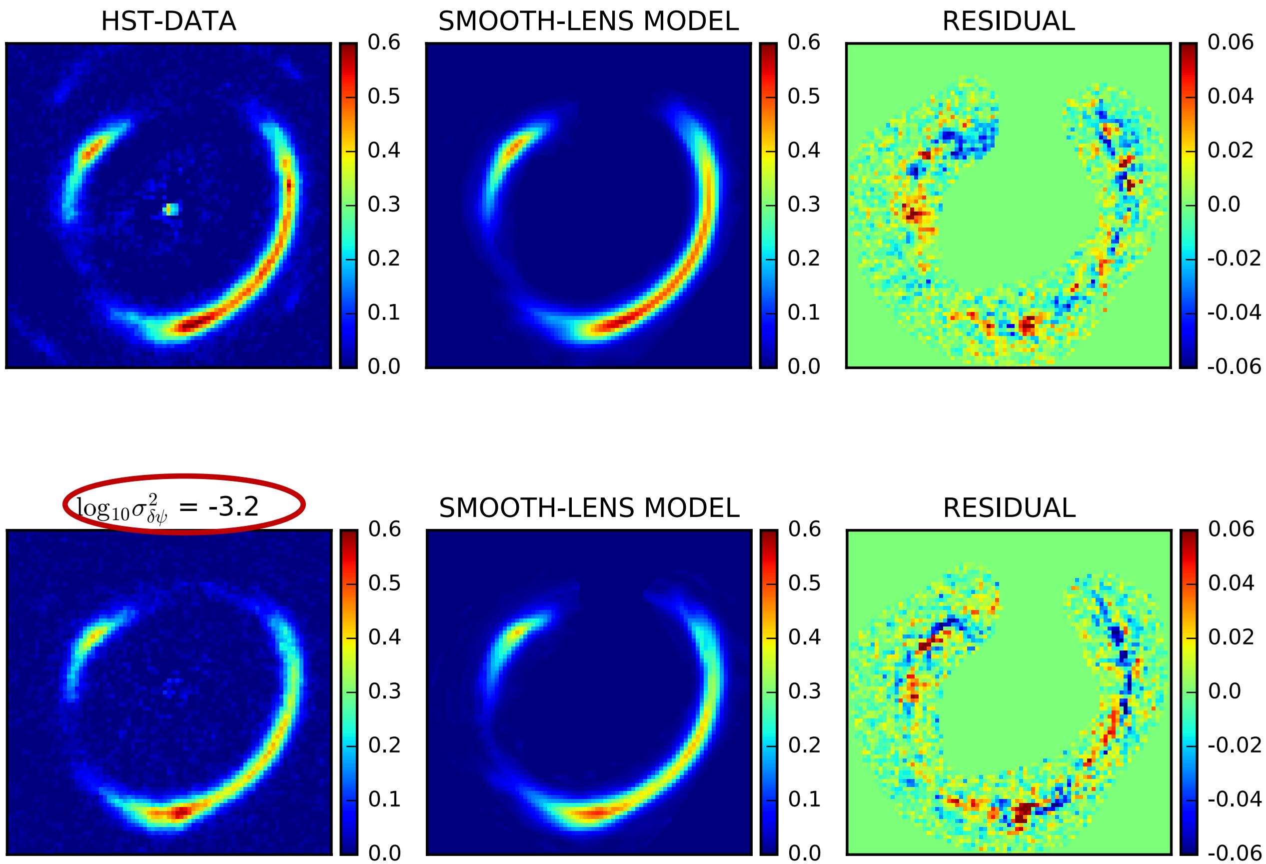
Constraints from the Double Ring system

UPPER LIMIT



Constraints from the Double Ring system

ALLOWED



Collaborators

Leon Koopmans

Saikat Chatterjee

Simona Vegetti

John McKean

Chris Fassnacht

Tomasso Treu

Summary & Future work

Summary

- Novel approach to modelling small-scale structure in galactic haloes
- Gaussian random fields density fluctuations
- Power spectrum of surface-brightness anomalies
- First constraints on sub-galactic mass power spectrum (1-10 kpc)

Future work

- Larger sample
- Machine-learning approach
- Comparison to hydrodynamical simulations
  - alternative dark matter models
  - various galaxy formation scenarios