

Hubble Frontier Fields: Gravitational Lensing Models

contributed by (PIs and primary lens modelers):

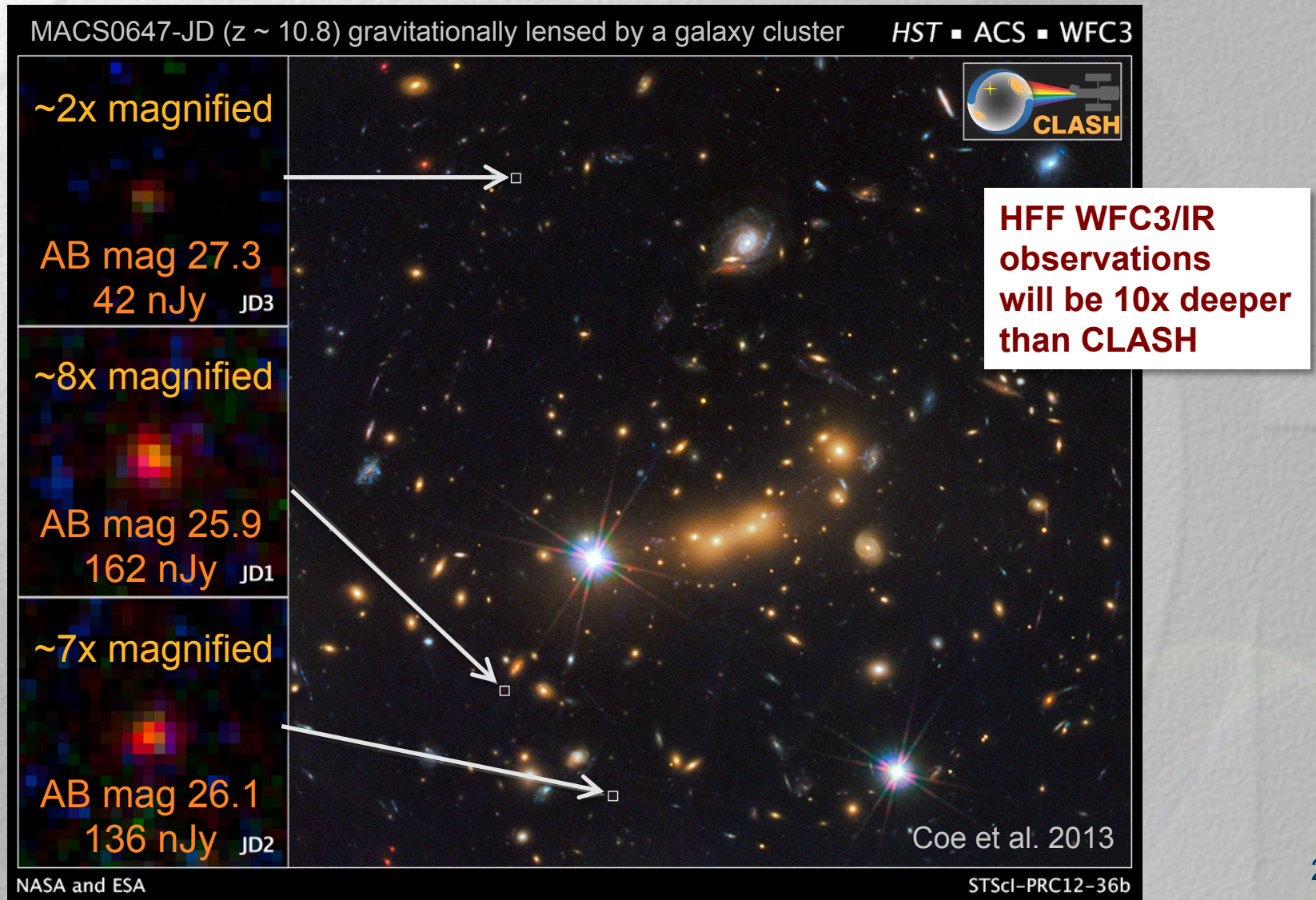
Marusa Bradac, Austin Hoag, Harald Ebeling, Johan Richard,
Marceau Limousin, Julian Merten, Adi Zitrin, Keren Sharon,
Traci Johnson, Liliya Williams, Kevin Sebesta

ingested for distribution to the community by STScI staff:

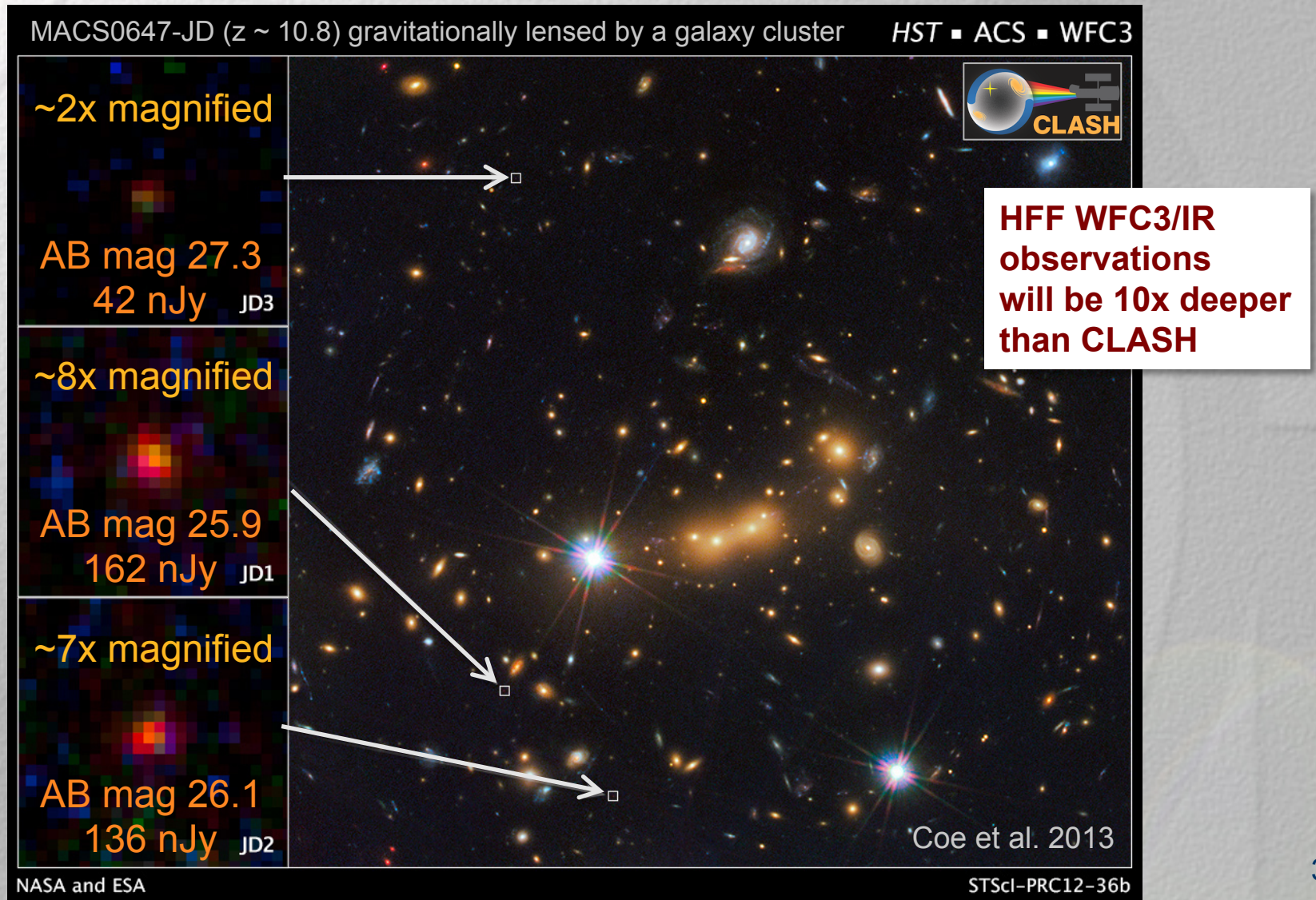
Dan Coe, Elizabeth Barker, Scott Fleming, Anton Koekemoer,
Karen Levay, Rick White, Jennifer Lotz

Dan Coe

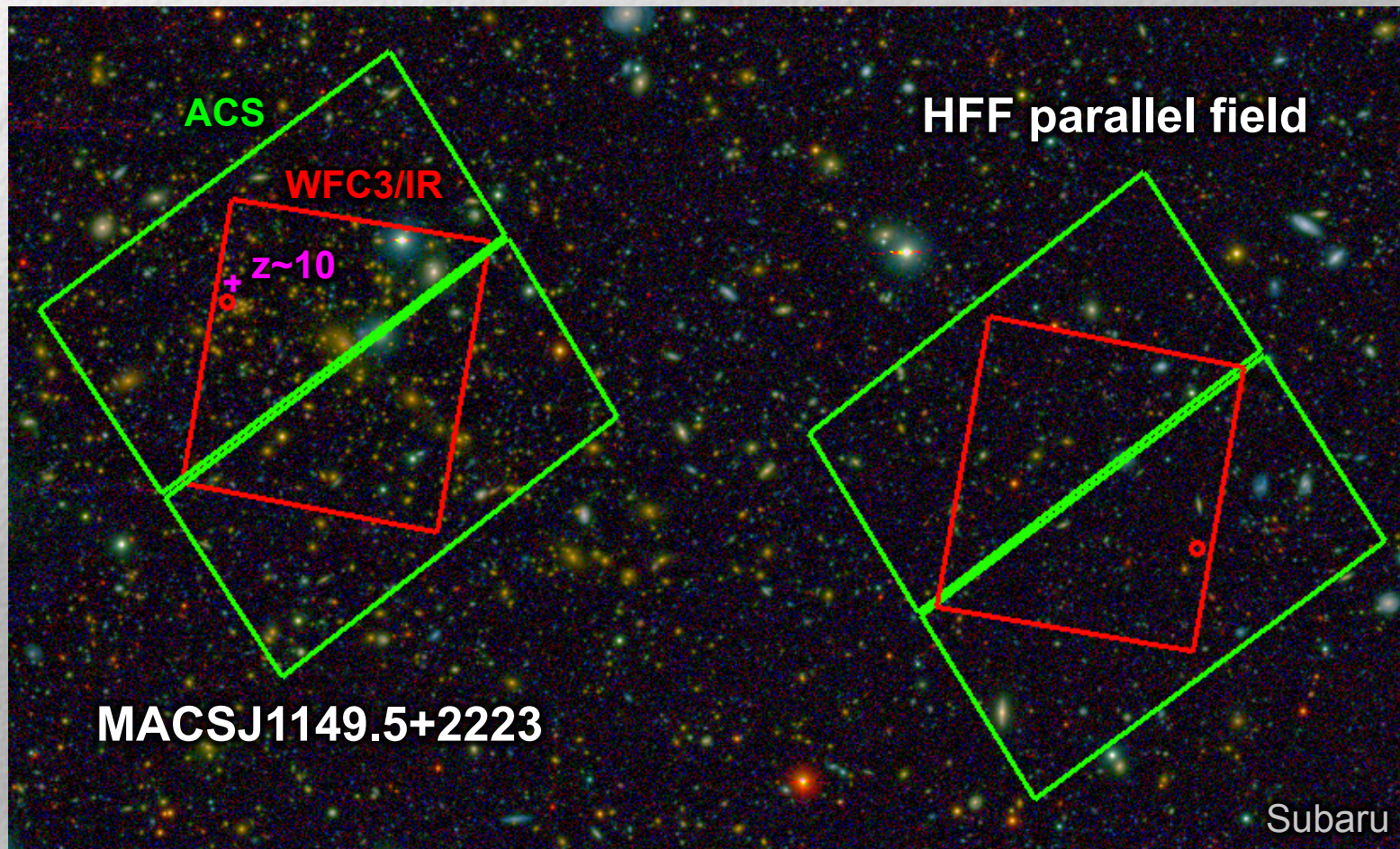
The Hubble Frontier Fields will reveal galaxies among the most distant yet known



Will lens model magnification uncertainties significantly affect high-redshift science?



Will the parallel “blank” fields be significantly magnified?



Efforts to address magnification uncertainties

initiated by Priya Natarajan and the HDFI SWG
(Hubble Deep Fields Initiative Science Working Group – chair: Bullock)

1. Simulated lensing to quantify model accuracies
2. Lens models of the observed HFF clusters contributed by multiple independent groups and distributed to the community

STScI call for proposals and lens model release

Goal: “Level the playing field” so non-experts in gravitational lensing will realize full utility of HFF

Unprecedented collaborative effort among lens modelers

Dec: HFF announced

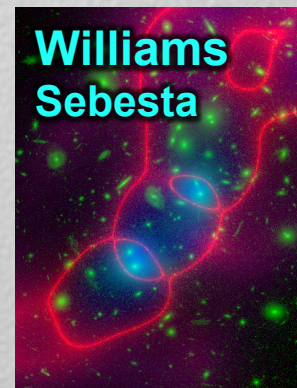
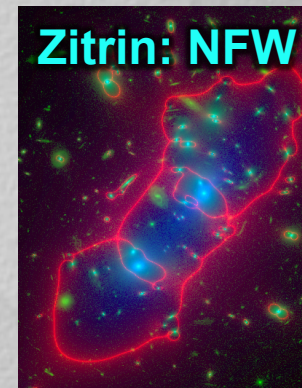
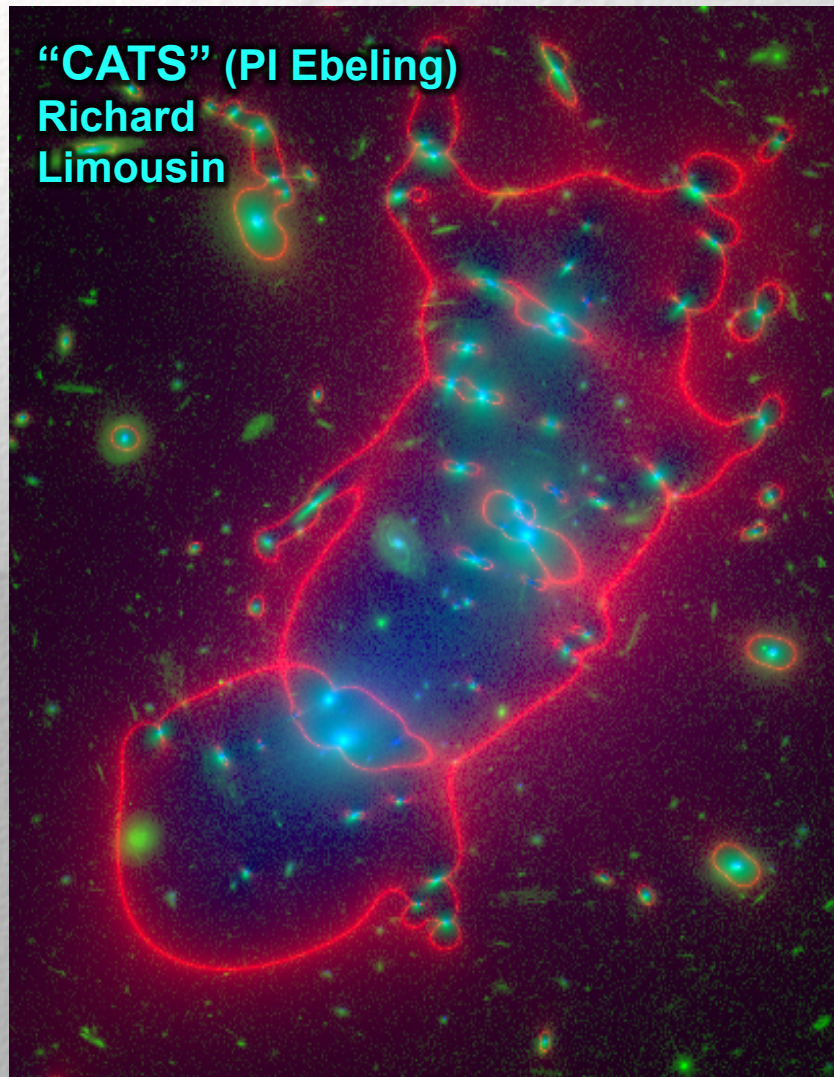
Jan: STScI call for proposals to create lens maps

May: Five teams awarded contracts

May – Aug: Lens modeling

- Teams collaborate to share identifications and redshifts of strongly lensed galaxies
 - Spectroscopic redshifts contributed and will be released for 29 galaxies strongly lensed by the HFF clusters
- Teams then work independently to derive lens models using robust, established, complementary methods

Lens models of the Frontier Fields clusters



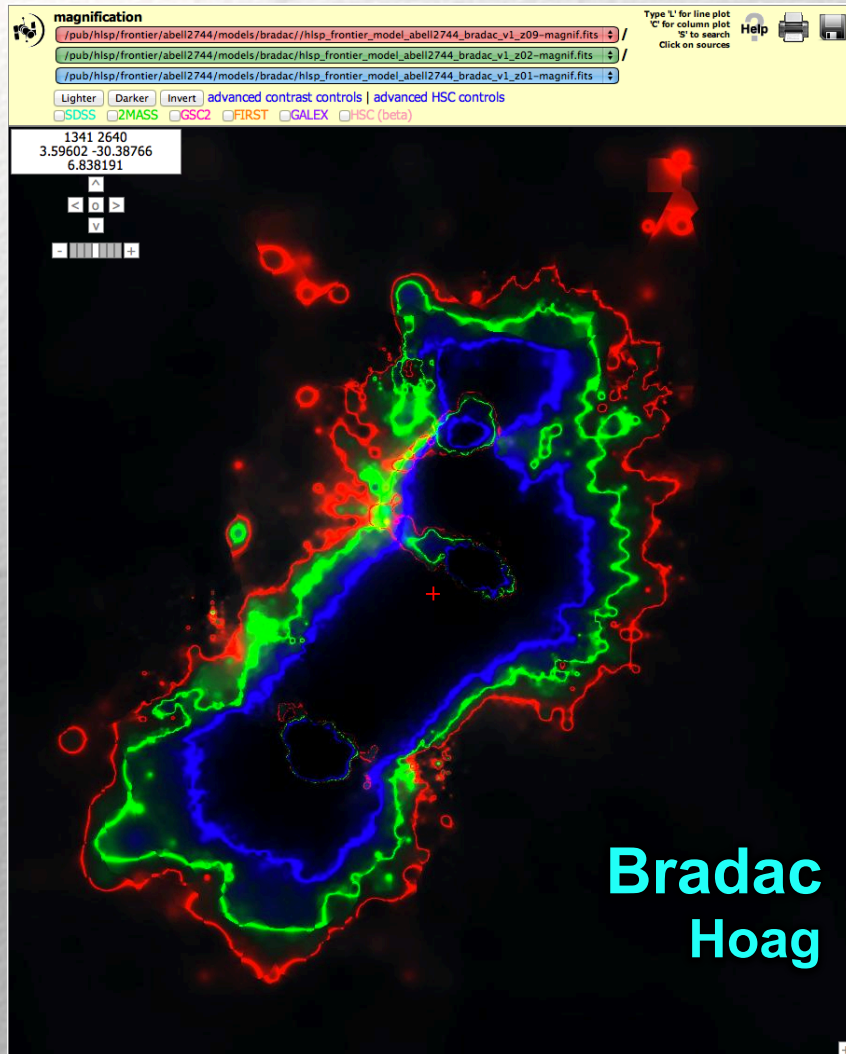
Abell 2744

red = magnification for a lensed galaxy at $z = 9$

green = HST

blue = mass

MAST interactive displays



magnification for a
lensed galaxy at
 $z = 1, 2, 9$

Magnification maps provided for
 $z = 1, 2, 4, 9$. For other redshifts,
magnification map must be
re-derived from mass and shear.

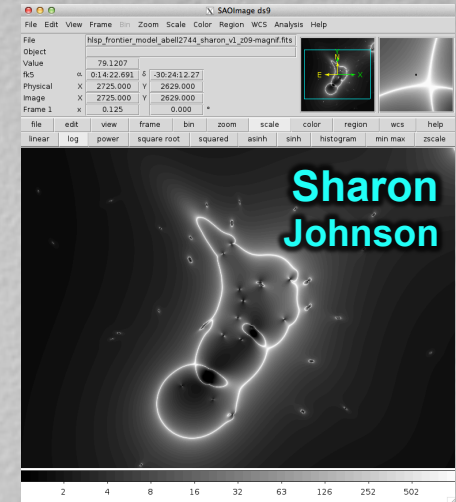
Lens model products submitted

- FITS maps

- magnifications for lensed sources at $z = 1, 2, 4, 9$
- mass and shear \rightarrow magnification at any redshift
 - STScI provides instructions and Python script
- ~ 100 additional models \rightarrow uncertainties

- README files (inputs, method, acknowledgments)

- catalogs of lensed images, redshifts, model parameters (from some teams)



Interactive model magnification web tool

[\[Click to close x\]](#)

Hubble Frontier Fields lens model magnification estimates

Abell 2744

☒ Single lensed galaxy:
RA: Dec: z = observed radius (arcseconds):
☐ List of lensed galaxies: RA, Dec, z, (optional) radius

```
0:14:23.219 -30:23:44.07 9 0
0h14m22.000s -30 24 00.00 4
(3.47968, -30.37596) 2
```

☐ Save results with run number and optional passcode:

Models: % confidence, calculated from a range of models provided by each group
[\(overview\)](#) ☐ show all results from each range of models, yielding likelihood distributions

CATS	<input checked="" type="checkbox"/>	with uncertainties	<input type="checkbox"/>
Sharon	<input checked="" type="checkbox"/>	with uncertainties	<input type="checkbox"/>
Zitrin-NFW	<input checked="" type="checkbox"/>	with uncertainties	<input type="checkbox"/>
Zitrin-LTM	<input checked="" type="checkbox"/>	with uncertainties	<input type="checkbox"/>
Williams	<input checked="" type="checkbox"/>	with uncertainties	<input type="checkbox"/>
Bradac	<input checked="" type="checkbox"/>	with uncertainties	<input type="checkbox"/>
Merten	<input checked="" type="checkbox"/>	with uncertainties	<input type="checkbox"/>

Uncertainty calculations add a few seconds response time per lensed galaxy per group.

This web-based lens model tool is not supported or maintained by MAST. If you have any questions about its use, or about the accuracy of its results, please email Dan Coe at DCoe@STScI.edu.

Input

Hubble Frontier Fields lens model magnification estimates

Abell 2744

RA, Dec = (00:14:23.219, -30:23:44.070) = (3.59675, -30.39558)

z = 9.0

observed radius = 0.0 arcseconds

CATS	2.87 best;	$2.93^{+0.11}_{-0.07}$	[2.86, 3.04]	median and 68.3% confidence range
Sharon	3.13 best;	$3.08^{+0.23}_{-0.18}$	[2.90, 3.32]	median and 68.3% confidence range
Zitrin-NFW	2.75 best;	$3.20^{+0.46}_{-0.34}$	[2.87, 3.66]	median and 68.3% confidence range
Zitrin-LTM	3.48 best;	$6.39^{+8.71}_{-2.51}$	[3.88, 15.11]	median and 68.3% confidence range
Williams	4.81 best;	$9.70^{+20.16}_{-5.00}$	[4.70, 29.86]	median and 68.3% confidence range
Bradac	4.42 best;	$4.43^{+0.10}_{-0.05}$	[4.37, 4.52]	median and 68.3% confidence range
Merten	4.14 best;	$11.79^{+33.04}_{-10.41}$	[1.37, 44.83]	median and 68.3% confidence range

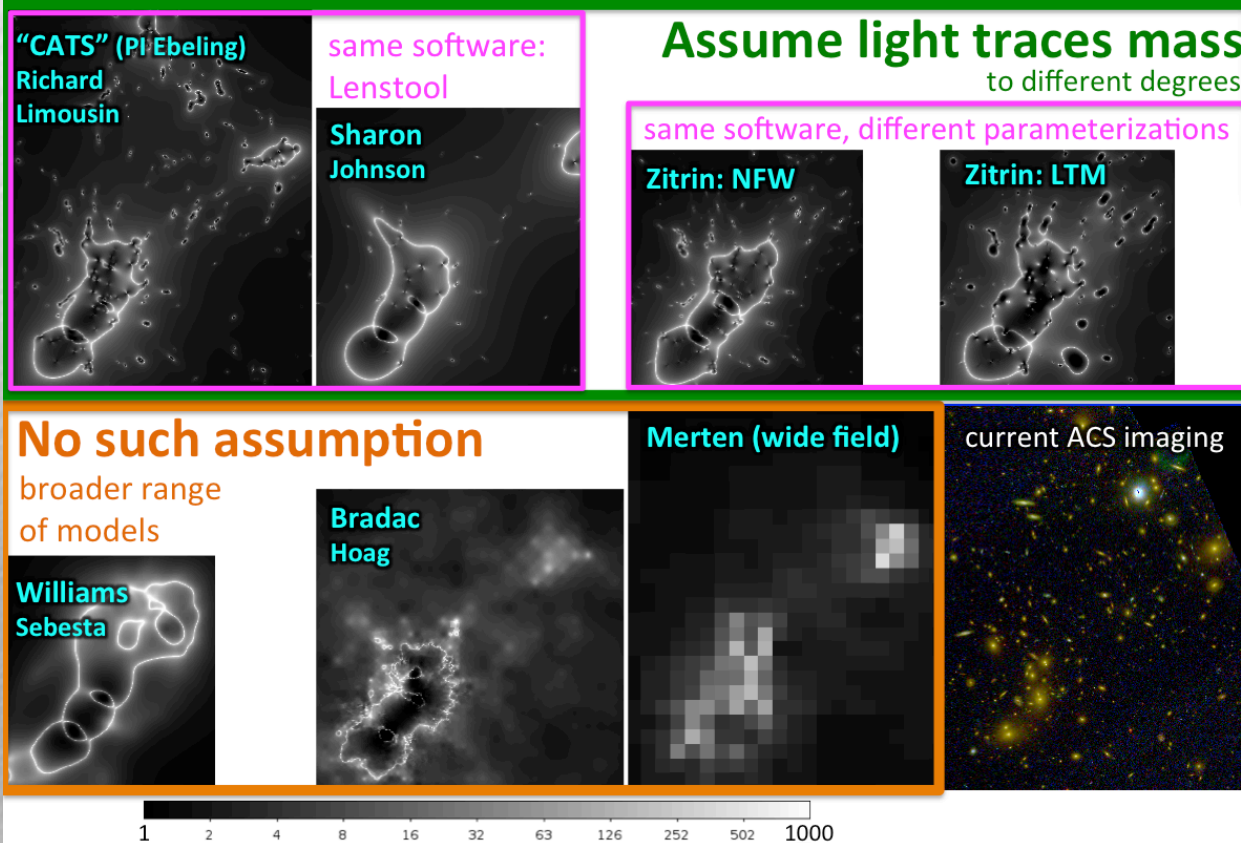
[Back to input page](#)

This web-based lens model tool is not supported or maintained by MAST. If you have any questions about its use, or about the accuracy of its results, please email Dan Coe at DCoe@STScI.edu.

Output

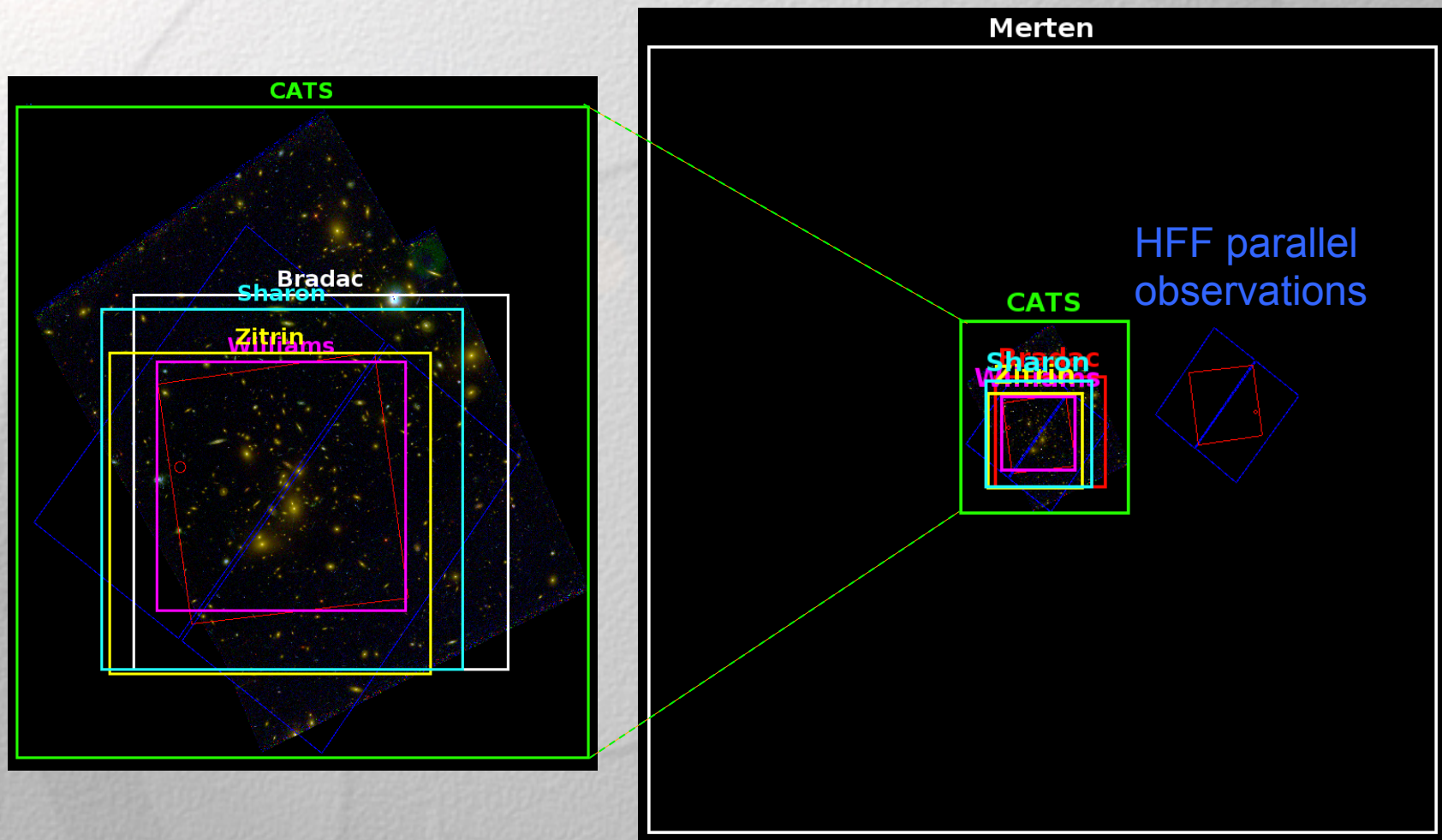
Overview text comparing methodologies written with input from lens modelers

Frontier Fields submitted lens models Abell 2744 magnification maps for a lensed source at $z = 9$



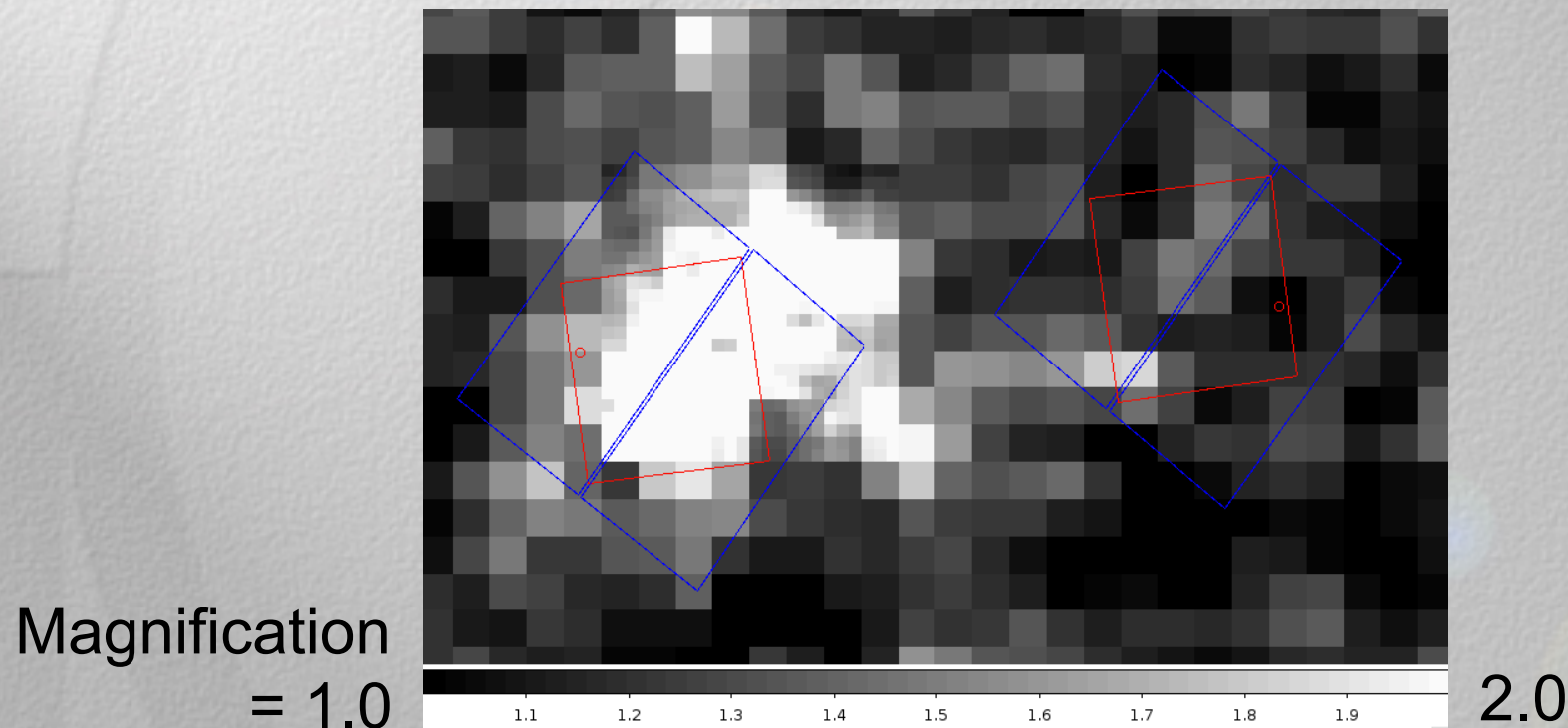
in addition to
READMEs
provided by
each team

Models cover different areas



Abell 2744 parallel field magnifications may be significant according to preliminary Merten model based on weak lensing analysis of single-band Subaru image with relatively poor seeing.

Model quality will improve significantly with HFF data.



Gravitational lensing primer written for the community

TUESDAY 15TH OCTOBER, 2013
Preprint typeset using L^AT_EX style emulateip v. 11/10/09

HUBBLE FRONTIER FIELDS: STRONG GRAVITATIONAL LENSING PRIMER

DAN COE¹
Tuesday 15th October, 2013

ABSTRACT

By combining the powers of the Hubble Space Telescope and gravitational lensing by galaxy clusters, the Hubble Frontier Fields (HFF) will obtain the deepest images of our universe to date. The lensed galaxies revealed will include some of the most distant yet known. Some, but not all, of their observed and derived properties will be affected by strong gravitational lensing. Lens models of the six HFF clusters have been produced by five teams for distribution to the community via MAST. To facilitate community use of those models, this short document explains the basics of strong gravitational lensing due to galaxy clusters.

Subject headings: gravitational lensing: strong – galaxies: clusters – cosmology: dark matter – galaxies: high redshift

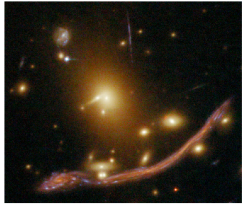


Figure 1. Examples of strong gravitational lensing observed in HST ACS/WFC imaging of Abell 370 obtained prior to the Frontier Fields. Most prominently, the bright red-blue arcs at bottom snakes between yellow cluster galaxies which deflect its light. Credit: NASA, ESA, the Hubble SM4 ERO Team, and ST-ECF.

1. INTRODUCTION

This primer is written for the Hubble Frontier Fields (HFF) Director's Discretionary Time (DDT) program which is observing six massive galaxy clusters with the Hubble Space Telescope. These images will reveal strong gravitational lensing of background galaxies due to the cluster mass (e.g., Fig. 1). By analyzing this lensing, we can derive the cluster mass distribution to a degree of accuracy which is being quantified in detail by ongoing research. For a recent review of cluster lensing, see Kneib & Natarajan (2011).

This primer is intended to facilitate use of lens models distributed by the HFF lens modelers to the community via the Mikulski Archive for Space Telescopes (MAST).² Below we briefly describe the effects of strong gravitational lensing on observables (§2) and the equations that govern strong lensing (§3).

¹ Space Telescope Science Institute, Baltimore, MD, USA;

² <http://archive.stsci.edu/prepds/frontier/lensmodels/>

2. OBSERVABLES AND DERIVED QUANTITIES AFFECTED BY LENSING

Table 1 summarizes the degree to which various observables are affected by gravitational lensing.

Lensing conserves surface brightness. Magnified lensed galaxies appear larger and thus brighter. Observed luminosities and derived quantities must be corrected for lensing magnifications, inheriting their full uncertainties from the lens modeling. These derived quantities include star formation rate and stellar mass. However, the ratio of these two quantities, specific star formation rate (sSFR), is not affected by lensing because both quantities are affected equally by the luminosity magnification. Lensing is achromatic (does not affect galaxy colors). So quantities derived from colors or spectra such as redshift, age, metallicity, extinction, and rest-frame UV slope (β) do not need to be corrected for lensing. (Second-order uncertainties may be introduced for derived quantities that depend on a luminosity prior.)

Quantities that depend on integrating over the lens model area are less susceptible to model uncertainties than local magnification estimates. Such derived quantities include lensed number counts, luminosity functions, and star formation rate densities. See upcoming work for the expected uncertainties in these quantities.

3. LENS EQUATIONS

Galaxies may be strongly lensed into multiple observed images and/or long arcs. As a shorthand, we often refer to all of these as “arcs”. For comparison, weak lensing (slight stretching or “shear”) may be detected statistically by averaging over many background galaxies observed further from the lensing cluster core.

Observed strong lensing deflections are proportional to, and thus constrain, the projected mass along the line of sight between us and the lensed galaxy. In the thin lens approximation, all of this mass is contained in the lens, or in our case, the galaxy cluster. The deflections also scale geometrically with the redshifts of the lens and the lensed galaxy (the “source”) to distinguish it from its observed (lensed) image as described below.

A massive body with projected mass surface density $\kappa(\theta)$ deflects light around it by an angle $\hat{\alpha}(\theta) = \hat{\theta} - \beta$

2

Coe 2013

Table 1
Observables and Derived Quantities Affected by Gravitational Lensing

Full uncertainties	Reduced uncertainties	No uncertainties introduced
Luminosity - Star Formation Rate - Stellar Mass	(Integrated quantities) Number counts - Luminosity function - Star formation rate density	Colors: - Redshift - Age - Metallicity - Extinction - Rest-frame UV slope (β) Specific star formation rate (SFR / mass)

from its true position on the sky β to its observed position $\hat{\theta}$ (Fig. 2):

$$\nabla \cdot \hat{\alpha} = 2\kappa. \quad (1)$$

The surface density $\kappa = \Sigma/\Sigma_{crit}$ is defined in units of the lensing critical density at the redshift of the lens. The critical density is that generally required for strongly lensed multiple images to be produced. It is a function of source redshift as given by:

$$\Sigma_{crit} = \frac{c}{4\pi G} \frac{D_S}{D_L D_{LS}}, \quad (2)$$

involving a ratio of the angular-diameter distances from observer to source $D_S = D_A(0, z_S)$, observer to lens $D_L = D_A(0, z_L)$, and lens to source $D_{LS} = D_A(z_L, z_S)$. For a flat universe ($\Omega = \Omega_m + \Omega_\Lambda = 1$), angular-diameter distances are calculated as follows (Fukugita et al. 1992, filled beam approximation; see also Hogg 1999 and online calculators such as iCosmos³):

$$D_A(z_1, z_2) = \frac{c}{1+z_2} \int_{z_1}^{z_2} \frac{dz'}{H(z')}, \quad (3)$$

$$= D_A(0, z_2) - \left(\frac{1+z_1}{1+z_2} \right) D_A(0, z_1) \quad (4)$$

where (again for a flat universe) the Hubble parameter varies with redshift as:

$$H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}. \quad (5)$$

Thus the critical density Σ_{crit} is a function of the source redshift. This follows because the deflection angle $\hat{\alpha}$ is a function of source redshift. As source redshift decreases, the light bend angle $\hat{\alpha}$ remains constant, which (imagine moving the galaxy in Fig. 2 inward along the top blue arrow) requires the image deflection to decrease by the distance ratio plotted in Fig. 3:

$$\hat{\alpha} \propto \frac{D_{LS}}{D_S}. \quad (6)$$

The normalized mass surface density also scales with this ratio:

$$\kappa \propto \frac{D_{LS}}{D_S}. \quad (7)$$

³ <http://www.icosmos.co.uk>

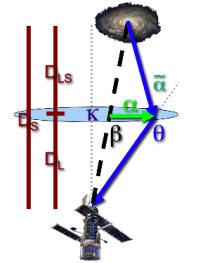


Figure 2. A lens with mass distribution κ deflects the light from a background galaxy by an angle $\hat{\alpha}$. In the absence of the lens, the background galaxy would appear at its true, or “source”, position β . The intervening mass deflects its light by an amount $\hat{\alpha}$ to position $\hat{\theta}$. The deflection angle α on our sky is related to the actual bend angle $\hat{\alpha}$ of the light ray via $\alpha D_S = \hat{\alpha} D_{LS}$. The distances D_S , D_{LS} , and D_L are measured as angular diameter distances. Reprinted from Coe et al. (2008).

as does the weak lensing shear:

$$\gamma \propto \frac{D_{LS}}{D_S}. \quad (8)$$

These distance ratios are plotted in Fig. 3 for lenses with redshifts between 0.2 and 0.9. Magnifications μ do not scale linearly with this ratio, but rather as:

$$1/\mu = (1 - \kappa)^2 - \gamma^2 \quad (9)$$

That is, each quantity κ and γ must be scaled to the appropriate redshift before calculating magnifications according to Equation 9. Lensing “critical curves”, or regions of high magnification, basically move outward to larger radius as the lensed source redshift increases.

Magnifications can take positive and negative values. A negative magnification merely indicates a flipped mirror image (or “parity”) with respect to the lensed source.

Hubble Frontier Fields: Strong Gravitational Lensing Primer

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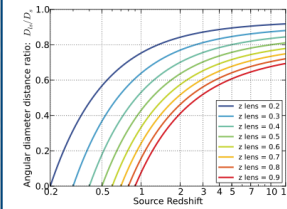


Figure 3. Angular diameter distance ratio D_{LS}/D_S as a function of lens redshift and source redshift. We assumed a flat concordance cosmology with $H_0 = 70$ km/s/Mpc, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$.

The lensed galaxy appears both larger (in area) and brighter (in flux) by the magnification factor μ . (Surface brightness is conserved by lensing.) Thus the observed magnitude = the intrinsic magnitude $- 2.5 \log_{10} \mu$. Point demagnified galaxy images may also be observed near the cluster core. These smaller images are generally more difficult to detect against the BCG (brightest cluster galaxy) light.

REFERENCES

The Hubble Frontier Fields is a Space Telescope Science Institute (STScI) Director's Discretionary Time (DDT) program of observations with the NASA/ESA Hubble Space Telescope's Advanced Camera for Surveys (ACS) and Wide Field Camera 3 (WFC3). As part of this program, five teams were funded to produce gravitational lensing models for distribution to the community via the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555. ACS was developed under NASA contract NAS 5-32864.

Facilities: HST (WFC3, ACS)

Coe, D., Fuslier, E., Benítez, N., Broadhurst, T., Frye, B., & Ford, H. 2008, *AJ*, 136, 814 [ADS]
Fukugita, M., Futamase, T., Kasai, M., & Turner, E. L. 1992, *AJ*, 104, 1 [ADS]
Hogg, D. W. 1999, *ArXiv Astrophysics e-prints*, astro-ph/9905116 [ADS]
Kneib, J.-P. & Natarajan, P. 2011, *MNRAS*, 414, 19, 47 [ADS]

Lens model uncertainties propagate to some, but not all, observables

Full uncertainties

Luminosity:

- Mass
- Star formation rate

Reduced uncertainties

(integrated quantities)

Number counts:

- Luminosity function
- Star formation rate cosmic density

No uncertainties introduced

Colors:

- Redshift
- Age (Balmer break)
- Metallicity
- UV slope β

Specific star formation rate (SFR / mass)

HFF lens model products released for Abell 2744

<http://archive.stsci.edu/prepds/frontier/lensmodel/>

- **Spectroscopic redshifts of lensed arcs**
- **Lens models**
- **Interactive display**
- **Interactive web tool**
- **Description of methods**
- **Lensing primer**
- **Script to generate magnification maps at arbitrary redshift**

<http://archive.stsci.edu/prepds/frontier/lensmodels>

Timeline

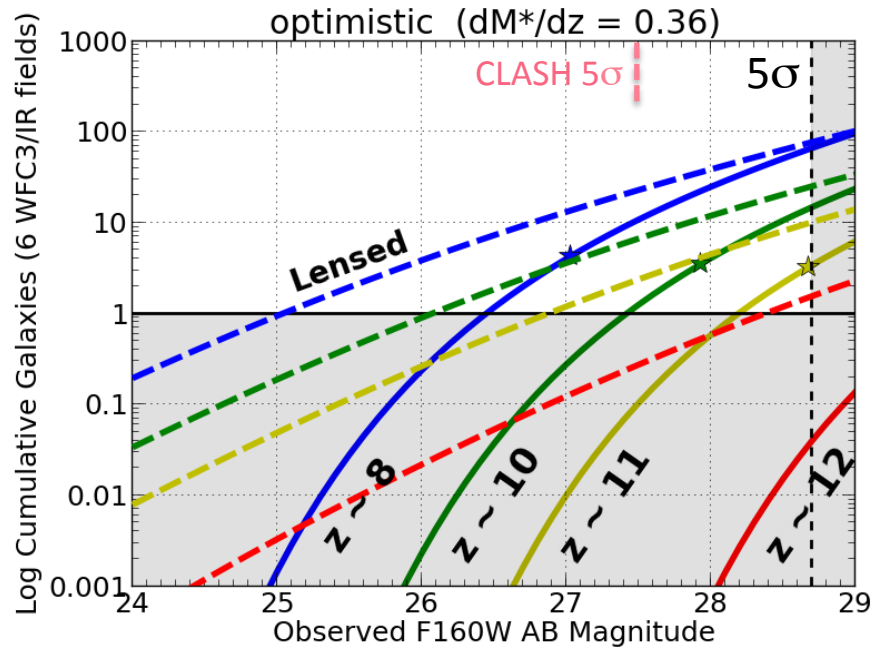
Date	Milestone
Aug. 31	HFF “version 1” lensing maps submitted
Oct. 16	Release Abell 2744 “version 1” lensing maps and web tools
Oct. 25	First HFF observations of Abell 2744
Nov. ~15	Release “version 1” lensing maps of all clusters
Nov. 15	Lens models due for first simulated HFF cluster
Dec. ~20	Deadline for MACSJ0416.1-2403 “version 2” model submissions
Jan. ~6	AAS HFF presentations
Jan. 10	First HFF observations of MACSJ0416.1-2403

Extra slides

Frontier Fields should yield $\sim 35 - 120$ $z > 8.5$ galaxies

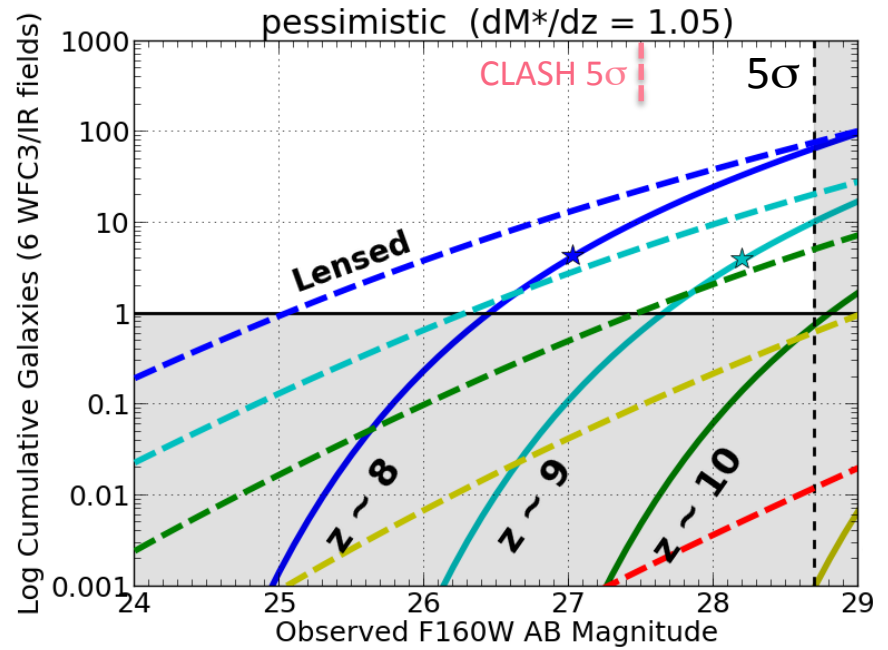
distinguishing between evolution scenarios

gradual evolution



redshift	lensed	field	total
$z \sim 9$	45	20	65
$z \sim 10$	25	15	40
$z \sim 11$	10	3	13
$z \sim 12$	1		1

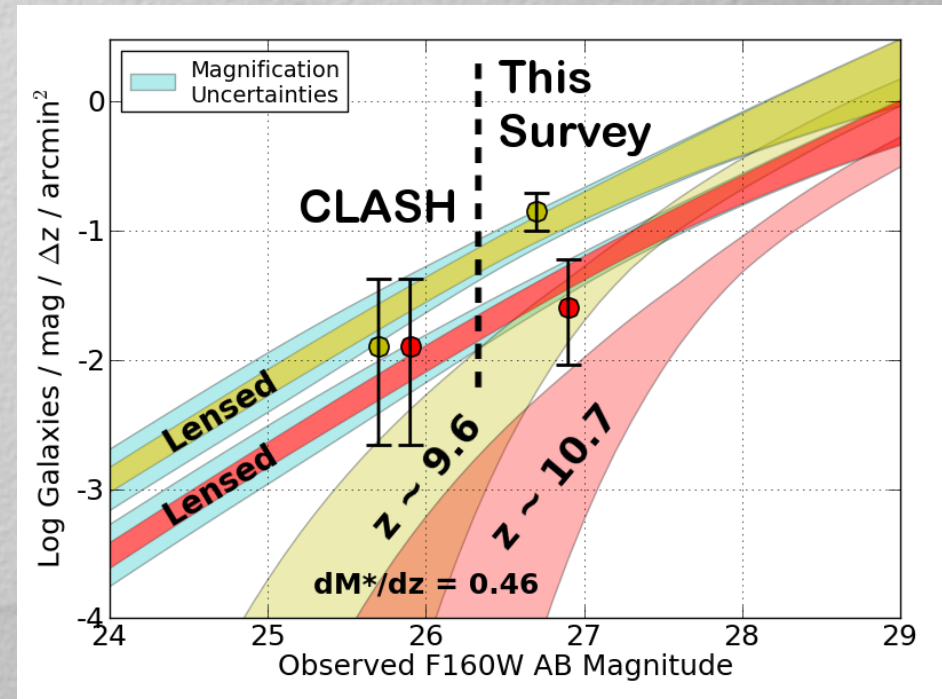
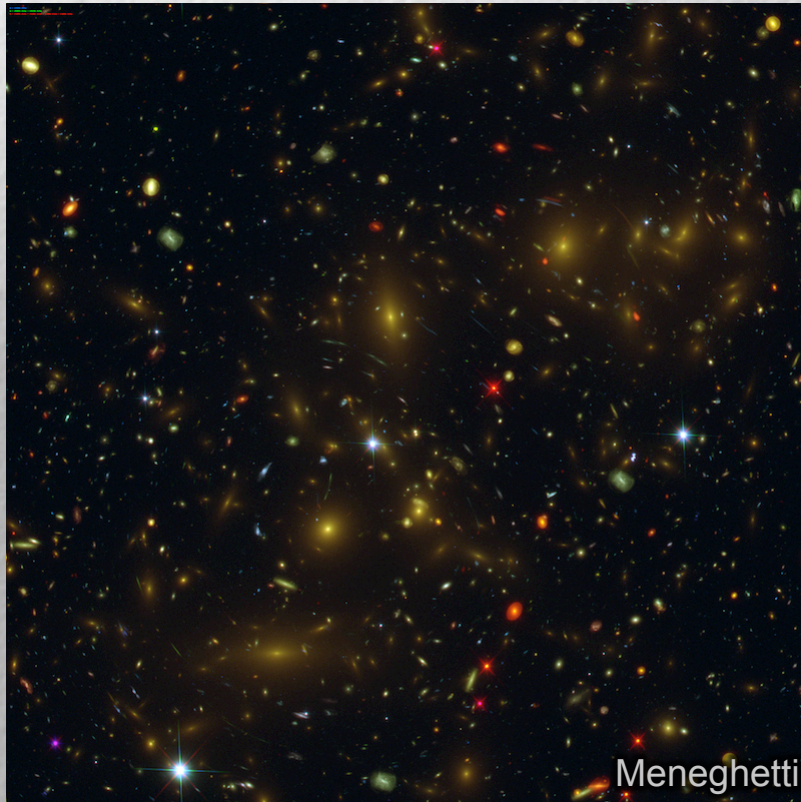
dramatic evolution



redshift	lensed	field	total
$z \sim 9$	20	10	30
$z \sim 10$	5		5
$z \sim 11$			
$z \sim 12$			

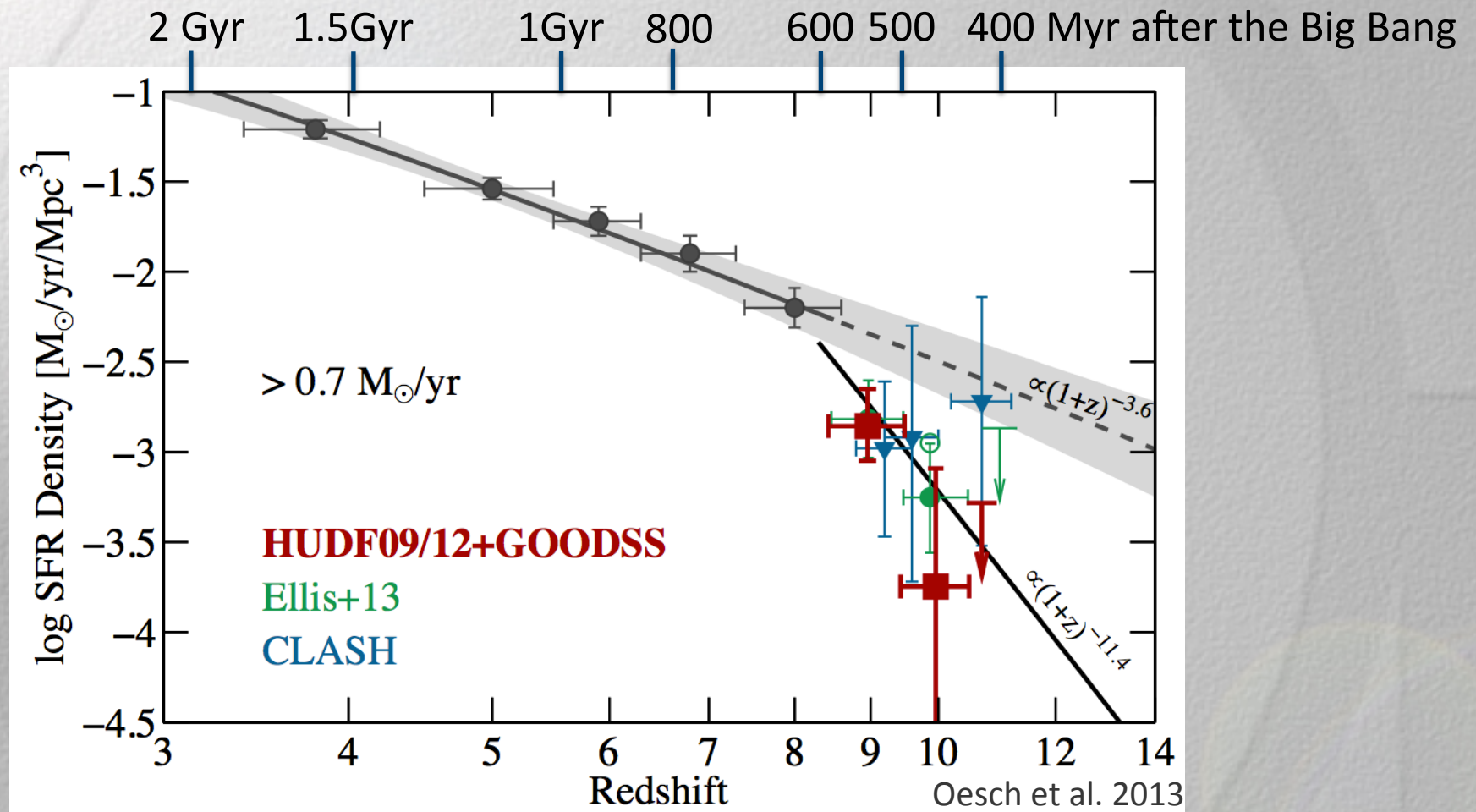
Simulations: Lens model uncertainties do not contribute significantly to luminosity function uncertainties

(SFR densities are derived from integrated luminosity functions)



White paper submission to the HDFI SWG
(Coe, Zheng, et al.)

Science question: Did the cosmic star formation rate density evolve dramatically between $z \sim 10$ and 8?

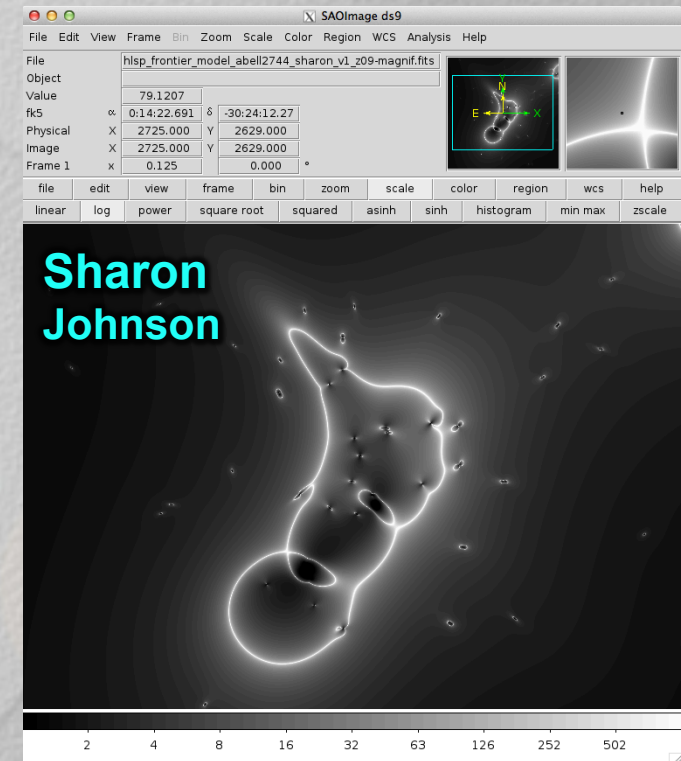


Lens models may also be downloaded directly as FITS images

Index of /pub/hlsp/frontier/abell2744/models/sharon

archive.stsci.edu/pub/hlsp/frontier/abell2744/models/sharon/

Name	Last modified	Size	Description
Parent Directory		-	
hlsp_frontier_model_abell2744_sharon_v1_gamma.fits	11-Oct-2013 18:30	173M	
hlsp_frontier_model_abell2744_sharon_v1_kappa.fits	11-Oct-2013 18:30	173M	
hlsp_frontier_model_abell2744_sharon_v1_readme.pdf	11-Oct-2013 18:33	687K	
hlsp_frontier_model_abell2744_sharon_v1_x-deflect.fits	11-Oct-2013 18:33	173M	
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hlsp_frontier_model_abell2744_sharon_v1_z09-magnif.fits	11-Oct-2013 18:30	173M	
range/	11-Oct-2013 18:33	-	



Magnification maps provided for $z = 1, 2, 4, 9$. Mass (κ) and shear (γ) maps enable the user to generate magnification maps for other redshifts using a script we provide. Each team also provided a range of lens models, enabling us to estimate uncertainties.

<http://archive.stsci.edu/prepds/frontier/lensmodels>