



# Strong Lens Modeling of Galaxy Clusters

**Your morning briefing:  
what you need to know  
to get through the day**

Keren Sharon  
University of Michigan  
[kerens@umich.edu](mailto:kerens@umich.edu)



Your morning briefing: what you need to know to get through the day

**Outline:**

- (strong) Lensing applications
- When do we need a lens model?
- SL modeling methods
- How does lens modeling work?
- What are lens model products?
- Main cluster SL surveys
- What should we worry about (uncertainties)?
- The future...

# Why do we care?



## Say cheese! Hubble Telescope spots smiley face in space

By Emma Lacey-Bordeaux, CNN

Updated 9:16 AM ET, Tue February 10, 2015



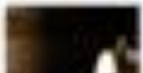
Space news



Complete coverage:  
Space + Science



Asteroid's moon seen during Earth flyby



Close encounter with distant Pluto under way



# Why do we care?

## Cluster physics\*, cosmology\*

- mass distribution
  - dark matter vs. baryons
  - slope, concentration
- mass-observable calibration → cosmology
- cosmological parameters ( $H_0$  ?? arc statistics)

\* when combined with other proxies

## Background Universe

- use clusters as cosmic telescopes

# Magnification of background sources

**Affects...** [measurements of all integrated quantities]

- Luminosity
- Stellar mass
- Star formation rate
- Sizes
- Background volume

**Doesn't affect...** [properties derived from ratios]

- Colors
- Line ratios\* (\*caveat: strong magnification gradients)
- Metallicity
- Specific star formation rate
- Gini coefficient ([Florian+16](#))

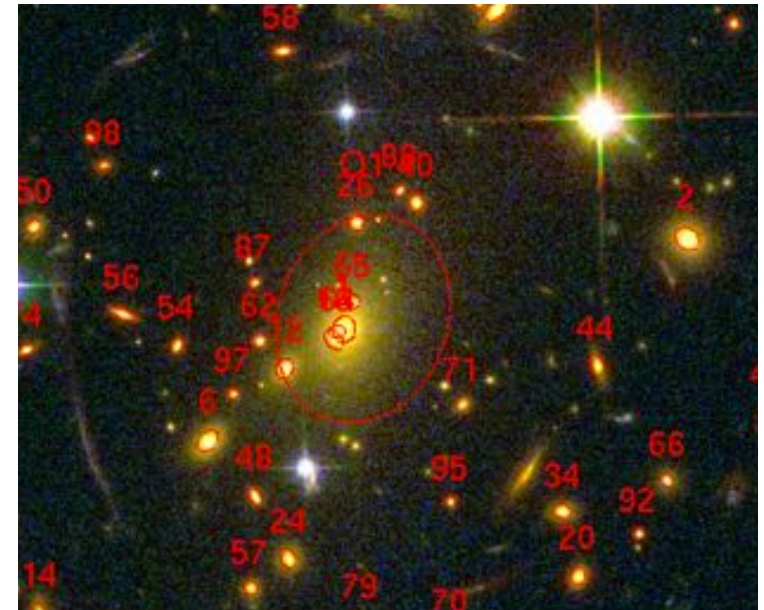
# Lens modeling approaches

“Parametric”

“non-parametric”

} hybrid

mass/light assumptions



4 *J. Liesenborgs, S. De Rijcke and H. Dejonghe (2006)*

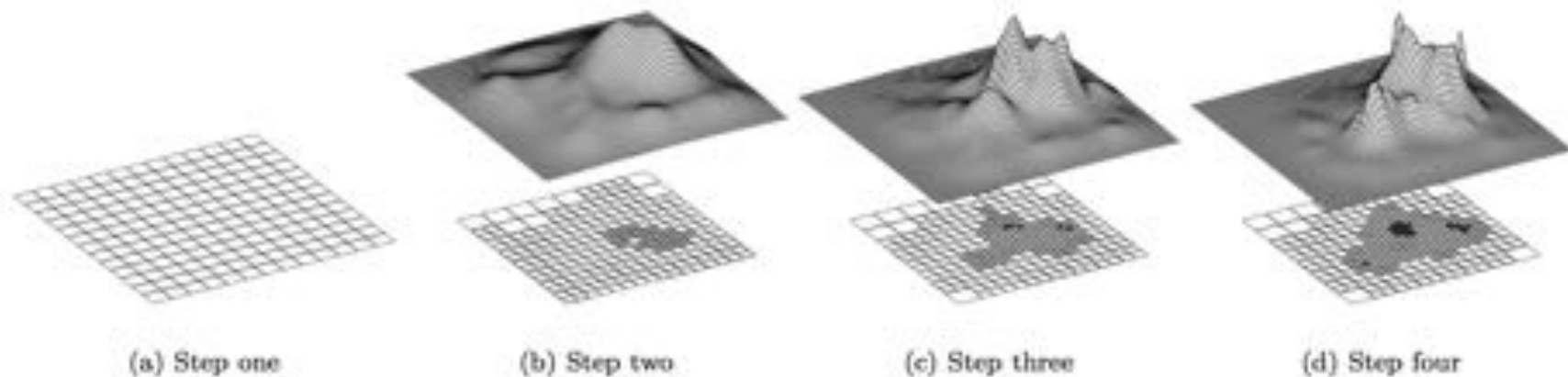
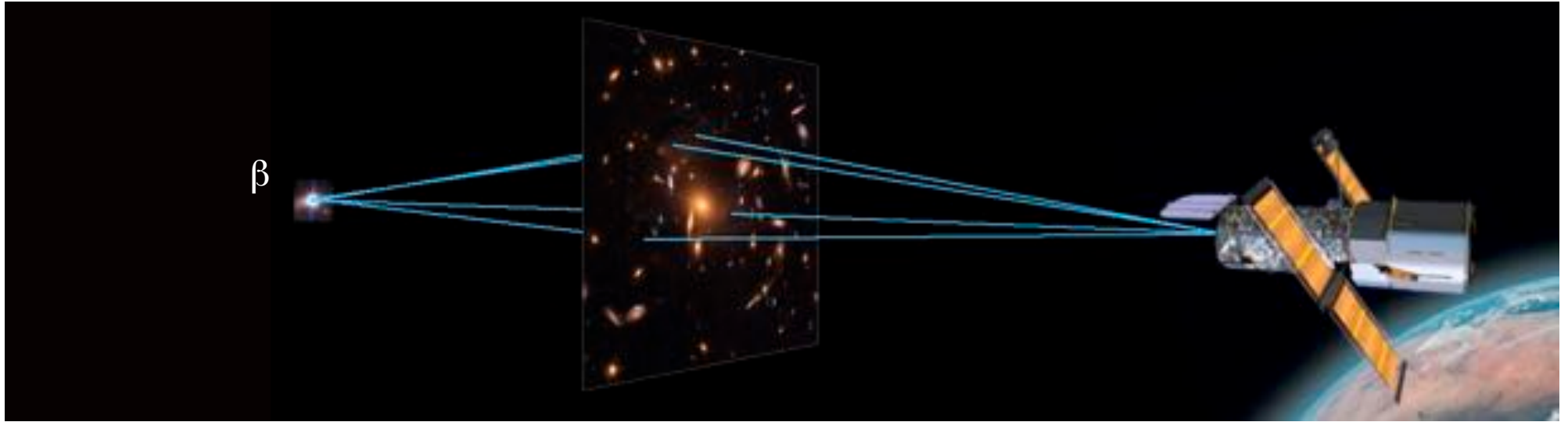


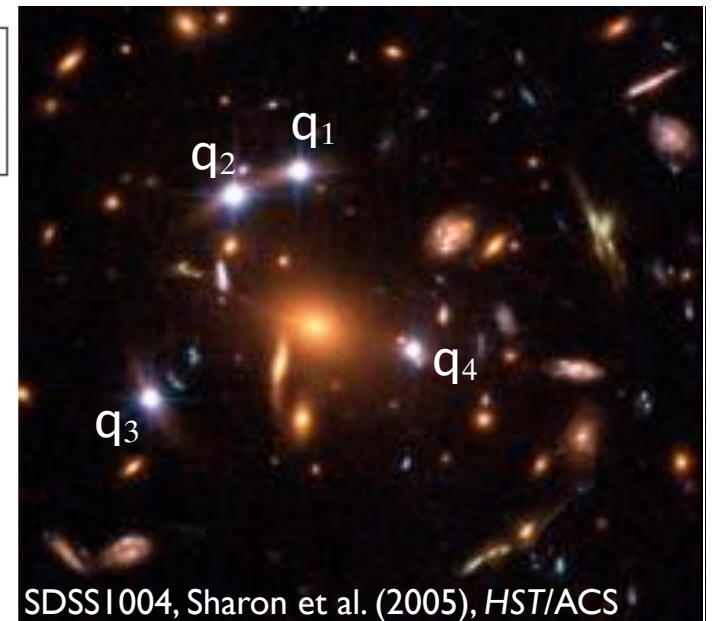
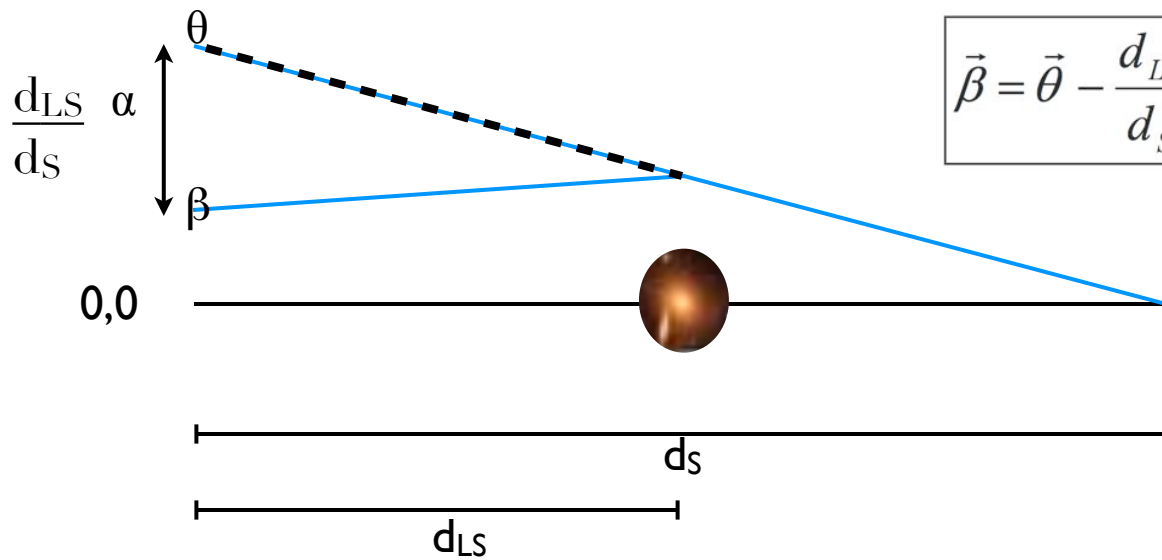
Figure 1. The use of a dynamic grid. The grid spacing is refined in those regions where individual grid cells contain a large fraction of the total mass of the lens or where the projected-density gradients are large.

# Lens modeling: figure out the “Optics” of a gravitational lens

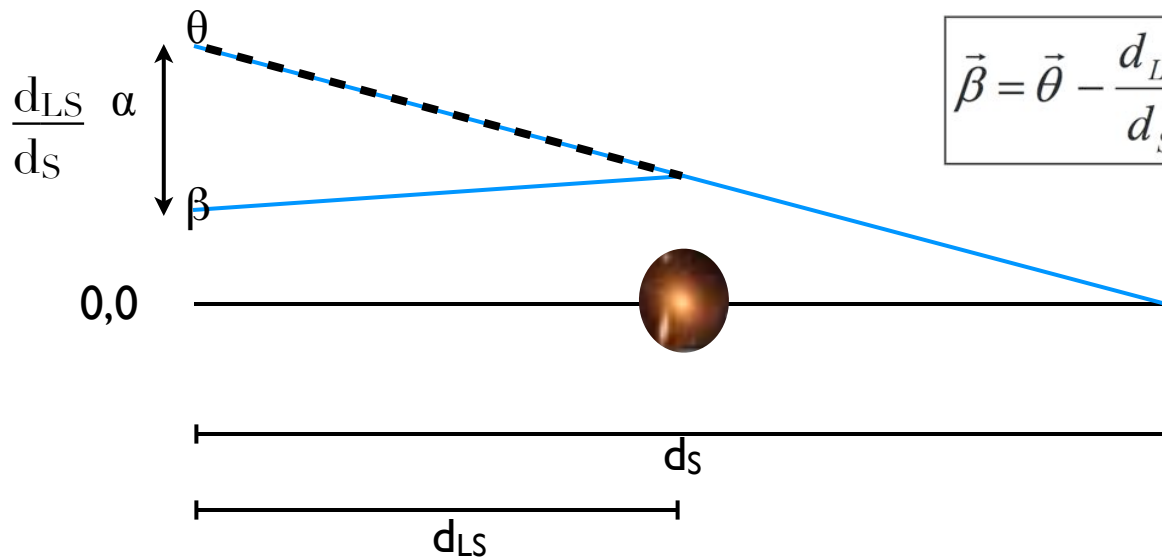
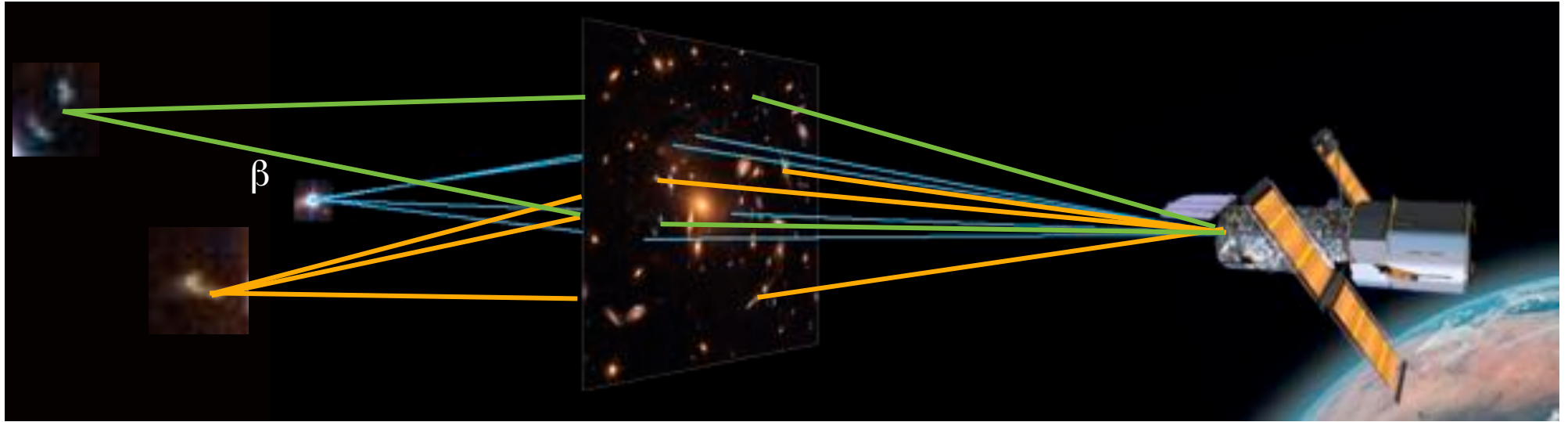


The lens equation

$$\vec{\beta} = \vec{\theta} - \frac{d_{LS}}{d_S} \vec{\alpha}(\vec{\theta})$$

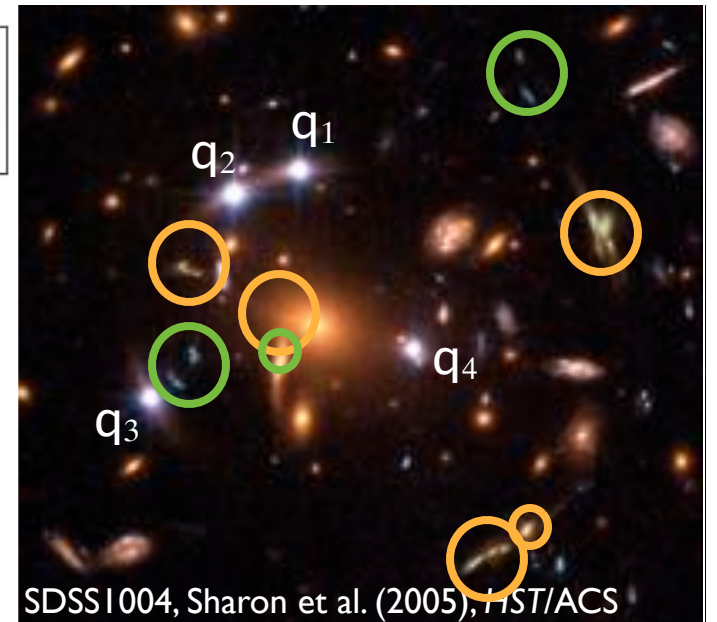


# Lens modeling: figure out the “Optics” of a gravitational lens



The lens equation

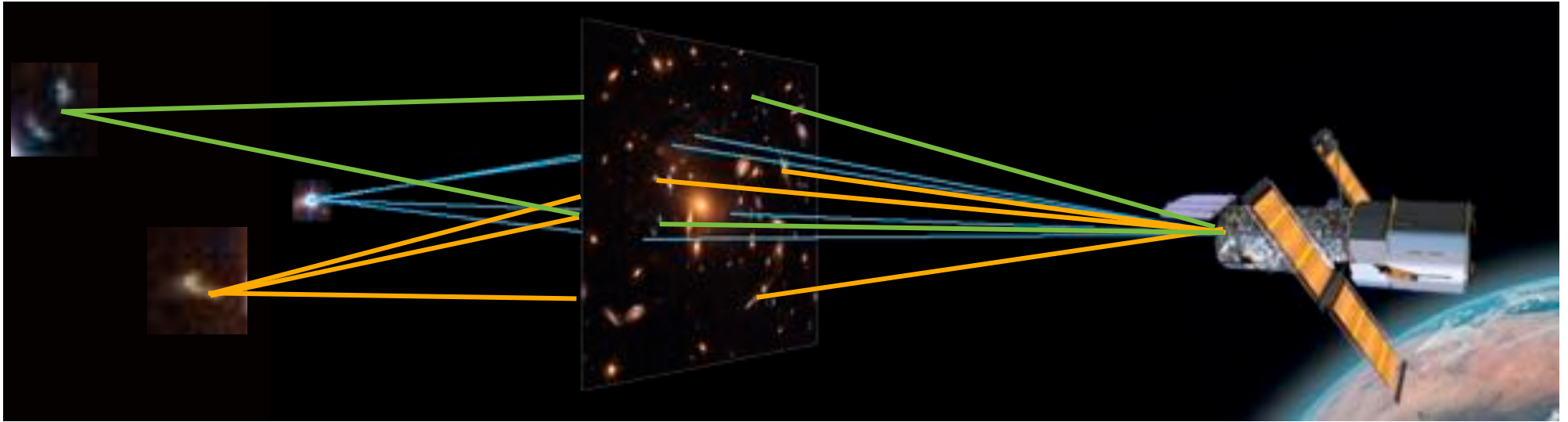
$$\vec{\beta} = \vec{\theta} - \frac{d_{LS}}{d_S} \vec{\alpha}(\vec{\theta})$$



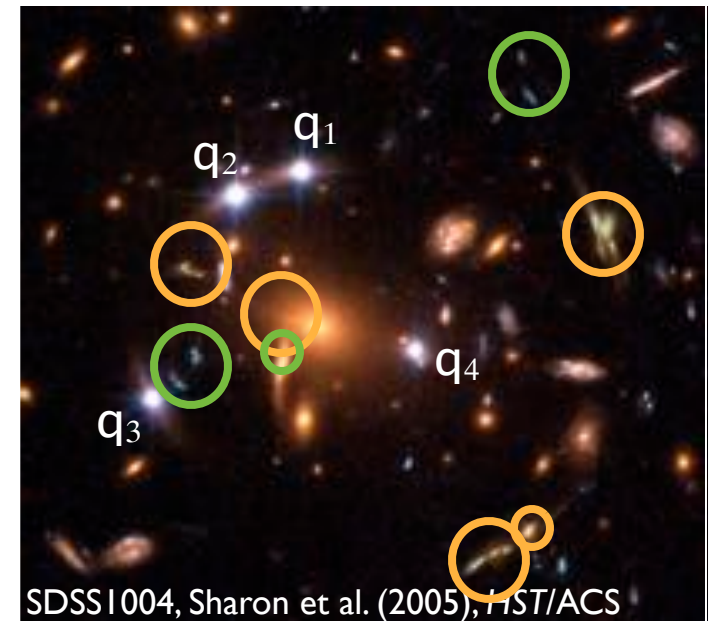
SDSS1004, Sharon et al. (2005), HST/ACS



# Lens modeling: figure out the “Optics” of a gravitational lens



- Detect multiple images of the same source
- Assume a mass distribution  $\rightarrow$  deflection
- Compute source/image locations
- Find the mass distribution that gives smallest scatter

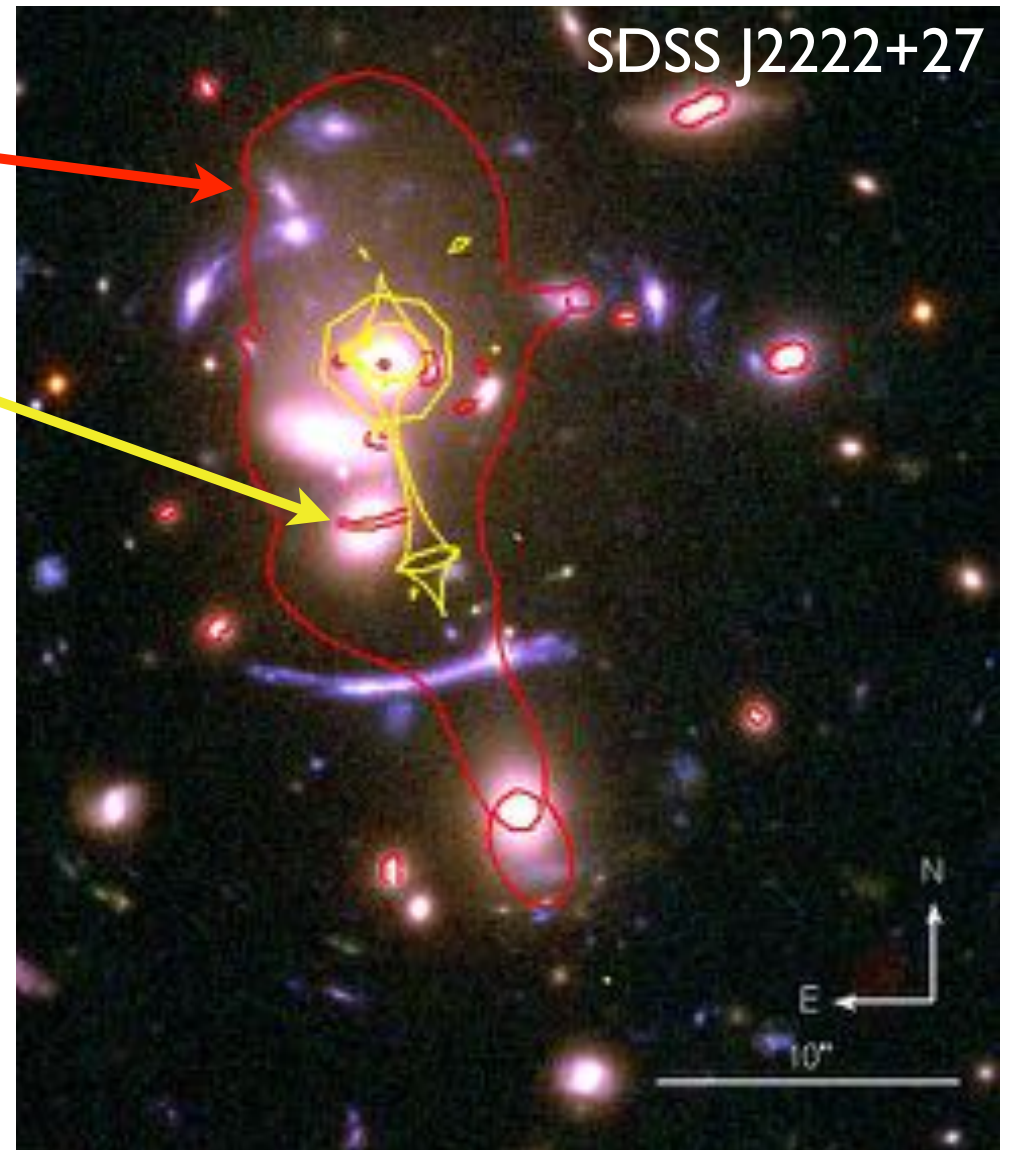


The “critical curve” represents points in the image plane with infinite\* magnification

critical curve

The “caustic” is the mapping of the critical curve into the source plane

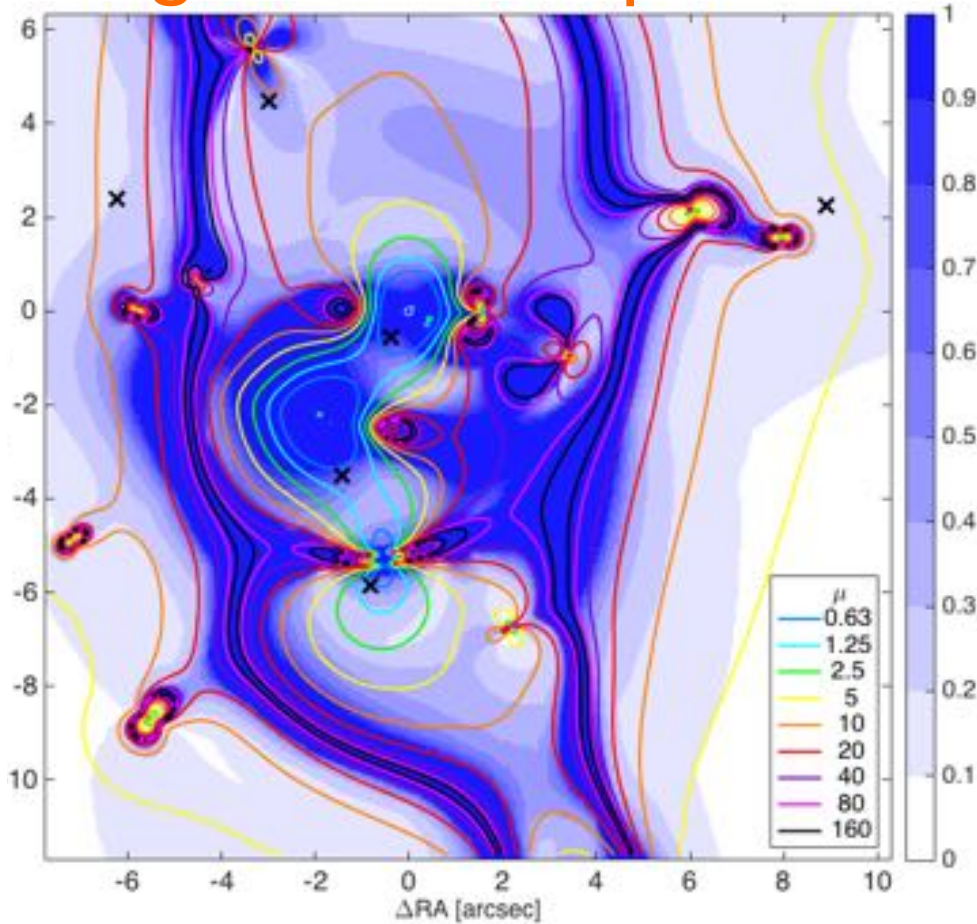
\*mathematically; in reality, sources are not infinitely small. so magnification is finite. nevertheless, close to the critical curves the magnification can reach hundreds.



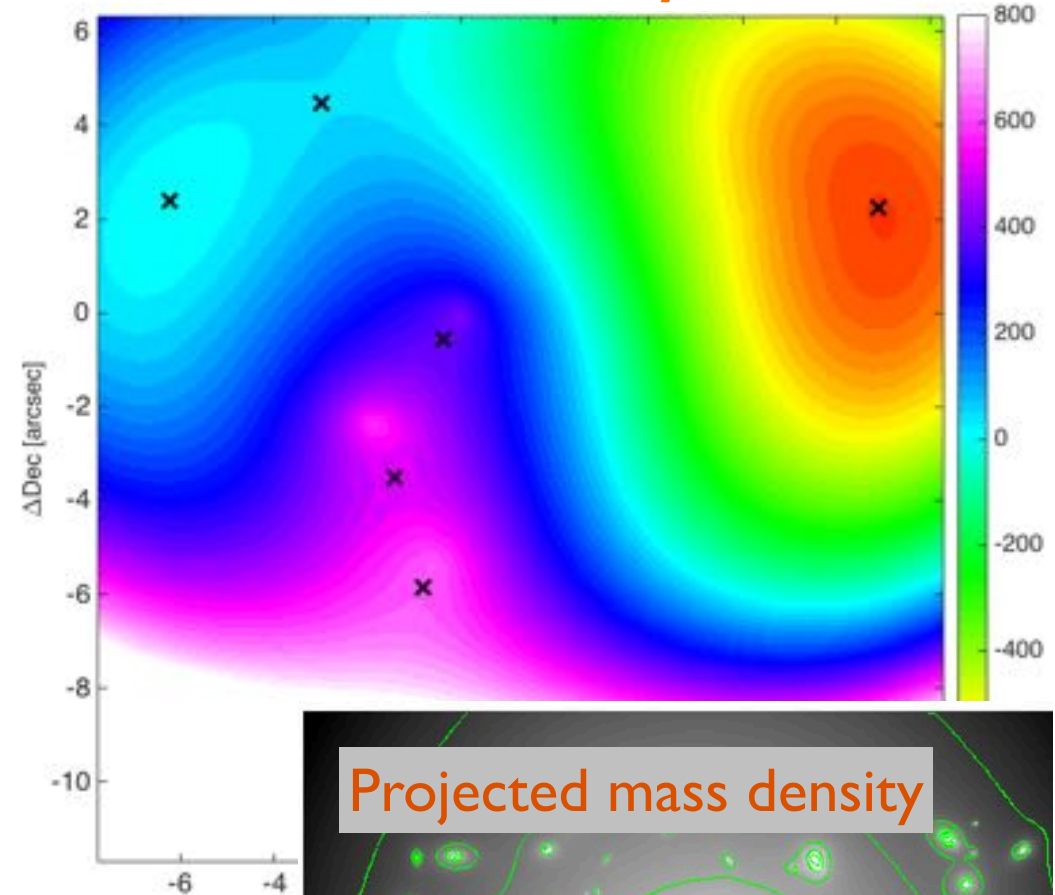
Sharon+2017 -SGAS-

# example lens model products

magnification map + unc

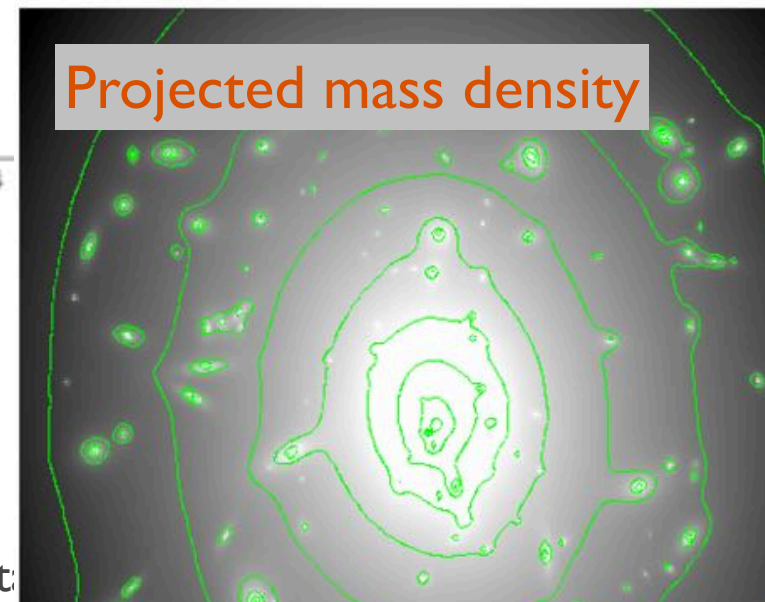


time delay

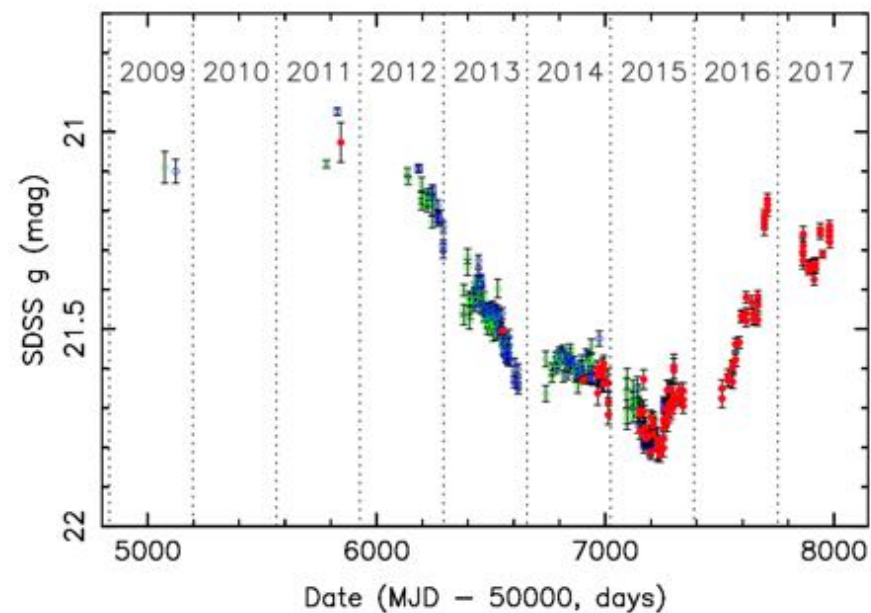
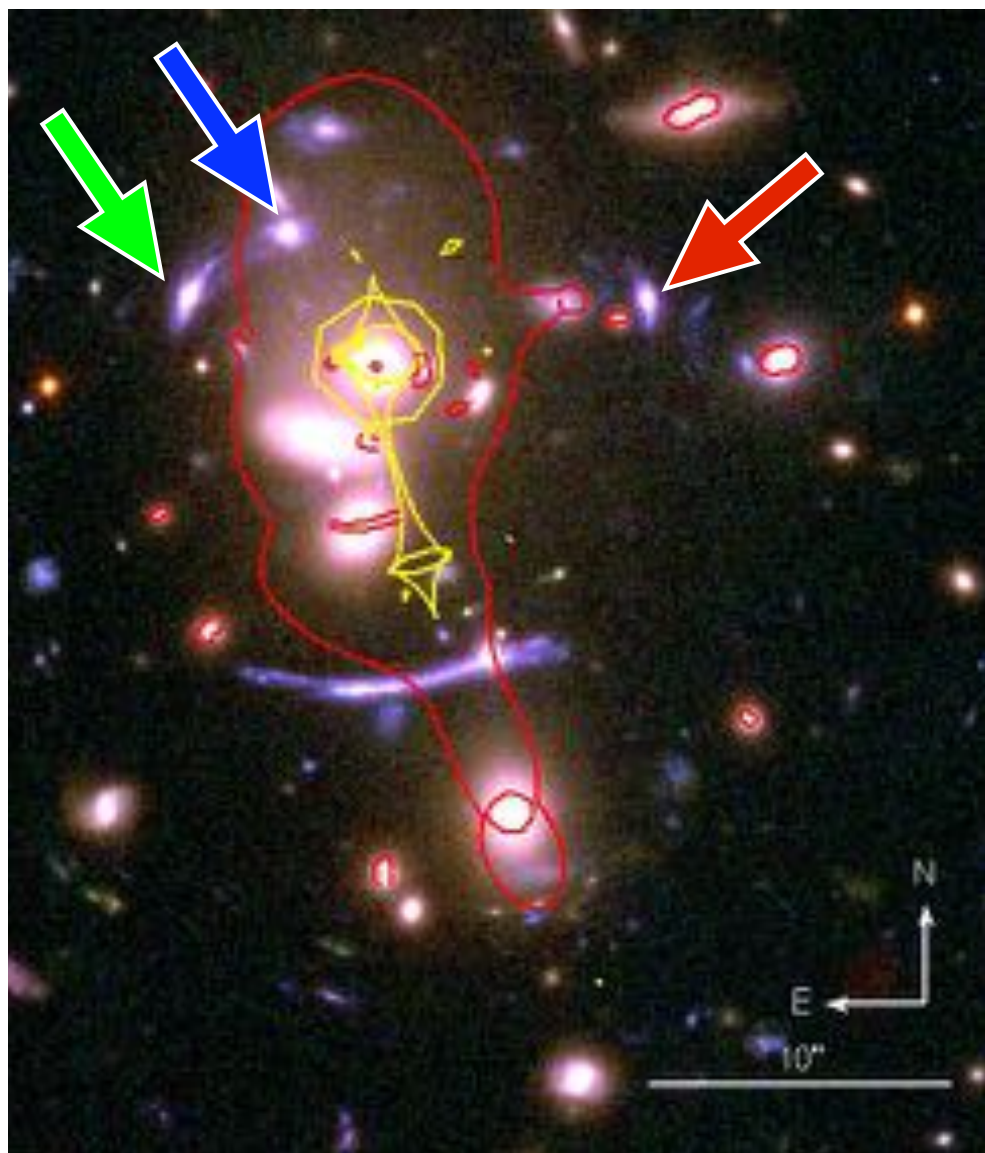


Sharon+2017 -SGAS-  
SDSS2222

Projected mass density



# ...We can tell the future!



## Dahle+2015

# strong lensing samples / surveys with HST:



107/37



840/6



524/25

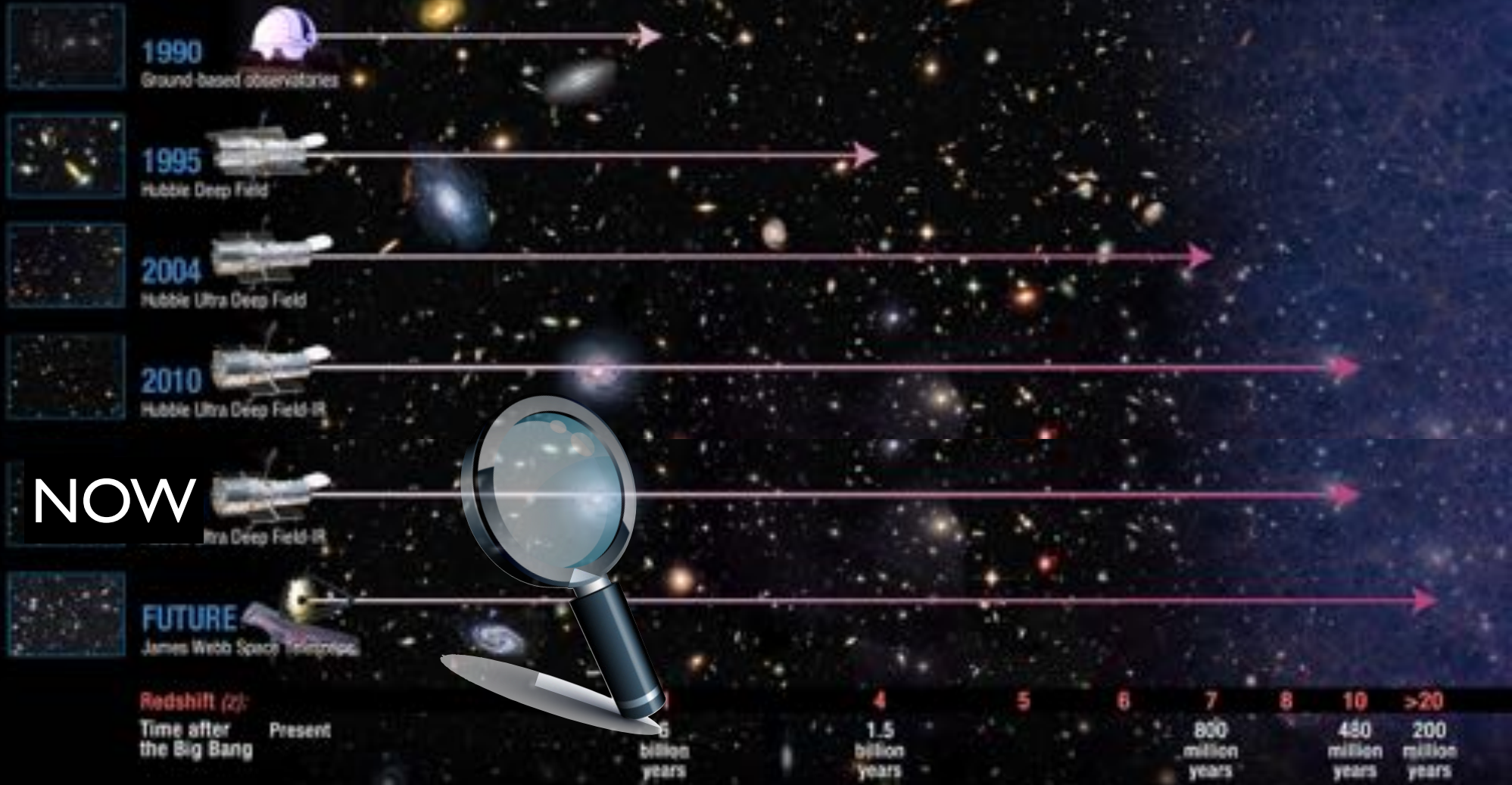


190/41

MACS, sMACS (snap)  
SPT (snap approved for C25)

public model products - most  
public data - all

# Hubble Probes the Early Universe



NOW

Redshift (z):  
Time after the Big Bang

6 billion years  
1.5 billion years  
800 million years  
480 million years  
>20 billion years

Keran Sharon

# Hubble Probes the Early Universe



**SGAS**  
Sloan Giant Arcs Survey



**RELICS**  
Reionization Lensing Cluster Survey

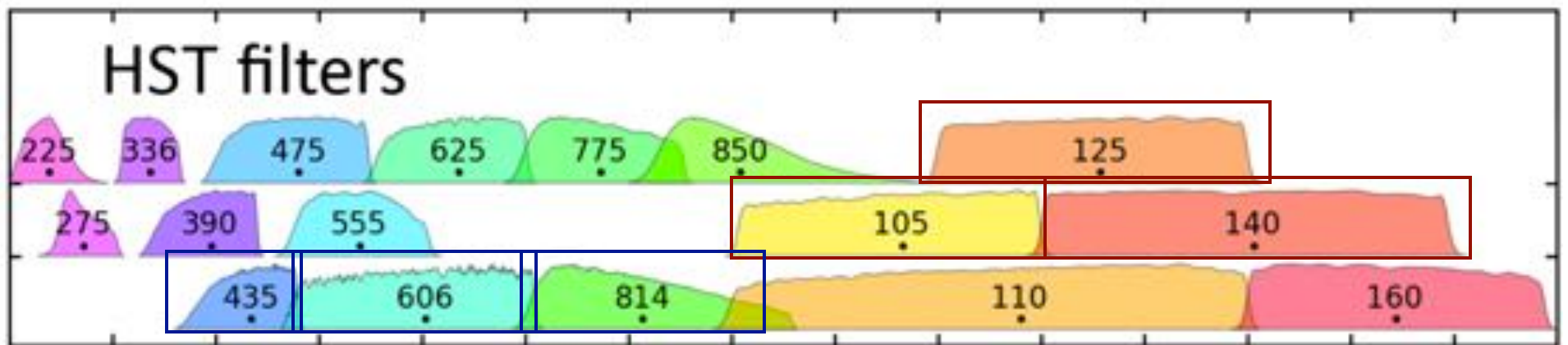
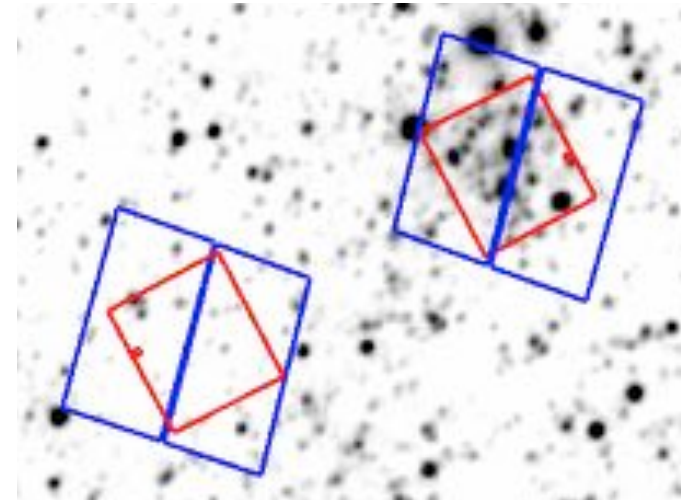


*Keran Sharon*

**RELICS**  
Reionization Lensing Cluster Survey



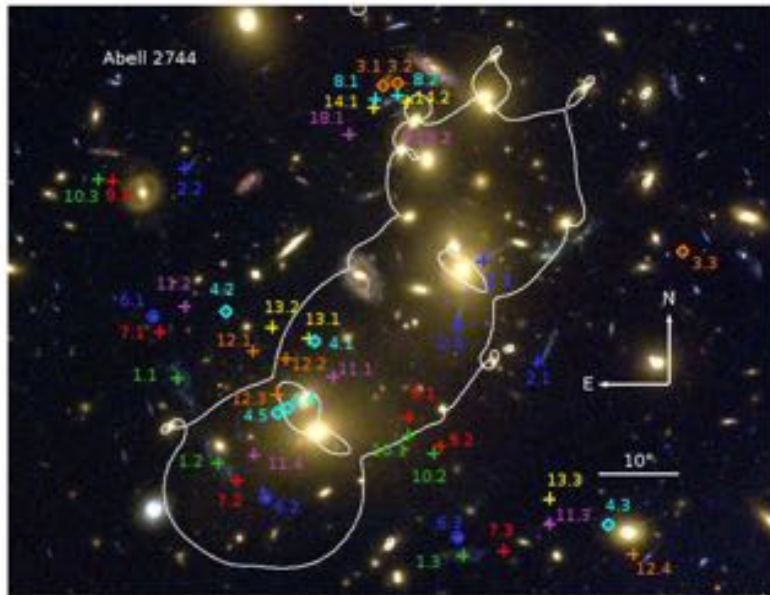
PI: Jennifer Lotz  
 6 massive lensing clusters  
 140 orbits (each)  
 public data, lens models





# LENS MODELS AND MAGNIFICATION MAPS OF THE SIX HUBBLE FRONTIER FIELDS CLUSTERS\*

TRACI L. JOHNSON<sup>1</sup>, KEREN SHARON<sup>1</sup>, MATTHEW B. BAYLISS<sup>2,3</sup>, MICHAEL D. GLADDERS<sup>4,5</sup>, DAN COE<sup>6</sup>, HARALD EBELING<sup>7</sup>  
 Submitted to ApJ: draft date September 11, 2014

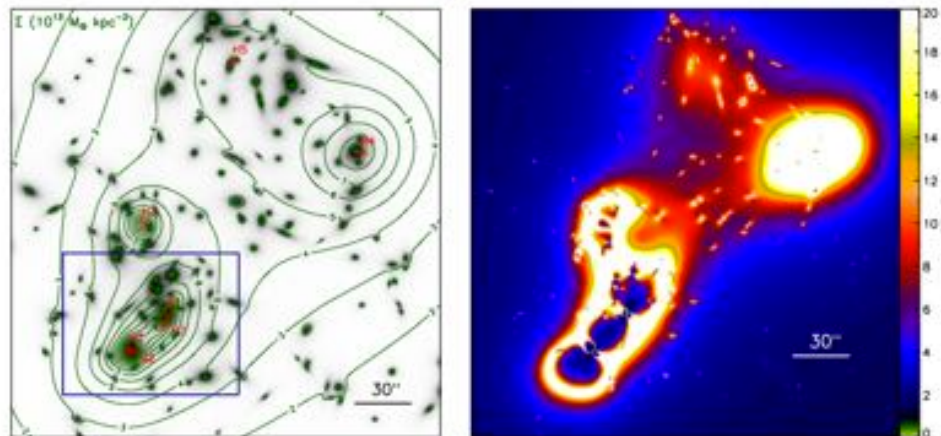


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## Hubble Space Telescope Frontier Fields

HST Overview  
 Phase I Proposing  
 Phase II Proposing  
 Scheduling  
 Post-Observation  
 Instruments  
 Documents



### Hubble Frontier Fields lens model magnification estimates

Click to close

Calculated at your input redshift(s) based on the mass and shear maps submitted by each team (see [lensing primer](#)).  
 (Not interpolated / extrapolated from the magnification maps pre-calculated at  $z = 1, 2, 4, 9$  available for download.)  
[Lens model main page](#)

\* Single lensed galaxy:  
 RA: 4 16 05.555  
 Dec: -24 03 53.0  
 $z = 0$   
 observed radius (arcseconds): 0

List of lensed galaxies: RA, Dec,  $z$ , (optional) radius

4956+12.356 -24*04*35.01s	7.8
1509.8691s, 37.77287s)	5.3
11 49 36.888 22 24 18.93	3.2
342.2026 -44.536809	2.1
2:39:51 -1:34:09	0.9
1:47:048, -30.37196	9.6

Save results with run number and optional passcode:

(All models are based on data obtained prior to the Frontier Fields. All are "version 1" unless otherwise noted.)

Models:  68.1% confidence, calculated from a range of models provided by each group

(README)  show all results from each range of models, yielding likelihood distributions

- CATS with uncertainties
- Sharon (version 1) with uncertainties
- Sharon (version 2) with uncertainties
- Zitrin-NFW with uncertainties
- Zitrin-ETM with uncertainties
- Zitrin-ETM-Gauss with uncertainties
- Williams with uncertainties
- Bradac with uncertainties
- Merhan with uncertainties

All None  All None

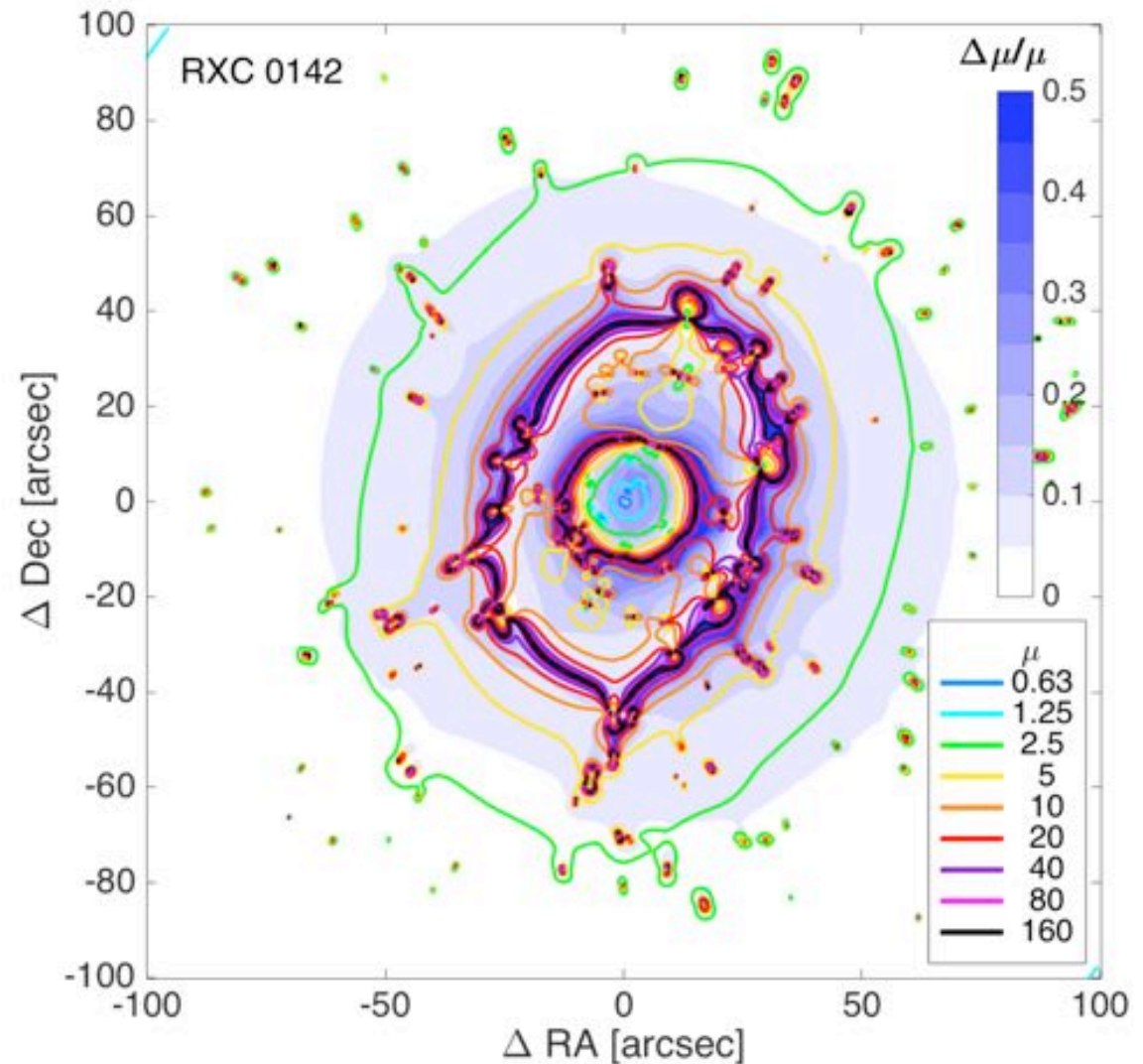
Uncertainty calculations add a few seconds response time per lensed galaxy per group.

Generate magnification plot

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](mailto:DCoe@STScI.edu).

# What do we need to worry about?

- Statistical error: higher in areas of high magnification
- Mass sheet degeneracy
- Structure along the line of sight
- Correlated substructure / subhalos / complexity
- Model assumptions
- # of constraints, spectroscopic redshifts

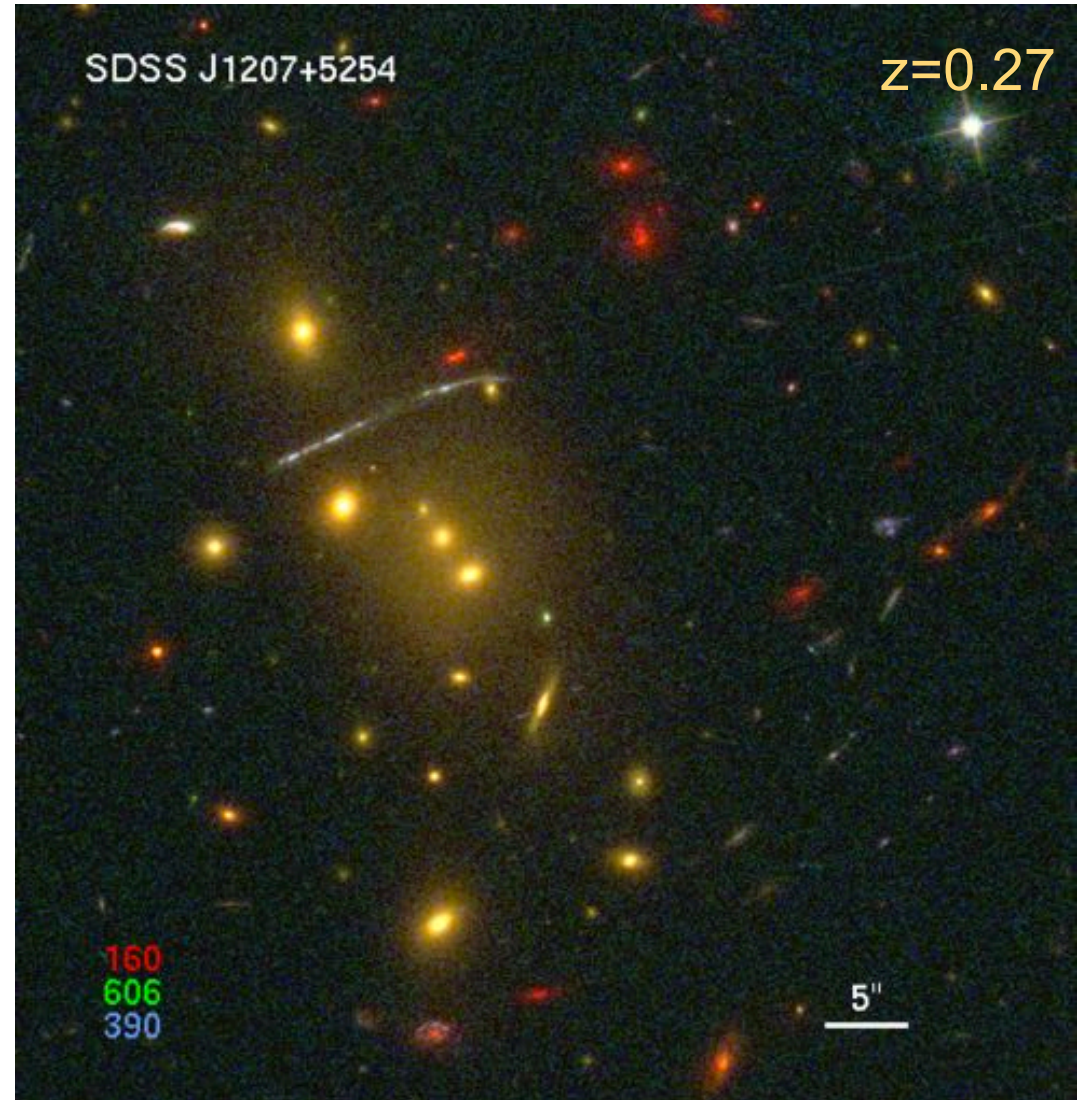


Cerny+2017 (in prep) - Relics

# What do we need to worry about?

Statistical error: higher in areas of high magnification

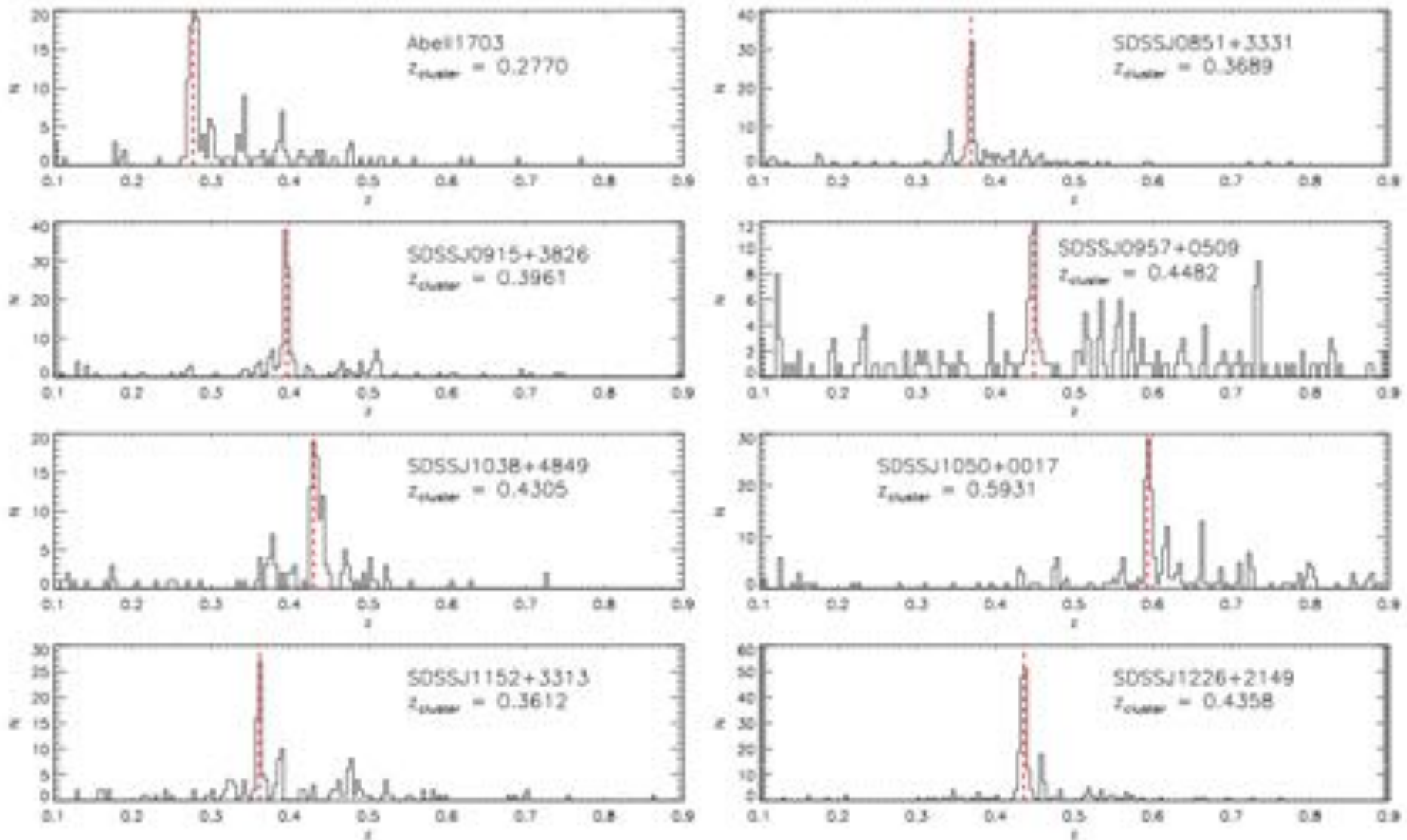
- Mass sheet degeneracy
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Sharon+2017 ; SGAS



# Mass on the Line of Sight



Bayliss et al. 2013

# What do we need to worry about?

Statistical error: higher in areas of high magnification

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## **NEW!!**

SL algorithms treat multi-plane lenses:

- Gravlens (C. Keeton+)
- GLEE (S. Suyu+)  
Chirivi, Suyu+ 2017 arXiv:1706.07815
- Lenstool\* (CATS, Jullo+)

# What do we need to worry about?

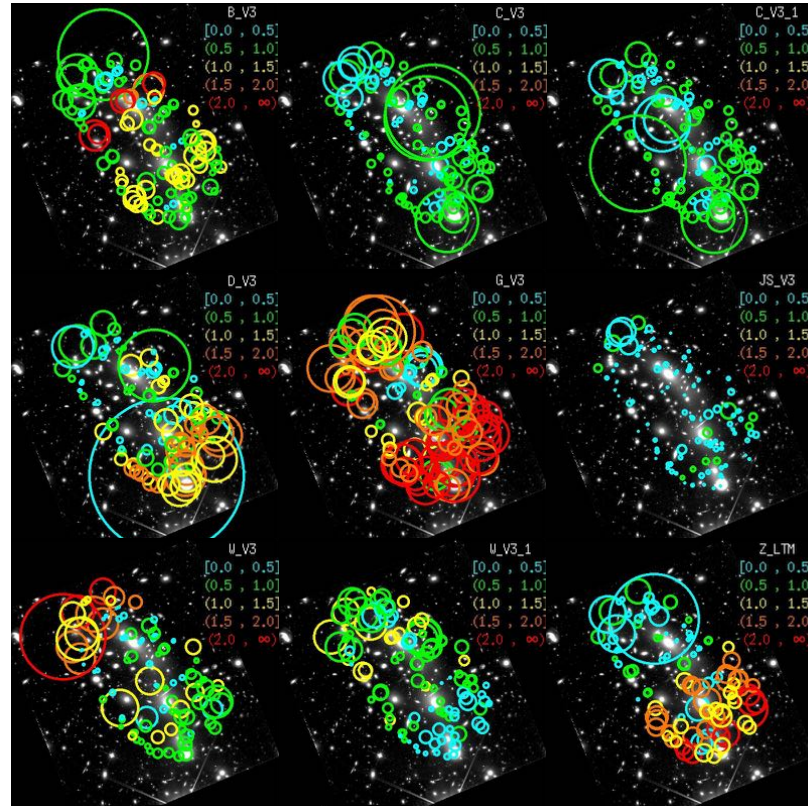
- Statistical error: higher in areas of high magnification
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- Structure along the line of sight
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10:15 -- 10:40		
10:40 -- 11:30	<b>Keren SHARON</b> Lensing II	
11:30 -- 11:55	<b>Jesús VEGA-FERRERO</b> Free-Form Lens Models of four Hubble Frontier Fields Clusters	Te
11:55 -- 12:20	<b>Rachel PATERNO-MAHLER</b> The Reionization Lensing Clusters Survey: Strong Lensing Analysis	En Qt
12:20 -- 12:45	<b>Jenny WAGNER</b> Model-independent characterisation of strong gravitational lenses	H
1:00 -- 3:00		

A problem for BG studies, an excitement for cluster physics and structure assembly!

# What do we need to worry about?

- Statistical error: higher in areas of high magnification
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Remolina+ in prep -- see poster!

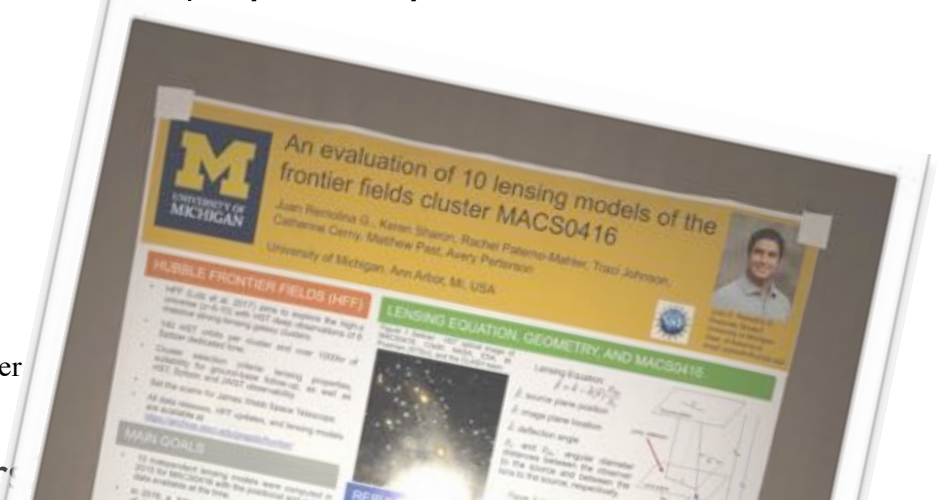
see also:

**Meneghetti+16** arXiv:1606.04548

The Frontier Fields Lens Modeling Comparison Project

**Priewe+16** arXiv:1605.07621

Lens Models Under the Microscope: Comparison of Hubble Frontier Field Cluster Magnification Maps





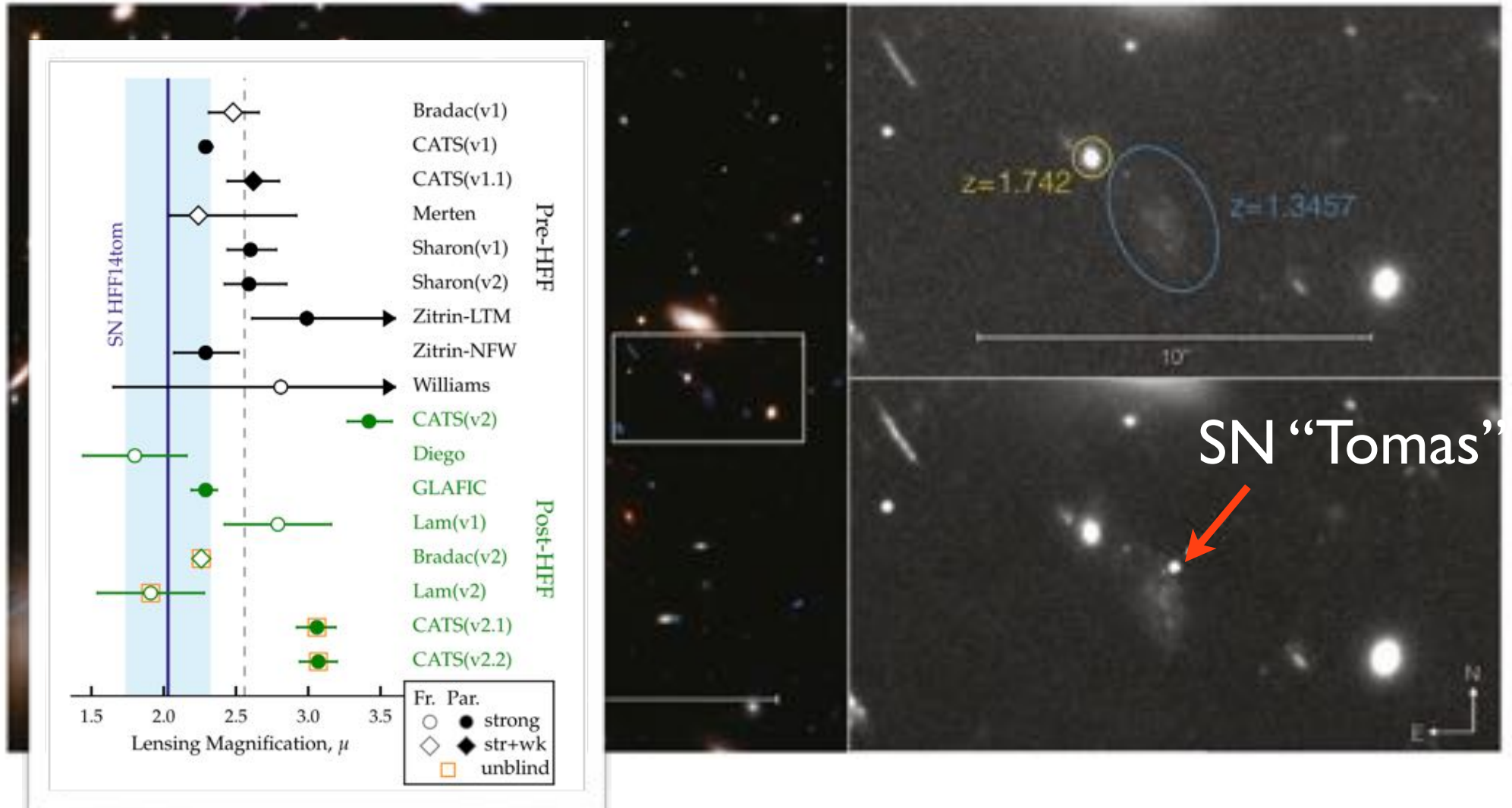
# What do we need to worry about?

- Model assumptions

Rodney+15 ApJ

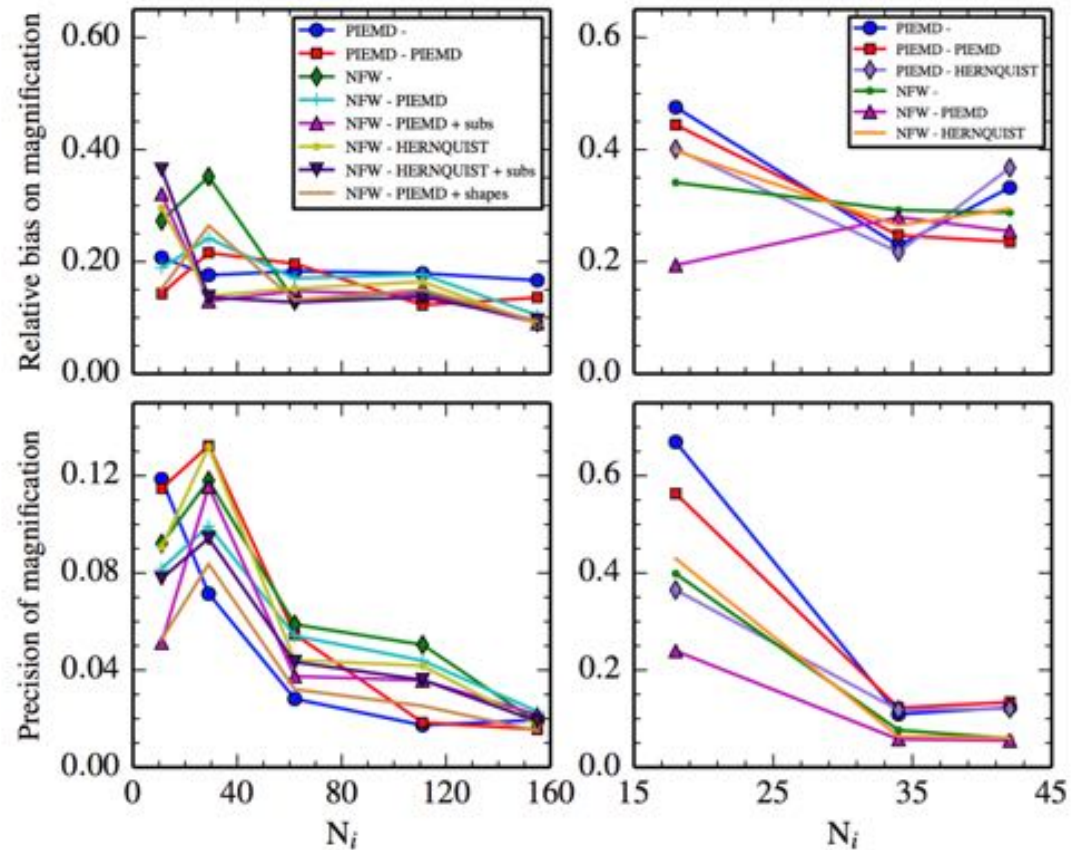
Illuminating a Dark Lens : A Type Ia Supernova Magnified by the Frontier Fields Galaxy Cluster Abell 2744

SN “Tomas”



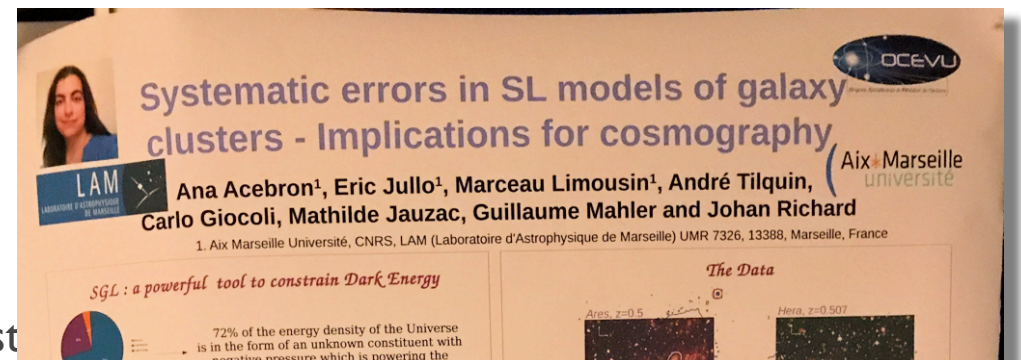
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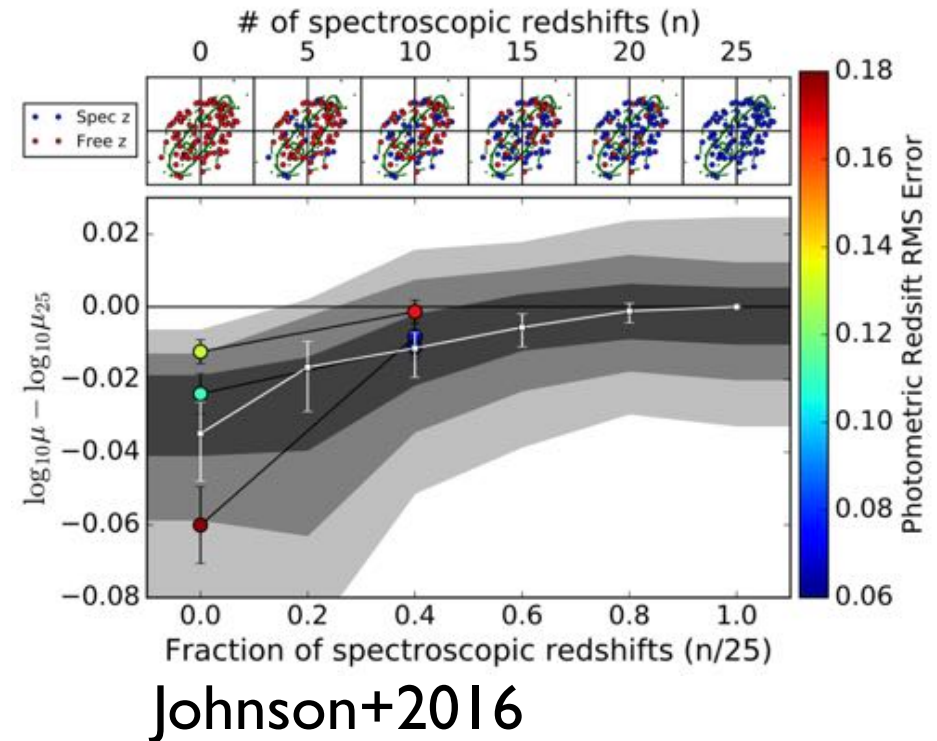
Acebron+2017

see poster behind you!

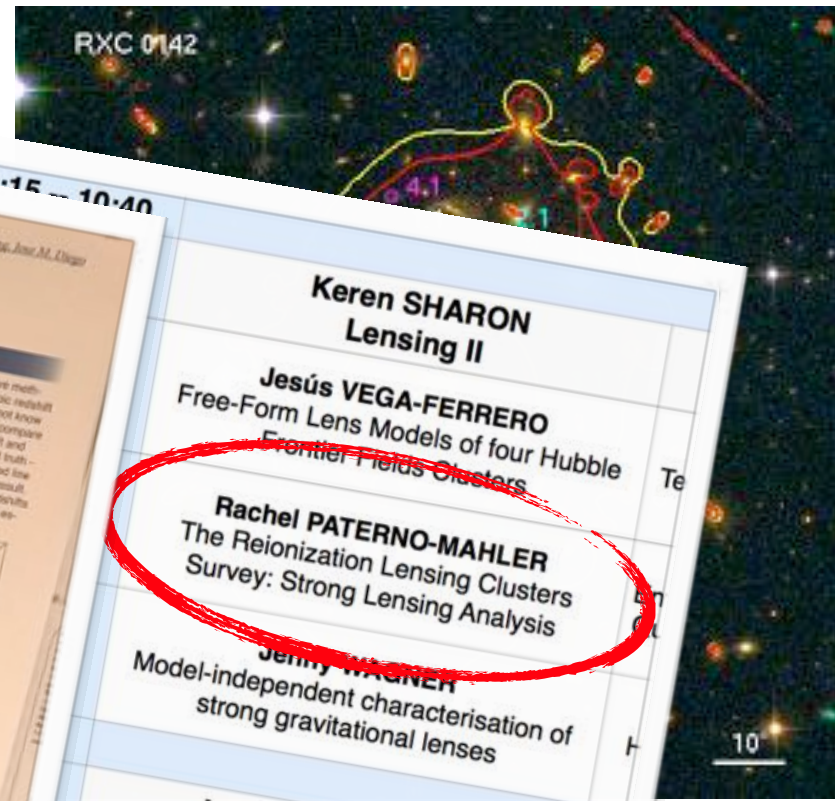
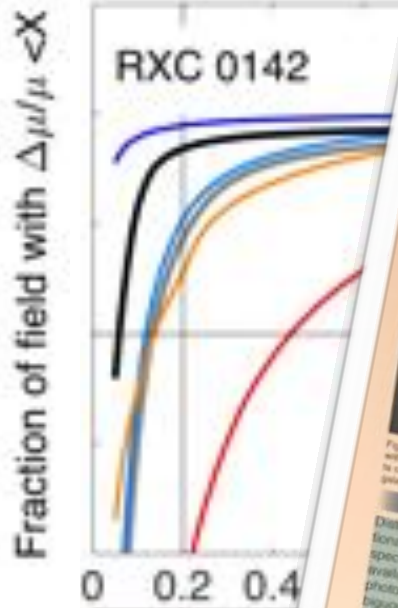
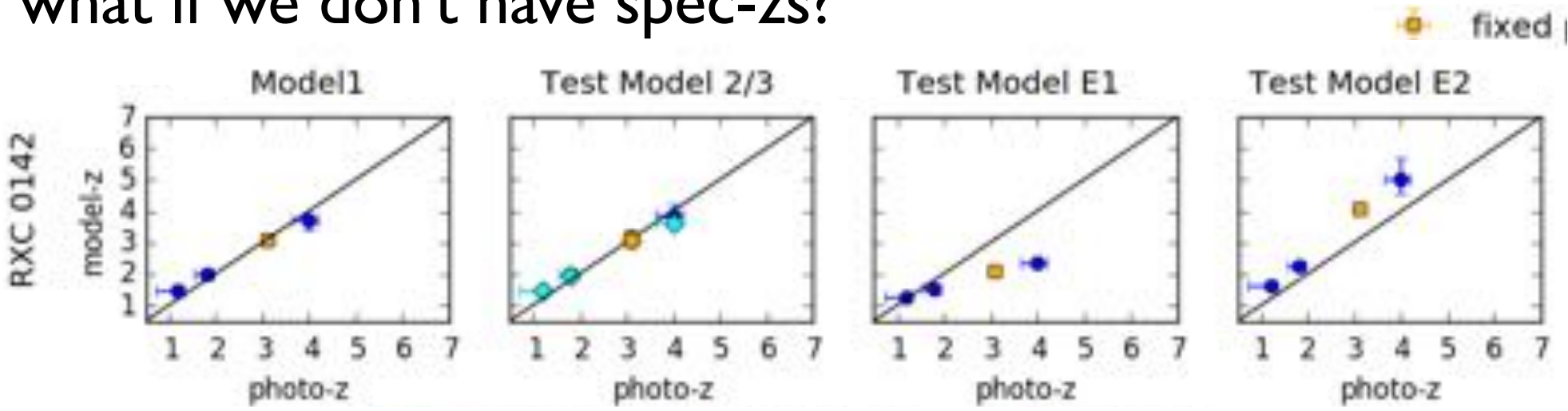


# What do we need to worry about?

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- Model assumptions
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# what if we don't have spec-zs?



Department of Physics  
 The University of Hong Kong  
 Author: Brian Chan, Tim Broadhurst, Jeremy Lim, Ann Wing, Joe M. Diego  
**DERIVING GEOMETRIC REDSHIFTS FOR LENSED GALAXIES IN AS1063 (RXC J2248)**  
**RESULTS**  
 We test the accuracy of the iterative method by applying it to the spectroscopic redshifts of lensed galaxies, pretending we do not know their actual redshifts. In Figure 3 we compare the performance of geometric redshift and photometric redshift versus the ground truth - show the best fit of the corresponding result. The graph shows that our geometric redshifts are superior to the photometric redshifts especially for high redshift systems.

**SUMMARY**  
 Distant galaxies, even those gravitationally lensed, are faint. Therefore, spectroscopic redshift is usually not available at their first discovery and photometric redshift often yields ambiguous solutions.

**GEOMETRIC REDSHIFT**  
 Provided with an accurate lens model, it is possible to infer the redshift of a lensed galaxy from the relative angle between multiple images. As a property of lensed higher redshift galaxies produce more separation between images. The redshift of a galaxy can be inferred by finding the value that best reproduces the observed separation. The redshift inferred by the method is called the 'geometric redshift'.

The iterative method is subsequently applied to all confirmed lensed galaxies. We derived the corresponding geometric redshifts of all confirmed lensed galaxies. We observe that geometric redshifts derived are very consistent with their input redshifts (Figure 4), except for the z=4 system where only two lensed images are available.

**ITERATIVE METHOD**  
 Investigating the galaxy cluster AS1063 (RXC J2248) in the CANDELS field, we find that the most reliably determined redshifts are those derived by the iterative method.

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<b>Keren SHARON</b> Lensing II	
<b>Jesús VEGA-FERRERO</b> Free-Form Lens Models of four Hubble Frontier Fields Clusters	
<b>Rachel PATERNO-MAHLER</b> The Reionization Lensing Clusters Survey: Strong Lensing Analysis	
<b>Jenny WAGNER</b> Model-independent characterisation of strong gravitational lenses	
<b>Louise EDWARDS</b> Observations I	

Cerny+20



Euclid



DARK ENERGY  
SURVEY



## Euclid: a satellite designed to do weak lensing

Euclid will survey 15000 deg<sup>2</sup>

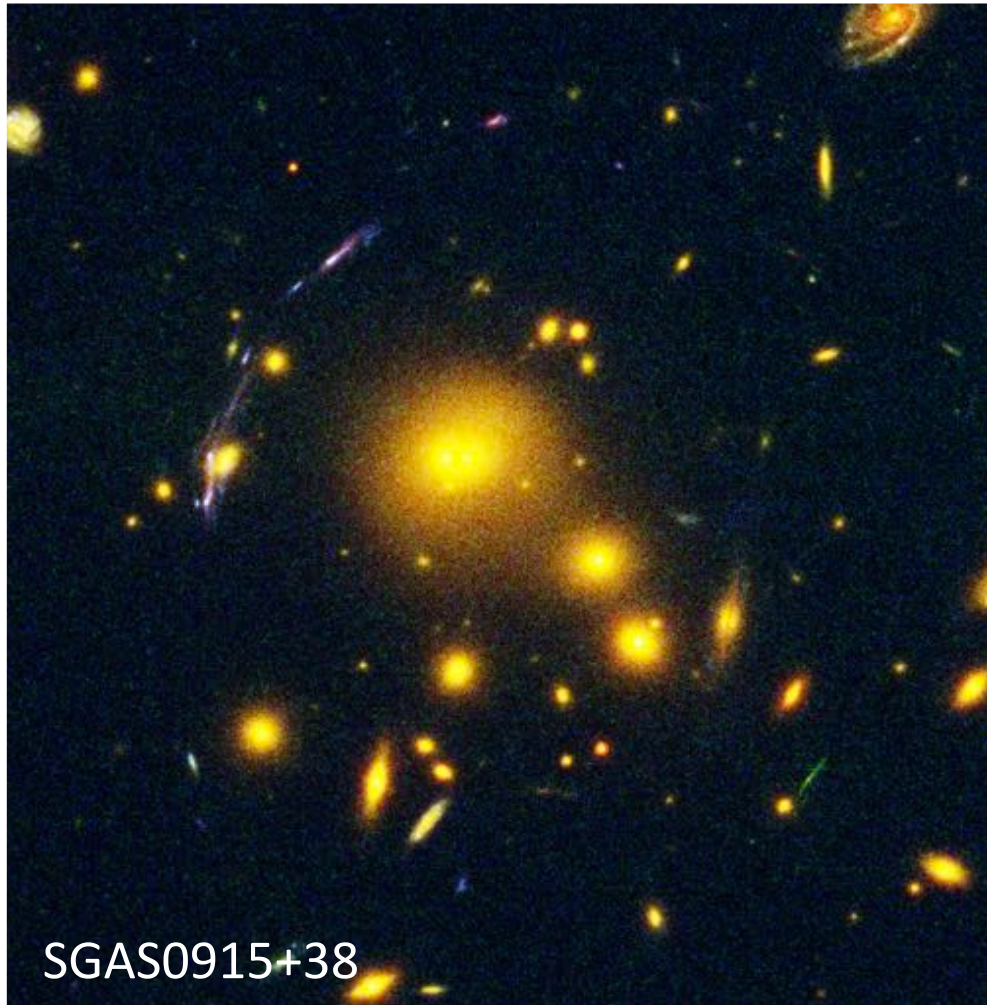
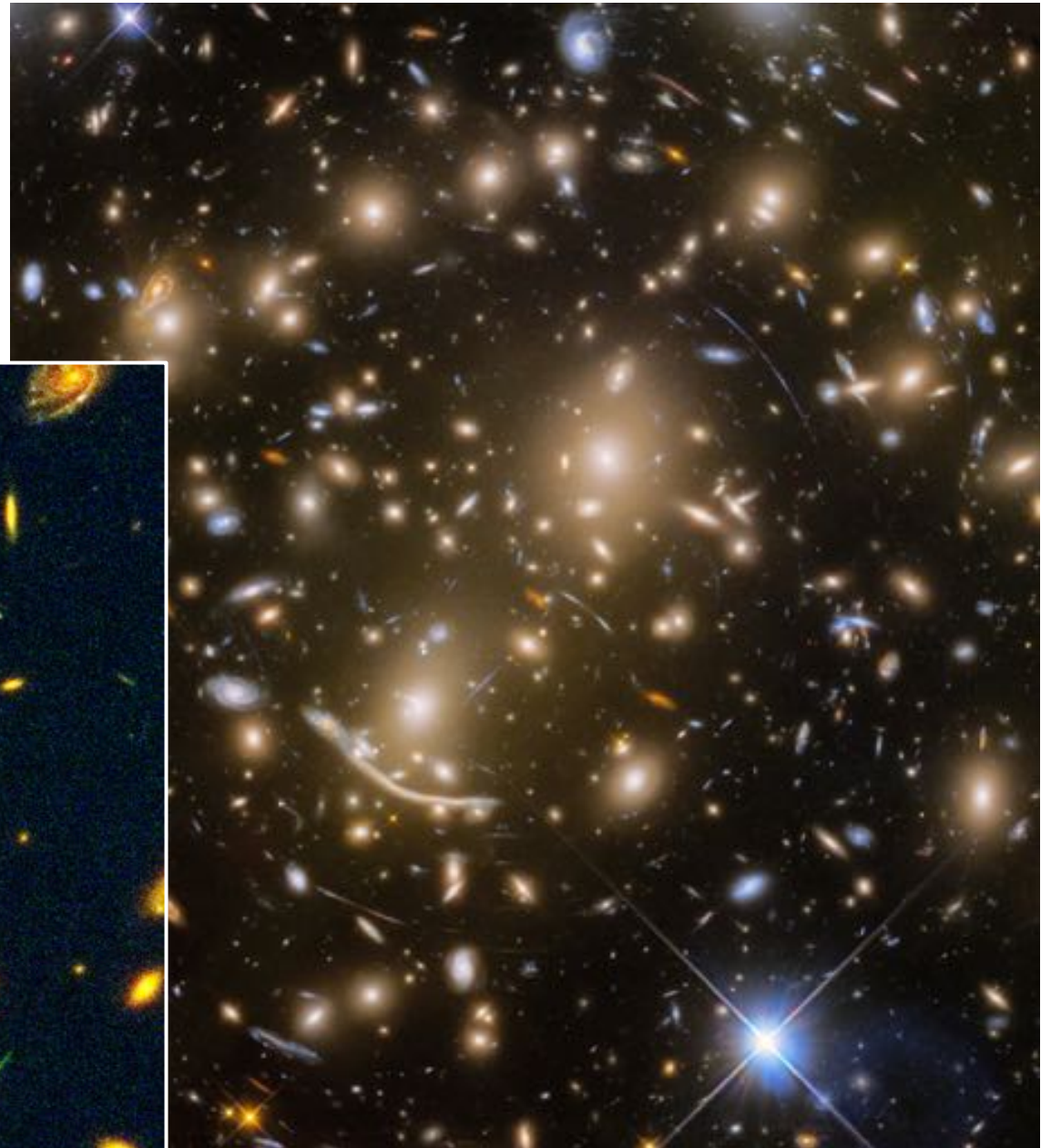
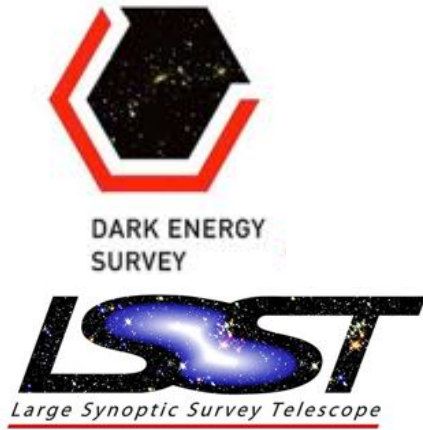
Optical (VIS) data: excellent for WL shape measurements.

NIR (YJH) imaging down to  $m_{AB} \sim 24$  will be great to find high-z clusters.

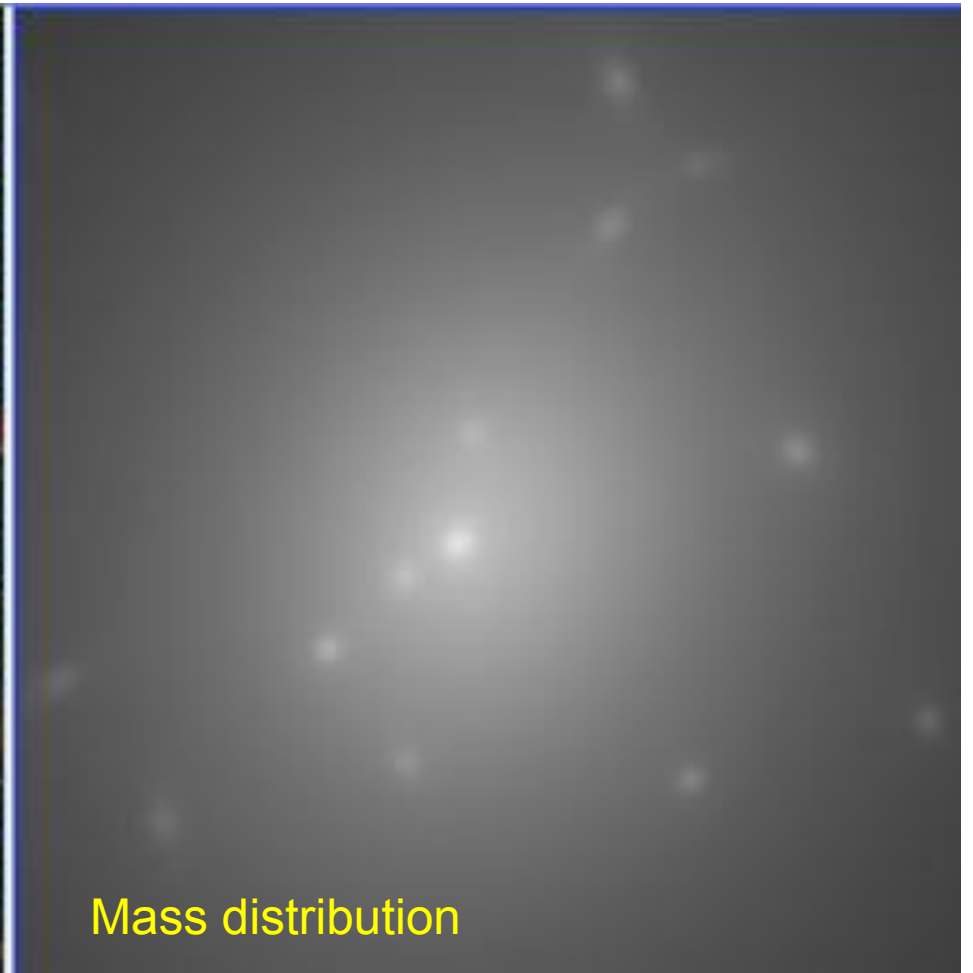
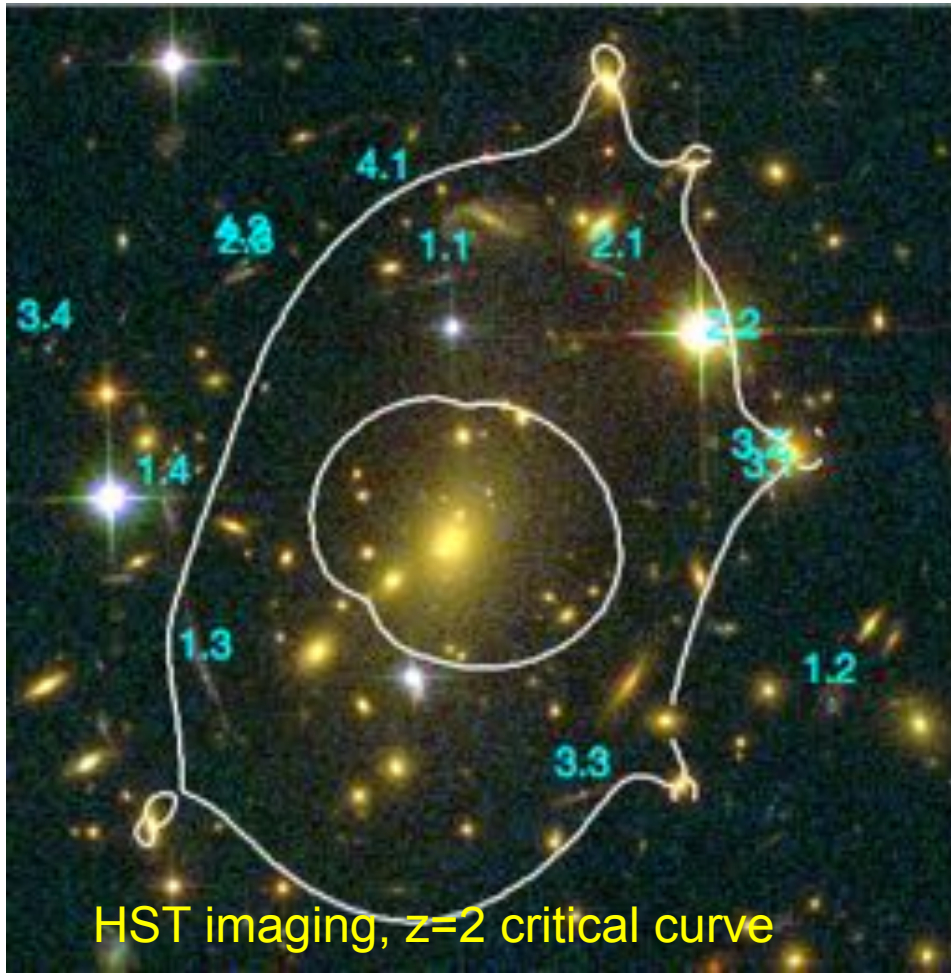
Euclid is expected to find 5000 cluster strong lenses.

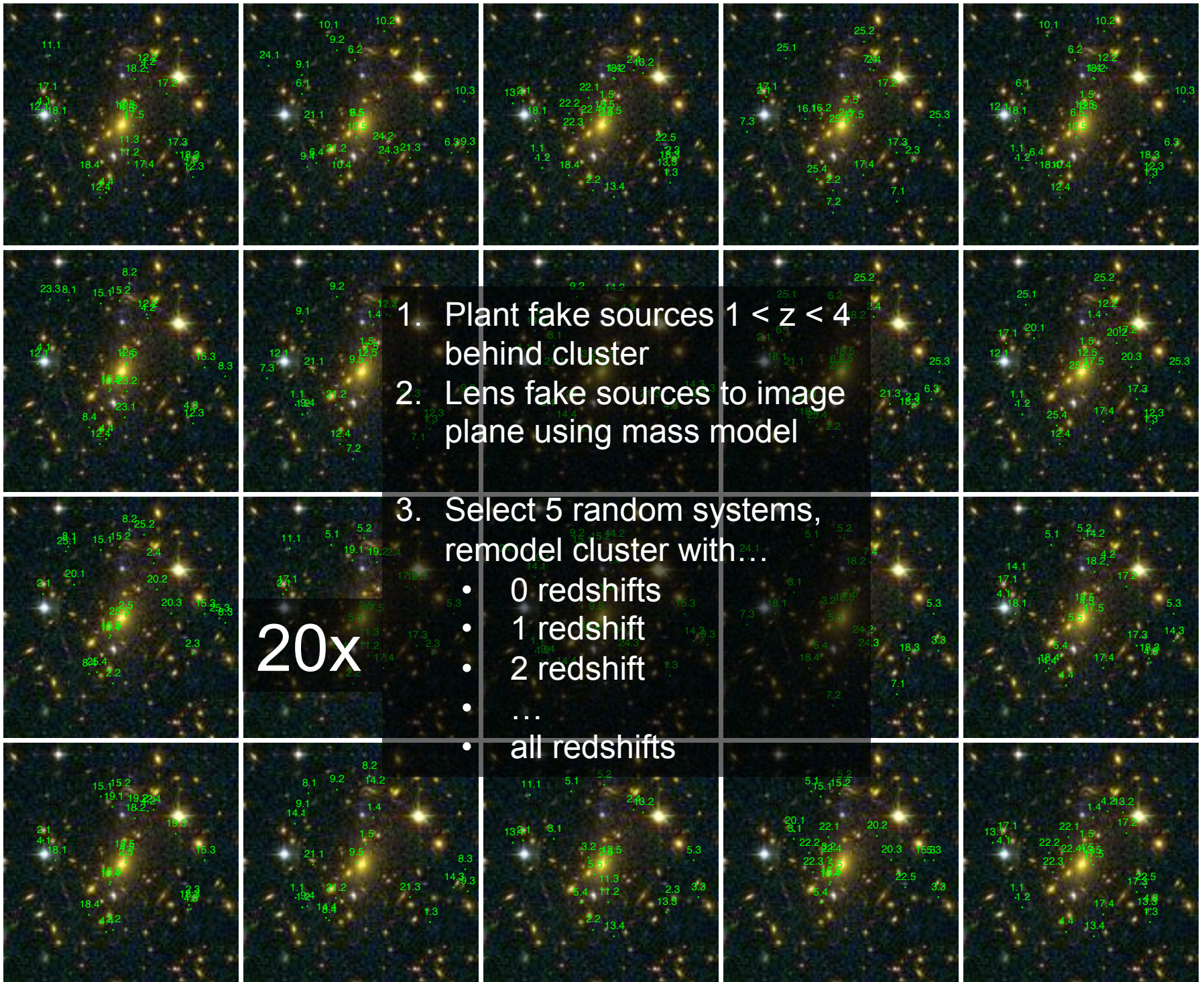


Cosmic shear studies drive the requirements for the weak lensing measurements: are these sufficient for cluster studies?



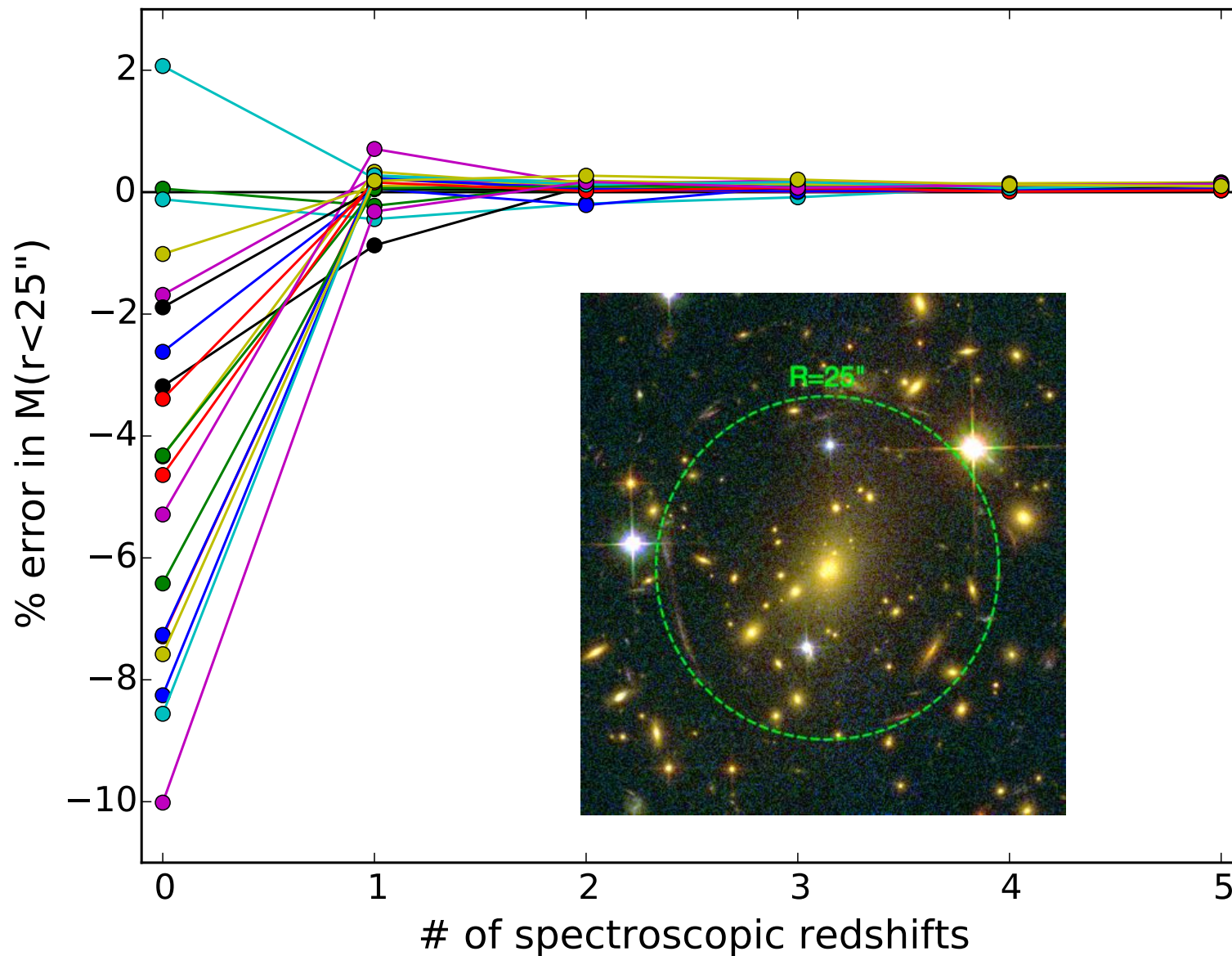
SGAS0915+38



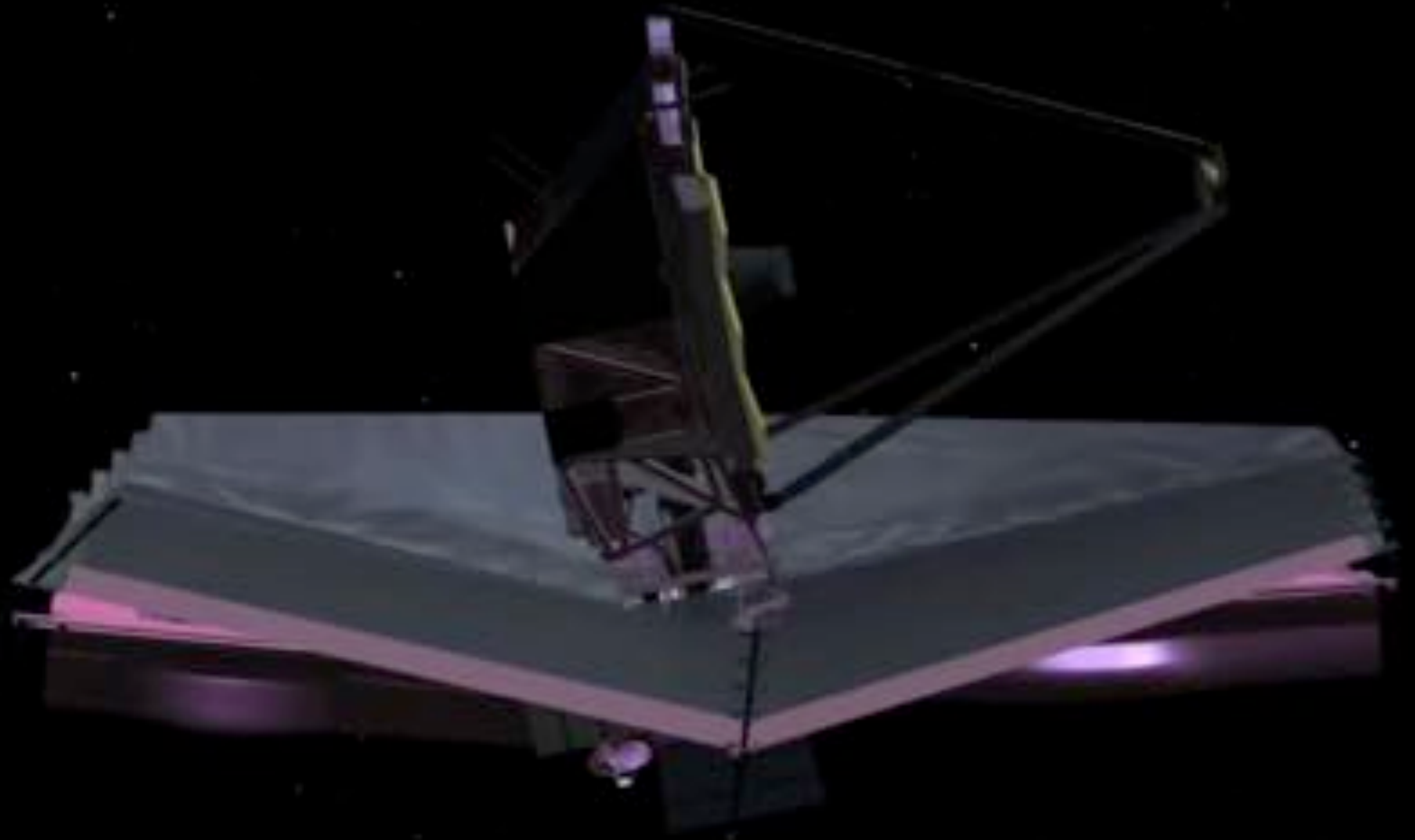




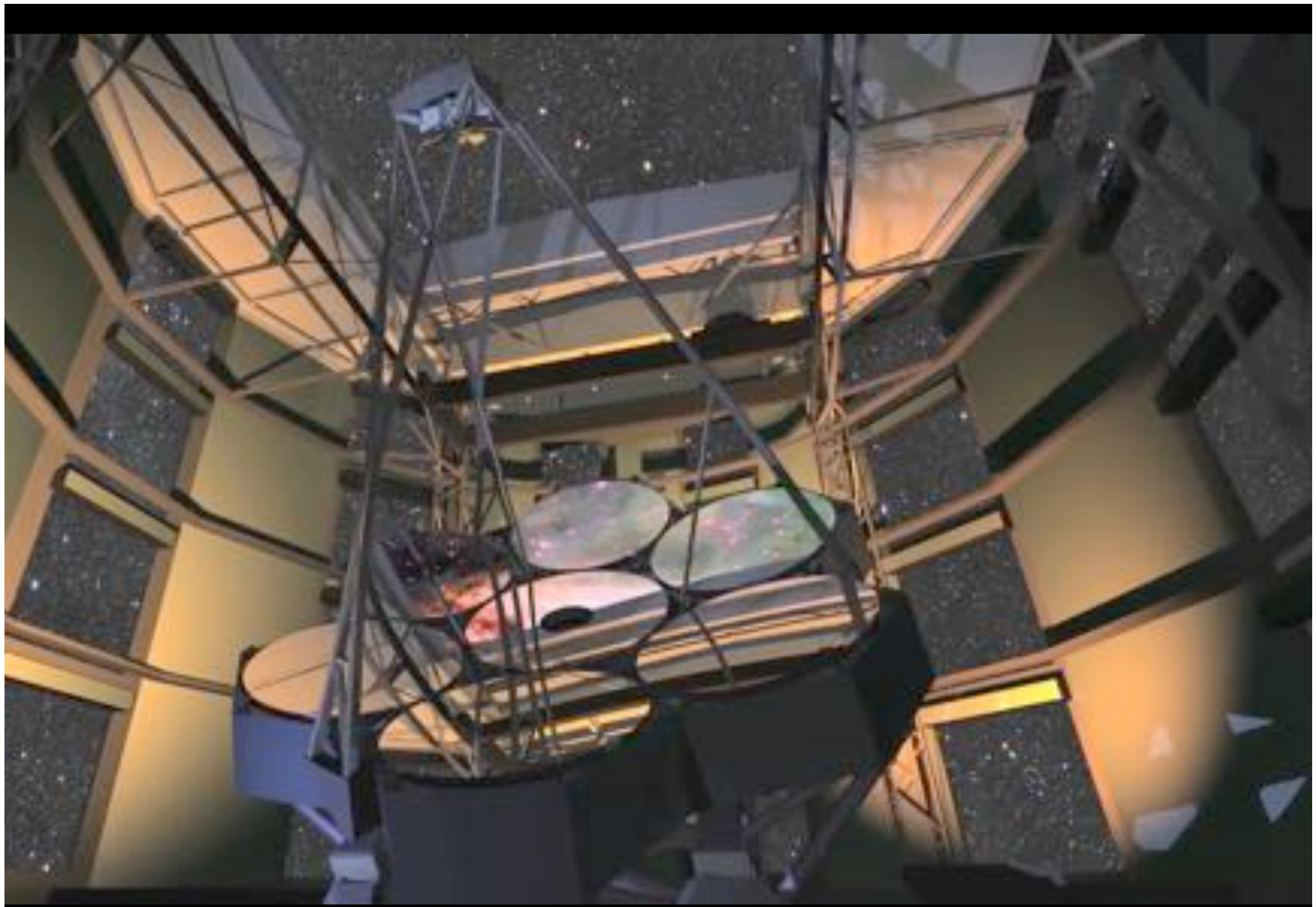
**Total mass inside the multiple image locations is well constrained if there are ~2 spectroscopic systems**



# THE FUTURE...

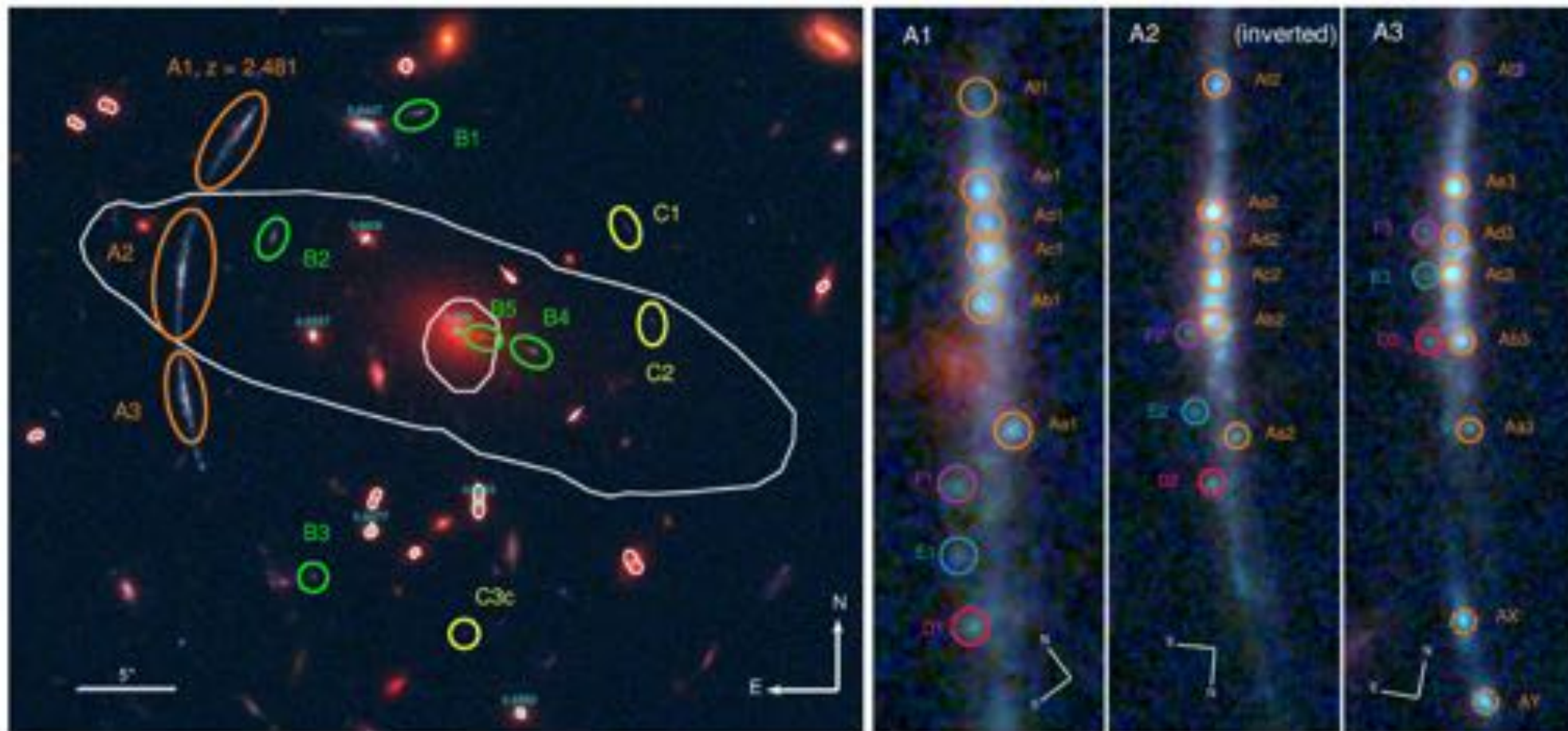


James Webb Space Telescope (2018)



**Giant Magellan Telescope (2021)**

# Star formation under the microscope: $z \sim 2$



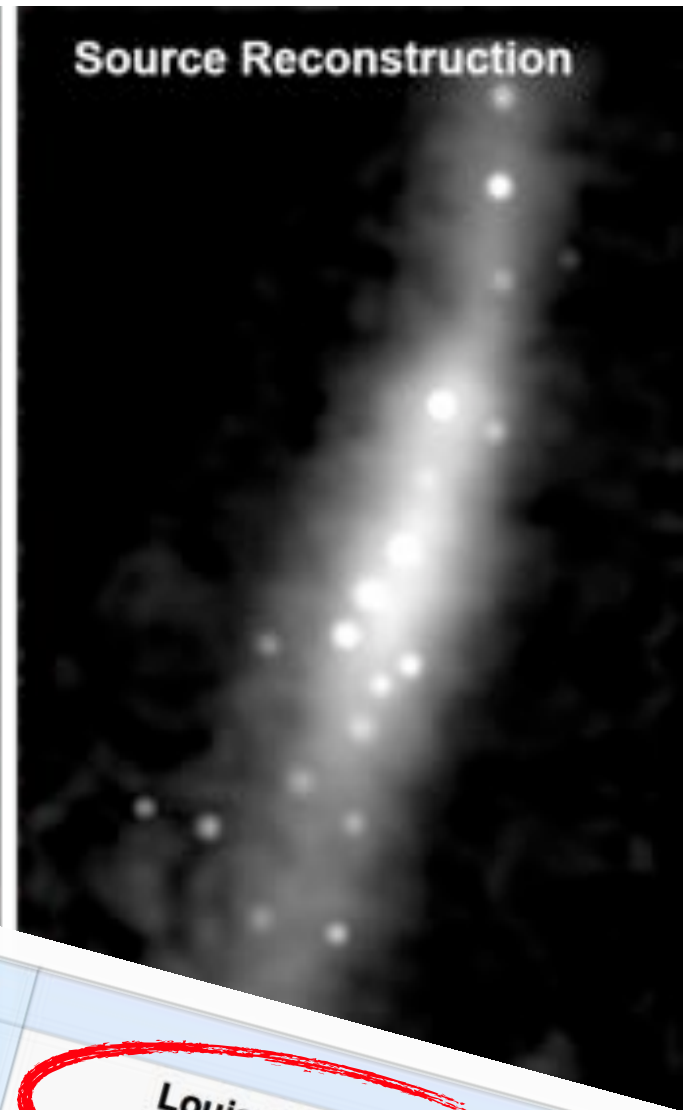
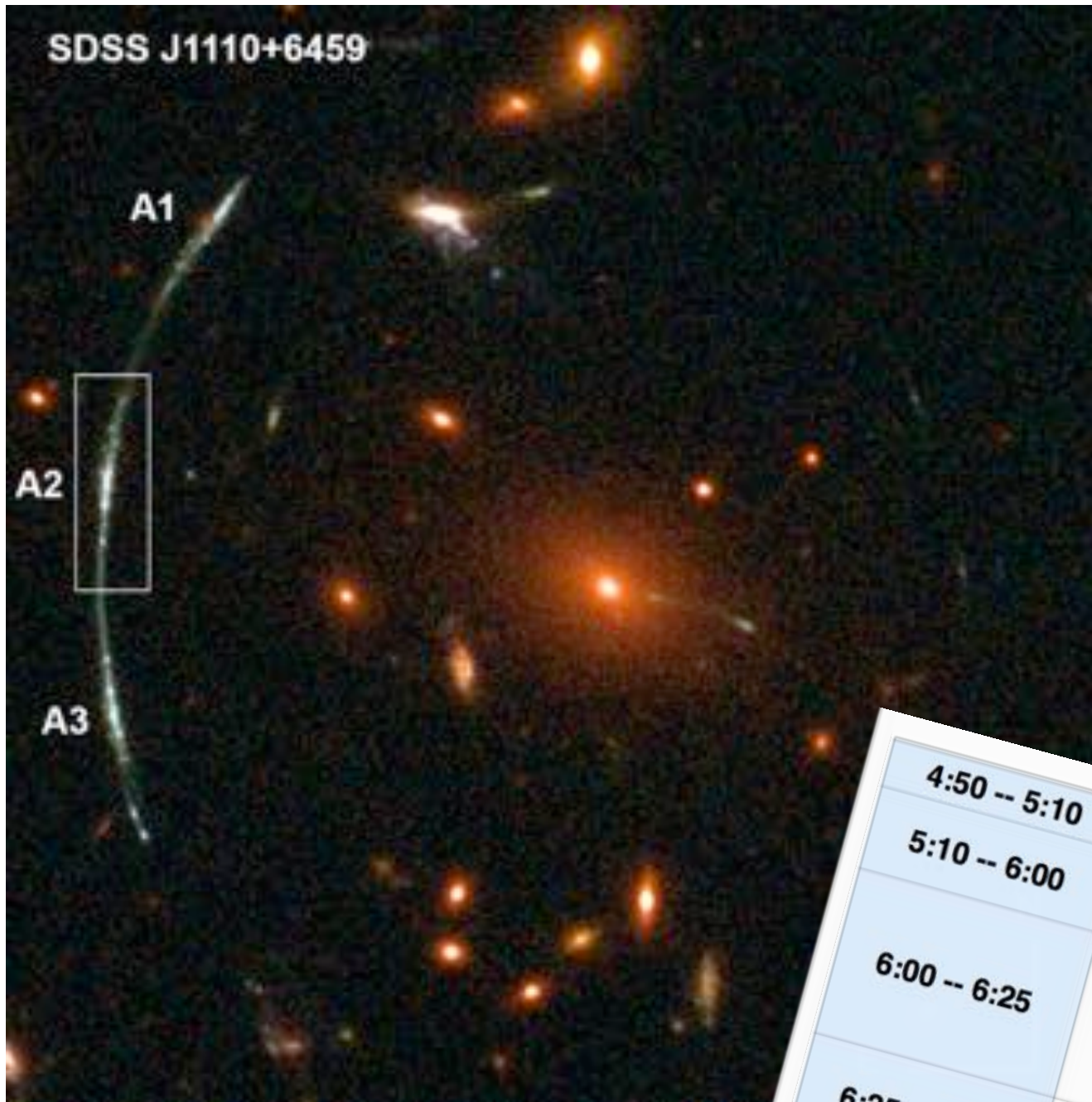
SDSSJ1110+64

Johnson+17a

arXiv:1707.00707

cluster  $z=0.659$ ; arc  $z=2.481$ ; Hybrid lenstool (Jullo+2007) model

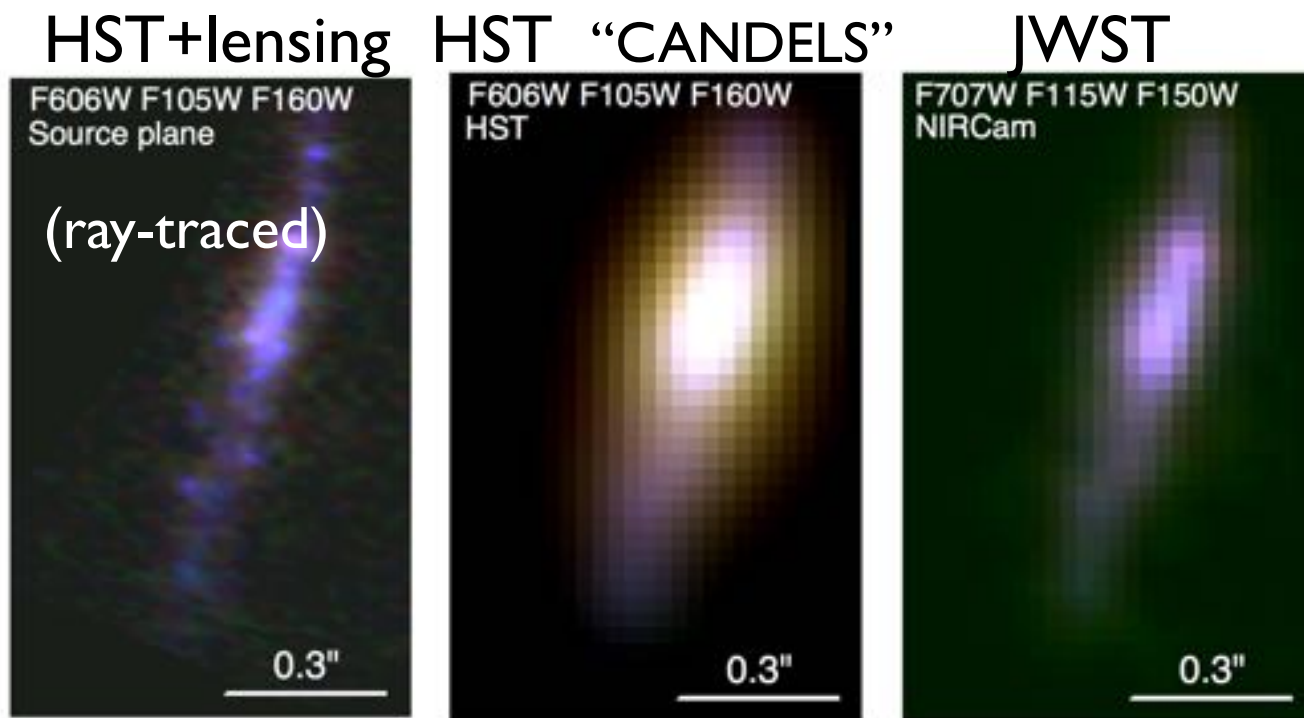




4:50 -- 5:10		
5:10 -- 6:00		
6:00 -- 6:25	<b>Louis ABRAMSON</b> Observations II	Covfefe Bre
6:25 -- 6:50	<b>Michael GREGG</b> Observing Ram Pressure Stripping and Morphological Transformation in the Coma Cluster	Th the
	<b>Tracy WEBB</b> Evidence for In-Situ Star Formati High Redshift Brightest	

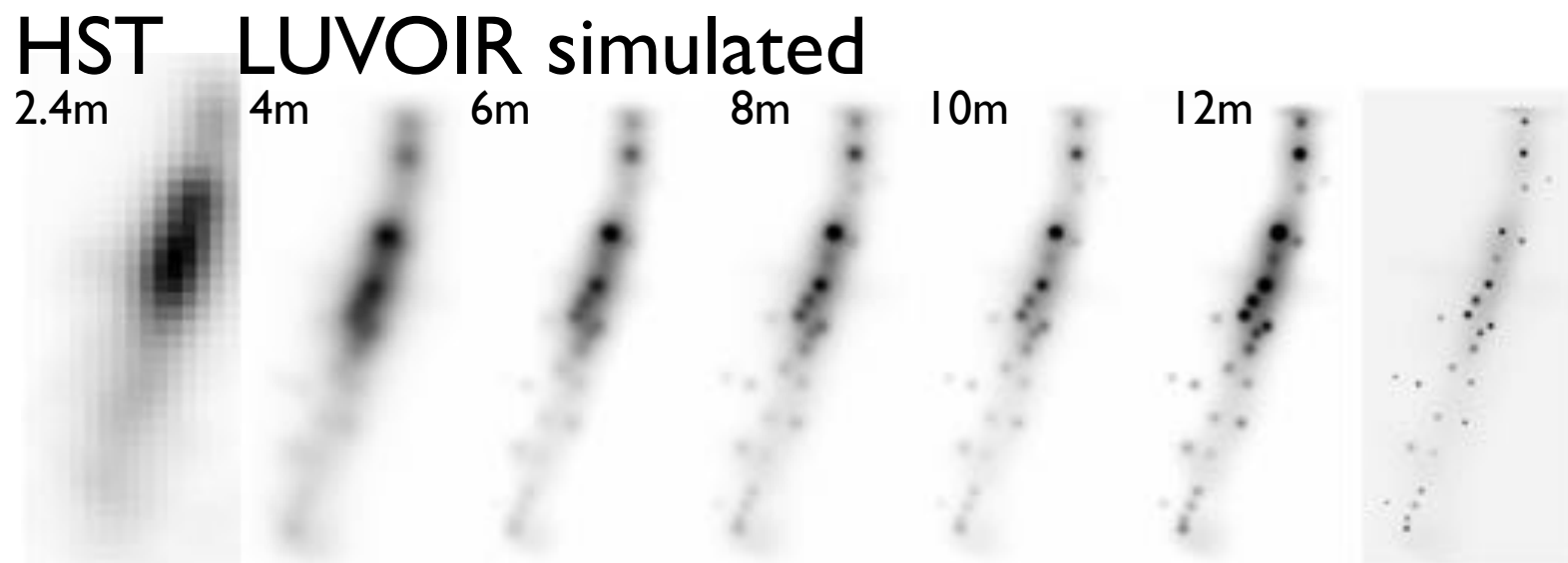
Johnson+17b arXiv:1707.00706

# Star formation under the microscope: $z \sim 2$



Rigby+17: what  
CANDELS may be  
missing?

arXiv:1707.00704



**What would  
JWST + lensing  
do ?!!!**



DEPARTMENT OF PHYSICS  
The University of New Mexico

Author: *Rises Chen, Tom Broadhurst, Jeremy Lim, Jon Bing, Jose M. Diego*

## DERIVING GEOMETRIC REDSHIFTS FOR LENSED GALAXIES IN AS1063 (RXC J2248)

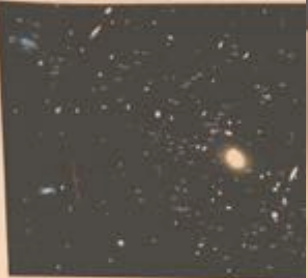


Figure 1: A colour image of the cluster Abell 31063, using HFF data. All with their corresponding E<sub>1</sub> filters whose spectroscopic redshifts or z<sub>sp</sub> colour. There are 10 sets of spectroscopically confirmed lensed galaxy galaxies and 24 other candidates with neither photo z or spectro z.

### SUMMARY

Distant galaxies, even those gravitationally lensed, are faint. Therefore, spectroscopic redshift is usually not available at their first discovery and photometric redshift often yields ambiguous solutions.

We developed a novel iterative method that converges lens models to a self-consistent solution, and determine the redshifts of multiply-lensed galaxies. The redshift was derived purely by the positions of the lensed galaxies and free of uncertainties in photometric information. The method is tested to have a better or comparable accuracy with photometric redshift.

### ITERATIVE METHOD

Investigating the galaxy cluster AS1063 (RXC J2248.7-4421), the most reliably determined redshifts - those with spectroscopic z<sub>sp</sub> in this case) to construct a relative mass model using the step (1) (Diego (Sendo et al. 2016)). Using the mass model, we can fit other lensed galaxies.

1. A preliminary lens model is reconstructed using all 10 spectroscopic galaxies.
2. We use the preliminary lens model to predict the geometric or source plane positions of the lensed galaxies.
3. A new lens model is reconstructed with the new galaxies and keeping the spectroscopic redshifts the same. We use the new geometric redshifts of those galaxies again. They are usually slightly different.
4. We use the new geometric redshift to constrain a new mass in geometric redshift converges with the input redshifts.

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## Systematic errors in SL models of galaxy clusters - Implications for cosmography

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### SJC: a powerful tool to constrain Dark Energy

77% of the energy density of the Universe is in the form of an unknown component with negative pressure which is powering the accelerating expansion of the Universe: dark energy.

It has already proven to be a very effective tool to constrain the cosmology (Jullo et al. 2017; Di Alessi & Natarajan 2011).

... so why do we need to improve the galaxy cluster modelling?

In spite of the numerous parametric and non-parametric SL modelling techniques to accurately constrain the cluster mass distribution and return the cosmology, it has recently become clear that lensing reconstructions are still significantly affected by systematic errors.

Efforts should now focus on improving the already existing lensing models in order to recover more precise cosmological parameters.

### GOAL: Analysing systematic errors in SL models to obtain robust estimates of cosmological parameters

The choice of the density profile and cluster configurations

Figure 2: The effect of the choice of the density profile and cluster configurations on the results of the SJC analysis.

### CONCLUSION

We have analysed two main SJC clusters and compared our reconstructions with the input cosmology and cluster masses. We use a novel iterative method to reconstruct the lensing models and return the cosmology. The results of the SJC analysis are significantly affected by systematic errors in the geometry of the lensing models.

UNIVERSITY OF MICHIGAN

## An evaluation of 10 lensing models of the frontier fields cluster MACS0416

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### HUBBLE FRONTIER FIELDS (HFF)

HFF (Suh et al. 2017) aims to explore the high-redshift Universe (z=4-10) with HST deep observations of 6 massive strong-lensing galaxy clusters.

140 HST orbits per cluster and over 1000h of Hubble dedicated time.

Cluster selection criteria: lensing properties, suitability for ground-based observations, as well as HST, Subaru, and JWST observability.

Get the science for James Webb Space Telescope.

All data releases, HFF updates, and lensing models are available at <http://hff.stsci.edu/analysis/cluster/>.

### LENSING EQUATION, GEOMETRY, AND MACS0416

Figure 1: Schematic of the lensing equation, geometry, and MACS0416.

1. source plane position  
2. image plane location  
3. deflection angle  
4.  $\theta_s$  and  $\theta_i$ : angular diameter distances between the observer to the source and between the lens to the source, respectively.

### RESULTS

Figure 3: Lensing models for MACS0416. The plot shows the lensing potential  $\psi(\theta)$  for different models. The color scale represents the lensing potential in units of  $10^{-4}$  arcmin<sup>2</sup>.

### METHODS

The algorithm used to compute the lens models involves the source in both the source and image plane.

Source Plane Scatter: The lensed images are traced using the lensing equation, the background position determined, and the source plane scatter calculated from distances between the projections and the background position.

Image Plane Scatter: The lensed arcs are traced back to the source plane using the lensing equation. Their lensed back to the image plane is then calculated from the distance between the projections and the observed images.

Predictive power: By comparing the scatter between the arcs that had redshifts and the ones that don't in 2013, we can compare how the lens models perform with low constraints that were not available at the time the models were computed.

### PRELIMINARY CONCLUSIONS

From Figures 2 and 3, we observe that the models in some ways exhibit a bias by a small group of lens (e.g., S<sub>1</sub>, U<sub>1</sub> and C<sub>1</sub>, V<sub>1</sub>) models.

For the majority of the lens models, the source and image plane scatter of the arcs are higher than that of the training set. Even though there is a difference in the scatter between the sets, it is not drastic, meaning that the models have a good predictive power.

Spatial dependencies in the source and image plane scatter are present mainly at the northwest and southeast corners of the galaxy cluster, where there is a higher scatter compared to the center. An explanation for this effect is that the lens models that are constrained in those particular regions at the time they were made.

Comparing parameters  $\sigma_s$ ,  $\sigma_i$ ,  $\beta$ , and  $\alpha$  across models, the  $\sigma_s$ ,  $\sigma_i$ ,  $\beta$ , and  $\alpha$  models, we find that the non-parametric models (with more constraints) were difficult to build.

### ACKNOWLEDGEMENTS