Strong Lens Modeling

of Galaxy Clusters

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

Keren Sharon

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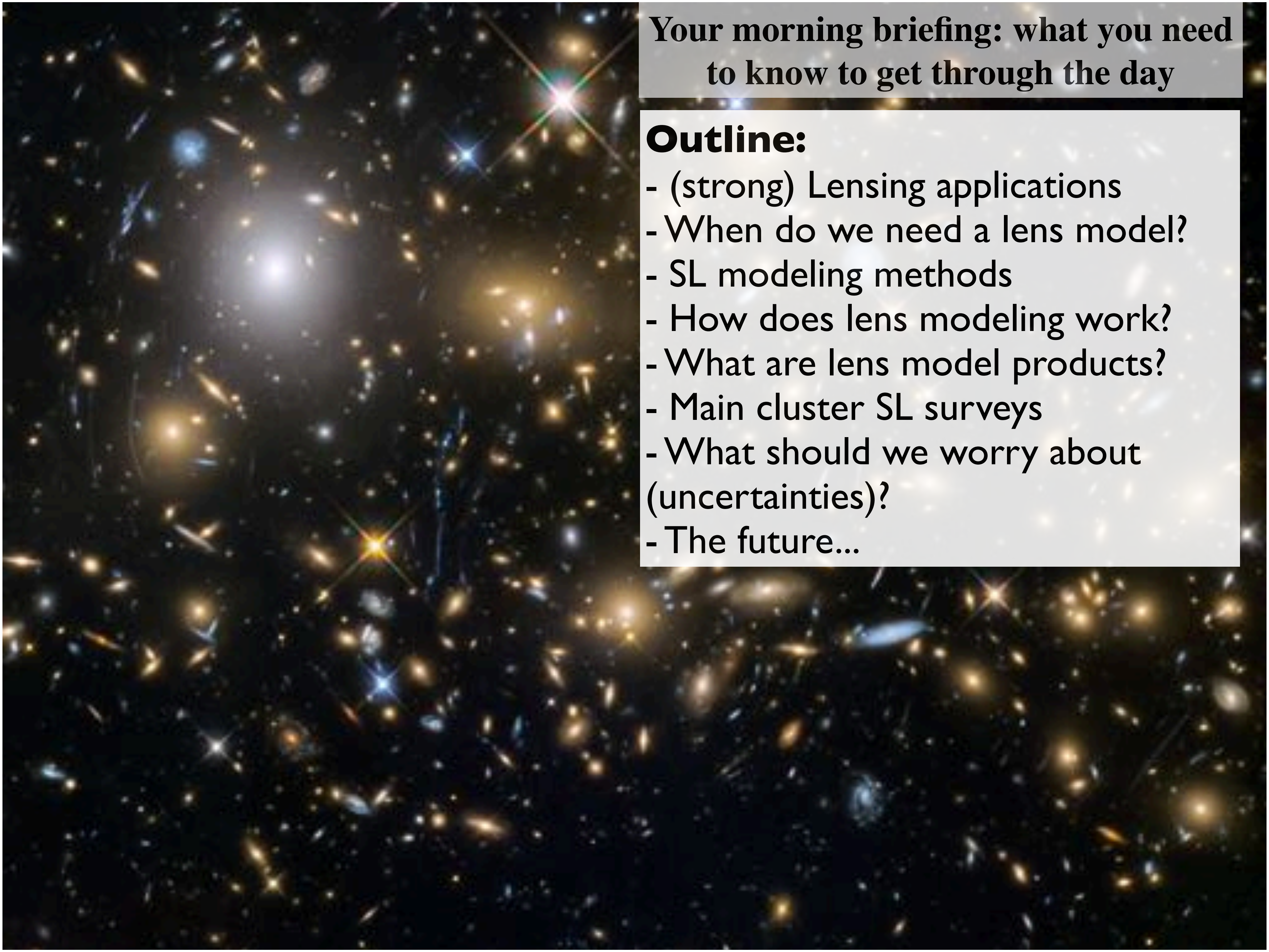


Your morning briefing: what you need to know to get through the day

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?

Why do we care?

Cluster physics*, cosmology*

> * when combined with other proxies

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

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)

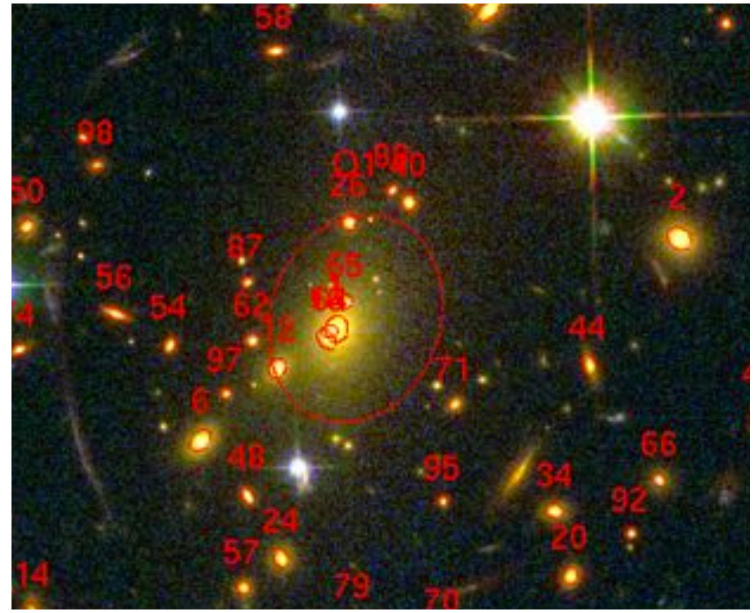
Lens modeling approaches

"Parametric"

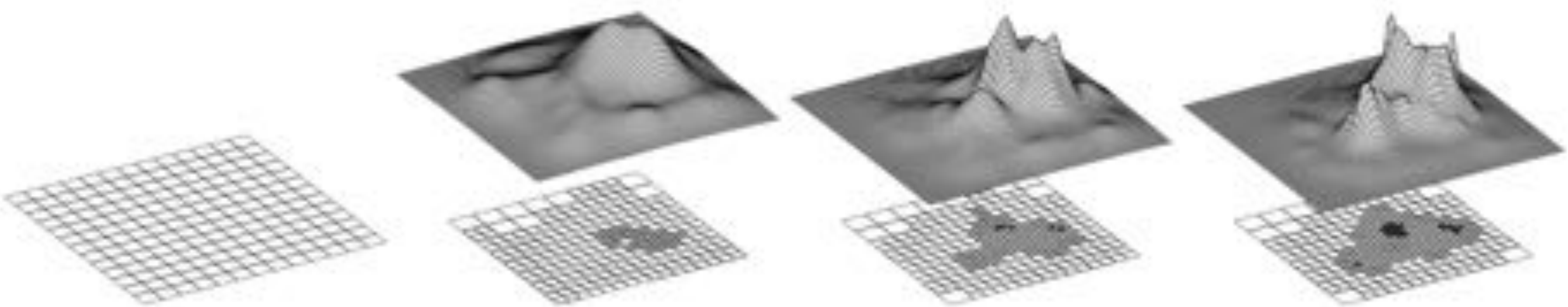
"non-parametric"

} hybrid

mass/light assumptions



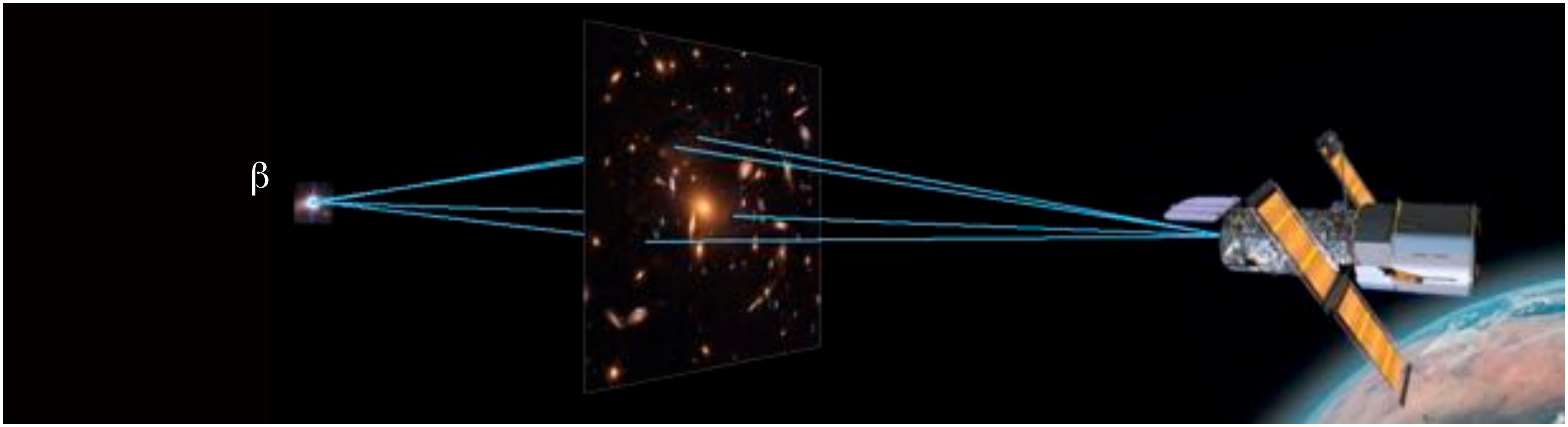
4 *J. Liesenborgs, S. De Rijcke and H. Dejonghe* *(2006)*



(a) Step one (b) Step two (c) Step three (d) Step four

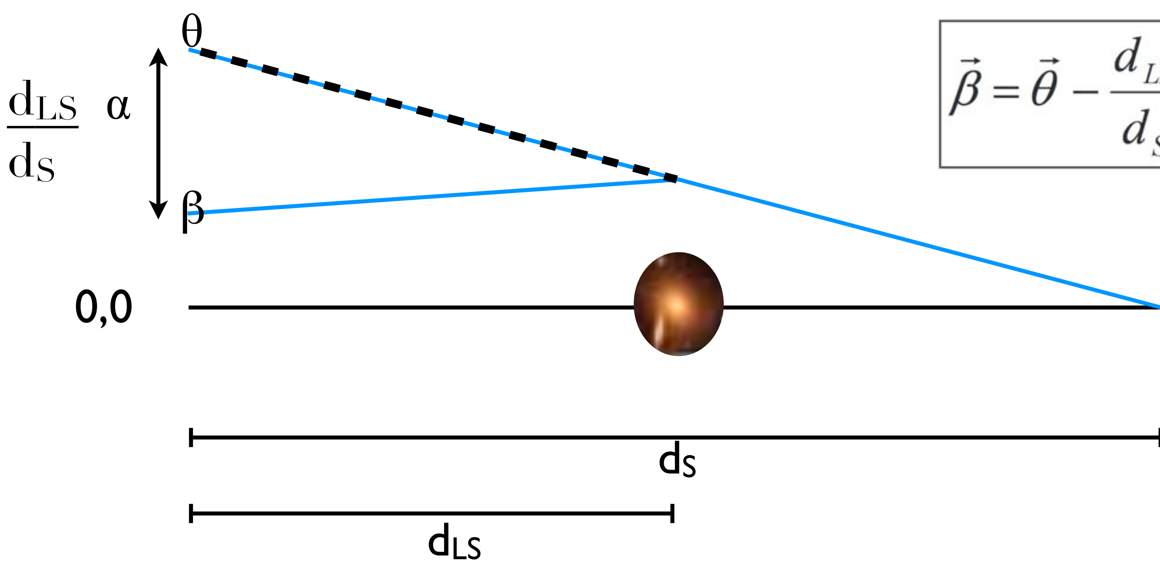
Figure 1. The use of a dynamic grid. The grid spacing is refined in those regions where individual grid cells contain a large fraction of the total mass of the lens or where the projected-density gradients are large.

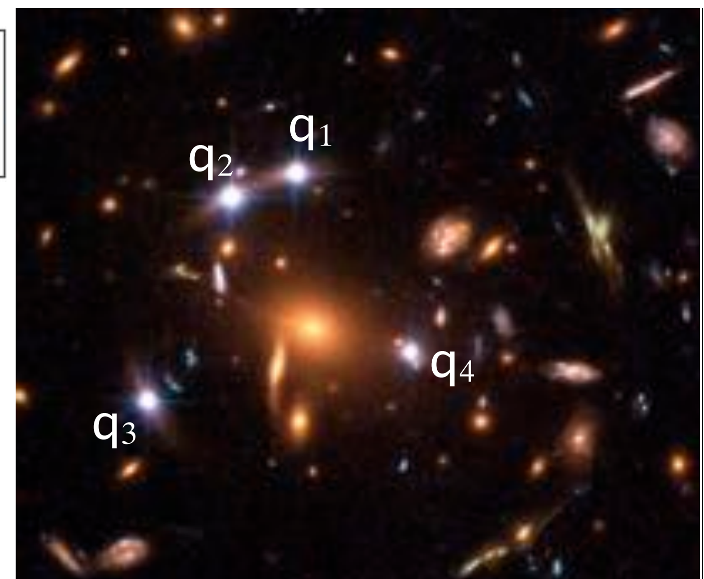
Lens modeling: figure out the "Optics" of a gravitational lens



The lens equation

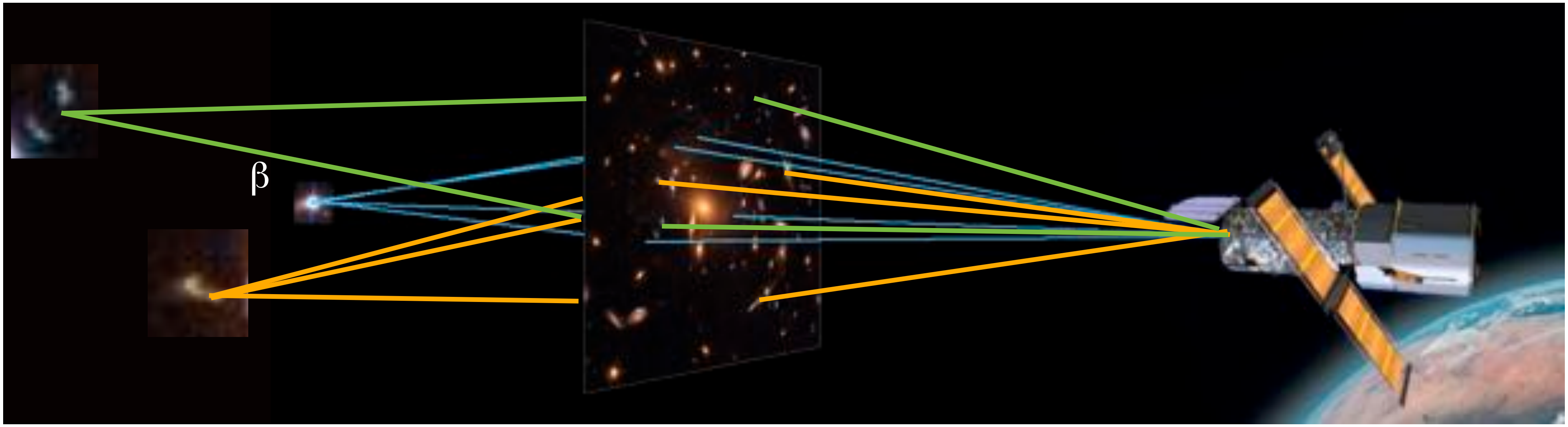
$$\vec{\beta} = \vec{\theta} - \frac{d_{LS}}{d_S}\vec{\alpha}(\vec{\theta})$$

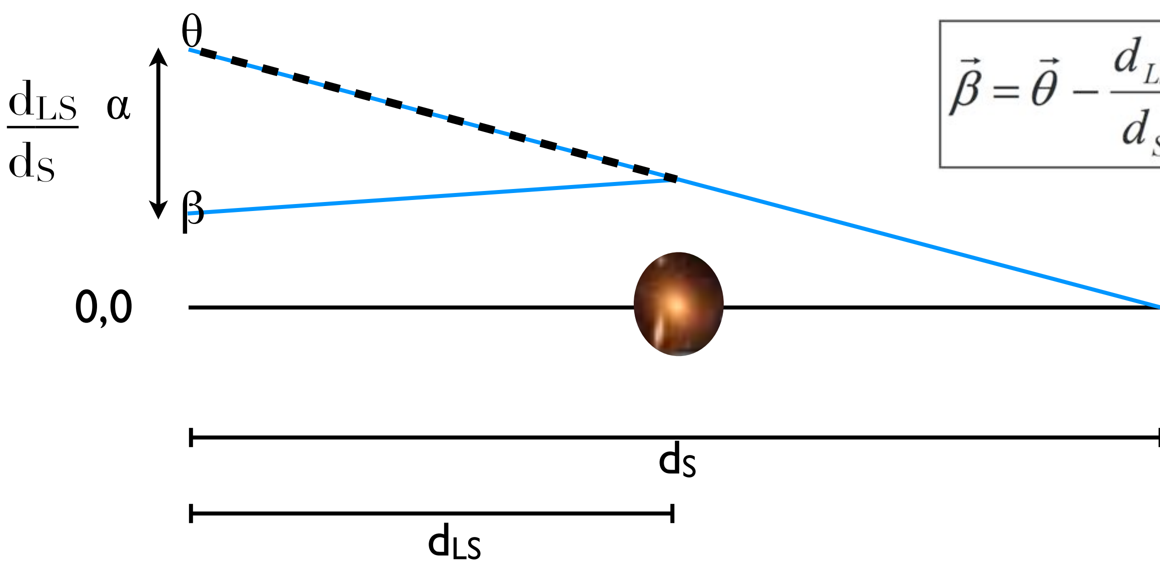




SDSS1004, Sharon et al. (2005), *HST*/ACS

Lens modeling: figure out the "Optics" of a gravitational lens





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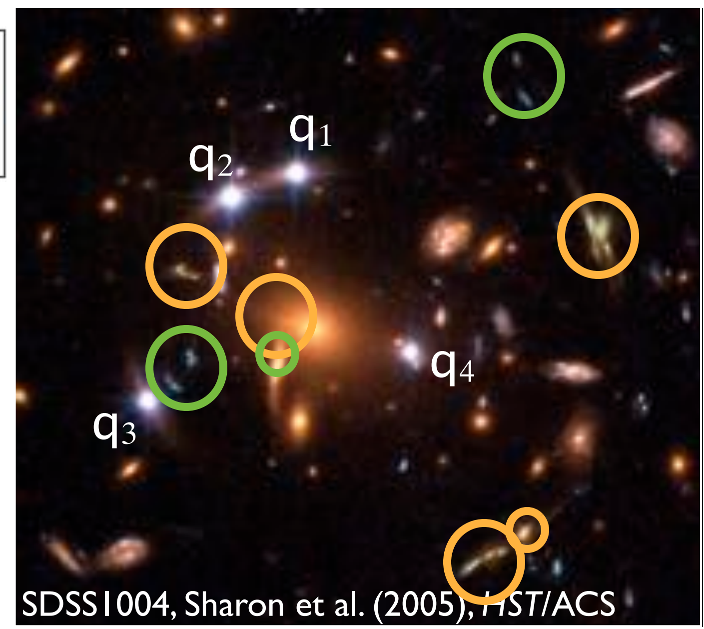
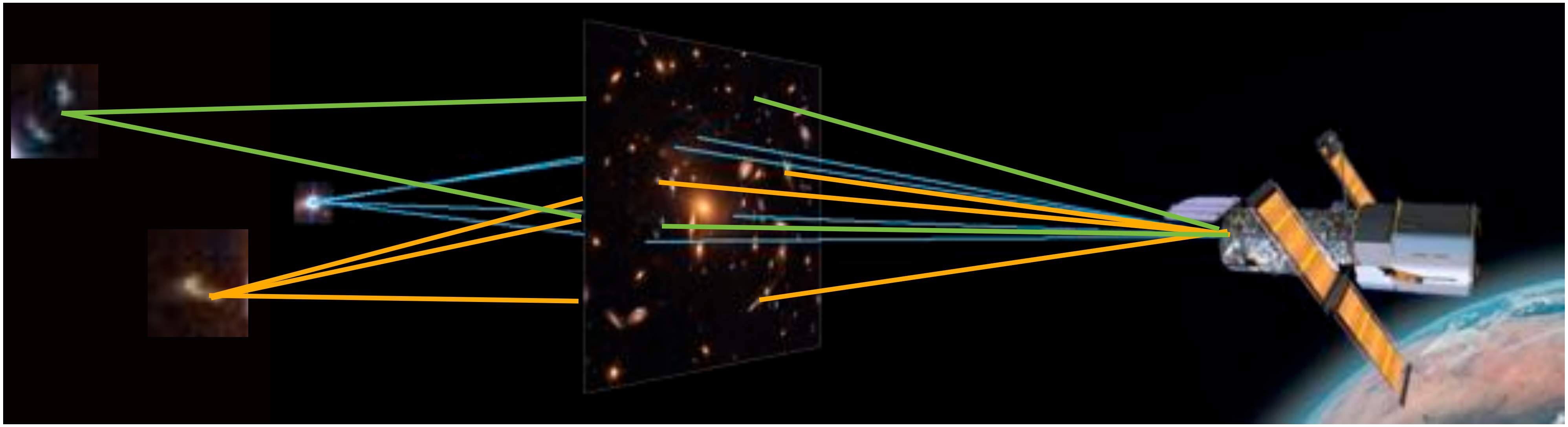
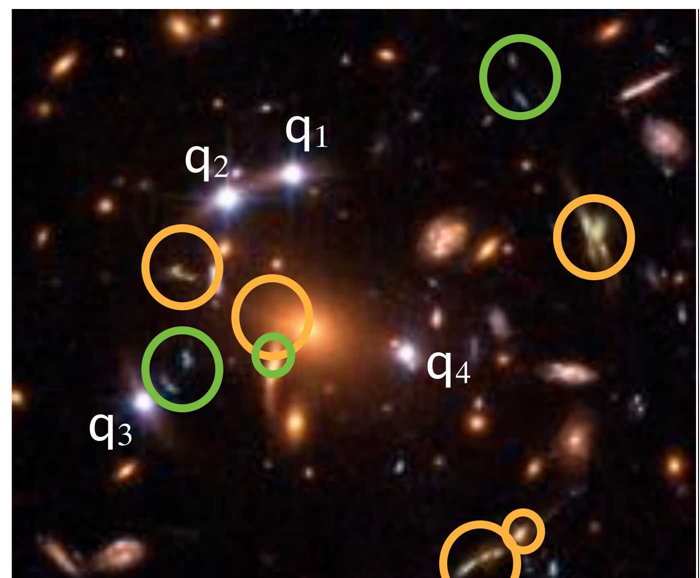


Lens modeling: figure out the "Optics" of a gravitational lens



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

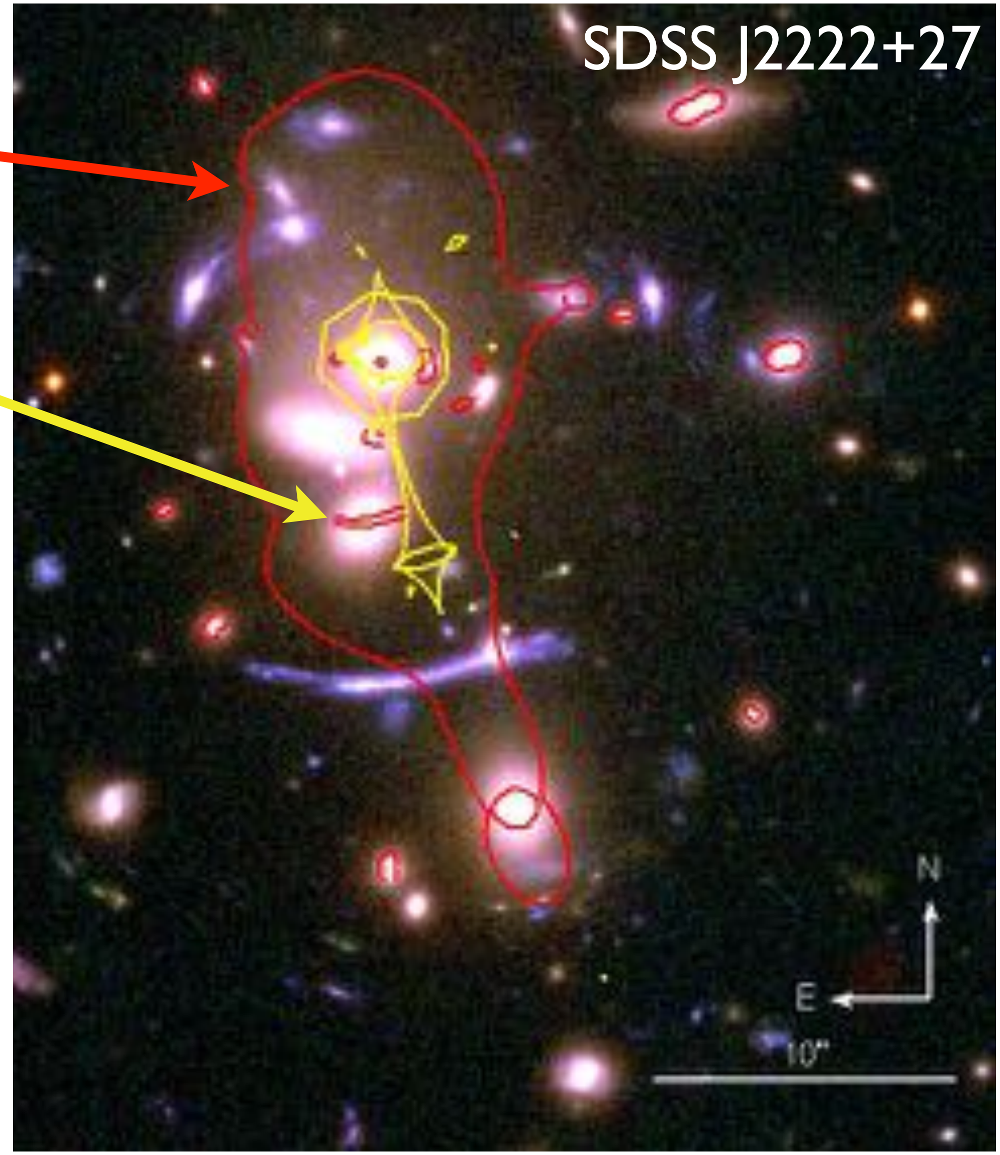


SDSS1004, Sharon et al. (2005), *HST/ACS*

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

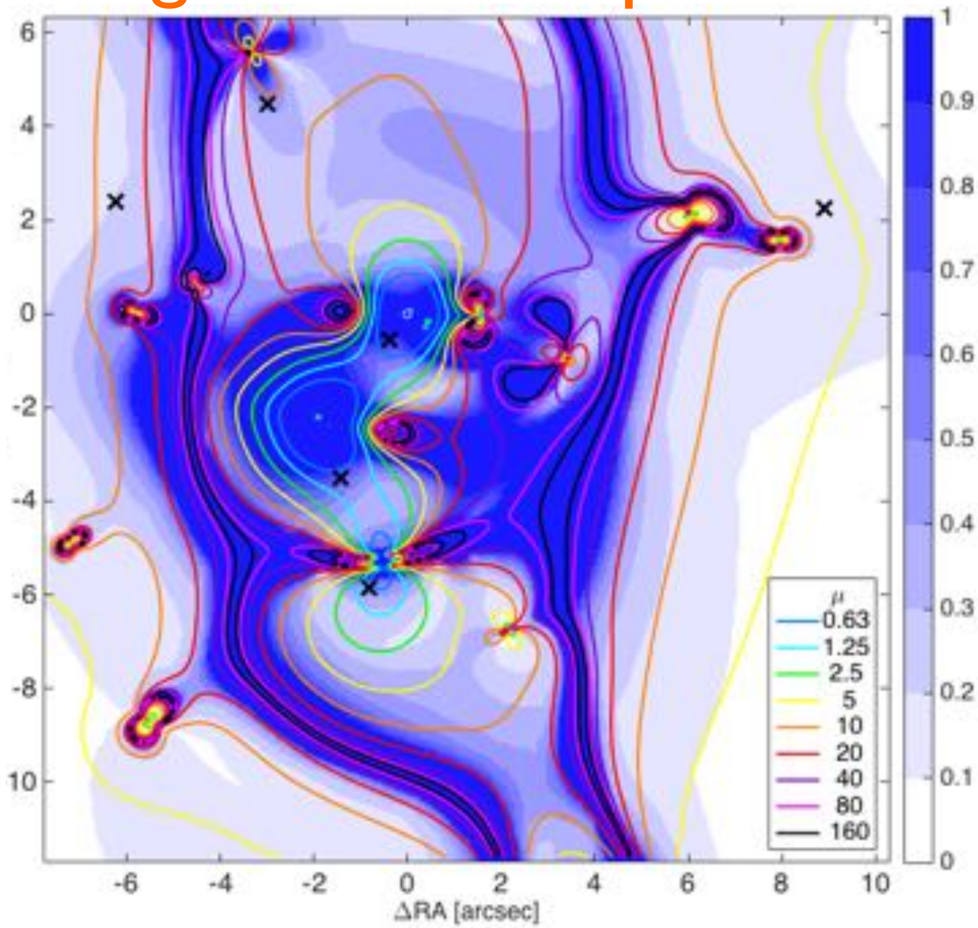


*mathematically; in reality, sources are not infinitely small. so magnification is finite. nevertheless, close to the critical curves the magnification can reach hundreds.

Sharon+2017 -SGAS-

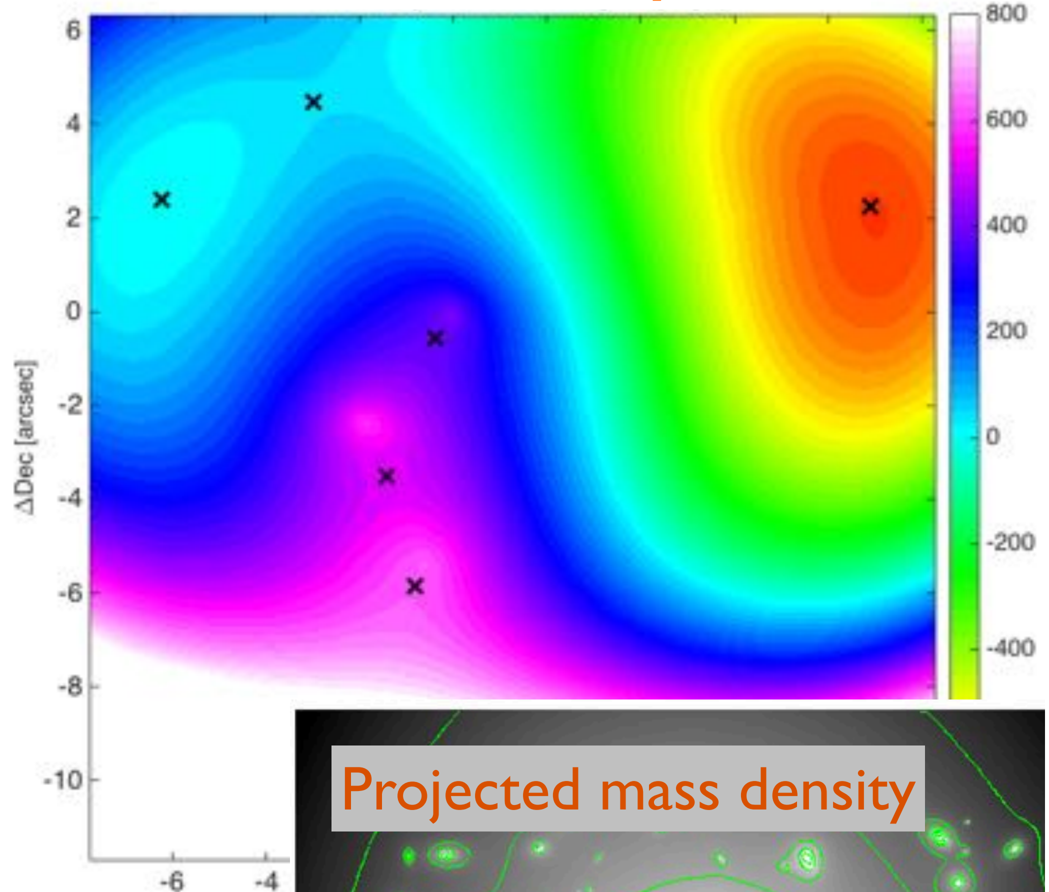
example lens model products

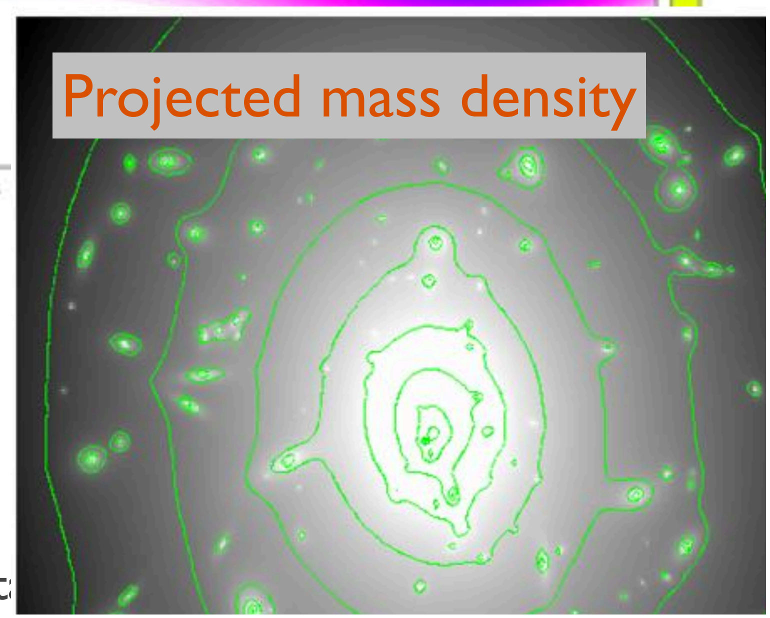
magnification map + unc



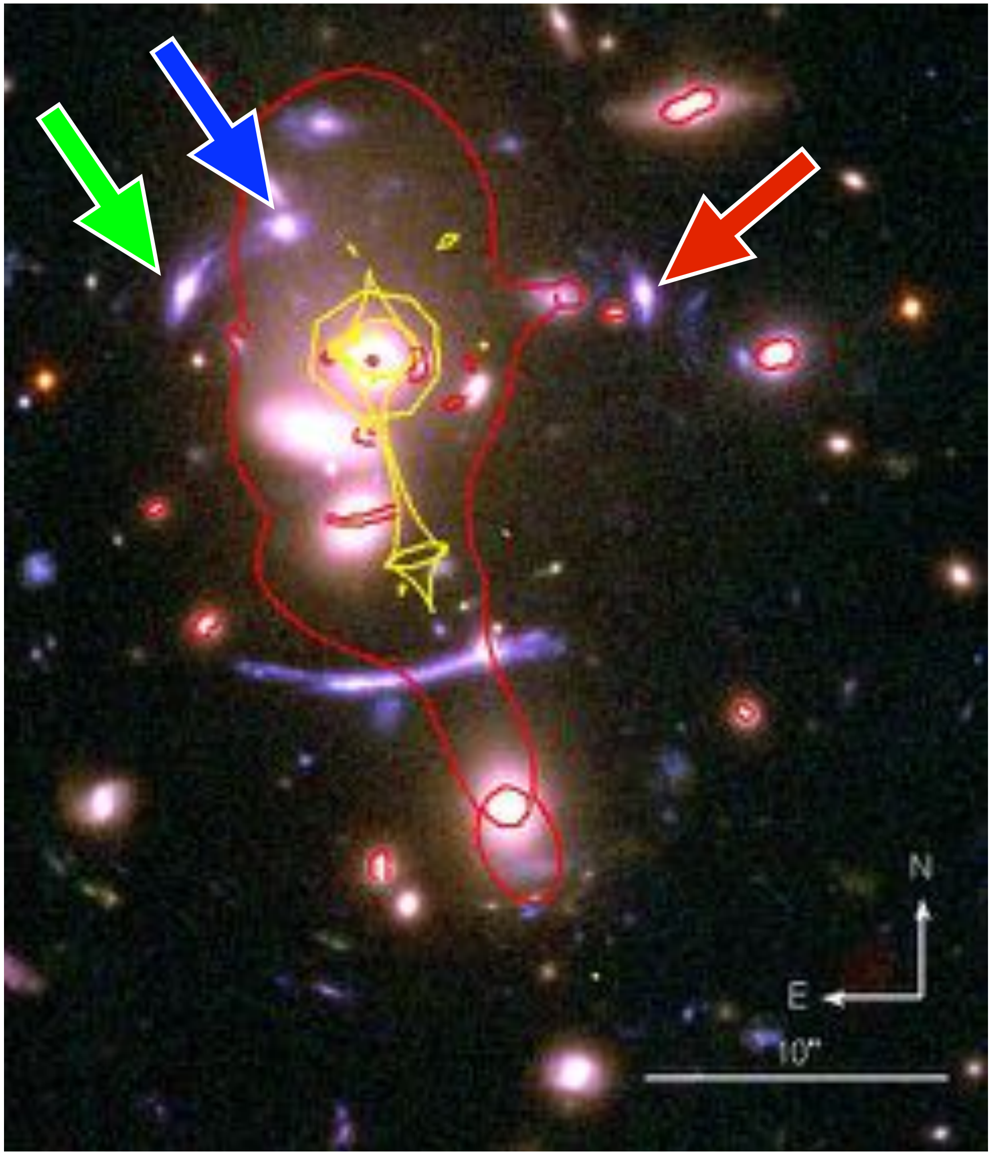
Sharon+2017 -SGAS-SDSS2222

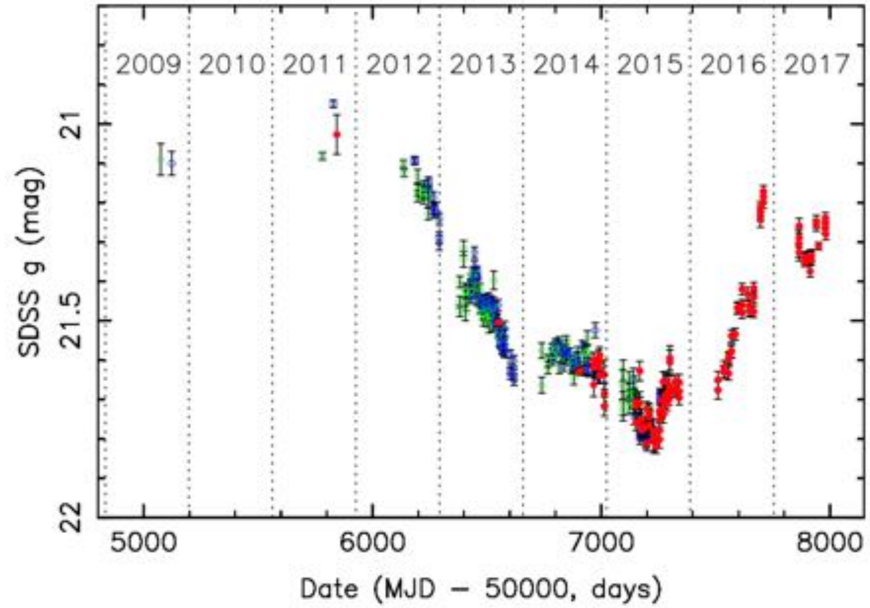
time delay





...We can tell the future!





Dahle+2015

strong lensing samples / surveys with HST:

SGAS
Sloan Giant Arcs Survey

107/37

CLASH

524/25

MEGaSaURA

FRONTIER FIELDS

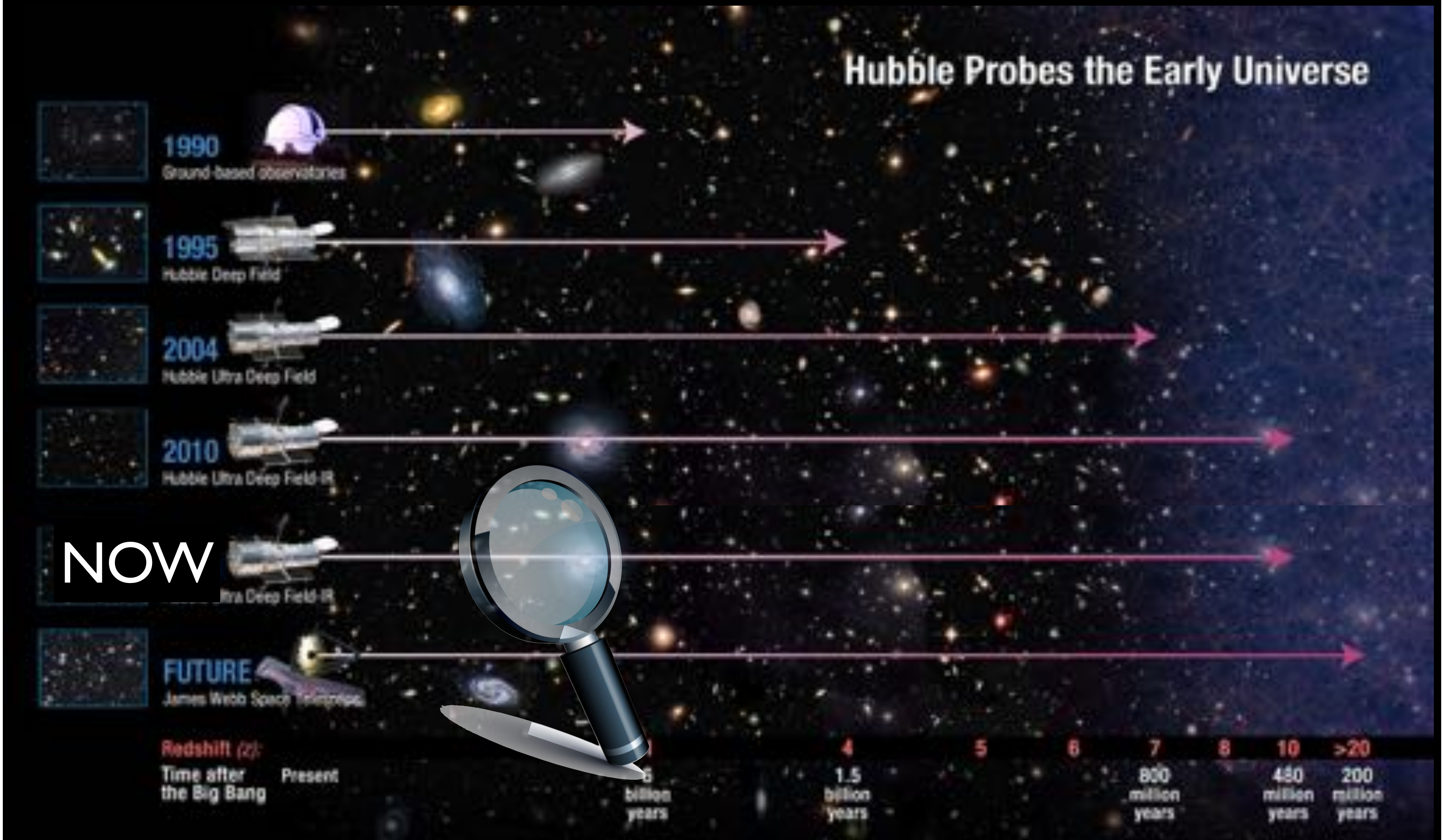
840/6

RELICS
Reionization Lensing Cluster Survey

190/41

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

public model products - most
public data - all



Hubble Probes the Early Universe
1990
Ground-based observatories
1995
Hubble Deep Field
2004
Hubble Ultra Deep Field
2010
Hubble Ultra Deep Field-IR
NOW
FUTURE
James Webb Space Telescope
Redshift (z):
4
5
6
7
8
10
>20
Time after the Big Bang
Present
billion years
1.5 billion years
800 million years
480 million years
200 million years

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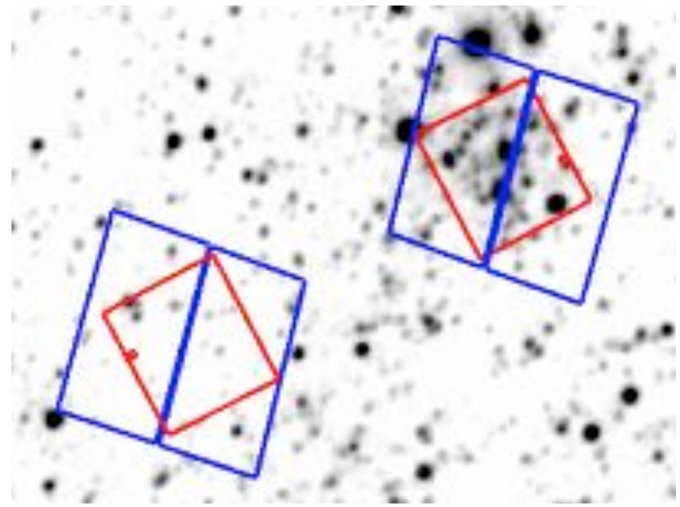
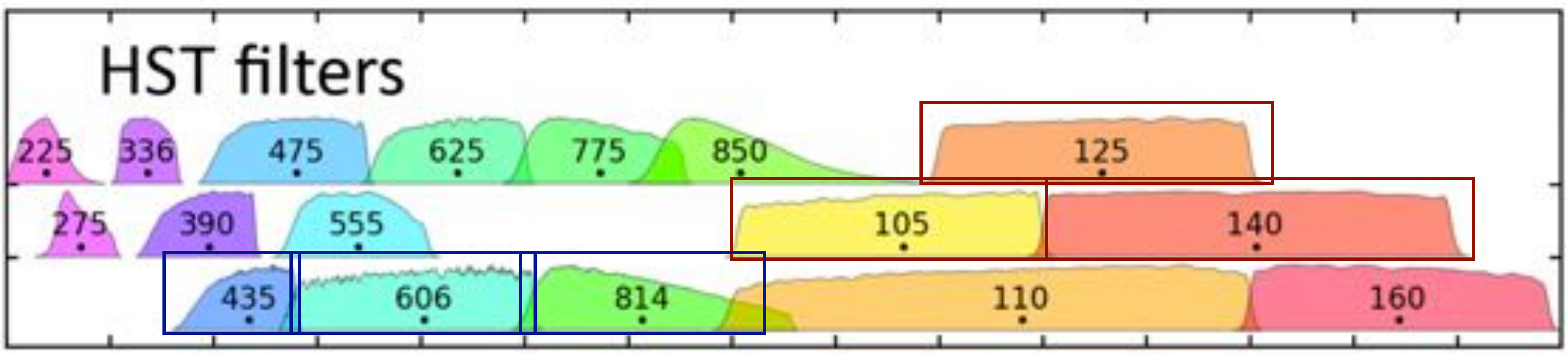
480 million years
200 million years

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



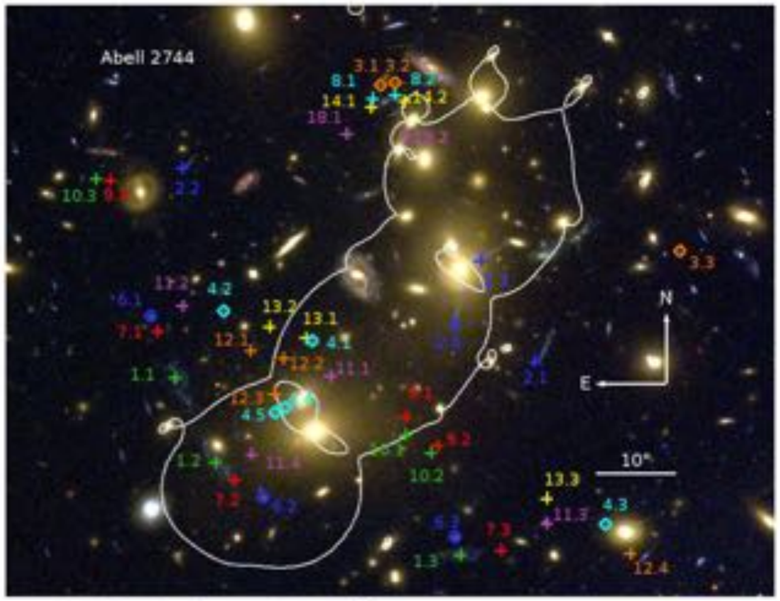


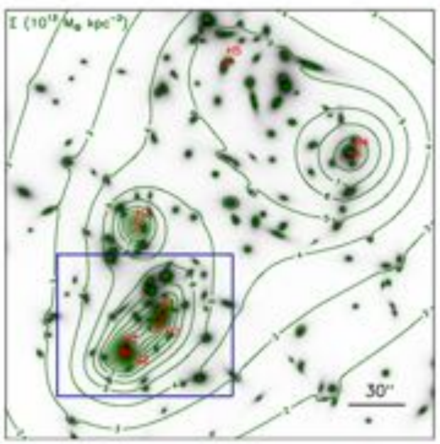
SUBMITTED TO ApJ: DRAFT DATE SEPTEMBER 11, 2014
Preprint typeset using LaTeX style emulateapj v. 11/10/09

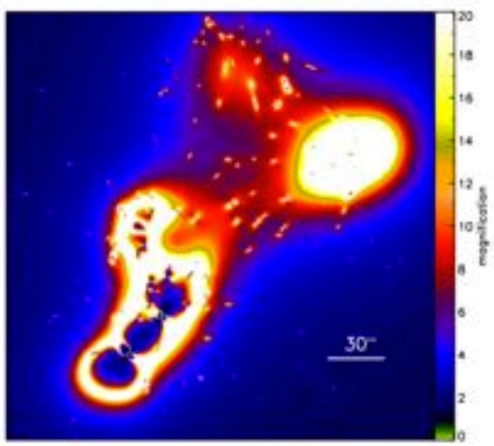
LENS MODELS AND MAGNIFICATION MAPS OF THE SIX HUBBLE FRONTIER FIELDS CLUSTERS*

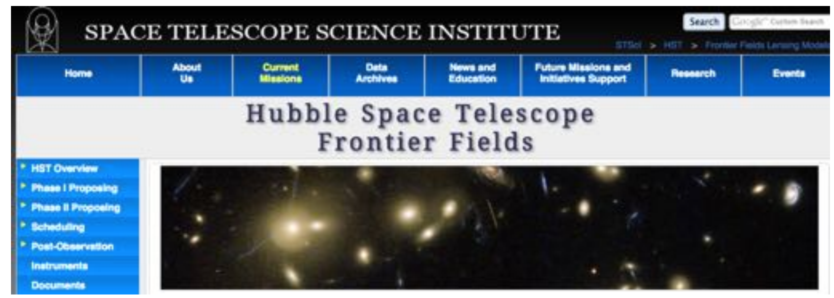
TRACI L. JOHNSON[1], KEREN SHARON[1], MATTHEW B. BAYLISS[2,3], MICHAEL D. GLADDERS[4,5], DAN COE[6], HARALD EBELING[7]

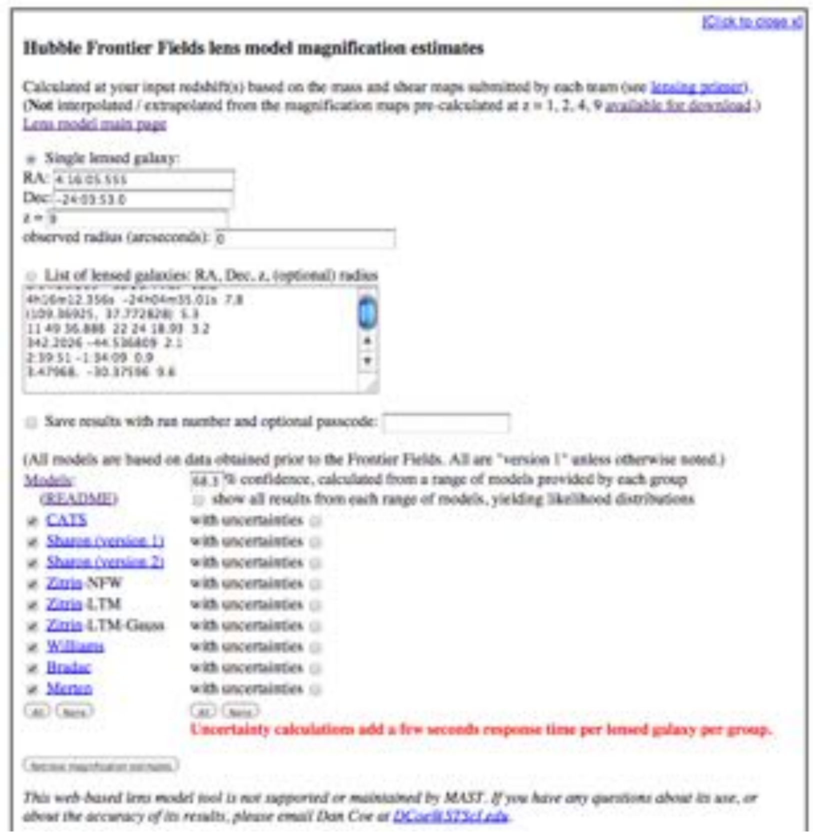
Submitted to ApJ: draft date September 11, 2014











[Click to close x]

Hubble Frontier Fields lens model magnification estimates

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 = 9
observed radius (arcseconds): 0

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

```
4h16m12.356s -24h04m35.01s 7.8
(109.86025, 37.772828) 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
3.47068, -30.37596 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.)

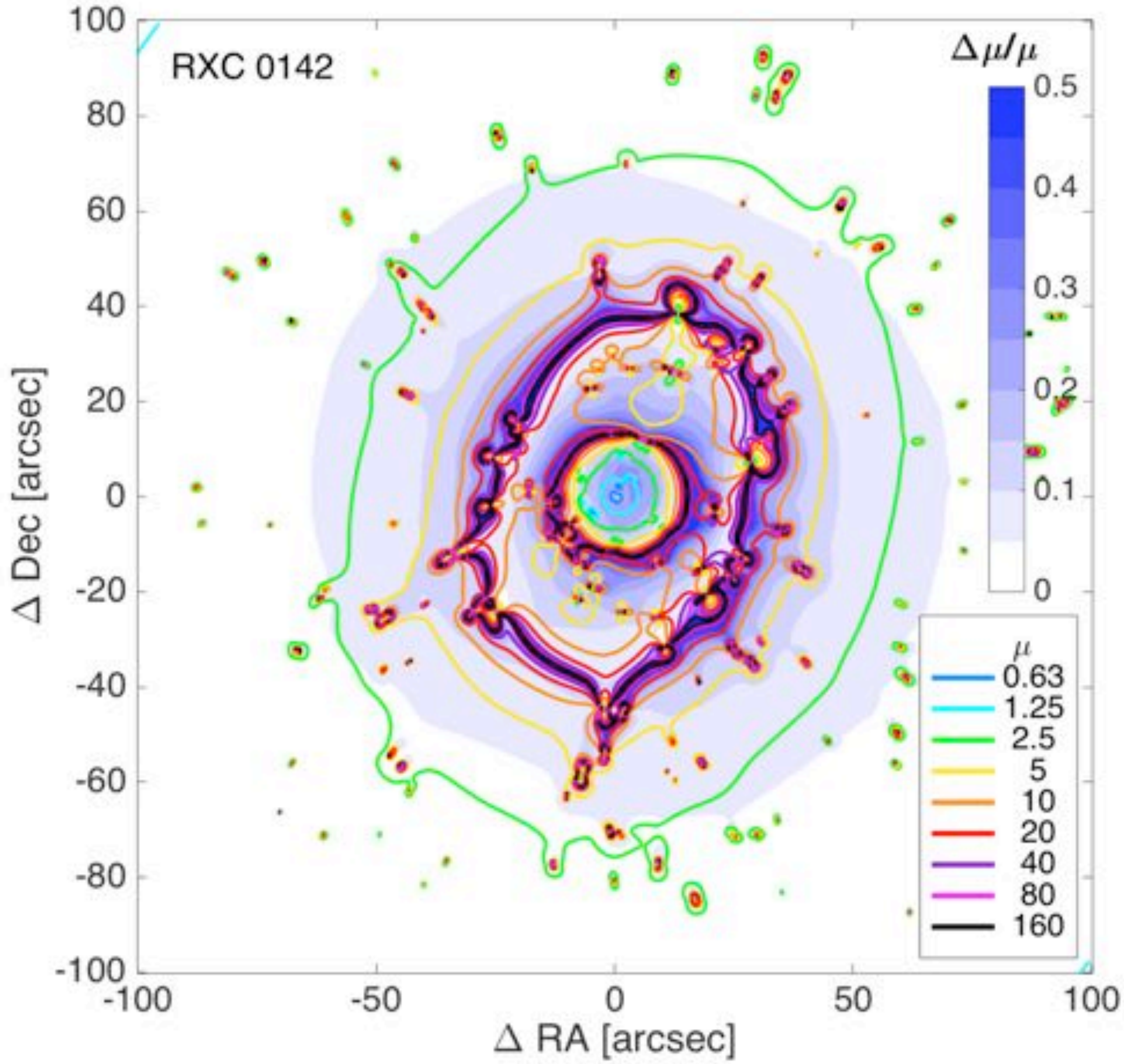
Models (README)	68.3 % confidence, calculated from a range of models provided by each group
	show all results from each range of models, yielding likelihood distributions
CATS	with uncertainties
Sharon (version 1)	with uncertainties
Sharon (version 2)	with uncertainties
Zitrin-NFW	with uncertainties
Zitrin-LTM	with uncertainties
Zitrin-LTM-Gauss	with uncertainties
Williams	with uncertainties
Bradac	with uncertainties
Merten	with uncertainties
All None	All None

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.

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

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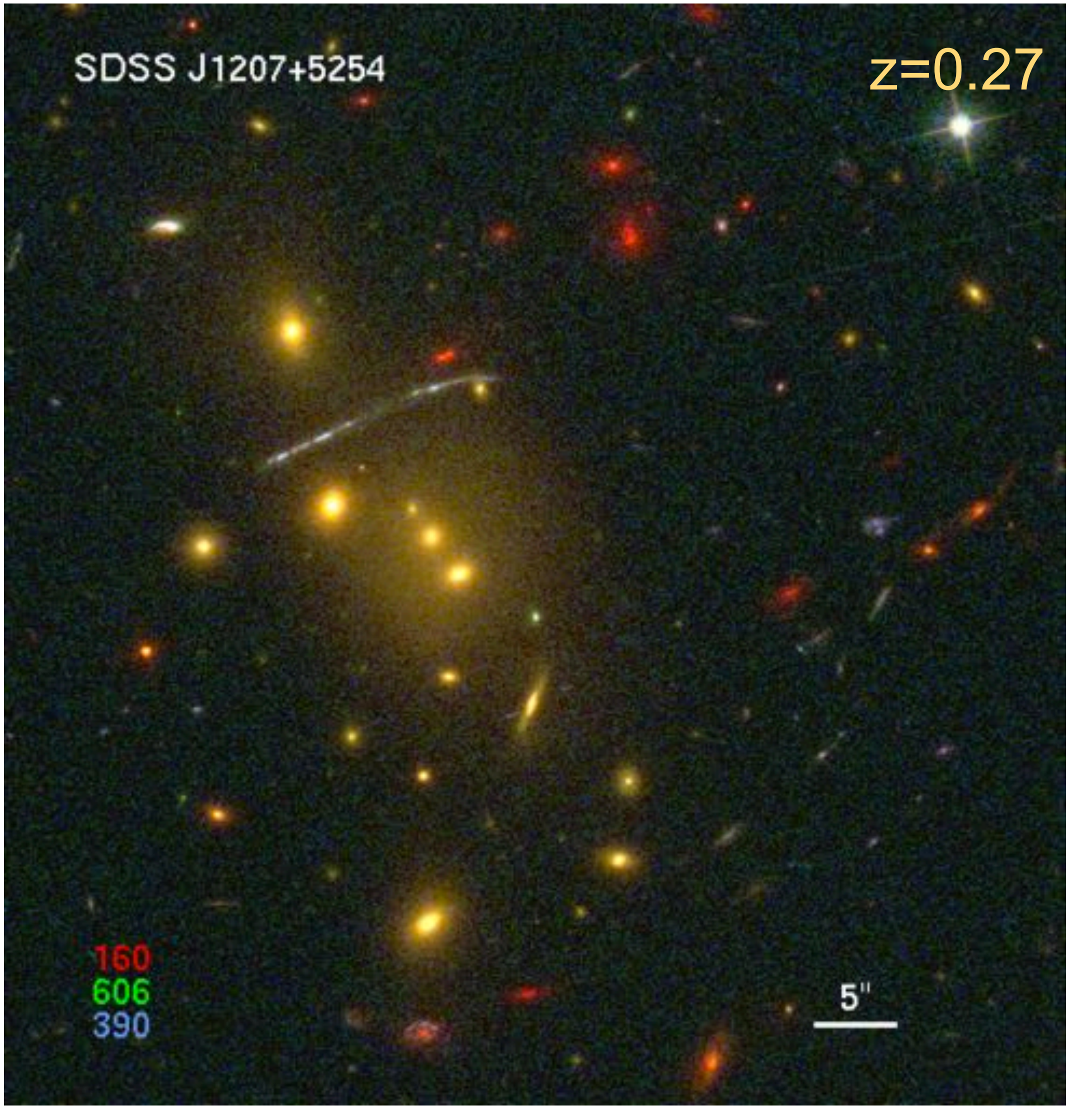
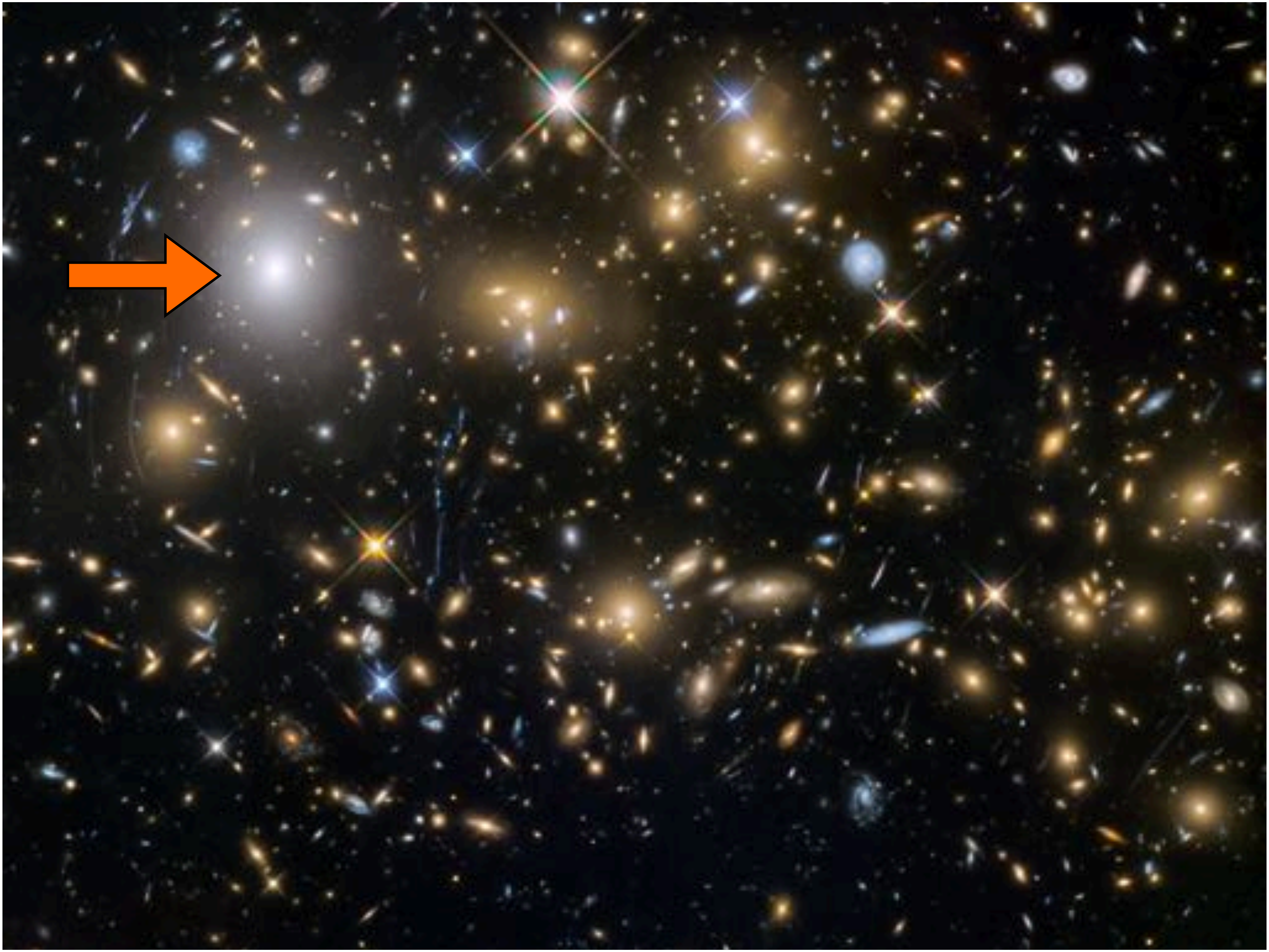
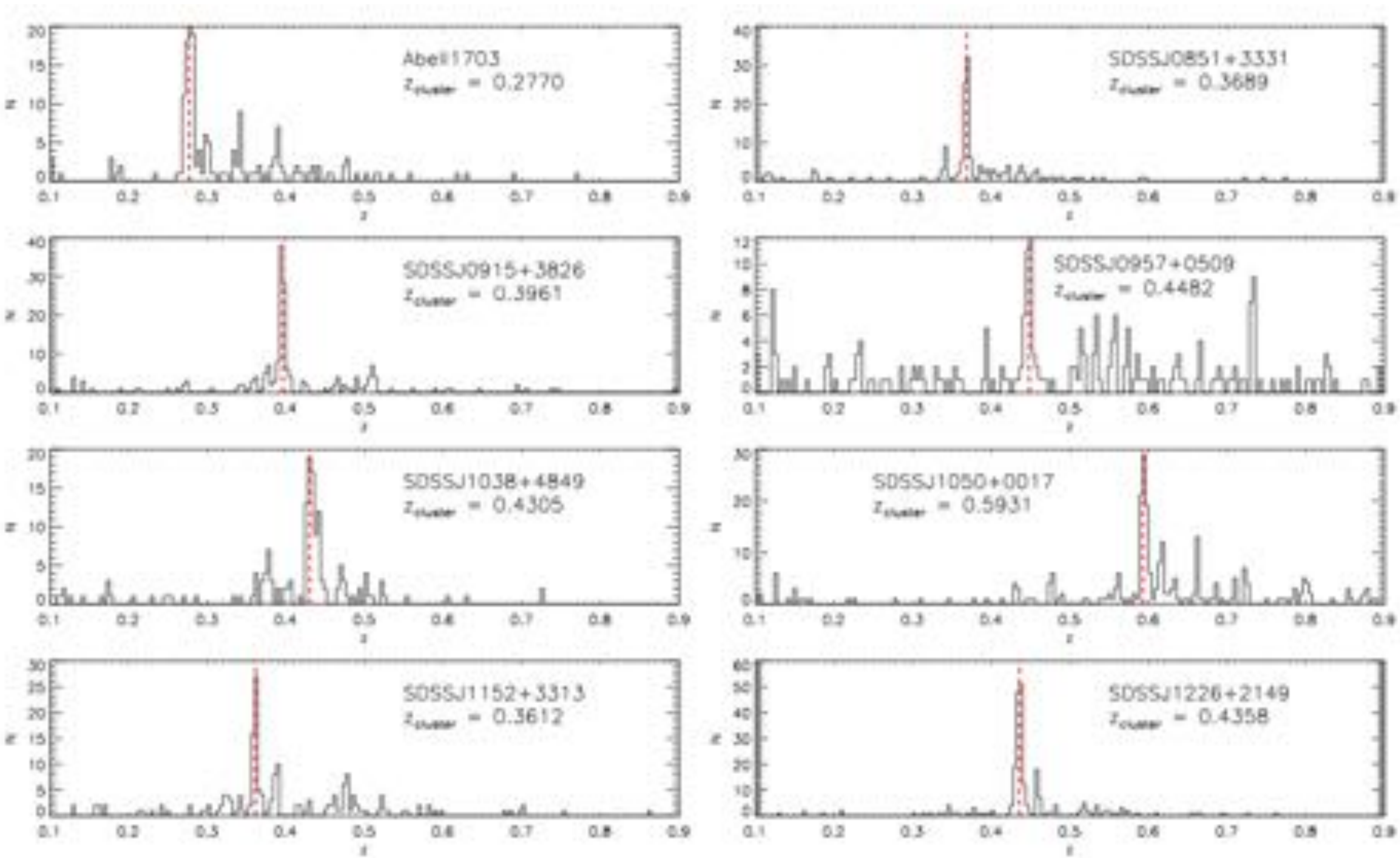


Sharon+2017 ; SGAS



Mass on the Line of Sight



Bayliss et al. 2013

What do we need to worry about?

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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+)

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10:15 -- 10:40	
10:40 -- 11:30	Keren SHARON Lensing II
11:30 -- 11:55	Jesús VEGA-FERRERO Free-Form Lens Models of four Hubble Frontier Fields Clusters
11:55 -- 12:20	Rachel PATERNO-MAHLER The Reionization Lensing Clusters Survey: Strong Lensing Analysis
12:20 -- 12:45	Jenny WAGNER Model-independent characterisation of strong gravitational lenses
1:00 -- 3:00	

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

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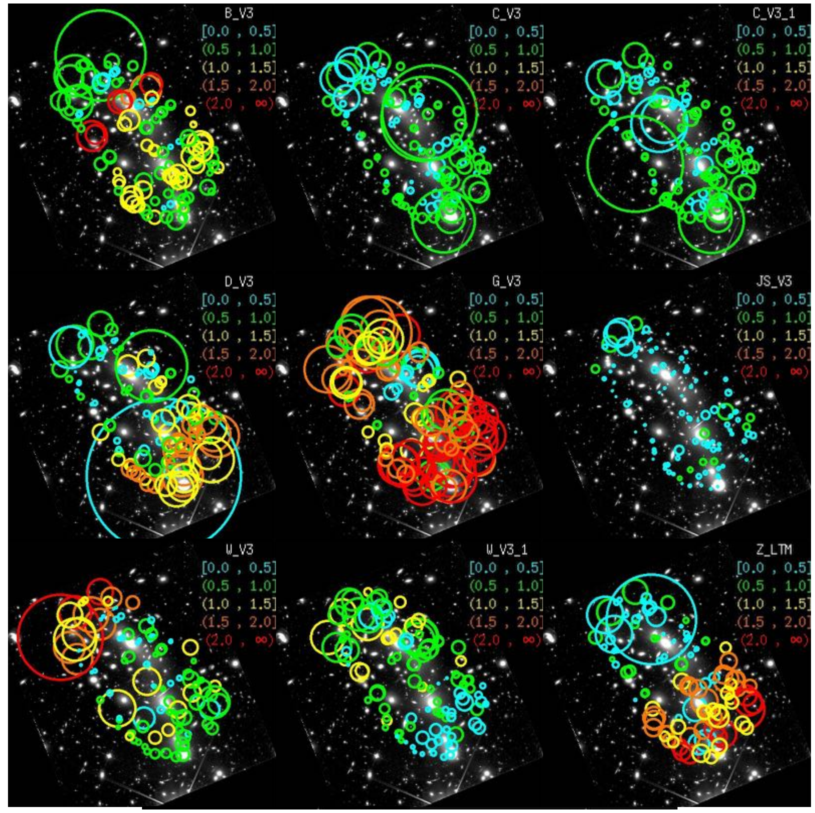
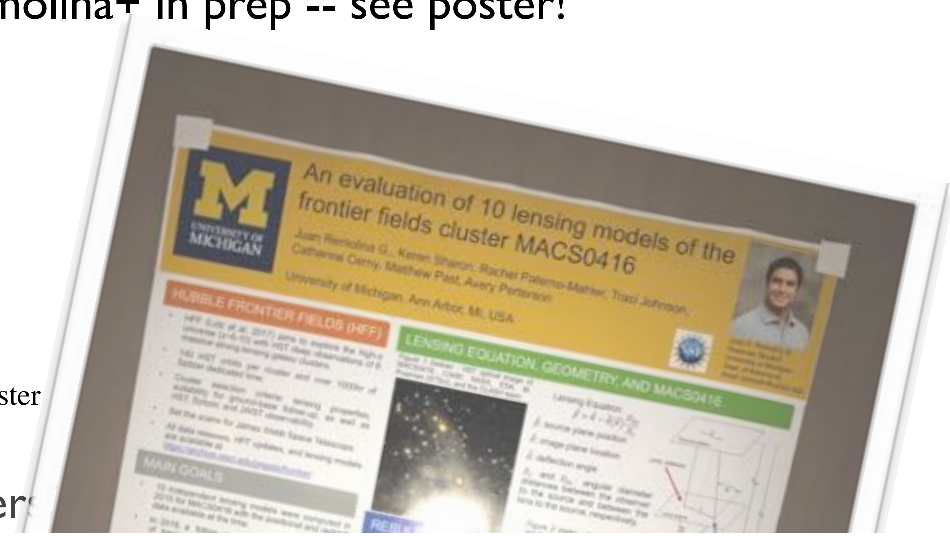


Remolina+ in prep -- see poster!



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

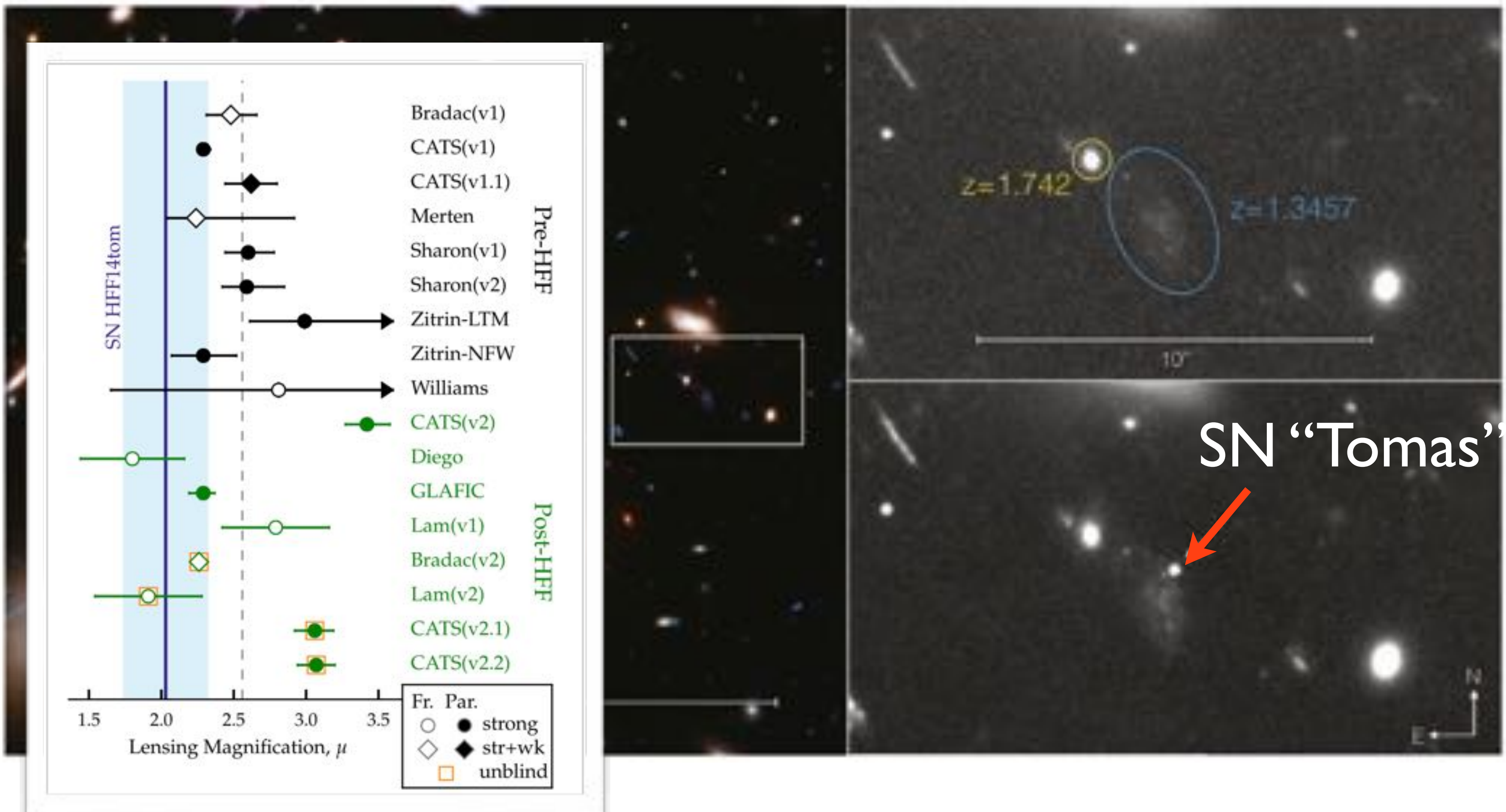
What do we need to worry about?

- 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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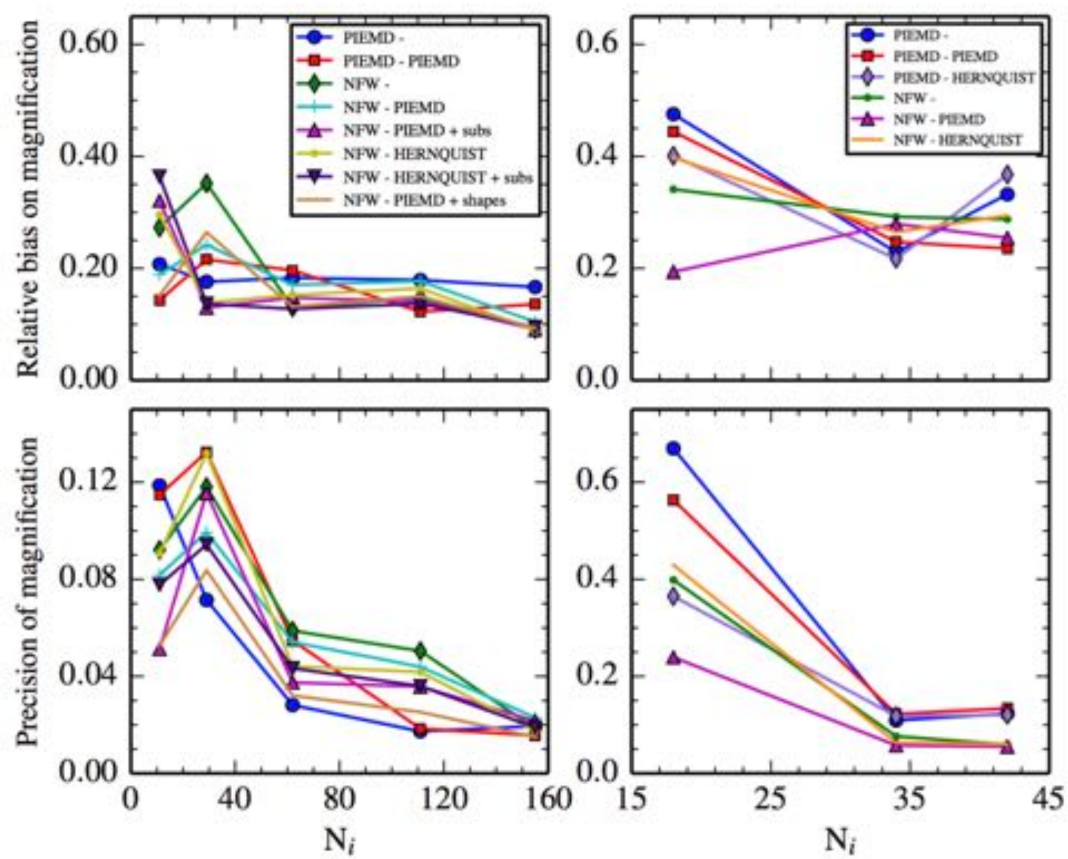
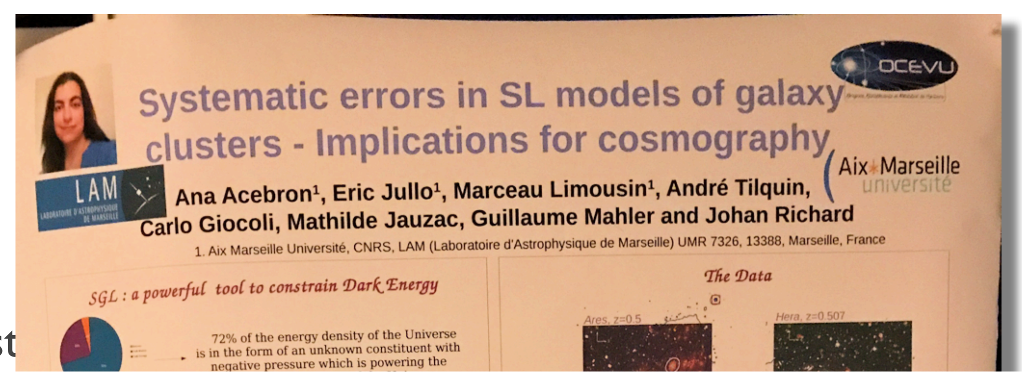


Acebron+2017

see poster behind you!



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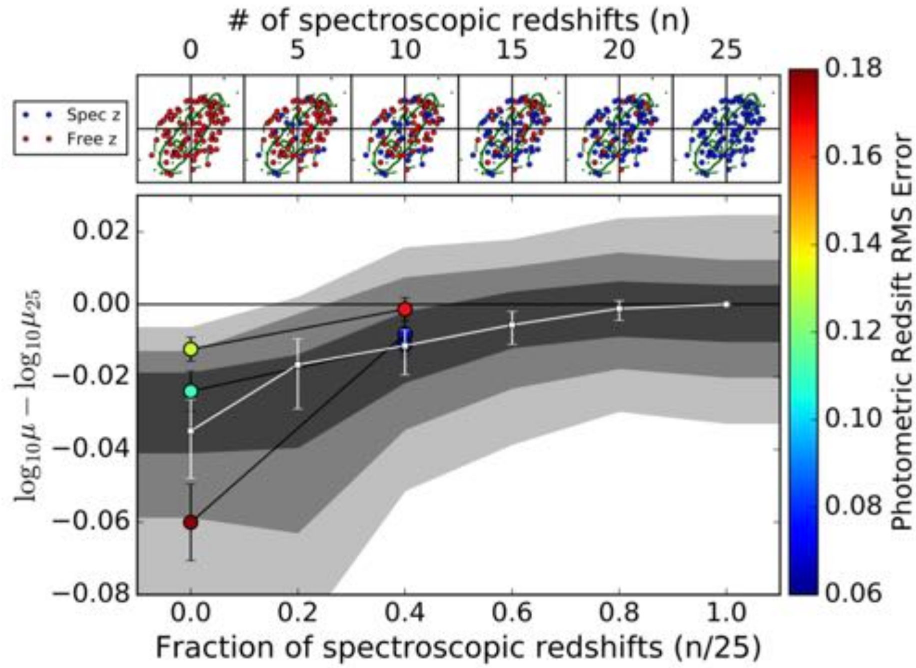
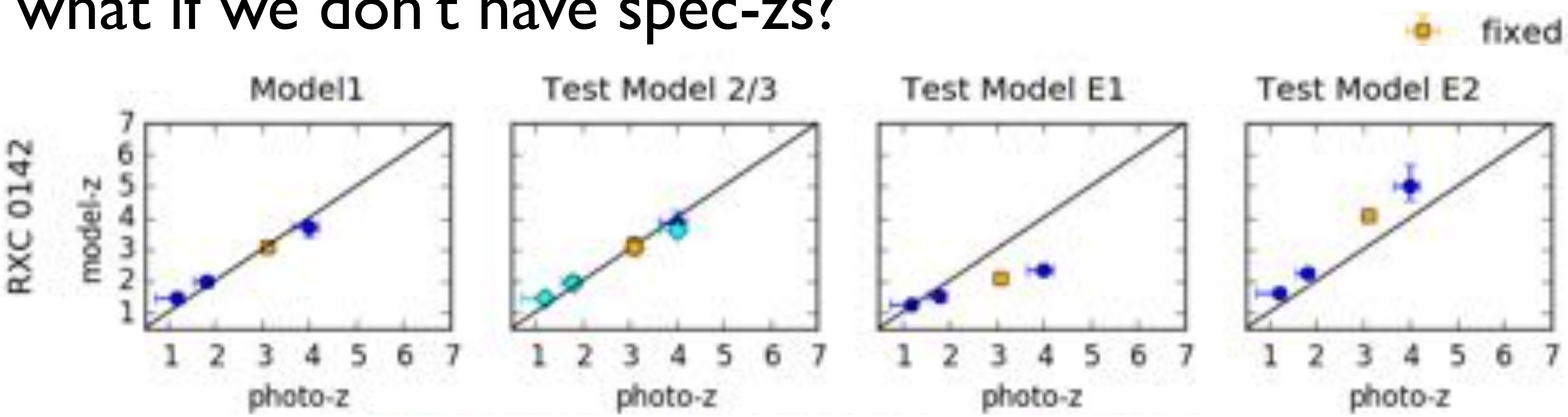


Johnson+2016

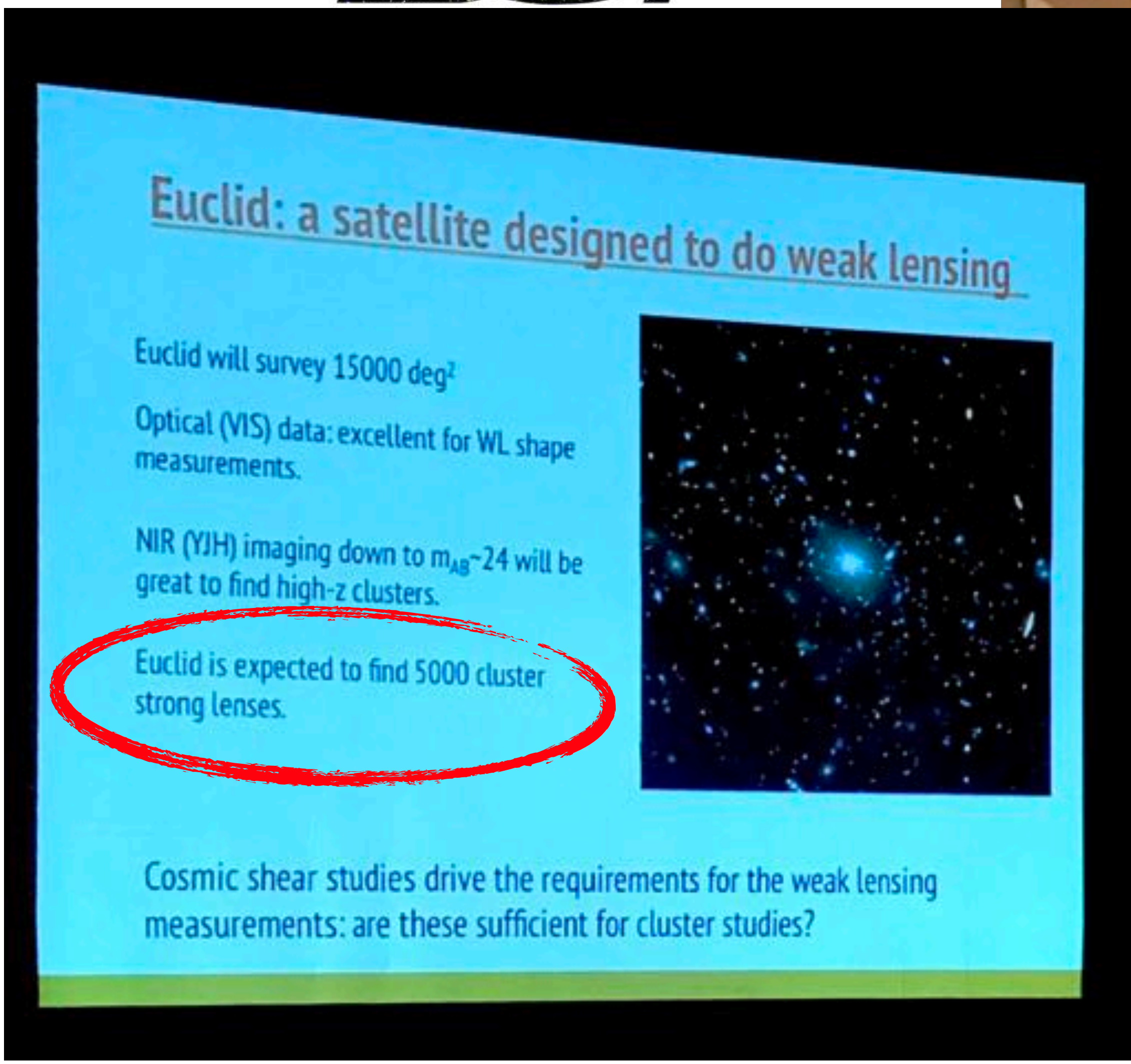
what if we don't have spec-zs?

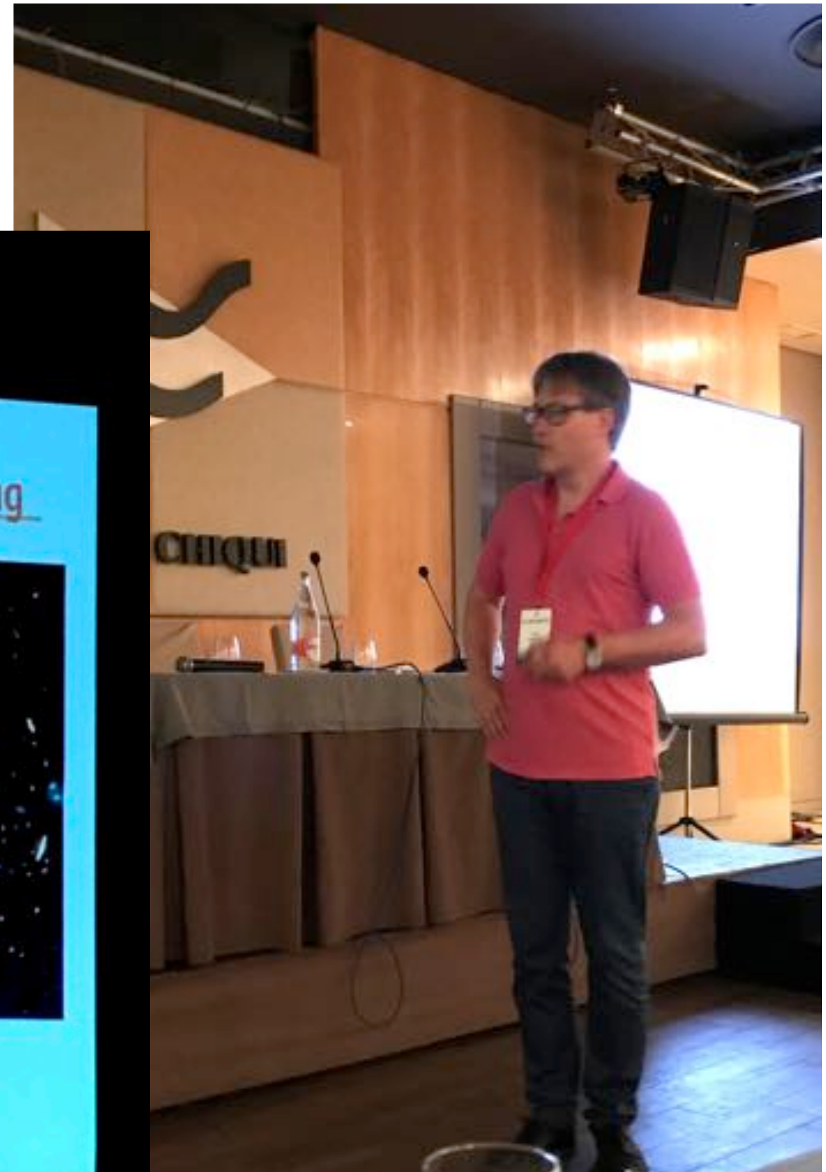


Cerny+2

DARK ENERGY
SURVEY

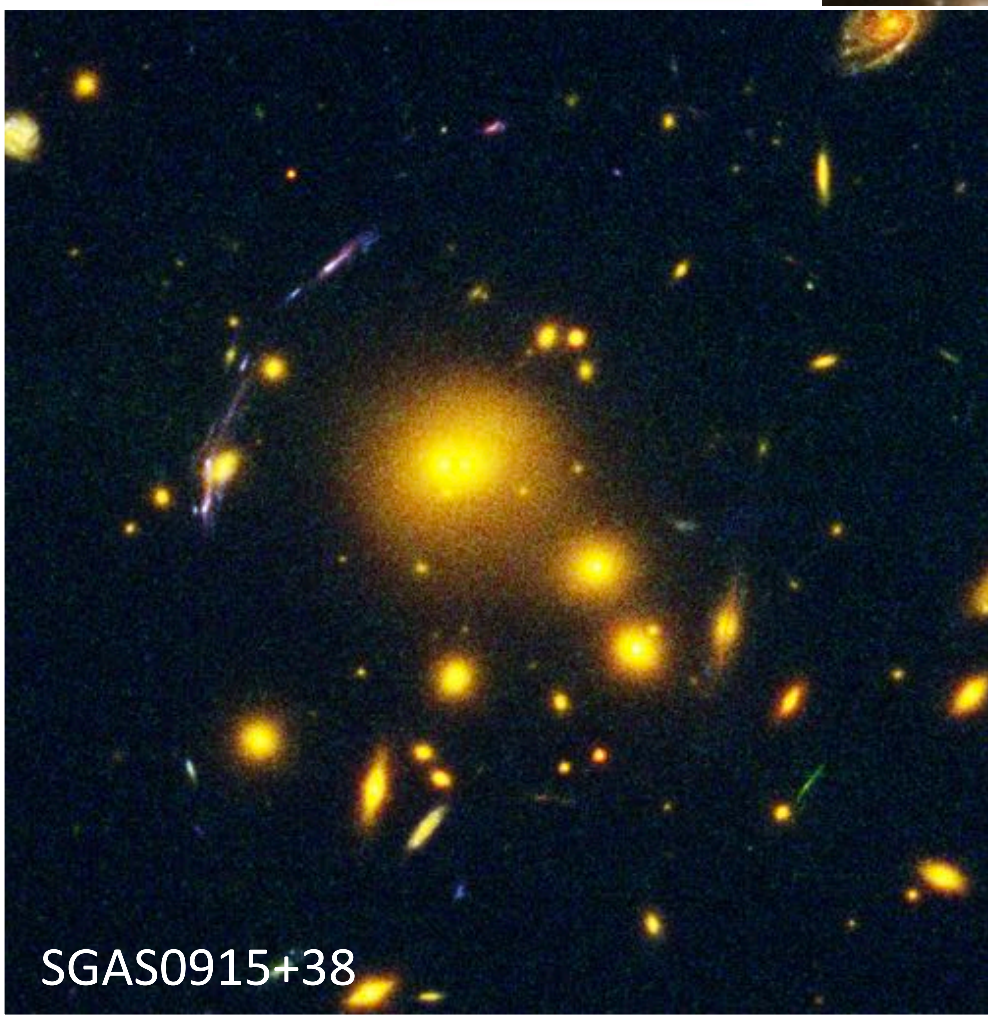
LSST

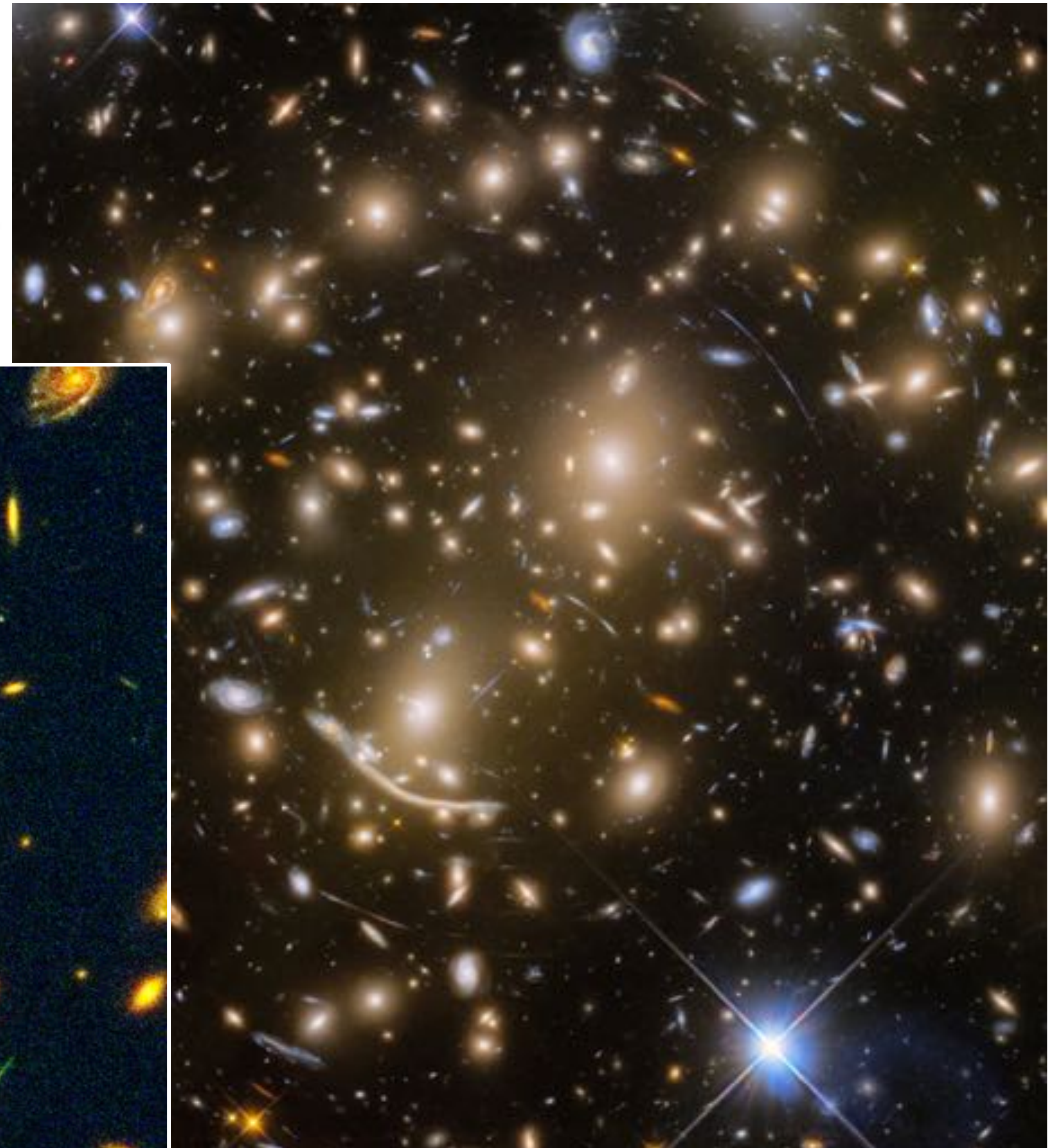


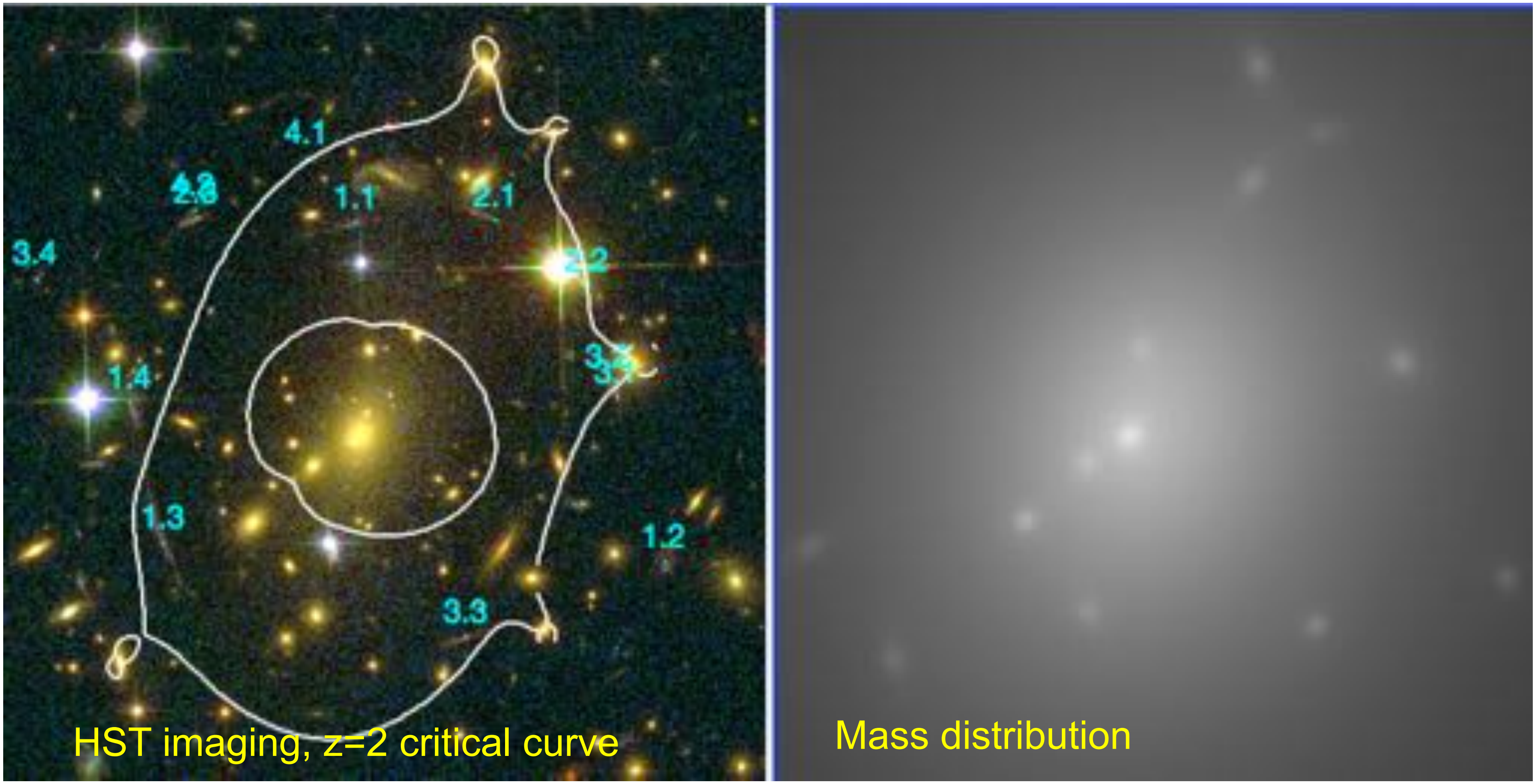


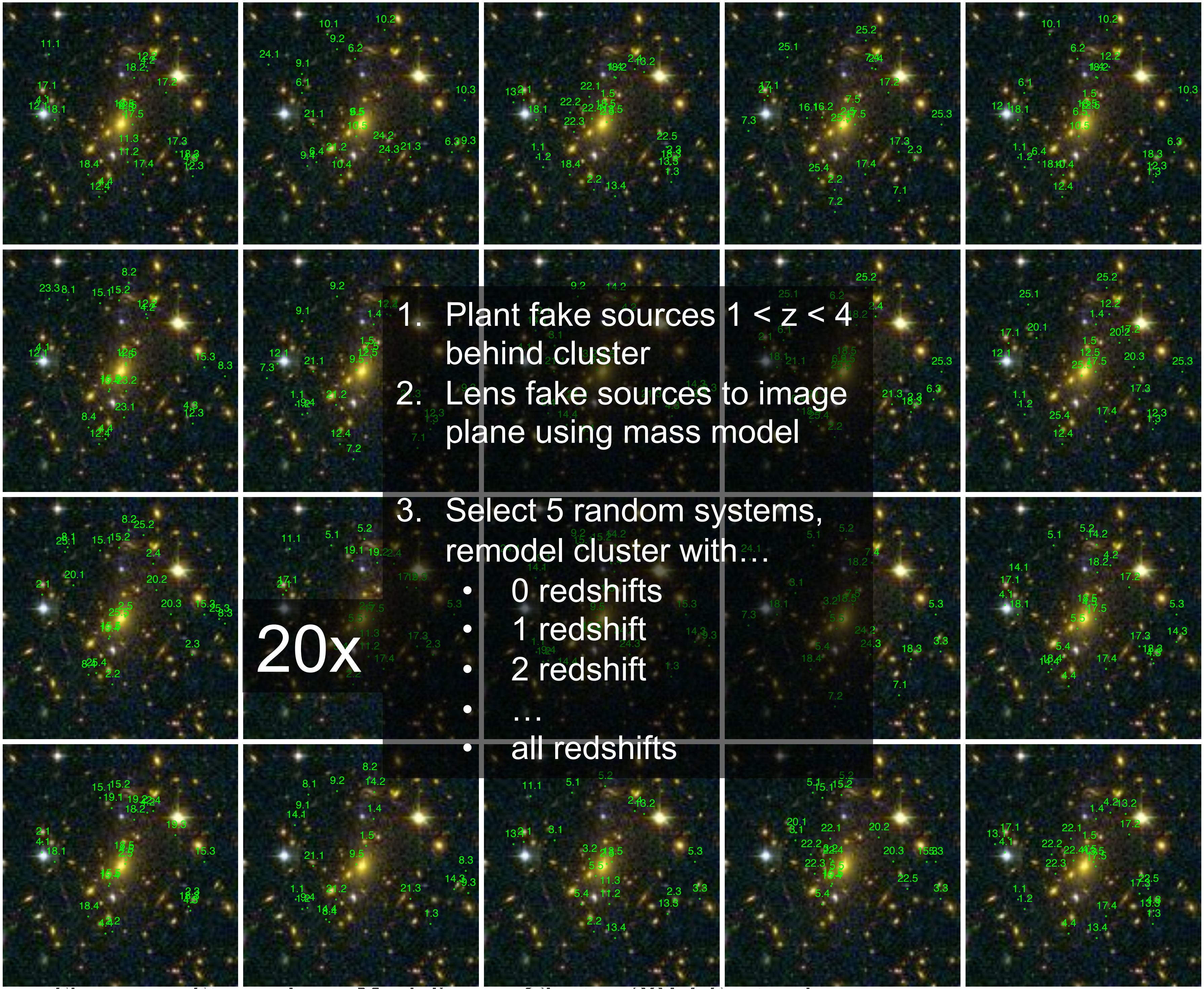
DARK ENERGY SURVEY

LSST
Large Synoptic Survey Telescope





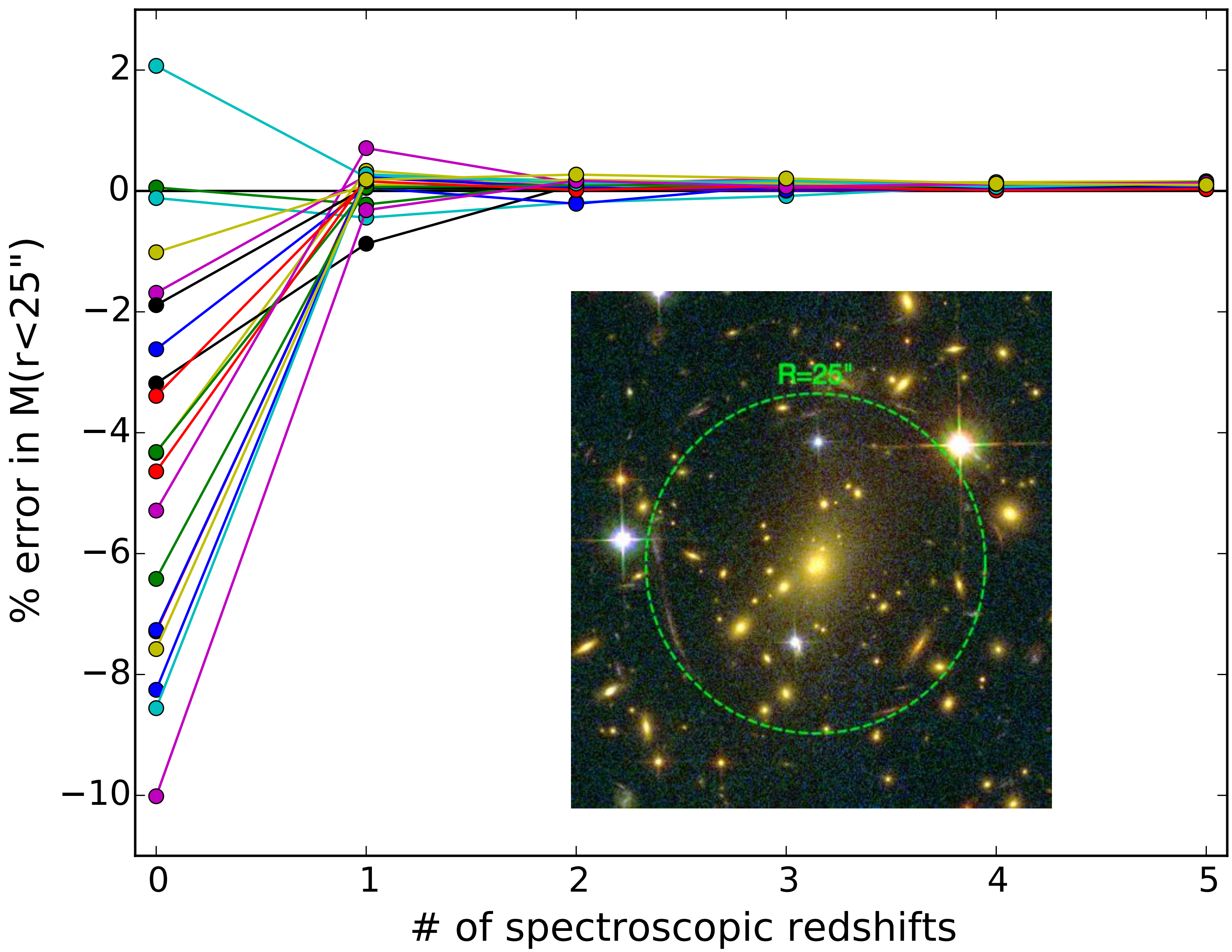

4.1
4.2
2.8
1.1
2.1
3.4
2.2
1.4
1.3
1.2
3.3
HST imaging, z=2 critical curve
Mass distribution



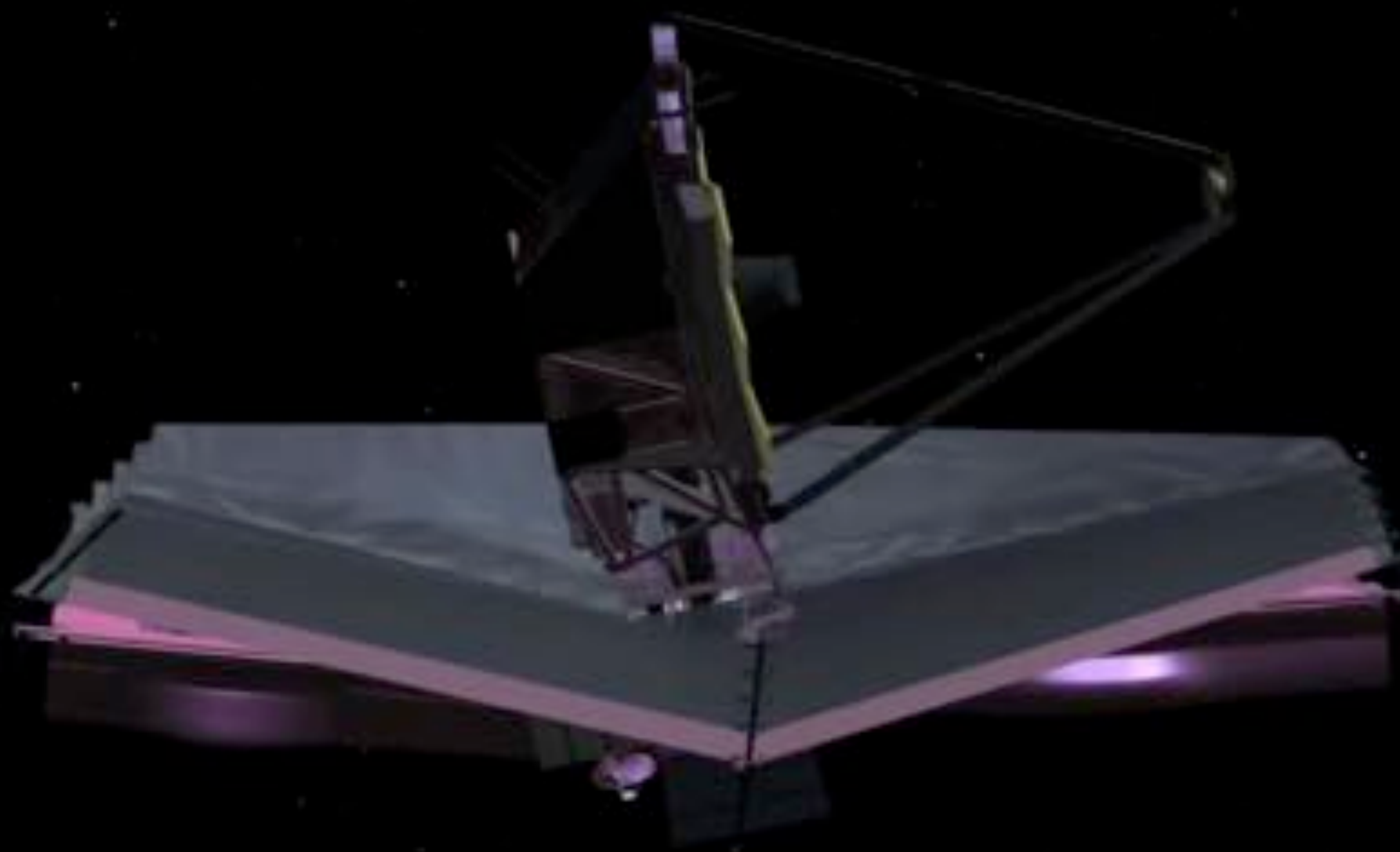
20x

1. Plant fake sources 1 < z < 4 behind cluster
2. Lens fake sources to image plane using mass model
3. Select 5 random systems, remodel cluster with…
   - 0 redshifts
   - 1 redshift
   - 2 redshift
   - …
   - all redshifts

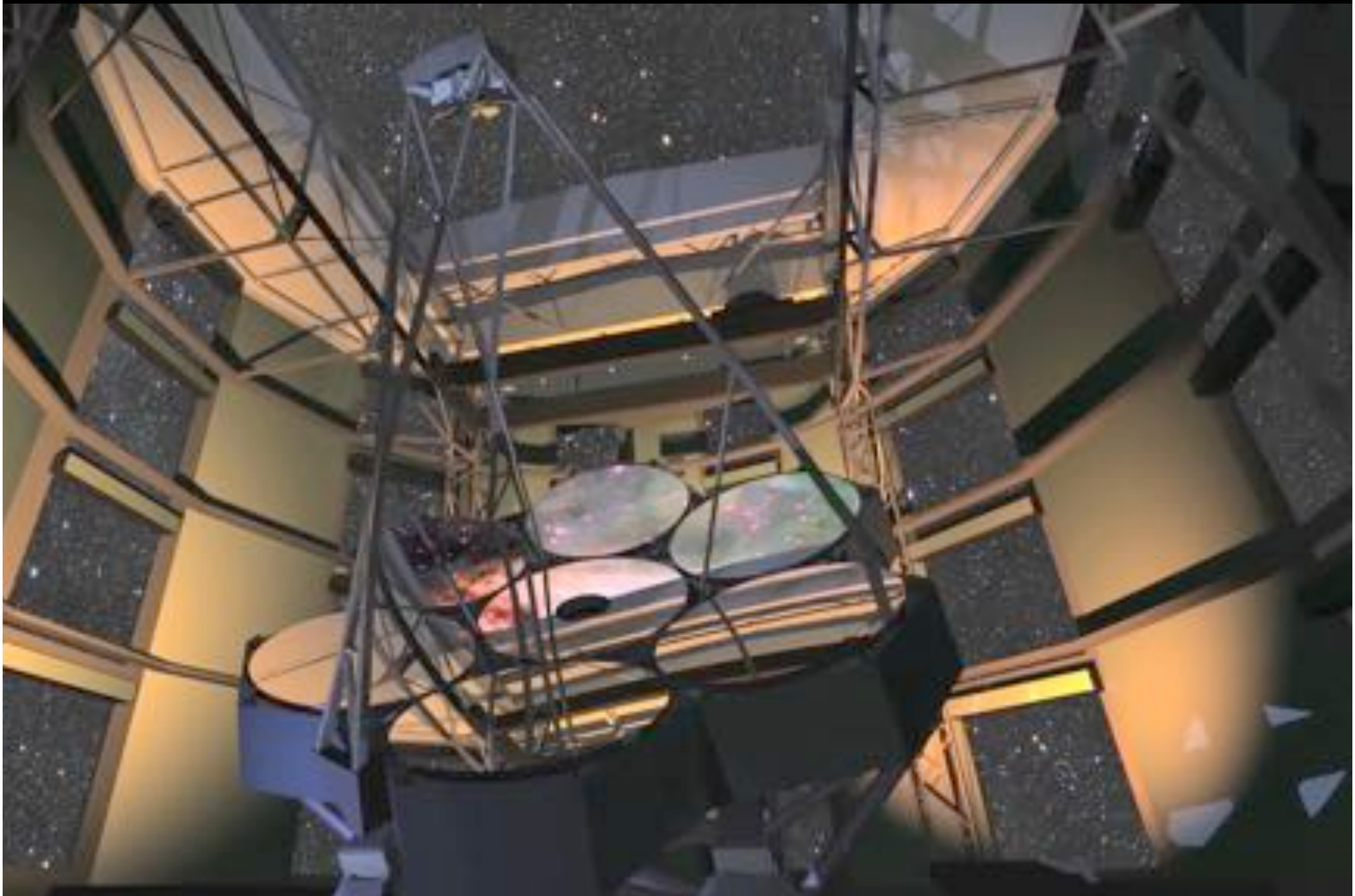
Total mass inside the multiple image locations is well constrained if there are ~2 spectroscopic systems



THE FUTURE...

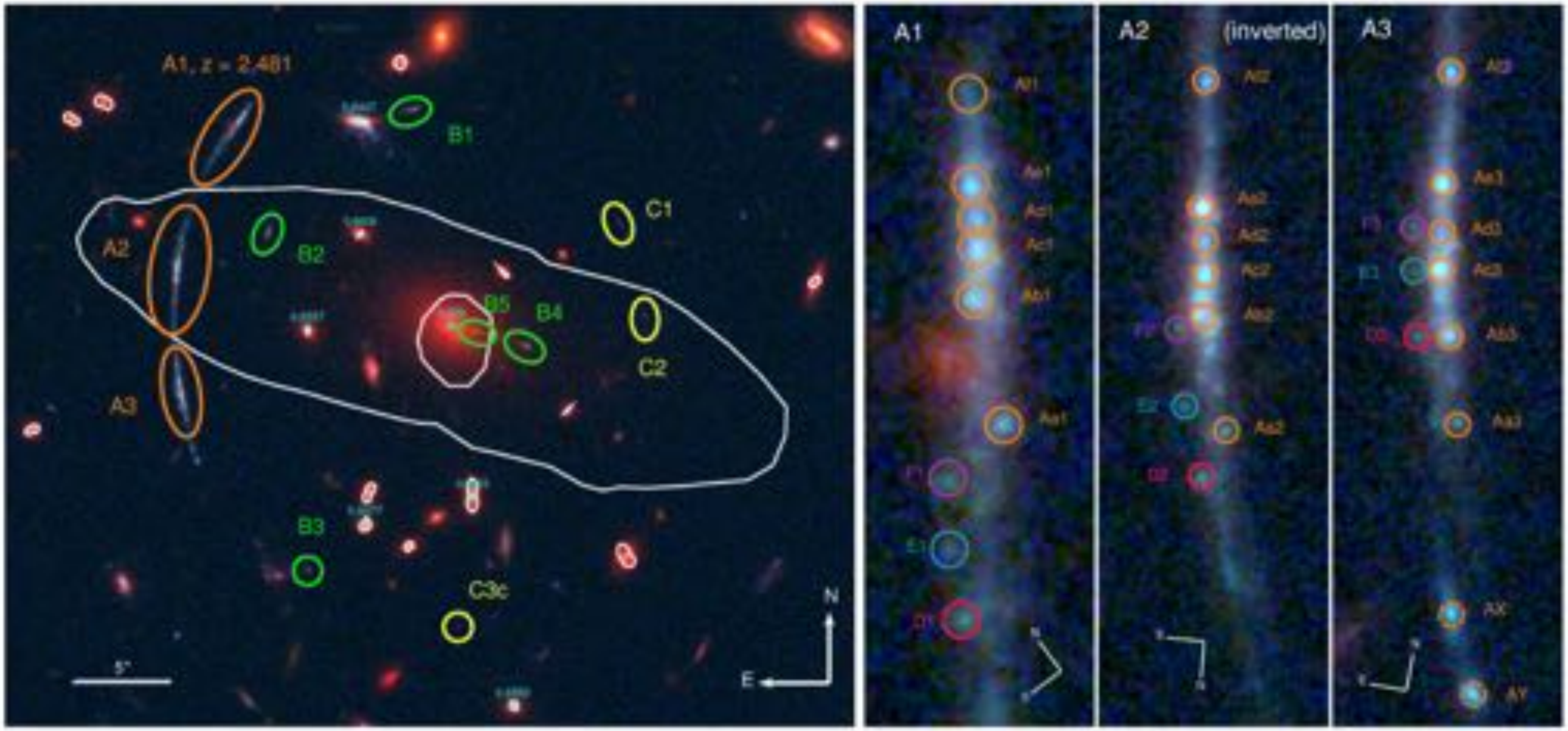


James Webb Space Telescope (2018)



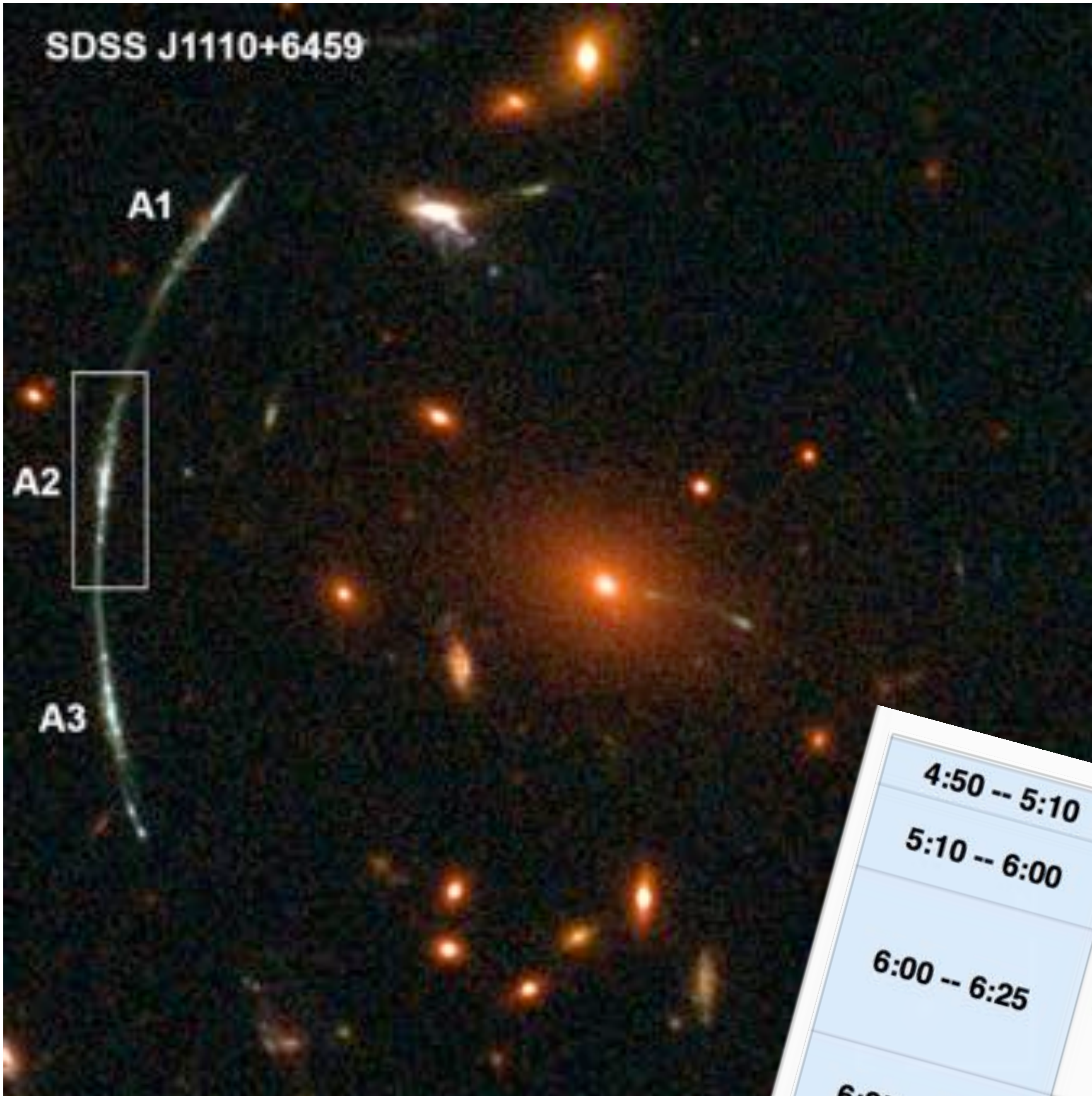
Giant Magellan Telescope (2021)

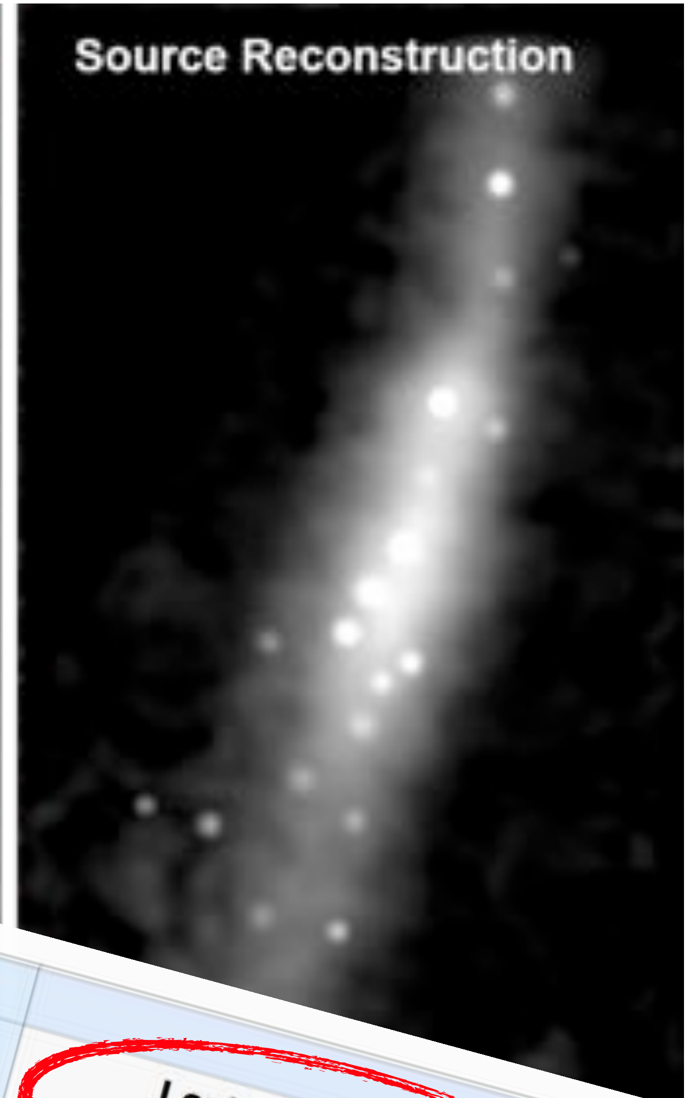
Star formation under the microscope: z~2

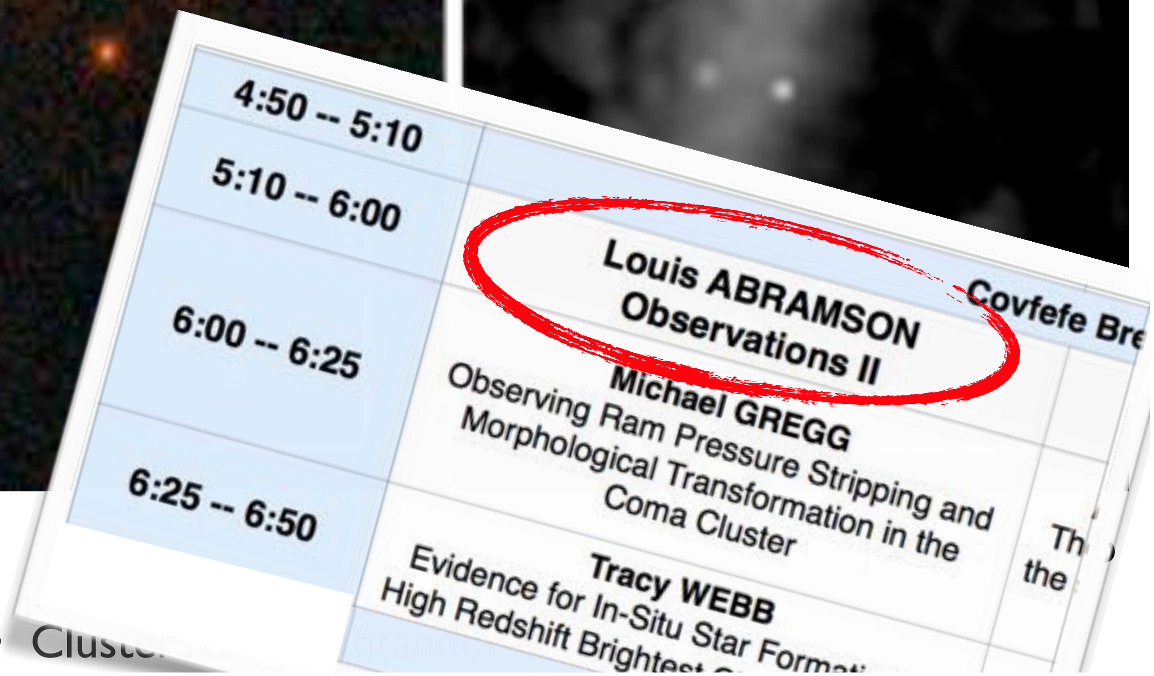


SDSSJ1110+64 Johnson+17a arXiv:1707.00707

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



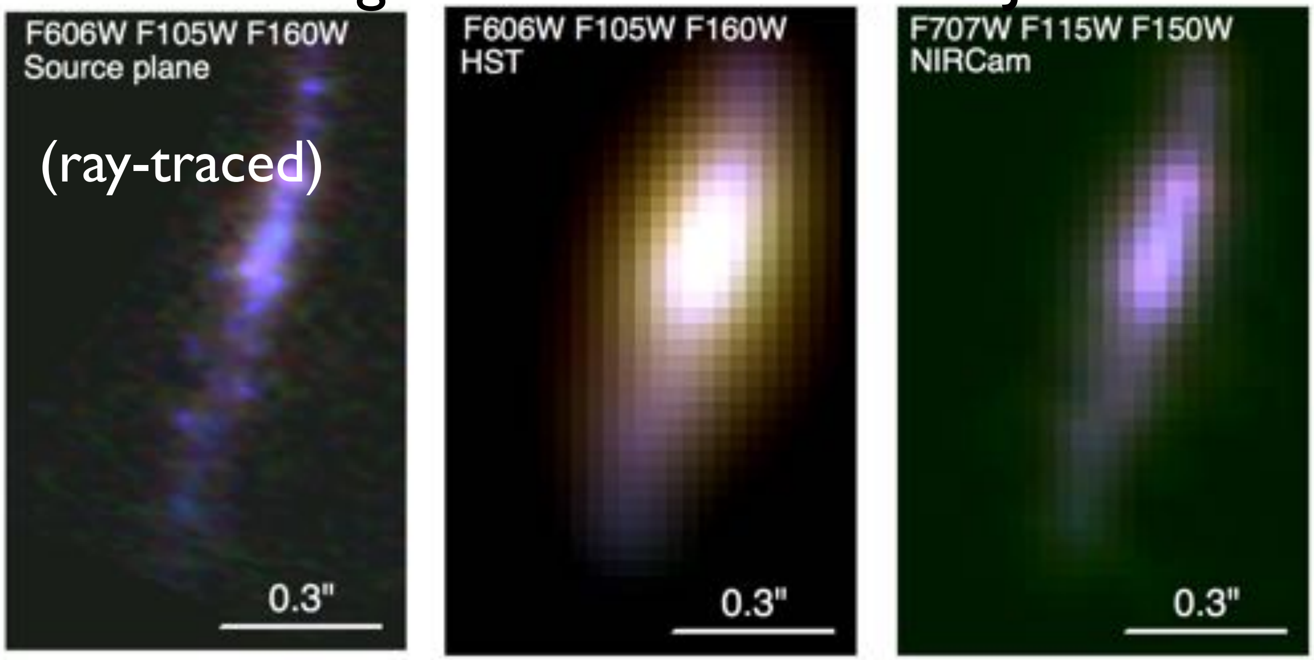




Johnson+17b arXiv:1707.00706

Star formation under the microscope: z~2

HST+lensing HST "CANDELS" JWST

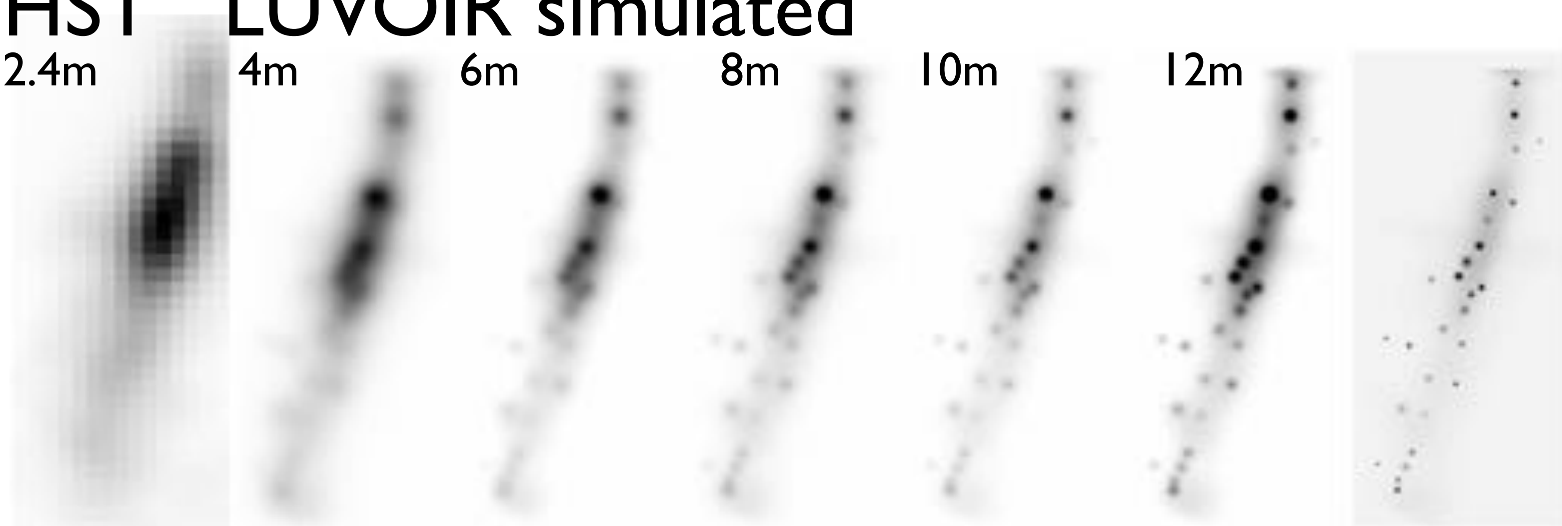


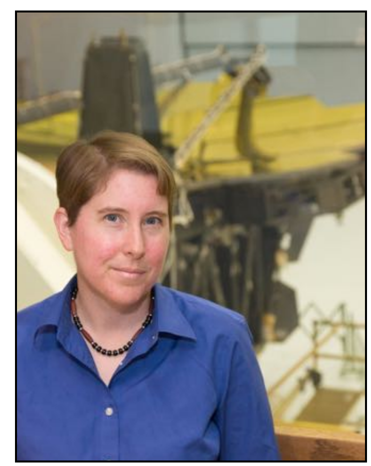
Rigby+17: what CANDELS may be missing?

arXiv:1707.00704

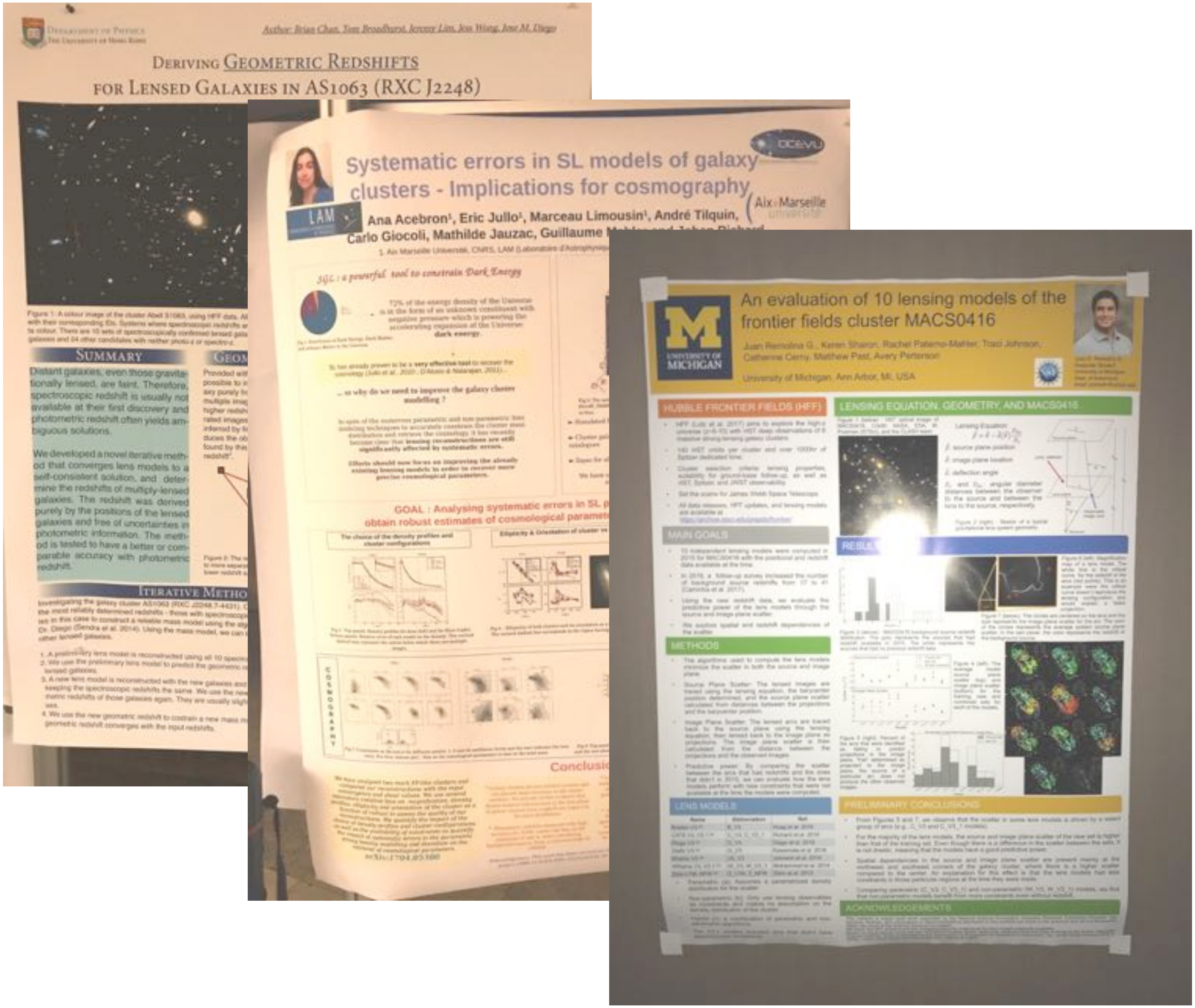
HST LUVOIR simulated

2.4m 4m 6m 8m 10m 12m





What would JWST + lensing do ?!!!


Author: Brian Chan, Tom Broadhurst, Jeremy Lim, Jess Wong, Jose M. Diego
Deriving Geometric Redshifts for Lensed Galaxies in AS1063 (RXC J2248)
Summary
Iterative Method
Systematic errors in SL models of galaxy clusters - Implications for cosmography
Ana Acebron[1], Eric Jullo[1], Marceau Limousin[1], André Tilquin,
Carlo Giocoli, Mathilde Jauzac, Guillaume
GOAL : Analysing systematic errors in SL
obtain robust estimates of cosmological parame
An evaluation of 10 lensing models of the frontier fields cluster MACS0416
Juan Remolina G., Keren Sharon, Rachel Paterno-Mahler, Traci Johnson, Catherine Cerny, Matthew Past, Avery Peterson
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Hubble Frontier Fields (HFF)
Lensing Equation, Geometry, and MACS0416
Main Goals
Methods
Lens Models
Preliminary Conclusions
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