

Abell 2163
(HST ACS)

Identifying Strongly Lensed High-Redshift Galaxies

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(The University of Tokyo)

on behalf of Masami Ouchi, Masamune Oguri and the RELICS team

Galaxy Evolution in Early Universe?

Q. When did the first galaxies form?

Q. How did they evolve?

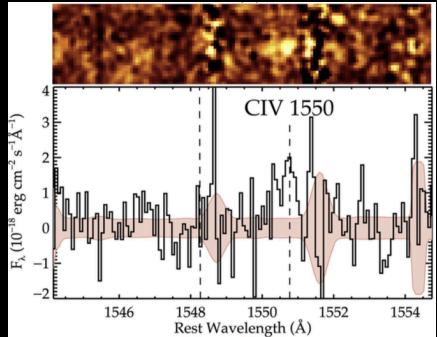
Q. What were their properties?

Q. Did they reionize the universe?



- Galaxy counting (luminosity functions)
 - Detailing individual galaxies in large samples
-

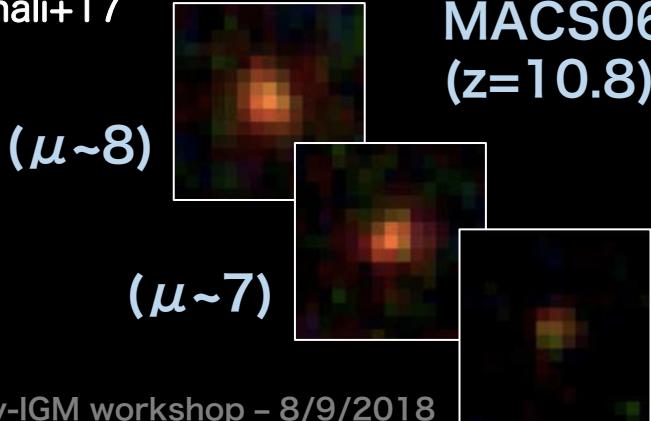
Brightly-Lensed Galaxies



CIV

RXCJ2248.7-4431-ID3
($z=6.1$, $\mu=5.5$)

Mainali+17

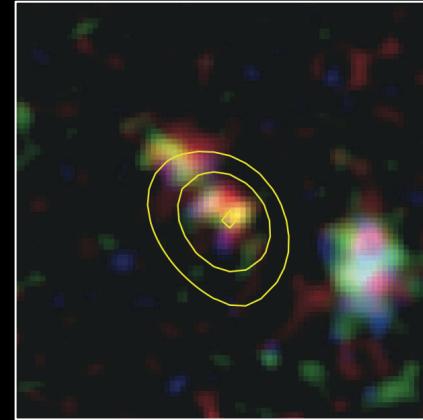


MACS0647-JD
($z=10.8$)

Coe+13

LBG

($\mu \sim 2$)

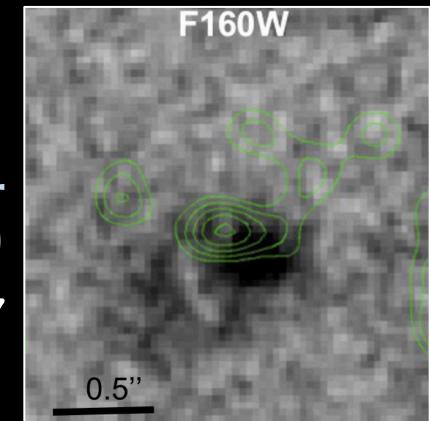


A1689-zD1
($z=7.5$, $\mu=9.3$)
Watson+15

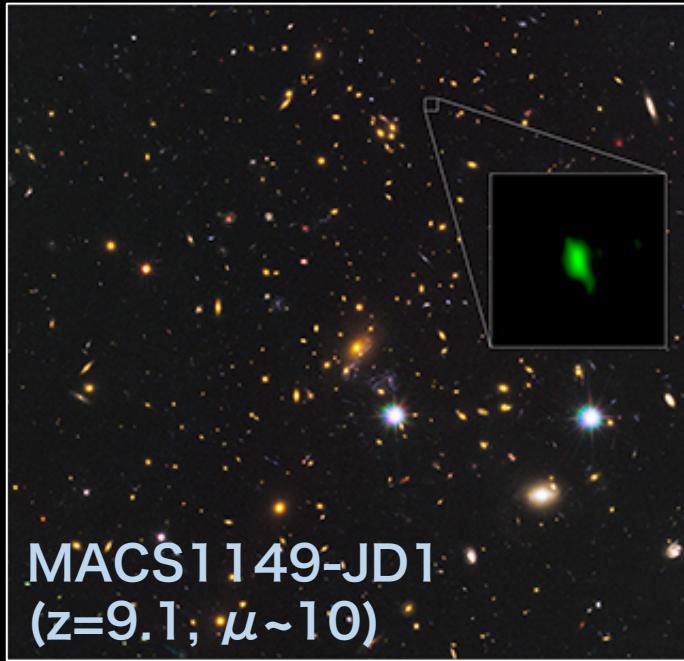
HST+ALMA

A2744-YD4
($z=8.4$, $\mu=1.8$)

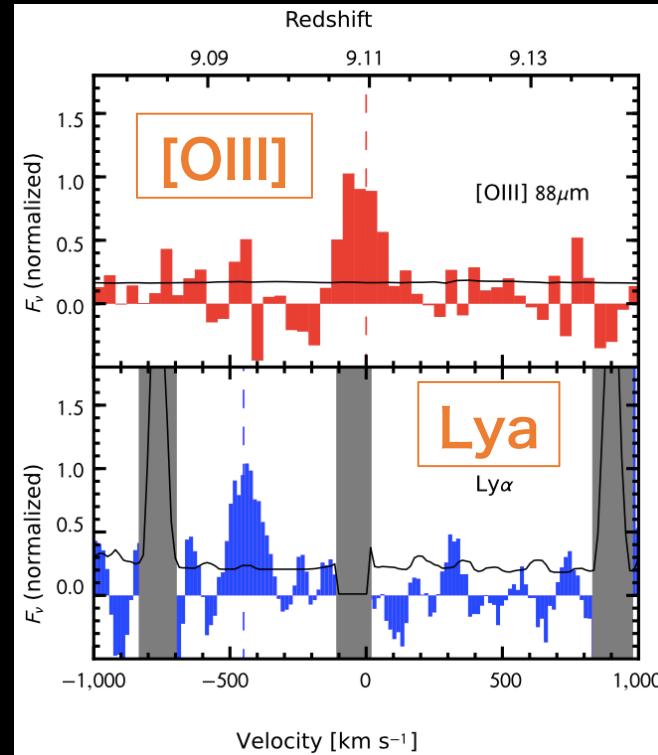
Laporte+17



Brightly-Lensed Galaxies



© ALMA (ESO/NAOJ/NRAO)



Hashimoto+18a



Lensed Galaxy Candidates



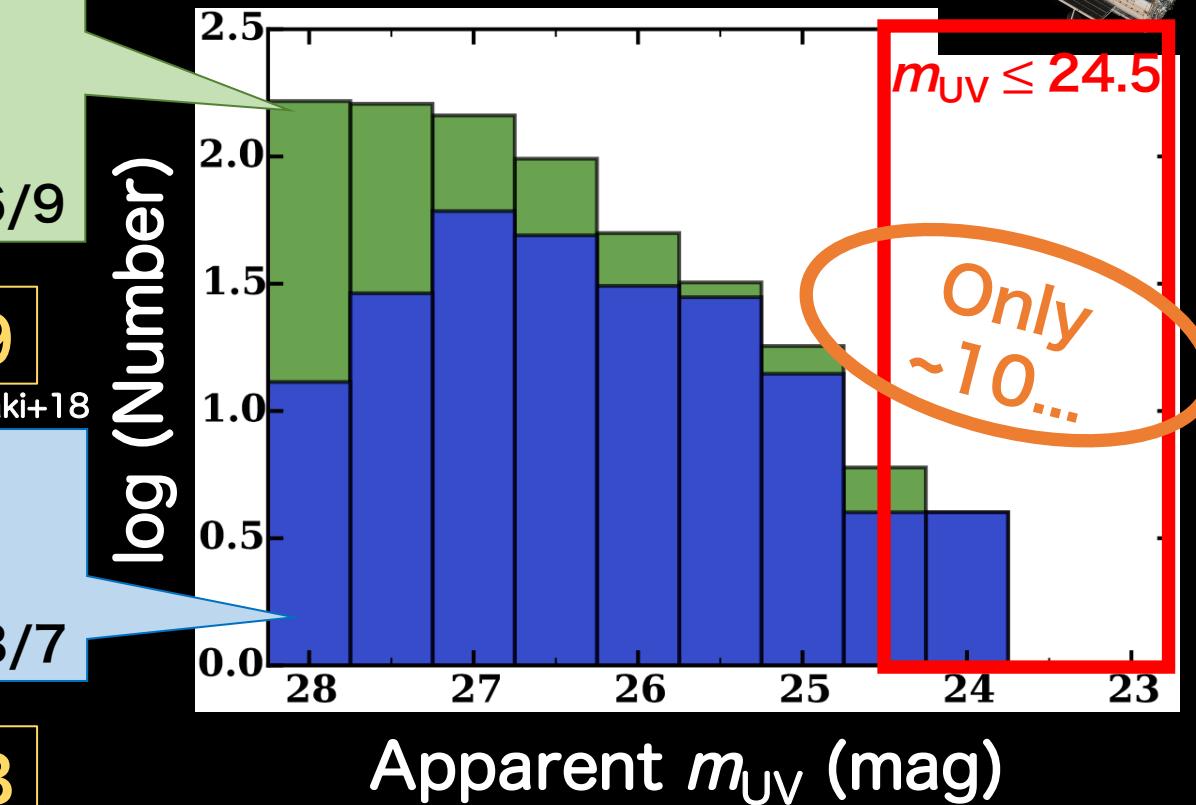
PI: Lotz
6 clusters
840 orbits
2013/10-2016/9

110 cand. at $z=6-9$

Ishigaki+18

PI: Postman
25 clusters
524 orbits
2010/11-2013/7

181 cand. at $z=6-8$



RELICS Overviews

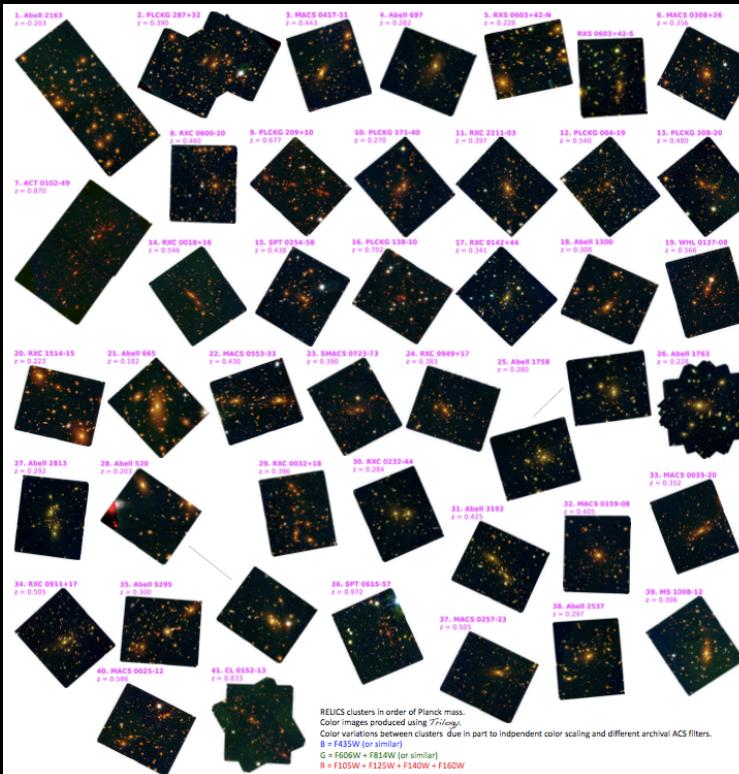
- REionization LensIng Cluster Survey
- HST Treasury Program
- PI: Dan Coe (STScI)
- Oct. 2015 – April 2017
- ~7 bands (ACS/WFC + WFC3/IR)
- 190 orbits (5σ depth = 26-27 mag)



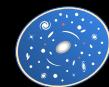
Abell 2163
(ACS falsecolor)

RELICS Targets

- 41 galaxy-cluster regions
- ~ 200 arcmin 2



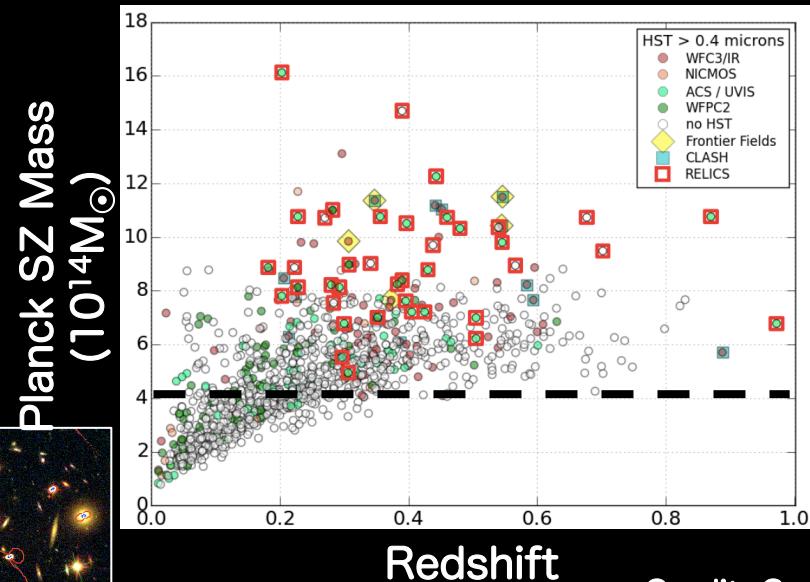
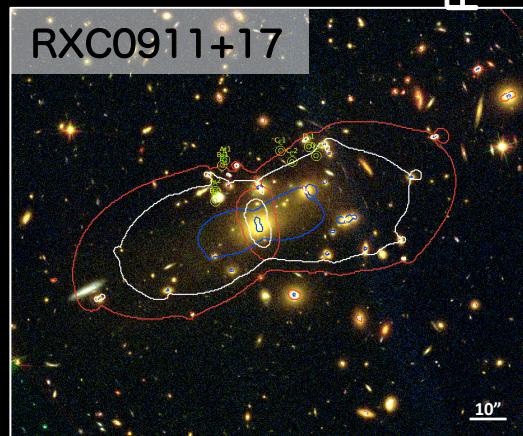
Credit: Coe



RELICS
Reionization Lensing Cluster Survey

RELICS Targets

- 41 galaxy-cluster regions
 - ~200 arcmin²
 - most massive ($> 4 \times 10^{14} M_{\odot}$), causing '*powerful*' strong-lensing
 - mass-modeling is ongoing (currently 20/41 released)

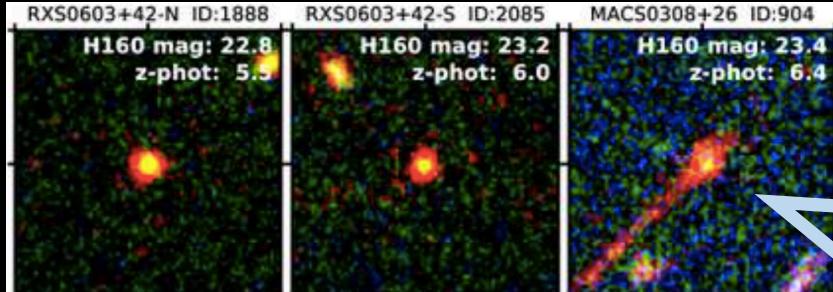


Credit: Coe

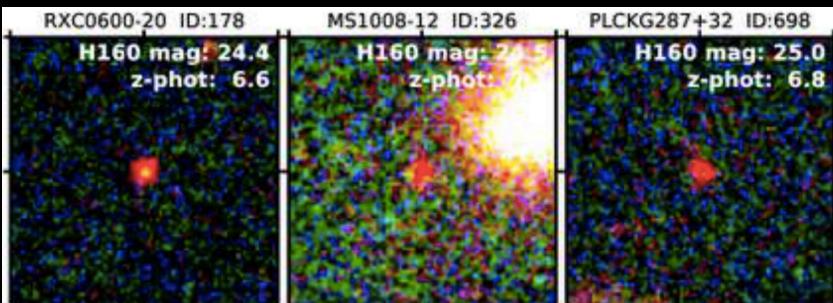
Kikuchi+⁺

321 galaxy candidates at $z \geq 6$

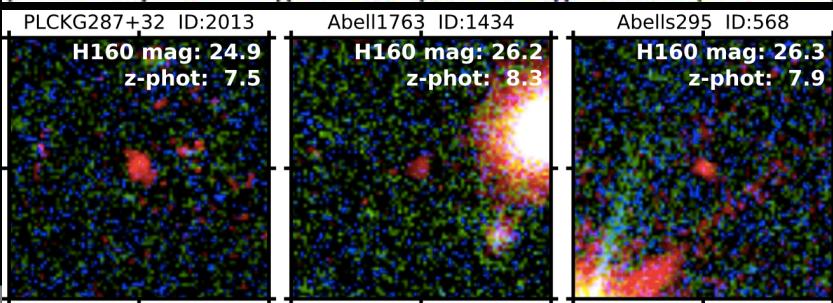
255 at $z=6$



57 at $z=7$



8 at $z=8$



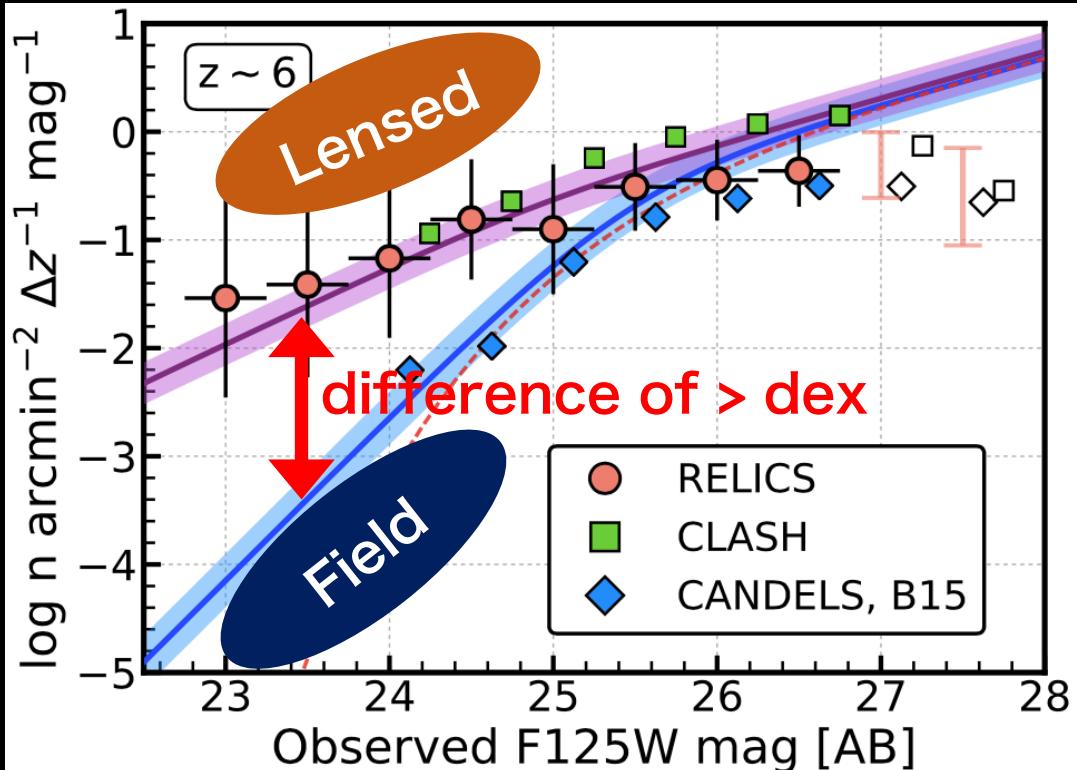
intrinsic (delensed):
25.4 mag

~ x23
magnified

apparent (lensed):
23.4 mag

Salmon+17

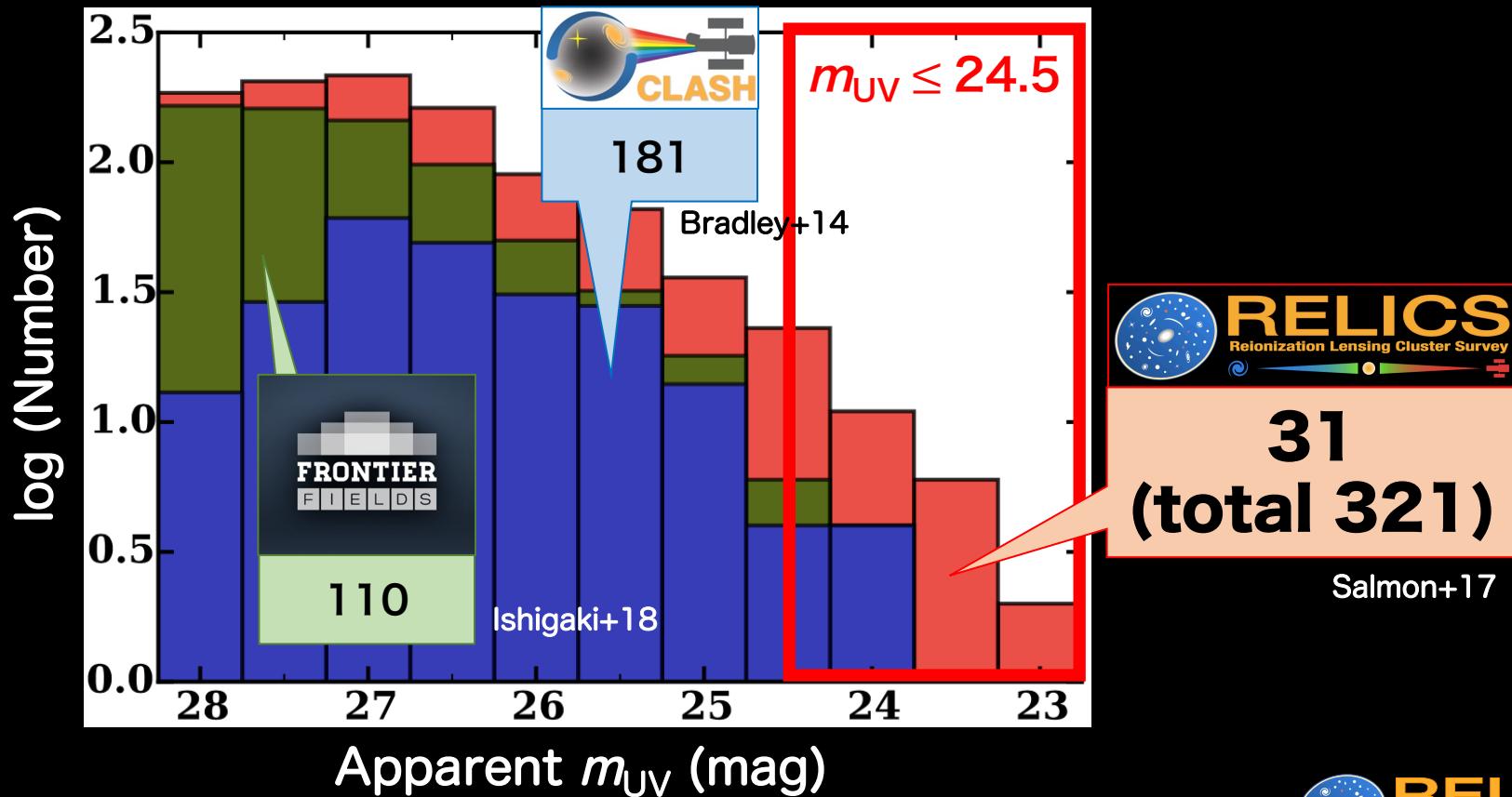
Lensing Advantage



Bright high-z galaxy candidates detected efficiently owing to lensing

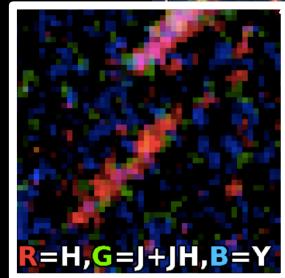
Salmon+17

Brightly-Lensed Galaxies in RELICS



$z=9.9$ Arc (?)

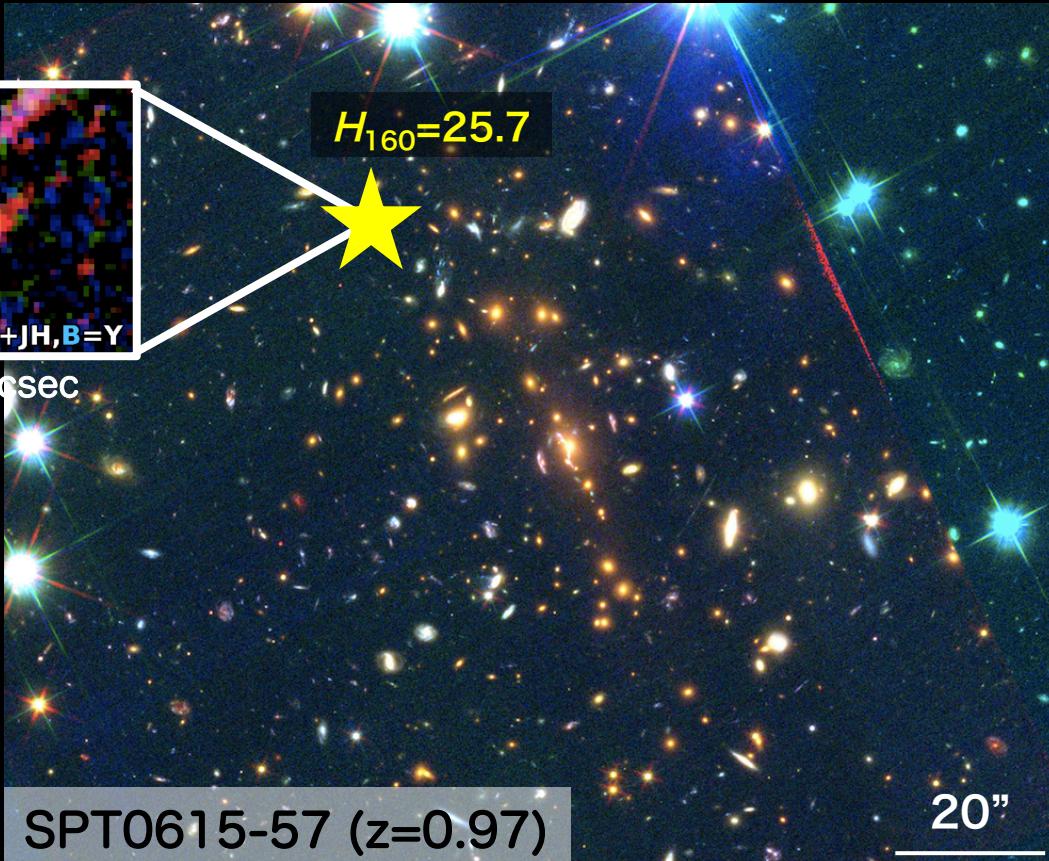
3 arcsec



$H_{160}=25.7$



3 arcsec

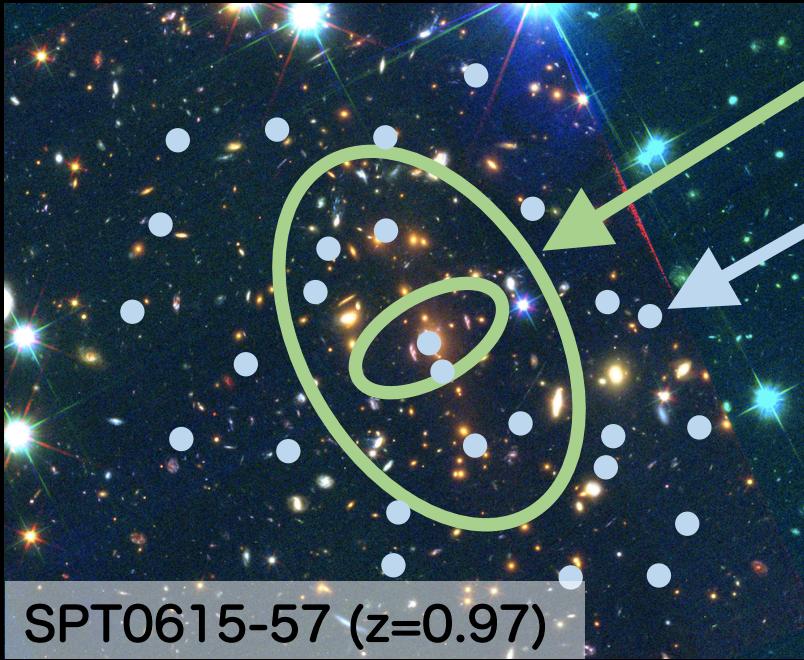


SPT0615-57 ($z=0.97$)

20''

SPT0615-57 Lens Modeling

① Assume Mass profiles



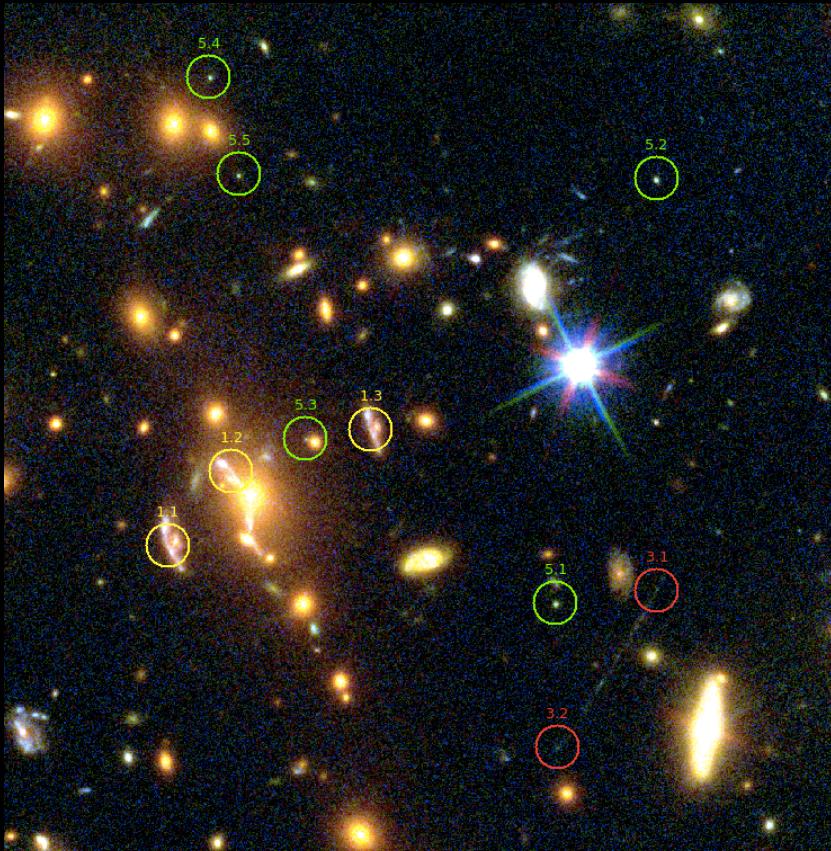
'NFW' profile

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

'gals' profile

$$\frac{\sigma}{\sigma_*} = \left(\frac{L}{L_*}\right)^{1/4}, \quad \frac{r_{\text{trunc}}}{r_{\text{trunc},*}} = \left(\frac{L}{L_*}\right)^\eta$$

SPT0615-57 Lens Modeling



① Assume mass profiles

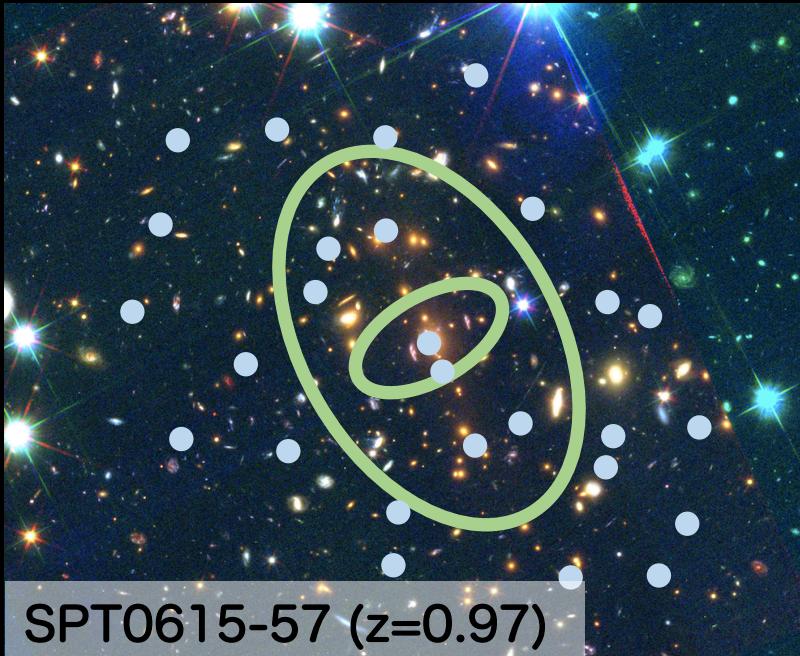
'NFW' profile $\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$

'gals' profile $\frac{\sigma}{\sigma_*} = \left(\frac{L}{L_*}\right)^{1/4}, \quad \frac{r_{\text{trunc}}}{r_{\text{trunc},*}} = \left(\frac{L}{L_*}\right)^\eta$

② Identify multiple image pairs

10 images (3 pairs)

SPT0615-57 Lens Modeling



① Assume mass profiles

'NFW' profile $\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$

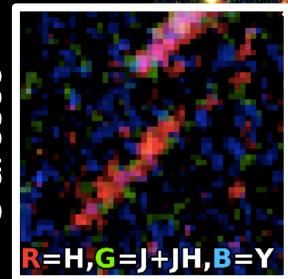
'gals' profile $\frac{\sigma_*}{\sigma} = \left(\frac{L}{L_*}\right)^{1/4}, \quad \frac{r_{\text{trunc}}}{r_{\text{trunc}*}} = \left(\frac{L}{L_*}\right)^\eta$

② Identify multiple image pairs

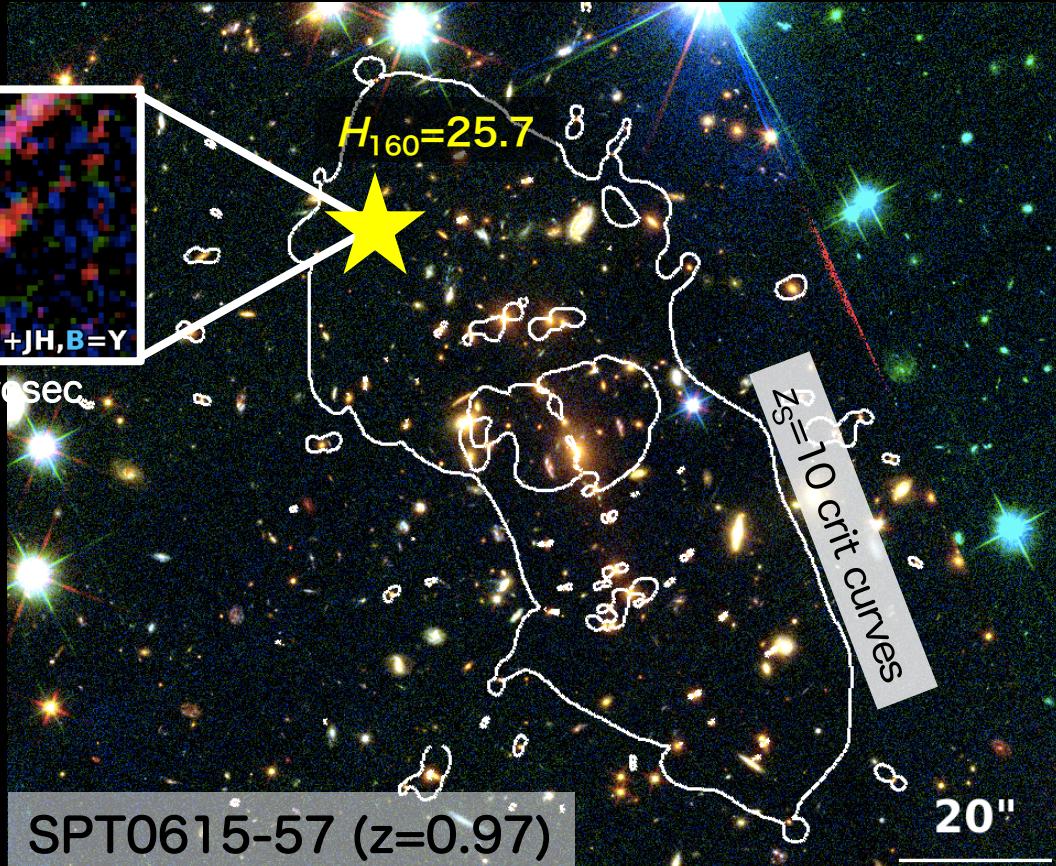
③ Constrain params. in ① to reproduce ② using GLAFIC

$z=9.9$ Arc (?)

3 arcsec



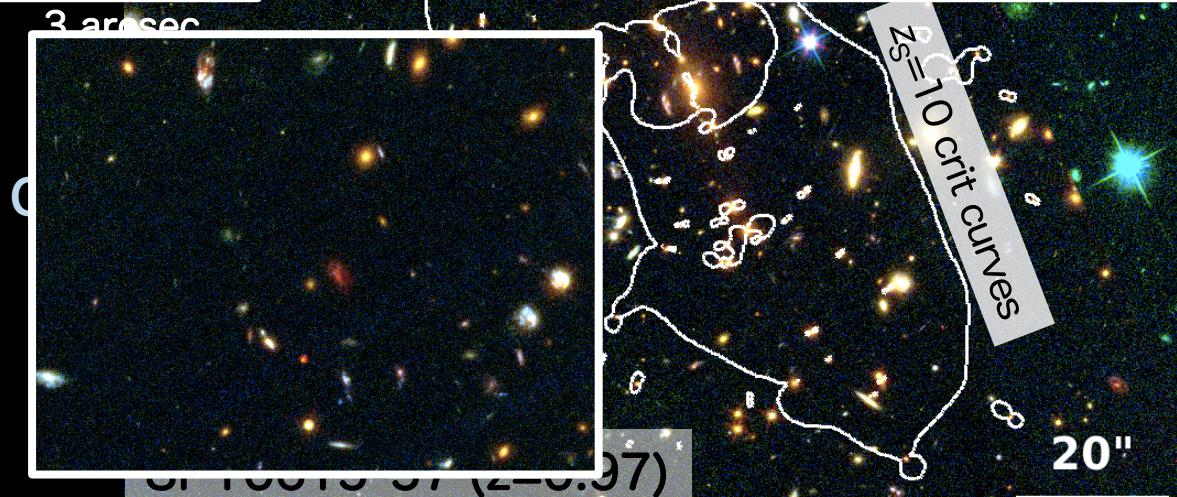
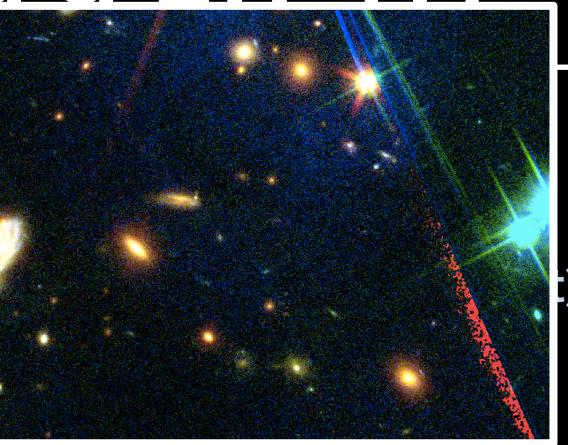
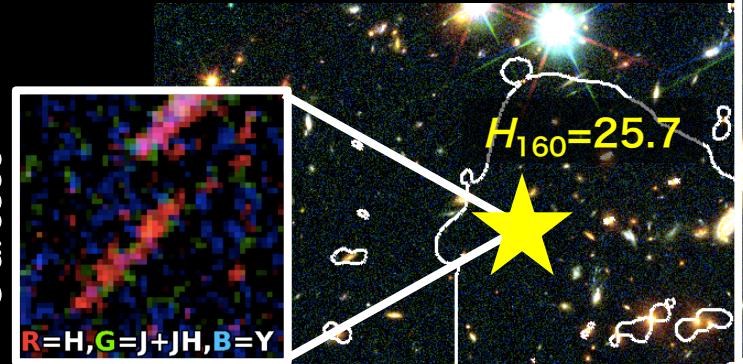
3 arcsec



Lens model constructed
by Kikuchi+ using
GLAFIC

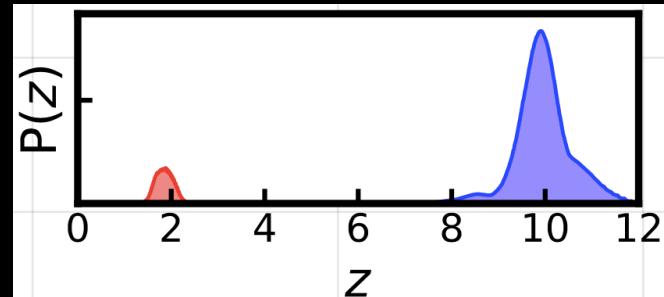
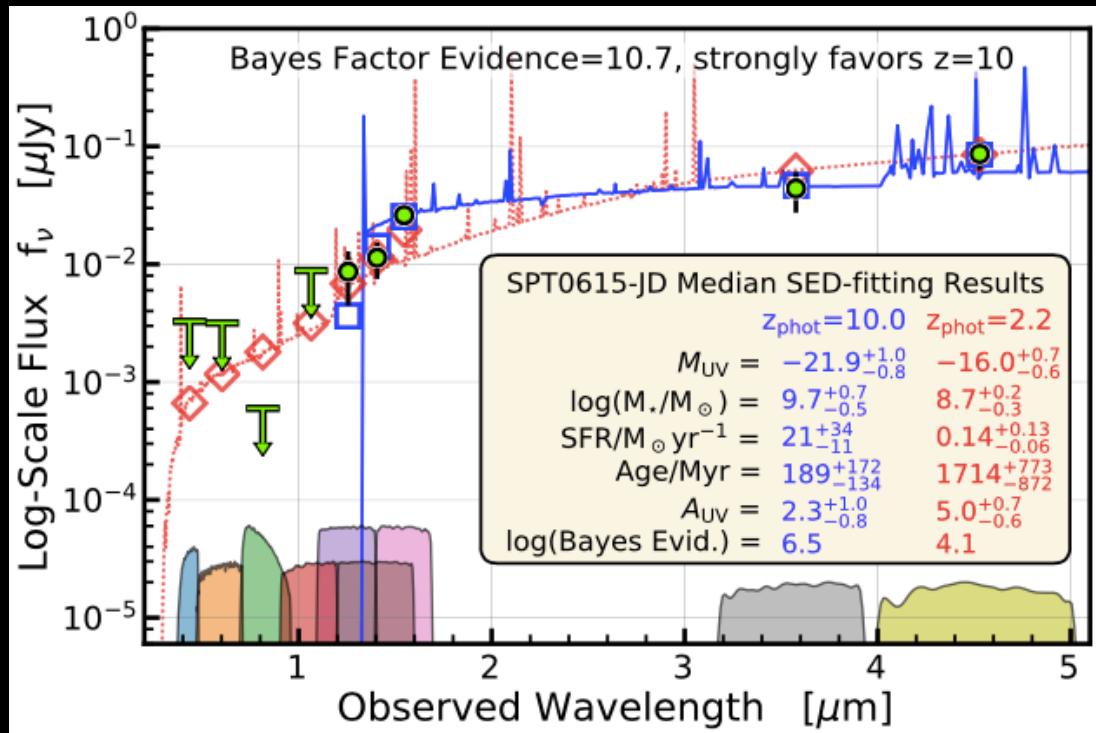
$z=9.9$ Arc (2)

3 arcsec



Prediction based on
the lens model
does not rule out
 $z=9.9$

$z=9.9$ Arc (?)



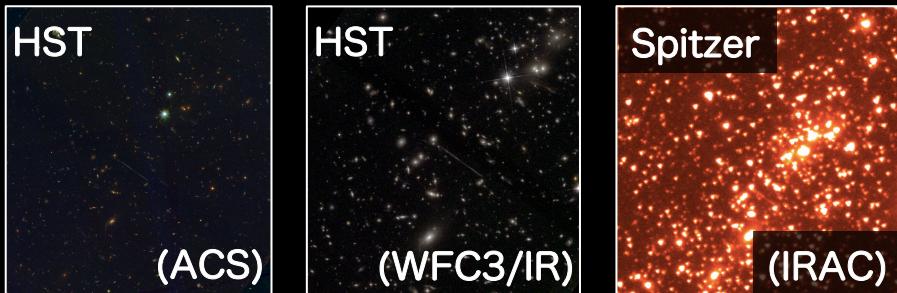
SED fitting prefers
 $z=10$

Salmon+18

Follow-up Observations

Spitzer

archive: 390hr for all clusters



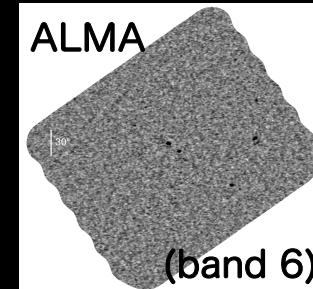
+

330 hr (accepted; cy14)

ALMA

archive: 1 cluster-field survey

ACT0102-49
‘El Gordo’



+

15 more (accepted; cy6)

As part of the **ALMA Lensing Cluster Survey**
(PI: Kohno)

Summary

- ① **RELICS** surveyed the 41 cluster regions with HST.
- ② 321 galaxy candidates were identified at $z=6-8$, including brightly-lensed sources (~23 mag).
- ③ Mass-modeling is ongoing (20/41 released).
- ④ Follow-up observations have been accepted (Spitzer, ALMA).