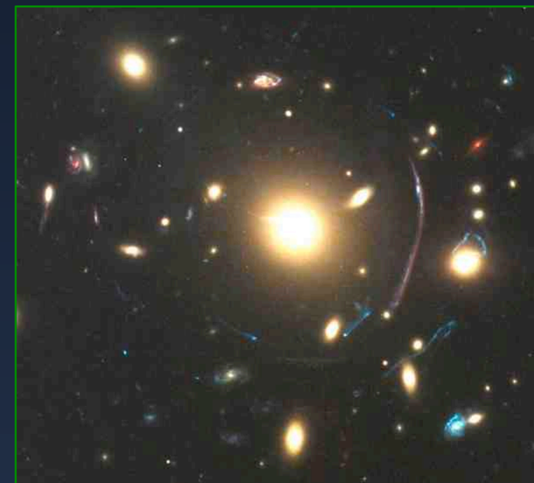
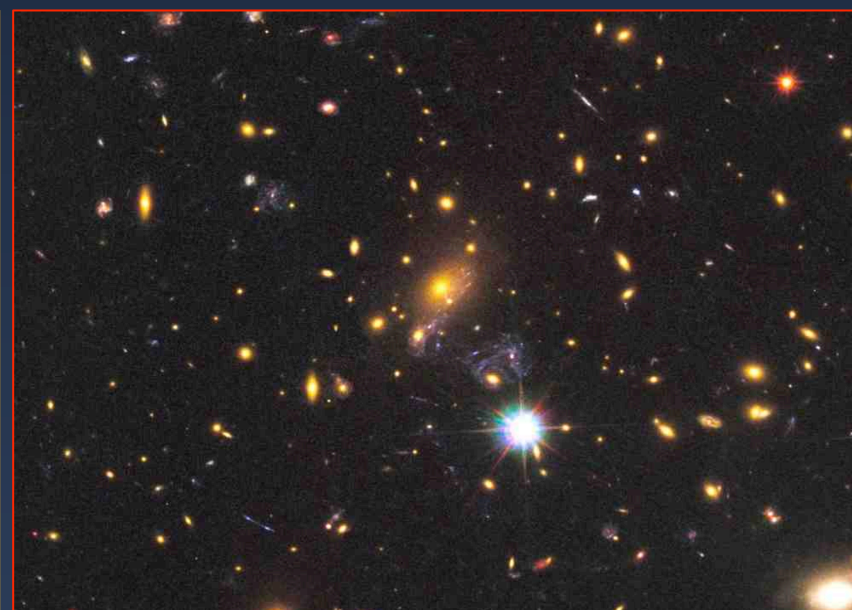
Cluster Lensing And Supernova survey with Hubble





Final Report to STUC, Marc Postman, CLASH P.I.

CLASH is a team effort!

CLASH science team at the RAS
September 2013
London

The CLASH Science Team: ~60 researchers, 30 institutions, 12 countries

Marc Postman, P.I.	Space Telescope Science Institute (STScI)
Begona Ascaso	UC Davis
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Dan Coe	STScI
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Holland Ford	JHU
Jorge Gonzalez	Universidad Catolica de Chile
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Leopoldo Infante	Universidad Católica de Chile
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Alberto Molino	IAA
John Moustakas	Siena College
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Brandon Patel	Rutgers University
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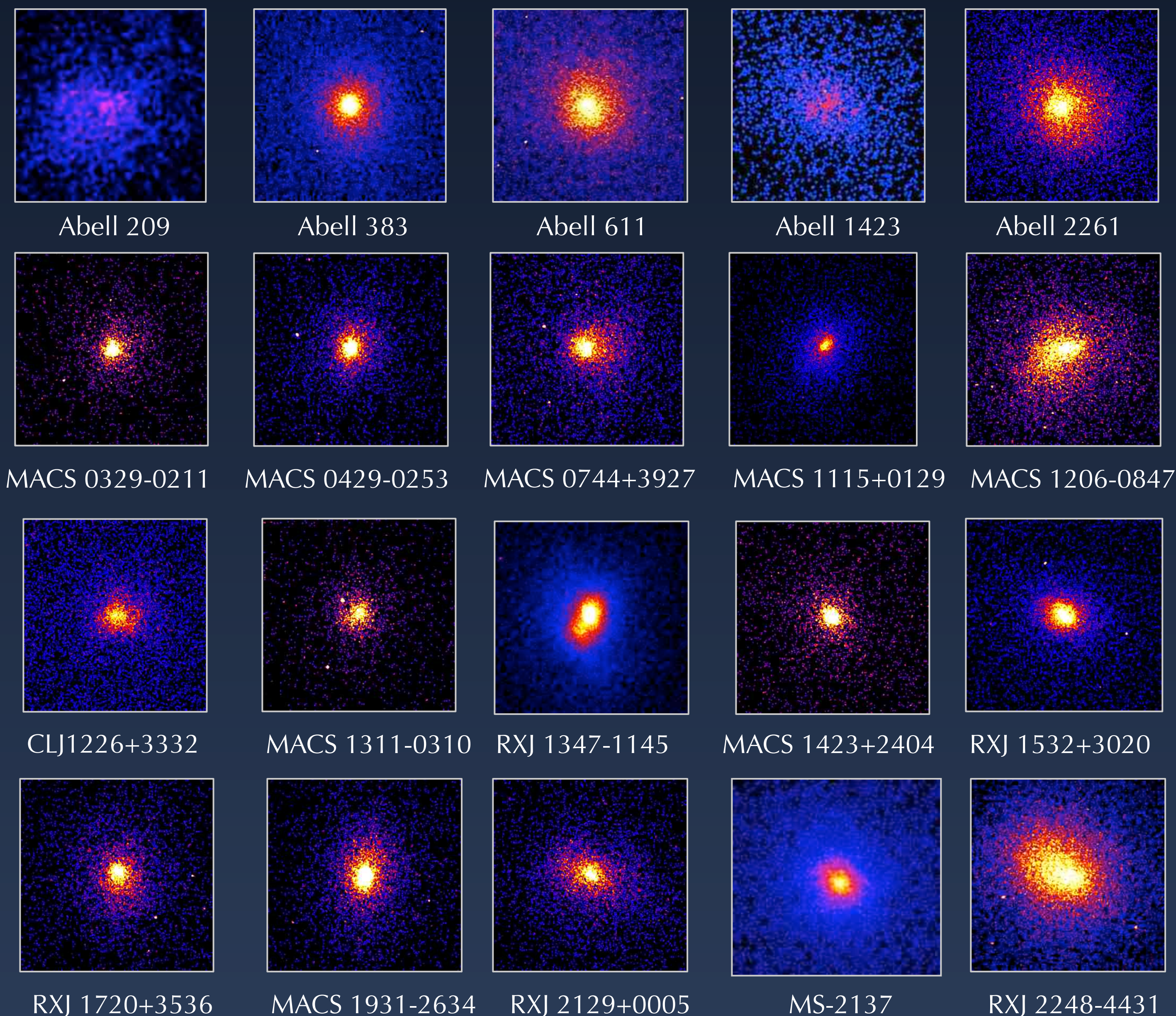
Adam Riess	STScI / JHU
Steve Rodney	JHU
Piero Rosati	European Southern Observatory
Jack Sayers	Caltech
Irene Sendra	Univ of Basque Country
Stella Seitz	Universitas Sternwarte München
Seth Siegel	Caltech
Renske Smit	Leiden University
Leonardo Ubeda	STScI
Keiichi Umetsu	Academia Sinica, Institute of Astronomy & Astrophysics
Arjen van der Wel	Max Planck Institüt für Astronomie
Bingxiao Xu	JHU
Wei Zheng	JHU
Bodo Ziegler	Universität Wein
Adi Zitrin	Caltech

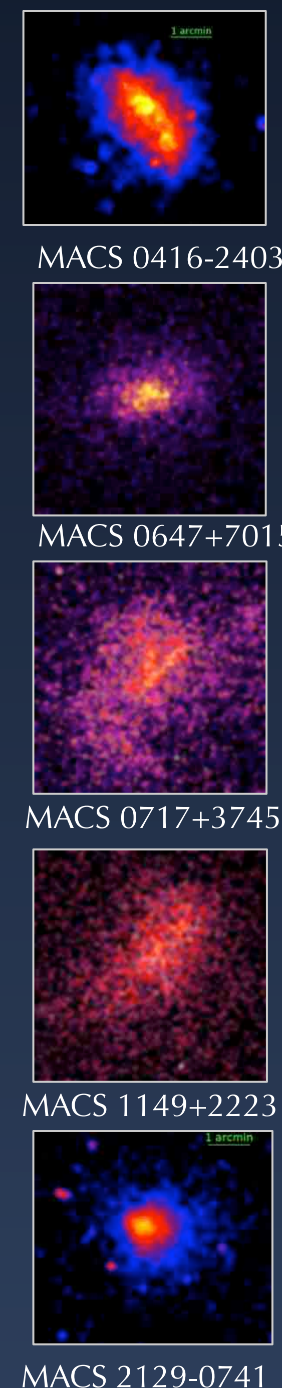
Post-doctoral fellow
Graduate student

CLASH achieved its prime scientific objectives

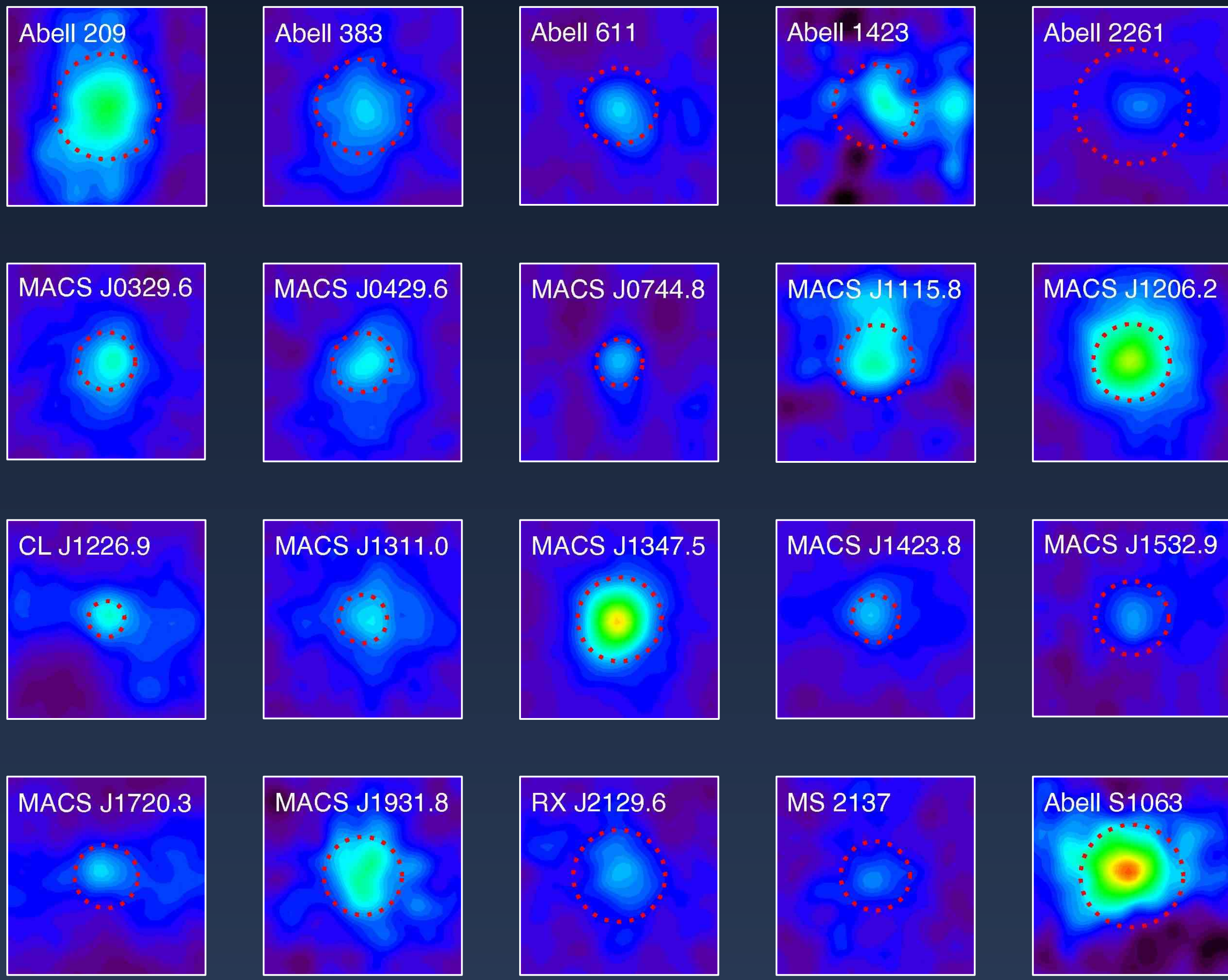
From our 2009 HST Proposal:

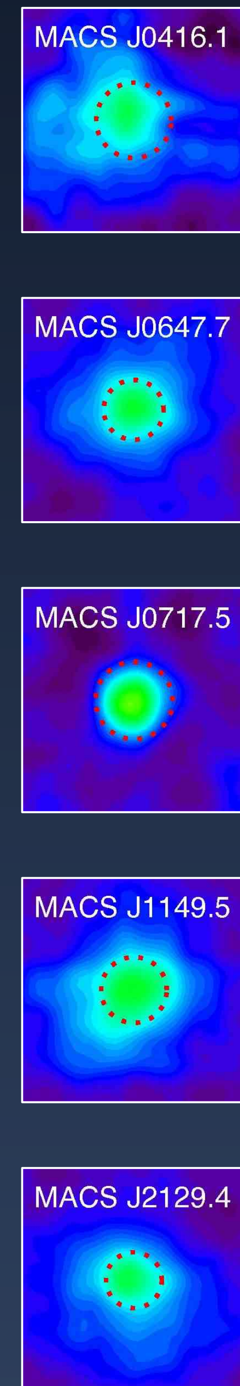
- Definitively derive the representative equilibrium mass profile shape of clusters.
- Robustly measure the cluster DM mass concentrations and their dispersion as a function of cluster mass and redshift. Understand origin of tension between observations and predictions seen in pre-CLASH era.
- Provide a reference cluster mass calibration dataset for cluster cosmology research.
- Obtain robust new measurements of the rate of $z>1$ type Ia supernovae to better constrain their progenitor origin and the history of cosmic chemical enrichment.
- Detect many (~50) bright (i.e., lensed to mag<26.7 AB) $z \geq 8$ galaxies to study the early phases of galaxy formation and evolution.





X-ray images of the 25 CLASH clusters. 20 are selected to be "relaxed" clusters (based on their x-ray properties only). 5 (last column) are selected specifically because they are strongly lensing $\theta_E > 35''$. **All CLASH clusters have Tx > 5 keV.**



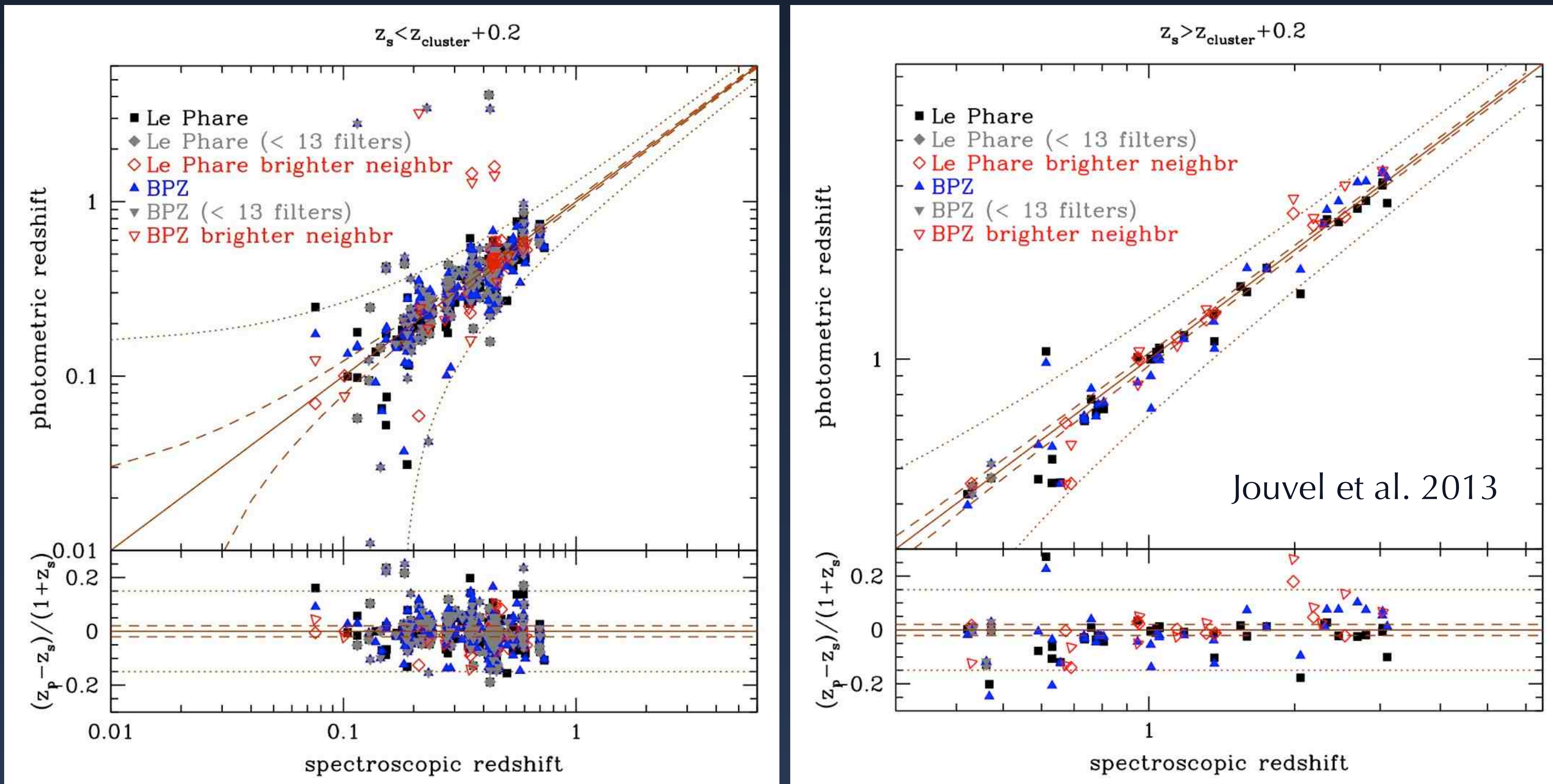


Deconvolved Bolocam SZE Images of the CLASH clusters, each image is 10′x10′.
Red dashed line: R_{2500}.
Lensing Mass-SZE scaling relations (N. Czakon)
Triaxial modeling of X-ray, lensing, SZ data (S. Siegel)

The CLASH (HST) Gallery

The final HST observation for CLASH was on 9-July-2013 … 963 days, 15 hrs, 31 min after first obs.

Photo-z Accuracy: 16 filters pay off!



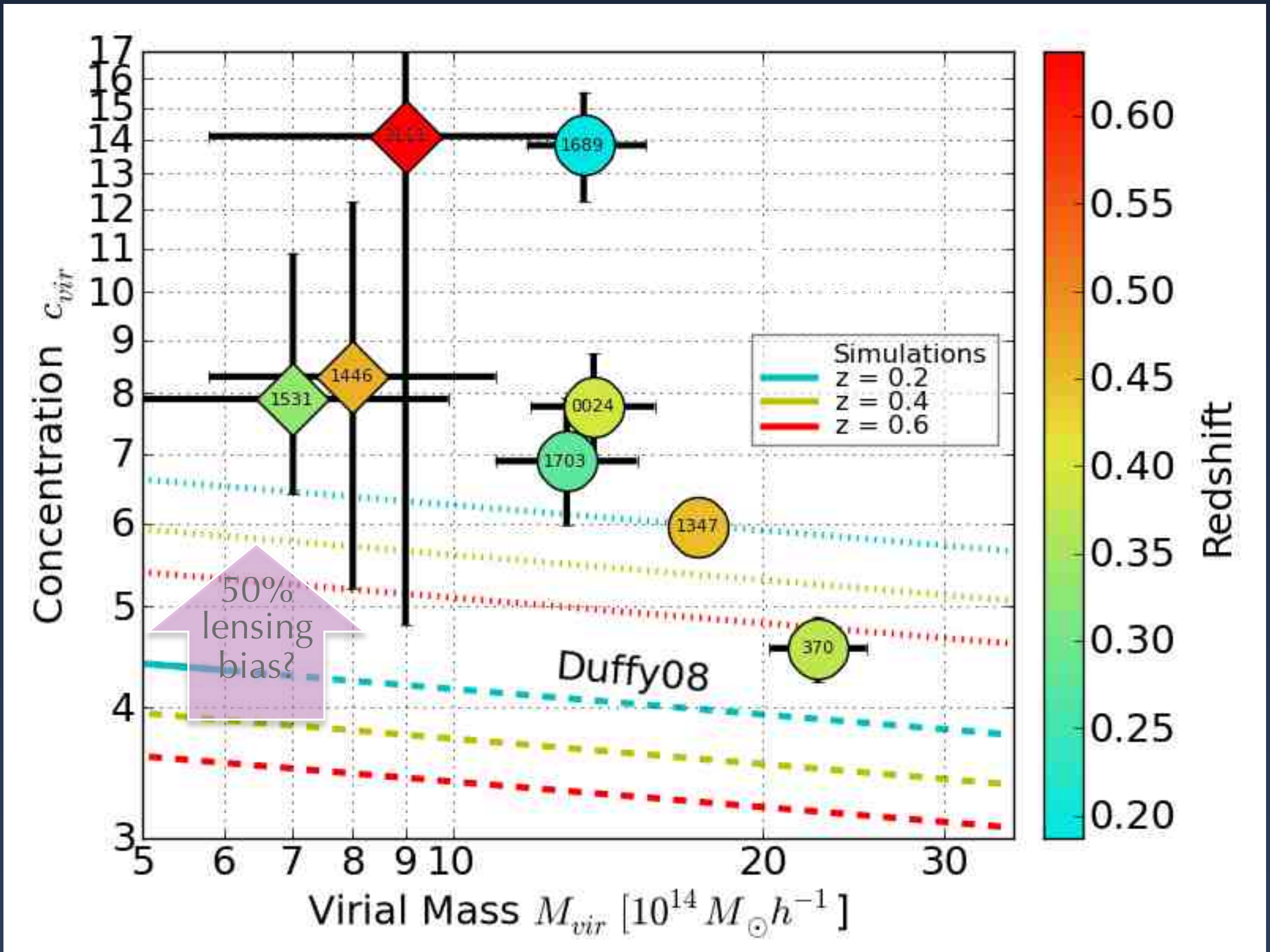
Most outliers due to contamination from an adjacent galaxy's light. When fixed, we reach an accuracy of ~0.03 (1 + z). Can do about 2x – 3x better when we apply more sophisticated sky subtraction. But 3% is good enough for most of our science. The majority of the CLASH spectroscopic data comes from our VLT Large Program.

Pre-CLASH:
Well-constrained cluster mass profiles were seen to be more concentrated than simulated clusters

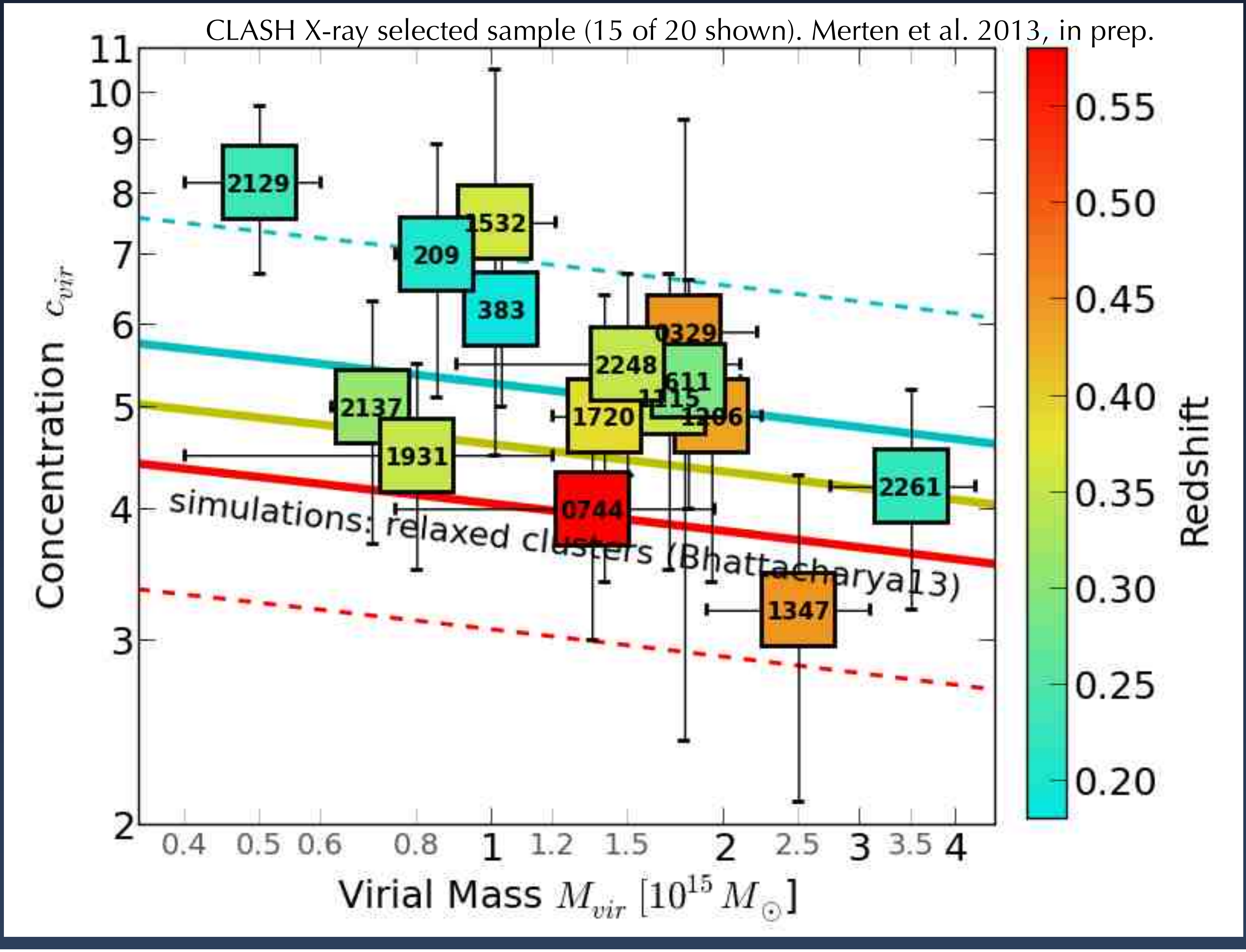
– Broadhurst08, Oguri09, Sereno10, Zitrin11a,b

Most likely due to significant (50-100%) lensing selection bias as estimated by Hennawi07, Oguri09, Meneghetti10,11

… but also could be due to issues with simulations.

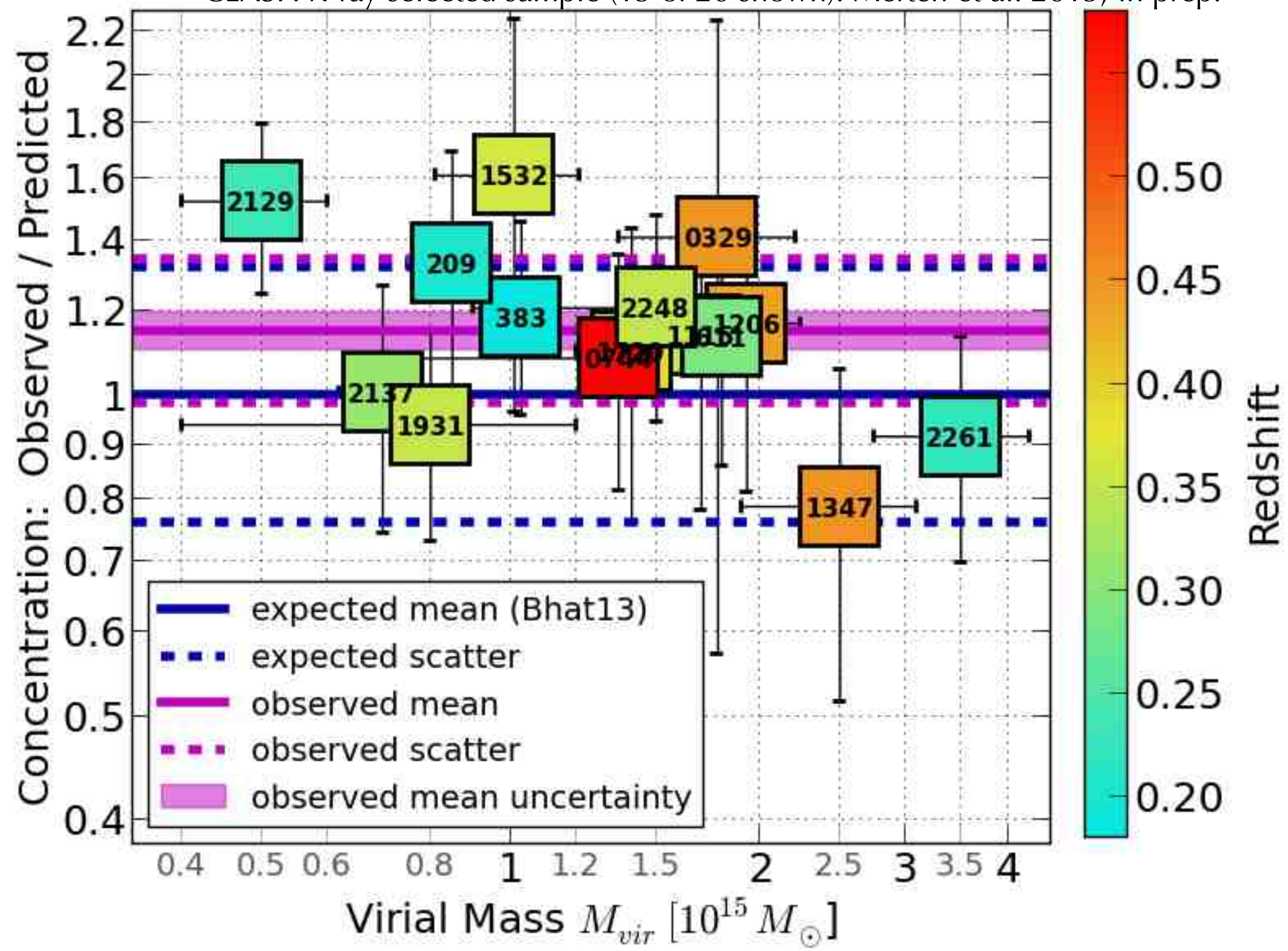


CLASH Mass-Concentration Relation



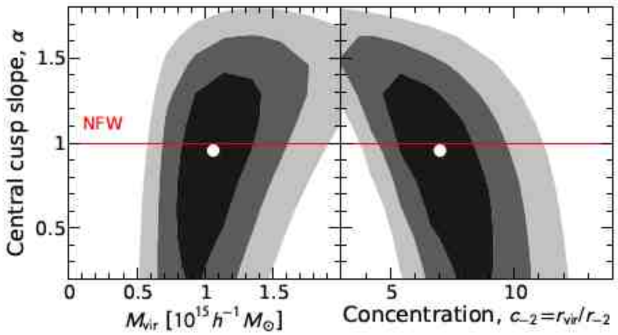
Ratio of CLASH M-c values to predicted values = 1.15 ± 0.05, with dispersion ~0.18. Tension between previous data and predictions largely a sample selection effect. CLASH M-c is consistent with LCDM.

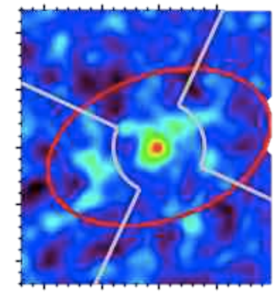
CLASH X-ray selected sample (15 of 20 shown). Merten et al. 2013, in prep.

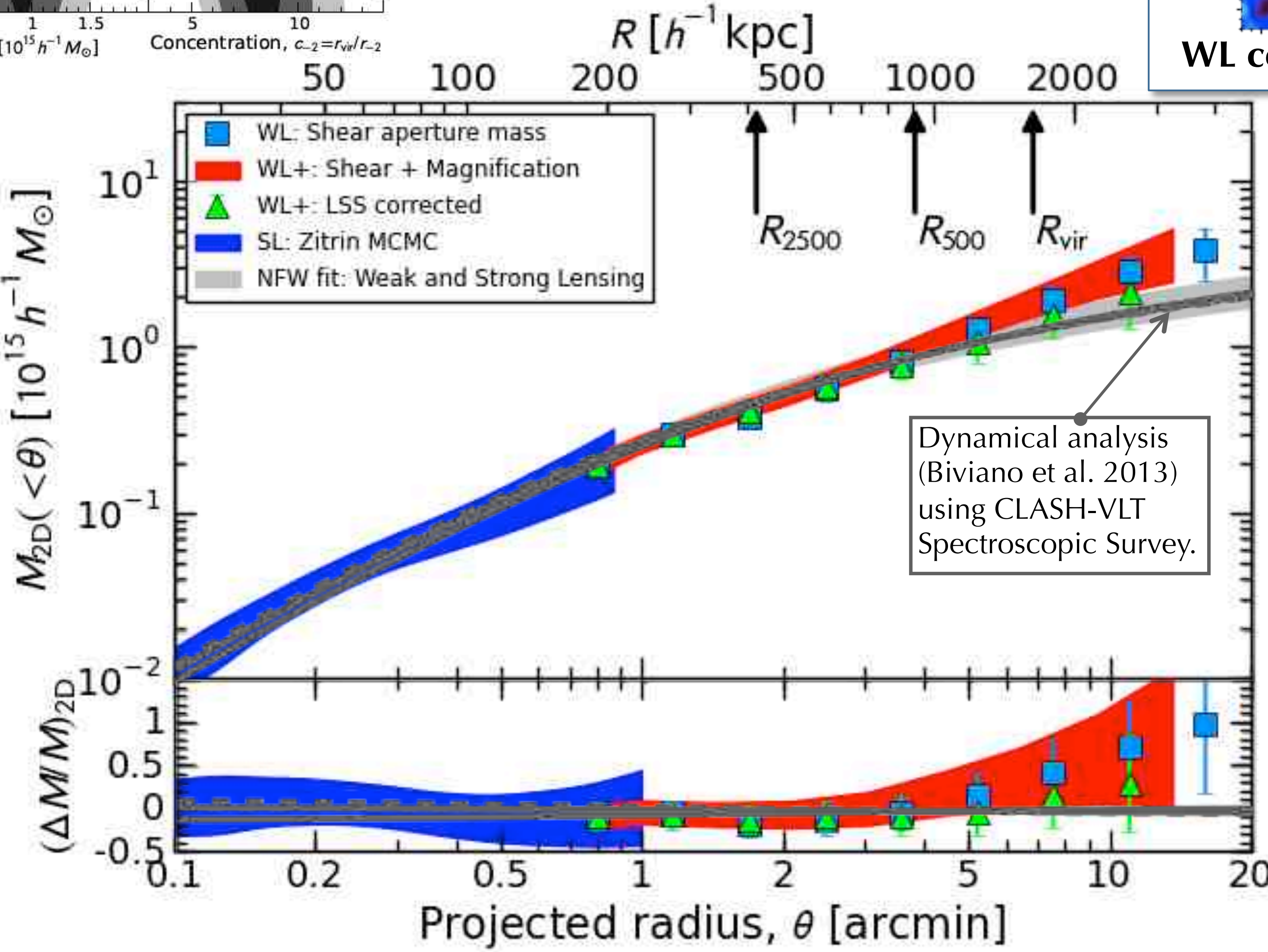


MACS1206 (z=0.45)

Total mass profiles from completely independent methods agree.

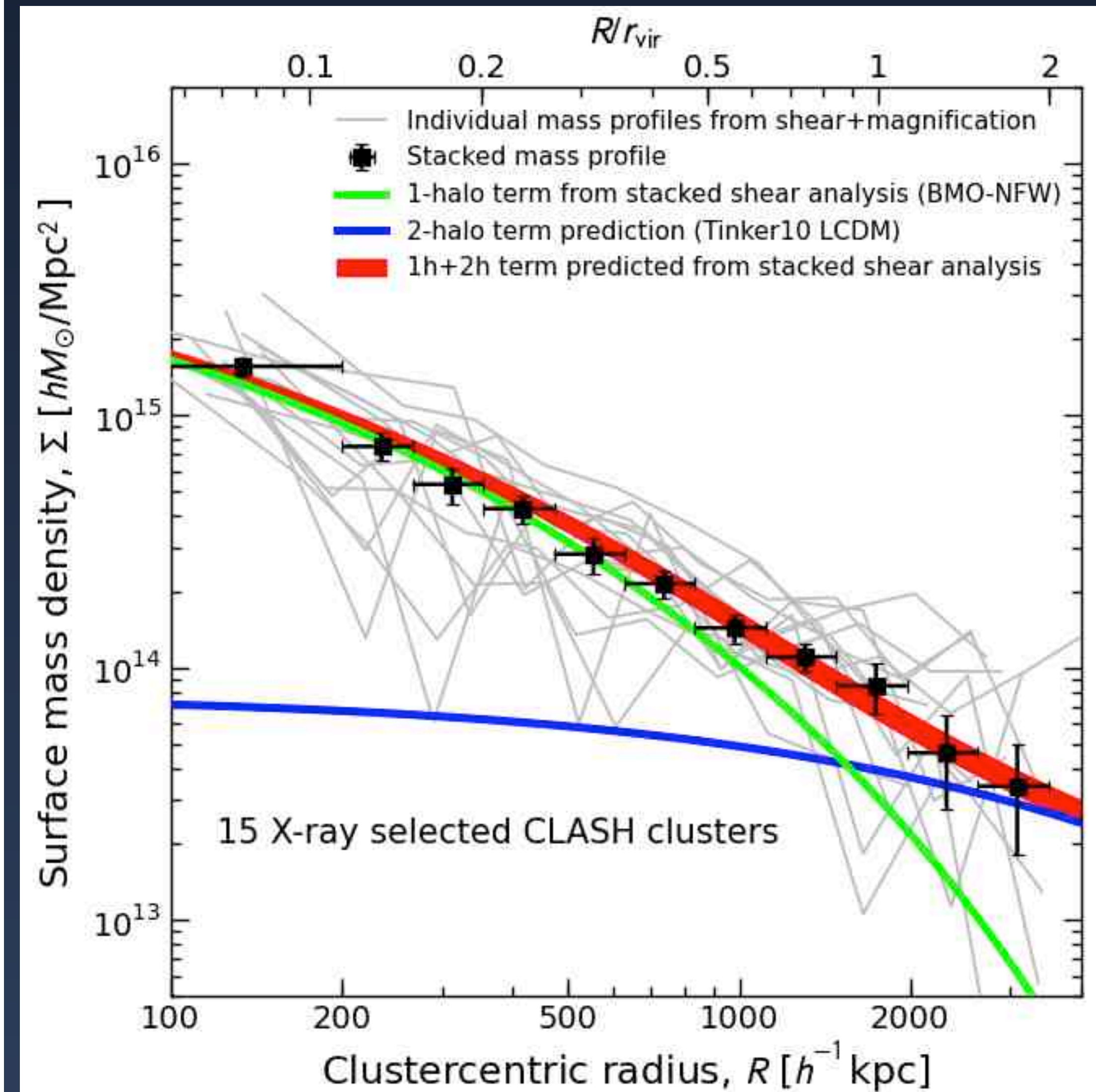


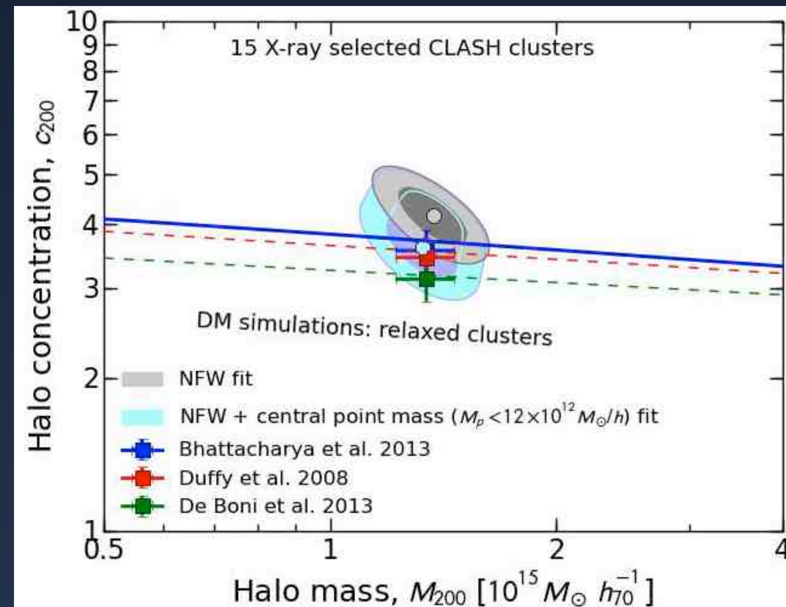




(Umetsu et al. 2012, Biviano et al. 2013)

Stacked cluster mass profile from CLASH combined WL shear & magnification measurements: 1+2-halo term shown is fit from shear signal data.





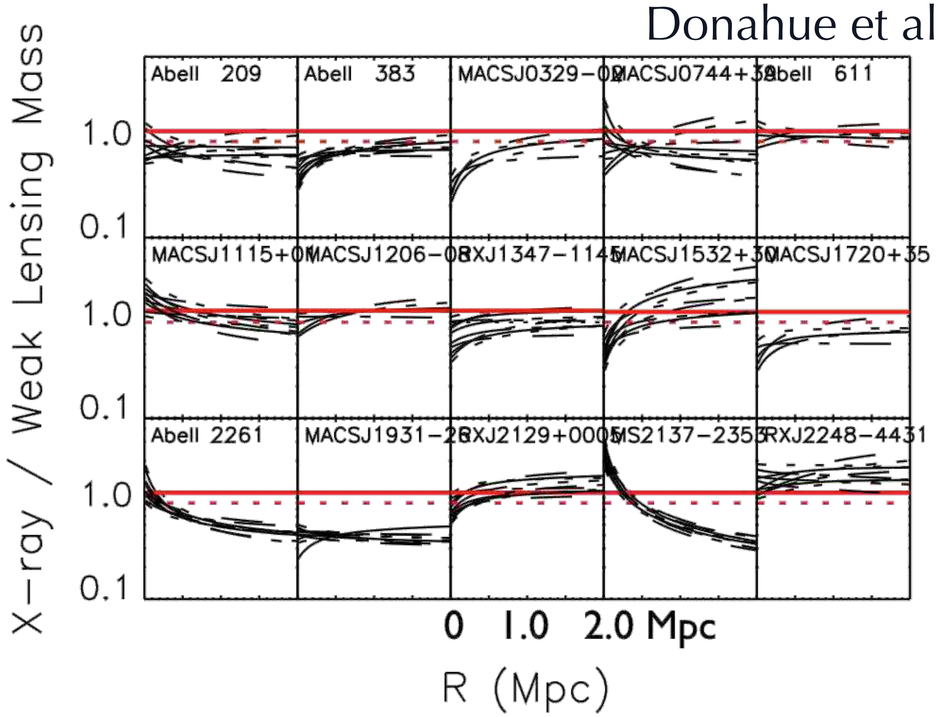
Data: Total mass vs. matter concentration
Theory: DM mass vs. DM concentration

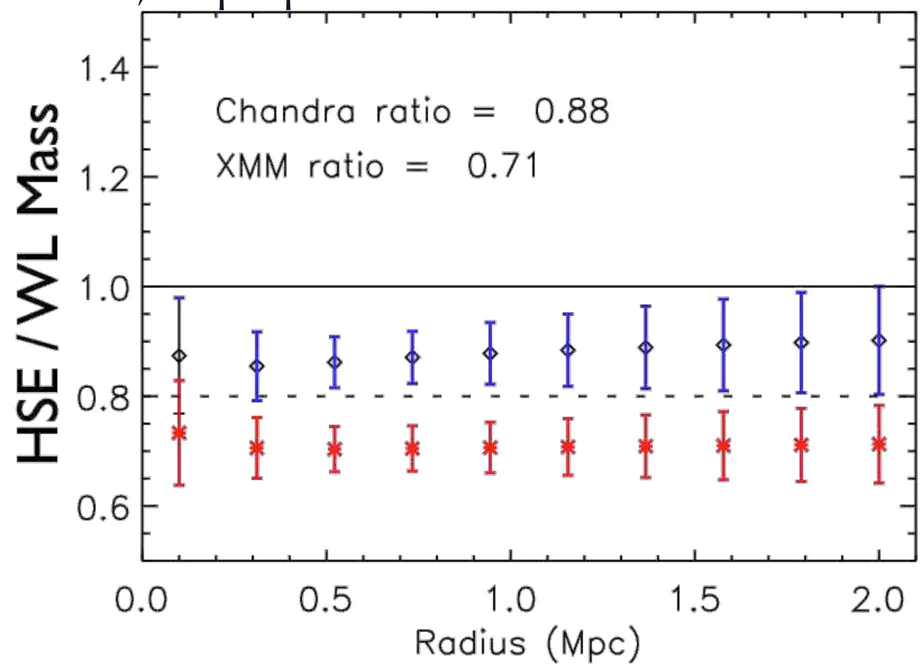
The 2-halo term is the predicted contribution from surrounding large-scale structure. A single 1-halo fit would under-estimate surface mass density at radii beyond 1 Mpc.

Umetsu, CLASH et al. 2013, in prep

Calibrating X-ray Mass Profiles

Donahue et al. 2013, in prep.





HSE = Hydrostatic Equilibrium

- A systematic calibration difference between XMM and Chandra exists even after the most recent calibration and PSF corrections are applied.
- X-ray HSE masses are less than weak lensing masses for 15 CLASH X-ray selected "relaxed" clusters: ~90% (90%-95% with PSF correction) if Chandra; ~70% if XMM (~80% with PSF correction).
- Expect HSE/WL mass ratio to be ≤ 1 (non-thermal support, turbulence, etc.)

CLASH: Magnified High-z Galaxies

CLASH finds a large number of high-redshift galaxies

- Steep LFs largely mitigate the decreased intrinsic source-plane area
- Higher spectral and spatial resolution than typical LBG surveys
- Detection of sources fainter than possible in most high-z surveys

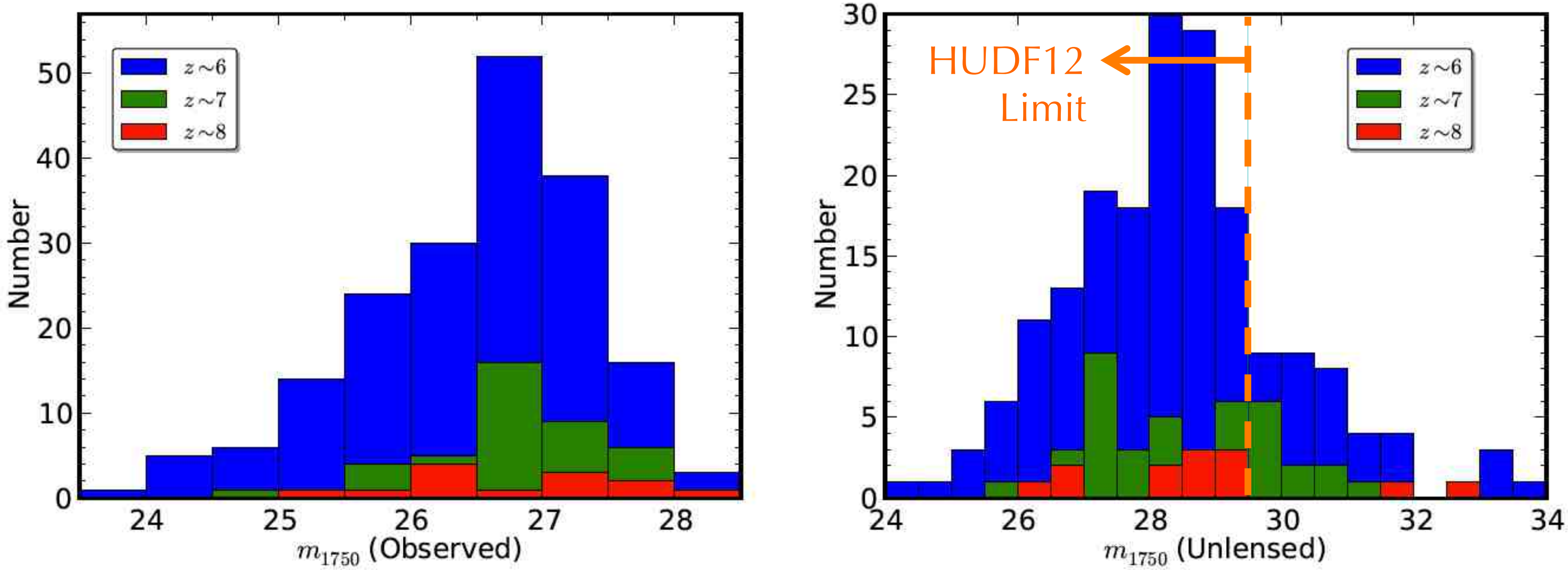
	$z \sim 6$	$z \sim 7$	$z \sim 8$	$z \sim 9$	$z \sim 10$	$z \sim 11$	Total
18 clusters	206	45	13	2	1	1	268
Survey extrapolation	~290	~65	~18	~3	~2	~2	~380

Largest sample of lensed star-forming galaxies at $z >\sim 5.5$ to date

7 multiply-imaged systems at $z >\sim 5.5$

Bradley et al. (2013)

CLASH: Magnified High-*z* Galaxies



Median magnifications: μ ~ 4.2, 4.2, 4.5 for *z* ~ 6, 7, 8 samples

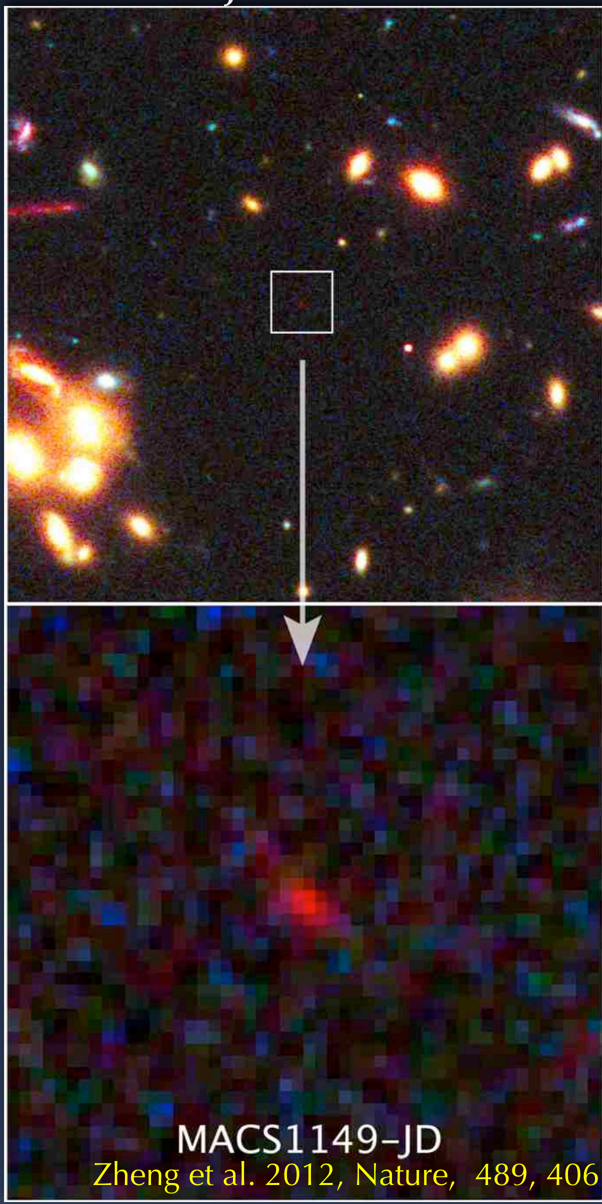
Instrinsic (unlensed) magnitudes nearly reach 34 mag

Caveat: largest magnifications have large uncertainties!

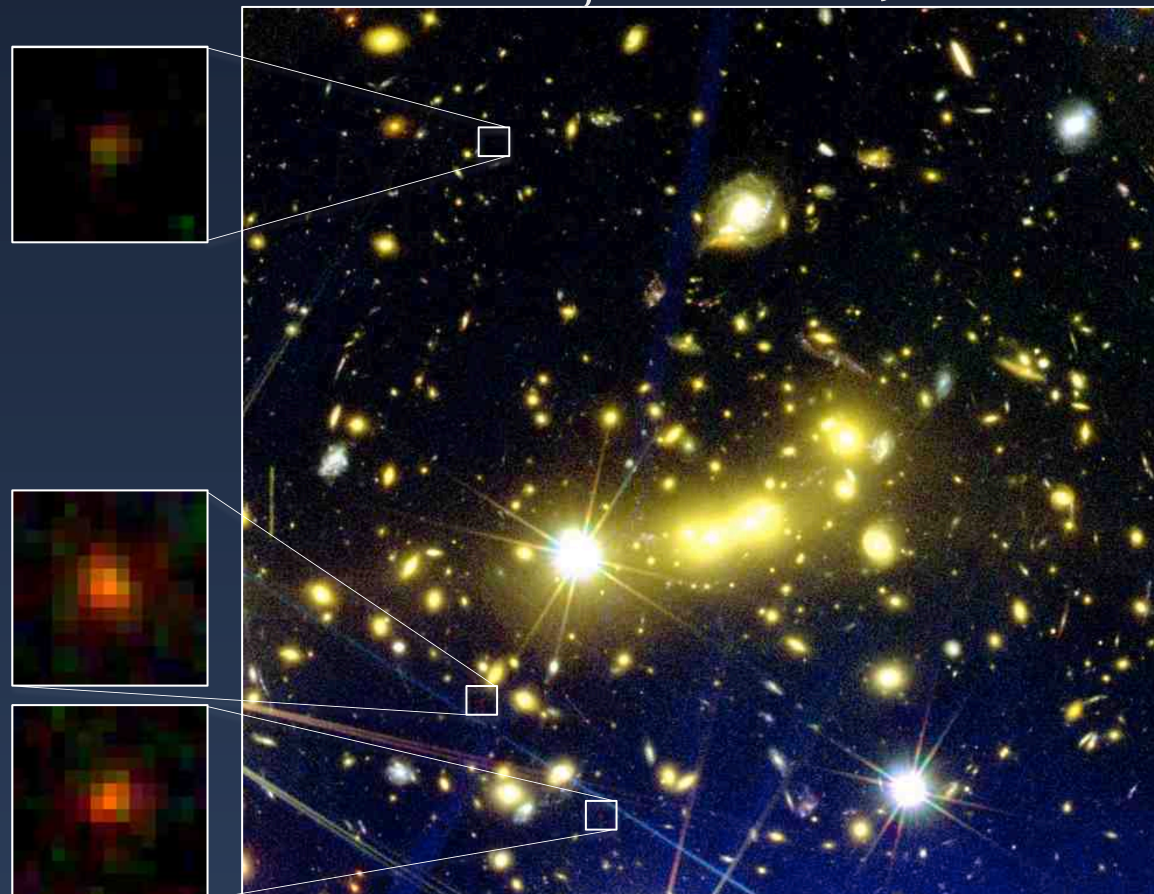
Bradley et al. (2013)

Two z > 9 Lensed Galaxies

z = 9.6 object in MACSJ1149+2223



z = 10.8 object in MACSJ0647+7015

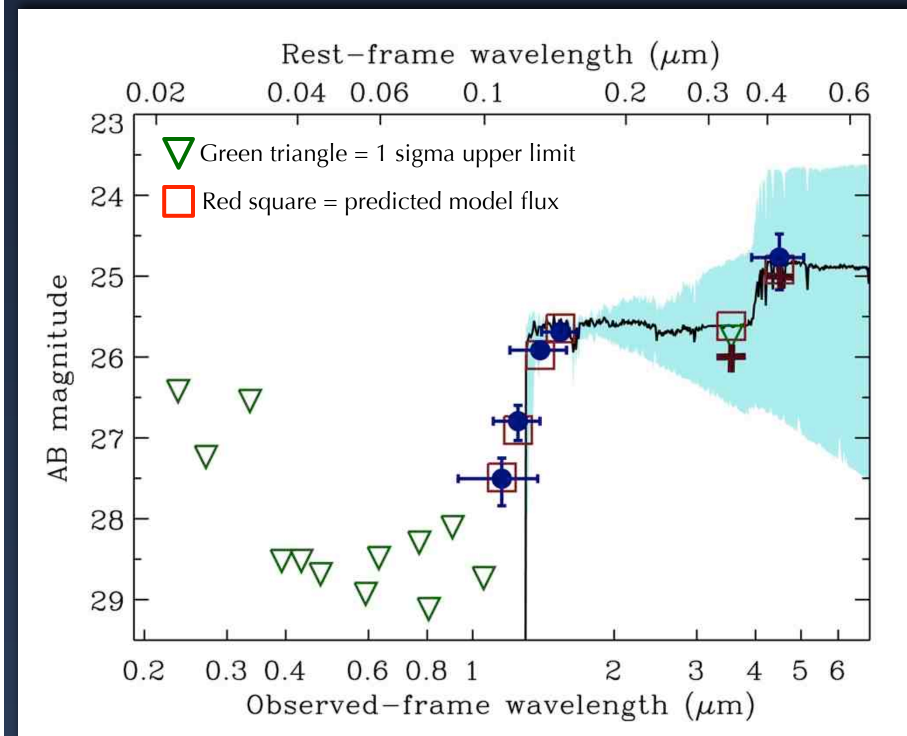


Coe et al. 2013, ApJ, 762, 32

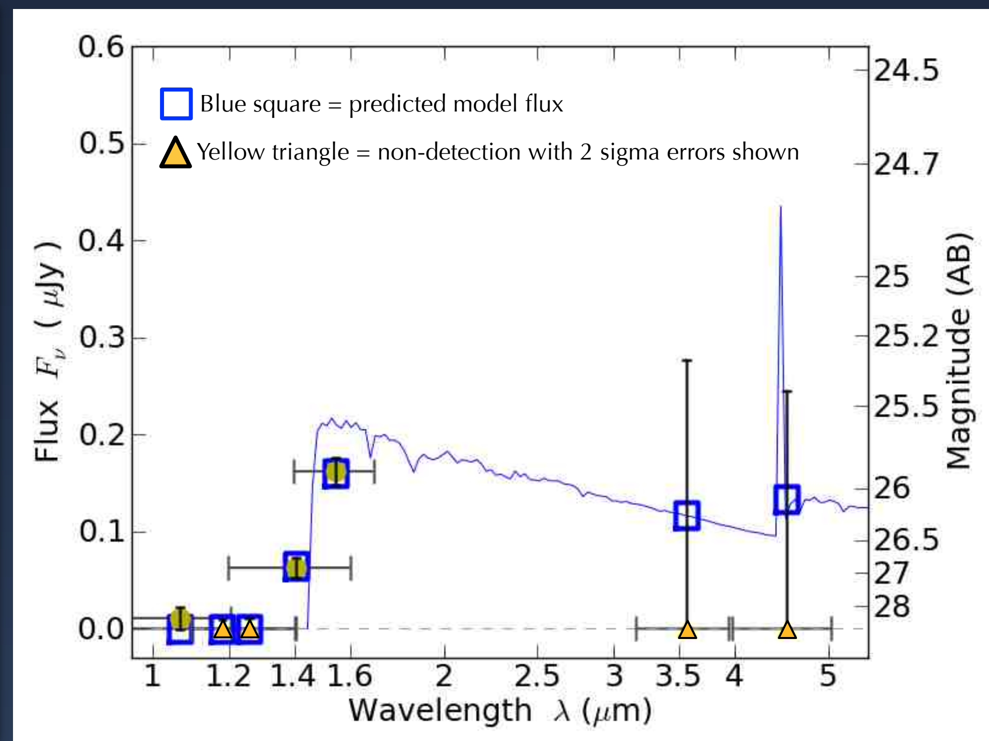
Spectral Energy Distributions

MACS1149-JD: $z = 9.6 \pm 0.2$
Stellar mass: ~$1.5 \times 10^8\ M_\odot$
SFR: ~$1.2\ M_\odot$/yr
Age: < 200 Myr (95% CL), $z_{Form} < 14.2$
$r_{1/2}$: ~0.14 kpc (de-lensed)

MACS0647-JD: $z = 10.8 \pm 0.5$
Stellar mass: 10^8 - $10^9\ M_\odot$
SFR: ~$4\ M_\odot$/yr (Salpeter IMF)
Age: < 400 Myr (95% CL)
$r_{1/2}$: < 0.10 kpc (de-lensed)

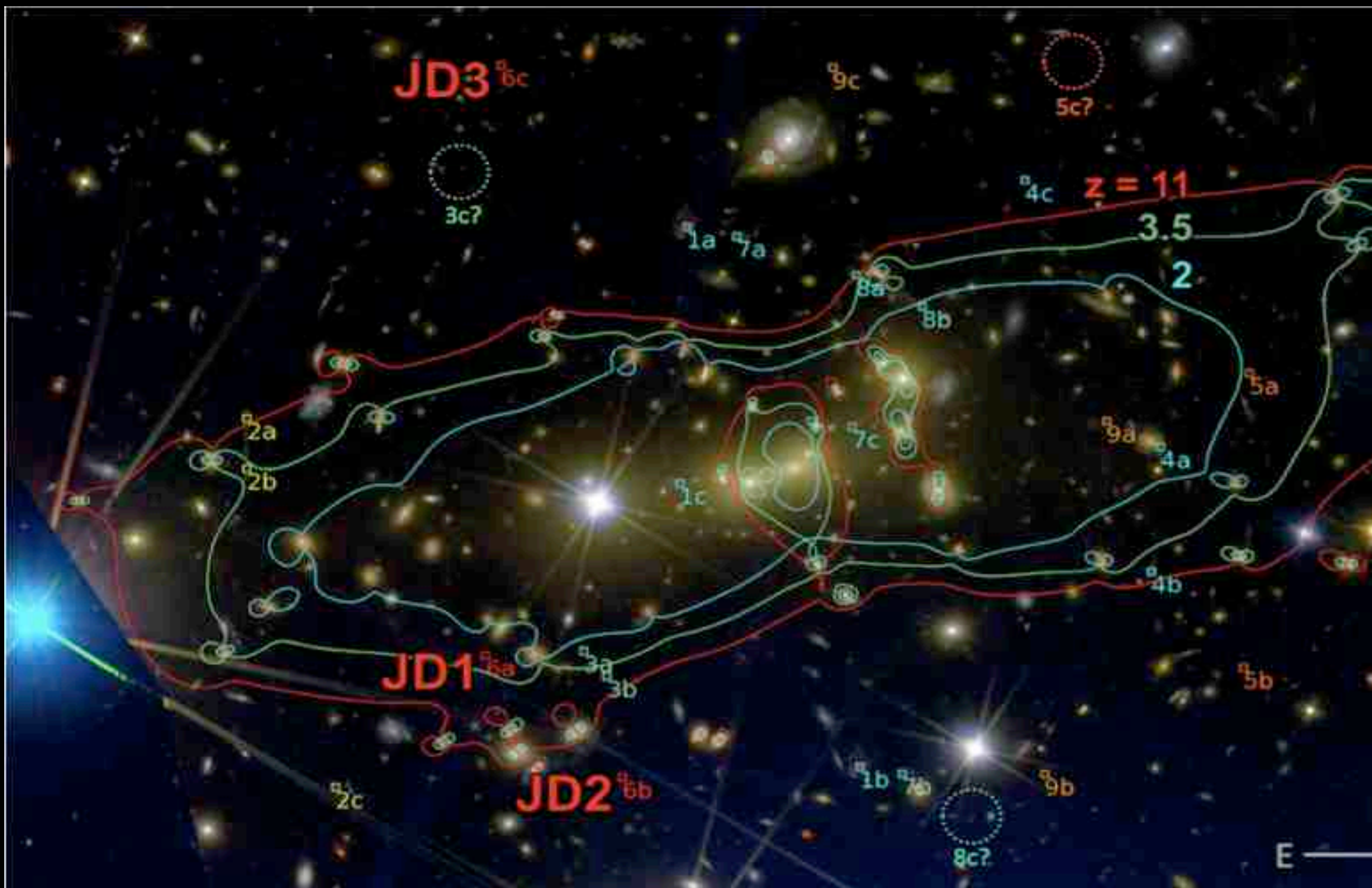


Plus symbols represent new, deeper IRAC data



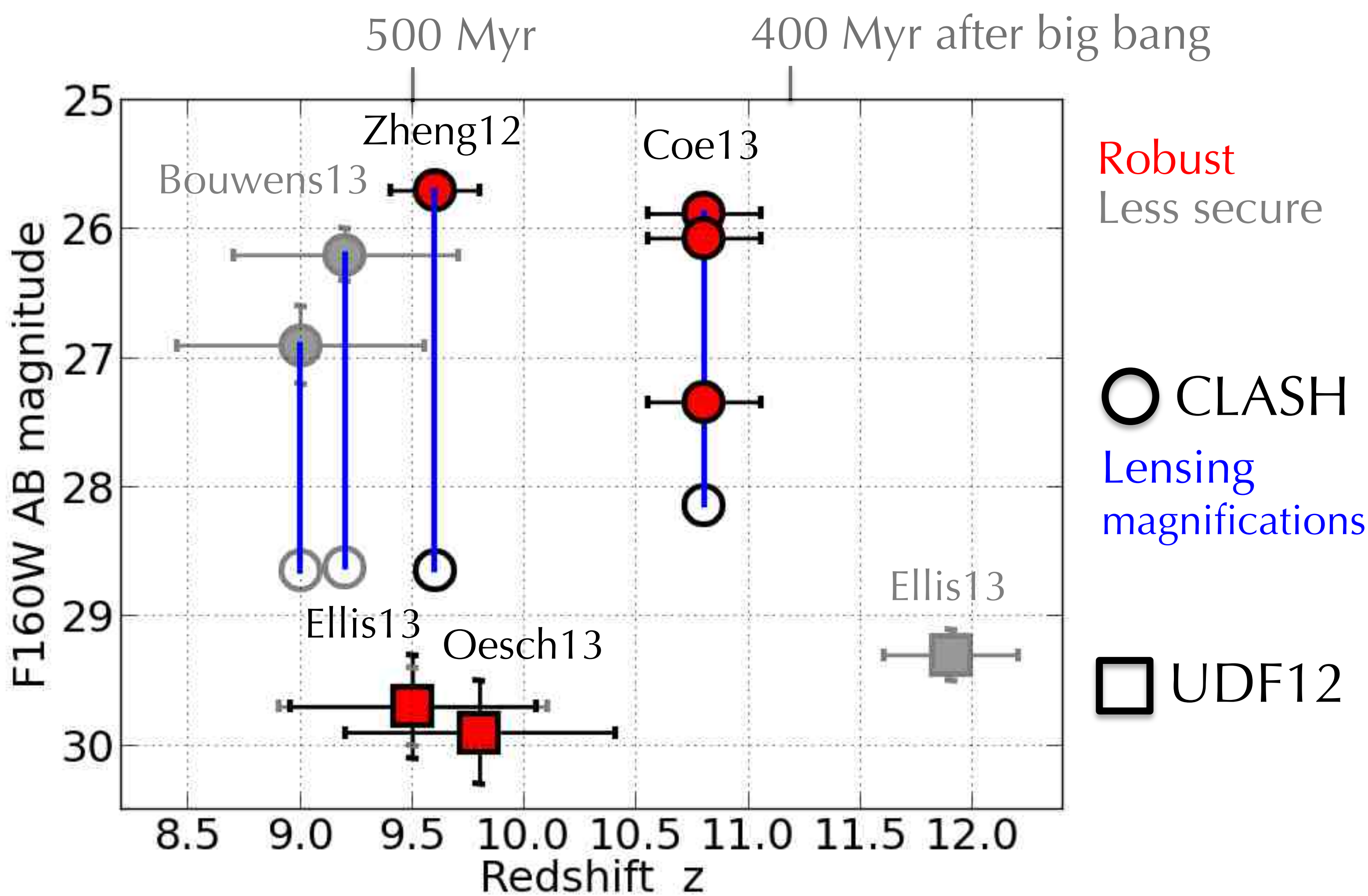
In both cases, best fit SED is a starburst galaxy

Observed positions and fluxes are consistent with our lens models. Models are based on 20 strongly lensed images of 8 other galaxies.

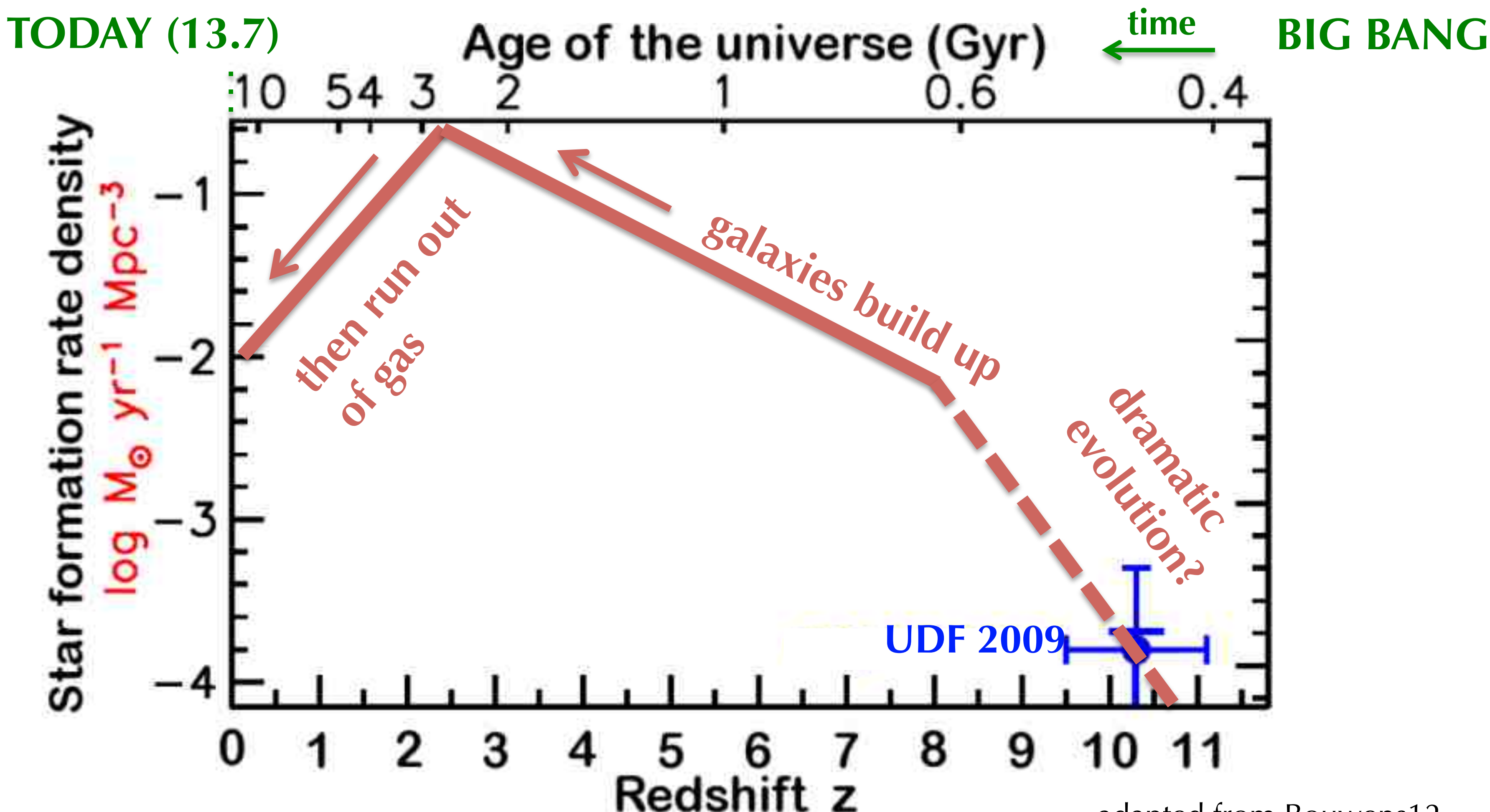


CLASH and UDF12 yield 4–8 candidates at z > 9 where previously only one was known

Highest spectroscopic redshift:
z = 7.215
(Shibuya12)



Previous searches for galaxies in the first 500 Myr came up short. Only one candidate was found where six were expected. This suggested a dramatic buildup in galaxy numbers.

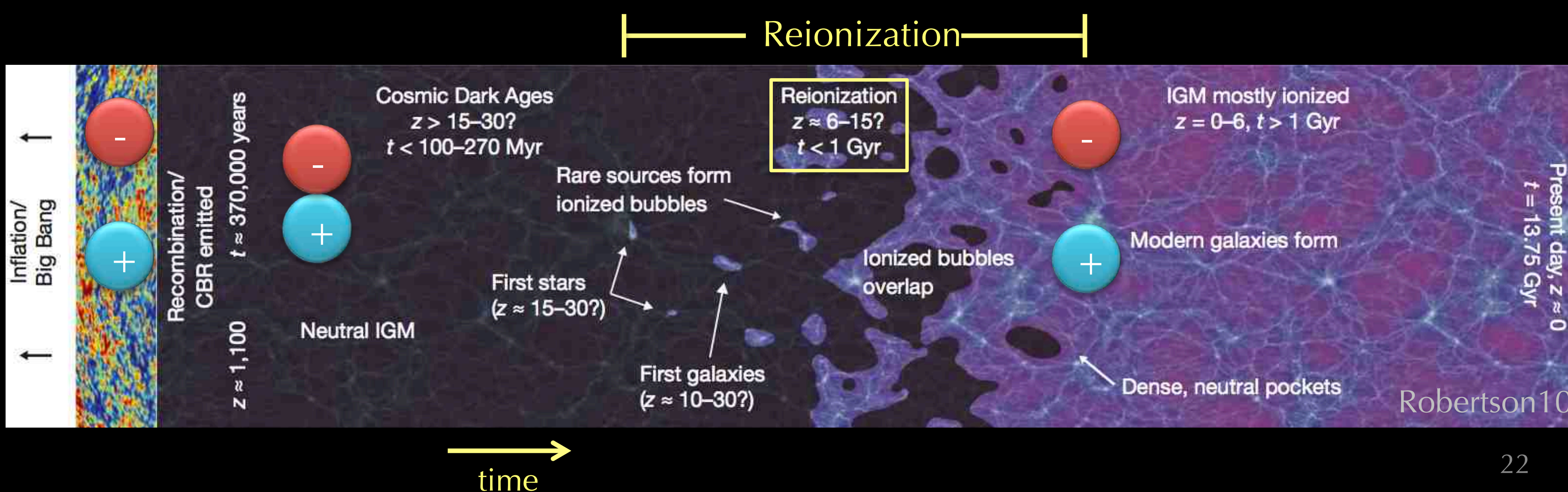


adapted from Bouwens12
see also Oesch12,13

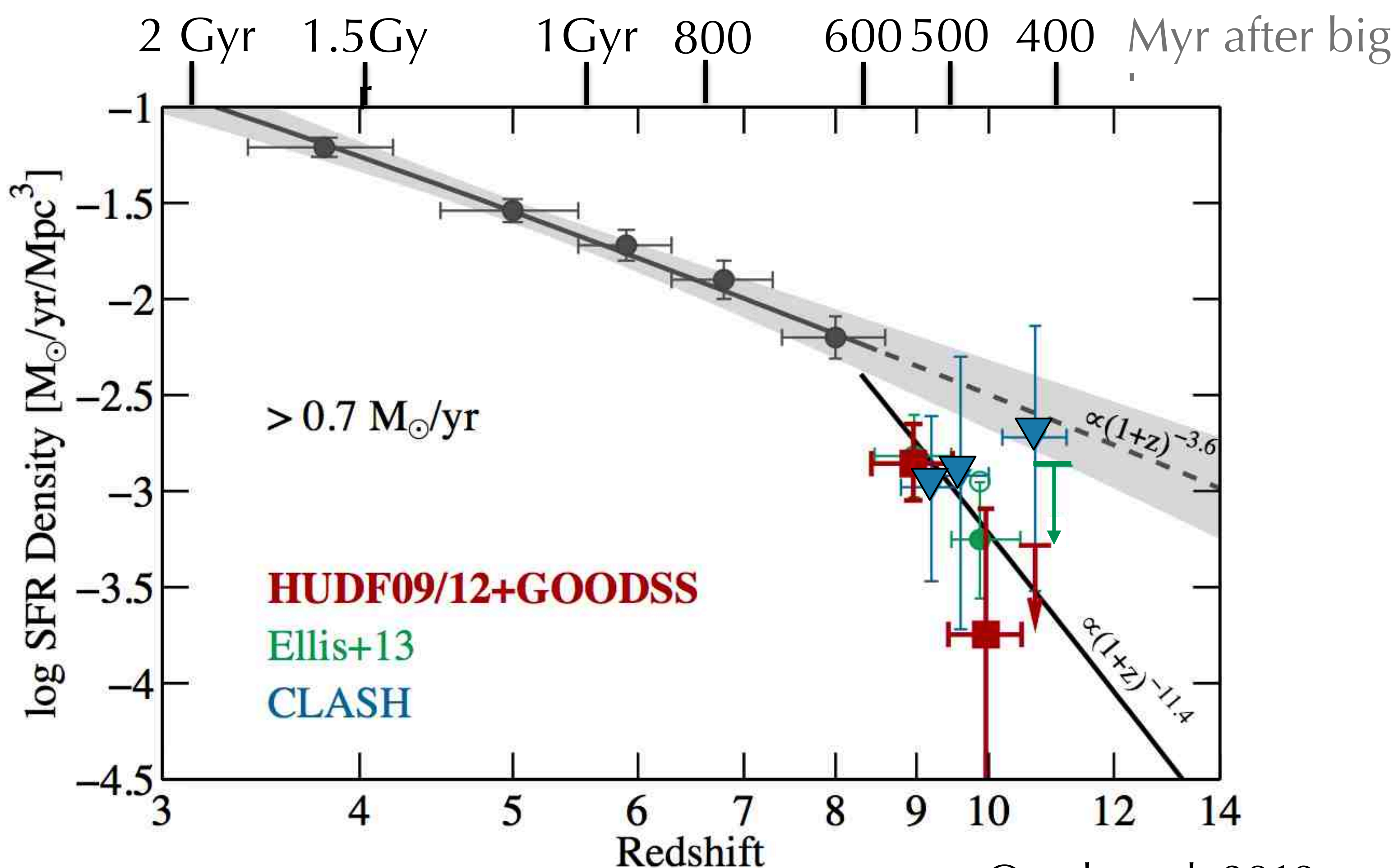
Such dramatic evolution has implications

(e.g., Trenti+2010, Jaacks+2011, Alvarez+2012, Bouwens+2012, Dunlop+2012/13, Robertson+2013)

- Low mass (<10^9) galaxies must be a dominant source of the ionizing radiation at z > 8
- The IGM at z>8 may have low clumping factors
- Sources may have harder UV energy output (higher beta) and/or higher escape fractions
- Not enough faint galaxies to re-ionize the z>8 universe? Other more exotic ionizing energy mechanisms may need to be invoked.



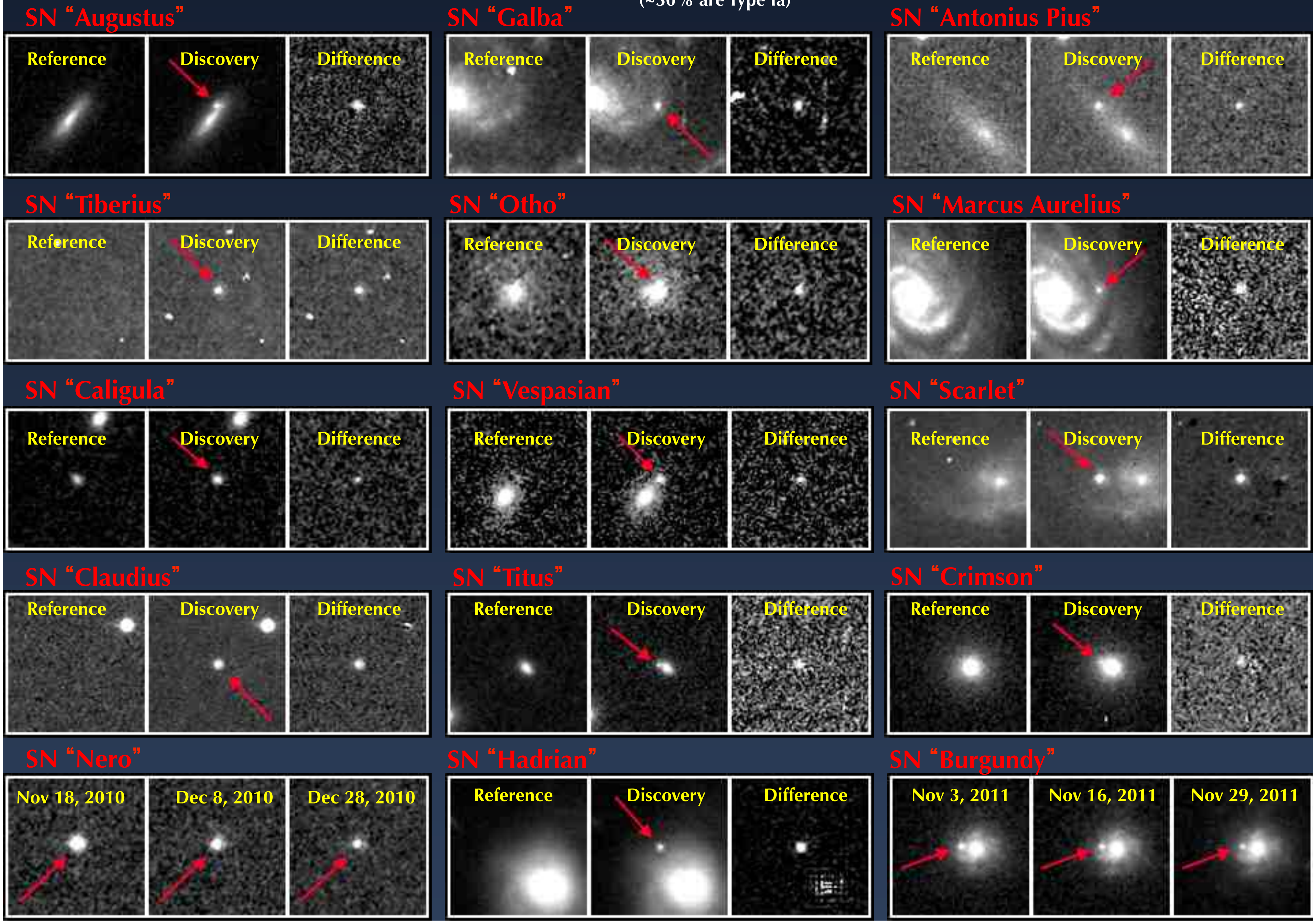
CLASH and UDF12 provide our first constraints on $z > 9$ galaxy evolution. Additional observations are required.



Oesch et al. 2013

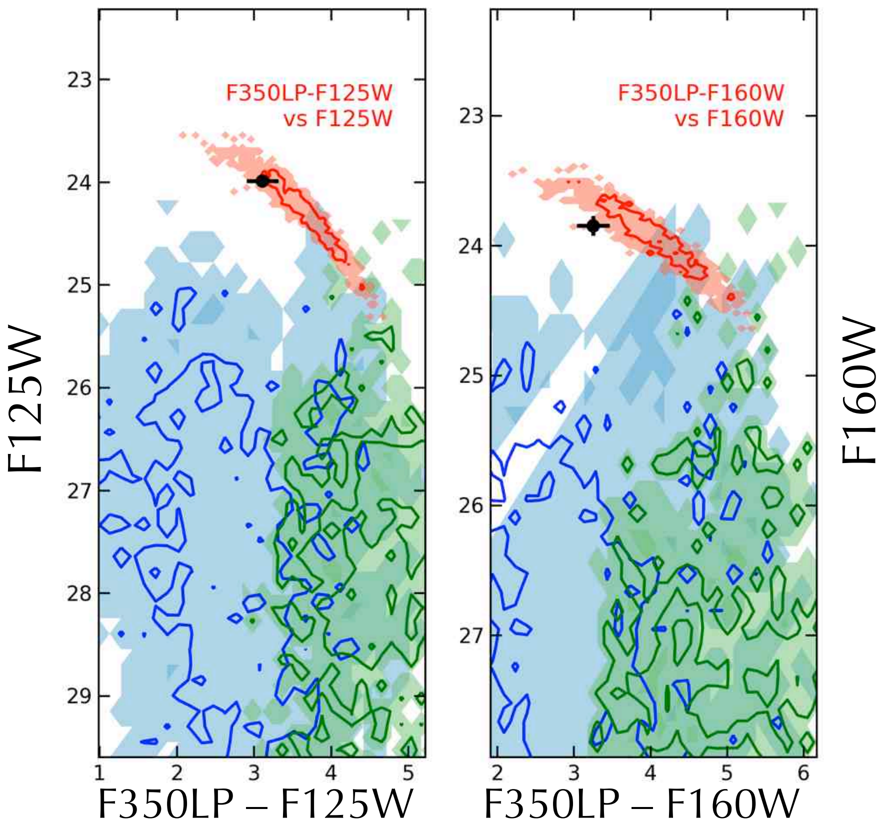
39 CLASH SNe Discovered (27 in par, 12 in prime field), 15 shown here

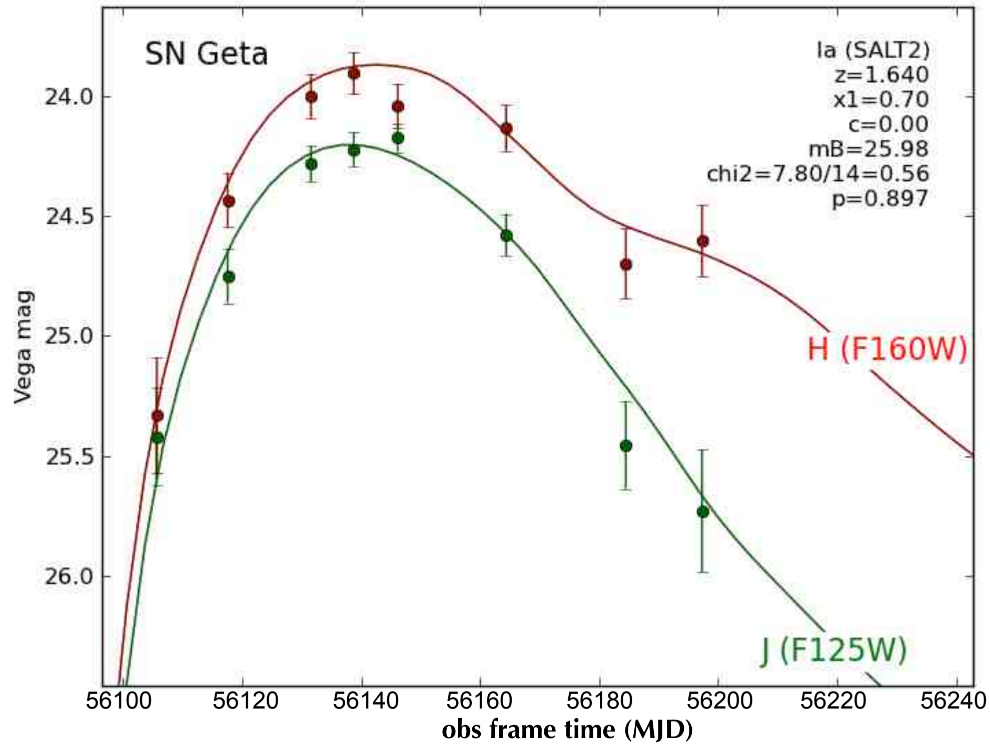
(~30% are Type Ia)

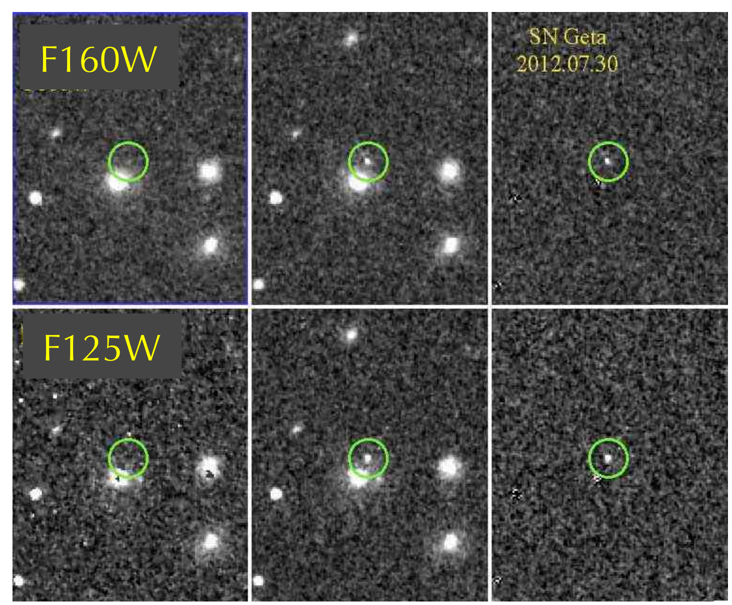


SN Geta (RXJ2129+0005)
Type Ia at z = 1.64

CMD plot 30 days pre-maximum (observer frame)





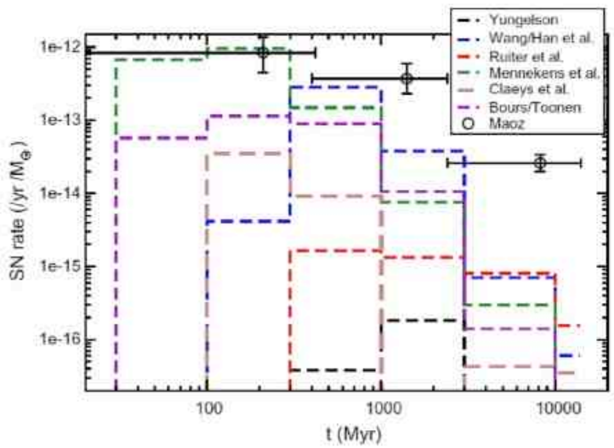


Type Ia (red)
Type Ib/c (green)
Type II (blue)

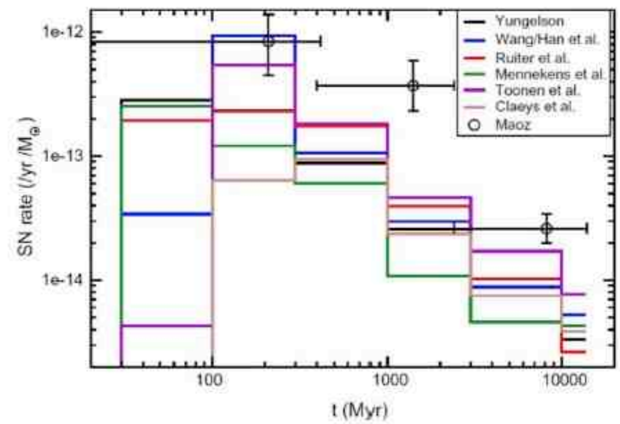
Publius Septimius Geta (189 – 211 AD, Rome)

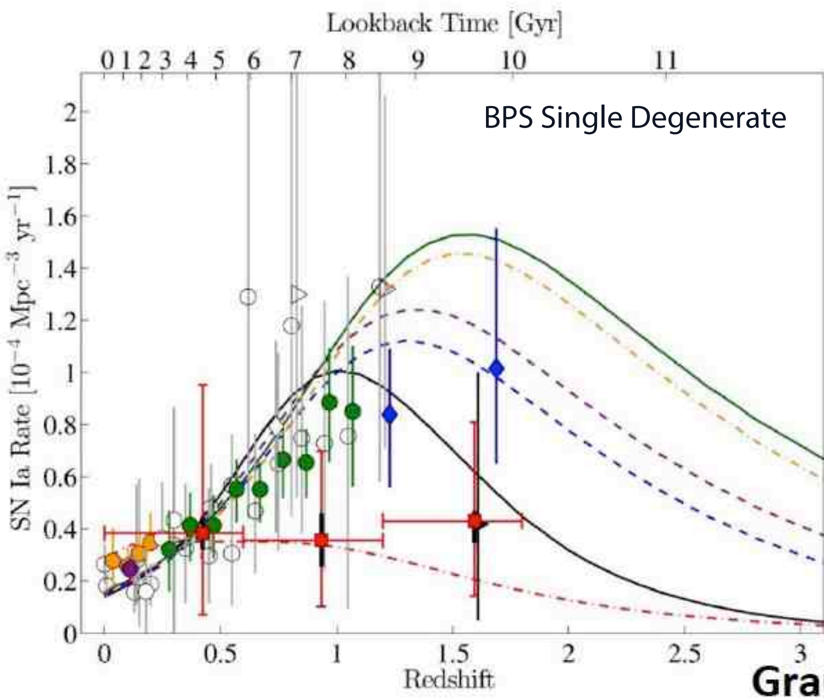
SN Ia rates favor the Double Degenerate DTDs

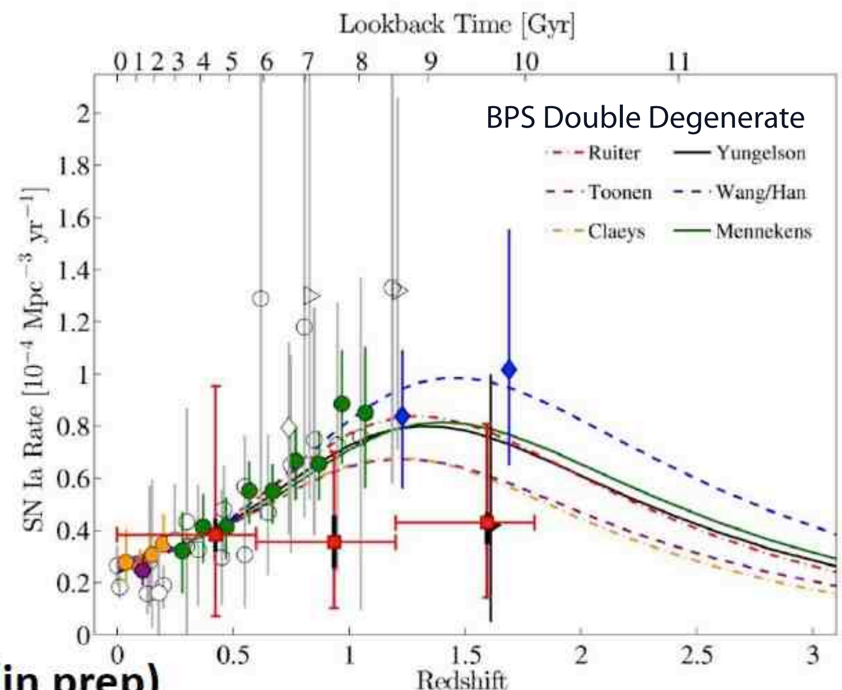
Single Degenerate



Double Degenerate





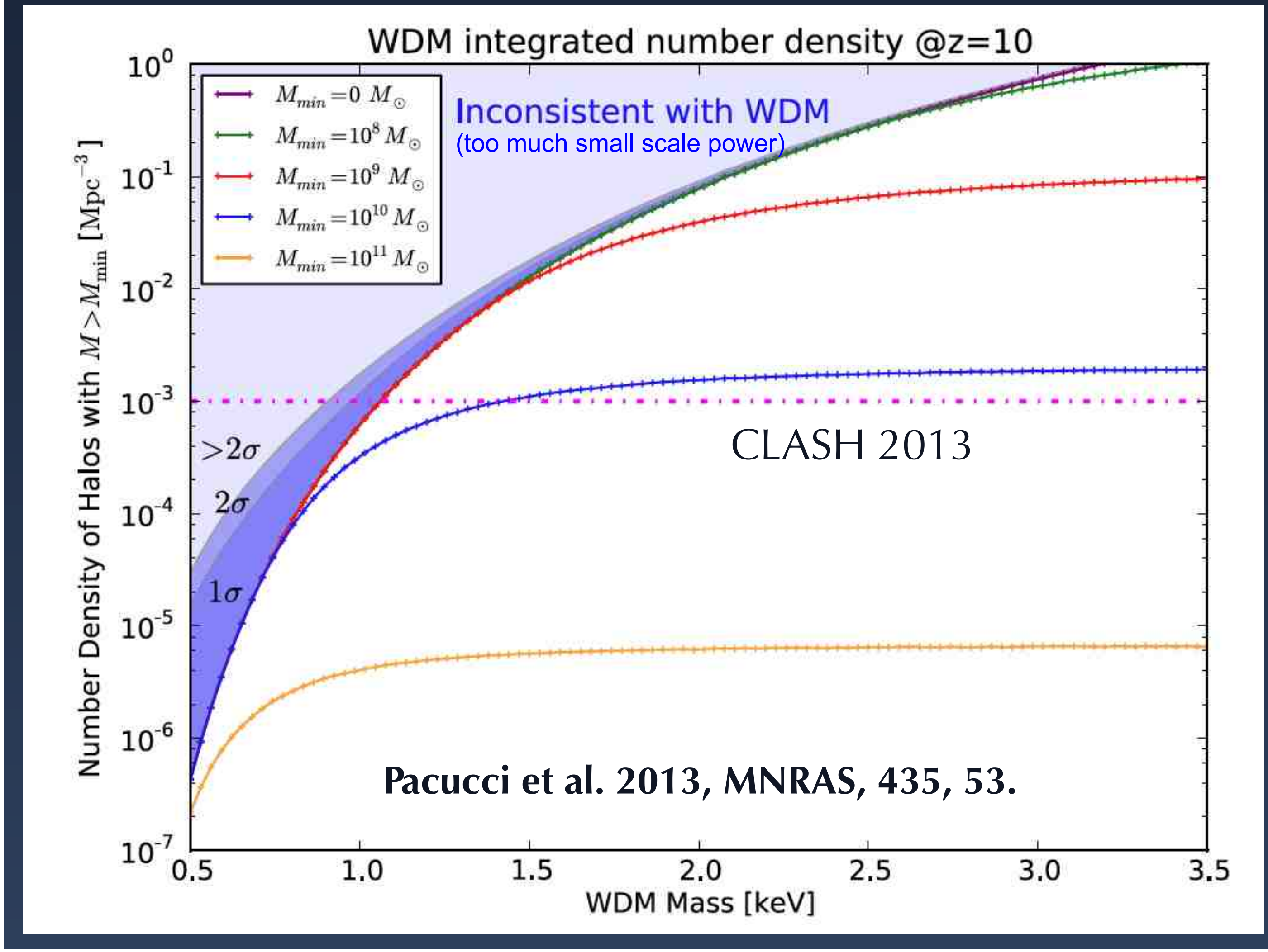


Graur+ (in prep)

Unanticipated Results from the CLASH MCT Program

Independent constraint on the nature of DM

- WDM particle mass $m_X > 1.0$ (0.9) keV at 68% (95%)
  - Limit depends only on WDM halo mass function, not on astrophysical modeling.



Pacucci+13: "Even a few galaxies found in such small volumes require a very high number density of collapsed dark matter (DM) haloes. This implies significant primordial power on small scales, allowing these observations to rule out popular alternatives to standard cold dark matter (CDM) models, such as warm dark matter (WDM)."

Constraining the DM Equation of State

- By testing whether the intra-cluster dark matter is pressureless.
- Test made possible by our high-quality lensing and kinematic mass profiles.
- Significantly improves on previous attempt (Serra & Romero 2011) on poor data for CL0024.

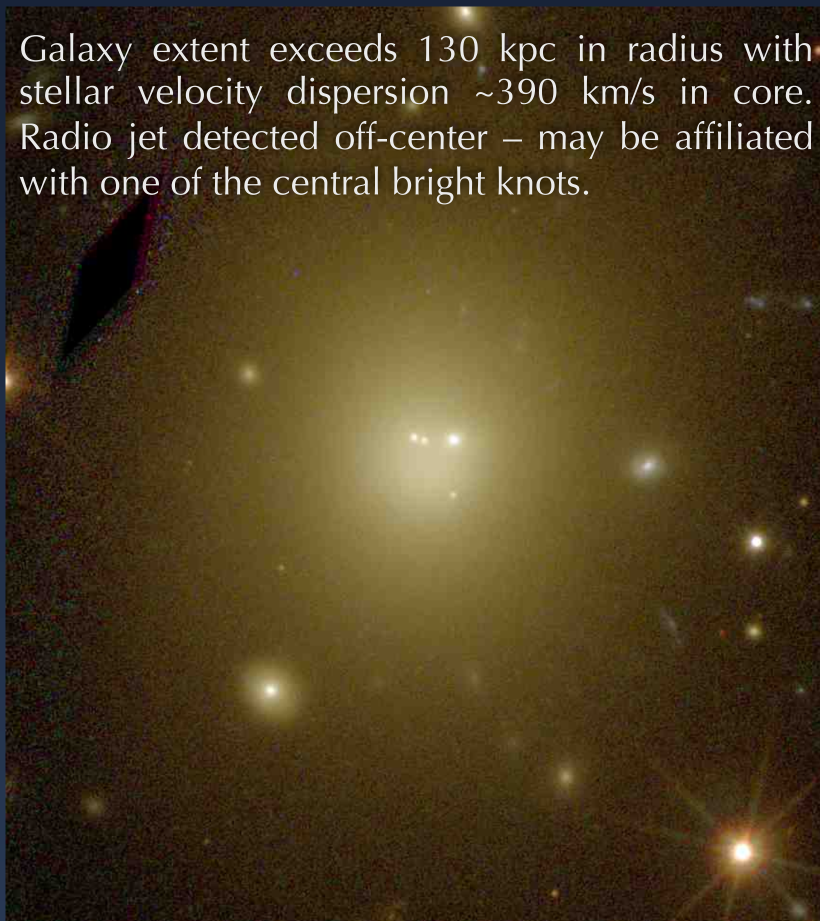
$$\omega = \frac{p_r + 2p_t}{c^2 3\rho}$$

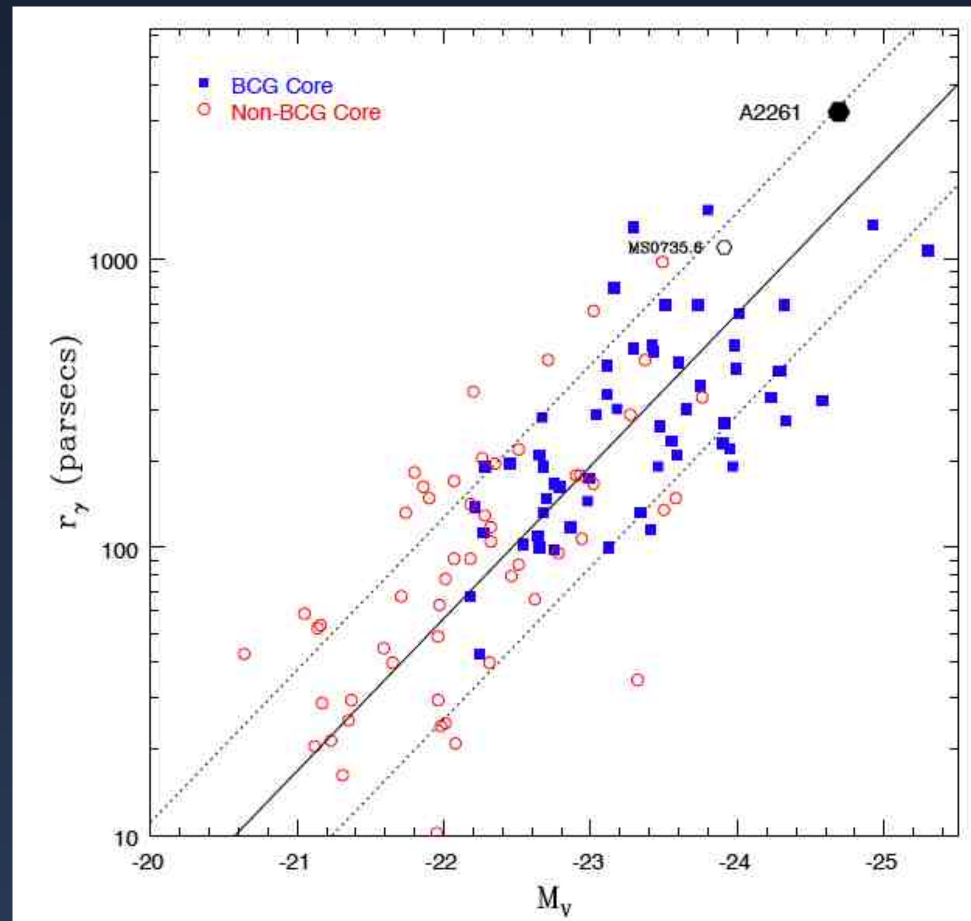
For MACS1206 (w/600 spec-z members):

ω = -0.05 ± 0.03 (stat) ± 0.1 (sys)

Sartoris et al. 2013, in prep.
using CLASH-VLT spectra.

Large Flat Core in A2261 BCG





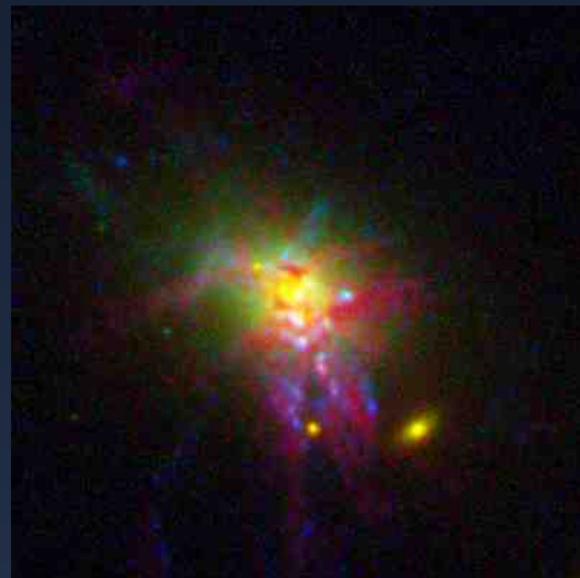
Core “break” radius vs. absolute rest-frame V magnitude

Abell 2261 (z=0.224) ~10^{10} $M_\odot$ SMBH

(Postman et al. 2012, ApJ, 756, 159)

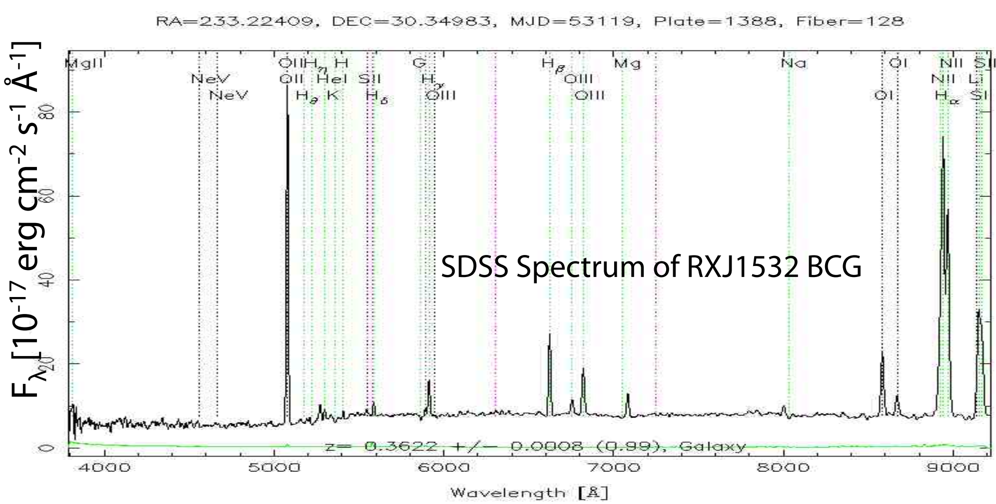
Active Brightest Cluster Galaxies

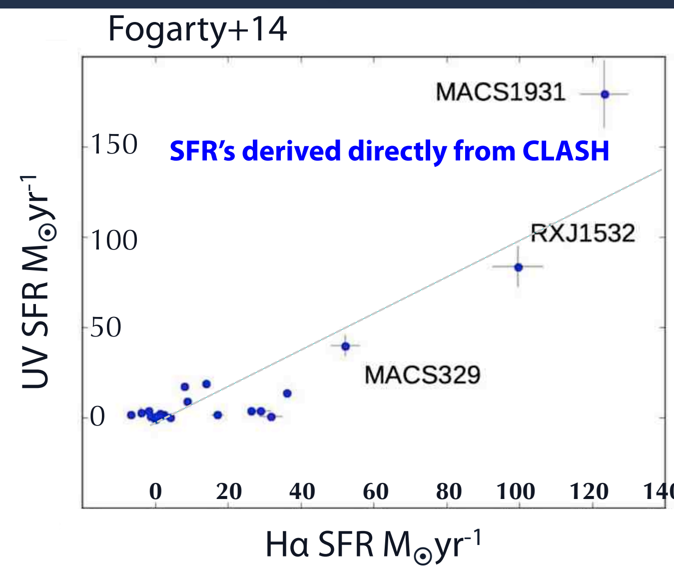
MACS J0329-0211
(z=0.450)



RXJ 1532+3021
(z=0.362)

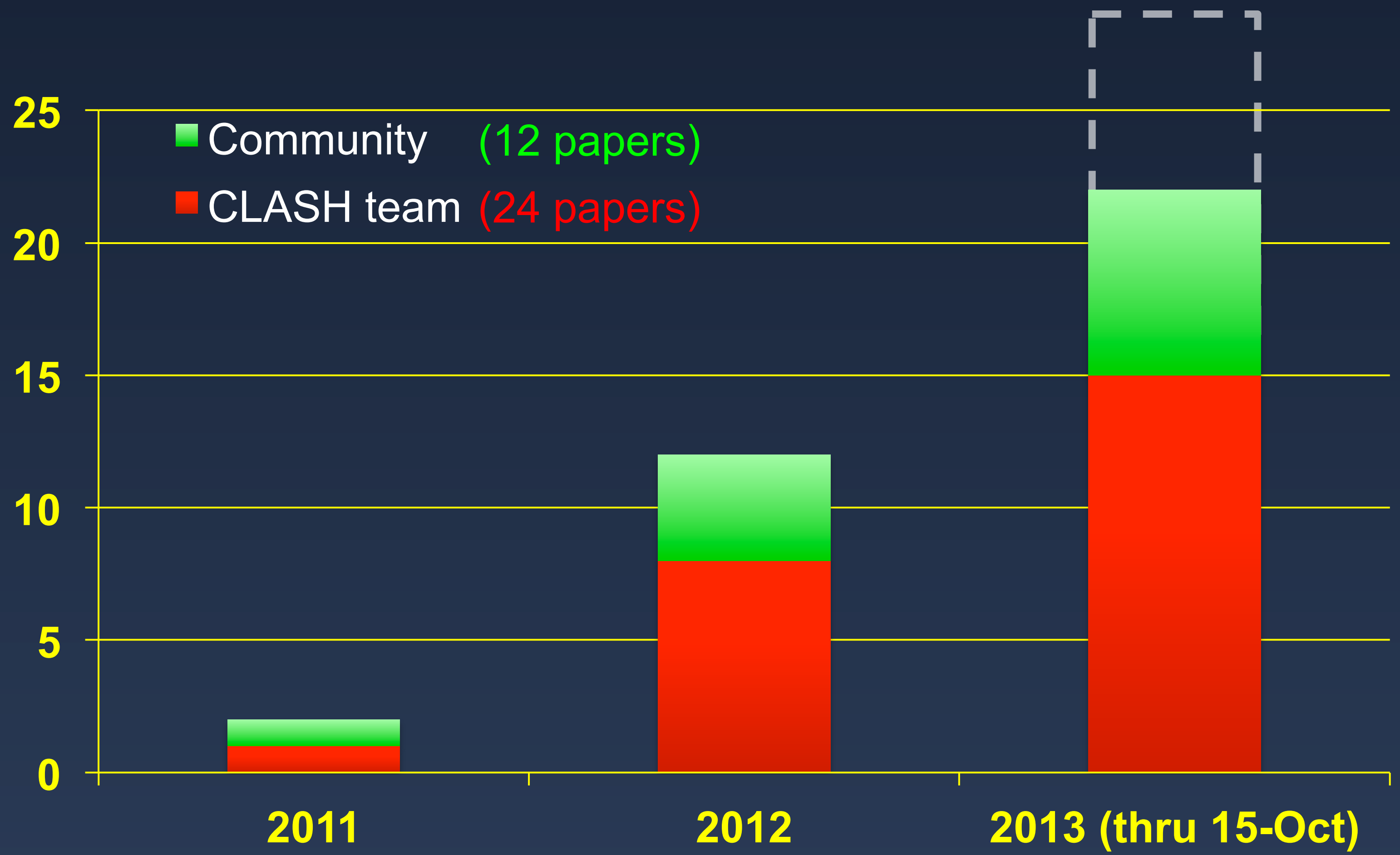
MACS J1931-2634
(z=0.352)





CLASH Publications

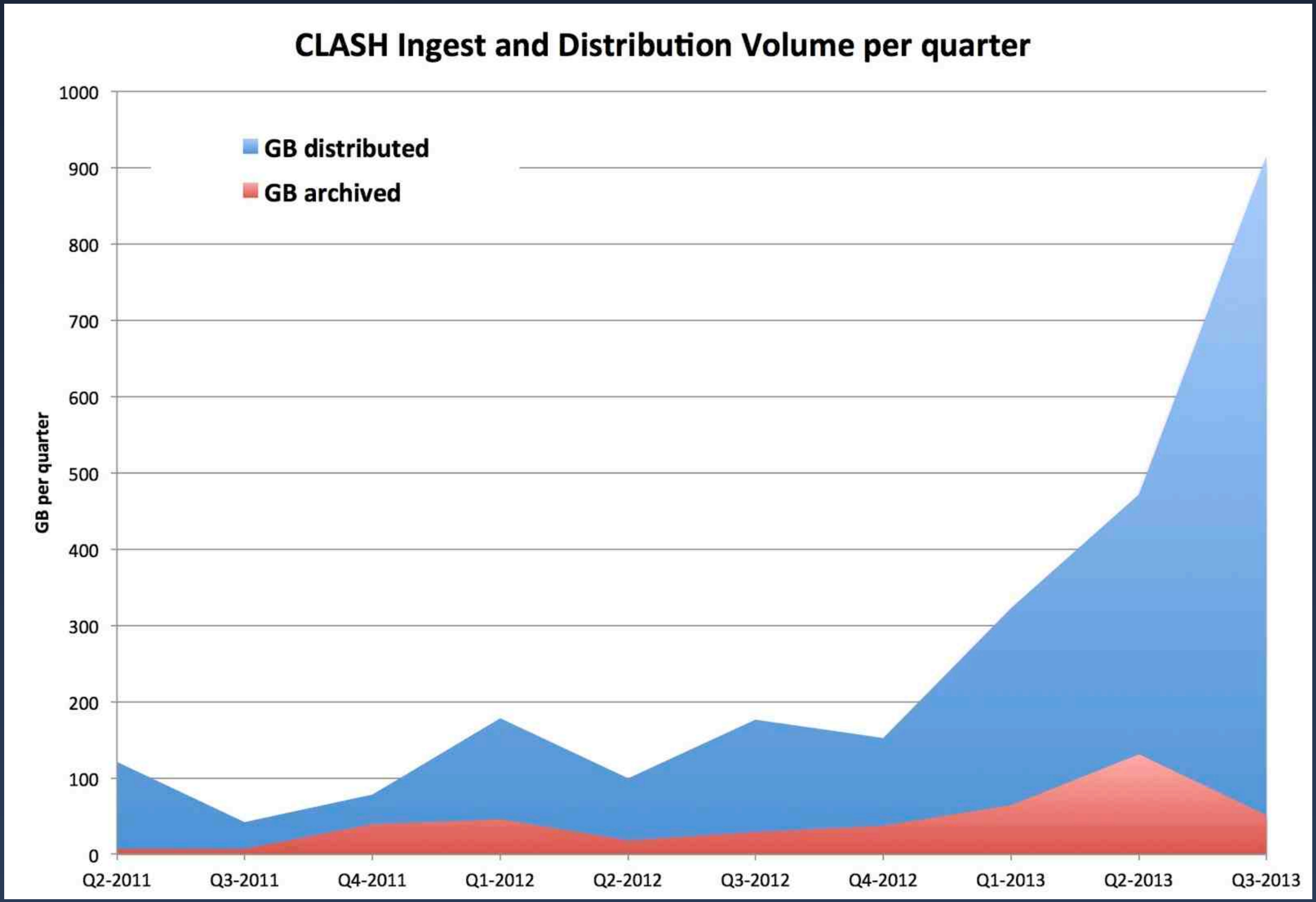
36 refereed papers (25 published / 11 submitted) to date.



373 Citations to CLASH team papers (as of 15-Oct-2013)

Community Usage

- CLASH HLSP Ingest & Retrieval Stats:



From Köhlinger & Schmidt (2013) paper: "This work profits immensely from the high-quality data made available by CLASH. We thank the whole CLASH team for their amazing effort and their community-friendly data release policy."

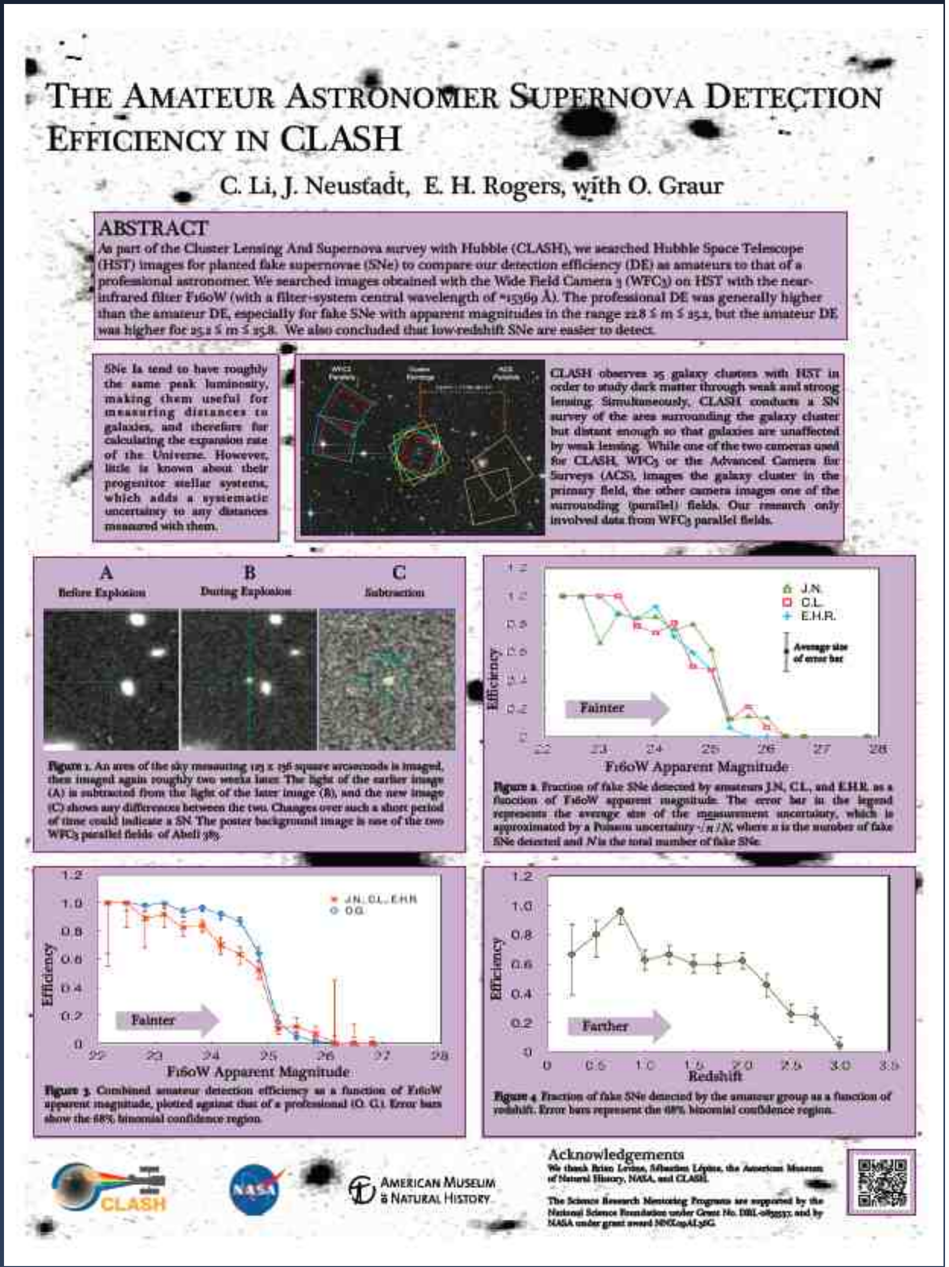
E/PO: Participation of high-school students in CLASH

As part of the Science Research Mentoring Program (SRMP) at the American Museum of Natural History, 6 high-school students have participated in the CLASH supernova survey during 2011-2013.

Students searched for supernovae and measured their detection efficiency.

Students presented their findings in a paper, poster, and presentation before their peers.

SRMP was partially funded by NASA grant award NNX09AL36G.



CLASH Data Product Teams

- HST Program Coordinator: B. Perriello
- HST Phase II prep & Raw Data Calibration: L. Bradley
- HST Drizzled Mosaics: A. Koekemoer
- HST Source Catalogs: D. Coe, D. Kelson
- Photometric Redshifts: N. Benitez, D. Coe, S. Jouvel, A. Molino
- Wide-field Ground-based Images & Catalogs: E. Medezinski, A. Molino, M. Nonino, S. Seitz, K. Umetsu
- Spitzer Mosaics & Catalogs: L. Moustakas, X. Shu, L. Ubeda, W. Zheng
- X-ray Data & Parameters: M. Donahue
- Spectroscopic Data: I. Balestra, D. Kelson, P. Melchior, A. Mercurio, M. Nonino, P. Rosati, et al.
- Mass Models (Lensing): M. Carrasco, D. Coe, C. Grillo, J. Merten, S. Seitz, K. Umetsu, A. Zitrin
- mm-wave (SZ) Data: N. Czakon, S. Golwala, J. Sayers, S. Siegel

CLASH HST Observation & Data Release Schedule

Cluster	HST Obs. Begin	HST Obs. End	1st Data Release	2nd Data Release	End Seq #
Abell 383	11/18/2010	03/01/2011	05/01/2011	09/01/2011	1
MACS1149	12/04/2010	03/09/2011	05/09/2011	09/09/2011	2
Abell 2261	03/09/2011	05/20/2011	07/20/2011	11/20/2011	3
RXJ1347	04/19/2011	07/11/2011	09/11/2011	01/11/2012	4
MACS2129	05/15/2011	07/11/2011	09/11/2011	01/11/2012	5
MACS1206	04/03/2011	07/19/2011	09/19/2011	01/19/2012	6
MS2137	08/21/2011	10/27/2011	12/27/2011	04/27/2012	7
MACS0329	08/18/2011	11/01/2011	01/01/2012	05/01/2012	8
MACS0647	10/05/2011	11/26/2011	01/26/2012	05/26/2012	9
MACS0717	08/31/2011	12/07/2011	02/07/2012	06/07/2012	10
MACS0744	09/22/2011	12/27/2011	02/27/2012	06/27/2012	11
MACS1115	12/11/2011	02/19/2012	04/19/2012	08/19/2012	12
RXJ1532	01/30/2012	04/10/2012	06/10/2012	10/10/2012	13
Abell 611	01/26/2012	05/14/2012	07/14/2012	11/14/2012	14
MACS1720	03/23/2012	05/30/2012	07/30/2012	11/30/2012	15
MACS1931	04/09/2012	06/30/2012	08/30/2012	12/30/2012	16
RXJ2129	04/03/2012	07/15/2012	09/15/2012	01/15/2013	17
Abell 209	06/25/2012	09/19/2012	11/19/2012	03/19/2013	18
MACS0416	07/23/2012	09/25/2012	11/25/2012	03/25/2013	19
RXC J2248	08/29/2012	10/30/2012	12/30/2012	04/30/2013	20
MACS0429	11/26/2012	01/29/2013	03/29/2013	07/29/2013	21
Abell 1423	11/30/2012	02/12/2013	04/12/2013	08/12/2013	22
MACS1423	12/31/2012	03/12/2013	05/12/2013	09/12/2013	23
CLJ1226+3332	04/06/2013	06/17/2013	08/17/2013	12/17/2013	24
MACS1311	04/11/2013	07/09/2013	09/09/2013	01/09/2014	25

Cluster	Subaru (or WFI) Release (Proposed)	Spectroscopy Release (Proposed)	Mass Model Releases (Proposed)	X-Ray Imaging Data Release (Proposed)	Spitzer Data Release (Proposed)*	SZE Data Release (Proposed)*
Abell 383	30-SEPT-2014	TBD	31-OCT-2013	31-JAN-2014: Our re-processed Chandra images, including co-added data where useful, for CXO products that were public as of summer 2012. 15-MAR-2014: HSE mass profiles (or by acceptance date of our paper) 15-JAN-2015: XMM data products	20-DEC-2013: • IRAC Mosaics • MIPS Mosaics • IRAC Source Catalogs 30-MAY-2014: • PyGFIT Source Catalogs 30-SEPT-2014: • MIPS Source Catalogs	30-JUN-2014
MACS1149	30-SEPT-2014	TBD	14-OCT-2013			31-OCT-2013
Abell 2261	30-SEPT-2014	TBD	31-DEC-2013			30-JUN-2014
RXJ1347	30-SEPT-2014	TBD	31-DEC-2013			30-JUN-2014
MACS2129	30-SEPT-2014	TBD	31-DEC-2013			30-JUN-2014
MACS1206	30-SEPT-2014	March 2014	31-OCT-2013			30-JUN-2014
MS2137	30-SEPT-2014	TBD	31-OCT-2013			30-JUN-2014
MACS0329	30-SEPT-2014	TBD	31-DEC-2013			30-JUN-2014
MACS0647	30-SEPT-2014	TBD	31-DEC-2013			30-JUN-2014
MACS0717	31-OCT-2013**	TBD	14-OCT-2013			31-OCT-2013
MACS0744	30-SEPT-2014	TBD	31-DEC-2013			30-JUN-2014
MACS1115	30-SEPT-2014	TBD	31-DEC-2013			30-JUN-2014
RXJ1532	30-SEPT-2014	TBD	31-DEC-2013			30-JUN-2014
Abell 611	30-SEPT-2014	TBD	31-DEC-2013			30-JUN-2014
MACS1720	30-SEPT-2014	TBD	31-DEC-2013			30-JUN-2014
MACS1931	30-SEPT-2014	TBD	31-OCT-2013			30-JUN-2014
RXJ2129	30-SEPT-2014	TBD	31-OCT-2013			30-JUN-2014
Abell 209	30-SEPT-2014	TBD	31-OCT-2013			30-JUN-2014
MACS0416	31-OCT-2013**	February 2014	14-OCT-2013			31-OCT-2013
RXC J2248	30-SEPT-2014	TBD	14-OCT-2013			31-OCT-2013
MACS0429	30-SEPT-2014	TBD	31-OCT-2013			30-JUN-2014
Abell 1423	30-SEPT-2014	TBD	31-DEC-2013			30-JUN-2014
MACS1423	30-SEPT-2014	TBD	31-OCT-2013			30-JUN-2014
CLJ1226+3332	30-SEPT-2014	TBD	31-OCT-2013			30-JUN-2014
MACS1311	30-SEPT-2014	TBD	31-OCT-2013			30-JUN-2014

FFI CLUSTER

** Already shared with FFI teams.

* Released through IPAC Data Archive Center

CLASH-inspired Science Software Products

- Trilogy – color image generator (D. Coe). Publicly available now.
- iSEDFit – SED fitting package (IDL-based) for galaxy evolution studies (J. Moustakas). Public port of this code made possible via CLASH GO funding.
- Automated arc finding software (B. Xu) – not yet released but will be eventually.

Lessons Learned

- Phase II planning & scheduling of MCT program is quite complex.
- HST data was easiest of all the data to handle thanks to well-developed pipeline. Data pipelines need to be developed ASAP in a large program.
- UV bands (WFC3) do benefit significantly from pre/post-flash if exposure times are only ~2 orbits. More UV exposure time should have been requested.
- Cluster regions present special challenges for precision photometry. Sky background fluctuations dominated by halo light from many cluster members and requires more sophisticated approach to model … FFI analyzers take note.
- Funding of MCT program is inadequate for full out-year data analysis. Not due to our lack of insight (proposed budget was ~50% higher) but rather limitations of FRC insight and available funds for MCT program. ***Most complex analyses done when all data in hand.***
- International team was very productive and brings key advantages but also critical to have U.S. funded post-docs and faculty.
- Maximizing attendance at team meetings is very important and thus teams with a significant number of non-U.S. co-investigators will need to have most of their team meetings at foreign sites. (50% of CLASH co-I's not U.S.)

Was an MCT Program Required to do CLASH Science? Yes!

Science Case	~100 orbit program	~200 orbit program	Full MCT Program (524 orbits)
Robustly test consistency of M-c with LCDM predictions	No	No	Yes
Find lensed $z \geq 9$ Galaxies	Yes but only if selecting strongest cluster lenses	Yes	Yes
Get statistically useful sample of $z \geq 6$ lensed galaxies (e.g., evolution of UV slope)	No	Marginal	Yes
Constrain DTD from SN Ia Rates	No	No	Yes
Detect lensed SNe at $z > 1$	No	No	Yes
Provide robust calibration of cluster masses	No	Marginal	Yes
Broad range of other science ALONG with all of the above	No	Partial	Yes

Intangible benefits of MCT status: comprehensive nature of science makes it easier to get significant amounts of supporting data from other facilities. Immediate community access to data. High motivation to provide a range of usable HLSPs to community.