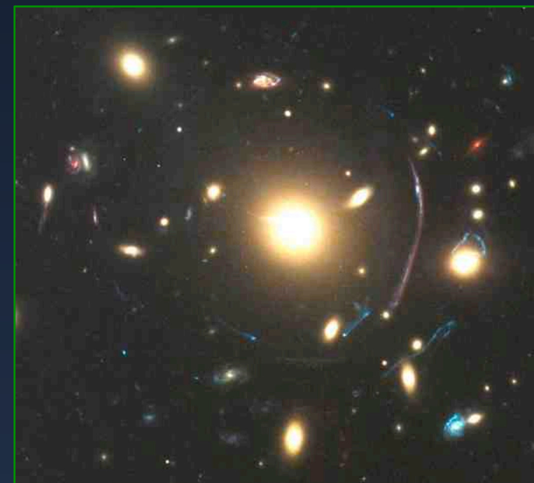
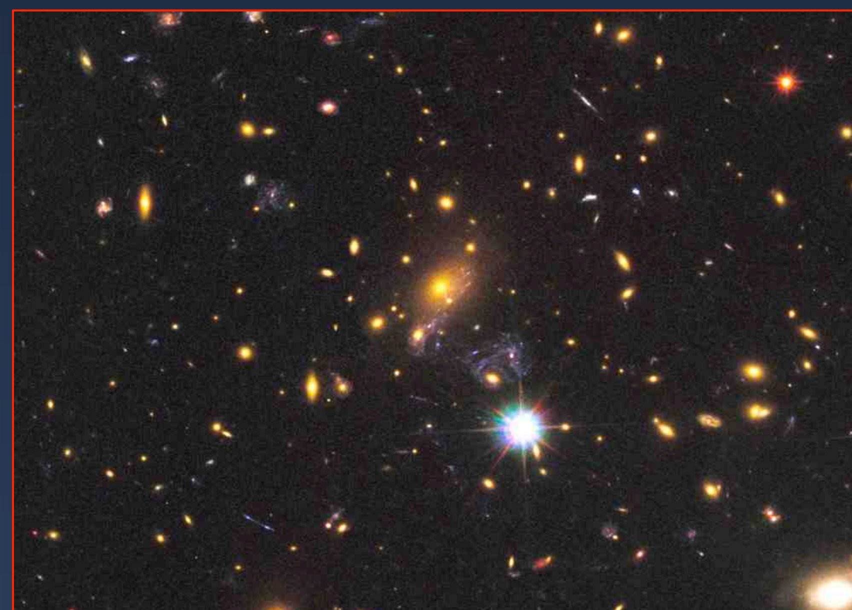
Cluster Lensing And Supernova survey with Hubble

CLASH





Marc Postman, STScI

LBL Physics Division RPM, May 20, 2014

Cluster Lensing And Supernova survey with Hubble

CLASH Team at RAS, London, Sept 2013

A HST Multi-Cycle Treasury Program designed to place new constraints on the fundamental components of the cosmos: dark matter, dark energy, and baryons.

To accomplish this, we are using galaxy clusters as cosmic lenses to probe dark matter and magnify distant galaxies.

Multiple observation epochs enable a z > 1 SN search in the surrounding field (where lensing magnification is low).

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

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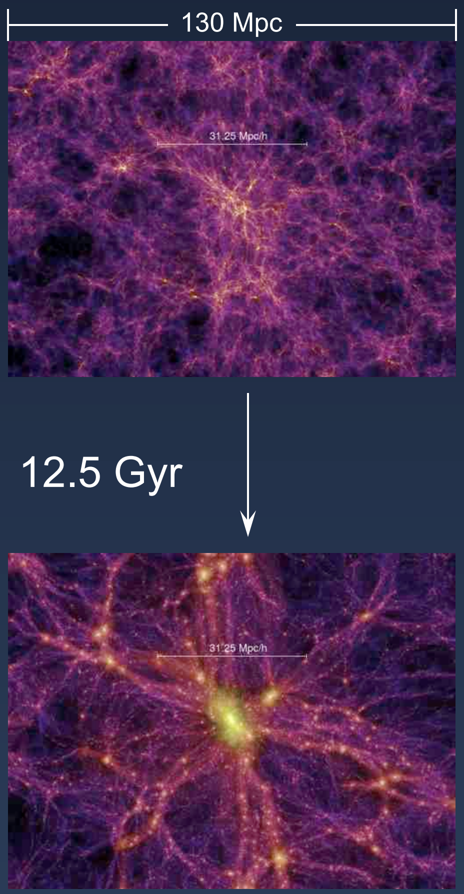
Wei Zheng	JHU
Bodo Ziegler	Universität Wein
Adi Zitrin	Caltech

Post-doctoral fellow
Graduate student

Fundamental Unanswered Questions in Astrophysics

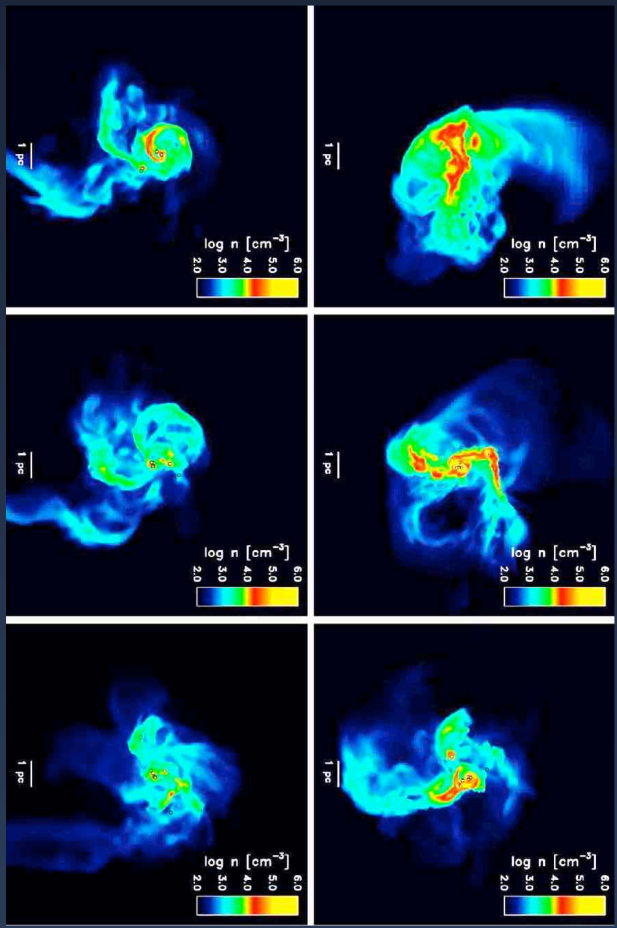
- How is dark matter distributed in cluster & galaxy halos?
  - How centrally concentrated is the DM? Implications for epoch of formation.
  - What degree of substructure exists? And on what scales?
  - How well do DM profiles match those predicted from simulations?
  - What correlations exist between the distribution of baryonic matter and DM?



“Millennium” simulation of DM
Springel et al. 2005

Fundamental Unanswered Questions in Astrophysics

- When was the epoch of first galaxy formation?
  - What are the characteristics (mass, “metal” abundance, star formation rates, global structure) of the most distant galaxies in the universe (t_U < 800 Myr)?
  - What was their role in ionizing the intergalactic medium?
  - How do galaxies build up and evolve at the earliest times?



Simulating the First Galaxies
Safranek et al. 2013

Fundamental Unanswered Questions in Astrophysics

- Why is the expansion of the universe accelerating?
  - Is it something other than Λ?
  - What are the parameters of the dark energy equation of state?
  - What is the rate of high-z type Ia supernovae? What does the rate tell us about their progenitors?
  - How standard are our "standard" candles (cosmic distance indicators)? Need better measurements of systematic effects at large lookback times.

$w = P / \rho c^2$

$w = -1$ (cosmo constant)

$w \neq$ constant; scalar field

e.g. Quintessence, k-essence

Is w a f(z)?

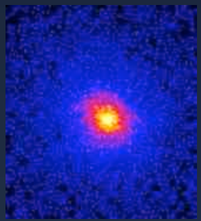
$w(z) = w_o + w_a\, z/(1+z)$

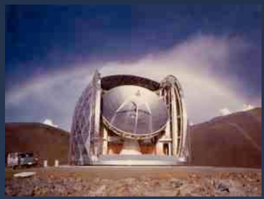
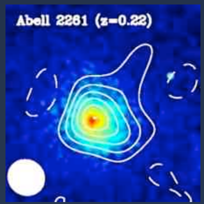
(e.g., Linder 2003)

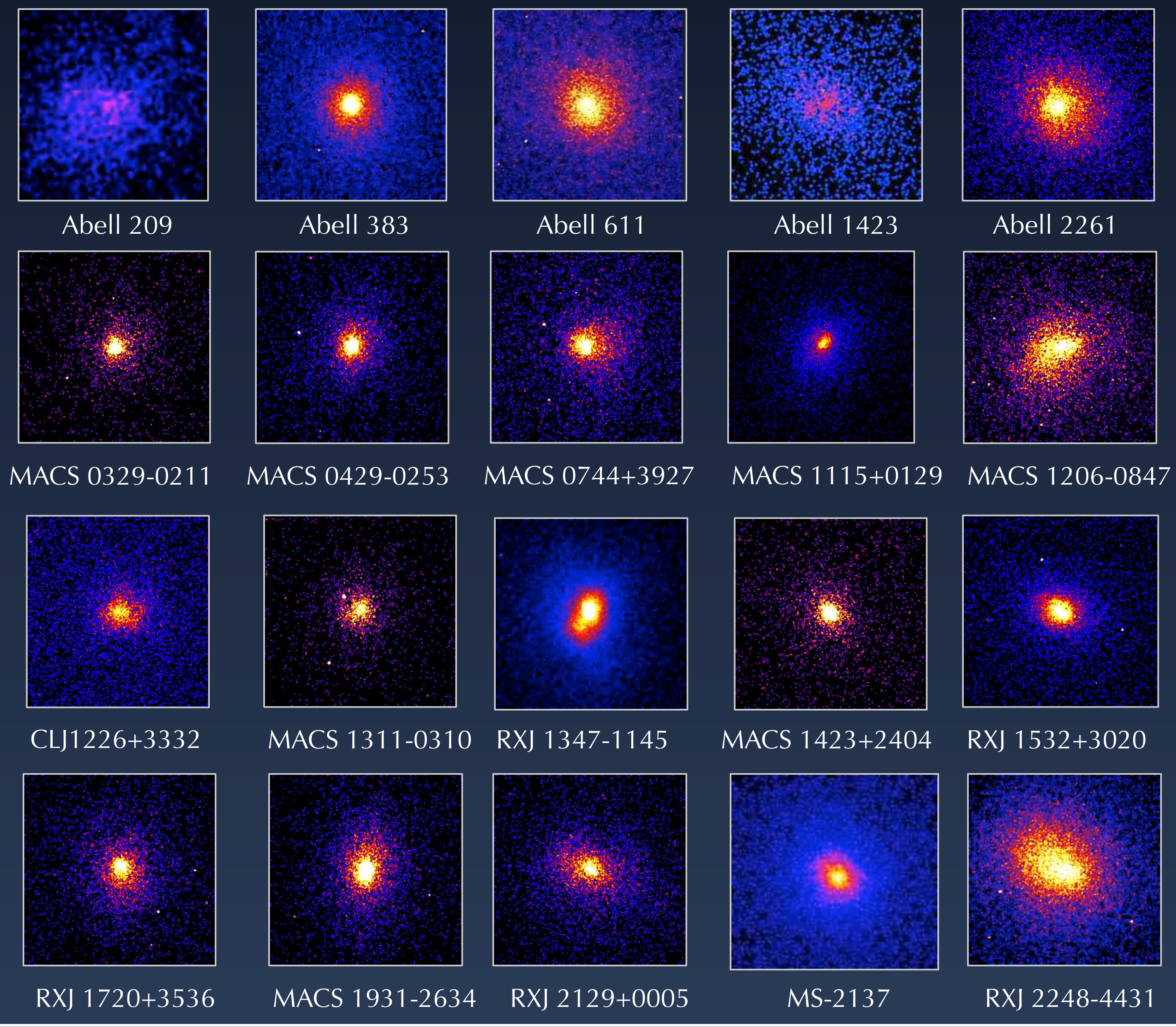
Comprehensive Multi-wavelength Coverage

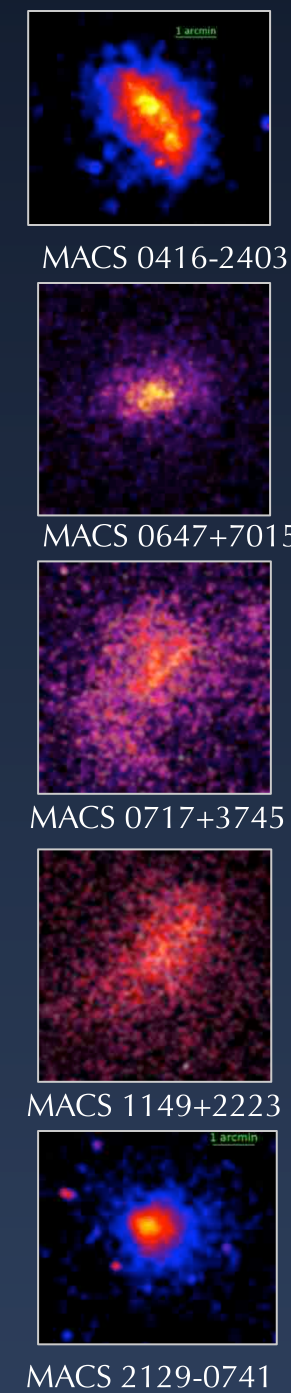
- HST 524 orbits: 25 clusters, each imaged in 16 passbands. (0.23 – 1.6 μm) ~20 orbits per cluster. HST survey complete.
- Subaru wide-field imaging (0.4 – 0.9 μm)
- Chandra x-ray Observatory archival data (0.5 – 7 keV) and XMM data.
- Spitzer Space Telescope archival and new cycle 8 data (3.6, 4.5 μm)
- SZE observations (Bolocam, Mustang) to augment existing data (sub-mm)
- VLT, LBT, Magellan, MMT, Palomar Spectroscopy **(~30,000 spectra to date)**



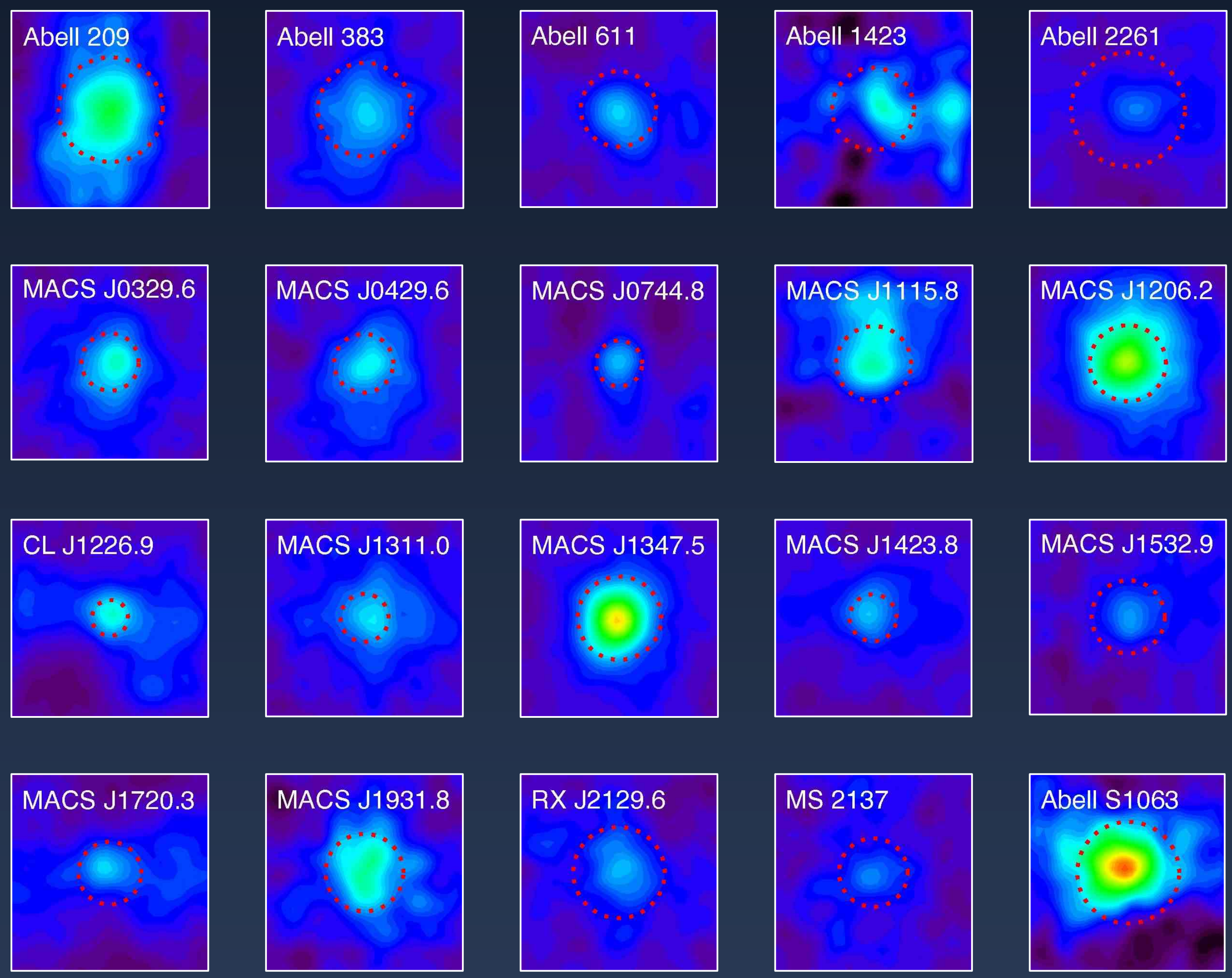



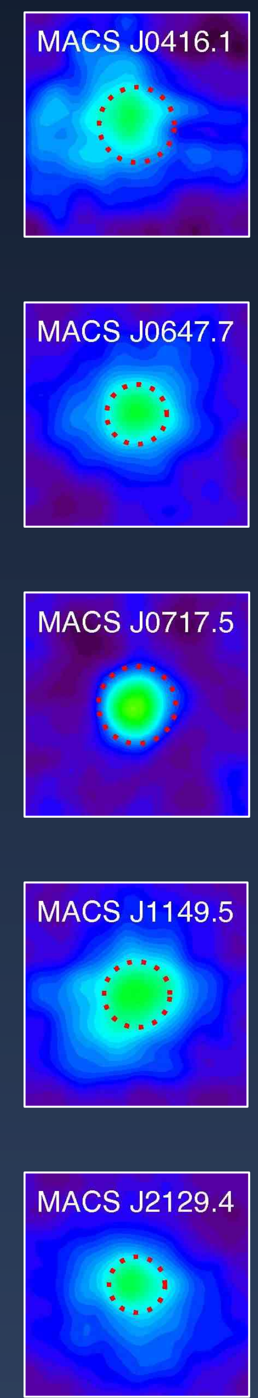






X-ray images of the 25 CLASH clusters. 20 are selected to be "relaxed" clusters (based on their x-ray properties only). 5 (last column) are selected specifically because they are strongly lensing $\theta_E > 35''$. **All CLASH clusters have Tx > 5 keV.**





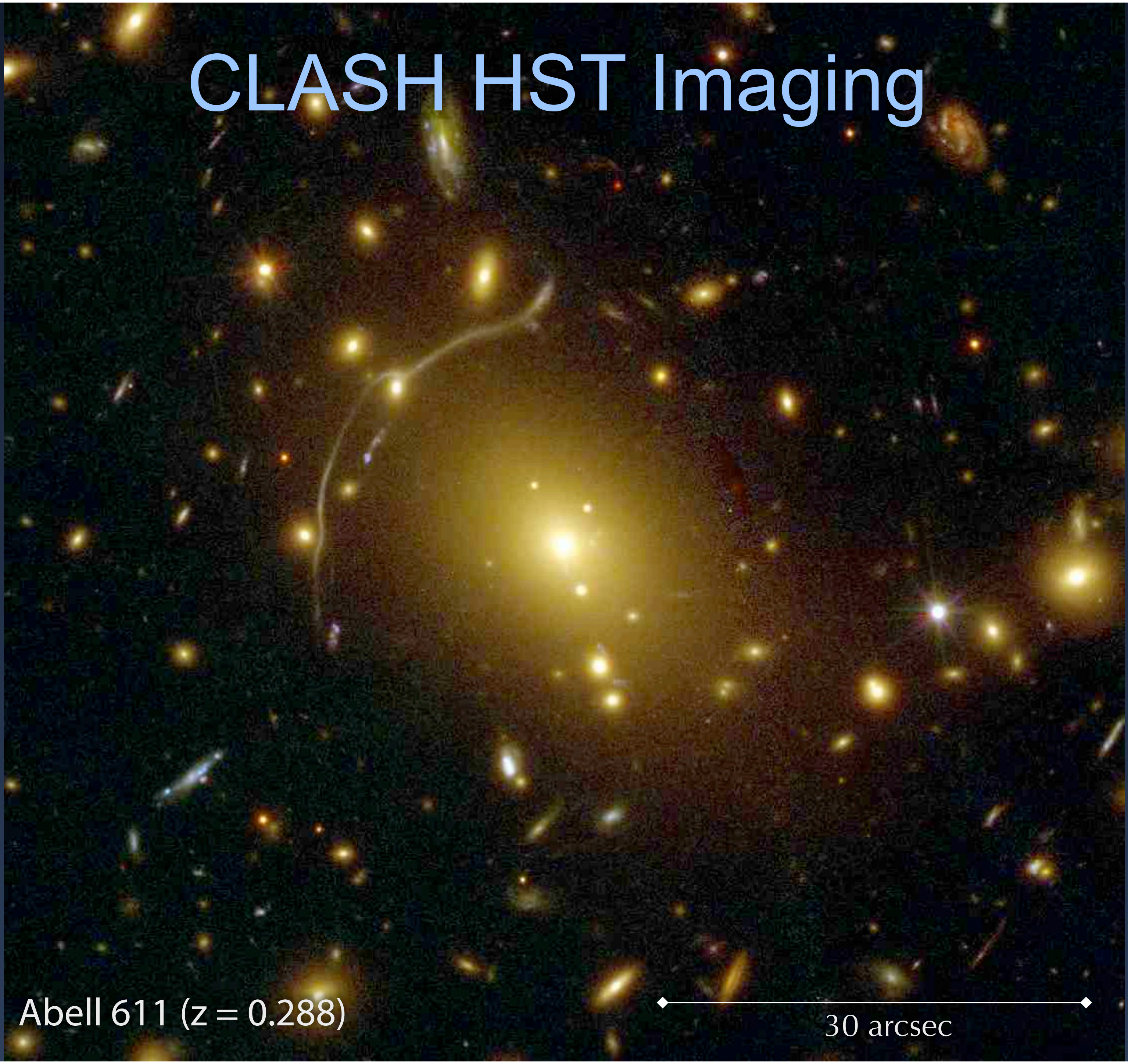
Deconvolved Bolocam SZE Images of the CLASH clusters, each image is 10′x10′.

Red dashed line: R_{2500}.

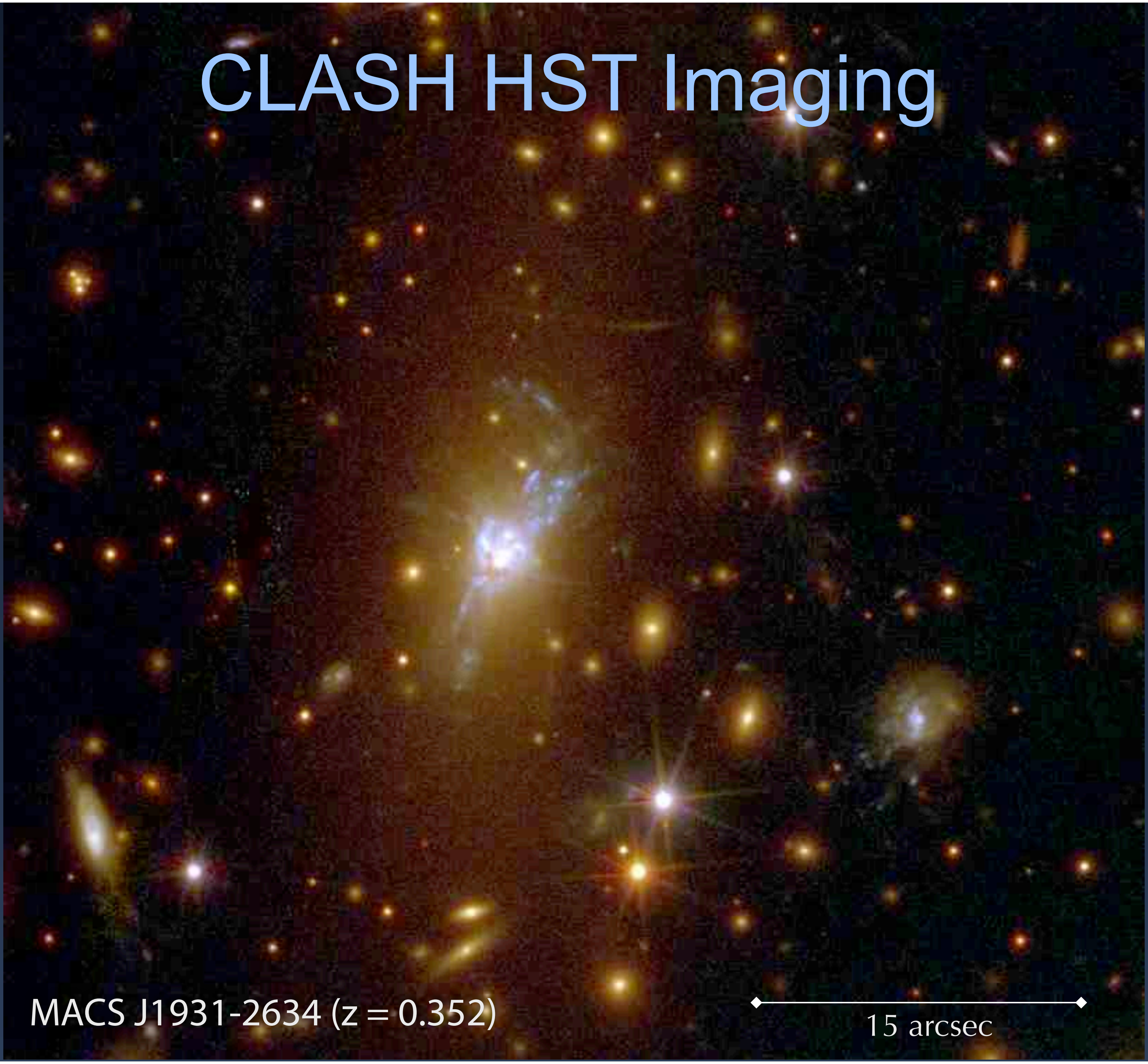
Lensing Mass-SZE scaling relations (N. Czakon)

Triaxial modeling of X-ray, lensing, SZ data (S. Siegel)

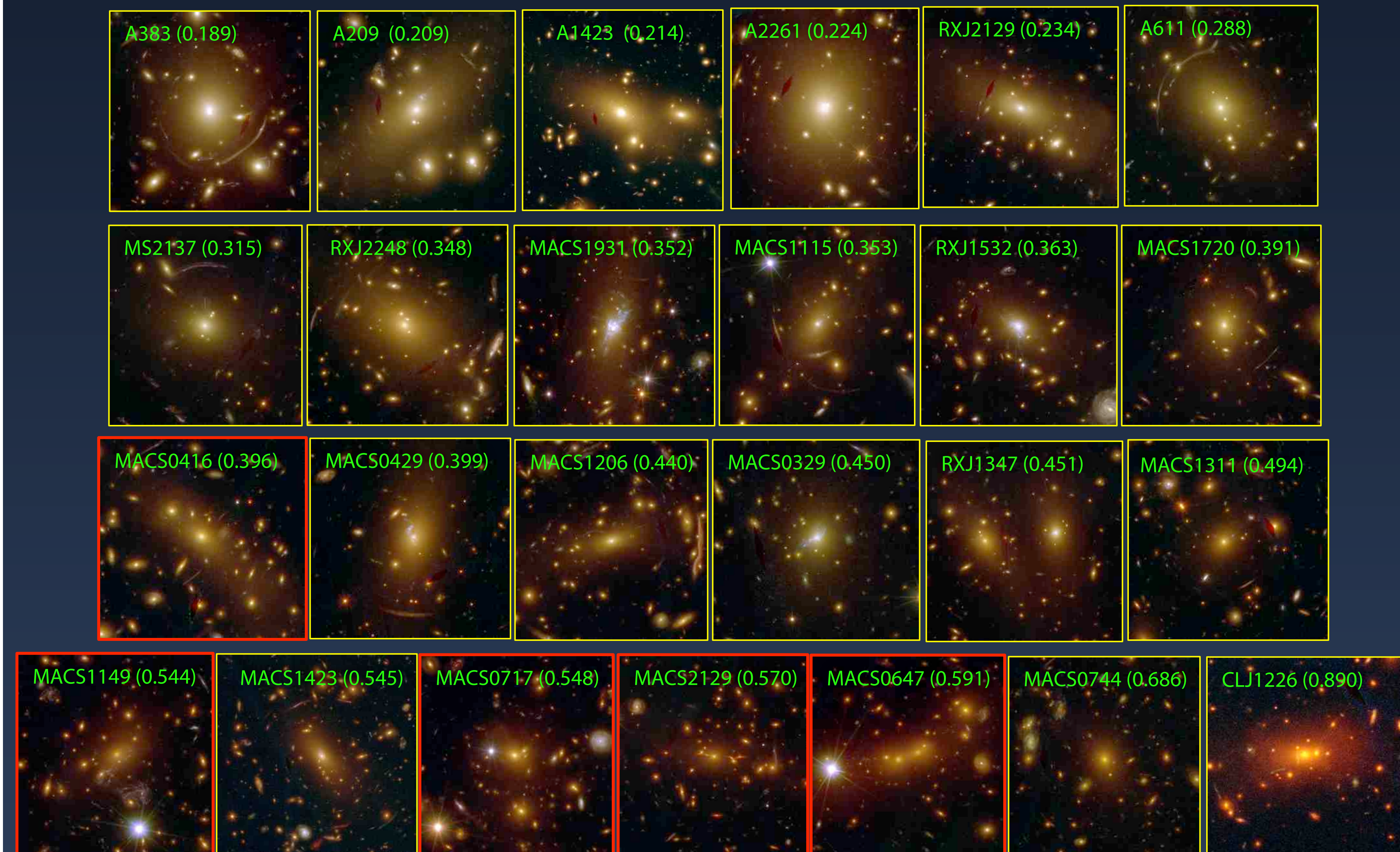
CLASH HST Imaging



CLASH HST Imaging



The CLASH (HST) Gallery



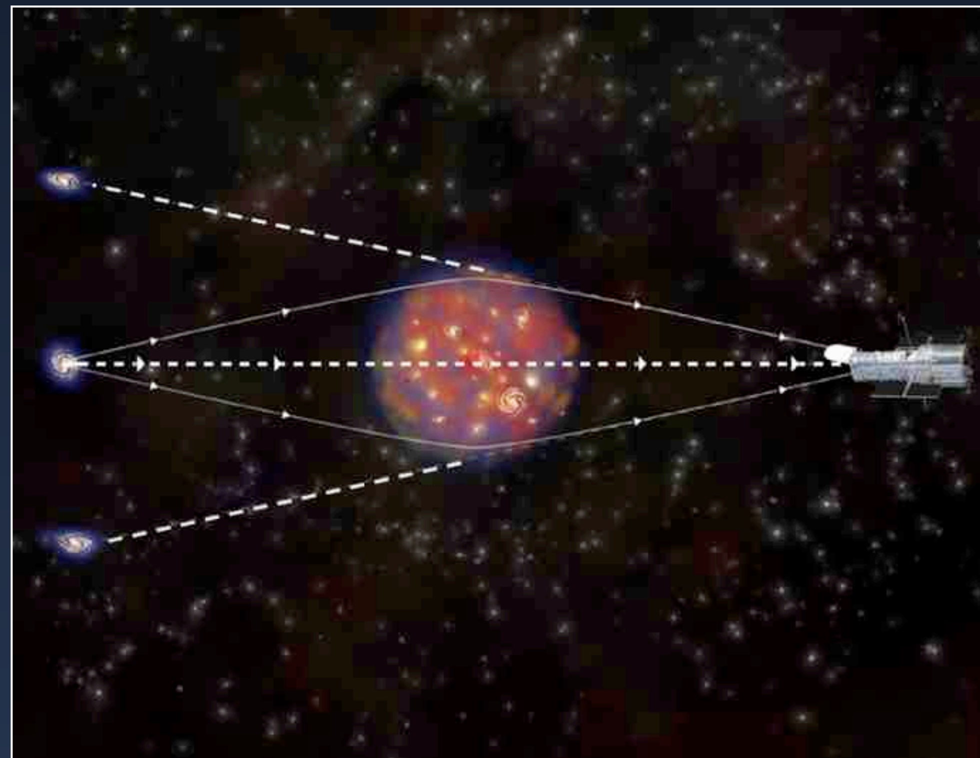
20 clusters are x-ray selected (Tx > 5 kev, low asymmetry),

5 clusters are very strong lenses (Einstein radii > 30 arcsec) .

Galaxy Clusters as Cosmic Telescopes

Strong Lensing Basics:

- Galaxy cluster mass density deforms local space-time.
- Pure geometrical effect with no dependence on photon energy.
- Provides large areas of high magnification (μ ~ 10).
- Amplifies both galaxy flux and size while conserving surface brightness.
- Can have multiply-imaged background galaxies.
- *Tradeoff: Dilution of the high-redshift source-plane area:* $A \sim 1/\mu$

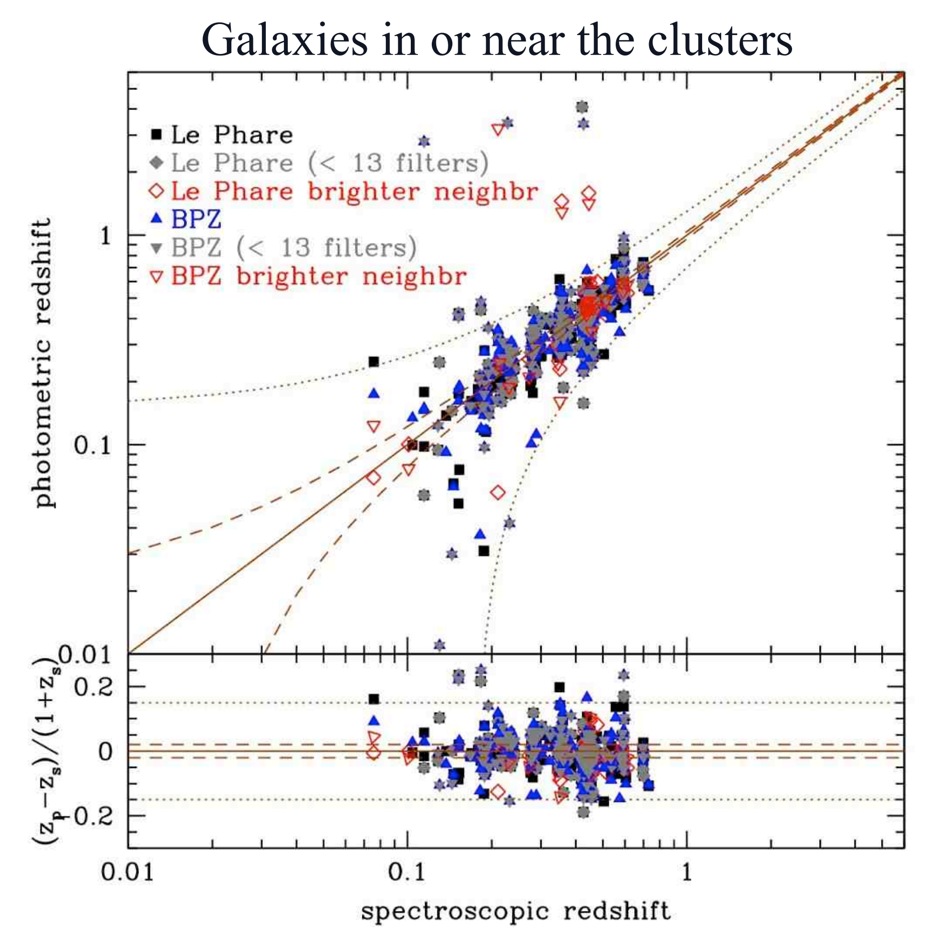


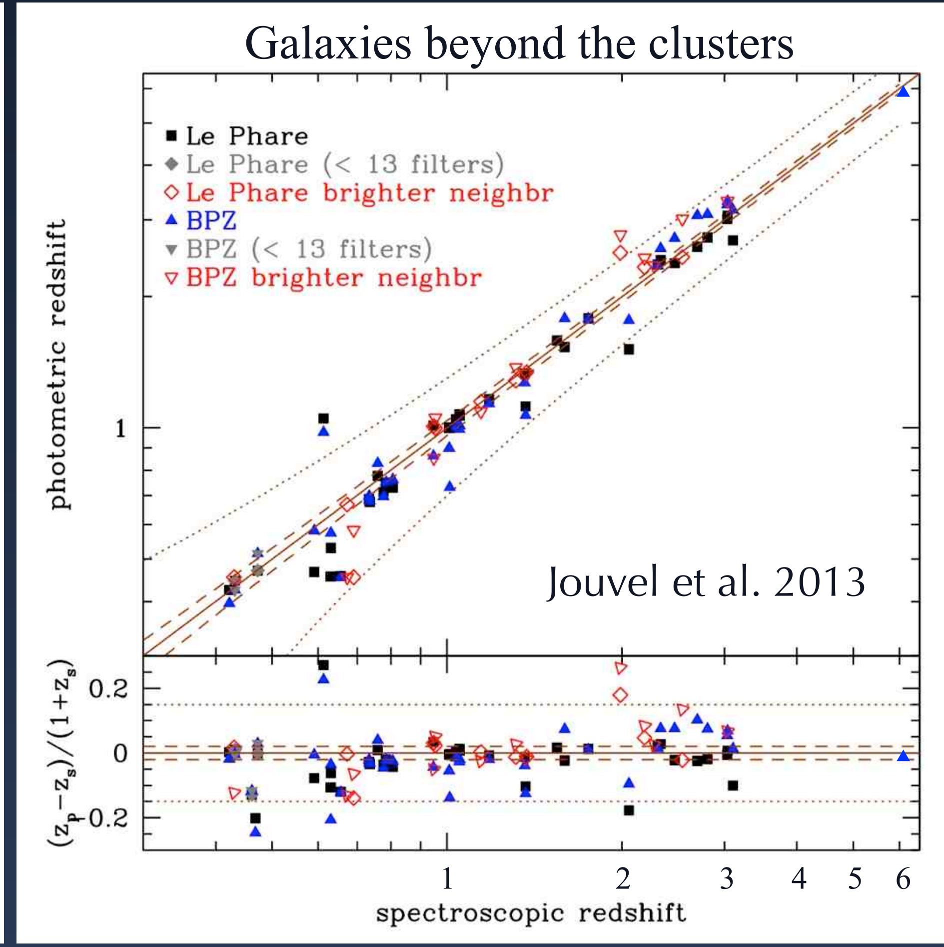
Weak Lensing Basics:

- Beyond regions of critical mass surface density, the galaxy distortions are subtle and are only detected statistically.
- No multiply imaged sources.
- Probes large-scale mass distribution.

Photo-z Accuracy: 16 filters pay off!

CLASH photometric redshifts can be obtained for ~6x as many z > 1 objects as could be obtained using spectrographs on 10-meter class ground-based facilities.





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.

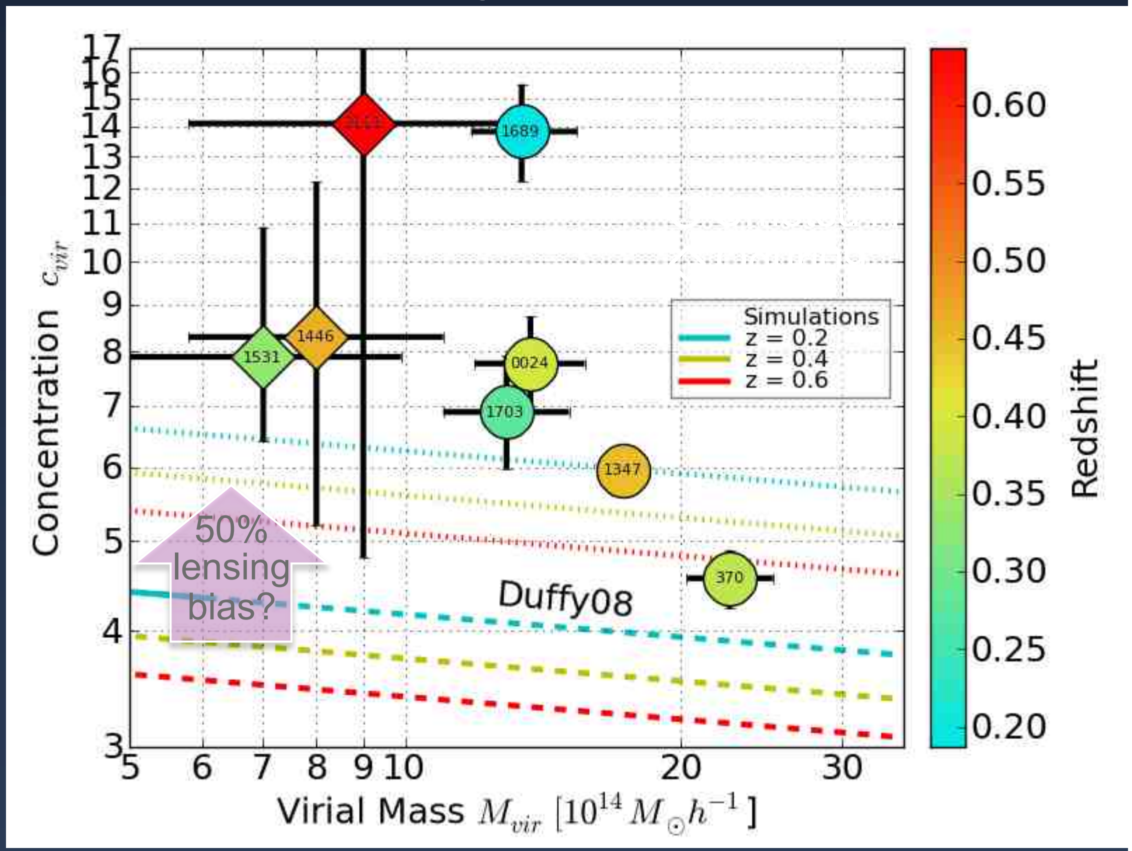
Pre-CLASH: Well constrained cluster mass profiles (from lensing) were more concentrated than simulated clusters

c-M relation is a direct test of CDM paradigm as it predicts a strong correlation between the two.

Observational studies of clusters with well constrained mass profiles yielded concentrations that were in tension with predictions.

Partially explained by significant (50-100%) lensing selection bias as estimated by Hennawi07, Oguri09, Meneghetti10,11

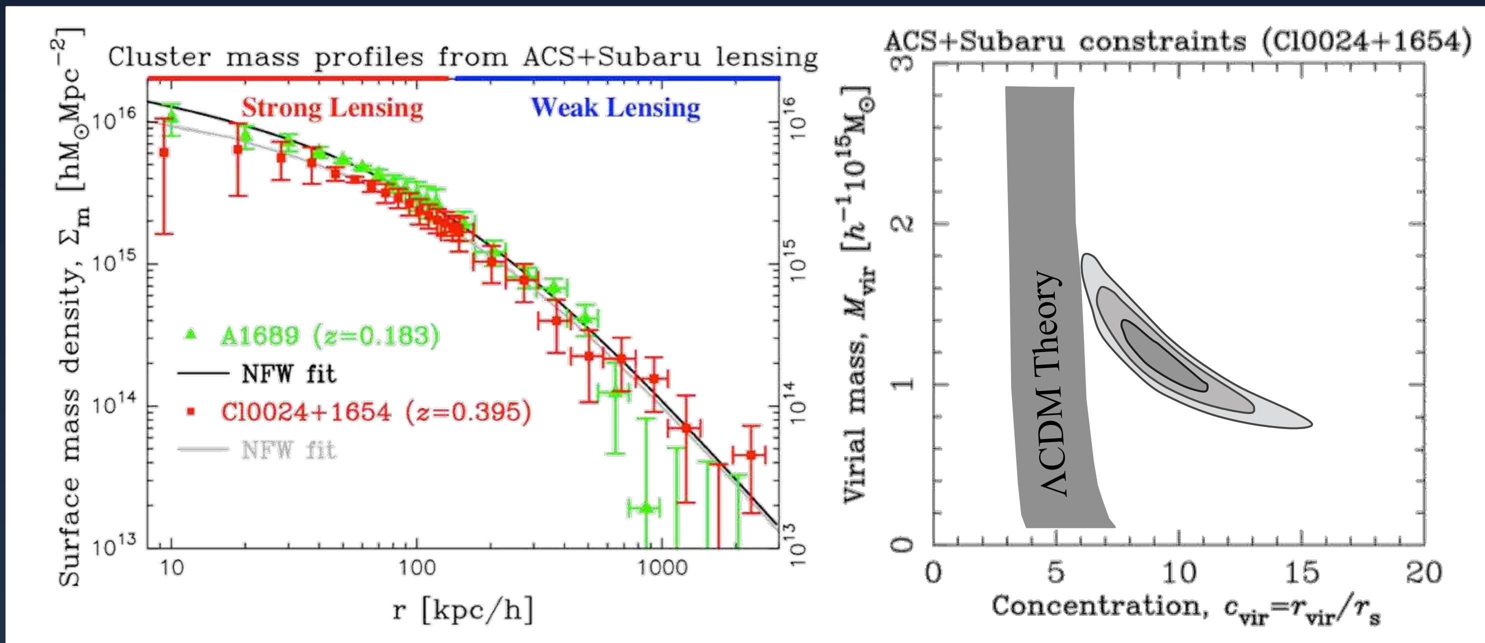
– Broadhurst08, Oguri09, Sereno10, Zitrin11a,b



Possible explanations for high observed concentrations

- **Lensing selection bias** (Henawi+07, Oguri+09, Meneghetti+10,11)
  - Significant (25-50%) but is it sufficient?
  - 20 CLASH clusters are x-ray selected (minimal lensing bias)
- **Baryons and adiabatic contraction**
  - Probably not a major (<10%) effect in clusters (Duffy+10, Mead+10, Fedeli11) … but needs to be checked.
- **Halo fitting procedure in simulations**
  - Hennawi+07 find ~30%+ higher concentrations
- **Halo Triaxiality and LSS**
- **Clusters formed sooner than in simulations**
  - Early Dark Energy (Fedeli & Bartelmann07, Sadeh & Rephaeli08, Francis+09, Grossi & Springel09)
  - Few percent EDE at z~10 has impact.

Both Strong & Weak Lensing Measurements Needed for Good Constraints



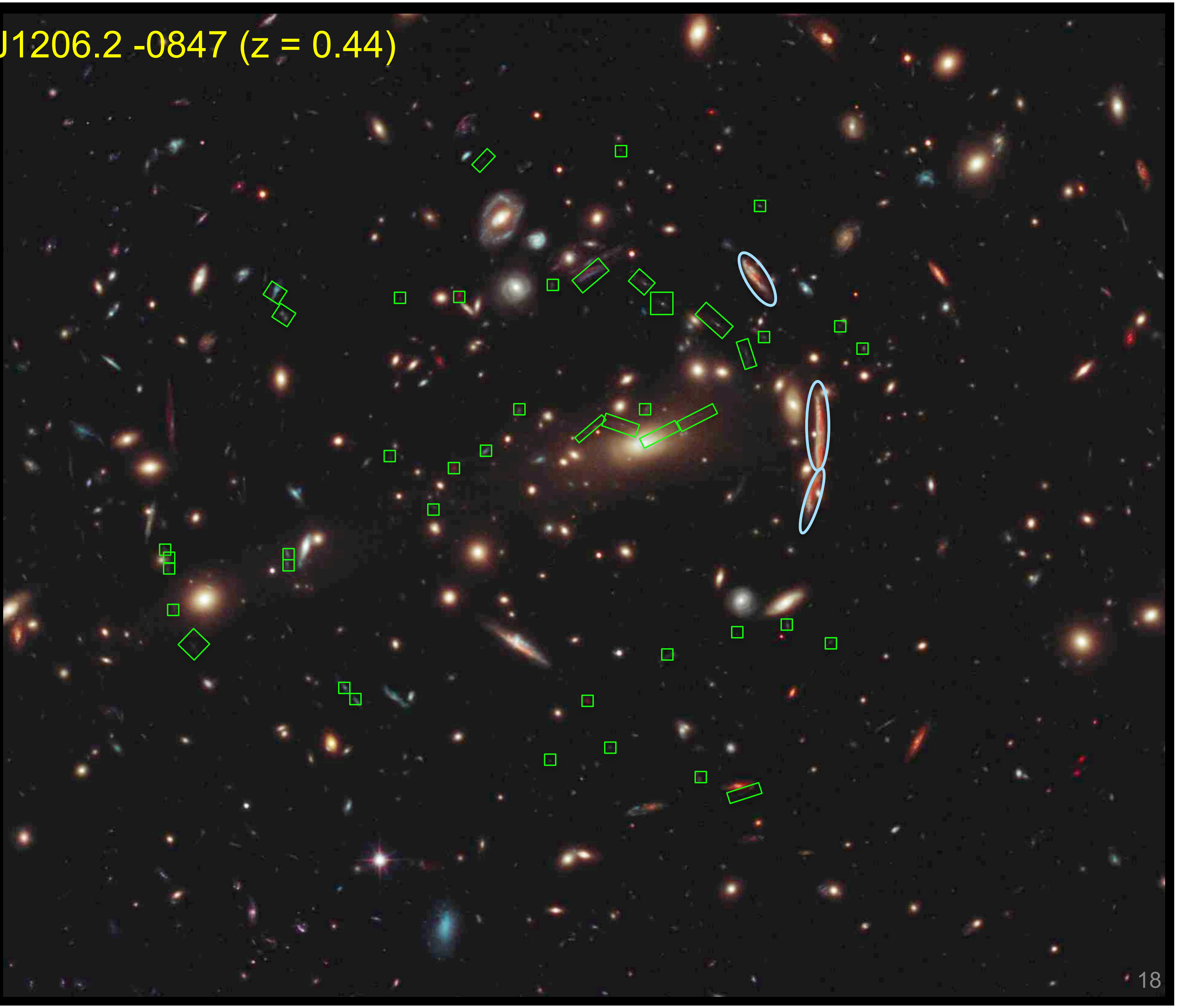
Umetsu et al. 2010

LCDM prediction from Duffy et al. 2008

CLASH provides:

- Three independent lensing constraints: SL, WL, and magnification bias
- Well-selected cluster sample with minimal lensing bias
- Definitive constraints on the representative equilibrium mass profile shape
- Robust measurement of cluster DM concentrations and their dispersion as a function of cluster mass (and possibly their redshift evolution).
- Excellent calibration of mass-observable relations for clusters (incl. dynamical, lensing, x-ray, and SZE for nearly all 25 clusters)

MACS J1206.2 -0847 (z = 0.44)



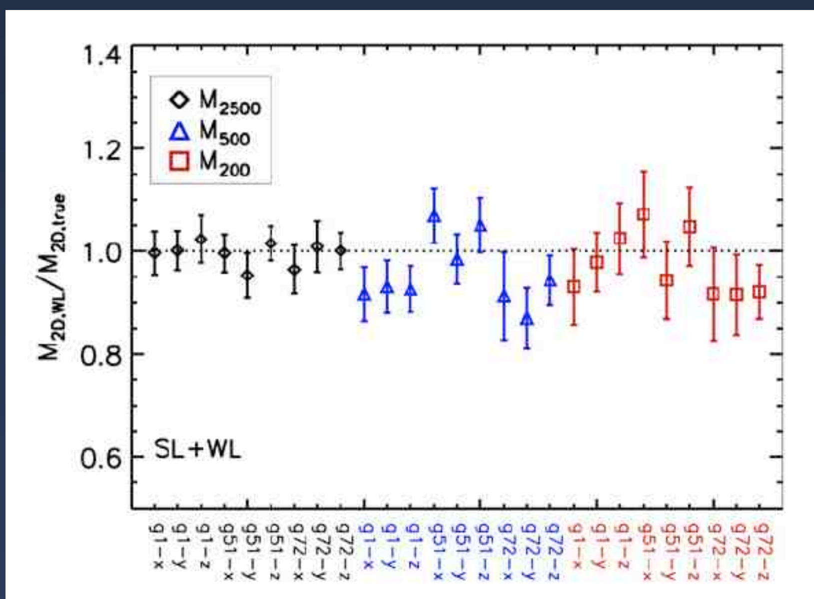
Previously known multiple images from a lensed galaxy at z=1.03 (Ebeling et al. 2009)

47 newly discovered multiple images from 12 distant lensed objects in CLASH image spanning range: 1.1 < z < 5.8

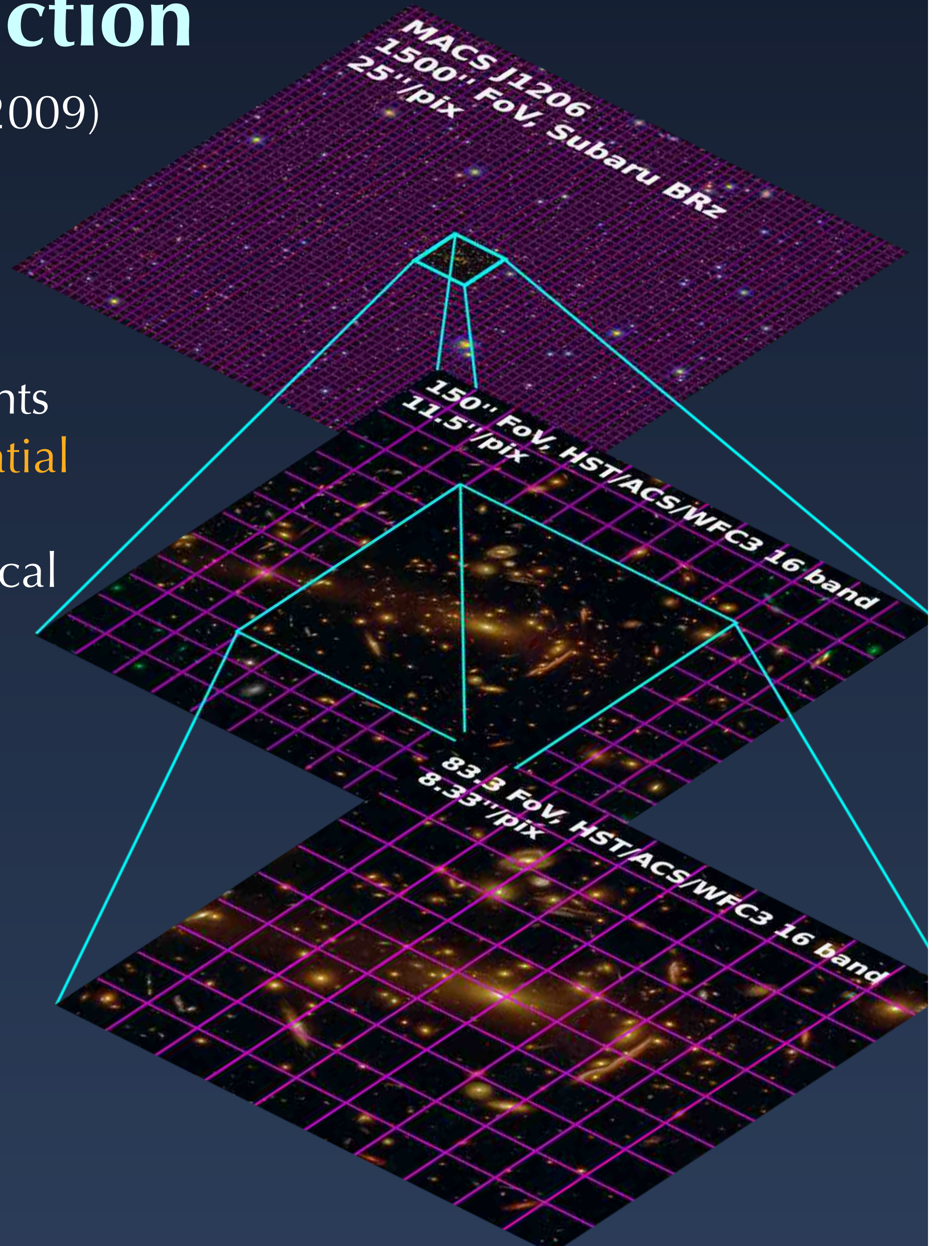
(Zitrin et al. 2012)

SaWLens Mass Reconstruction

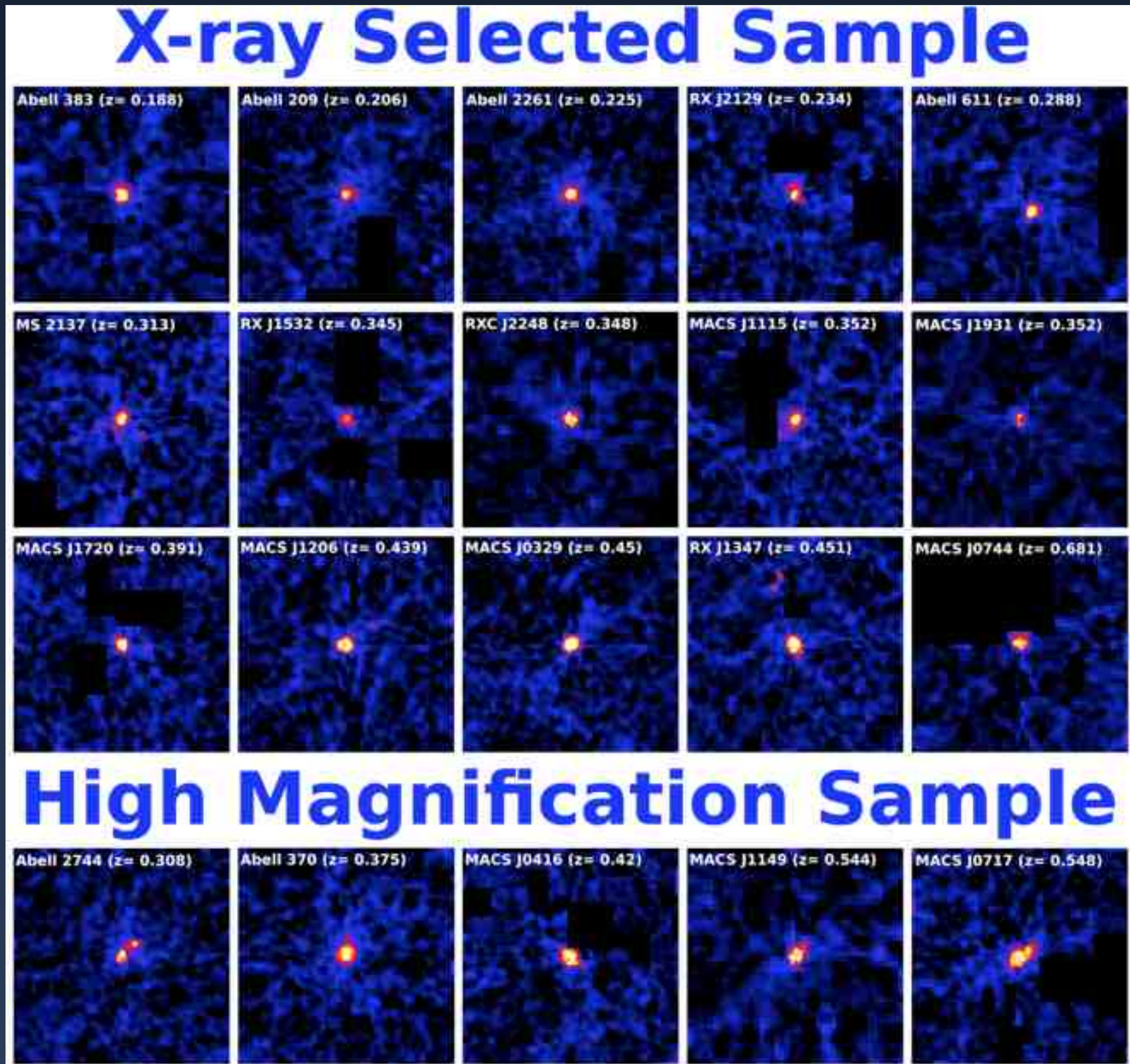
- Fully non-parametric approach (Merten+ 2009)
- *No assumption that light traces mass*
- Adaptive mesh reconstruction
  WL: Subaru/HST shear measurements
  SL: Multiple image positions and redshifts
  Can be extended to include other constraints
- Spans at least 3 orders of magnitude in spatial range (~20 kpc to ~5 Mpc)
- Method has proven reliability with numerical simulations.



Meneghetti, Rasia, Merten et al. 2010



Convergence Maps for CLASH Clusters



Merten et al. 2014, arXiv:1404.1376

Full 2D Mass Reconstructions:

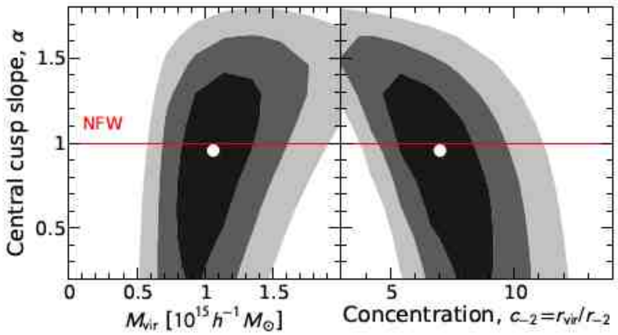
Such reconstructions have only been applied to single clusters with different combinations of data (e.g., Merten: A2744; Bradac: Bullet Cluster, MACSJ 0025)

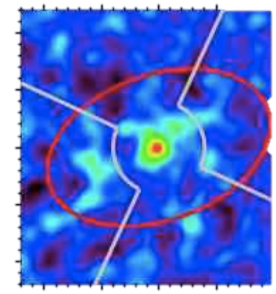
Now 24 CLASH clusters are analyzed with uniform data quality and reconstruction parameters.

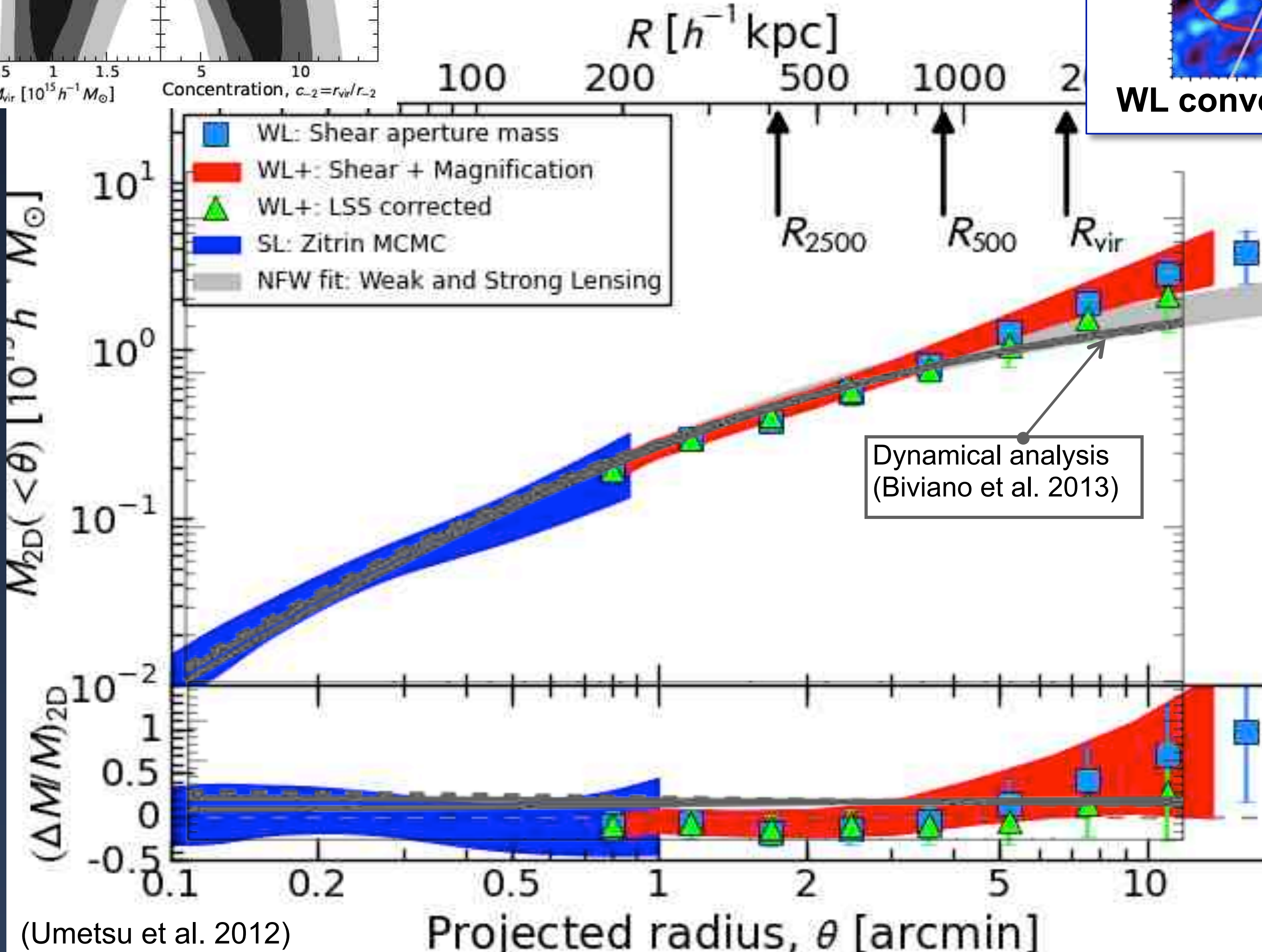
Each mass model set consists of 2,000 bootstrap re-samplings for error analysis.

MACS1206 (z=0.45)

Total mass profile from completely independent methods







(Umetsu et al. 2012)

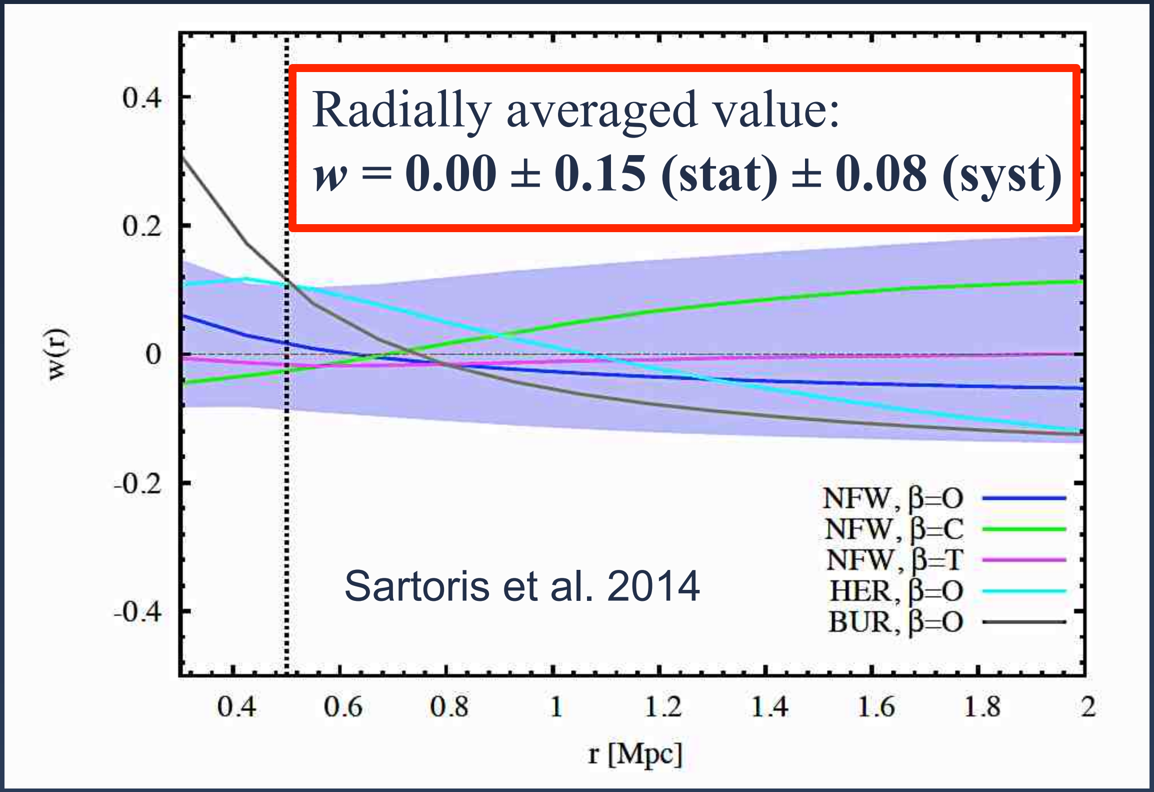
Directly Measuring The Equation of State of Dark Matter

- A pressureless scenario for the Dark Matter (DM) fluid is a widely adopted hypothesis, despite the absence of direct observational evidence.
- In GR, the total mass-energy content of a system shapes the gravitational potential well, but different test particles perceive this potential in different ways depending on their properties.
- Cluster galaxy orbital velocities, being $\ll$ c, depend solely on the gravitational potential, whereas photon trajectories (lensing) reflect the contributions from the gravitational potential plus, if a non-pressureless dark matter fluid exists, a relativistic-pressure term that depends on the derivative of the cluster mass profile.

DM Equation of State Parameter, *w(r):*

$$w(r) = \frac{p_r(r) + 2p_t(r)}{3\rho(r)} \approx \frac{2}{3}\,\frac{m'_{\rm K}(r) - m'_{\rm lens}(r)}{2\,m'_{\rm lens}(r) - m'_{\rm K}(r)}$$

where $p_r(r)$ and $p_t(r)$ are the radial and tangential DM pressure profiles and ρ(r) is the density.

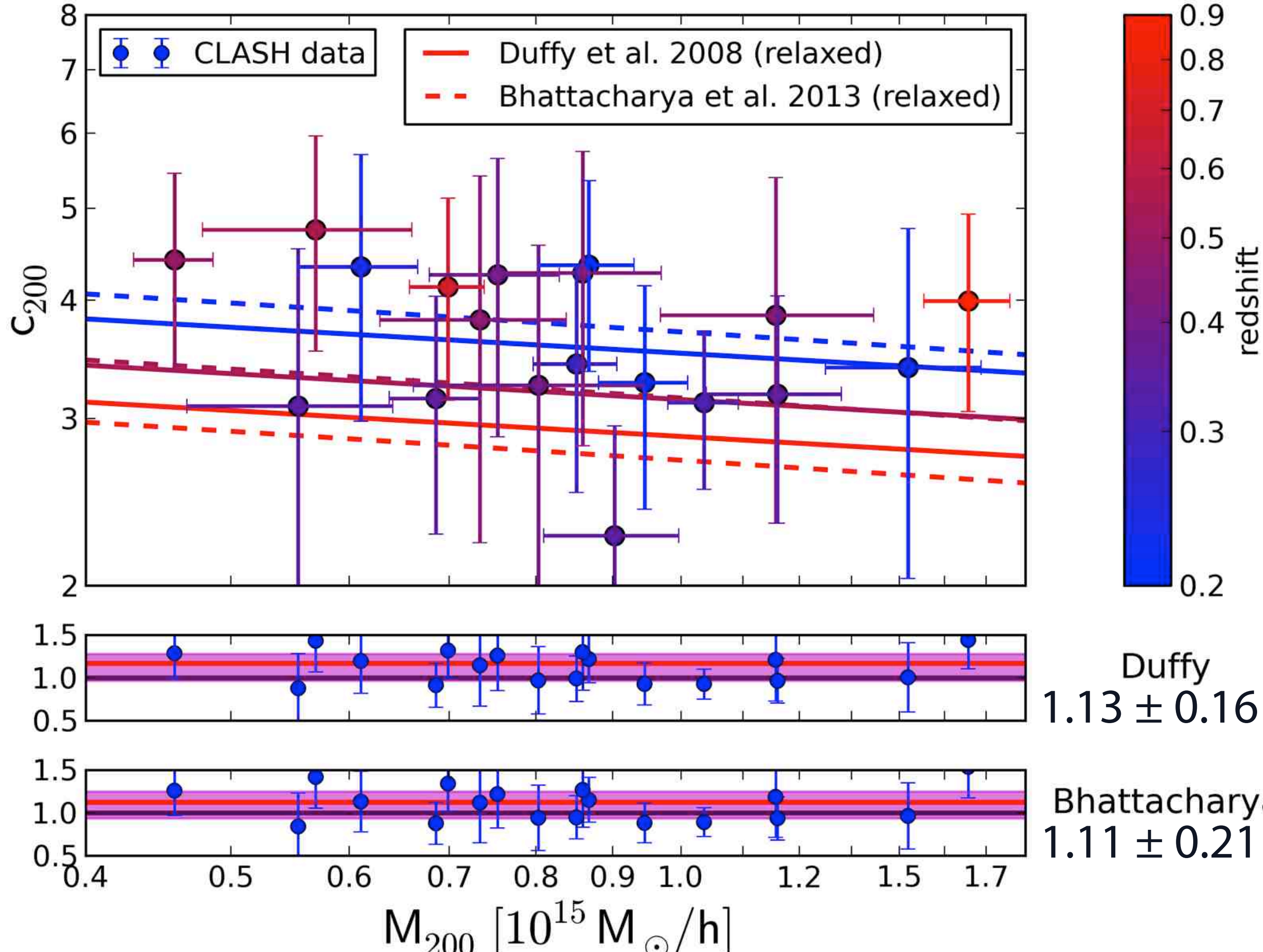


Since baryons contribute at most 15% to the total mass in clusters and their pressure is negligible, the EoS parameter we derive describes the behavior of the DM fluid. The result here is currently the most stringent constraint on the DM EoS parameter.
DM in clusters is indeed consistent with a pressureless fluid.

Above: The constraints on the EoS parameter, *w(r)*, using different assumptions about the total mass and orbital velocity distributions.

CLASH Mass-Concentration Relation

Bhatta+13 are from Multi-DARK simulations



Ratio of Data to Model Conc.

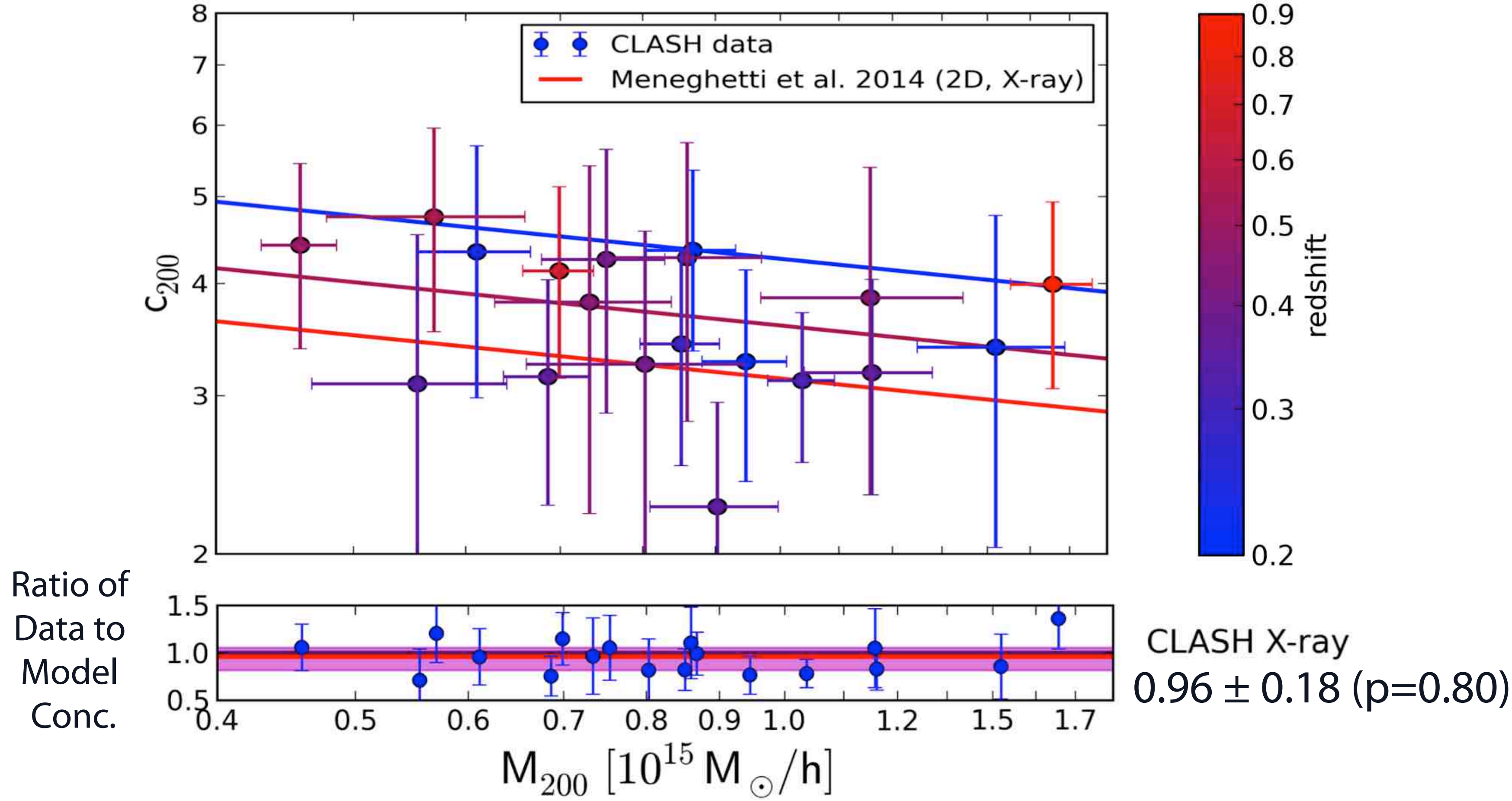
Duffy
1.13 ± 0.16 (p=0.99)

Bhattacharya
1.11 ± 0.21 (p=0.89)

Merten et al. 2014

CLASH Mass-Concentration Relation

Meneghetti+14 are from Multi-DARK simulations + more gas physics



Tension between previous data and predictions largely a sample selection effect. CLASH M-c relation is fully consistent with LCDM.

CLASH Mass-Concentration Relation

Merten et al. 2014

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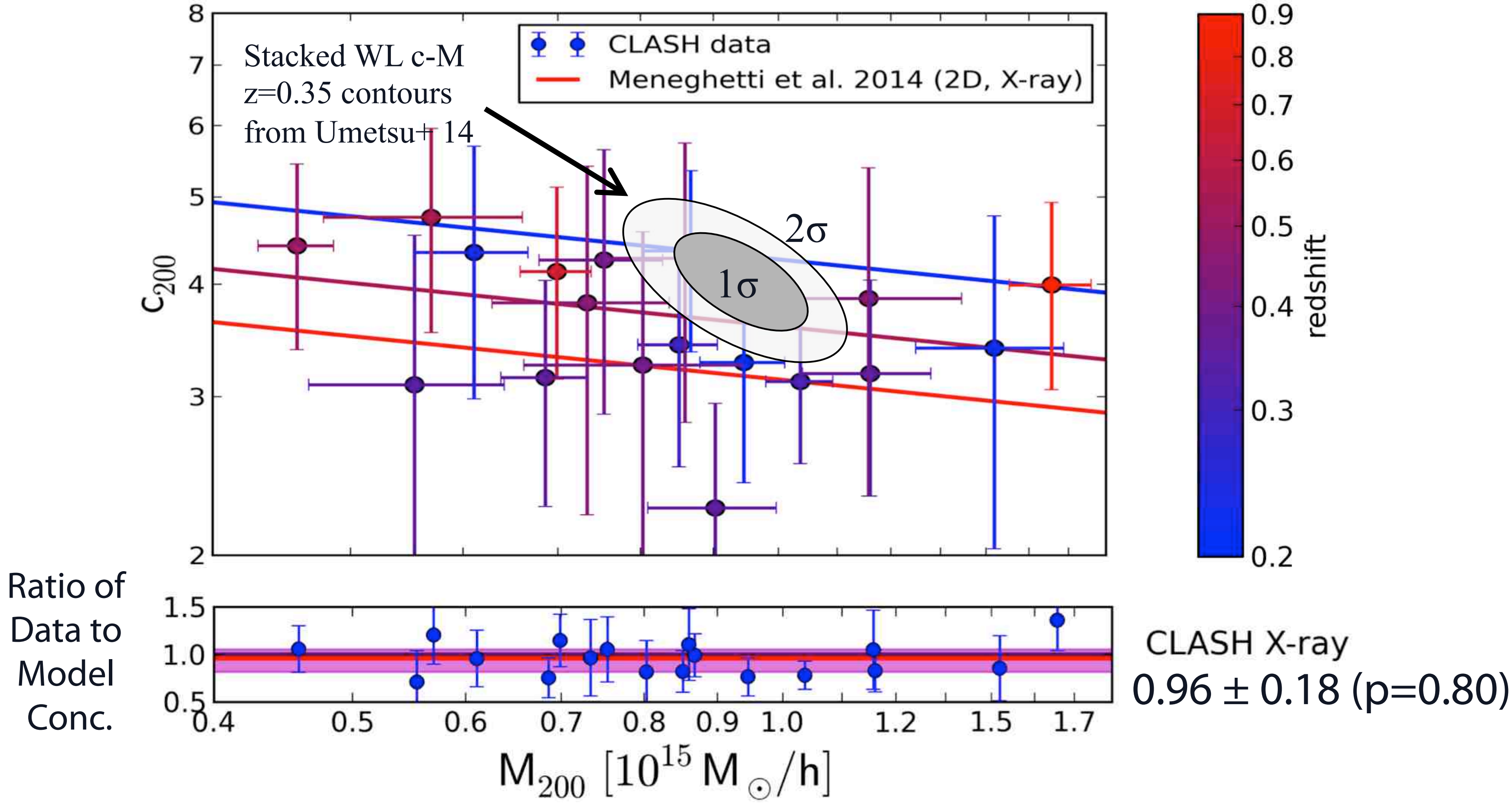
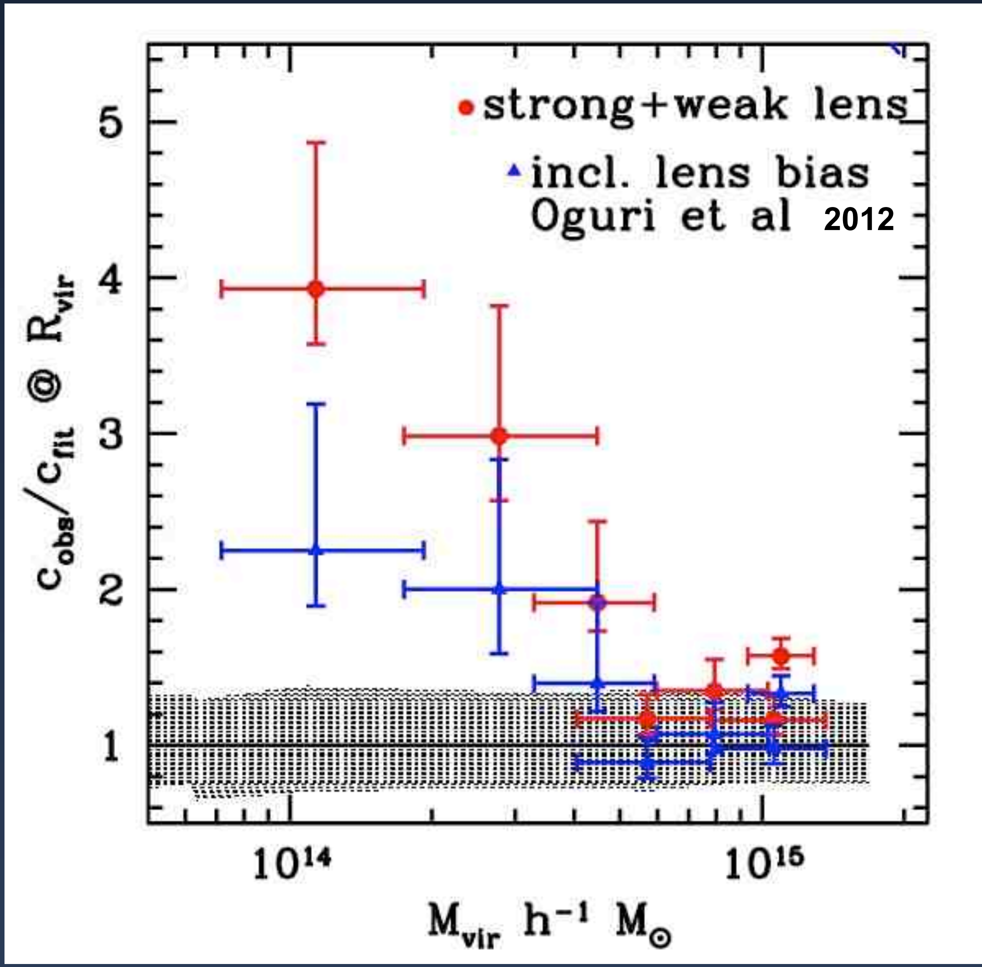


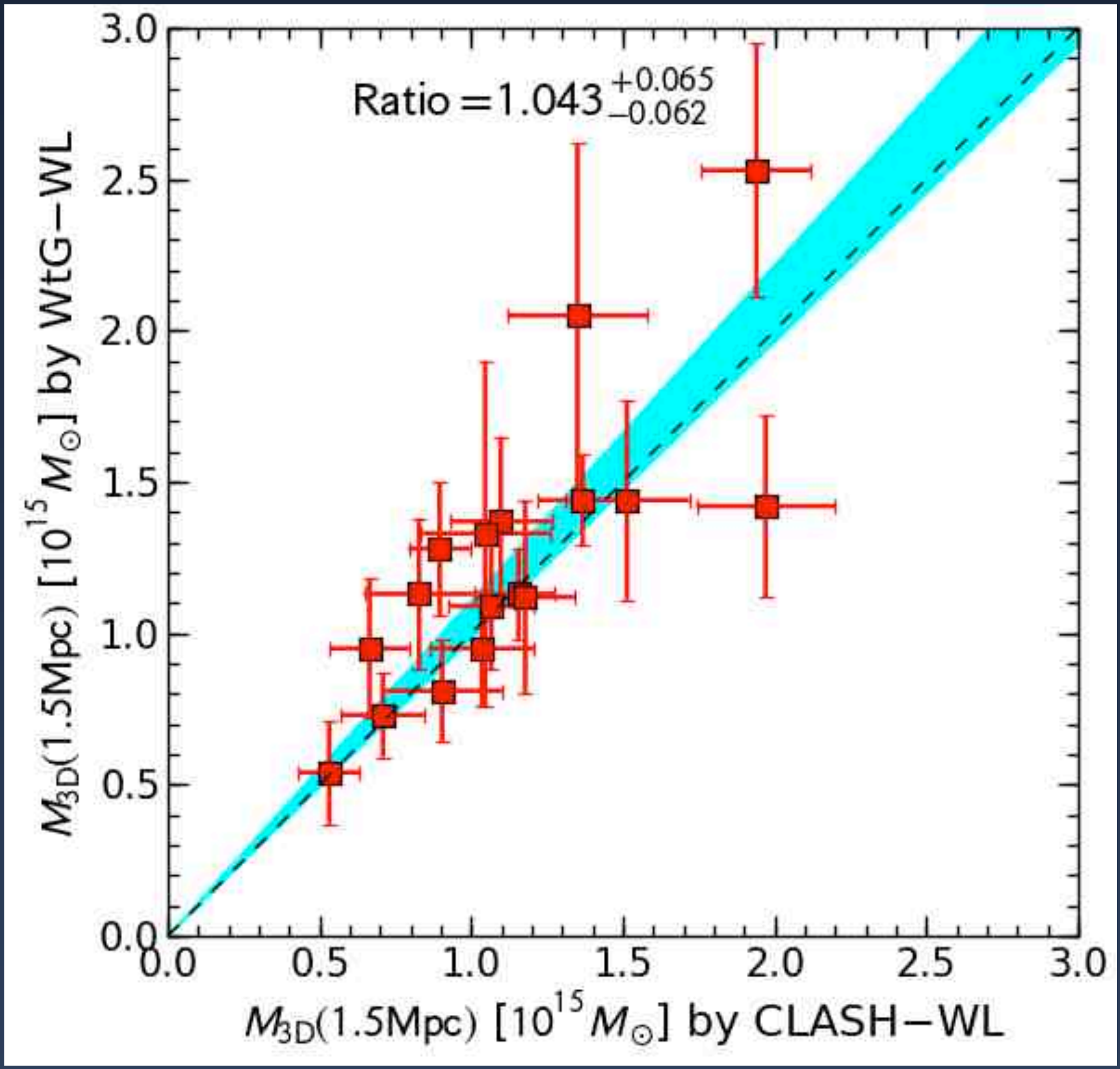
Tension between previous data and predictions largely a sample selection effect. CLASH M-c relation is fully consistent with LCDM.

If any tension between obs & simulations remains, it may be at lower (< 5 x 10^{14} $M_\odot$) cluster mass:



From Bhattacharya+13

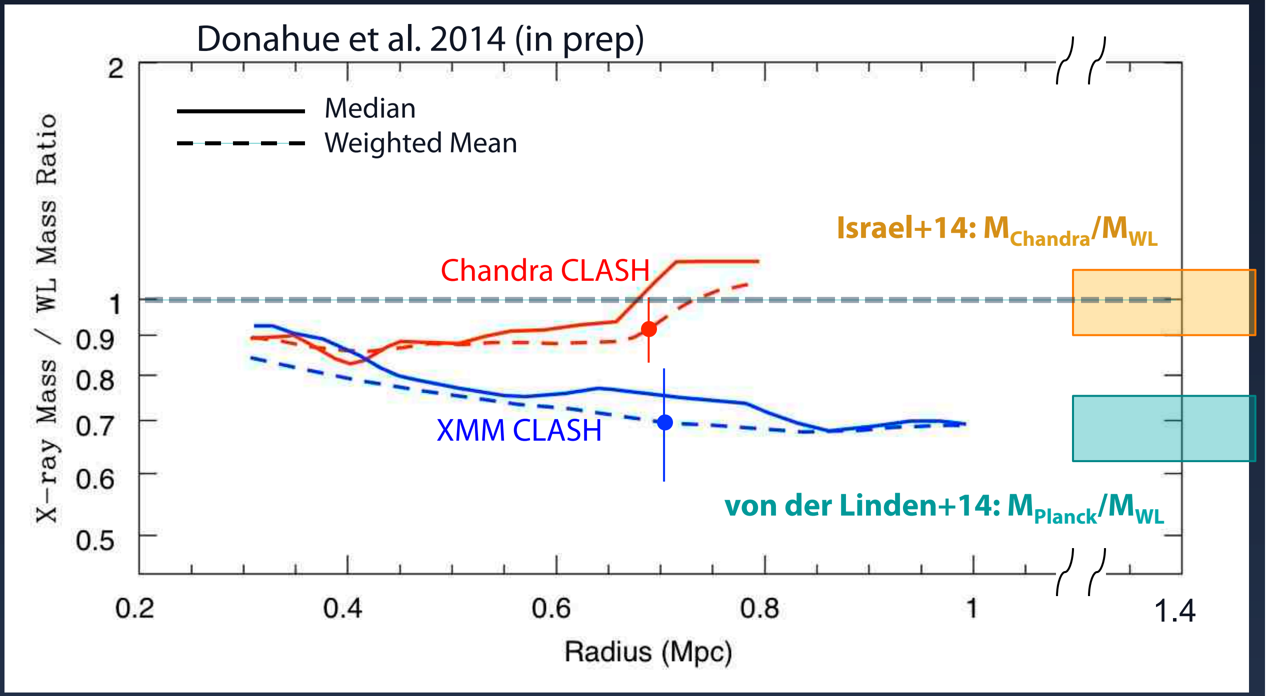
CLASH WL Masses Agree With WL Masses from the "Weighing The Giants" Project (von der Linden et al. 2014)



Calibrating X-ray Mass Profiles

$$\frac{dP_{gas}}{dr} = -\rho_{gas}(r)\frac{GM_{tot}}{r^2}$$

HSE = Hydrostatic Equilibrium

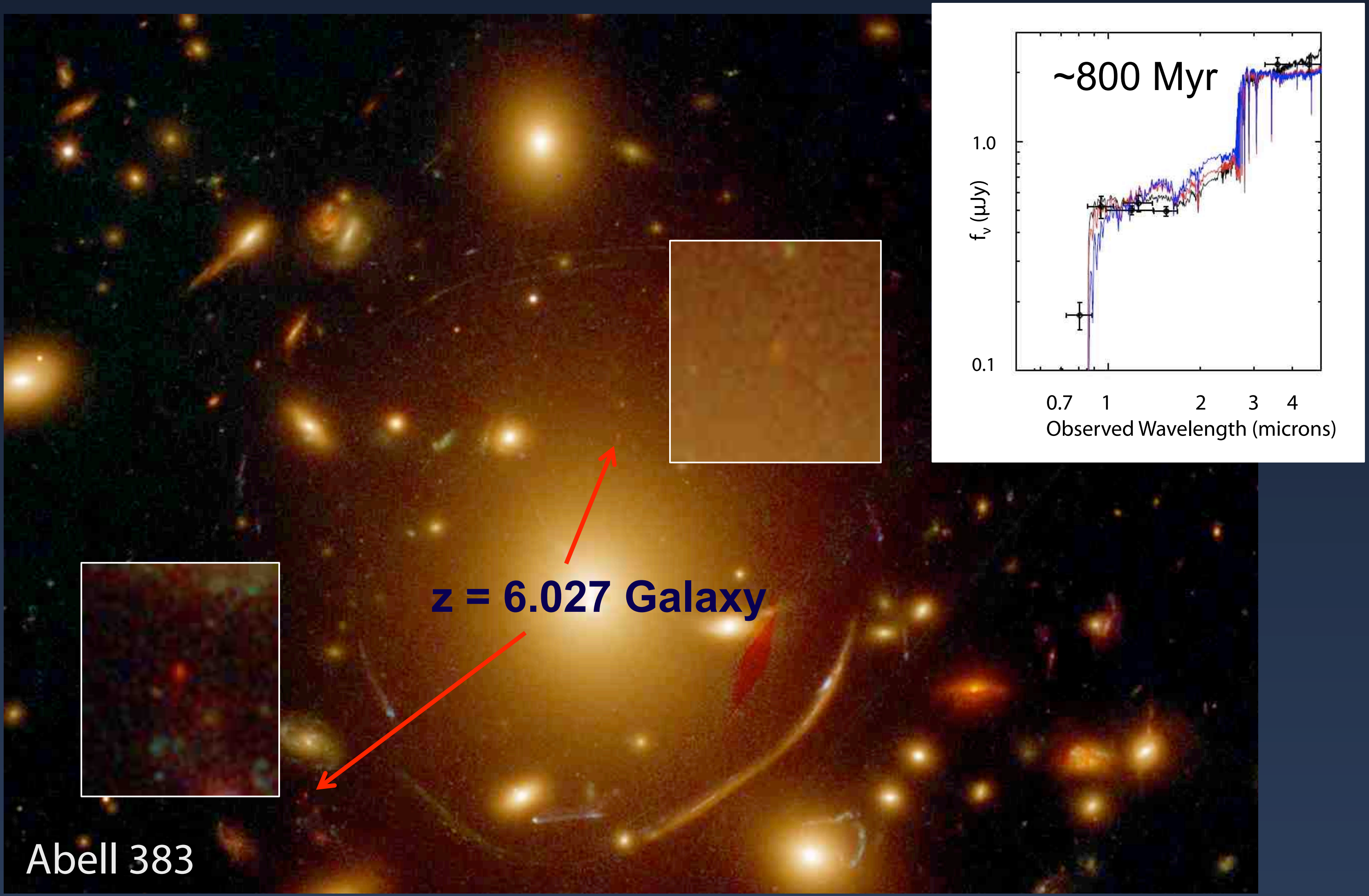


- A systematic difference between XMM and Chandra HSE mass to WL mass ratios exists even after the most recent calibration and PSF corrections are applied.
- Chandra and XMM electron density and gas mass estimates are consistent with each other. However, XMM Tx declines systematically relative to Chandra Tx as radius increases beyond ~200 kpc. Most plausible explanation may be large-angle scattering of soft X-ray photons beyond what is included in standard XMM PSF correction.
- Generally expect HSE/WL mass ratio to be < 1 (some non-thermal support, turbulence, bulk motion, etc.). Face value interpretation: non-thermal support of gas is <27% (from XMM) and <10% (from Chandra). But since the above results are for the SAME clusters, this cannot be the correct interpretation.
- These results have implications for resolving the discrepancy between Planck cluster counts and CMB cosmological constraints. Currently working with Planck team on this topic.

CLASH Lensing So Far …

- CLASH discovering up to 10x as many multiple images as previously known, even in well studied systems. All with reliable photo-z. Enables precise SL mass profile shape measurements.
- Excellent consistency between WL and SL mass profiles in range where they overlap. Dynamical analyses also provide consistent mass profiles (can constrain DM EoS – no significant pressure term).
- CLASH finds that x-ray selected clusters follow a mass-concentration relation that is consistent with predictions from LCDM N-body simulations. No tension remains between the data and the predictions at the high mass end.
- CLASH masses provide an important calibration for larger DM surveys.

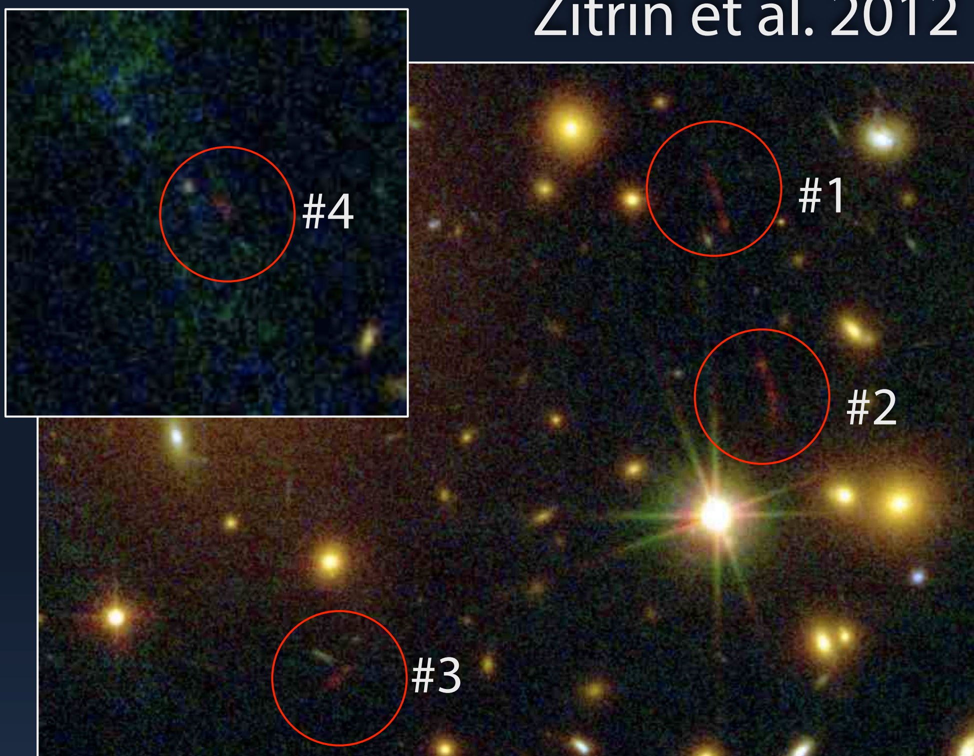
Richard et al. 2011: z = 6 lensed Galaxy



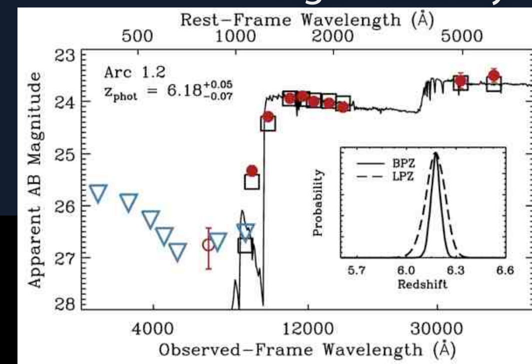
11.4 x magnification

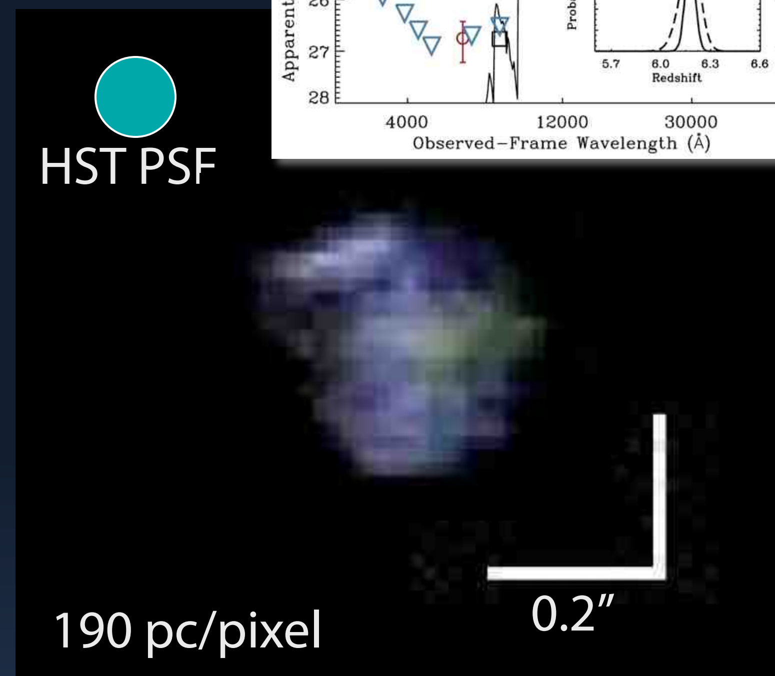
MACS J0329-02: Quadruply-lensed Galaxy at $z_{ph} = 6.18$

Zitrin et al. 2012



Age <400 Myr





Magnifications: #1 = 11.6, #2 = 17.6, #3 = 3.9, #4 = 3.7

~10^9 M_{sol}, (Z/Z_{sol})~0.5, SFR: 3.2 M_{sol}/yr
(similar to local dwarf galaxies)

De-lensed view
(source plane)

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

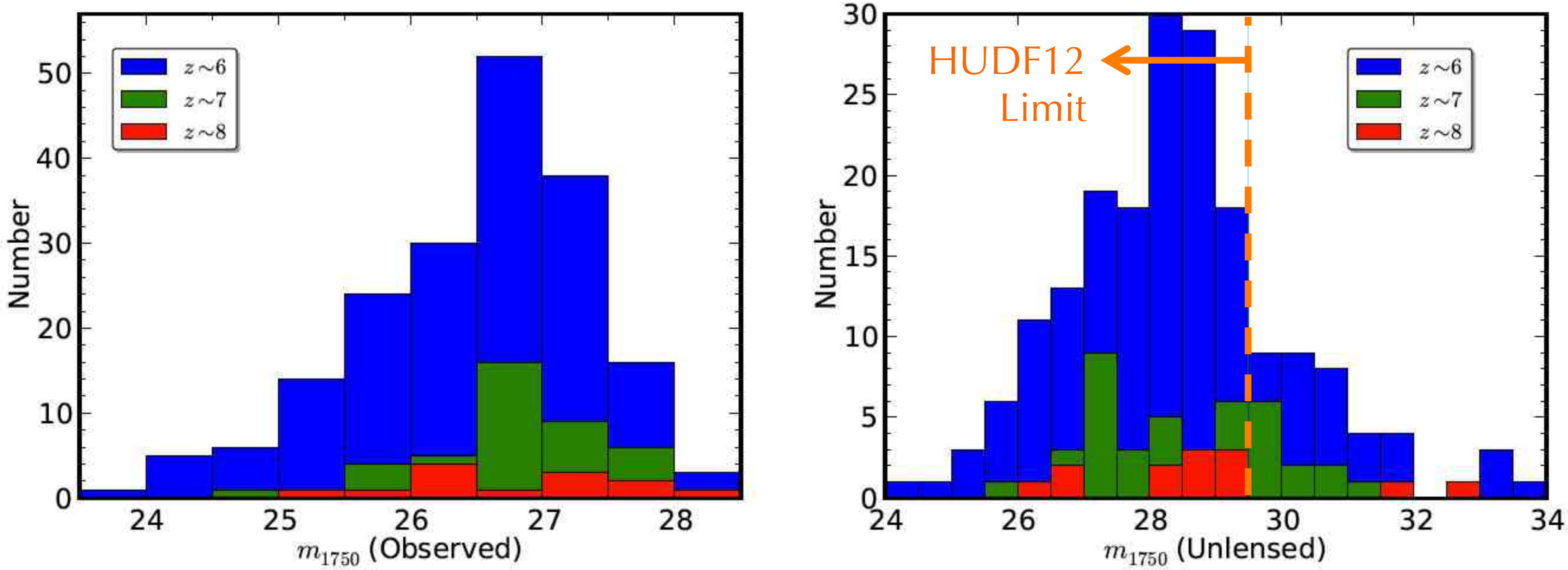
	$z \sim 6$	$z \sim 7$	$z \sim 8$	$z \sim 9$	$z \sim 10$	$z \sim 11$	Total
18 clusters	206	45	13	2	1	1	268
Survey extrapolation	~290	~65	~20	~4	~2	~2	~385

Largest sample of lensed star-forming galaxies at z >~ 5.5 to date

7 multiply-imaged systems at z >~ 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

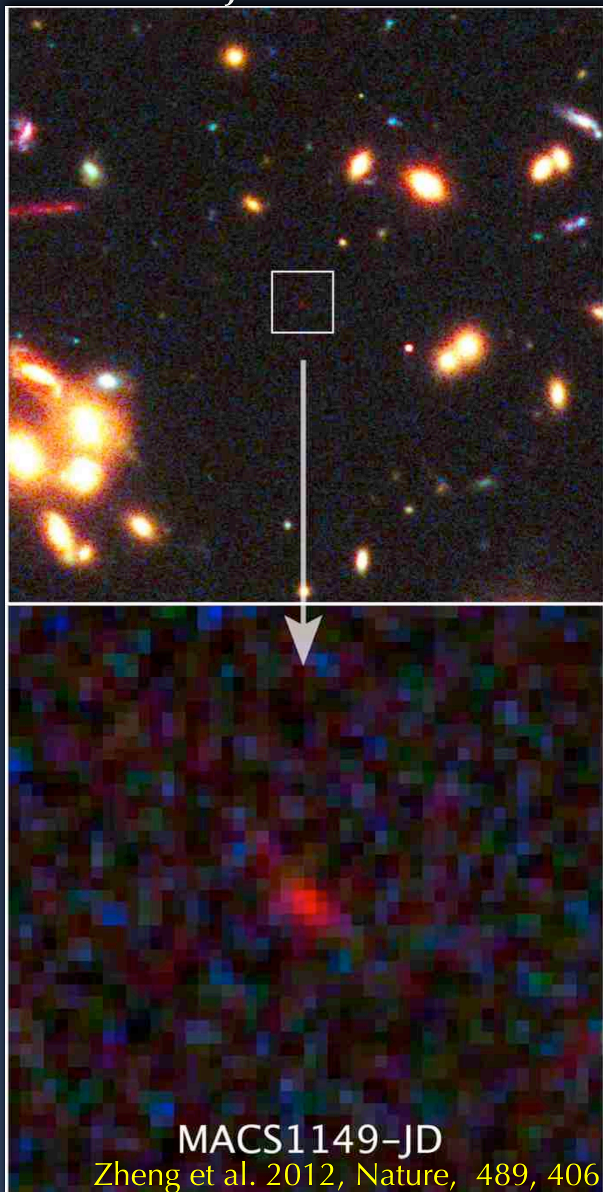
Instrinsic (unlensed) magnitudes nearly reach 34 mag

Caveat: largest magnifications have large uncertainties!

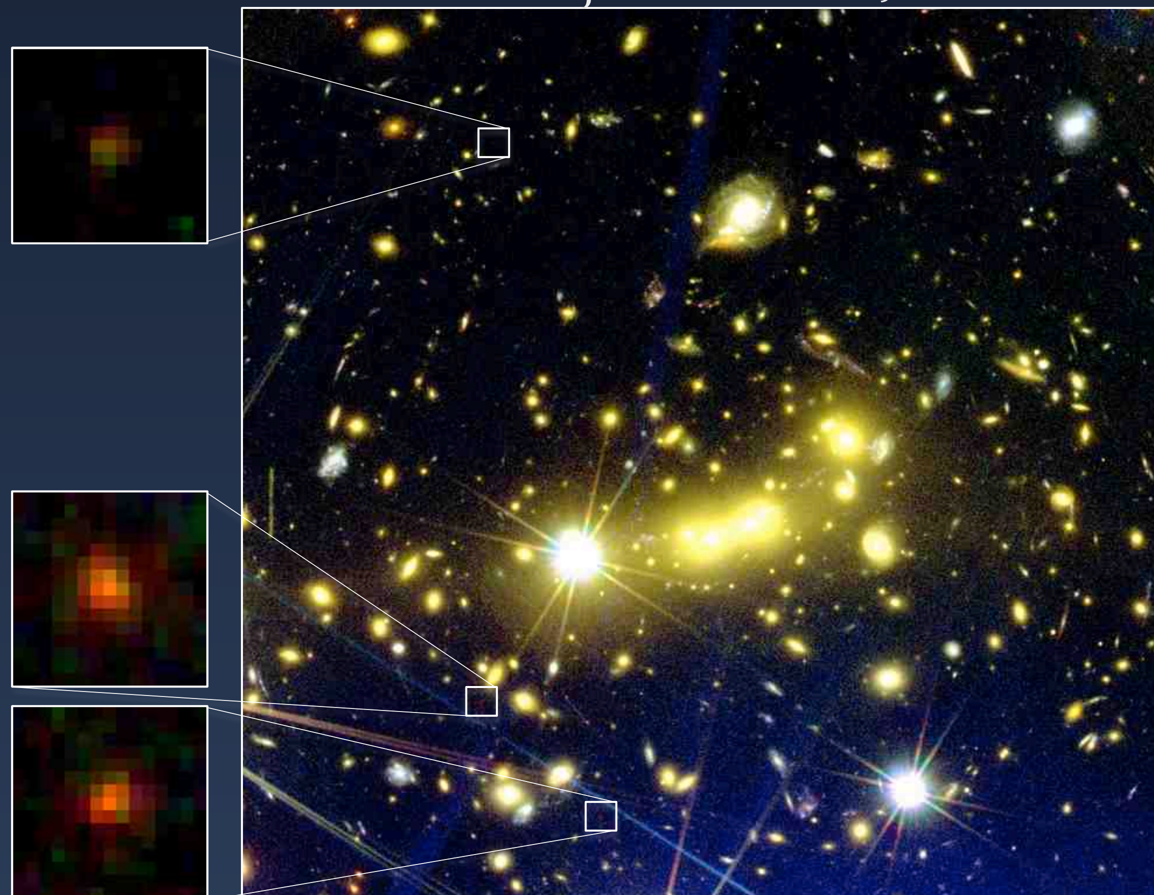
Bradley et al. (2013)

Two z > 9 Lensed Galaxies

z = 9.6 object in MACSJ1149+2223



z = 10.8 object in MACSJ0647+7015

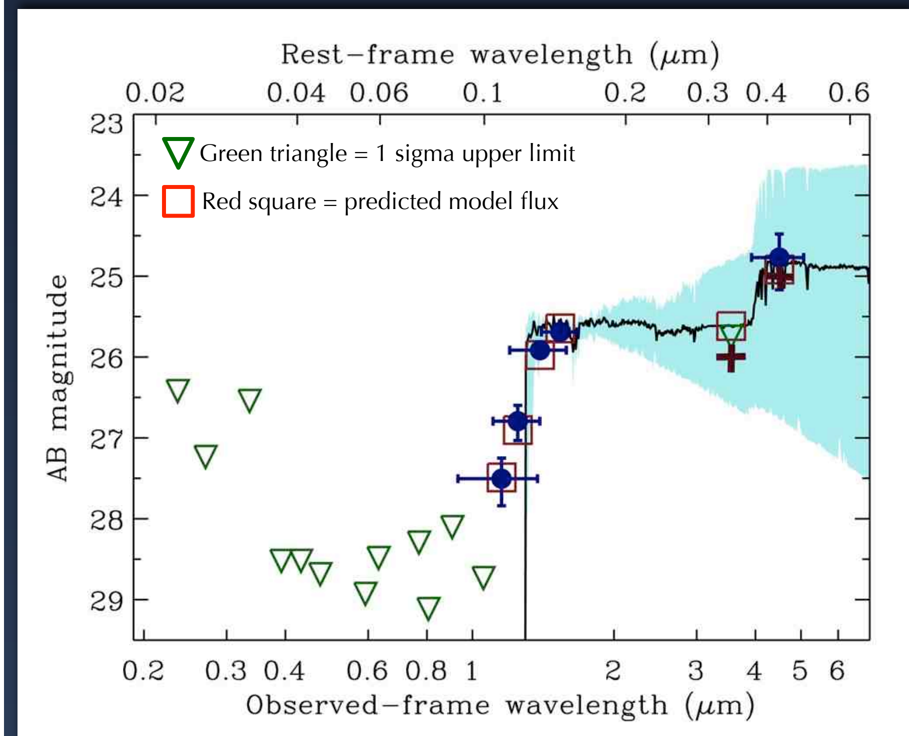


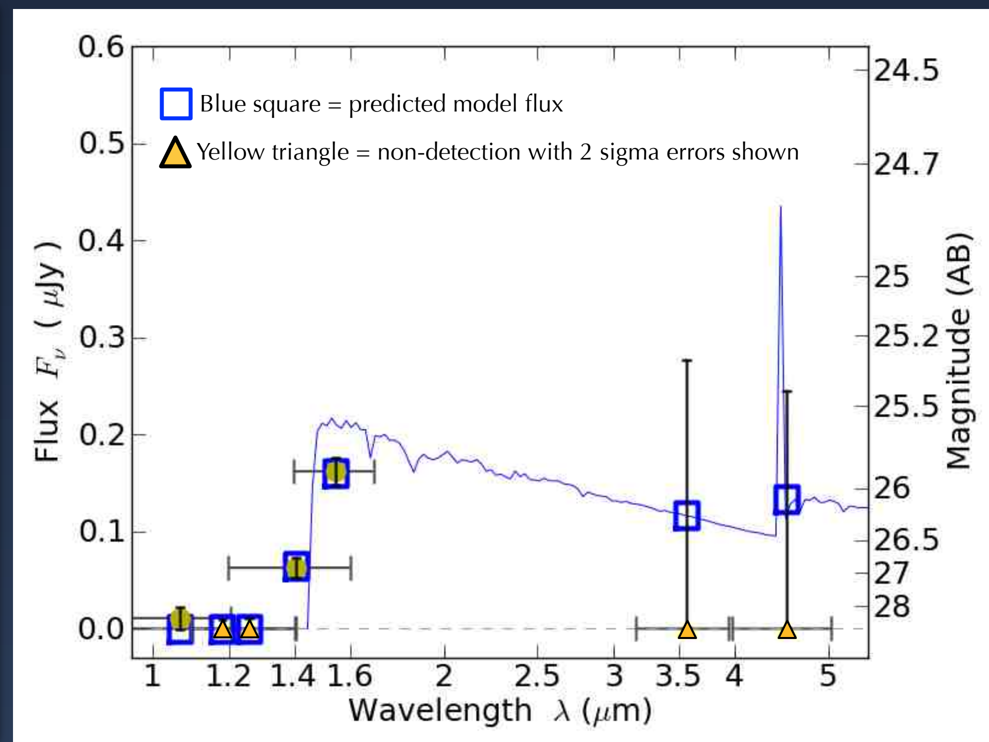
Coe et al. 2013, ApJ, 762, 32

Spectral Energy Distributions

MACS1149-JD: z = 9.6 +/- 0.2
Stellar mass: ~1.5 x 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 +/- 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)

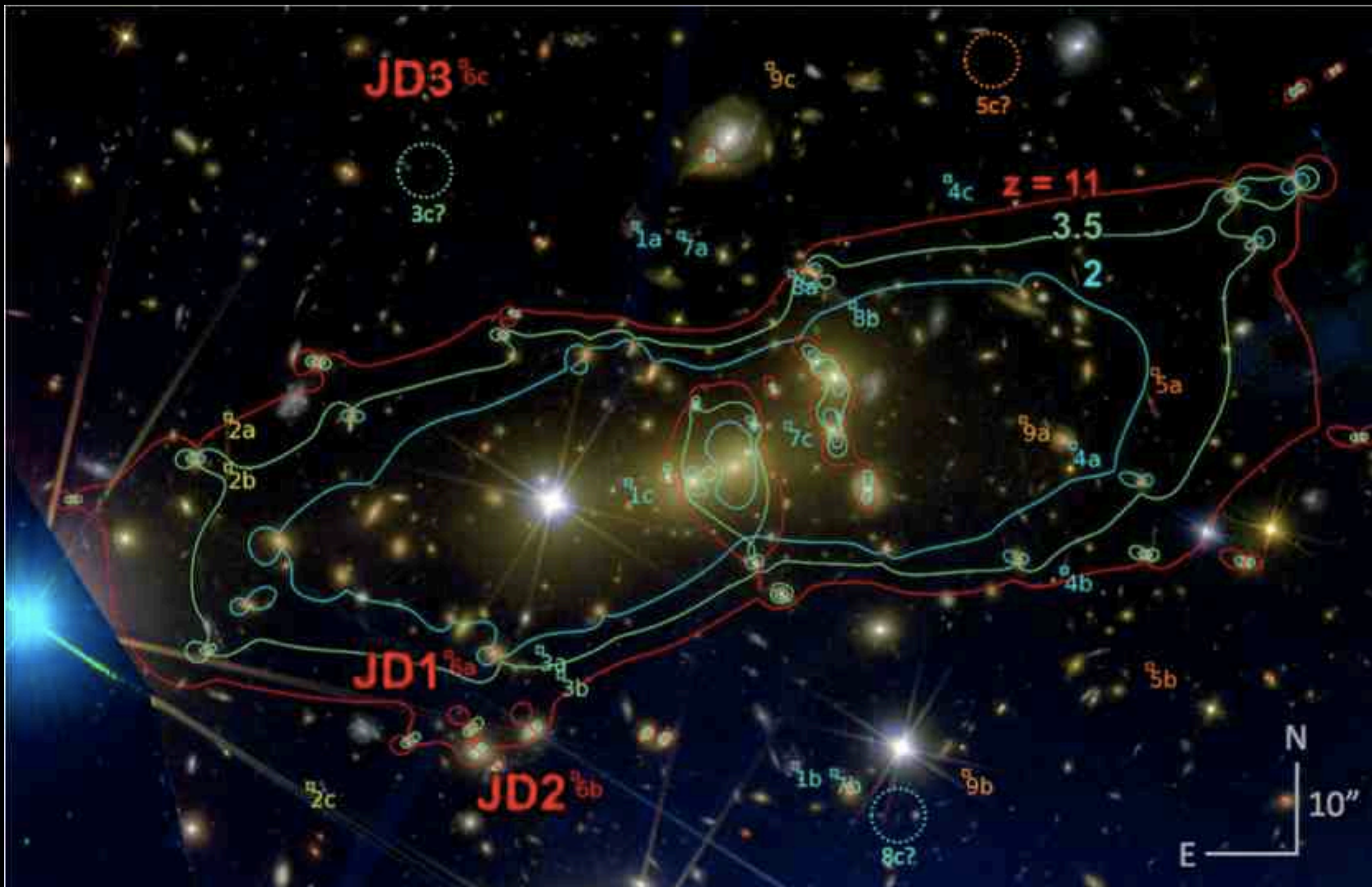




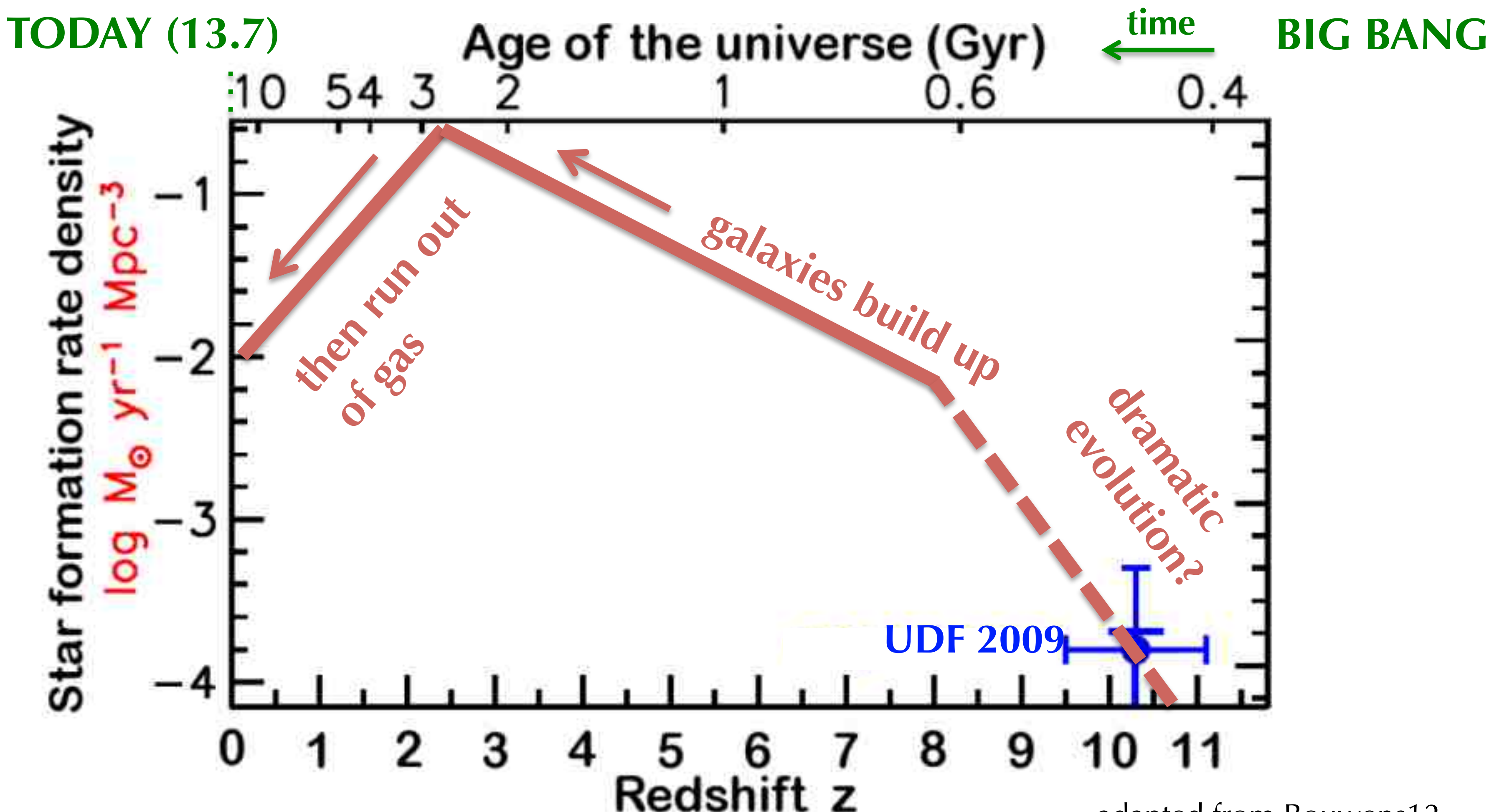
Plus symbols represent new, deeper IRAC data

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.

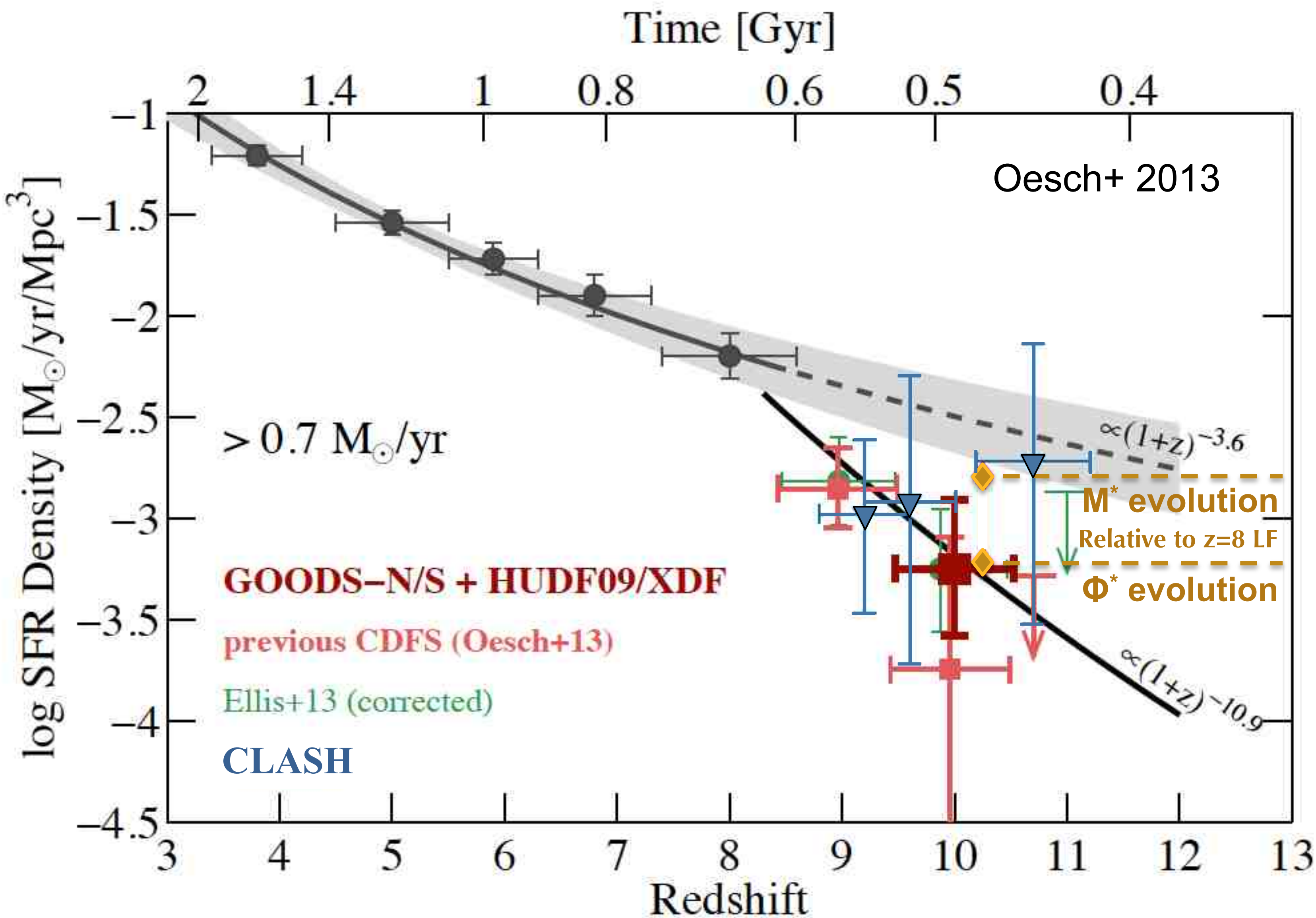


UDF search for galaxies in the first 500 Myr came up short. Only one candidate was found where six were expected. This suggested a dramatic buildup in galaxy numbers.



adapted from Bouwens12
see also Oesch12,13

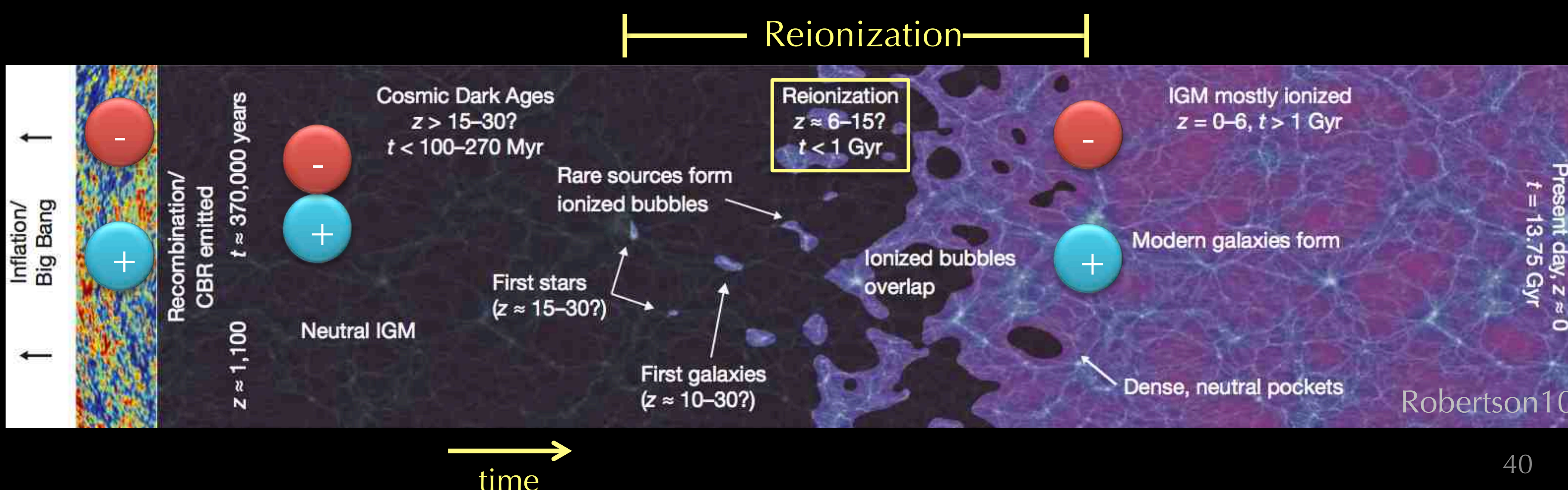
CLASH and UDF12 yielded 4 – 8 candidates at z > 9 where previously only one was known. Now CANDELS provides more candidates. Combined, these datasets do favor a steeper decline (relative to z<8) in the SFR density at z > 9. More data needed.



Such 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.

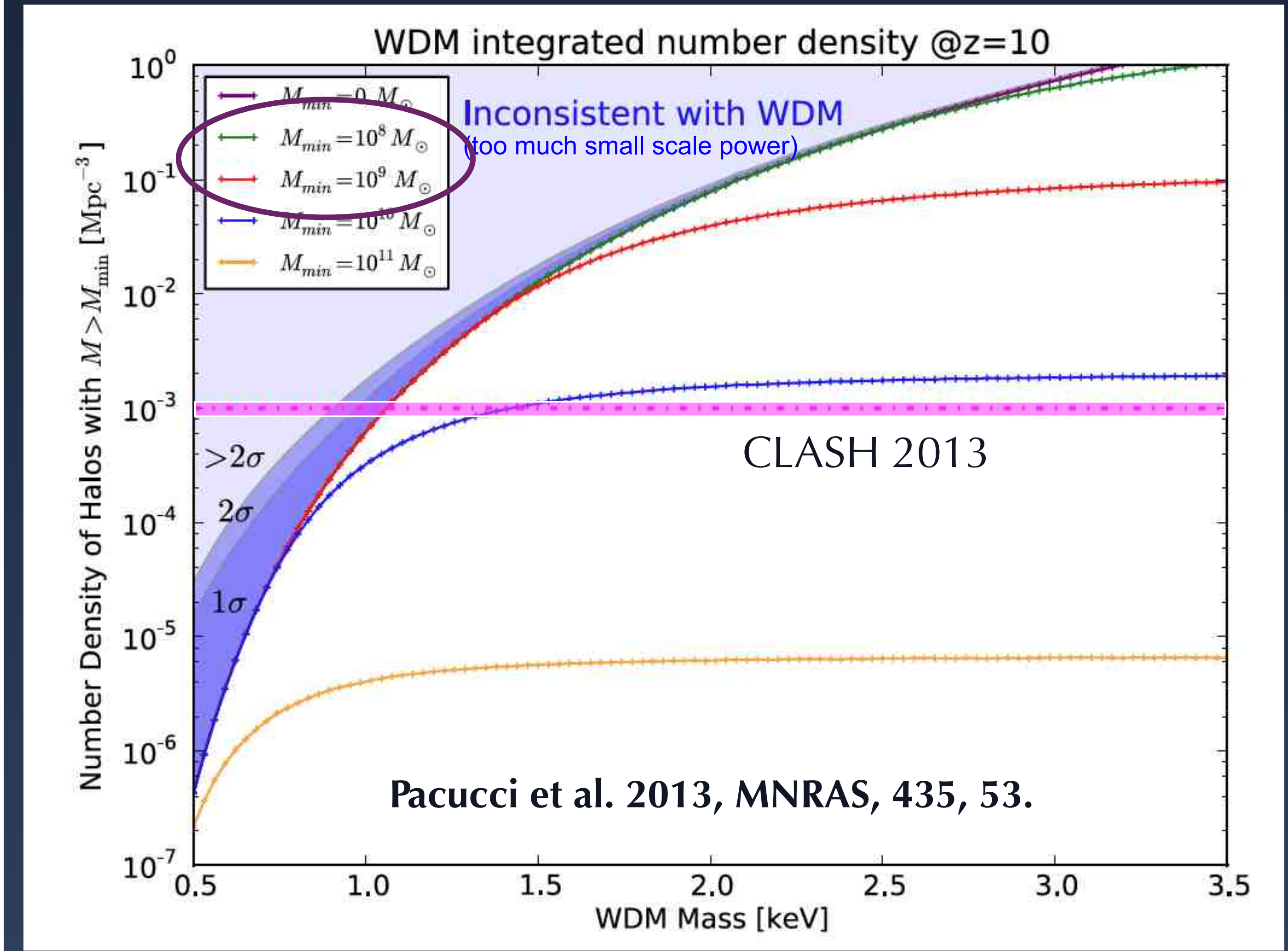


Using CLASH Lensed Galaxies to Constrain Dark Matter Properties

- Finding structures in the early universe can place a constrain the mass of the warm dark matter particle, if it exists.
- WDM is a relativistic particle whose mass is expected to be inversely proportional to its free streaming length.
- WDM tends to smooth out structure. Hence, if one sees structure at a given scale at early epochs then it suggests the free streaming length of WDM must be SMALLER than such structure. Hence, providing an LOWER limit to the mass of the WDM particle.
- Too much structure found on small scales can rule out WDM altogether.

Independent constraint on the nature of DM

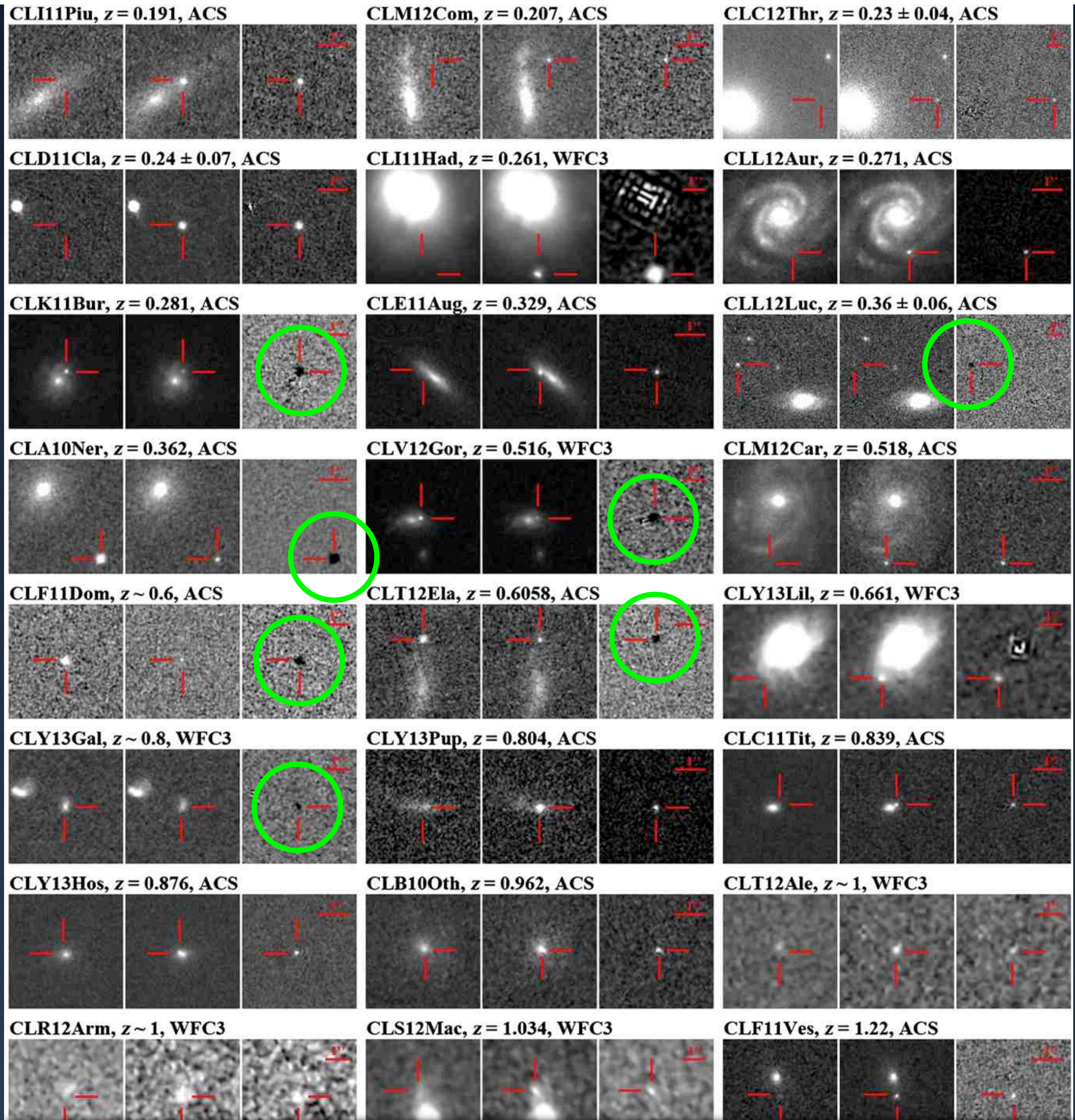
- WDM particle mass $m_X > 1.0$ (0.9) keV at 68% (95%)
  - Limit depends only on WDM halo mass function, not on astrophysical modeling.



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)."

CLASH High-z Galaxy Summary

- We have found hundreds of lensed LBGs at high-redshift. Largest $z > 6$ lensed galaxy sample to date.
- We have discovered two candidate $z > 9.5$ dwarf galaxies. H-mag = 25.7 – 25.9; 8x - 15x brighter than if in unlensed field.
- Lensing provides most detailed look at structure of $z > 6$ galaxies. Often reach ~200 pc resolution at these redshifts.
- Detection of even two $z \sim 10$ galaxies provides new lower limit on WDM particle mass.
- Still to come: constraints on UV slope and galaxy contribution to re-ionization of universe.



39 CLASH SNe Discovered Over 3 years.

(27 in parallel fields, 12 in prime fields).

The 27 SNe discovered in the parallel fields are shown here.

Each triple image set here shows the template image, the discovery image, and the difference image (SN image – template image)

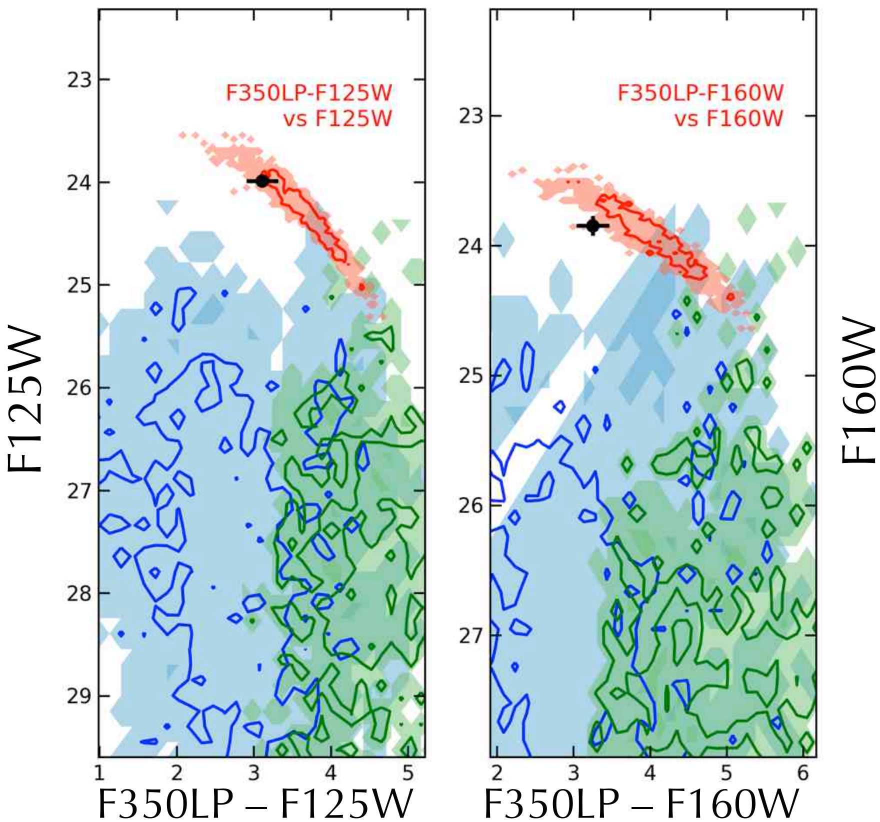
~48% of the SNe are classified as Type Ia.

At least 7 (18%) of the 39 SNe are at z > 1.

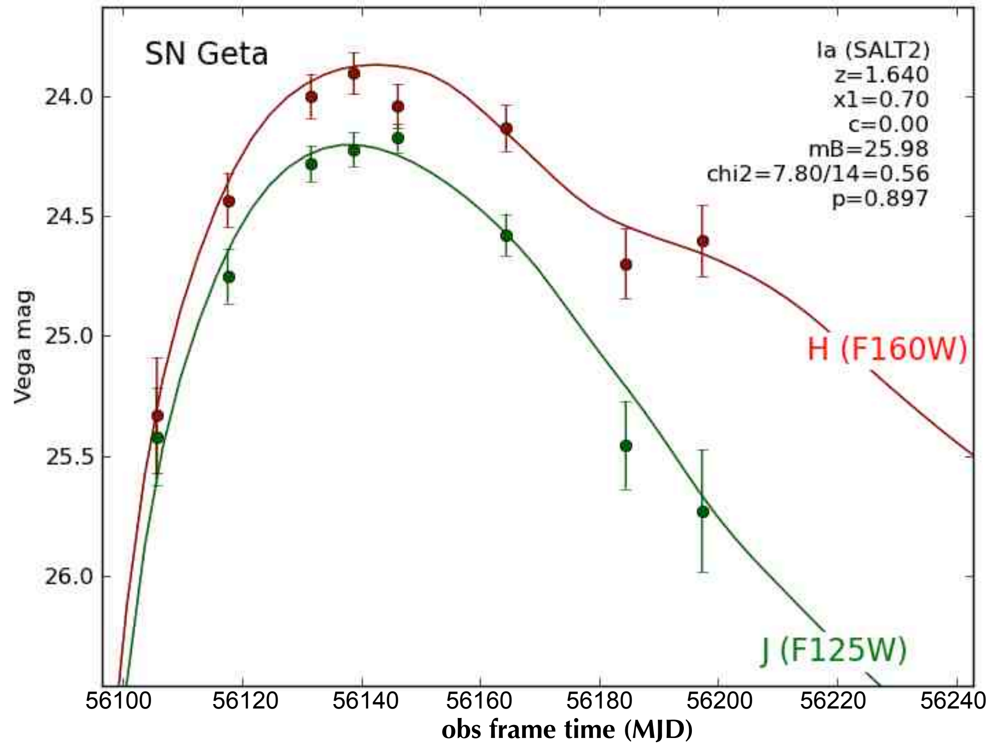
Date of maximum light can occur up to 40 days before and 20 days after the duration of the survey for each cluster

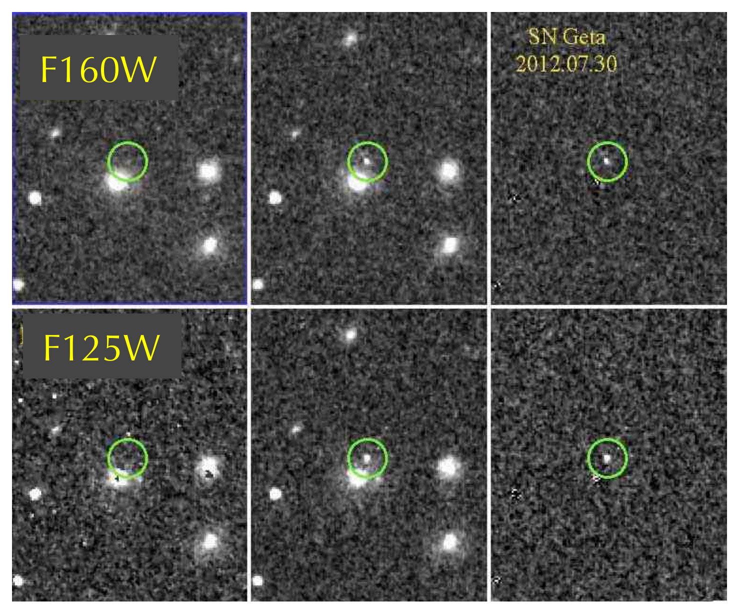
SN Geta (RXJ2129+0005)
Type Ia at z = 1.64

CMD plot 30 days pre-maximum (observer frame)



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

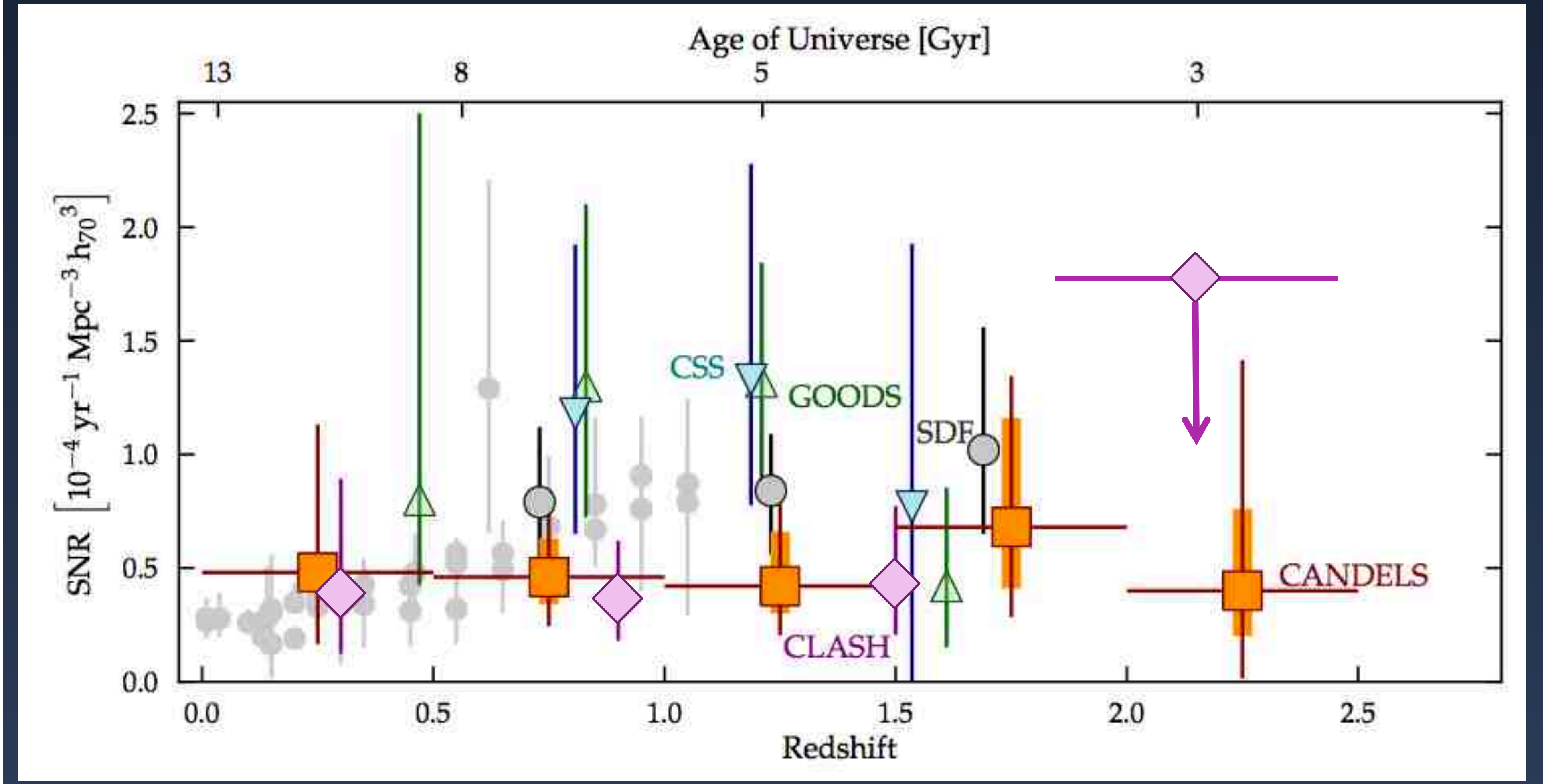




Template Discovery Difference

Publius Septimius Geta (189 – 211 AD, Rome)

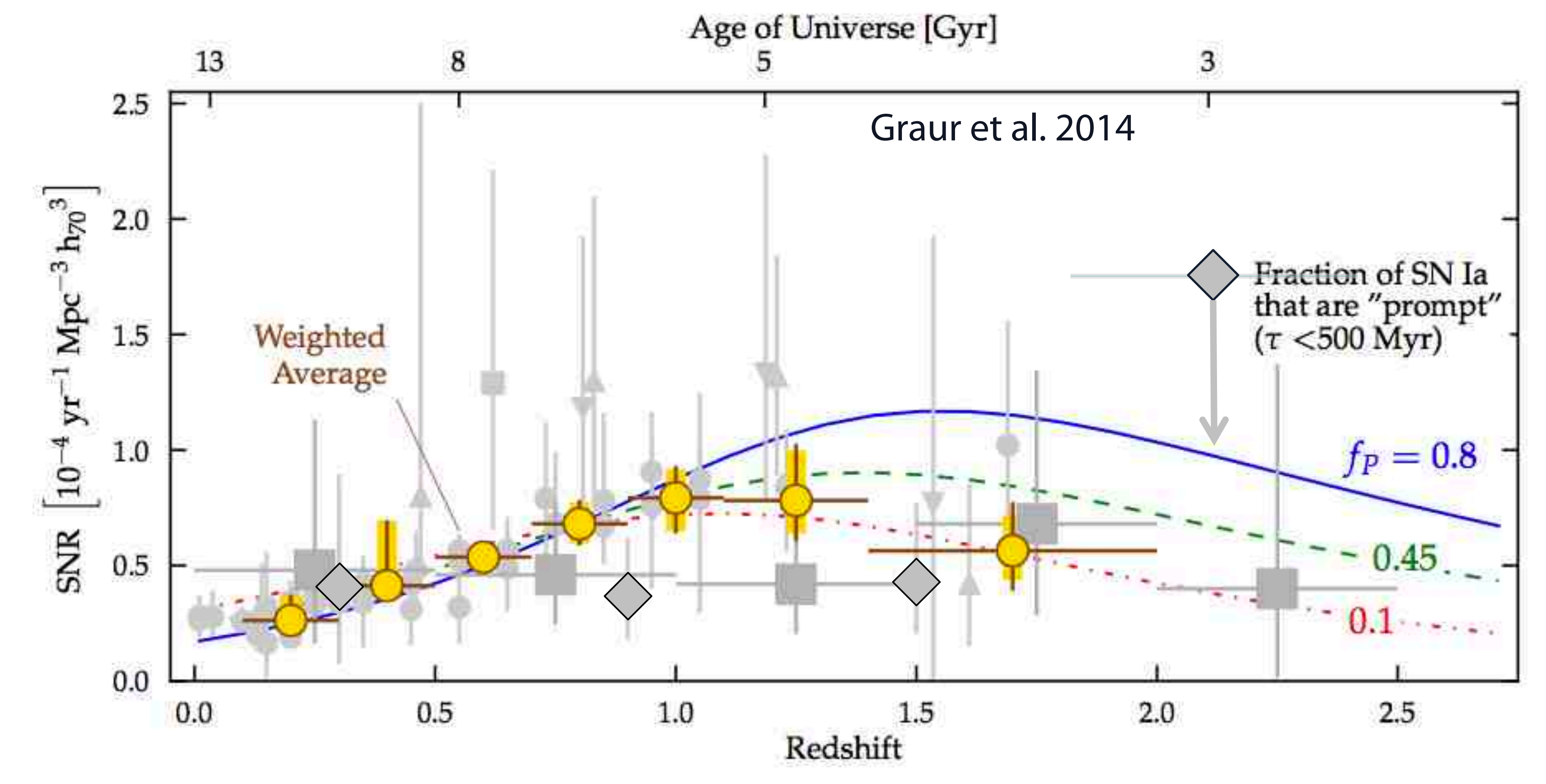
Combined CLASH+CANDELS SN Ia Rate to z ~ 2



See Graur et al. 2014 & Rodney et al. 2014 (in prep)

Constraining the Delay Time Distribution

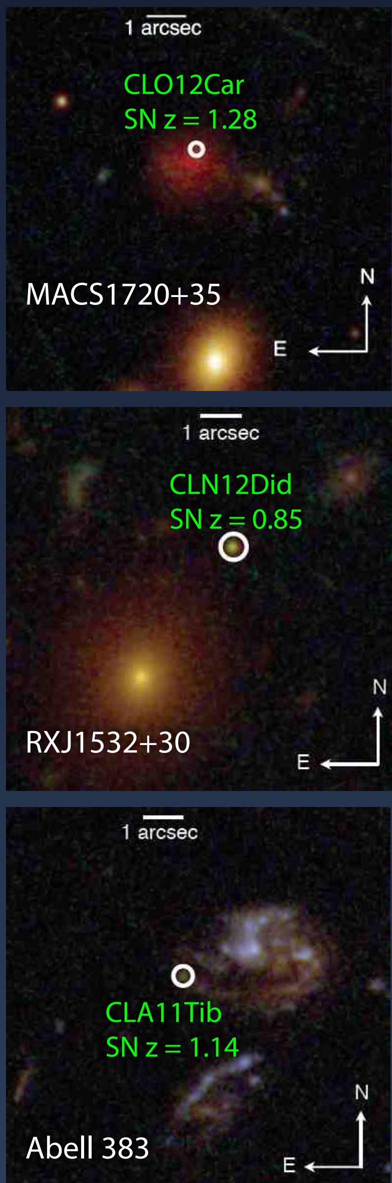
(the distribution of times that elapse between a short burst of star formation and the subsequent SN Ia explosions)

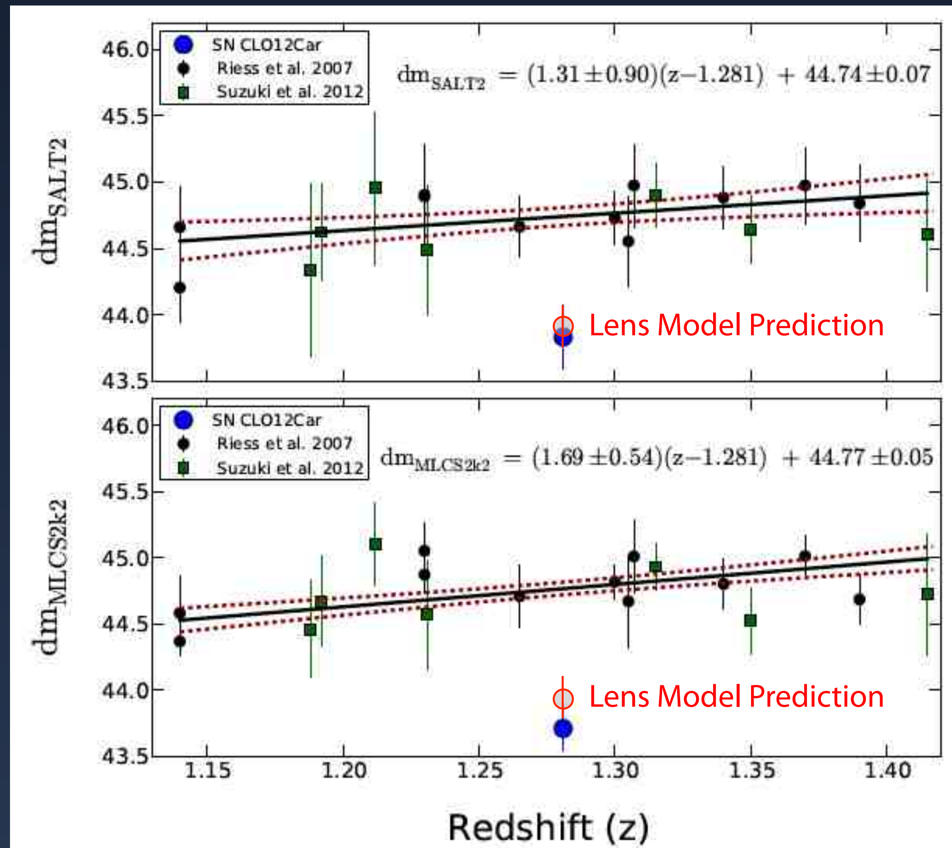


The combined SN Ia Rates favor
Double Degenerate Progenitor Models (DTD ~ t^{-1})
Measured exponent: 1.00 ± 0.06 (stat) ± ~0.10 (sys)

Using SNe to Check Mass Models

See Patel et al. 2014 and Nordin et al. 2014





Hubble Diagram with SN CLO12Car shown relative to 18 field SN in similar redshift range.

CLASH SNe name	SALT2: predicted mag offset	MLCS2k2: predict. mag offset	CLASH Lens Model magnif.
CLO12Car	0.91±0.25	1.06±0.17	0.83±0.16
CLN12Did	0.24±0.15	0.15±0.09	0.28±0.08
CLA11Tib	0.52±0.20	0.64±0.15	0.43±0.11

Values given in magnitudes

Overall CLASH Summary

- Survey revealing many new and exciting discoveries. To date, 50+ refereed papers that use, or are inspired by, CLASH observations.
- Joint SL+WL producing precise measurements of mass concentrations. X-ray selection criteria important for unbiased test of LCDM. Lens models consistent with several independent cross-checks.
- Providing our first look at "JWST's Universe" – the epoch when the Universe was < 500 Myr old.
- SN Ia survey reveals low rates at $z > 1$, suggesting low fraction of prompt (delay time <500 Myr) supernovae. Rate data currently disfavors single degenerate progenitor scenario at $z > 1$.
- Enables new independent constraints on WDM particle mass and DM EoS (pressureless DM is consistent with observational constraints).
- Providing superb mass calibrators for larger cluster surveys:
  - WL + SL + X-ray + SZE + Dynamics
- The HST survey is complete but CLASH results continue to flow. Co-added HST and Subaru images and lens models are available at the STScI MAST website. CLASH Spitzer data available at IRSA / IPAC.