

# Constraining Dark Energy with Clusters of Galaxies

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MACS 1149+2223  $z = 0.544$

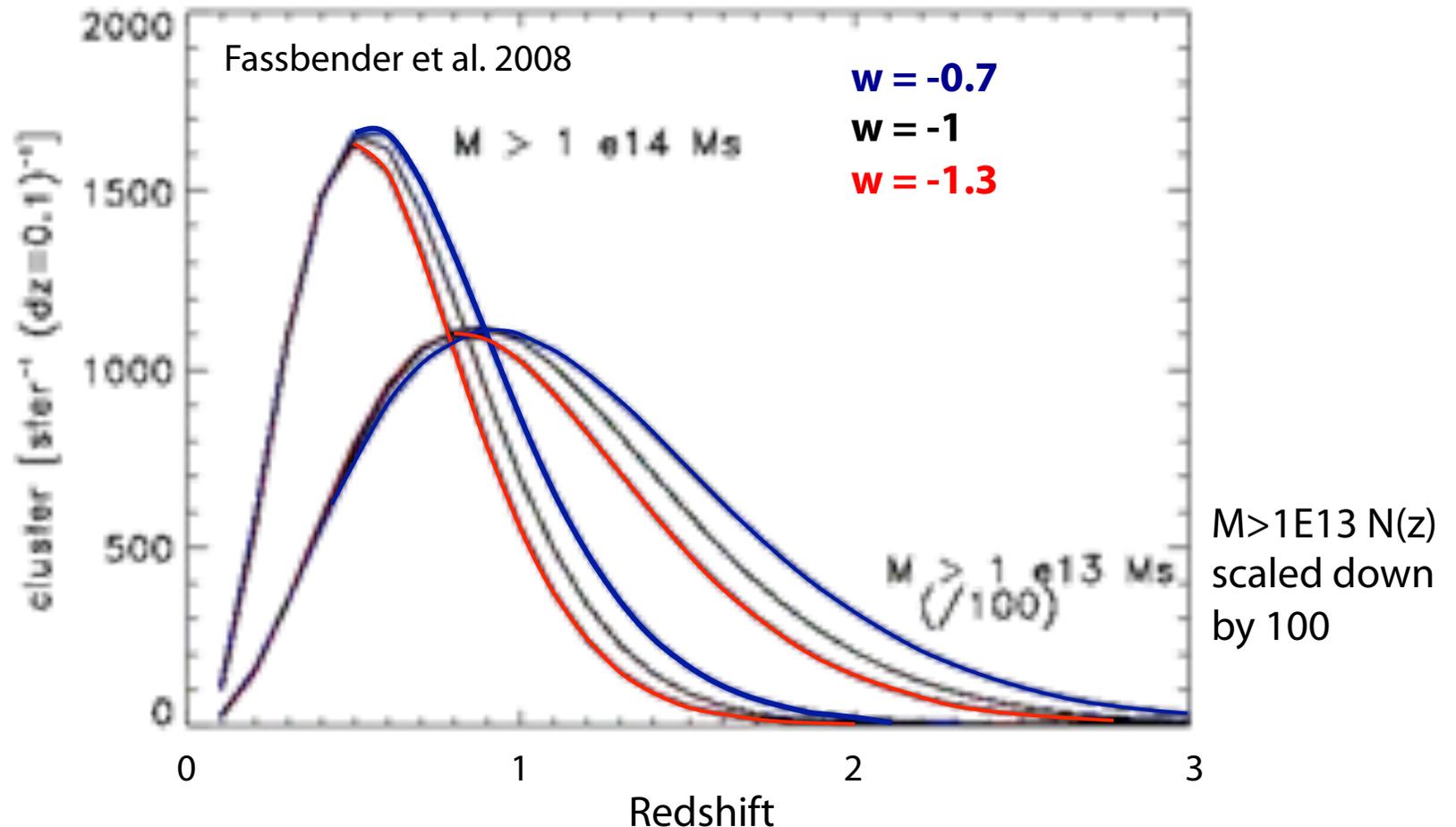
# Constraining Dark Energy with Galaxy Clusters

- Clusters as cosmological probes are useful because they complement other techniques (i.e., the biases are different)
- Can extract the required imaging data directly from an AFTA-WFIRST high-latitude survey program – will not require a separate cluster-survey program.
- A 2.4-meter telescope will provide superb data, far better than DRM1 or DRM2, for cluster-based cosmology.

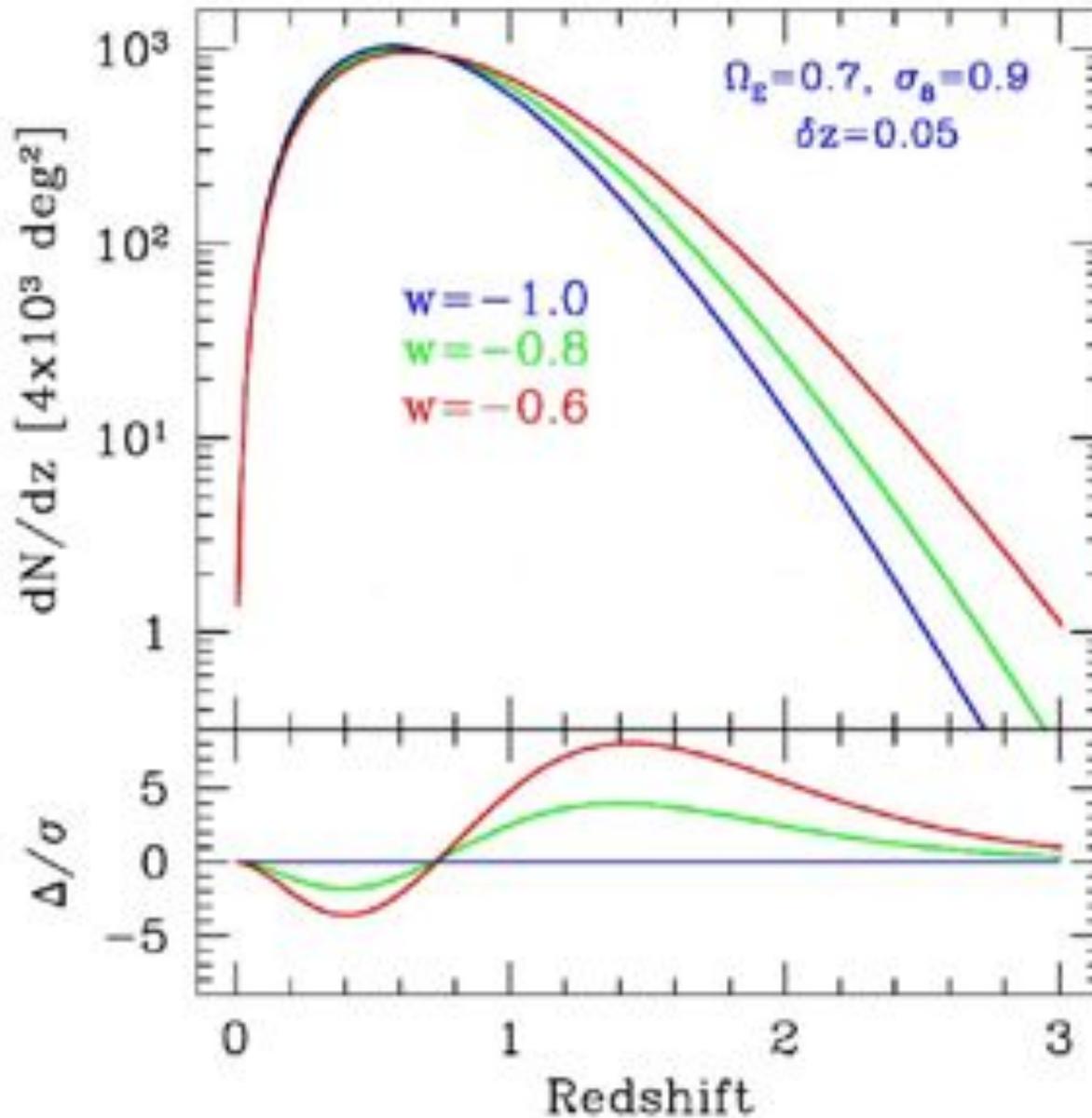
# Constraining Dark Energy with Galaxy Clusters

- Two basic approaches:
  - Growth of structure test = cluster abundance vs. redshift and mass. *“Both growth and expansion rates due to the presence of dark energy sensitively affect the abundance of collapsed structures, and the sensitivity increases toward the high mass end.” (LSST Sci Book 2009)*
  - Direct geometric test = lensing-based estimate of angular diameter vs. redshift relation.
- Will focus on above two methods here.
- Lensing time delay monitoring also a potential application but probably more suited to galaxy-scale lenses.

# Cluster Abundance Test



- Need to calibrate cluster selection function and need to reliably estimate cluster masses for abundance test to yield useful cosmological constraints.
- Most sensitive to different cosmologies at  $z > 1$ : need NIR data.



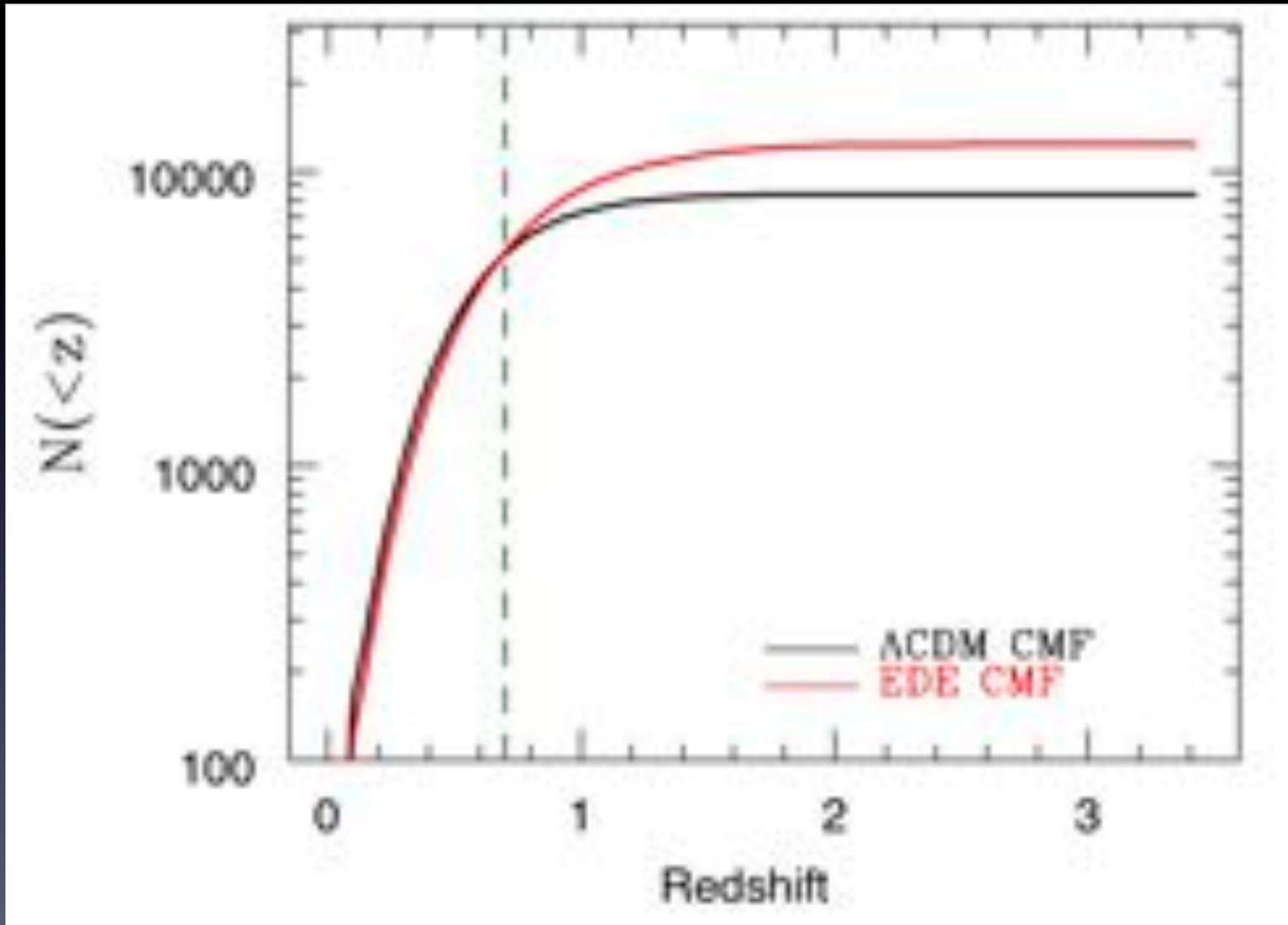
LSST Science Book 2009

Significance of difference in  $dN/dz$  versus redshift.

- Growth of structure sensitivity maximal at  $1 < z < 2$  (for 4,000 sq deg LSST survey).

# Cluster Survey with 2.4m Space Telescope

Cumulative Number of Clusters ( $M > 3E14$ ) as a  $f(z)$  for AFTA-WFIRST Survey

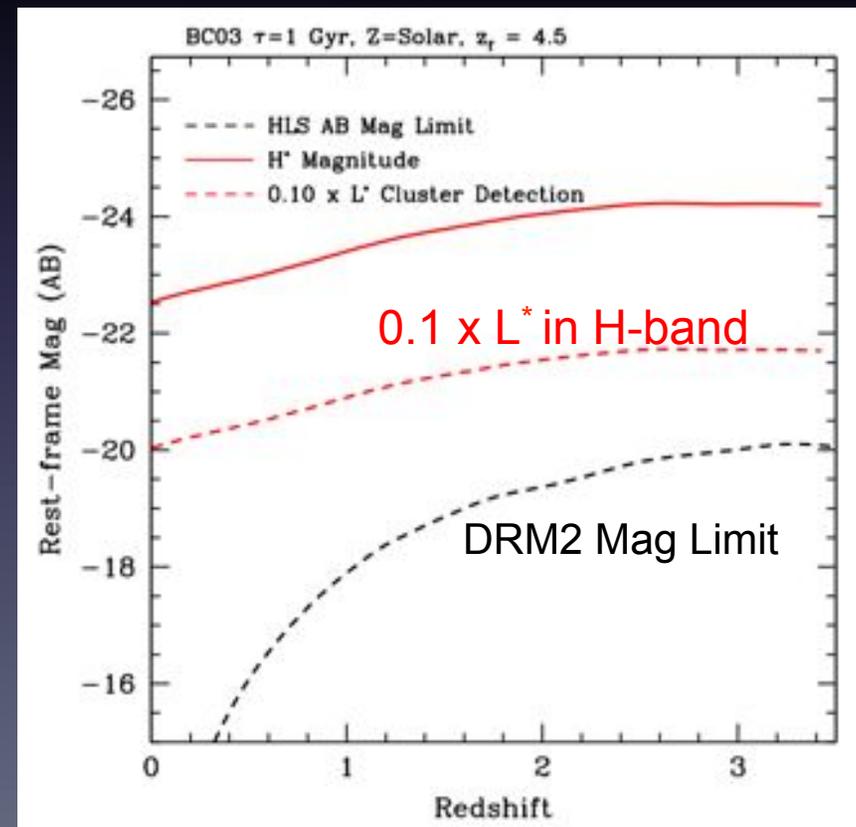


$N(z)$  Based on observed K-band LF evolution combined with WFIRST/  
NRO survey parameters

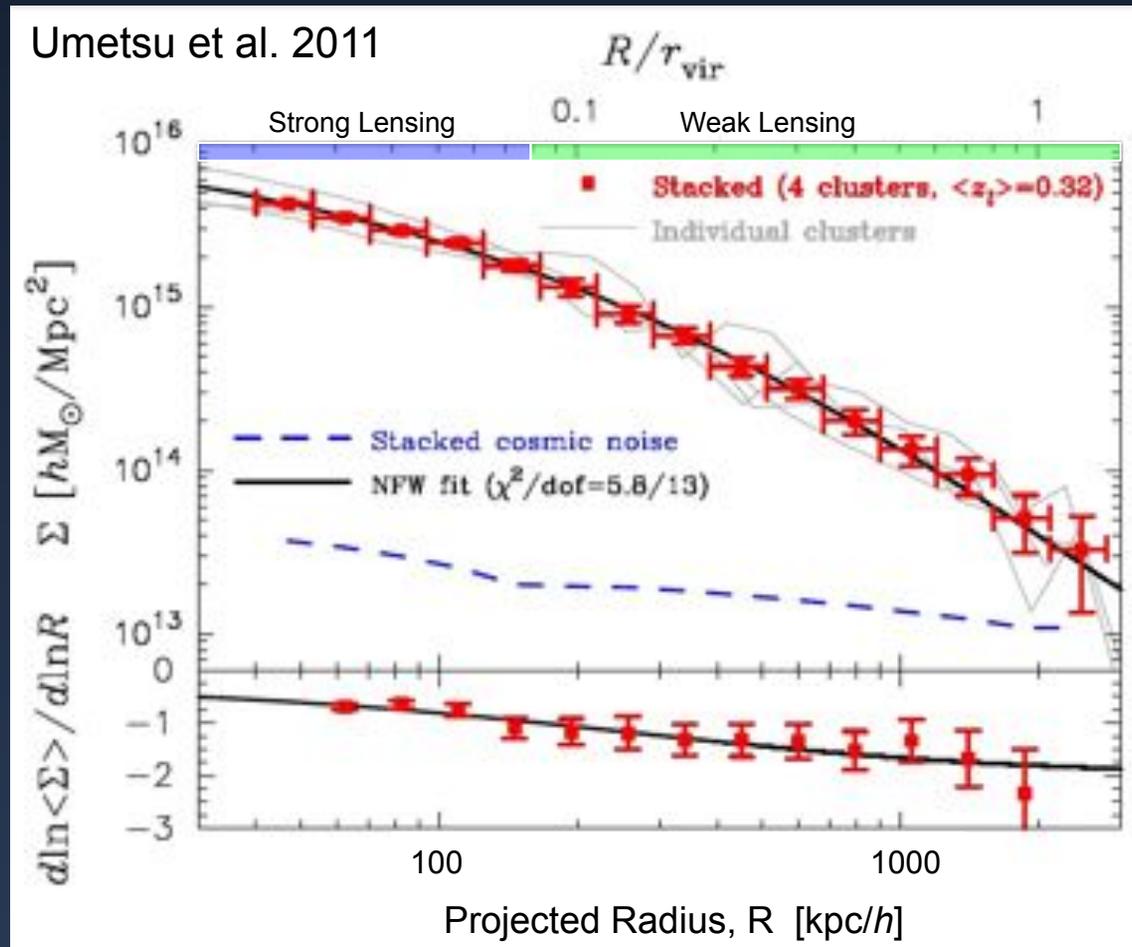
# Cosmology and the Space Density of Clusters

- A deep NIR wide area survey is ideal for the cluster abundance study as  $z > 1$  clusters have relatively high contrast in H-band.
- Depth is also key because at  $z > 1$  cluster  $L^*$  corresponds to  $H > 21$  mag and you'll want to probe at least down to  $H = 26$  to get good measure of weak and strong lensing (for mass estimation).
- NEED ACCURATE CLUSTER MASSES

Massive  $z = 1.4$  Cluster:  
XMMU J2235.3-2557  
(Rosati et al. 2009)



# Both Strong & Weak Lensing Measurements Needed for Good Cluster Mass Profiles

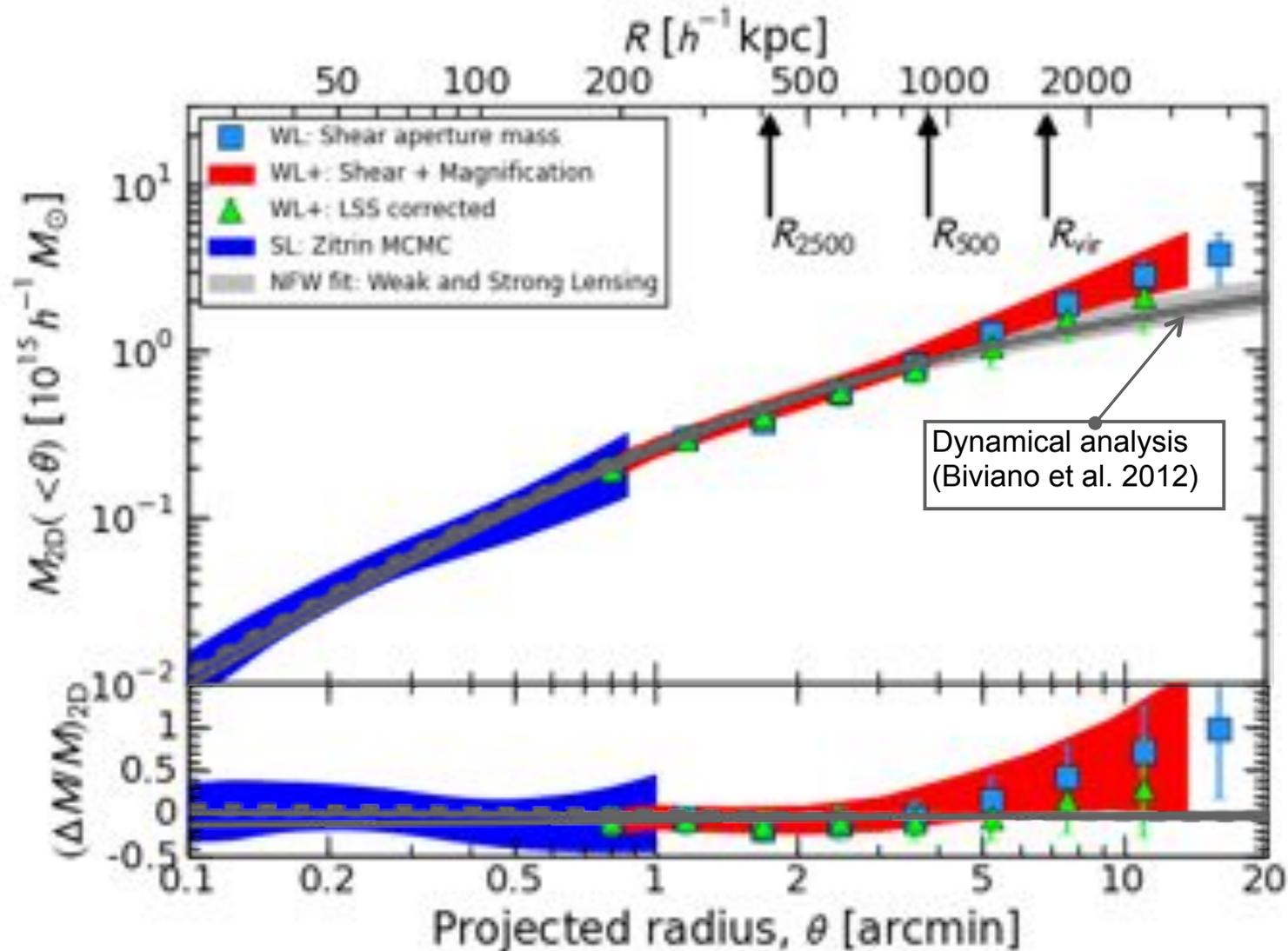


## Cluster Lensing + AFTA-2.4m survey provides:

- Three independent lensing constraints: SL, WL, mag bias
- Well-selected cluster sample and sensitive to  $z > 1$  clusters
- Definitive constraints on the representative equilibrium mass profile shape

# MACS J1206.2-0848 ( $z=0.45$ )

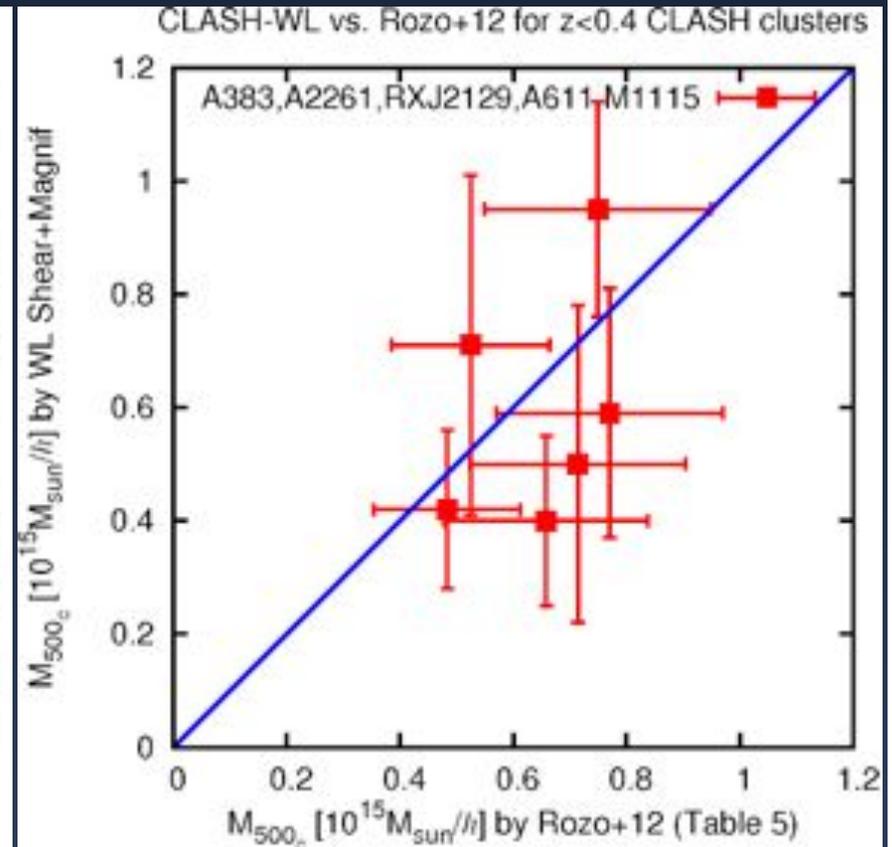
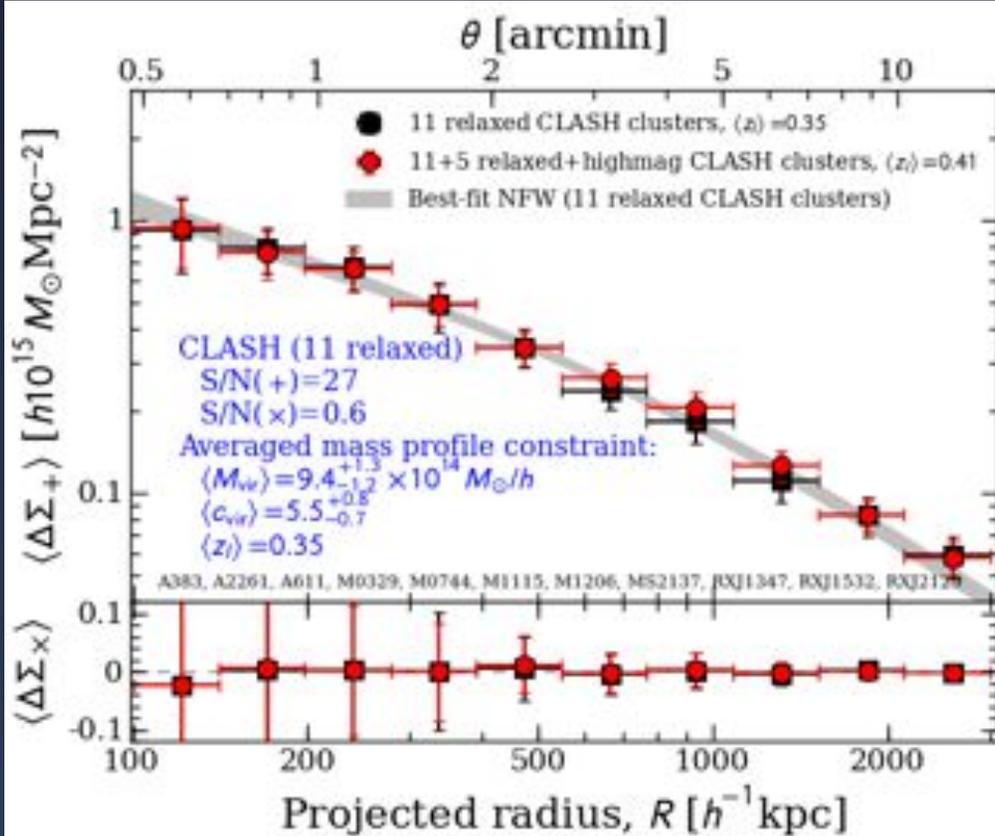
## Total mass profile from completely independent methods



(Umetsu et al. 2012, ApJ, 755, 56)

# Stacked Weak Lensing Analysis

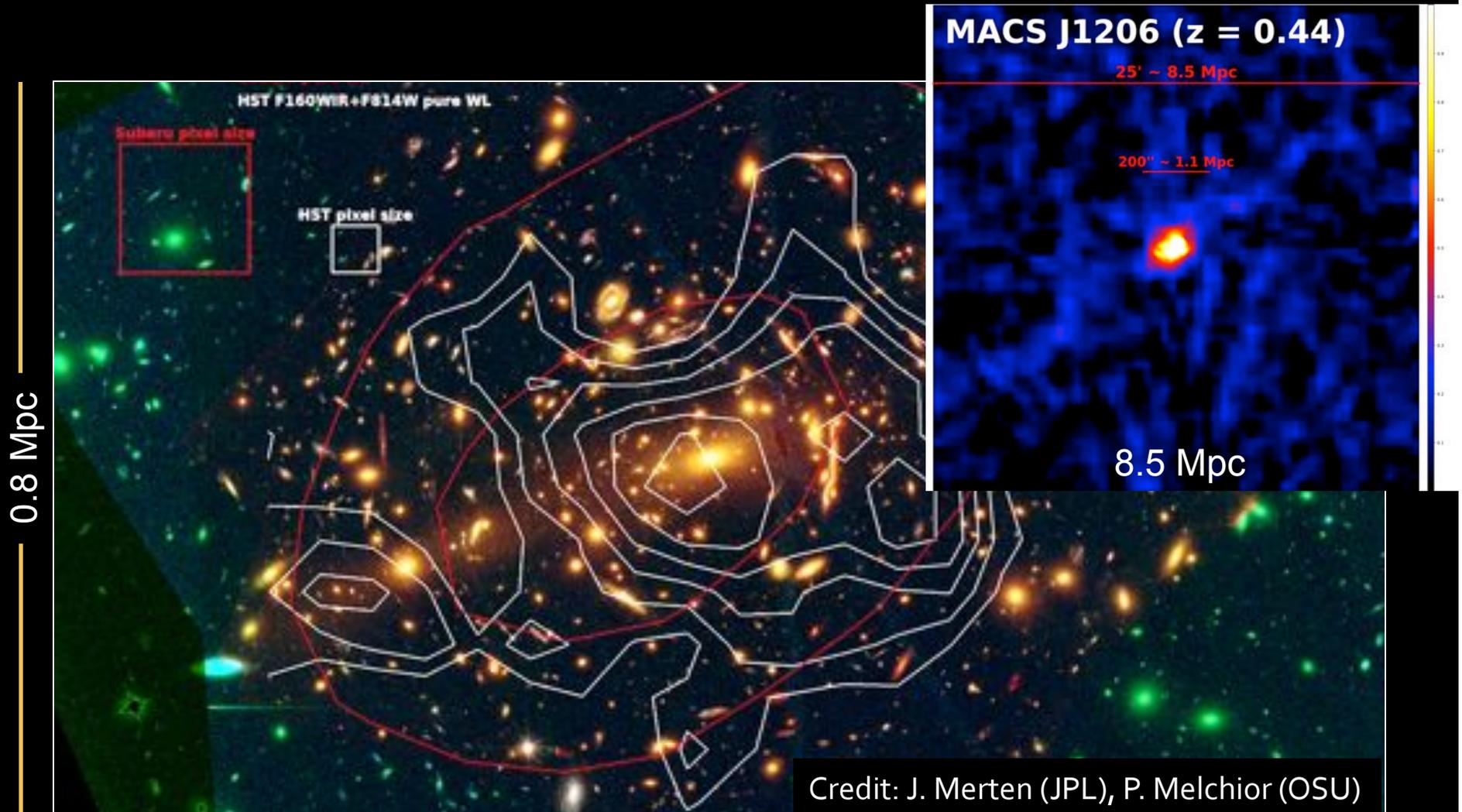
## Even better when SL constraints added



Umetsu et al., in prep

X-ray mass on x-axis  
(from Rozo et al 2012)

# NIR Survey in Space: Depth and Resolution Advantage on Cluster-scales for Weak Lensing



Subaru: Usable source density: 8 galaxies / arcmin<sup>2</sup> → 25'' WL map resolution (142 kpc)  
HST in H-band (WFC3): 112 galaxies / arcmin<sup>2</sup> → 7.5'' WL map resolution (43 kpc)

# Issues

- Need good fore/background discrimination for weak lensing – but WFIRST will, by design, provide that. To depths of  $\sim 26$  AB mag, can get very high background galaxy densities.
- For best SL mass models, need many multiple-image systems. Requires good depth and angular resolution. We know we can do this well with HST. AFTA should provide comparably good results.
- Optimal sensitivity of  $dN/dz$  to different growth histories will occur in range  $1 < z < 2$ . NIR survey best option.
- Need robust and accurate mass-observable relationships. WL+SL will suffice but even better when combined with SZE and X-ray estimates.

# Angular Diameter – Redshift Test

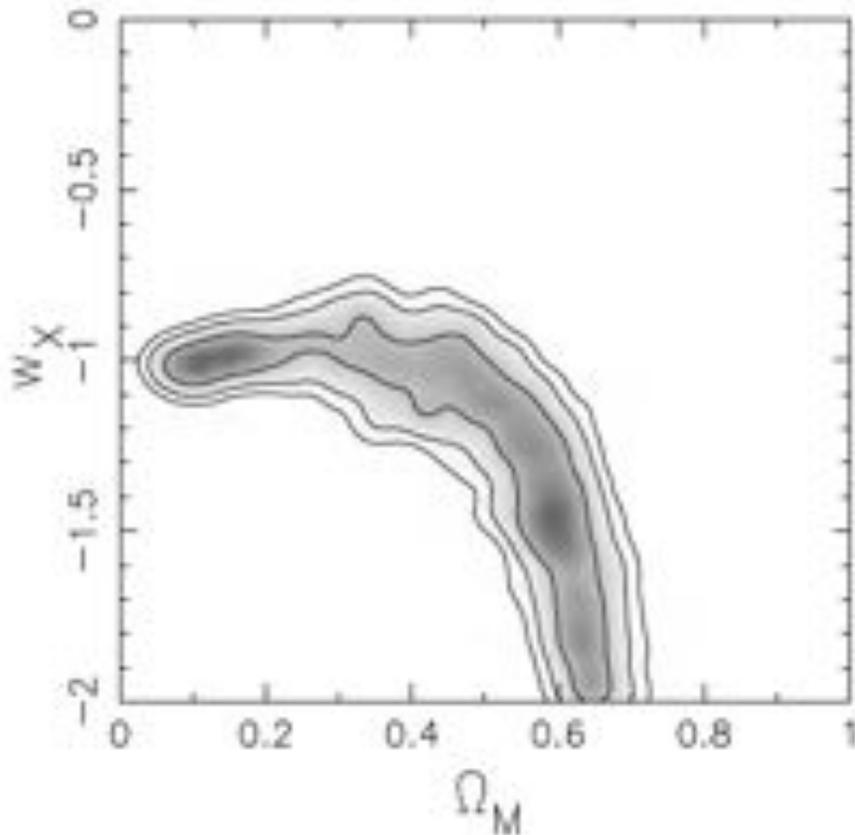
(e.g., Jullo et al. 2010, Science, 329, 924)

$$D_A = \frac{cH_0^{-1}}{1+z} \int_{z_1}^{z_2} dz \left( \Omega_m(1+z)^3 + (1+z)^{3(w_x+1)}\Omega_x \right)^{-1/2}$$

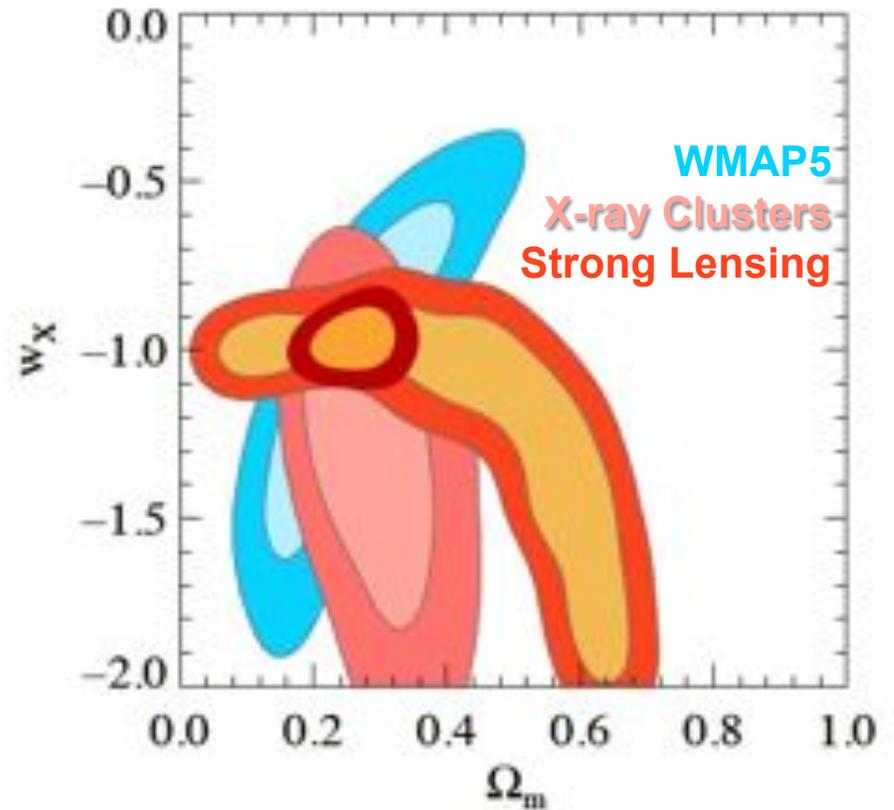
- Strong lensing can result in multiple lensed images of the same source in the image plane.
- If multiple sources at different redshifts are available then one can, in principle, extract cosmological constraints.
- Lens equation:  $\beta = \theta - \alpha (D_{LS}/D_S)$
- $F(z_L, z_{s1}, z_{s2}; \Omega_M, \Omega_X, w_X) = [D(z_L, z_{s1}) * D(0, z_{s2})] / [D(0, z_{s1}) * D(z_L, z_{s2})]$
- Requires good lens model and accurate source redshifts.



# Lensing-based Cosmological Constraints from A1689

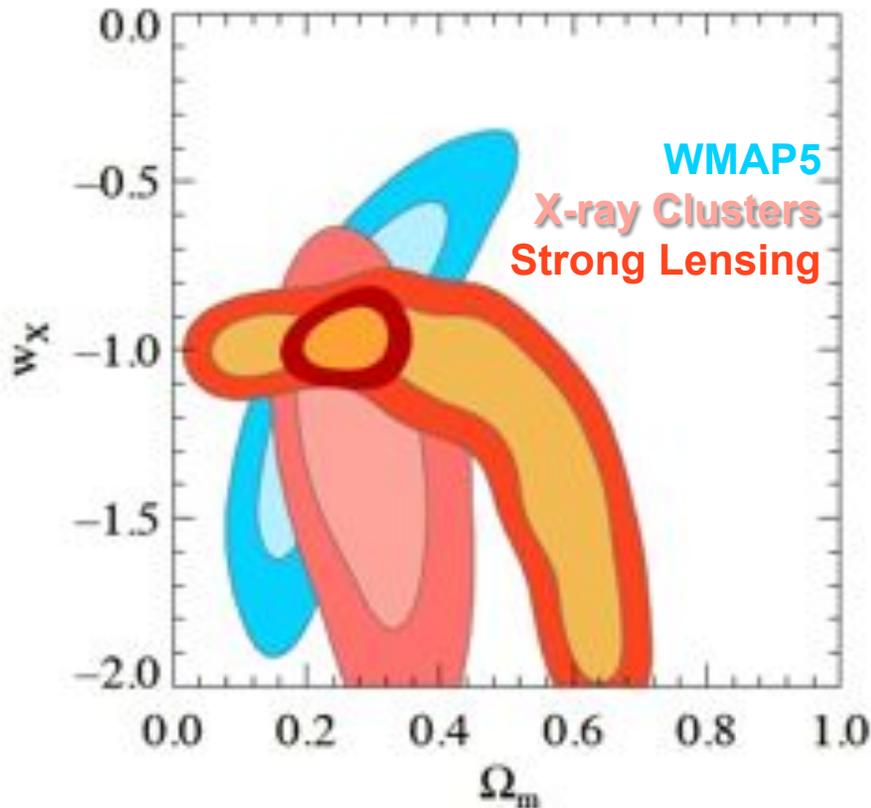


From Jullo et al. 2010: Constraints on  $\Omega_M$ - $w_X$  plane based solely on 28 multiple images from 12 unique sources in A1689. Limited data to objects with spec-z and inside high SNR lens model regions.

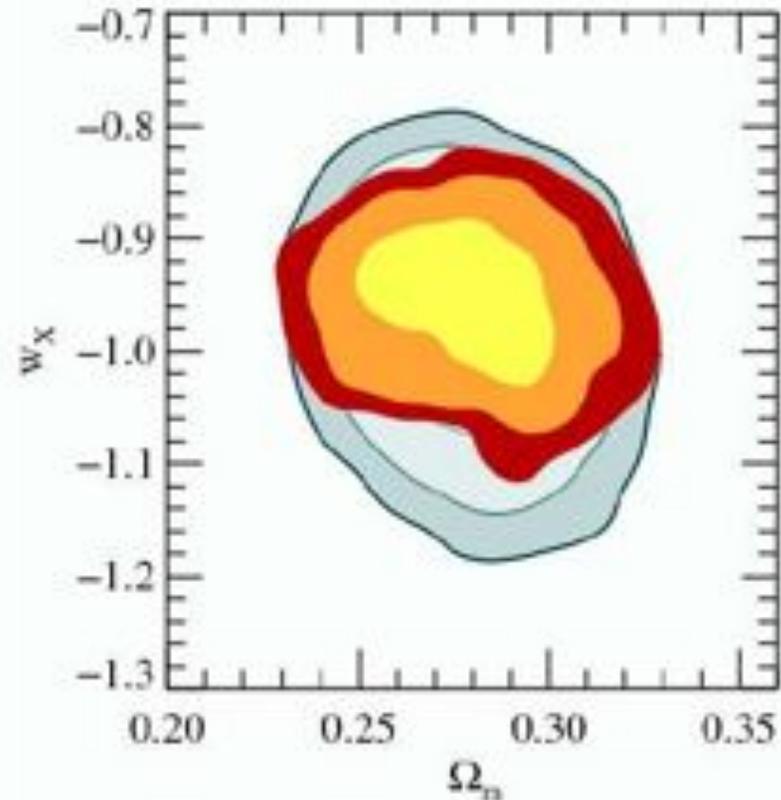


Constraints after combining A1689 lensing results with those from WMAP5 + cluster evolution studies from X-ray.

# Lensing-based Cosmological Constraints from A1689



Constraints after combining A1689 lensing results with those from WMAP5 + cluster evolution studies from X-ray.



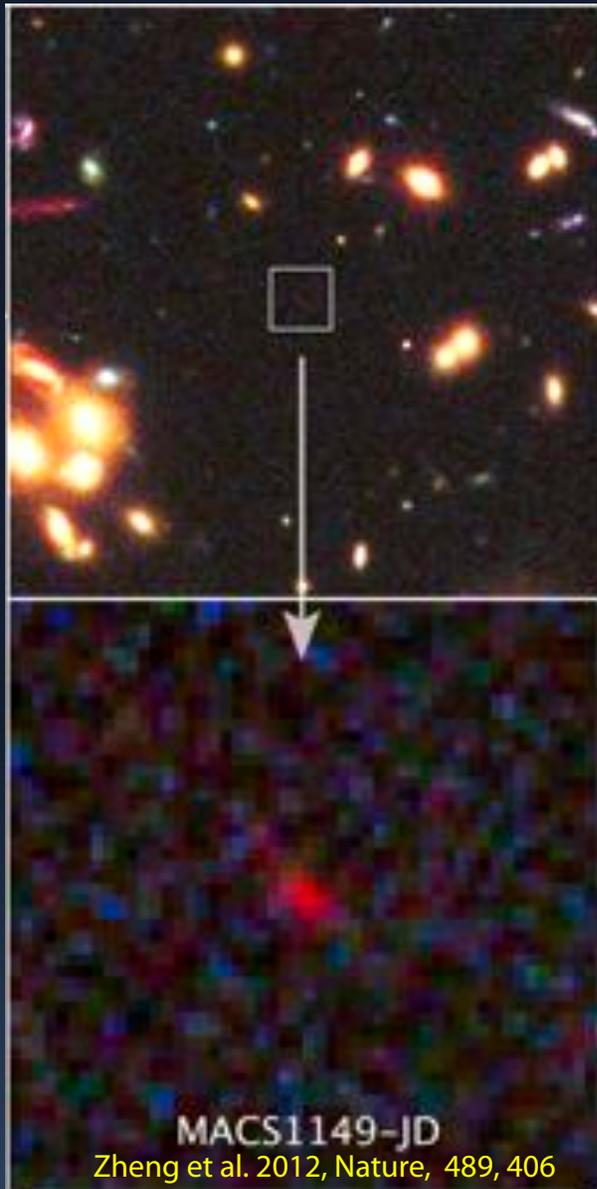
Constraints after combining A1689 lensing results with those from WMAP5 + SNLS + SNEssence + SN-Gold-Sample + SDSS/BAO. Jullo et al. claim  $\sim 30\%$  reduction in 2sigma contours on  $w_x$ .

# Issues

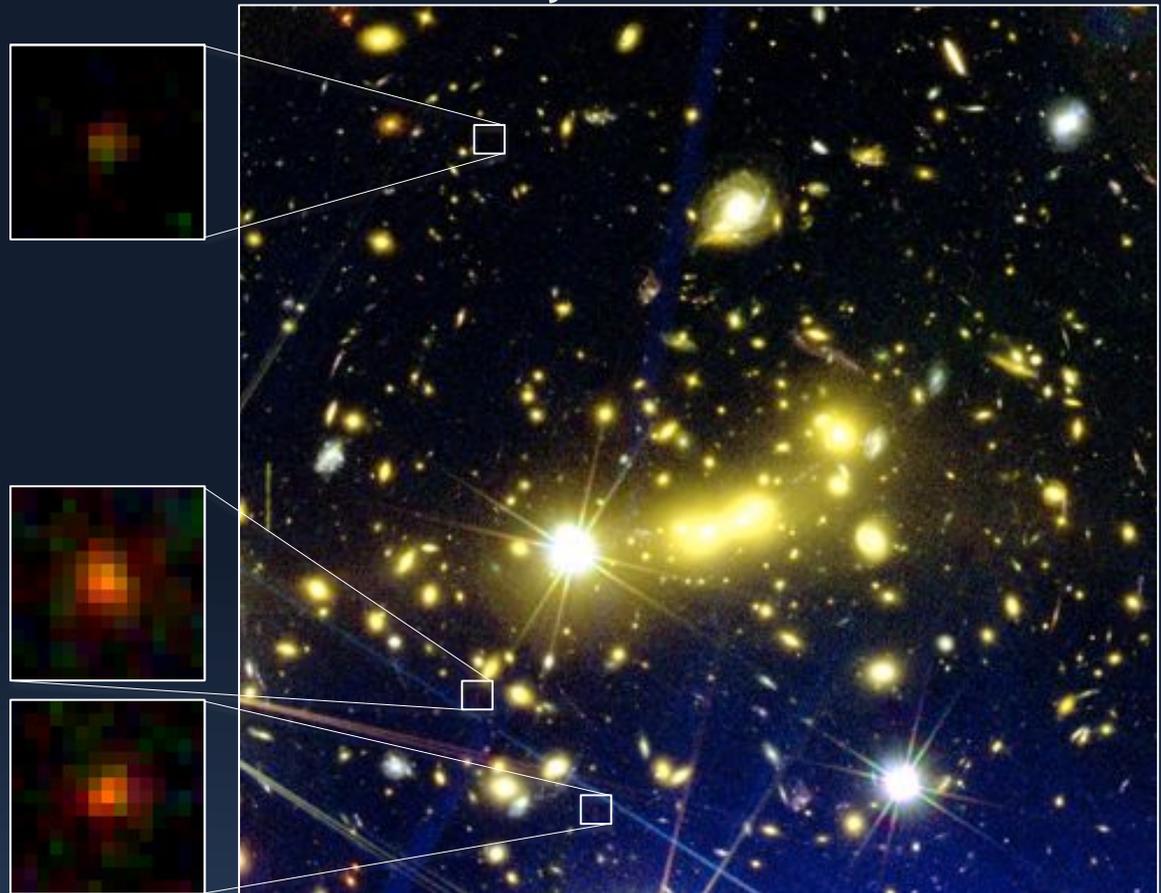
- Jullo et al. 2010 lens model assumes a cosmological model. Hence, constraints are not completely free of assumptions about cosmology. Is it feasible to get around this issue? Currently under study.
- Need accurate lensed galaxy redshifts. Hence, significant amount of spectroscopic follow-up required.
- If above issues addressed, lensing-based  $D_{\text{ANG}}$ -redshift test could provide important constraint on dark energy in conjunction with other methods.

# Two $z > 9$ Lensed Galaxies Discovered

$z = 9.6$  object in MACSJ1149+2223



$z = 10.8$  object in MACSJ0647+7015



Coe et al. 2012, ApJ, in press  
(see arXiv:1211.3663)

# Spectral Energy Distributions

MACS1149-JD:  $z = 9.6 \pm 0.2$

Stellar mass:  $\sim 1.5 \times 10^8 \text{ Msol}$

SFR:  $\sim 1.2 \text{ Msol/yr}$

Age:  $< 200 \text{ Myr}$  (95% CL),  $z_{\text{Form}} < 14.2$

$r_{1/2}$ :  $\sim 0.14 \text{ kpc}$  (de-lensed)

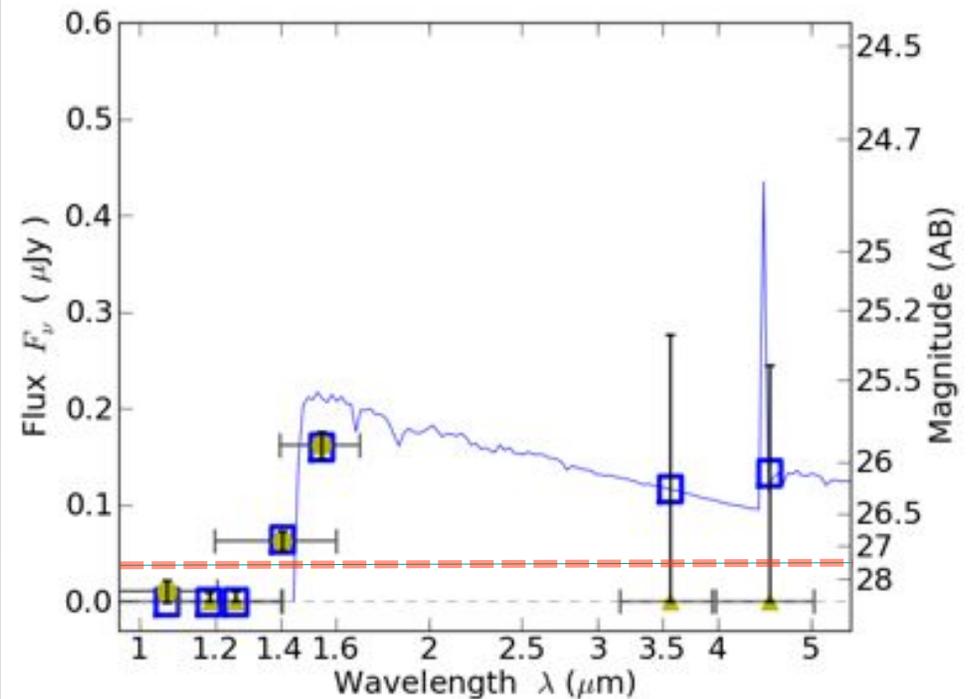
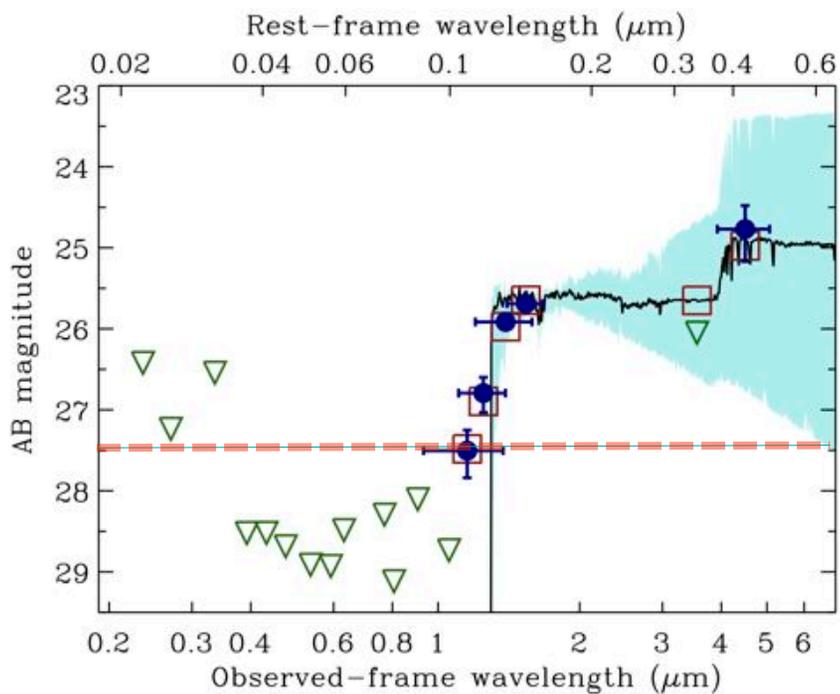
MACS0647-JD:  $z = 10.8 \pm 0.5$

Stellar mass:  $10^8 - 10^9 \text{ Msol}$

SFR:  $\sim 4 \text{ Msol/yr}$  (Salpeter IMF)

Age:  $< 400 \text{ Myr}$  (95% CL)

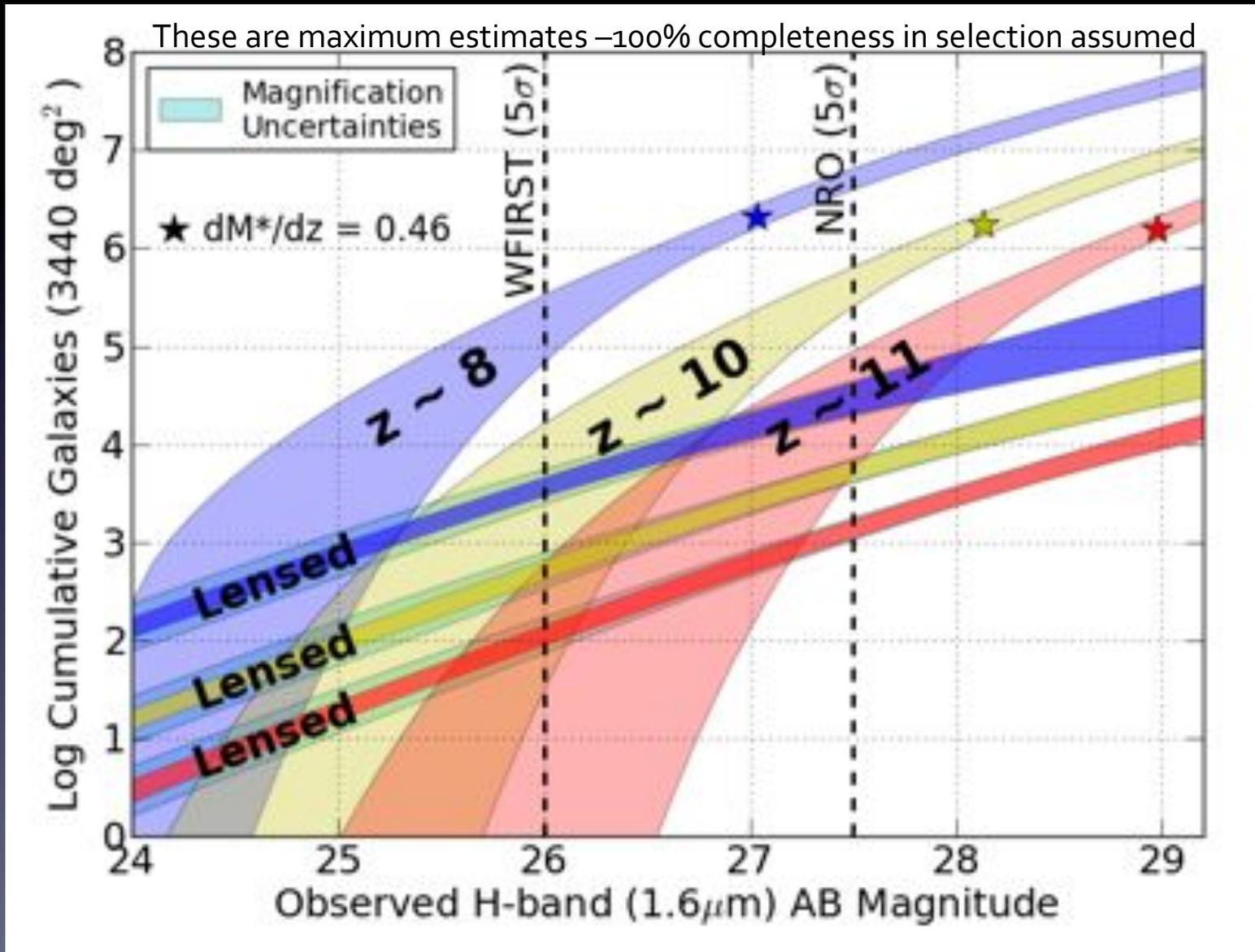
$r_{1/2}$ :  $< 0.10 \text{ kpc}$  (de-lensed)



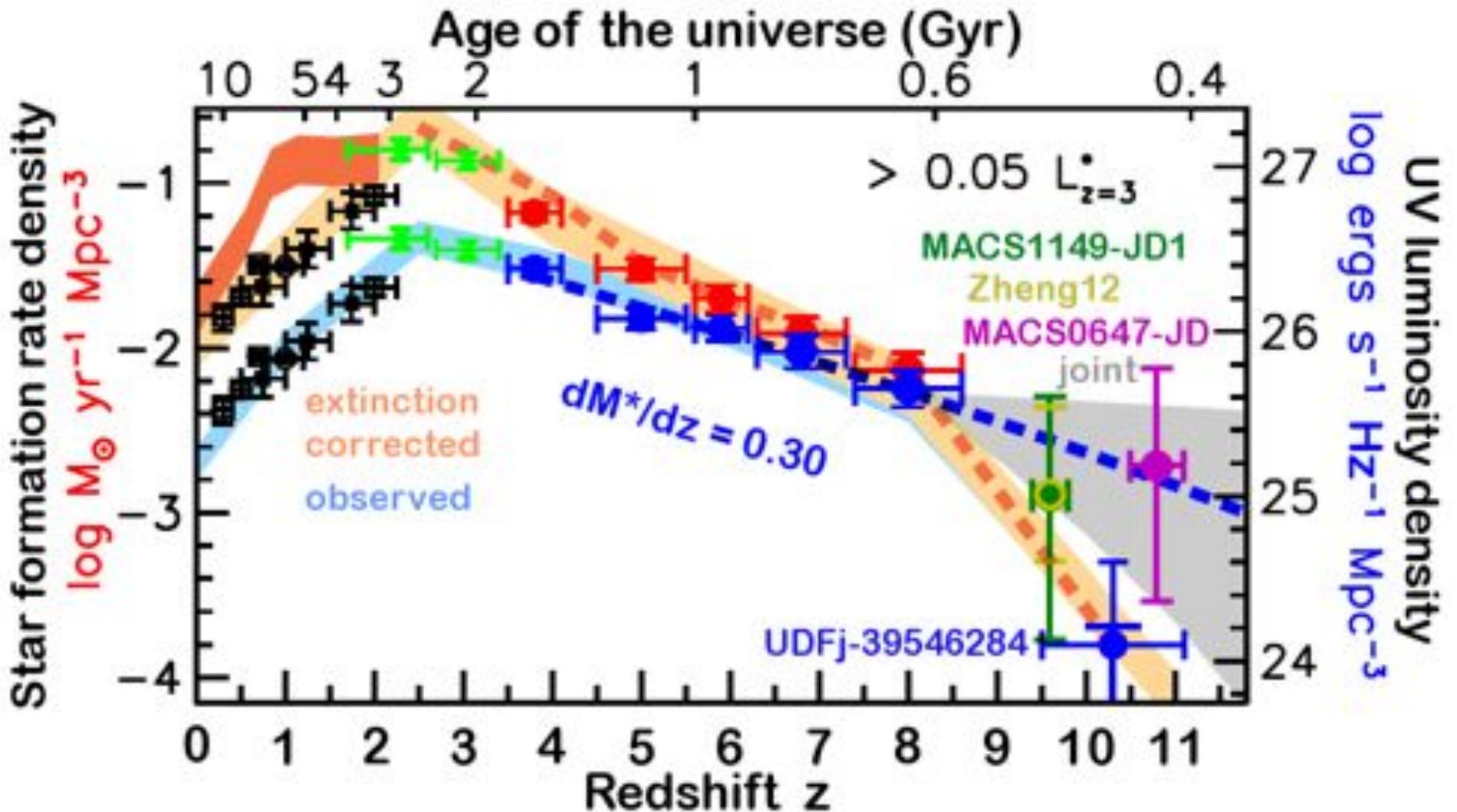
In both cases, best fit SED is a starburst galaxy

# Expectations for High-z Galaxy Discoveries

Unlensed  $z=8$  LF constrained by BoRG data for 26 – 29 mag. Extrap. to  $z=9,10$  assume  $dM^*/dz=0.46$ .  
Lensed Galaxy counts assume  $\sim 1$  strongly lensing cluster per sq degree with typical CLASH mass model.



# Constraining the Cosmic Star Formation Density



- = Bouwens et al. (2011a,b)  $4 < z < 8$  Rest-UV LF, prior to dust obscuration correction
- = Bouwens et al. (2011)  $4 < z < 8$  Rest-UV LF, after dust obscuration correction (no dust assumed at  $z > 7$ )
- ↓ = Oesch et al. 2012 = UDFj-39546284
- = Reddy & Steidel 2009, Bouwens et al. 2007, Schiminovich et al. 2005

# Summary: Cluster Cosmology with AFTA

- Accurate cluster masses from WL+SL measurements out to beyond Virial radius will provide mass measurements with uncertainties  $<15\%$  per cluster.
- Sample of several thousand clusters in WFIRST+NRO survey will superbly measure the cluster mass function as a function of redshift  $\rightarrow$  strong and independent test of cosmology. Best sensitivity at  $z > 1$ . NIR survey optimal for this redshift range.
- Use of multiply imaged lensed galaxies at different redshifts may provide useful and independent  $z$ - $D_A$  cosmological test, if one can do modeling in cosmologically self-consistent manner.
- **BONUS:**  
The depth and area of the NRO (2.4m) survey would be sufficient to discover thousands of  $z > 8$  galaxies and, potentially, tens to hundreds of highly magnified  $z \sim 10$  galaxies that would be within reach of EELT and JWST spectrographs.