Through a Lens, Darkly:
An Innovative Multi-cycle Hubble Treasury Program to Study the Dark Universe

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Science with HST III, Venice, Italy

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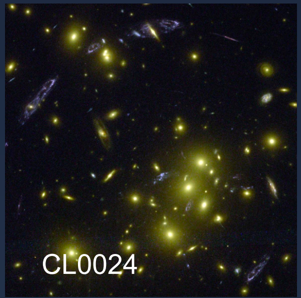
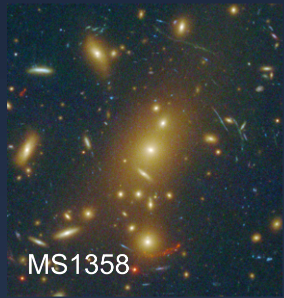
MACS 2129-0741   z = 0.57   HST/ACS image (Ebeling et al.)

CLASH:

Cluster Lensing And Supernova survey with Hubble

An 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 will use galaxy clusters as cosmic lenses to reveal dark matter and magnify distant galaxies.

Multiple observation epochs enable a z > 1 SN search in the surrounding field (where lensing magnification is low). This allows us to improve the constraints on both the time dependence of the dark energy equation of state and on the amplitude of systematic errors in cosmological parameters.

The CLASH Science Team:

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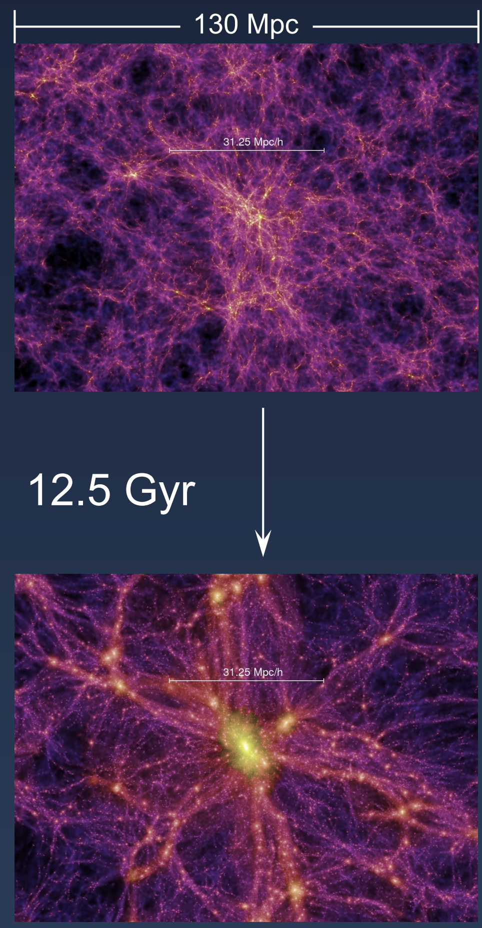
CLASH

Post-doctoral fellow
Graduate student

Fundamental Questions That Remain Unanswered or Unverified

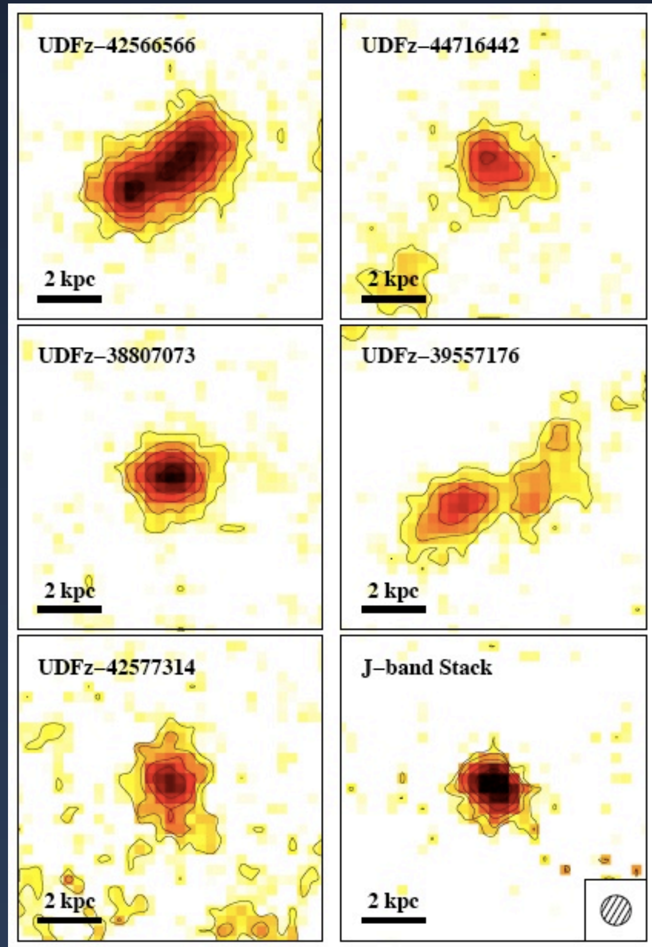
- How is dark matter distributed in cluster & massive galaxy halos?
  - How centrally concentrated is the DM? Implications for epoch of formation.
  - What degree of substructure exists? And on what scales?
  - How does the DM distribution evolve with time?
  - What is the characteristic shape of a typical cluster DM halo?



“Millennium” simulation of DM
Springel et al. 2005

Fundamental Questions That Remain Unanswered or Unverified

- 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?



Young galaxies (z ~ 7)
Oesch et al. 2010

Fundamental Questions That Remain Unanswered or Unverified

- 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 time derivative of the equation of state?
  - 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)

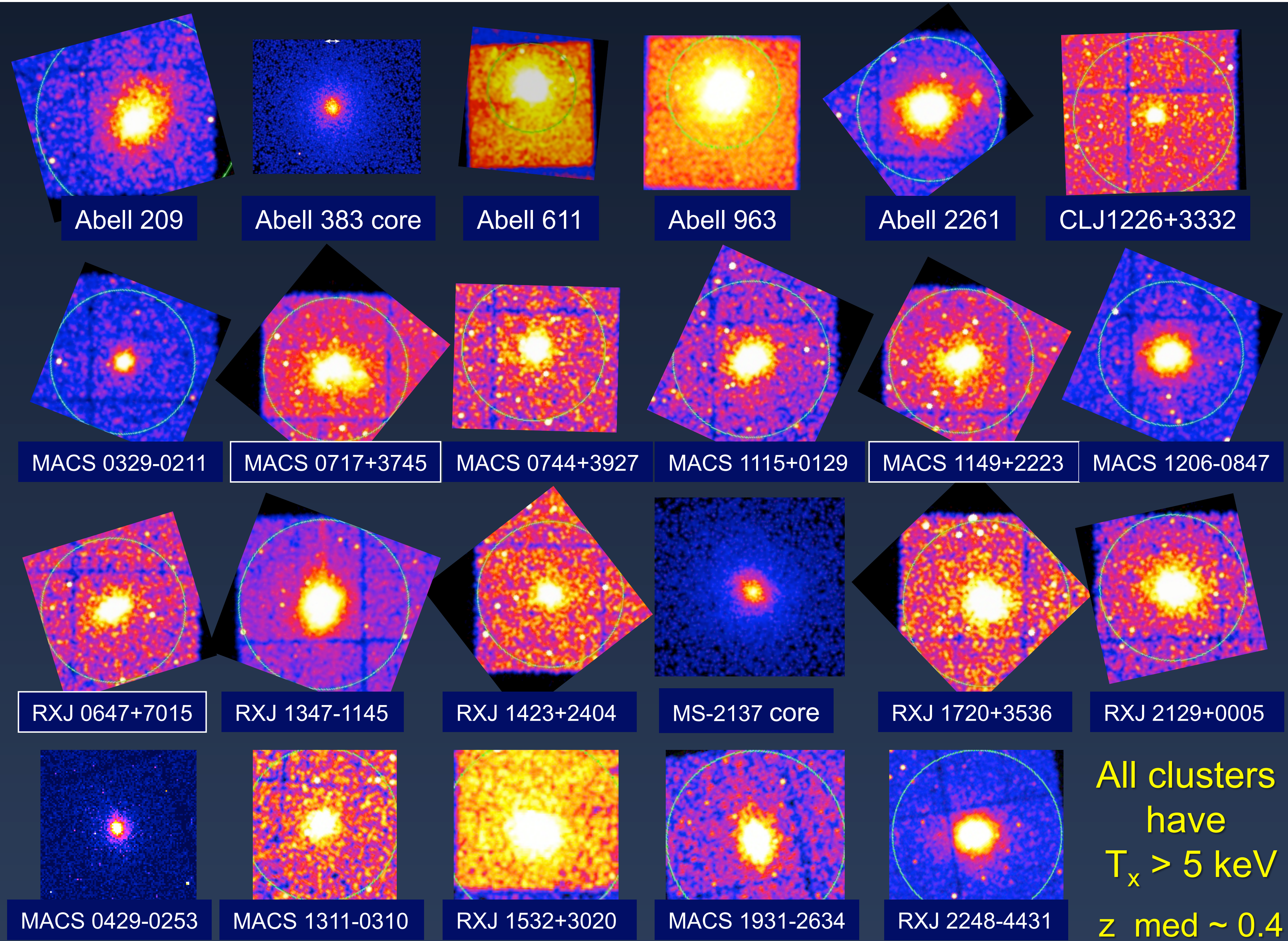
$w \neq$ constant; scalar field

e.g. Quintessence, k-essence

Is w a f(z)?

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

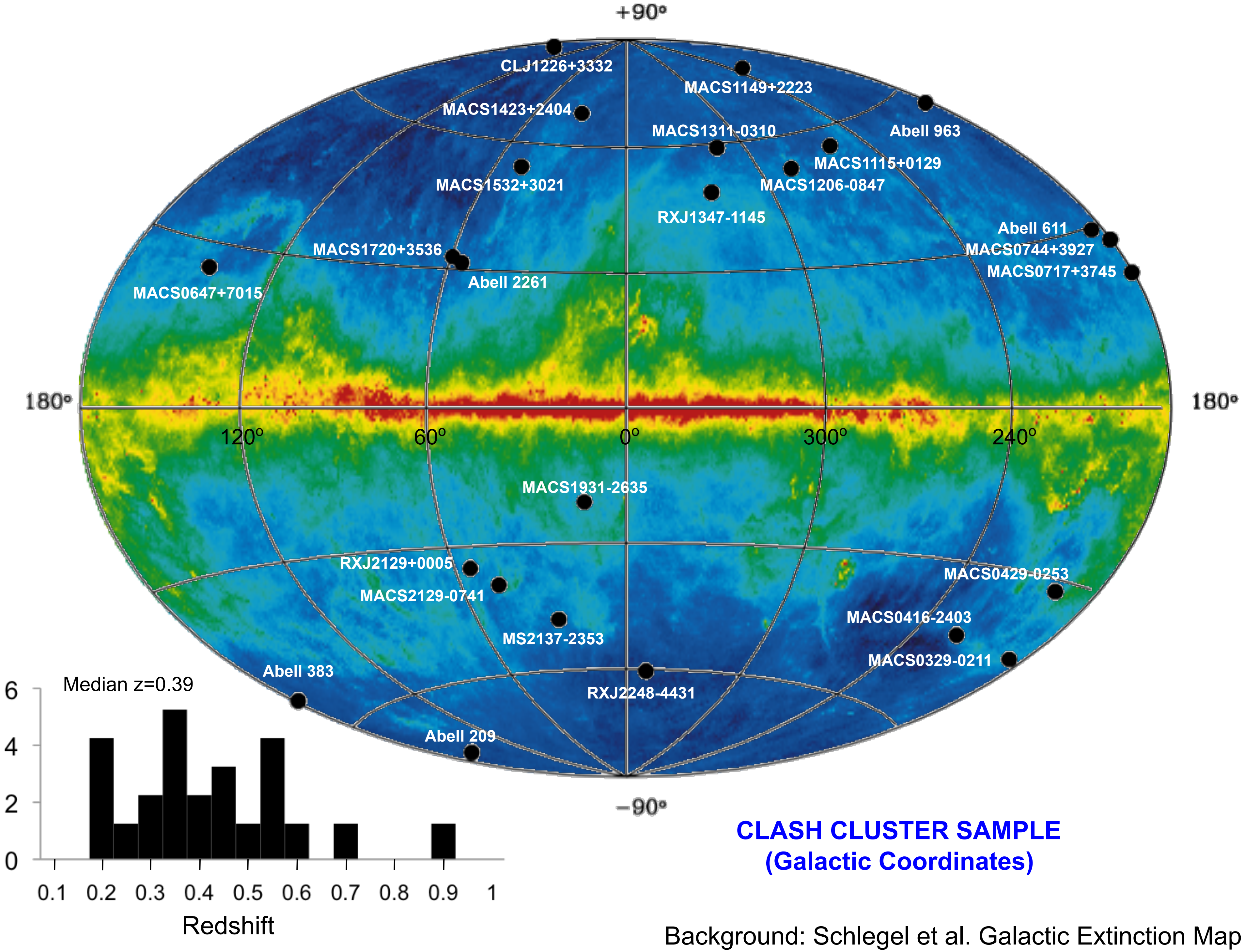
(e.g., Linder 2003)



All clusters have $T_x > 5$ keV

z_med ~ 0.4

Cutouts of x-ray images of 23 of the 25 CLASH clusters from Chandra Observatory



+90°
−90°
180°
180°
120°
60°
0°
300°
240°
CLJ1226+3332
MACS1149+2223
MACS1423+2404
MACS1311-0310
Abell 963
MACS1115+0129
MACS1532+3021
MACS1206-0847
RXJ1347-1145
Abell 611
MACS1720+3536
MACS0744+3927
MACS0717+3745
Abell 2261
MACS0647+7015
MACS1931-2635
RXJ2129+0005
MACS0429-0253
MACS2129-0741
MACS0416-2403
MS2137-2353
MACS0329-0211
Abell 383
RXJ2248-4431
Abell 209
Median z=0.39
6
4
2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Redshift
CLASH CLUSTER SAMPLE
(Galactic Coordinates)
Background: Schlegel et al. Galactic Extinction Map

Cluster Sample Size Justification

Observational

- Want to measure mean "concentration" of DM profile to ~10% accuracy:

$$N_{CL} \approx (\sigma_{tot} / f)^2$$

$$f = 0.10$$

$$\sigma_{tot}^2 = \sigma_{LSS}^2 + \sigma_{int}^2 + \sigma_{Meas}^2$$

σ_{LSS} = 0.13 (e.g., Hoekstra et al. 2003)

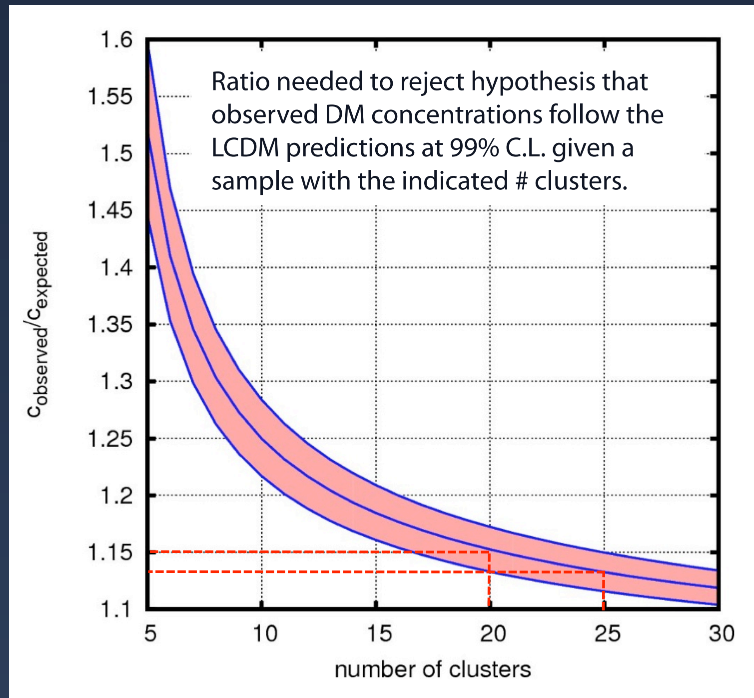
σ_{int} = 0.30 (e.g., Neto et al. 2007)

σ_{Meas} = 0.22 ($N_{arc,\ CL0024}$ / N_{arc})$^{1/2}$ (Umetsu et al. 2010)

$$N_{CL} = 24$$

Theoretical

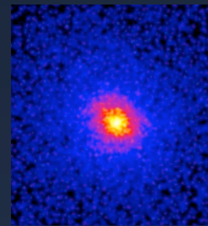
- N-body simulations show DM profile concentration distns are log-normal with σ~ 0.25±0.03 (e.g., Jing 2000; Meneghetti et al. 2009).



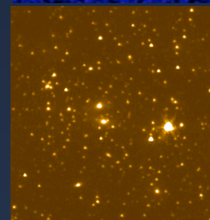
Comprehensive Multi-wavelength Coverage

- HST 524 orbits: 25 clusters, each imaged in 16 passbands. (0.23 – 1.6 μm) ~20 orbits per cluster.

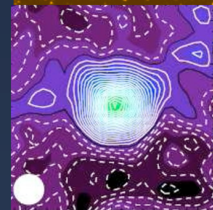

- Chandra x-ray Observatory archival data (0.5 – 7 keV)

- Spitzer IR Space Telescope archival data (3.6, 4.5 μm)

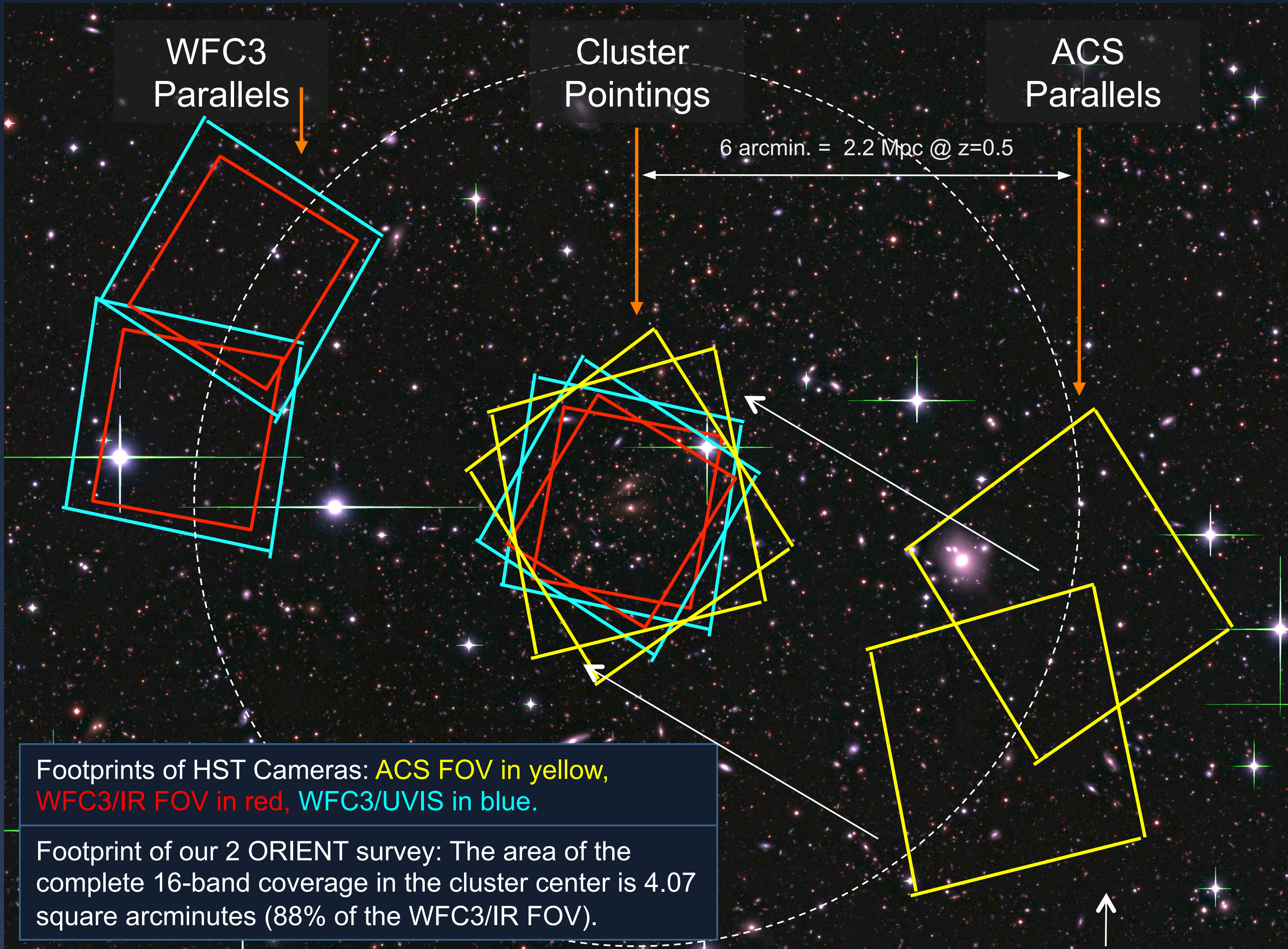



- SZE observations (Bolocam, Mustang) to augment existing data (sub-mm)

- Subaru wide-field imaging (0.4 – 0.9 μm)
- VLT, Magellan Spectroscopy


CLASH: An HST Multi-Cycle Treasury Program

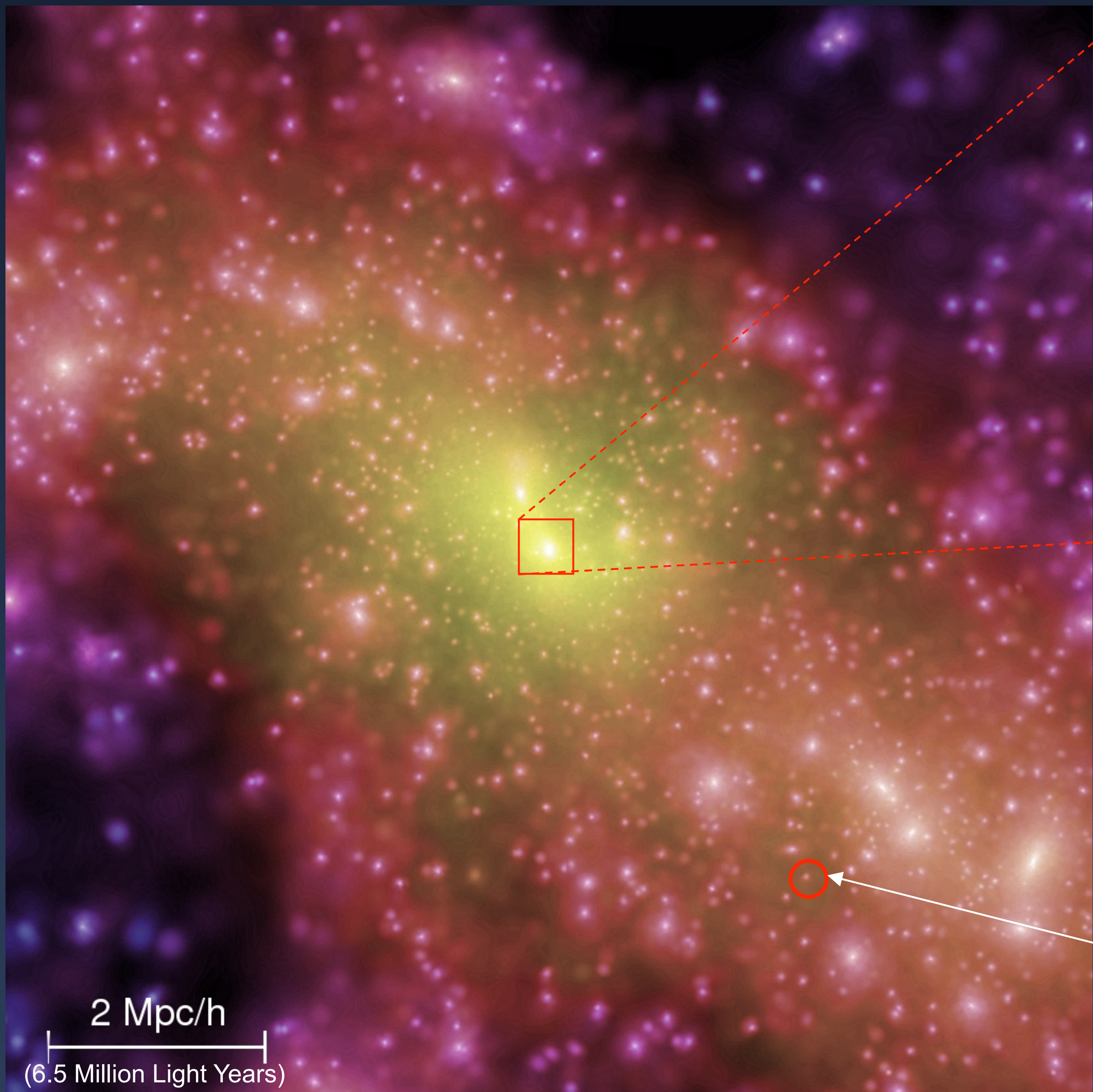


SN search cadence: 10d-14d, 4 epochs per orient

Image: Subaru Suprime Cam

Lensing amplification small at these radii

CLASH: An HST Multi-Cycle Treasury Program



Simulation of dark matter around a forming cluster (Springel et al. 2005)

Deep HST image of massive cluster

$$R \propto \frac{\theta_{Einstein}}{\sqrt{N_{Arcs}}}$$

WHERE R IS THE RESULTING SPATIAL RESOLUTION OF THE DARK MATTER MAP

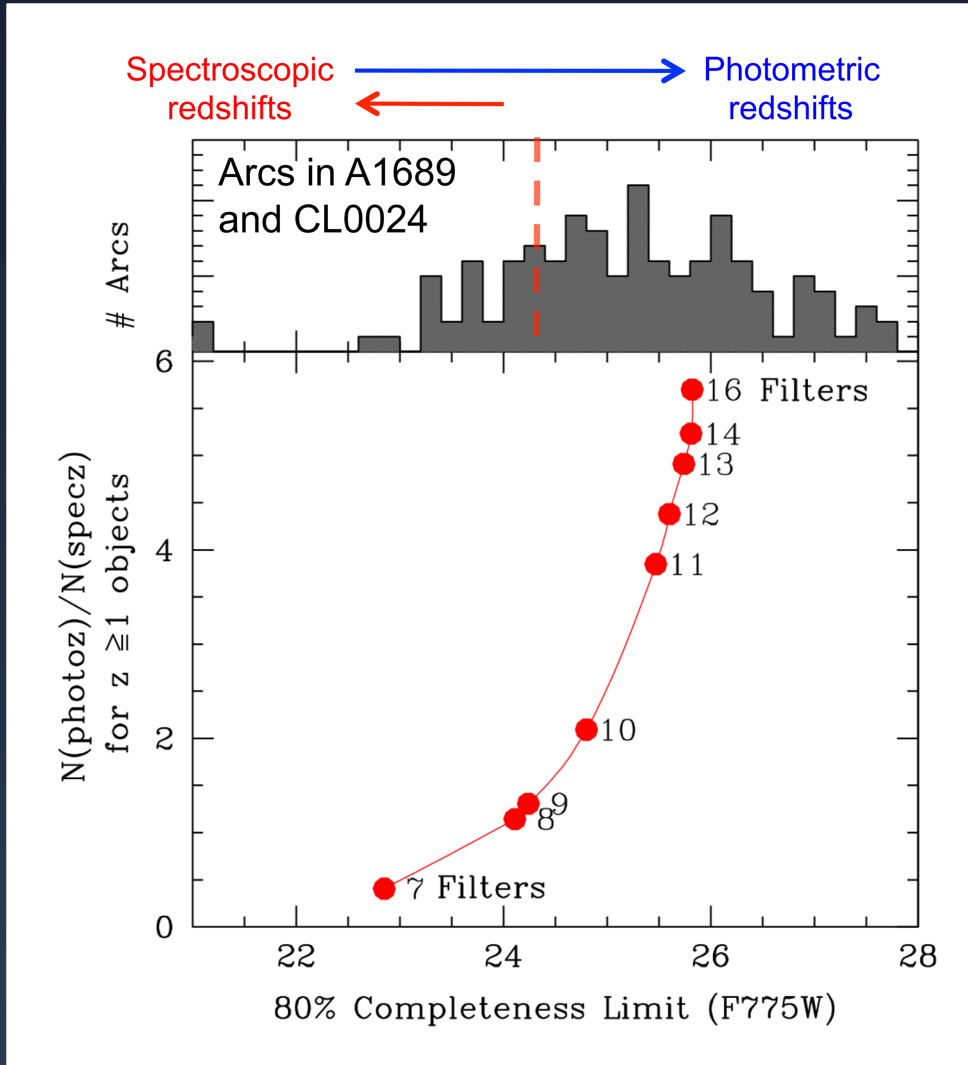
CLASH: An HST Multi-Cycle Treasury Program

Why 16 filters?

F225W … 1.5 orbits WFC3/UVIS
F275W … 1.5 orbits WFC3/UVIS
F336W … 1.0 orbit WFC3/UVIS
F390W … 1.0 orbit WFC3/UVIS

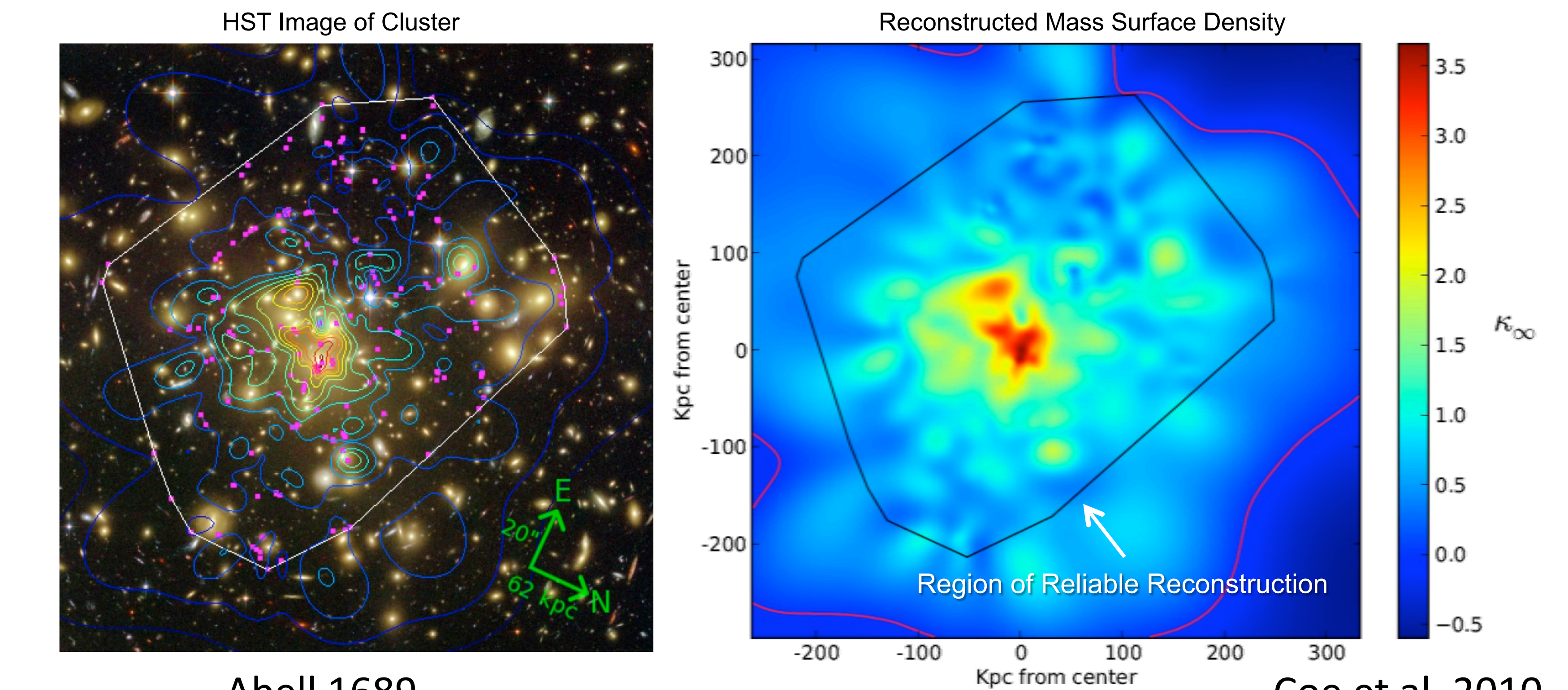
F435W … 1.0 orbit ACS/WFC
F475W … 1.0 orbit ACS/WFC
F606W … 1.0 orbit ACS/WFC
F625W … 1.0 orbit ACS/WFC
F775W … 1.0 orbit ACS/WFC
F814W … 2.0 orbits ACS/WFC
F850LP … 2.0 orbits ACS/WFC

F105W … 1.0 orbit WFC3/IR
F110W … 1.0 orbit WFC3/IR
F125W … 1.0 orbit WFC3/IR
F140W … 1.0 orbit WFC3/IR
F160W … 2.0 orbits WFC3/IR



Will yield photometric redshifts with rms error of ~2% x (1 + z) for sources down to ~26 AB mag.

Gravitational lensing analysis reveals dark matter substructure



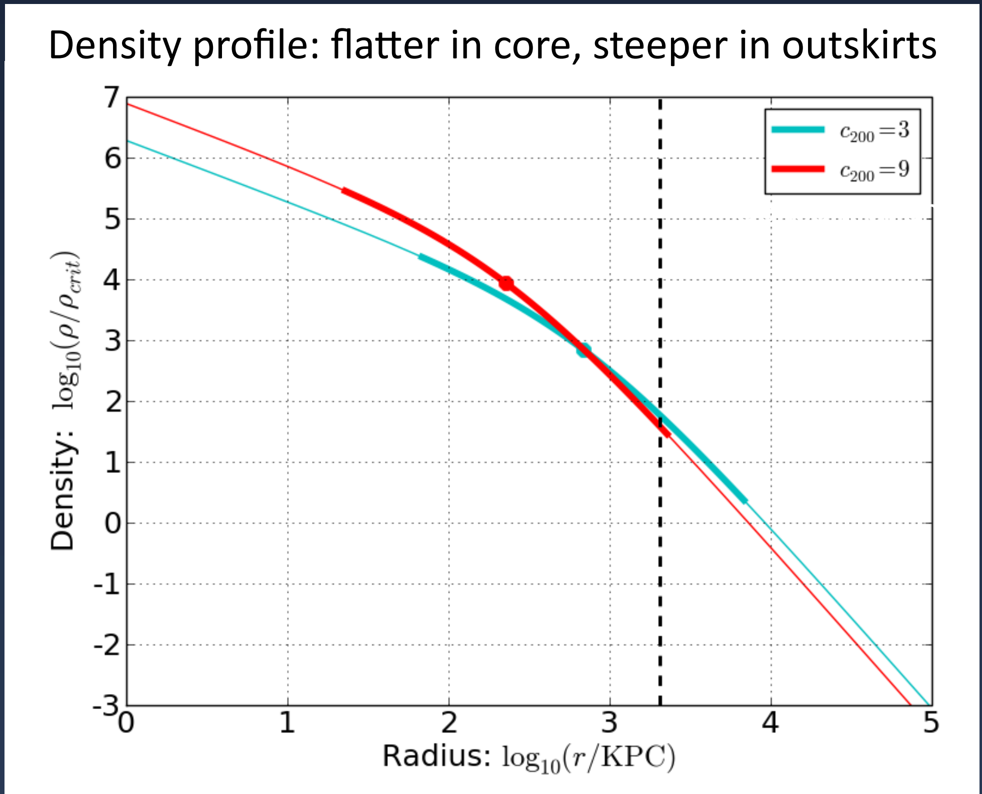
Abell 1689

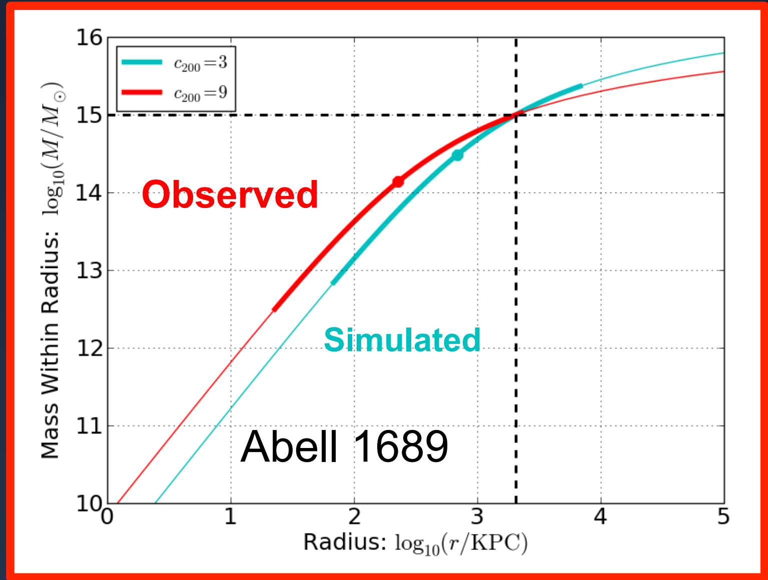
Coe et al. 2010

DM substructure resolution in this map is ~23 kpc. DM substructure resolution for typical CLASH cluster will be ~30 – 40 kpc.

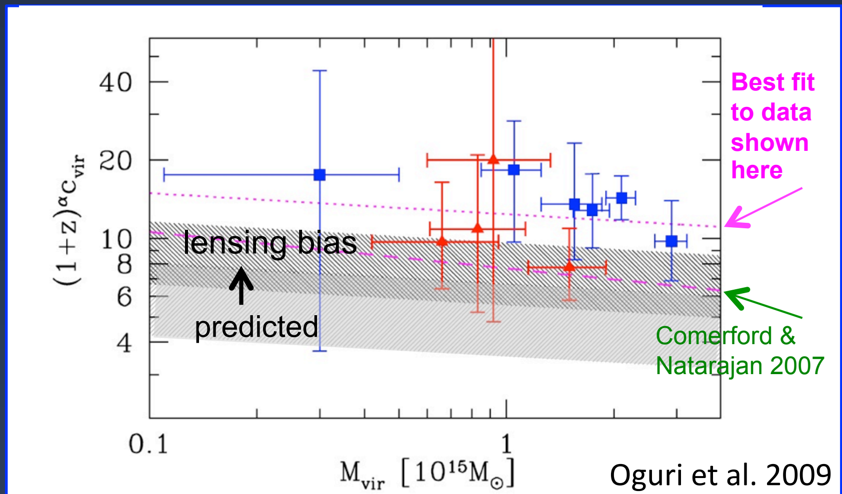
Structure Formation History and DM properties are encoded in DM Halo profiles and shapes

Dark matter halos are predicted to have a *roughly universal* density profile (NFW / Sersic / Einasto)

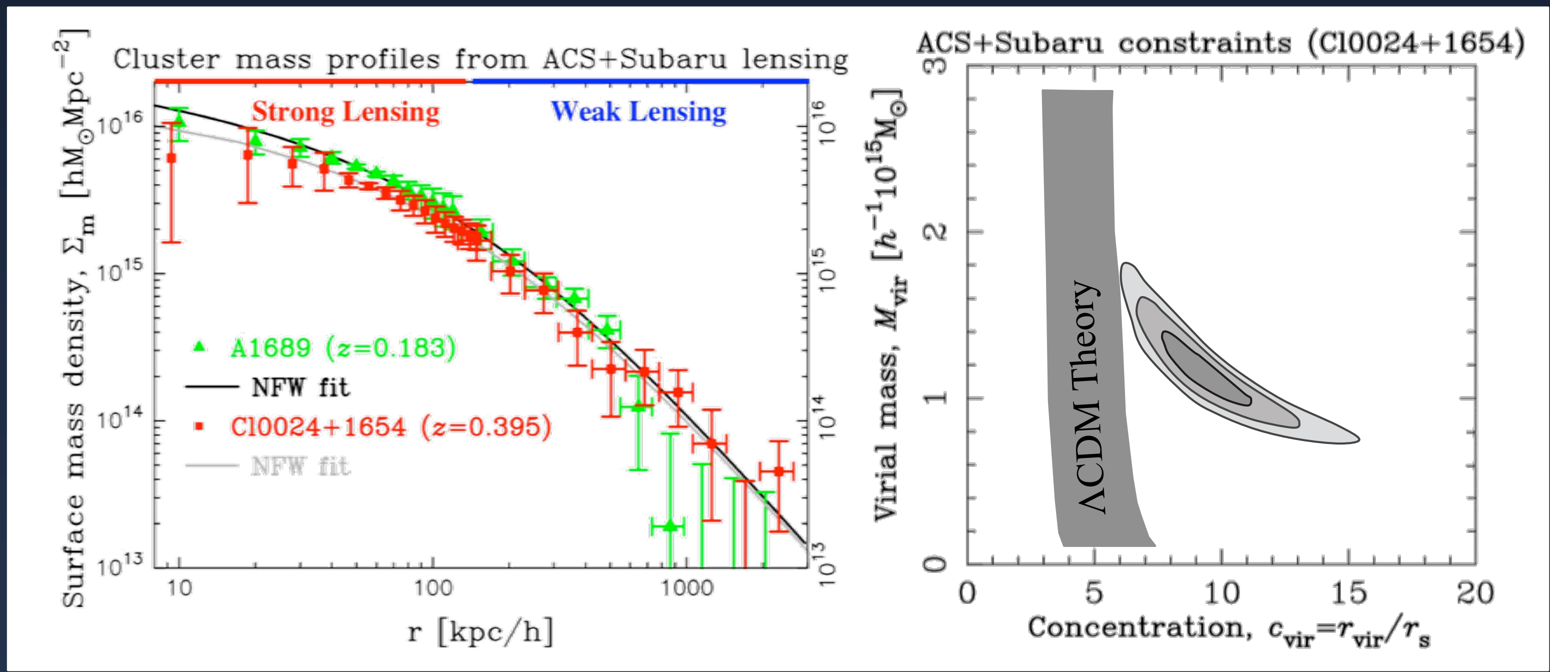




The DM concentration is predicted to decline with increasing cluster mass because in the hierarchical model massive clusters collapse later, when the cosmological background density is lower.



Both Strong & Weak Lensing Measurements Needed for Good Constraints

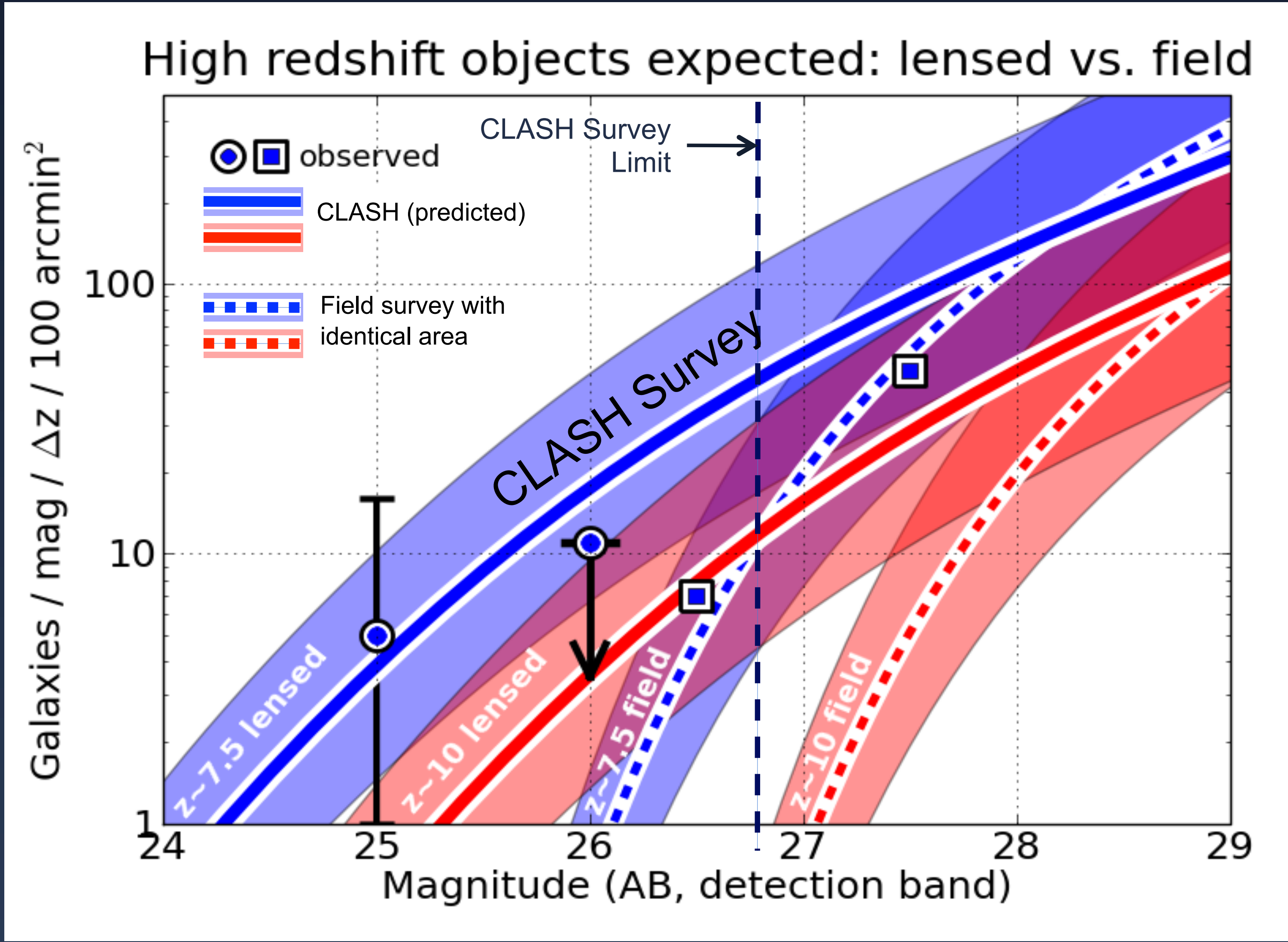


Umetsu et al. 2010

LCDM prediction from Duffy et al. 2008

CLASH will:
- Use 3 independent lensing constraints: SL, WL, mag bias
- Have a well-selected cluster sample with minimal lensing bias
- Definitively derive the representative equilibrium mass profile shape
- Robustly measure cluster DM concentrations and their dispersion as a function of cluster mass (and possibly their redshift evolution).
- Provide excellent calibration of mass-observable relations for clusters

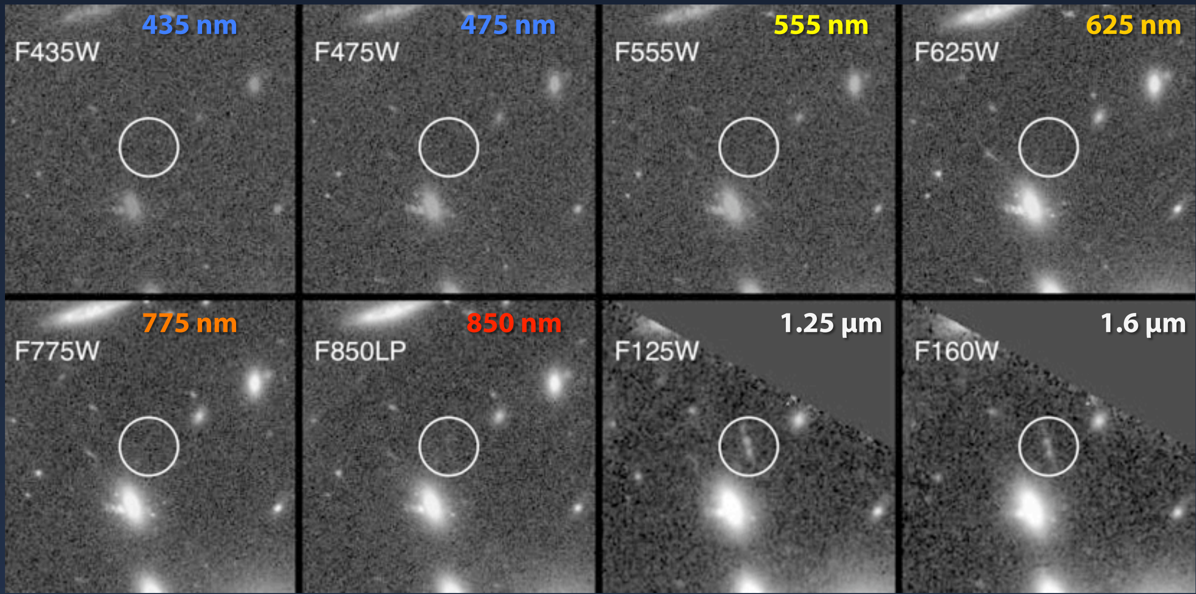
We expect to find tens of bright (m < 26.5 AB) z > 7 galaxies



Lensing greatly enhances the ability to detect distant galaxies and provides an additional constraint on their redshifts, as the projected position of the lensed object is a function of the source redshift.

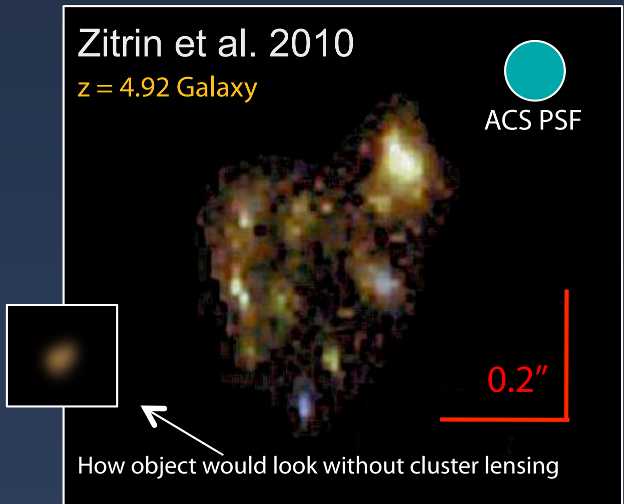
WFC3/IR *z*-band dropouts

Bradley et al. 2010 (in prep): Abell 1703



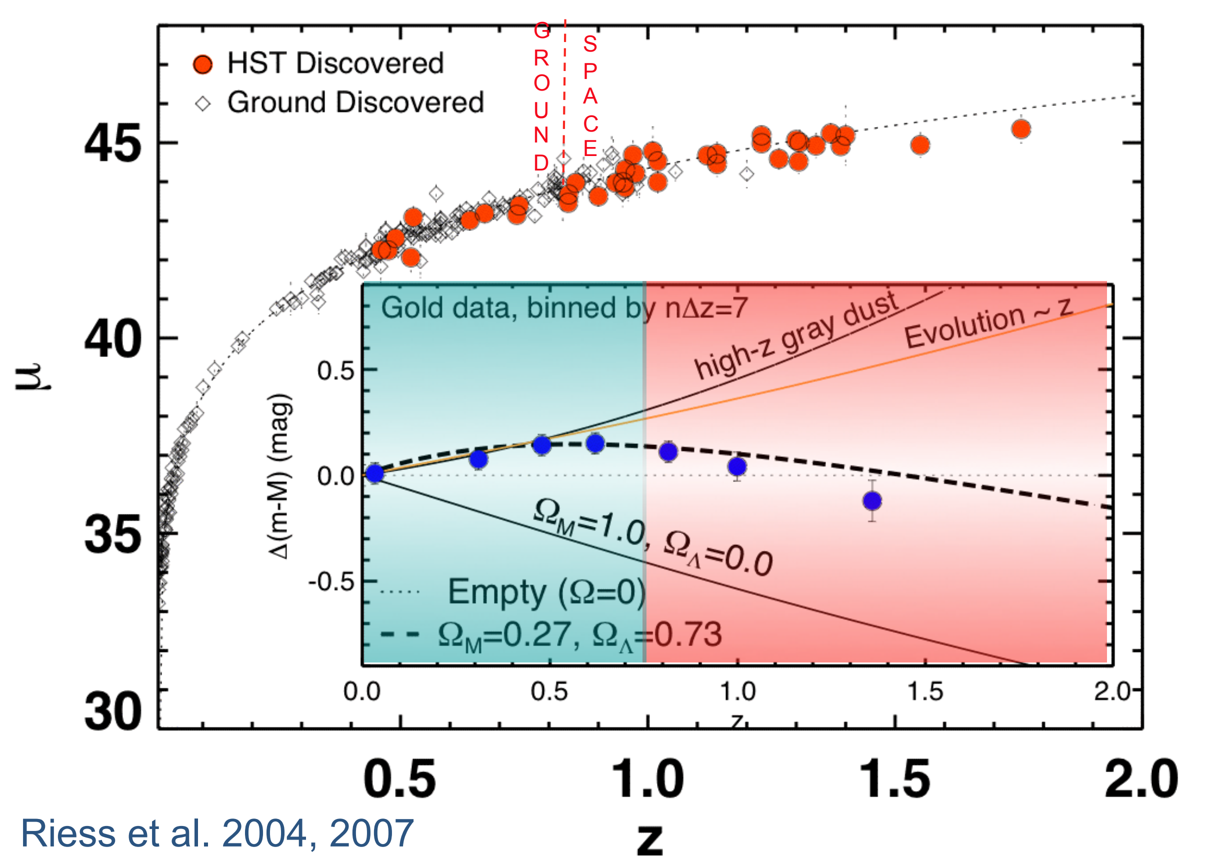
- 1 orbit each in WFC3/IR F125W (J) and F160W (H)
- $\mu \sim 3 - 5$
- Brightest candidate: $z \sim 6.9$, $H160 \sim 24.3$ AB (brightest $z \sim 7$ candidate known)
- Can reliably constrain SED

Highly Magnified z ~ 5 galaxies



- Reconstruction of a $z = 4.92$ source lensed by the $z = 0.33$ cluster MS1358+62.
- Best resolved high-z object: spatial resolution of ~50 pc (rest-frame UV)
- *Equivalent to 20-m space telescope resolution of a non-lensed z=5 galaxy!*

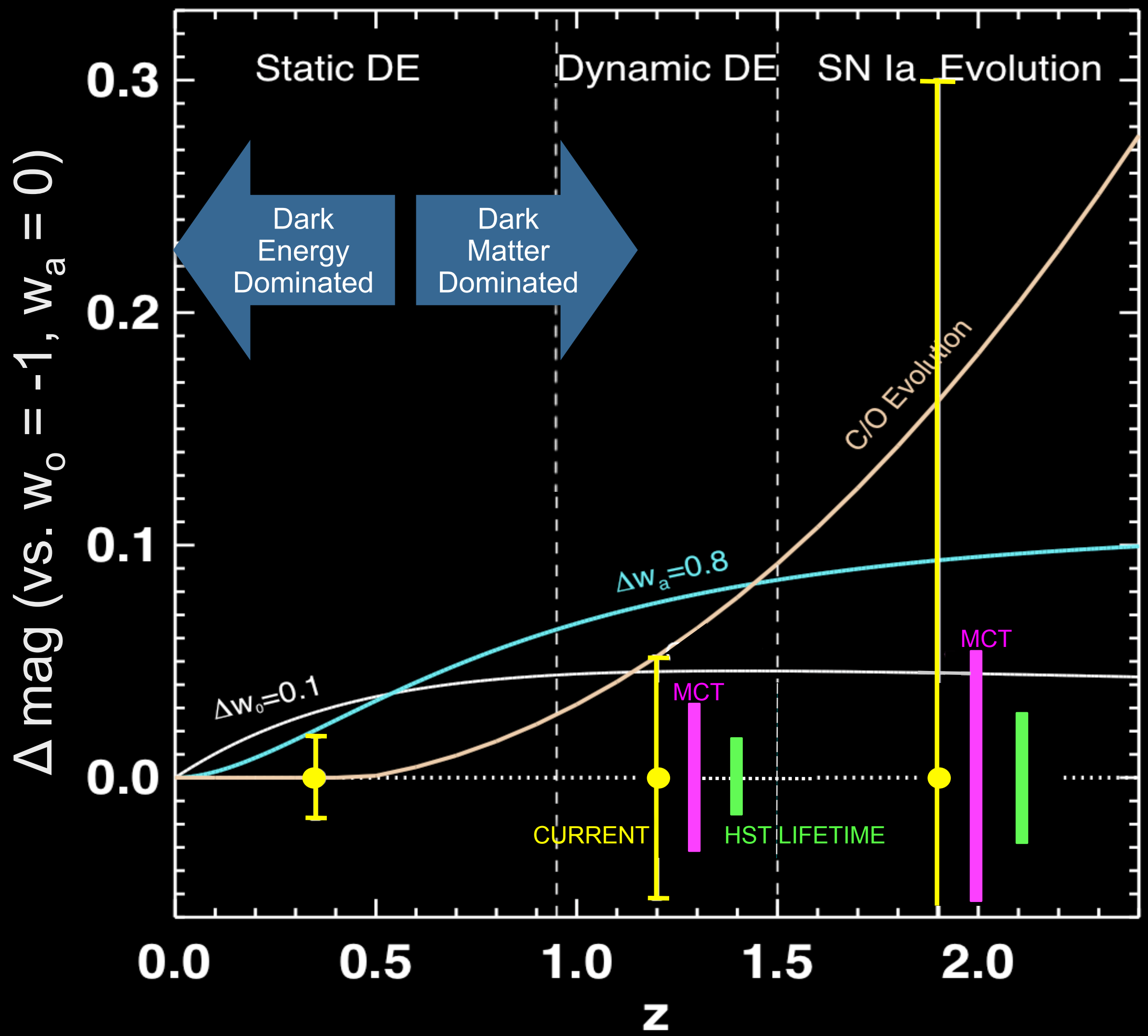
HST: 23 SNe Ia at z>1 Find Past Deceleration, Confirms Dark Energy+Dark Matter Model



z>1 is a particularly important regime for testing "astrophysical contamination" of SN cosmology signal, such as dust or evolution. Also key for constraining dw/dz.

HST & WFC3-IR, Gateway to SNe Ia at z>2

Assuming a mixed SN delay time distn (~50% prompt, ~50% 2-3 Gyr): expect CLASH to find 10 – 20 SNe at z>1; and ~6 with z > 1.5, doubling the known number of z > 1 SN



Two MCT HST programs (CLASH + CANDELS) will detect SNe Ia at 1.0 < z < 2.5. They will provide a direct test of the SN systematics in a matter-dominated universe (e.g., Riess & Livio 2006).

Concluding Comments

- CLASH observations with HST to begin in November. 25 clusters will be observed over the course of cycles 18-20 (~3 years): 10, 10, 5.
- Represents a major observational initiative to constrain the properties of DM, high-z galaxies, and advance our understanding of DE.
- Immediate public access to all HST data.
- High-level science products will be released on a regular schedule, including compilations of x-ray, IR, sub-mm, and spectroscopic data.
- http://www.stsci.edu/~postman/CLASH

Current Schedule