Through a Lens, Darkly:
An Innovative Hubble Survey to Study the Dark Universe

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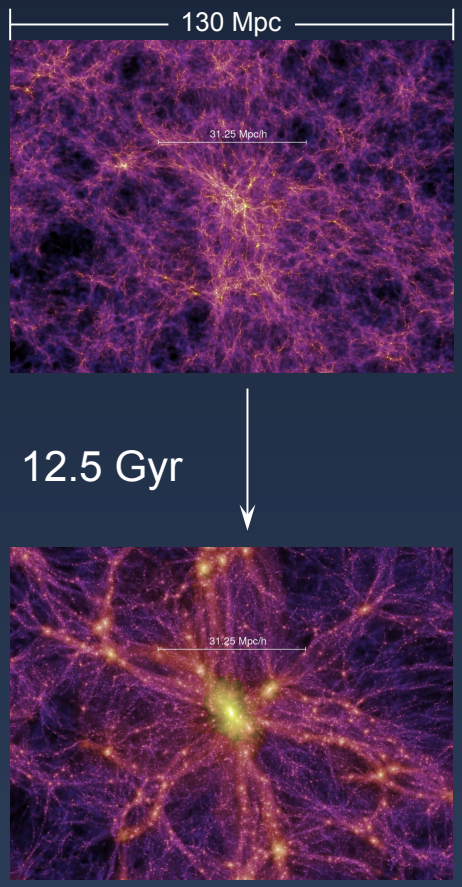
MACS 2129-0741 z = 0.57 HST/ACS image (Ebeling et al.)

Fundamental Questions That Remain Unanswered or Unverified

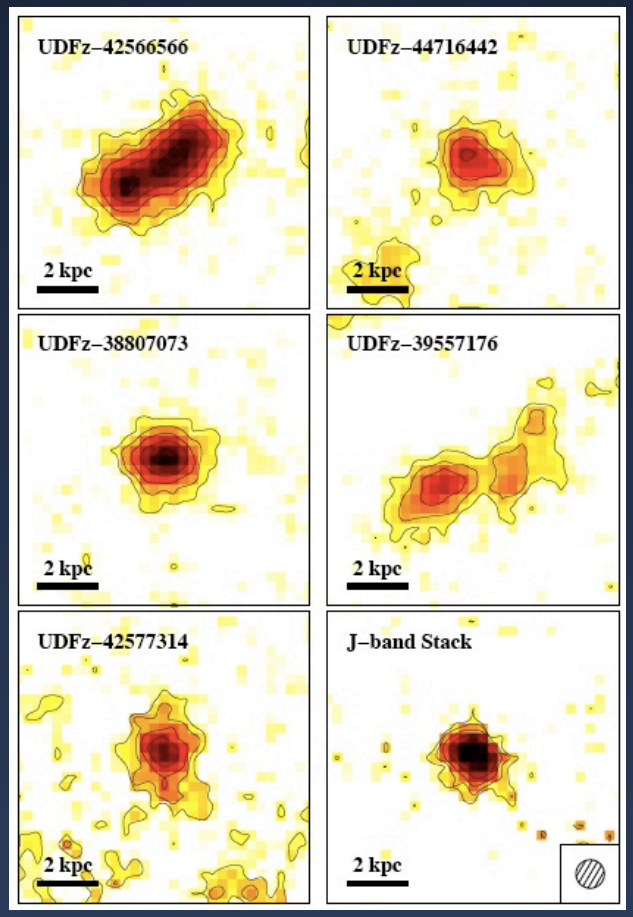
- How is dark matter distributed in cluster & galaxy halos?
  - How centrally concentrated is the DM? Implications for epoch of formation.
  - What degree of substructure exists? And on what scales?
  - How does the DM distribution evolve with time?
  - What correlations exist between the distribution of baryonic matter and DM?



"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?
  - What role do massive black holes play in their formation?



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)

CLASH:

Cluster Lensing And Supernova survey with Hubble

An Hubble Space Telescope 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.

The galaxy clusters are chosen based on their smooth and symmetric x-ray surface brightness profiles: “simpler” lenses to model and minimizes lensing bias. All clusters have masses ranging from ~5 to ~30 x 10^{14} M_{SUN}. Redshift range covered: $0.18 < z < 0.90$ (11.3 Gyr > t_U > 6.3 Gyr).

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

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Post-doctoral fellow
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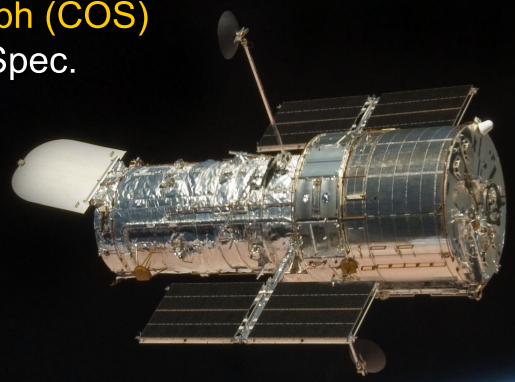
Hubble Space Telescope Servicing Mission 4
May 11 - 24, 2009

New Scientific Instruments:
- Wide-field Camera 3 (WFC3)
  - UVIS Channel
  - NIR Channel
- Cosmic Origins Spectrograph (COS)
  - High-throughput UV Spec.

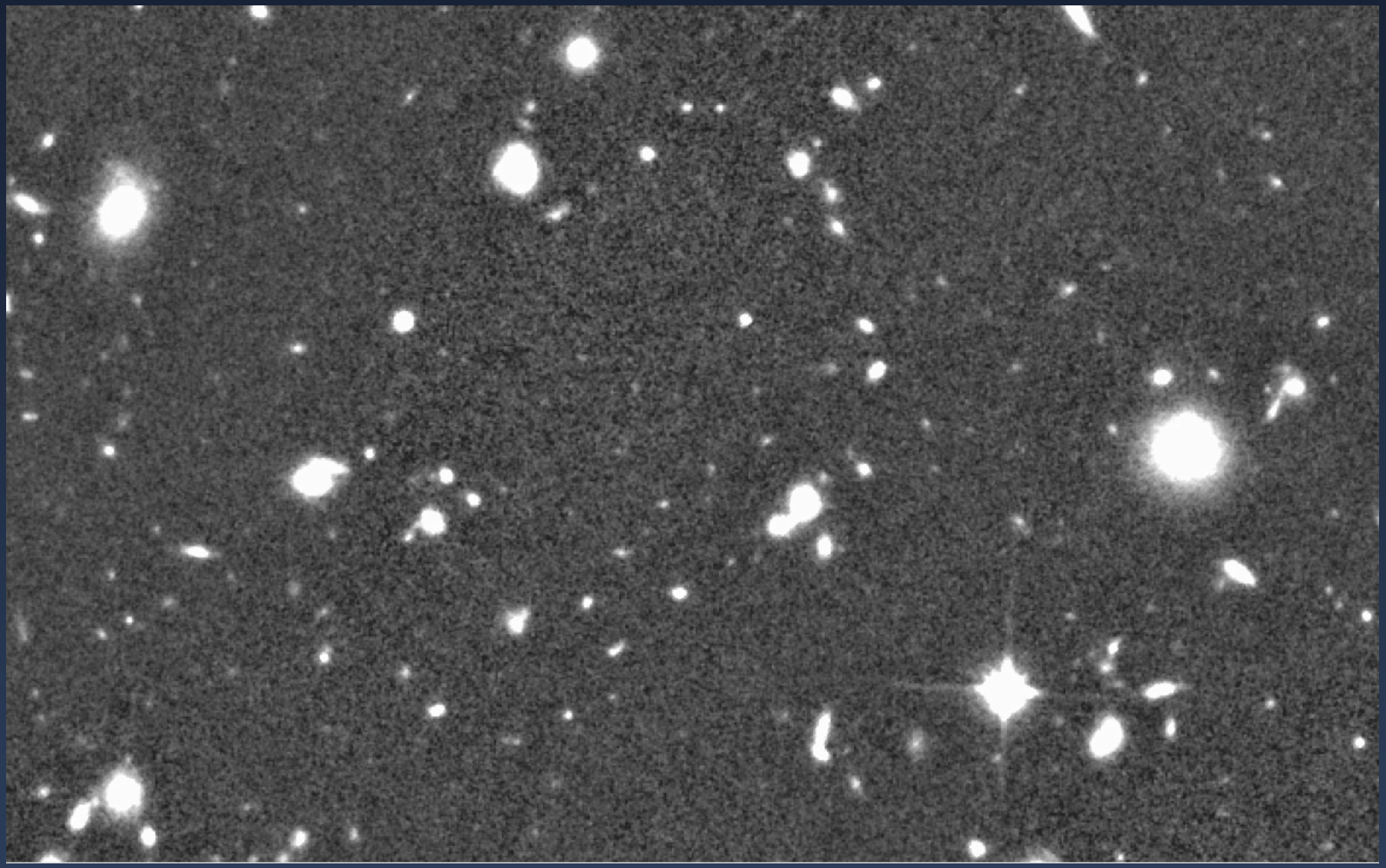
Repaired Scientific Instruments:
- Advanced Camera for Surveys (ACS)
  - Wide-field Channel
- Space Telescope Imaging Spectrograph (STIS)



Additional Scientific Instruments:
- Near-IR Camera and Multi-Object Spectrograph (NICMOS)
- ACS/Solar blind Channel (Far-UV imager)
- Fine Guidance Sensor (High-precision astrometry)

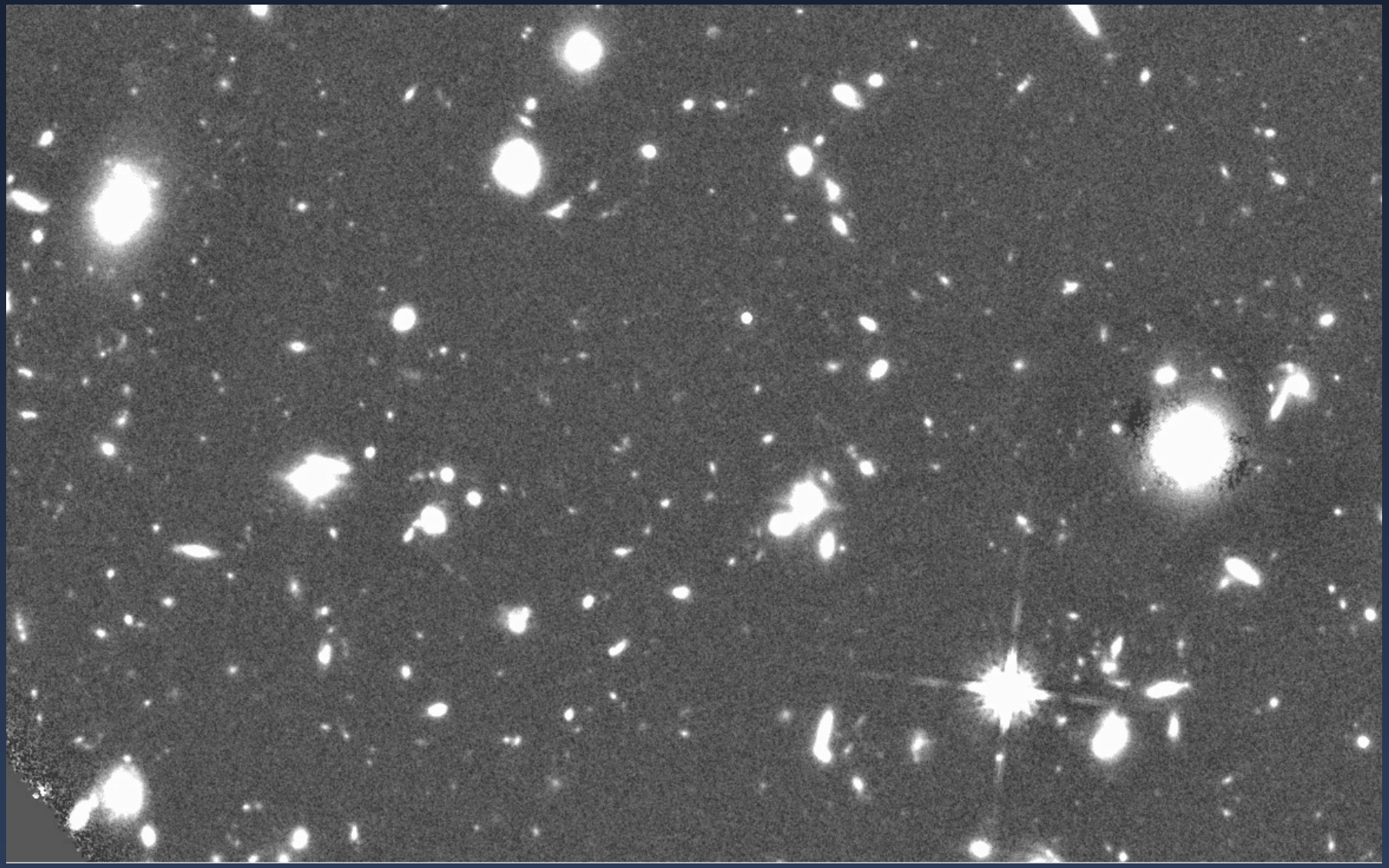
Photo credit: STS-125 Crew, May 19, after HST deployment

Old HST NIR Camera – 72 orbits



Slide credit: Garth Illingworth, UCSC, Lick Observatory

New HST NIR Camera – 16 orbits



Slide credit: Garth Illingworth, UCSC, Lick Observatory

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)

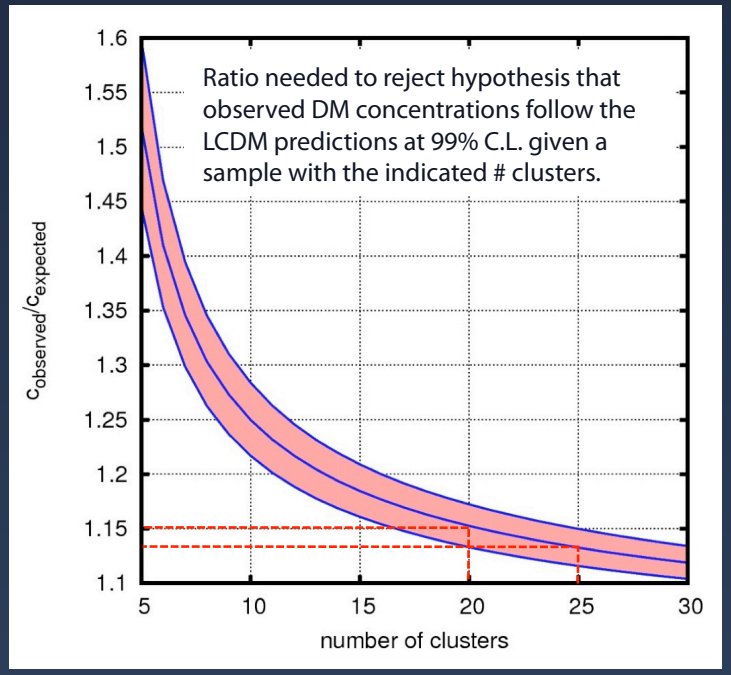
σ_{int} = 0.30 (e.g., Neto et al. 2007)

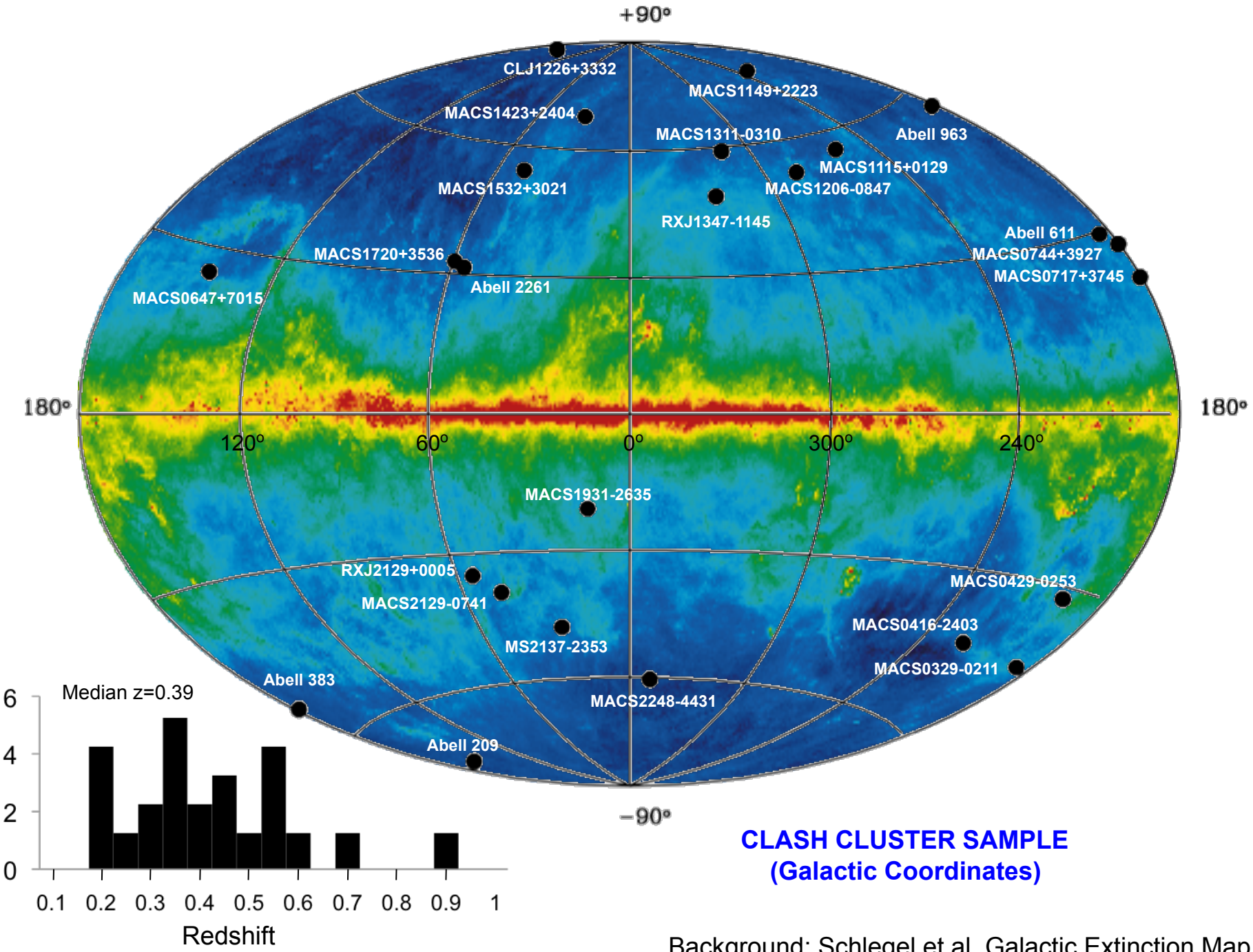
$\sigma_{Meas} = 0.22 (N_{arc,\ CL0024} / N_{arc})^{1/2}$ (Umetsu et al. 2010)

$$N_{CL} = 24$$

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).





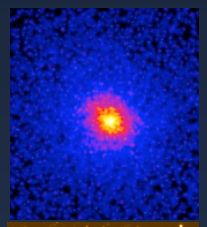
CLASH CLUSTER SAMPLE
(Galactic Coordinates)

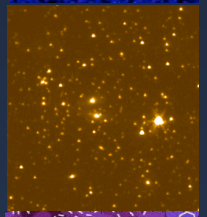
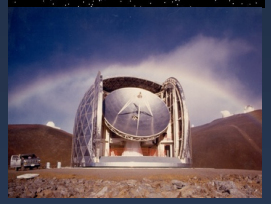
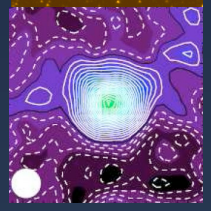
Background: Schlegel et al. Galactic Extinction Map

Multiple Facilities Will Be Used

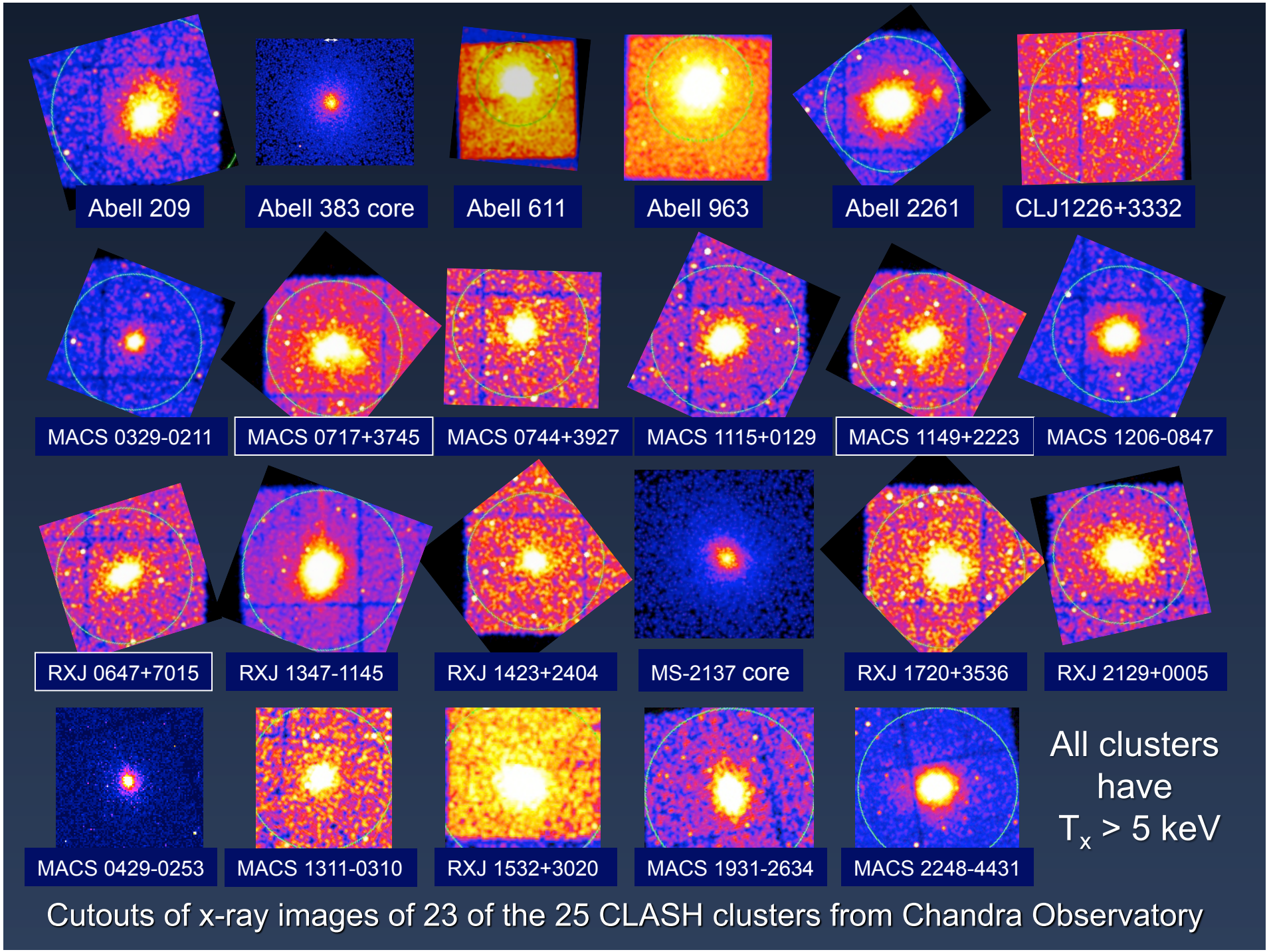
- HST 524 orbits: 25 clusters, each imaged in 16 passbands. (0.23 – 1.6 μm)


- Chandra x-ray Observatory archival data and possibly new data. (0.5 – 2 keV)
- Spitzer IR Space Telescope archival data and possibly new data (3.6, 4.5 μm)
- SZE observations proposed to augment existing data (sub-mm)

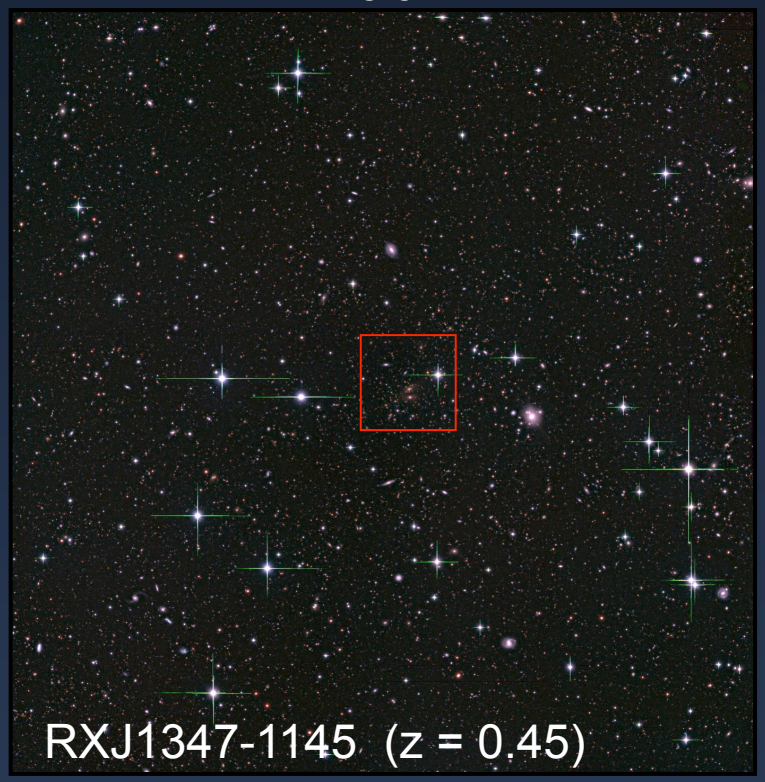
- Subaru wide-field imaging (0.4 – 0.9 μm)
- GTC, VLT, and Magellan Spectroscopy

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

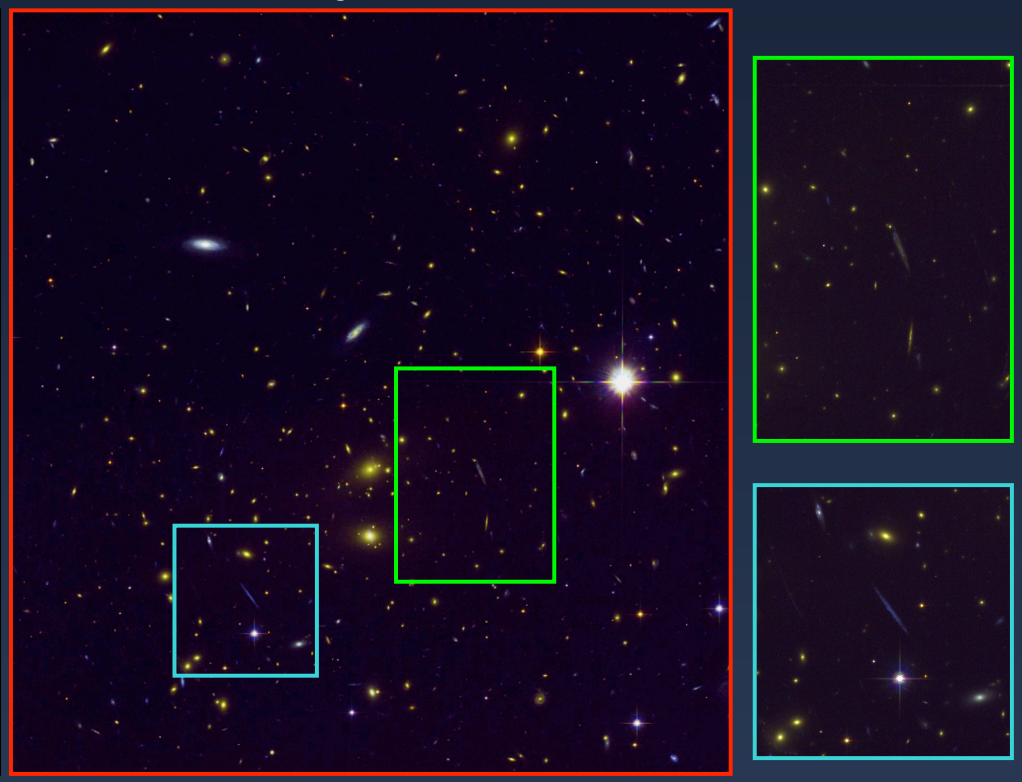
CLASH: An HST Multi-Cycle Treasury Program

28.5'



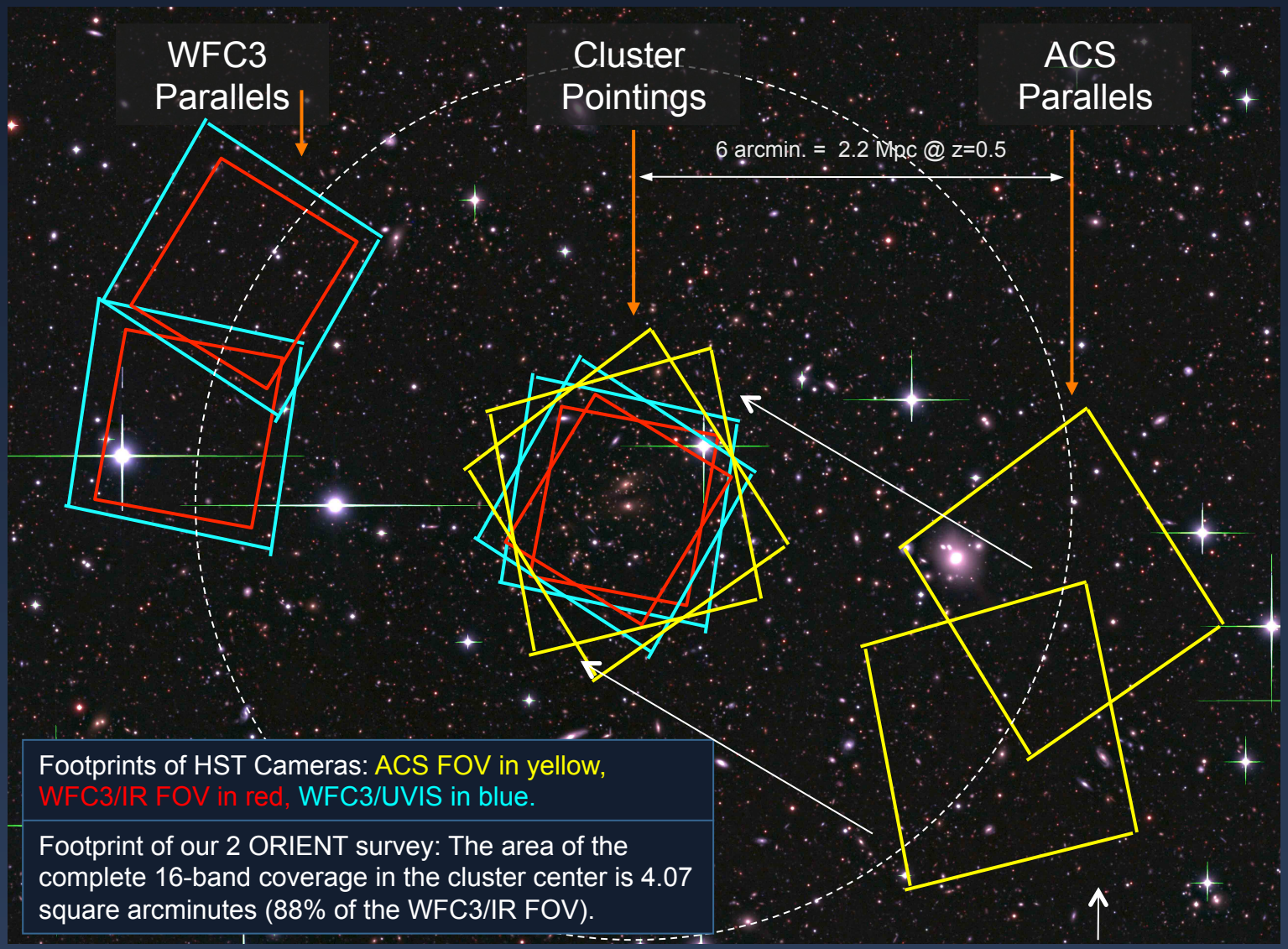
SUPRIME CAM Image
(Subaru 8m Telescope)
K. Umetsu

3.4'



ACS/WFC Image
T. Erben

CLASH: An HST Multi-Cycle Treasury Program



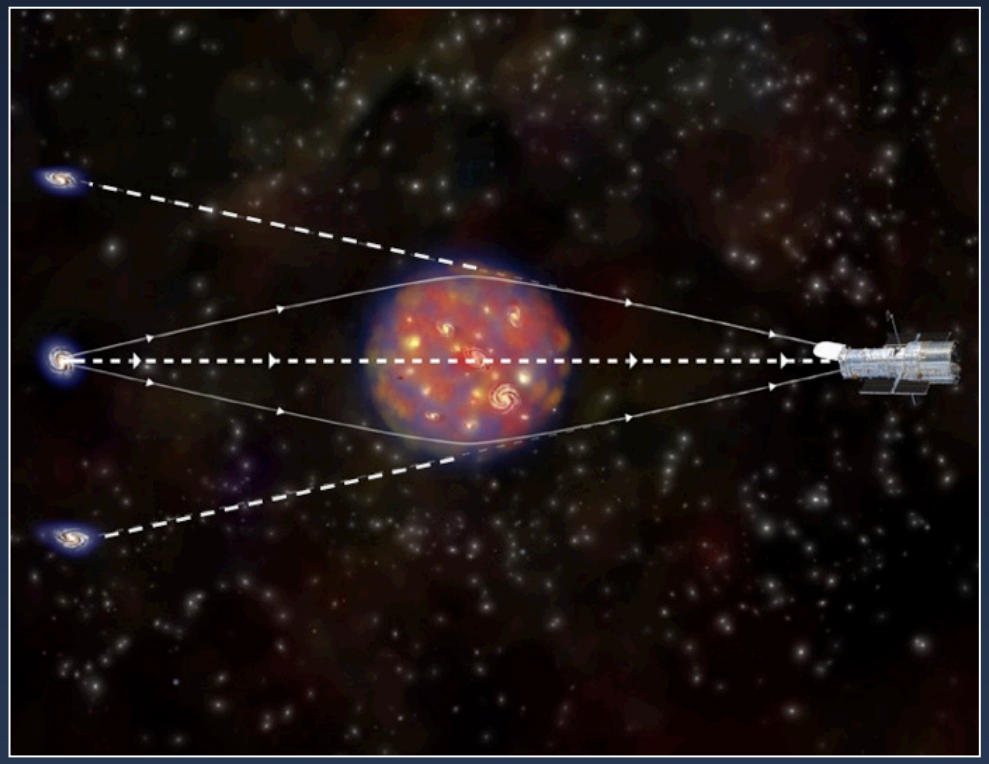
SN search cadence: 10d-14d, 4 epochs per orient

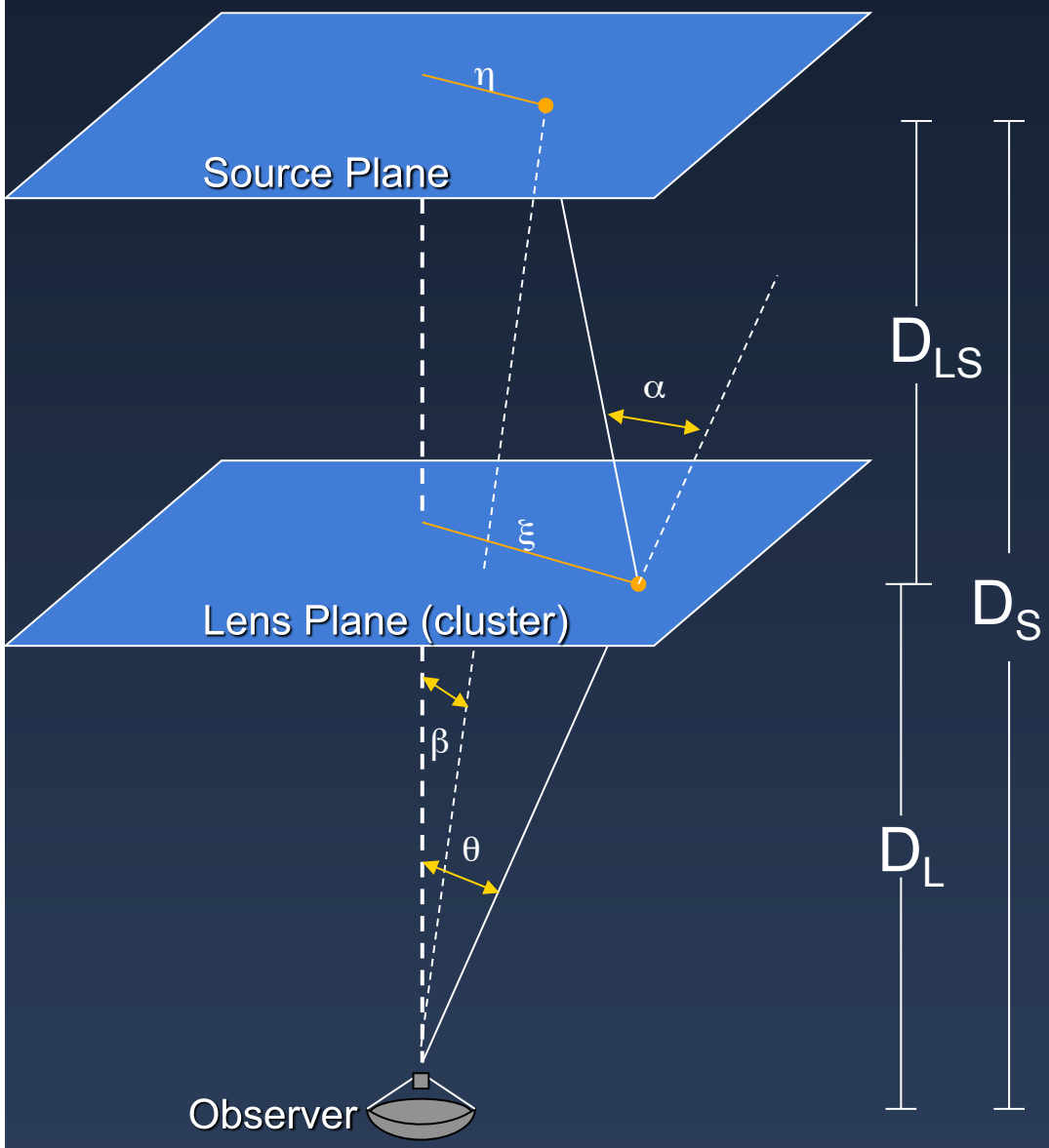
Lensing amplification small at these radii

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 ($\mu \sim 10$)
- Amplifies both galaxy flux and size while conserving surface brightness
- Shows multiply-imaged background galaxies
- *Tradeoff:* Dilution of the source-plane area ($\sim 1/\mu$)





Alignment Mass Distance

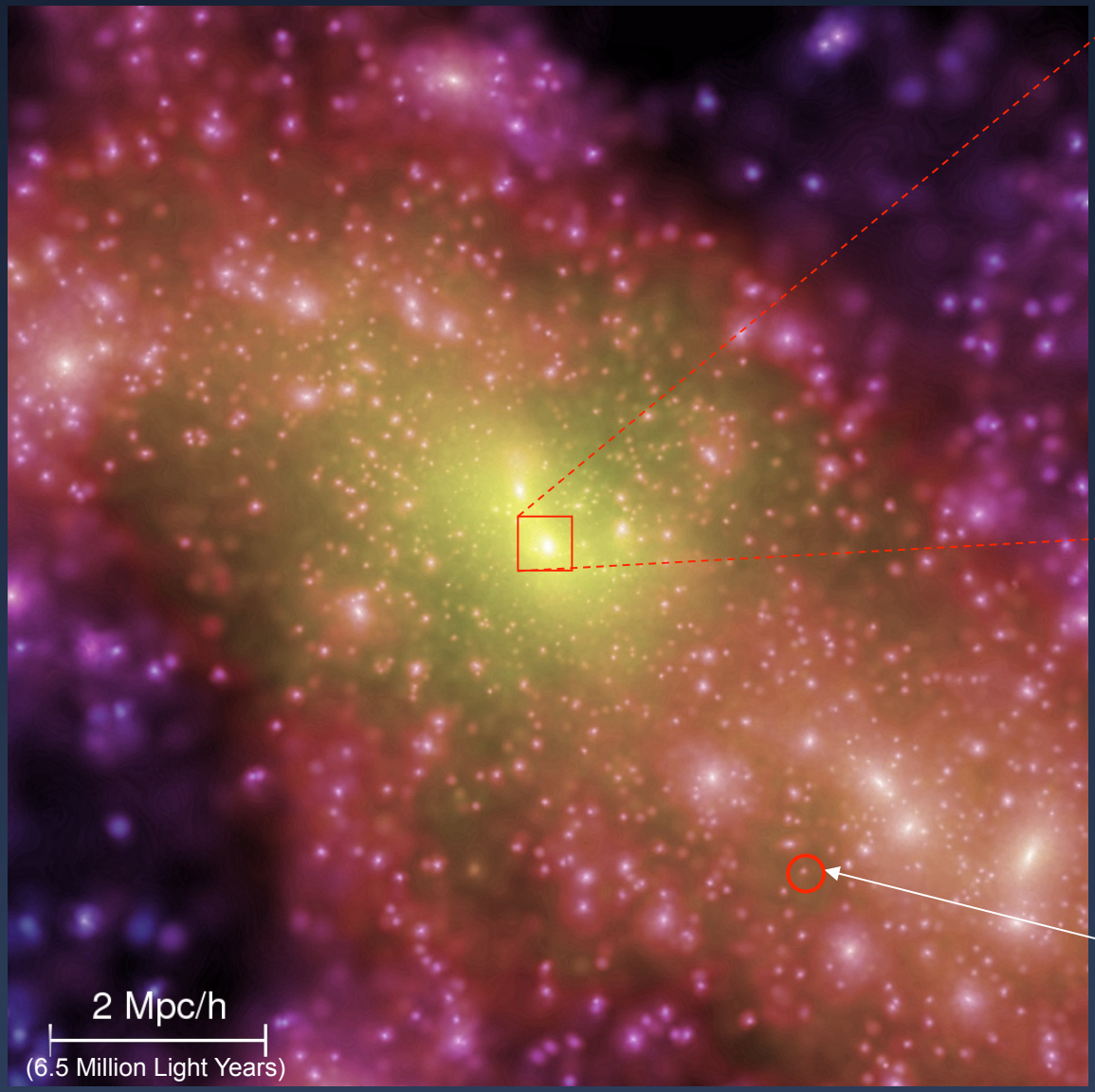
$$\beta = \theta - \alpha(D_{LS}/D_S)$$

$$\text{div}\ \alpha = \nabla\cdot\alpha = 2\kappa$$

$$\kappa = \Sigma(\theta) / \Sigma_{CRIT}$$

Where $\Sigma(\theta)$ is the mass surface density projected along the line of sight and $\Sigma_{CRIT} = (c^2/4\pi G)\, D_S/(D_L D_{LS})$

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

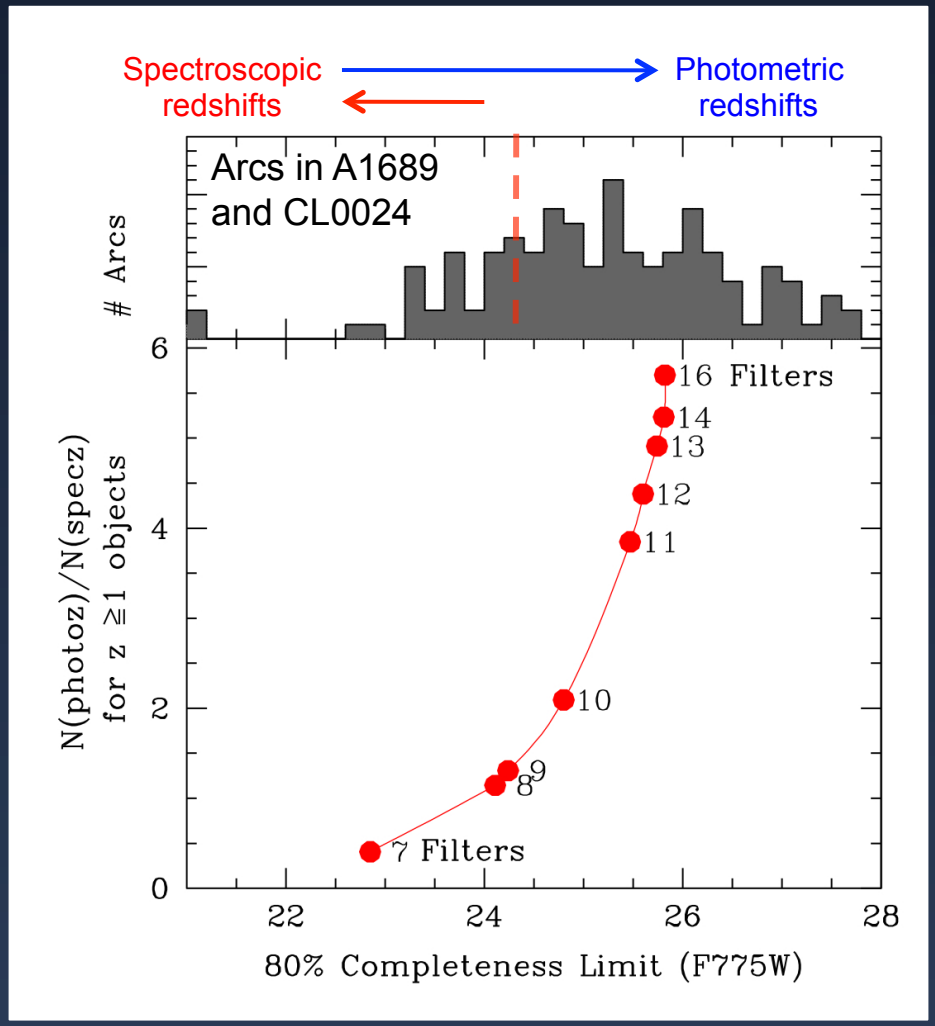
$$R \propto \frac{\theta_{Einstein}}{\sqrt{N_{Arcs}}}$$

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

CLASH: An HST Multi-Cycle Treasury Program

Why 16 filters?

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

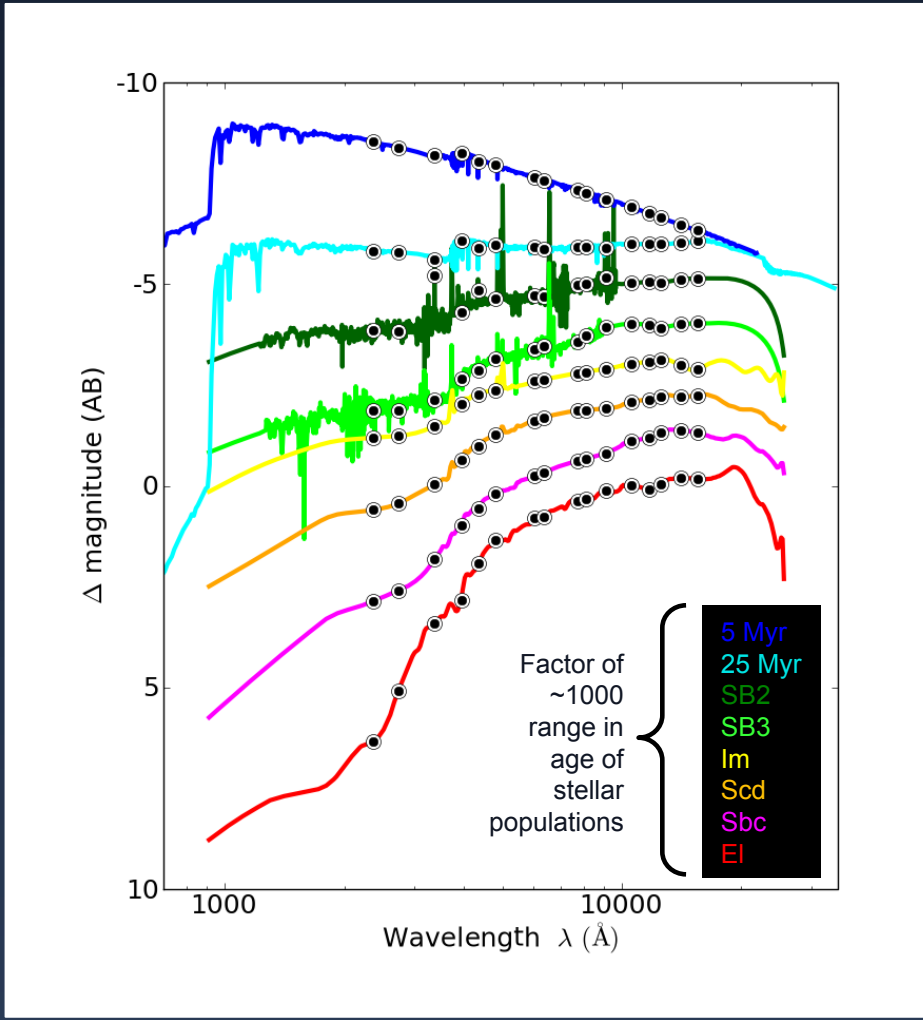


With 16 filters, 80% photo-z completeness is reached at AB ~26 mag and useful high redshift information is available for ~6 times as many objects than would be possible solely from spectroscopically acquired redshifts.

CLASH: 524 orbits, ~20 orbits per cluster, 3 cycles

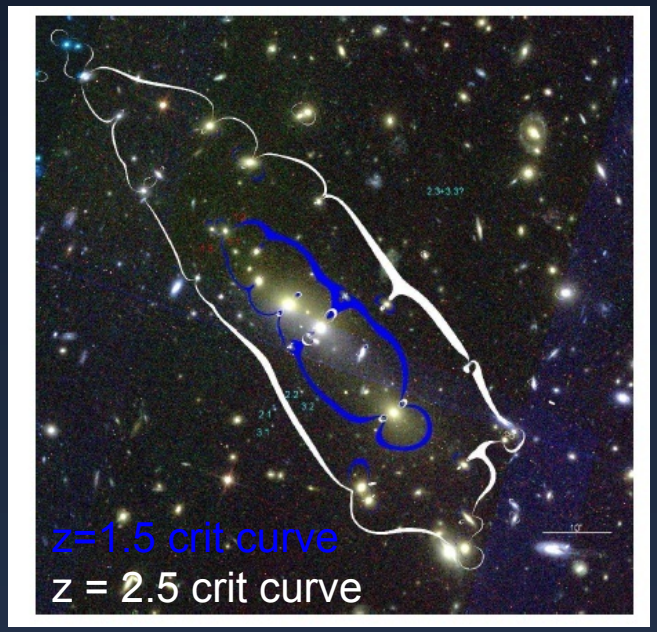
Which 16 filters?

F225W … 235.9 nm WFC3
F275W … 270.4 nm WFC3
F336W … 335.5 nm WFC3
F390W … 392.1 nm WFC3
F435W … 430.6 nm ACS
F475W … 474.2 nm ACS
F606W … 592.0 nm ACS
F625W … 629.8 nm ACS
F775W … 769.4 nm ACS
F814W … 806.9 nm ACS
F850LP … 906.0 nm ACS
F105W … 1.055 μm WFC3
F110W … 1.152 μm WFC3
F125W … 1.248 μm WFC3
F140W … 1.392 μm WFC3
F160W … 1.536 μm WFC3

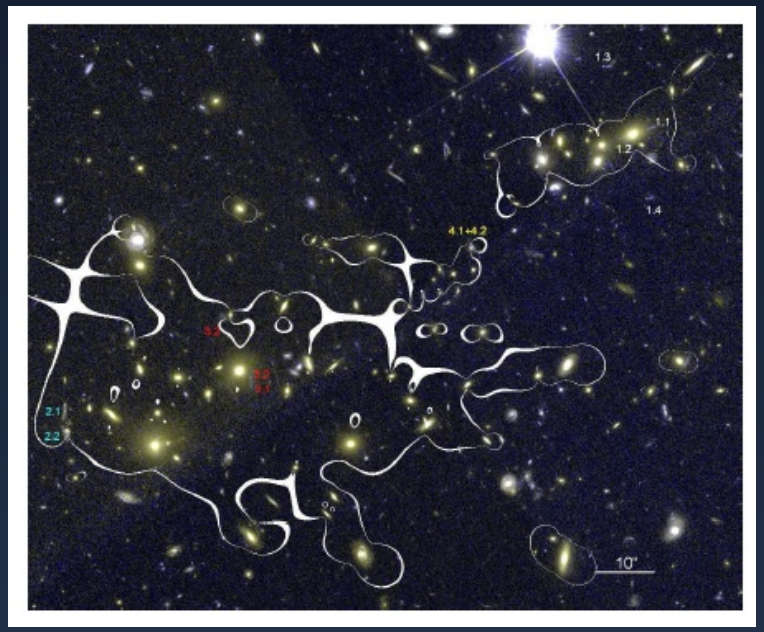


Nearly complete redshift information for all objects as faint as 26 AB mag (~1.45 x 10^{-33} watts/m^2/Hz) will allow reliable identification of multiply imaged sources, breaking of "mass-sheet" degeneracy and, hence, yield robust, accurate mass profiles of these clusters. Such extensive redshift info for such faint objects is enabled by HST's new instruments.

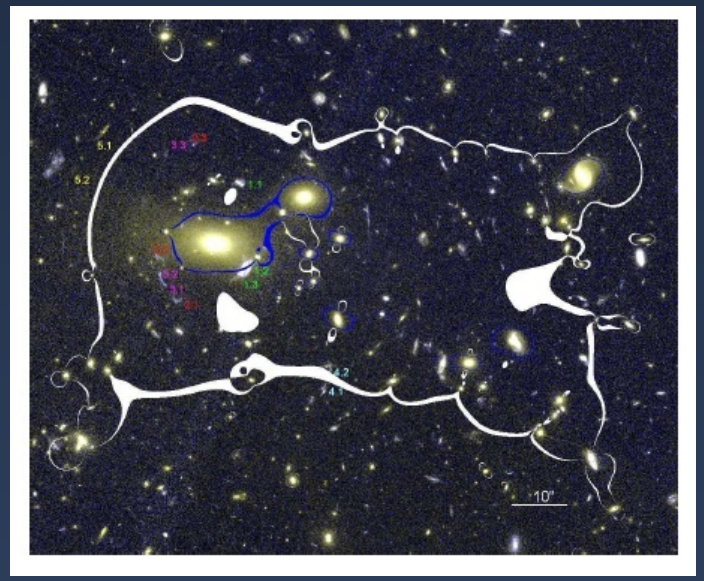
MACS J0018+1626, z = 0.55



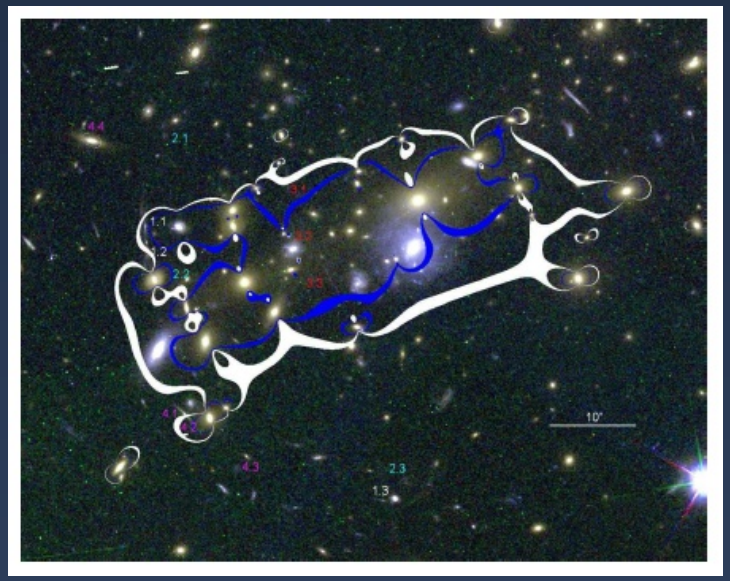
MACS J0025-1222, z = 0.58



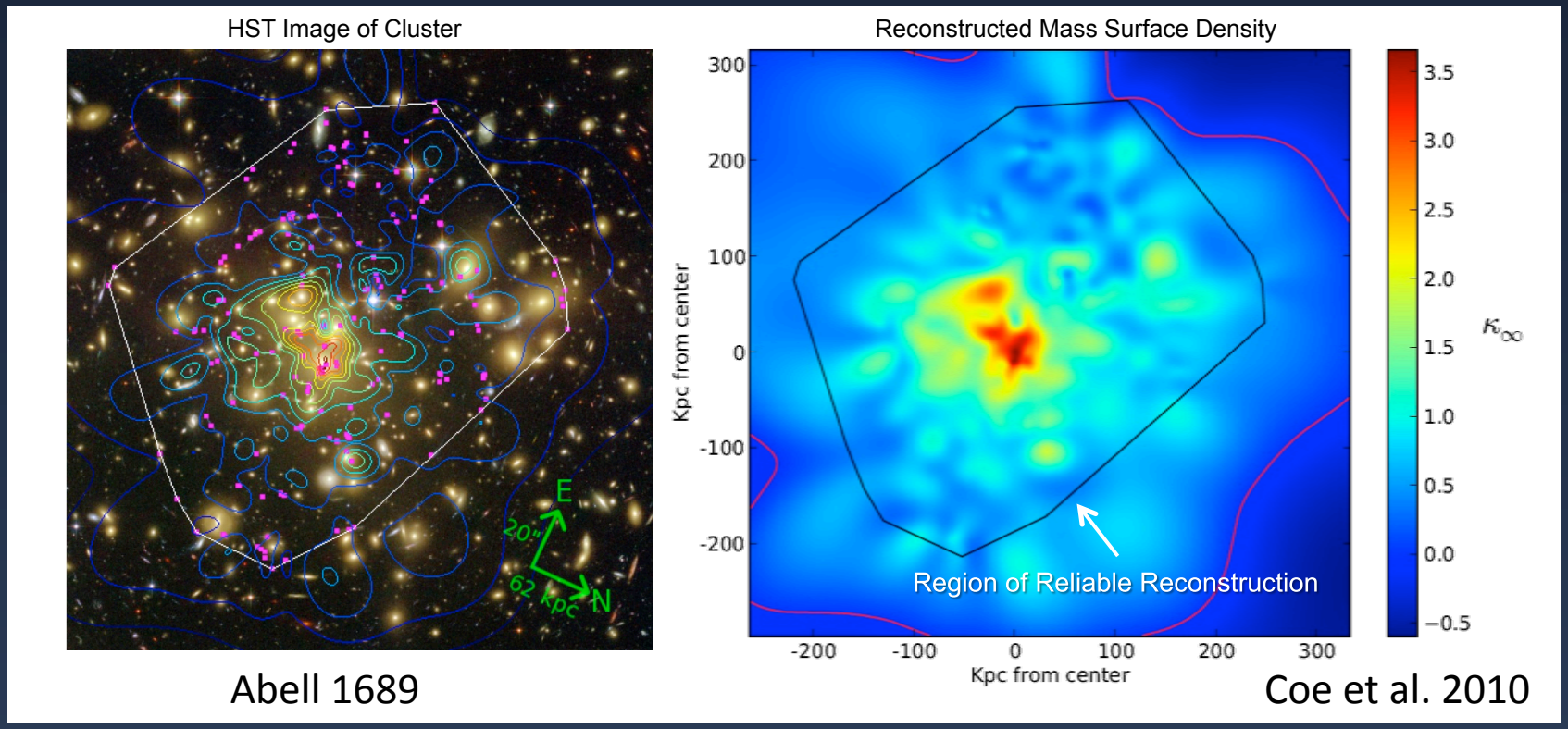
MACS J0257-2325, z = 0.51



MACS J0454-0300, z = 0.54



Gravitational lensing analysis reveals dark matter structure



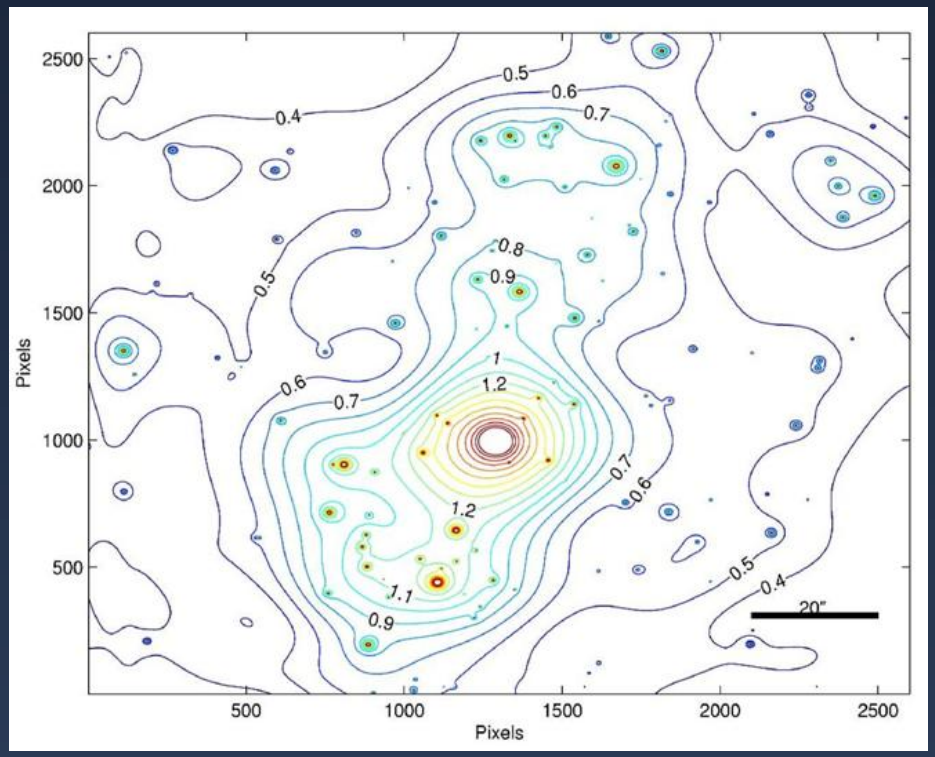
Abell 1689

Coe et al. 2010

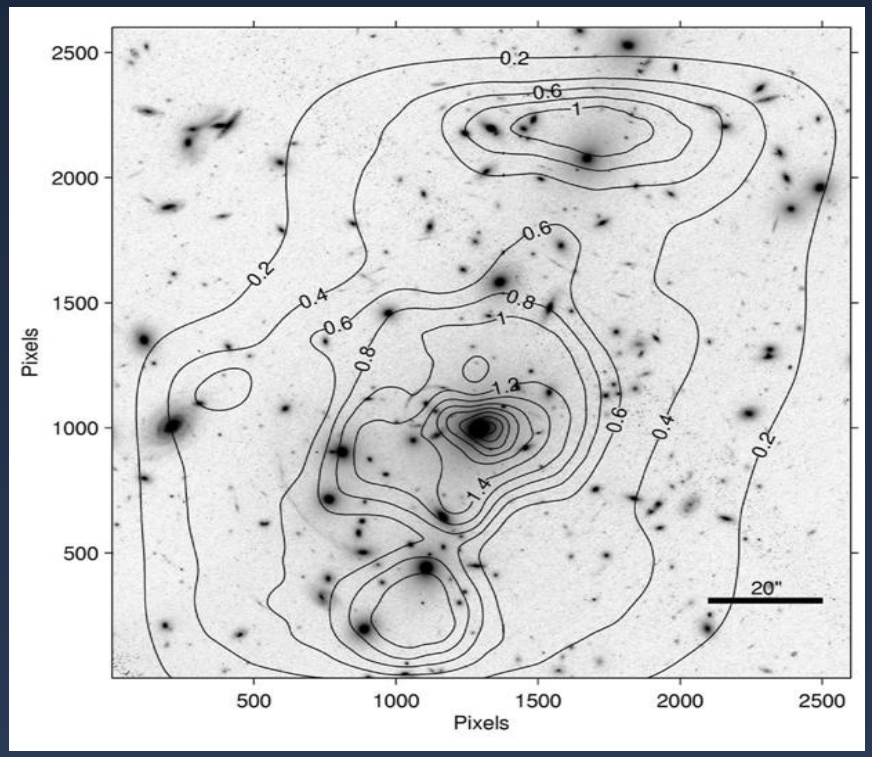
DM substructure resolution in this map is ~23 kpc. DM substructure resolution for typical CLASH cluster will be ~30 – 40 kpc.

Independent techniques yield similar mass distributions.

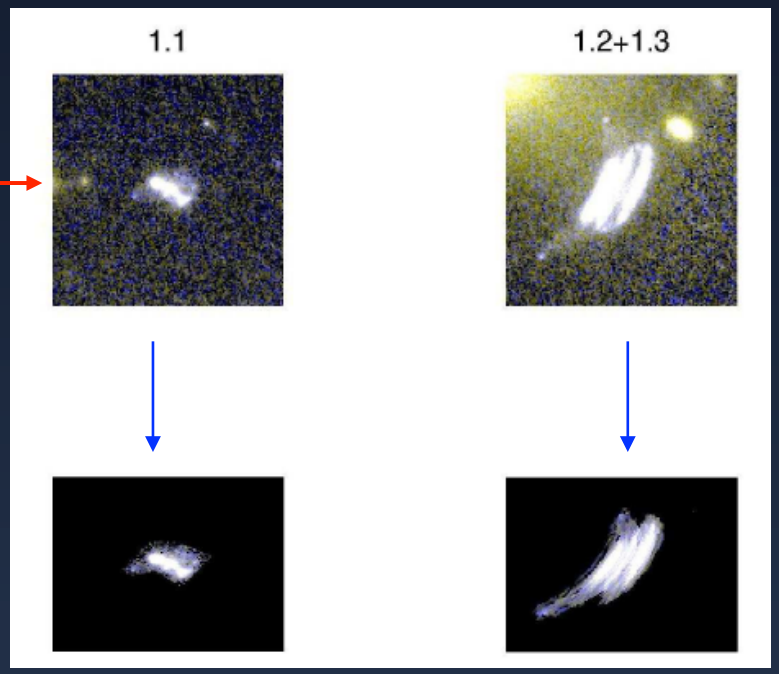
Abell 1703: Zitrin et al. 2010



Parametric model: MTL (approx), galaxies used as starting point, plus DM. Successfully predicts location of arcs.



Non-Parametric model: primary input is just the positions and redshifts of multiply imaged arcs.

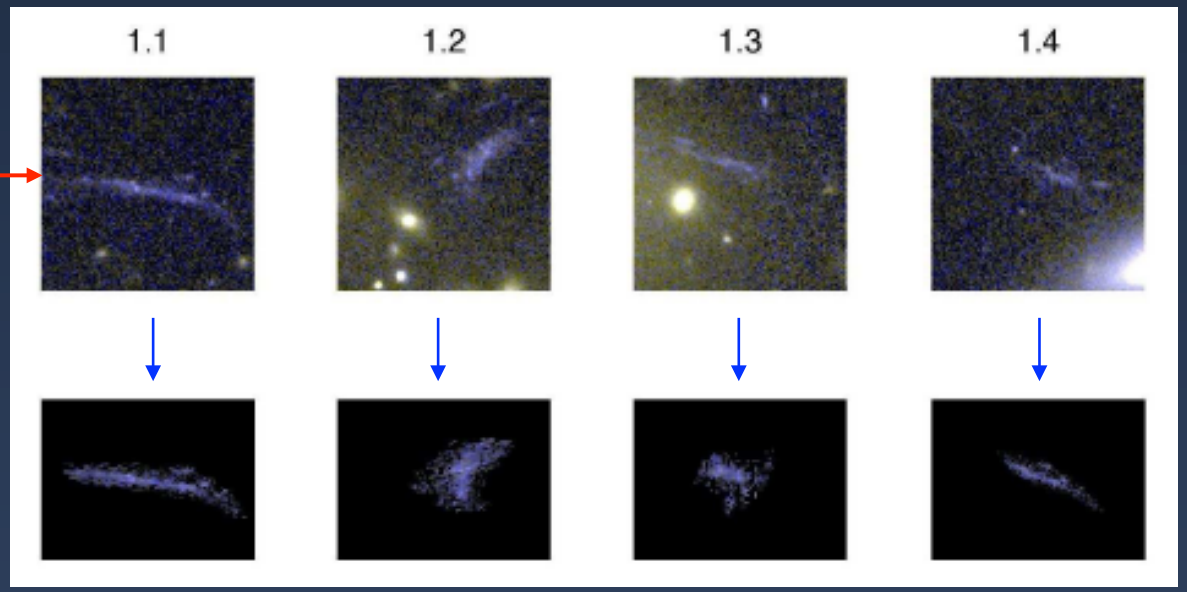


Demonstration that derived mass model for cluster accurately reproduces locations and distortions of background galaxies

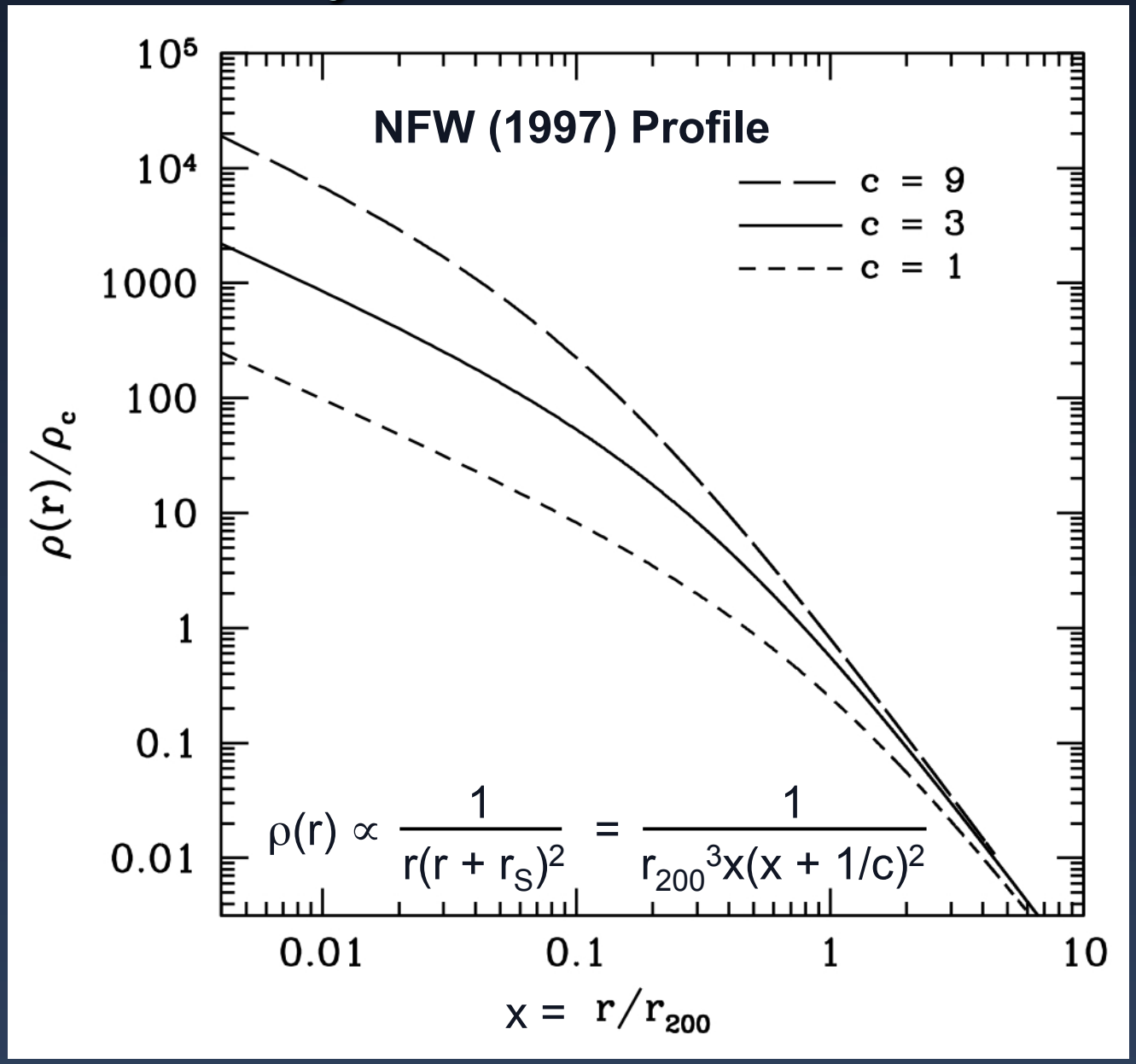
Zitrin et al. 2010

Objects in top row are actual observations.

Objects in bottom row have been de-lensed (source plane reconstruction) and then re-imaged through mass model



Density Profile of Dark Matter Halos

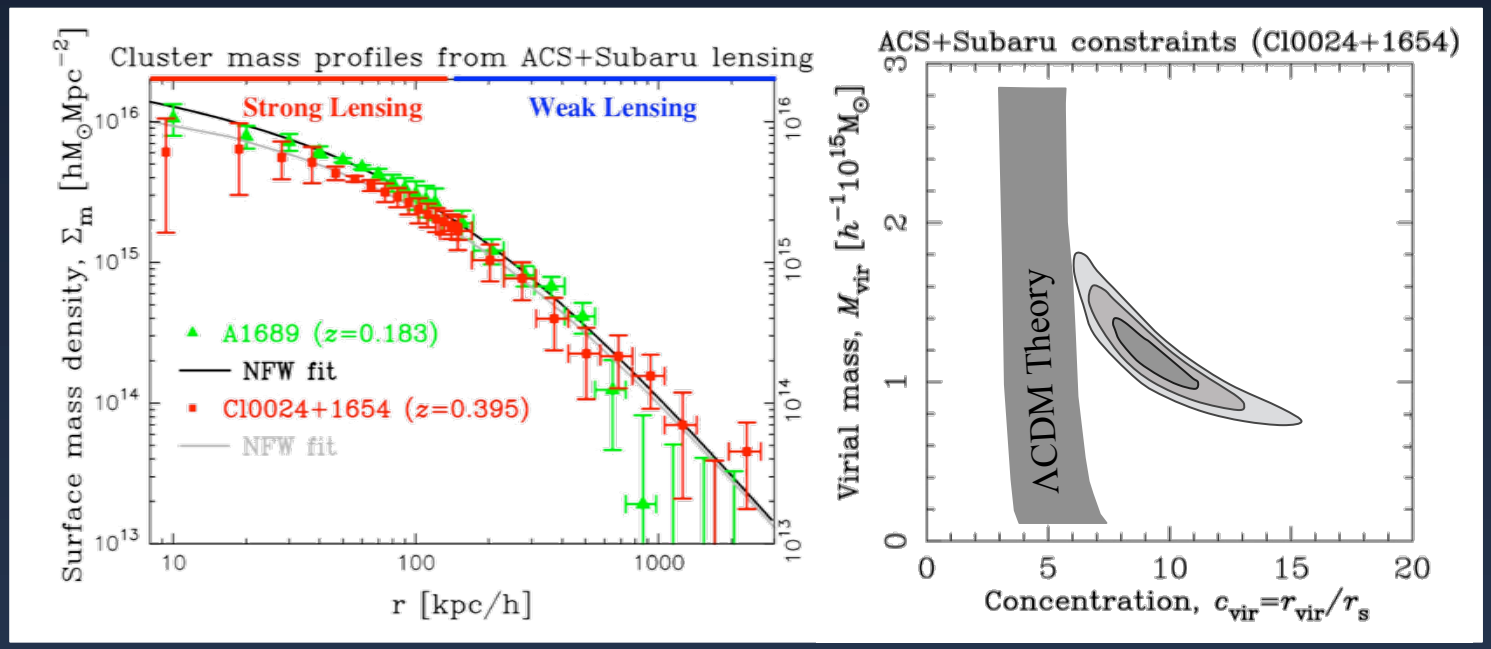


Other forms also used, e.g., Einasto: $\rho(r) \propto \exp(-Ar^{\alpha})$

Shapes of DM halos in LCDM simulations all exhibit a steeper slope as radius increases with a roll-over defined by a characteristic scale or central concentration, c.

$c\downarrow$ Mass$\uparrow$ $t_U\uparrow$ $\rho\downarrow$

Both Strong & Weak Lensing Measurements Needed for Good Constraints



Umetsu et al. 2010

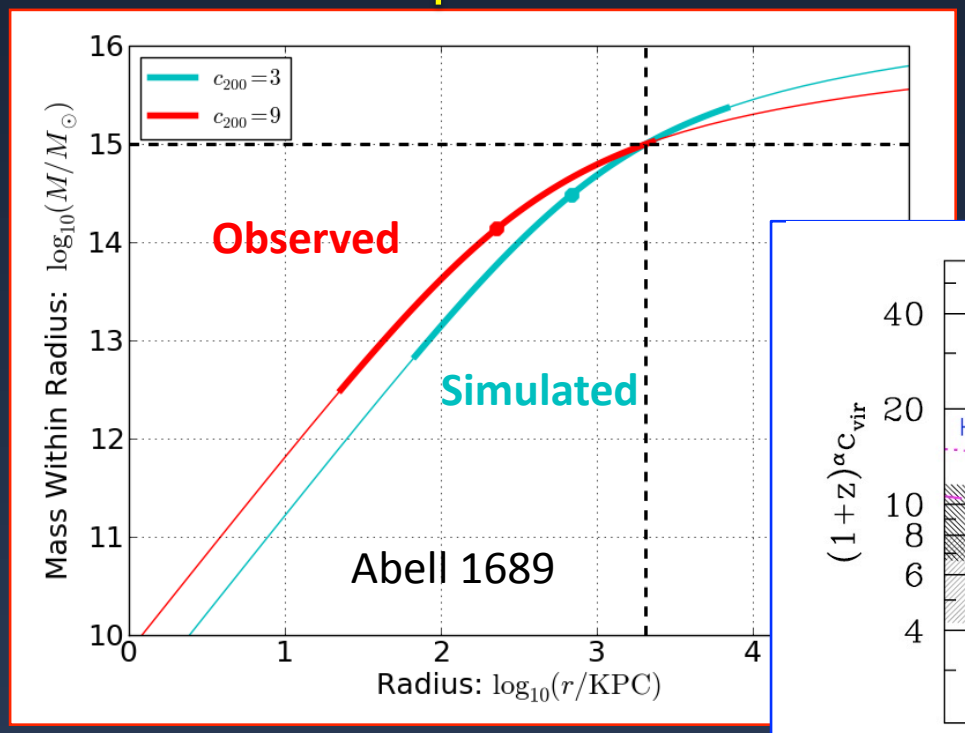
LCDM prediction from Duffy et al. 2008

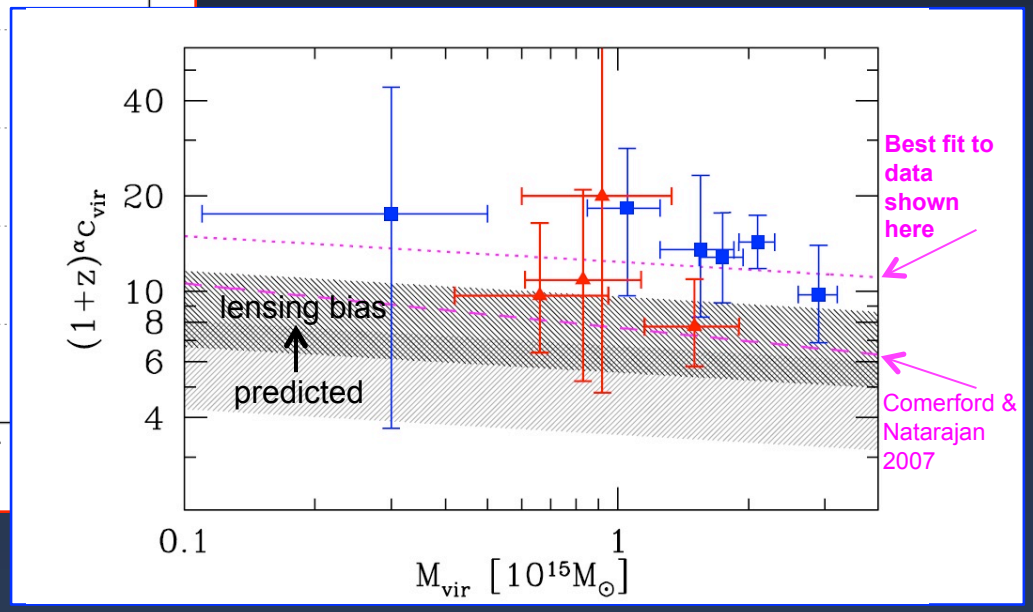
Both strong AND weak lensing measurements are needed to make accurate constraints on the DM profile. Not only to span required physical scale but also to remove mass-sheet degeneracy.

CLASH data will allow us to definitively derive the representative equilibrium mass profile shape and robustly measure the cluster DM concentrations and their dispersion as a function of cluster mass *and their evolution with redshift.*

Some (lensing-biased) clusters appear over-concentrated

Strong Lensing → | ← Weak Lensing

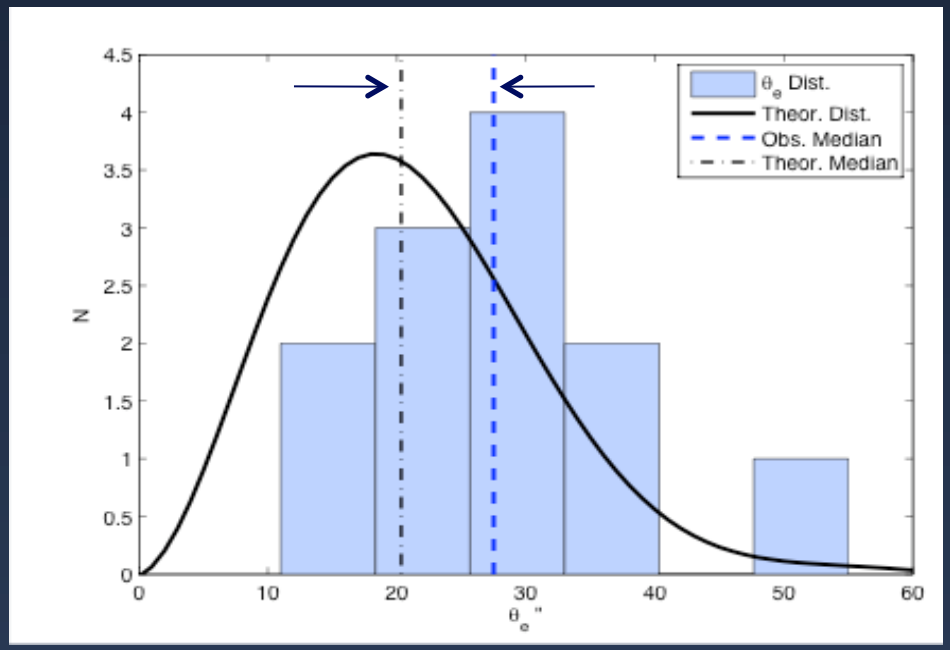


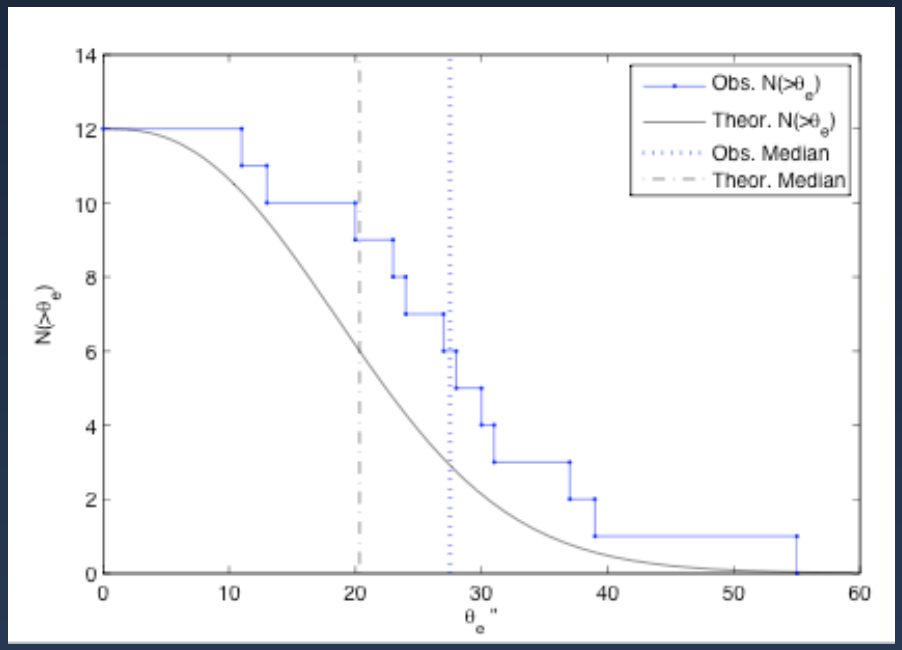


Oguri et al. 2009

Distribution of Einstein Radii: Observations vs. Theory

Sample of 12 Massive Clusters from Ebeling et al. MACS survey





Zitrin et al. 2010

x-axes: Einstein Radius (arc sec) for z = 2

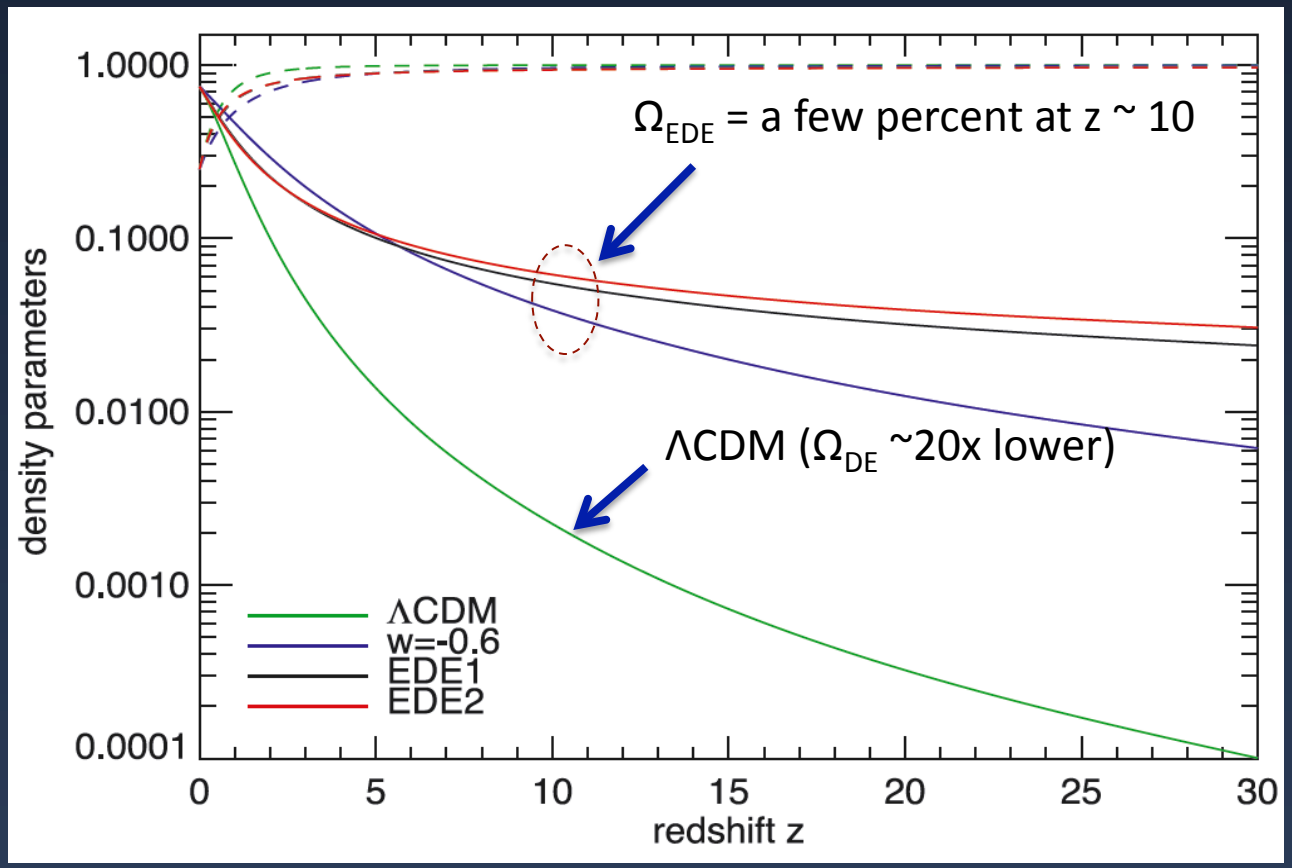
The LCDM predicted curve, after accounting for projection bias, is lower by a factor of ~1.4 from the observed distribution. The K-S test gives only 7.4% chance that the observed distribution arises from the predicted one, which is equivalent to about ~2 sigma discrepancy.

A FULLY X-RAY SELECTED SAMPLE, LIKE CLASH, WILL DEFINITIVELY TEST THE REALITY OF SUCH DISCREPANCIES.

Possible explanations for high observed concentrations

- Lensing selection bias
  - Significant (25-50%) but probably not sufficient
  - CLASH will be free of lensing bias
- Baryons and adiabatic contraction
  - Probably not a major effect in clusters (Duffy et al. 2010, Mead et al. 2010) … but needs to be checked.
- Halo fitting procedure in simulations
  - Hennawi et al. 2007 find ~30%+ higher concentrations
- Clusters formed sooner than in simulations
  - Early Dark Energy?

Clusters with high concentrations and early formation times *may* be giving us hints of "Early Dark Energy"



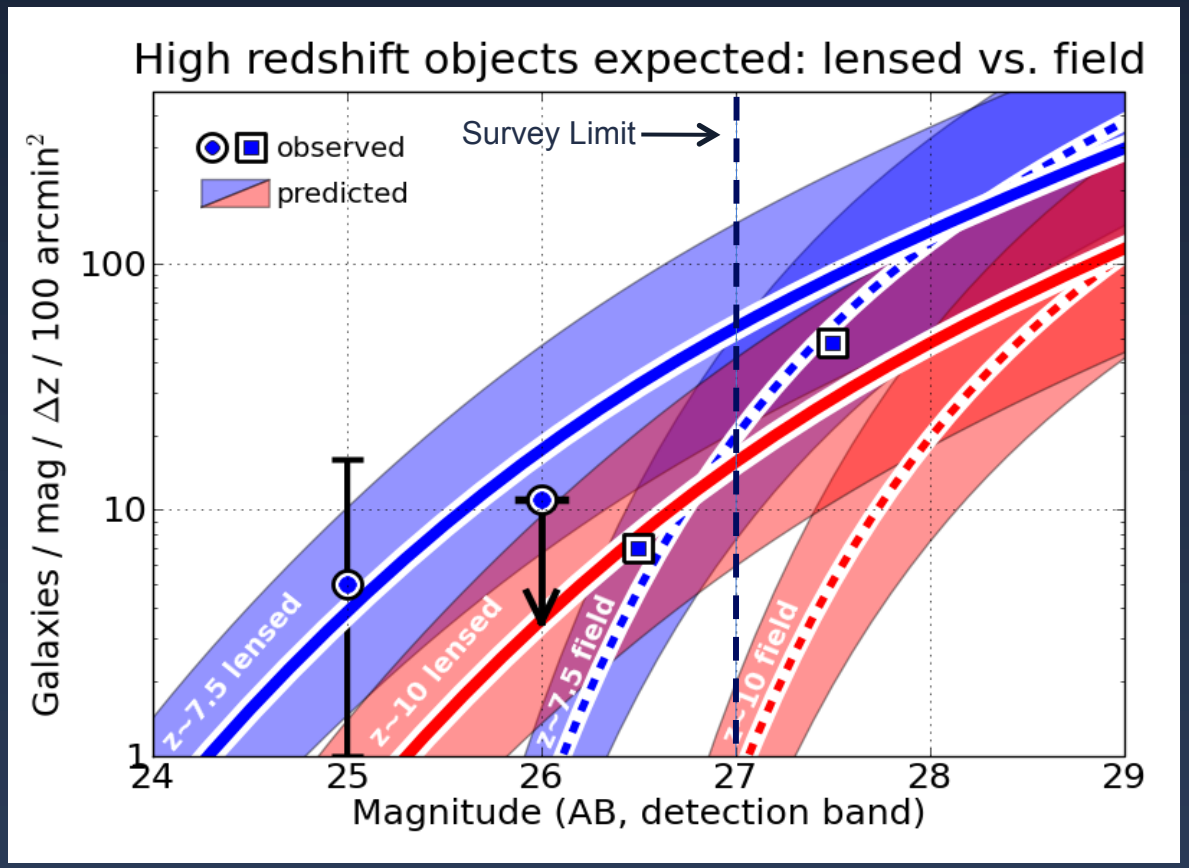
Grossi & Springel 2009

Dark energy suppresses the growth of structure.

In EDE models, cluster growth was suppressed earlier.

So clusters must have started forming earlier *to achieve the abundances observed today.*

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

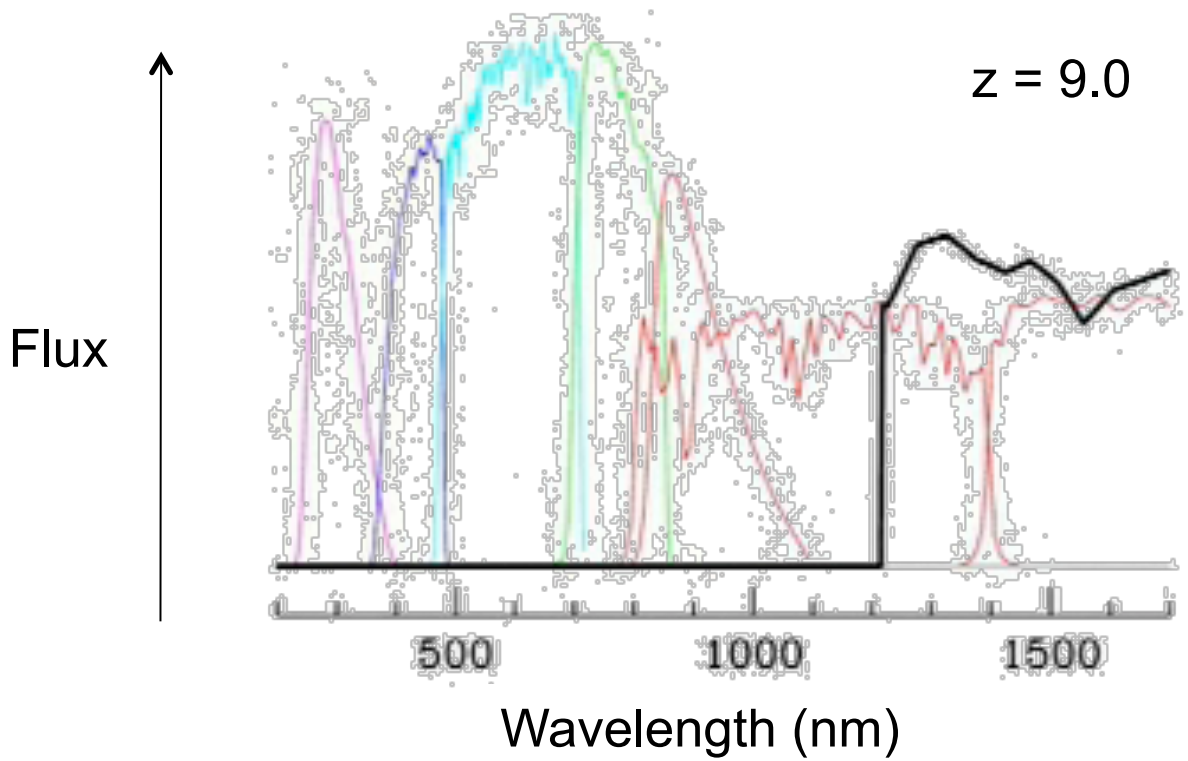


The blue and red solid curves show the expected number of $z=8$ and $z=10$ galaxies, respectively, to be discovered behind our 25 clusters as a function of magnitude in the detection band (F110W at $z=8$ and F140W at $z=10$).

A significant advantage of searching for high-z objects behind strongly lensing clusters is that the lens model can also be used to discriminate between highly-reddened objects and truly distant, high-z objects as the projected position of the lensed image is a strong function of the source redshift.

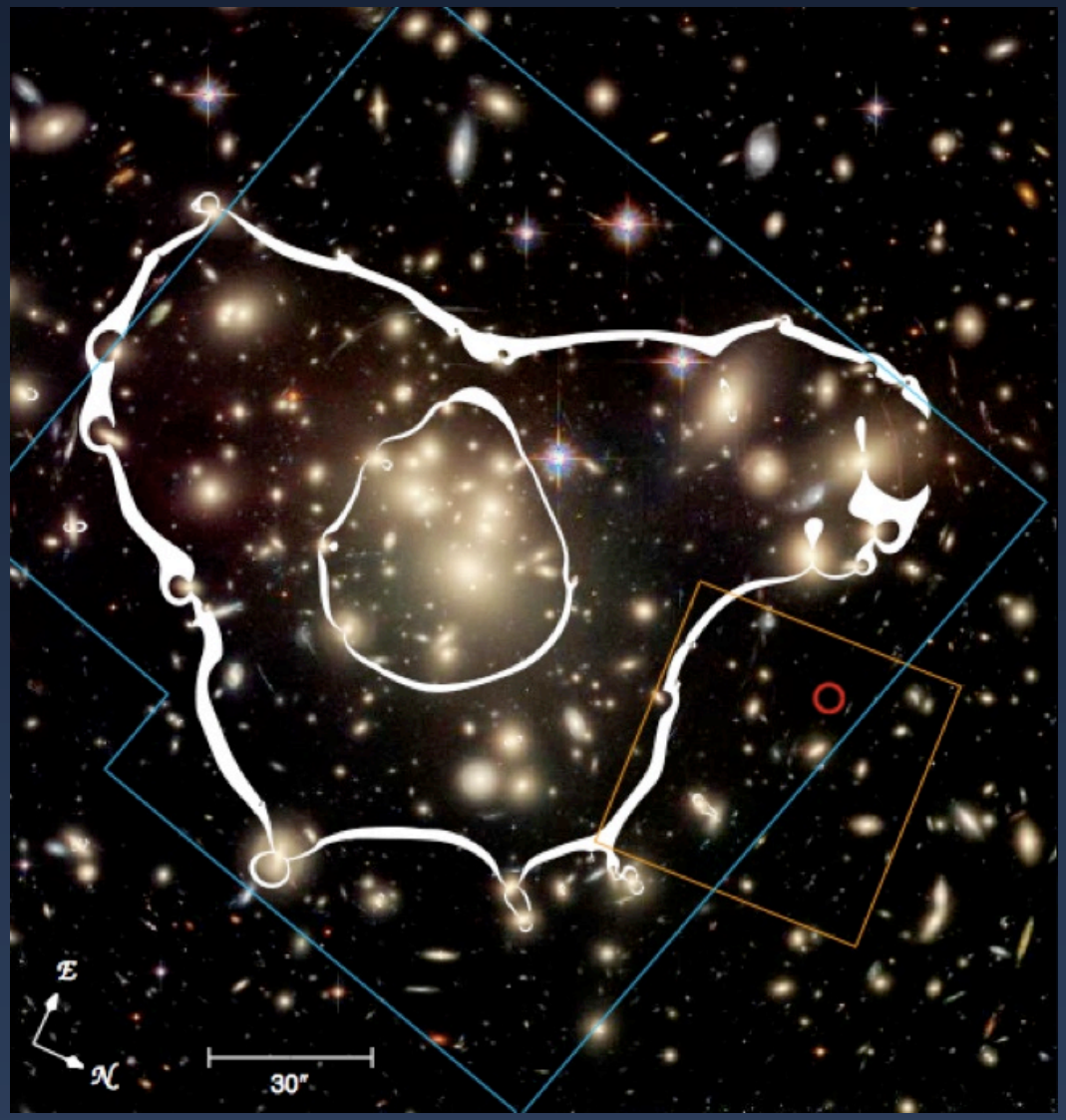
Lensing greatly enhances the ability to detect distant galaxies

LBG = Lyman Break Galaxy



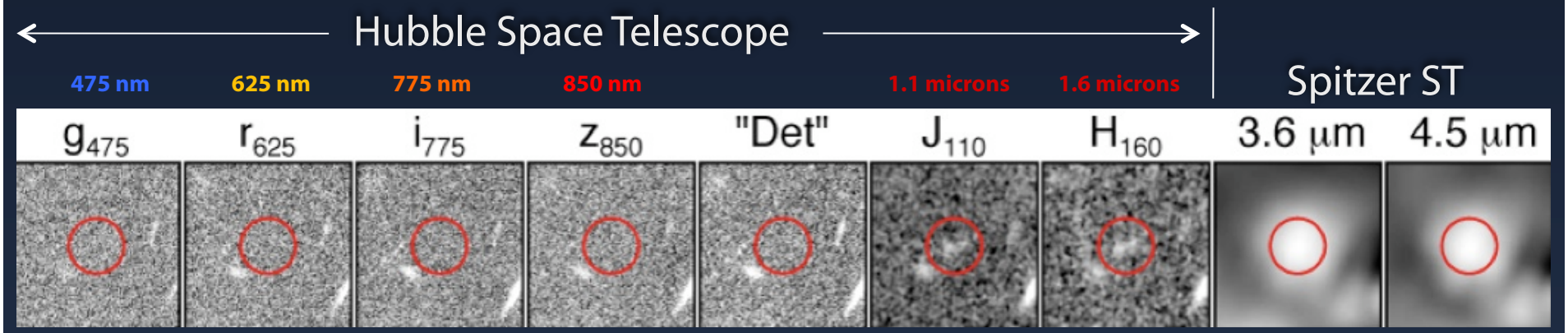
From R. Bouwens … www.firstgalaxies.org

Strong Lensing Cluster Abell 1689



- Abell 1689
  - $z = 0.18$
  - $R_E \sim 50''$
  - M_{cl} ($\leq R_E$) ~ $2 \times 10^{14}\ M_\odot$
- ACS/WFC data g, r, i, z (20 orbits)
- blue: NIC3 J_{110} (18 orbits)
- orange: NIC3 H_{160} (1 orbit)

LBG Candidate: A1689-zD1



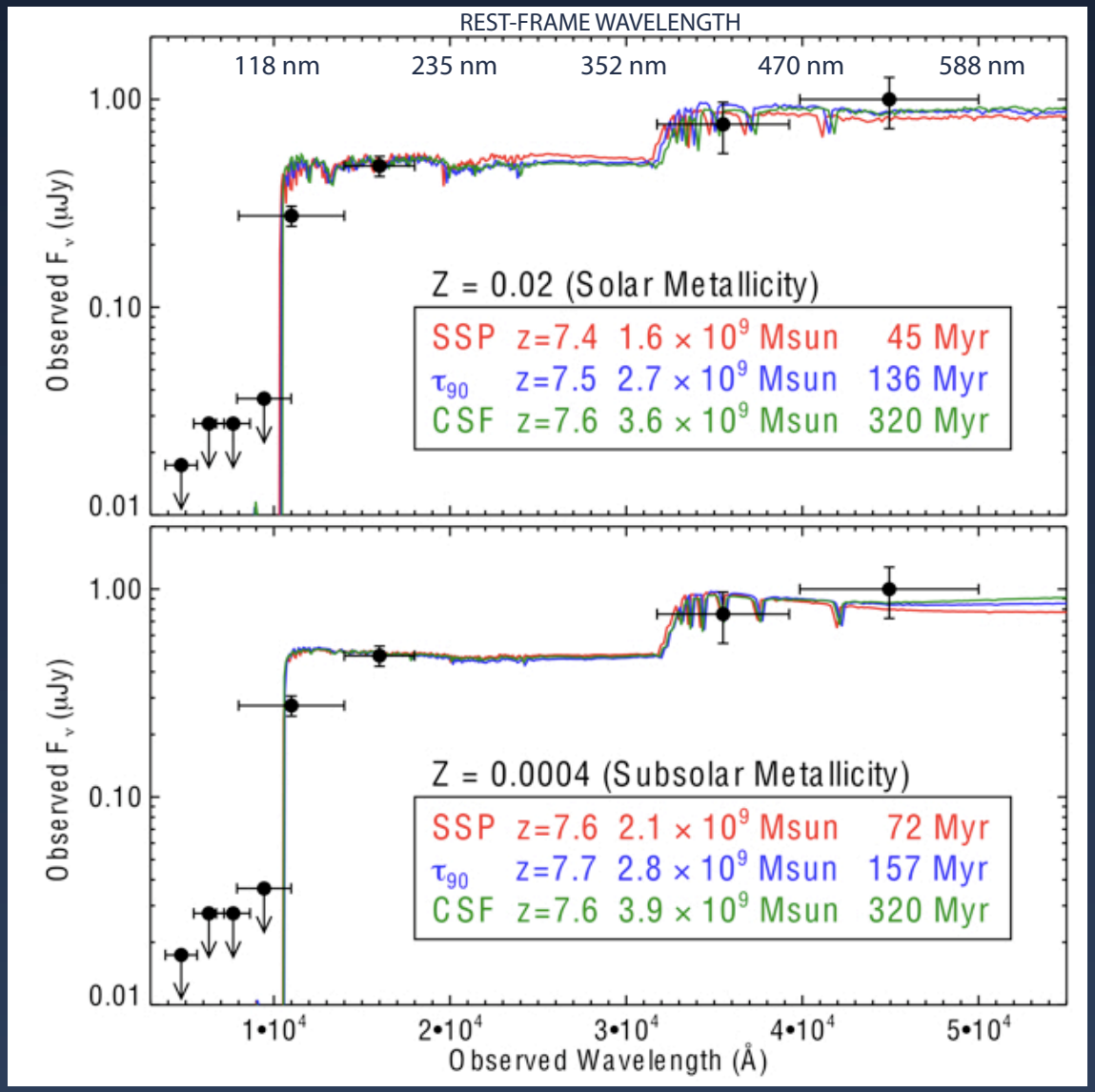
> 28.3	> 27.8	> 27.8	> 27.5	25.3	24.7	24.2	23.9

- J_{110} = 25.3 AB (8σ) observed
- Completely undetected (< 1σ) in ACS data
- Very strong "break": $(z_{850} - J_{110}) > 2.2$
- Blue color redward of the break: $(J_{110} - H_{160}) = 0.6 \pm 0.2$

Interpretation: A1689-zD1 is very bright strongly lensed LBG at z ~ 7.6 ± 0.4

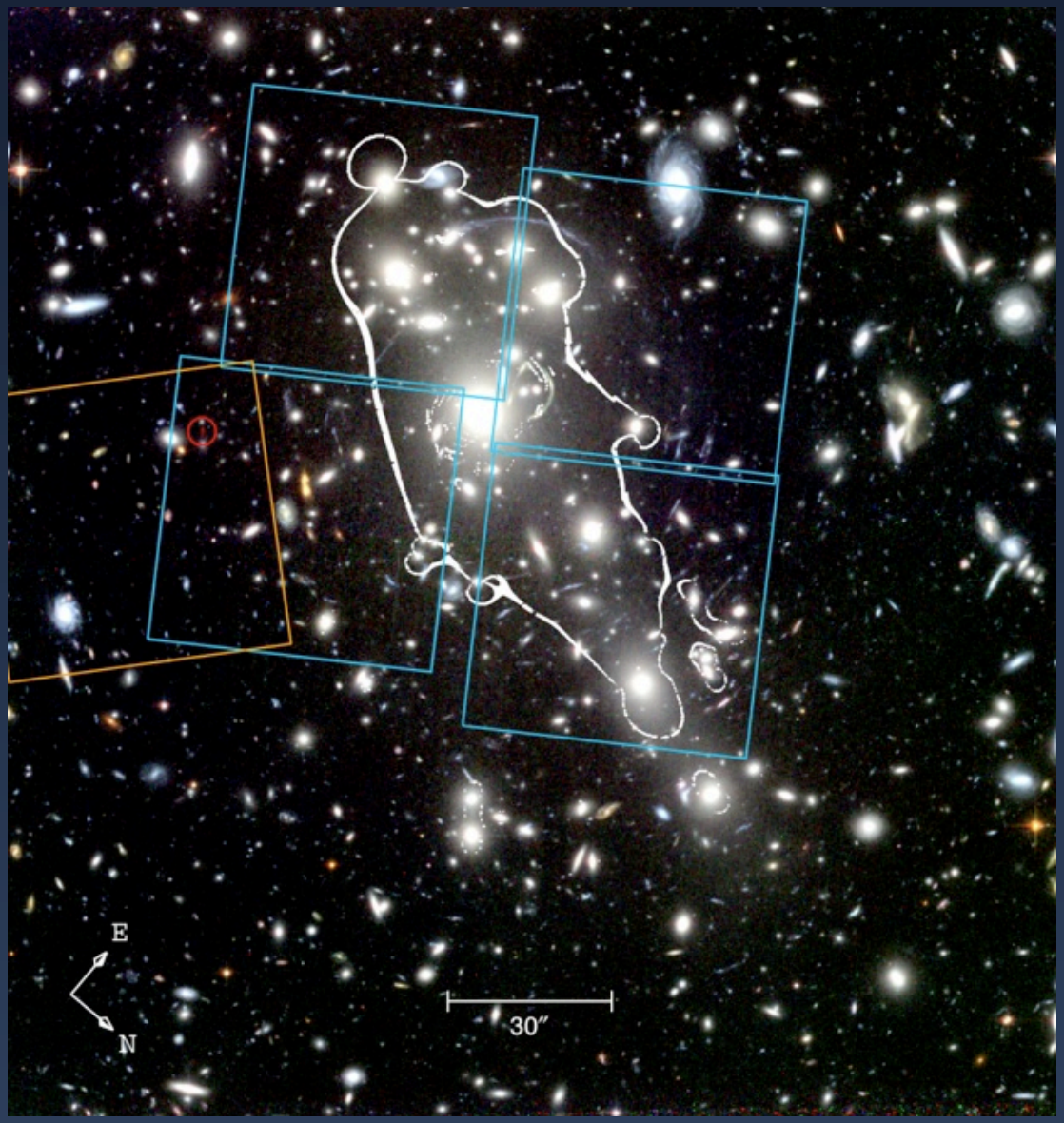
Bradley et al. 2008

A1689-zD1 Stellar Population Models



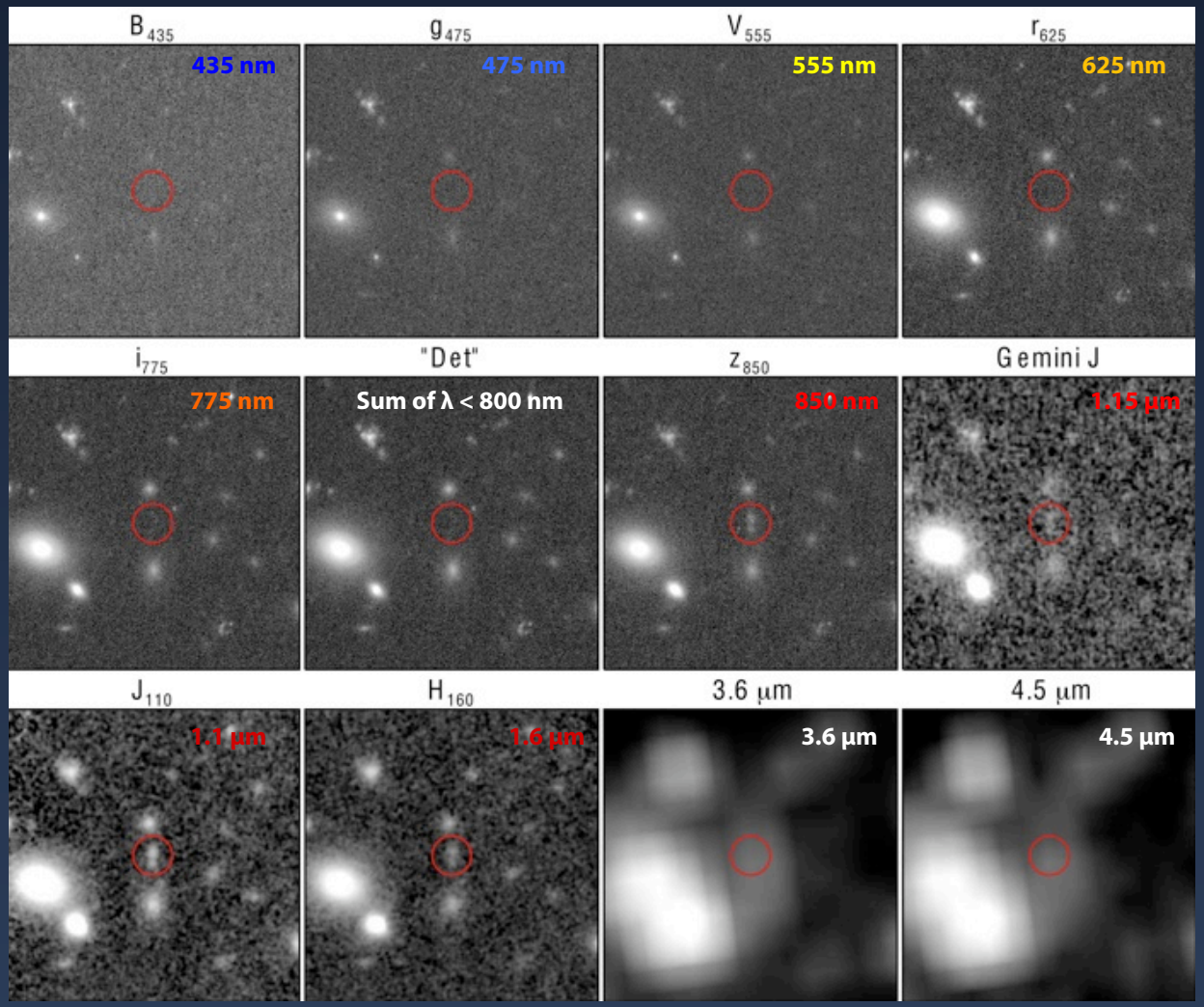
- $z \sim 7.6 \pm 0.4$
- IRAC (SST imager) data constrain stellar masses: (1.6 – 3.9) × 10^9 $M_\odot$
- Stellar Ages: 45 – 320 Myr
- SFR: < 7.5 $M_\odot$/yr
- A_V < 0.3 (most models require no reddening)

Abell 1703



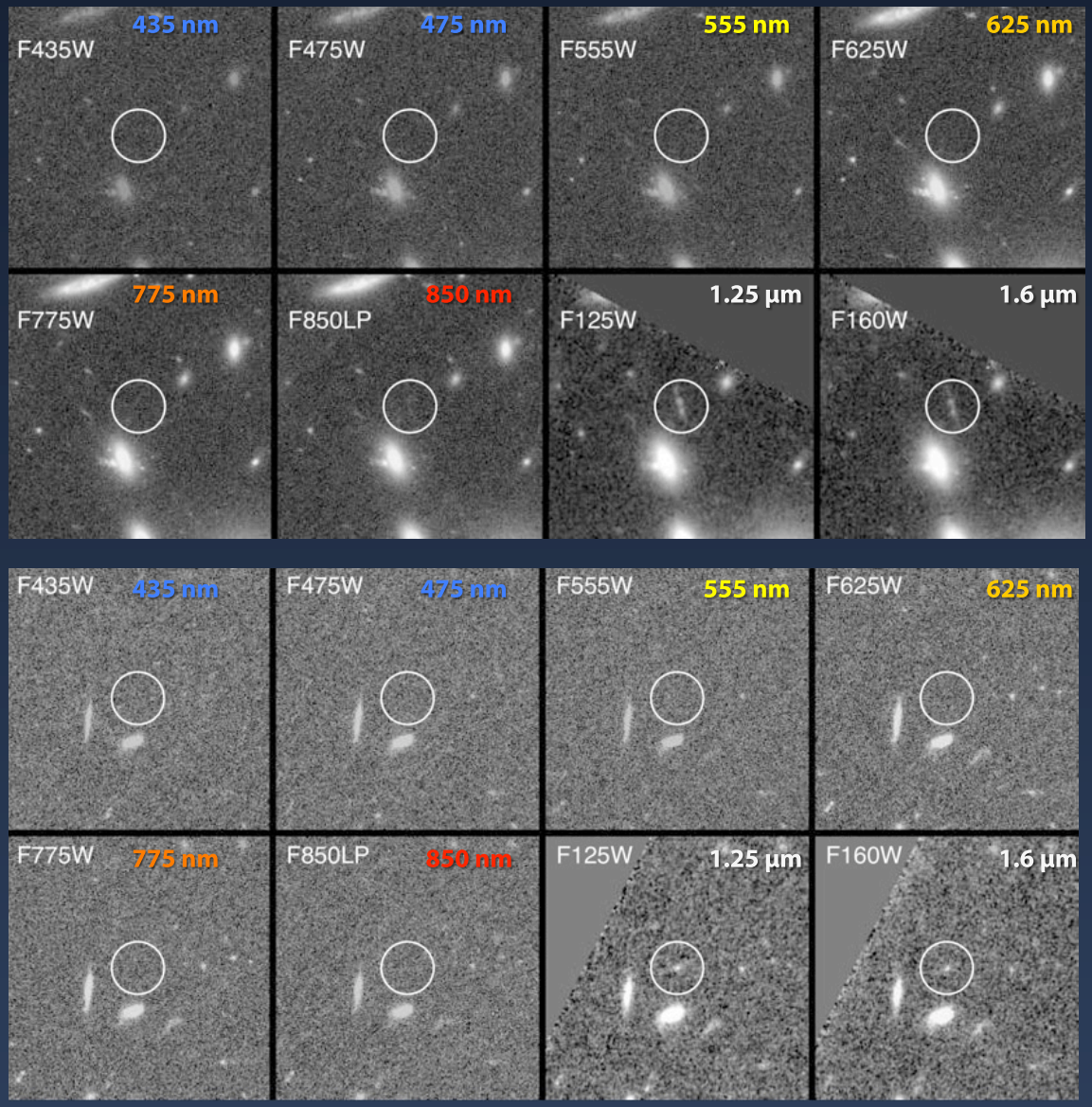
- Abell 1703
  - $z = 0.26$
  - $R_E \sim 35''$

A1703 Bright *i*-Dropout



- H_{160} = 23.9 AB
- One of the brightest $z > 5.5$ galaxies known
- $\mu = 3.1$
- H_{160} = 25.2 AB (intrinsic)
- Morphology: 2 bright knots

A1703 WFC3/IR *z*-dropouts

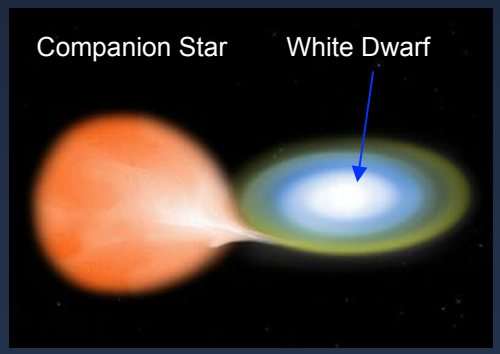


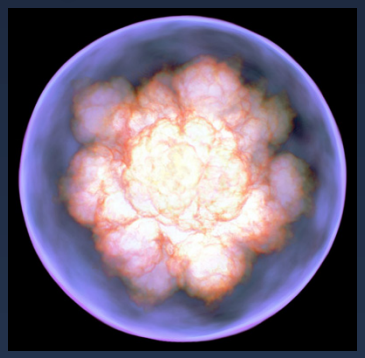
- 1 orbit each in WFC3/IR F125W (J) and F160W (H)
- 5+ *z*-dropout candidates! (some may be multiply-imaged)
- Typically $\mu \sim 3 - 5$
- Brightest candidate: $z \sim 6.9$, $H160 \sim 24.3$ AB (brightest $z \sim 7$ candidate known)

Bradley et al. 2010 (in prep)

Constraining Dark Energy by measuring the change in the cosmic scale factor with time

F. Ropke 2009





White Dwarf in binary system. Progenitor of a “Type 1a” supernova.

Accretion of material onto the white dwarf (WD) leads to compressional heating of WD core. This generally leads to a runaway thermonuclear deflagration front of Carbon and Oxygen burning. WDs are susceptible to runaway fusion as degeneracy pressure is independent of temperature.

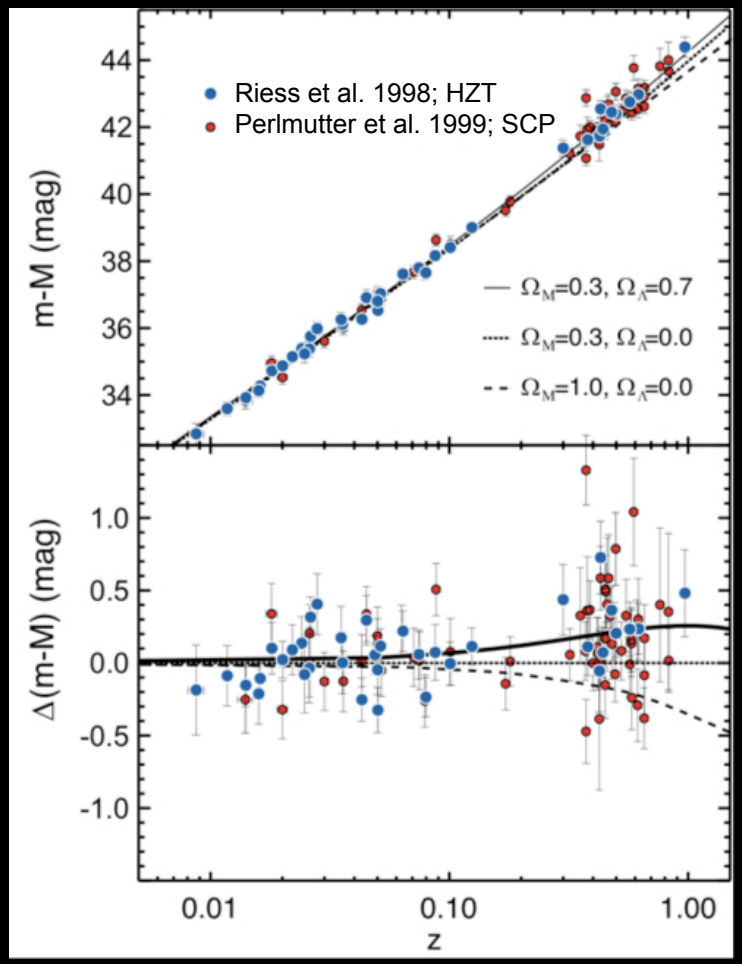
The star ultimately explodes when Chandrasekhar mass limit is approached. Homogeneous (few %) explosion mass produces a nearly constant amount of light. Since we know the intrinsic luminosity, distance to the SN (and its host galaxy) can be accurately computed.

Surprise: $q_0<0$, expansion accelerating, Universe dominated by Dark Energy!

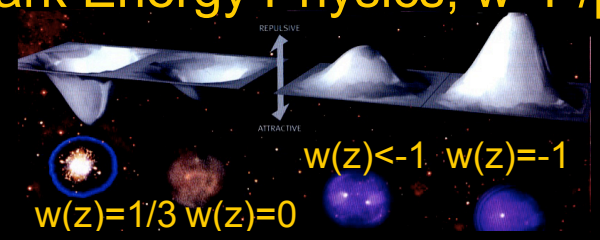
$$q_0 = \frac{\Omega_M}{2} + (1+3w)\frac{\Omega_{DE}}{2}$$

Fainter

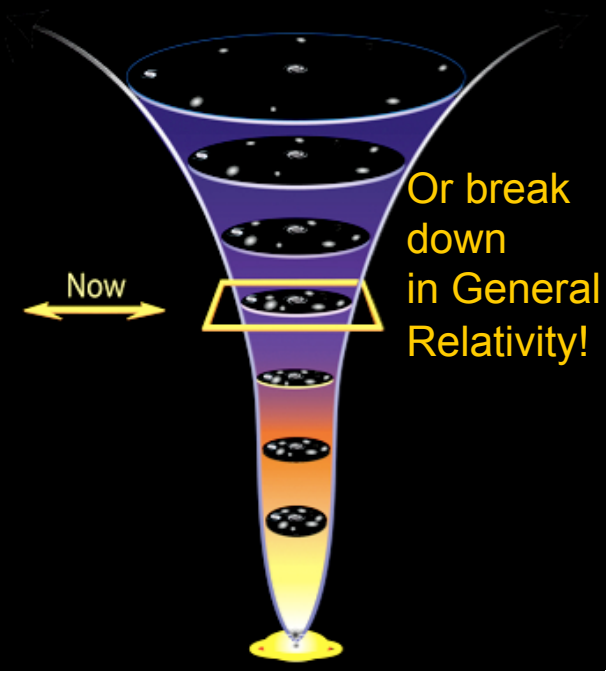
Brighter



Dark Energy Physics, $w=P/\rho c^2$



Radiation Matter Scalar Field Cosmological constant



Or break down in General Relativity!

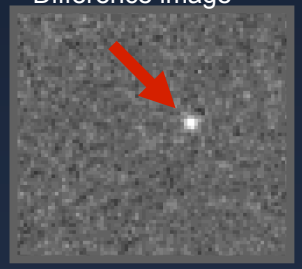
Discovering Type Ia SNe at z>1 with HST:

Step 1: Detection:

Pre-explosion image

SN Detection image

Difference image

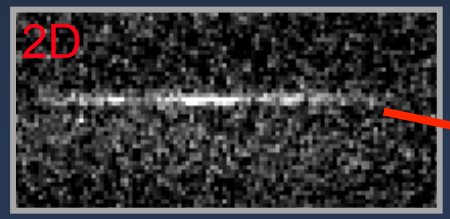


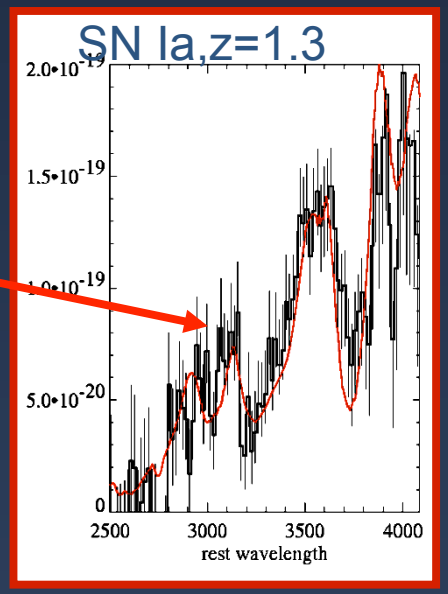
Step 2: Winnowing

SN Ia
are red
in UV

Step 3: Identification, redshift

Obtain HST grism
spectrum:



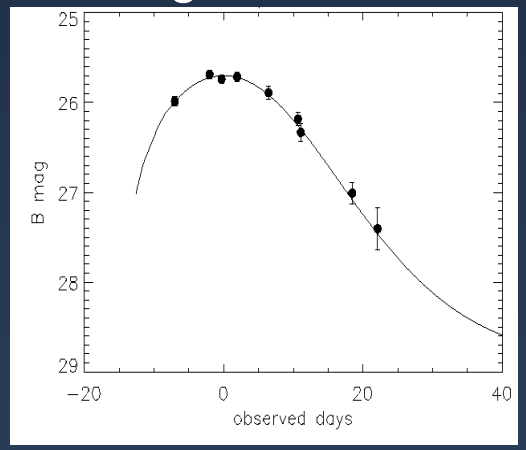


Ground has
never measured
redshift this high

Step 4: Follow-up, near-IR

Light Curve

NICMOS:



Peak and shape yields distance

Higher-z SNe Ia from ACS

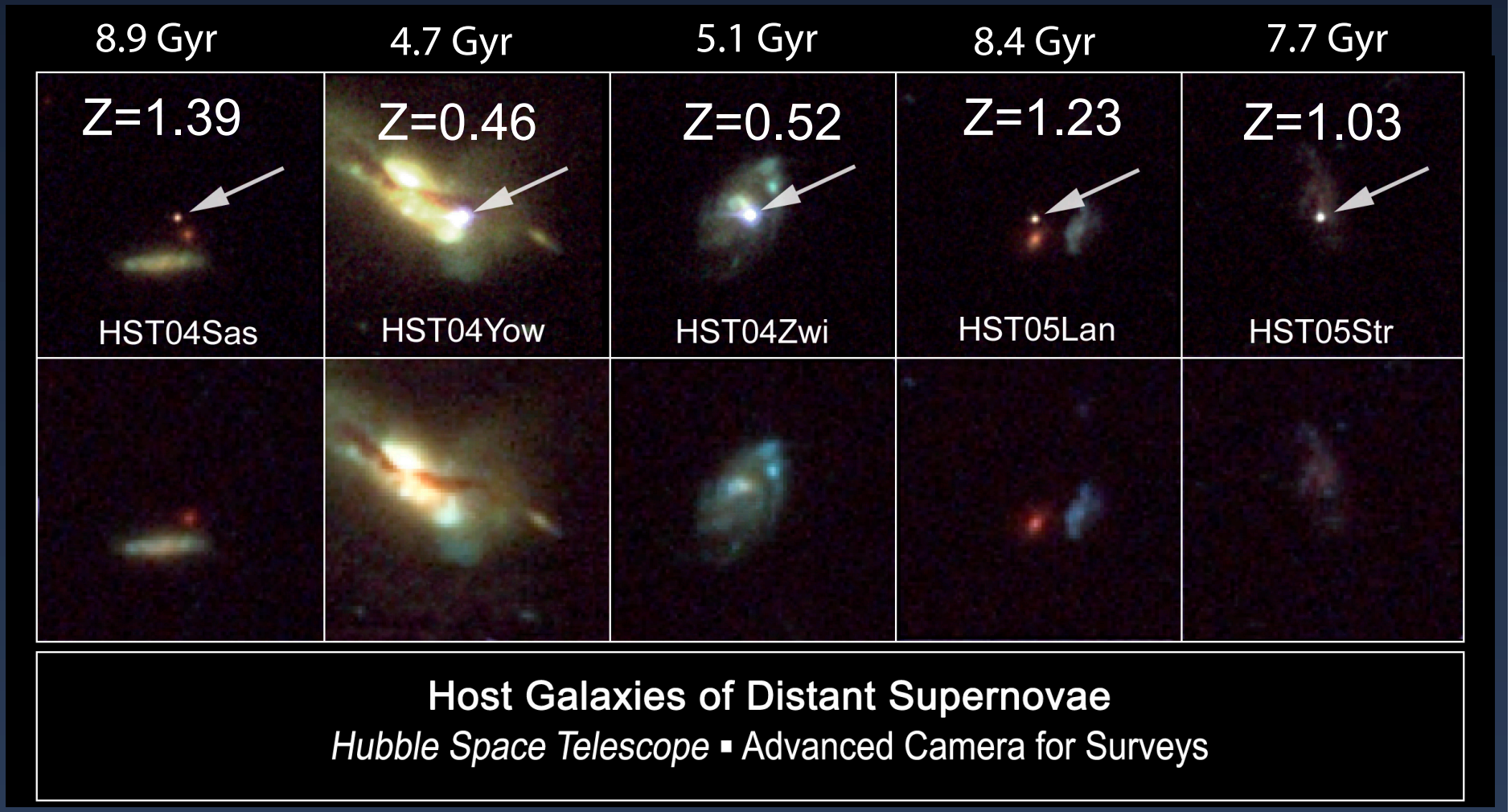
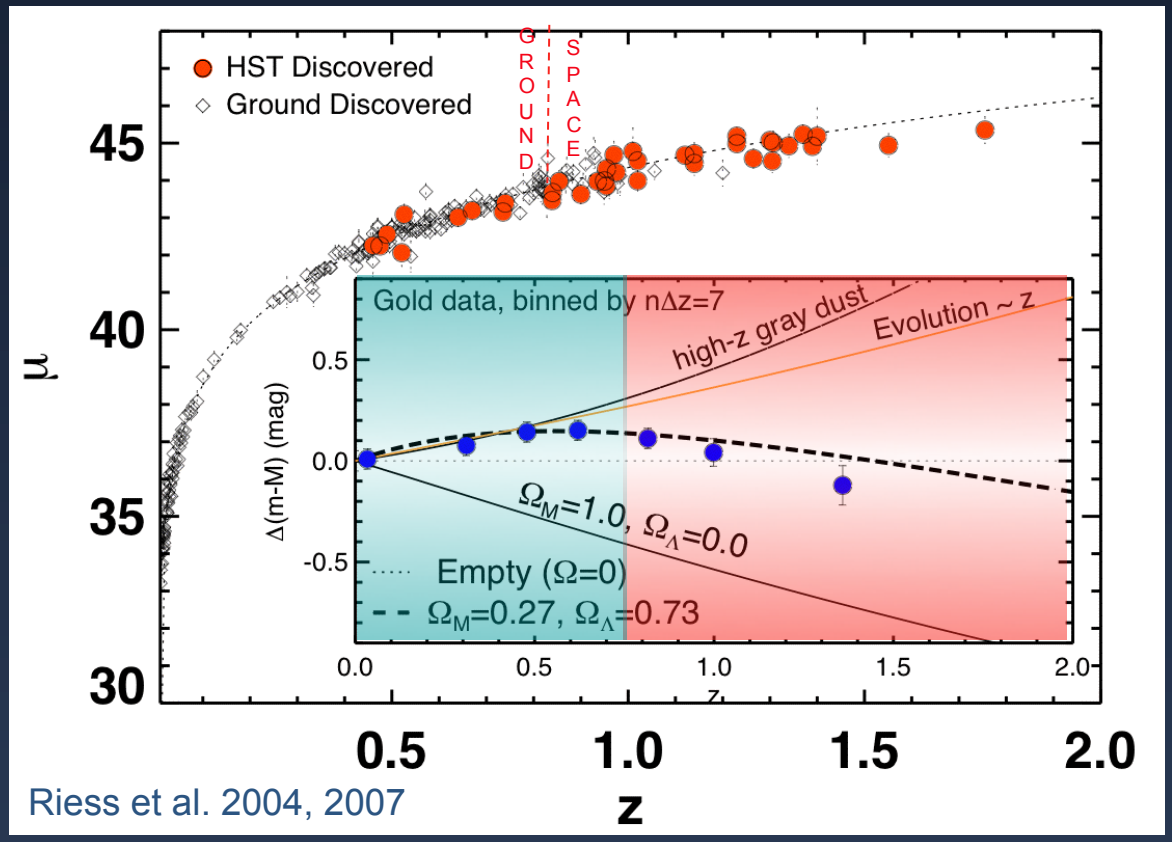


Image credit: NASA, ESA, Riess et al. (2006)

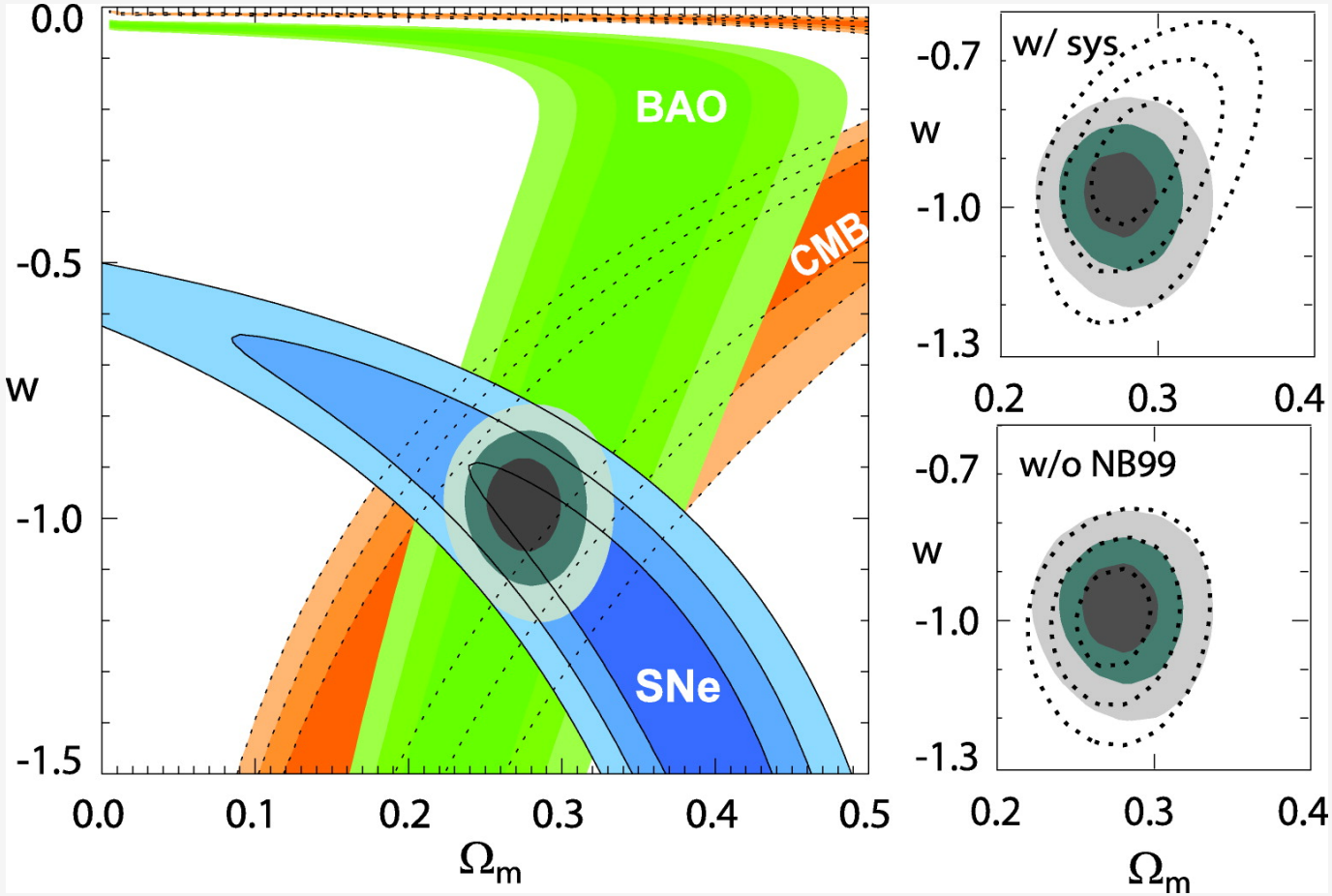
HST: 23 SNe Ia at z>1 Find Past Deceleration, Confirms Dark Energy+Dark Matter Model



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.

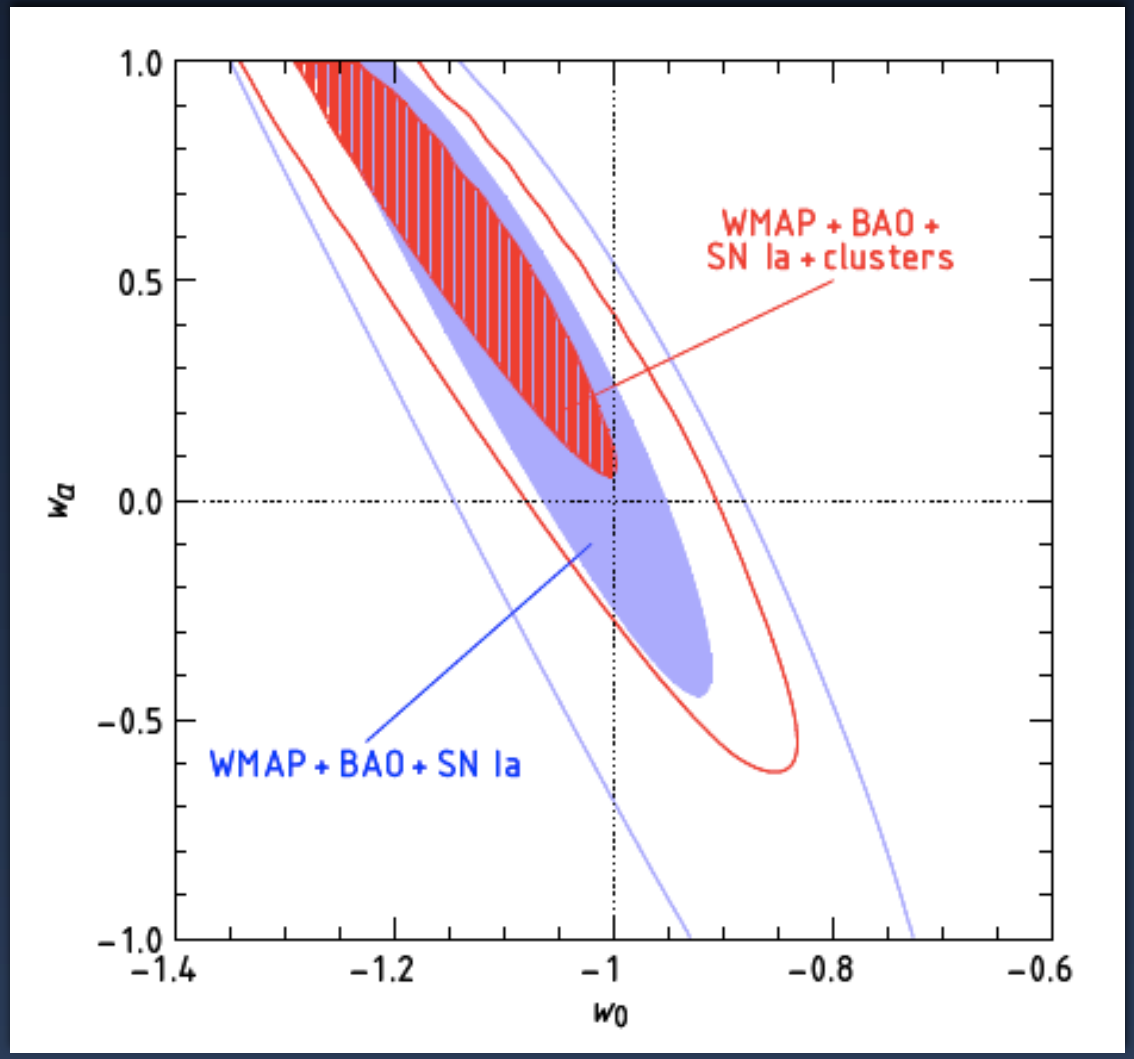
Current Constraints on w

Kowalski et al. 2008: $w = -0.969^{+0.059}_{-0.063}$ (stat) $^{+0.063}_{-0.066}$ (sys)



SNe data: SNLS, ESSENCE, high-z HST SNe, plus a few other datasets
BAO: Baryon Acoustic Oscillations; SDSS (Eisenstein et al. 2005)
CMB: WMAP 5-year data release (Dunkley et al. 2009)

Constraints on w'

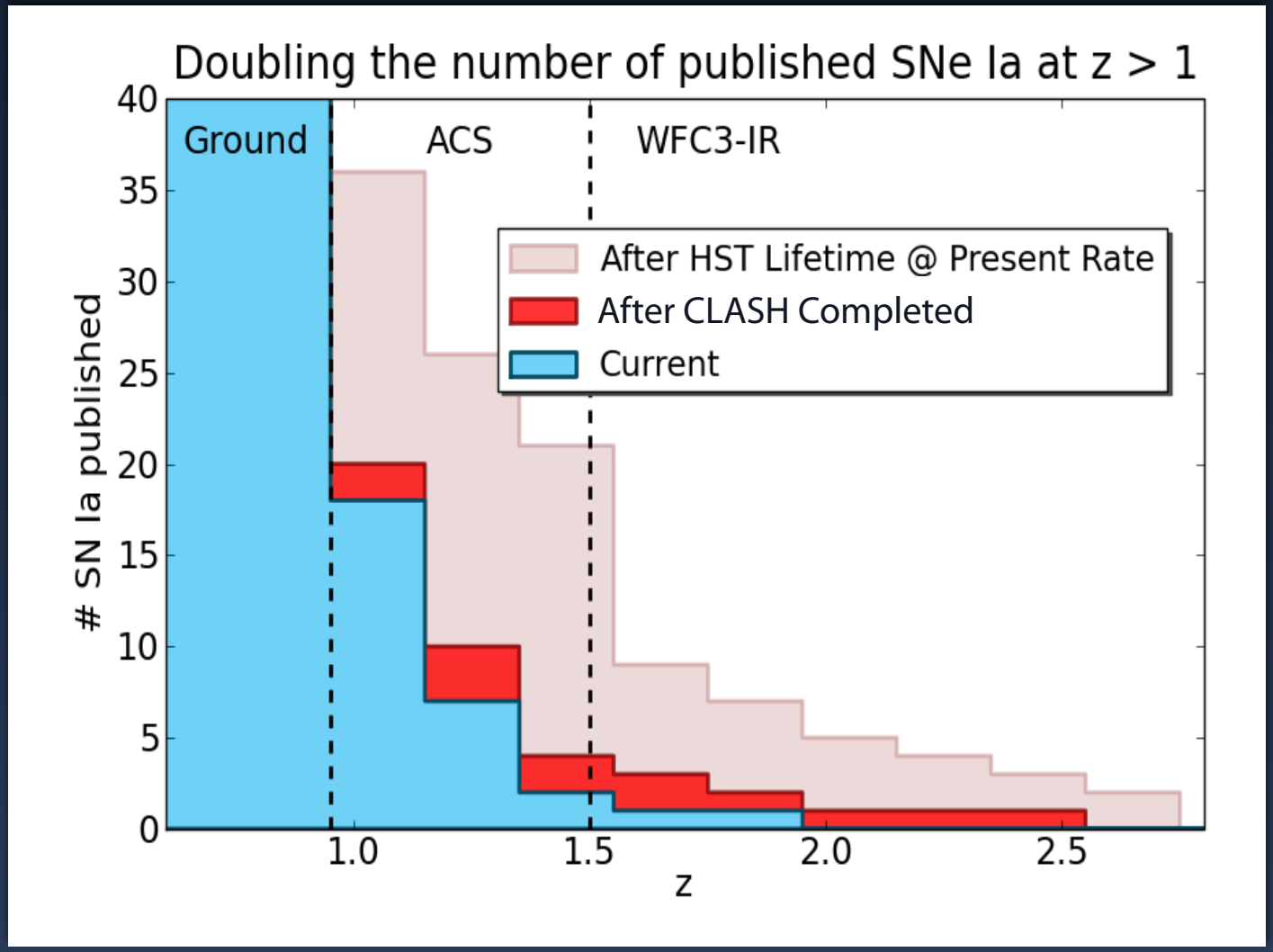


Vikhlinin et al. 2009: Chandra Cluster Cosmology Project

Assumes flat universe and simple form for w(z):

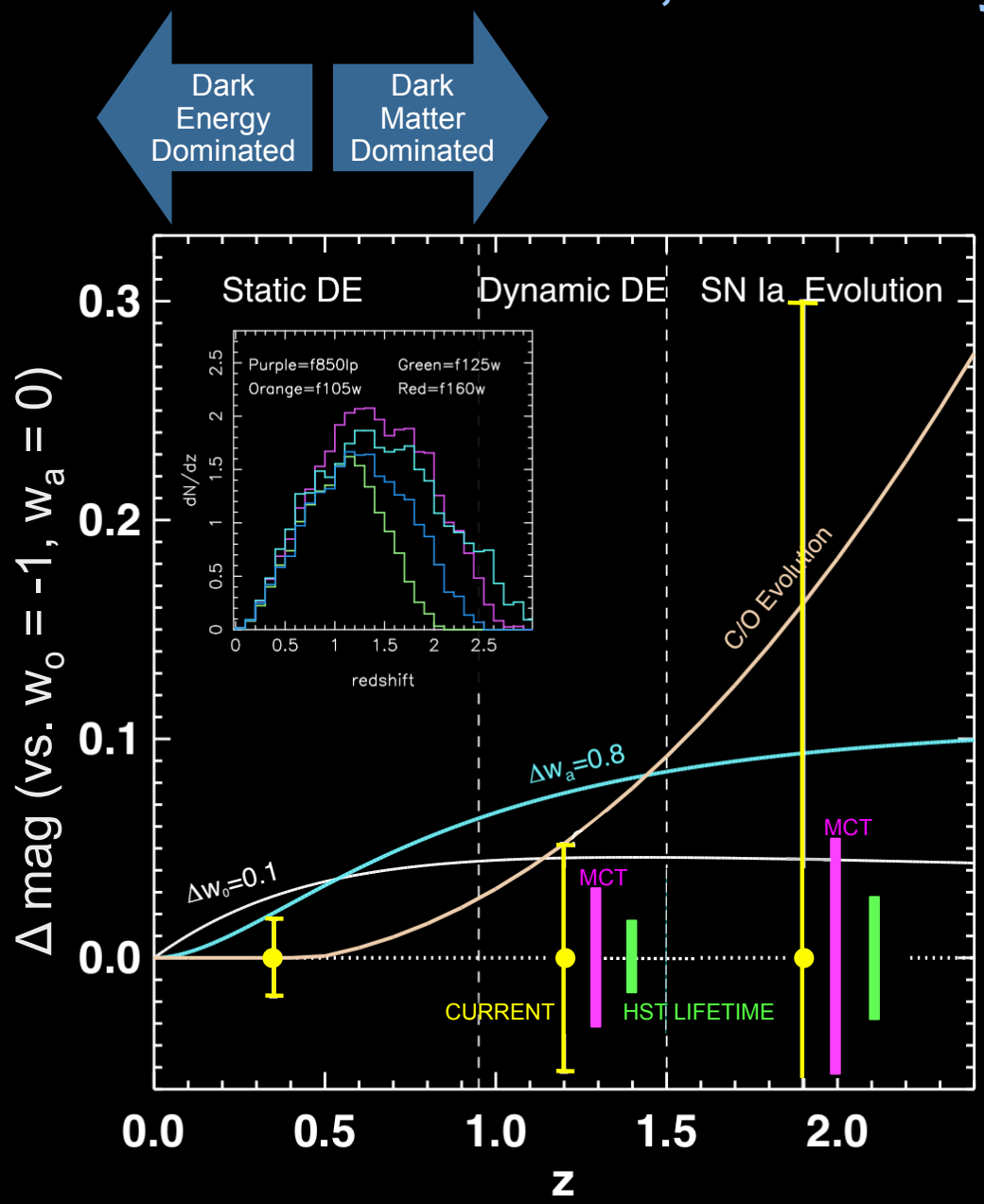
$w_0 + w_a z/(1+z)$

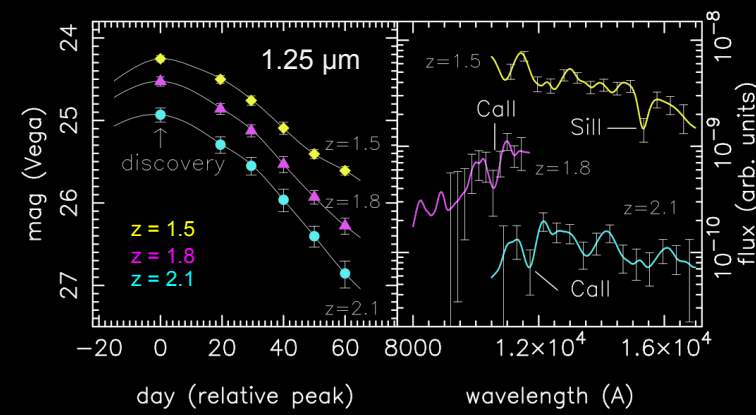
We expect to double the number of Type Ia supernovae at z > 1



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

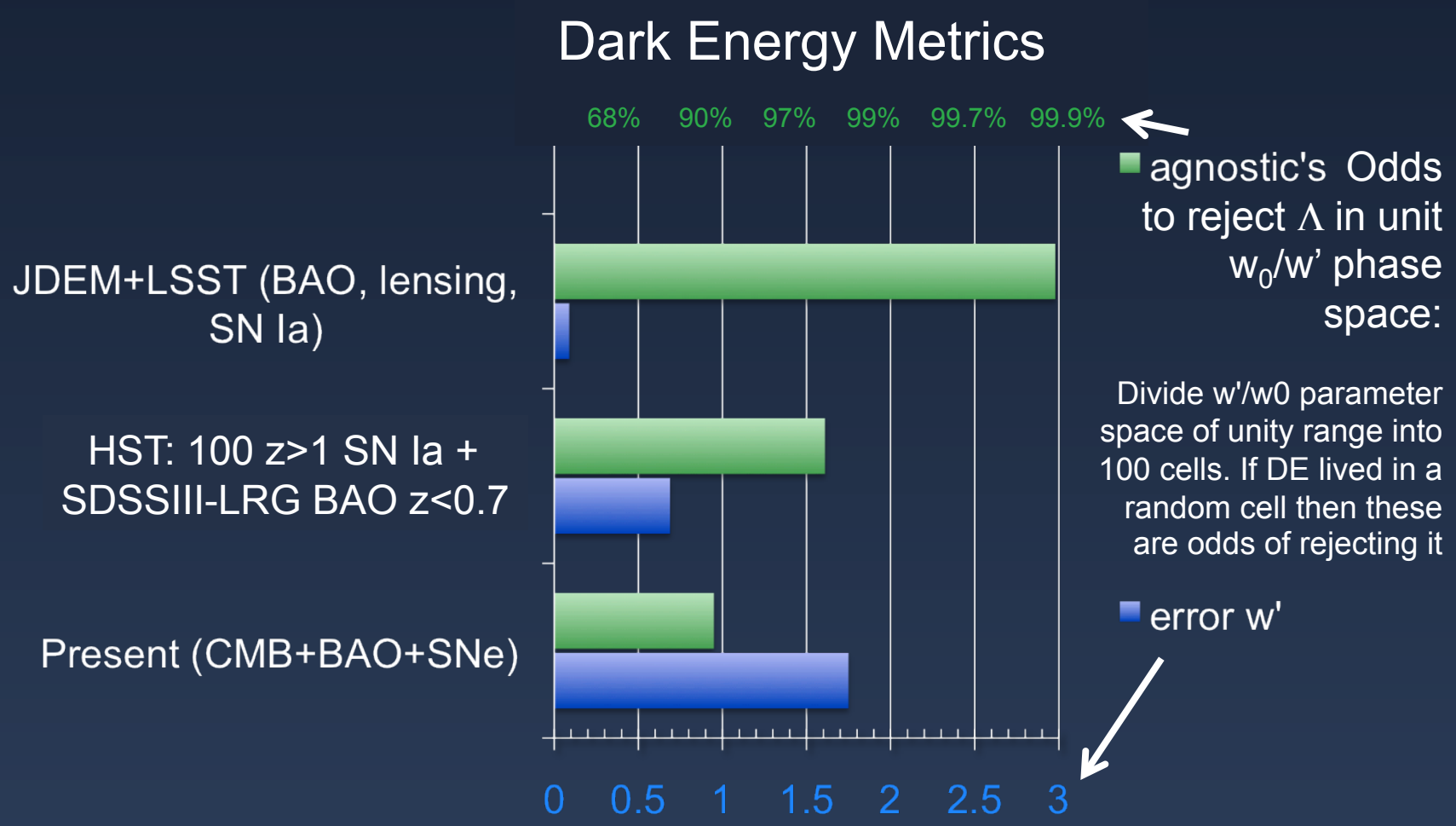
HST & WFC3-IR, Gateway to SNe Ia at z>2





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

The Future of Dark Energy Measurements



Present=Planck CMB priors, SDSS II BAO, SN World compilation, 5% H_0 prior
(slide credit: A. Riess)

Concluding Comments

- CLASH observations with HST to begin this fall. 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.
- Mass calibrators for cluster cosmology surveys.
- 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