

# Magnifying the Past: Galaxy Clusters and Gravitational Lensing

(Magnifying Objects in the Distant Early Universe, and What It Tells Us - More Later...!)

Ray A. Lucas, STScI

# Being Single, See(m)ing Double, Triple, Quadruple, ...

(Multiple images, and Seeing the  
Same Thing Here and There and  
There... - More Later...!)

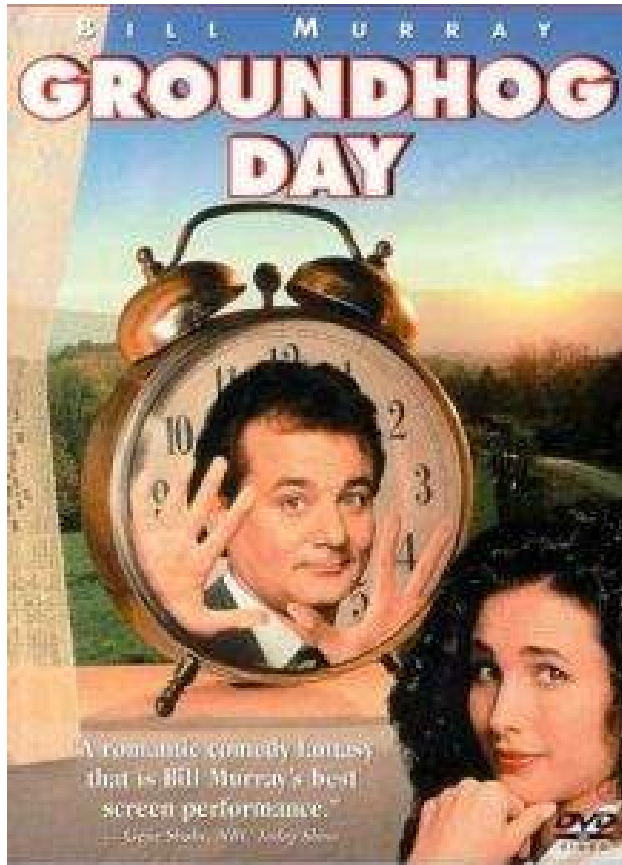
Ray A. Lucas, STScI

# Like Bill Murray in “Groundhog Day”: See Me Now, and See Me Later...

(Time Delays, Bending Light, and Seeing the Same Thing Over and Over and Over... - More Later...!)

Ray A. Lucas, STScl

# Do you know what day it is (was)?



- My gratuitous nod to a funny movie that helped inspire the idea of doing this talk on that day...!
- (Talk was originally scheduled for Feb. 02, 2010, which was Groundhog Day, but was delayed due to snow...)

# Why the Multiple Titles?

- I was not trying to torture Frank Summers!  
(He may have thought so...)
- Multi-faceted nature of gravitational lensing:
  - (1) magnifies the distant objects of the past,
  - (2) distortions reveal the shape of dark matter halos and gravitational potential by producing multiple images of the same thing, and
  - (3) illuminates the time-related phenomena that are due to effects of bending/deflecting light-path of distant objects

# Motivation...

# A few personal notes...

- Humility, and my own motivation for the talk...
- CL0939+4713 (1994, Dressler, Oemler, Sparks, & Lucas) SM1 ERO, Early WFPC2 “deep” image (~10 orbits, one of the deepest optical images ever taken at the time!), part of inspiration for HDF and its successors...
- Abell 2218 (1995, Couch, Ellis, Smail et al.)
- Abell 2218 again (1999, Fruchter et al. SM3A ERO)
- Abell 370 again (2009, Noll, Chiaberge et al. SM4 ERO)

# CL0939+4713 (Abell 851) - 1994, WFPC2, ~10 orbits, V



Dressler, Oemler, Sparks, & Lucas, 1994, CL0939+4713,  $z \sim 0.4$ ,  $\sim 4.2$  Billion L.Y.  
One of the deepest images ever taken at the time; it helped inspire the HDF and successors, partly because distant galaxies had higher surface brightnesses than expected, which meant that, completely contrary to predictions, HST was an excellent, in fact consummate, tool for this!

# Outline

- Gravitational Lensing: various scales, multiple kinds of phenomena (magnification, multiple imaging, and time delays from light-bending)
- Some History
- Different kinds of examples and their importance
- Galaxy Clusters and gravitational lensing (main topic) plus a bit more about clusters, if time...
- Present & Future: New ACS-R ERO; JWST & Beyond

# Gravitational Lensing: Some Aspects...

- Nature's gravitational magnifying glass, magnifies images of distant objects
- Einstein Rings, arcs, multiple images, distorted images
- Bent light, time delays, etc.

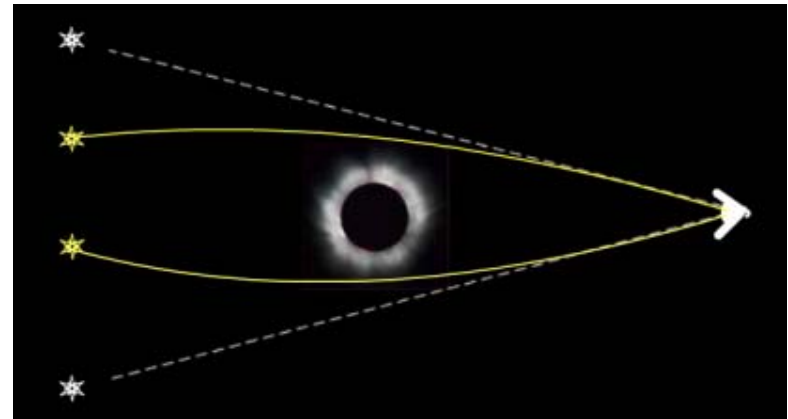
# Some History:

- Einstein predicted bending of light and displacement of images, for example, by gravitational effects of the sun on the apparent positions of more distant stars as seen very near the sun during an eclipse, but first thought it might be too small to be visible on Earth.
- Eddington observed this effect during the total solar eclipse of 1919.

# Some History (continued)

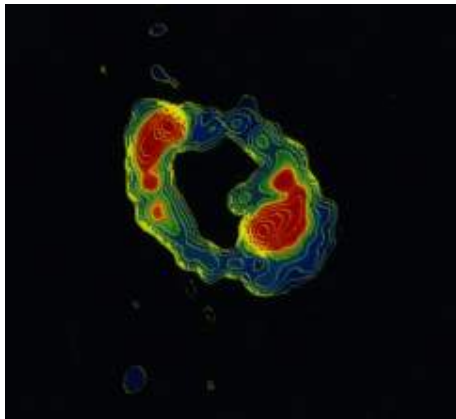
- Einstein's theory was developed before the true nature of the Milky Way and other galaxies was known, much less the phenomenon of large, massive galaxies and clusters of galaxies.
- Massive galaxies and especially clusters of galaxies offered the possibility of seeing this phenomenon on much larger scales than Einstein had originally envisioned.

# Einstein, Eddington and the Solar Eclipse of 1919



Eddington, a devout Quaker, felt that proof of the validity of Einstein's relativity would build a bridge to "German" science, and would help to humanize the recent "enemy" in the wake of WWI. Some claimed that the observations and measurements were not accurate enough at the time, but they were widely accepted as legitimate, and the effect has since been verified. Einstein became famous, and lionized, overnight.

# Also from Einstein's predictions:



- Einstein rings and partial rings and arcs, double rings, etc. (above)
- Effect also works in other wavelengths like radio, e.g. PKS 1830-211 (lower left)

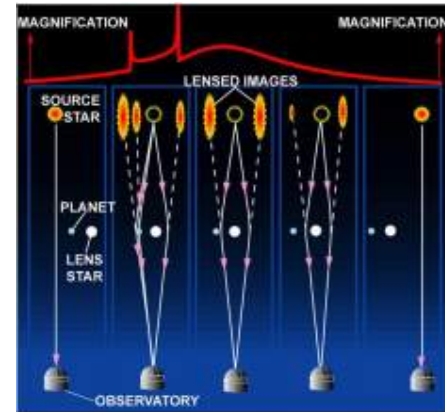
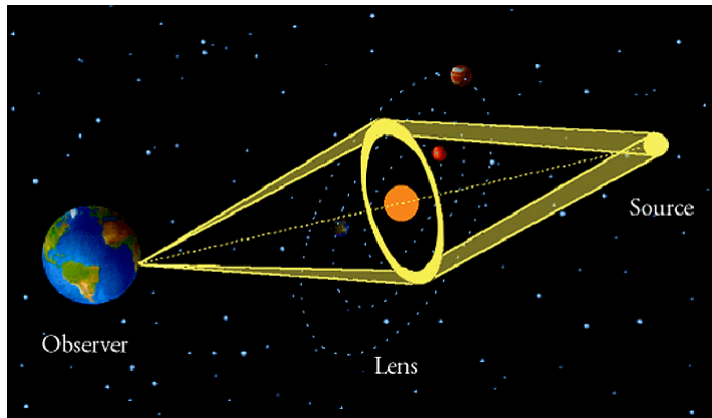
# Expansion of the concept...

- Microlensing (important for studying stars and finding planets) - Bohdan Paczynski (1980s)
- Galaxies can be lenses - Fritz Zwicky (1930s)
- Weak lensing (important for studying large-scale extragalactic structure and related alignment/orientation effects)
- Single-galaxy strong lensing, Einstein Rings, Einstein's Cross, etc. - Einstein Rings require axial symmetry of the lensing mass.
- Widely-separated identical quasar "pair"
- Galaxy Clusters and Lensing (main topic) - strong & weak lensing both play major roles...

# Strong, Weak, Micro: Multiple Facets of One Phenomenon...

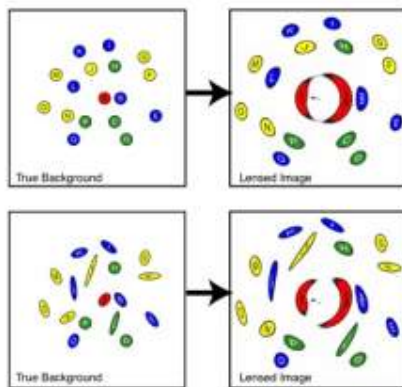
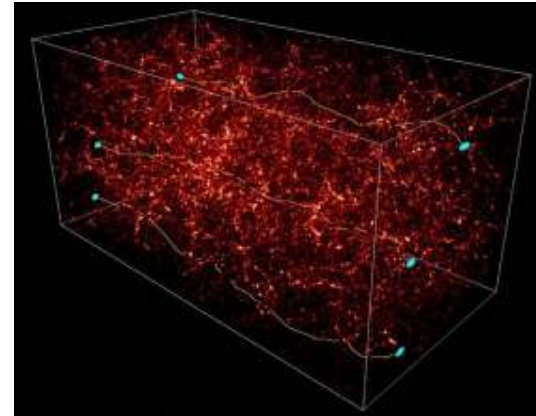
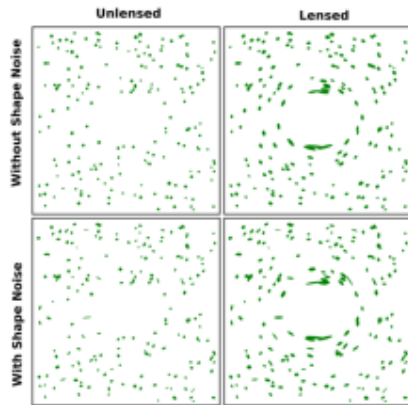
- Manifestation of a given lensing type depends cumulatively upon source geometry & size, lens geometry & mass, distance between the two, & distance and alignment between the sources, the lens, & the observer. It's a convolution of perspective, geometry, mass, & scale, etc. among all the components.
- The same thing seen from a different place or perspective yields a different manifestation.

# Microlensing



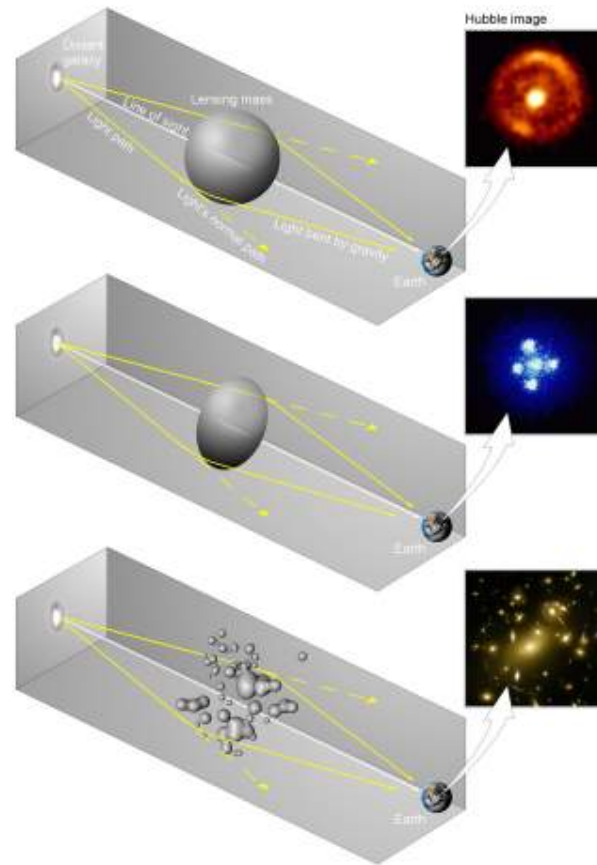
- Positions of distant source stars deflected slightly by presence of nearer intervening planets near lensing stars; positions of more distant stars also deflected slightly by presence of more nearby stars or smaller black holes, etc. as well as/instead of planets. Source magnification varies with position, mass of lensing star, planet, black hole, etc. (Bohdan Paczynski, 1980s)

# Weak Lensing



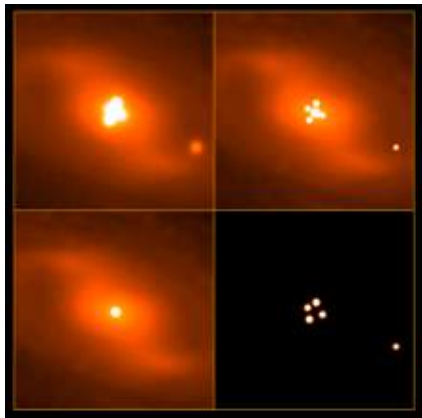
Both strong and weak gravitational lensing happens in the field and in galaxy clusters. Rings, arclets and other strongly distorted and magnified features are strongly-lensed, but all distorted objects are at least weakly lensed.

# Strong Lensing: Rings, Multiple Images, Arcs



Schematic showing comparison of three types of scenarios for strongly-lensed objects. Note that all 3 types of lensing may also exist in the same field of view due to a plethora of sources of various sizes, masses, and types which may intervene between distant source and observer, and the unique geometry which each intervening lensing source has in terms of location with respect to the distant source and the observer.

# Strong Lensing (examples)



Einstein's Cross



(As seen a few slides earlier...)



CL2244-02 (ESO VLT)

# First Extragalactic Lens found: Quasar “Pair” Q0957+561

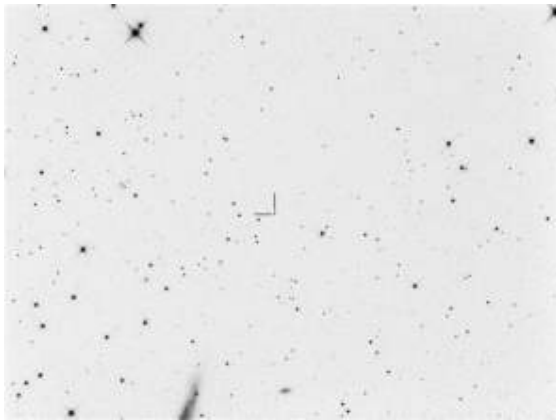
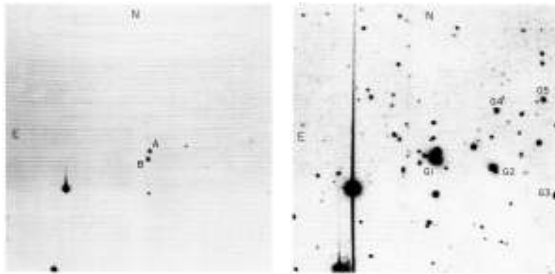


Photo credit:  
A. Ayiomamitis



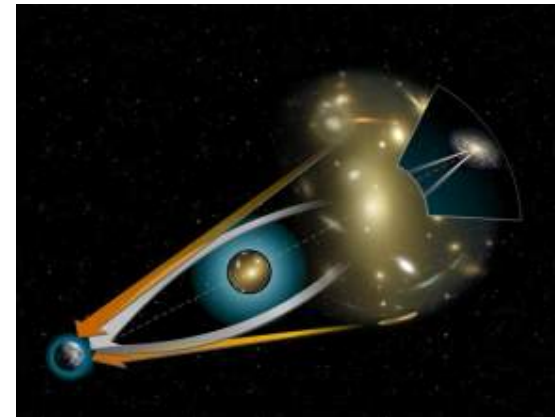
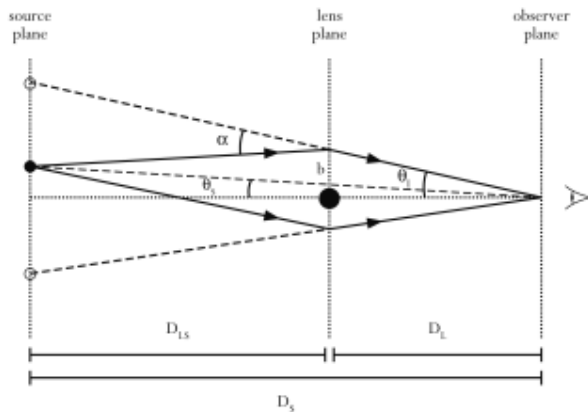
CCD images from P. Young et al., ApJ, 1980

- Discovered by Walsh et al. - 1979 - "Old Faithful"
- Separation = 6 arcsec, but spectrally confirmed
- Time delay =  $417 \pm 3$  days between the two images
- Flickering intrinsic, not from intervening objects as previously thought, but still a lensed pair... (L. Goicoechea et al., 2009)

# And now, the main topic...!

- Galaxy Clusters and Gravitational Lensing:
- (1) How does it work?
- (2) What is it good for?
- (3) What are some limitations of its use?
- (4) Some images from HST WFPC2 and ACS imaging... (More soon from WFC3 & ACS! - Large, Multi-Cycle Treasury prop.: Postman, Ford, et al. recently approved - 25 clusters...!)
- (5) Abell 370 ACS-R SM4 Early Release Observations: preliminary results; JWST & Beyond.

# Galaxy Clusters and Lensing: How Does it Work?

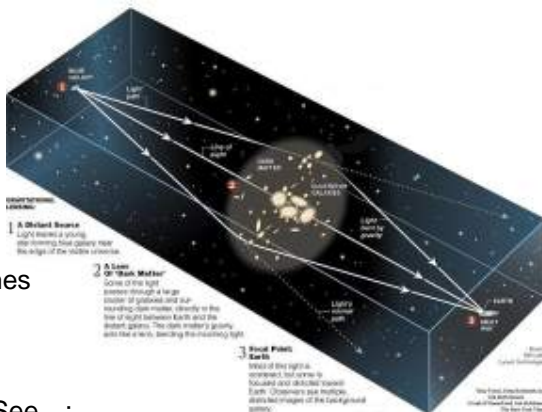


(STScI)

Bell Labs, Lucent Technologies

T. Tyson, G. Kochanski, I. Dell'Antonio

F. O'Connell & J. McManus, NY Times



Want more info? See....:

From 1994, a good introductory review by B. Fort & Y. Mellier:

[http://nedwww.ipac.caltech.edu/level5/Mellier/Mellier\\_contents.html](http://nedwww.ipac.caltech.edu/level5/Mellier/Mellier_contents.html)  
&  
[http://en.wikipedia.org/wiki/Gravitational\\_lensing\\_formalism](http://en.wikipedia.org/wiki/Gravitational_lensing_formalism)

In gravitational lensing:

- Convergence term magnifies size while preserving surface brightness
- Shear term stretches images tangentially; weak lensing stats imp.
- Displacement equations may have multiple solutions = multiple images

# Galaxy Clusters and Lensing: How Does it Work? (cont'd)

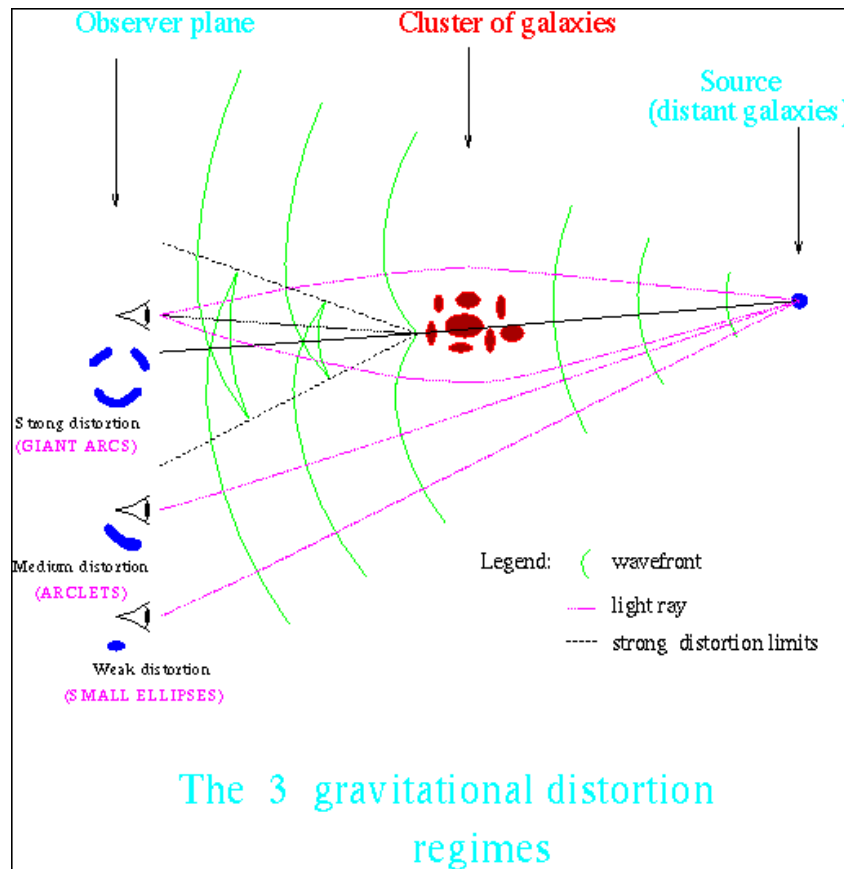


Diagram From Fort & Mellier, 1994

Multiple manifestations of the same phenomenon. Appearance of lensed objects depends on relative alignment of source, lens, and observer, as well as other factors such as distances between source, lens, and observer, and the size of the source, the mass of the lensing object, etc. What you see is just a convolution of all of these factors and more, including surface brightness and color etc. of the source, and other factors as well.

# Galaxy Clusters and Lensing

- What is it good for? Some principal benefits:
- Gives clues to dark matter content (mass) and halo shape of foreground cluster
- Magnifies distant galaxies in early universe, aiding studies of galaxy formation, morphological structure (shapes), stellar populations, dust & metals content, etc. (i.e. revealing early star-forming history & rates)
- Enables study of supernovae etc. at much higher redshifts, giving clues to cosmology
- Time delays, AGN flickering --> cosmology

# Galaxy Clusters and Lensing

- What else is it good for?
- Makes beautiful, amazing images, showing us just how rich Nature can be in its array of phenomena, and that it also works in amazing but normal ways that are actually predictable.
- Scientists are not immune to the power of beautiful images. We love them too, and they are part of our inspiration - part of what attracted us to go into science, to discover the beauty of how something looks AND how it works!

# Galaxy Clusters and Lensing: Some Limitations

- Degeneracies between lensing effects and cosmological time dilation effects can make interpretation of high- $z$  SNe results more difficult.
- Need highest resolution and largest number of multiply-imaged sources to derive best constraints on mass models of clusters and to properly reconstruct morphologies of distant objects.
- Multiple colors needed for best matching of source IDs of multiply-lensed objects, etc.

# Early Ground-based Observations and Discoveries

- Abell 370 (Genevieve Soucail et al., CFHT, mid-1980s: One of the first lensing clusters found and ID'd) - We'll return to this one later!
- Others joined in, as well...
- Some fundamental questions raised: Tidal tails or gravitationally-lensed arcs? Near or far? Two, three, four etc. objects or just one seen over and over and over...? Time delays if multiply- imaged objects, AGN flickering, supernovae, etc.? Implications for distance scale and cosmology?

# NGC4038/9: “Antennae” Tidal Tails



Ground-based



HST - B. Whitmore et al.

- Tidal tails sometimes mimic the appearance of gravitationally-lensed arcs, or vice-versa, even with very high-resolution HST data!
- A case in point: New ACS/WFC Abell 370 images! (We'll return to that later... But first, two older ones of Abell 370, taken from the ground...)

# Abell 370 (CFHT, mid-1980s)

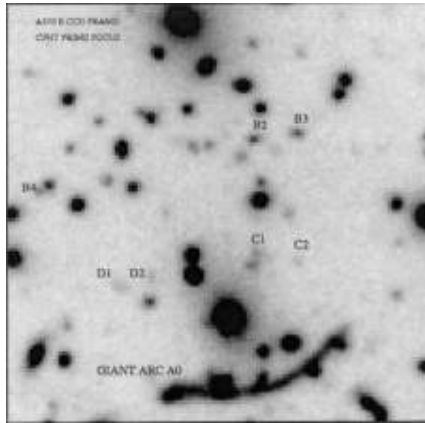


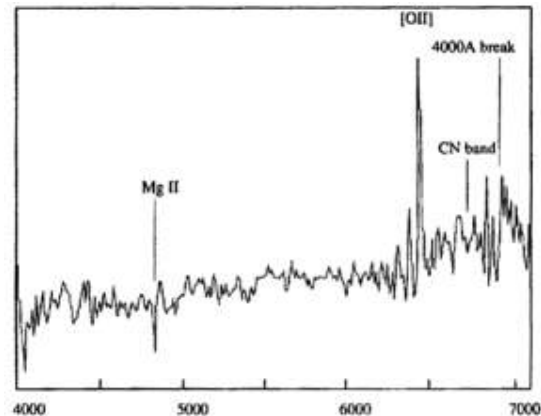
Image: CFHT Prime Focus



Image: CFHT, B. Fort & Y. Mellier

- Lynds & Petrosian (1986) and Soucail et al. (1987) point out existence of large curved arcs around two clusters of galaxies
- Paczynski (1987) announces correct interpretation...
- Soucail et al. (1988) spectroscopically confirm that redshift of A370 arc much greater than that of cluster --> lensing in clusters confirmed!

# Abell 370 Spectrum



Soucail et al., 1988, Using ESO 3.6m Telescope + EFOSC/PUMA2 Spectrograph

- Oxygen II [OII] line confirms the nature of the large arc as a galaxy.
- Presence of the [OII] with same redshift all along the arc indicates that it is the same galaxy, distorted, and stretched out into an arc, possibly imaged multiple times in the same arc.

# Abell 370 - CFHT (mid-1980s)

- Spectra confirm that giant arc is the same more distant galaxy magnified and imaged multiple times. The basic phenomenon is confirmed via essential spectroscopy! But other cases still questionable... Could some still just be tidal tails? Of course...! But most in the vicinity of massive galaxy clusters and galaxies are usually lensed arcs... Spectra tell the tale... Phot-z's used if too faint...
- Spec/Phot-z evidence critical; mass models and lensing equations help untangle things...

# Abell 370 - Distant galaxy at $z \sim 6.56$ - Its the tiny object!

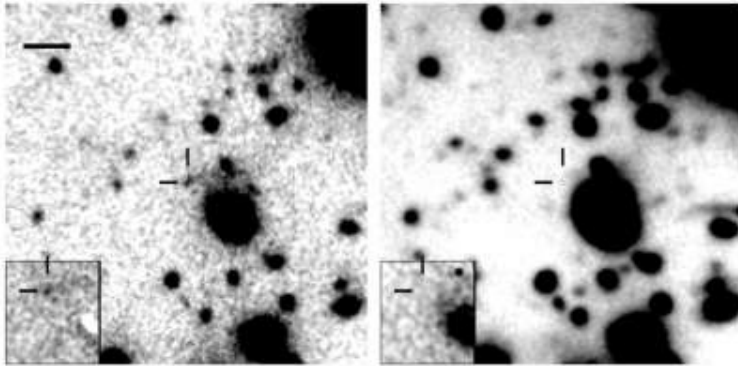
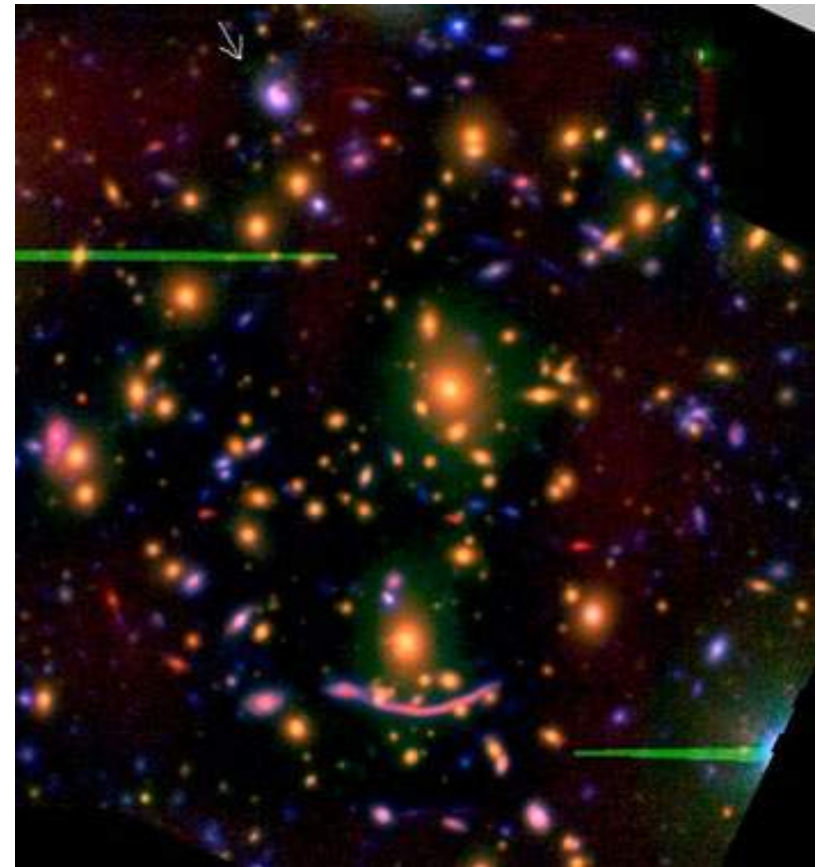


FIG. 1.—Narrowband 9152 Å/118 Å image (left panel) and *R* band image (right panel) of the emission-line object IBCM 6A, which is marked with the vertical and horizontal lines. An image in the narrowband filter with a normalized local continuum (*Z* band) subtracted (inset in left panel) shows that the object, which appears as two fragments, is a strong emission-line object. (We have slightly oversubtracted the *Z* band to completely remove the neighboring galaxy, whose core appears white.) The galaxy is not seen in the much deeper *R*-band image ( $>8$  hr on the Keck 10 m telescope) or in a 5600 Å F675W image taken with the WFPC2 on *HST*, shown in the inset in the right-hand panel. The neighboring bright galaxy to the southwest is a cluster member with a redshift of 0.375 ("BO #39" in Mellier et al. 1988), so that the emission is not associated with this object—in particular,  $H\alpha$  lies shortward of the filter bandpass. The images are centered on coordinates (J2000.0)  $R.A. = 2^{\text{h}}39^{\text{m}}54^{\text{s}}.73$ ,  $decl. = -1^{\circ}35'32''.3$  and are  $37''$  on a side. The bar in the upper left corner of the narrowband image shows a  $5''$  scale.

From ApJ Letters, Hu et al., 2002



E. Hu et al., 2002, strong emission-line object discovered in Keck LRIS Narrowband image, left-most in the panels above.

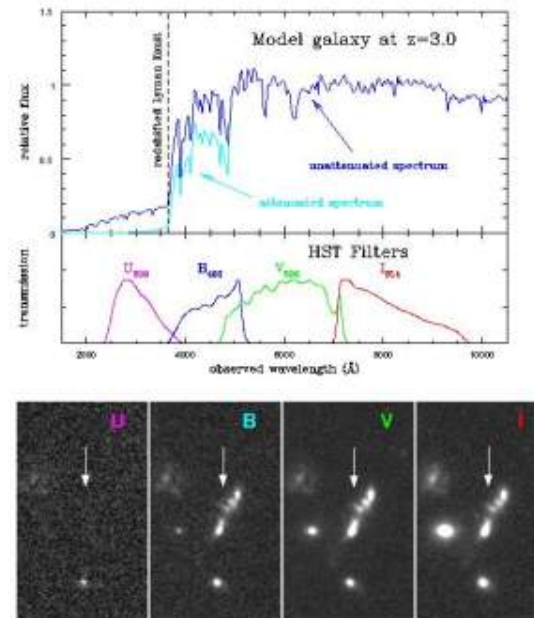
# HST and Lensing Clusters

- Wide-field high-resolution capabilities of first WFPC2 (1994) and later ACS/WFC (2002) provide richer data for interpretation over wider fields. (Ground-based adaptive optics only yield high-resolution over very small area... Wide area high-resolution is critical!)
- +
- Nature's gift (distant galaxies have higher surface brightnesses than expected)
- = A bonanza of great new HST data of observations of lensing clusters!

# HST NICMOS, WFC3, and Spitzer Multiwavelength Obs.

- Some of the highest-redshift objects are not even found in ACS images, but require data from the infrared + optical to identify. They are “dropouts” from bluer light & filters due to cosmological expansion, i.e. redshift.
- NICMOS and Spitzer have provided near-IR and “farther” IR observations to detect such “dropouts”; WFC3 will do so in near-IR in the future (now), as well! (JWST will probe farther into the IR, like Spitzer, but with better sensitivity and resolution.)

# “Dropouts” and “Phot-z’s”: Important in Field & Clusters



Galaxies “drop out” of view from UV towards red and infrared filters etc., depending on how distant they are and thus how far their light is redshifted.

This is also shown relative to the filter response or throughput curves for HST WFPC2 Ultraviolet (U), Blue (B), Visual (V), and long red (I) filters. Many very distant objects are too faint to observe spectroscopically. The time required would be too long even with massive ground-based telescopes like Keck. So, by observing in many well-chosen and well-calibrated filters, and then making careful note of how objects drop out of them at successively redder wavelengths, photometric redshifts are obtained. With use of proper “priors”, these are also now understood to be reliable indicators of the redshift and therefore the distance of sources in both field surveys as well as distant lensed galaxies found behind galaxy clusters.

Graphic courtesy of Mark Dickinson.

# HST and Lensing Clusters

- Some prime examples... (Just a very few of the many clusters and lenses imaged by HST, and only a small sample of the work done - by no means a comprehensive review of all the work done on these objects - many apologies to those not mentioned here!):
- Abell 2218, Abell 1689, Abell 1703, Bullet Cluster, CL2244-02, CL0024+1654, MACS Cluster J0025.5-1222, etc., and Abell 370 again, after SM4...

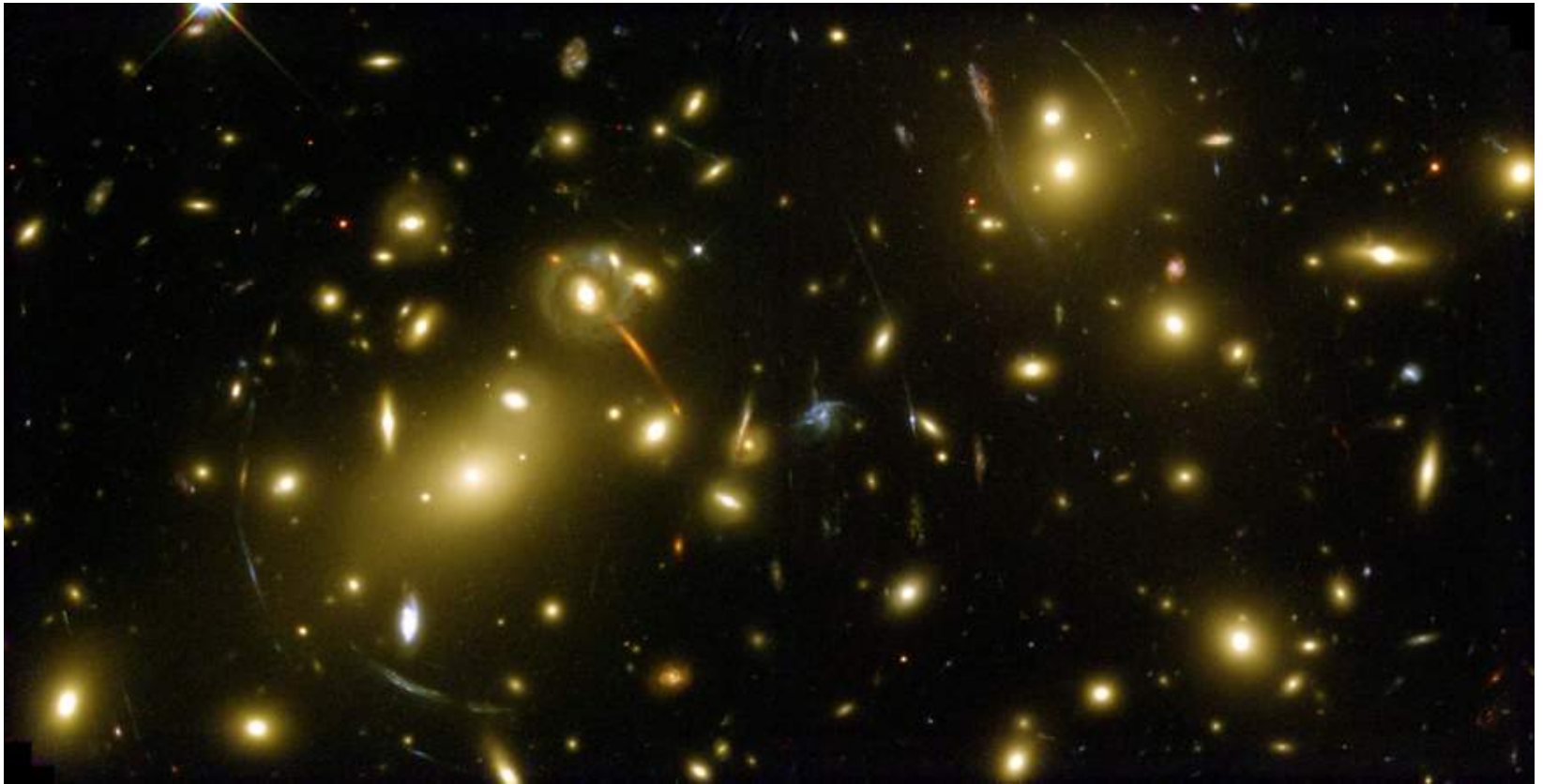
# Abell 2218, HST+WFPC2 circa 1995



A2218 by W. Couch, R. Ellis, I. Smail et al., ~1995

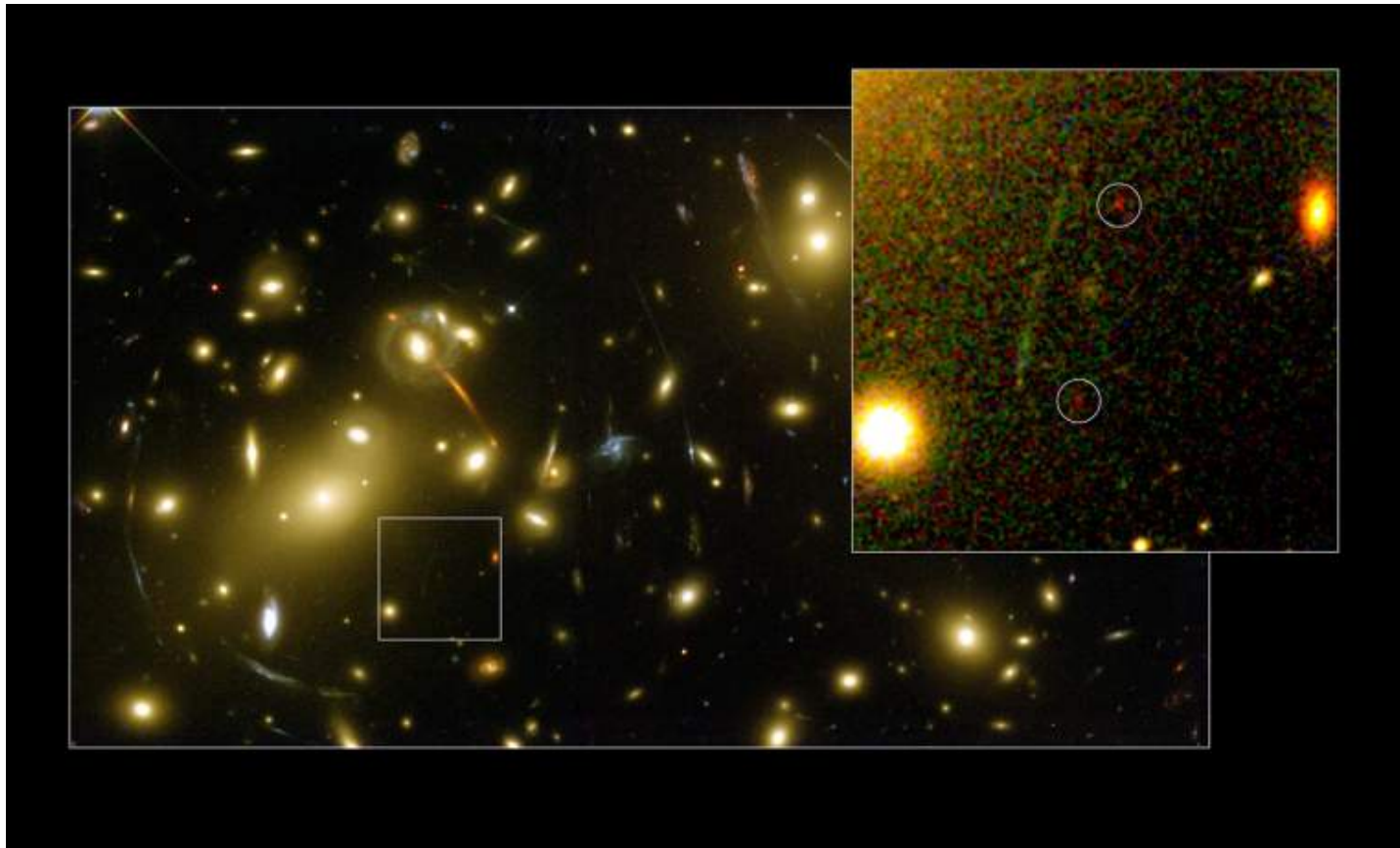
- Single filter (i.e. one broad-band color); but still spectacular!
- Showed richness of high-resolution detail, but not as much about fine details of colors of objects.
- Also maybe one of the only programs ever to be taken totally from end-to-end in hands-on fashion by one STScI contact person... ;-)

# Abell 2218 (ca. 1999-2000) SM3A ERO



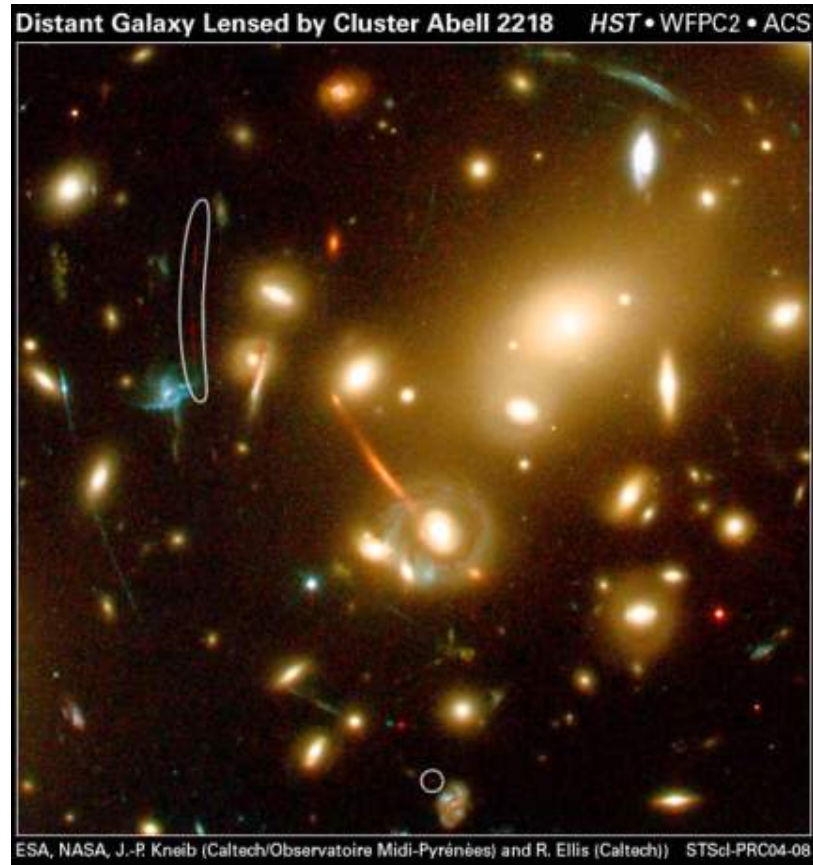
A. Fruchter and the SM3A ERO Team  
Abell 2218  $z \sim 0.176$  or  $\sim 2$  Billion l.y. Distant

# Abell 2218 (Details) - Most Distant Galaxy, 2004

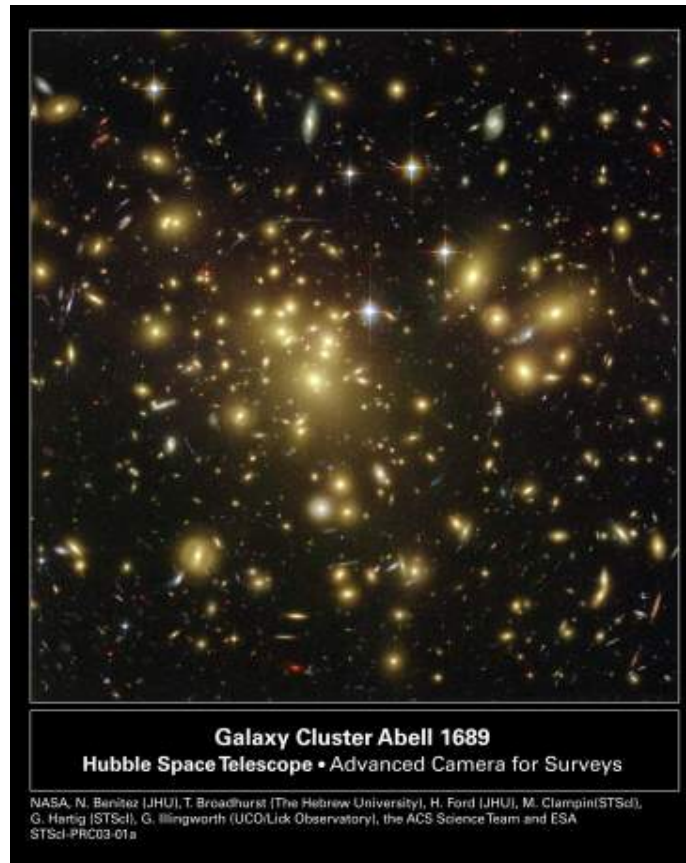


Kneib, Ellis et al., 2004, Distant galaxy, at  $z \sim 7.0$ ,  $\sim 13$  billion yrs old, "pair" of red objects are same object encircled twice; Orange arc = E gal @  $z \sim 0.7$ ; Blue Galaxies = star-forming galaxies at  $z \sim 1-2.5$ .

# Abell 2218 (More Details - Distant Objects)

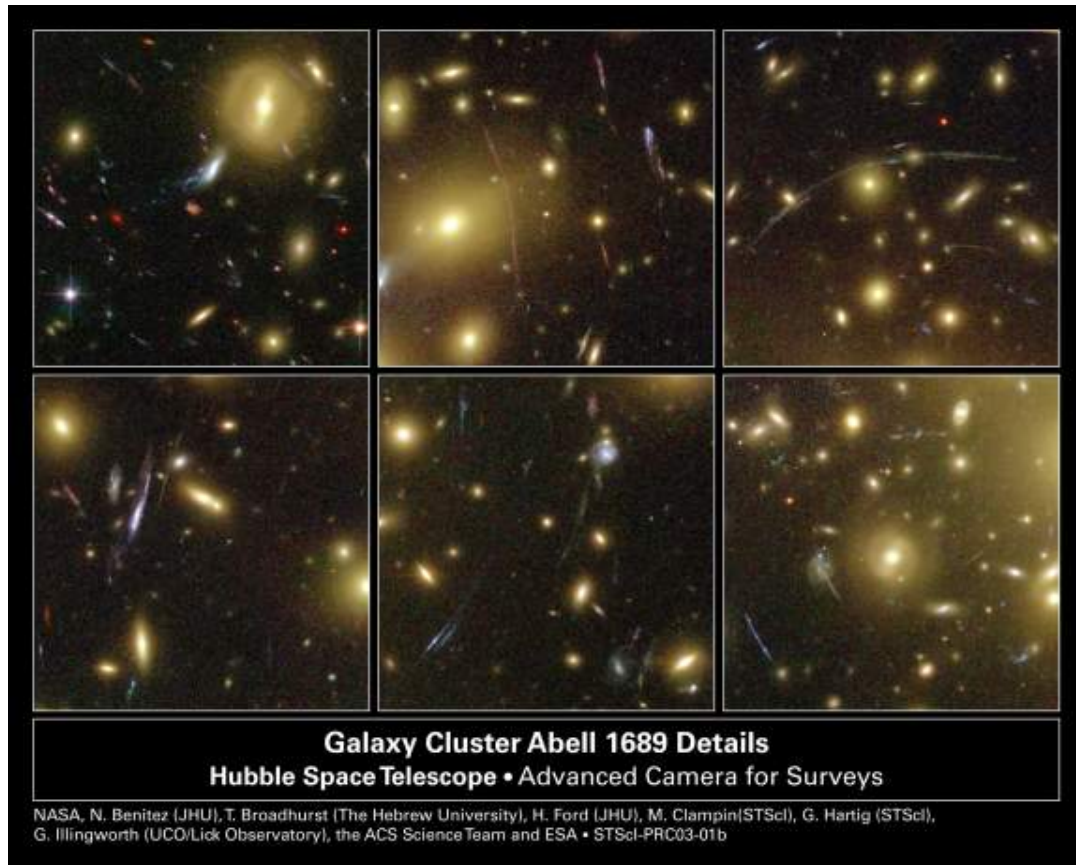


# Abell 1689

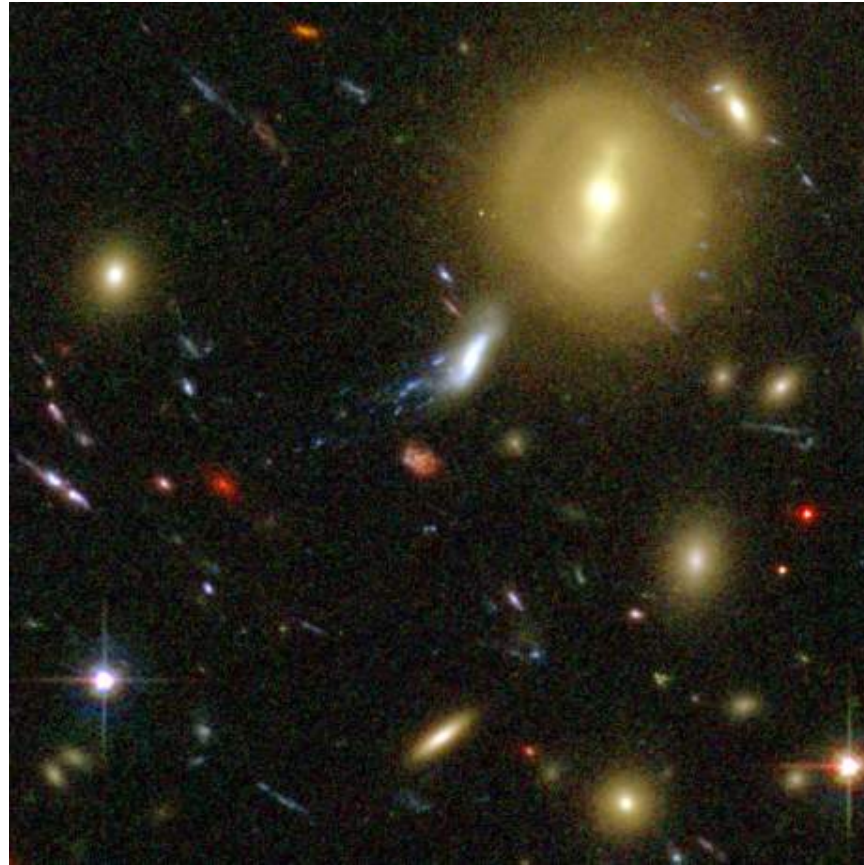


Abell 1689,  $z \sim 0.183$ ,  $\sim 2.2$  Billion l.y. Distant  
Largest Einstein radius known -  $\sim 50$  arcsec. (Einstein radius is the angular size of an Einstein Ring, if such were present.) Abell 1689 also represents the largest number of strong-lensing constraints (multiply-lensed sources, etc.) in one field of any galaxy cluster known. This means the mass model can be more accurate.

# Abell 1689 (details)



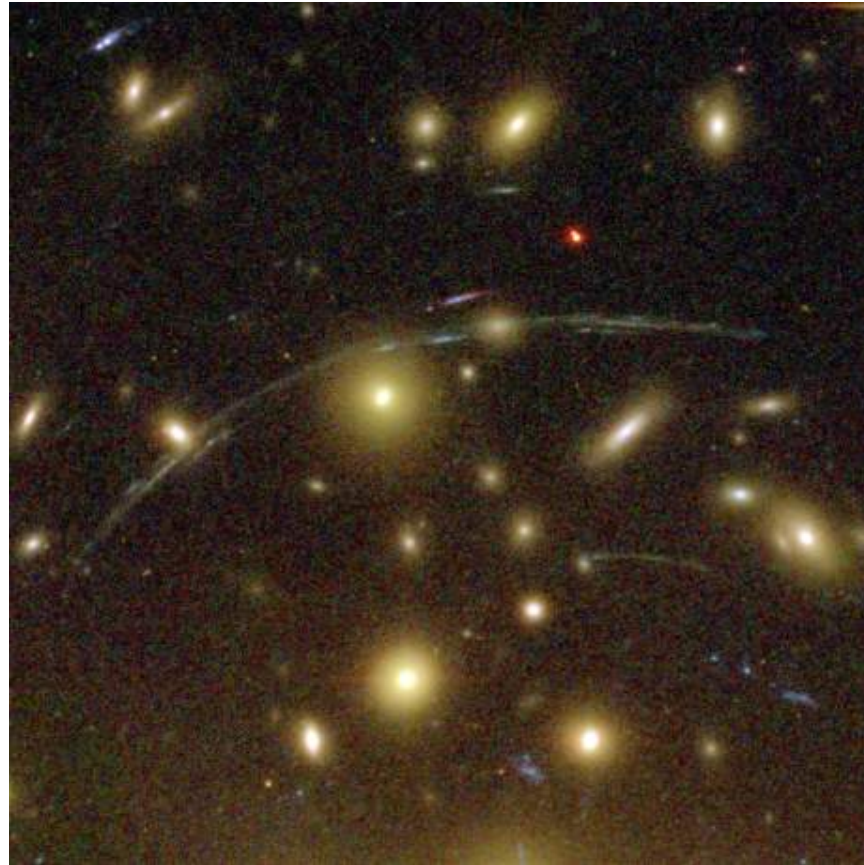
# Abell 1689 (details)



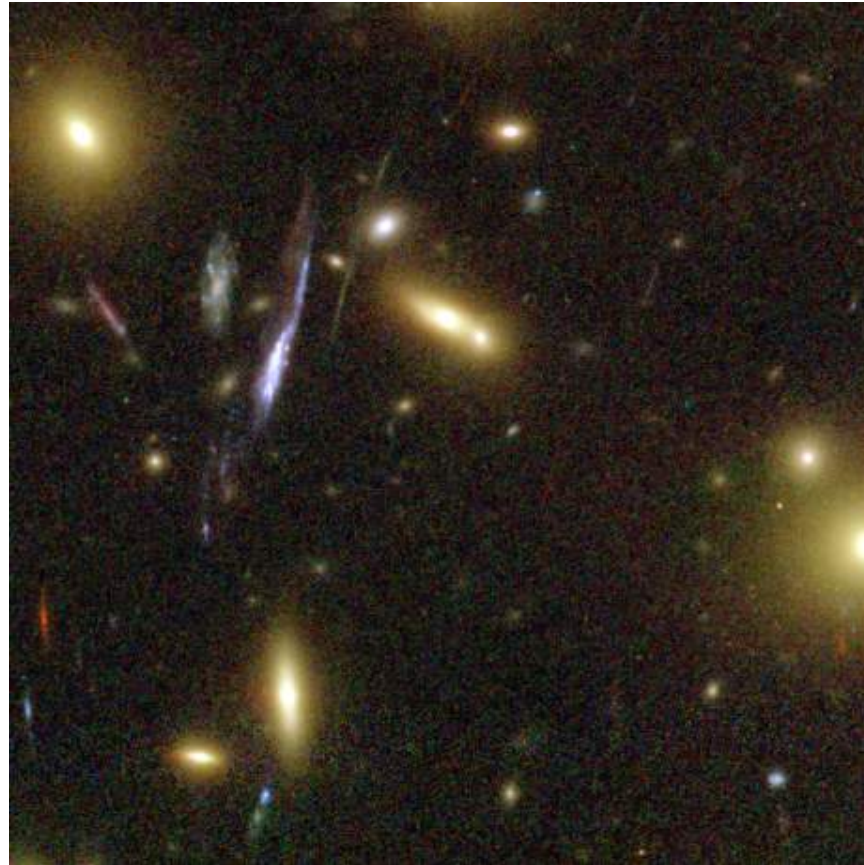
# Abell 1689 (details)



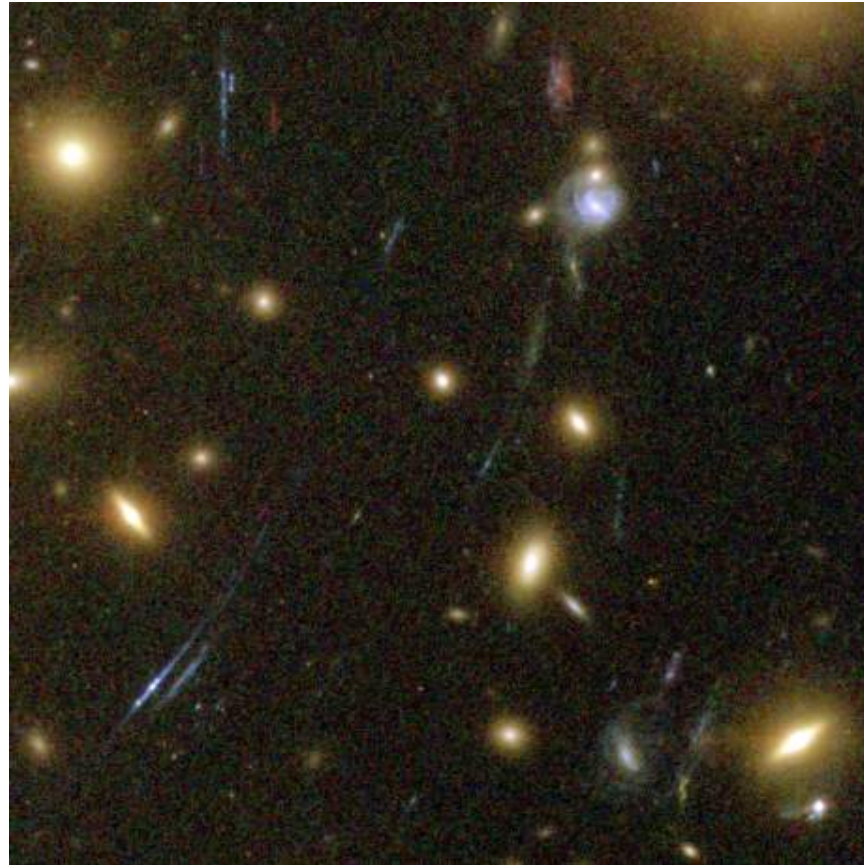
# Abell 1689 (details)



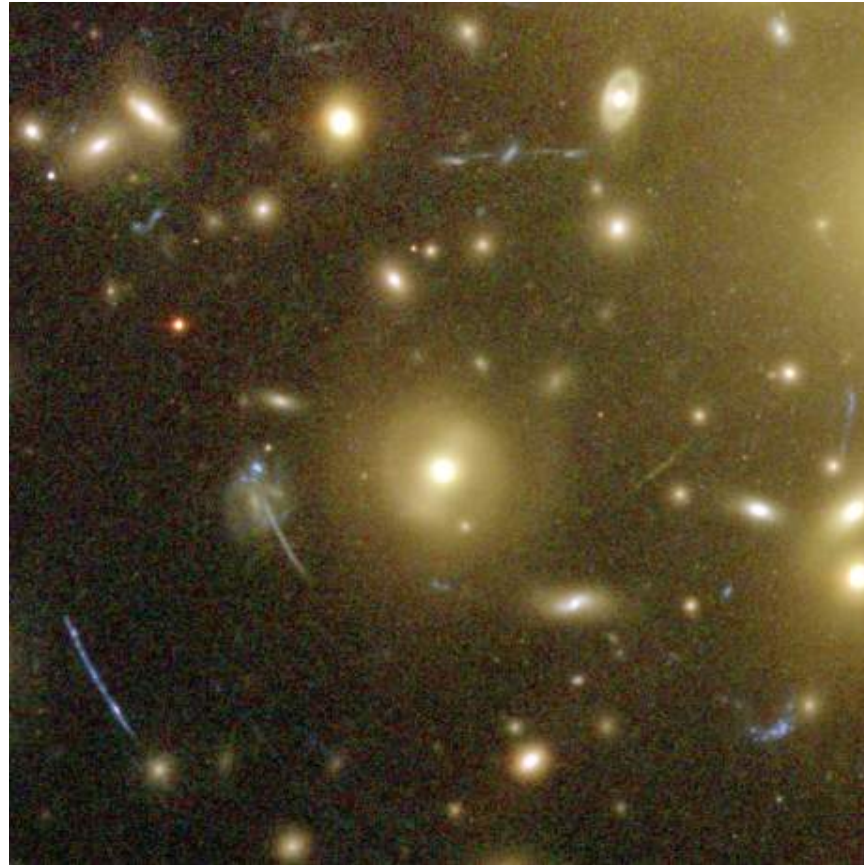
# Abell 1689 (details)



# Abell 1689 (details)

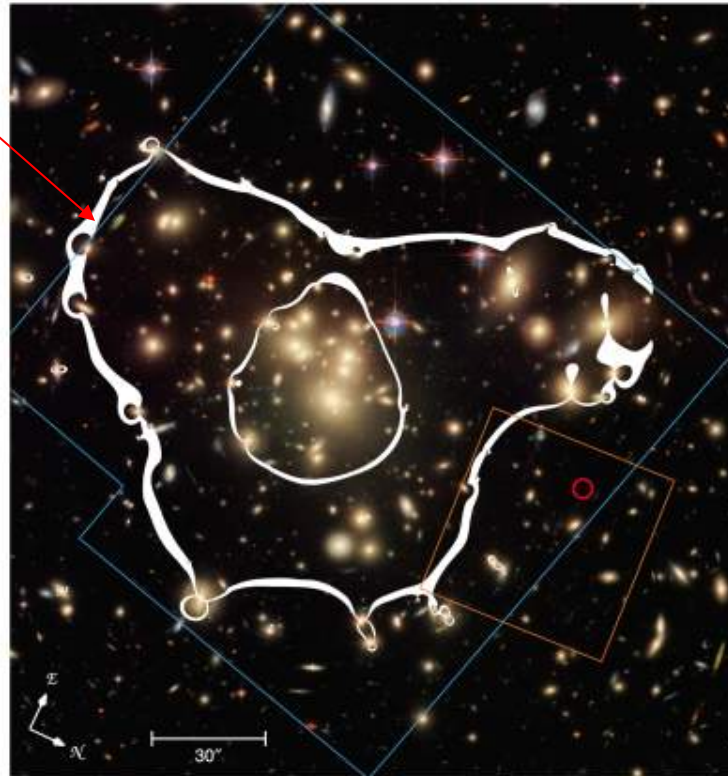


# Abell 1689 (details)



# Abell 1689 - HST ACS+NICMOS & Spitzer

Line of infinite magnification;  
Magnification increases as  
you approach this line from  
either side, and there is a  
trough of lower magnification  
between this and the line  
around the nucleus of the  
cluster.



The magnification factor of the  
distant lensed galaxy in the circle  
at left is a factor of about 9x.

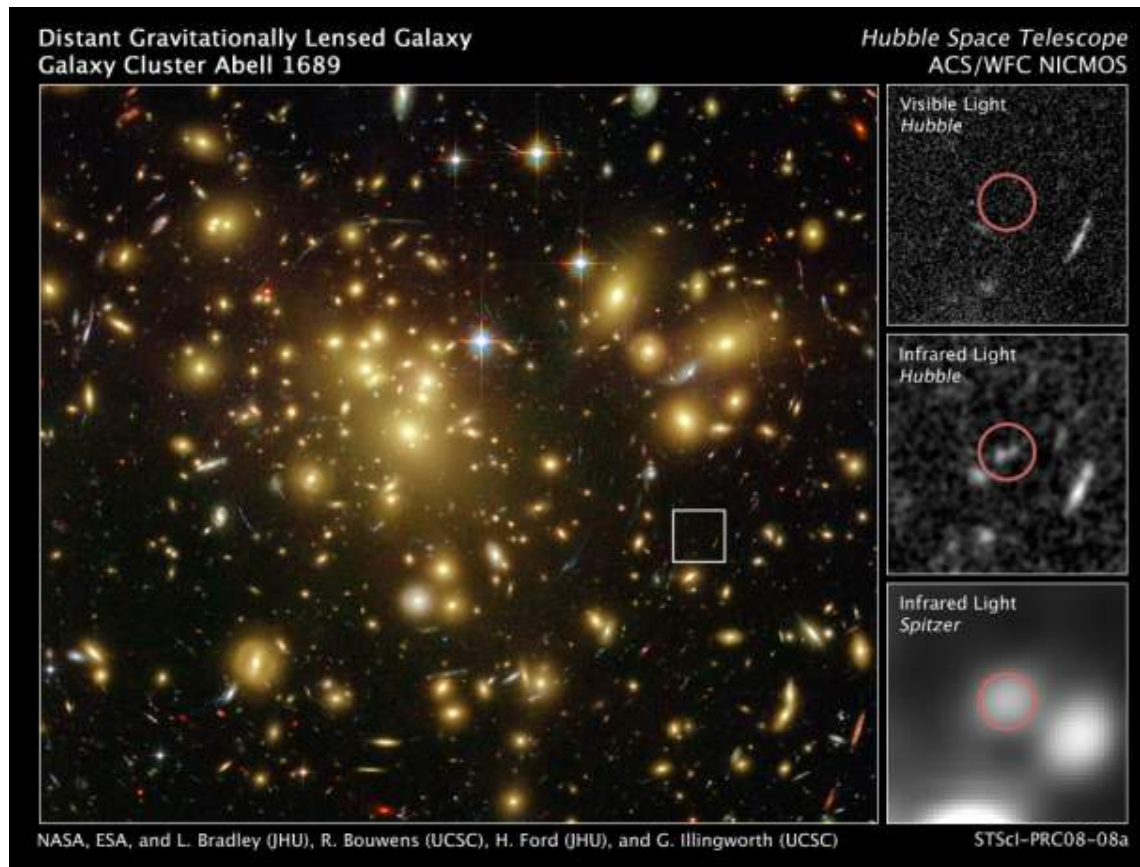
FIG. 1.— ACS color image ( $3.4' \times 3.4'$ ) of Abell 1689. The regions surveyed by our followup NICMOS  $J_{110}$  and  $H_{160}$  images are illustrated by the blue and orange outlines, respectively. A1689-zD1 is located at J2000 coordinates  $\alpha = 13^{\text{h}}11^{\text{m}}29.96^{\text{s}}$ ,  $\delta = -1^{\circ}19'18.7''$  and is denoted by the red circle. The white contours represent the  $z = 7.6$  critical curves ( $\mu \geq 200$ ).

L. Bradley et al., ApJ, 2008

ACS/WFC image; Blue = NICMOS J, Orange = NICMOS H

H-band image is used to verify that its not a dusty, lower-redshift object masquerading as high-z object.

# Abell 1689 - A Newer Most Distant Galaxy - 2008



Abell 1689,  $z \sim 0.183$ , 2.2 Billion l.y.; Galaxy A1689-zD1,  $z \sim 7.6$ ,  $\sim 12.97$  Billion l.y.

This object is a “dropout” from bluer wavelengths, hence only visible in the infrared. This also illustrates the importance of multiwavelength observing. More distant objects have since been found, e.g. a GRB at  $z \sim 8$  and some  $z \sim 8$ -8.5 galaxies in Bouwens, Illingworth, and Stiavelli’s new HUDF GOODS-South WFC3 deep “boreholes” recently announced in January 2010.

# Abell 1703



HST+ACS/WFC, H. Ford et al. (ACS GTO Team); M. Limousin et al., 2008,, J. Richard, 2008.  
Abell 1703,  $z=0.26$ , or  $\sim 3$  Billion l.y.; Large Einstein radius, and one of the most massive clusters found in SDSS.

# Abell 1703 - Multiply-Lensed Systems

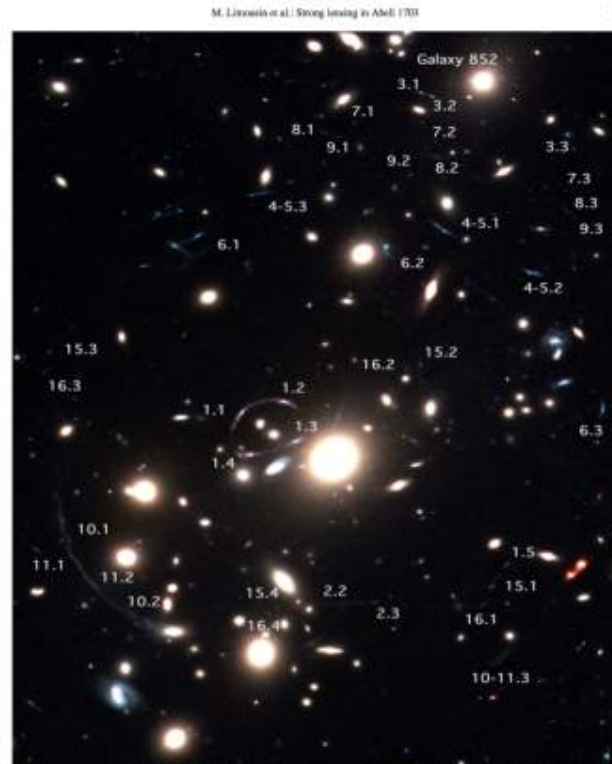
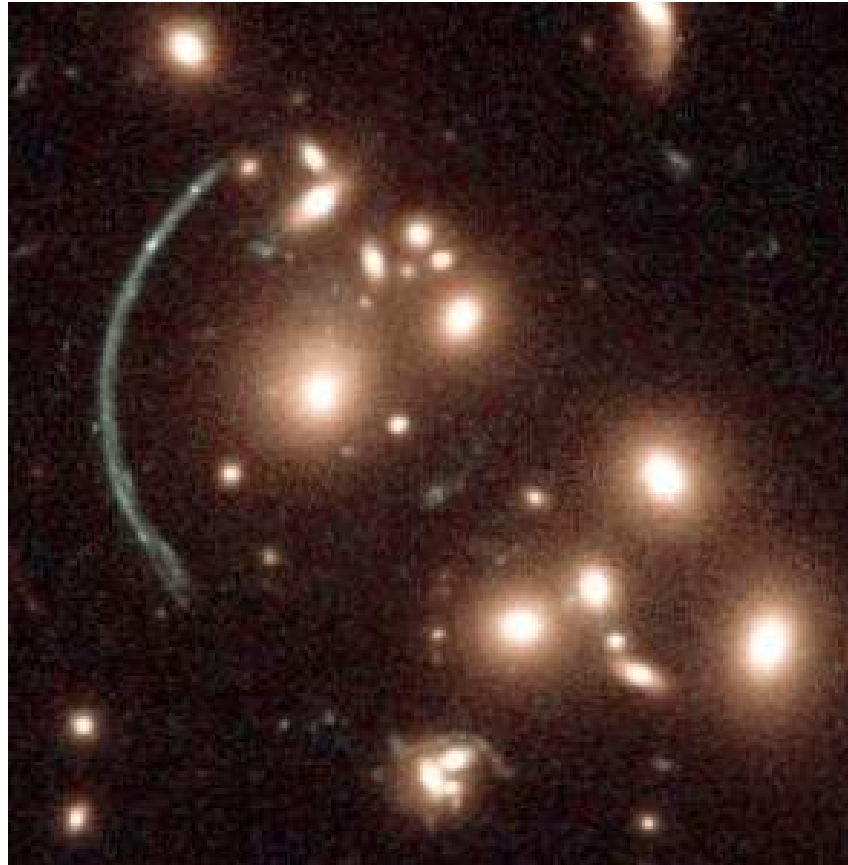


Fig. 1. Colour image of Abell 1703 from F850W, F625W and F475W observations (Sart 2007). North is up, east is left. Size of the field of view is equal to  $77' \times 107'$ , corresponding to  $536 \text{ kpc} \times 454 \text{ kpc}$ . Multiply imaged systems used in the analysis are shown, and colour images are given in Appendix. The central ring formed by four bright images is found close to the zD galaxy. The giant arc (systems 10-11) falls south-east, at distance of  $\sim 35'$ . System 2 is a straight arc located south of the zD and composed of two merging images. Systems 15 and 16 follow each other, forming a kind of Einstein cross configuration. In the north, we find a set of tangential systems 4-5, 6-7, 8-9. Then, two bright merging images form systems 3, located close to galaxy 852 which present a blue nearby lensing feature. The filamentary structure can be appreciated on this image. See also the Subaru *H* band image in Appendix, which is more extended.

# CL2244-02 - Truncation of Galaxies' Dark Matter Halos



HST+WFPC2 - I. Smail et al., 1997, P. Natarajan et al. 2002. Data show two sub-clumps of mass distribution. Tidal stripping of galaxies' dark matter halos may also be important in the cluster. The DM halos of galaxies in clusters appears truncated compared to the DM halos of galaxies in the field.

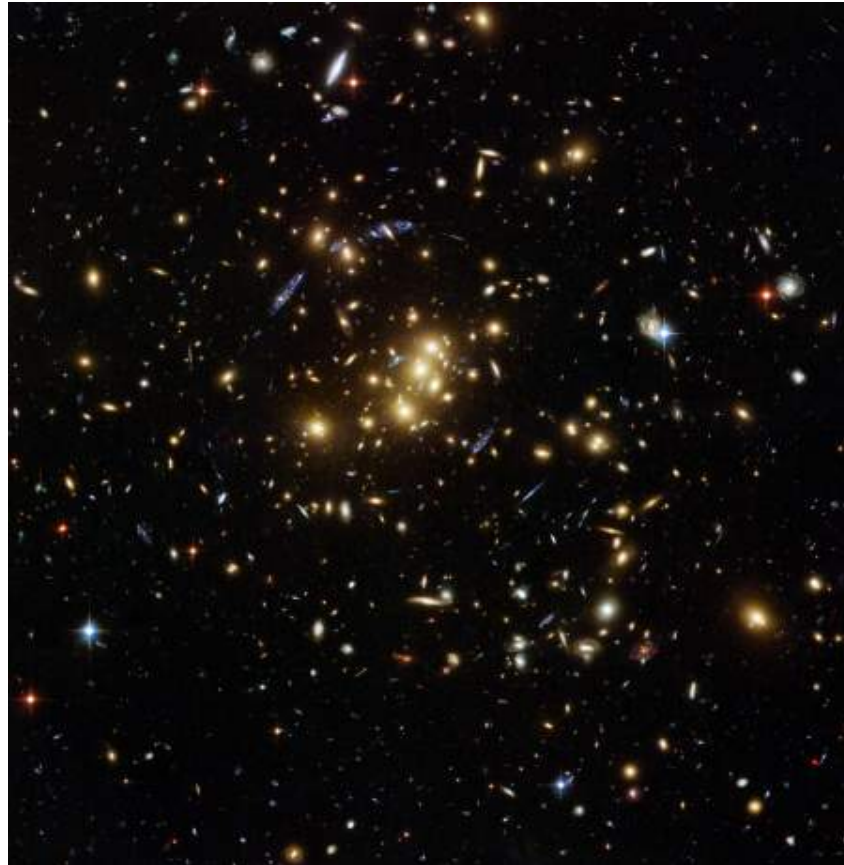
# CL0024+1654



HST+WFPC2 (1994-96): Colley, Turner, & Tyson  
CL0024+1654  $z \sim 0.391$  or  $\sim 4.2$  Billion l.y. Distant

“Blue arc” galaxies at  $z \sim 1.675$ , or  $\sim 9.7$  Billion l.y. distant: same one appears  $\sim 5$  more times, lensed...

# CL0024+1654 - ACS Wide Field Camera



M. J. Jee, H. Ford, et al. - ACS GTO Team

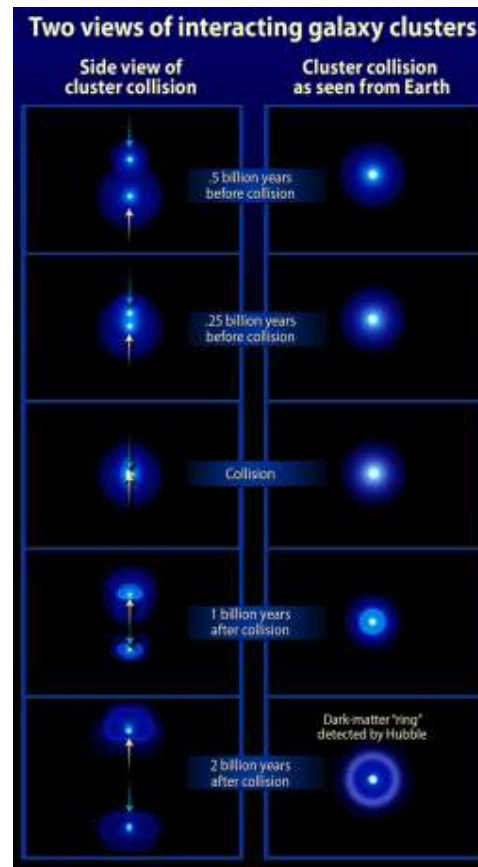
ACS/WFC has a wider field of view, higher sensitivity, and higher resolution than WFPC2, so is better for cluster lensing studies. The same is true of the UVIS channel of the new WFC3 camera, and the IR channel of the new WFC3 camera has a much wider field, higher sensitivity, and higher resolution than the largest NICMOS camera.

# CL0024+1654 - Dark Matter Ring - Result of a Collision?



M. J. Jee, H. Ford et al., 2007  
"Ring" is ~5 Million l.y. wide.

# CL0024+1654 - Simulation of Collision of Two Clusters



# CL0024+1654 - Like a Giant Cartwheel Phenomenon?



Cartwheel Galaxy - HST+WFPC2 (1994) - Kirk Borne, Ray Lucas et al.

# CL0024+1654

## Multiply-Lensed •Galaxies



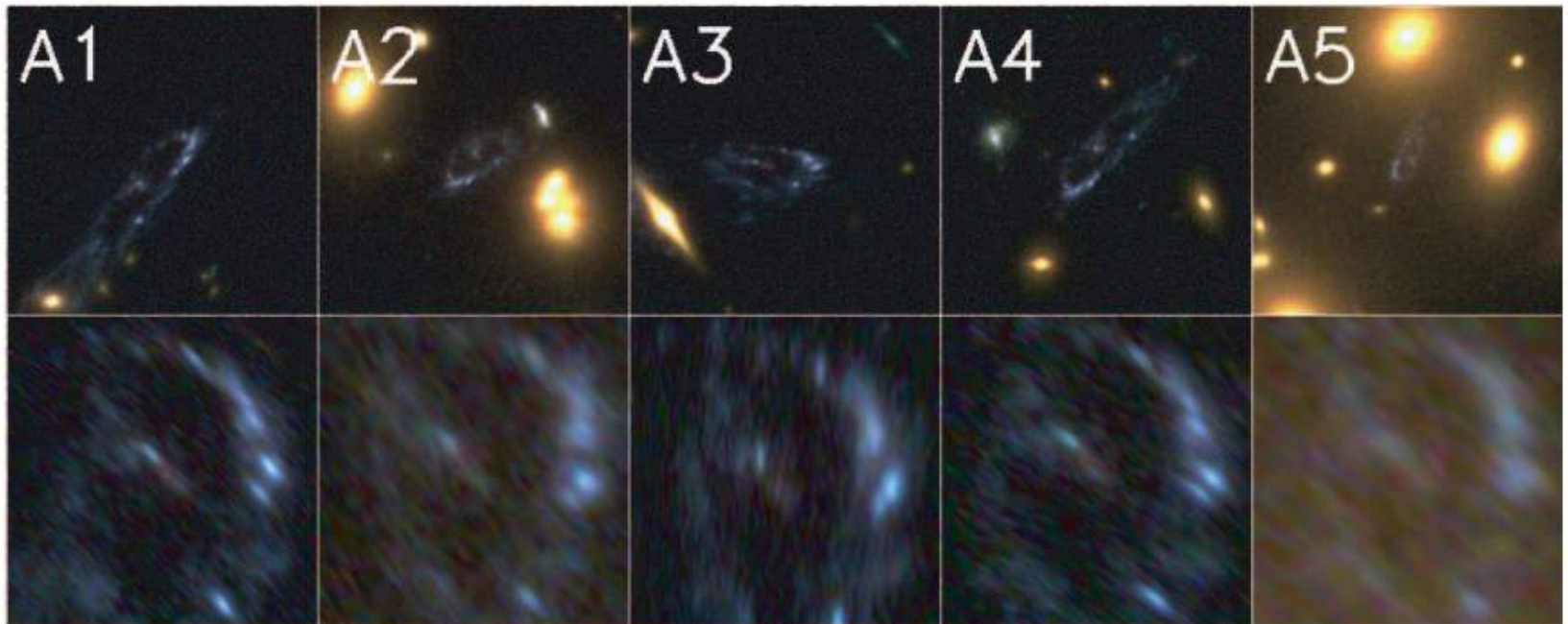
Jee, Ford et al., 2007

# CL0024+1654 - More Multiply-Lensed Galaxies



Jee, Ford et al., 2007

# CL0024+1654 - Image De-Projection: Multiply- Lensed Galaxy



Jee, Ford et al., 2007  
Galaxy at  $z \sim 1.675$

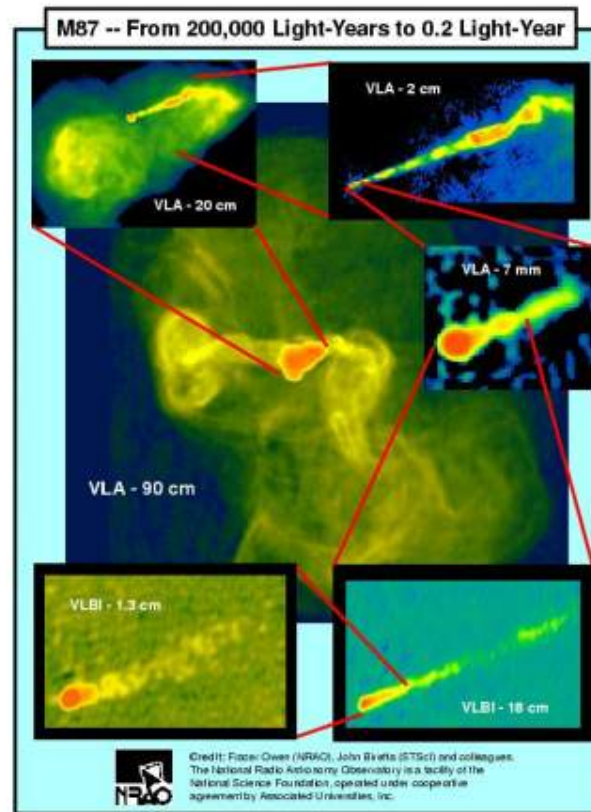
# So, the main points are:

- Clusters useful for magnifying distant galaxies & telling us information about their structure & formation, their dust and stellar content, their star-forming history, and therefore the star-forming history of the universe.
- Location and shapes of lensed galaxies tell us about the shape and amount of mass in the dark matter halos of the lensing galaxies or galaxy cluster.
- Large samples of these (ongoing) will make scientific understanding of these more robust. And many more multiply-lensed distant galaxies per cluster make the mass models better for studying lensing cluster dark matter halo structure + reliably deprojecting lensed galaxies to better study their morphologies, etc.

# Brief Detour: More Benefits of Multiwavelength Observations

# Massive Galaxies in Clusters

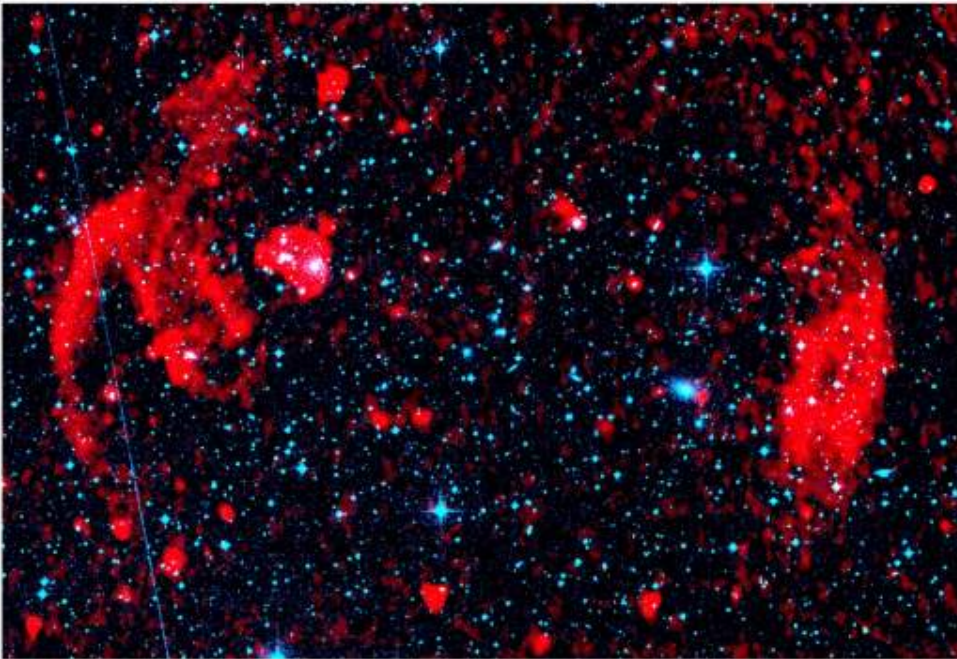
## M87 in Virgo - Radio (VLA)



Energetic phenomena like jets are present in some massive elliptical galaxies in cores of clusters such as M87, in the Virgo Cluster of galaxies.

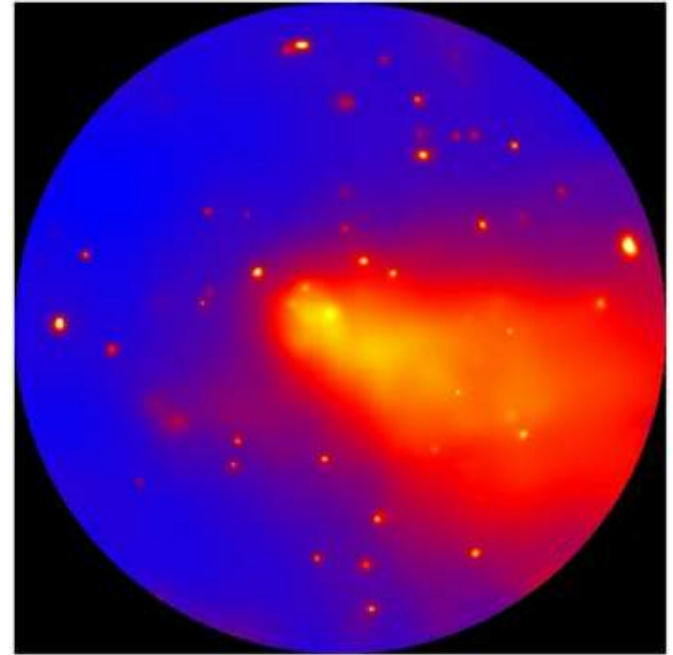
# Abell 3376 - Multiwavelength Observations Reveal More

Similar to the “Bullet Cluster”?



VLA Radio Observations reveal shells of gas, possibly blown off by shock waves from violent collisions between galaxies in the cluster. They do not appear to be gravitationally-lensed arcs though lensing is undoubtedly present at some level in the cluster, as it is in practically all clusters.

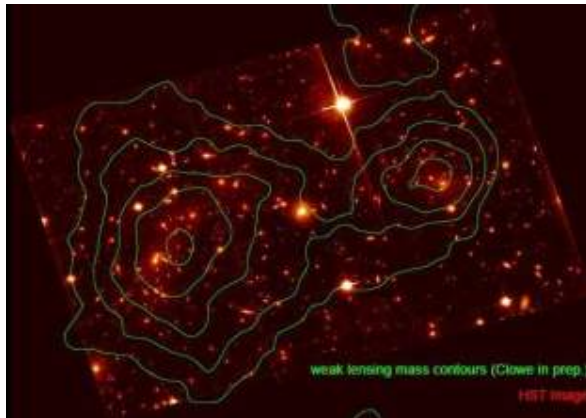
J. Bagchi, 2008, IUCAA, NRAO/AUI/NSF



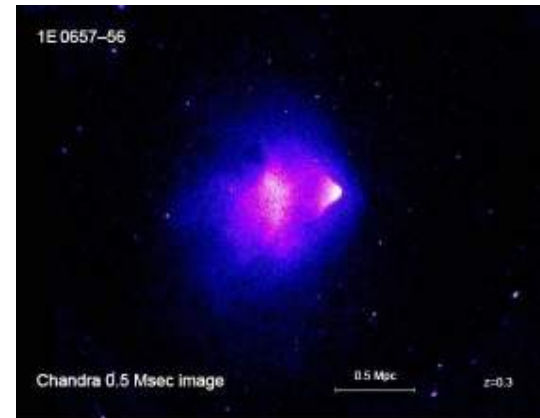
XMM-Newton x-ray image. X-rays are coming from gas heated to 60 million degrees Kelvin. The “bullet” shape is due to the supersonic collision of a smaller galaxy sub-cluster with the main body of the cluster.

J. Bagchi, 2008, IUCAA, ESA

# 1E0657-56 - “Bullet Cluster”



Clowe et al.



Clowe et al.

- Weak lensing contours on the image to left show larger, wider area concentration of mass on the left, smaller on the right...
- X-ray gas imaged by Chandra on the image to right shows a bullet shape, again probably due to collision of two sub-components of the merging cluster...

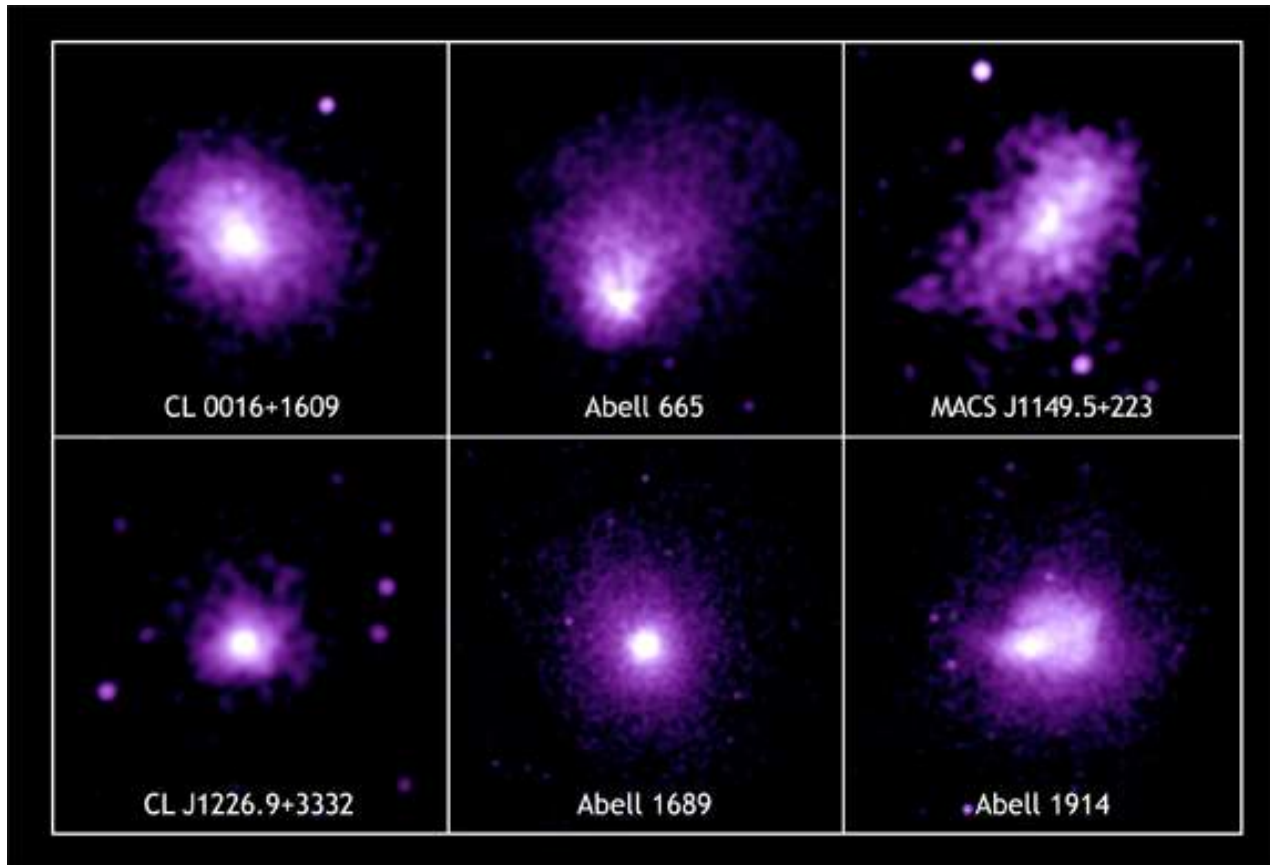
# MACS J0025.4-1222: Dark Matter & Collision of Clusters



MACS Clusters = Massive Cluster Survey - HST optical + Chandra X-ray; HST ACS - M. Bradac et al., Chandra - S. Allen et al. Similar to the "Bullet Cluster", but no "bullet". It is at ~5.7 l.y. distant from us & much older than the "Bullet". However, it was still very violent and as a "prequel" to the "Bullet Cluster", shows clear separation between dark and ordinary matter. Total mass = blue (dark matter + ordinary matter) <sup>68</sup> pink is hot x-ray gas, or ordinary matter. X-ray gas collided & slowed down, dark matter did not slow down, and thus dark matter particles interact only weakly with themselves other than via gravity. Finding such as this are a major achievement of modern astronomy. Lensing analysis of HST images helped.

# Another Use for Multiwavelength Galaxy Cluster Observations

# Chandra X-ray Observations Used for Distance Scale



N. Bonamente et al., 2008, NASA/CXC/MSFC; Distances: CL0016  $z \sim 0.54$ ,  $\sim 5.3$  Billion l.y., A665  $z \sim 0.18$ ,  $\sim 2.2$  Billion l.y., MACSJ1149.5  $z \sim 0.54$ ,  $\sim 5.3$  Billion l.y., CLJ1226.9  $z \sim 0.89$ ,  $\sim 7.3$  Billion l.y., A1689  $z \sim 0.18$ , 2.2 Billion l.y., A1914  $z \sim 0.17$ , 2.1 Billion l.y. 70

# Sunyaev-Zeldovich Effect and the Cosmic Distance Scale

- Galaxy clusters are observed in x-ray and radio wavelengths; find cluster hot x-ray gas
- Radio telescopes measure amount of distortion in Cosmic Microwave Background
- Photons from CMB interact with electrons in hot gas observed in x-rays; photons gain energy from interaction, distorting the signal from the CMB in direction of the cluster
- Magnitude of distortion depends on density and temperature of hot electrons and physical size of cluster

# Sunyaev-Zeldovich (cont'd)

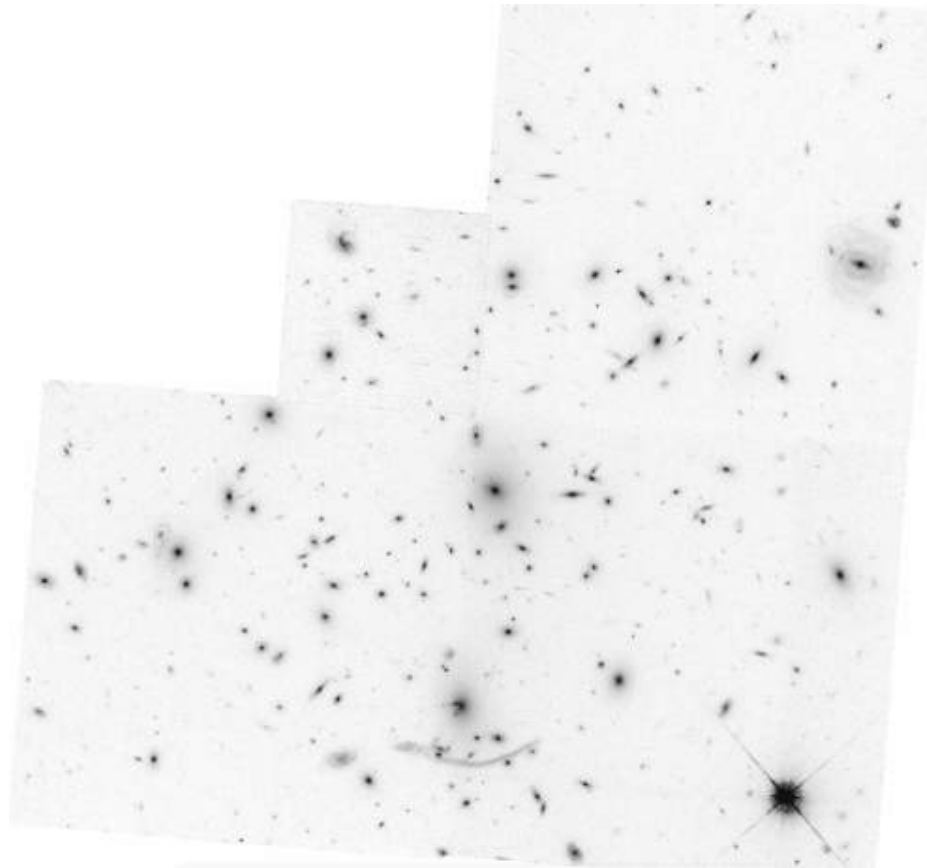
- Measurements of physical size allow the cluster distance to be derived.
- For the clusters shown, the Hubble Constant was measured to be  $\sim 76.9$  km per second per Mpc (1 Mpc=3.26m l.y.), putting the age of the universe at about 13-14 billion years, in basic agreement with other methods from Hubble etc.

ACS-R SM4 ERO

Observations of Abell 370 and  
its Bright Arc -16 July, 2009

(40th Anniversary of Launch  
of Apollo 11 to the Moon)

# Abell 370 - WFPC2 V-band



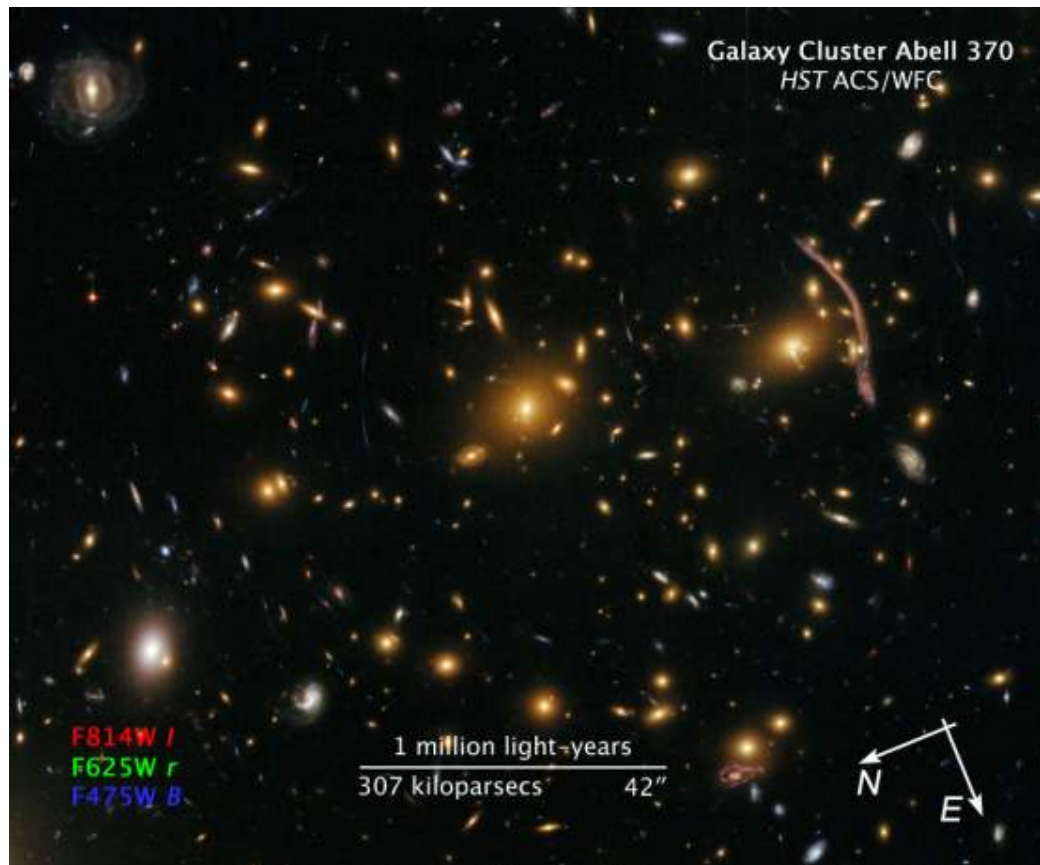
Bezecourt, Kneib, et al., mid-to-late 1990s

# Abell 370 - ACS-R 2009 ERO



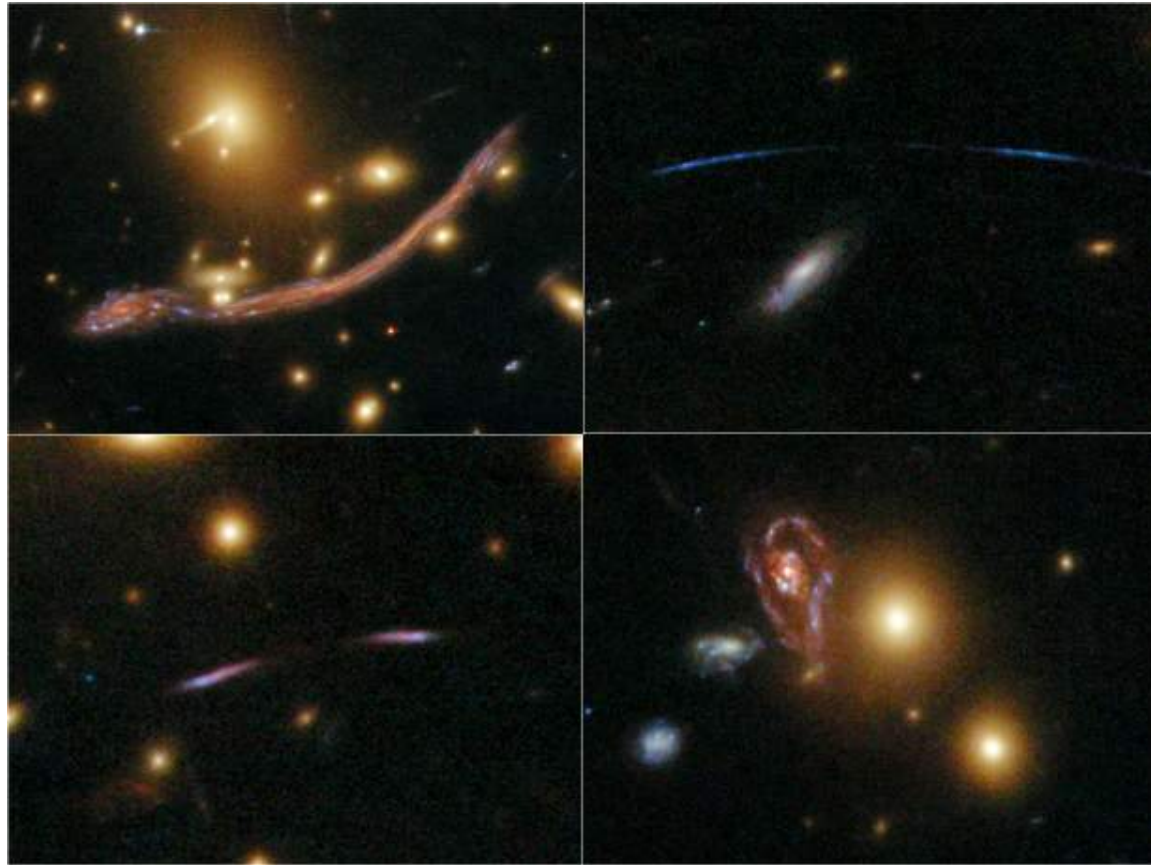
K. Noll, PI, and ACS-R ERO Team: M. Chiaberge, M. Sirianni, D. Golimowski, M. Mutchler, R. A. Lucas, (STScI) + R. Hook at ST-ECF, Garching-bei-Munchen, Germany + Numerous others at STScI, GSFC, NASA HQ, ST-ECF, etc.

# Abell 370 - ACS-R 2009 ERO



Abell 370 Cluster at  $z=0.375$  or  $\sim 4.1$  Billion l.y.; and Giant "Dragon" arc at  $z=0.725$ , or  $\sim 6.4$  Billion l.y., somewhat less than twice the distance farther. The reddish, lensed, distorted ring galaxy near the bottom of the image is at  $z=1.062$ , or  $\sim 7.97$  Billion l.y. NOTE: Some published "lookback time" distances are from different sources, so may vary some from these...! (Not always sure what went into their calculations in terms of cosmology, etc.) But the values given still show basic relative distances between different systems, between the lensing cluster and more distant lensed galaxies...

# Abell 370 - ACS-R 2009 ERO (Details)



# Abell 370 - ACS-R 2009 ERO “The Dragon”



# Abell 370 - ACS-R 2009 ERO

- The “Dragon” Galaxy: Long known to be the same more distant galaxy imaged multiply by the foreground galaxy cluster, based on solid spectroscopic observations from the ground.
- But we had never had such a good, detailed view before!
- So, when we first saw the new images from the repaired ACS/WFC, we all still thought it looked like a huge tidal tail, and double-checked the references in the literature...!

# Abell 370 - ACS-R 2009 ERO

## New Results

- First science paper already submitted and made public on astro-ph, a “hot spot” for astronomers’ new publications, by J. Richard, J.-P. Kneib et al.
- Chief findings are:
  - (1) Multi-color imaging is critical to better identifying multiply-lensed objects.
  - (2) Bright arc composed of 5 images of the same distant spiral; other components also multiply-imaged.

# Abell 370 - ACS-R 2009 ERO

## New Results (cont'd)

- (3) Einstein radius and cluster mass refined (Einstein Radius= $\sim 39 \pm 2$  arcsec for source at  $z=2$ , corresponding to mass (inside Einstein radius) of  $\sim 2.82 \times 10^{14}$  solar masses, and, inside 250 kpc (a wider area), of  $3.8 \times 10^{14}$  solar masses, thus mass model is refined...
- (4) Bi-modal mass distribution, with very small offset between dark matter, x-ray gas, & stellar mass, which, combined with velocity distribution, reveals that Abell 370 likely a merger of 2 equally massive clusters along sight line: high mass density = strong lensing<sup>8,1</sup>

# Abell 370 - ACS-R 2009 ERO New Results (cont'd)

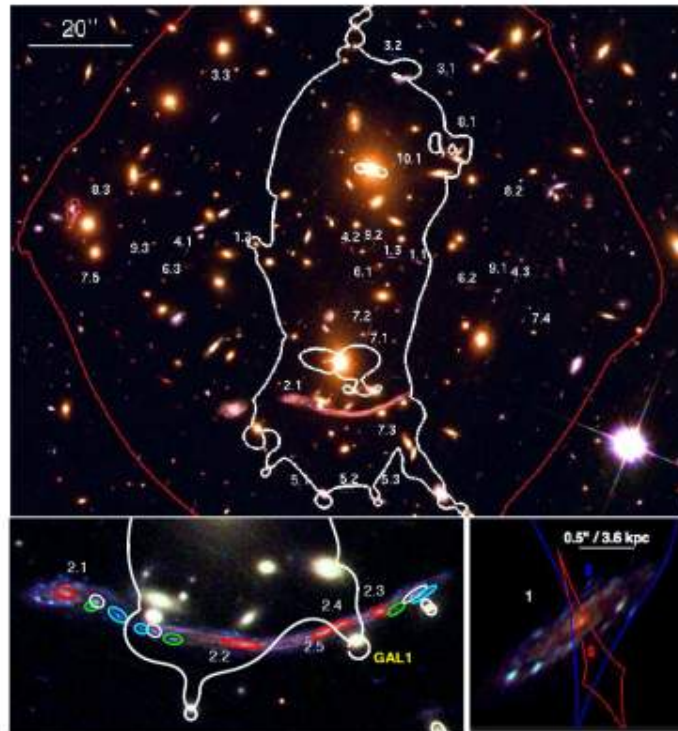


Figure 1. (Top panel) ACS F475W/F625W/F814W color image showing the location of the identified multiple systems, along with the critical line at  $z=1.2$  (redshift for the majority of the multiple images). The red line defines the region of multiple images for very high redshift sources (here assuming  $z=0$ ). (Bottom panels) System 2: Location of matched regions (identified with colored ellipses) in each part of the giant arc. The white line shows the critical curve at  $z=0.725$ . The right panel shows the source plane reconstruction for image 2.1. Overlaid are the caustic curve originated from the cluster-scale clump (blue) and the galaxy GAL1 (red), delimiting three regions of image multiplicity.

Richard, Kneib et al., 2009; Red = 5 images of Galaxy Nucleus;  
Blue, Green, White = Other multiply-imaged regions of spiral galaxy

# Abell 370 - ACS-R 2009 ERO Multiple Images in Arc



Good, high-resolution color images were crucial to identifying the multiple images of the nucleus and other components.

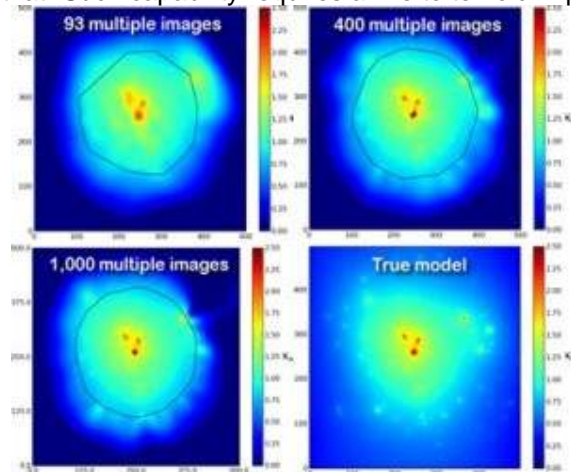
# JWST and Beyond: Clusters, and Lensing

- JWST will probe ever more deeply with its greater sensitivity and longer infrared wavelength range, searching for the first galaxies and stars.

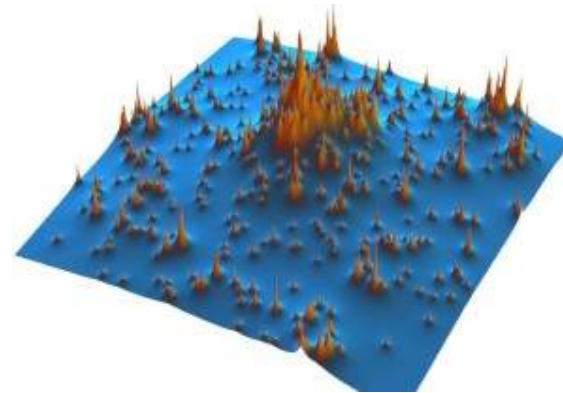
From Marc Postman's Fall 2009 Stsci Newsletter article on "Beyond JWST - the Next Steps in Ultraviolet-Optical-Near-IR Space Astronomy":

- "amplitude of distortion" and "number of 'multiple images' of a background source produced provide fundamental constraints on the distribution of matter in the foreground objects", which "allows the mass profile of the foreground 'lensing' object to be derived with unprecedented accuracy." And, strong lensing in the direction of massive galaxy clusters provides "unique constraints on cosmological parameters and on the structure of very distant background galaxies."
- Postman adds that "highly stable, diffraction-limited imaging" of a space-based optical telescope would allow us to investigate:
  - (1) How dark matter is distributed over scales of 10 kpc to 5 Mpc
  - (2) What links x-ray gas and dark matter? Or not!
  - (3) Distribution of dark matter halo masses and radii

Postman concludes that detection of ~1000 sets of multiple images will be required to study substructure in clusters at the sub-halo level, and says that "Such capability requires a five to tenfold improvement in angular resolution in the optical band over that available with Hubble."



D. Coe, 2009 - Mass models; more images = better approximation to the "True Model",  
Reproduced from M. Postman's article above.



T. Treu et al., 2003 - Mass map of CL0024+16 at  $z=0.40$  from HST+WFPC2  
With much greater resolution and higher sensitivity, sub-halo structure can be studied. Reproduced from M. Postman's article above.

# Summary

- They're beautiful!
- They're interesting!
- They're useful!
- Watch out if you wake up tomorrow and it seems like Groundhog's Day all over again!!! If you see Bill Murray (or me?) again, you know you're in trouble...! ;-)

# Thank you to...:

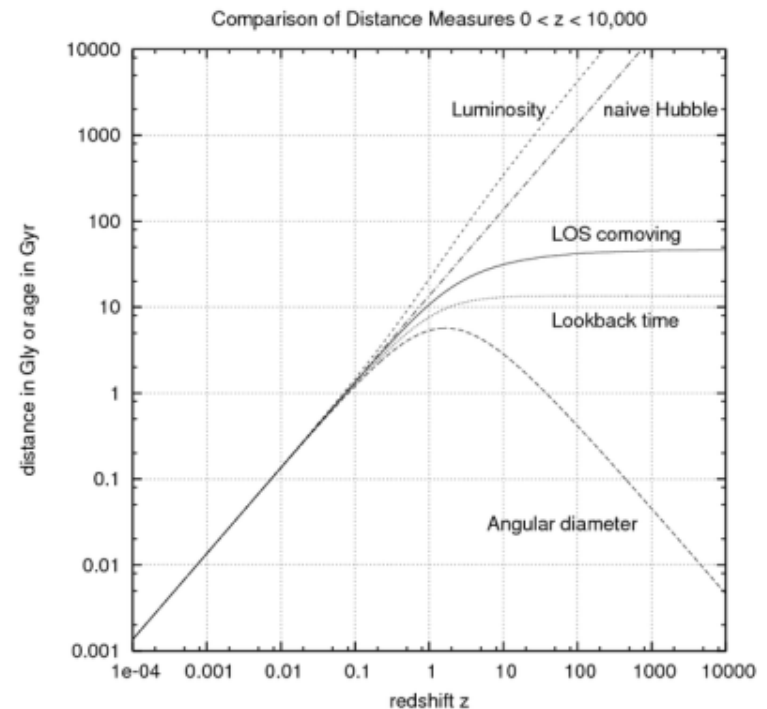
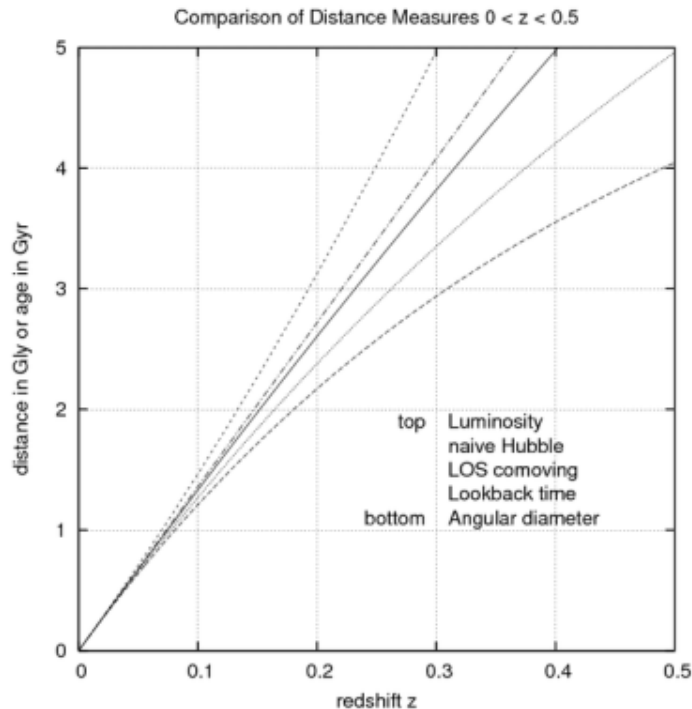
- SM4 astronauts (and those on all other HST servicing missions!), NASA + ESA folks + contractors, including our fellow co-workers here at STScI; WFPC2 & ACS GTOs, WFC3 SOC; all those who spent years developing.
- Observers who have proposed for these objects, the TACs who have selected them, and all those other colleagues world-wide who have helped bring these images and associated science to everyone else...
- Nature: Higher-surface-brightness galaxies!
- You: Taxpayers of USA, Canada, & Europe!

# Questions?

- I may or may not know the answer...!
- Observing with a telescope just after this talk?

# Extra Slide(s)

# Extra Slide: Distance Scale per Cosmology - Wikipedia



Comparison of cosmological distance measures, from redshift 0 to 0.5. Cosmology is Hubble constant of 72 Km/s/Mpc,  $\Omega_{\text{lambda}}=0.732$ ,  $\Omega_{\text{matter}}=0.266$ ,  $\Omega_{\text{radiation}}=0.266/3454$ , and  $\Omega_{\text{k}}$  chosen such that Omega parameters' sum to 1.

Comparison of cosmological distance measures, from redshift 0 to 10,000, corresponding to epoch of matter/radiation equality. Cosmology is Hubble constant of 72 km/s/Mpc,  $\Omega_{\text{lambda}}=0.732$ ,  $\Omega_{\text{matter}}=0.266$ ,  $\Omega_{\text{radiation}}=0.266/3454$ , and  $\Omega_{\text{k}}$  chosen such that Omega parameters' sum to 1.

From (credit): [http://en.wikipedia.org/wiki/Distance\\_measures\\_\(cosmology\)](http://en.wikipedia.org/wiki/Distance_measures_(cosmology))

See also: <http://en.wikipedia.org/wiki/Redshift>

Ned Wright's Cosmology Calculator: <http://www.astro.ucla.edu/%7Ewright/CosmoCalc.html> ---> See also links to Cosmology FAQ, etc.

<http://www.astro.ucla.edu/%7Ewright/DittCalc.html> ---> See also links to Age, Distance, Relativity, etc.

Ned Wright's Cosmology Tutorial: <http://www.astro.ucla.edu/%7Ewright/cosmolog.htm> ---> See also links to Ned Wright's home page