Gravitational Lensing as a tool to probe the first generation of stars

Piero Rosati
(ESO)

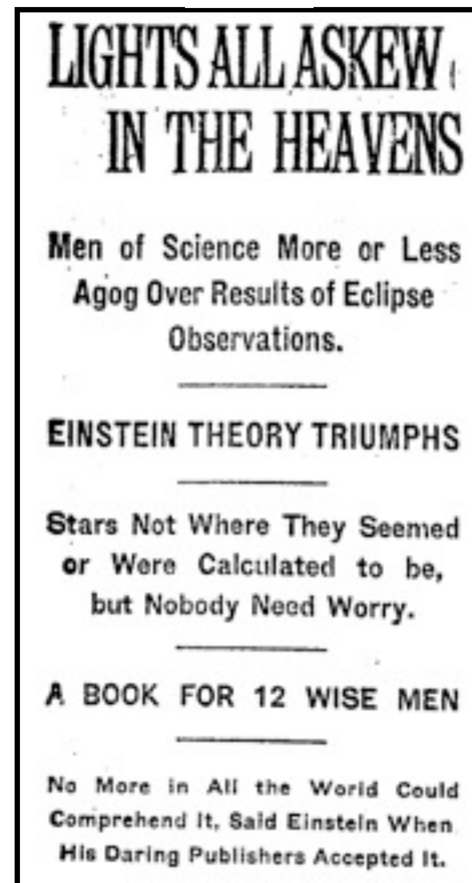
Galaxies, Near and Far - Bob’s conference - Villa Aureli, 25 May 2011

Brief historical perspective

- Eddington (1919) confirms Einstein’s deflection prediction of stars near the solar limb

The New York Times

1919



LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

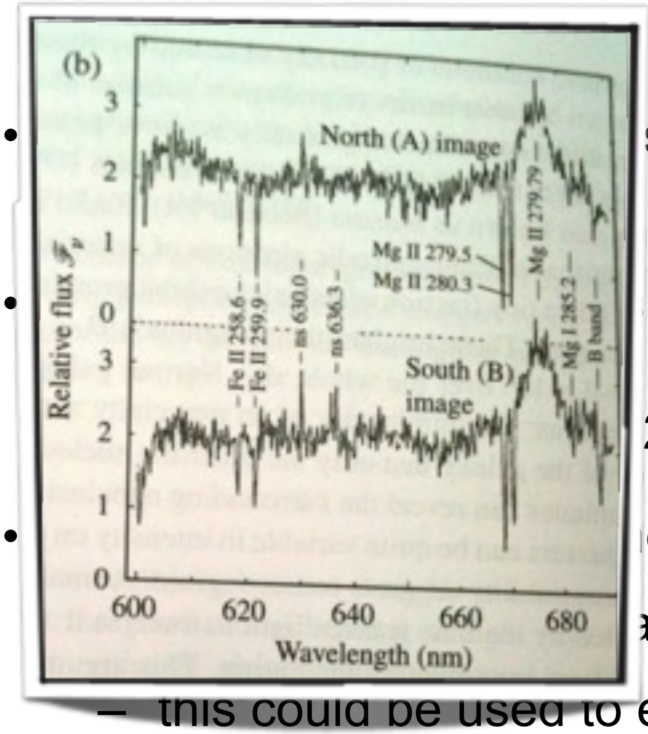
A BOOK FOR 12 WISE MEN

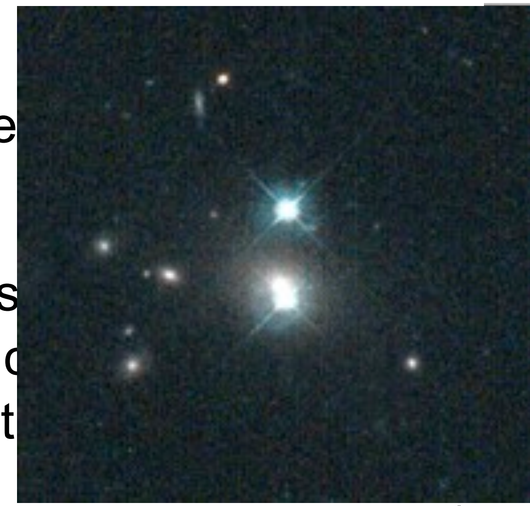
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

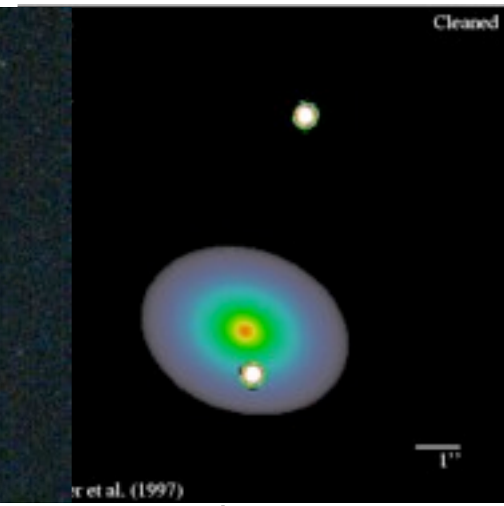
Brief historical perspective

- Eddington (1919) confirms Einstein's deflection prediction of stars near the solar limb
- Einstein (1936) considers the possibility of multiple images and rings of stars by stars but concludes there is little chance to observe the effect for stellar-mass lenses.. (also Cholson 1926 "fictitious stars")
- Zwicky (1937) using his new galaxy mass estimates (~4×11 $M_{\odot}$) concluded:
  - lensing by galaxies can split images to large observable angles
  - this could be used to estimate galaxy masses
  - magnification can lead to access distant faint galaxies!

Brief historical perspective







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- Walsh et al. (1979) discover lensed QSO0957+561 (6” apart)

Brief historical perspective

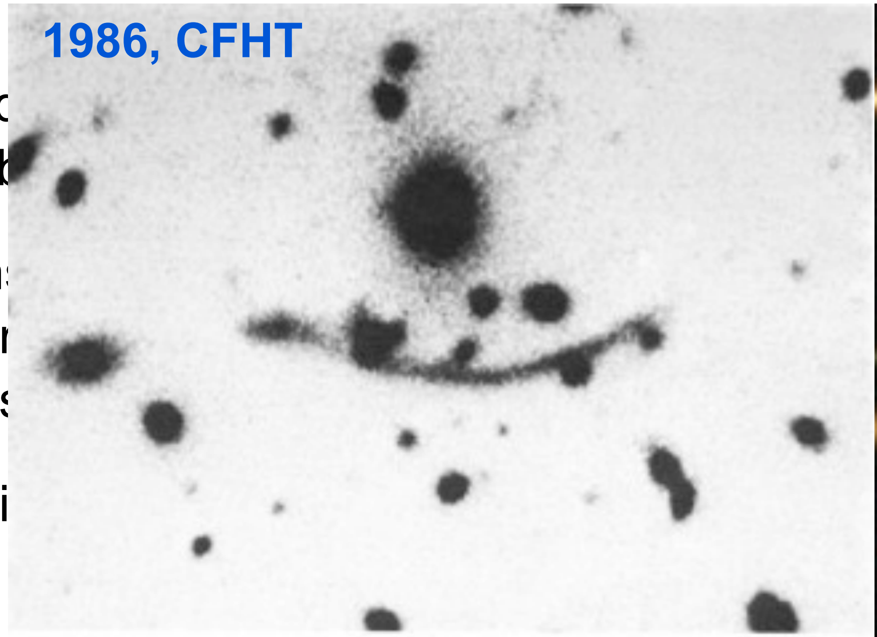
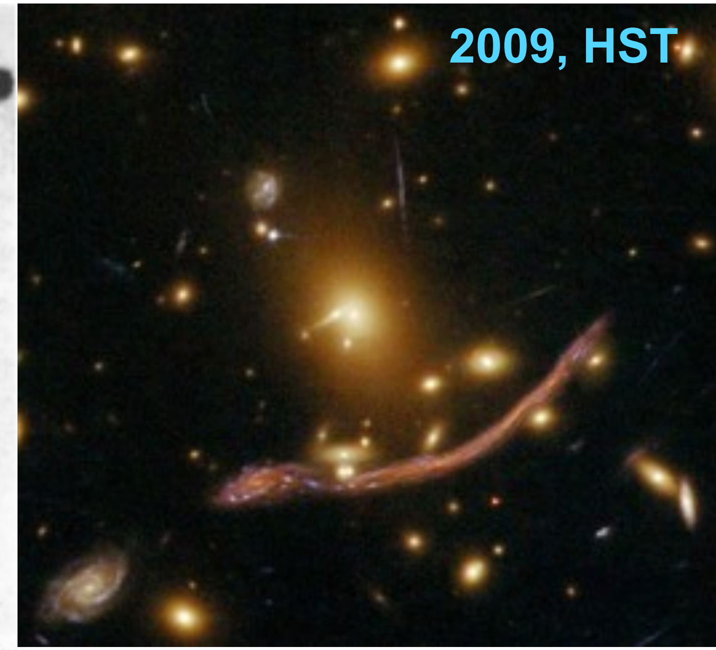


Figure 2: The giant luminous arc in Abell 370. CFHT, 0.2/pixel, 10 min., seeing 0.7, November 25, 1986.



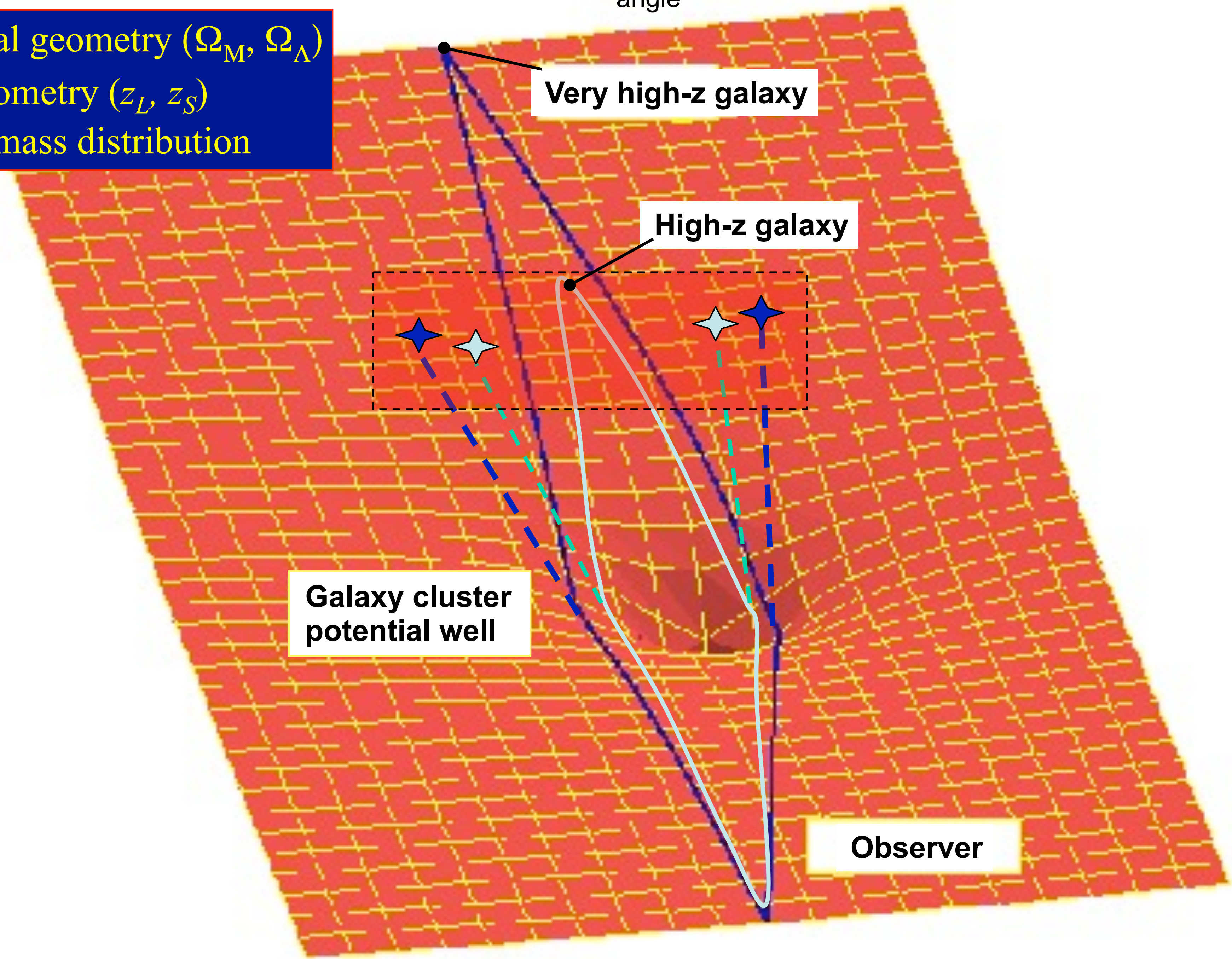
- Edc … e solar limb
- Ein… ars by star… ass lens…
- Zwi… d:
  - …
  - … nasses
  - magnification can lead to access distant faint galaxies!
- Walsh et al. (1979) discover lensed QSO0957+561 (6” apart)
- First giant arcs discovered (Soucail et al. 87). Paczynski (87): right interpretation
- Great ride ever.. since, thanks to *Hubble* which has unleashed the full power of gravitational lensing (esp. in the strong regime)

Lensing mapping: $y = x - D(\Omega_M, \Omega_\Lambda, z_L, z_S) \cdot \underbrace{\nabla\psi(x)}_{\text{Deflection angle}}$

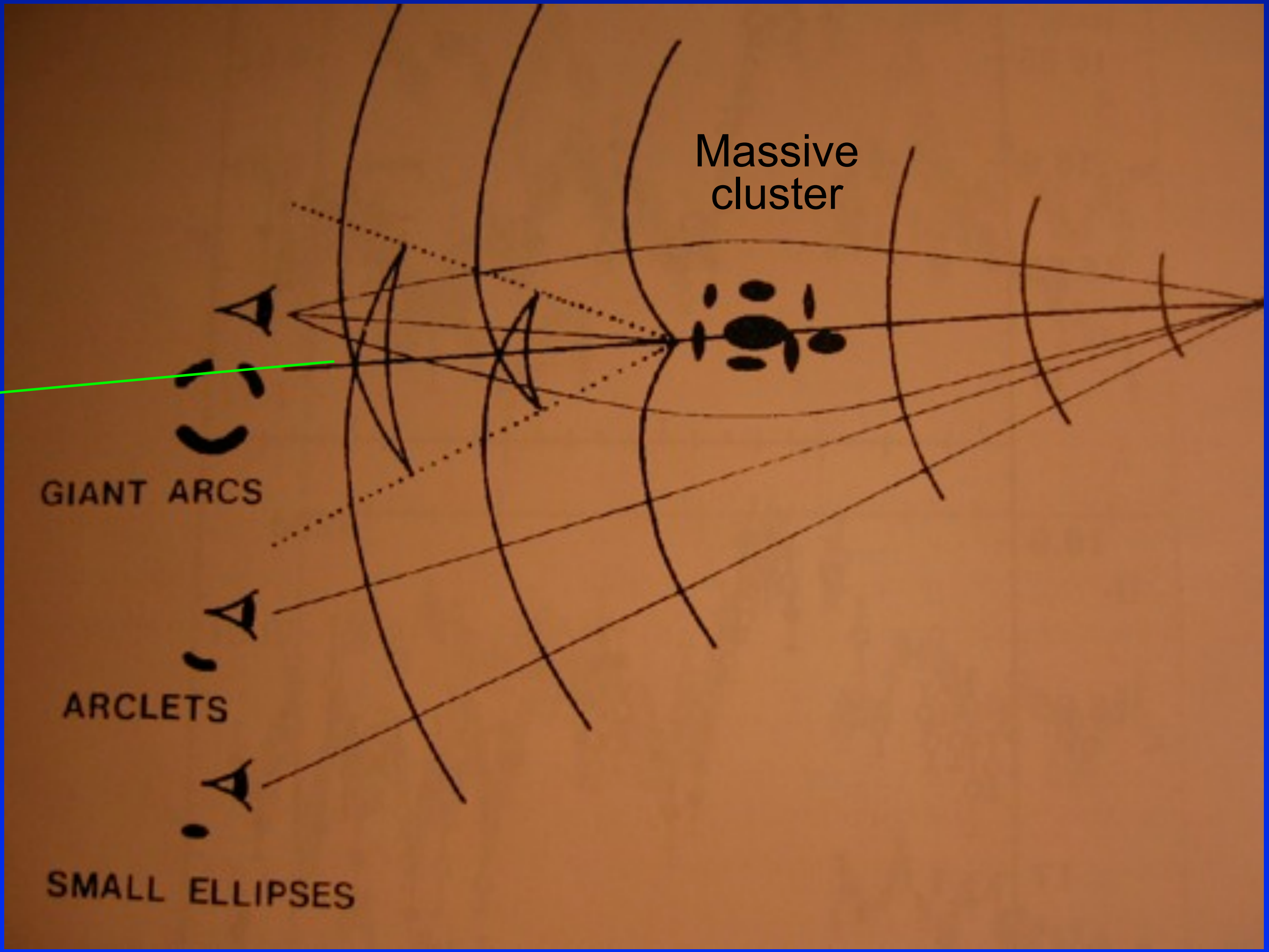
y: source plane

x: image plane

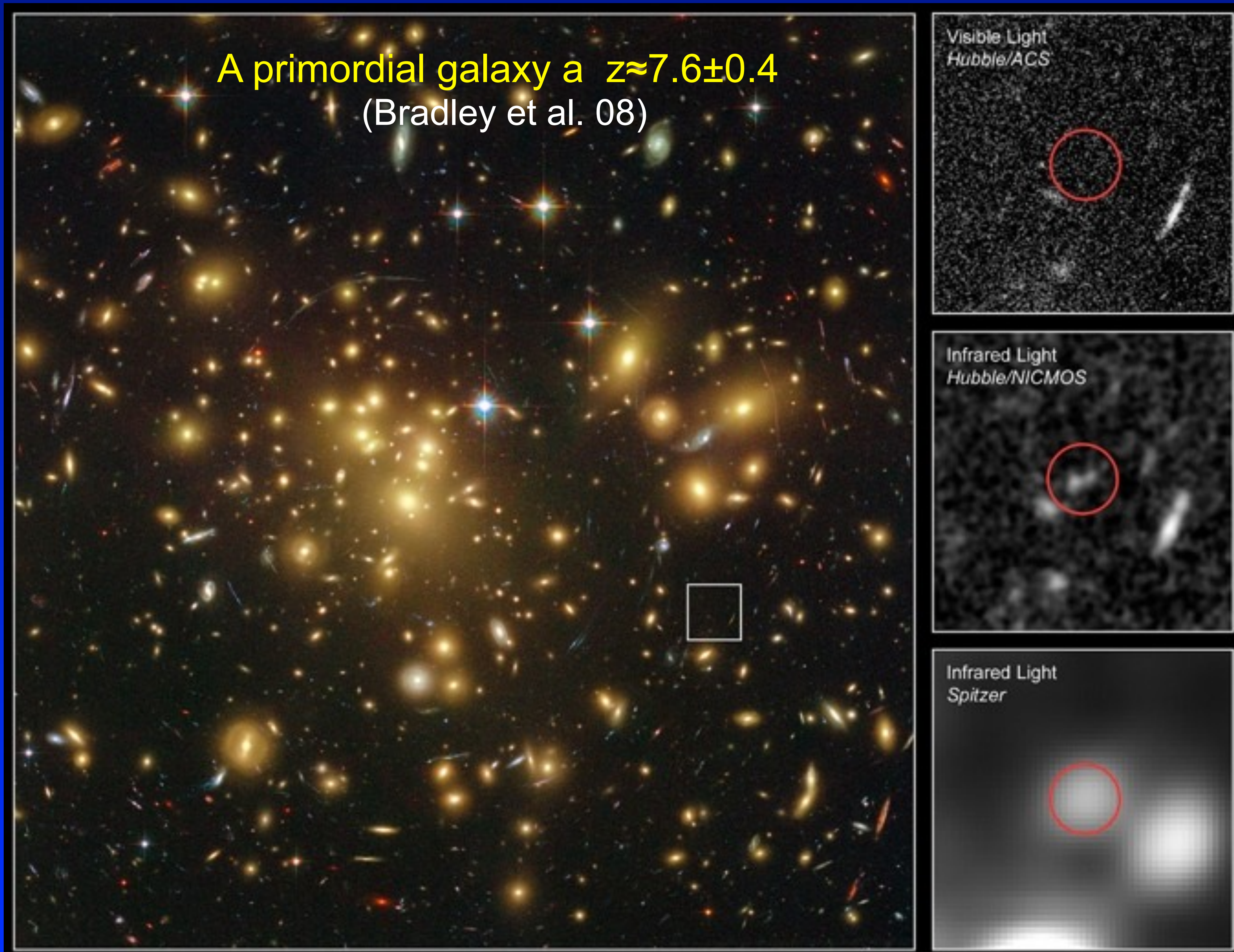
- Universal geometry (Ω_M, Ω_Λ)
- Lens geometry (z_L, z_S)
- Cluster mass distribution



Lenses as Gravitational Telescopes



A primordial galaxy a $z \approx 7.6 \pm 0.4$
(Bradley et al. 08)



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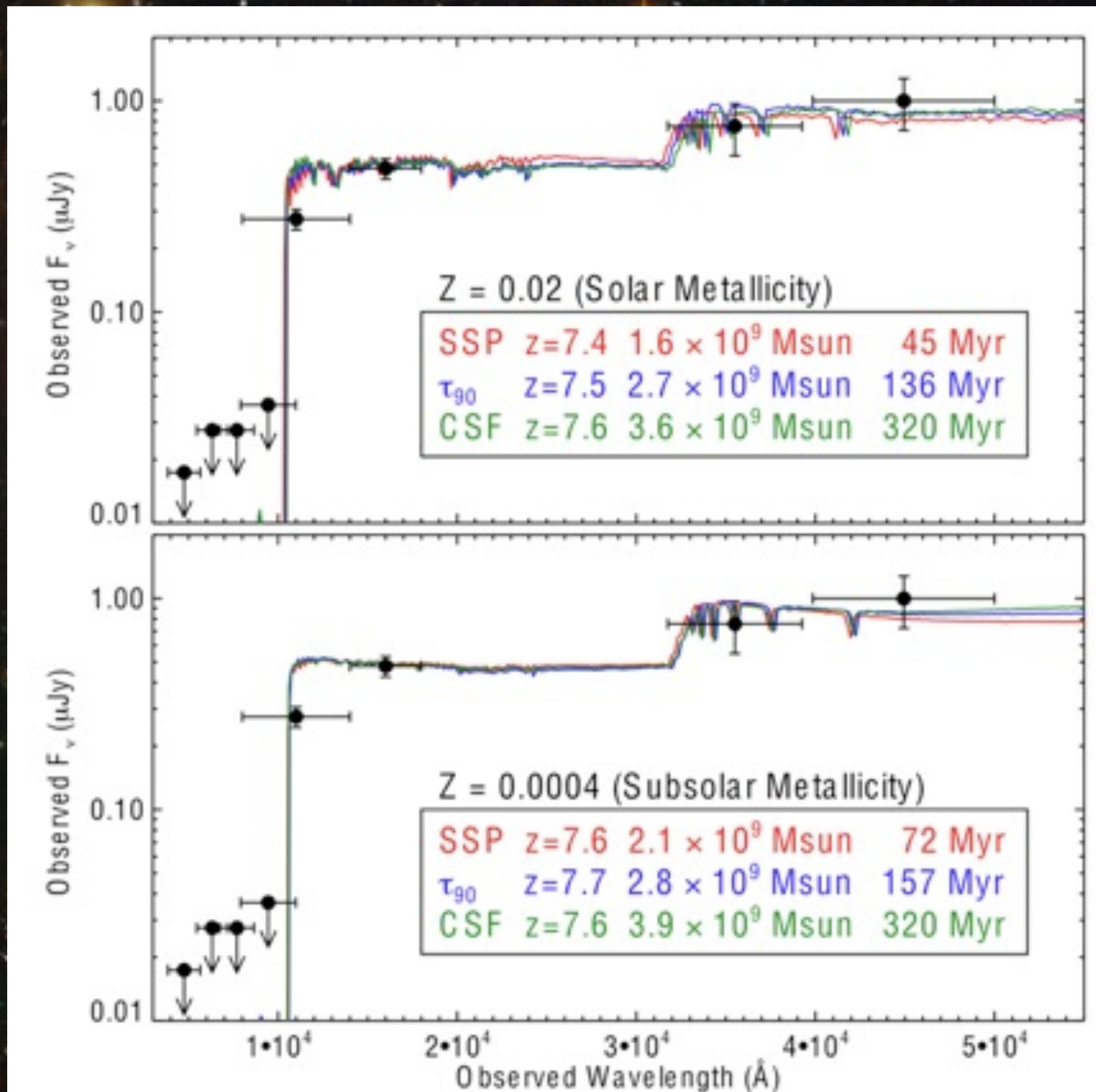
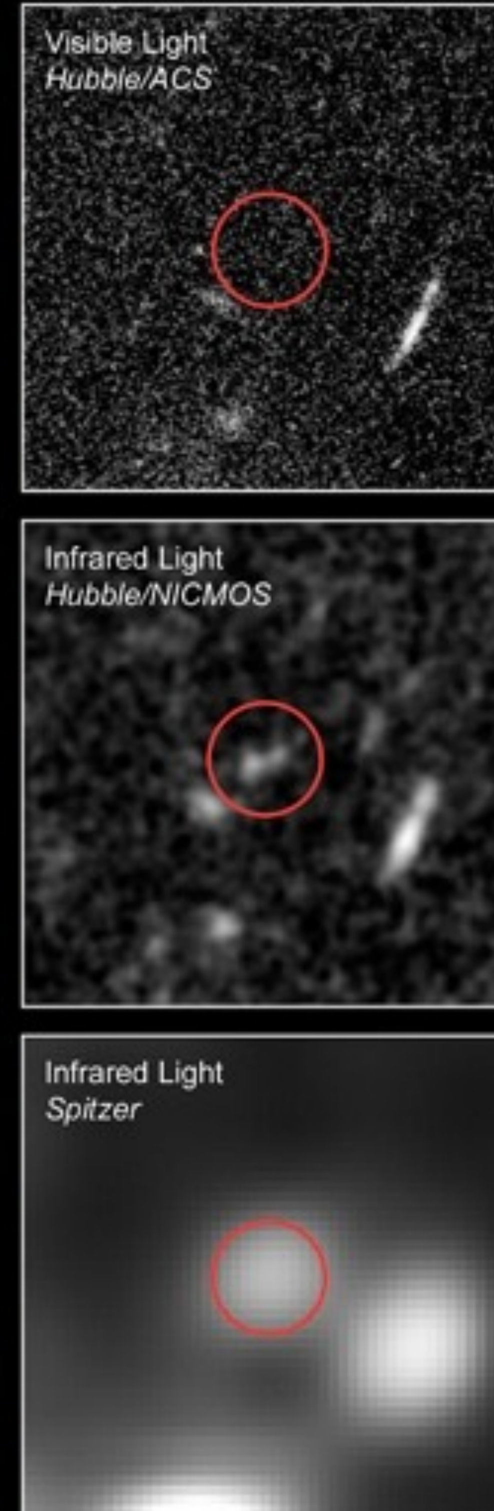
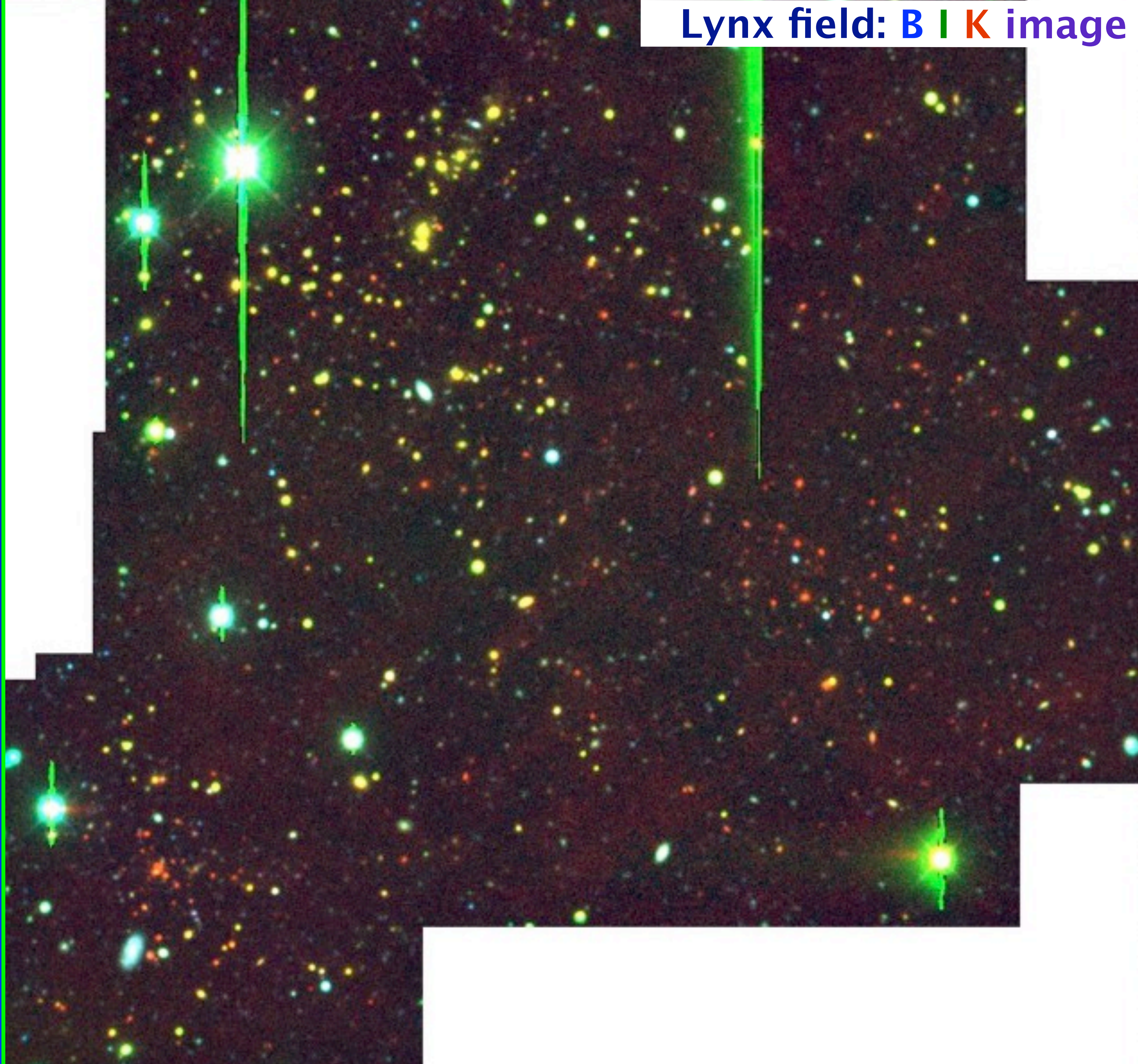




The Lynx Arc

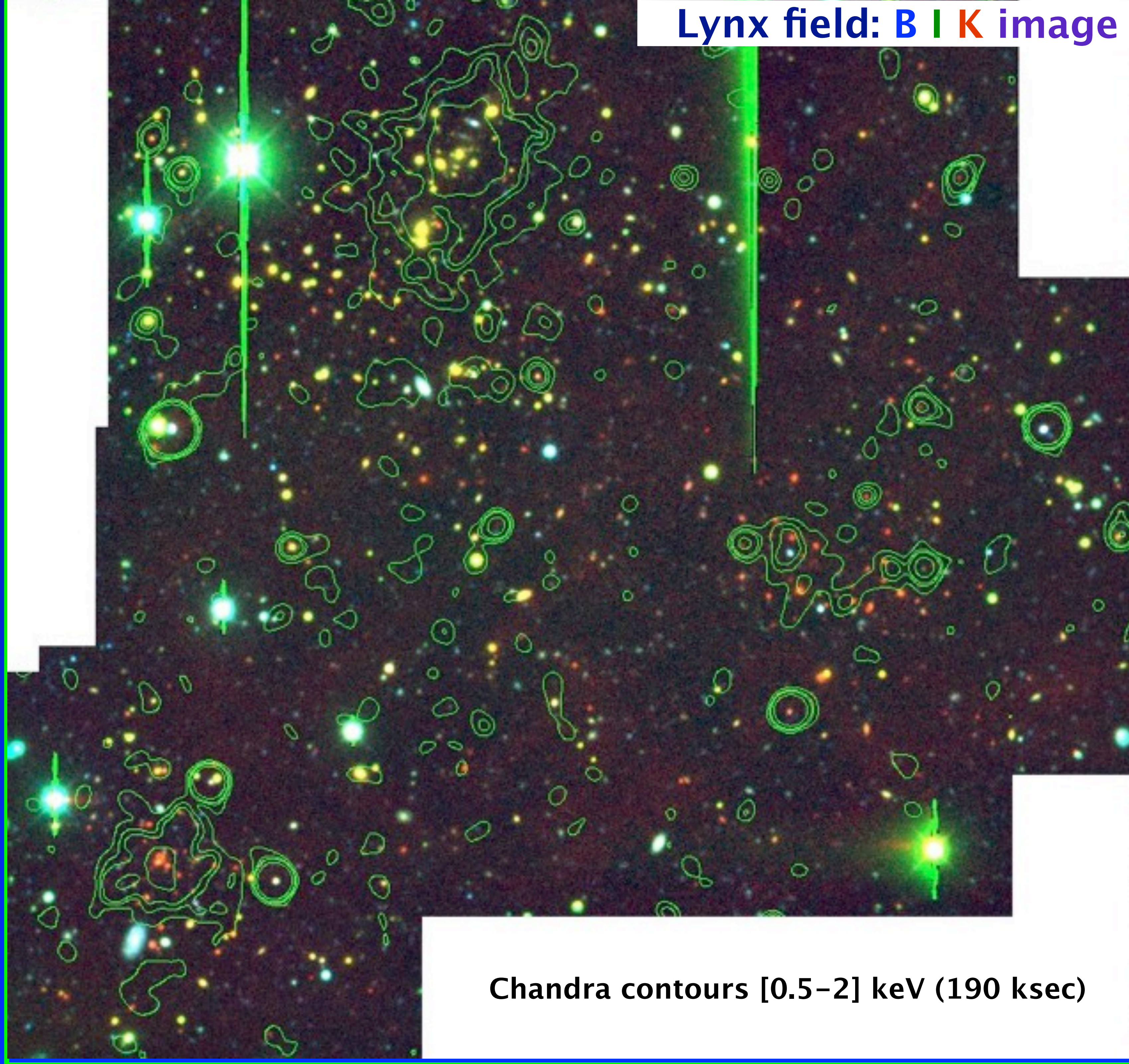
http://www.spacetelescope.org/images/heic0312b/ (Oct 2003)

Lynx field: B I K image



1 Mpc/h_{50}
2 arcmin

(Stanford et al. 97, Rosati et al. 99)
SPICES field



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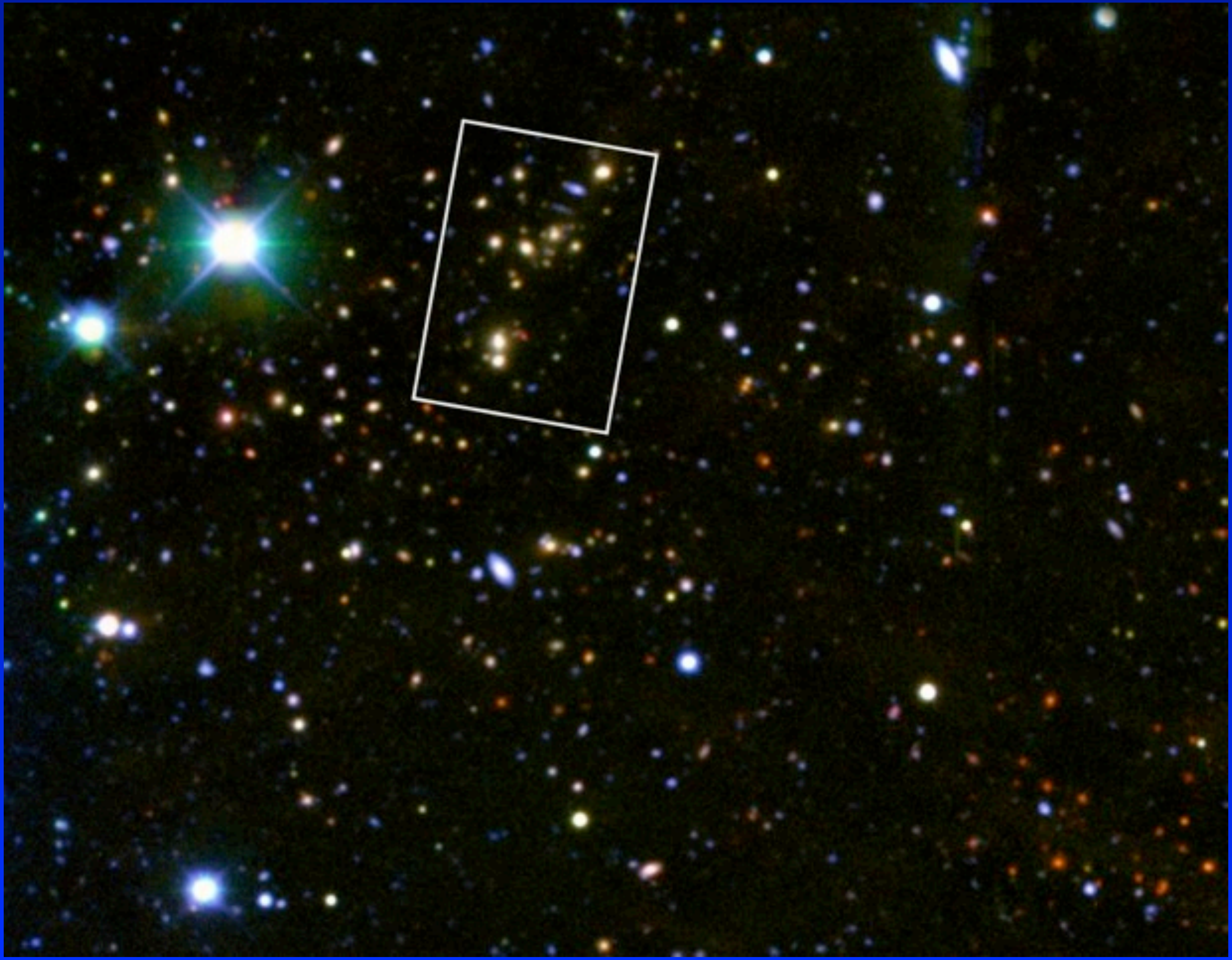

The Lynx Arc

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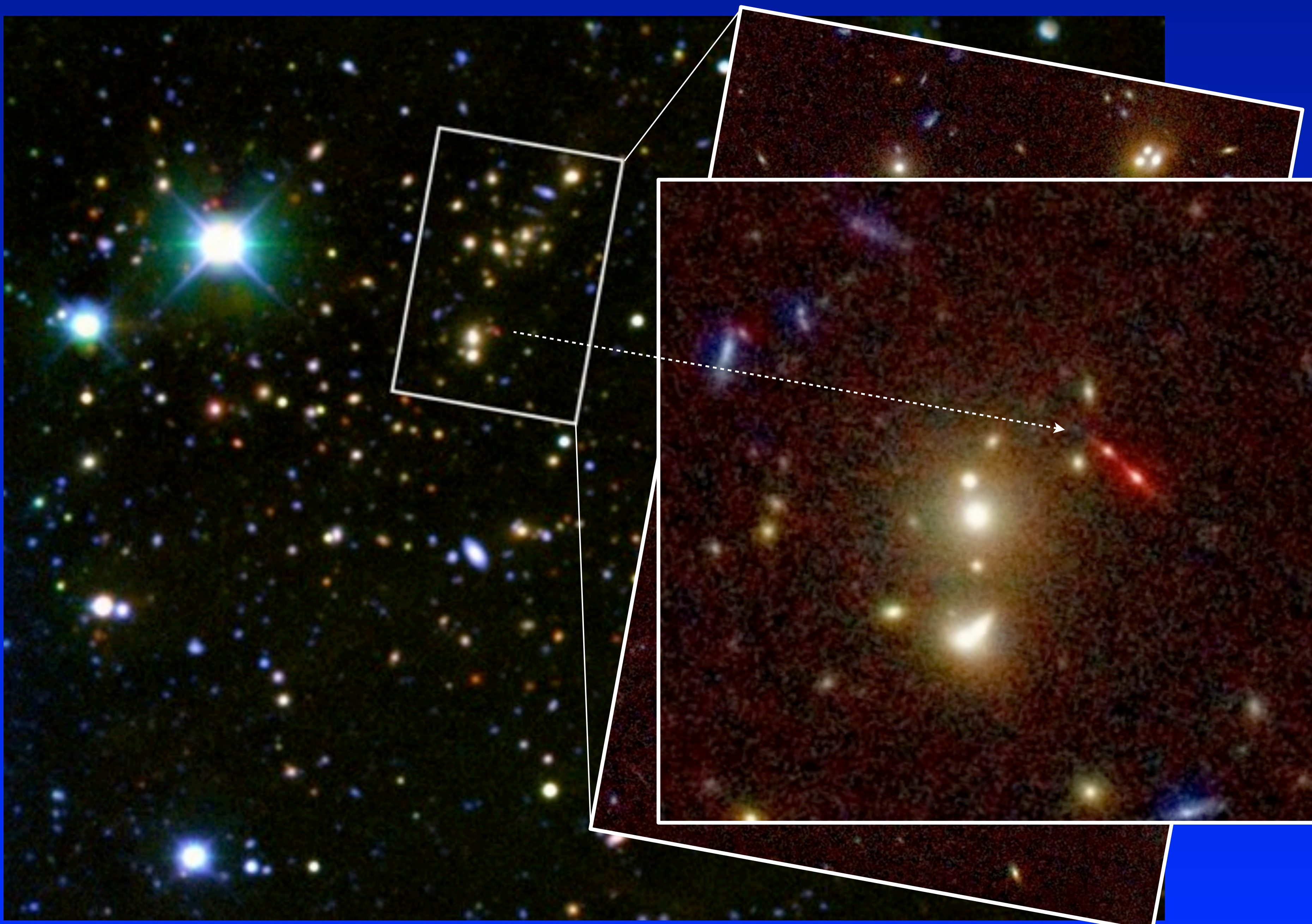

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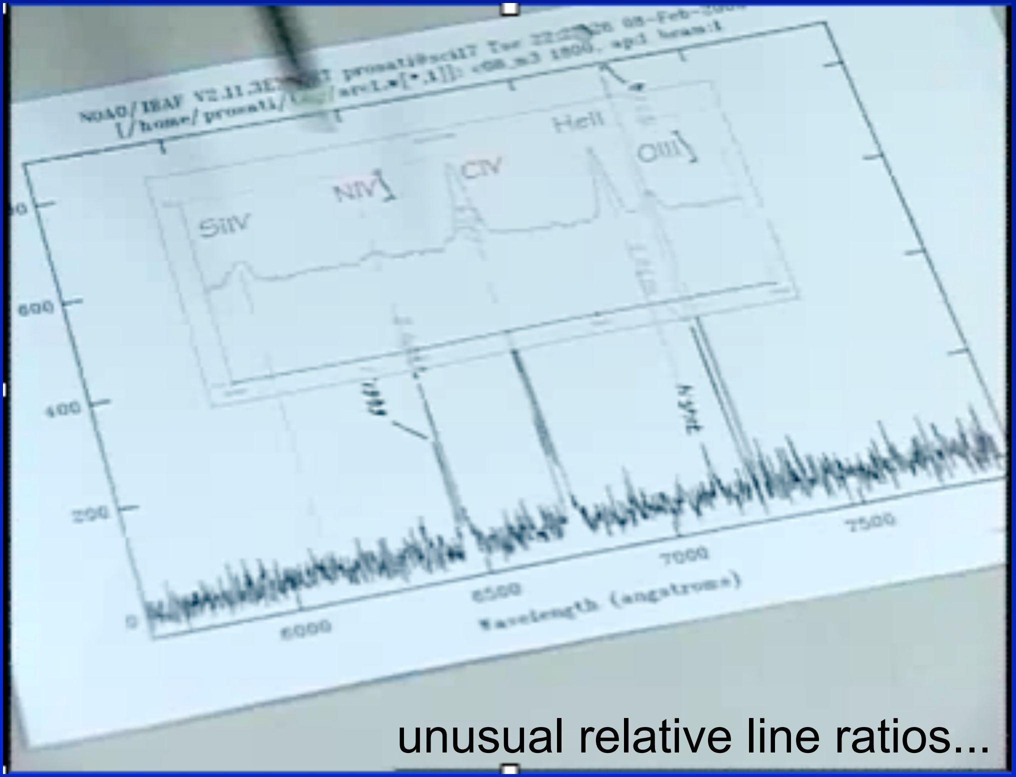
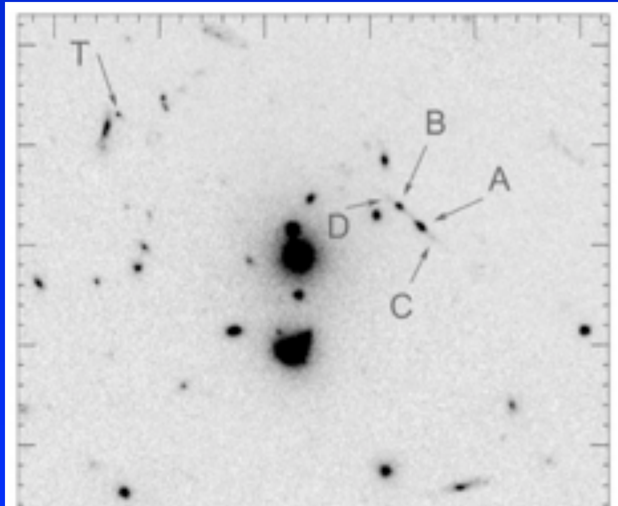
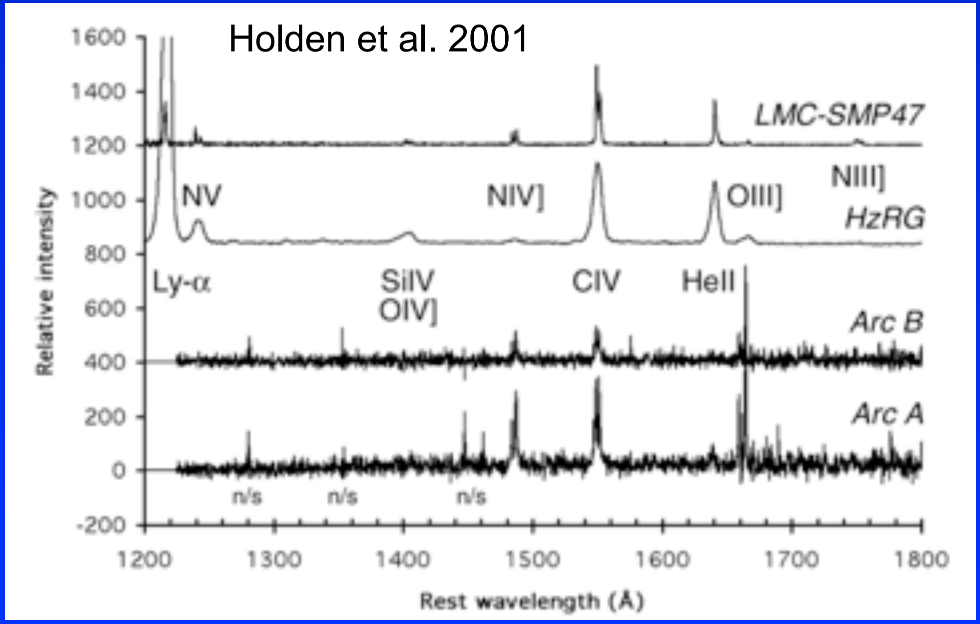




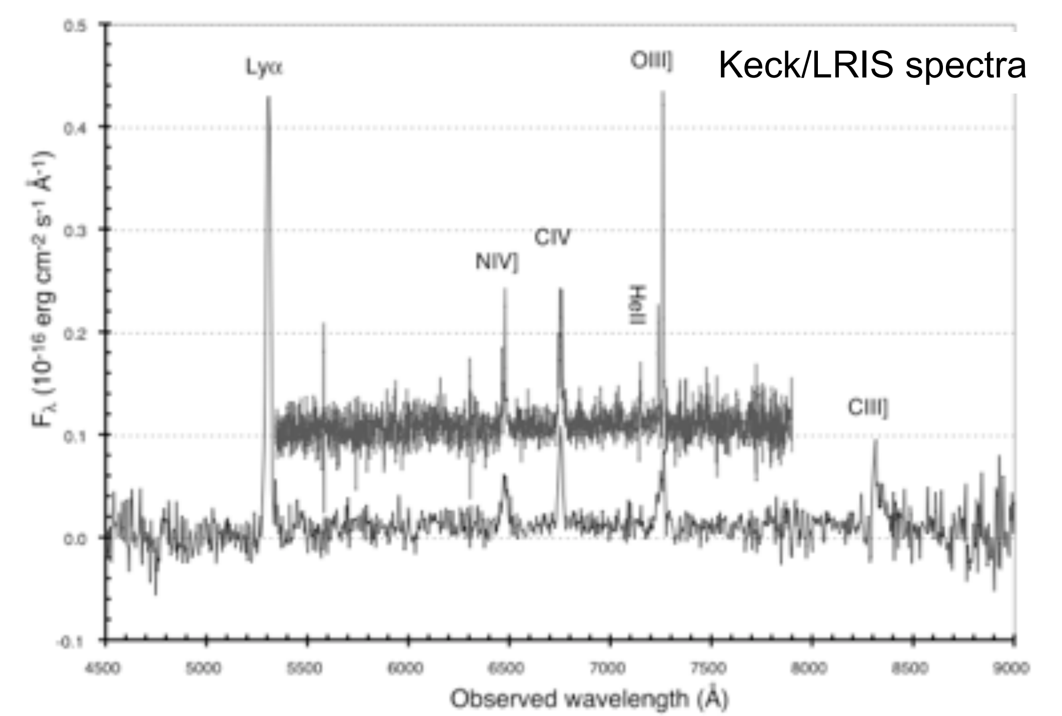
WFCP2 follow-up of RDCS cluster
(Rosati et al. 98, Holden et al. 2001)

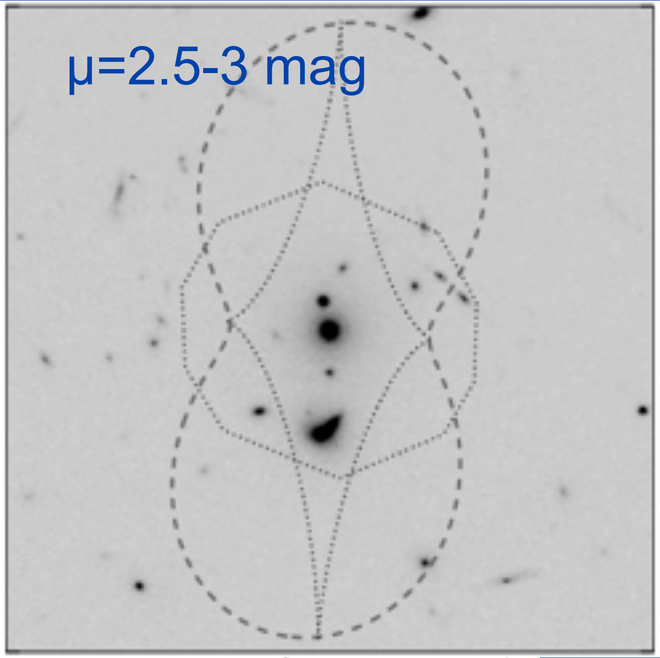


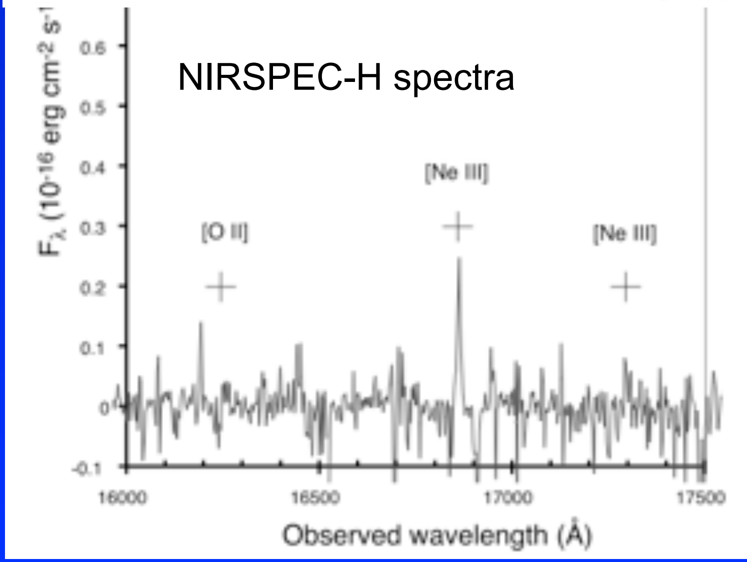
The Lynx Arc: interpretation

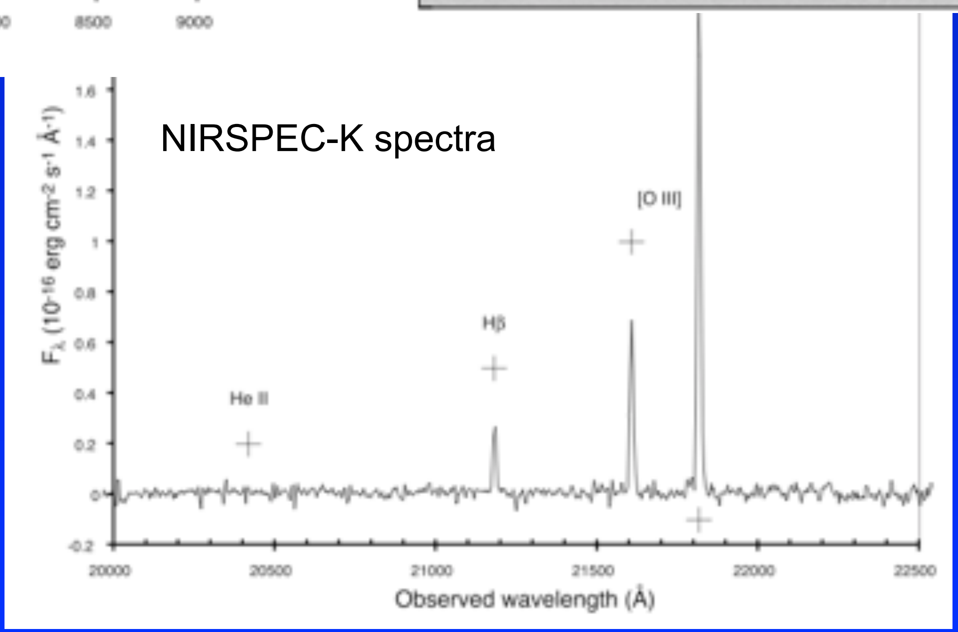
MASSIVE STAR FORMATION IN A GRAVITATIONALLY LENSED H II GALAXY AT $z = 3.357$

R.A.E. Fosbury, M.Villa-Martin, A.Humphery, M.Lombardi, P.Rosati, D.Stern, R.N.Hook, B.P.Holden, S.A.Stanford, G.K.Squires, M.Rauch, W.L.W.Sargent - *Ap.J, 596, 2003* (+ Binette et al. 03, Villa-Martin et al. 04)









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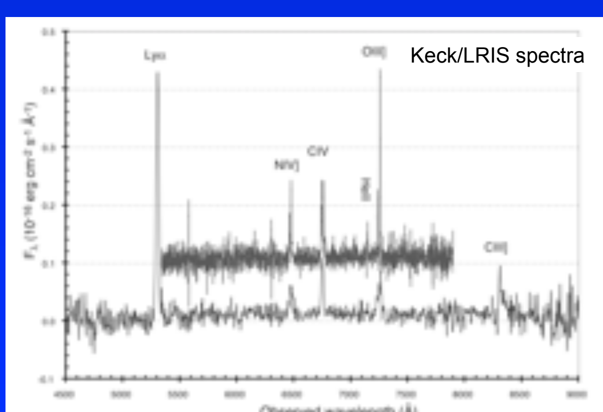
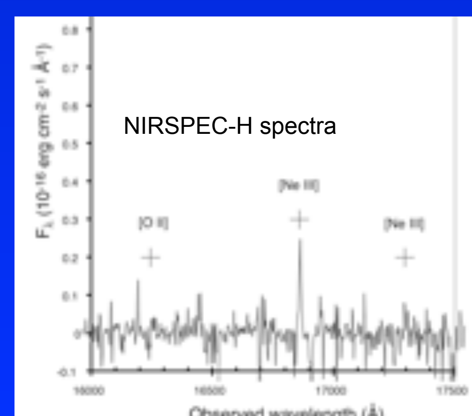
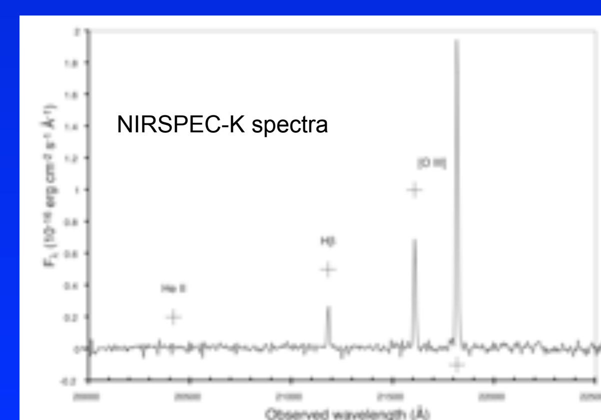
- Ionizing spectrum not as hard as AGN (no N V1238,42 and weak He II 1640, no He II 4866) but rather hot black-body like (strong inter-combination lines of N and O)
- Photoionization models indicate the presence massive, luminous, very low Z stars (~10^6 O stars) with:
  - T_{BB}=80,000±10,000 K (N spectrum, prominent N IV] over N V N III)
  - gas-phase metallicity $Z \approx 0.05\ Z_\odot$ (He II /C IV, [O III] /Hβ ratios)
  - high ionization parameter $U \approx 0.1$
  - low gas σ_v (narrow lines) and no stellar continuum: low mass-to-light ratio
- Qualitatively consistent with models of Pop III stars and surrounding nebulae
- Outflowing winds (Lyα, C IV self-absoption), overabundance of Si (Si III]1883,92)?

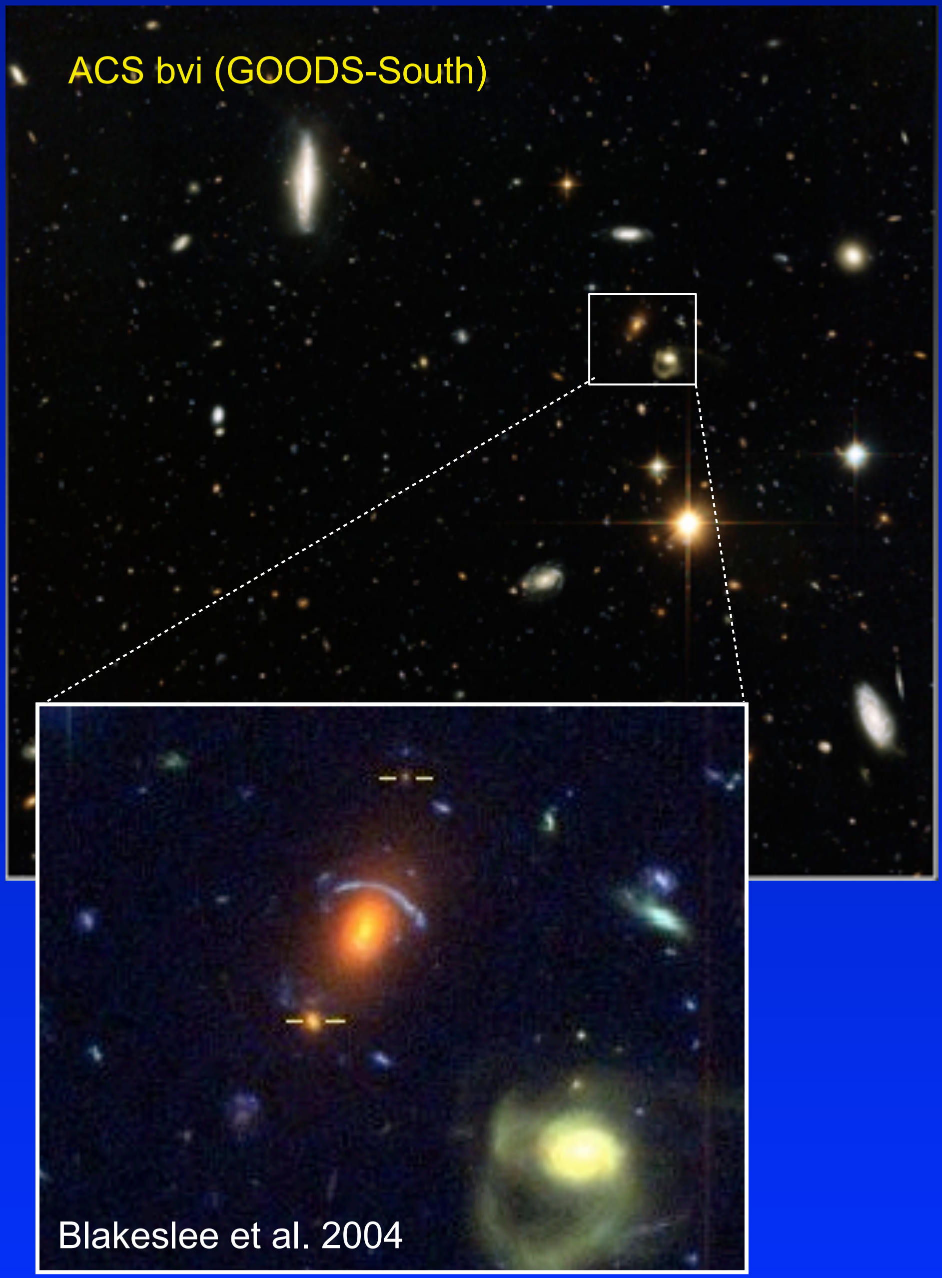


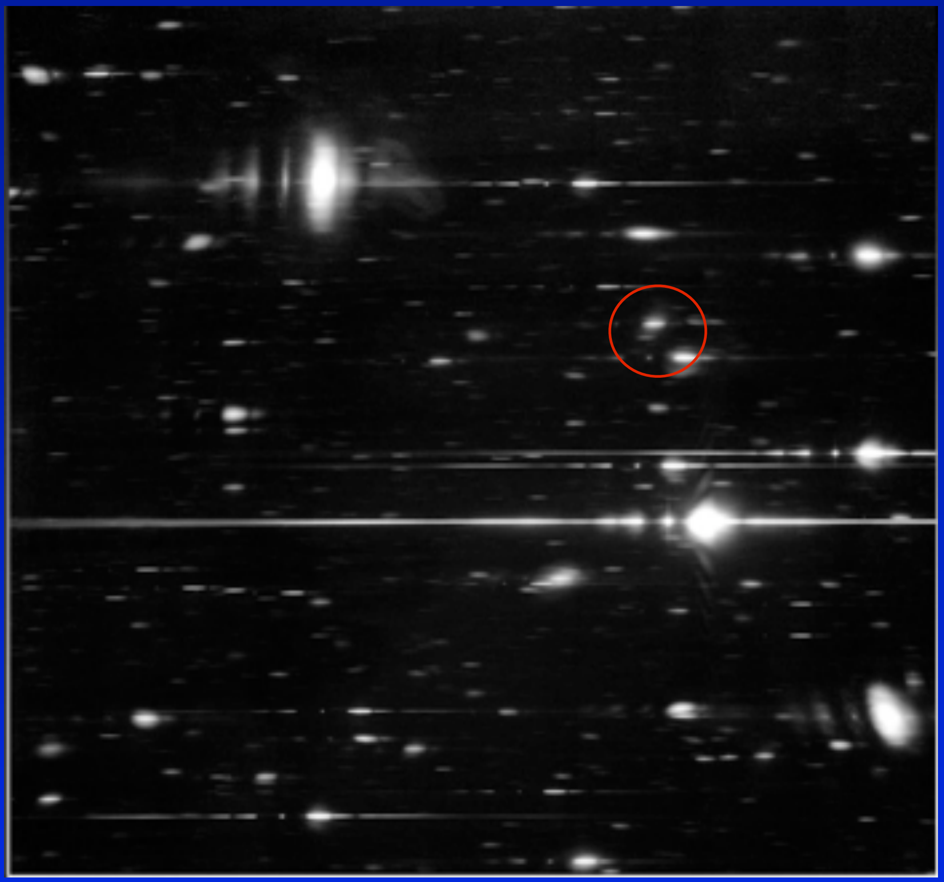


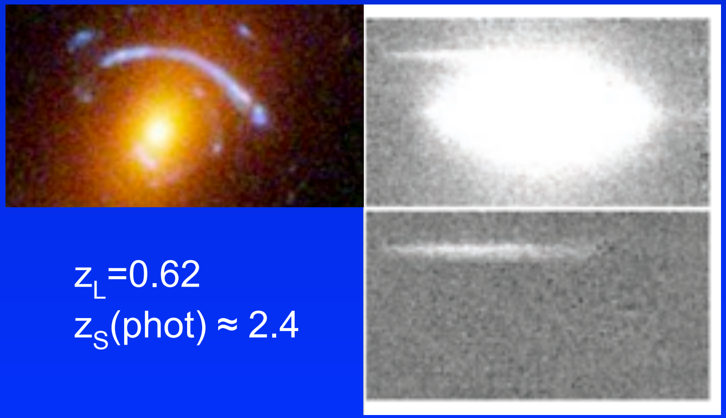


A serendipitous discovery in the ST-ECF ACS Grism Spectra Release

A serendipitous discovery in the ST-ECF ACS Grism Spectra Release



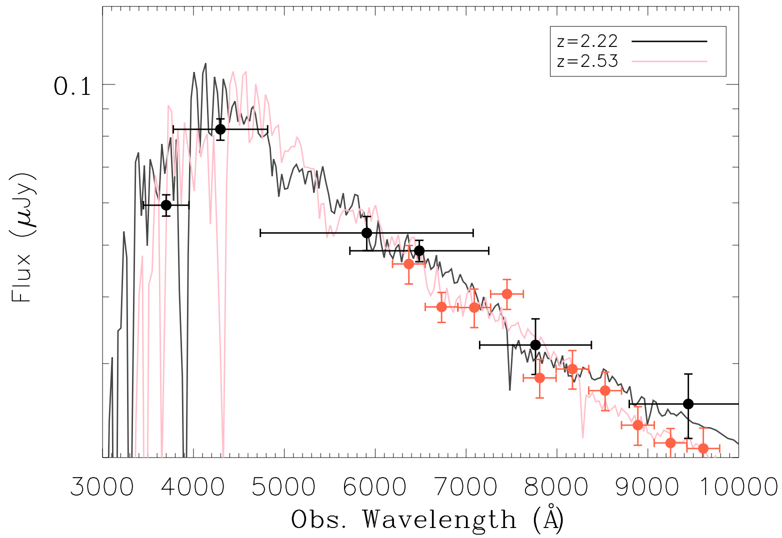


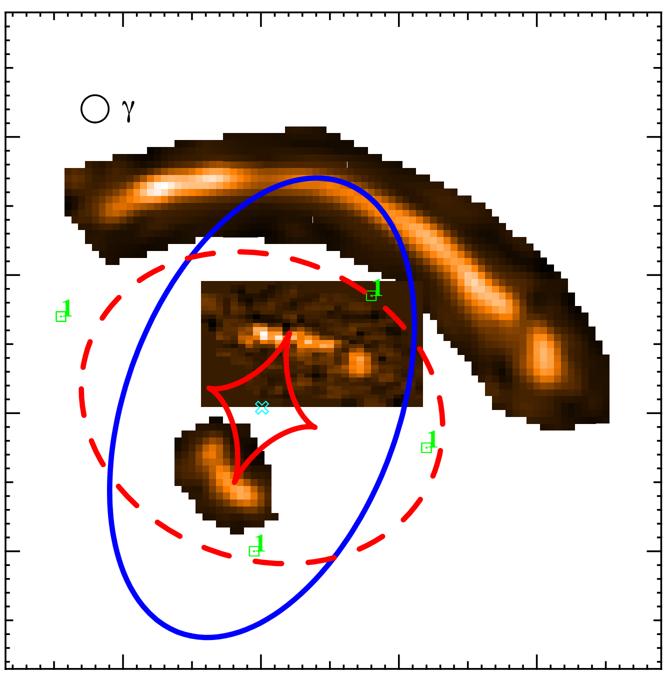


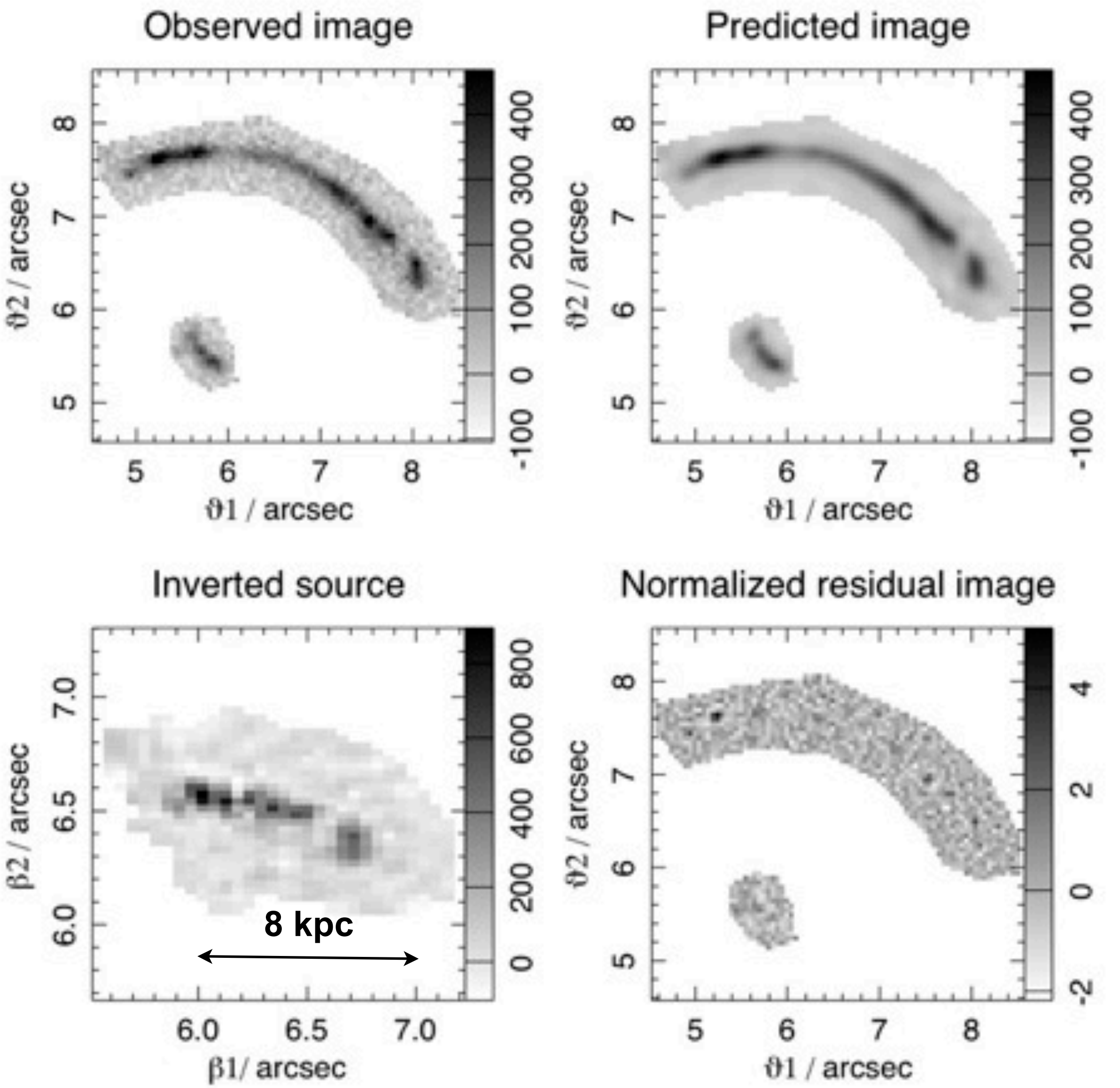
z_L=0.62
z_S(phot) ≈ 2.4

Accurate lensing model

(Grillo, Alkola and ex-ECF people, in prep.)







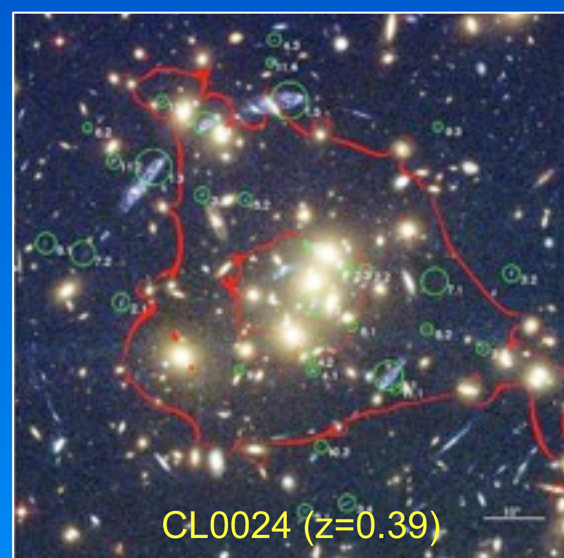
Through a Lens, Darkly:
An Innovative Hubble Survey to Study
the Dark Universe

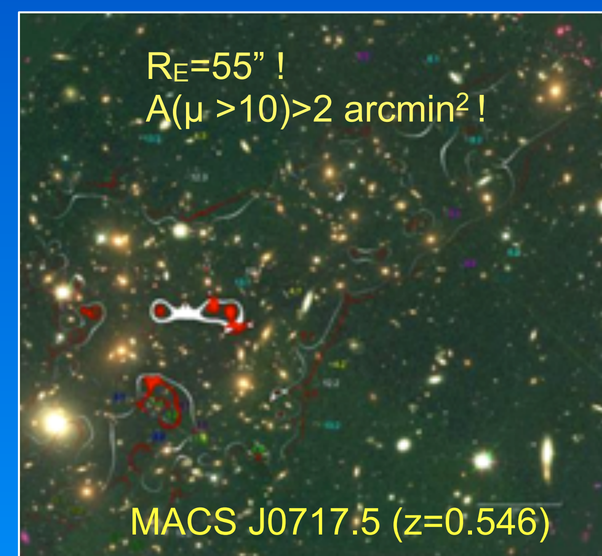
Cluster Lensing And Supernova survey with Hubble

HST multi-cycle Treasury Program (530 orbits) - PI: M.Postman

- Panchromatic (ACS+WFC3 16 filters) imaging of 25 massive intermediate-z galaxy clusters
- Measure DM mass profiles over 10-3000 kpc with unprecedented precision
- “Wide-field” gravitational telescopes on the very high-z Universe
- SNe Ia search at $1<z<2$ from parallel fields (doubling SNe at $z>1.2$)


MACS J1149.5 (z=0.544)


CL0024 (z=0.39)



MACS J0717.5 (z=0.546)

Zitrim, Broadhurst et al. 09

http://www.stsci.edu/~postman/CLASH

See Postman et al. 2011 (soon on astro-ph)

The CLASH Science Team: 34 researchers, 18 institutions, 10 countries

Marc Postman, P.I.	Space Telescope Science Institute (STScI)
Matthias Bartelmann	Universität Heidelberg
Narciso "Txitxo" Benitez	Instituto de Astrofisica de Andalucia (IAA)
Rychard Bouwens	Leiden University
Larry Bradley	STScI
Thomas Broadhurst	University of the Basque Country
Dan Coe	STScI
Megan Donahue	Michigan State University
Holland Ford, Dep-P.I.	The Johns Hopkins University (JHU)
Or Graur	Tel Aviv University (TAU)
Genevieve Graves	University of California, Berkeley
Øle Host	University College London (UCL)
Leopoldo Infante	Universidad Católica de Chile
Yolanda Jimenez-Teja	IAA
Stéphanie Jouvel	UCL
Daniel Kelson	Carnegie Institute of Washington
Ofer Lahav	UCL
Ruth Lazkoz	University of the Basque Country
Doron Lemze	JHU
Dan Maoz	TAU
Elinor Medezinski	JHU
Peter Melchior	Universität Heidelberg
Massimo Meneghetti	INAF / Osservatorio Astronomico di Bologna
Julian Merten	Universität Heidelberg
Alberto Molino	IAA
Leonidas Moustakas	JPL/Caltech
Mario Nonino	JPINAF Triest, Italy
Enikö Regös	European Laboratory for Particle Physics (CERN)
Adam Riess	STScI / JHU
Piero Rosati	European Southern Observatory
Stella Seitz	Universitas Sternwarte München
Keiichi Umetsu	Academia Sinica, Institute of Astronomy & Astrophysics
Arjen van der Wel	Max Planck Institüt für Astronomie
Wei Zheng	JHU
Adi Zitrin	TAU/JHU

Chile
Germany
Israel
Italy
Netherlands
Spain
Switzerland
Taiwan
U.S.A.
U.K.

CLASH

Post-doctoral fellow
Graduate student

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)

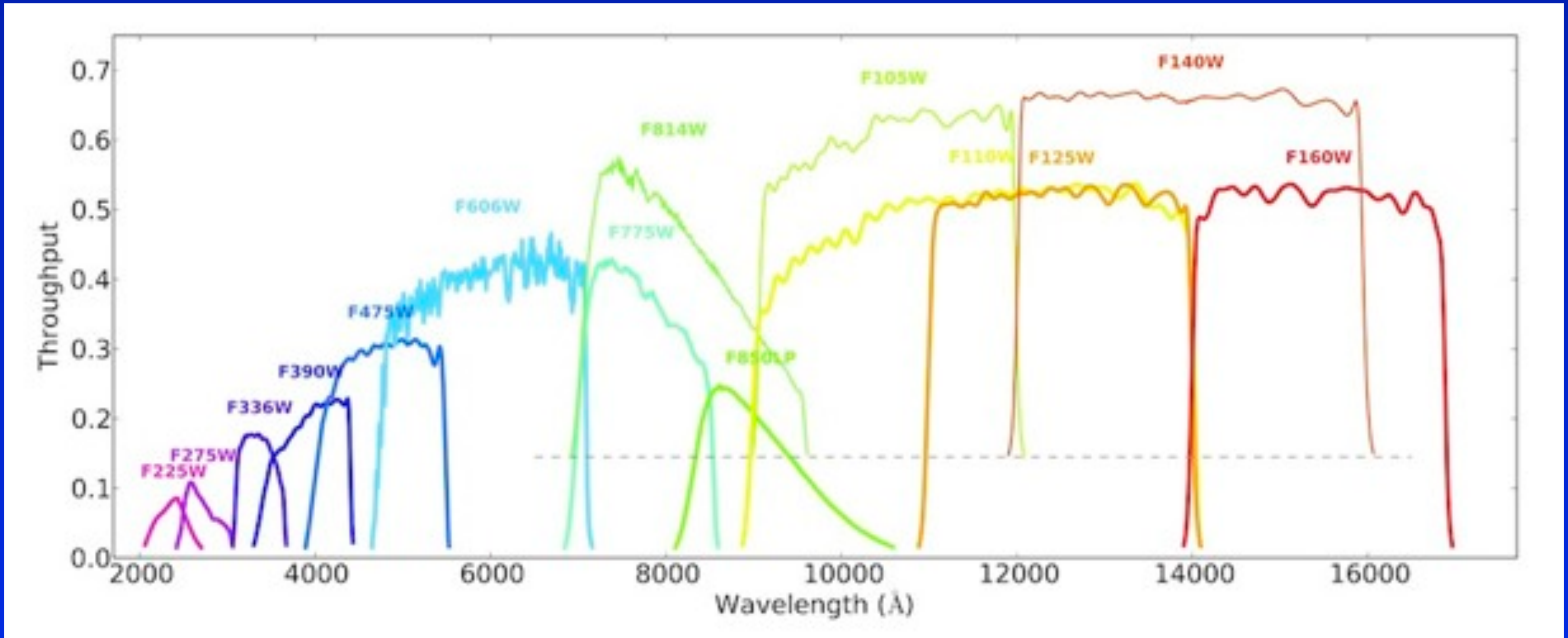
Additional Scientific Instruments:

- 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

CLASH: An HST Multi-Cycle Treasury Program

16 filters will yield photometric redshifts with rms error of ~2% x (1 + z) for sources down to ~26 AB mag, using thousands of spec-z's for calibration



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

CLASH multiple facilities: DM & Baryonic Mass Distribution from independent probes over the 10 kpc ~ 3 Mpc range

PI: M. Donahue

Baryon mass distribution
X-ray masses
ICM physics & metallicity

PI: S.Ettori

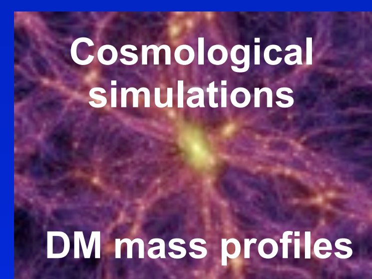
VLT

VIMOS Large Prog (230 hr)
~500 members per cluster
+ arcs redshifts

High-z gals
Dynamical analysis
Stellar masses

PI: P. Rosati

DM and Baryons in Clusters



Subaru (+ ESO-WFI)

WL masses profile
Stellar masses

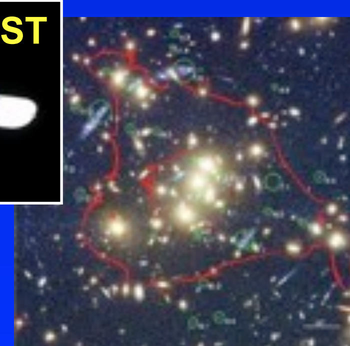
PI: K. Umetsu

AMiBA

ICM physics
DM&Baryon masses
SZ observations

PI: K. Umetsu

Strong Lensing
Mass profile in the core



Treasury Program
(530 orbits)
PI: M. Postman

High-z galaxies
Stellar masses

Spitzer

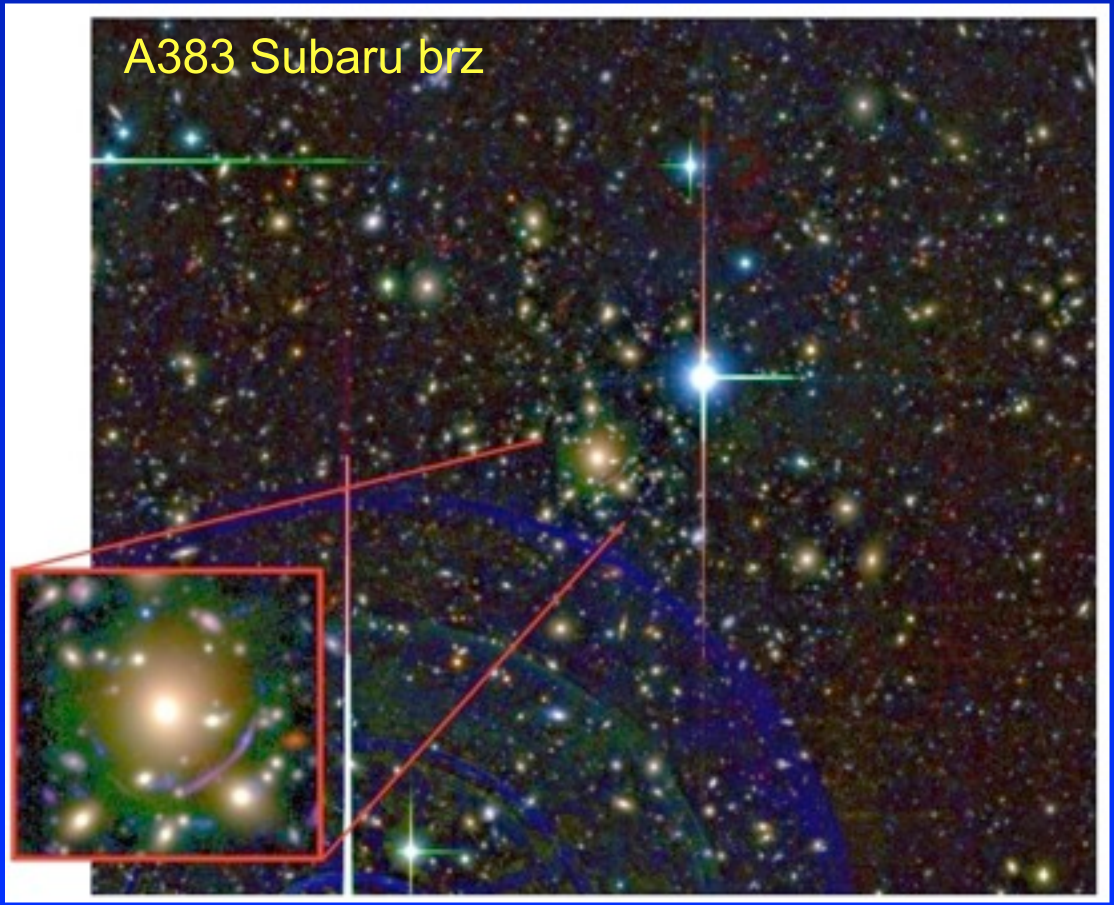
PI: W. Zheng

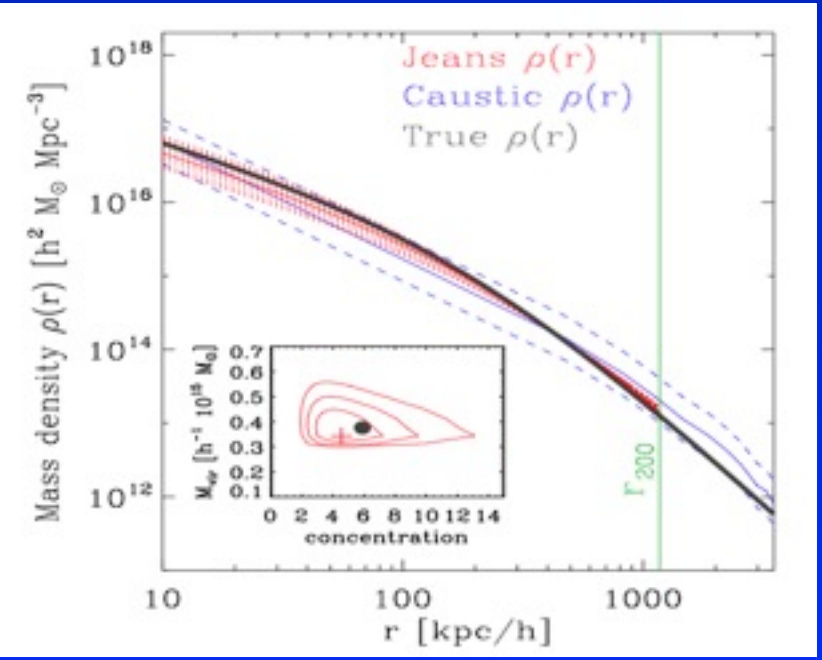
CLASH-VLT

VIMOS Large Programme (225 hr over 2 years)

All data products will go public in the ESO Archive

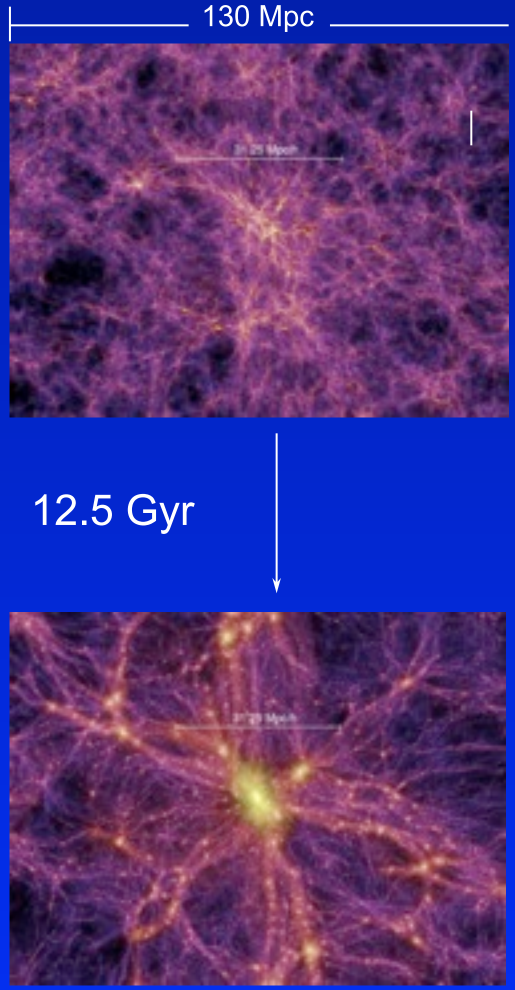
- Panoramic (r≳3 Mpc) spectroscopic survey of 14 southern CLASH clusters at z=0.3-0.6 Multi-band Subaru SupCam + HST data used for target selection
- Dynamical analysis out to R_{vir} and beyond (r>3 Mpc) with ~500 members per cluster
- Highly magnified galaxies out to z~7
- Galaxy structure and stellar pop properties from high to low density environments





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?
  - Is the DM mass profile universal?



"Millennium" simulation of DM (Springel et al. 2005)

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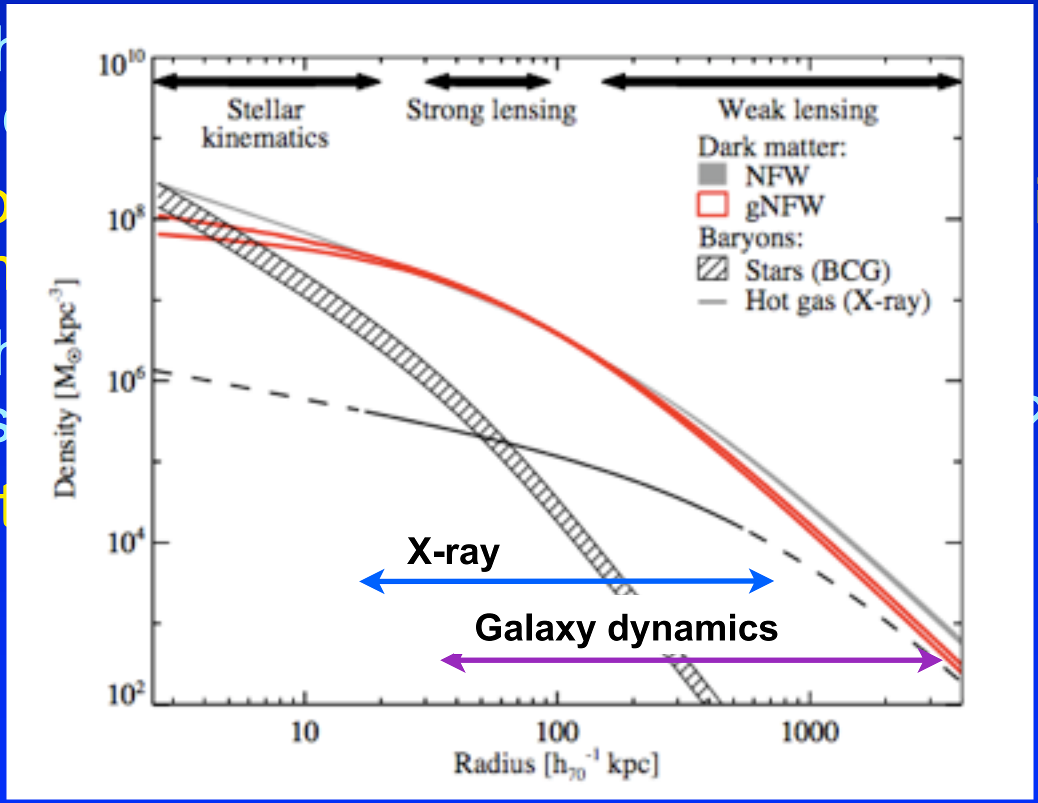
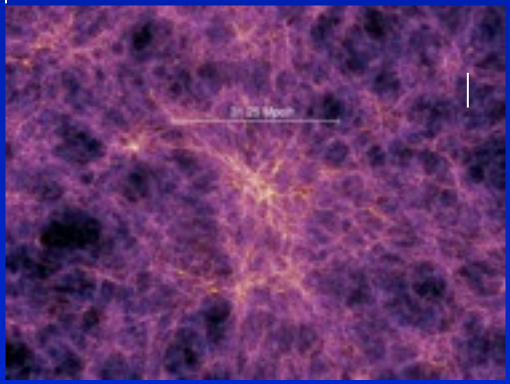


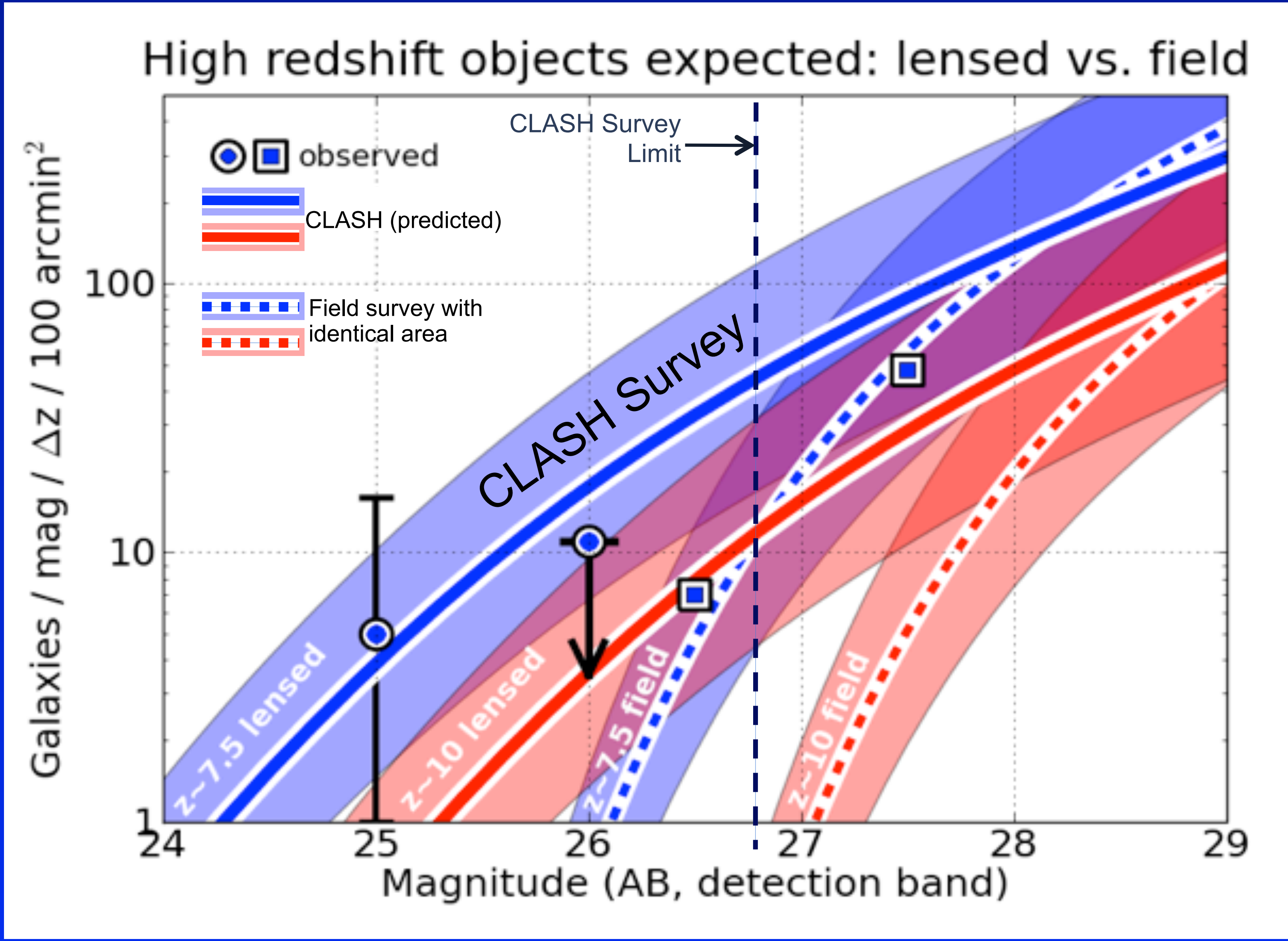
130 Mpc



12.5 Gyr

“Millennium” simulation of DM (Springel et al. 2005)

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



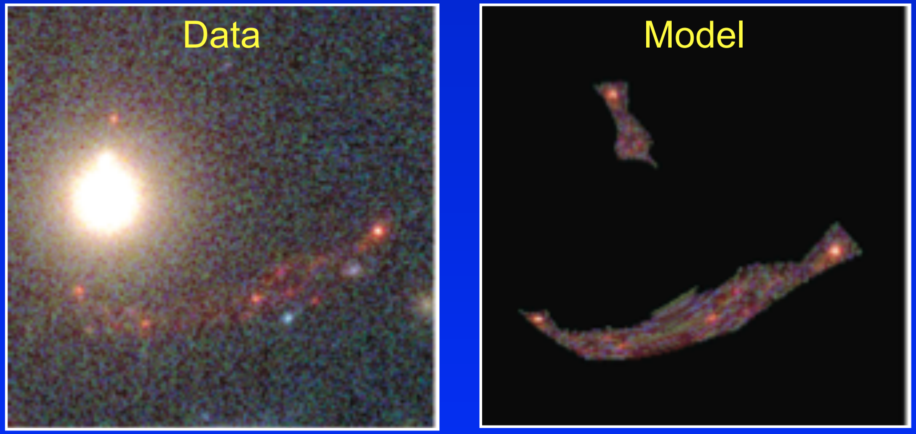
- With the current constraints on the faint of z>6 LF, the use of large cluster lenses is more efficient makes the search of high-z sources more efficient

Spatial magnification of (strongly) lensed sources

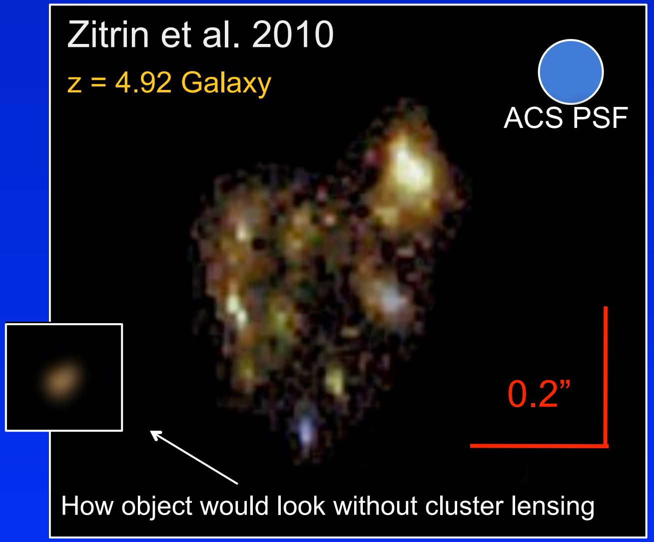
Zitrin et al. 2010:

- Reconstruction of a z = 4.92 source lensed by the z = 0.33 cluster MS1358+62.
- Best resolved high-z object: μ≈100, spatial resolution of ~50 pc ! (rest-frame UV)
- *Equivalent to 20-m space telescope resolution of a non-lensed z=5 galaxy!*
- *Typical (or better) resolution of ELTs*

Lens plane

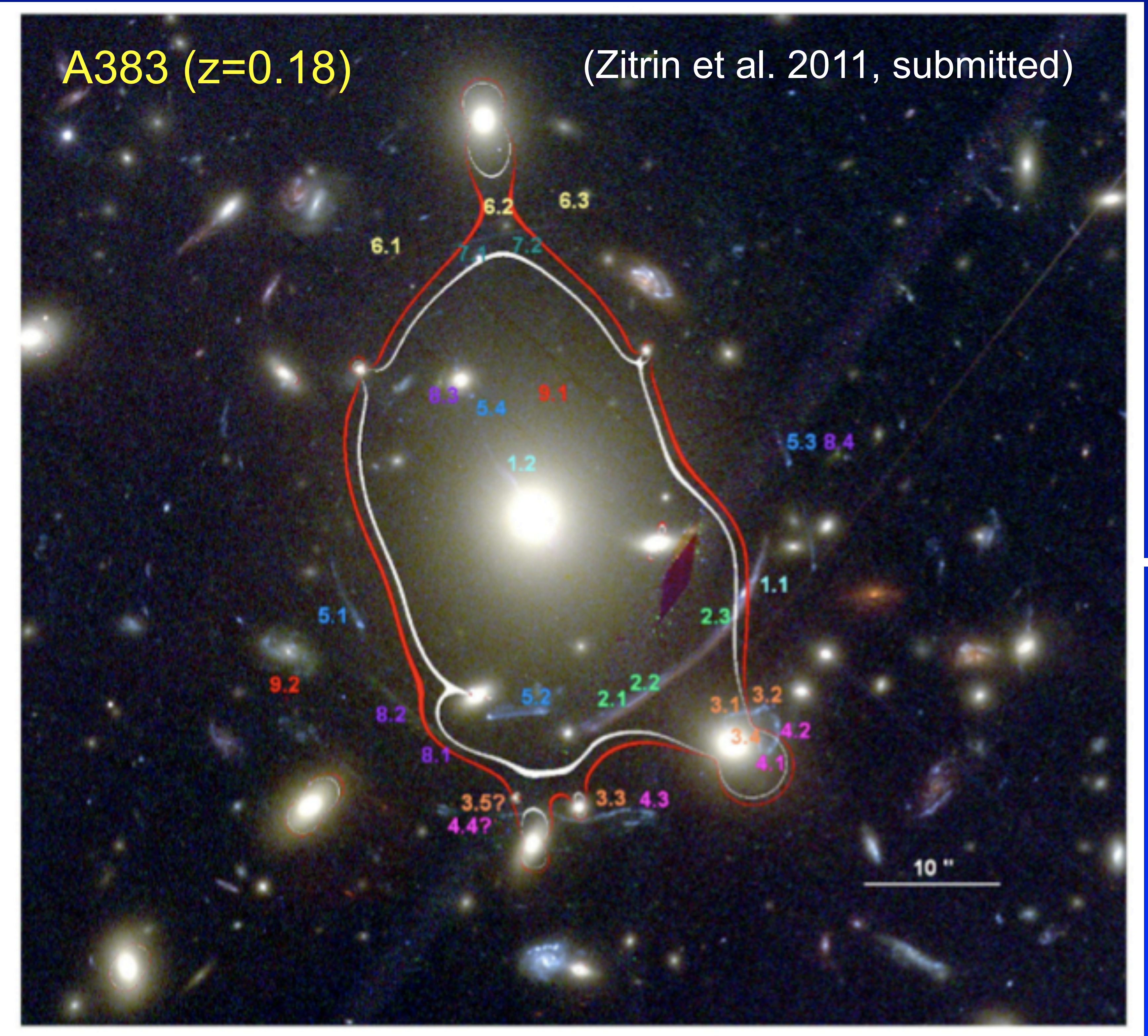


Source plane

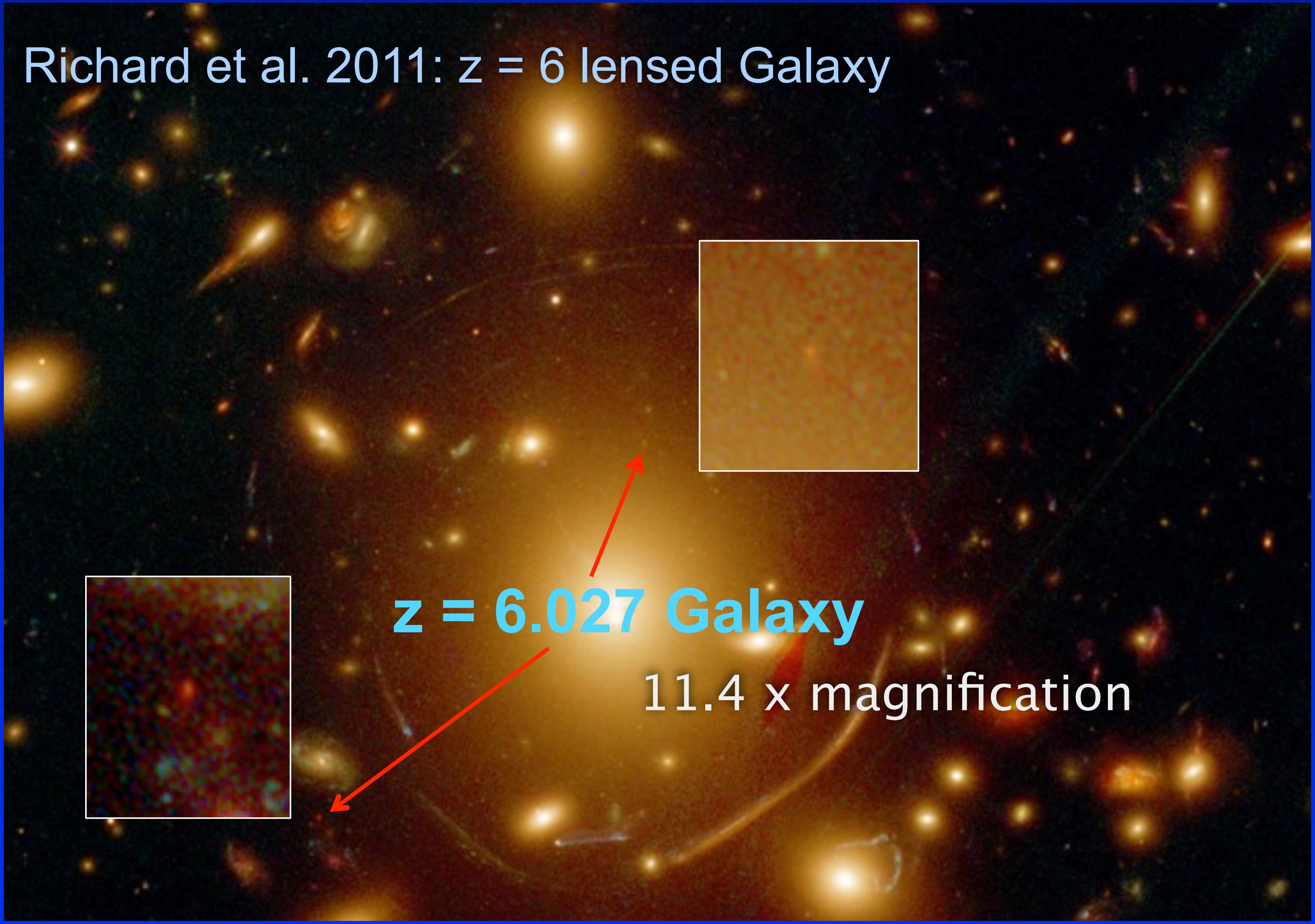


First CLASH snapshots...

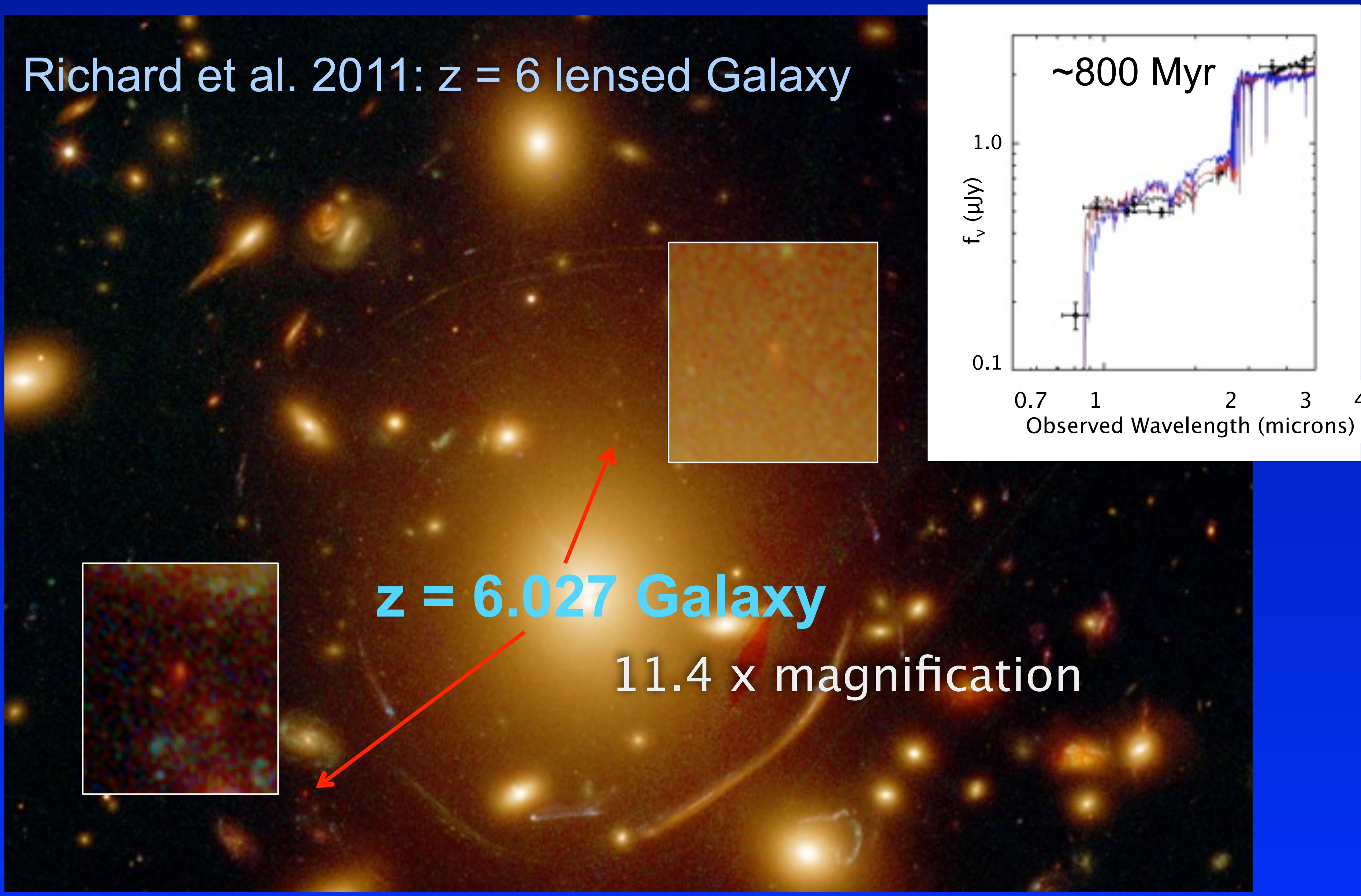
Credits: CLASH Team


A383 (z=0.18)
(Zitrin et al. 2011, submitted)
6.1
6.2
6.3
7.1
7.2
8.3
5.4
9.1
5.3 8.4
1.2
1.1
2.3
5.1
9.2
8.2
8.1
5.2
2.1
2.2
3.1
3.2
3.4
4.2
4.1
3.5?
4.4?
3.3
4.3
10 "

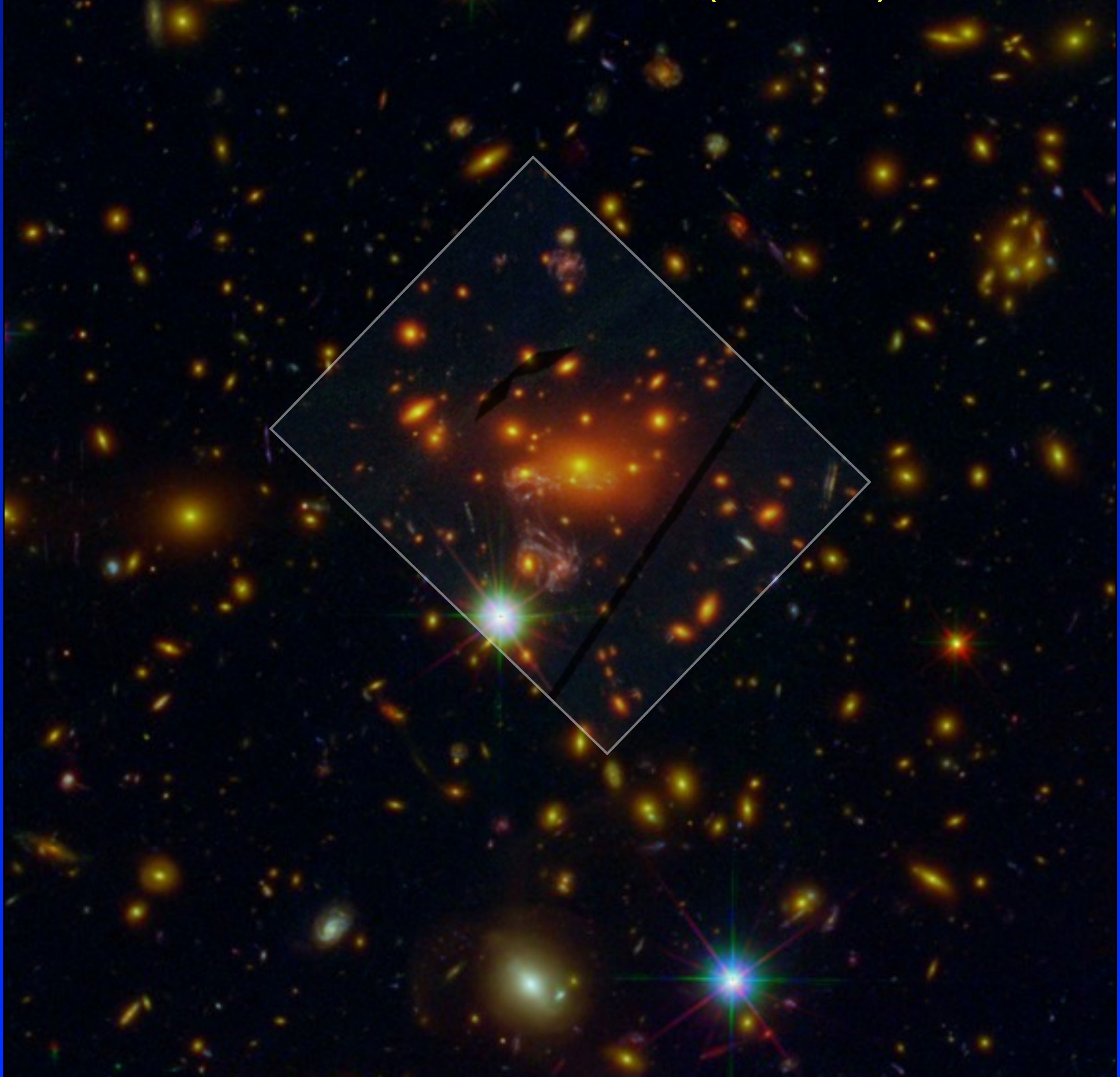
Abell 383 (z=0.18)



Abell 383 (z=0.18)

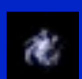


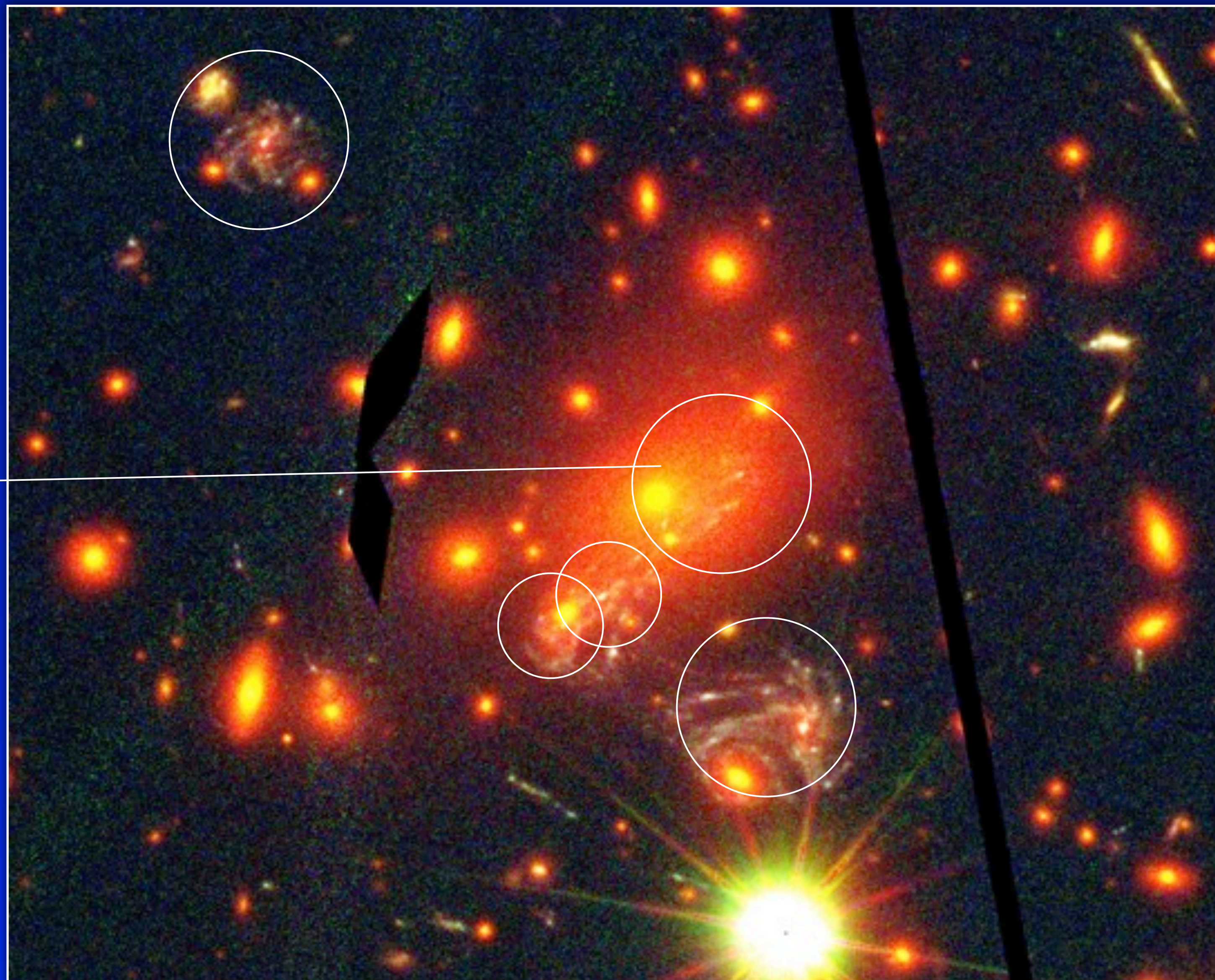
MACS 1149+2223 (0=0.54)



MACS 1149+2223 (z=0.54)

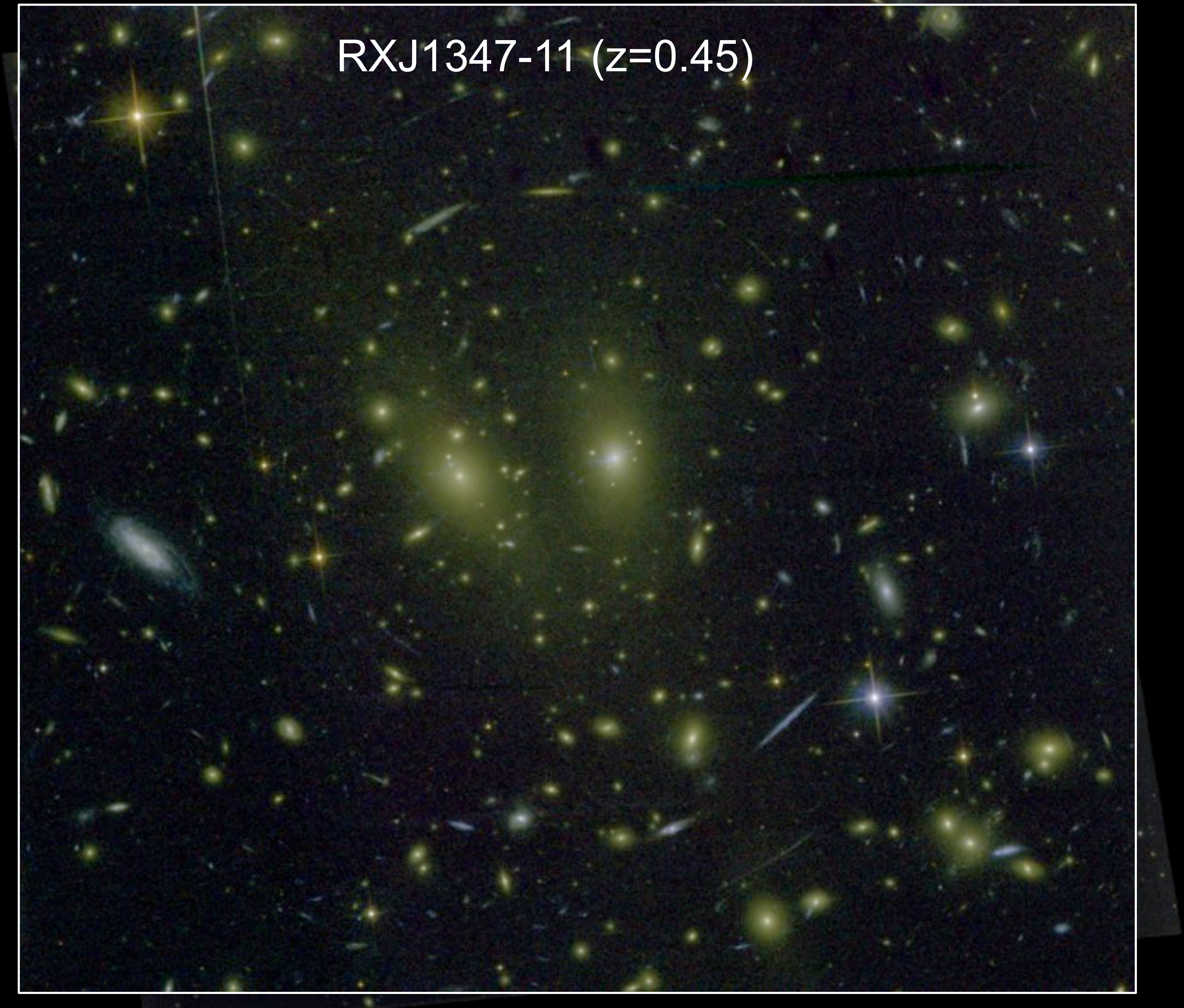
Unlensed
source size



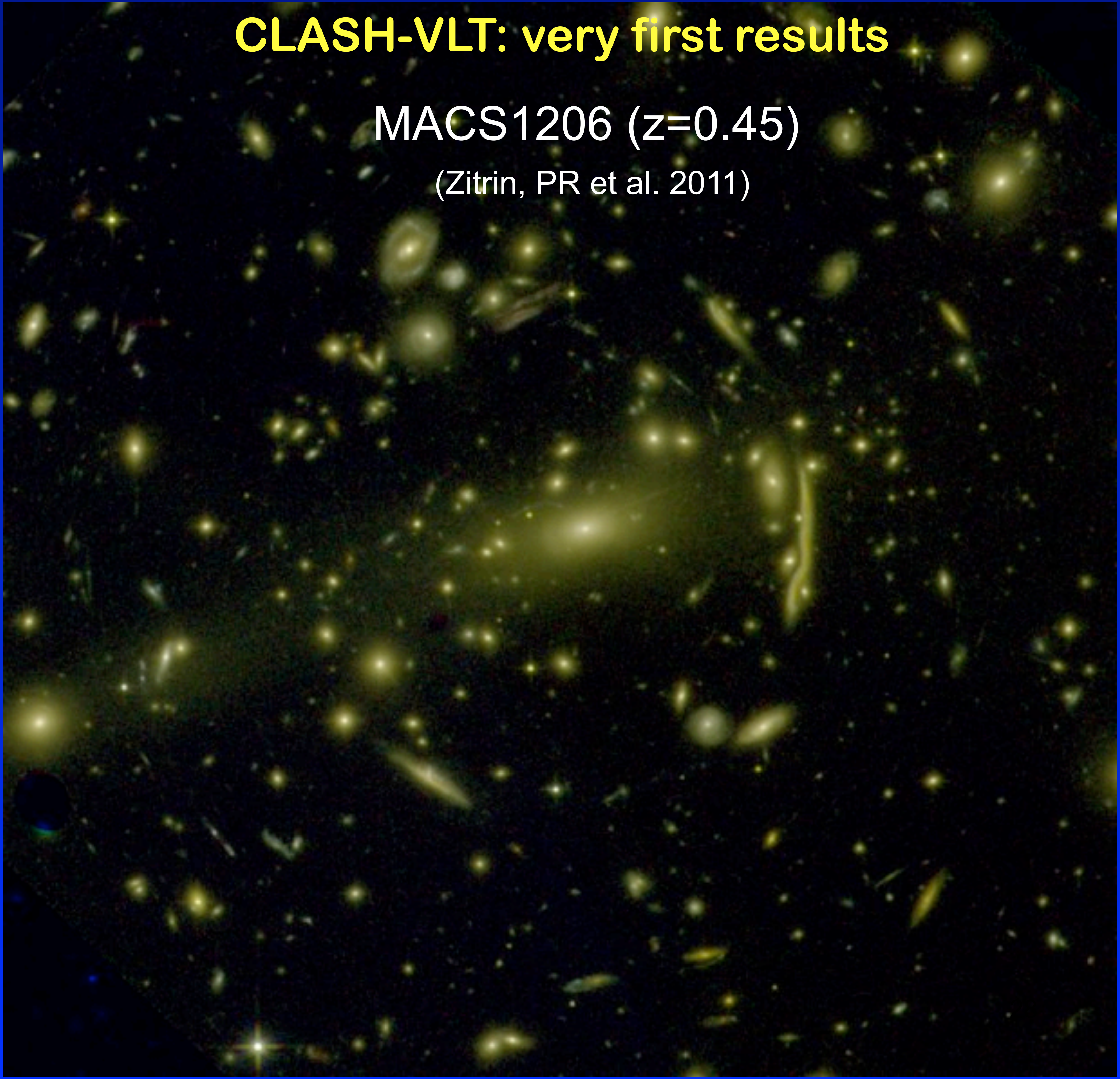


40”

Quintuply-lensed spiral at z=1.49, magnification: ~22x
(Zitrin & Broadhurst 2009; Smith et al. 2009; Yuan et al. 2011)


RXJ1347-11 (z=0.45)

CLASH-VLT: very first results

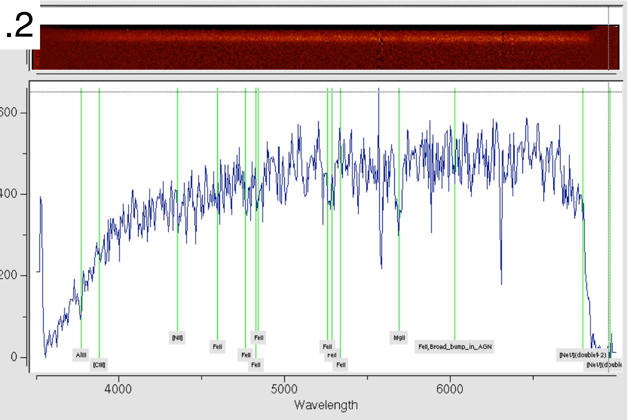


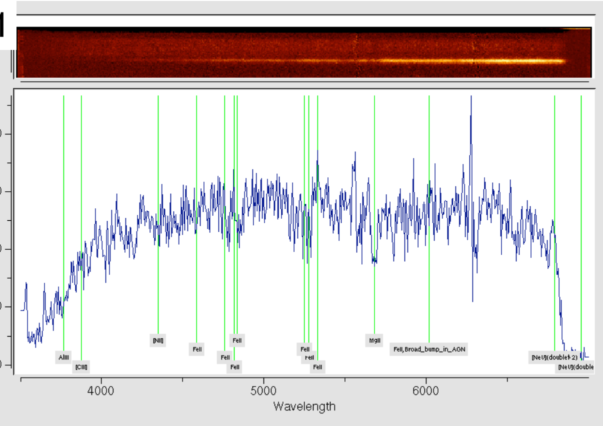
MACS1206 (z=0.45)

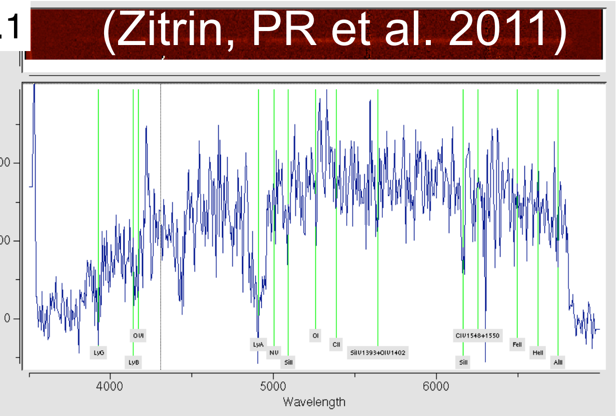
(Zitrin, PR et al. 2011)

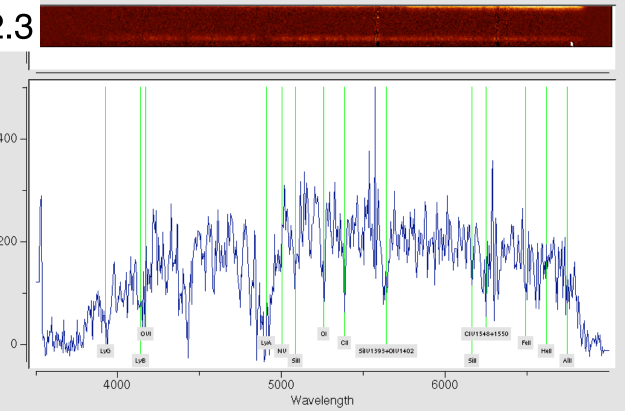
CLASH-VLT: very first results

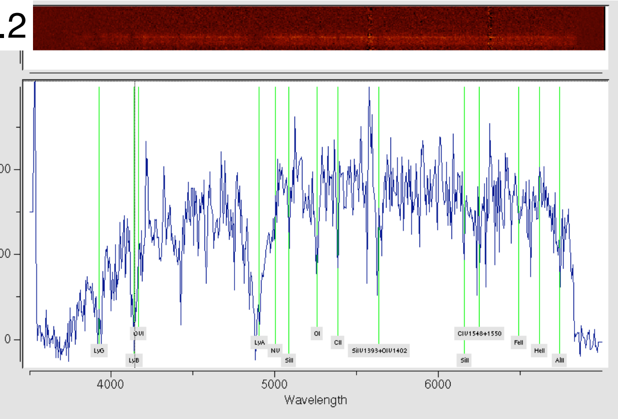
z=1	z=3	z=2.5

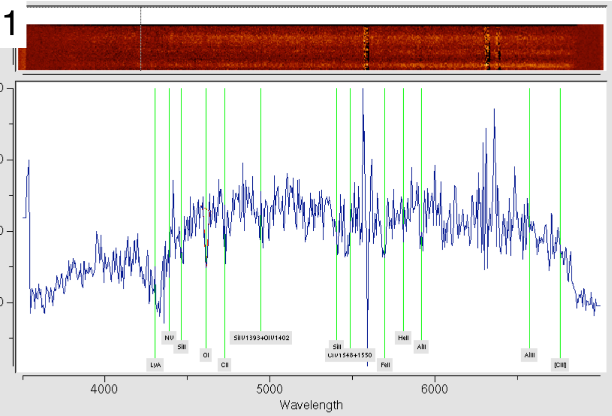
1.2


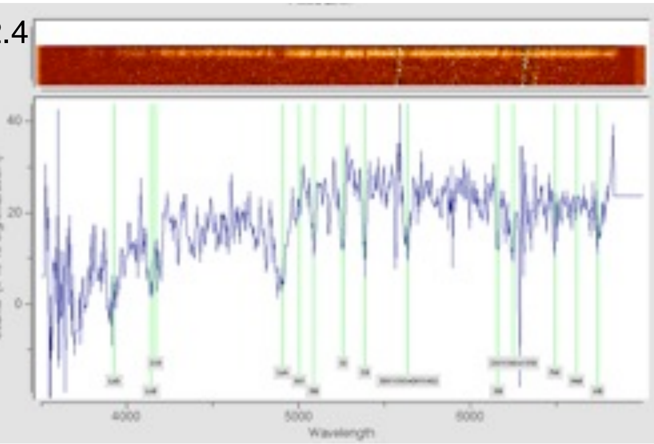
1.1


2.1


2.3


2.2


3.1


2.4


Final thoughts and thanks..

- Don't need to wait for ELTs or even JWST to find and characterize the first stars, GL tool is already in hand with intermediate R follow-up spectroscopy
- The privilege of having Bob's office within close range for more than a decade...
- Broad-band scientific curiosity (on all kind of physical phenomena) as driving force..
- Importance of serendipitous discoveries (Nature revealing to us with no filters, thinking outside the box)
  - ★ they are not details! may indicate important missing components, the path to solve outstanding problems
  - ★ but one needs to explore new territories (parameter space, observational techniques)
- Thanks for all the many illuminating brain storming discussions and for sharing the excitement of first looking at new data, new results, new ideas..
- Hoping they won't kick us out of our nearby offices any time soon...