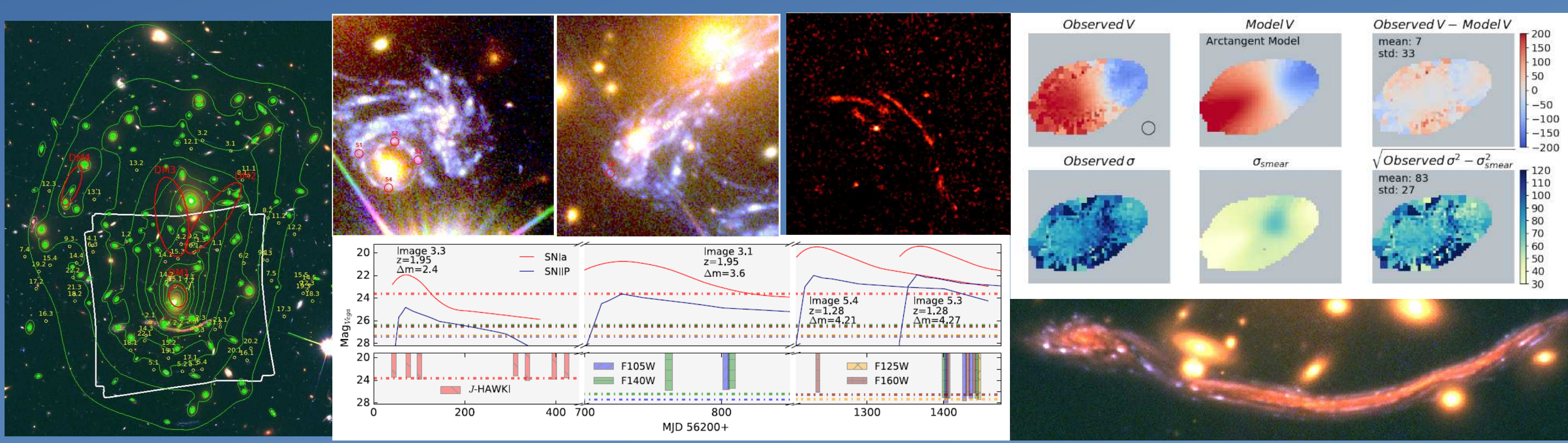
Lensed Galaxies and MUSE

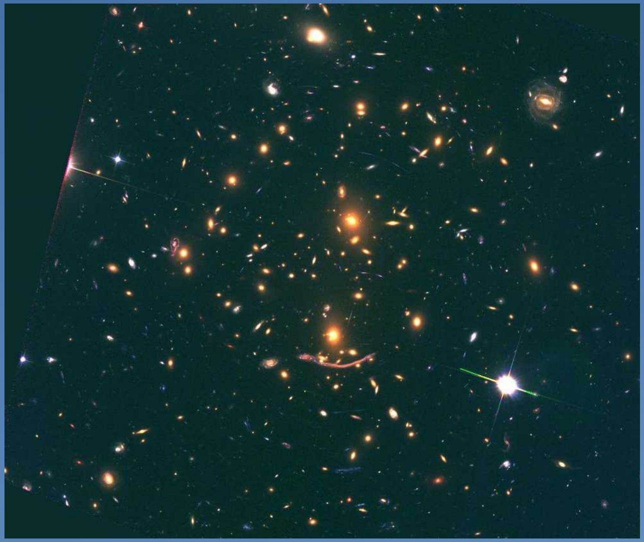
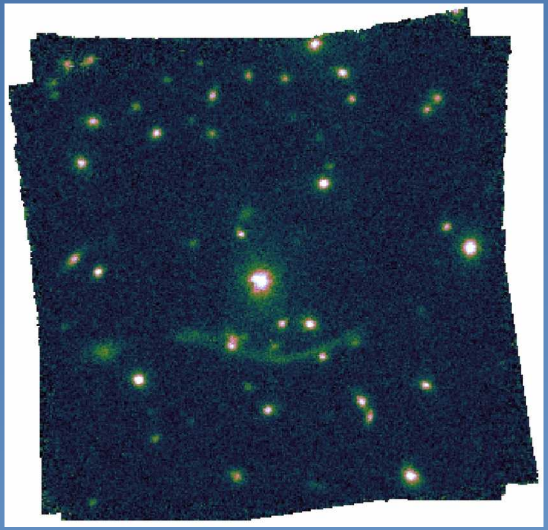
David Lagattuta



Franco-Indian Astronomy School IUCAA, Pune, India 13 Feb 2018

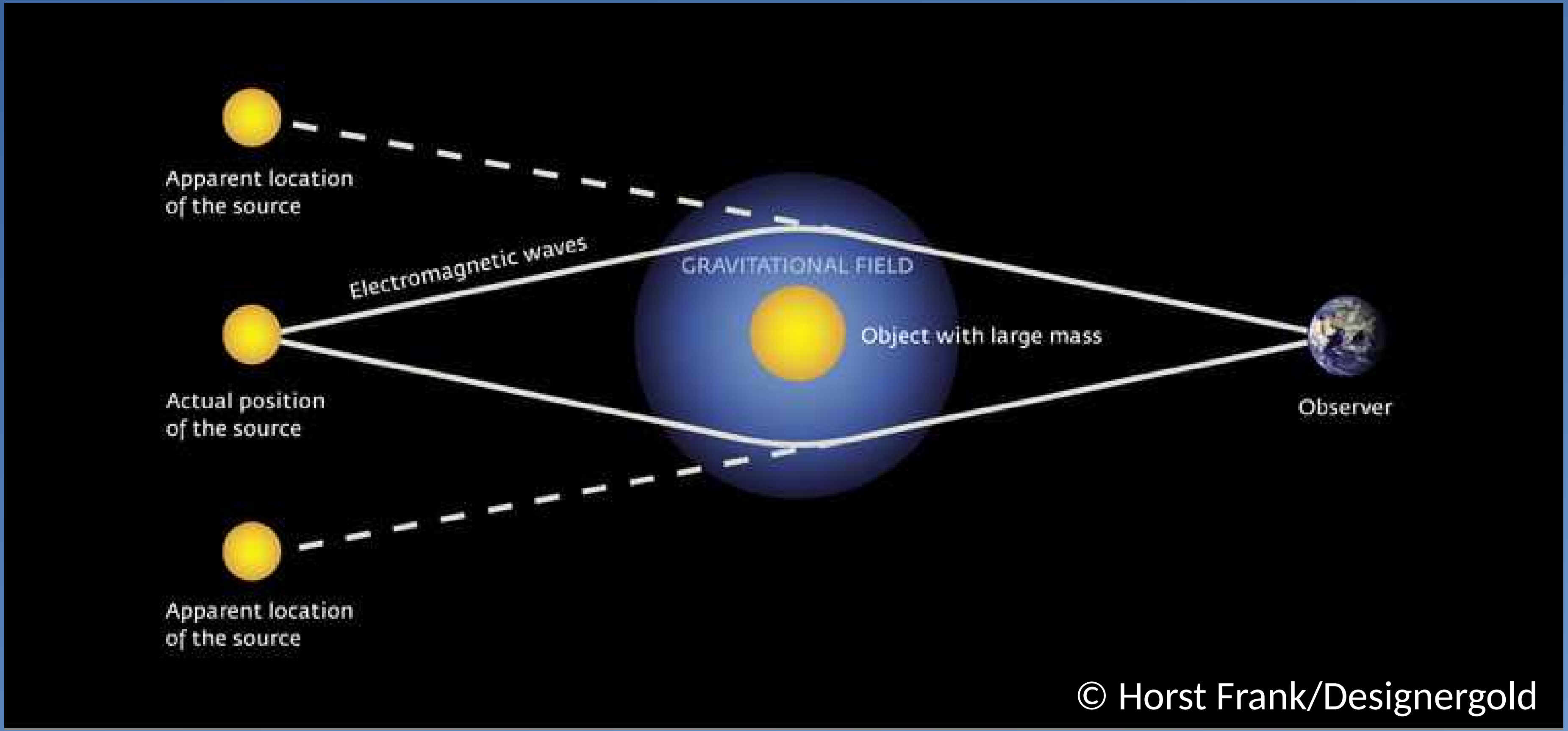
Outline

- Brief introduction to gravitational lensing
  - More in-depth discussion on Thursday
- Description of MUSE (and other IFUs)
- Science with Lensing+MUSE

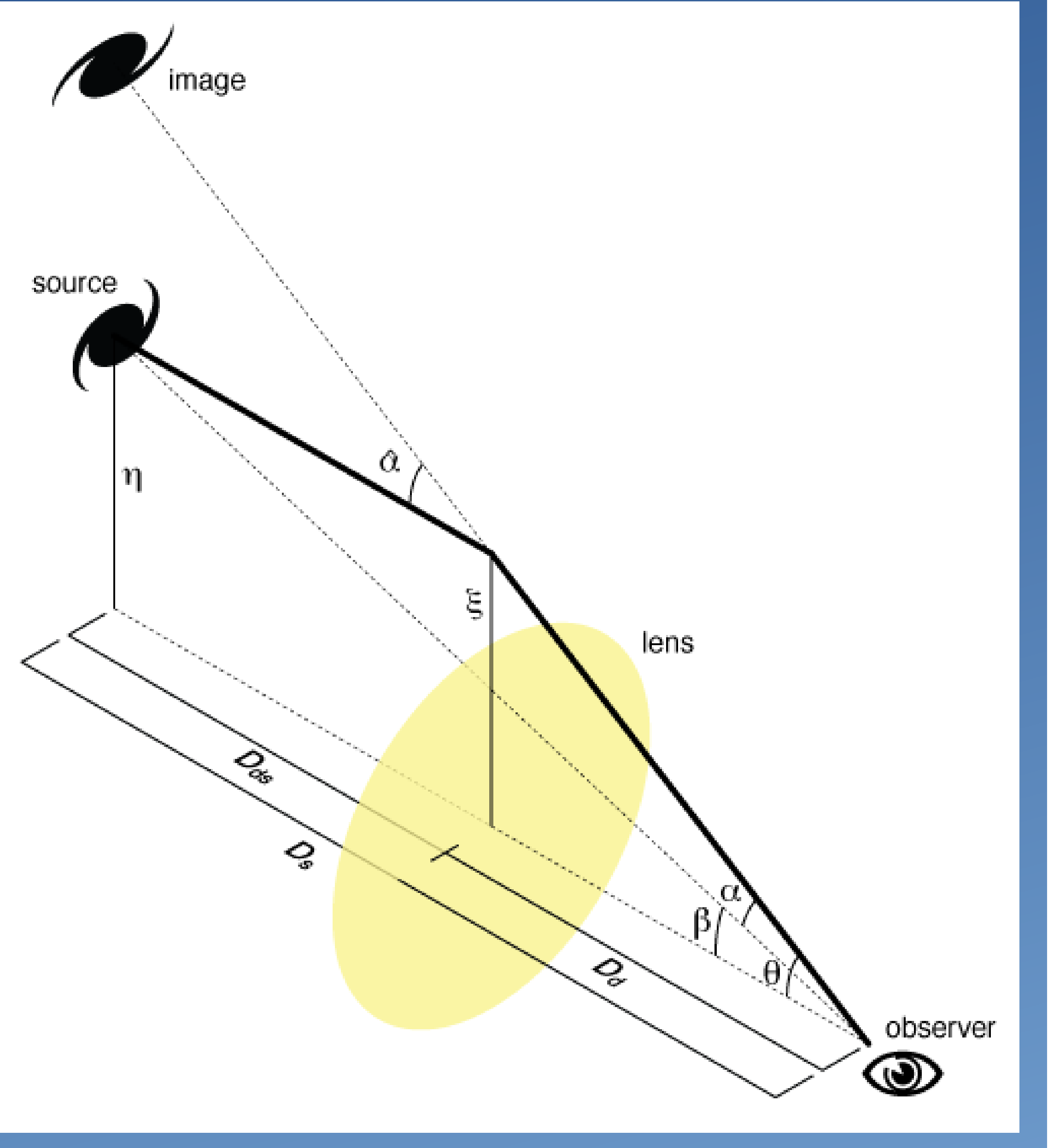

What is Gravitational Lensing?

- Generally, a deflection of light due to gravity
  - Similar to geometric lensing (with glass)
  - However, light is not focused...merely redirected



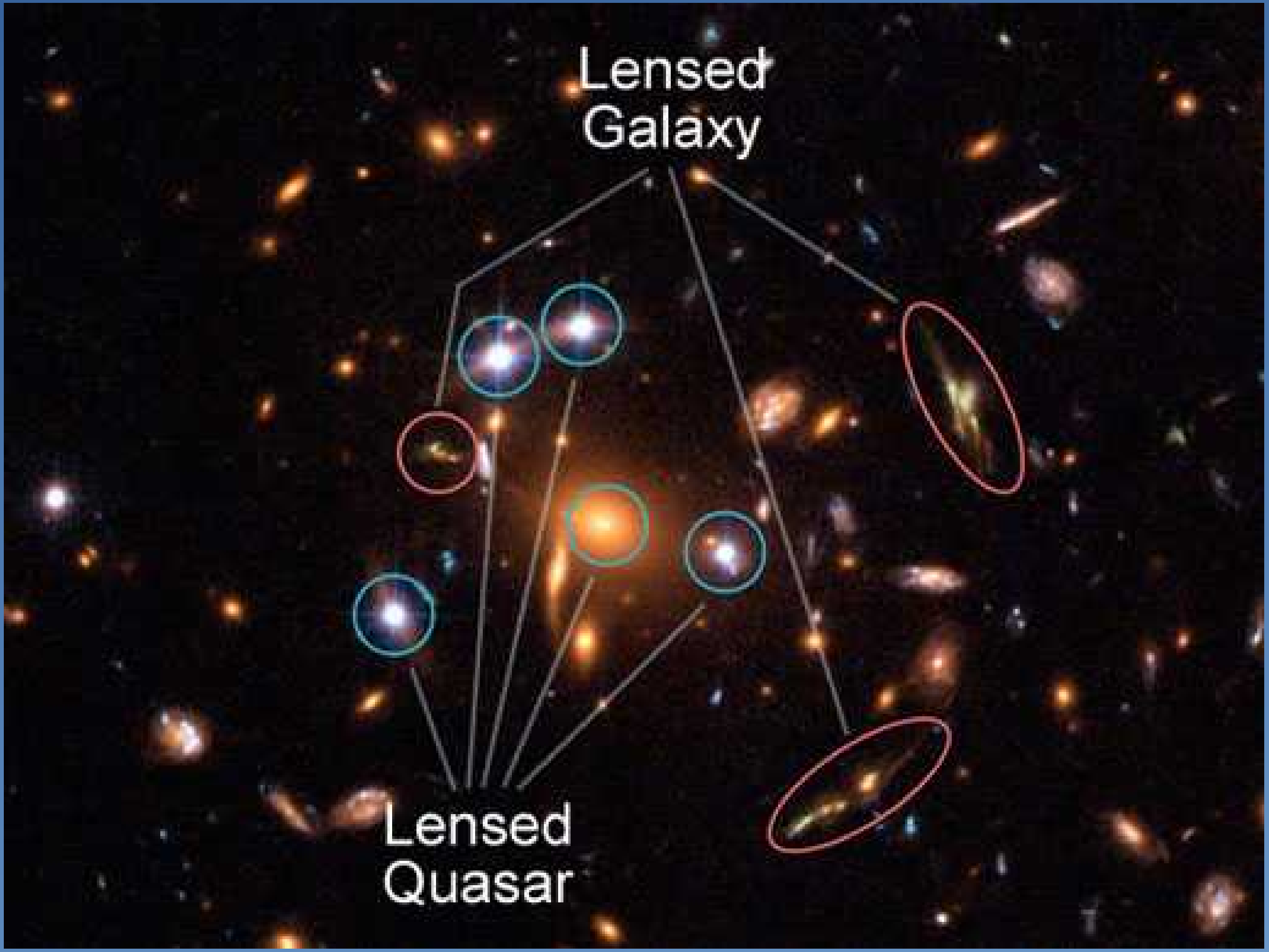
How does lensing work?

- Dependent on two main factors:
  - Geometry
  - Mass
- Changing either will change what you see
  - Can also determine the “type” of lensing observed



Strong Lensing

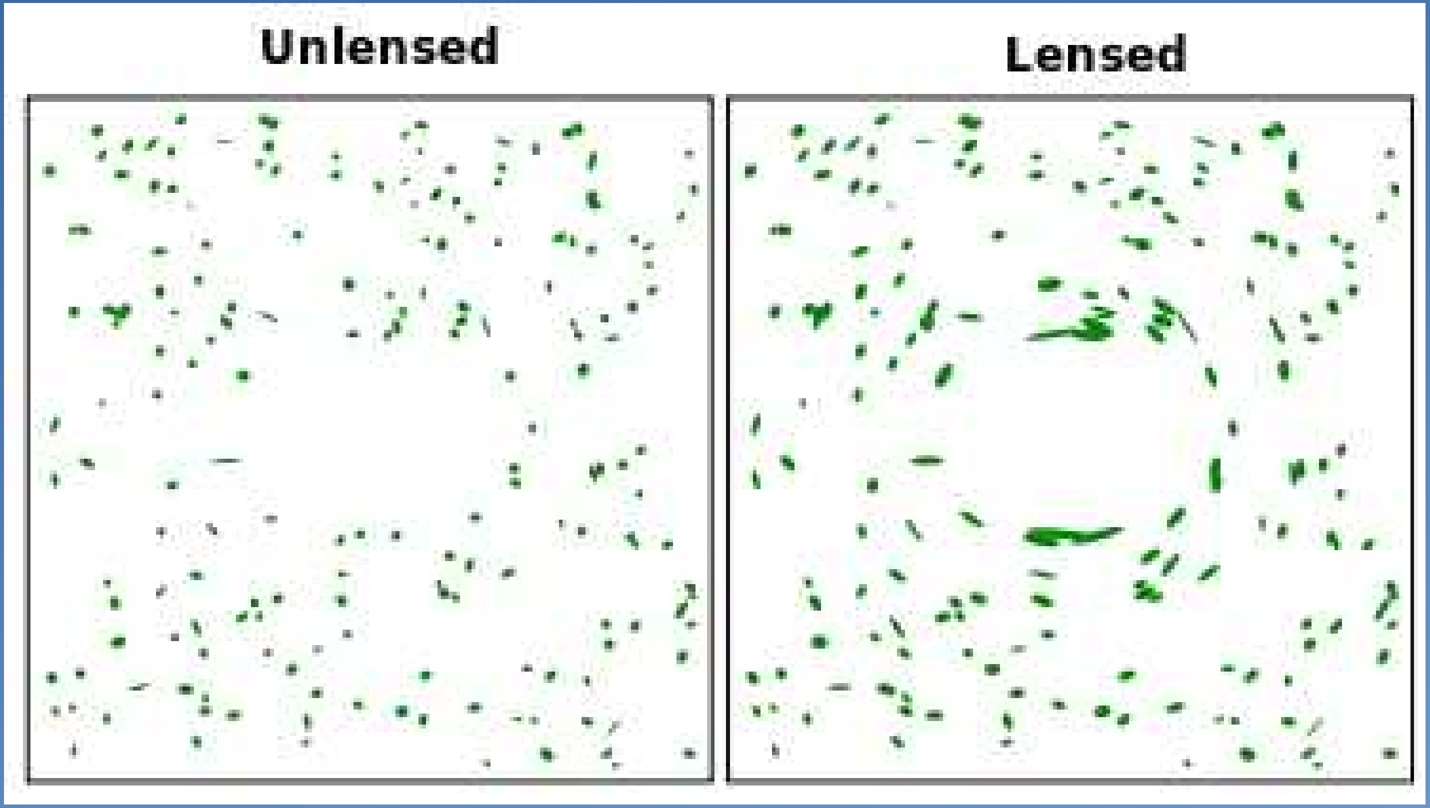
- Occurs when the foreground and background galaxies are close to each other in the unlensed ("source") plane
  - Multiple images of the background appear



NASA, ESA, K. Sharon (Tel Aviv University) and E. Ofek (Caltech)

Weak Lensing

- Occurs when the foreground and background galaxies are far away (or foreground galaxy is not very massive)
  - Images are distorted, but only one per galaxy



Lensing at home

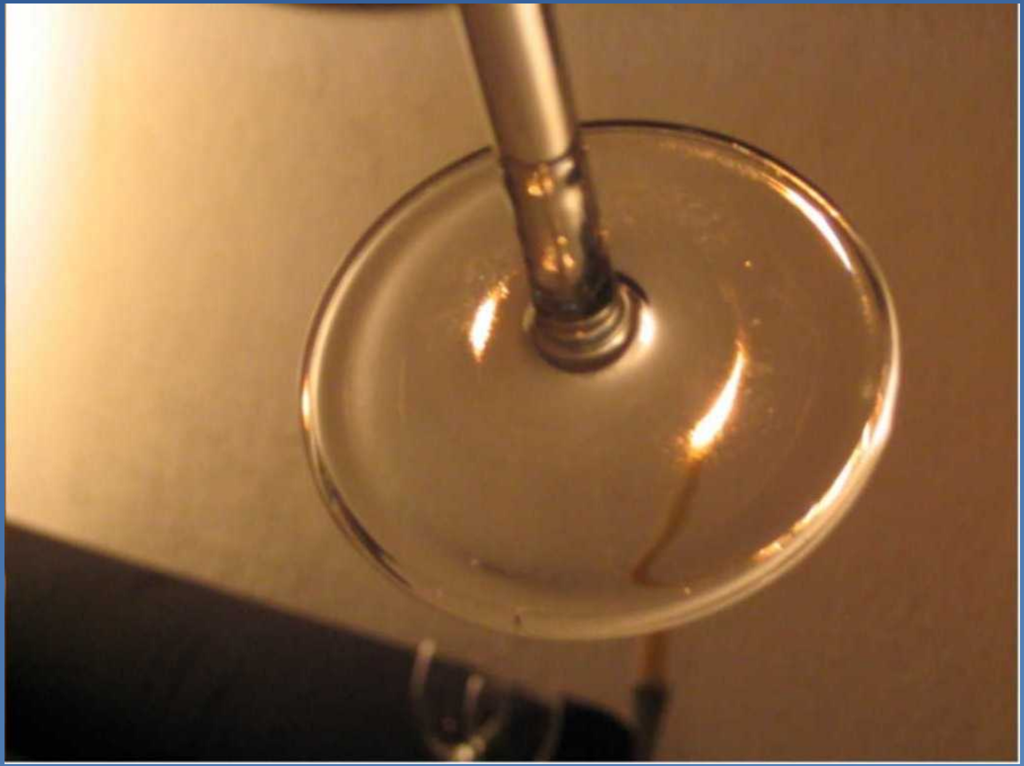
- You can even simulate gravitational lensing at home
  - Only need two things:

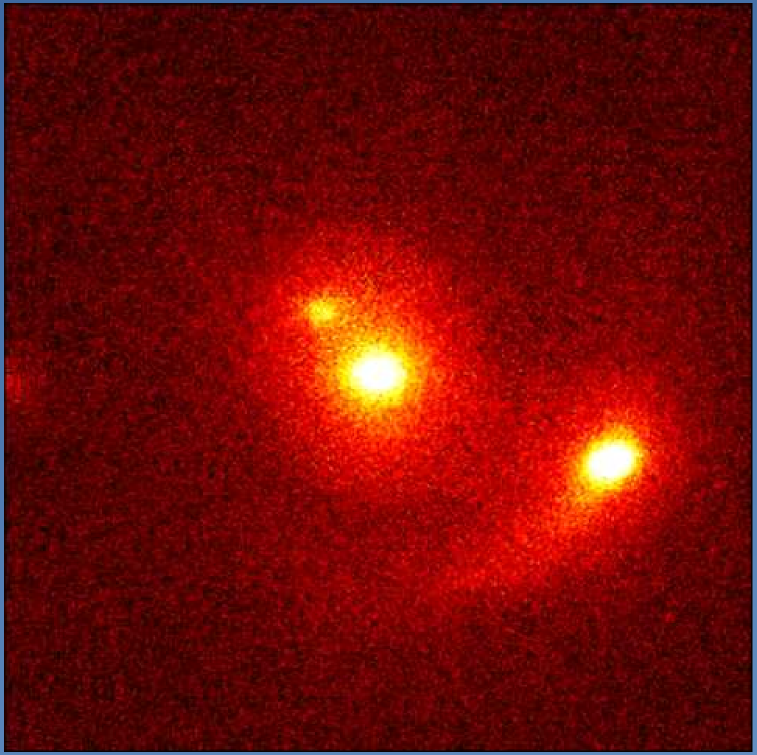
Source Galaxy

Lensing Galaxy

Wine-glass lensing

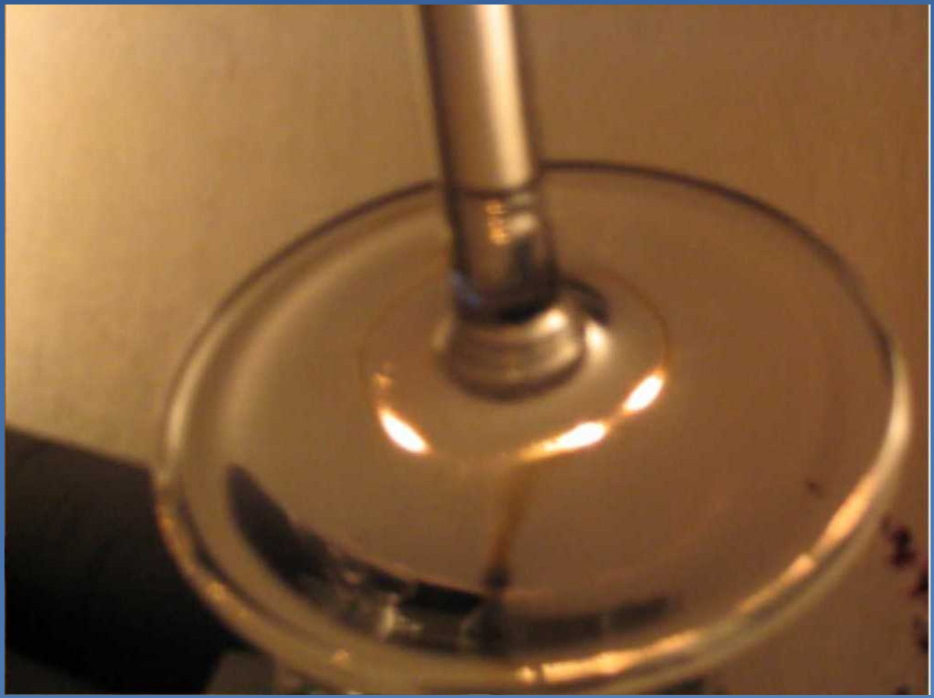
Double Image Lens

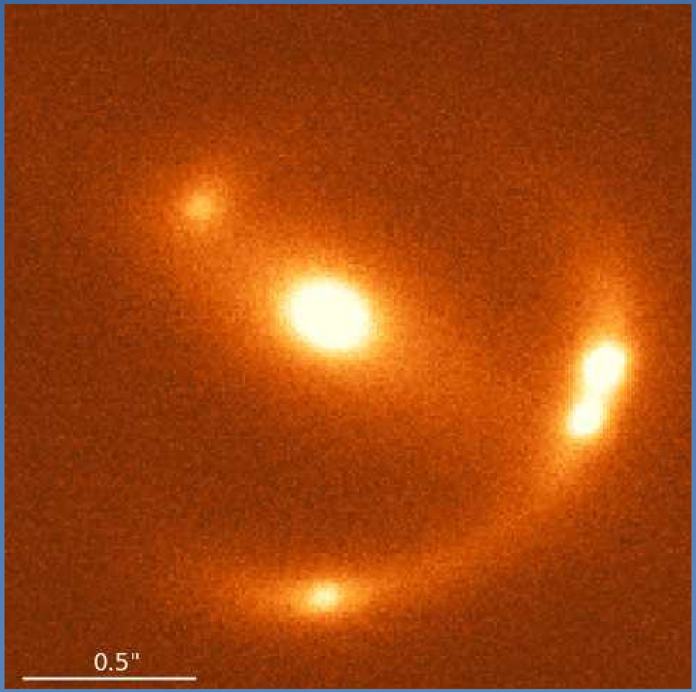




Wine-glass lensing

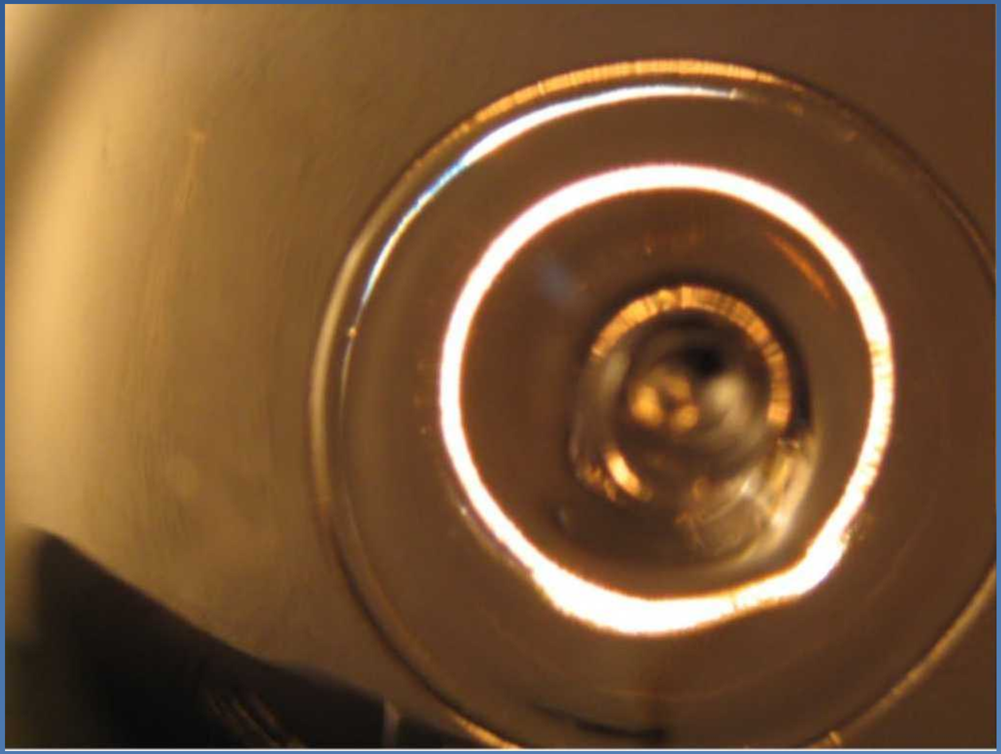
(Merging) Quad Lens





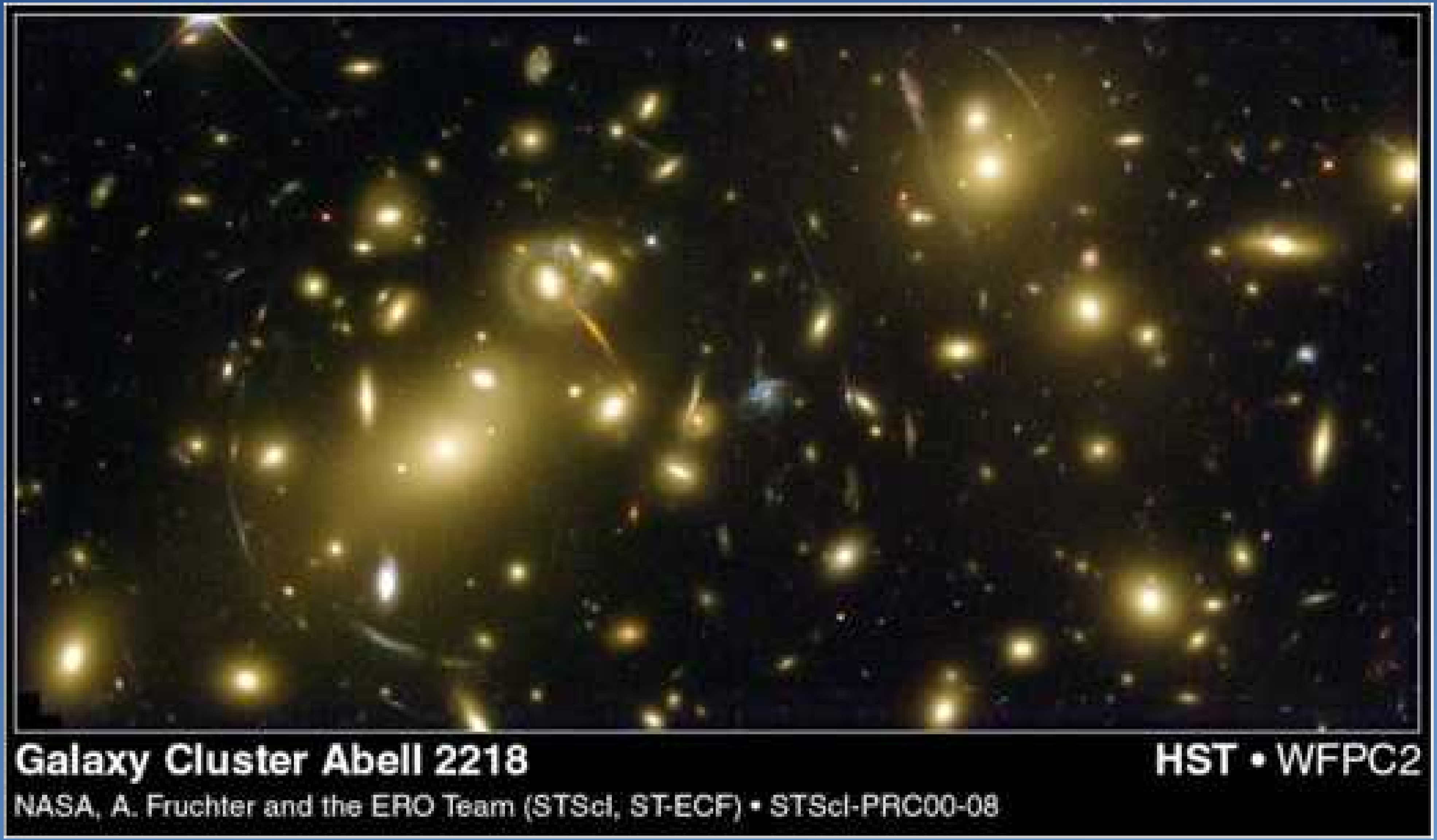
Wine-glass lensing

Einstein Ring



Cluster Lenses

Galaxy clusters can also act as gravitational lenses

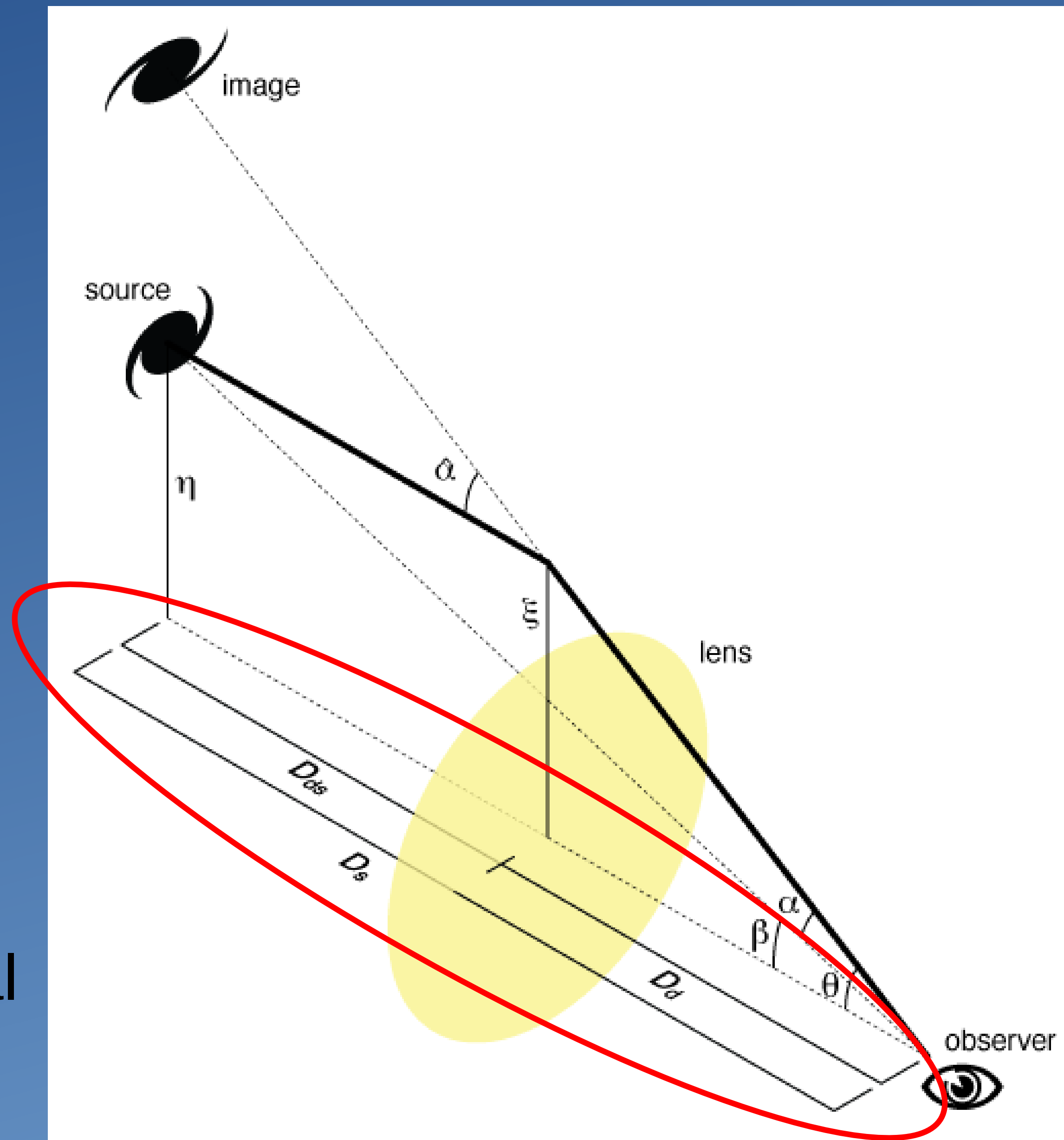


Increased total mass (10^{15} M_{sol} vs 10^{12} M_{sol}) makes them more efficient deflectors

Science with lensing

Recall:

- Dependent on two main factors:
  - Geometry
  - Mass

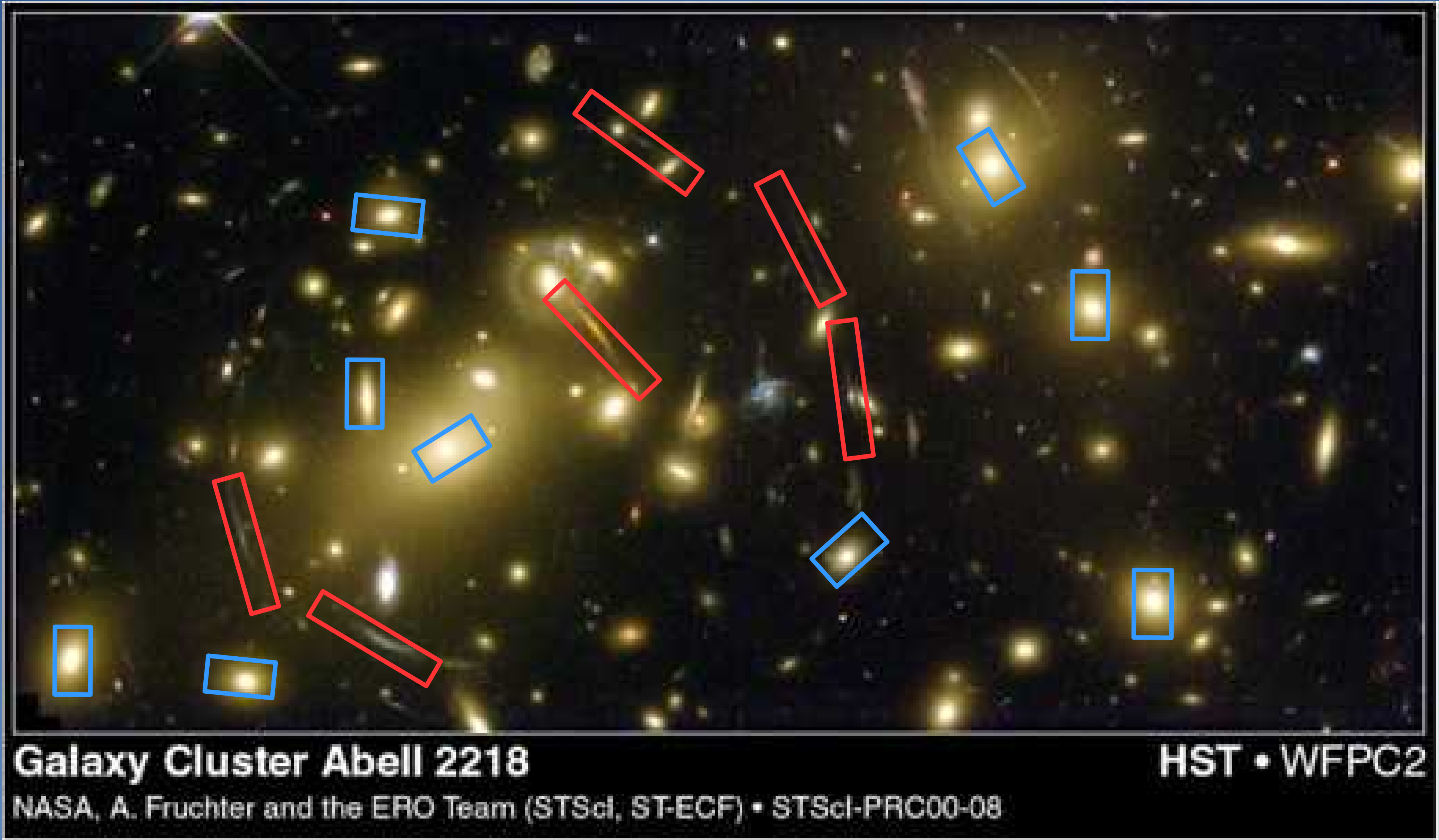


Accurate redshifts are crucial for quantitative analysis

Spectroscopy

- Spectroscopic data is valuable, but can be hard to obtain

Example: the “classic” way



Enter the IFU

- The Integral Field Unit (IFU): a new type of spectrograph
  - Creates "spectral images" of objects simultaneously
  - thousands of spectra in one exposure
  - Ancillary data included for free

CALIFA Survey

muse
multi unit spectroscopic explorer

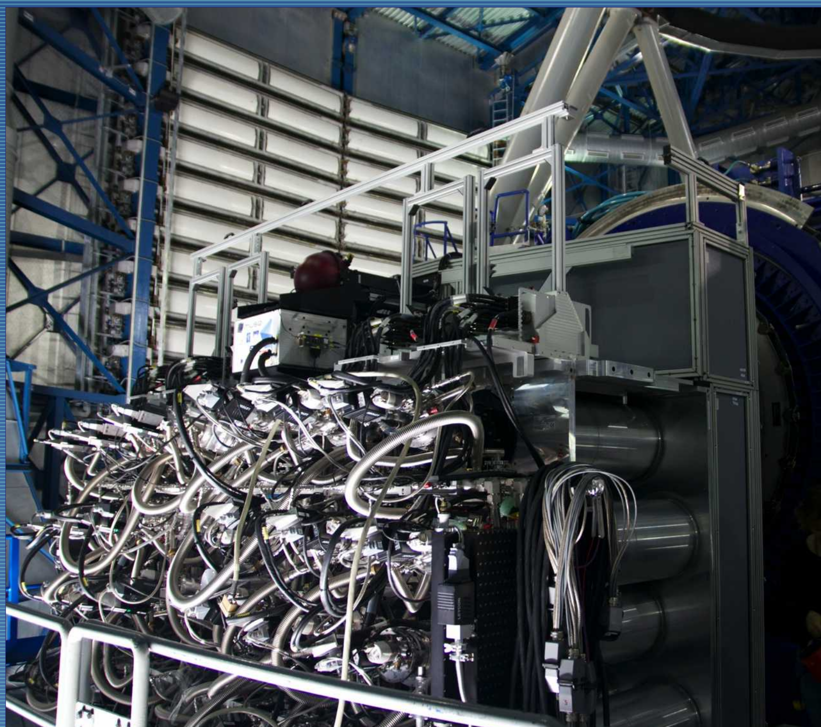
Sauron

ESI

X-shooter

MUSE is leading the way

Vital Statistics



Name: MUSE

Category: integral field spectrograph

Size: 1x1 arcmin^2

Spatial sampling: 0.2”

Image Quality: <0.2”

Coverage: 4650-9300 Å

Resolution: 1500-3500

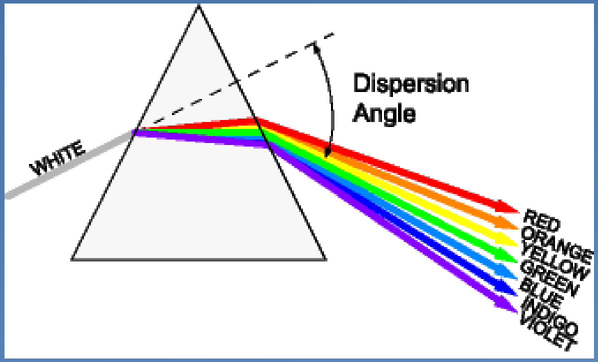
Throughput: 35% end-to-end

multi unit spectroscopic explorer

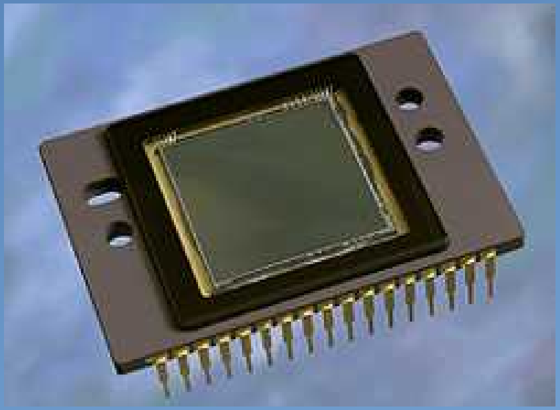
How does it work?

- Cut the field of view into slices

- Each slice is like an individual long slit

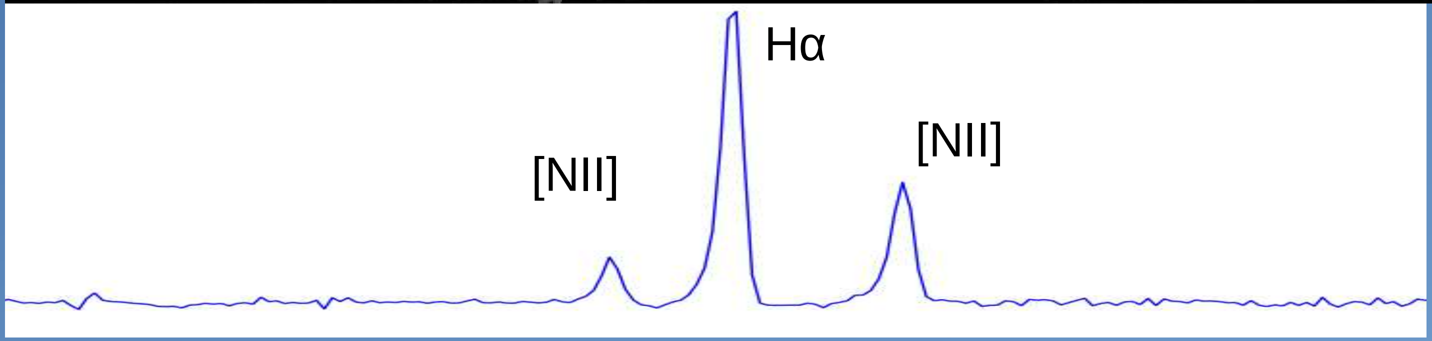


- Disperse the light through a disperser (prism)



- Capture the light with a (CCD) detector

The Result



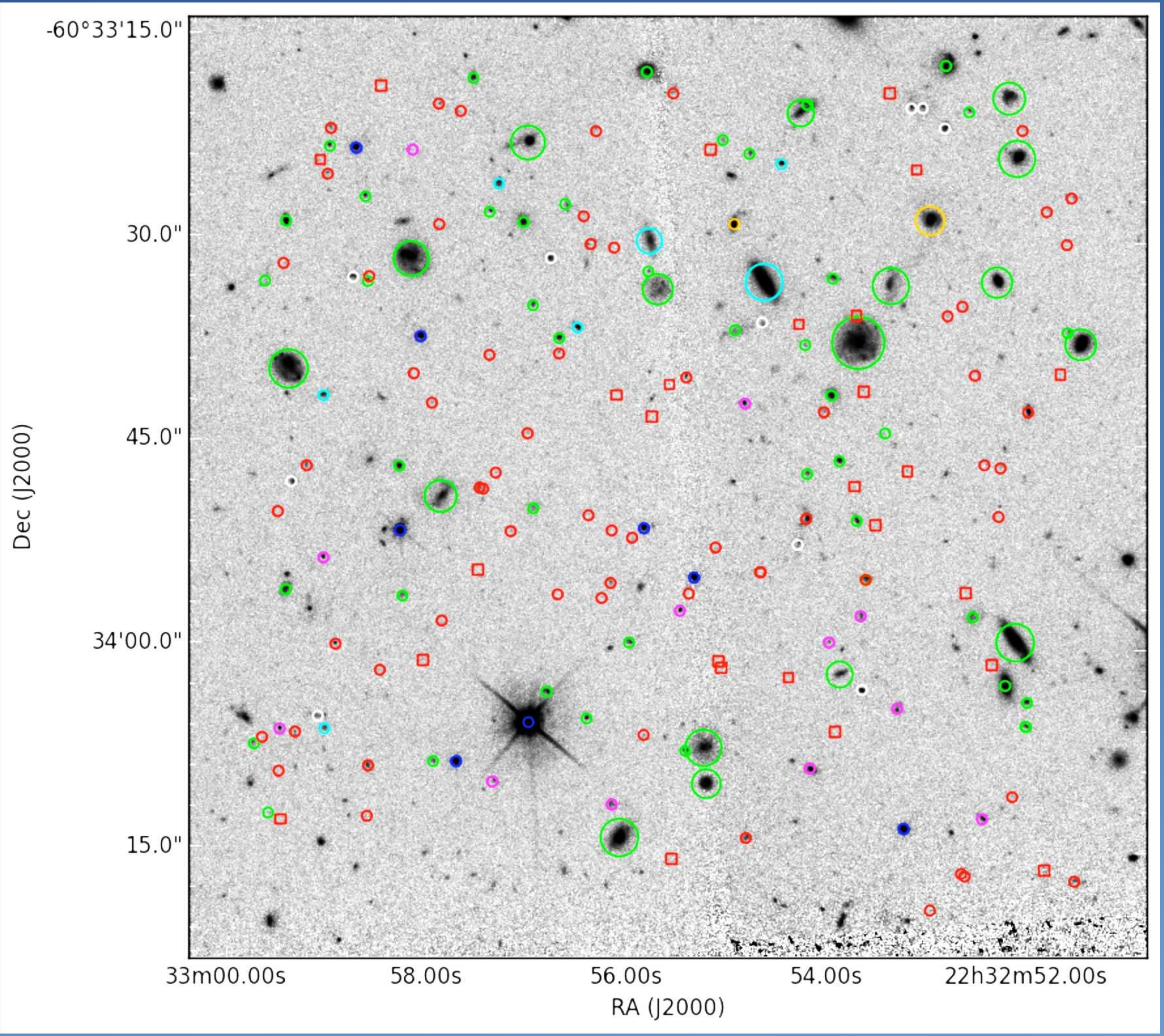
- 3D (2 spatial + 1 specral) information of the object
- Emission line regions clearly shown
  - along with kinematic information

Census of the HDFS Field

Extremely efficient redshift machine

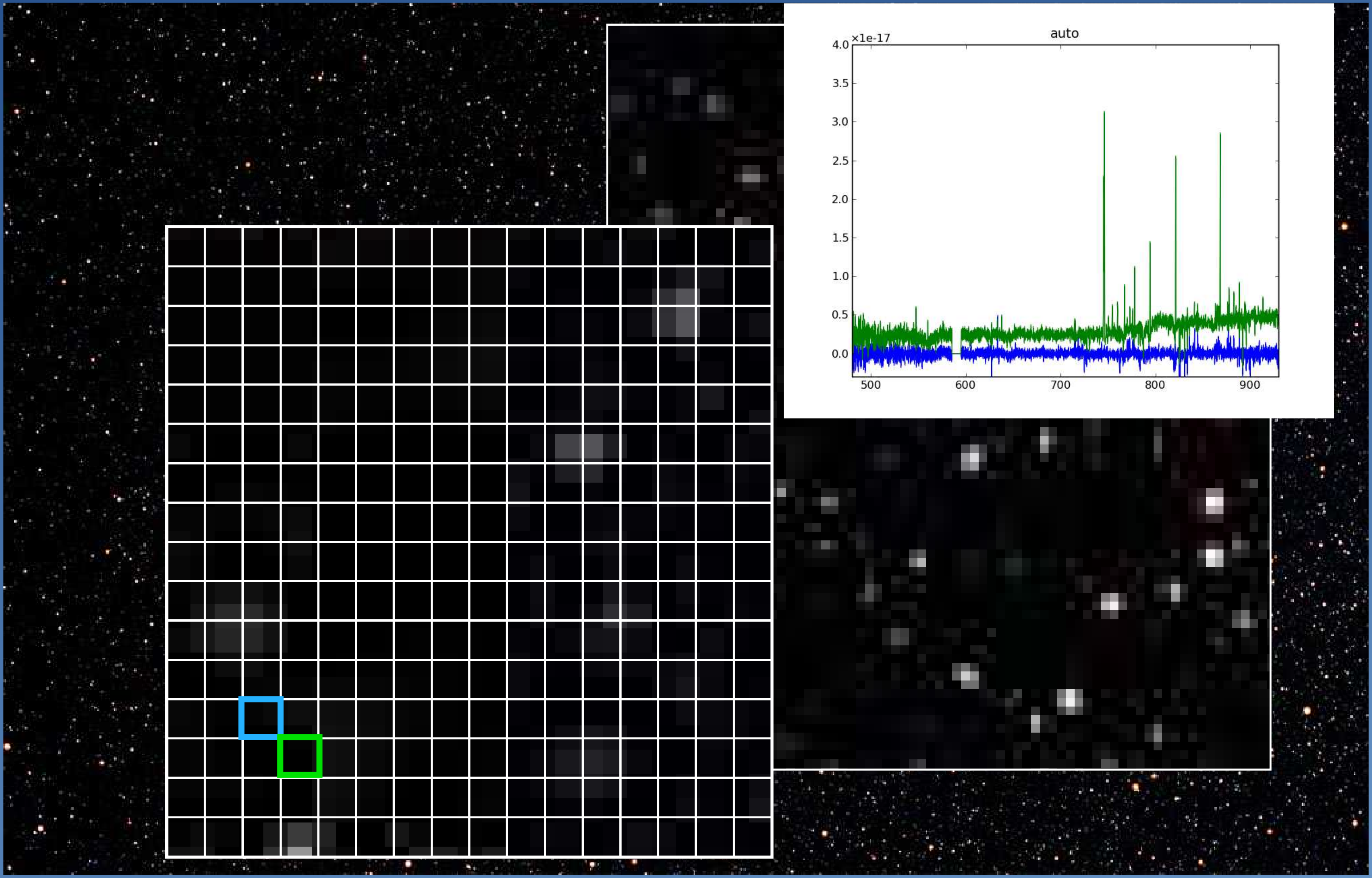
- 18 Previously-Known Spectroscopic Redshifts
- 189 sources identified in MUSE data cube

- 8 stars
- 7 nearby galaxies
- 61 [OII] 3727 emitters
- 10 absorption lines galaxies
- 12 CIII] 1909 emitters
- 2 AGNs
- 89 Lya emitters



Bacon et al., 2015

Needles in the haystack ...



IFUs are also able to detect “blind” emission lines from continuum-free sources

Combining Lensing + MUSE

Lenses, IFUs both open windows into high-resolution science
Many studies take advantage of both

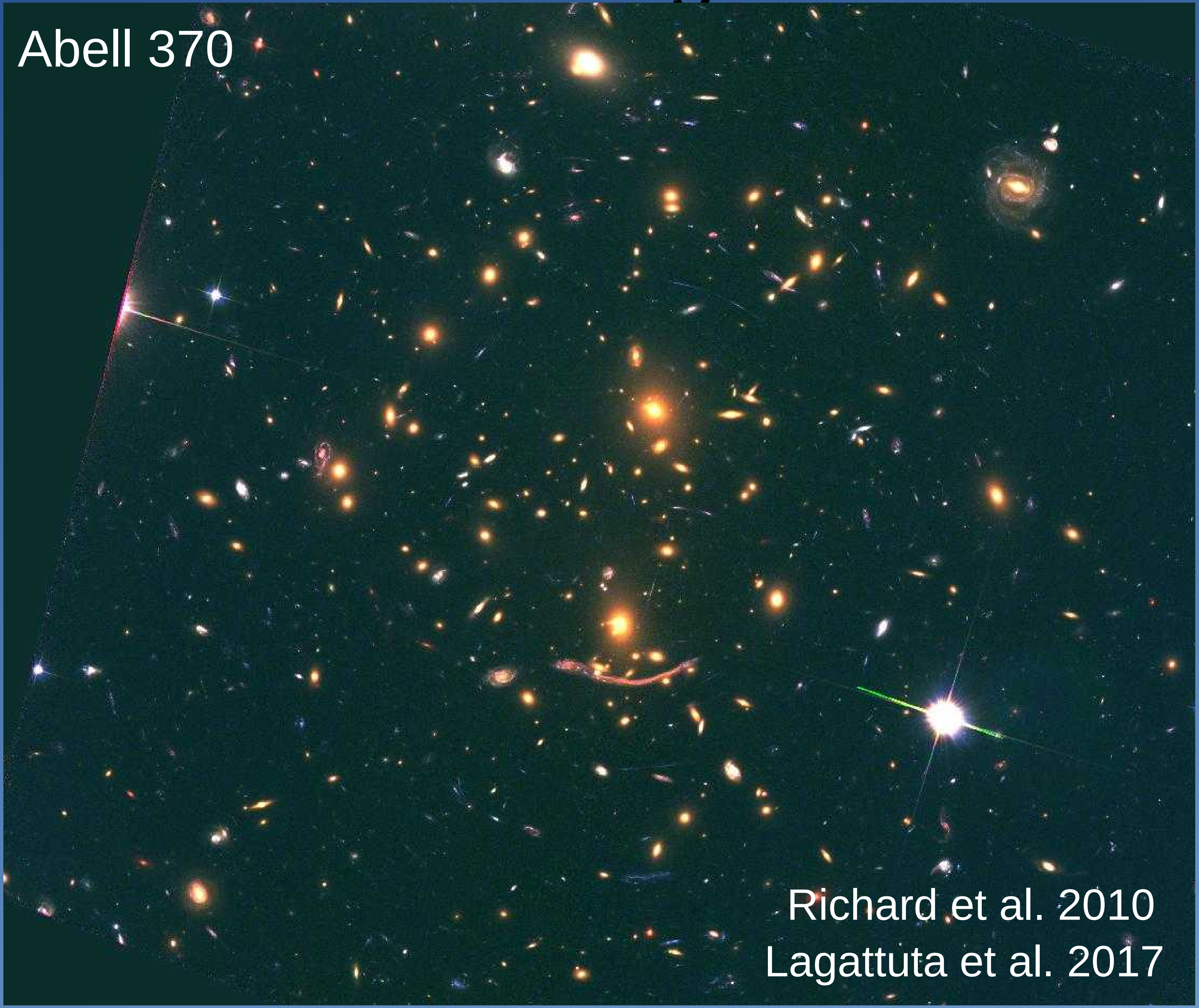
- Some examples include:
  - Cluster mass modeling
  - Resolved spectral properties of galaxies
  - Epoch of Reionization (Ly-α emitters)
  - Cosmology

And now, a whirlwind tour...

Mass Modeling

Mass modeling

Lensed galaxies act as constraints for mass models

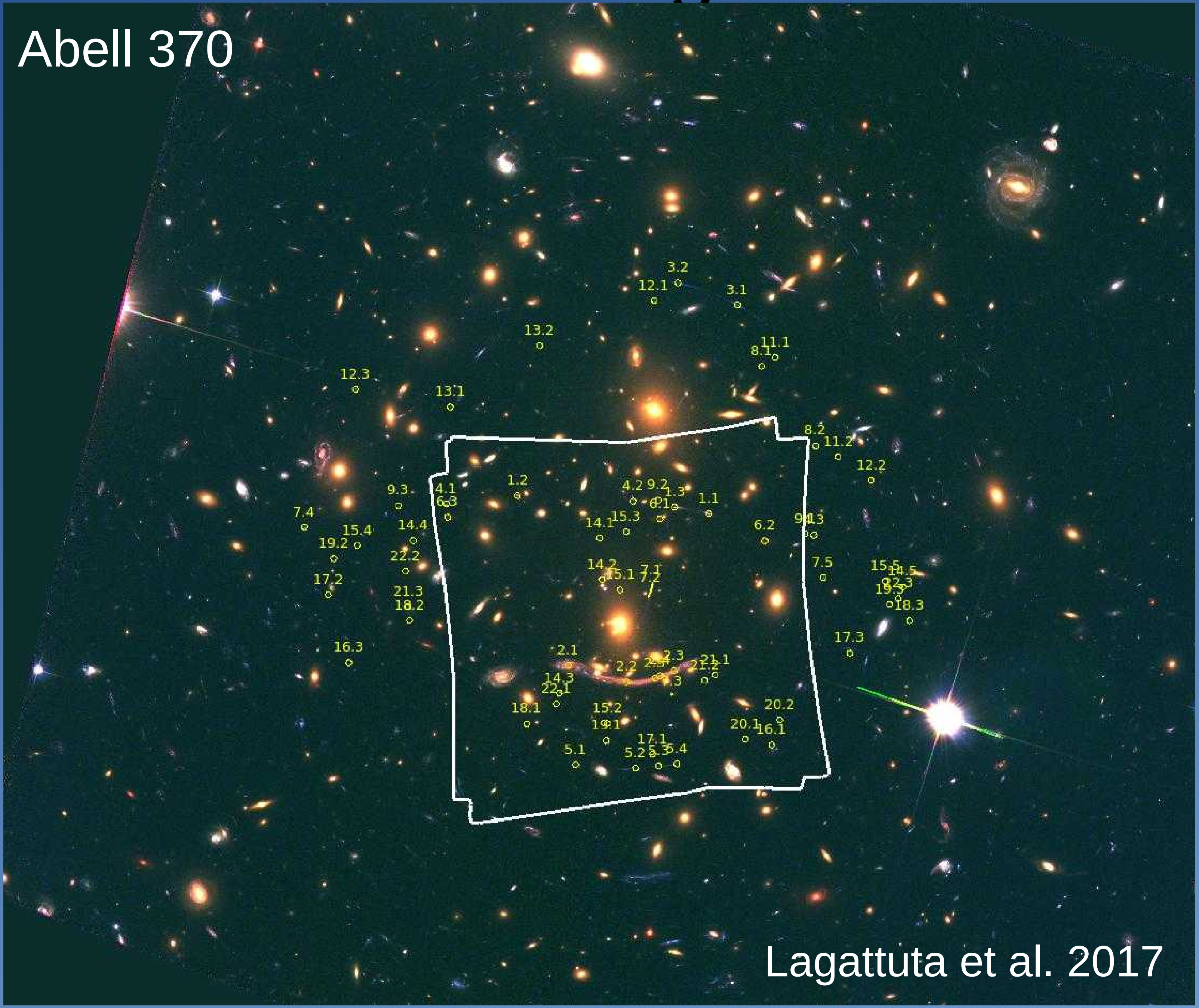


Mass modeling

Lensed galaxies act as constraints for mass models

22 multiply-imaged systems discovered in A370 (so far)

17 with MUSE redshifts



Mass modeling

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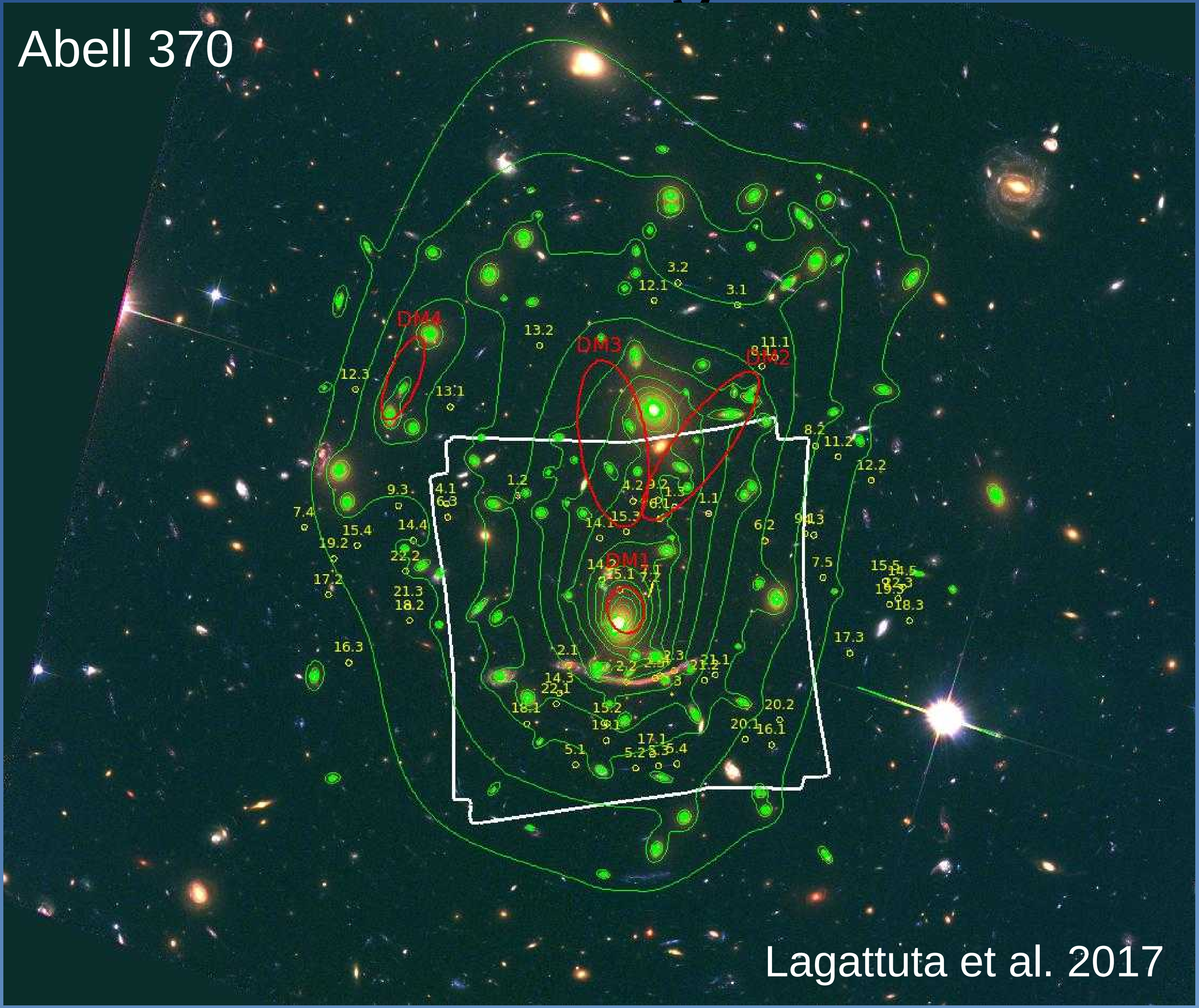

Mass modeling

Lensed galaxies act as constraints for mass models

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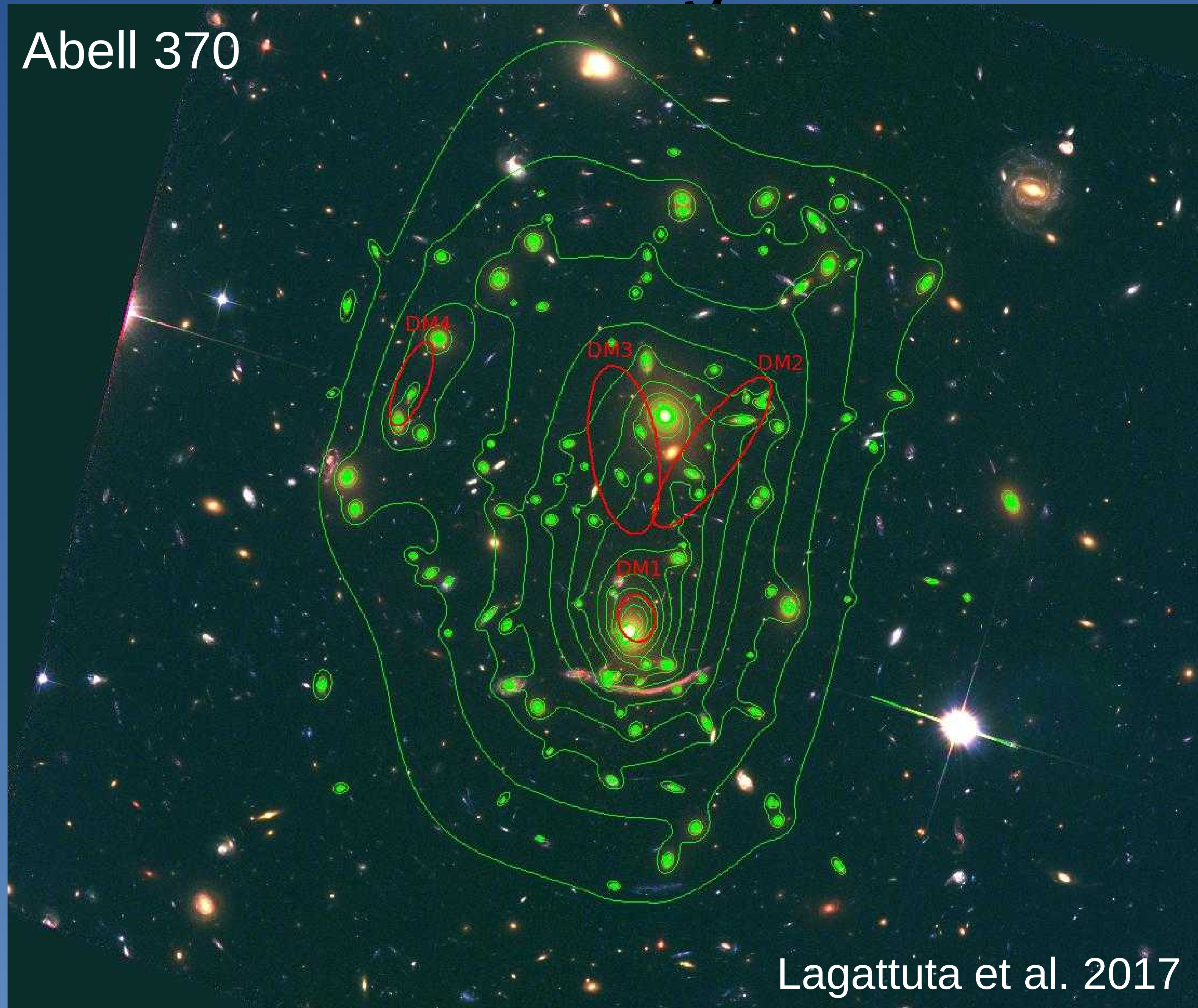
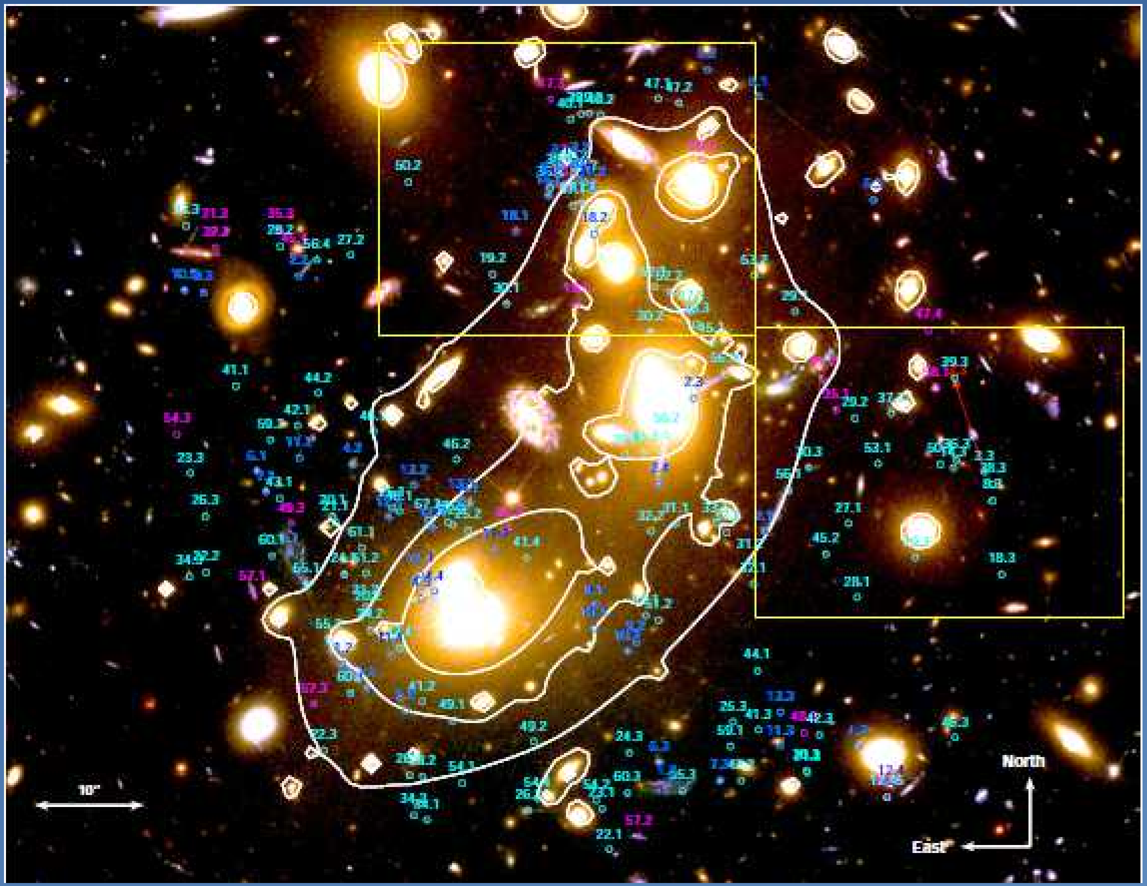
Best-fit model favors a new “crown” mass clump separate from BCGs

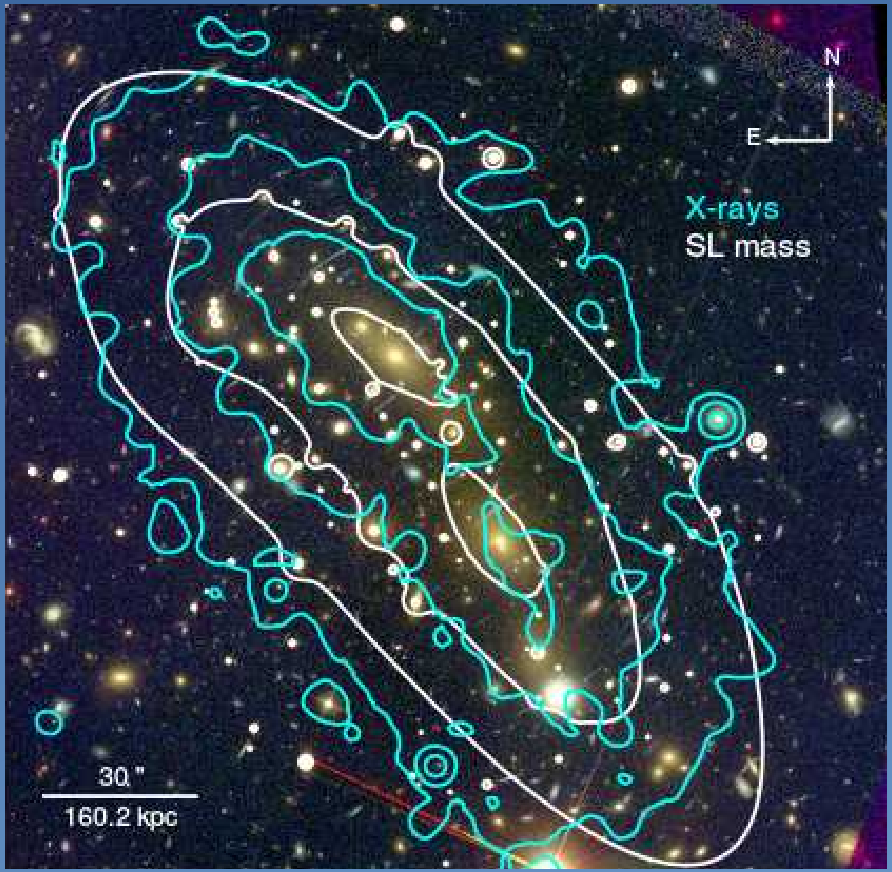


Mass Modeling

- Also used in other clusters



Abell 2744



MACS 0416

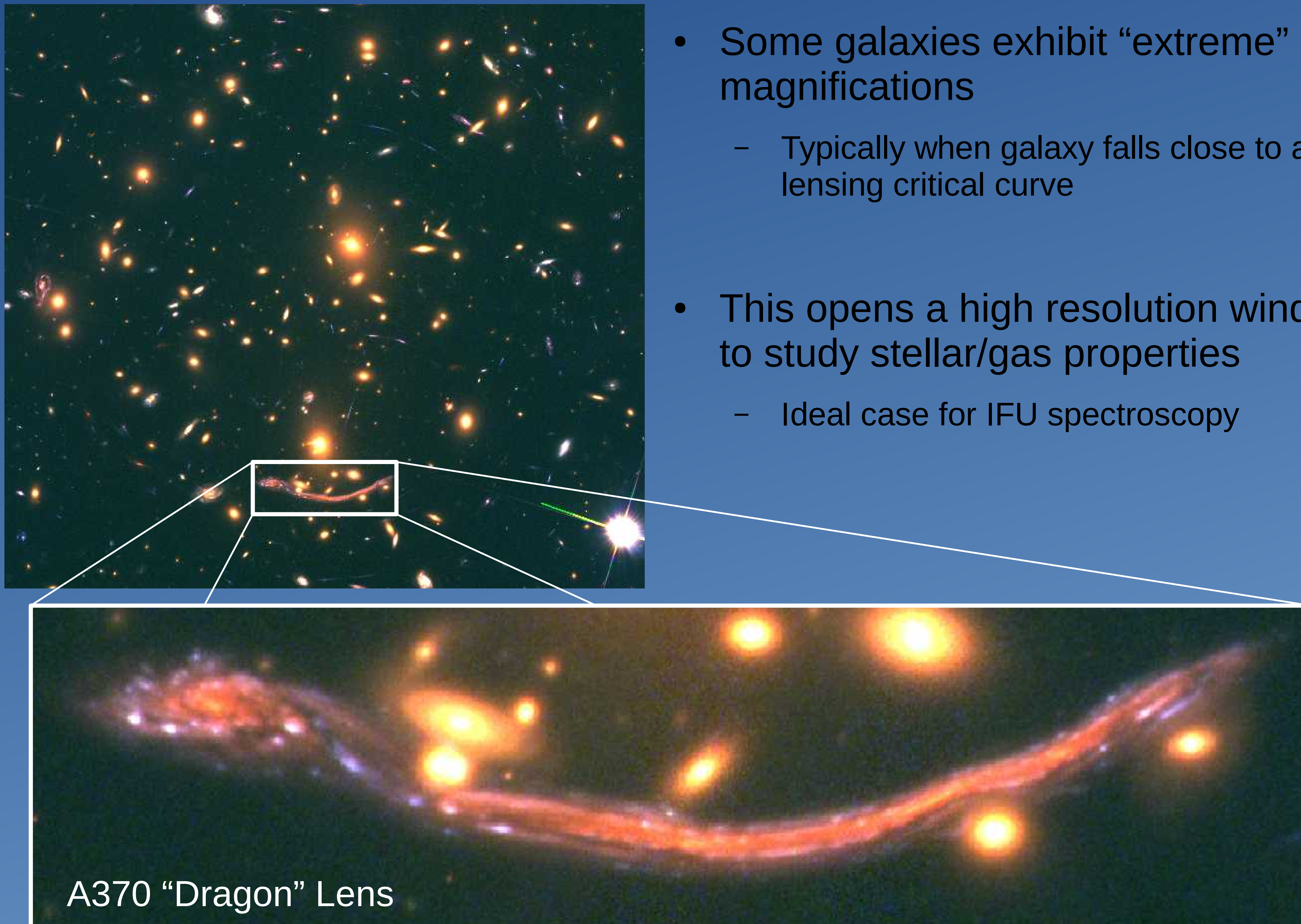
Jauzac et al. 2015
Mahler et al. 2018

Caminha et al. 2017

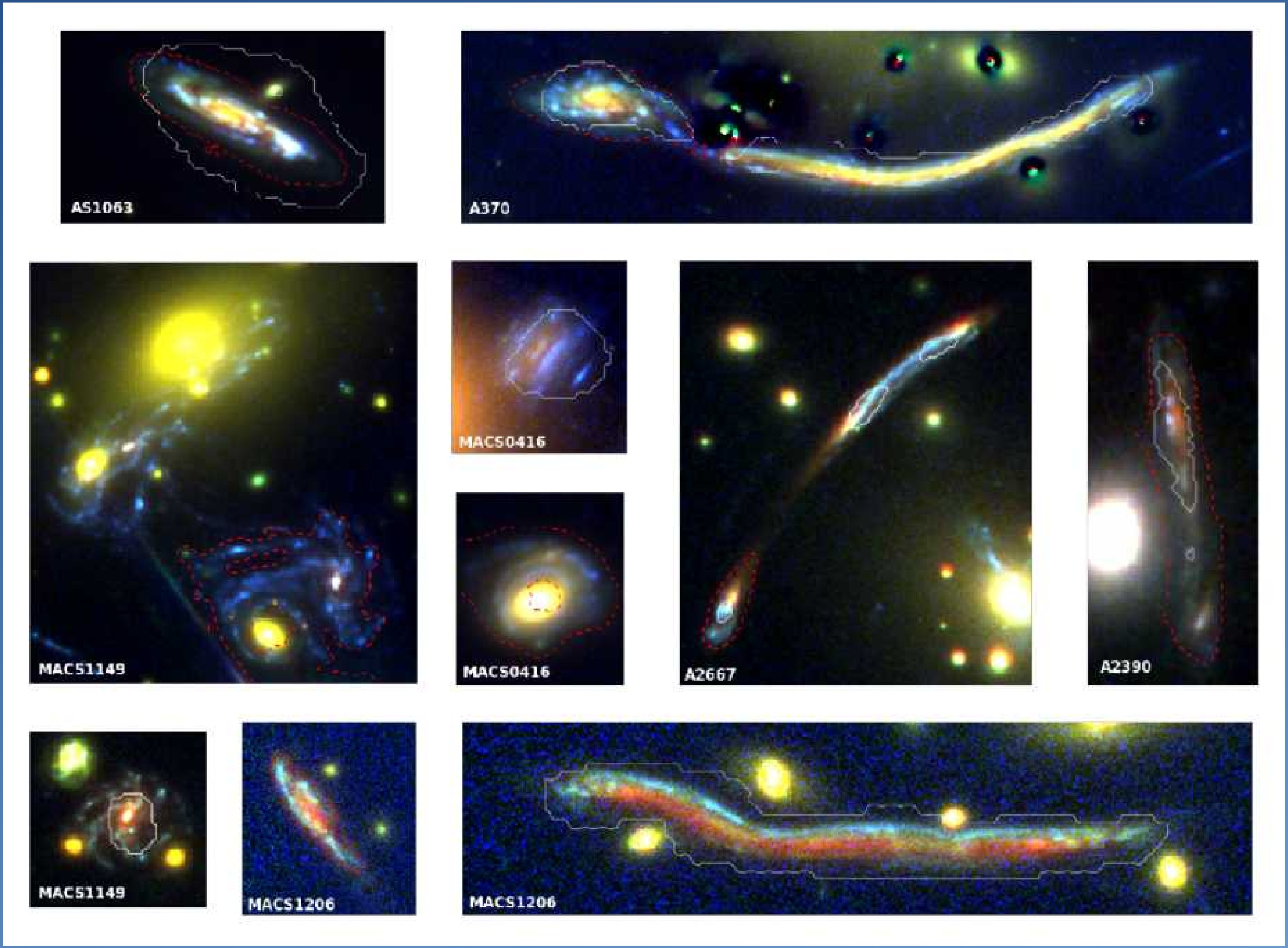
Resolved Properties of Galaxies

Resolved Properties

- Some galaxies exhibit “extreme” magnifications
  - Typically when galaxy falls close to a lensing critical curve
- This opens a high resolution window to study stellar/gas properties
  - Ideal case for IFU spectroscopy



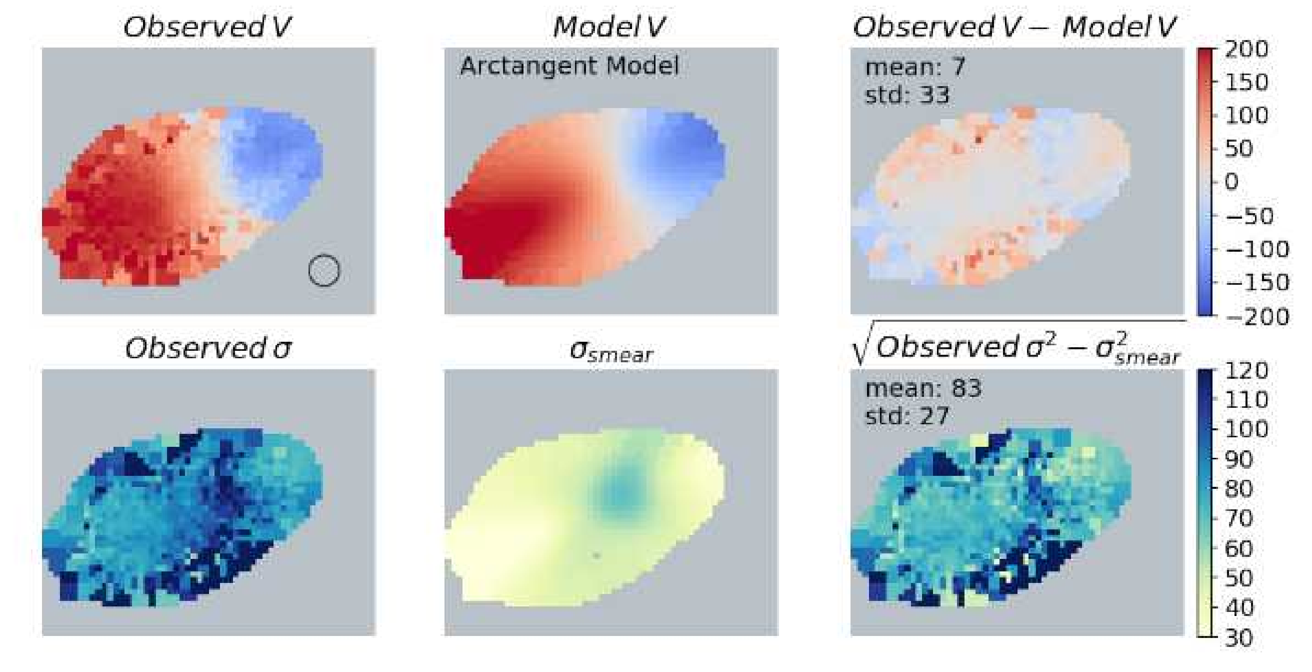
Giant arcs

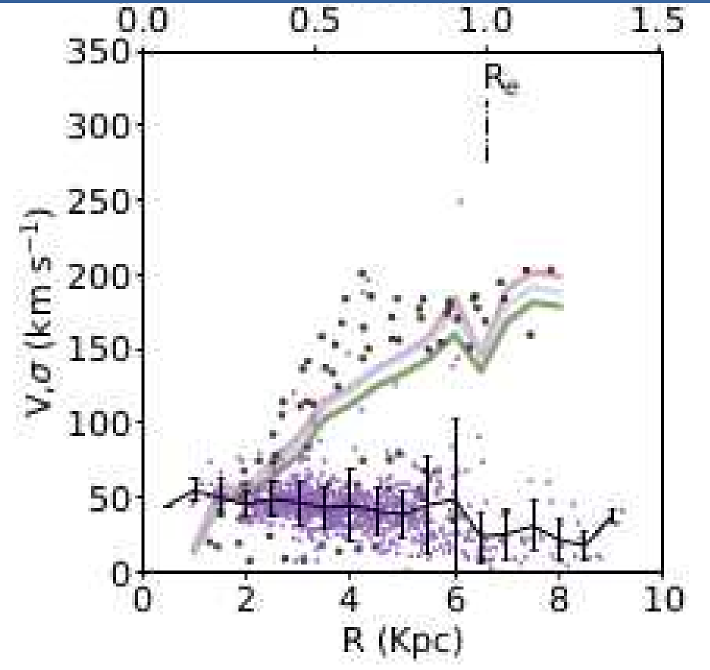


- Many other arc systems found throughout GTO and GO datasets

Patricio et al. 2018

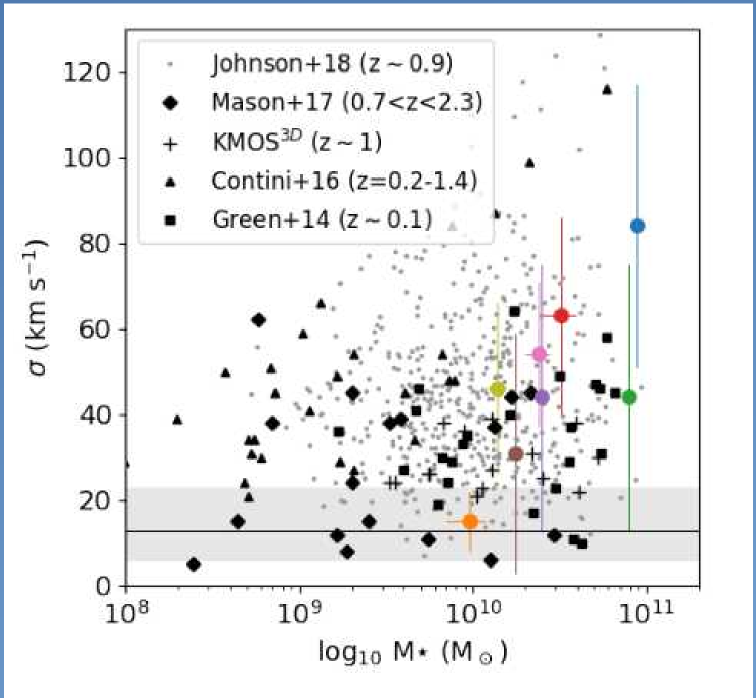
Giant arcs





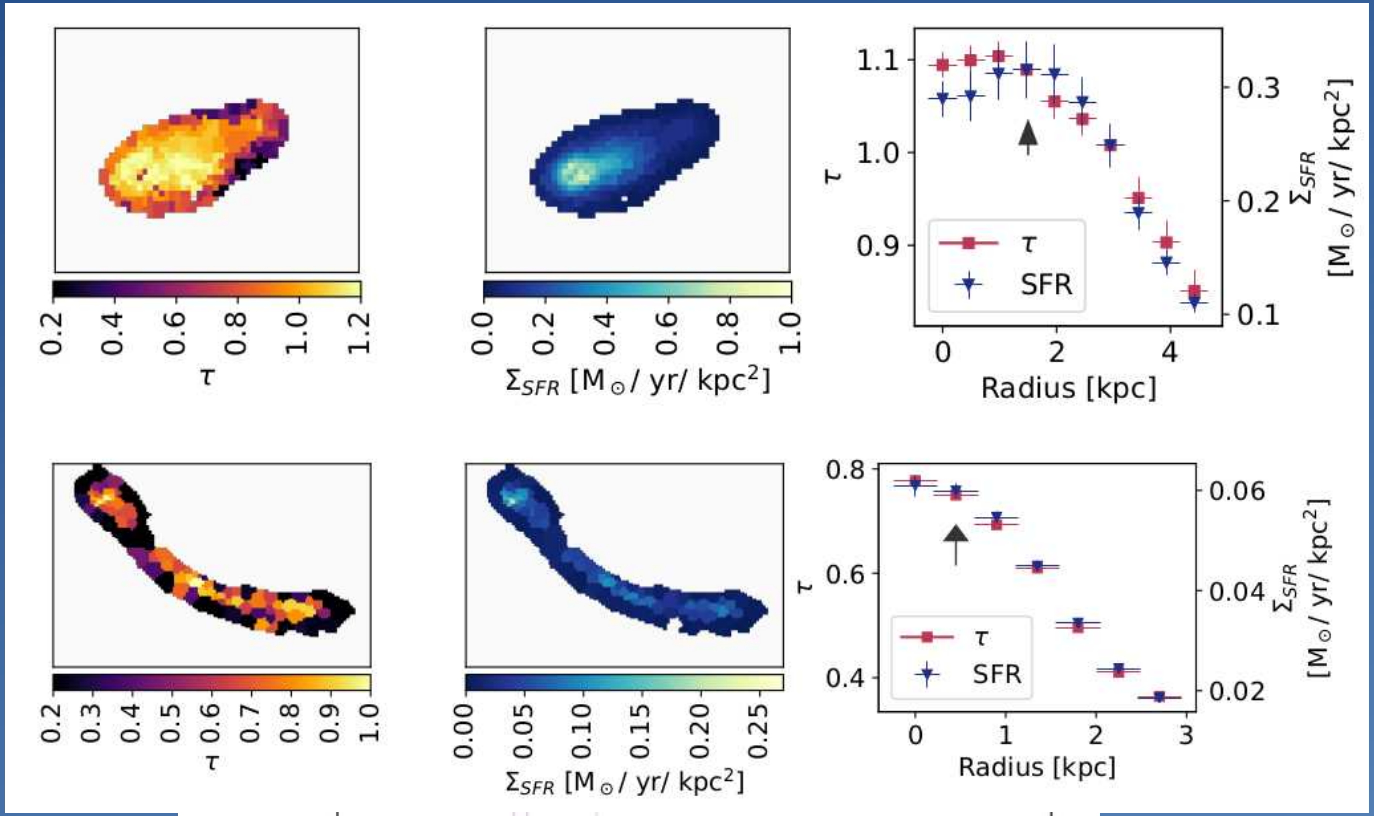
- Velocity maps (σ_c, V_{rot}, etc) provide kinematic information
  - Also a window into galaxy formation

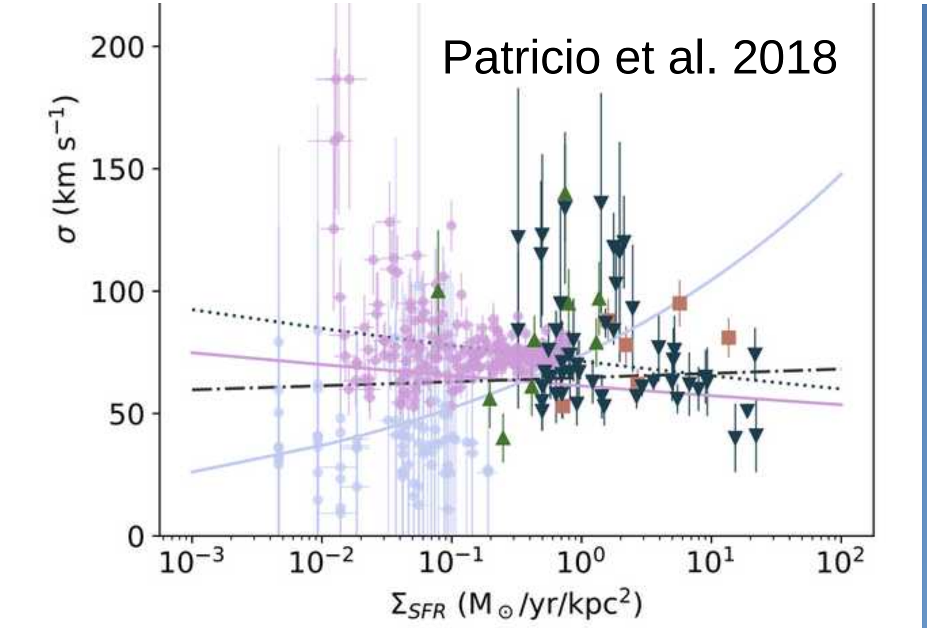
- Serve as proxies for other physical properties
  - e.g., Tully-Fisher, Fundamental Plane



Patricio et al. 2018

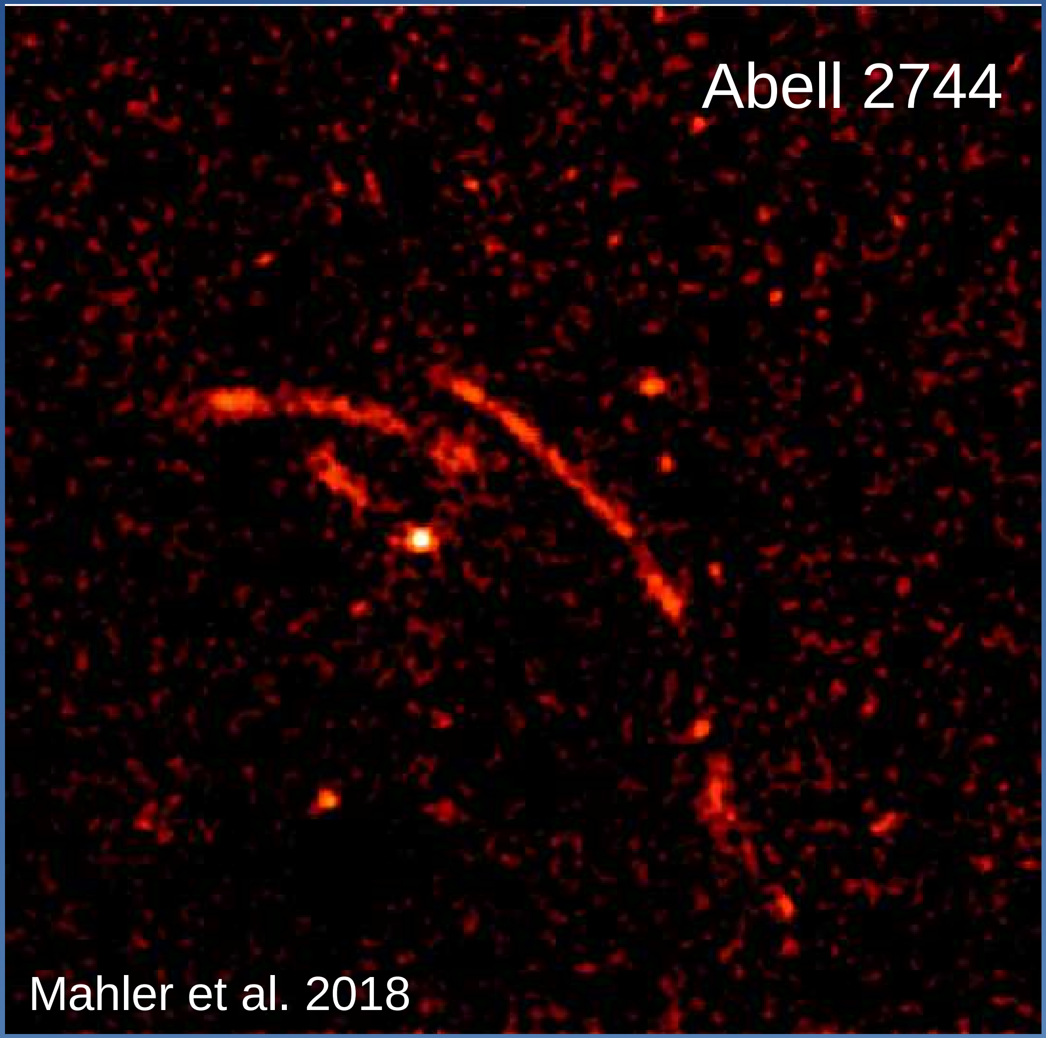
Giant arcs

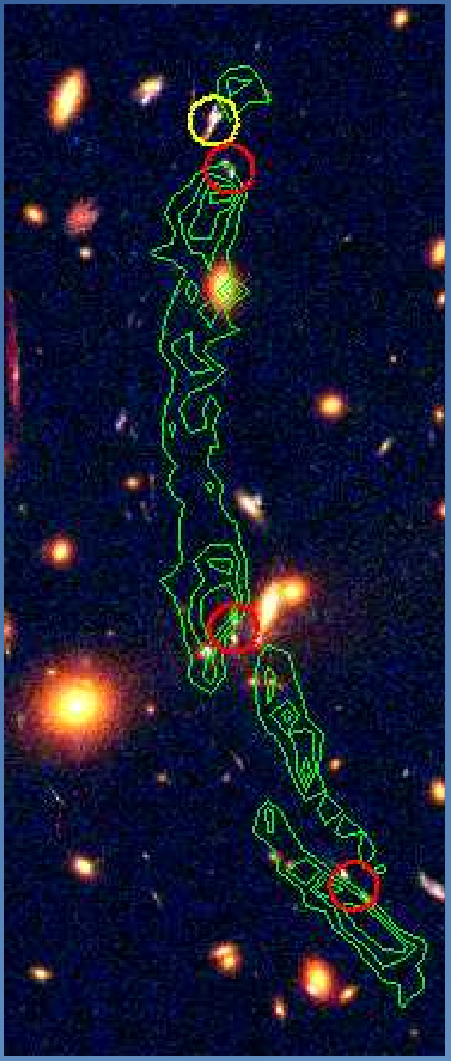




- Line ratios and/or Equivalent Widths trace star formation rate (SFR)
- Also informs on metallicity, stellar age, IMF, etc…
- Possible thanks to stellar population modeling codes

Ly-α Arcs

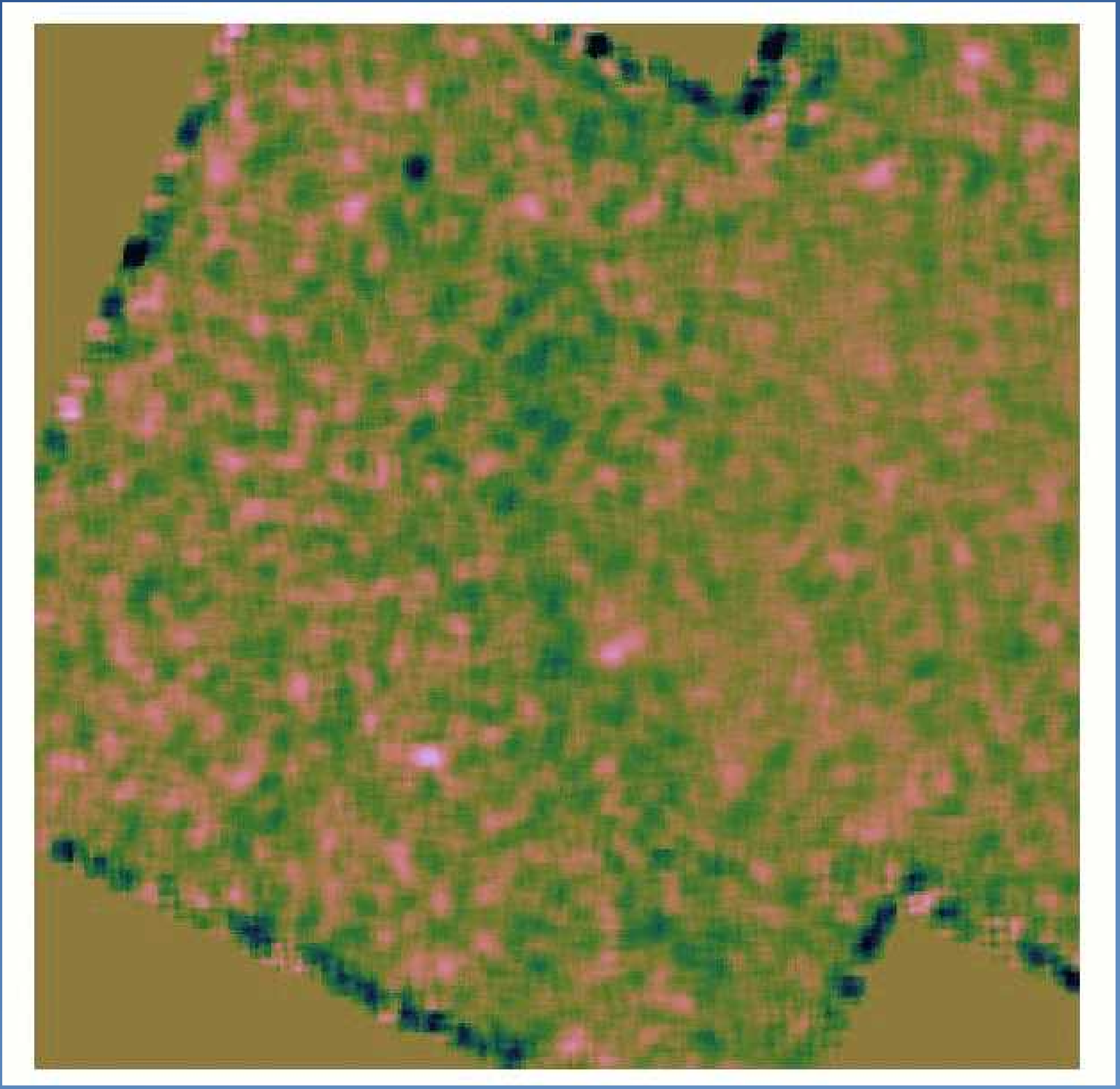




Lagattuta et al. (2018)

- Not just “naked eye” arcs...Ly-a can also be found in “blind” mode

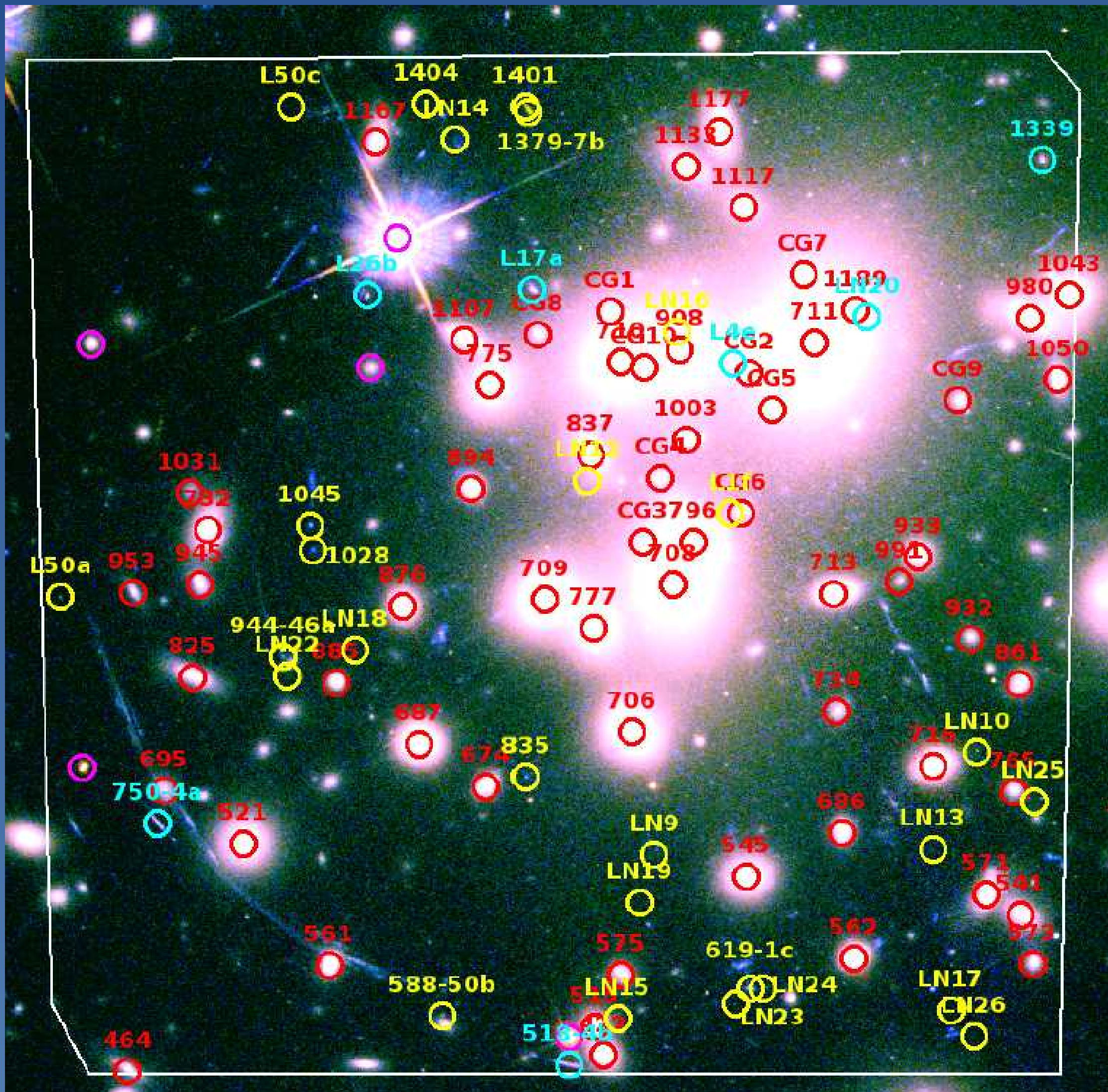
Ly-α Arcs



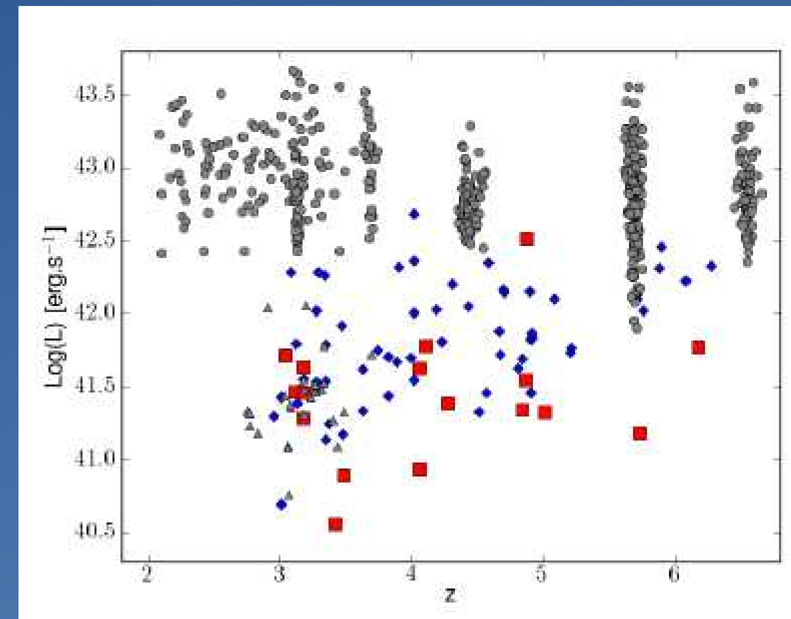
- Velocity gradient perpendicular to stretching axis

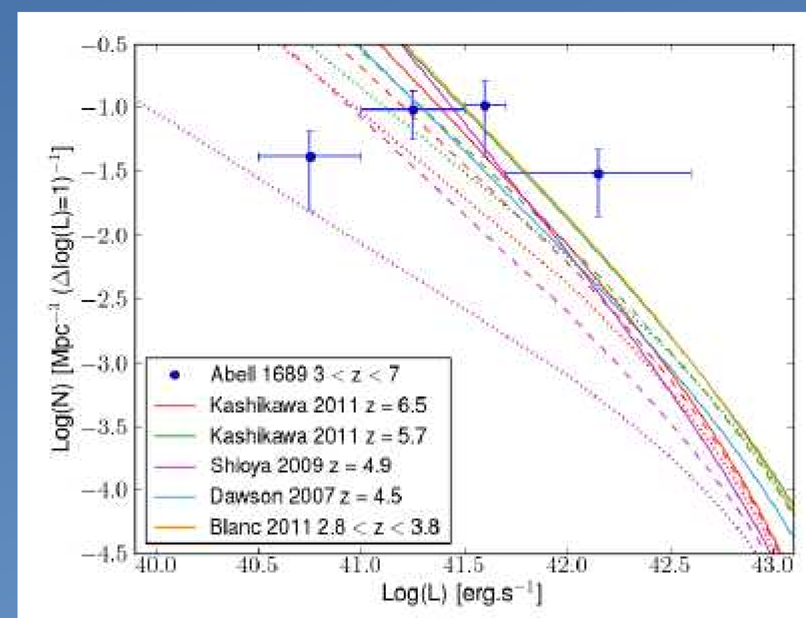
Lyman-α and Reionization

UV Luminosity Function



Abell 1689

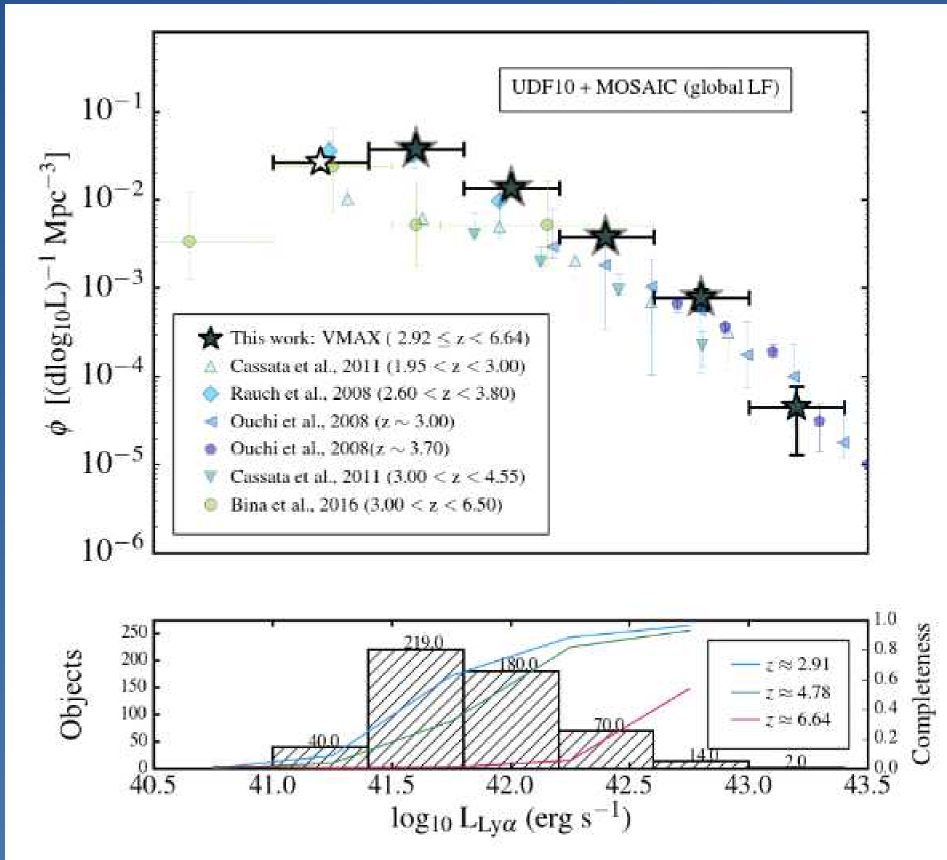




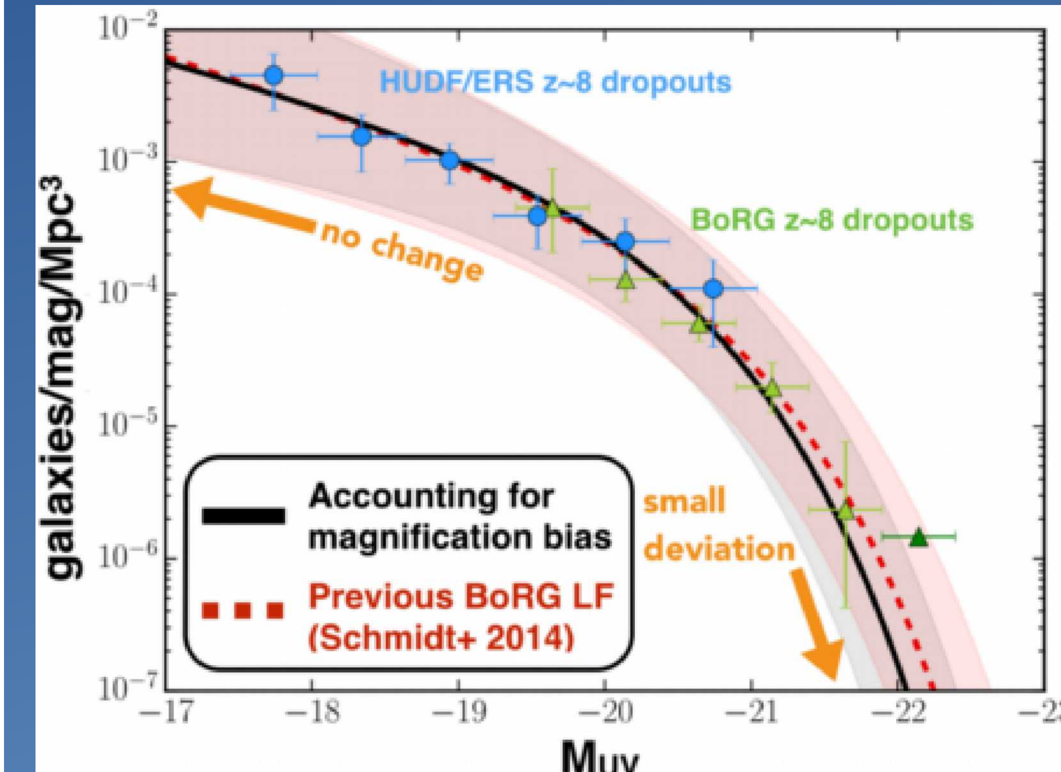
Bina et al. 2015

- Detect Ly-α galaxies (2.9 < z < 6.7) in a field, quantify brightness and construct a luminosity function

Accounting for Lensing



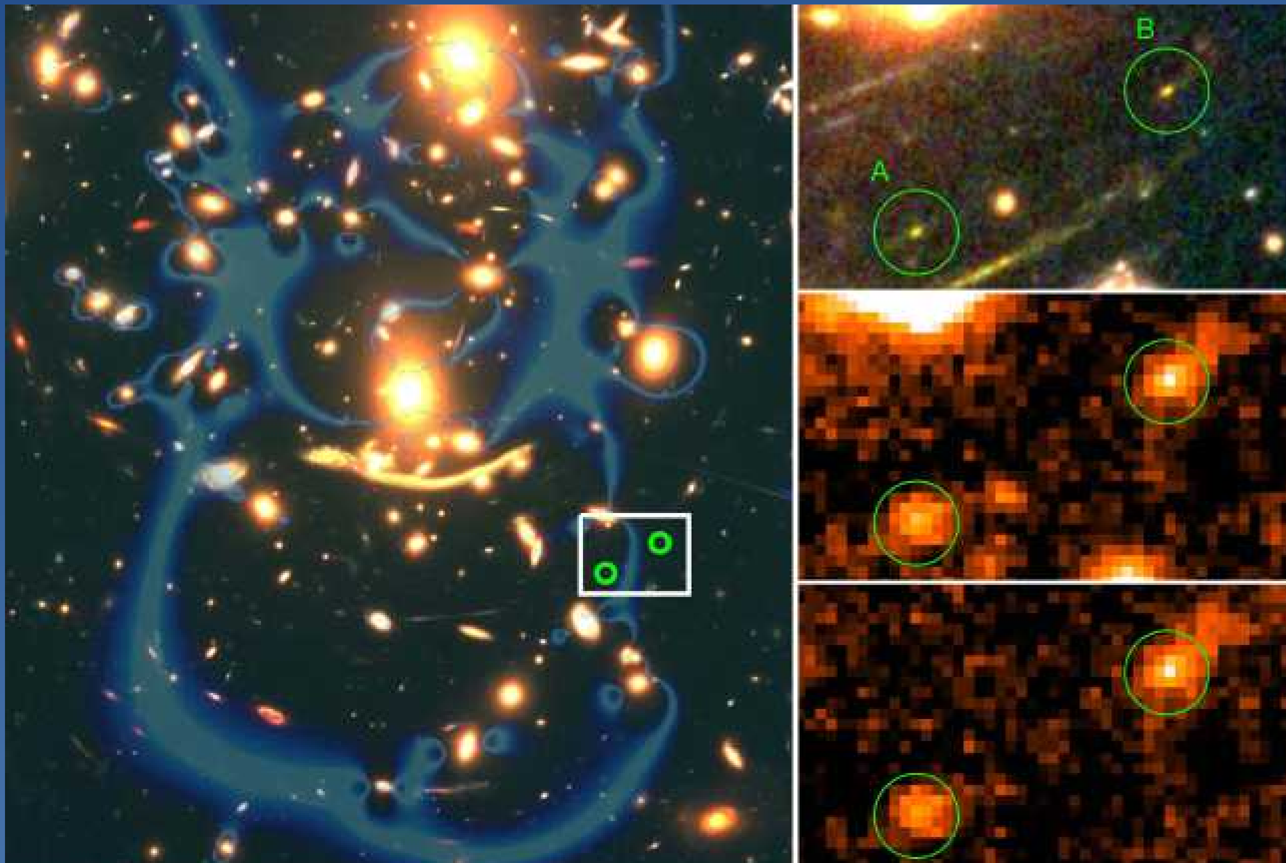
Hubble/MUSE UDF
Drake et al. 2017

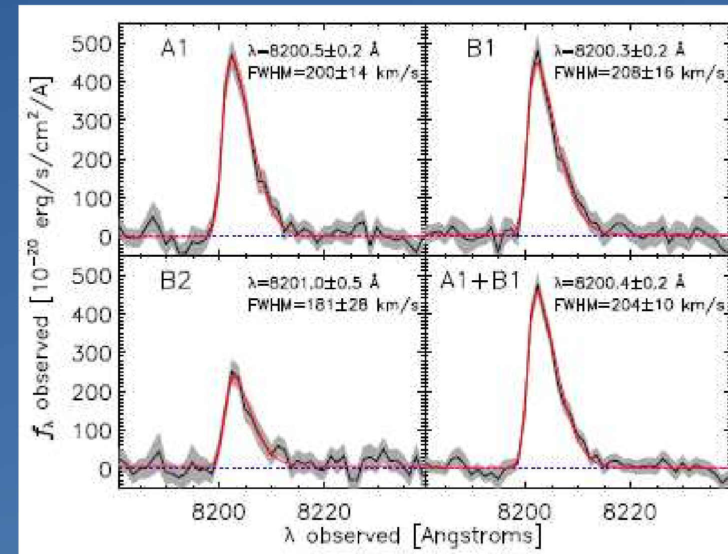


BoRG Survey
Mason et al. 2015

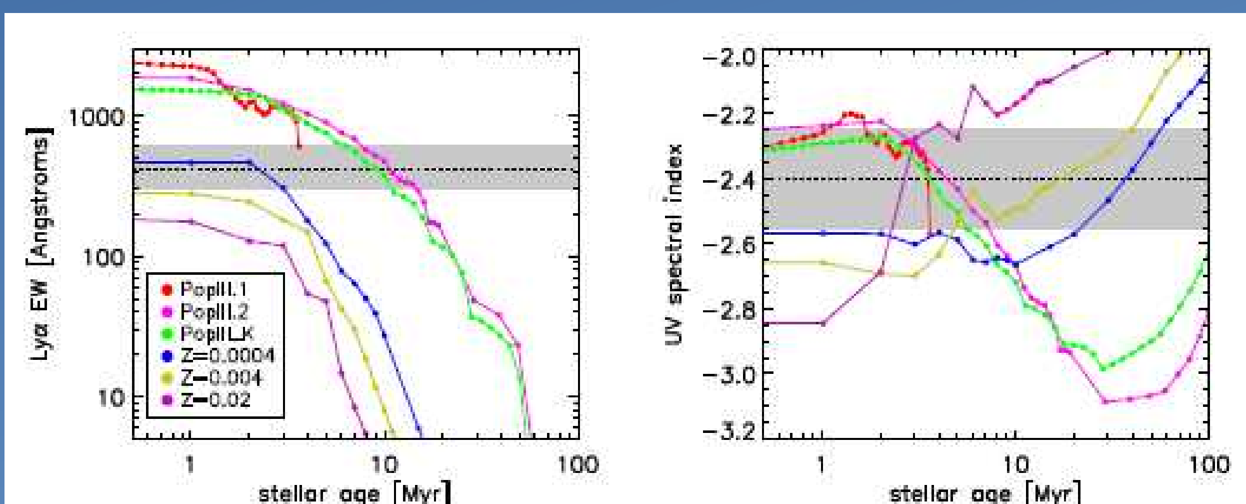
- Must account for volume/bias effects that are altered due to lensing magnification

Individual Reionizers





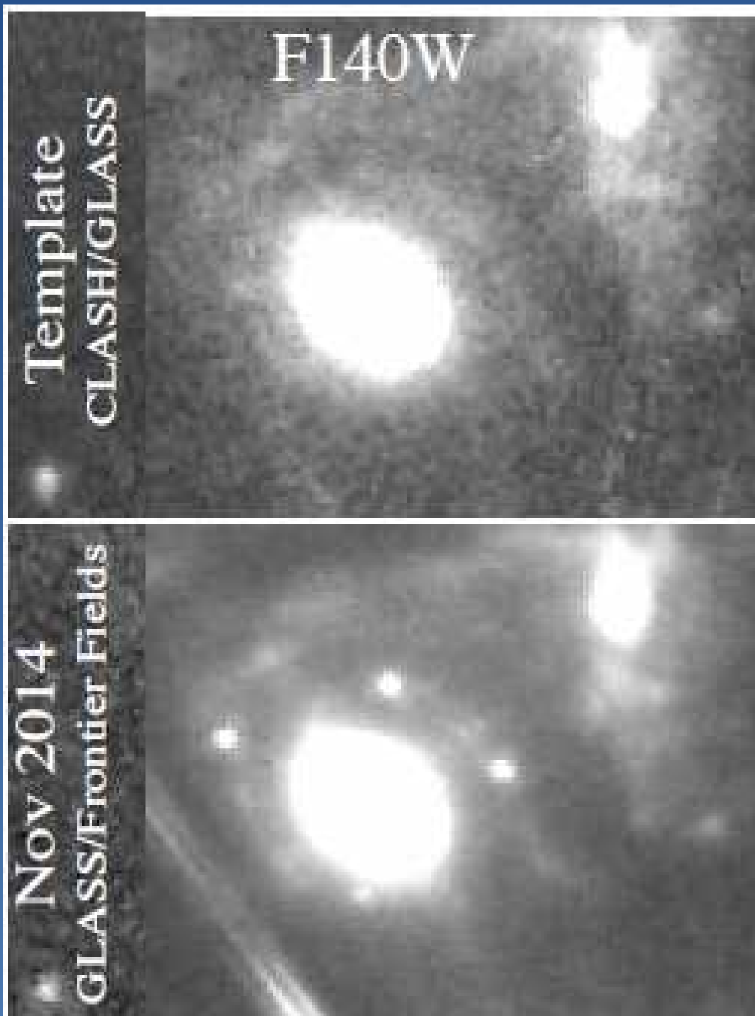
Hernan-Caballero et al. 2017



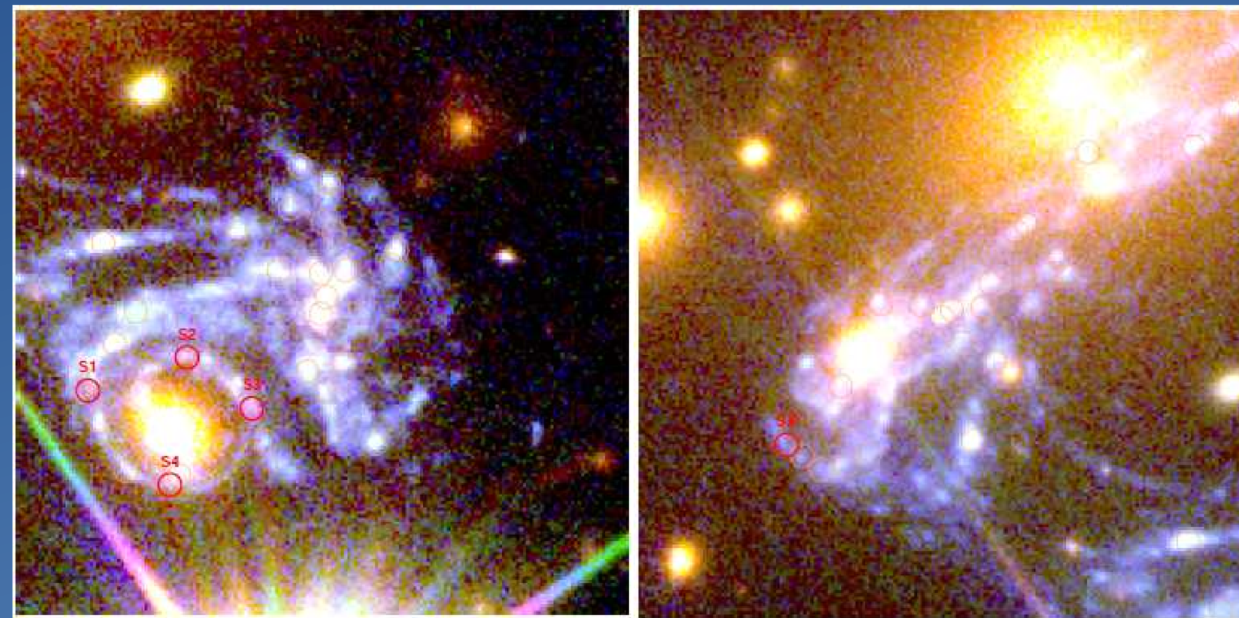
- Faint-end (low Equivalent Width) Lyman-α emitters easier to see due to lensing magnification boost
- These objects thought to be more efficient at re-ionizing their local environments

Cosmology

Supernova Refsdal



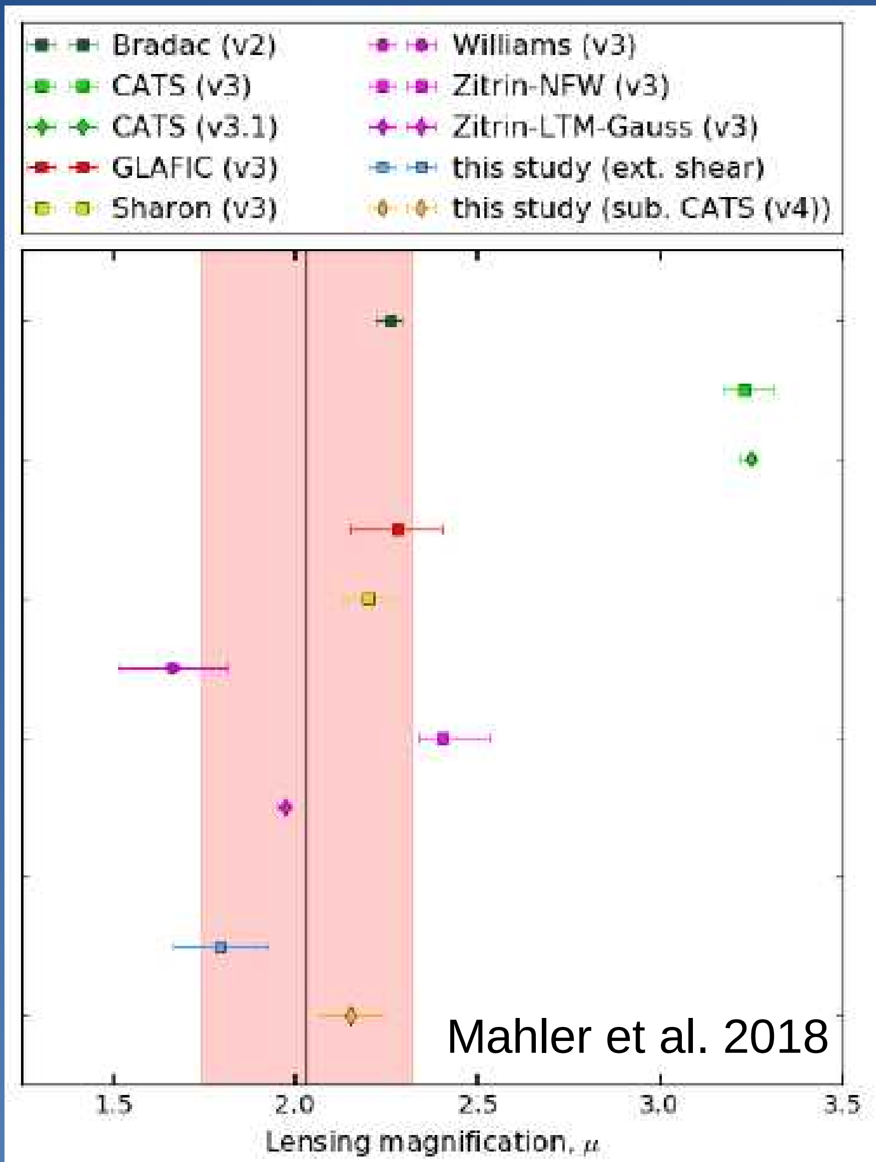
Data (Kelly et al. 2015)



Model+Prediction (Jauzac et al. 2016)

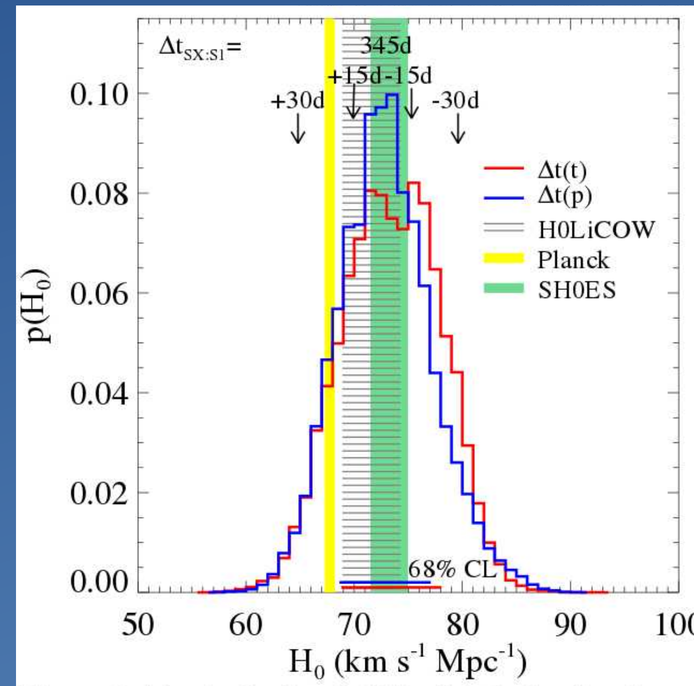
- First detection of multiply-imaged (well separated) Supernova
- Counterimage of galaxy provided test case for lens models
  - Also constrains value of H_0

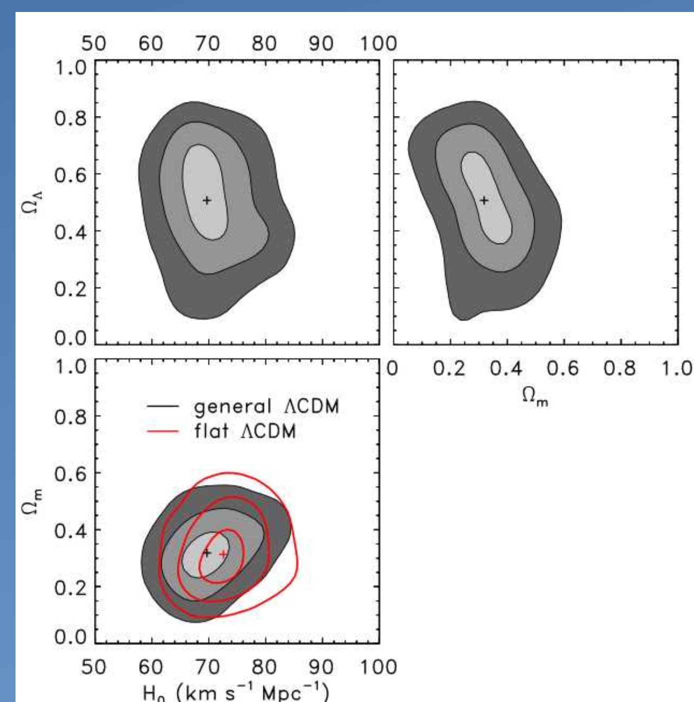
Cosmology with Supernovae



Mahler et al. 2018

Advanced spectroscopic data used to construct the most accurate lens models

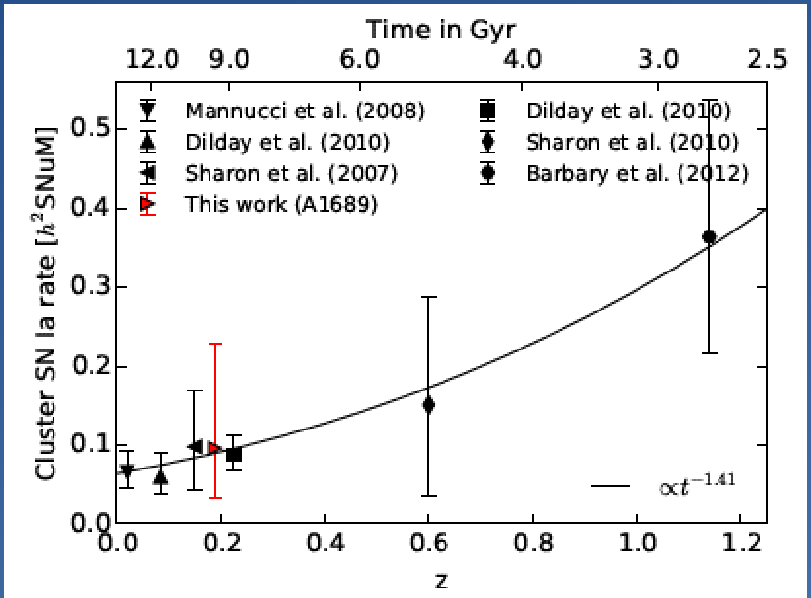




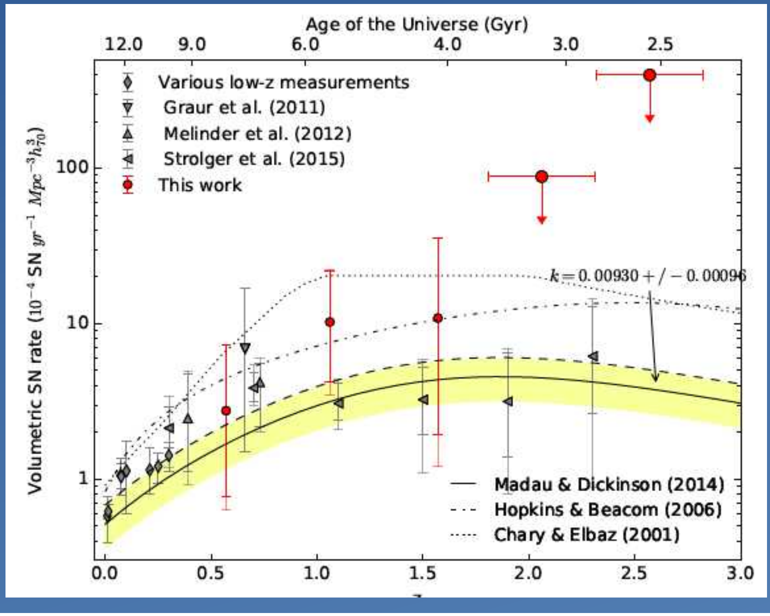
These models are used to estimate cosmological parameters

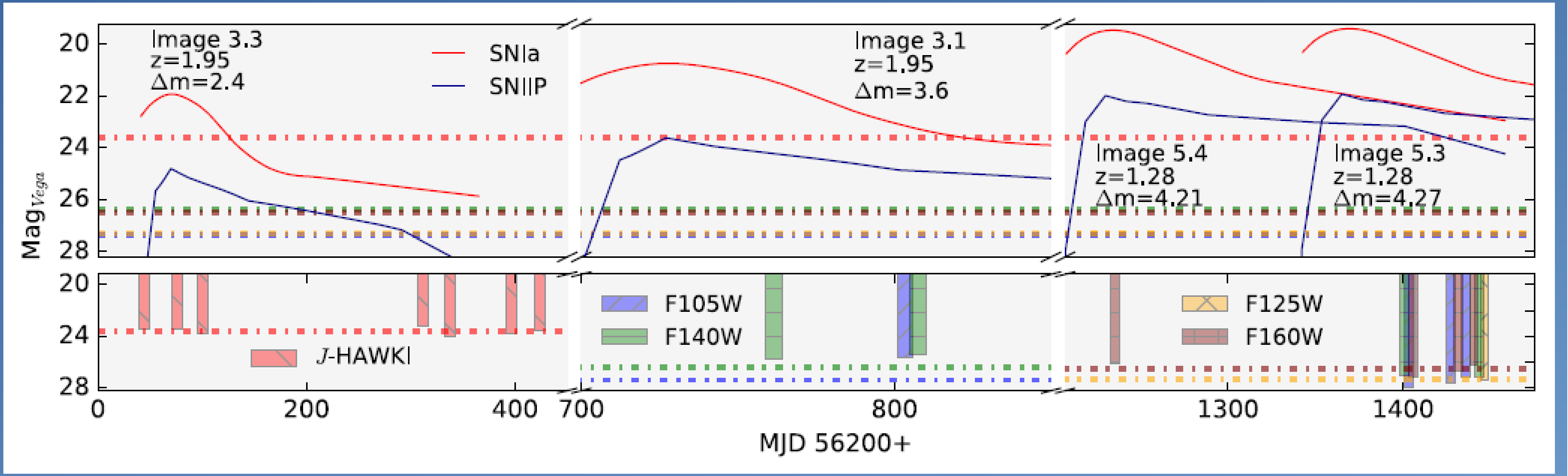
Grillo et al. 2018

The search for more



Petrushevska et al. 2015, 2018





- Additional lensed SN will improve statistics and reduce systematic error
  - Search ongoing in Frontier Fields and other clusters

Conclusions

- Gravitational lensing offers a unique look into the faint and distant universe
- IFUs (like MUSE) are a natural complement
- Research involving both is active and ongoing
  - And there is still room to expand