Lensed Galaxies and MUSE

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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
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 ($10^{15} \ M_{\text{sol}}$ vs $10^{12} \ M_{\text{sol}}$) 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

MUSE is leading the way
Vital Statistics

Name: MUSE

Category: integral field spectrograph

Size: 1x1 arcmin

Spatial sampling: 0.2"

Image Quality: <0.2"

Coverage: 4650-9300 Å

Resolution: 1500-3500

Throughput: 35% end-to-end
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

Sombrero Galaxy (M104)

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

Courtesy Eric Emsellem
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 Ly\alpha 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

Abell 370

Richard et al. 2010
Lagattuta et al. 2017
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

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

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

Lagattuta et al. 2017
Mass Modeling

- Also used in other clusters

Abell 2744
Jauzac et al. 2015
Mahler et al. 2018

MACS 0416
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 ($\sigma_c$, $V_{\text{rot}}$, 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-\(\alpha\) Arcs

- Not just “naked eye” arcs...Ly-\(\alpha\) can also be found in “blind” mode
Ly-α Arcs

- Velocity gradient perpendicular to stretching axis
Lyman-\(\alpha\) and Reionization
Detect Ly-α galaxies (2.9 < z < 6.7) in a field, quantify brightness and construct a luminosity function
Accounting for Lensing

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

Hubble/MUSE UDF
Drake et al. 2017

BoRG Survey
Mason et al. 2015
Individual Reionizers

- 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.

Hernan-Caballero et al. 2017
Cosmology
Supernova Refsdal

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

Data (Kelly et al. 2015)

Model+Prediction (Jauzac et al. 2016)
Cosmology with Supernovae

These models are used to estimate cosmological parameters

Advanced spectroscopic data used to construct the most accurate lens models

Grillo et al. 2018

Mahler et al. 2018
The search for more

- 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