Robotic Searches for Strong Gravitational Lenses

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Robotic Searches for Strong Gravitational Lenses

The HAGGLeS team:
David Hogg, Chris Fassnacht, Lexi Moustakas,
Tim Schrabback, Roger Blandford, Marusa Bradac,
Dave Lagattuta (measuring weak lensing, see poster),
Eric Morganson (searching for strings),
Ellie Newton (robot testing in SLACS with Tommaso Treu)
Robotic Searches for Strong Gravitational Lenses

Some thoughts on butterfly collection:

• *If you want to understand the Origin of Species, you'd better collect some butterflies first*

• *If you want a serious collection, you need to*
  
  a) be prepared to look everywhere
  
  b) have a very good net
Robotic Searches for Strong Gravitational Lenses

Plan:
• A bit of motivation and advertising
• The HAGGLeS robot: concepts, education, performance
• The HAGGLeS survey: progress, some new lenses
• A more detailed look at some new image-survey lenses
• Eric Morganson's cosmic string search (if time)
Strong lens surveys

Current no. of strong lenses observed at high resolution:

\[ \sim 200 \]

SLACS survey (Bolton et al 2008 etc):
- massive ellipticals are standard masses, isothermal model fits all, and they fairly sample the massive galaxy population
- extended source enables accurate mass modelling
- *limited to brightest, low redshift \( (z \sim 0.2) \) galaxies*

Where are the large samples of higher redshift, lower mass strong lenses going to come from?

*Support your local billion-dollar survey telescope!*
JDEM - SNAP?

- 2m class telescope, 0.7 sq degree field of view
- IFU Spectrograph for SNe
- 9 filters (350nm–1700nm)
- PSF 0.14 arcsec FWHM
- 0.1 arcsec pixels

_HST-quality imaging over 1000+ square degrees_

SNAP: one possible vision for JDEM that would be _fantastic_ for strong lensing
High etendue survey telescope:
- 6.5m effective aperture
- 10 sq degree field
- 24 mag in 30 seconds
- Visible sky mapped in four nights
- Cerro Pachon, Chile: 0.7” seeing

Ten year movie of the entire Southern sky

Primary mirror casting begun, First light 2016?
Near-future facilities will enlarge our sample of galaxy-scale strong lenses by **at least 2 orders of magnitude**:

- PanSTARRS-1: 30,000 sq deg, shallow, fair seeing, 2000 lenses
- DES: 5000 sq deg, deep, good seeing, > 1000 lenses
- LSST: 20,000 sq deg, deep, excellent seeing, 10,000 lenses
- JDEM: 1000+ sq deg, very deep, from space, > 10,000 lenses
- not to mention Euclid, radio surveys, SKA...

**How shall we go about finding 10,000 new gravitational lenses?**
Examining elliptical galaxies

Most of the lensing cross-section in the universe is in massive elliptical galaxies (a subset of the easily-selected “Bright Red Galaxies”); most of the sources are faint blue galaxies.

IDEA: OPTIMISE SEARCH FOR “TYPICAL” LENSES

1000 sq deg of JDEM imaging will contain
\( \sim 10^7 \) BRGs and \( \sim 10^4 \) lenses:

Visual inspection of all BRGs would take a team of 10 undergrads 70 weeks at a cost of \( \sim \$700k \)

Selection function? Repeatability? Errors?

Develop automated lens detection software, start quantifying completeness and purity of sample
A Robot for Finding Lenses

- Detect **bright, red, extended objects** (BRGs)
- Make small cutout images
- Subtract off smooth flux from bright galaxy
- Examine **blue residuals** for signs of lensing

**IDEA:**
MODEL EVERY OBJECT AS IF IT WERE A LENS
• Familiar image configurations
• Typical lenses easily modeled
A Robot for Finding Lenses

- Detect bright, red, extended objects (BRGs)
- Make small cutout images
- Subtract off smooth flux from bright galaxy
- Examine blue residuals for signs of lensing

IDEA:
MODEL EVERY OBJECT AS IF IT WERE A LEN

For each candidate, optimise simple lens model parameters (mass, shear) and output 4 pieces of information:

- goodness of fit of predicted image to blue residuals,
- uncertainty on mass parameter,
- brightness of source,
- uniqueness of model
Example BRGs from the HST EGS survey

Cutout | Subtraction residuals | Masked input | Lens model mass | Output source | Predicted image
Helping the Robot Understand its Results

- Robot produces information (“data”) about “lensiness”
- Need a framework for interpreting these data

Q1: Is this candidate a gravitational lens, or not?

Q2: What classification parameter $H$ would a human gravitational lens inspector have given this candidate?

IDEA:
ONLY ANSWER WELL-DEFINED QUESTIONS

$$H_r = \frac{\sum_i i \Pr(H = i | \text{data})}{\sum_i \Pr(H = i | \text{data})}$$
Educating the Robot

- Training set of simulated lenses, and real non-lenses from EGS
- Humans classify (H=0,1,2,3)
- Robot produces “data”

4 lens model numbers for each candidate
Educating the Robot

- Training set of simulated lenses, and real non-lenses from EGS
- Humans classify ($H=0,1,2,3$)
- Robot produces “data”
- Make analytic (multivariate Gaussian) model of $Pr(\text{data}|H=i)$

\[ e.g. \ H = 3 \]

(humans thought they were definitely lenses)
Educating the Robot

- Training set of simulated lenses, and real non-lenses from EGS
- Humans classify (H=0,1,2,3)
- Robot produces “data”
- Make analytic (multivariate Gaussian) model of $\Pr(\text{data}|H=i)$

e.g. $H = 0$
(humans thought they were definitely NOT lenses)
Educating the Robot

- Training set of simulated lenses, and real non-lenses from EGS
- Humans classify (H=0,1,2,3)
- Robot produces “data”
- Make analytic (multivariate Gaussian) model of Pr(data|H=i)
- Estimate robot class as Posterior mean:

\[
Pr(H|\text{data}) \propto \sum_i Pr(\text{data}|H = i)Pr(H = i)
\]

\[
H_r = \frac{\sum_i iPr(H = i|\text{data})}{\sum_i Pr(H = i|\text{data})}
\]

- What should we use as the Prior PDF Pr(H)?

**IDEA: A HUMAN WOULD FACTOR IN THE KNOWN RARITY OF GRAVITATIONAL LENSES**
Purity and Completeness

- Assign "realistic" prior $\Pr(H=0,1,2,3) = [0.900,0.080,0.019,0.001]$
- Calculate completeness and purity – how well does the robot do?
Prior = Robot “Character”

- Now assign “optimistic” prior $Pr(H) = [0.050, 0.100, 0.250, 0.600]$
- Calculate completeness and purity – how well does the robot do?
Outlook for JDEM

- A SNAP survey would contain >10,000 strong lenses, allowing us to extend the SLACS science with much higher precision.
- Extracting them is potentially very expensive: a robot is needed.
- All the information is in the lens model.
- This information can be interpreted to estimate the classification a human would have made.
- The character of the robot determines the completeness and purity of the final sample.

- The SNAP analysis could be done with our current robot, discovering 2000 lenses with no human inspection at all.
- A ~90% complete sample could be generated by human inspection of just ~7% of the BRGs – saving $650k.
- We are quantifying the strong lens selection function...
Historical context – and a warning

- The HAGGLeS Robot “knows” about gravitational lensing – hence name, claims of artificial intelligence, machine learning etc
- Previous (semi-)automated search methods did not include an explicit lens model, eg

- Faure et al, Jackson: LRG selection and inspection
- Kubo & Dell'Antonio, Alard, Seidel & Bartelmann etc: detection of arcs by geometrical criteria
- Gavazzi et al: LRG selection and subtraction, measurement of arc geometry
- Estrada et al: neural network, with arc data input

- Working lens model is primary requirement for a lens detection
- But - a little understanding is a dangerous thing: robots like this one will only find things that they know about! The model must be flexible enough to find everything we want...
We are searching the entire HST/ACS imaging archive for galaxy-scale gravitational lenses

- Exposure time > 2000s in each of at least 2 bands – register and stack to make the deepest possible image
- Parallel fields, individual galaxies, clusters, GRBs, large surveys etc etc - a range of lens environments
- Predict ~10 strong gravitational lenses per sq degree - some will already be known...

http://www.slac.stanford.edu/~pjm/HAGGLEs
- High precision registration, exposures masked for satellites etc, all filters drizzled onto the same pixel grid, WCS tied to USNOB: Schrabback is enforcing “weak lensing image quality”
- Image processing ~90% complete
- Reduced images to be returned to HLA
- Preliminary results from 246 fields ~ 0.75 sq deg
Preliminary results from 246 fields ~ 0.75 sq deg
~10,000 Bright Red Galaxies selected...
BRG selection in the GO archive

- Select elliptical galaxies by magnitude and colour – include 250km/s galaxies at z < 1.5 (typically “red” mag < 22 or so)
BRG selection in the GO archive

- Same physical criteria for 11 red-blue band pairings:
Preliminary results from 246 fields ~ 0.75 sq deg
- ~10,000 BRGs selected
- Optimistic robot run (to maximise completeness)
- 4000 candidates (Hr > 1.5) inspected
- Fast web-based classification (flick between cutouts and residuals, 20 at a time) – c. 50 candidates per minute, ~2 hours for whole search
- Some new lenses!
HAGGLeS lens candidates
HAGGLeS lens candidates
HAGGLeS lens candidates

Targeted CASTLeS lenses
HAGGLeS disk lens candidates

• Need better modelling to show multiple imaging...
HAGGLeS disk lens candidates

- Need better modelling to show multiple imaging...
- ... and lens light subtraction needs improving too (sechlets?!)
Preliminary results from first 0.75 sq deg:
- ~ 20 good lens candidates (human class 2-3), either showing potential counter-images or long merging-image arcs
- More detailed models needed for confirmation
- Some sources too faint for spectroscopy
- Surprising(?) number of edge-on disks
- If confirmed, lens abundance is high – archive contains many overdense (eg cluster) fields
- Imaging survey seems sensitive to lower mass, and/or higher redshift lenses than SLACS

Can we say more about these last two points in fields where we have more information?
The SLACS fields

- SDSS provides more information (photo-z) etc of candidates
- Exploit clustering of massive galaxies to increase lens yield, as in the case of B1608 (3 for the price of one! Fassnacht et al 2006)
- Search the 44 SLACS fields that have deep ACS data
- Test robot on SLACS-type lenses...
The SLACS main lenses

- Robot completeness is lower than in EGS
  - $H_r > 2.5$: 30% cf 90%
  - $H_r > 1.5$: 80% cf 100%

- Lensed images are brighter and thicker than in training set

- Subtraction residuals from brighter lens galaxies are higher S/N
SLACS field lenses (and one candidate)
The SLACS field lenses

- 4 class-3 lenses, plus 1 class-2 lens candidate
- Abundance = 30 (+/-24/8) per sq deg, cf. 12 in COSMOS: lenses are clustered

- Lens redshift from SDSS 5-band photometry
- Fundamental Plane (Treu et al 2006) predicts velocity dispersion (+/- 12%)
- Robot models (on cleaner subtractions) give Einstein radii
- From SIS model, infer geometric redshift of source:
The SLACS field lenses

- SLACS field lenses are **higher redshift and lower mass** than the SLACS main lenses
Conclusions

- To make the most of future observatories like SNAP and LSST we will need to be efficient at detecting lenses.
- The HAGGLeS robot is a first attempt at a fully-automated lens-finder, that would allow the galaxy-scale lens selection function to be quantified, and explicitly includes the confirmation of lenses by modelling.
- Running the robot on a variety of HST/ACS archive fields we have found ~20 new lenses.
- These lenses seem to be clustered, and appear to have lower masses and higher redshifts than the SLACS sample.
- Samples from imaging surveys like this one will enable post-taxonomic evolutionary astrophysics.
Limits on cosmic string tension and density from the HST/ACS archive:

Morganson et al (2009)
Extra Slides
What would a cosmic string look like in an HST/ACS archive image?

The “deficit angle” \( \theta = 8 \frac{G}{c^2} \sin \theta \frac{G}{c^2} \) is the string tension, a fundamental parameter.
What would a cosmic string look like in an HST/ACS archive image?
An efficient algorithm for finding long strings

- Treat each close pair of faint galaxies as a potential string lens
- Aligned galaxy pairs appear as *bright objects* in the Hough space image

Morganson et al 2008 in prep
Cosmic strings as gravitational lenses

Sazhin et al (2003) reported a possible case, CSL-1:

...HST/ACS imaging ruled it out (Agol et al 2006, Sazhin et al 2007)

It's a pair of merging ellipticals

We expect any string-lensed sources to be faint blue galaxies
The image processing for the HAGGLeS project is at a fairly advanced state:

<table>
<thead>
<tr>
<th>Survey</th>
<th>Sky area / sq deg</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL</td>
<td>0.7</td>
<td>2 filters, &gt;2000s exptime, 90% done</td>
</tr>
<tr>
<td>WL</td>
<td>1.9</td>
<td>1 filter, &gt; 1500s exptime, 80% done</td>
</tr>
<tr>
<td>EGS</td>
<td>0.19</td>
<td>2 filters, 1 orbit each, 100% done</td>
</tr>
<tr>
<td>GEMS</td>
<td>0.19</td>
<td>2 filters, 1 orbit each, 100% done</td>
</tr>
<tr>
<td>GOODS</td>
<td>0.09</td>
<td>4 filters, 2-5 orbits each, 100% done</td>
</tr>
<tr>
<td>COSMOS</td>
<td>2.0</td>
<td>1 filter, 1 orbit, 100% done</td>
</tr>
</tbody>
</table>

Total: 5.1 sq deg
Predictions for High Resolution Imaging Surveys

Predicted number density of string lensing events:

If no detection, 95% limit is given by tension such that $N\Omega = 2.996$

- HAGGLeS (5 sq deg at 0.3” resolution), $G/c^2 < 3 \times 10^{-7}$
- SNAP-WL (1000 sq deg at 0.3” resolution) $G/c^2 < 5 \times 10^{-8}$
- SKA (20000 sq deg at 0.03” resolution), $G/c^2 < 10^{-8}$
Results from the HST EGS survey

- 988 BRGs not used in training set
- 3 known lenses found by Moustakas et al (2007)
- Optimistic robot: 100% complete, ~50% BRG rejection rate
- Realistic robot: 0/3 lenses recovered (~expected)
- 4 new (class 2) candidates missed by 2007 eyeball search
Lensed quasars

- Note the different appearance...
- So far the HAGGLeS robot has identified TWO of these as lenses, not all fields searched yet
  Robot seems blinded by the quasars: the high S/N ratio demands a better lens model than the robot can provide

The CASTLeS objects are atypical lenses – the robot was trained on typical lenses...
Examining elliptical galaxies

1 in 40000 elliptical galaxies is lensing a quasar,

1 in 200 is lensing a normal galaxy (but you may only realise it once every 5 times)

Predict:
c. 20 lenses per square degree with SNAP
Web interface makes human classification fast!

~Few seconds per candidate

Farm out to wider community? LensZOO?