Strong lens simulations: the 'un'-natural telescopes to probe galaxy formation and Hubble constant

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In collaboration with

SEAGLE
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COSMICLENS
Prof. Dominique Sluse
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Prof. Sherry Suyu
Dr. Stefan Hilbert
Lyne VandeVyverre

HOLiCOW collaboration
Timeline of (Strong) Gravitational Lensing

1801 Soldner proposed GL in context of Newtonian theory. He found a deflection angle for the sun in 0.85”.

1915 With general relativity, Einstein derived the new result for the sun as 1.7”

1919 Using solar eclipse, Eddington measured a value close to GR, 1.6”

1937 Zwicky suggested that galaxies would produce well separated images that could be observed.

1979 The discovery of QSO 957+561 A,B found at z~1.4 (Walsh et al.1979).

1986 Lynds & Petrosian discovered cluster lensing.

1993 The Cosmic Lens All-Sky Survey (CLASS) initiated.

2002 The Sloan Lens ACS (SLACS) survey: discovery of ~100 Strong lenses.

2010 SL2S, SWELLS and BELLS, observational surveys: ~20-50 SLs each.

2016–2025 DES, KiDS, EUCLID, LSST, SKA, etc >100,000 lenses.
Strong Gravitational Lensing

What can we learn from Strong Lensing?

1. Total mass (within Einstein radius) !!!
2. Stellar mass profile
3. DM mass profile
4. Ellipticity/orientation
5. Substructure
6. Hubble constant via Time-delay

Advantage of using Gravitational Lensing

Gravitational Lensing measures the total matter distribution independent of the nature of the matter and of its state

SDSS J073728.45+321618.5
courtesy: HST, NASA/ESA
Auger et. al 2009
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courtesy: HST, NASA/ESA
Auger et. al 2009
How many strong lenses do we need & why?

A. 1% error on mass slopes —needs—> 50+ lenses per parameter-space (e.g. Barnabe et al. 2011).

B. 0.1% error in the mass fraction in substructure —needs—> 50+ lenses with extended images (e.g. Vegetti & Koopmans 2009).

Probing a wide range of masses, environments and galaxy types requires $10^{(4-5)}$ lenses
Euclid: online in 2020-2025; will yield >100,000 lenses

Credits: Koopmans/Euclid
A novel pipeline for Simulating EAGLE Lenses

based on

SEAGLE—I: A pipeline for simulating and modelling strong lenses from cosmological hydrodynamic simulations

Mukherjee et al. 2018
MNRAS 2018, 479, 4108
**Evolution and Assembly of Galaxies and their Environments (EAGLE)**

A suite of hydrodynamical simulations of the **$\Lambda$CDM universe**

- **13 galaxy formation scenarios**

  Simulation box sizes: **100, 50, 25, 12, cMpc**

  Matter content: **Gas, Star, Dark Matter, Bhs**

**Major improvement:**

Feedback from Stars & AGN

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Image courtesy: Durham University & Schaye et al. 2015
Gravitational Lensing (Courtesy: NASA/ESA)
The Pipeline: Simulations & Modeling of Mock Strong Lenses

EAGLE → Subfind / FOF → Lensing Galaxy → 'GLAMER' → Lens → 'LENSED' → Modelled Parameters of Lens

Science goal I
Science goal II

The SEAGLE pipeline

Start

Model Variation 1
Model Variation 2
Model Variation 3
........
Model Variation N

Start

Extract all relevant sub-halos.
Selection based on:
1. Redshift (zL)
2. Stellar mass (Mstar)
3. Effective radius (Reff)
4. Stellar velocity dispersion

Extract all relevant sub-halos.
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Project the galaxy in x, y, z axes

Mass maps
A- Proj on x
B- Proj. on y
C- Proj. on z

Mass maps
A- Proj on x
B- Proj. on y
C- Proj. on z

GLAMER: Create convergence maps, inverse mag. maps.
Calculate critical curves and caustics.
Use galaxy mass map as lens and put an analytic source
(zs>zl) and ray trace.

1. Strong Gravitational Lenses
2. Convergence maps

Automatic Mask creation

LENSED & Minimiser:
Lens properties. Mass power law.
Reconstructed lens residulas.

LENSED: Model the lenses with Elliptical profile (EPL),
Singular Isothermal Ellipsoid (SIE)
Both with shear & Source: Sersic
MINIMISER: Model the convergence maps
with Elliptical profile (EPL)

SEAGLE-I: Mukherjee+ 2018 MNRAS

The ray-tracer

The modelling code

GLAMER (Metcalf+ 14, Petkova+ 14)

LENSED (Tessore+ 16)
<table>
<thead>
<tr>
<th>Observable</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_*$</td>
<td>$\geq 1.76 \times 10^{10} M_\odot$</td>
<td>Stellar mass lower threshold. Taken from Auger et al. (2010a)</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>$&gt; 120 \text{ km/sec}$</td>
<td>Stellar Velocity dispersions are kept lower than SLACS</td>
</tr>
<tr>
<td>$R_{50}$</td>
<td>$&gt; 1 \text{ kpc}$</td>
<td>Half mass projected radius</td>
</tr>
</tbody>
</table>

**Lens Candidates**

<table>
<thead>
<tr>
<th>Object-Properties</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim. used</td>
<td>REFERENCE (L050N0752)</td>
<td>50 cMpc box is best for each axis</td>
</tr>
<tr>
<td>Orientation</td>
<td>x, y and z axis</td>
<td>Projected surface density maps are made for each axis</td>
</tr>
<tr>
<td>Redshift</td>
<td>$z_{lens} = 0.271$</td>
<td>Consistent with SLACS’ mean lens-redshift of 0.3</td>
</tr>
<tr>
<td>No. of galaxies</td>
<td>252</td>
<td></td>
</tr>
<tr>
<td>No. of proj. galaxies</td>
<td>756</td>
<td></td>
</tr>
</tbody>
</table>

**Source Properties**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source Type</td>
<td>Sérsic</td>
<td>Consistent with analysed SLACS lenses (Newton et al. 2011)</td>
</tr>
<tr>
<td>Brightness</td>
<td>23 apparent mag.</td>
<td></td>
</tr>
<tr>
<td>Size ($R_{eff}$)</td>
<td>0.2 arcsec</td>
<td></td>
</tr>
<tr>
<td>Axis ratio ($q_s$)</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Sérsic Index</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$z_{source}$</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Position</td>
<td>Random within caustics</td>
<td>Producing more rings and arcs lens systems, consistent with SLACS</td>
</tr>
</tbody>
</table>

**Instrumental Settings**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSF</td>
<td>Gaussian, FWHM=0.1 arc-sec</td>
<td></td>
</tr>
<tr>
<td>Noise</td>
<td>HST ACS-F814W, 2400 sec</td>
<td></td>
</tr>
</tbody>
</table>

**Image Properties**

<table>
<thead>
<tr>
<th>Map used</th>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface density</td>
<td>Size</td>
<td>512×512 pixels</td>
</tr>
<tr>
<td></td>
<td>Units</td>
<td>kpc</td>
</tr>
<tr>
<td>$\kappa$, Inv. mag. map and Lens</td>
<td>Size</td>
<td>161×161 pixels</td>
</tr>
<tr>
<td></td>
<td>Units</td>
<td>degrees (converted from arcsec)</td>
</tr>
</tbody>
</table>
Results

Are we getting what we wanted?
Some Strong Lenses from Sloan Lens ACS (SLACS) Survey

Some Strong lenses from EAGLE (REFERENCE) 50 cMpc, z =0.271

Comparison of observables like Stellar Mass, Einstein radius, etc with SLACS Lenses, will put constraints on the galaxy formation scenarios of EAGLE.
The distribution of weighted mass density slope of EAGLE at $z=0.271$ and also compared with SLACS & SL2S.

Mean density slope

**SLACS** – 2.08  
**SL2S** – 2.18  

<table>
<thead>
<tr>
<th>log $M_\star$ (M$_\odot$)</th>
<th>Mean</th>
<th>RMS</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.0 – 11.5</td>
<td>2.26</td>
<td>0.26</td>
<td>2.26</td>
</tr>
<tr>
<td>11.5 – 12.0</td>
<td>2.28</td>
<td>0.21</td>
<td>2.23</td>
</tr>
<tr>
<td>11.0 – 12.0</td>
<td>2.26</td>
<td>0.25</td>
<td>2.26</td>
</tr>
</tbody>
</table>

Consistent with

- **Remus+ 2017**  
- **Xu+ 2017**  
- **Tortora+ 2014**
Impact of sub grid physics on total mass density slope

based on

SEAGLE—II: Constraints on feedback models in galaxy formation from massive early-type strong lens galaxies

Mukherjee et al.
submitted to MNRAS
arXiv:1901.01095
**SEAGLE- II: Constraining 10 galaxy evolution scenarios**

(Crain et al. 2015)

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Side length [cMpc]</th>
<th>$N$</th>
<th>$\gamma_{eos}$</th>
<th>$n_H^*$ [cm$^{-3}$]</th>
<th>$f_{th}$-scaling</th>
<th>$f_{th,\text{max}}$</th>
<th>$f_{th,\text{min}}$</th>
<th>$n_{H,0}$ [cm$^{-3}$]</th>
<th>$n_n$</th>
<th>$C_{\text{visc}}/2\pi$</th>
<th>$\Delta T_{\text{AGN log10}}$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBconst</td>
<td>50</td>
<td>752</td>
<td>4/3</td>
<td>Eq. 1</td>
<td>–</td>
<td>1.0</td>
<td>1.0</td>
<td>–</td>
<td>–</td>
<td>$10^3$</td>
<td>8.5</td>
</tr>
<tr>
<td>FB$\sigma$</td>
<td>50</td>
<td>752</td>
<td>4/3</td>
<td>Eq. 1</td>
<td>$\sigma_{DM}^2$</td>
<td>3.0</td>
<td>0.3</td>
<td>–</td>
<td>–</td>
<td>$10^2$</td>
<td>8.5</td>
</tr>
<tr>
<td>FBZ</td>
<td>50</td>
<td>752</td>
<td>4/3</td>
<td>Eq. 1</td>
<td>$Z$</td>
<td>3.0</td>
<td>0.3</td>
<td>–</td>
<td>–</td>
<td>$10^2$</td>
<td>8.5</td>
</tr>
<tr>
<td>Ref (FBZ$\rho$)</td>
<td>50</td>
<td>752</td>
<td>4/3</td>
<td>Eq. 1</td>
<td>$Z, \rho$</td>
<td>3.0</td>
<td>0.3</td>
<td>0.67</td>
<td>2/ln10</td>
<td>$10^0$</td>
<td>8.5</td>
</tr>
<tr>
<td>Ref-100 (FBZ$\rho$)</td>
<td>100</td>
<td>1504</td>
<td>4/3</td>
<td>Eq. 1</td>
<td>$Z, \rho$</td>
<td>3.0</td>
<td>0.3</td>
<td>0.67</td>
<td>2/ln10</td>
<td>$10^0$</td>
<td>8.5</td>
</tr>
<tr>
<td>ViscLo</td>
<td>50</td>
<td>752</td>
<td>4/3</td>
<td>Eq. 1</td>
<td>$Z, \rho$</td>
<td>3.0</td>
<td>0.3</td>
<td>0.67</td>
<td>2/ln10</td>
<td>$10^2$</td>
<td>8.5</td>
</tr>
<tr>
<td>ViscHi</td>
<td>50</td>
<td>752</td>
<td>4/3</td>
<td>Eq. 1</td>
<td>$Z, \rho$</td>
<td>3.0</td>
<td>0.3</td>
<td>0.67</td>
<td>2/ln10</td>
<td>$10^{-2}$</td>
<td>8.5</td>
</tr>
<tr>
<td>AGNdT8</td>
<td>50</td>
<td>752</td>
<td>4/3</td>
<td>Eq. 1</td>
<td>$Z, \rho$</td>
<td>3.0</td>
<td>0.3</td>
<td>0.67</td>
<td>2/ln10</td>
<td>$10^0$</td>
<td>8.0</td>
</tr>
<tr>
<td>AGNdT9</td>
<td>50</td>
<td>752</td>
<td>4/3</td>
<td>Eq. 1</td>
<td>$Z, \rho$</td>
<td>3.0</td>
<td>0.3</td>
<td>0.67</td>
<td>2/ln10</td>
<td>$10^0$</td>
<td>9.0</td>
</tr>
<tr>
<td>NOAGN</td>
<td>50</td>
<td>752</td>
<td>4/3</td>
<td>Eq. 1</td>
<td>$Z, \rho$</td>
<td>3.0</td>
<td>0.3</td>
<td>0.67</td>
<td>2/ln10</td>
<td>$10^0$</td>
<td>–</td>
</tr>
</tbody>
</table>

**Reference Variations**

Remus+ 2017 — 3 sims  
Xu+ 2017 — 2 sims  
Peirani+ 2018 — 2 sims
<table>
<thead>
<tr>
<th>NOAGN</th>
<th>AGNdT9</th>
<th>AGNdT8</th>
<th>Visc-Hi</th>
<th>Visc-Lo</th>
<th>FBσ</th>
<th>FBZ</th>
<th>FBconst</th>
<th>Reference</th>
</tr>
</thead>
</table>

**SEAGLE-II.** Mukherjee et al. sub. MNRAS, arXiV:1901.01095
The graph shows the normalized number of strong lenses as a function of the total mass density slope ($t$). The data is compared across different studies:

- **Reference - 100**
- **SLACS** (Auger et al. 2010b)
- **SL2S** (Sonnenfeld et al. 2013a)
- **BELLS** (Bolton et al. 2012)

The x-axis represents the total mass density slope ($t$), while the y-axis shows the normalized number of strong lenses.
Total Mass density slopes of EAGLE’s 9 model variations
Total Mass density slopes of EAGLE’s 9 model variations

Distribution of the normalized weighted number of Strong Lenses

Distribution of the total mass density slope (t)

SEAGLE-II: Mukherjee+ sub. in MNRAS
SEAGLE-II: Mukherjee+ sub. in MNRAS
Inner dark matter fractions of early type galaxies in EAGLE model variations

based on

**SEAGLE—III**: The observed and simulated dark matter fractions in the central regions of early-type lens galaxies

**Mukherjee** et al.
To be submitted in few week(s) to MNRAS
Comparison of DMF in **EAGLE-Ref 100** with **SLACS** & **SPIDER**

See **Tortora+ 2012 MNRAS** for **SPIDER**

**SEAGLE-III: Mukherjee+** to be sub. in MNRAS
Lensing properties of early type galaxies in variable IMF scenarios

**SEAGLE—IV**: *Impact of IMF variation on dark matter fraction and dark matter slope of EAGLE strong lenses*

Mukherjee et al. 2019

to be submitted to MNRAS
SEAGLE- IV: Impact of IMF variation on DMF

IMF-BottomHeavy (LoM)

IMF-TopHeavy (HiM)

See Barber et al. 2018a MNRAS

SEAGLE-IV: Mukherjee+ to be sub. in MNRAS
SEAGLE-IV: Mukherjee+ to be sub. in MNRAS
Shear-Ellipticity degeneracy

**SEAGLE VI:** Impact of galaxy formation physics on `shear-ellipticity' degeneracy in strong lens modeling

**Mukherjee** et al. 2019

to be submitted to MNRAS
Shear-Ellipticity correlation

Normalized distribution of Angle between shear and ellipticity

SEAGLE-VI: Mukherjee+ to be sub. in MNRAS
Shear-Ellipticity correlation

Normalized distribution of Angle between shear and ellipticity

SEAGLE-VI: Mukherjee+ to be sub. in MNRAS
Can we do some Microlensing too?
The Most Powerful Lenses in the Universe: Quasar Microlensing as a Probe of the Lensing Galaxy

Thematic Areas:
- Planetary Systems
- Star and Planet Formation
- Formation and Evolution of Compact Objects
- Cosmology and Fundamental Physics
- Stars and Stellar Evolution
- Resolved Stellar Populations and their Environments
- Galaxy Evolution
- Multi-Messenger Astronomy and Astrophysics
Microlensing with **SEAGLE**

*Mukherjee*+ in prep

Implementing clustering algorithm

**Stacked lensed systems with their brightest pixel**

**Individual lensed systems with their brightest pixel**

\[ z_{\text{lens}} = 0.271 \text{ and } z_{\text{source}} = 1.0 \]
# Upcoming SEAGLE Papers in 2019-2020

<table>
<thead>
<tr>
<th>1. Mukherjee et al. ——</th>
<th>Shear Ellipticity degeneracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Chatterjee, Mukherjee et al.</td>
<td>Mass power spectrum with EAGLE</td>
</tr>
<tr>
<td>3. Bayer, Mukherjee et al.</td>
<td>HST lens P.S. with EAGLE.</td>
</tr>
</tbody>
</table>

---

Using **SEAGLE** pipeline

| 4. Tortora, Mukherjee et al. —— | EAGLE lenses in KiDS. |
| 5. Tortora, Mukherjee et al. —— | EAGLE lenses in KiDS II. |
| 6. Spiniello, Mukherjee et al. —— | EAGLE quasar lenses in KiDS. |
| 7. Vernardos, Mukherjee, Sluse — | GERLUMPH and EAGLE. |
| 8. Mukherjee, Vernardos, Sluse —— | Shear-convergence correlation in EAGLE |
| 9. Denzel, Saha, Mukherjee — | New strong lens modelling code |
Time delay and Hubble constant

For cosmography we need:
1. Lens mass model
2. Time-delay
3. Mass along Line of sight

Independent measurements are needed!

Credit: S. Suyu
Time delay and Hubble constant

For cosmography we need:

1. Lens mass model
2. Time-delay
3. Mass along Line of sight

Independent measurements are needed!

Simulations: Hydro, DM only or semi analytic

Credit: S. Suyu
COSMICLENS: Cosmology with Strong Gravitational Lensing

Prof. Frédéric Courbin (EPFL)
Prof. Dominique Sluse (U. Liege)

ERC Advanced Grant
H2020-EU.1.1. ERC-2017-ADG
Oct 2018 —— Sept 2023
COSMICLENS: Cosmology with Strong Gravitational Lensing

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COSMOGRAIL: the COSmological MOonitoring of GRAvitational Lenses

- time delays of lensed quasars from optical monitoring
- expect to have delays with a few percent error for ~20 lenses

The H0LiCOW Collaboration:
Cosmology with Quasar Time Delays
COSMICLENS: Cosmology with Strong Gravitational Lensing

ERC Advanced Grant
H2020-EU.1.1. ERC-2017-ADG
Oct 2018 —— Sept 2023

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Prof. Dominique Sluse (U. Liege)

COSMOGRAIL: the COSmological MOonitoring of GRAvitational Lenses
• time delays of lensed quasars from optical monitoring
• expect to have delays with a few percent error for ~20 lenses

3- Providing a modular **end-to-end simulation framework** to mock lensed systems from hydro-simulations and to evaluate in detail the impact model degeneracies on Hubble constant (H0).

The H0LiCOW Collaboration:
Cosmology with Quasar Time Delays

4 work plan project
Quasar Strong Lensing
Observed Quasar Lenses

Credit: F. Courbin
COSMICLENS

GLAMER
• Analytic + N-body
Time delay ($\delta t$)
Line of sight
Multi plane/Light cone

SEAGLE
COSMICLENS

Lenstronomy
• Analytic + N-body
  Time delay ($\delta t$)
  Line of sight
  Instrumentation

SEAGLE

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Lenstronomy
- Analytic + N-body
  Time delay ($\delta t$)
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  Instrumentation

Hilbert-code
- Analytic + N-body
  Time delay ($\delta t$)
  Line of sight
  Multi plane lensing

SEAGLE

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pYSPT
- Analytic
  Time delay ($\delta t$)
  Source systematics
  Convergence test
COSMICLENS

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  Source systematics
  Convergence test
Conclusions

1. An automatic pipeline for creating & modelling mock lenses with a suite of hydrodynamic simulations, EAGLE, mimicking observational surveys and analysing them similar to real lenses. **(SEAGLE-I: Mukherjee et al. 2018 MNRAS)**

2. Applying the pipeline to a variety of EAGLE scenarios can constrain the galaxy-formation mechanisms via total mass density slope and mass-size relationship. **(SEAGLE-II: Mukherjee et al. sub. MNRAS, arXiv:1901.01095)**

3. **SEAGLE-III to VI and others**: with one pipeline it is possible to deal with multiple science questions and mock lensed images from simulations has a variety of applications.

4. Time-delay measurement is independent probe to calculate Hubble constant. A systematic and flexible pipeline (**COSMICLENS**) will be very effective in giving crucial handle to constrain it <1% **uncertainty**.

*Take home message*

Simulation of realistic mock Strong Lenses is a very promising tool to probe galaxy formation and H0