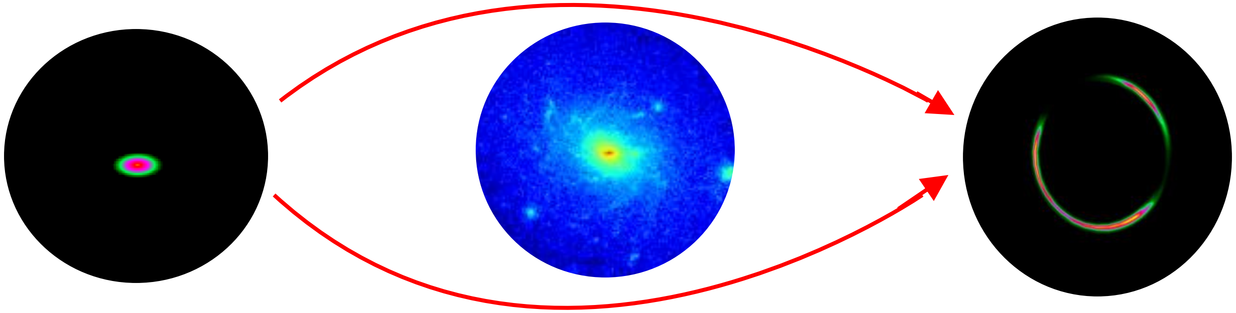
SEAGLE: Constraining galaxy evolution scenarios by Simulating EAGLE LEnses

arXiv: 1802.06629



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Kapteyn Astronomical Institute, University of Groningen (RUG)

In collaboration with
Prof. Léon Koopmans (RUG, supervisor)
Prof. Joop Schaye (Leiden Observatory, co-supervisor)
Prof. R. Benton Metcalf (University of Bologna, co-promoter)
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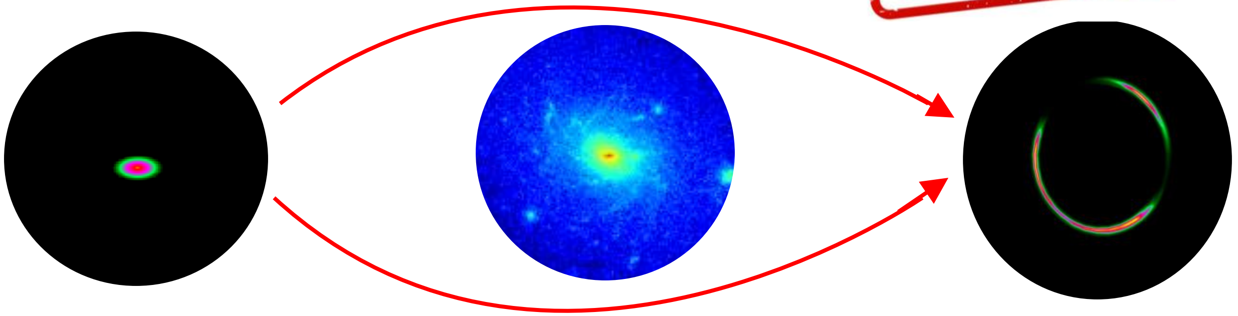
SEAGLE: Constraining galaxy evolution scenarios by Simulating EAGLE LEnses

arXiv: 1802.06629 ACCEPTED



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How many strong lenses do we need & why?

I. If we want to achieve 1% error on mass slopes we require 50+ lenses **per** parameter-space (e.g. ***Barnabe et al. 2011***).

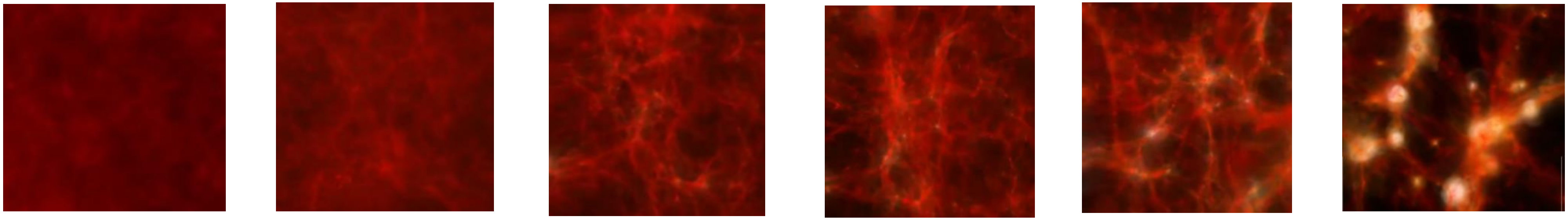
II. If we want to reach up-to 0.1% error in the mass fraction in substructure needs 50+ lens system with **extended** images (e.g. ***Vegetti & Koopmans 2009***).

Probing a wide range of masses, environments and galaxy types requires $\mathbf{10^{(4\text{-}5)}}$ lenses to beat sample variance, noise & biases.

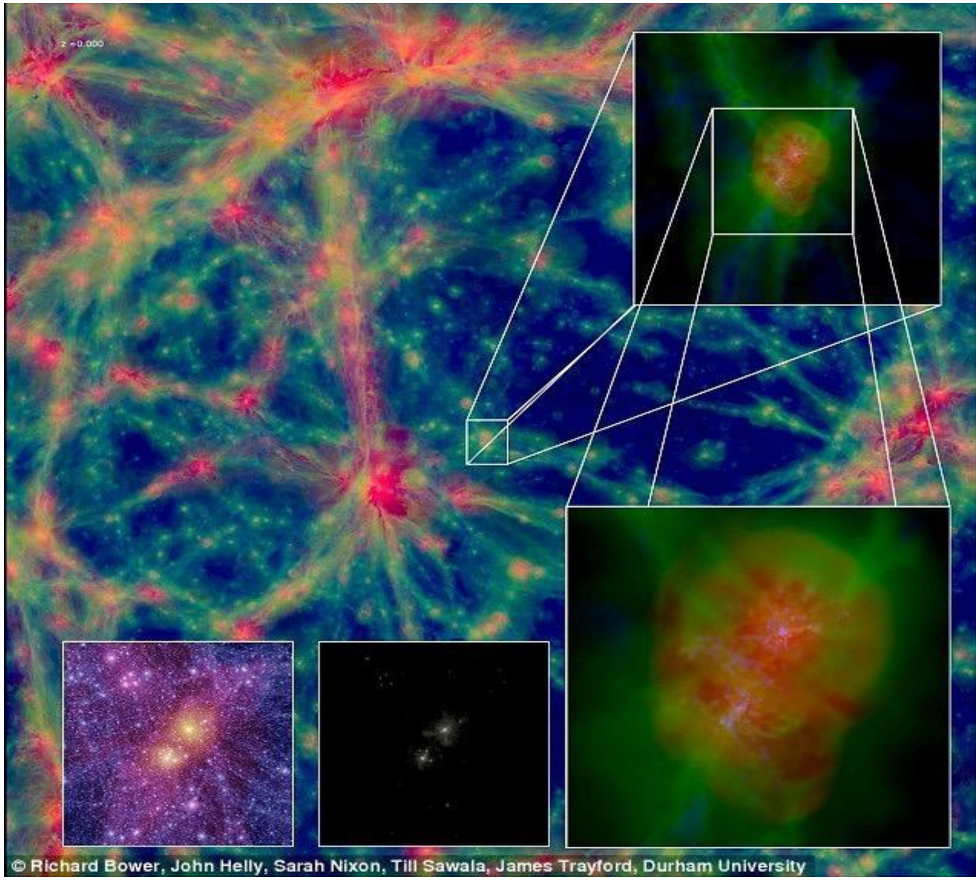
Why do I want to simulate so many strong lenses?

1. Galaxy structure and evolution as a function of mass, redshift and type: **DM** & **Stellar** mass profiles.
2. Setting constraints on galaxy evolution scenarios.
3. To predict future Strong Lenses from KiDS, Euclid and SKA.

Evolution and **A**ssembly of **G**a**L**axies and their **E**nvironments (**EAGLE**)



$z = 12.9$ $z = 10.4$ $z = 5.0$ $z = 3.8$ $z = 2.6$ $z = 0.0$



© Richard Bower, John Helly, Sarah Nixon, Till Sawala, James Trayford, Durham University

100x100x20 cMpc slice of Ref-L100N1504 at z = 0.0

EAGLE: A suite of hydrodynamical simulations

ΛCDM universe **(13 Formation scenarios)**

Cosmological parameters from **Planck 2013**

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

Maximum number of particles : **1504^3**

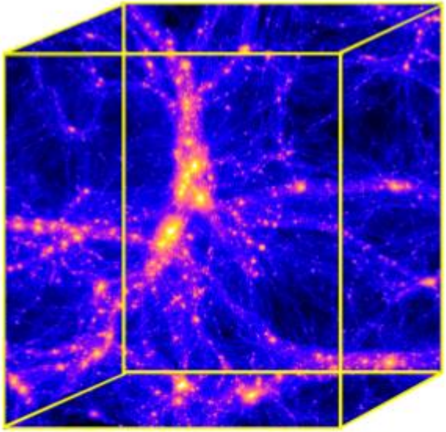
Matter content : **Gas**, **Star**, **Dark Matter**, **Bhs**

Maximum mass resol. : $2.26 * 10^5$ $M_{sun}(m_g)$
$1.21 * 10^6$ M_{sun} (m_{dm})

Major improvement:
Feedback from Stars & AGN

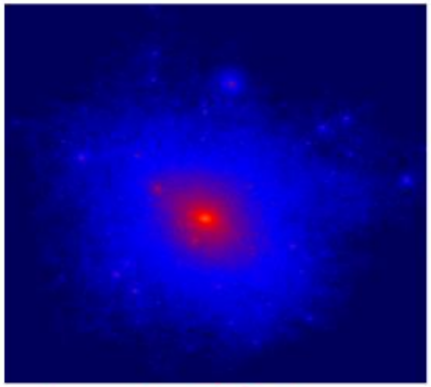
Image courtesy: Durham University & Schaye et al. 2015

The Pipeline: Simulations & Modeling of Mock Strong Lenses



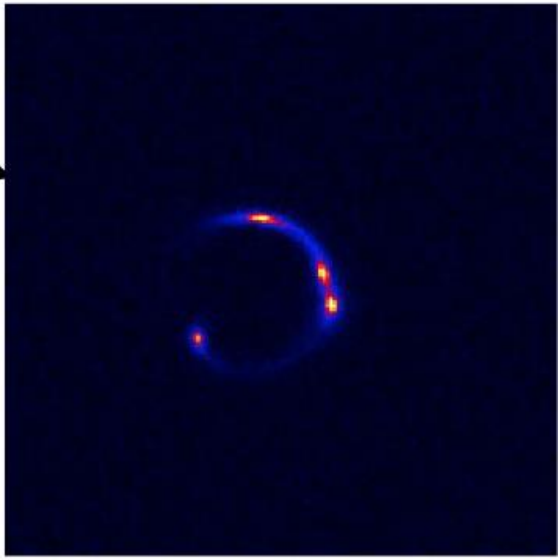
EAGLE

Subfind / FOF



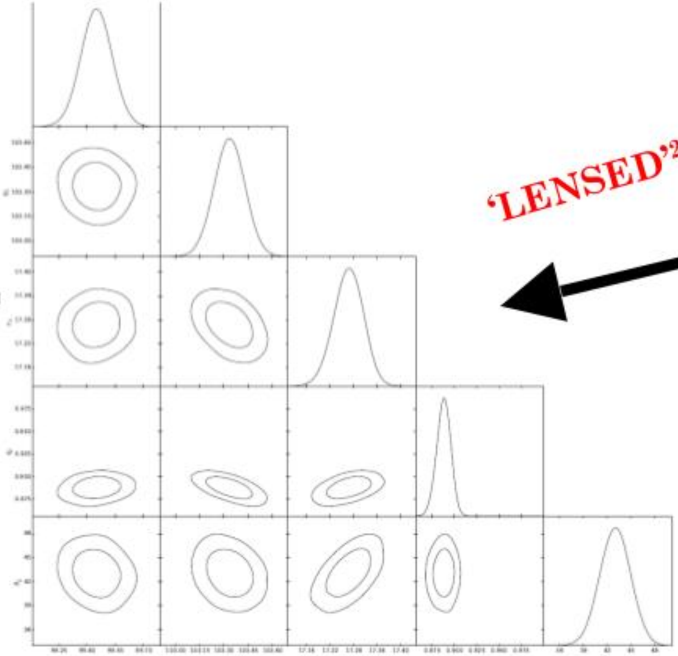
Lensing Galaxy

'GLAMER'[1]



Lens

'LENSED'[2]



Modelled Parameters of Lens

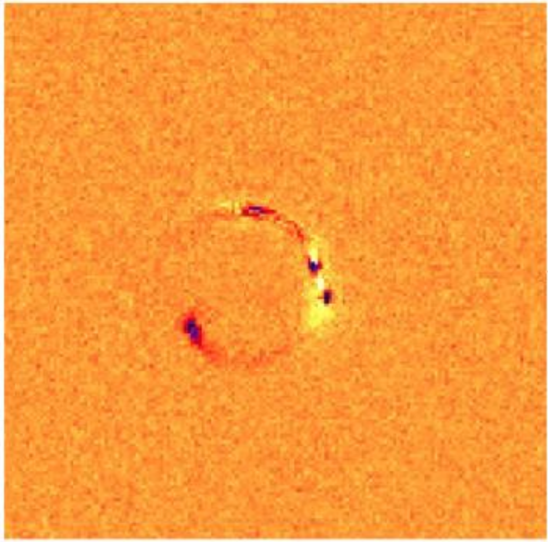
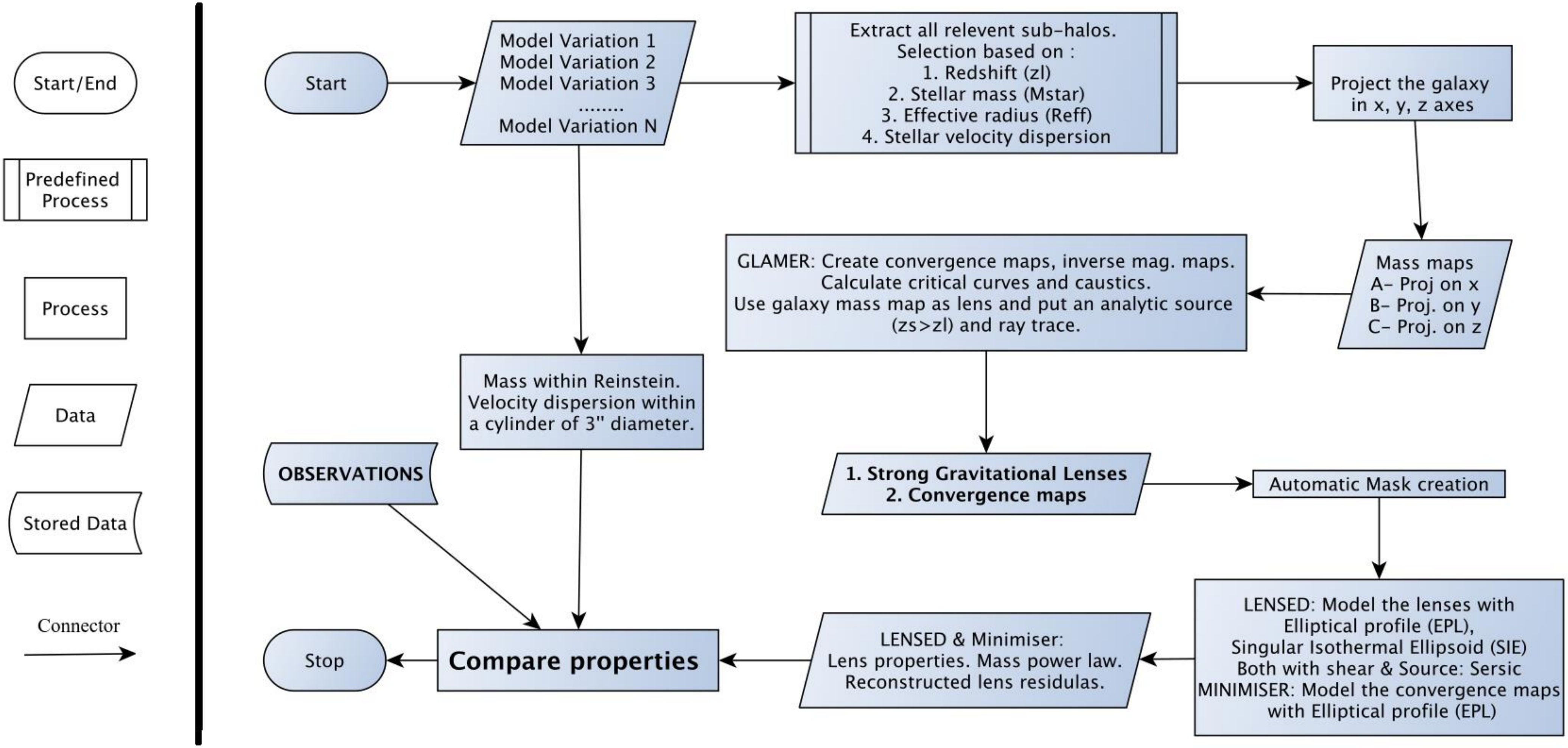


Image Residual

(Mock - Reconstructed)

[1] http://glenco.github.io/glamer/

[2] http://glenco.github.io/lensed/



Start/End

Predefined Process

Process

Data

Stored Data

Connector

Start

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

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

Project the galaxy in x, y, z axes

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.

Mass within Reinstein.
Velocity dispersion within a cylinder of 3" diameter.

OBSERVATIONS

1. Strong Gravitational Lenses
2. Convergence maps

Automatic Mask creation

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)

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

Compare properties

Stop

Flow chart diagram of the SEAGLE pipeline

SEAGLE-I: *Mukherjee+* 2018 MNRAS

SEAGLE can be applied to ANY Gadget based simulation

GLAMER

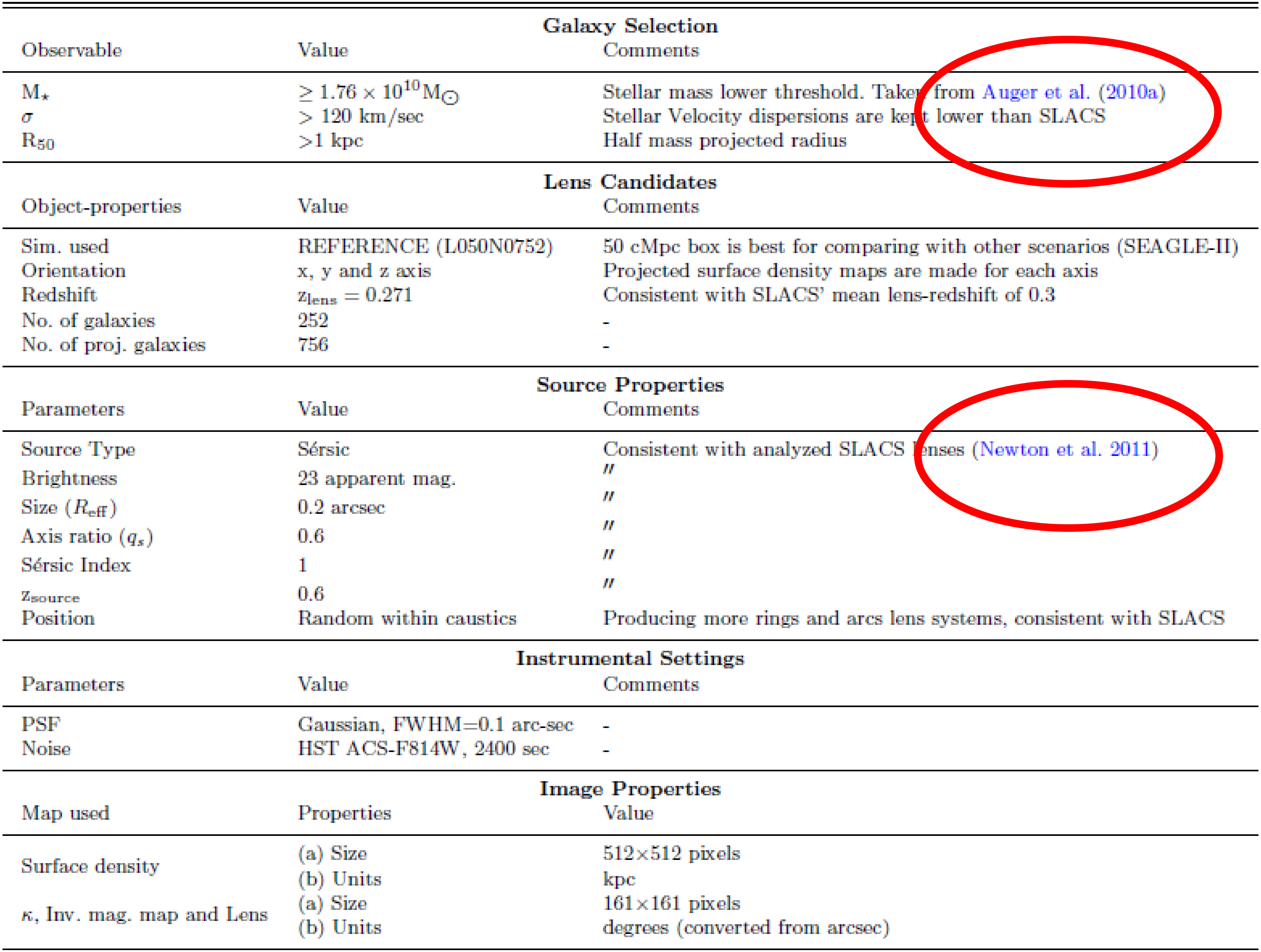
(*Metcalf+ 14, Petkova+ 14*)

- incorporates adaptive mesh refinement
- read in mass maps and use them as lens planes

LENSED

(*Tessore+ 16*)

- performs forward parametric modeling of strong lenses
- applied to sub-sample of the SLACS lenses



Galaxy Selection

Observable	Value	Comments
$M_\star$	$\geq 1.76 \times 10^{10} M_\odot$	Stellar mass lower threshold. Taken from Auger et al. (2010a)
σ	$>$ 120 km/sec	Stellar Velocity dispersions are kept lower than SLACS
R_{50}	$>$1 kpc	Half mass projected radius

Lens Candidates

Object-properties	Value	Comments
Sim. used	REFERENCE (L050N0752)	50 cMpc box is best for comparing with other scenarios (SEAGLE-II)
Orientation	x, y and z axis	Projected surface density maps are made for each axis
Redshift	$z_{\rm lens} = 0.271$	Consistent with SLACS' mean lens-redshift of 0.3
No. of galaxies	252	-
No. of proj. galaxies	756	-

Source Properties

Parameters	Value	Comments
Source Type	Sérsic	Consistent with analyzed SLACS lenses (Newton et al. 2011)
Brightness	23 apparent mag.	"
Size ($R_{\rm eff}$)	0.2 arcsec	"
Axis ratio (q_s)	0.6	"
Sérsic Index	1	"
$z_{\rm source}$	0.6	"
Position	Random within caustics	Producing more rings and arcs lens systems, consistent with SLACS

Instrumental Settings

Parameters	Value	Comments
PSF	Gaussian, FWHM=0.1 arc-sec	-
Noise	HST ACS-F814W, 2400 sec	-

Image Properties

Map used	Properties	Value
Surface density	(a) Size	512×512 pixels
	(b) Units	kpc
κ, Inv. mag. map and Lens	(a) Size	161×161 pixels
	(b) Units	degrees (converted from arcsec)

SEAGLE-I: *Mukherjee*+ 2018 MNRAS

Some Strong Lenses from Sloan Lens ACS (SLACS) Survey

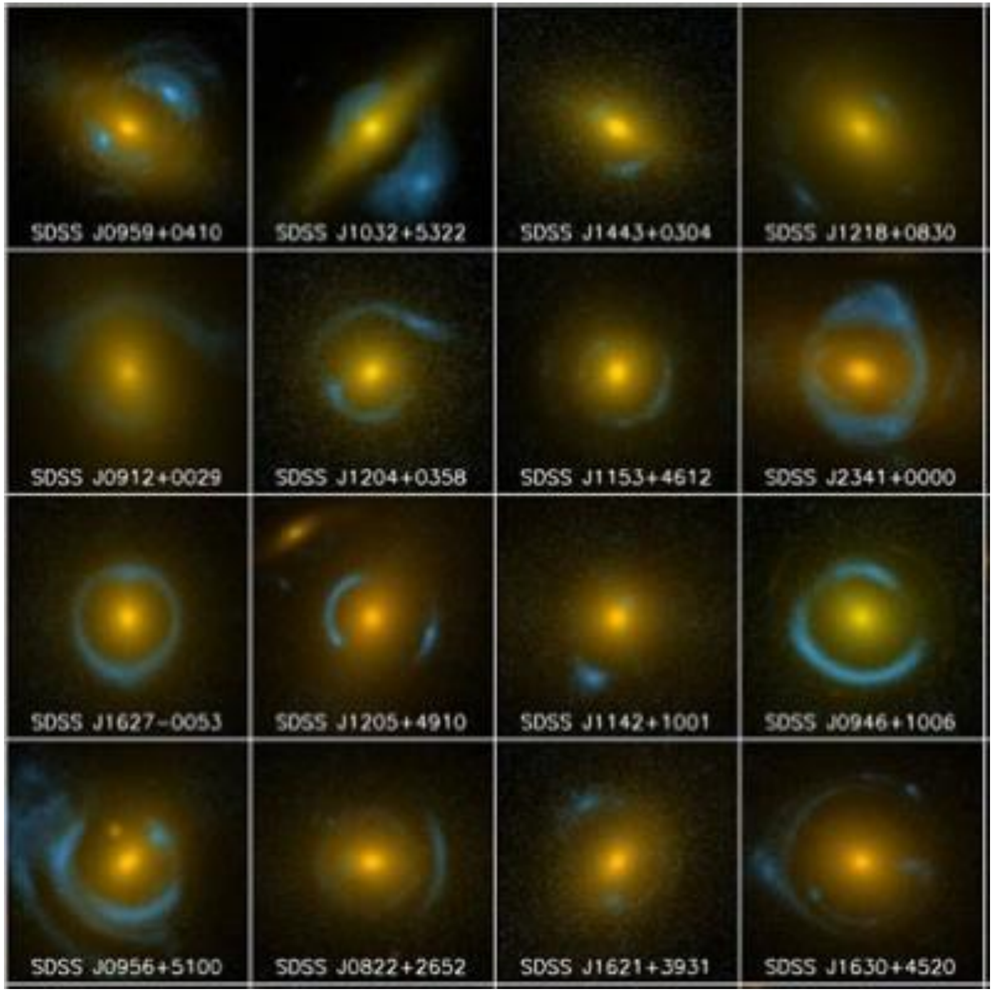
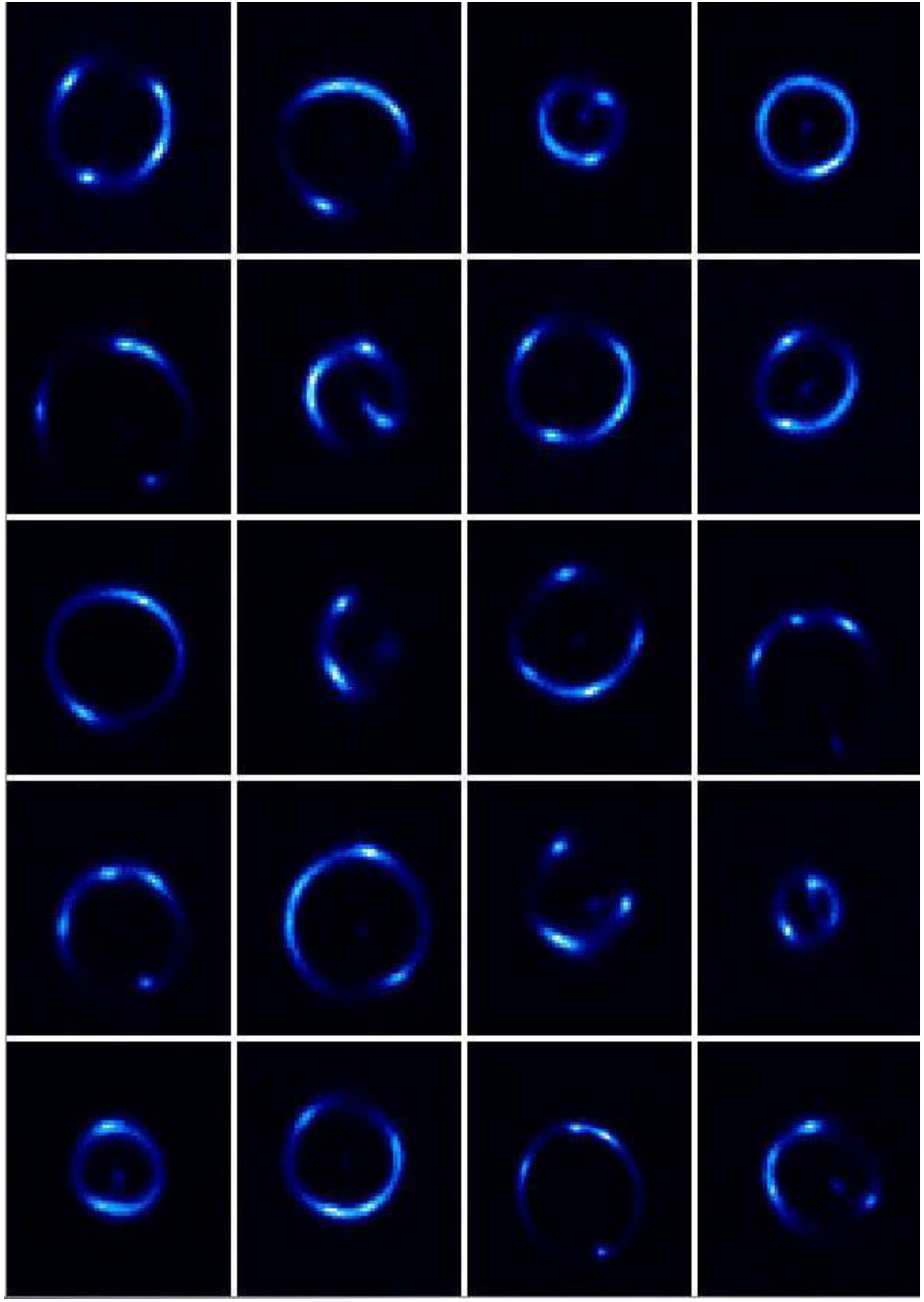
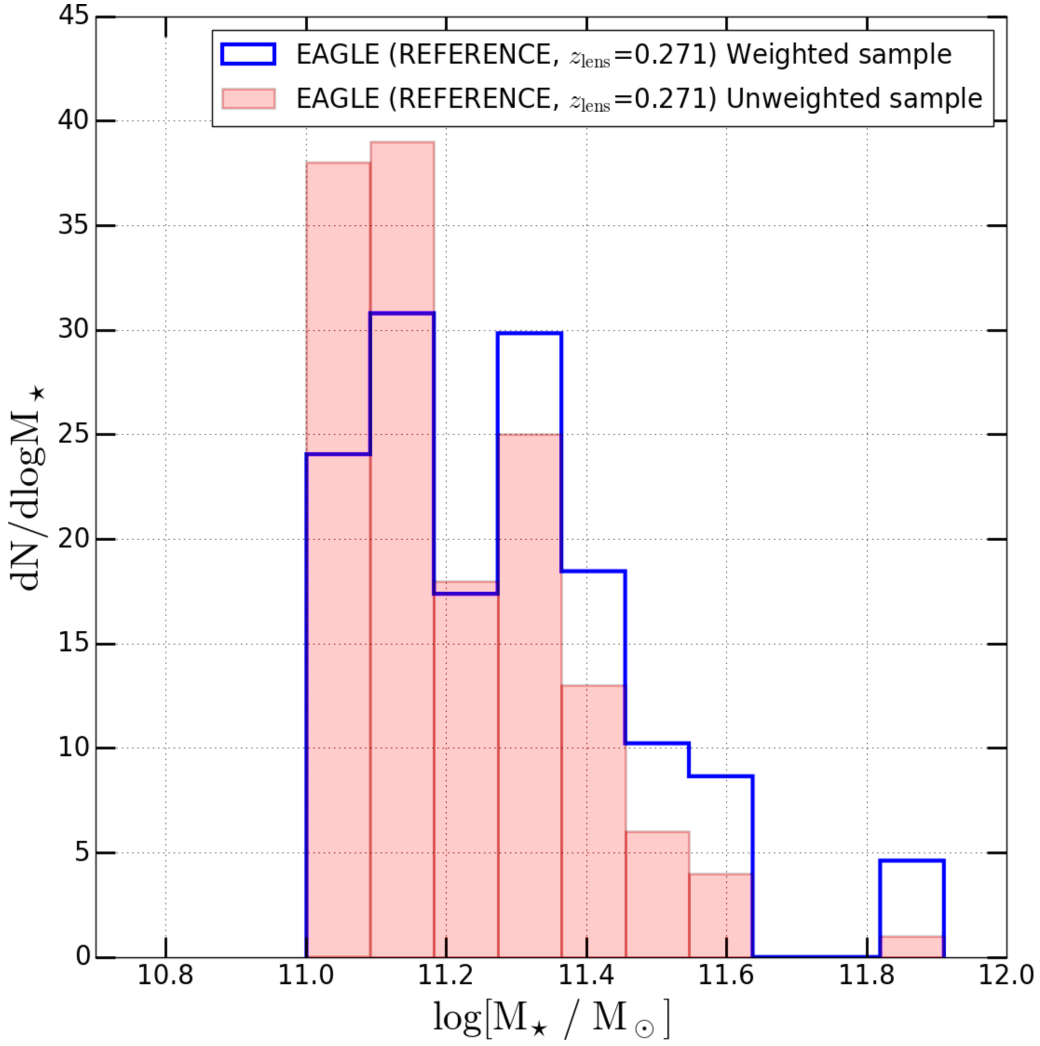


Image: A. Bolton (UH/IfA) for SLACS and NASA/ESA.

Comparison of observables like Stellar Mass, Einstein radius, etc with SLACS Lenses, will put constraints on the galaxy formation scenarios of EAGLE

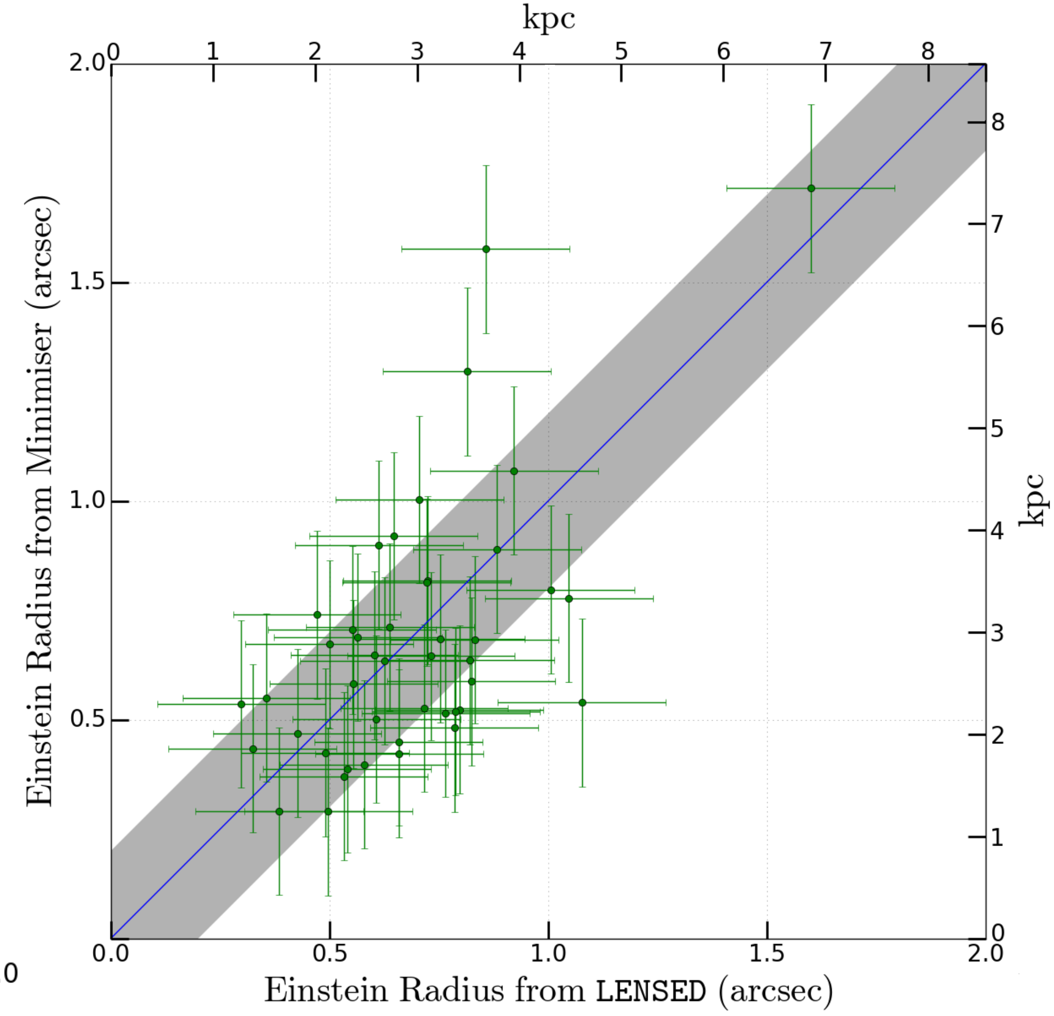
Some Strong lenses from EAGLE (REFERENCE) 50 cMpc, z =0.271





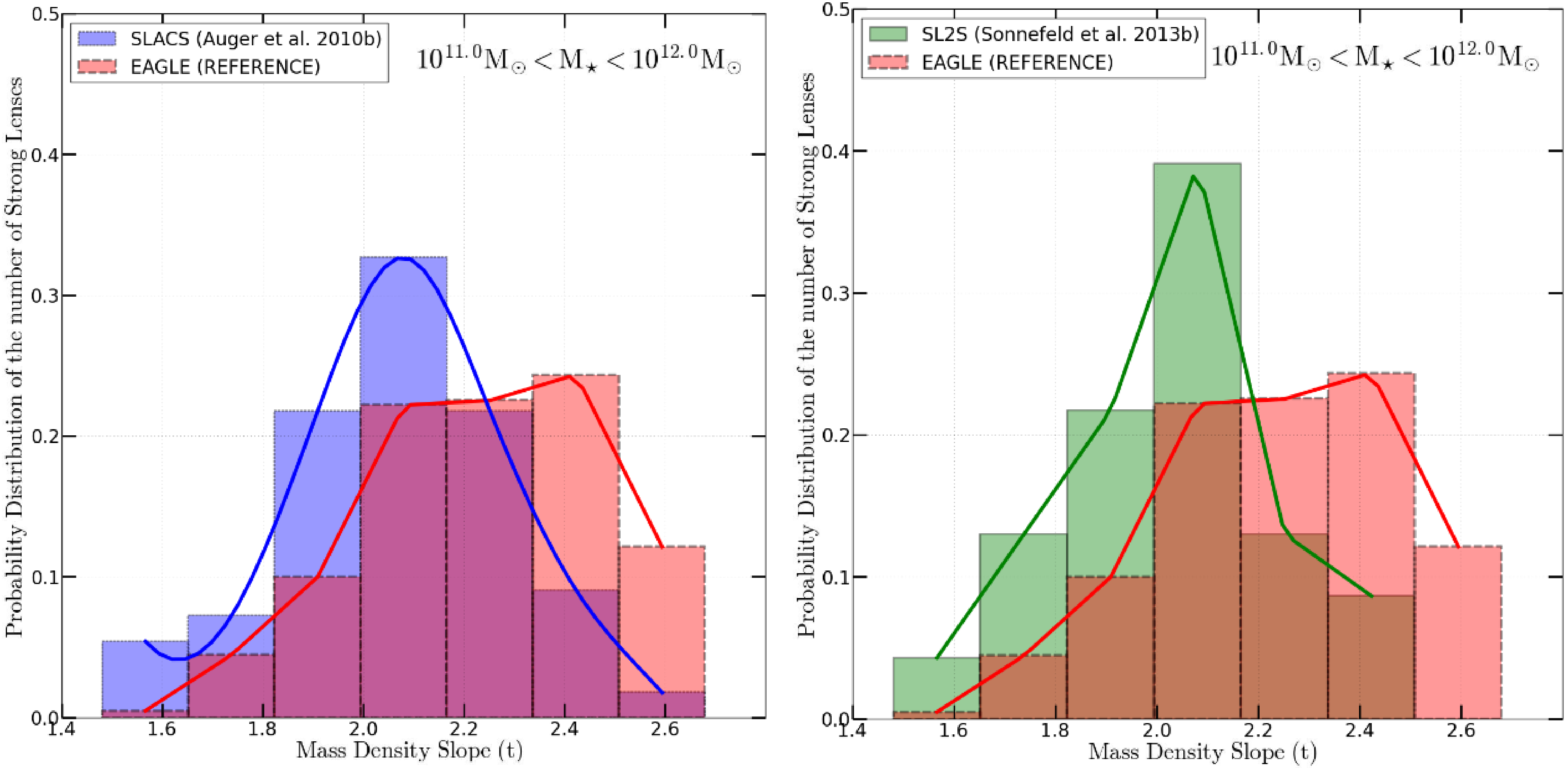
The mass function of galaxies having stellar masses $M_* > 10^{11} M_{sun}$, including and excluding the weighting scheme related to the lensing cross-section based on their stellar mass i.e.,

$W(M) = (M_* / < M_* >)$



Comparison of the Einstein radius of EAGLE lenses from Minimiser and LENSED output

SEAGLE-I: *Mukherjee+ 2018* MNRAS



The distribution of weighted mass density slope of EAGLE at **z=0.271**
and also compared with SLACS & SL2S.

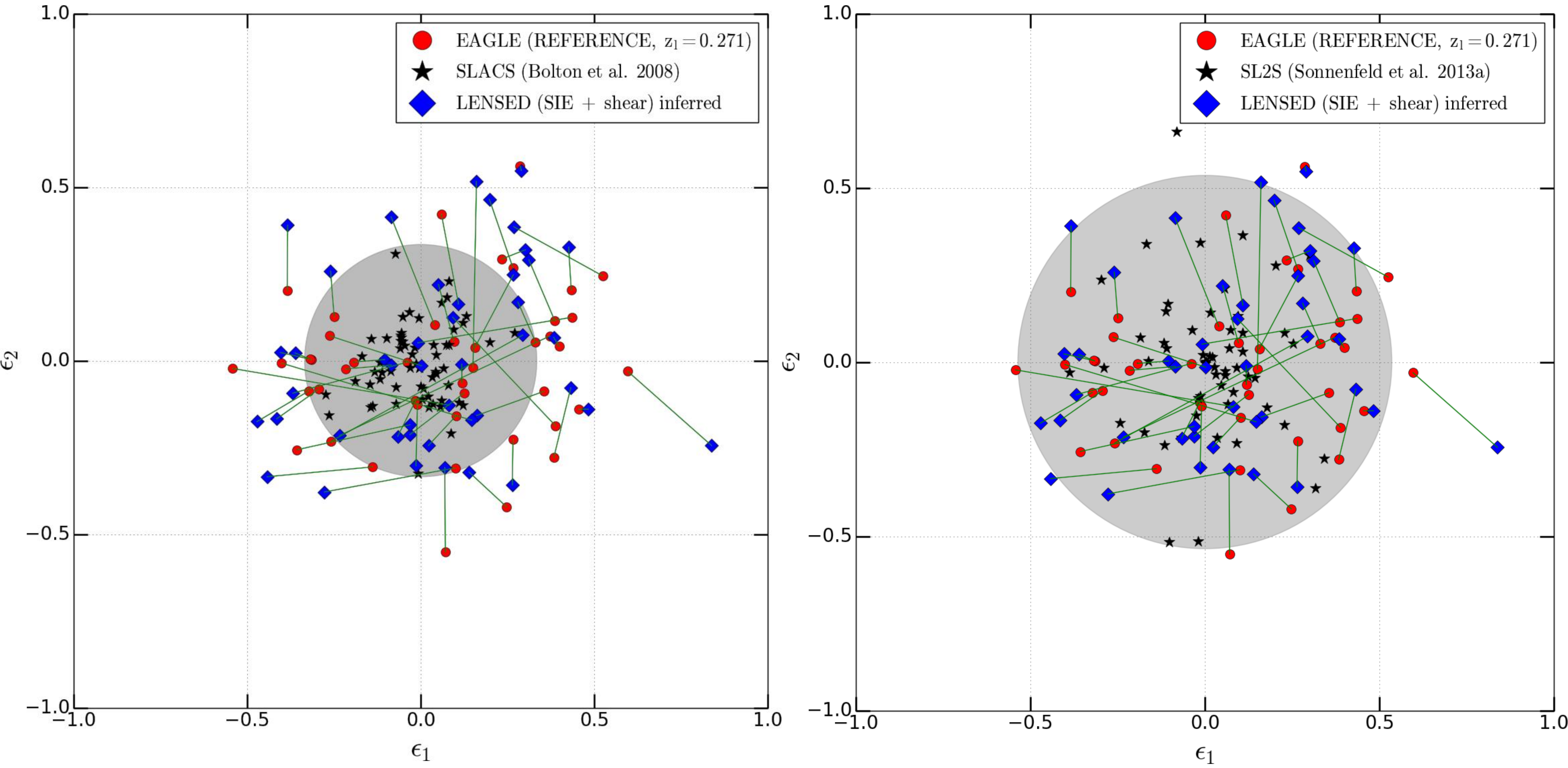
Mean density slope
SLACS – 2.08
SL2S – 2.18

$\log \mathrm{M}_\star$ ($\mathrm{M}_\odot$)	Mean	RMS	Median
11.0 – 11.5	2.26	0.26	2.26
11.5 – 12.0	2.28	0.21	2.23
11.0 – 12.0	2.26	0.25	2.26

Consistent with
Remus+ 2017
Xu+ 2017
Tortora+ 2014

SEAGLE-I: *Mukherjee+* 2018 MNRAS

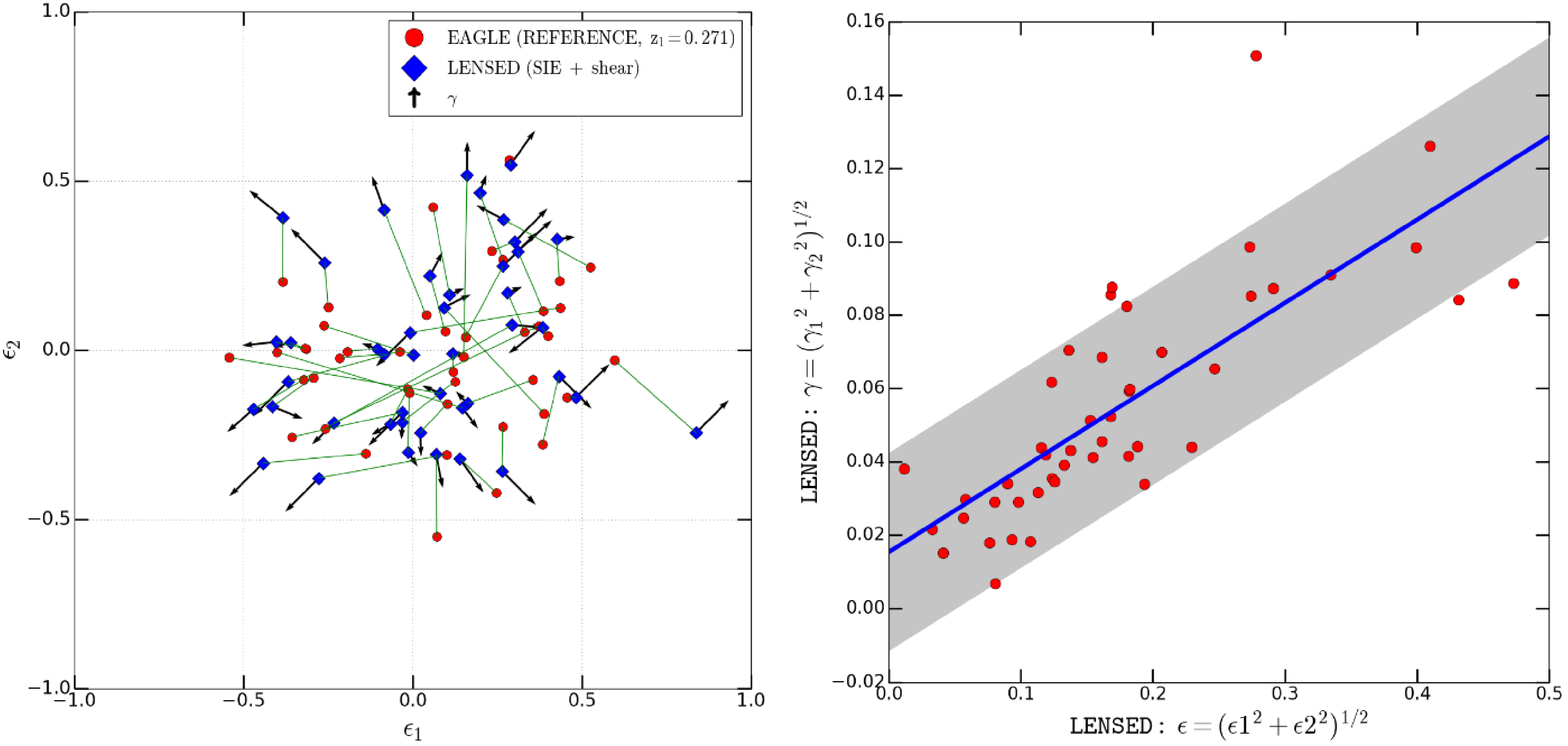
‘Conspiracy’ between axis ratio (q) and position angle (Φ)



Complex Ellipticity (∈) : $\in = (1-q)/(1+q)\,\exp(-2\,i\,\Phi)$

In this complex space the **agreement** depends **on the distance in a combined space of ‘q’ and ‘PA’.**

SEAGLE-I: ***Mukherjee+ 2018*** **MNRAS**



Left: The complex ellipticity of the SIE lens models from LENSED and from a direct fitting.

- The **shear** points **radially outwards**, so the ellipticity is degenerate with the shear.
- So differences in the ellipticity in the direction of the shear, deviates the true lens mass model

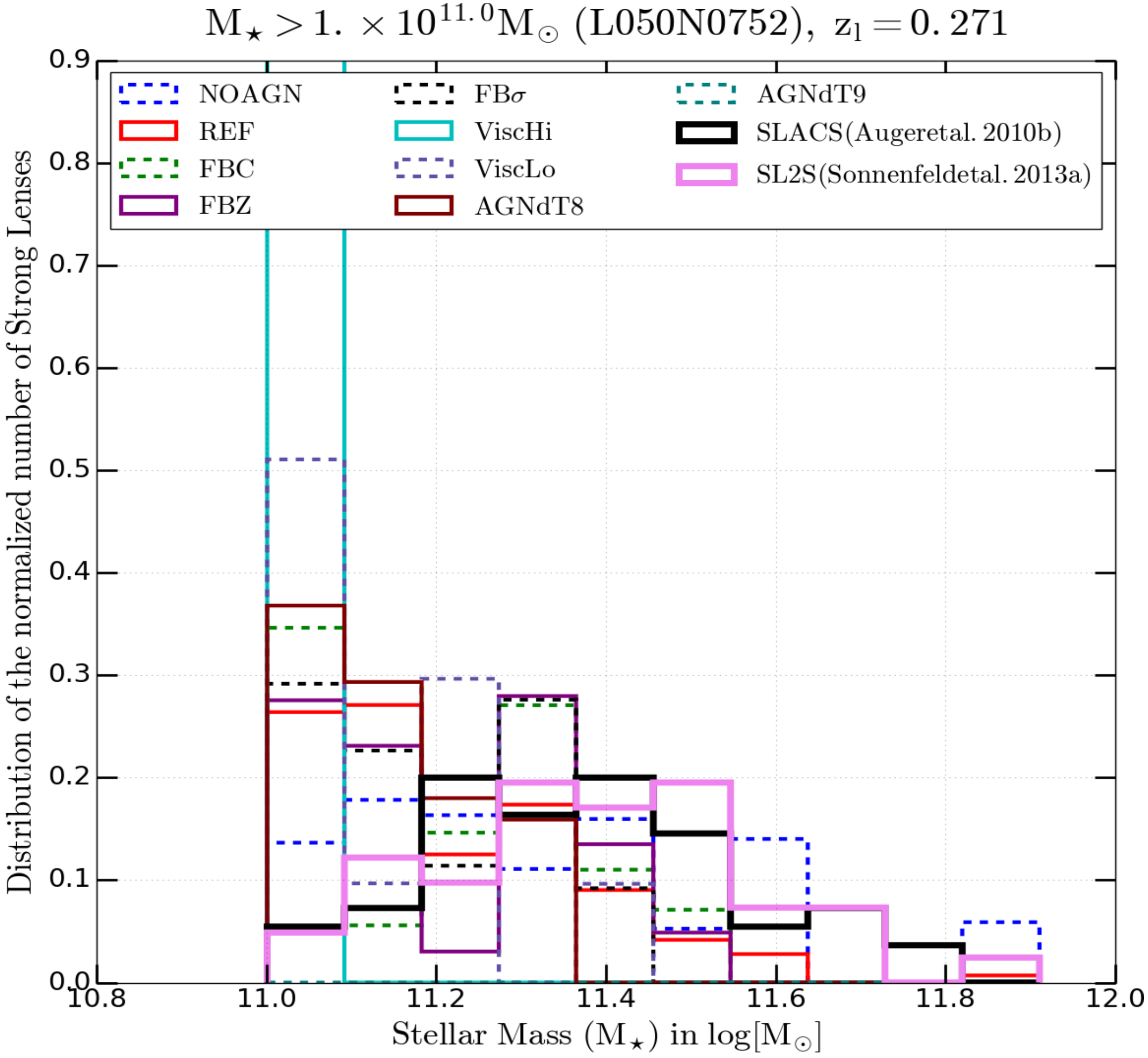
Right: Complex ellipticity versus shear suggests a strong correlation among them. The shaded region shows the 1б (=0.027) interval. **$\gamma = 0.226\varepsilon + 0.015$**

For a tighter constraint on the correlation we need :

(i) shear, axis ratio and PA parameters of more modelled lenses
(ii) lenses made from different galaxy formation scenarios

SEAGLE-I: *Mukherjee+* 2018 MNRAS

SEAGLE- II: Constraining galaxy evolution scenarios



Comparison of the **EAGLE** lenses with **SLACS** and **SL2S** lenses having Stellar masses **$M_* > 10^{11} M_{sun}$** .

Total **9** galaxy-formation scenarios, out of which **4** are calibrated simulation models

(Crain et al. 2015)

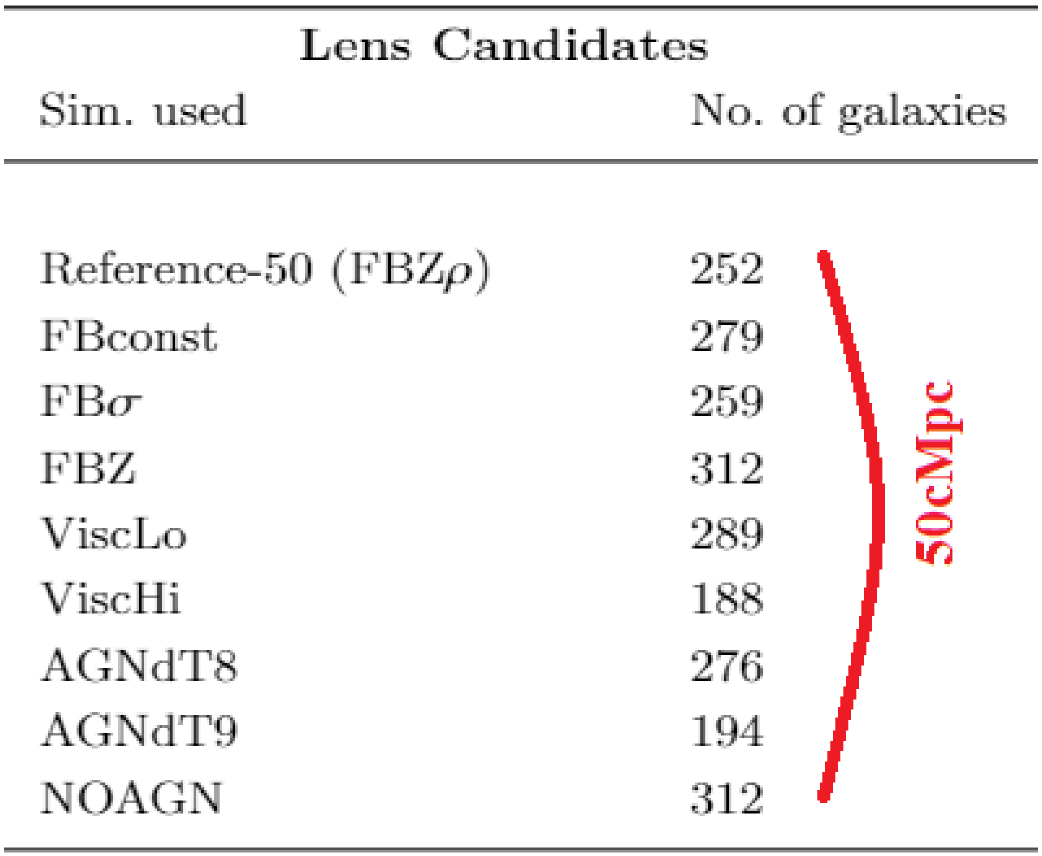
Effect of galaxy formation scenarios on number statistics

- **NOAGN** produced 30% more lenses than any other scenarios.
- **ViscHi** fails to give more massive ETGs
- **FBC** (Feedback constant) is next best to **NOAGN**.
- **FBZ** although gives relatively more lenses in mass range $10^{11.5} M_{sun} > M_* > 10^{11} M_{sun}$ but fails beyond it.
- **REF** is next best after **FBZ** and closely followed by remaining scenarios.

SEAGLE-II: ***Mukherjee+ 2018*** **to be sub. in MNRAS**

SEAGLE- II: Constraining galaxy evolution scenarios

(Crain et al. 2015)



Lens Candidates	
Sim. used	No. of galaxies
Reference-50 (FBZρ)	252
FBconst	279
FBσ	259
FBZ	312
ViscLo	289
ViscHi	188
AGNdT8	276
AGNdT9	194
NOAGN	312

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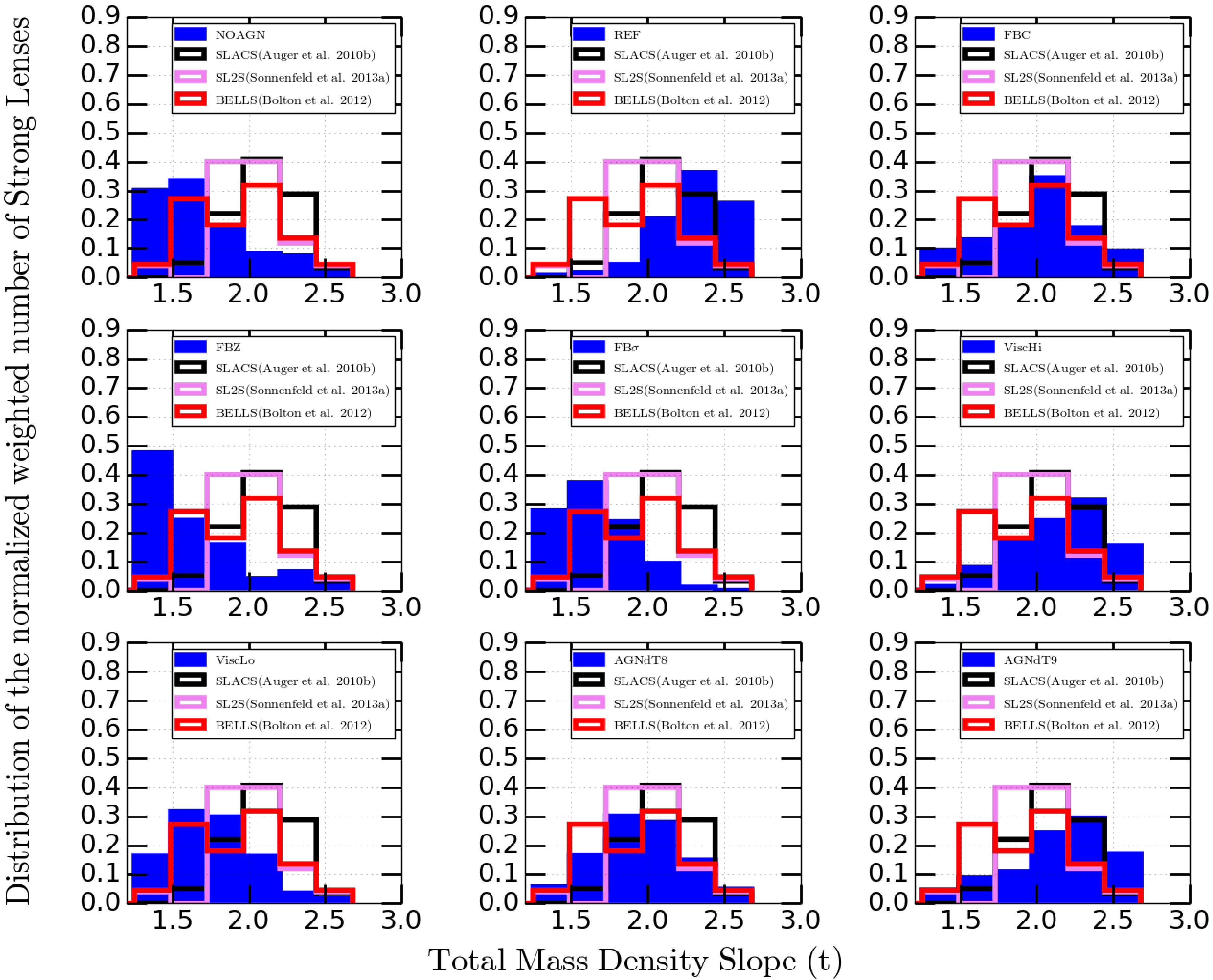
Total **9** galaxy-formation scenarios, out of which **4** are calibrated simulation models

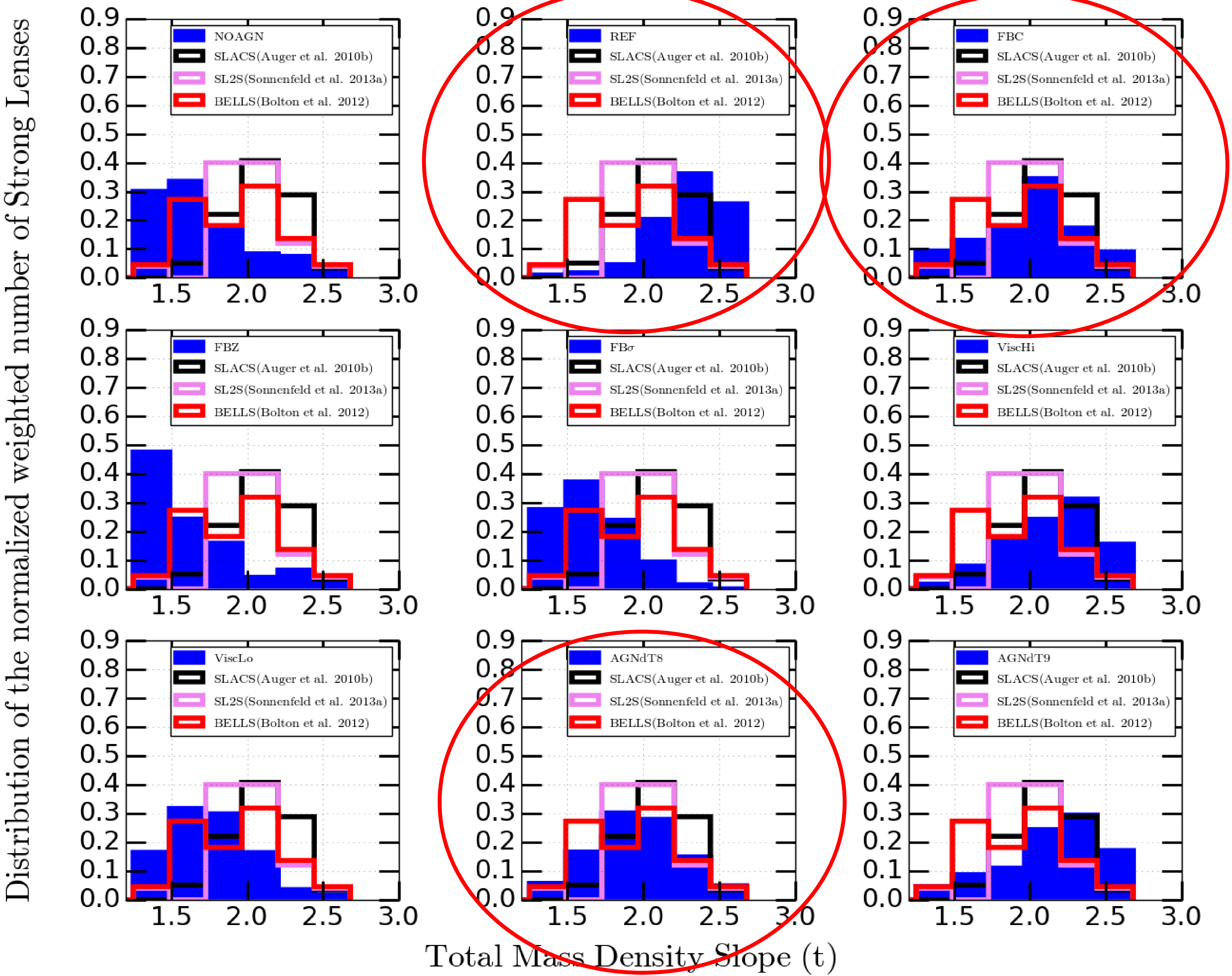
SEAGLE-II: ***Mukherjee+ 2018*** **to be sub. in MNRAS**

Total Mass density slopes of EAGLE's 9 model variations



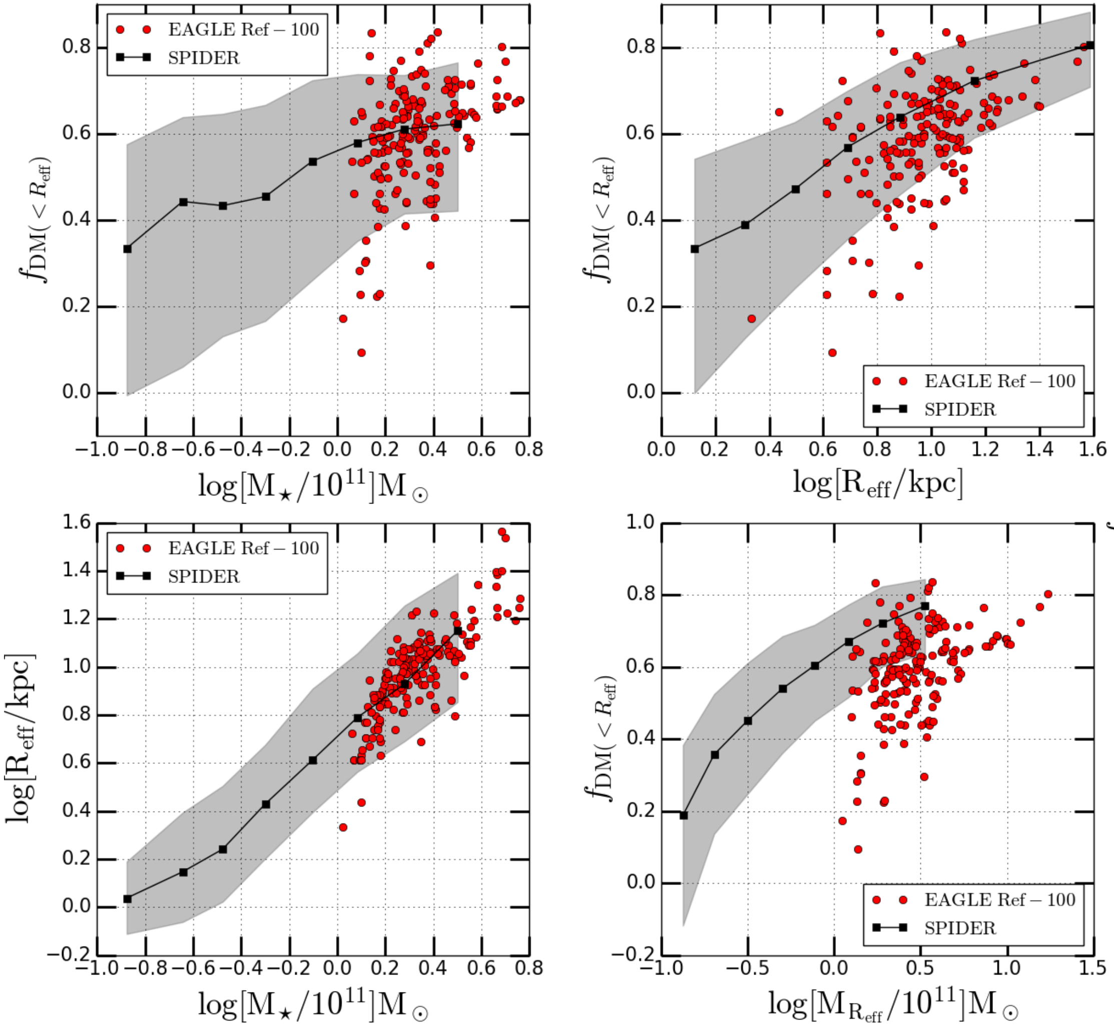
SEAGLE-II: ***Mukherjee+ 2018*** **to be sub. in MNRAS**

Total Mass density slopes of EAGLE's 9 model variations

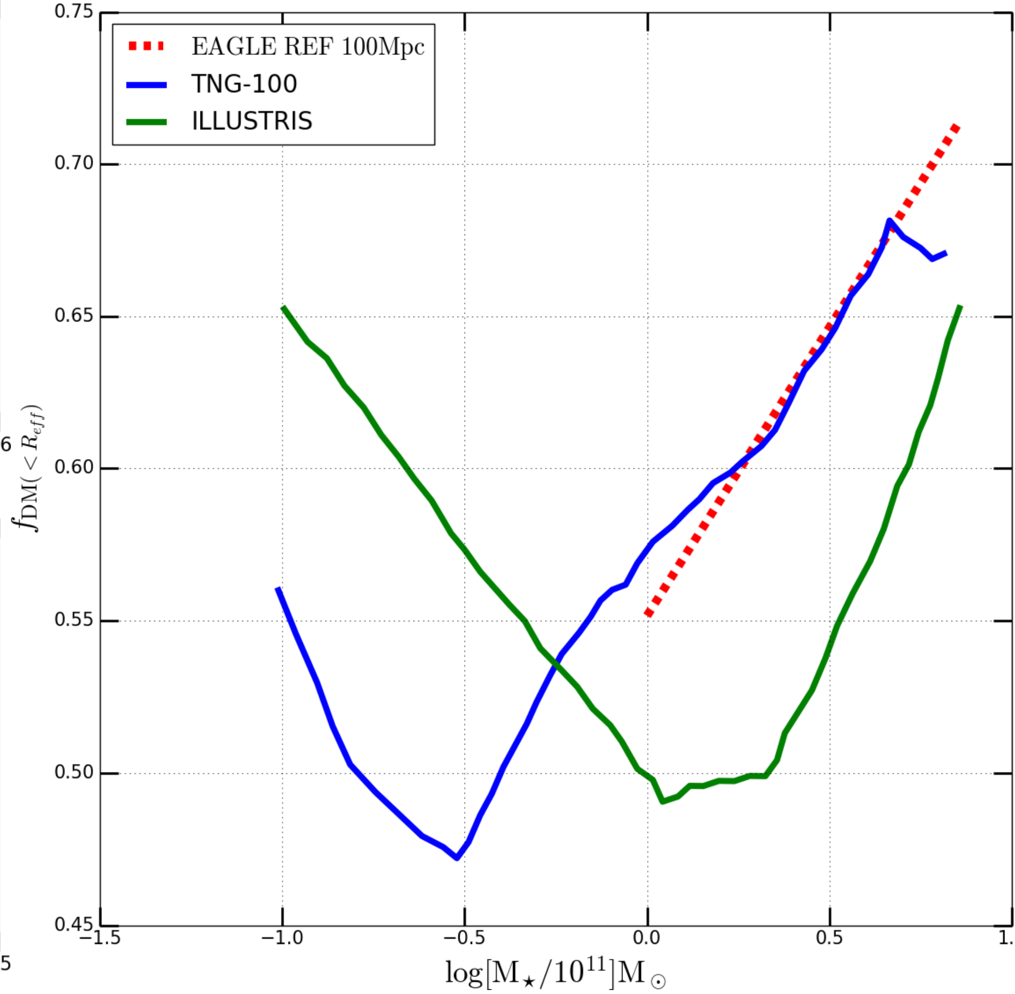


SEAGLE-II: *Mukherjee+ 2018* to be sub. in MNRAS

SEAGLE- III: Dark Matter Fraction (DMF) of EAGLE galaxies



Comparison of DMF in
EAGLE-Ref 100 with **SPIDER**



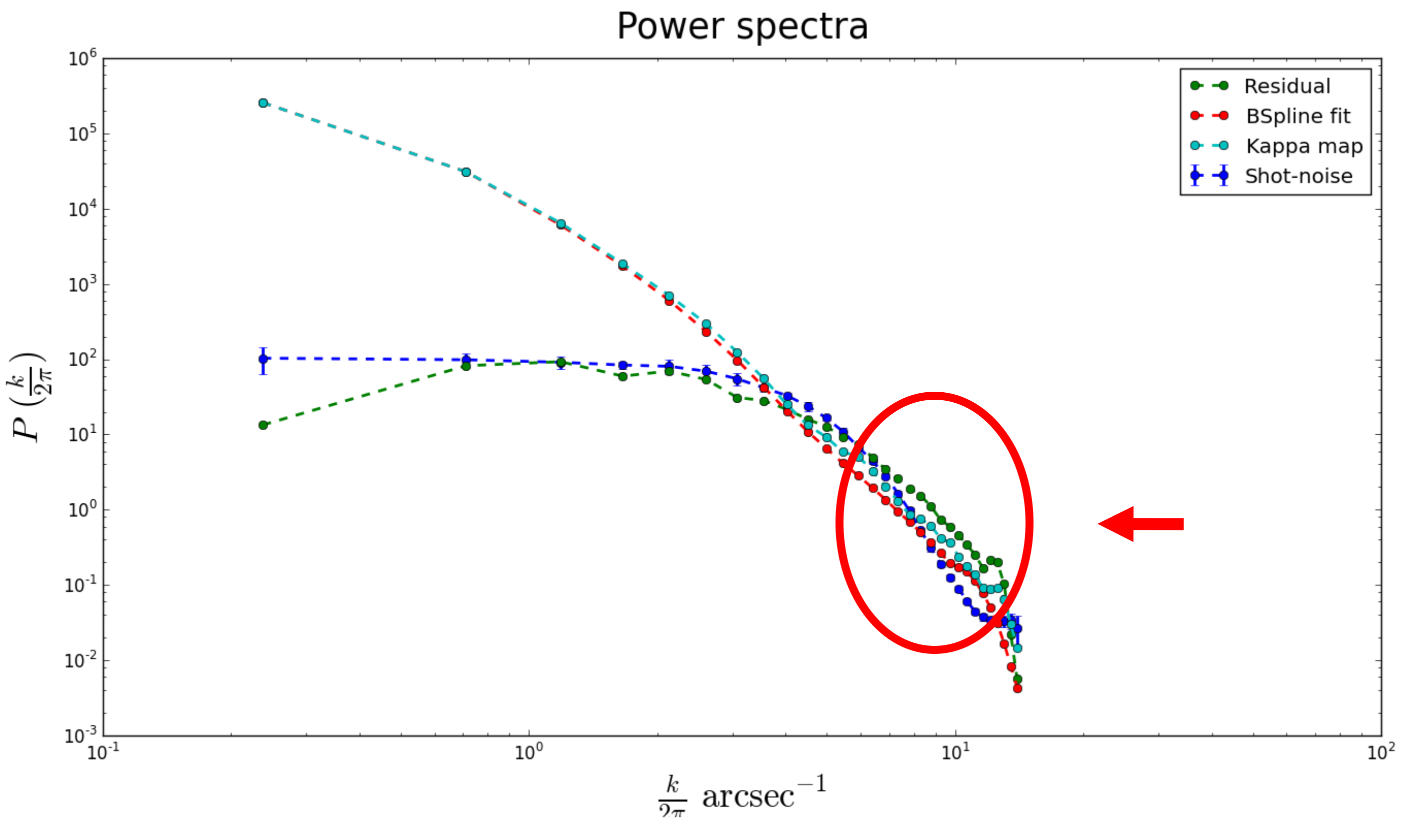
Comparison of DMF in
EAGLE-Ref 100 with **Illustris** and **TNG**

See Tortora+ 2012 MNRAS for **SPIDER**

See Lovell+ 2018 ArXiv for **TNG**

SEAGLE-III: *Mukherjee+ 2018* to be sub. in MNRAS

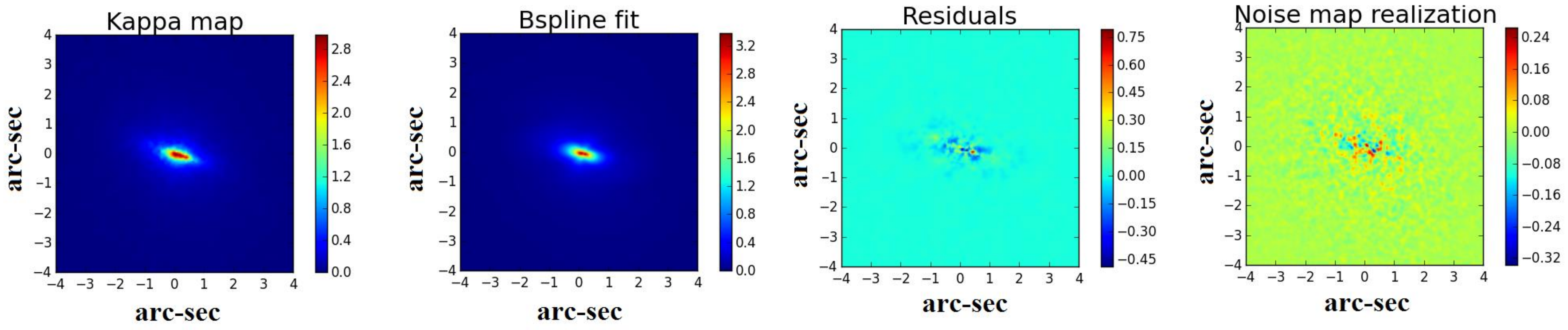
SEAGLE-IV: The study of small-scale mass density structure of galaxies via mass powerspectrum (PS) analysis



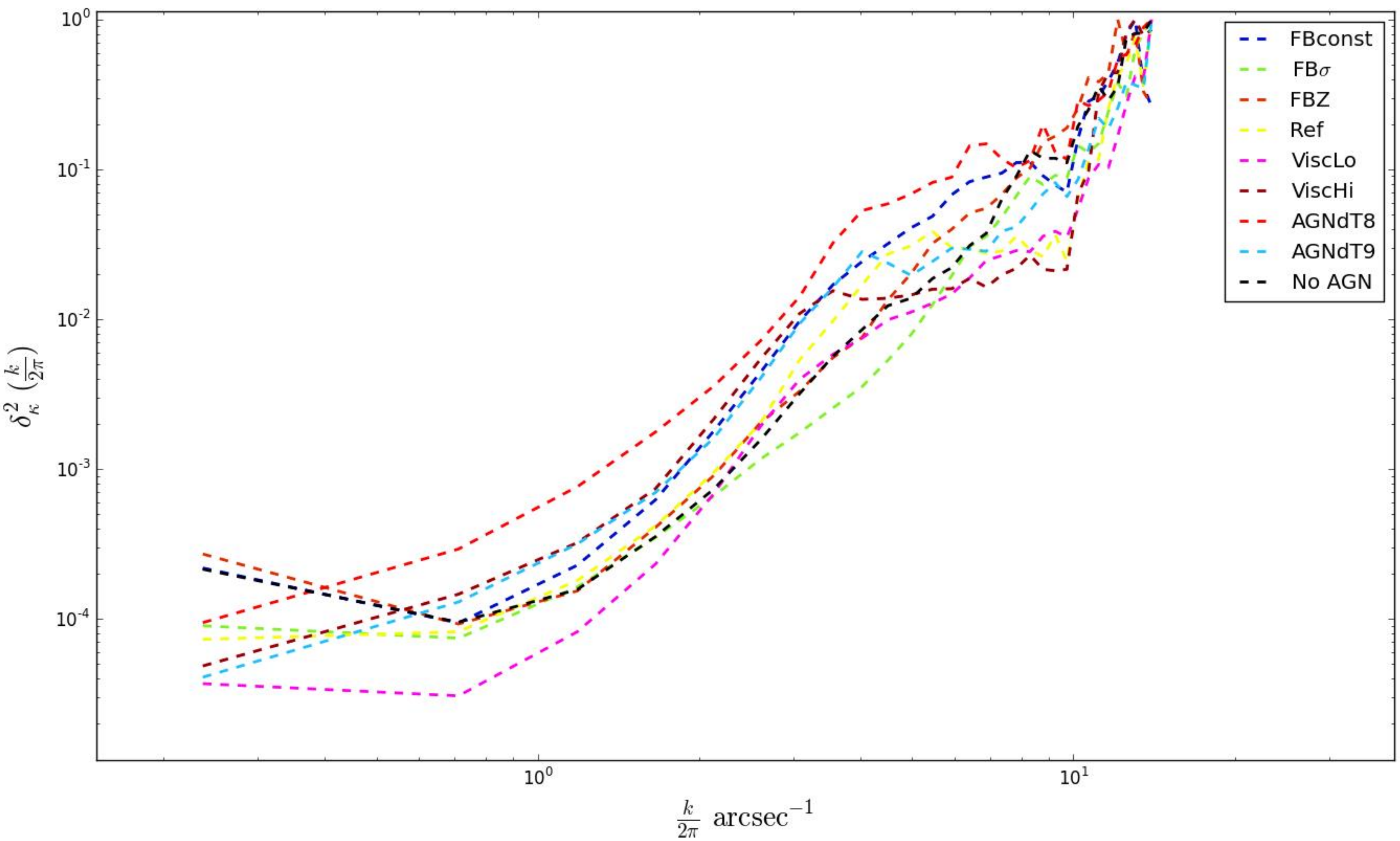
The comparative PS of the Kappa map, B-spline fit, Residual and Shot noise.

As we move towards **higher *k*** we find some residual power suggesting:

the presence of some **small-scale mass fluctuations**.



SEAGLE-IV: Chatterjee & *Mukherjee+ 2018* to be sub. in MNRAS



The variance of the convergence maps in power spectrum space is defined as follows:

$$\sigma^2_{\kappa(k)} = \langle \kappa^2(k) \rangle - \langle \kappa(k) \rangle^2$$

In terms of the power spectrum we can interpret the first term of the above equation as the average of the power spectra and the second term as the power spectrum of the average:

$$\sigma^2_\kappa = \langle P^\kappa \rangle - P^{\langle \kappa \rangle}$$

The fractional power spectrum with respect to the relatively smoother power spectrum of the average, $P(\langle \kappa \rangle)$ is defined as follows:

$$\boxed{\delta^2_\kappa = [\langle P^\kappa \rangle - P^{\langle \kappa \rangle}] \,/\, P^{\langle \kappa \rangle} = \sigma^2_\kappa / P^{\langle \kappa \rangle}}$$

See Chatterjee & Koopmans 2018 MNRAS

SEAGLE-IV: Chatterjee & *Mukherjee+ 2018* to be sub. in MNRAS

Summary

1. An automatic pipeline for **creating & modelling** mock lenses with a suite of hydrodynamic simulations, EAGLE, mimicking observational surveys and analyzing them similar to real lenses.

2. We quantify the effect(s) of **projection/orientation** of galaxies and compare properties of simulated mock strong lenses with SLACS & SL2S Lenses.

3. Applying the pipeline to a variety of EAGLE scenarios constrains the galaxy-formation mechanisms via **total mass density slope**.

4. Mass Power-spectrum analysis on simulated Strong Lenses (with Saikat) reveals presence of **different small scale mass fluctuations**.

Future Work

1. Comparison of mass powerspectrum with observed SLACS' Strong Lenses (with *Dorota Bayer*).

2. Statistical study of EAGLE and KiDS lenses (with *Cresenzo Tortora*).

Take home message

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

SEAGLE


Me


Leon Koopmans


Ben Metcalf


Joop Schaye


C. Tortora


N. Tessore


M. Schaller


R. A. Crain


T. Theuns


G. Vernardos


F. Bellagamba


S. Chatterjee


D. Bayer