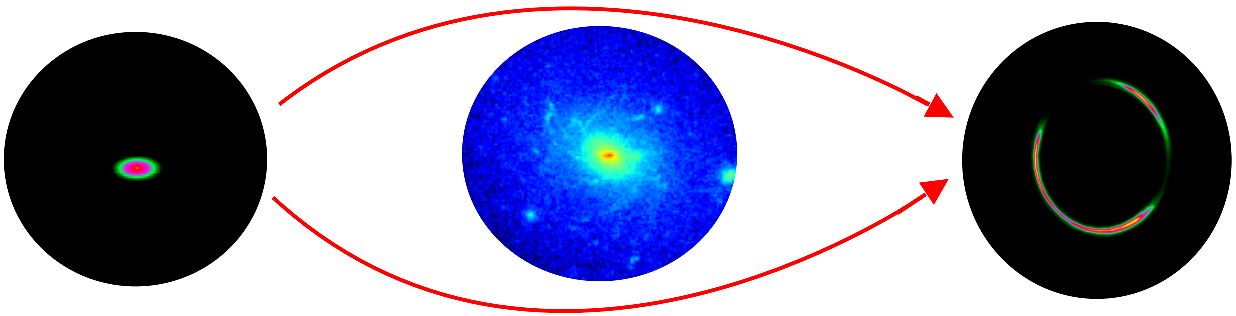
Strong lens simulations: the 'un'-natural telescopes to probe galaxy formation and Hubble constant



Sampath Mukherjee

University of Groningen (RUG) ——————> University of Liege (ULiege)

In collaboration with

SEAGLE

Prof. Léon Koopmans
Prof. Joop Schaye
Prof. R. Benton Metcalf
Dr. Mathhieu Schaller
Dr. Crescenzo Tortora
Dr. Robert Crain
Dr. Georgios Vernardos

COSMICLENS

Prof. Dominique Sluse
Prof. Frederic Courbin
Prof. Sherry Suyu
Dr. Stefan Hilbert
Lyne VandeVyvere
+
H0LiCOW collaboration

Timeline of (Strong) Gravitational Lensing

1801 Soldner proposed GL in context of Newtonian theory.
He found a deflection angler 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.

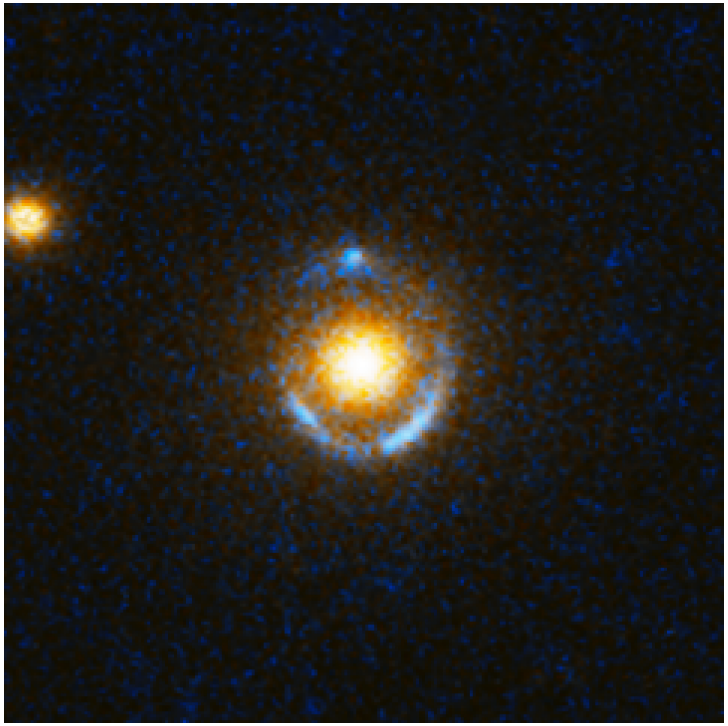
2010 **SL2S**, **SWELLS** and **BELLS**, observational surveys: **~20-50** SLs each.

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



SDSS J073728.45+321618.5

courtesy: HST, NASA/ESA
Auger et. al 2009

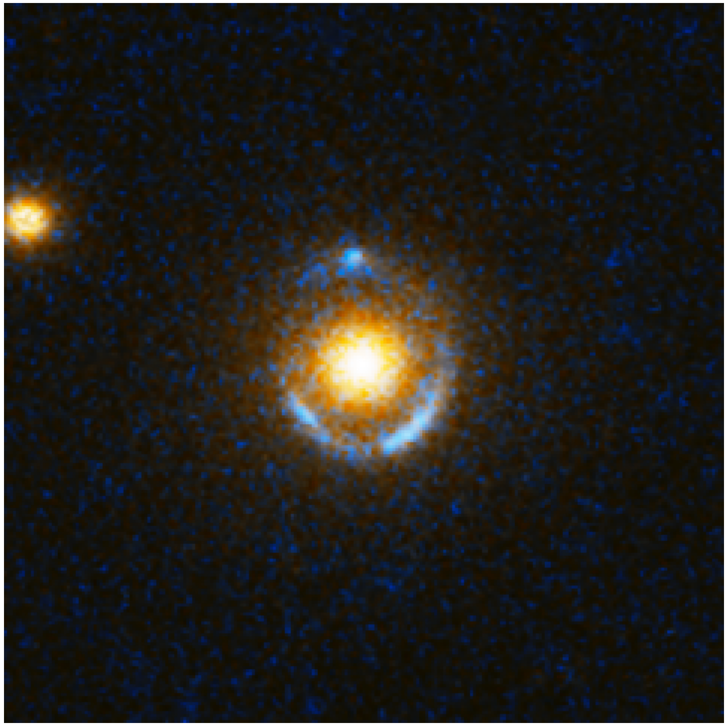
Advantage of using Gravitational Lensing

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

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



SDSS J073728.45+321618.5

courtesy: HST, NASA/ESA
Auger et. al 2009

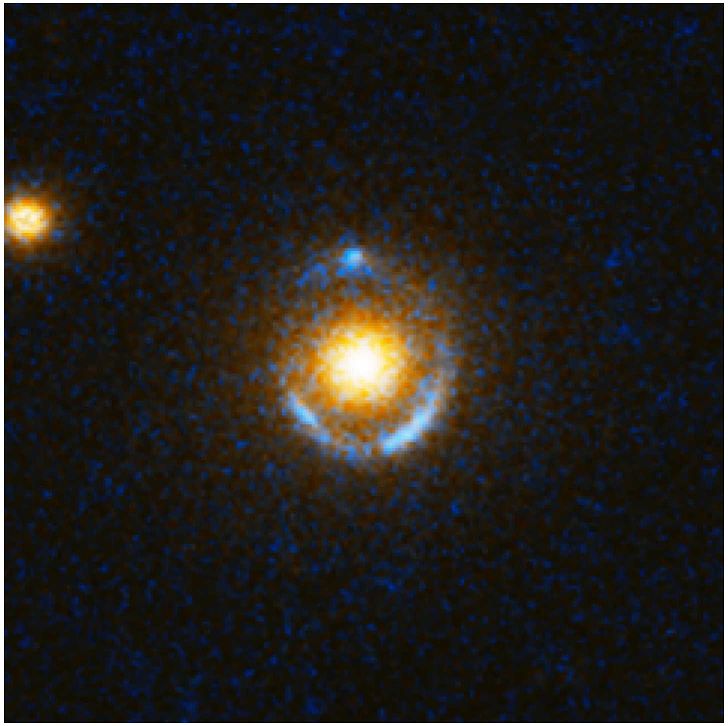
Advantage of using Gravitational Lensing

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

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



SDSS J073728.45+321618.5

courtesy: HST, NASA/ESA
Auger et. al 2009

Advantage of using Gravitational Lensing

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

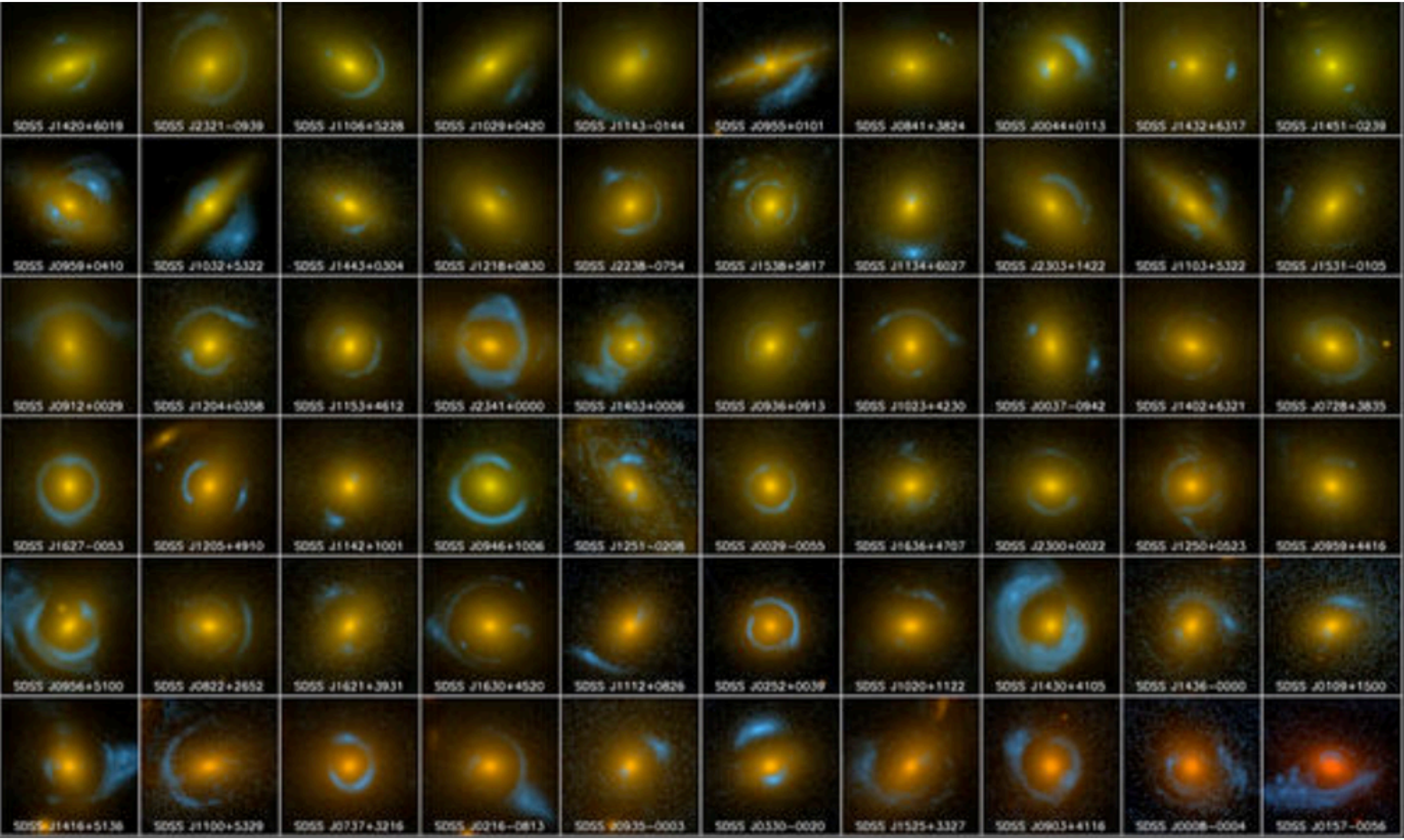
How many strong lenses do we need & why?

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**

Lens Galaxies: SLACS



credit: Adam Bolton/SLACS

Euclid: online in 2020-2025; will yield >100,000 lenses

Credits: Koopmans/Euclid

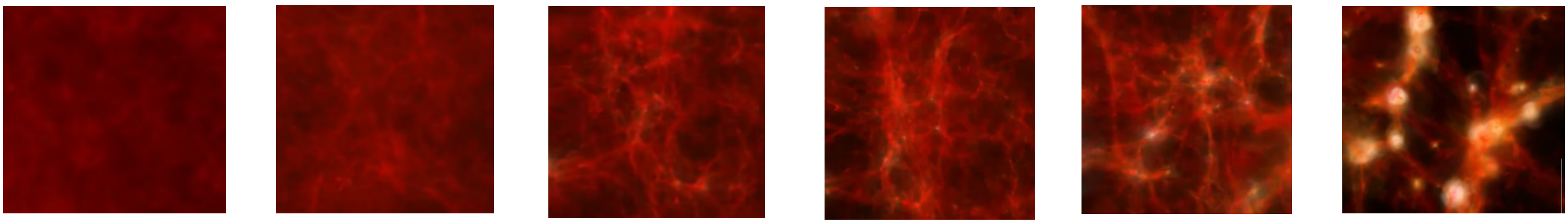
A novel pipeline for **S**imulating **EAG**LE **LE**nses

based on

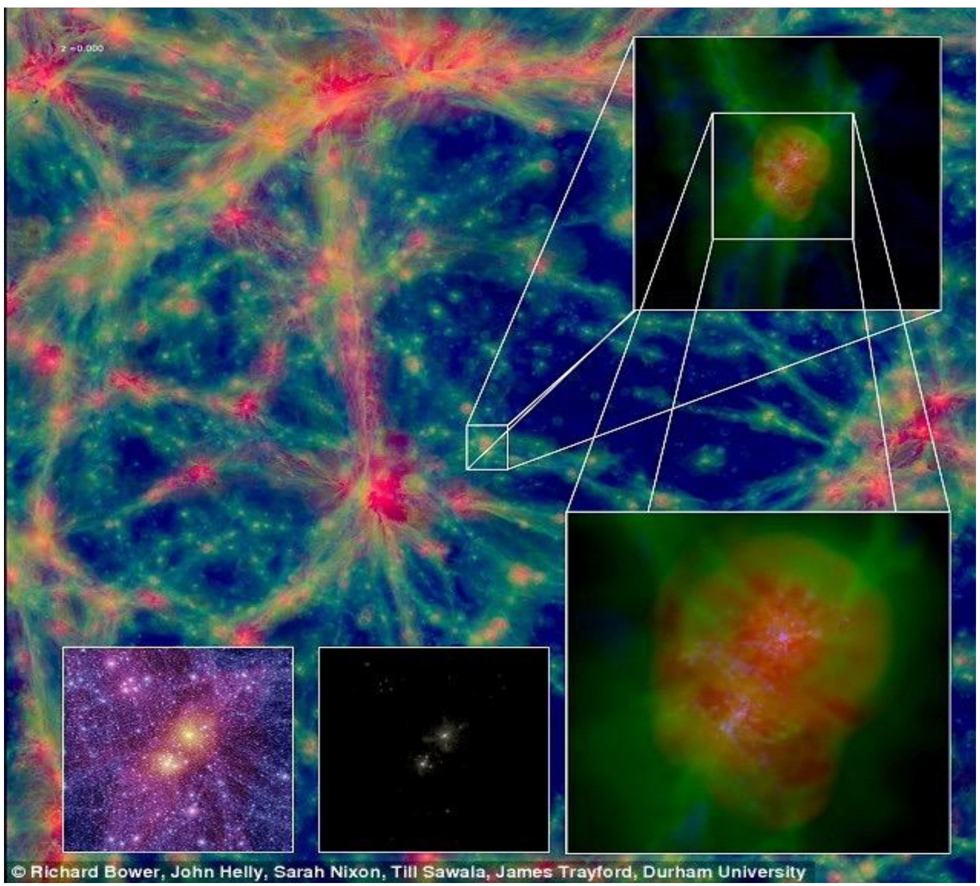
***SEAGLE—I**: A pipeline for simulating and modelling strong lenses from cosmological hydrodynamic simulations*

Mukherjee et al. 2018
MNRAS 2018, 479, 4108

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



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



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

A suite of hydrodynamical simulations

ΛCDM universe

13 galaxy formation scenarios

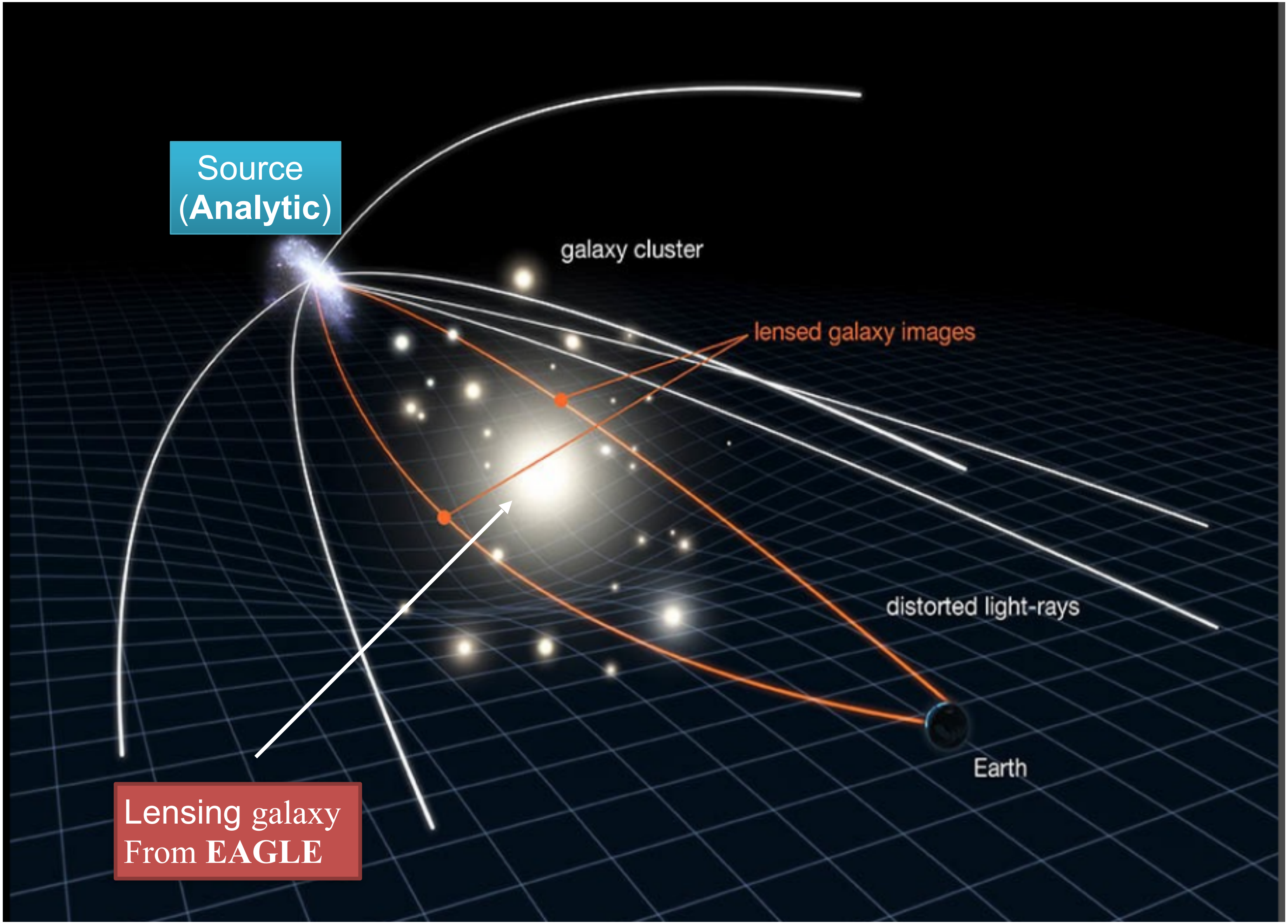
Simulation box sizes : **100, 50, 25, 12, cMpc**

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

Major improvement:

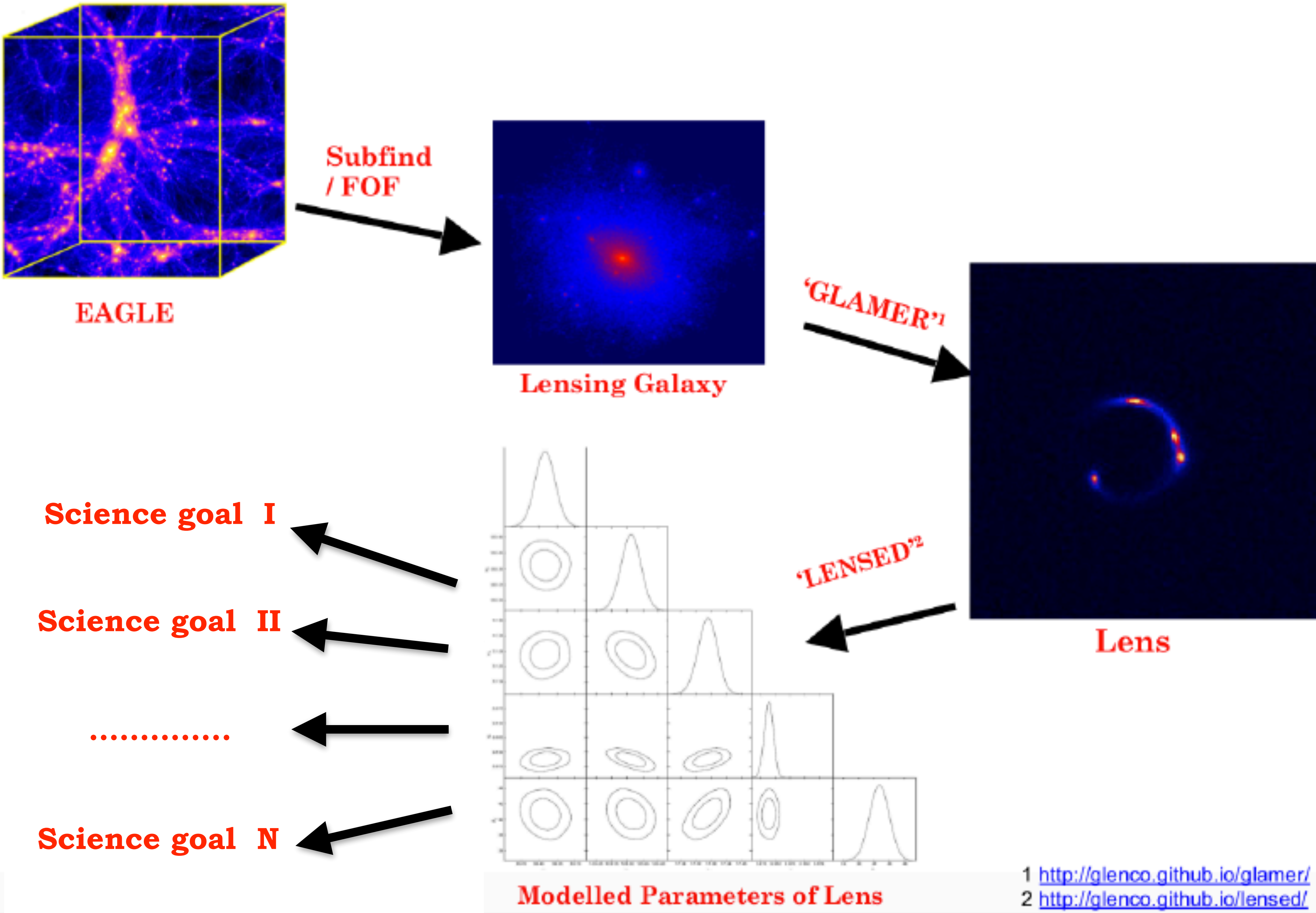
Feedback from Stars & AGN

Image courtesy: Durham University & Schaye et al. 2015



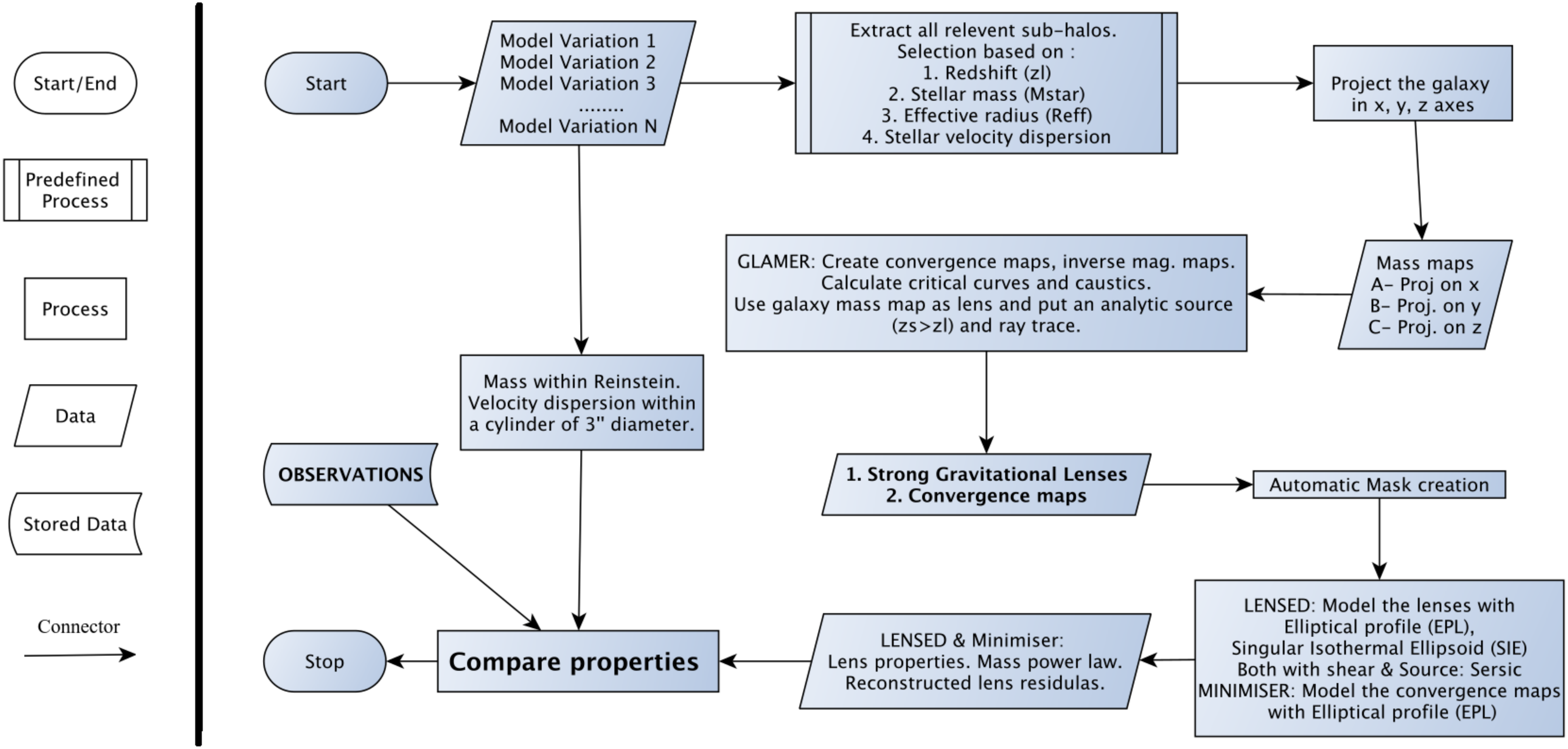
Gravitational Lensing (Courtesy: NASA/ESA)

The Pipeline: Simulations & Modeling of Mock Strong Lenses



1 http://glenco.github.io/glamer/
2 http://glenco.github.io/lensed/

The SEAGLE pipeline



SEAGLE-I: *Mukherjee+* 2018 MNRAS

GLAMER (*Metcalf+ 14, Petkova+ 14*)

The ray-tracer

LENSED (*Tessore+ 16*)

The modelling code

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 f[illegible]
Orientation	x, y and z axis	Projected surface density maps are made for each axis
Redshift	$z_{lens} = 0.271$	Consistent with SLACS' mean lens-redshift of 0.3
No. of galaxies	252	-
No. of proj. galaxies	756	-

Lensing galaxies from EAGLE

Source Properties

Parameters	Value	Comments
Source Type	Sérsic	Consistent with analysed 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_{source}	0.6	"
Position	Random within caustics	Producing more rings and arcs lens systems, consistent with SLACS

SOURCE- Analytic

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

Results

Are we getting what we wanted ?

Some Strong Lenses from Sloan Lens ACS (SLACS) Survey

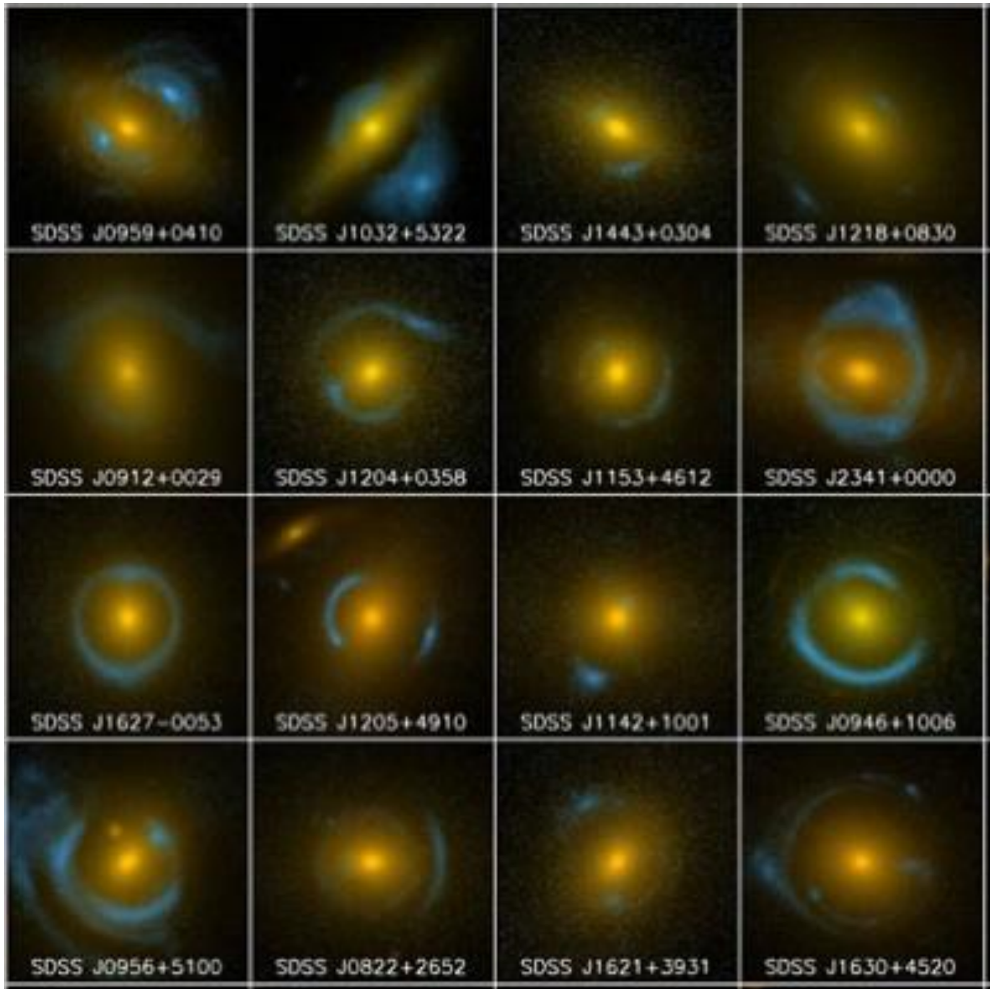
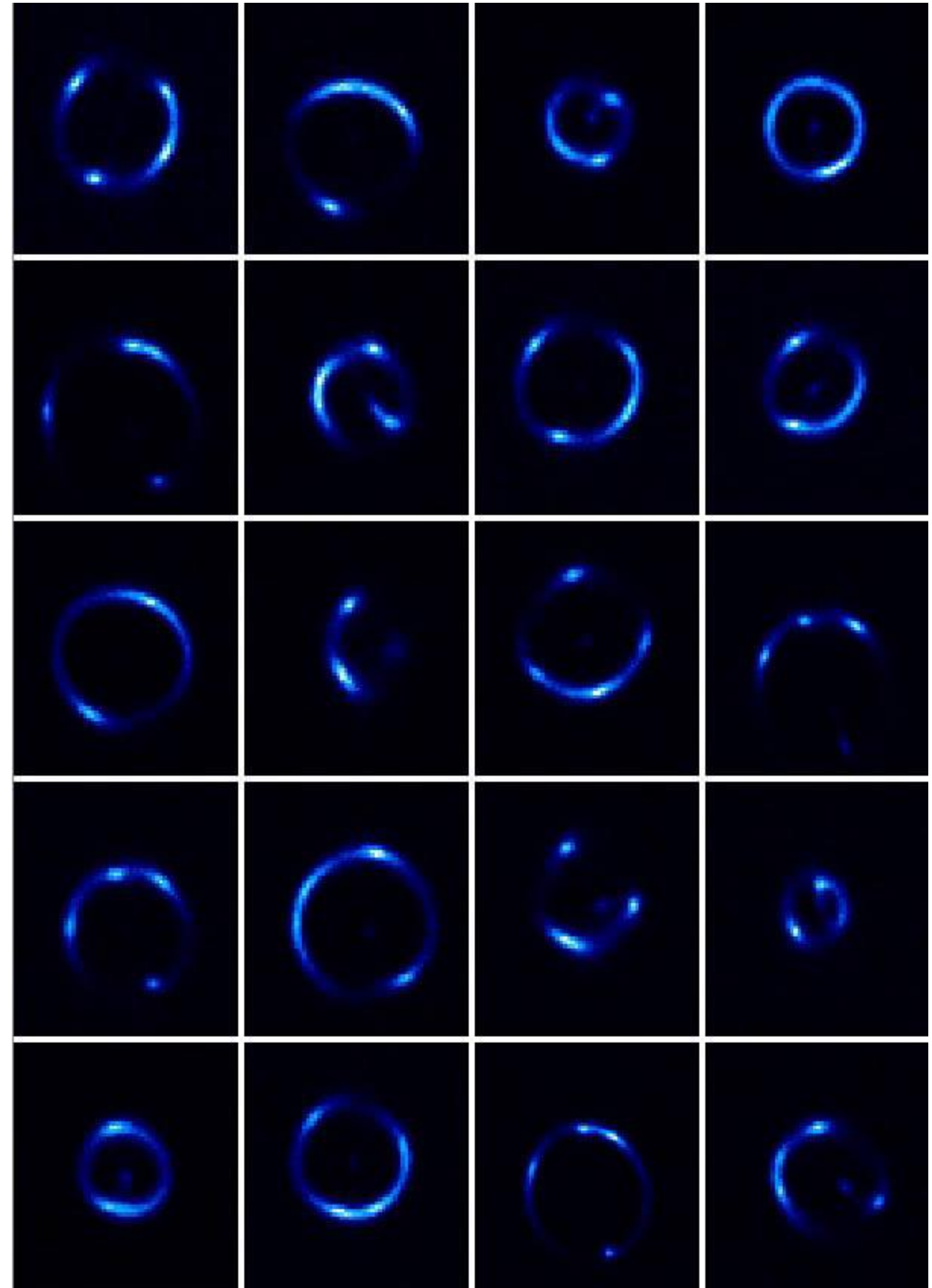
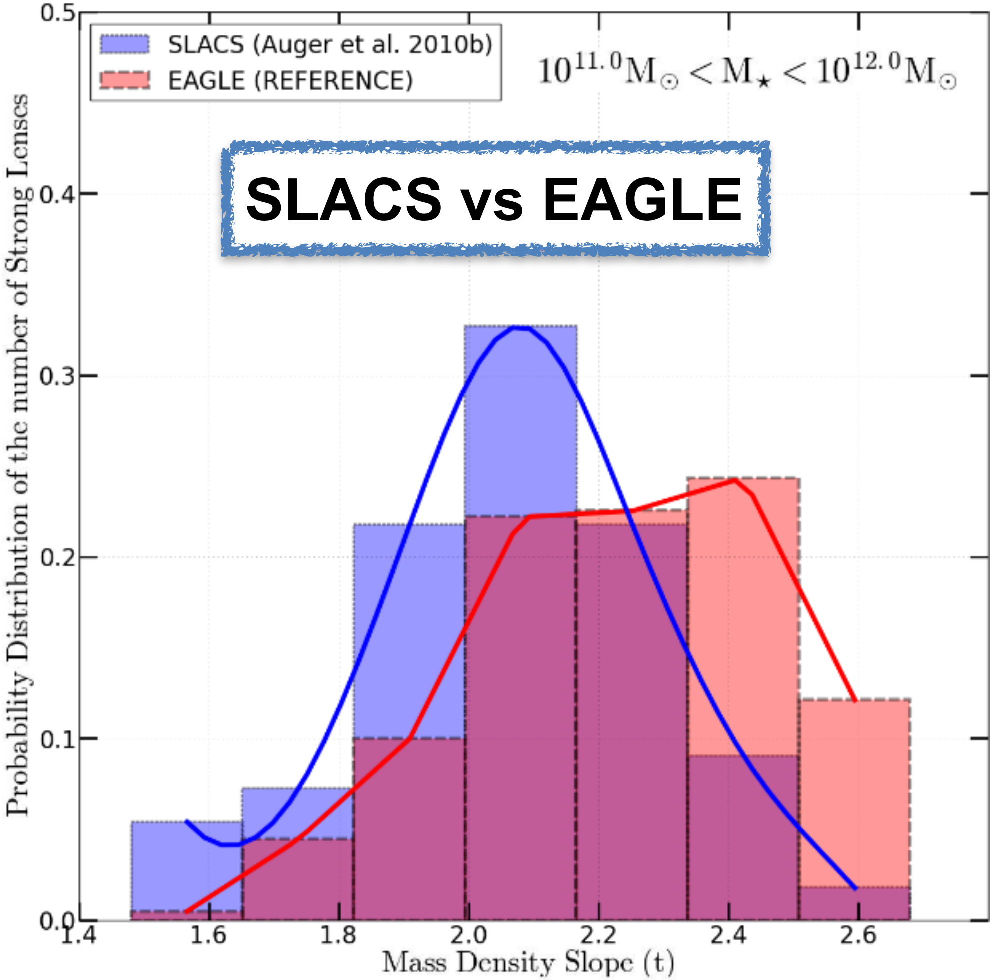


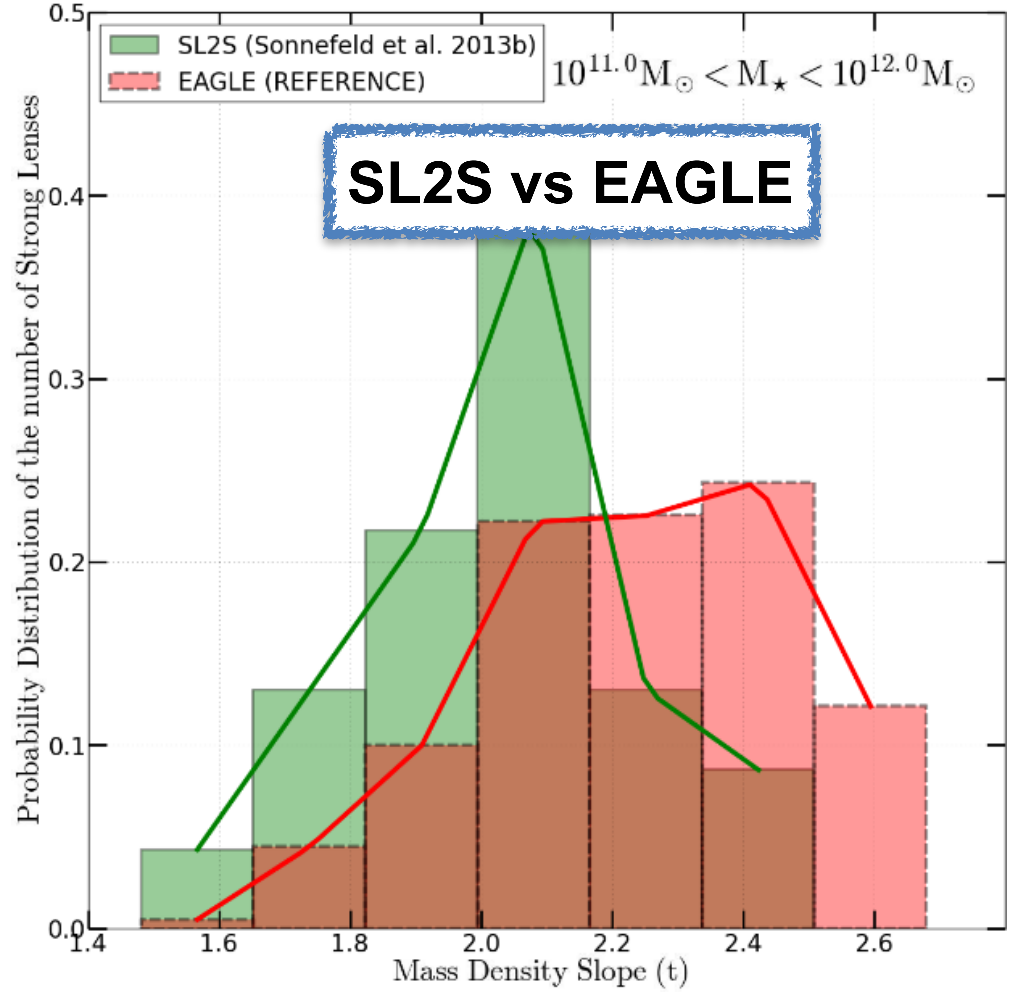
Image: A. Bolton (UH/IfA) for SLACS and NASA/ESA.

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

$\log M_\star$ ($M_\odot$)	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

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

Feedback

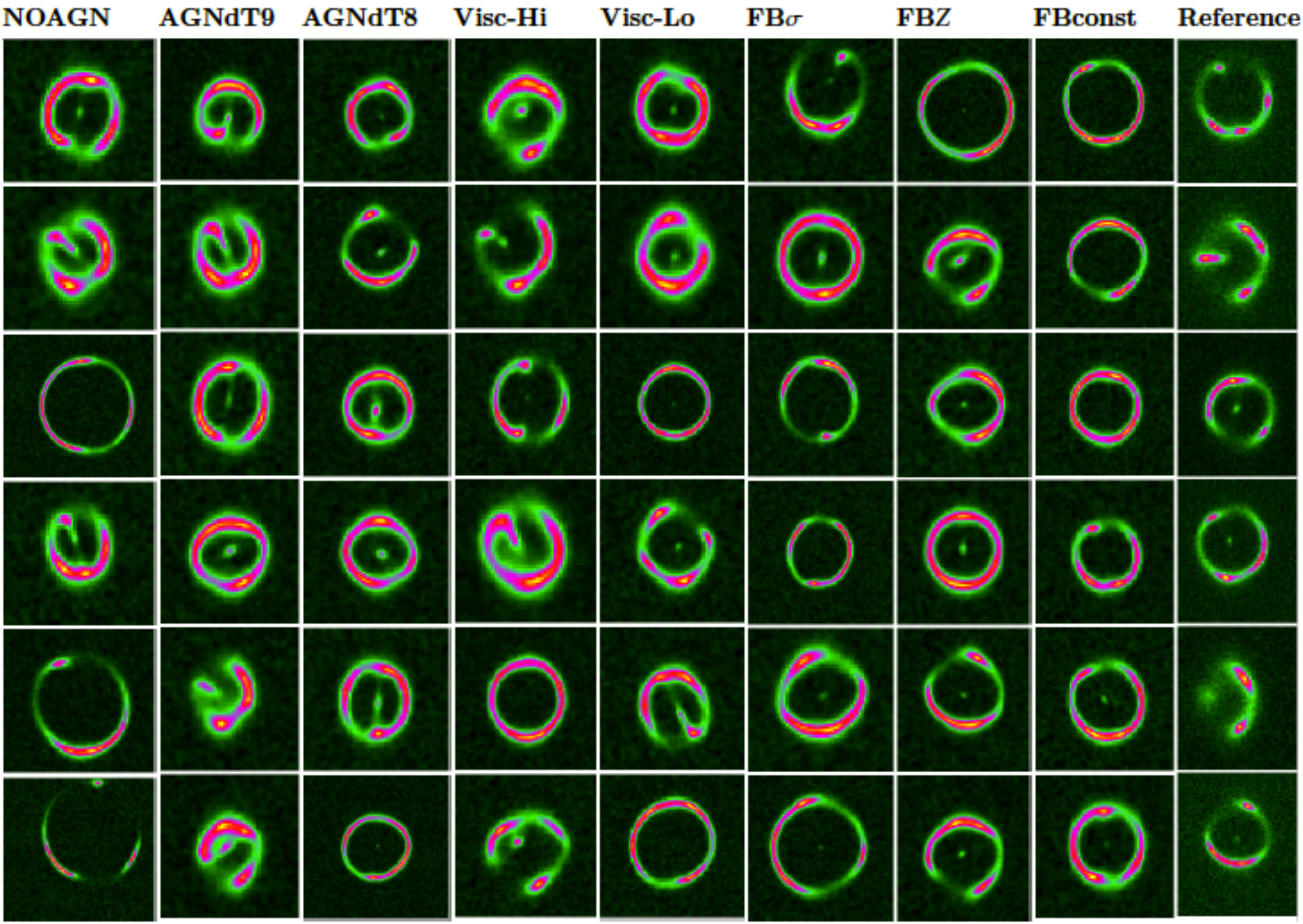
Identifier	Side length [cMpc]	N	γ_{eos}	$n_H^\star$ [cm^{-3}]	f_{th}-scaling	$f_{th,max}$	$f_{th,min}$	$n_{H,0}$ [cm^{-3}]	n_n	$C_{visc}/2\pi$	ΔT_{AGN} log$_{10}$ [K]
Calibrated models											
FBconst	50	752	4/3	Eq. 1	–	1.0	1.0	–	–	10^3	8.5
FBσ	50	752	4/3	Eq. 1	σ^2_{DM}	3.0	0.3	–	–	10^2	8.5
FBZ	50	752	4/3	Eq. 1	Z	3.0	0.3	–	–	10^2	8.5
Ref (FBZρ)	50	752	4/3	Eq. 1	Z, ρ	3.0	0.3	0.67	2/ln 10	10^0	8.5
Ref-100 (FBZρ)	100	1504	4/3	Eq. 1	Z, ρ	3.0	0.3	0.67	2/ln 10	10^0	8.5
Reference-variations											
ViscLo	50	752	4/3	Eq. 1	Z, ρ	3.0	0.3	0.67	2/ln 10	$\mathbf{10^2}$	8.5
ViscHi	50	752	4/3	Eq. 1	Z, ρ	3.0	0.3	0.67	2/ln 10	$\mathbf{10^{-2}}$	8.5
AGNdT8	50	752	4/3	Eq. 1	Z, ρ	3.0	0.3	0.67	2/ln 10	10^0	**8.0**
AGNdT9	50	752	4/3	Eq. 1	Z, ρ	3.0	0.3	0.67	2/ln 10	10^0	**9.0**
NOAGN	50	752	4/3	Eq. 1	Z, ρ	3.0	0.3	0.67	2/ln 10	10^0	**–**

(Crain et al. 2015)

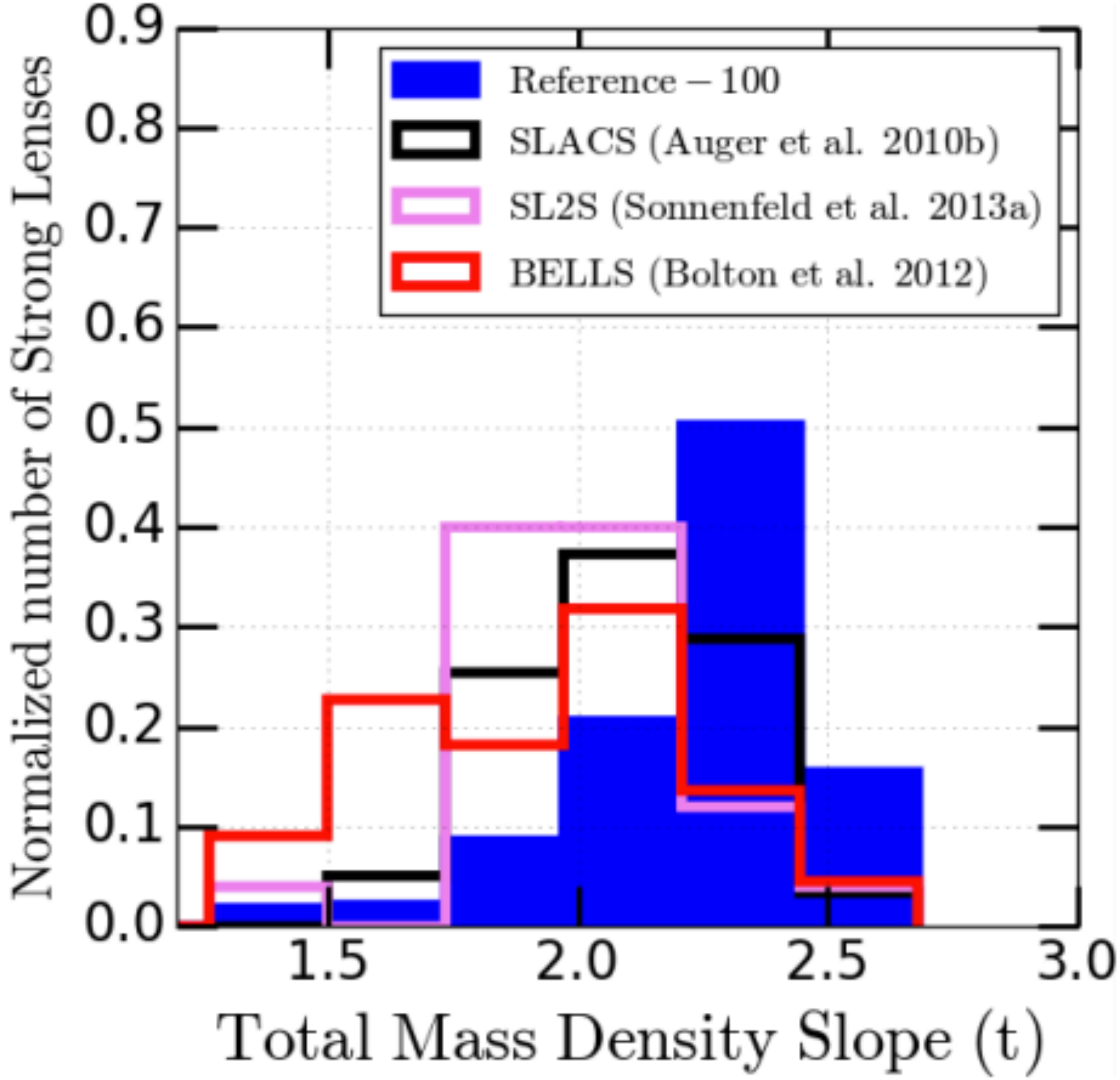
Reference Variations

Remus+ 2017 —- 3 sims
Xu+ 2017 —- 2 sims
Peirani+ 2018 —- 2 sims

SEAGLE-II: *Mukherjee+* sub. in MNRAS

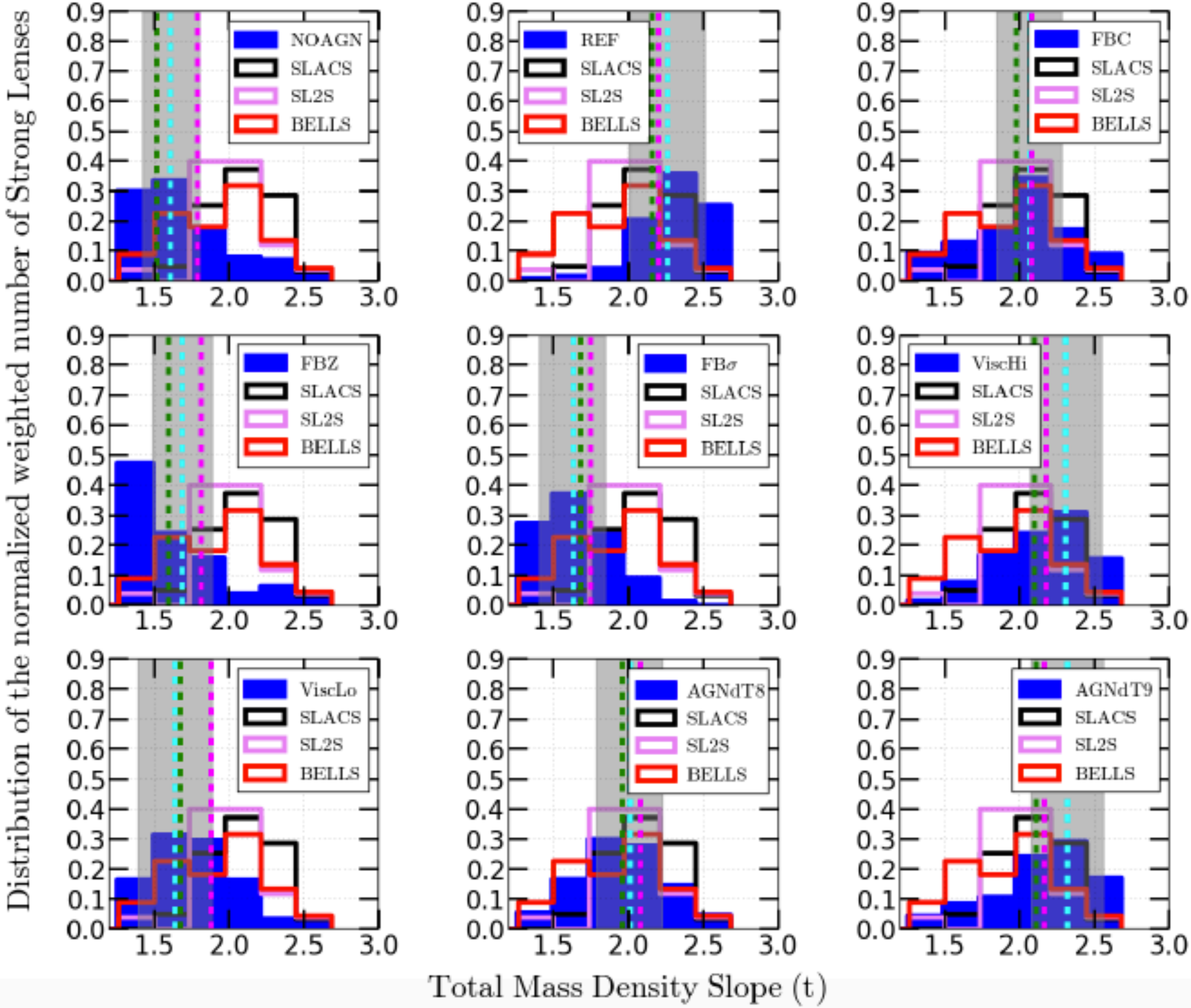


SEAGLE-II. Mukherjee et al. sub. MNRAS, arXiV:1901.01095



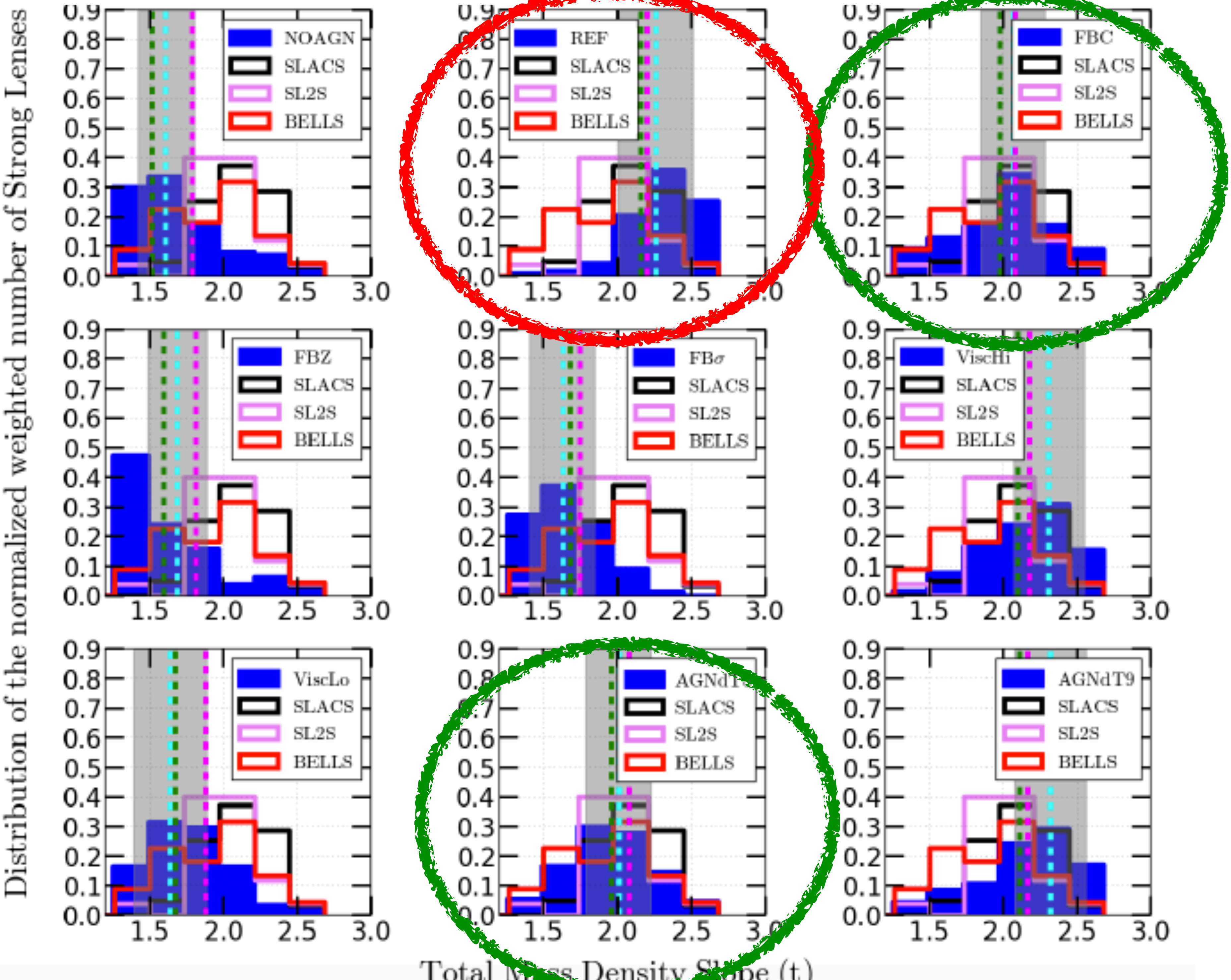
Reference − 100
SLACS (Auger et al. 2010b)
SL2S (Sonnenfeld et al. 2013a)
BELLS (Bolton et al. 2012)
Normalized number of Strong Lenses
Total Mass Density Slope (t)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.5
2.0
2.5
3.0

Total Mass density slopes of EAGLE's 9 model variations

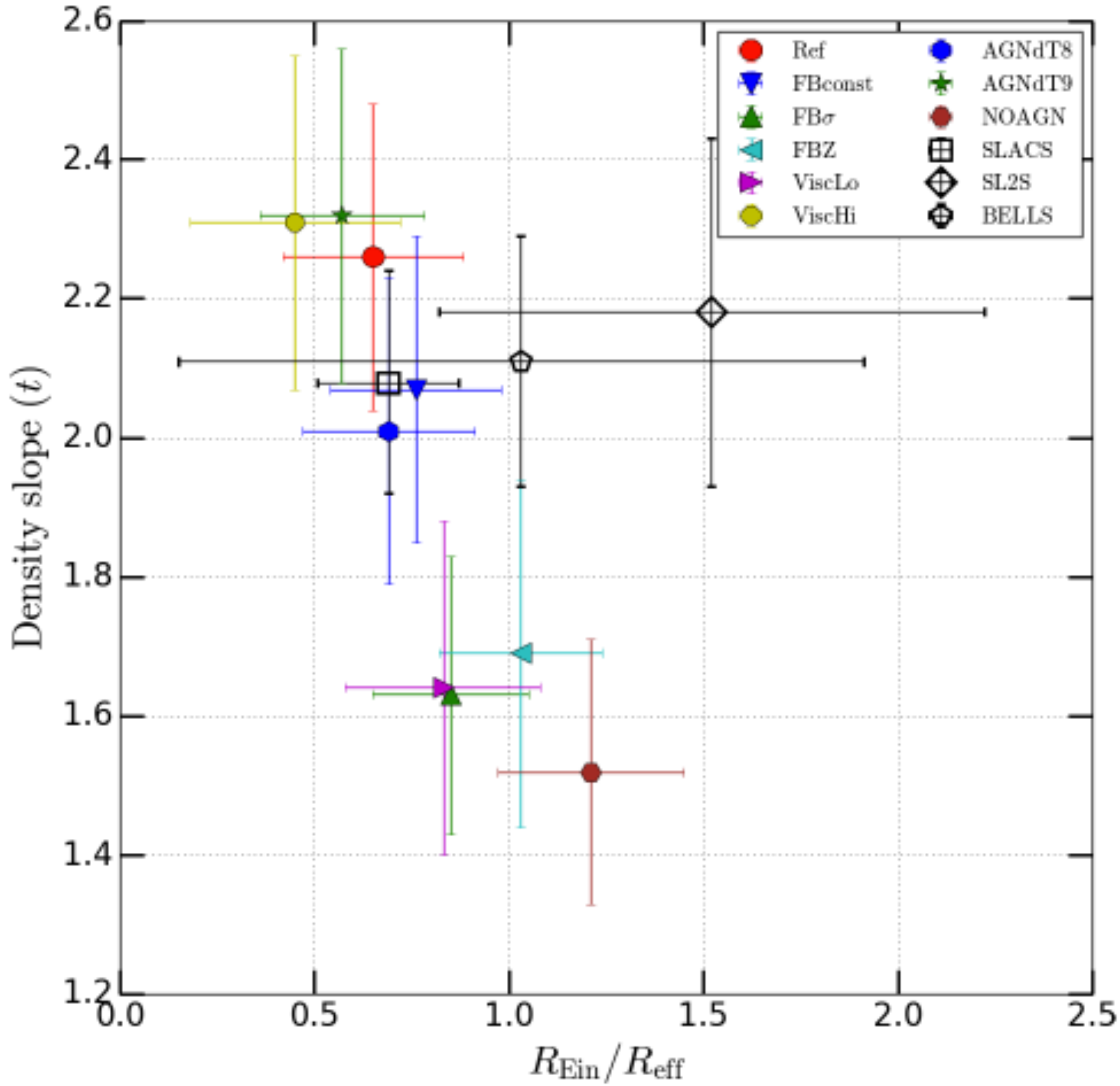


SEAGLE-II: *Mukherjee+* sub. in MNRAS

Total Mass density slopes of EAGLE's 9 model variations



SEAGLE-II: *Mukherjee+* sub. in MNRAS



SEAGLE-II: ***Mukherjee+*** **sub. in MNRAS**

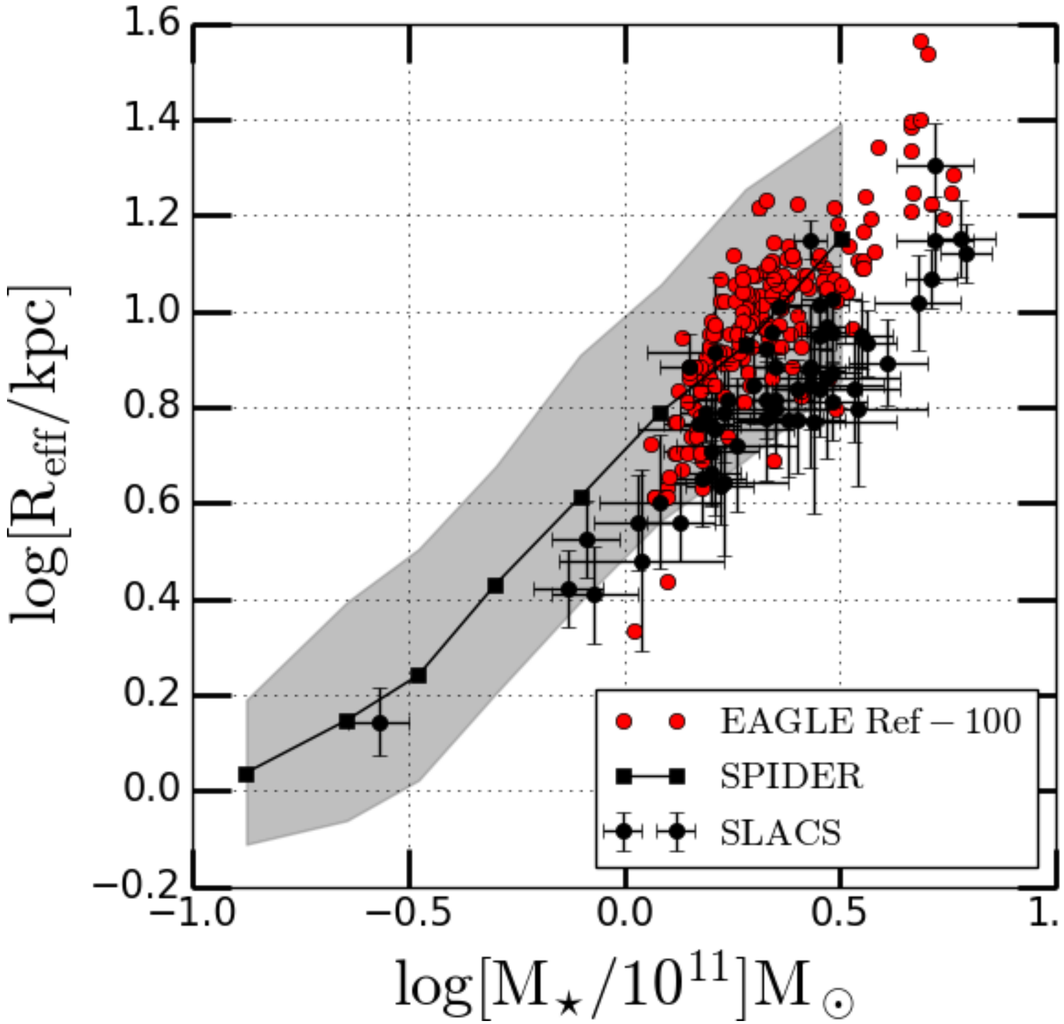
Inner dark matter fractions of early type galaxies in EAGLE model variations

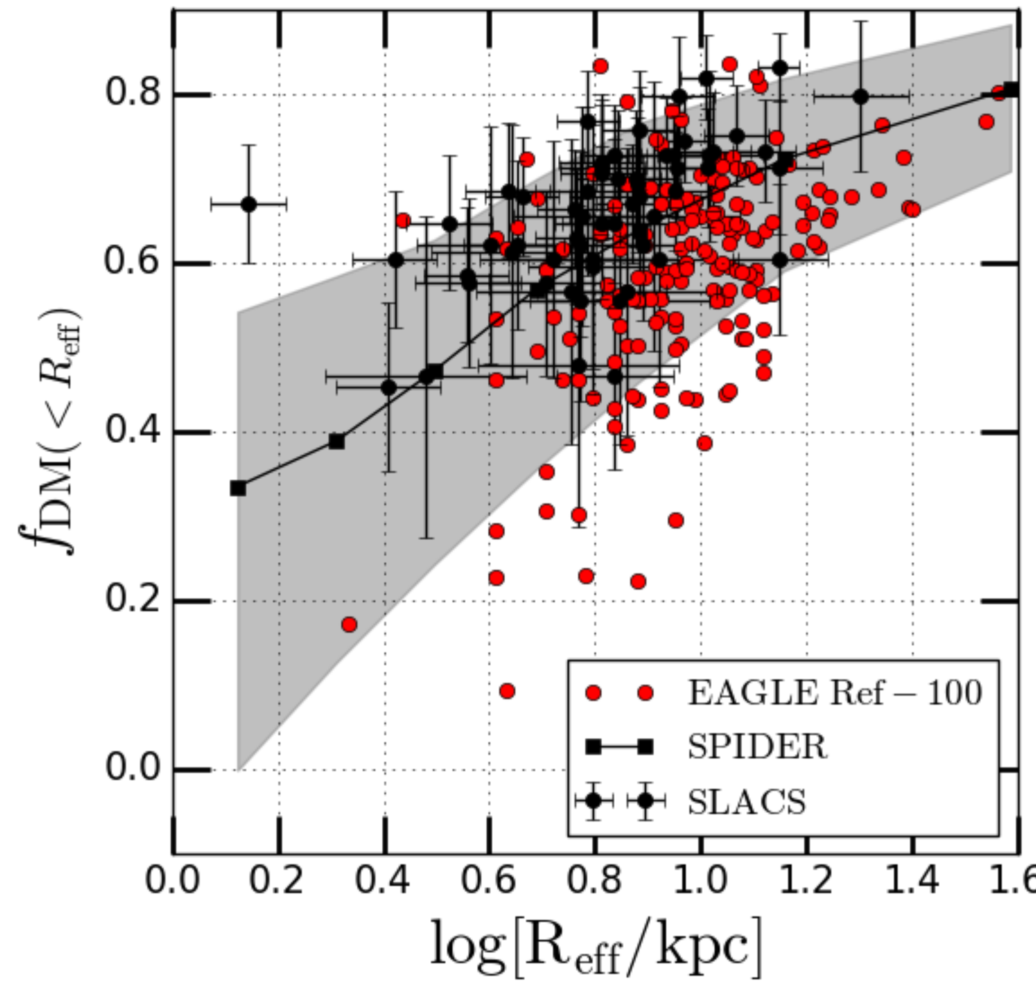
based on

***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

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





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

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

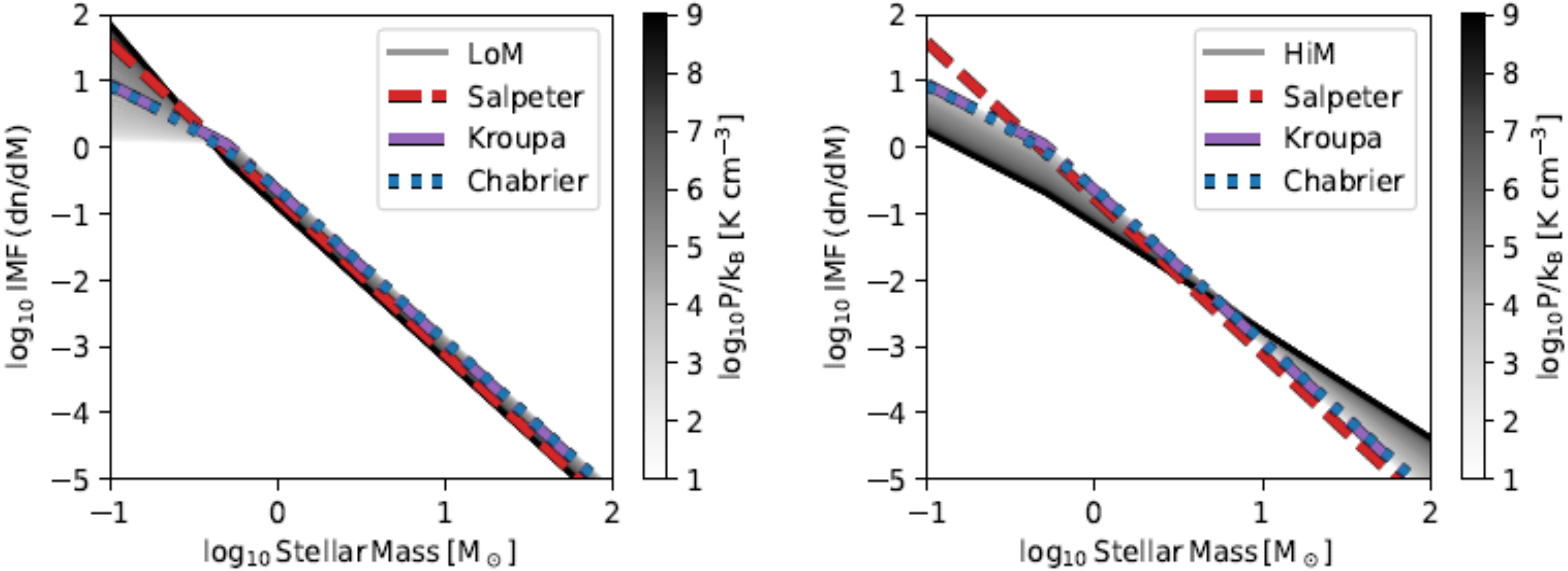
SEAGLE-III: ***Mukherjee+*** **to be sub. in MNRAS**

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

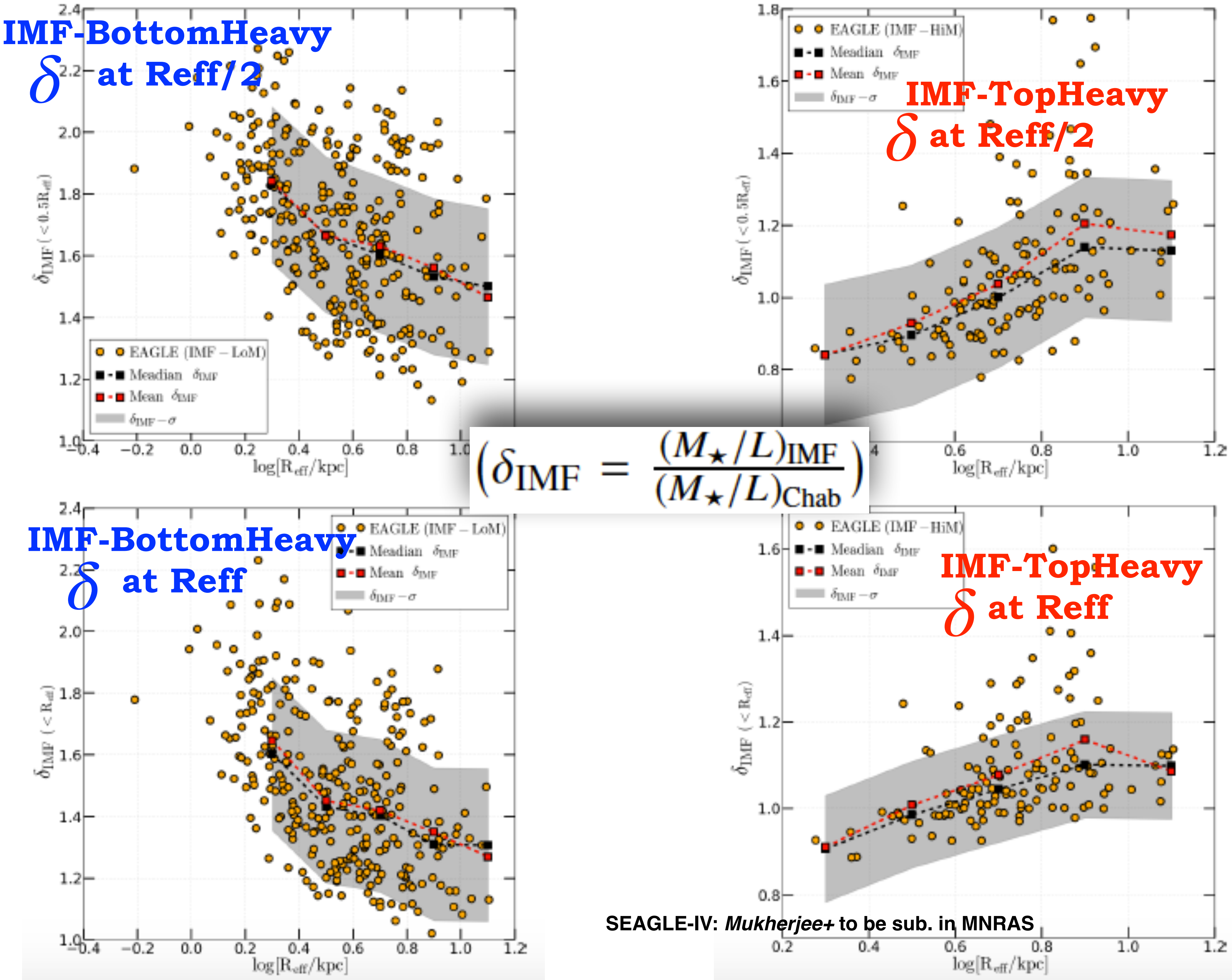
SEAGLE- IV: Impact of IMF variation on DMF



IMF-BottomHeavy (LoM) **IMF-TopHeavy (HiM)**

See Barber et al. 2018a MNRAS

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



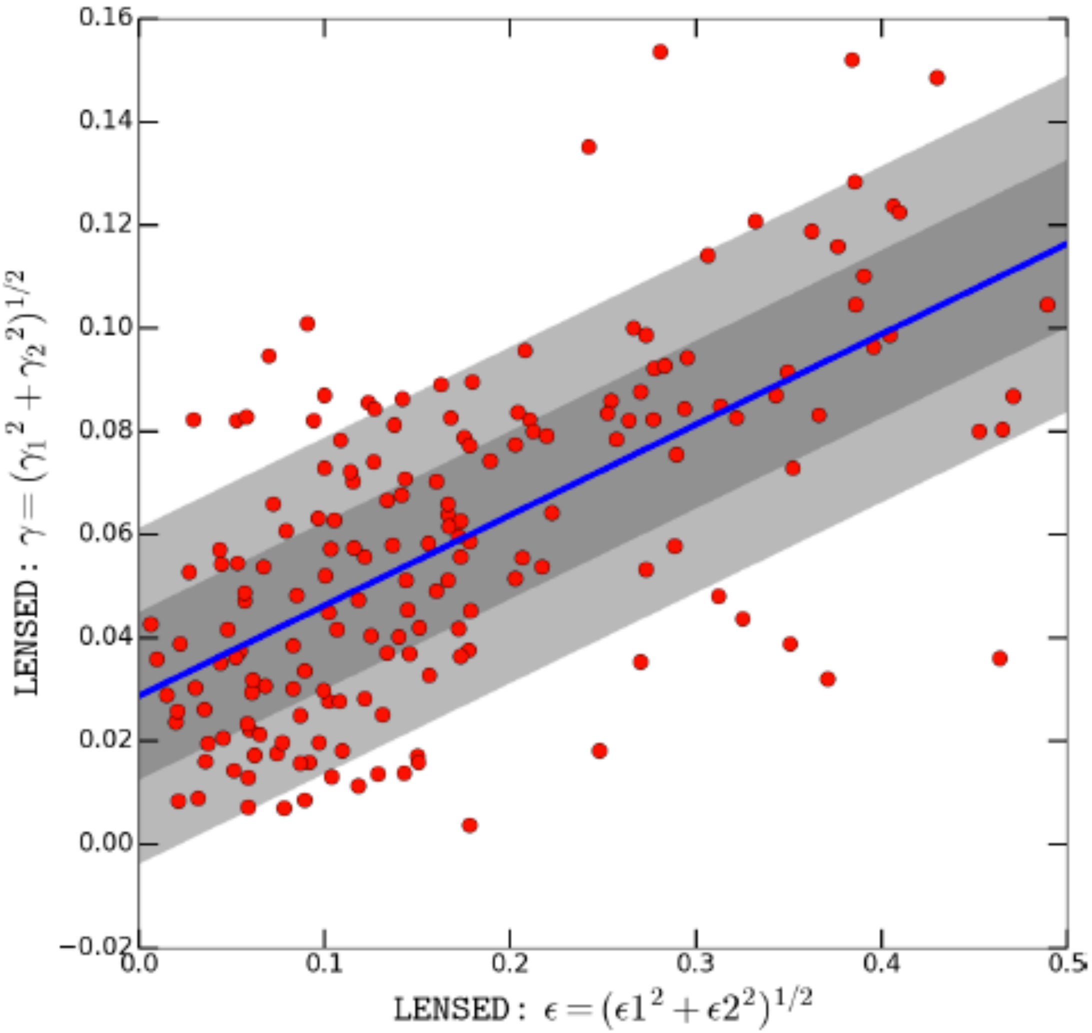
$$\left(\delta_{\rm IMF} = \frac{(M_\star/L)_{\rm IMF}}{(M_\star/L)_{\rm Chab}}\right)$$

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

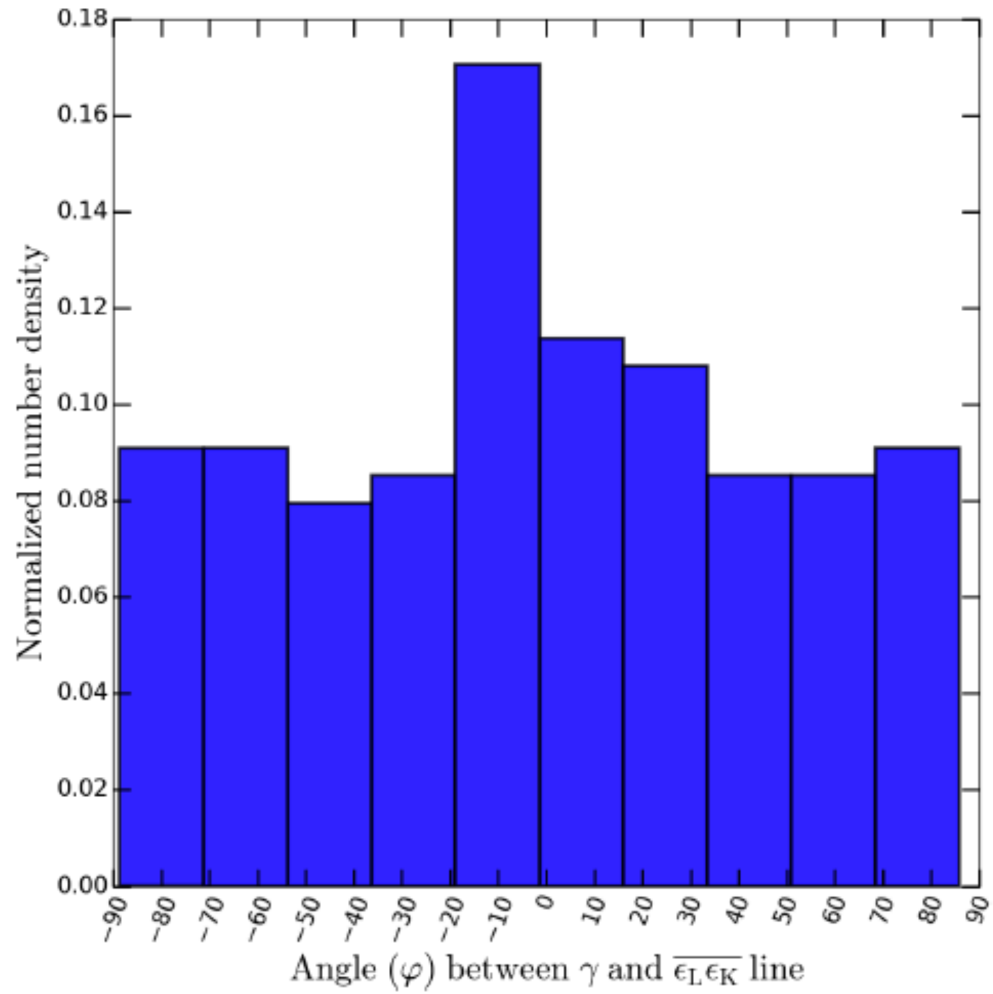
Shear-Ellipticity degeneracy

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

Mukherjee et al. 2019
to be submitted to MNRAS

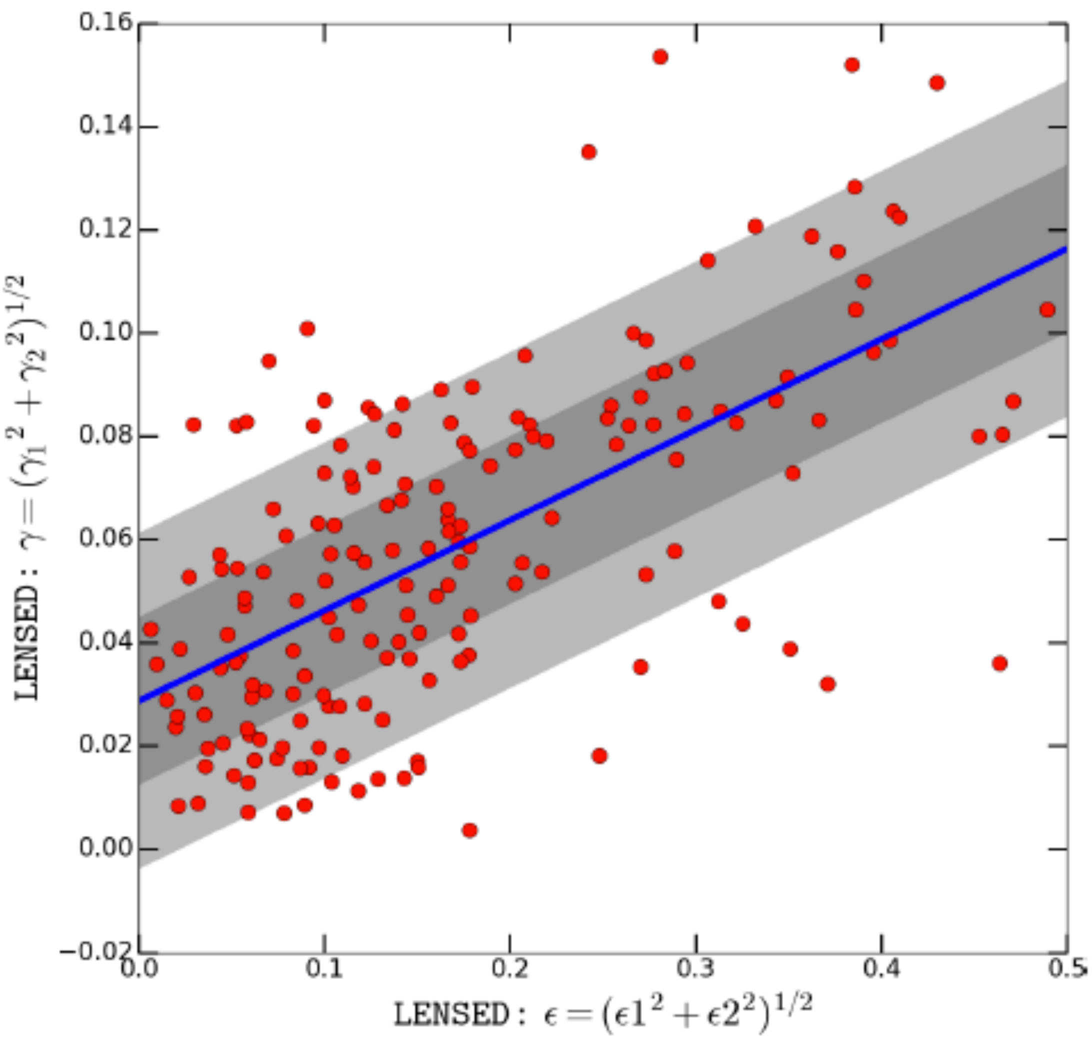


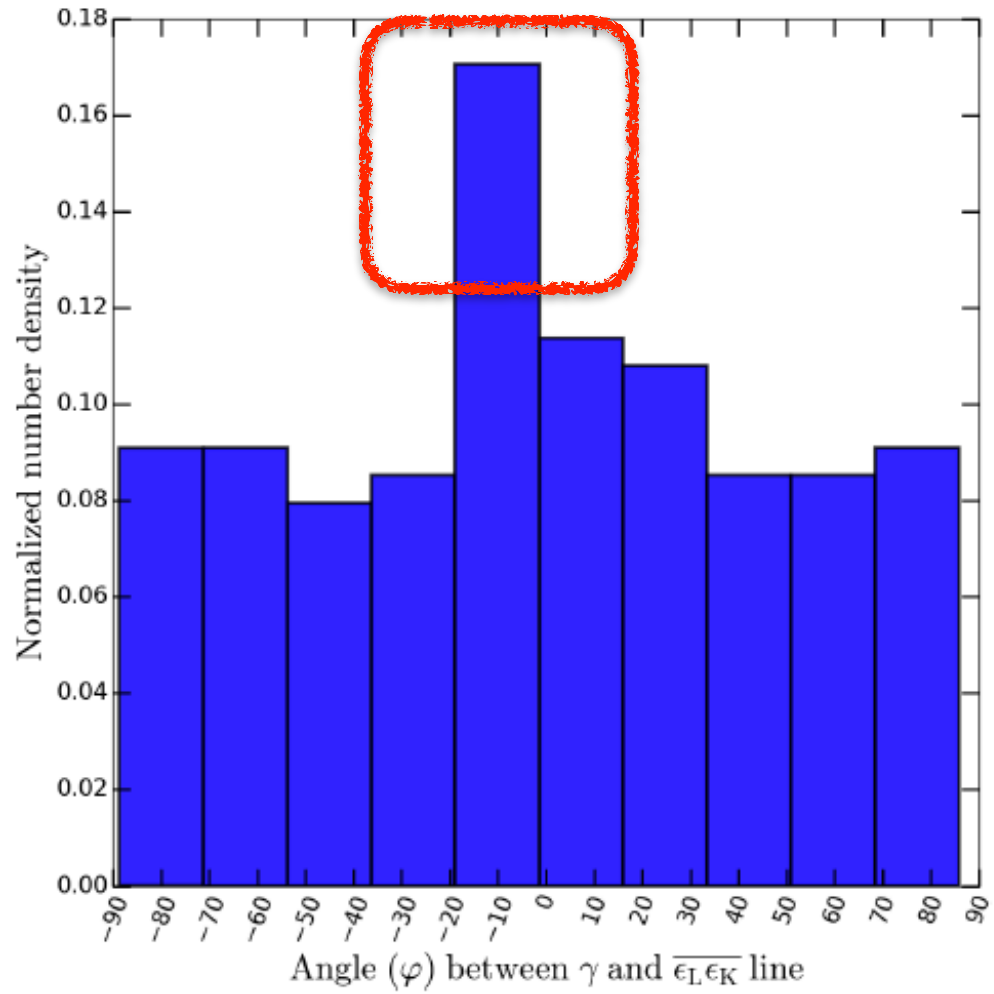
Shear-Ellipticity correlation



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?

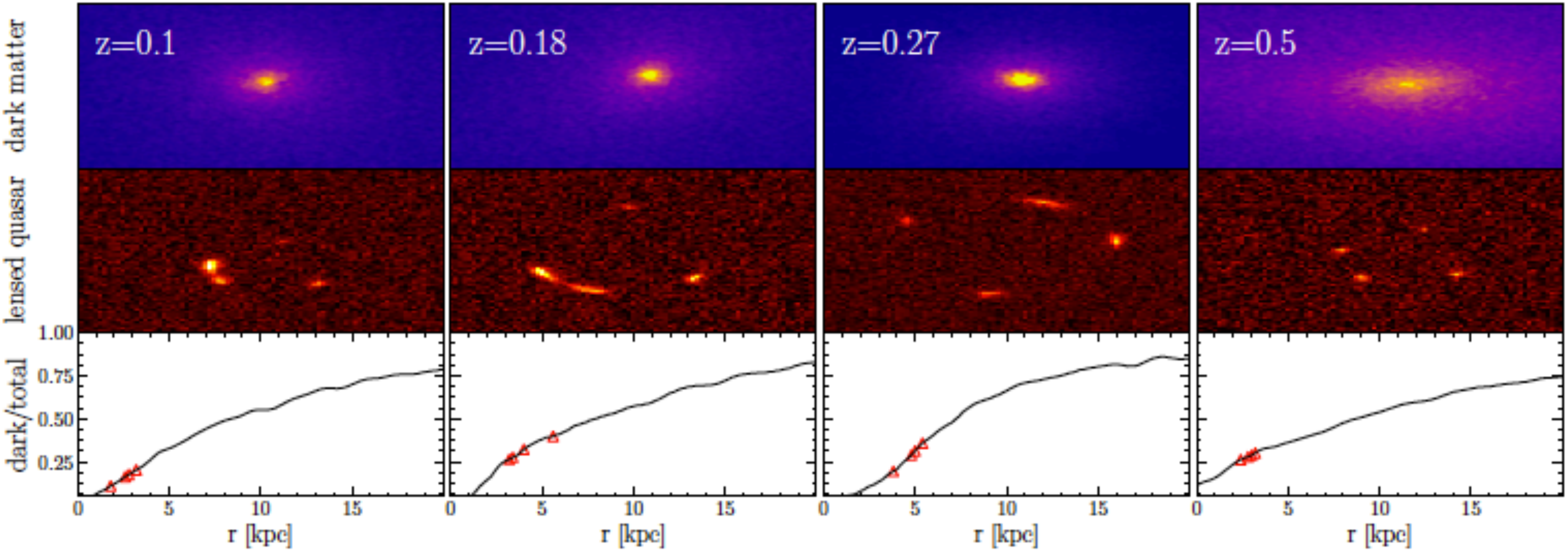
Astro2020 Science White Paper

arXiv:1904.12968

Pooley et al. 2019

The Most Powerful Lenses in the Universe: Quasar Microlensing as a Probe of the Lensing Galaxy

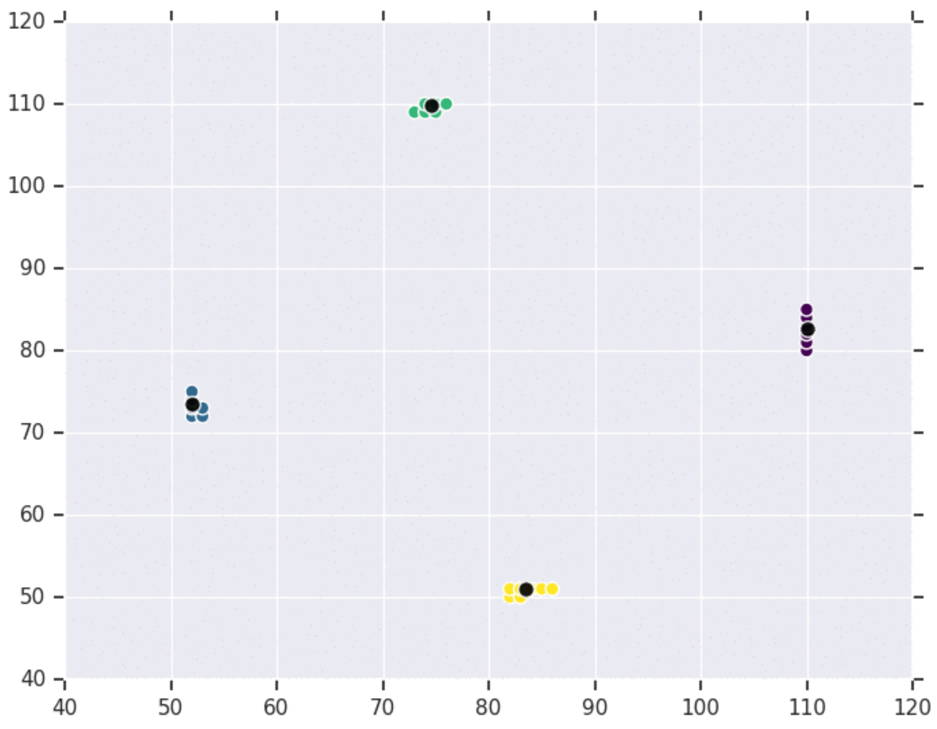
Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☑ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

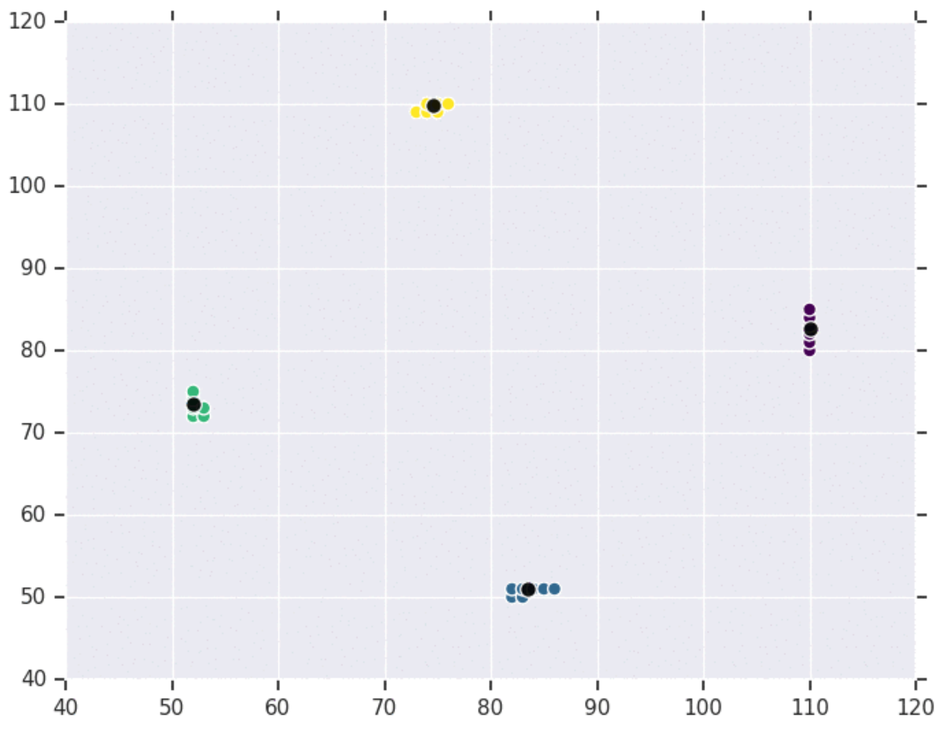


Microlensing with **SEAGLE**

Mukherjee+ in prep

Implementing clustering algorithm





Stacked lensed systems with their brightest pixel

Individual lensed systems with their brightest pixel

z_lens= 0.271 and z_source= 1.0

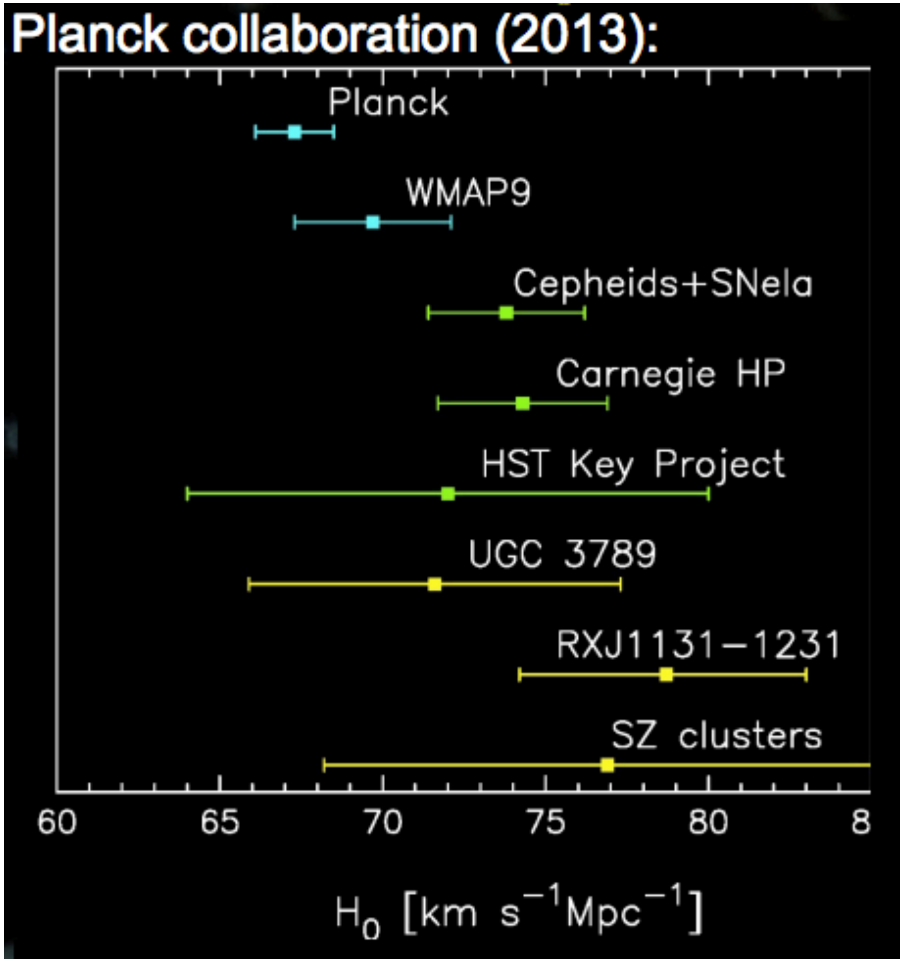
Upcoming SEAGLE Papers in 2019-2020

1. **Mukherjee** et al. —- Shear Ellipticity degeneracy
2. Chatterjee, **Mukherjee** et al.—- Mass power spectrum with EAGLE
3. Bayer, **Mukherjee** et al. —— HST lens P.S. with EAGLE.

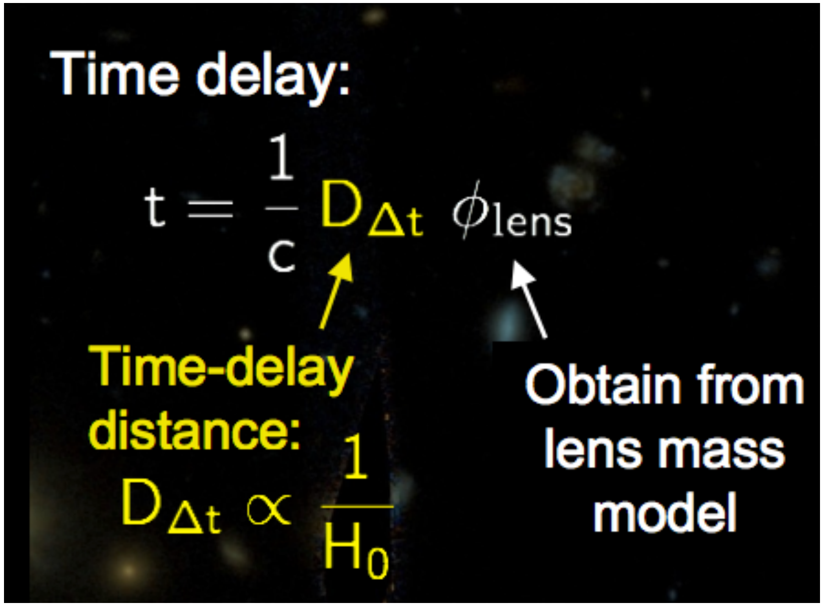
Using **SEAGLE** pipeline

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



Independent measurements are needed!

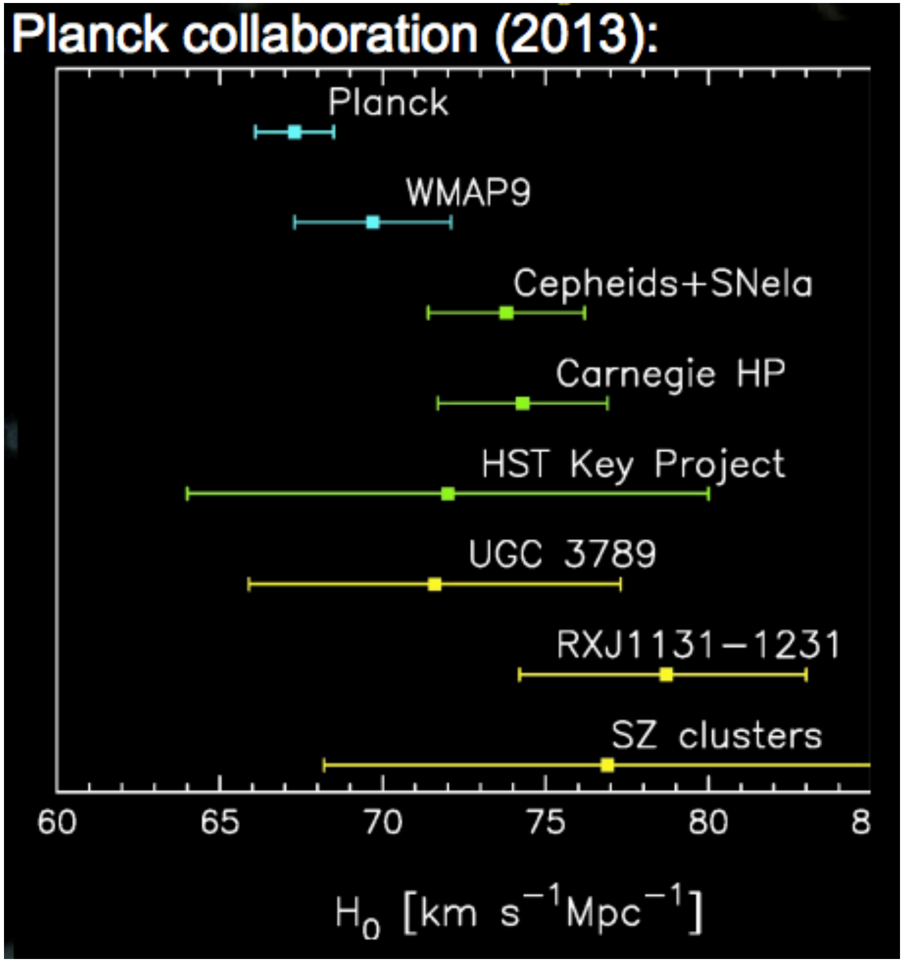


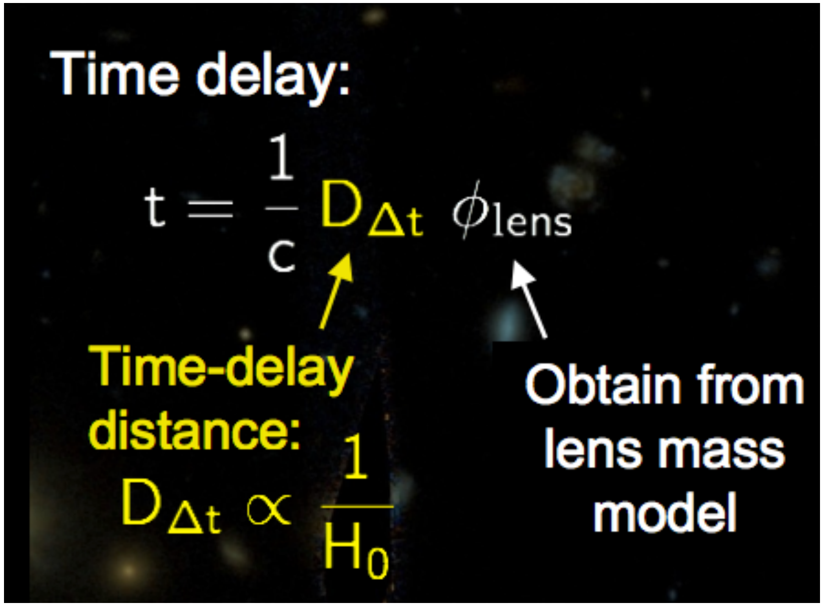
For cosmography we need:

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

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

ERC Advanced Grant

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

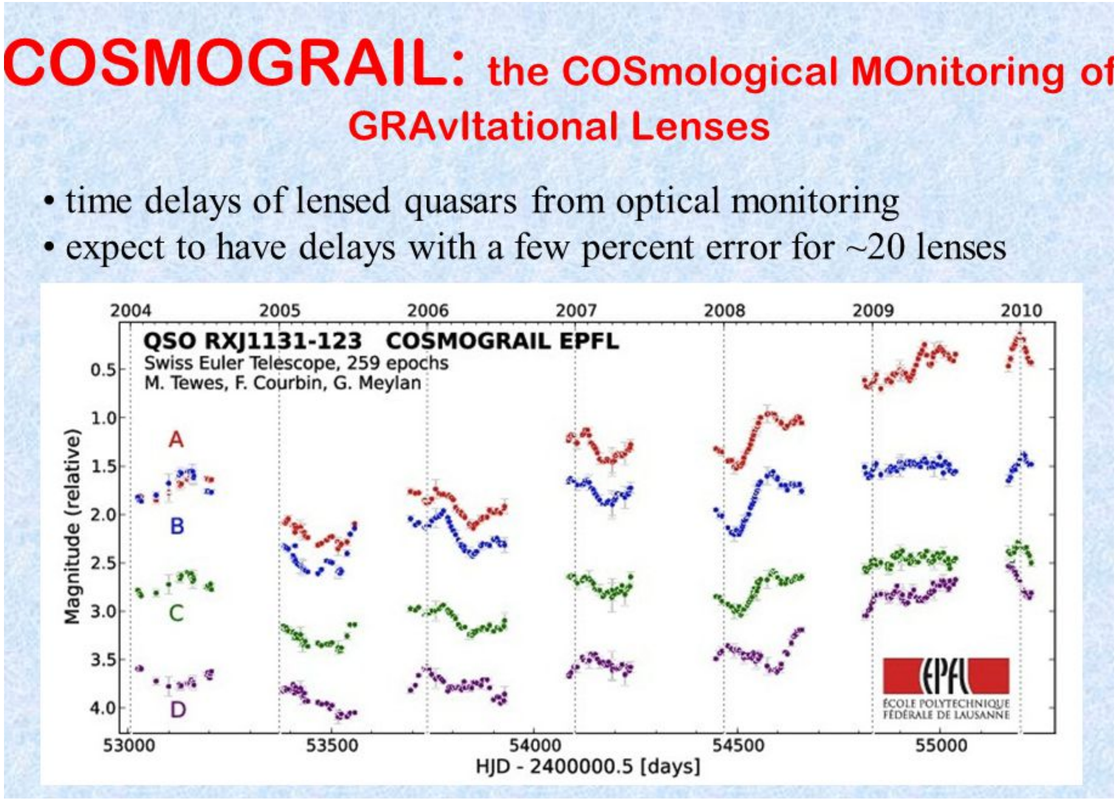
H2020-EU.1.1. ERC-2017-ADG
Oct 2018 —— Sept 2023

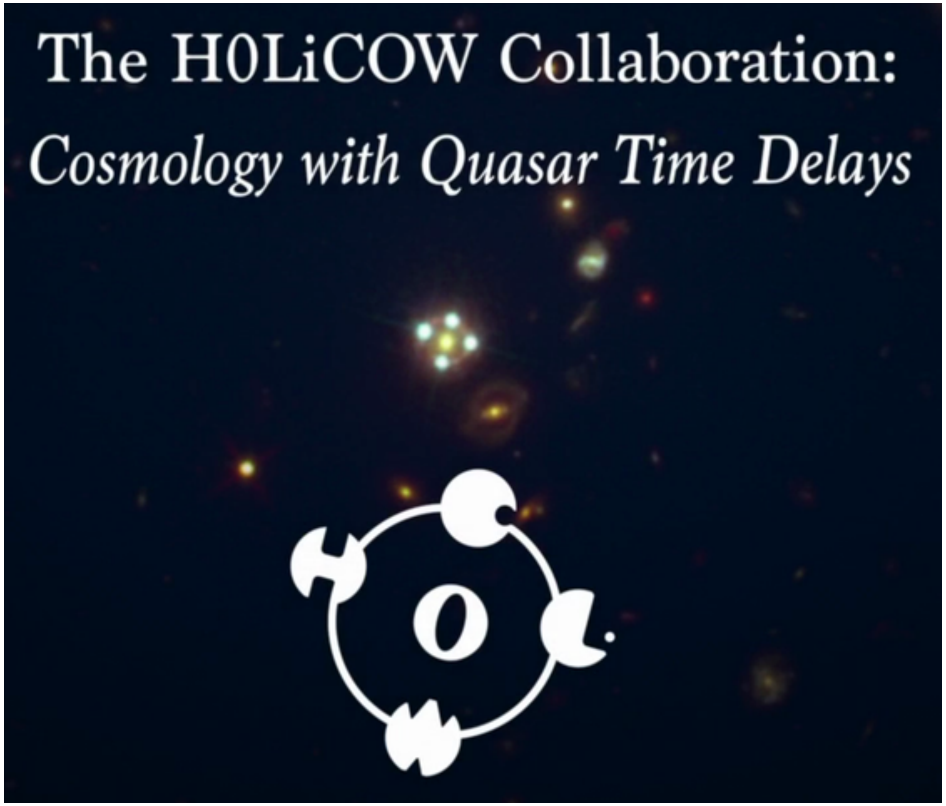
COSMICLENS: Cosmology with Strong Gravitational Lensing

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

ERC Advanced Grant

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



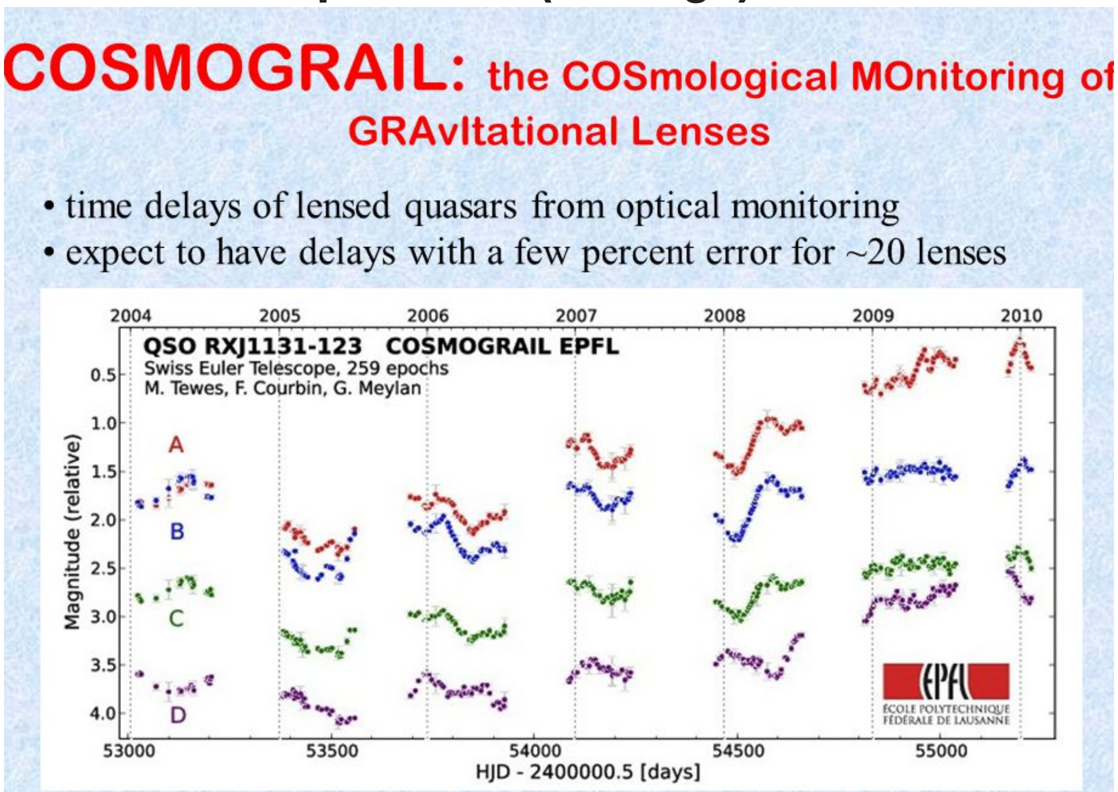


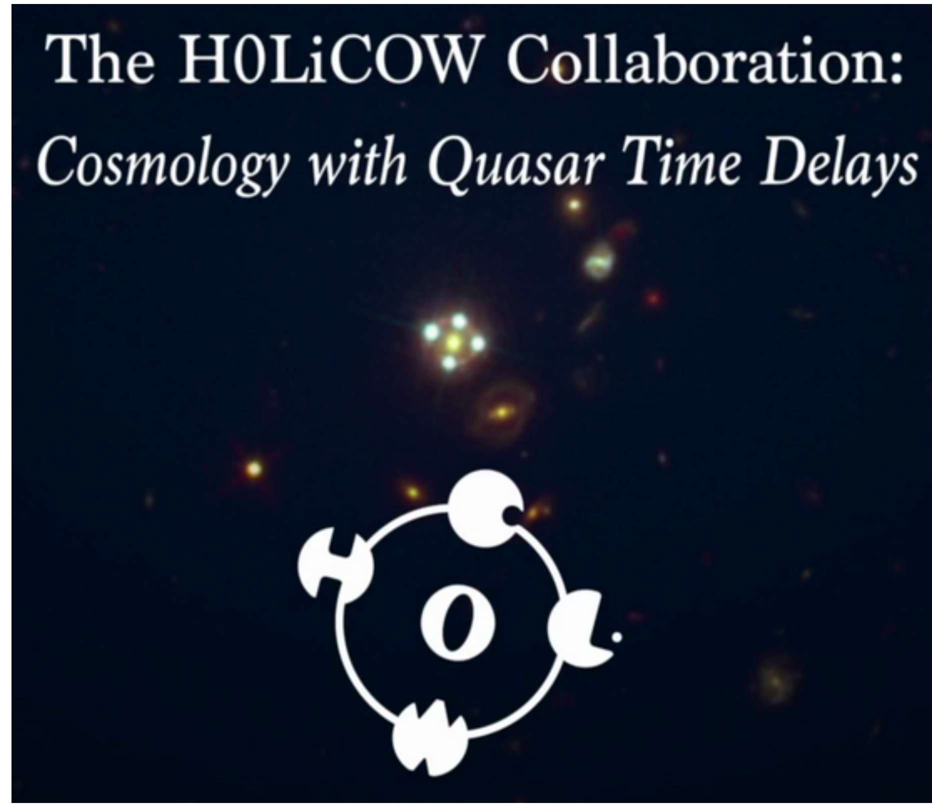
COSMICLENS: Cosmology with Strong Gravitational Lensing

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

ERC Advanced Grant

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

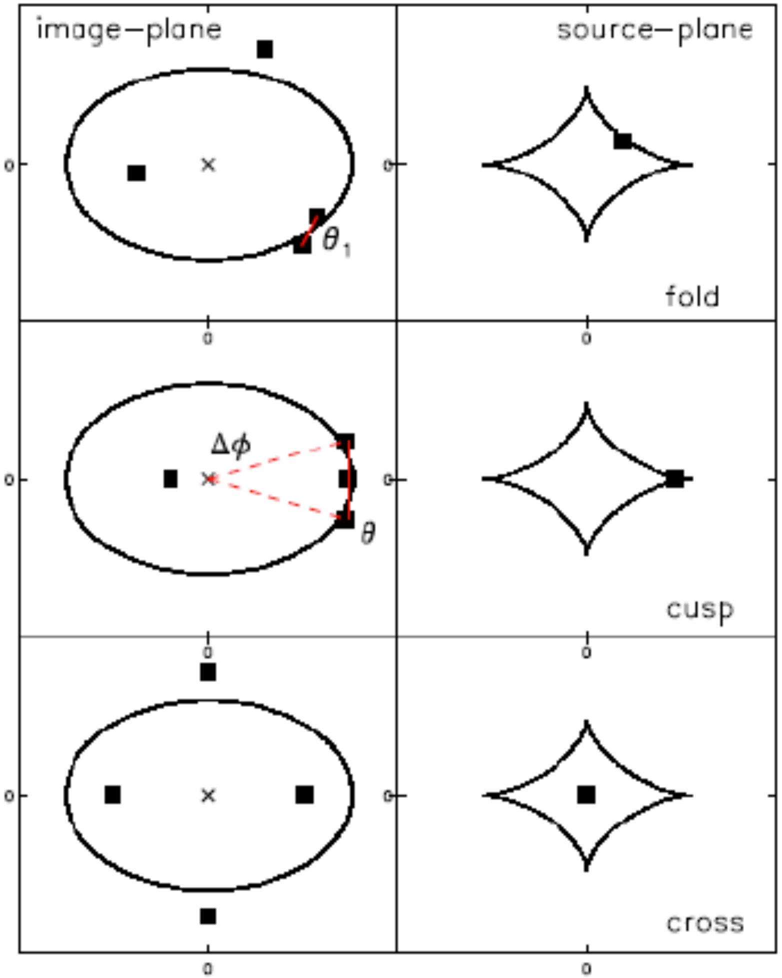


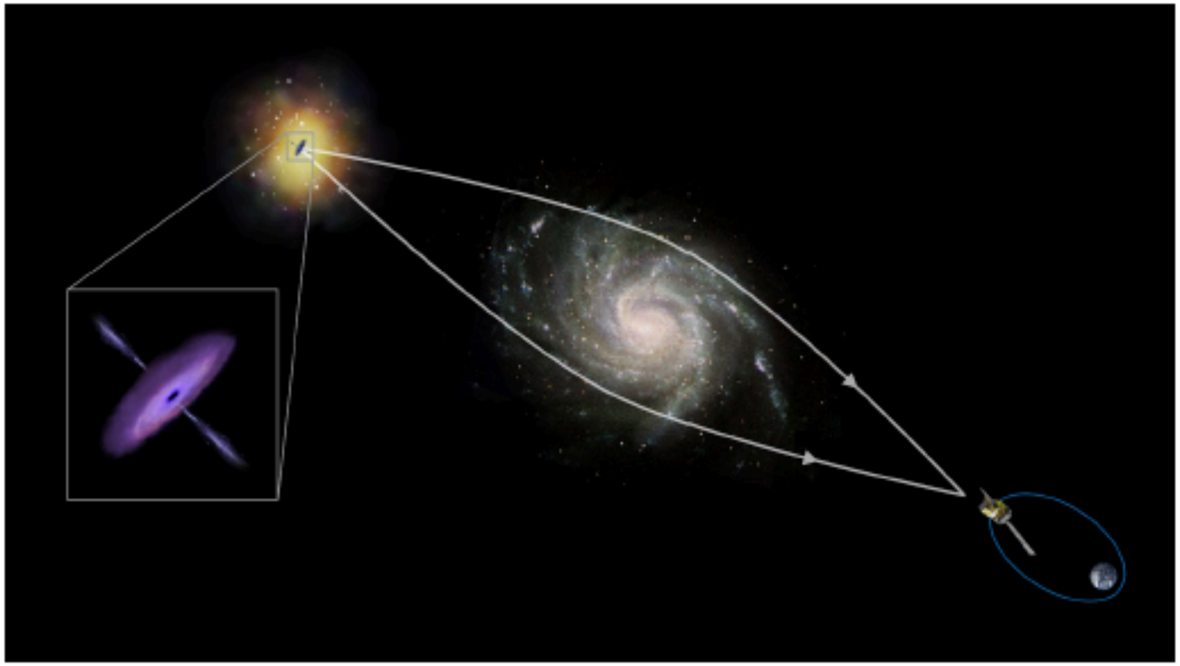


4 work plan project

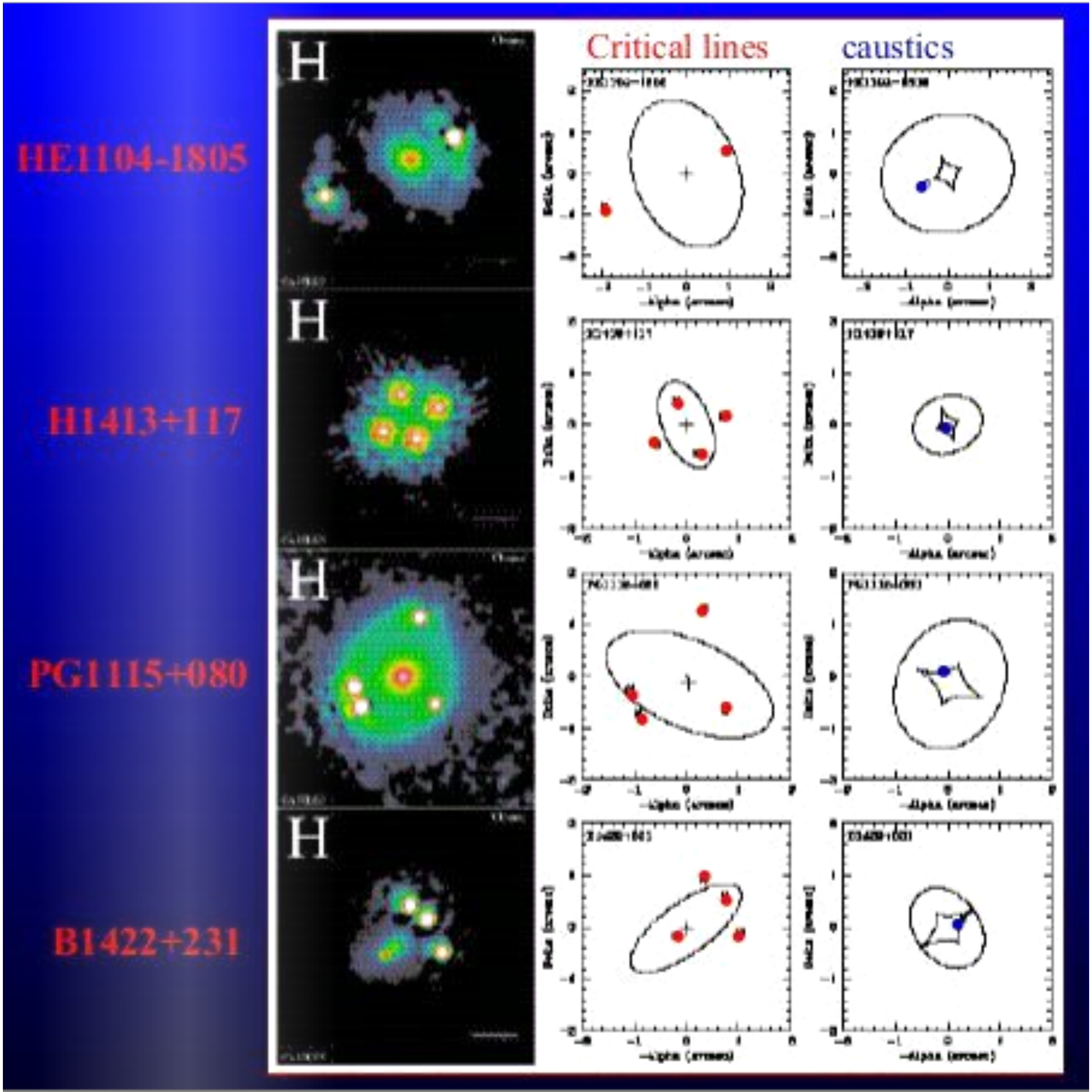
3- Providing a modular **end-to-end simulation framework** to mock lensed systems from hydro-simulations and to evaluate in detail the impact model degeneracies on Hubble constant (H0).

Quasar Strong Lensing





Observed Quasar Lenses

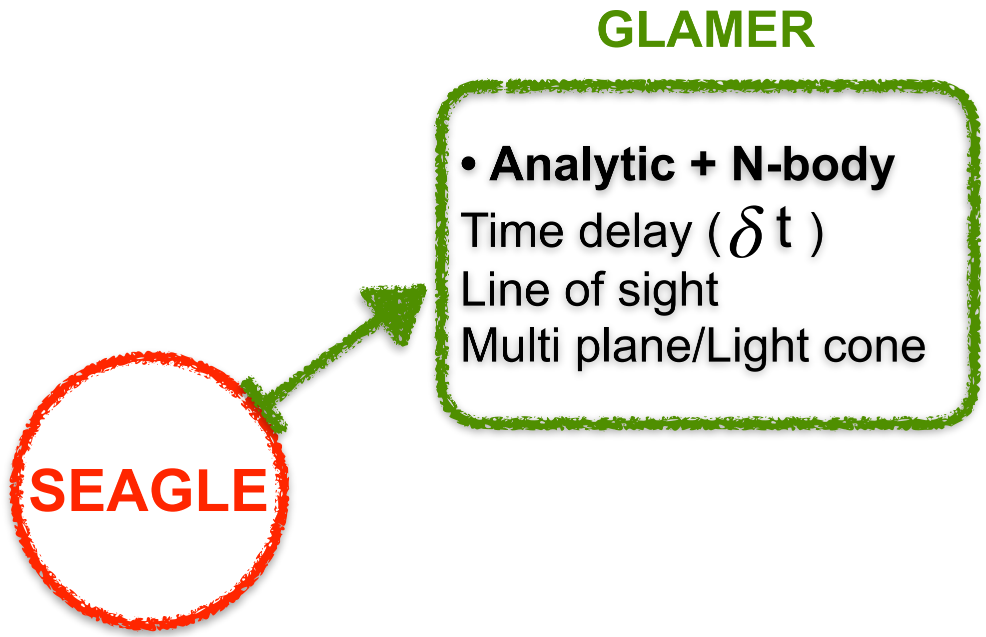


Credit: F. Courbin

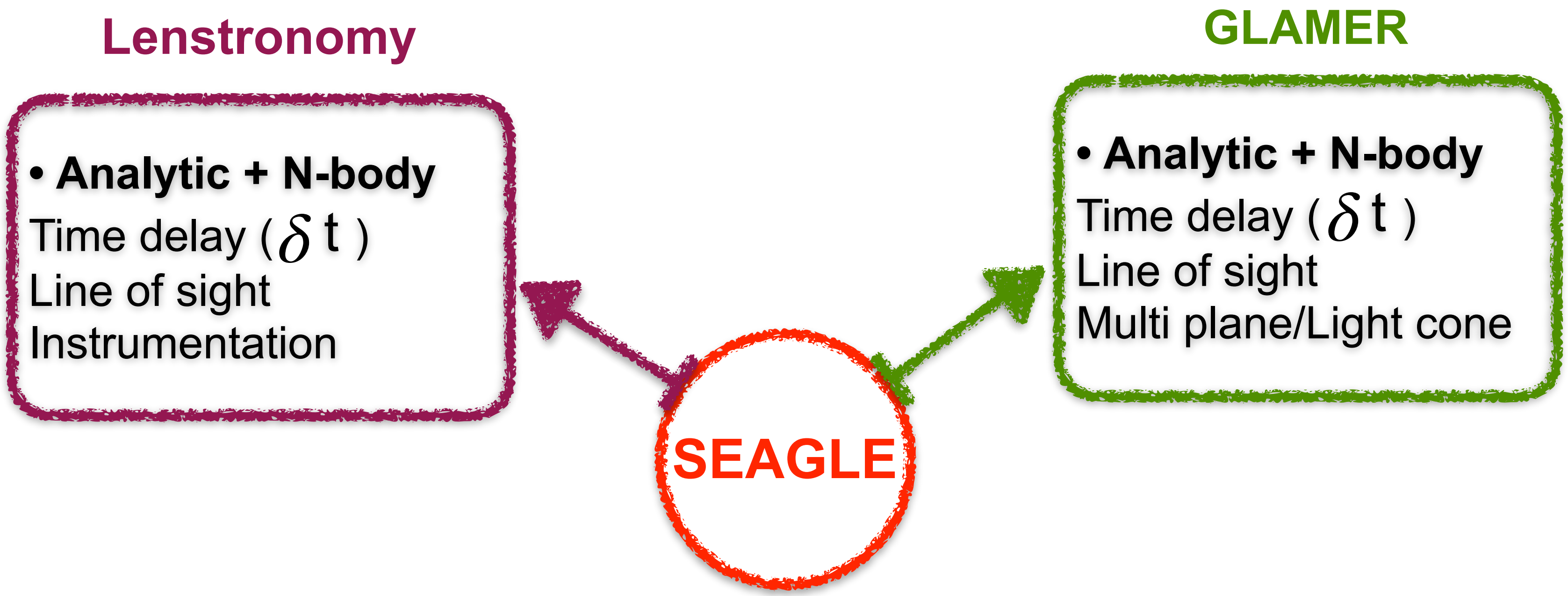
COSMICLENS

SEAGLE

COSMICLENS

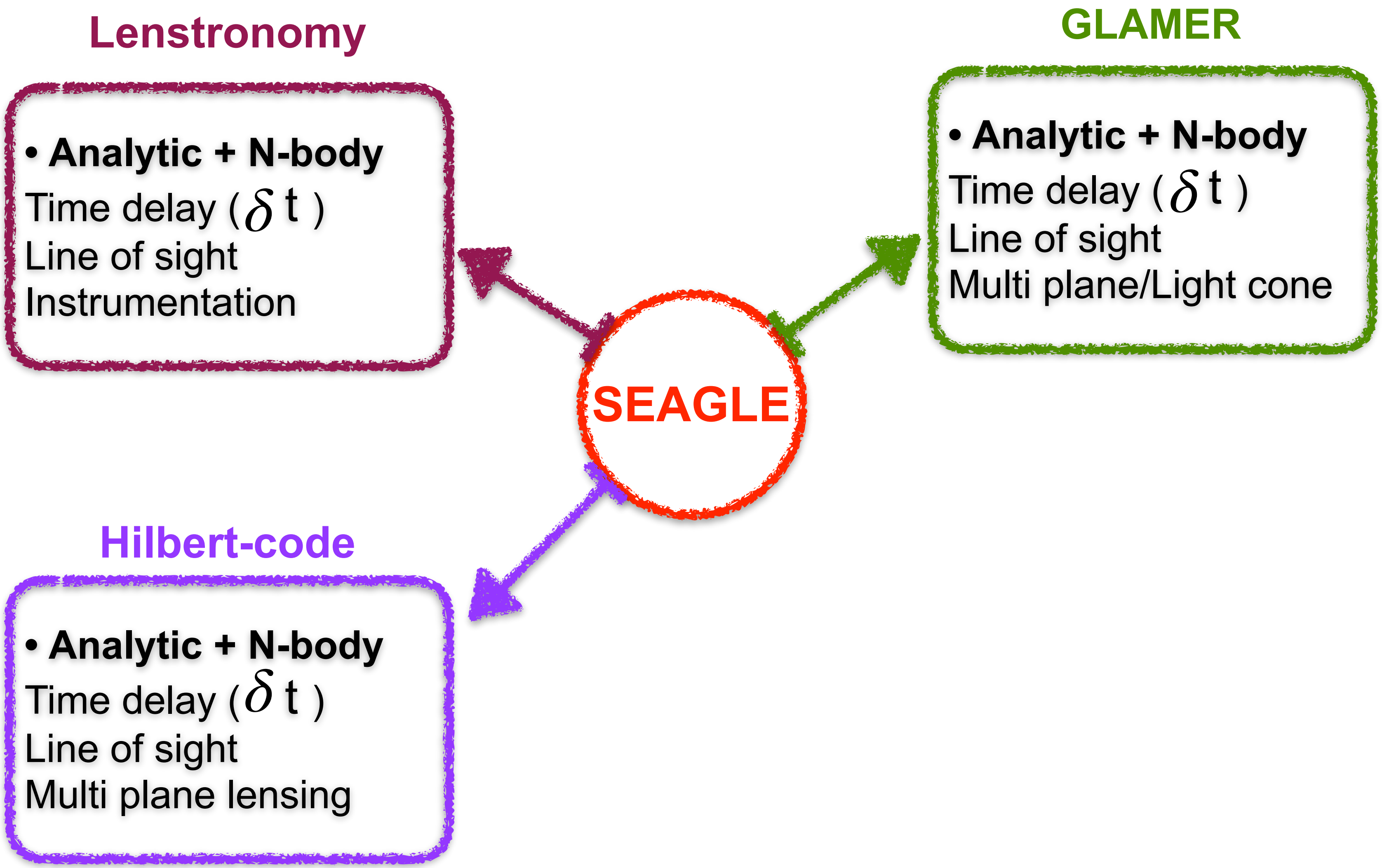

GLAMER
• Analytic + N-body
Time delay (δ t)
Line of sight
Multi plane/Light cone
SEAGLE

COSMICLENS

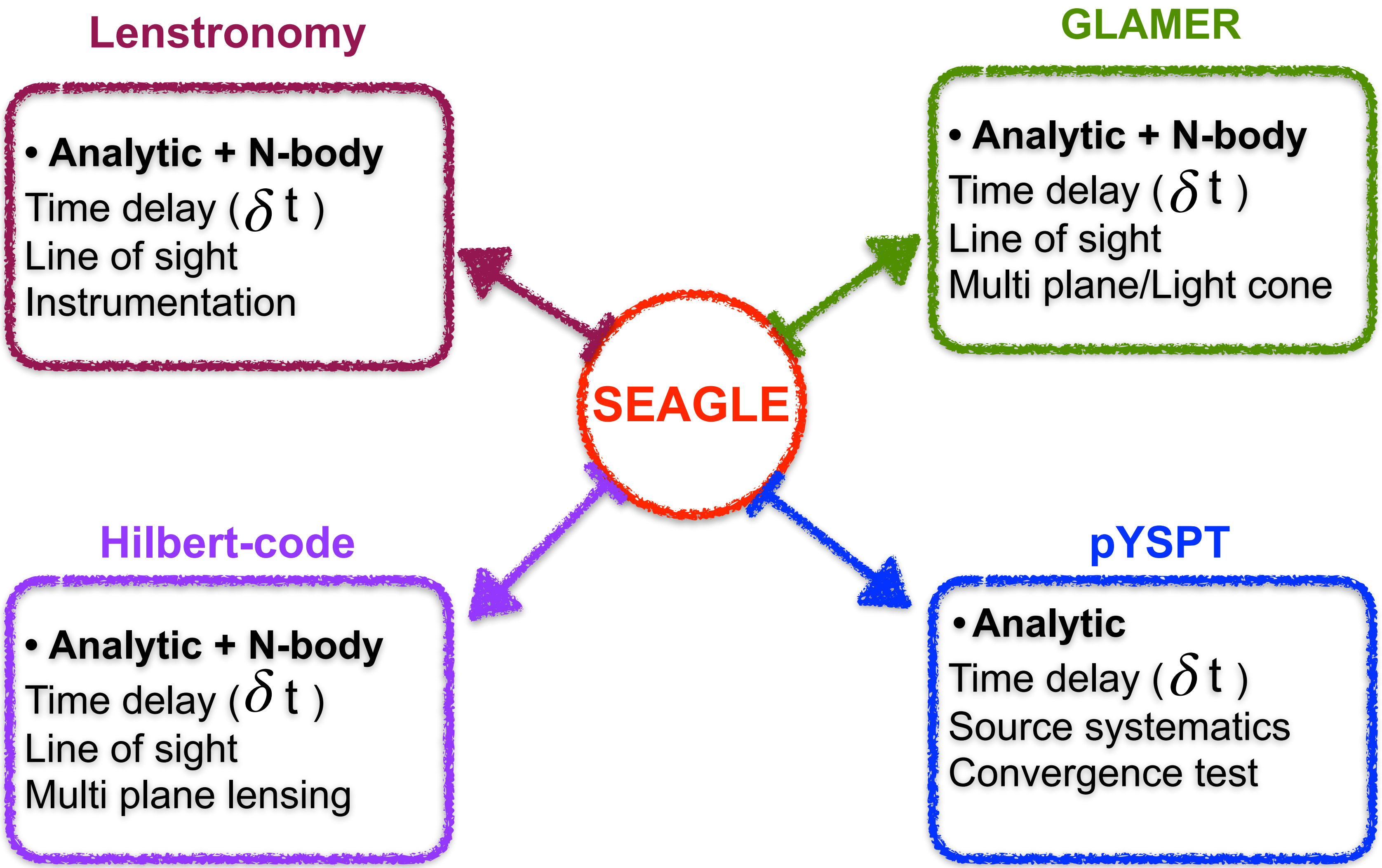


Lenstronomy
• Analytic + N-body
Time delay (δ t)
Line of sight
Instrumentation
GLAMER
• Analytic + N-body
Time delay (δ t)
Line of sight
Multi plane/Light cone
SEAGLE

COSMICLENS

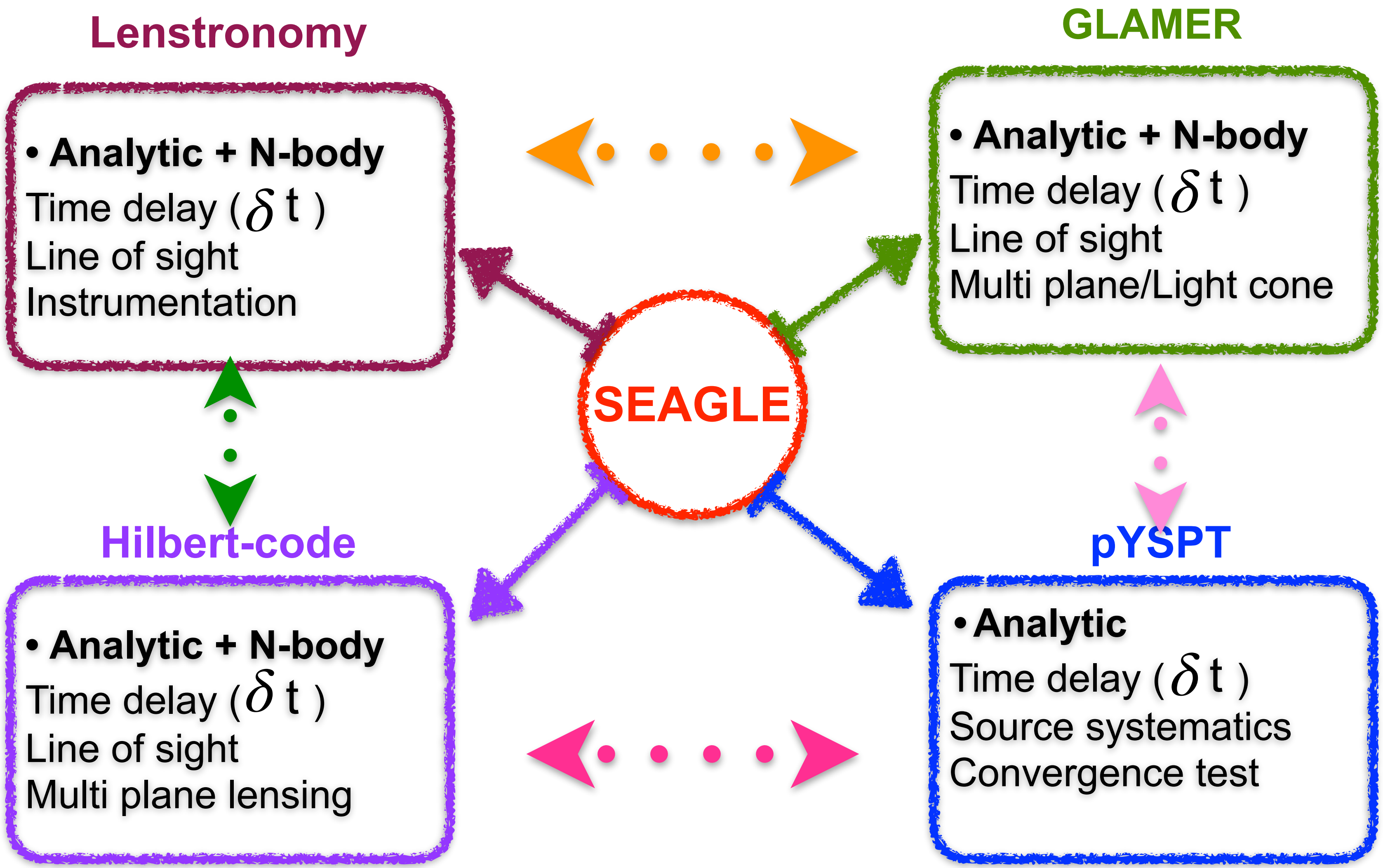

Lenstronomy
• Analytic + N-body
Time delay (δ t)
Line of sight
Instrumentation
GLAMER
• Analytic + N-body
Time delay (δ t)
Line of sight
Multi plane/Light cone
SEAGLE
Hilbert-code
• Analytic + N-body
Time delay (δ t)
Line of sight
Multi plane lensing

COSMICLENS

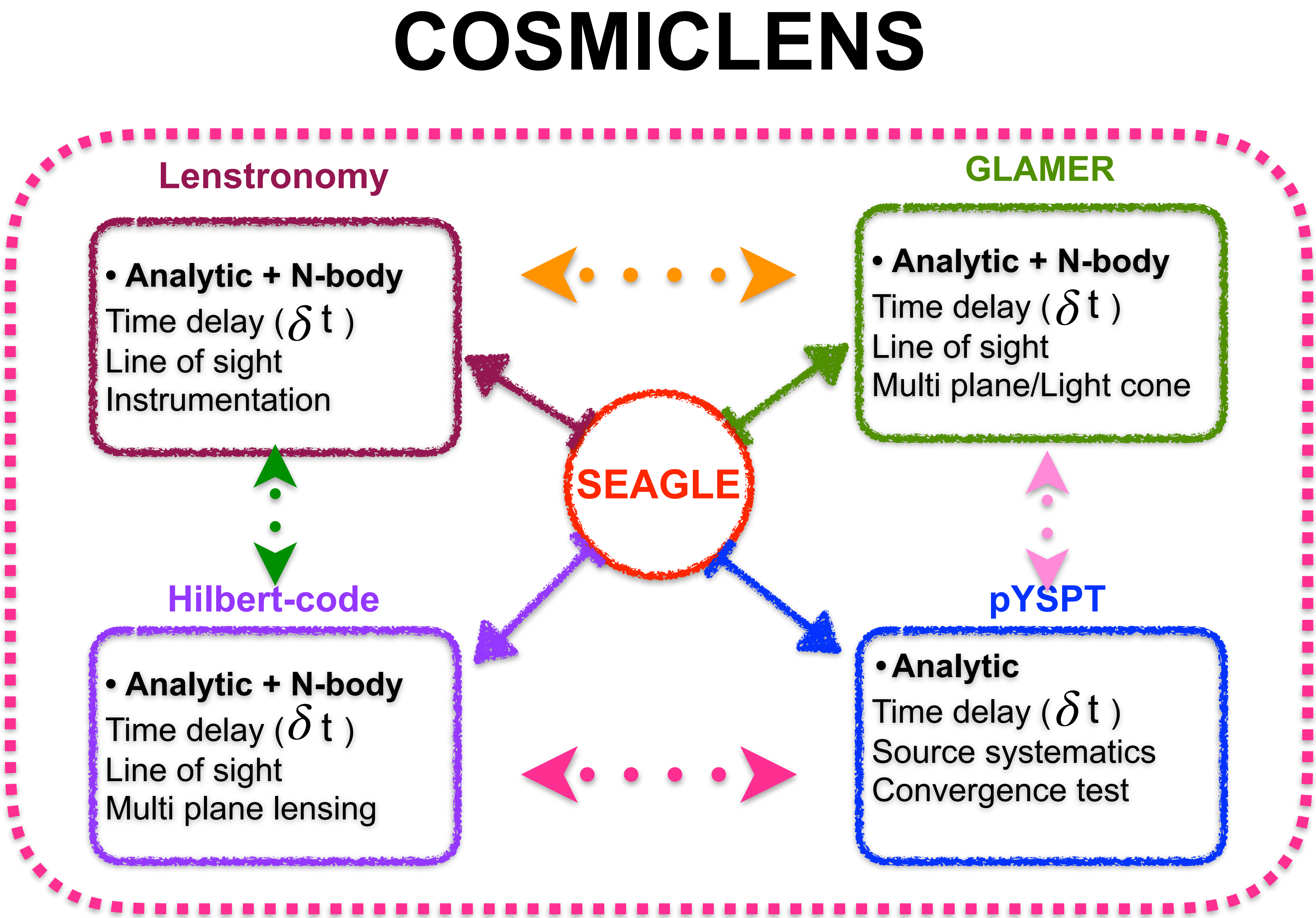


Lenstronomy
• Analytic + N-body
Time delay (δ t)
Line of sight
Instrumentation
GLAMER
• Analytic + N-body
Time delay (δ t)
Line of sight
Multi plane/Light cone
SEAGLE
Hilbert-code
• Analytic + N-body
Time delay (δ t)
Line of sight
Multi plane lensing
pYSPT
• Analytic
Time delay (δ t)
Source systematics
Convergence test

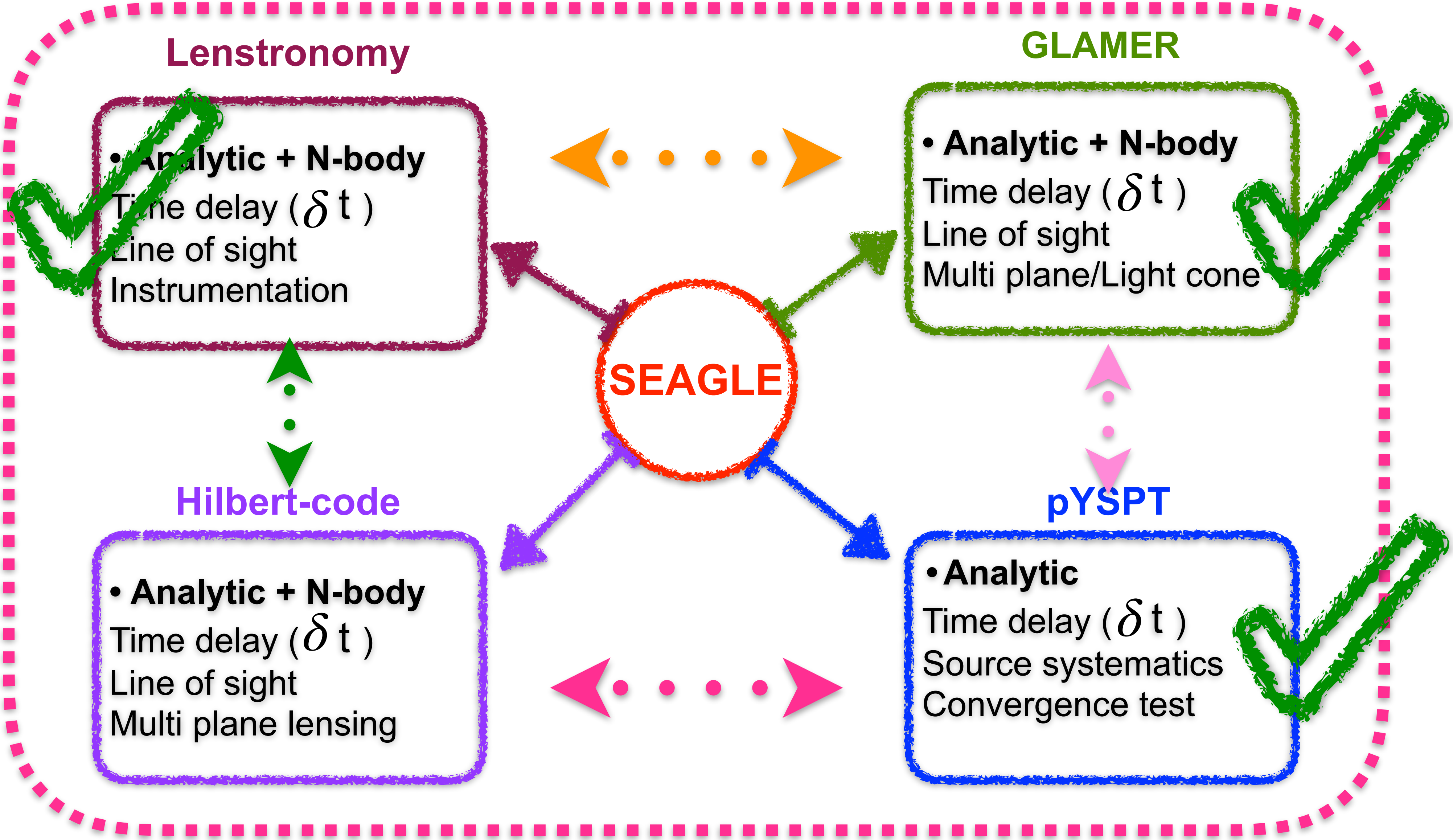
COSMICLENS



Lenstronomy
• Analytic + N-body
Time delay (δ t)
Line of sight
Instrumentation
GLAMER
• Analytic + N-body
Time delay (δ t)
Line of sight
Multi plane/Light cone
SEAGLE
Hilbert-code
• Analytic + N-body
Time delay (δ t)
Line of sight
Multi plane lensing
pYSPT
• Analytic
Time delay (δ t)
Source systematics
Convergence test


COSMICLENS
Lenstronomy
• Analytic + N-body
Time delay (δ t)
Line of sight
Instrumentation
GLAMER
• Analytic + N-body
Time delay (δ t)
Line of sight
Multi plane/Light cone
SEAGLE
Hilbert-code
• Analytic + N-body
Time delay (δ t)
Line of sight
Multi plane lensing
pYSPT
• Analytic
Time delay (δ t)
Source systematics
Convergence test

COSMICLENS



Lenstronomy
• Analytic + N-body
Time delay (δ t)
Line of sight
Instrumentation
GLAMER
• Analytic + N-body
Time delay (δ t)
Line of sight
Multi plane/Light cone
SEAGLE
Hilbert-code
• Analytic + N-body
Time delay (δ t)
Line of sight
Multi plane lensing
pYSPT
• Analytic
Time delay (δ t)
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