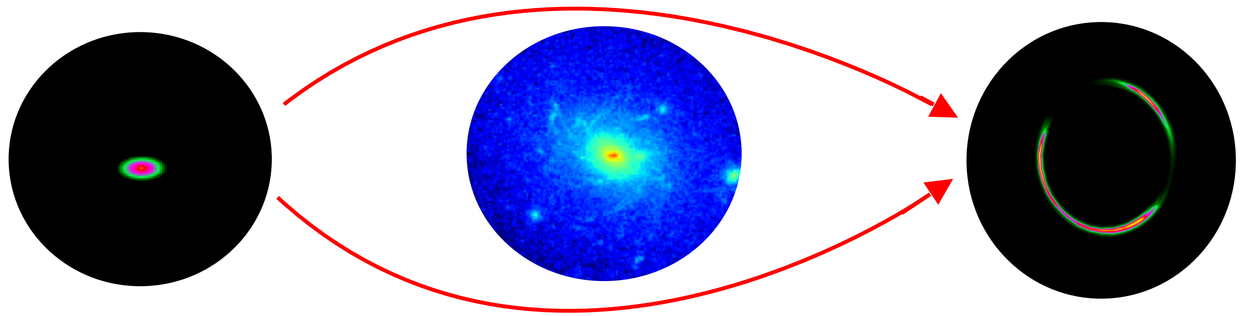
Constraining galaxy formation, dark matter and time delay cosmography with simulated strong lenses



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

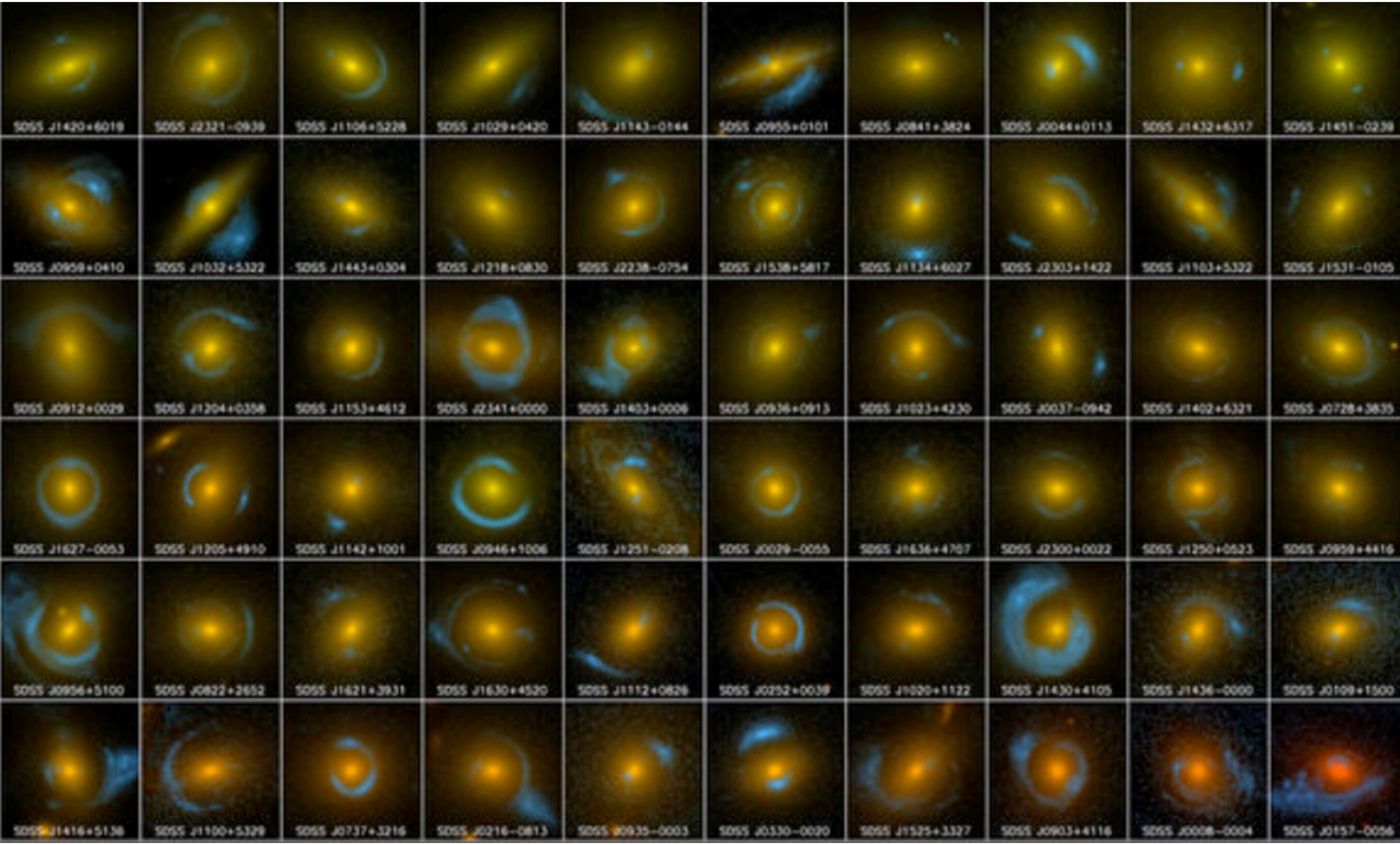
How many strong lenses do we need & why?

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 **$10^{(4\text{-}5)}$ lenses**

Lens Galaxies: SLACS



credit: Adam Bolton/SLACS

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

Credits: Koopmans/Euclid

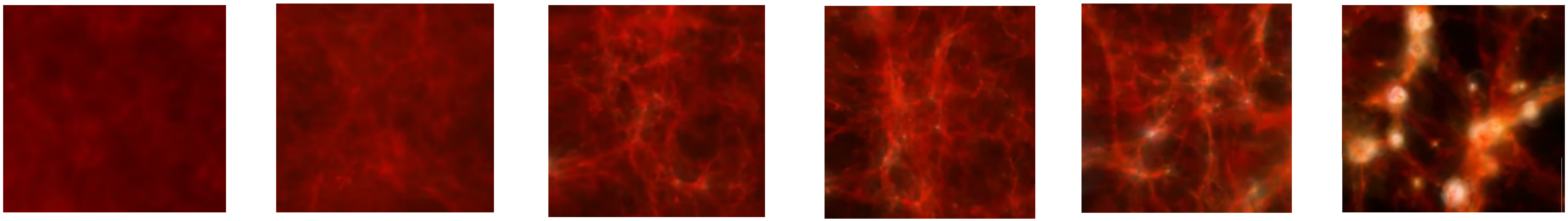
A pipeline for **S**imulating **EAG**LE **LE**nses

based on

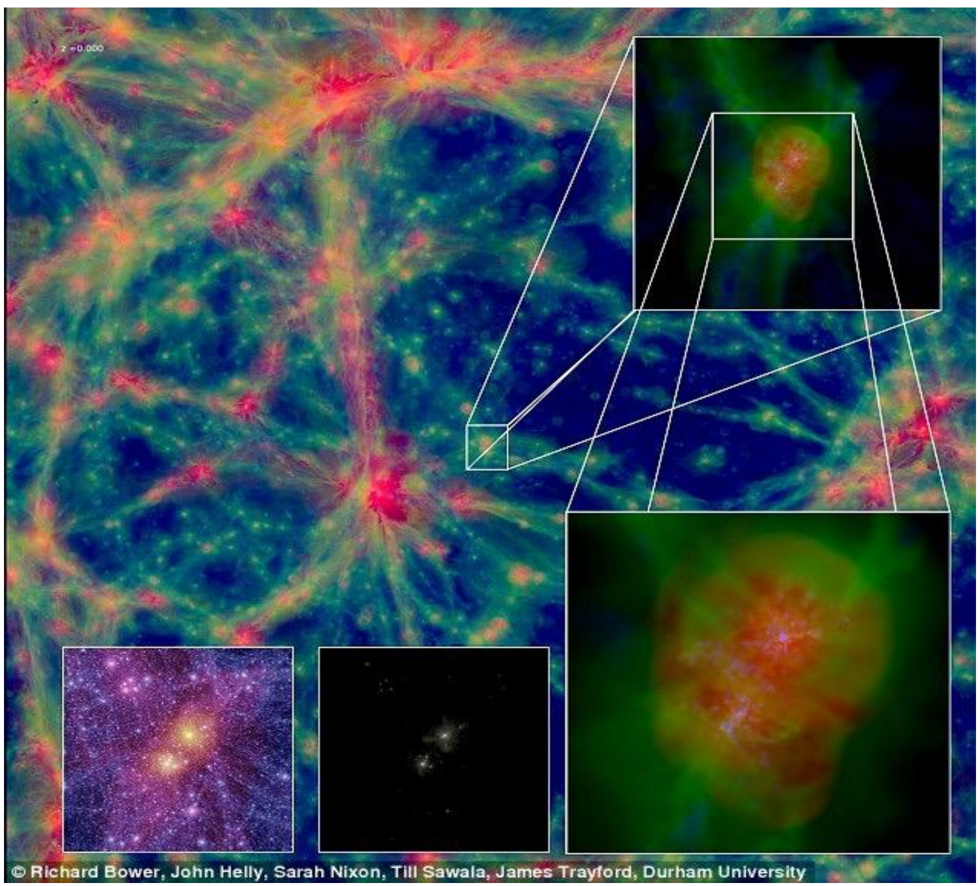
***SEAGLE—I**: A pipeline for simulating and modelling strong lenses from cosmological hydrodynamic simulations*

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

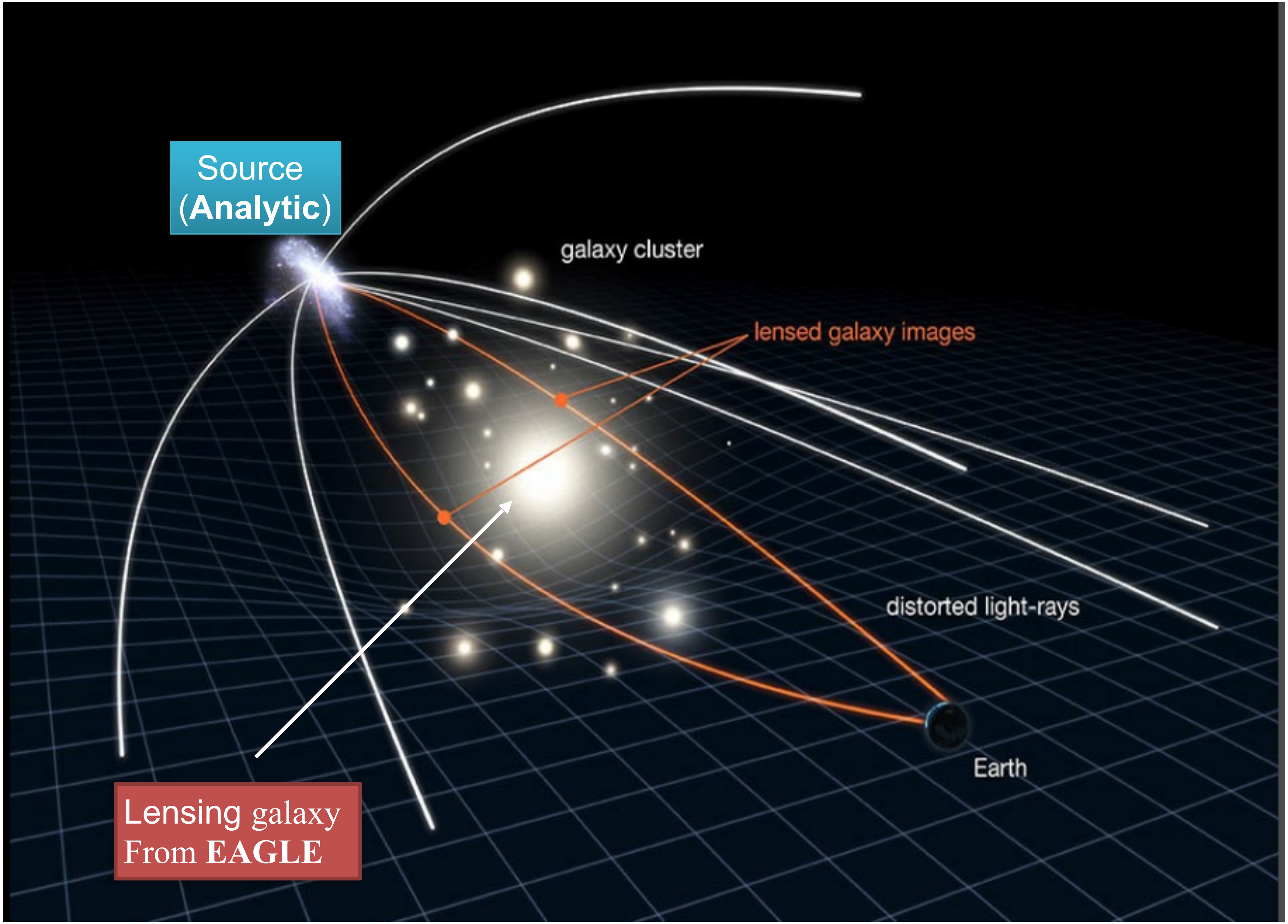
Simulation box sizes : **100, 50, 25, 12, cMpc**

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

Major improvement:

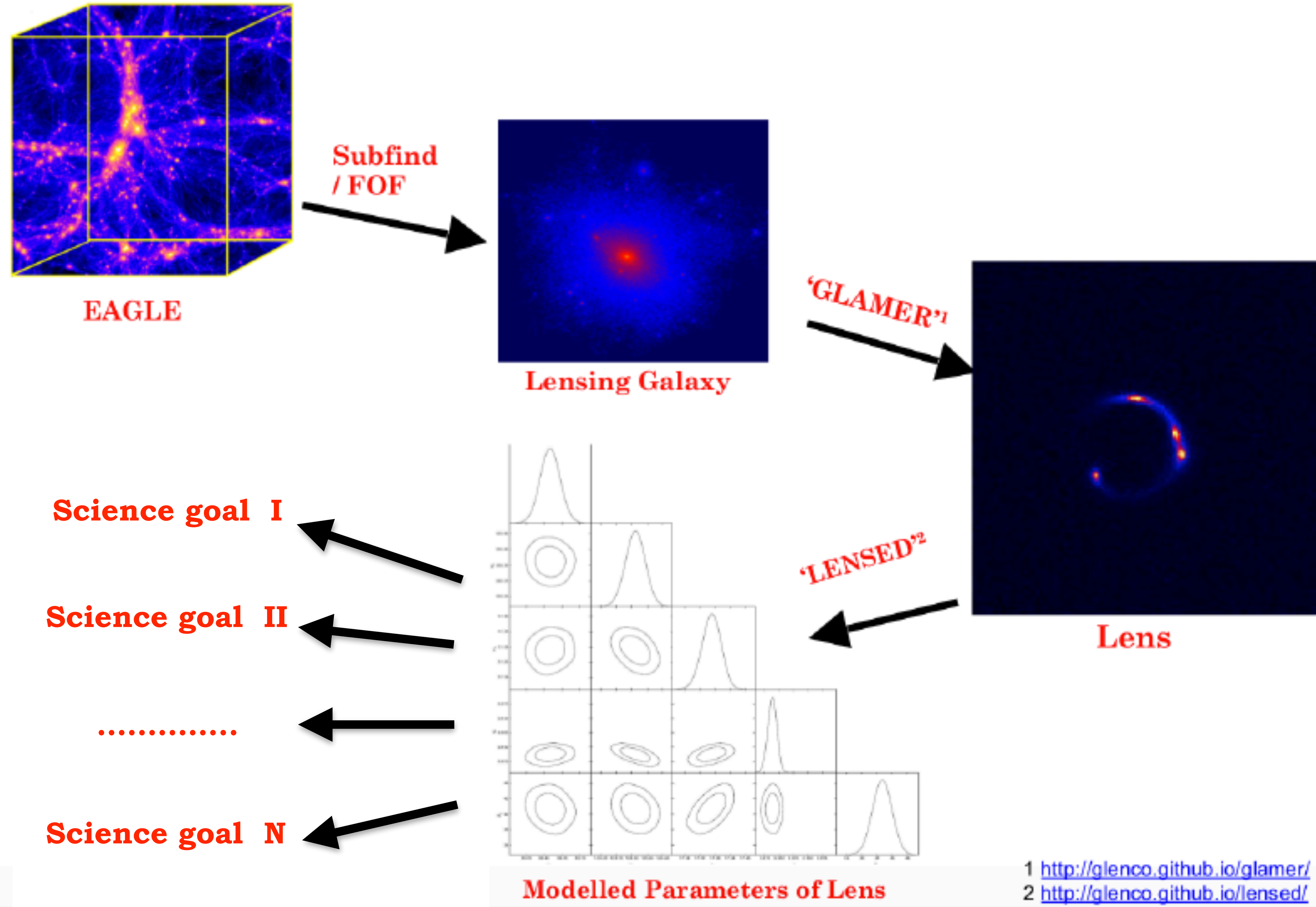
Feedback from Stars & AGN

Image courtesy: Durham University & Schaye et al. 2015



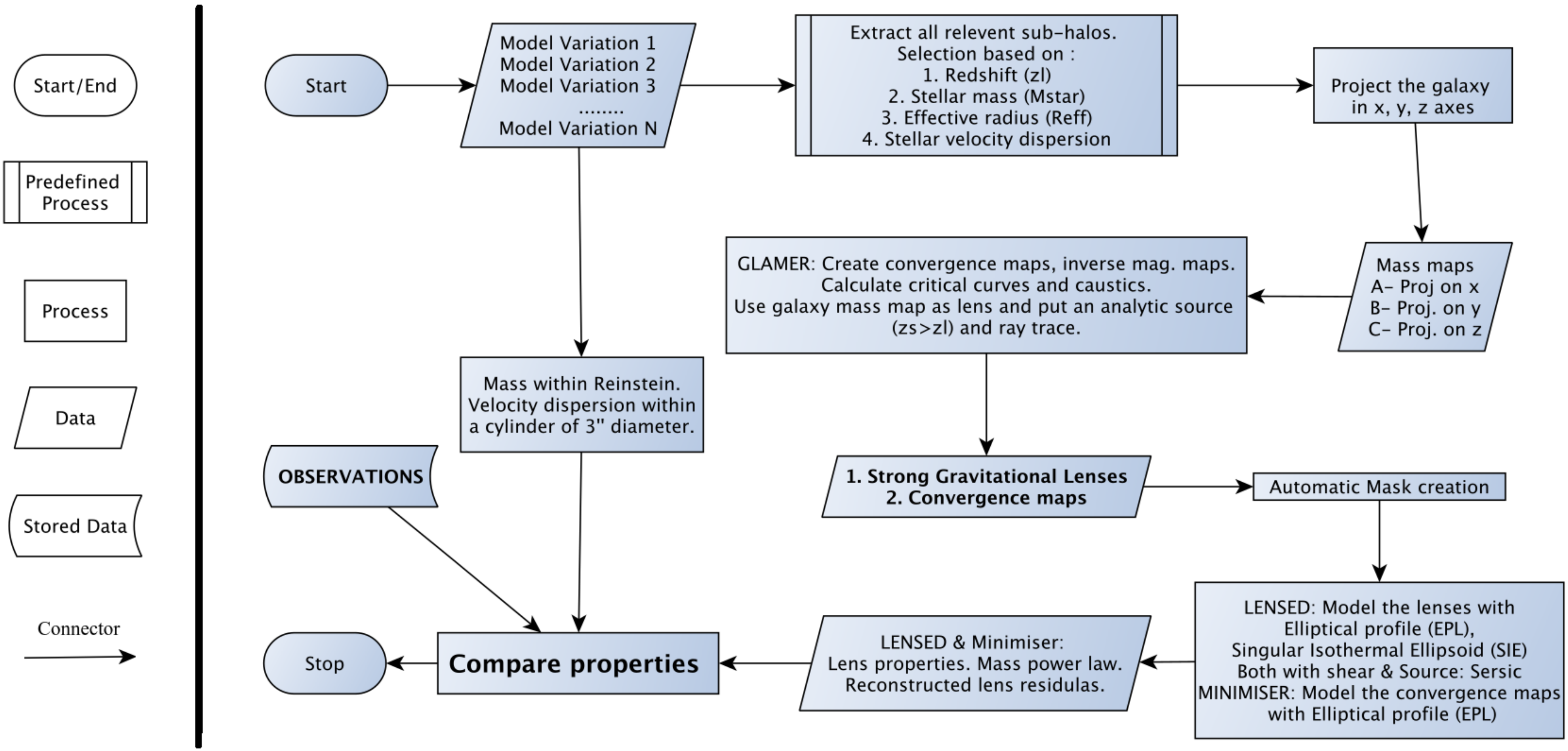
Gravitational Lensing (Courtesy: NASA/ESA)

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 for
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	-

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_{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)

Lensing galaxies from EAGLE

SOURCE- Analytic

SEAGLE-I: *Mukherjee+* 2018 MNRAS

Some Strong Lenses from Sloan Lens ACS (SLACS) Survey

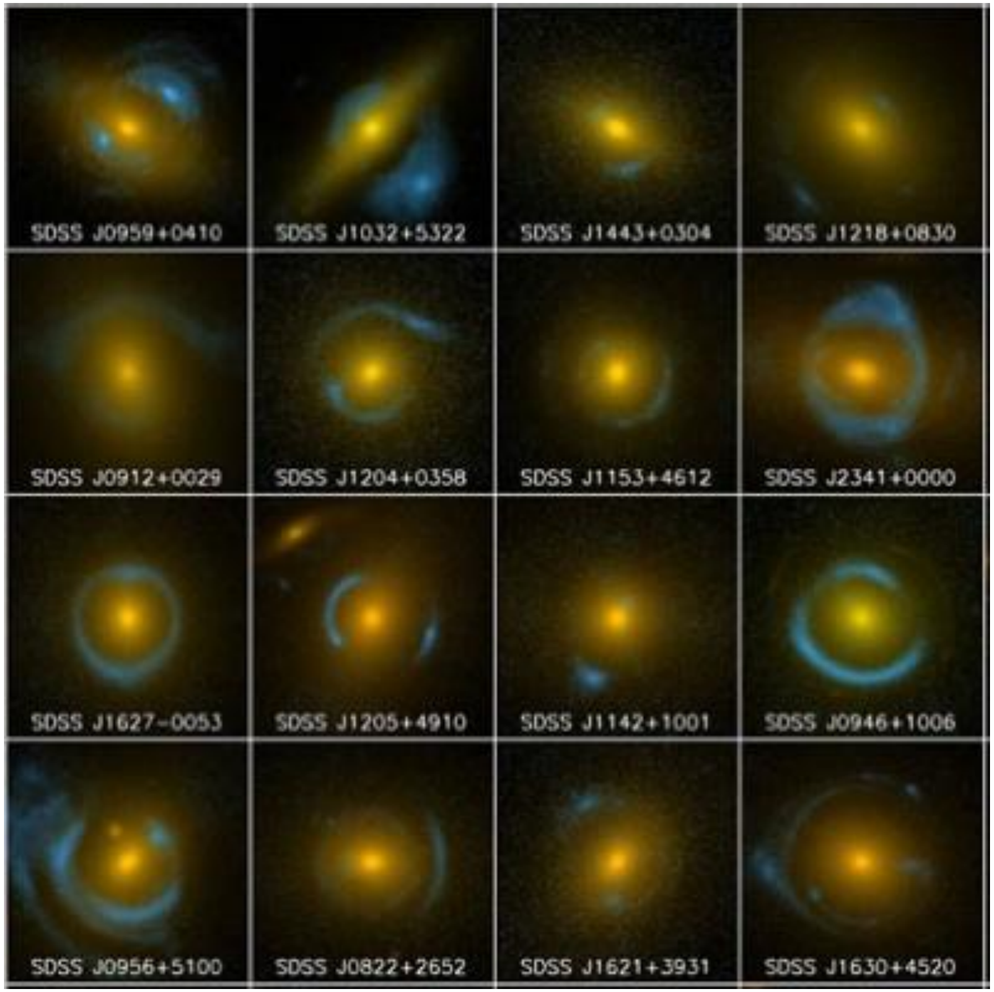
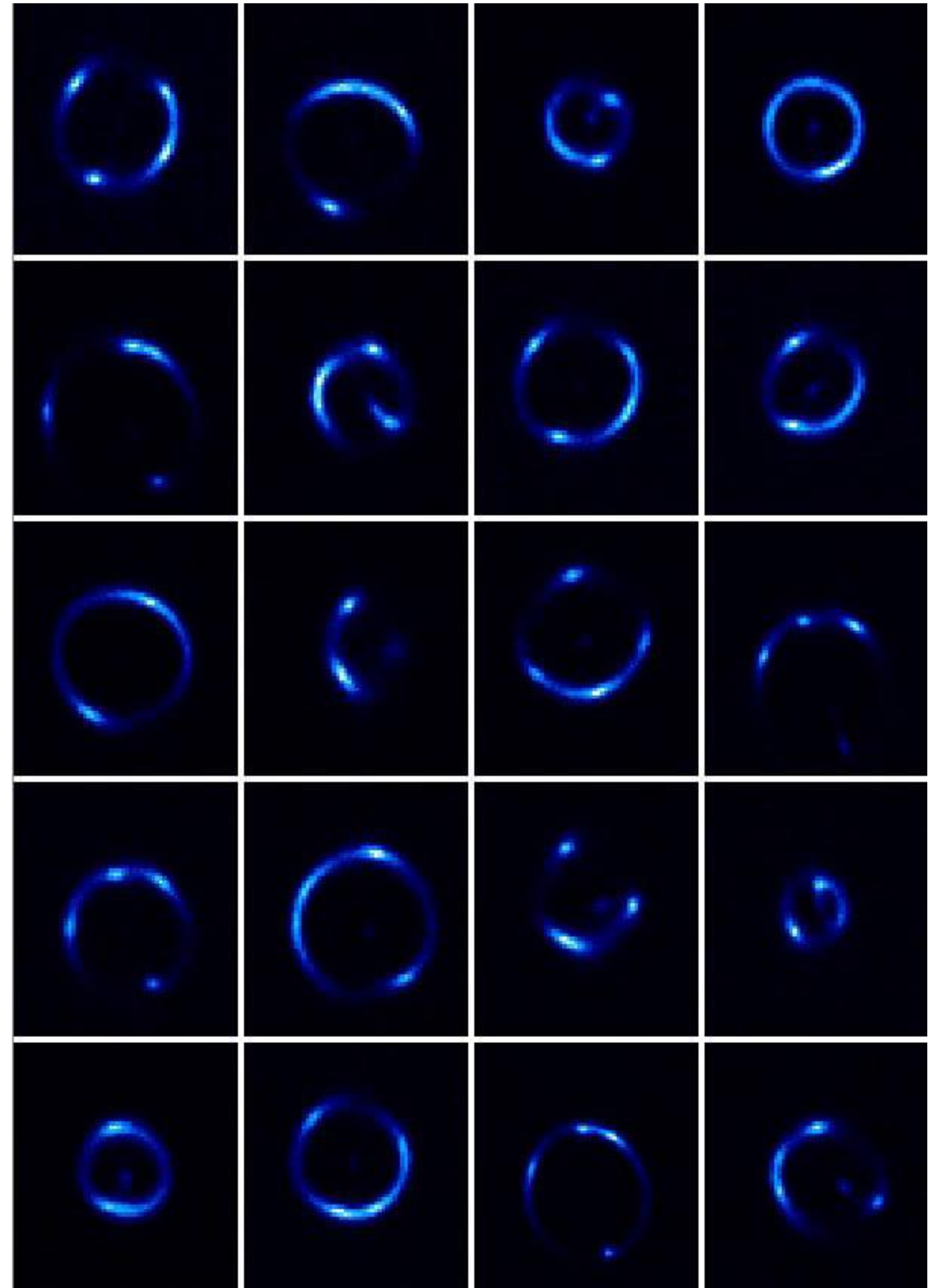
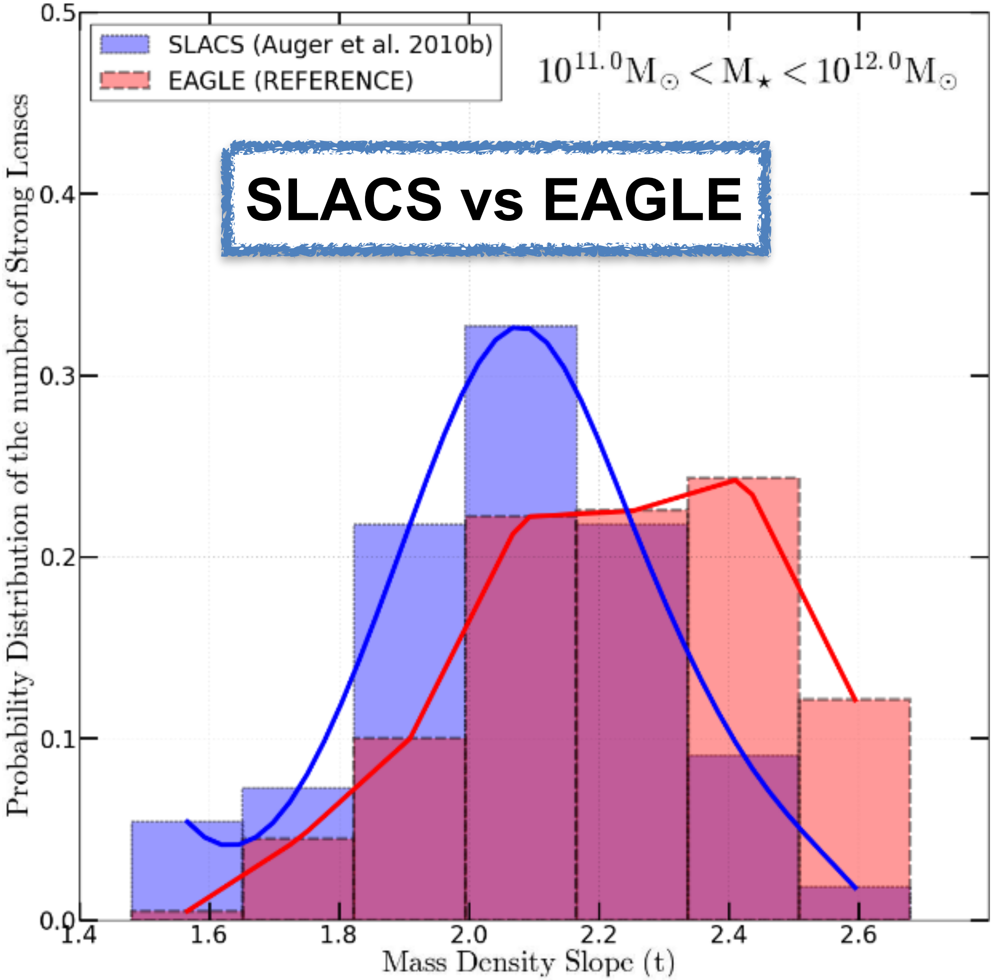
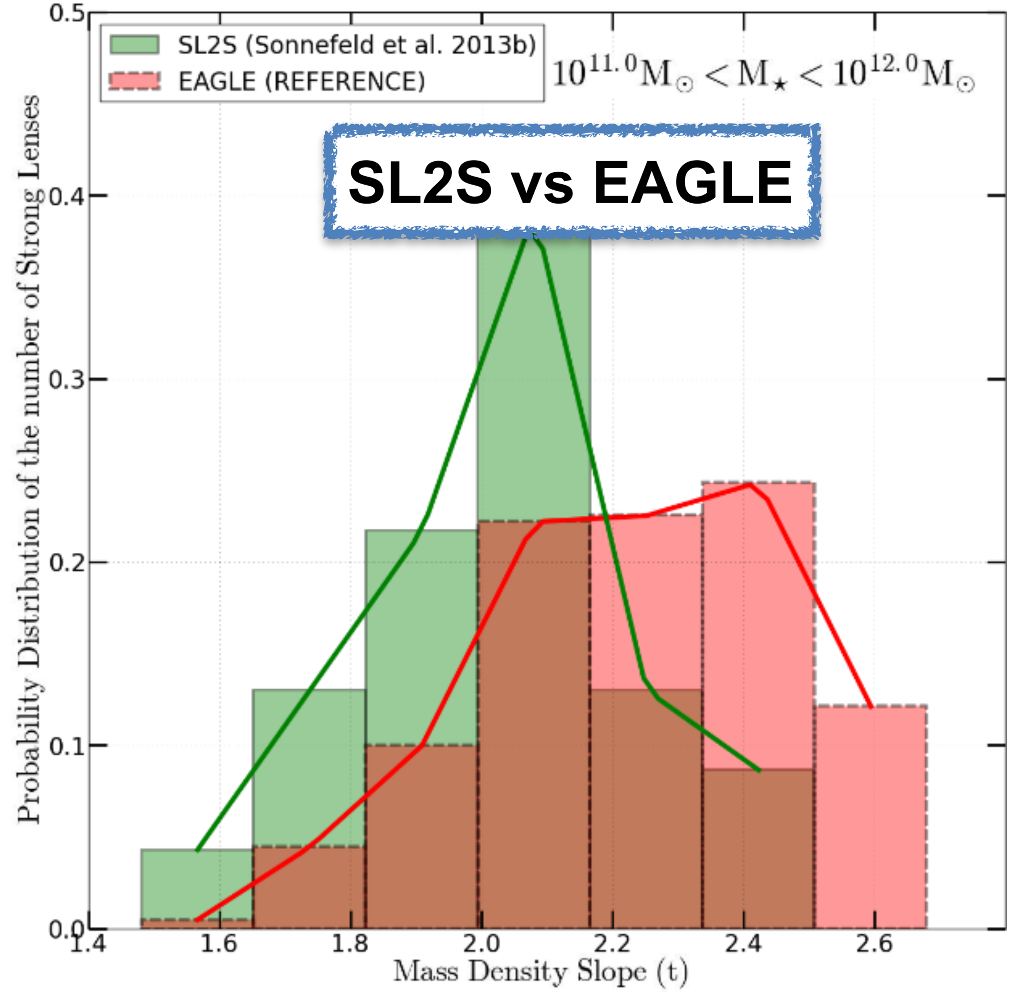


Image: A. Bolton (UH/IfA) for SLACS and NASA/ESA.

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







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	**–**

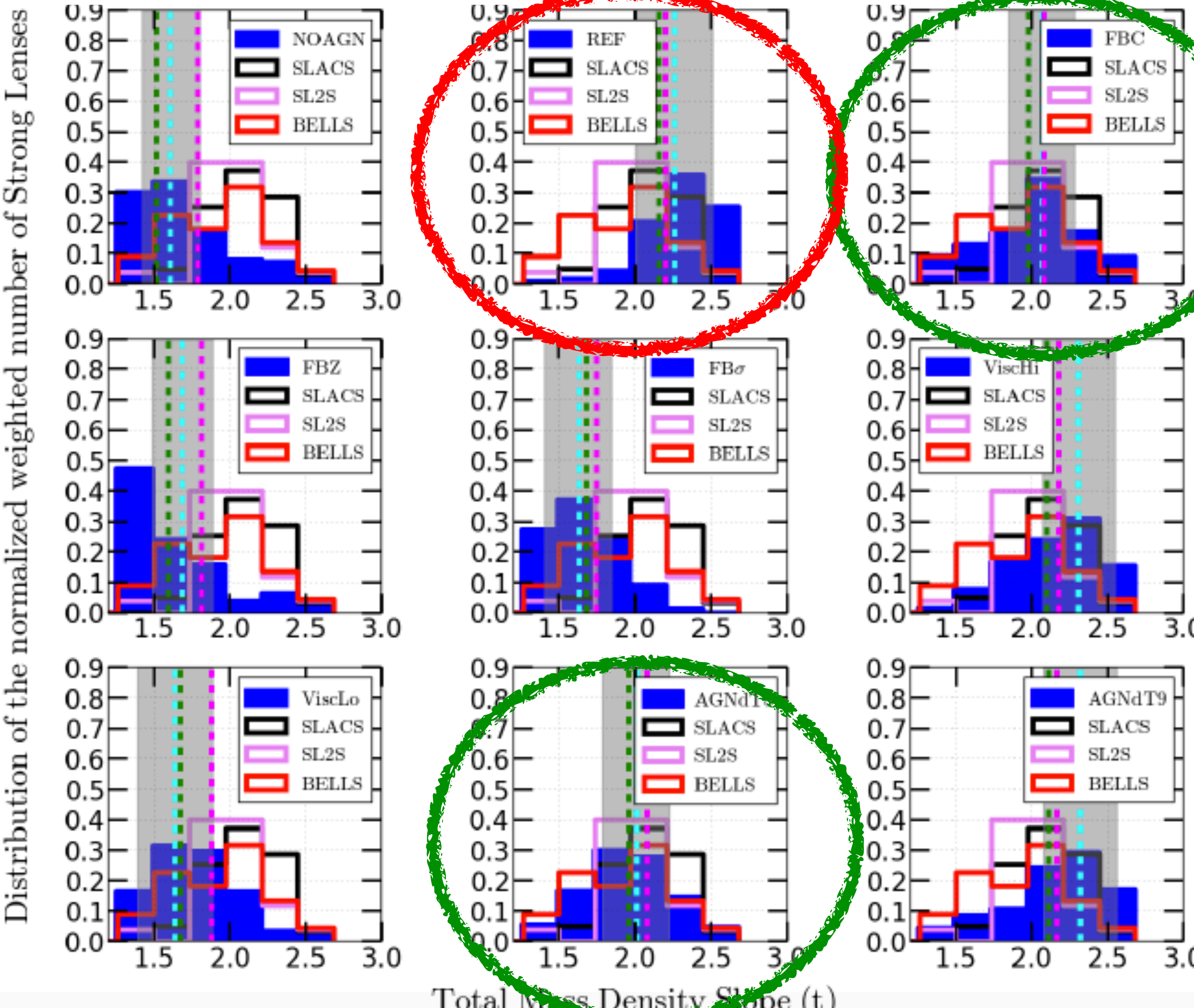
(Crain et al. 2015)

Reference Variations

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

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

Total Mass density slopes of EAGLE's 9 model variations



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

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

Mukherjee et al.
to be submitted to MNRAS

SEAGLE—V*: A mass-powerspectrum analysis of EAGLE strong lenses in variable galaxy formation scenario.*

Chatterjee, **Mukherjee** and Koopmans.
to be submitted to MNRAS

Thesis

Can we do some Microlensing too?

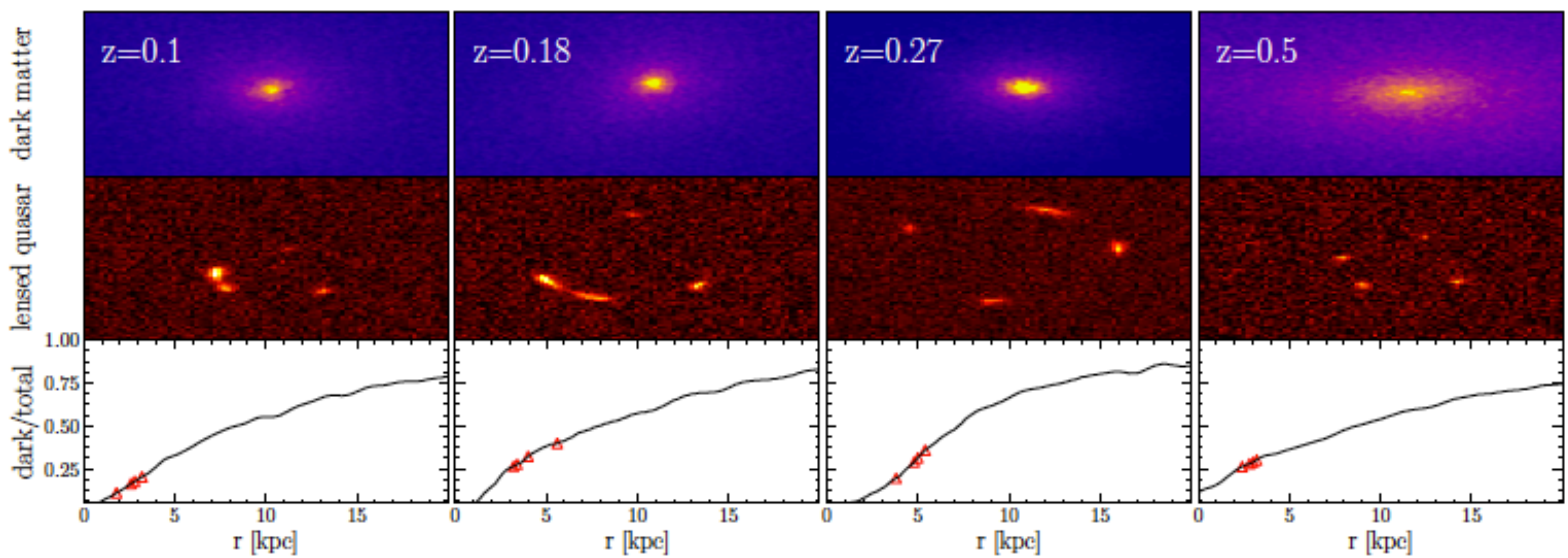
Astro2020 Science White Paper

arXiv:1904.12968

Pooley et al. 2019

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

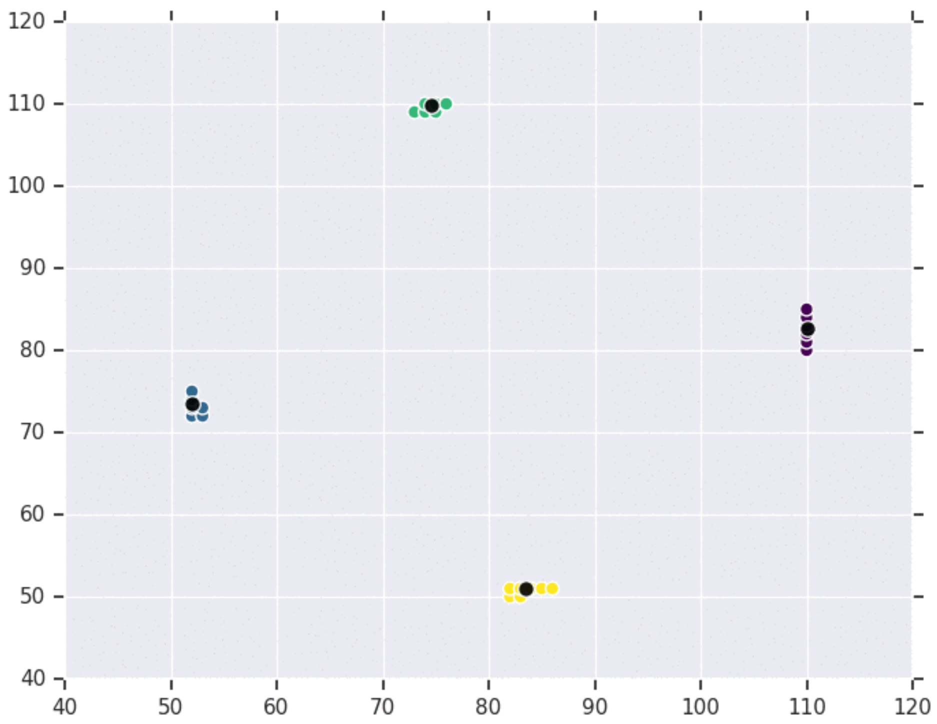
Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☑ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

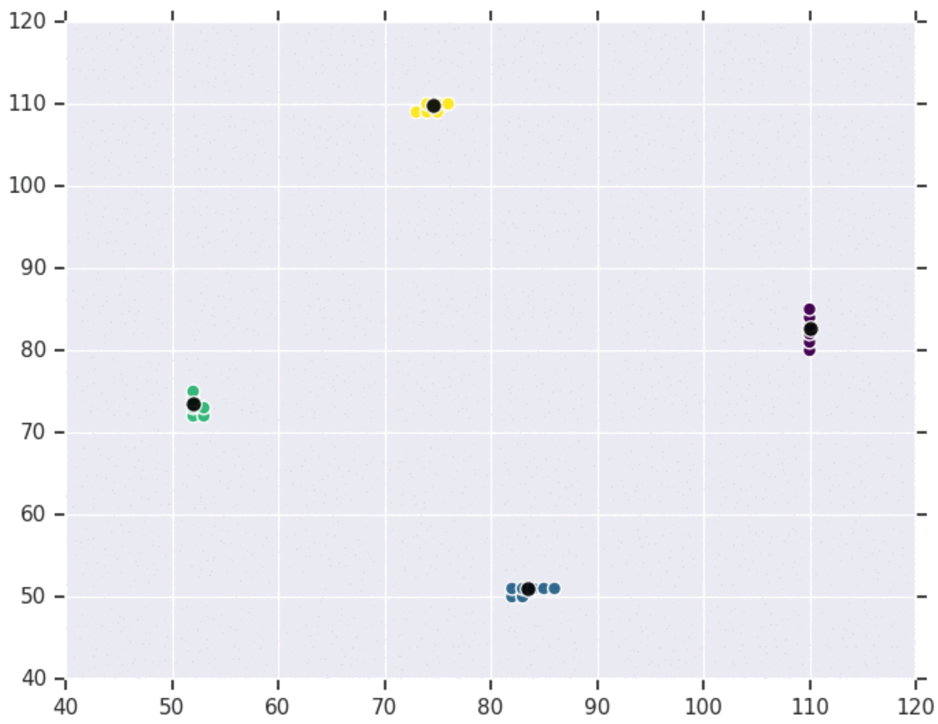


Microlensing with **SEAGLE**

Mukherjee+ in prep

Implementing clustering algorithm

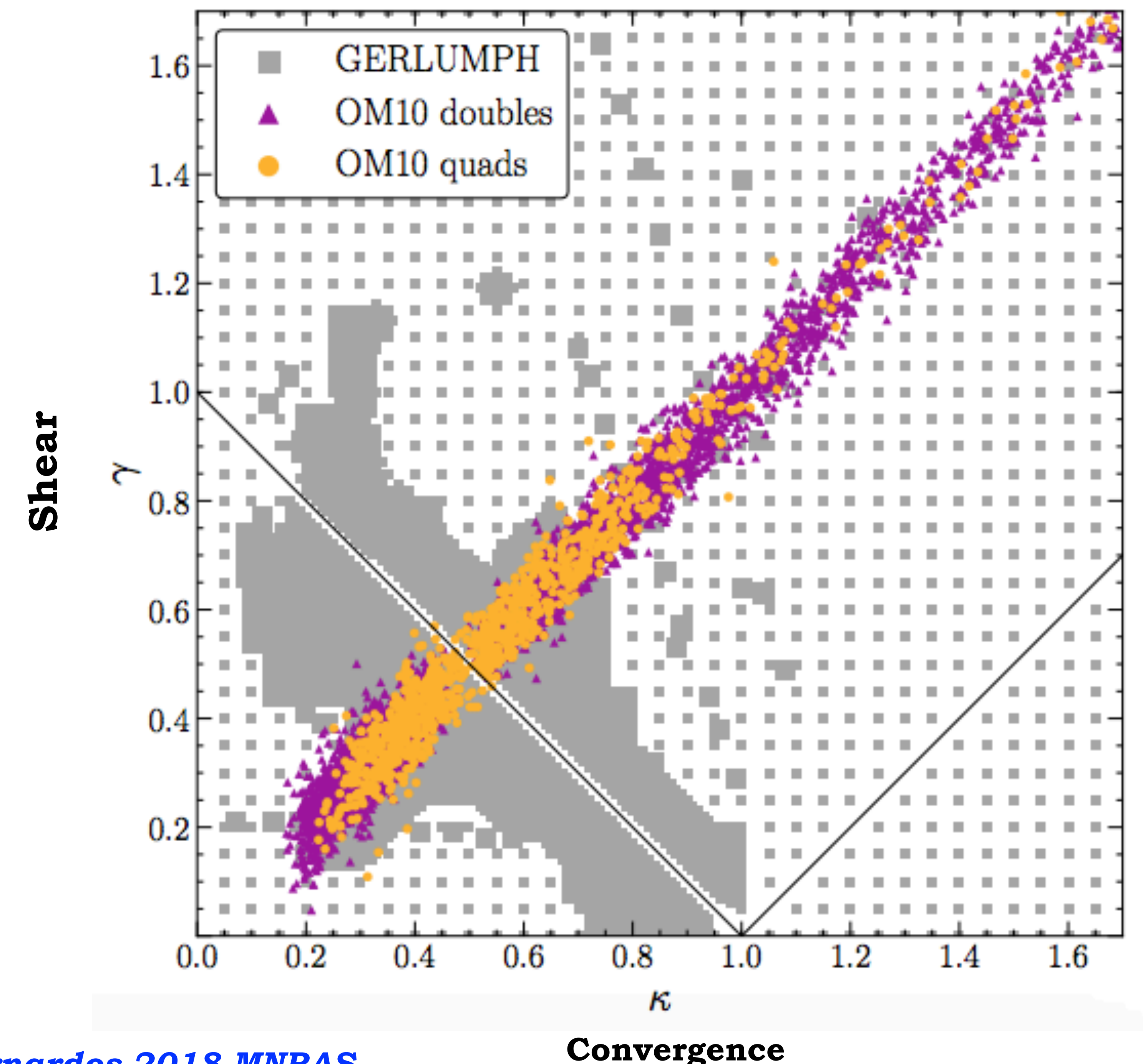




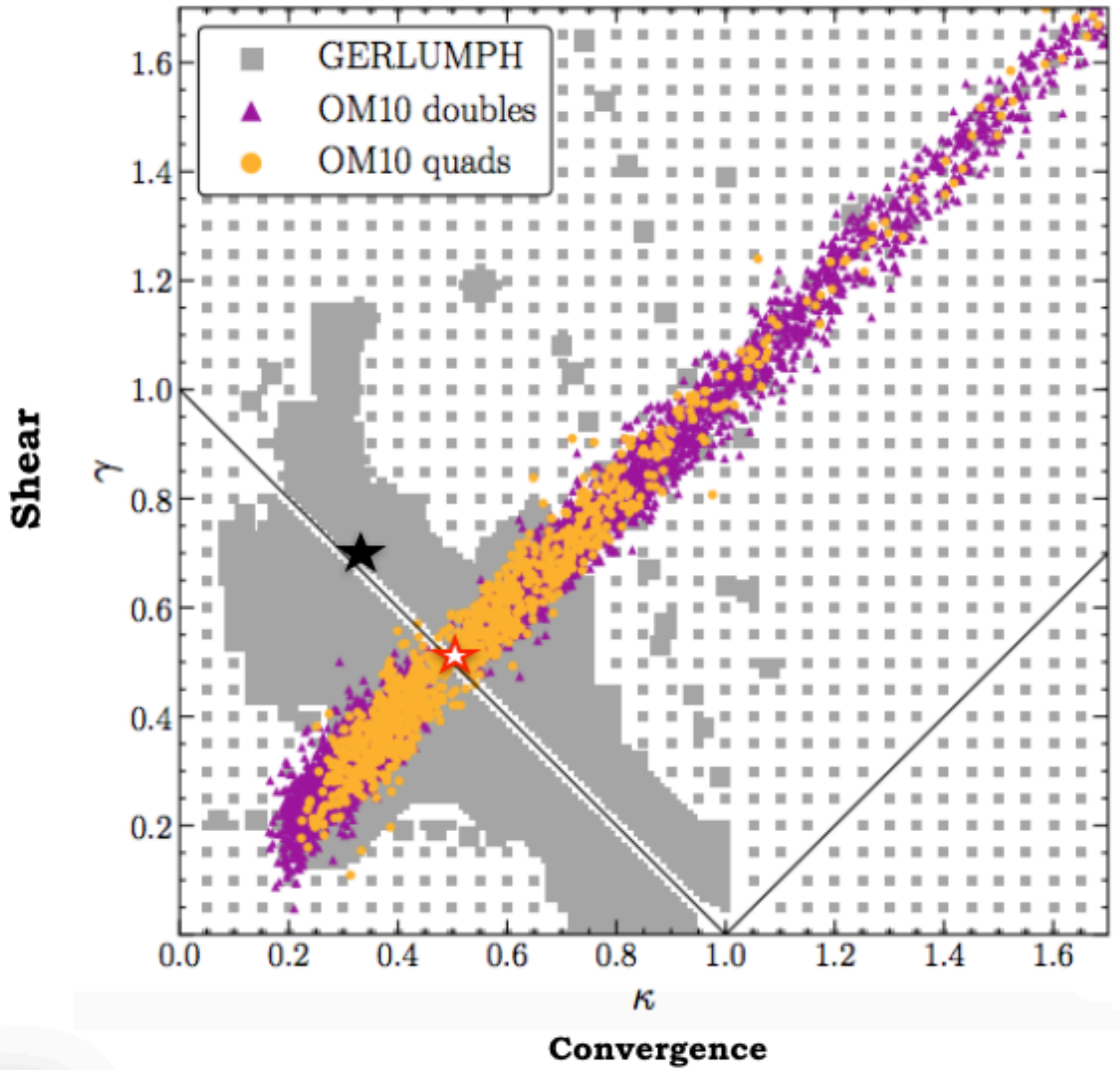
Stacked lensed systems with their brightest pixel

Individual lensed systems with their brightest pixel

z_lens= 0.271 and z_source= 1.0



Vernardos 2018 MNRAS



Mukherjee+ in prep

EAGLE Ref-100

EAGLE AGNdT8

Free Form Modelling on SEAGLE lenses

MNRAS **000**, 1–20 () Preprint 2 September 2019 Compiled using MNRAS LATEX style file v3.0

Testing free-form lens reconstruction techniques with simulated lenses

Philipp Denzel,[1,2] ⋆ Sampath Mukherjee,[3] Jonathan Coles,[4] Prasenjit Saha[1,2]

[1] *Physics Institute, University of Zurich, 8057 Zurich, Switzerland*
[2] *Institute for Computational Science, University of Zurich, 8057 Zurich, Switzerland*
[3] *Labo de physique atmosphérique et planétaire, University of Liège, 4000 Liège 1, Belgium*
[4] *Physik-Department, Technische Universität München, James-Franck-Str. 1, 85748 Garching, German*

Denzel et al. to be submitted

Free Form Modelling on SEAGLE lenses

Philipp Denzel (U. Zurich), Me (U. Liege), Prasenjit Saha (U. Zurich), Jonathan Coles (TUM)

- Uses GLASS code (*Coles et al. 2014,* also see *Kung,Saha+ 2015, 2017*)
- It finds the models of convergence that fits the maxima, minima, and saddle points
- Additional priors :
  - Centrally concentrated Mass distribution
  - a convergence gradient that differs no more than 85 degrees

θ, angular position coordinates

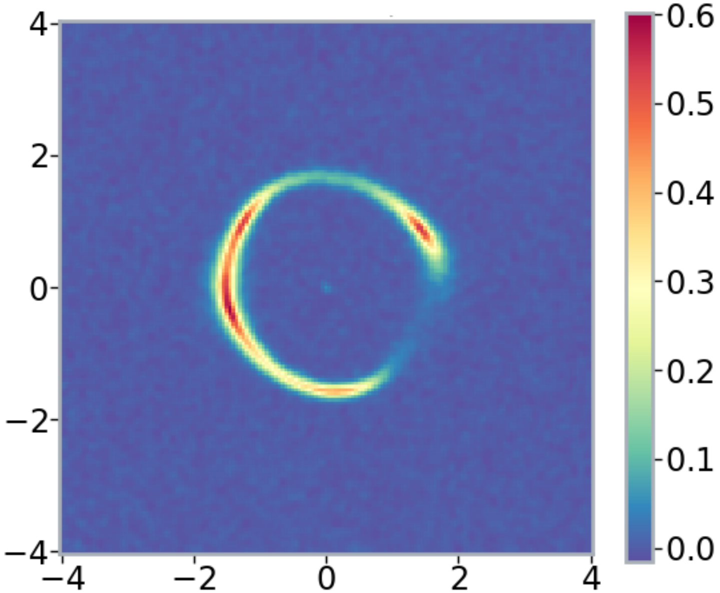
"Roche potential" $\tau = 1/2\ \theta\hat{}2 - \varphi$

φ, the lensing potential.

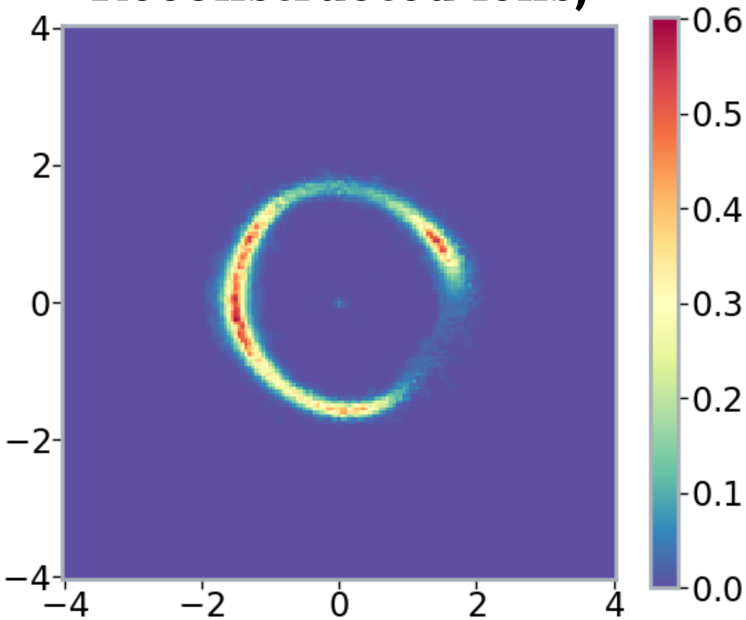
Denzel et al. to be submitted

Advantage: consists of only the terms which stay unaffected by the mass-sheet degeneracy

Data (EAGLE lens)

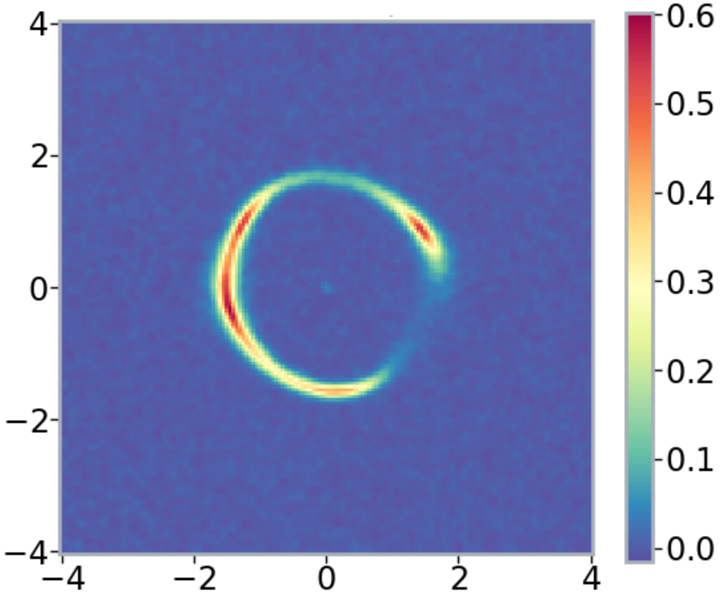


Reconstructed lens)

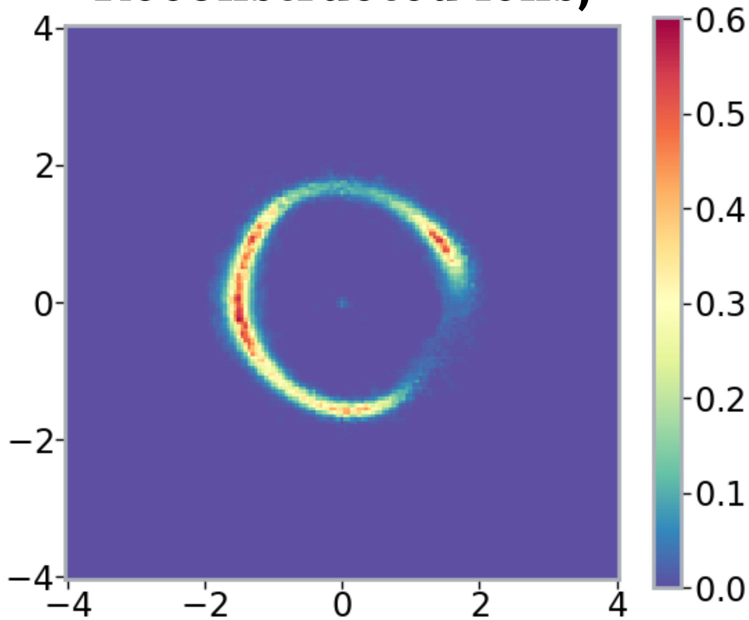


Denzel et al. to be submitted

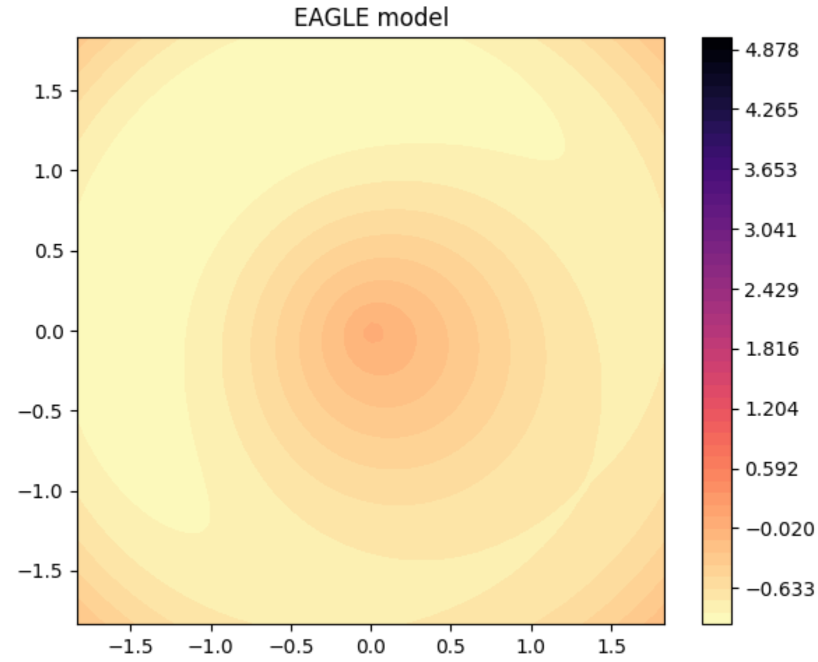
Data (EAGLE lens)

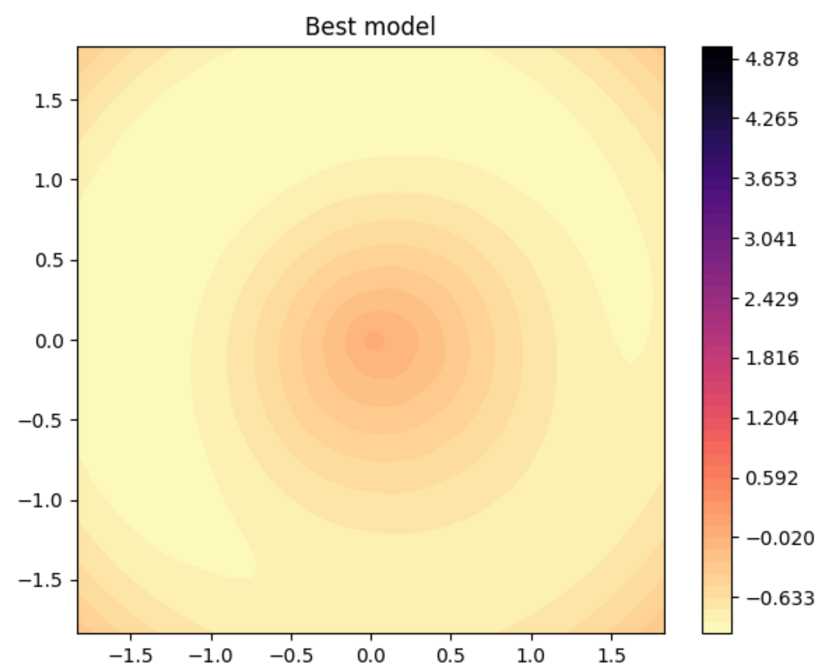


Reconstructed lens)



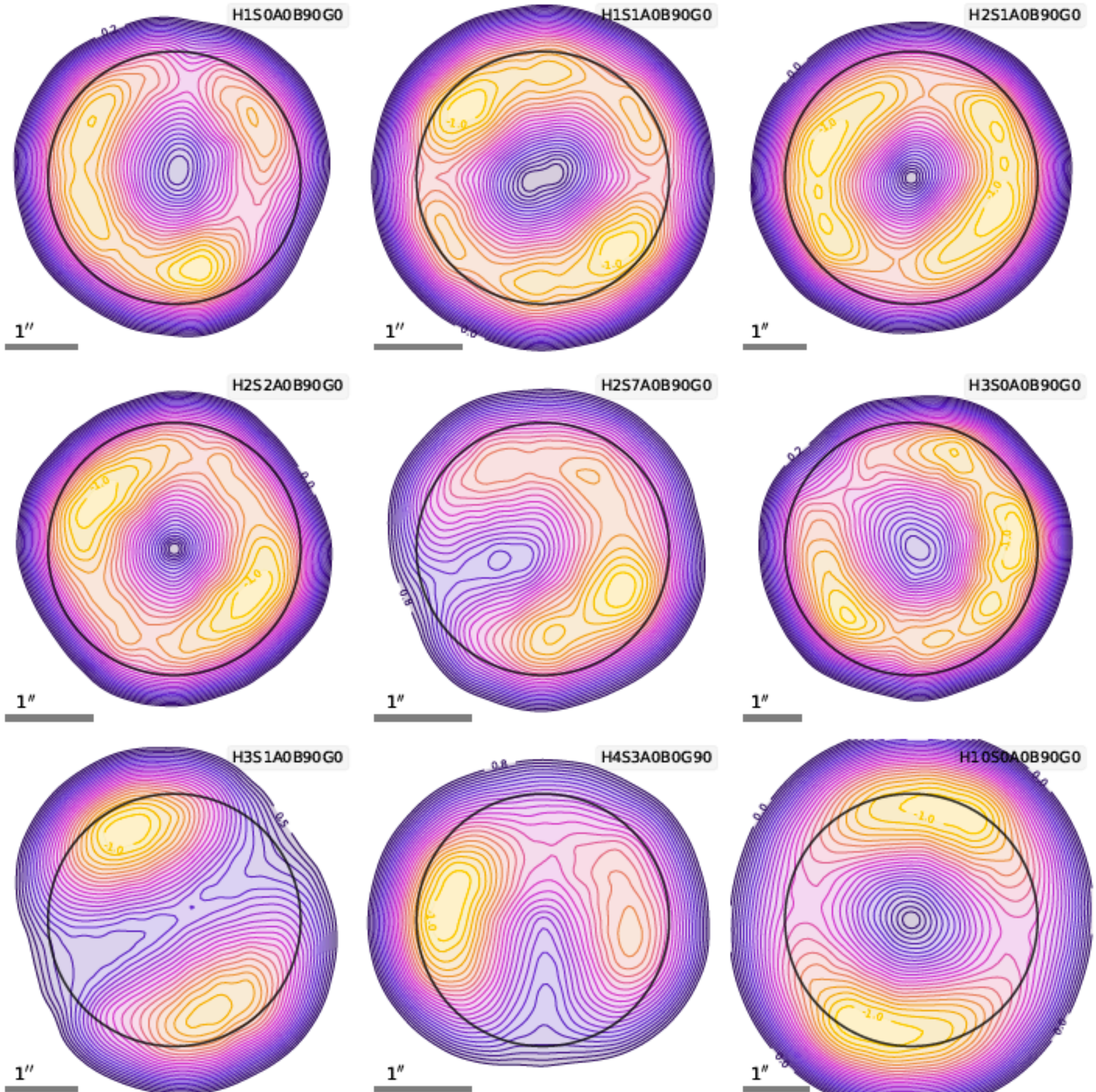
“Roche potential”





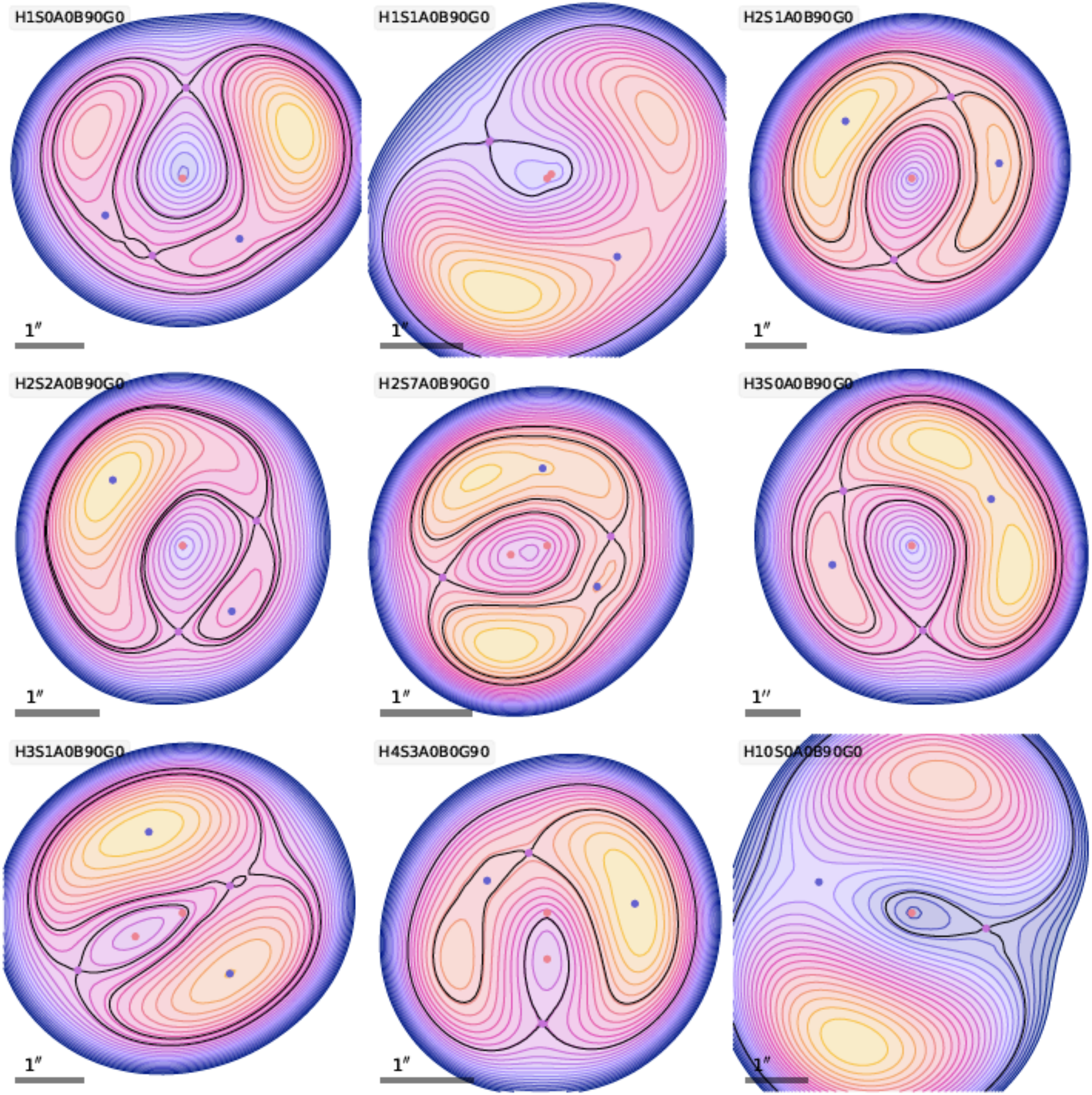
Denzel et al. to be submitted

“Roche potential”



Denzel et al. to be submitted

Time Arrival map



Denzel et al. to be submitted

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. Vernardos, **Mukherjee,** Sluse — GERLUMPH and EAGLE.
7. **Mukherjee,** Vernardos, Sluse —- Shear-convergence correlation in EAGLE
8. Denzel, **Mukherjee,** Cole, Saha —— New strong lens modelling code

COSMICLENS

Time delay and Hubble constant

Why Time delay from SL are crucial?

- Cosmological distances — — — > the discovery of the expansion of the Universe.
- More precise distance measurements — — — > expansion is accelerating.

Questions ?

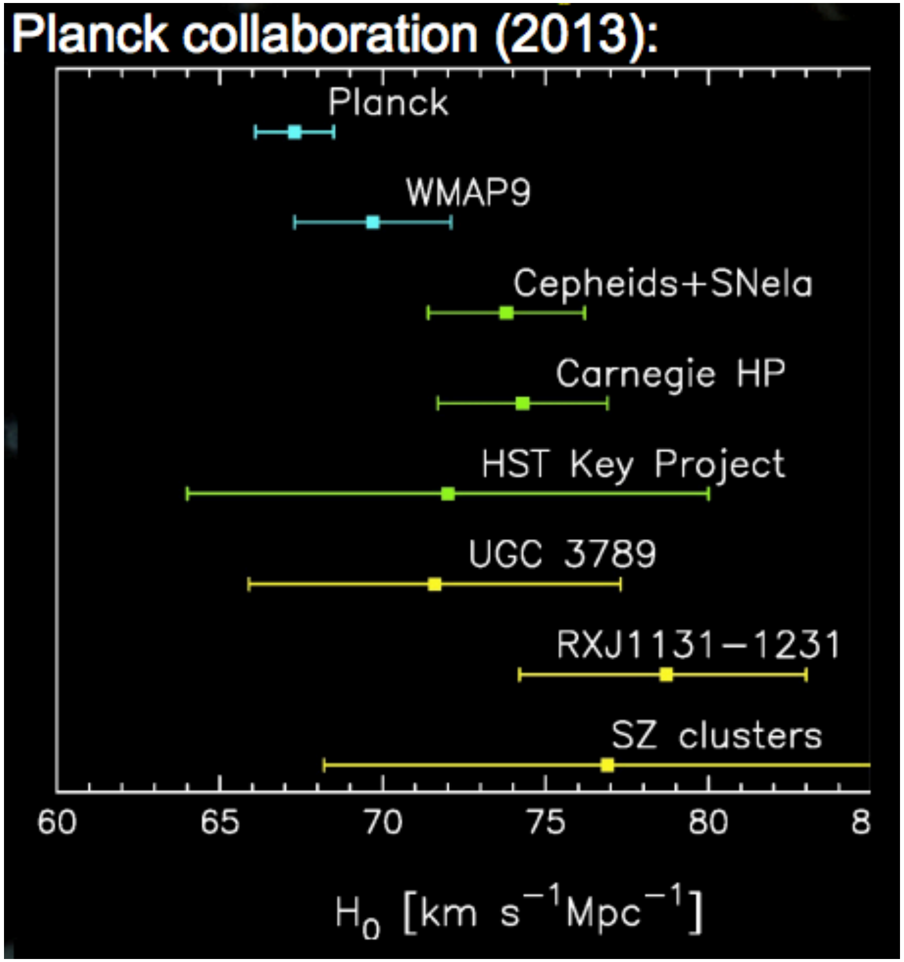
- Is the acceleration due to some repulsive form of dark energy?
- To Einstein's cosmological constant?
- Do we need to consider new physics?

Answer requires a precise measurement of the Hubble parameter, H_0.

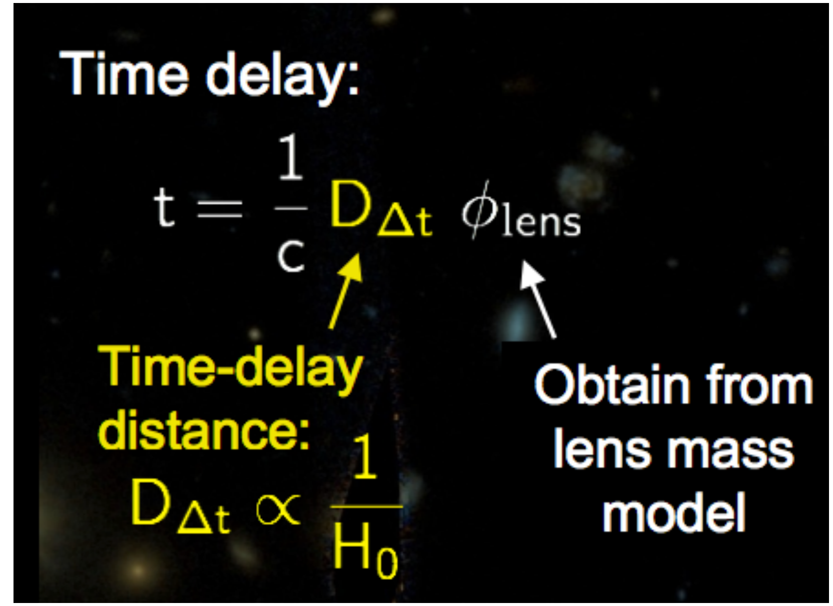
Advantage:

- Can yield H_0 to <2%
- No calibration
- Independent of any other cosmological probe

Time delay and Hubble constant



Independent measurements are needed!

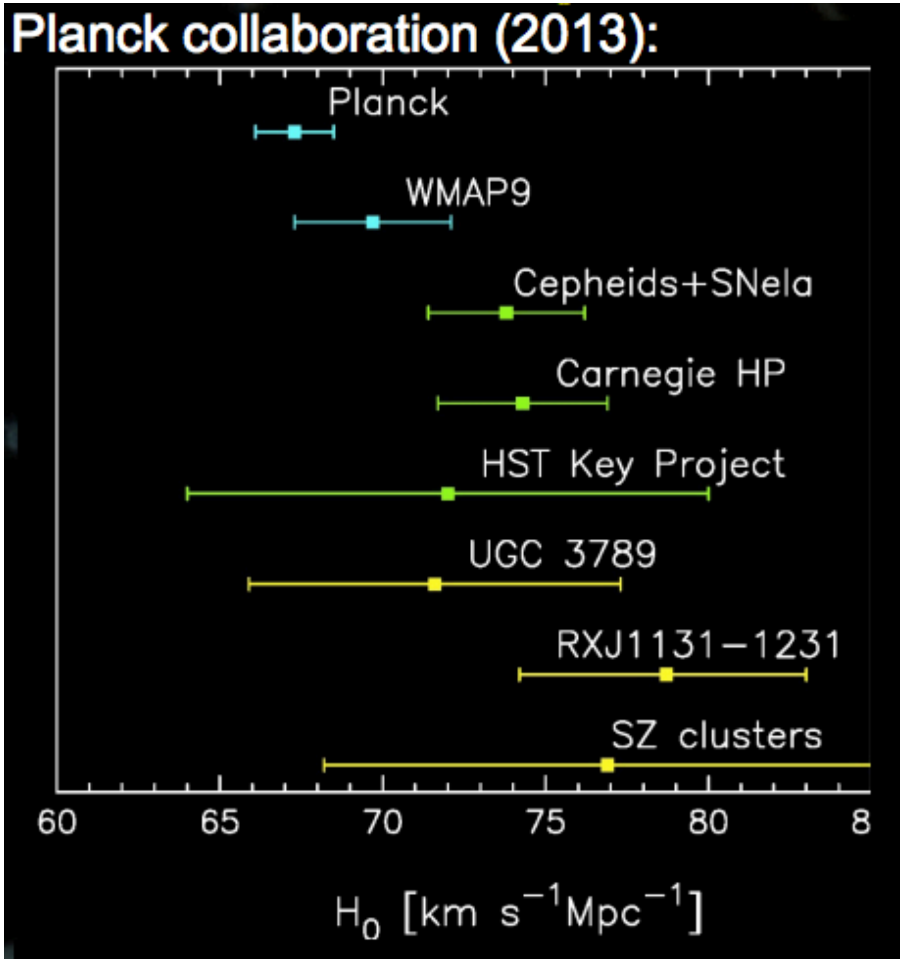


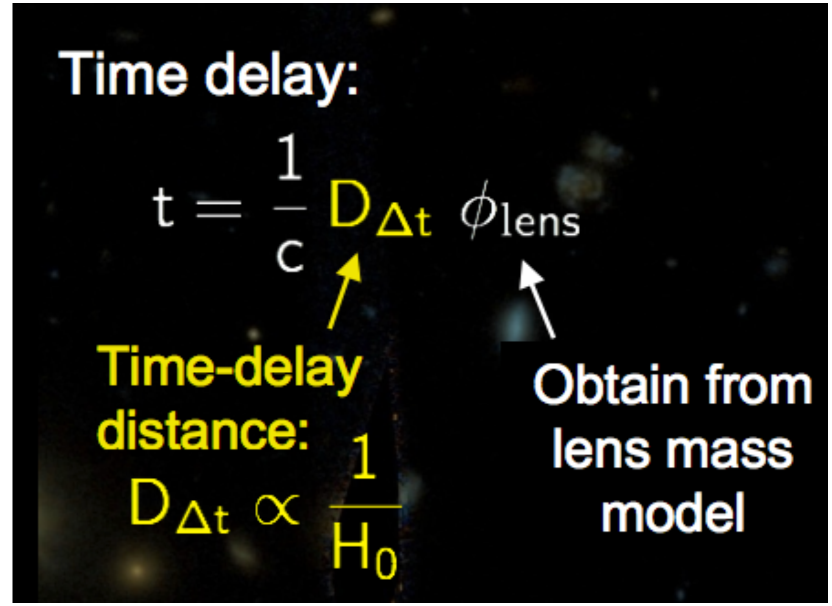
For cosmography we need:

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

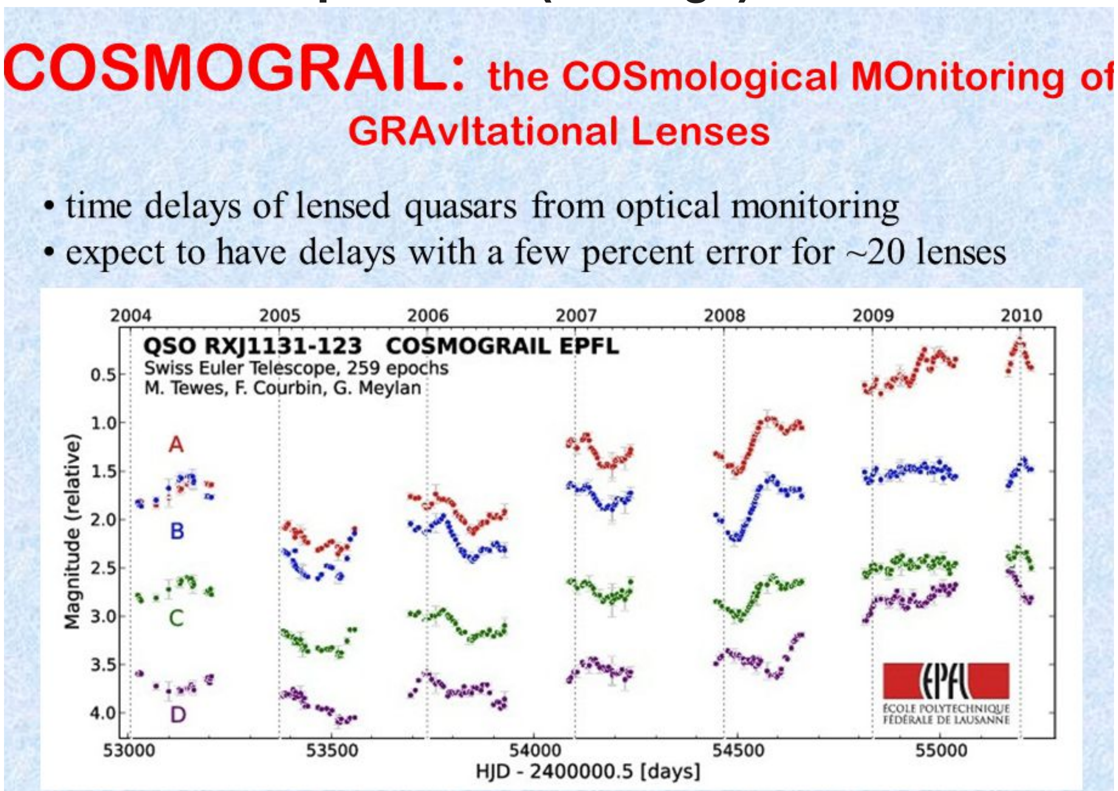
Credit: S. Suyu

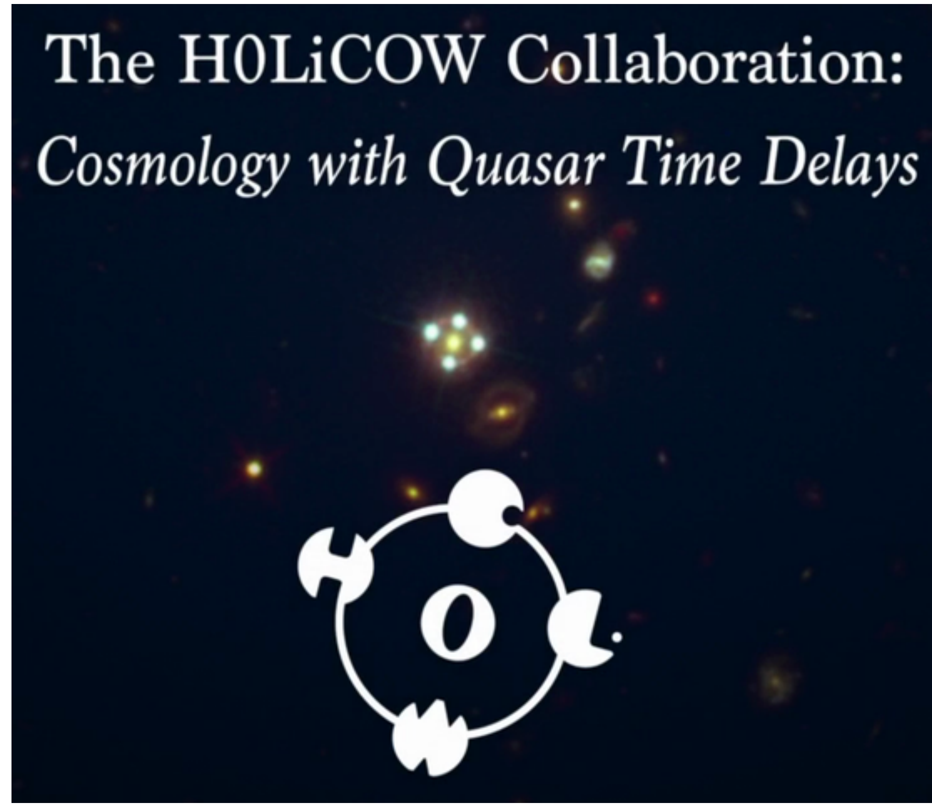
COSMICLENS: Cosmology with Strong Gravitational Lensing

ERC Advanced Grant

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

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





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).

COSMICLENS

SEAGLE

COSMICLENS

SEAGLE

GLAMER

- **Analytic + N-body**

Time delay (δ t)
Line of sight
Multi plane/Light cone

COSMICLENS

Lenstronomy

- **Analytic + N-body**

Time delay (δt)
Line of sight
Instrumentation

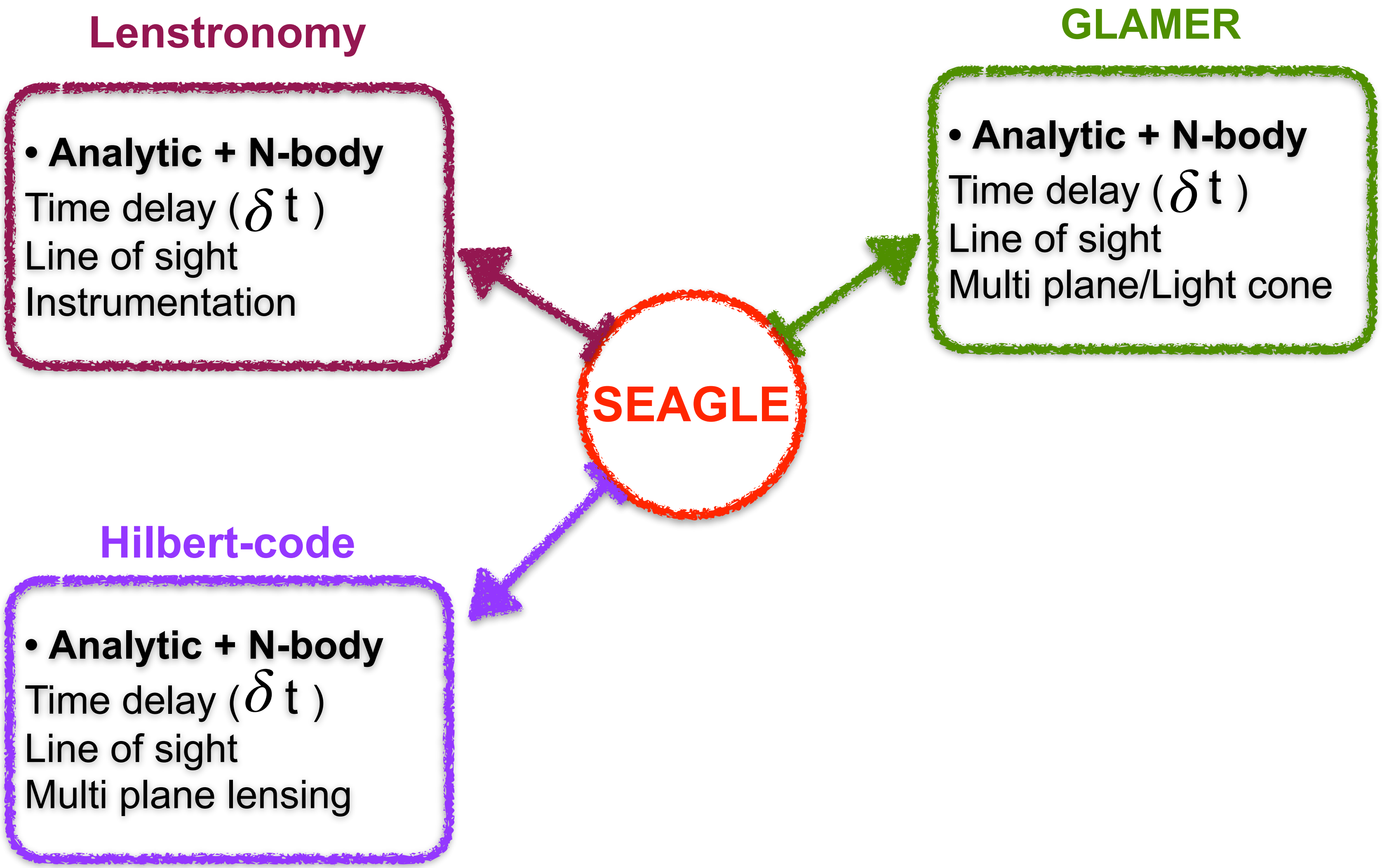
GLAMER

- **Analytic + N-body**

Time delay (δt)
Line of sight
Multi plane/Light cone

SEAGLE

COSMICLENS



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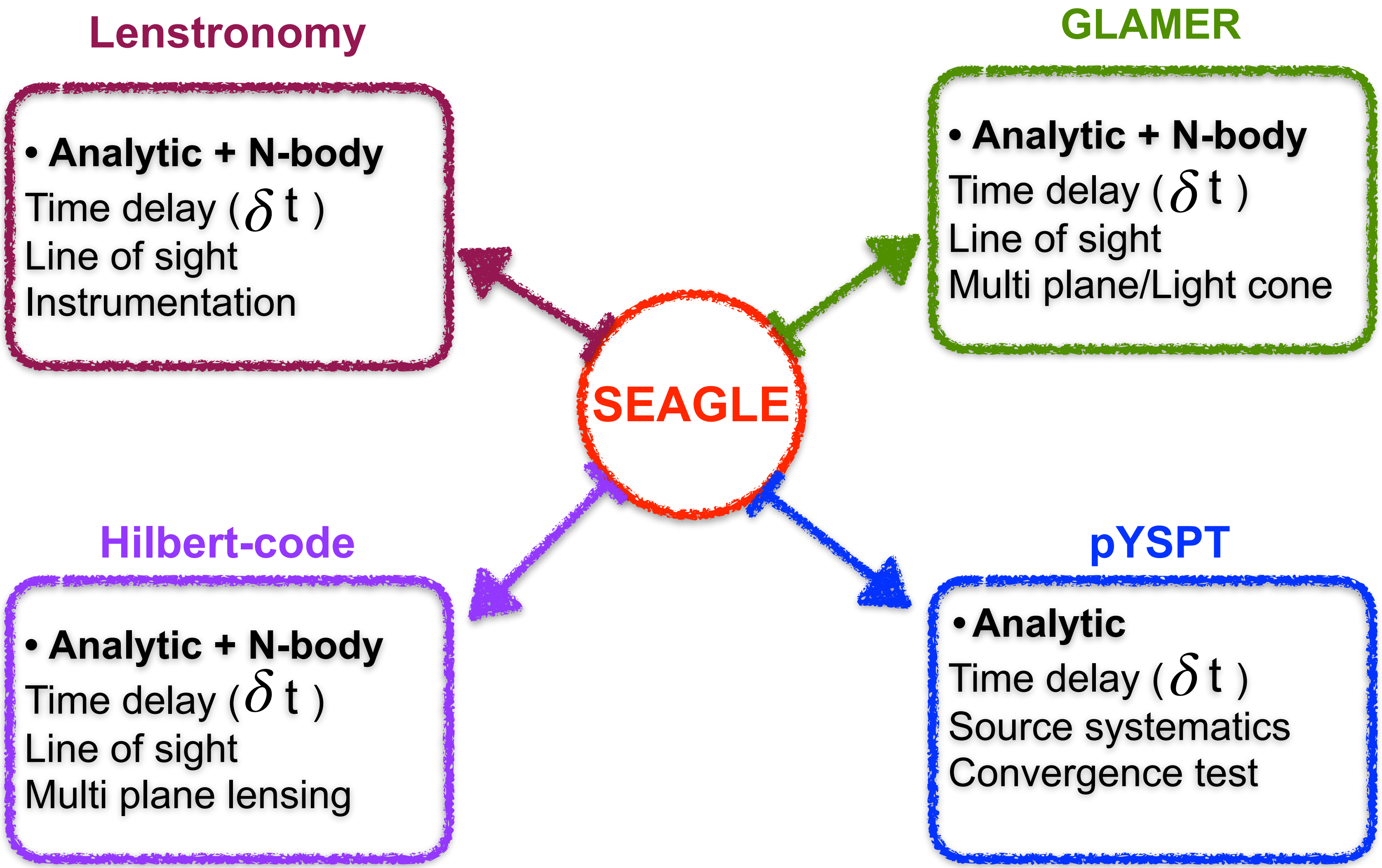
Multi plane/Light cone
SEAGLE
Hilbert-code
• Analytic + N-body
Time delay (δt)
Line of sight
Multi plane lensing

COSMICLENS



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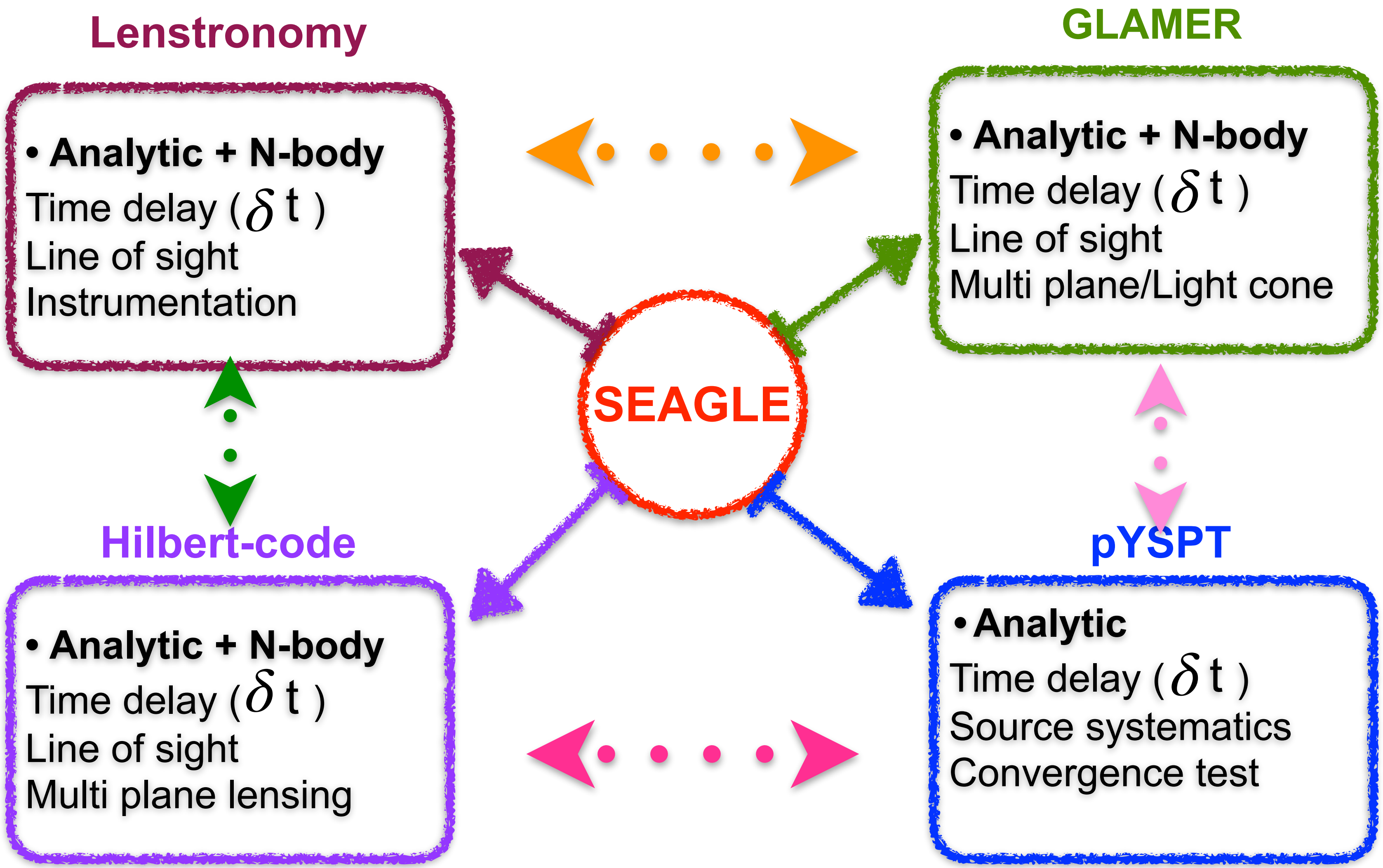
Hilbert-code
• Analytic + N-body
Time delay (δ t)
Line of sight
Multi plane lensing
pYSPT
• Analytic
Time delay (δ t)
Source systematics
Convergence test

COSMICLENS



Lenstronomy
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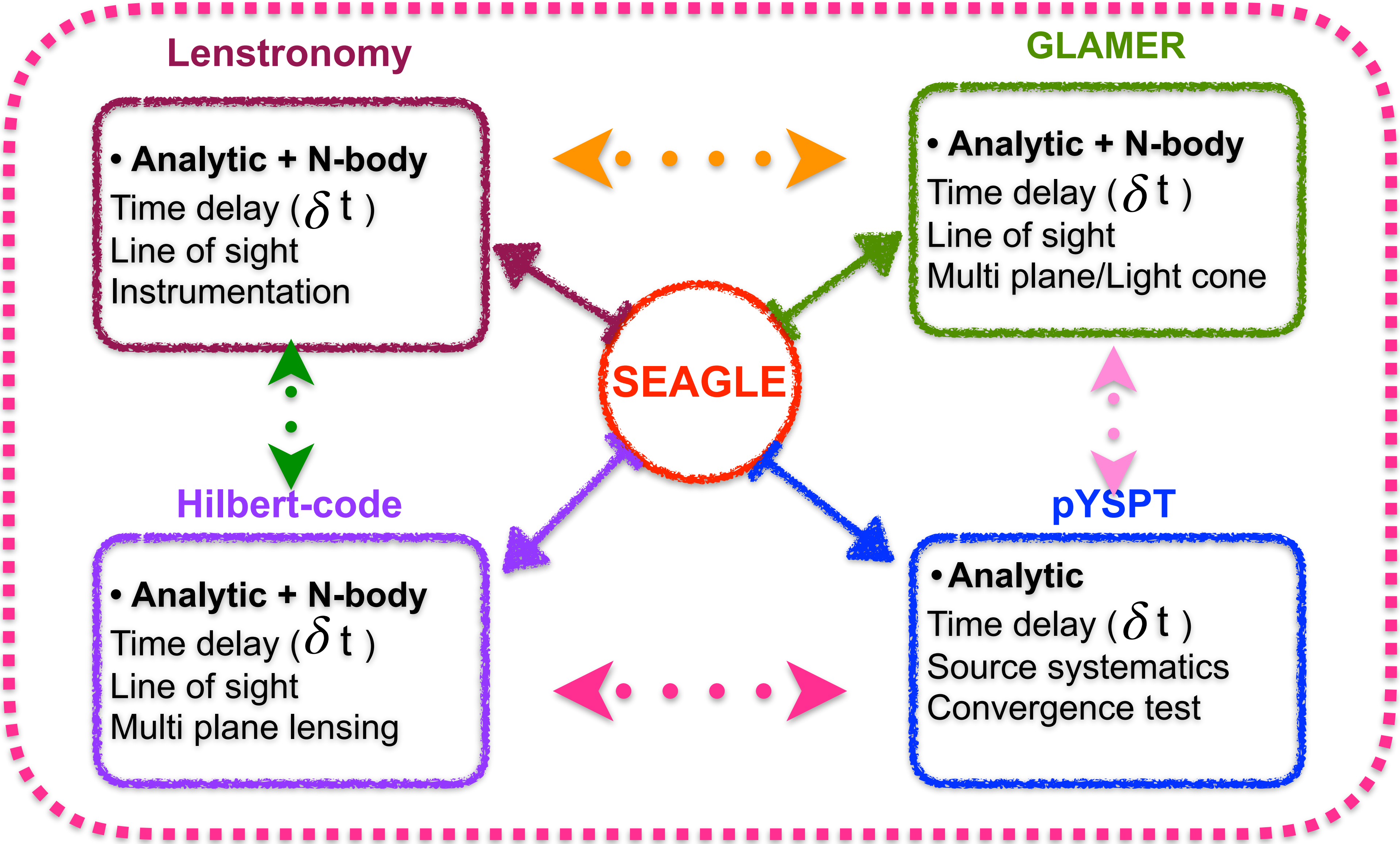
COSMICLENS


Lenstronomy
• Analytic + N-body
Time delay (δ t)
Line of sight
Instrumentation
GLAMER
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Time delay (δ t)
Line of sight
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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

Effect of baryonic prescriptions on lensing LOS and H_0

Background

H0LiCOW obtained external convergences (k)
using Millennium simulation (DM only) + SAM

See **H0LiCOW III**: Rusu, Fassnacht+ 2017

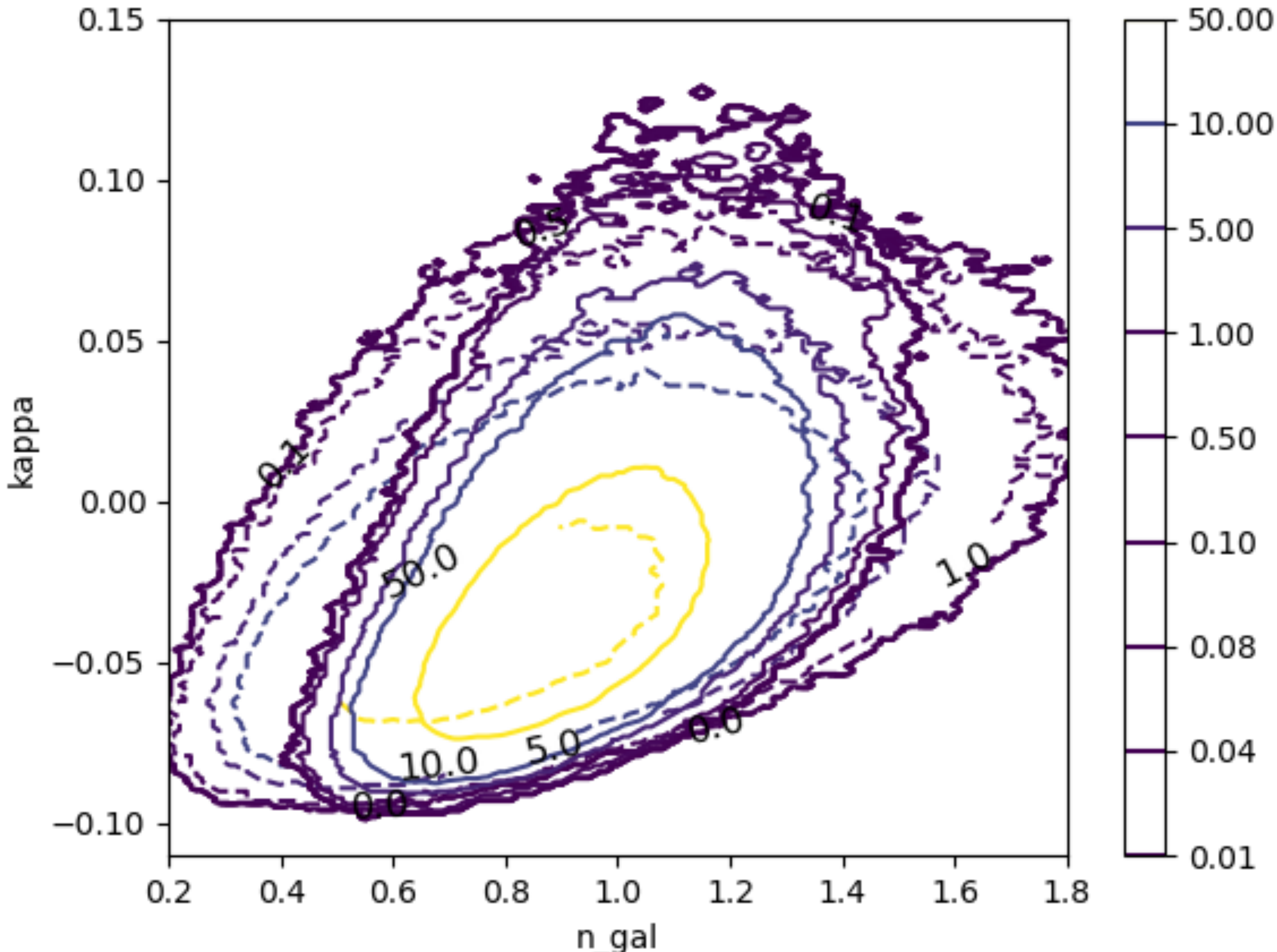
Goals

What happens when when we change the Baryonic physics
On Millenium Simulation ?

Have a database of k and shear for a range of redshifts and baryonic models

COSMICLENS: ***Mukherjee***, *Hilbert+ et al in prep*

Effect of baryonic prescriptions on lensing LOS and Ho



(solid line)

Henriques 2014

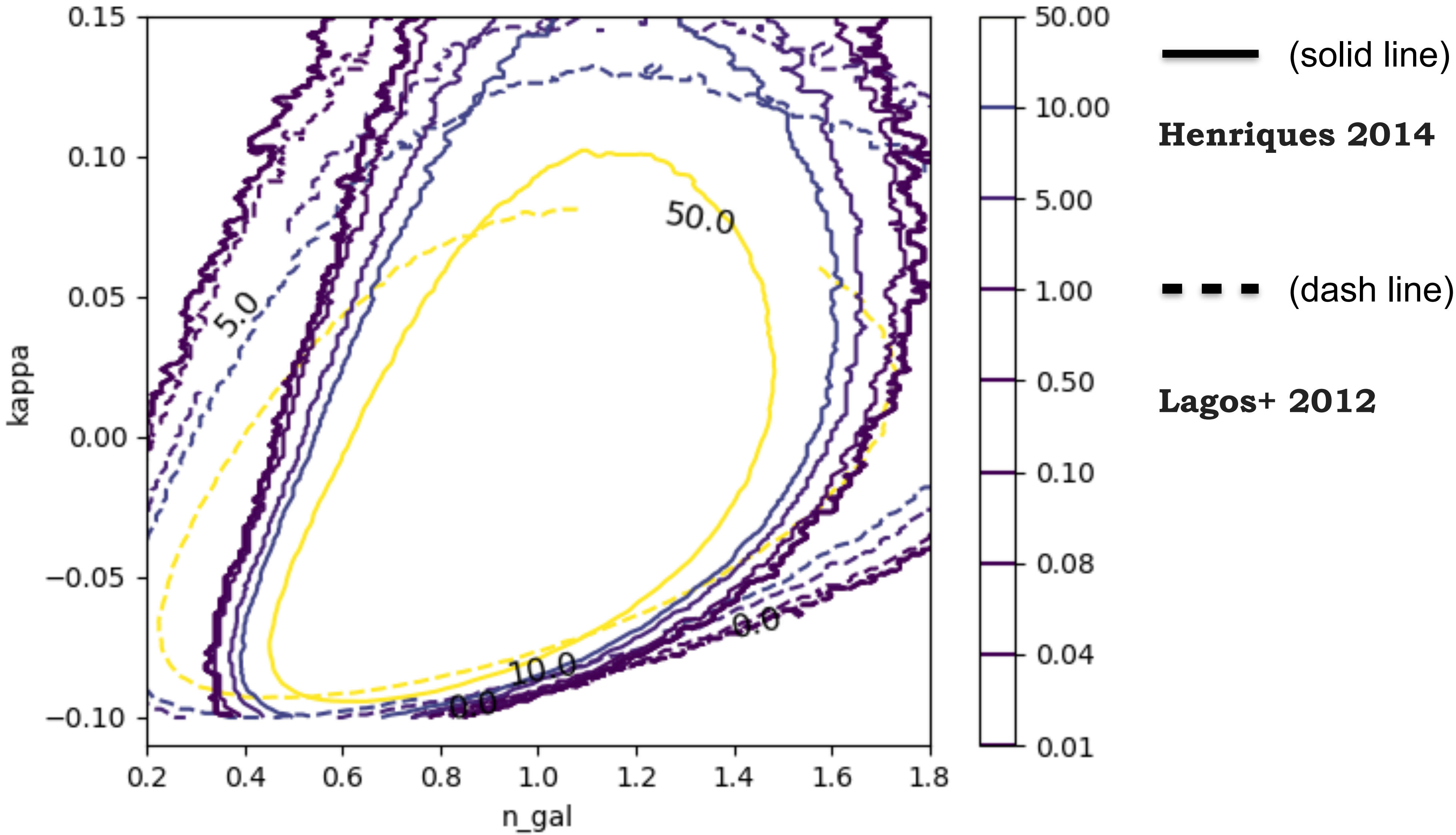
(dash line)

Lagos+ 2012

gamma= 0.00

COSMICLENS: ***Mukherjee***, *Hilbert+ et al in prep*

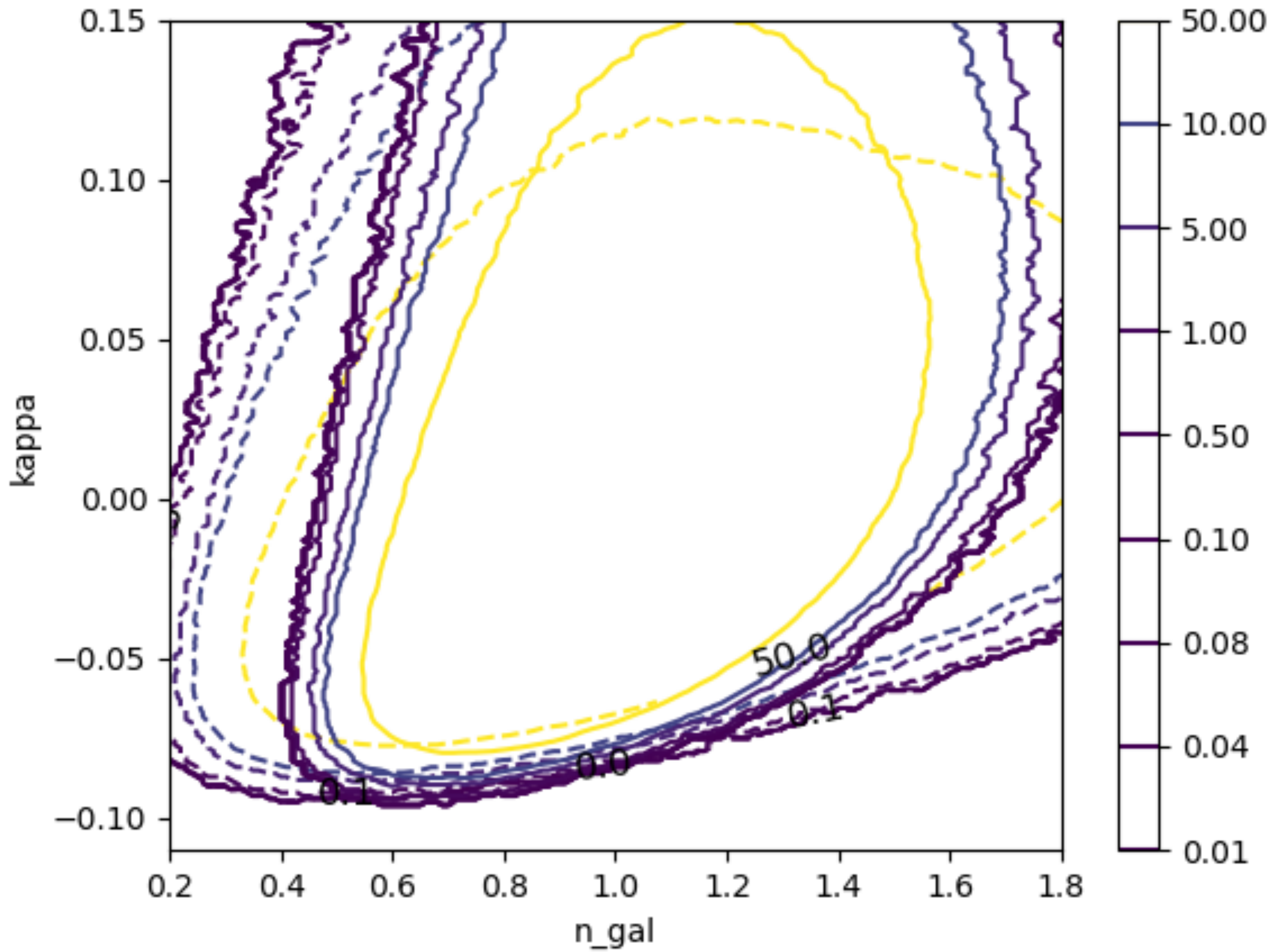
Effect of baryonic prescriptions on lensing LOS and Ho



gamma= 0.01

COSMICLENS: ***Mukherjee***, *Hilbert+ et al in prep*

Effect of baryonic prescriptions on lensing LOS and Ho



(solid line)

Henriques 2014

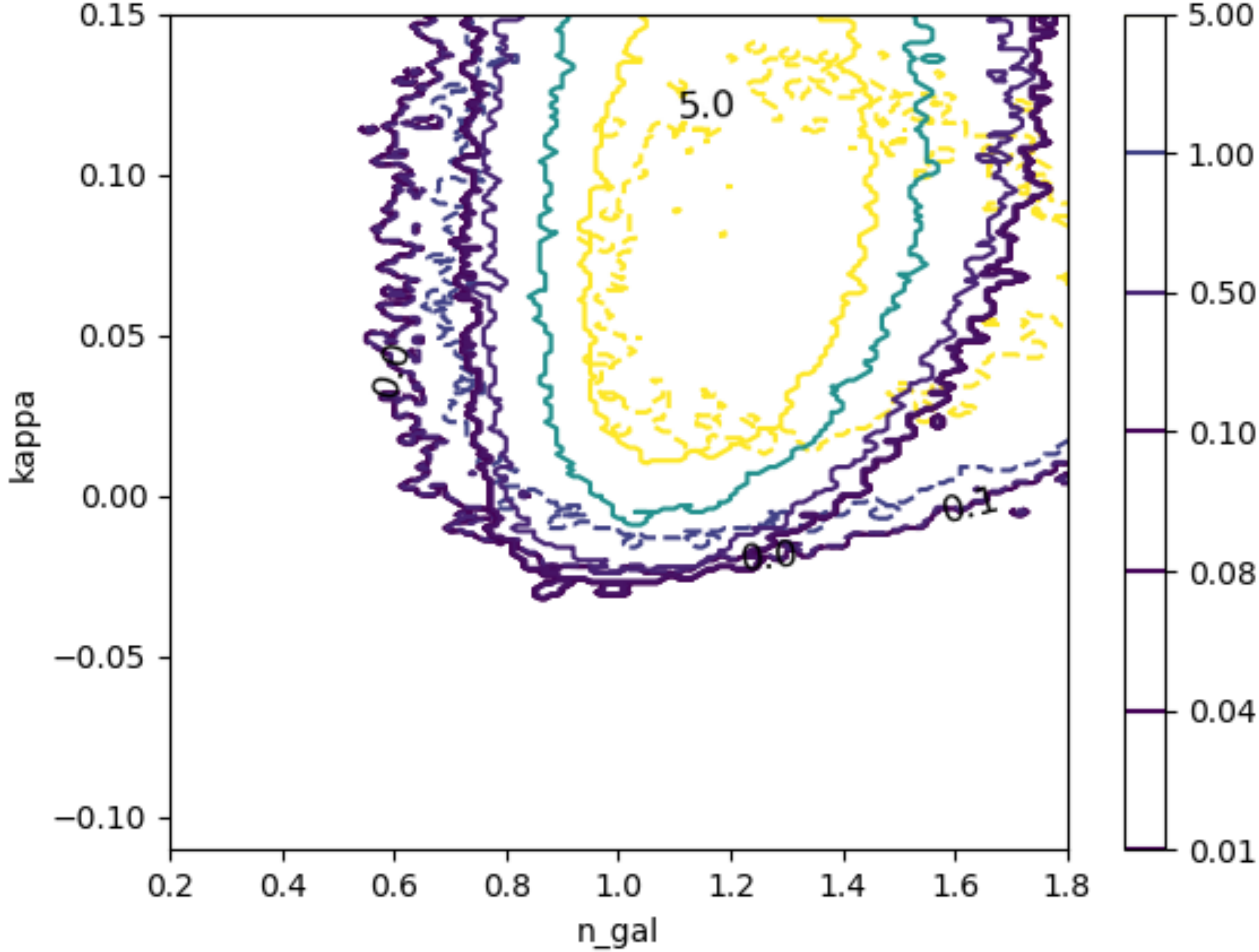
(dash line)

Lagos+ 2012

gamma= 0.07

COSMICLENS: ***Mukherjee***, *Hilbert+ et al in prep*

Effect of baryonic prescriptions on lensing LOS and H0



(solid line)

Henriques 2014

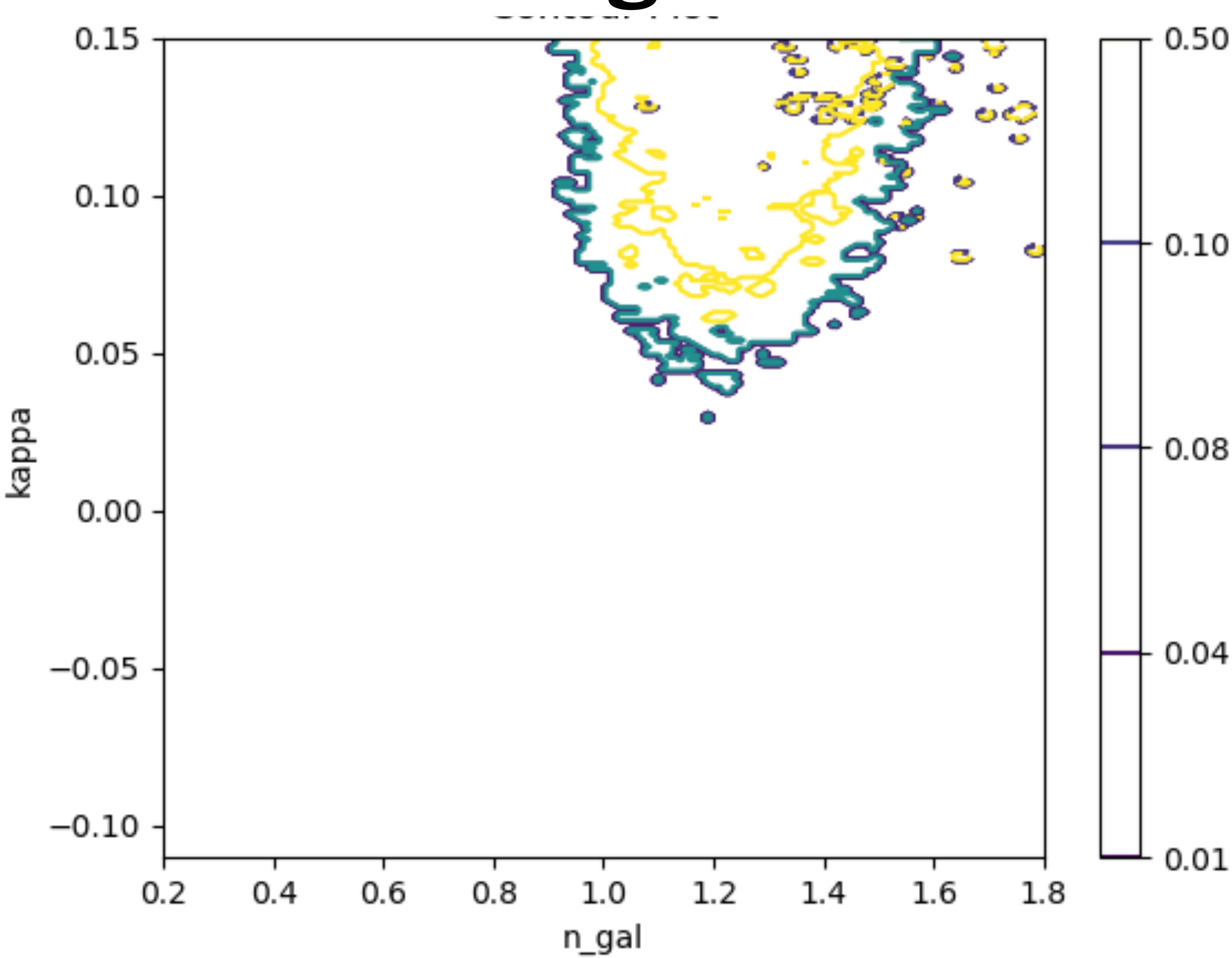
(dash line)

Lagos+ 2012

gamma= 0.16

COSMICLENS: ***Mukherjee***, *Hilbert+ et al in prep*

Effect of baryonic prescriptions on lensing LOS and Ho



(solid line)

Henriques 2014

(dash line)

Lagos+ 2012

gamma= 0.2

COSMICLENS: ***Mukherjee***, *Hilbert+ et al in prep*

Study of degenerecies in mock lensing system

Creation of mock images

Image modeling

A

Seagle lens

Add quasar

Add extended source

Mock image with time delay

<u>Other specification :</u>
Gaussian PSF
No noise
No lens light

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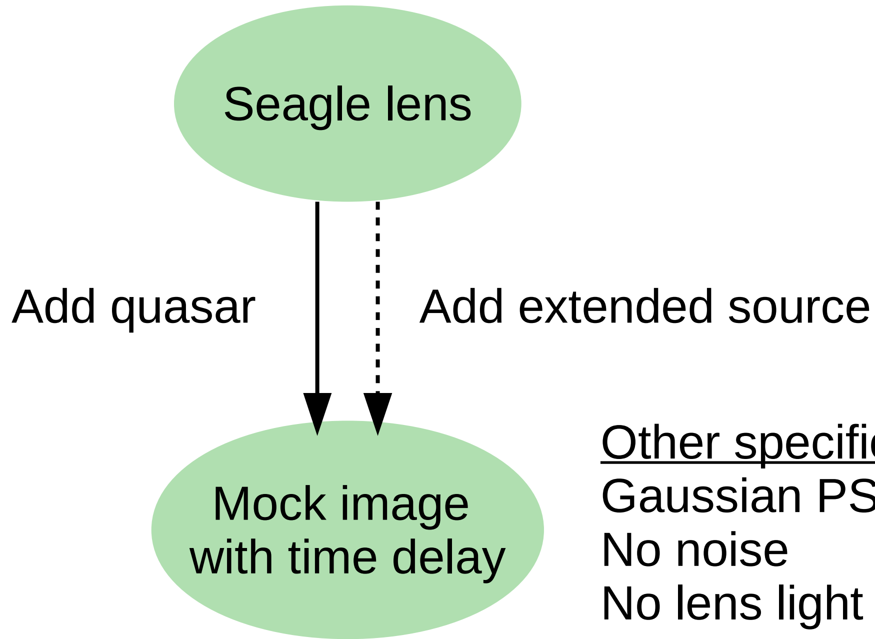
Sampath Mukherjee
Dominique Sluse

erc Cosmiclens

Study of degenerecies in mock lensing system

Creation of mock images | Image modeling | Analysis



<u>Other specification :</u>
Gaussian PSF
No noise
No lens light

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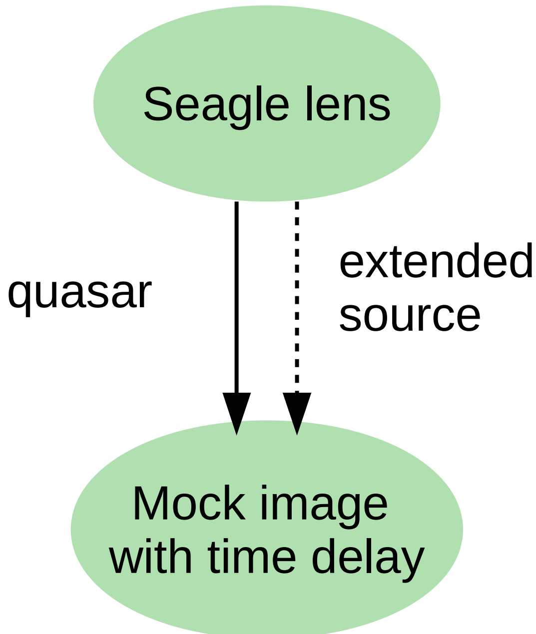
Study of degenerecies in mock lensing system

Creation of mock images | Image modeling | Analysis



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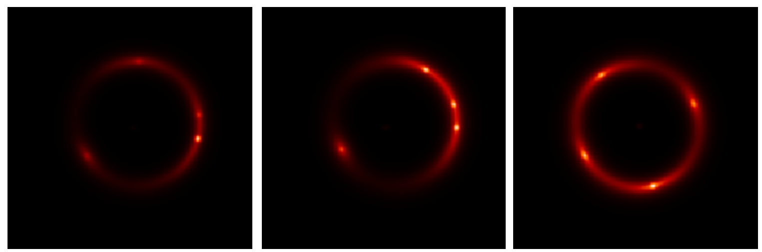

Seagle lens

quasar

extended source

Mock image with time delay

Source → Fixed / Not fixed

Lens → Power law +shear / Power law + core +shear / ...

Other: Time delay, Velocity dispersion

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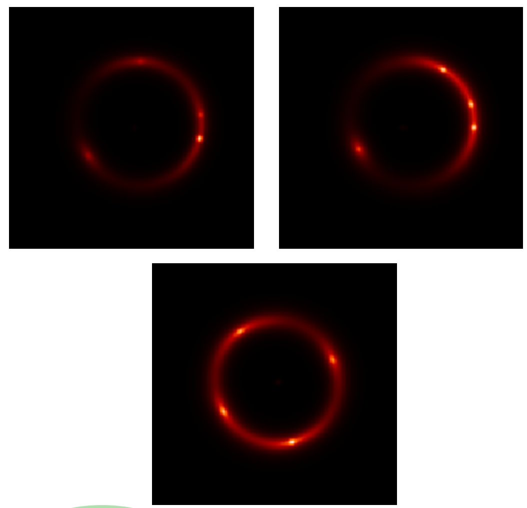
Mock image with time delay



Source

Other

Lens

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Creation of mock images

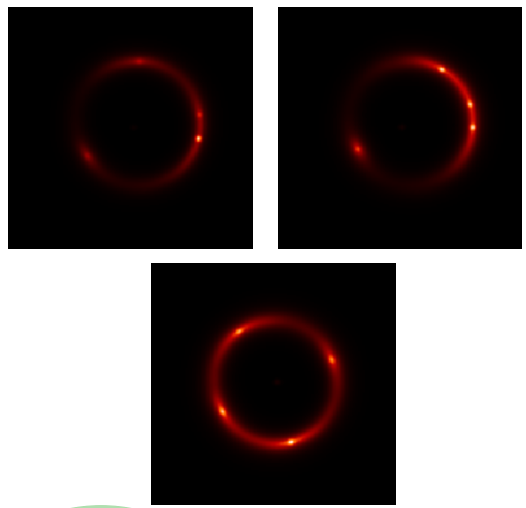
Seagle lens

quasar

extended source

Mock image with time delay

Image modeling



Source

Other

Lens

Analysis

→ MSD and SPT ?
→ Other degeneracies ?
→ Impact on H_0 ?
→ Stonger impact depending on configuration ?
→ Influence of the contrast between the quesar and the extended source ?
→ ...

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✦ **Finished**

- Selection of ETGs for lens
- Source parameters selection
- Caustic and Critical-curve
- Lens creation
- Sensitivity and S/N check

★**ONGOING**

- Lens Modelling
- Comparing with observation

Conclusions

1. An automatic pipeline for creating & modelling mock lenses with 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 and matter content via total mass density slope. (**SEAGLE-II:** Mukherjee et al. sub., arXiv:1901.01095)

3. With **ONE** pipeline it is possible to deal with **multiple** science questions and mock lensed images from simulations has a variety of applications.

4. A systematic and flexible pipeline (**COSMICLENS**) will be very effective in giving crucial handle on systematics of TD to constrain H_0.

Take home message

Simulation of realistic mock Strong Lenses is a very promising tool to probe galaxy formation and H_0