Self-consistent Modelling of Strong Gravitational Lensing and Stellar Dynamics

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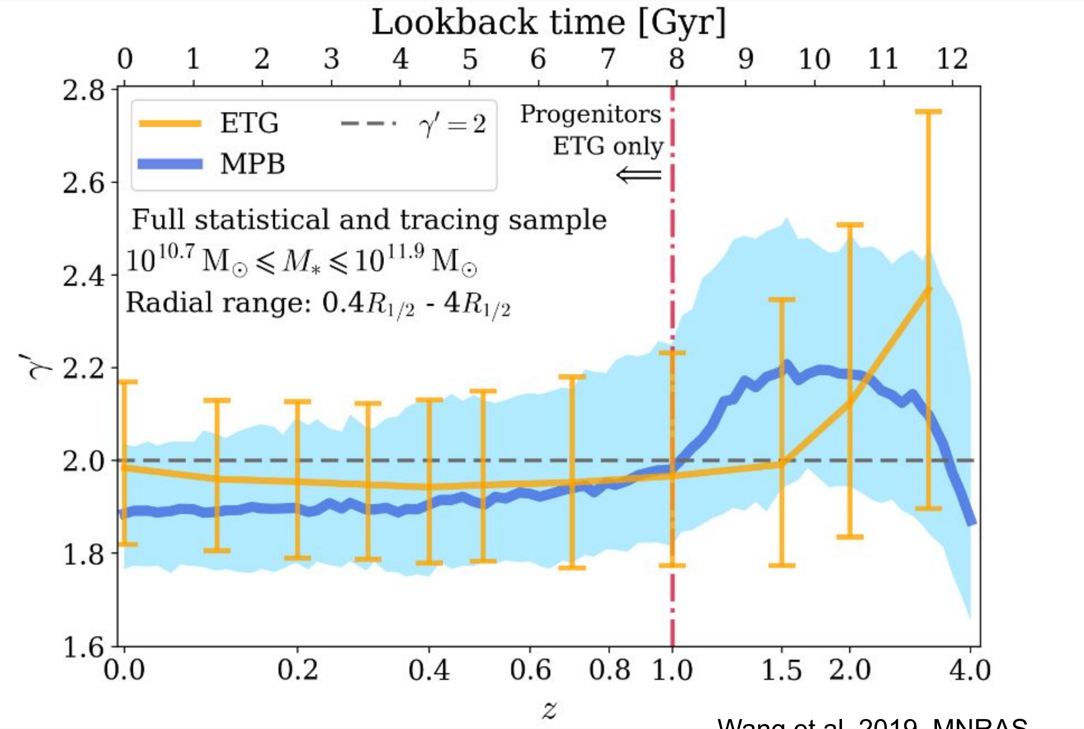
Overview and Motivations

- Early-Type Galaxies (ETGs)
  - gravitationally bound systems
  - stars, planets, gas, dust + something dark
  - typically red and old
  - end product of galaxy formation and evolution processes
  - “bulge-halo” conspiracy
  - two-phase scenario (maybe three-phase?)



Wang et al. 2019, MNRAS

Mass distribution

(gravitational potential)

Other related properties

- assembly history
- stellar content
- dark matter distribution
- merger rate
- IMF calibration
- probes of gravity

Approaches

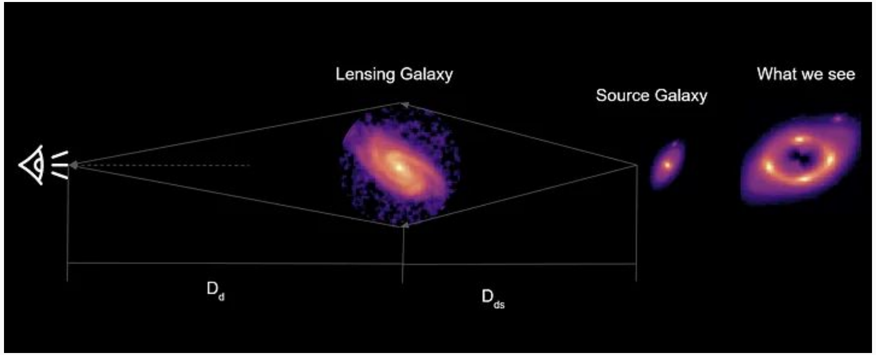
- dynamical modelling
  - stars, PNe, GCs
- gravitational lensing
- SED fitting and stellar population synthesis

Mass distribution

(gravitational potential)

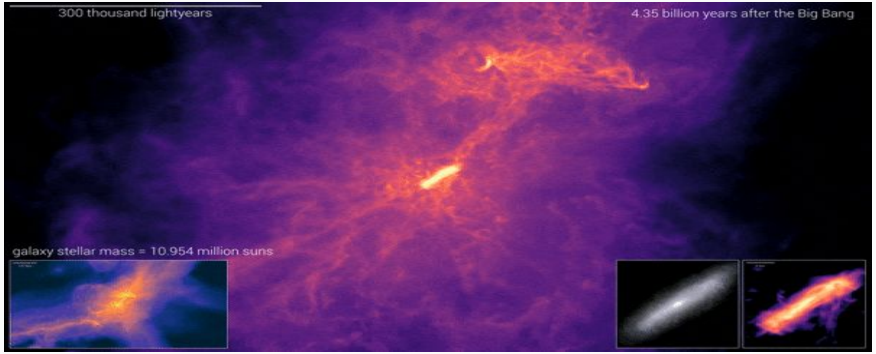
Strong Gravitational Lensing

Stellar Dynamics



Mandelbaum R, Lackner C, Leauthaud A, Rowe B 2012, Zenodo

- mass-sheet degeneracy
- only within R_{Ein}



D. Nelson (MPA) and IllustrisTNG team

- mass-anisotropy degeneracy
- longer integration time

Goals

➔ combine different **tracers** of the mass profile to reduce degeneracies

- strong gravitational lensing and stellar second velocity moment (V_{rms})

➔ provide insights into the **biases** present in such self-consistent modelling

- total mass, stellar mass, dark matter fraction, dark matter halo parameters

For ETGs

Multi-Gaussian Expansion (MGE) Formalism

- Surface brightness profile

Mass-to-light

- Projected mass profile
- Mass density profile
    - stellar
    - dark matter

$$I(x', y') = \sum_{j=1}^{N} \frac{L_j}{2\pi\sigma_j^2 q_j'} \exp\left[-\frac{1}{2\sigma_j^2}\left(x'^2 + \frac{y'^2}{q_j'^2}\right)\right]$$

Lens Equation

- thin lens approximation

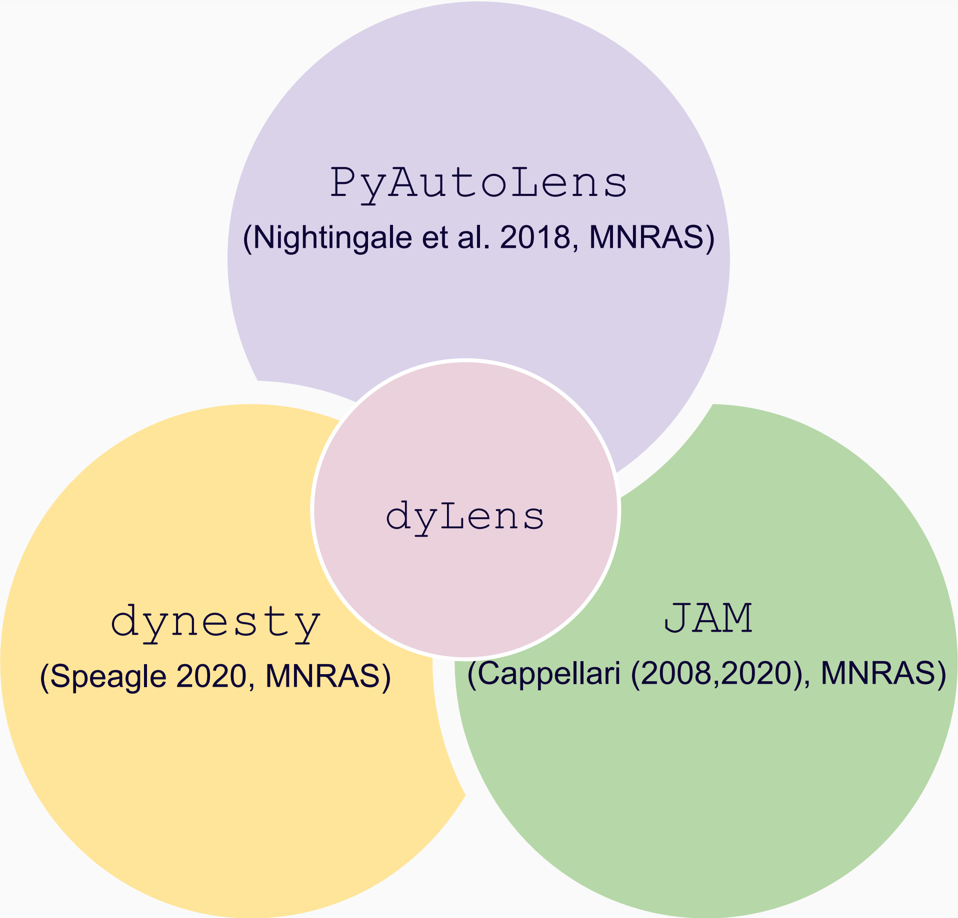
+

Jeans Equations

- collisionless system
- steady-state
- axisymmetric configuration

Emsellem, Monnet & Bacon 1994, AA;
Cappellari 2002, MNRAS

General Framework & Sample

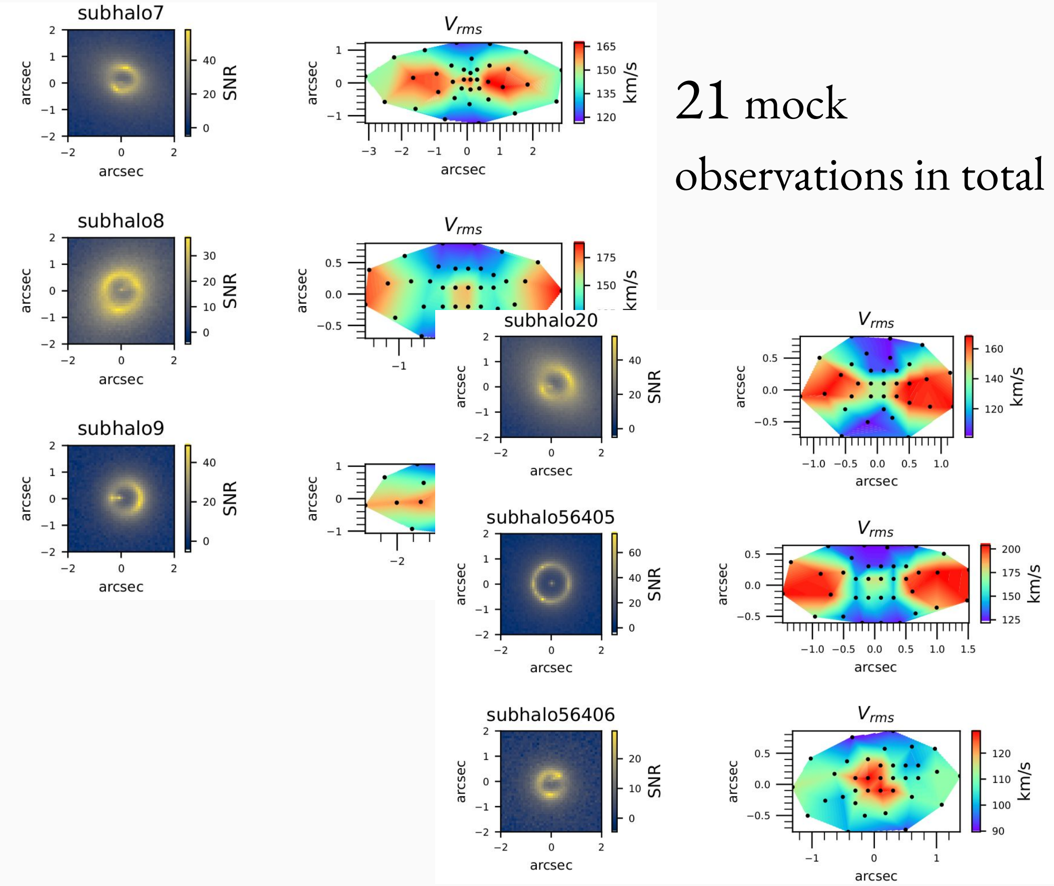


- self-consistent modelling
- dynamical-only modelling
- lens-only modelling
- automatic pipeline
- plenty of customisations:
  - M/L
  - dark matter profile
  - stellar anisotropy profile
  - supermassive black hole
  - pixelisation and regularisation
  - sampler
- easy to analyse
- easy to parallelise

General Framework & Sample

IllustrisTNG-50 mock sample

- ETGs at z = 0.05 or z = 0.5
  - Rodriguez-Gomez et al. 2019, MNRAS
  - Huertas-Company et al. 2019, MNRAS
  - Varma et al. 2022, MNRAS
- track to z = 0.2
- lens and source z consistent with SLACS
- source parameters randomly sampled
- HST and MUSE-like data
  - 0.09 arcsec (image)
  - ~ 50 SNR (image)
  - 35 kinematical tracers (fiducial)
  - deep investigation on spectra features and V_{rms} recovery



21 mock observations in total

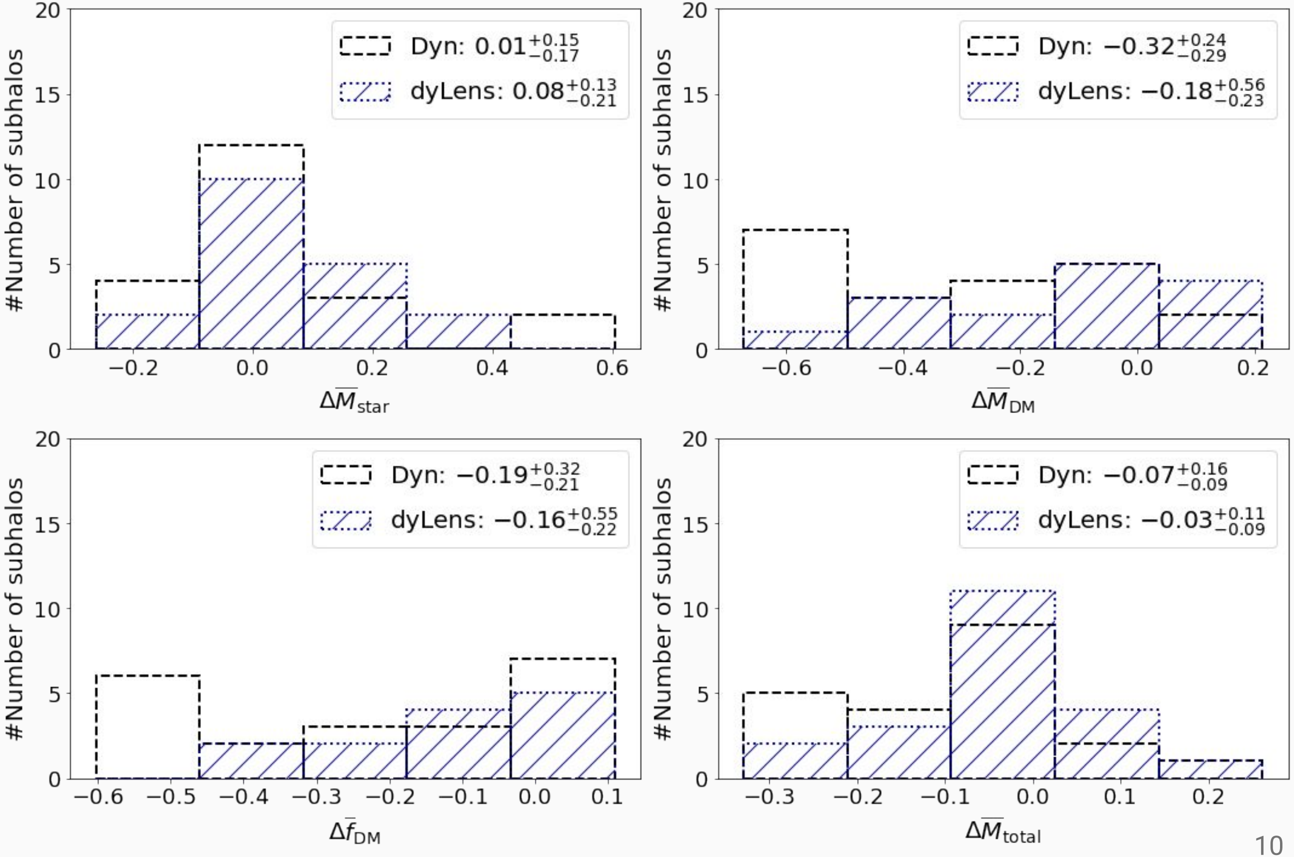
General Framework & Sample

Mass profile parameters
inclination
constant stellar mass-to-light ratio
constant stellar anisotropy
gNFW profile (r_s, ρ_s, γ_{DM})
external shear

dyLens: Recovering the mass distribution of lens galaxies

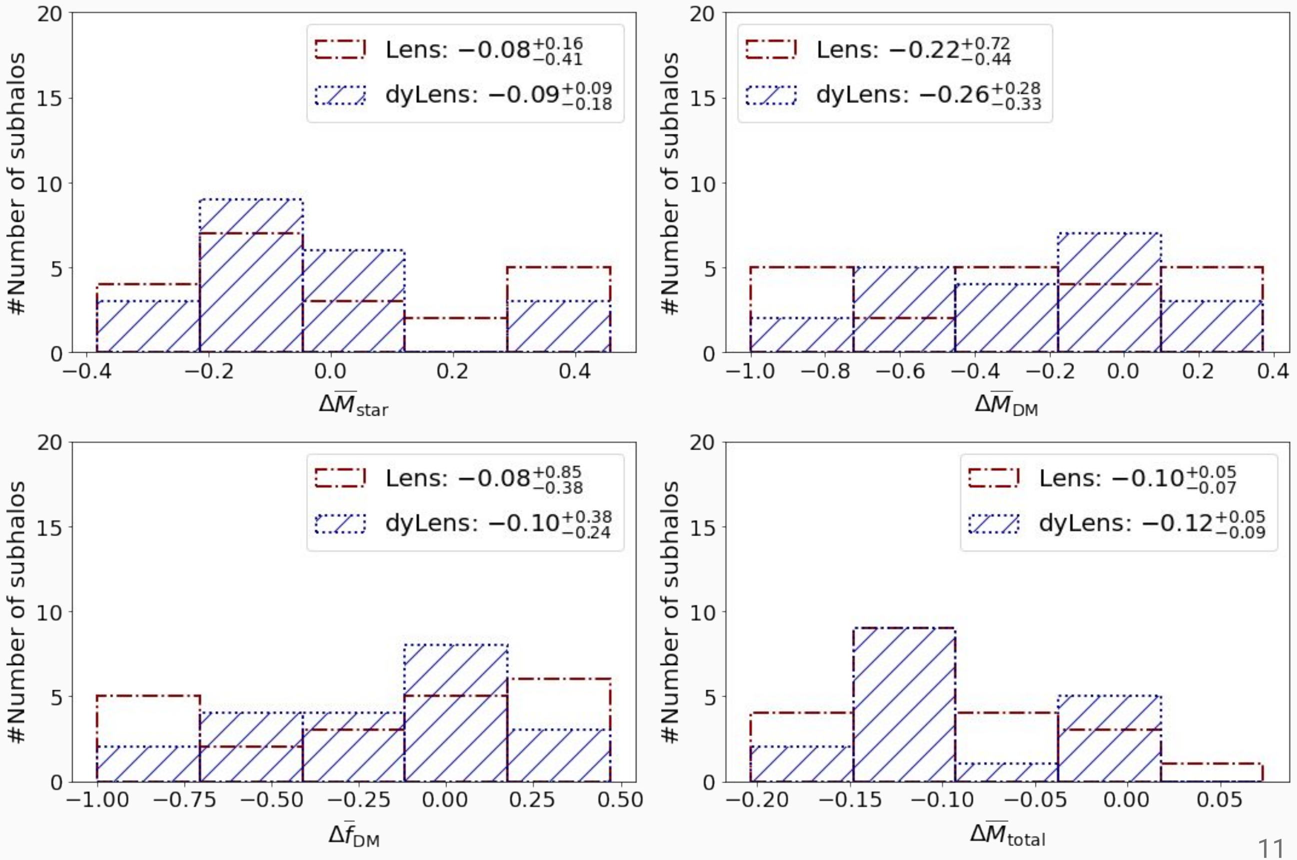
Fiducial model

3D intrinsic enclosed quantities within $2.5R_{eff}$



Fiducial model

2D enclosed quantities within R_{Ein}

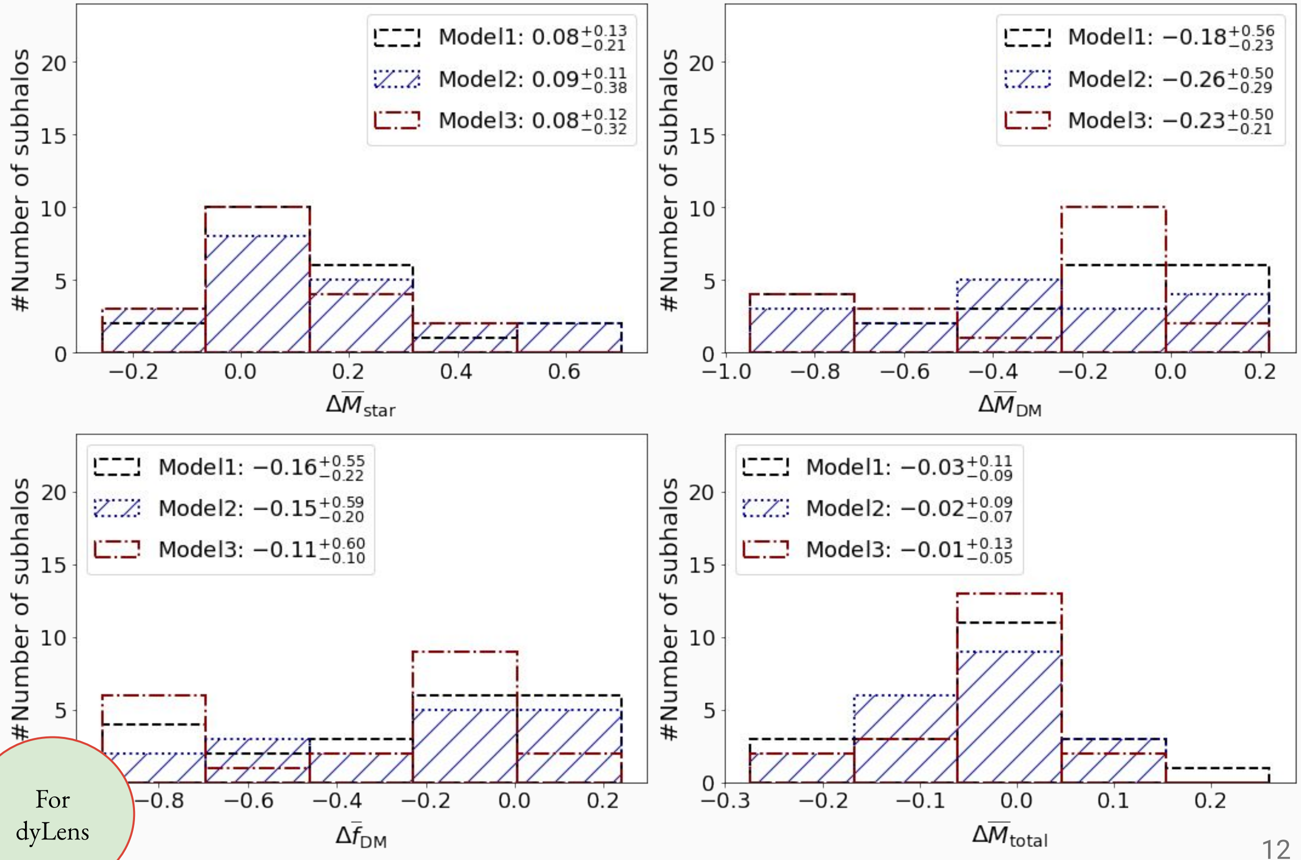


dyLens: Recovering the mass distribution of lens galaxies

Spatial Resolution of kinematical data

3D intrinsic enclosed quantities within $2.5R_{eff}$

- Model1 ~ 35 bins (black)
- Model2 ~ 15 bins (blue)
- Model3 ~ 55 bins (red)



For dyLens

Take-home messages

- good at recovering the total mass (all models)
- good at recovering the total density slope (all models)
- roughly good/good at recovering the stellar mass and M/L (model dependent)
- always bad in recovering dark matter parameters (all models)
- can be decent in recovering dark matter enclosed quantities (model dependent)
- insensible to number of kinematical constraints

Systematics in ETG Mass Profile Modelling: Strong Lensing & Stellar Dynamics

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Strong gravitational lensing and stellar dynamics are independent and powerful methods to probe the total gravitational potential of galaxies, and thus, their total mass profile. However, inherent degeneracies in the individual models makes it difficult to obtain a full understanding of the distribution of baryons and dark matter (DM), although such degeneracies might be broken by the combination of these two tracers, leading to more reliable measurements of the mass distribution of the lens galaxy. We use mock data from IllustrisTNG50 to compare how dynamical-only, lens-only, and joint modelling can constrain the mass distribution of early-type galaxies (ETGs). The joint model consistently outperforms the other models, achivieng a 2% accuracy in recovering the total mass within $2.5R_{\rm eff}$. The Einstein radius is robustly recovered for both lens-only and joint models, with the first showing a median fractional error of -5% and the latter a fractional error consistent with zero. The stellar mass-to-light ratio and total mass density slope are well recovered by all models. In particular, the dynamical-only model achieves an accuracy of 1% for the stellar mass-to-light ratio, while the accuracy of the mass density slope is typically of the order of 5% for all models. However, all models struggle to constrain integrated quantities involving DM and the halo parameters. Nevertheless, imposing more restrictive assumptions on the DM halo, such as fixing the scale radius, could alleviate some of the issues. Finally, we verify that the number of kinematical constraints $(15, 35, 55$ bins) on the kinematical map does not impact the models outcomes.

Comments: 42 pages, 13 Figures, and 2 Tables

Subjects: **Astrophysics of Galaxies (astro-ph.GA)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO)

arXiv:2407.02297

submitted to JCAP

Any questions?

You can also find me at:

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EXTRAS

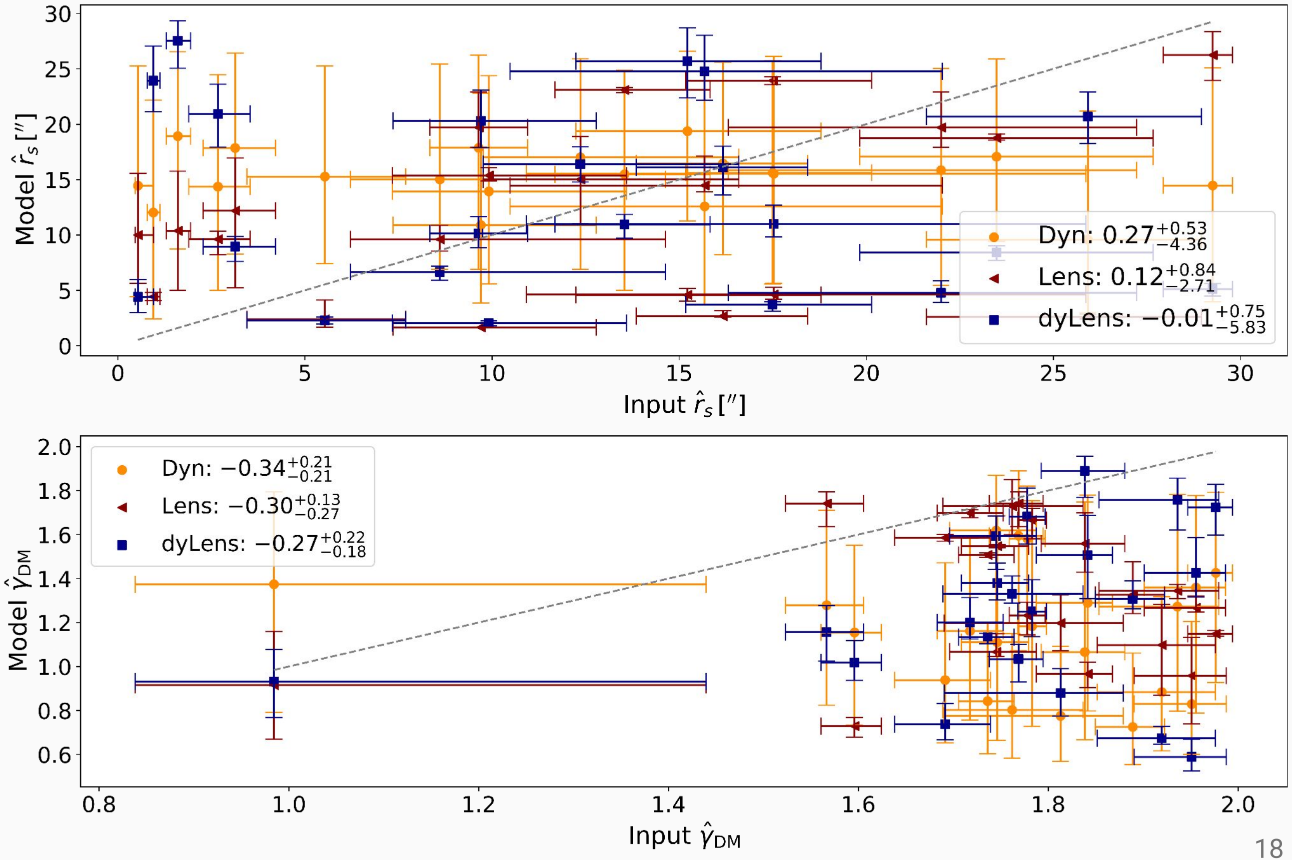
What’s next?

- Apply to real data (!)
- Improve the methodology (?)
  - are these mock galaxies fair?
  - is it possible to improve the constraints on the dark matter parameters?
  - add your suggestion: _____________
- Investigate impacts on the slip parameter (relevant for modified theories of gravity)

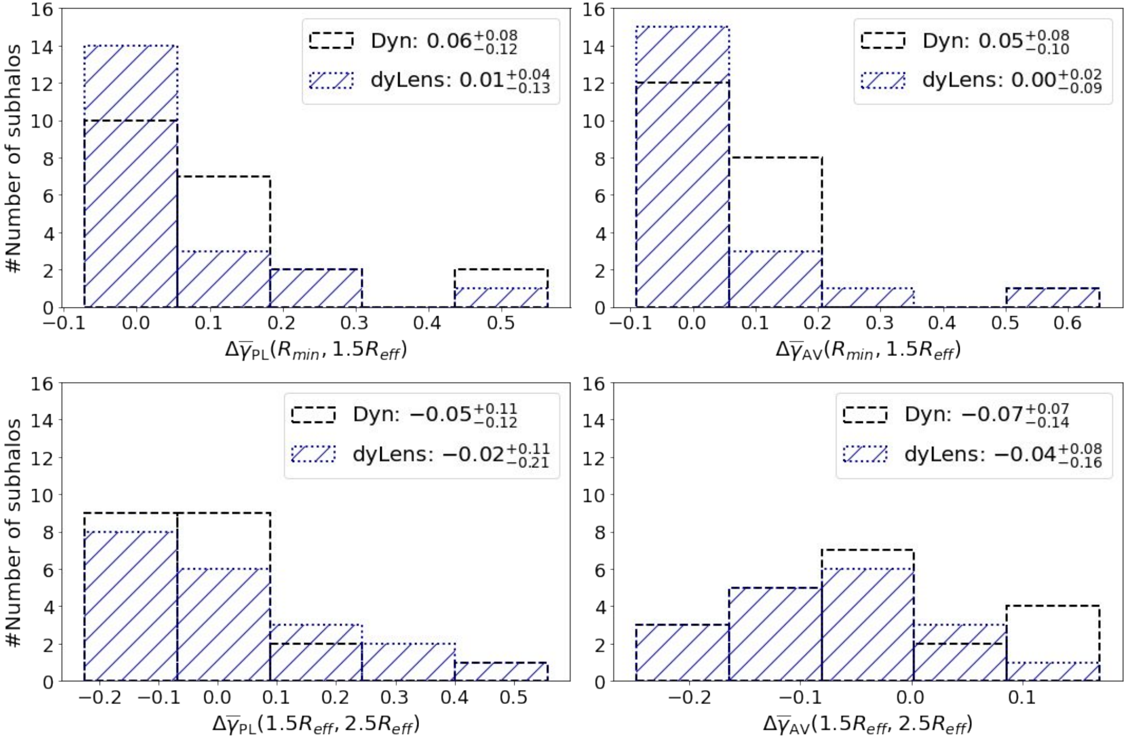
dyLens: Recovering the mass distribution of lens galaxies

Fiducial model

Dark Matter Parameter estimation



Fiducial model



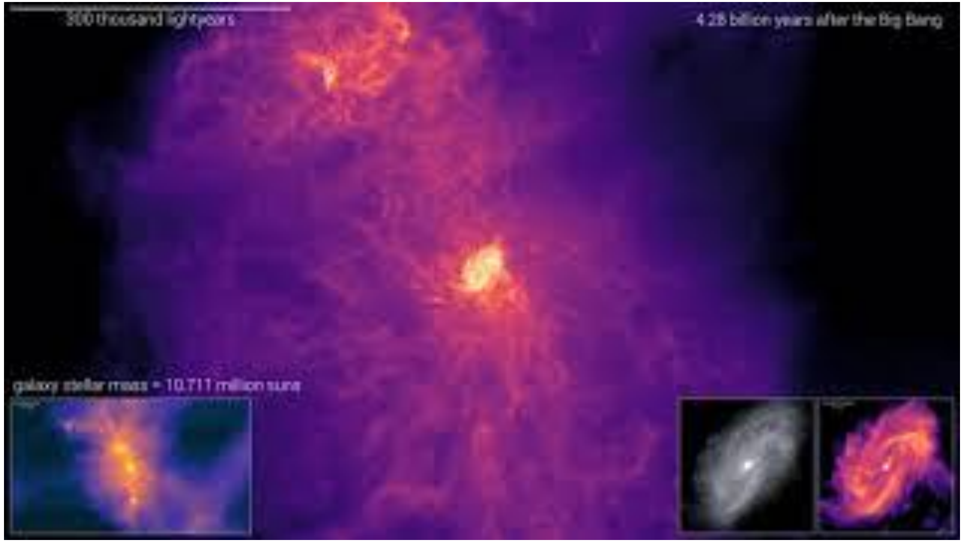
General Framework & Sample

Mass profile parameters
inclination
constant stellar mass-to-light ratio
constant stellar anisotropy
gNFW profile (r_s, ρ_s, γ_{DM})
external shear

- **Phase 1 (Ph1):** Parametric Source, Lens + Dynamical modelling
  - Sersic source profile
  - broad priors
- **Phase 2 (Ph2):** Pixelisation
  - DelaunayMagnification
  - Constant regularisation
- **Phase 3 (Ph3):** Model Refinement I
  - fixed pixelisation (Ph2)
  - priors are updated
- **Phase 4 (Ph4):** Adaptive Brightness-based Pixelisation and Regularisation
  - DelaunayBrightnessImage
  - AdaptiveBrightnessSplit regularisation
- **Phase 5 (Ph5):** Model Refinement II
  - fixed pixelisation (Ph4)
  - likelihood cap
  - priors are updated

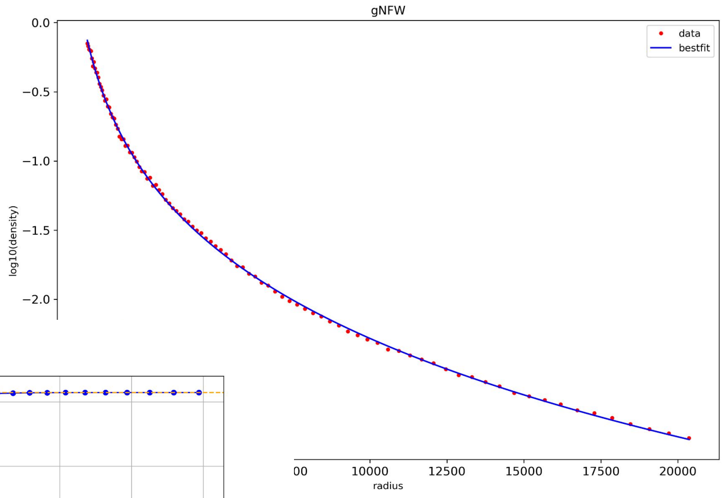
- cosmological hydrodynamical simulation
- stars, dark matter, gas, black holes, and magnetic fields
- initial conditions from Planck Collaboration et al. 2016, A&A.

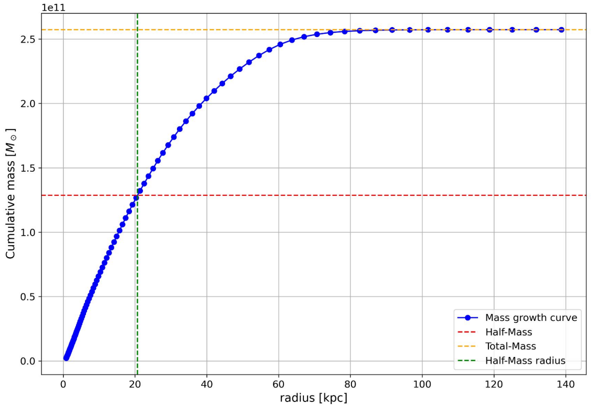
Feature	Units	TNG50
Volume	[Mpc^3]	51.7^3
L_{box}	[Mpc/h]*	35
N_{gas}	-	2160^3
N_{DM}	-	2160^3
m_{baryon}	[$\mathrm{M}_\odot$]	8.5×10^4
m_{DM}	[$\mathrm{M}_\odot$]	4.5×10^5
$\epsilon_{\mathrm{gas,min}}$	[pc]	74
$\epsilon^{z=0}_{\mathrm{DM,stars}}$	[pc]	288
CPU time	[Mh]	130



- Radial profiles
  - 100 logarithmically spaced spherical shells
  - until the half-mass radius
- Dark matter profiles
  - gNFW profile
  - non-linear fit
  - same priors as in the pipeline

$$\rho(r) = \rho_s \left(\frac{r}{r_s}\right)^{-\gamma_{\mathrm{DM}}} \left(1 + \frac{r}{r_s}\right)^{\gamma_{\mathrm{DM}}-3}$$





- **Within 2.5R_{eff}**
  - stellar mass
  - dark matter mass
  - dark matter fraction
  - total mass

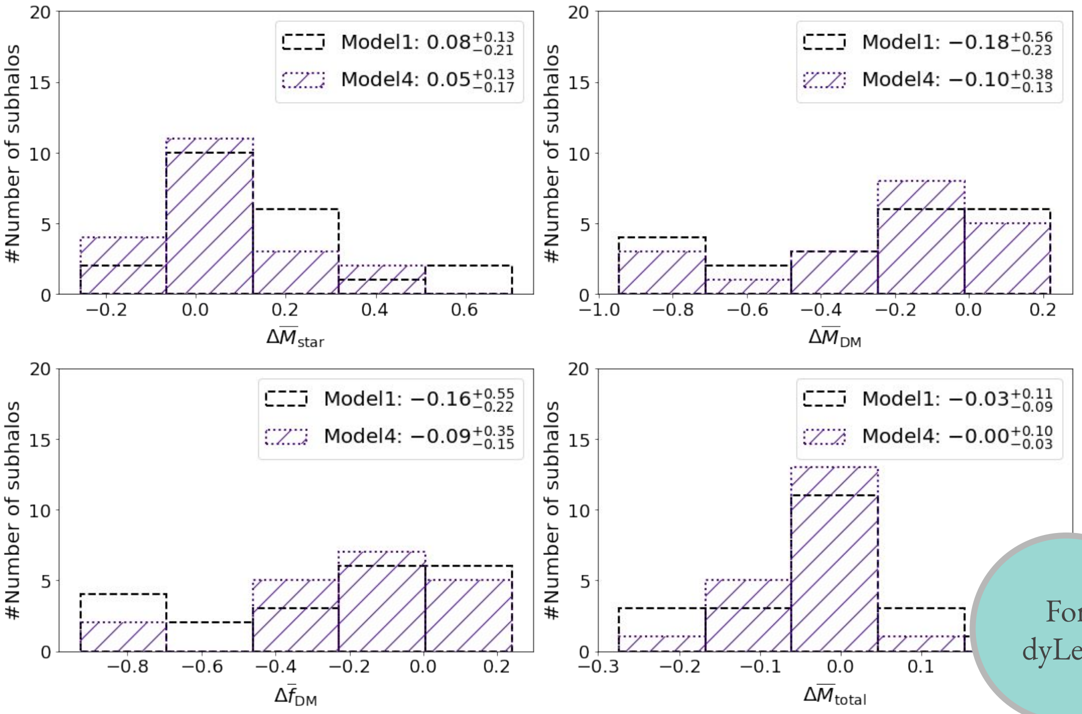
$$\Delta Q(r) = \frac{Q(r)_{\mathrm{model}} - Q(r)_{\mathrm{data}}}{Q(r)_{\mathrm{data}}}$$

- **Total mass density slope**
  - power-law
  - average slope (Xu et al. 2017, MNRAS)

$$\gamma_{\rm AV}(r_1, r_2) = \frac{\ln\left[\rho(r_2)/\rho(r1)\right]}{\ln\left(r_1/r_2\right)}$$

DM assumptions

- Model1 - gNFW
- Model4 - gNFW (fixed radius)

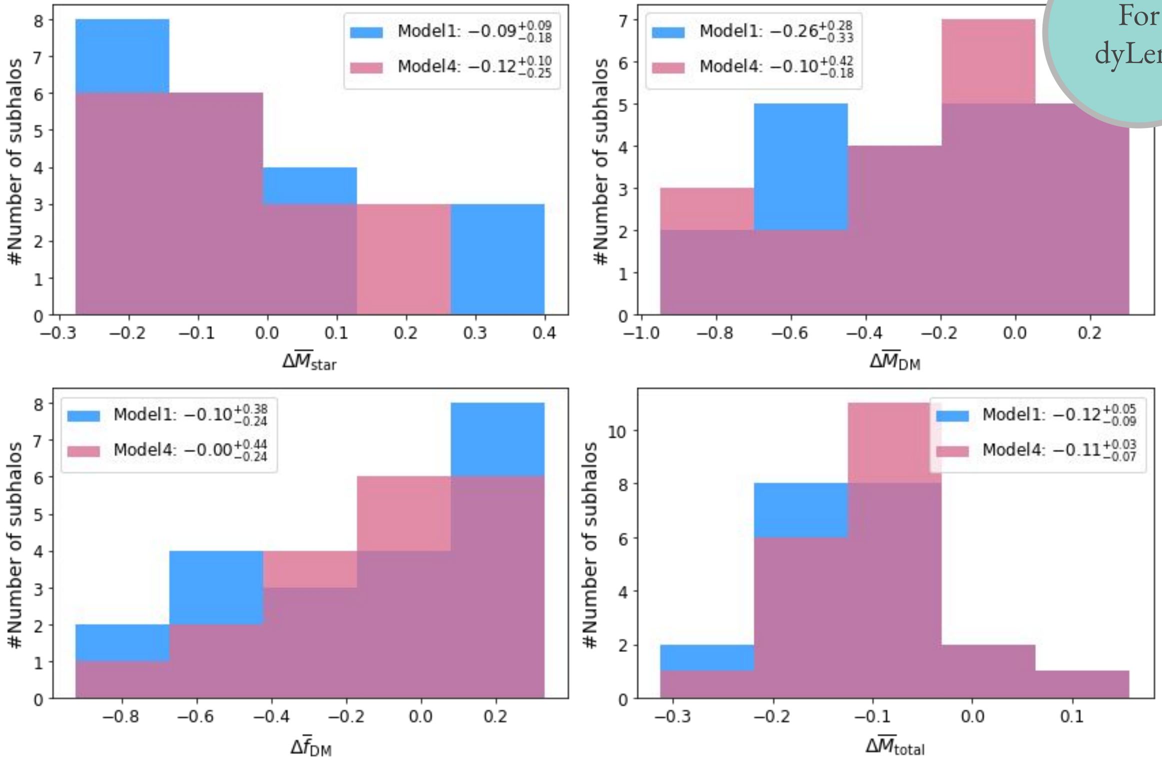


For dyLens

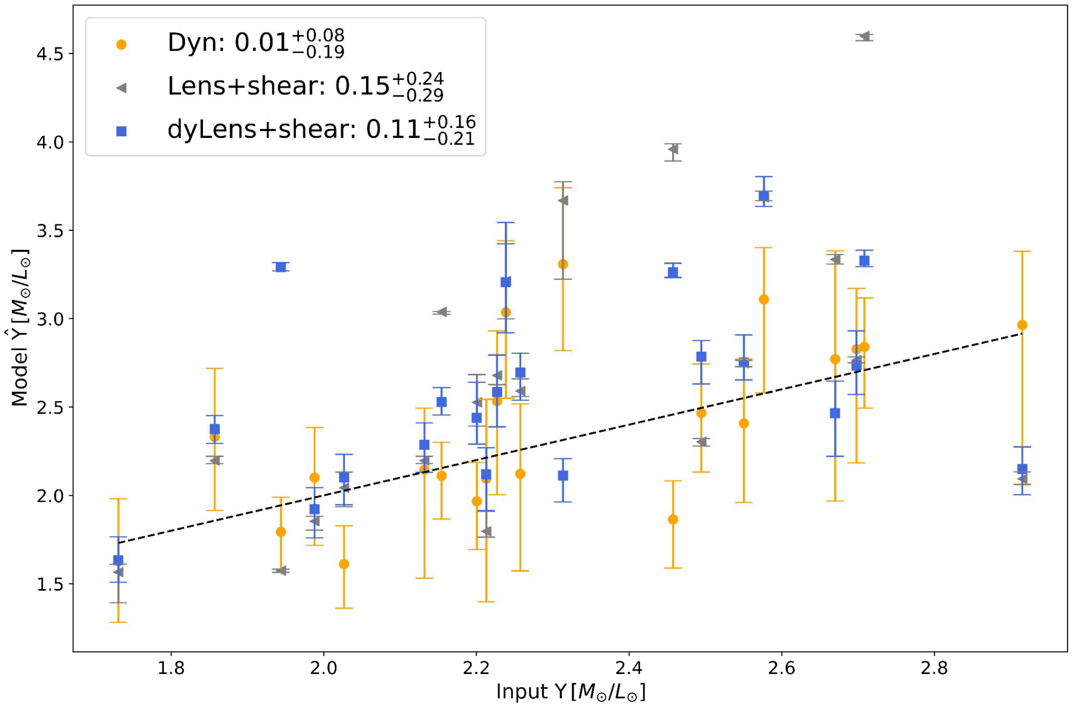
DM assumptions

For dyLens

- Model1 - gNFW
- Model4 - gNFW (fixed radius)

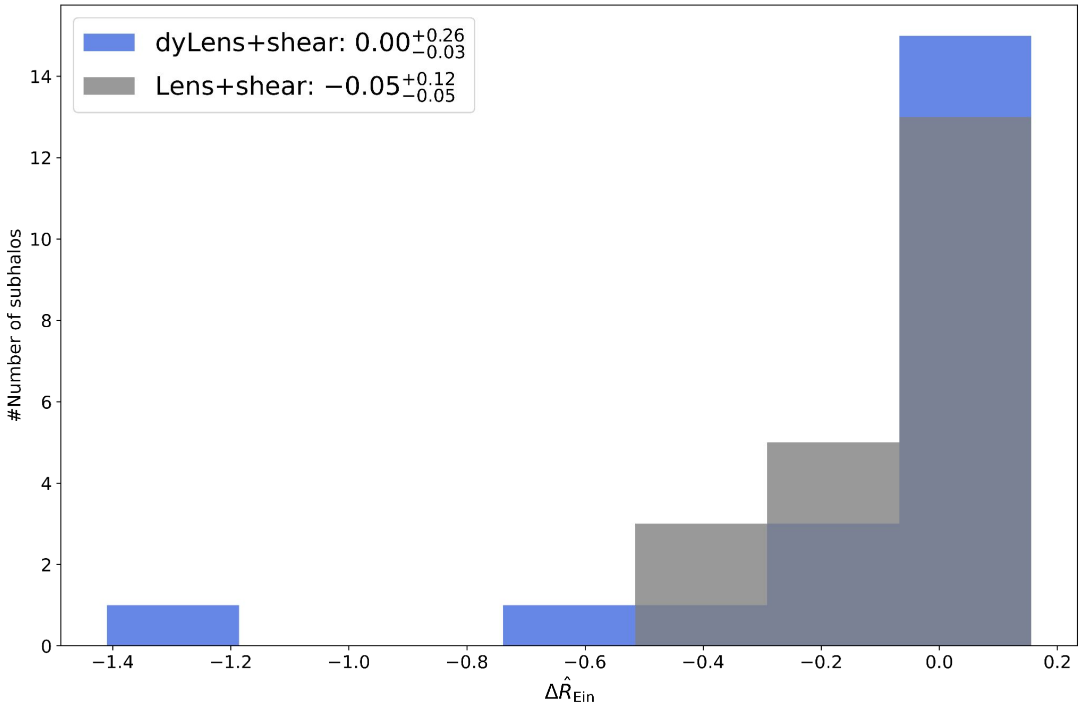


Fiducial model



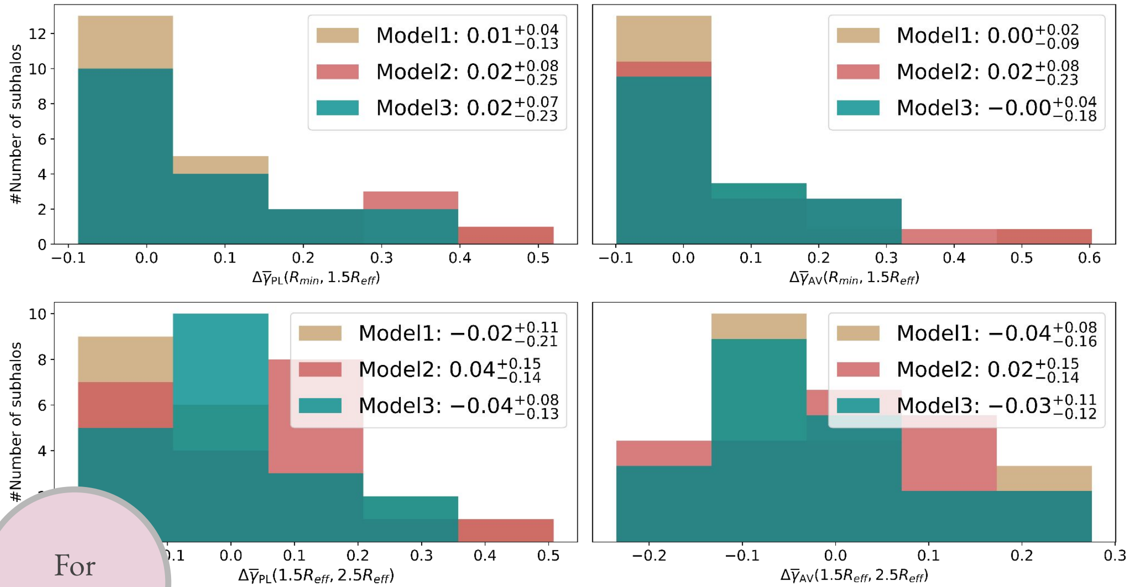
Fiducial model

dyLens: Recovering the mass distribution of lens galaxies



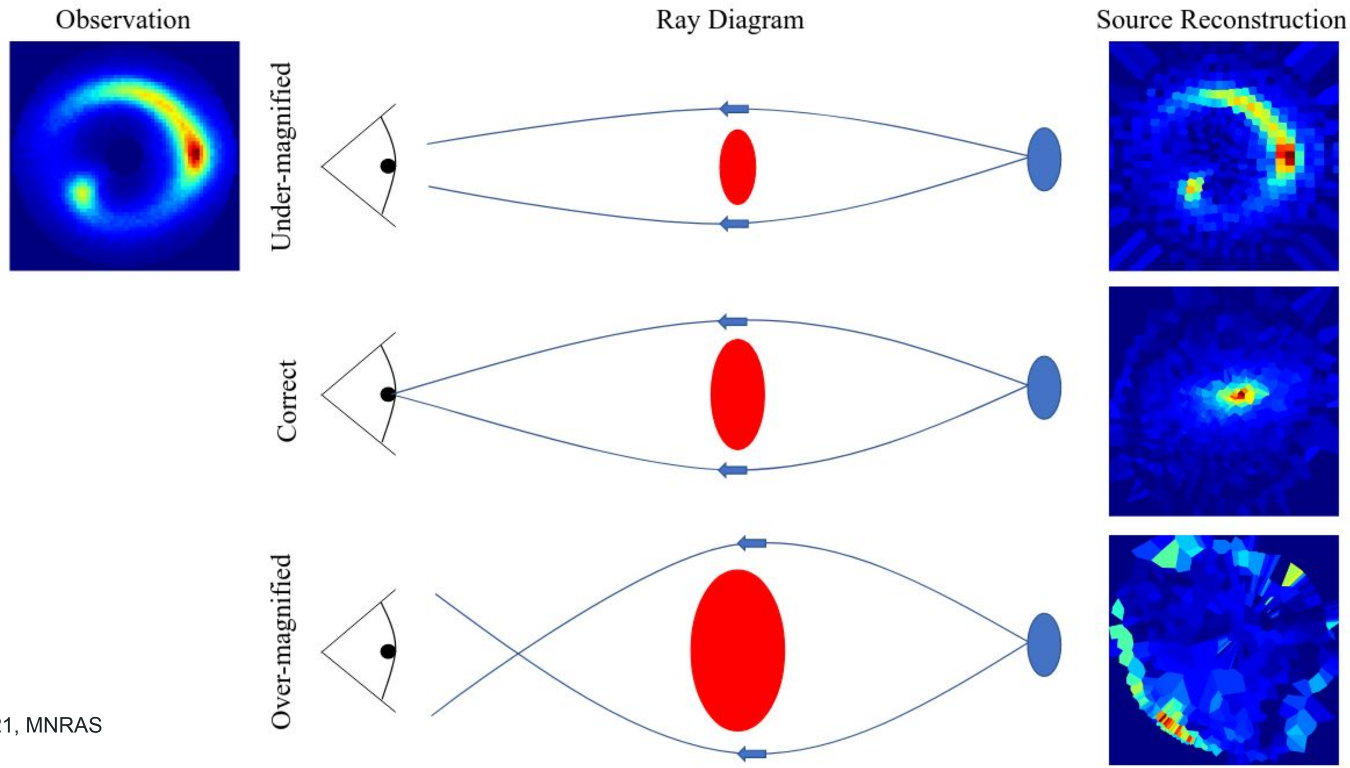
Number of kinematical bins

- Model1 ~ 35 bins
- Model2 ~ 15 bins
- Model3 ~ 55 bins



For dyLens

Under/Over-magnified solutions



Maresca et al. 2021, MNRAS

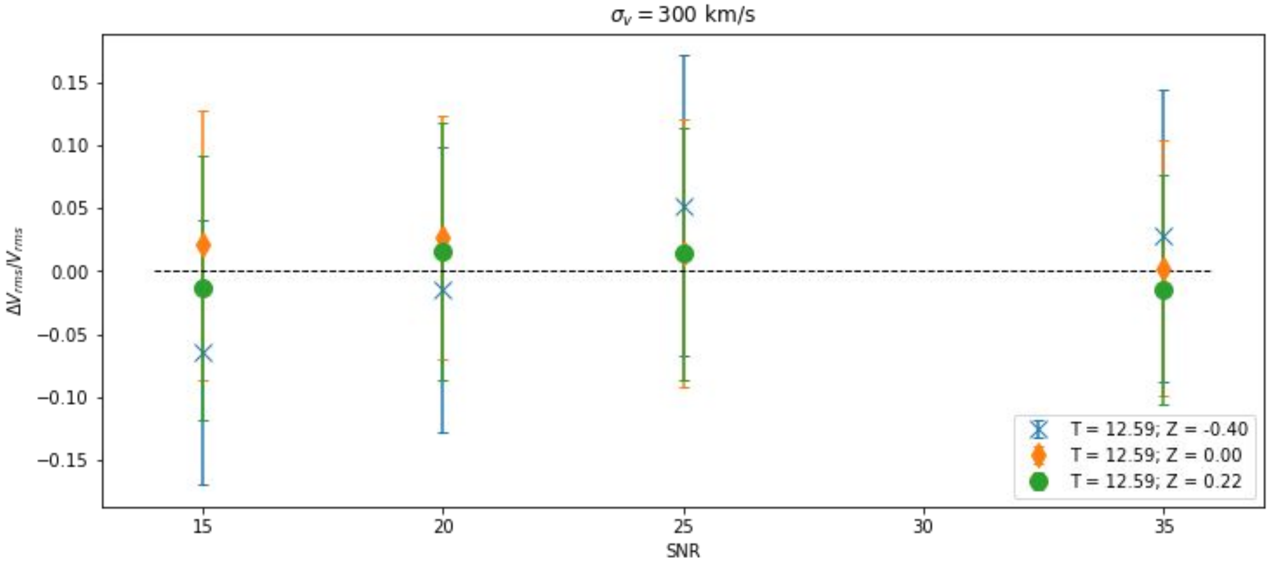
- Age = [2.5, 6.3, 12.6] Gyrs
- [Z/H] = [−0.4, 0.0, 0.22]
- σ_v = [250, 280, 300, 350] km/s
  - v = 40 km/s
- SNR = [15, 20, 25, 35]
- MUSE-like
- E-MILES SSPs

→

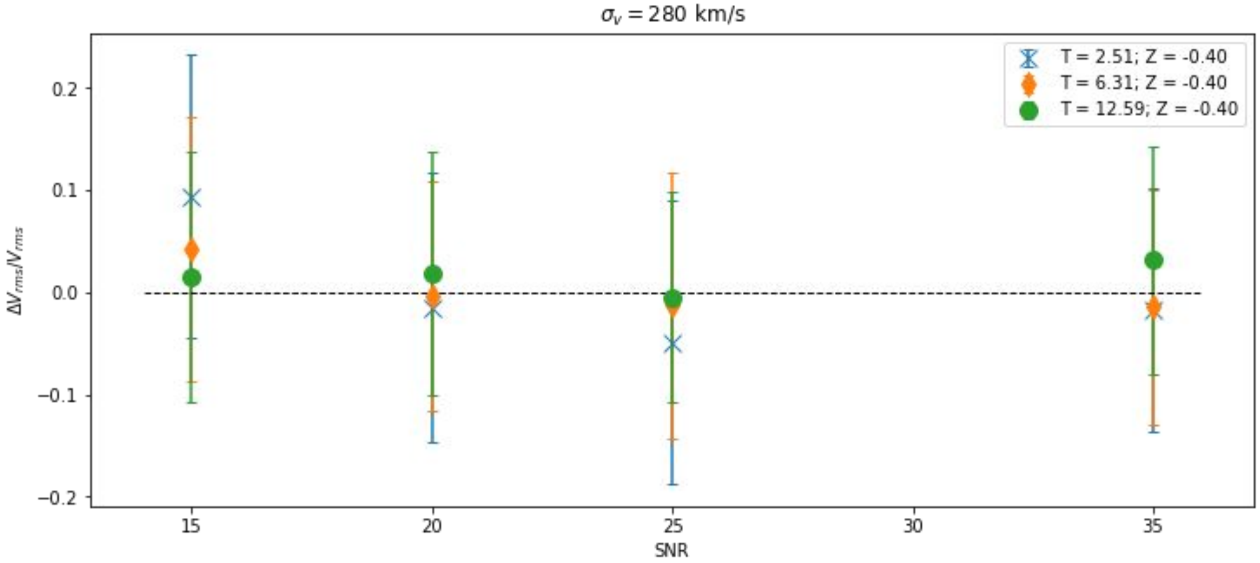
- 144 spectra
- modelled uniformly by pPXF (Cappellari 2012, MNRAS)
  - Indo-US templates
- Monte Carlo approach for uncertainties
  - 200 iterations

Harrison+2010, AA; McDermid+2015, MNRAS

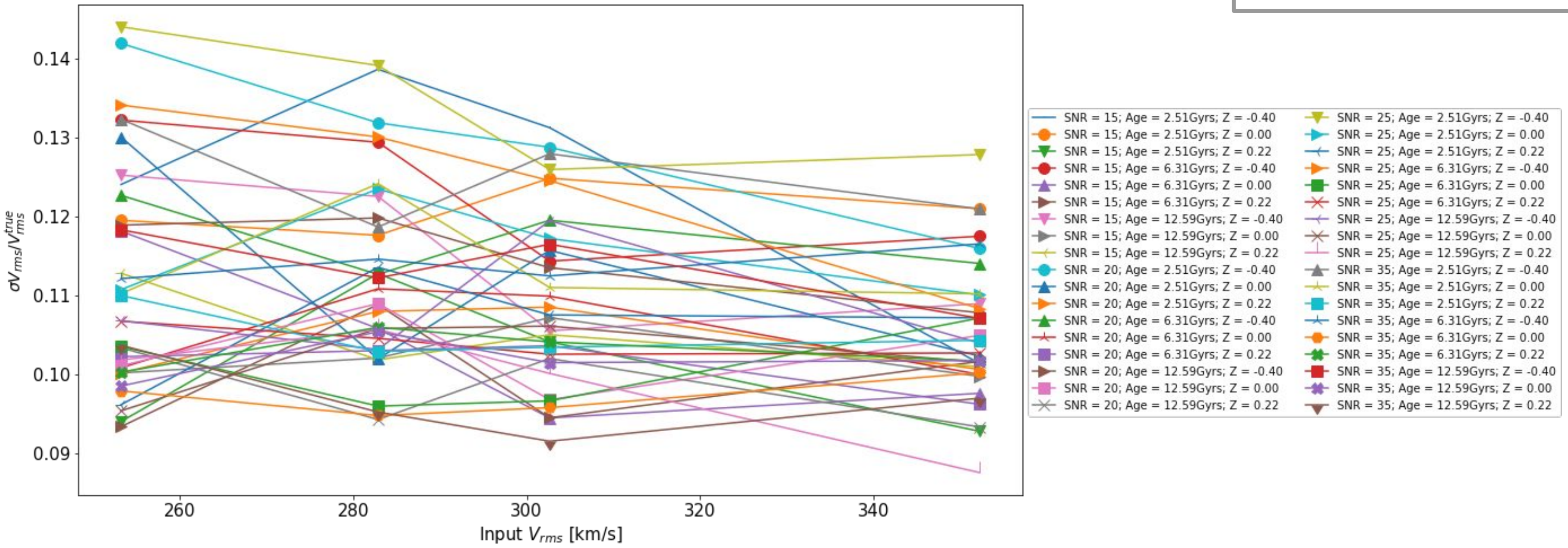
same age, different metallicities



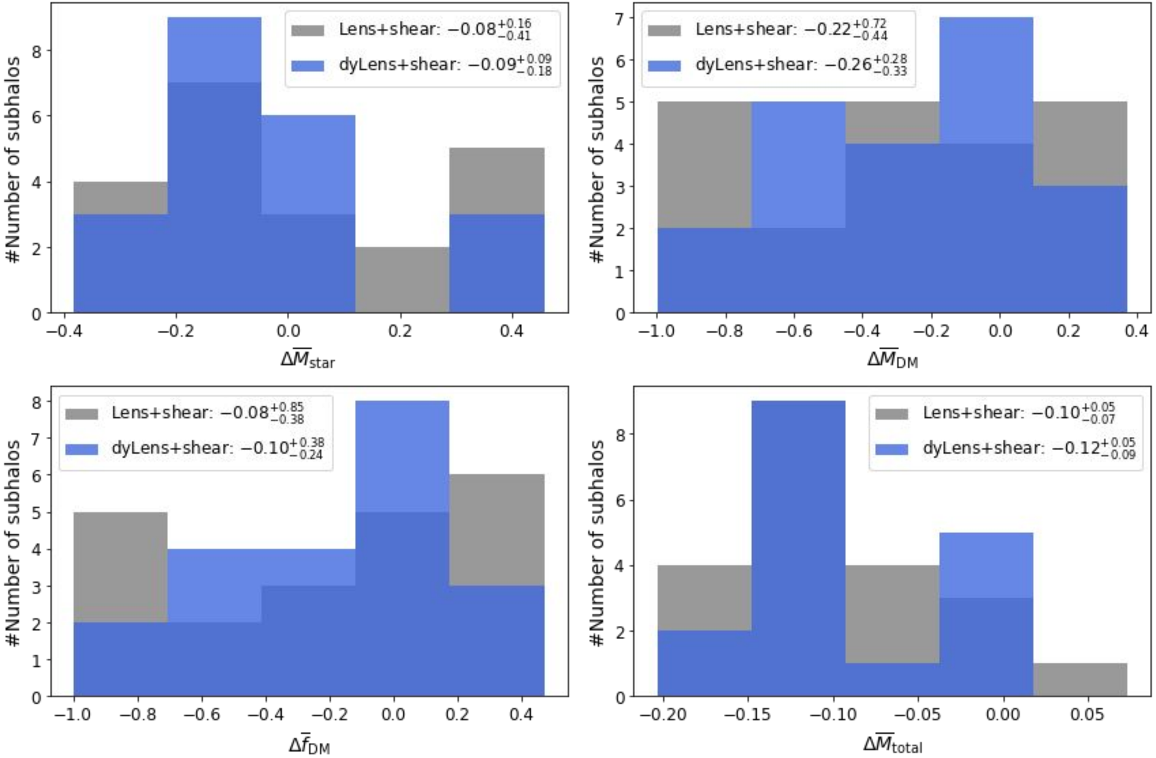
same metallicities, different ages



messy, but complete

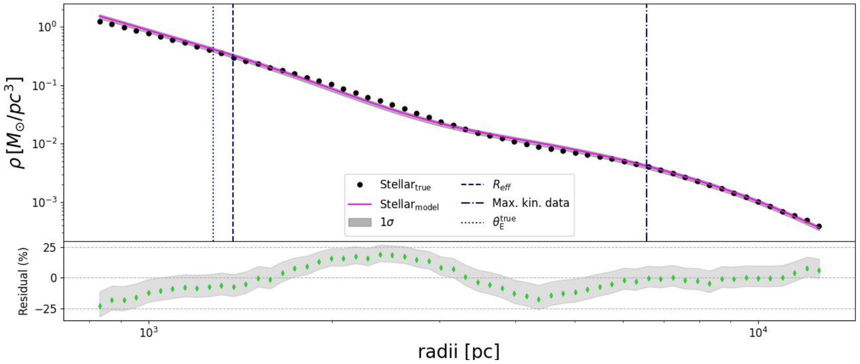


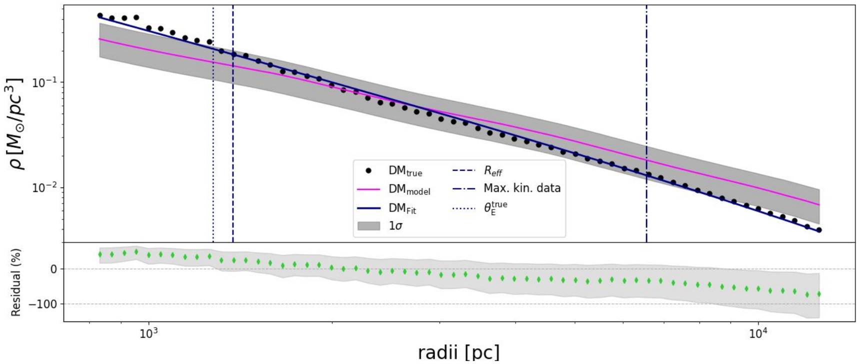
Fiducial model

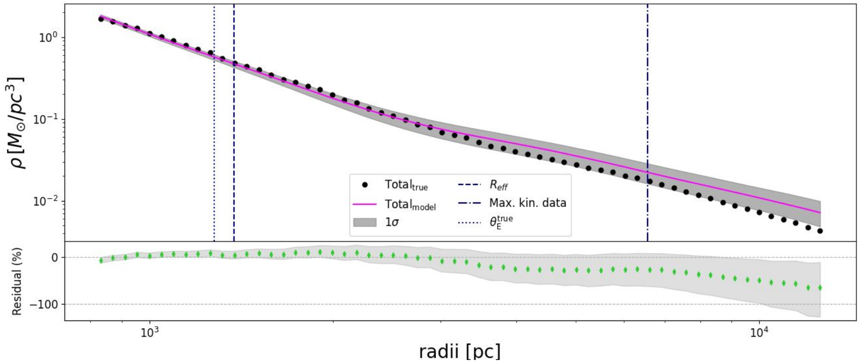


subhalo485608

dyLens: Recovering the mass distribution of lens galaxies







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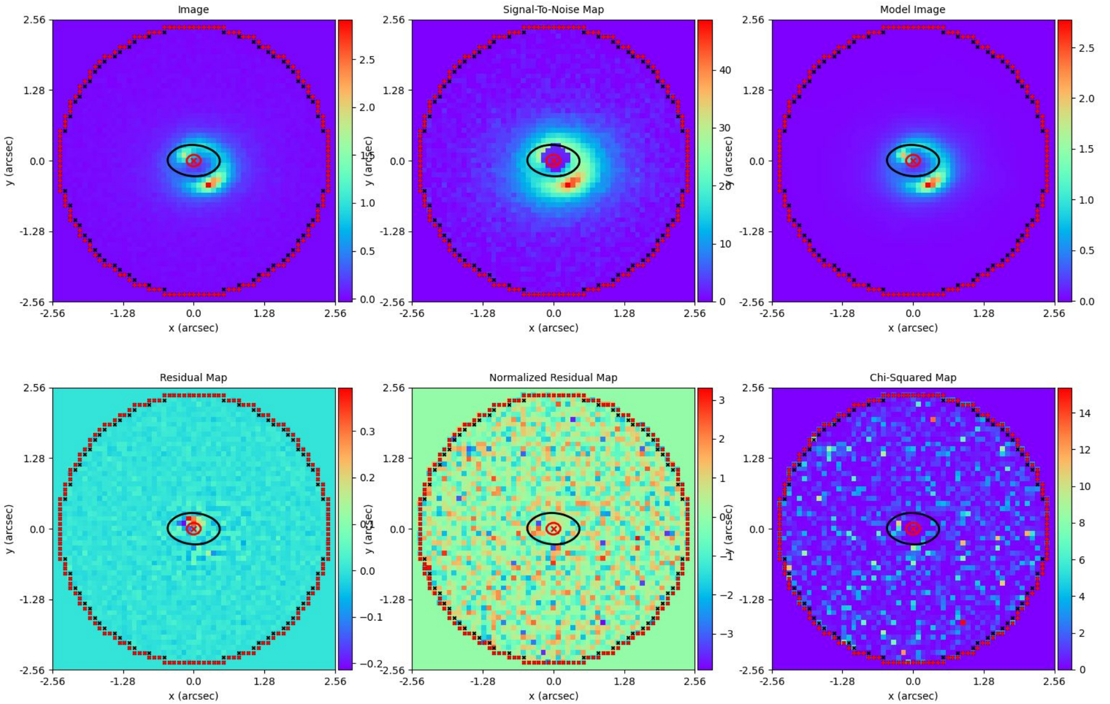

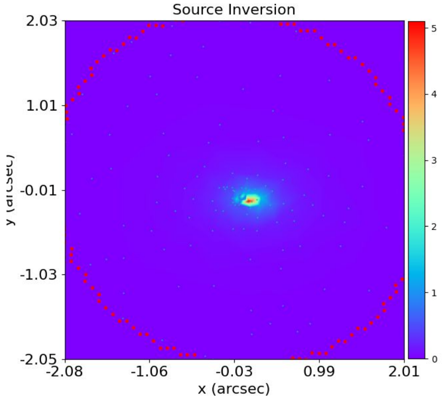

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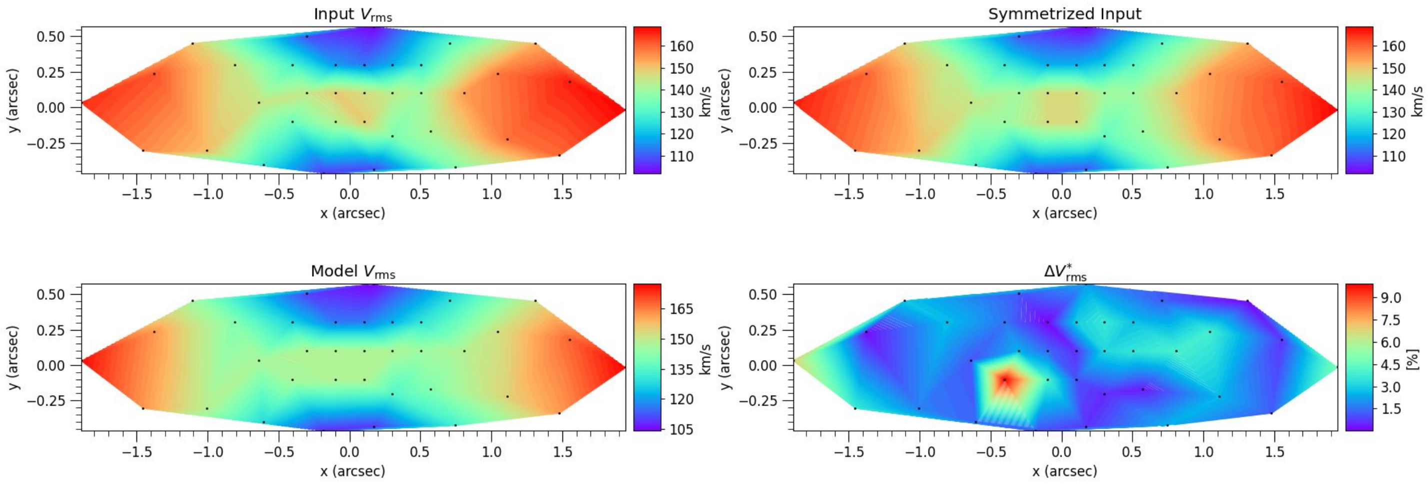
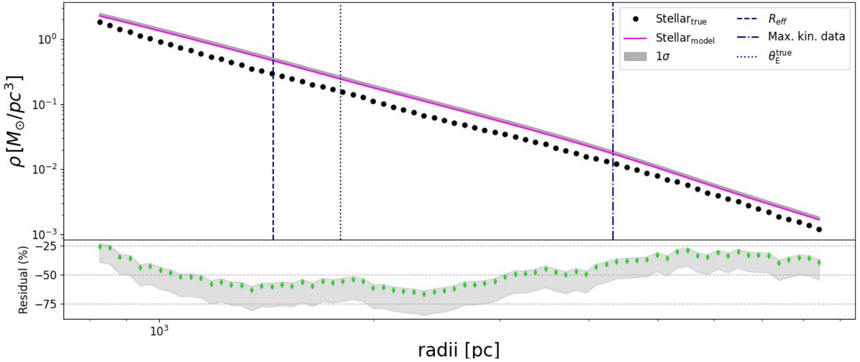
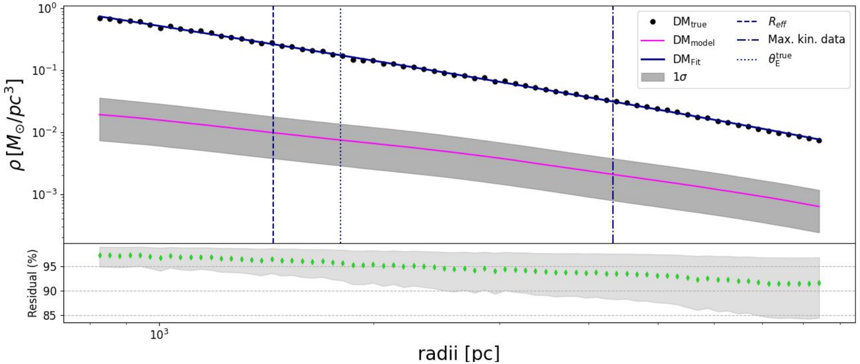


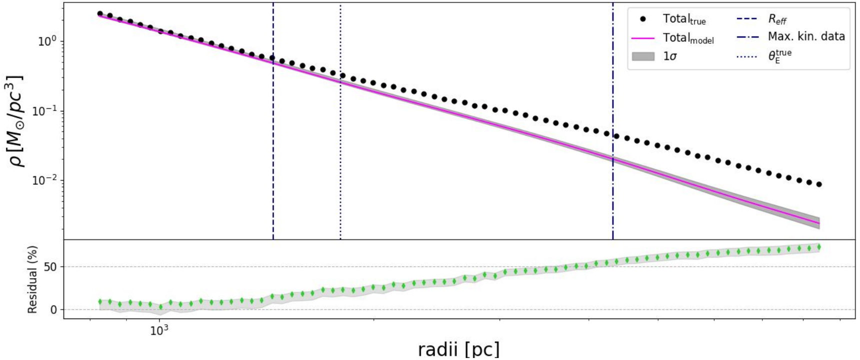
subhalo11



$\rho\,[M_\odot/pc^3]$
Residual (%)
radii [pc]
Stellar$_{true}$
Stellar$_{model}$
1σ
R_{eff}
Max. kin. data
θ_E^{true}



$\rho\,[M_\odot/pc^3]$
Residual (%)
radii [pc]
DM$_{true}$
DM$_{model}$
DM$_{Fit}$
1σ
R_{eff}
Max. kin. data
θ_E^{true}



$\rho\,[M_\odot/pc^3]$
Residual (%)
radii [pc]
Total$_{true}$
Total$_{model}$
1σ
R_{eff}
Max. kin. data
θ_E^{true}

subhalo11

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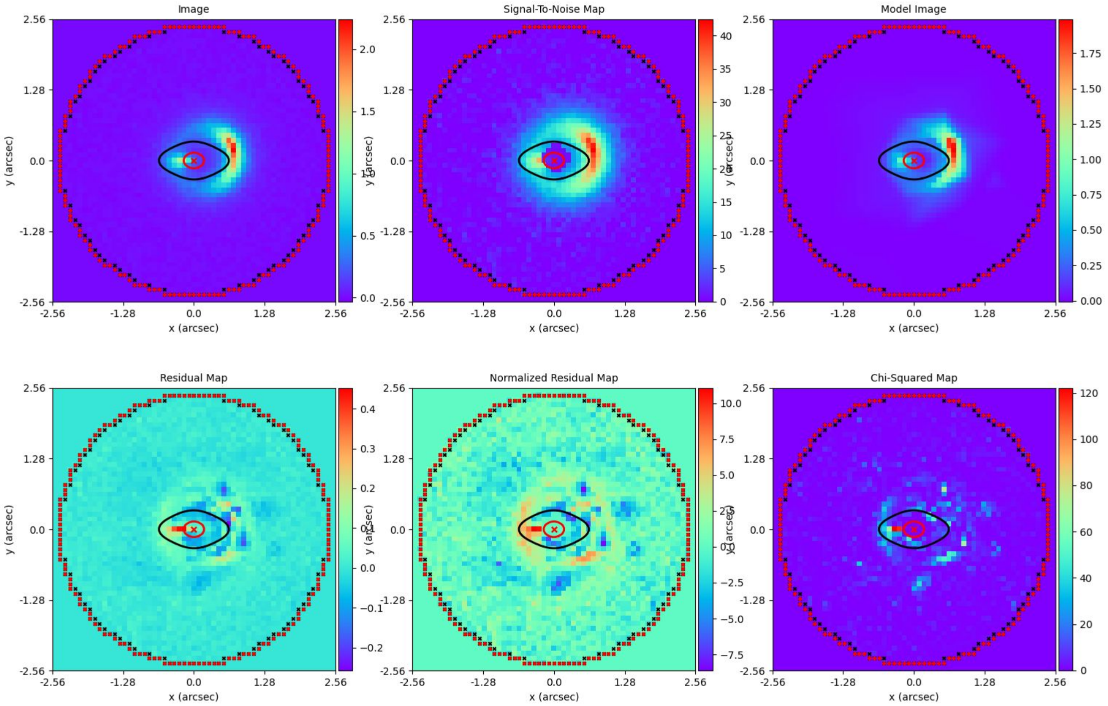

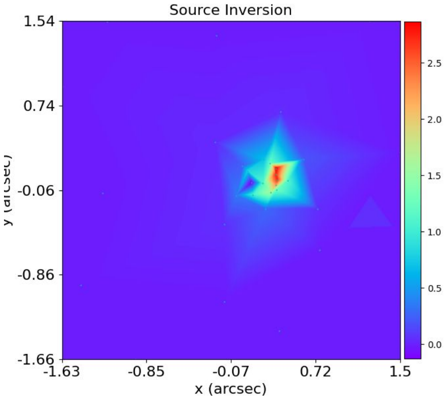

dyLens: Recovering the mass distribution of lens galaxies