Self-consistent Modelling of Strong Gravitational Lensing and Stellar Dynamics

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Road Map

01
Overview and Motivations

02
General Framework & Sample

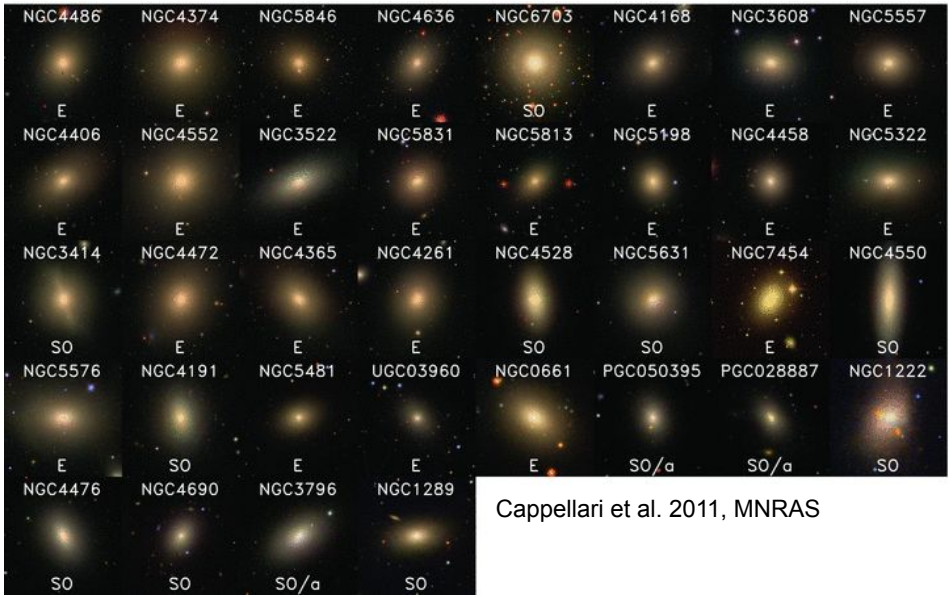
03
dyLens: Recovering the mass distribution of lens galaxies

04
Perspectives

Overview and Motivations

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
  - many scaling relations

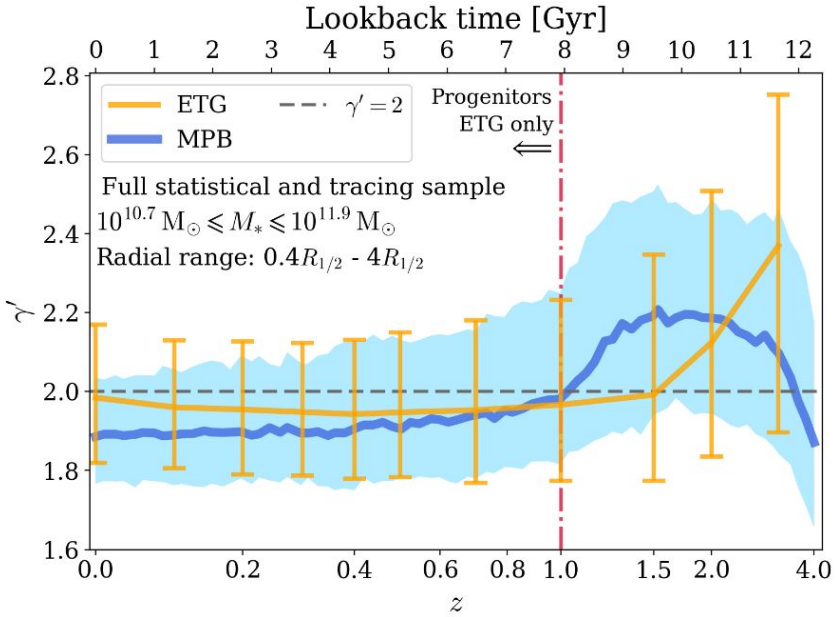


Cappellari et al. 2011, MNRAS

Overview and Motivations

- Early-Type Galaxies (ETGs)
  - “bulge-halo” conspiracy
  - two-phase scenario (maybe three-phase?)

Wang et al. 2019, MNRAS



Mass distribution

(gravitational potential)

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

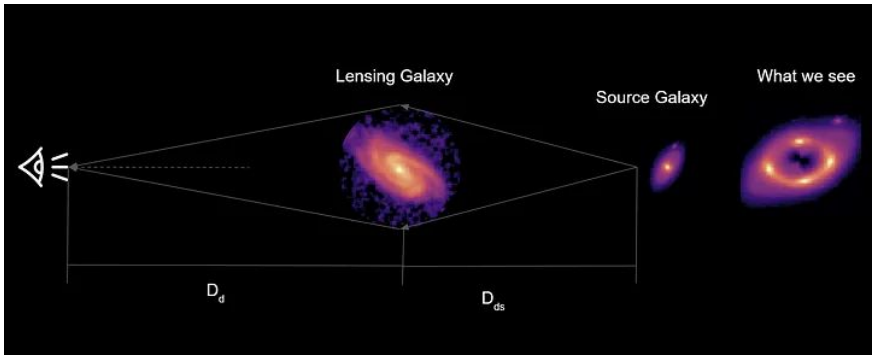
Methods

- dynamical modelling
- planetary nebulae and globular clusters
- SED fitting and stellar population synthesis
- gravitational lensing

Mass distribution

(gravitational potential)

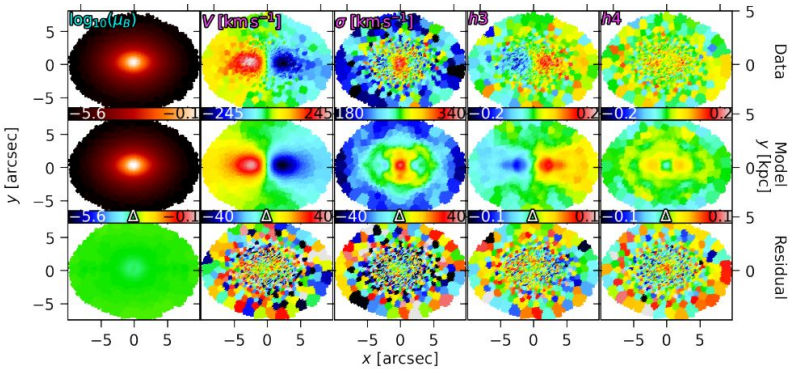
Strong Gravitational Lensing



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

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

Stellar Dynamics



- mass-anisotropy degeneracy
- longer integration time

Poci, A., & Smith, R. J. 2022, MNRAS

Goals

- combine different tracers of the mass profile to reduce degeneracies;
- provide insights into the biases present in such self-consistent modelling;
- develop a tool (code) to make such modelling straightforward;

For ETGs

General Framework & Sample

Multi-Gaussian Expansion (MGE) Formalism

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

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

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

Lens Equation

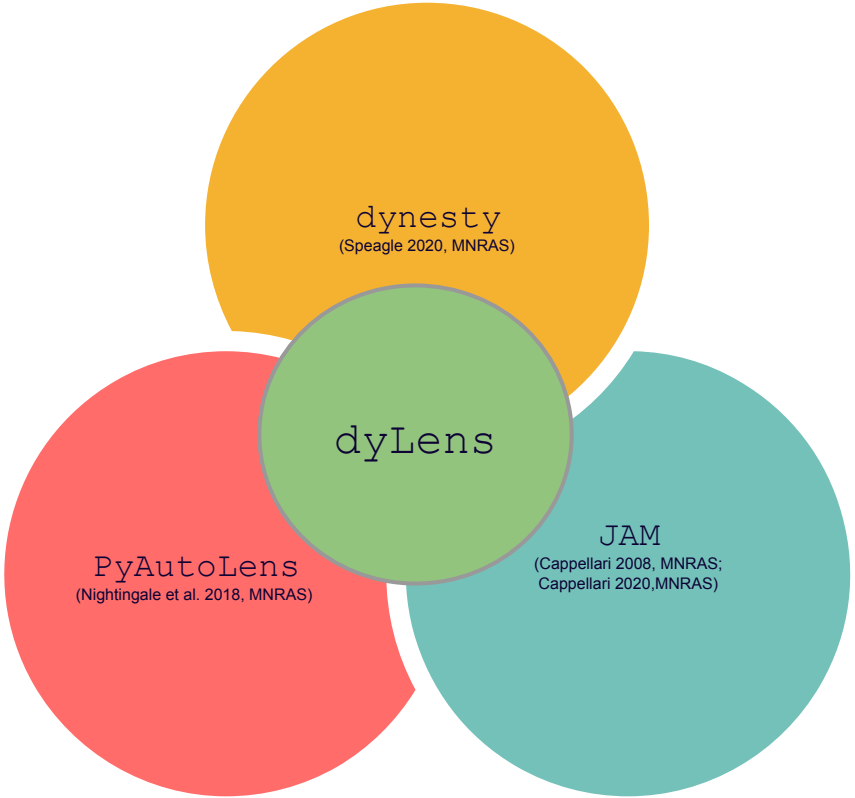
- thin lens approximation

+

Jeans Equations

- collisionless system
- steady-state
- axisymmetric configuration

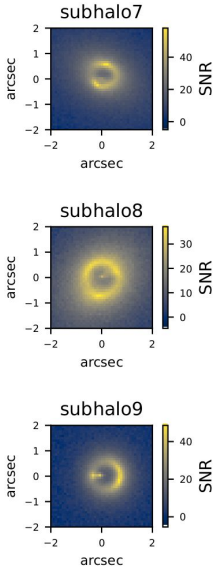
General Framework & Sample

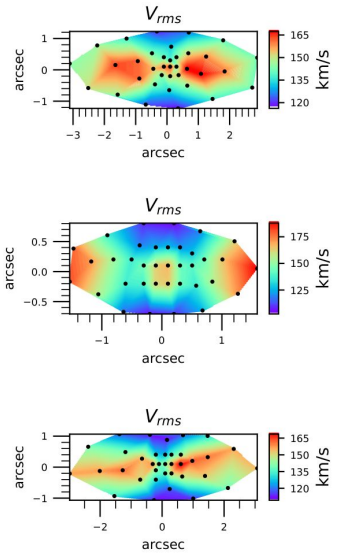


- combined (and self-consistent) modelling
- dynamical only-modelling
- lens-only modelling
- automatic pipeline
- plenty of customisations:
  - M/L
  - dark matter profile
  - stellar anisotropy profile
  - supermassive black hole
  - pixelisation and regularisation
  - sampler
- easy to analyse
- easy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

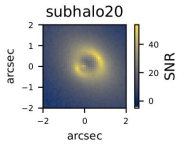
IllustrisTNG-50 - mock sample

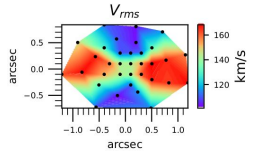
- ETGs at z = 0.05 or z = 0.5
  - Rodriguez-Gomez et al. 2019, MNRAS
  - Huertas-Company et al. 2019, MNRAS
  - Varma et al. 2022, MNRAS
- back to z = 0.2
- lens and source z consistent with SLACS
- source parameters randomly sampled
- HST and MUSE-like data
  - 0.09 arcsec (image)
  - ~ 50 SNR (image)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

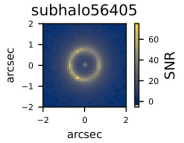


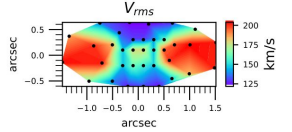


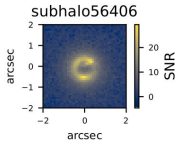
21 mock observations in total

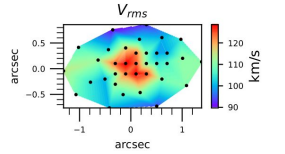












Modelling Pipeline

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

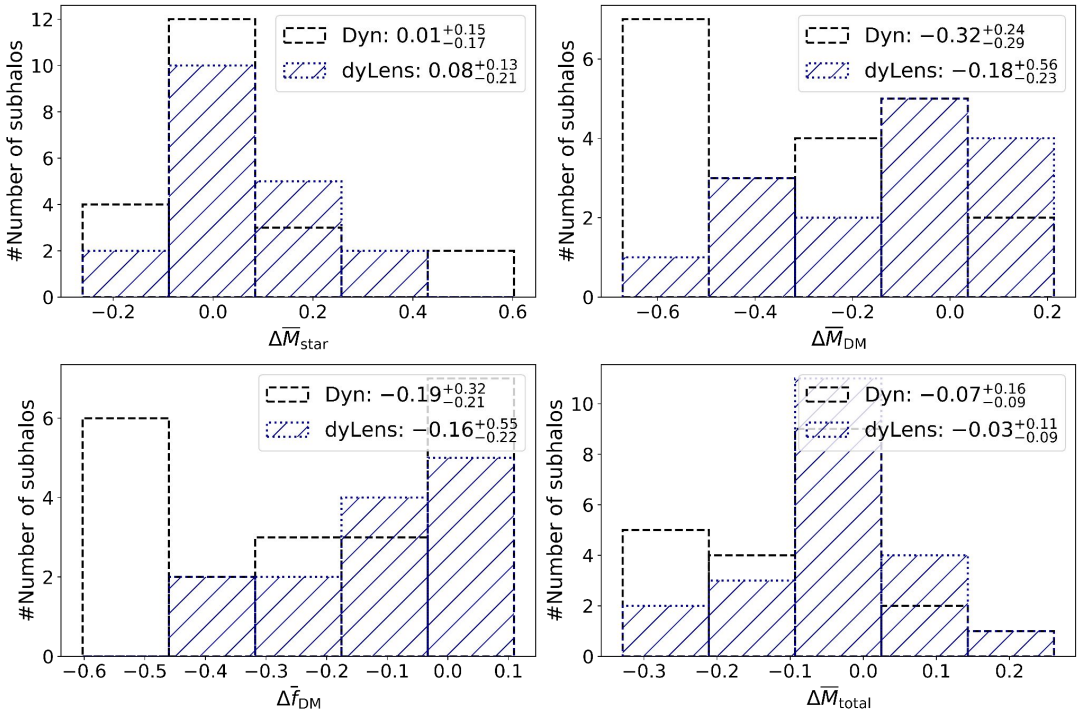
- **Phase 1 (Ph1):** Parametric Source, Lens + Dynamical modelling
  - Sersic source profile
  - broad priors
- **Phase 2 (Ph2):** Pixelisation
  - `DelaunayMagnification`
  - `Constant` regularisation
- **Phase 3 (Ph3):** Model Refinement I
  - fixed pixelisation (Ph2)
  - priors are updated
- **Phase 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

(as far as we know)
First systematic study of
self-consistent modelling

dyLens: Recovering the mass distribution of lens galaxies

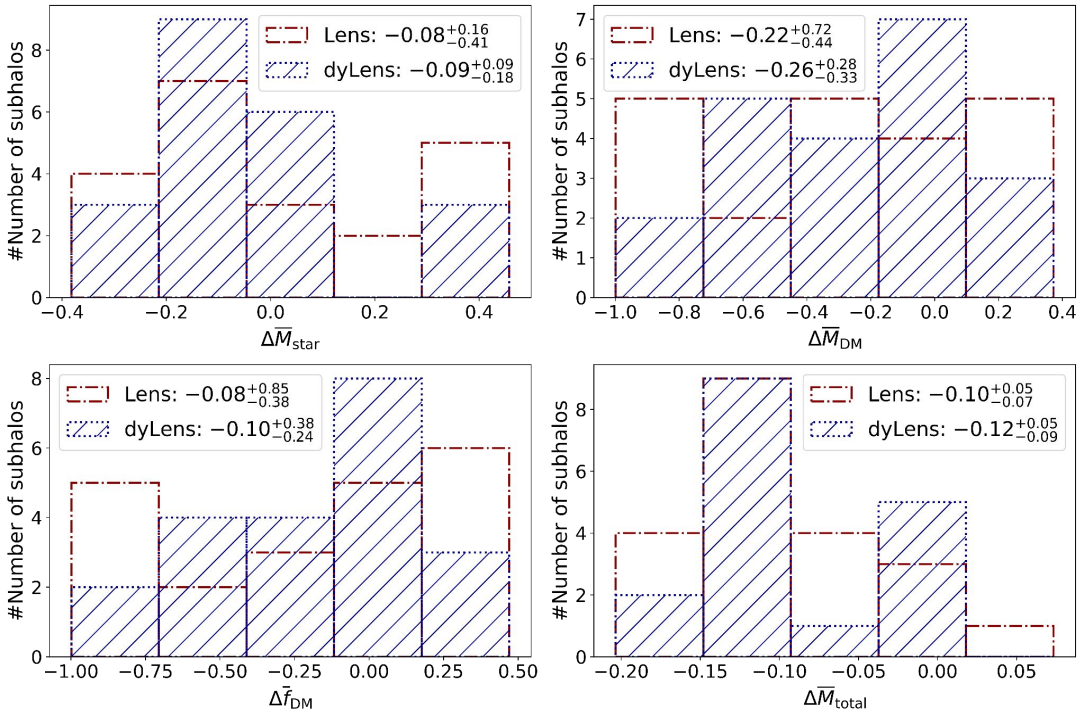
Fiducial model

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



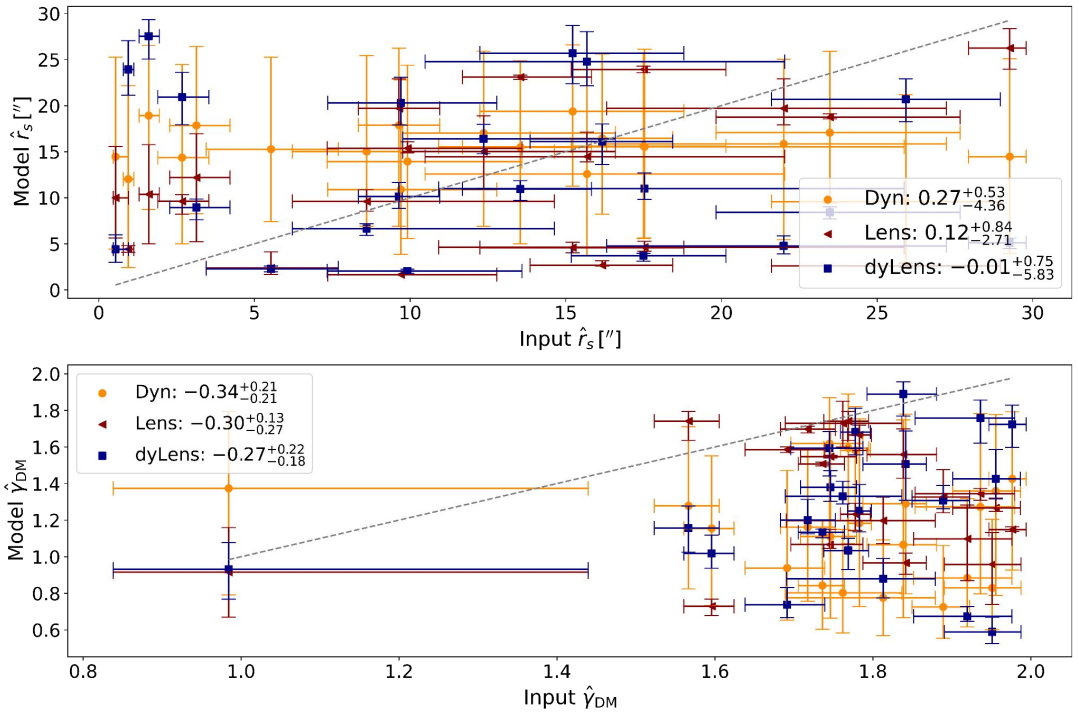
Fiducial model

2D enclosed quantities within R_{Ein}



Fiducial model

Parameter estimation

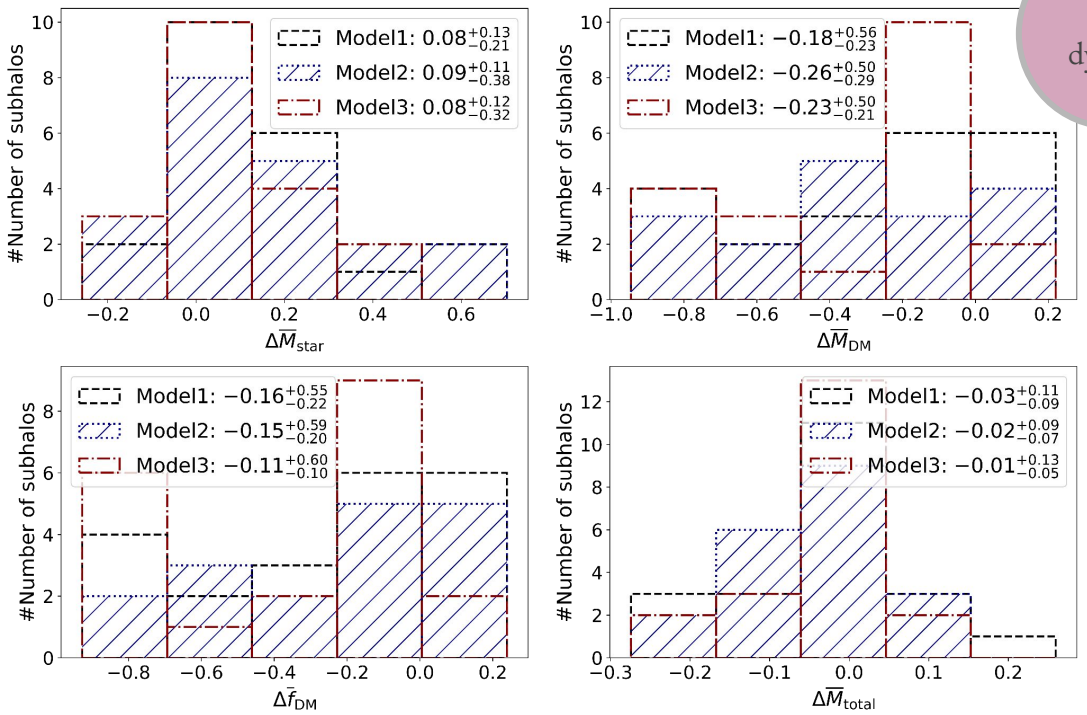


Spatial resolution of kinematical data

For dyLens

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

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



Take-home messages

- good in recovering the total mass (all models)
- good in recovering the total density slope (all models)
- roughly good/good in 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

What's now?

- 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

Thanks!

Any questions?

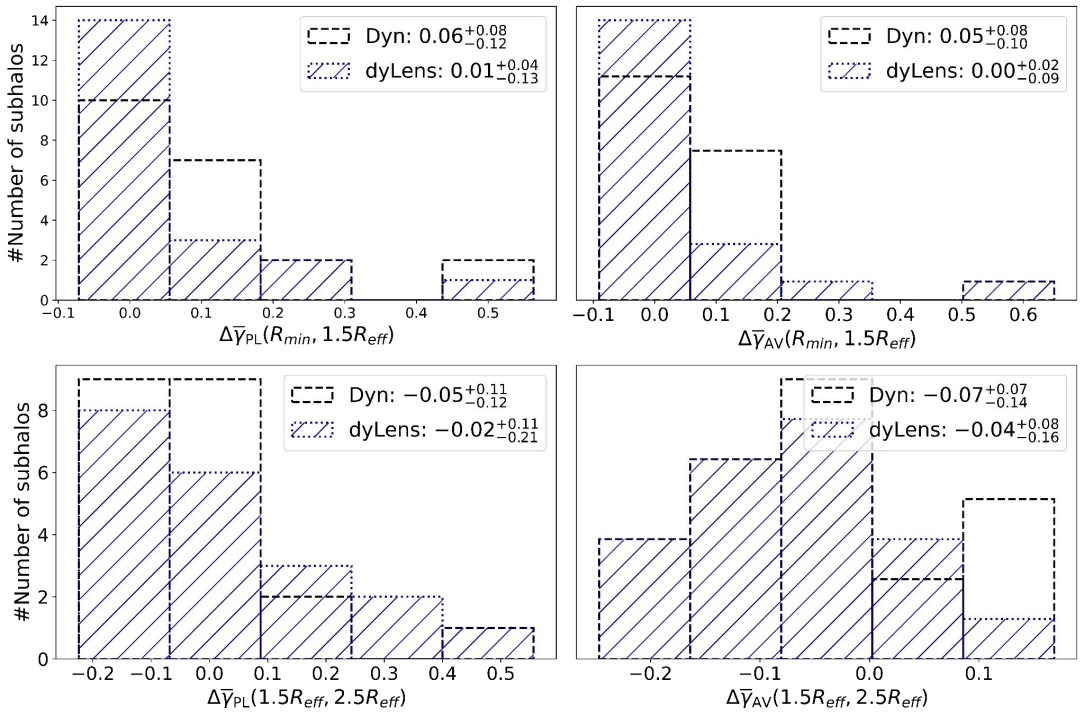
You can find me at:

- carlos.melo@ufrgs.br

EXTRAS

Fiducial model

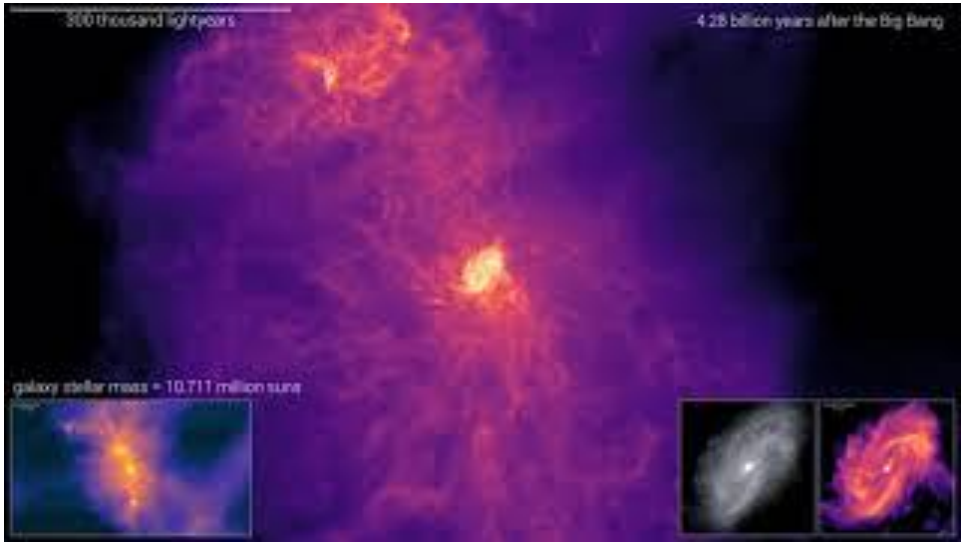
Total mass density slope



IllustrisTNG-50

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

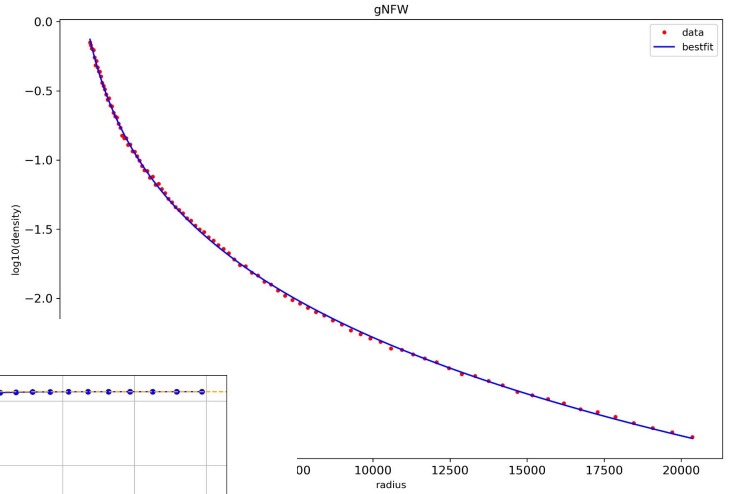
Feature	Units	TNG50
Volume	[Mpc^3]	51.7^3
$L_{\rm box}$	[Mpc/h]*	35
$N_{\rm gas}$	-	2160^3
$N_{\rm DM}$	-	2160^3
$m_{\rm baryon}$	[M$_\odot$]	8.5×10^4
$m_{\rm DM}$	[M$_\odot$]	4.5×10^5
$\epsilon_{\rm gas,min}$	[pc]	74
$\epsilon^{z=0}_{\rm DM,stars}$	[pc]	288
CPU time	[Mh]	130

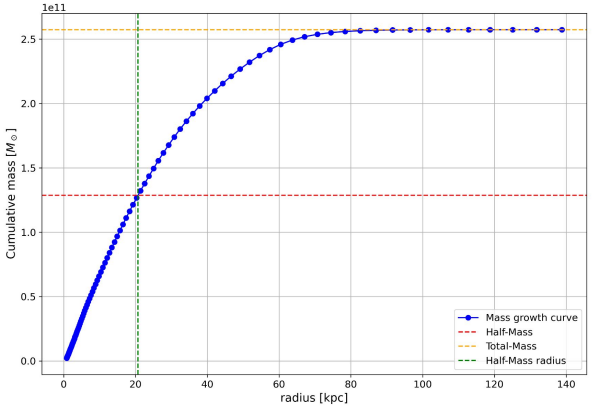


IllustrisTNG-50 -

mock sample

- 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

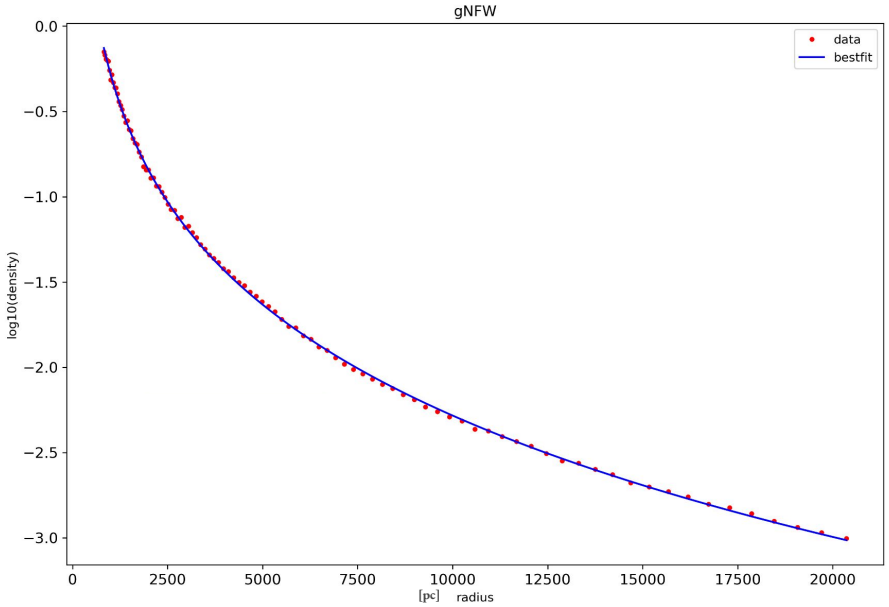




IllustrisTNG-50 - mock sample

- Radial profiles
  - 100 logarithmically spaced spherical shells
  - until the half-mass radius
- Dark matter profiles
  - gNFW profile (r_s, ρ_s, γ_{DM})
  - non-linear fit
  - same priors as in the pipeline

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



Bias evaluation

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

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

Bias evaluation

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

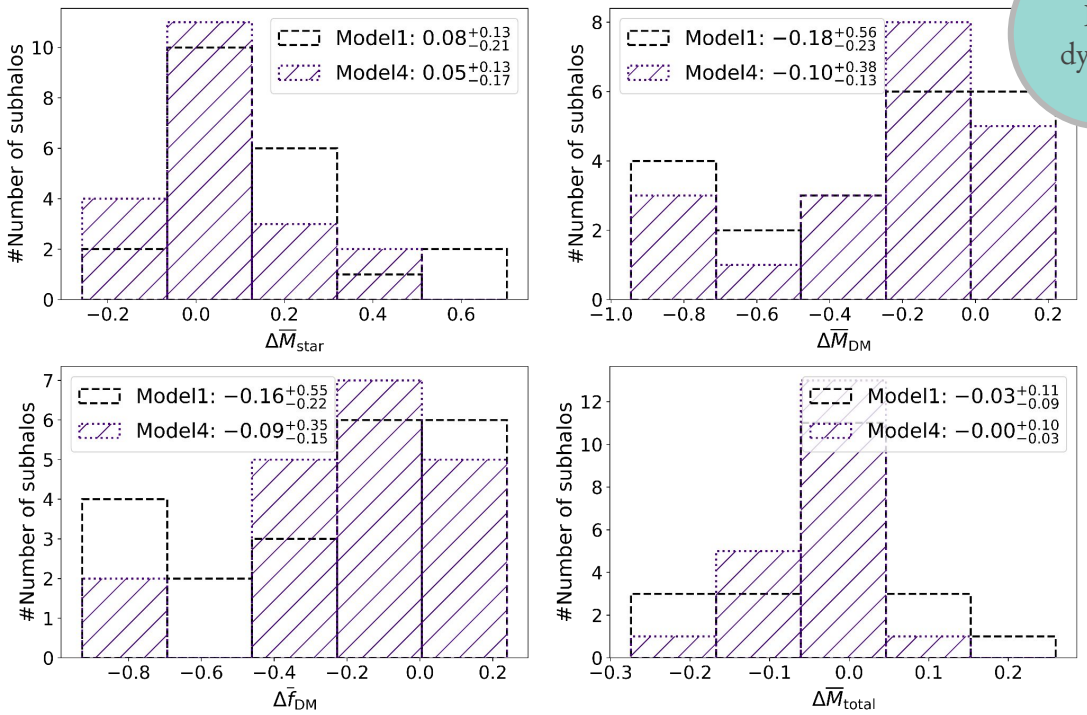
$$\gamma_{\rm AV}(r_1, r_2) = \frac{\ln\left[\rho(r_2)/\rho(r1)\right]}{\ln\left(r_1/r_2\right)}$$

The mass profile

For dyLens

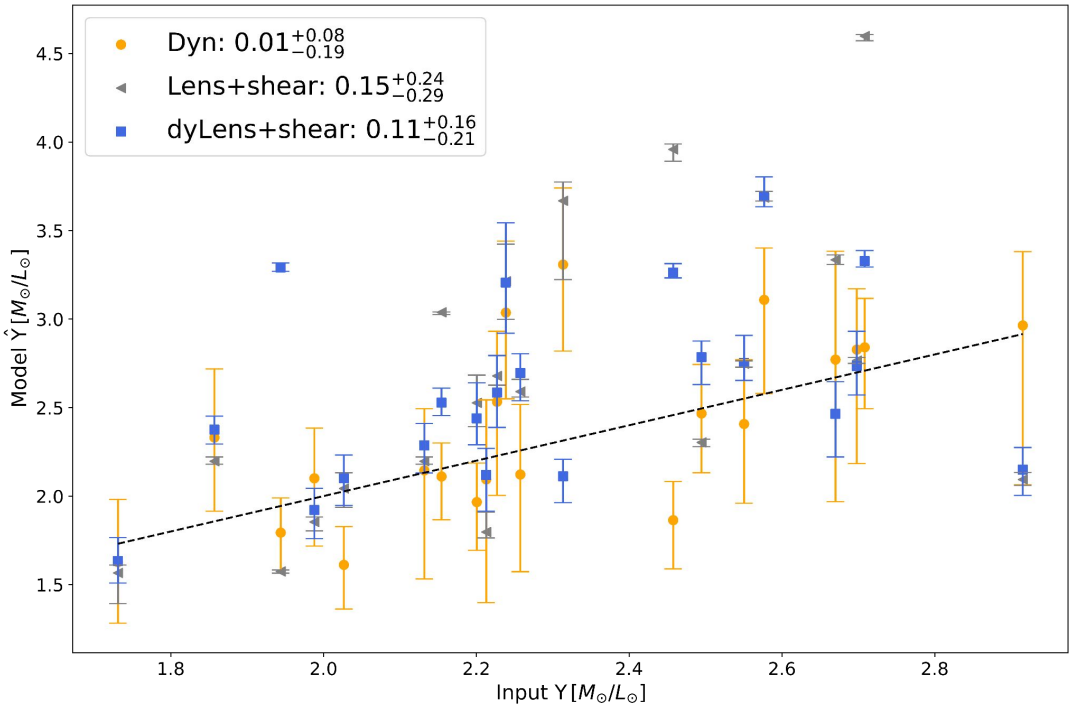
3D intrinsic enclosed quantities within $2.5R_{eff}$

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



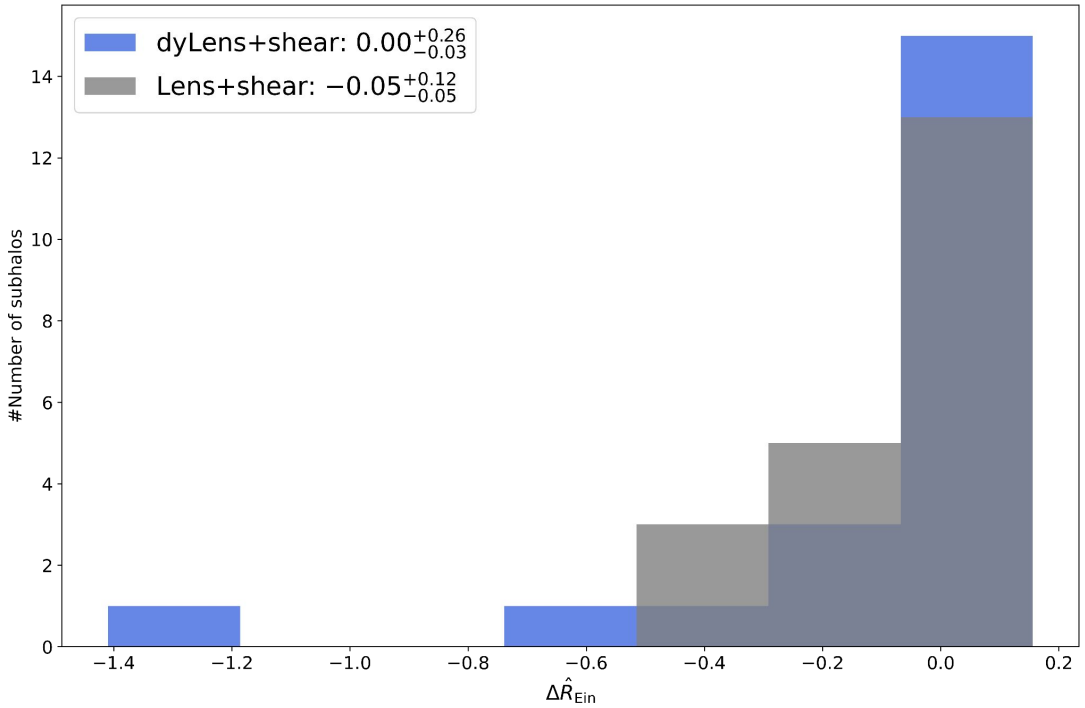
Fiducial model

Parameter estimation



Fiducial model

Einstein radius

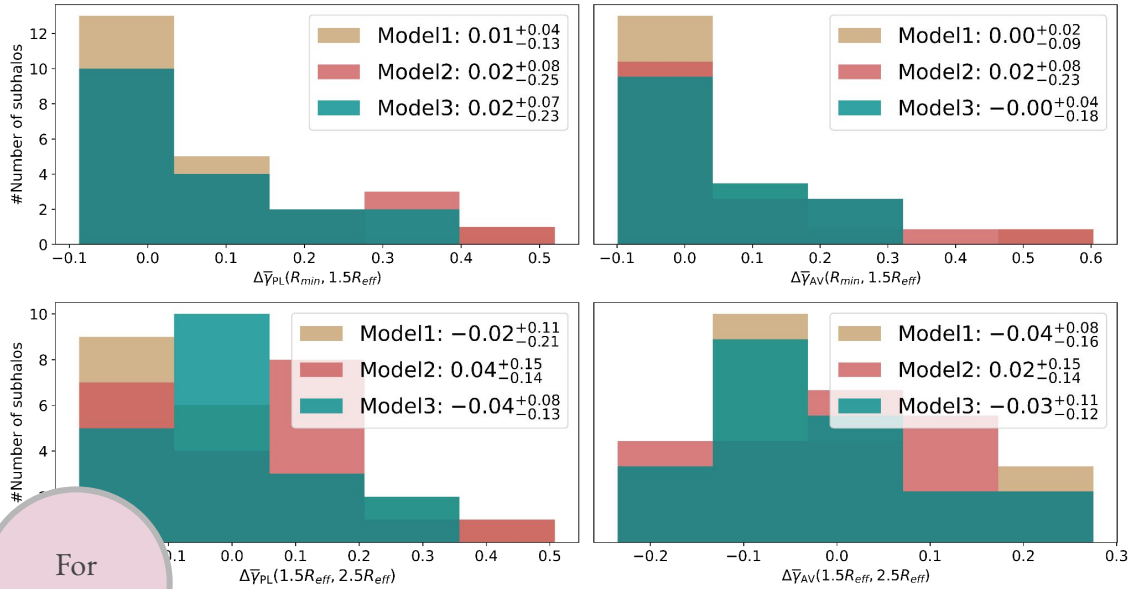


Spatial resolution of kinematical data

galaxies

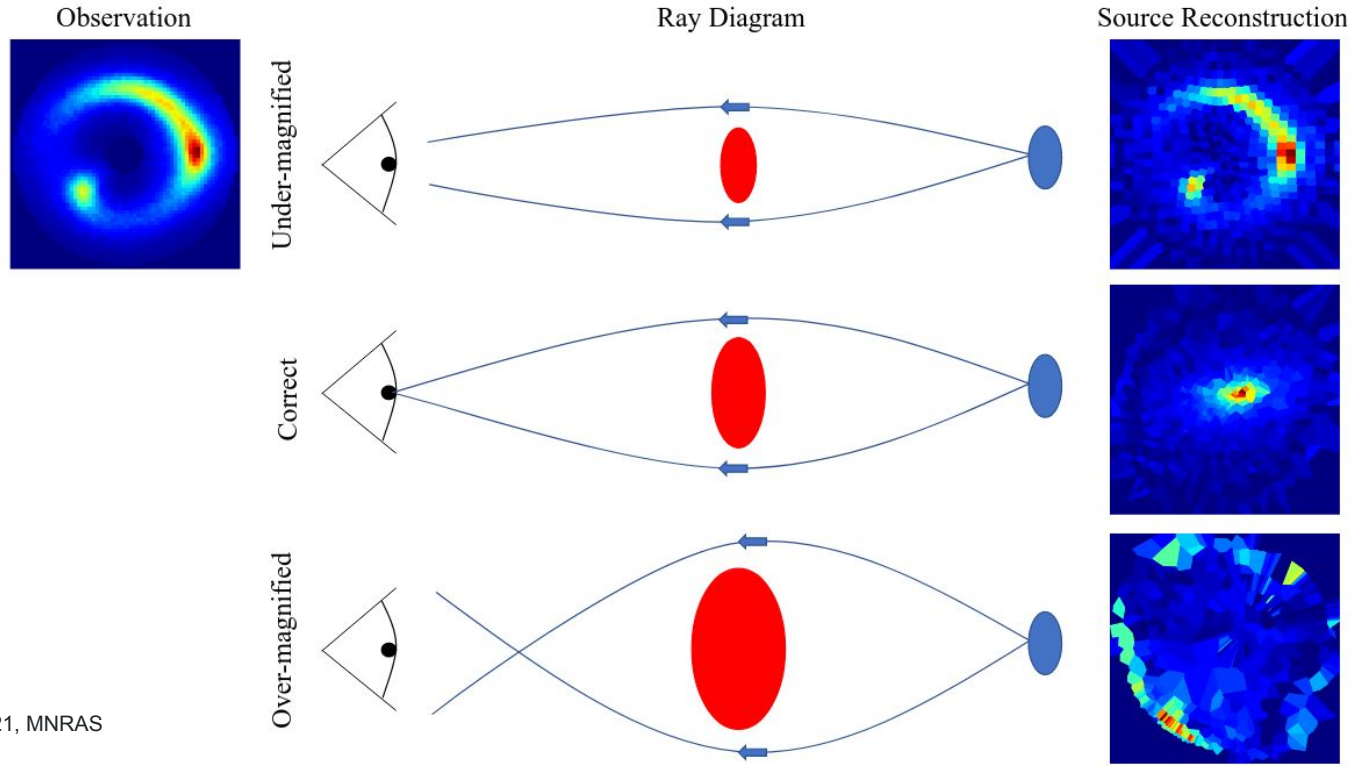
Total mass density slope

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



For dyLens

Under/Over-magnified solutions



Maresca et al. 2021, MNRAS

Spectra simulation and uncertainties

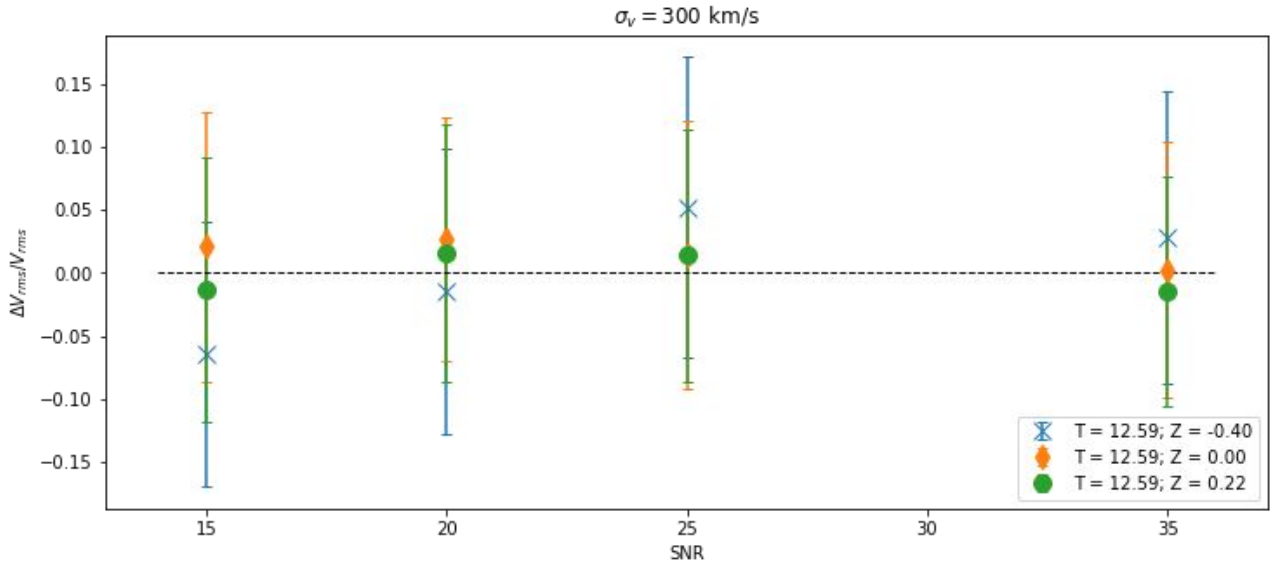
- Age = [2.5, 6.3, 12.6] Gyrs
- [Z/H] = [−0.4, 0.0, 0.22]
- σ_v = [250, 280, 300, 350] km/s
  - v = 40 km/s
- SNR = [15, 20, 25, 35]
- MUSE-like
- E-MILES SSPs

Harrison+2010, AA; McDermid+2015, MNRAS

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

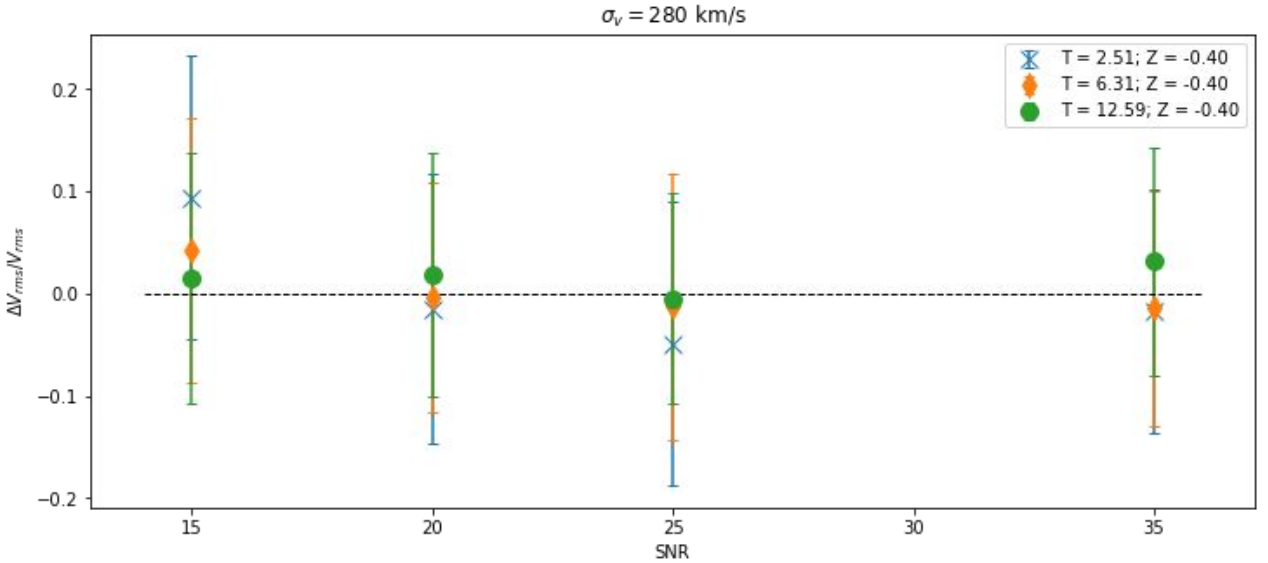
Spectra simulation and uncertainties

same age, different metallicities



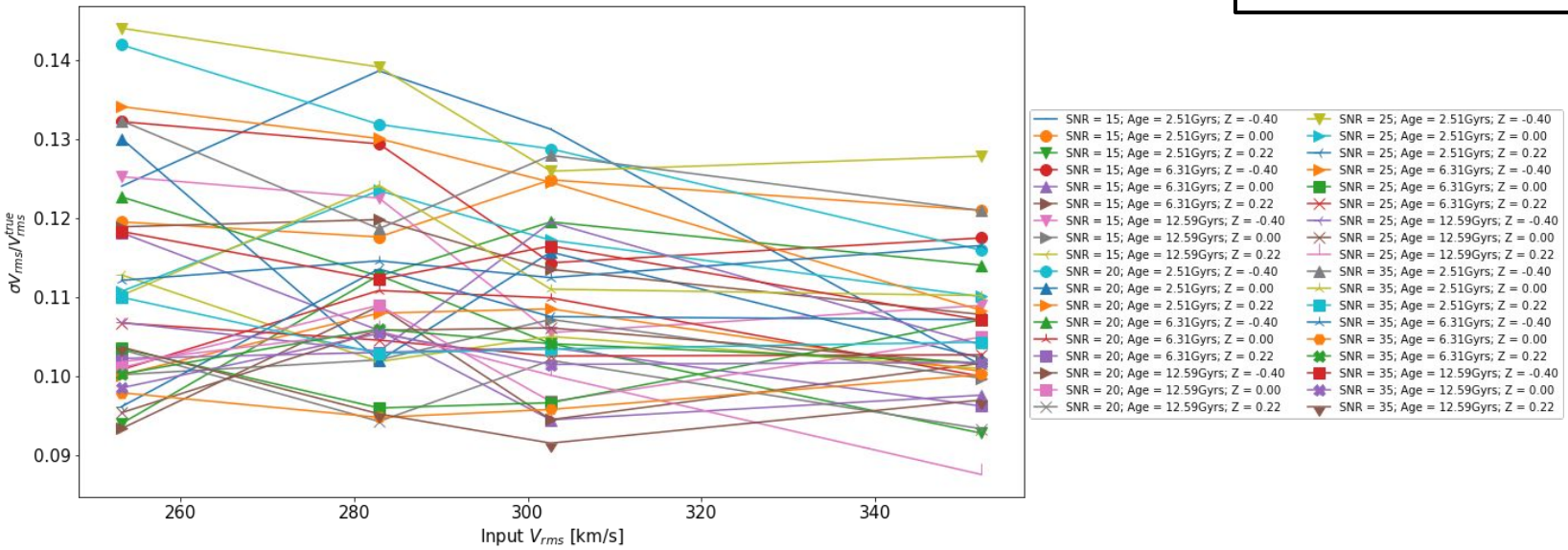
Spectra simulation and uncertainties

same metallicities, different ages



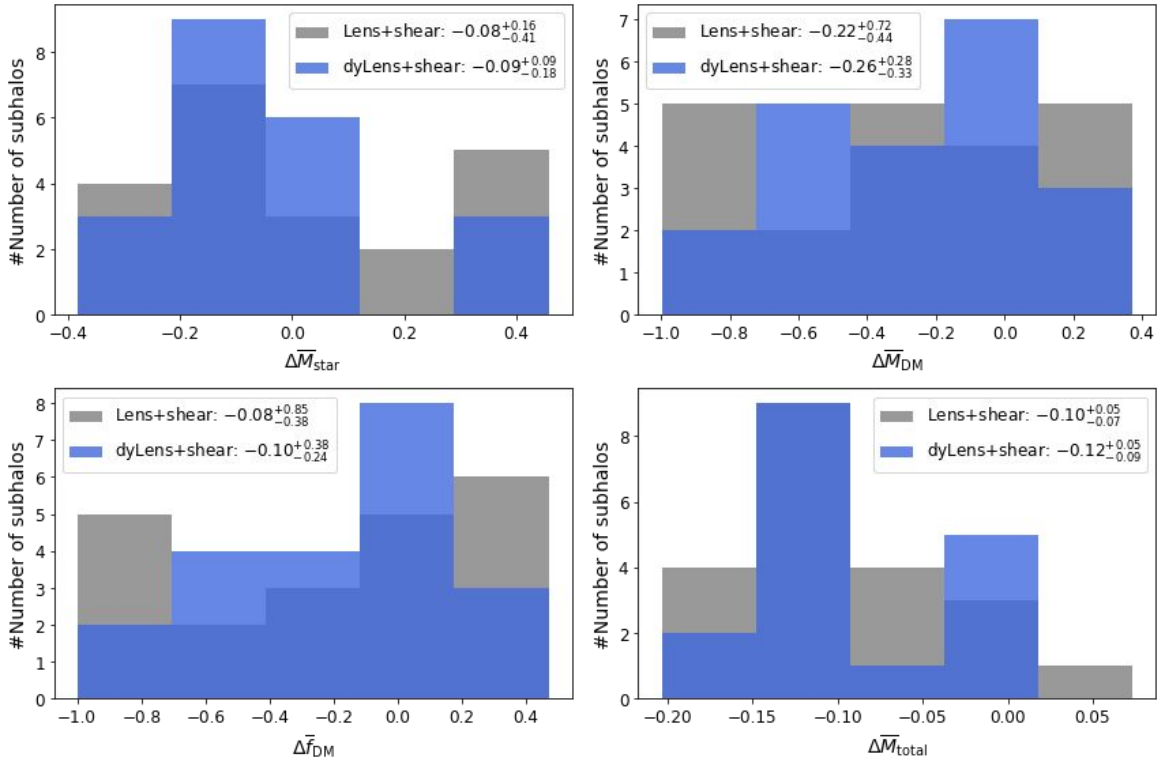
Spectra simulation and uncertainties

messy, but complete



Fiducial model

2D enclosed quantities within R_{Eins}



The mass profile

For dyLens

2D enclosed quantities within R_{Eins}

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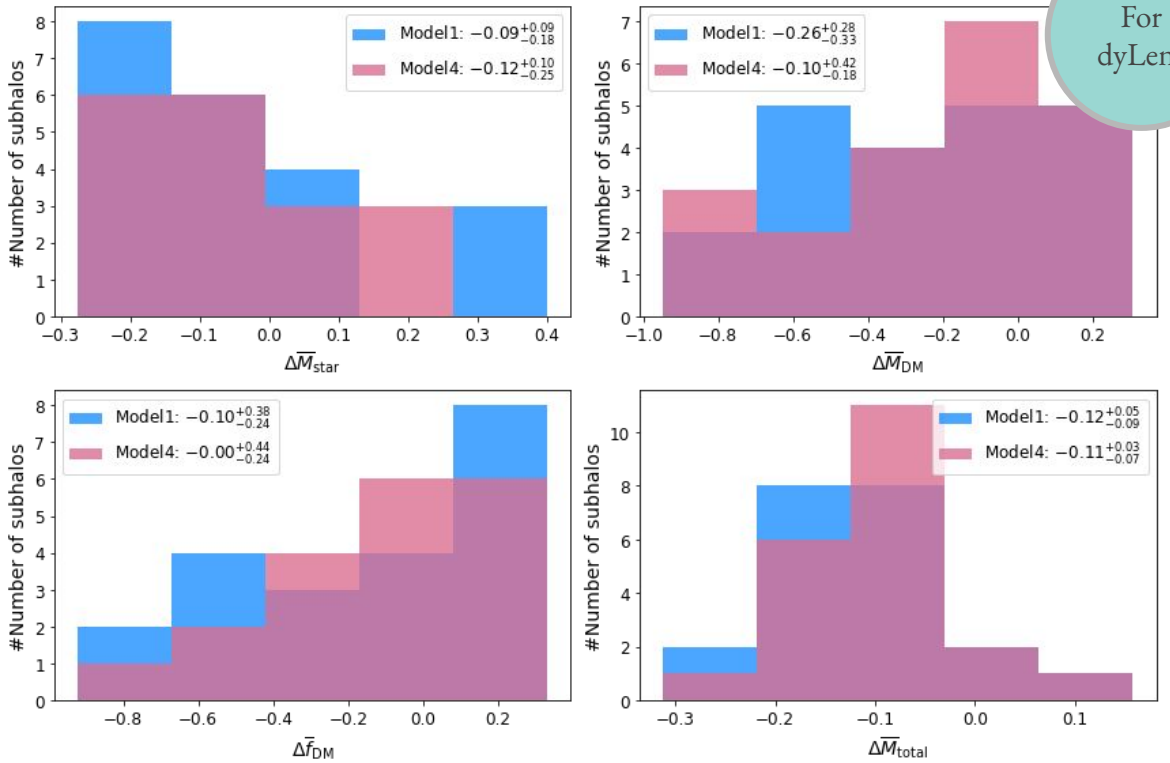
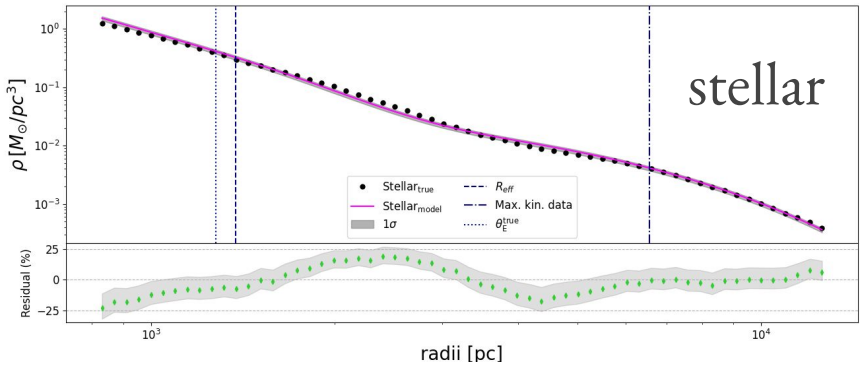
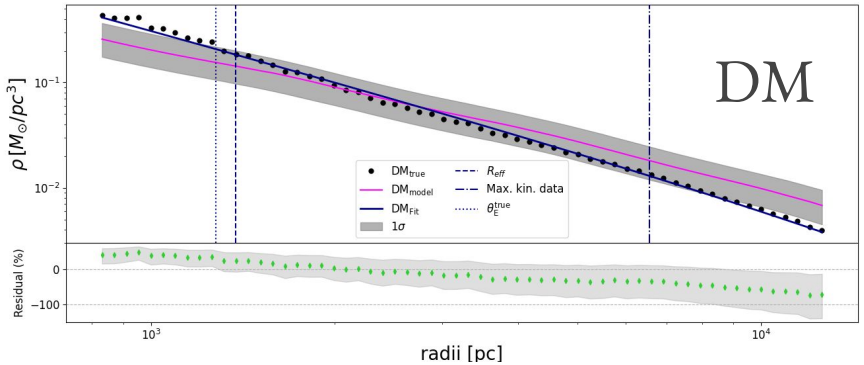
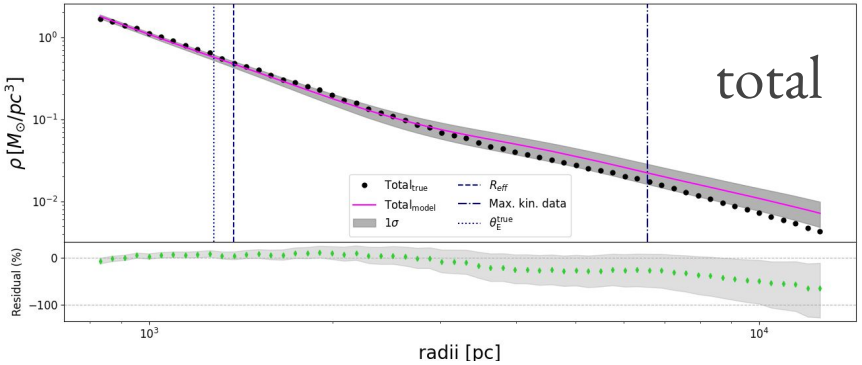


subhalo485608

galaxies







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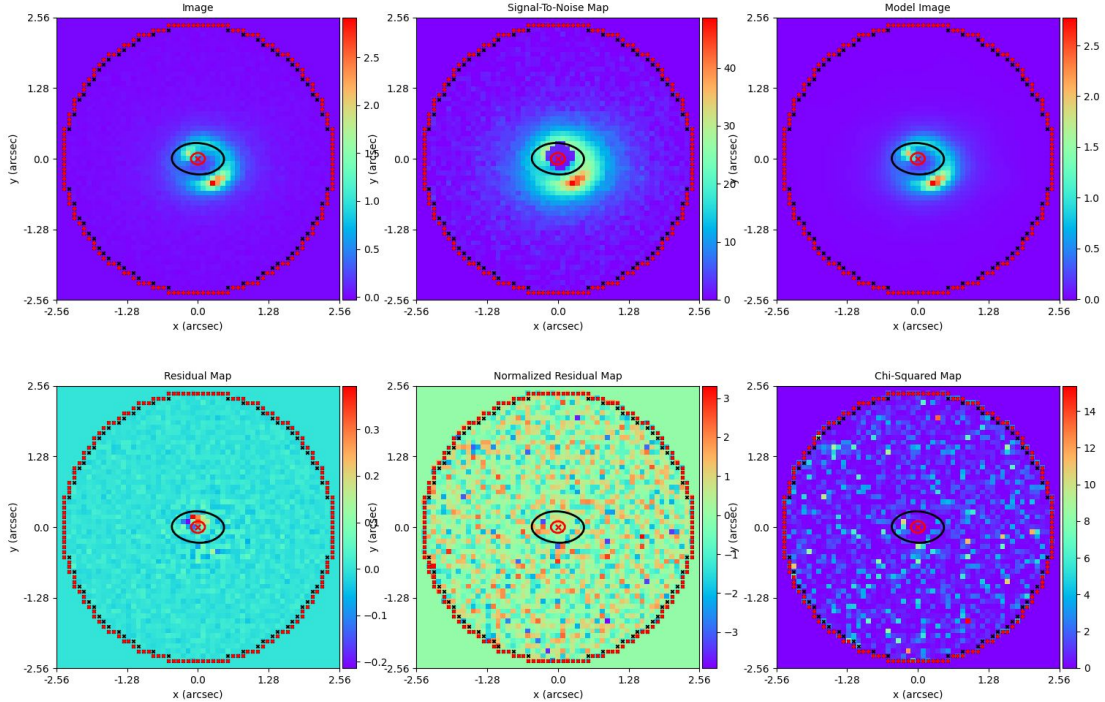
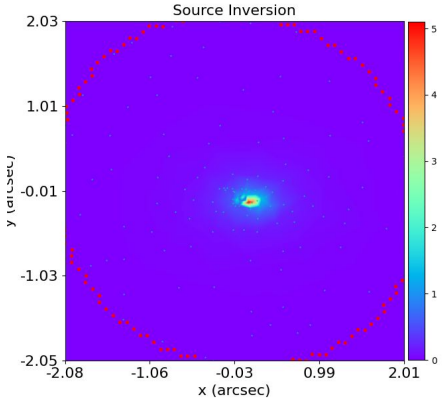
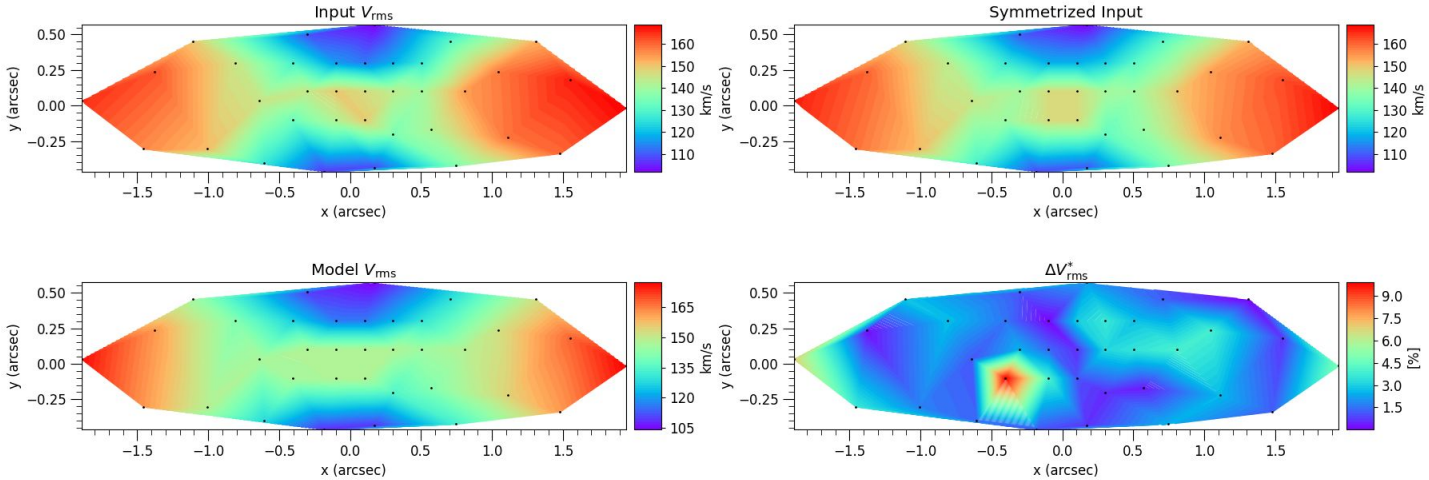
galaxies



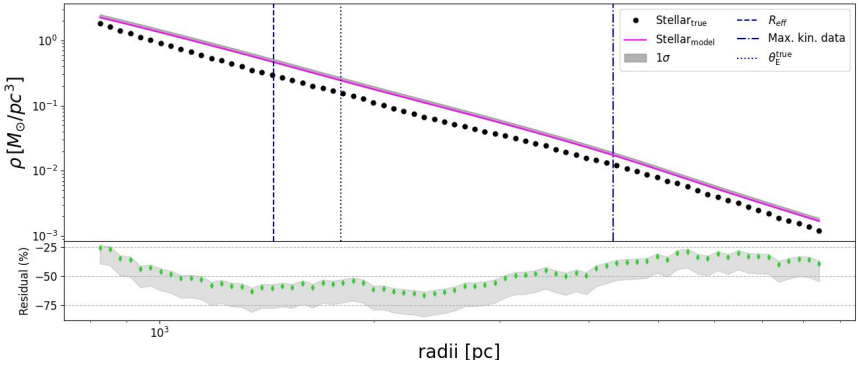


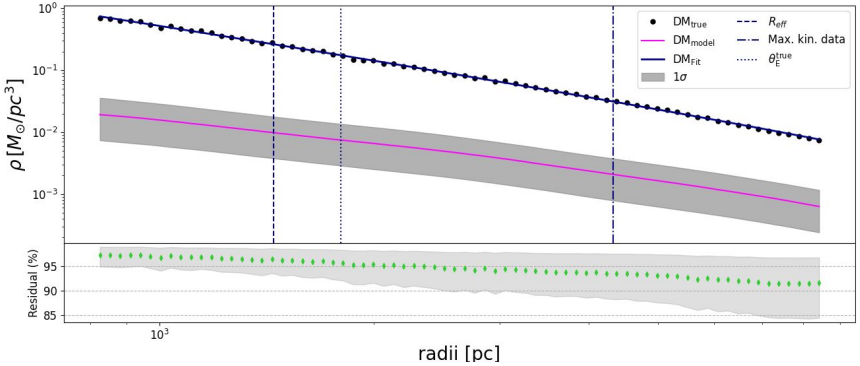
galaxies

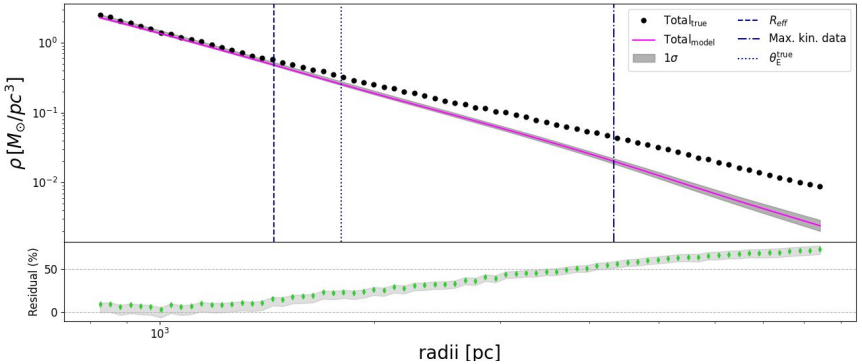

Input V_{rms}
Symmetrized Input
Model V_{rms}
ΔV^{*}_{rms}
x (arcsec)
y (arcsec)
km/s
[%]

subhalo11

galaxies

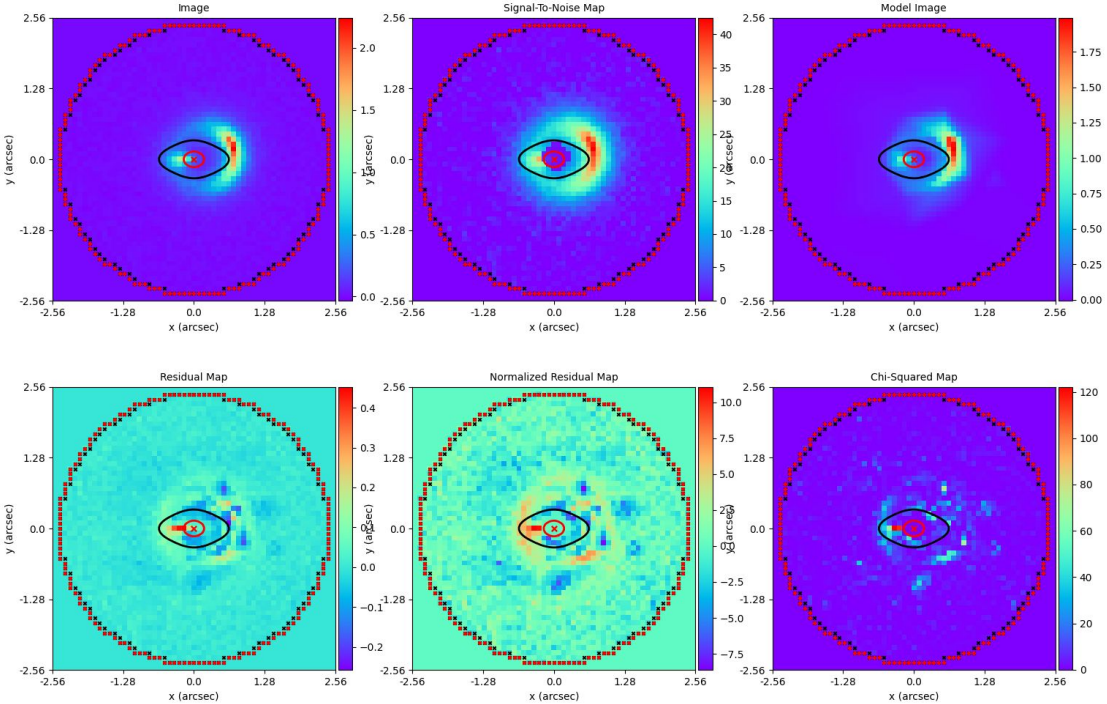


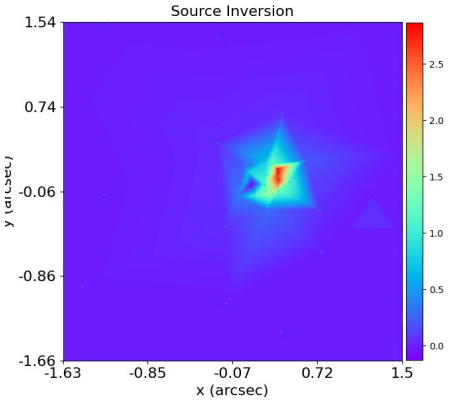




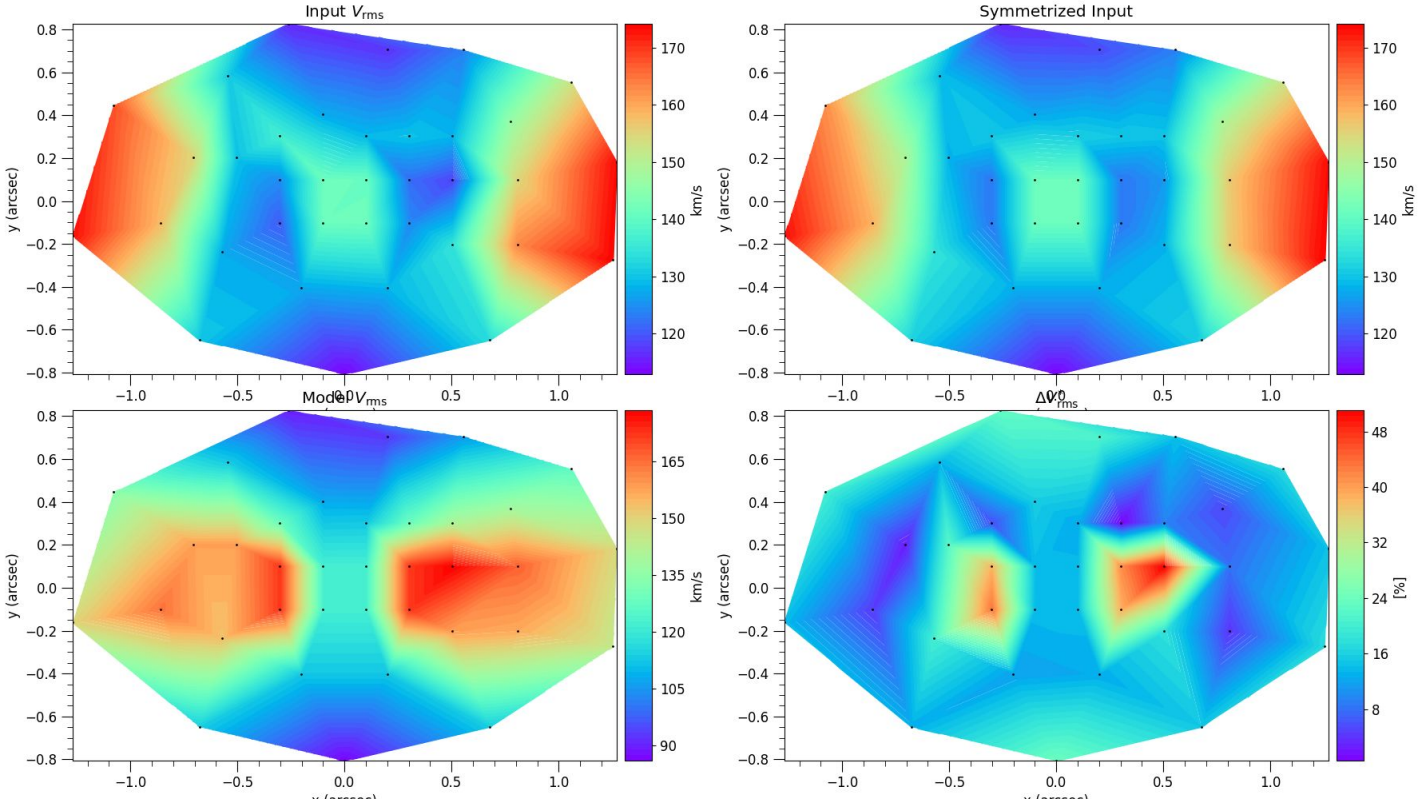
subhalo11

galaxies





galaxies


Input V_{rms}
Symmetrized Input
Model V_{rms}
ΔV_{rms}
y (arcsec)
km/s
[%]