Euclid consortium

Large-scale automated gravitational lens modelling with BNNs in Euclid

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arXiv:2503.15329

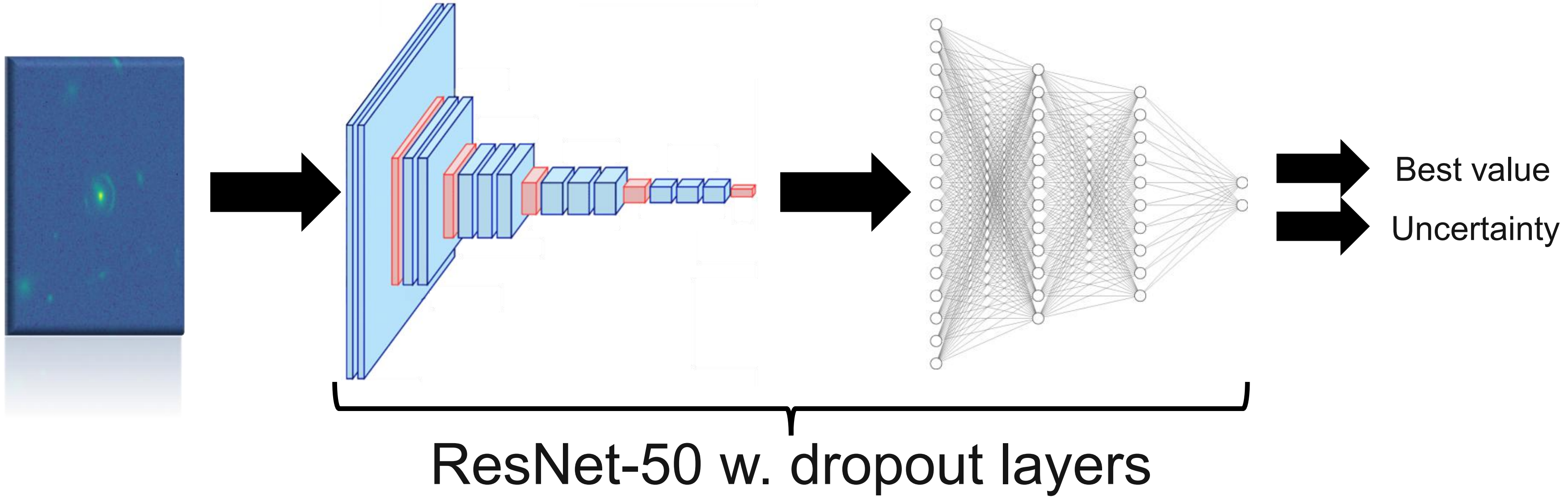
Euclid: Need for automation

- Pre-Euclid, only a small number ($\sim 10^2$) of lenses have been detected.
- In Euclid Q1 ($\mathrm{Area:}\ 63\ \mathrm{deg}^2$), 497 new galaxy-galaxy lenses have been found.
(Euclid Collaboration: M. Walmsley et al. 2025)
- The **Euclid WIDE survey** will scan $\sim 10^9$ galaxies over $\sim 14{,}000\ \mathrm{deg}^2$ of sky.
- Number of lenses expected at the end of the survey: $\sim 10^5$.
(Scaramella+22; Mellier+24)
- Traditional modelling techniques (maximum likelihood, MCMC) are **computationally expensive** (run times between hours to months, depending on complexity).

We need automated methods for lens modeling!

LEMON: introduction

- **LEMON** (LEns MOdelling with Neural networks): Bayesian neural network, based on the ResNet-50 architecture. (He+15; Gentile+22; Busillo+25)
- **Goal**: numerically estimate gravitational lenses' mass and light parameters.
- **Peculiarity**: LEMON can estimate both the aleatoric (associated to **intrinsic quality of the image**) and epistemic (associated to **quality of the training set**) components of the uncertainty.



Why LEMON?

- **Speed and efficiency**: LEMON is fast, and can speed-up traditional modelling techniques;
- **Scalability**: LEMON can handle large amounts of lenses;
- **Accuracy**: LEMON provides accurate estimates of key lens parameters, robust on both simulated and real data;
- **Cross-validation with classical modelling**: LEMON can double check if results from classical modelling are correct;
- **Uncertainty quantification**: Bayesian uncertainty estimates of parameters can be used to quantify reliability of results.

LEMON: data

Simulated sample

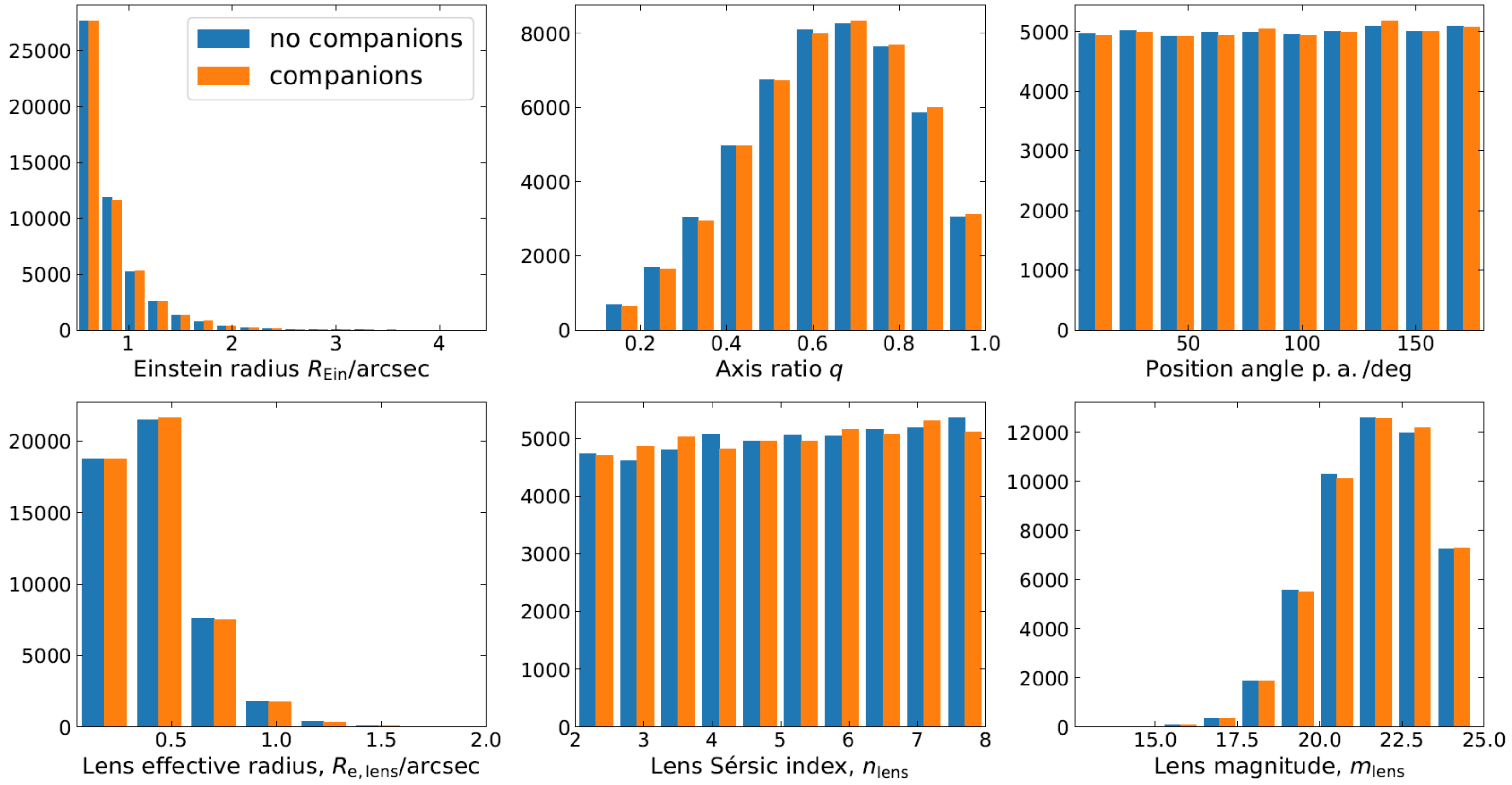
- **Training set**: 80,000 mock Euclid lenses with SIE mass model;
- **Validation and test set**: 10,000 mock Euclid lenses, as above;

Real sample

- **Euclidised lenses**: 60 HST lenses (spectroscopically confirmed), degraded to match Euclid WIDE observation conditions;
- **ERO lenses**: 5 grade A + B lenses detected in the Perseus ERO field, chosen such that their classical modelling is valid; (Acevedo-Barroso+25)
- **Q1 lenses**: 292 expert-vetted grade A + B lenses from Q1 data.

(Walmsley+25, Rojas+25)

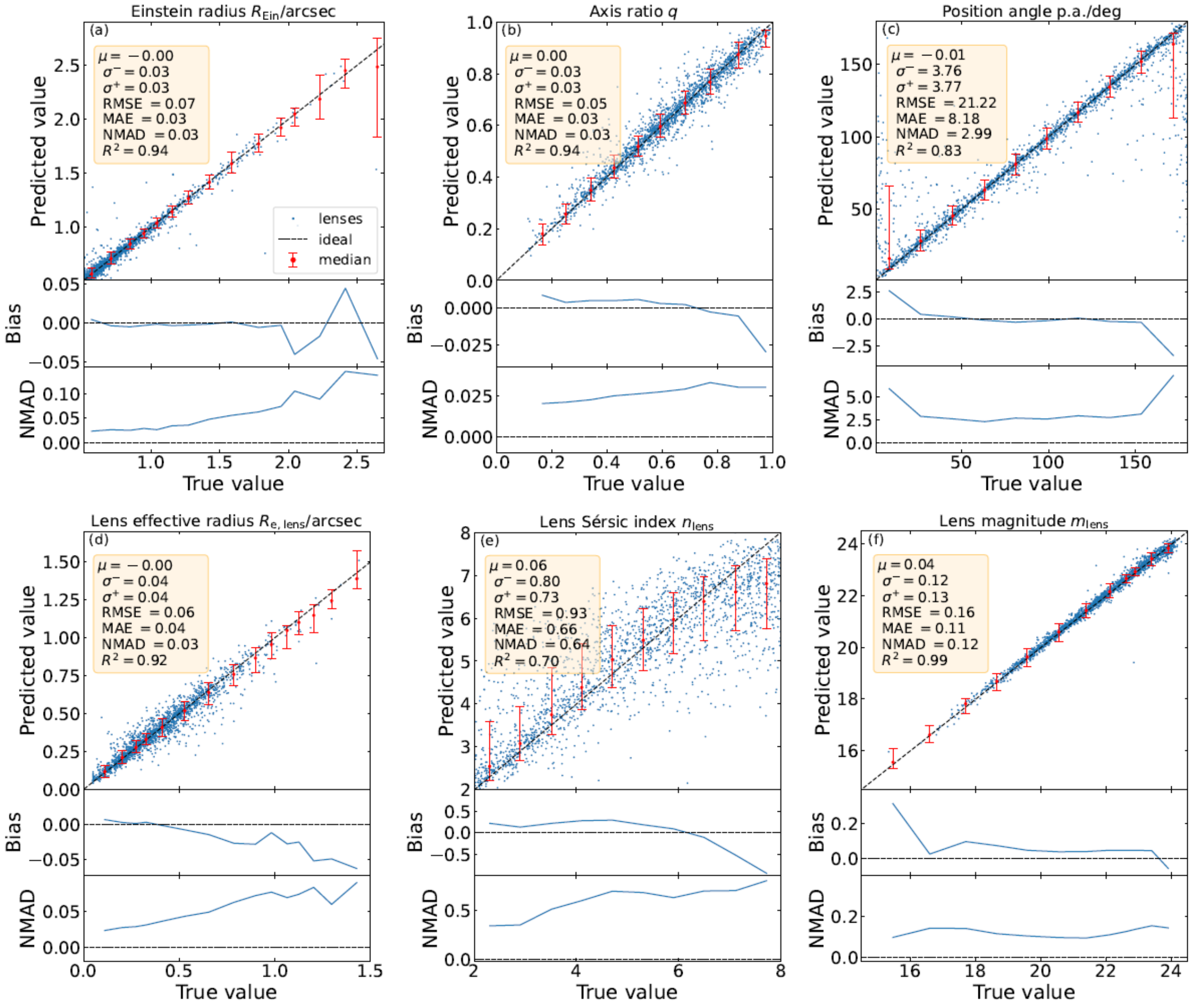
LEMON: prior on parameters



Distributions for R_{Ein}, R_{e} and m_{lens} extracted from empirical distributions derived from the Euclid Flagship simulation.

(Castander+24)

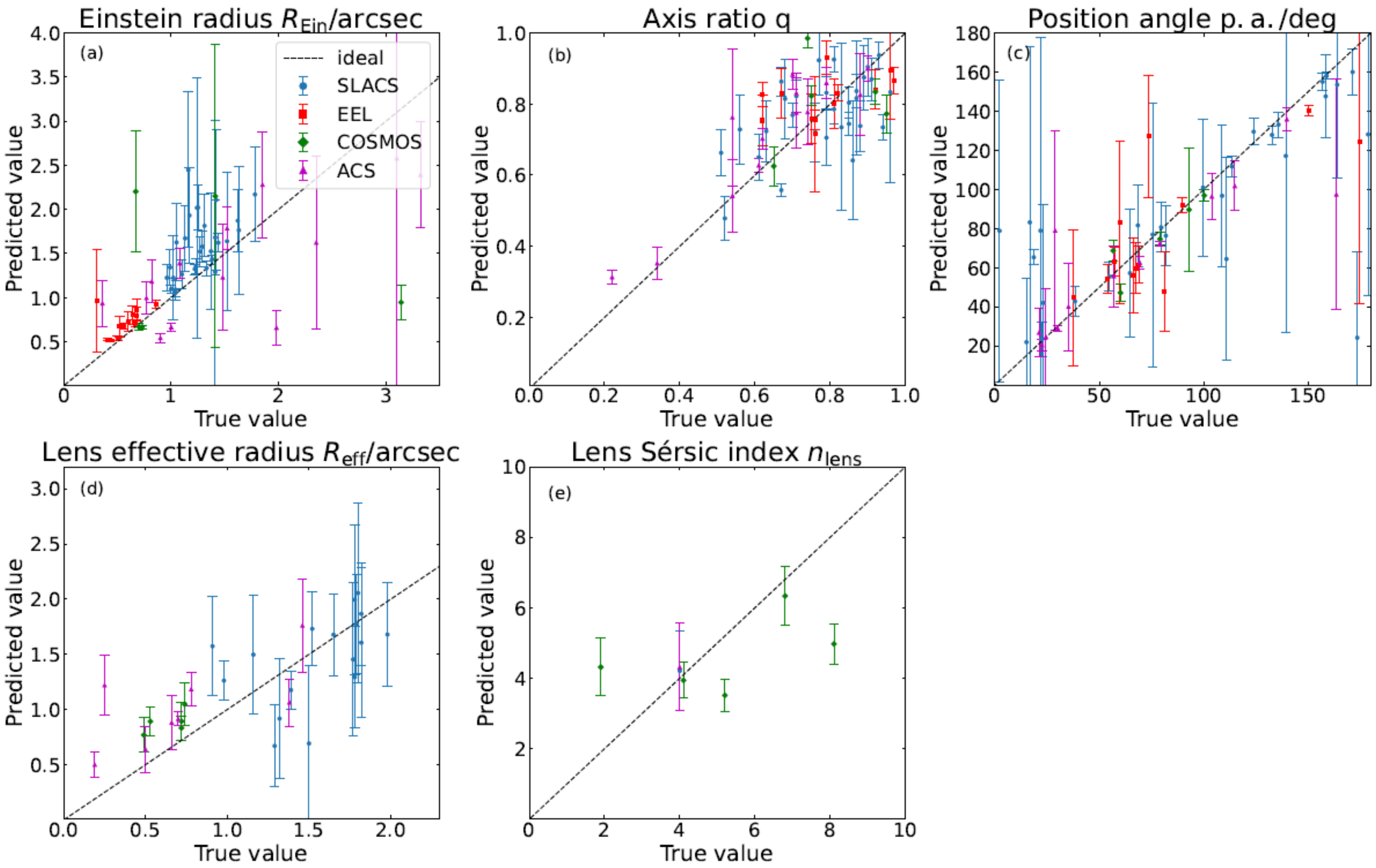
LEMON: results on test-set



Results

- The model shows high accuracy in recovering most parameters, **especially the Einstein radius**.
- Sérsic index shows **non-linear, scattered recovery**.

LEMON: results on Euclidised lenses



Results

All parameters are well recovered. No conclusions on the Sérsic index, due to low statistics.

LEMON: results on Euclidised lenses

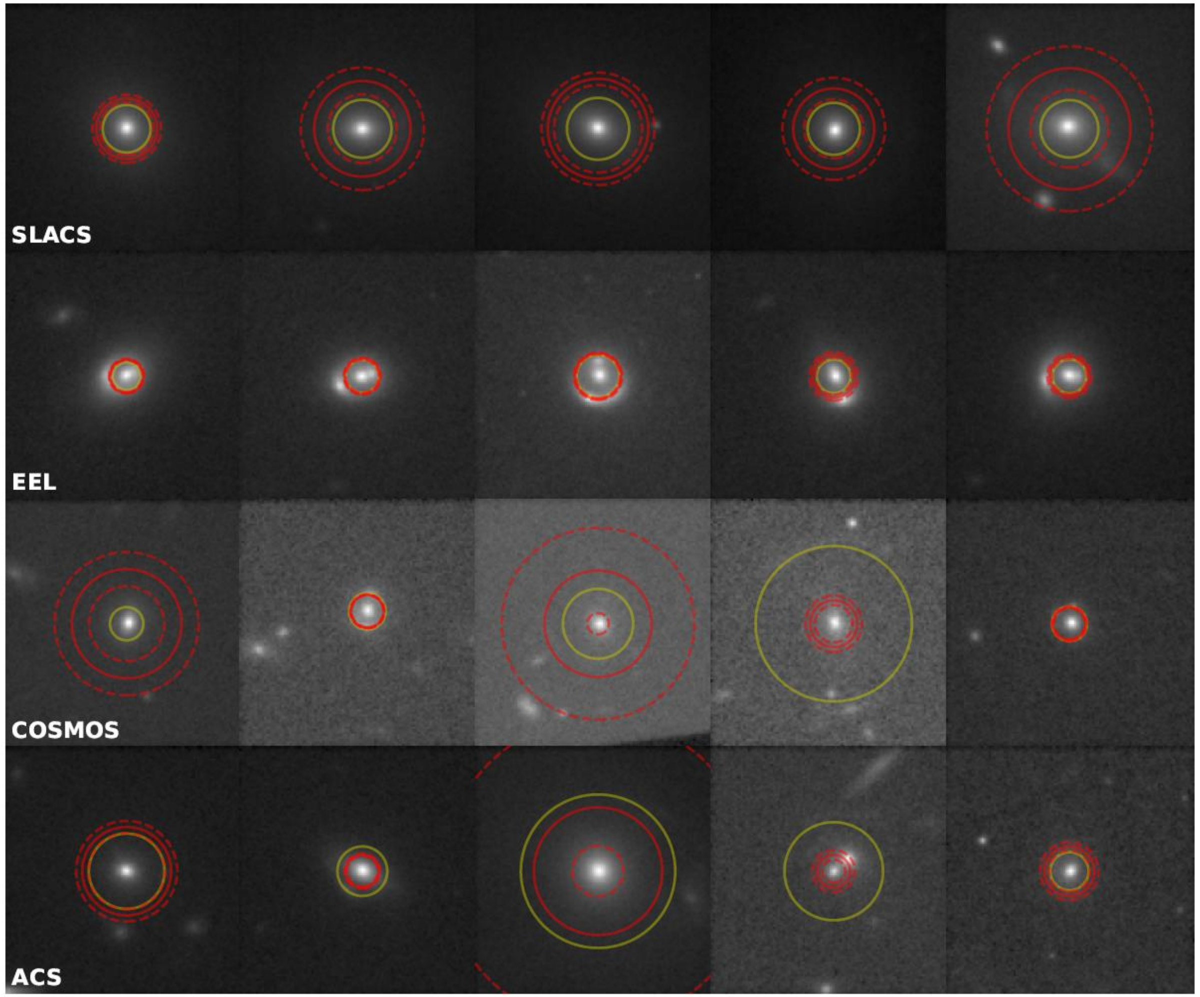
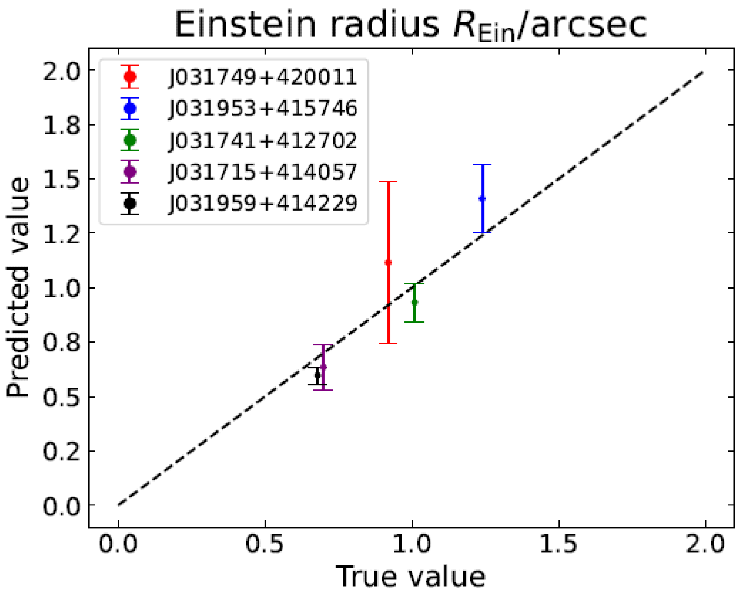
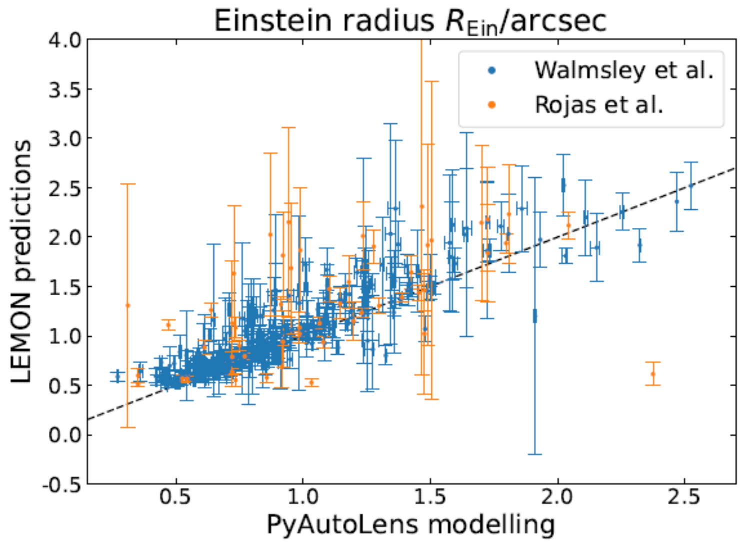


Fig. 9. Random selection of 20 10″ × 10″ cutouts of Euclidised lenses taken from the SLACS, EEL, COSMOS, and ACS subsamples. Red circles show the best predictions for the Einstein radius from LEMON, with corresponding 16th and 84th percentiles shown with dashed red circles. Yellow circles show the values for the Einstein radii reported in Bolton et al. (2008), Oldham et al. (2017), Faure et al. (2008), and Pawase et al. (2014), respectively. For ACS lenses, the radius of the arc is taken instead, due to lack of Einstein radius measurement.

Results on real Euclid lenses





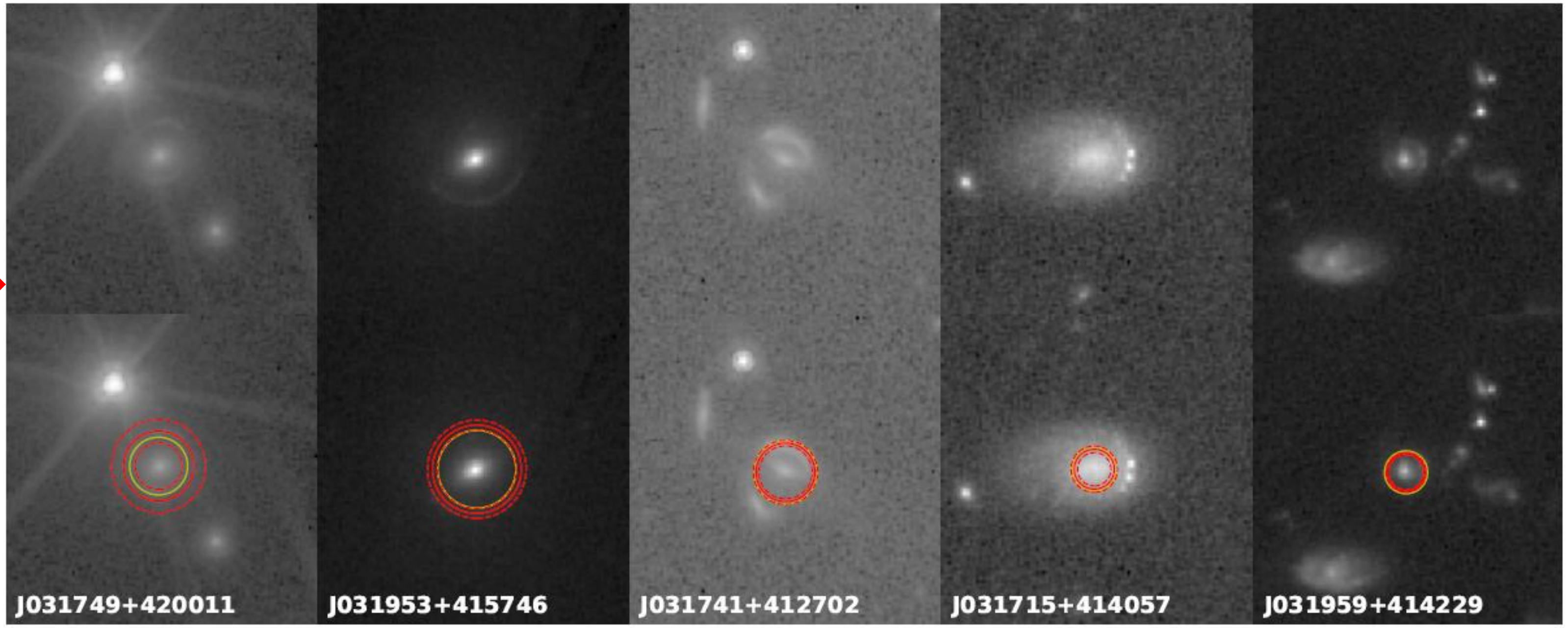


Fig. 11. 10″ × 10″ cutouts of the five *Euclid* gravitational lenses found in the Perseus ERO field and modelled in Acevedo Barroso et al. (2024). *Top row*: unedited cutouts centred on the lenses. *Bottom row*: the same cutouts, with the predicted Einstein radius (red circles, with dashed circles showing the uncertainty bands) and the value obtained from the classical modelling (yellow circle) superimposed on them.

Recovery of Einstein radius of real Euclid lenses is successful.

Speed-up of classical modelling pipeline

- The standard modelling method for modelling in Euclid is a nested sampling algorithm.

(Castander+24)

Time to model 20 mock lenses: 7 hrs

- PyAutoFit can also work in “hybrid mode” with LEMON, using a gradient ascent optimizer with starting points given by LEMON.

Time to model 20 mock lenses: 16 min

- Speed-up of up to 26 times with LEMON. This cannot be achieved by random initialization of starting points.

Conclusions and improvements

- LEMON manages to recover accurately both mock and real Euclid lenses' parameters for Q1 lenses.
- LEMON can speed-up the standard Euclid modelling pipeline up to 26x the standard speed.
- Objective for DR1: integrate LEMON (if possible) and fully automatise the modelling pipeline.
- Future improvements:

  1. Introduce external shear, disalign mass from light, handle generic power-law profiles;
  2. Enhance predictions' accuracy with lens/source deblending;
  3. Train LEMON to predict unlensed source position.