Galaxies, Dark Matter and Supermassive Black Holes with Strong Gravitational Lensing

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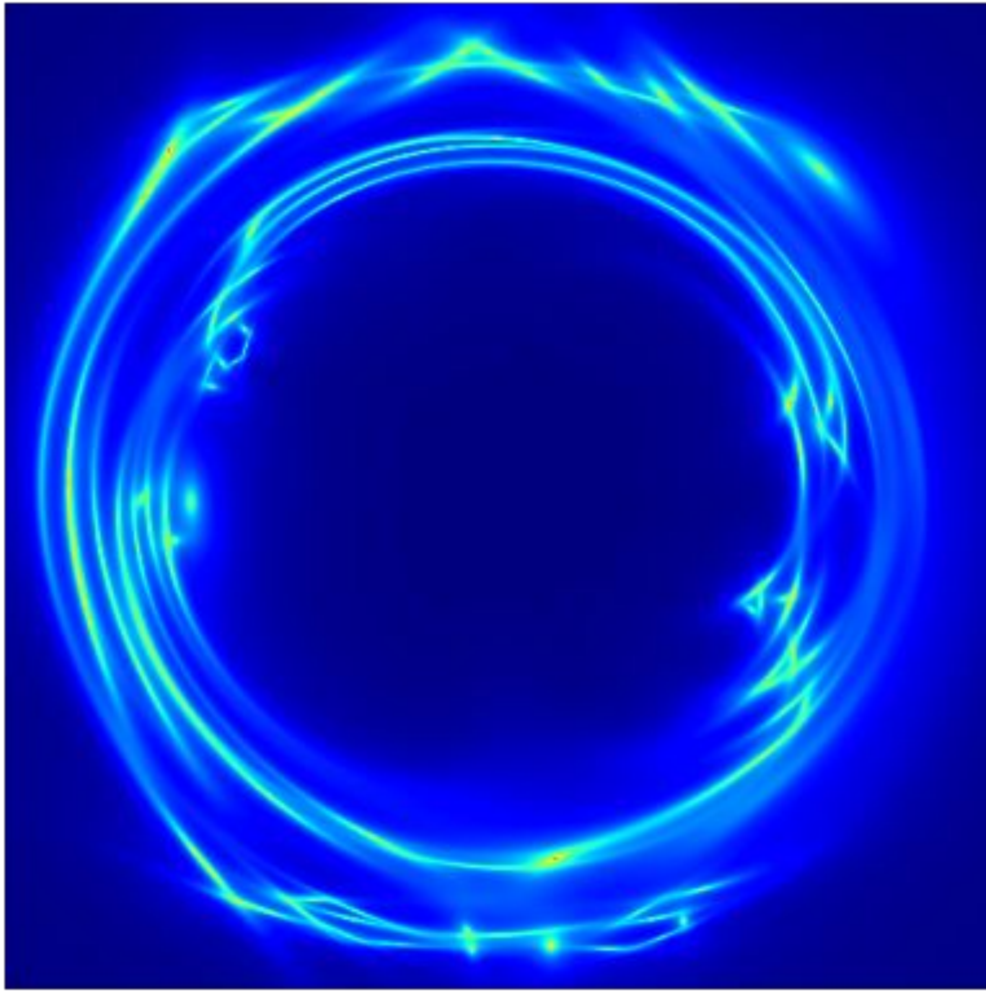
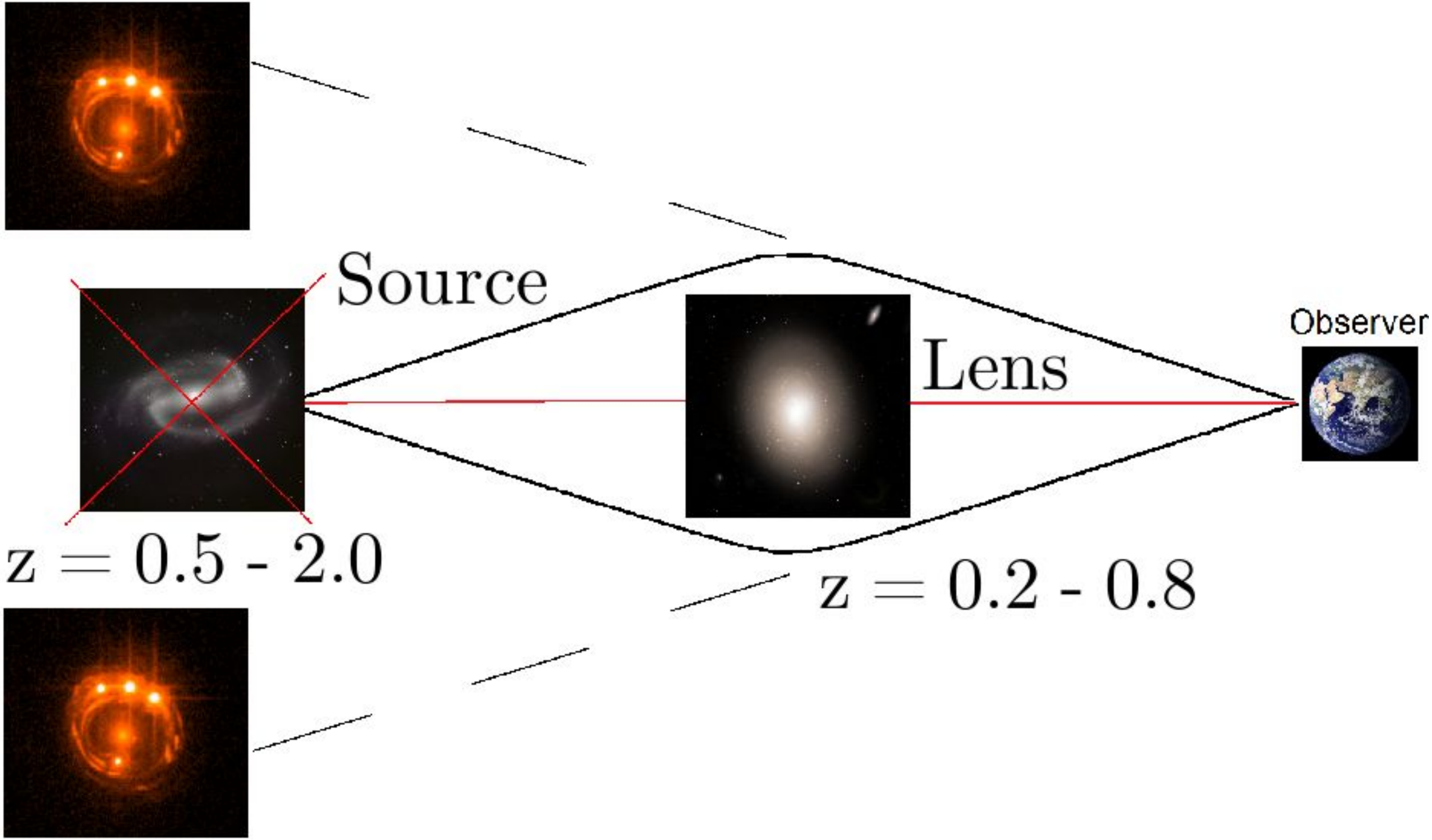
Nicola Amorisco, Aristeidis Amvrosiadis, Xiaoyue Cao, Shaun Cole, Amy Etherington, Carlos Frenk, Richard Hayes, Qiuhan He, Ran Li, Andrew Robertson, Richard Massey, Sam Lange



Strong Lensing

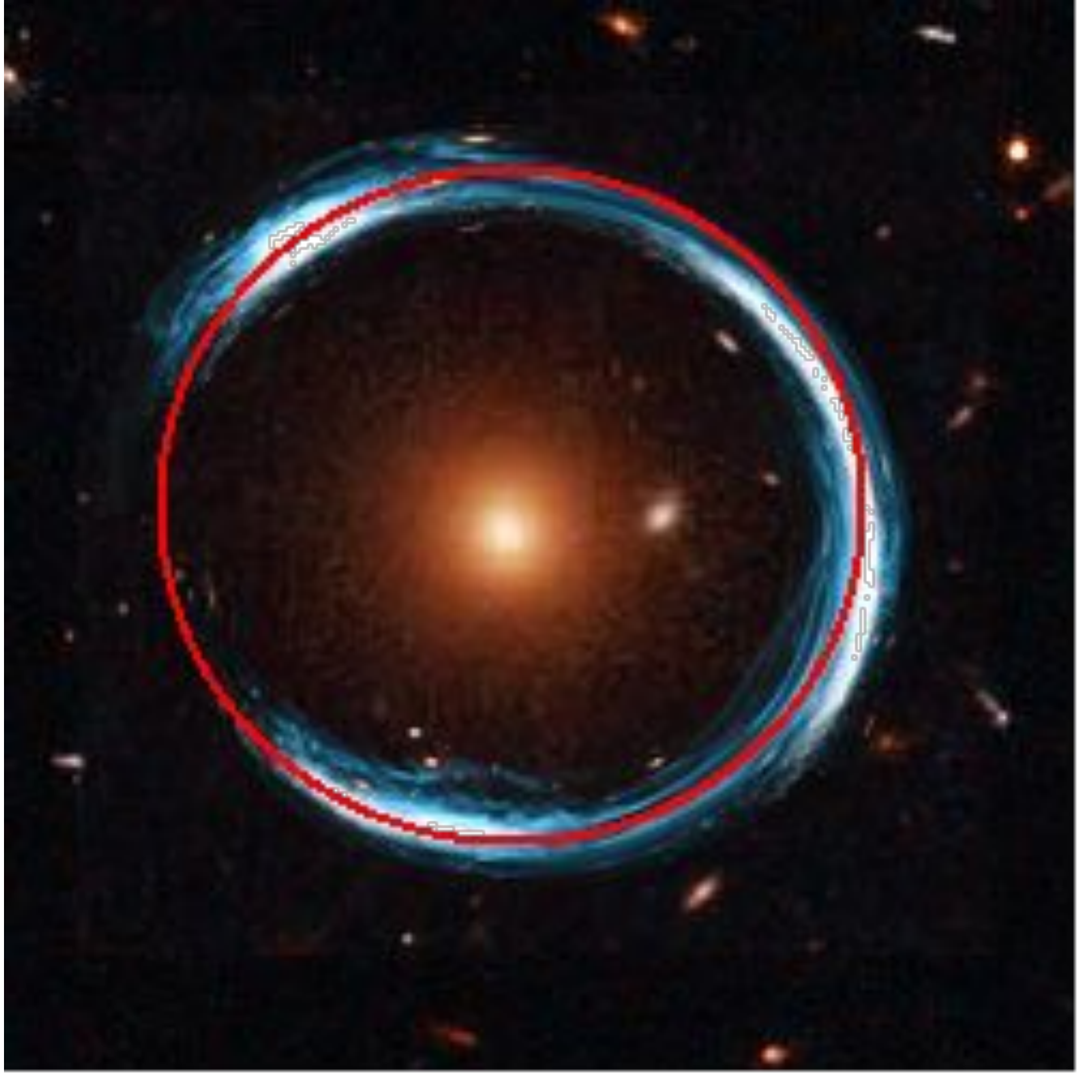

Source
z = 0.5 - 2.0
Lens
z = 0.2 - 0.8
Observer

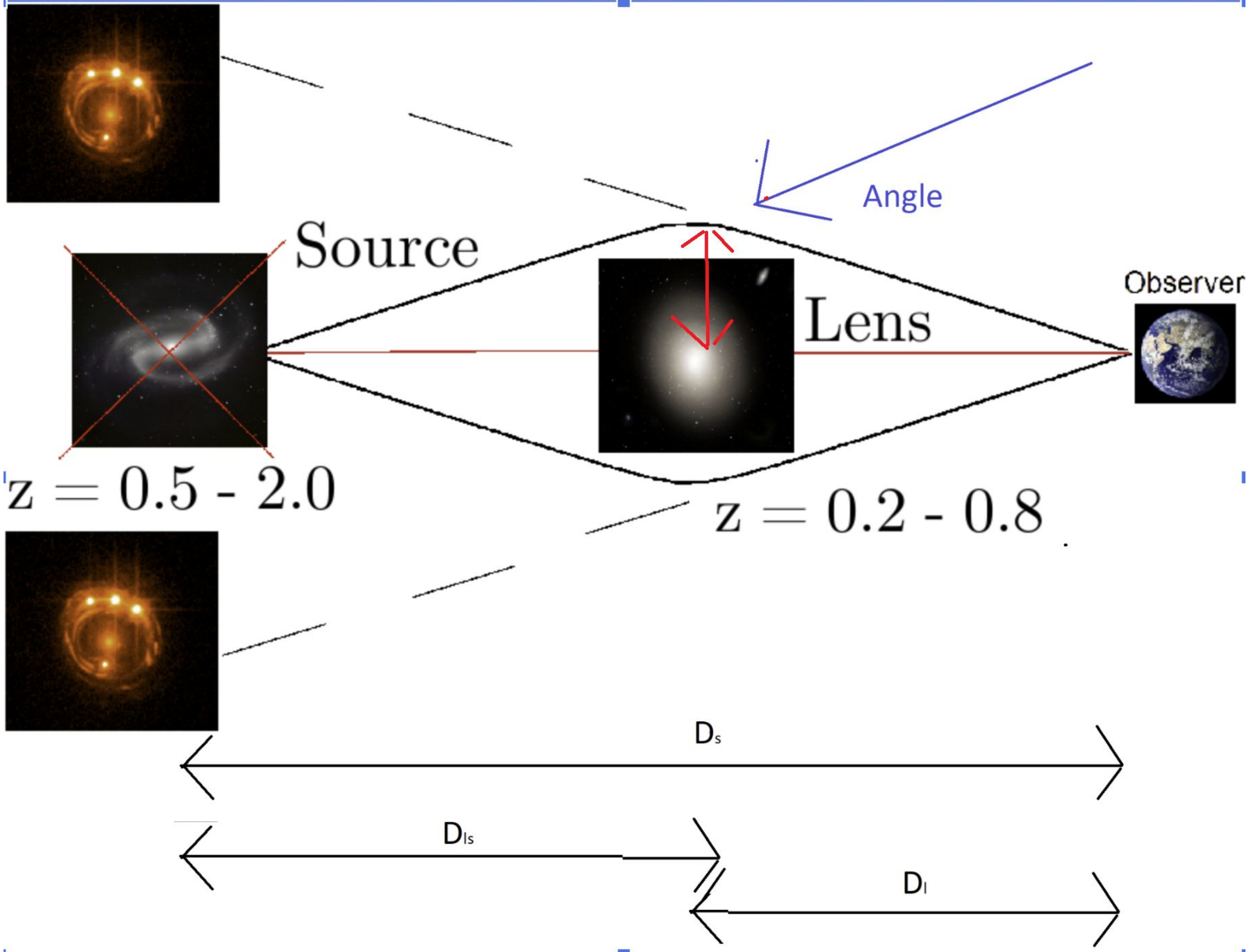
Einstein Mass

Uses: the lensed source position and source + lens redshifts.

Measures: The Einstein Mass, M_{Ein}. Total mass within source aperture (red circle).

Example: Compare total Einstein masses to stellar masses (from stellar populations) and test the initial mass function.



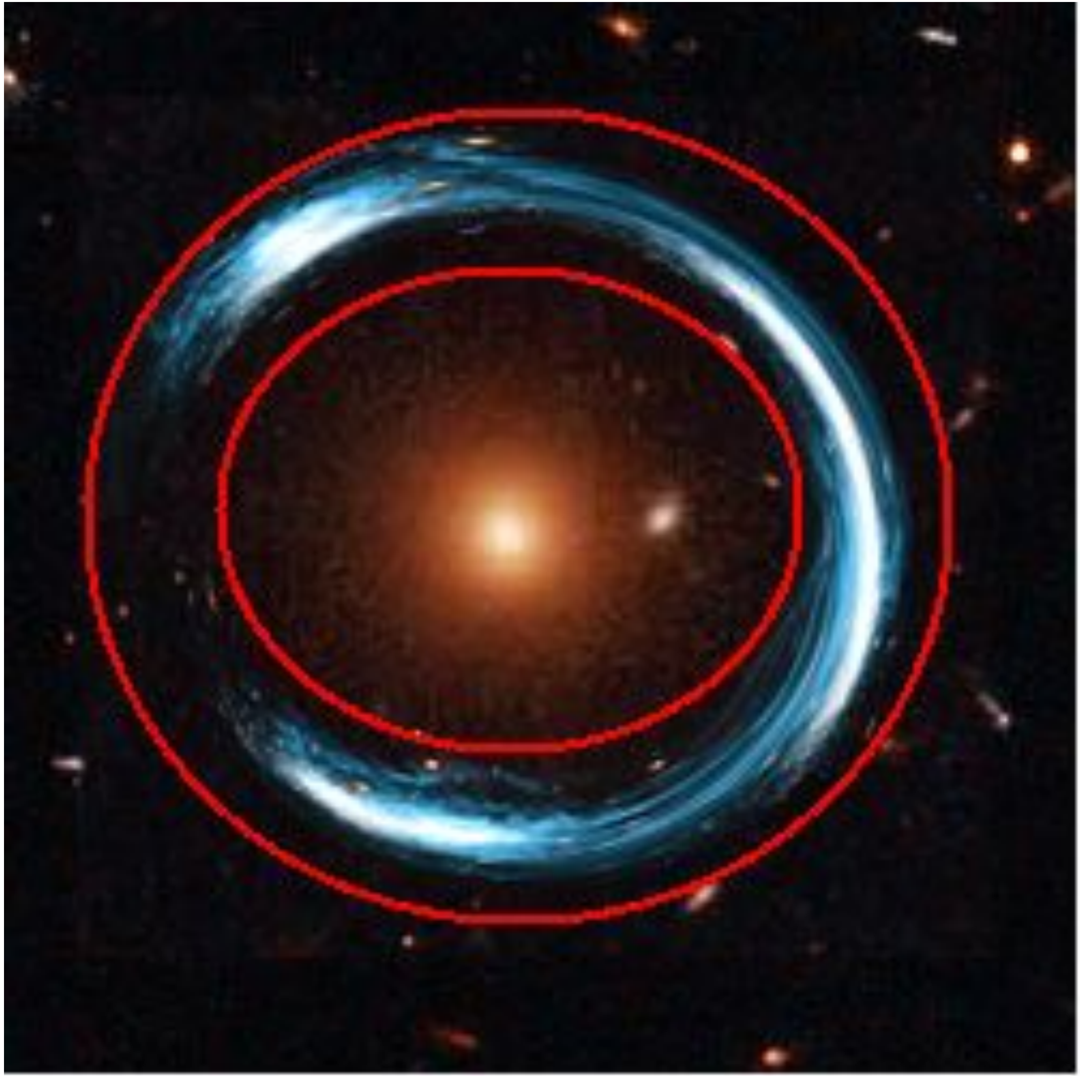

Angle
Source
Lens
Observer
z = 0.5 - 2.0
z = 0.2 - 0.8
D_s
D_{ls}
D_l

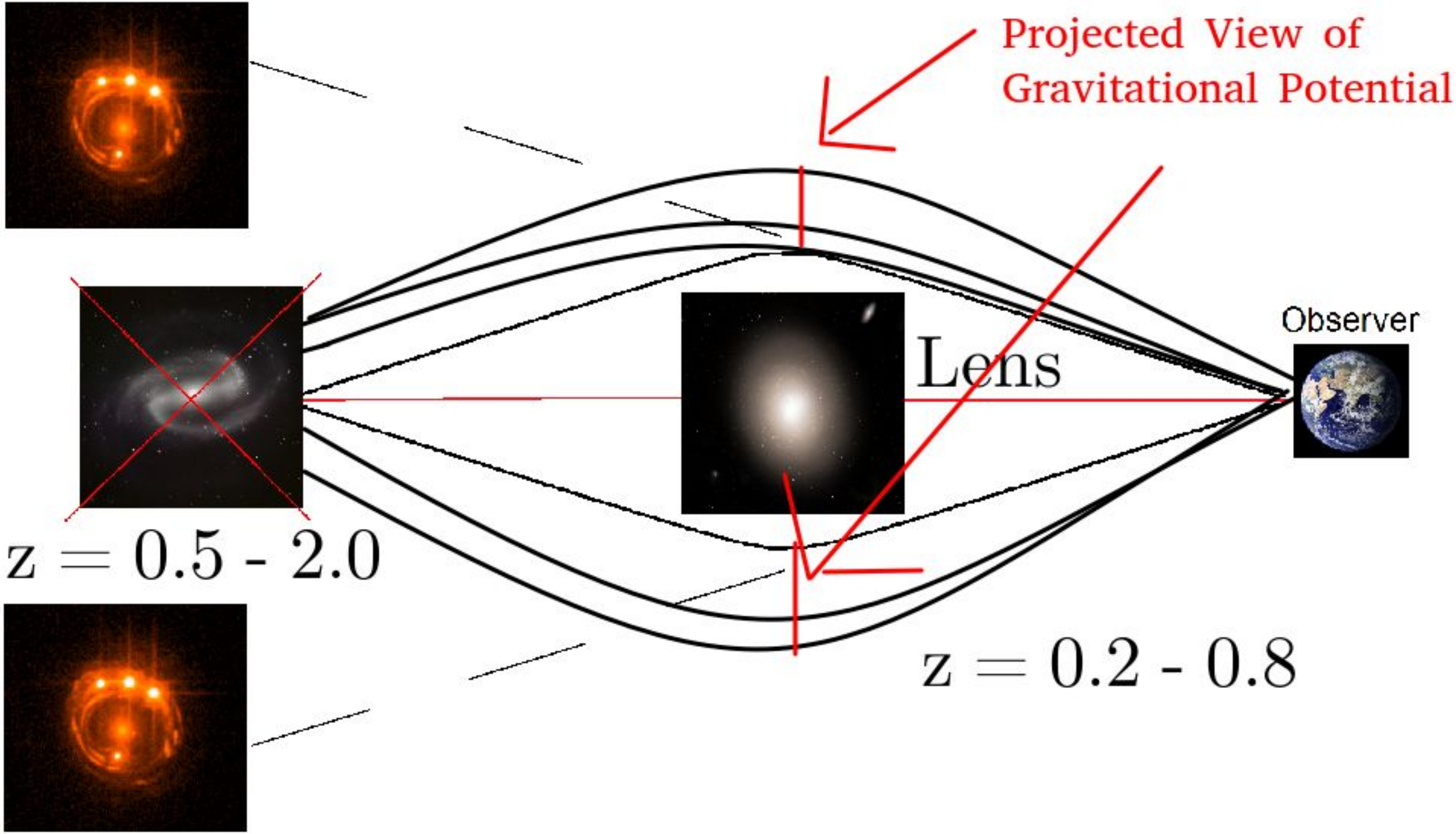
Extended Source Strong Lensing

Uses: The source’s extended lensed surface brightness.

Measures: The lens's mass distribution, at the Einstein Radius, R_{ein}.

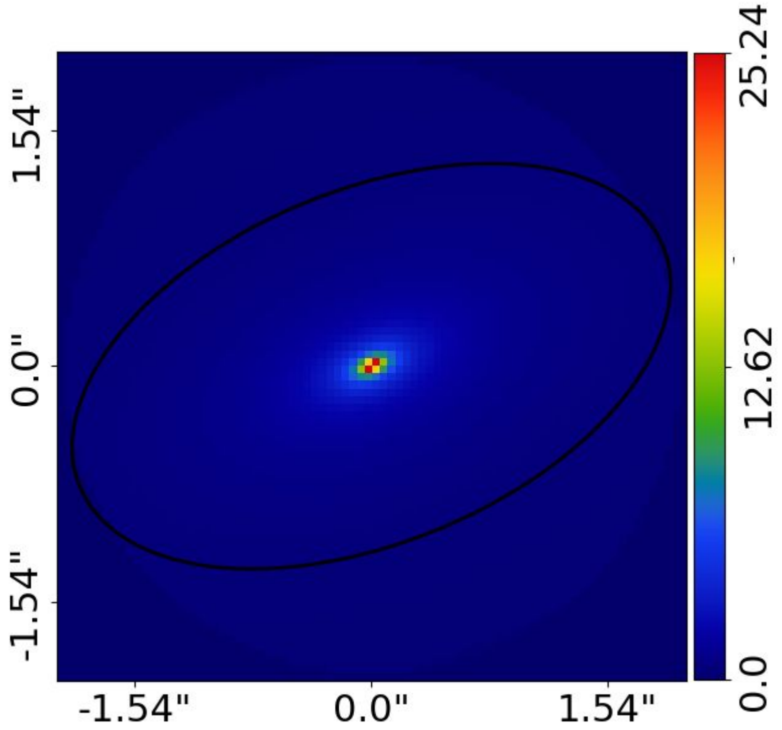
Example: Everything

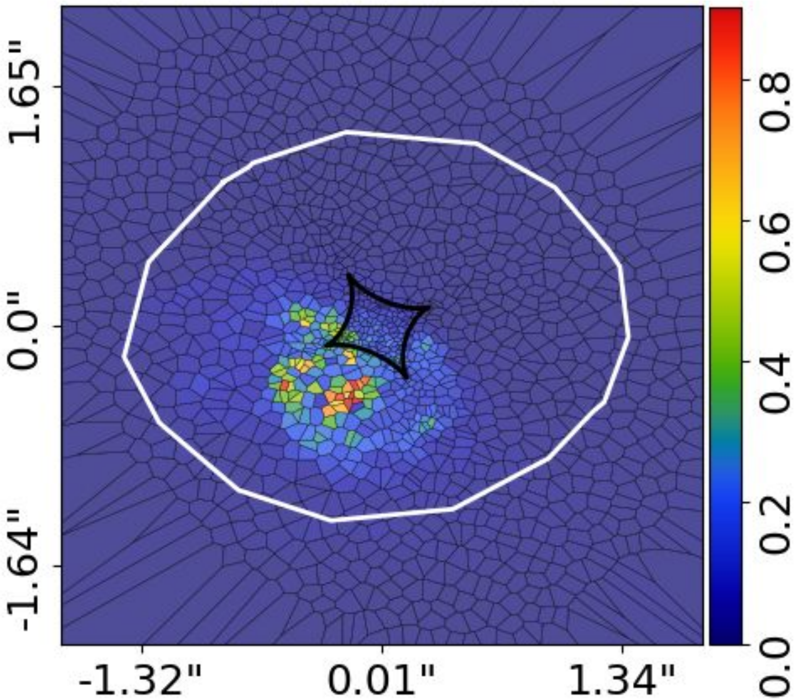



Projected View of
Gravitational Potential
Lens
Observer
z = 0.5 - 2.0
z = 0.2 - 0.8

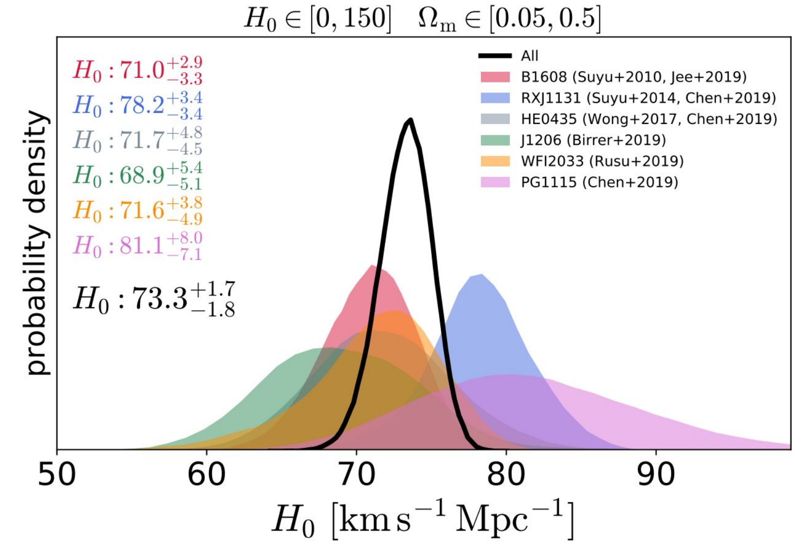
Strong Lens Modeling

Combination of ray-tracing, linear algebra and Bayesian inference.

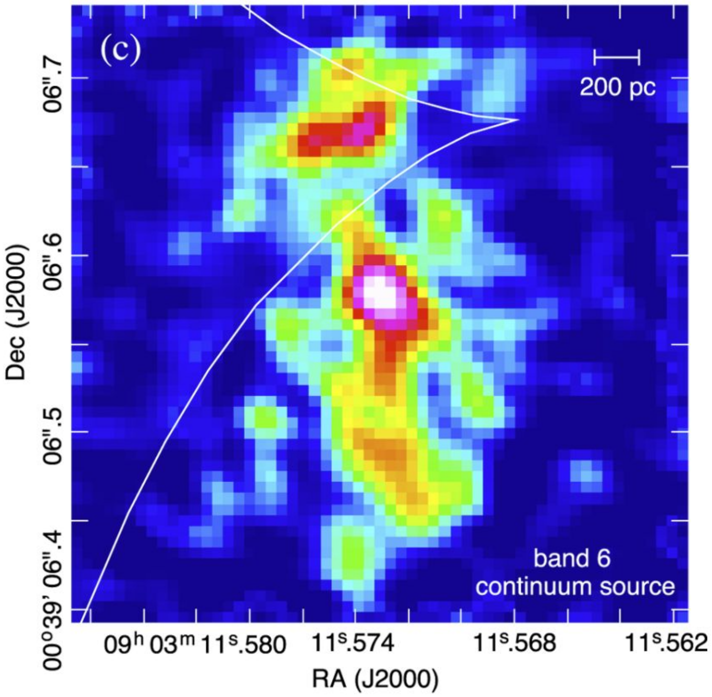

Mass (e.g Convergence / Surface Density)


Source

Science Cases (Cosmology / Source Science)



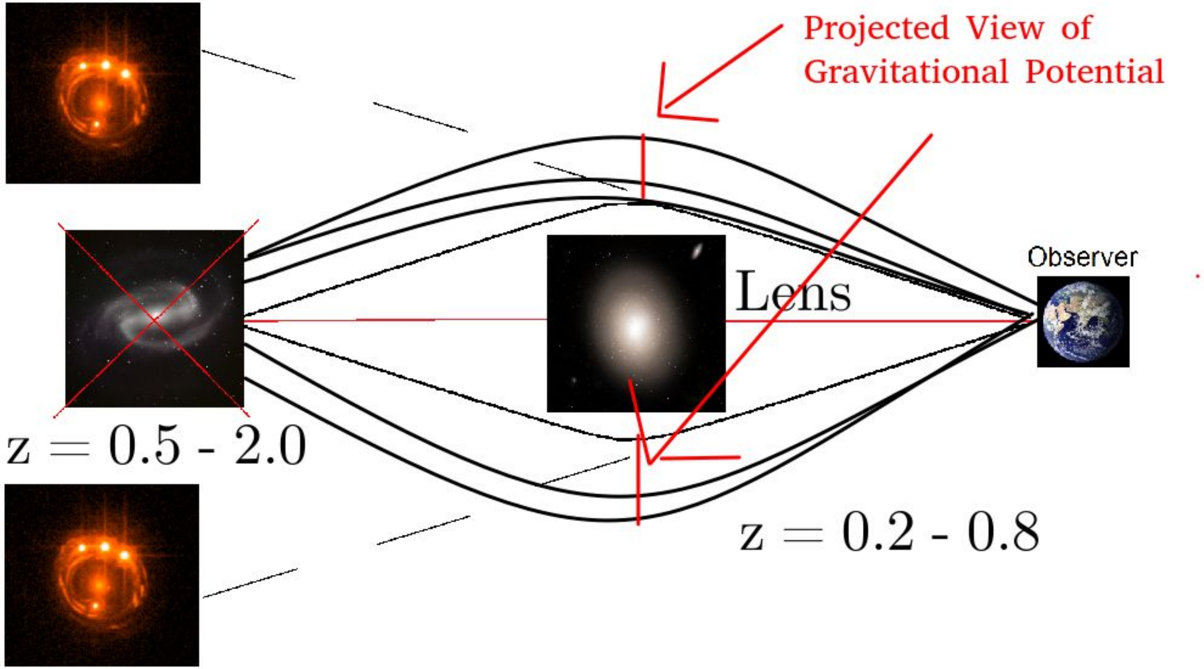
Wong et al 2019: https://arxiv.org/abs/1907.04869



Overview

What can this unique observation tell us about:

- Galaxies.
- Dark Matter.
- Supermassive Black Holes.



PyAutoLens

PyAutoLens: Open Source Lensing

GitHub:

https://github.com/Jammy2211/PyAutoLens

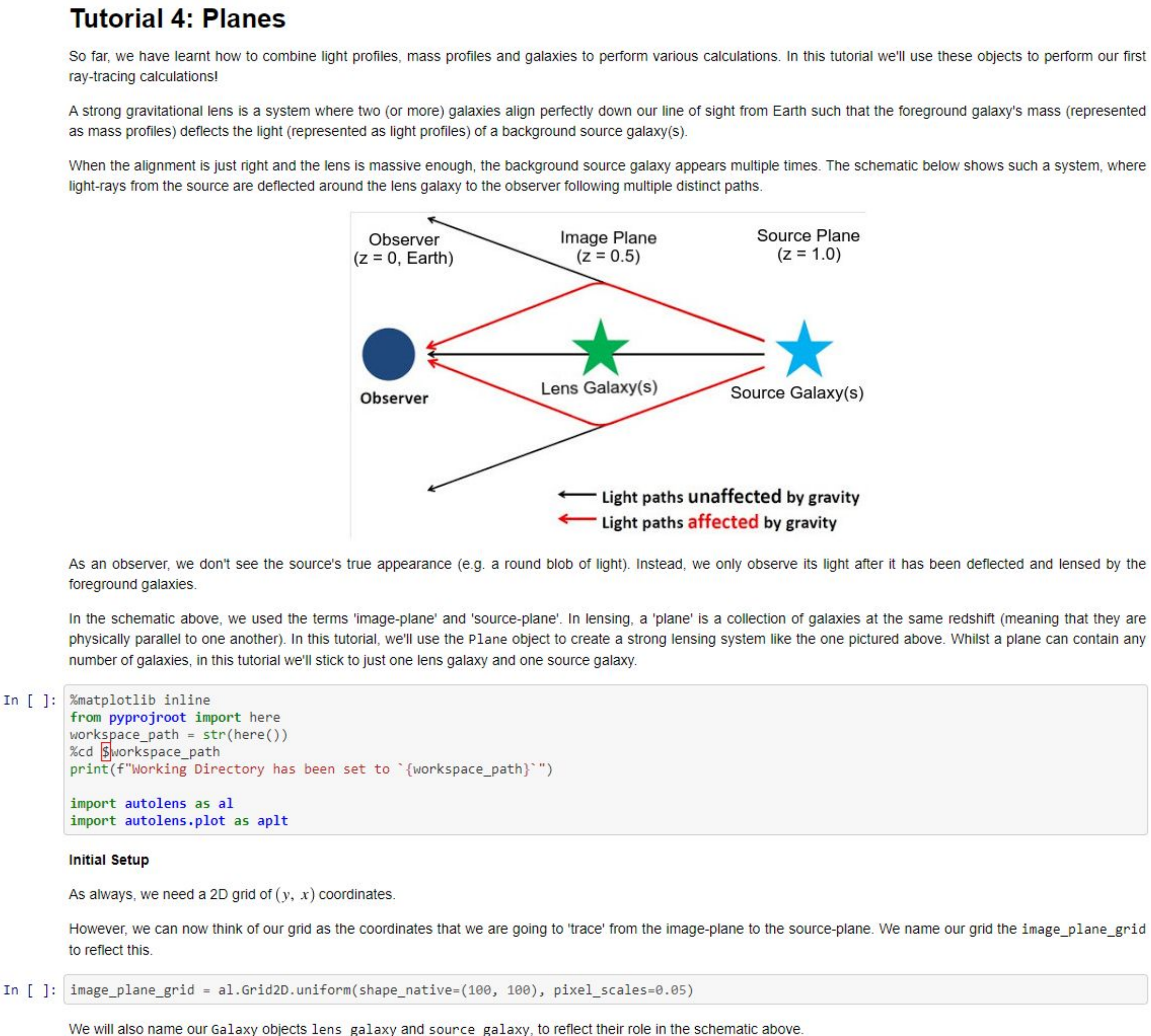
Readthedocs:

https://pyautolens.readthedocs.io/en/latest/

JOSS paper:

https://github.com/Jammy2211/PyAutoLens/blob/master/paper/paper.md

HowToLens: Free online Jupyter Notebook lectures aimed at undergrads, teaching them how to model strong lenses.



Tutorial 4: Planes

So far, we have learnt how to combine light profiles, mass profiles and galaxies to perform various calculations. In this tutorial we'll use these objects to perform our first ray-tracing calculations!

A strong gravitational lens is a system where two (or more) galaxies align perfectly down our line of sight from Earth such that the foreground galaxy's mass (represented as mass profiles) deflects the light (represented as light profiles) of a background source galaxy(s).

When the alignment is just right and the lens is massive enough, the background source galaxy appears multiple times. The schematic below shows such a system, where light-rays from the source are deflected around the lens galaxy to the observer following multiple distinct paths.

As an observer, we don't see the source's true appearance (e.g. a round blob of light). Instead, we only observe its light after it has been deflected and lensed by the foreground galaxies.

In the schematic above, we used the terms 'image-plane' and 'source-plane'. In lensing, a 'plane' is a collection of galaxies at the same redshift (meaning that they are physically parallel to one another). In this tutorial, we'll use the `Plane` object to create a strong lensing system like the one pictured above. Whilst a plane can contain any number of galaxies, in this tutorial we'll stick to just one lens galaxy and one source galaxy.

In [ ]:

```
%matplotlib inline
from pyprojroot import here
workspace_path = str(here())
%cd $workspace_path
print(f"Working Directory has been set to `{workspace_path}`")

import autolens as al
import autolens.plot as aplt
```

Initial Setup

As always, we need a 2D grid of (y, x) coordinates.

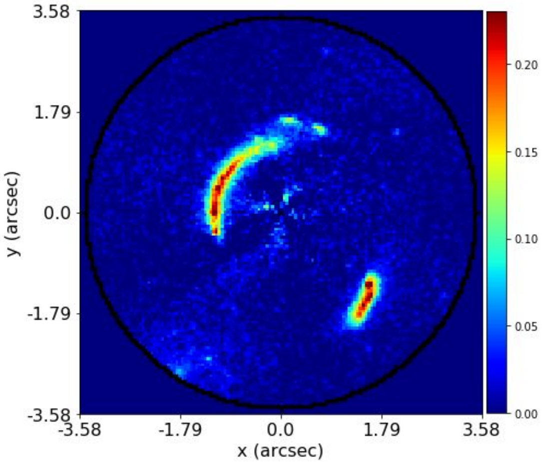
However, we can now think of our grid as the coordinates that we are going to 'trace' from the image-plane to the source-plane. We name our grid the `image_plane_grid` to reflect this.

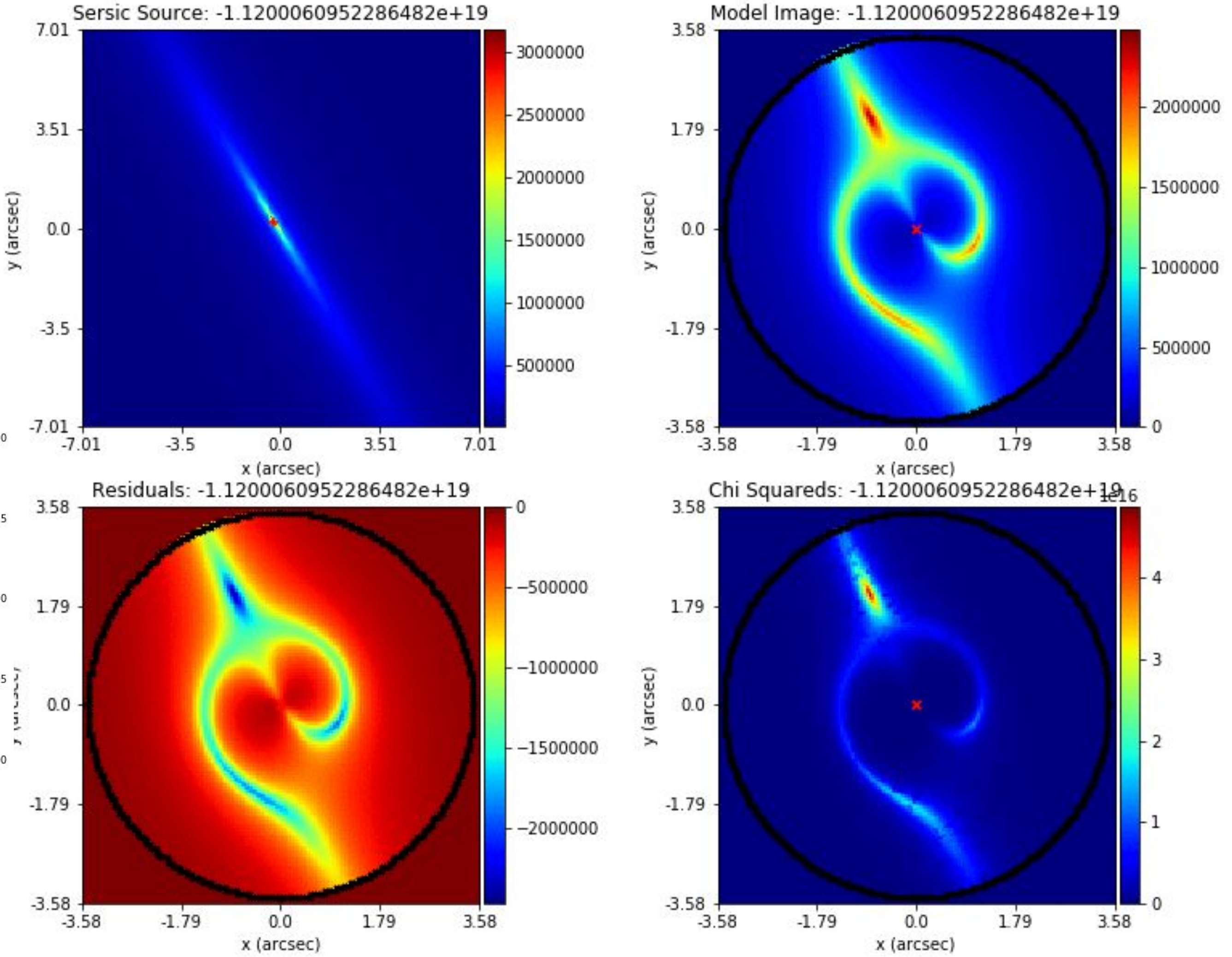
In [ ]:

```
image_plane_grid = al.Grid2D.uniform(shape_native=(100, 100), pixel_scales=0.05)
```

We will also name our `Galaxy` objects `lens_galaxy` and `source_galaxy`, to reflect their role in the schematic above.

Lens Modeling





Automated galaxy-galaxy strong lens modelling: no lens left behind

Amy Etherington[1,2]*, James W. Nightingale[1,2], Richard Massey[1,2], XiaoYue Cao[3,4], Andrew Robertson[5], Nicola C. Amorisco[1], Aristeidis Amvrosiadis[2], Shaun Cole[2], Carlos S. Frenk[2], Qiuhan He[2], Ran Li[3,4], & Sut-Ieng Tam[6]

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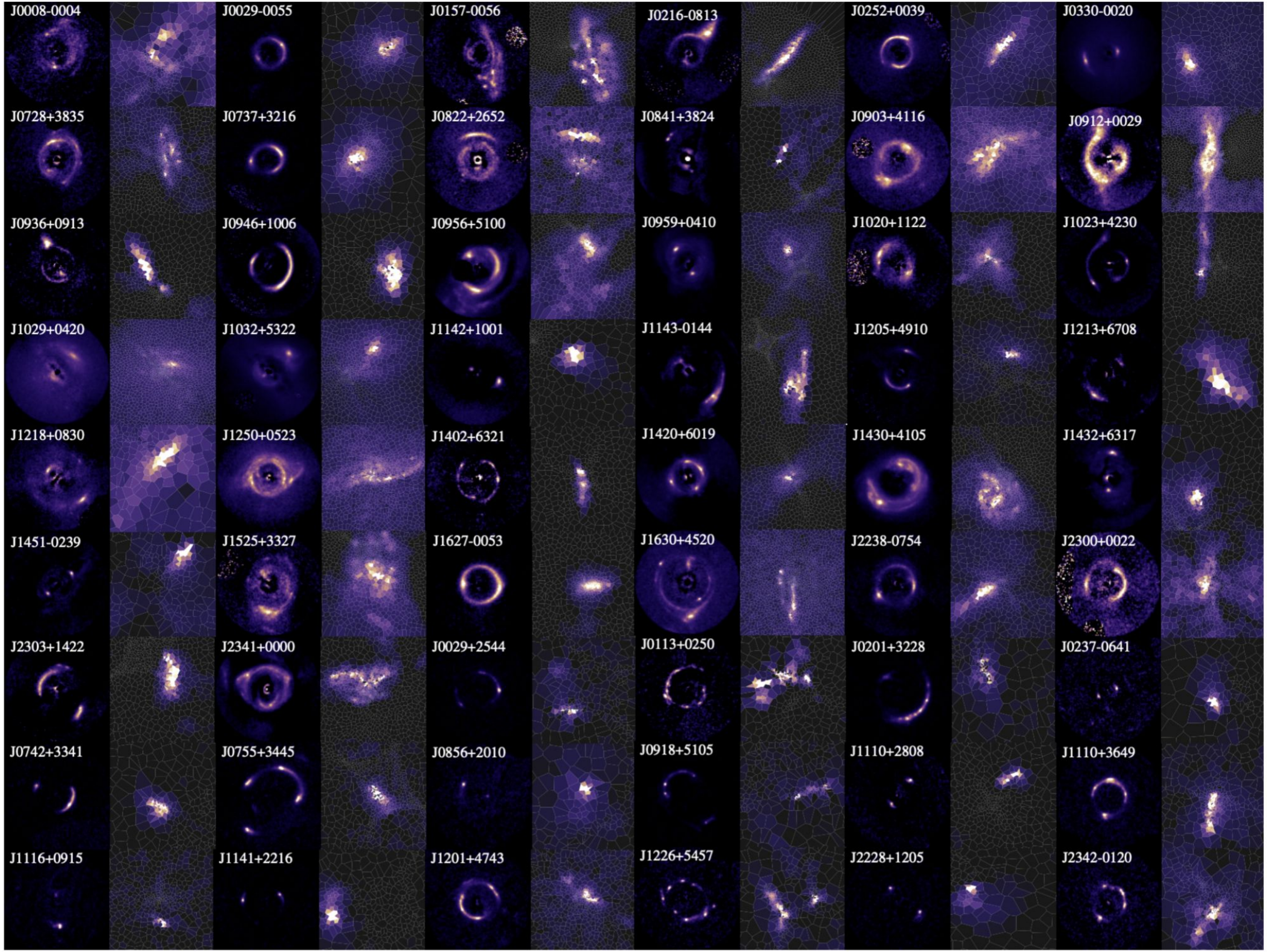
[4] *School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China*
[5] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA*
[6] *Academia Sinica Institute of Astronomy and Astrophysics (ASIAA), No. 1, Sec. 4, Roosevelt Road, Taipei 10617, Taiwan*

Automation

Automated modeling of 59 strong lenses observed with HST.

Successful measurement of density slope in **54/59 objects.**

Made numerous improvements as a result of this study since!



Galaxies (Amy Etherington)

Beyond the bulge-halo conspiracy? Density profiles of Early-type galaxies from extended-source strong lensing

Amy Etherington[1,2]★, James W. Nightingale[1,2], Richard Massey[1,2],
Andrew Robertson[3], XiaoYue Cao[4,5], Aristeidis Amvrosiadis[2], Shaun Cole[2],
Carlos S. Frenk[2], Qiuhan He[2], David J. Lagattuta[1], Samuel Lange[2] & Ran Li[4,5]

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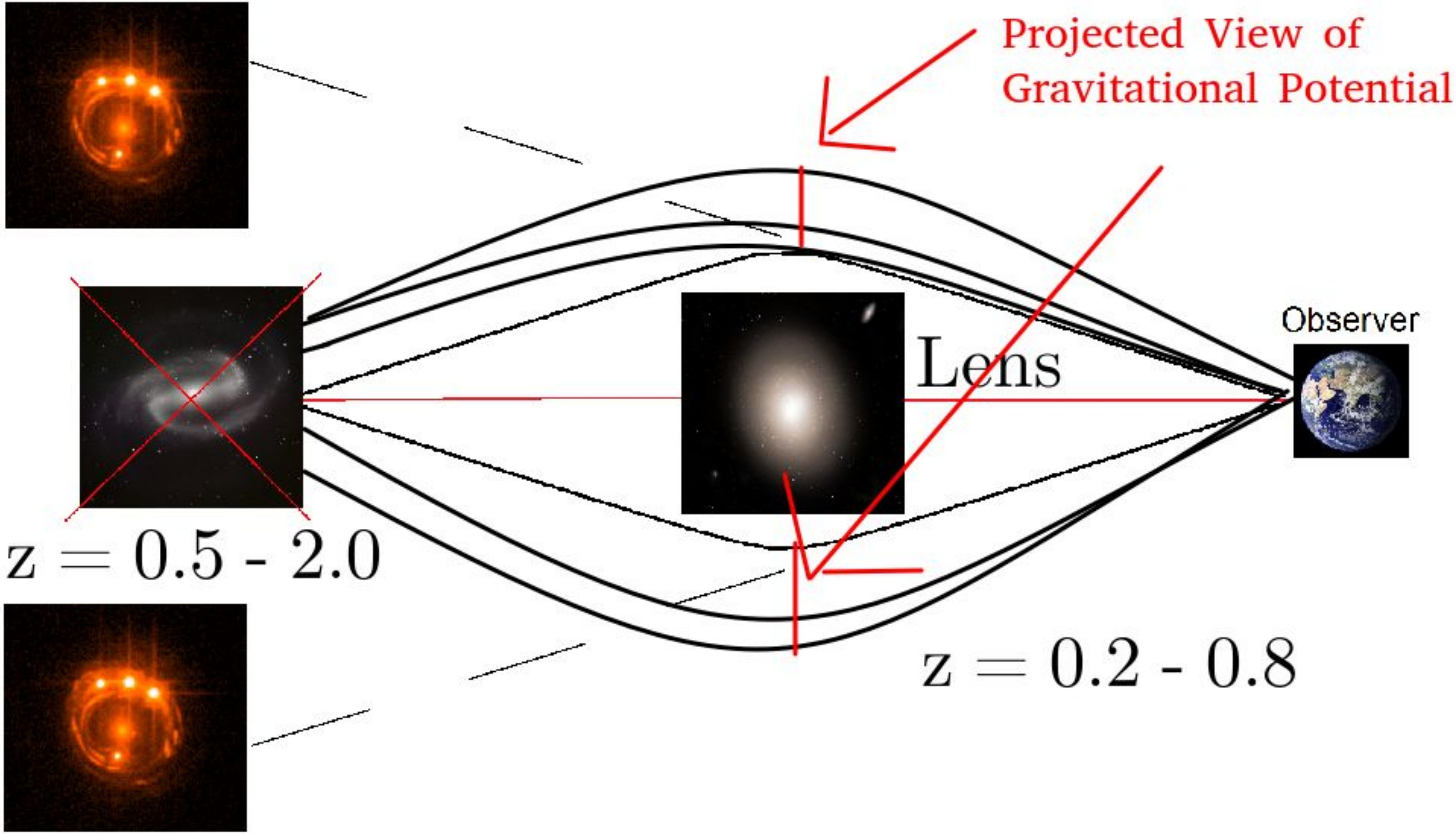
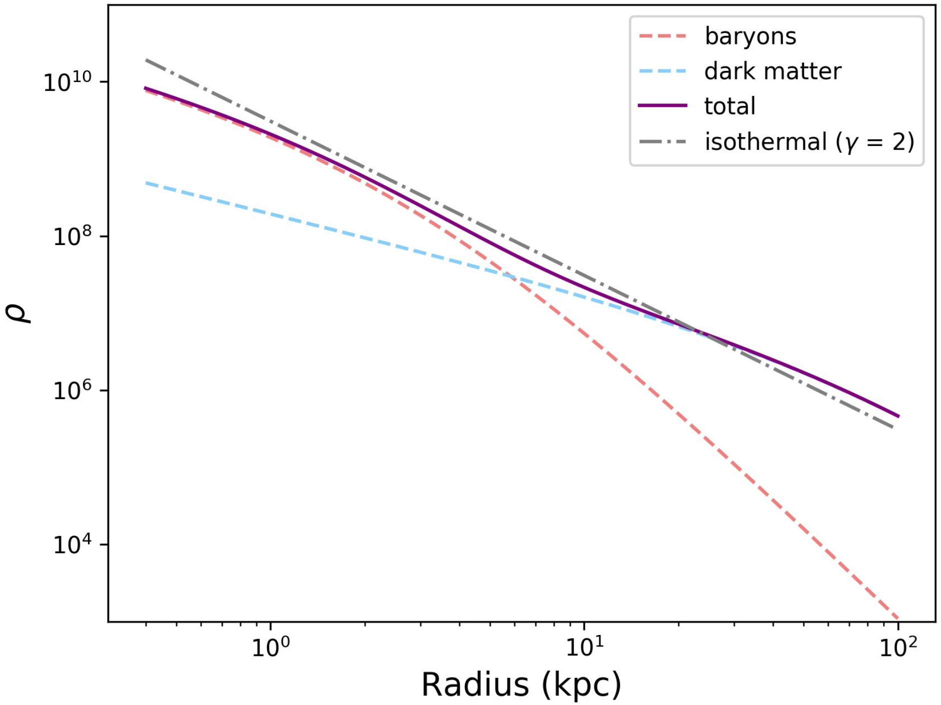
The Bulge-Halo Conspiracy


Projected View of
Gravitational Potential
Observer
Lens
z = 0.5 - 2.0
z = 0.2 - 0.8

Bulge-halo Conspiracy

“Bulge-halo conspiracy”: neither the stellar or dark matter of massive ellipticals are power-laws, but their combination produces one within ~ 10kpc.

$$\rho \propto r^{-\gamma}$$



Sample Distribution

Lensing:

- $\langle\gamma\rangle = 2.075 \pm 0.02$
- $\sigma = 0.172 \pm 0.03$

The inner density of massive elliptical strong lenses are approximately isothermal.

Why is galaxy formation so predictable?

[See also: Fundamental Plane, other scaling relations].

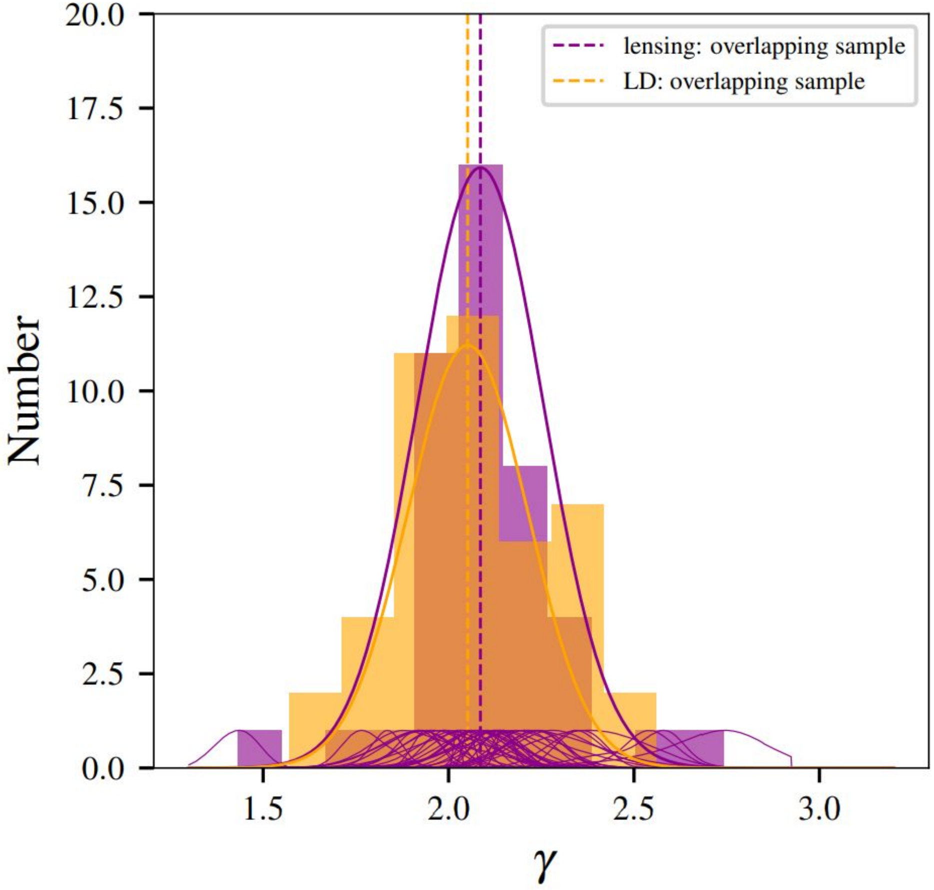


Figure 5. Comparison of the distributions of slopes inferred with lensing only and lensing + dynamics for the samples that overlap.

Sample Distribution

Lensing:

- <γ> = 2.075 ± 0.02
- σ = 0.172 ± 0.03

Strong agreement between lensing only and lensing + dynamics (L&D) slopes at a sample level.

Lensing & Dynamics:

- <γ> = 2.050 ± 0.03
- σ = 0.156 ± 0.03

Overlapping sample of 48 lenses.

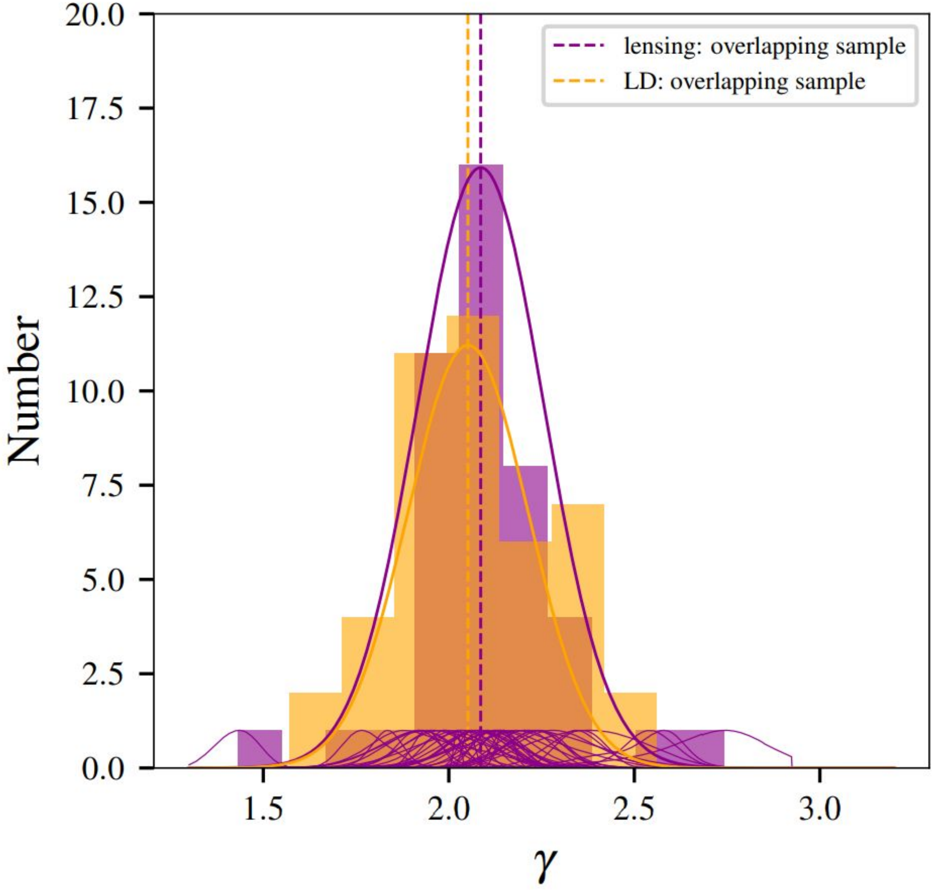


Figure 5. Comparison of the distributions of slopes inferred with lensing only and lensing + dynamics for the samples that overlap.

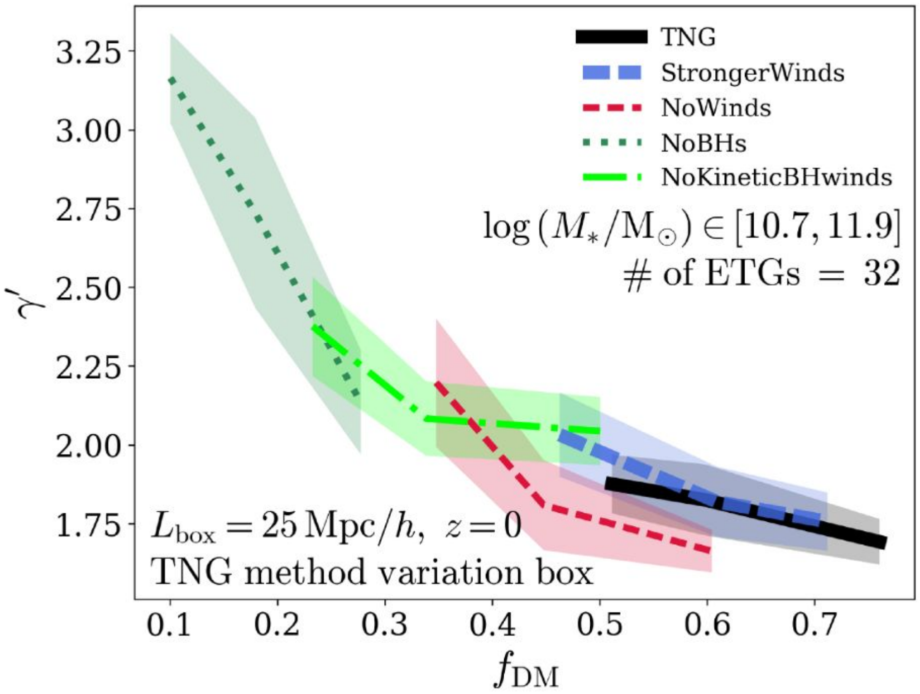
Why study density profiles?

Different galaxy formation models make different predictions for the density slope.

Wang et al 2019

See also SEAGLE [Mukherjee et al 18-22]

Correlations with other galaxy properties (e.g. redshift, stellar mass) are observed and add more information.

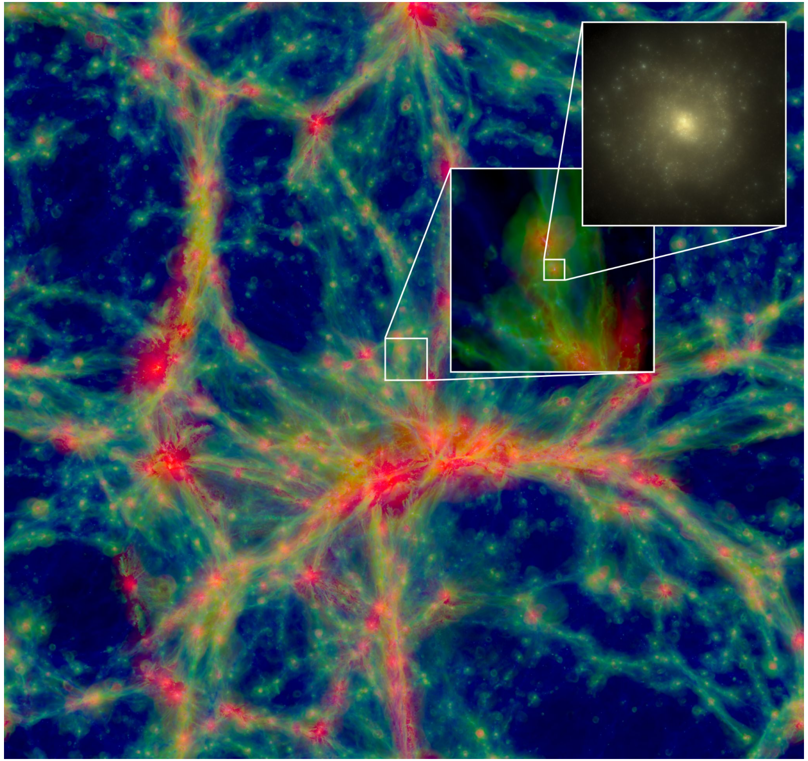


Future: Density Slopes

Density slopes can inform galaxy formation & evolution models.

- **Imaging Only (e.g. Euclid wide field imaging):** Doesn't need expensive dynamics measurements (caveat: photometric redshifts).
- **Simulations:** Provides orthogonal information to traditional calibration data (e.g. stellar mass function, size-mass relation).

Future: stop measuring total-mass density slopes and start measuring stellar and dark matter mass properties (e.g. dark matter fractions).



Strong gravitational lensing's 'external shear' is not shear

Amy Etherington[1,2], James W. Nightingale[1,2]*, Richard Massey[1,2], Sut-Ieng Tam[3], XiaoYue Cao[4,5], Anna Niemiec[1], Qiuhan He[2], Andrew Robertson[6], Ran Li[5,4], Aristeidis Amvrosiadis[2], Shaun Cole[2], Jose M. Diego[7], Carlos S. Frenk[2], Brenda L. Frye[8], David Harvey[9], Mathilde Jauzac[1,2,10,11], Anton M. Koekemoer[10], David J. Lagattuta[1], Marceau Limousin[11], Guillaume Mahler[1], Ellen Sirks[12] & Charles L. Steinhardt[13]

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[8] *Department of Astronomy/Steward Observatory, University of Arizona, 933 N Cherry Ave., Tucson, AZ 85721, USA*
[9] *Laboratoire d'Astrophysique, EPFL, Observatoire de Sauverny, 1290 Versoix, Switzerland*
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[11] *Aix Marseille Univ, CNRS, CNES, LAM, F-13388 Marseille, France*
[12] *Sydney Consortium for Particle Physics and Cosmology, School of Physics, The University of Sydney, NSW 2006, Australia*
[13] *Niels Bohr Institute, University of Copenhagen, Lyngbyvej 2, København Ø 2100, Denmark*

What is Shear?

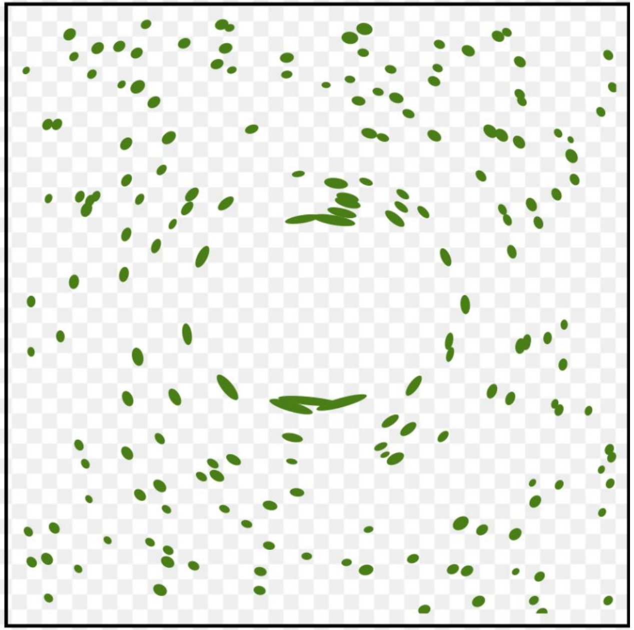
An established quantity in weak lensing:

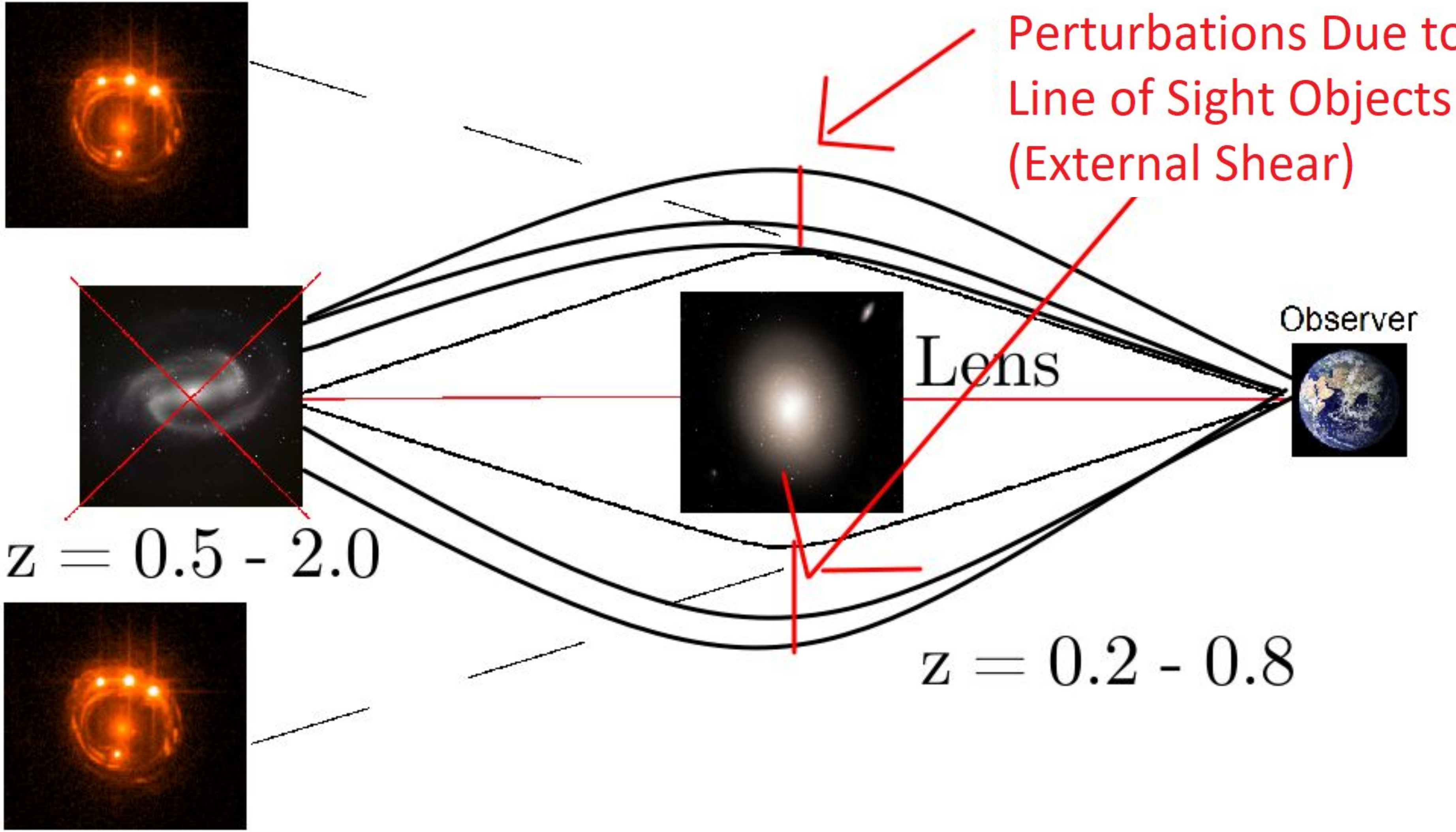
$$\left(\gamma_1,\ \gamma_2\right) = \left(\frac{1}{2}\left(\frac{\partial^2\psi}{\partial\theta_1^2} - \frac{\partial^2\psi}{\partial\theta_2^2}\right),\ \frac{\partial^2\psi}{\partial\theta_1\partial\theta_2}\right)$$

Don’t need to worry about the details, take home point is:

- Well understood quantity theoretically.
- We have a clear understanding of how large shear should be in different cosmological environments.

Included in strong lens models “as a standard”.





Perturbations Due to
Line of Sight Objects
(External Shear)

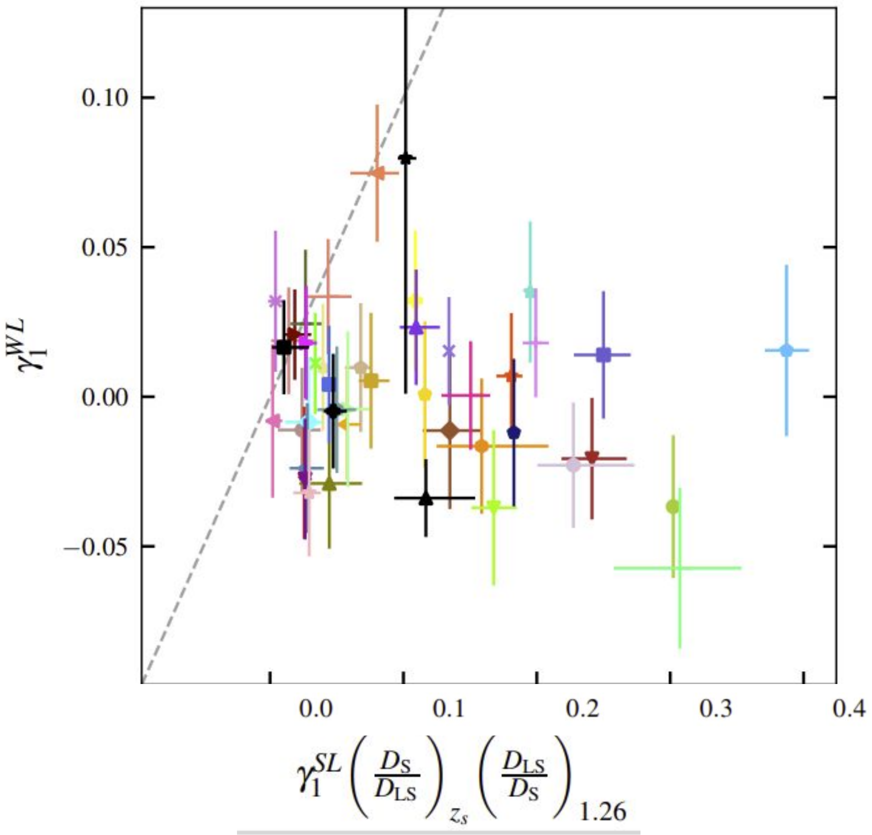
Lens

Observer

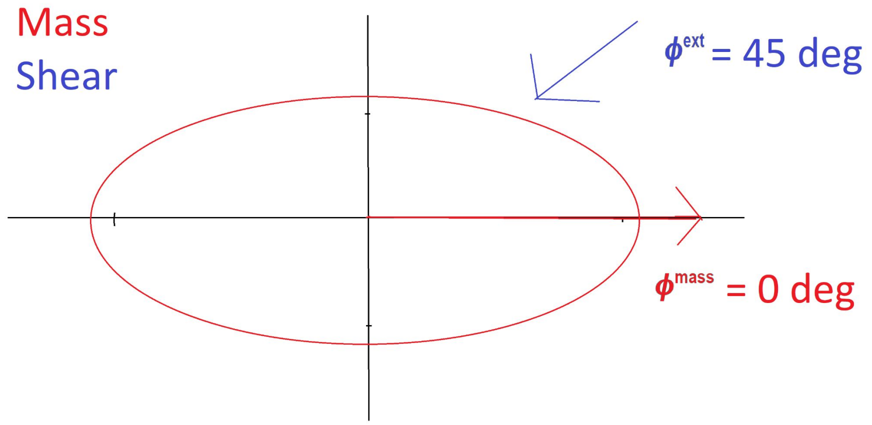
$z = 0.5 - 2.0$

$z = 0.2 - 0.8$

Strong vs Weak Lensing Shear



Shear / Mass Orientation



Aligned ($|\phi^{mass} - \phi^{ext}| < 30$): Mass and shear angle aligned in 68% of lenses.

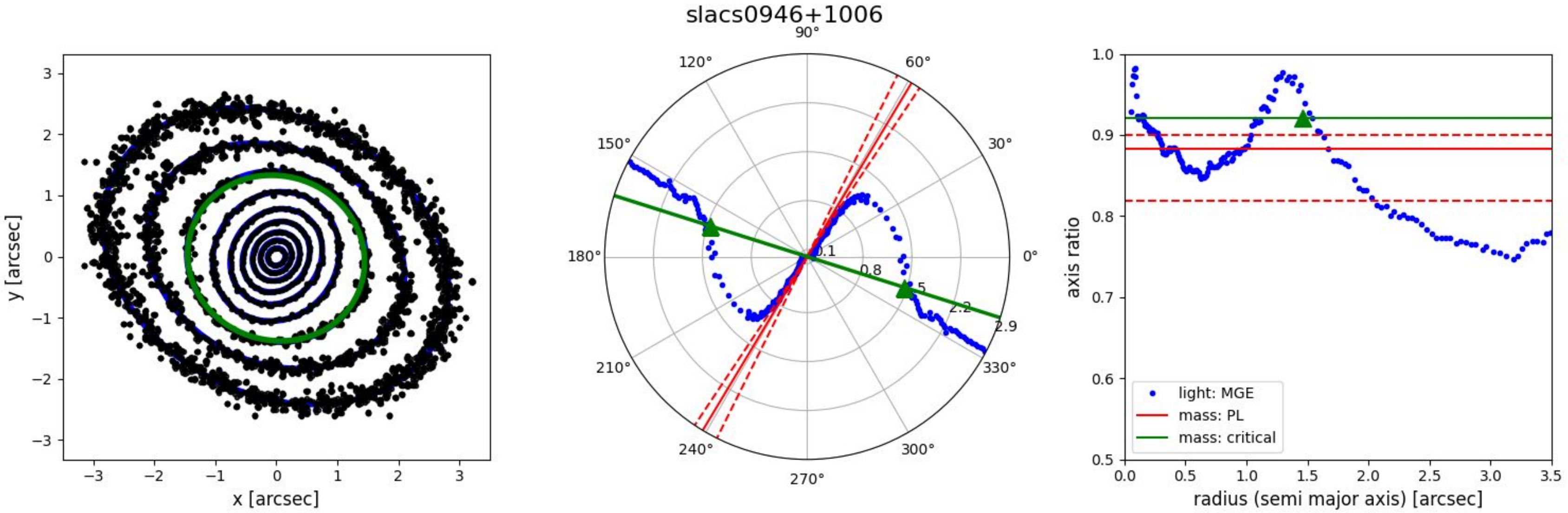
Anti-aligned ($|\phi^{mass} - \phi^{ext}| > 60$): 20% of lenses.

What Is Responsible?

- Twisting Mass distributions.
- Radial ellipticity variations.
- Offset stellar centres.
- Boxiness / diskiness.
- Morphological features (e.g. bulges, bars etc).

Blue Line:

Stellar Light via MGE


slacs0946+1006

Future: “External Shear”

Strong lenses contain untapped information on galaxy structure: boxiness, diskiness, twisting, centroid offsets, azimuthal structure, etc.

Unprecedented view of high redshift galaxy structure and dark matter structure!

Advances in lens galaxy mass models required to turn this systematic into science.

Dark Matter

Dark Matter

Force: Dark Matter **only interacts through gravity** and **not electrostatic forces.**
Invisible: Dark Matter does not emit light – **we cannot see it with our eyes!**

Dark matter makes up approximately 85% of the Universe's mass!

The Standard Model of Particle Physics does not supply any "fundamental particle(s)" which can explain dark matter.

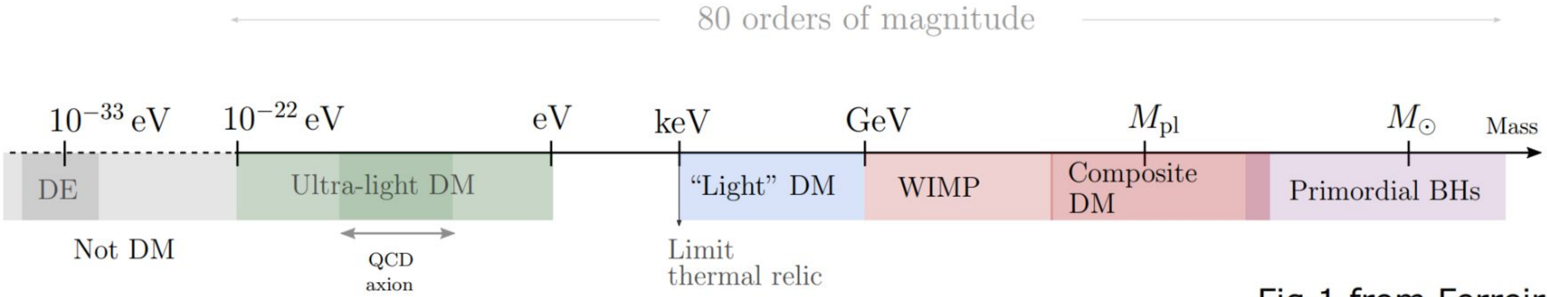


Fig 1 from Ferreira 2021

Known particles: v e^- p Higgs

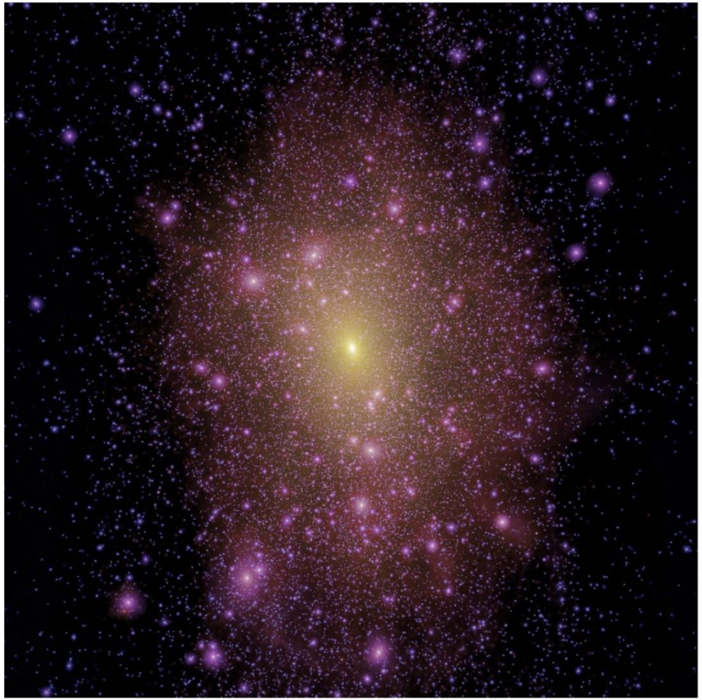
thermal production: hot warm cold

Dark Matter Simulations

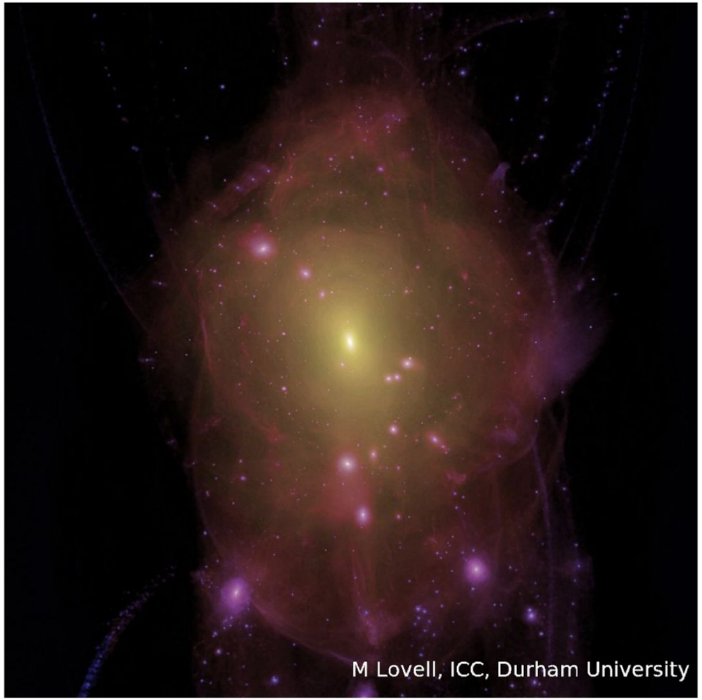
Two simulated Universes assuming two different mass dark matter particles.

The **pink / purple clumps** are **dark matter structures** (this is a false color image).

Large Scales: Cold and Warm Dark Matter models are identical.



Cold Dark Matter
(e.g. Weakly Interacting Massive Particle)



M Lovell, ICC, Durham University

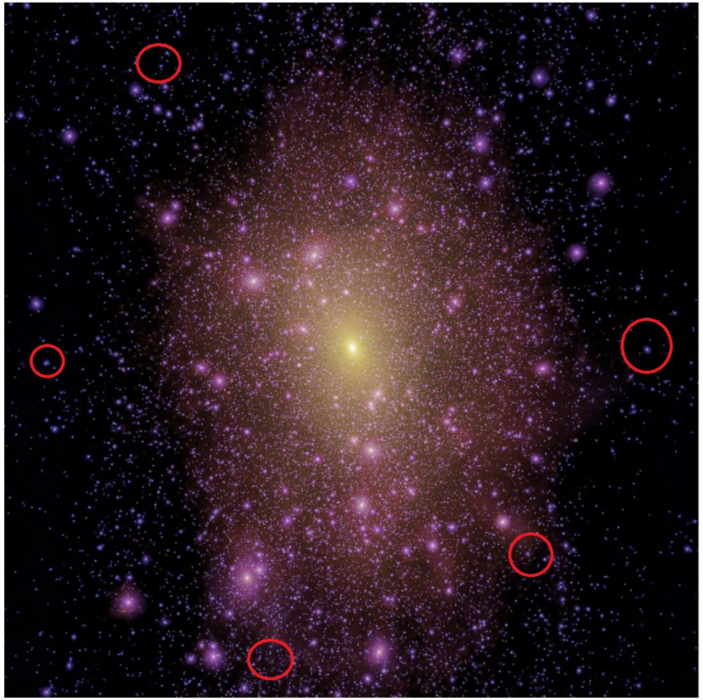
Warm Dark Matter
(e.g. Sterile Neutrino)
[see also Fuzzy Dark Matter, Self Interacting Dark Matter, etc.]

Dark Matter Simulations (Small Scale Structure)

Different dark matter particles predict different small scale structure.

Sizes: Dark matter clumps **< ~10^9 MSun do not form for warm dark matter!**

We don't know whether dark matter clumps this small exist.



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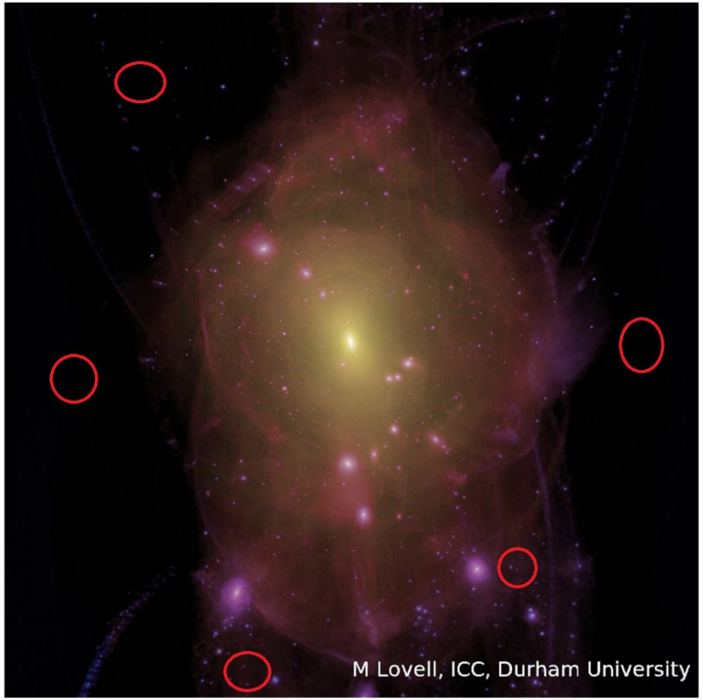

M Lovell, ICC, Durham University

Warm Dark Matter
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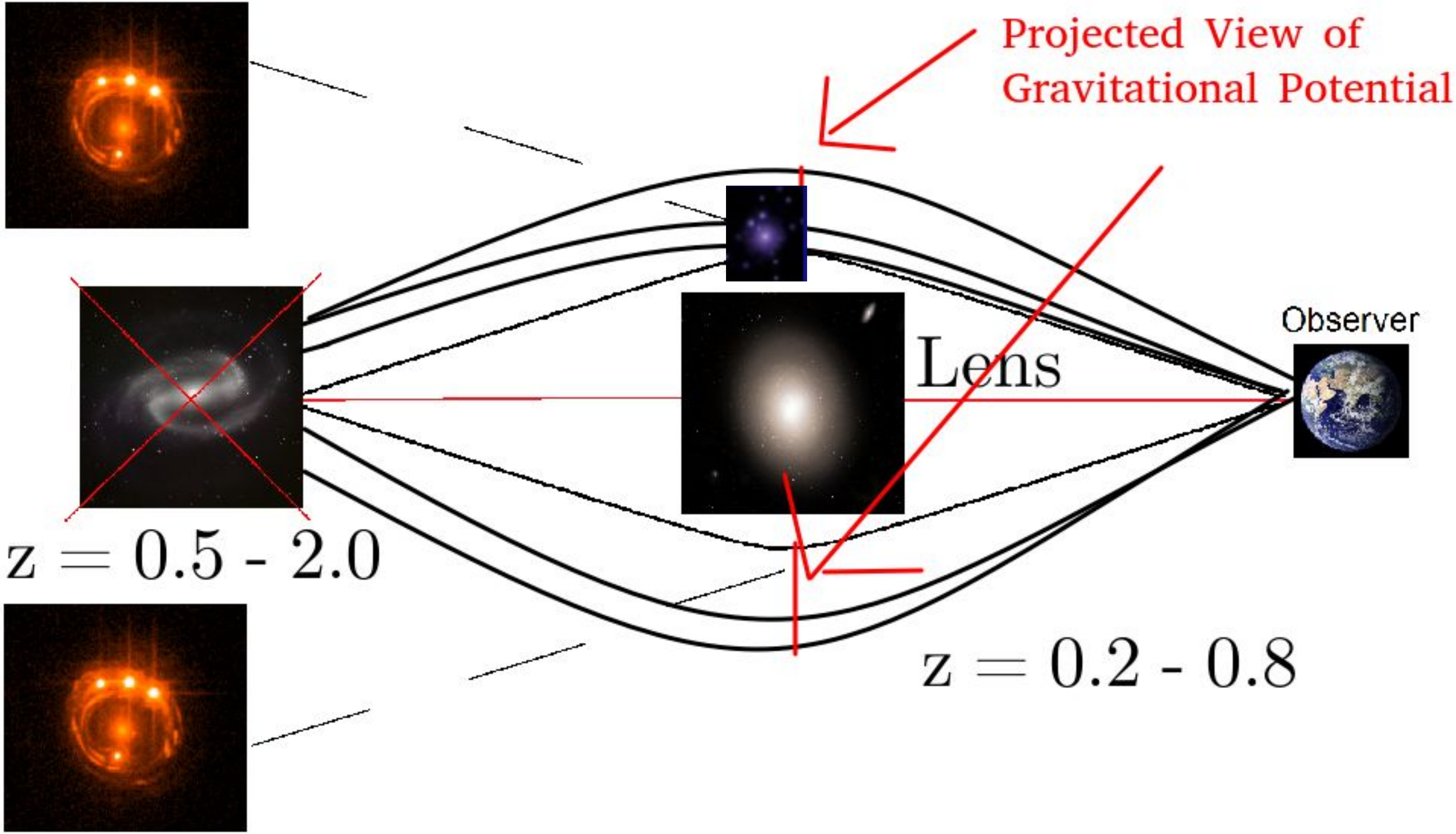
Projected View of
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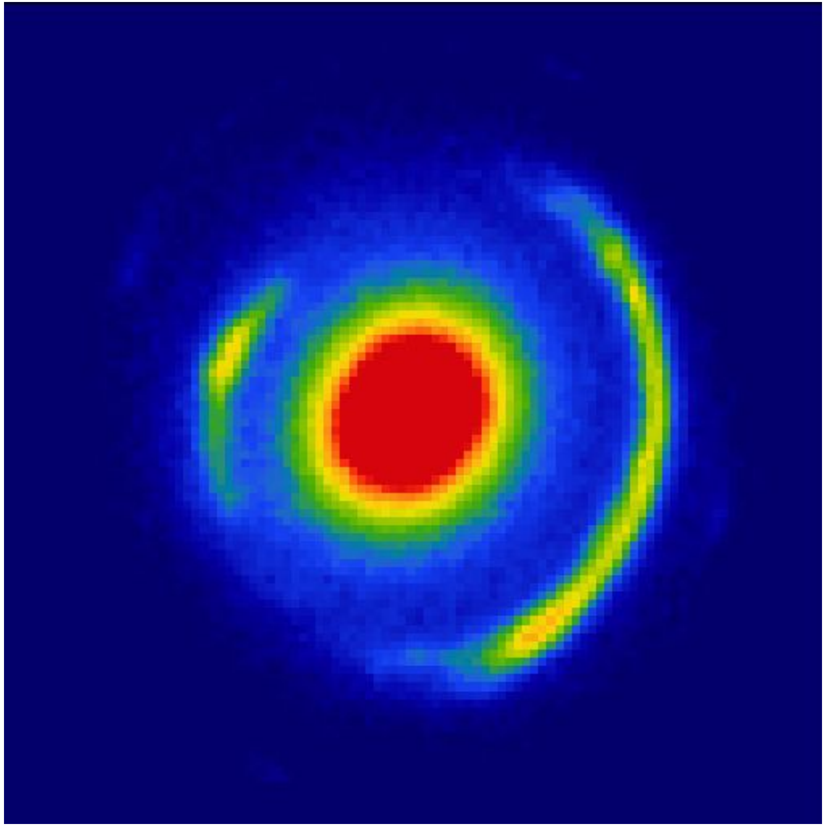
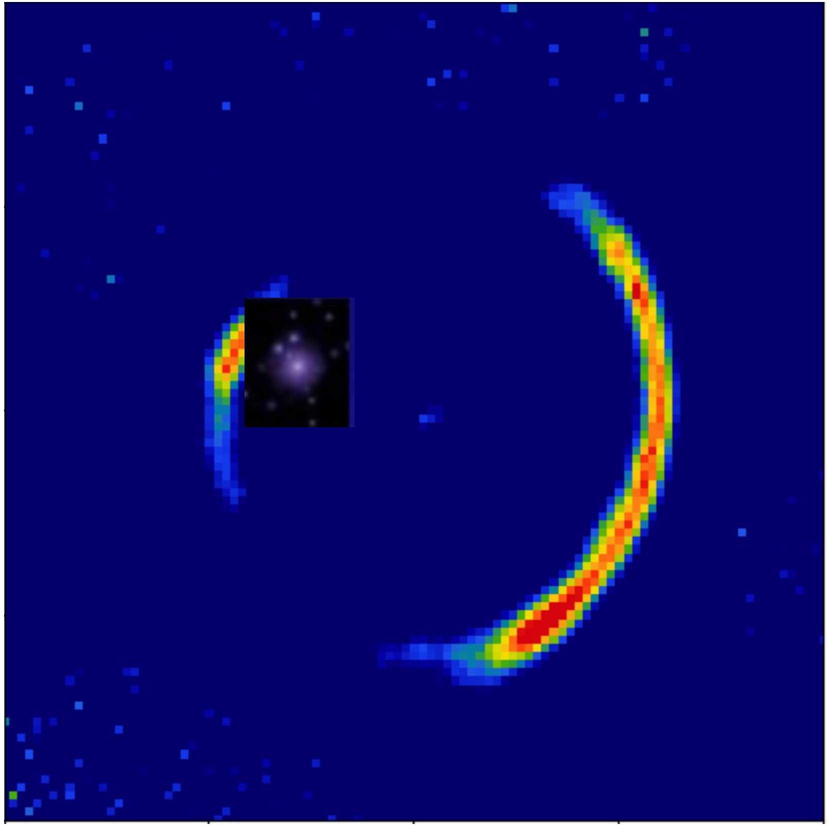
Gravitational lensing: Dark Matter Substructure Detections

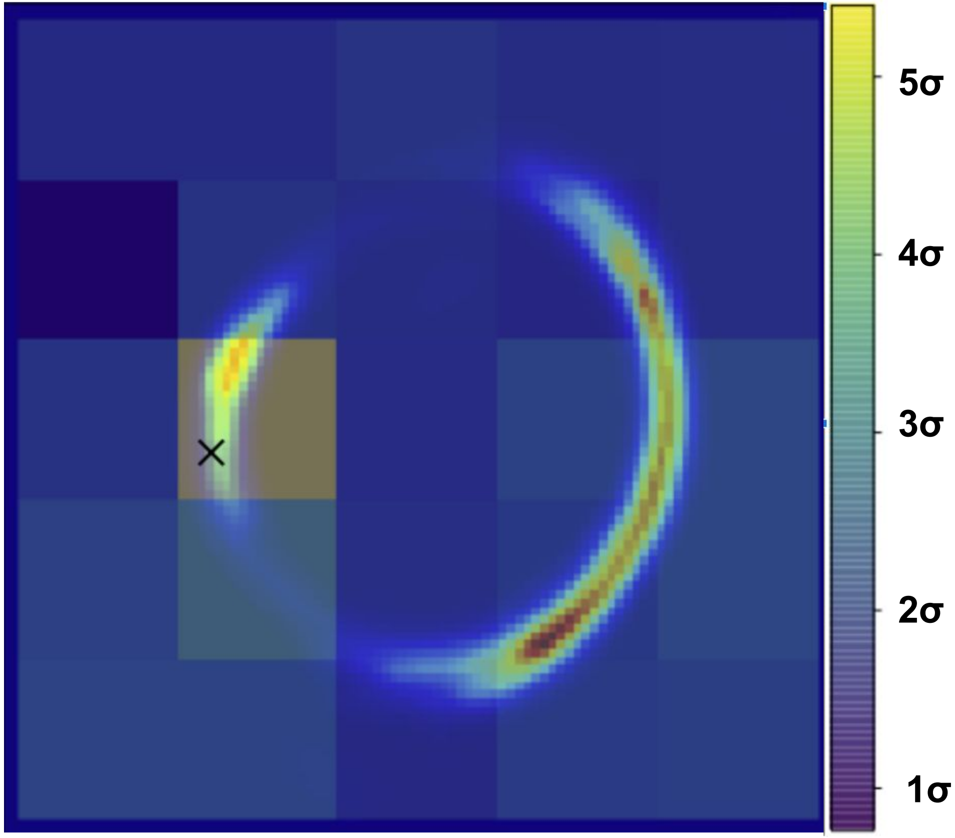


Gravitational lensing: Dark Matter Substructure Detections



Gravitational lensing: Dark Matter Substructure Detections

Proven Technique: Multiple groups reproduce this 10^10MSun detection independently [***Nightingale et al 2023,*** *Vegetti et al 2010, 2012*].



Testing strong lensing subhalo detection with a cosmological simula

Qiuhan He[1]★, James Nightingale[1,2], Andrew Robertson[3], Aristeidis Amvrosiadis[1], Shaun Cole
Carlos S. Frenk[1], Richard Massey[1,2], Ran Li[4,5], Nicola C. Amorisco[1], R. Benton Metcalf[6], Xia
Amy Etherington[1,2]
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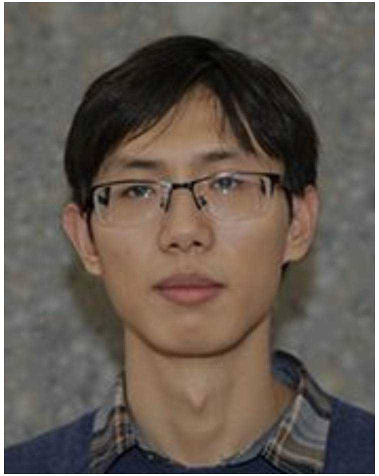
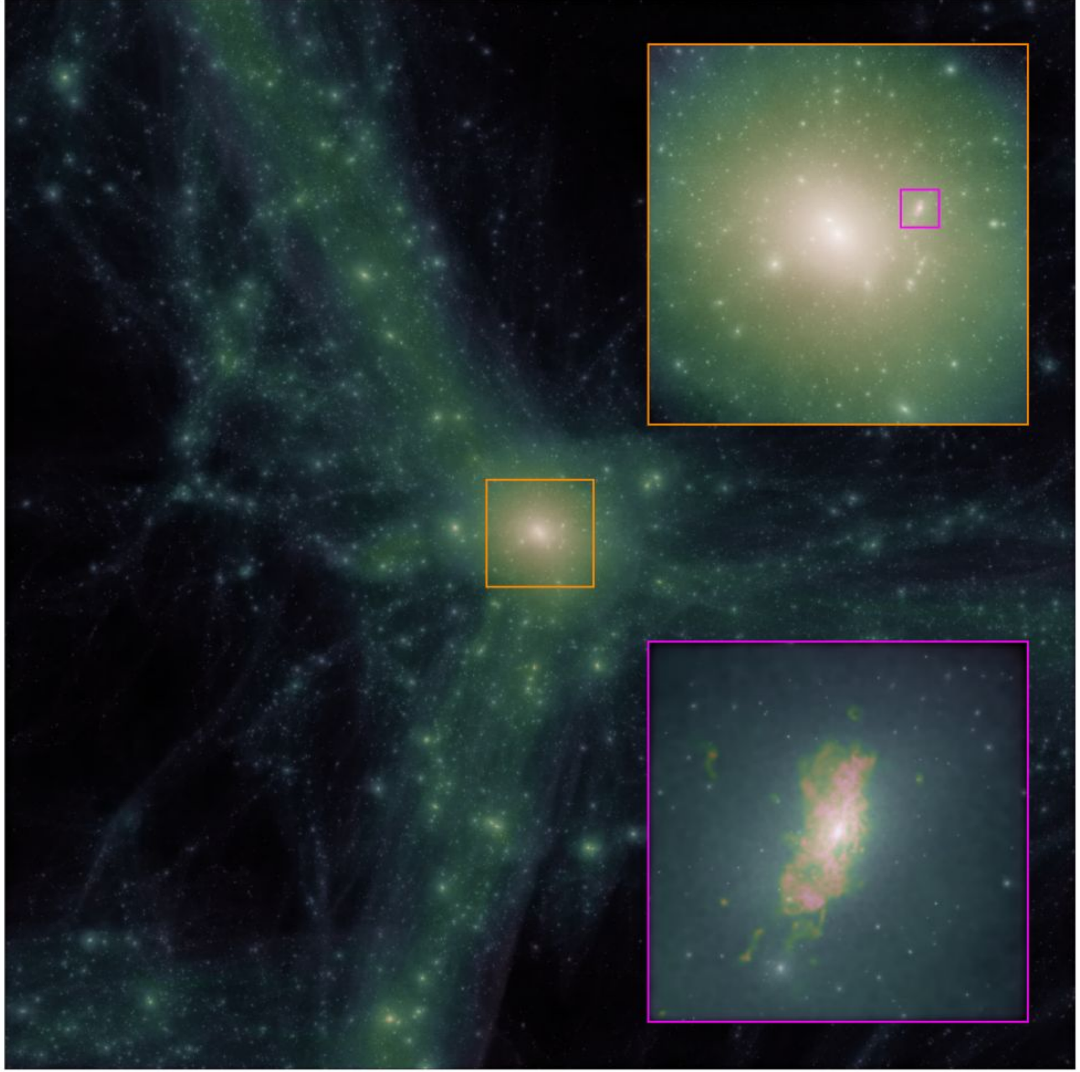


Strong Lens Simulation

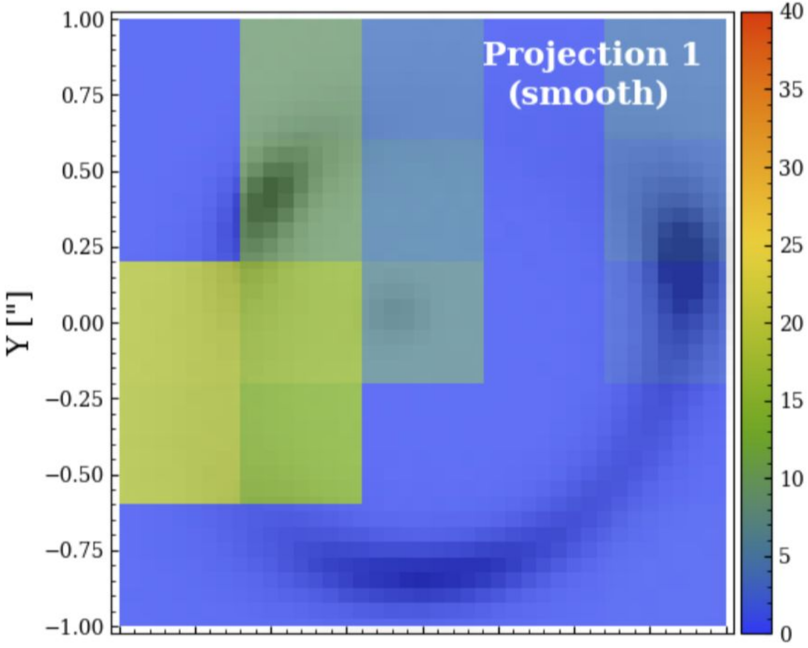
Richings et al 2020 - https://arxiv.org/abs/2005.14495

Very high resolution of a 10^{13}MSun massive elliptical using EAGLE.

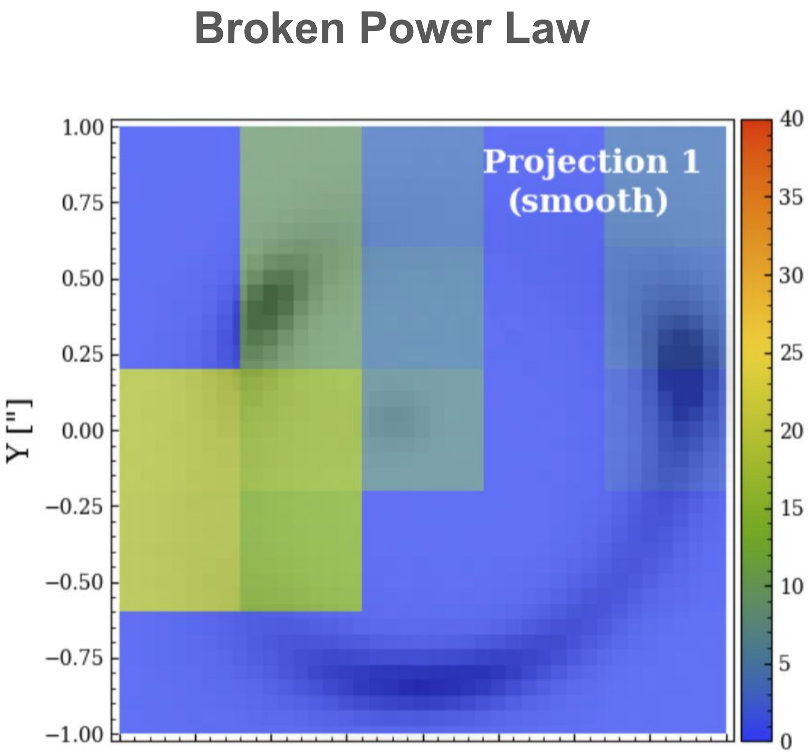


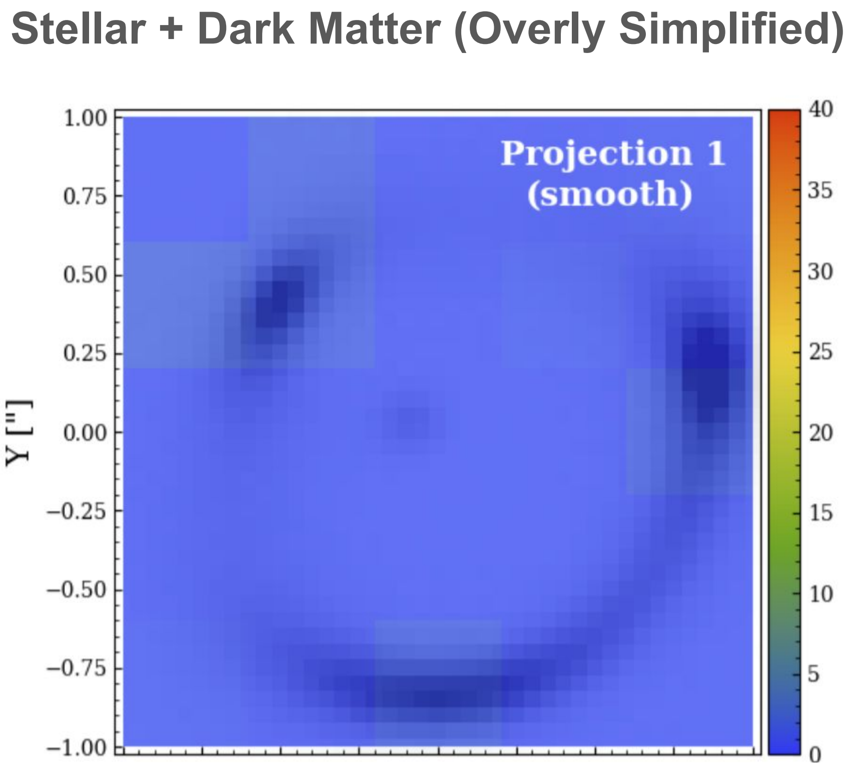
False Positives

Broken Power Law



False Positives

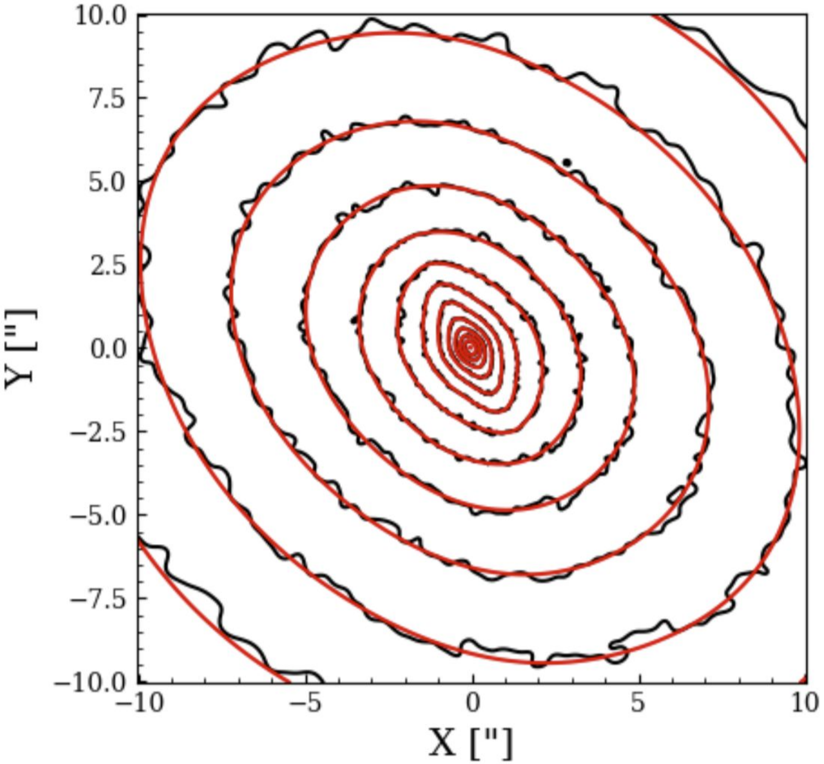




False Positives (Qiuhan He)

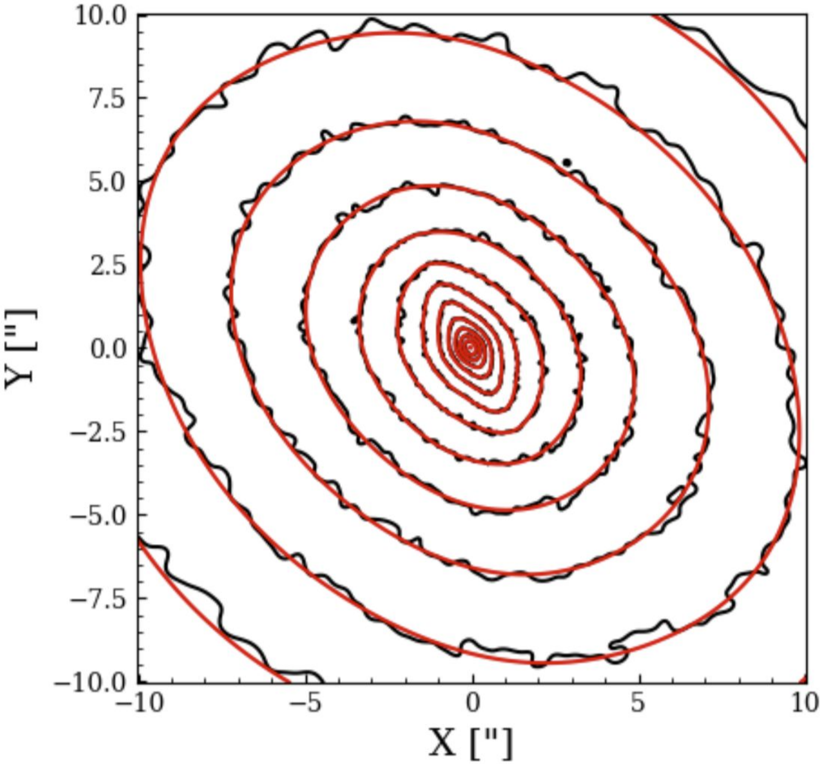
False positives are due to changing ellipticity / position angle in mass distribution.

Fixed by stellar + dark matter as each component has its own ellipticity / position angle.



False Positives (Qiuhan He)

This is the same missing complexity that we believe causes the “External Shears”.



Scanning For Dark Matter Subhalos in *Hubble Space Telescope* Imaging of 54 Strong Lenses

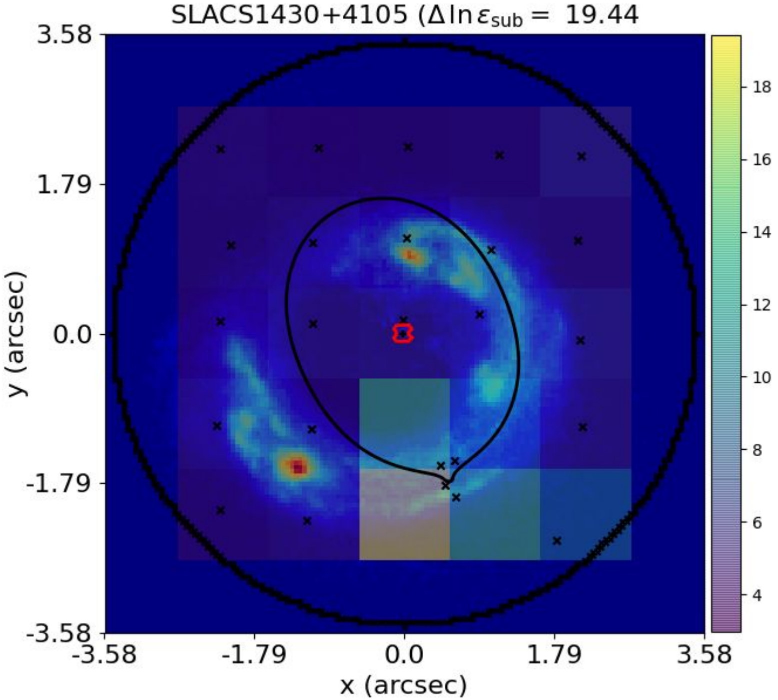
James W. Nightingale[1,2]★, Qiuhan He[2], Xiaoyue Cao[4,5,3], Aristeidis Amvrosiadis[2], Amy Etherington[1], Carlos S. Frenk[2], Richard G. Hayes[1], Andrew Robertson[6], Shaun Cole[2], Samuel Lange[2], Ran Li[3,5,4] & Richard Massey[1,2]

[1] *Department of Physics, Centre for Extragalactic Astronomy, Durham University, South Rd, Durham, DH1 3LE*
[2] *Department of Physics, Institute for Computational Cosmology, Durham University, South Road, Durham DH1 3LE, UK*
[3] *National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, China*
[4] *School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China*
[5] *Institute for Frontiers in Astronomy and Astrophysics, Beijing Normal University, Beijing 102206, China*
[6] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA*

Mass Model False Positive (4/54): SLACS1430+4105

Elliptical Power Law + Shear:

$\Delta \ln \varepsilon = 19.4$



Mass Model False Positive (4/54): SLACS1430+4105

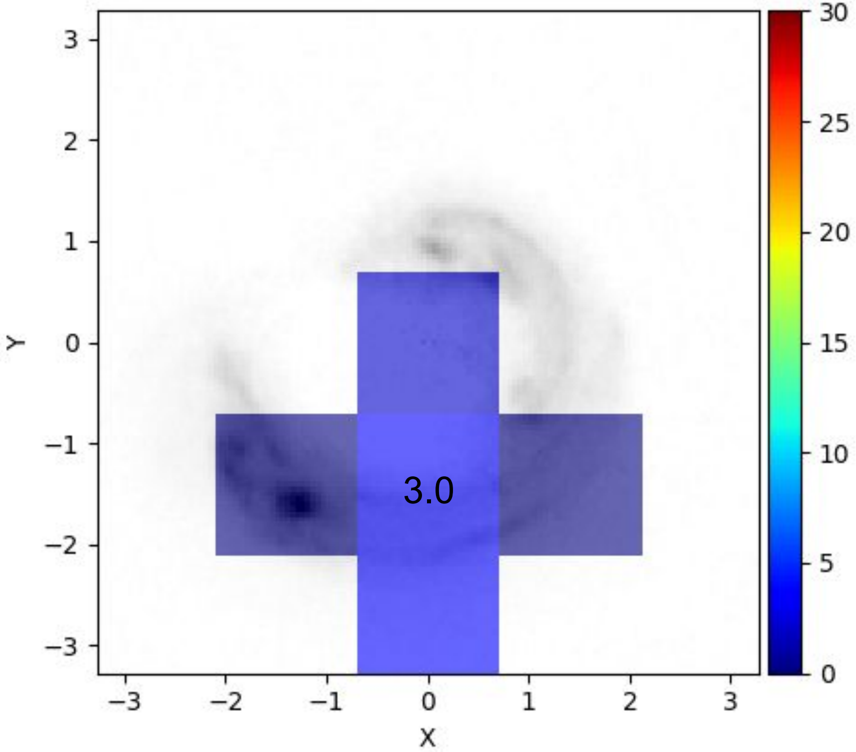
Elliptical Power Law + Shear:

ΔInε = 19.4

Decomposed Stellar plus Dark Matter mass model.

ΔInε = 3.0

False positive was due to unaccounted for ellipticity variations and lopsidedness in mass distribution!



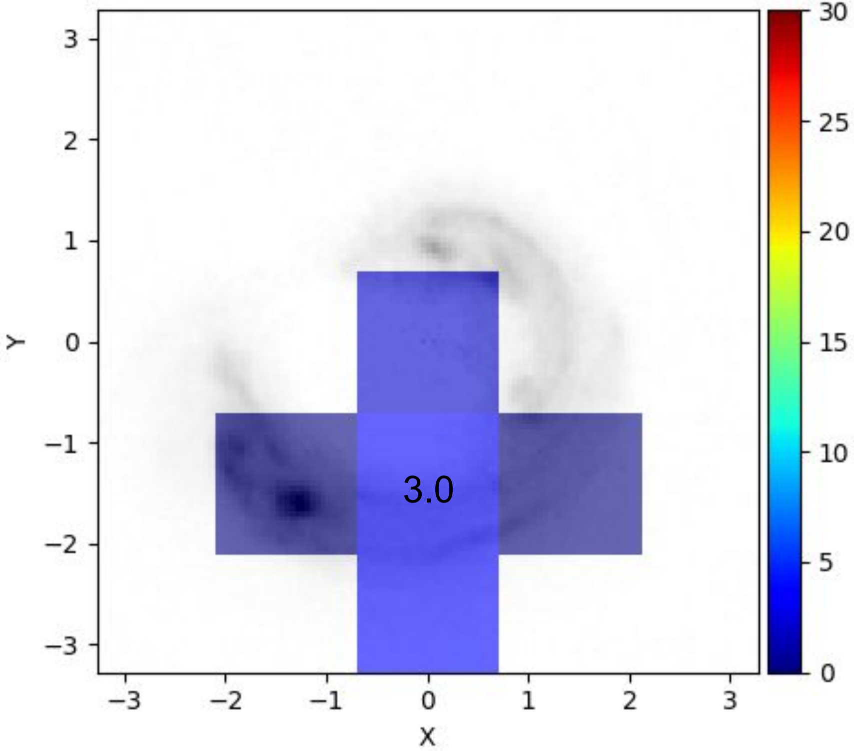
Mass Model False Positive (4/54): SLACS1430+4105

Theoretical Brick Wall: There is no one mass model that removes all false positives.

Different forms of complexity work and do not work in different lenses:

- Decomposed stellar + dark models.
- Models which vary the radial density.
- Models which smoothly vary the azimuthal structure (e.g. multipoles, diskyness / boxyness).

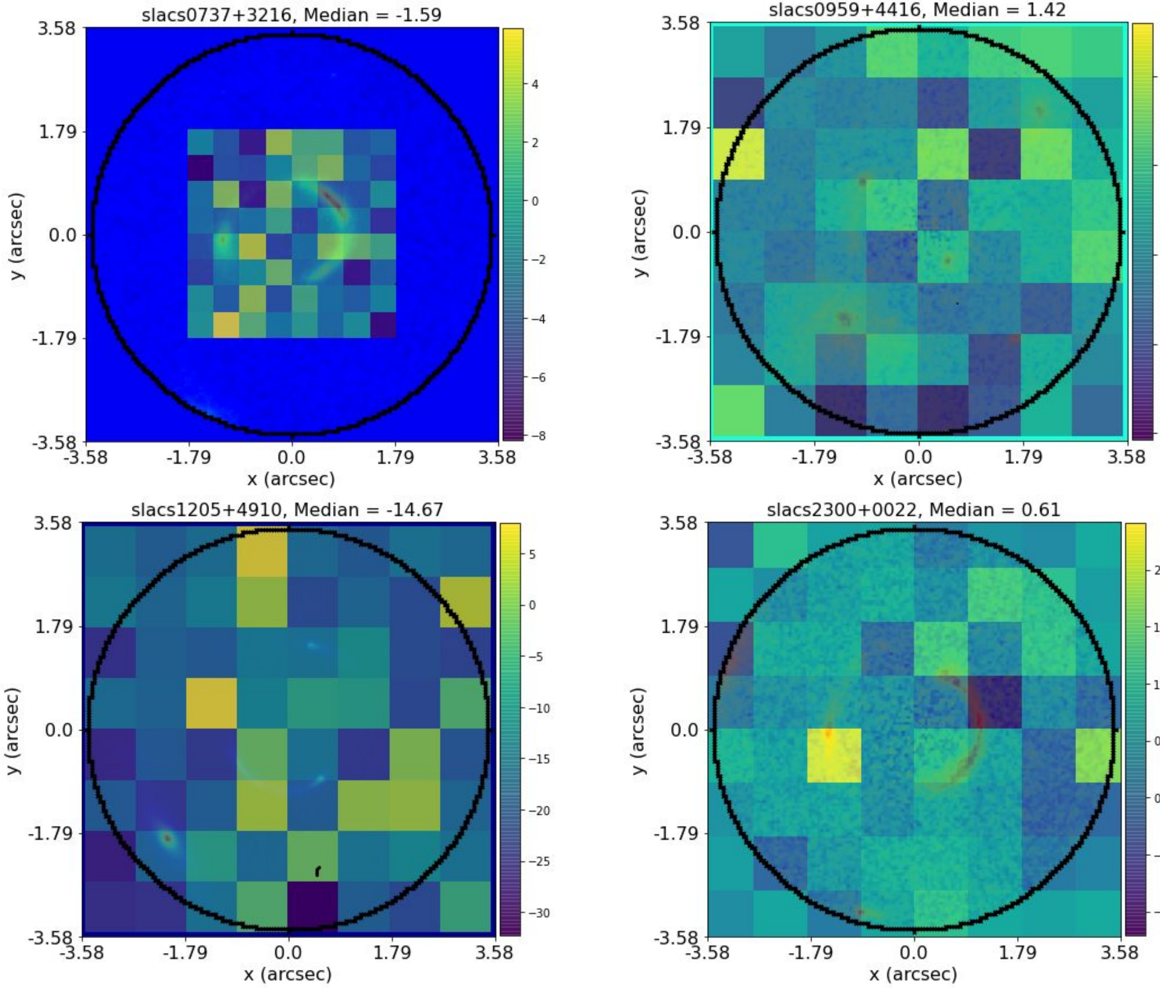
We need a theoretical breakthrough in lens modeling.



Non-Detections (44/54)

Important for constraining dark matter models.

WDM models predict we should detect **nothing** below certain masses.



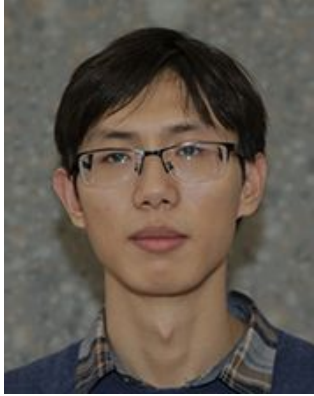
Summary… So Far

After 7+ years working on this problem… we've still not got much to show for it.

- No meaningful constraints on dark matter.
- A lot of bashing our heads against lens modeling systematics.

I am very optimistic we're not that far off though (after being pretty pessimistic for a few years).!

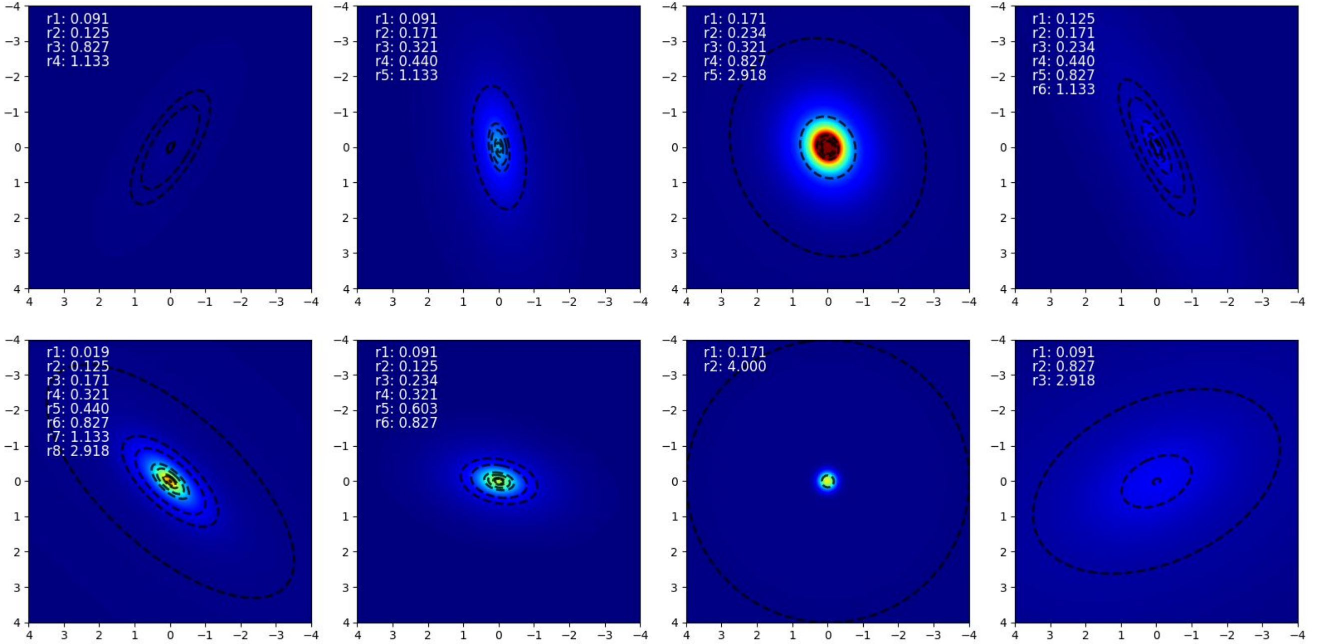
Future: Multi Gaussian Expansion Lens Model



Decompose lens light and (stellar) mass into Gaussians.

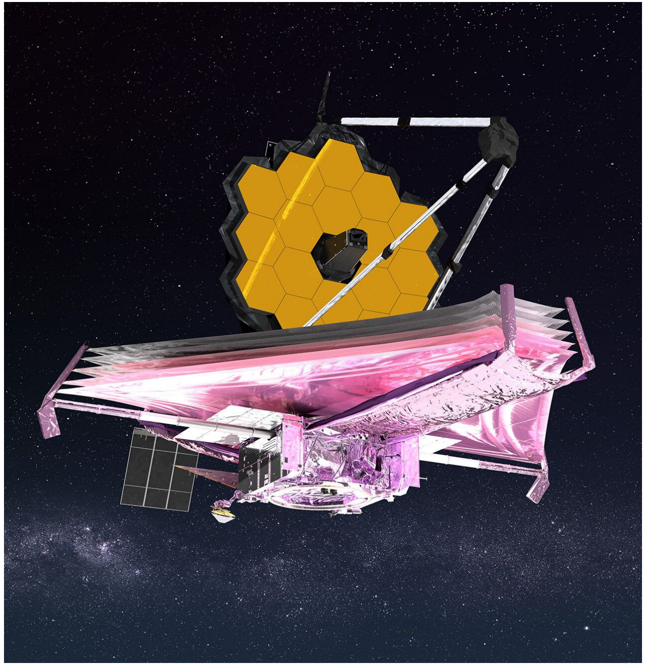
Incorporate missing complexity into lens.

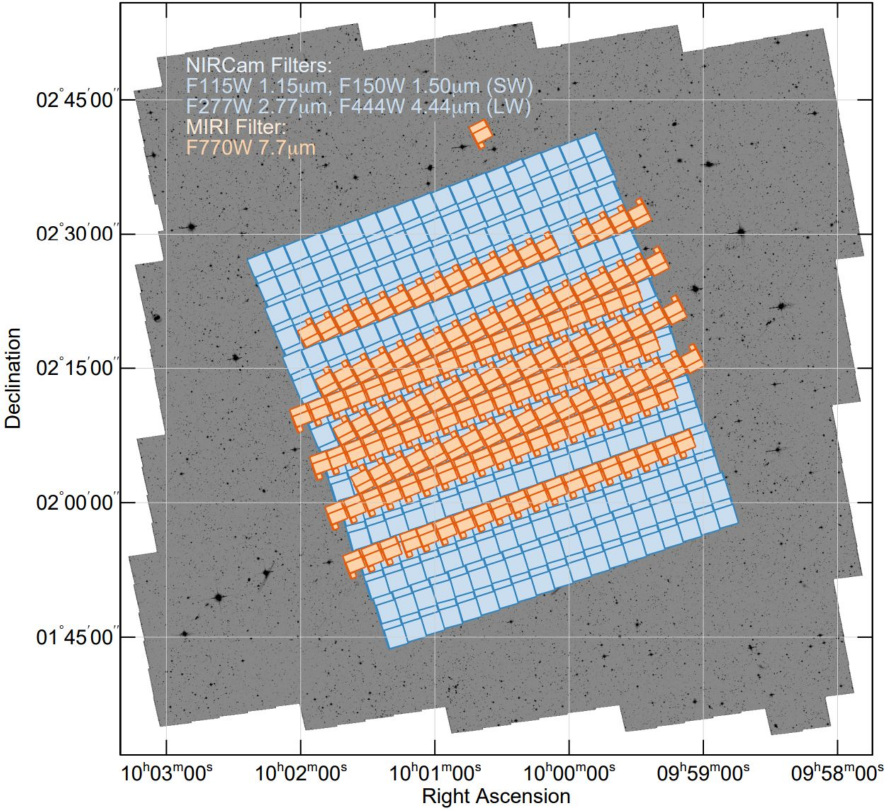
Could also address "External Shear" systematic?



Future: JWST / COSMOS-Web

COSMOS-Web: An international collaboration with the largest single allocation of JWST time so far!

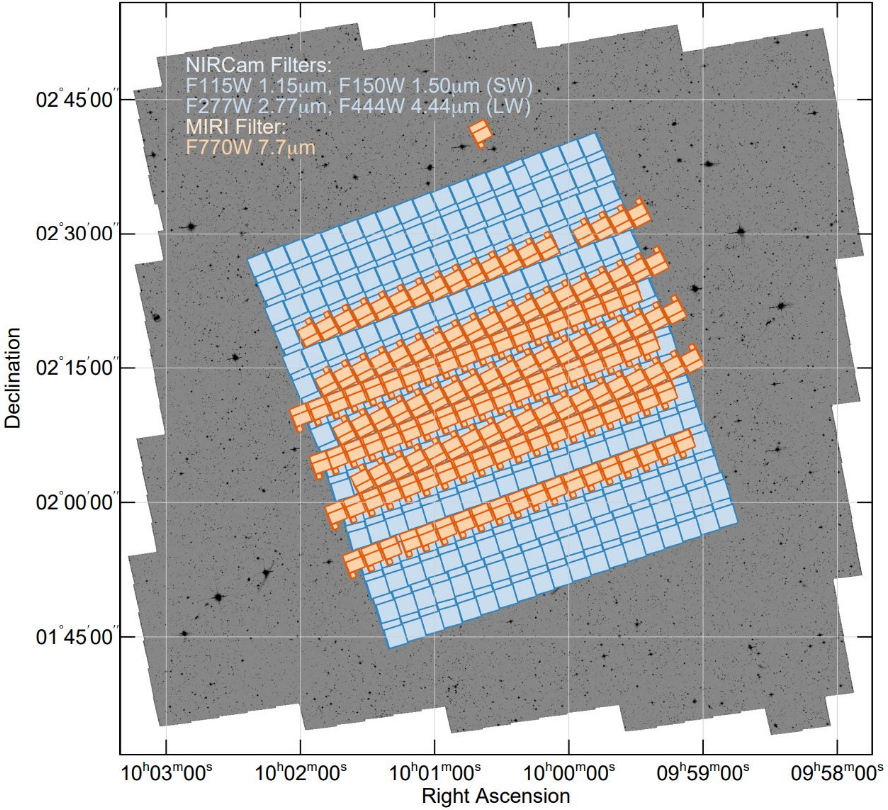




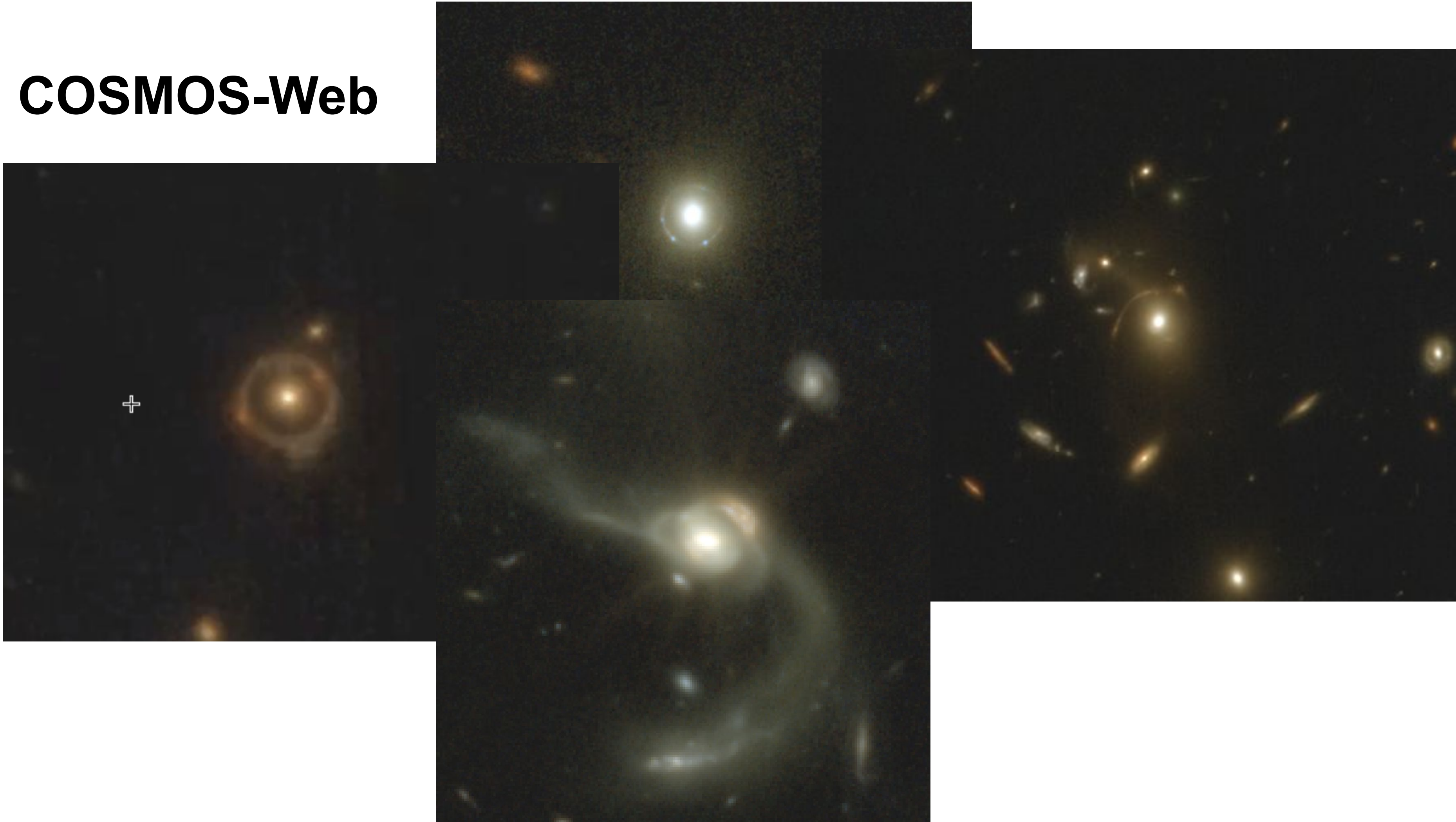
Future: JWST / COSMOS-Web

Lead of the COSMOS-Web lensing science working group**:** Coordinate lens finding, follow up and analysis.

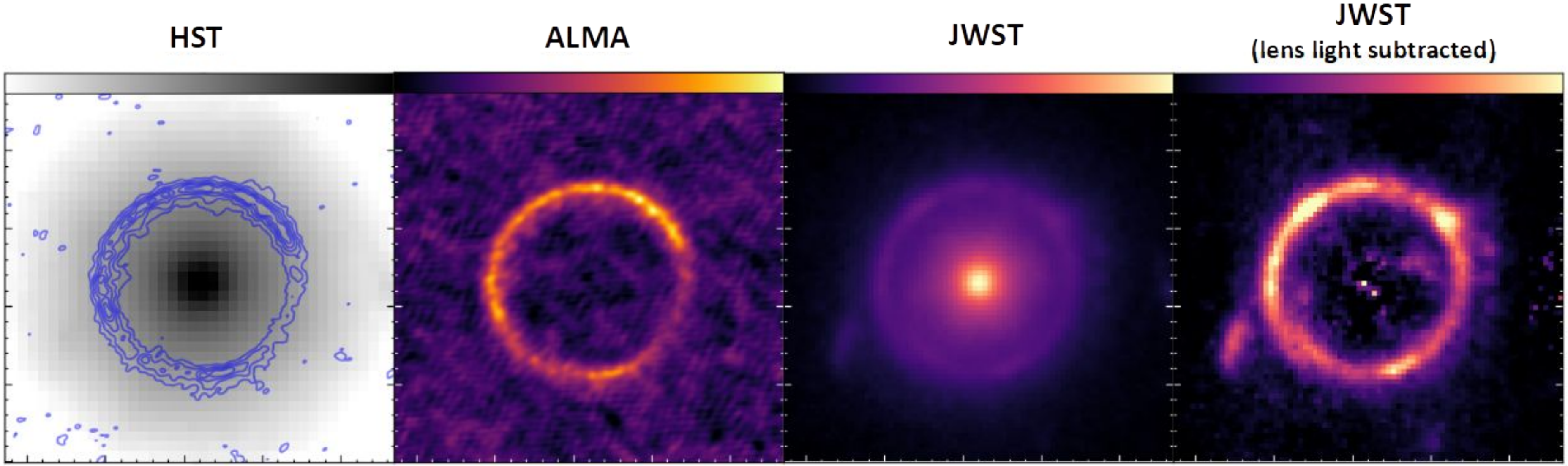
Quantity: I forecasted COSMOS-Web will find **~90 gravitational lenses**.
[*COSMOS-Web Overview Paper 2023***]**

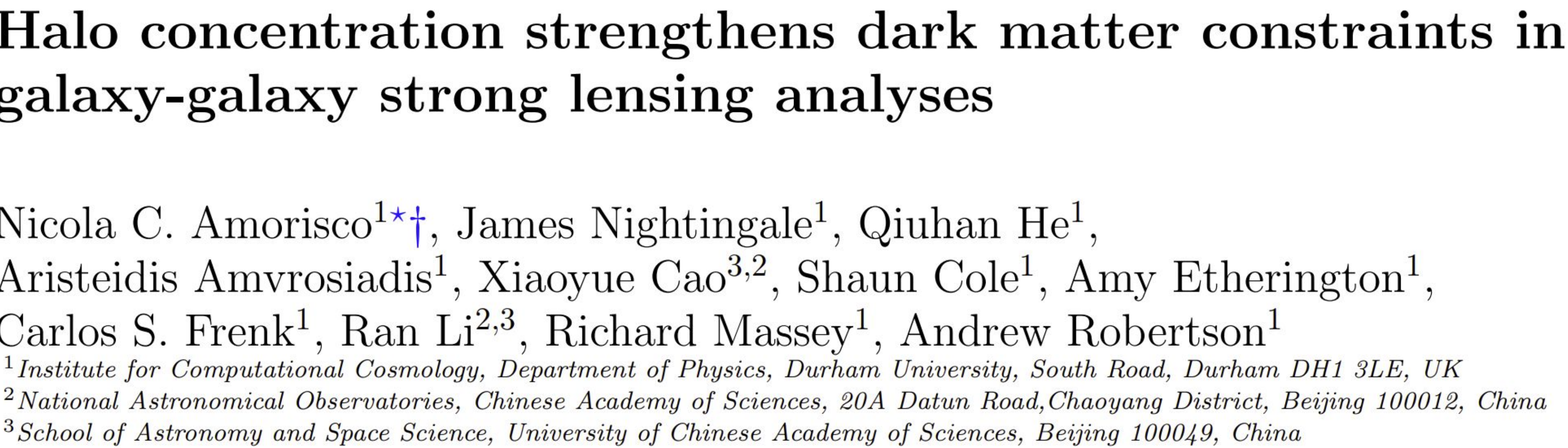


COSMOS-Web



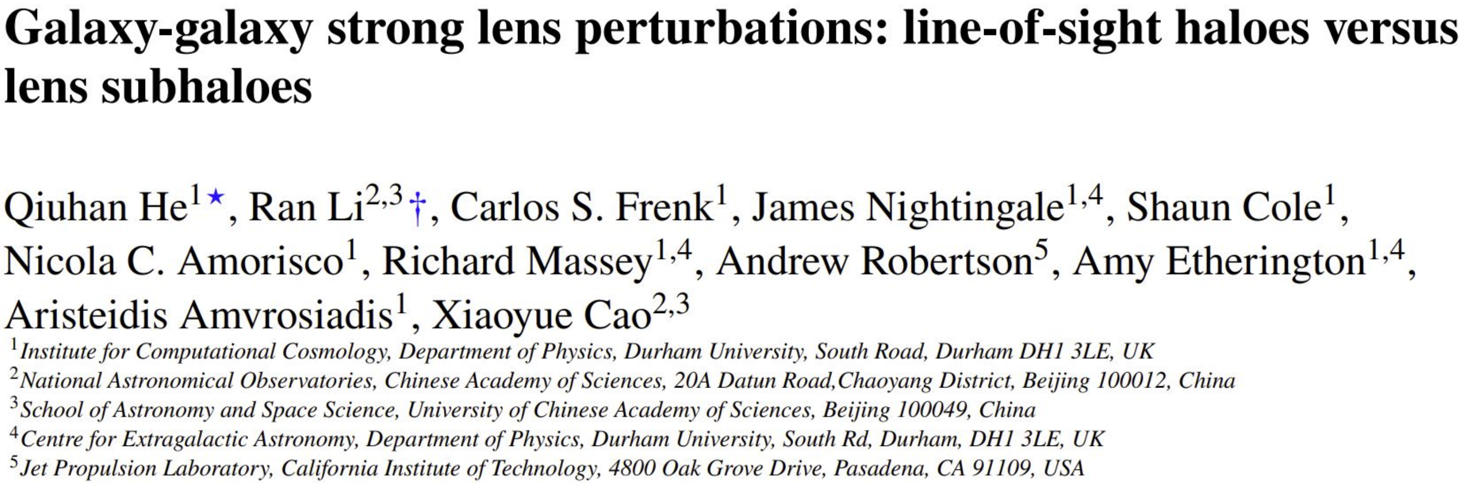
Future: Interferometer Analysis (+ Multiwavelength)





Halo concentration strengthens dark matter constraints in galaxy-galaxy strong lensing analyses

Nicola C. Amorisco[1⋆†], James Nightingale[1], Qiuhan He[1],
Aristeidis Amvrosiadis[1], Xiaoyue Cao[3,2], Shaun Cole[1], Amy Etherington[1],
Carlos S. Frenk[1], Ran Li[2,3], Richard Massey[1], Andrew Robertson[1]
[1] *Institute for Computational Cosmology, Department of Physics, Durham University, South Road, Durham DH1 3LE, UK*
[2] *National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road,Chaoyang District, Beijing 100012, China*
[3] *School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China*



Galaxy-galaxy strong lens perturbations: line-of-sight haloes versus lens subhaloes

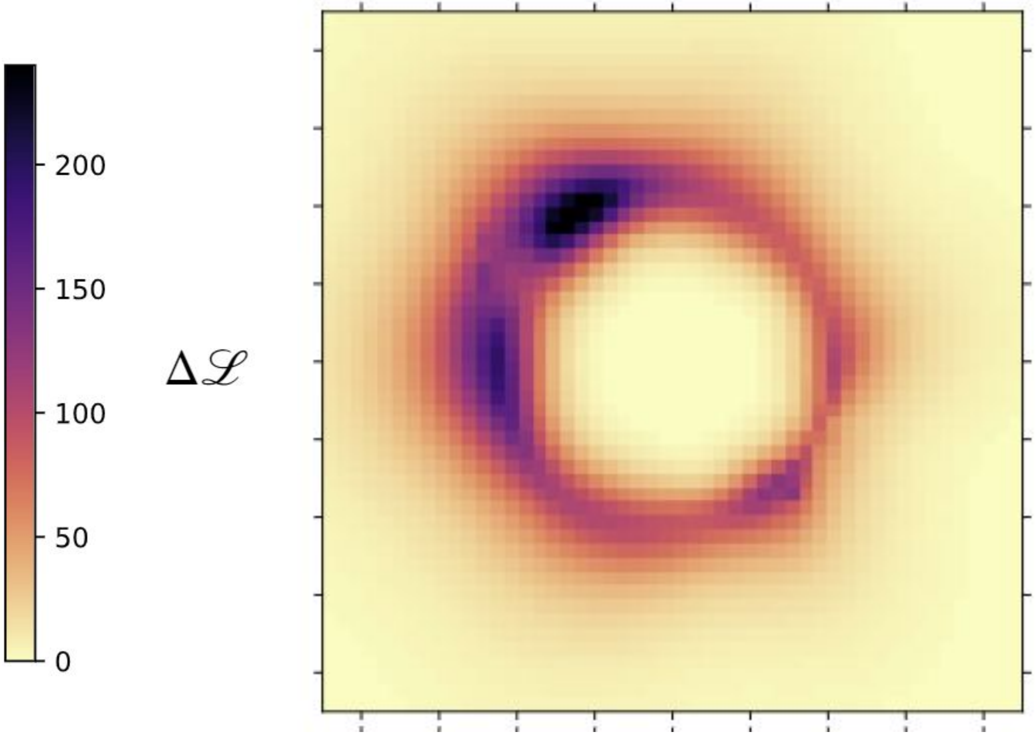
Qiuhan He[1⋆], Ran Li[2,3†], Carlos S. Frenk[1], James Nightingale[1,4], Shaun Cole[1],
Nicola C. Amorisco[1], Richard Massey[1,4], Andrew Robertson[5], Amy Etherington[1,4],
Aristeidis Amvrosiadis[1], Xiaoyue Cao[2,3]
[1] *Institute for Computational Cosmology, Department of Physics, Durham University, South Road, Durham DH1 3LE, UK*
[2] *National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road,Chaoyang District, Beijing 100012, China*
[3] *School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China*
[4] *Centre for Extragalactic Astronomy, Department of Physics, Durham University, South Rd, Durham, DH1 3LE, UK*
[5] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA*

Sensitivity Mapping (Nicola Amorisco)

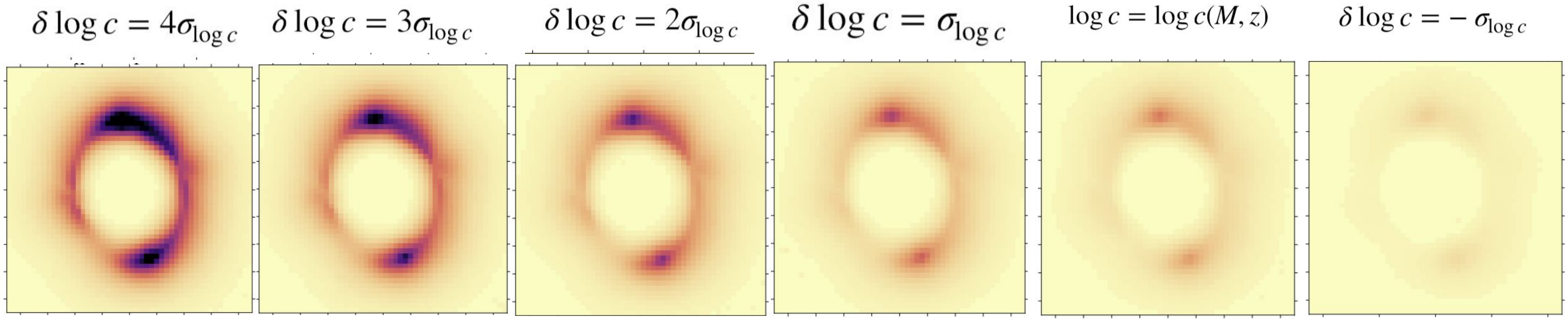
1) **We know** how many dark matter subhalos **we did** detect.

2) **We do not know how** many dark matter subhalos **we could of detected**.

Perform sensitivity mapping to determine (statistically) how many dark matter substructures we could have detected.

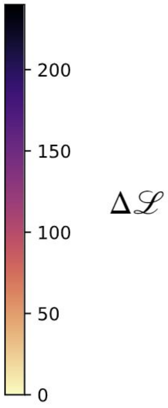


Sensitivity Mapping Over Concentration (Nicola Amorisco)



Mapping over concentration reveals that increasing the concentration of the subhalo increases our sensitivity to it.

- Increasing the concentration makes mass profile more dense, stronger lensing effects.



Sensitivity Mapping Over Concentration (Nicola Amorisco)

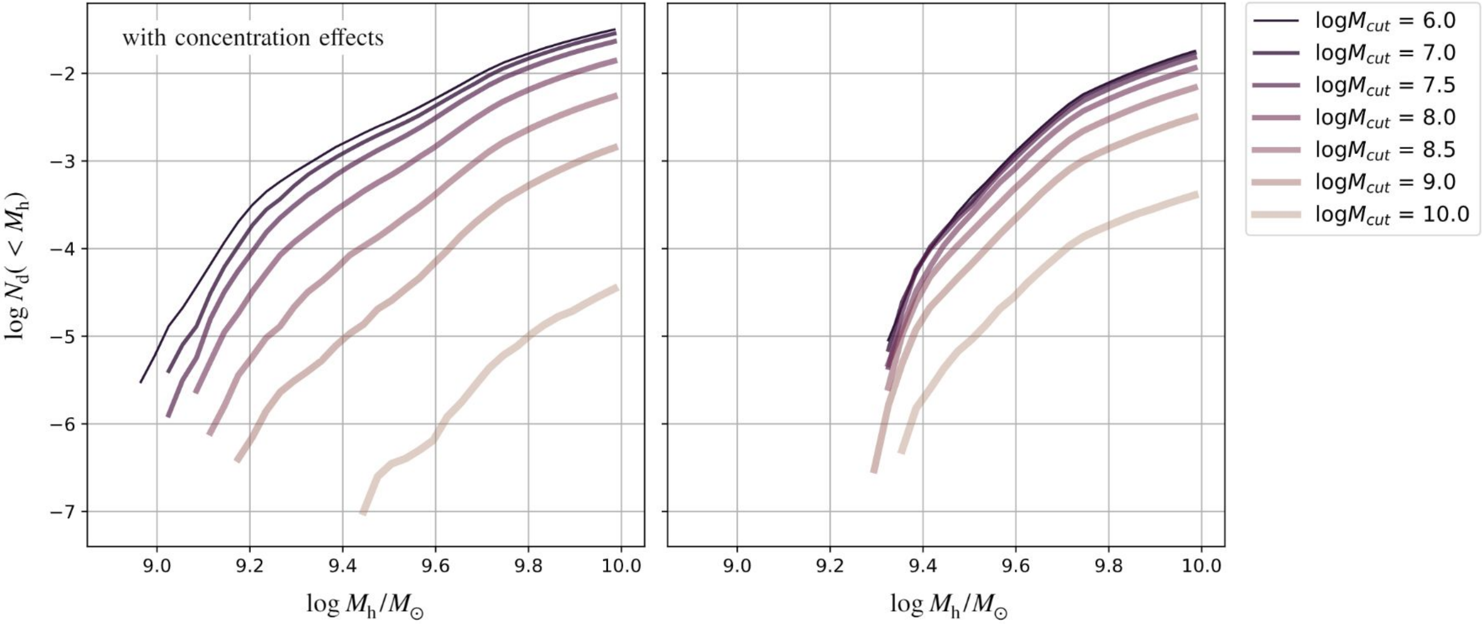


Figure 12. A comparison between the cumulative number of expected detections for our 'quad' configuration (threshold for detection, $\Delta\mathscr{L}_{\rm th} = 30$) when including both (i) the scatter in the mass-concentration relation and (ii) the dependence of the median concentration on the DM model (left), and when concentration effects are neglected (right). Concentration substantially enhances the spread between the expected detections in WDM models with different cutoff masses, $M_{\rm cut}$.

Future: Cosmological Forecasts

Feasibility: Dark Matter Detection Forecasts

Cold Dark Matter: 2.7 ± 0.7 detections of < 10^9 MSun DM clumps per 50 JWST lenses.

Warm Dark Matter: 0.2 ± 0.2 detections of < 10^9 MSun DM clumps per 50 JWST lenses.

COSMOS-Web will discriminate between dark matter models at 3 sigma confidence!

[See also: WP2 Interferometer Analysis]

[Amorisco, Nightingale et al 2021]
See also [He, Li, Frenk, Nightingale et al 2021]

Supermassive Black Holes (SMBH)

Abell 1201: Detection of an Ultramassive Black Hole in a Strong Gravitational Lens

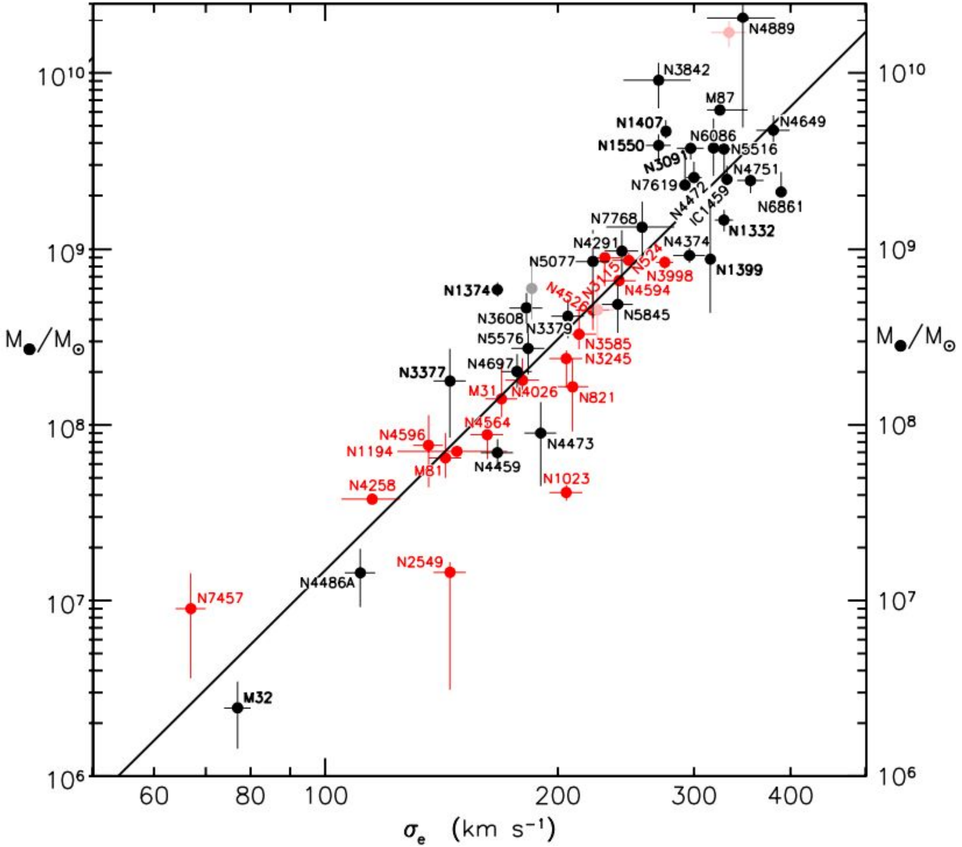
J. W. Nightingale[1⋆], Russell J. Smith[1], Qiuhan He[1], Conor M. O'Riordan[2], Jacob A. Kegerreis[3], Aristeidis Amvrosiadis[1], Alastair C. Edge[1], Amy Etherington[1], Richard G. Hayes[1], Ash Kelly[1], John R. Lucey[1], Richard J. Massey[1]

Why Are Supermassive Black Holes (SMBH) Important?

M-σ Relation: Observed correlation between SMBH mass and host galaxy bulge velocity dispersion σ.

Other correlations: Found between SMBH mass and galaxy luminosity, stellar mass, bulge mass, Sersic index, etc.

Key ingredient of galaxy formation?

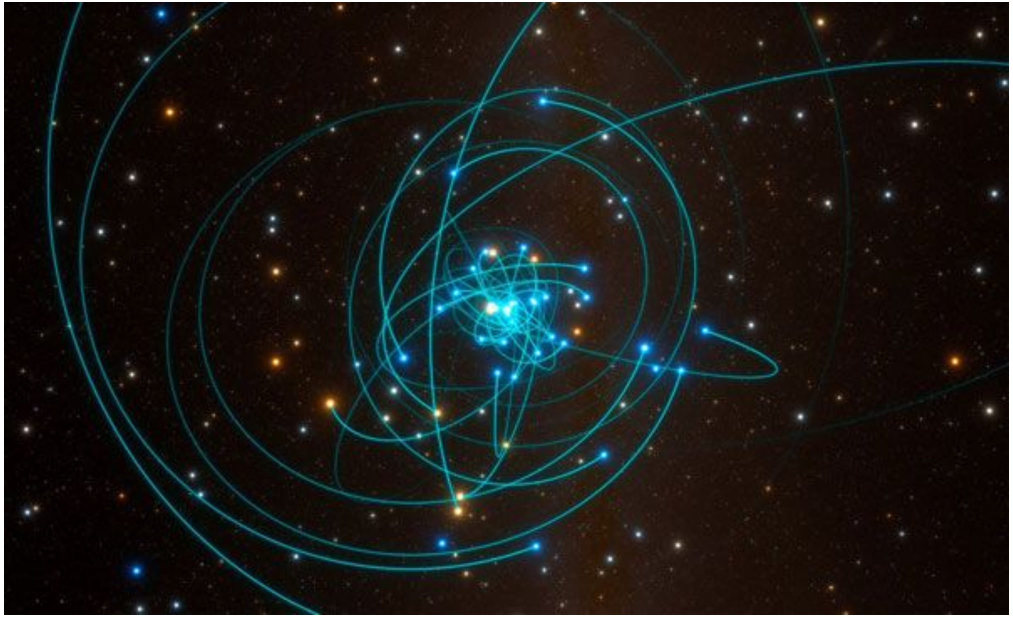


How do we measure SMBH masses – Local Universe

Method: Radial orbits of stars around SMBHs in nearby galaxies.

Downsides:

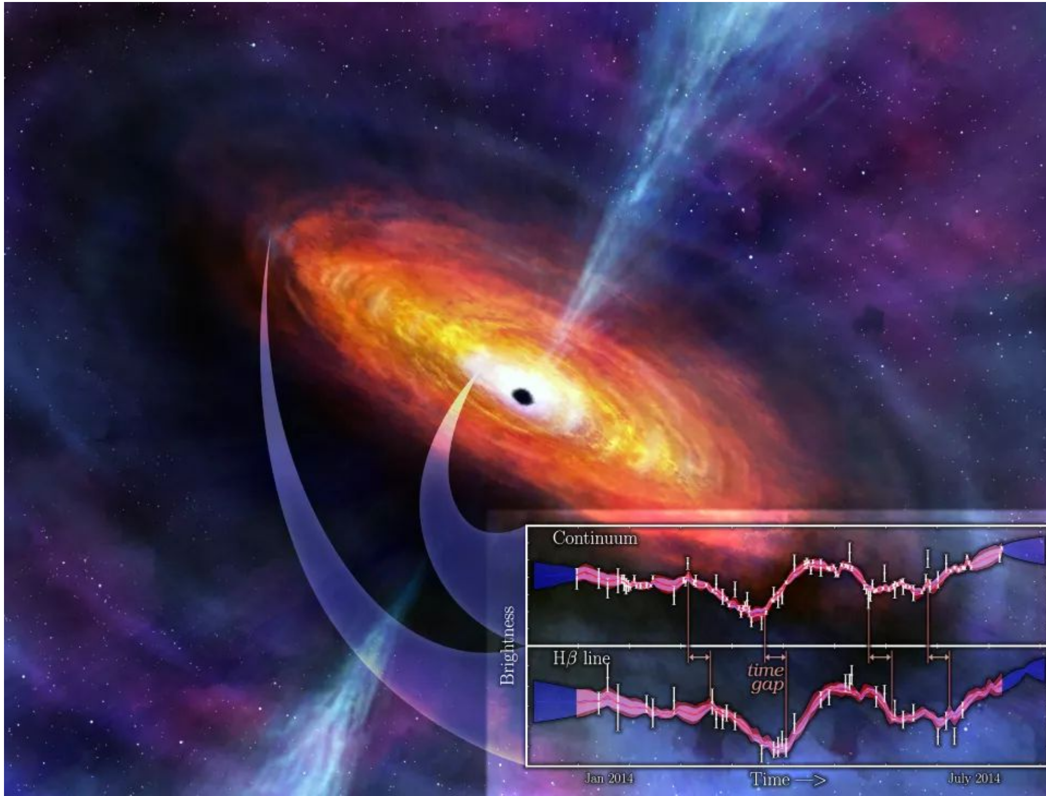
- Only possible in very nearby galaxies.



https://skyandtelescope.org/astronomy-news/star-swings-around-black-hole-tests-gravity/

How do we measure SMBH masses: High Redshift

https://www.space.com/39347-black-hole-mass-measurement-survey.html



Method: Reverberation Mapping of active galactic nuclei.

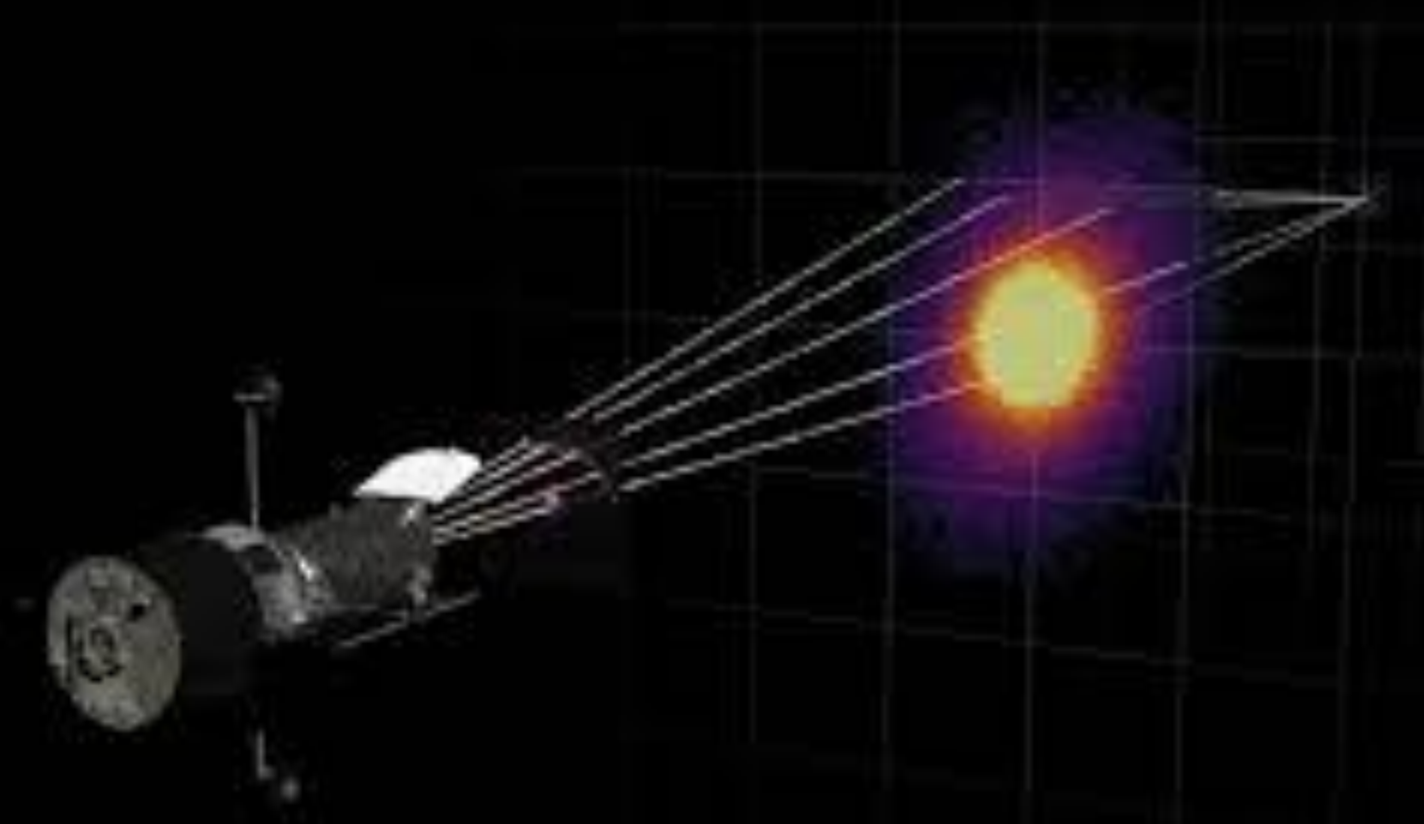
Downsides:

- Requires SMBH to be actively accreting and emitting light (selection effects).

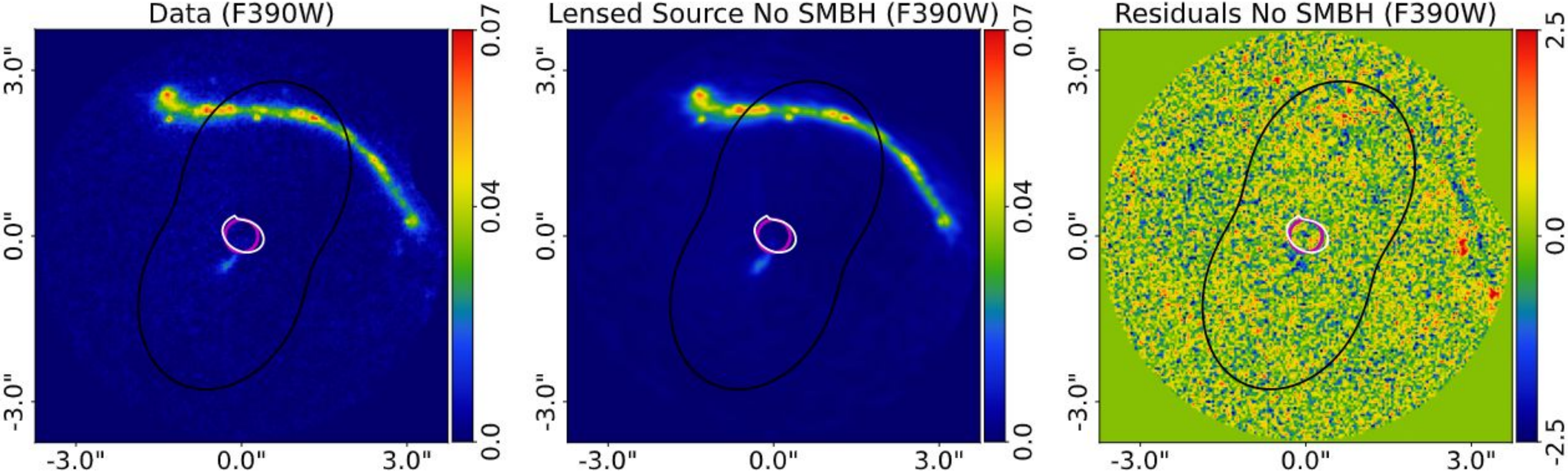
A complementary approach to measuring SMBH masses

Given the available methods out there, it would be nice if we had a method which could:

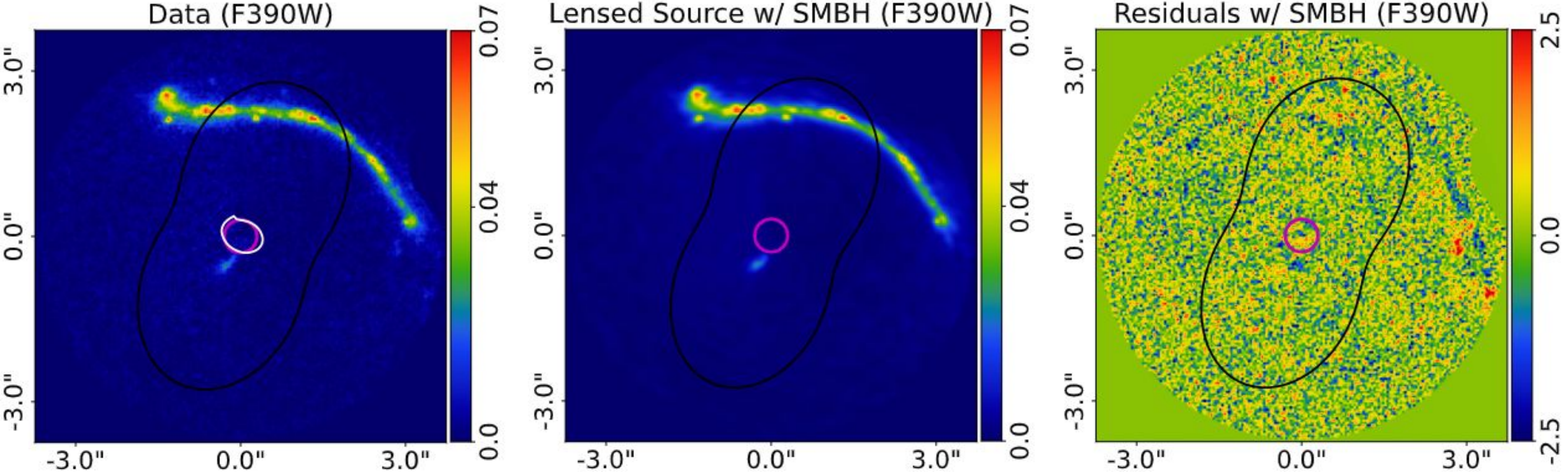
- Measure high redshift SMBH masses which are not active.



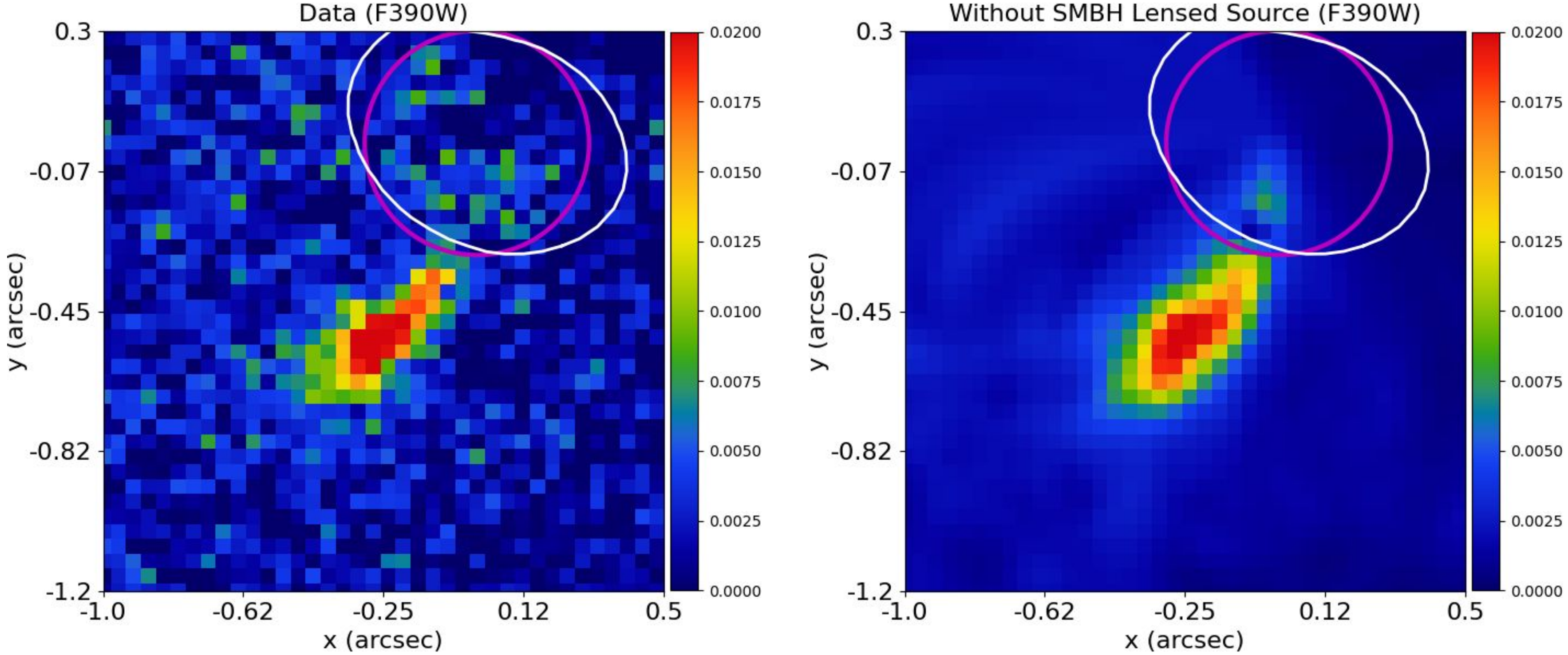
Lens Model: No SMBH



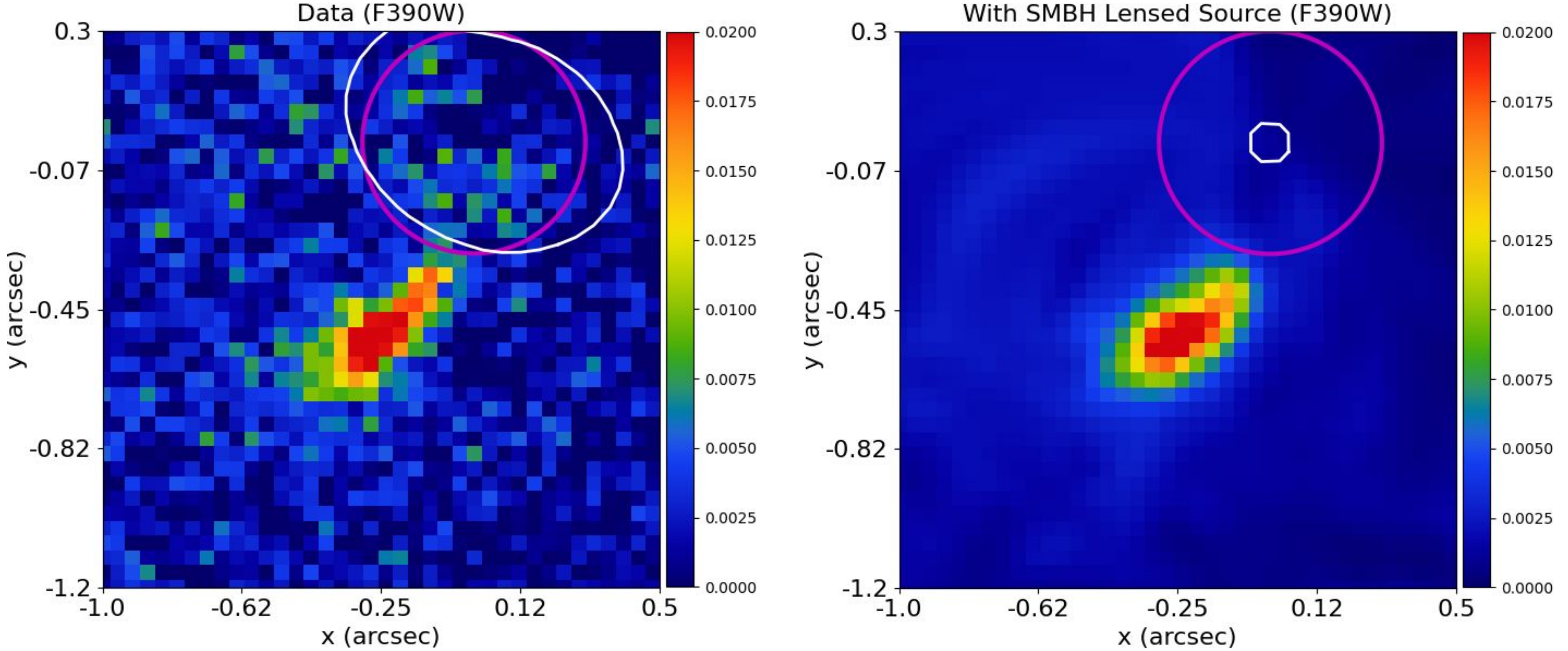
Lens Model: With SMBH



Abell 1201: No SMBH



Abell 1201: With SMBH **(M_{BH} = 3.27 x 10^{10} MSun)**

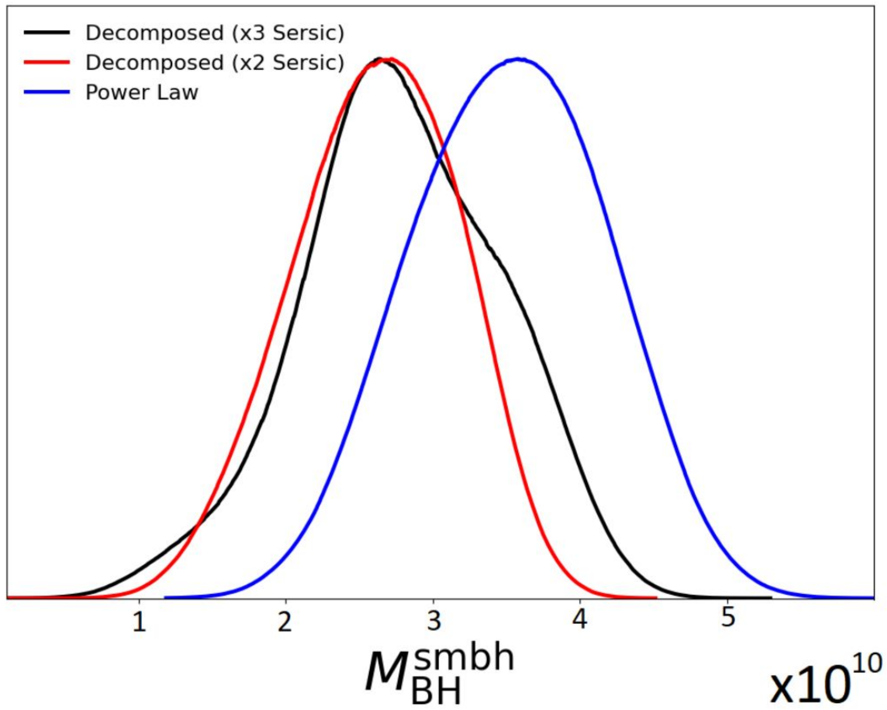


Bayesian Evidence (Residuals)

The Bayesian Evidence of the model with a SMBH is over 60 the model without.

This is a > 5σ detection.

M_{BH} = 3.27 x 10^{10}MSun



M_{BH}-Sigma Relation

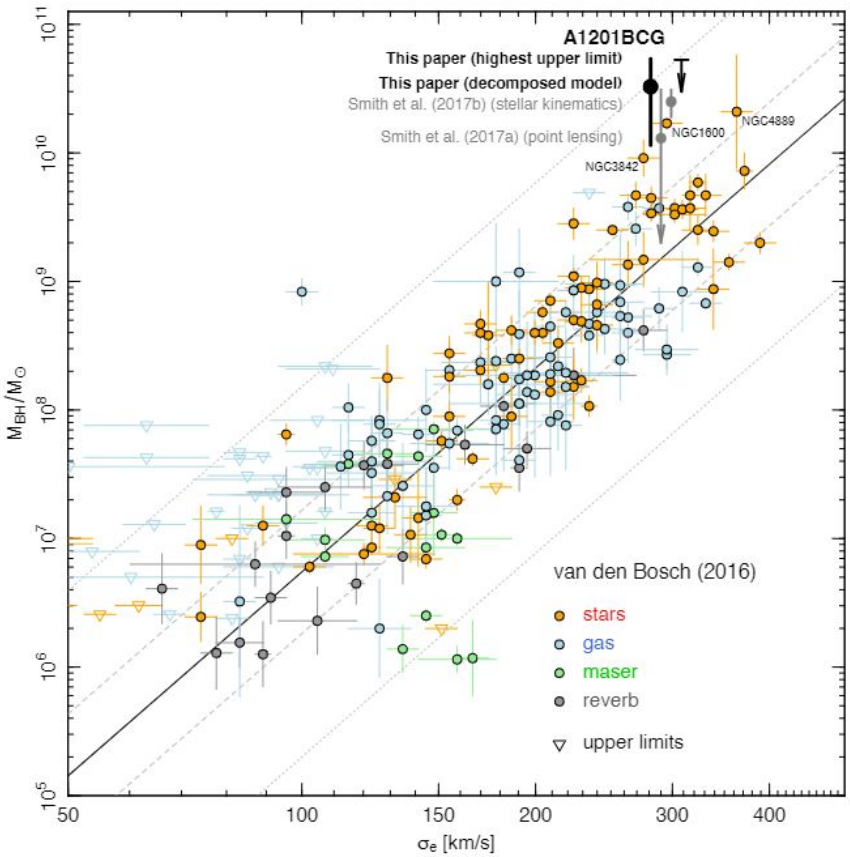
M_{BH} = 3.27 x 10^{10}MSun

Velocity Dispersion = ~280 km/s

~ 2σ positive outlier on M-σ relation:

- **Scale:** The SMBH mass inferred from lensing is consistent with expectations.
- **Size:** This SMBH is huge, one of the largest known to humanity!

An *ultramassive black-hole*.



Press Attention

'Ultramassive' black hole discovered by Durham astronomers

29 March

ESA/HUBBLE/DIGITIZED SKY SURVEY/NICK RISINGER

Future: SMBHs with strong lensing

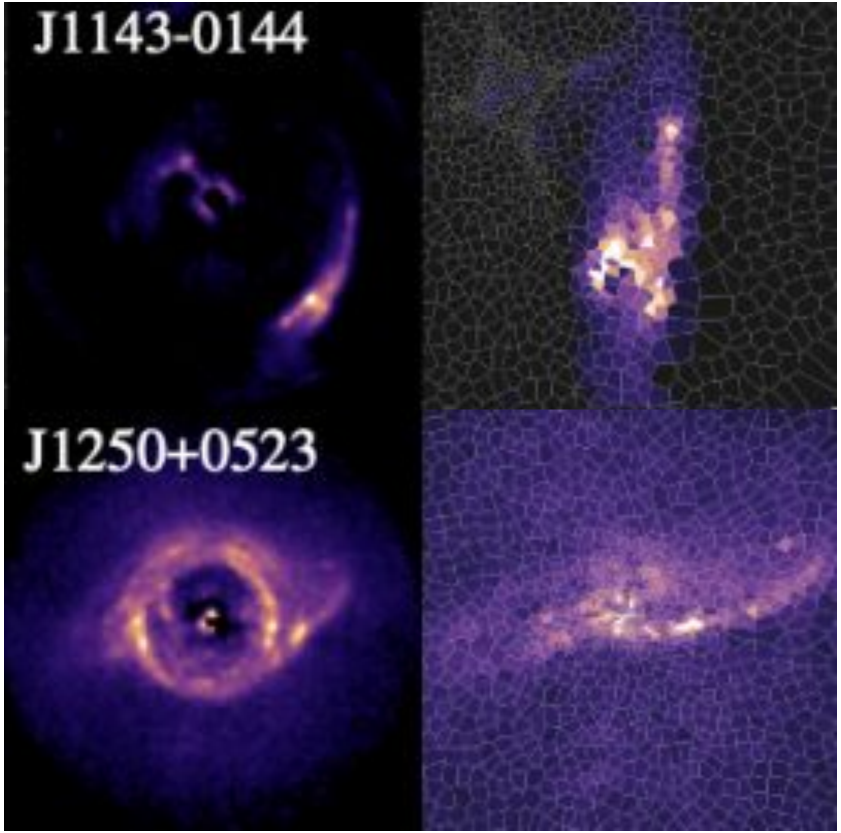
Abell 1201 might not be so weird!

Existing Samples: lenses exist with source light near the lens centre to be sensitive to the SMBH.

Selection: Existing samples selected against sources with a counter image close to the lens.

Future: Samples of 100000+ lenses are coming from this year via Euclid.

Can strong lensing become a competitive technique for measuring SMBH masses?



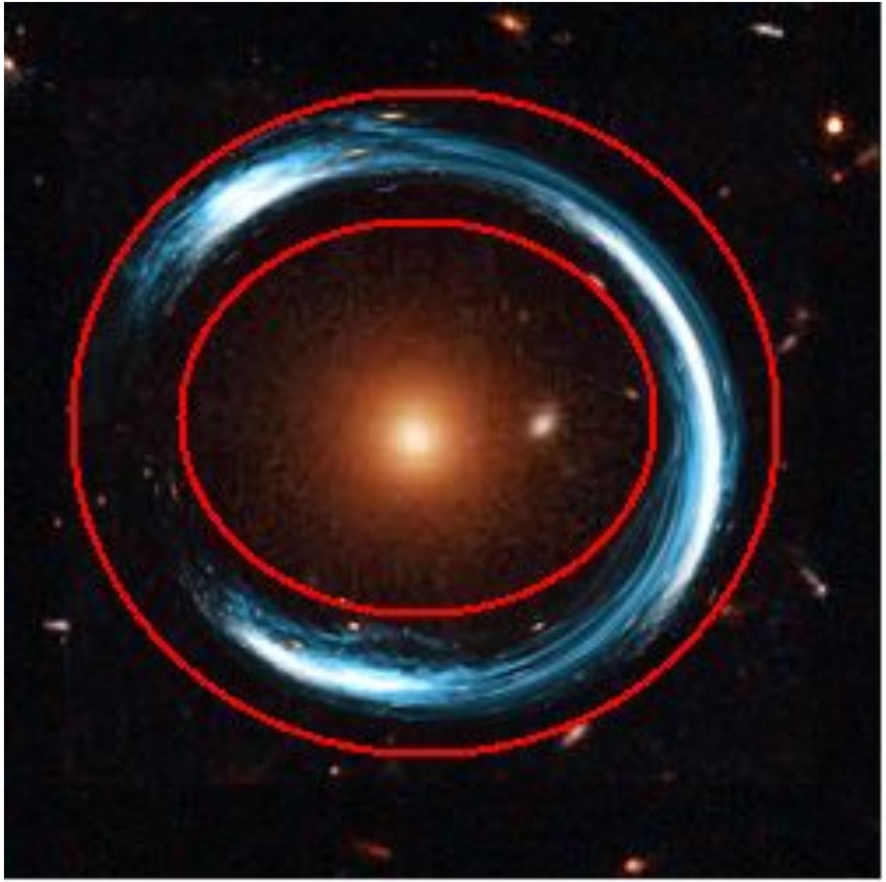
Future: The Most Massive Black Holes In the Universe

Other techniques (stellar orbits, reverberation mapping) select against the most massive galaxies.

Strong lensing selects towards it.

Could find the most massive black hole known to civilization!

Ask me about supermassive black hole binaries!

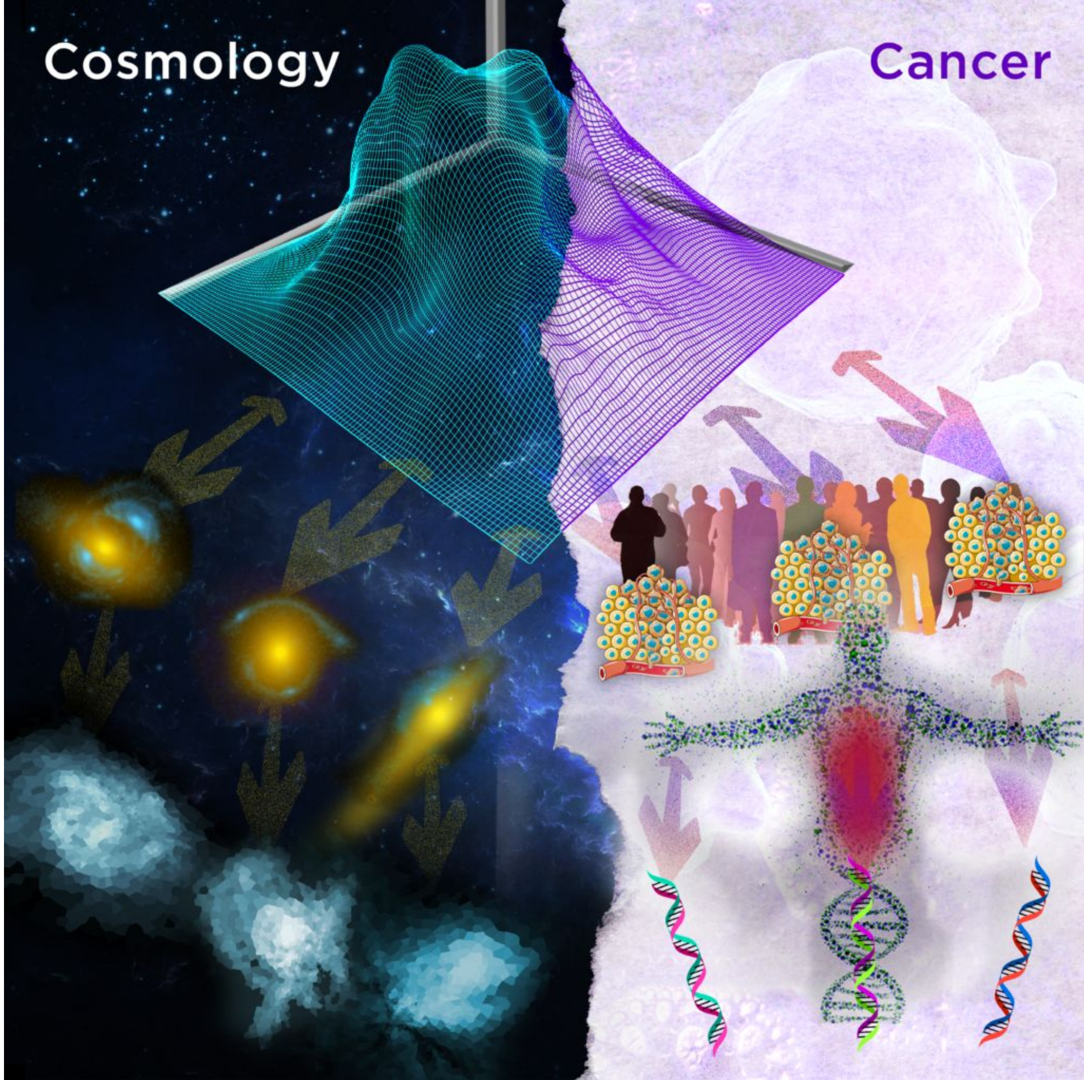


Cosmology & Cancer

Open-source framework to scale Bayesian methods up to 100000+ strong lenses.

Collaborative development with cancer therapy researchers.

https://github.com/rhayes777/PyAutoFit

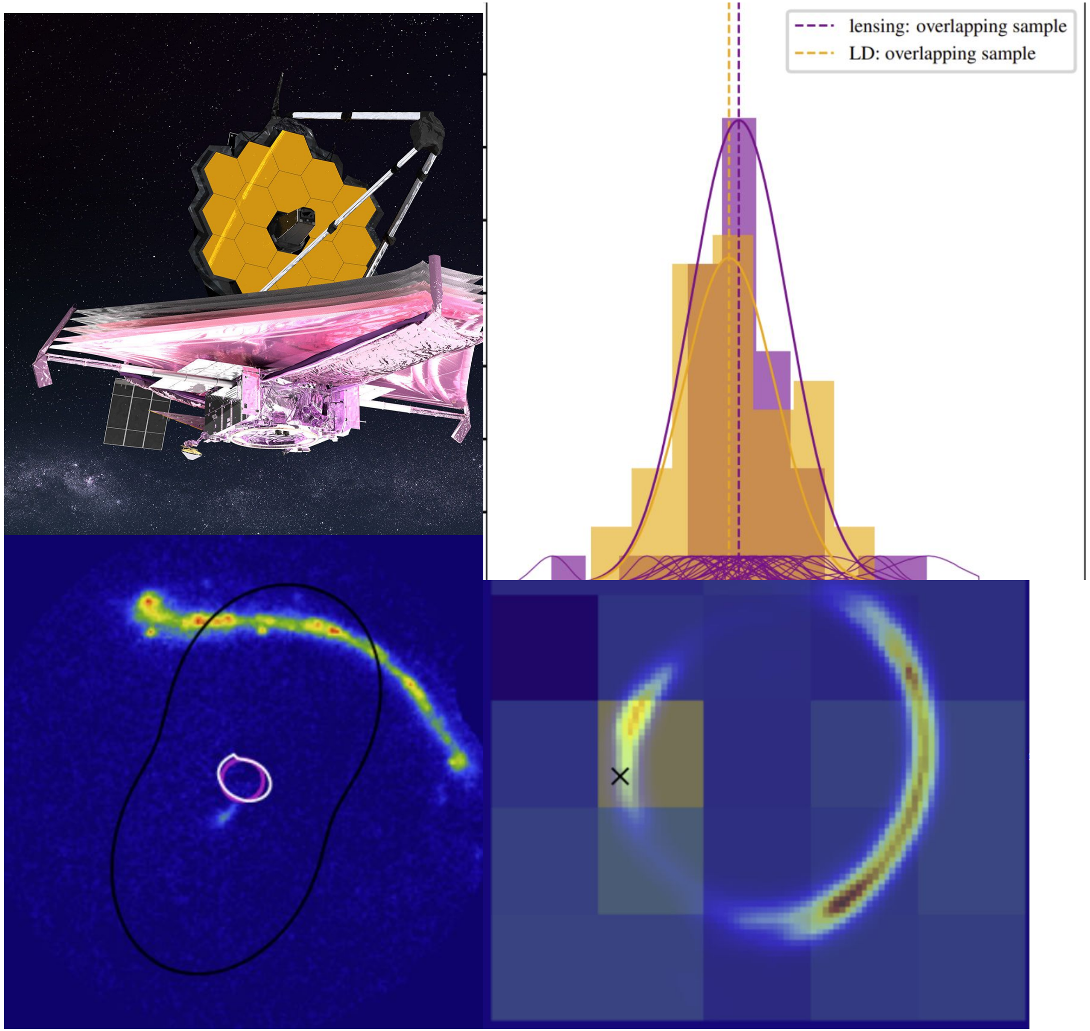


Summary

Galaxies: New insights on high redshift galaxy structure and formation.

Dark Matter: A compelling tool to verify / rule out warm dark matter.

Supermassive Black Holes: A new window on high redshift SMBHs.



Future

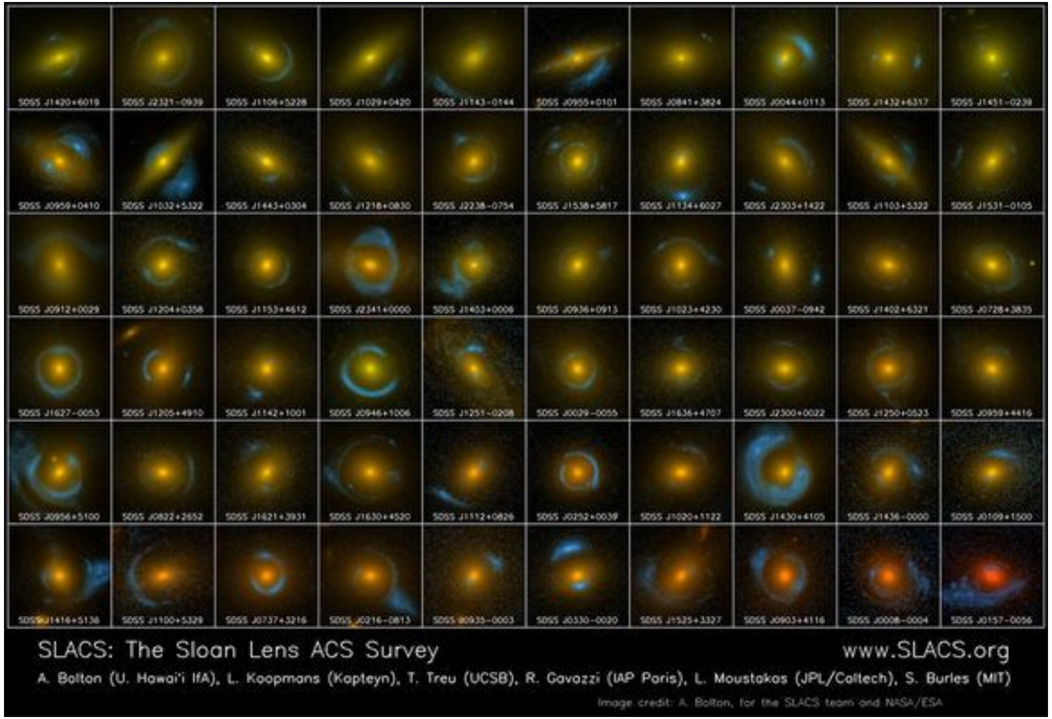
Galaxies: Large Samples Are Coming

Euclid will find 100000+ strong lenses.

Vera Rubin 10000+

SKA 250000+

50 years of lens hunting ->



SLACS: The Sloan Lens ACS Survey

www.SLACS.org

A. Bolton (U. Hawai'i IfA), L. Koopmans (Kapteyn), T. Treu (UCSB), R. Gavazzi (IAP Paris), L. Moustakas (JPL/Caltech), S. Burles (MIT)

Image credit: A. Bolton, for the SLACS team and NASA/ESA

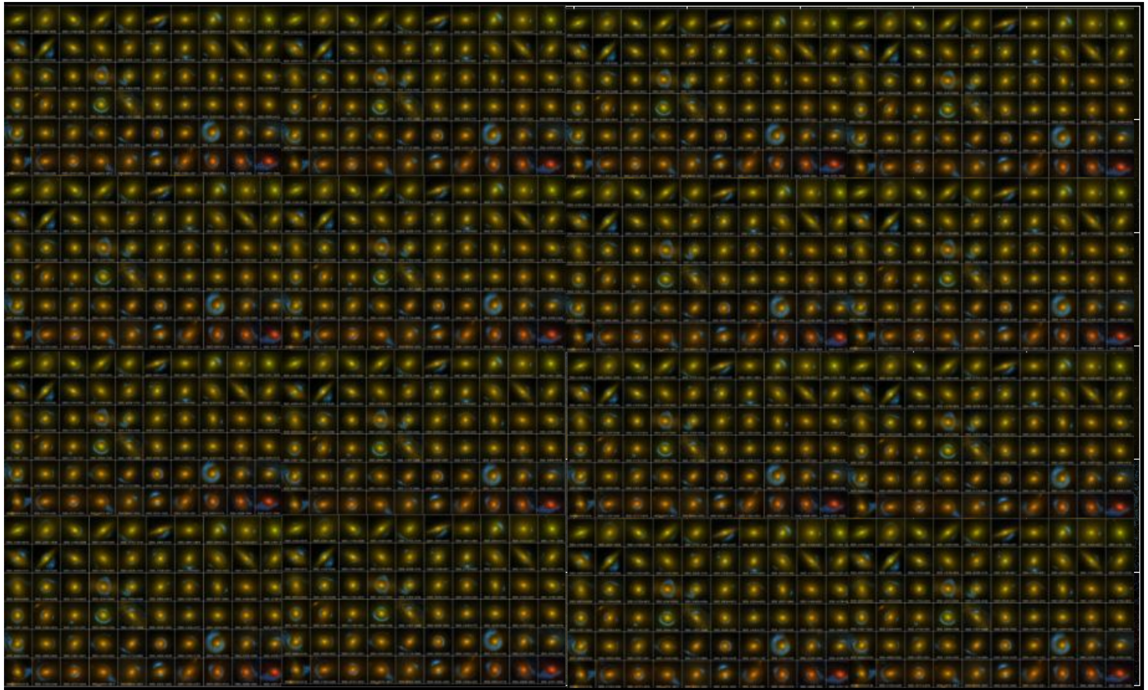
Galaxies: Large Samples Are Coming

Euclid will find 100000+ strong lenses.

Vera Rubin 10000+

SKA 250000+

1 week of Euclid ->



SLACS: The Sloan Lens ACS Survey www.SLACS.org

A. Bolton (U. Hawai'i IfA), L. Koopmans (Kapteyn), T. Treu (UCSB), R. Gavazzi (IAP Paris), L. Moustakas (JPL/Caltech), S. Burles (MIT)

Image credit: A. Bolton, for the SLACS team and NASA/ESA

Summary

Galaxies: Strong lensing can offer new information on high redshift galaxy structure, **but we need to rethink our lens mass models.**

Dark Matter: Strong lensing is a compelling tool to verify / rule out warm dark matter, **but we need to rethink out lens mass models (again!).**

Supermassive Black Holes: A new window on high redshift SMBH masses, **but we don’t yet know how much insight this technique can ultimately offer.**

Boxiness / Diskiness

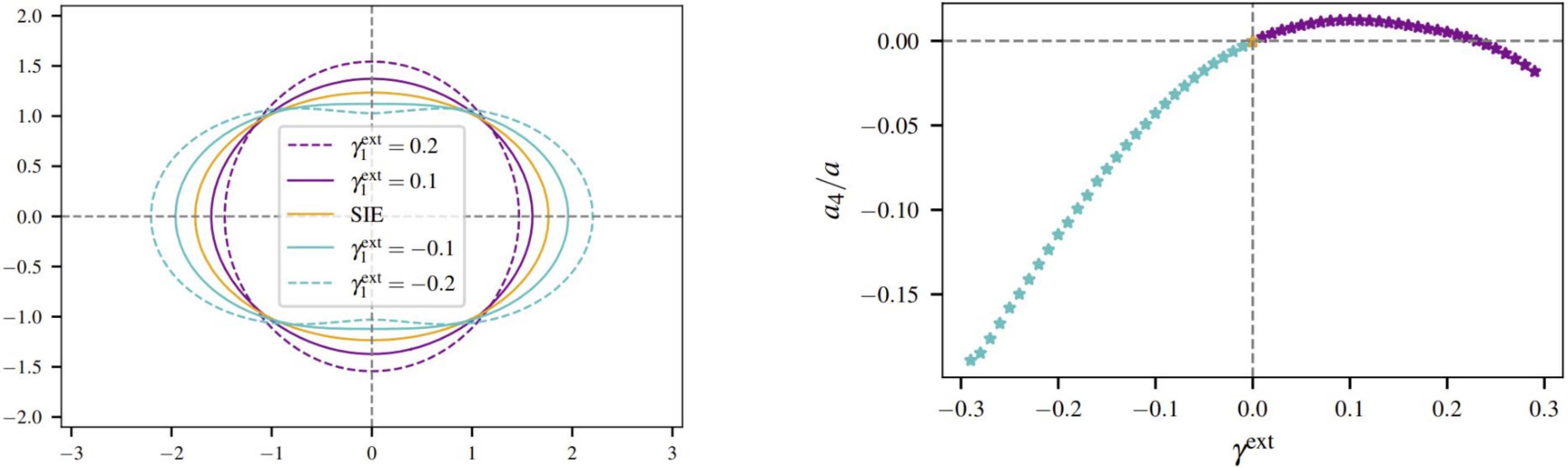


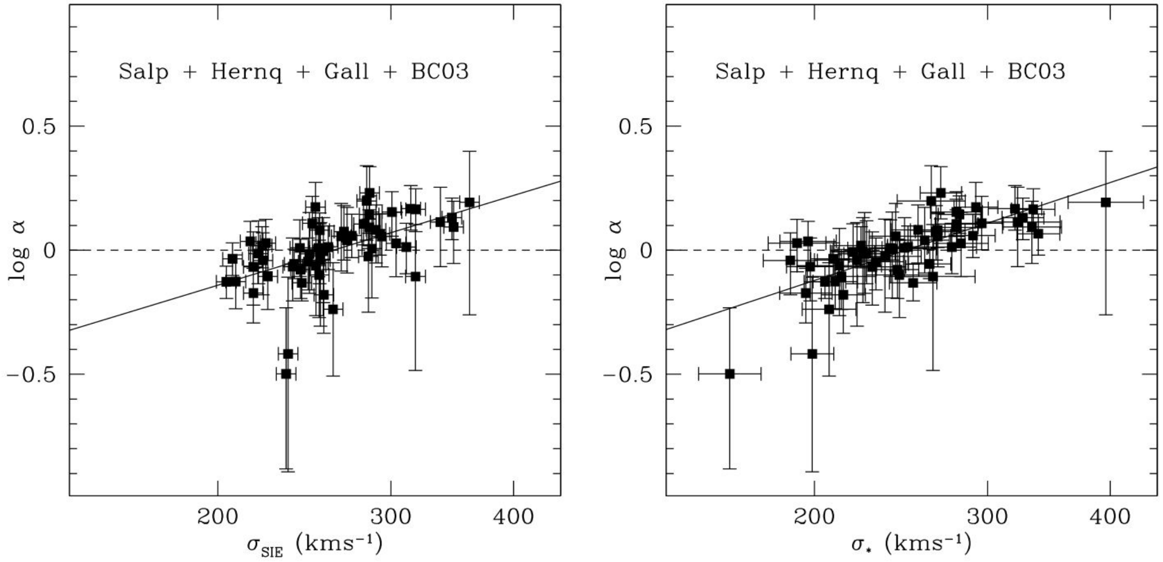
Figure 4. What causes boxiness or diskiness? A Singular Isothermal Elliptical (SIE) mass distribution with a horizontal major axis has critical curves that are also elliptical with a horizontal major axis (orange). The critical curves are perturbed if the slope of the density profile $\gamma \neq 2$ (top left panel) or the external shear $\gamma^{\rm ext} \neq 0$ (bottom left panel). In particular, an aligned shear ($\gamma_1^{\rm ext} > 0$) stretches the critical curves vertically (and the image horizontally); an anti-aligned shear ($\gamma_1^{\rm ext} < 0$) does the opposite. Multipole measurements a_4/a of the critical curve are shown as a function of slope (top right panel) and external shear (bottom right panel), where $a_4/a > 0$ is "disky" and $a_4/a < 0$ is "boxy".

Initial Mass Function – Universality?

Measure mass at Einstein radius via lensing.

Measure mass at another radius via stellar dynamics.

Estimate stellar mass via synthesis models – compare.


Treu et al. 2009

Lensing Measurements

Strong len measurements do not degrade with redshift.

Extremely powerful way to study high redshift galaxy evolution!

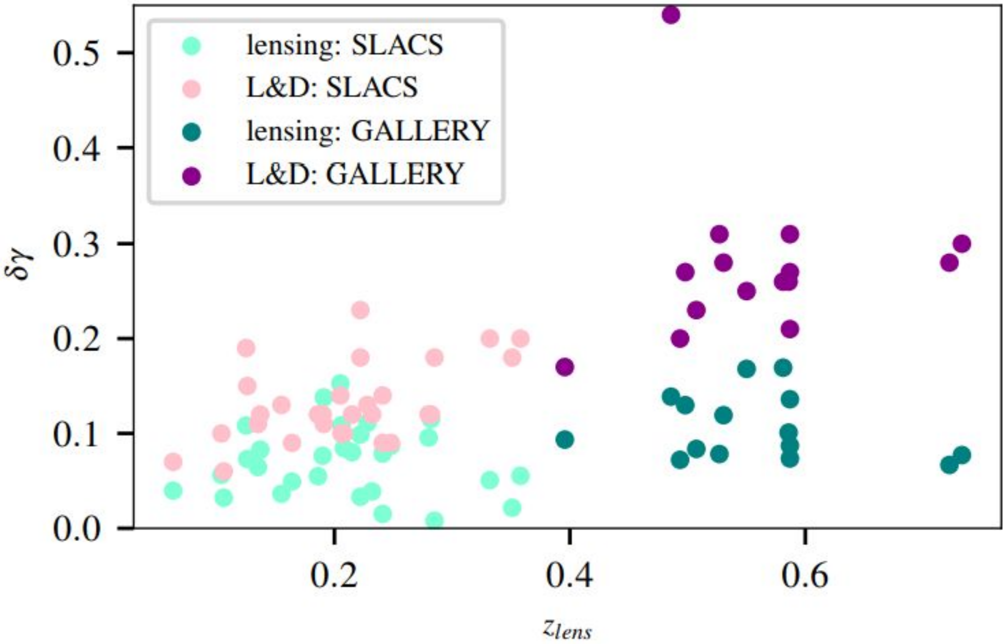


Figure 2. Measurement uncertainties on the slopes from lensing only and lensing & dynamics as a function of redshift of the lens galaxy.

Shear in Strong Lens Models (ManGa Simulations)

Simulate 50 strong lenses using mass distributions from ManGa dynamical models:

- **Mass Model:** Stars (many Gaussians) plus dark matter (spherical gNFW).
- **Does not contain external shear!**

Fit all 50 lenses with power-law model.

[Cao, Li, Nightingale et al 21].

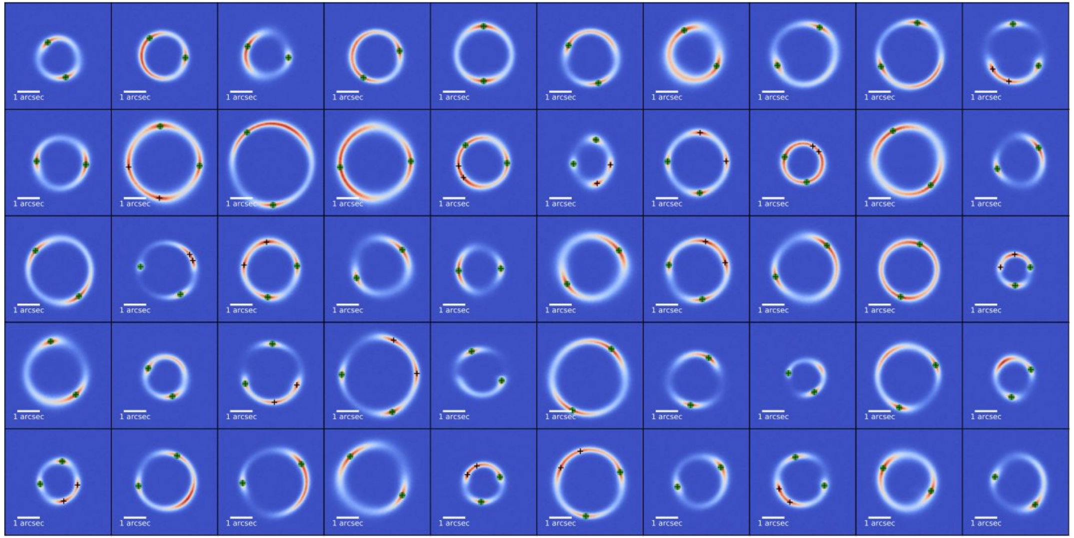


Fig. 1: Images of 50 “MaNGA lenses”. For each lens, locations marked by the black crosses represent the lensed positions of the source center; the points marked by the green circle are used to calculate the excess time-delay between different images as shown in Figure 16. The scale-bars mark the angular scale of 1 arcsecond.

Shear / Mass Position Angle (PA) Alignment (Mocks).

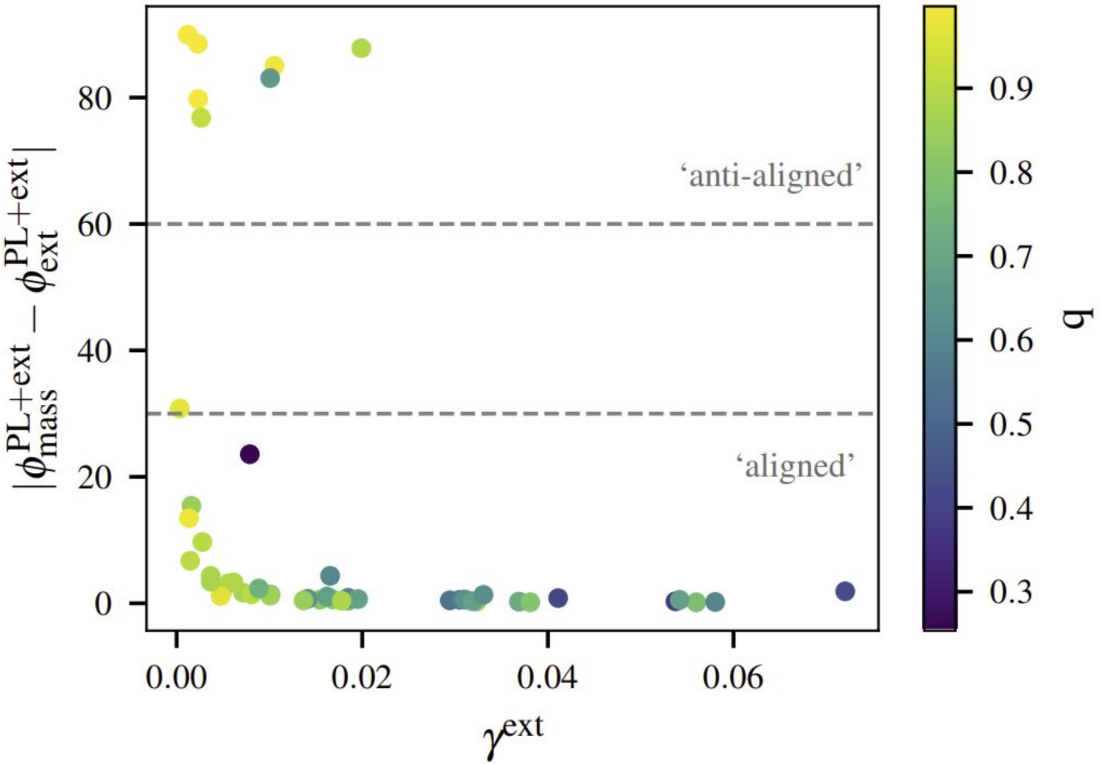
ϕ^{mass}: Inferred PA of power-law mass model.

ϕ^{ext}: Inferred PA of external shear.

Simulated lenses have no input external shear, however:

Magnitudes: values of γ = 0.01 - 0.08 are inferred.

Alignments: Preferentially align (**$|\phi^{mass} - \phi^{ext}| = 0$**) or anti-align (**$|\phi^{mass} - \phi^{ext}| = 90$**) with mass distribution.

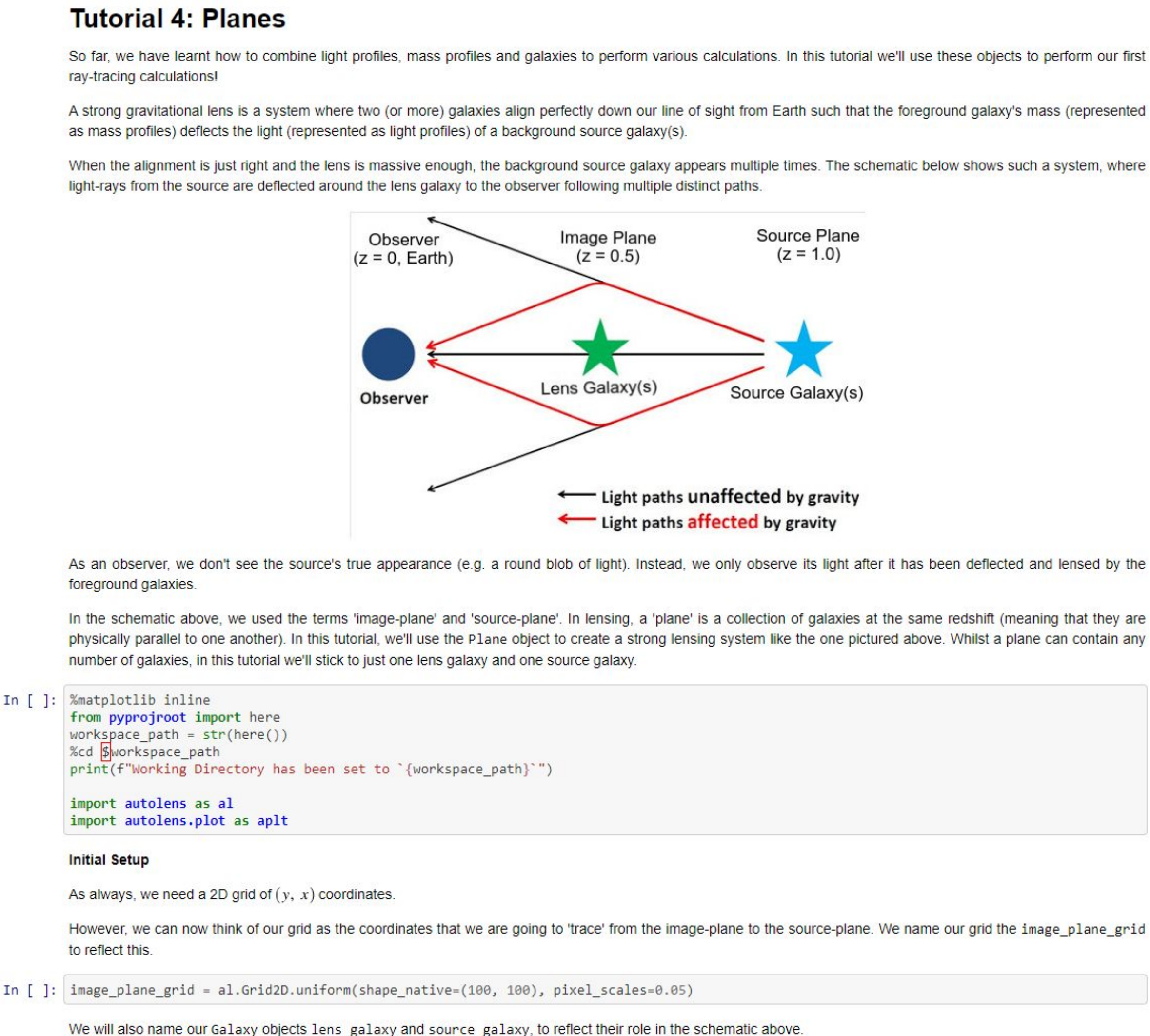


HowToLens

Jupyter Notebook lecture course aimed at undergrads and above.

Teaches:

- What strong lensing is.
- Bayesian statistics required to model strong lenses.
- How to use PyAutoLens.



Tutorial 4: Planes

So far, we have learnt how to combine light profiles, mass profiles and galaxies to perform various calculations. In this tutorial we'll use these objects to perform our first ray-tracing calculations!

A strong gravitational lens is a system where two (or more) galaxies align perfectly down our line of sight from Earth such that the foreground galaxy's mass (represented as mass profiles) deflects the light (represented as light profiles) of a background source galaxy(s).

When the alignment is just right and the lens is massive enough, the background source galaxy appears multiple times. The schematic below shows such a system, where light-rays from the source are deflected around the lens galaxy to the observer following multiple distinct paths.

As an observer, we don't see the source's true appearance (e.g. a round blob of light). Instead, we only observe its light after it has been deflected and lensed by the foreground galaxies.

In the schematic above, we used the terms 'image-plane' and 'source-plane'. In lensing, a 'plane' is a collection of galaxies at the same redshift (meaning that they are physically parallel to one another). In this tutorial, we'll use the `Plane` object to create a strong lensing system like the one pictured above. Whilst a plane can contain any number of galaxies, in this tutorial we'll stick to just one lens galaxy and one source galaxy.

```
In [ ]: %matplotlib inline
        from pyprojroot import here
        workspace_path = str(here())
        %cd $workspace_path
        print(f"Working Directory has been set to `{workspace_path}`")

        import autolens as al
        import autolens.plot as aplt
```

Initial Setup

As always, we need a 2D grid of (y, x) coordinates.

However, we can now think of our grid as the coordinates that we are going to 'trace' from the image-plane to the source-plane. We name our grid the `image_plane_grid` to reflect this.

```
In [ ]: image_plane_grid = al.Grid2D.uniform(shape_native=(100, 100), pixel_scales=0.05)
```

We will also name our `Galaxy` objects `lens_galaxy` and `source_galaxy`, to reflect their role in the schematic above.

Faux External Shear

Simulate: Lens via more complex stars + dark matter model **[no external shear].**

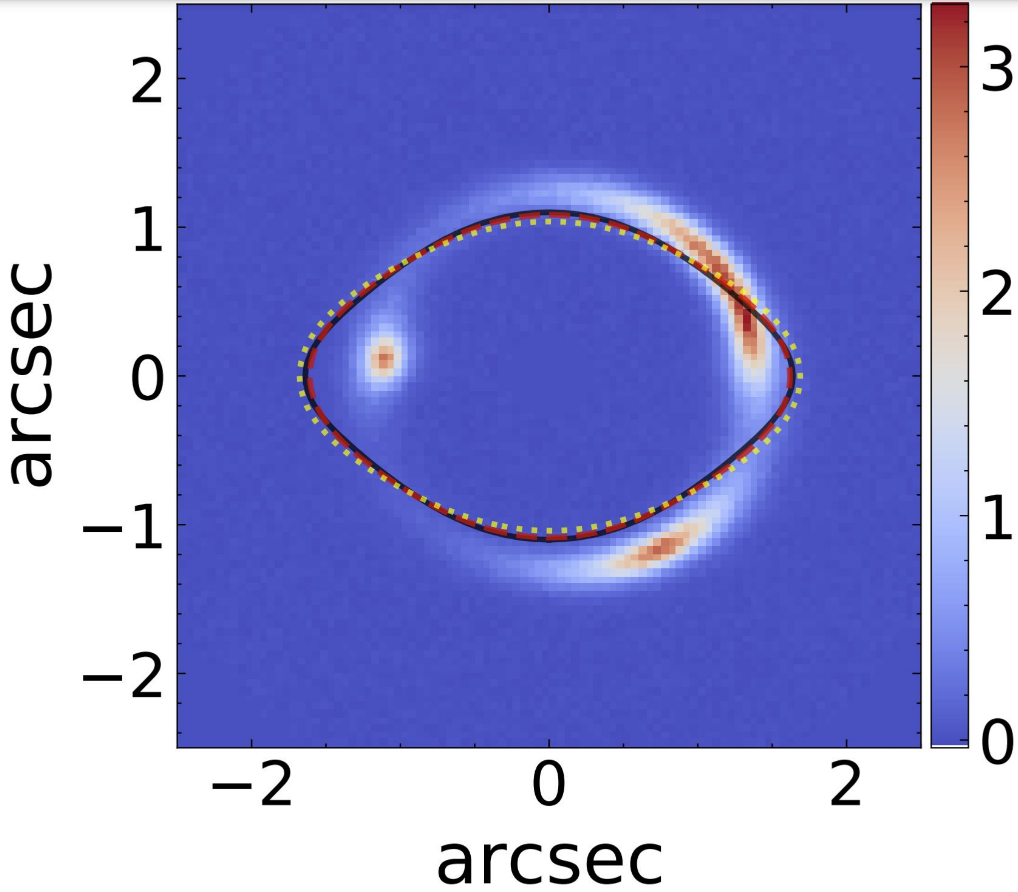
Fit: Power-Law + External Shear.

Fit infers a shear of magnitude γ = 0.08

Black Line: True critical curve (stars + dark matter mass model).

Yellow line: Inferred model critical curve power-law alone.

Red line: Inferred model critical curve (power-law + shear).



Slope Correlations (redshift, stellar surface mass density)

Correlation between density slope and (stellar) surface mass density.

We probably expect that more dense galaxies have a higher surface mass density!

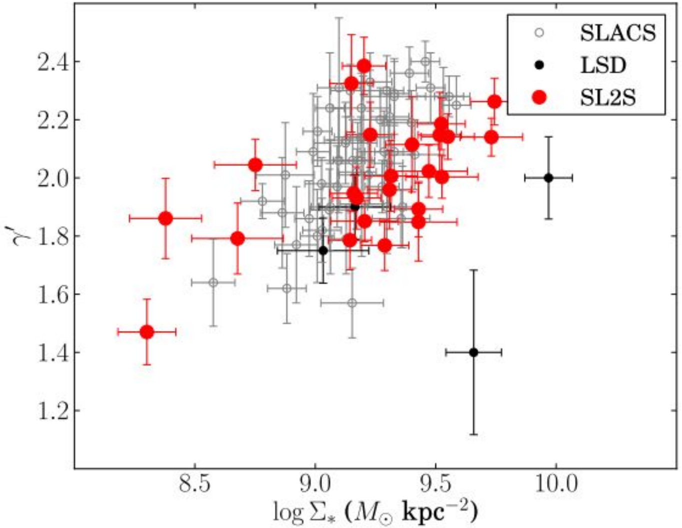


FIG. 9.— Density slope as a function of stellar mass density.

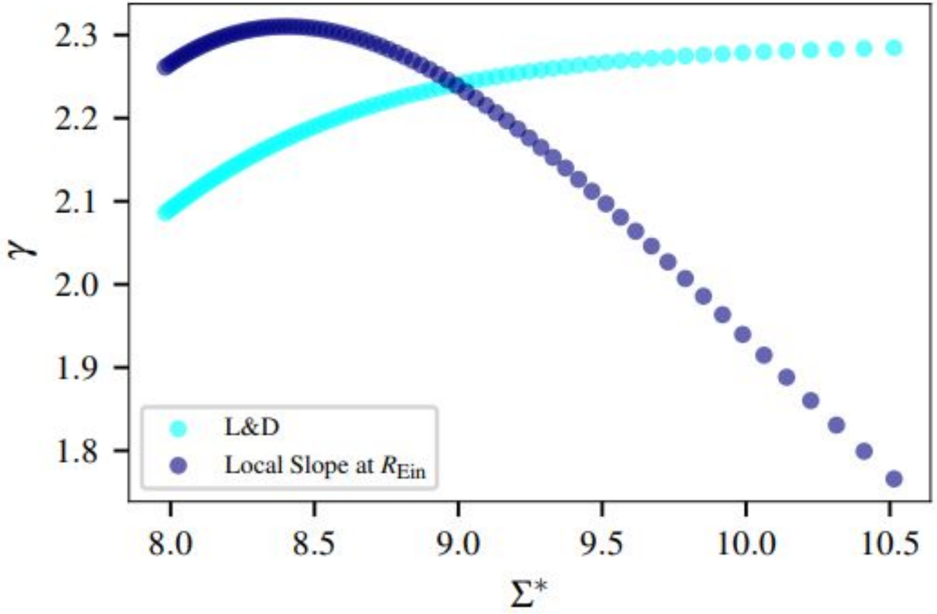
Sonnenfeld et al 2013

Measuring Density Slopes (Extended Source Lensing)

Slope Measurement

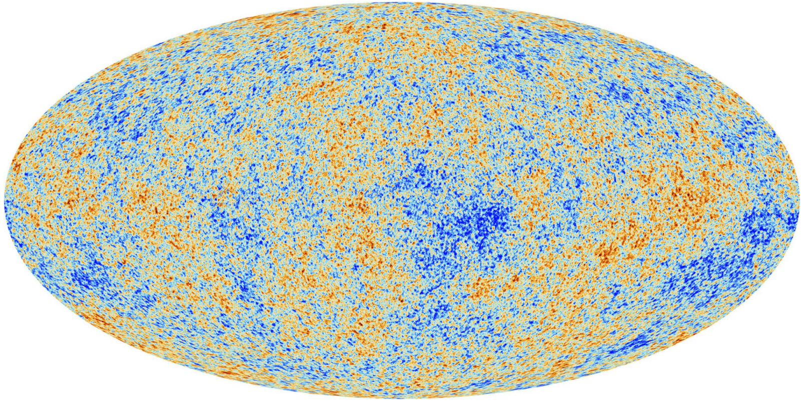
Varying measurements of slope across a galaxy can inform us of their stellar / dark matter distributions.

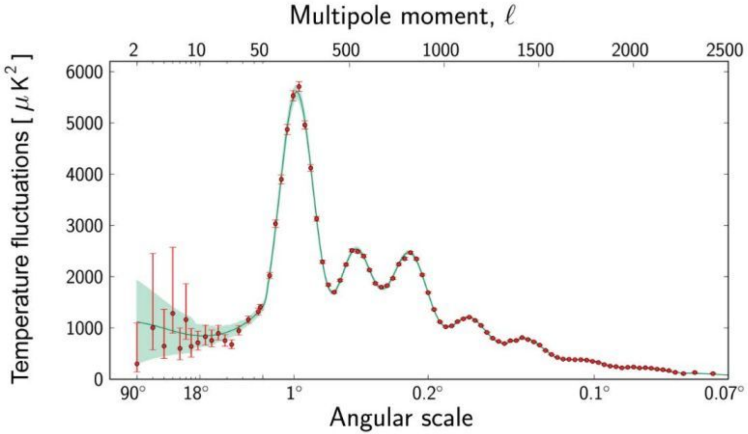
Undoubtedly an over simplification!



Cold Dark Matter / ƛCDM

Cosmological model which has satisfied all **large-scale** Universe observations (e.g. Cosmic Microwave Background, Baryonic Acoustic Oscillations) for 20+ years.



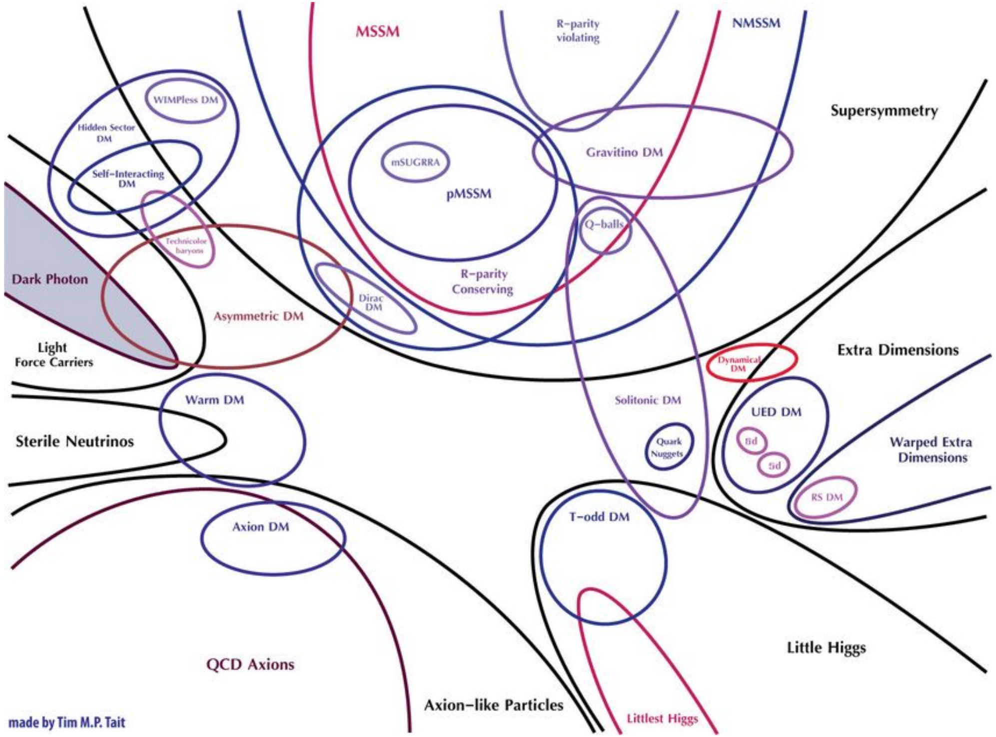


Cold Dark Matter / ƛCDM

Cosmological model which has satisfied all **large-scale** Universe observations (e.g. Cosmic Microwave Background, Baryonic Acoustic Oscillations) for 20+ years.

Particle Physics:

Cold dark matter has many particle candidates, and many different particle models fit CMB + other data equally well!



made by Tim M.P. Tait

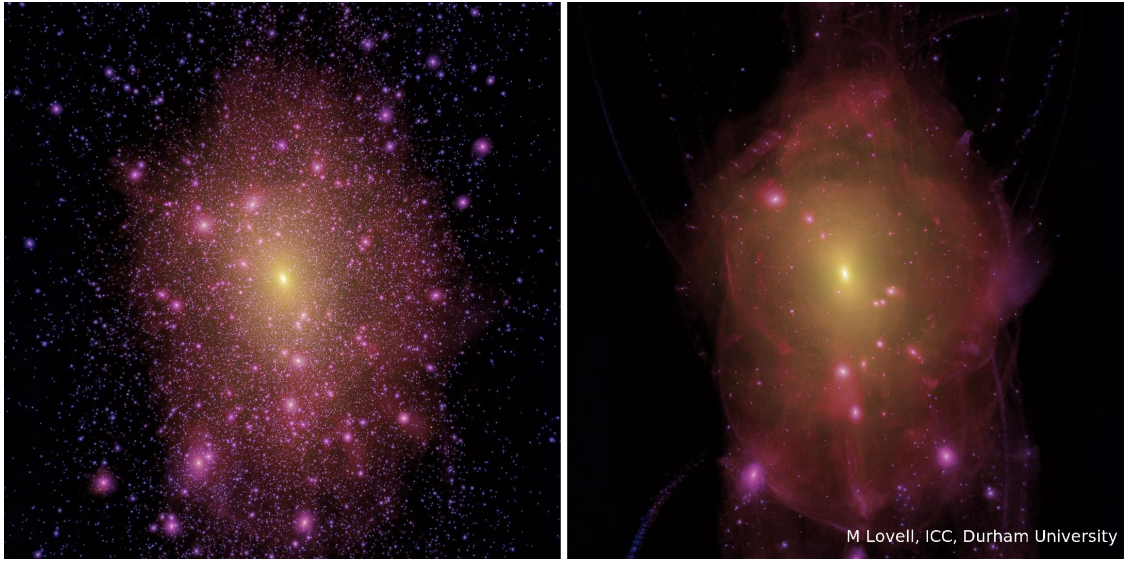
ƛCDM on smaller scales

Galaxy Clusters: ~ 10^{14-15} MSun
Milky Way: ~ 10^{12}MSun
Milky Way Dwarfs: ~ 10^{9}MSun

Key untested predictions of DM models on smaller scales:

CDM predicts many low mass dark matter halos with masses below 10^{8}MSun, which are absent in \`warmer\` DM models (e.g. sterile neutrino).

See also, core/cusp discrepancy, too big to fail + others


M Lovell, ICC, Durham University

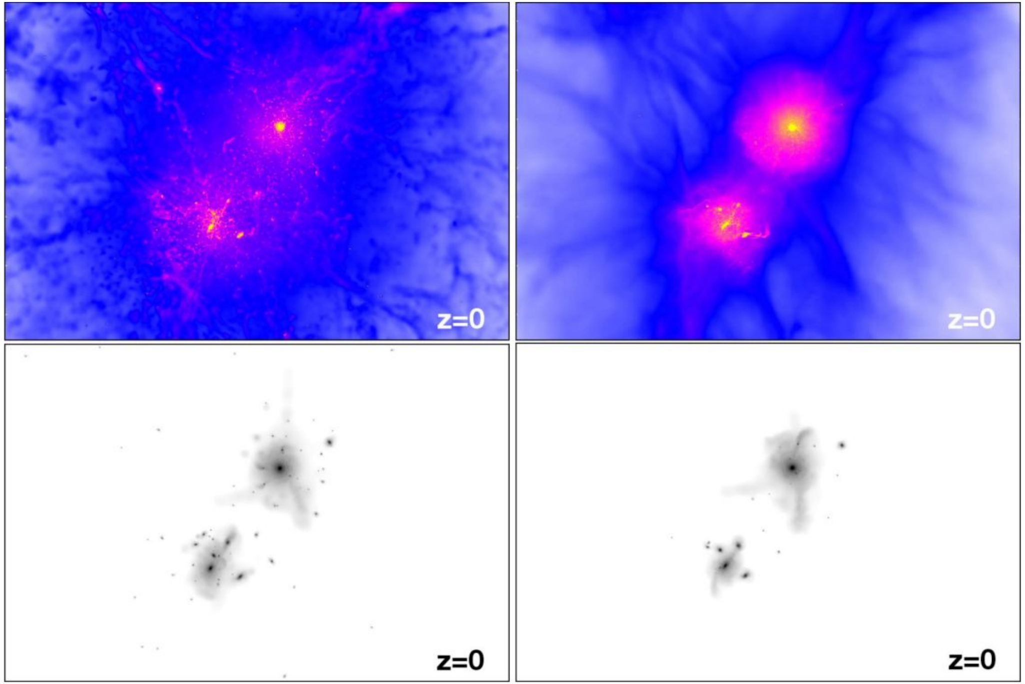
Observing low mass dark matter halos

In CDM, many dark matter halos below masses of 10^8 MSun are *completely dark*.

- Star formation ceased in early Universe by ultraviolet radiation background / supernova feedback.
- Makes observing these objects and testing CDM on small scales **challenging.**

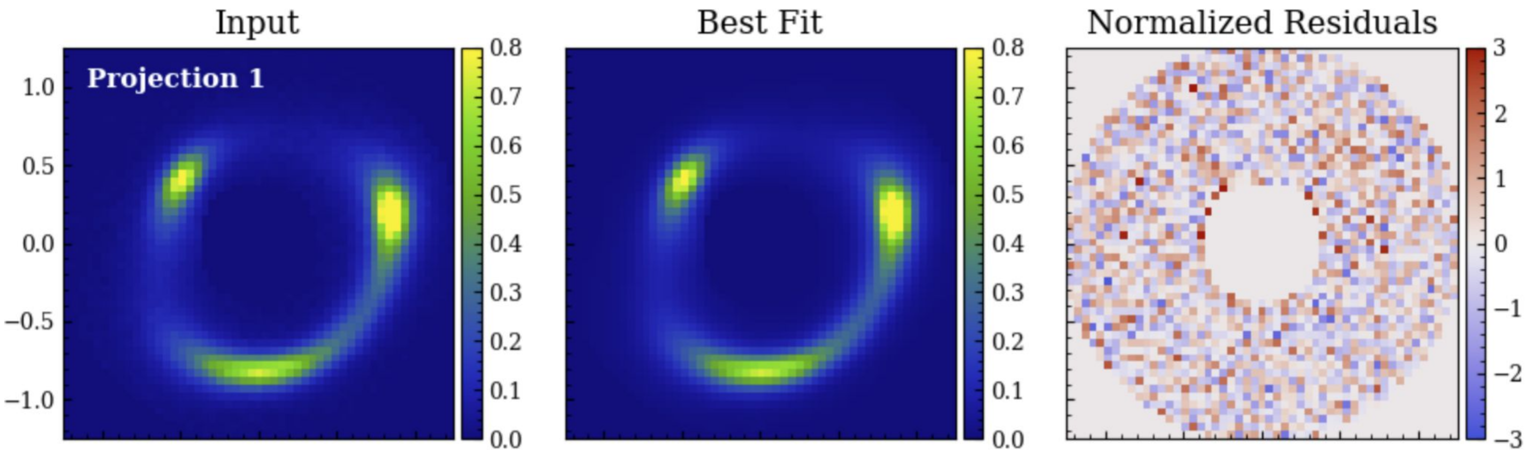
Want a method which despite their lack of emission can quantify the number counts of dark matter halos between 10^{6-10}MSun.

See also: Number counts of Milky Way Satellites (the `Missing satellite problem`), stellar streams.

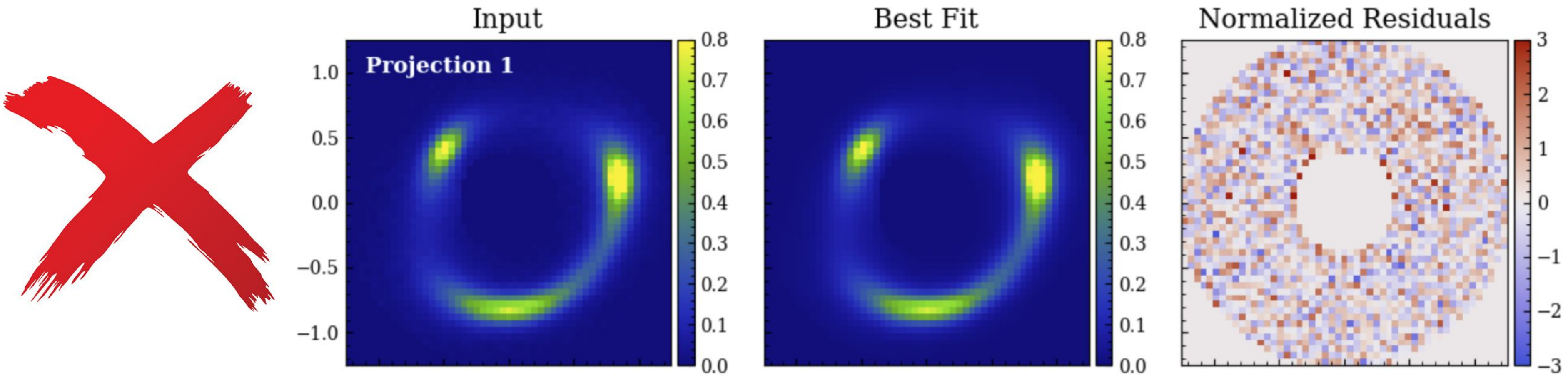


Sawala et al 2016: 10.1093/mnras/stv2597

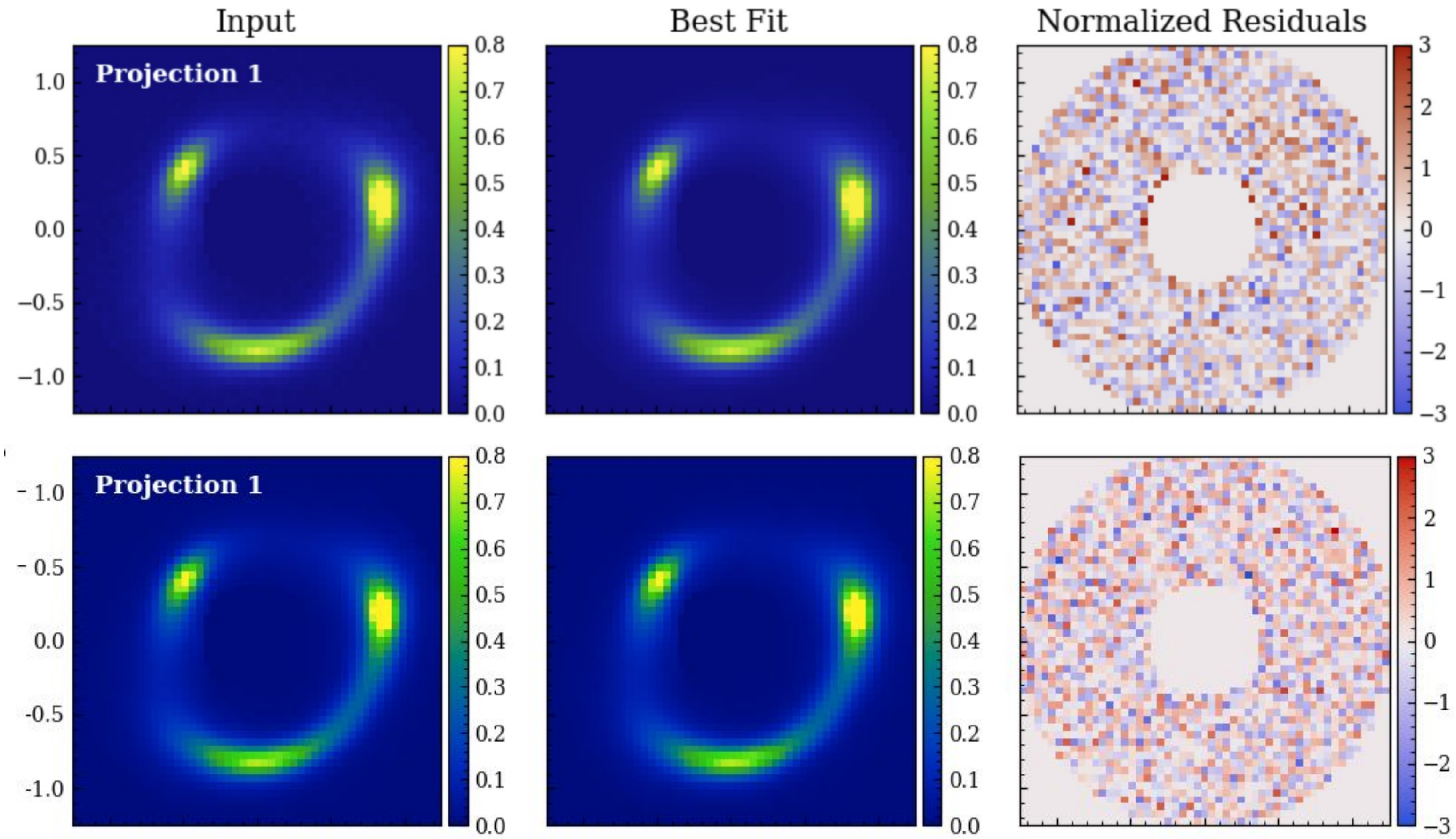
Why this is so hard…



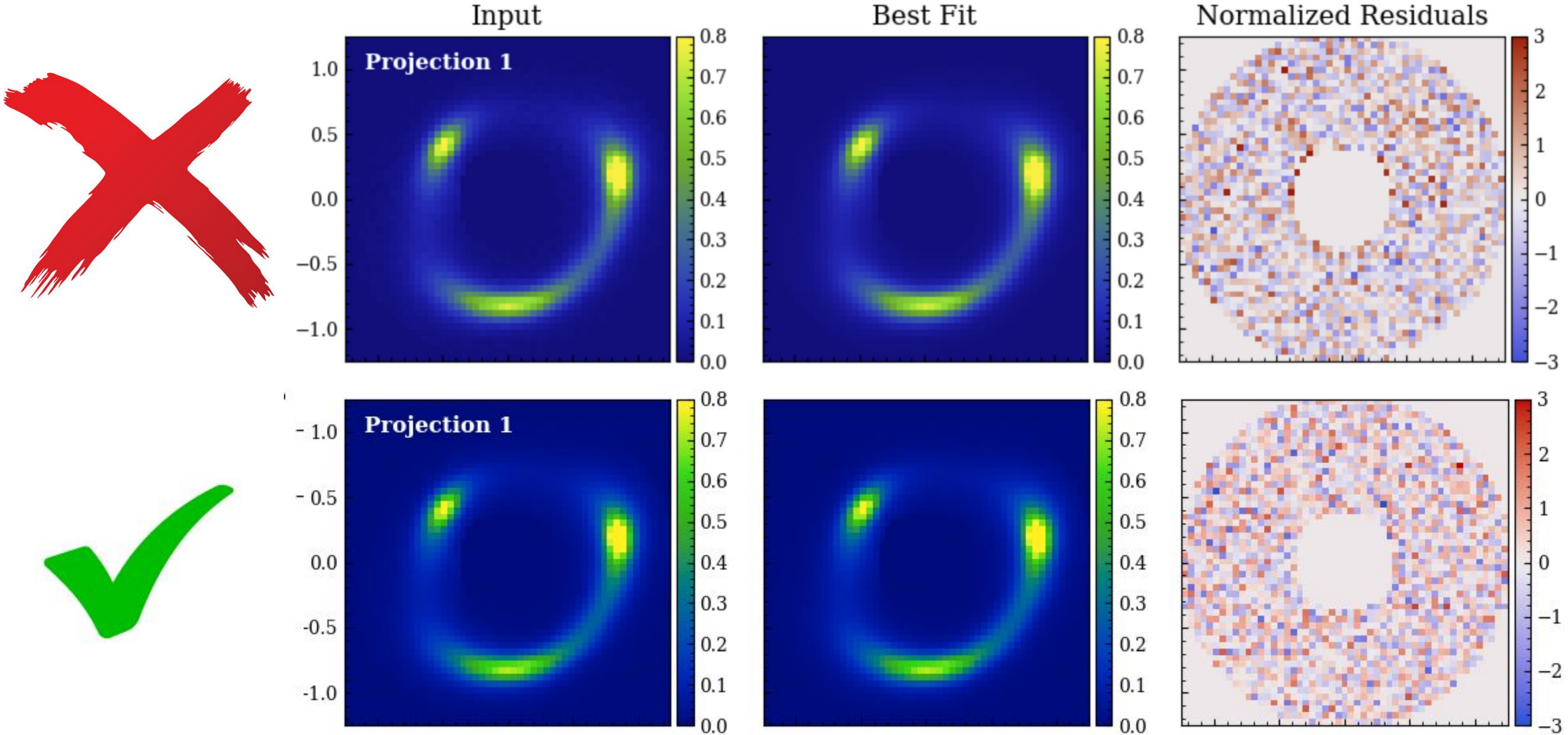
Why this is so hard…



Why this is so hard…



Why this is so hard…



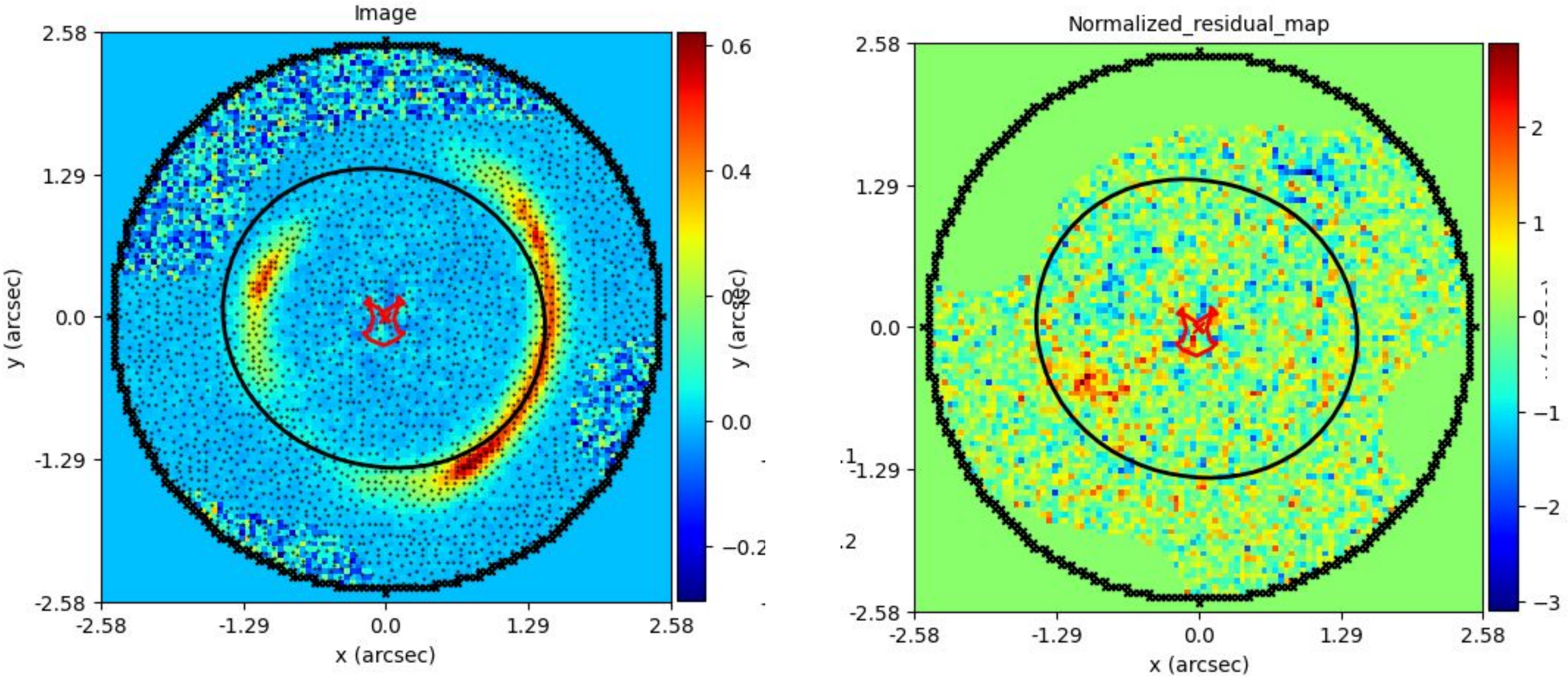
Previous Studies (e.g. Vegetti et al 2014)

Previous studies: To consider a DM subhalo detection a candidate previous studies require a Bayesian evidence increase > 50 or 100 – a >5σ detection (plus other criteria).

Increases in log evidence / likelihood of 10 - 50 are common, but considered false positives due to systematics.

This Study: Categorize false positives in this regime to determine how to improve future analyses.

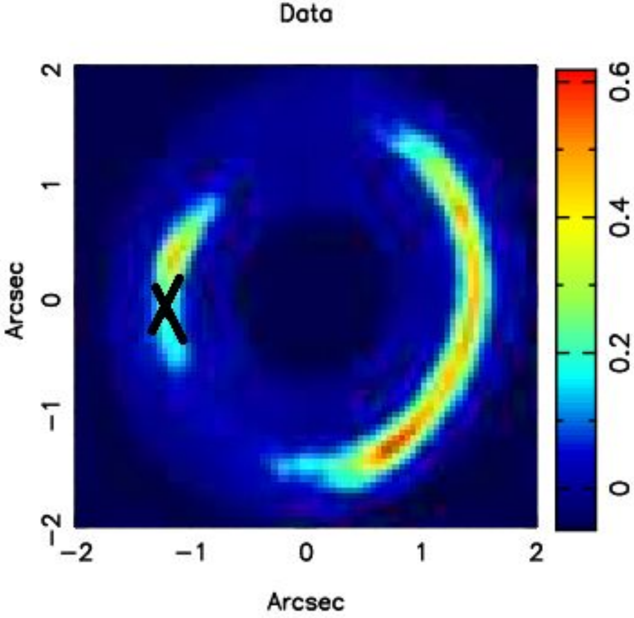
Detections (2/54): SLACS0946+1006

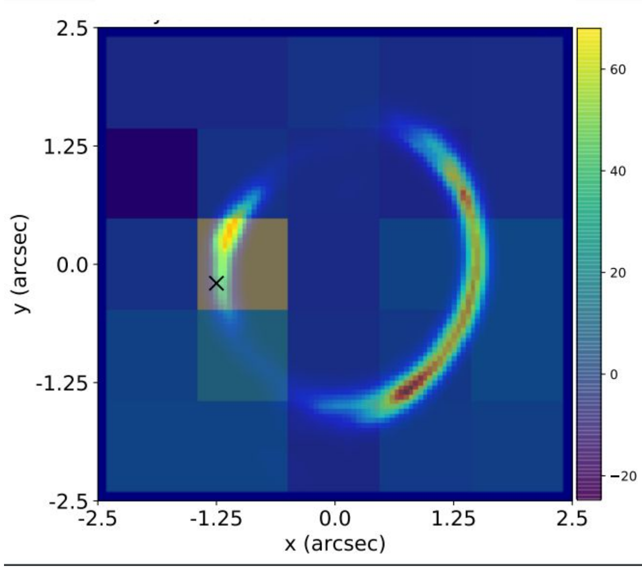


Candidate detections (2/54): SLACS0946+1006

Bayesian evidence increase at the same location as Vegetti et al 2009.

- Bayesian Evidence increase ~ 50 (> 10sigma).
- (y,x) position and mass consistent within 3 sigma.
- Our inferred mass is **7.8 +- 2.0 x 10^{10} solMass** for a spherical NFW mass profile.

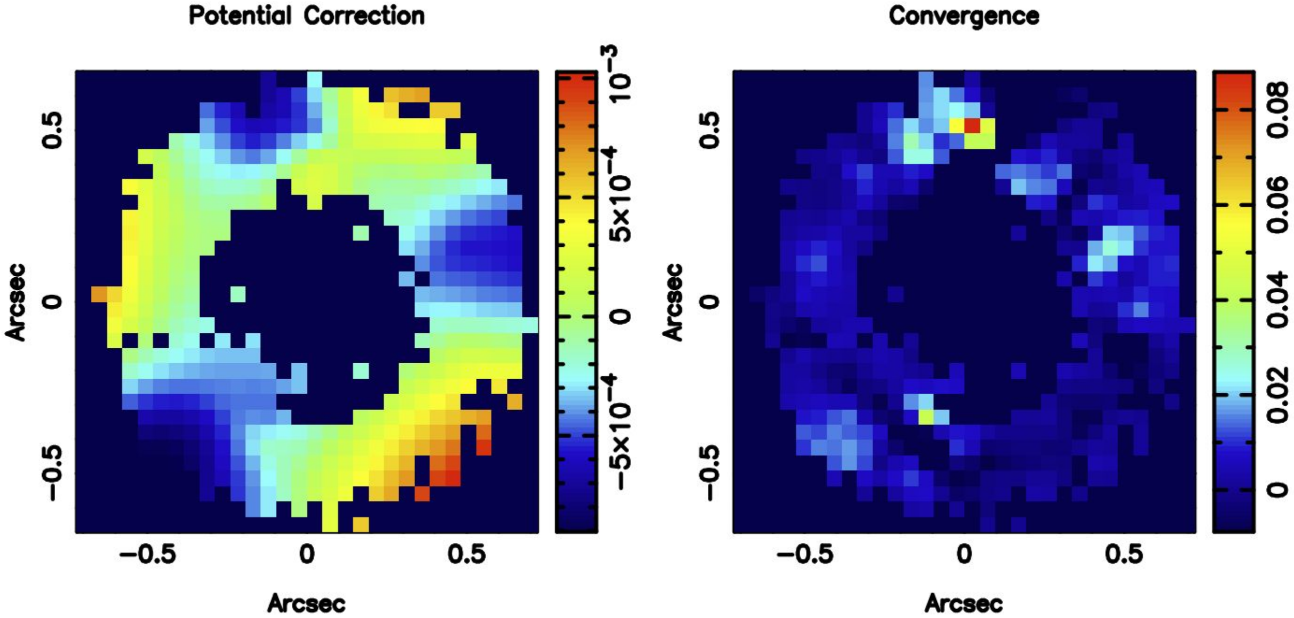




Candidate detections (2/54): SLACS0946+1006

To consider a DM subhalo detection genuine, require:

- Potential corrections to produce a consistent signal.



Different Cosmology Predictions

Different dark matter models:

- Make different predictions for the mass-concentration relations.
- Don’t have dark matter subhalos below a cut off mass to scatter “up”.

Strong lensing is sensitive to more than just dark matter number counts.

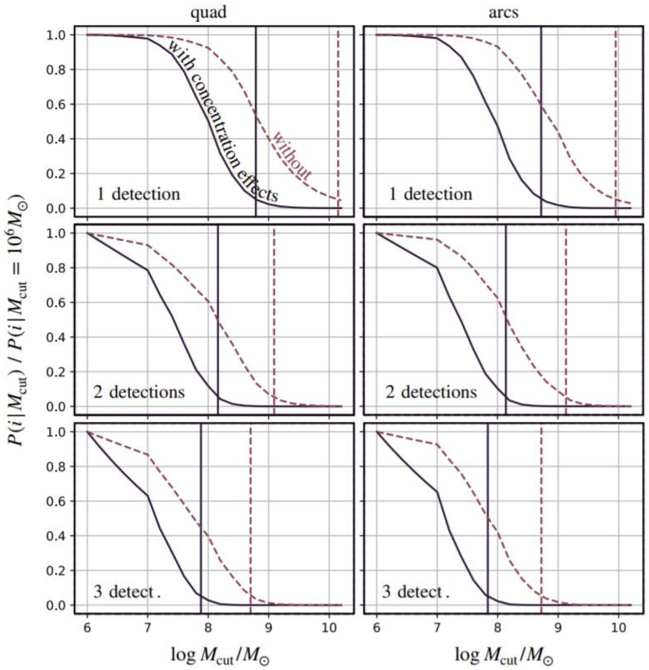
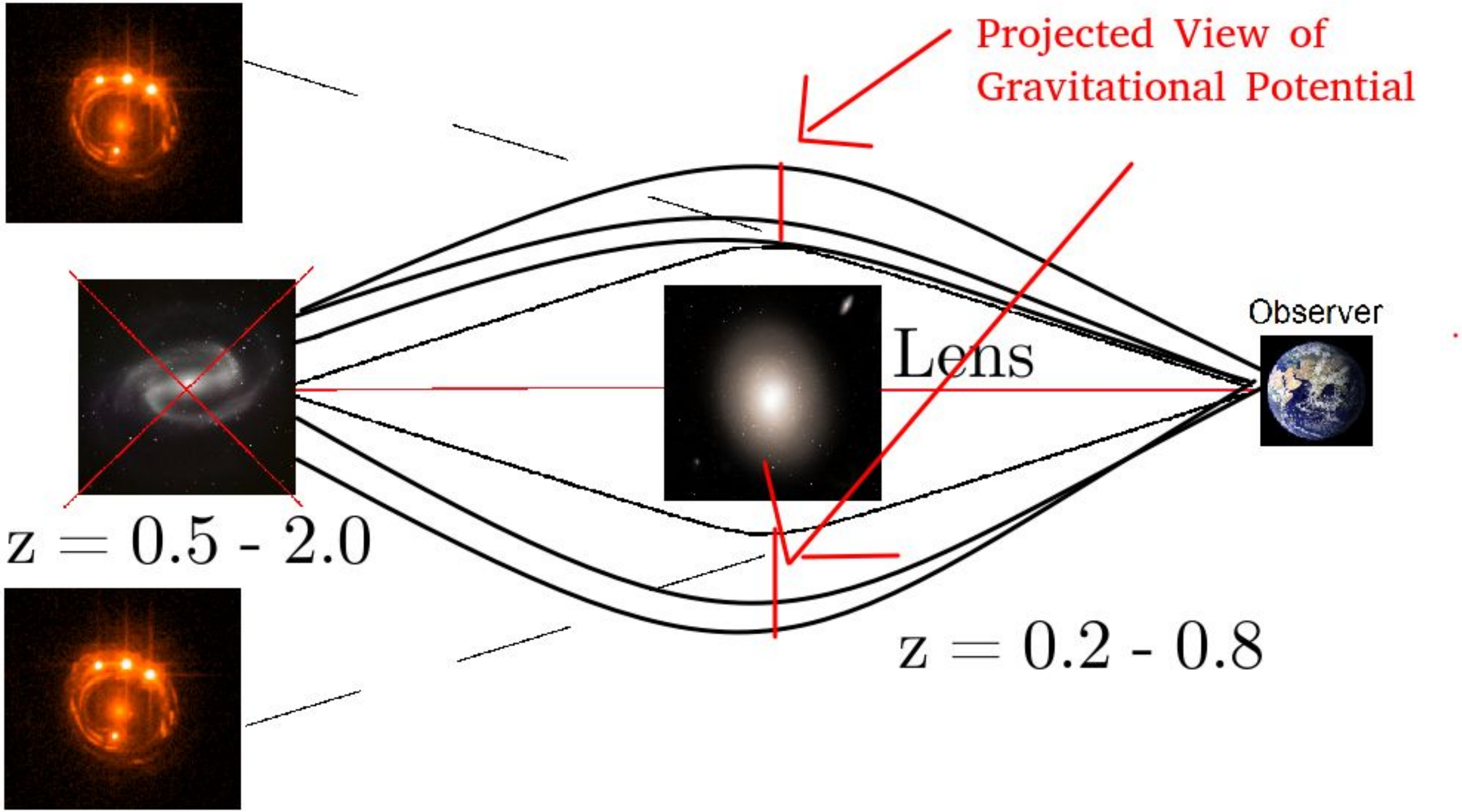


Figure 13. The change on limits to the WDM cutoff mass, M_{cut}, from including concentration effects, at a fixed number of expected detections for a CDM universe: $N_{\mathrm{d,CDM}} = 1$. Lines show likelihood ratios (see text) resulting from the detection of (1, 2, 3) perturbers, respectively, from the top to the bottom row. Dashed lines display the inference based on predictions that ignore concentration effects. These are included in the solid lines.

Strong Lensing (Extended Source)



Projected View of Gravitational Potential

Lens

Observer

$z = 0.5 - 2.0$

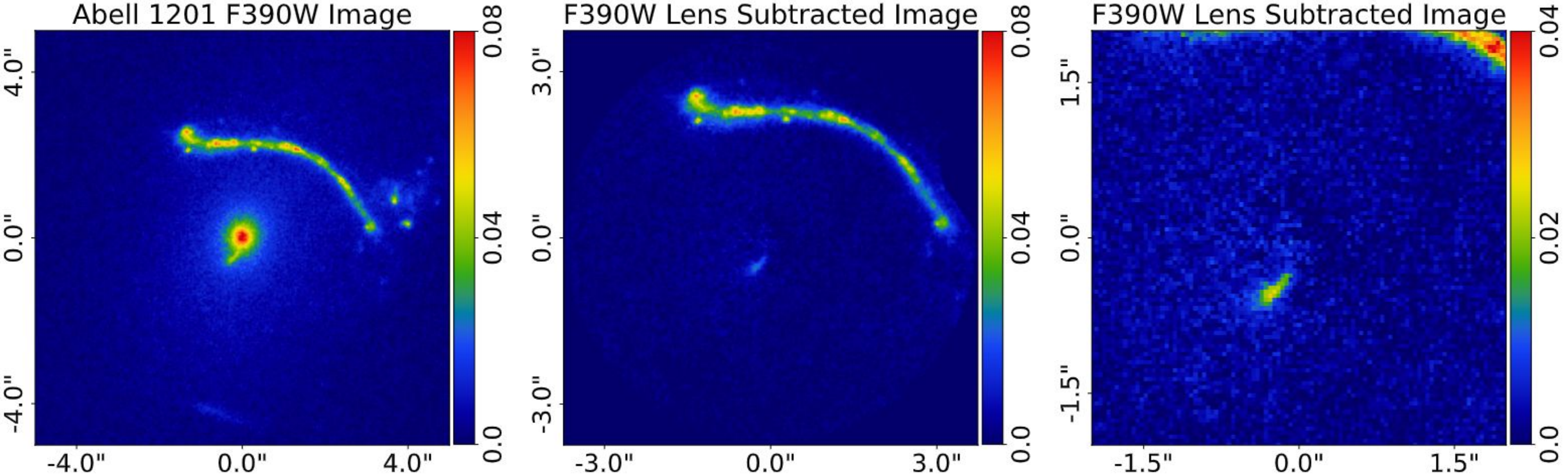
$z = 0.2 - 0.8$

SMBH Masses

The lensed source light is too far from the lens galaxy centre for its SMBH to impact the ray tracing in a resolved manner.

[Note 1 exception, central image Winn 2003 which placed upper limit of < 2 x 10^8 MSun]

Abell 1201: Observations (F390W)



Abell 1201 F390W Image

F390W Lens Subtracted Image

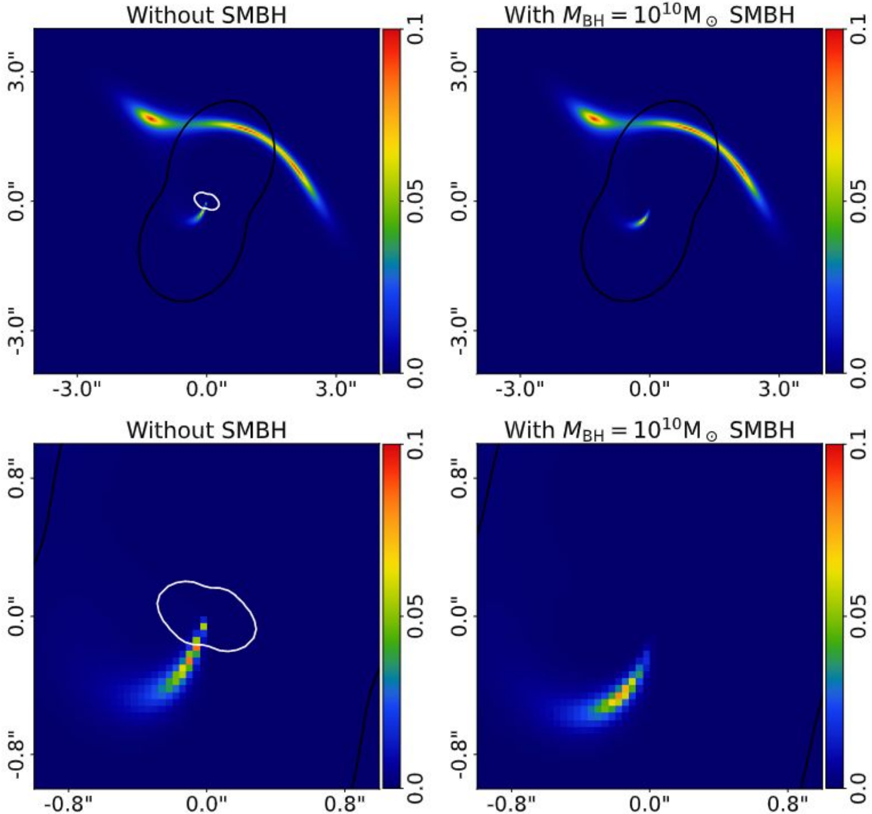
F390W Lens Subtracted Image

Abell 1201: SMBH Sensitivity

Simulations of Abell 1201 with and without a 10^{10}MSun SMBH:

- **Top row:** The giant arc does not change its appearance when the SMBH is included.

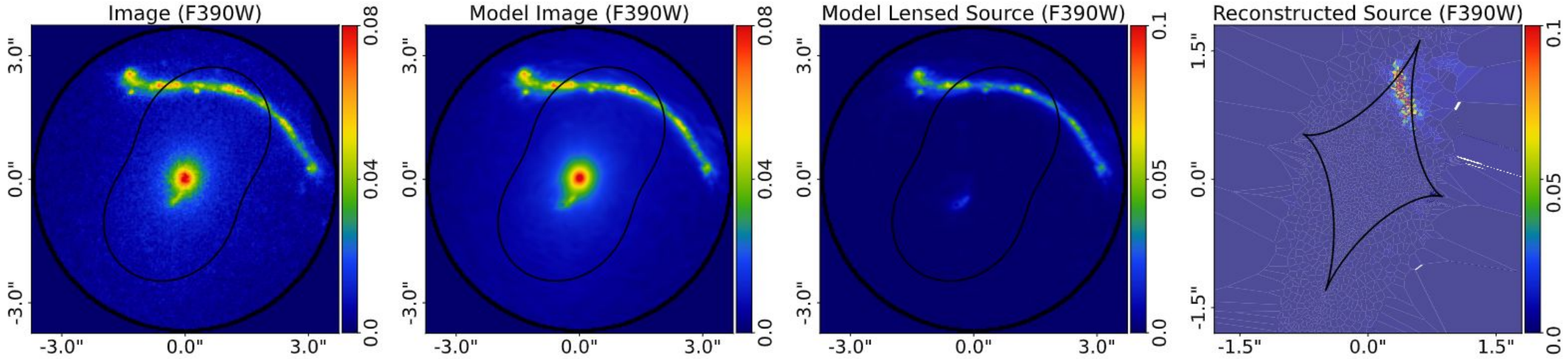
- **Bottom row:** The counter image changes is position, shape and surface brightness.



Abell 1201: Lens Models

Lens Light: x3 elliptical Sersic light profiles.

Source Reconstruction: Adaptive Voronoi Mesh

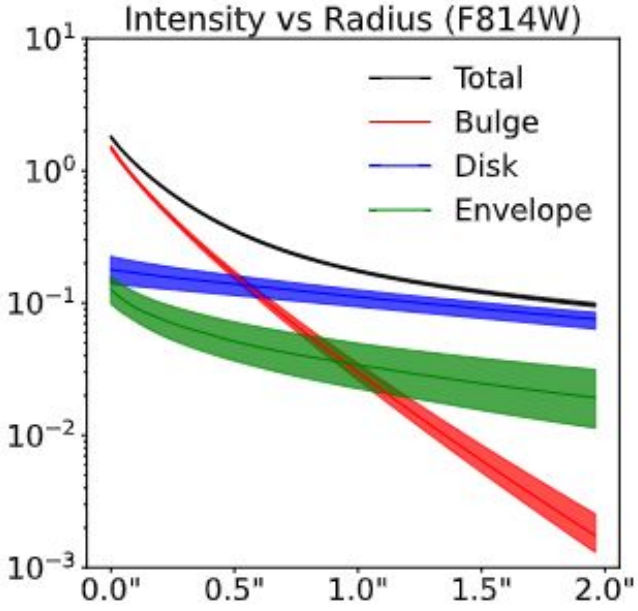


Abell 1201: Mass Models

Represent separately the lens galaxy's **stellar mass** and **dark matter**.

Stellar Mass: x3 Sersic profiles (bulge / disk / envelope) with **independent mass-to-light ratios** and **mass-to-light gradients.**

Dark Matter: Elliptical NFW profile (centre free from stellar light).



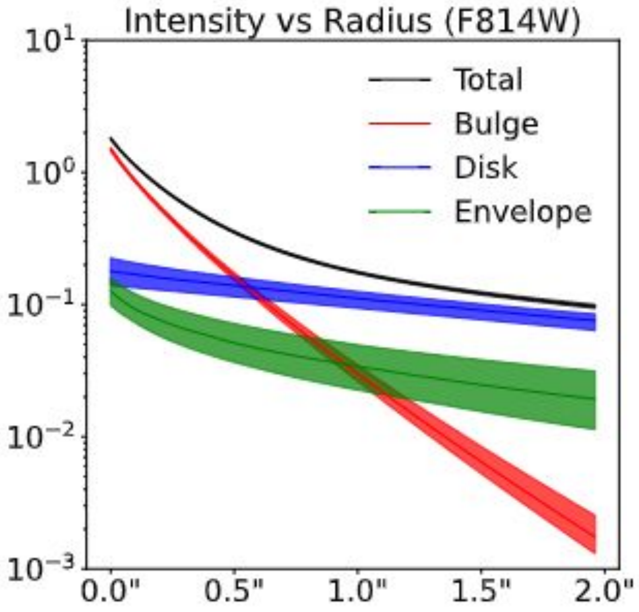
Abell 1201: Mass Models

Represent separately the lens galaxy’s **stellar mass** and **dark matter**.

Stellar Mass: x3 Sersic profiles (bulge / disk / envelope) with **independent mass-to-light ratios** and **mass-to-light gradients.**

Dark Matter: Elliptical NFW profile (centre free from stellar light).

Philosophy: Maximum flexibility in mass model to ensure we do not favour a SMBH due to overly simple model.



Sanity Checks

We have done many checks to ensure the result is robust:

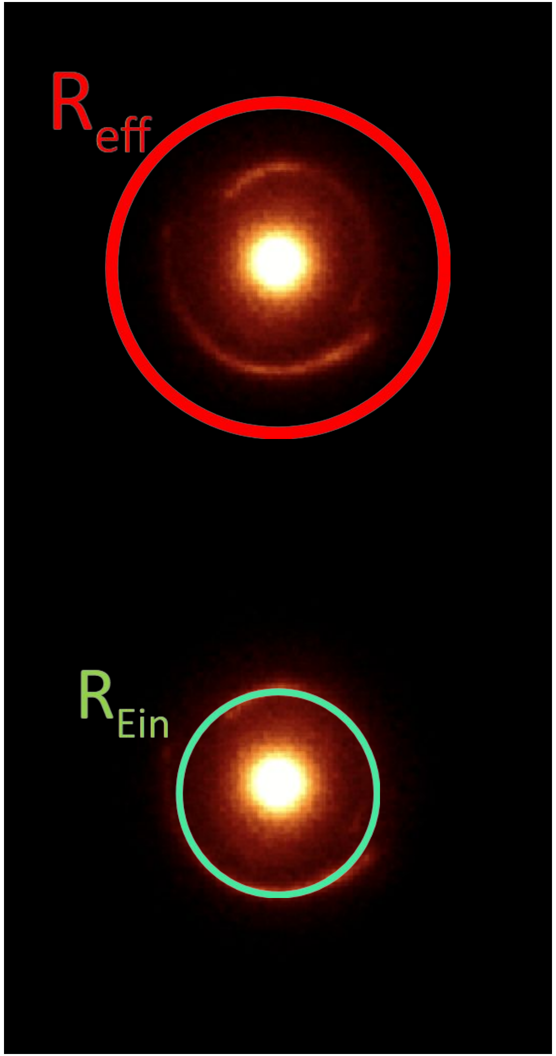
- **Lens modeling of F814W data:** shows same phenomenology as F390W data (e.g. forms extraneous flux in counter image reconstruction) but not enough S/N to disfavour SMBH > 3 sigma.
- **Different lens models:** Power-law mass model, 2 or 3 Sersics in stellar mass, dark matter with variable concentration, include line-of-sight galaxies.
- **Cored mass profiles:** Models with cored inner mass distributions which form large radial critical curves.

Measuring Density Profiles

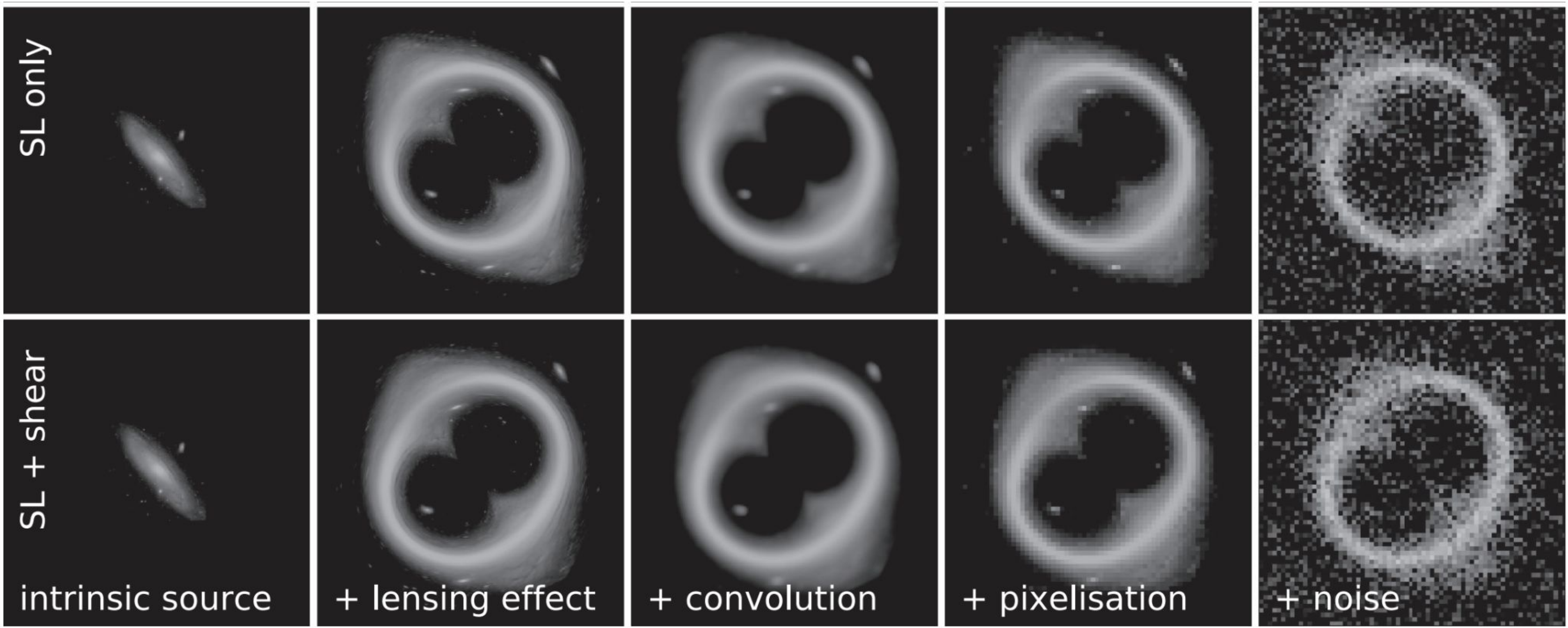
Combine Jeans anisotropic modeling to fit velocity dispersion of lens with Einstein radius mass measurement.

Two masses at two radii -> density slope!

Downside: Requires dynamics – **Expensive!**



Enhance Weak Lensing Cosmology with Strong Lensing



Birrer et al. 2018