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

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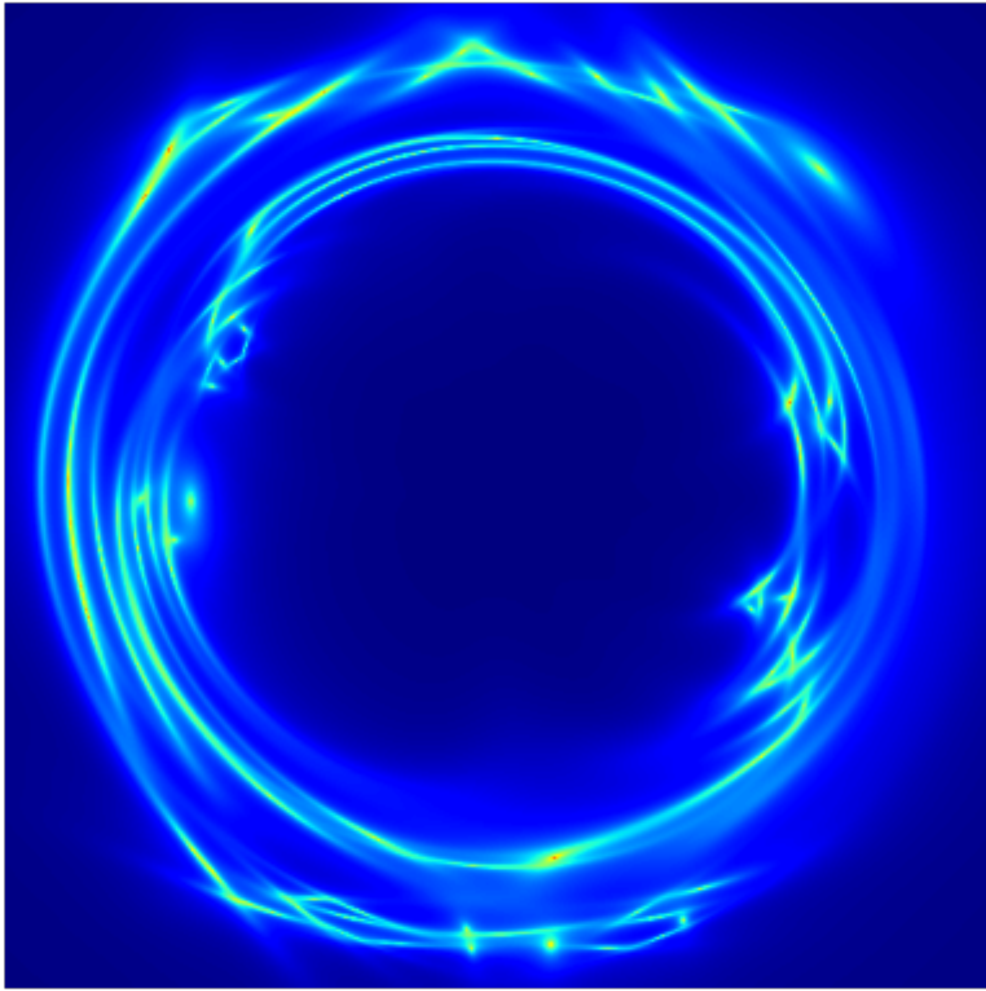
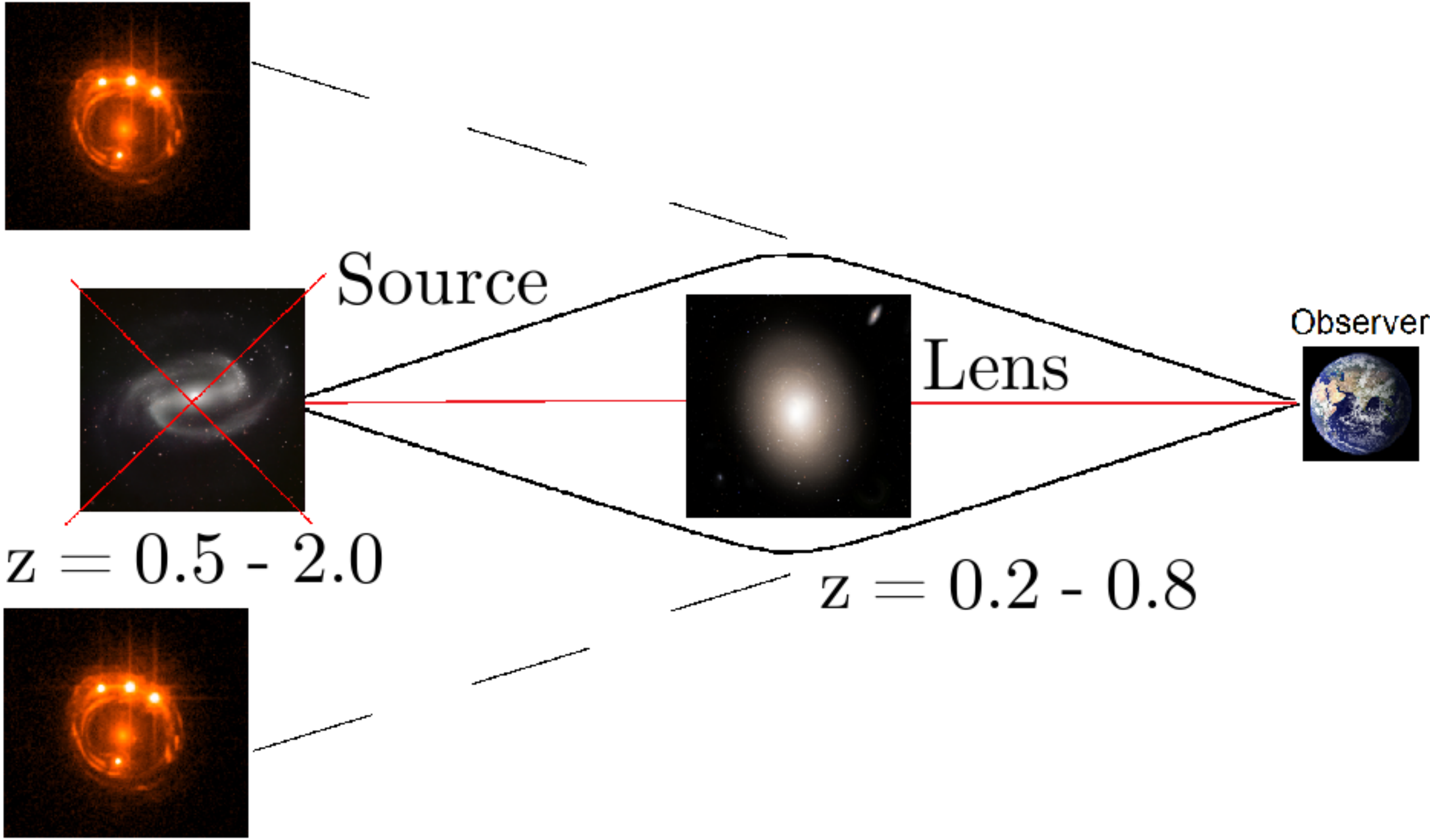
Nicola Amorisco, Aristeidis Amvrosiadis, Xiaoyue Cao, Shaun Cole, Amy Etherington, Carlos Frenk, Richard Hayes, Qiuhan He, Ran Li, Andrew Robertson, Richard Massey, Sam Lange



Strong Lensing

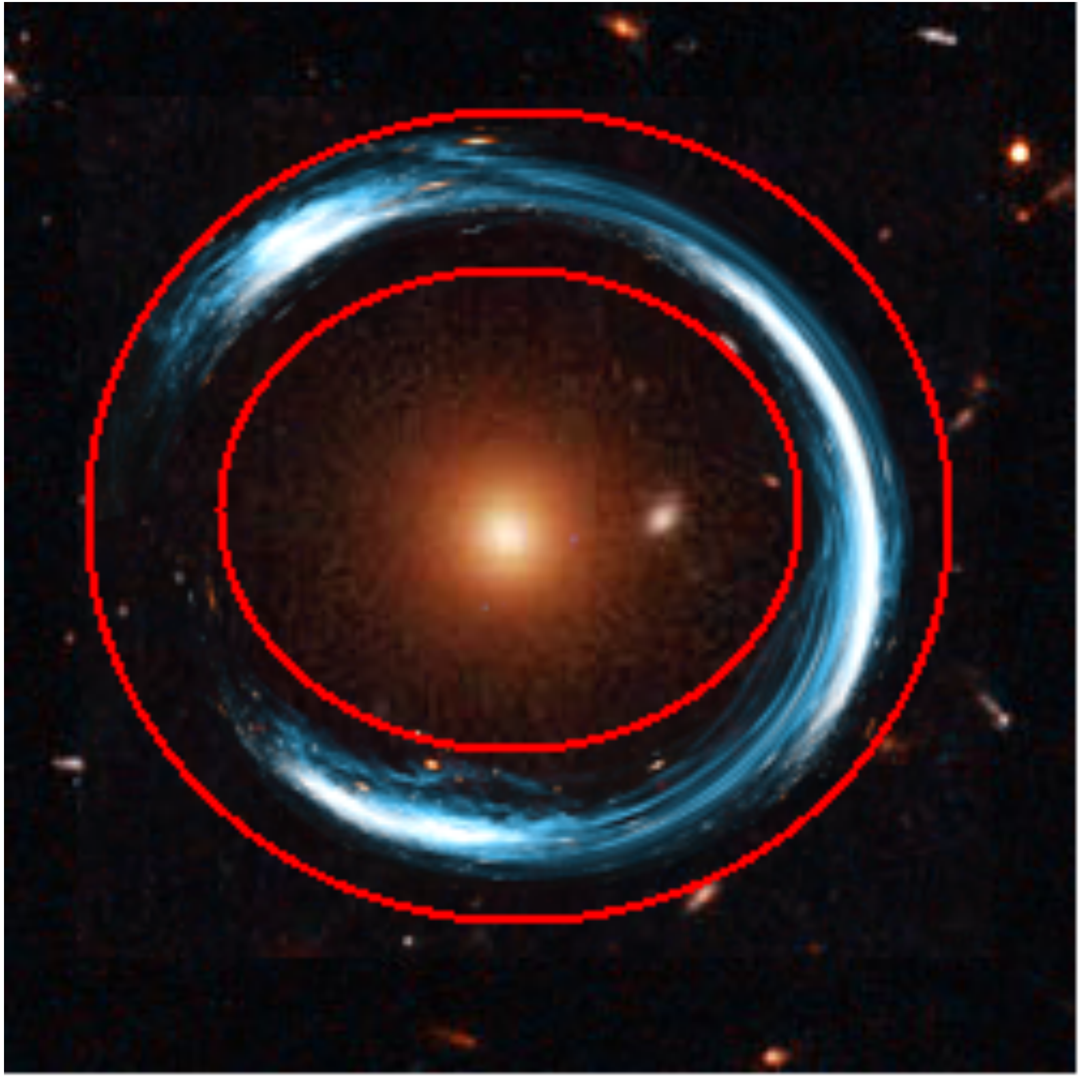


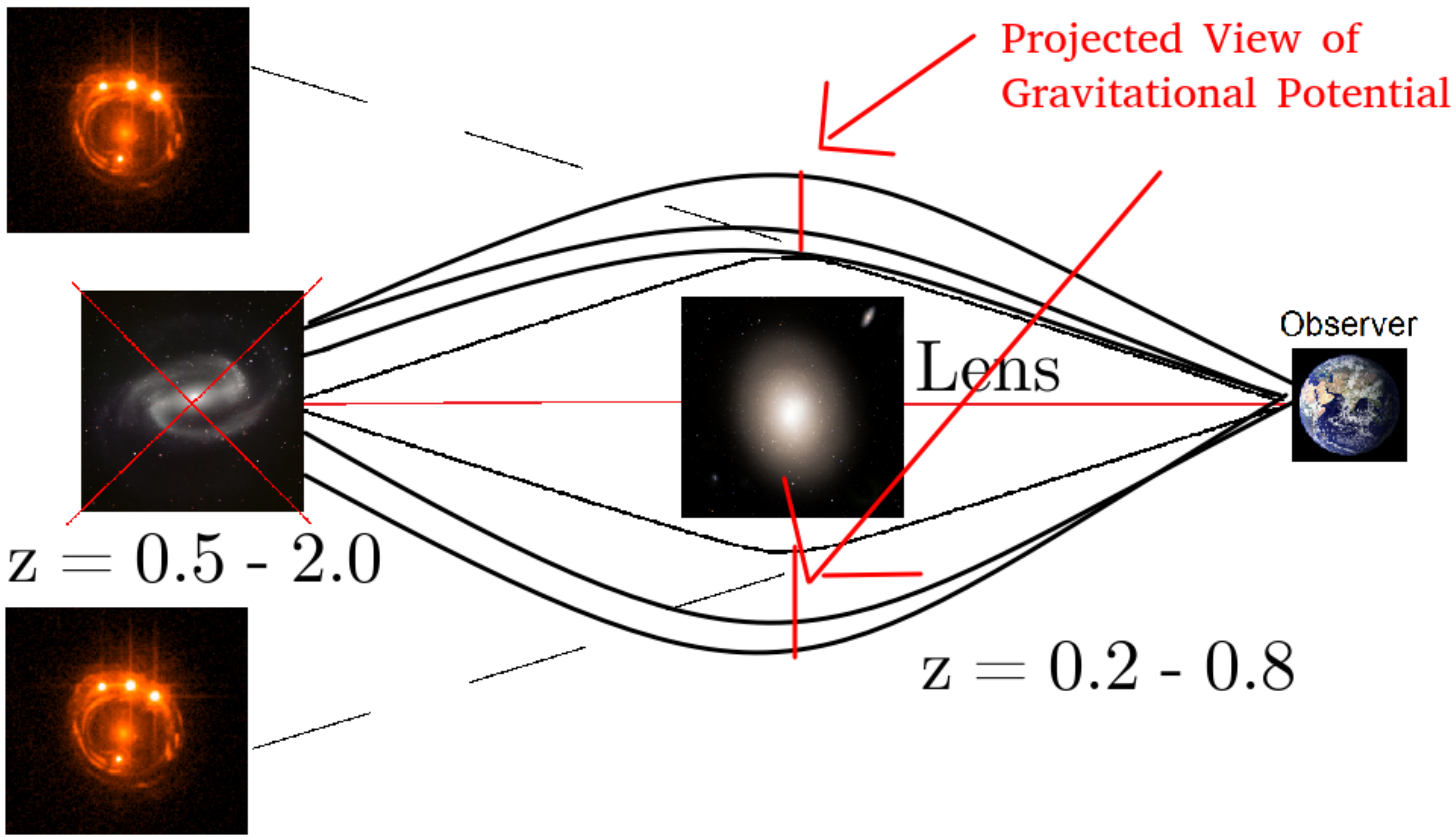
Source
Lens
Observer
z = 0.5 - 2.0
z = 0.2 - 0.8

Extended Source Strong Lensing

Uses: The source's extended lensed surface brightness.

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



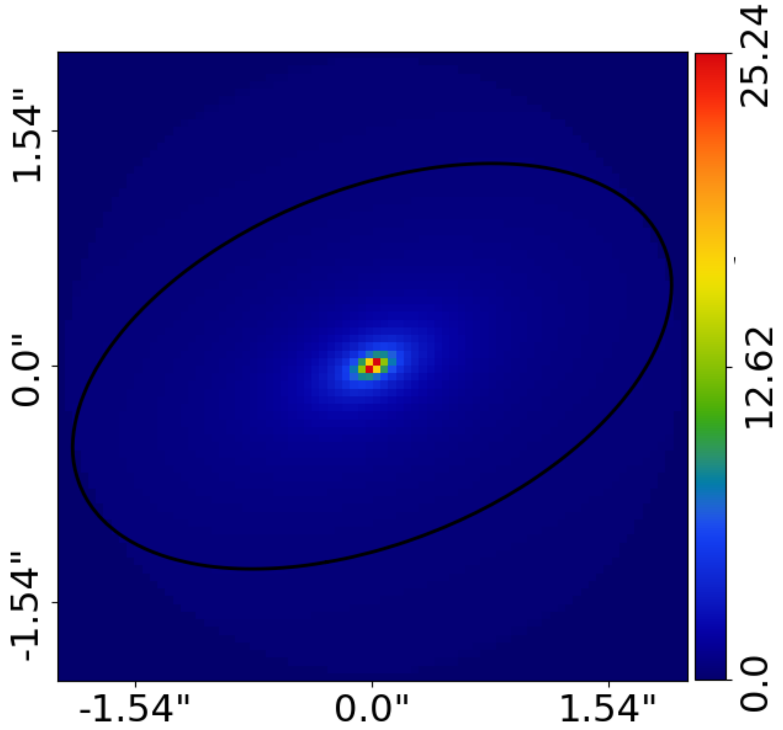


Projected View of
Gravitational Potential
Observer
Lens
z = 0.5 - 2.0
z = 0.2 - 0.8

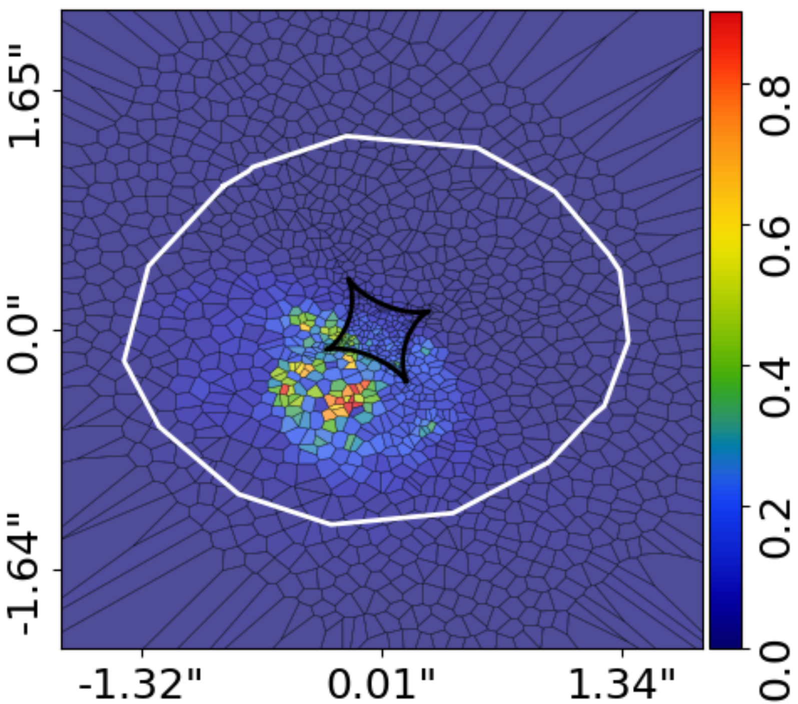
Strong Lens Modeling

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

Mass (e.g Convergence / Surface Density)



Source



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

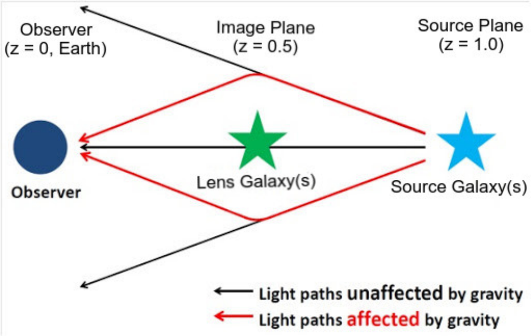
HowToLens: Free online Jupyter Notebook lectures aimed at undergrads, teaching them how to model strong lenses.

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.

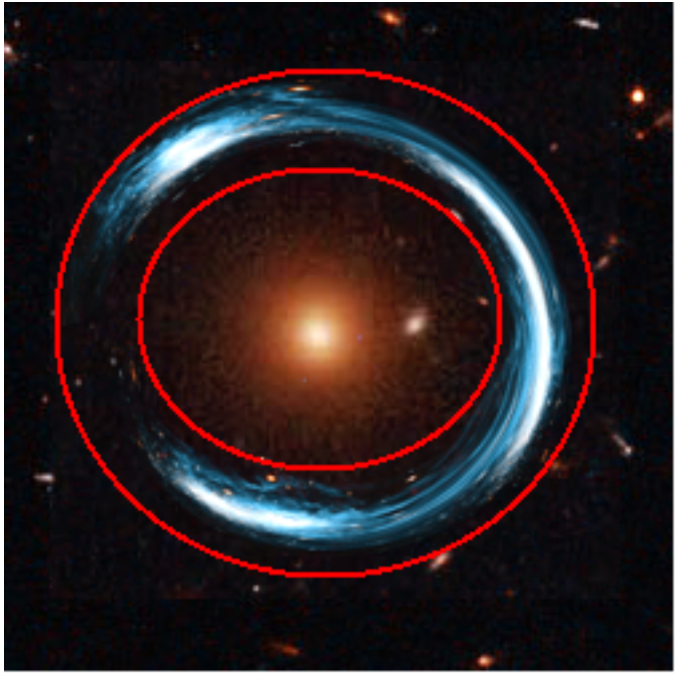
In [ ]:
```
image_plane_grid = al.Grid2D.uniform(shape_native=(100, 100), pixel_scales=0.05)
```

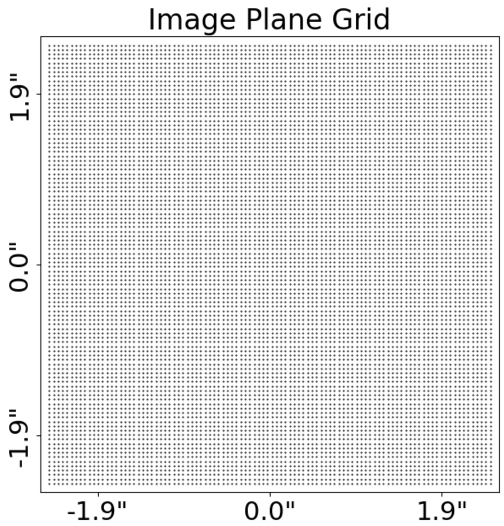
We will also name our `Galaxy` objects `lens_galaxy` and `source_galaxy`, to reflect their role in the schematic above.

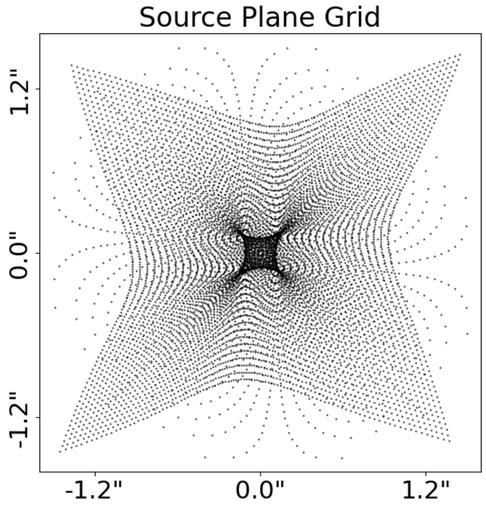
Ray Tracing

Compute deflection of light due to lens galaxy at each (y,x) coordinate.

Subtract deflection angle from coordinate to ray-trace to source plane.







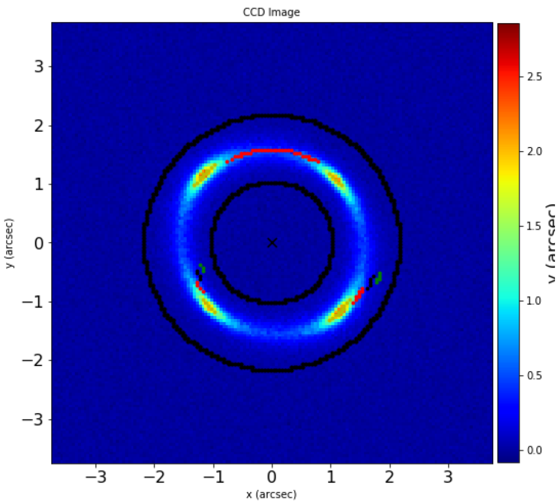
Linear Algebra

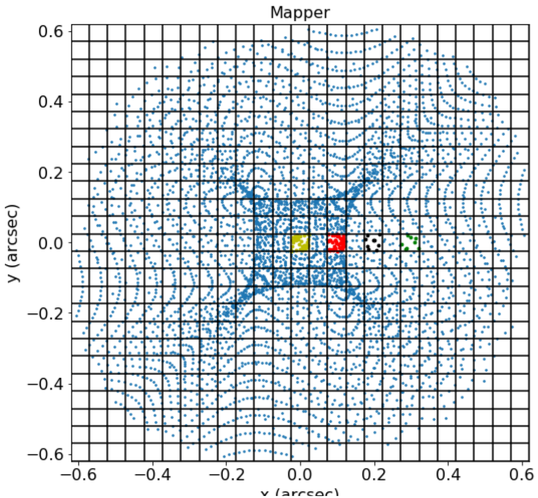
Map every Voronoi source pixel (~2500 pixels) to every image pixel (~10000+ pixels).

Create matrix of dimensions: [image_pixels, source_pixels] =
[10000, 2500]

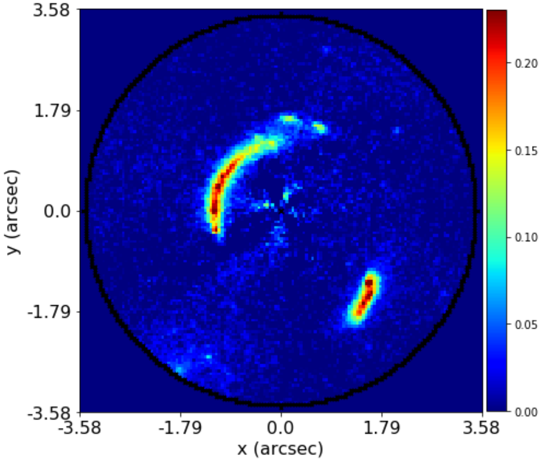
Perform linear inversion to solve for source pixel fluxes:

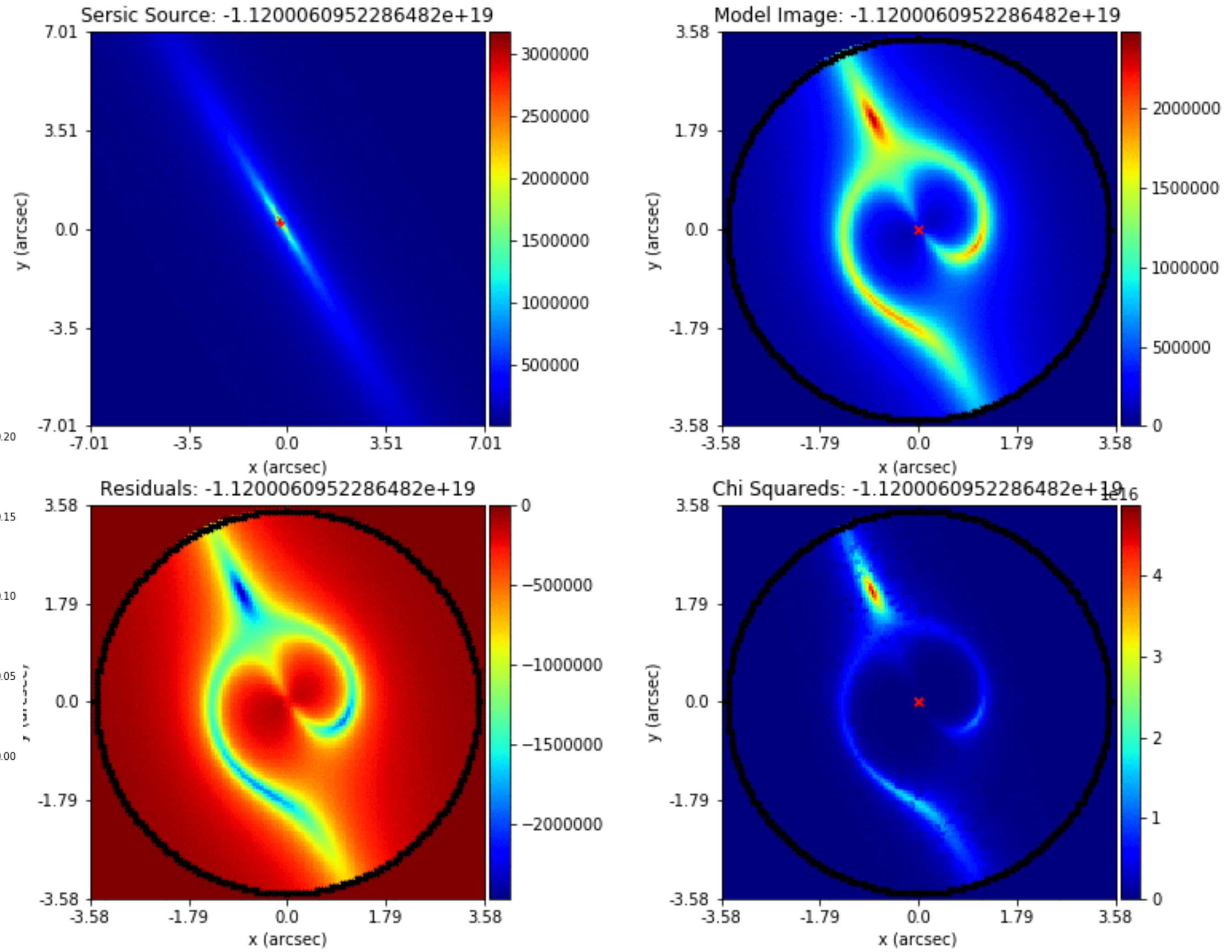
y = Ax





Lens Modeling



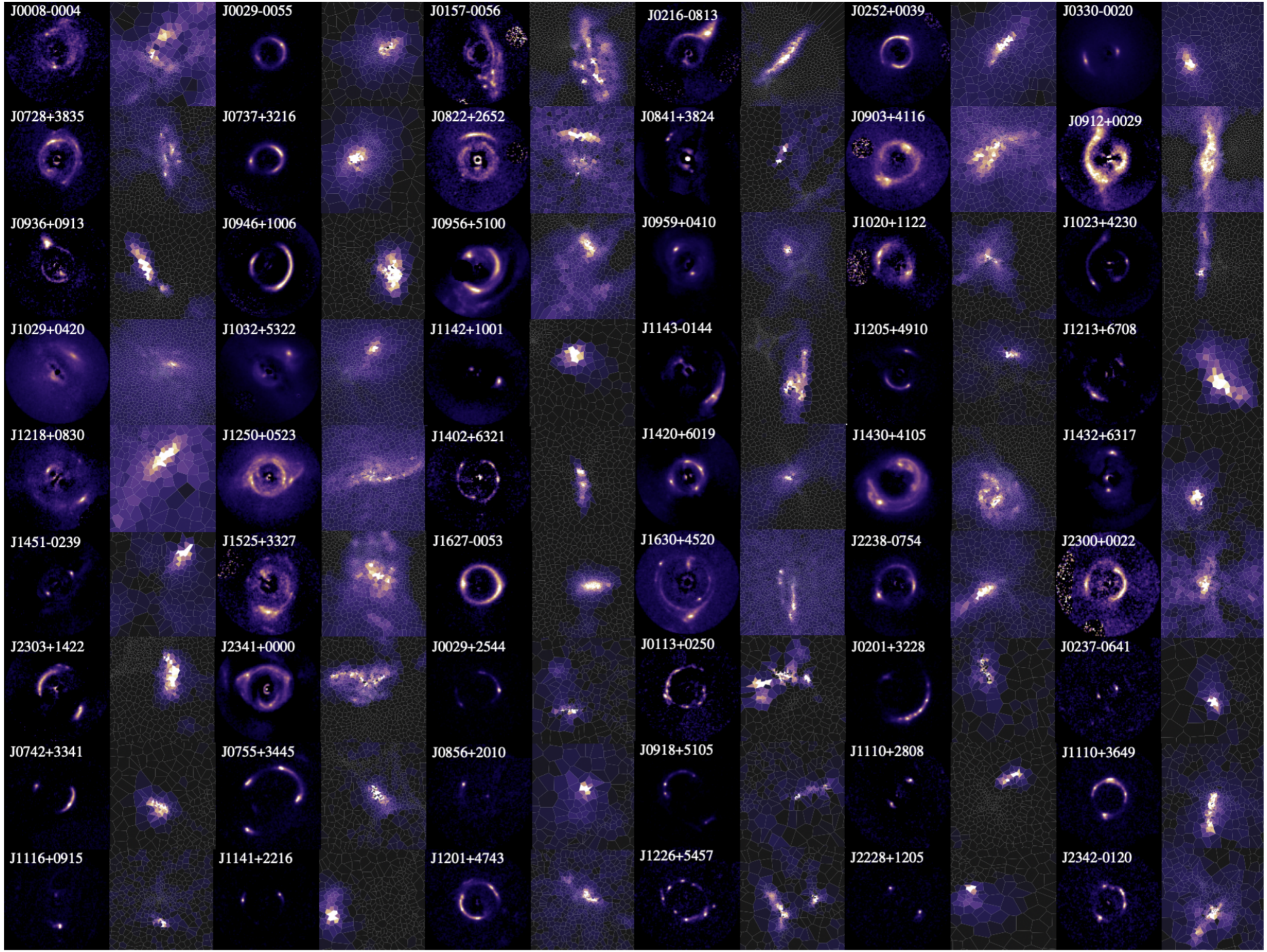


Automation

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!



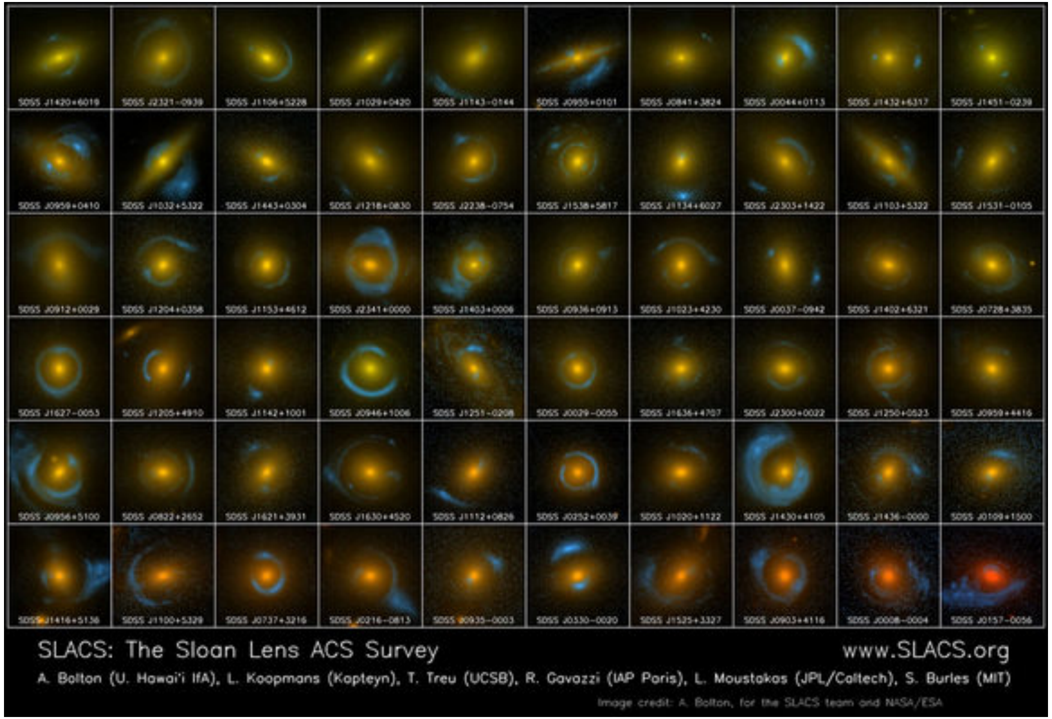
Galaxies: Large Samples Are Coming

Euclid will find 100000+ strong lenses.

Vera Rubin 10000+

SKA 250000+

50 years of lens hunting ->



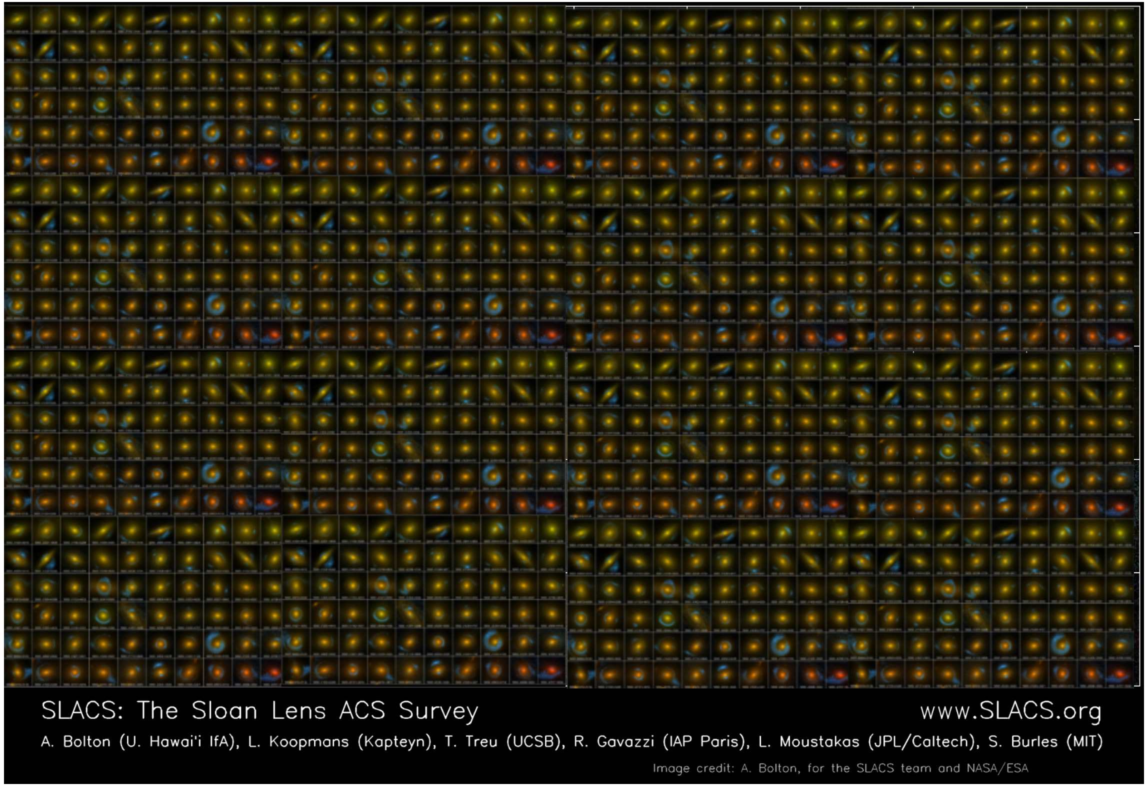
Galaxies: Large Samples Are Coming

Euclid will find 100000+ strong lenses.

Vera Rubin 10000+

SKA 250000+

1 week of Euclid ->



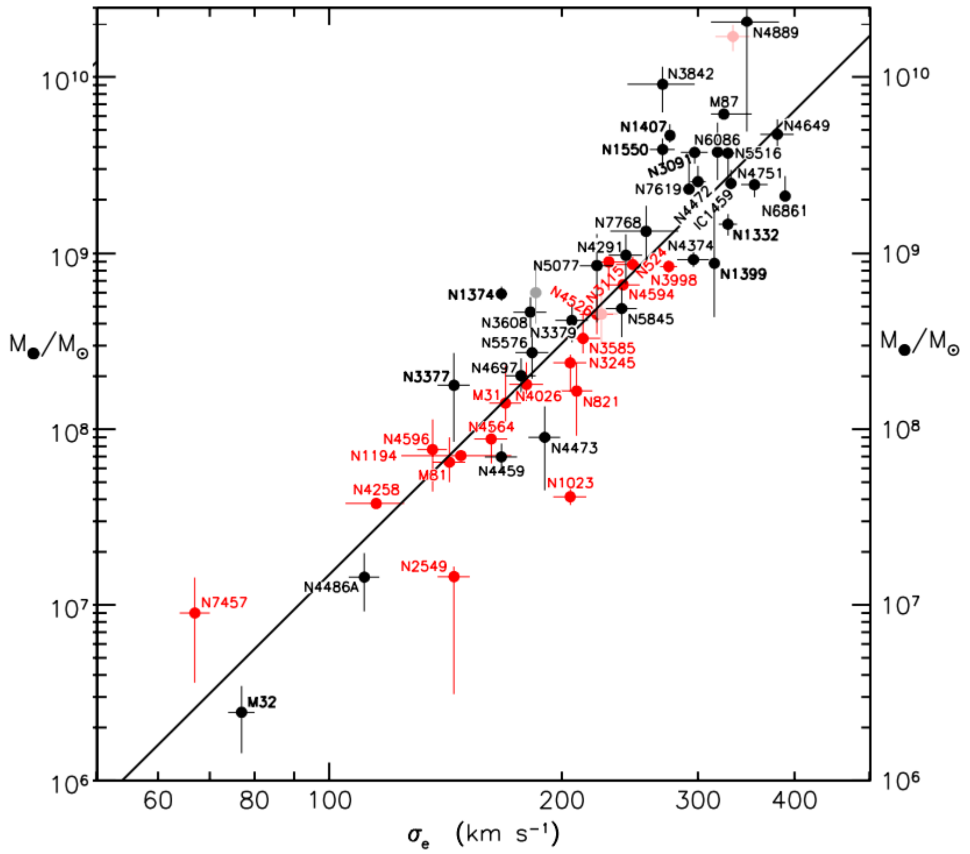
Supermassive Black Holes (SMBH)

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?

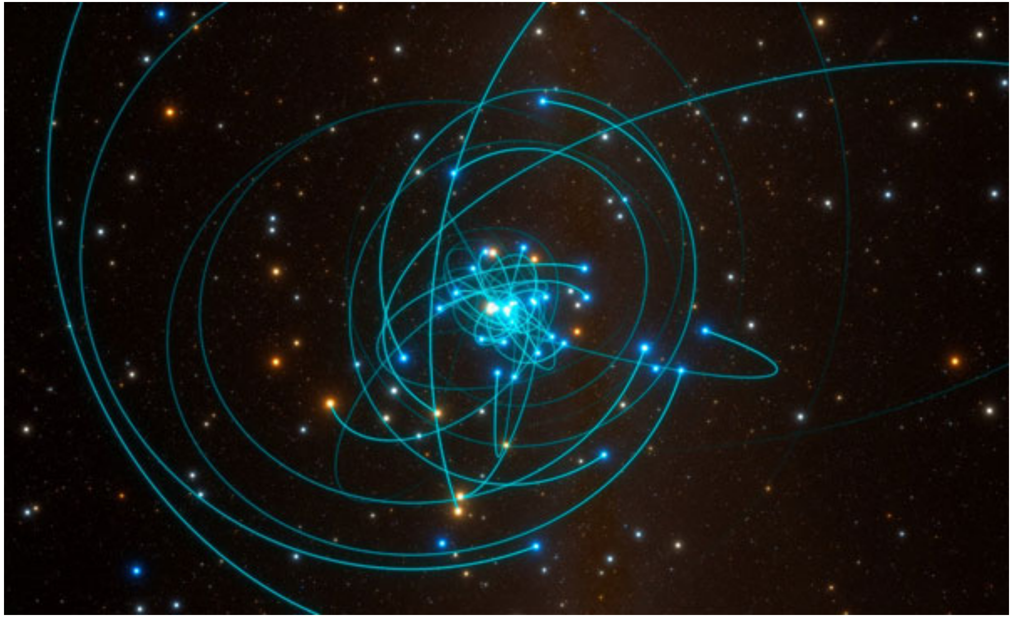


How do we measure SMBH masses – Local Universe

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

Downsides:

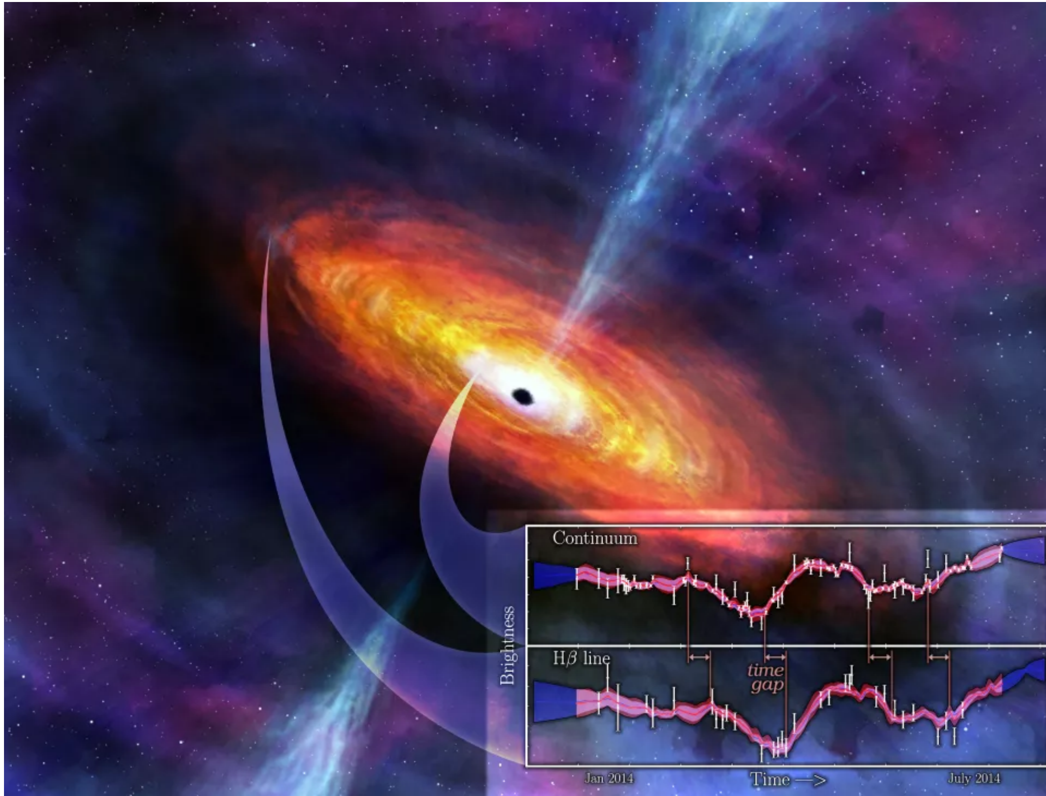
- Only possible in very nearby galaxies.



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

How do we measure SMBH masses: High Redshift

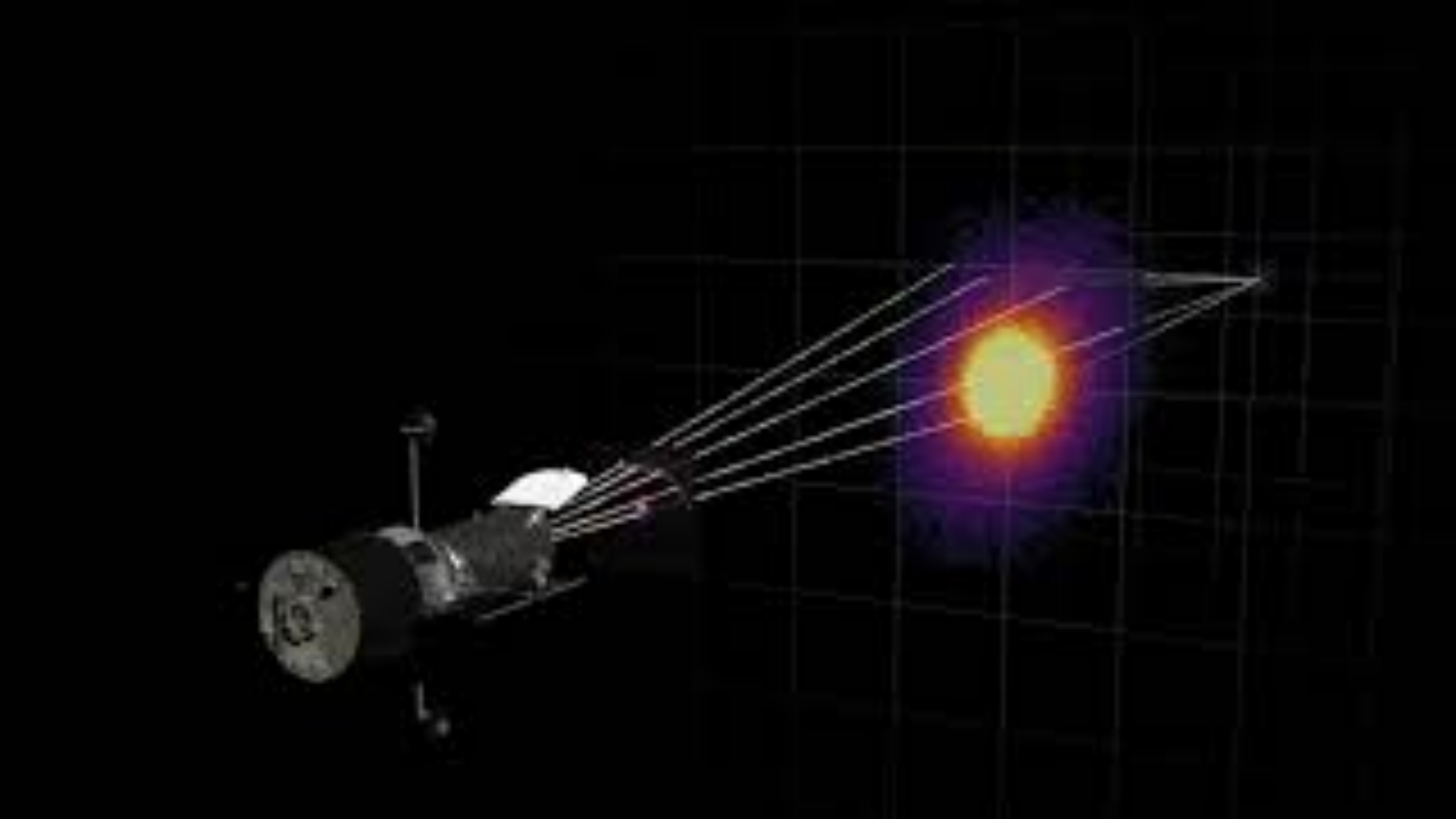
https://www.space.com/39347-black-hole-mass-measurement-survey.html



Method: Reverberation Mapping of active galactic nuclei.

Downsides:

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



M_{BH}-Sigma Relation

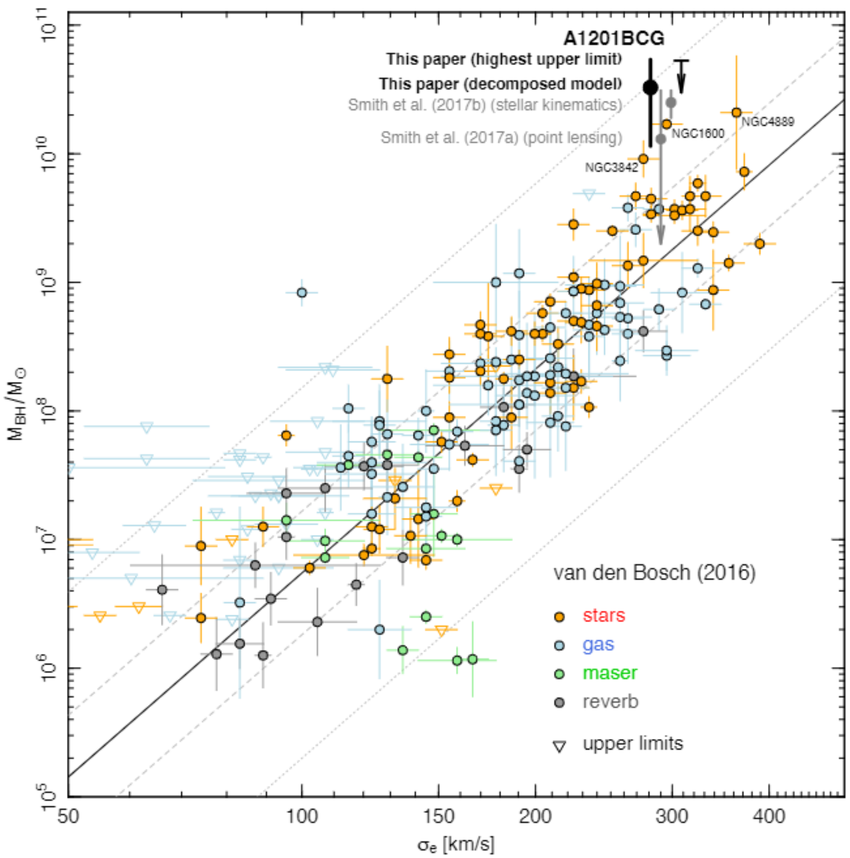
M_{BH} = 3.27 x 10^{10}MSun

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

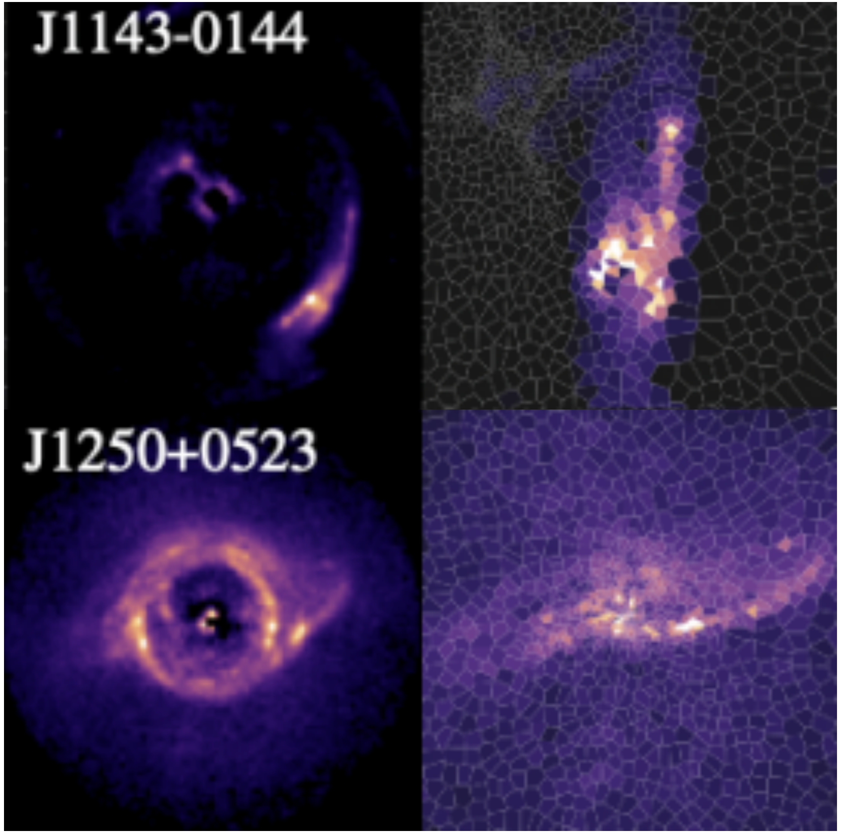

ESA/HUBBLE/DIGITIZED SKY SURVEY/NICK RISINGER

Future: SMBHs with strong lensing

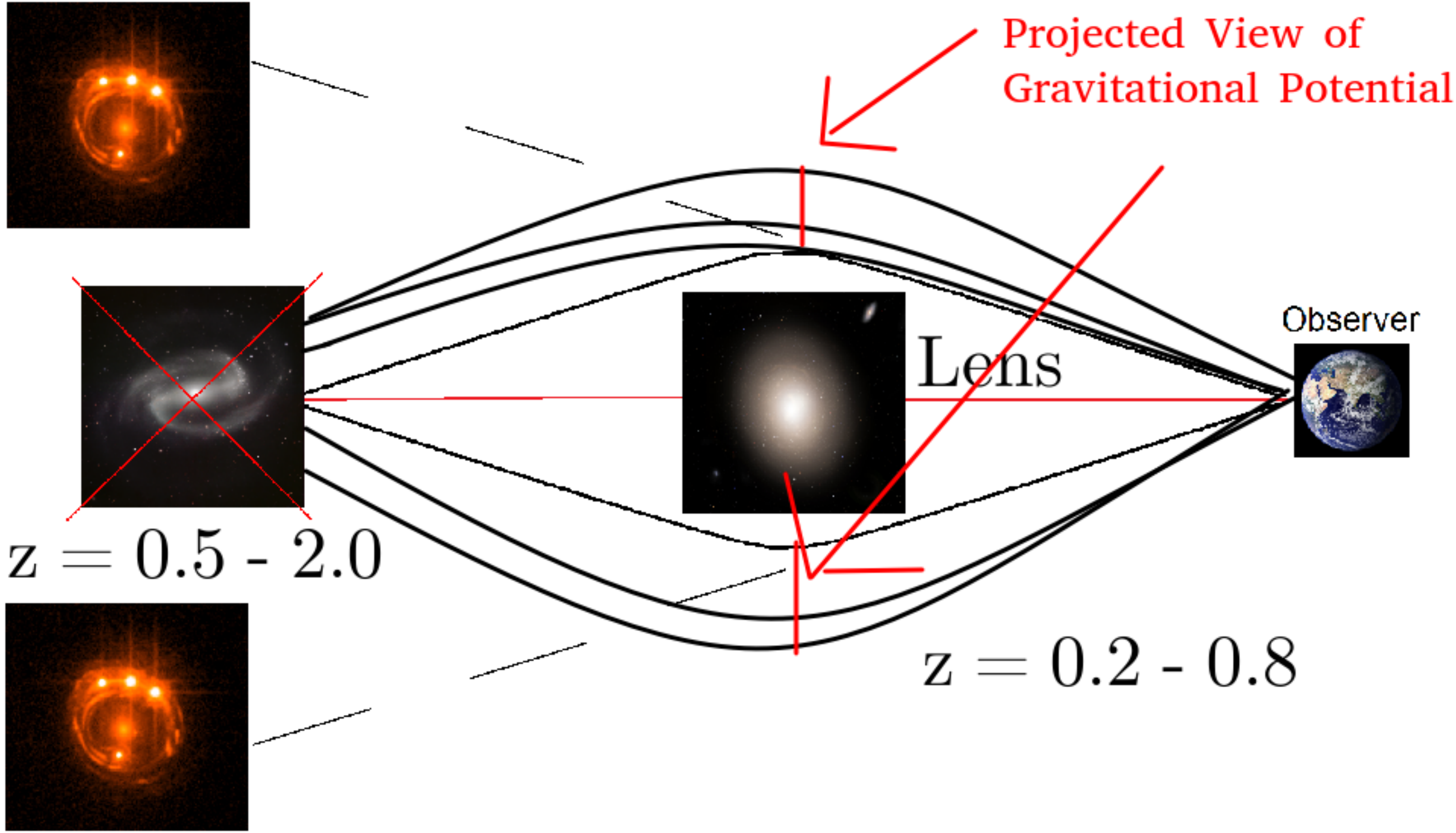
How massive are the most massive black holes in the Universe?

Are there galaxies without a central SMBH?

What can strong lensing tell us about SMBH binaries?



Galaxies



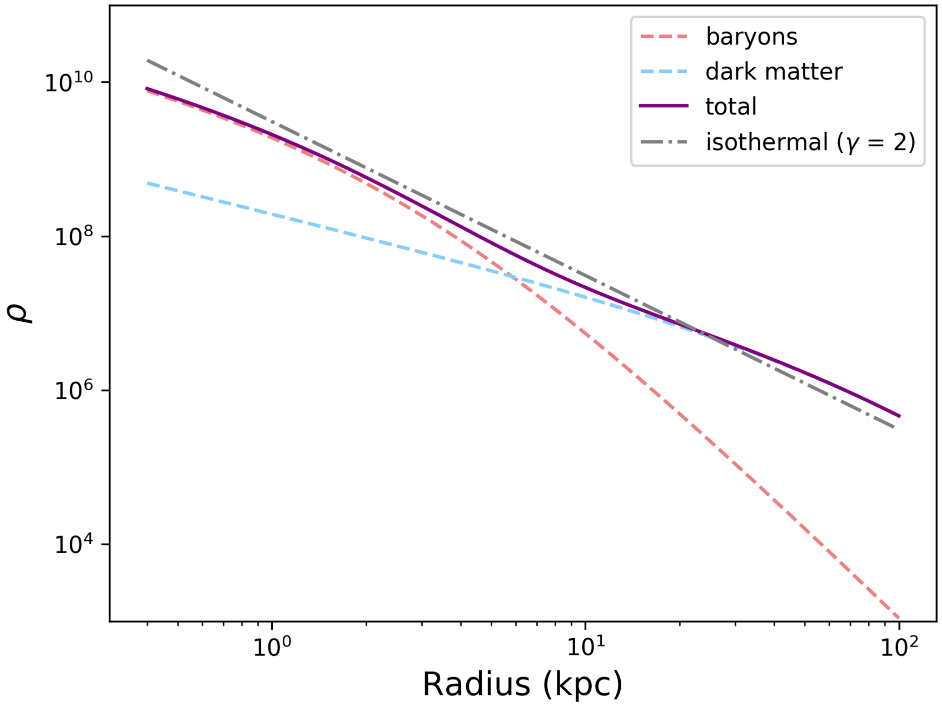
Projected View of
Gravitational Potential
Observer
Lens
z = 0.5 - 2.0
z = 0.2 - 0.8

Mass Distributions: Measurement

How is the mass within galaxies distributed?

How are stars distributed relative to dark matter?

What does this tell us about galaxy formation?



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]

[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]*Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA*
[4]*National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, China*
[5]*School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China*

SLACS: Bulge-Halo Conspiracy

Lensing + Dynamics study of ~100 massive elliptical strong lenses found all mass profiles are approximately isothermal.

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

Why is galaxy formation so predictable?

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

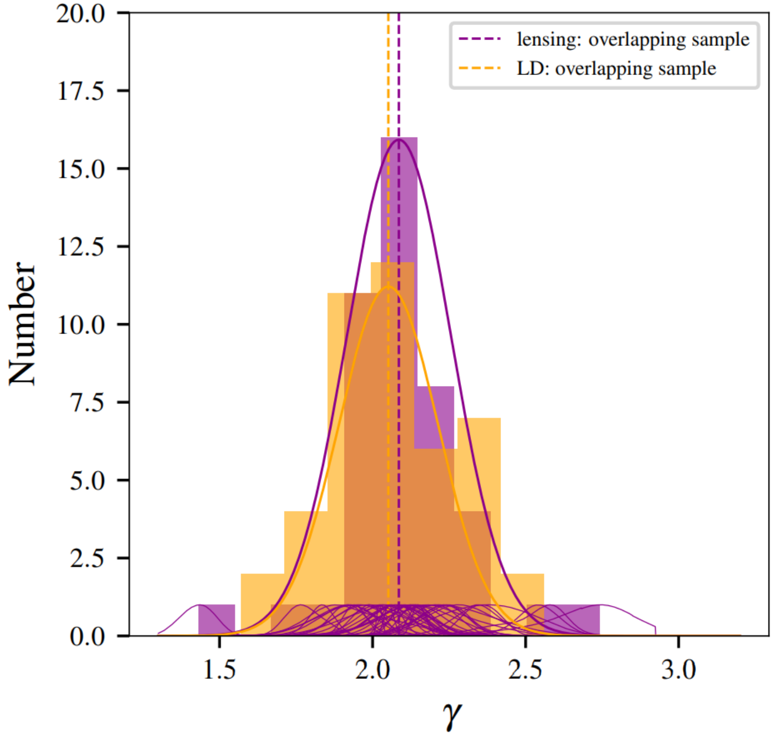
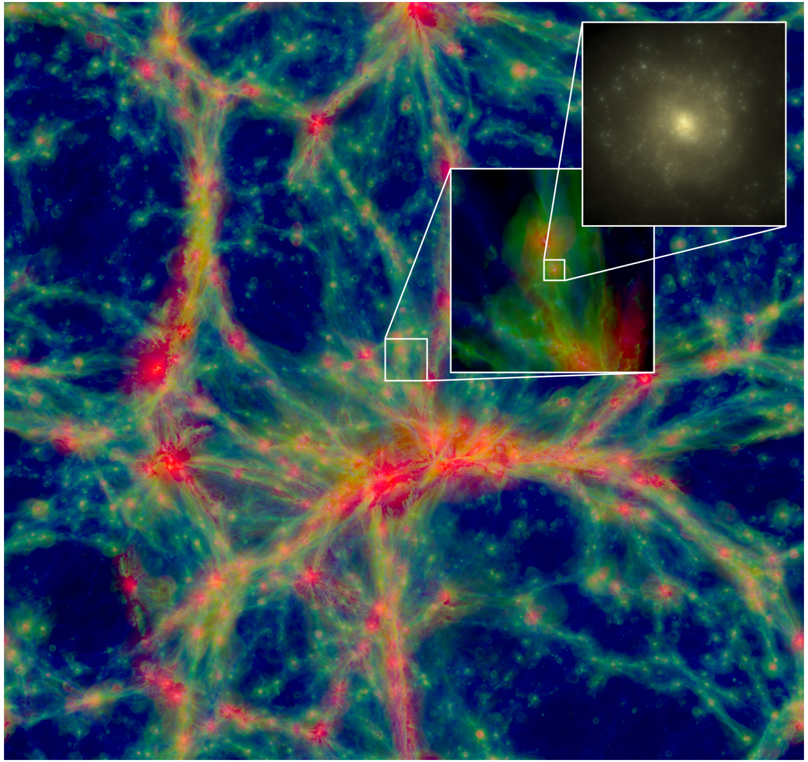
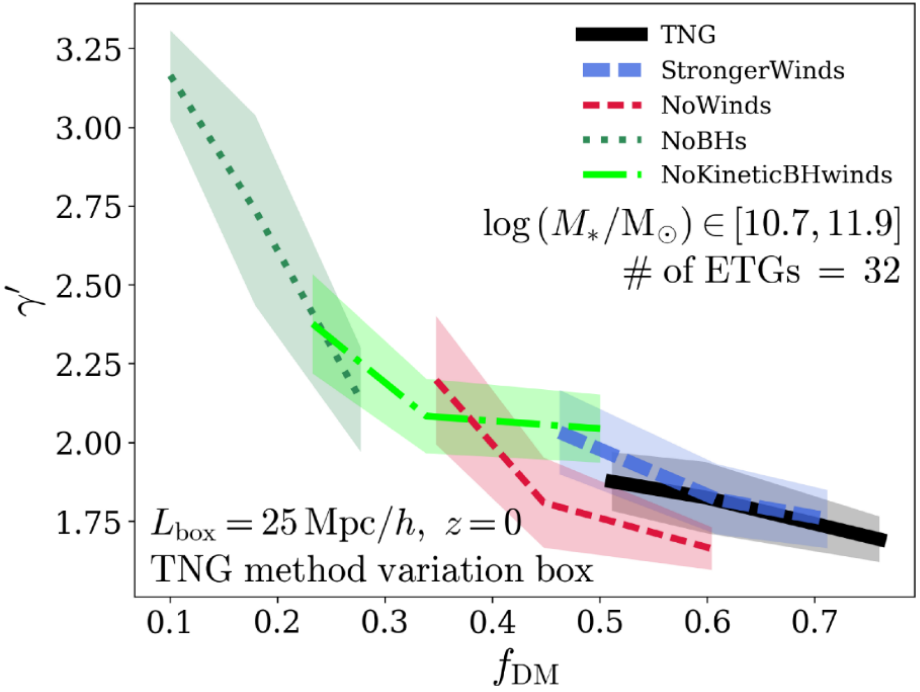


Figure 5. Comparison of the distributions of slopes inferred with lensing only and lensing + dynamics for the samples that overlap.

Mass Distributions: Simulations

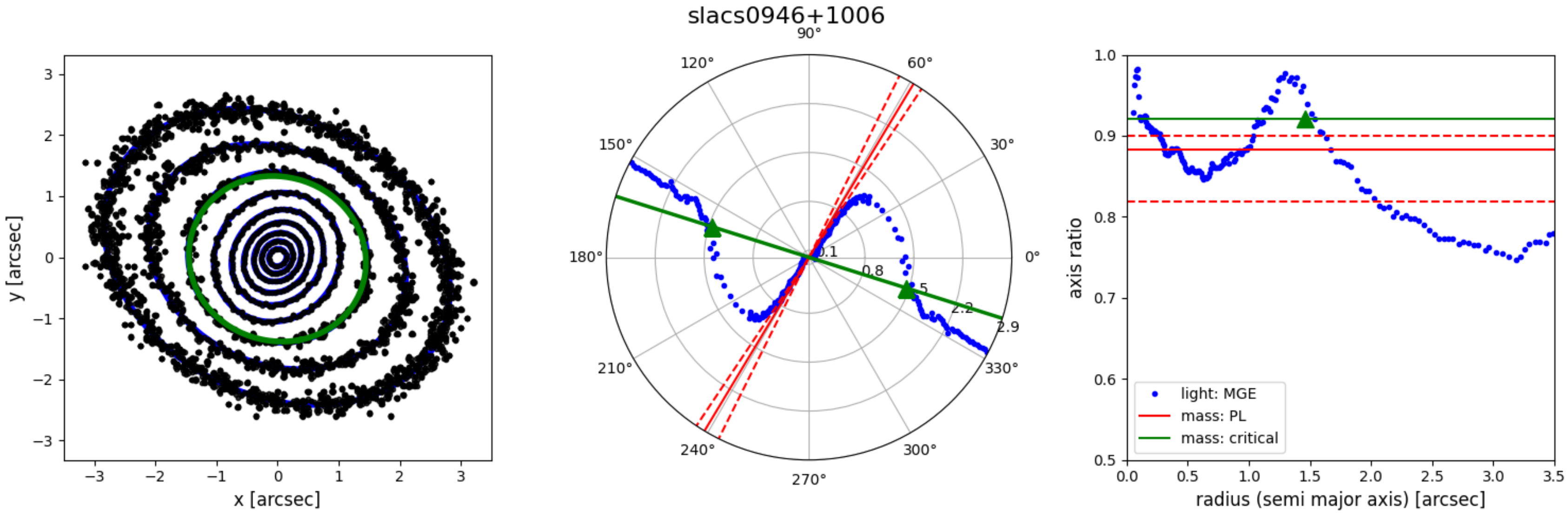




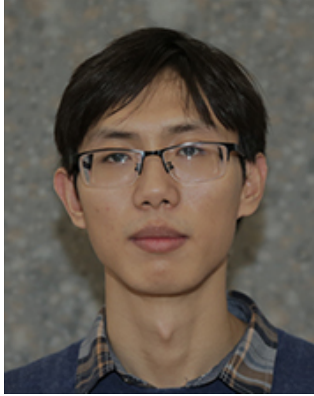
Mass Distributions: Angular Complexity

- Twisting Mass distributions.
- Radial ellipticity variations.
- Lopsidedness.
- Boxiness / diskiness.

Strong lens models typically assume an **elliptical power-law**!

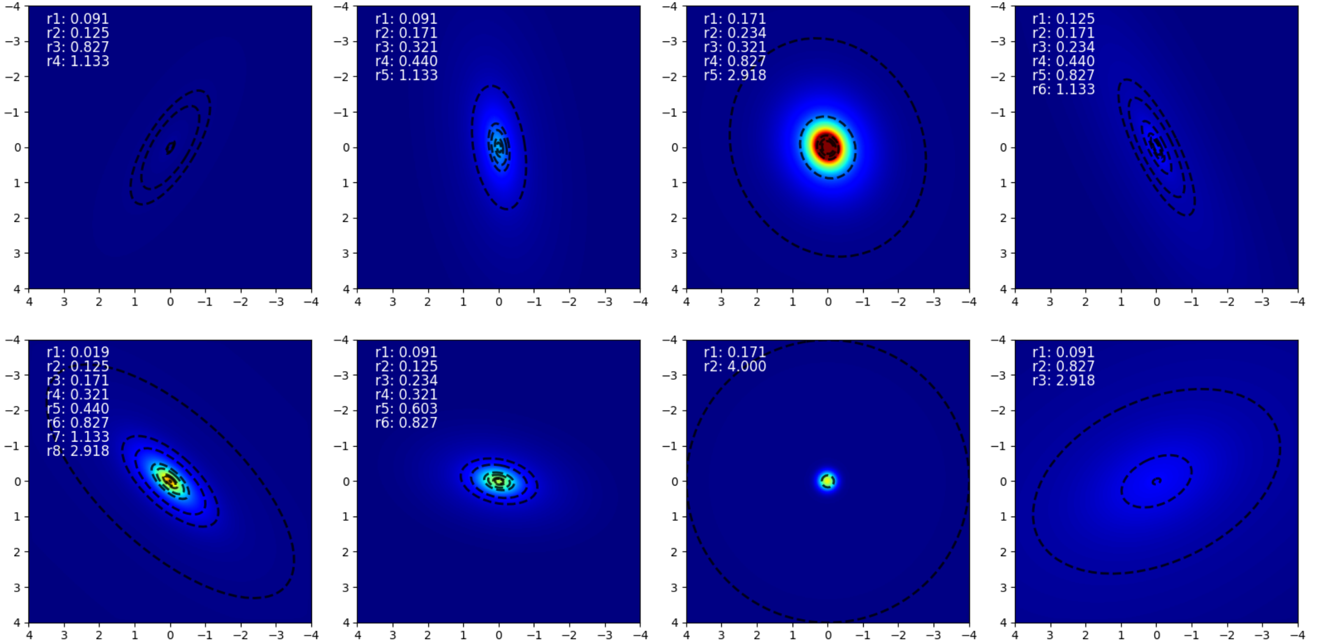


Future: Multi Gaussian Expansion Lens Model

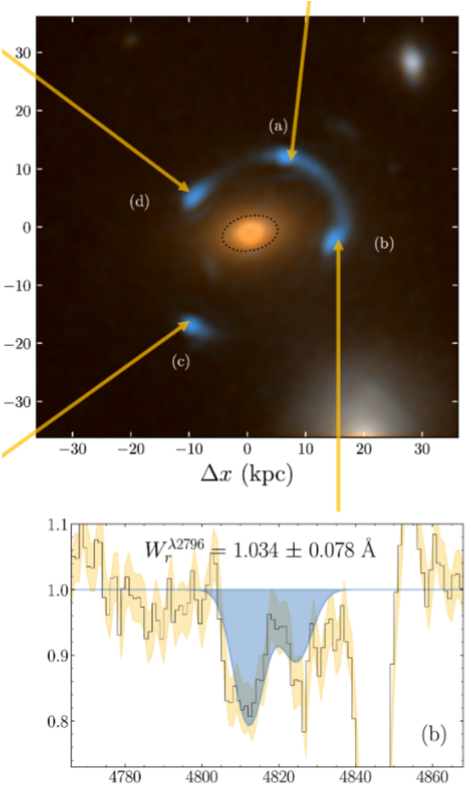


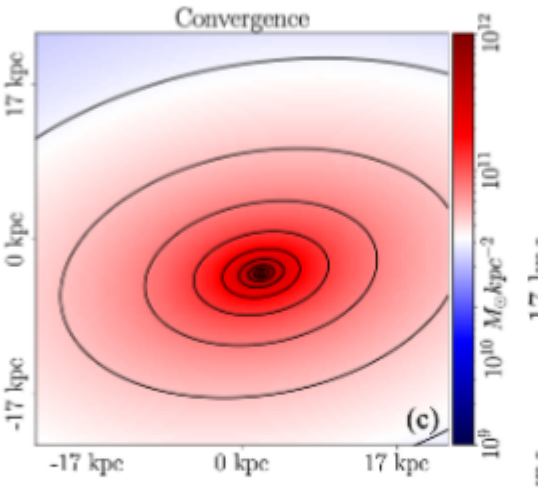
Decompose lens light and (stellar) mass into Gaussians.

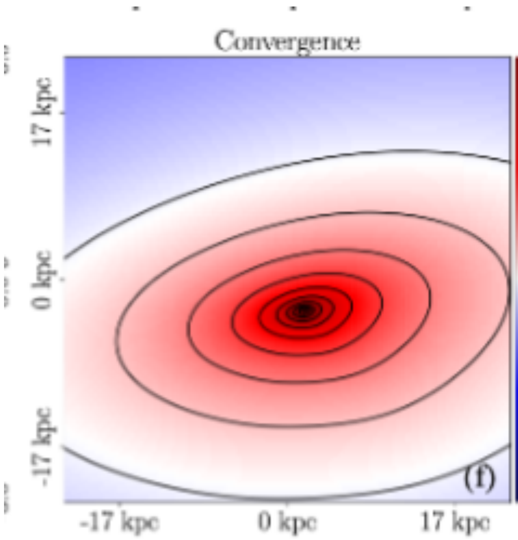
Incorporate missing complexity into lens.



Mass Distributions: Gas, Dust, the CGM?







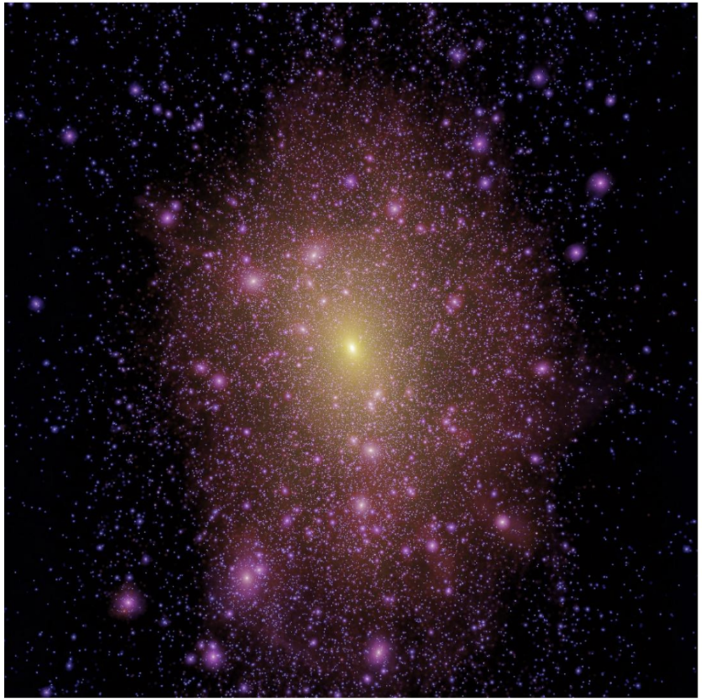
Dark Matter

Dark Matter Simulations

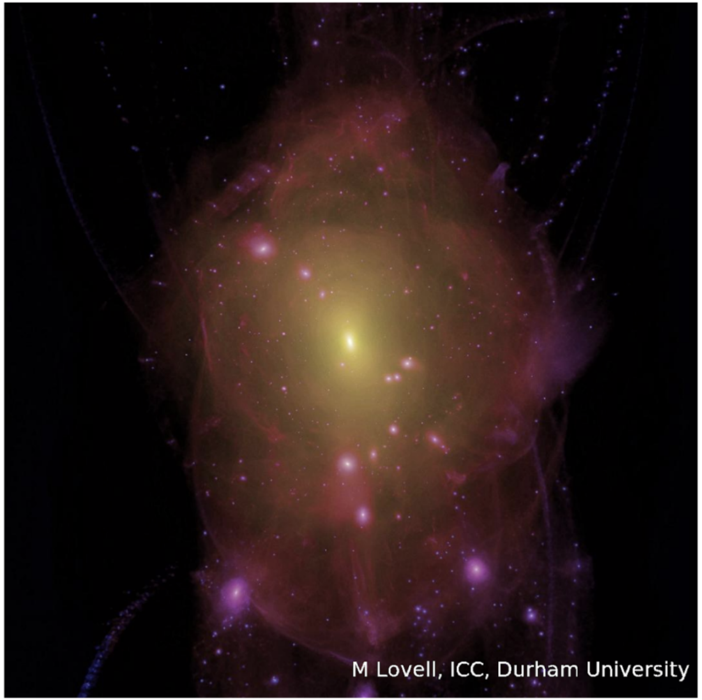
Two simulated Universes assuming two different mass dark matter particles.

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)



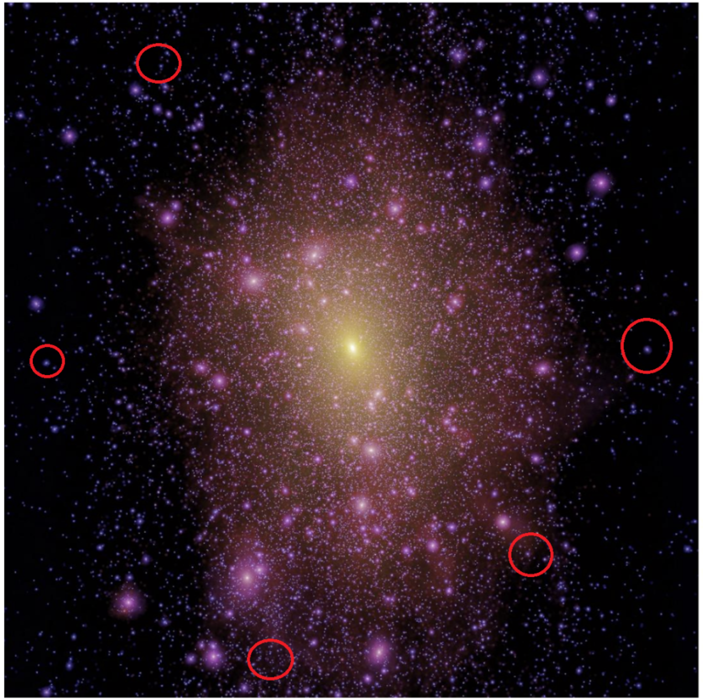
Warm Dark Matter
(e.g. Sterile Neutrino)
[see also Fuzzy Dark Matter, Self Interacting Dark Matter, etc.]

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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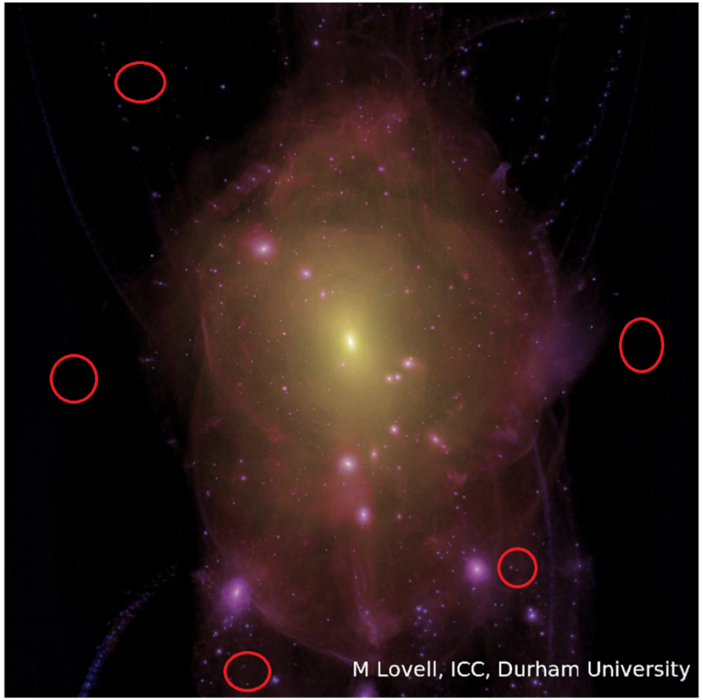

Warm Dark Matter
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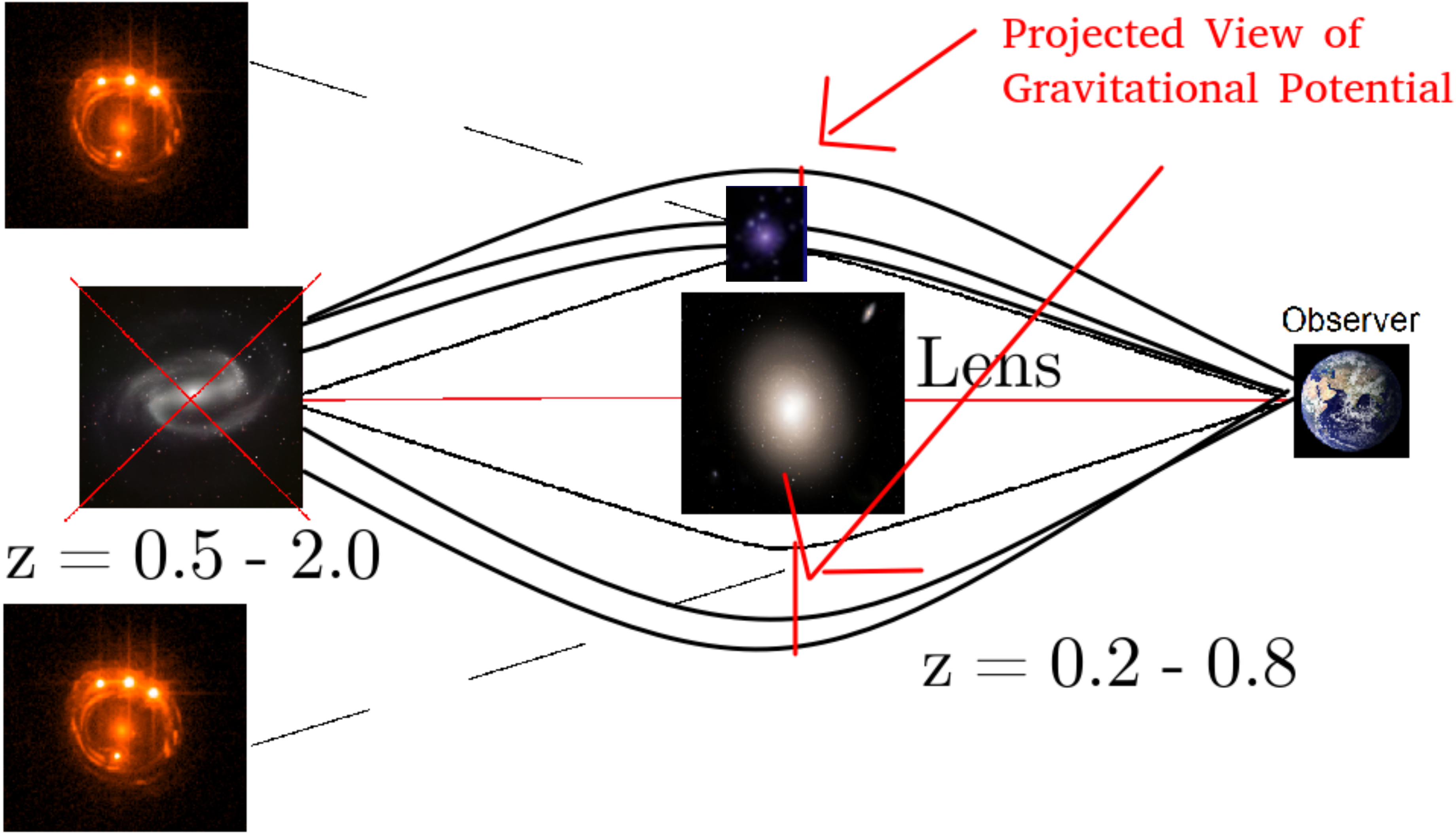
Projected View of
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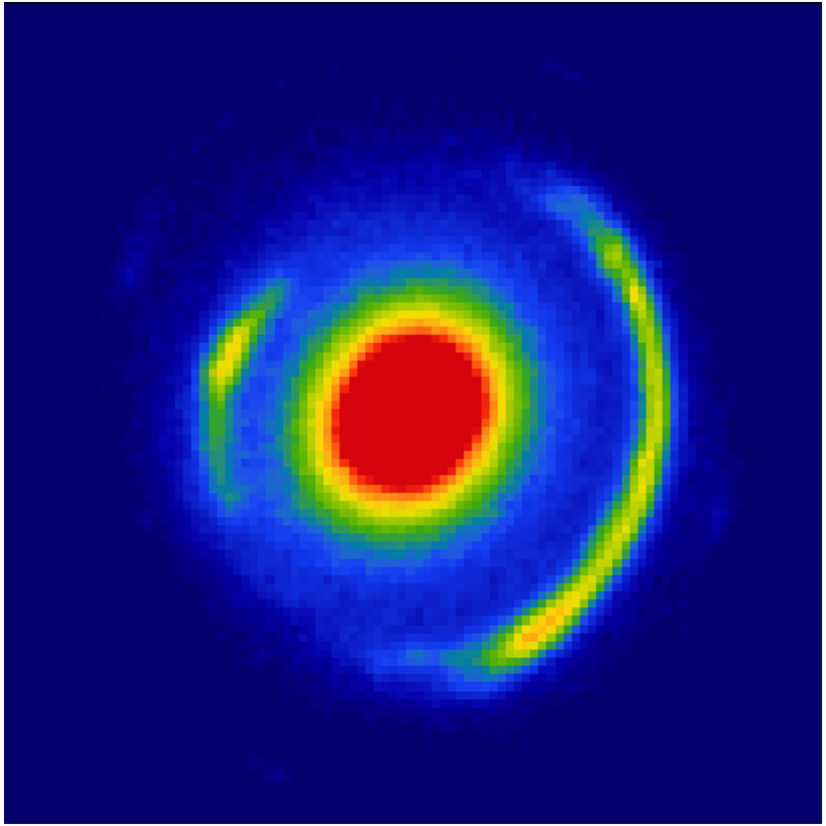
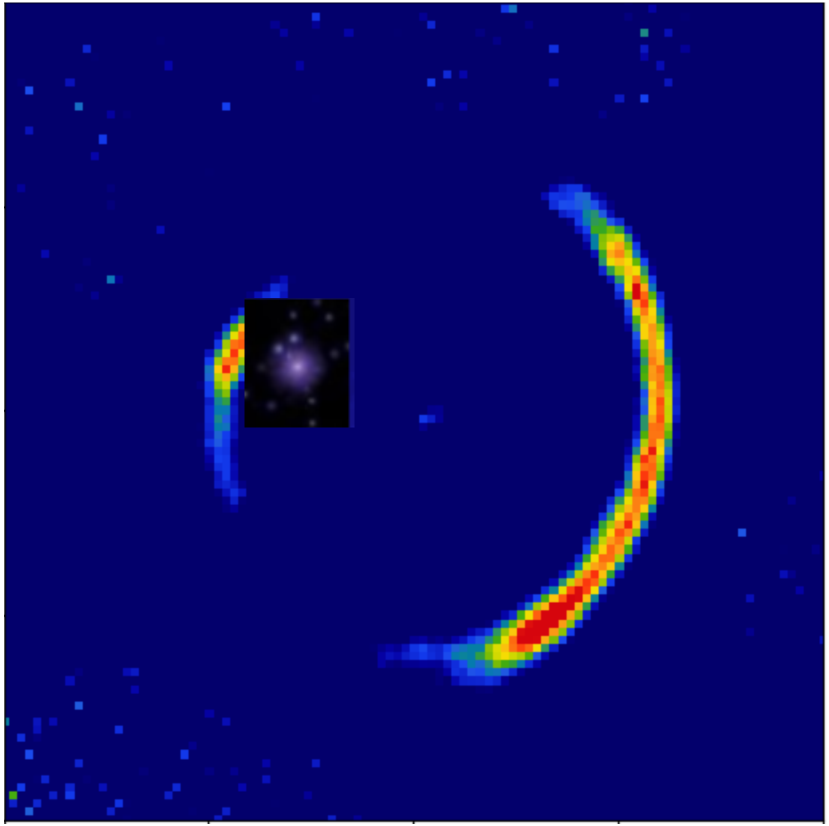
Gravitational lensing: Dark Matter Substructure Detections

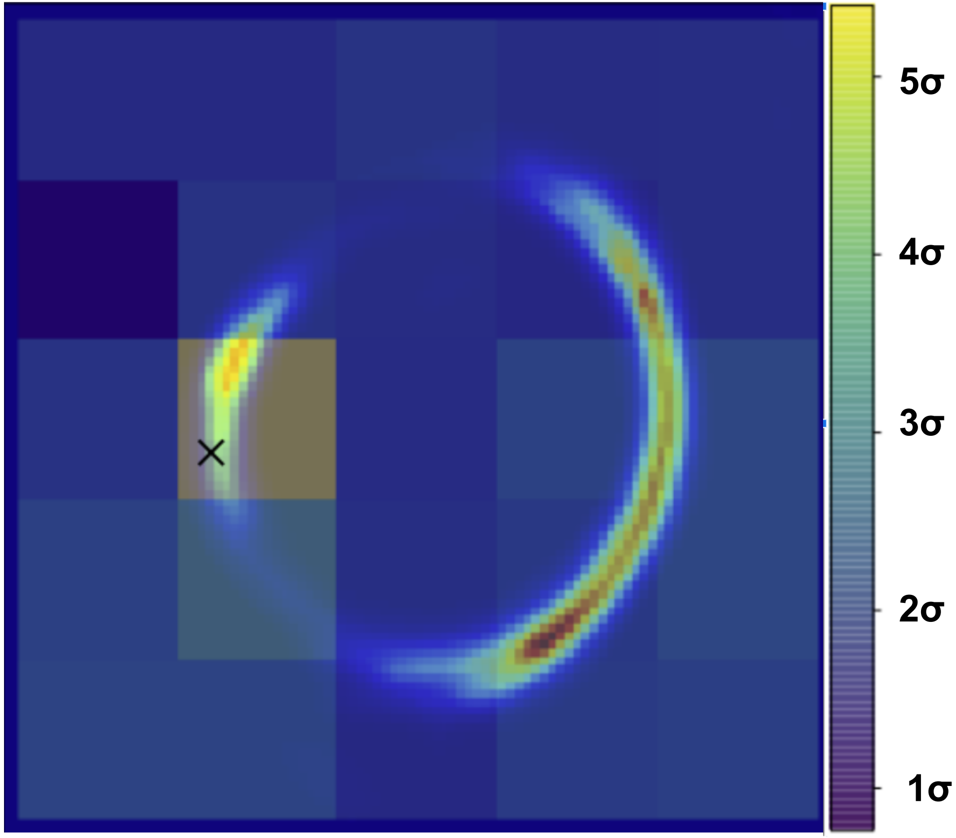


Gravitational lensing: Dark Matter Substructure Detections



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*].



Dark Matter

Is dark matter cold, warm or something else?

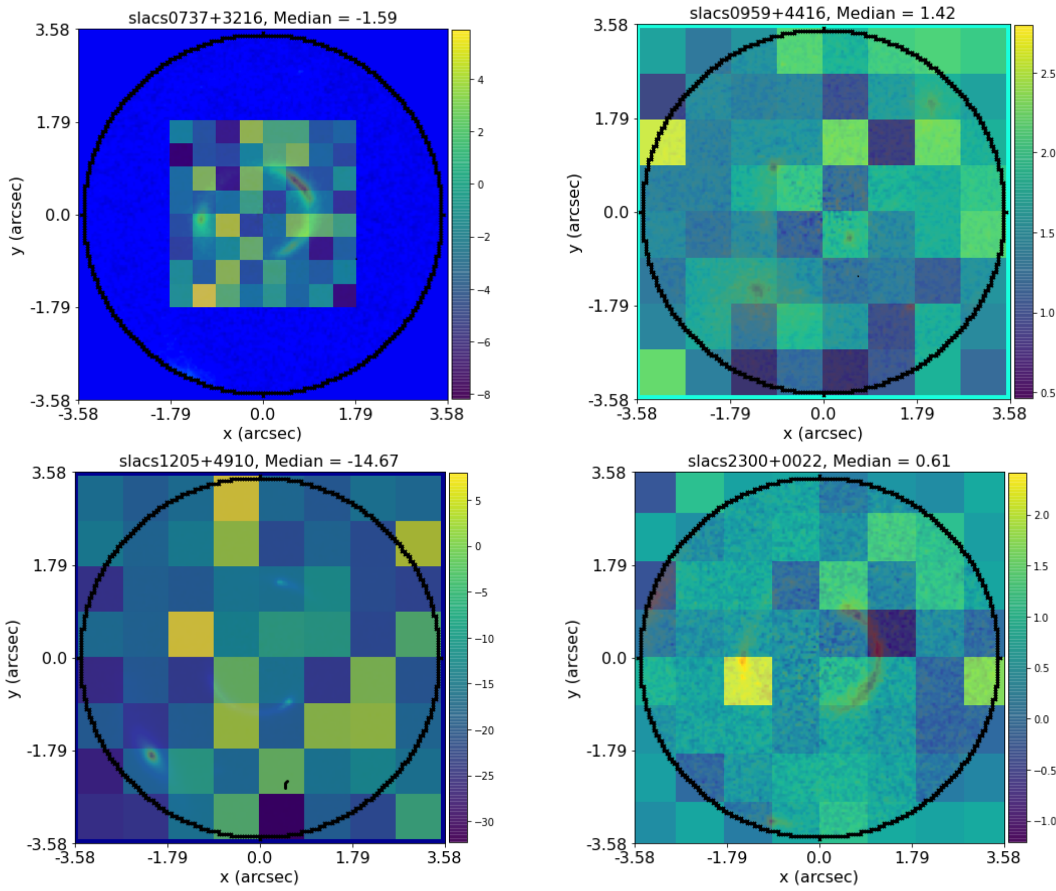
Can we overcome lens modeling systematics to answer this question?

Dark Matter

Is dark matter cold, warm or something else?

Can we overcome lens modeling systematics to answer this question?

If its WDM, non-detections are the signal we want to measure!



Dark Matter

Is dark matter cold, warm or something else?

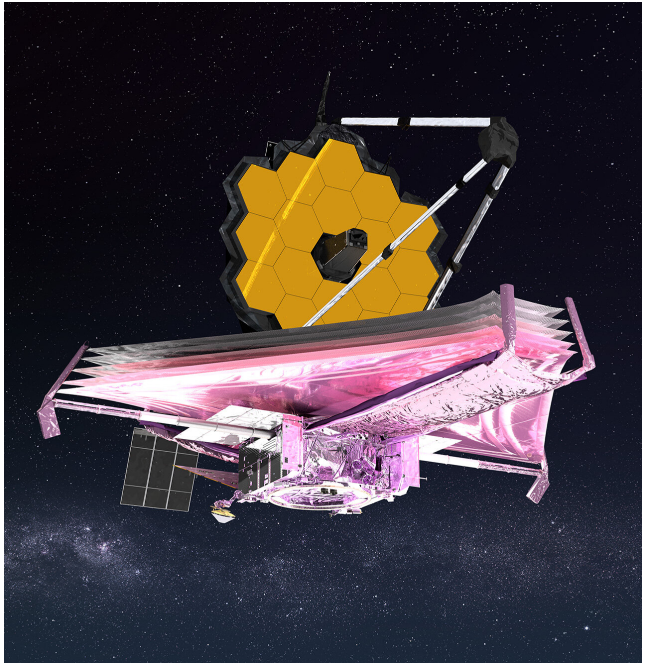
Can we overcome lens modeling systematics to answer this question?

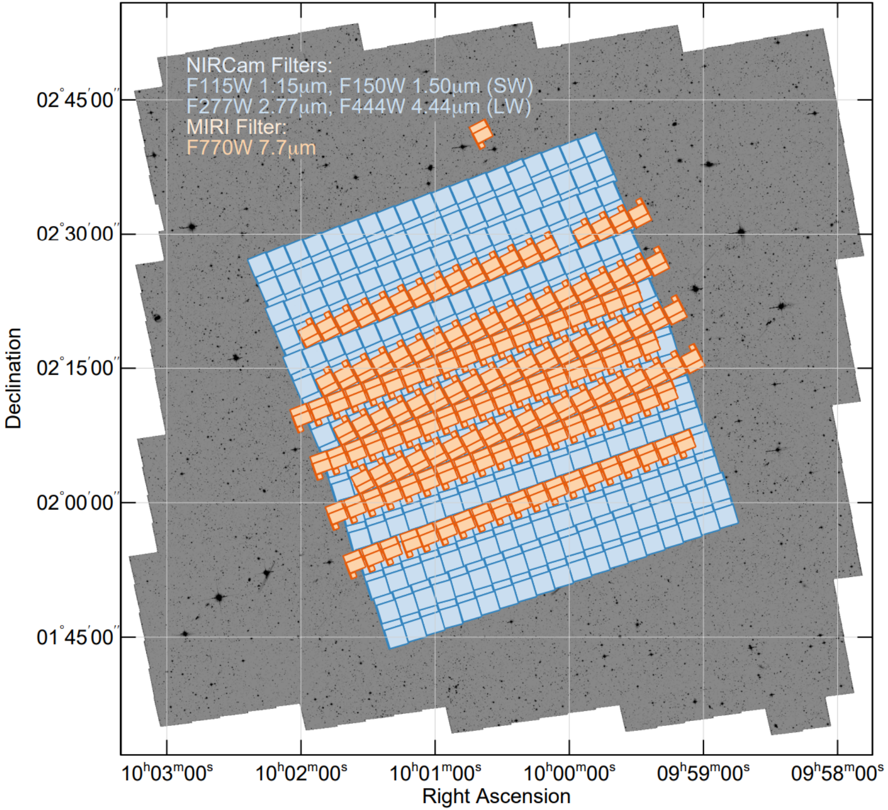
7+ years and no meaningful results on dark matter.

COSMOS Web / ALMA

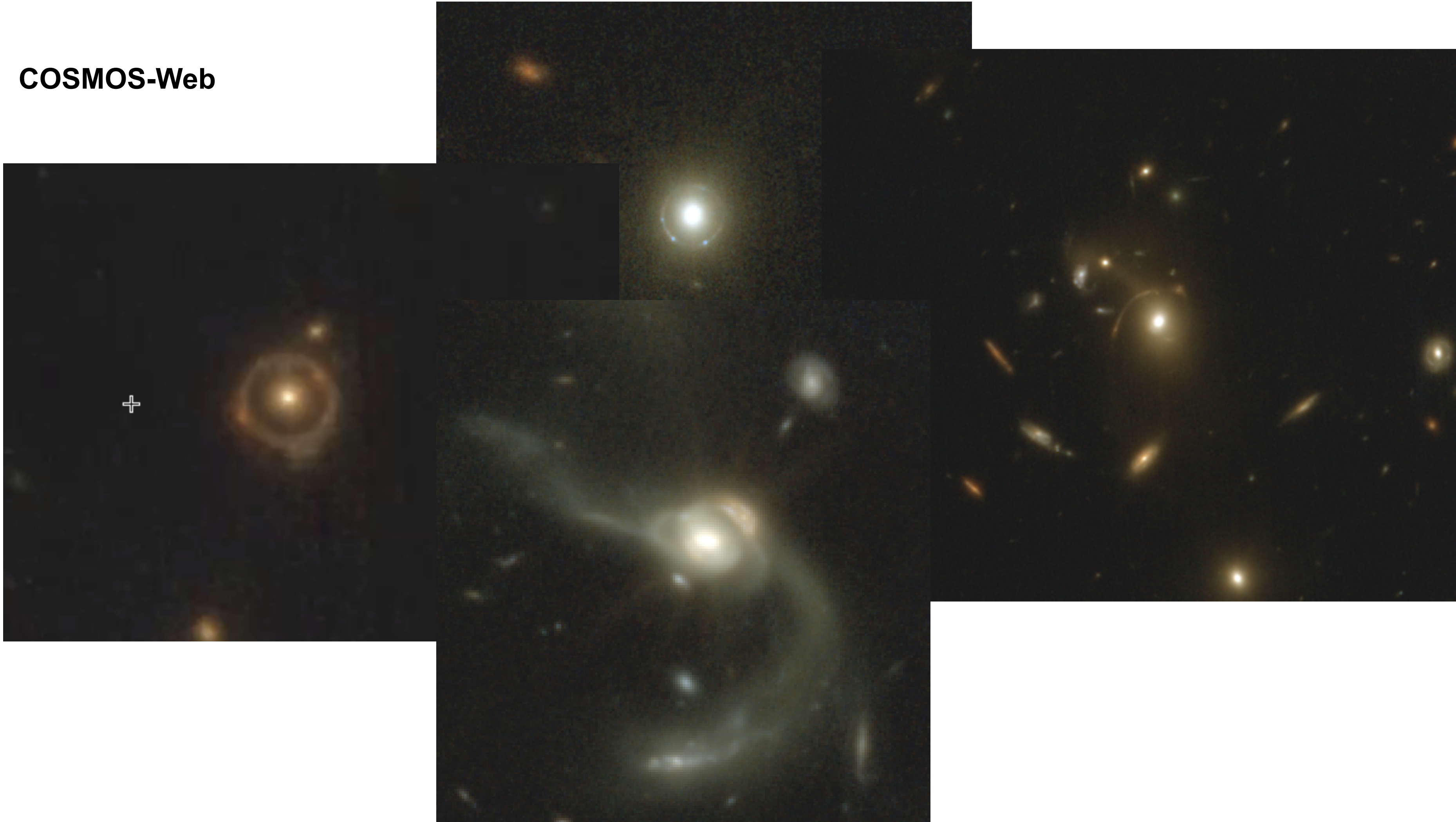
Future: JWST / COSMOS-Web

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

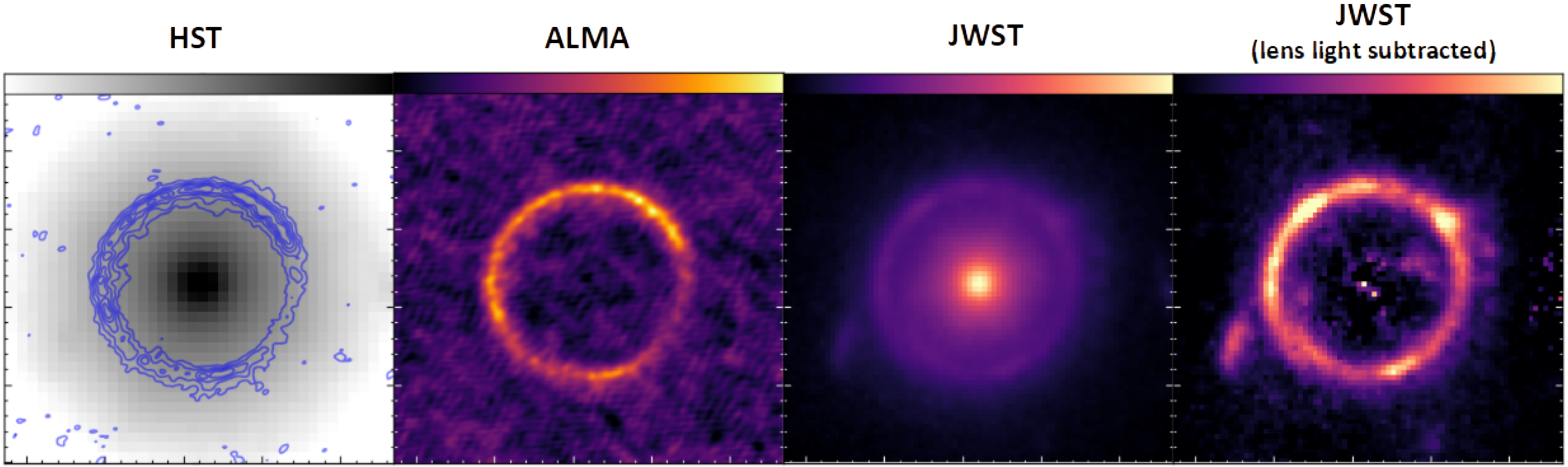




COSMOS-Web



Future: Interferometer Analysis (+ Multiwavelength)



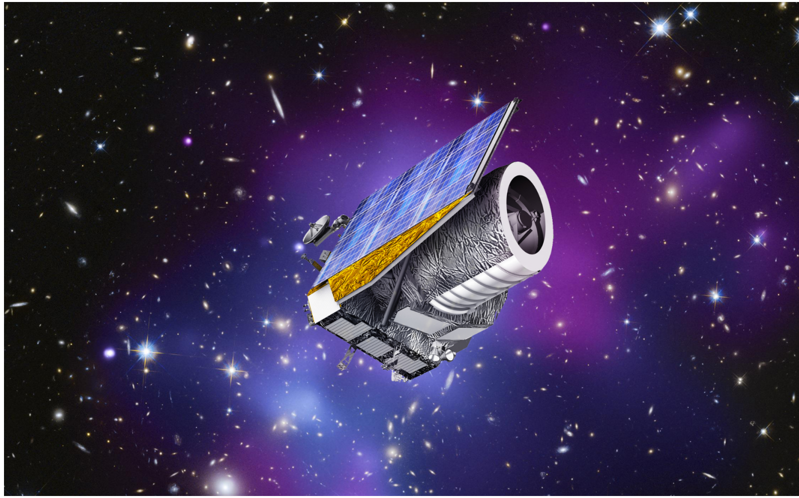
Euclid

Euclid

7+ years developing radiation damage correction / calibration software for Euclid data reduction.

I know many details of VIS processing.

Euclid:UK lead.



Cosmology & Cancer

Multidisciplinary research / industry collaboration

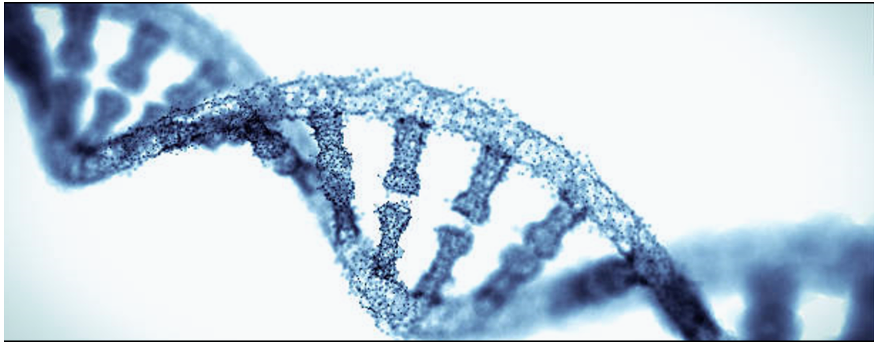
Concr

Deep Science Ventures Biotech company

https://www.concr.co/

CTO developed a Nested Sampling Algorithm for his PhD.

Met at a London Coworking space.

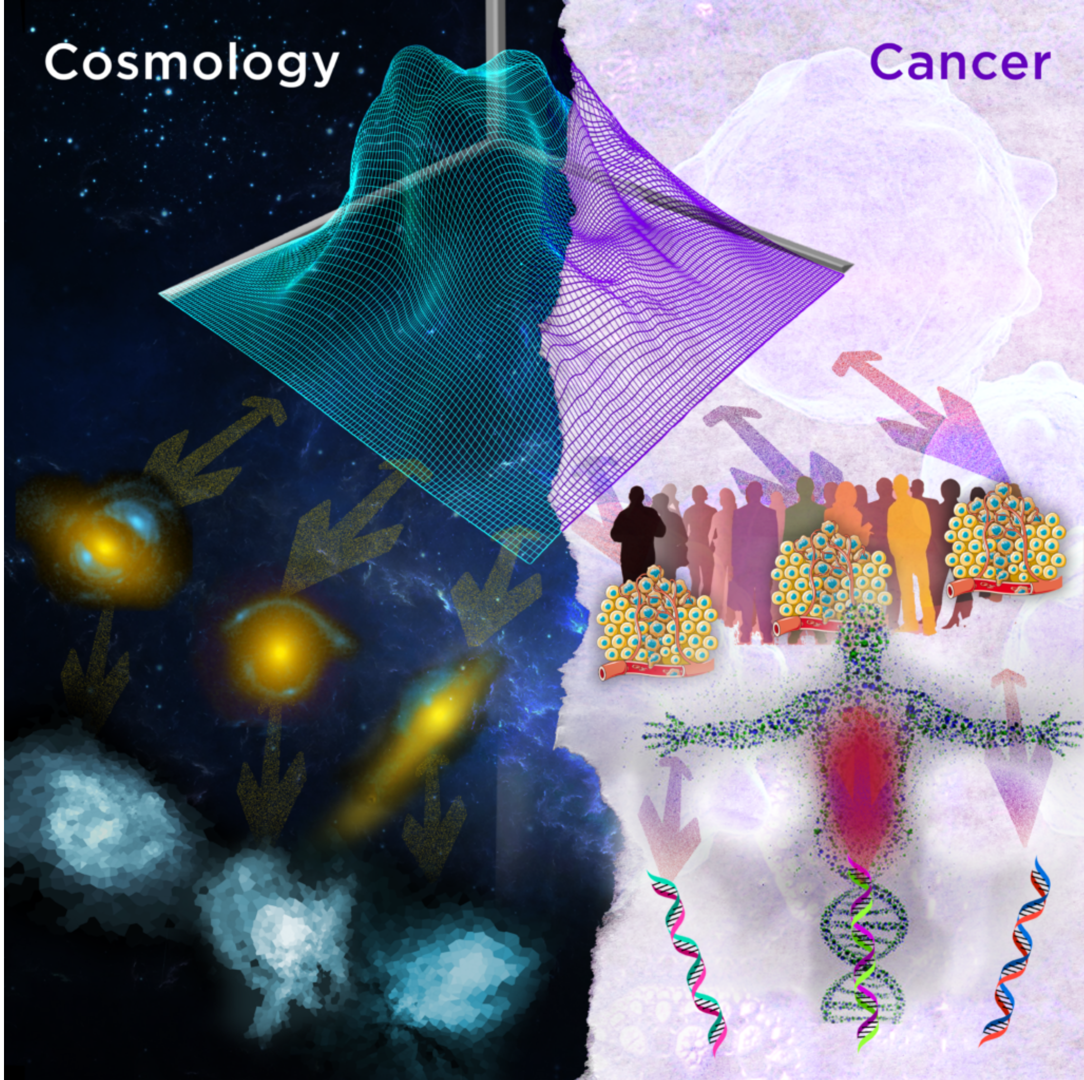


Cosmology & Cancer

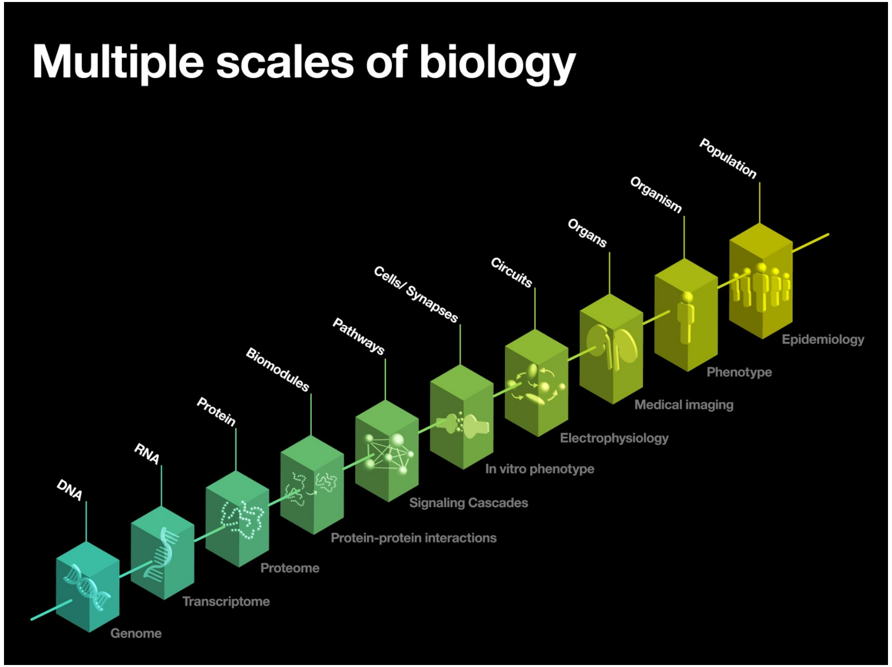
Open-source framework to scale Bayesian methods up to 100000+ strong lenses.

Collaborative development with cancer therapy researchers.

https://github.com/rhayes777/PyAutoFit



Multiscale Complexity



https://www.dkfindout.com/uk/space/stars-and-galaxies/scale-universe/
https://researcher.watson.ibm.com/researcher/view_group.php?id=5372

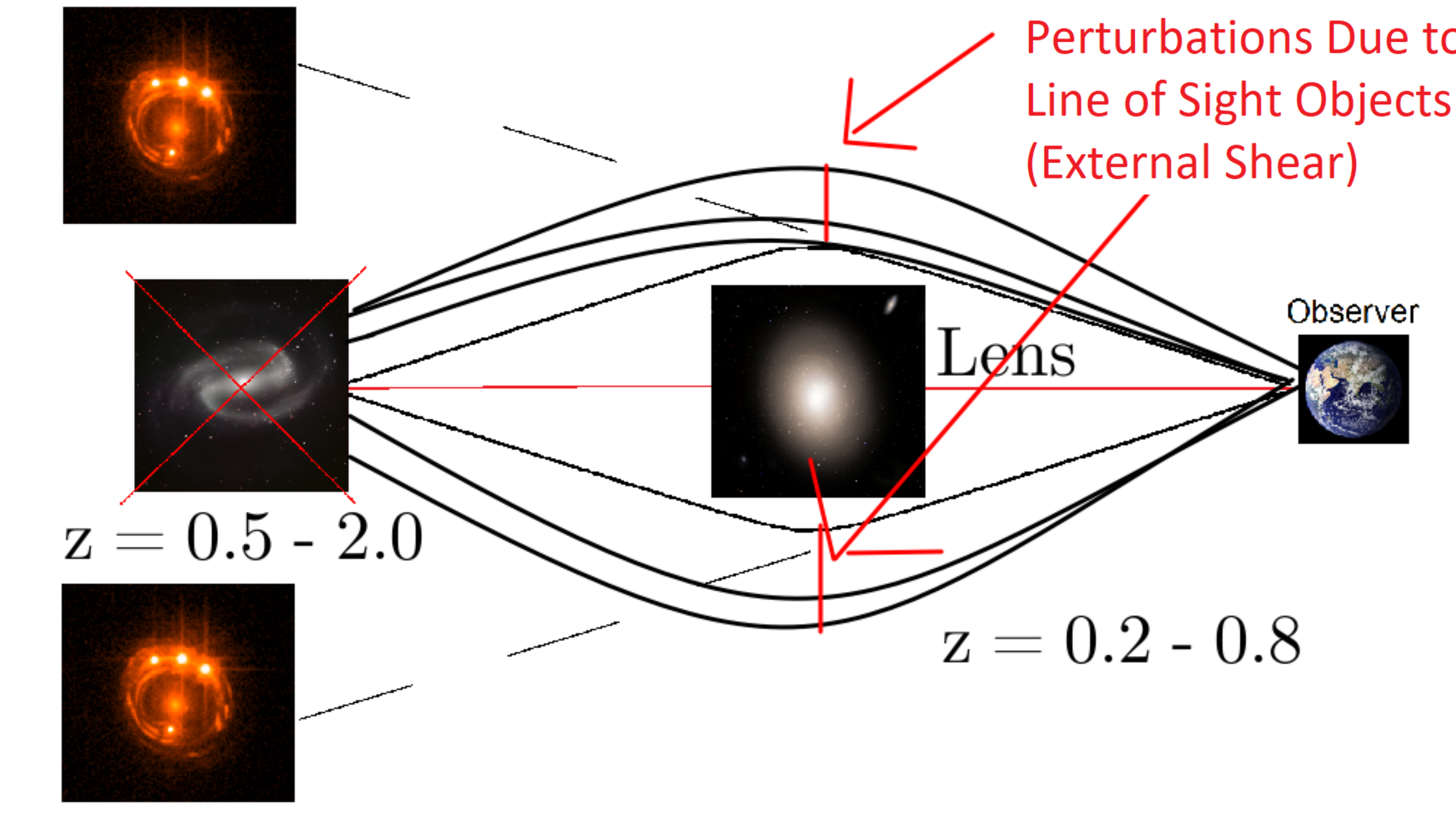
Summary

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.**

External Shear

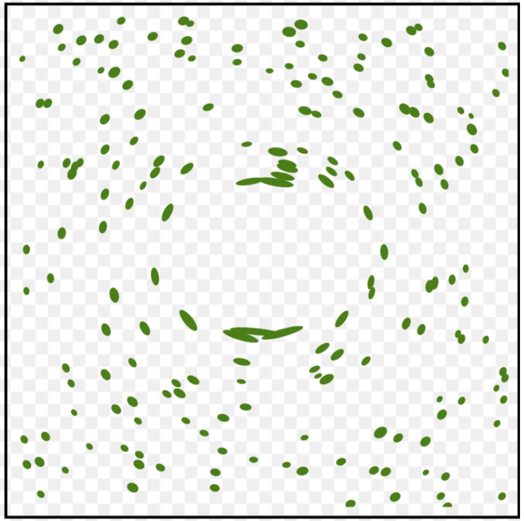


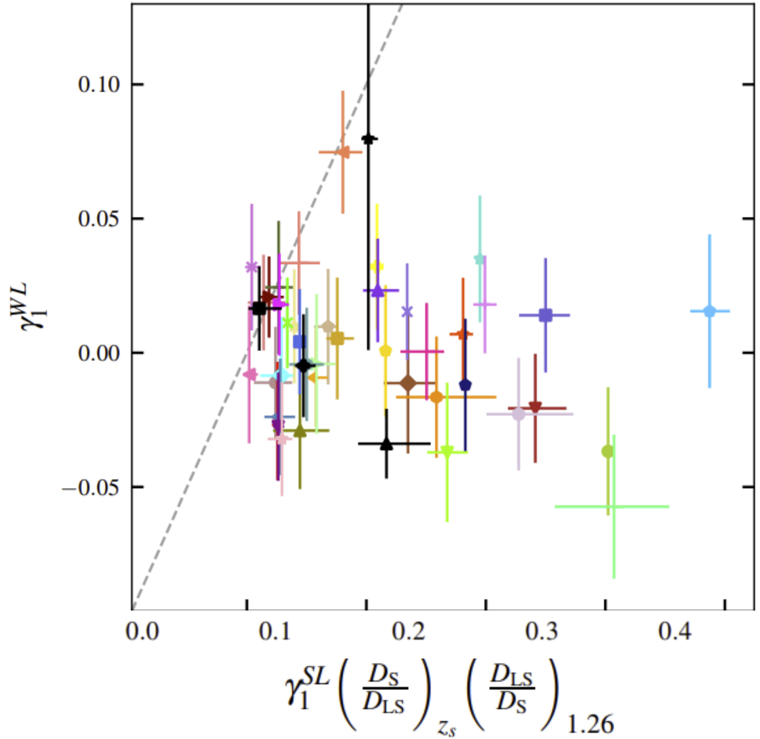
Perturbations Due to
Line of Sight Objects
(External Shear)
Observer
Lens
z = 0.5 - 2.0
z = 0.2 - 0.8

What is Shear?

An established quantity in weak lensing:

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





What is Strong Lensing Shear Measuring?

What is the shear in strong lens models?

Why is it not an external shear?

Can we measure weak lensing shear and use this to do Cosmology?