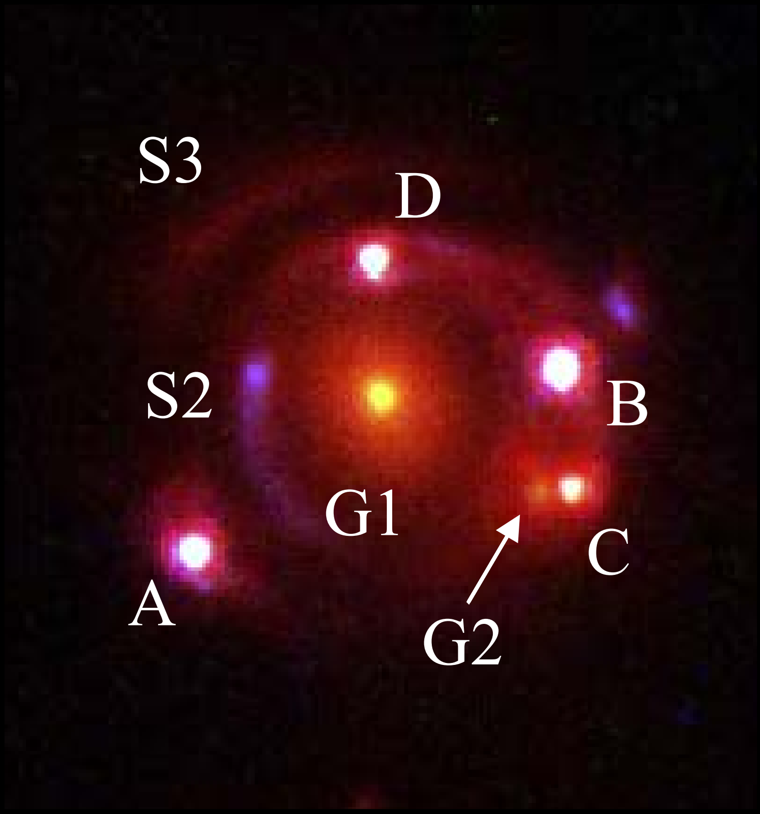
Strong lensing and dark matter. I: fundamentals, history, and future prospects



TOMMASO TREU
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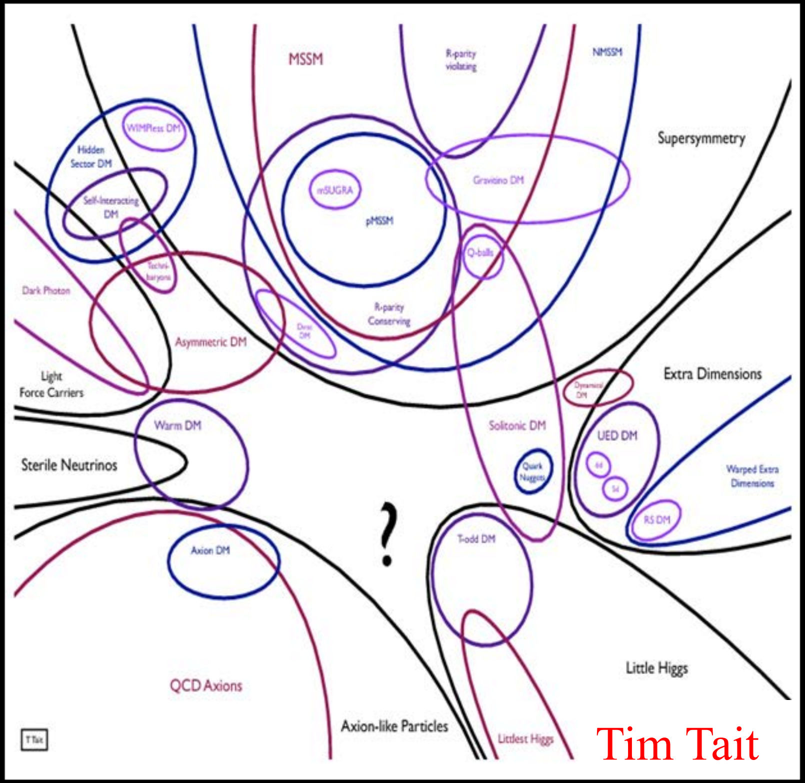
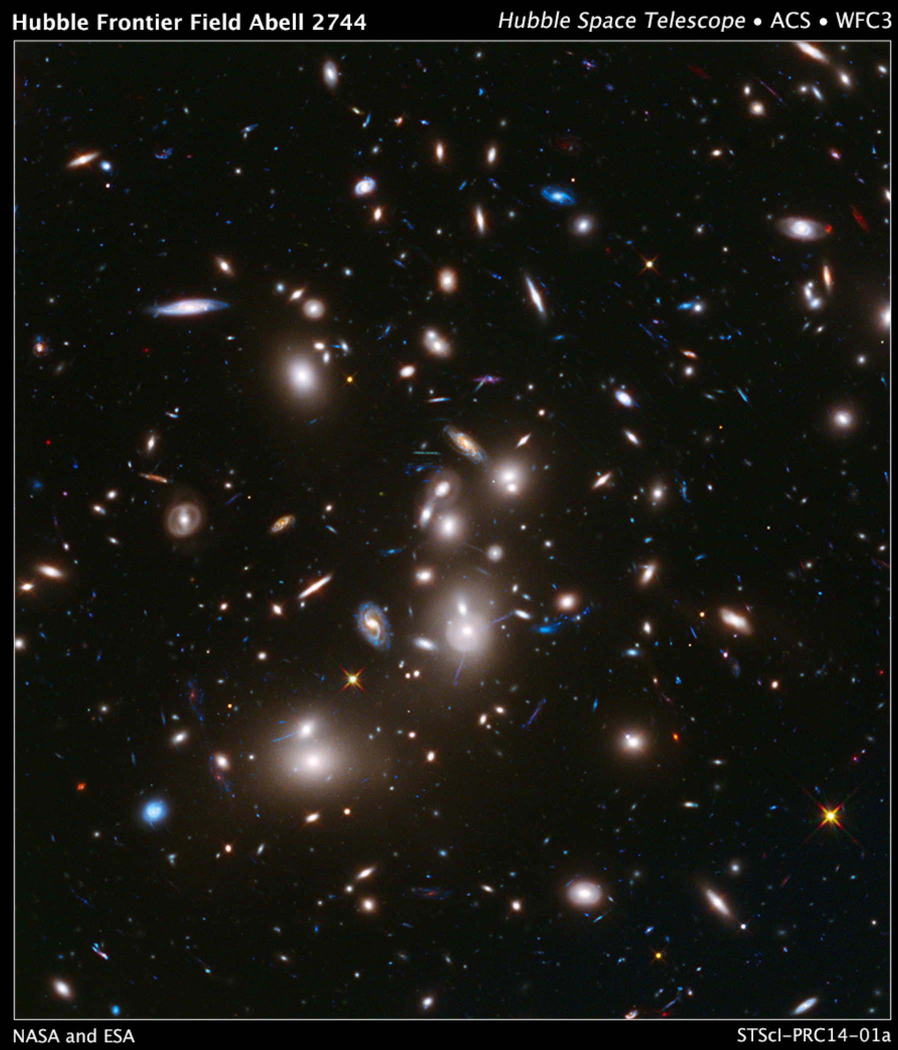
Outline

- Introduction.
  - The nature of dark matter
  - The missing satellite problem and other problems
- Lensing Probes:
    - Flux ratio anomalies
    - Gravitational imaging
    - Challenges
- Future outlook

A theorist's view



An observer’s view



A simulator’s view

Bolshoi collaboration

End to end dark matter experiment

Particle Physics ↔ **Cosmology (Growth of Structure)** ↔ General Relativity (Gravitational Lensing) ↔ Data

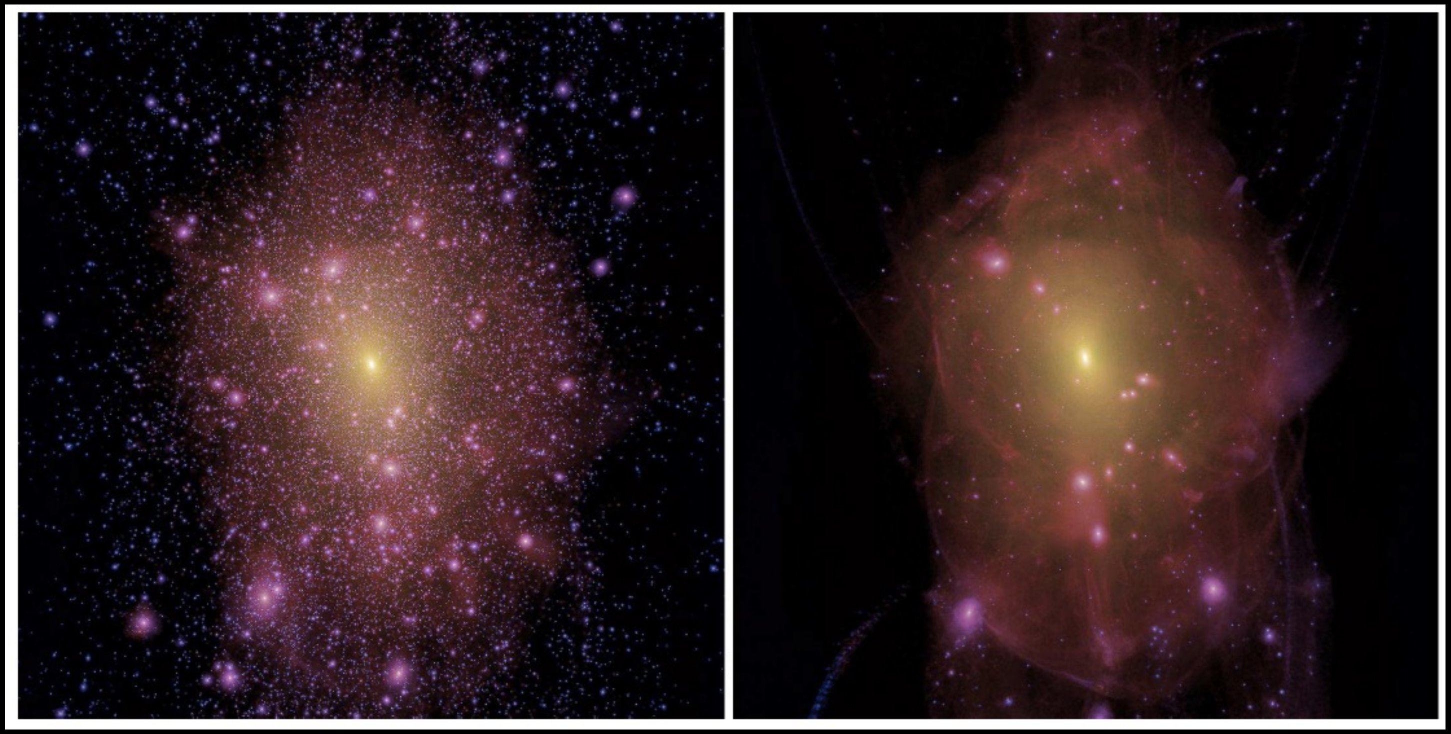
Particle Physics	Cosmology (Growth of Structure)	General Relativity (Gravitational Lensing)	Data
Kusenko **Zelko** **Keeley** **Gilman** **Treu** **....**	**Du** **Zelko** **Benson** **Gilman** **Nierenberg** **Treu** **...**	**Paugnat** **Gilman** **Birrer** **Nierenberg** **Schmidt** **Williams** **Treu** **....**	**Sheu** **Knabel** **Gilman** **Nierenberg** **Zelko** **Shajib** **Treu** **....**

Subhalos as a probe of The NATURE OF DARK MATTER

Examples of Astrophysical effects that can be probed by subhalos

- Is dark matter not completely cold ("non zero free streaming length")?
  - "warm" dark matter (WDM) changes the subhalo mass function
- Does dark matter interact with itself?
  - "self-interacting" dark matter (SIDM) can change the internal structure of subhalos
- Is dark matter made of primordial black holes?
  - Depending on PBH mass, very dense
- Is dark matter a light axion ("fuzzy")
  - Debroglie subhalos and changes mass profile

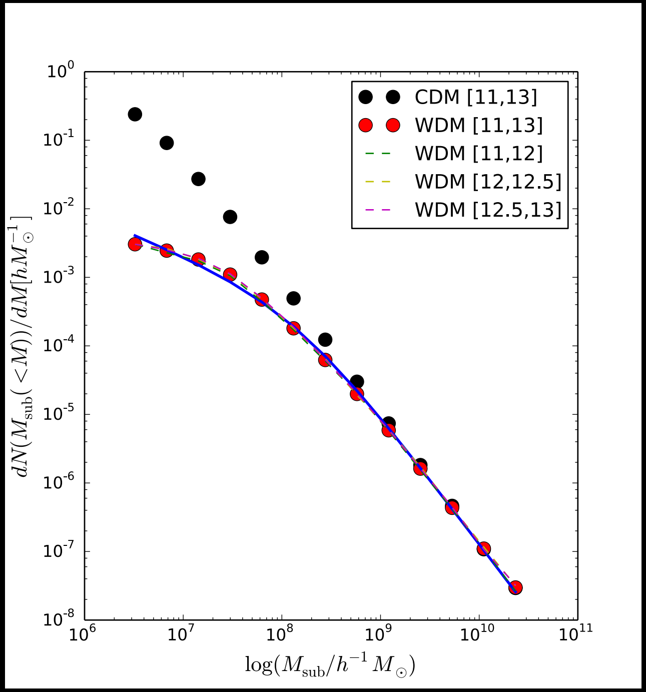
Warm Dark Matter



Free streaming ~kev scale thermal relic

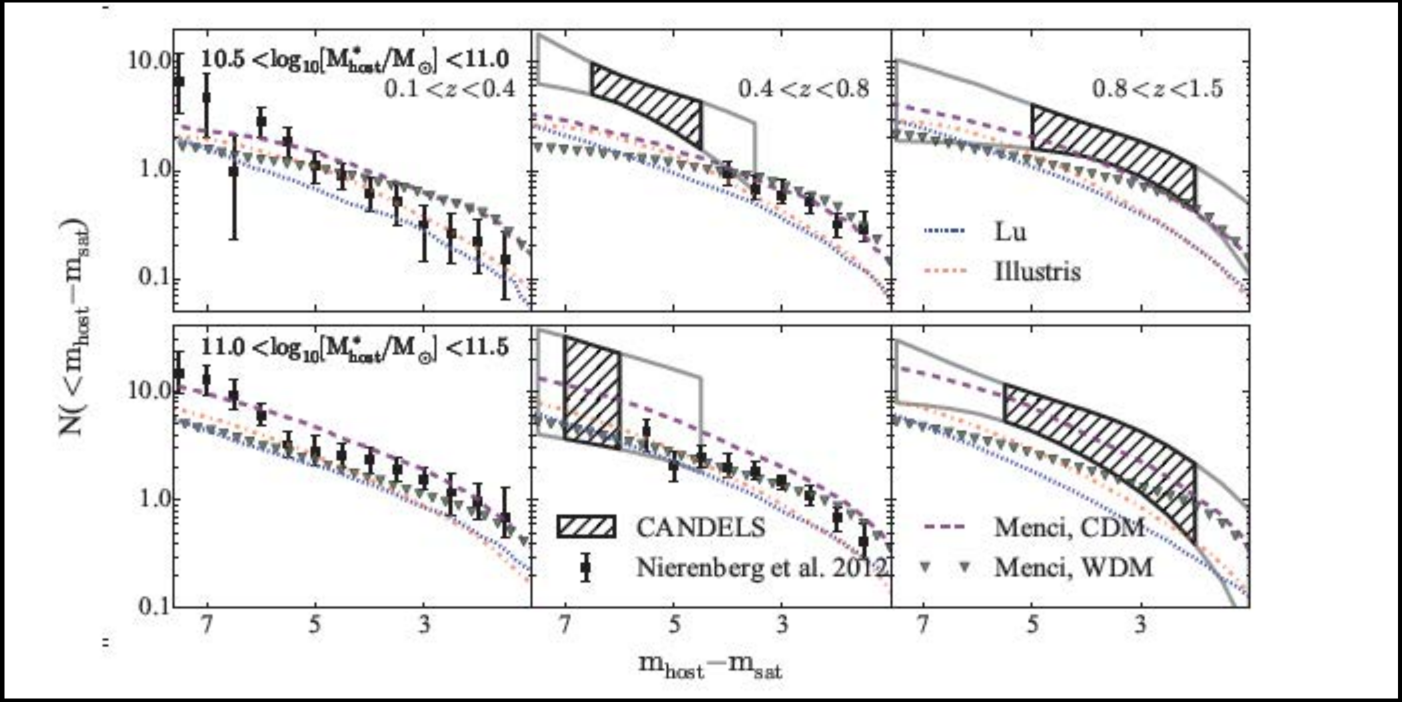
Lovell et al. 2014

Subhalos in CDM vs WDM



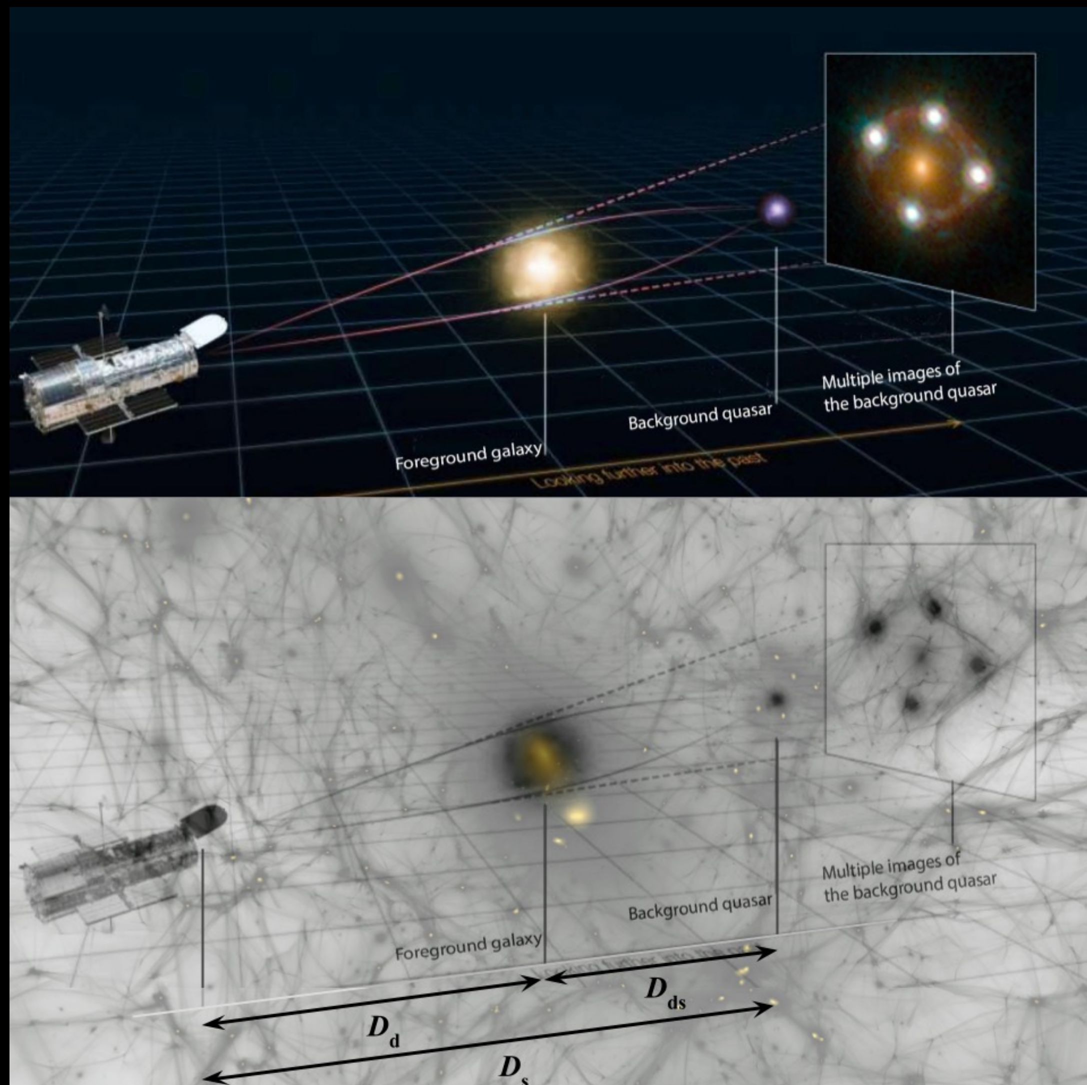
Li et al. 2016; Nierenberg et al. 2013

Luminous Satellites in CDM vs WDM



Nierenberg, Treu, Menci et al. 2016

What is Gravitational Lensing?



What is Gravitational Lensing?

Movie courtesy of Y. Hezaveh

Strong Lensing Basics. I

Surface mass density

$$\Sigma(\vec{\xi}) = \int \rho(\vec{\xi}, z)\, dz$$

Deflection angle

$$\vec{\hat{\alpha}}(\vec{\xi}) = \frac{4G}{c^2} \int \frac{(\vec{\xi} - \vec{\xi}')\Sigma(\vec{\xi}')}{|\vec{\xi} - \vec{\xi}'|^2}\, d^2\xi'$$

$$\hat{\alpha}(\xi) = \frac{4GM(\xi)}{c^2 \xi}$$

$$M(\xi) = 2\pi \int_0^{\xi} \Sigma(\xi')\xi'\, d\xi'$$

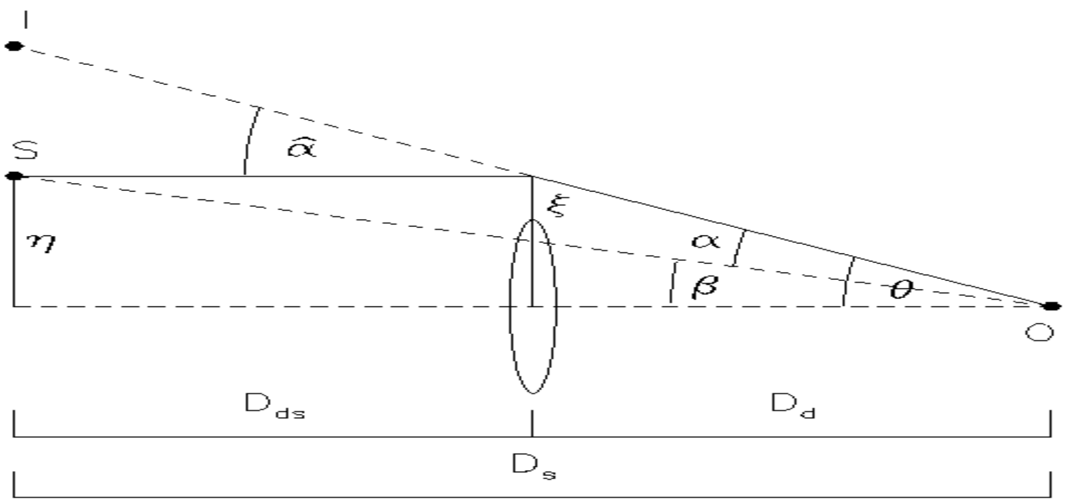
$$\vec{\alpha} = \frac{D_{\rm ds}}{D_{\rm s}} \vec{\hat{\alpha}}$$

$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$$

Lens equation

$$\Sigma_{\rm cr} = \frac{c^2}{4\pi G} \frac{D_{\rm s}}{D_{\rm d} D_{\rm ds}} = 0.35\,{\rm g\,cm^{-2}} \left(\frac{D}{1\,{\rm Gpc}}\right)^{-1}$$

Critical density



Strong Lensing Basics. II

2D potential

$$\psi(\vec{\theta}) = \frac{D_{\rm ds}}{D_{\rm d} D_{\rm s}} \frac{2}{c^2} \int \Phi(D_{\rm d}\vec{\theta}, z)\, dz$$

$$\vec{\nabla}_\theta \psi = D_{\rm d} \vec{\nabla}_\xi \psi = \frac{2}{c^2} \frac{D_{\rm ds}}{D_{\rm s}} \int \vec{\nabla}_\perp \Phi \, dz = \vec{\alpha}$$

2D Poisson Equation

$$\nabla^2_\theta \psi = \frac{2}{c^2} \frac{D_{\rm d} D_{\rm ds}}{D_{\rm s}} \int \nabla^2_\xi \Phi \, dz = \frac{2}{c^2} \frac{D_{\rm d} D_{\rm ds}}{D_{\rm s}} \cdot 4\pi G \Sigma = 2 \frac{\Sigma(\vec{\theta})}{\Sigma_{\rm cr}} \equiv 2\kappa(\vec{\theta})$$

$$\vec{\alpha}(\vec{\theta}) = \vec{\nabla}\psi = \frac{1}{\pi} \int \kappa(\vec{\theta}') \frac{\vec{\theta} - \vec{\theta}'}{|\vec{\theta} - \vec{\theta}'|^2} \, d^2\theta'$$

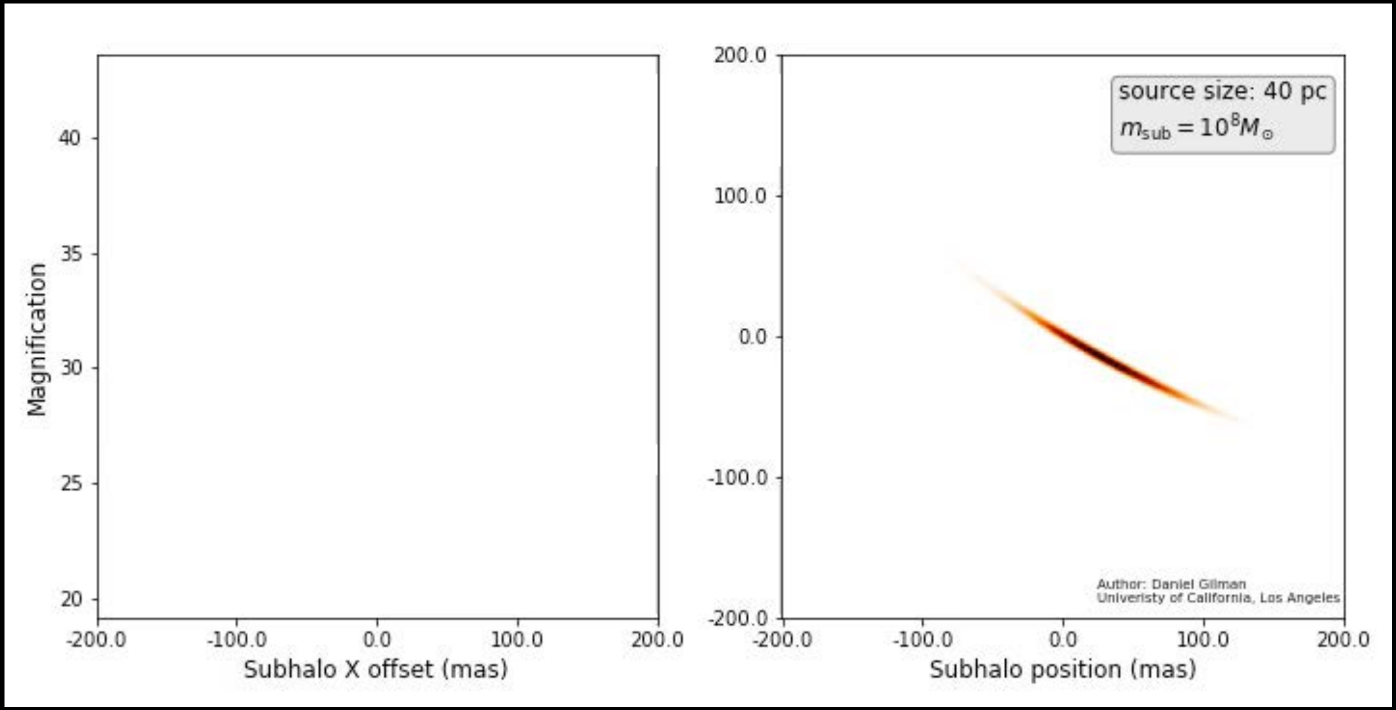
$$\mathcal{A} \equiv \frac{\partial \vec{\beta}}{\partial \vec{\theta}} = \left(\delta_{ij} - \frac{\partial \alpha_i(\vec{\theta})}{\partial \theta_j} \right) = \left(\delta_{ij} - \frac{\partial^2 \psi(\vec{\theta})}{\partial \theta_i \partial \theta_j} \right) = \mathcal{M}^{-1}$$

Jacobian matrix and magnification

Subhalos and lensing

- Strong lensing can detect subhalos based solely on mass!
- subhalos are detected as “anomalies” in the gravitational potential ψ and its derivatives
  - ψ'' = Flux anomalies
  - ψ' = Astrometric anomalies
  - ψ = Time-delay anomalies
- **Natural scale is a few milliarcseconds. Astrometric perturbations of 10mas are expected**

“Missing satellites” and lensing



Courtesy of D.Gilman

1998. The beginning

Evidence for substructure in lens galaxies?

Shude Mao and Peter Schneider

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Accepted 1997 November 7. Received 1997 November 7; in original form 1997 July 24

ABSTRACT
We discuss whether one should expect that multiply imaged QSOs can be understood with 'simple' lens models that contain only a few parameters. Whereas for many lens systems such simple mass models yield a remarkably good description of the observed properties, there are some systems which are notoriously difficult to understand quantitatively. We argue that at least in one case (B 1422 + 231) these difficulties are not (solely) due to a 'wrong' parametrization of the lens model, but that the discrepancy between observed and model-predicted flux ratios is due to substructure in the lens. As in microlensing for optical fluxes, such substructure can distort also the radio flux ratios predicted by 'simple' mass models, in particular for highly magnified images, without appreciably changing image positions. Substructure also does not change the time delay significantly, and therefore has little effect on the determination of the Hubble constant using time delays. We quantify these statements with several simple scenarios for substructure, and propose a strategy to model lens systems in which substructure is suspected.

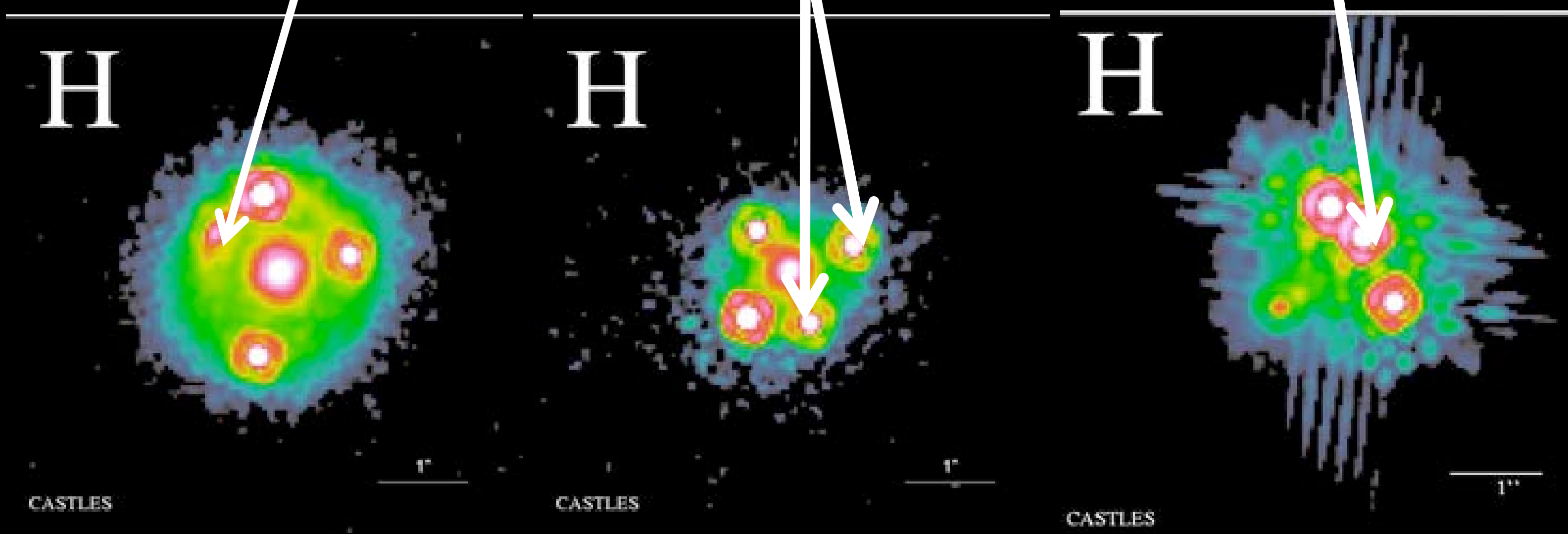
Flux Ratio Anomalies

A smooth mass distribution would predict:

This to be 100x brighter

These to be 2x brighter

This to be 10% brighter

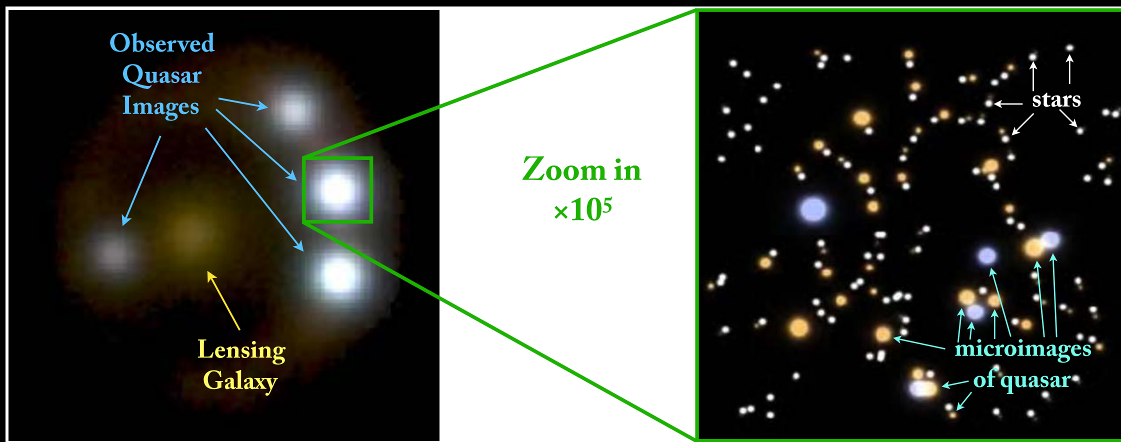


What causes this the anomaly?

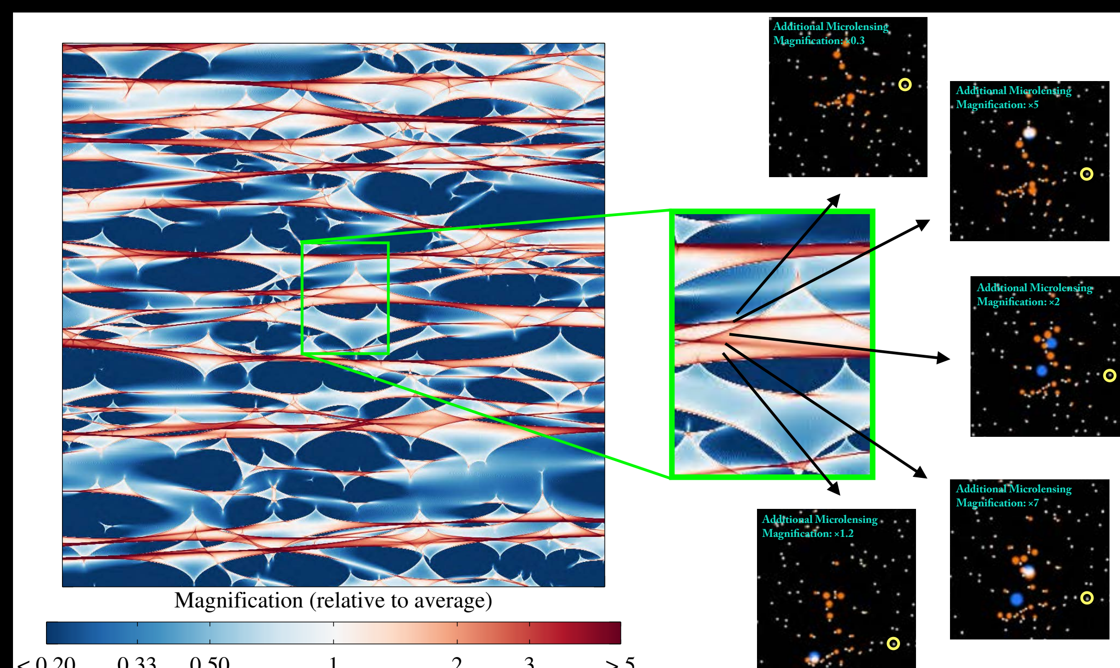
1.Dark satellites?

2.Astrophysical noise? (microlensing, dust, azimuthal structure)

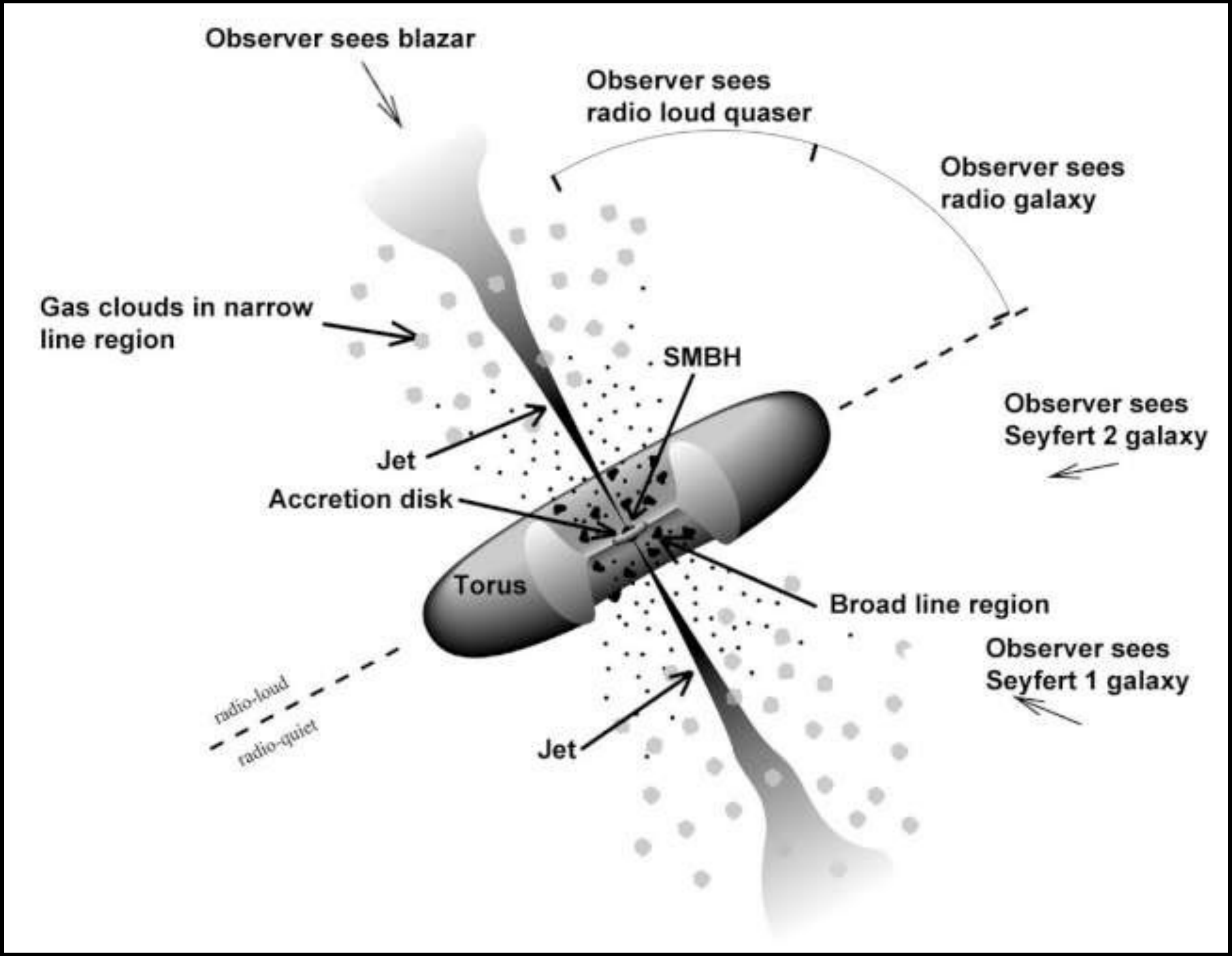
Optically Thick Microlensing



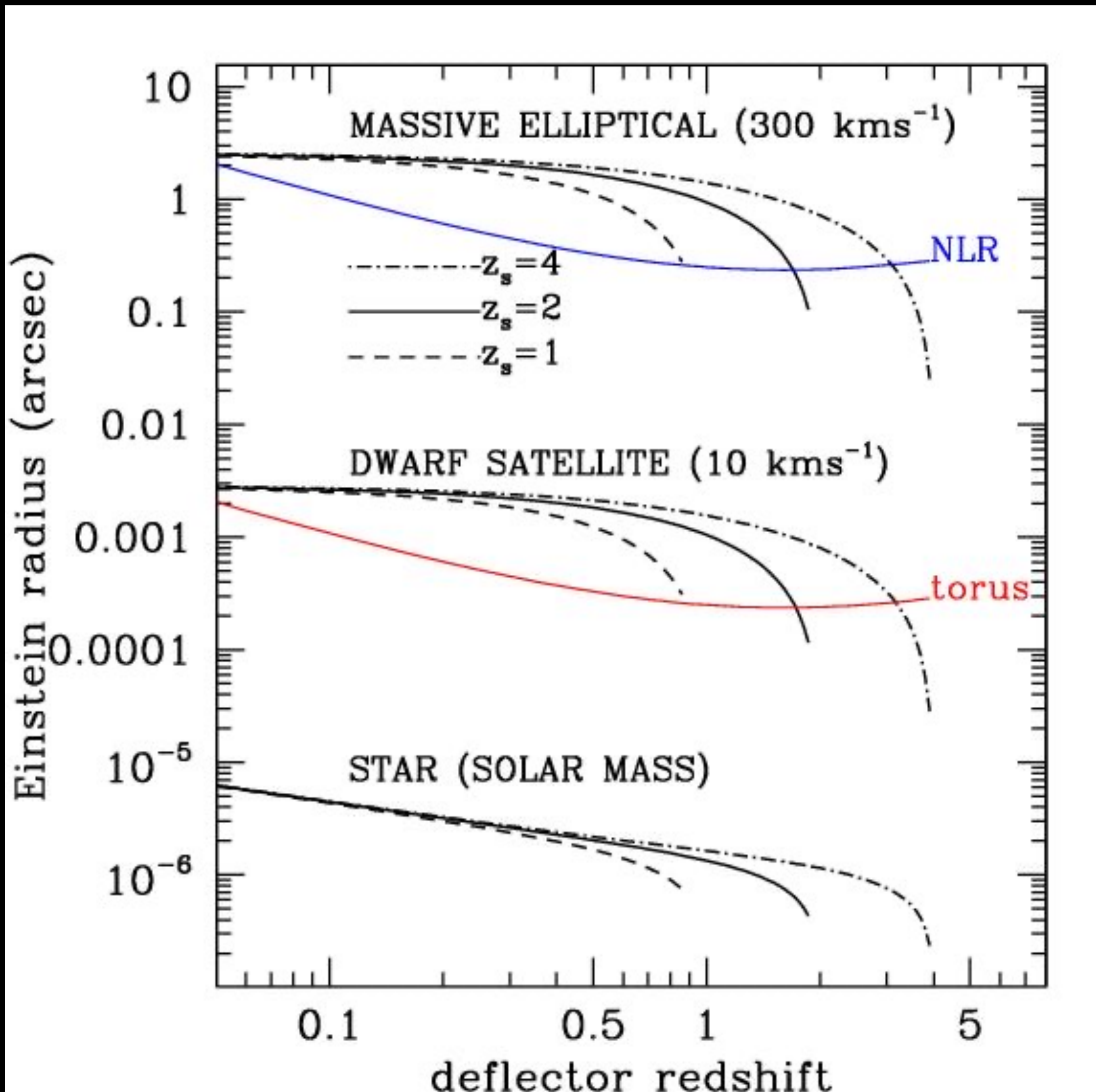
Pooley et al. 2019



Why source size matters?



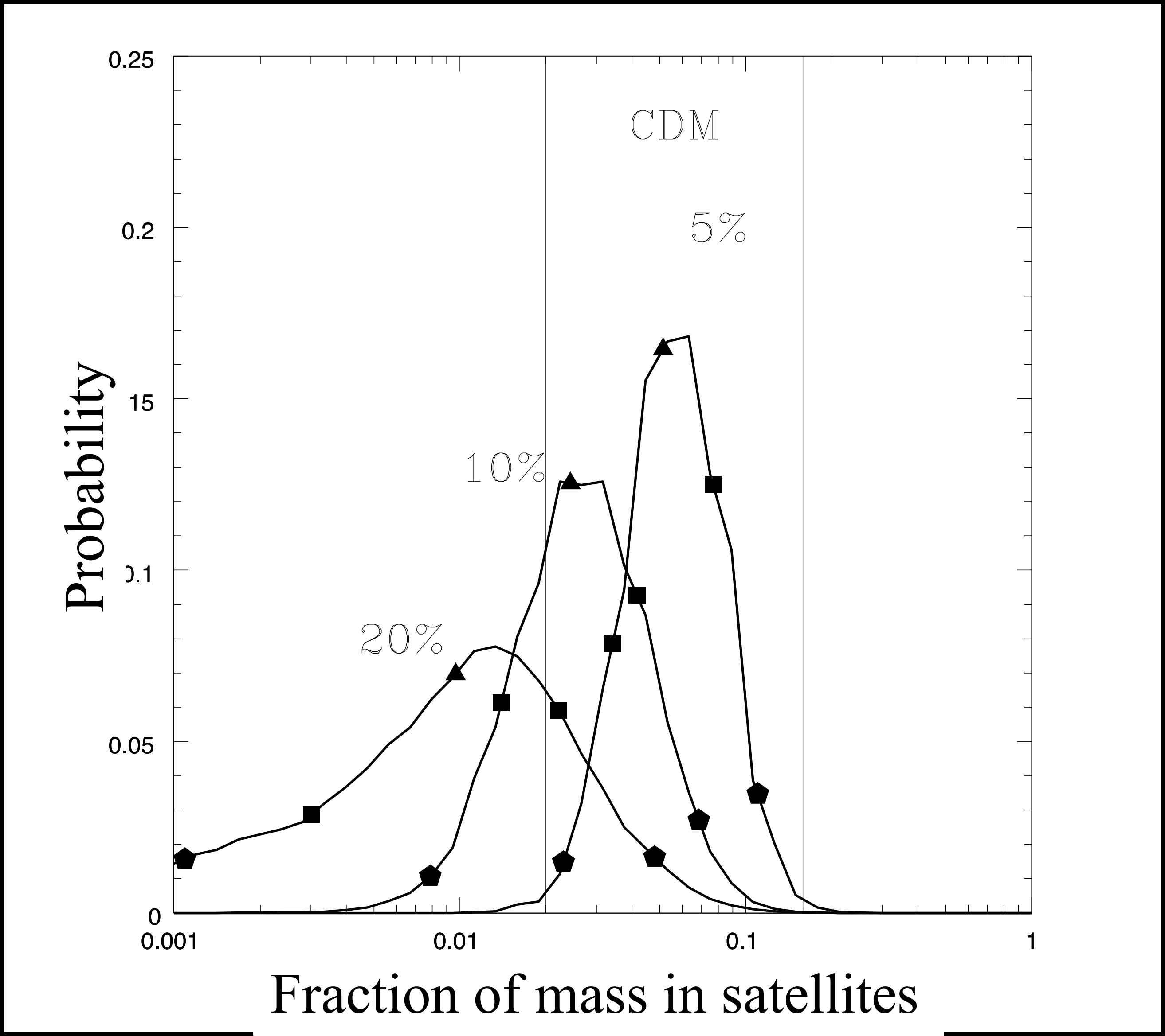
Dusty Torus and Narrow Line Region (and jet) Are not affected by microlensing (and dust)



Moustakas & Metcalf 2003

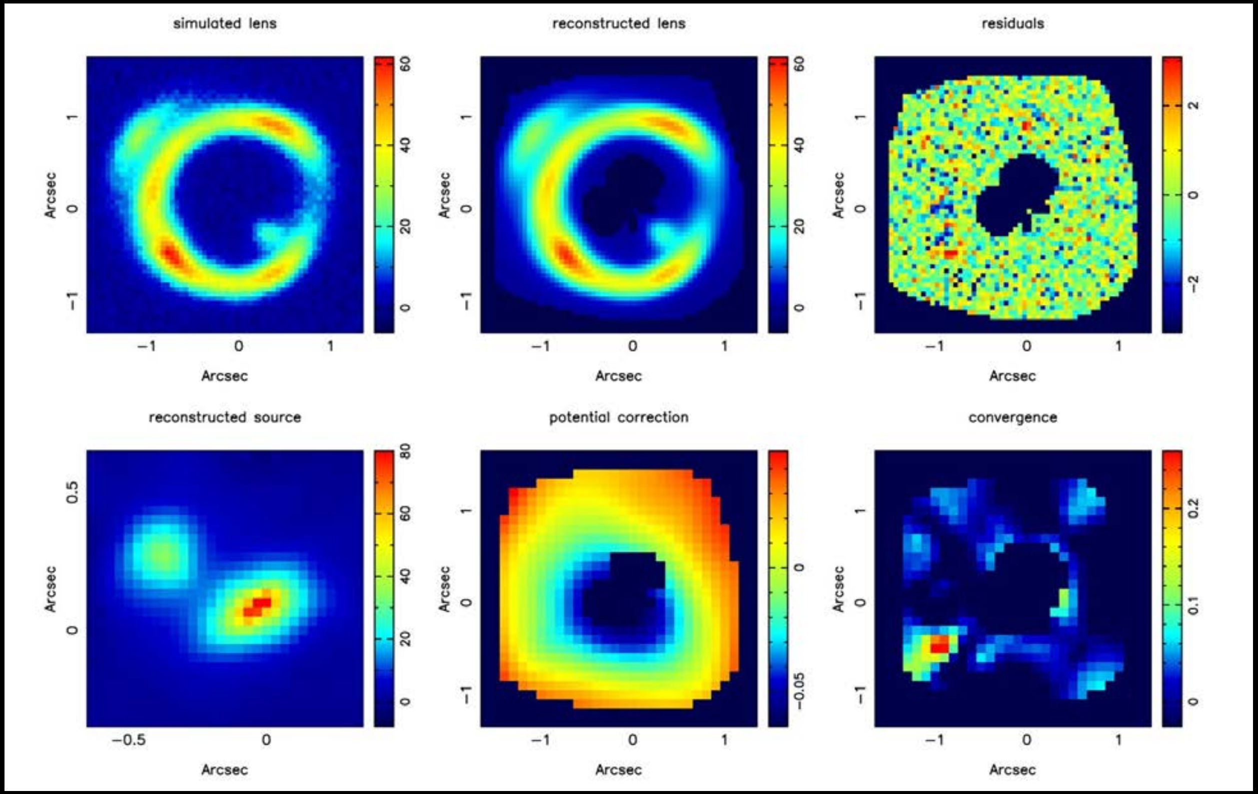
Chiba+ 2005

2002. Anomalies detected in 7 radio lenses



Dalal and Kochanek 2002

2005. Gravitational Imaging



Koopmans 2005

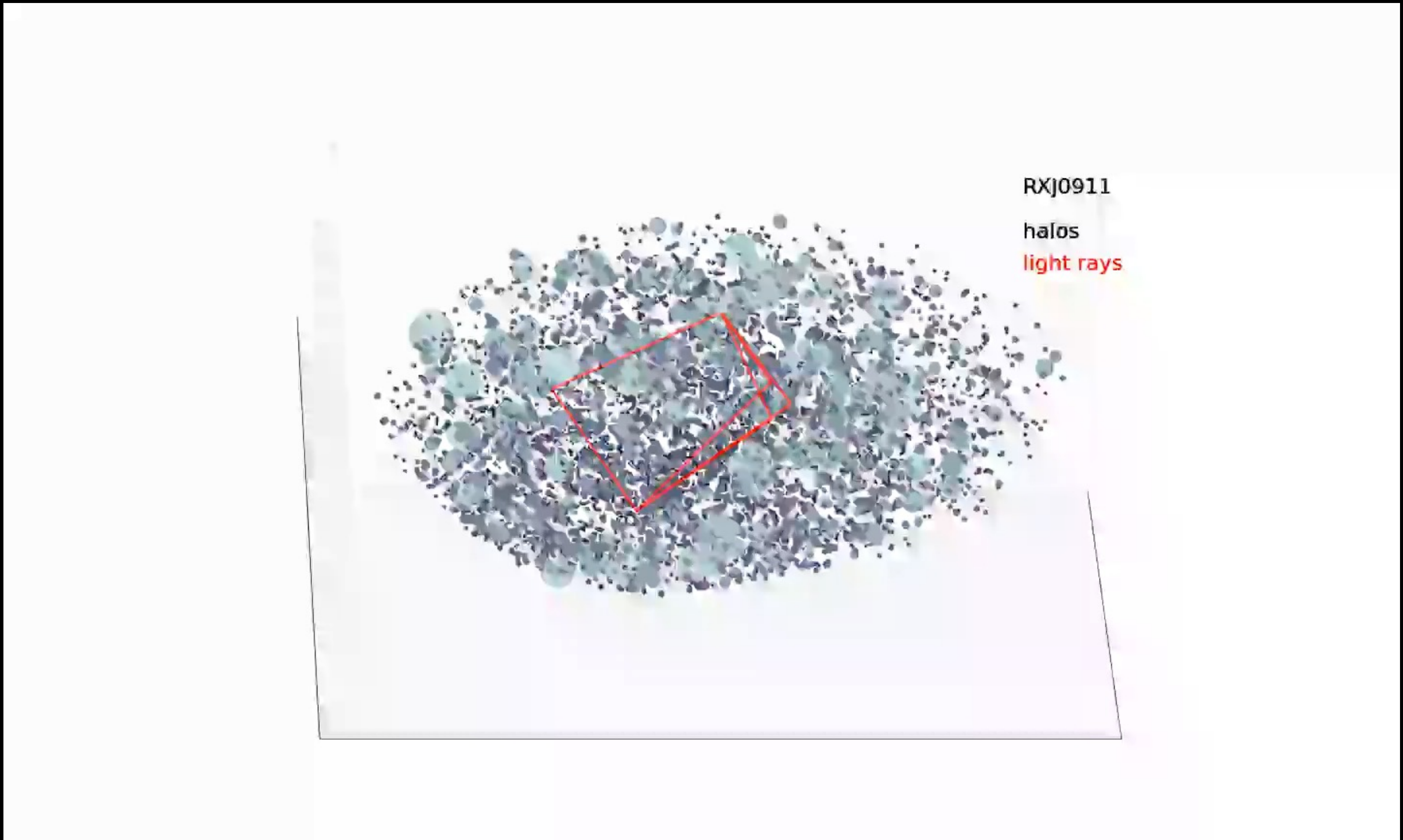
Questions in the mid 2000

1. Can azimuthal complexity of the deflector mimic substructure (Evans and Witt 2003)?
2. What are the contributions from the line of sight?
3. How do we translate substructure detection to dark matter properties?

Answers

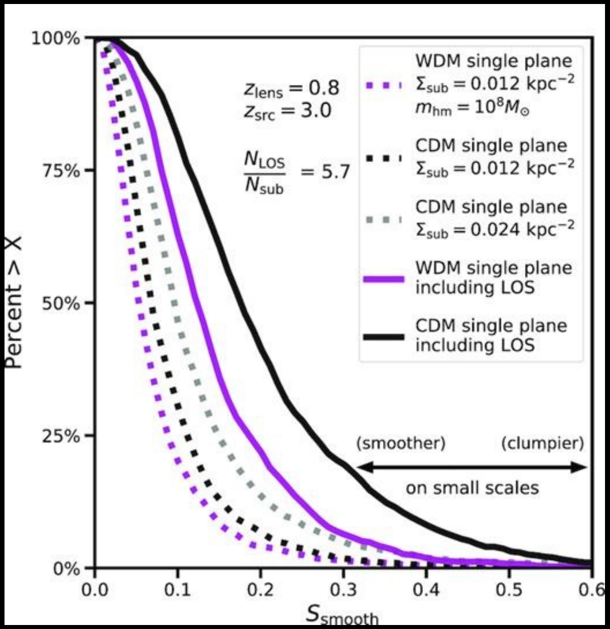
1. Azimuthal complexity?
   1. Avoid disky lenses and model azimuthal structure (Gilman et al. 2017)
2. Contributions from the line of sight?
   1. Significant, they need to be included (Gilman et al. 2019)
3. Inference of dark matter properties
   1. Detailed calculations of structure growth, especially tidal effects (Du et al. 2024)

Line of sight: The problem in 3D

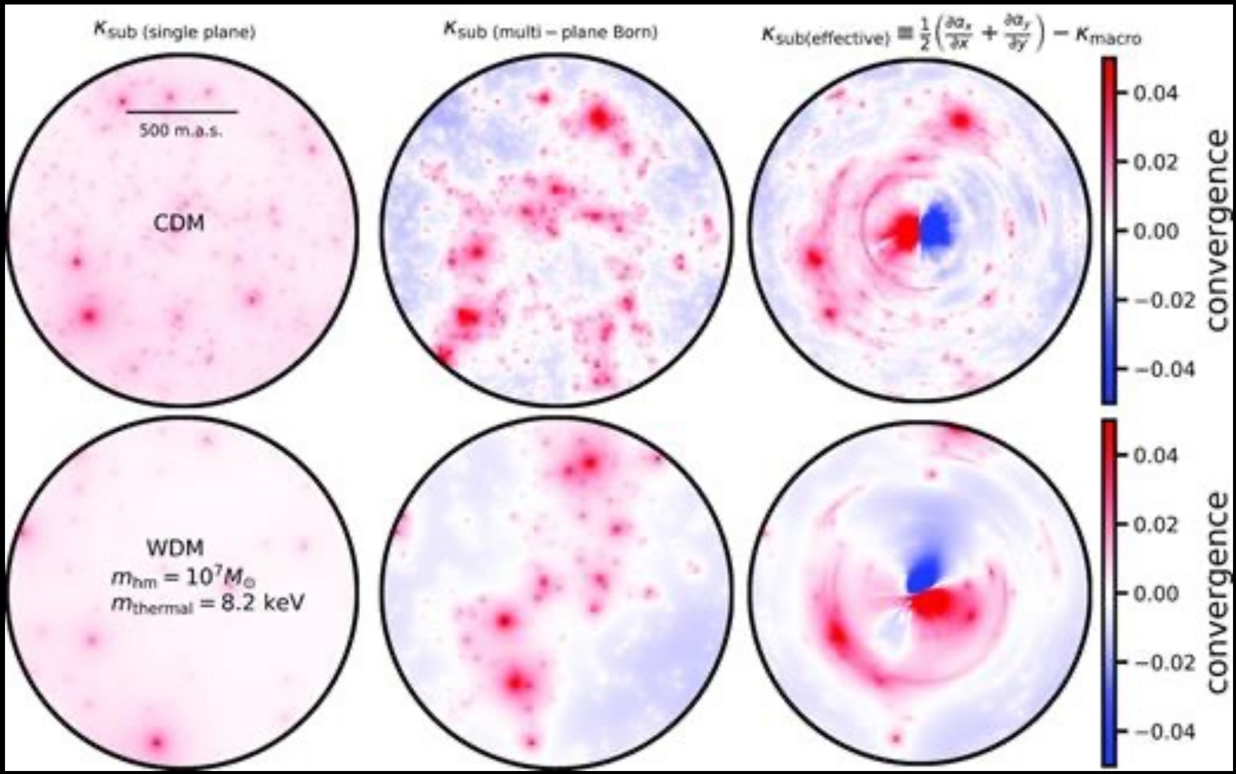


Courtesy of Daniel Gilman

Flux ratio anomalies: statistical treatment including LOS



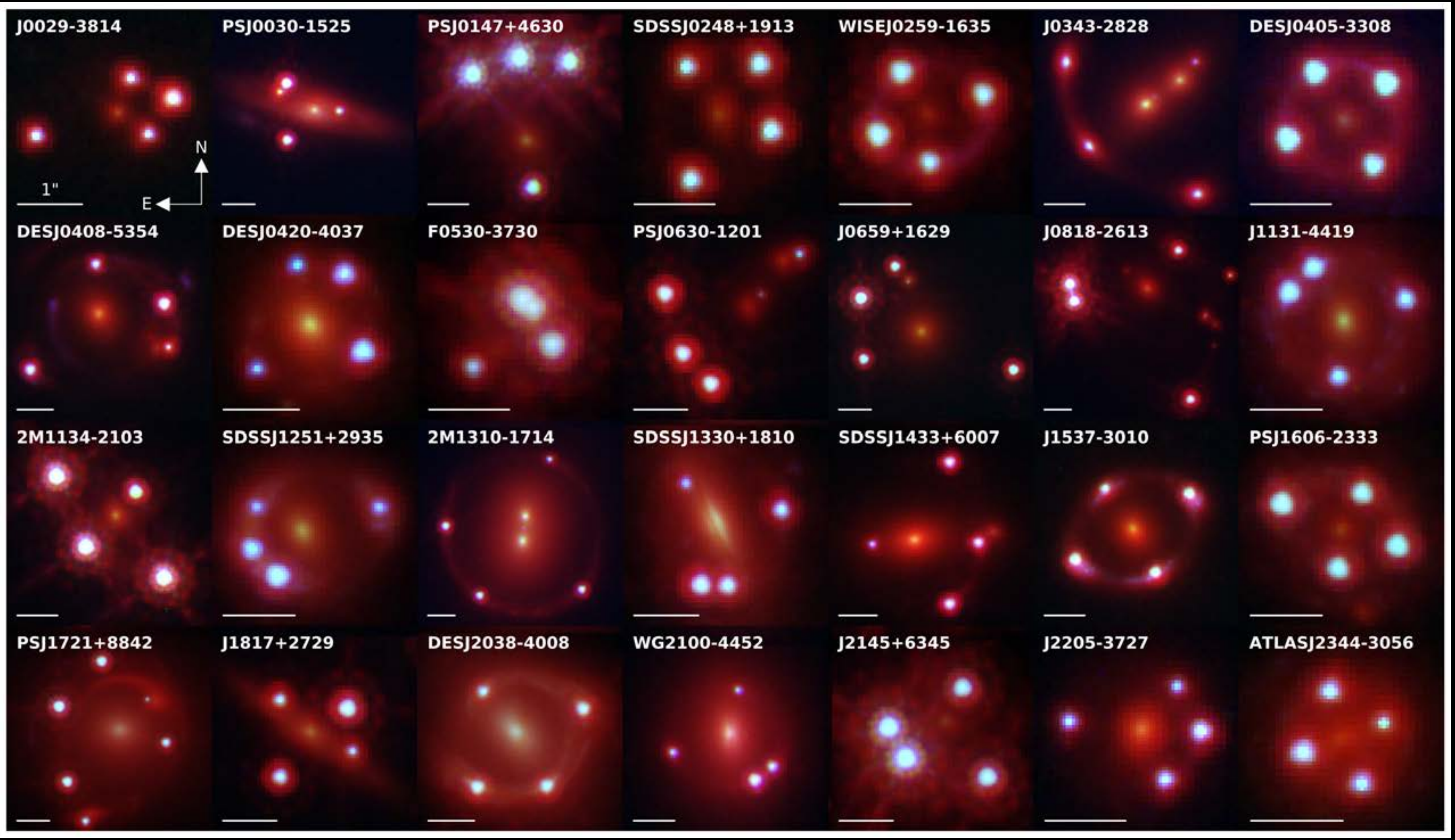
Gilman, Birrer, Treu et al. 2019



How do we make progress in practice?

1. Larger samples
2. Extract more information per system
3. Work on the connection between particle theory and astronomical observables

Larger samples



Schmidt, TT et al. 2023

Quads are rare ($0.01/deg^2$) but we are making progress!

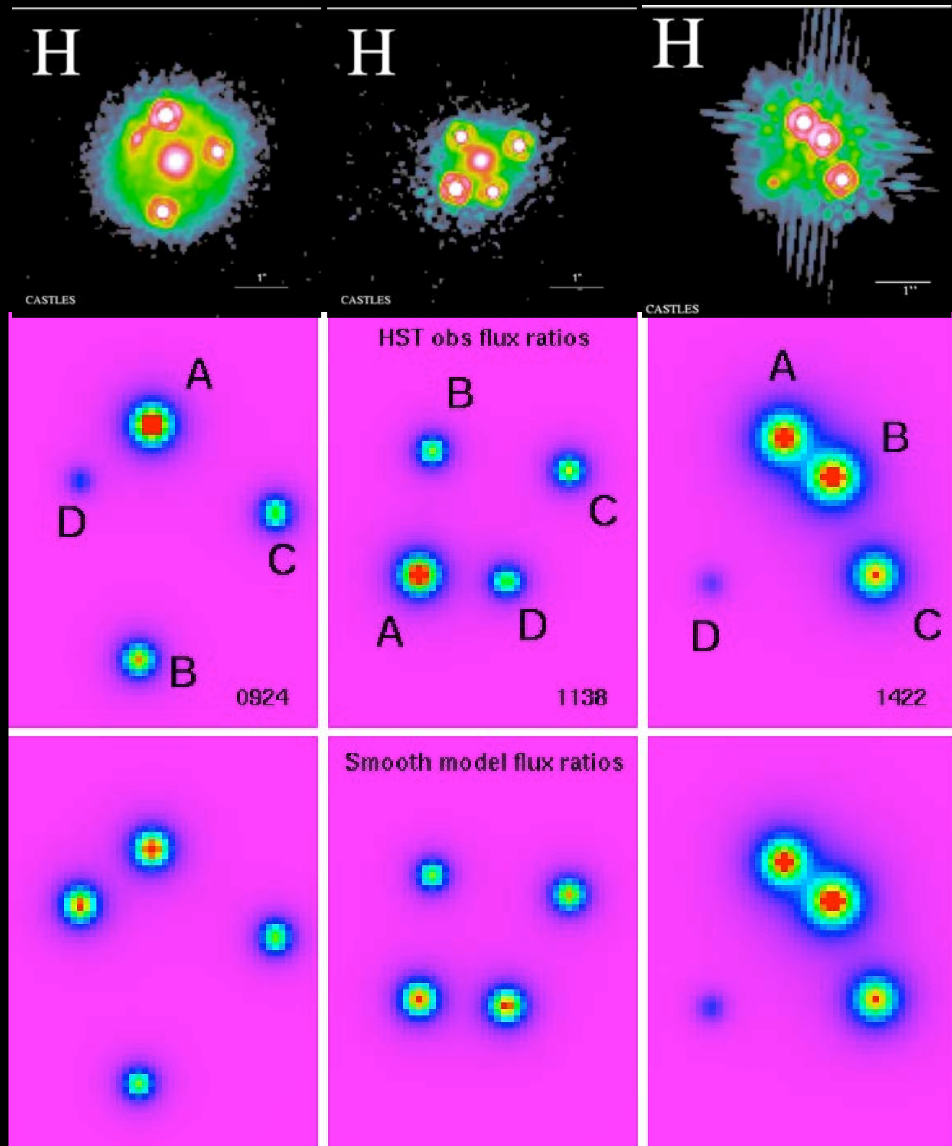
Larger Samples:Narrow line flux ratios of lensed AGN

Benefits:

1. Confirm/eliminate microlensing

2. High resolution spectroscopy rules out wavelength-dependent suppression (e.g. dust)

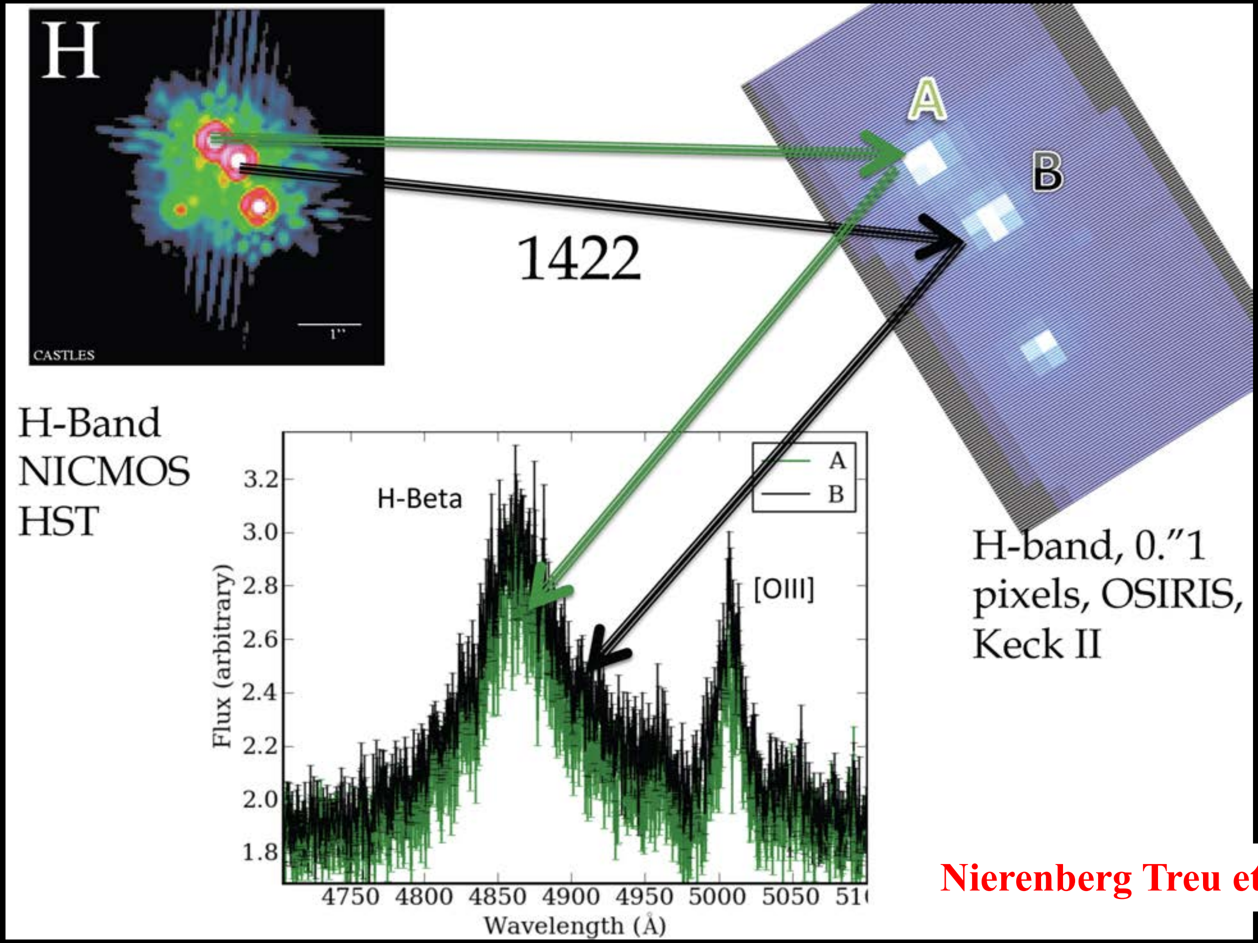
3. Excellent astrometry and photometry



If the anomaly is from substructure…

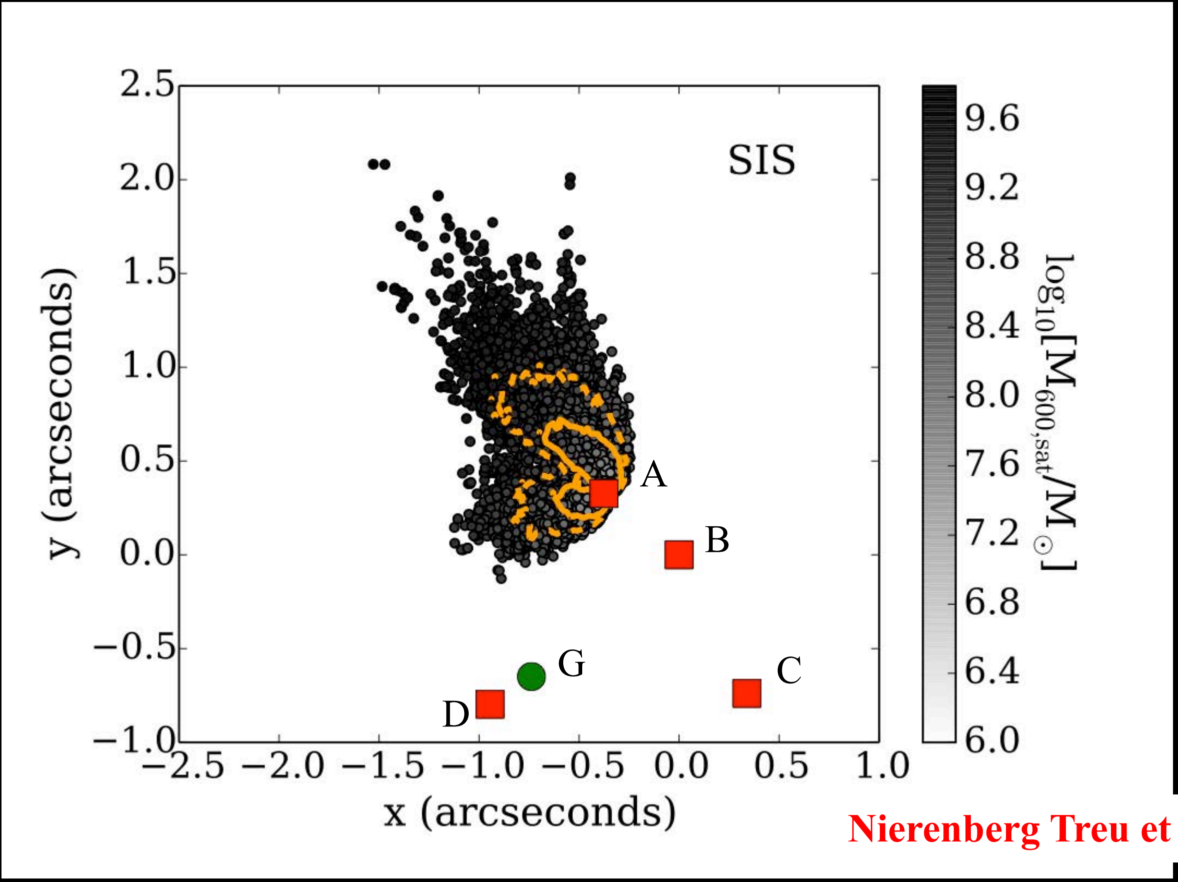
If the anomaly is from microlensing…

OSIRIS detection of substructure



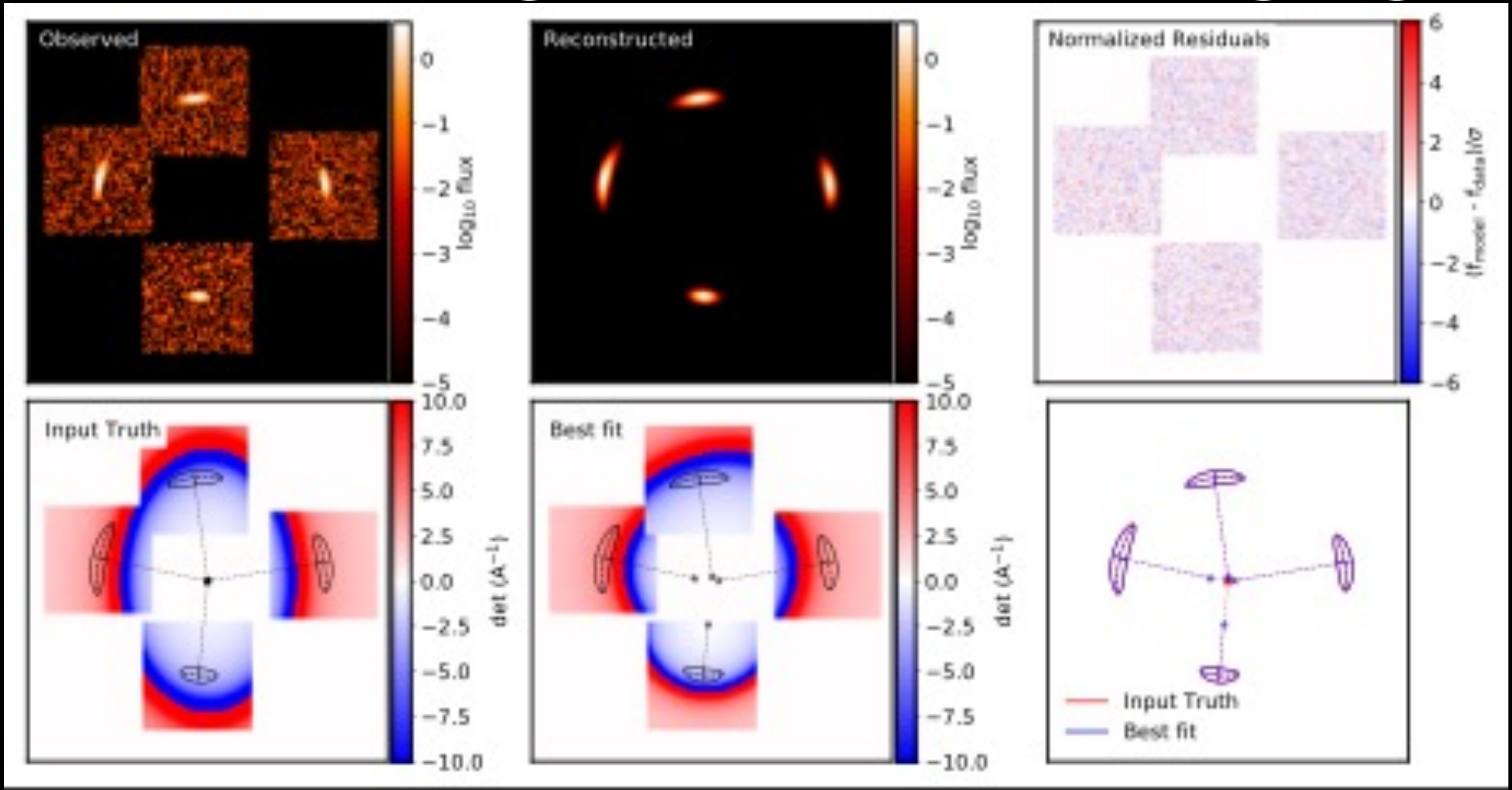
Nierenberg Treu et al 2014

OSIRIS detection of substructure



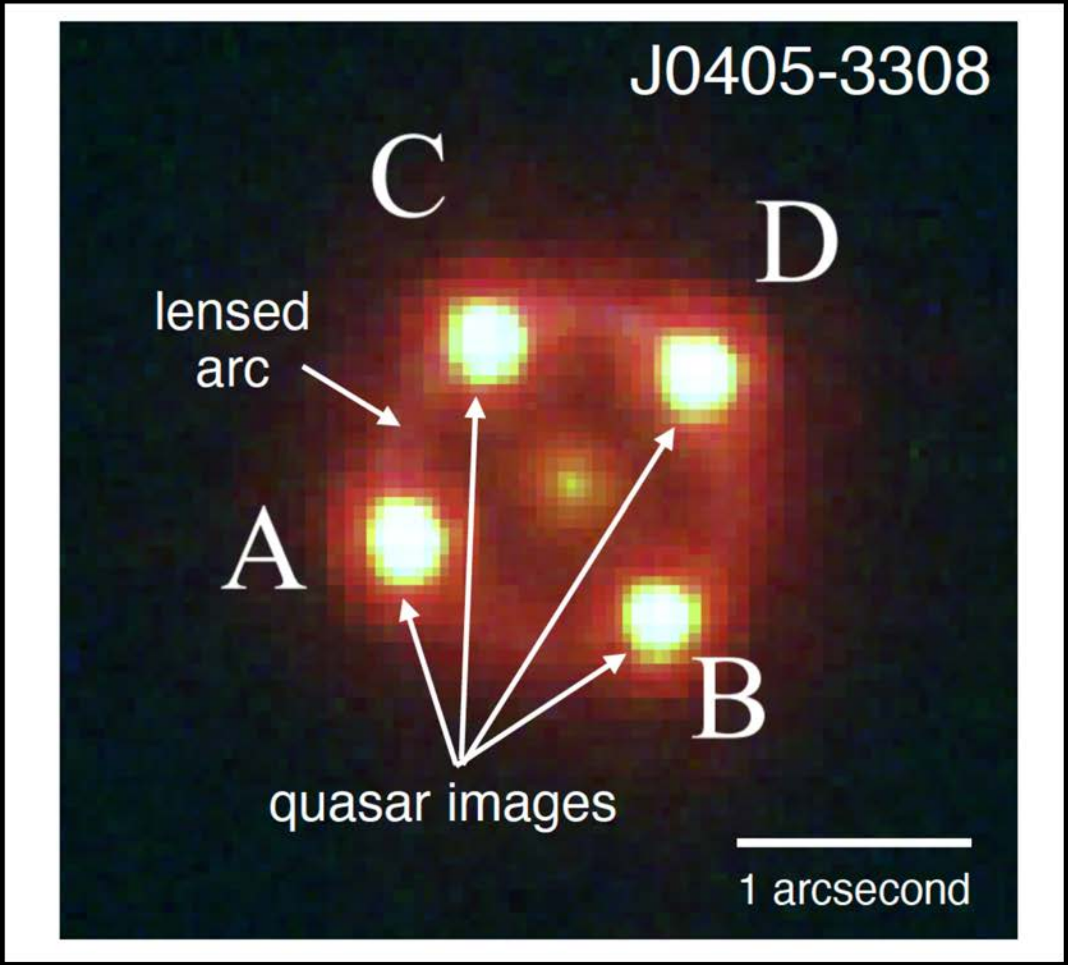
Nierenberg Treu et al 2014

Bridging the gap between flux ratios and gravitational imaging



Birrer 2021

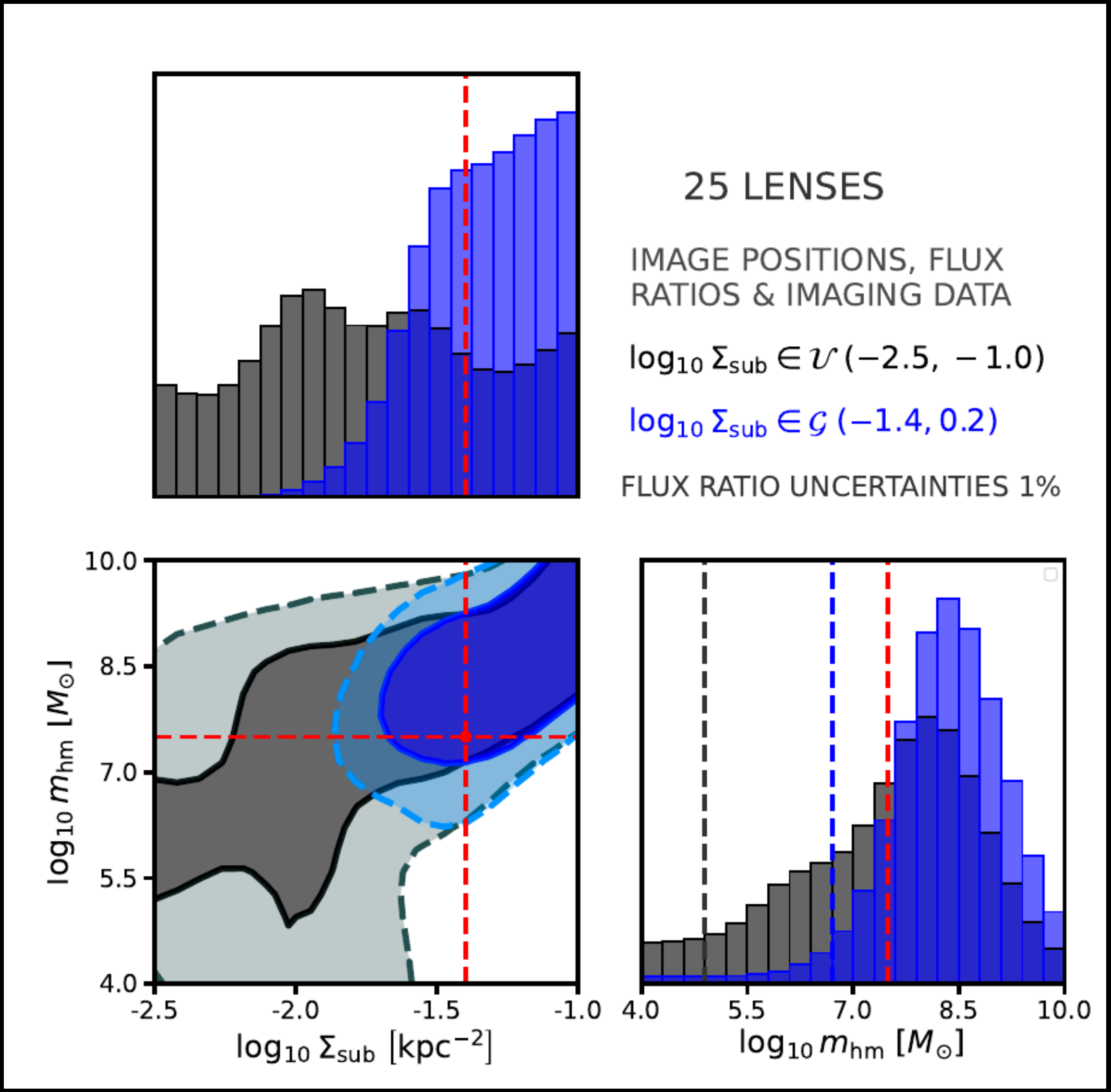
Using the information from the arc and the flux ratios



Gilman et al. 2024

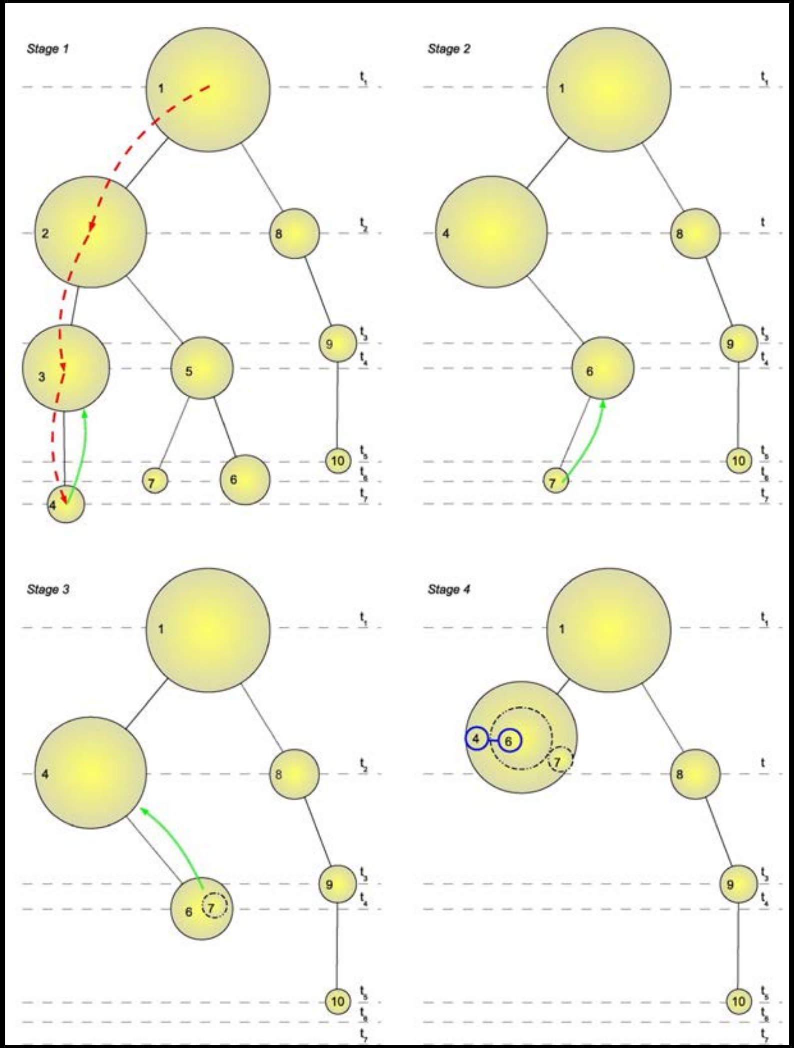
Simulation of WDM

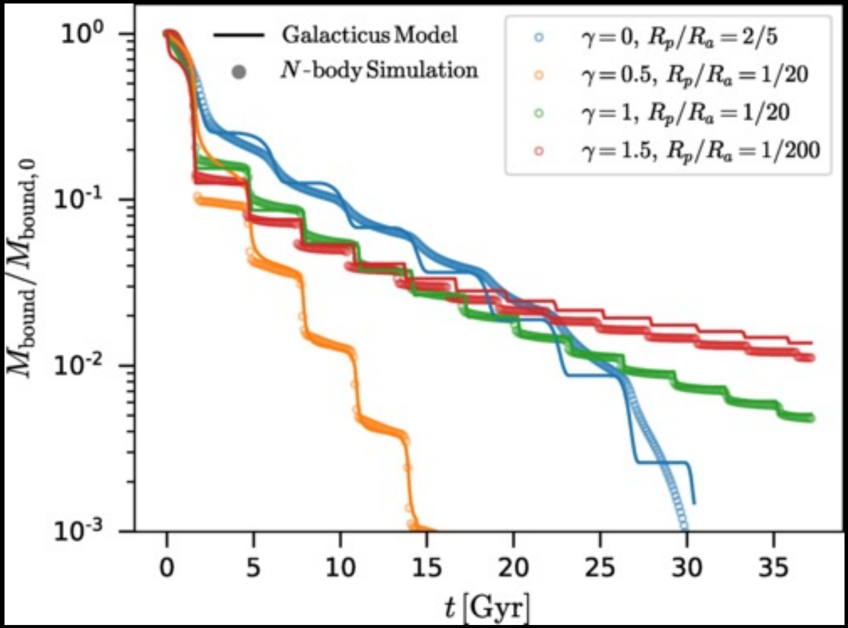
Using all the information
Breaks degeneracies
And increases sensitivity to WDM turnover mass



Gilman et al. 2024

Progress in non-linear growth



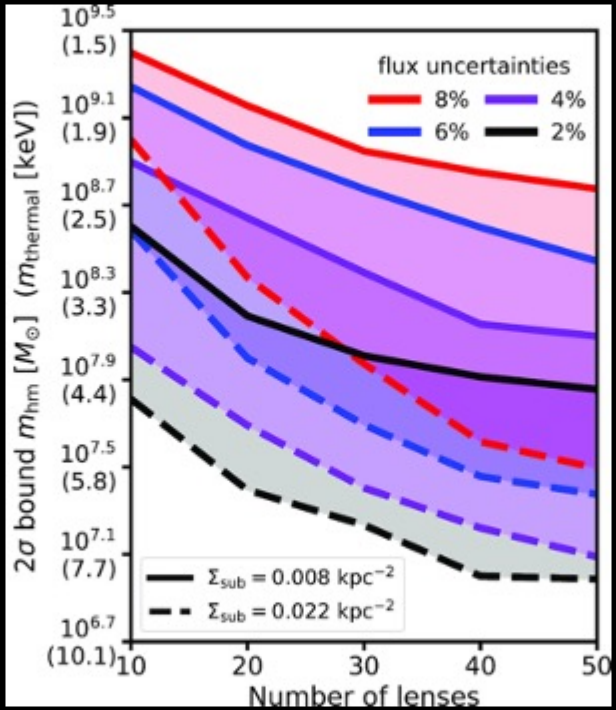


Du et al 2024

Benson 2010

Flux ratio anomalies: Forecasts

•Narrow line flux ratio anomalies can currently be studied for 20 systems
•100-1000s systems are being discovered and will be discovered
•Large telescopes with AO will provide spectroscopic follow-up and emission line flux ratios
•JWST revolutionized the field by allowing MID-IR measurements

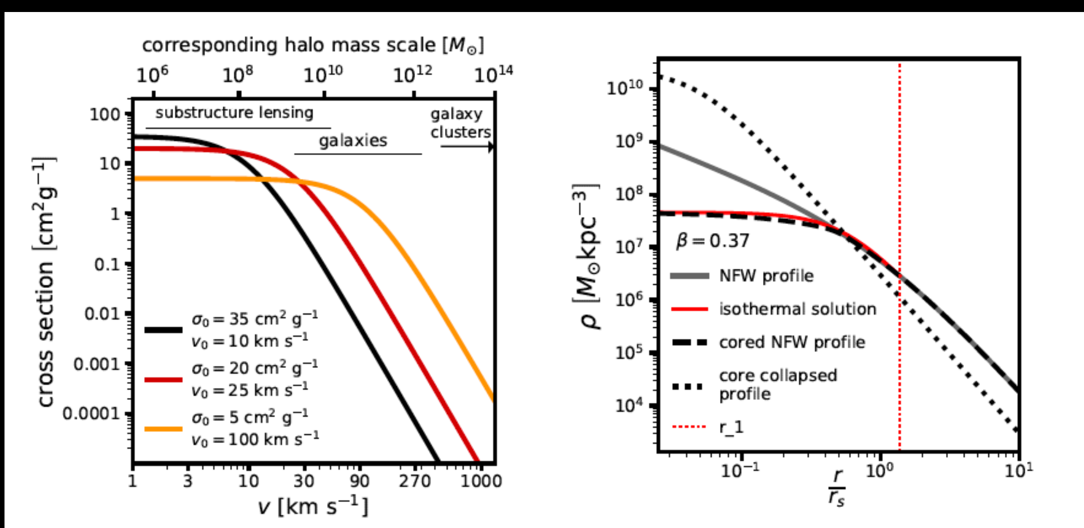


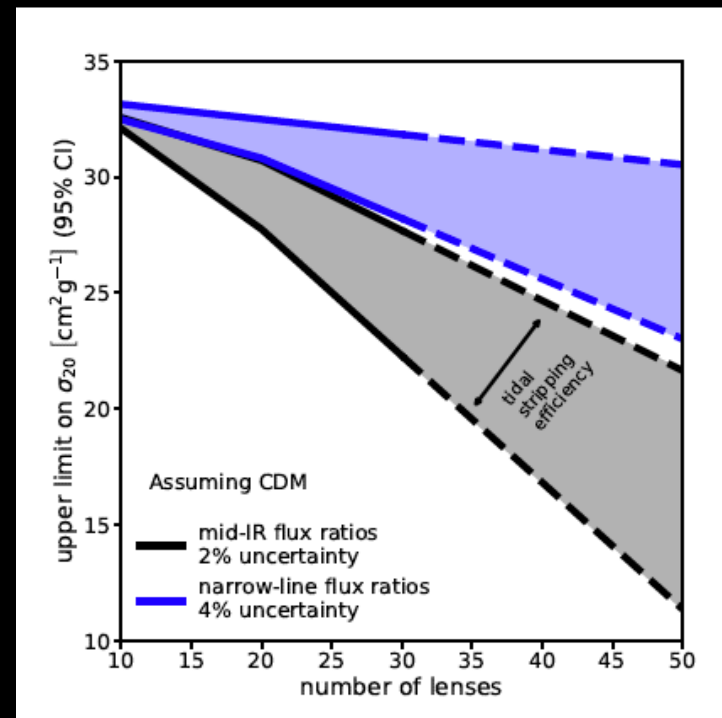
Gilman et al. 2019

Flux ratio anomalies: Forecasts

- As new systems are discovered one can explore new models, e.g. self-interacting dark matter

$$\sigma\left(\sigma_0, v_0, v\right) = \sigma_0 \left(1 + \frac{v^2}{v_0^2}\right)^{-2}$$





Gilman et al. 2021

Recent results. I: sterile neutrino

Constraints on Sterile Neutrino Models from Strong Gravitational Lensing, Milky Way Satellites, and the Lyman-α Forest

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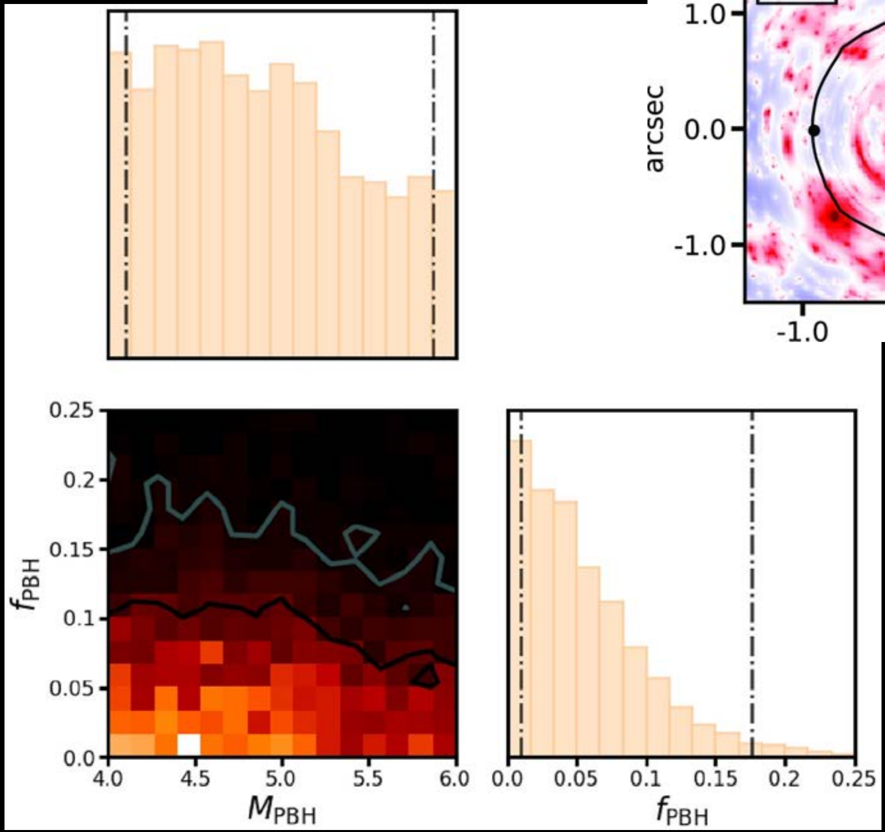
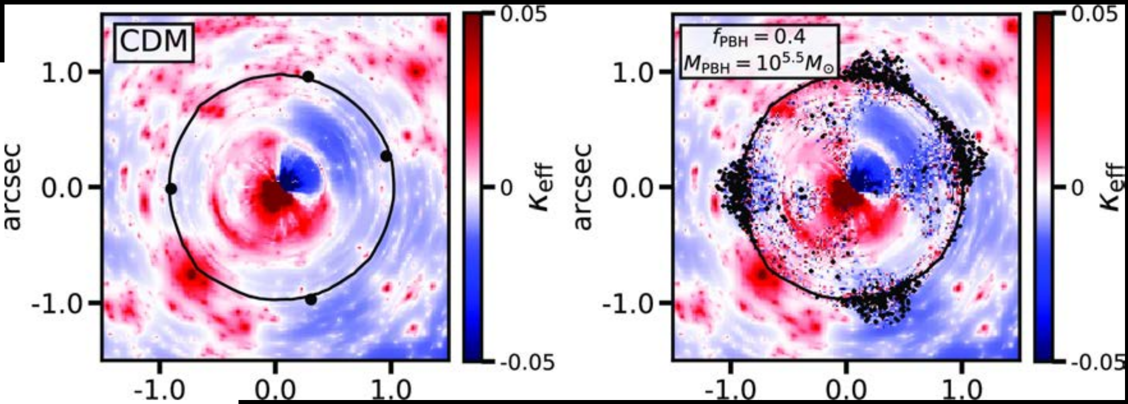
The nature of dark matter is one of the most important unsolved questions in science. Some dark matter candidates do not have sufficient nongravitational interactions to be probed in laboratory or accelerator experiments. It is thus important to develop astrophysical probes which can constrain or lead to a discovery of such candidates. We illustrate this using state-of-the-art measurements of strong gravitationally lensed quasars to constrain four of the most popular sterile neutrino models, and also report the constraints for other independent methods that are comparable in procedure. First, we derive effective relations to describe the correspondence between the mass of a thermal relic warm dark matter particle and the mass of sterile neutrinos produced via Higgs decay and grand unified theory (GUT)-scale scenarios, in terms of large-scale structure and galaxy formation astrophysical effects. Second, we show that sterile neutrinos produced through the Higgs decay mechanism are allowed only for mass > 26 keV, and GUT-scale scenario > 5.3 keV. Third, we show that the single sterile neutrino model produced through active neutrino oscillations is allowed for mass > 92 keV, and the three sterile neutrino minimal standard model (νMSM) for mass > 16 keV. These are the most stringent experimental limits on these models.

Recent results. II:PBHs





Dike, Gilman, Treu 2023

Summary

- The nature of dark matter is unknown, many alternatives to CDM are viable
    - Lensing provides unique insights on the small scale structure
        - Lensing probes mass directly
    - Stringent tests of broad classes of DM models are possible
- See talks by Gilman and Nierenberg for recent results and developments!