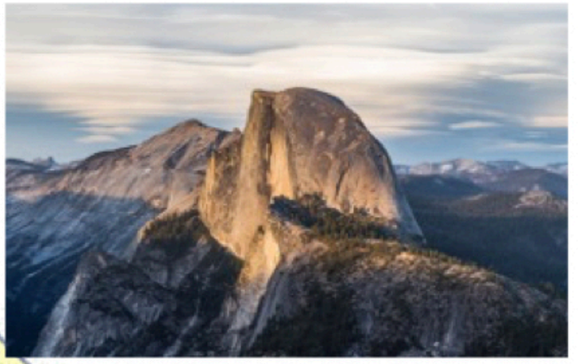
Galaxy-scale strong gravitational lensing probes of dark matter

Valencia SIDM

Anna Nierenberg, UC Merced

About University of California, Merced

- Founded in 2005
- 20 faculty in physics
- 50 grad students in physics PhD program (9 in astrophysics)
- 90 minutes to Yosemite national park
- A part of UC Observatories

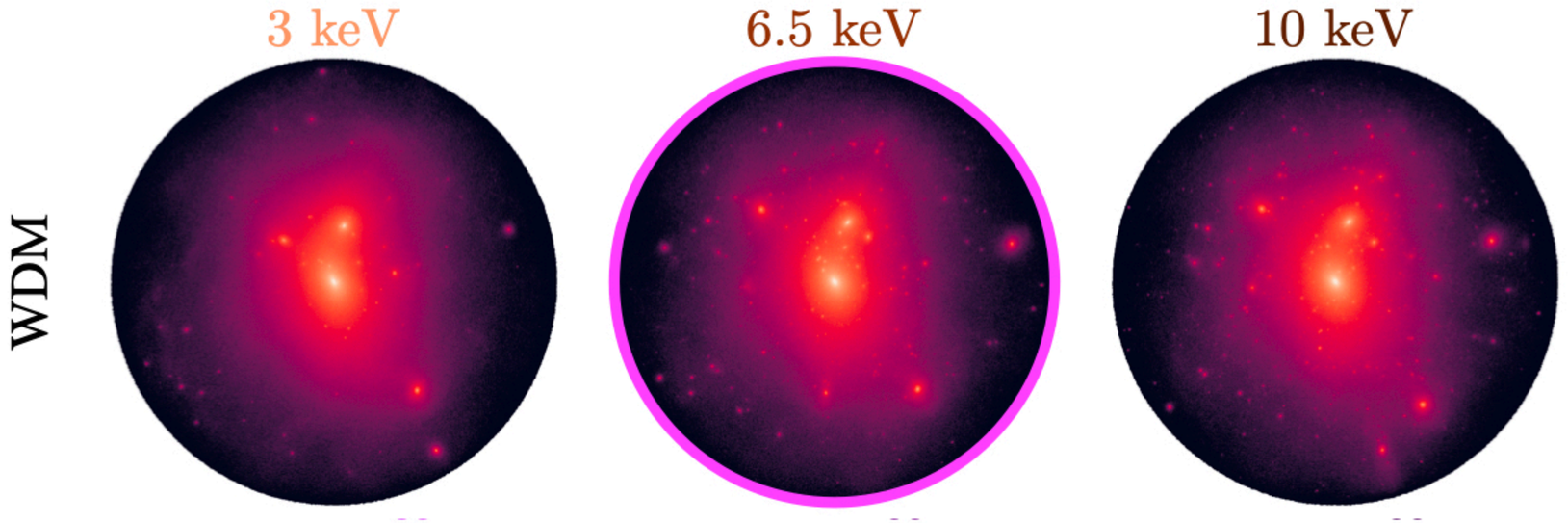


Overview

- Gravitational lensing-dark matter connection
- Overview of methods and technical developments
- Exciting new results
- The future

Different dark matter models can predict different dark matter halos

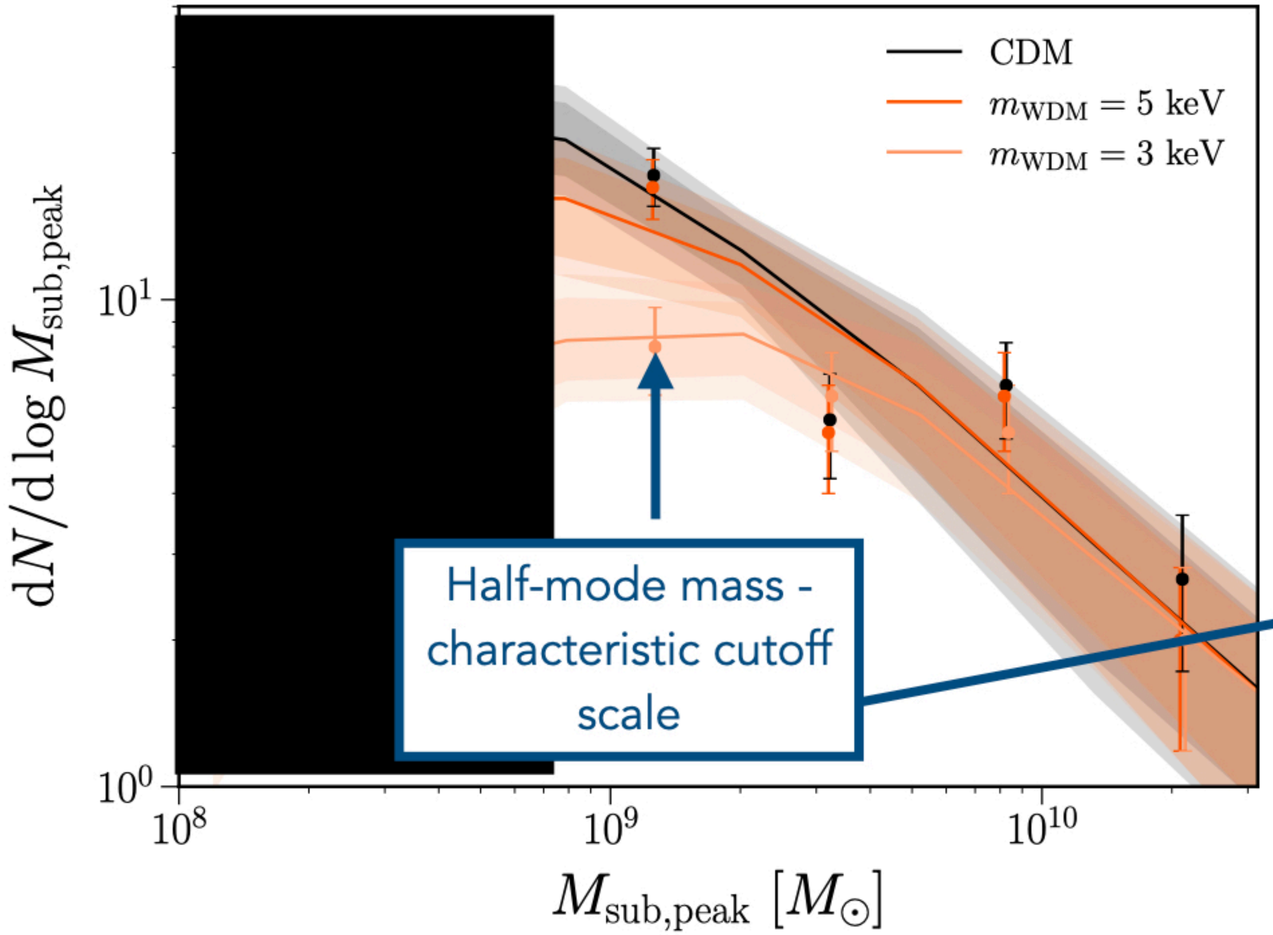
Milky Way mass halo with subhalos in Warm Dark Matter (Nadler et al. 2024)



Longer free-streaming length

Shorter free-streaming length (CDM-like)

The halo mass function depends on dark matter model

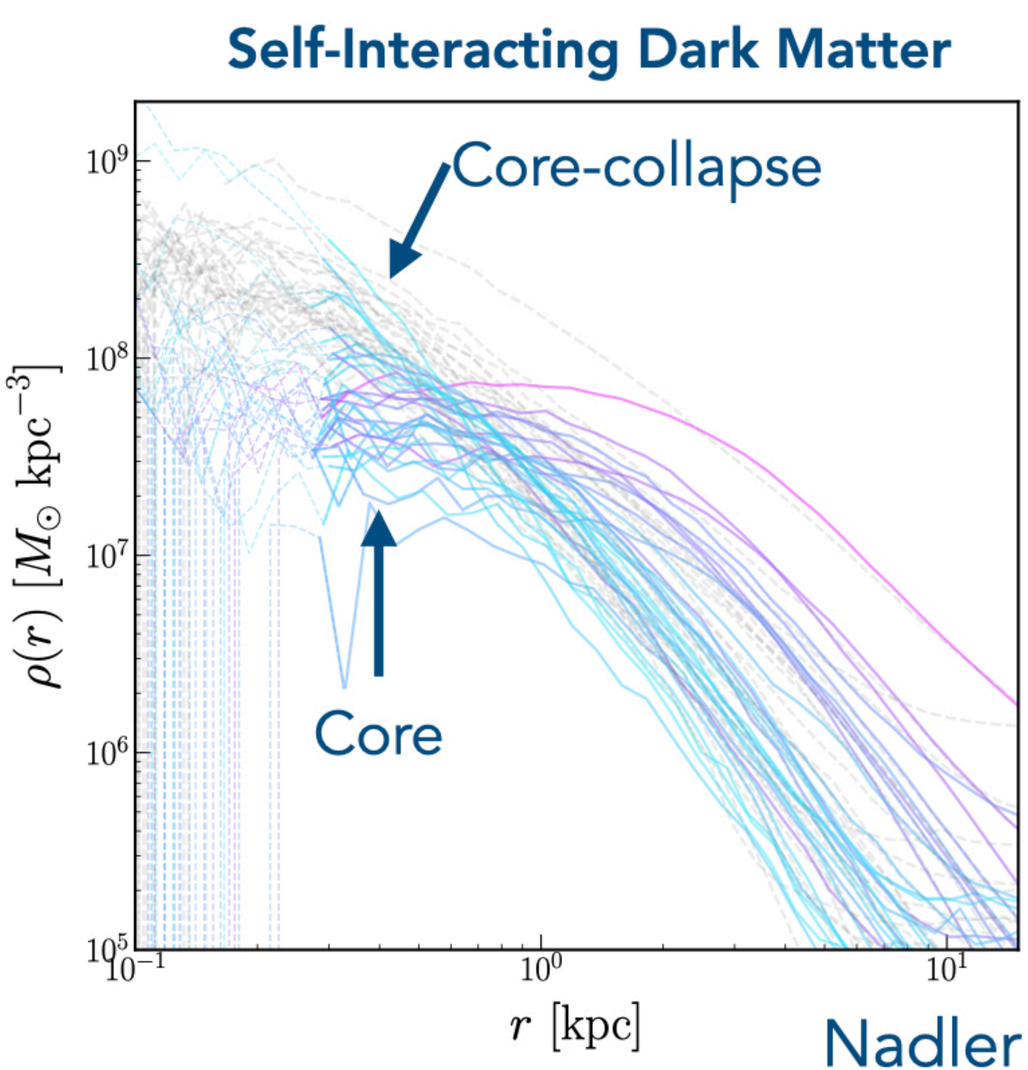


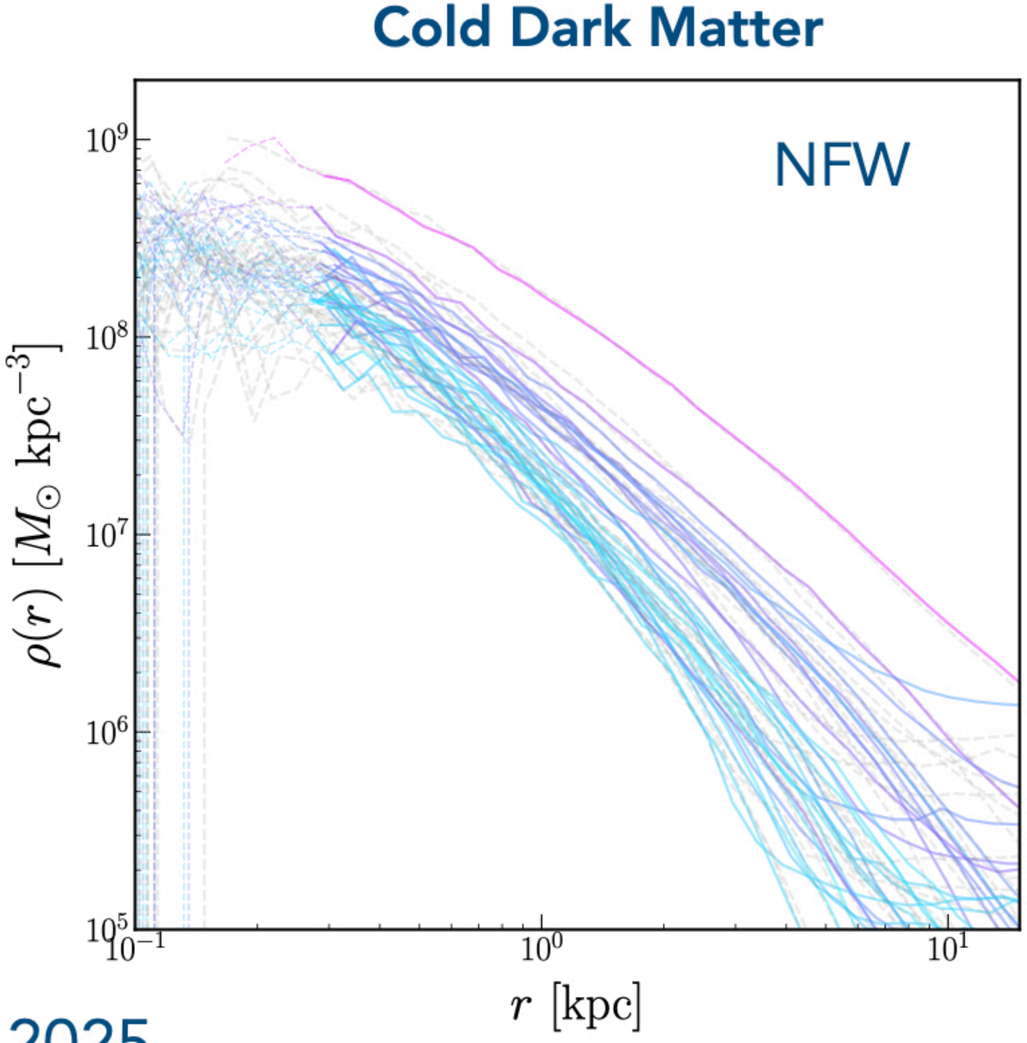
$$\frac{d^2N_{\rm WDM}}{dMdV} = \frac{d^2N_{\rm CDM}}{dMdV} f_{\rm WDM}\left(M, M_{\rm hm}\right)$$

$$f_{\rm WDM}\left(M, M_{\rm hm}\right) = \left(1 + \left(\alpha \frac{M_{\rm hm}}{M}\right)^{\beta}\right)^{\gamma}$$

Nadler et al. 2024

Halo density profiles depend on dark matter model

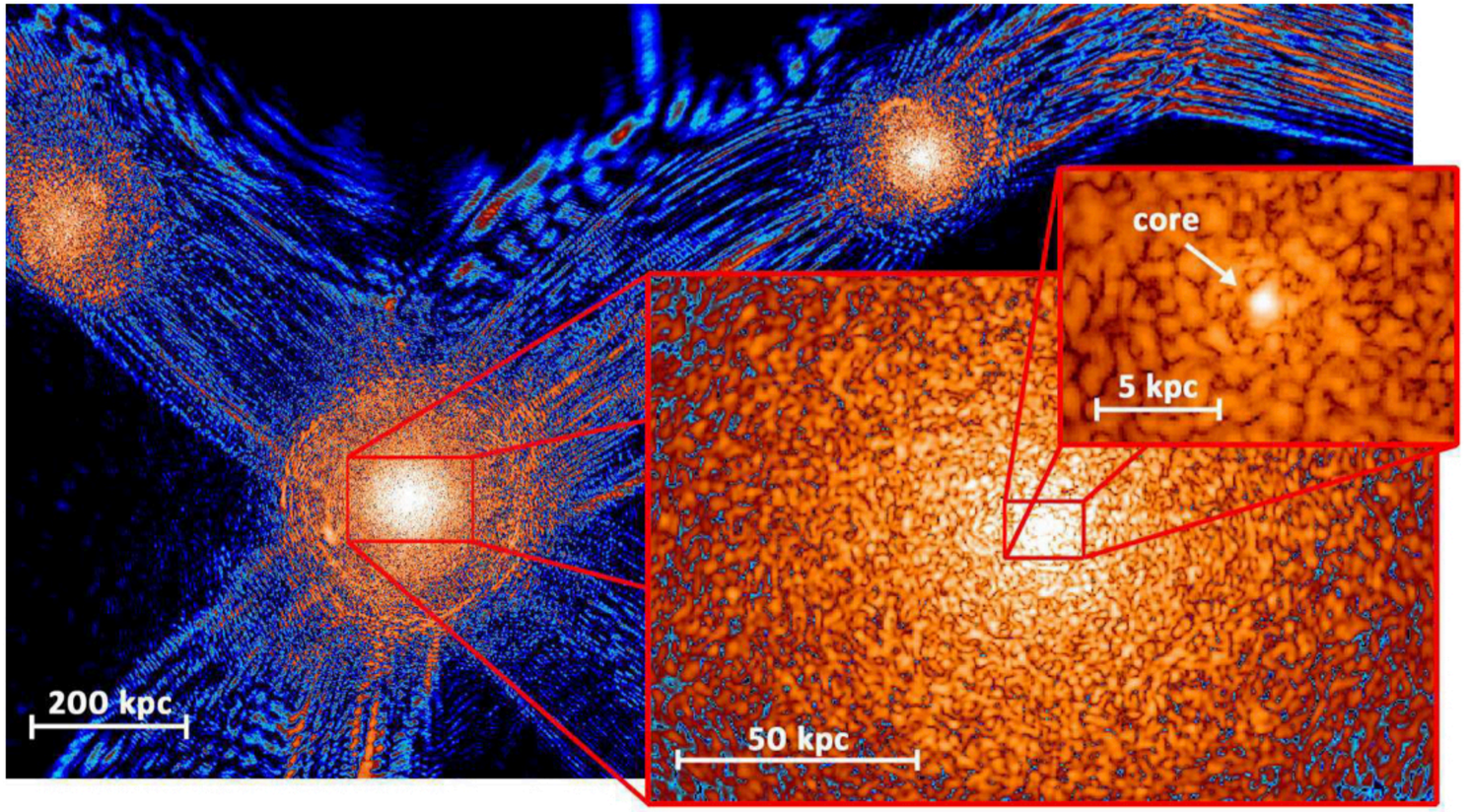




Nadler et al. 2025

By measuring the properties of dark matter halos we can test different dark matter models

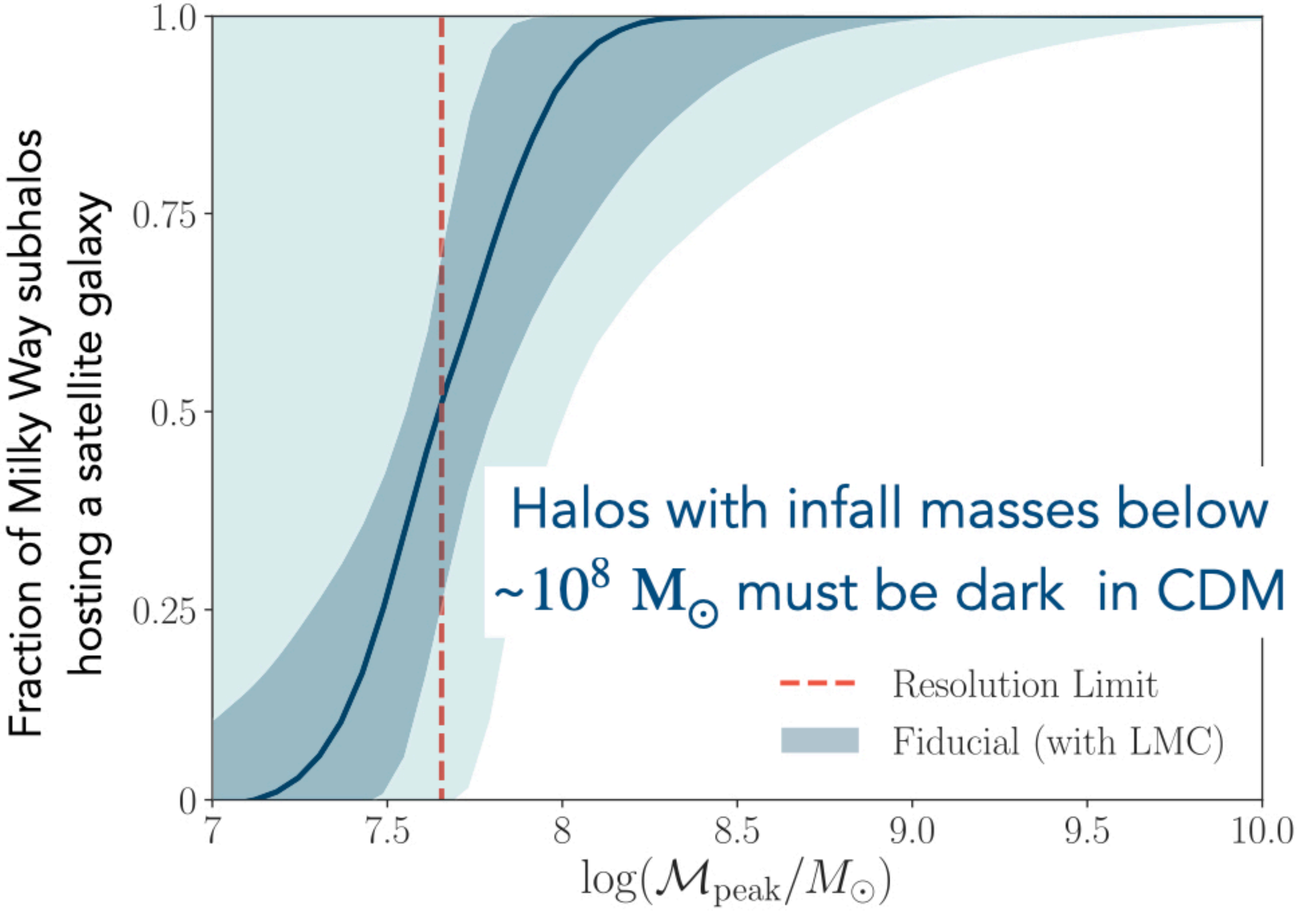
- WIMPS
- Sterile Neutrinos
- Axions
- Primordial Black Holes
- Self-Interacting Dark Matter



Schive et al. 2014

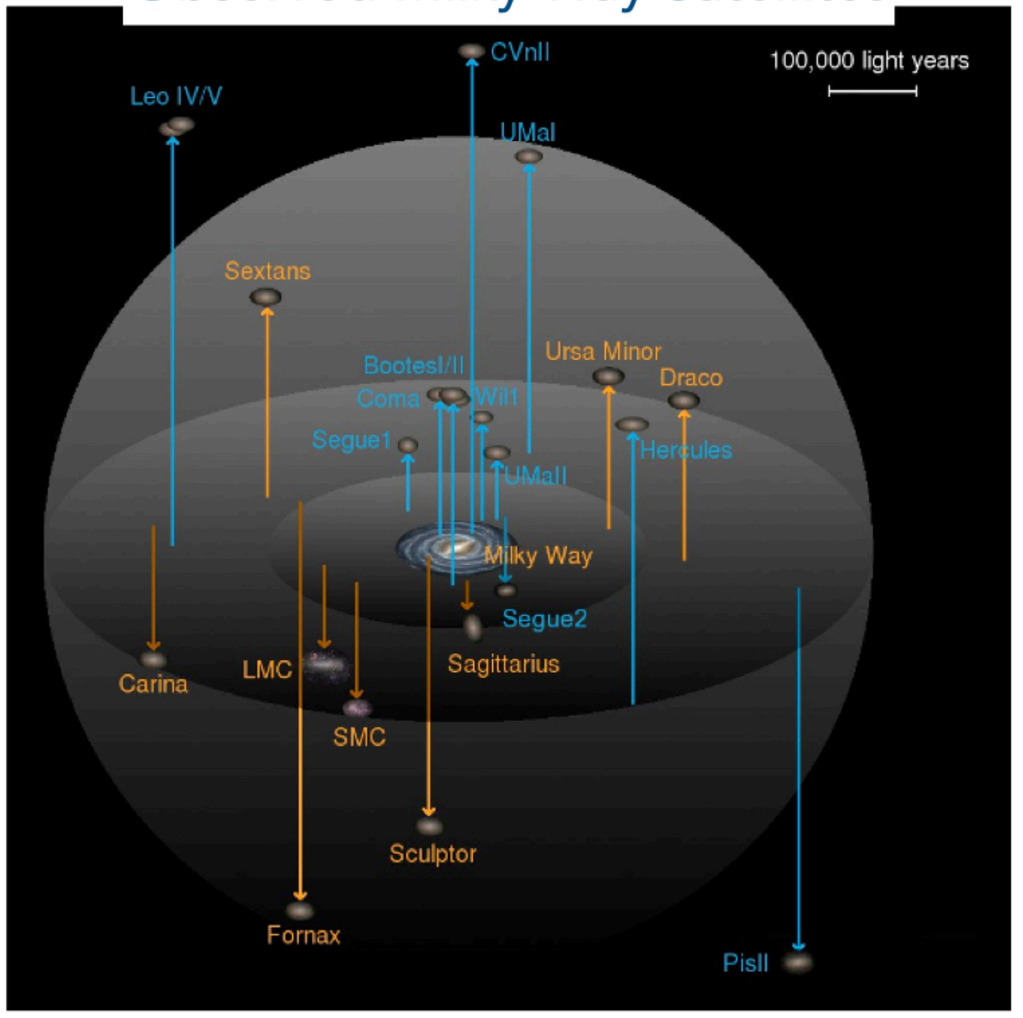
Traditional measurements of dark matter halos rely on galaxies as tracers

Nadler et al. 2020



Credit: J.T.A. de Jong

Observed Milky Way Satellites



The power of strong gravitational lensing

Credit NASA/ESA HST GO-15177, 13732 PI Nierenberg

The power of strong gravitational lensing

- Enables the measurement of density profiles and mass function of completely dark halos

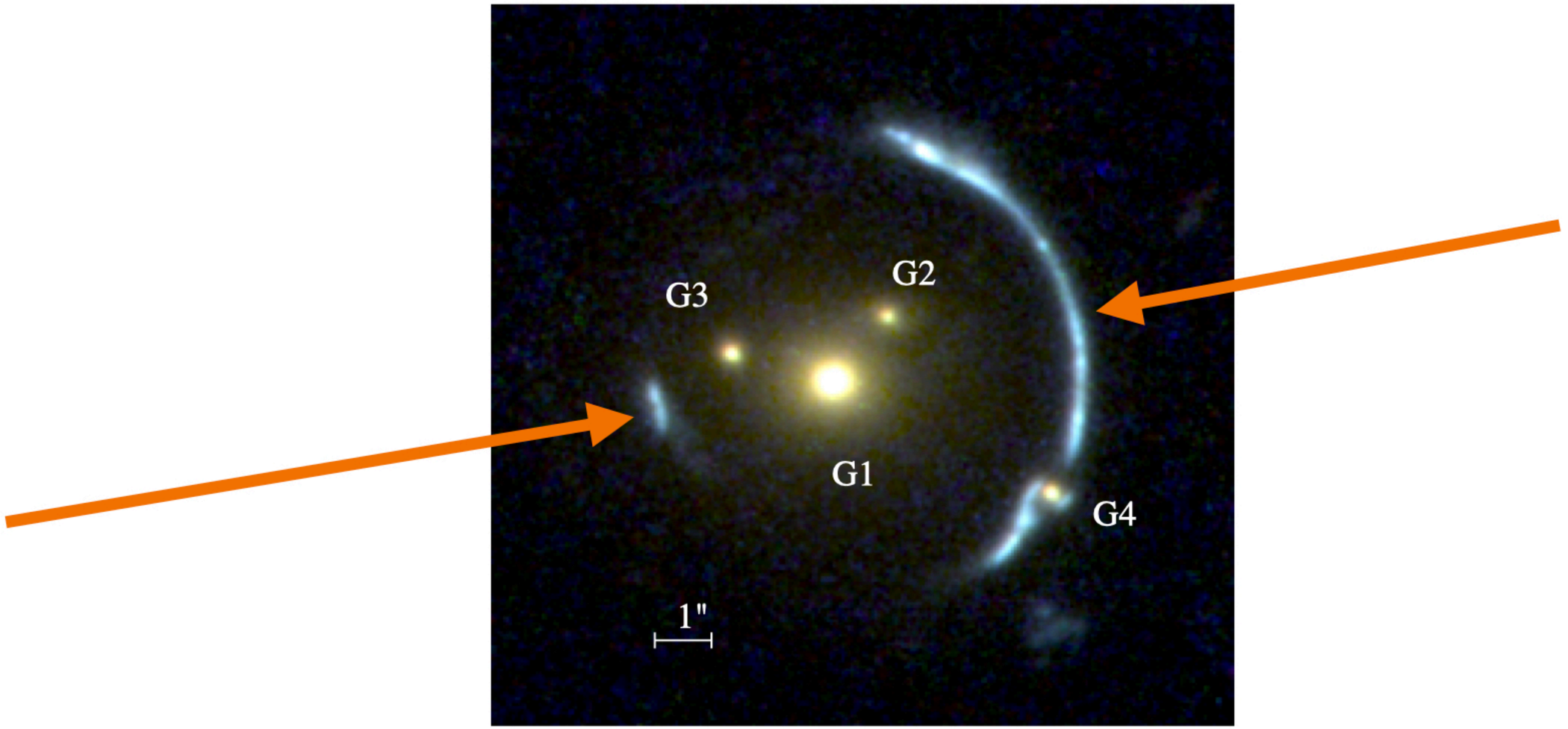
Credit NASA/ESA HST GO-15177, 13732 PI Nierenberg

The power of strong gravitational lensing

- Enables the measurement of density profiles and mass function of completely dark halos
- Works over cosmological distances

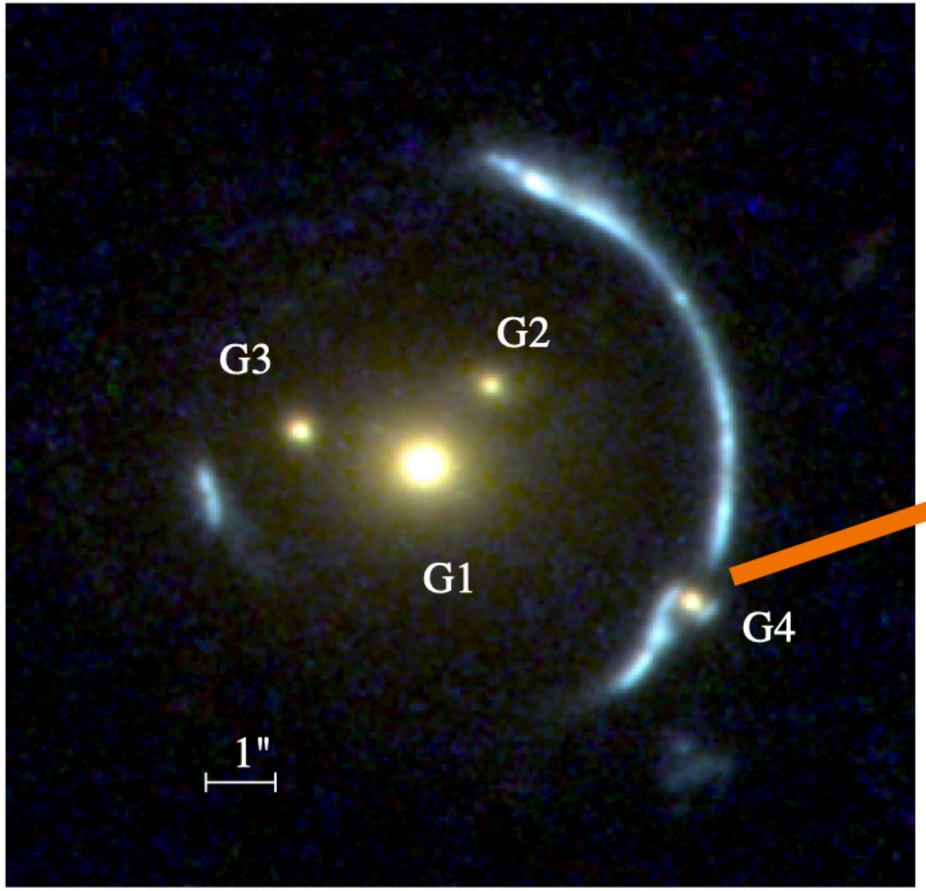
Credit NASA/ESA HST GO-15177, 13732 PI Nierenberg

Strong lenses have multiple images of one background source

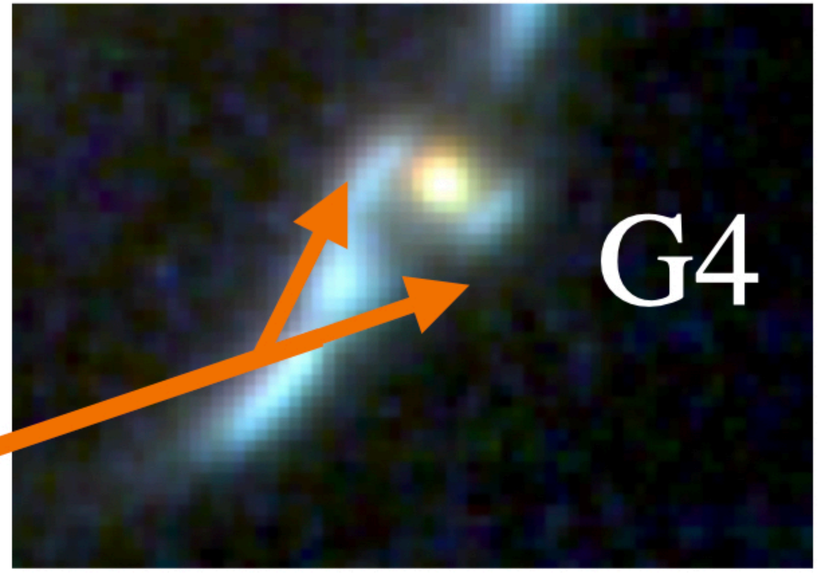


Vegetti et al. 2010

Lensed images can be affected by dark matter halos



Vegetti et al. 2010



Low mass perturbers cause **deflections** and **magnifications** to lensed images

Effect of low-mass halos

Gravitational Potential

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

Deflection ∝ first derivative

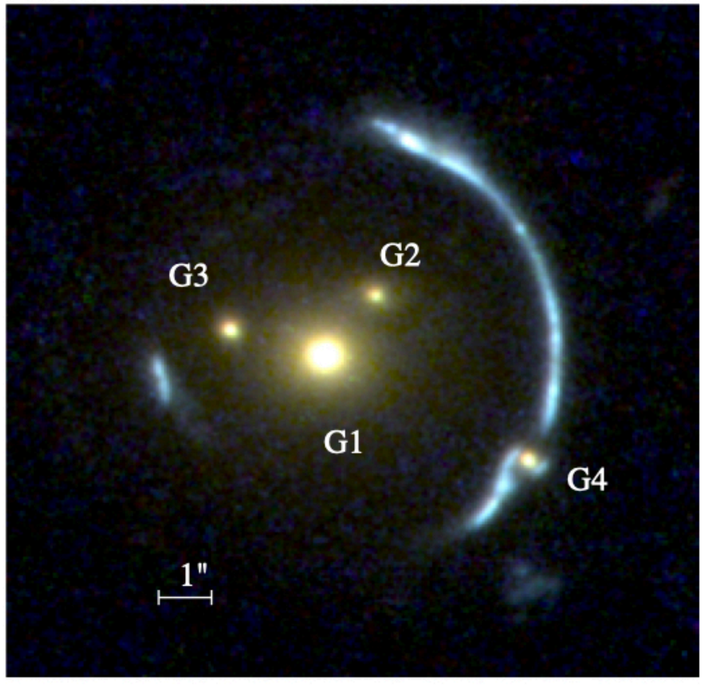
$$\vec{\alpha}(\vec{\theta}) = \vec{\nabla}\psi$$

Magnification ∝ second derivative

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

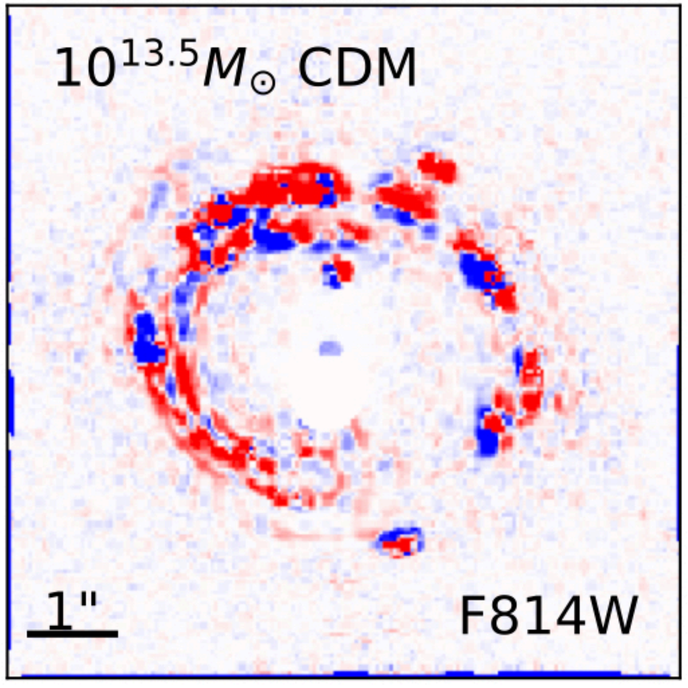
Strong gravitational lensing studies of dark matter measure **deflections** and **magnifications** of images relative to the main lens gravitational potential

Resolved source, single detection



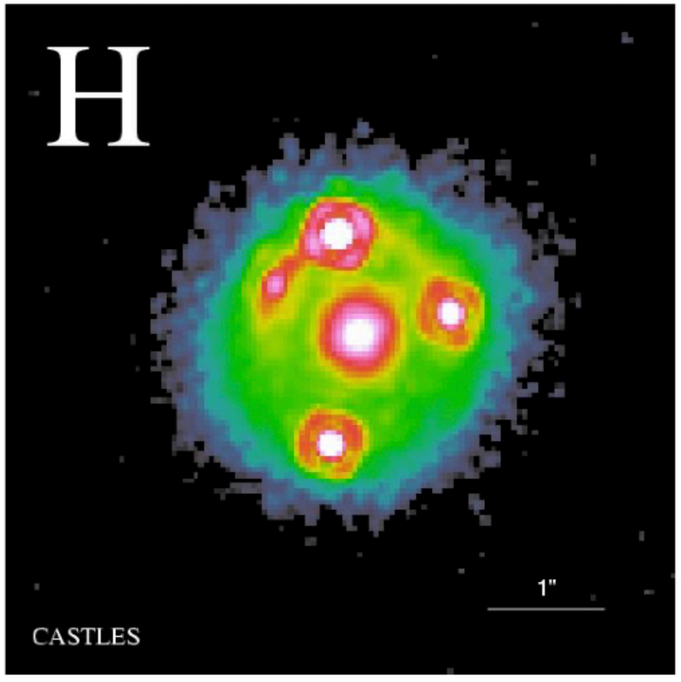
Vegetti et al. 2010

Resolved source, multi-detection



Birrer et al. 2017

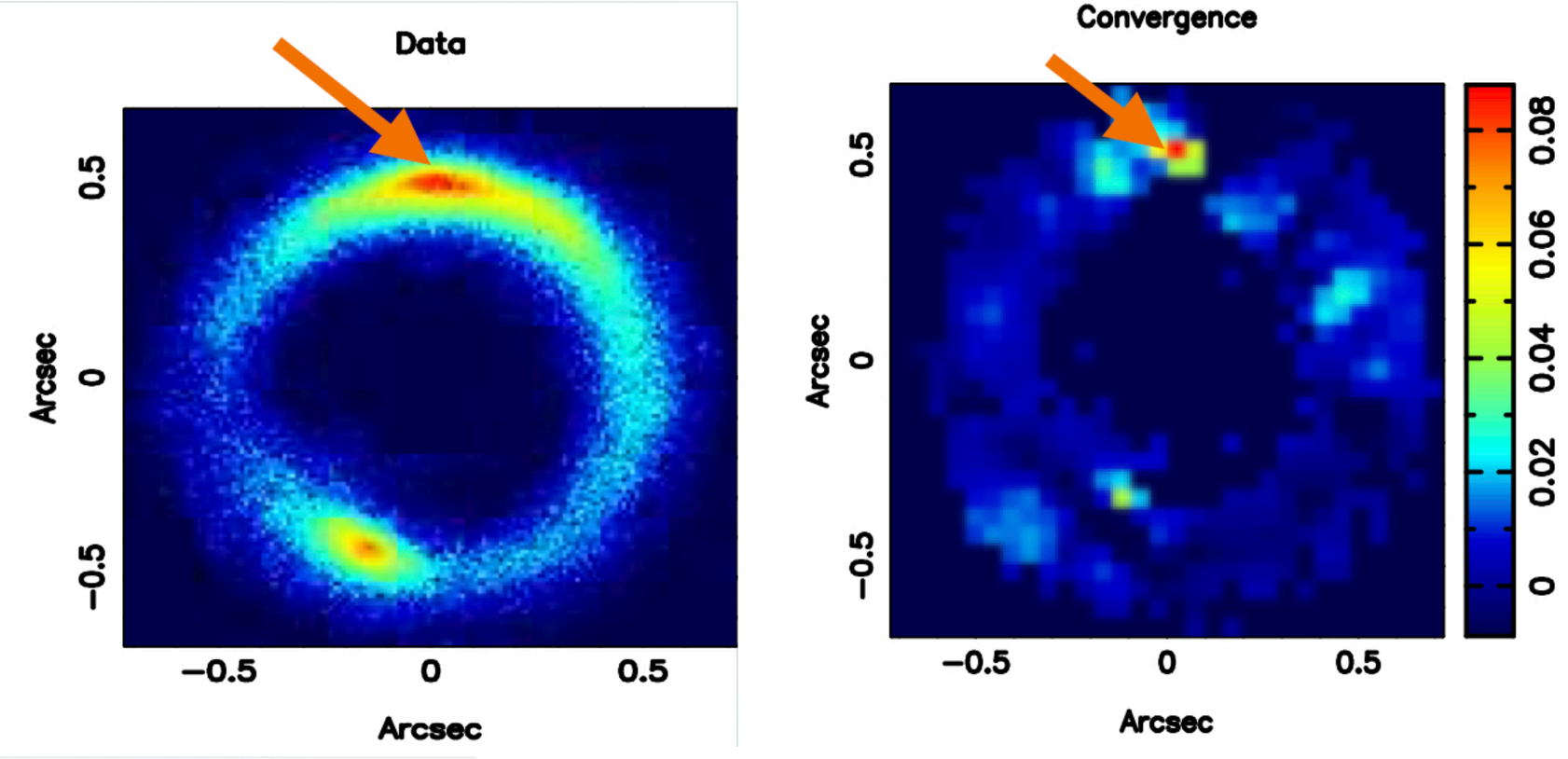
Unresolved source, multi-detection



Example of imaging detection of a dark subhalo

$\sim 10^{10}\ \mathrm{M}_{\odot}$ subhalo

detected not visible in imaging



Vegetti et al. 2012

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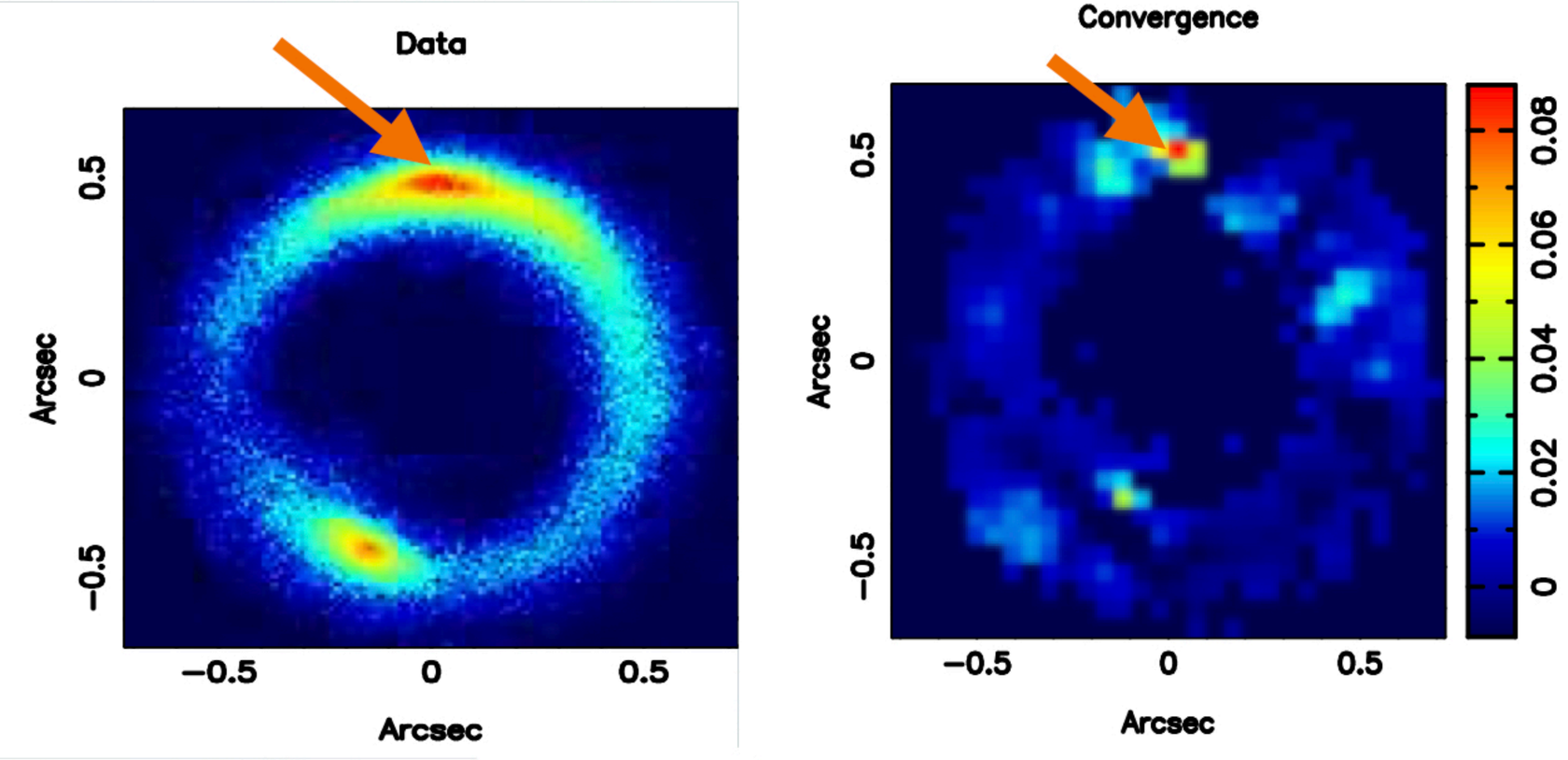
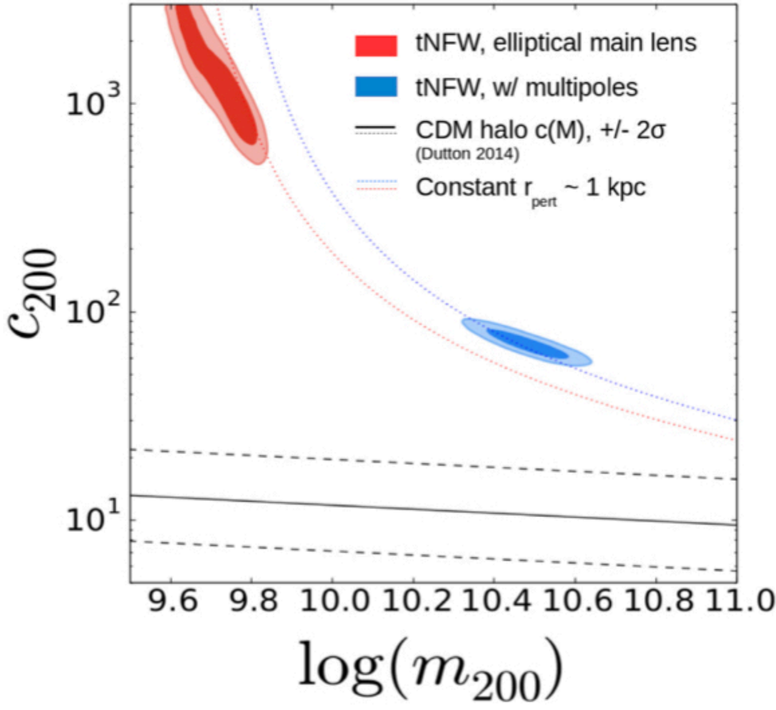


Vegetti et al. 2012



Minor et al. 2021

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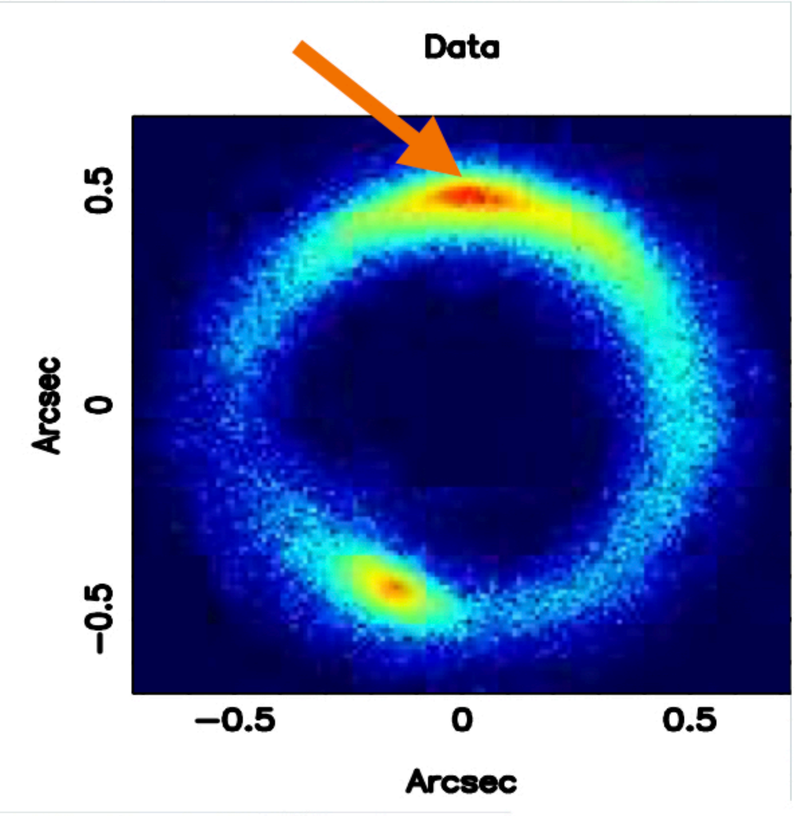
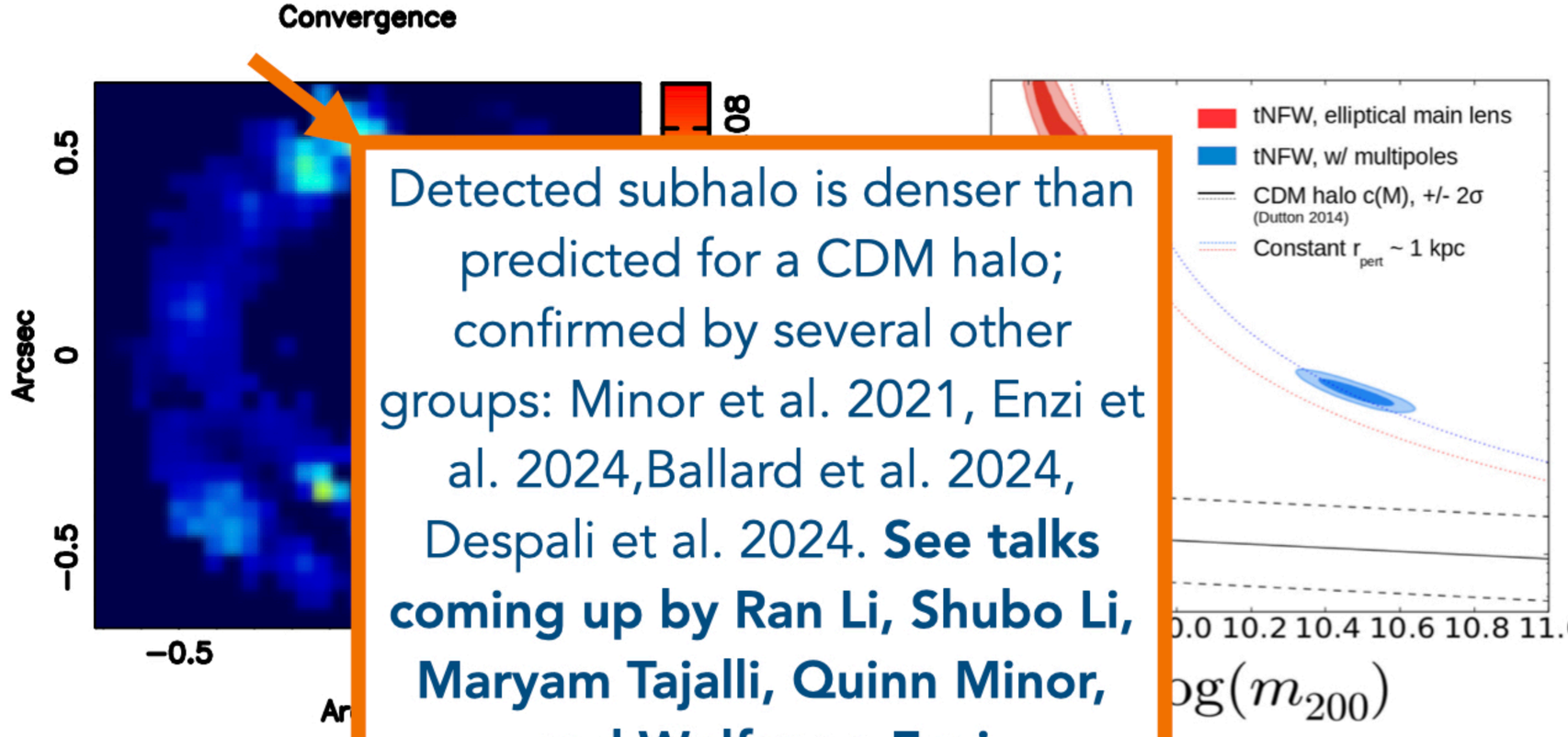


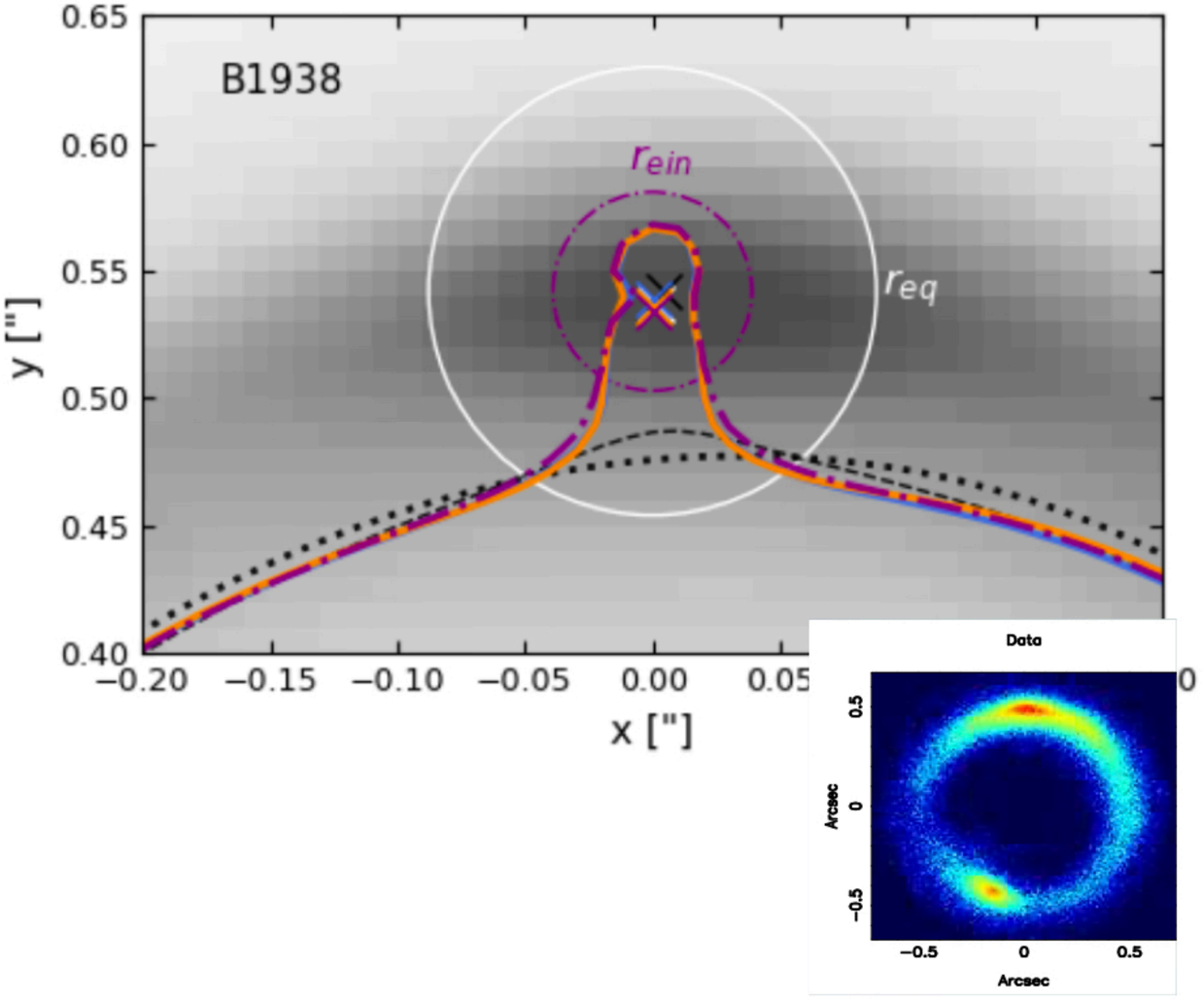
Vegetti et al. 2012

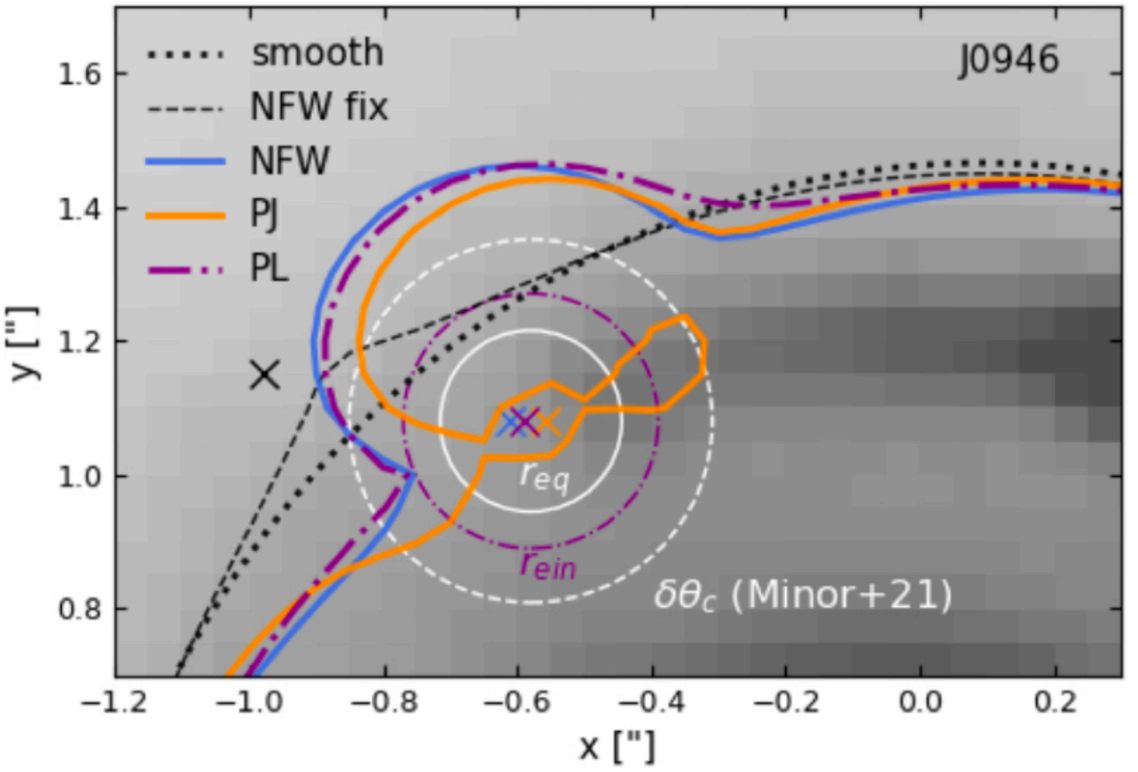


Minor et al. 2021

Detected subhalo is denser than predicted for a CDM halo; confirmed by several other groups: Minor et al. 2021, Enzi et al. 2024,Ballard et al. 2024, Despali et al. 2024. **See talks coming up by Ran Li, Shubo Li, Maryam Tajalli, Quinn Minor, and Wolfgang Enzi**

Sensitivity to the density profile

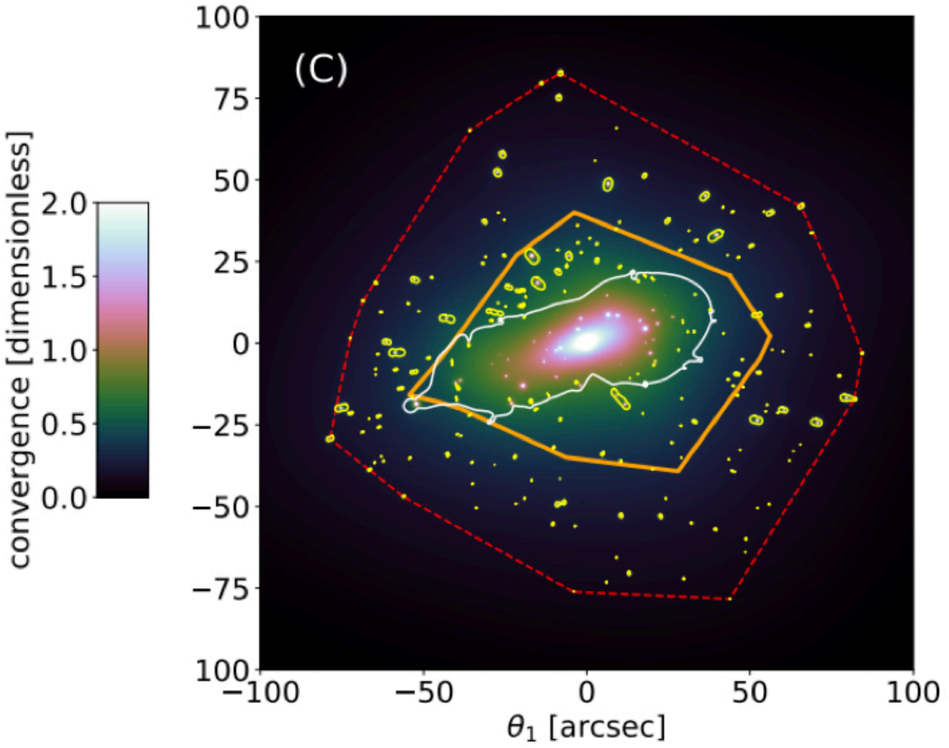




Despali et al. 2024

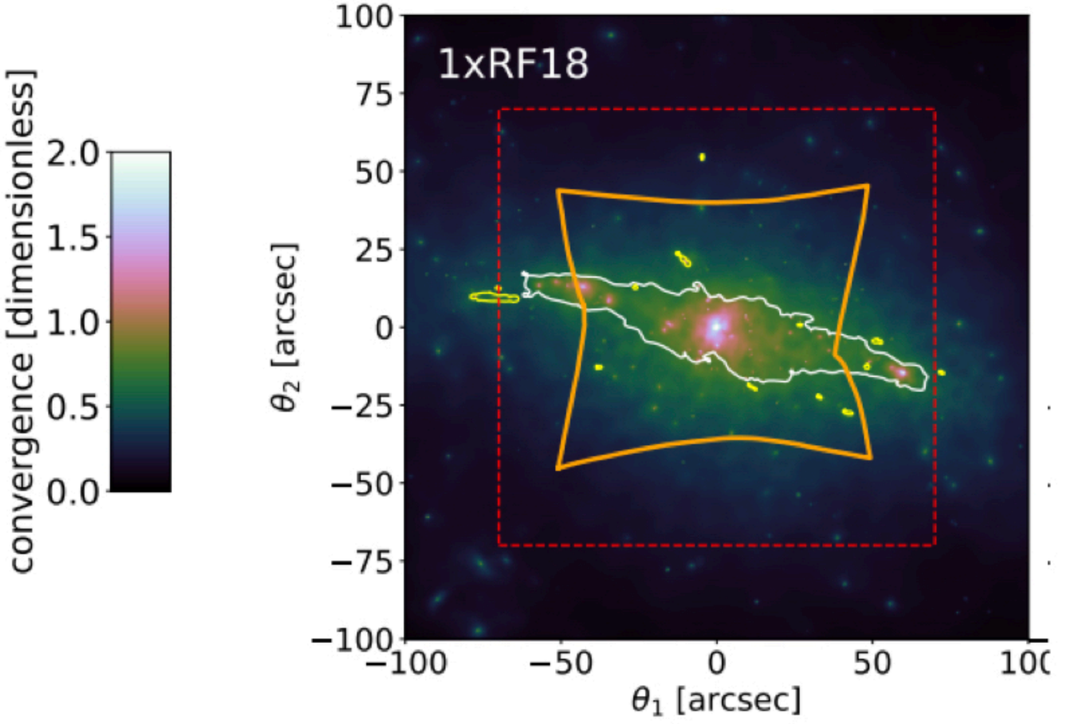
Lensing and clusters

Real Cluster



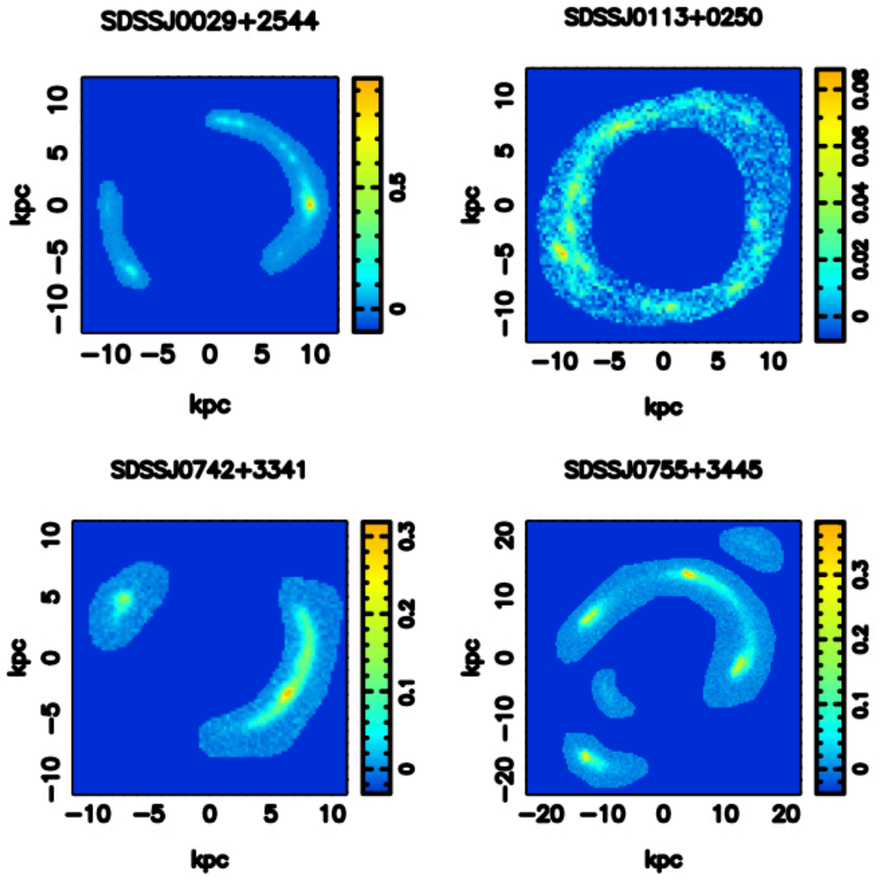
Menghetti et al. 2022

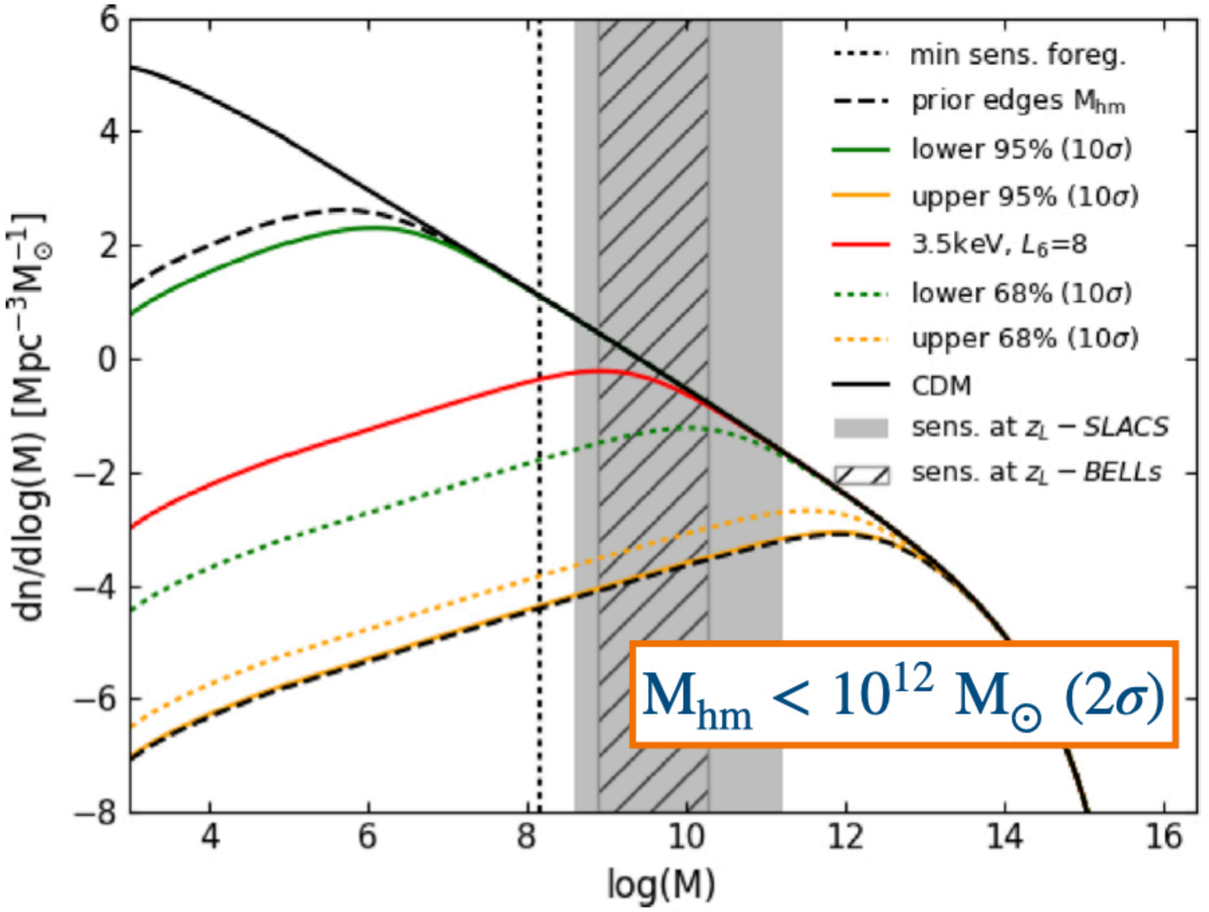
Simulated Cluster



Strong and weak lensing can also be used to constrain cluster density profiles

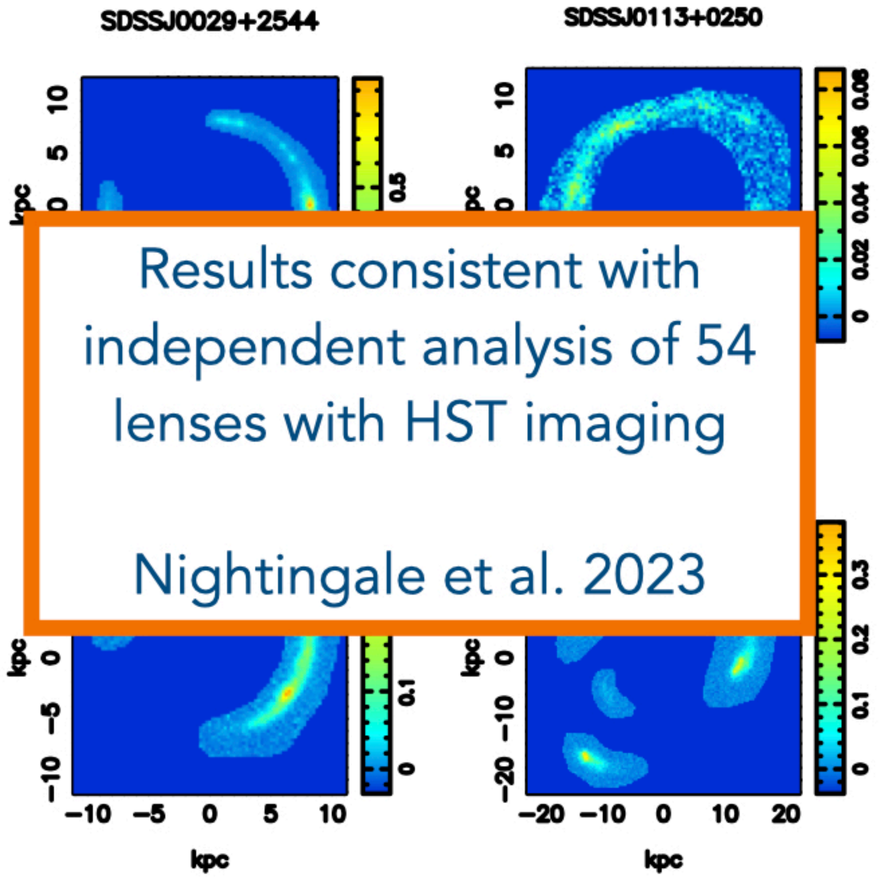
Individual detection results from 28 lenses with HST





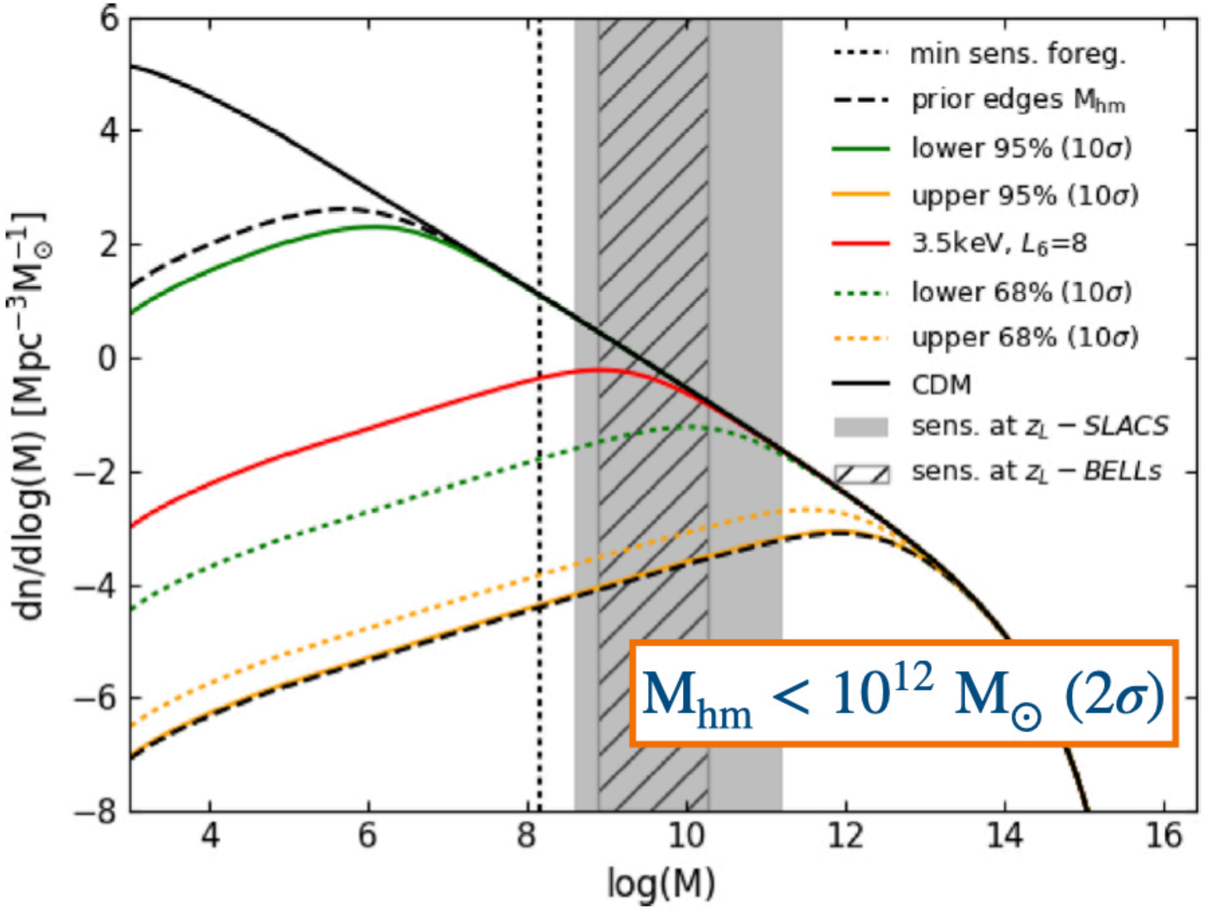
Ritondale et al. 2017

Individual detection results from 28 lenses with HST



Results consistent with independent analysis of 54 lenses with HST imaging

Nightingale et al. 2023

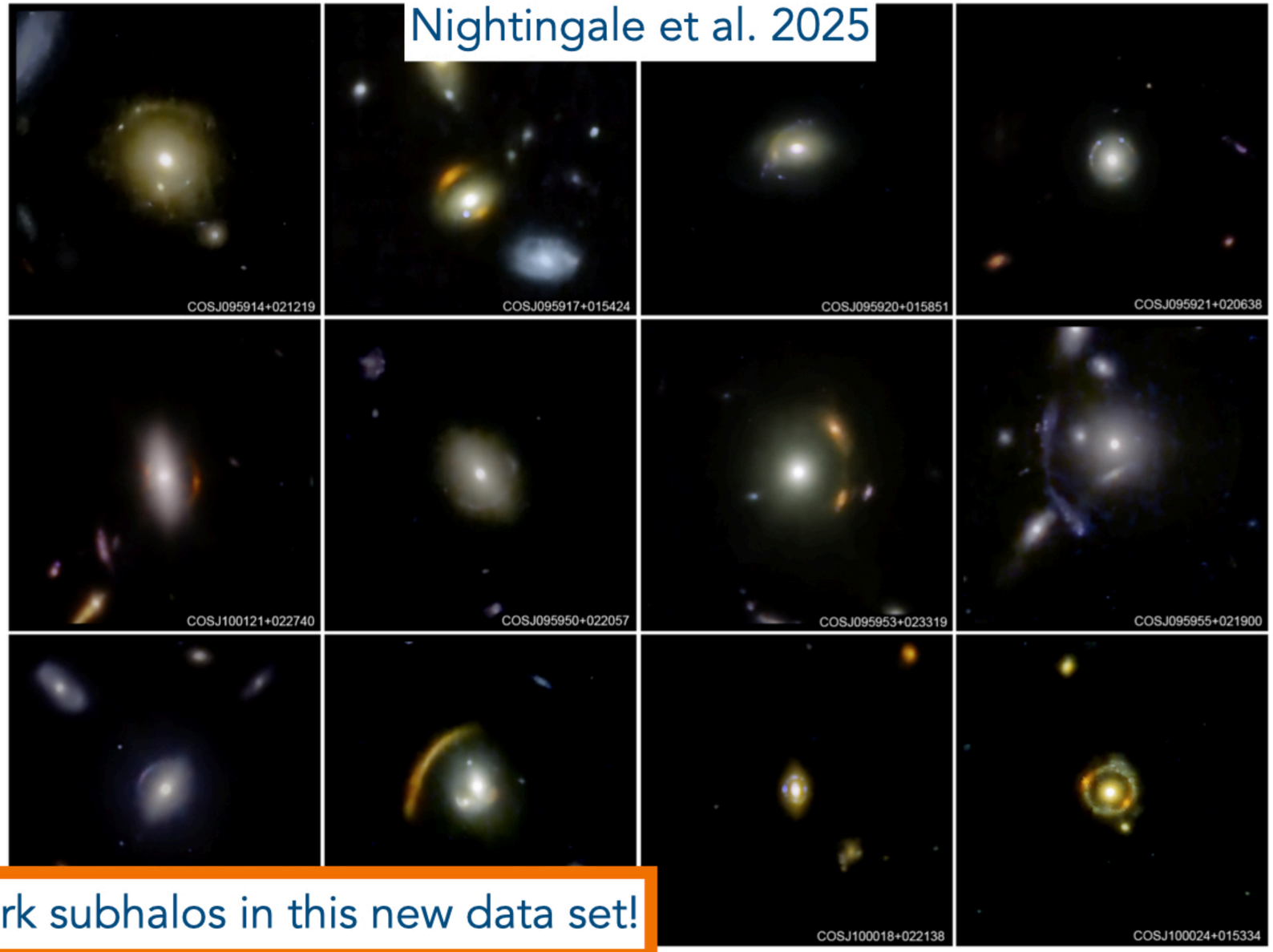


Ritondale et al. 2017

COWLS survey: new JWST imaging of lenses

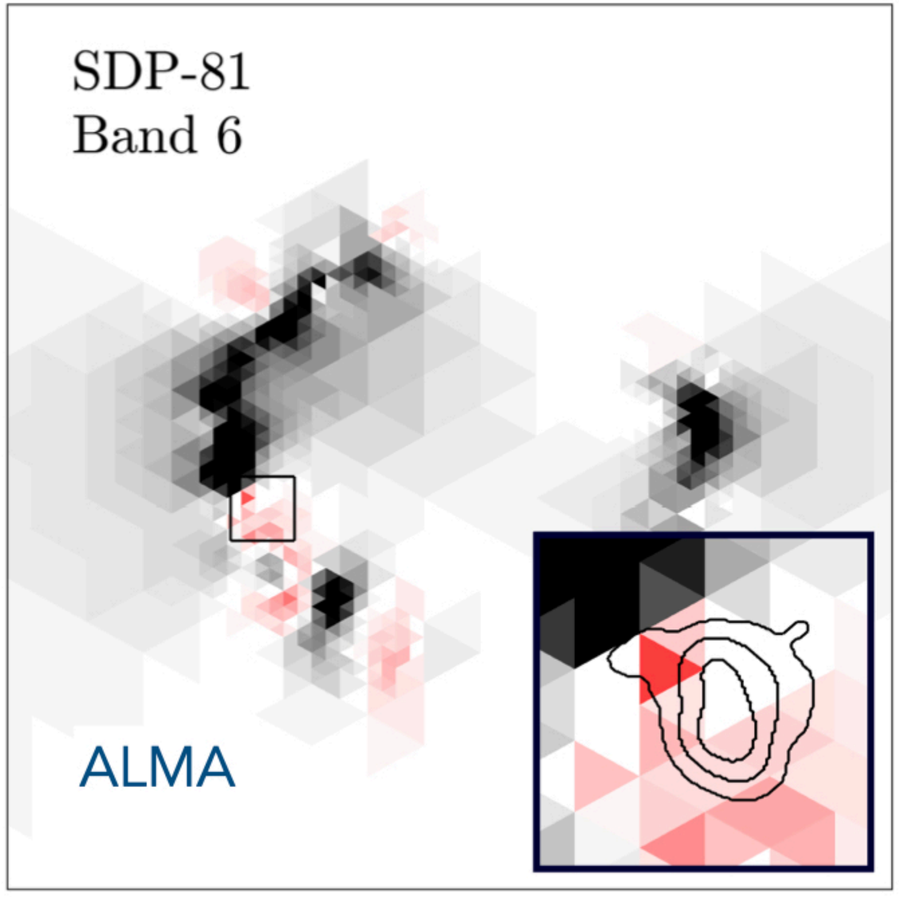
Discovery of > 100 strong lenses with multi-band JWST imaging.

Lens (z ~ 2) and source (z ~ 5 - 11) redshifts **maximize sensitivity to line-of-sight dark matter halos.**

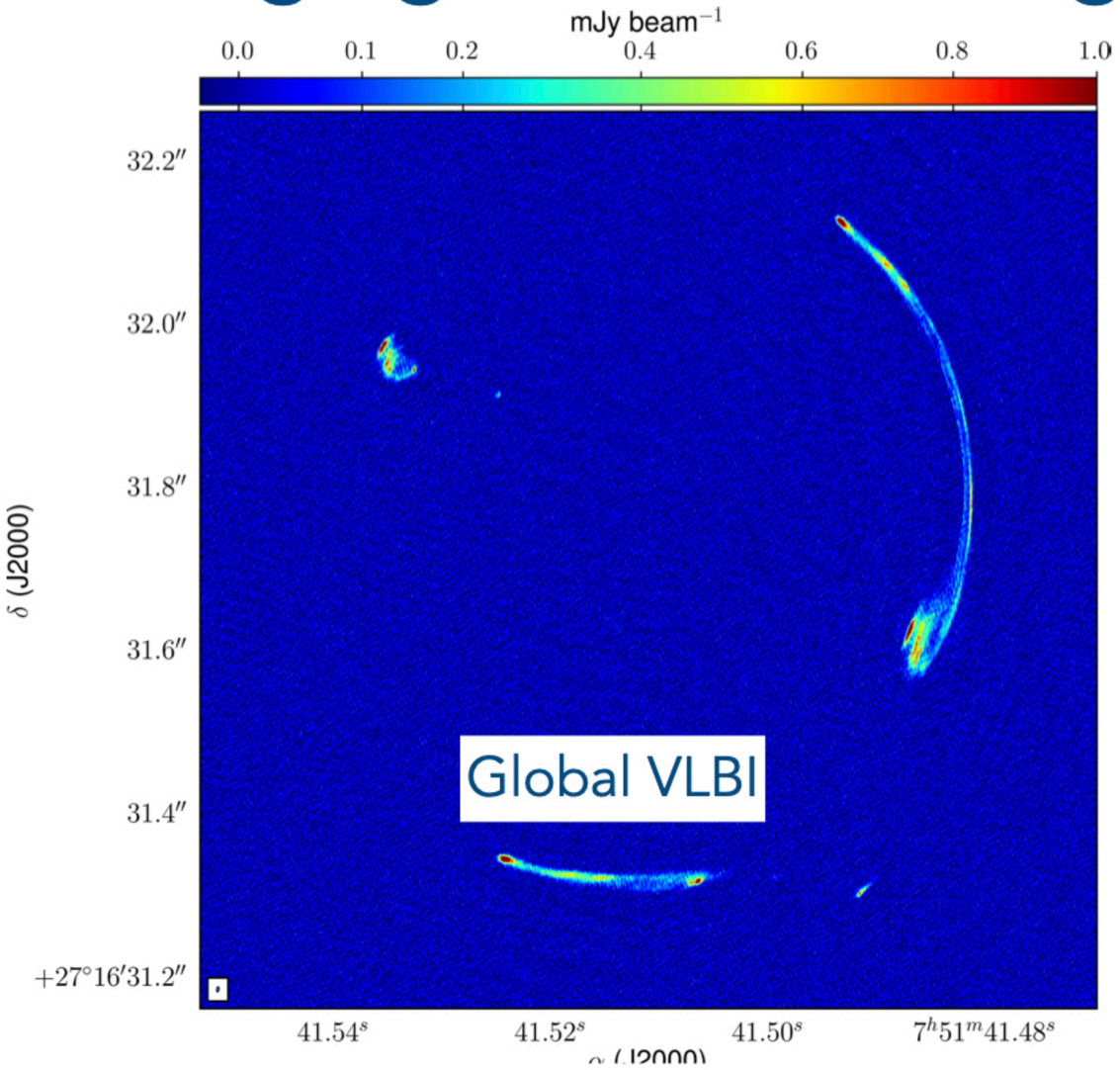


Work in progress to detect dark subhalos in this new data set!

Method can be applied to imaging at all wavelengths



Hezaveh et al. 2016



Spignola et al. 2018

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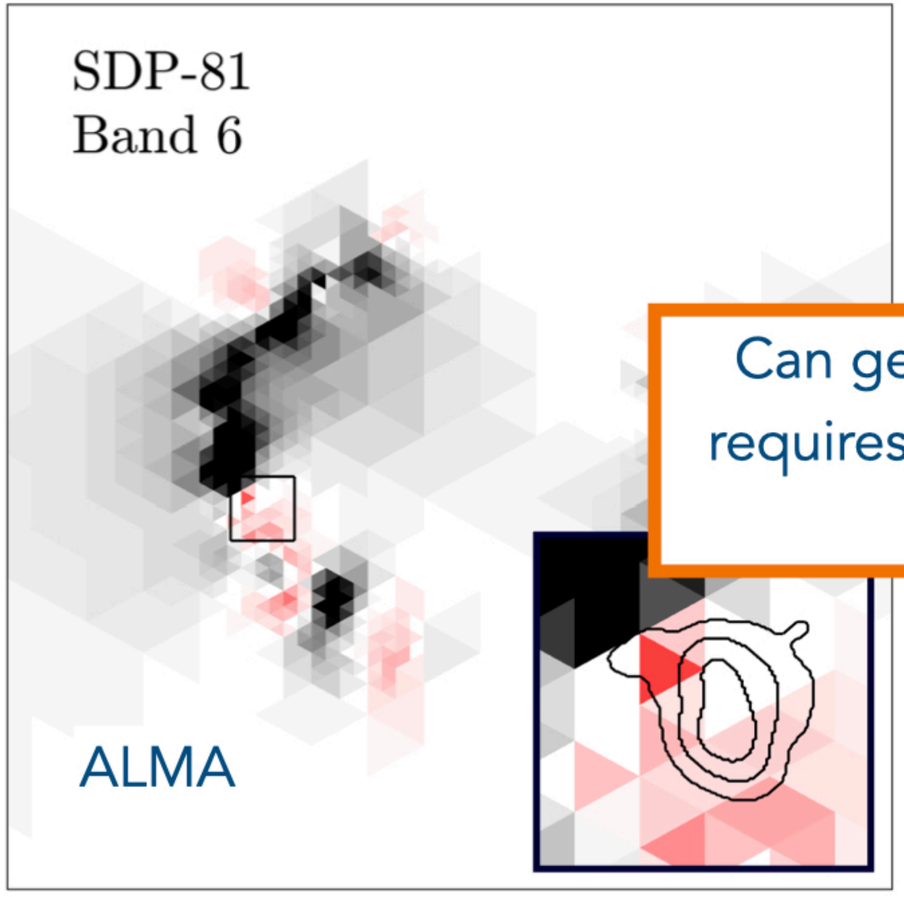
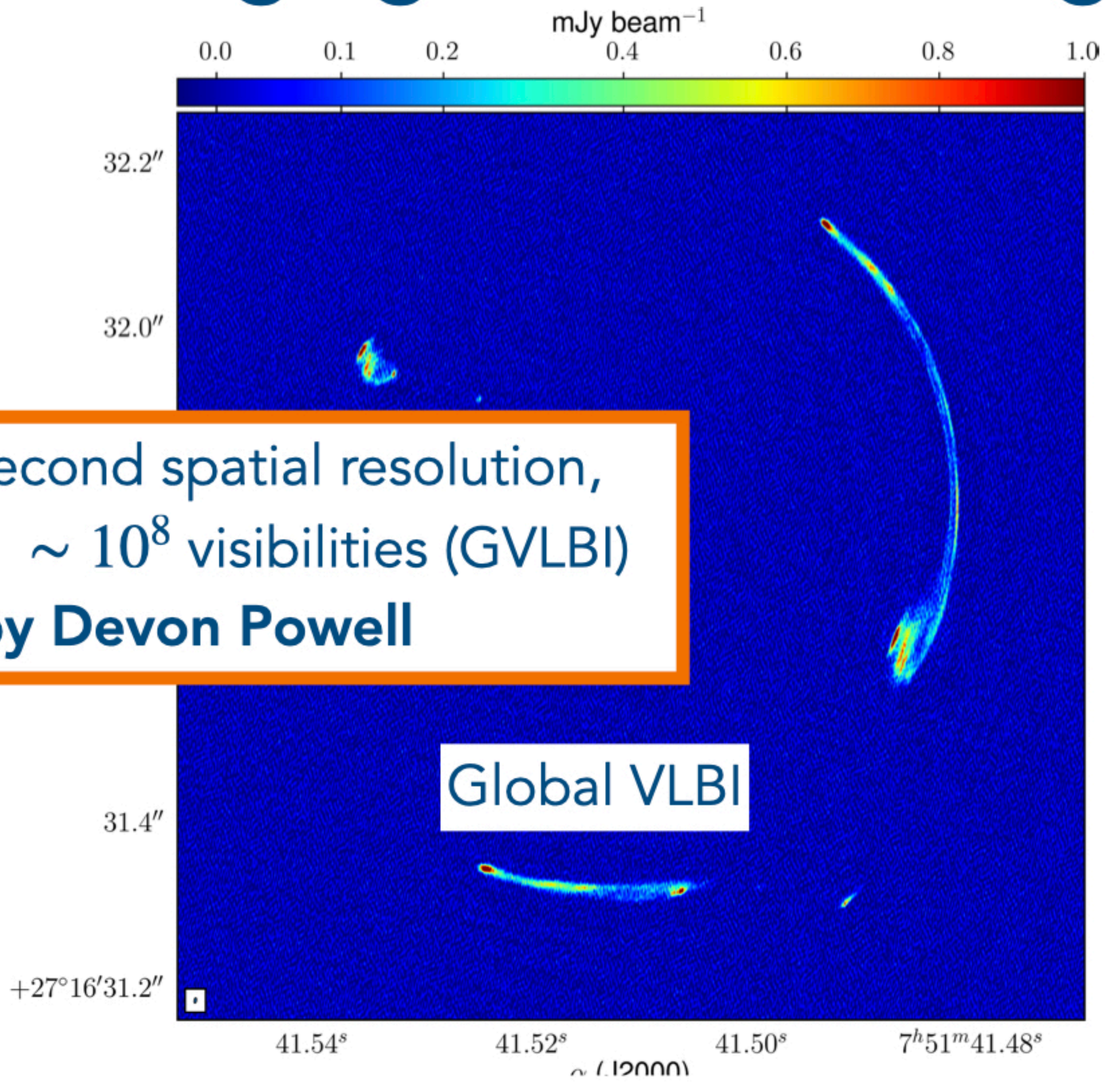


Hezaveh et al. 2016

Can get milli-arcsecond spatial resolution, requires modelling $\sim 10^8$ visibilities (GVLBI)

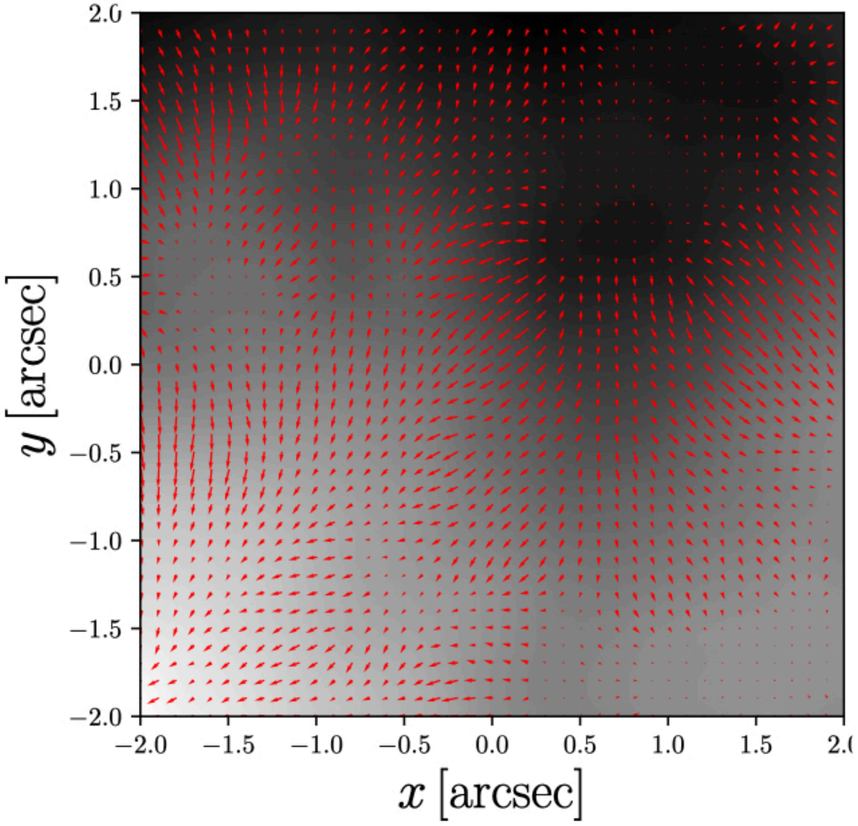
See talk by Devon Powell



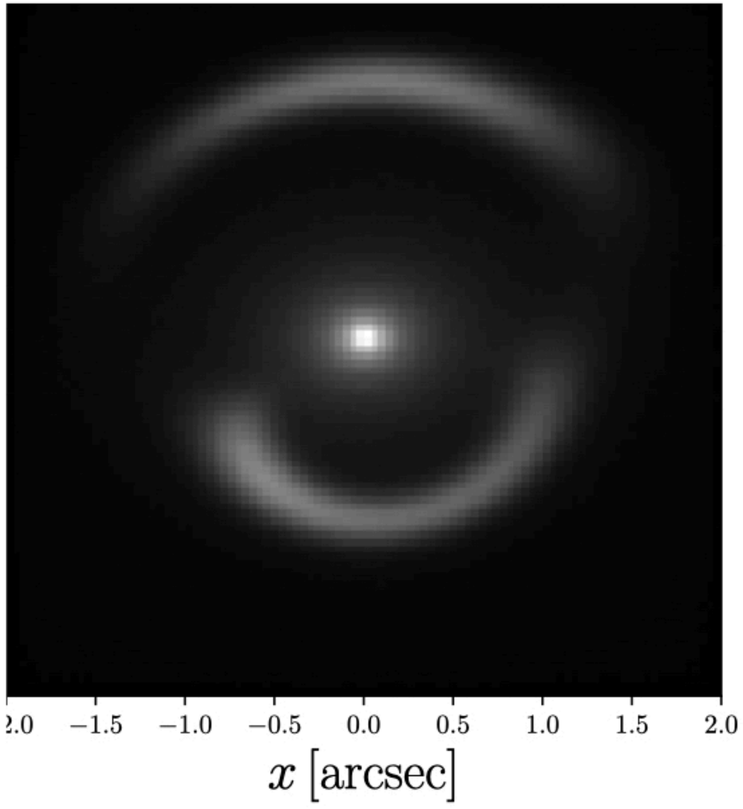
Spignola et al. 2018

Detection of the subhalo field

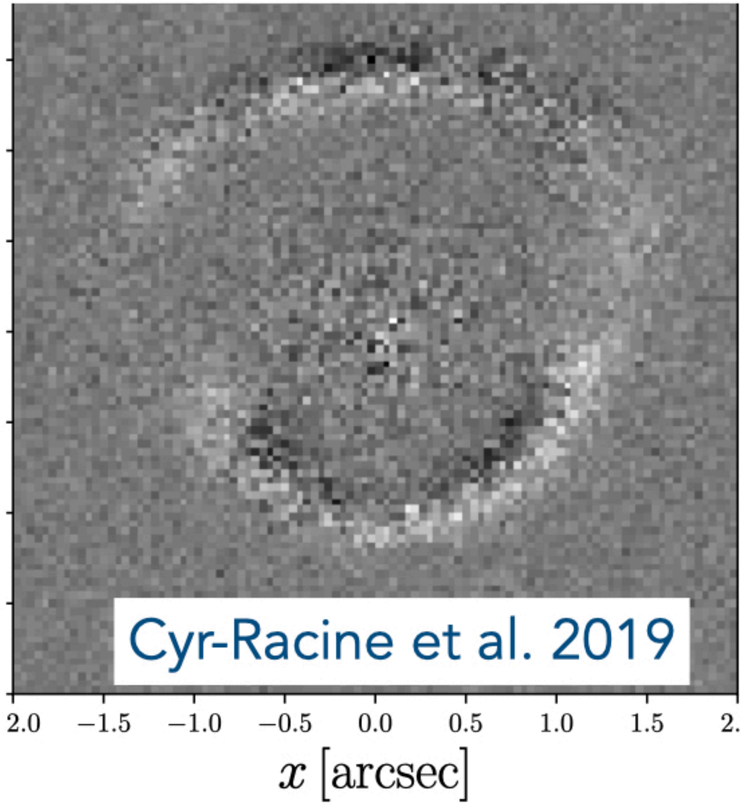
Substructure Deflection Field



Mock observed lens



Mock Residuals

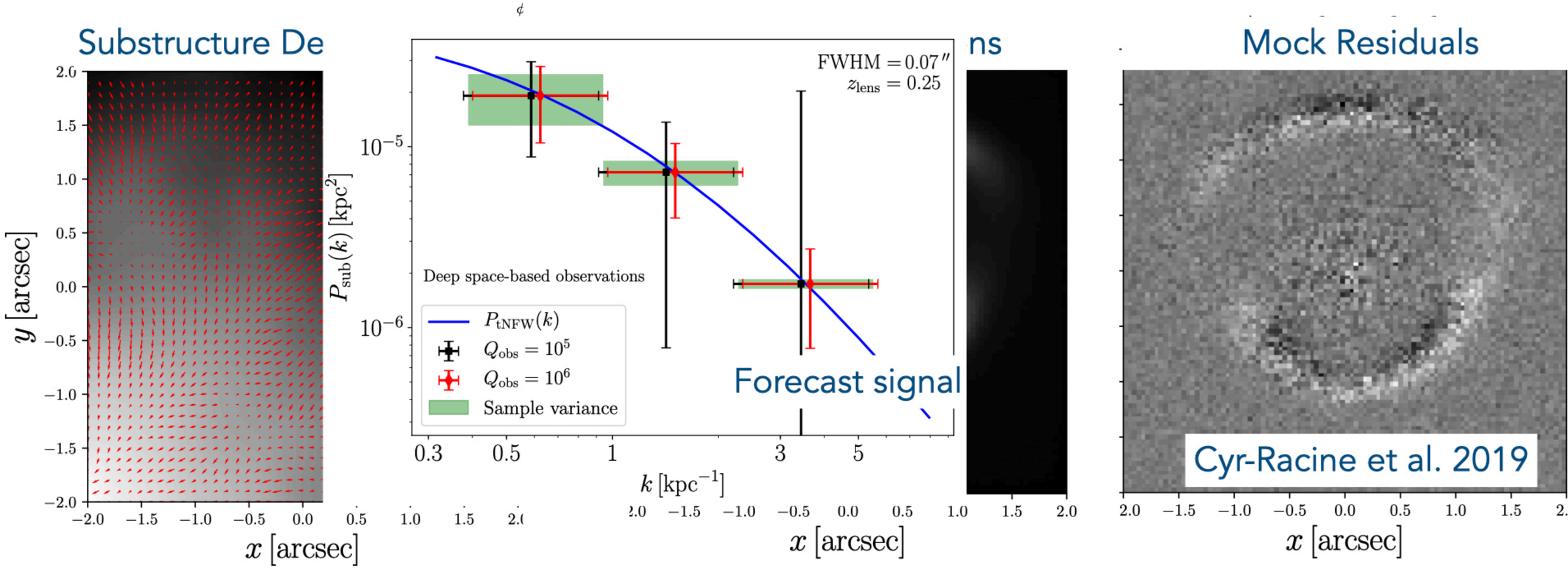


Cyr-Racine et al. 2019

The power spectrum of the residuals is connected to the substructure deflection field

In practice, challenging with current detectors given effects like IPC (Bayer et al. 2023)

Detection of the subhalo field



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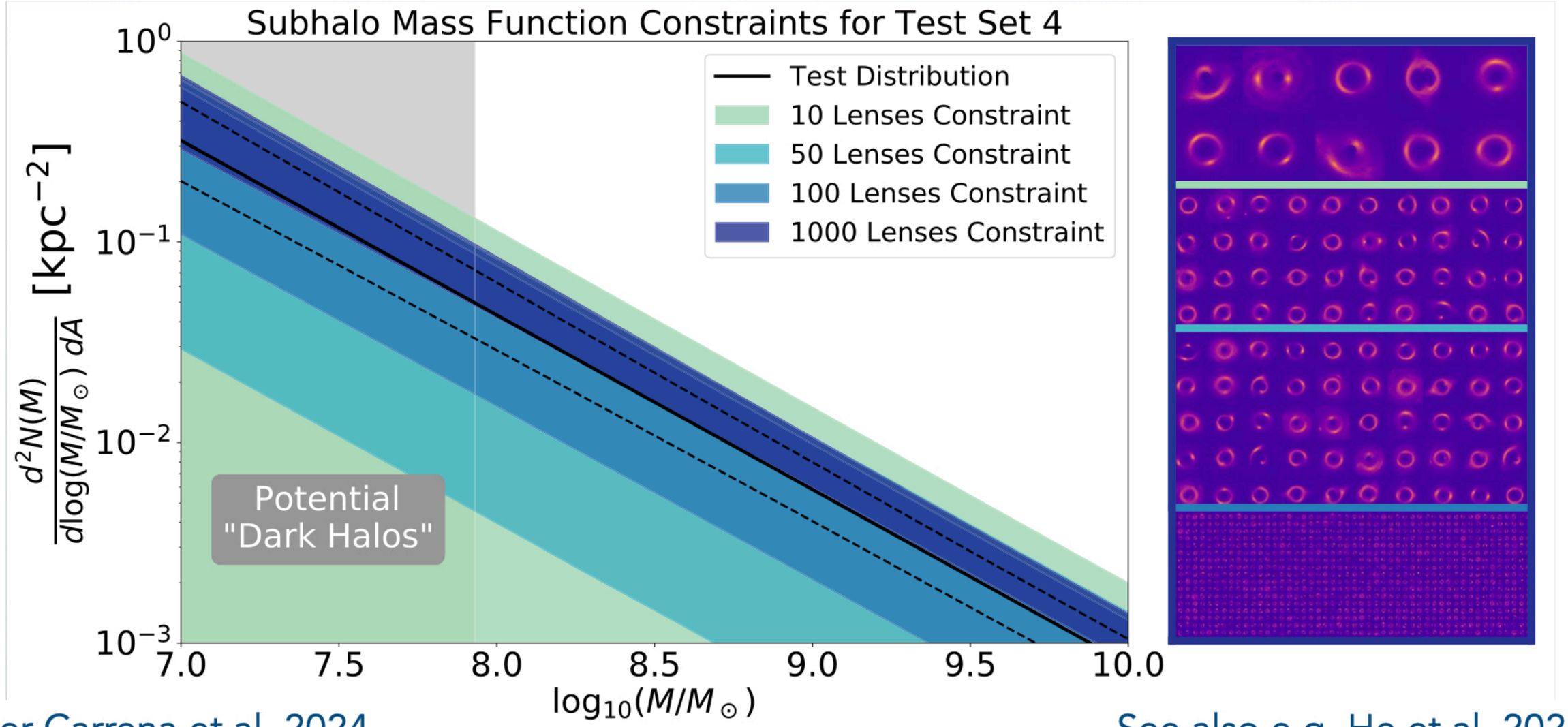
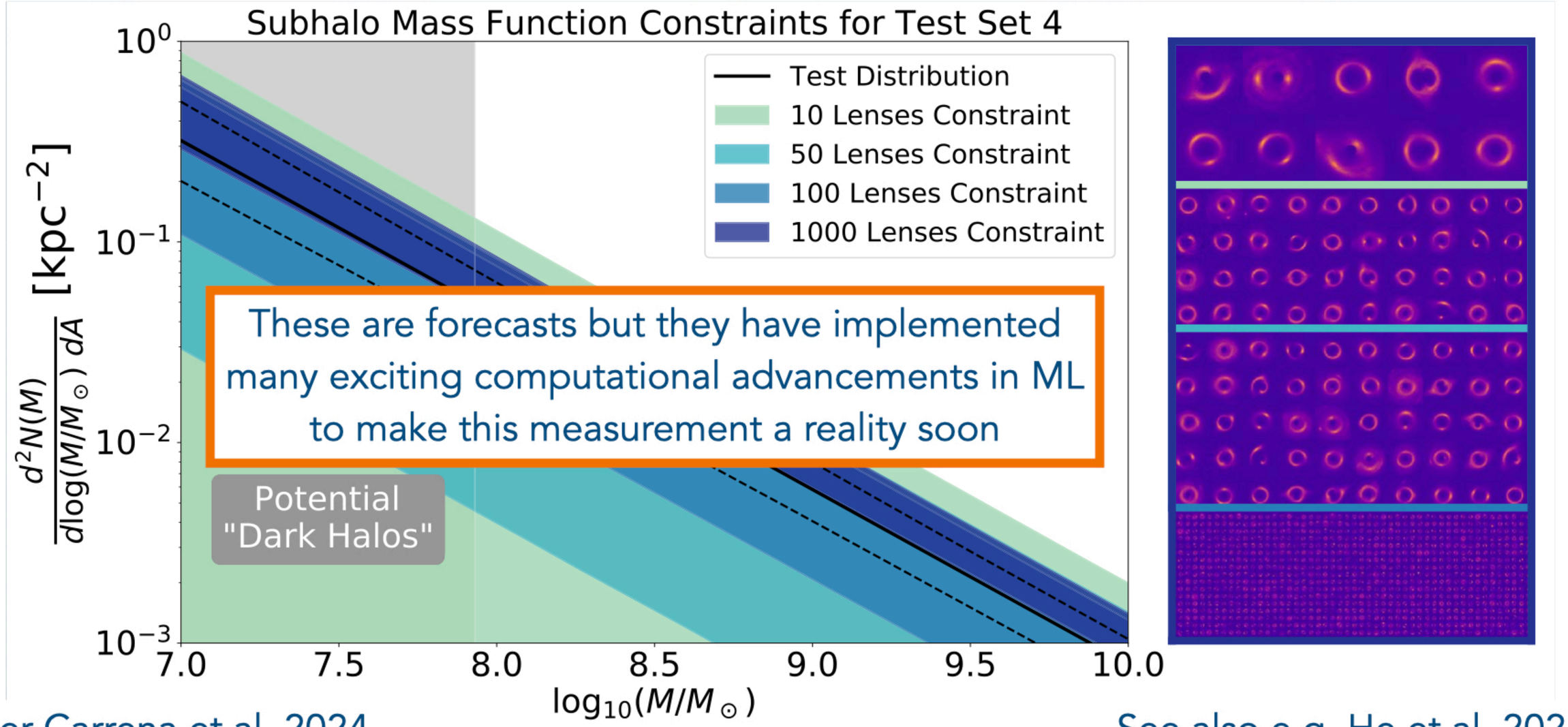
Forward modelling with machine learning



Wagner-Carrena et al. 2024

See also e.g. He et al. 2022

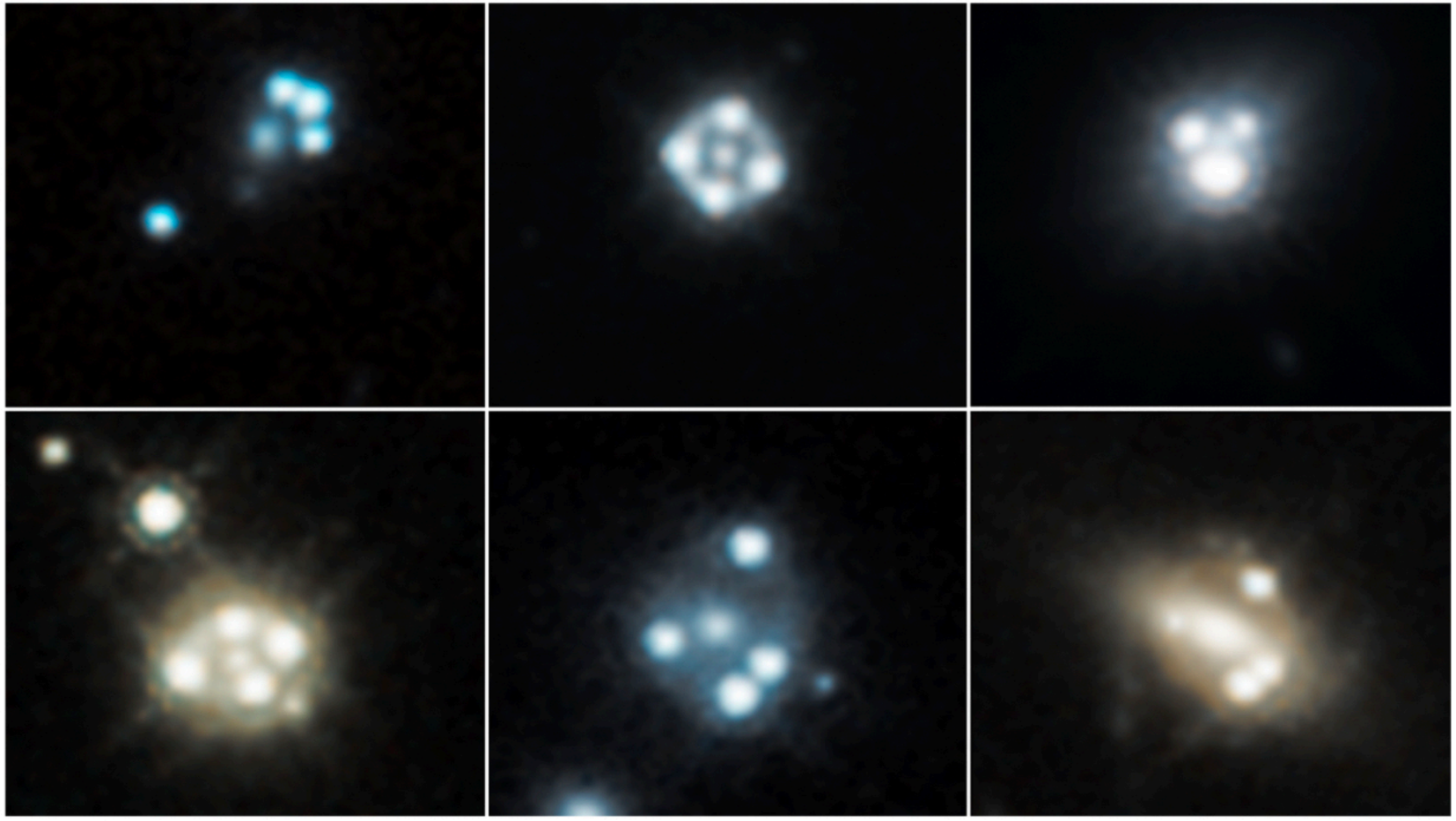
Forward modelling with machine learning



Wagner-Carrena et al. 2024

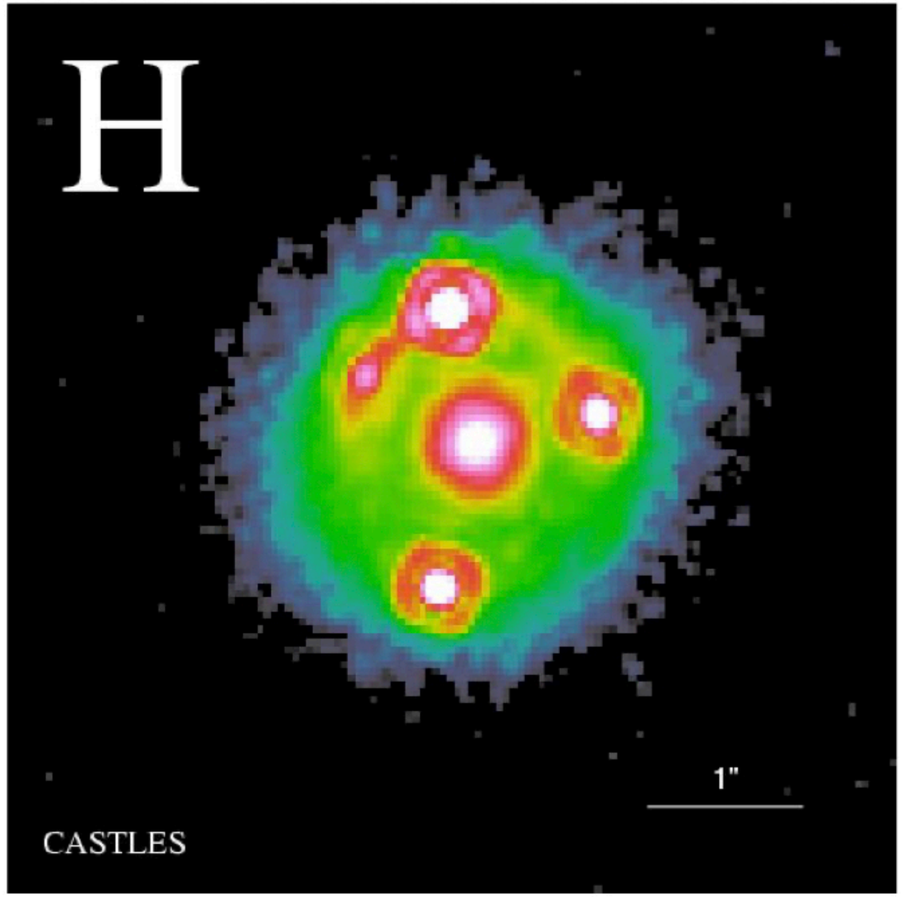
See also e.g. He et al. 2022

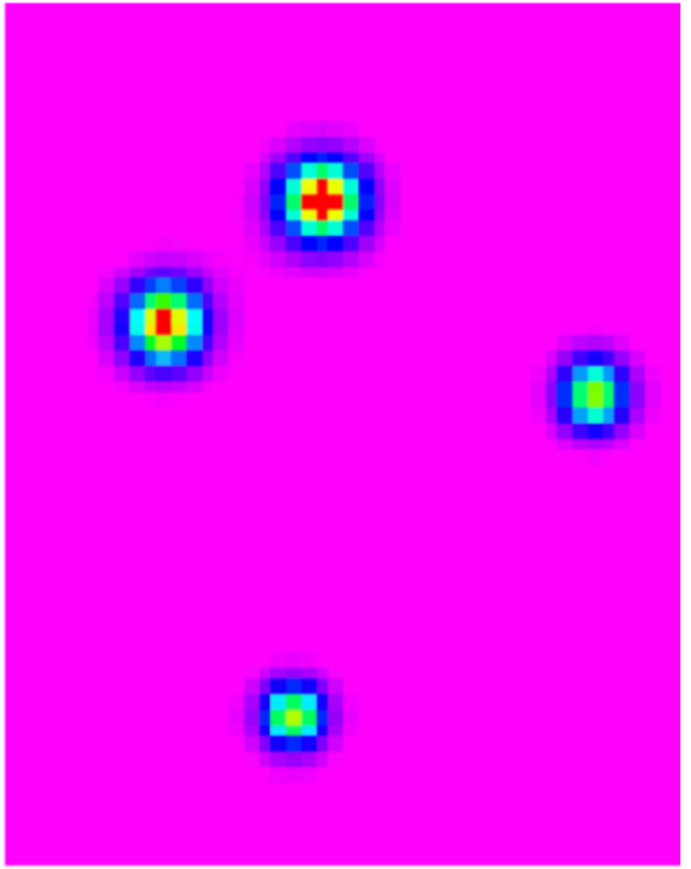
Unresolved source a.k.a. ‘flux ratios’



Credit: STSCI, GO-15177, 13732 PI Nierenberg

Example of the signal





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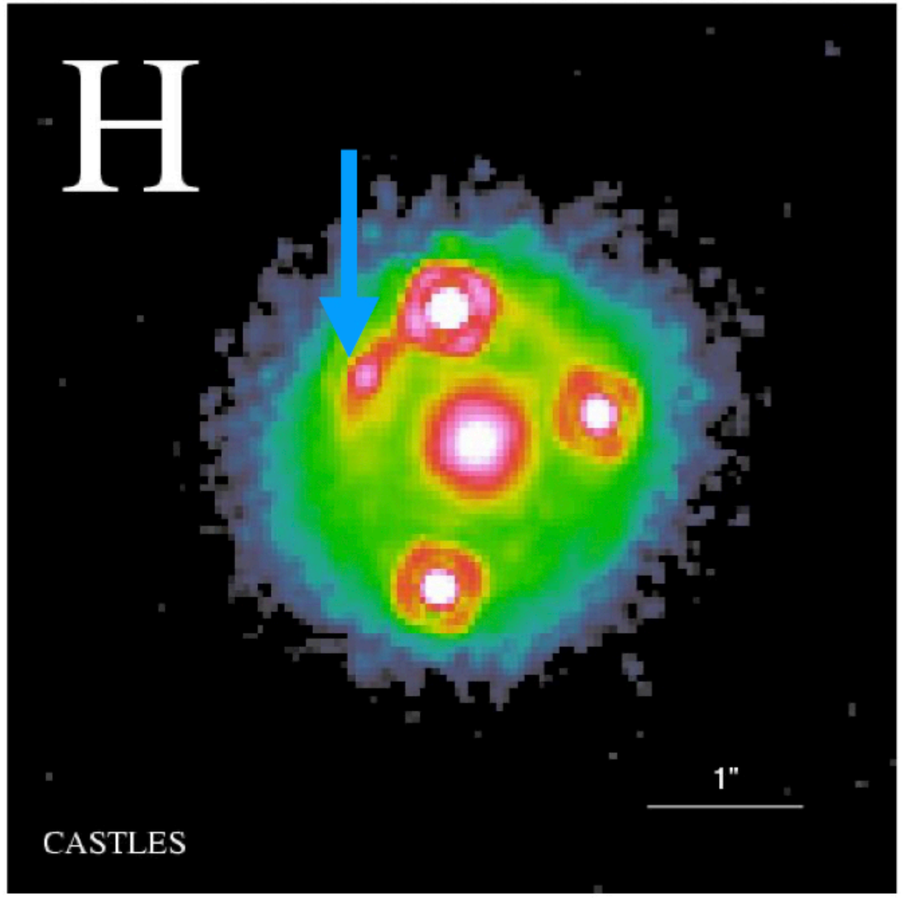

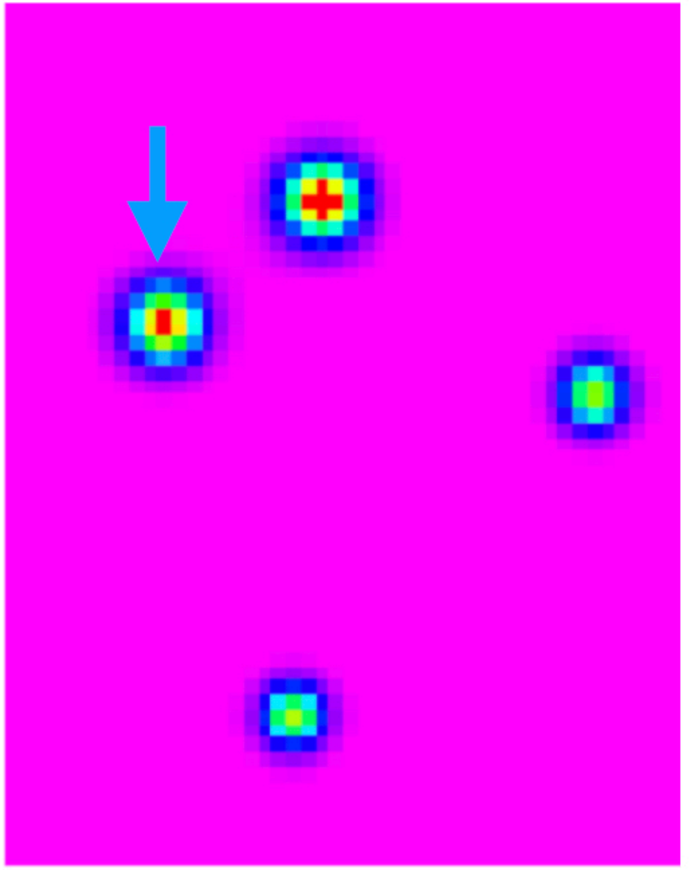

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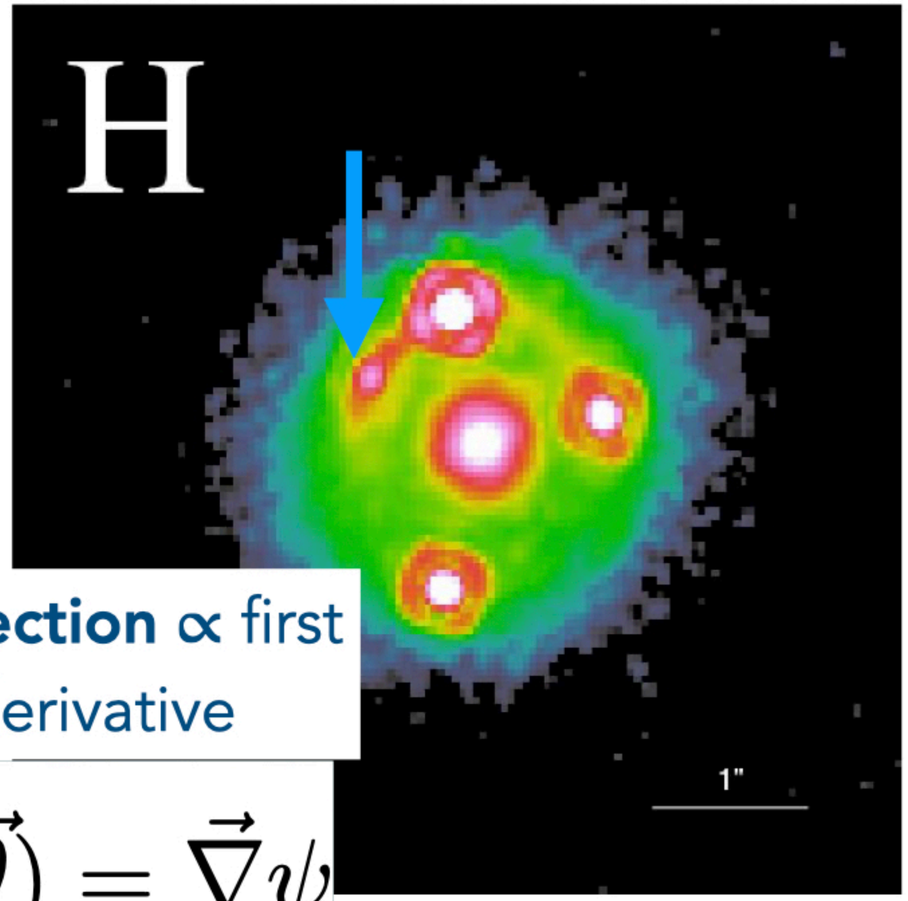
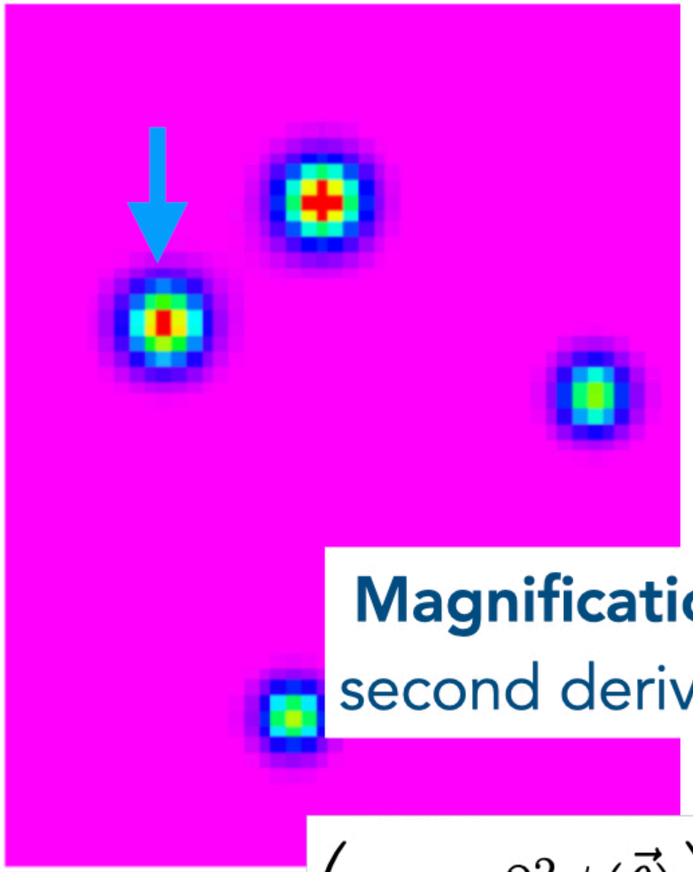


Deflection ∝ first derivative

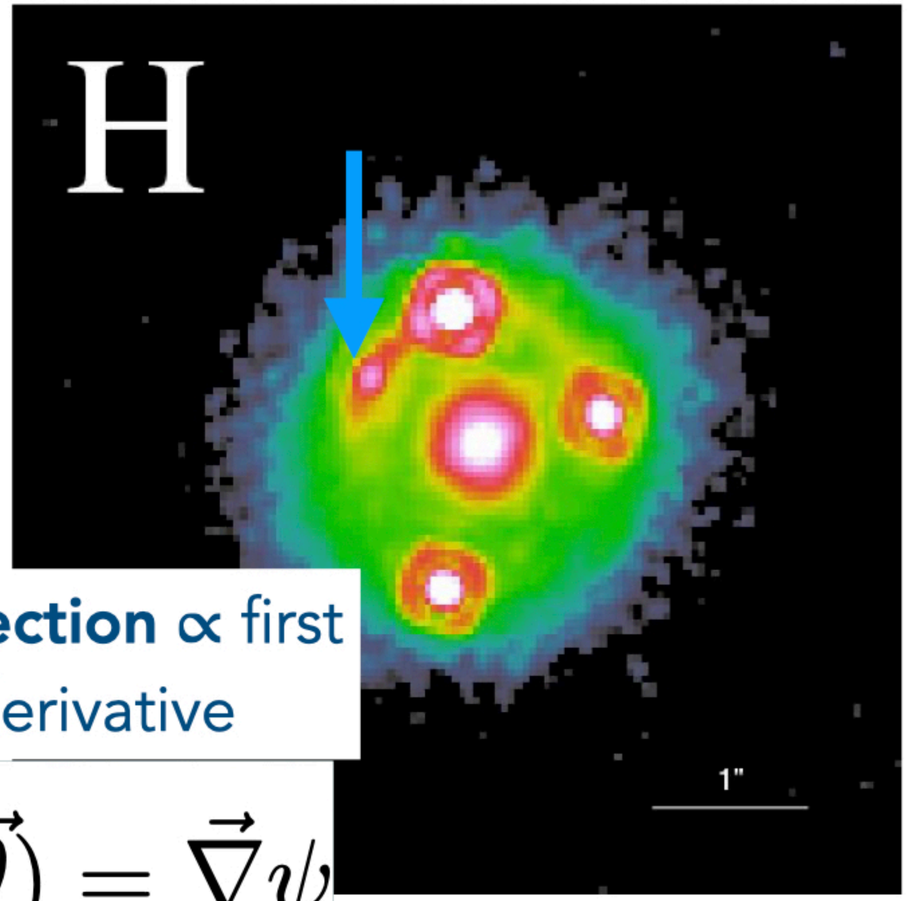
$$\vec{\alpha}(\vec{\theta}) = \vec{\nabla}\psi$$



Magnification ∝ second derivative

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

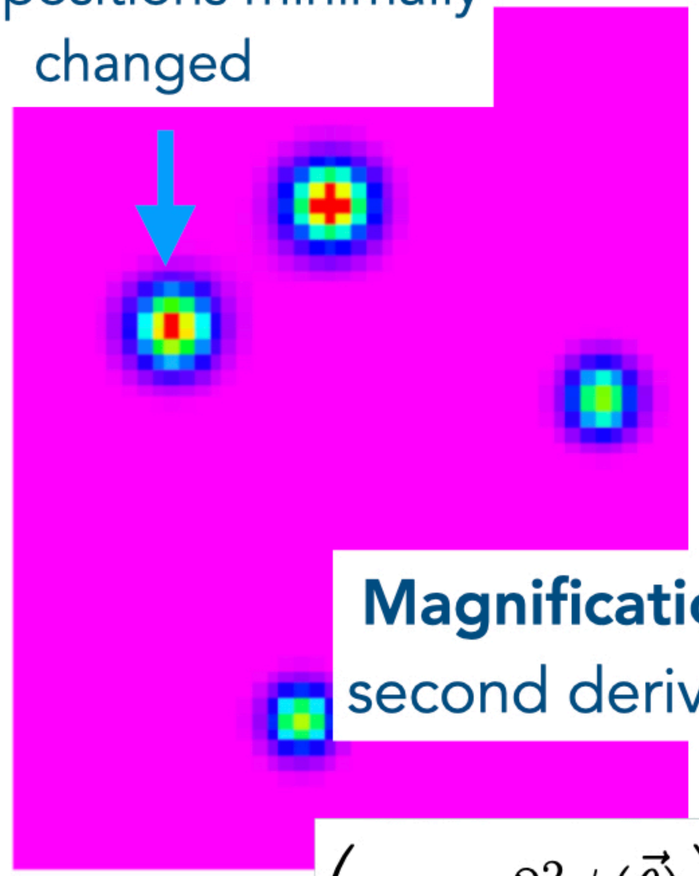
Example of the signal



Deflection ∝ first derivative

$$\vec{\alpha}(\vec{\theta}) = \vec{\nabla}\psi$$

Localized perturbations change the image magnifications while leaving positions minimally changed

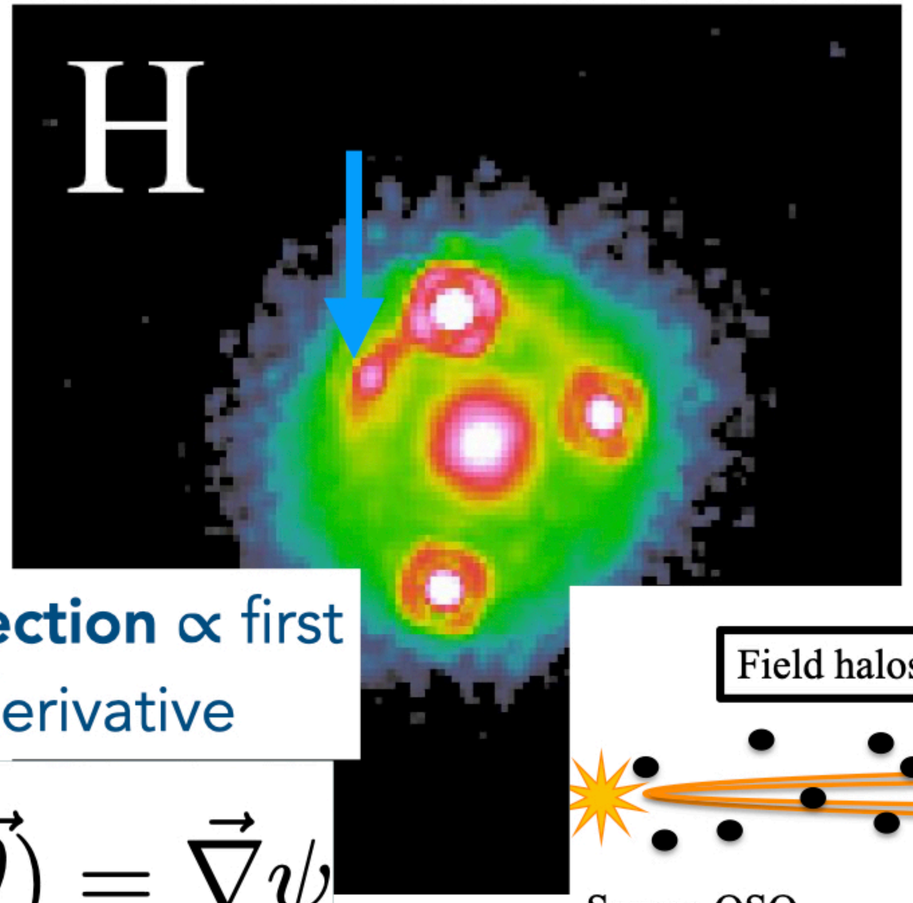


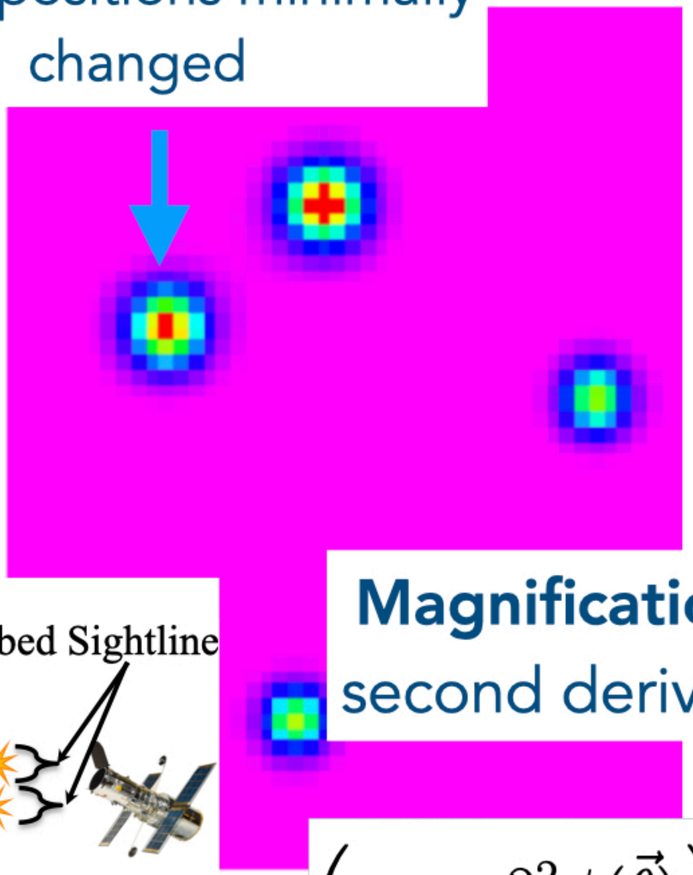
Magnification ∝ second derivative

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

Example of the signal

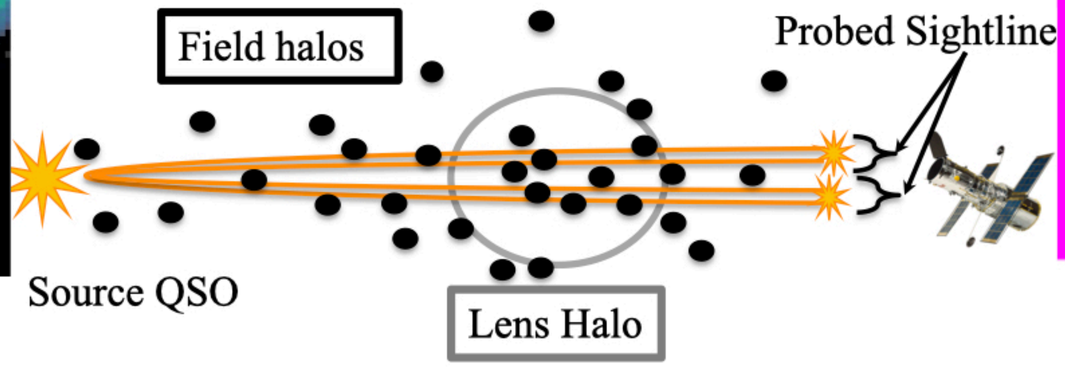
Localized perturbations change the image magnifications while leaving positions minimally changed





Deflection ∝ first derivative

$$\vec{\alpha}(\vec{\theta}) = \vec{\nabla}\psi$$



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Example of the signal

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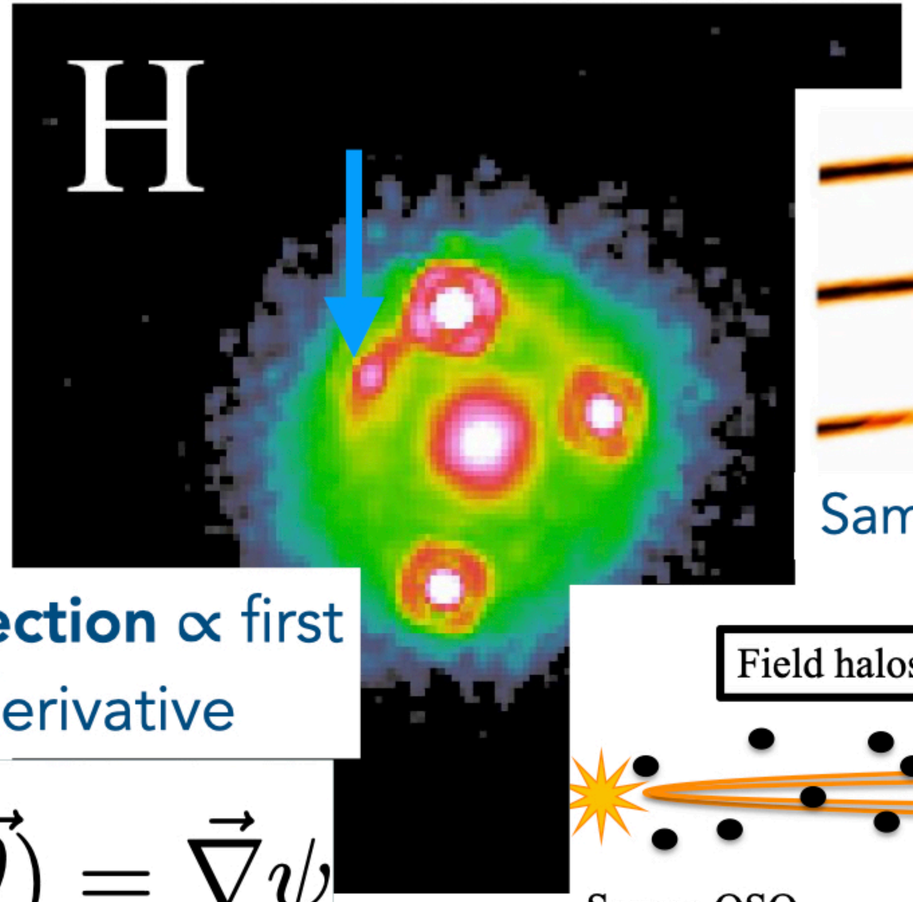
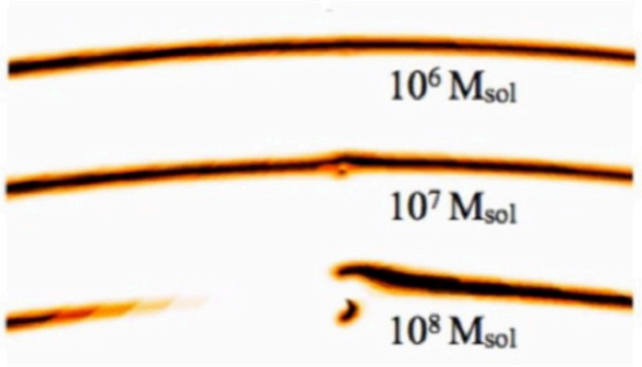
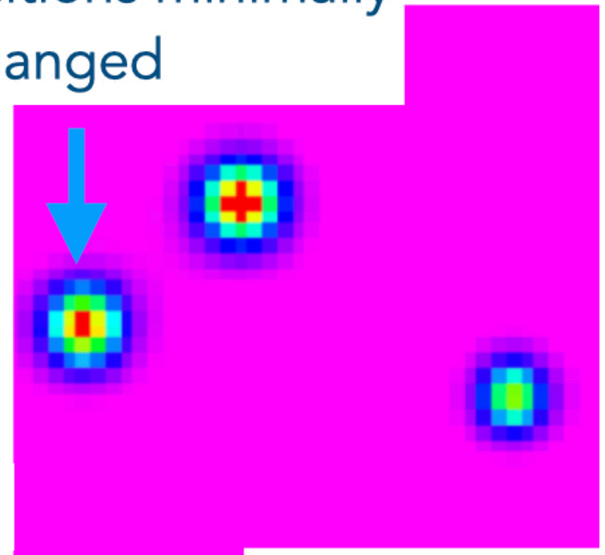




Same physics, just smaller



Deflection ∝ first derivative

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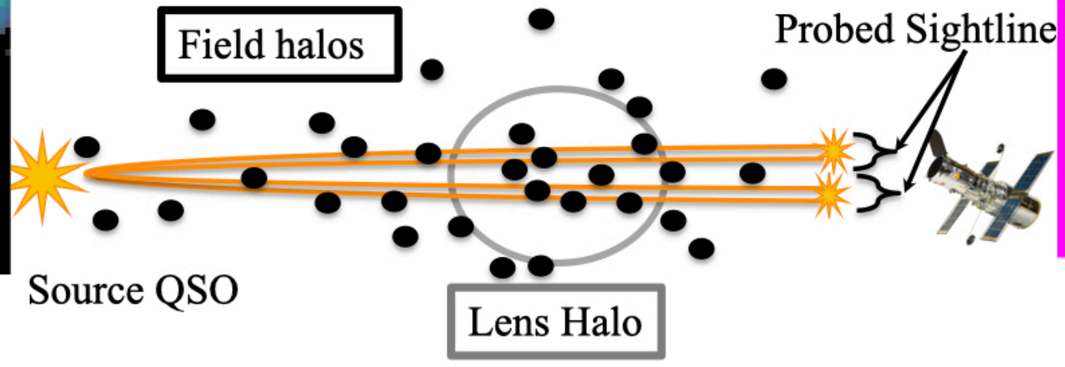
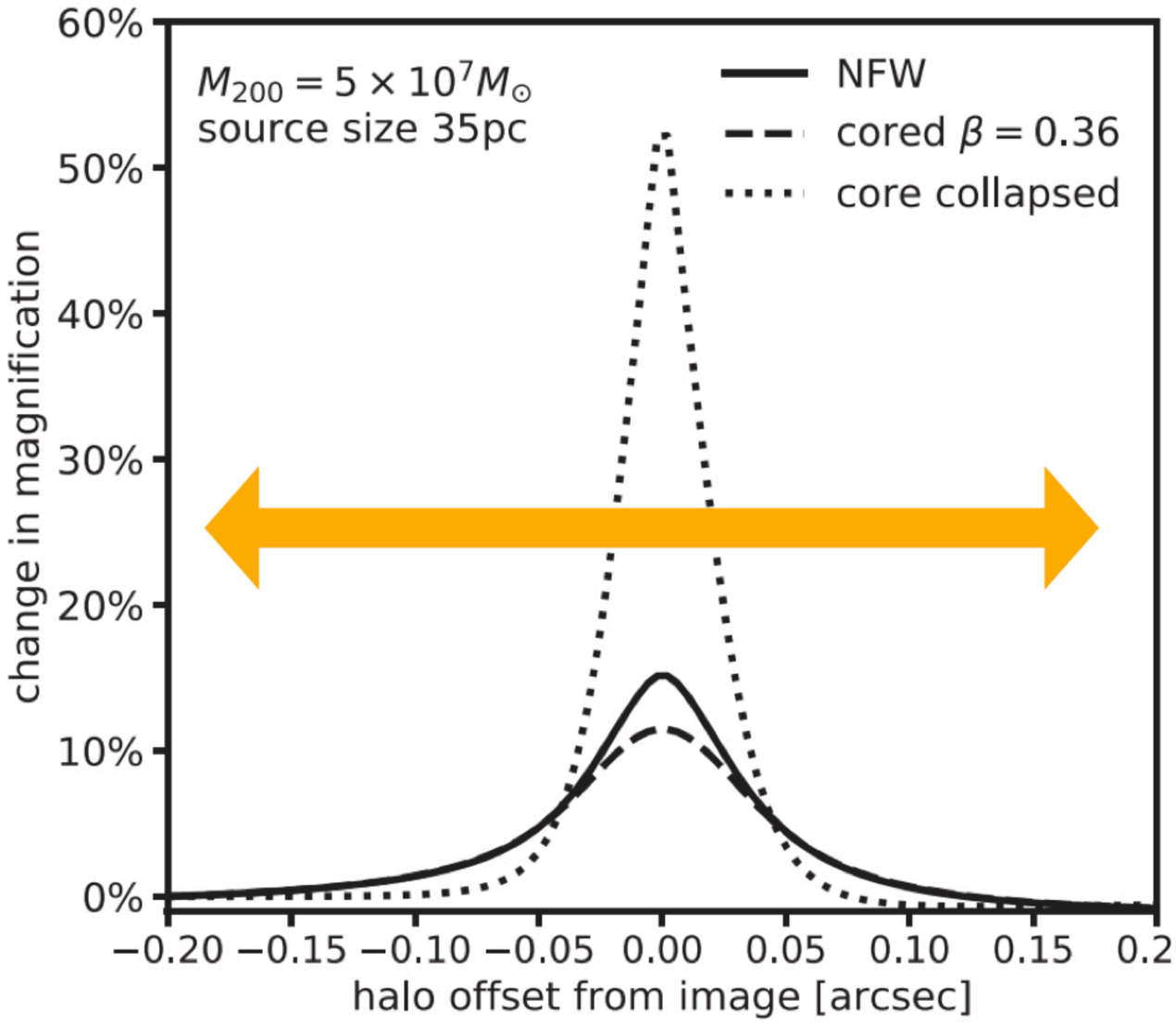


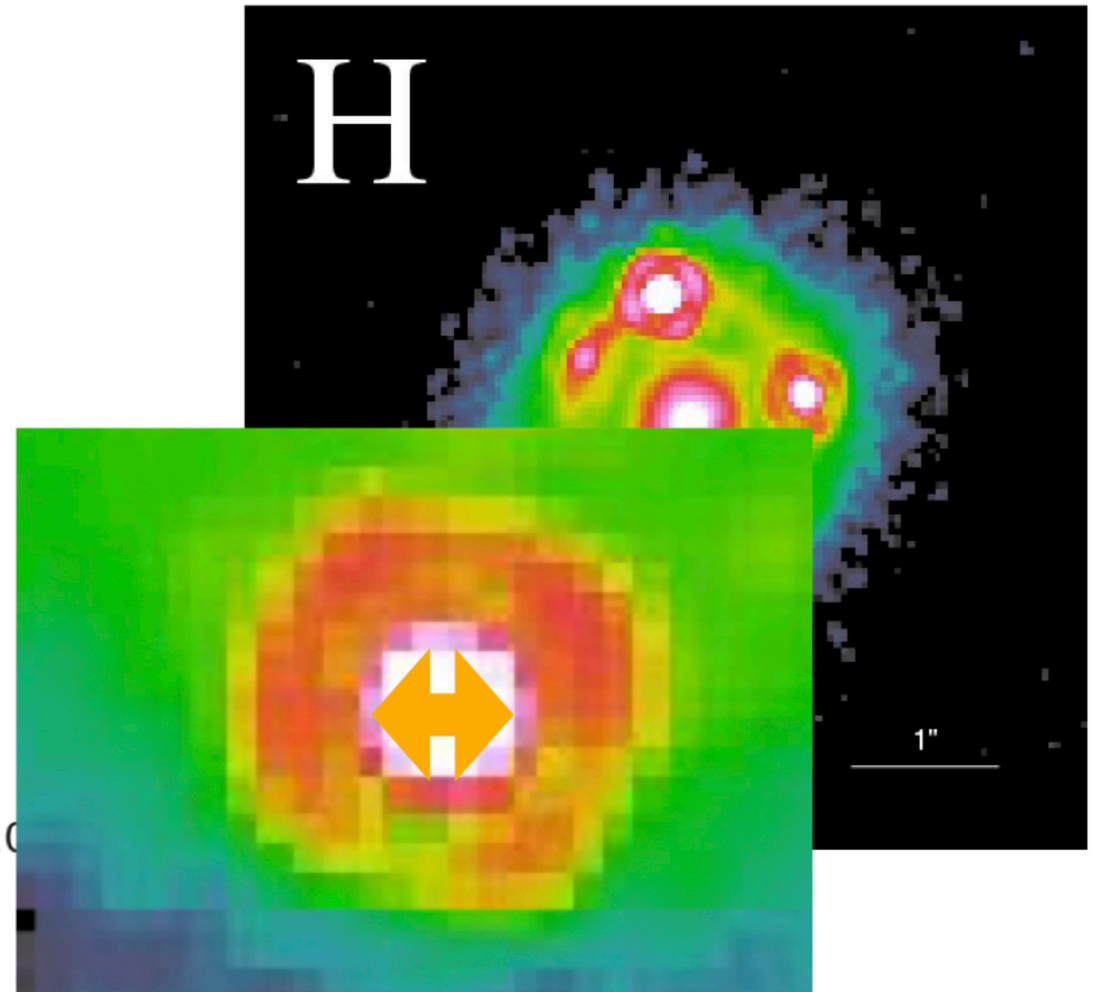
Magnification ∝ second derivative

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

Lensing signal with varying density profile

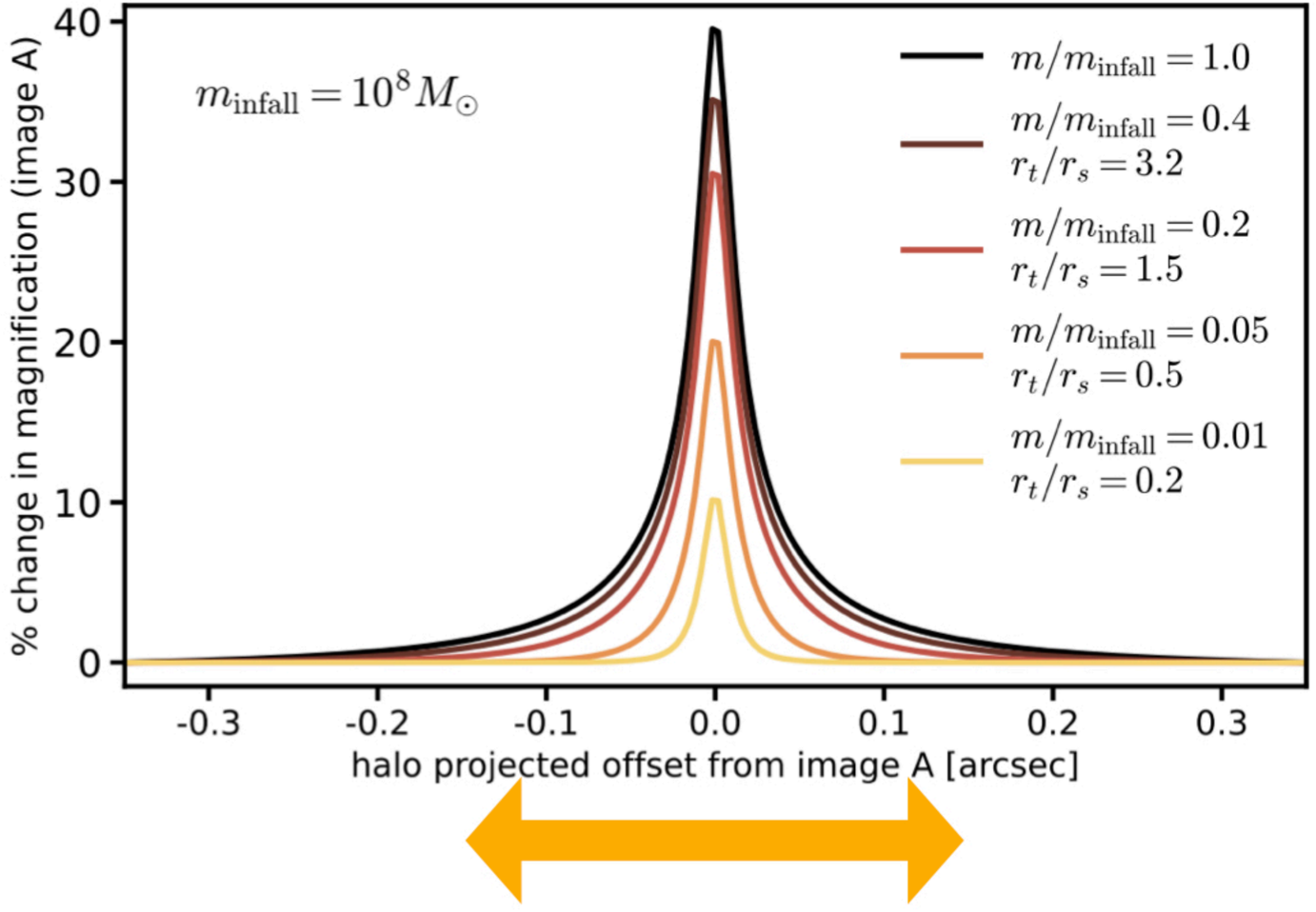


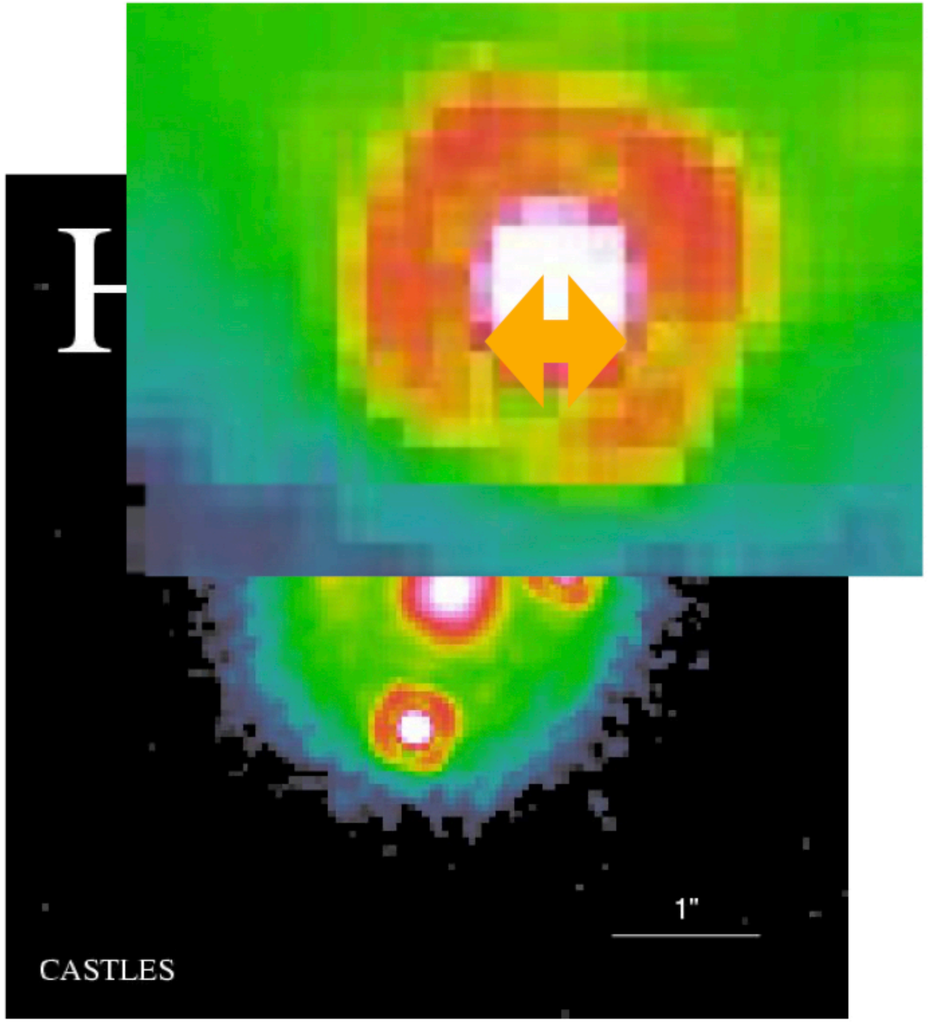
For fixed halo mass, denser profiles create higher magnifications



Lensing signal with varying density profile

Tidal stripping must remove ~95% of mass before we see a significant change in lensing signal (for one halo)

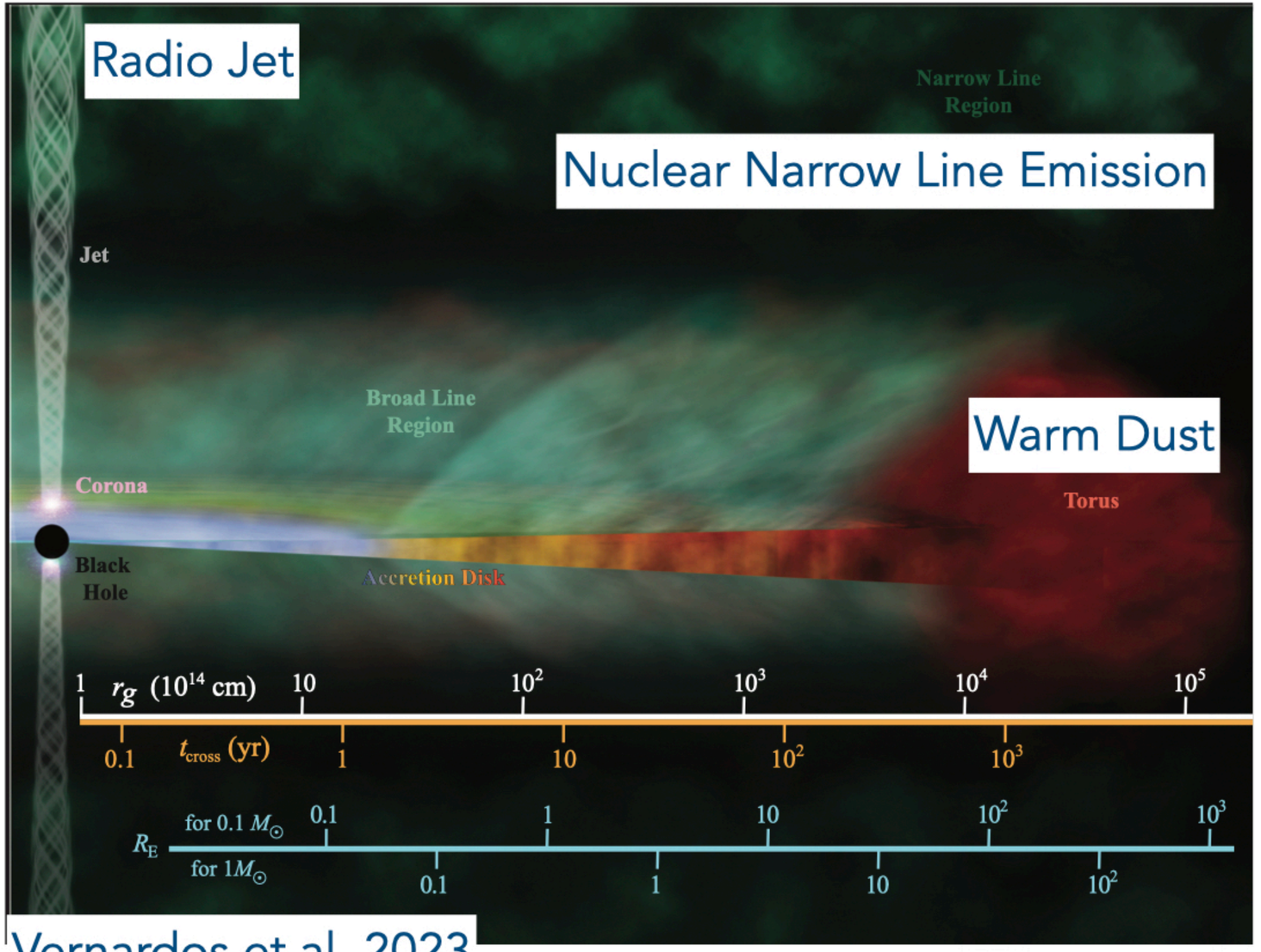




Have to use a large enough source

- Quasar Radio Jet (Mao and Schneider 1998, Dalal and Kochanek 2002)
- Quasar narrow-line emission (Moustakas and Metcalf 2003)
- Quasar warm dust (e.g. Algol et al. 2000, Chiba et al. 2005 and more)

All ~milli-arcseconds given typical source redshifts



Vernardos et al. 2023

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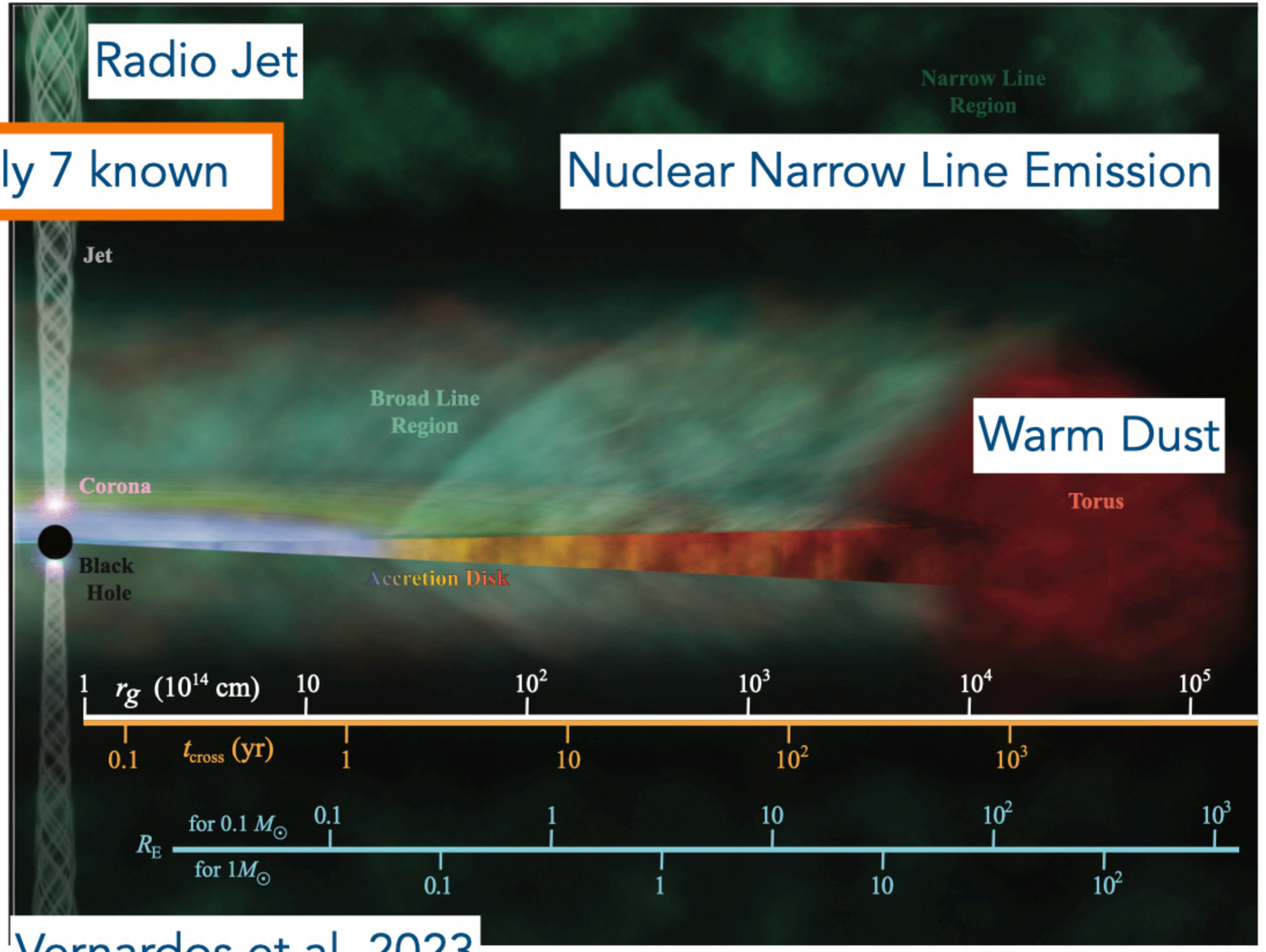
Only 7 known



Vernardos et al. 2023

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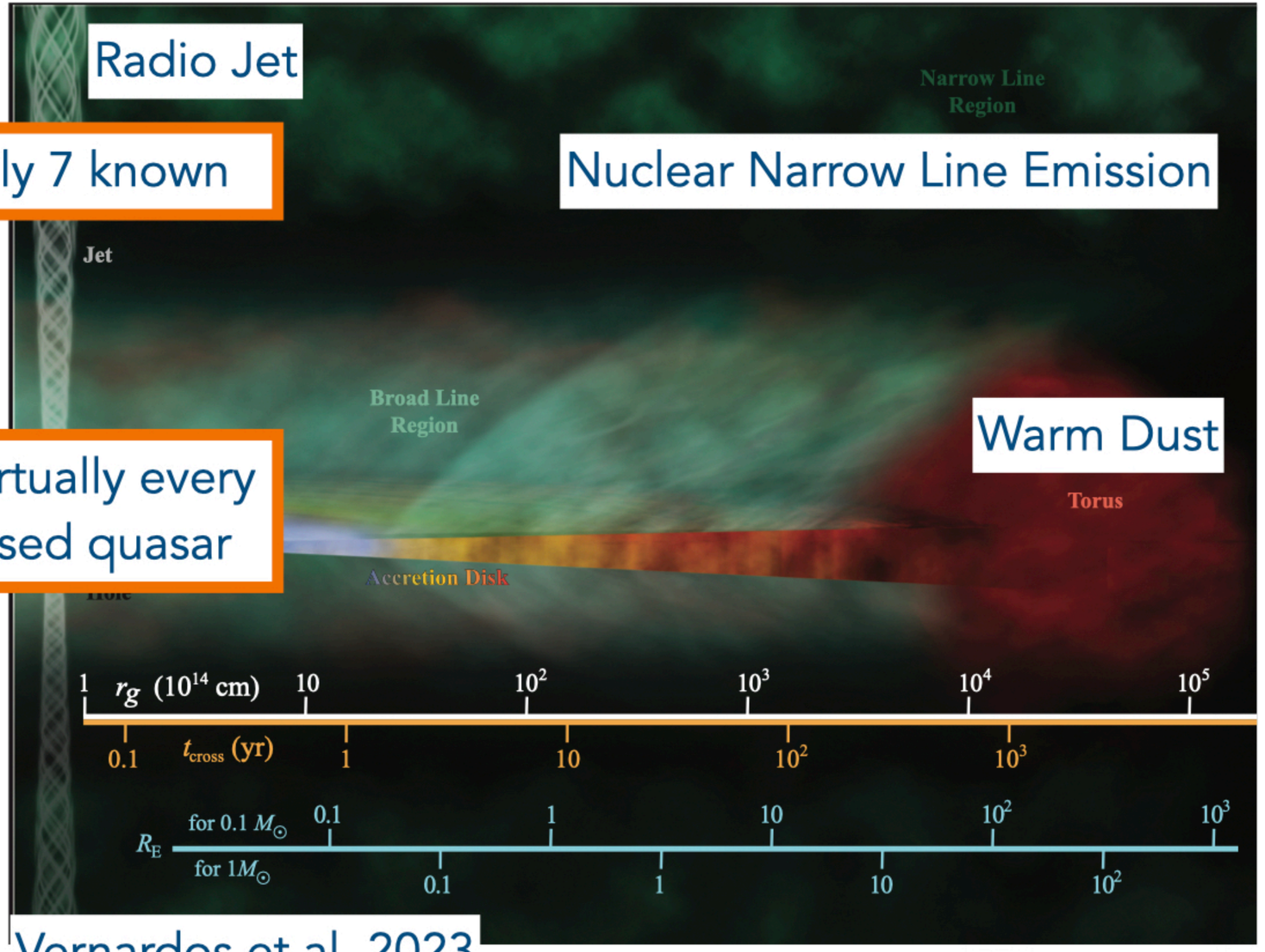
All ~milli-arcseconds given typical source redshifts

Only 7 known

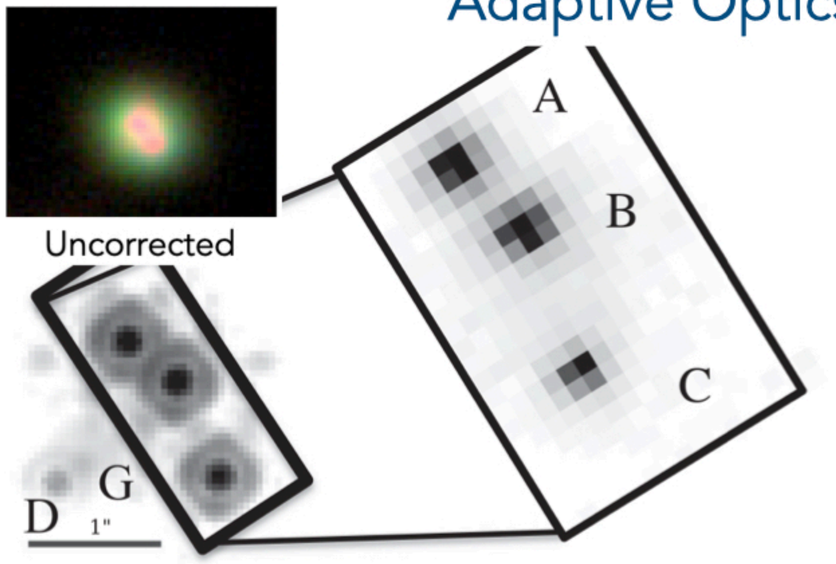
In virtually every lensed quasar



Vernardos et al. 2023

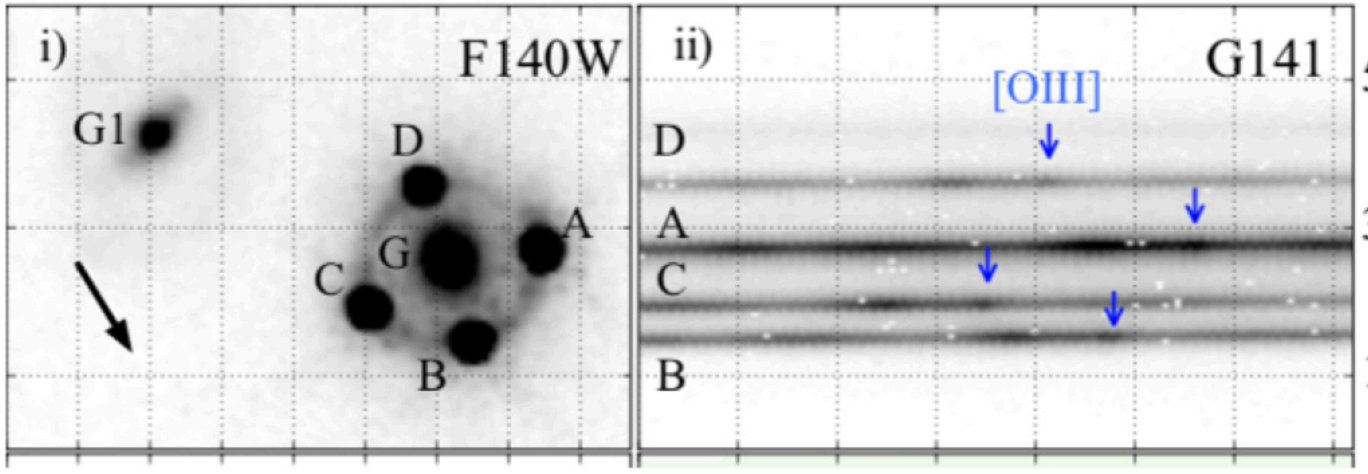
Narrow-line measured with Keck OSIRIS/HST

Keck OSIRIS with Adaptive Optics



Nierenberg et al. 2014

Nierenberg et al. 2017



HST GO-15177, 13732, PI Nierenberg

Narrow-line measured with Keck OSIRIS/HST

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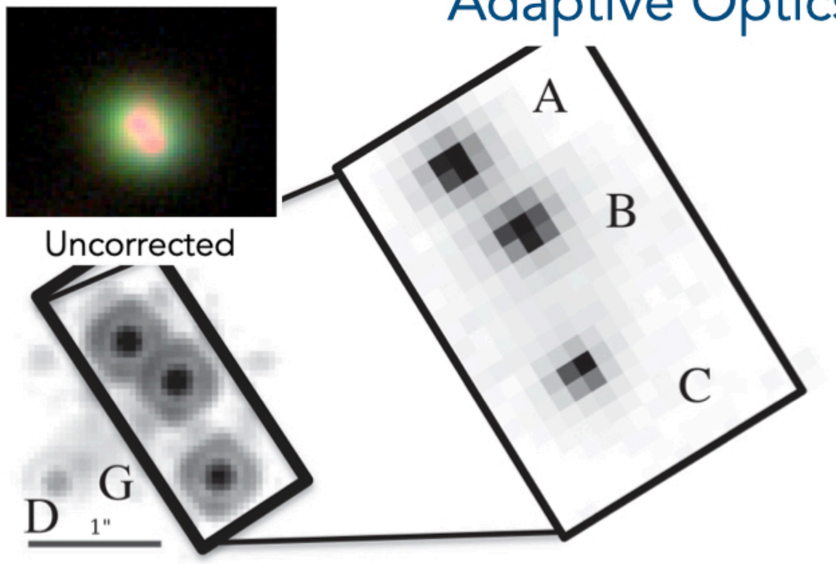
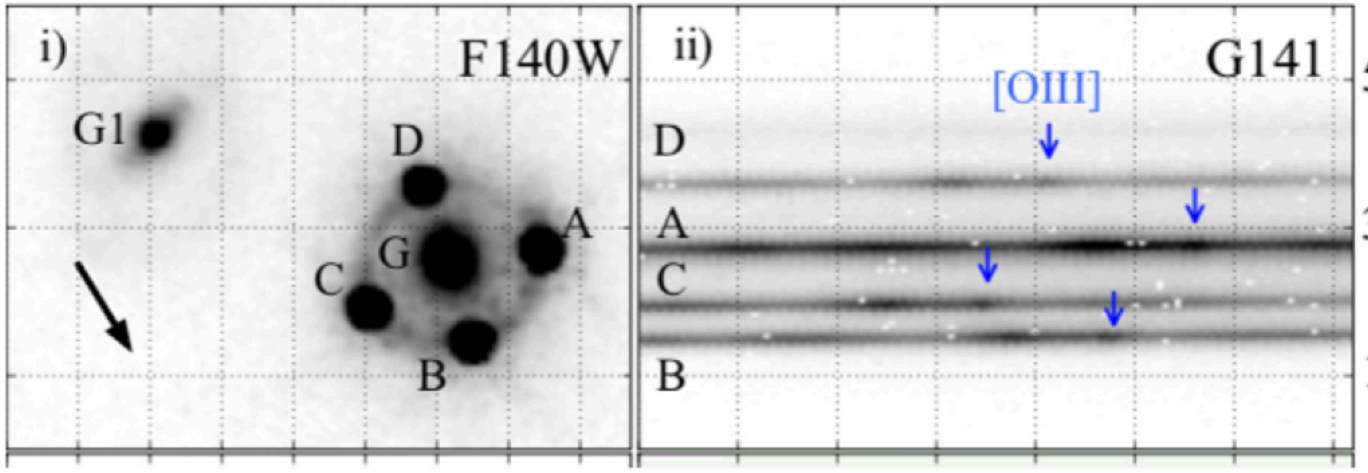


Nierenberg et al. 2014

Nierenberg et al. 2017



HST GO-15177, 13732, PI Nierenberg

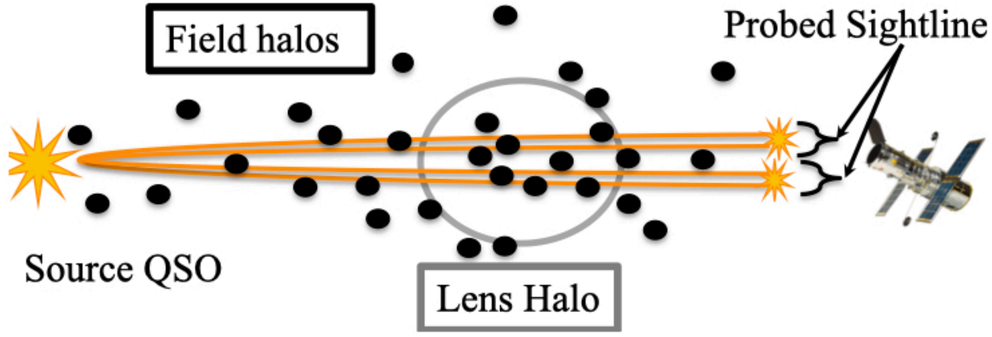
Results from 11 lenses…

Forward modelling pipeline

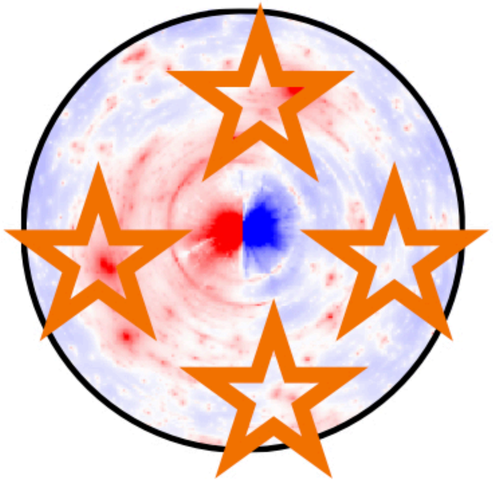
We generate millions of realizations of dark matter halos and subhalos, marginalizing over:

- ✳Dark matter properties (e.g. half-mode mass)
- ✳Tidal stripping of subhalos
- ✳Mass distribution of main deflector (including deviations from ellipticity)
- ✳Source size

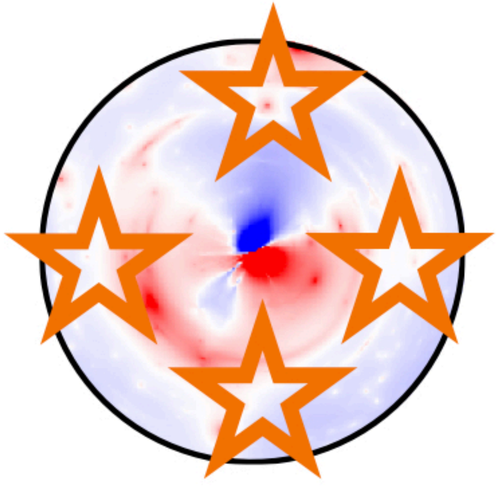
Multi-plane lensing convergence maps



CDM Realization



WDM Realization



Gilman, Birrer, Nierenberg et al. 2020a

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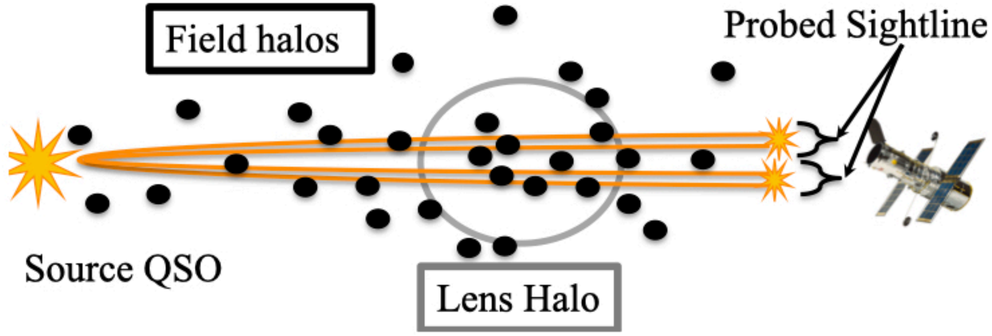
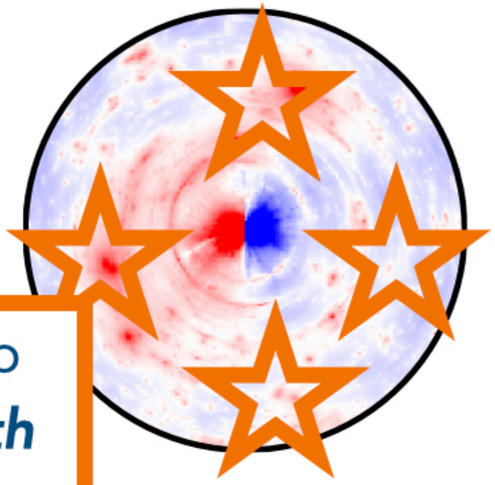
Pipeline and data can be used to *test* ***any dark matter model with analytic description for non-linear density field***

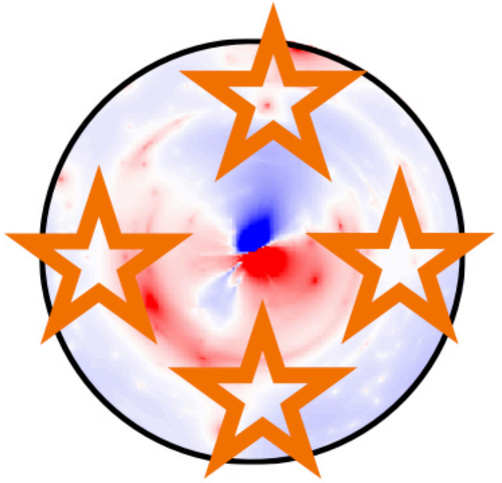
Multi-plane lensing convergence maps



CDM Realization



WDM Realization

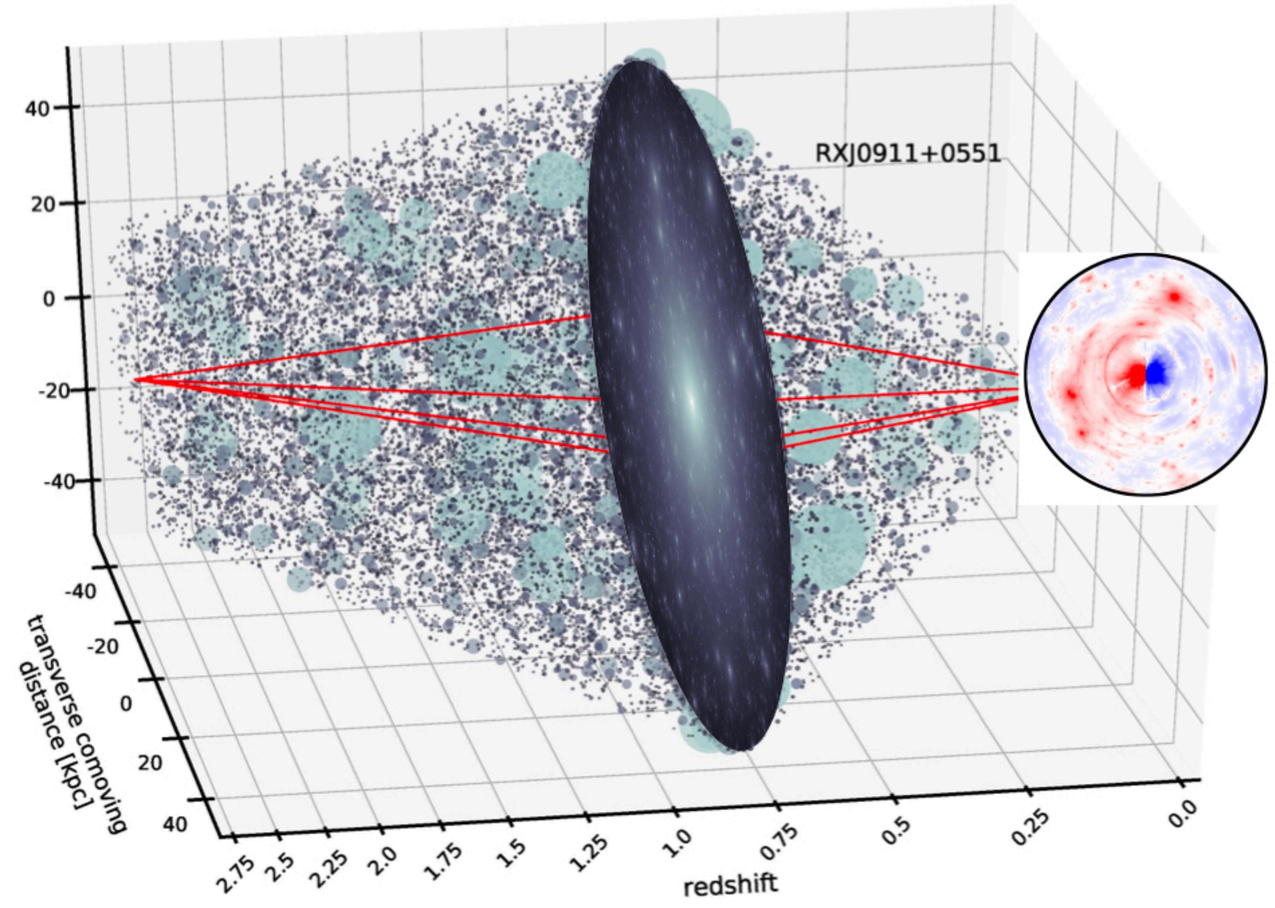


Gilman, Birrer, Nierenberg et al. 2020a

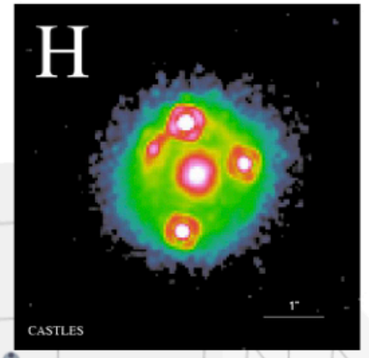
Simulation Pipeline Example

$\sim 10^5 - 10^6$ simulations per lens for accurate statistics

CDM



WDM



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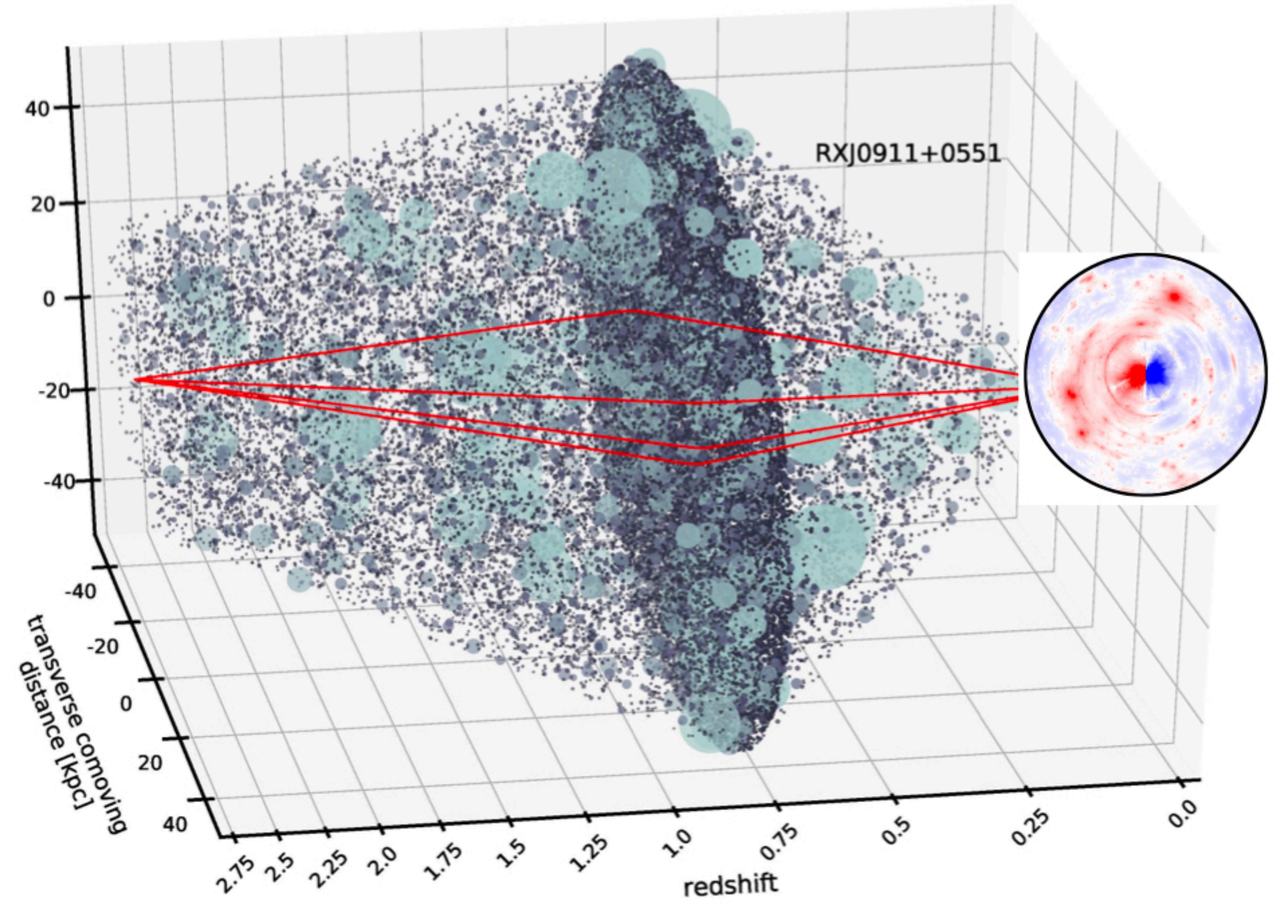
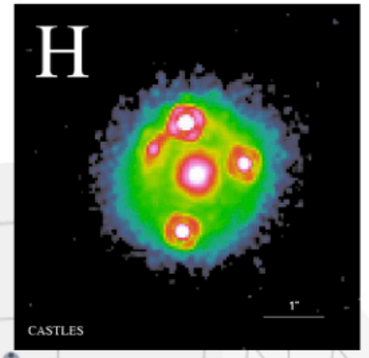
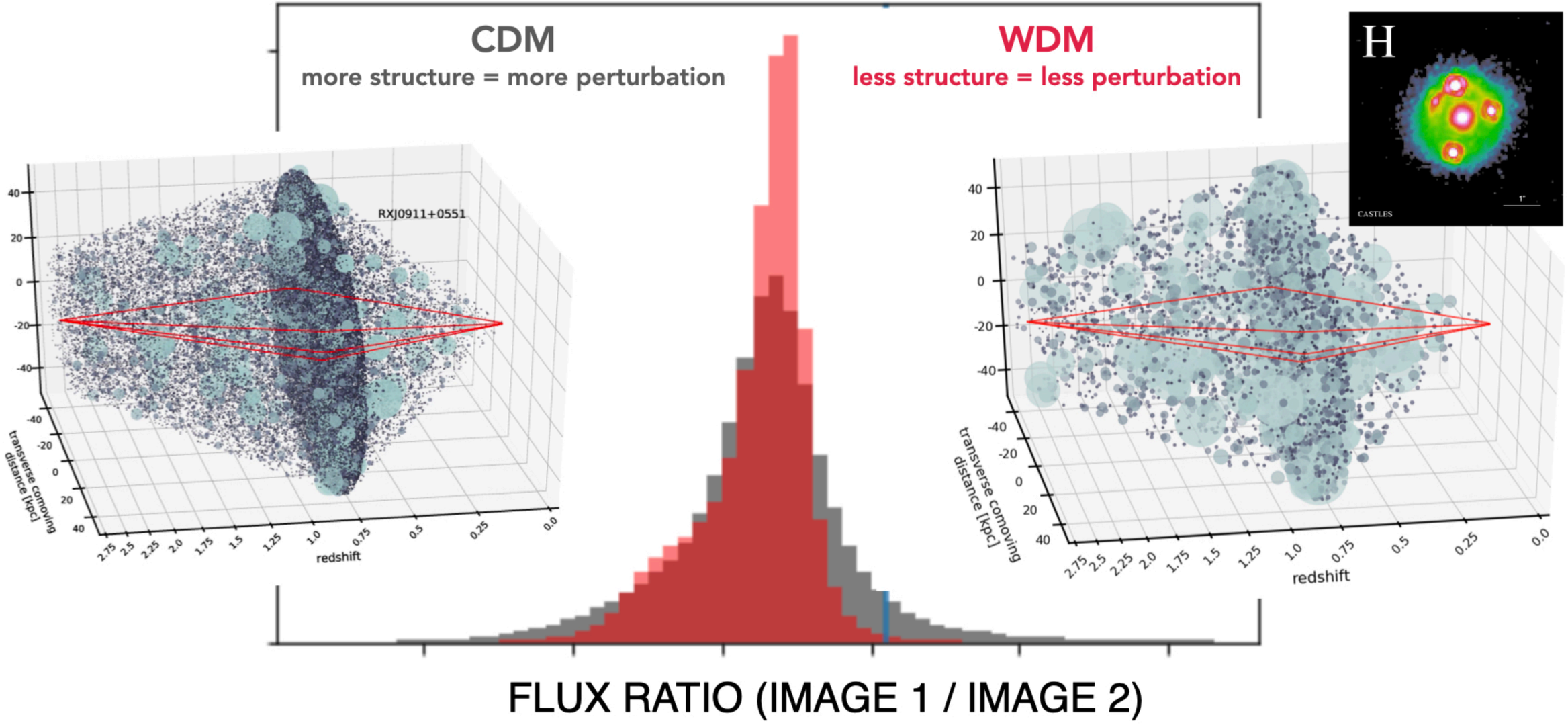


WDM



Compare measurement with simulation distribution



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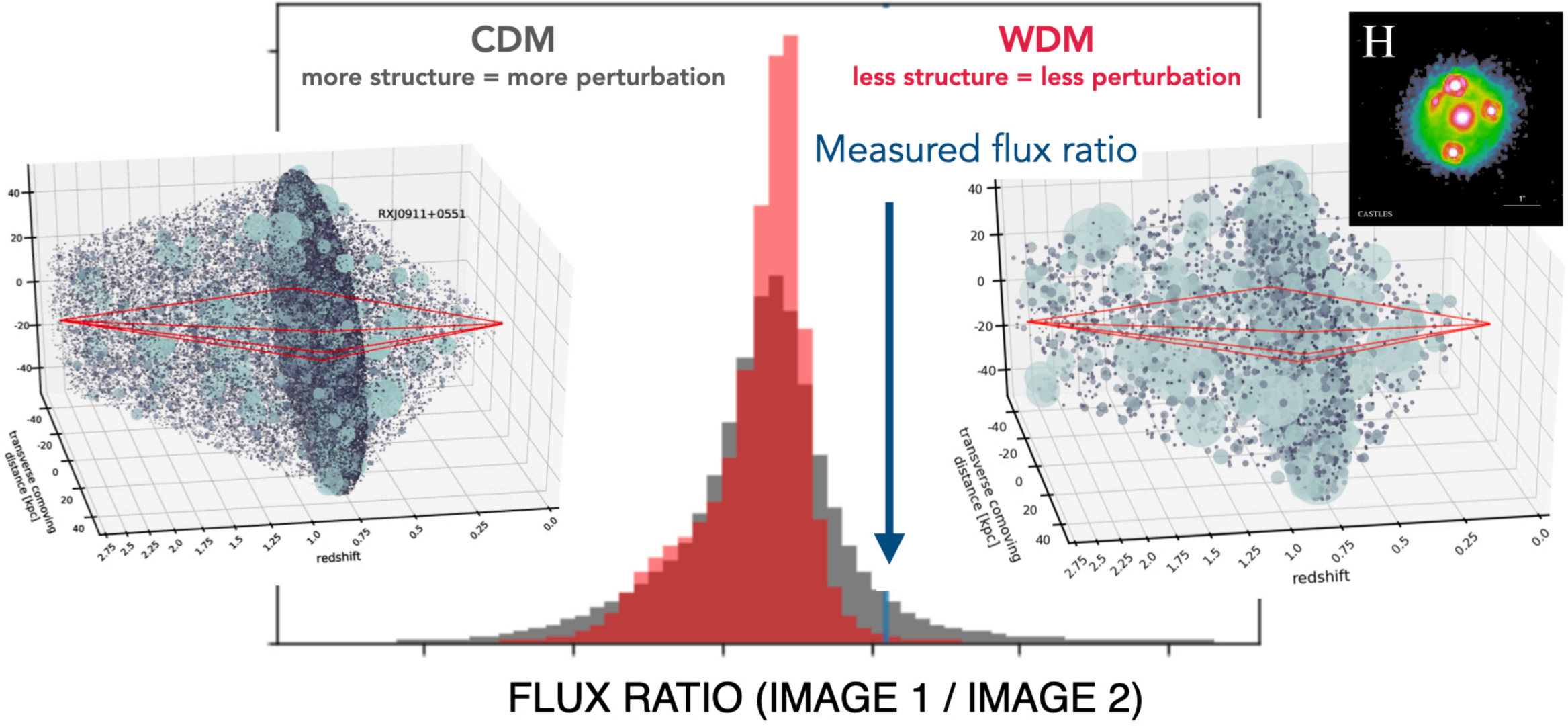
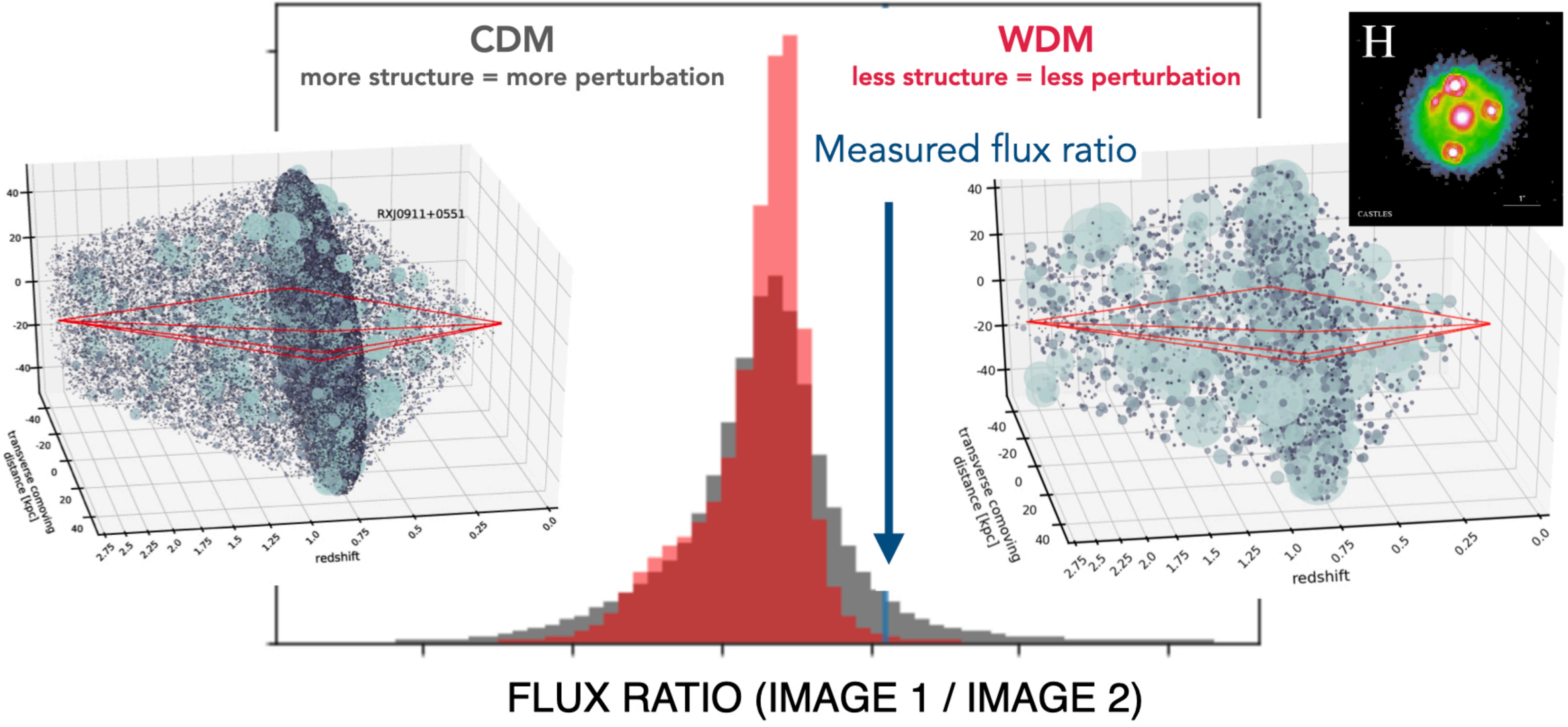


Compare measurement with simulation distribution

3 flux ratios per lens each with different responses to variations in macromodel/substructure



Compare measurement with simulation distribution

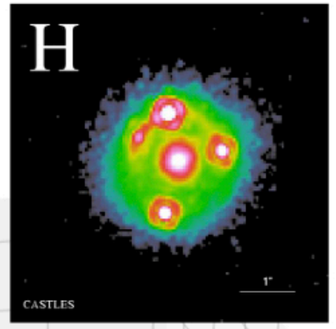
3 flux ratios per lens each with different responses to variations in macromodel/substructure

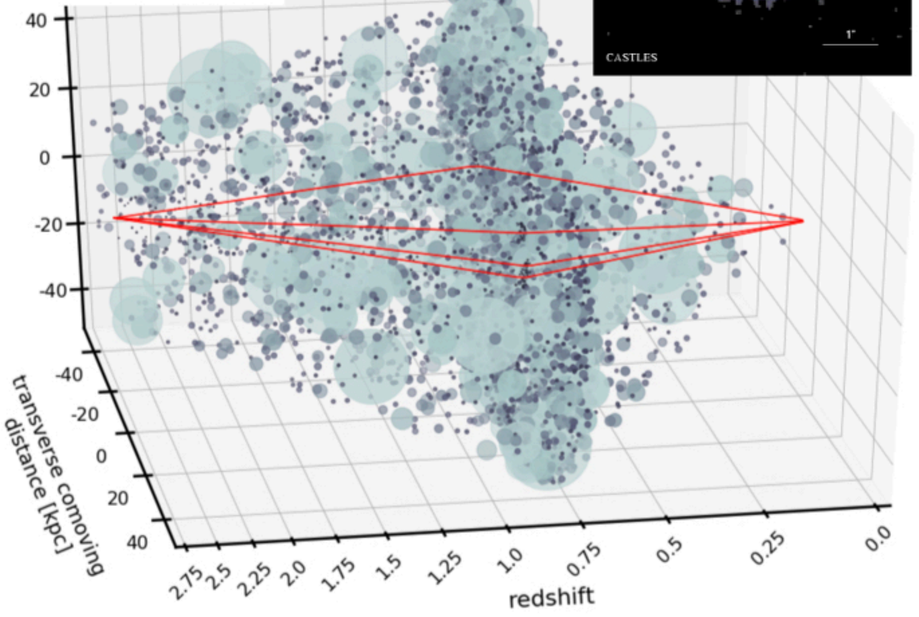
Daniel Gilman, Postdoc
U. Chicago Brinson Fellow

CDM
more structure = more perturbation

WDM
less structure = less perturbation

Measured flux ratio

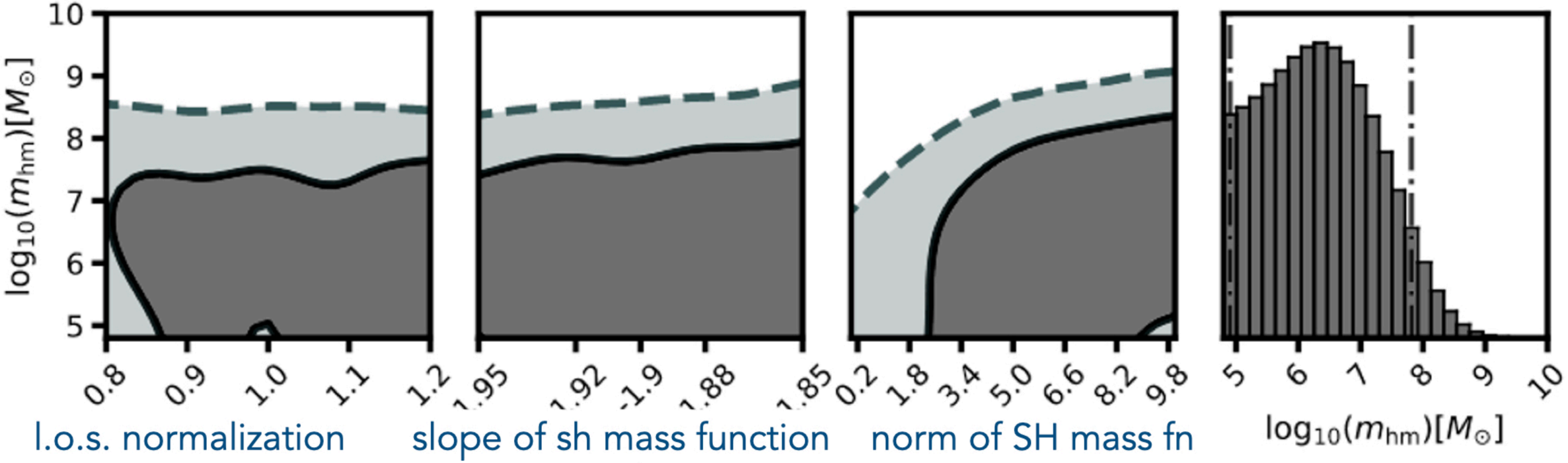




FLUX RATIO (IMAGE 1 / IMAGE 2)

Constraint on halo half-mode-mass

$M_{hm} < 10^{7.8}\ M_\odot,\ m_{th} > 5.2$ keV



l.o.s. normalization

slope of sh mass function

norm of SH mass fn

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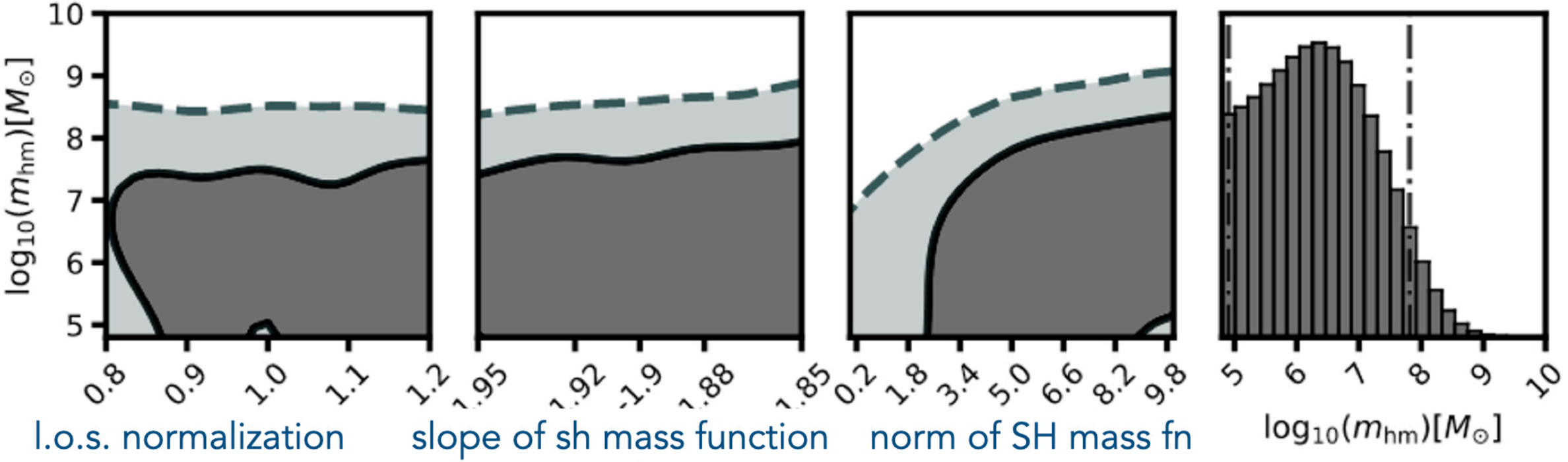


l.o.s. normalization slope of sh mass function norm of SH mass fn

Gilman, Birrer, Nierenberg et al. 2020

An end-to-end dark matter experiment

Dark matter particle physics

Alex Kusenko (UCLA)
Kevork Abazajian,
Manoj Kaplinghat (UCI)

Non-linear structure

Anna Nierenberg,
Charles Gannon,
Ryan Keeley (UCM)
Andrew Benson (Carnegie)
Risa Wechsler (Stanford)
Ethan Nadler (UCSD)
Tommaso Treu,
Xiaolong Du (UCLA)
Daniel Gilman (U. Chicago)

Gravitational Lensing

Anna Nierenberg,
Ryan Keeley (UCM)
Simon Birrer (Stony Brook)
Tommaso Treu,
Hadrian Paugnat (UCLA)
Daniel Gilman (U. Chicago)

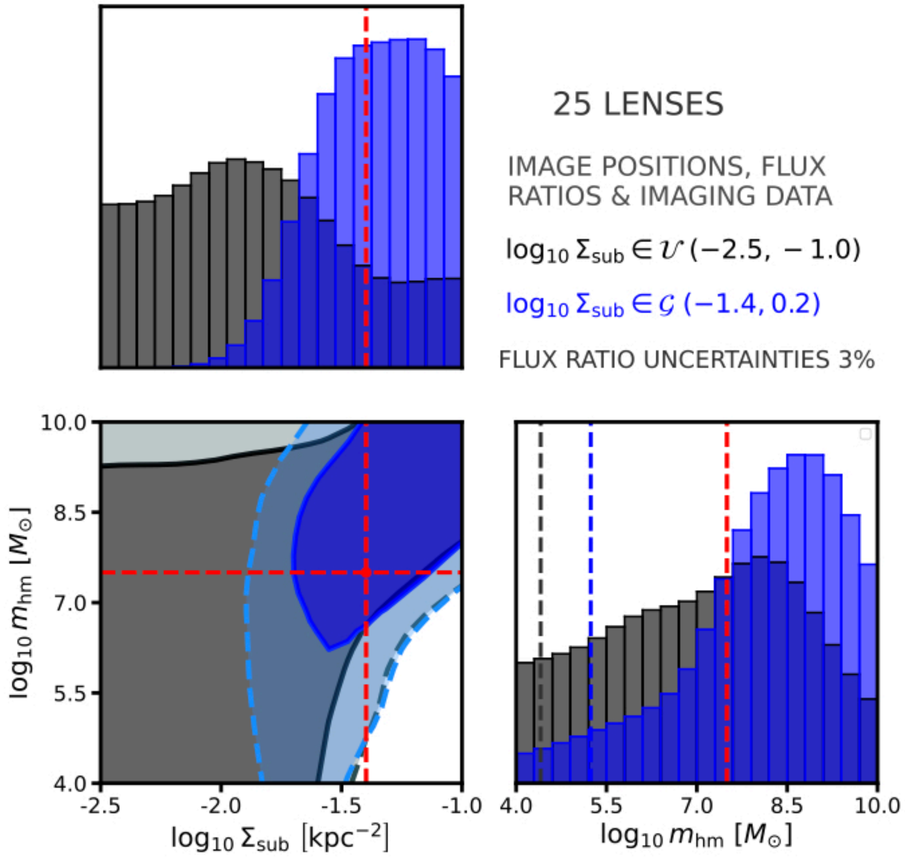
Flux Measurement and inference

Anna Nierenberg,
Ryan Keeley,
Maria Perez Mendoza (UCM)
Daniel Gilman
(U. Chicago)

Open source and validated on mock data

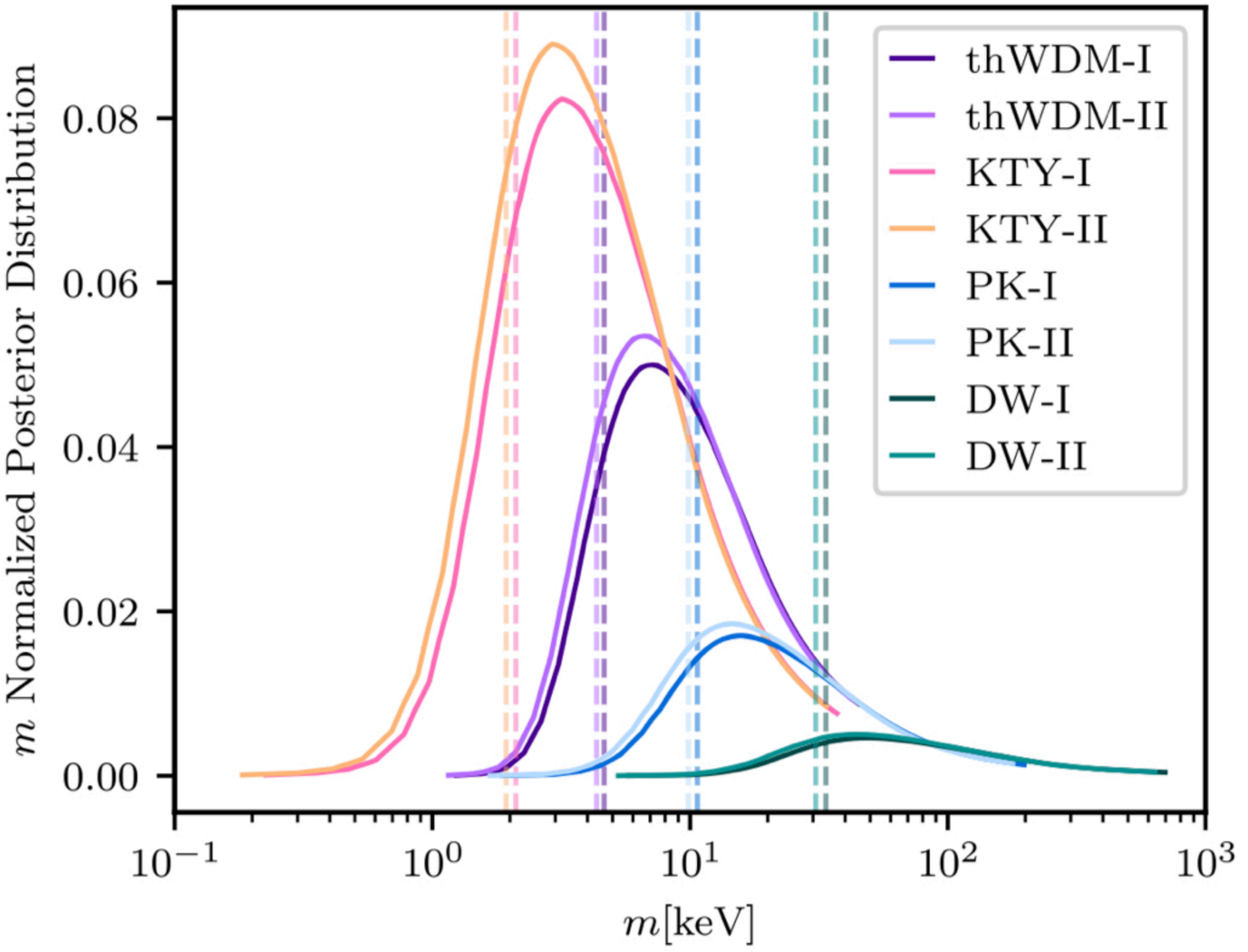
- **Lenstronomy** (Birrer and Amara 2018, Birrer et al. 2021)
- **Pyhalo** (Gilman et al. 2022)
- **Samana** (Gilman et al. 2024, inc AMN)

See Daniel Gilman's Talk



Gilman, Birrer, Nierenberg et al. 2024

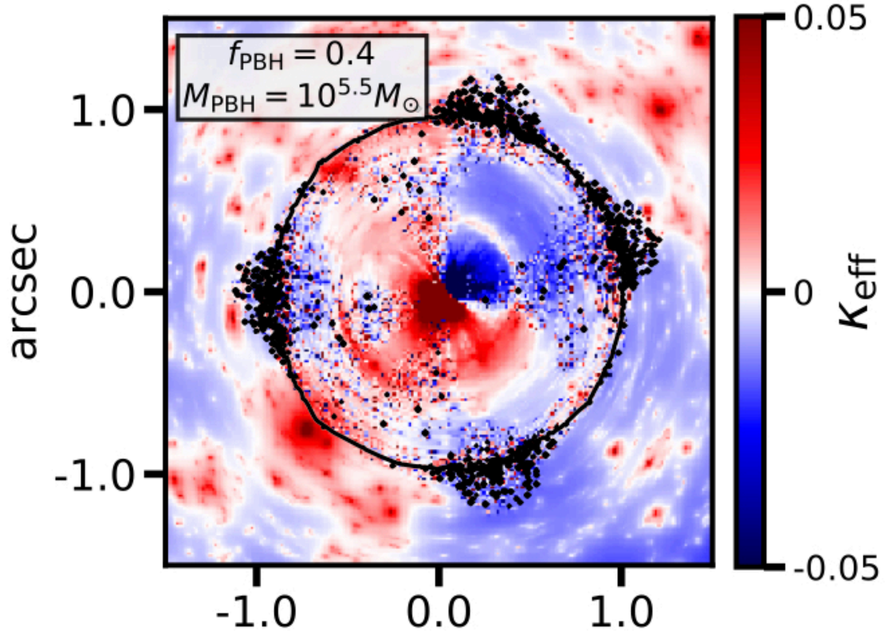
Sterile Neutrino Models



Zelko et al. inc. AMN 2022

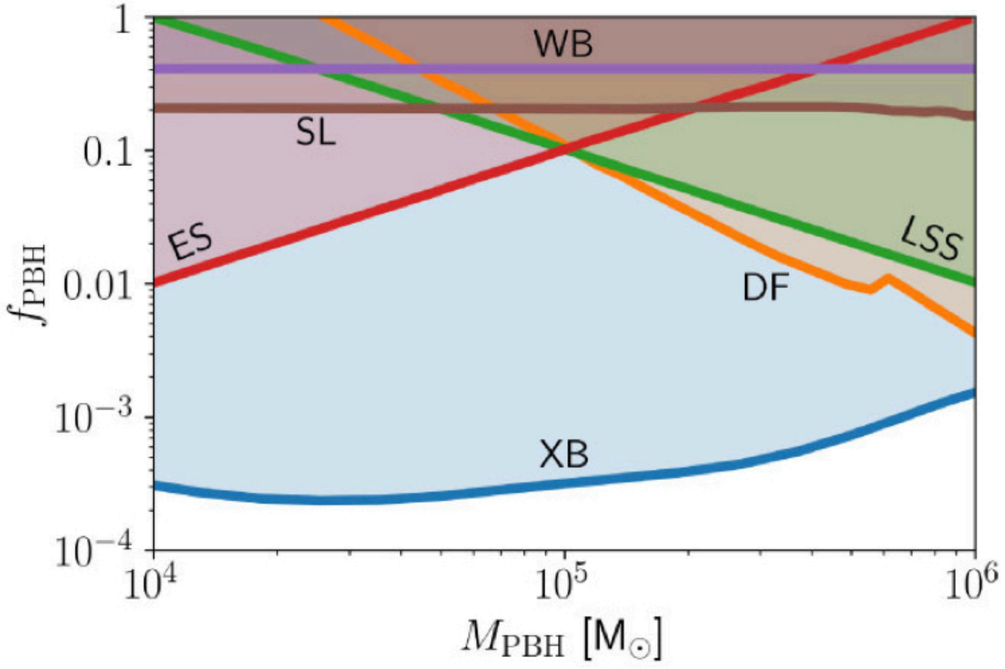
Primordial Black Holes

Primordial Black Holes



Dike et al. 2023

Narrow-line flux ratios



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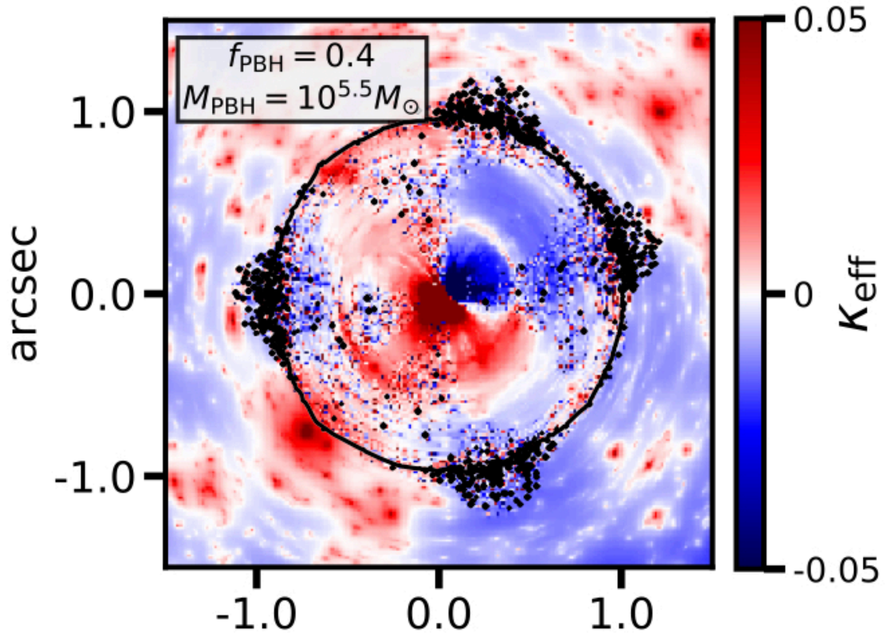

Dike et al. 2023

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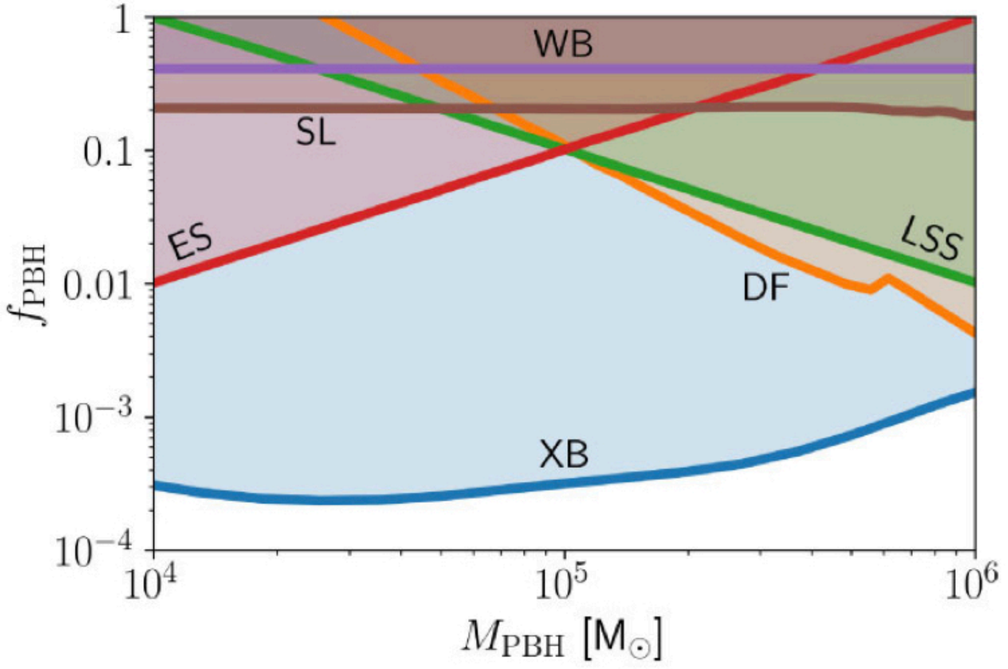
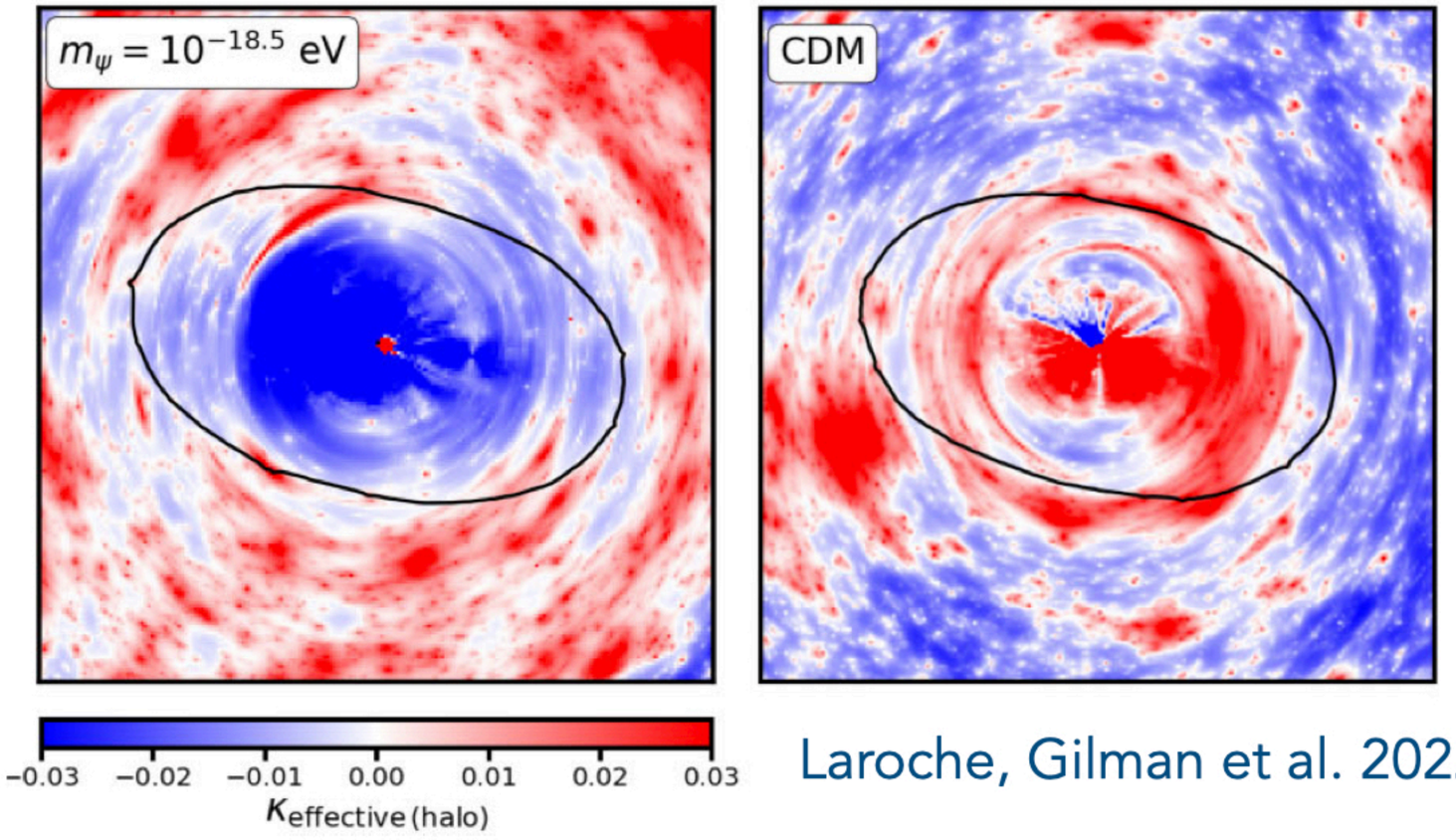
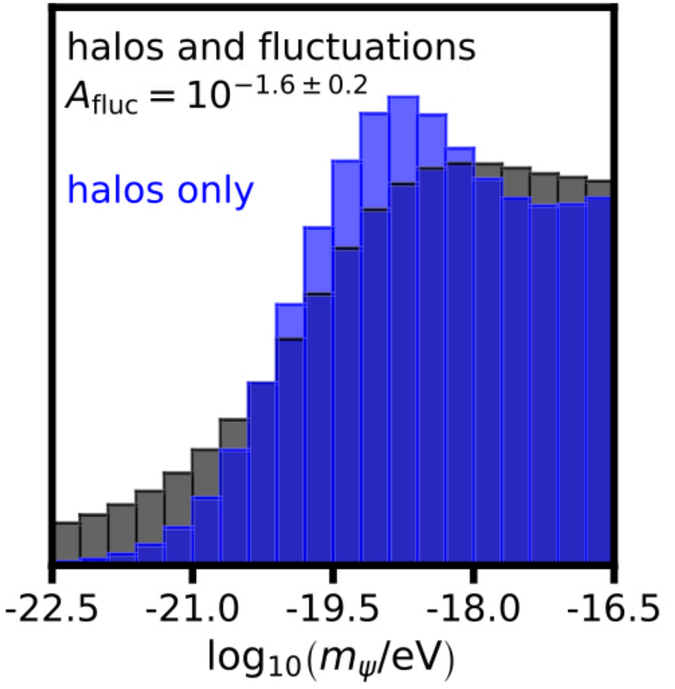


Rule out dm black hole fraction
>0.1 for $10^4 < M_{pbh}/M_\odot < 10^6$

Fuzzy dark matter



Laroche, Gilman et al. 2022



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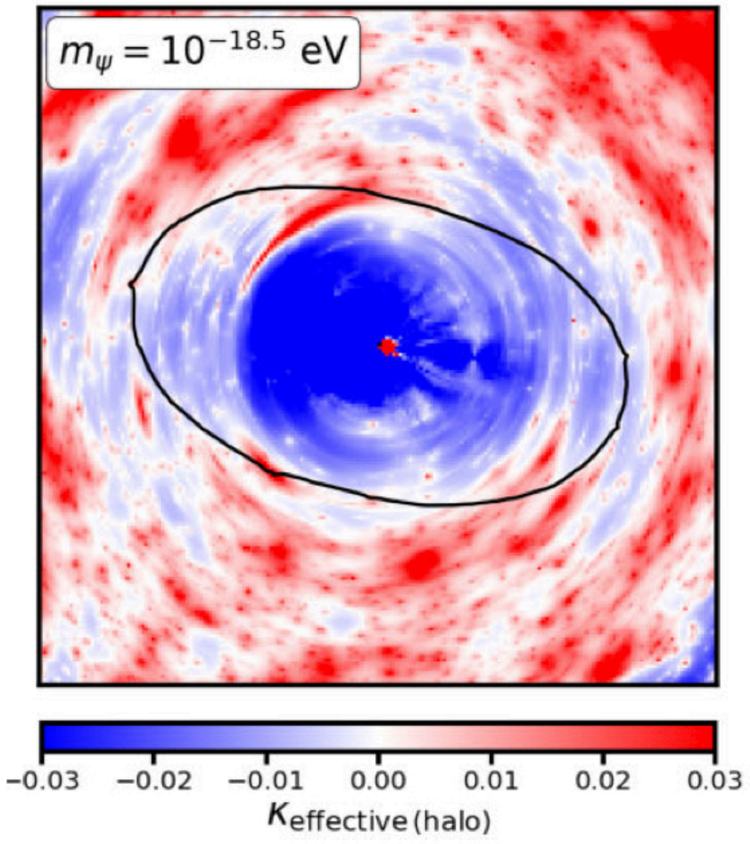
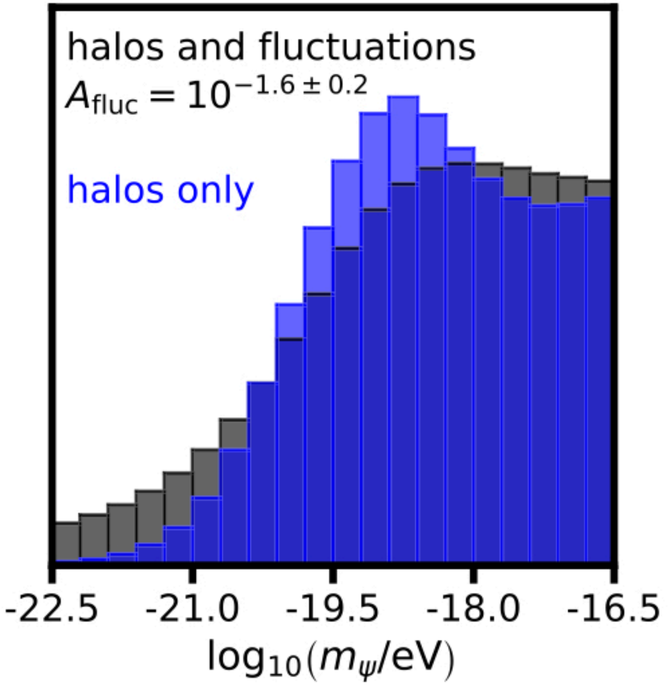


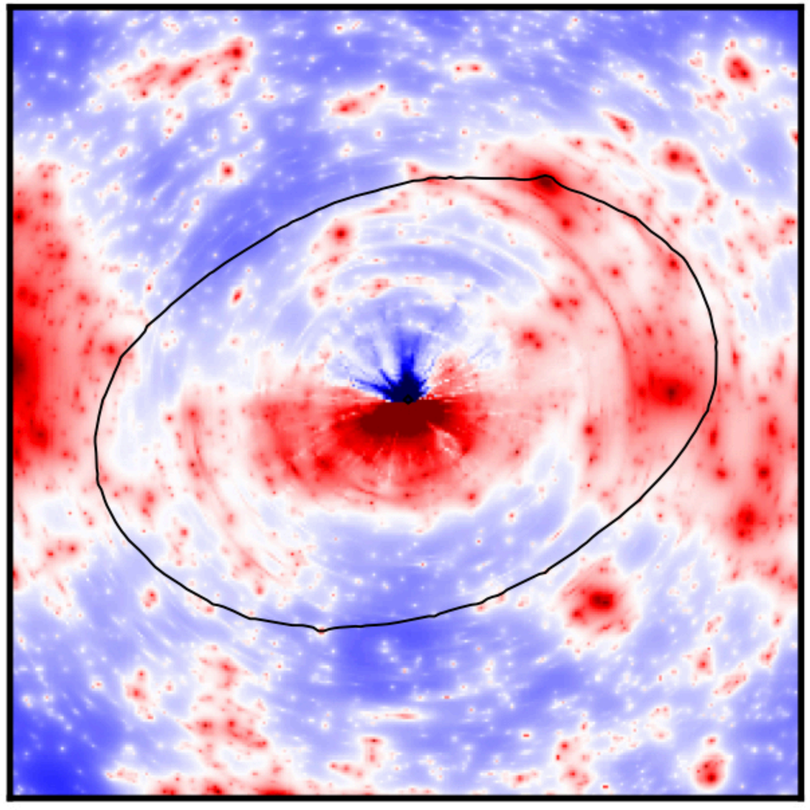
Laroche, Gilman et al. 2022



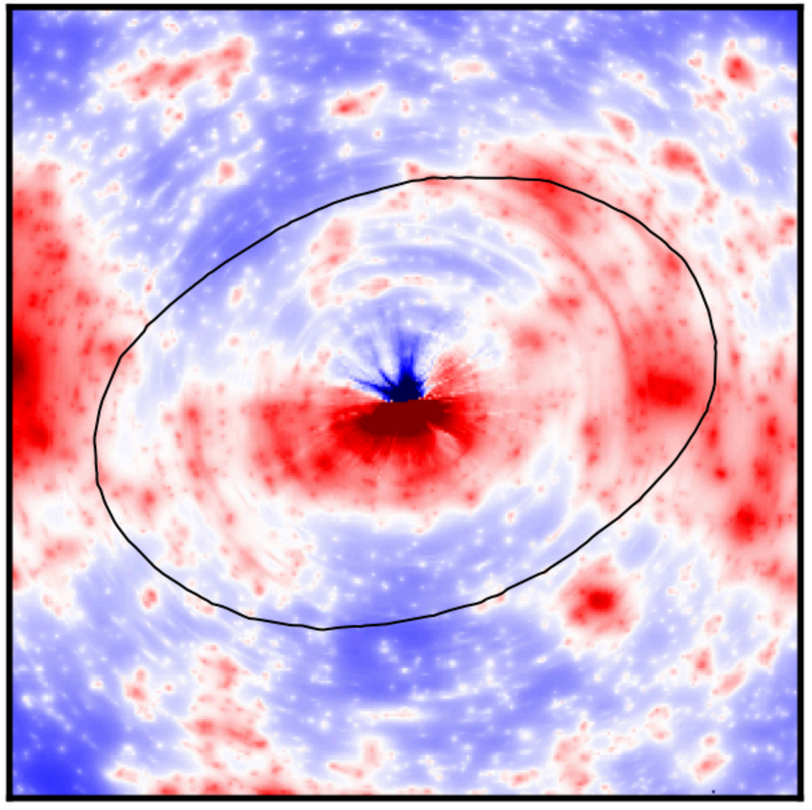
See also Powell et al. 2023 for complementary gravitational imaging result

Many dark matter models tested

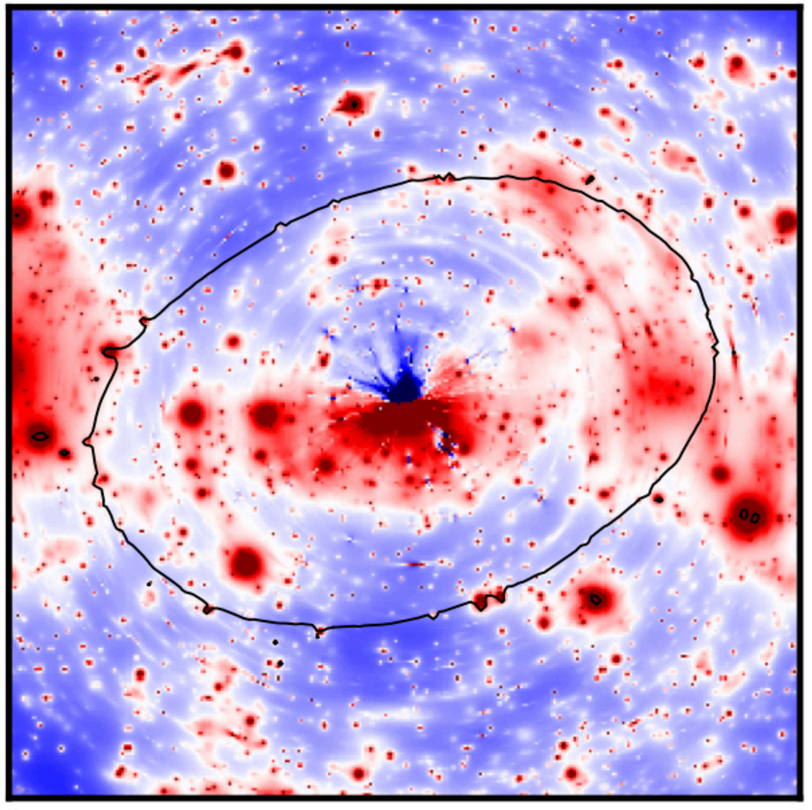
CDM



SIDM with cores only



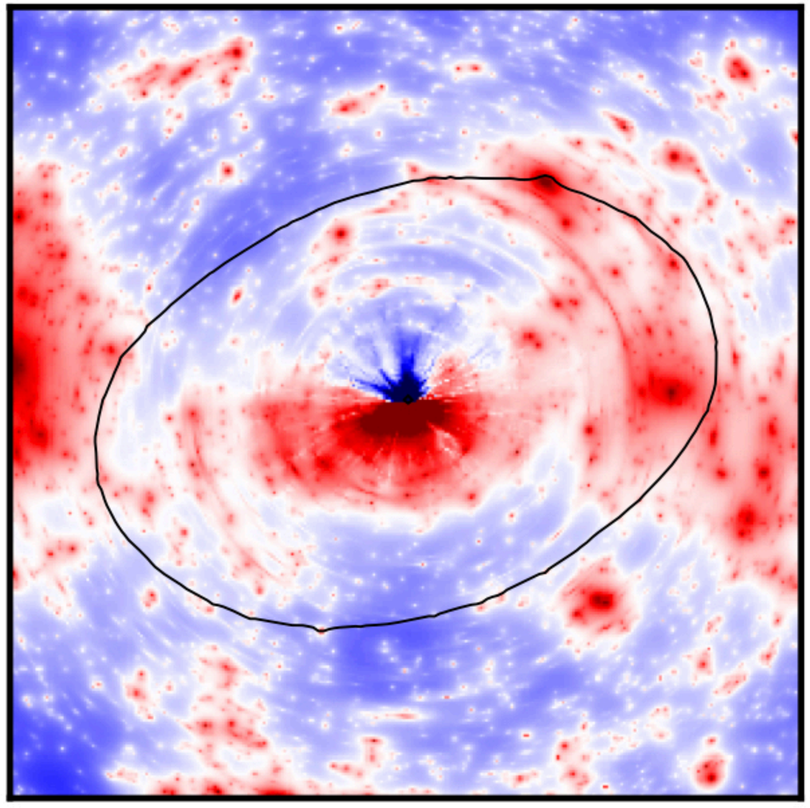
SIDM cores+core collapse



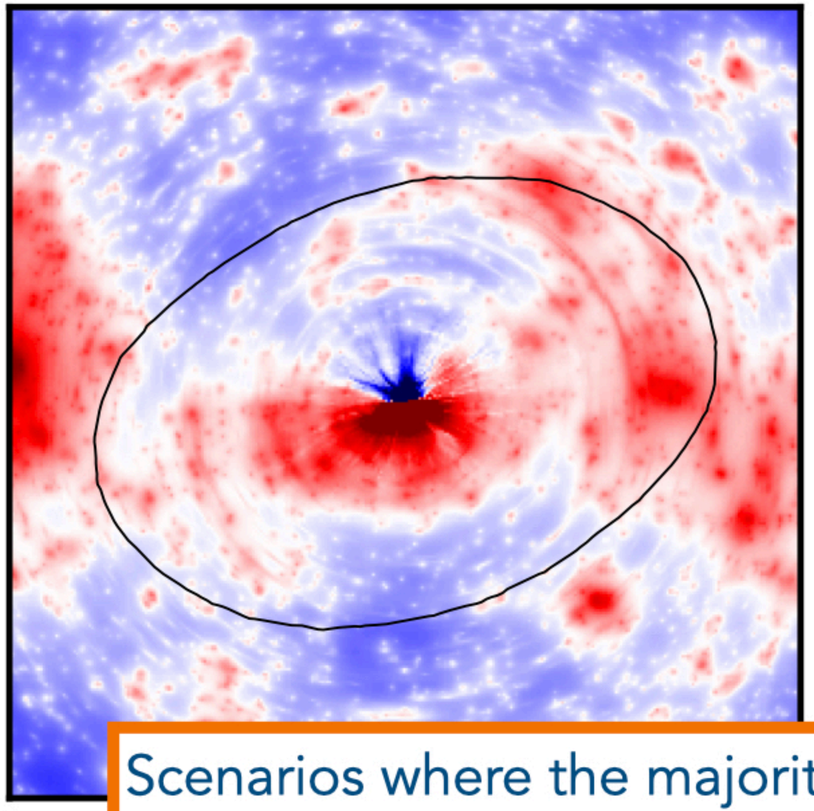
Gilman et al. 2022

Many dark matter models tested

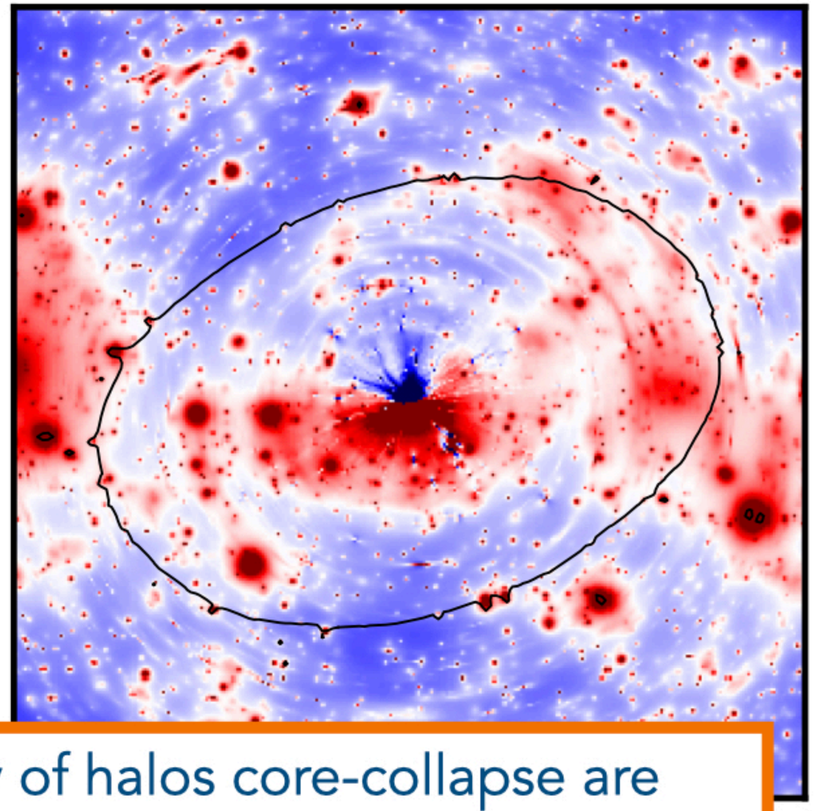
CDM



SIDM with cores only



SIDM cores+core collapse

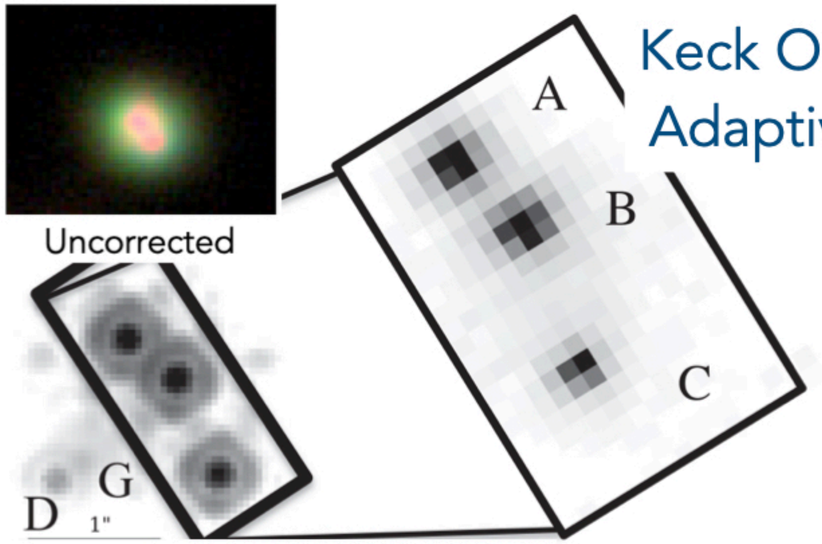


Scenarios where the majority of halos core-collapse are disfavored

Gilman et al. 2022

Adding a new source

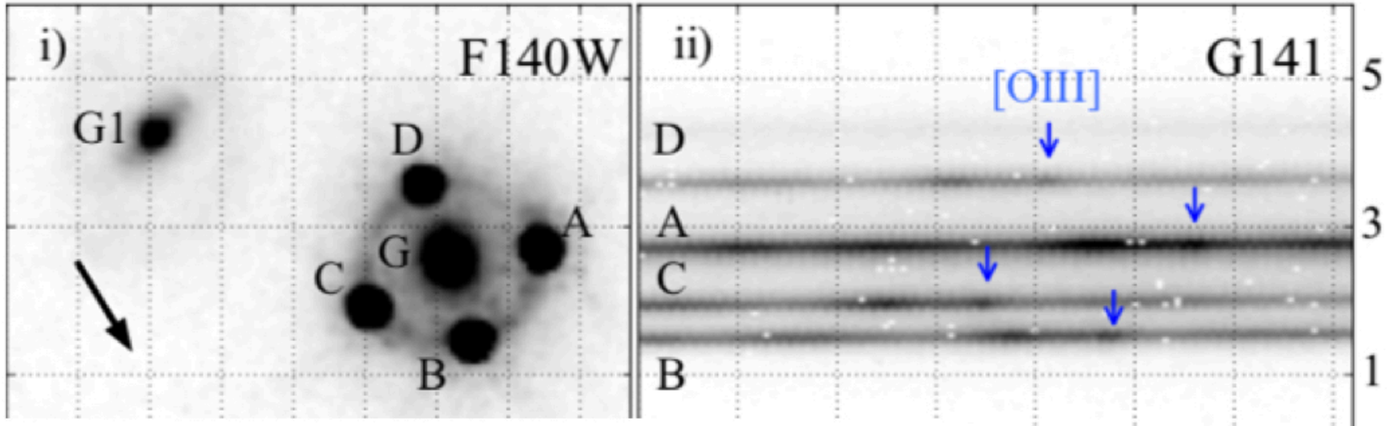
Previous results with 11 narrow-line lenses



Keck OSIRIS with Adaptive Optics

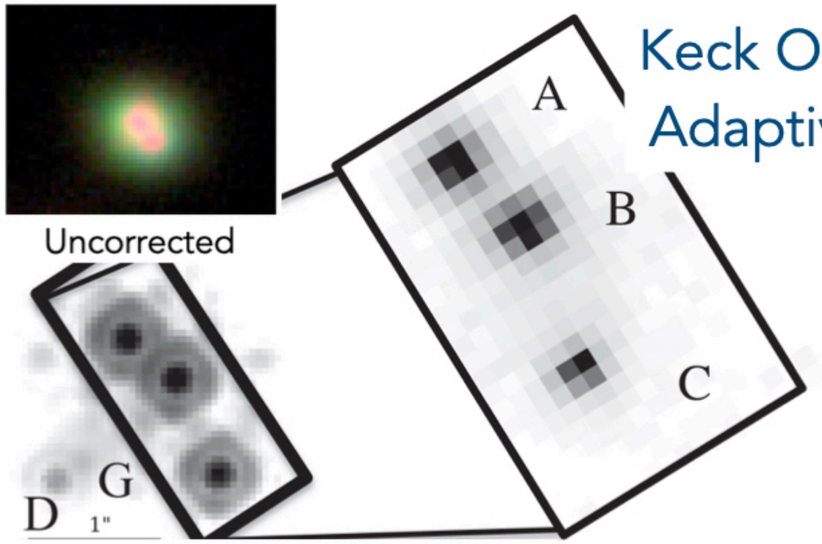
Nierenberg et al. 2014

Nierenberg et al. 2017



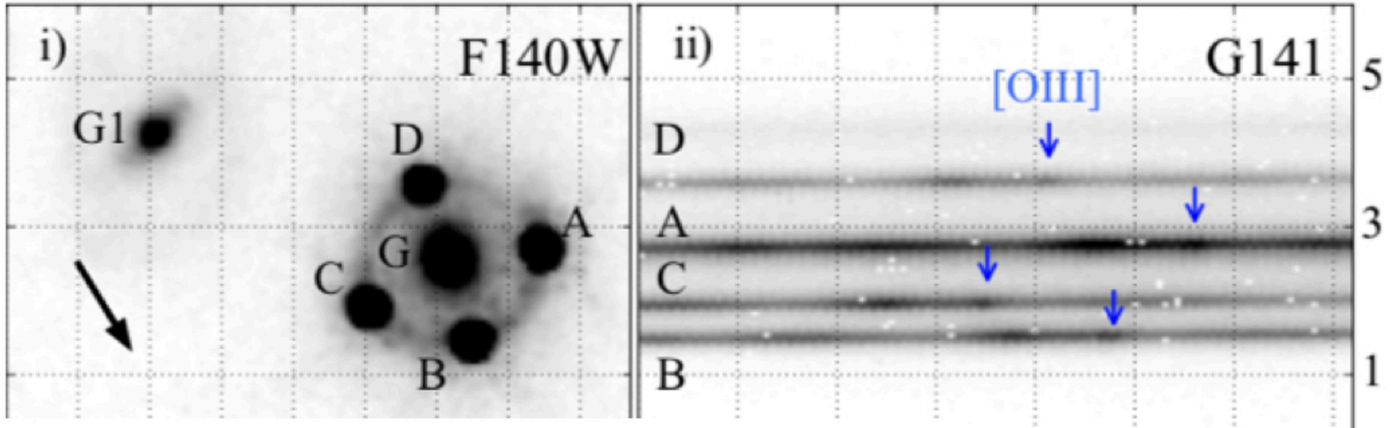
HST GO-15177, 13732, PI Nierenberg

Previous results with 11 narrow-line lenses



Keck OSIRIS with Adaptive Optics

Nierenberg et al. 2014

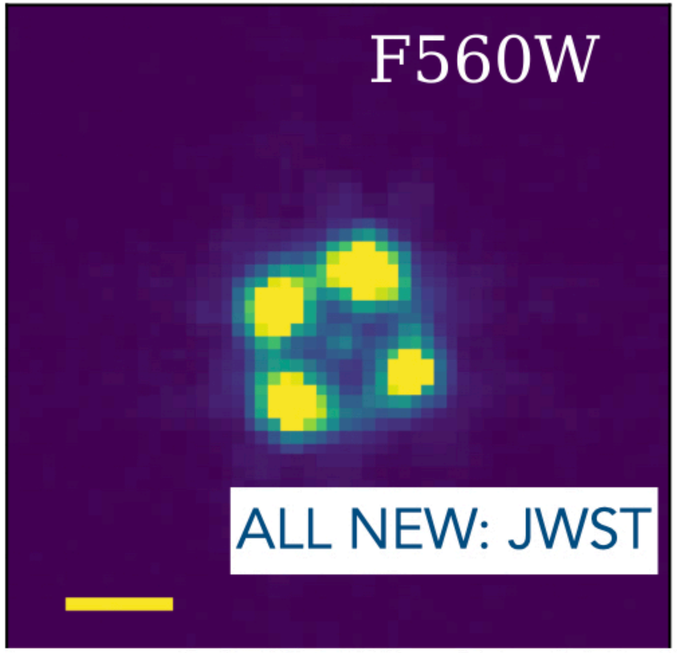


Nierenberg et al. 2017

HST GO-15177, 13732, PI Nierenberg

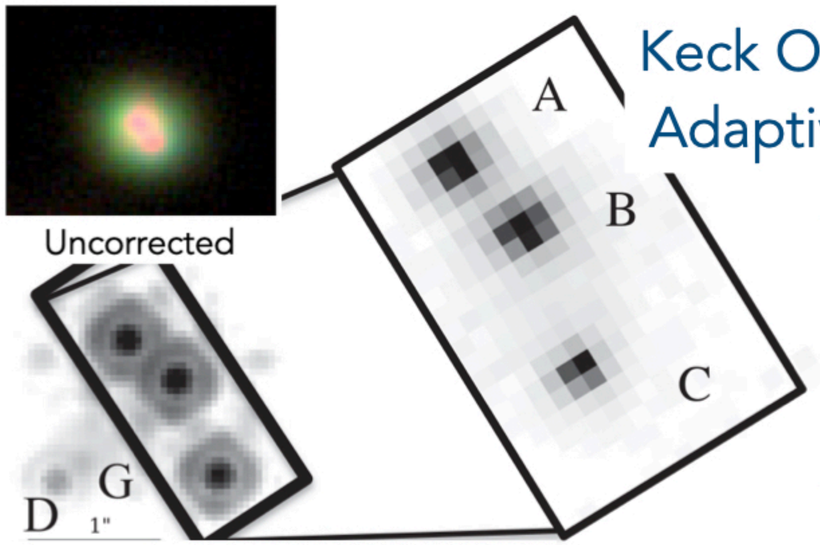
New Results: 31 lenses with JWST

JWST GO-2046 PI Nierenberg



Nierenberg et al. 2024

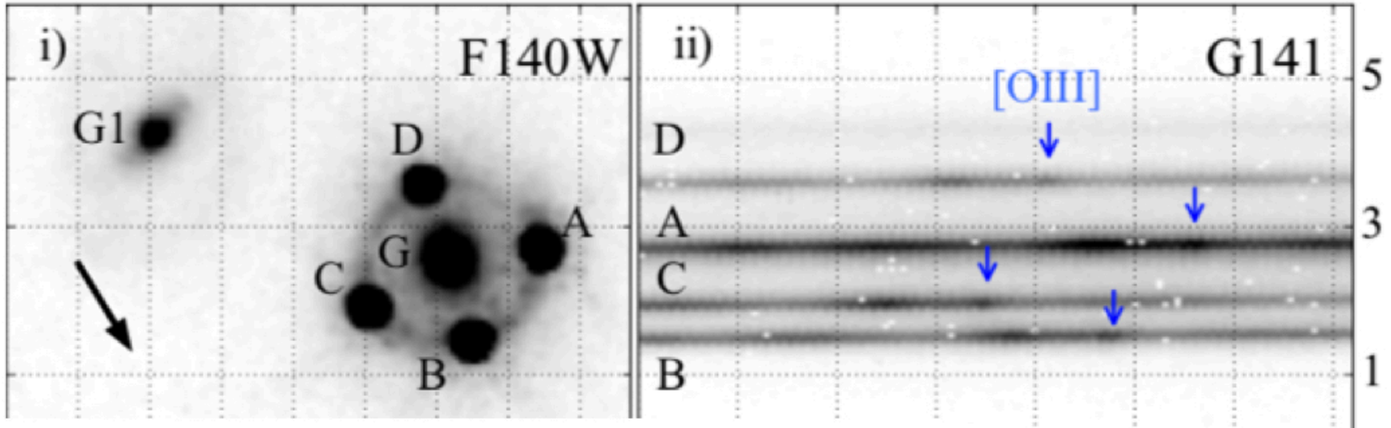
Previous results with 11 narrow-line lenses



Keck OSIRIS with Adaptive Optics

Quasar nuclear narrow-line emission ~80 pc

Nierenberg et al. 2014

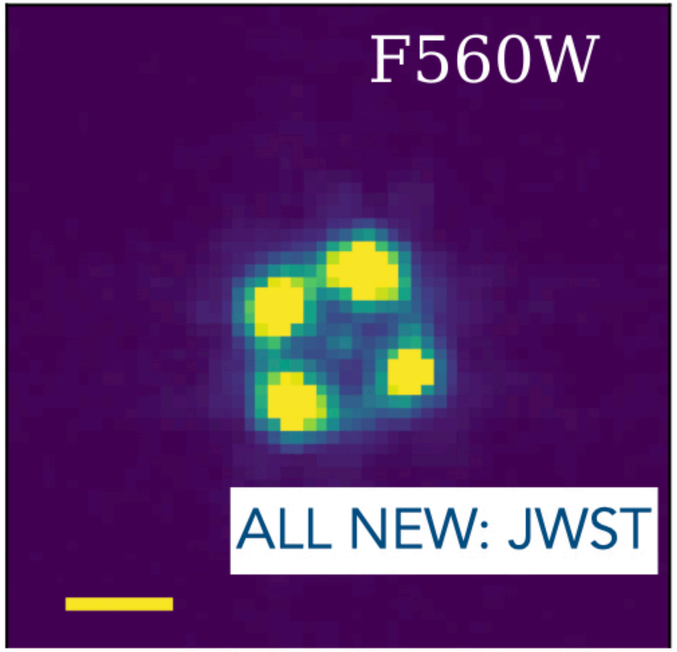


HST GO-15177, 13732, PI Nierenberg

Nierenberg et al. 2017

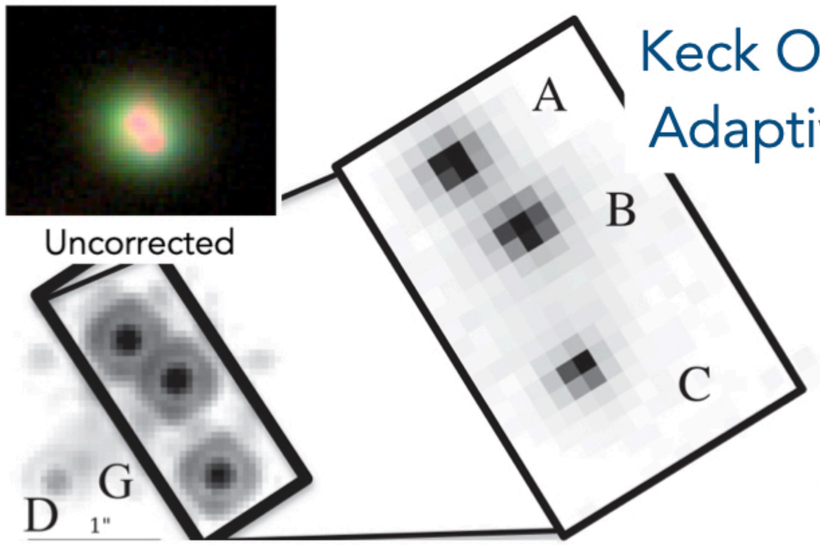
New Results: 31 lenses with JWST

JWST GO-2046 PI Nierenberg



Nierenberg et al. 2024

Previous results with 11 narrow-line lenses



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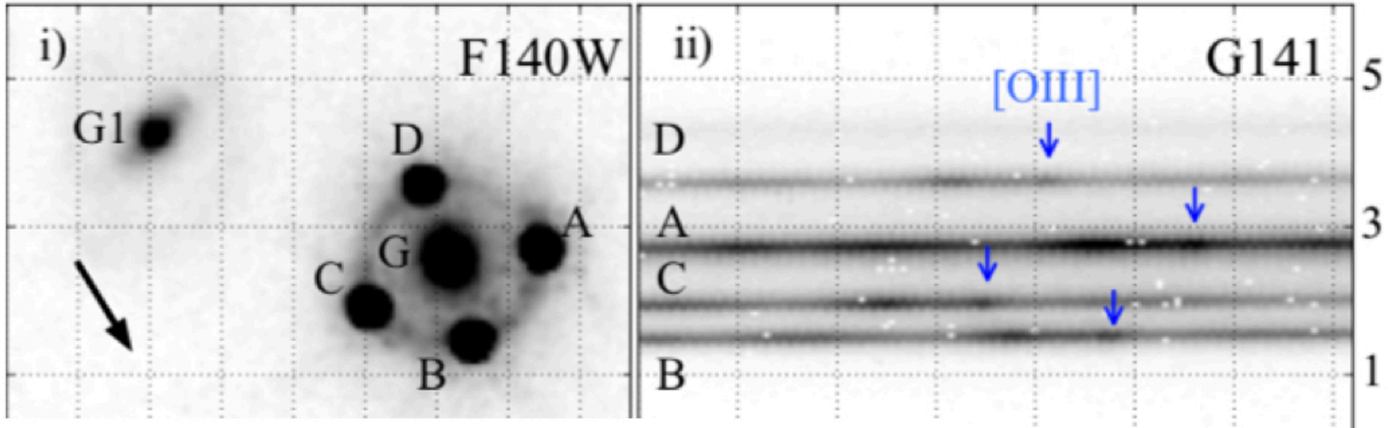
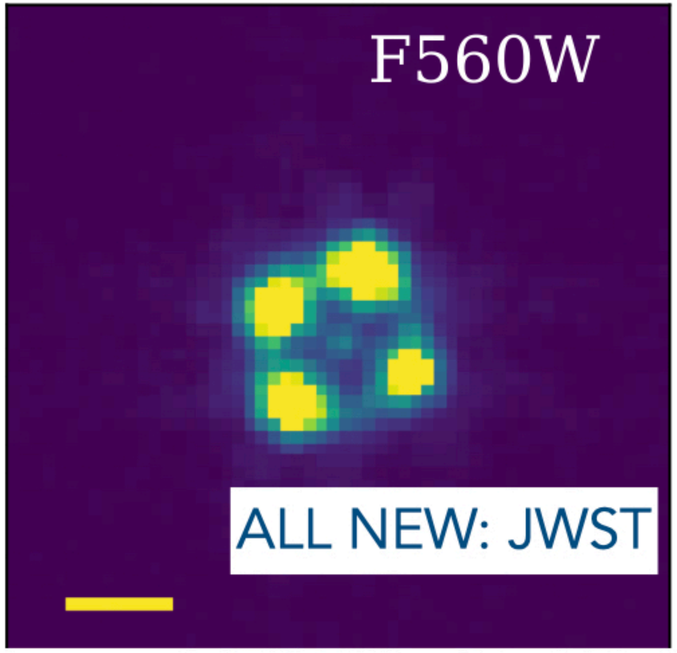


HST GO-15177, 13732, PI Nierenberg

Nierenberg et al. 2017

New Results: 31 lenses with JWST

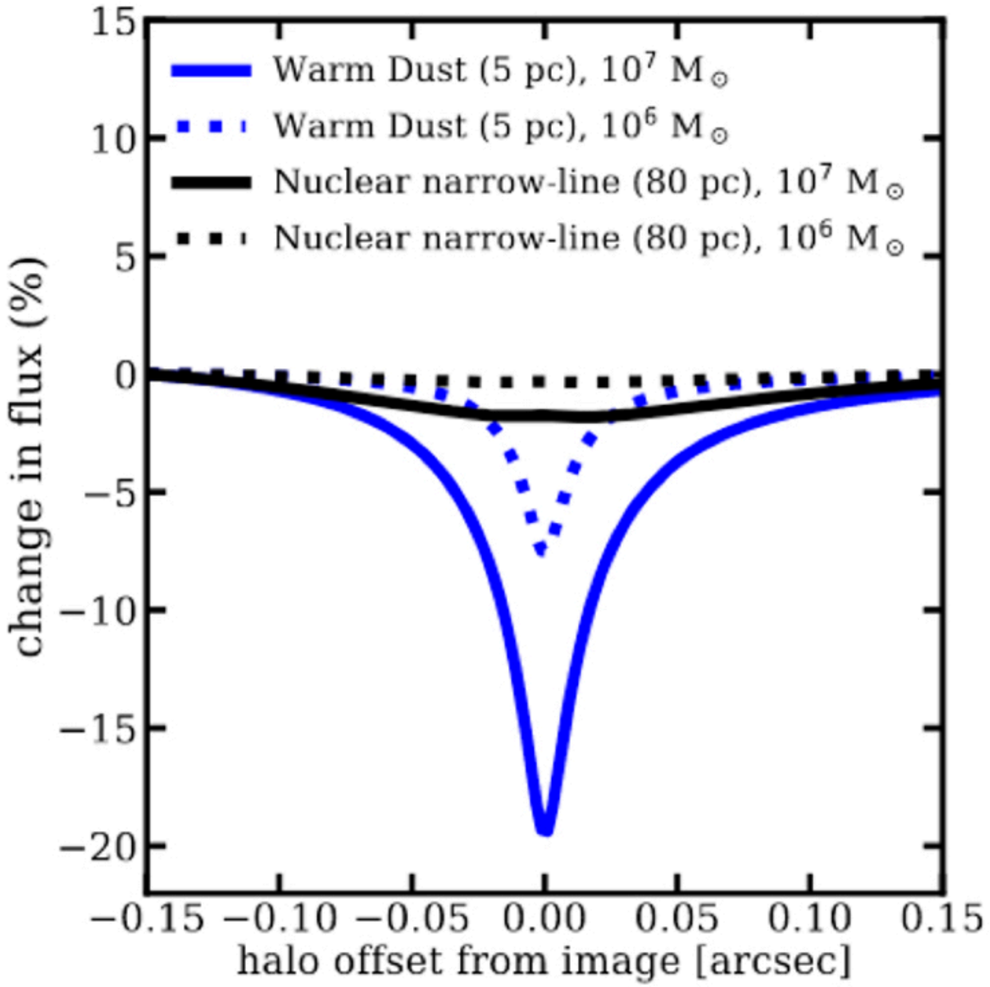
JWST GO-2046 PI Nierenberg

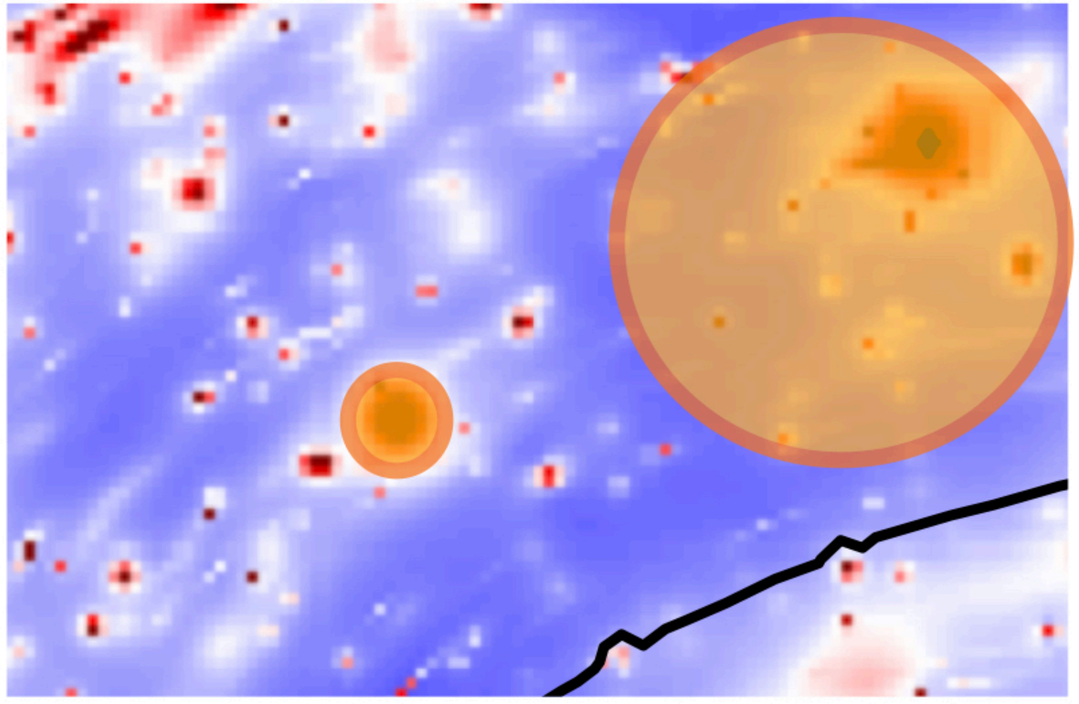


Nierenberg et al. 2024

Quasar warm dust emission ~1-10 pc

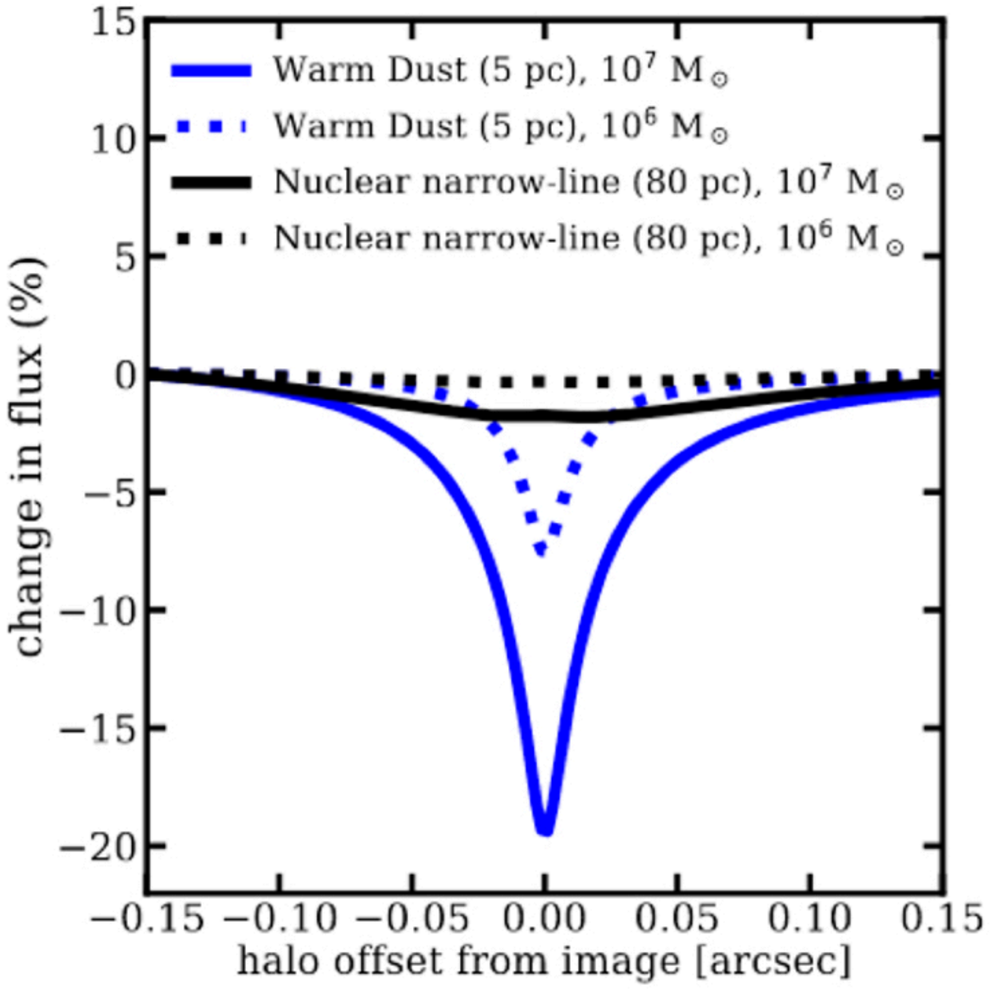
Comparison of nuclear narrow-line and warm dust sensitivity





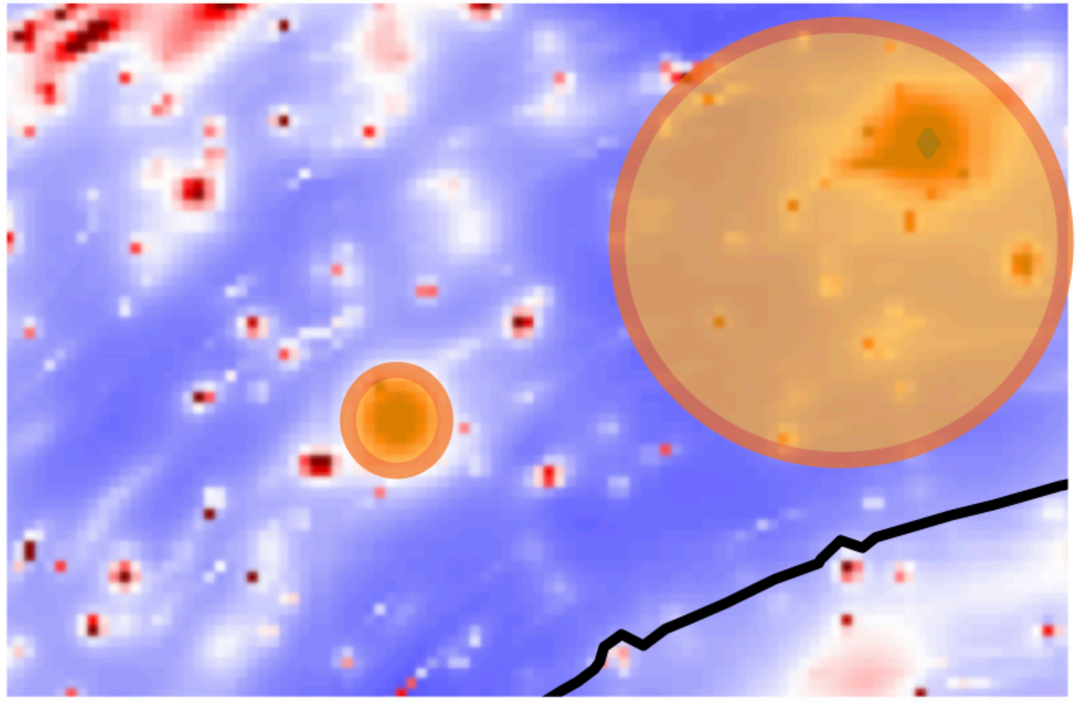
Nierenberg et al. 2024

Comparison of nuclear narrow-line and warm dust sensitivity



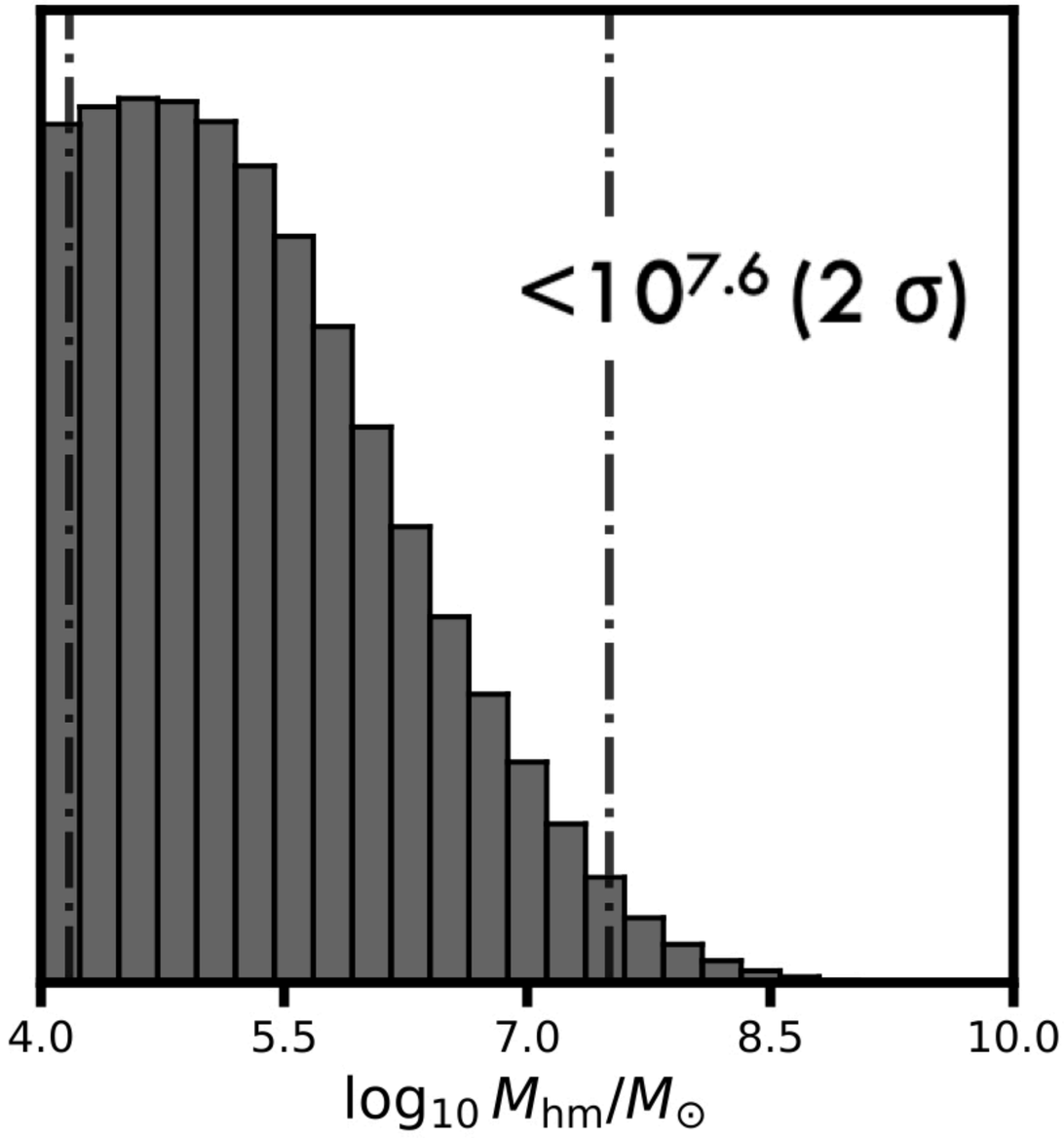
Nierenberg et al. 2024

Warm dust sensitive to perturbations below 10^7 $M_\odot$



First results: 5 Narrow-line + 9 JWST lenses

Ryan Keeley
UCM Postdoc

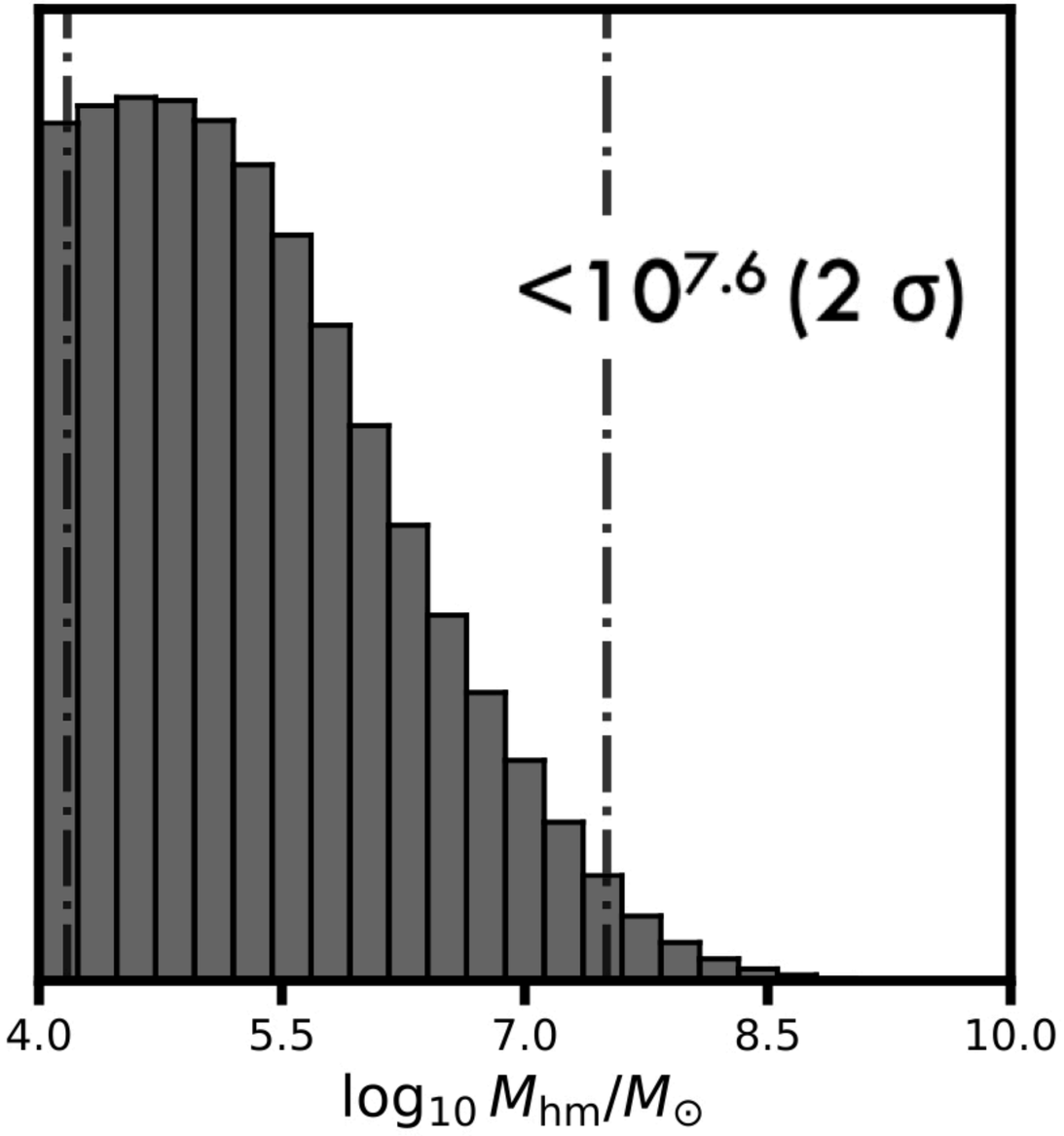


Keeley, Nierenberg et al. 2024

First results: 5 Narrow-line + 9 JWST lenses

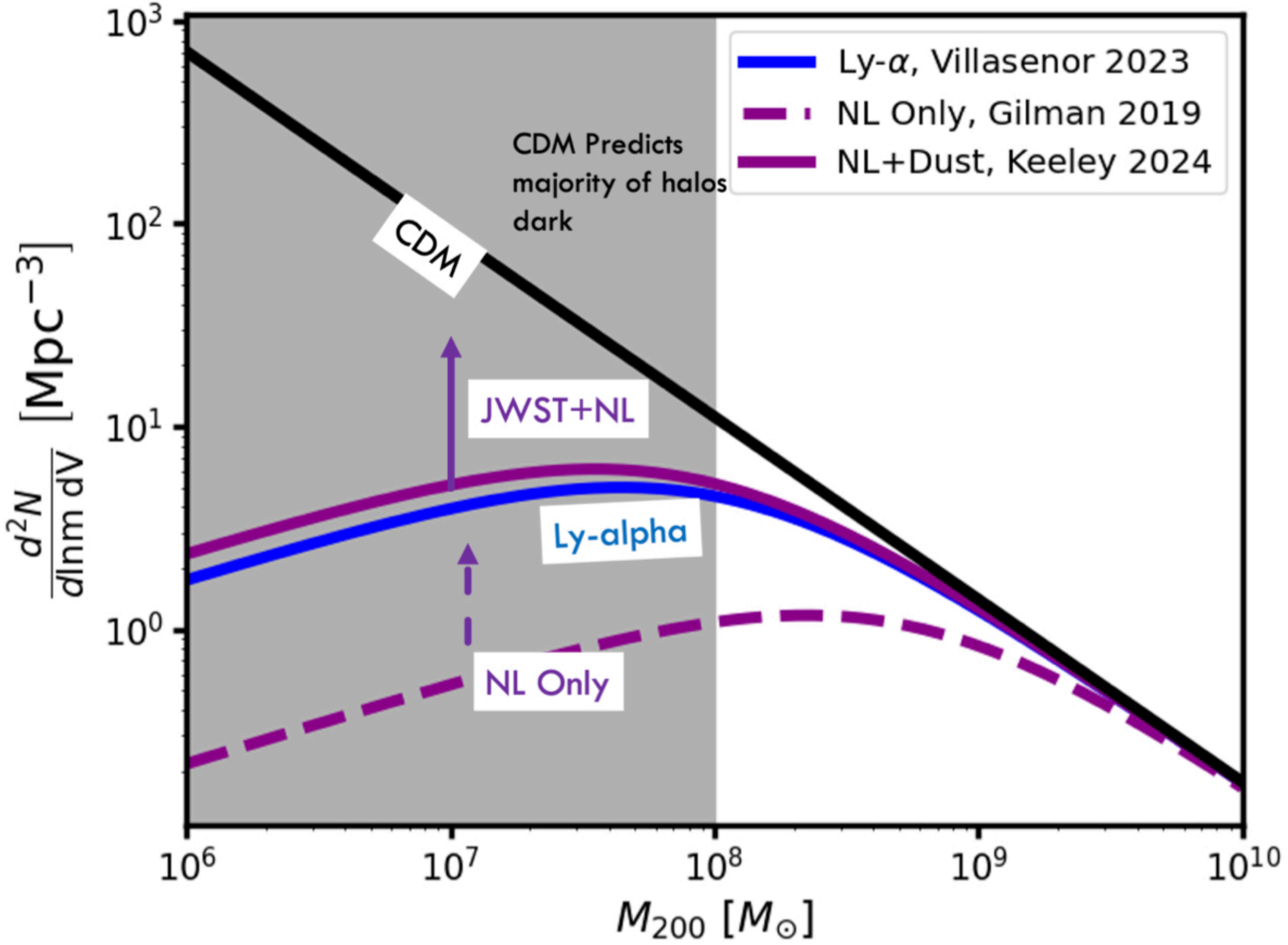
One of the strongest constraints ever on the dark matter half-mode mass

Ryan Keeley
UCM Postdoc



Keeley, Nierenberg et al. 2024

Comparison with other results



Coming soon…new WDM and SIDM measurements with all 31 JWST lenses

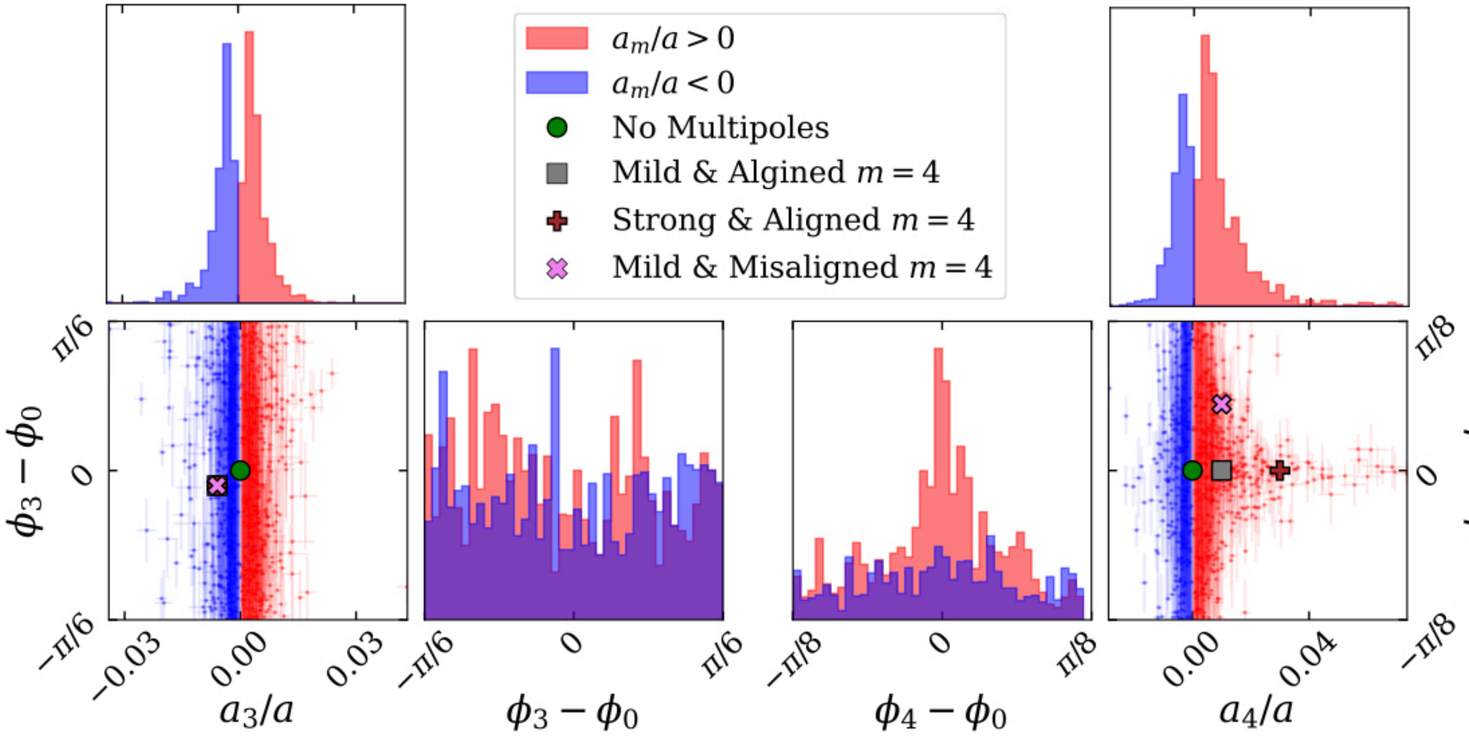
Look for Keeley et al. and Gilman et al. 2025 on arXiv!

Pushing the method forward

- Improved modelling of the mass distribution of the lens
- Tidal evolution of dark matter subhalos

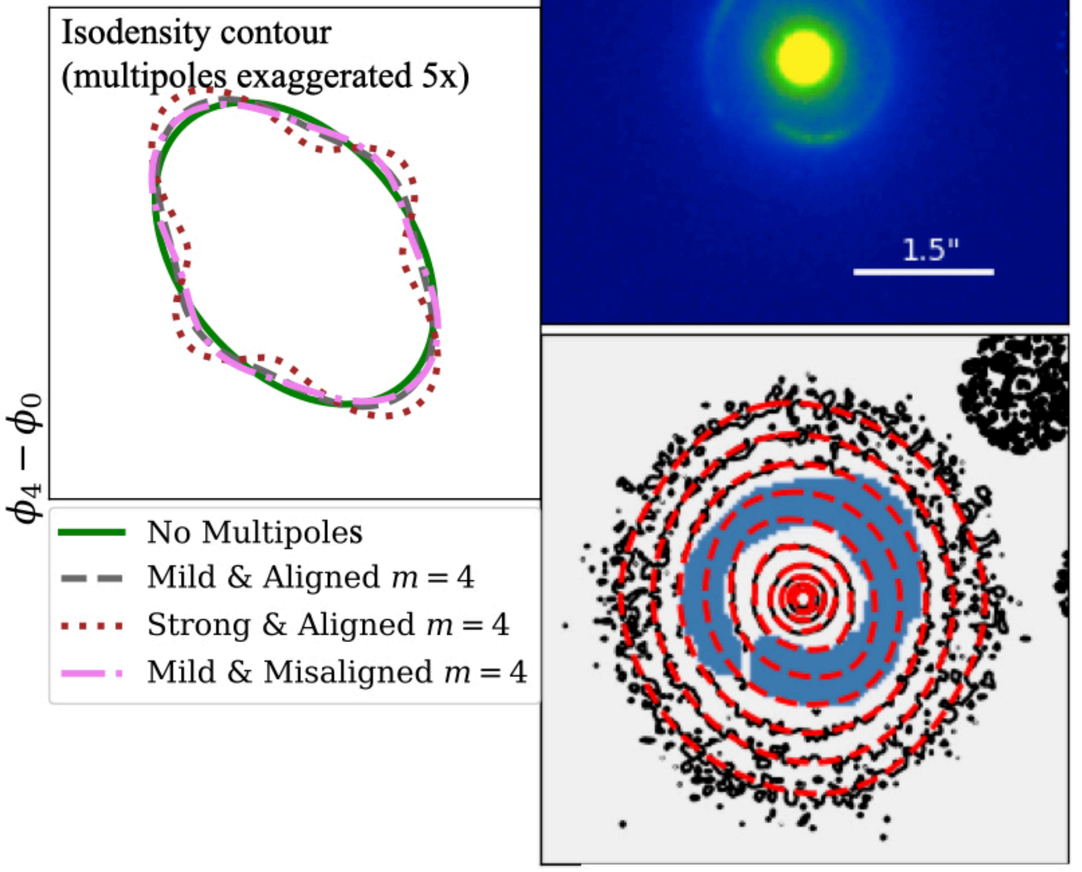
Deviations from ellipticity in the deflector

Multipole deviations from ellipticity in field ellipticals



Oh, Nierenberg et al. 2024,
based on Hao et al. 2006

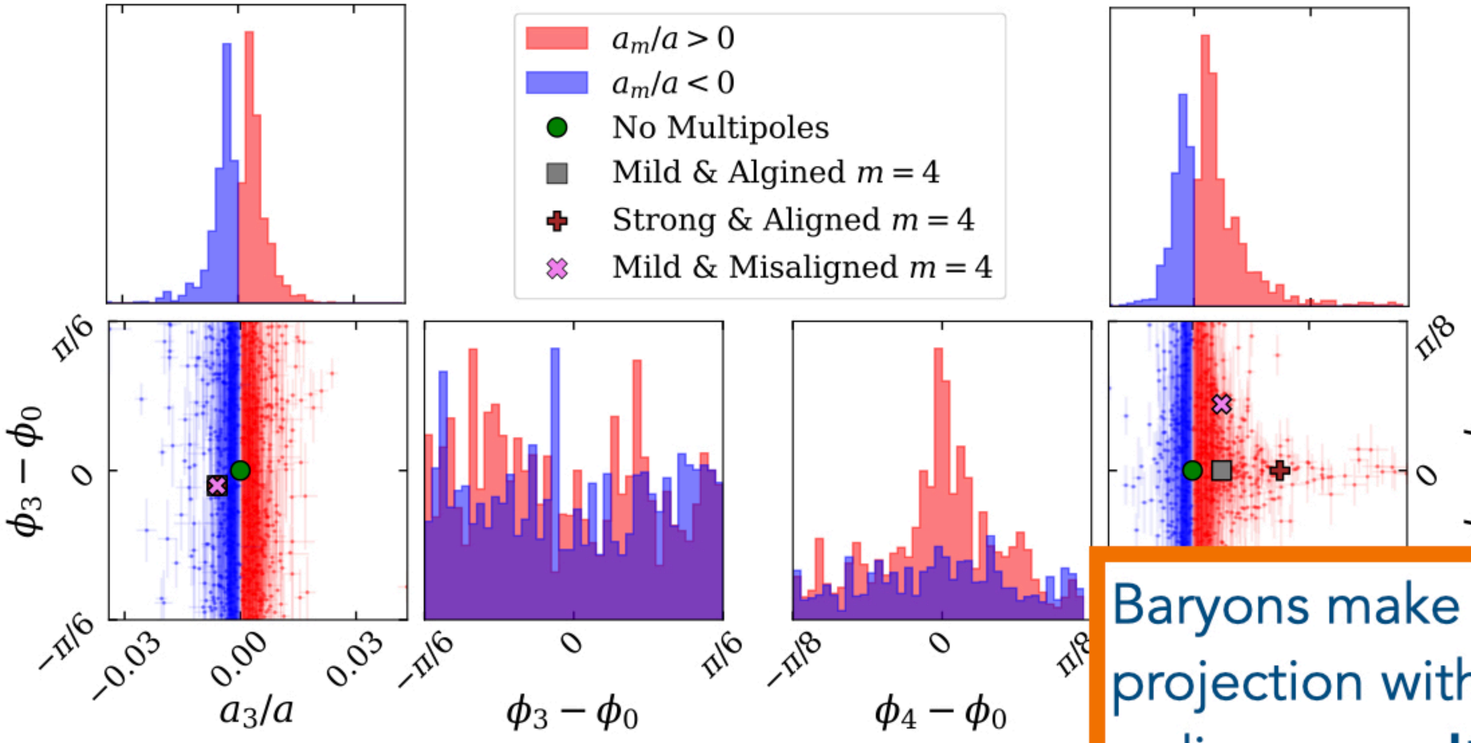
Isophotes of a gravitational lens



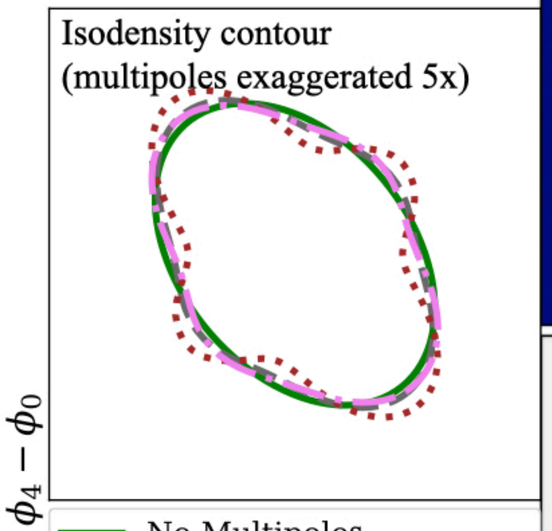
He et al. 2024

Deviations from ellipticity in the deflector

Multipole deviations from ellipticity in field ellipticals

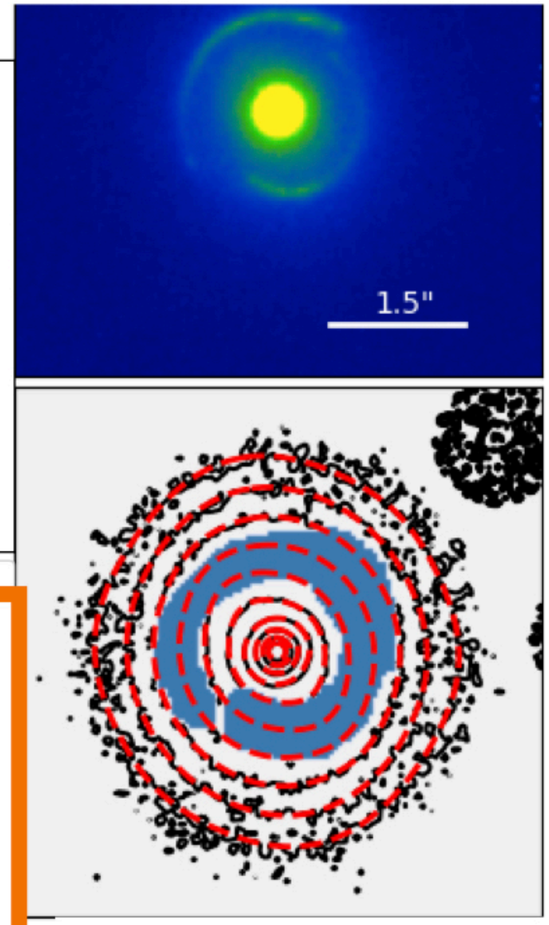


Oh, Nierenberg et al. 2024, based on Hao et al. 2006



Baryons make up ~70% of mass in projection within the Einstein radius, so **multipoles should be dominated by contribution from light**

Isophotes of a gravitational lens

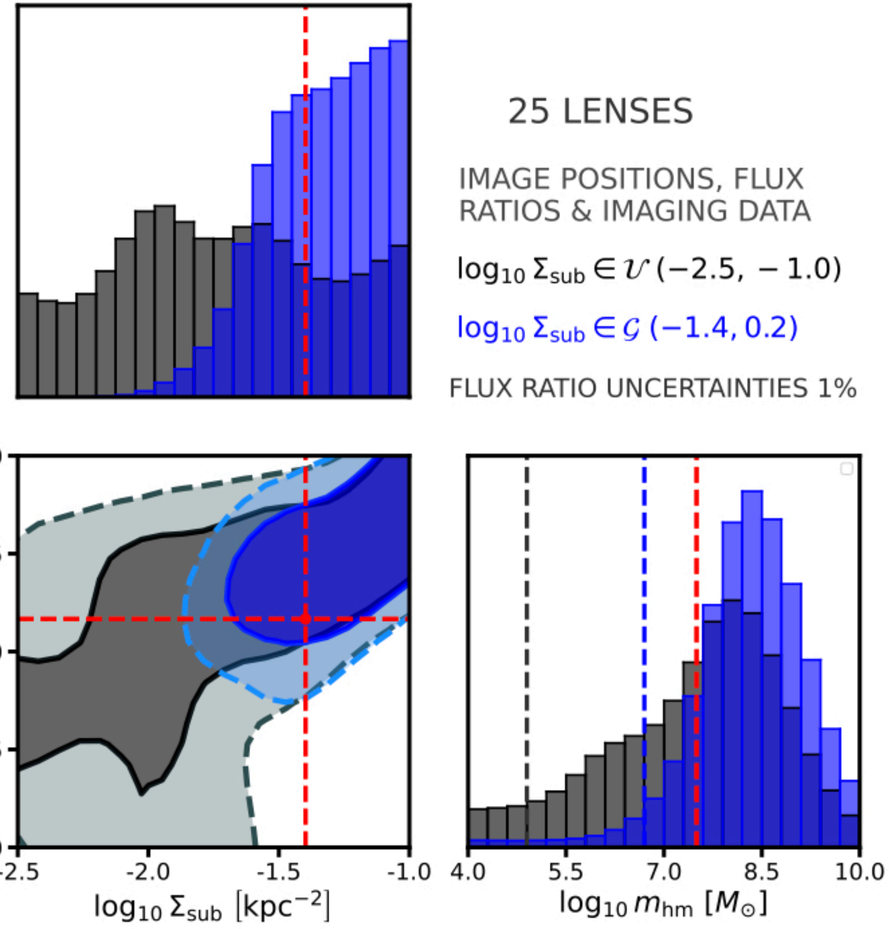


He et al. 2024

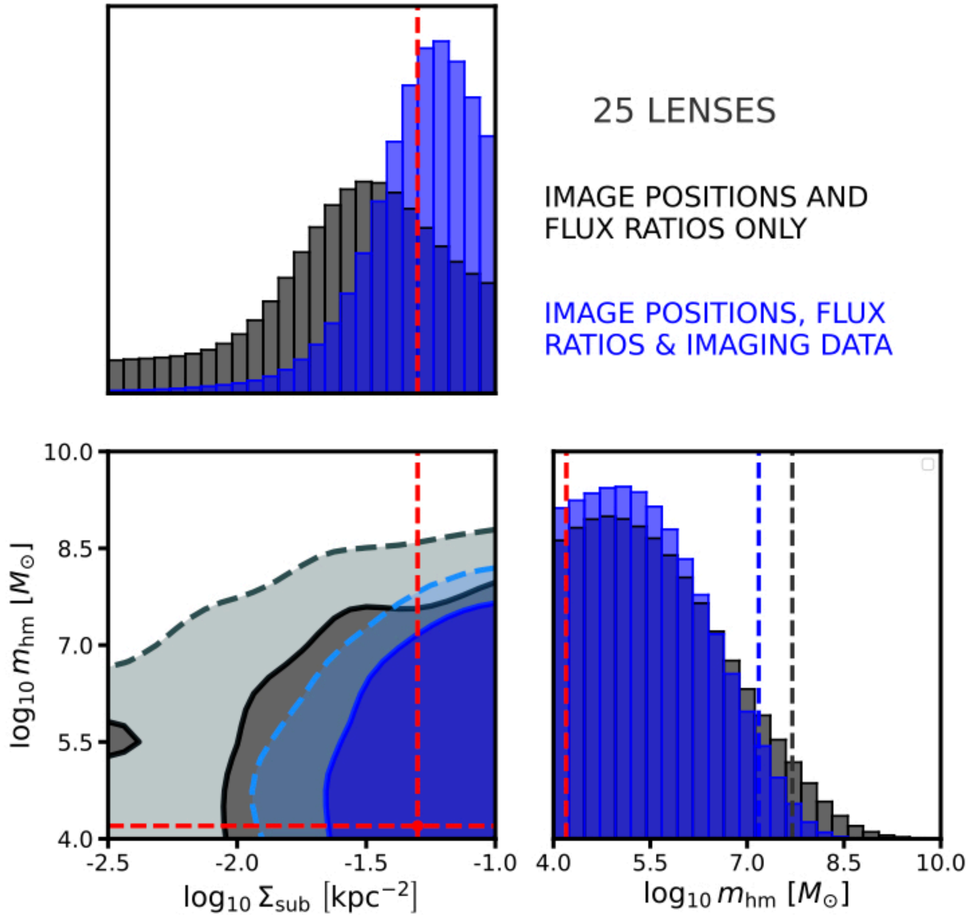
Combining angular complexity with detections: unresolved sources

Correct dark matter inferred with simulated data in the presence of multipoles

Warm Dark Matter Truth

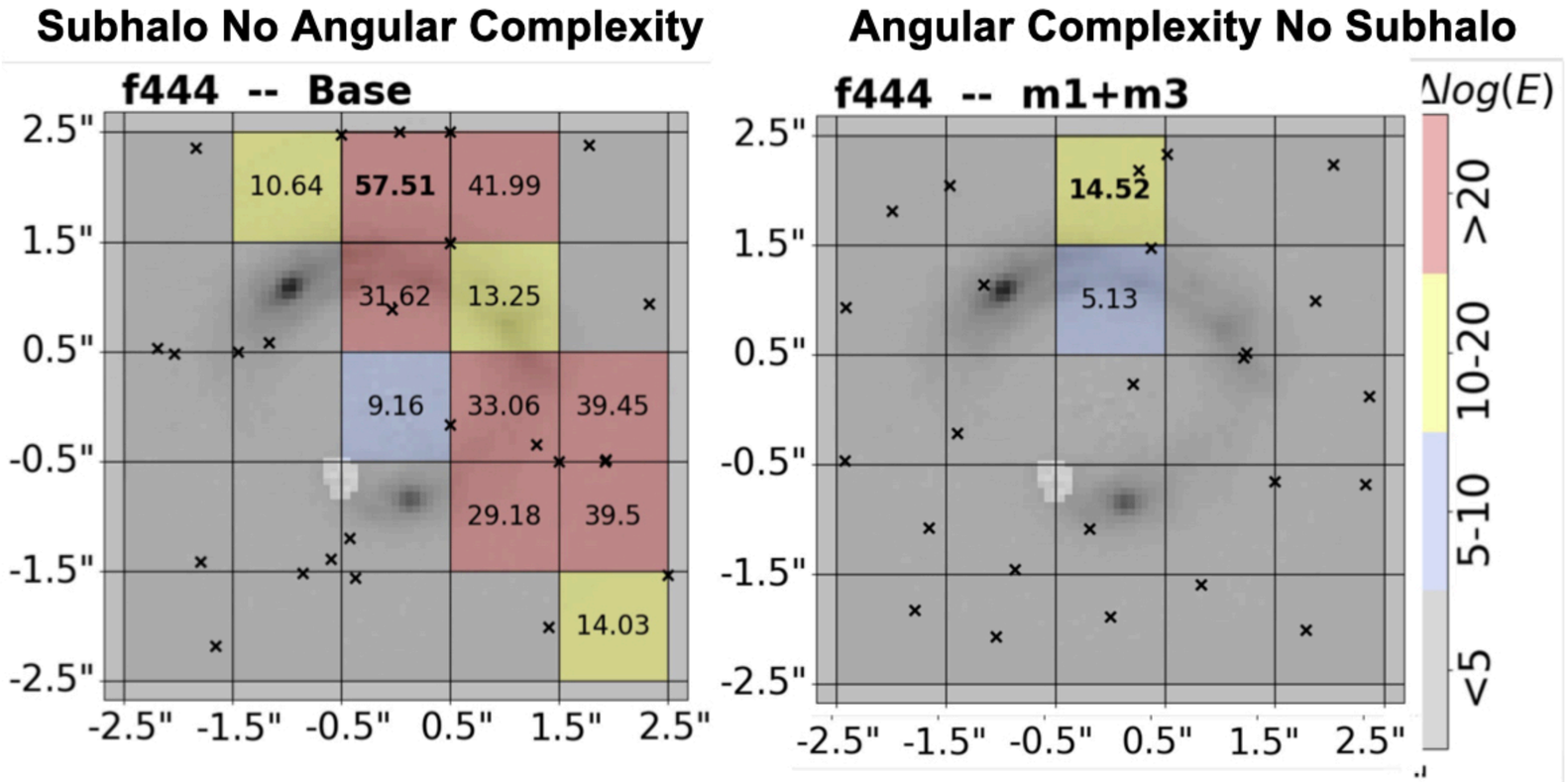


Cold Dark Matter Truth



Gilman, Birrer, Nierenberg et al. 2024

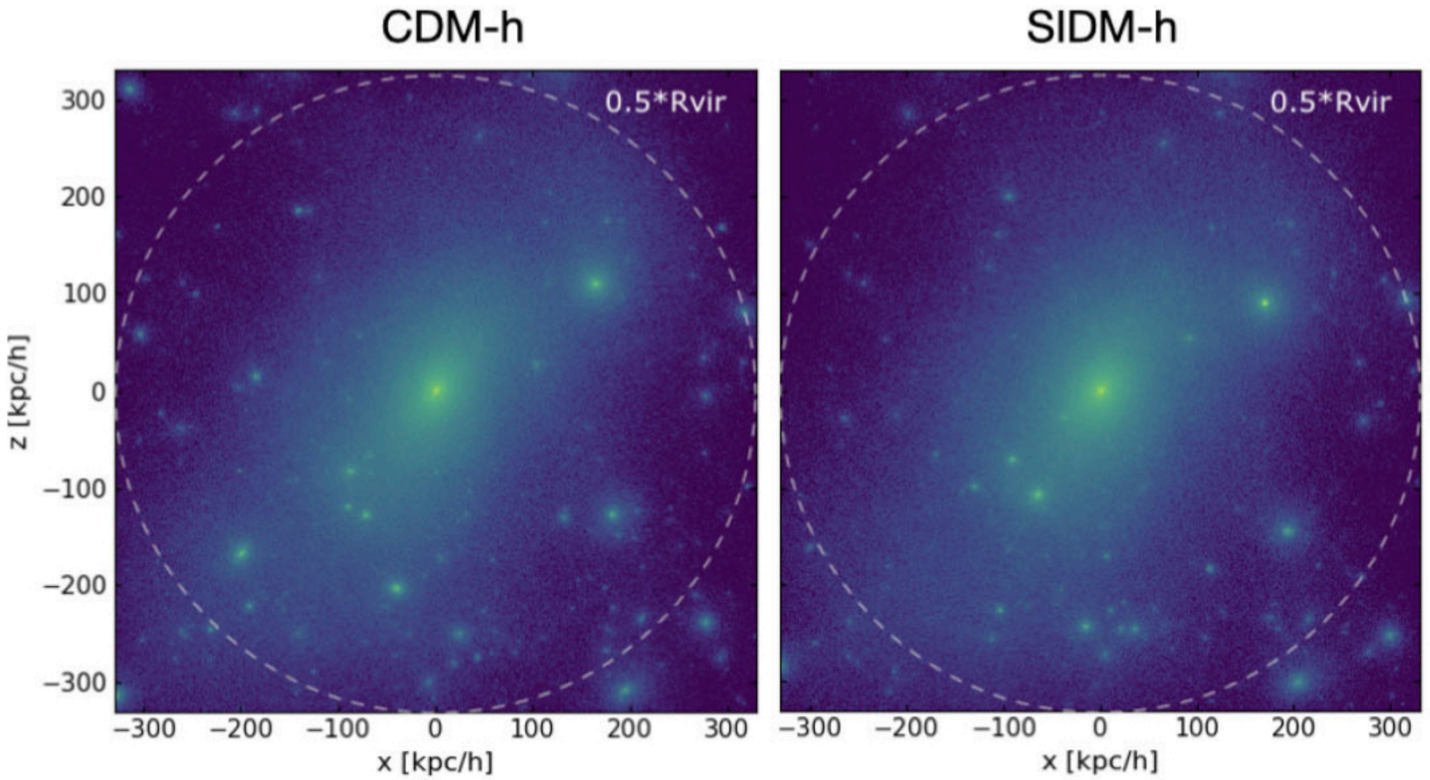
Combining angular complexity and halo detection with resolved sources



- First **dark matter subhalo candidate in JWST data.**
- Including angular complexity in mass model **reduces detection significance**, but **subhalo still favoured.**

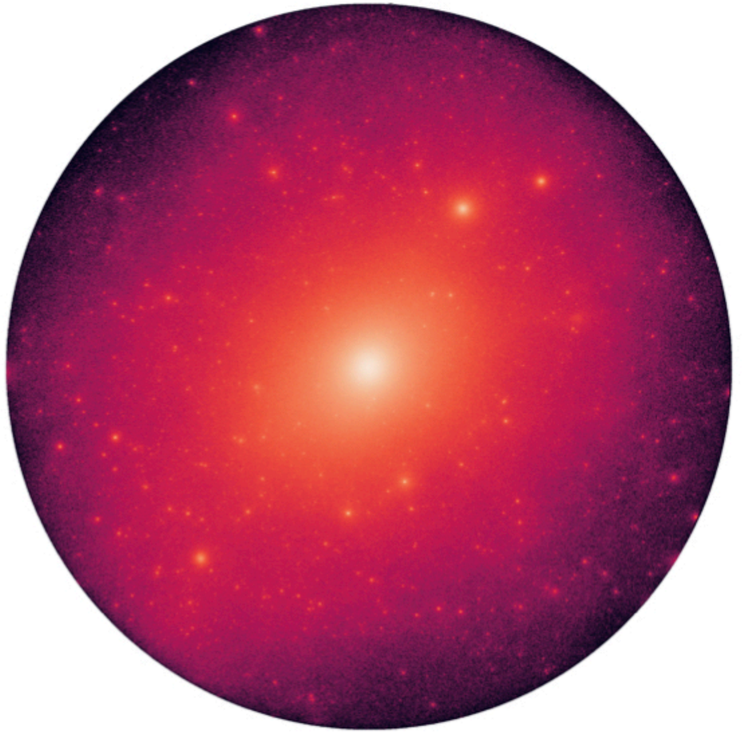
Lange et al. 2024

New simulations of group scale halos with different dark matter models



Despali et al. 2022

Group

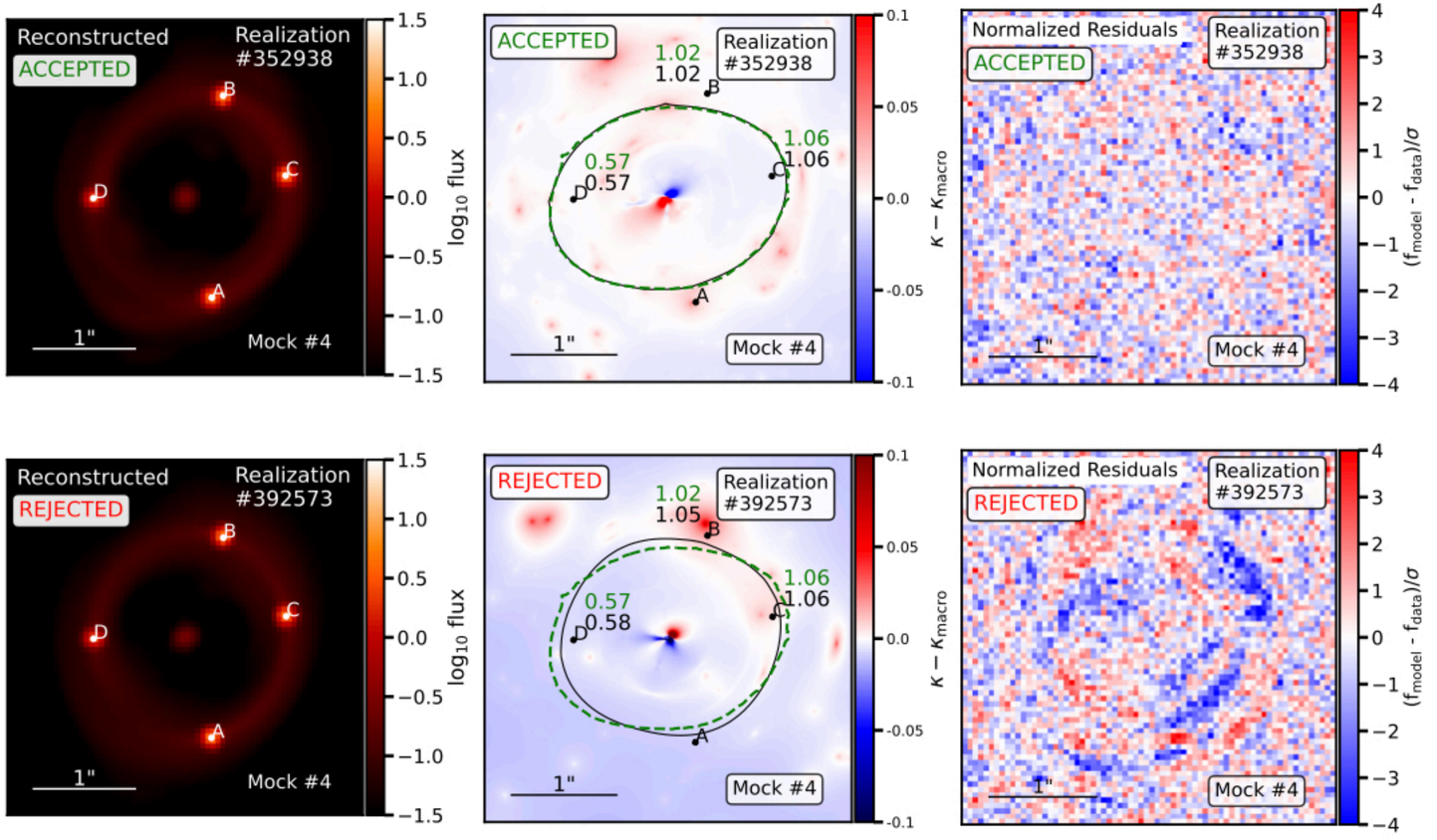


Nadler et al. 2025

Including information from quasar host galaxy

- Lensed quasar host galaxy dramatically decreases uncertainty on the lens mass distribution
- Leads to better dark matter constraints

See Daniel Gilman's Talk



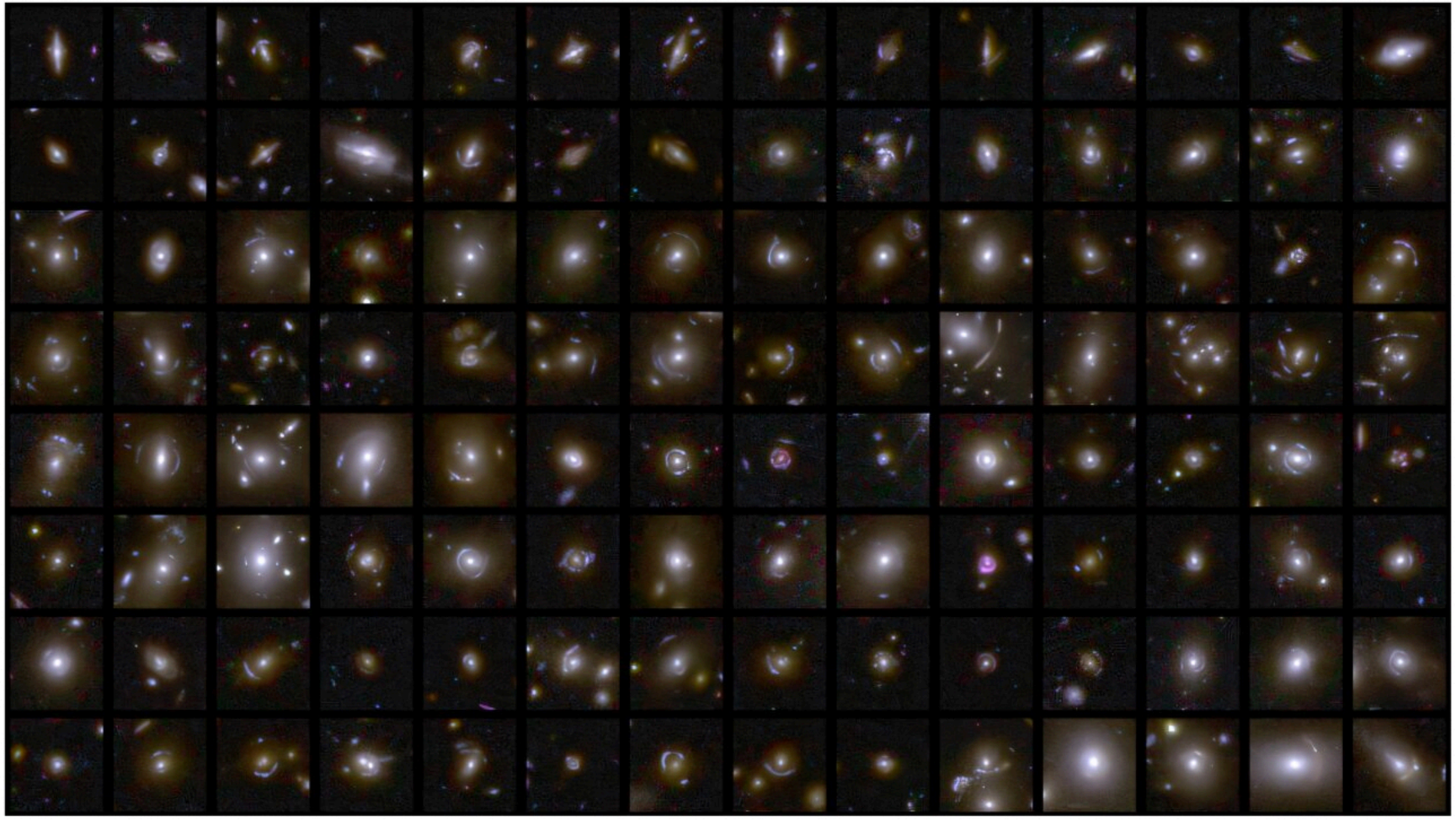
Gilman, Birrer, Nierenberg et al. 2024

Summary of what have we learned

- Lenses reveal low-mass structure with many different methods
- Forward modelling lets us test many different dark matter models
- Hints of very dense subhalos relative to CDM predictions?

Looking to the future - resolved imaging

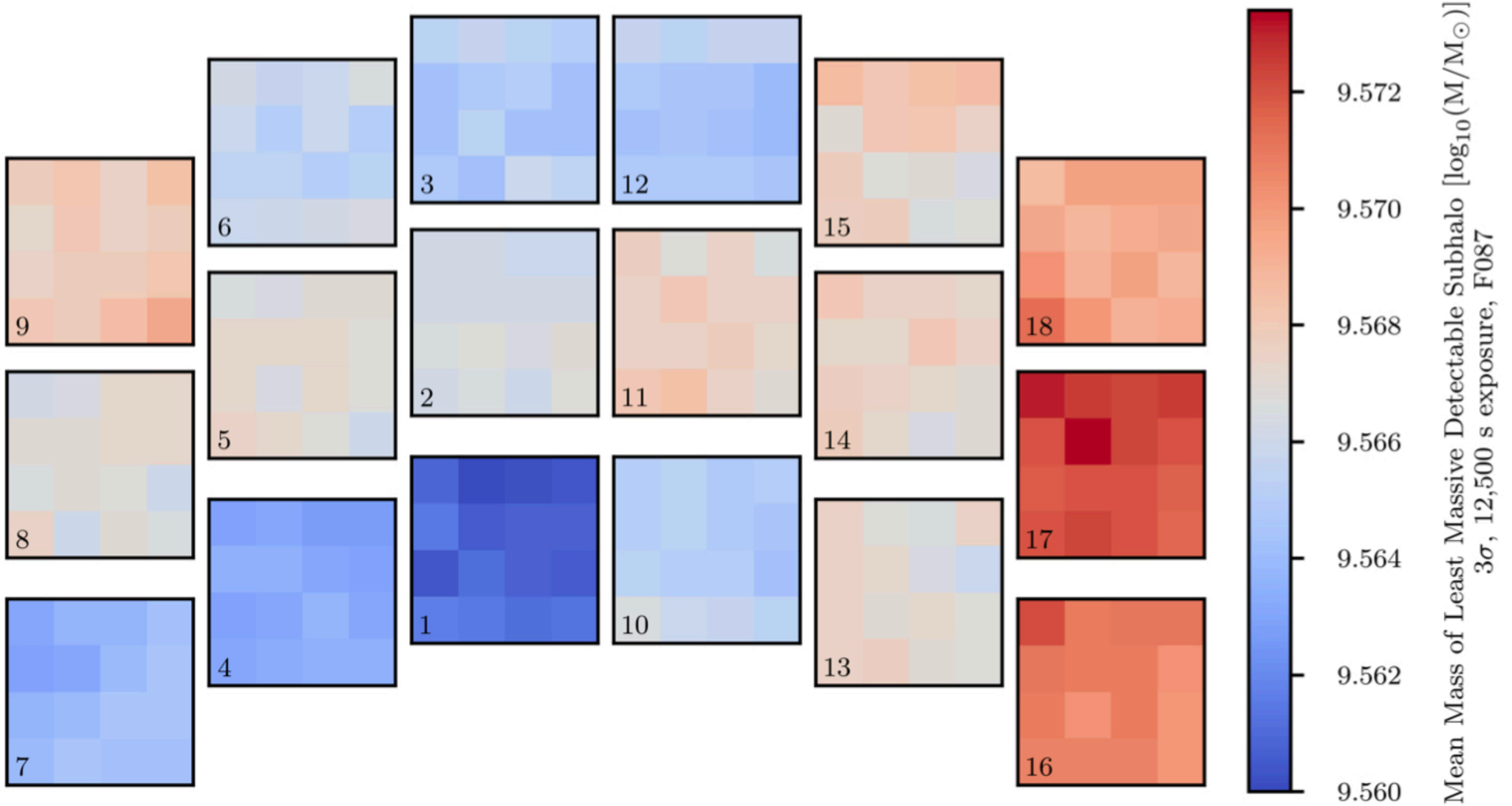
The future is happening 100,000 new galaxy-galaxy lenses in Euclid/ LSST



Credit: ESA/Euclid/Euclid Consortium/NASA, image processing by M. Walmsley, M. Huertas-Company, J.-C. Cuillandre

Looking to the future - resolved imaging

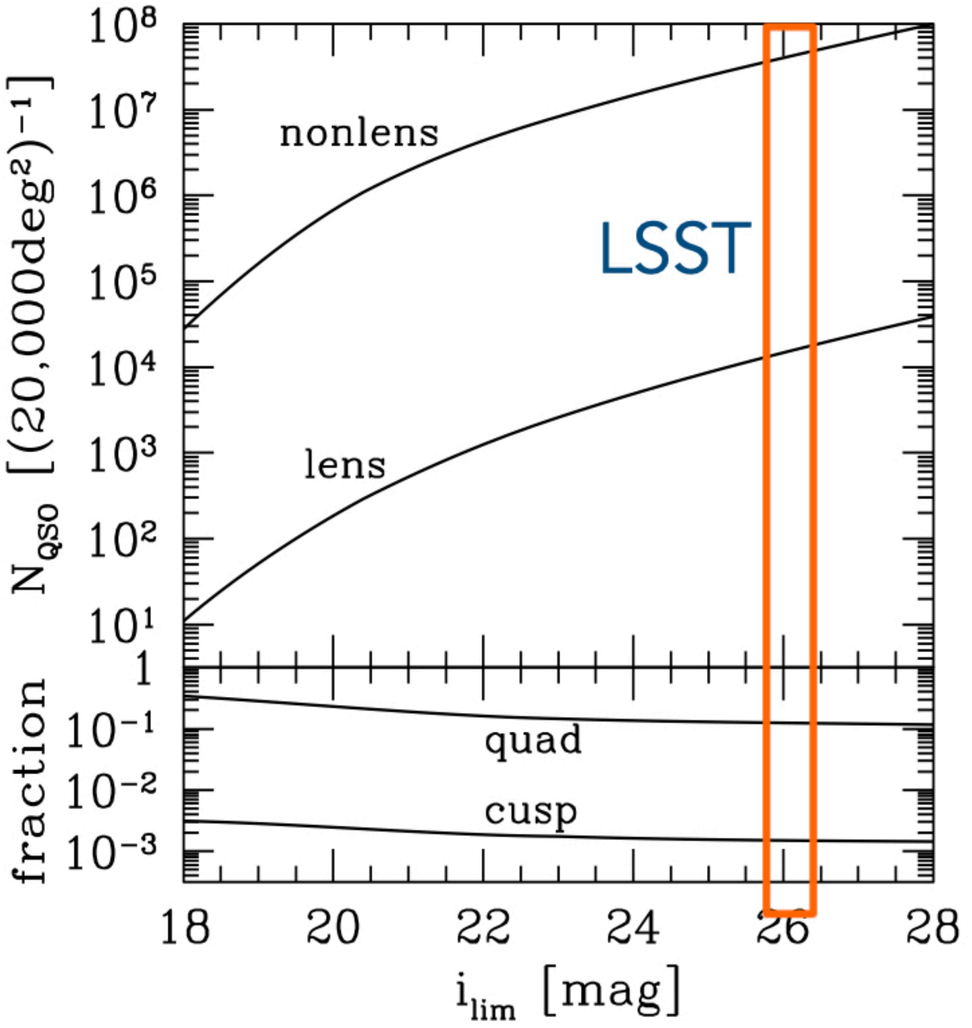
Forecast for imaging detection sensitivities with Roman



Wedig et al. inc AMN 2025

Looking to the future-flux ratios

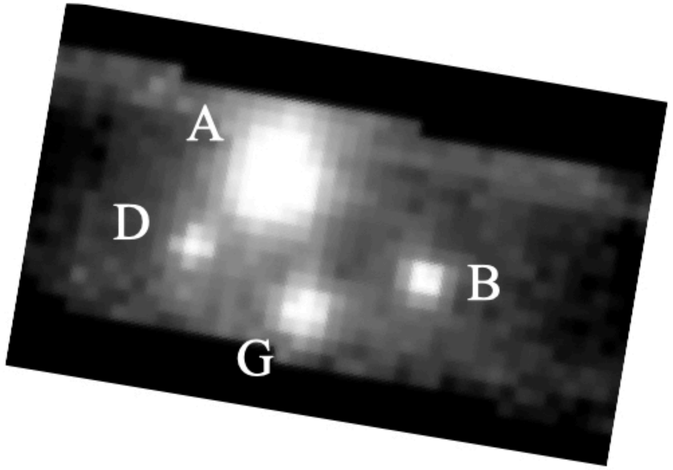
- Hundreds of quadruply imaged quasars will be discovered in LSST and Euclid
- ~200 NL flux ratios can be followed up with Keck in the next ~5 years



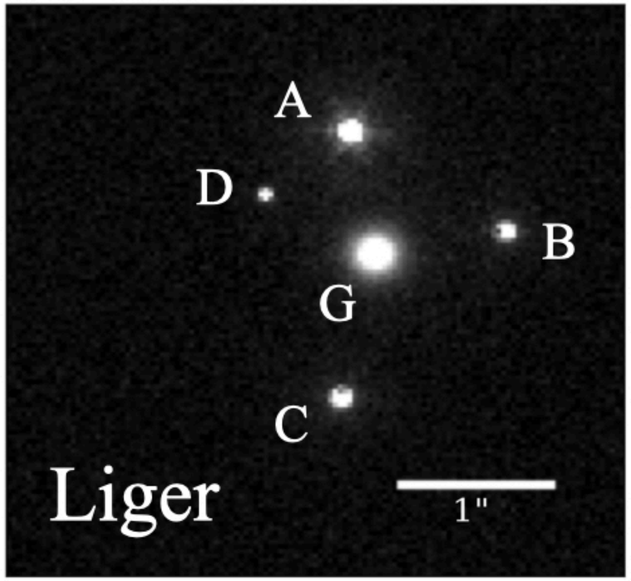
Oguri and Marshall 2010

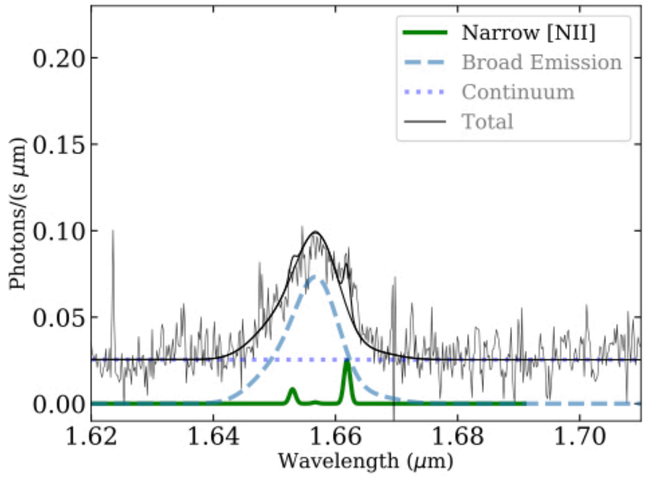
Next generation detectors

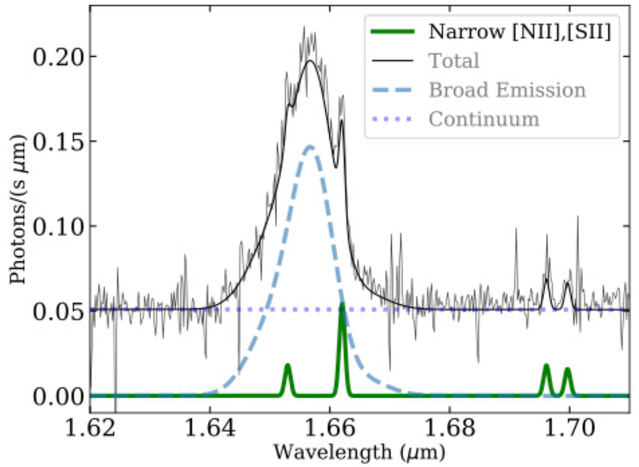
- Enable measurement of flux ratios in fainter lenses



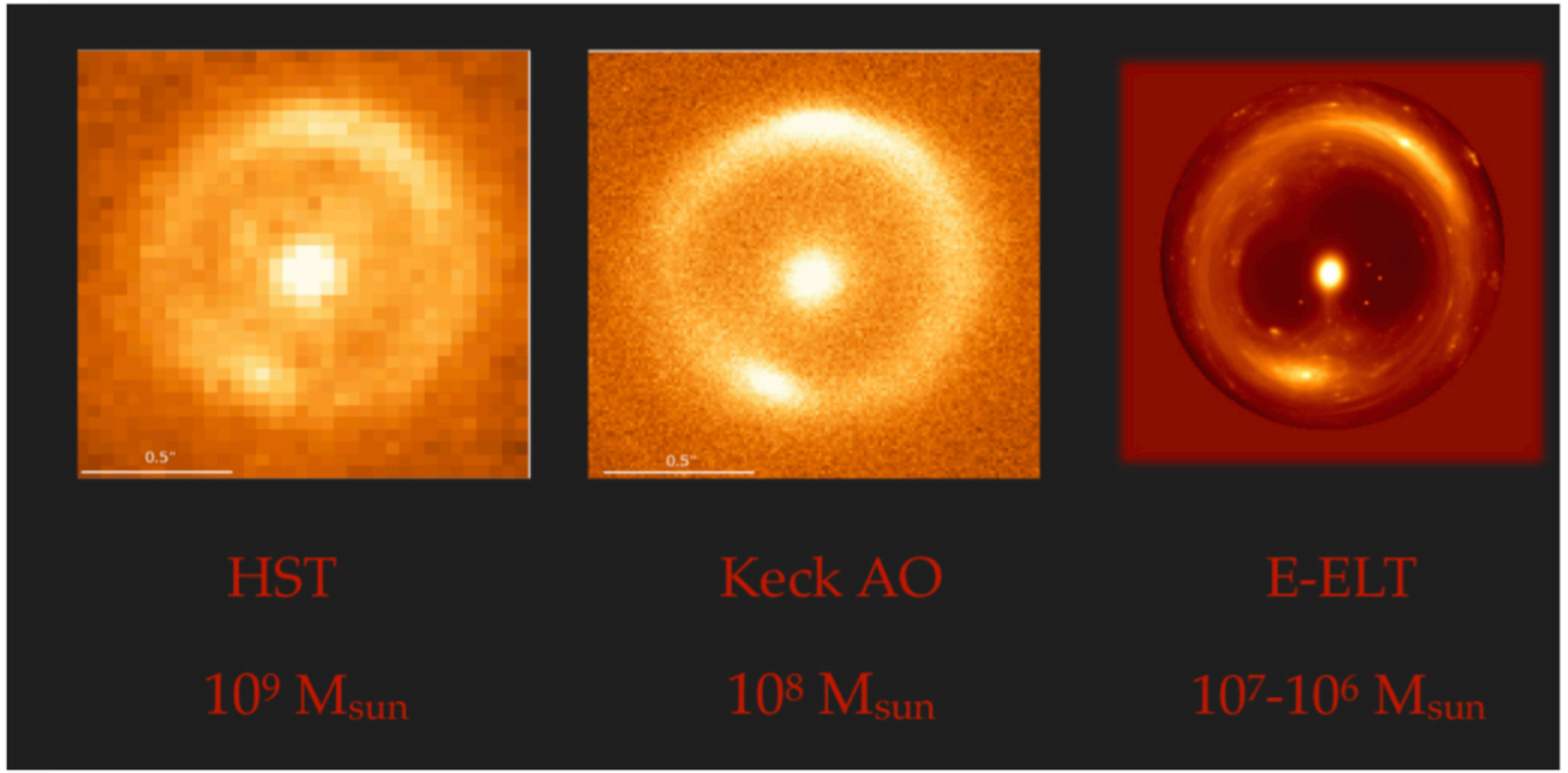
OSIRIS







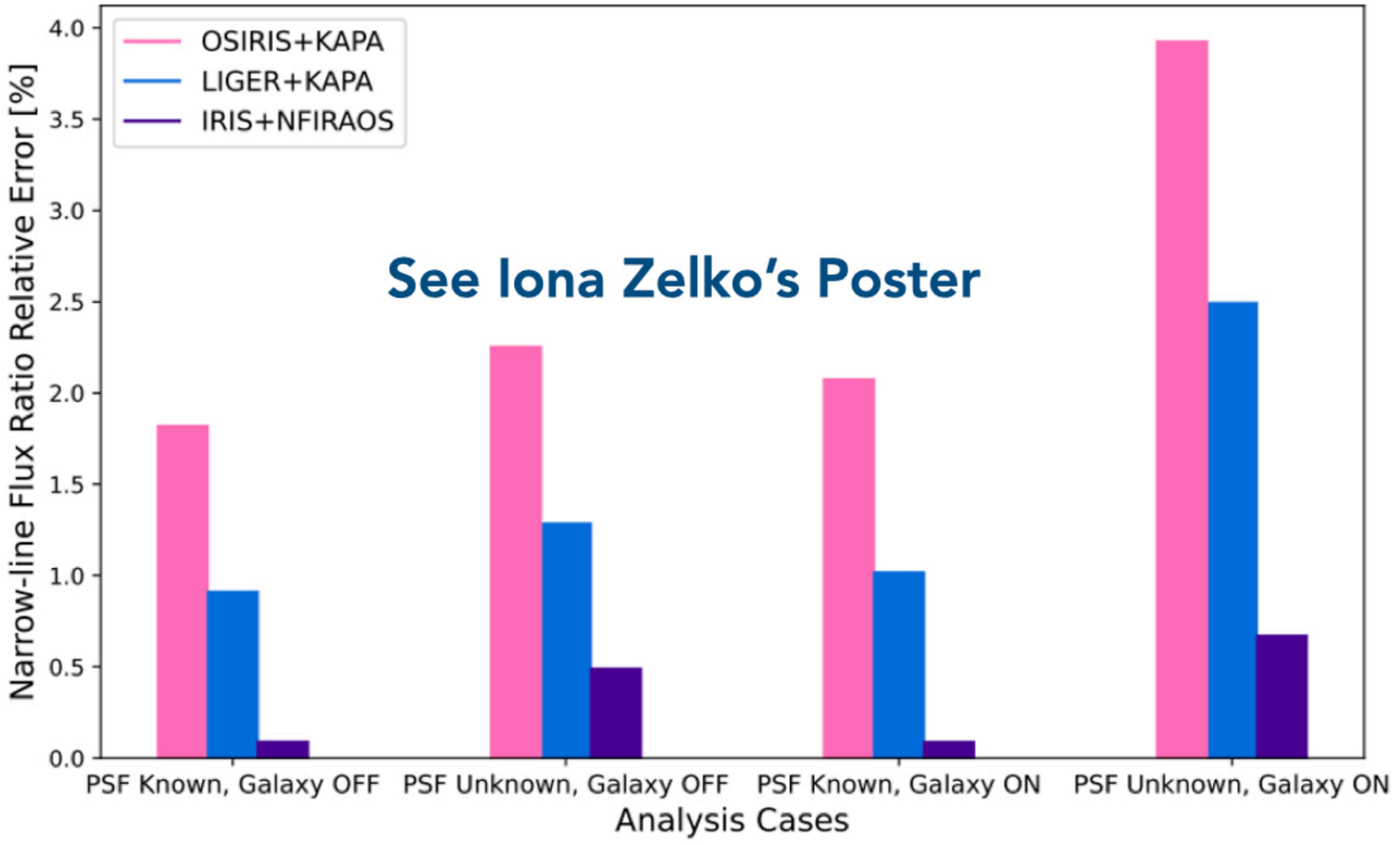
Next Generation Telescopes -Resolved sources



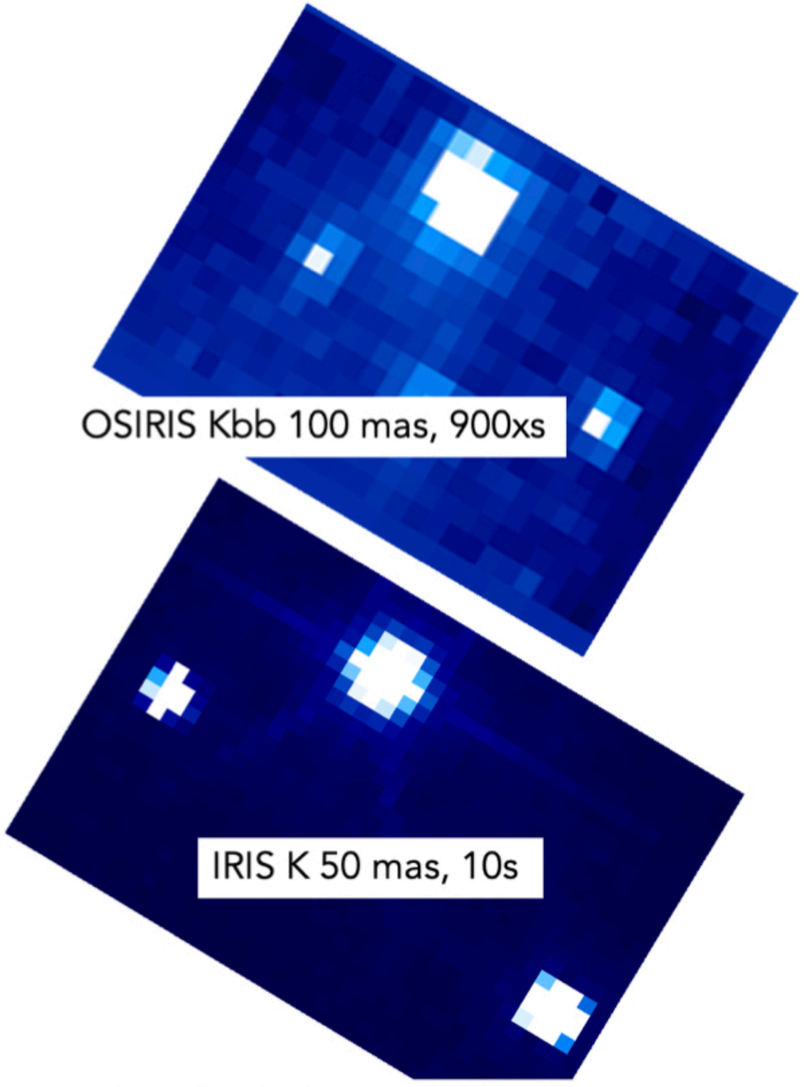
Vegetti

Higher resolution leads to lower halo mass sensitivity: EELTs and next generation adaptive optics will enable detection of lower mass subhalos

Next Generation Telescopes - Flux Ratios



Zelko, Nierenberg et al. 2023 (600s exposures)



IRIS Simulation by Nils-Erik Rundquist (UCSD)

Conclusions

- Many different teams are using independent gravitational lensing techniques to measure the properties of dark matter, **consistently revealing low-mass structure signals in lenses**.
- Current methods enable a **broad range of dark matter models** to be tested
- Lensing has a **bright future** with many new lenses being discovered and new instruments/telescopes being built

This work supported by

NSF CAREER Award

NASA