



Strong lensing as a probe of dark matter



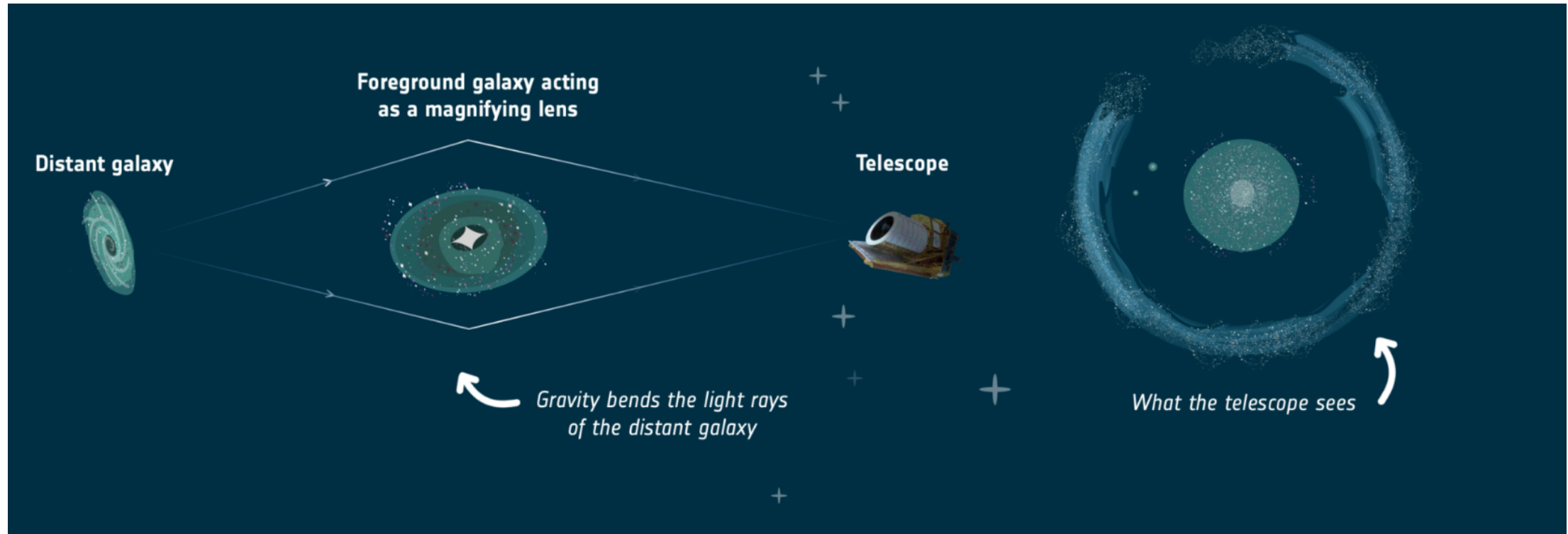
Simona Vegetti

Lise Meitner Group Leader

Max Planck Institute for Astrophysics



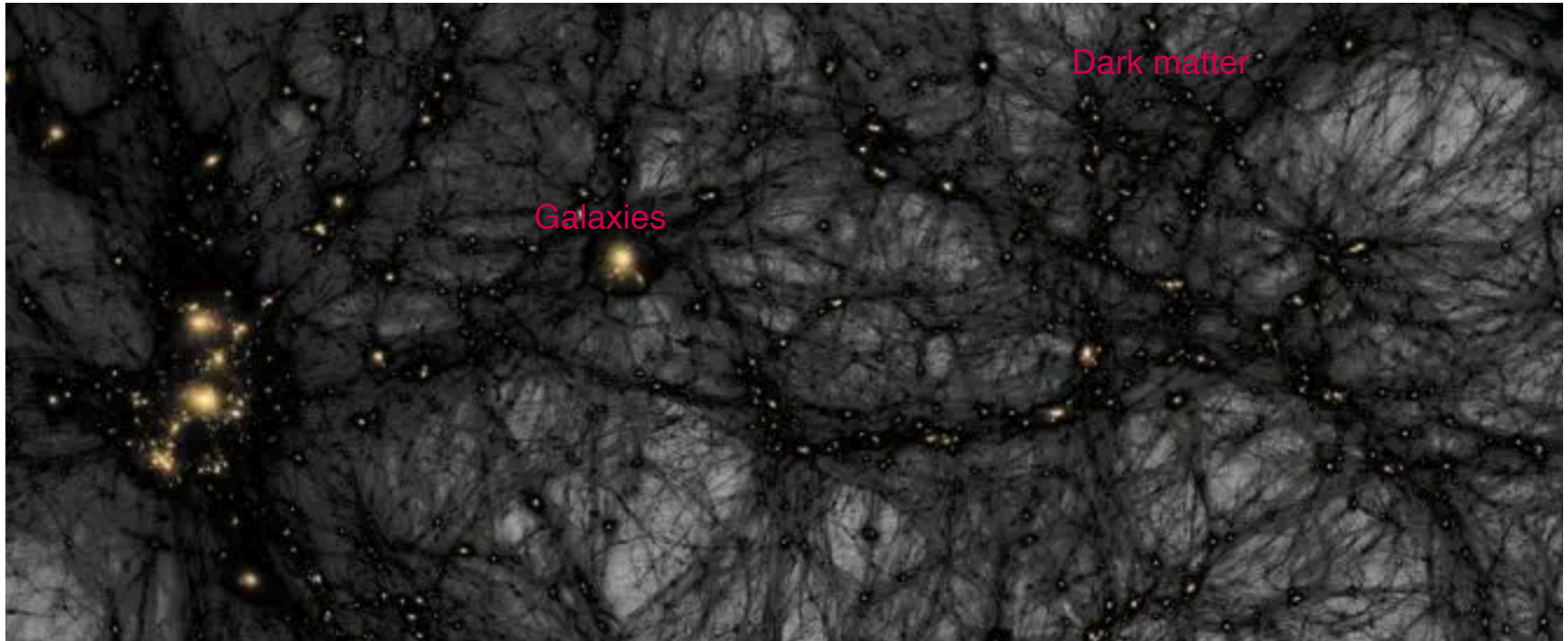
What is strong gravitational lensing?



When the light from a distant galaxy passes close to another galaxy, due to the distortion of space-time one observes multiple distorted images, that we call Einstein rings

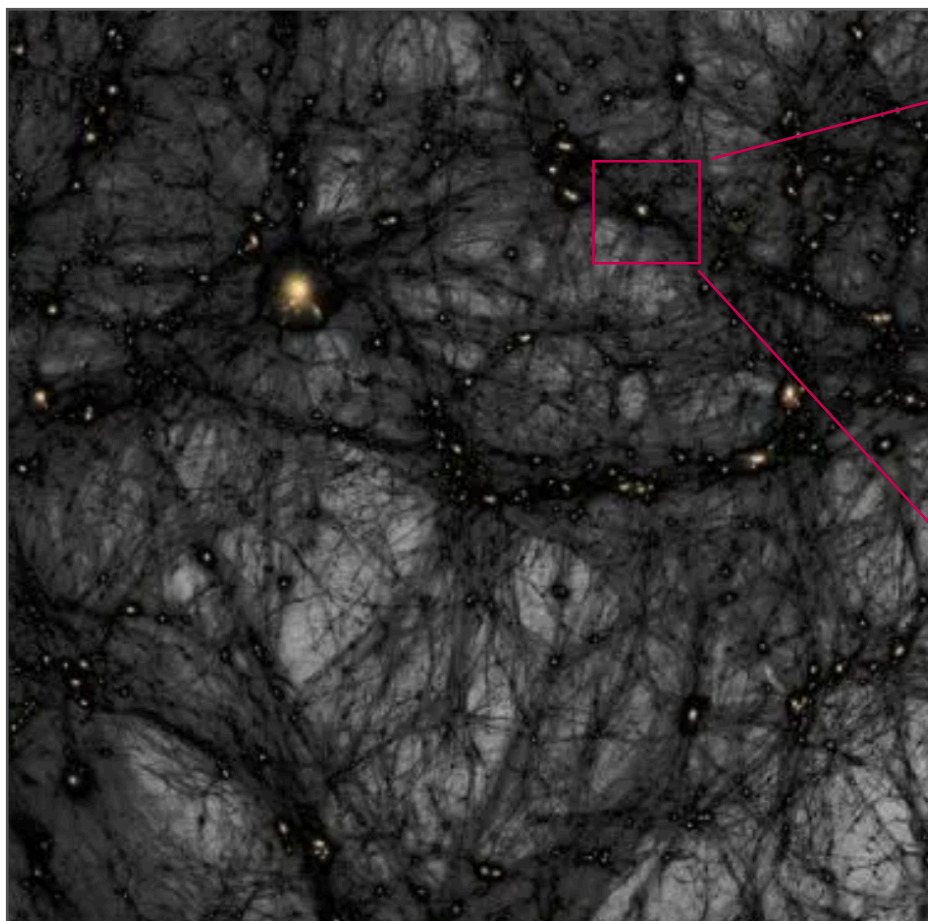


The Universe according to Astronomers

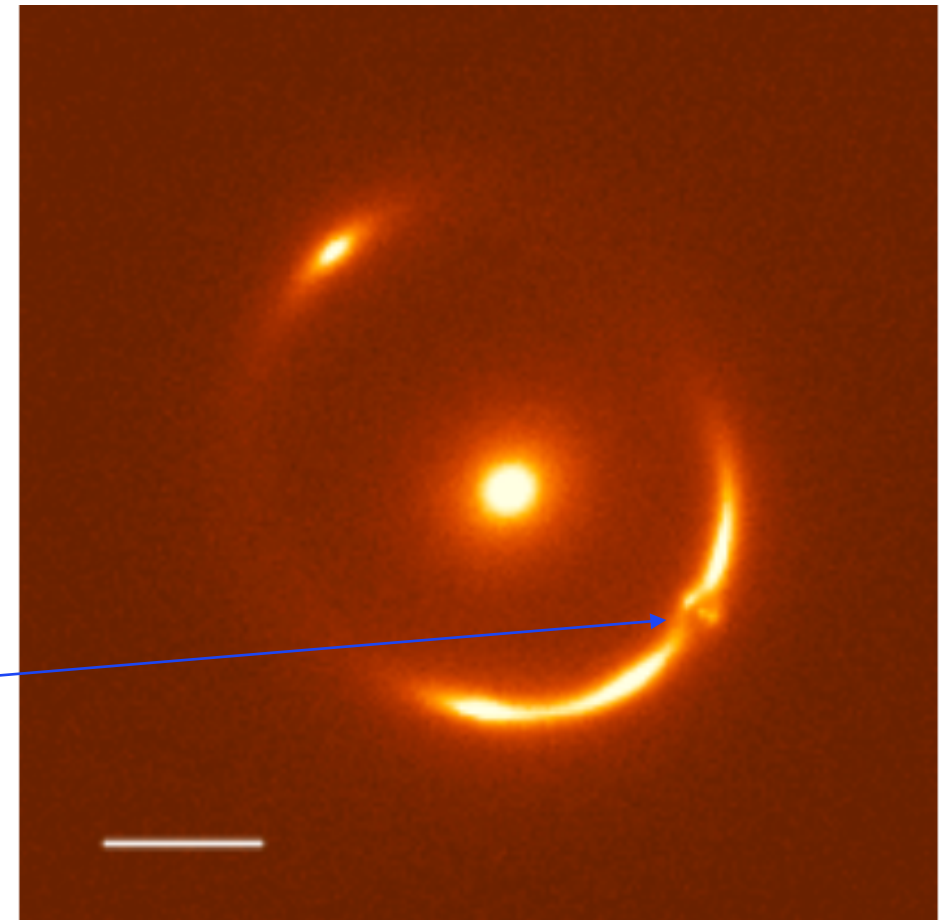
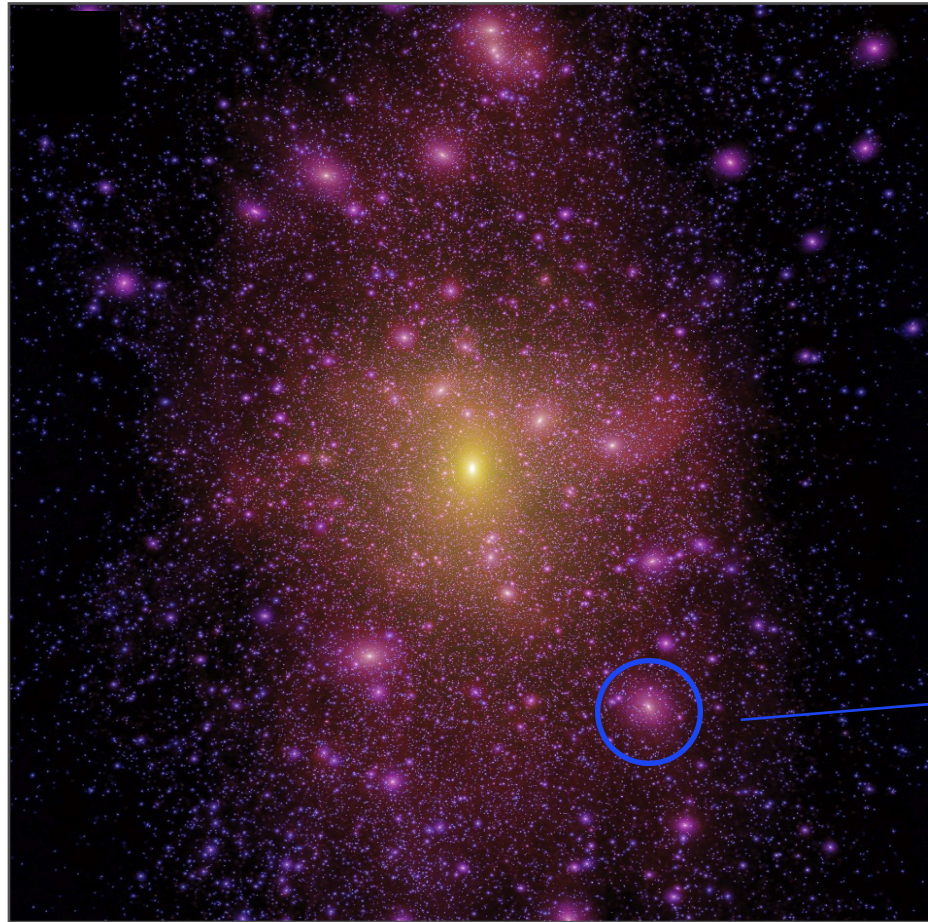


Small dark matter structures

Lovell et al. 2016



Gravitational imaging of dark matter



Different dark matter clumps leave a gravitational inprints on Einstein ring



Which DM models can be probed?

Any model for which we have predictions on the DM distribution. In this talk I will focus on:

Standard **CDM** model and **WDM** alternatives - Key predictions:

- Existence of a large population of low-mass haloes
- NFW mass density profile with a specific mass-concentration relation
- The number of haloes and their concentration is suppressed in WDM proportionally to the particle mass
- Examples: **WIMPs**, **sterile neutrinos**

SIDM - Key predictions:

- Existence of a large population of low-mass haloes
- Existence of very dense core-collapsed haloes

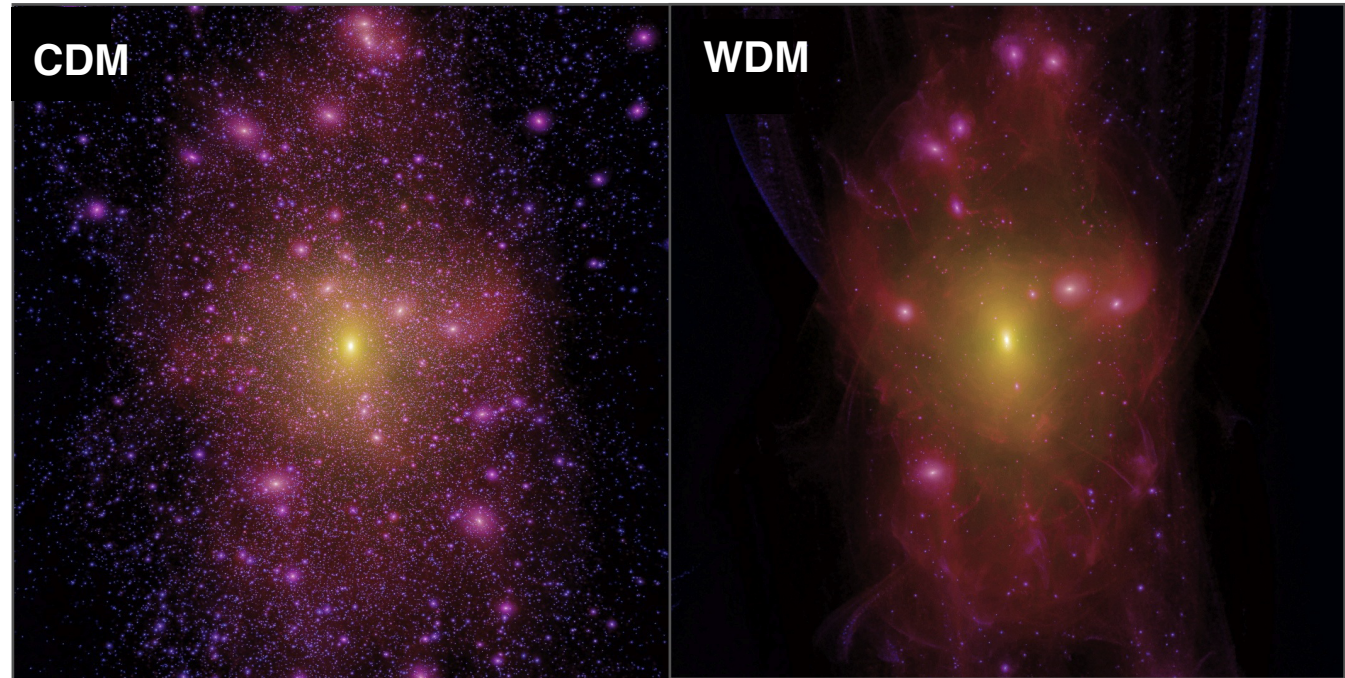
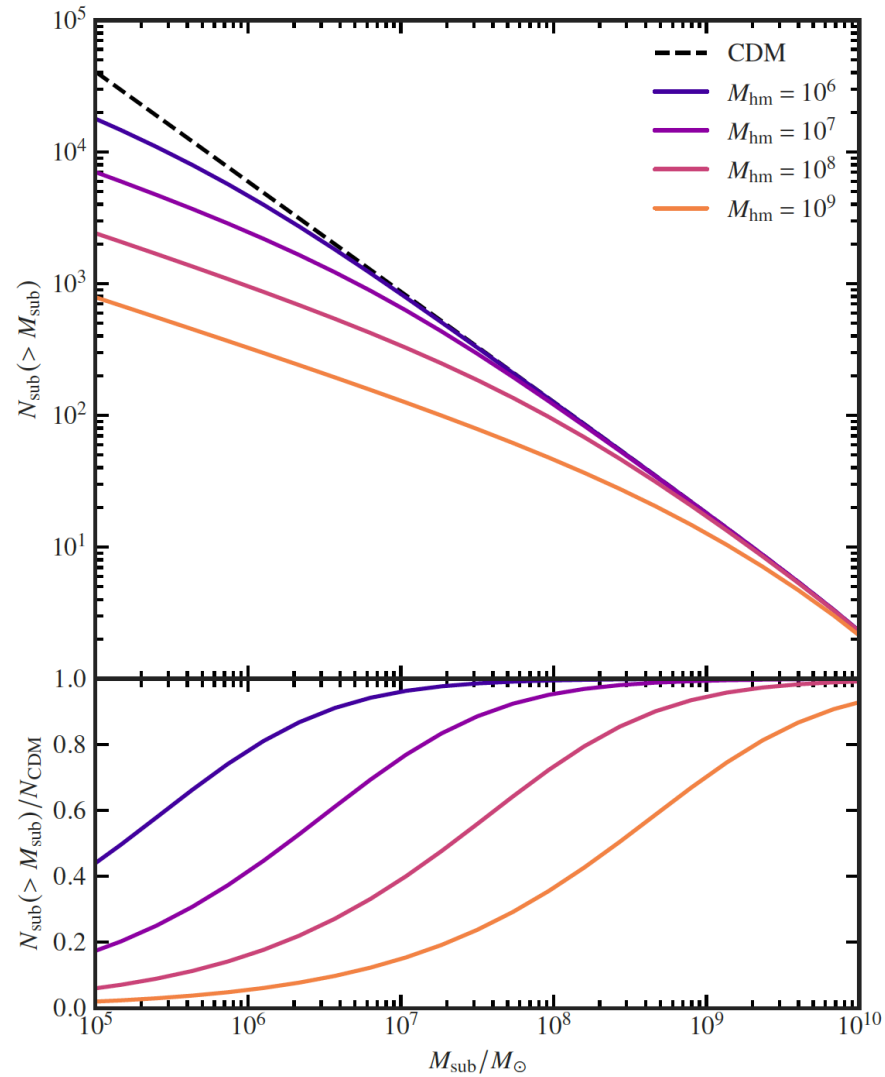
FDM/ALPs - Key predictions:

- Granular mass density distribution of galaxies
- Polarised sources experience birefringence
- The presence of a large population of low-mass haloes



CDM and WDM predictions

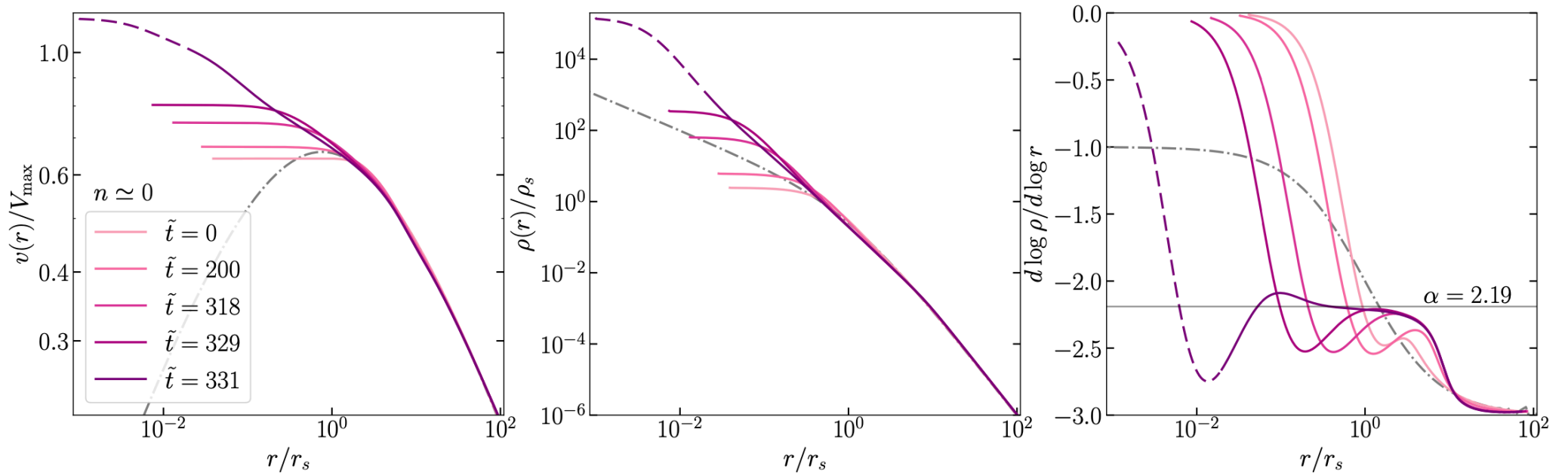
Well-defined mass function and mass density profile



SIDM predictions

Still viable SIDM models predict a number density of low-mass haloes comparable to CDM

But their mass density profile is very different

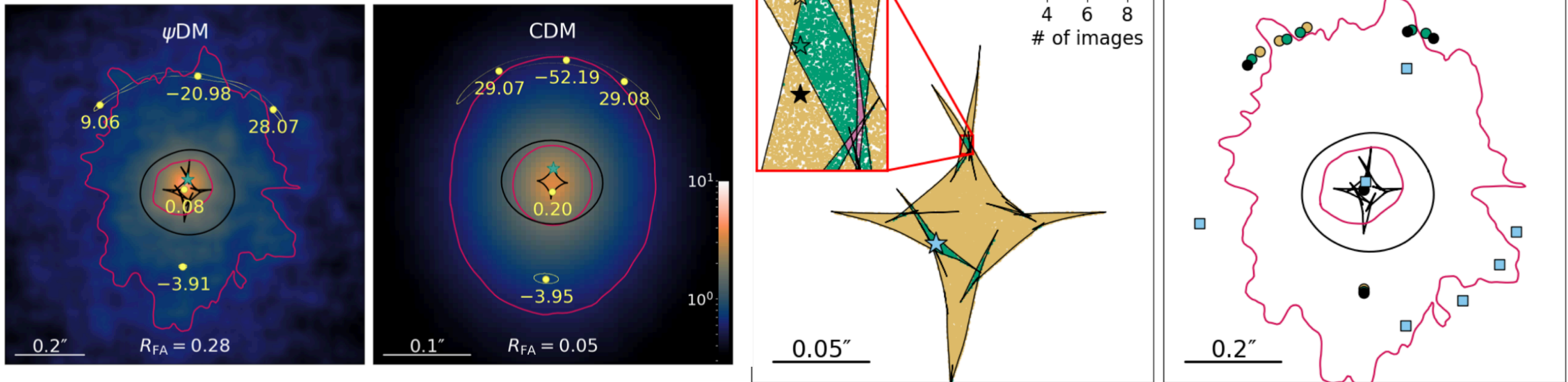


Core-collapsed haloes are more efficient lenses



Lensing signature of FDM

Chan et al. 2020

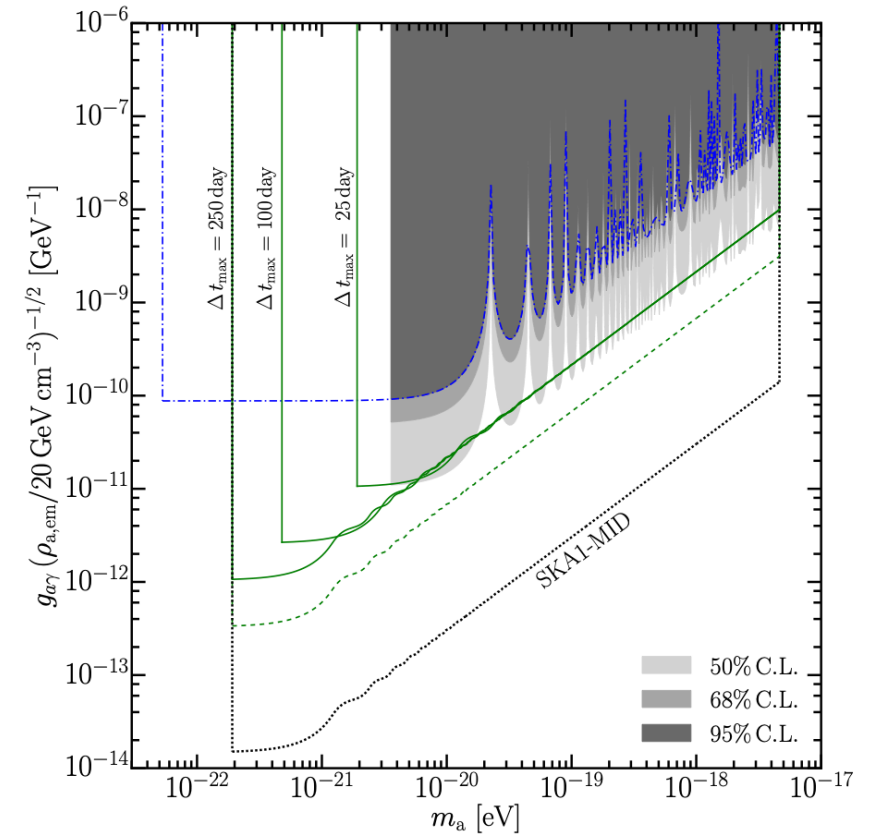
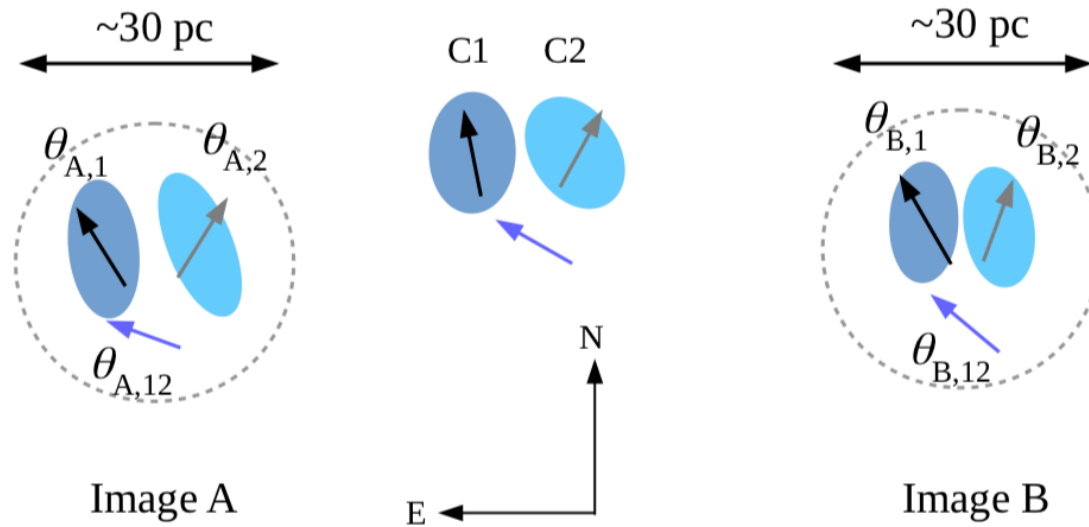


A granular mass distribution is more likely to create unusual image configurations and a different distribution of FA



Lensing signature of ALPs

ALPs induce differential birefringence



For a particle mass in the FDM range, we expect both birefringence and granularity



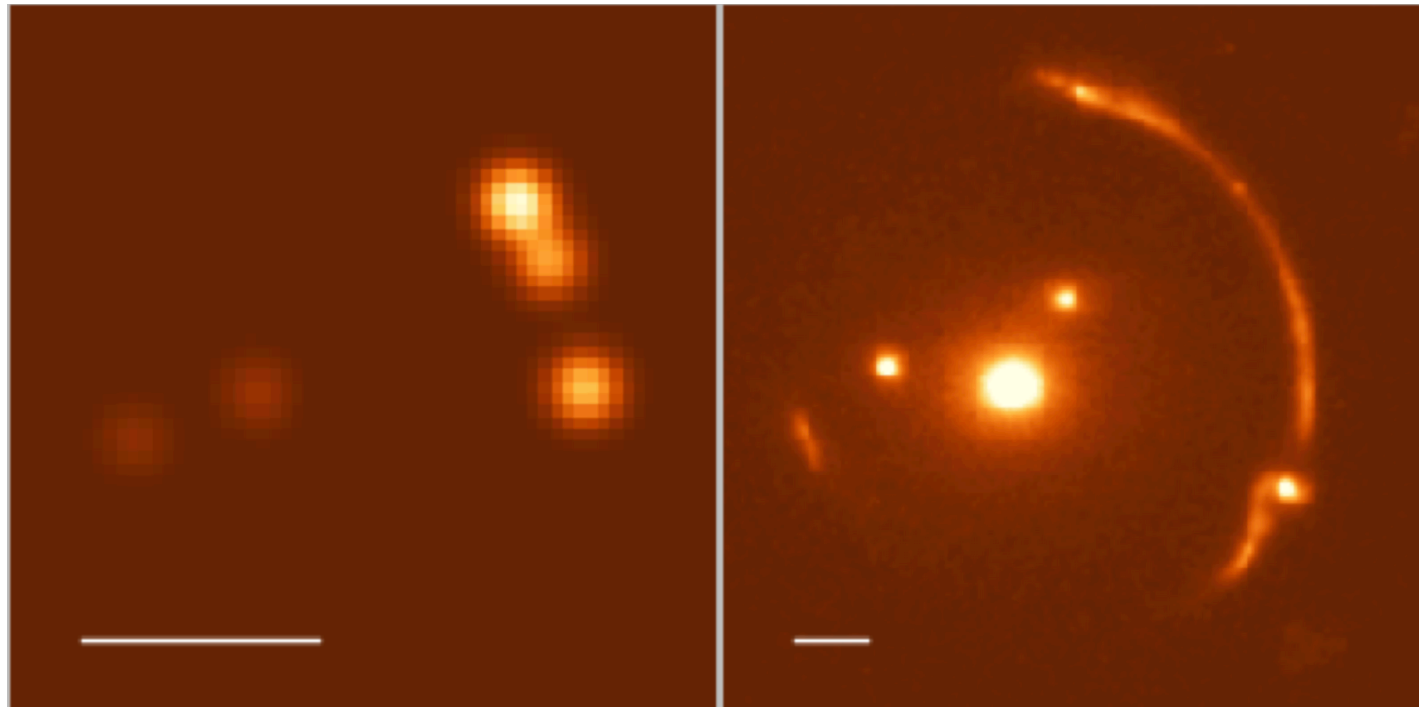
Challenges



Lensing & DM inference

Unresolved source

Resolved source



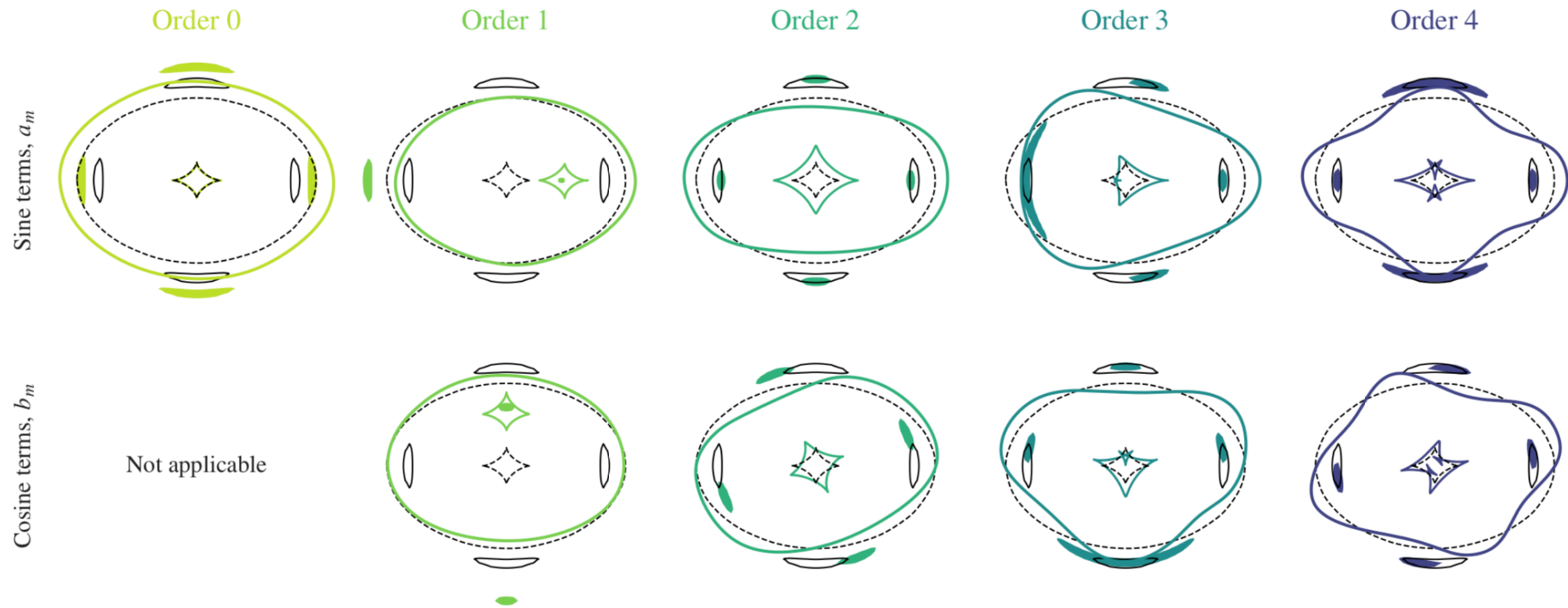
Data = flux or surface brightness distribution of the lens and lensed image, a set of visibility for interferometric data

Unknown = un-lensed light distribution of the background source

Unknown = main lens potential

Unknown = contribution of dark matter to the lensing potential or polarisation angle

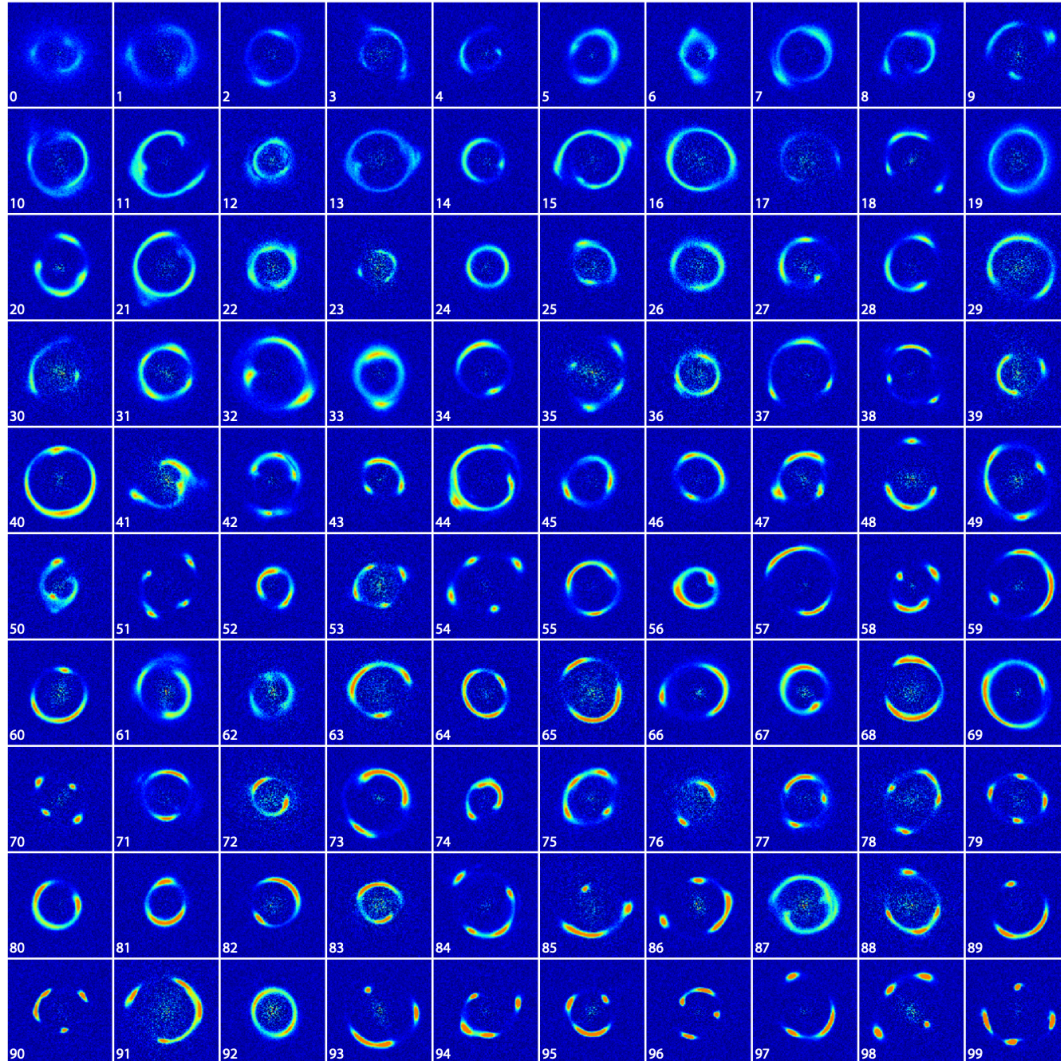
Degeneracy with the lens model



Galaxies have complicated mass distributions with angular structure

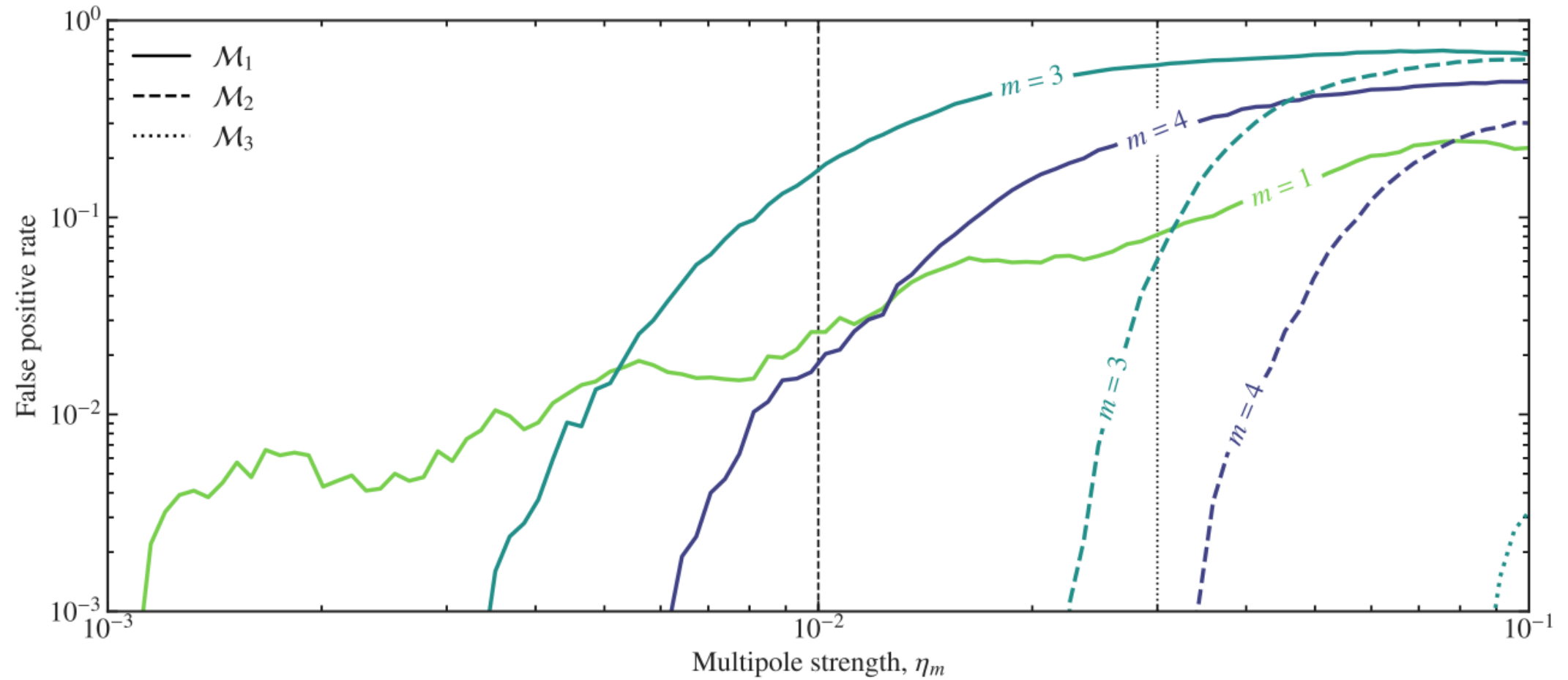
Degeneracy with the lens model

100 mock HST lenses

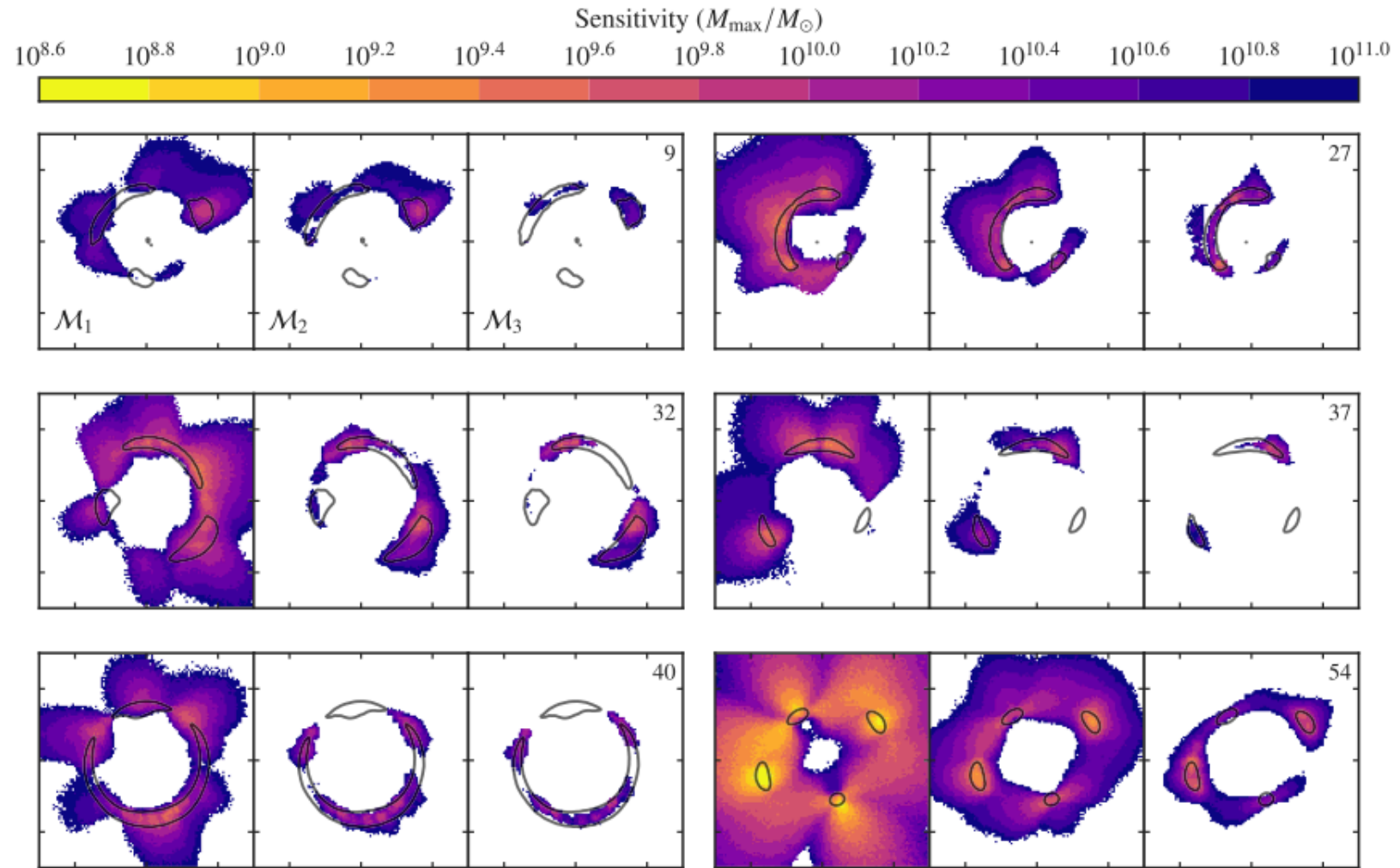


Model	θ_E	q	γ	$ \gamma_{\text{ext}} $	m	η_m
\mathcal{M}_1	0.5–3.0	0.4–1.0	1.8–2.2	<0.1	None	0.0
\mathcal{M}_2	0.5–3.0	0.4–1.0	1.8–2.2	<0.1	1, 3, 4	<0.01
\mathcal{M}_3	0.5–3.0	0.4–1.0	1.8–2.2	<0.1	1, 3, 4	<0.03

Degeneracy with the lens model



Degeneracy with the lens model

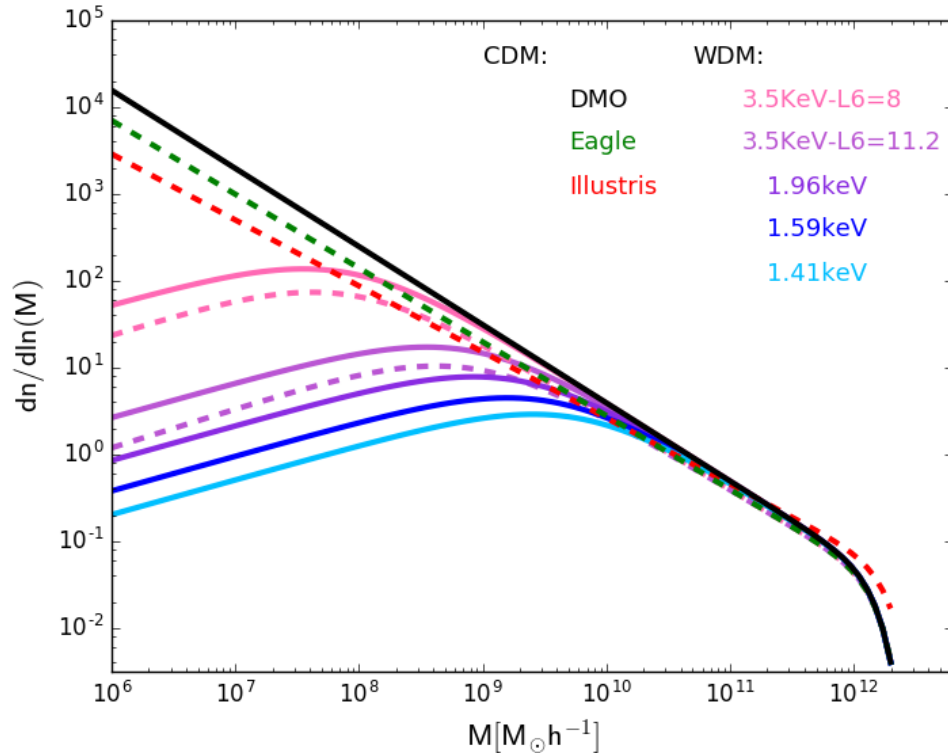


Multipoles don't affect the depths of the sensitivity, significantly reduces its area

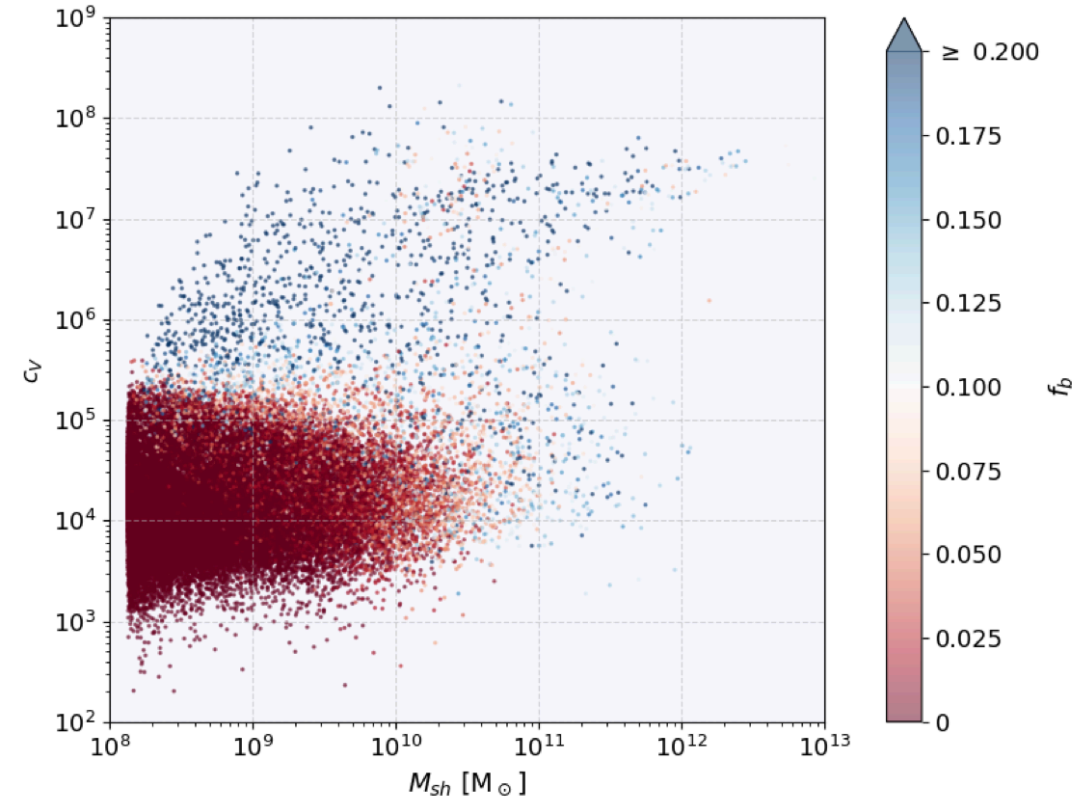
Every lens needs to be modelled in detail

The effect of baryons

Different galaxy formation models lead to different depletion of low-mass sub-haloes



Baryons change the total mass profile



EAGLE: 20% fewer sub-haloes between 10^8 and $10^9 M_{\text{sun}}$

ILLUSTRIS: 40% fewer sub-haloes between 10^8 and $10^9 M_{\text{sun}}$



Status



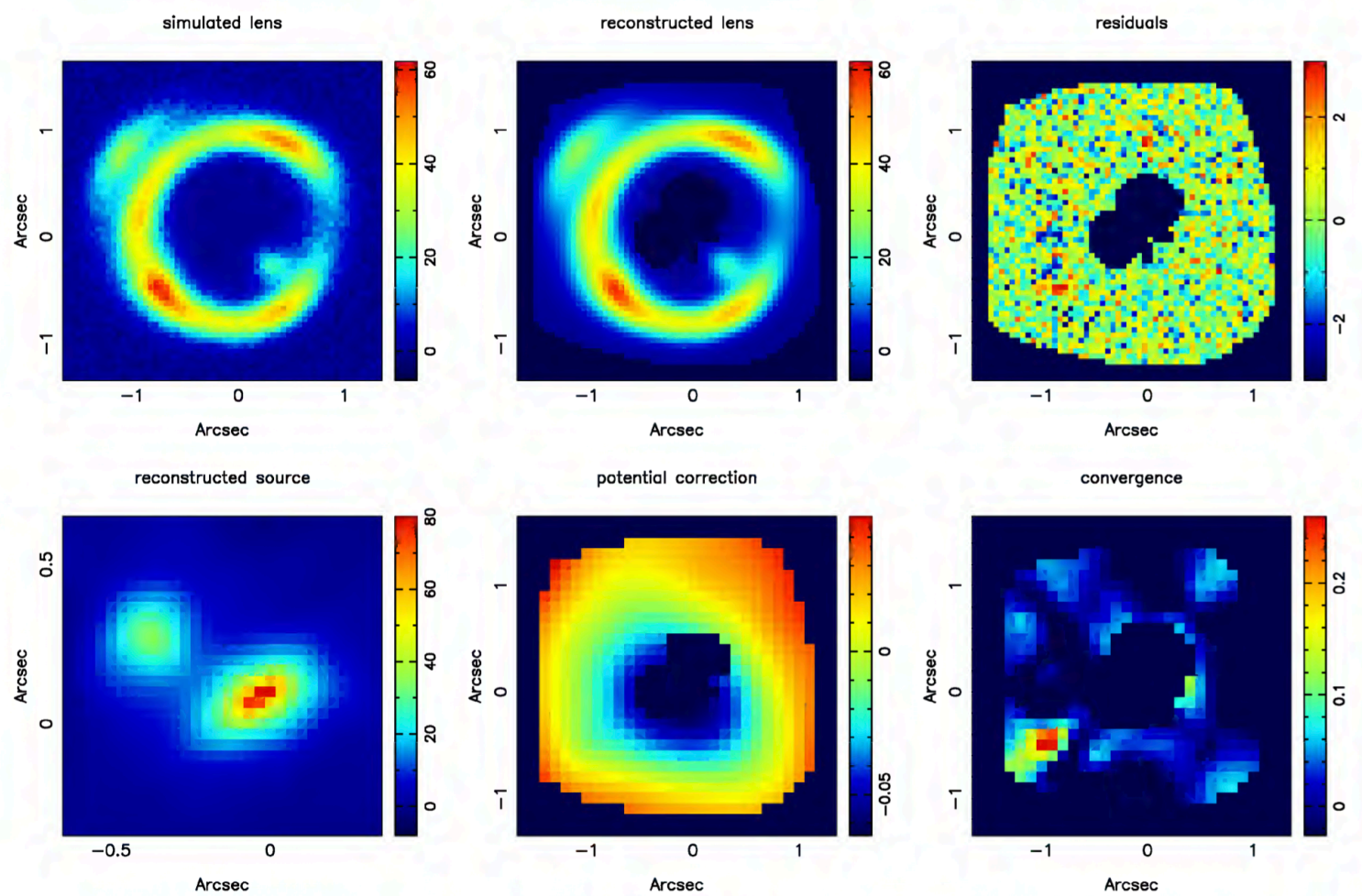
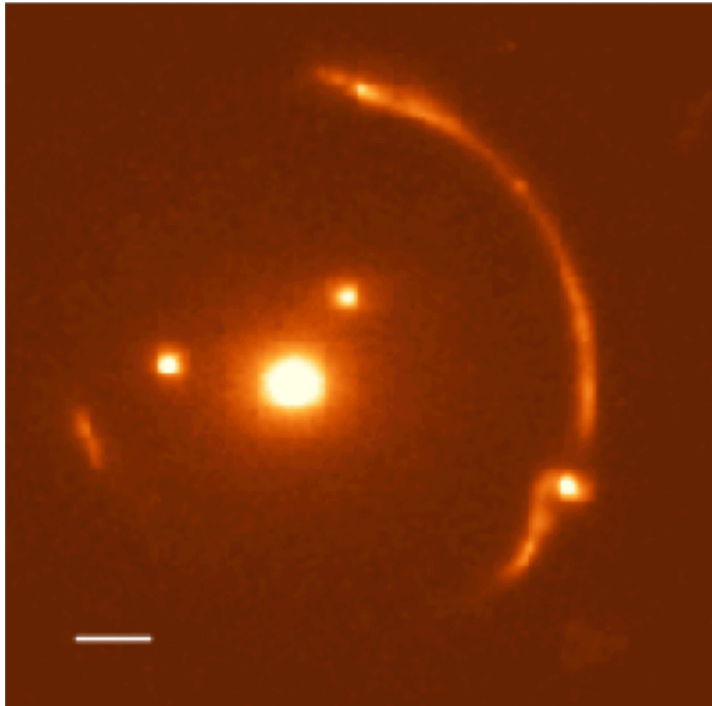
Current status



Analysed 30 gravitational lens systems observed with Hubble and Keck-AO optics

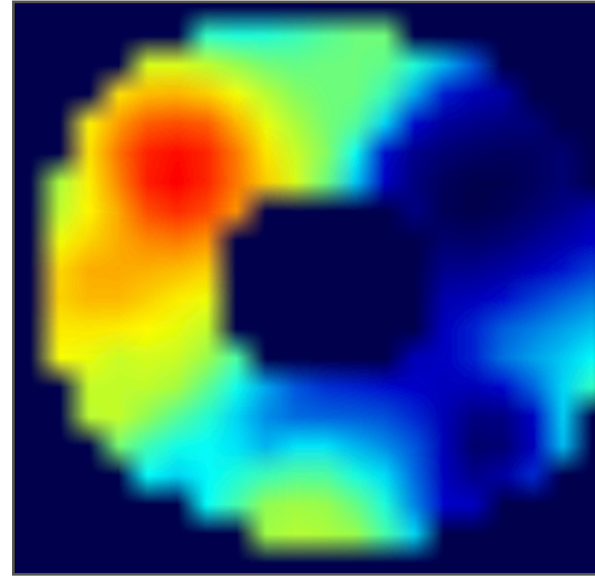
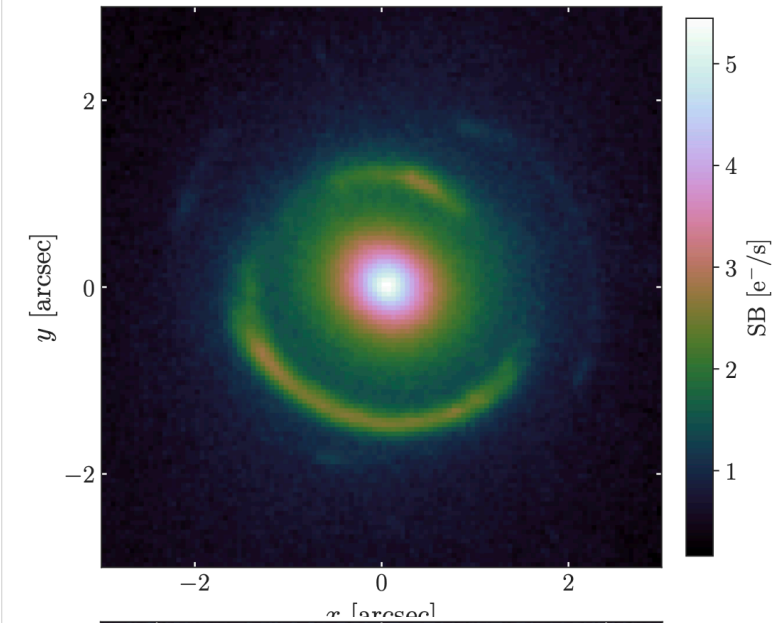
Since collected data for 30 more systems

The gravitational imaging technique



Low-mass dark matter haloes are detected as pixellated corrections to the otherwise smooth mass density distribution

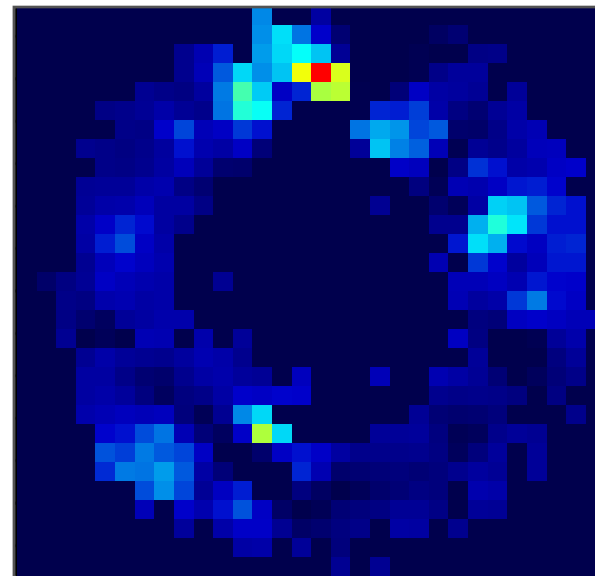
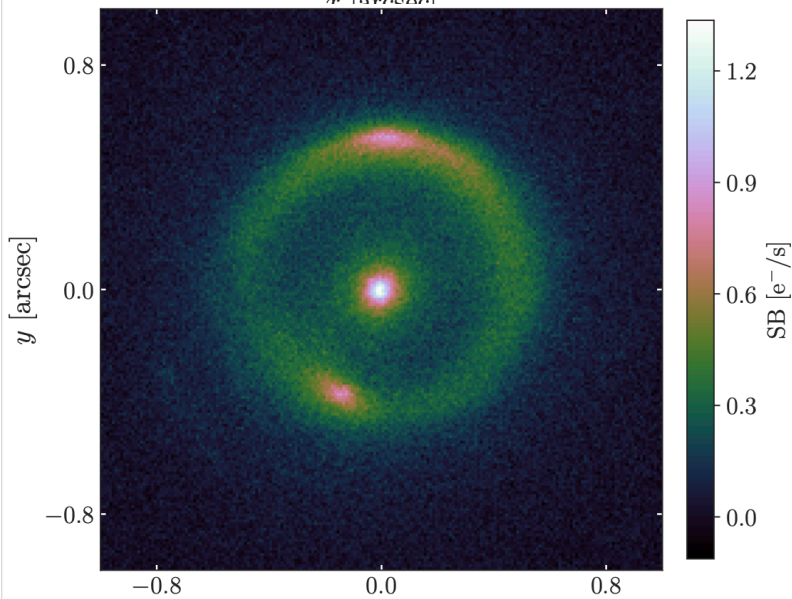
Current status



Both independently confirmed

$z = 0.2$

$$M_{PJ} = (3.51 \pm 0.15) \times 10^9 M_{\odot}$$

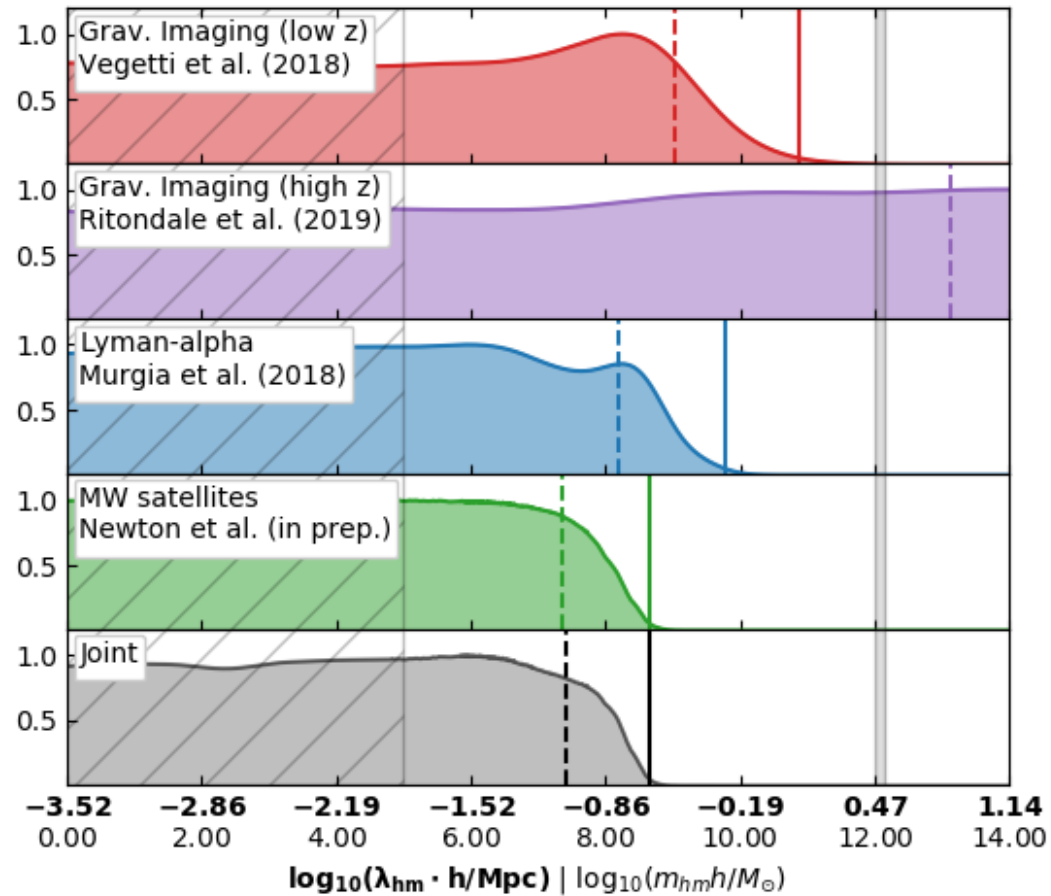


$z = 0.3$

$$M_{PJ} = (1.9 \pm 0.18) \times 10^8 M_{\odot}$$

Number density constraints

$$m_{\text{th}} > 6.733 \text{ keV}$$

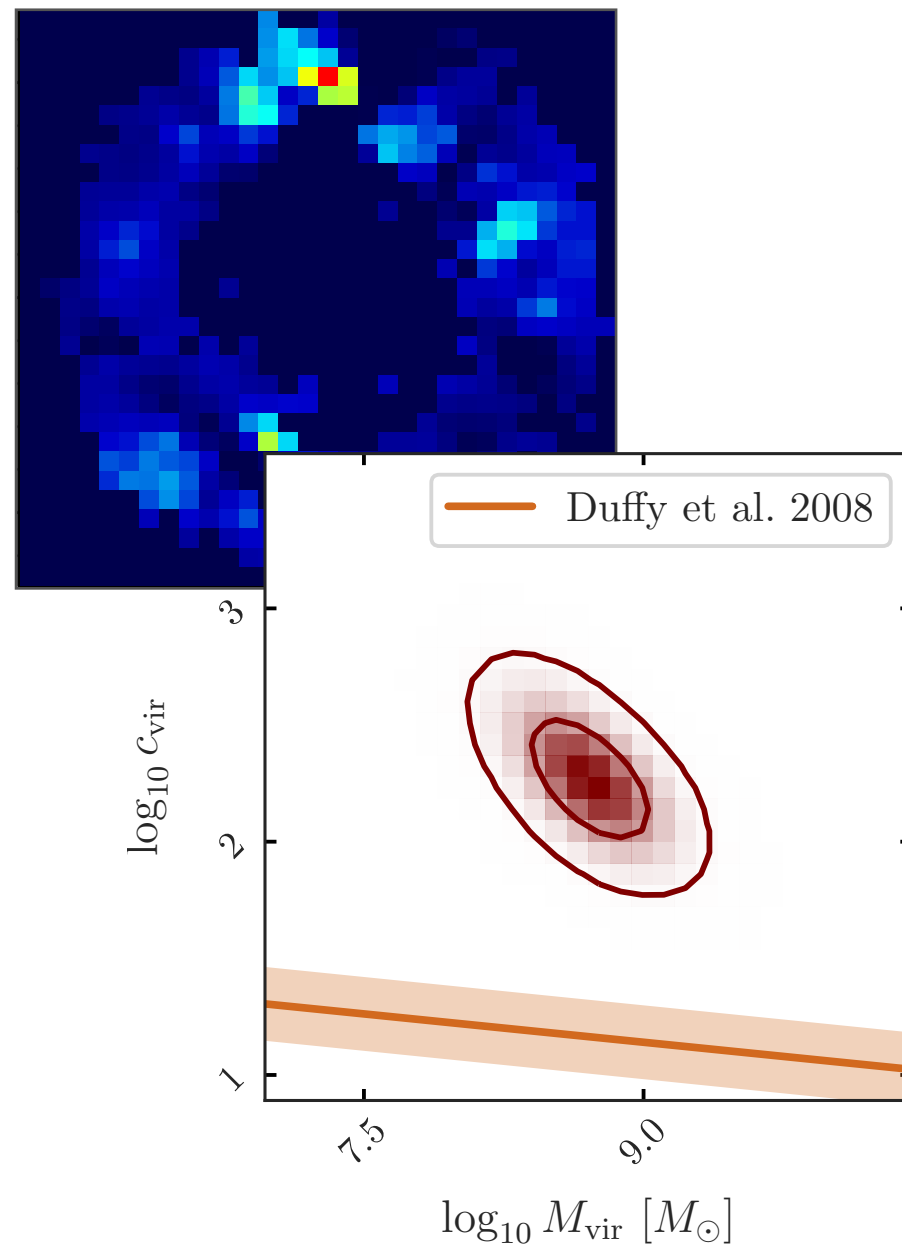
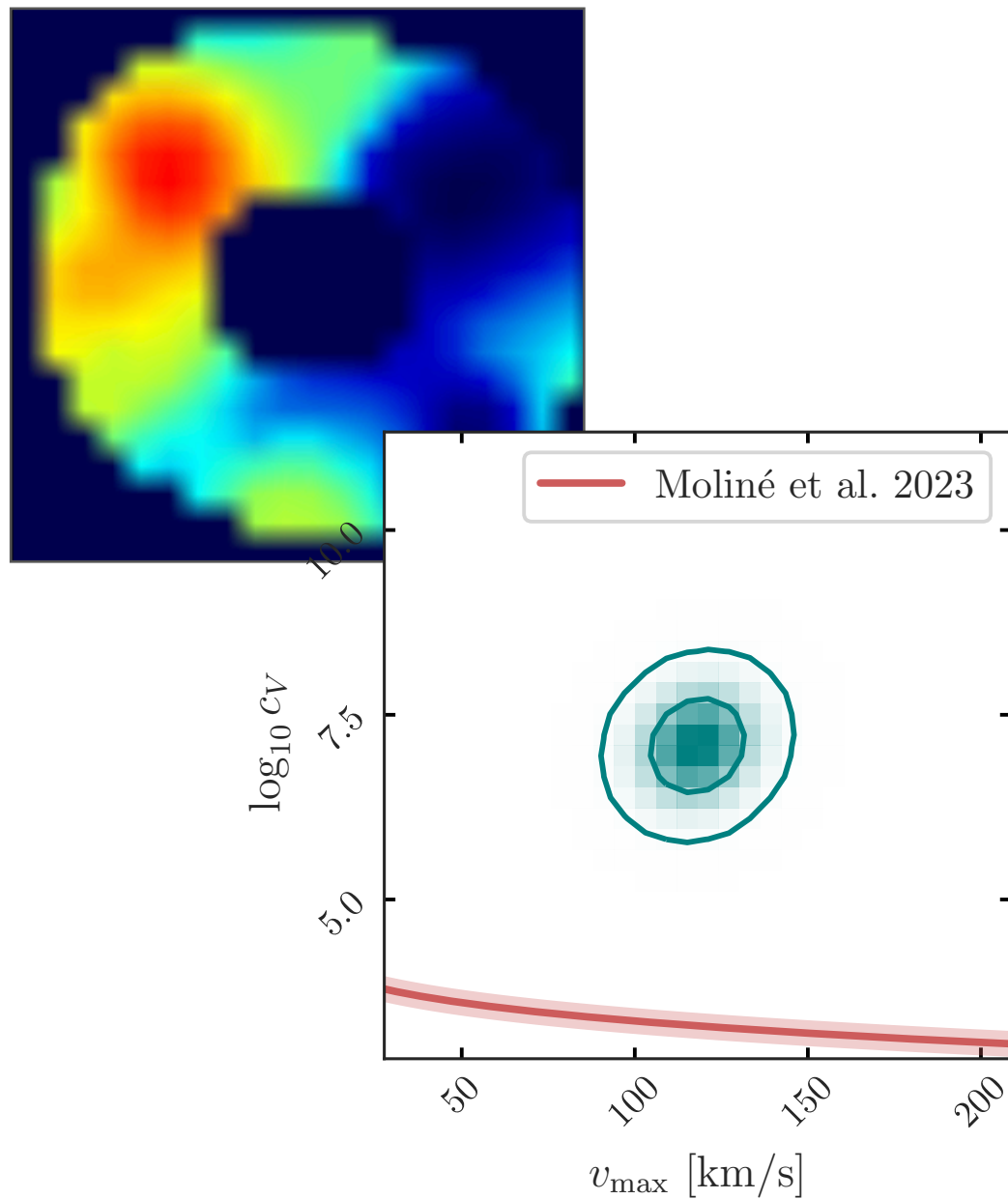


Current lensing constraints based on 30 HST-observed systems are more robust but less competitive than other probes

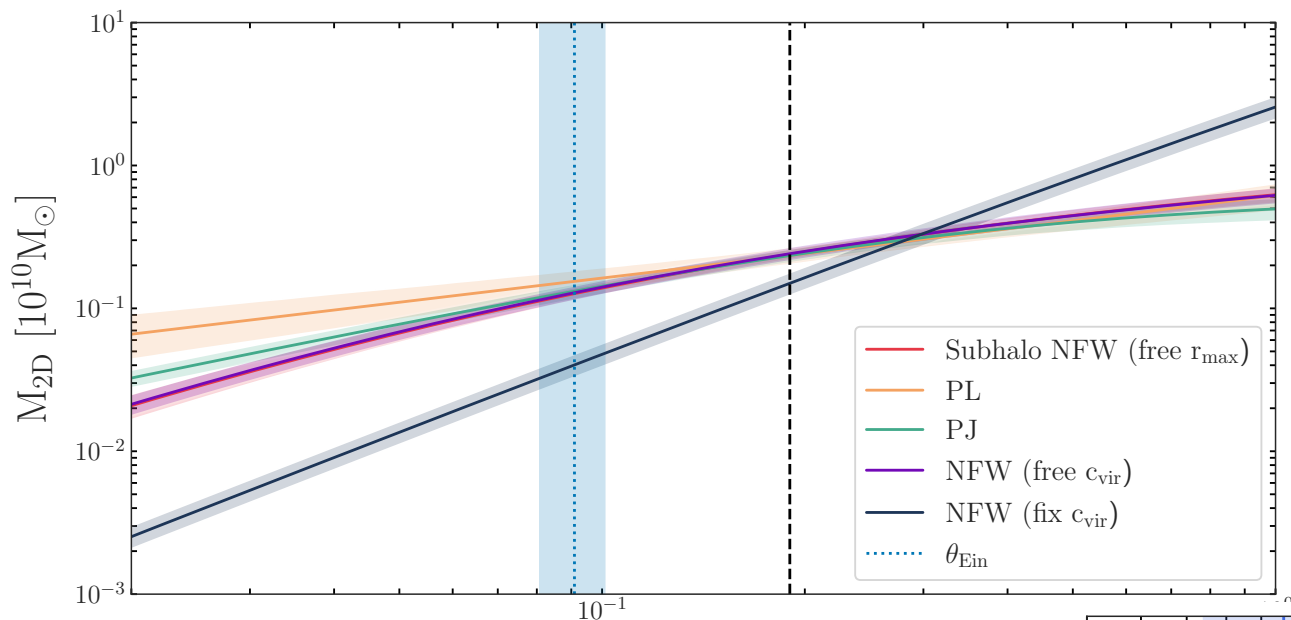
Reasons: limited sample size & limited AR

How do we move forward?

Individual detections and their unusual properties

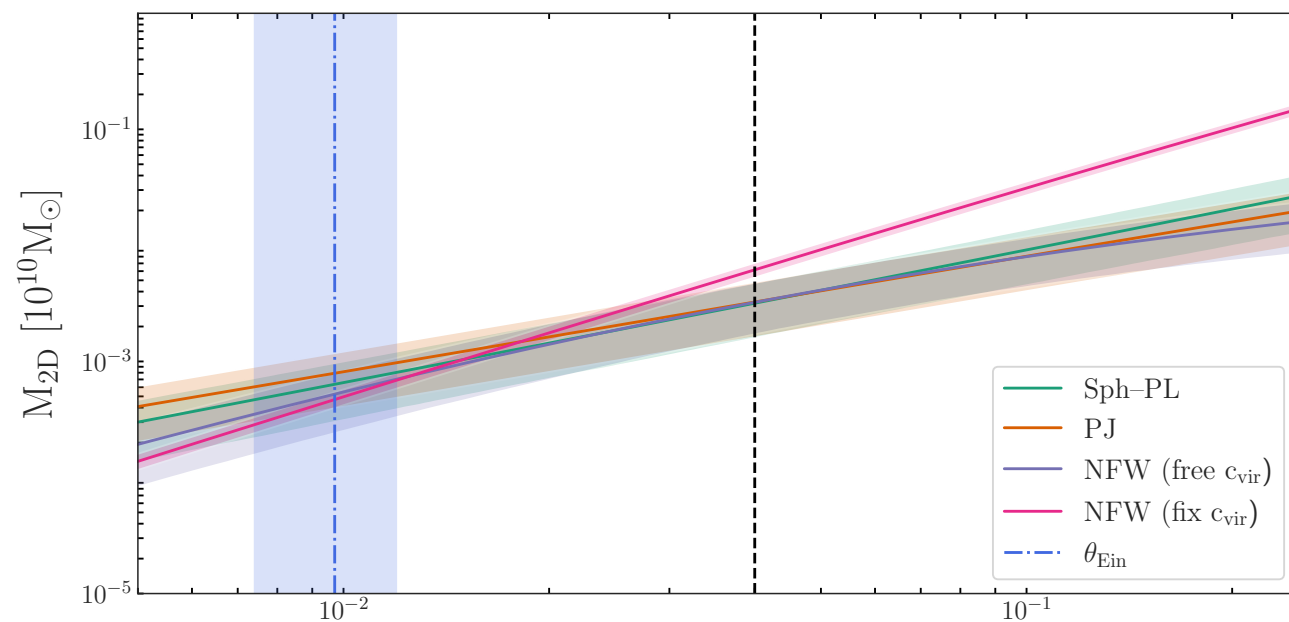


Robust quantities



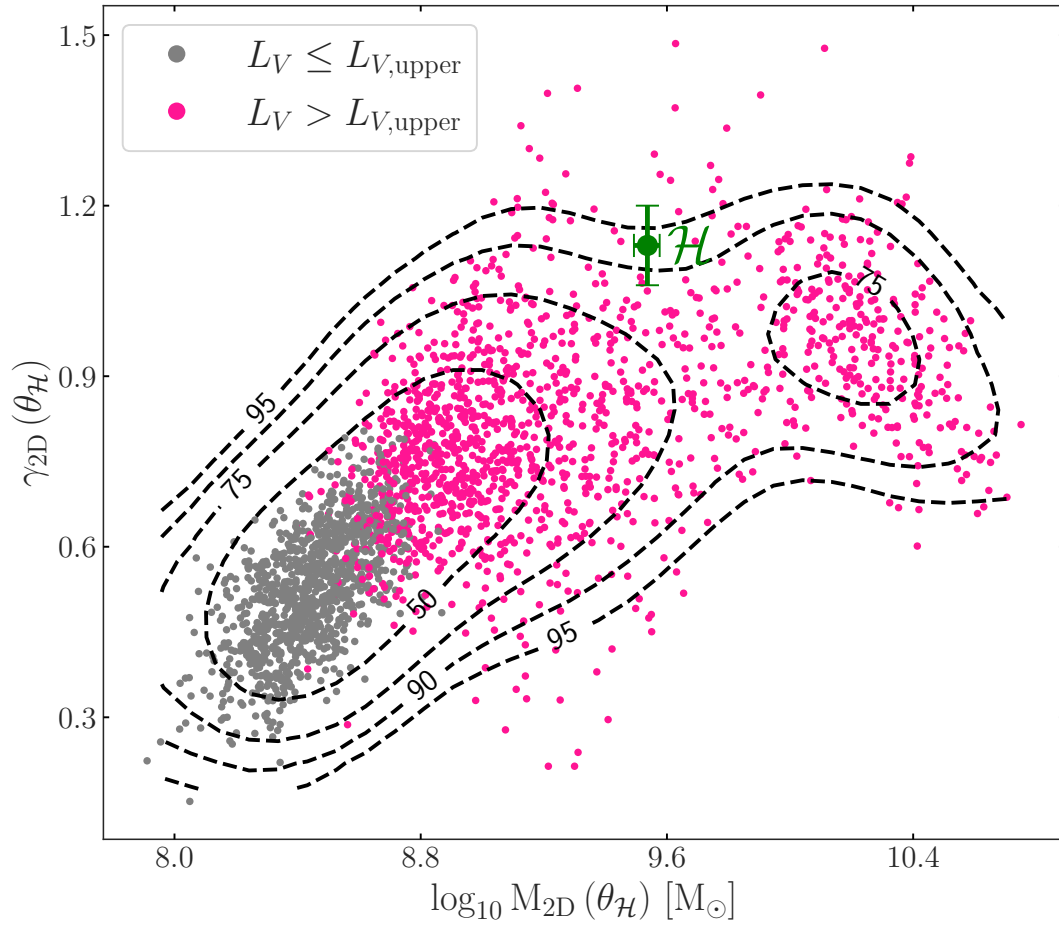
There exist a radius where the amplitude and effective slope decorrelate

Properties are measured robustly around the radius of minimum relative error on the deflection angle



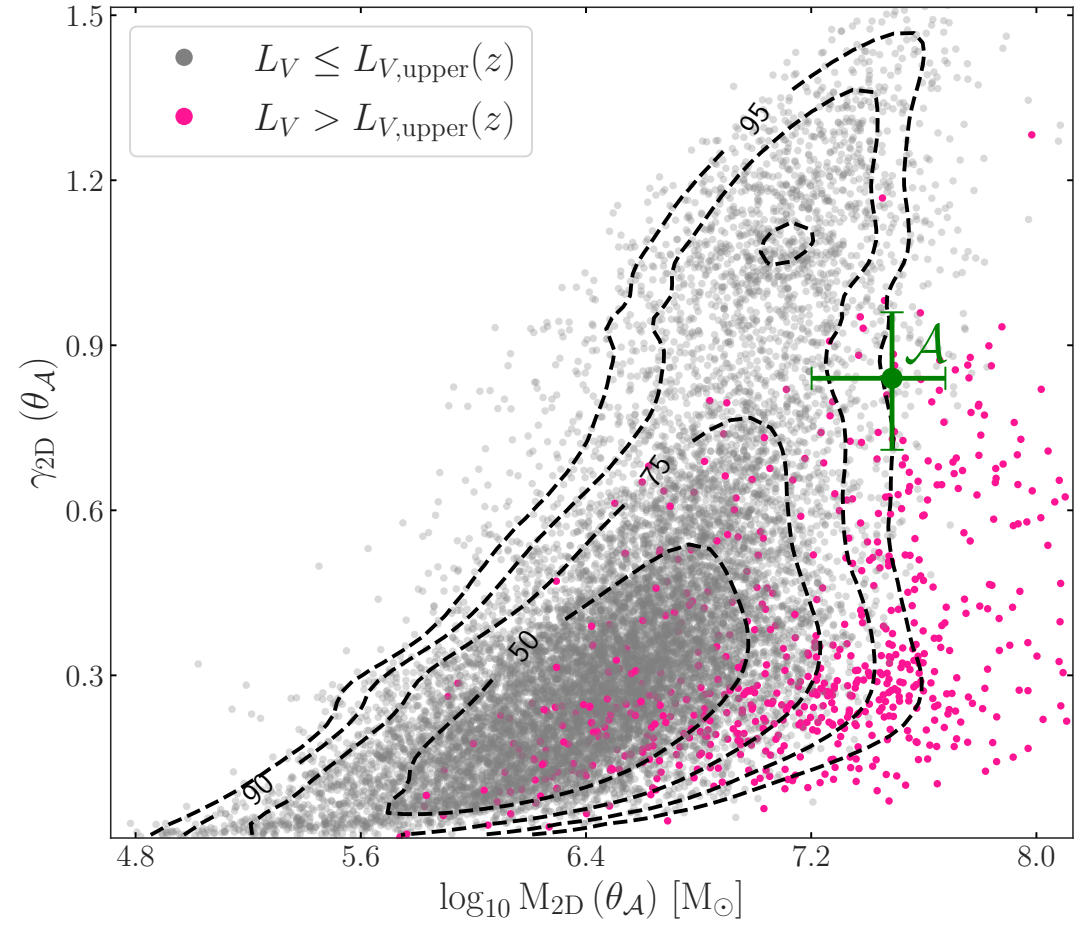
How common are these in CDM?

Tajalli et al., 2025
Despali et al., 2024



$$M_{2d}(< 0.04) = (3.07^{+1.68}_{-1.48}) \times 10^7 M_{\odot}$$

$$\gamma_{2d} = 0.84^{+0.13}_{-0.12}$$

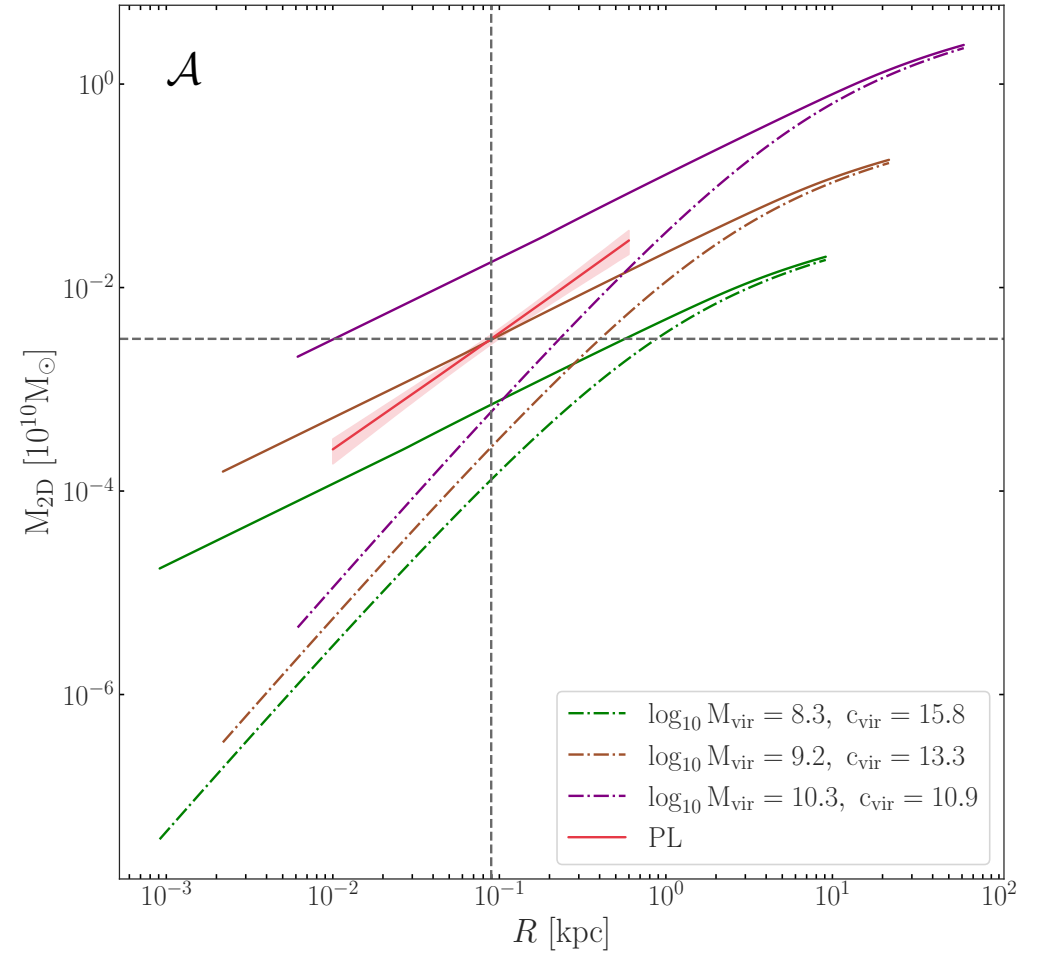
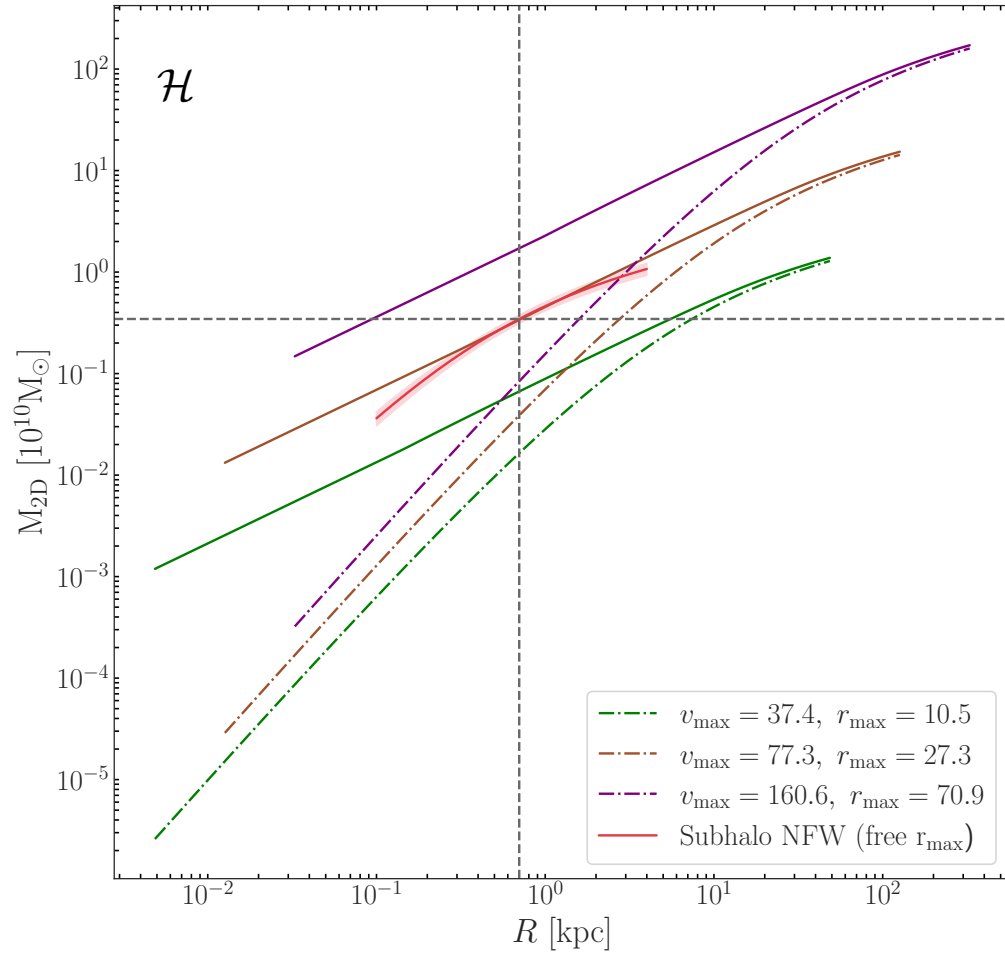


$$M_{2d}(< 0.19) = (2.38^{+0.23}_{-0.18}) \times 10^9 M_{\odot}$$

$$\gamma_{2d} = 1.24^{+0.08}_{-0.02}$$



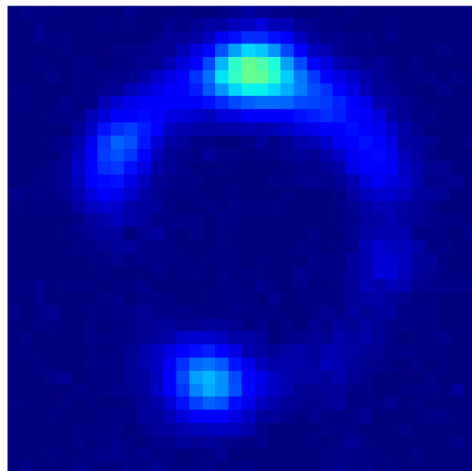
and SIDM?



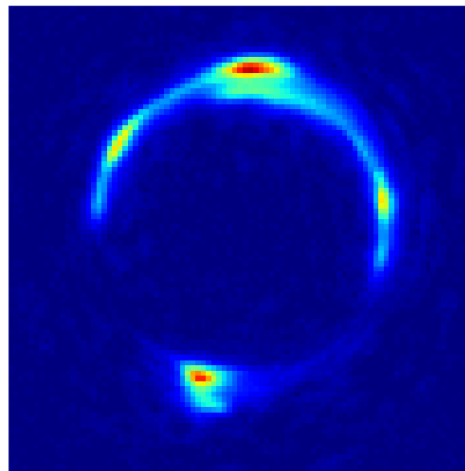
From a gravothermal fluid model: $\sigma_{c,0}/m_{\text{dm}} > 344 \text{ cm}^2 \text{g}^{-1}$

Improving upon current constraints

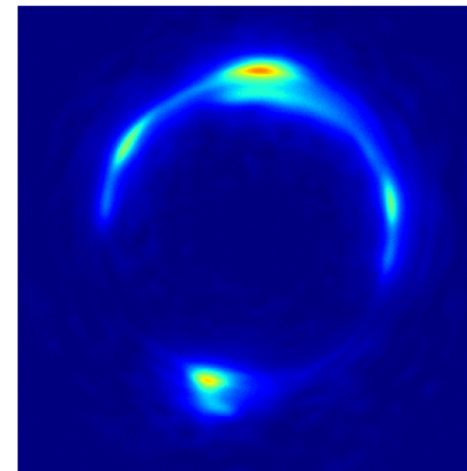
Euclid-like



HST-like



KeckAO-like



- HST images from the BELLS-GALLERY sample (*Ritondale et al. 2019*)
- Keck-AO images from the SHARP sample (*Vegetti et al. 2012*)
- ALMA data from *Stacey et al. 2021* (sub.)
- $z_l > 0.5, z_s > 2$

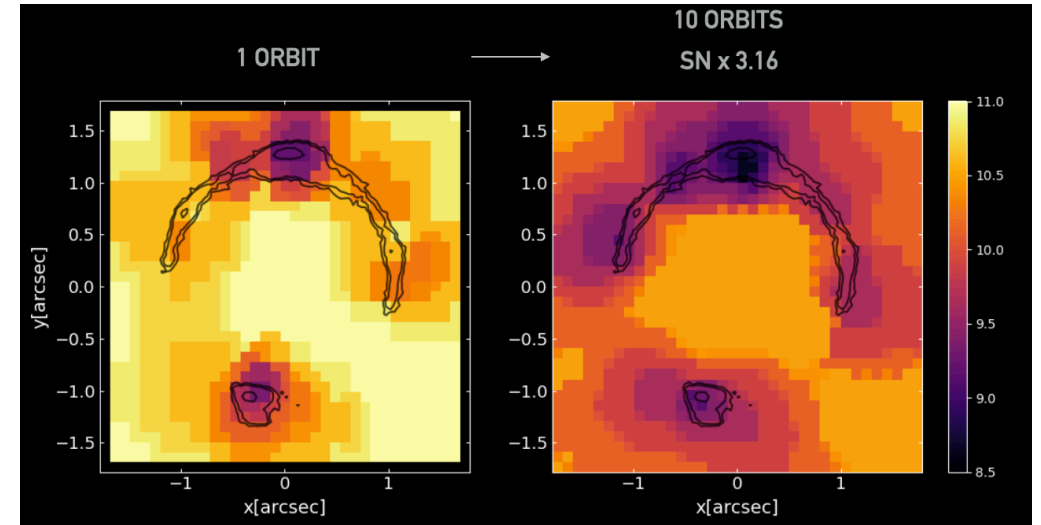
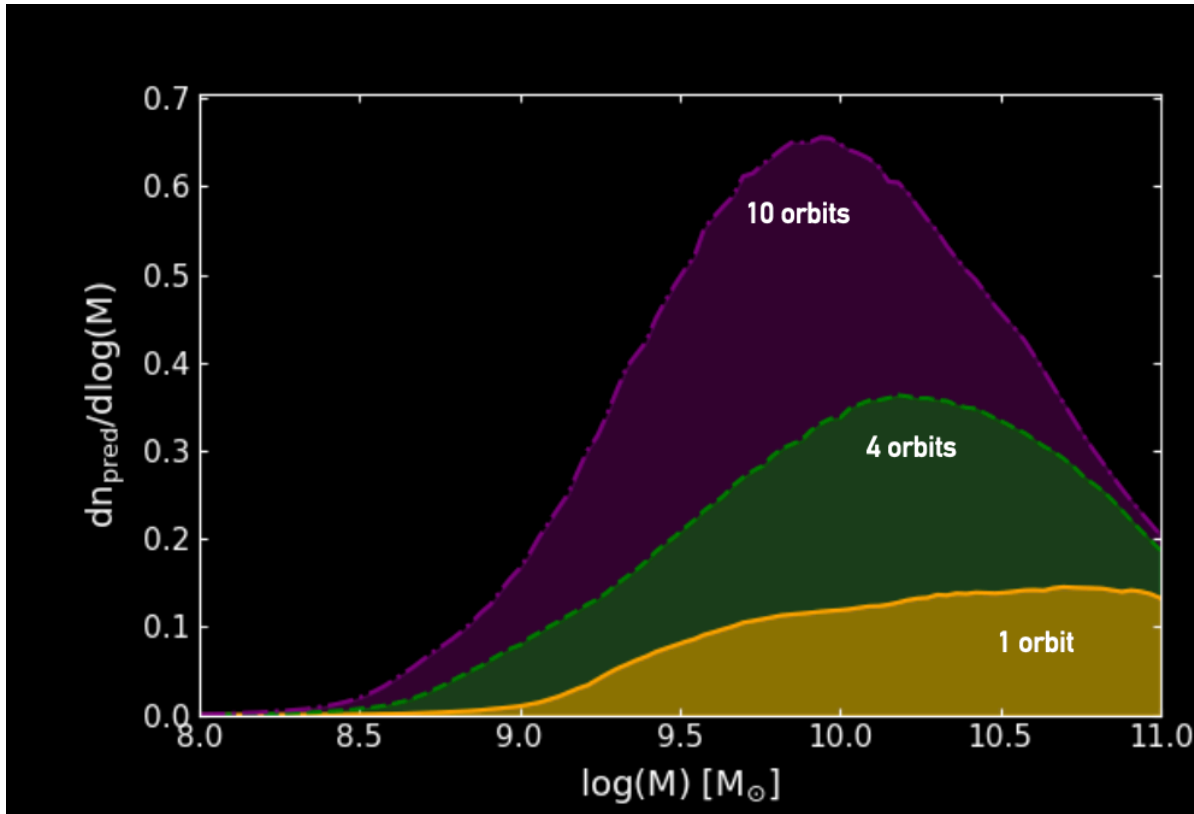
QUESTION 2:

what is the best observational strategy
to achieve this goal?

QUESTION 1:

how many lenses do we need to test CDM?

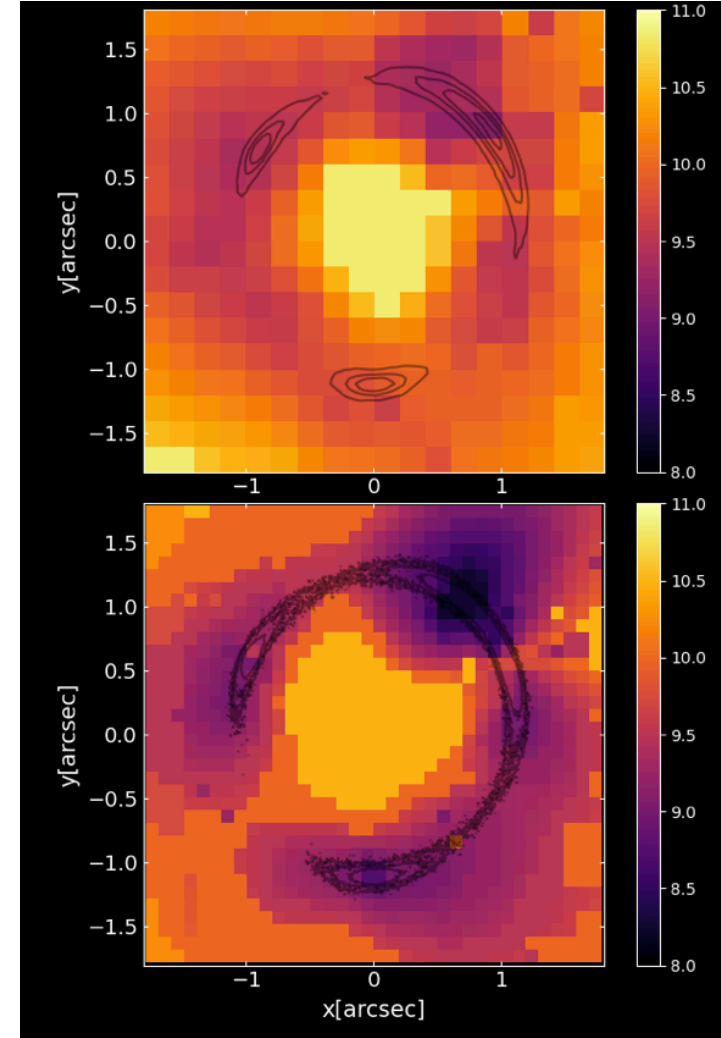
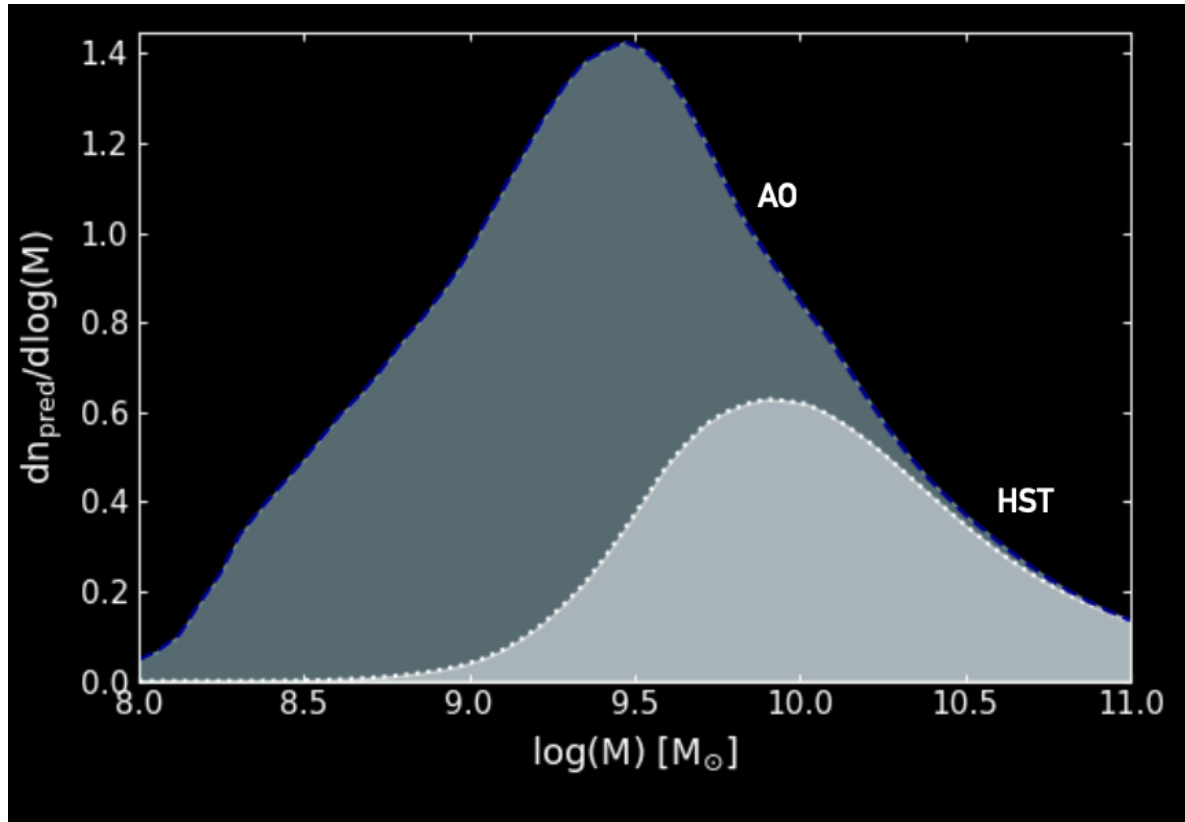
Increasing signal-to-noise ratio



Higher SNR means a larger area in the sky at fixed sensitivity

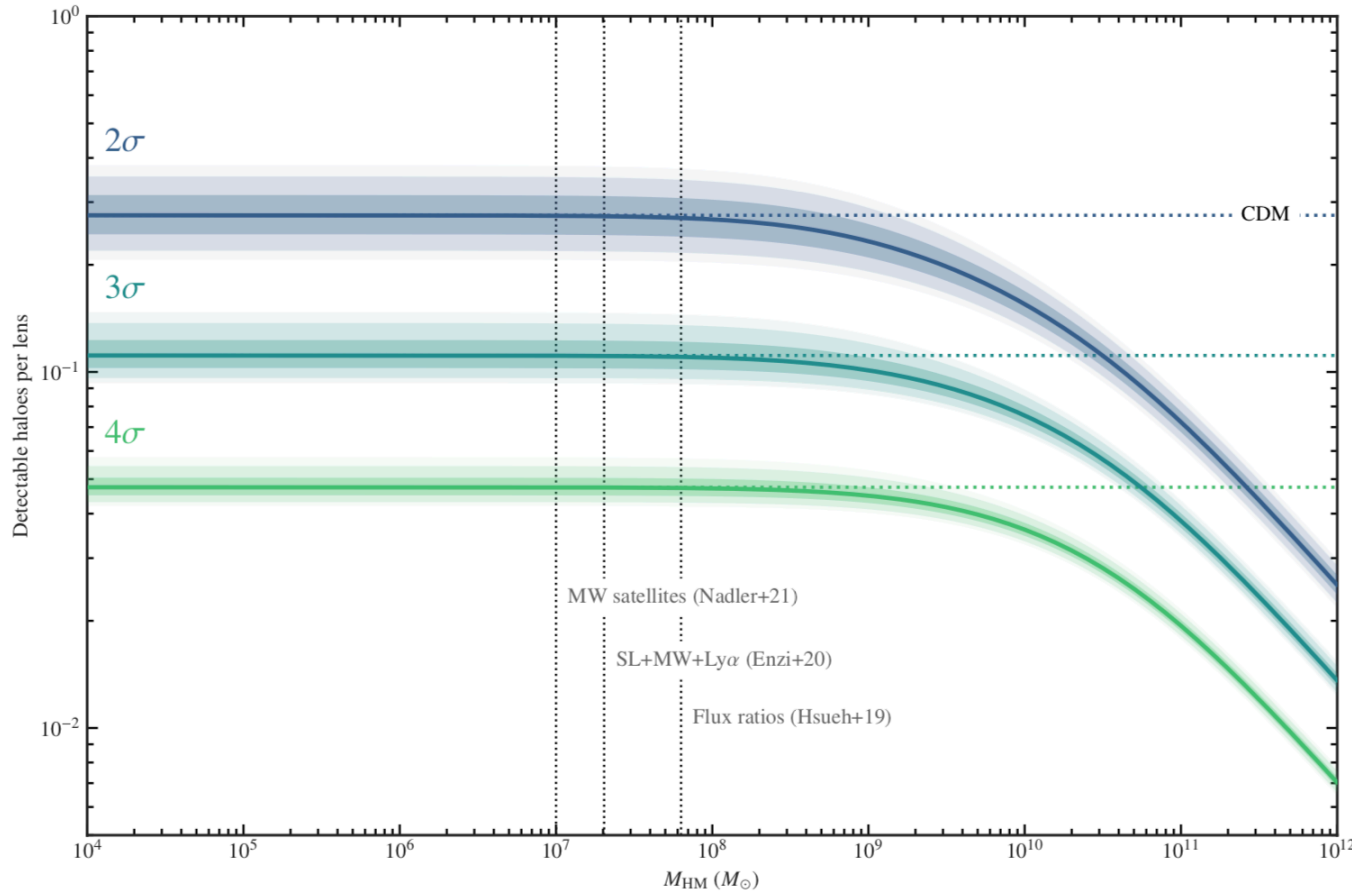
Increasing angular resolution

Higher resolution means better sensitivity within fixed area



The role of Euclid

Most sensitive pixel at $10^{8.8}$ Msun Most lenses are not sensitive at all



In CDM we expect to detect:

$(1.43 \pm 0.1)/f_{\text{sub}}$ detections per lens

$f_{\text{sub}} = 0.01 \rightarrow$ **one every ~70 lenses**

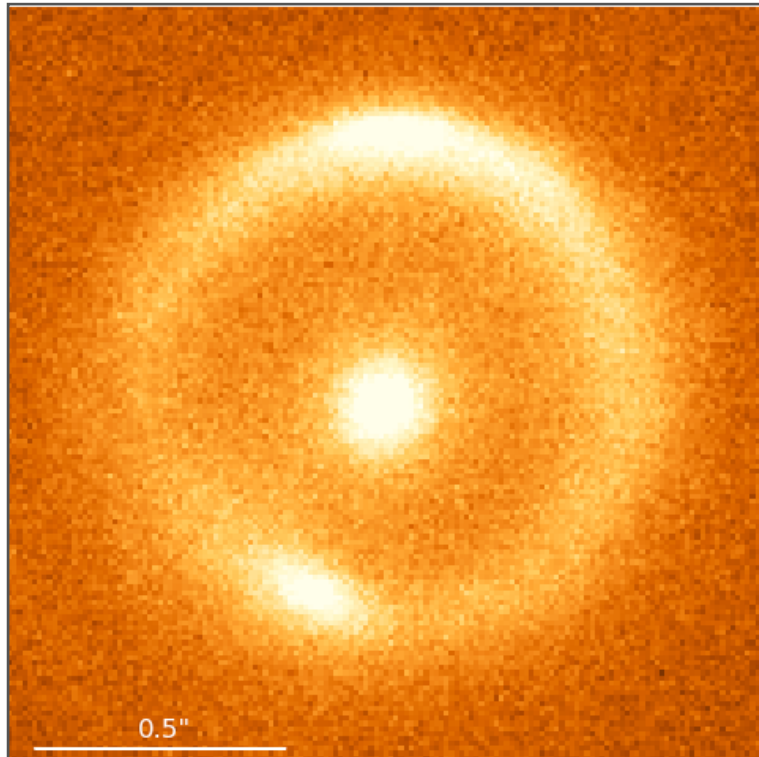
This is consistent with CDM for any WDM model that has not already been ruled out

Euclid will allow us to measure f_{sub} but not rule out alternative models

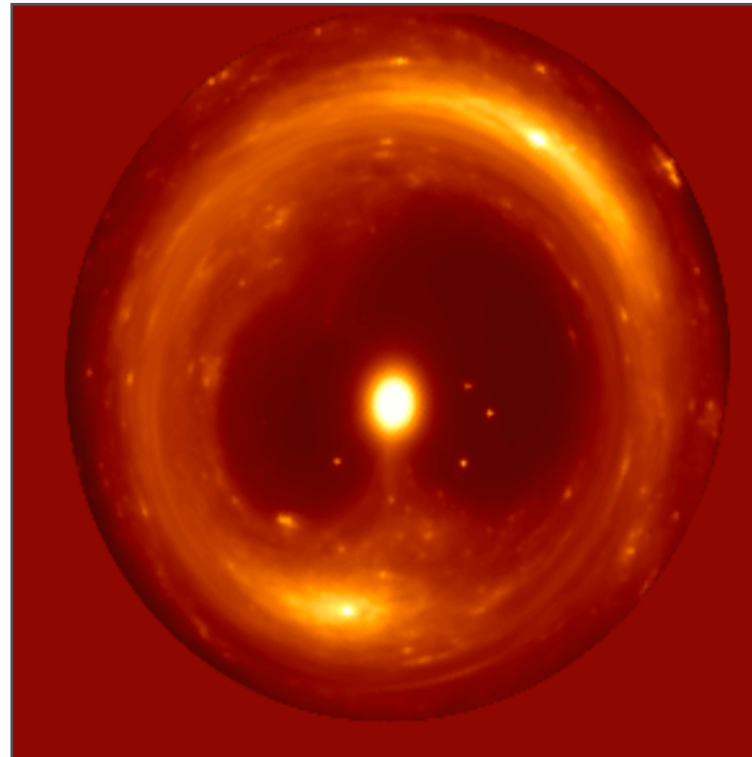
$$\frac{dn}{dm} \propto f_{\text{sub}} m^{-\alpha} \left(1 + \alpha_2 \frac{M_{\text{hm}}}{m} \right)^{\gamma}$$

The need for high-resolution

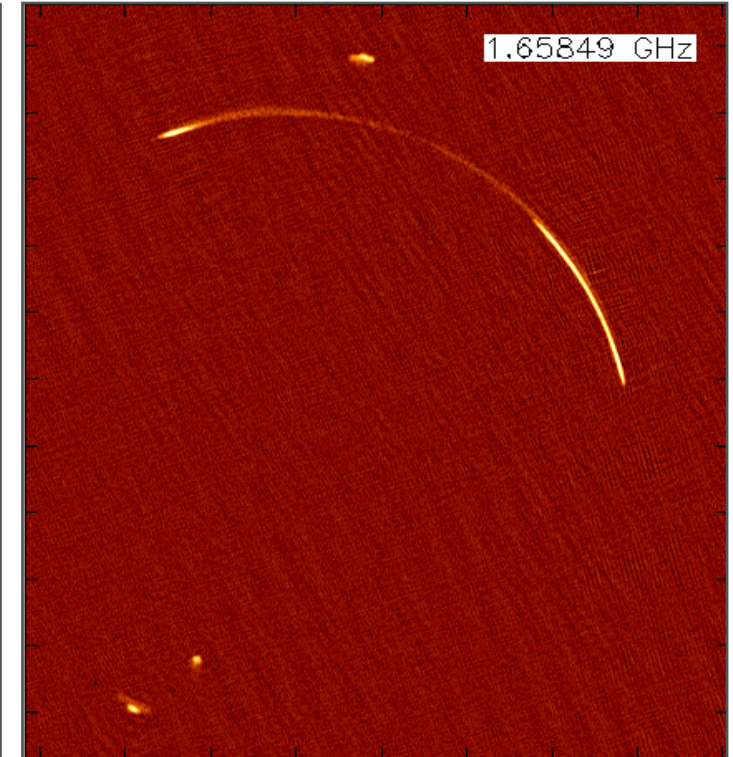
$10^8 - 10^9 M_{\text{sun}}$



$10^6 - 10^7 M_{\text{sun}}$



$10^6 - 10^7 M_{\text{sun}}$



Keck - AO 100 milli-arcseconds

ELT - 4 milli-arcseconds

GVLBI - 3 milli-arcseconds

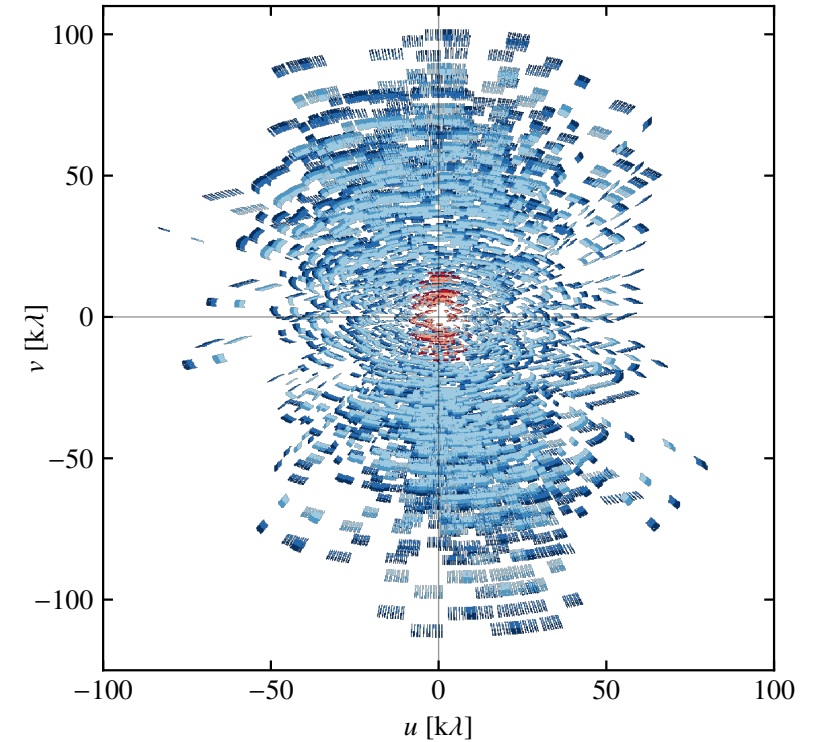
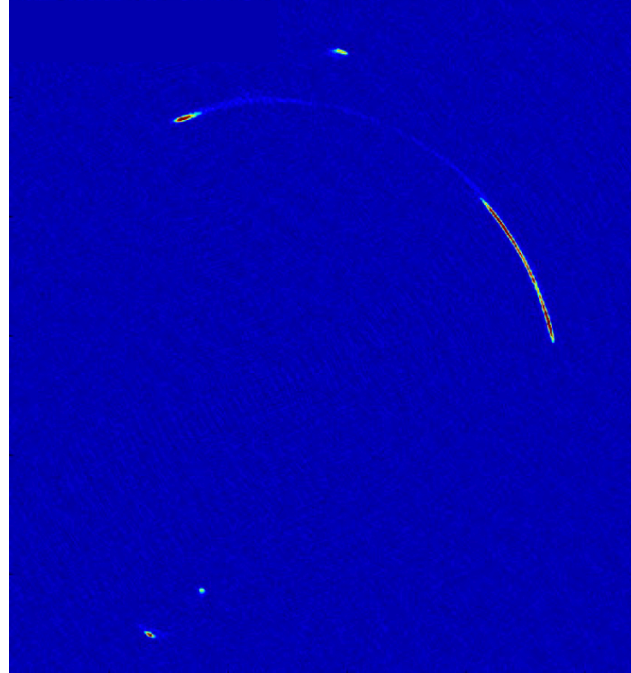
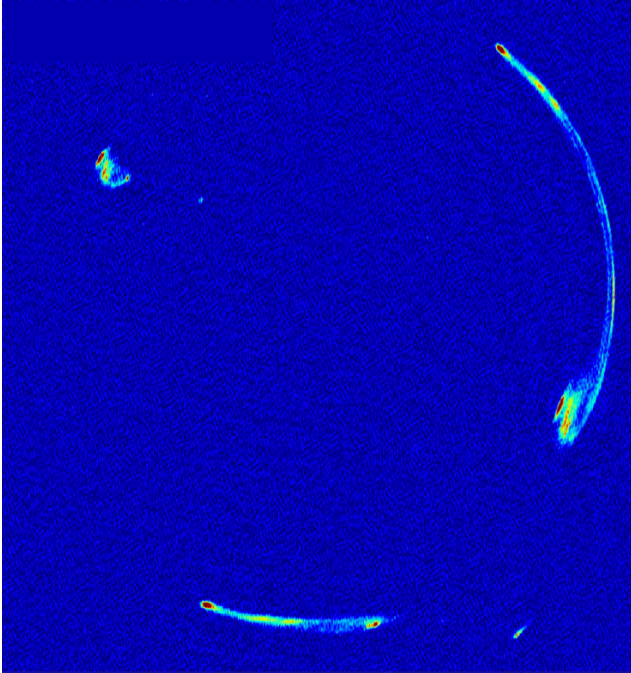
Very long baseline interferometry



Probing low-mass haloes with VLBI

Powell, Vegetti et al. 2021

Powell, Vegetti et al. 2022



Need dedicated lens modelling code to model the large number of visibility points

Extension of the V&K09 method: optical, radio, polarimetry, 2D and 3D with pixellated sources

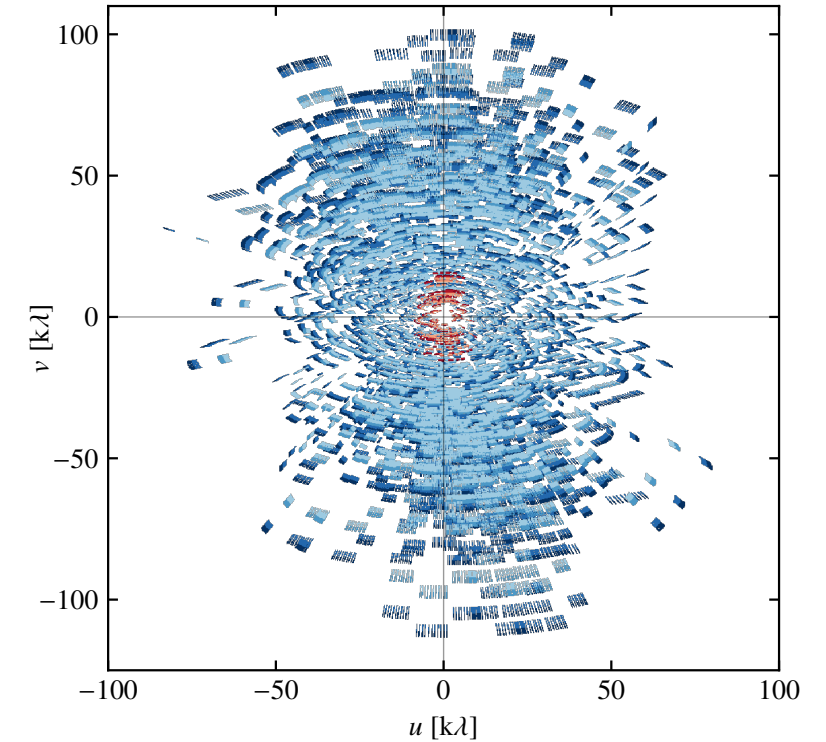
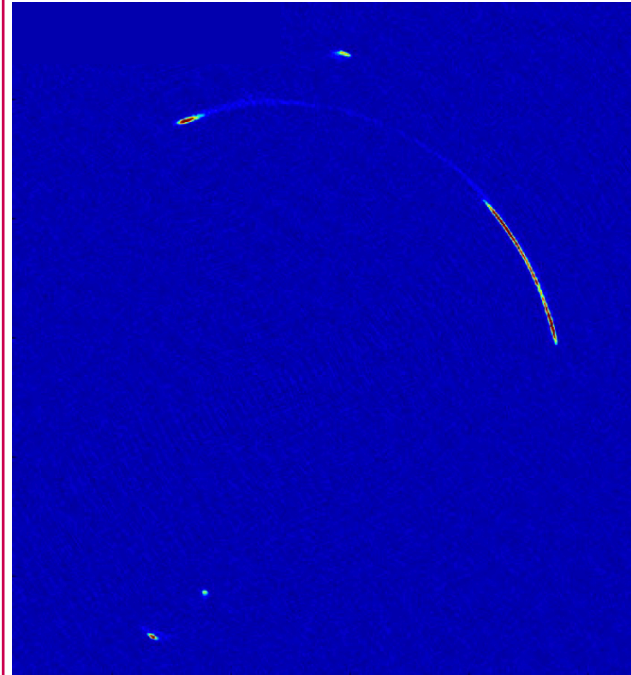
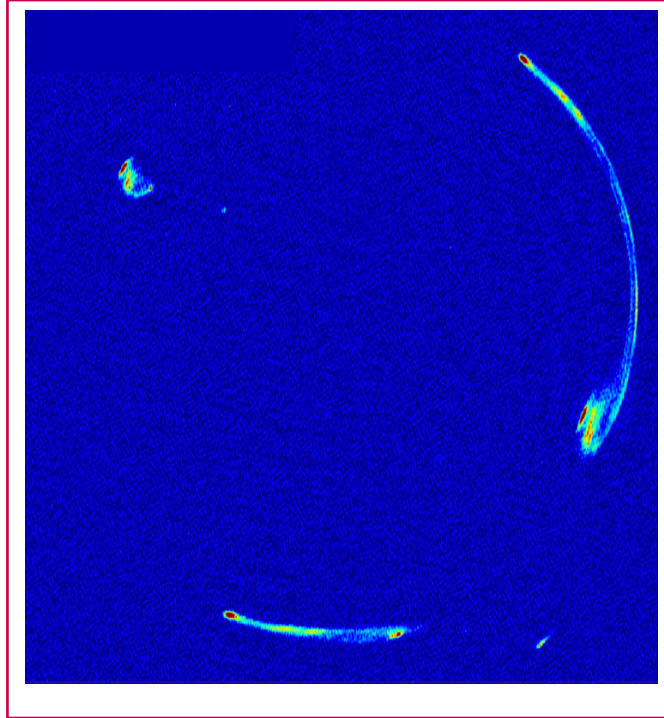
Kinematic hyper-prior for modelling of emission lines

Faraday screen for modelling of B field

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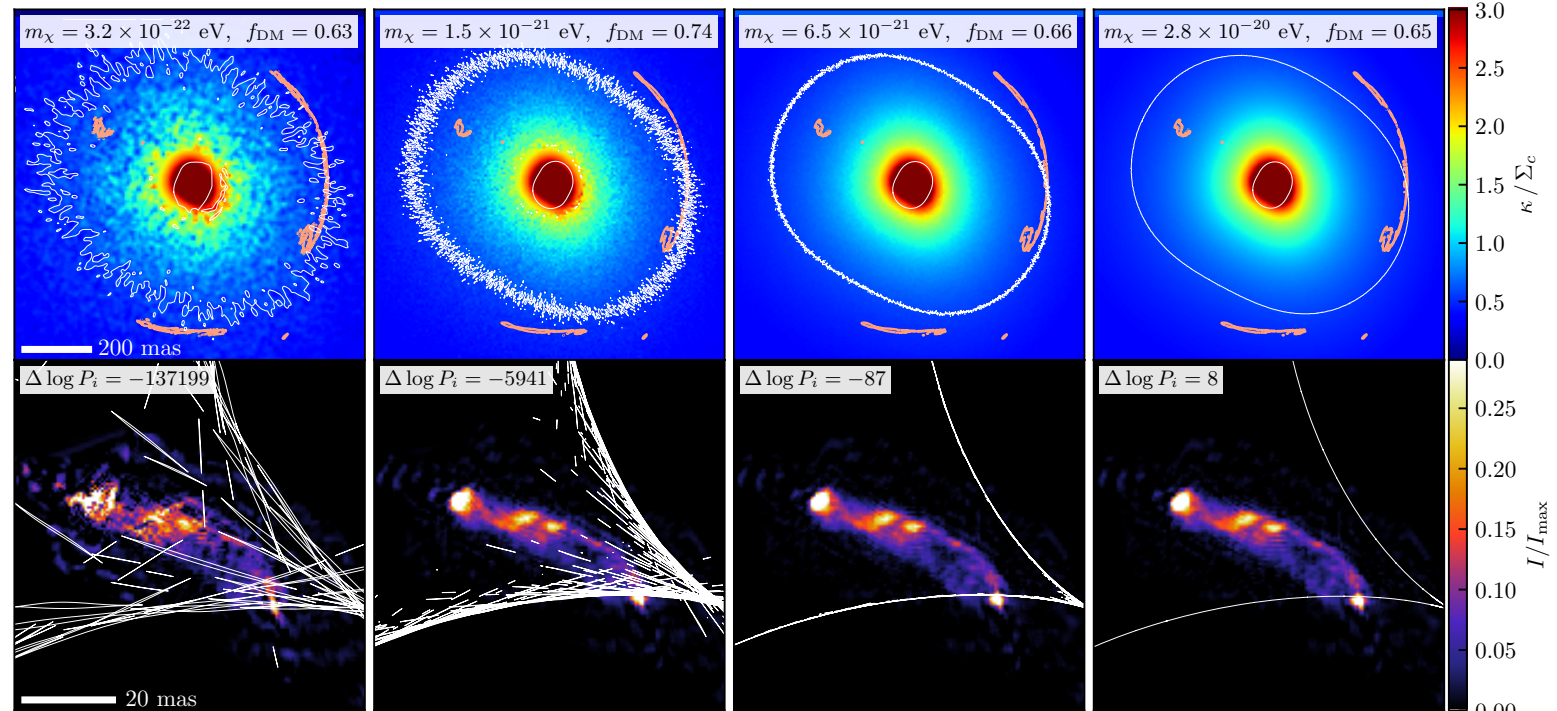
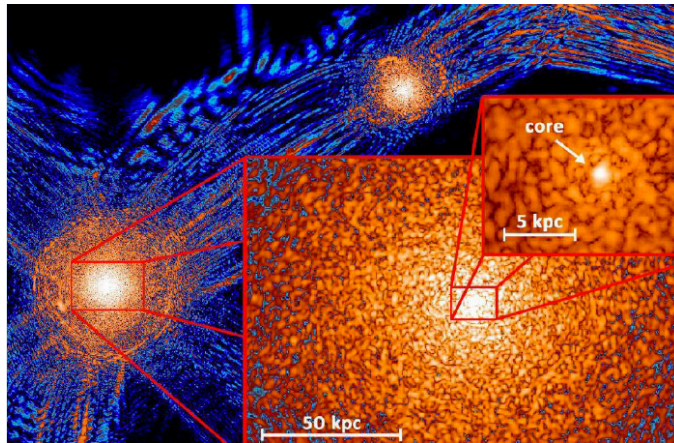
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Fuzzy Dark Matter

Quantum interference leads to the formation of granules in the mass density distribution
This affects the number of lensed images in a measurable way

Powell, Vegetti et al. 2023

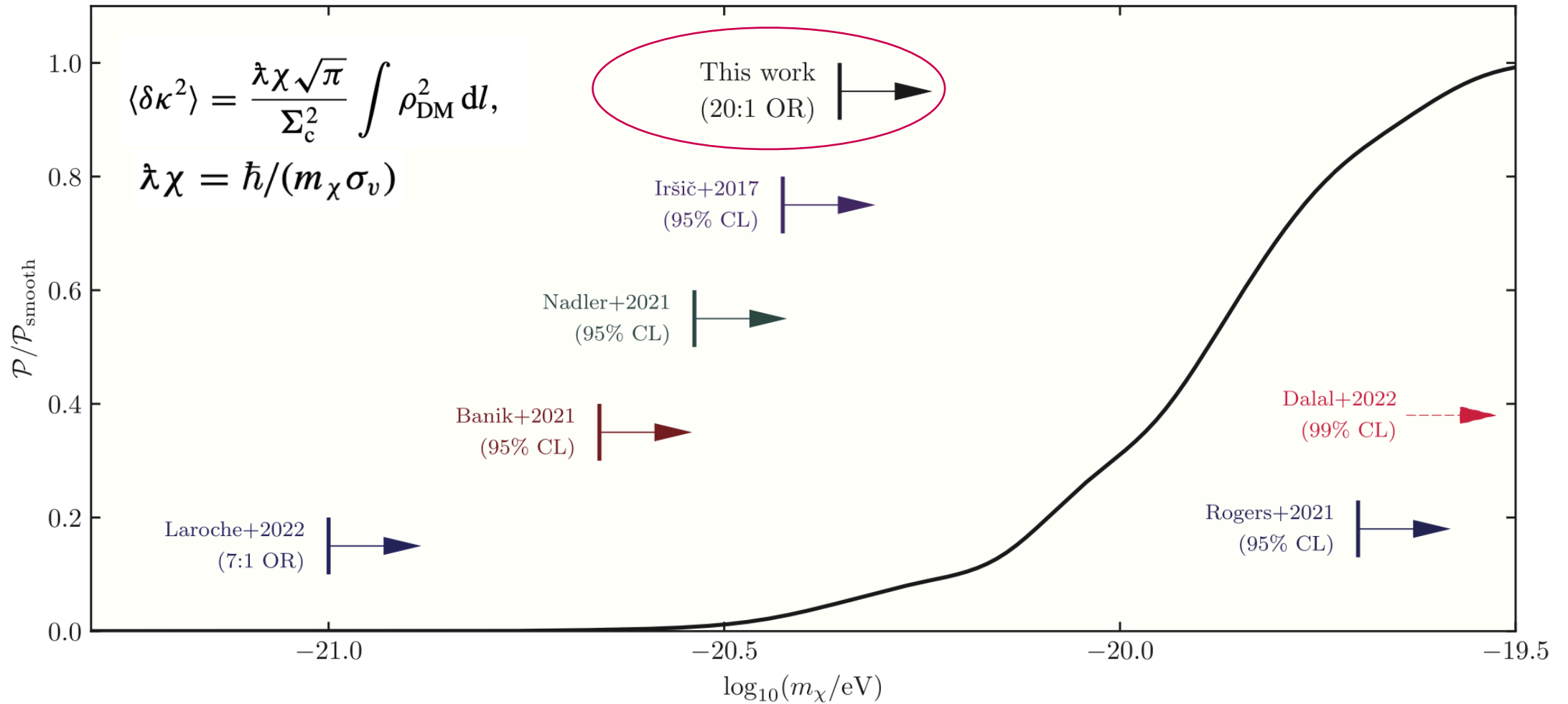


When the particle mass m_χ is low, the fuzzy DM density granules make the proposed lens model too lumpy

The inferred source model takes on a disrupted morphology in an attempt to fit the data



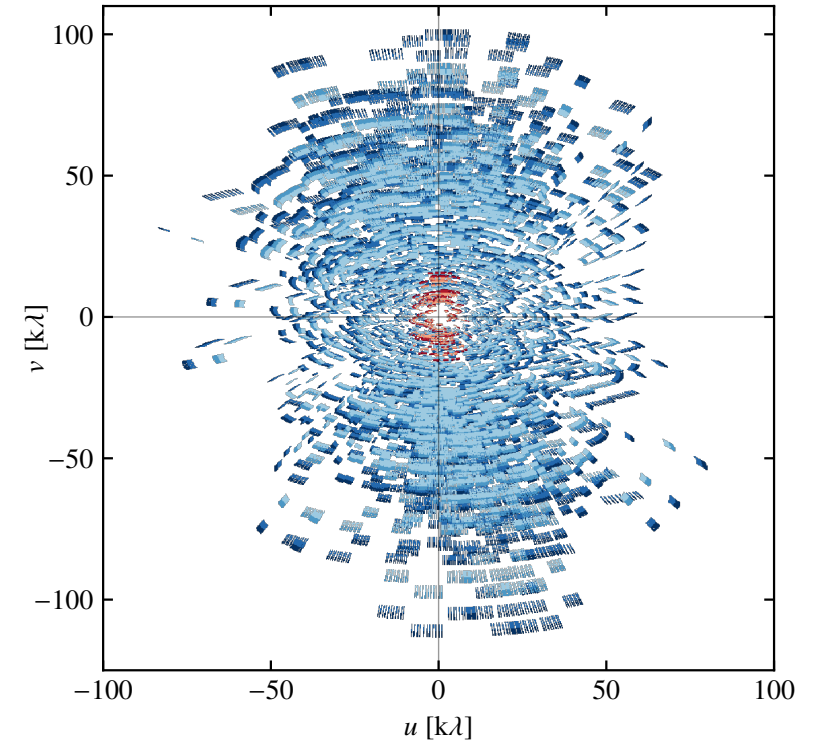
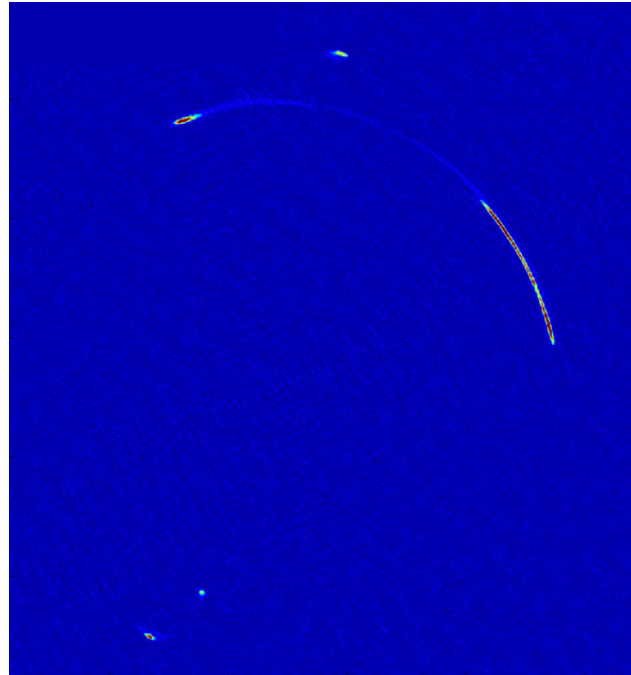
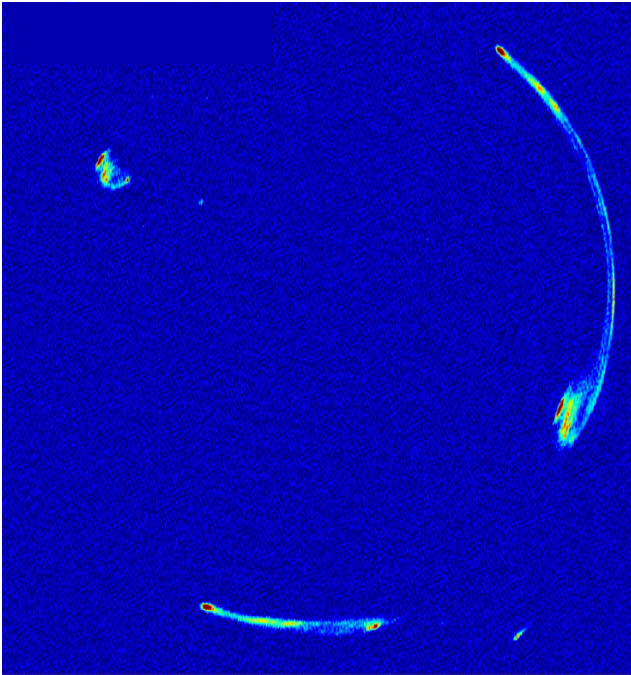
Fuzzy Dark Matter



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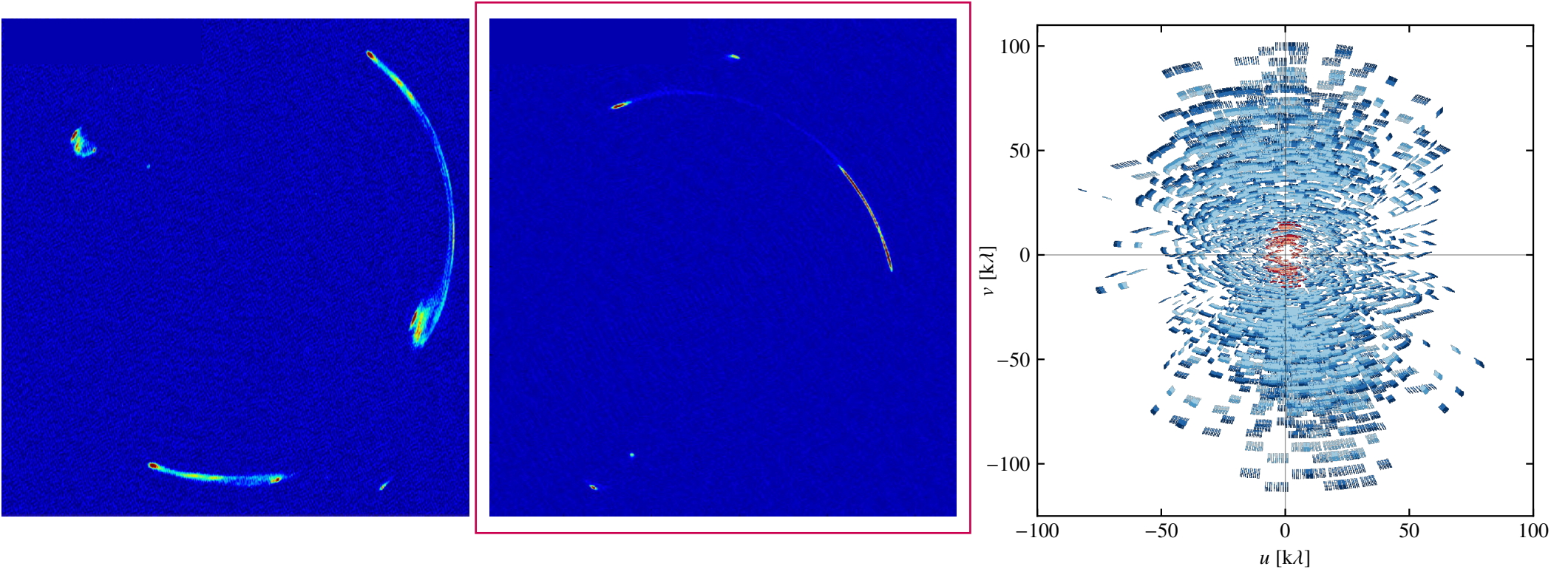
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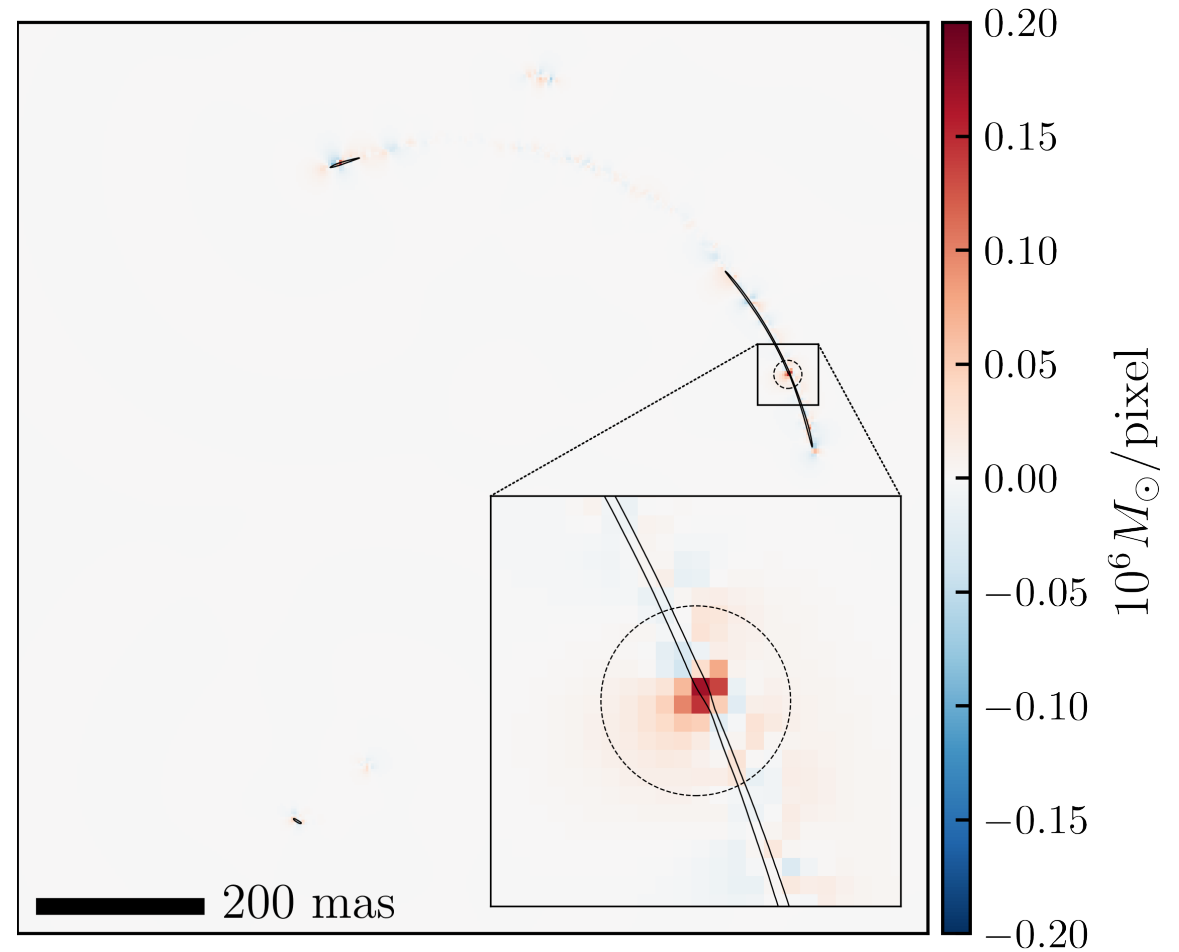
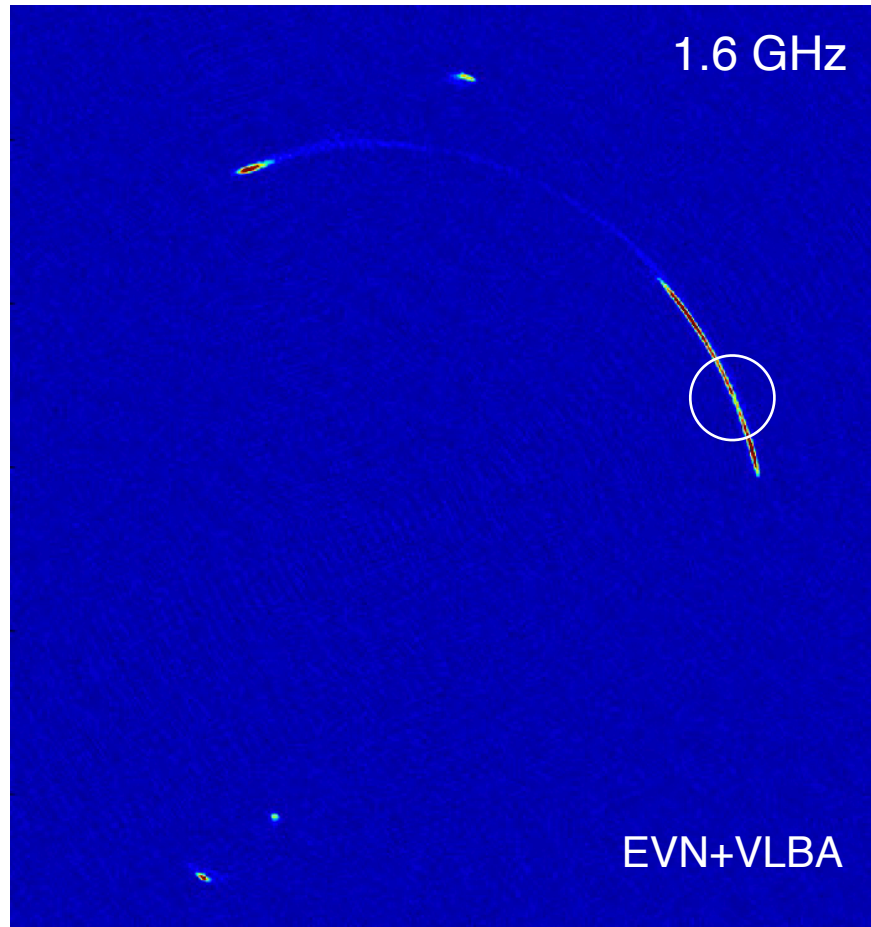
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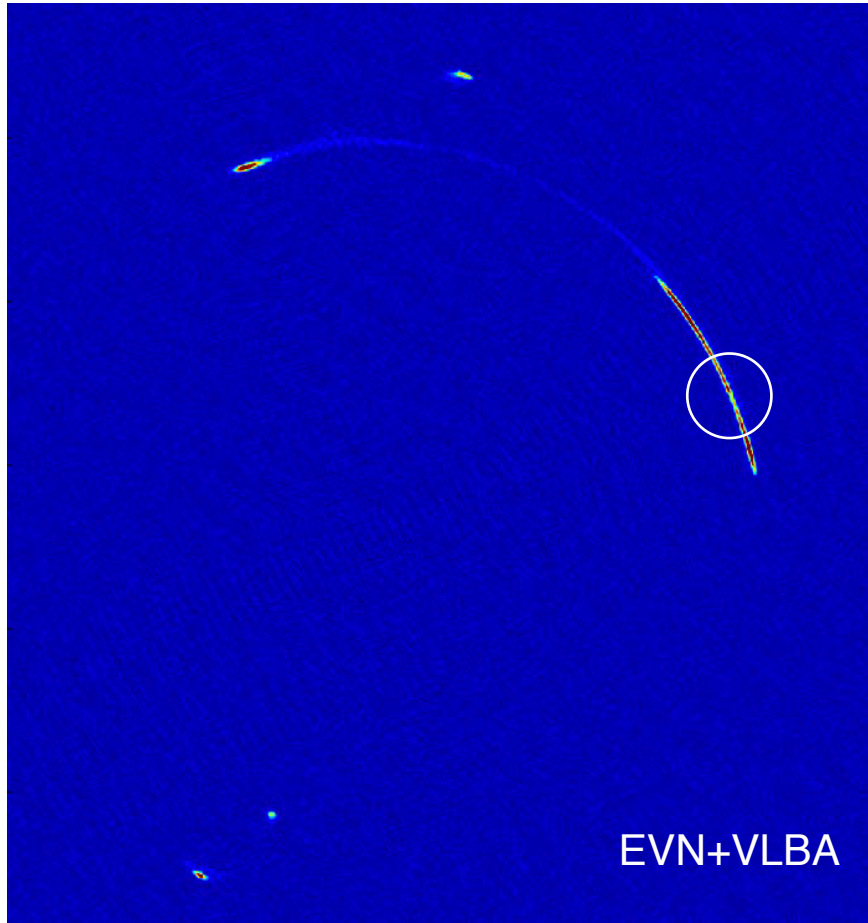
Faraday screen for modelling of B field

Smallest detection so far



The break in the arc is consistent with a very low-mass perturber $M_t \sim 2 \times 10^6 M_{\odot}$

Robust and precise detection



Tested 23 different models: PL, SER, PJ, NFW, KG and PM

The detection is robust against different assumptions on its profile:

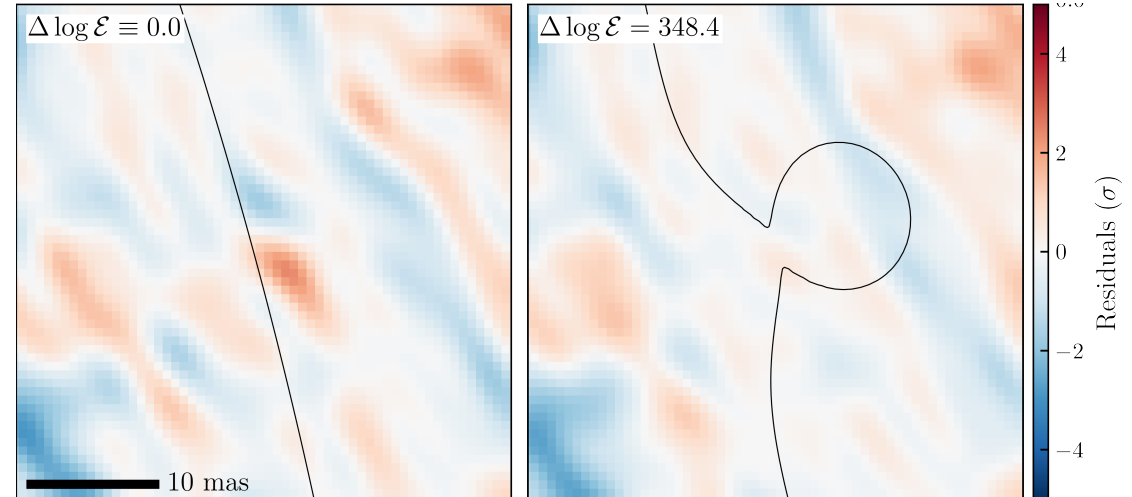
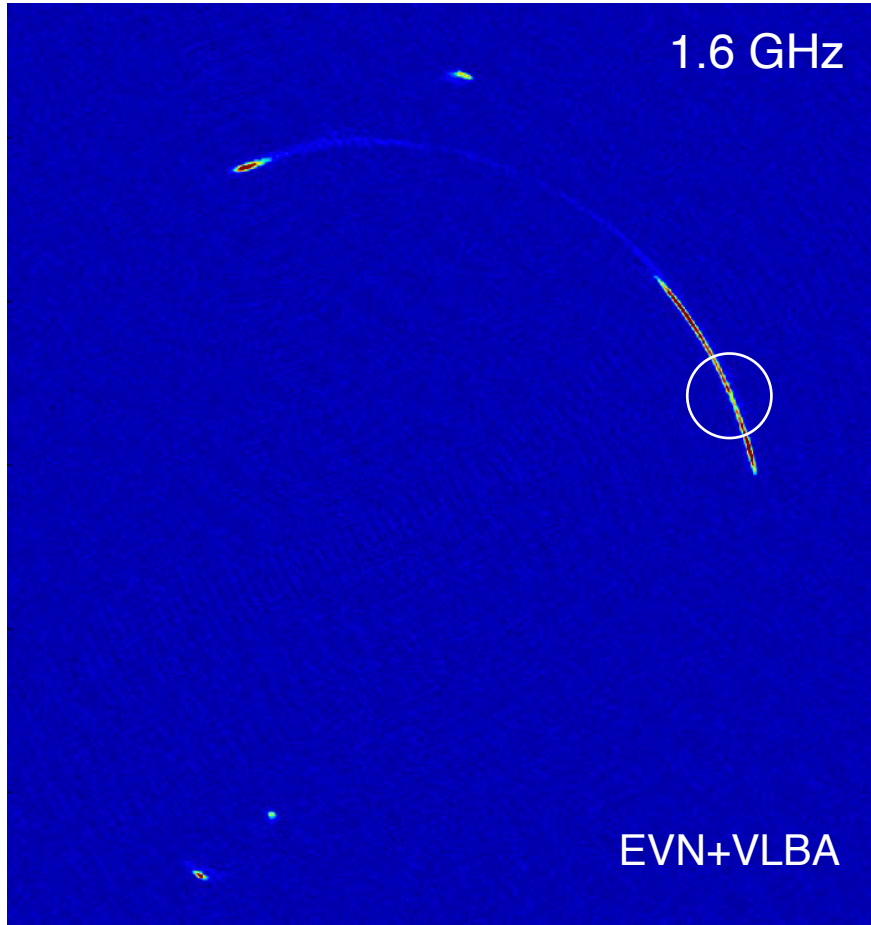
$$259 \leq \Delta \log \mathcal{E}_s \leq 351$$
$$23 - 26\sigma$$

Average error on x and y: 0.1 and 0.2 mas

With a standard deviation of 1.3 and 1.6 mas for different models

The mass density normalisation of the power-law models with a relative error between 2 and 10 per cent

Smallest detection so far



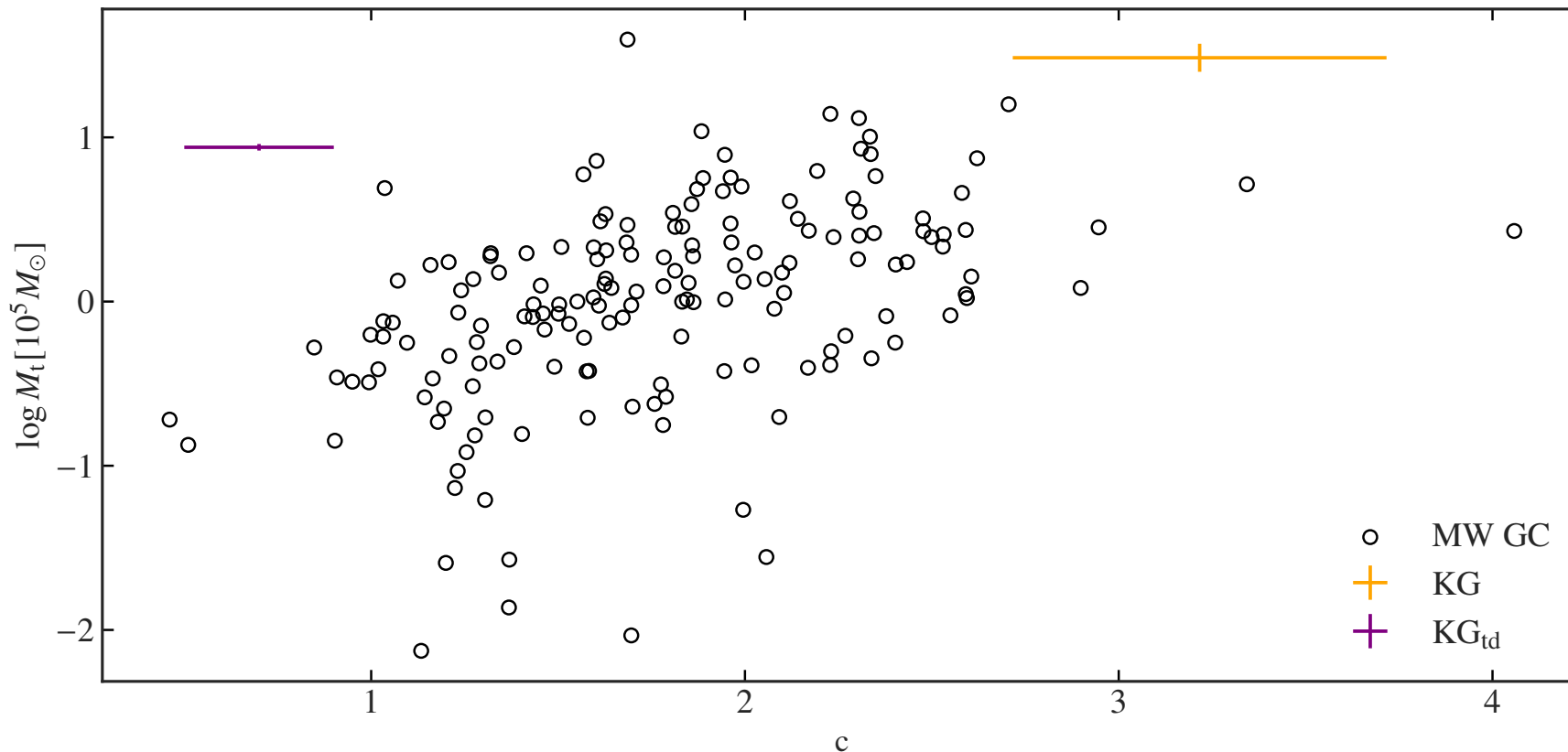
The probability of detecting at least one subhalo with $M = 10^6 - 10^7 M_\odot$ is:

$$p(n \geq 1) = 0.65 \text{ in CDM}$$

$$p = 0.36 \text{ for 9.1 keV thermal relic WDM}$$

$$p = 0.14 \text{ for 4.6 keV WDM}$$

... not a naked BH or a globular cluster

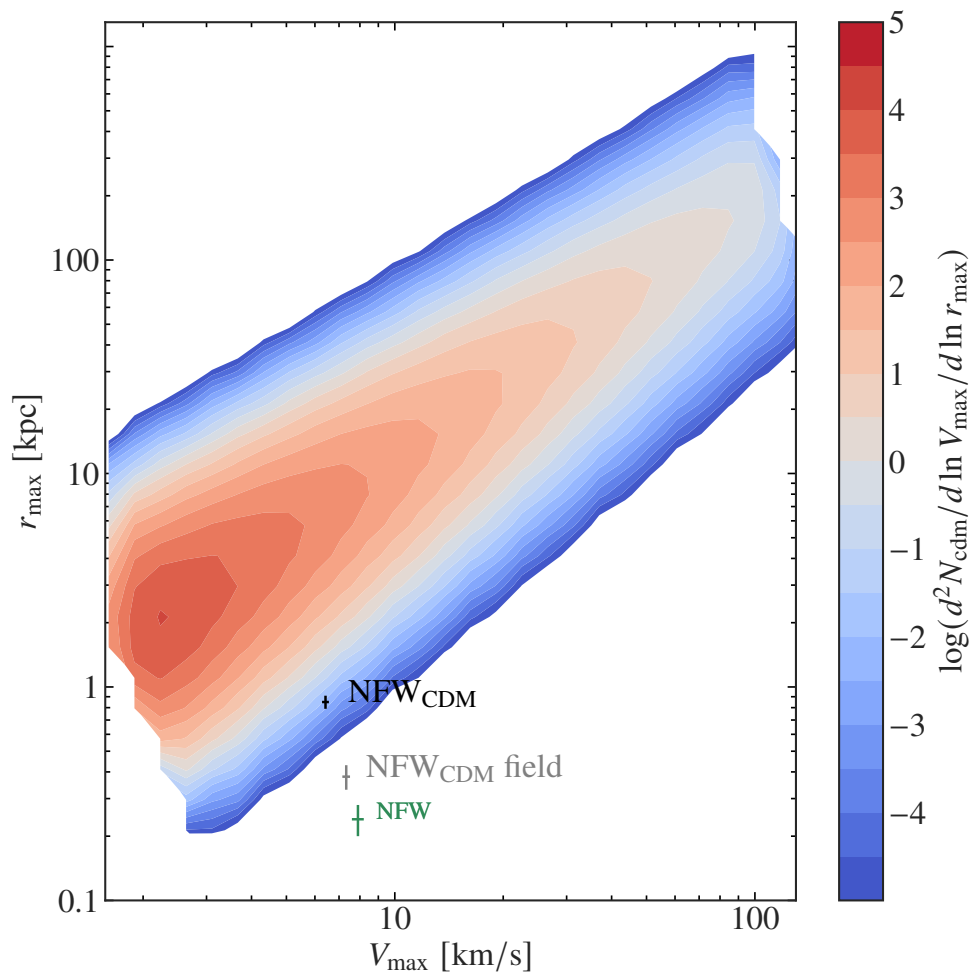


The data rules out a BH with $\Delta \log \mathcal{E} = -95$ all KG profiles are disfavoured by $\Delta \log \mathcal{E} = -85$ to -16

Expected number of GCs ~ 250 , subhaloes $\sim 10^3$

...not a CDM or WDM halo

The best NFWs are disfavoured by $\Delta \log \mathcal{E} = -2.9$ to -6.9 and have extreme concentrations



$$c_{\text{vir}} = 814 \pm 179$$

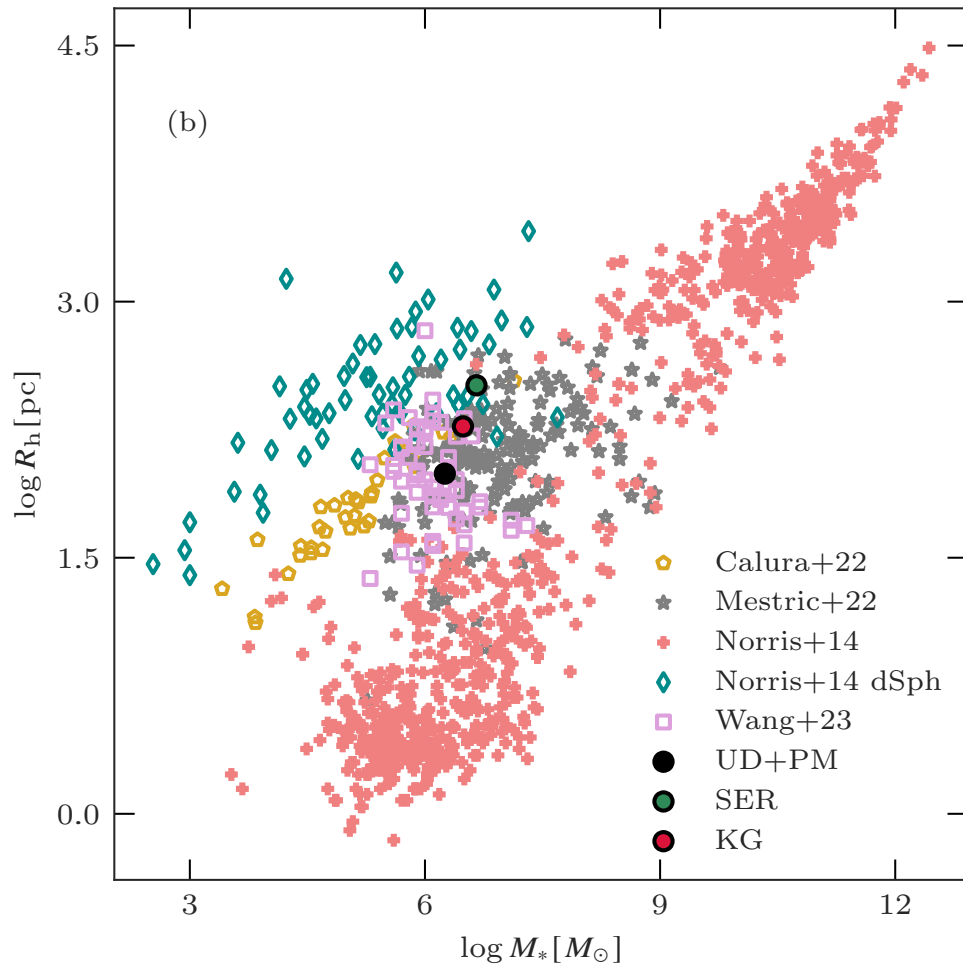
$$r_{\text{max}} = 24.2 \pm 3.8 \text{ pc}$$

Imposing a prior from DMO N-body simulations:
 $\Delta \log \mathcal{E} = -38$ and $\Delta \log \mathcal{E} = -109.7$

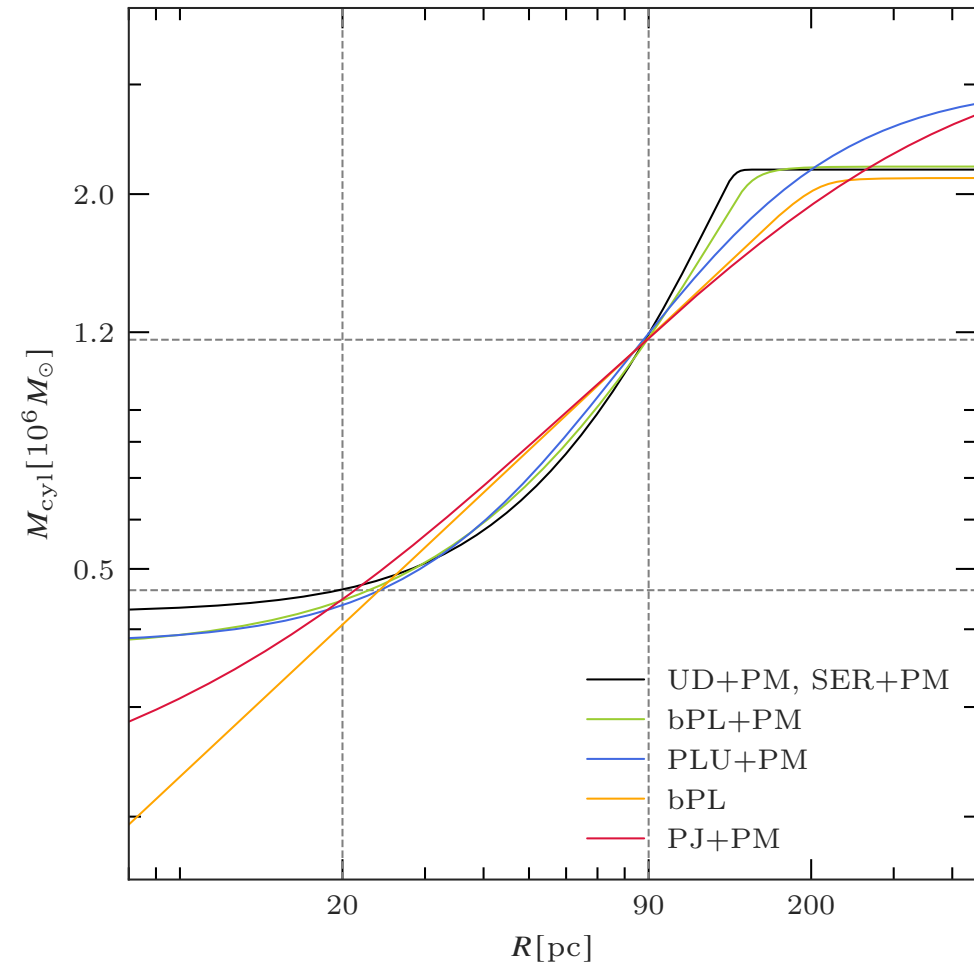
Our detection rules out CDM at a statistical level
between 8 and 15σ

... maybe an eUCD

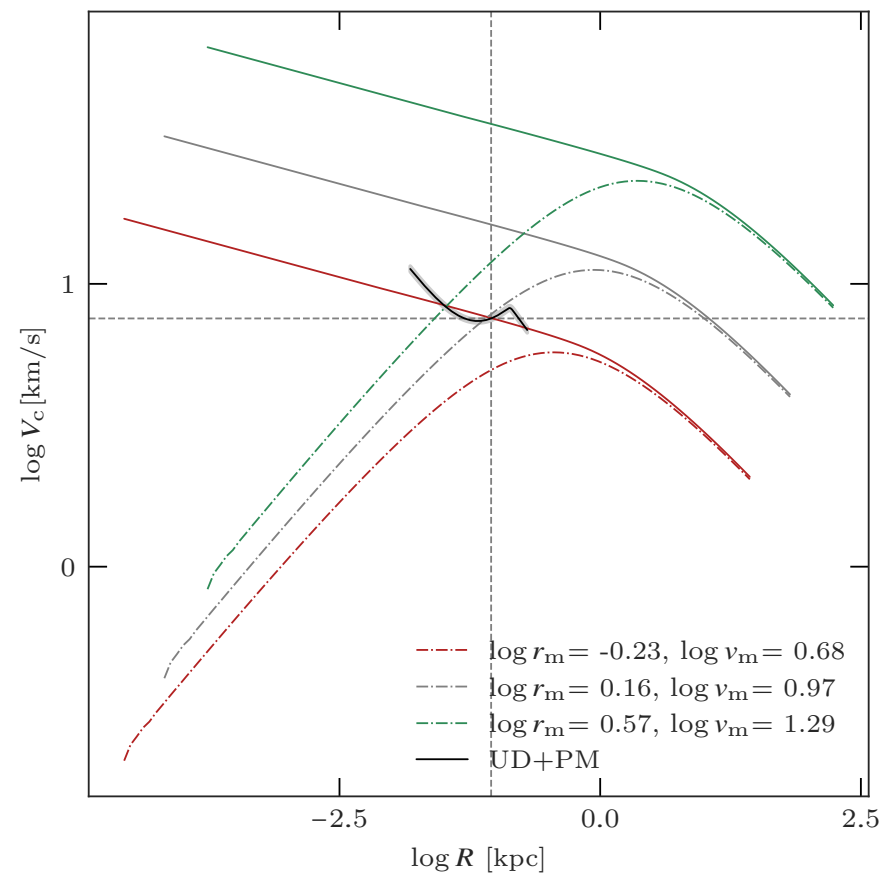
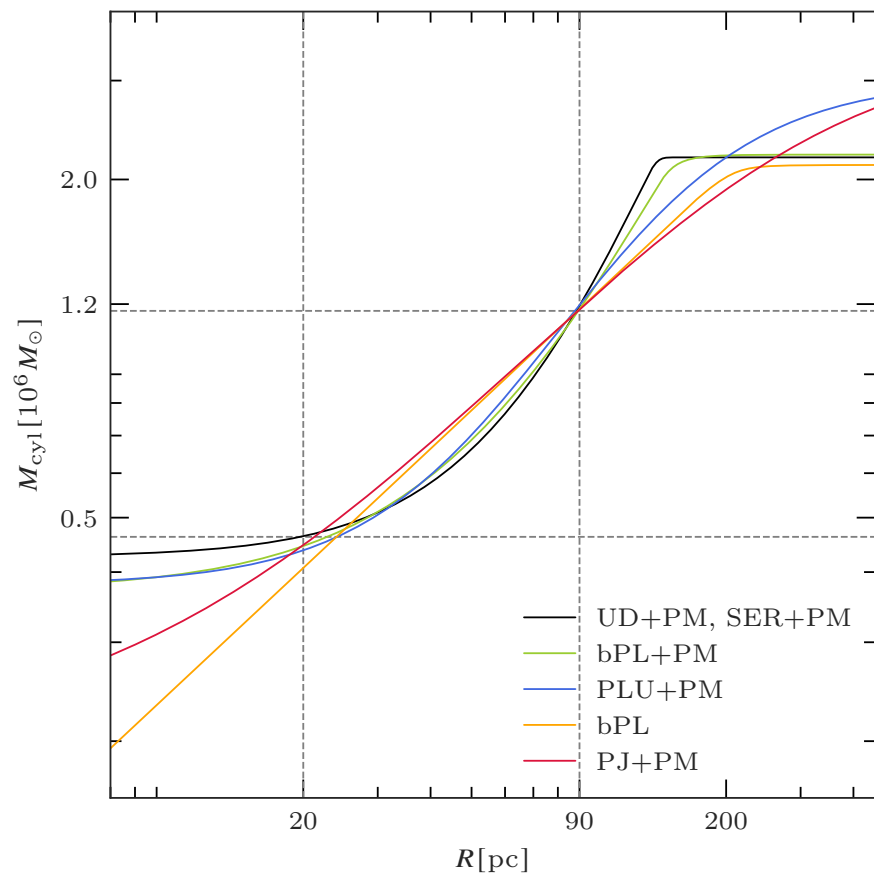
Global properties match those of known eUCDs



But, the best-fitting model is a composite model with an unresolved point-mass of radius ≤ 10 pc centred on an extended mass distribution with an almost constant surface density out to a truncation radius of 139 pc.



... or a post core-collapsed SIDM halo

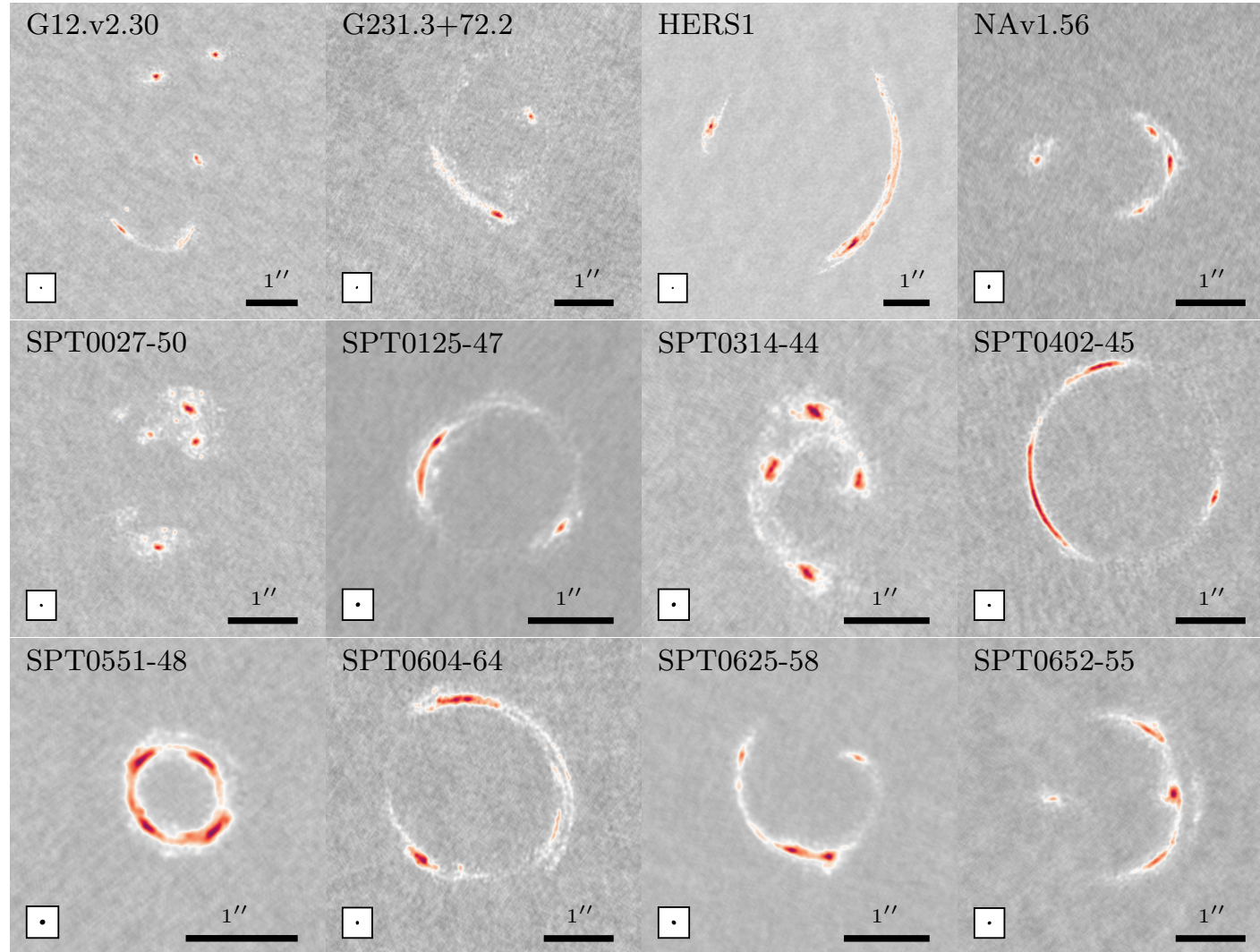


The mass density profiles are consistent within 1σ with gravothermal fluid models, with $\sigma_{c,0}/m_{\text{dm}} > 775 \text{ cm}^2 \text{g}^{-1}$

These properties do not resemble any known astronomical object.



Looking for more



High-resolution observations with ALMA






What next?

Issue	A&A Volume 697, May 2025 <i>Euclid</i> on Sky
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***Euclid*: The Early Release Observations Lens Search Experiment**★

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Euclid: Finding strong gravitational lenses in the Early Release Observations using convolutional neural networks

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Euclid Quick Data Release (Q1). The Strong Lensing Discovery Engine D -- Double-source-plane lens candidates

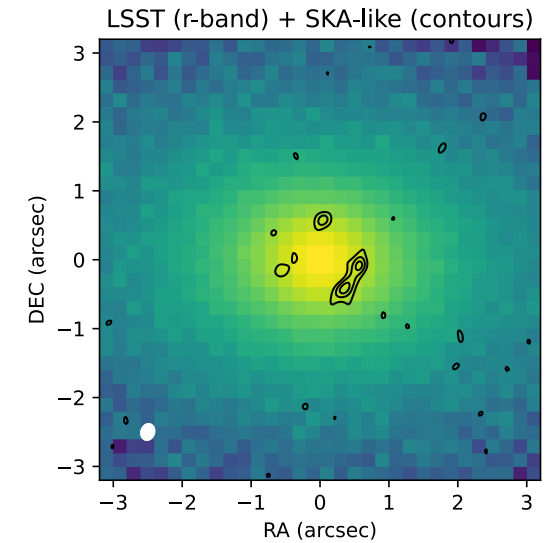
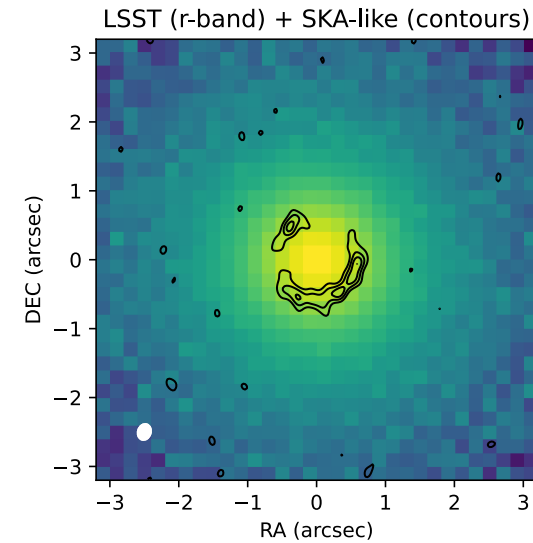
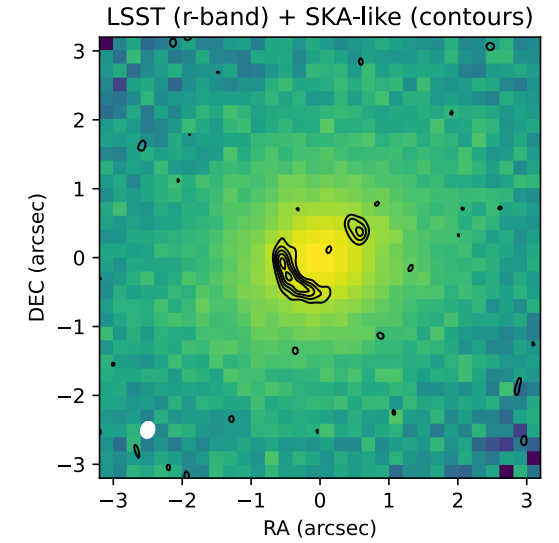
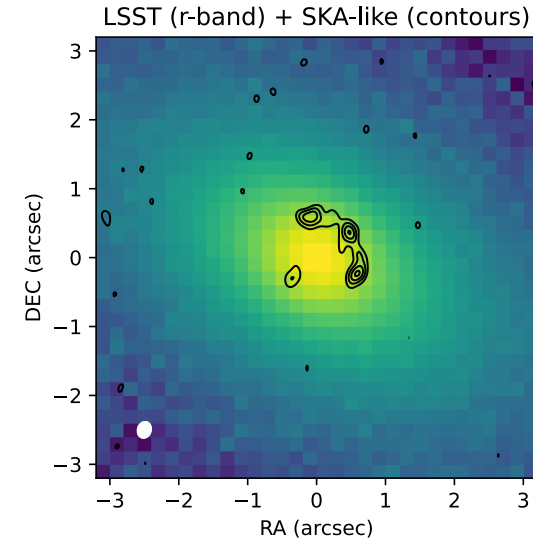
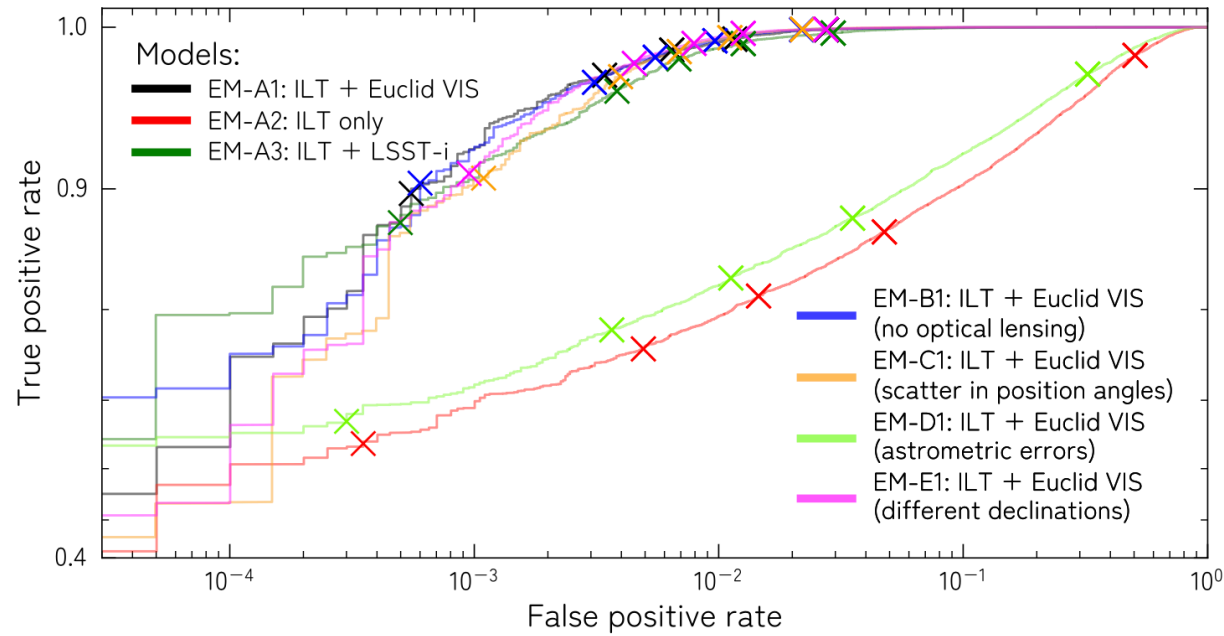
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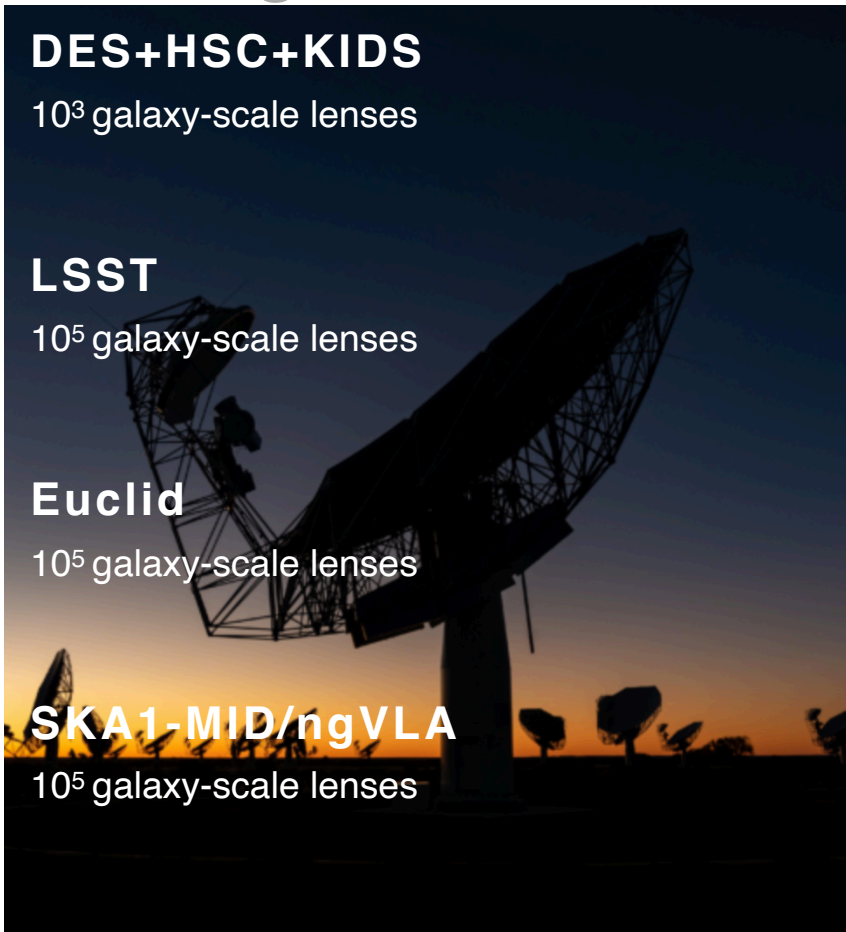
Gravitational Lens Searches with the SKA—LSST

Synergies between SKA and LOFAR (0.3 arcsec resolution) and LSST could find 10^5 lensed radio sources for dark matter studies



What next?

Large Numbers



DES+HSC+KIDS
10³ galaxy-scale lenses

LSST
10⁵ galaxy-scale lenses

Euclid
10⁵ galaxy-scale lenses

SKA1-MID/ngVLA
10⁵ galaxy-scale lenses

High Quality



Keck-AO
100 mas resolution

E-Merlin
50 mas resolution

ALMA
25 mas resolution

ngVLA - ELT
3 to 4 mas resolution

Many high-quality physics labs to investigate out favourite astrophysical questions



Galaxy-galaxy strong lensing provides a robust method to test different dark matter models

Milli-arcseconds angular resolution is key to detecting low-mass haloes

Euclid and SKA will provide a significant increase in the number of known systems and some interesting constraints on the higher-end of the halo mass function

High-resolution follow-up observations with ALMA, ELT and the ngVLA are needed to push the sensitivity

So far, three objects have been detected with properties in tension with CDM at different statistical levels

These are potentially more consistent with SIDM but significantly more work is needed on the numerical side

And, of course, we need to keep improving our understanding of systematic errors!

