Constraining dark matter

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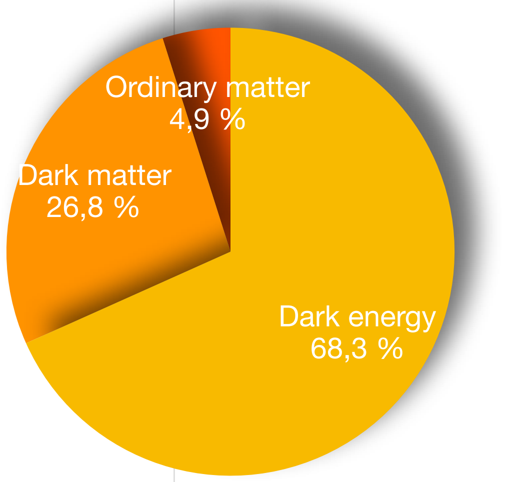
with high-resolution strong lensing observations

What is the nature of Dark Matter?

About 80% of the mass in the Universe is Dark Matter.
Yet, there is no Dark Matter particle in the standard model of particle physics

AstroPhysics

Dark Matter in the whole Universe

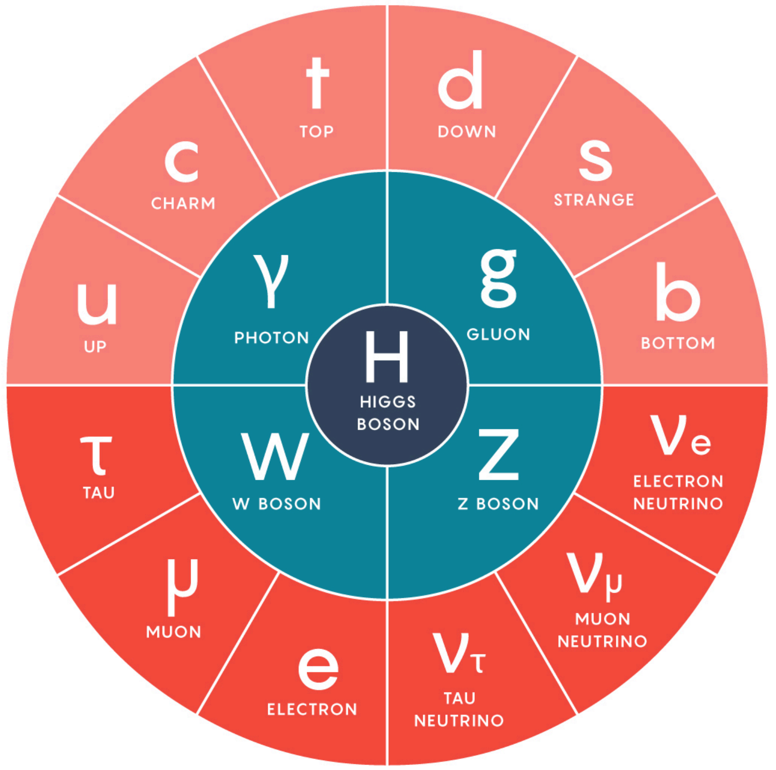


Mass-Energy budget

Particle Physics

All currently known elementary particles

The Standard Model

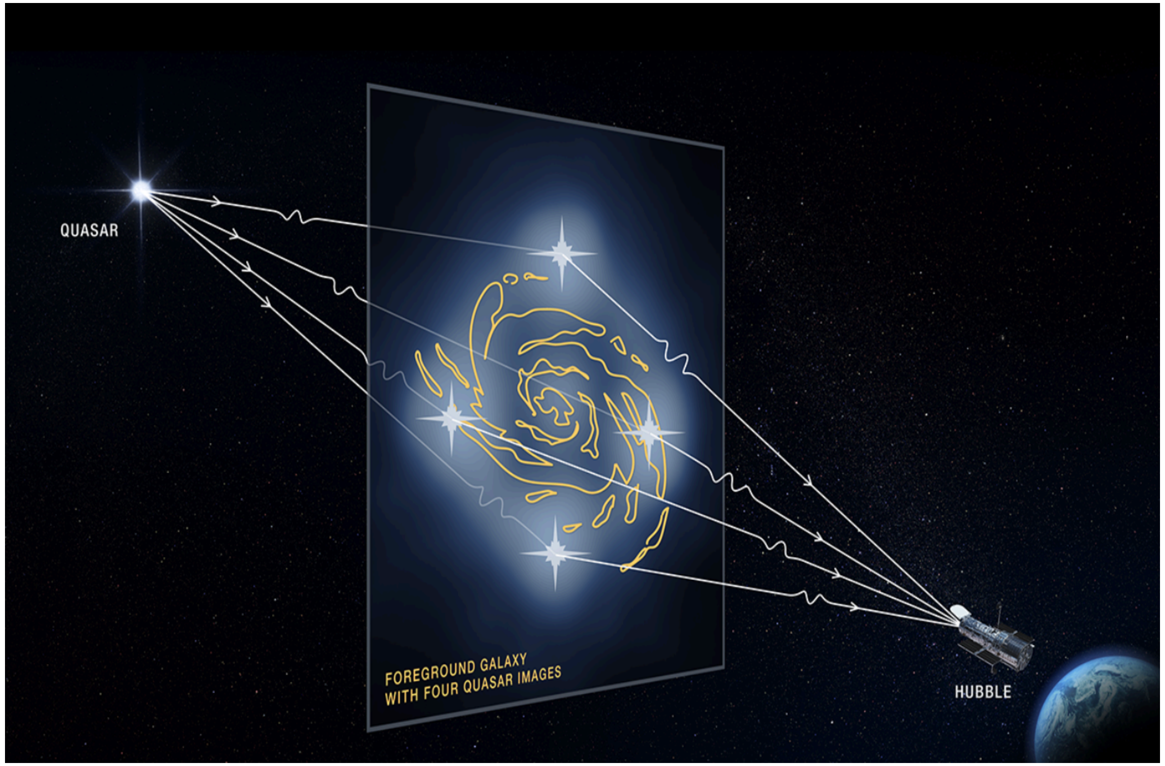


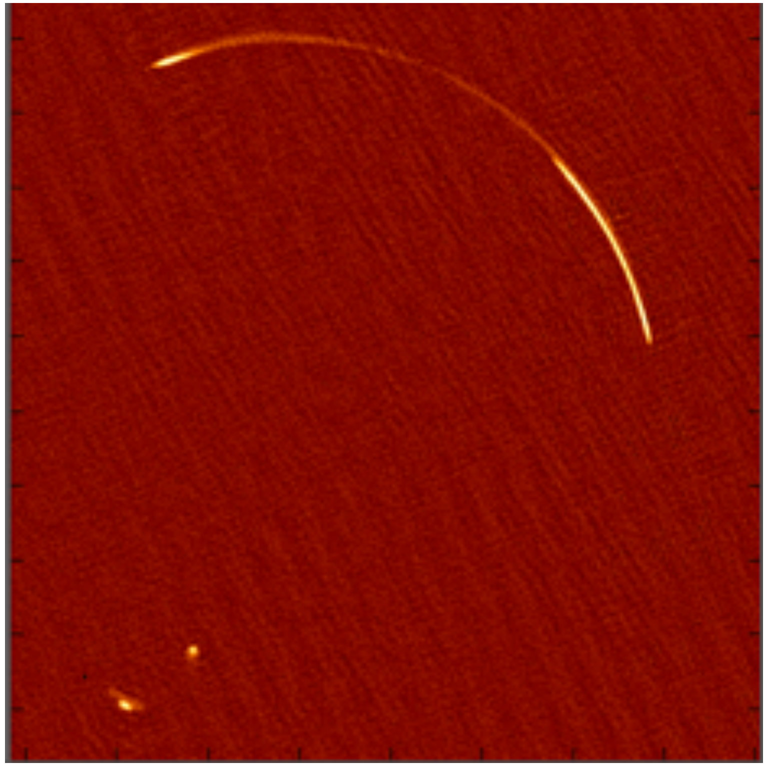
(No Dark Matter)

Many possible extensions: different Dark Matter candidates

What is strong gravitational lensing?

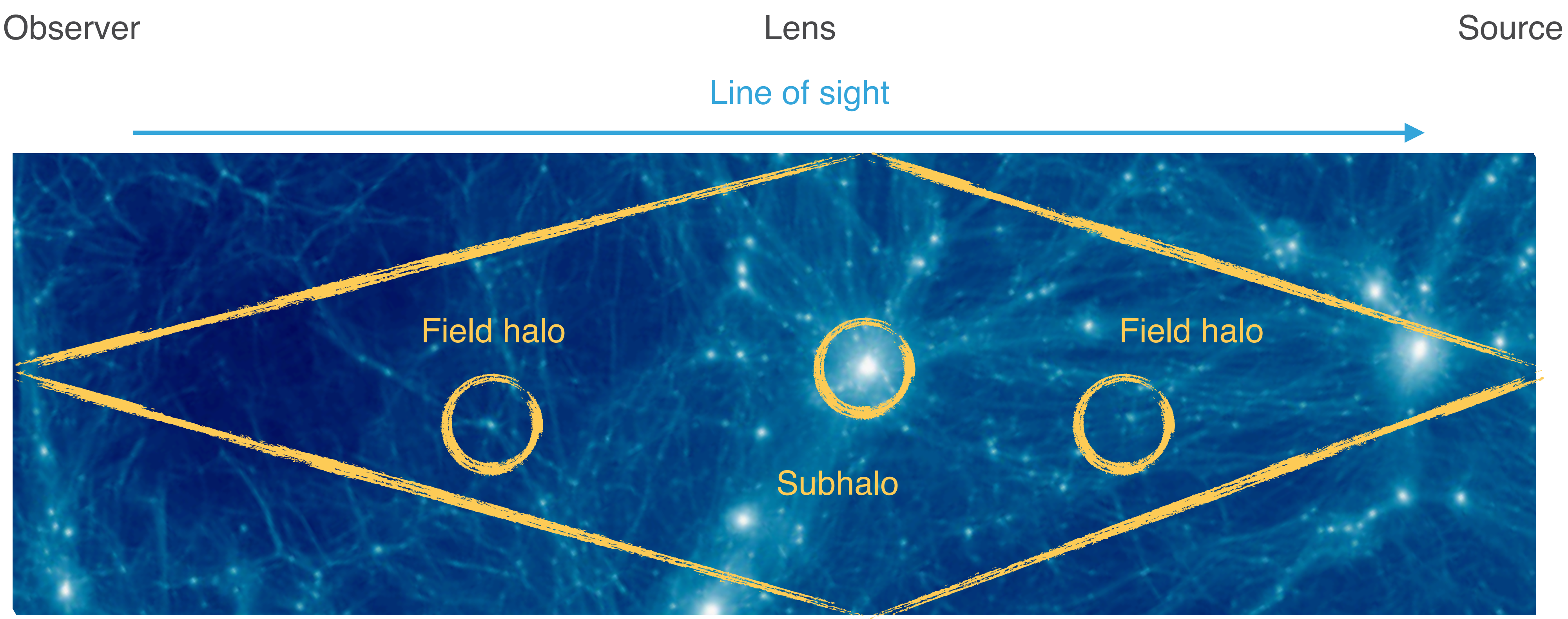
When the light from a distant galaxy passes close to another galaxy, due to the distortion of Space-Time one observes multiple distorted images, that we call Einstein rings





Einstein rings contain invaluable information on the matter distribution along the line of sight

Lensing sees all matter



Lensing is sensitive to

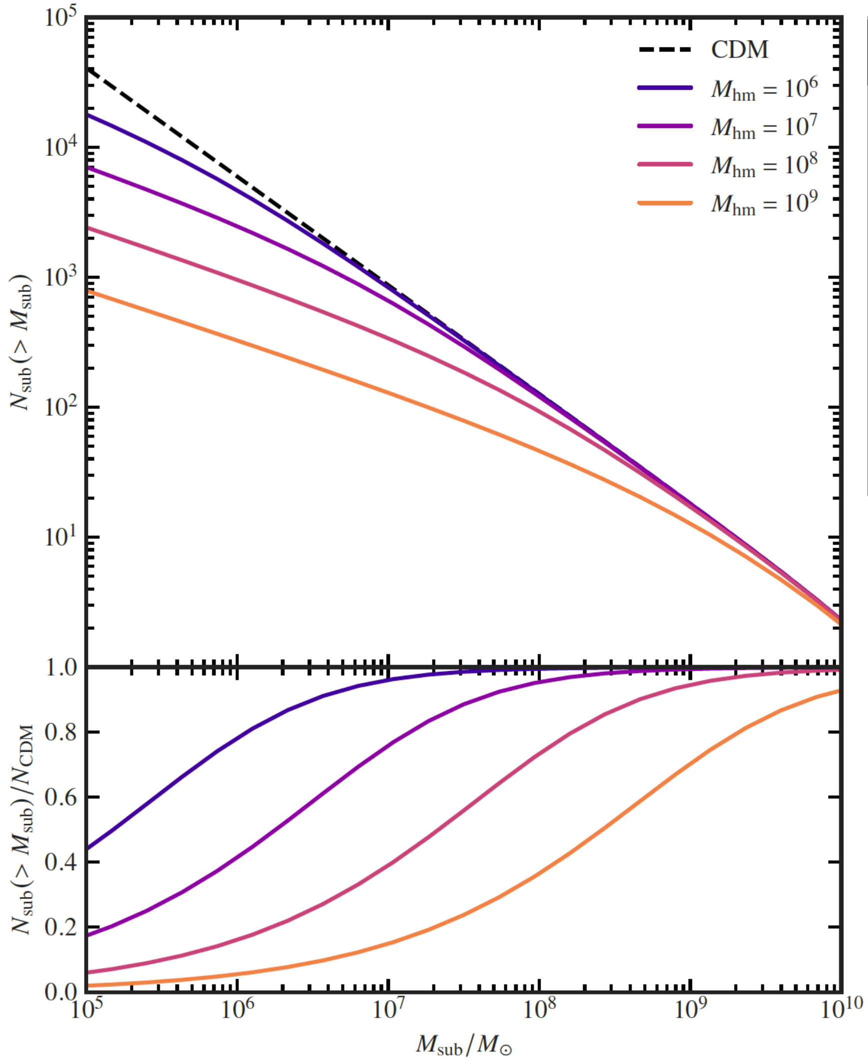
Total mass in the lens

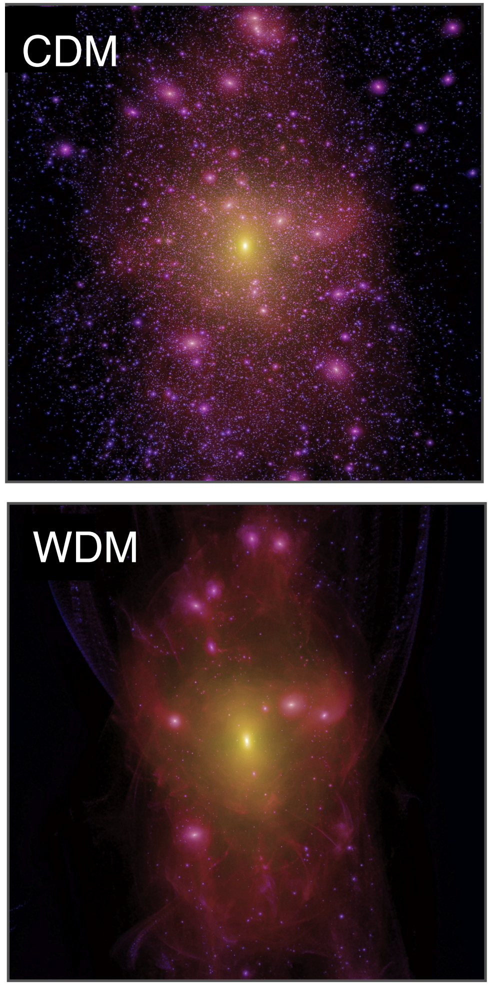
Low-mass haloes along the LOS

Subhaloes

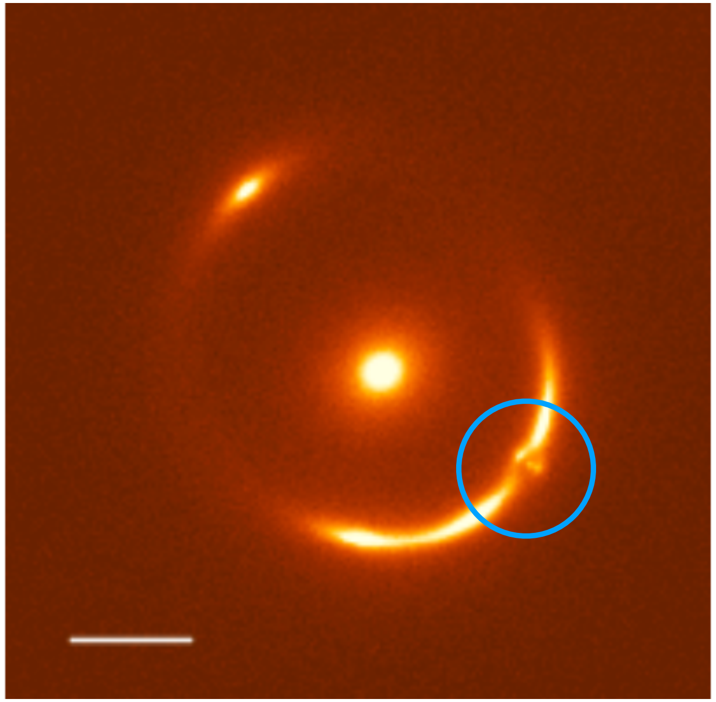
Structure formation and Dark Matter

Lovell et al. 2016, O' Riordan et al. 2023





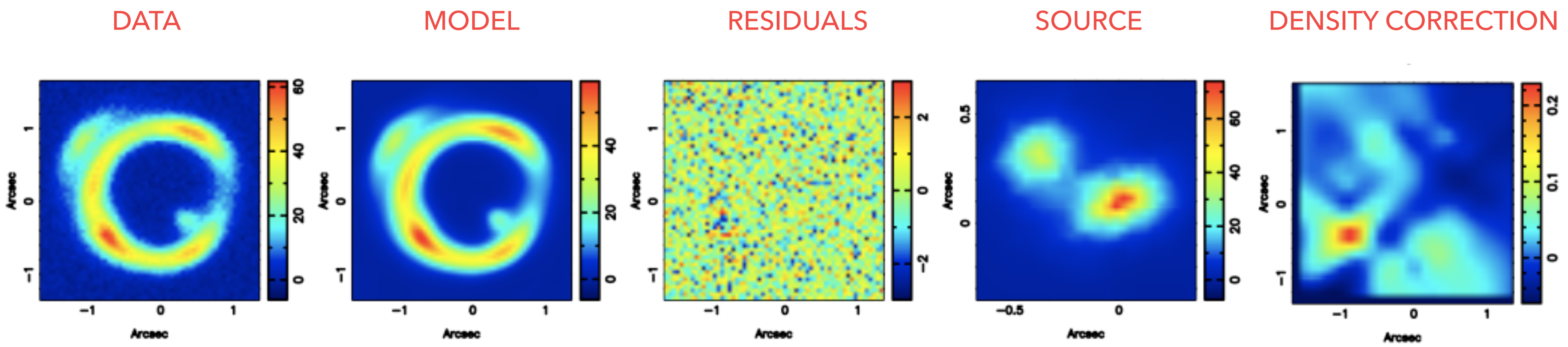
The distribution of dark matter within and around galaxies is set by the properties of dark matter



The presence of a small DM clump locally distorts the lensed image

Gravitationally imaging dark matter

Vegetti & Koopmans, 2009



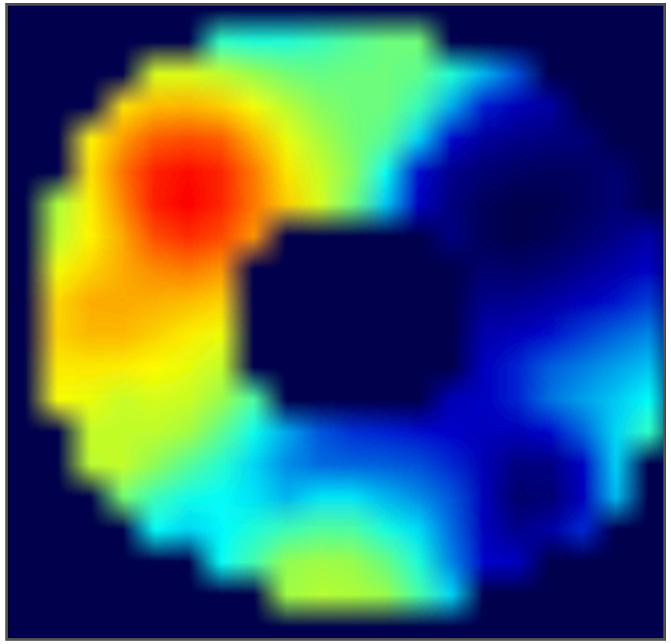
Dark haloes are detected as positive and localised corrections to the overall smooth potential: no a prior assumption on the number and properties

Fully embedded within Bayesian statistics

Individual detections so far

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

z = 0.6

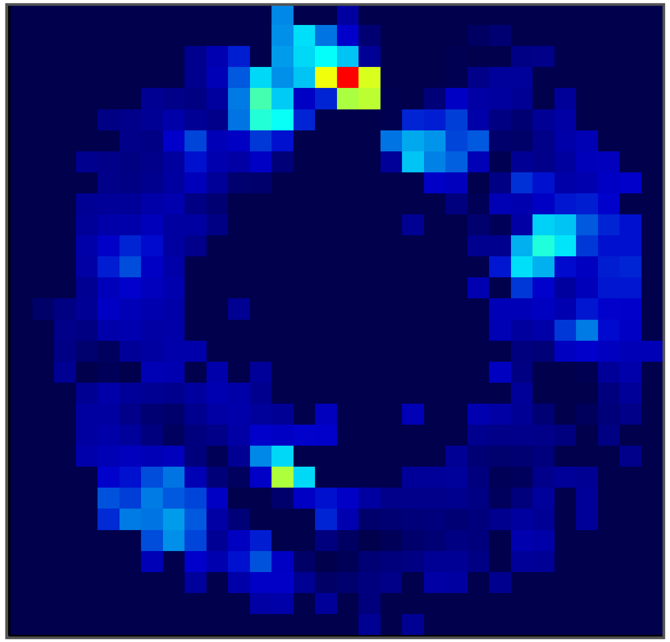


HST

Independently confirmed

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

z = 0.8



Keck-AO

Independently confirmed

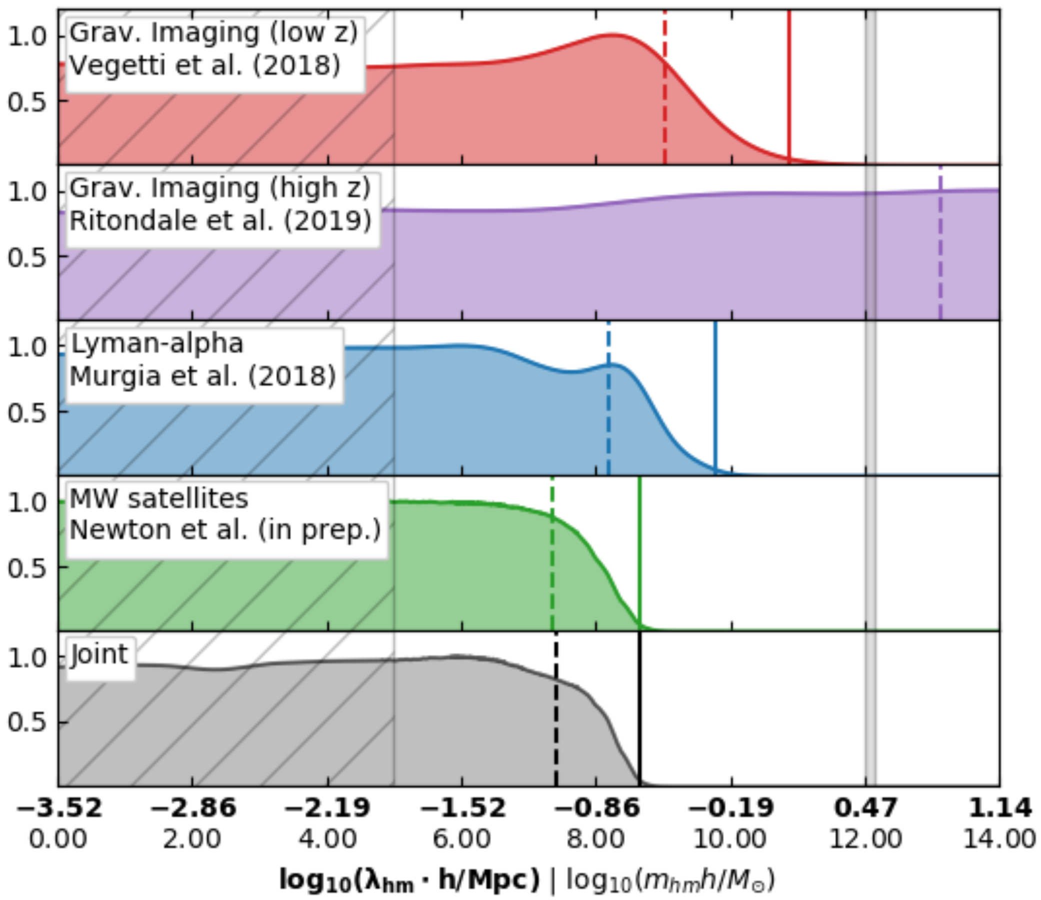
Now maybe a field halo

Vegetti et al. 2010,12 Nature

Statistical constraints so far

Vegetti et al. 2010/14,Ritondale, Vegetti et al. 2020, Enzi, Vegetti et al. 2021

$m_{\rm th} > 6.733$ 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?

Large Samples

DES+HSC+KIDS

10^3 galaxy-scale lenses

LSST

10^5 galaxy-scale lenses

Euclid

10^5 galaxy-scale lenses

SKA1-MID

10^5 galaxy-scale lenses

High Resolution

Keck-AO

100 mas resolution

E-Merlin

50 mas resolution

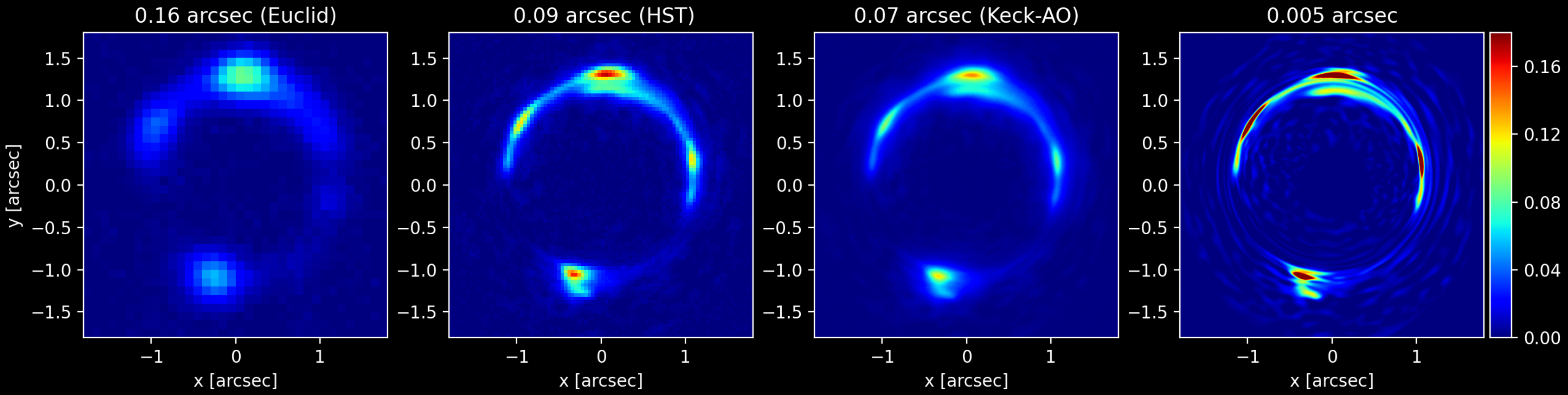
ALMA

25 mas resolution

VLBI - ELT

3 to 4 mas resolution

MOCK DATA FOR ACCURATE PREDICTIONS



- 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.)
- zl>0.5, zs>2

QUESTION 1:

how many lenses do we need to test CDM and/or distinguish it from alternative WDM models?

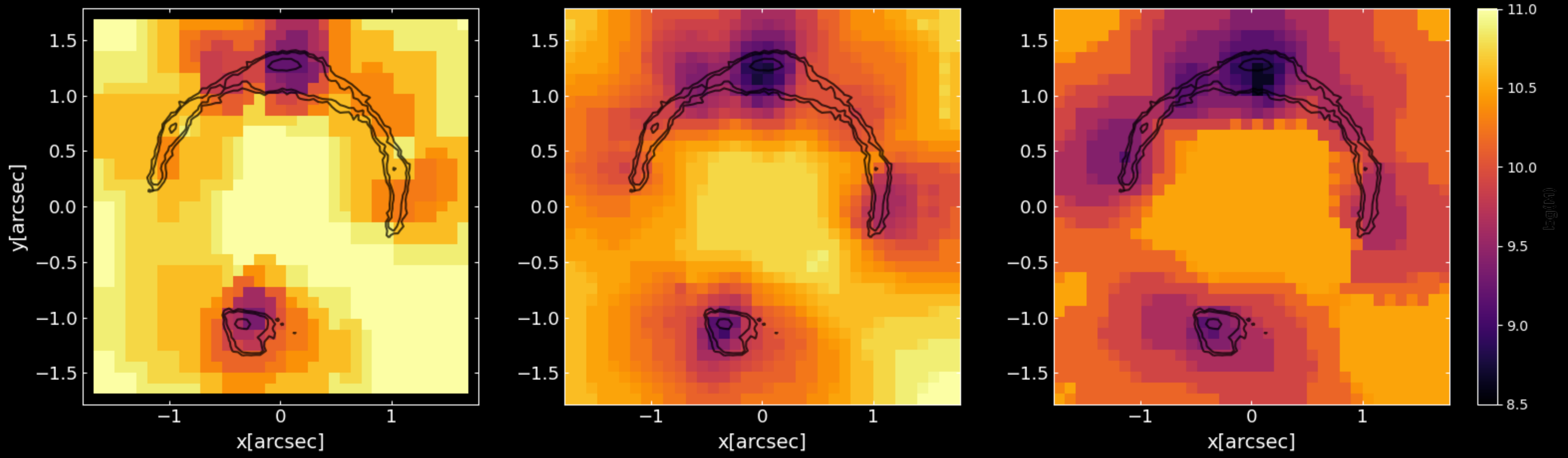
QUESTION 2:

what is the best observational strategy to achieve this goal?

(Despali et al. 2021)

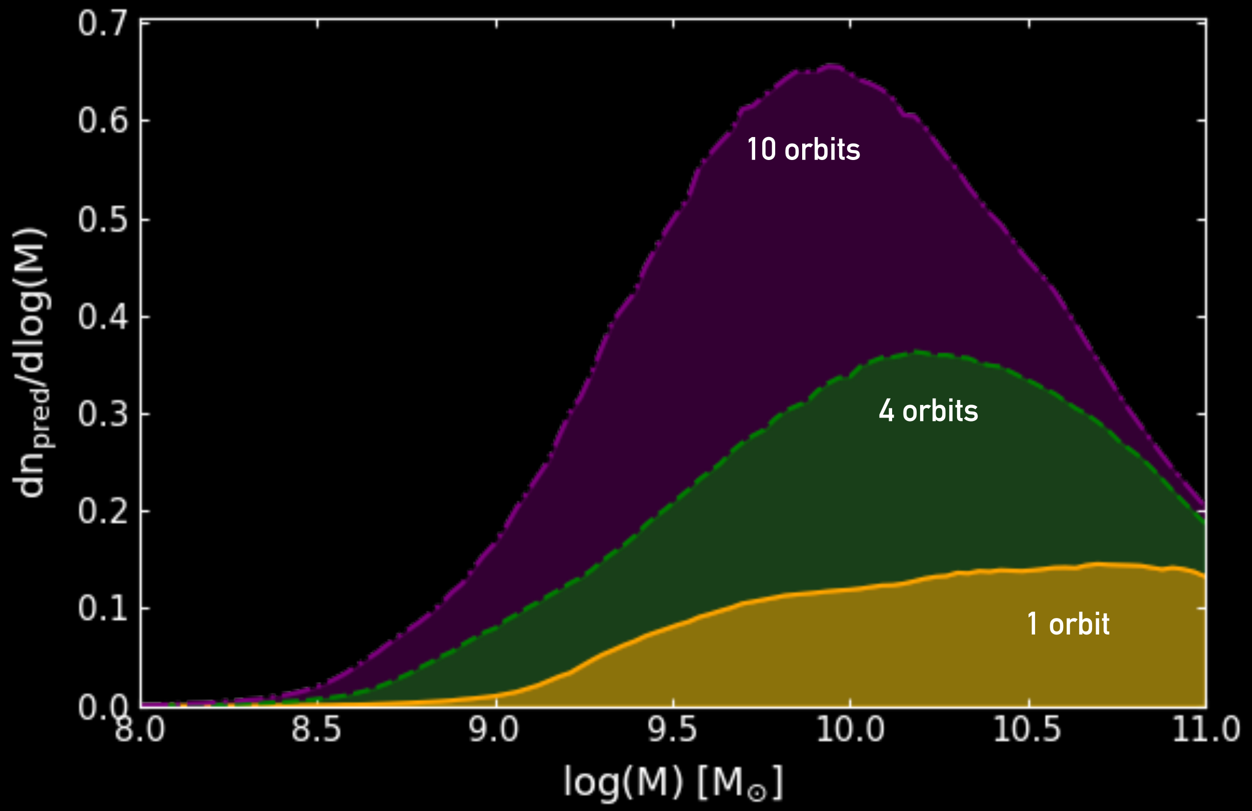
VARYING SIGNAL-TO-NOISE RATIO

1 ORBIT → 4 ORBITS SN x 2 → 10 ORBITS SN x 3.16



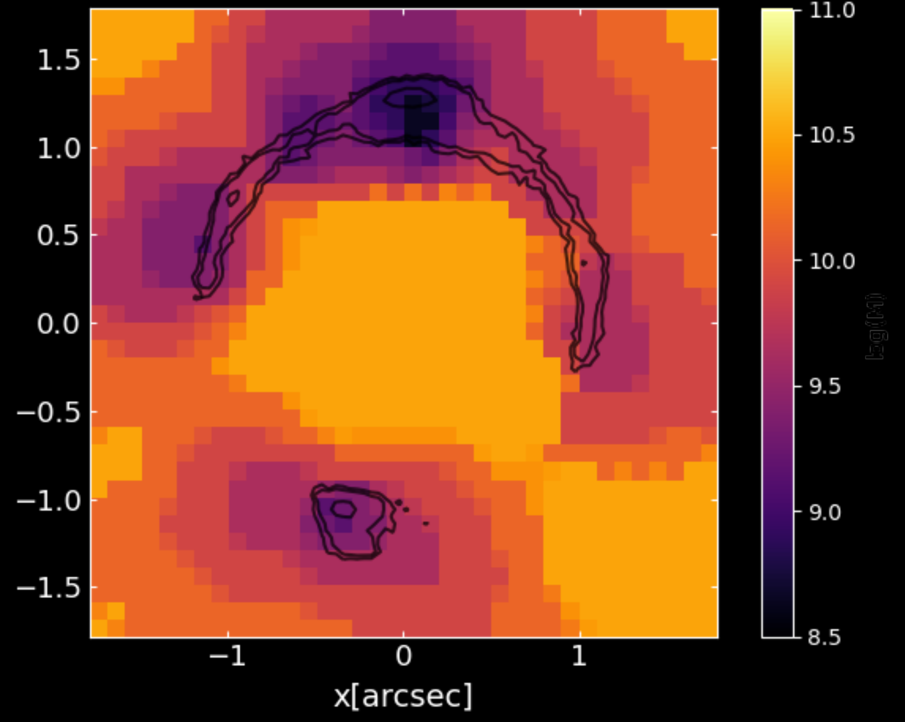
(Despali et al. 2021)

VARYING SIGNAL-TO-NOISE RATIO



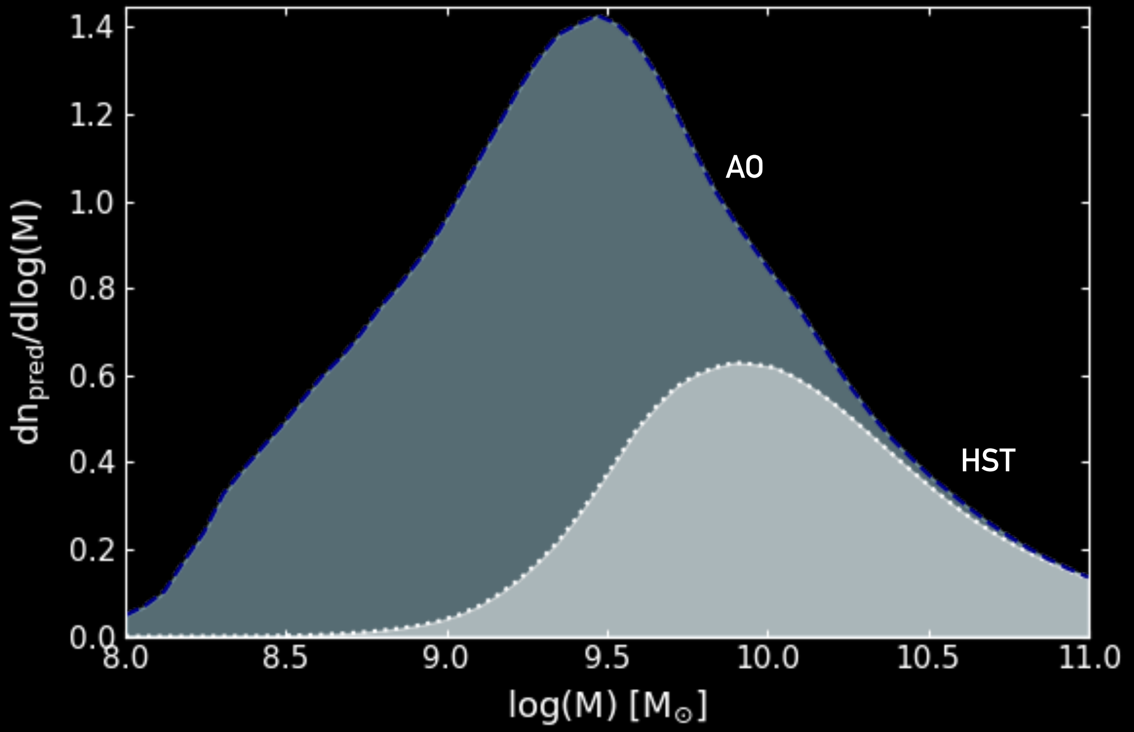
10 ORBITS

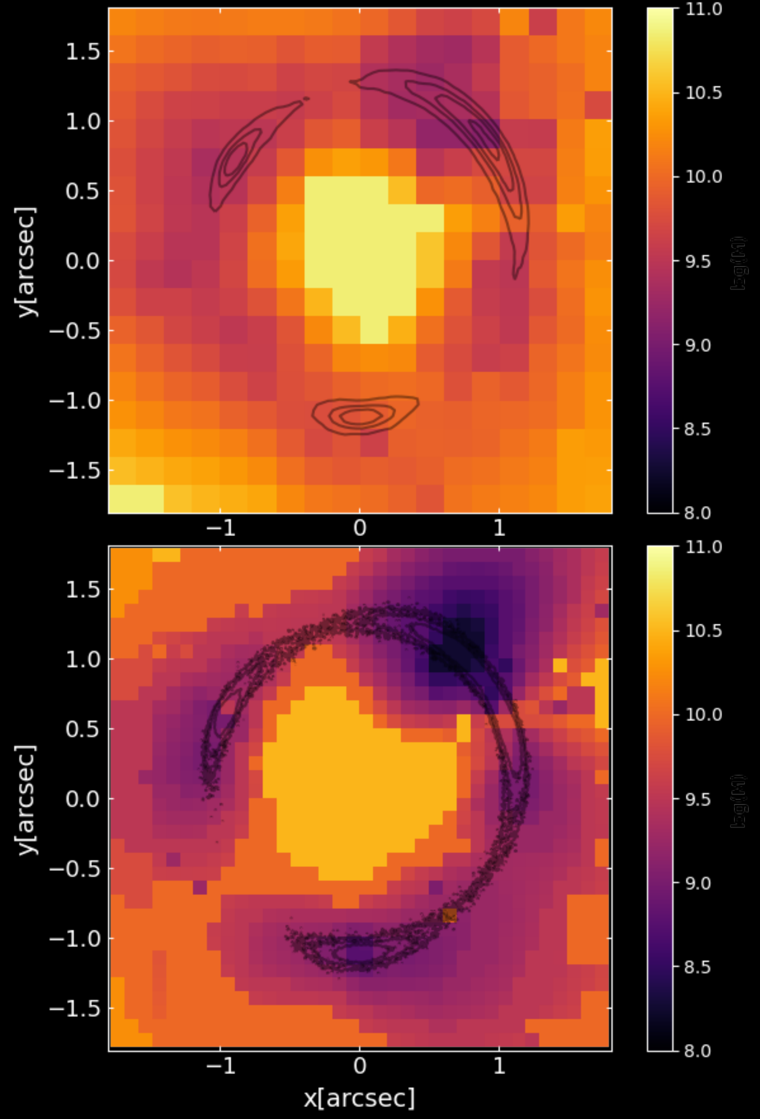
SN x 3.16



(Despali et al. 2021)

VARYING ANGULAR RESOLUTION



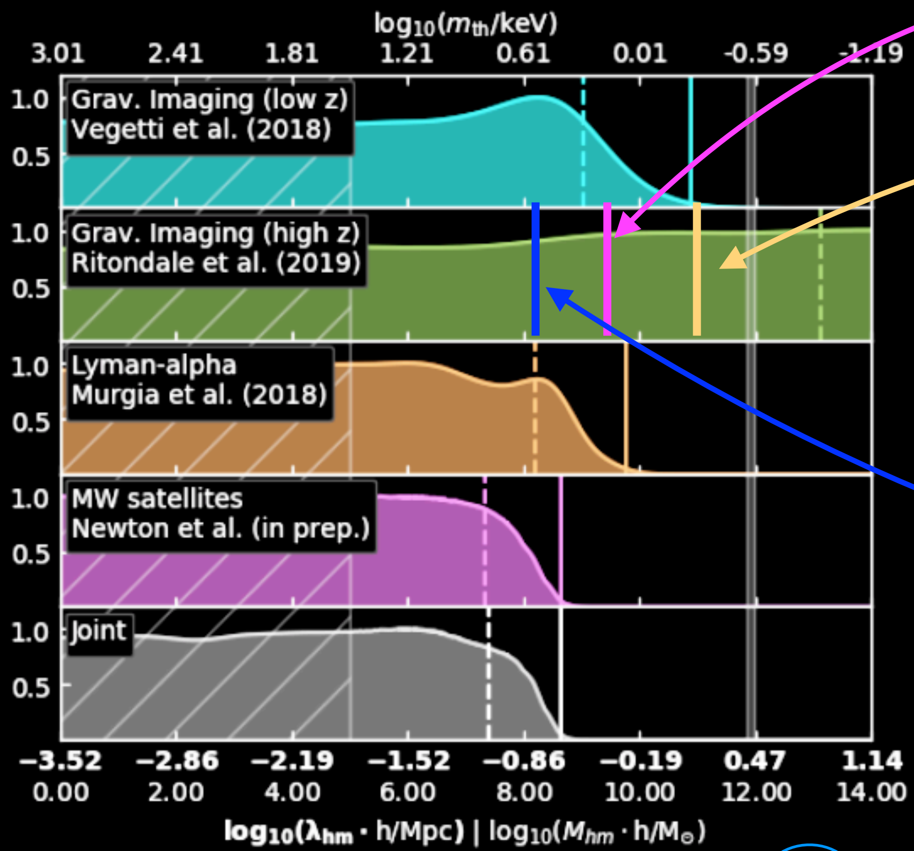


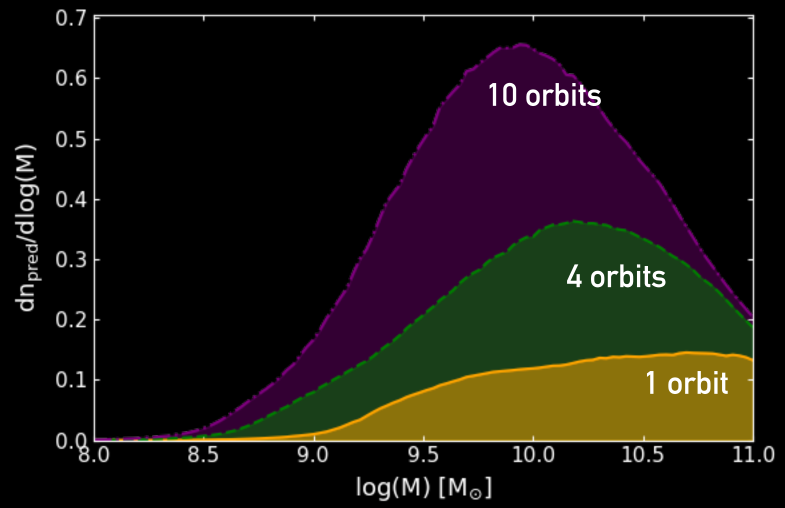
(Despali et al. 2021)

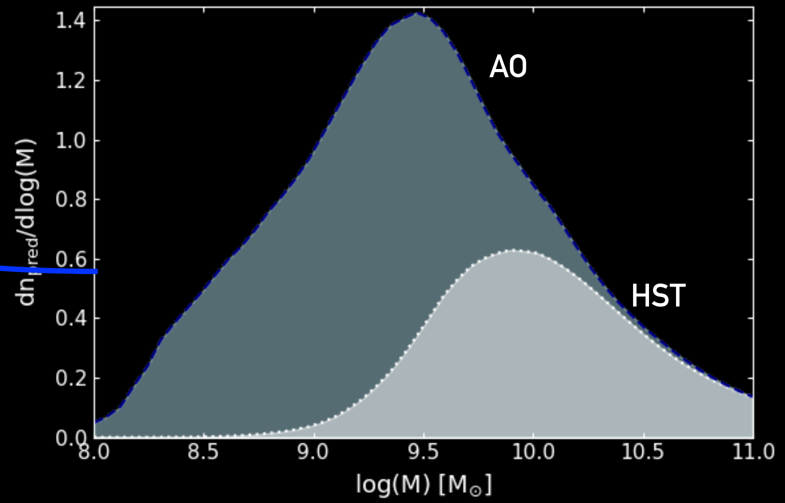
CDM VS WDM

QUESTION 2:

what is the best observational strategy
to achieve this goal?







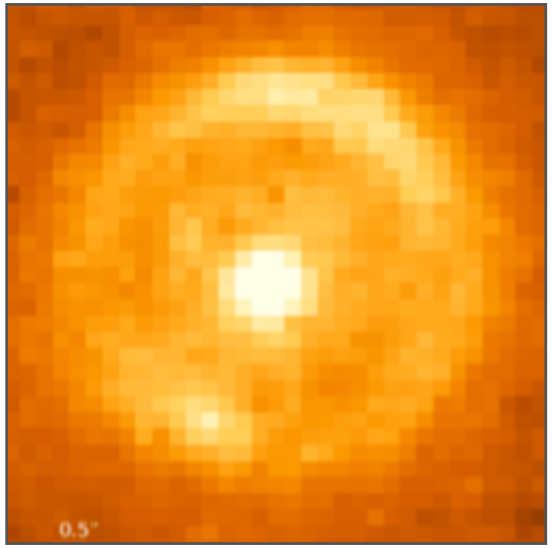
$$\frac{n_{WDM}}{n_{CDM}} = (1 + \gamma M_{hm} M^{-1})^{\beta}$$

(Enzi et al. 2021)

(Despali et in prep.)

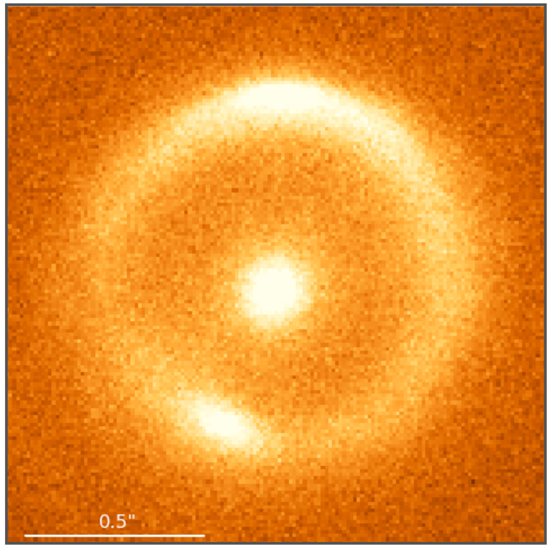
The power of high-res data

10^9 - $10^{10}M_{sun}$



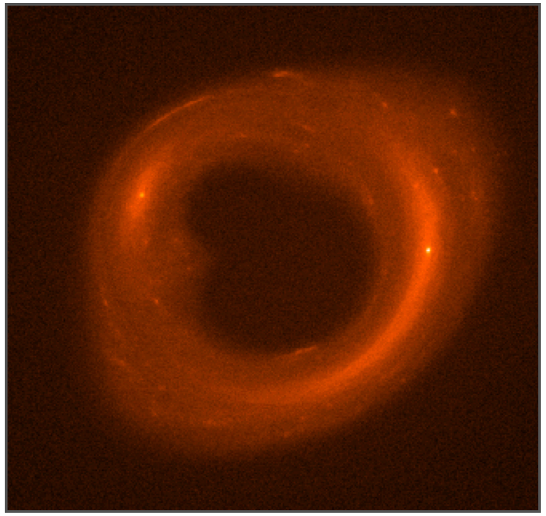
NICMOS - 500 mas

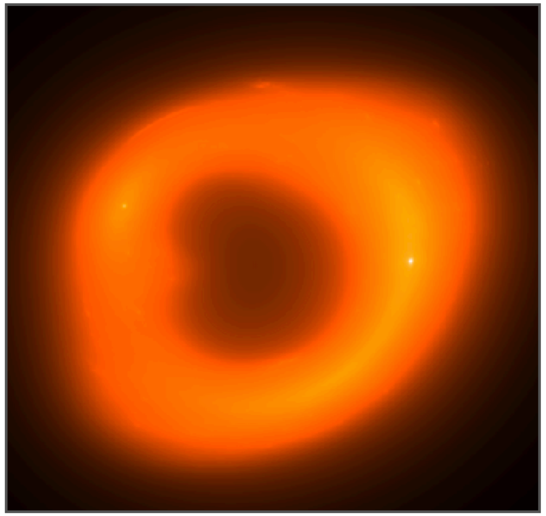
10^8 - 10^9M_{sun}



Keck - AO 100 mas

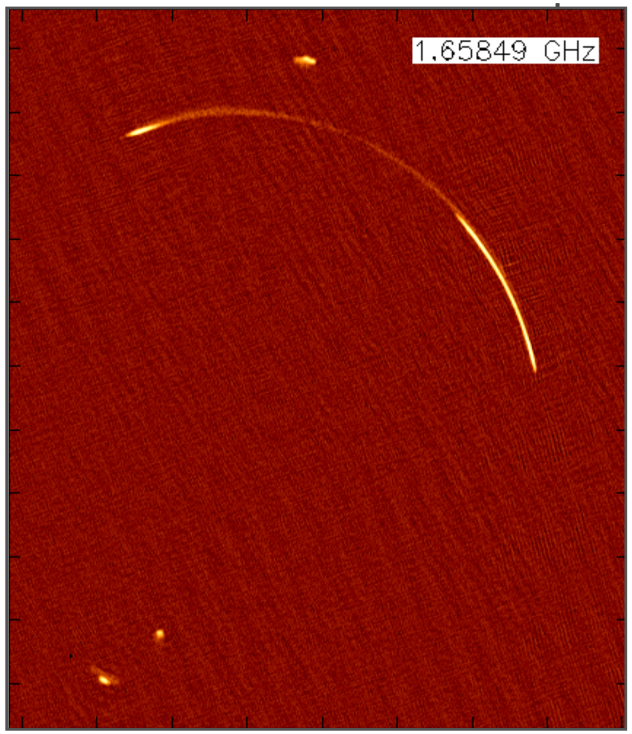
10^6 - 10^7M_{sun}





ELT- Expected detection limit ~10^7 M_{sun}
BUT very much dependent on the PSF

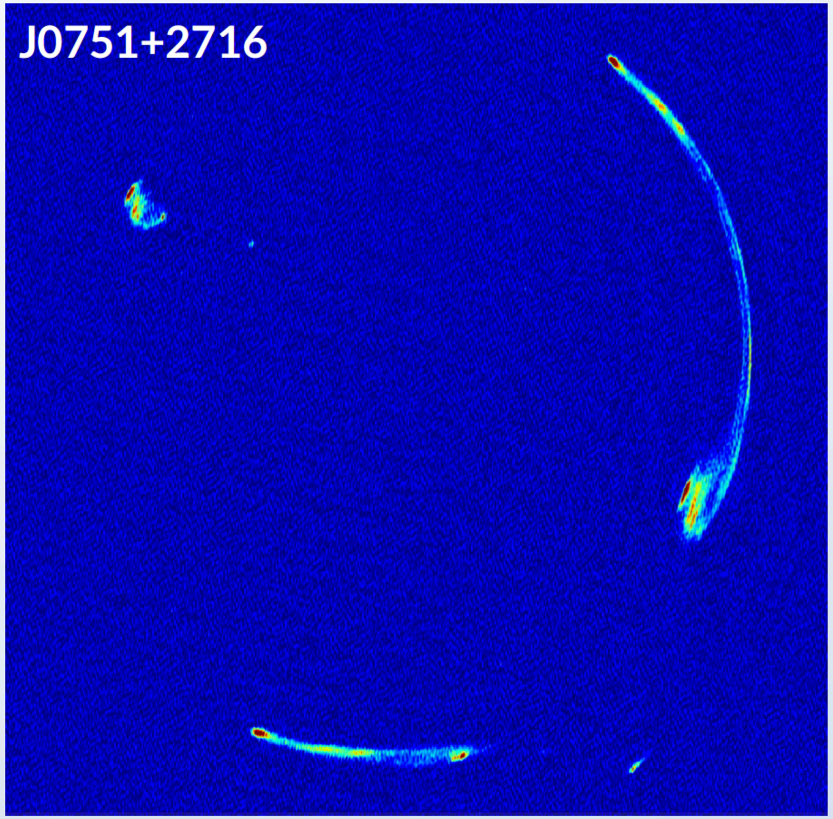
10^6 - 10^7M_{sun}



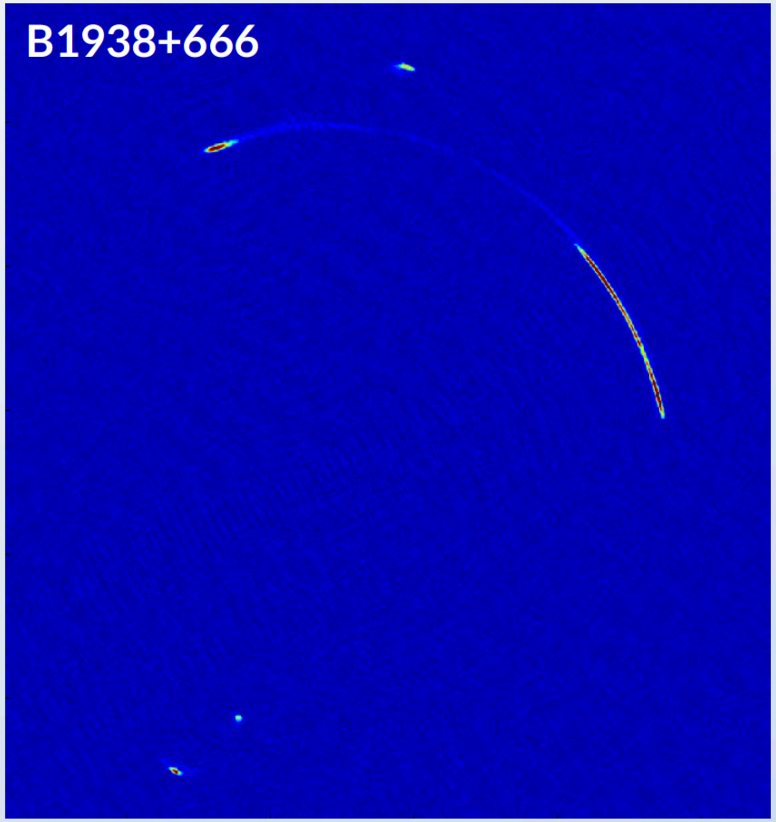
GVLBI - 3 mas

Probing low-mass haloes with VLBI

Earth-scale antenna spacings give ~5 mas resolution at 1.6 GHz
Long, thin arcs are extremely sensitive to mass structure in the lens galaxy!



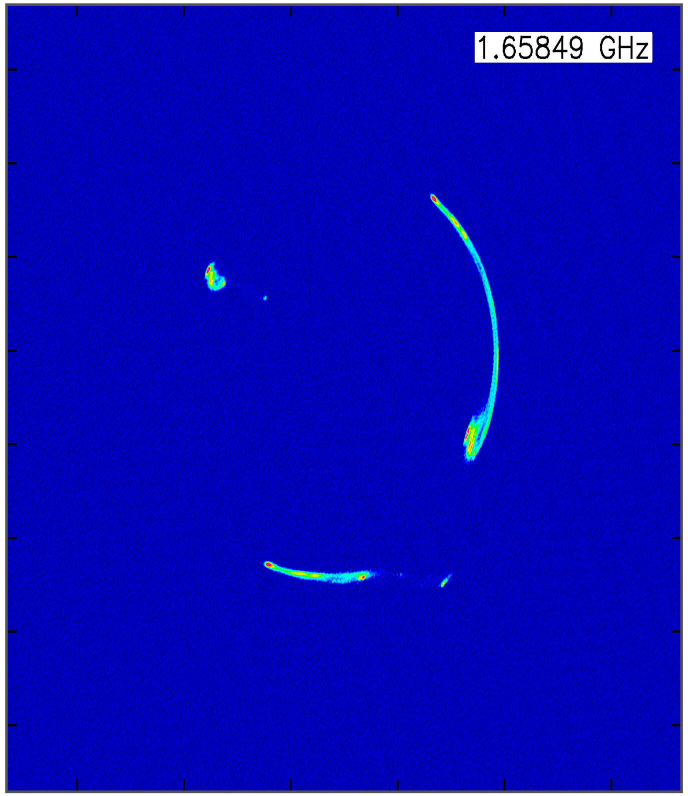
Spingola, McKean, et al. 2018

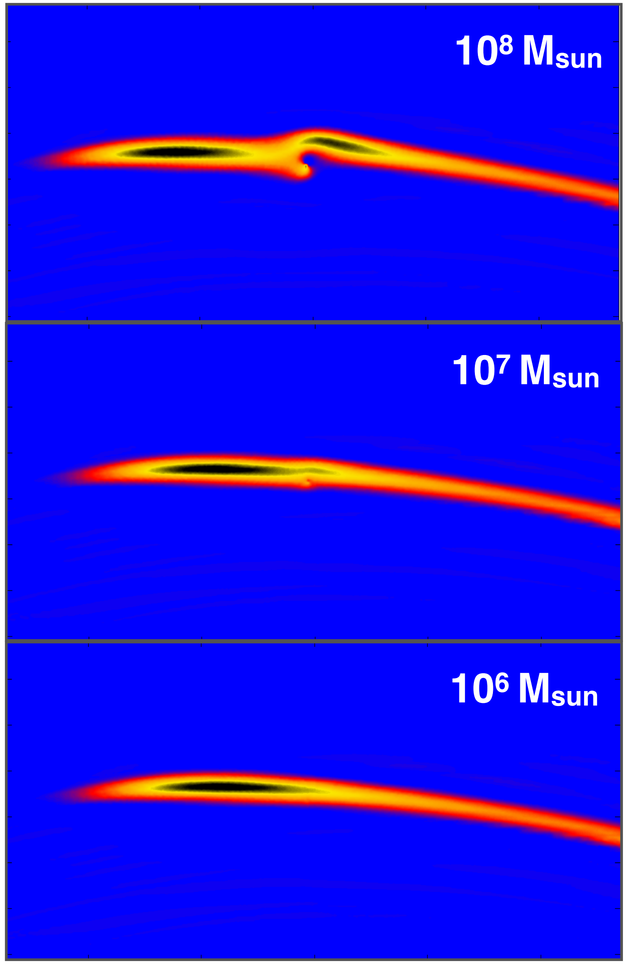


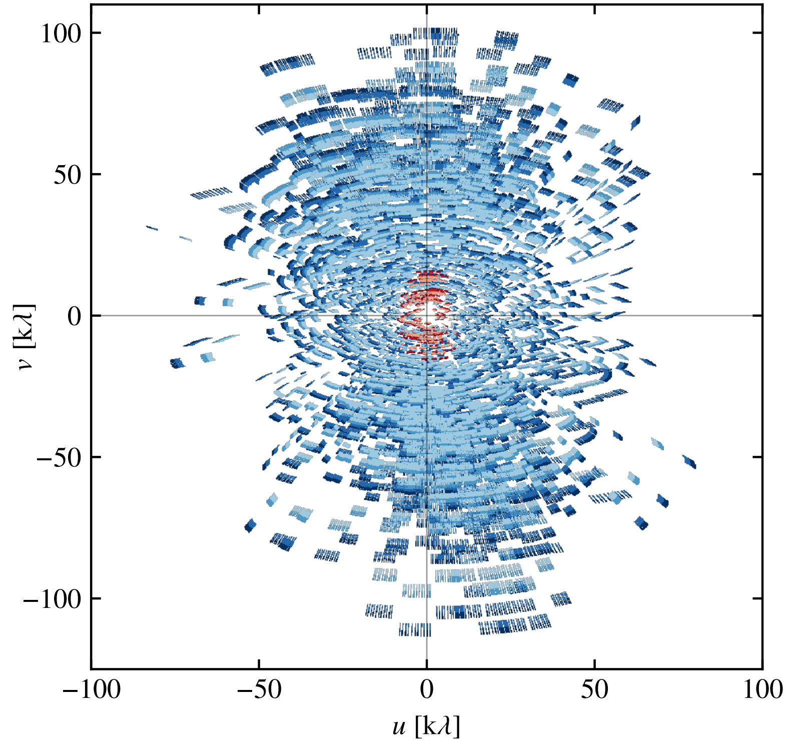
McKean

Probing low-mass haloes with VLBI

Powell, Vegetti et al. 2021 Powell, Vegetti et al. 2022







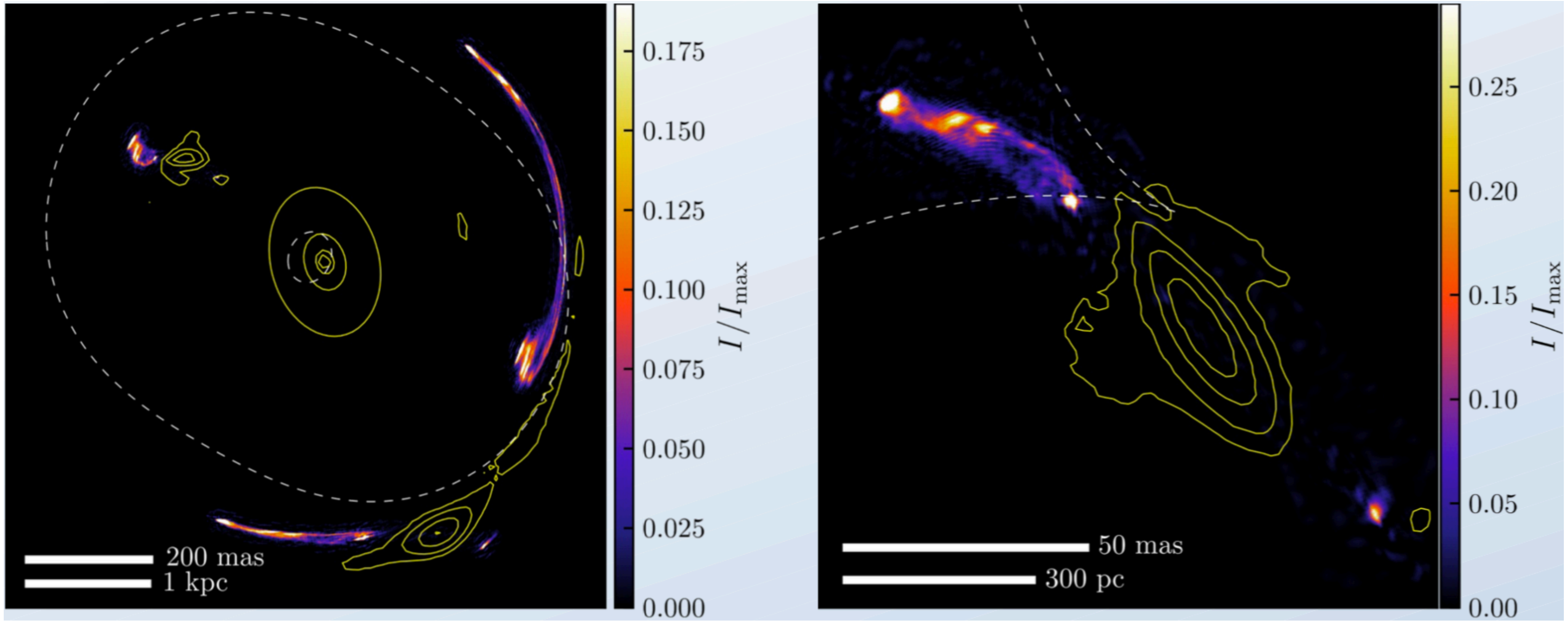
Probing low-mass haloes with VLBI

The actual data is an incomplete, non-uniform sampling of the Fourier transform of the sky brightness.

Typical observation has ~10^9 visibilities (or more), and needs an image-plane grid of 2048^2.

Computationally challenging!

Powell, Vegetti et al. 2021   Powell, Vegetti et al. 2022



Recovers a pixellated source brightness model, as well as the likelihood, for a given lens model.

Allows us to quantify how well a given lens mass distribution explains the observed data.

Fitting is in the visibility plane, with no intermediate imaging step.

GPU acceleration allows for efficient computations

Fuzzy dark matter

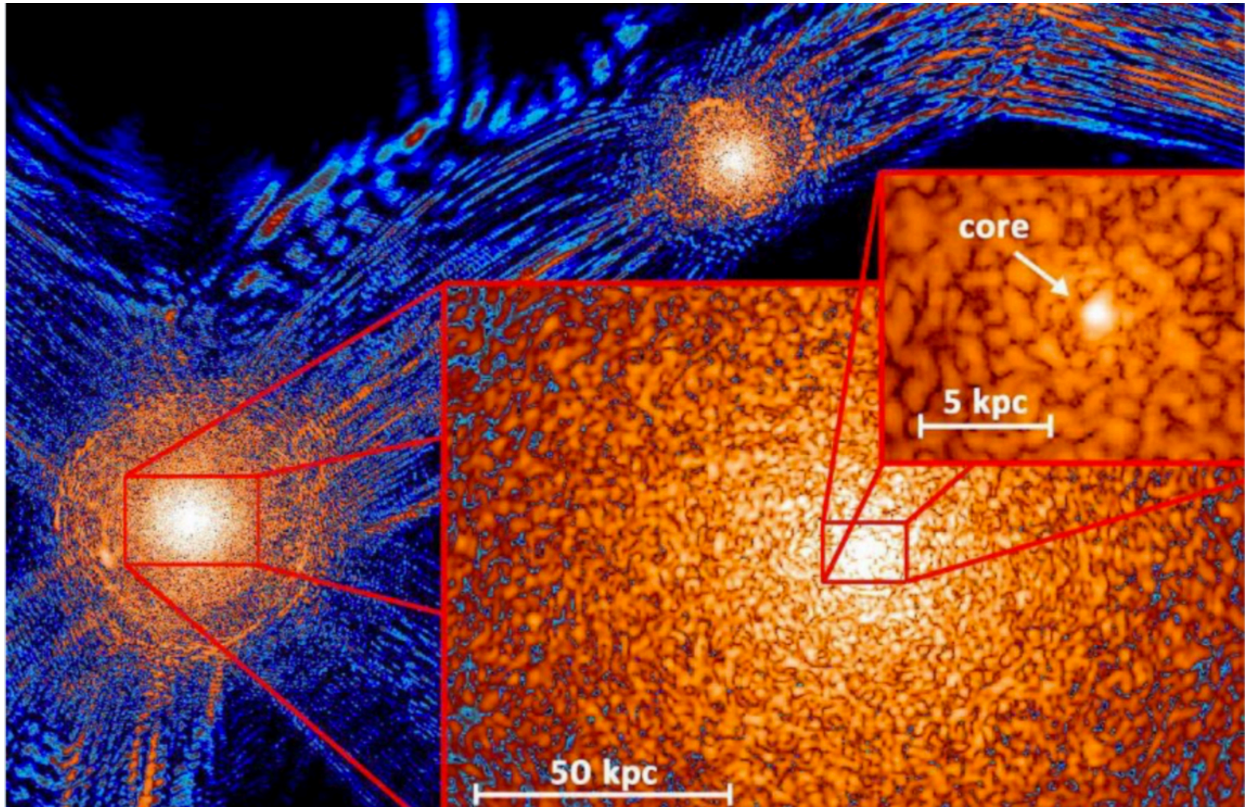
Fuzzy dark matter (FDM) is a class of ultra-light DM (ULDM) that exhibits a ~kpc-scale de Broglie wavelength

Main observable phenomena:

Suppressed halo mass function at low masses

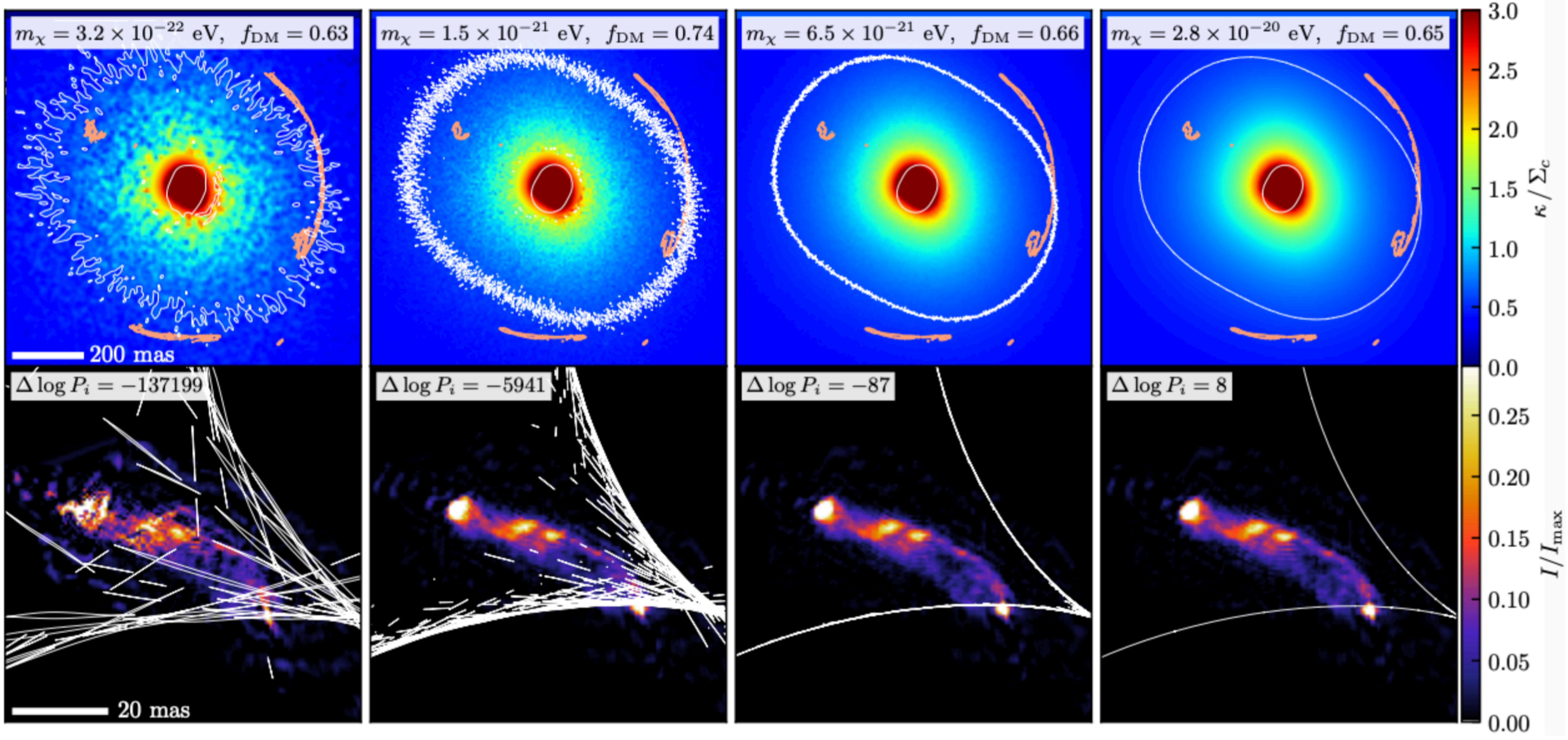
Cored density profiles

“Granules” due to wave interference



Fuzzy dark matter

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

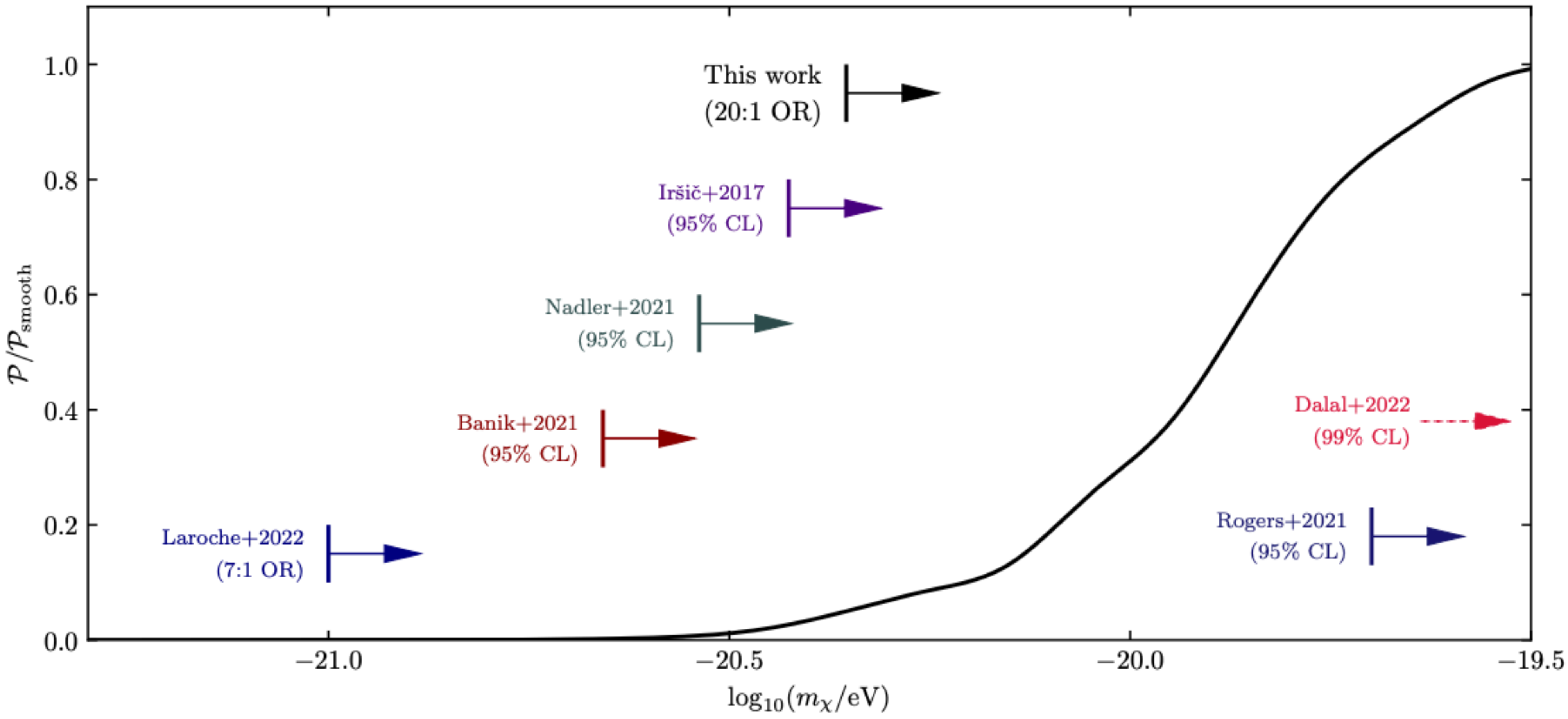


The inferred source model takes on a disrupted morphology in an attempt to fit the data, given the lens model

Powell, Vegetti et al. 2023

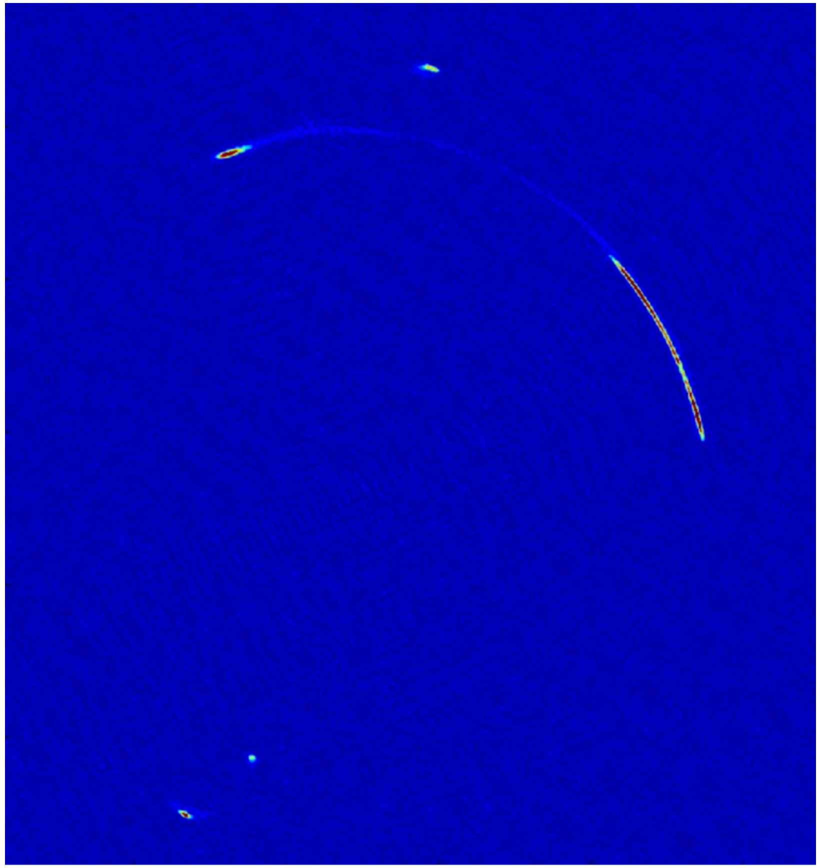
Fuzzy dark matter

From a single lens observation we rule out $m_\chi = 4.4\text{x}10^{-21}$ eV with a 20:1 posterior odds ratio



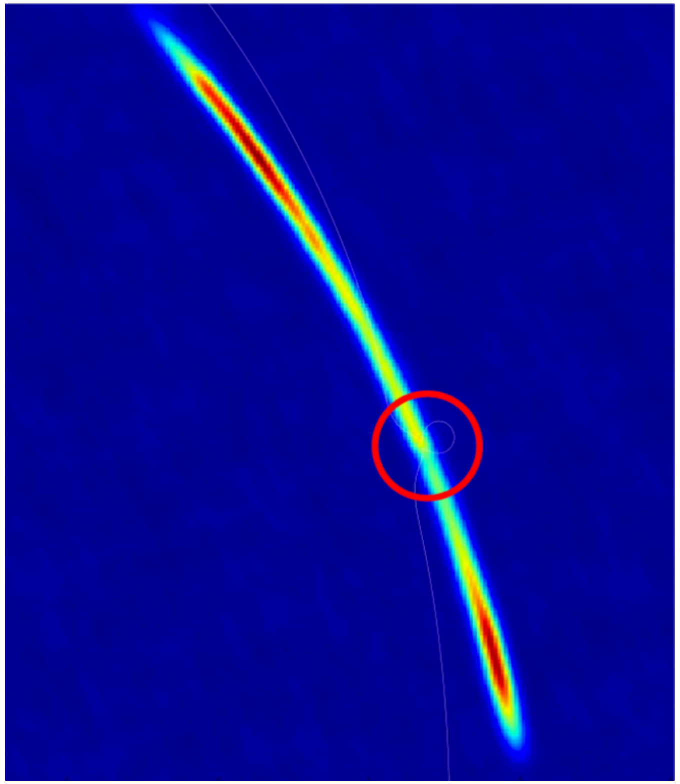
Powell, Vegetti et al. 2023

B1938+666



~5 mas resolution at 1.6 GHz, also have 5GHz data at less than 2 mas resolution

Very compact source leading to a very thin arc



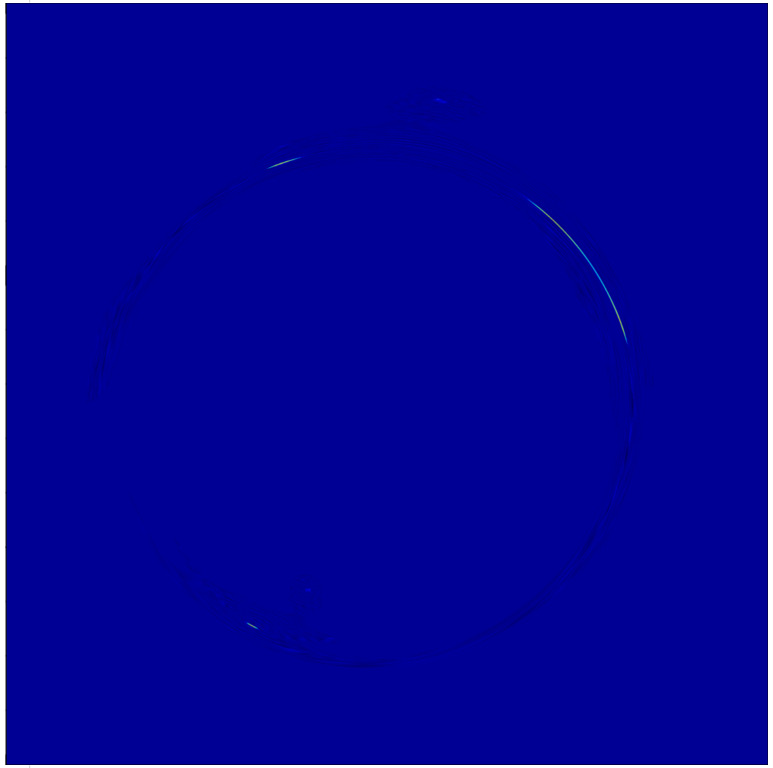
Preliminary:

M~3×10^6 M_{sun}, assuming truncated PL

NFW is too diffuse

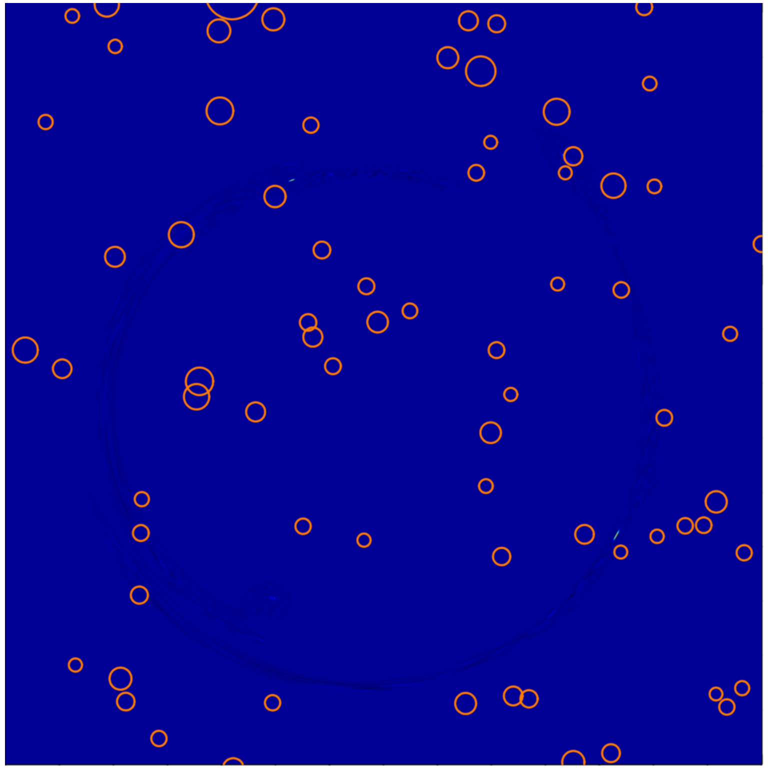
Arc morphology and a population of subhaloes

Smooth



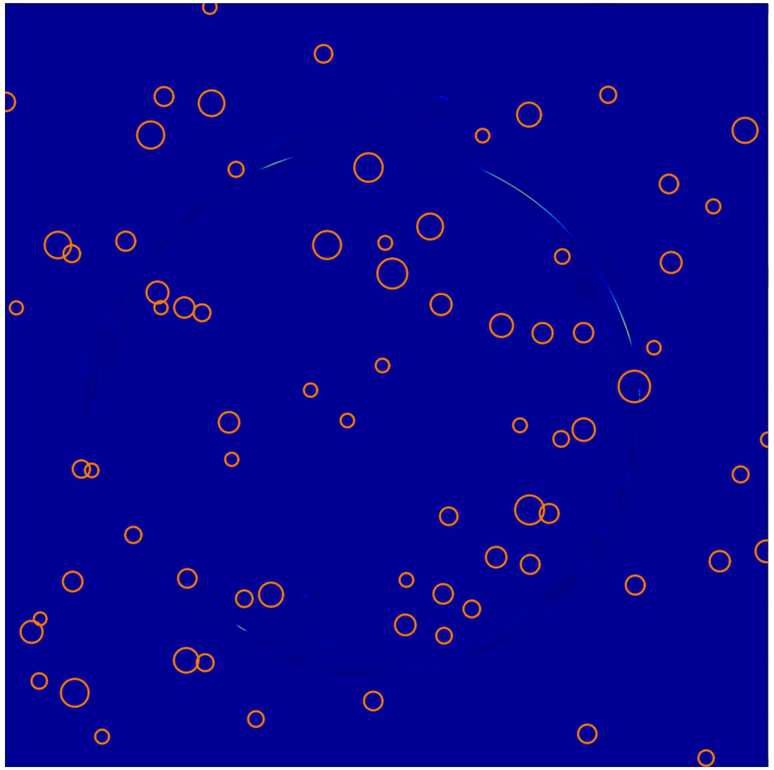
$N_{sub} = 0$

CDM, $M_{hm} = 10^{-6}\ M_{sun}$



$N_{sub} = 100$

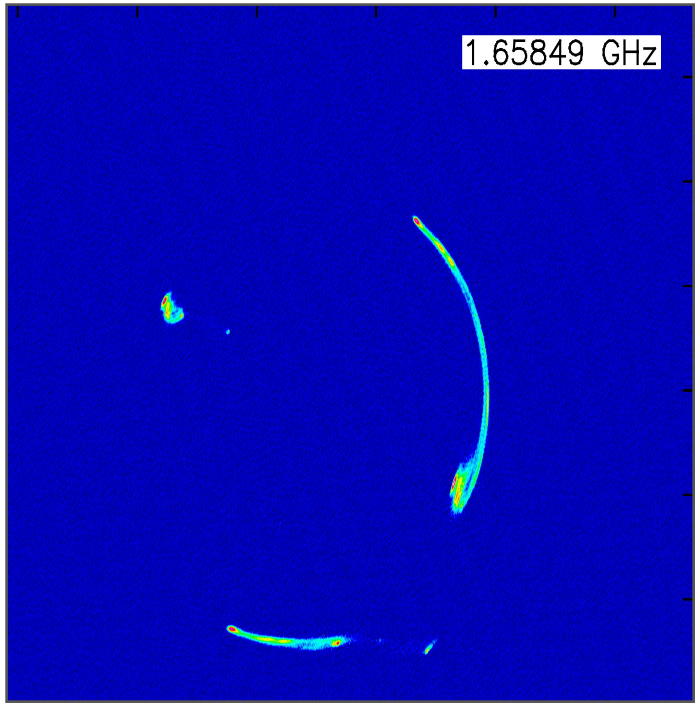
CDM, $M_{hm} = 10^{-6}\ M_{sun}$

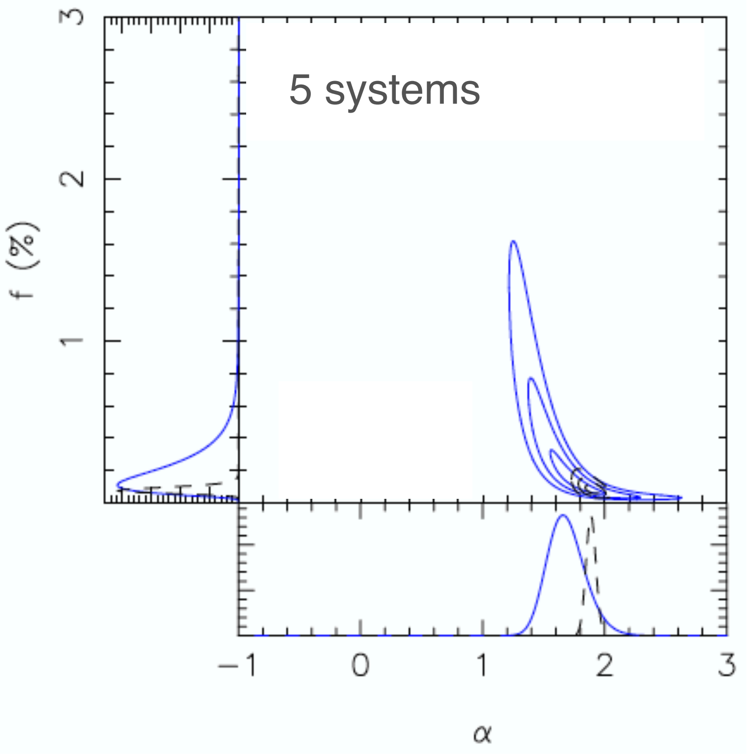


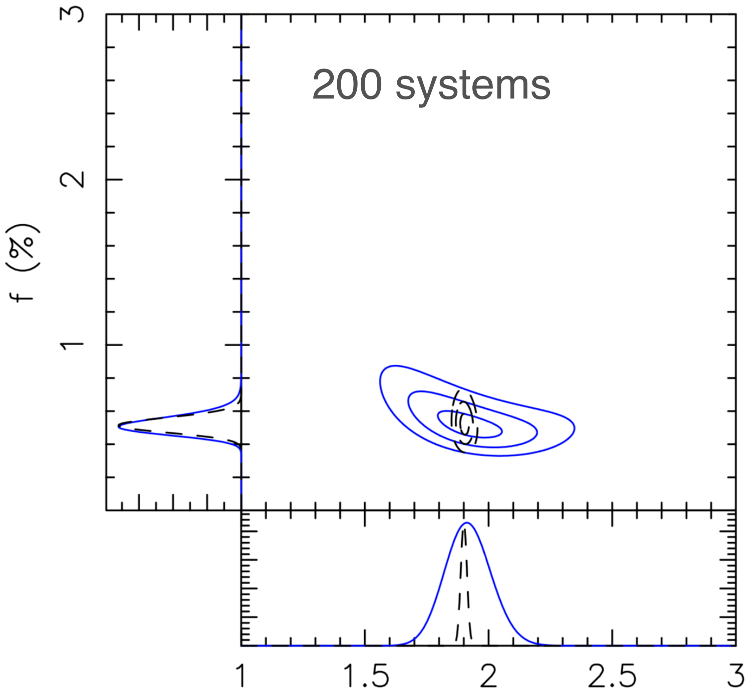
$N_{sub} = 100$

VLBI & CDM

Constraints on CDM mass function from sub haloes only







$$\frac{dn}{dm} \propto f m^{-\alpha}$$

Large Samples

DES+HSC+KIDS

10^3 galaxy-scale lenses

LSST

10^5 galaxy-scale lenses

Euclid

10^5 galaxy-scale lenses

SKA1-MID

10^5 galaxy-scale lenses

High Resolution

Keck-AO

100 mas resolution

E-Merlin

50 mas resolution

ALMA

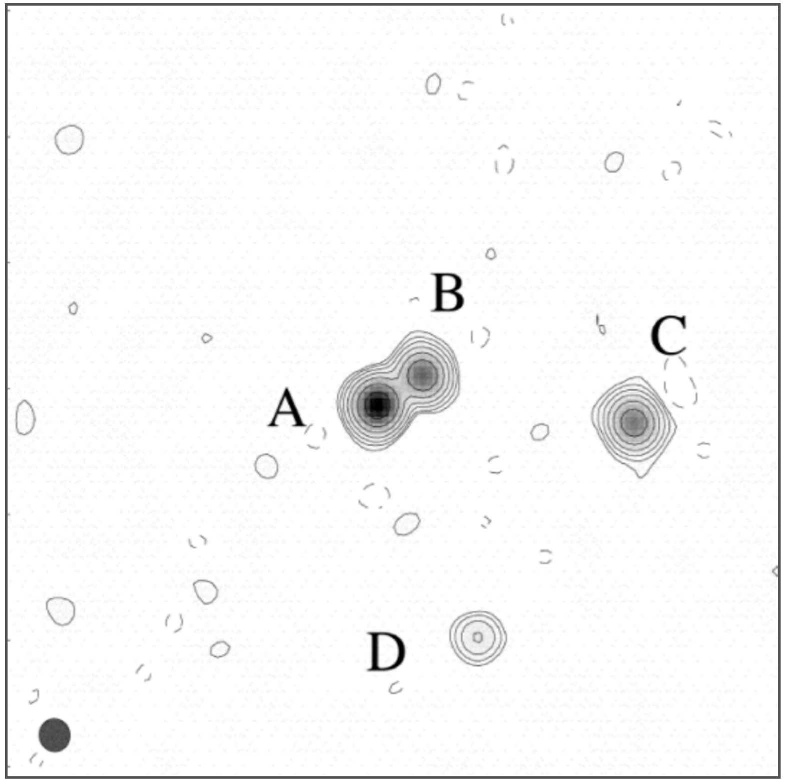
25 mas resolution

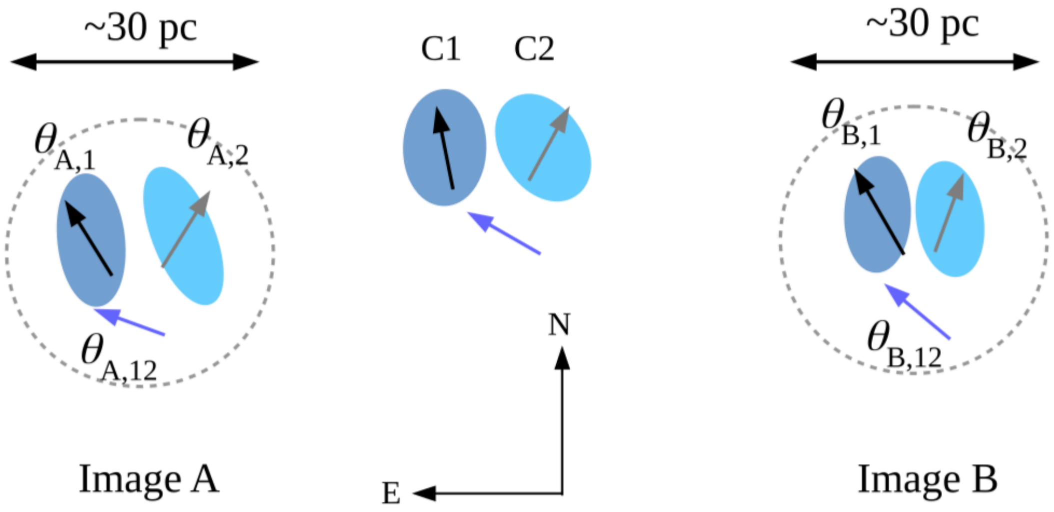
VLBI - ELT

3 to 4 mas resolution

Strong lensing and ALPs

Lensing conserves the polarisation angle of a linearly polarised source





A field of ALPs is expected to lead to differential faraday rotation, also known as differential birefringence

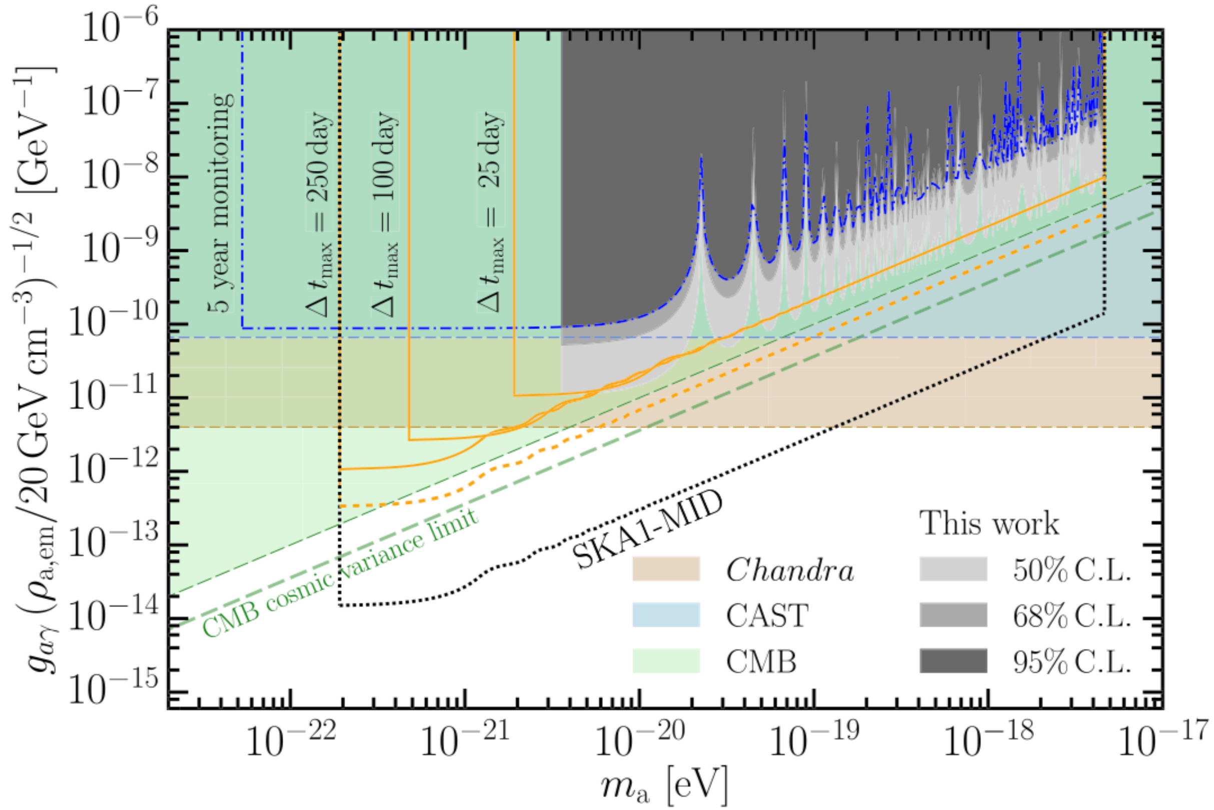
Basu & Schwarz 2021

Strong lensing and ALPs

$$\Delta\theta_{a,\mathrm{lens}} = K \sin\left[\frac{m_a \Delta t}{2}\right] \sin\left(m_a t_{\mathrm{em}} + \delta_{\mathrm{em}} - \pi/2\right).$$

Here, K in normalized units is

$$K = 10^{\circ} \left[\frac{\rho_{a,\mathrm{em}}}{20\ \mathrm{GeV\,cm^{-3}}}\right]^{1/2} \frac{g_{a\gamma}}{10^{-12}\ \mathrm{GeV^{-1}}} \left[\frac{m_a}{10^{-22}\ \mathrm{eV}}\right]^{-}$$



Single epoch observations allow one to constrain the coupling with photons for a given ALP mass

With monitoring observations one can also constrain the mass

Conclusions

Strong gravitational lensing in combination with high-performance computation lens modelling has become a unique tool to answer fundamental questions on the physics of the Universe and in particular about the nature of dark matter

SKA and Euclid will mark the beginning of a new era in strong gravitational lensing studies with $\sim 10^5$ lenses

Observations at mas resolution with ALMA, ELT and the VLBI will allow us to test and potentially rule out whole families of dark matter models

Dark matter

Devon Powell

Visibility Fitting algorithms
for large data sets
from VLBI observations

Conor O’Riordan

Machine learning tools
for large samples from
Euclid and SKA

Aleksandra Grudskaia

ABC approaches
to WDM inference

Visibility Fitting
algorithms
for polarised data

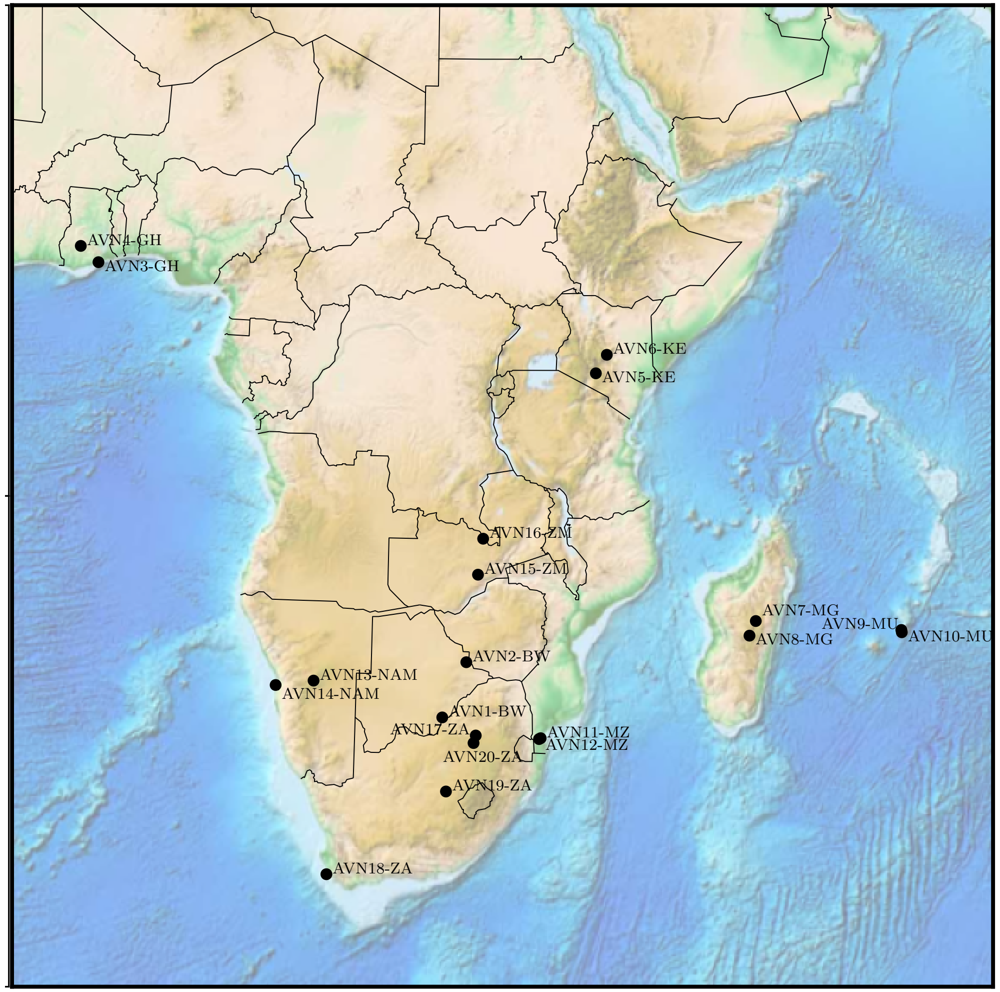
Aniruddh Herle

Simon Ndiritu

YOU?

South African Research Chair Initiative (SARChI) in VLBI

John McKean - RUG & UP



- 5 yr x 3 project to develop VLBI on the African continent (African VLBI Network).
  - Phase 1: Develop local knowledge base.
  - Phase 2: Develop local infrastructure.
  - Phase 3: Deploy antenna systems.

- Science goals:
  - Carryout gravitational lens surveys (w/ ILT, SKA).
  - Detailed lensing analysis for cosmology (w/ EVN).
  - Wide-field VLBI for AGN/SF studies (lens searches) (w/ ILT, EVN).