Fuzzy dark matter constraints using a single VLBI observation of a gravitationally lensed radio jet

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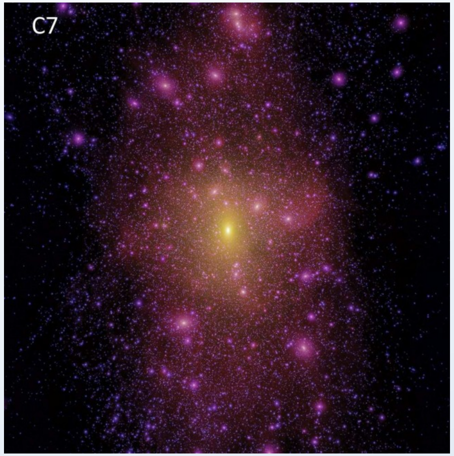
with Simona Vegetti, John McKean, Simon White,
Elisa Ferreira, Simon May, Cristiana Spingola

2302.10941 (this work, submitted to MNRAS Letters)
2207.03375 (smooth lens modeling, published in MNRAS)
2005.03609 (inference method, published in MNRAS)

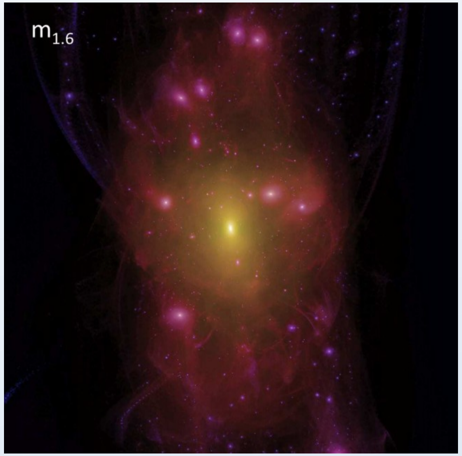
Background: Dark matter phenomenology

Cold DM



Lovell+2014

Warm DM

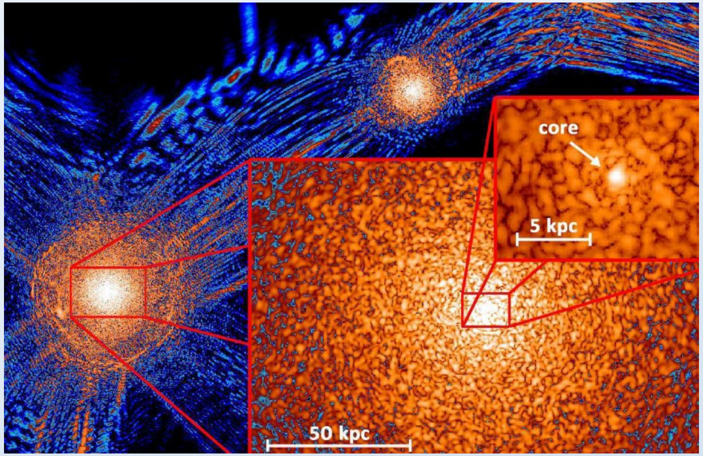


Lovell+2014

Self-interacting DM

Rocha+2013

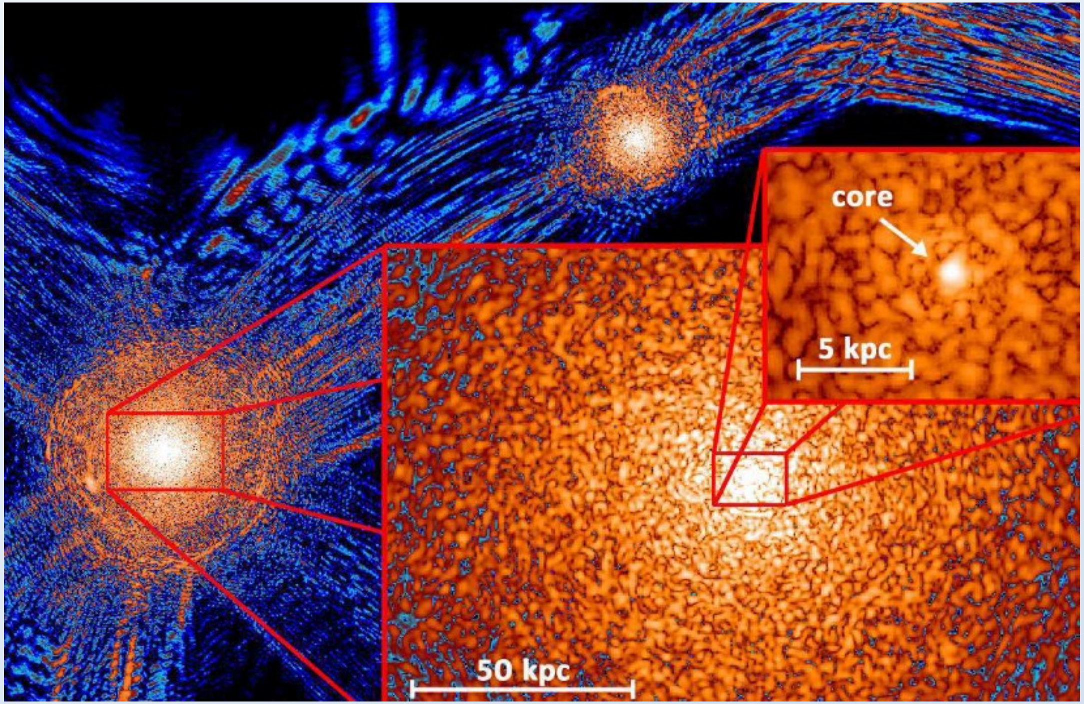
Fuzzy DM



Schive+2014

Background: Fuzzy dark matter

- Fuzzy dark matter (FDM) is a class of ultra-light DM that exhibits a ~kpc-scale de Broglie wavelength (originally motivated by the mass of the QCD axion, but also may explain sub-galaxy-scale phenomena better than CDM)
- Main observable phenomena:
  - Suppressed halo mass function at low masses (Nadler+2021, Banik+2022, Laroche+2022)
  - Cored density profiles (most apparent in dwarf galaxies: Chen+2017, Safarzadeh+2020, Hayashi+2021)
  - **“Granules” due to wave interference (This work, Marsh+2019, Laroche+2022)**

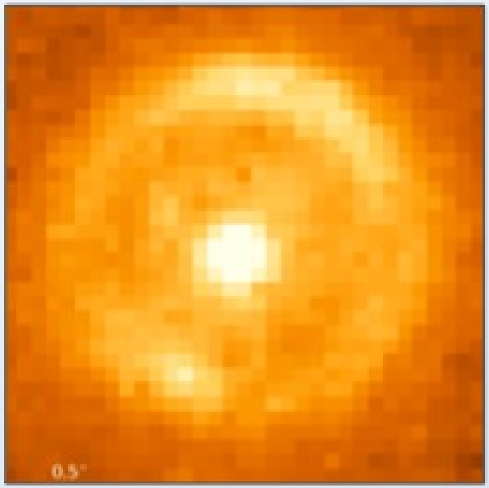


Schive+2014

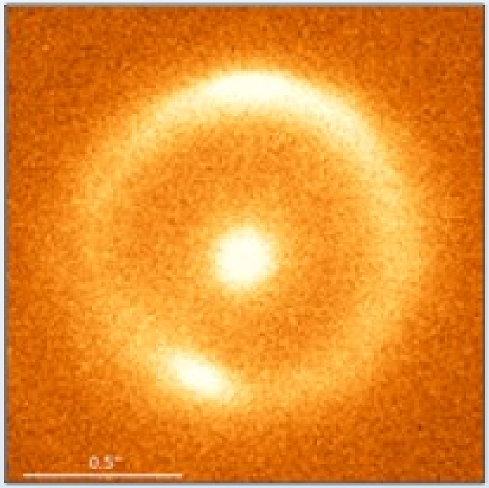
Background: angular resolution

- The sensitivity of a gravitational lens observation to low-mass dark structures is mainly determined by angular resolution.

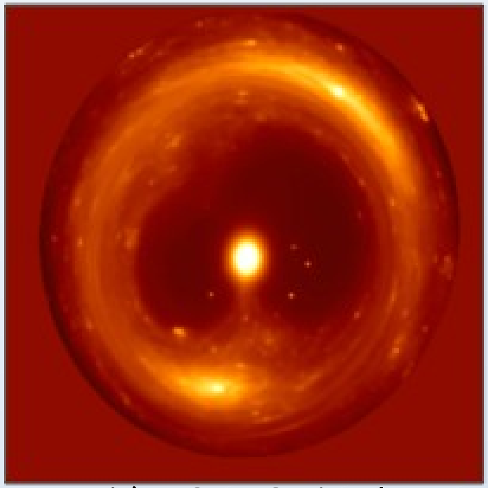
HST *(real data)*
~10^9 M_{sun}



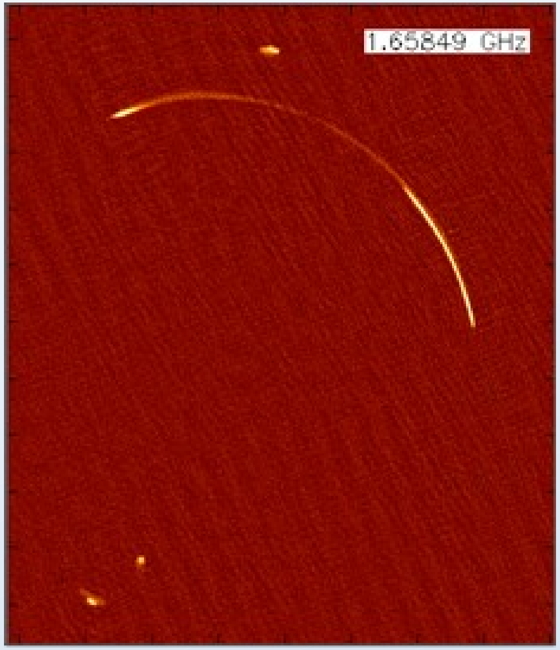
Keck AO *(real data)*
~10^8 M_{sun}



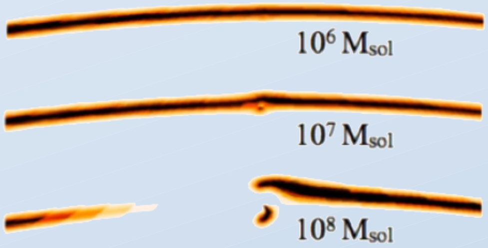
E-ELT *(mock data)*
~10^{7}-10^6 M_{sun}



Vegetti (MICADO simulator, 3 hours on-source)



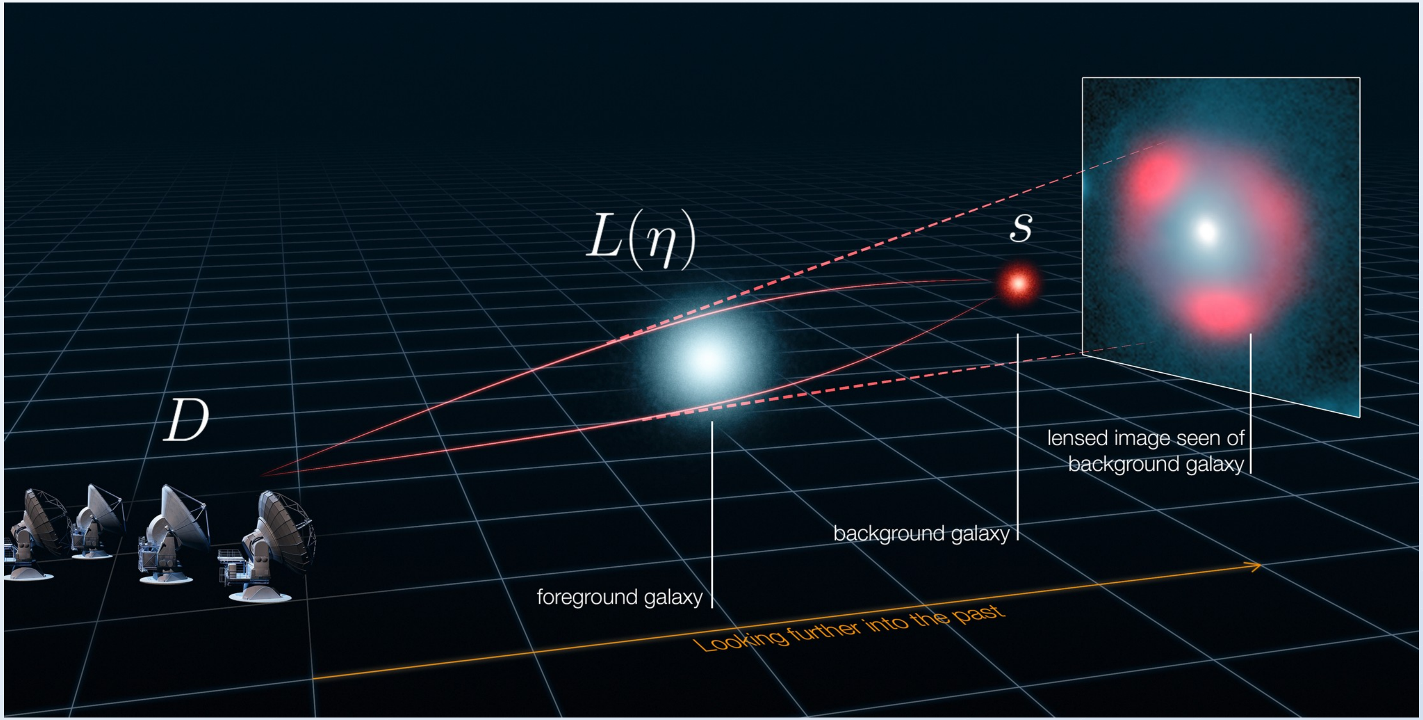
VLBI *(real data)*
~10^6 M_{sun}



McKean

Background: Radio interferometry

- Array of radio antennas samples Fourier modes of the sky brightness
- Each pair of antennas measures a “visibility” corresponding to one Fourier component
- The response of the instrument is a Fourier transform (D in the schematic below)
- **Distance between antennas and observing wavelength determines angular resolution ~λ/d**



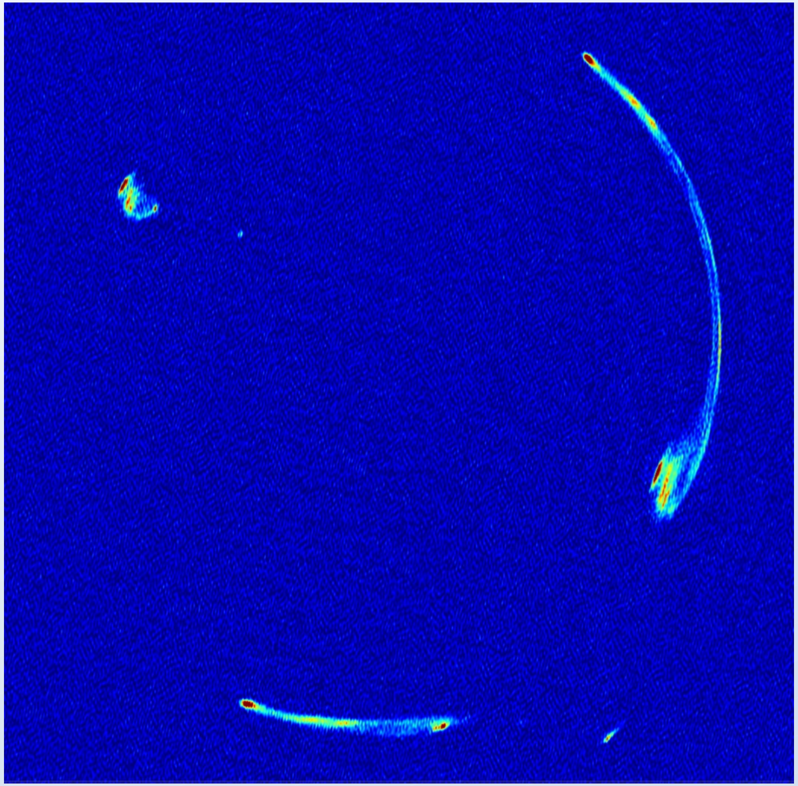
ALMA (ESO/NRAO/NAOJ), L. Calada (ESO), Y. Hezaveh et al.

Background: Gravitational lensing with VLBI

- We use global very long baseline interferometry (VLBI)
- **Earth-scale antenna spacings give ~5 mas resolution at 1.6 GHz.**
- **Long, thin arcs are extremely sensitive to perturbations by low-mass dark structures in the lens!**

MG J0751+2716

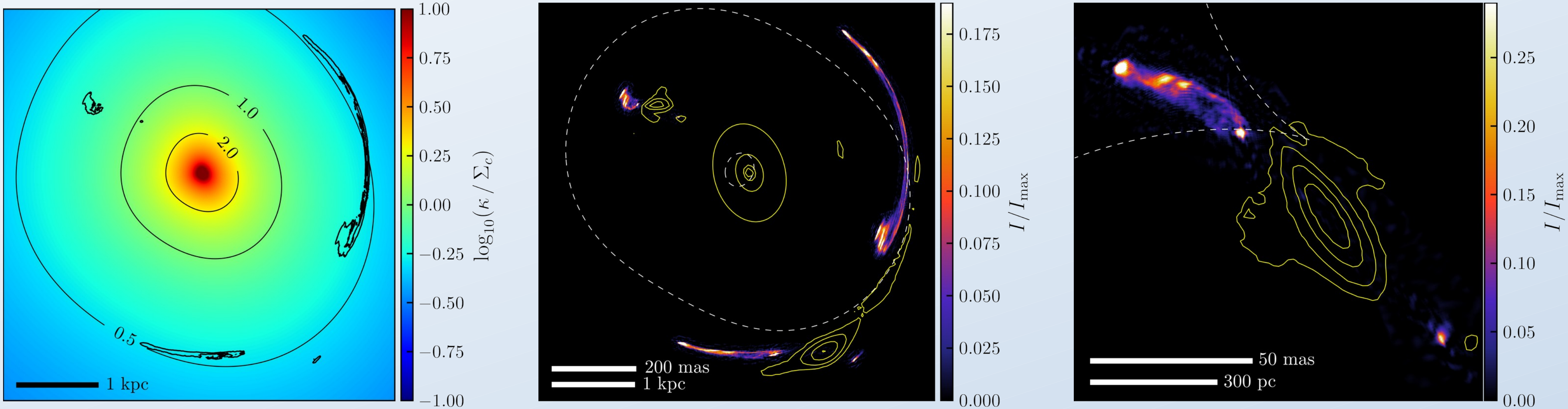
Einstein radius is ~0.4 arcsec



Spingola+2018

Method: Forward modeling with VLBI data

- **Forward modeling**: Recover a pixellated source brightness model, **as well as a likelihood,** for a given lens model: **Allow us to quantify how well a given lens mass distribution explains the observed data.**
- I developed a tractable method for forward-modeling milli-arcsecond-resolution VLBI lens observations (Powell+2021).
- The first application to data was a global VLBI observation of the lensed radio jet MG J0751+2716 (Powell+2022, see below)
- **A smooth parametric lens model describes the data surprisingly well. This will be our baseline model for the FDM inference**



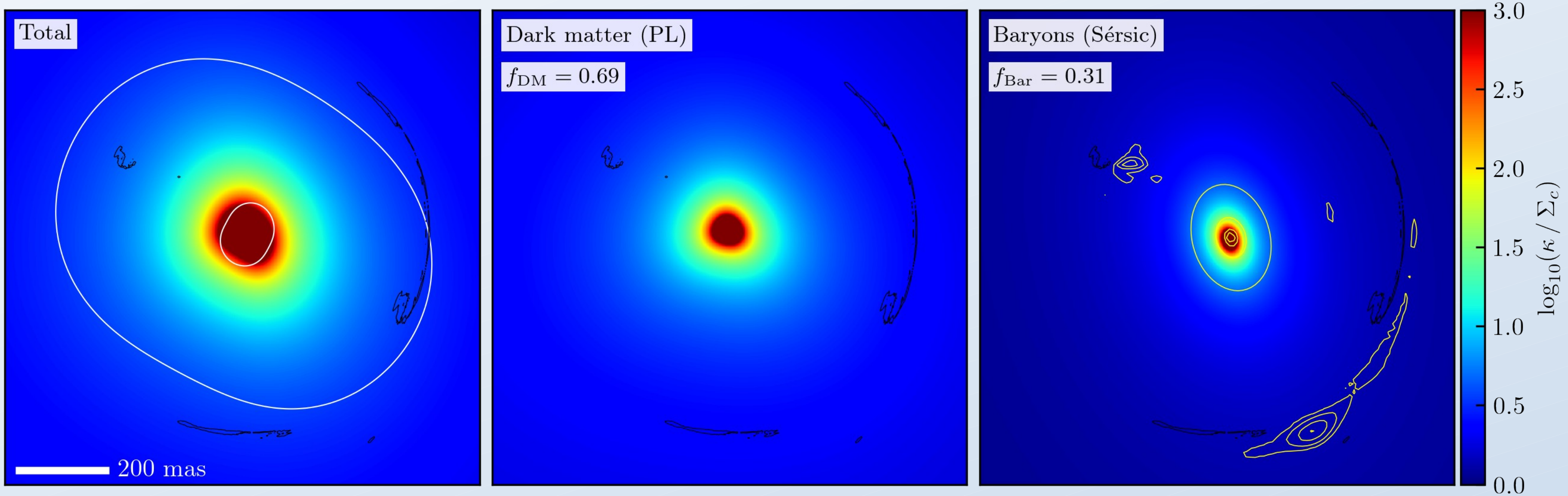
Method: Generating fuzzy lenses

- Chan+2020 analytically describes the density statistics of virialized wave dark matter in a potential well.
- The variance of the projected surface density fluctuations is a function of the dark matter density profile and the de Broglie wavelength:

$$\langle \delta\kappa^2 \rangle = \frac{\lambda\!\!\!^{-}_\chi \sqrt{\pi}}{\Sigma_c^2} \int \rho_{\rm DM}^2 \, dl,$$

- The (reduced) de Broglie wavelength is:

$$\lambda\!\!\!^{-}_\chi = \hbar/(m_\chi \sigma_v)$$



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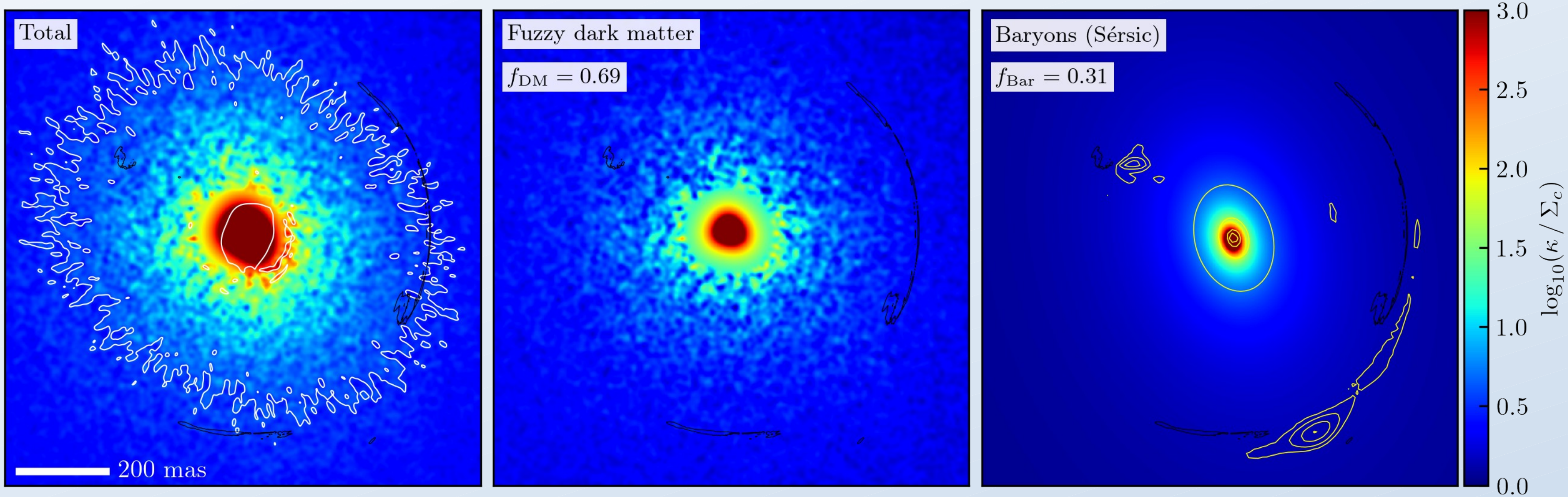
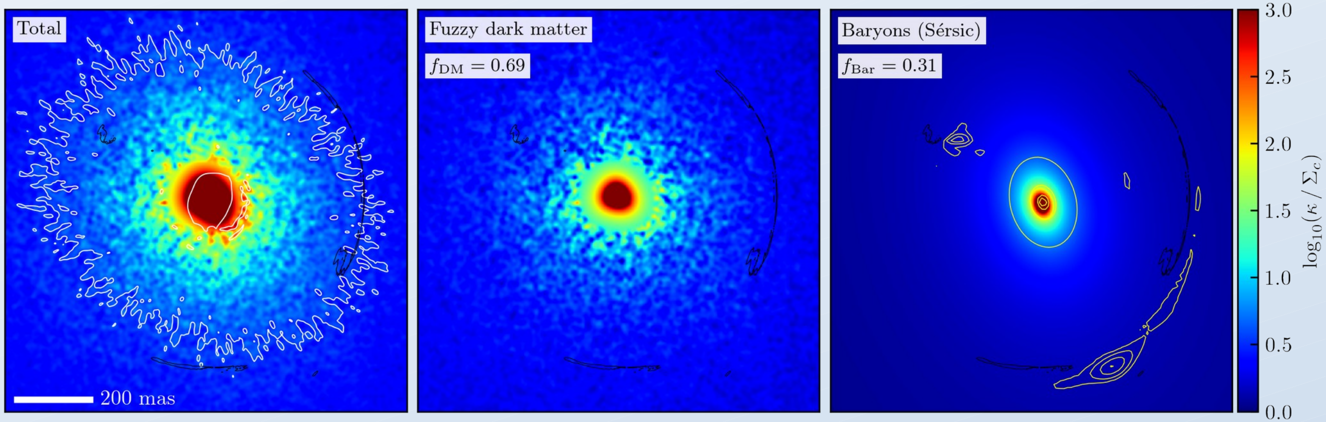


Method: Inference on FDM lens models

1) For a single fuzzy lens realization, we compute the likelihood $P_i(\, \boldsymbol{d} \mid m_\chi, f_{DM}, \sigma_v, \boldsymbol{\eta}, \lambda_s\,)$, where:

- $\boldsymbol{d}$ are the data (interferometric visibilities)
- m_χ is the DM particle mass
- FDM is the dark matter fraction in the lens
- σ_v is the velocity dispersion of the dark matter (a proxy for the depth of the potential well)
- $\boldsymbol{\eta}$ are the smooth lens model parameters
- λ_s is a hyper-parameter that controls the source regularization strength.
- The subscript *i* denotes that this likelihood is one of an infinite number of random fuzzy DM realizations that are possible given these parameters.



Method: Inference on FDM lens models

2) We generate ~40k fuzzy lens realizations, with parameters drawn from the following priors:

Parameter	Description	Prior
$\log_{10}(m_\chi)$	DM particle mass (eV)	$\mathcal{U}(-21.5, -19.0)$
$f_{\rm DM}$	Projected DM mass fraction	$\mathcal{U}(0.5, 0.8)$
σ_v	DM velocity dispersion (km/s)	$\mathcal{U}(100, 110)$
$\boldsymbol{\eta}$	Smooth lens model parameters	$\mathcal{N}(\boldsymbol{\mu}_{\boldsymbol{\eta},\lambda_s}, \boldsymbol{\Sigma}_{\boldsymbol{\eta},\lambda_s})$
λ_s	Source regularization strength	

3) We accept a sample if its likelihood P_i is above the 3σ contours of the baseline smooth model.

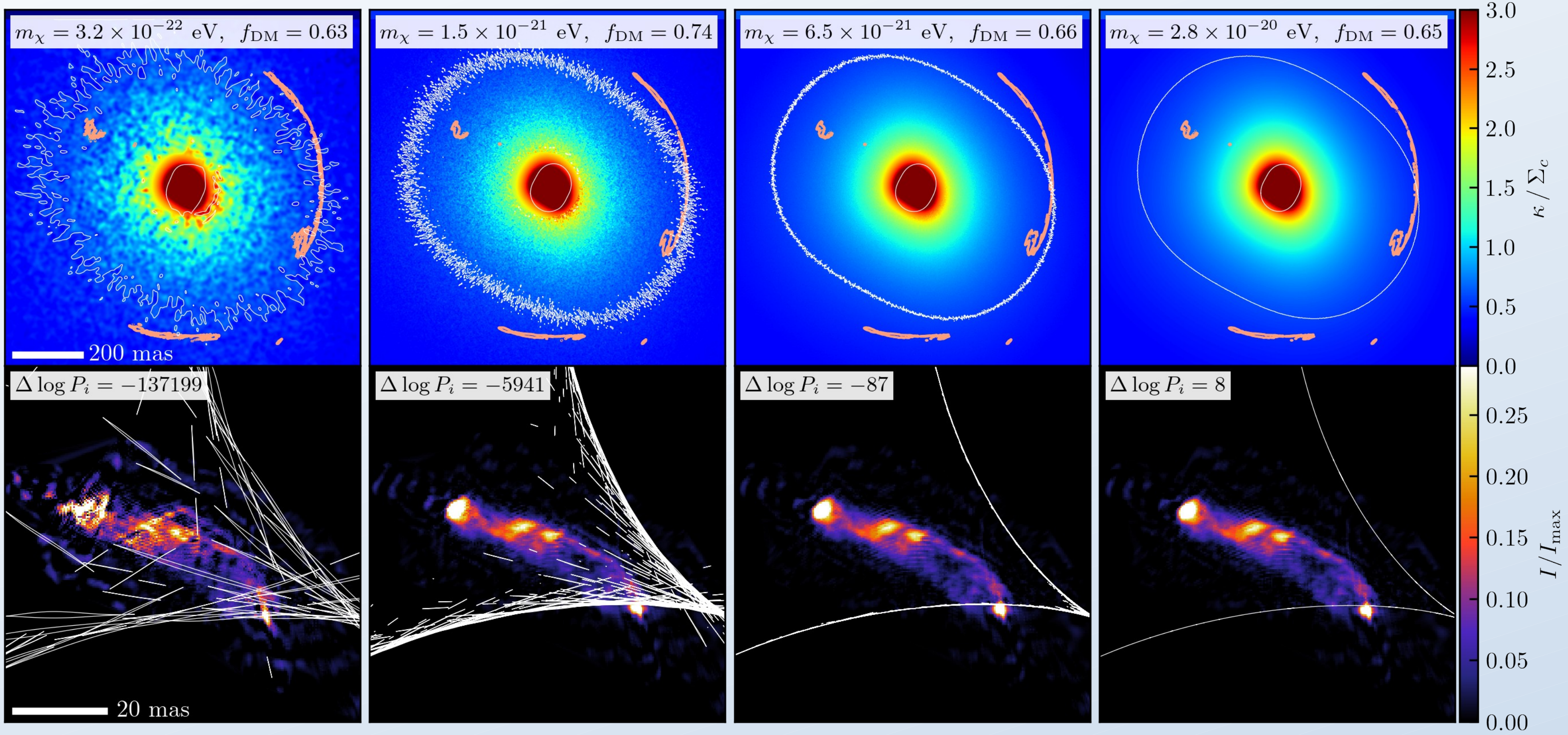
- i.e., for a FDM lens realization to be accepted, it must explain the data at least as well as the worst 0.3% of the smooth model posterior samples.
- In practice, we define a relative log-likelihood $\Delta\log P_i$, where samples are accepted if $\Delta\log P_i > 0$.

4) We build a histogram of the accepted samples to obtain an empirical posterior on m_χ

- All other parameters are marginalized over automatically
- In principle, it is possible to compute an analytic posterior, but the large random variance between individual realizations makes a converged posterior computationally prohibitive
- We instead opt for a conservative threshold, and uniformly weight the accepted samples

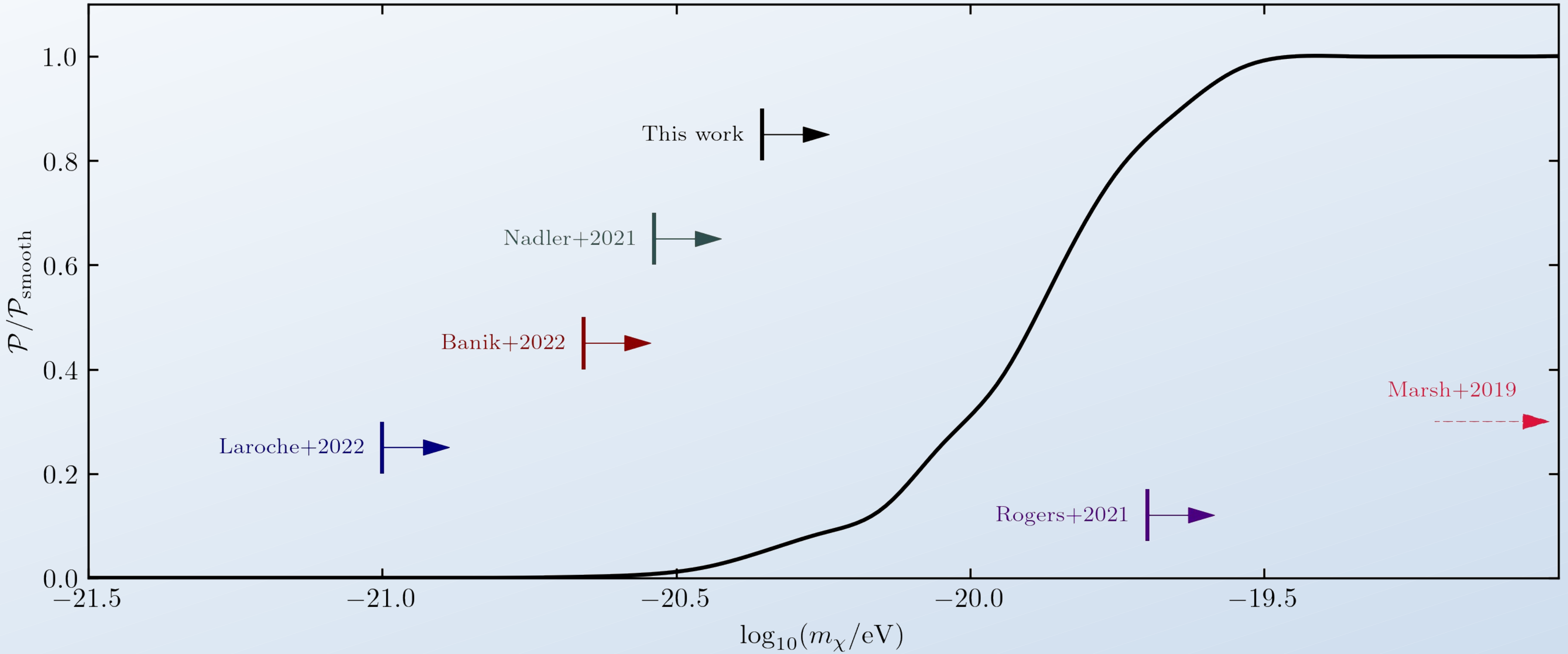
Results: disruption of the source morphology

- When the particle mass m_χ is low, the FDM 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
- The inability of a fuzzy lens realization to explain the data is penalized in the likelihood, $\Delta \log P_i$



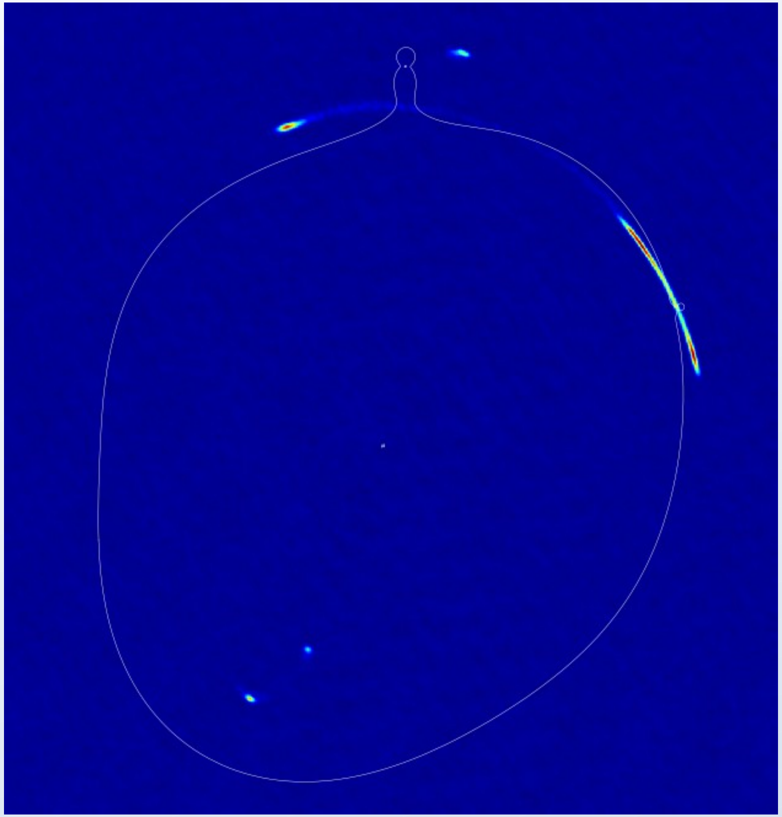
Results: Posterior odds ratio, relative to the smooth model

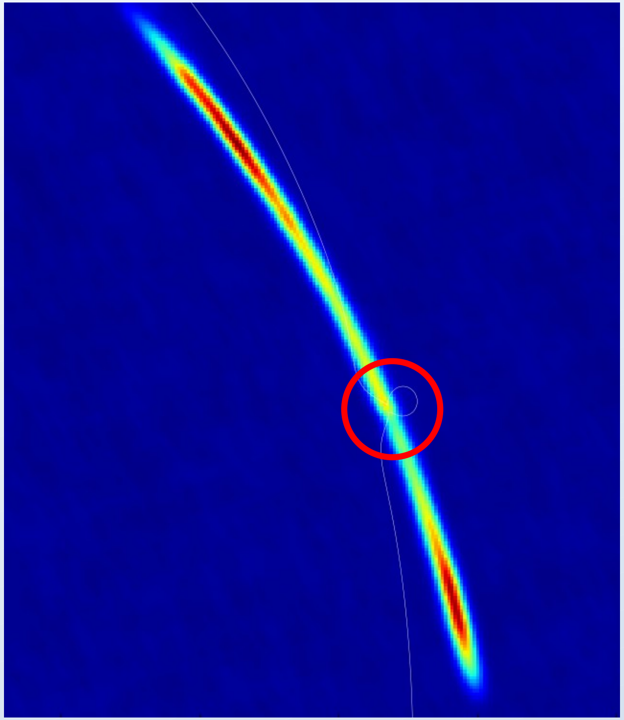
- m_χ = 4.4x10^{-21} eV is ruled out with a 20:1 posterior odds ratio (POR)
- For *vector* fuzzy DM (3 DOF), m_χ > 1.4x 10^{-21}
- This constraint is from a single lens observation!



Work in progress: B1938+666

- Very compact source sitting right on the caustic produces extremely smooth arcs.
- **A “kink” in the arc indicates a low-mass perturber object near the critical curve.**
- This dataset has ~5 mas resolution at 1.6 GHz, and the feature also appears in the 5GHz data at <2 mas resolution.





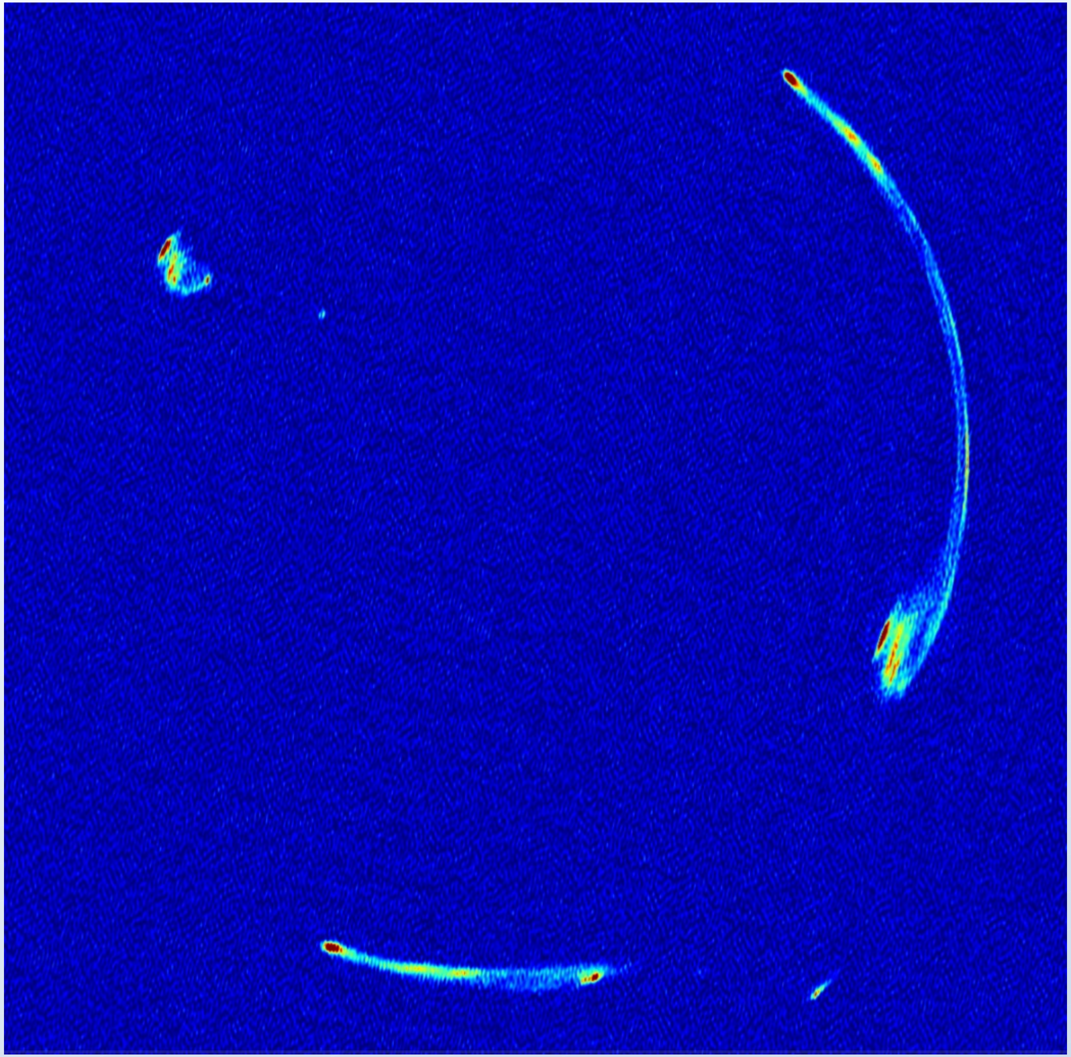
Observation and data reduction by John McKean

PRELIMINARY:

- ~4×10^6 M_{sun}, assuming truncated PL
- Must also consider different possible density profiles, as well as redshift.

Conclusions

- VLBI provides the highest-resolution lens observations available to date. (< 5 mas, future will push to < 1 mas)
- Long, thin, smooth arcs are great for probing small-scale dark structure in strong lenses: Gives us direct sensitivity to the presence or absence of fuzzy DM granules in the lens.
- We expect sensitivity in m_χ to scale with angular resolution.
- SKA will discover tons of new radio-bright lenses with extended structure like this one.
- Sensitive to 10^6 M_{sun} subhaloes in WDM, analysis for WDM population statistics is ongoing
- Characterizing the sub/LOS-halo population should give constraints on WDM m_χ ~ 20 keV



Spingola+2018

Recap: Fuzzy dark matter

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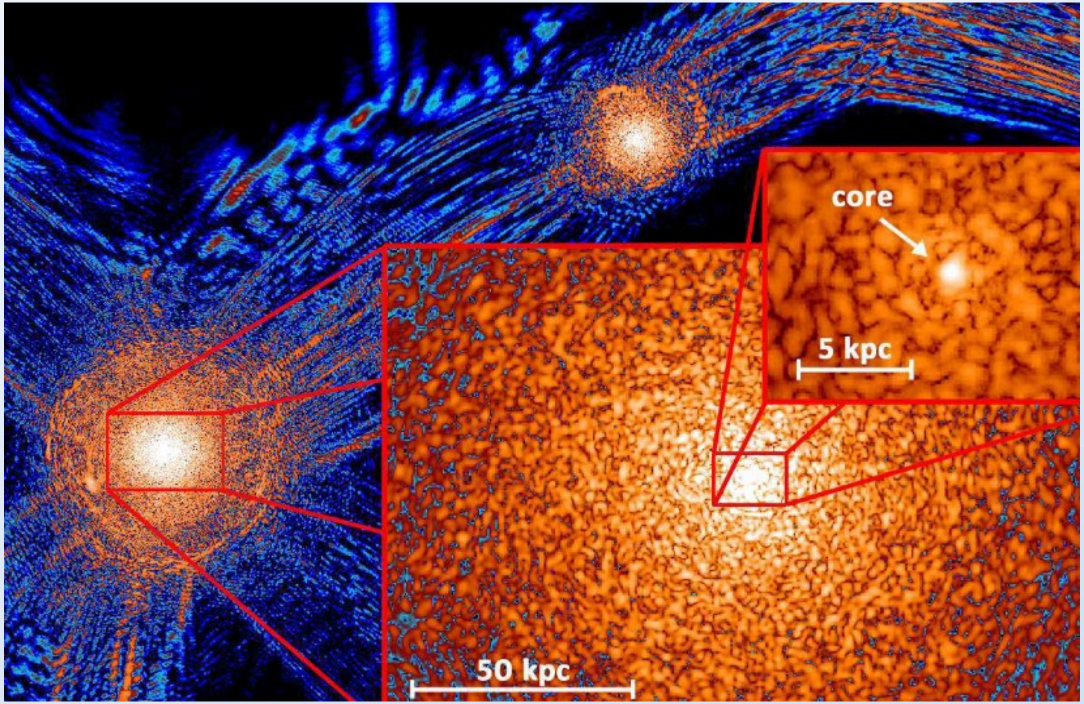
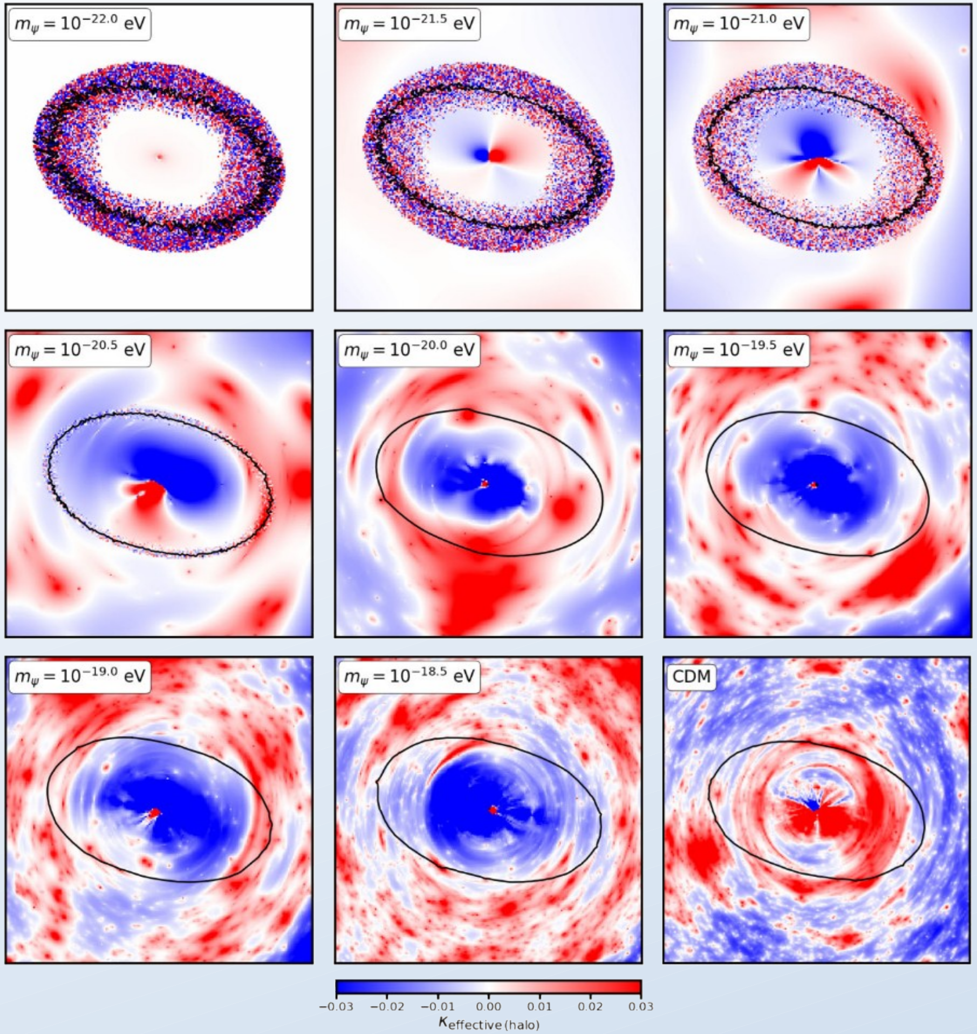


Schive+2014

Subhaloes in FDM



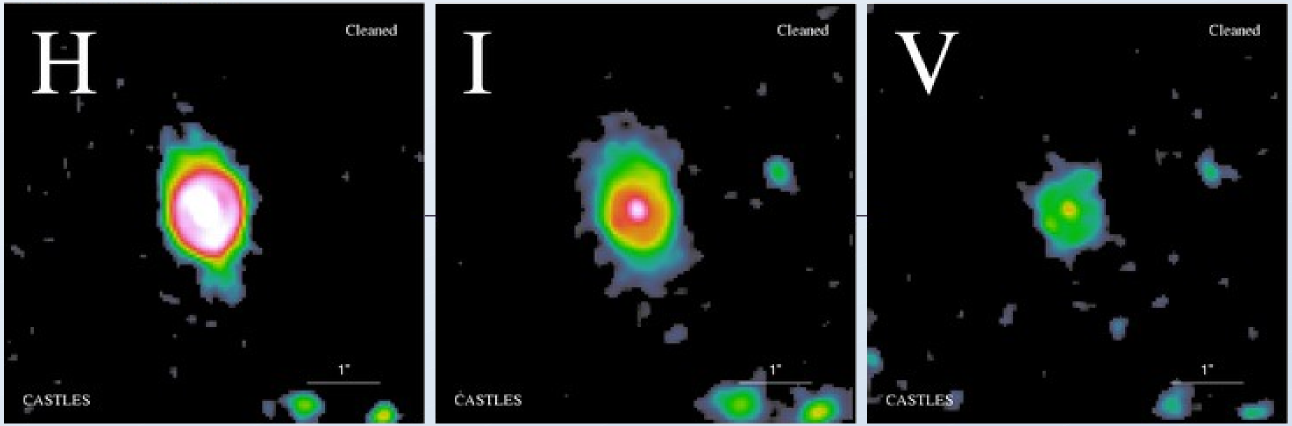
Laroche+2022

f_{DM} from HST photometry

- WFPC2 *V*- and *I*-band photometry gives ~8×10^9 M_{sun} stellar mass component.
- In good agreement with our composite smooth lens modeling, which gives 8.6×10^9 M_{sun}

Data from Castles			
Observations		**G**	**Source**
Position	**RA(arcsec)**	0	-0.634±0.021
	Dec(arcsec)	0	-0.225±0.026
fluxes	**F160W**	18.87±0.16	21.66±0.25
	F555W	23.24±0.11	25.10±0.25
	F814W	21.26±0.03	23.72±0.05

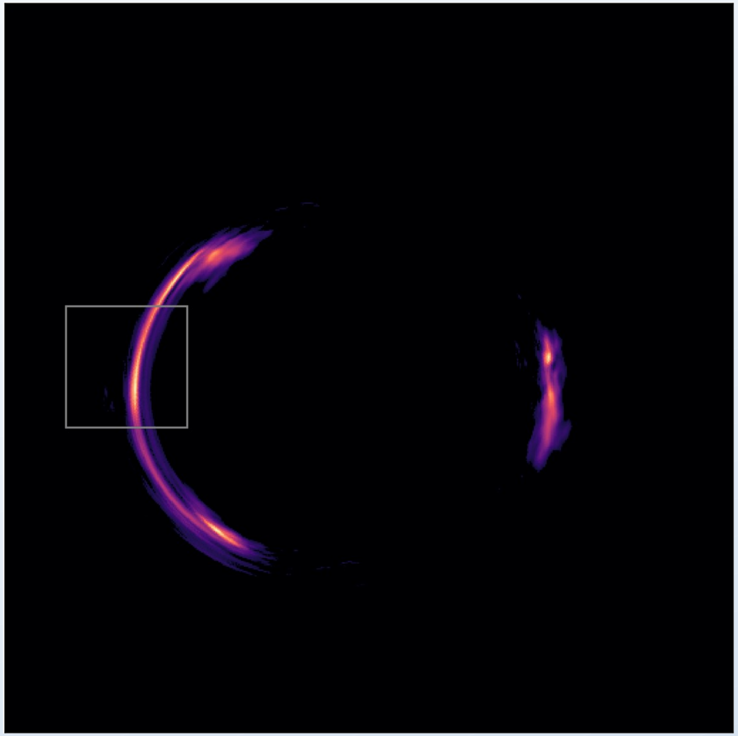
Cleaned data:

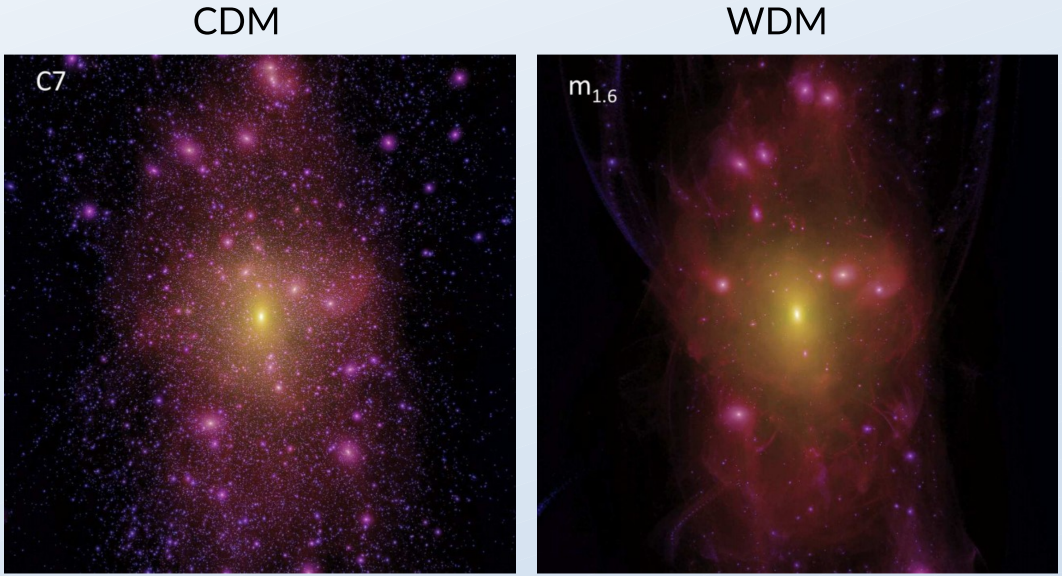


CASTLES survey

Background: Strong gravitational lensing (galaxy-galaxy)

- We can infer the properties of subhaloes (or granules, or other dark structures) via their effect on the lensed arcs.
- **In this talk, we are focusing on the case of extended (resolved) sources, *not* unresolved point images.**
- **This slide is just an illustrative example of a single subhalo in CDM/WDM**. The rest of the talk is about fuzzy DM, which produces a very different mass distribution in the lens galaxy (wait a few slides).





Lovell+2014

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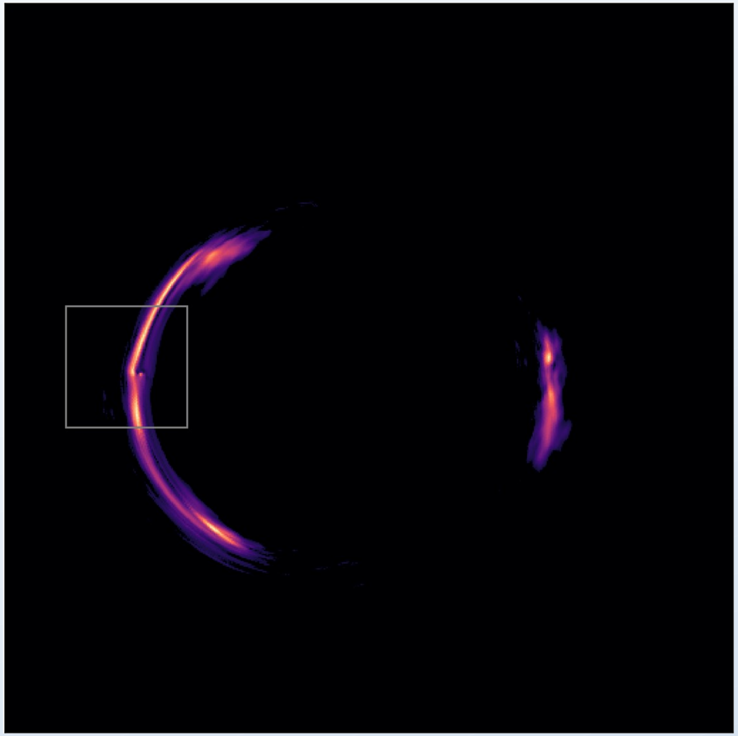
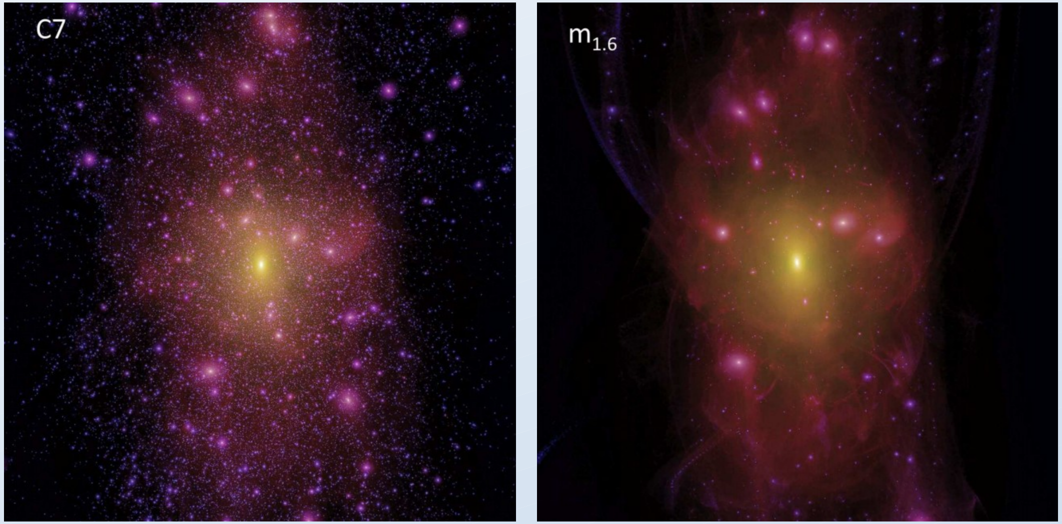
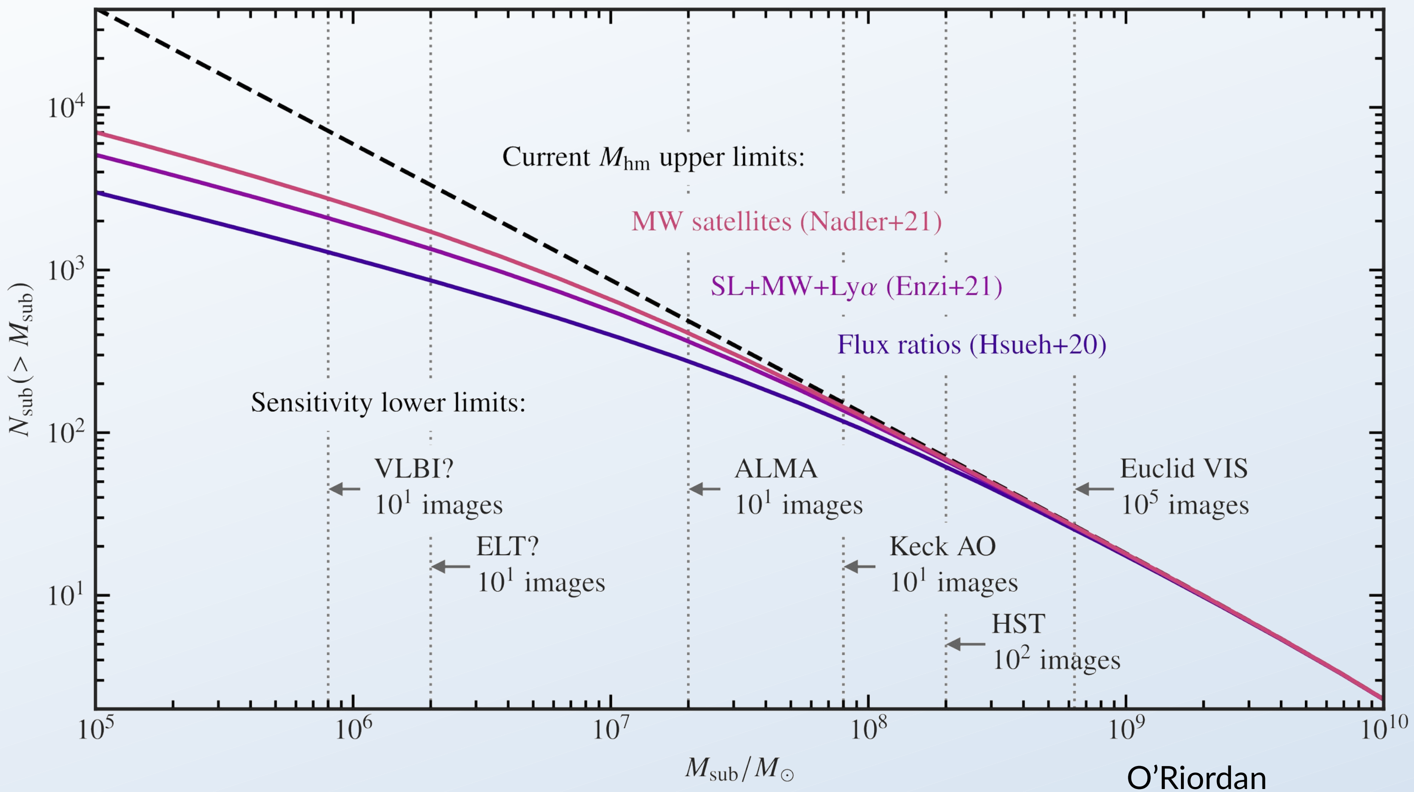


CDM WDM

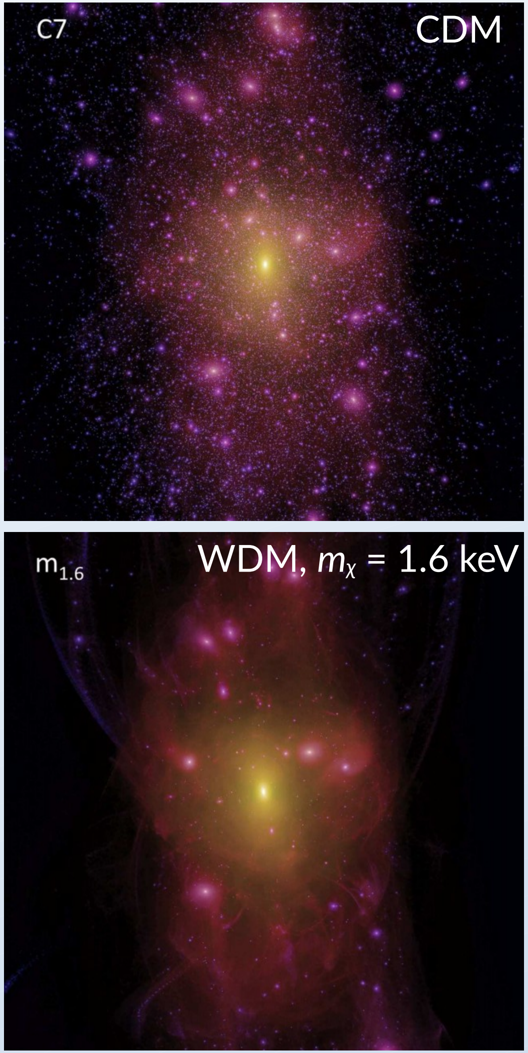


Lovell+2014

WDM constraints



O'Riordan

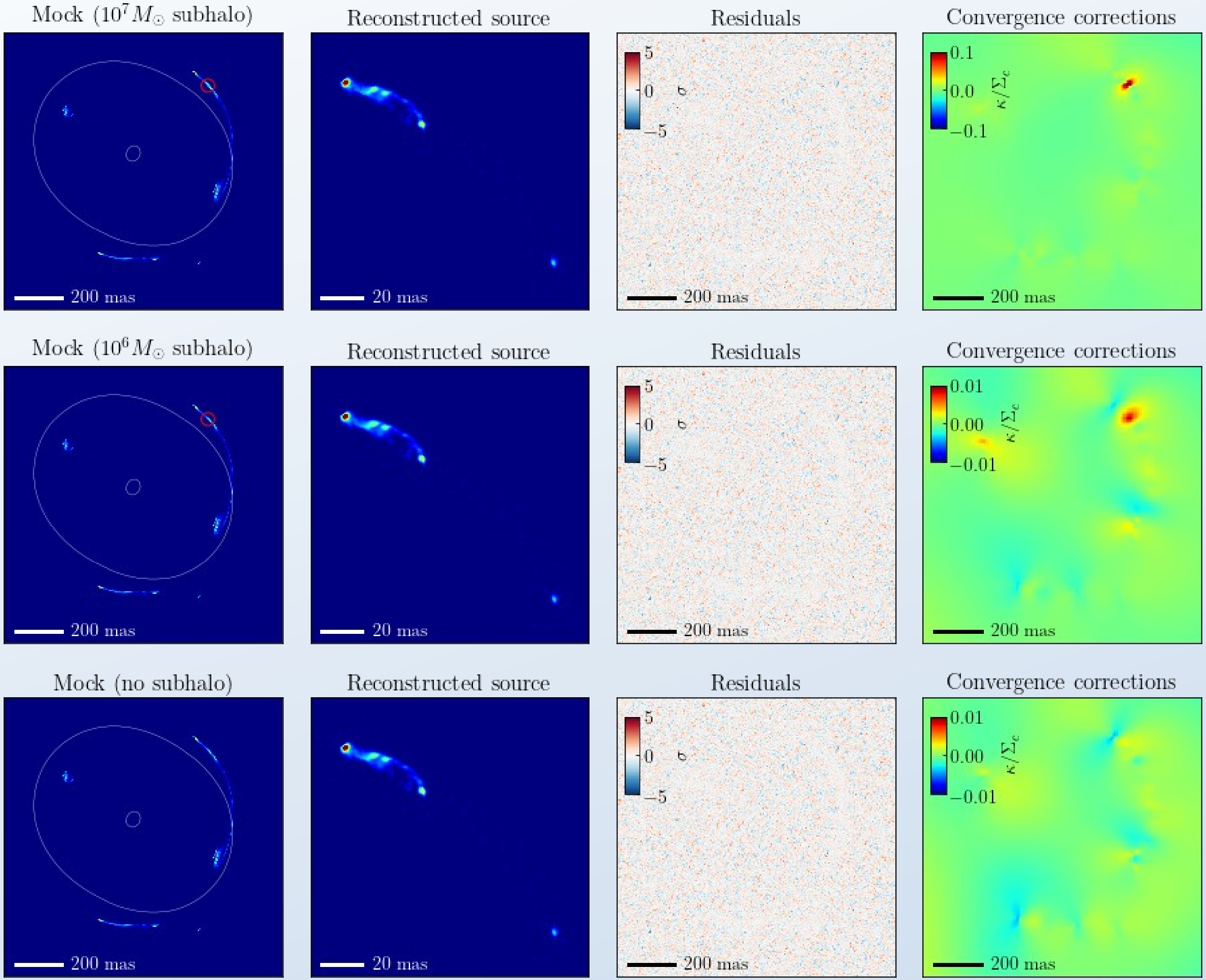


Lovell+2014

(Current best constraint is m_χ > 9.7 keV by Nadler+2021)

Warm DM
(mock data)

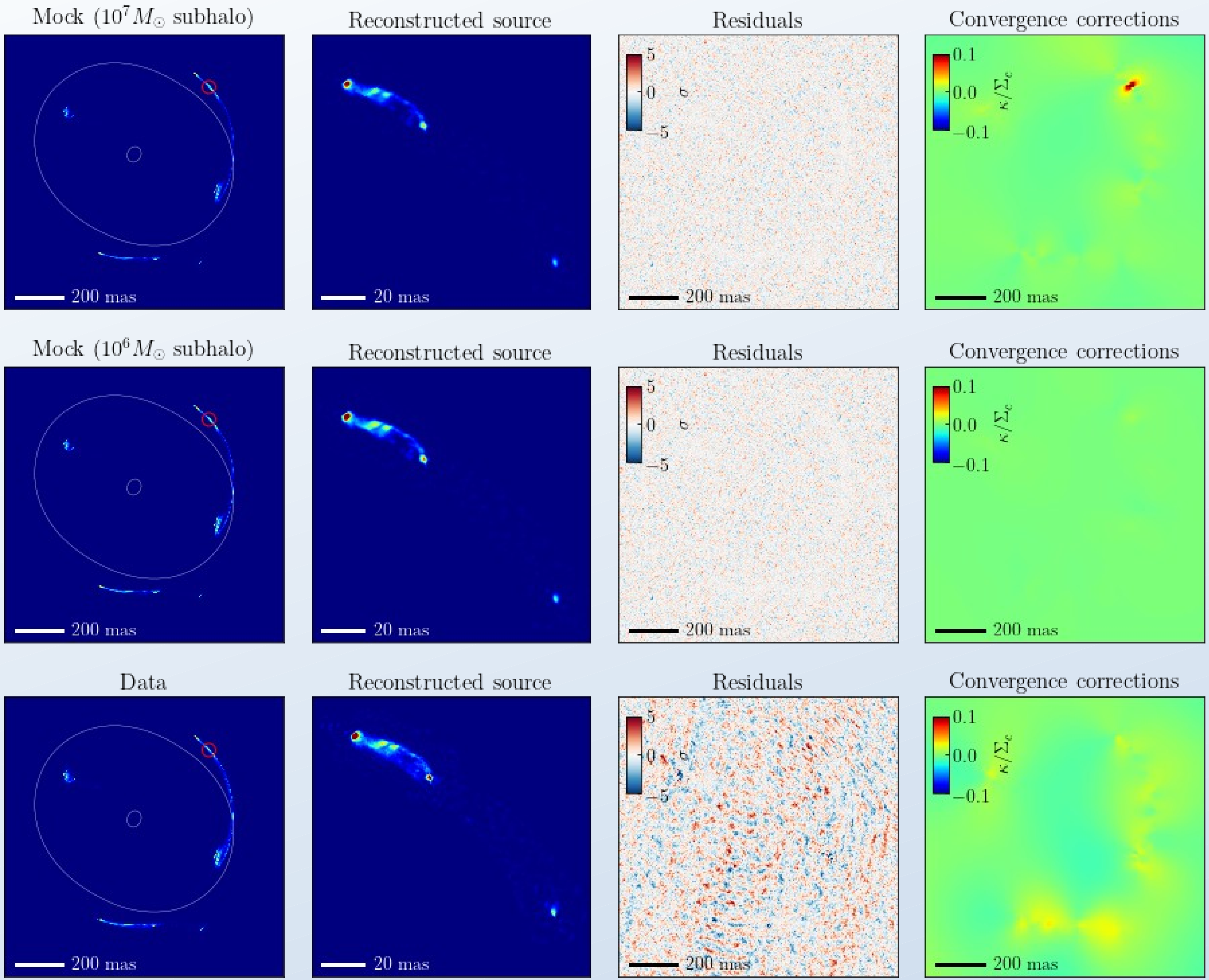
- Gravitational imaging analysis on mock data. Same resolution, array configuration, SNR as the real MG J0751+2716 observation.
- *Isolated* 10^6 and 10^7 M_{sun} subhaloes are easily detected with data of this quality.
- Halo mass function constraints will require a statistical approach, e.g. ABC (see Aleksandra Grudskaia)
- **Characterizing the sub/LOS-halo population will give constraints on m_χ ~ 20 keV, using a single lens observation.**



Warm DM
(real data)

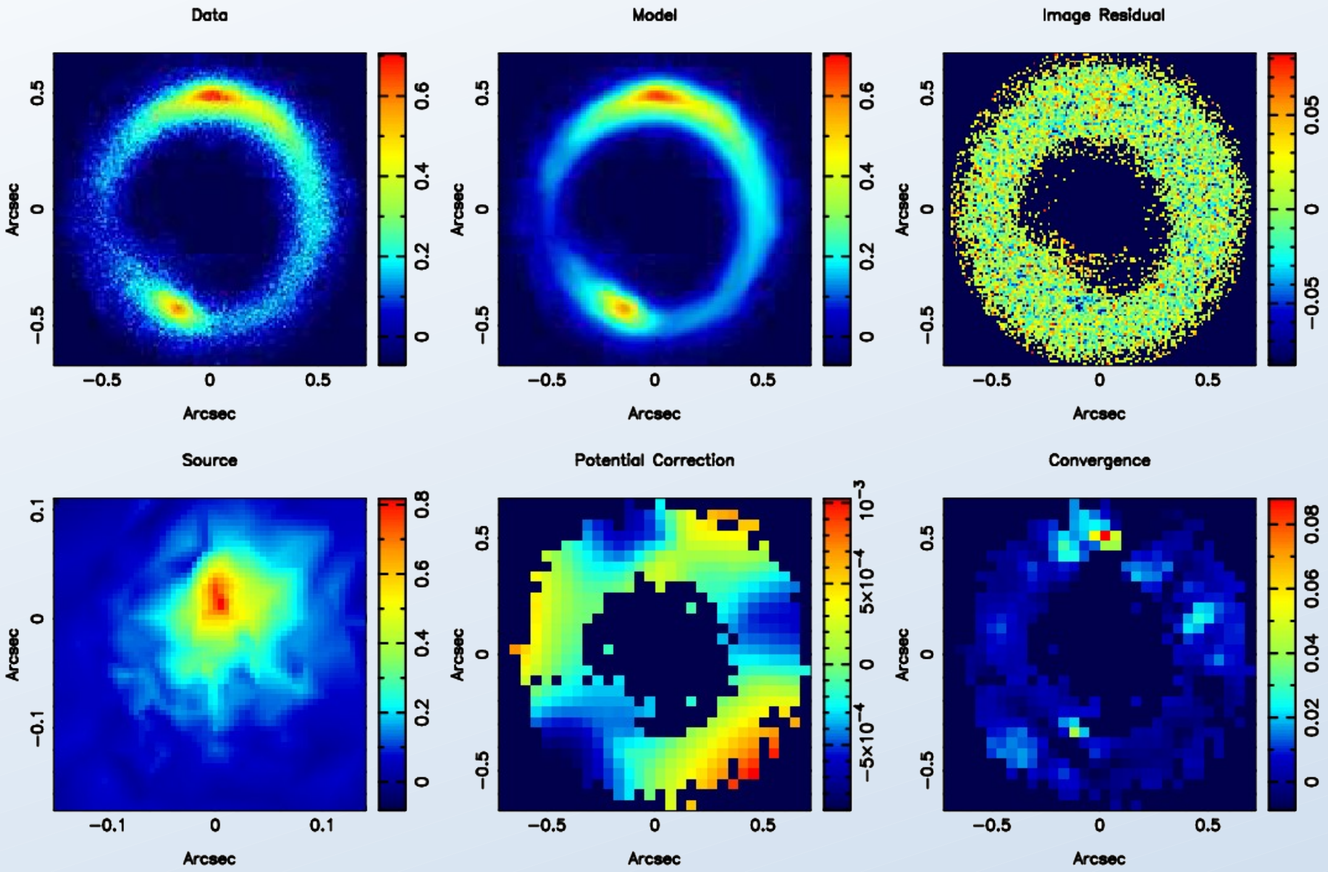
Color scales are consistent now

The real data show no obvious 10^7 M_{sun} features...



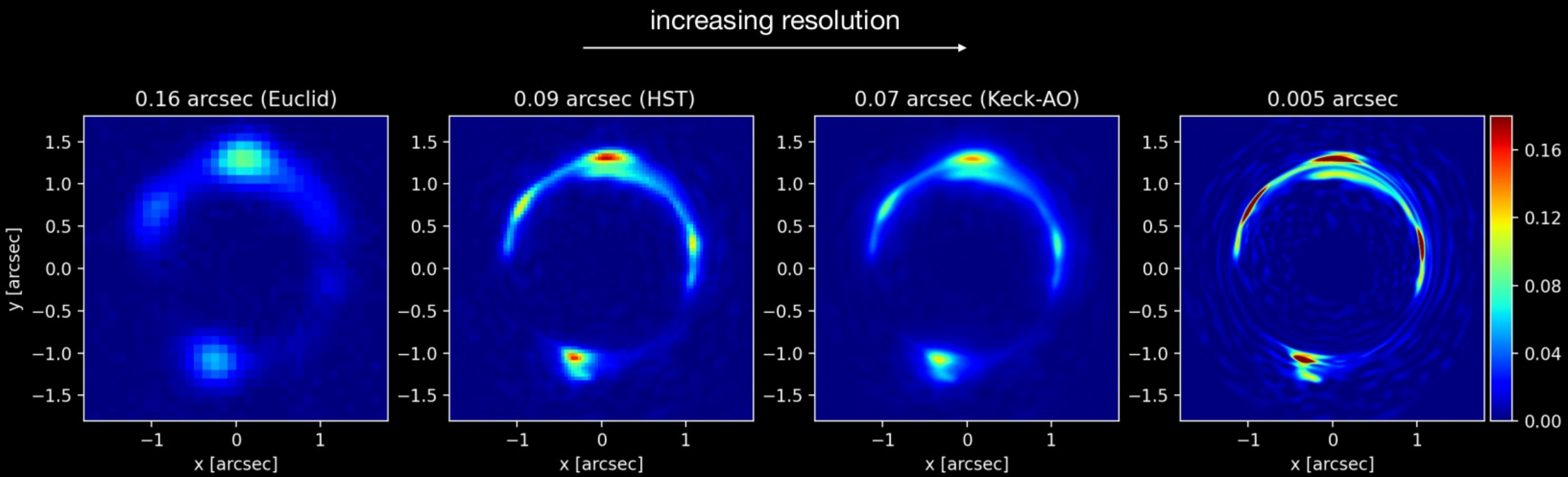
Gravitational imaging

A ~10^8 M_{sun} dark structure detected in Keck AO data:
(Vegetti+2012)




The Global VLBI - Array
Brewster
North Liberty
Hancock
Green Bank
Jodrell Lovell
Jodrell Mk2
Cambridge
Onsala 25m and 20m
Metsähovi
Los Alamos
Owens Valley
Pie Town
Mauna Kea
Kitt Peak
Urumqi
Shanghai
Westerbork
Medicina
Noto
EVN
VLBA
European VLBI Network (EVN)
Very Long Baseline Array (VLBA)
High Sensitivity Array (HSA)
Ft. Davis
St. Croix
V L A
Arecibo
Effelsberg
Yebes
Wettzell
Torun
Hartebeesthoek

SENSITIVITY FUNCTION

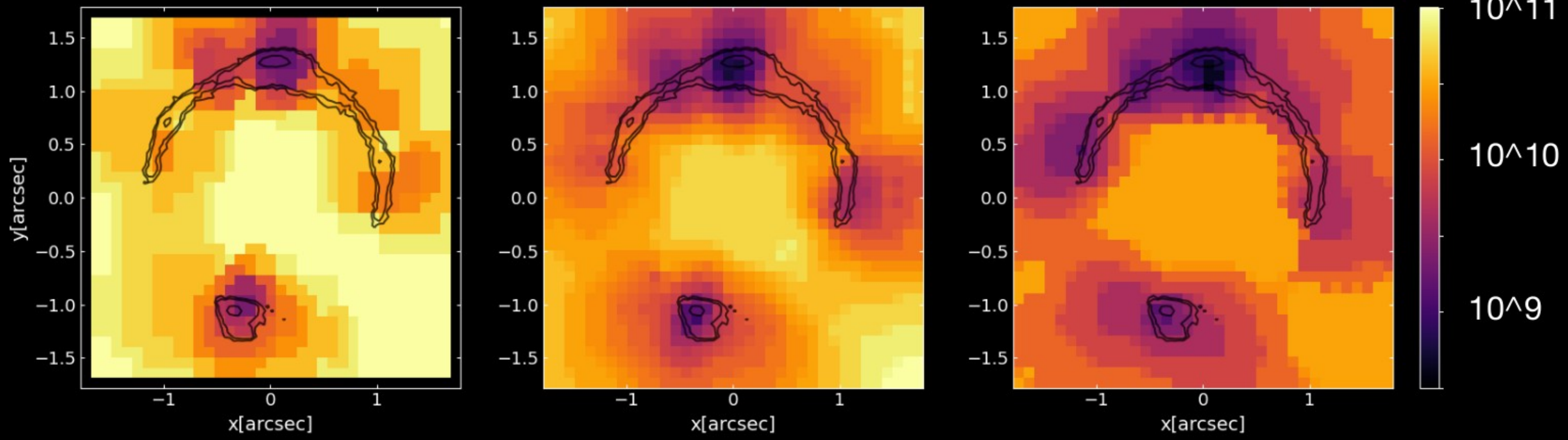


- HST images from the BELLS-GALLERY sample *(Ritondale et al. 2019)*
- Keck-AO images from the SHARP sample *(Vegetti et al. 2012)*
- ALMA data from *Stacey et al. 2021* (sub.)
- zl>0.5, zs>2

(Despali et al. 2021)

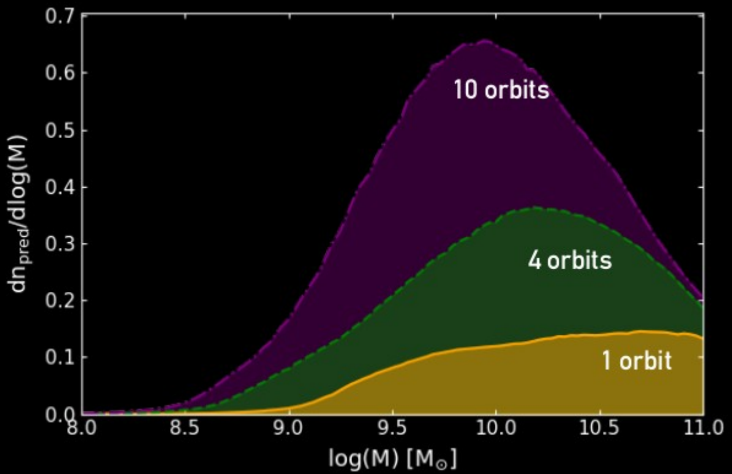
PREDICTIONS

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



increasing SN ratio at fixed resolution:

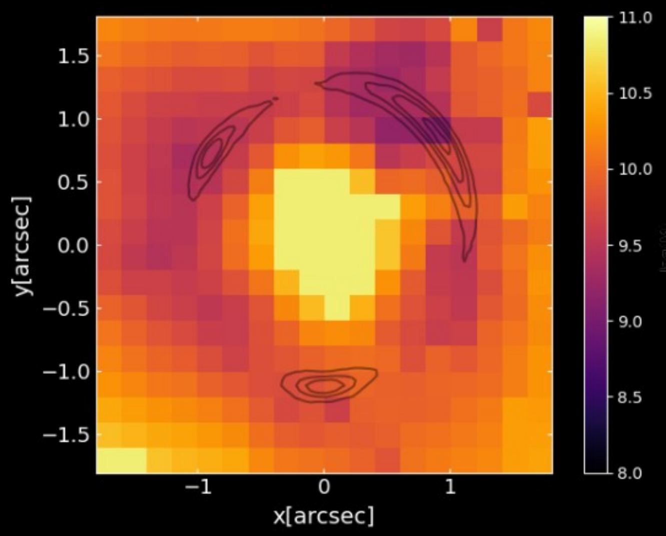
more detections



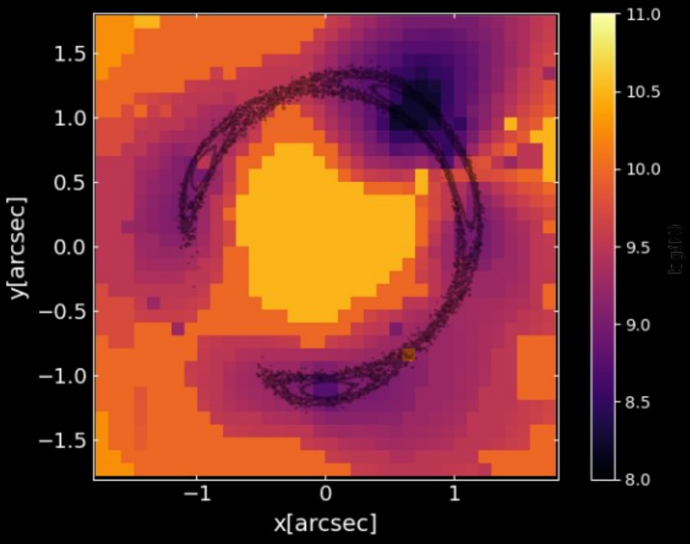
(Despali et al. 2021)

PREDICTIONS

HST (0.05")

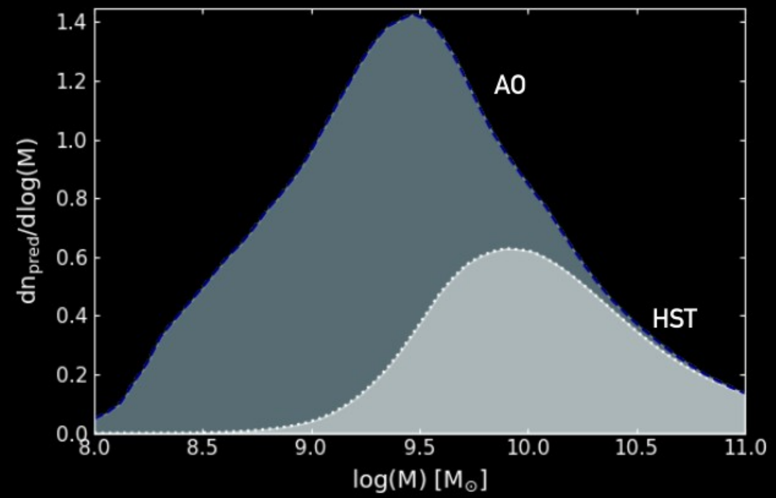


KECK AO (0.01")



increasing resolution:

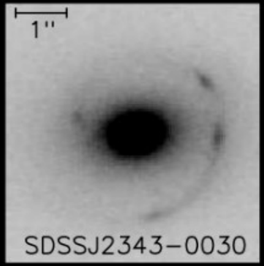
more detections
AND
lower mass limit



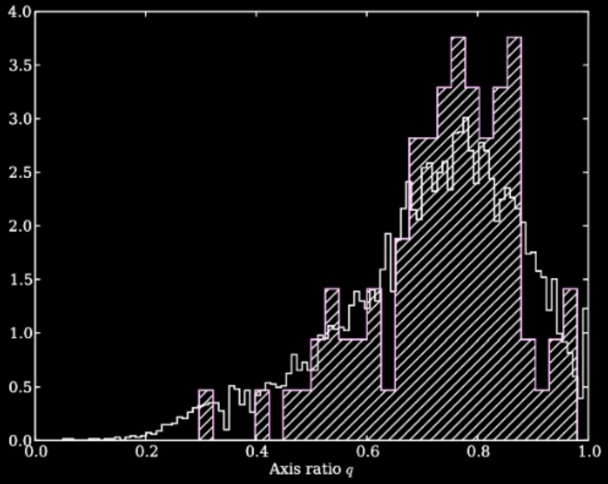
(Despali et al. 2021)

SHAPES IN SELF-INTERACTING DM

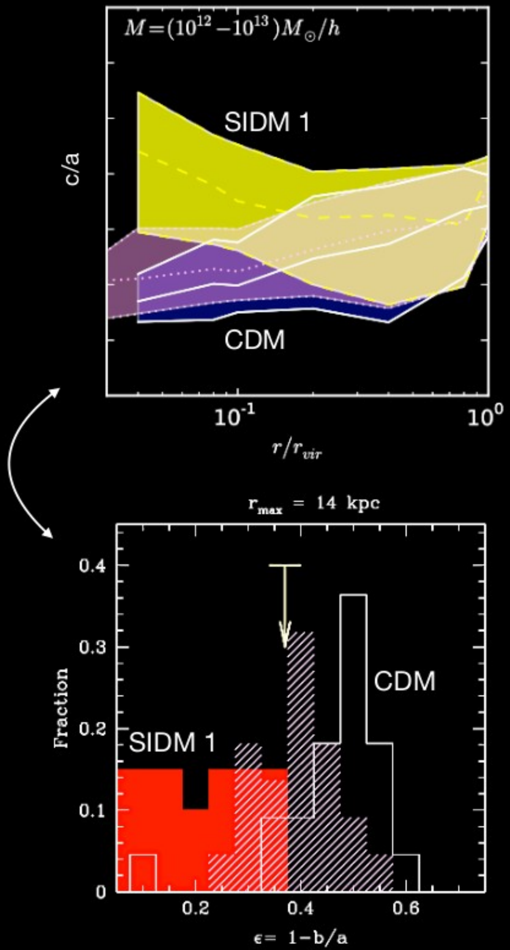
Grav. Lensing - galaxies are SIE with constant axis ratio in the center



(Auger+10)



(Peter+13) - SIDM produces rounder haloes

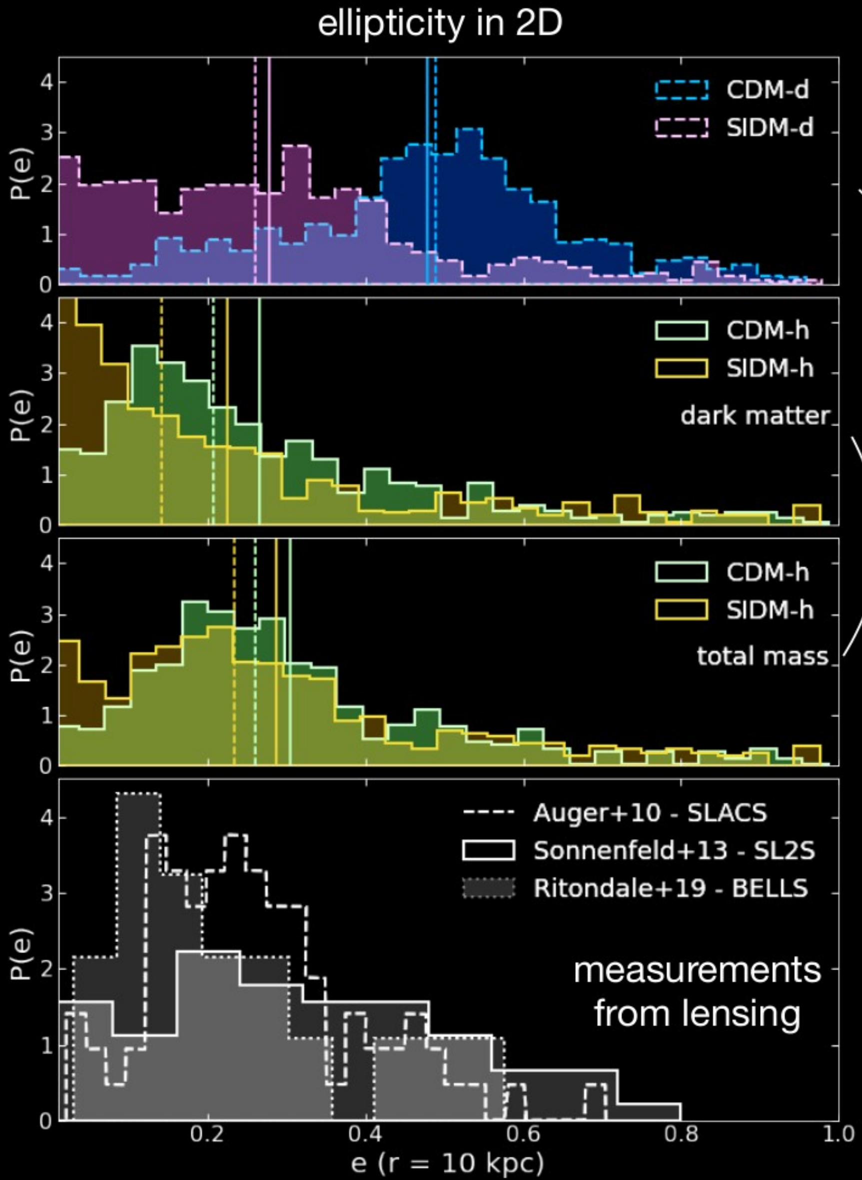


one of the strongest constraints on SIDM comes from shapes: $\sigma \leq 0.1$

BUT: based on DM-only simulations

SHAPES IN SELF-INTERACTING DM

(Despali et al. 2022)



hydro simulations with AREPO and TNG model in CDM and SIDM with σ=1

DM-only shapes are very different and SIDM is much more spherical

including baryons the two distributions are very similar

the comparison with lensing shapes prefers CDM hydro halos (higher p-value), but <u>SIDM with σ=1 is not excluded</u>

baryons can significantly alter the predictions