A VLBI view of strong gravitational lenses

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European Research Council
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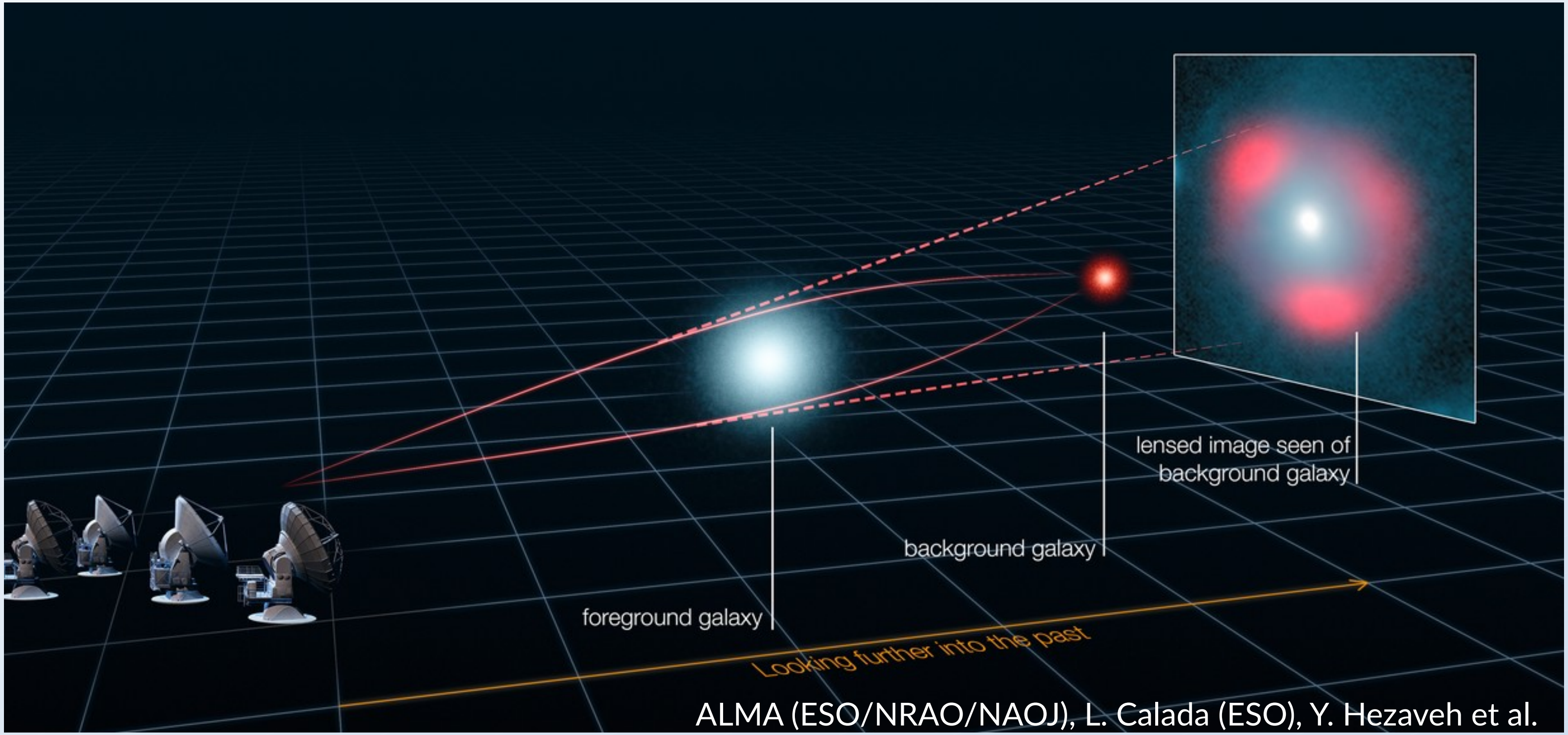
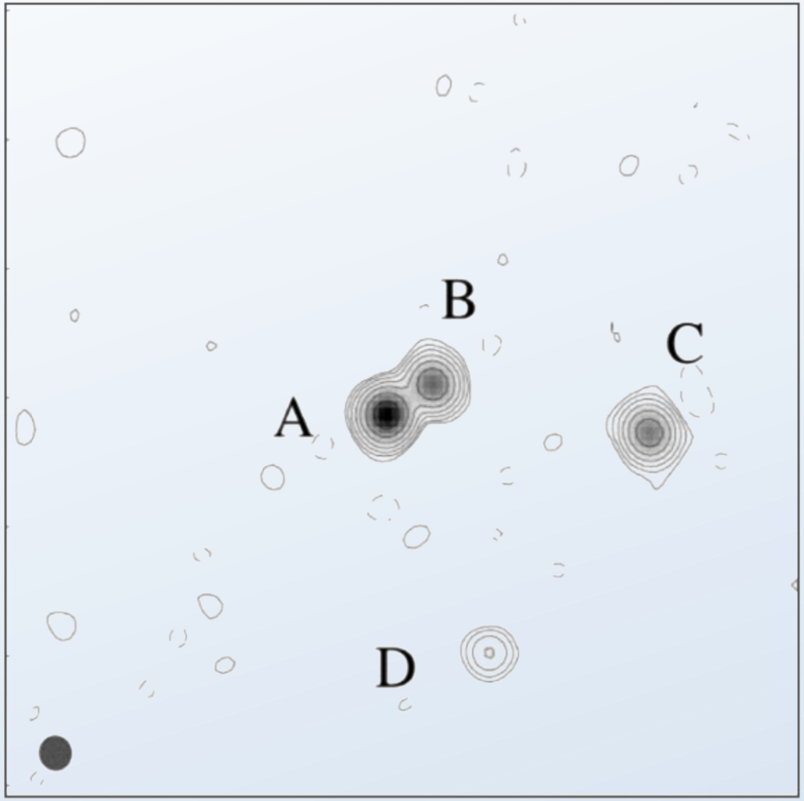
Galaxy-scale strong gravitational lensing

- The mass of a foreground galaxy (the lens galaxy) deflects the light of a background source, producing multiple magnified (but distorted) images.
- The lensed images probe the gravitational potential of the lens galaxy, and hence the mass distribution.
- **Multiple images break the degeneracy between the source light distribution and lens-plane (or line-of-sight) effects.**



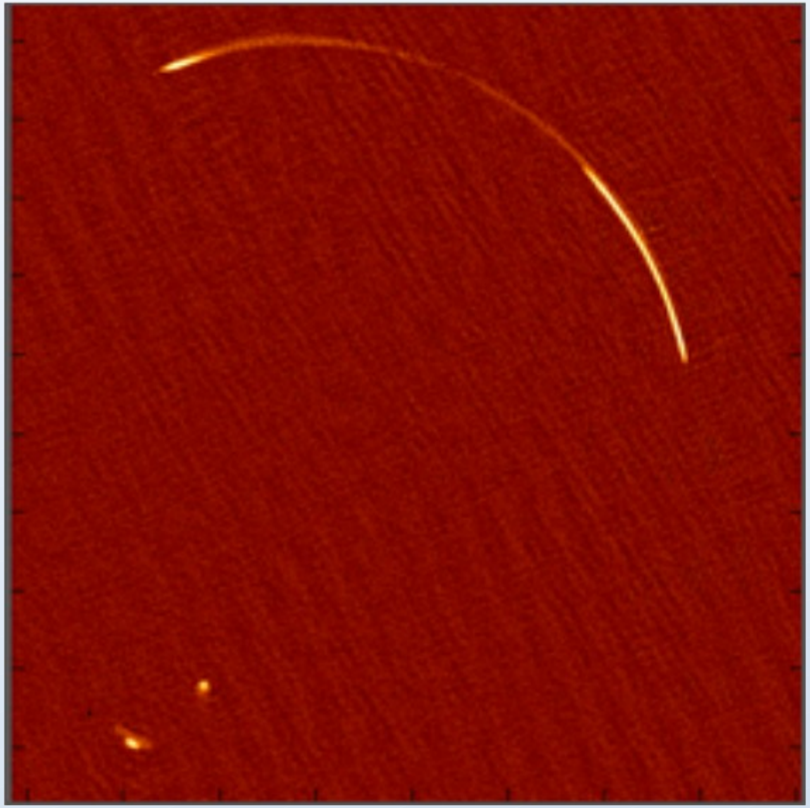
Types of gravitational lens systems

Unresolved background source



AGNs and QSOs

Resolved background source



Galaxies and radio jets

Vegetti

Types of gravitational lens systems

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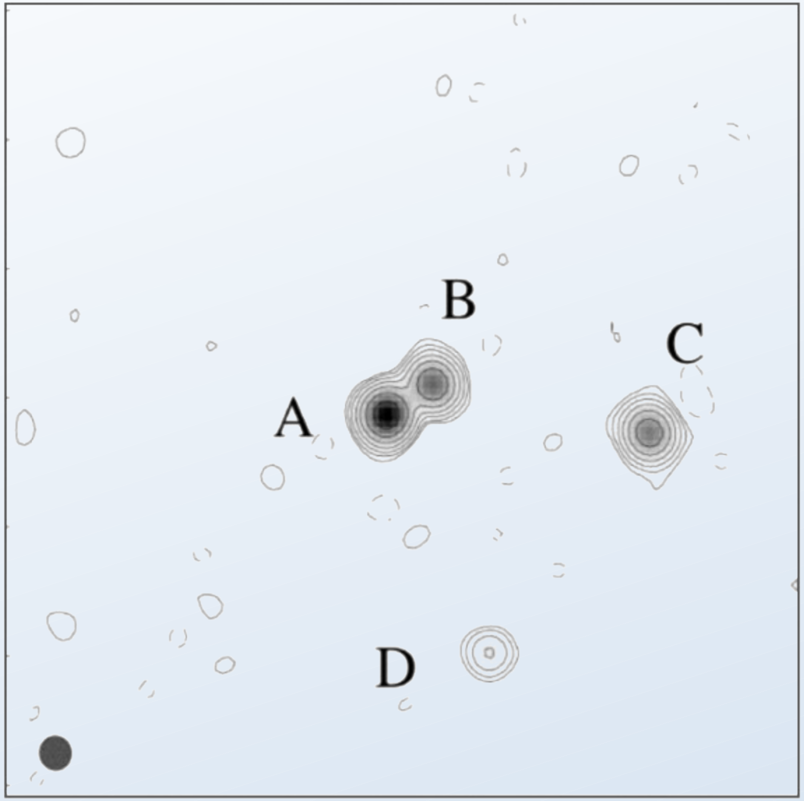

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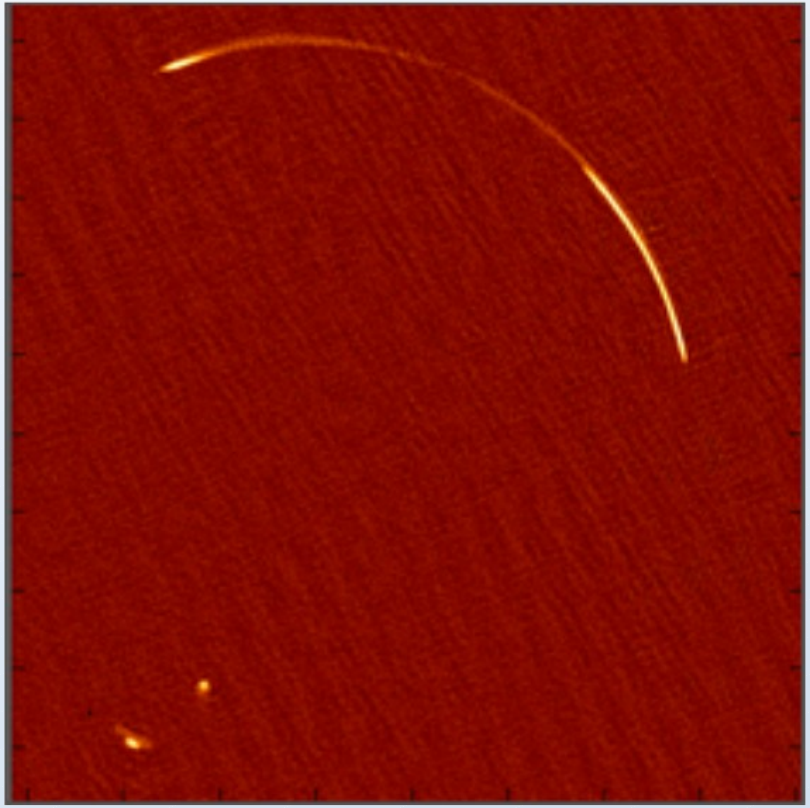

Galaxies and radio jets

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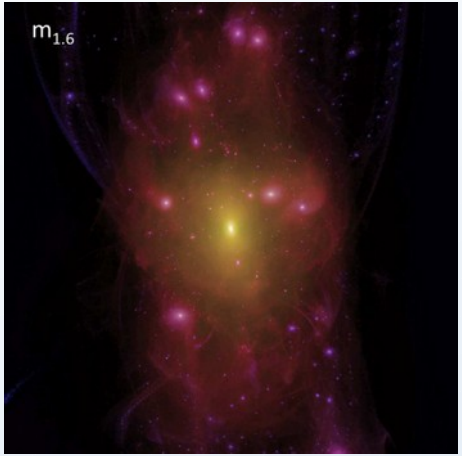
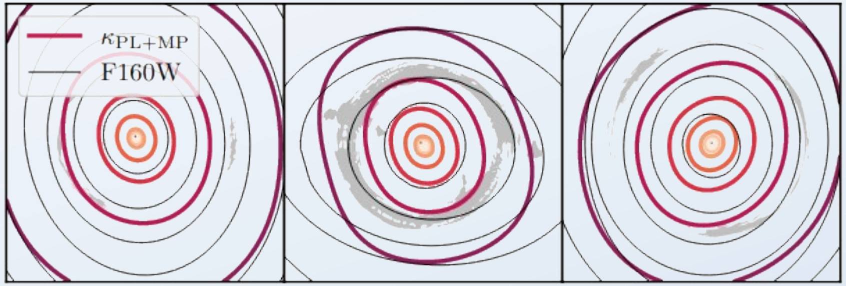
What can we learn from observations of strong lens galaxies?

The nature of dark matter



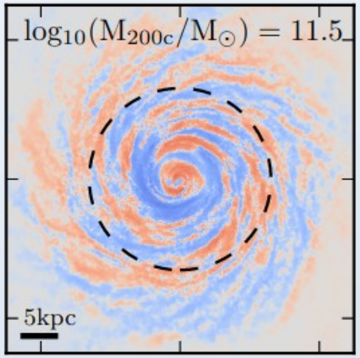
Lovell+2014

Galaxy-scale distribution of baryons and dark matter



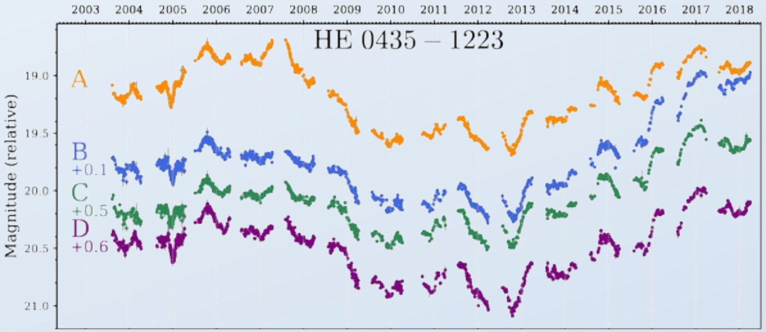
Stacey+2024

Magnetic field structure (with radio observations)



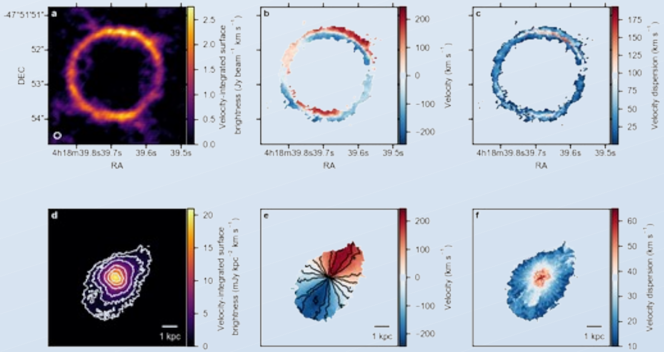
Pakmor+2024

Time-delay cosmography



Birrer+2022

High-redshift sources



Rizzo+2020

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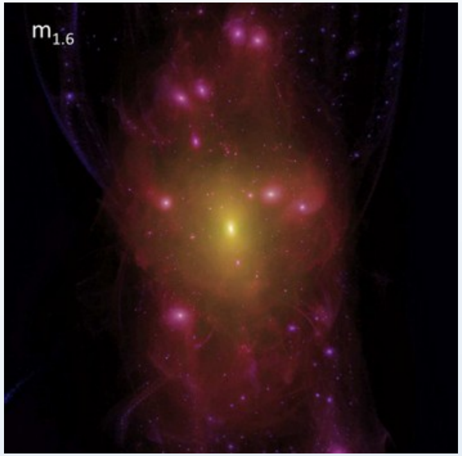

Lovell+2014

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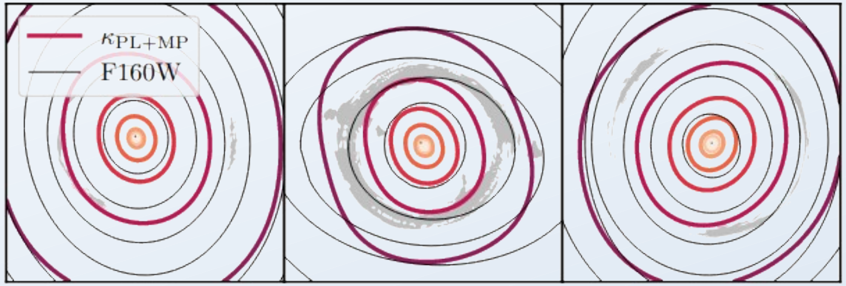

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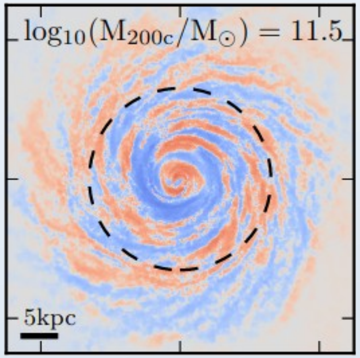

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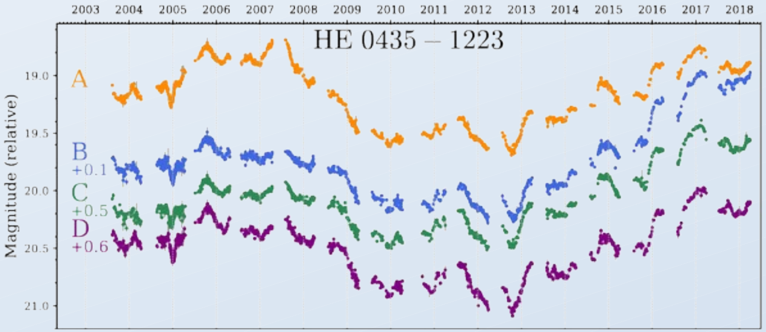

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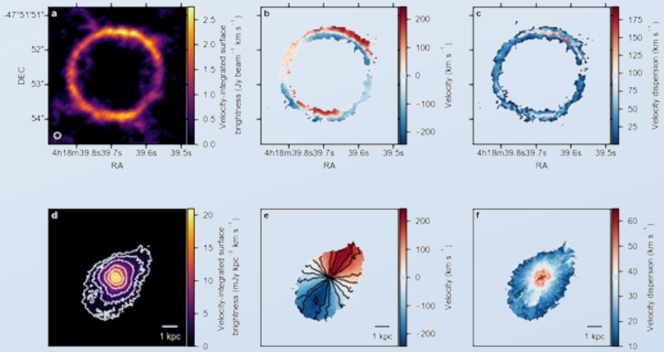

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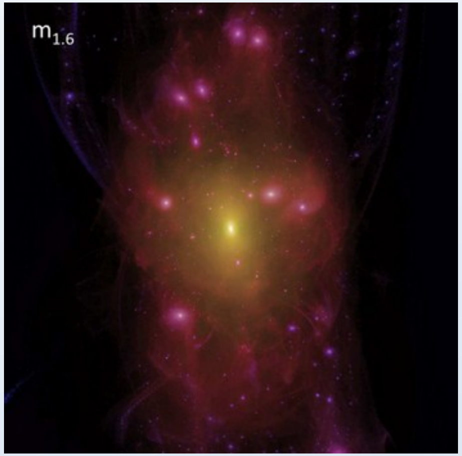
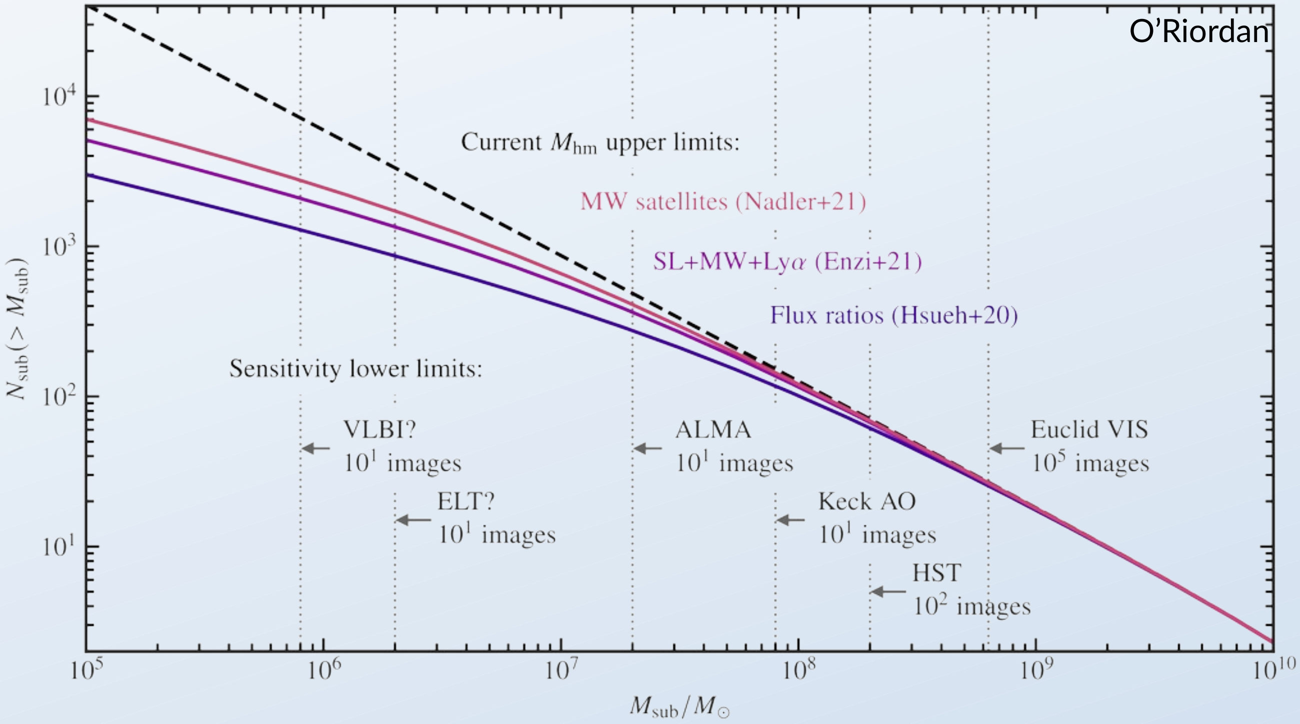


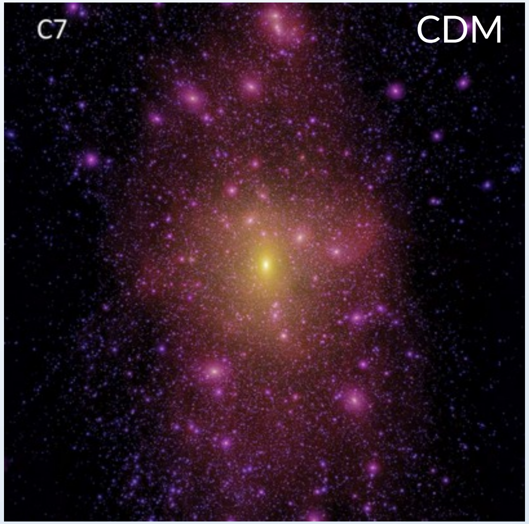
Lovell+2014

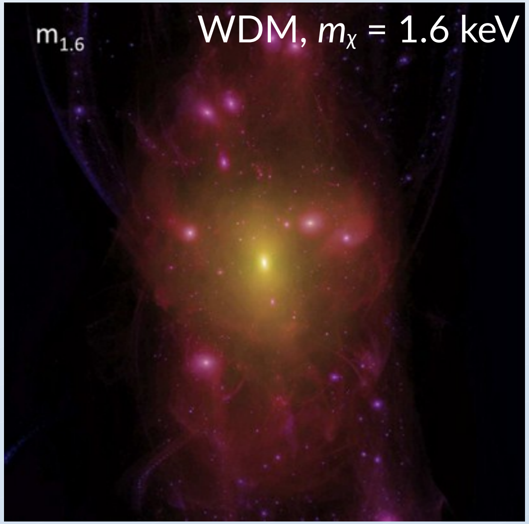
The nature of dark matter (warm DM)

Key predictions:

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



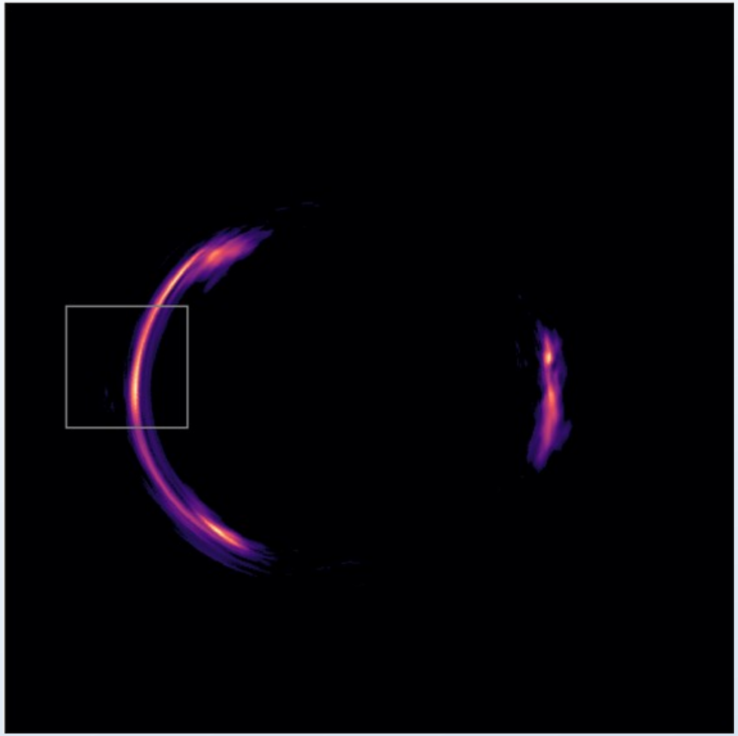


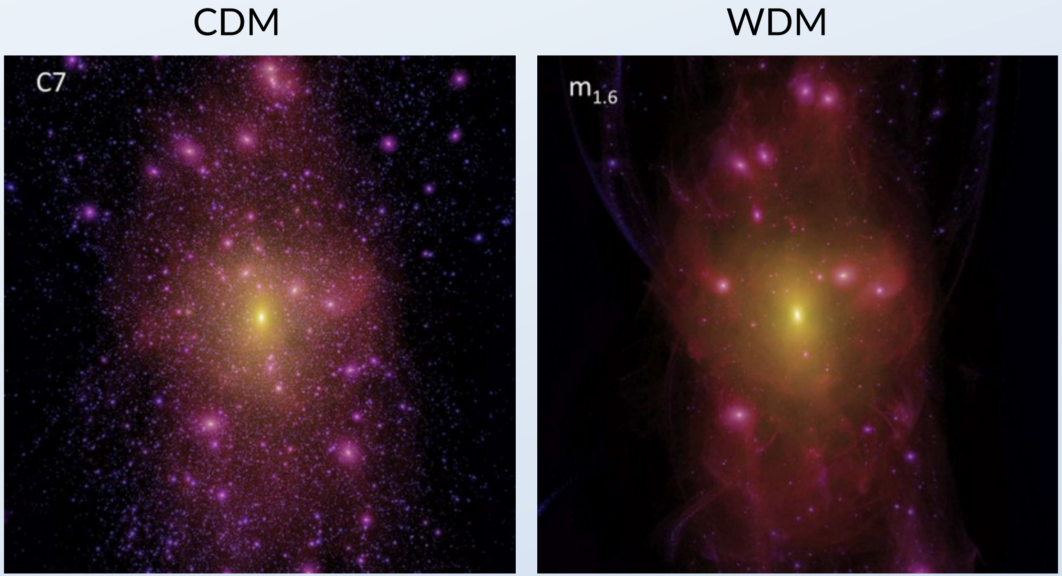


Lovell+2014

The nature of dark matter (warm DM)

- We can infer the properties of subhaloes (or granules, or other dark structures) via their effect on the lensed images.
- **This slide is just an illustrative example of a single subhalo in CDM/WDM, in a lens system with resolved arcs.**





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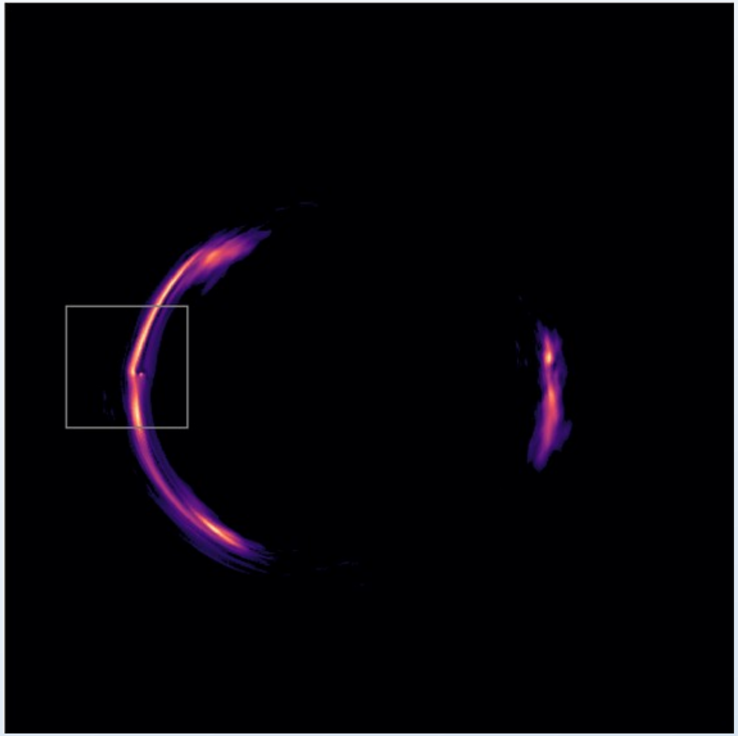
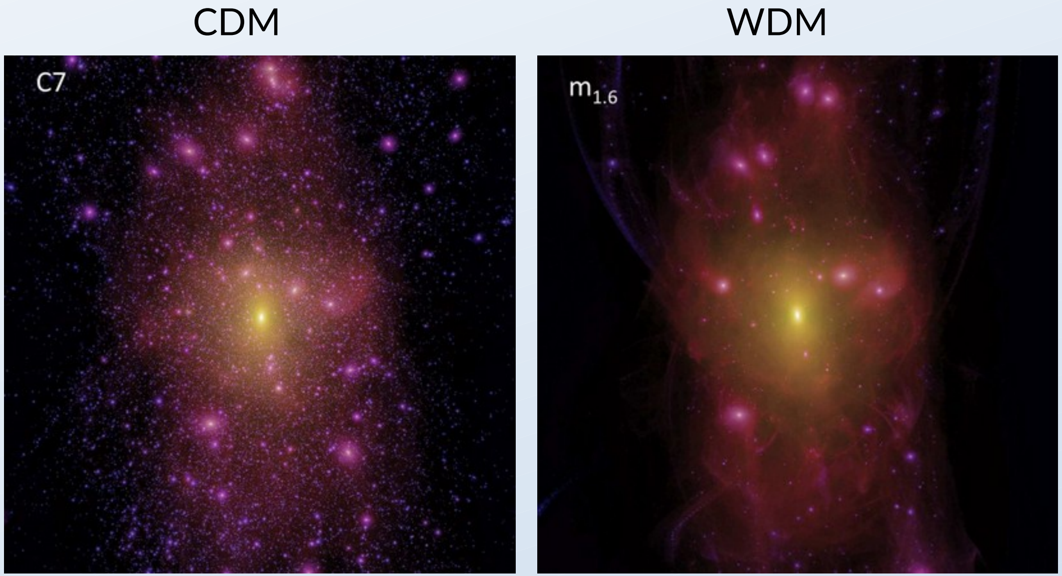


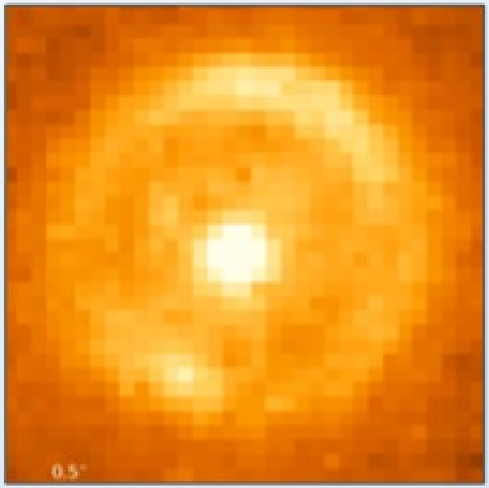


Lovell+2014

Why radio interferometry?

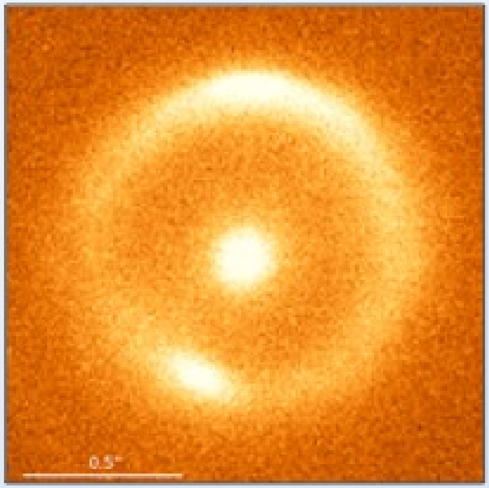
- ***Milli-arcsecond angular resolution.***
- Sensitivity to extremely low-mass dark objects.
- Detailed measurement of galaxy shapes.
- Can measure Faraday rotation in the lens galaxy.
- ***No light from the lens itself.***

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



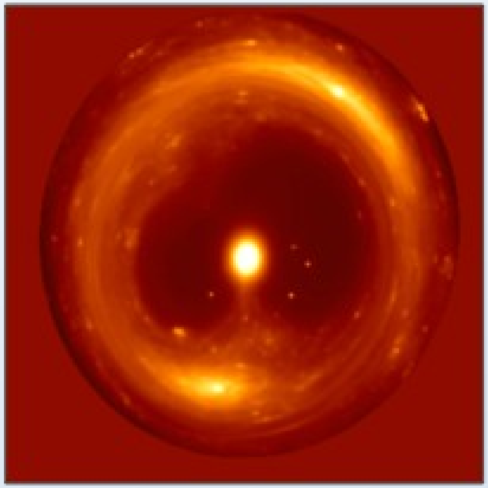
Lagattuta

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

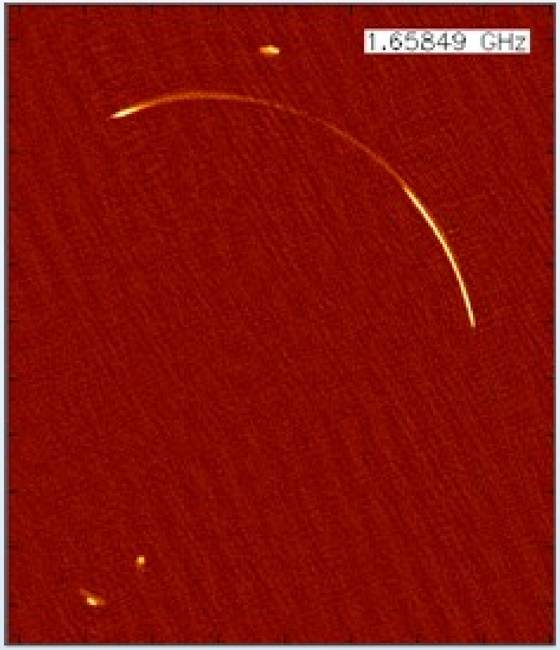


Lagattuta

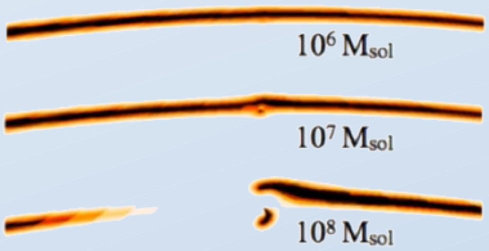
E-ELT *(mock data)*
~10^7-10^6 M_{sun}



Vegetti (MICADO simulator,
3 hours on-source)



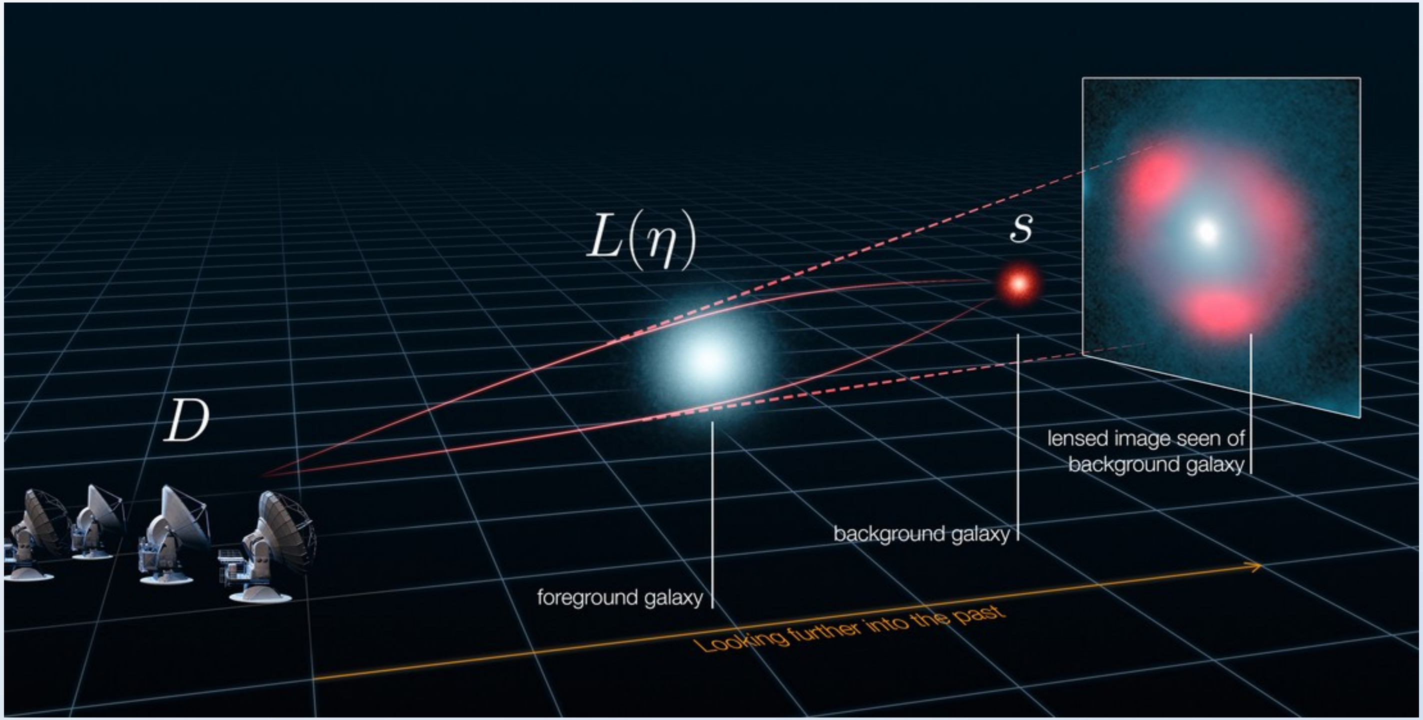
VLBI *(real data)*
~10^6 M_{sun}



McKean

Methods: Forward modeling

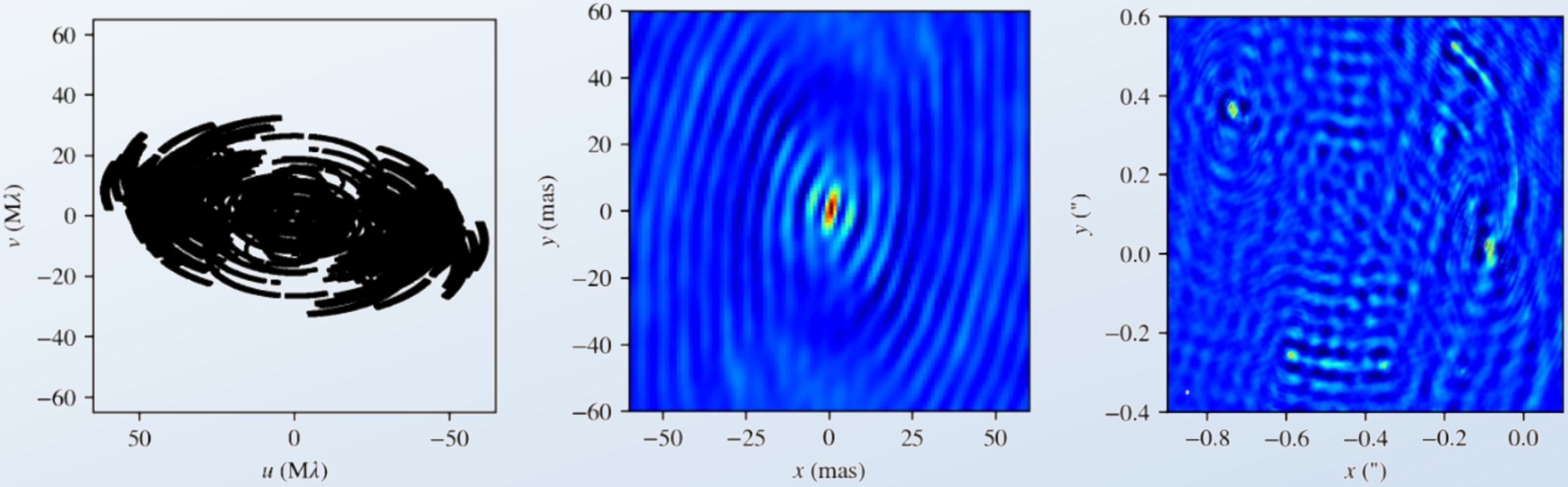
- Array of radio antennas samples Fourier modes of the sky brightness
- Each pair of antennas measures a “visibility” corresponding to one Fourier component
- The response of the instrument is a Fourier transform (D in the schematic below)
- **Distance between antennas and observing wavelength determines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



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

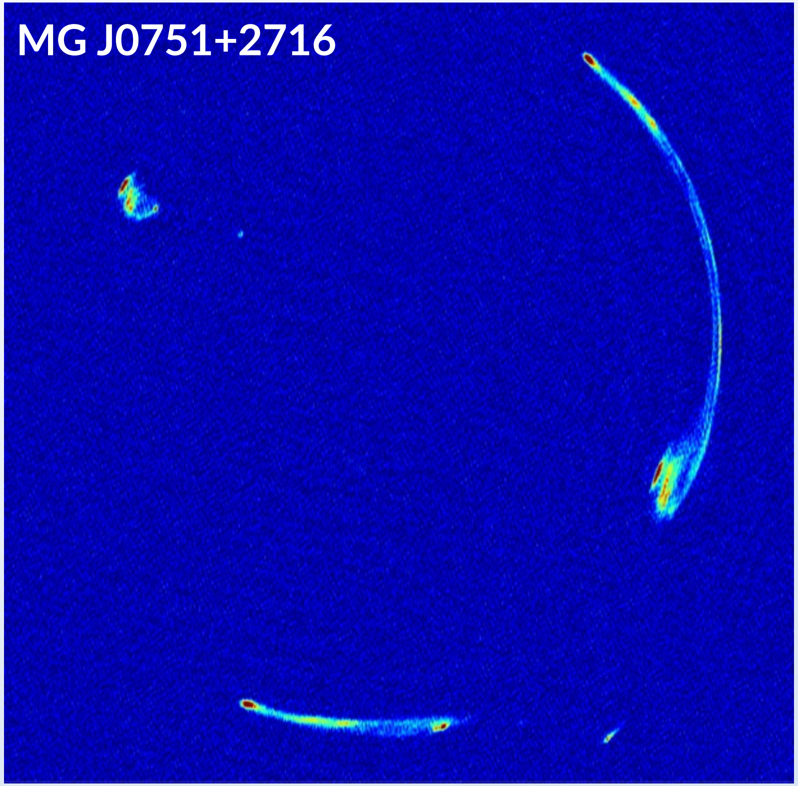
Methods: Radio interferometry

- The actual data is an incomplete, non-uniform sampling of the Fourier transform of the sky brightness.
- Noise is correlated across the sky!
- Typical observation has ~10^9 visibilities (or more), and needs an image-plane grid of 2048^2.
- **A computational challenge.**

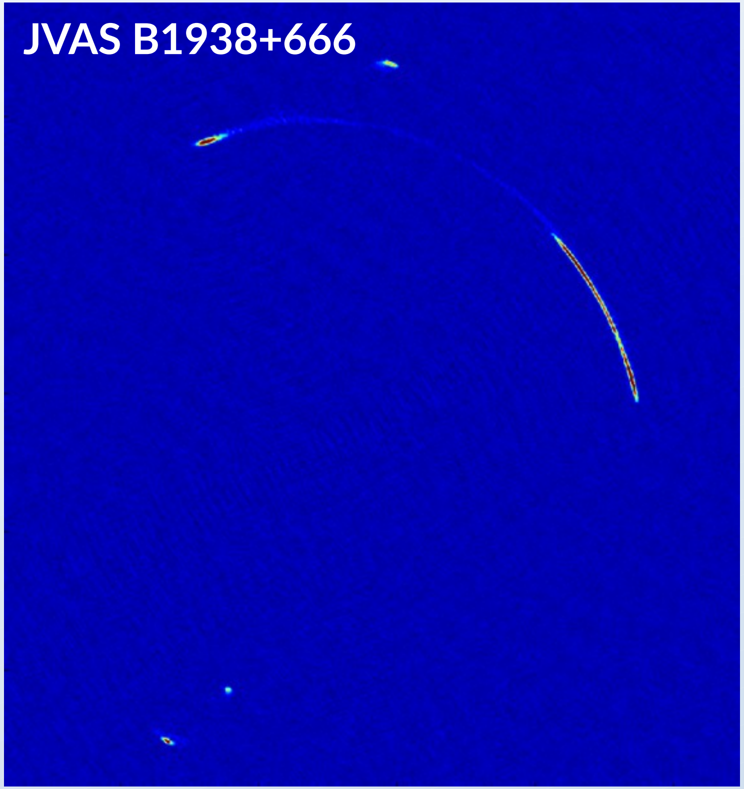


Data: Global VLBI observations of lensed radio arcs

- Global very long baseline interferometric (VLBI) data (PI: McKean).
- **Earth-scale antenna spacings give < 5 mas resolution at 1.6 GHz.**



Spingola, McKean, et al. 2018



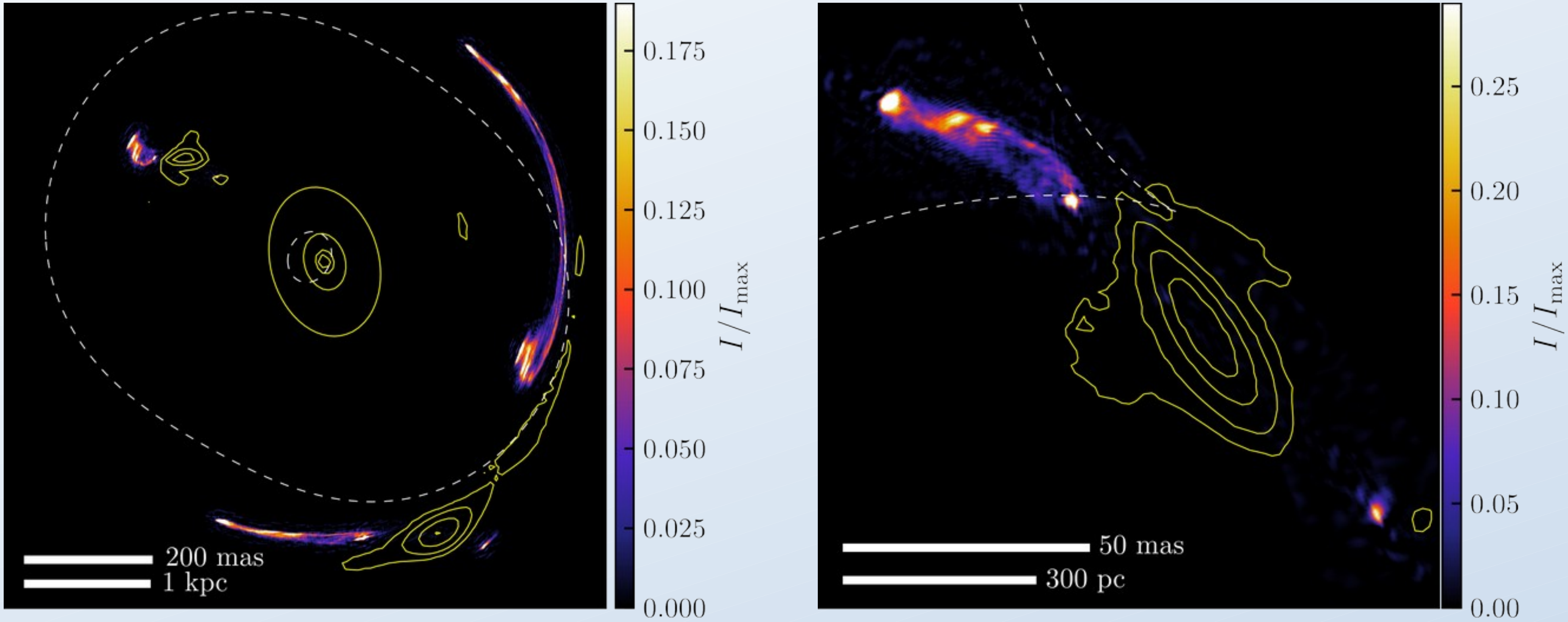
McKean

Technical challenges

- ☐ Forward modeling of radio interferometric data in the visibility plane
- ☐ With 10^9 visibilities per observation
- ☐ At < 5 milli-arcsecond resolution (2048^2 pixels in the image plane)
- ☐ Computationally tractable (model an observation in < 24 hours)
- ☐ Sensitivity to dark matter sub-/LOS-haloes in the 10^6 solar mass regime

`pronto`: a cutting-edge lens modeling code

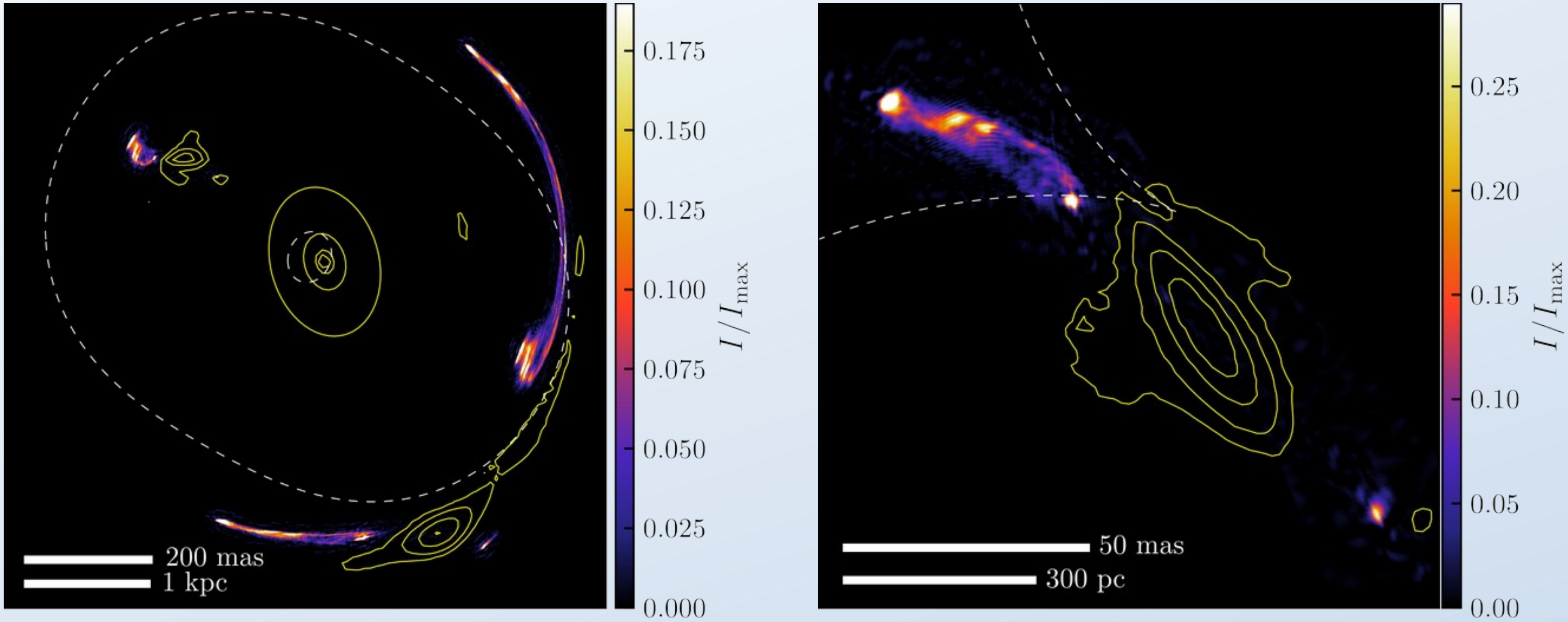
- **I developed the numerical machinery for modeling VLBI lens observations.**
- Recovers a pixellated source brightness model, as well as the likelihood, for a given lens model.
- **Allows us to quantify how well a given lens mass distribution explains the observed data.**
- Nested sampling integrates the Bayesian evidence, **letting us compare different lens model parameterizations**.
- **Take away the lens mass model, and it's a Bayesian radio imager.**



Powell et al. 2021, 2005.03609

`pronto`: a cutting-edge lens modeling code

- **The only code capable of modeling milli-arcsecond VLBI observations in the visibility plane.**
- `pronto` uses an **iterative linear solver** (preconditioned conjugate gradient), with **FFTs on the GPU** at each iteration, and a **custom preconditioner.** Parallelized with **MPI, OpenMP, CUDA.**
- **Under 30 seconds per likelihood evaluation. Methods still under development.**



Powell et al. 2021, 2005.03609

My favorite `pronto` publications (I am an author on all of them)

- **Powell et al. (2021)** is the initial methods paper, with tests on mock VLBI data.
- **Powell et al. (2022)** fit a parametric “macro model” to MG J0751+2716, showing that higher-order multipoles in the lens galaxy shape are crucial for fitting the lensed images at milli-arcsecond resolution.
- **Powell et al. (2023)** used a VLBI observation of a single lens to place **the strongest lensing-based constraints to date on the particle mass in a fuzzy DM cosmology**.
- **Rizzo et al. (2020, *Nature*) and (2021)** analyzed ALMA **molecular line observations** (**`pronto` is 3D)** of gravitationally-lensed galaxies. She discovered cold, rotationally-supported disks at z ~ 4, challenging current assumptions of galaxy formation.
- **O'Riordan, *Euclid* consortium, et al. (2024)** used `pronto` to model the first strong gravitational lens system discovered using the *Euclid* space telescope. Its extremely large Einstein radius (2.5 arcsec) and high signal-to-noise ratio allowed for an extremely detailed model for the mass and light in the lens galaxy.
- **N’diritu et al. (submitted)** implemented **polarimetric imaging and models for Faraday rotation in `pronto`**, finding that the differential Faraday rotation of polarized emission from an extended source can reliably probe the magneto-ionic structure of lens galaxies.

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- ☑ Forward modeling of radio interferometric data in the visibility plane
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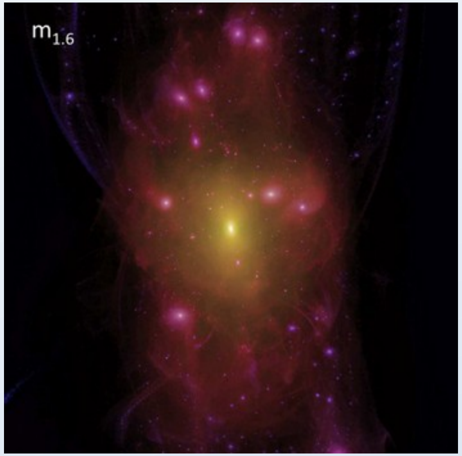
- ☐ Sensitivity to dark matter sub-/LOS-haloes in the 10^6 solar mass regime

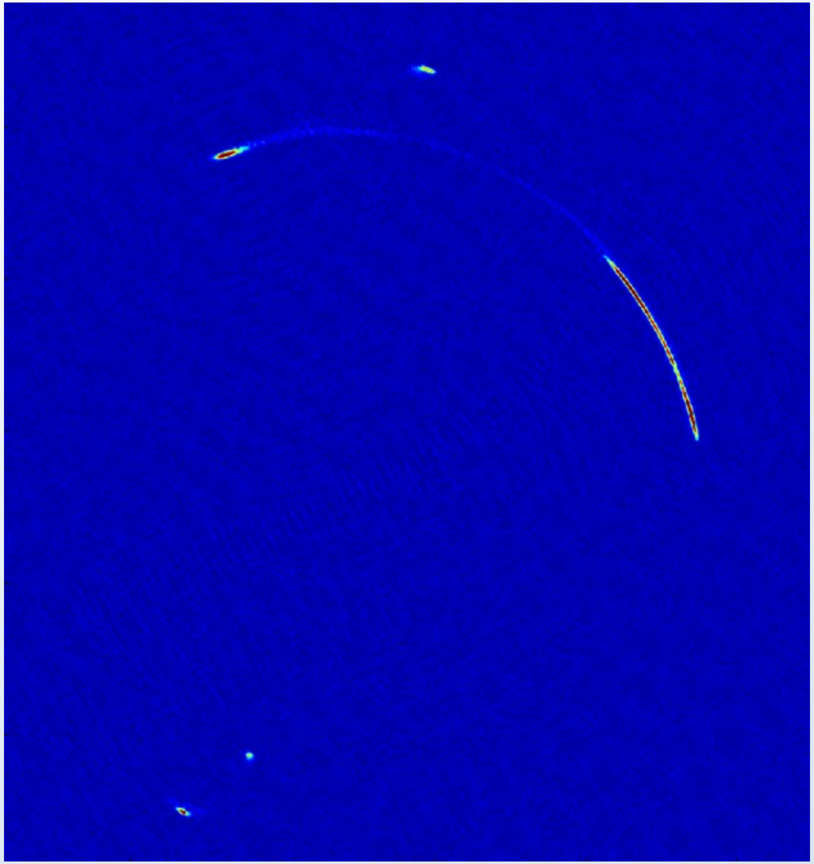
The nature of dark matter

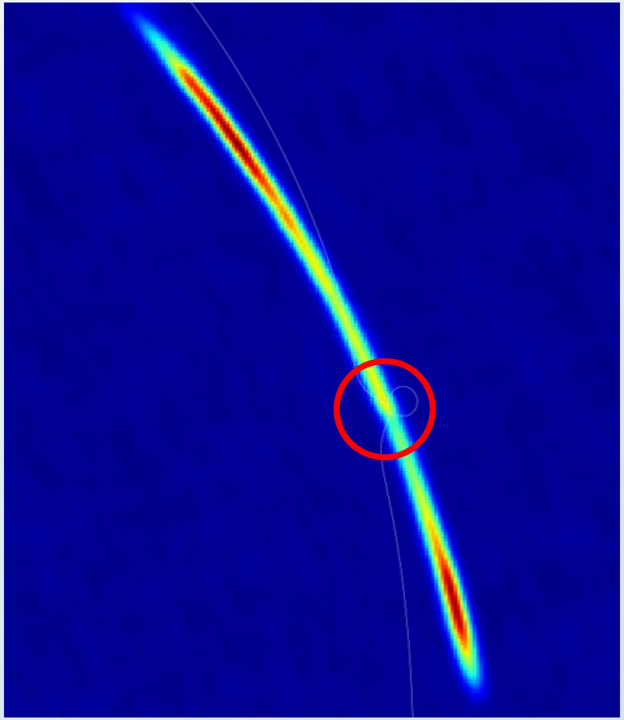


Lovell+2014

A 10^6 solar mass object! (*in preparation*)

- **A "kink" in the arc indicates a low-mass perturber object near the critical curve.**
- This observation is at 1.6 GHz, and the feature also appears in the 5GHz data at <2 mas resolution.





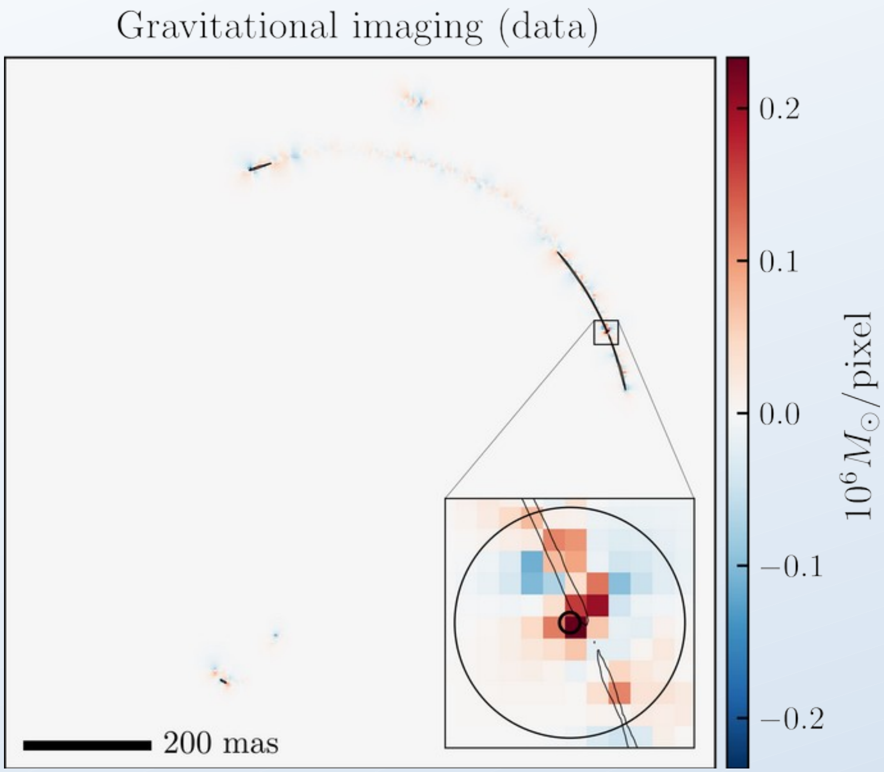
Observation and data reduction by John McKean

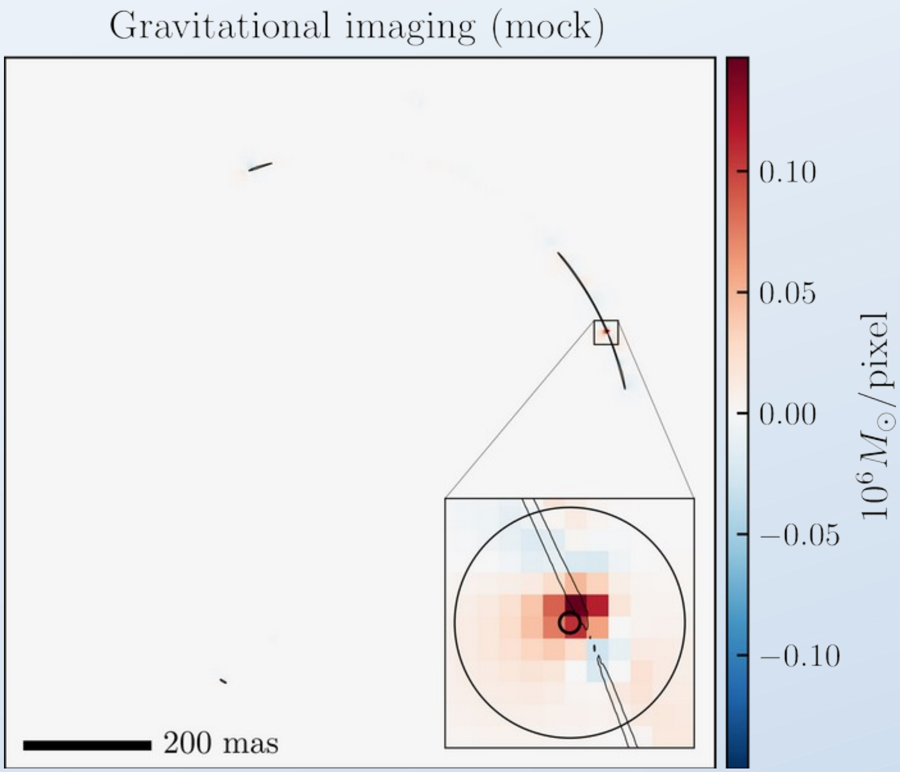
PRELIMINARY:

- ~2×10^6 M_{sun}, assuming truncated PL
- **Standard NFW is much too diffuse!**
- Must consider different possible density profiles, as well as redshift.

A 10^6 solar mass object: Gravitational imaging

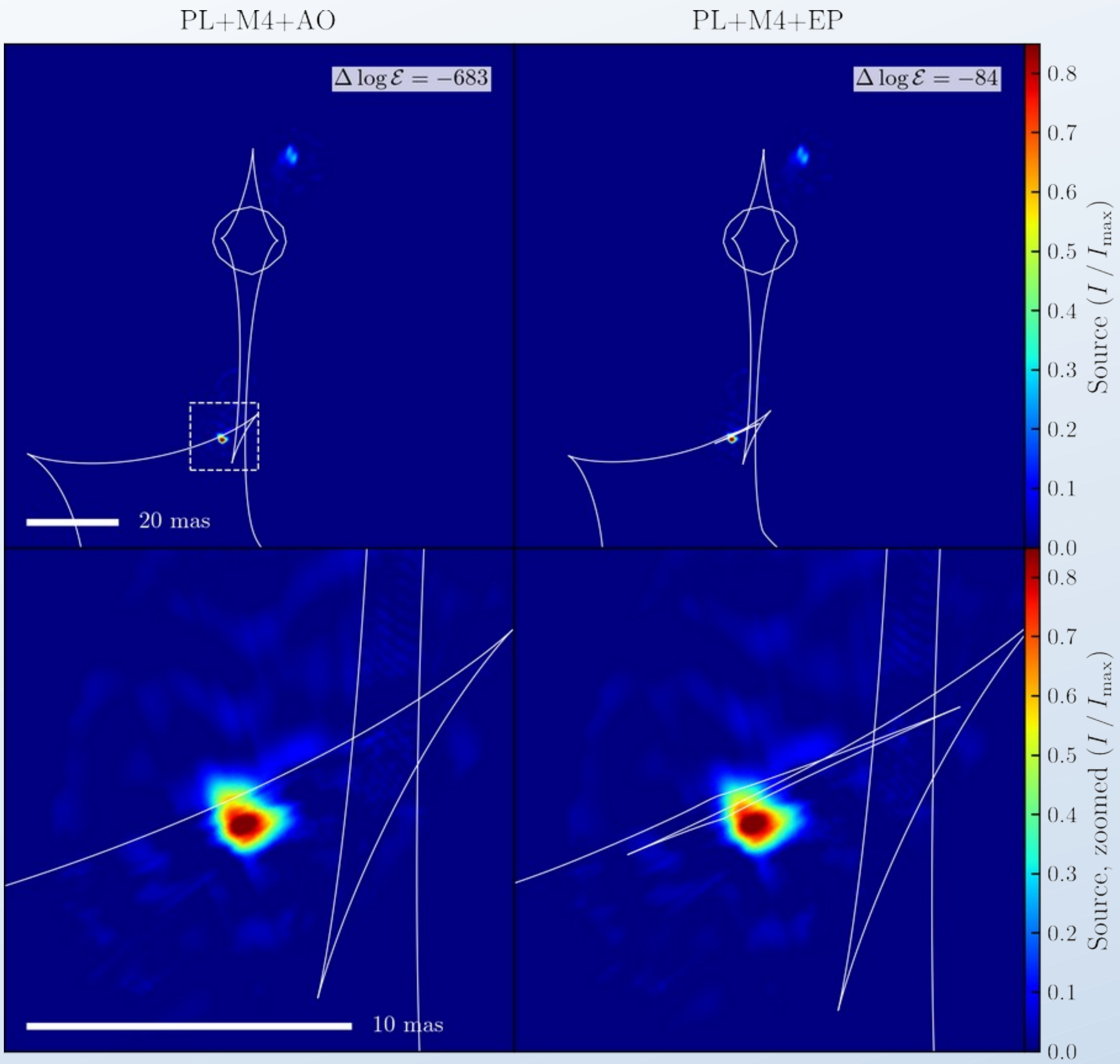
- Gravitational imaging (Koopmans 2005) detects this object independently from parametric modeling.
- Noise-like features are due to residual phase and amplitude calibration errors.





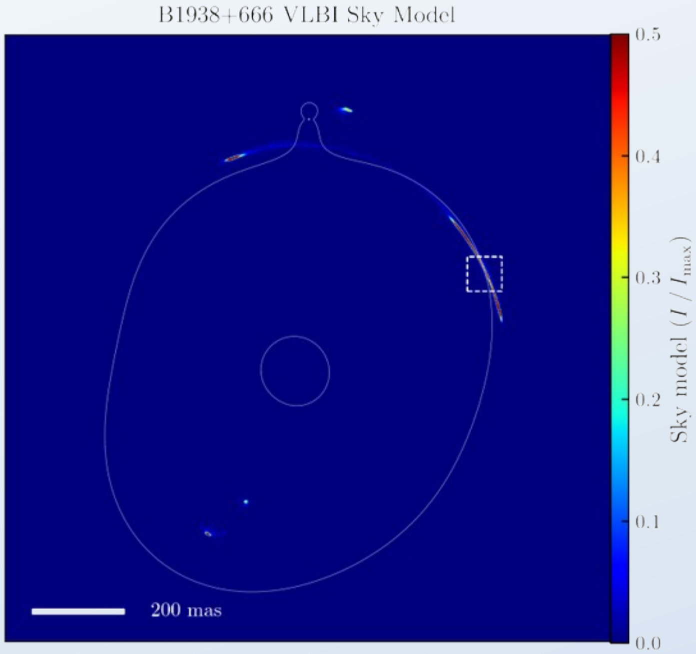
A 10^6 solar mass object: Source model comparison

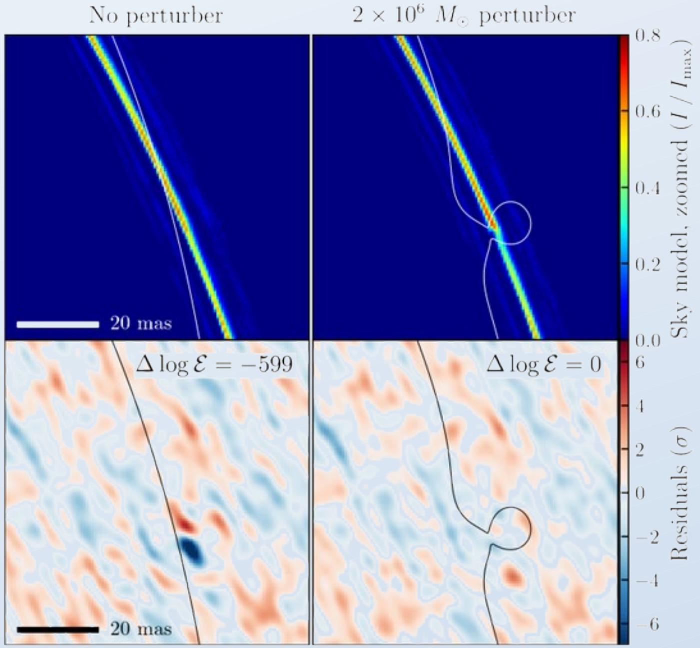
- Any attempt to fit away the feature using source structure leads to sharp discontinuities in the source model, which is penalized by a Bayesian prior.
- This fit is indirectly driven by the source prior, as well as the chi-squared.



A 10^6 solar mass object: What does it mean for CDM?

- We expect to detect 0.7 dark matter sub-/LOS-halo (for f_{sub} = 0.012), and we see 1.
- **If we observe 8 more** B1938-like lenses and still find only this one detection, we have ruled out CDM at 3σ (assuming f_{sub} = 0.012).
- *Euclid* will measure f_{sub}.
- ***We need to robustly quantify expected detections and non-detections for a given observation.***





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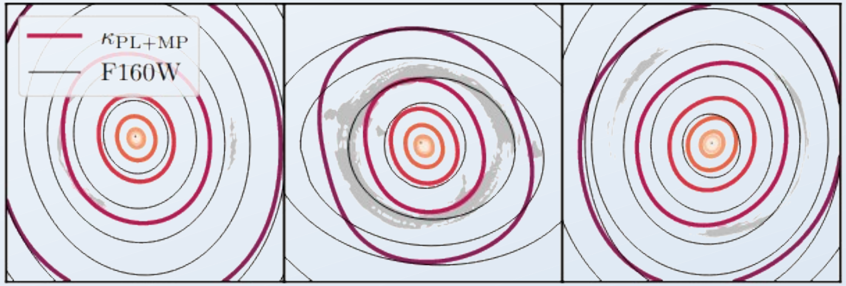


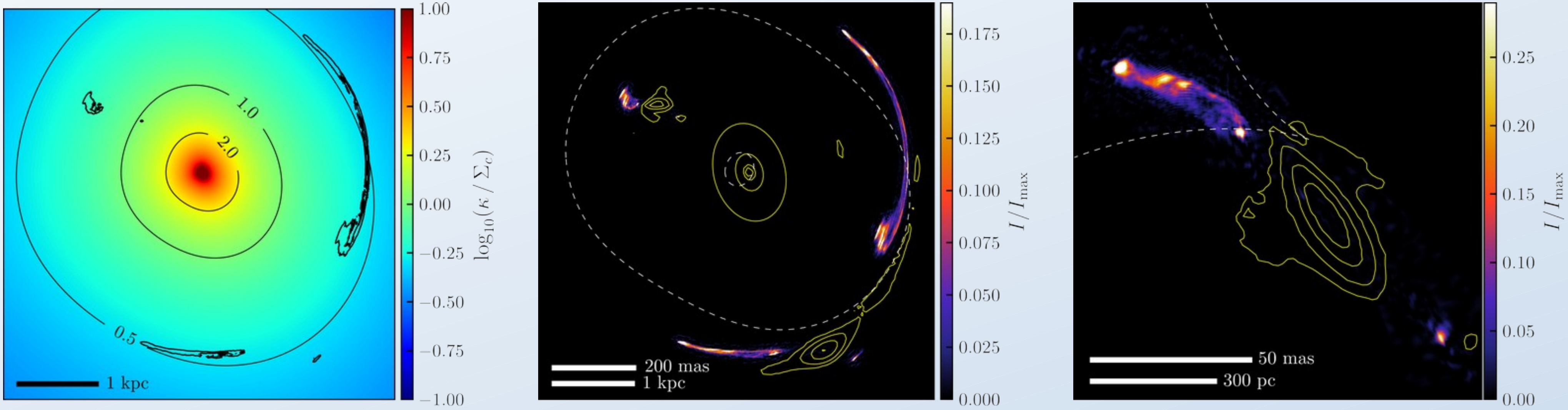
Stacey+2024

Parametric lens modeling with `pronto`

- **A smooth parametric lens model describes the data quite well:**

  Elliptical power-law (dark matter) plus Sersic (baryons) plus 4th-order multipoles (boxy/diskyness) plus 3rd-order external tidal terms.

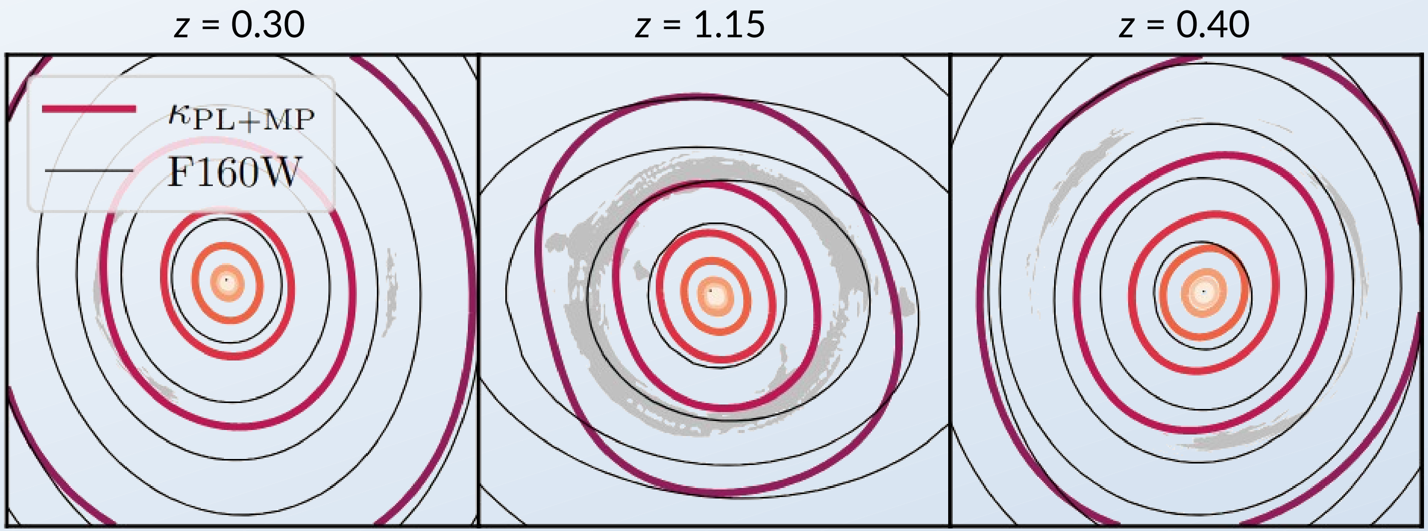
- Multipoles are required by the data: Bayes factor of 9327. **Only apparent with VLBI data.**
- **Flux ratios and H_0 can be off by ~7% with a macro-model that is too simple!**



Powell et al. 2022, 2207.03375

Misalignment of isophotes and lens mass

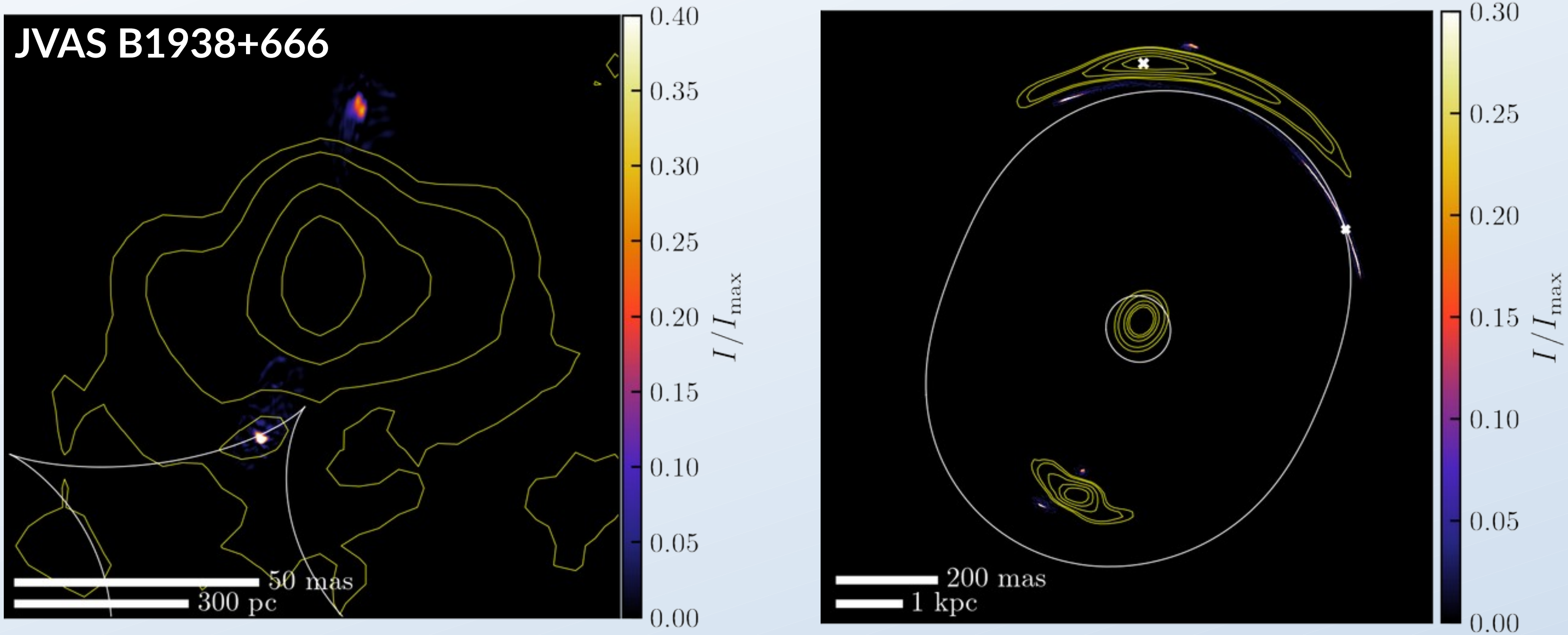
- Stacey et al. (2024) modeled 3 ALMA lenses and compared the lens mass models with optical isophotes.
- The higher-redshift lens galaxy shows the biggest misalignment in the *m* = 3 and *m* = 4 multipoles.
- **Extending this study to a population of lenses with radio and optical observations will provide a window into galaxy assembly.**



Stacey...+Powell+...2024

Multi-wavelength joint modeling

- **This will be the first fully joint radio-optical composite DM+baryons lens model. Pronto is the only code that can do it.**
- Radio and optical image locations complement each other to form a more complete Einstein ring.
- Absence of lens light in radio gives the radio arcs constraining power over baryonic mass component (M/L).



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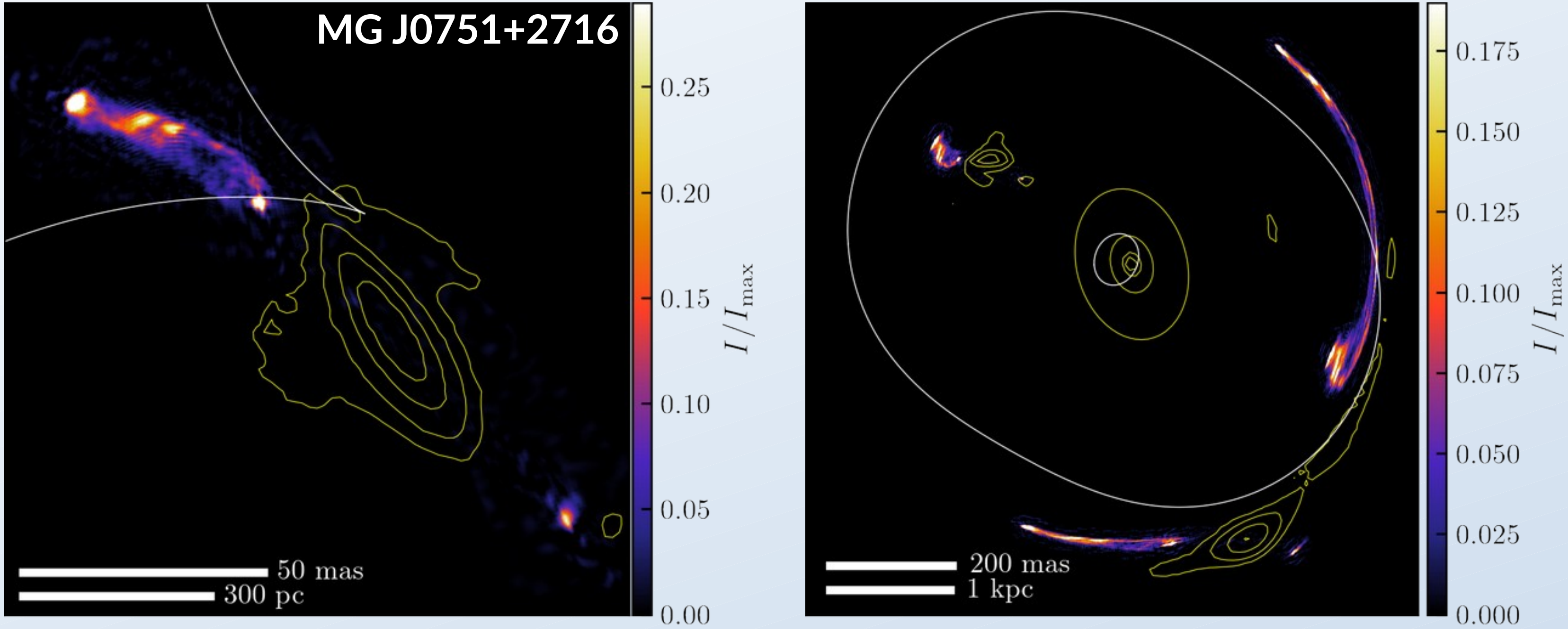
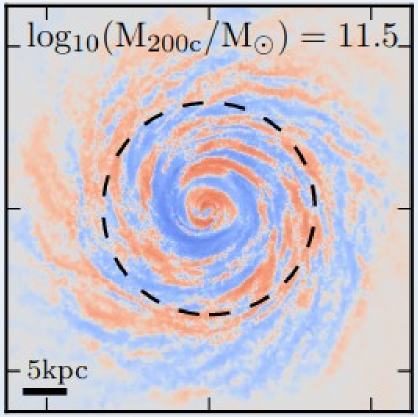


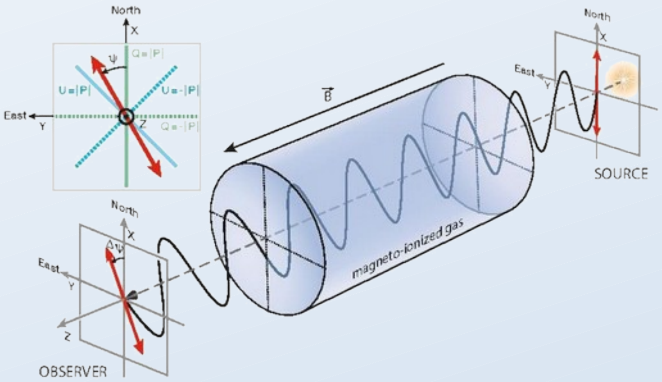
Magnetic field structure

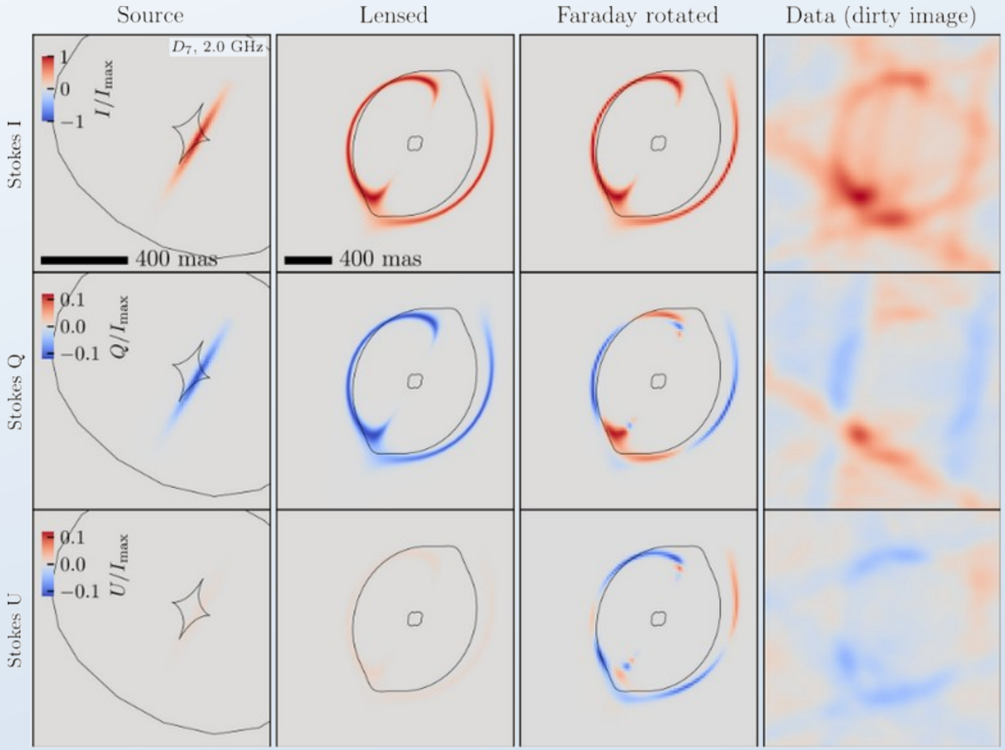


Pakmor+2024

Differential Faraday rotation in the lens galaxy ISM

- Measuring polarization angles at different image positions gives information on the magnetic field structure in the lens galaxy, independently of the source and foreground.
- **Ndiritu et al. (2024) implemented a forward model for (ordered) magnetic fields in lens galaxies.**
- **Can recover RM to within ten percent at the image locations.**

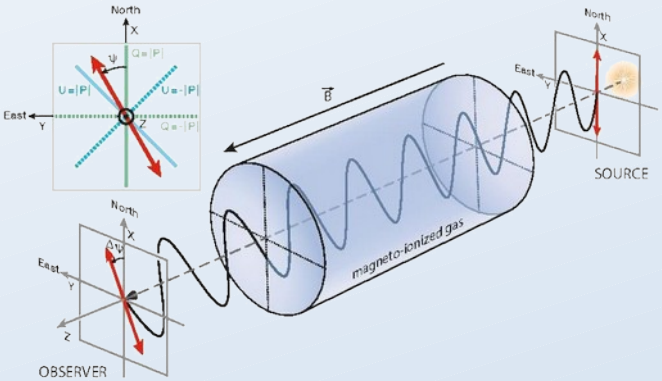


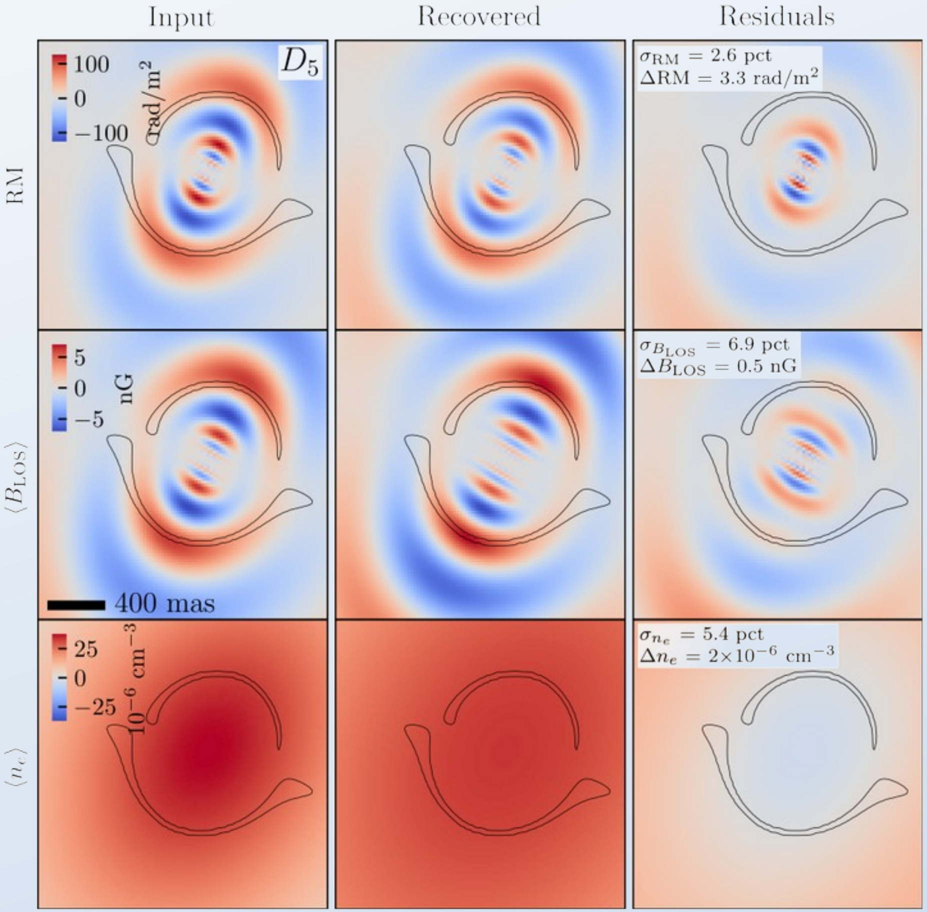


Ndiritu, Vegetti, Powell, McKean (2024)

Differential Faraday rotation in the lens galaxy ISM

- Measuring polarization angles at different image positions gives information on the magnetic field structure in the lens galaxy, independently of the source and foreground.
- **Ndiritu et al. (2024) implemented a forward model for (ordered) magnetic fields in lens galaxies.**
- **Can recover RM to within ten percent at the image locations.**

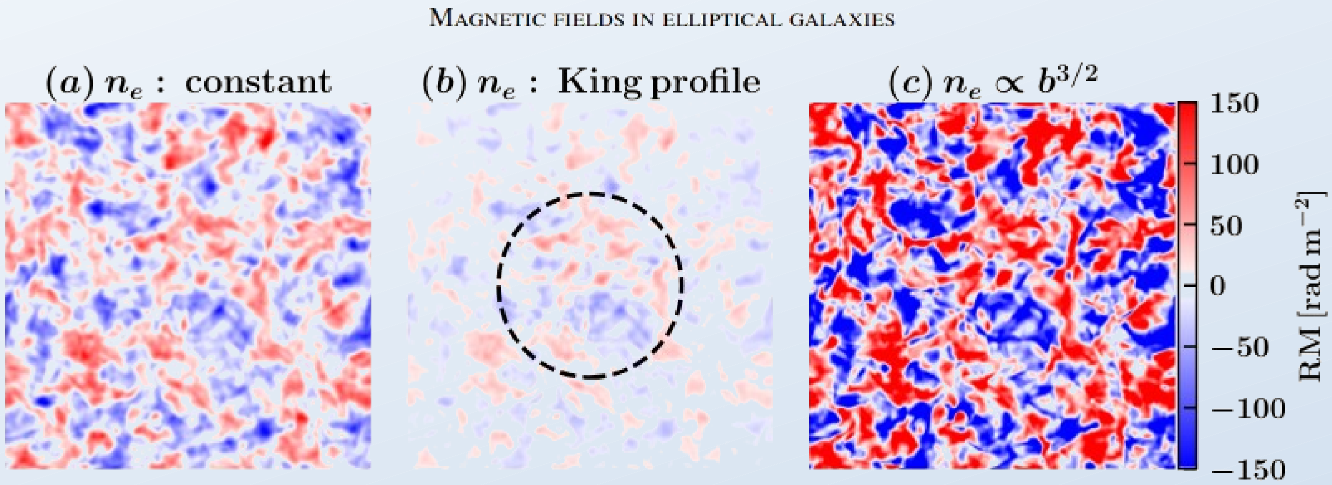




Ndiritu, Vegetti, Powell, McKean (2024)

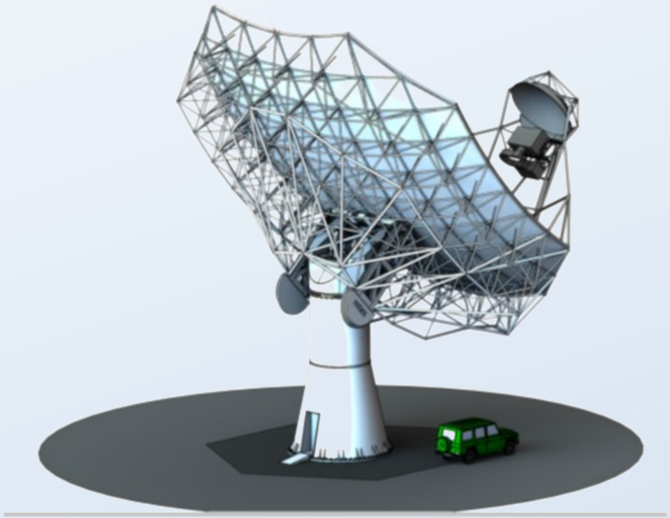
Differential Faraday rotation in the lens galaxy ISM

- **Most strong lenses are massive elliptical galaxies.**
- Massive ellipticals are expected to have a disordered magnetic fields supported by a turbulent dynamo.
- Will further develop `pronto` to include this random component.



Seta+2020

Looking to the future



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

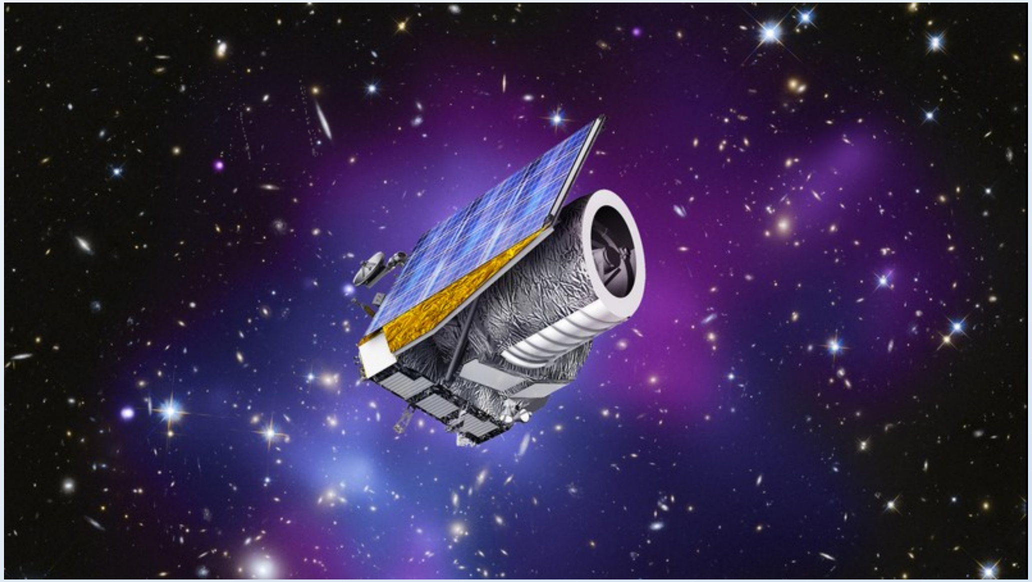
VLBI - ELT

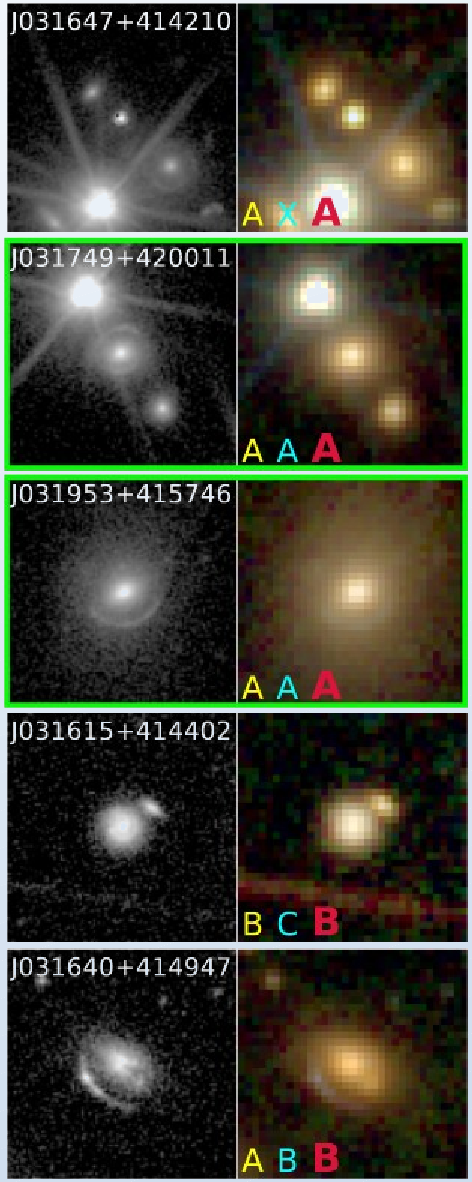
3 to 4 mas resolution

3+ years:

Euclid with VLBI follow-up

- *Euclid* is already discovering new lenses!
- We expect ~10^5 new lenses (total)
- Will cross-correlate Euclid lens positions with radio emission in the LOFAR radio surveys for promising VLBI lens candidates



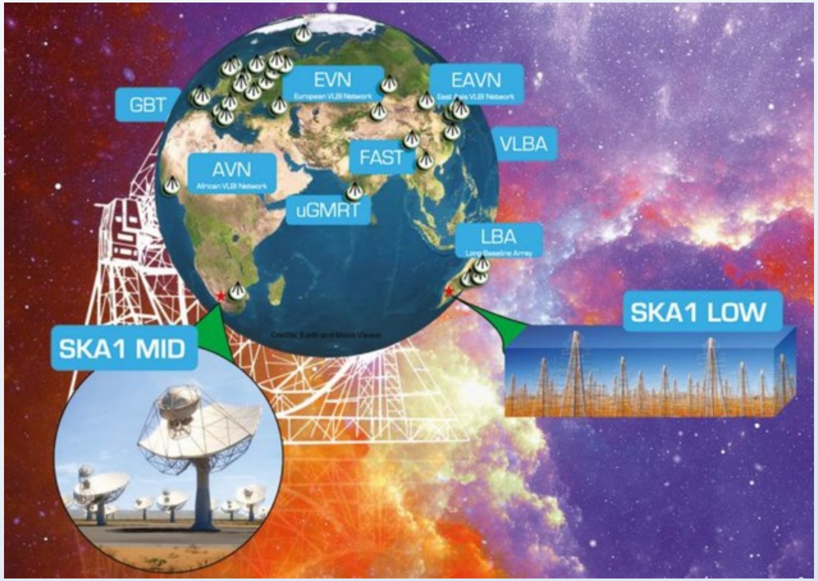


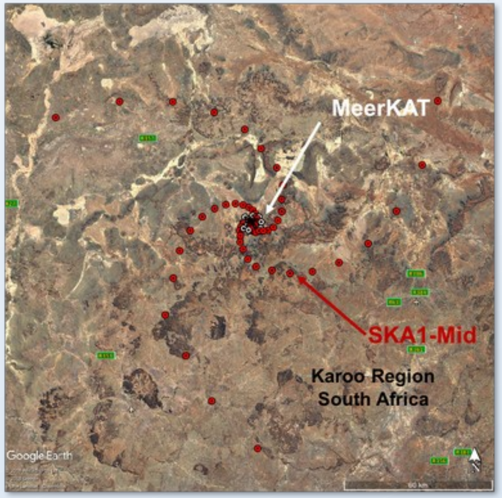
Acevedo Barroso + … + Powell + *Euclid* consortium (2024)

3+ years:

Square Kilometre Array (plus VLBI)

- Square Kilometre Array will discover ~10^5 radio lenses
- Phased-up SKA1-MID array (South Africa) will be used as a highly sensitive antenna along with existing global VLBI facilities.
- 133 15m SKA dishes and 64 13.5m Meerkat dishes
- Roughly the same angular resolution, but massive gain in sensitivity (on baselines containing SKA1-MID)
- Science verification begins in 2027





Science Verification begins 2027

AA*	144 (80+64)	2028 Q1	307	2028 Q1
Operations Readiness Review		2028 Q2		2028 Q2
End of Staged Delivery		2029 Q1		2029 Q1

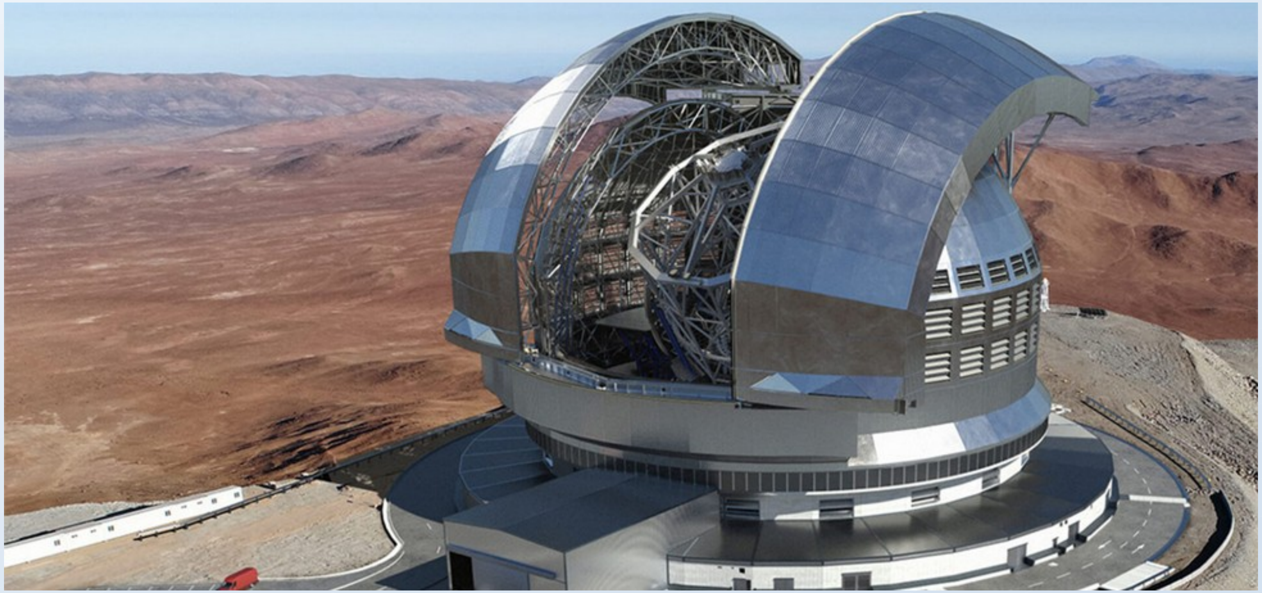
Early Operations begin 2029 (shared risk)

AA4 (Full Design Baseline SKA1)	197 (133+64)	TBD	512	TBD

5+ years:

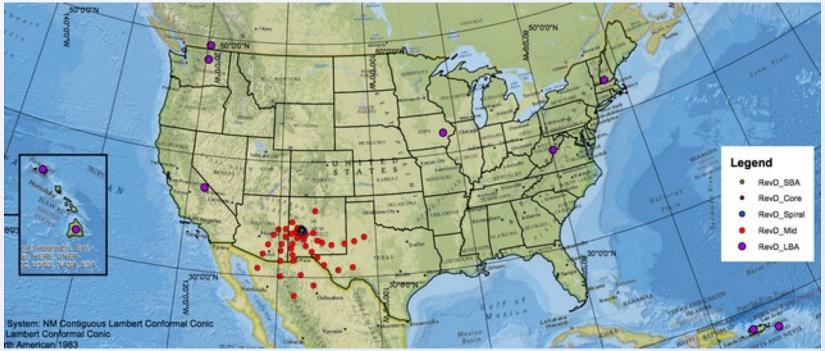
European Extremely Large Telescope (E-ELT)

- 39-meter main mirror.
- < 5 milli-arcsecond resolution (comparable to VLBI)
- **Science verification planned for 2028**
- ***Many of the computational methods I developed for VLBI data can be applied to high-resolution optical data.***

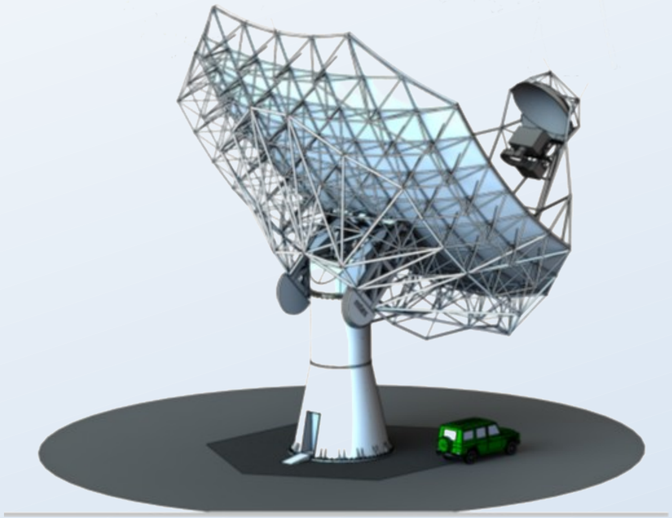


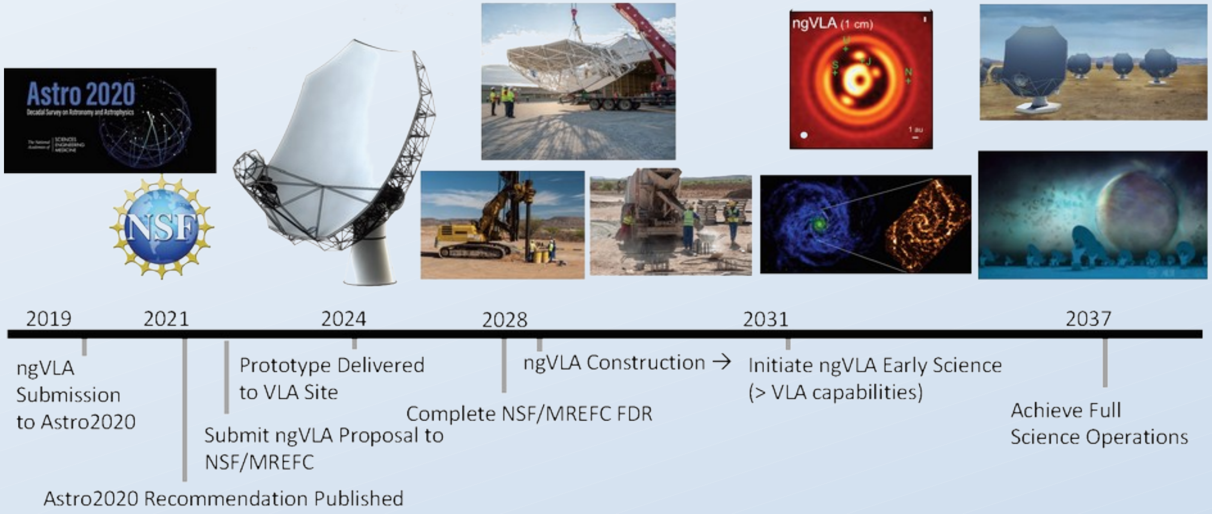
7+ years:

Next-Generation Very Large Array (ngVLA)



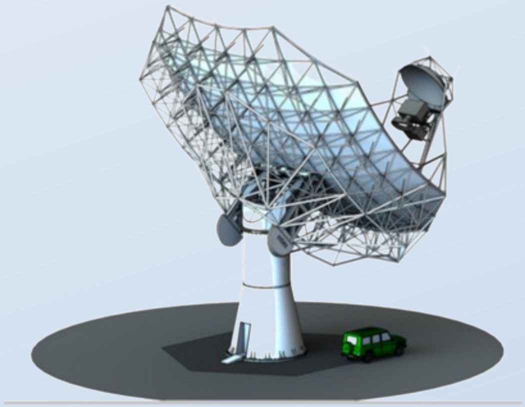
- American VLBI array to supersede VLA and VLBA
- Heavy German involvement in ngVLA construction and science
- 244 18m dishes plus 19 6m dishes (mostly homogeneous array)
- 10x the sensitivity of VLA and sub-milli-arcsecond resolution.
- **“Early science operations” in 2031, “full science operations” in 2037.**





7+ years:
Next-Generation Very Large Array (ngVLA)

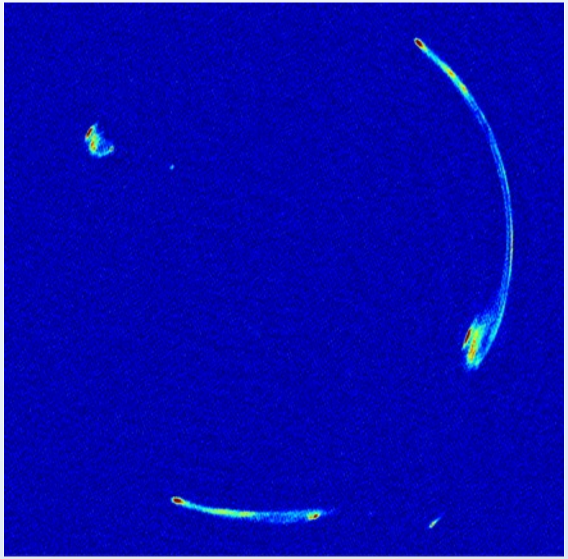
- Interferometric data volume scales as N^2 in the number of antennas. **ngVLA will have 263 (vs. ~20).**
- **High-SNR interferometric data is more computationally intensive to model**. Developing improved preconditioners and iterative solver techniques, as well as more efficient approaches to Bayesian analysis will be key for next-generation VLBI data from SKA-VLBI and ngVLA.
- In the case of both SKA-VLBI and ngVLA, the format of the final data will likely consist of pre-reduced, pre-calibrated data cubes, which would preclude direct analysis of the visibilities. In this case, **work will be required to modify `pronto` so that we can properly model the instrumental noise, noise correlation across the image plane, and the proper treatment of residual calibration errors** in the absence of complete visibility data.



Pathfinding for a future of abundant VLBI lens observations

- ☑ Forward modeling of radio interferometric data in the visibility plane
- ☑ With 10^9 visibilities per observation
- ☑ At < 5 milli-arcsecond resolution (2048^2 pixels in the image plane)
- ☑ Computationally tractable (full posterior sampling for VLBI data in < 12 hours)
- ☑ Sensitivity to dark matter sub-/LOS-haloes in the 10^6 solar mass regime
- ☐ With 10^{11} visibilities per observation?
- ☐ Computationally tractable and automated (for 1000 observations? 10000 observations?)

Conclusions and future prospects



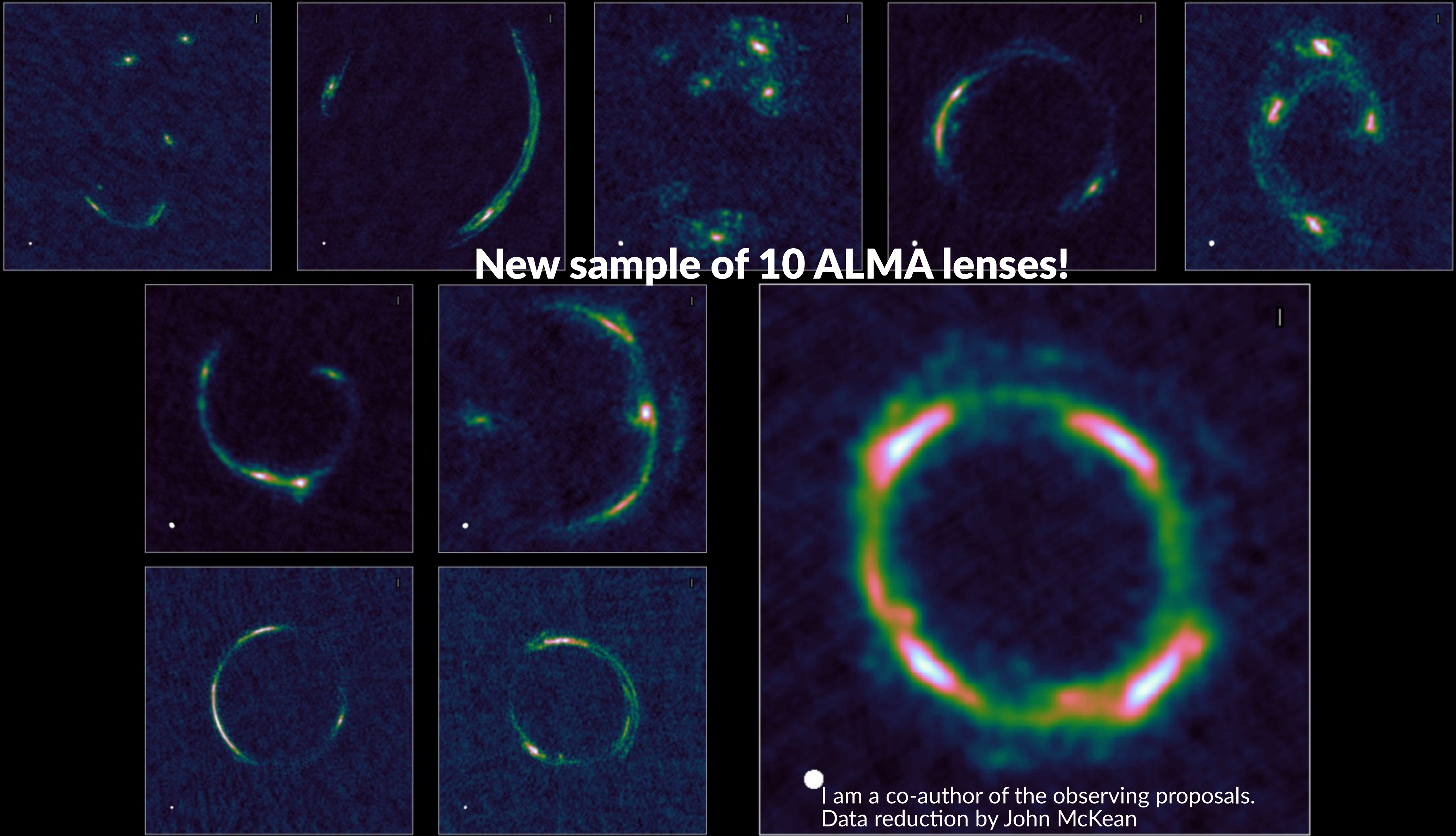
- **VLBI** provides the highest-resolution lens observations available to date
- Should strengthen constraint on WDM to m_χ ~ 20 keV (work in progress)
- **Modeling halo population effects is not straightforward with thin arcs.**
- **Can probe lens galaxy assembly history.**
- **Also useful for modeling Faraday rotation in the lens galaxy.**

- **ALMA** sample is growing, and can approach VLBI resolution in Band 9, but with relatively low SNR.
- **Euclid** will discover thousands of new lenses (but resolution of Euclid data is not useful for DM constraints)
- **SKA** will discover lots of new radio-bright lenses with extended arcs that can be followed up with **VLBI**
- **ngVLA** will give exquisite *uv*-coverage and sensitivity

- **We need to develop improved ways of extracting information from data in an efficient but in an interpretable way.**

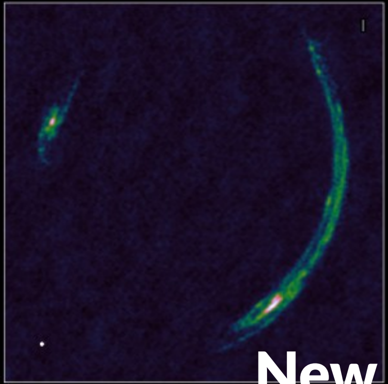
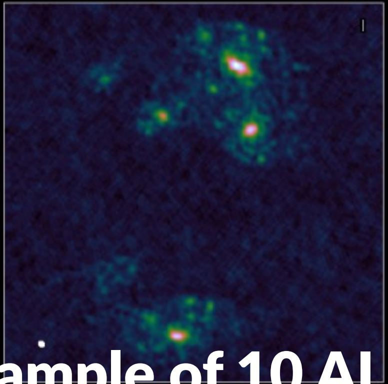
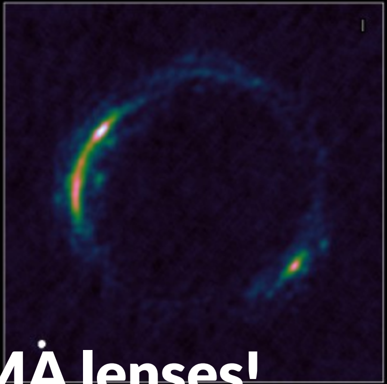
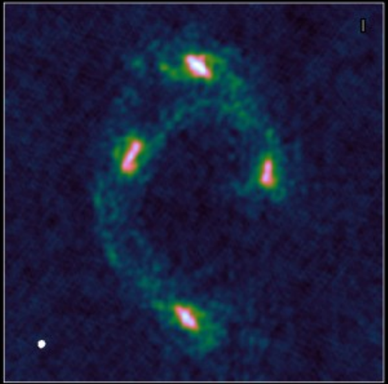
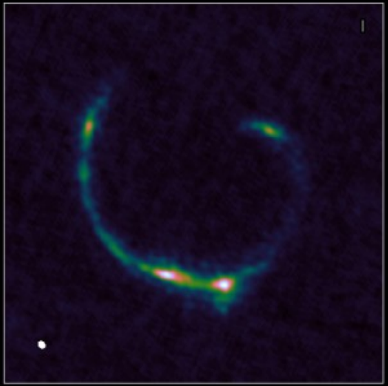
- ***I am interested in talking to someone about:***
  - **How to easily model phase and amplitude calibration errors in a simulated observation?**
  - **Machine learning, especially diffusion models.**

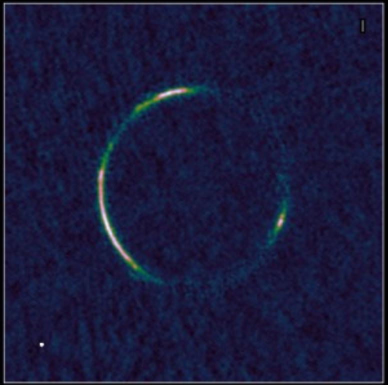
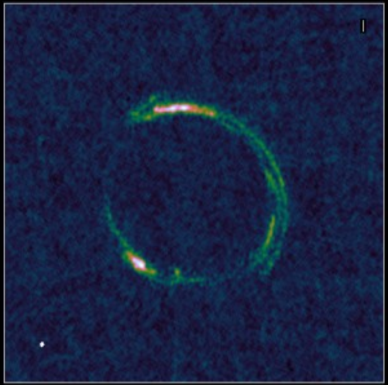
New sample of 10 ALMA lenses!



I am a co-author of the observing proposals.
Data reduction by John McKean

New sample of 10 ALMA lenses!
...and 6 more on the way.

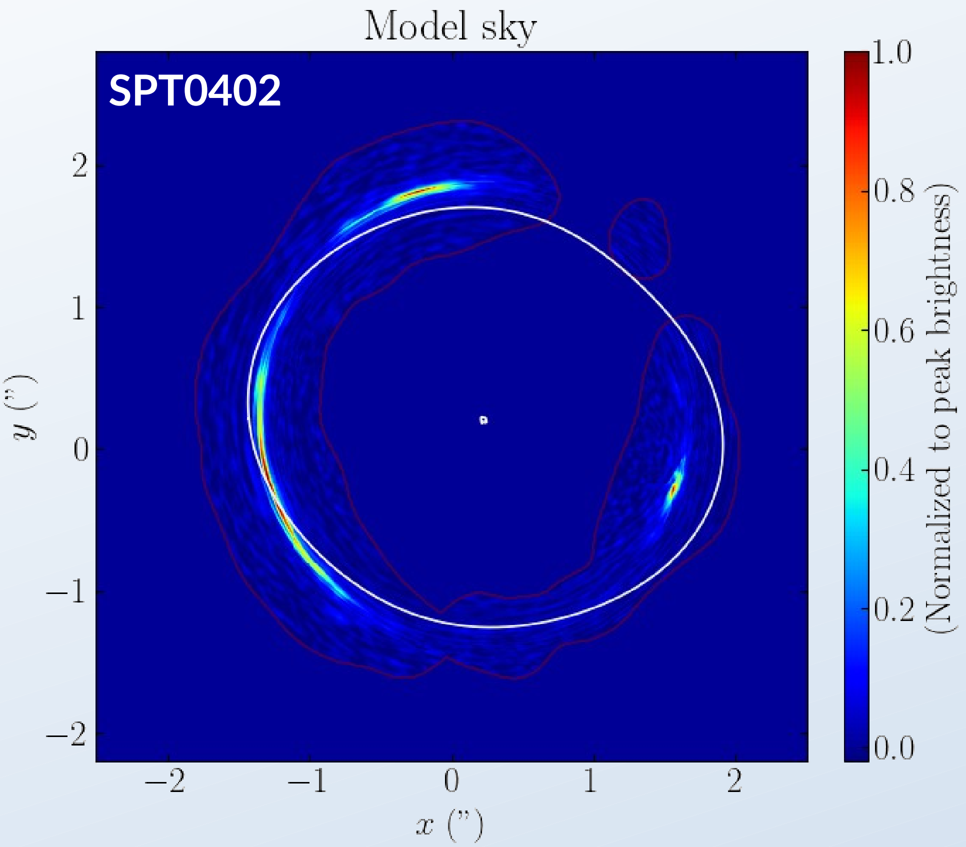







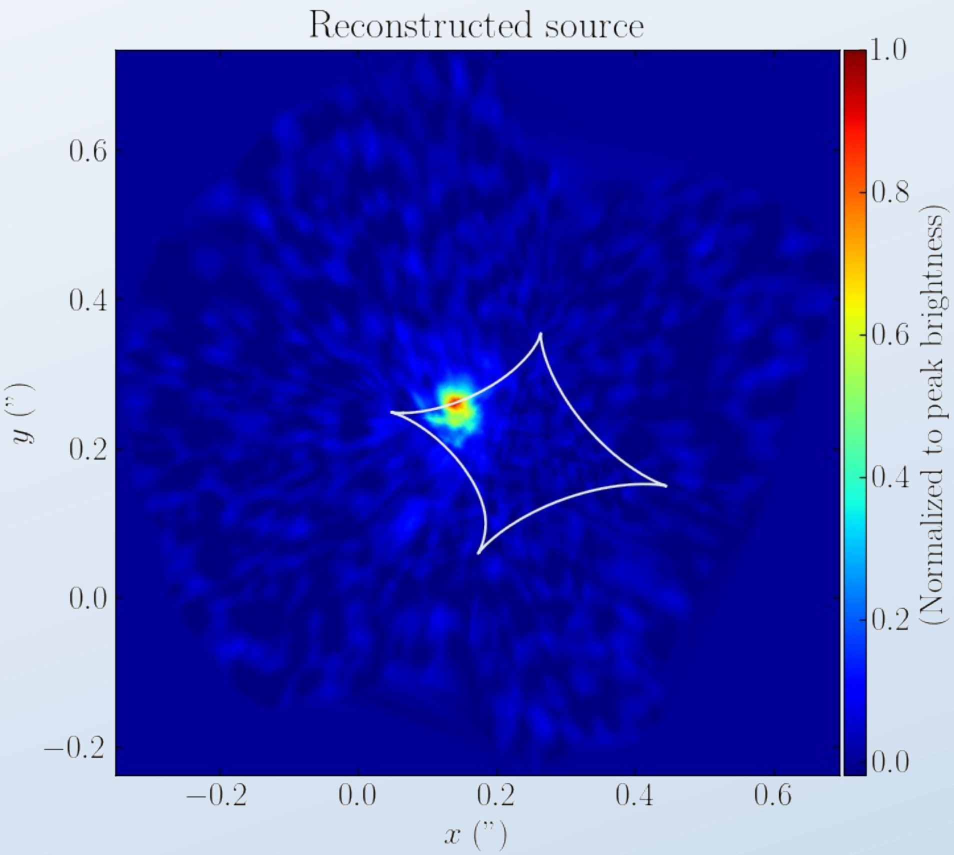




I am a co-author of the observing proposals.
Data reduction by John McKean

New ALMA lenses

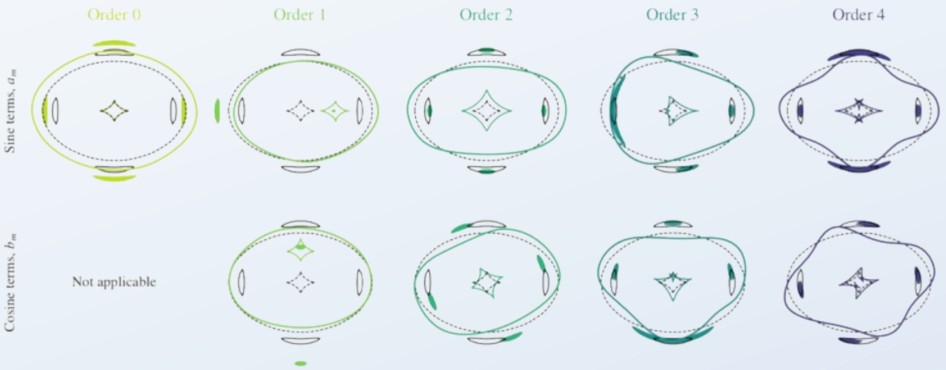
- 25 milli-arcsecond resolution, ~1 hour per source
- Nested posterior sampling in < 3 hours per observation!

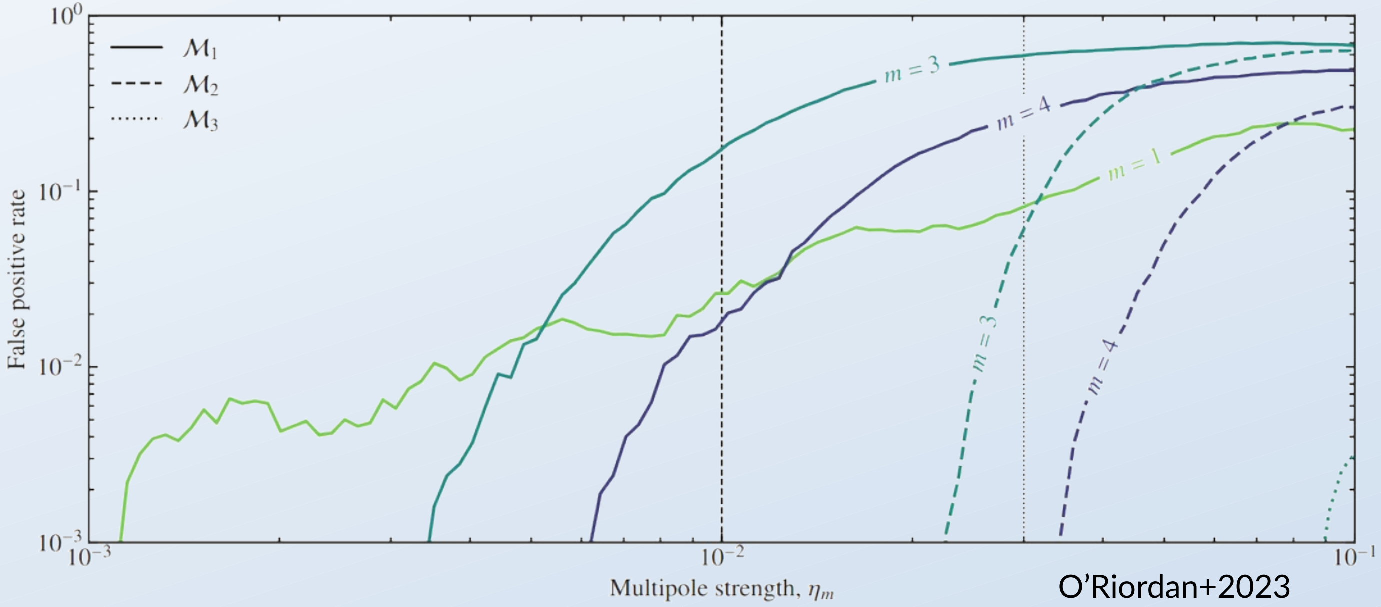




Multipoles and the sensitivity function

- O'Riordan et al. (2023) show empirically that any departure from ellipticity can masqeurade as dark sub/LOS-haloes.
- **Composite radio-optical modeling will let us compute the most robust sensitivity map and minimize false positives and false negatives.**

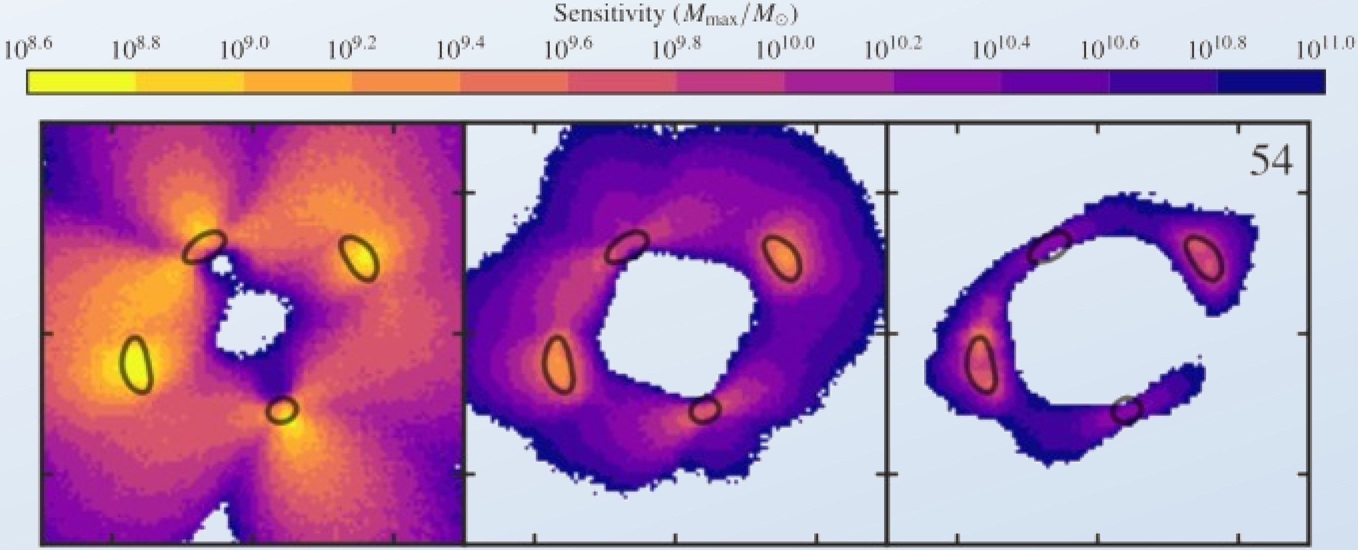




O'Riordan+2023

A sensitivity function for radio interferometric data

- The "sensitivity function" quantifies how many dark substructures we should expect to detect in an observation, as a function of position, mass, concentration, redshift, etc.
- **Only studied in the context of optical data so far. Radio data is fundamentally different due to Fourier-plane measurement.**
- **Expensive to compute, but recent machine learning work is solving this.**
- Understanding the sensitivity function for radio data will inform which *Euclid* and SKA lenses to follow up at high resolution.

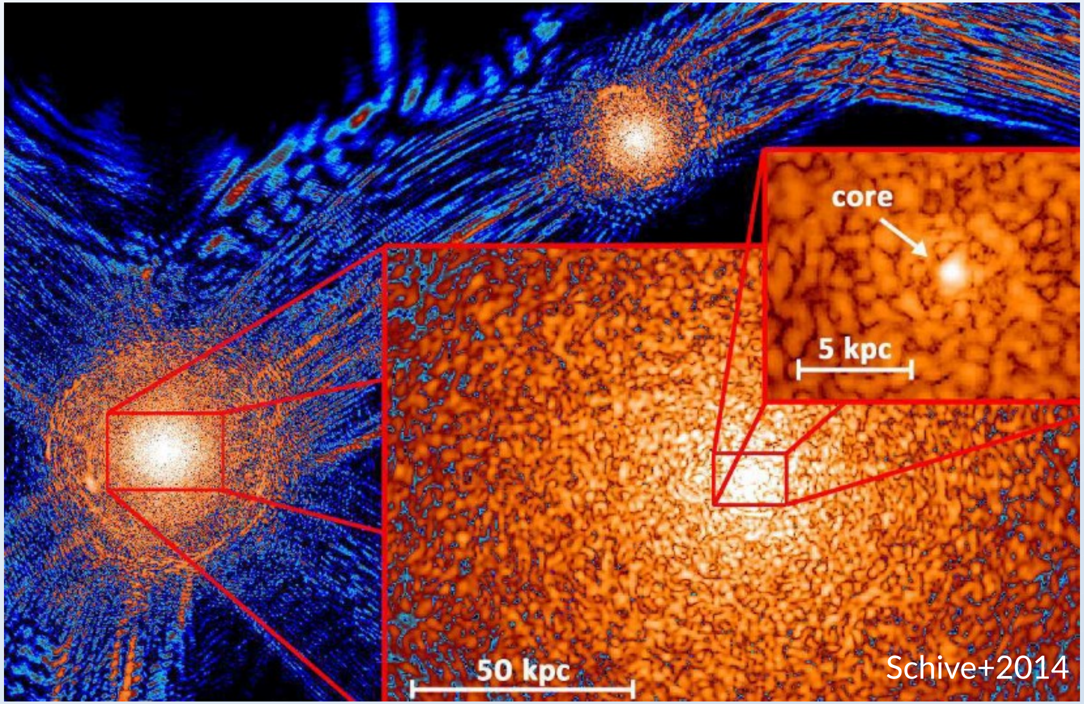


O'Riordan+2023

Fuzzy dark matter (FDM)

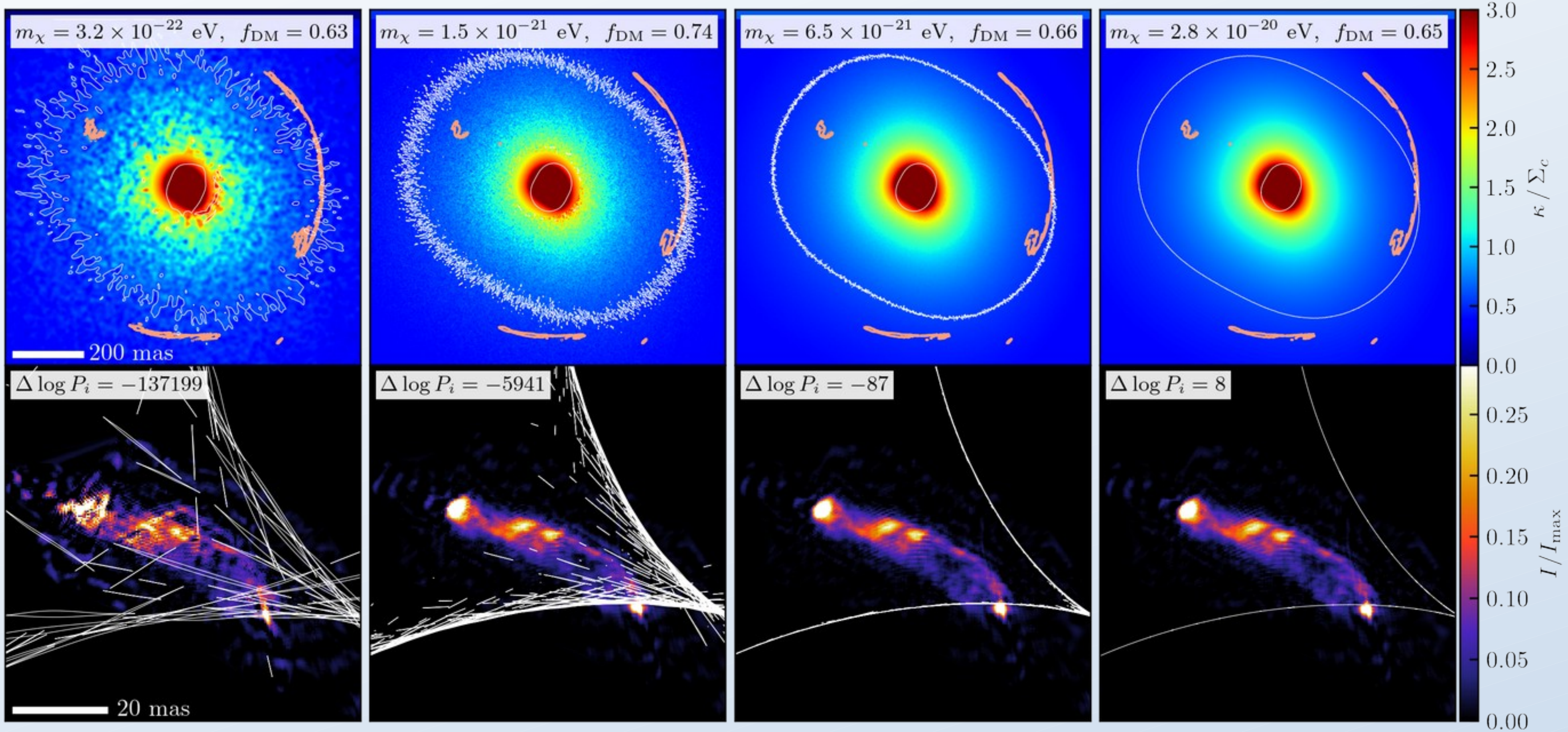
- Fuzzy dark matter (FDM) is a class of ultra-light DM (ULDM, $m_\chi \sim 10^{-21}$ eV) with a ~kpc-scale de Broglie wavelength

  Key predictions:
  - 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)**



Fuzzy dark matter with `pronto`

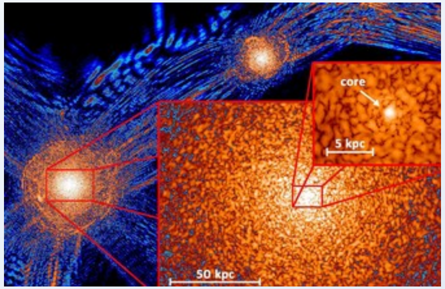
- When the particle mass m_χ is low, the fuzzy DM density granules make the proposed lens model too lumpy
- The inferred source model takes on a disrupted morphology in an attempt to fit the data, given the lens model
- The inability of a fuzzy lens realization to explain the data is penalized in the likelihood, $\Delta\log P_i$

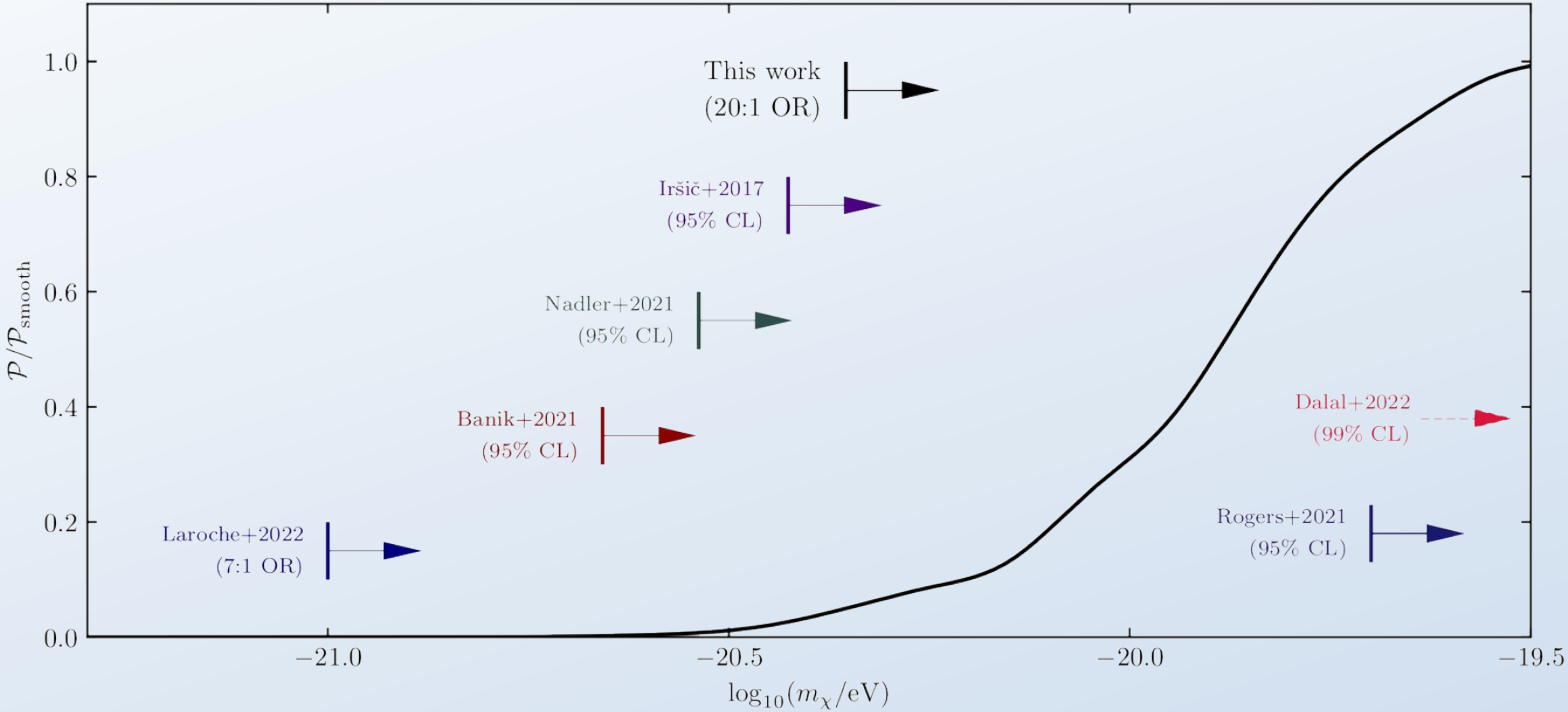


Powell et al. 2023, 2302.10941

Fuzzy dark matter with `pronto`

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





Powell et al. 2023, 2302.10941

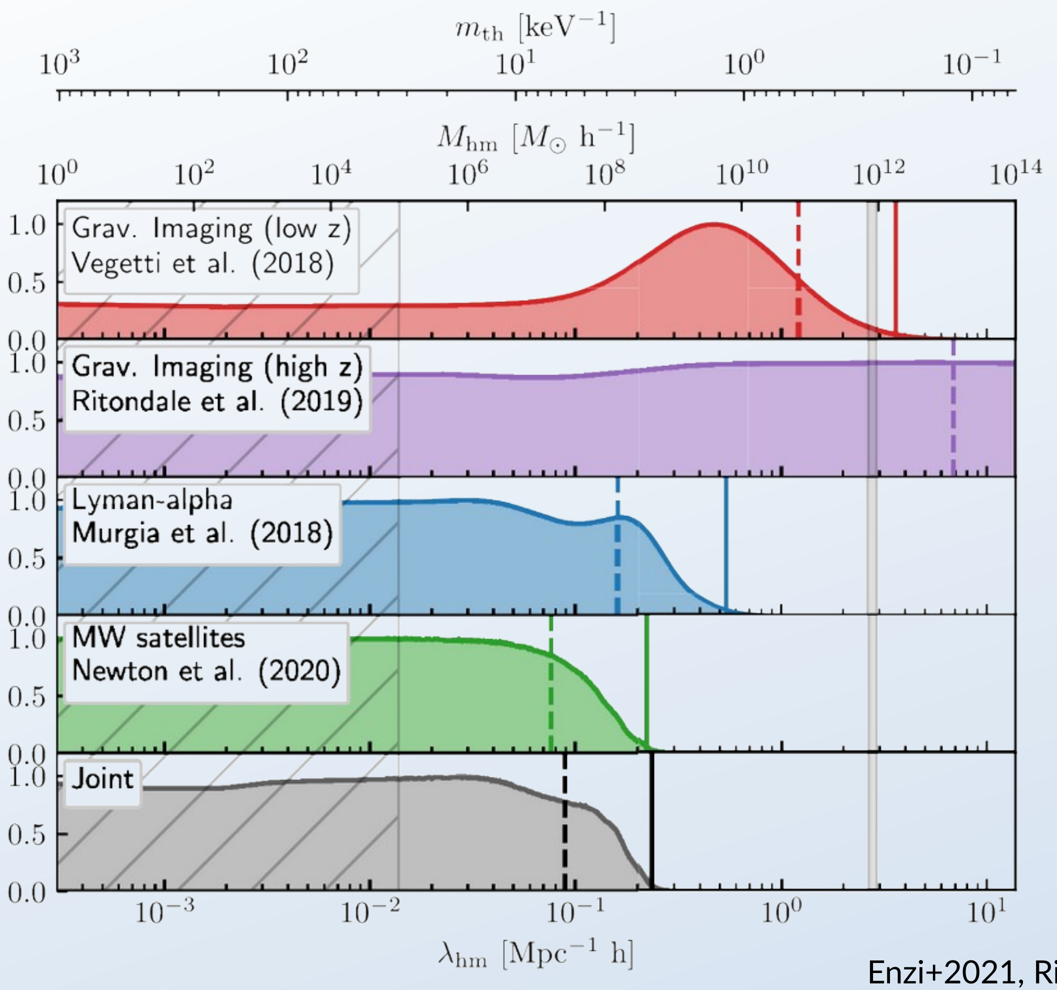
Summary

- **I developed `pronto`, the only code capable of modeling milli-arcsecond resolution VLBI lens observations in a computationally efficient manner.** I demonstrated these capabilities by
  - Publishing the first joint lens model and pixellated source reconstruction of a VLBI observation at < 5 mas resolution.
  - Publishing the strongest lensing-based constraints on fuzzy dark matter using a single lens observation
  - Detecting a 10^6 solar mass perturber at redshift 0.88 from its gravitational effect alone

- **In the next 5 years I will**
  - Develop an efficient method for computing sensitivity maps for radio observations
  - Publish warm dark matter constraints in the 15-20 keV regime derived from our sample of 16 ALMA lenses
  - Publish the first self-consistent joint analysis of VLBI and optical observations from the same lens system
  - Publish the first population study of joint ALMA-JWST strong lens observations for a sample of 16 lenses
  - Propose VLBI follow-up of promising SKA and *Euclid* lens systems

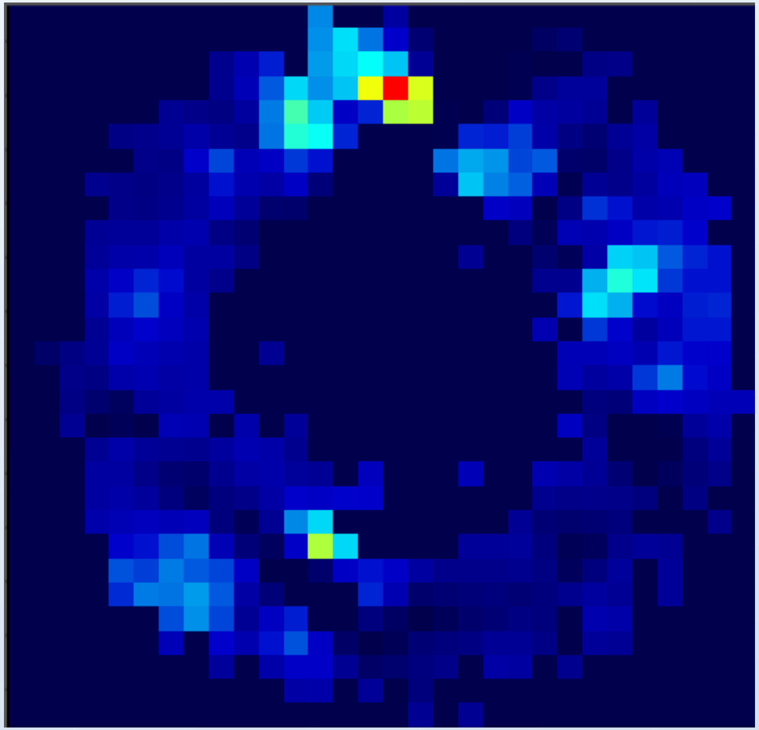
- **In the next 10 years I will**
  - Build a large sample of high-quality VLBI lens observations (long arcs at high SNR)
  - Publish WDM constraints from a large sample of ~10 best VLBI lenses (could rule out CDM)
  - Develop the intellectual capital, analysis tools, and observing strategies needed to lead the strong lensing field in the era of abundant strong lens observations with SKA-VLBI and ngVLA.

Warm dark matter (WDM)



Resolved sources

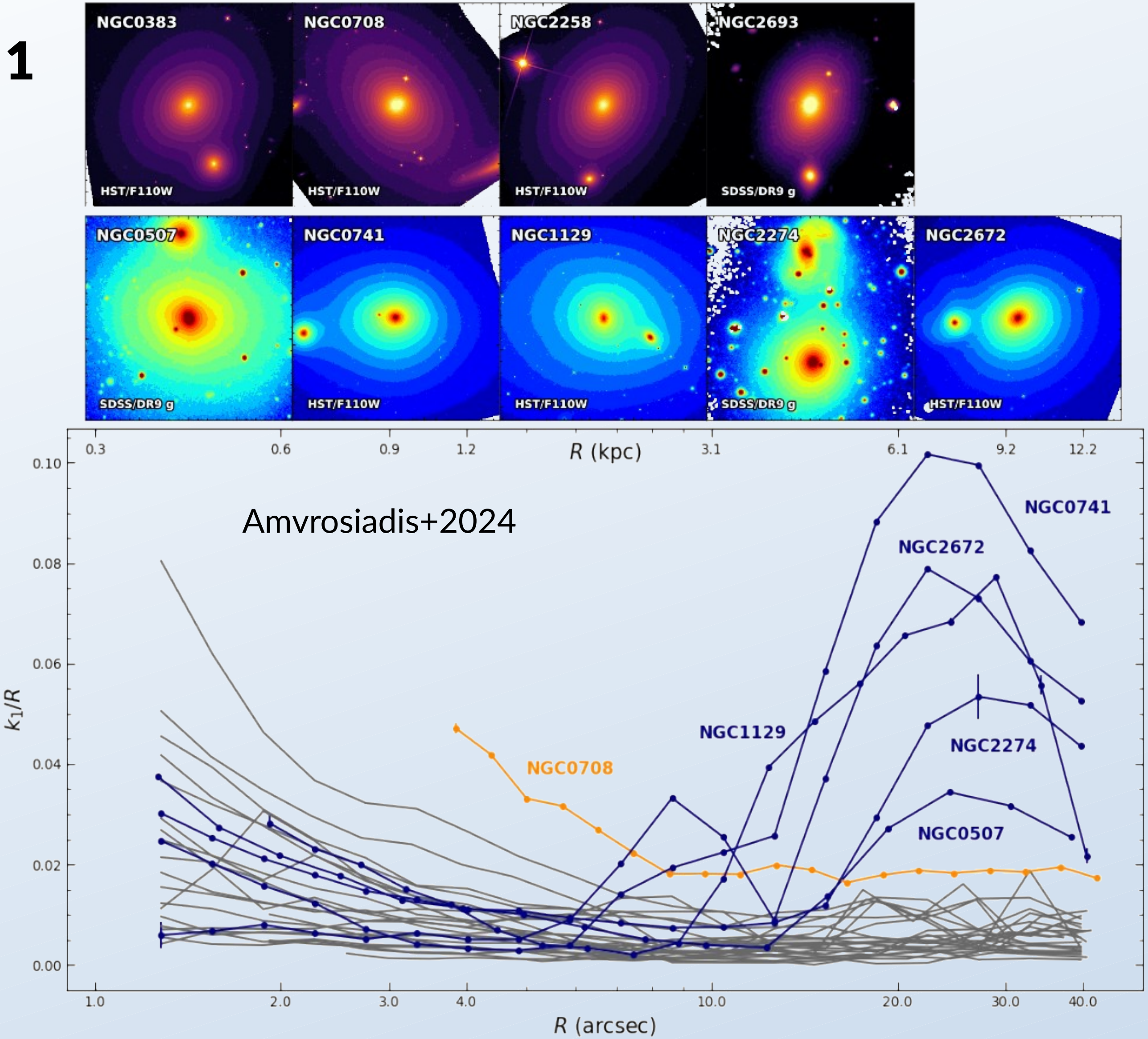
- Resolved sources give a robust, but weak, constraint
- Higher resolution and larger sample size are needed.



Enzi+2021, Ritondale+2019, Vegetti+2018

Tidal interactions induce $m = 1$ centroid offset

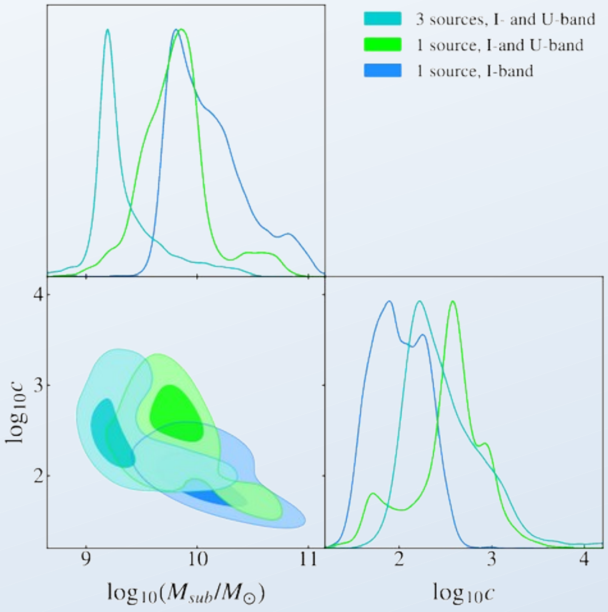
- Amvrosiadis et al. (2024) modeled a sample of HST galaxies (not lenses)
- Galaxies with nearby perturbers show a large centroid offset (m = 1 multipole)
- ***This DOF has not yet been included in any lens models!***

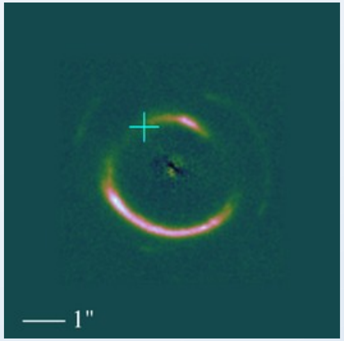


Highly-concentrated dark objects!

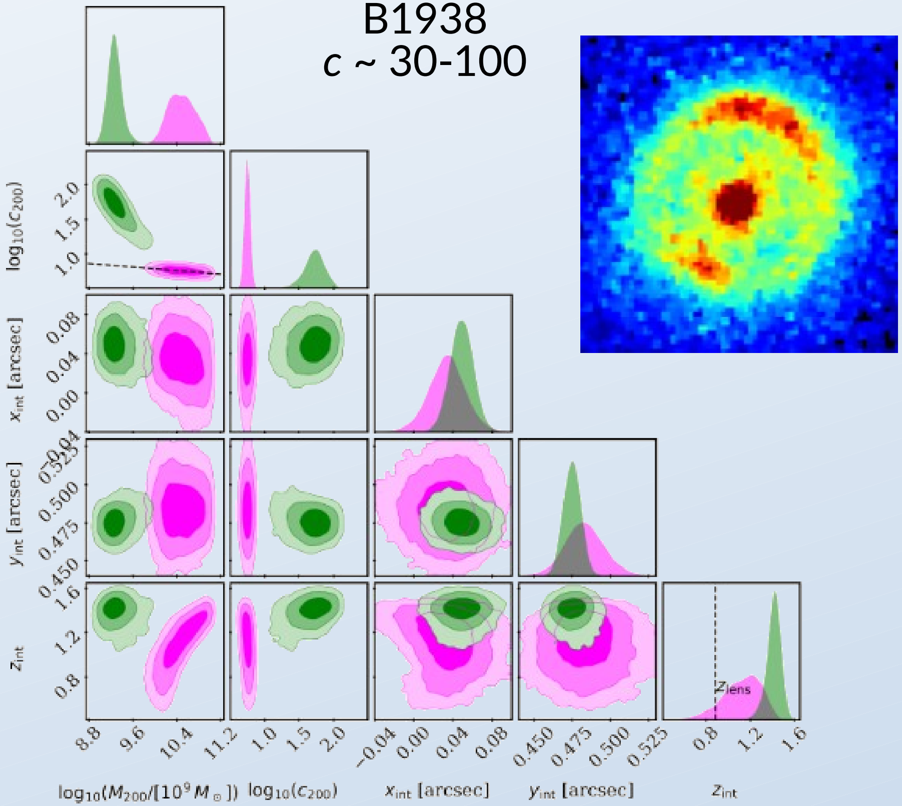
- **Three recent analyses of confirmed sub/LOS detections are much too compact for CDM subhaloes.**
- Wandering black holes? SIDM?

Ballard+2023
J0946
c ~ 100-1000

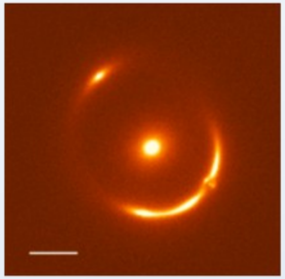




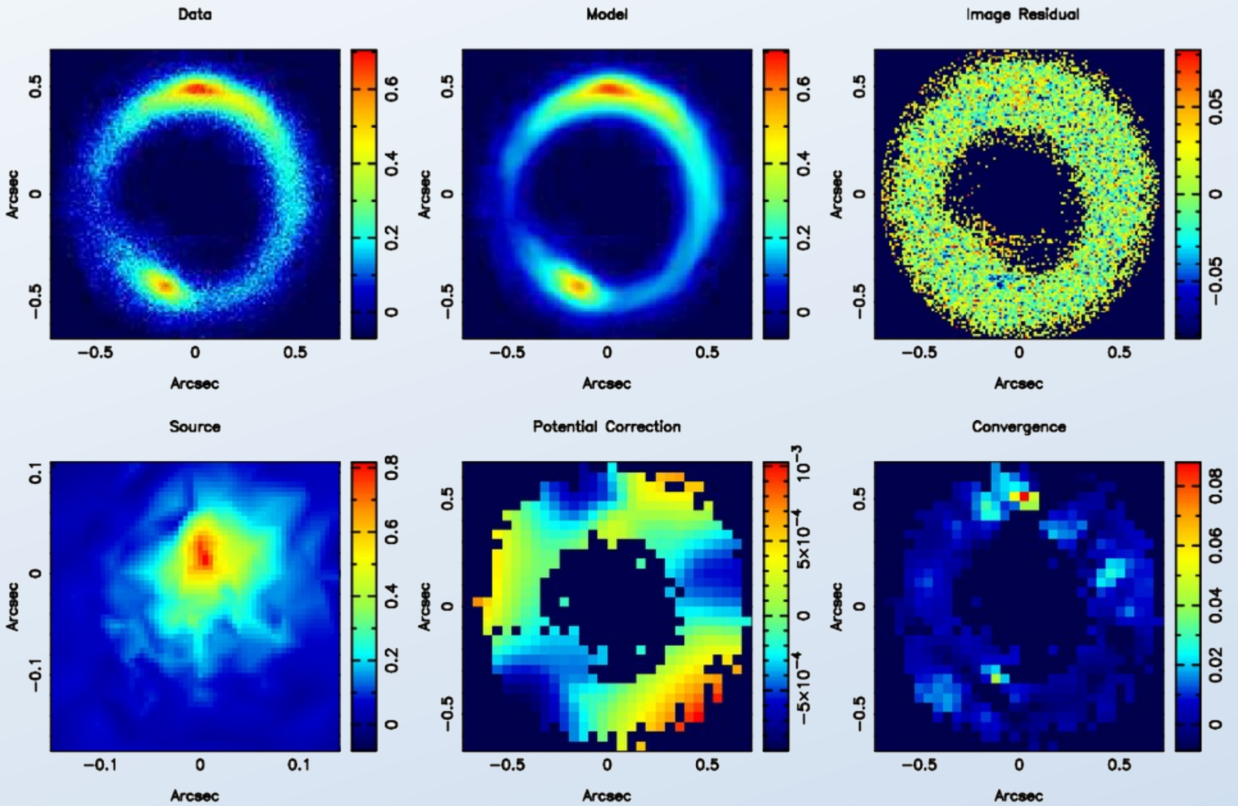
Sengul+2022
B1938
c ~ 30-100



Inference on resolved, extended images



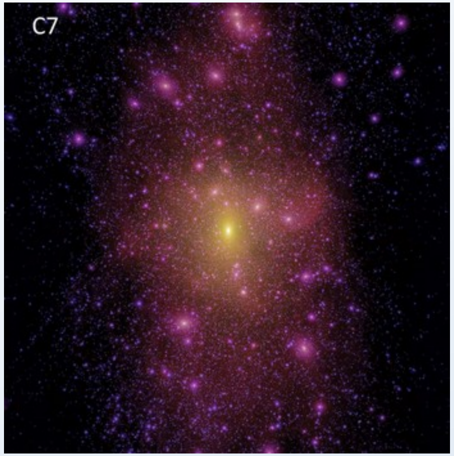
- Data analysis is computationally more expensive
- **Interpreting low numbers of individual (non-) detections is tricky: Need a "sensitivity function"**
- **Pixellated source has more freedom, can absorb gravitational perturbations into the source**
- **Tends to be biased towards "warmer" models (less low-mass structure)**



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

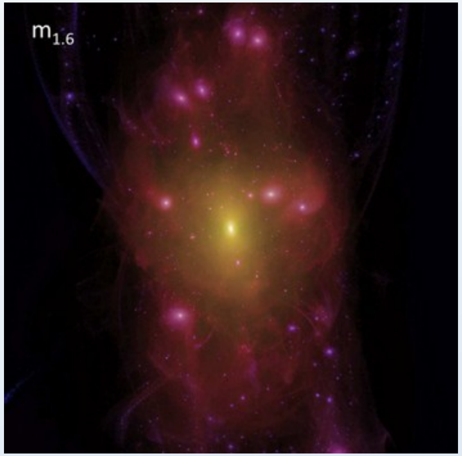
Dark matter phenomenology

Cold DM



Lovell+2014

Warm DM

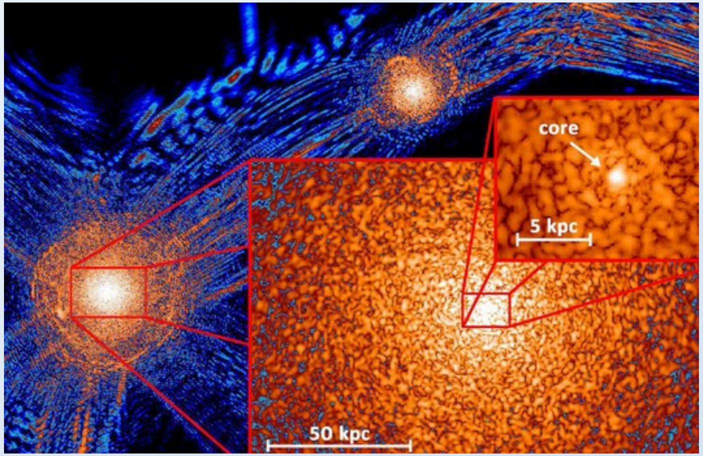


Lovell+2014

Self-interacting DM

Rocha+2013

Fuzzy DM



Schive+2014

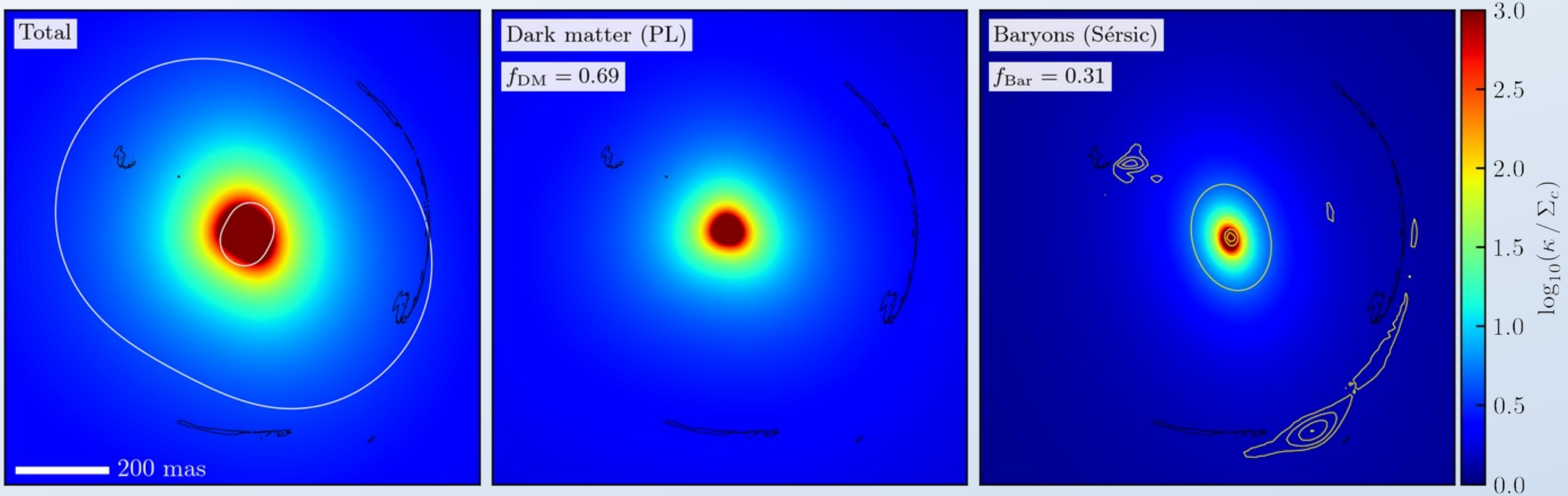
Method: Generating fuzzy lenses

- 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:

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

- The (reduced) de Broglie wavelength is:

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



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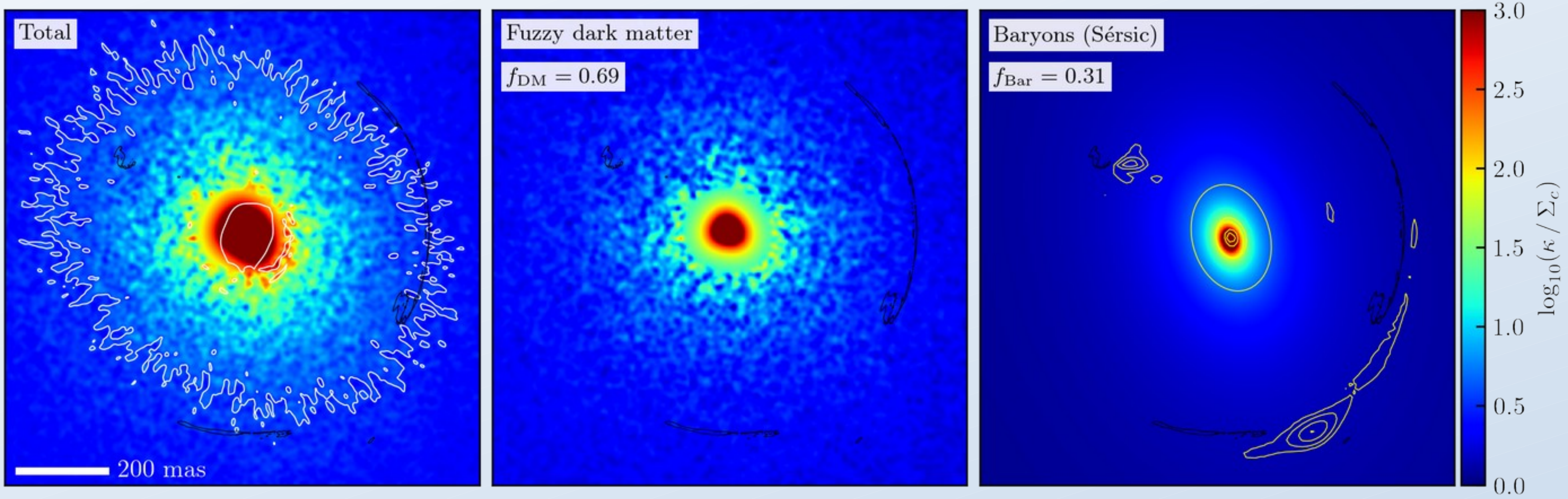
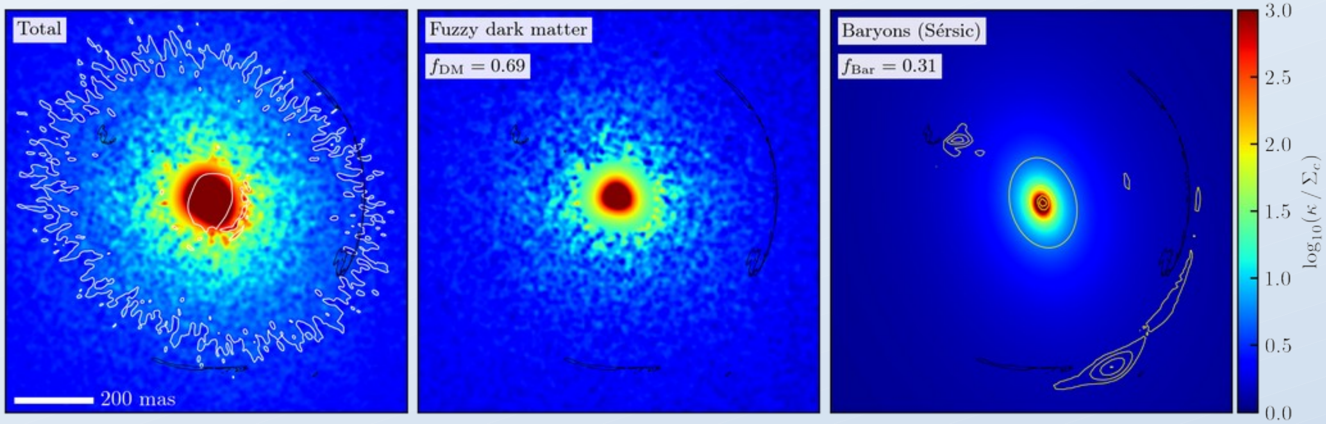


Method: Inference on FDM lens models

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
- f_{DM} 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.

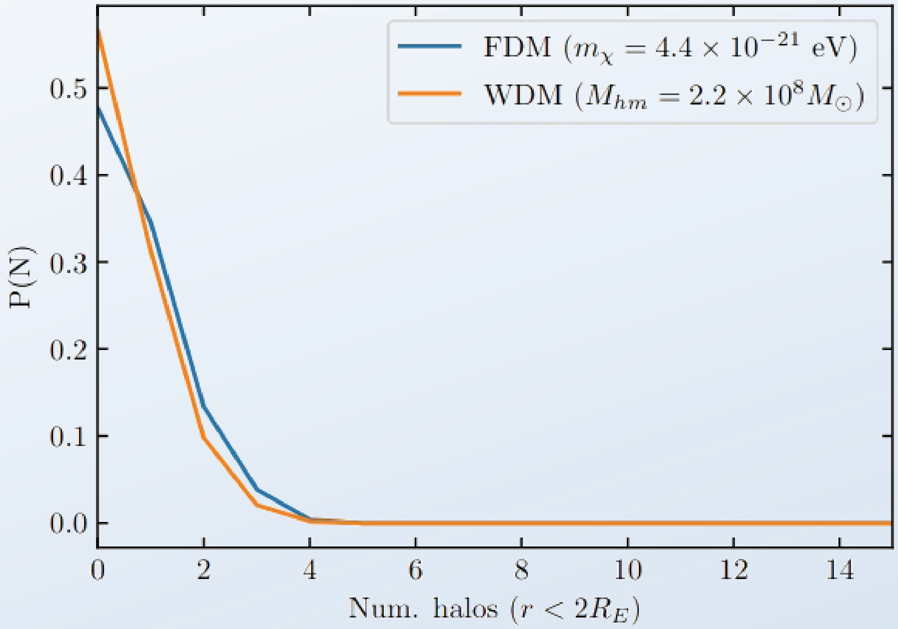
- i.e., for a FDM lens realization to be accepted, it must explain the data at least as well as the worst 0.3% of the smooth model posterior samples.
- In practice, we define a relative log-likelihood $\Delta\log P_i$, where samples are accepted if $\Delta\log P_i > 0$.

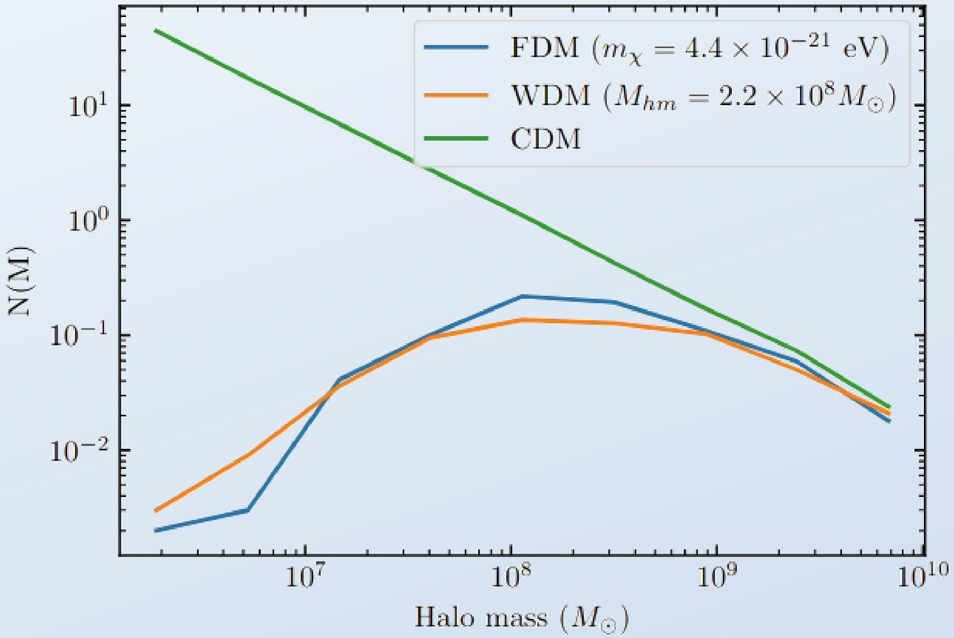
4) We build a histogram of the accepted samples to obtain an empirical posterior on m_χ

- 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

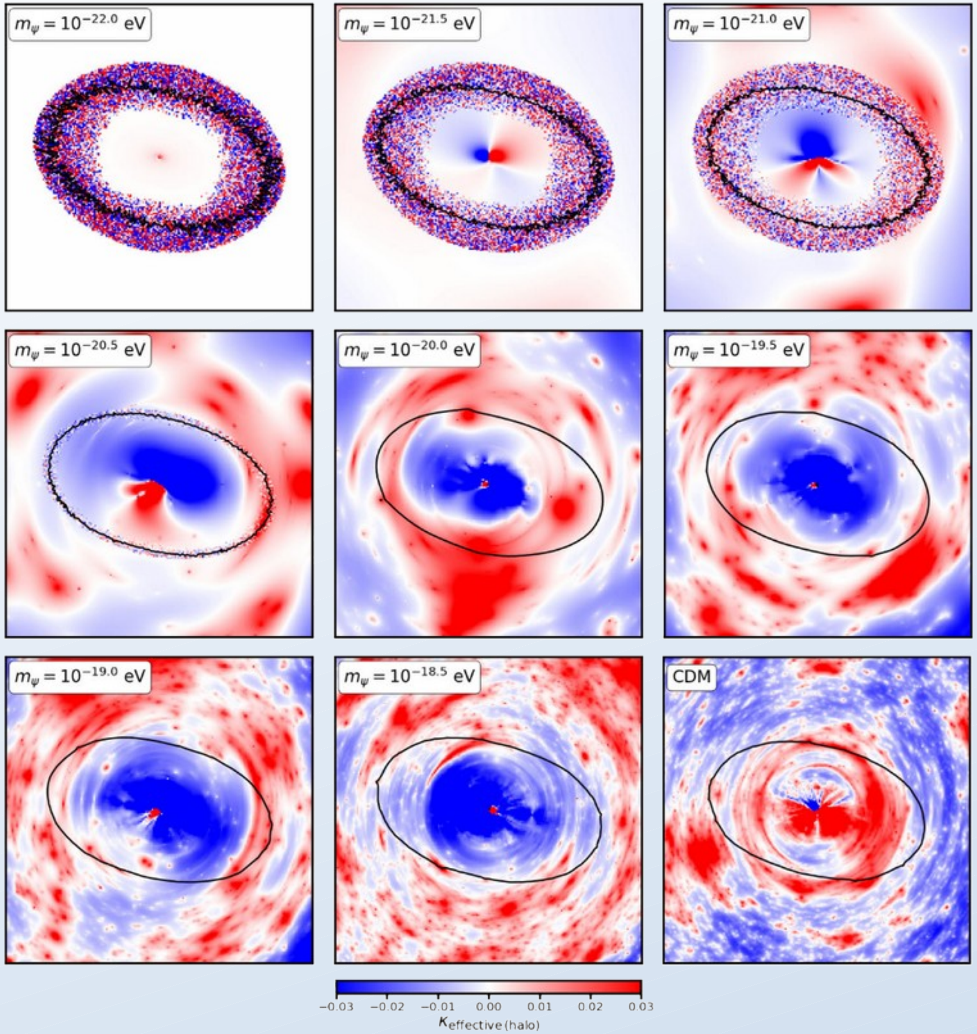
Expected sub- and LOS-halo population

- We do not explicitly include low-mass haloes in this analysis
- An estimate using PyHalo (Daniel Gilman) predicts O(1) subhaloes and LOS-haloes in the 10^8 to $10^9 M_{sun}$ range within twice the Einstein radius of our lens



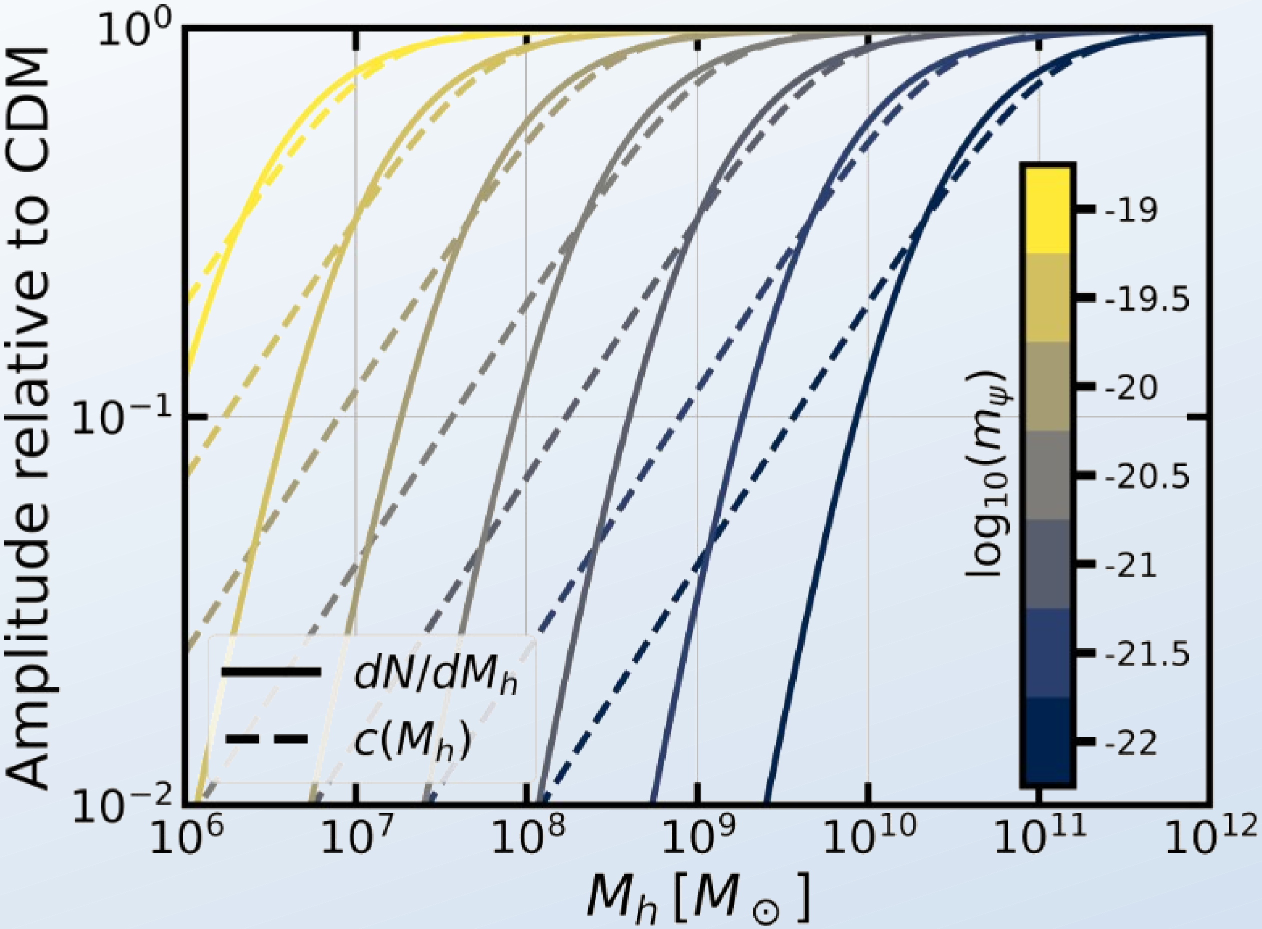


Subhaloes in FDM



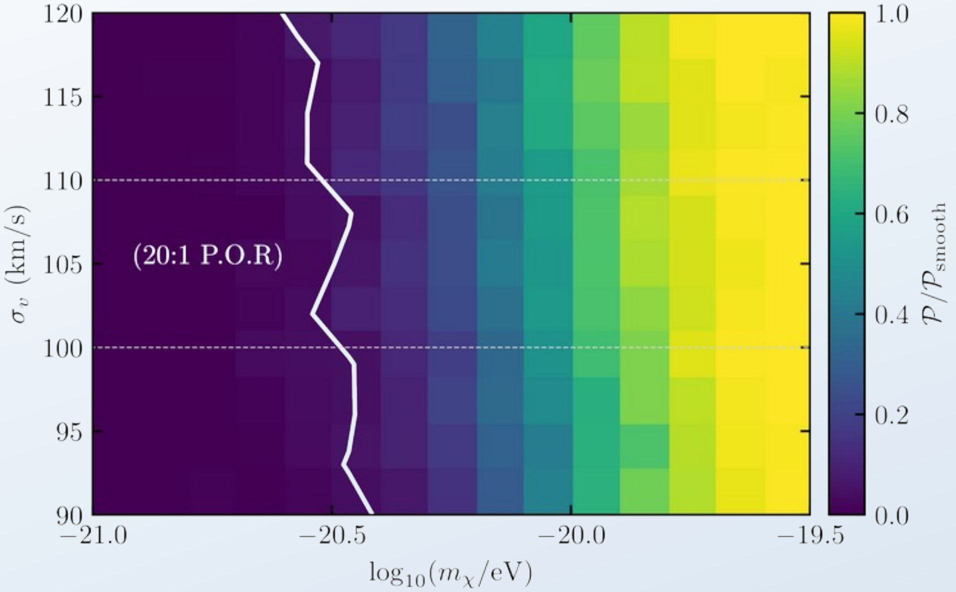
Laroche+2022

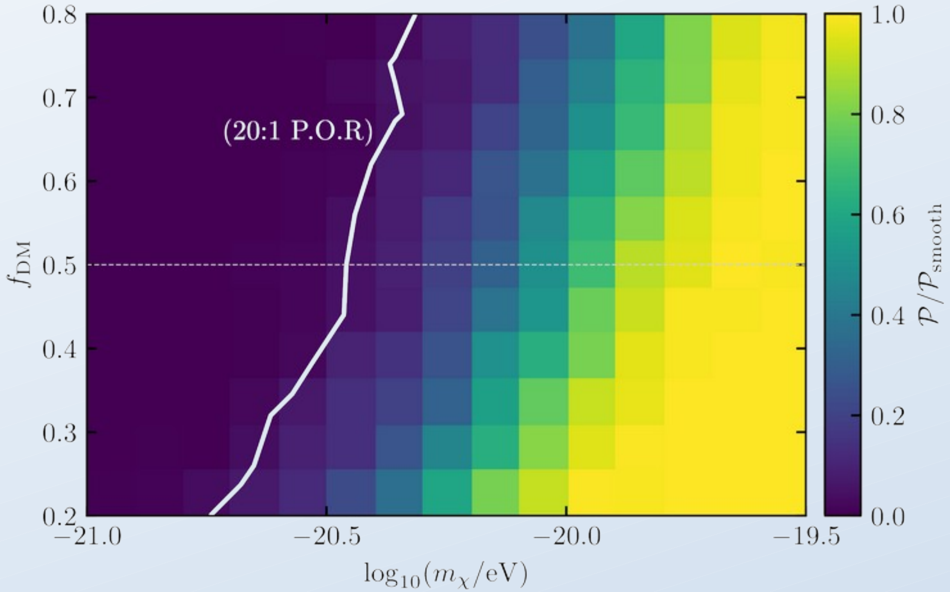
Subhaloes in FDM



Laroche+2022

Unmarginalized posterior odds ratios



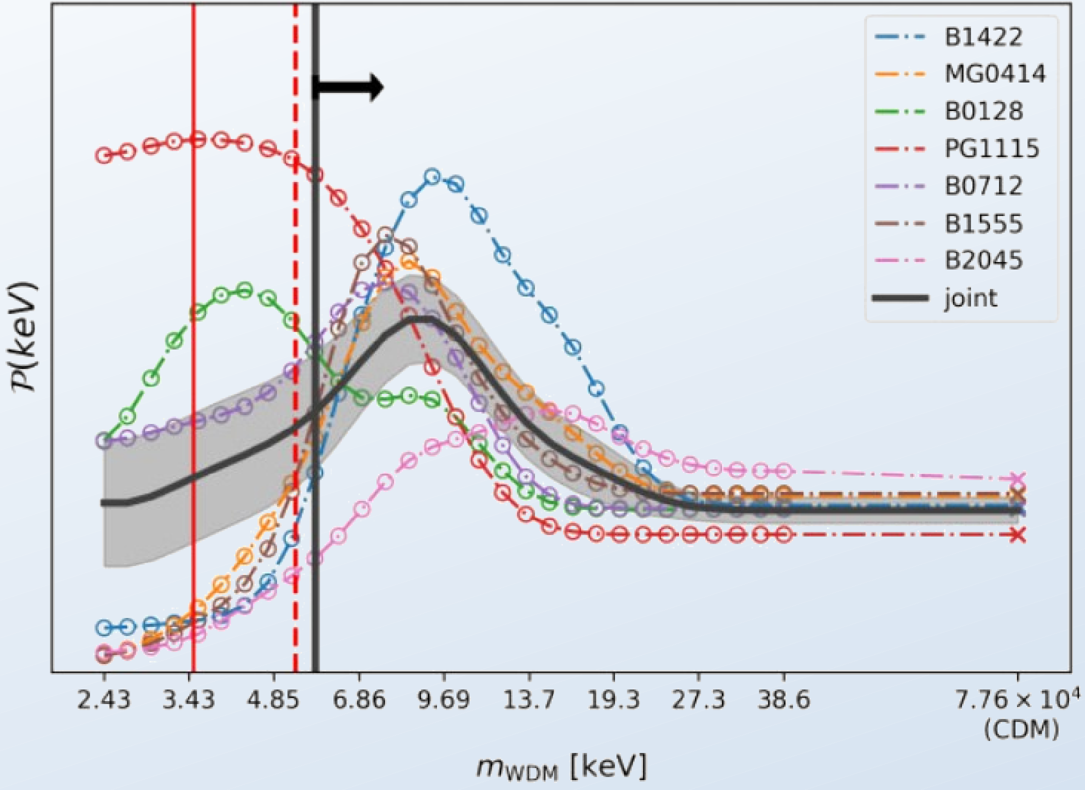


Warm dark matter (WDM)

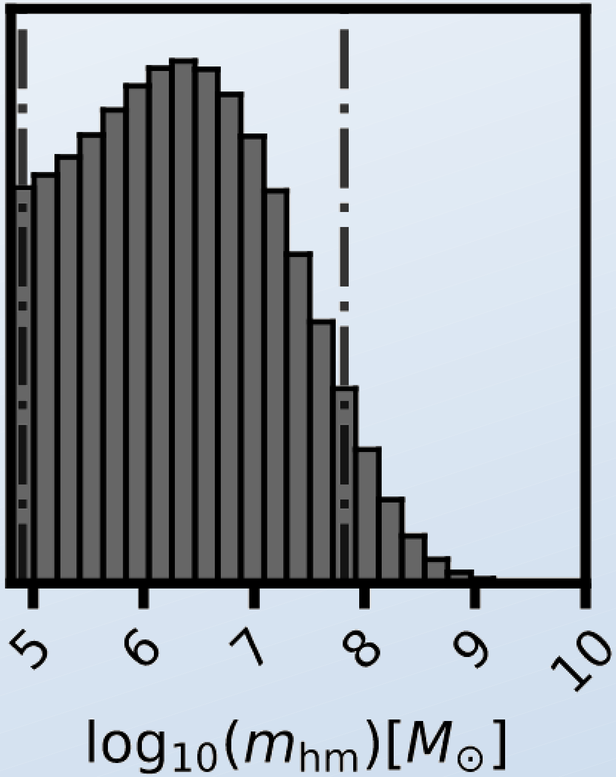
Flux ratio anomalies

- Relatively strong constraint, but requires careful consideration of prior assumptions.
- Larger sample size is needed.

Hsueh+2020: 5.6 keV



Gilman+2020: 5.2 keV



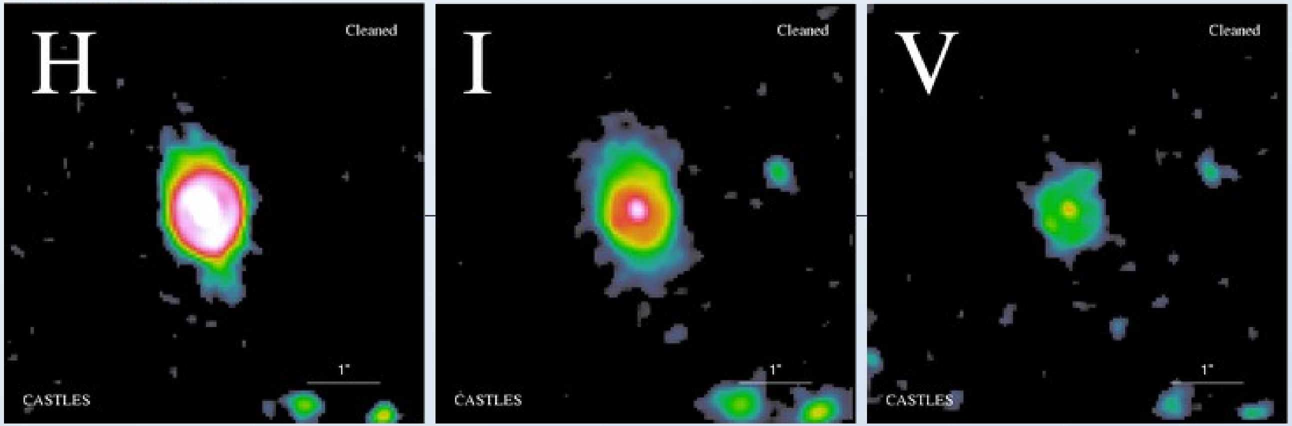
f_{DM} from HST photometry

- 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

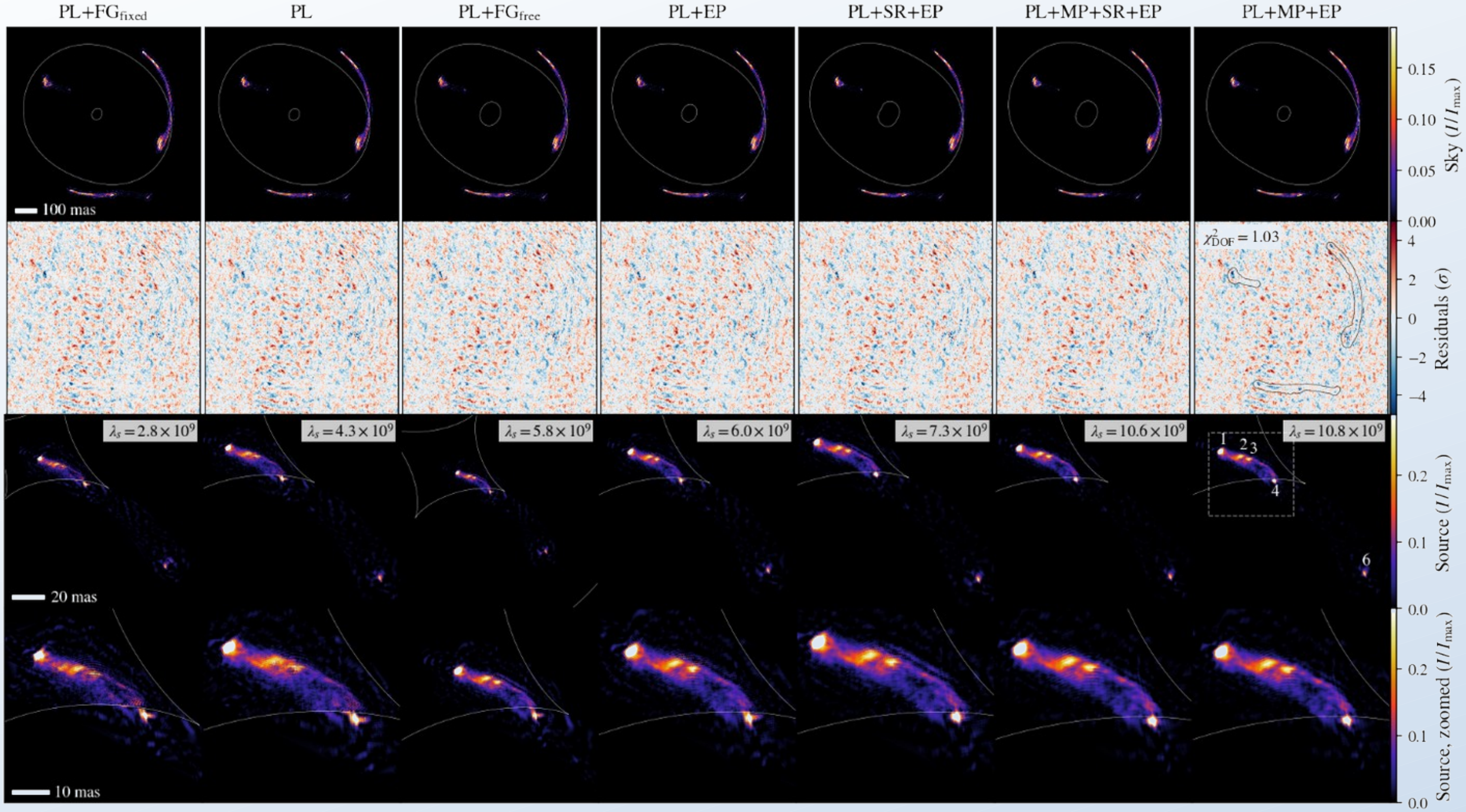
Observations		G	Source
Position	RA(arcsec)	0	-0.634±0.021
	Dec(arcsec)	0	-0.225±0.026
fluxes	F160W	18.87±0.16	21.66±0.25
	F555W	23.24±0.11	25.10±0.25
	F814W	21.26±0.03	23.72±0.05

Cleaned data:



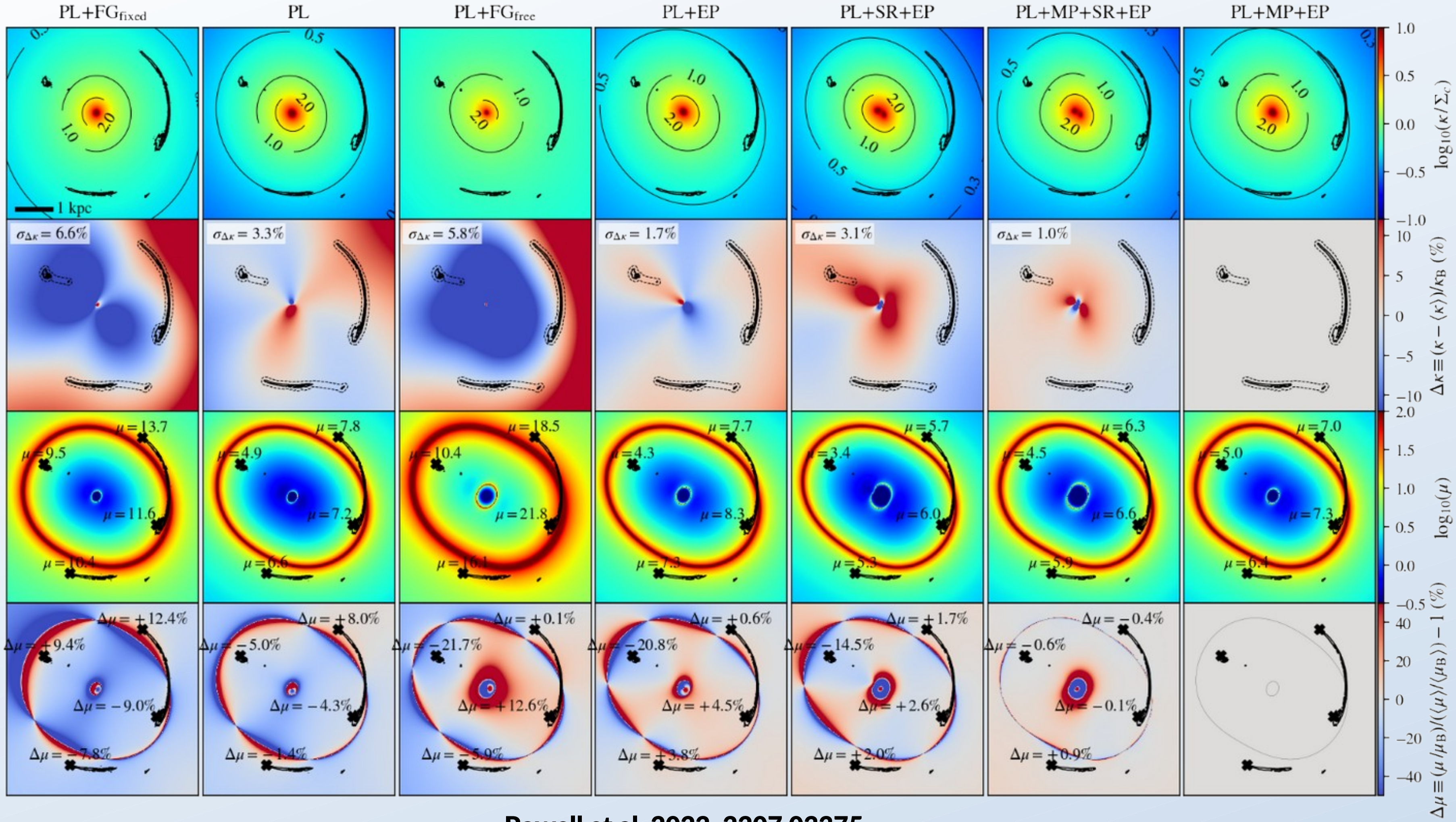
CASTLES survey

Results: Smooth lens model ranking



Powell et al. 2022, 2207.03375

Results: Smooth lens model ranking

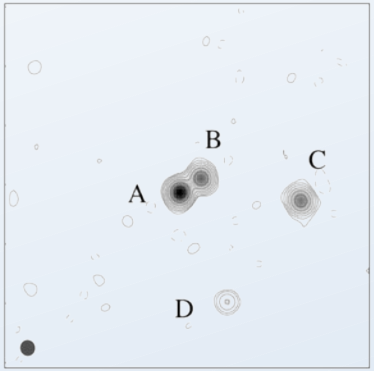


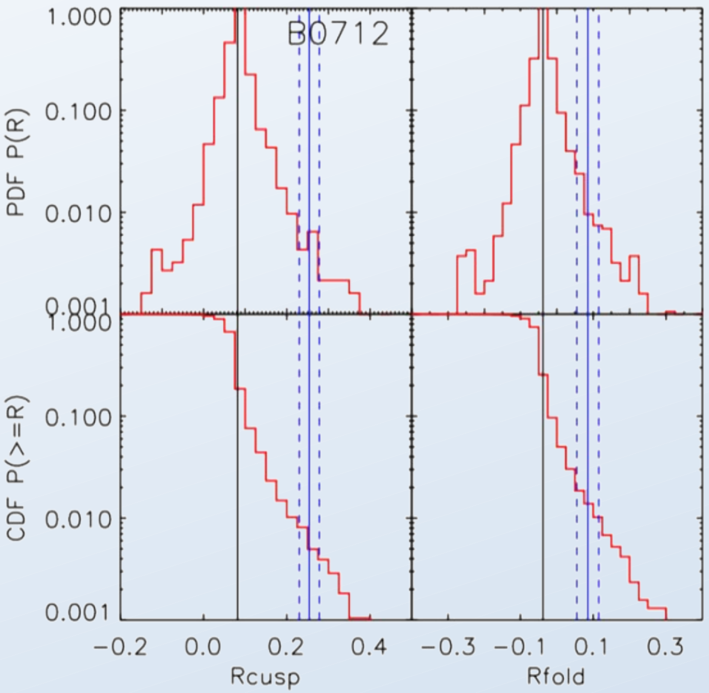
Powell et al. 2022, 2207.03375

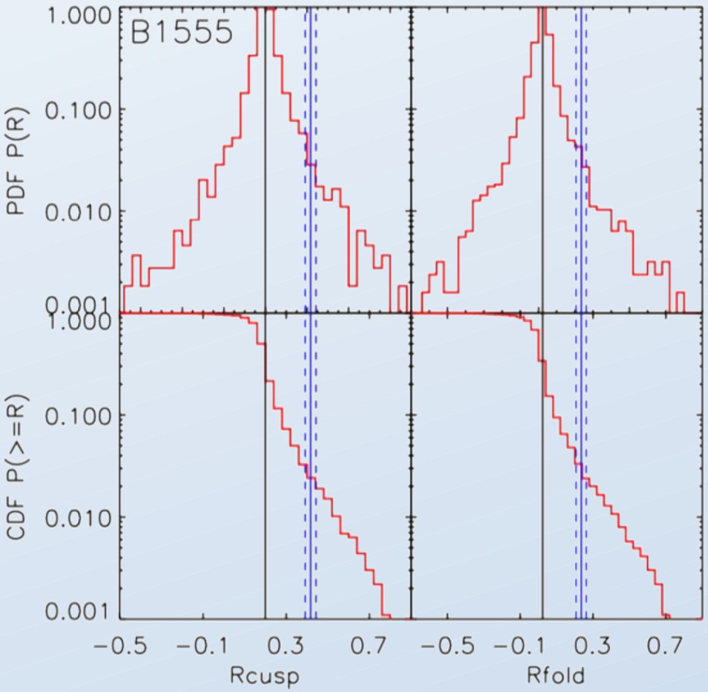
The Global VLBI - Array
Brewster
North Liberty
Hancock
Green Bank
Jodrell Lovell
Jodrell Mk2
Cambridge
Onsala 25m and 20m
Metsähovi
Los Alamos
Owens Valley
Pie Town
Mauna Kea
Kitt Peak
Urumqi
Shanghai
Westerbork
Medicina
Noto
EVN
VLBA
European VLBI Network (EVN)
Very Long Baseline Array (VLBA)
O High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

Flux ratio and position anomalies in lensed quasars

- Data analysis is computationally inexpensive (only 9 degrees of freedom in the model)
- Randomly draw large numbers of lens realizations from whatever cosmology you want to test (WDM, SIDM, etc.), and compare the likelihood to the null hypothesis (CDM).
- In principle, localized probe is sensitive to very low-mass structures (~10^7 M_{sun} or lower).
- **Must be careful with source size, to avoid contamination by stellar micro-lensing.**

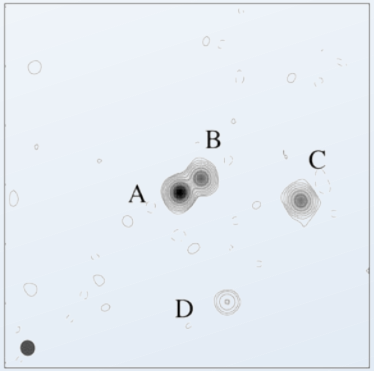




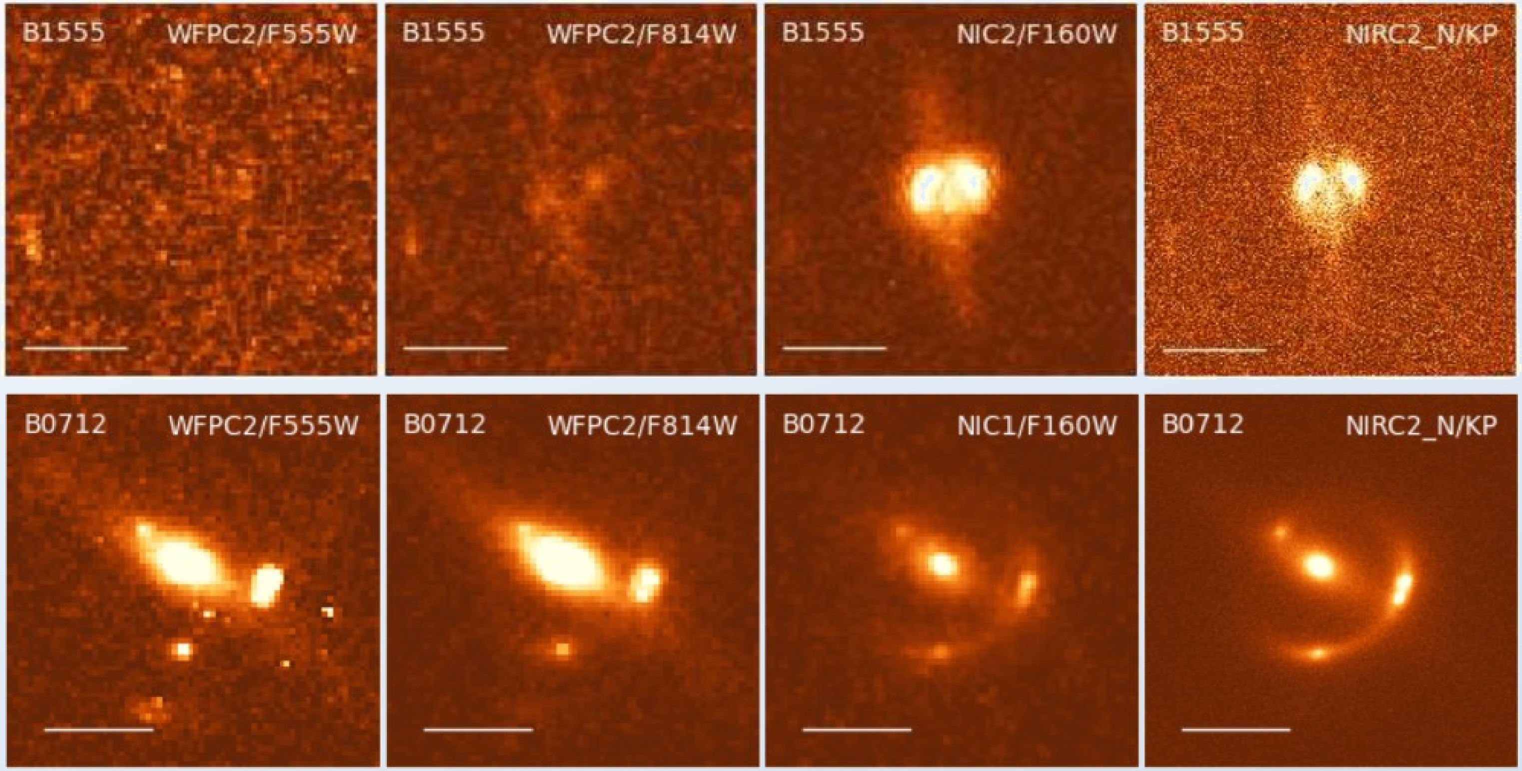


Xu+2013

Flux ratio and position anomalies in lensed quasars



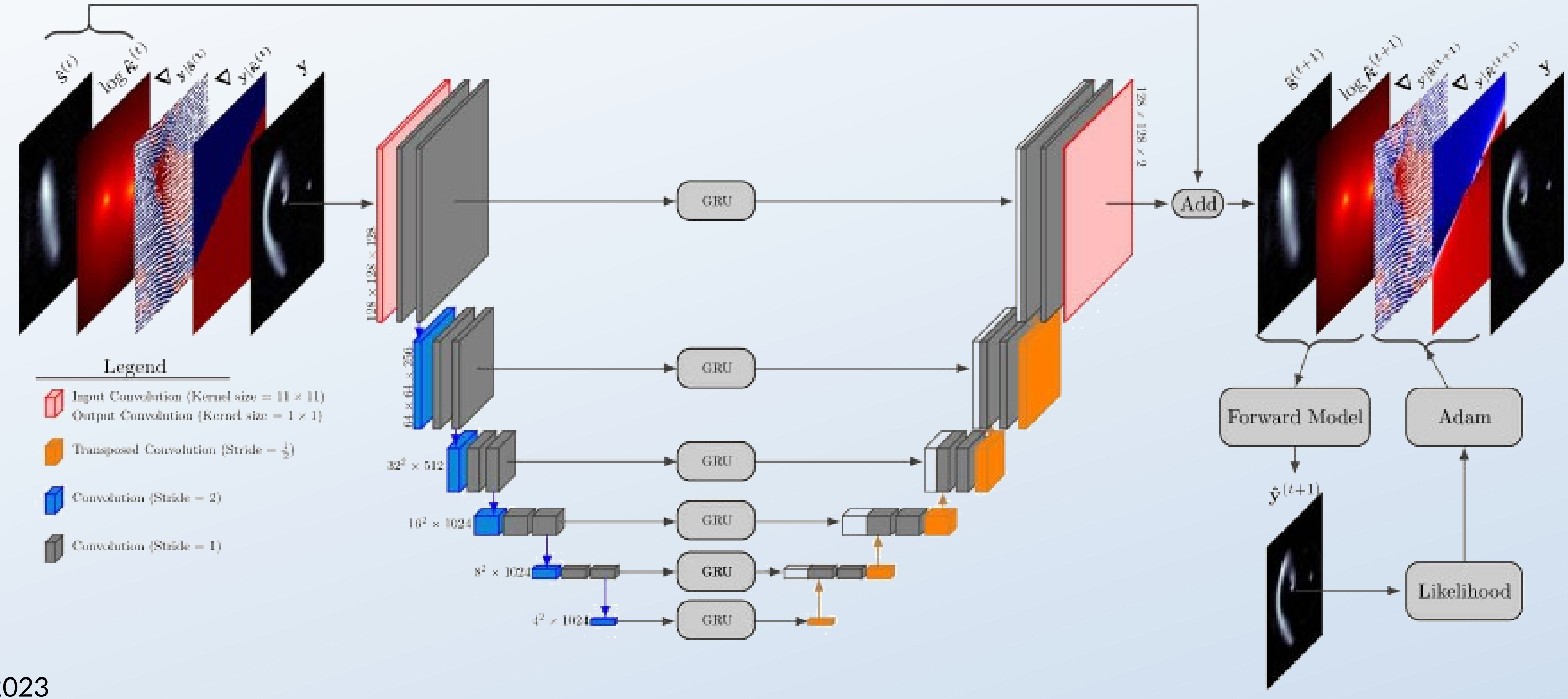
- Must be very careful to include *all* possible sources of flux/position anomalies.
- Tends to be biased towards “colder” models (more low-mass structure)



Hsueh+2016,2017

Machine learning

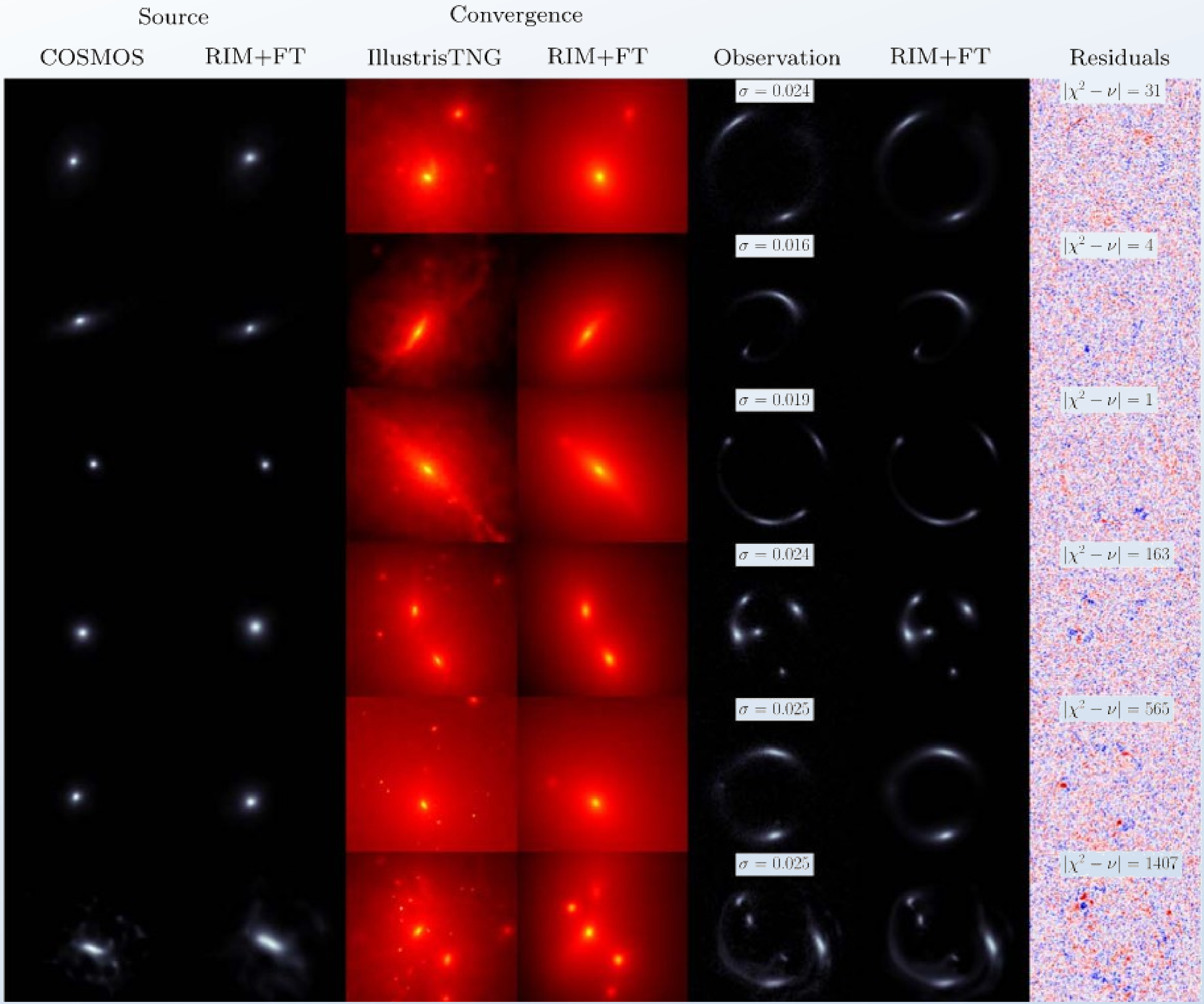
- A hot topic lately, a lot of theoretical/methods work has been done in recent years.



Adam+2023
(see also work by, Hezaveh, Morningstar)

Machine learning

- Impressive results on mock data under controlled conditions.
- No application to observational data yet.
- Main challenges:
  - Interpretability
  - Uncertainty quantification
  - Bias from training data



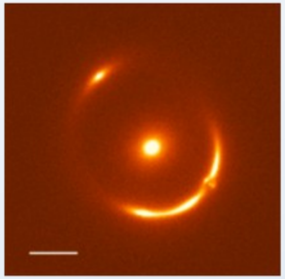
Adam+2023
(see also work by Hezaveh, Morningstar)

Warm dark matter (WDM)

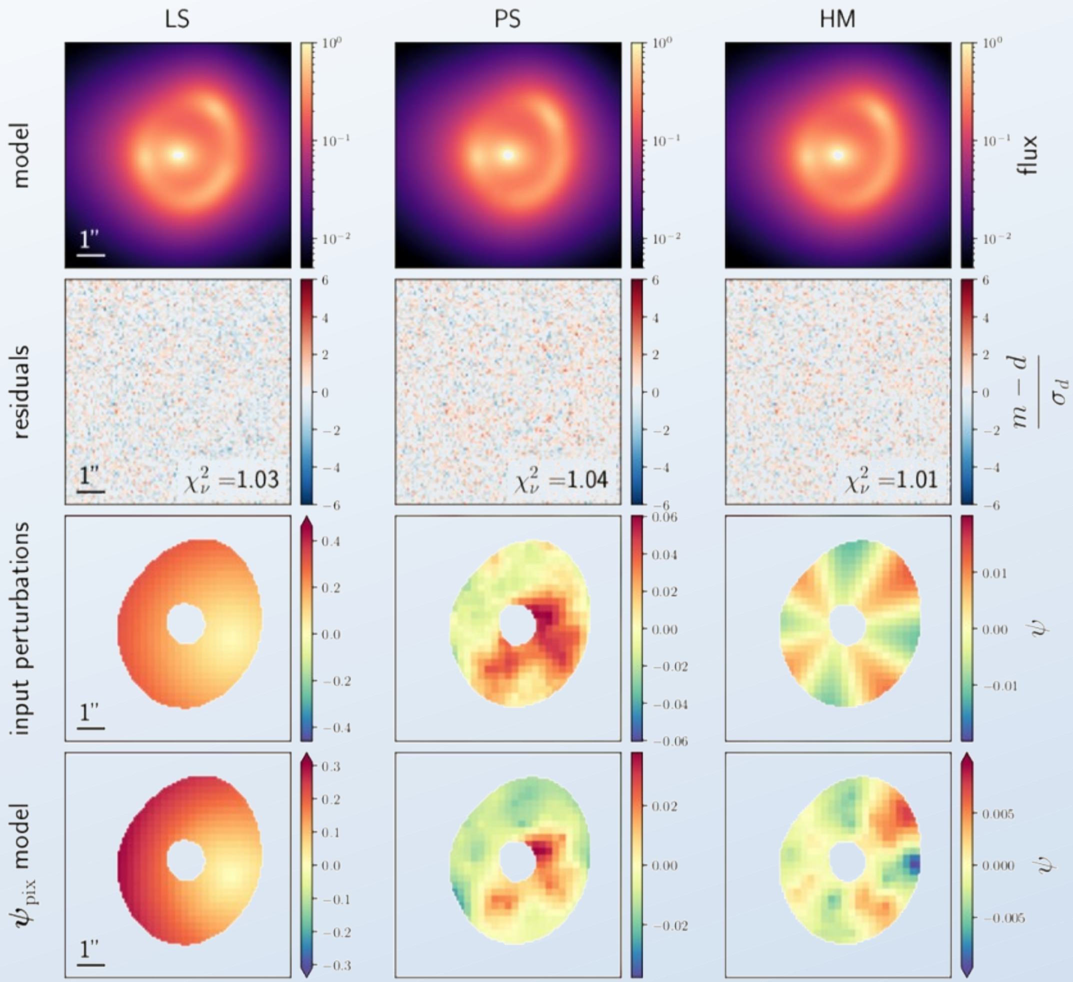
Reference	Probe	$\frac{m_{\rm th}}{\rm keV}$ 95% c.l.
This work	See Section 3	6.048
Birrer et al. (2017)	Grav. Imaging	2.0
V18 (Original)	Grav. Imaging	0.3
R19 (Original)	Grav. Imaging	0.26
Gilman et al. (2019a)	Flux Ratios	3.1, 4.4
Gilman et al. (2019b)	Flux Ratios	5.2
Hsueh et al. (2019)	Flux Ratios	5.6
Banik et al. (2018, 2019)	Stellar streams	4.6, 6.3
Alvey et al. (2021)	Dwarf spheroidals	0.59, 0.41
Viel et al. (2005)	Ly α	0.55
Viel et al. (2006)	Ly α	2.0
Seljak et al. (2006)	Ly α	2.5
Iršič et al. (2017)	Ly α	3.5, 5.3
M18 (Original)	Ly α	2.7, 3.6
Polisensky & Ricotti (2011)	MW satellites	2.3
Kennedy et al. (2014)	MW satellites	1.3, 5.0
Jethwa et al. (2017)	MW satellites	2.9
Nadler et al. (2019b)	MW satellites	3.26
Nadler et al. (2021a)	MW satellites	6.5
Nadler et al. (2021b)	MW satellites & Flux Ratios	9.7
N20 (Original)	MW satellites	2.02, 3.99

Enzi+2021

Inference on resolved, extended images



Pixellated potential corrections can in principle capture effect of any mass structure, but interpretability is a challenge.

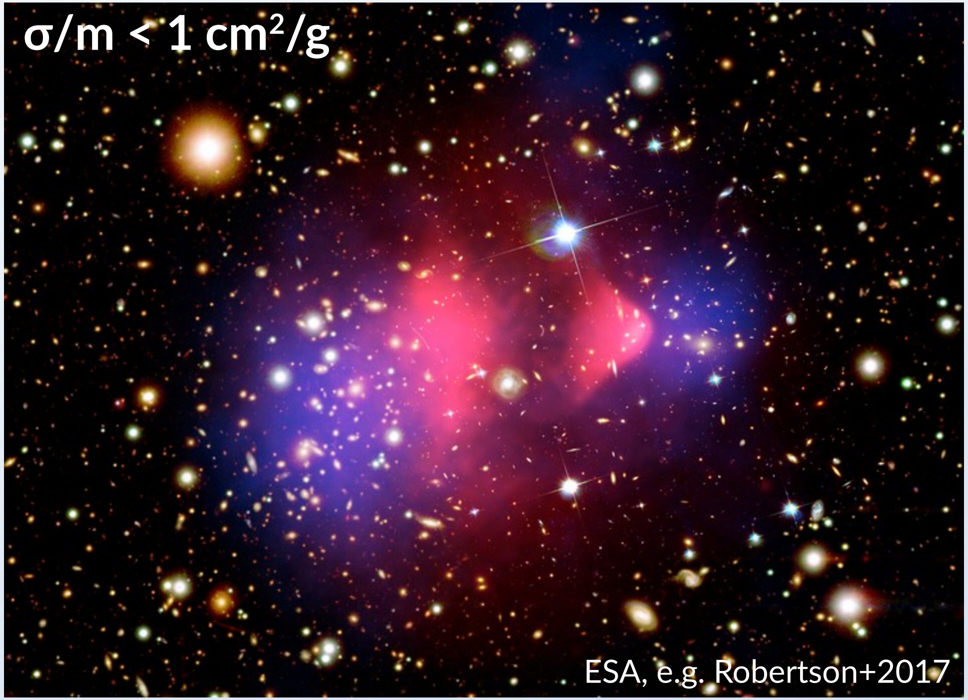


Galan+2022
(see also work by Vernardos, Koopmans, Vegetti)

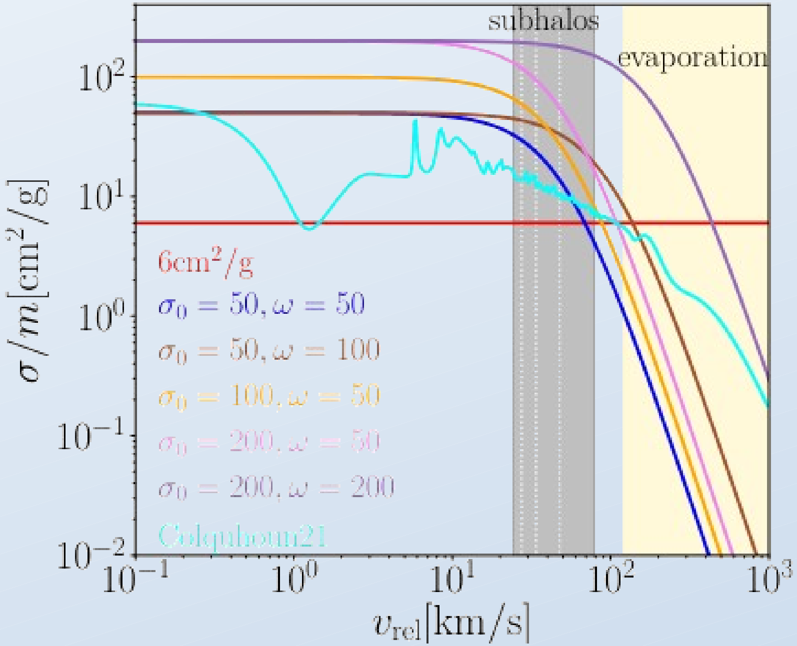
Self-interacting dark matter (SIDM)

Key predictions:

- Cored density profiles in galaxy-scale haloes, large population of low-mass haloes
- **Some fraction of haloes are very dense core-collapsed objects**
- **SIDM can be made to behave differently in different velocity/mass regimes and fit a variety of observations (namely, Bullet cluster vs. DG rotation curves).**



ESA, e.g. Robertson+2017

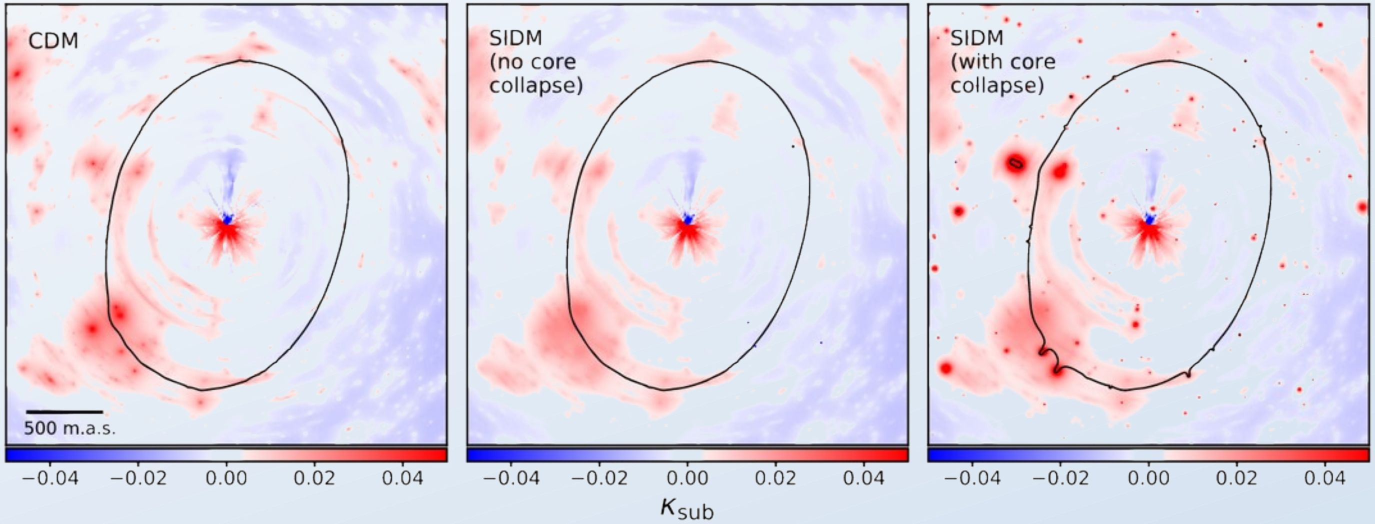


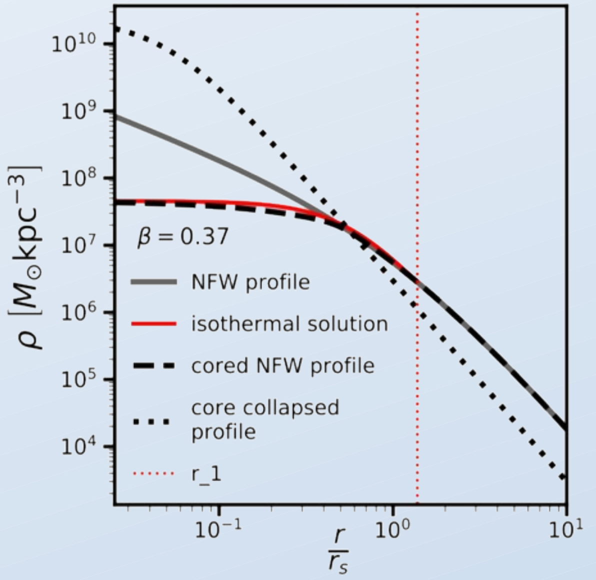
Zeng+2023, see also recent work by Haibo Yu, Xiaolong Du, Ethan Nadler, Annika Peter

Self-interacting dark matter (SIDM)

- *Dense, compact haloes are more efficient at lensing (more easily detected)*
- *But, modeling the fraction of collapsed objects at the population level adds complexity*
- *Theory is not robustly worked out yet. (Resonant self-interactions? Profile shapes?)*
- *No lensing-based constraints (yet).*

σ/m ~ 100 cm²/g

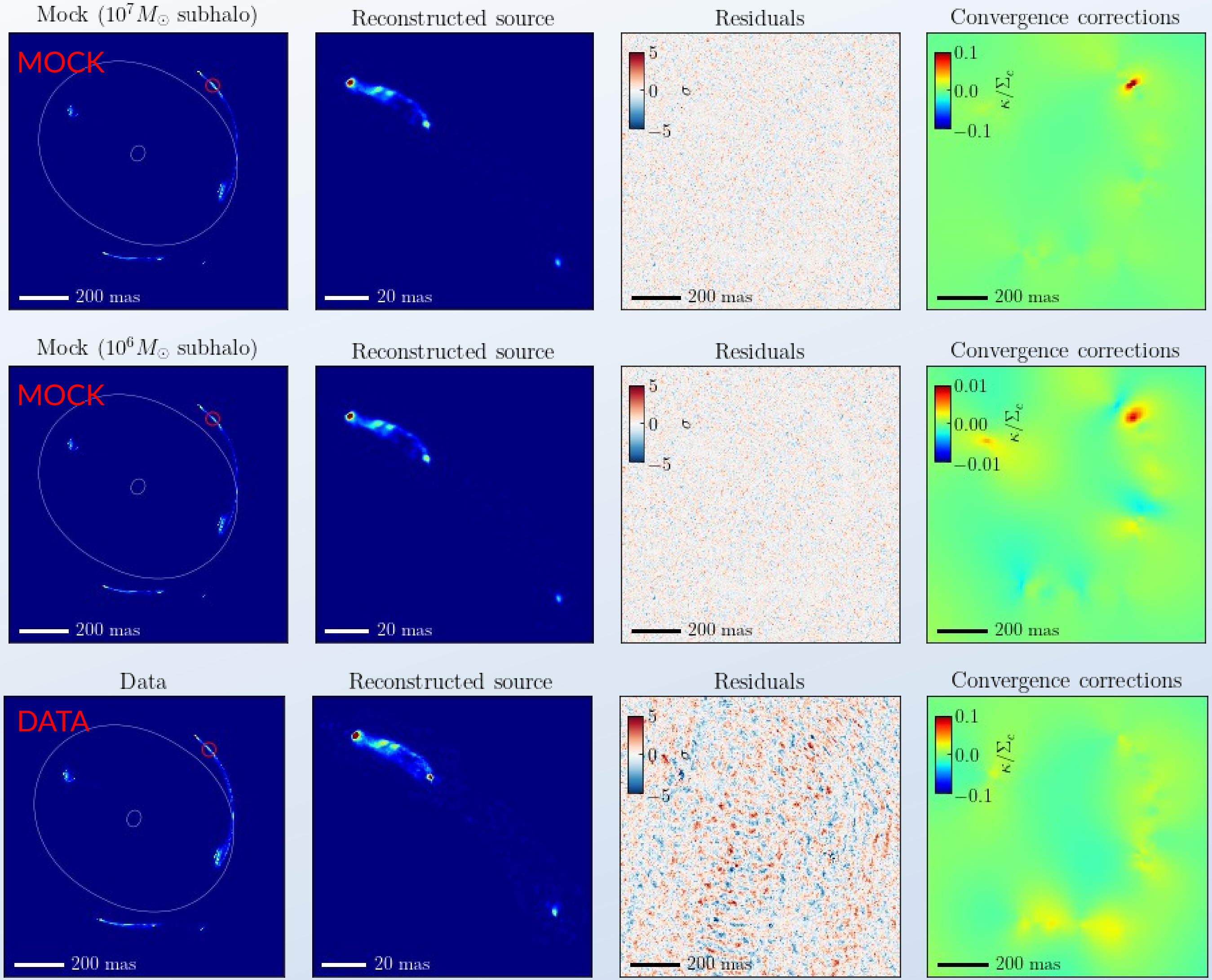




Gilman+2021

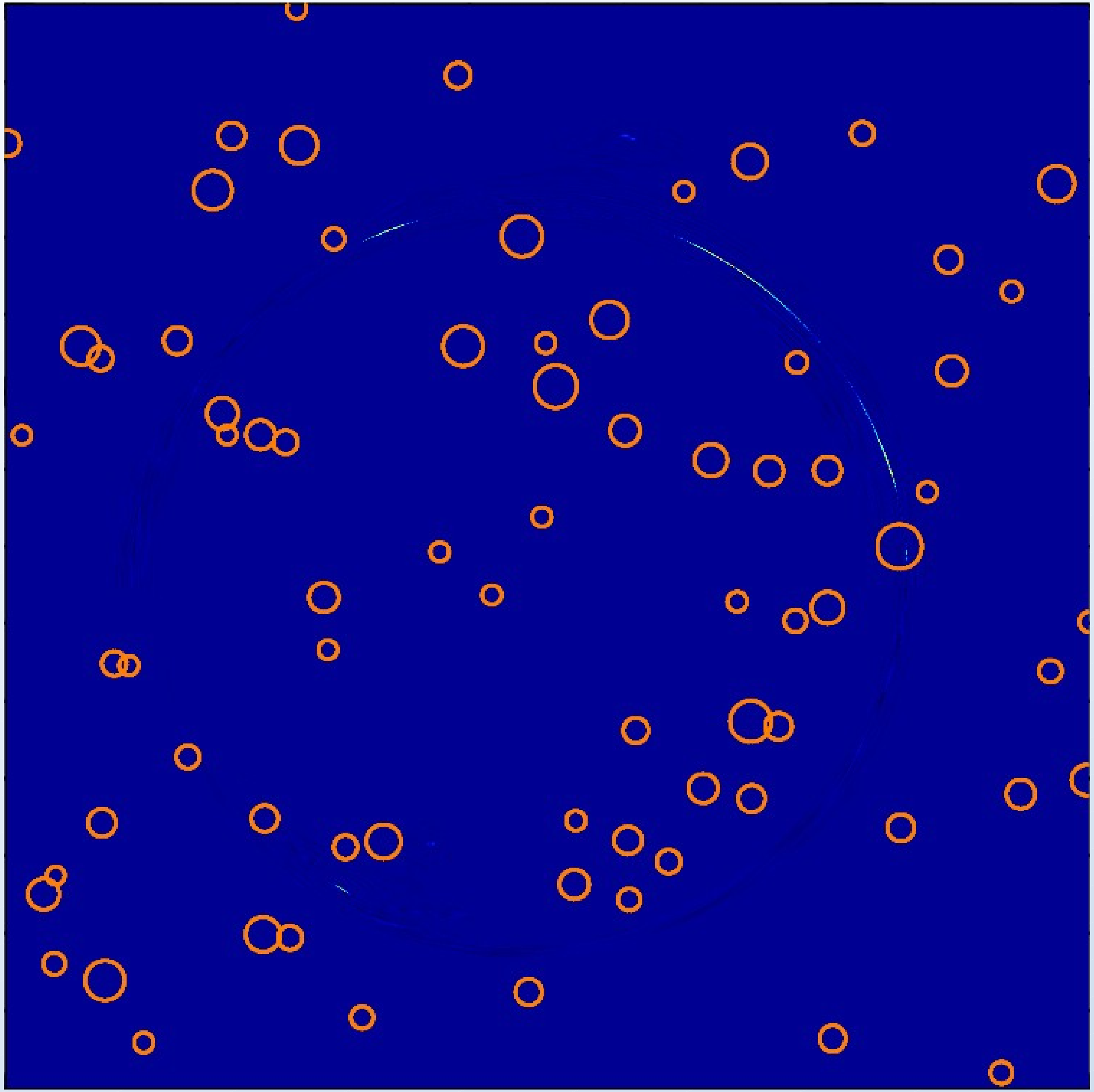
Work in progress: Gravitational imaging on J0751+2716 *(mock vs real data)*

- Gravitational imaging analysis on mock data. Same resolution, array configuration, SNR as the real J0751+2716 observation.
- ***Isolated*** 10^6 and 10^7 M_{sun} subhaloes are easily detected with data of this quality, ***if they lie on the arc***.
- Halo mass function constraints will require a statistical approach on the population level



Work in progress: B1938+666 *(mock data with subhaloes)*

- Subhaloes can shift the arc around, but true l**ocalized perturbations appear only when a subhalo lies directly on an arc!**
- The rest of the subhalo population (mostly) blends into the smooth model
- Begs the questions: **How do we differentiate between intrinsic shape of the lens galaxy (boxy/disky) vs. large-scale effects of a sub/LOS-halo population?**



Mock realization by Simona Vegetti

Introduction

- We are on the brink of a revolution in the field of galaxy-scale strong lensing. The next few years will see the discovery of over 105 strong
- lens systems thanks to the Euclid space telescope, the Vera C. Rubin observatory, and the Square Kilometre Array (SKA). Follow-up of newly
- discovered lens systems with high-resolution imaging (adaptive optics in the optical/infrared and interferometry in the radio) will provide a
- unique opportunity to make major contributions to the strong lensing field within the next five years, and to develop analysis tools capable of
- handling a further flood of high-resolution data from next-generation VLBI observatories like SKA-VLBI and ngVLA within the decade. My
- research plan will take advantage of the newest high-resolution strong lens data and our state-of-the-art modeling code to answer three major
- questions:
- (i) Is dark matter cold, warm, or something else?
- (ii) How are the dark matter and baryonic mass components distributed in lens galaxies?
- (iii) How are magnetic fields structured in lens galaxies?