Shifting Landscapes in Astrophysics: New Frontiers to Explore with Roman

Dark matter constraints from strongly lensed quasars - recent advances and perspectives for Roman

Hadrien Paugnat (UCLA)
In collaboration with : Tommaso Treu, Daniel Gilman, Anna Nierenberg

July 16, 2026
Caltech

Flux-ratio anomalies in lensed quasars (1/2)

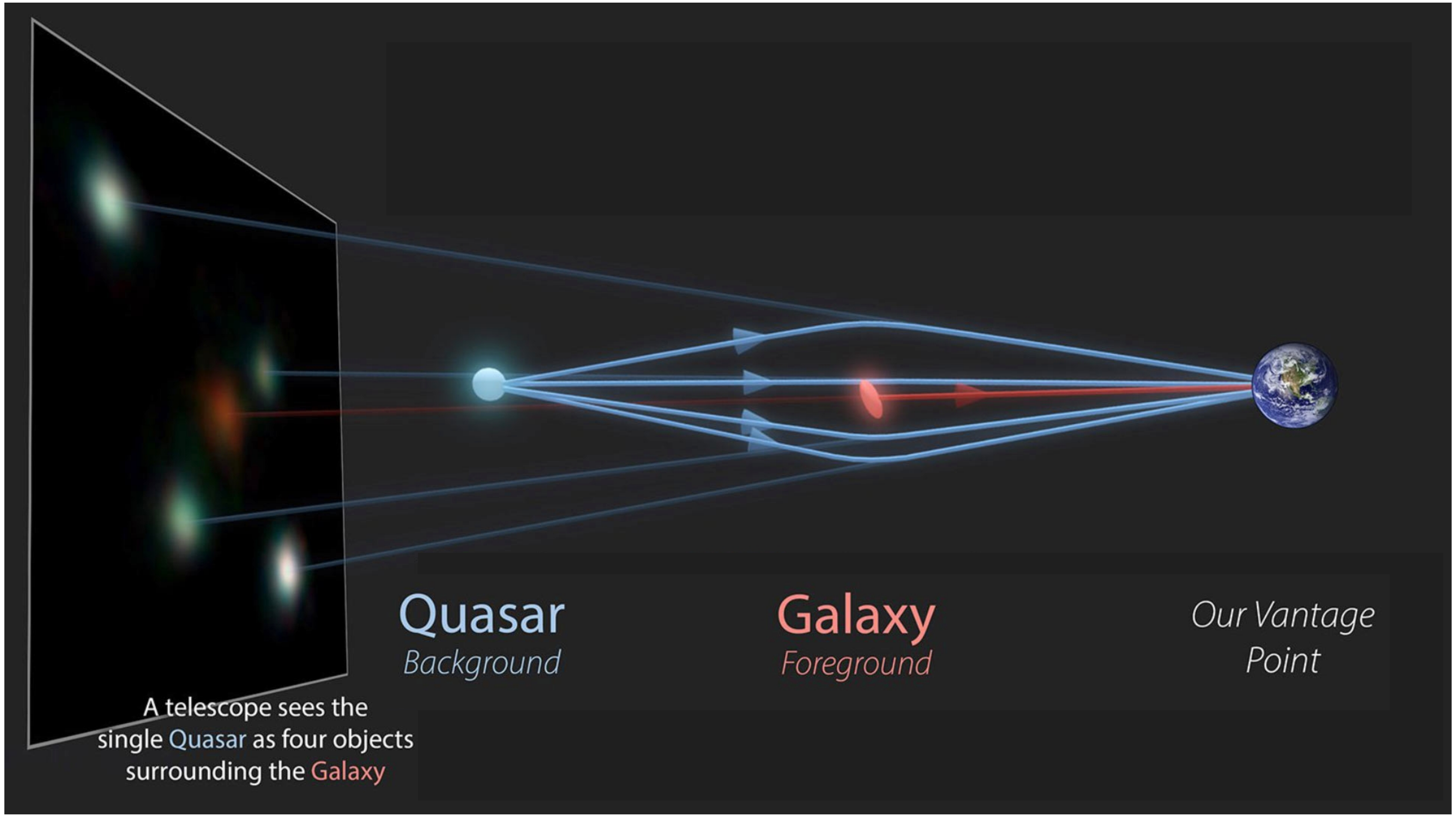


Image credit: R. Hurt, IPAC & Caltech / Gaia Gravitational Lenses group.

Flux-ratio anomalies in lensed quasars (1/2)

Flux-ratios
= magnification
ratios of smooth
lens model

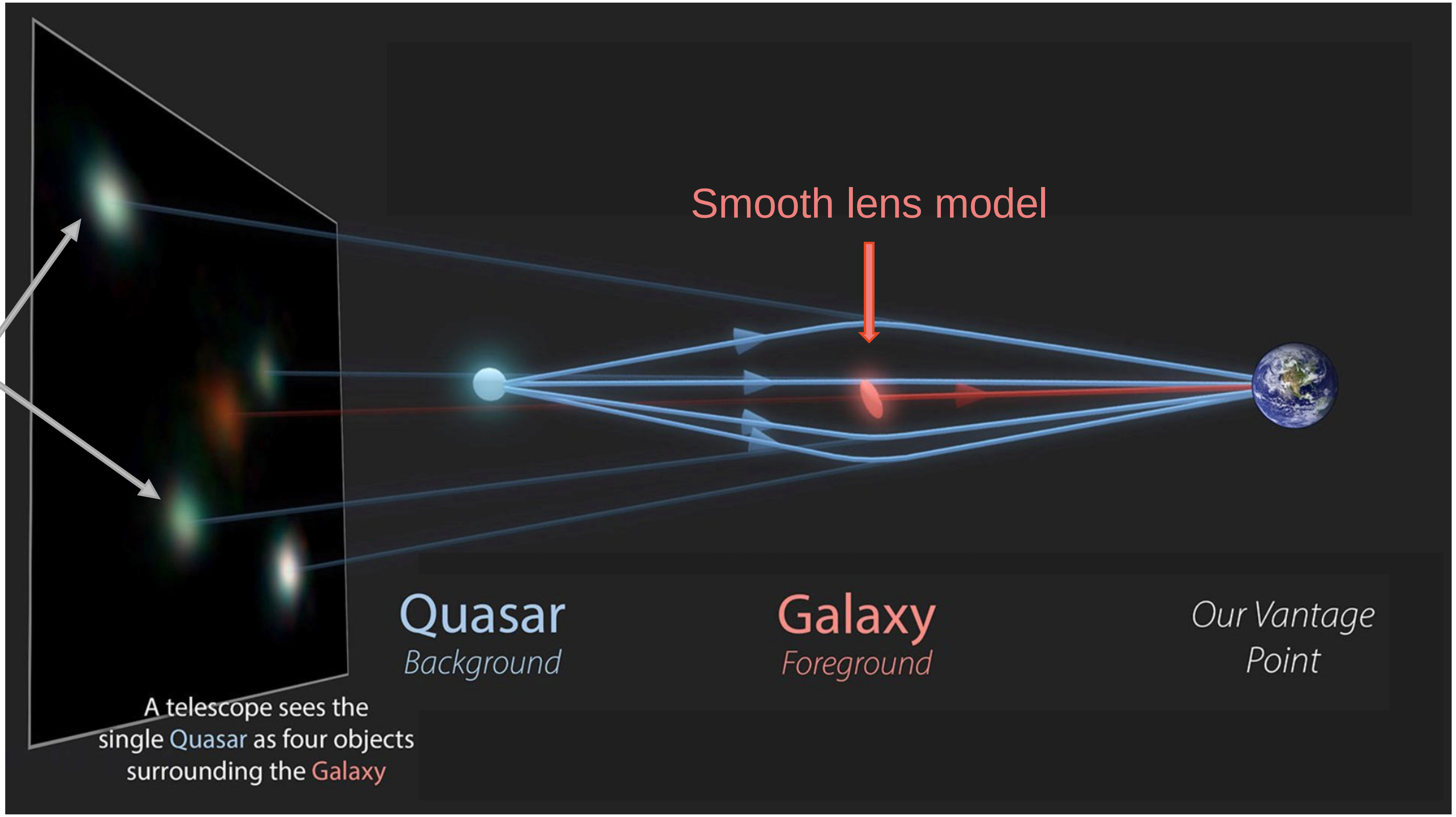


Image credit: R. Hurt, IPAC & Caltech / Gaia Gravitational Lenses group.

Flux-ratio anomalies in lensed quasars (2/2)

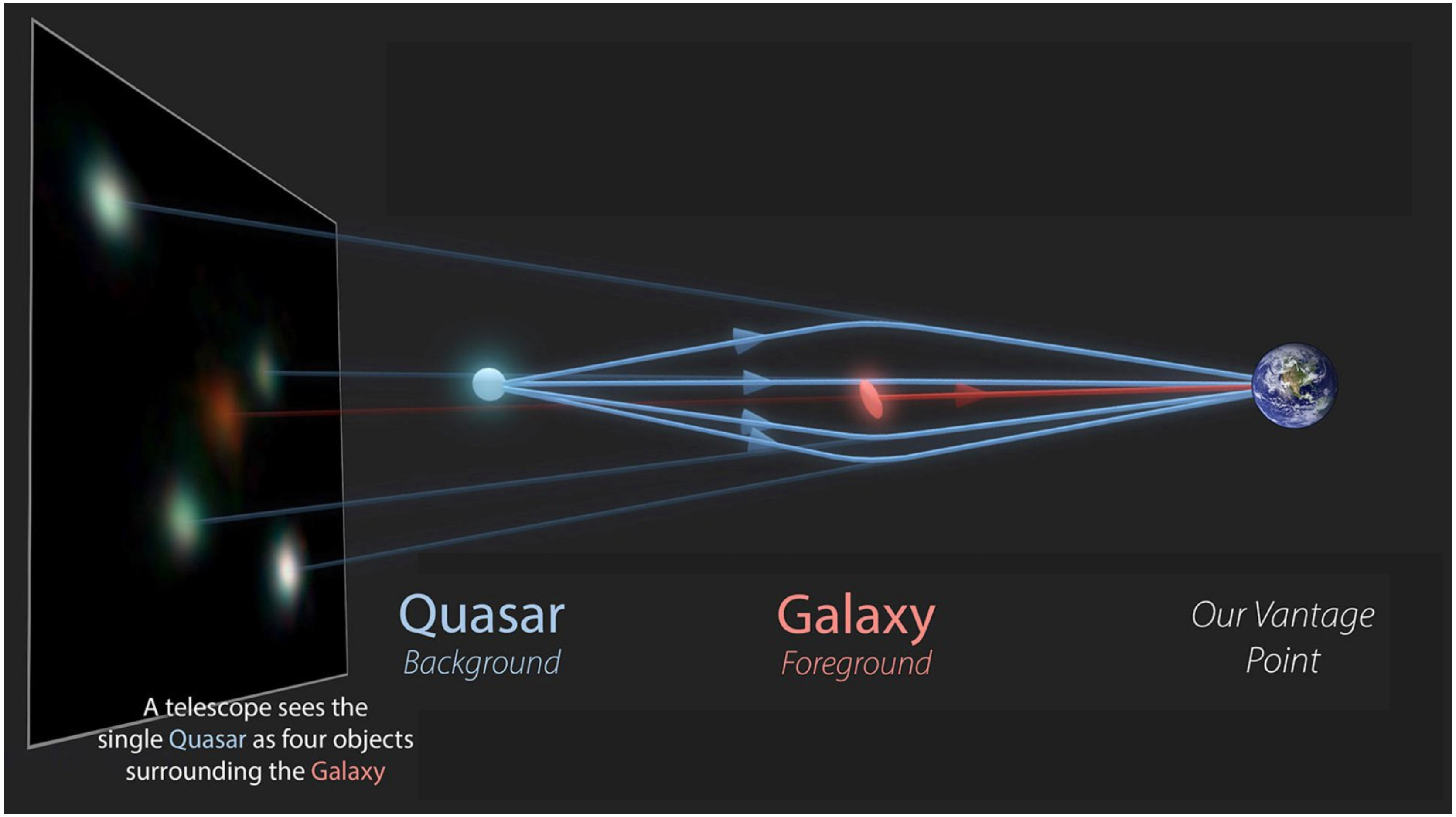
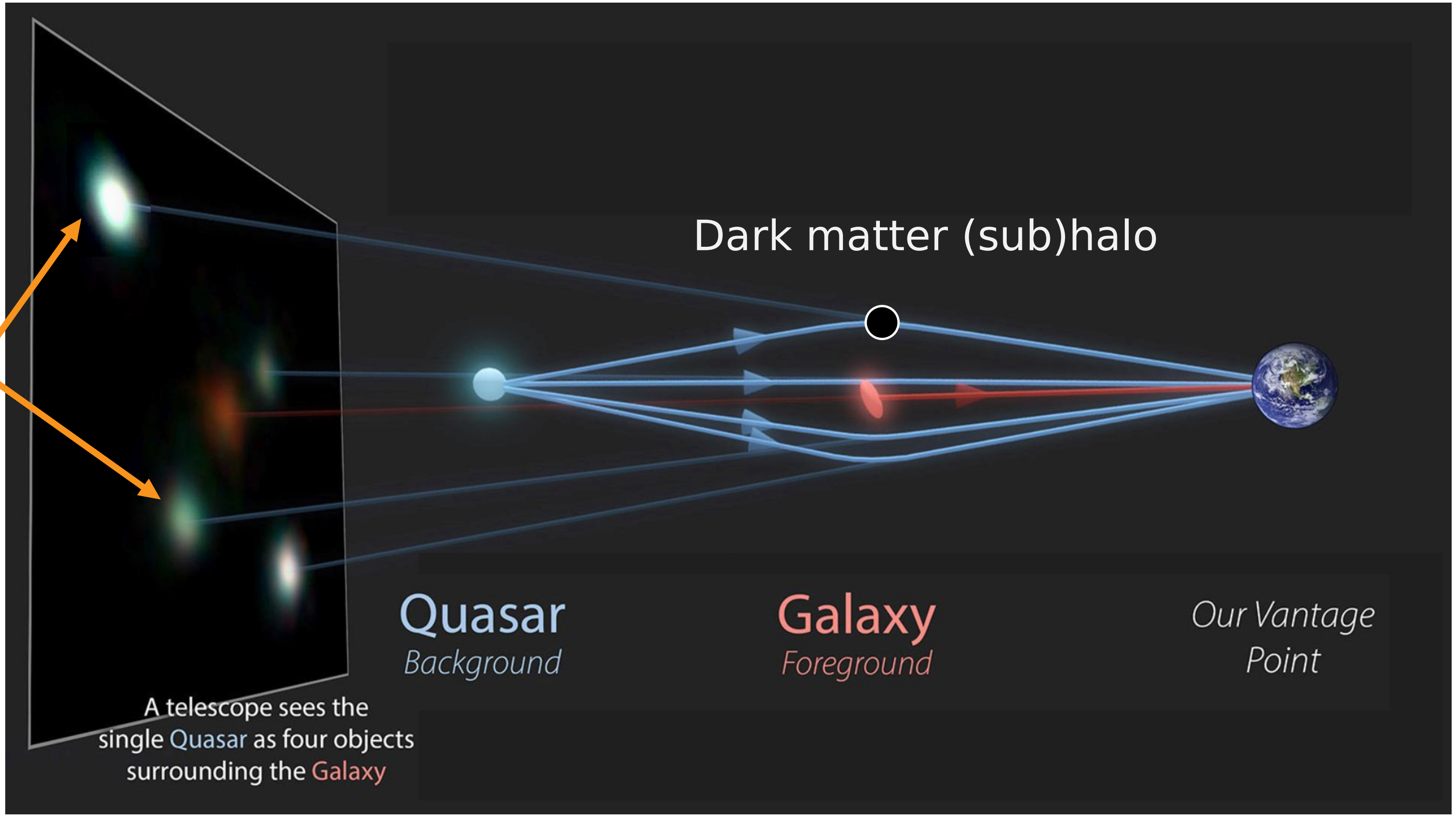


Image credit: R. Hurt, IPAC & Caltech / Gaia Gravitational Lenses group.

Flux-ratio anomalies in lensed quasars (2/2)

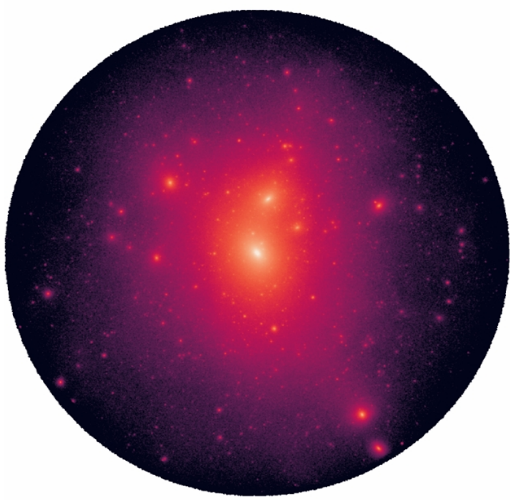


Flux-ratio anomaly

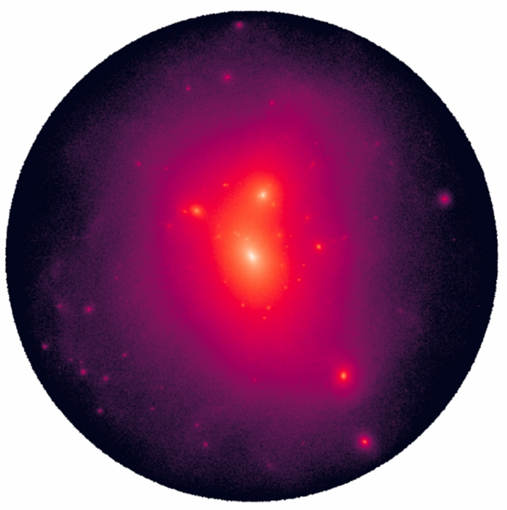
Image credit: R. Hurt, IPAC & Caltech / Gaia Gravitational Lenses group.

Anomaly statistics encode DM properties

Cold DM



Warm DM



<u>Image credit</u>: *Nadler et al. 2025 a,c (COZMIC I & III)*

Anomaly statistics encode DM properties

Cold DM Warm DM

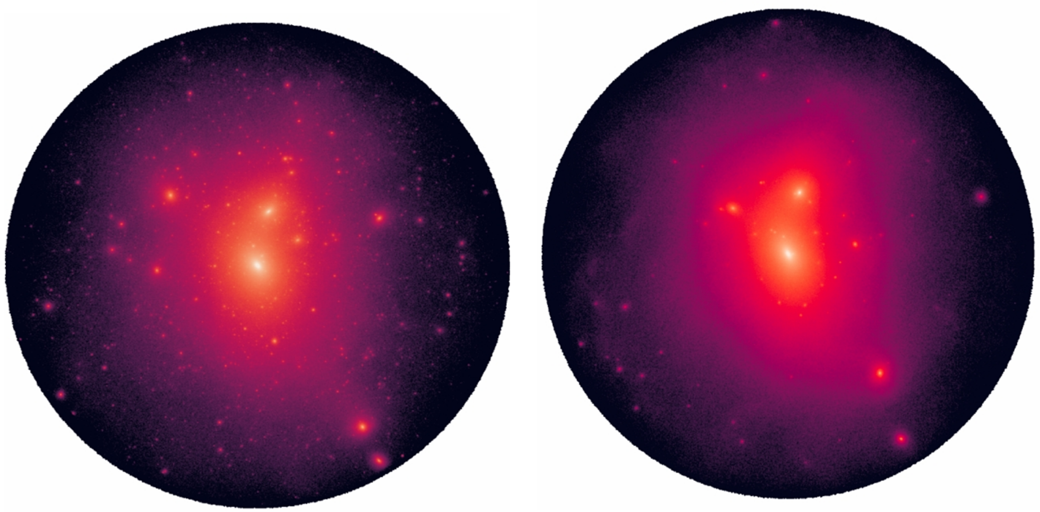
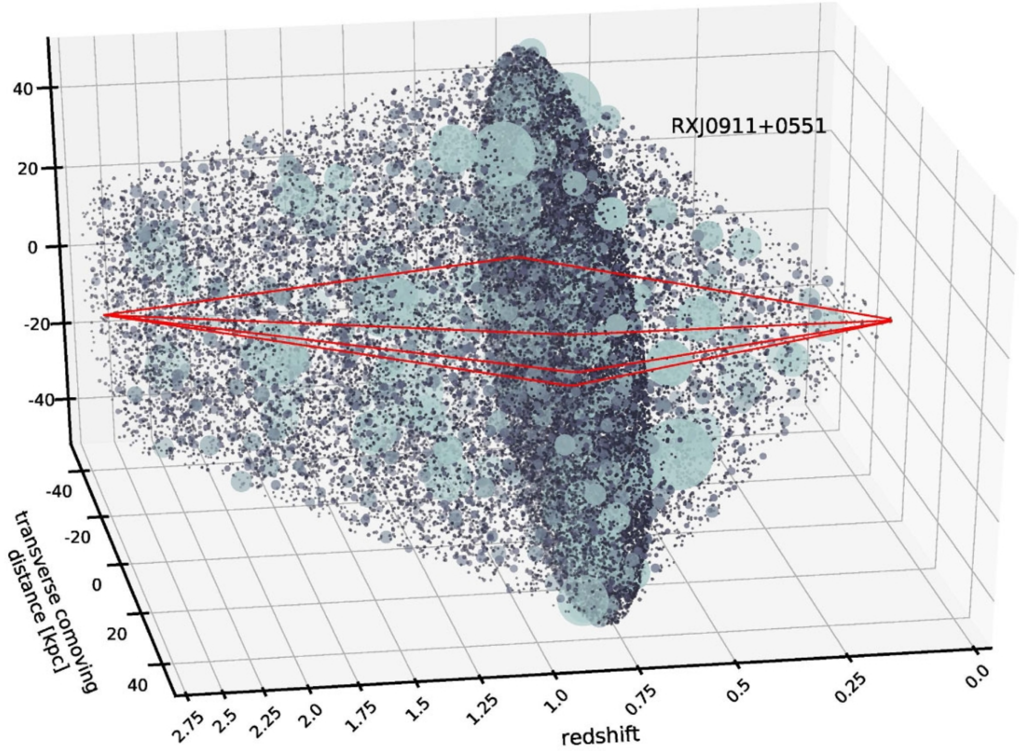


Image credit: *Nadler et al. 2025 a,c (COZMIC I & III)*

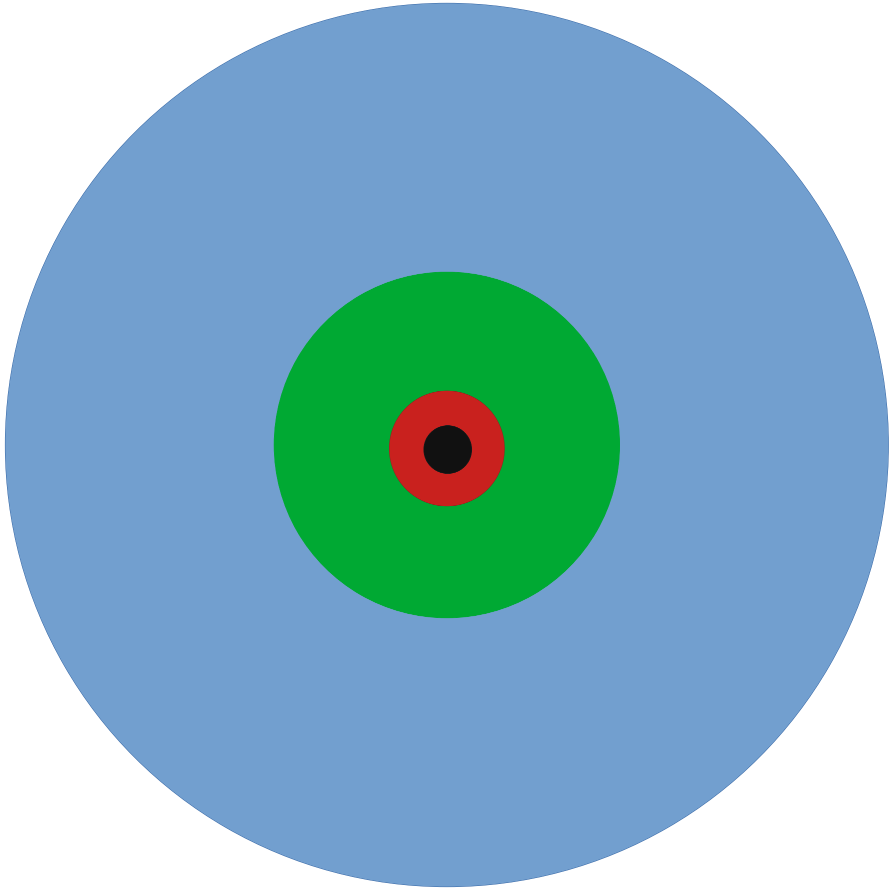
Credit: *Gilman et al. (2022)*



Consider:
- collective effect of DM substructure down to $10^6\ M_\odot$
- flux-ratio anomaly **statistics** at a population level

What fluxes are we measuring ?

Simplified picture of quasar emission



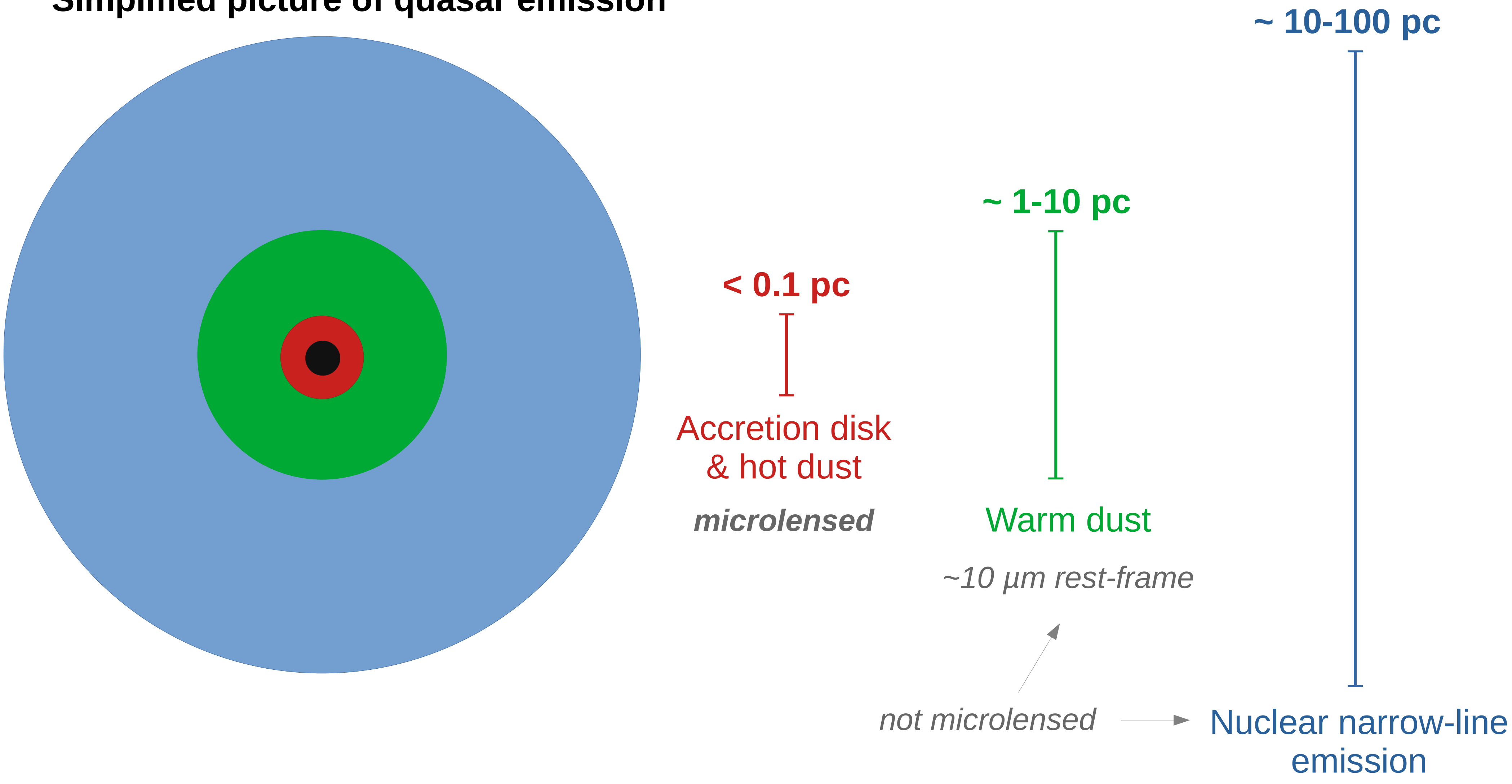
< 0.1 pc

Accretion disk
& hot dust

microlensed

What fluxes are we measuring ?

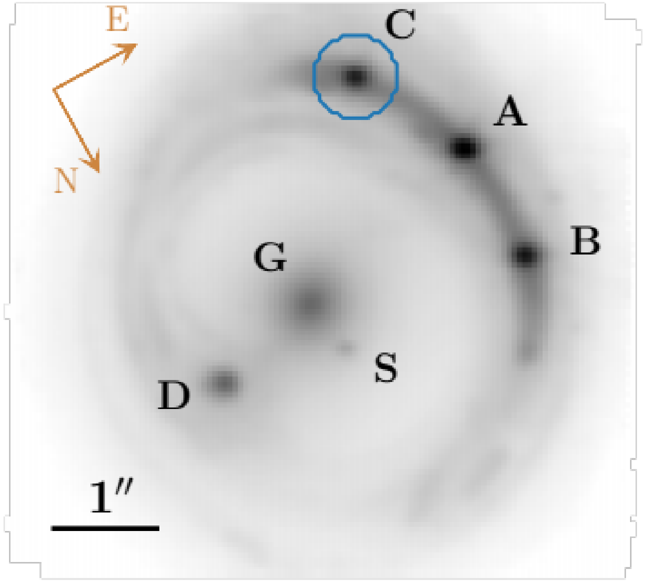
Simplified picture of quasar emission

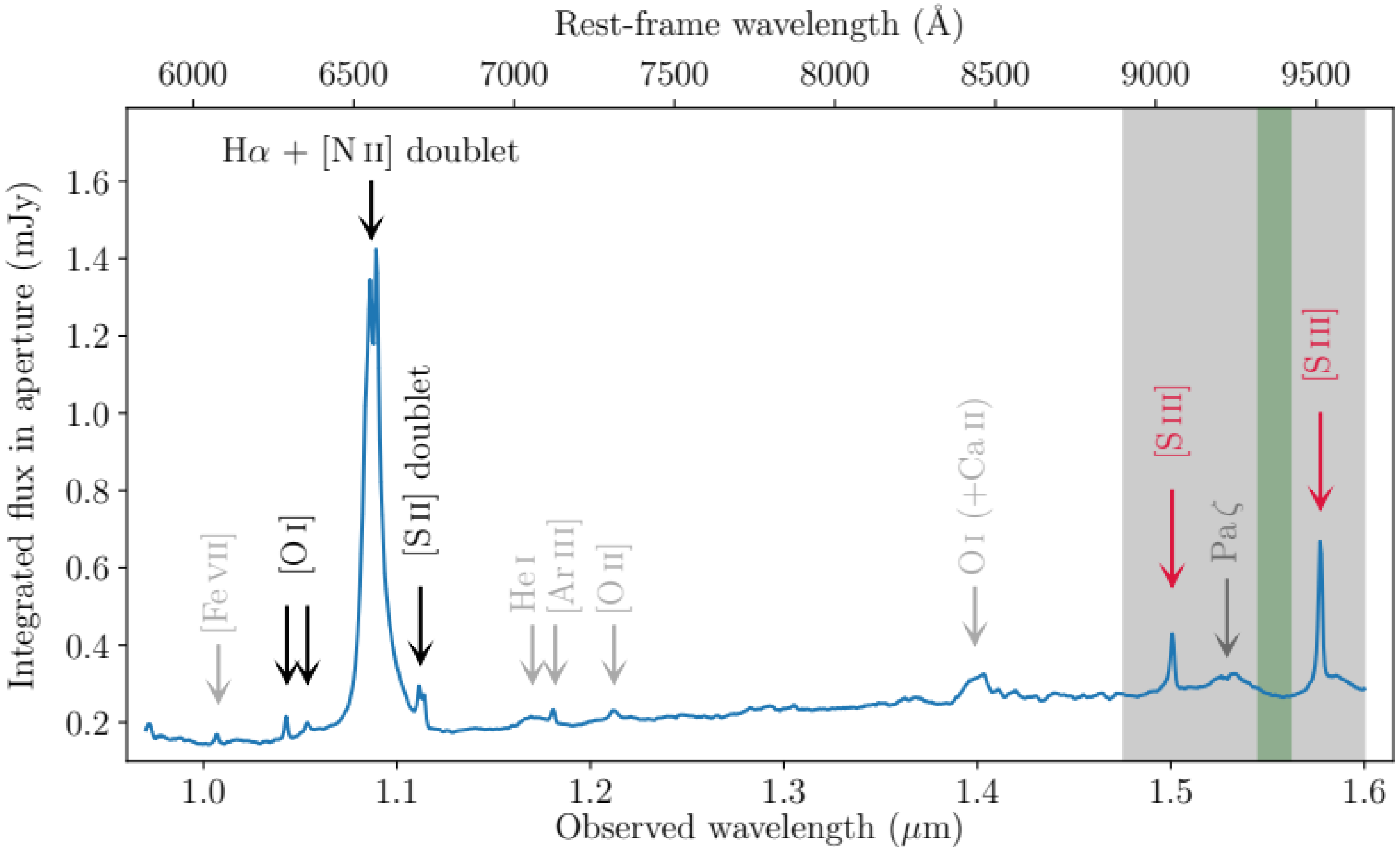


“First measurement of narrow-line flux ratios for a lensed quasar with JWST/NIRSpec IFS.”

Paugnat et al. (2026), arXiv:2606.23808, submitted to Phys. Rev. D

RXJ1131-1231:
z = 0.654 (source)

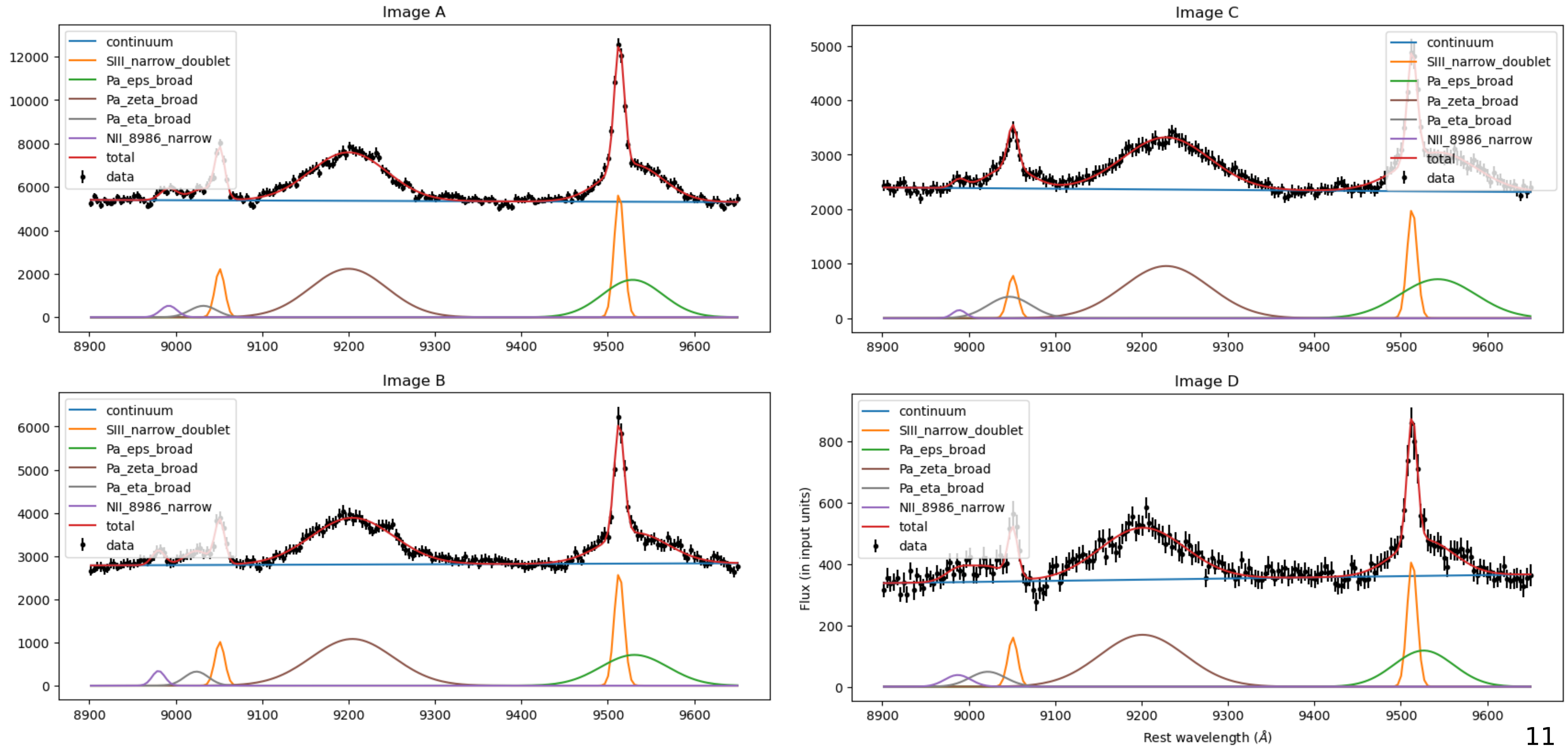




Need to remove the contribution from the extended emission (will not be millilensed) !

Spectral model around the narrow [S III] doublet

lensqso-specfit



Results from the JWST lensed quasar survey

(PI: A. Nierenberg): warm dust flux ratios with MIRI for ~30 lenses

Papers III & IV
from the series

Results from the JWST lensed quasar survey

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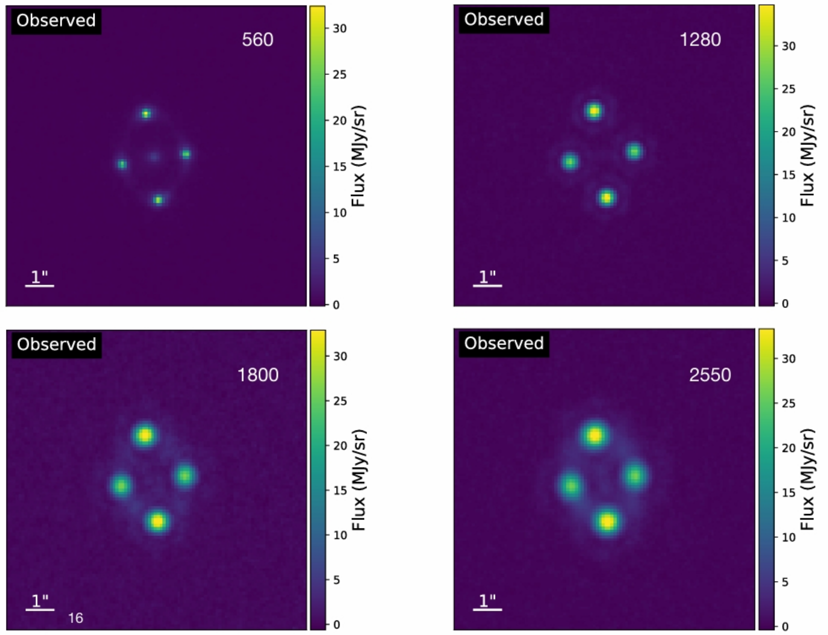
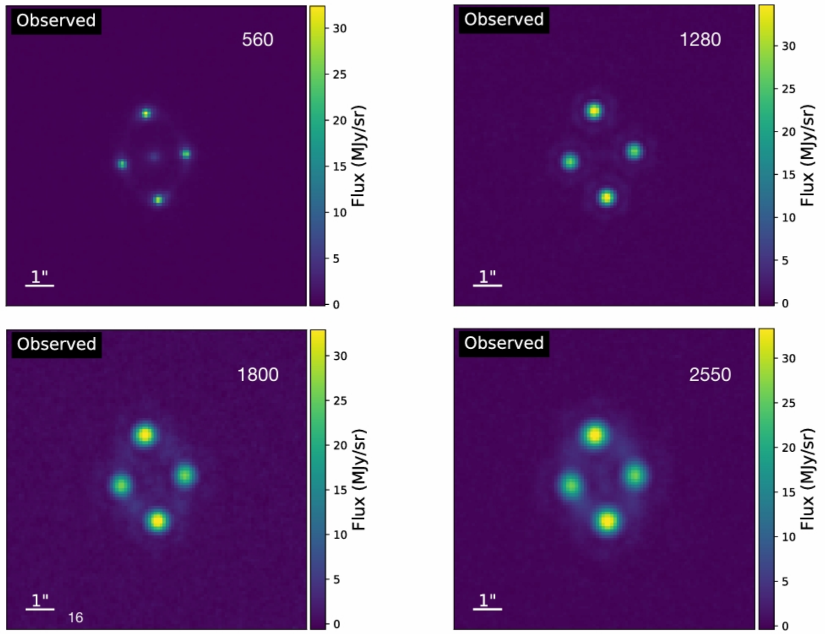


Credit: Keeley, Nierenberg et al. (2025)

Results from the JWST lensed quasar survey

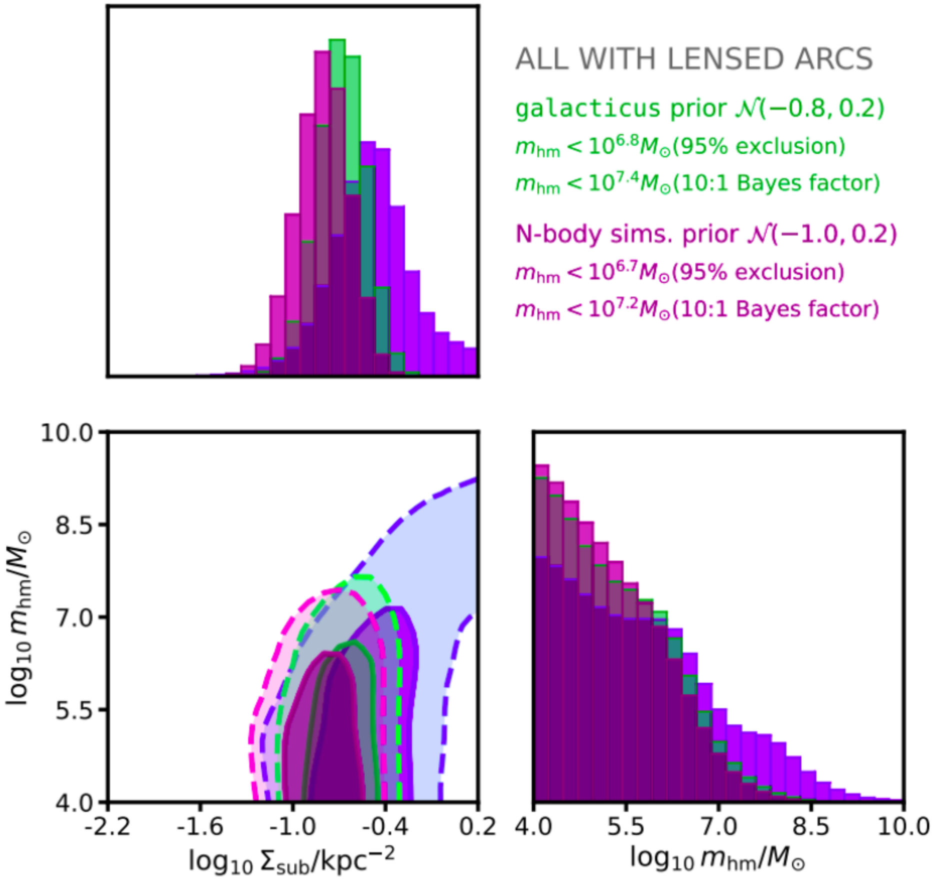
(PI: A. Nierenberg): warm dust flux ratios with MIRI for ~30 lenses

Papers III & IV from the series



Credit: Keeley, Nierenberg et al. (2025)

Constraints on Warm Dark Matter



Credit: Gilman et al. (2025)

Perspectives for Roman (1/2)

Biggest limiting factor

= sample size

(~100 known quads, ~30 in JWST survey)

Roman lensed AGN forecast

Credit : **Paras Sharma** (Stony Brook)

Survey	Total Lensed AGN	Doubles	Quads	Quad Fraction	Image Sep Cuts (")	Mag Cuts (2nd Brightest Image)
HLWAS Medium Tier	1,983	1,826	157	7.9%	0.2 - 4.0	F106 < 26.5 F129 < 26.4 F158 < 26.4
HLWAS Medium Tier (2-year)	412	384	28	6.8%	0.2 - 4.0	F106 < 26.5 F129 < 26.4 F158 < 26.4
HLWAS Wide Tier	2,233	2,038	195	8.7%	0.2 - 4.0	F158 < 26.2

~400 new quads

STRENGTH IN NUMBERS

Perspectives for Roman (1/2)

Biggest limiting factor

= sample size

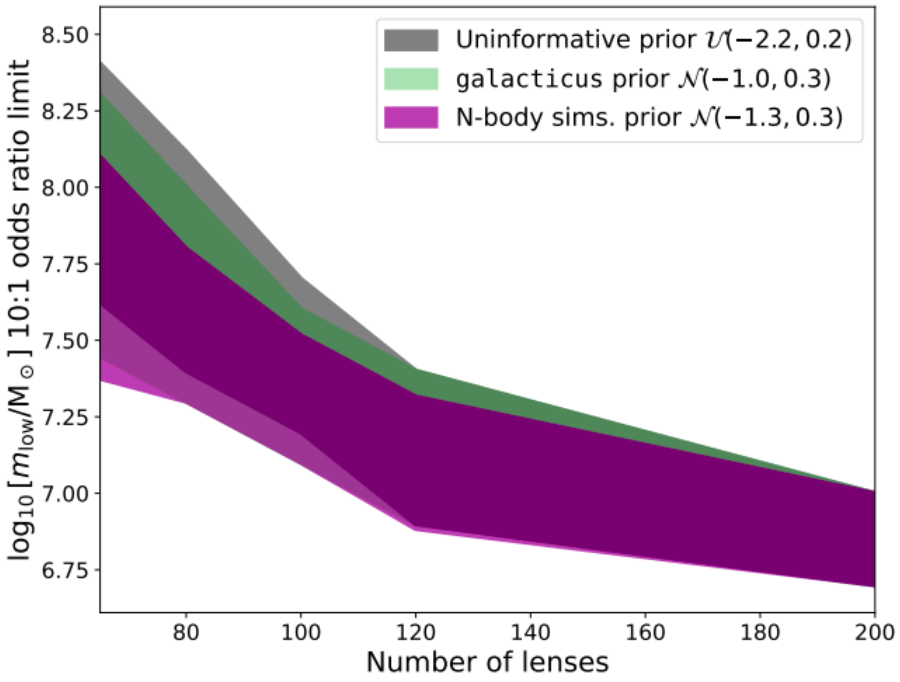
(~100 known quads, ~30 in JWST survey)

~400 new quads

→ order of magnitude improvement on DM constraints !

A few objects will have flux-ratio measurements thanks to grism data in HLWAS Medium tier, but most will need follow-up observations.

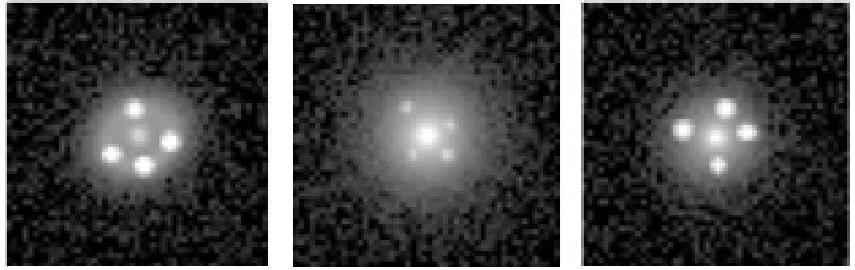
Lowest halo mass limit in CDM that can be placed with FR anomalies



Credit: Nierenberg et al. (2026)

Perspectives for Roman (2/2)

Deep images with sharp & stable PSF → lensed arcs

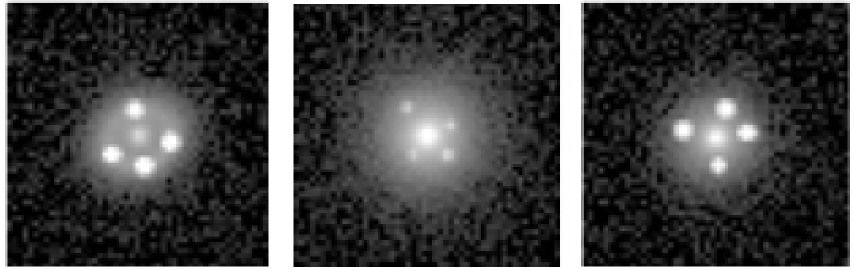


Credit: Paras Sharma

Perspectives for Roman (2/2)

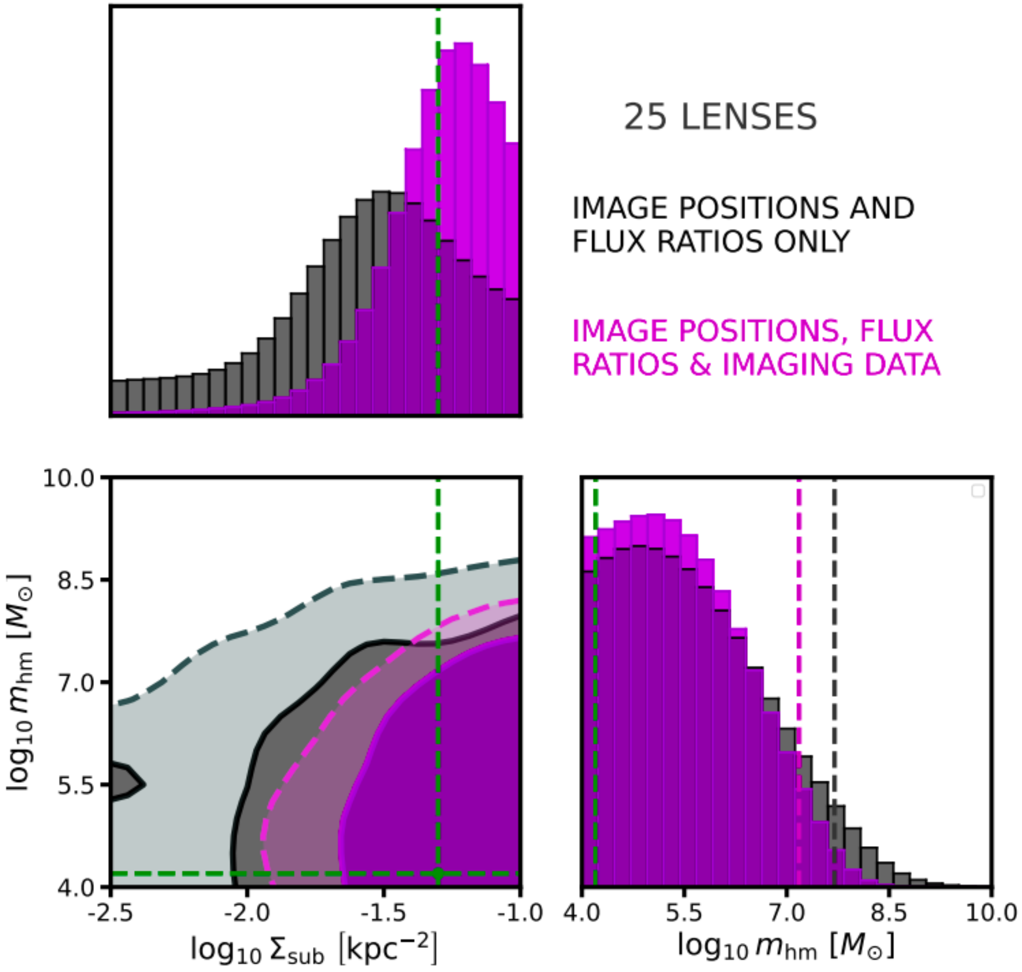
STRENGTH IN PRECISION

Deep images with sharp & stable PSF → lensed arcs



Credit: Paras Sharma

✔ Strengthens DM constraints by improving lens model precision

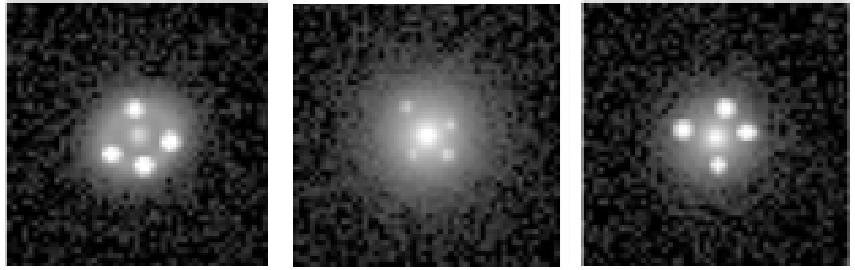


Credit: Gilman et al. (2024)

Perspectives for Roman (2/2)

STRENGTH IN PRECISION

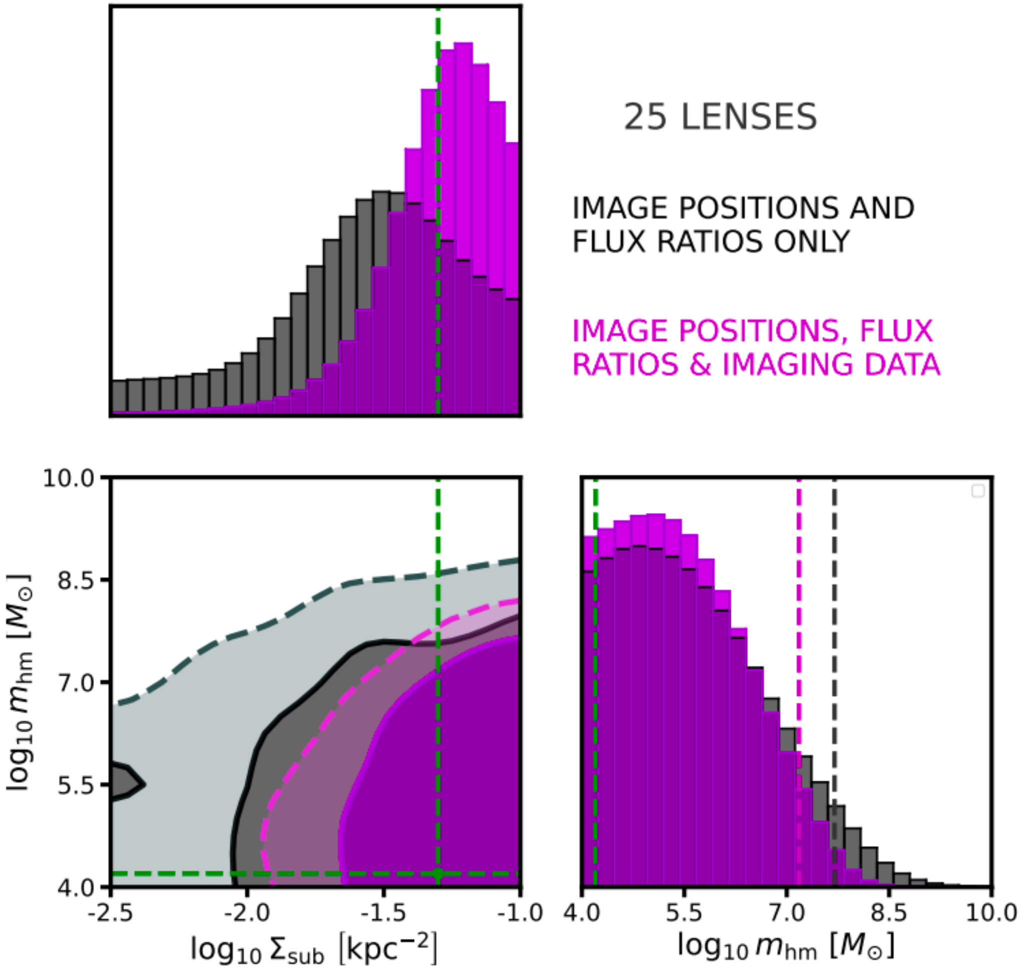
Deep images with sharp & stable PSF → lensed arcs



Credit: Paras Sharma

- ✔ Strengthens DM constraints by improving lens model precision
- ✔ Allows local modeling approach (using extended arcs) to control systematics

Paugnat, Treu & Gilman (2025)

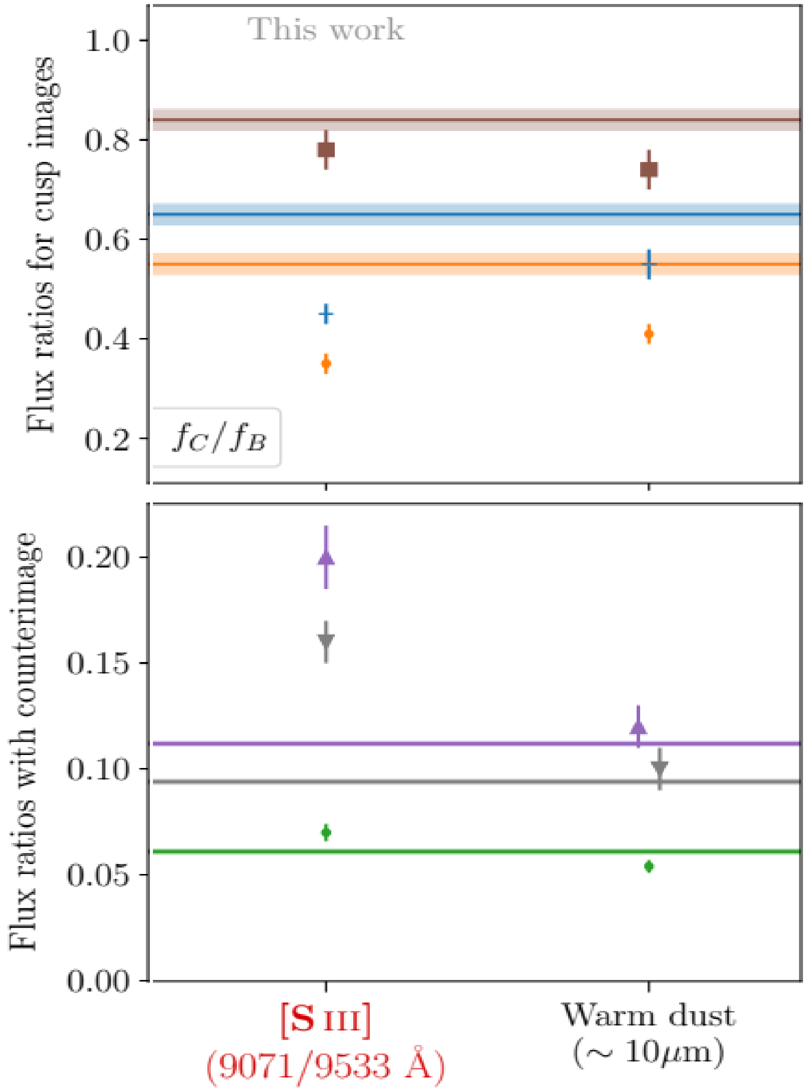


Credit: Gilman et al. (2024)

Thank you !

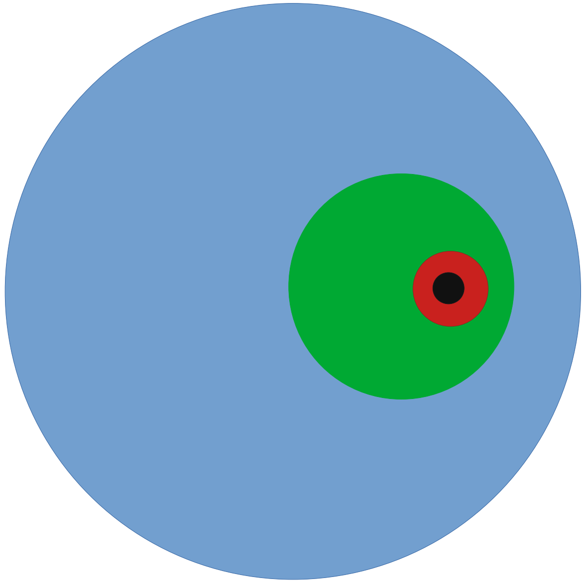
Backup slides

Dual source flux-ratio measurements ?

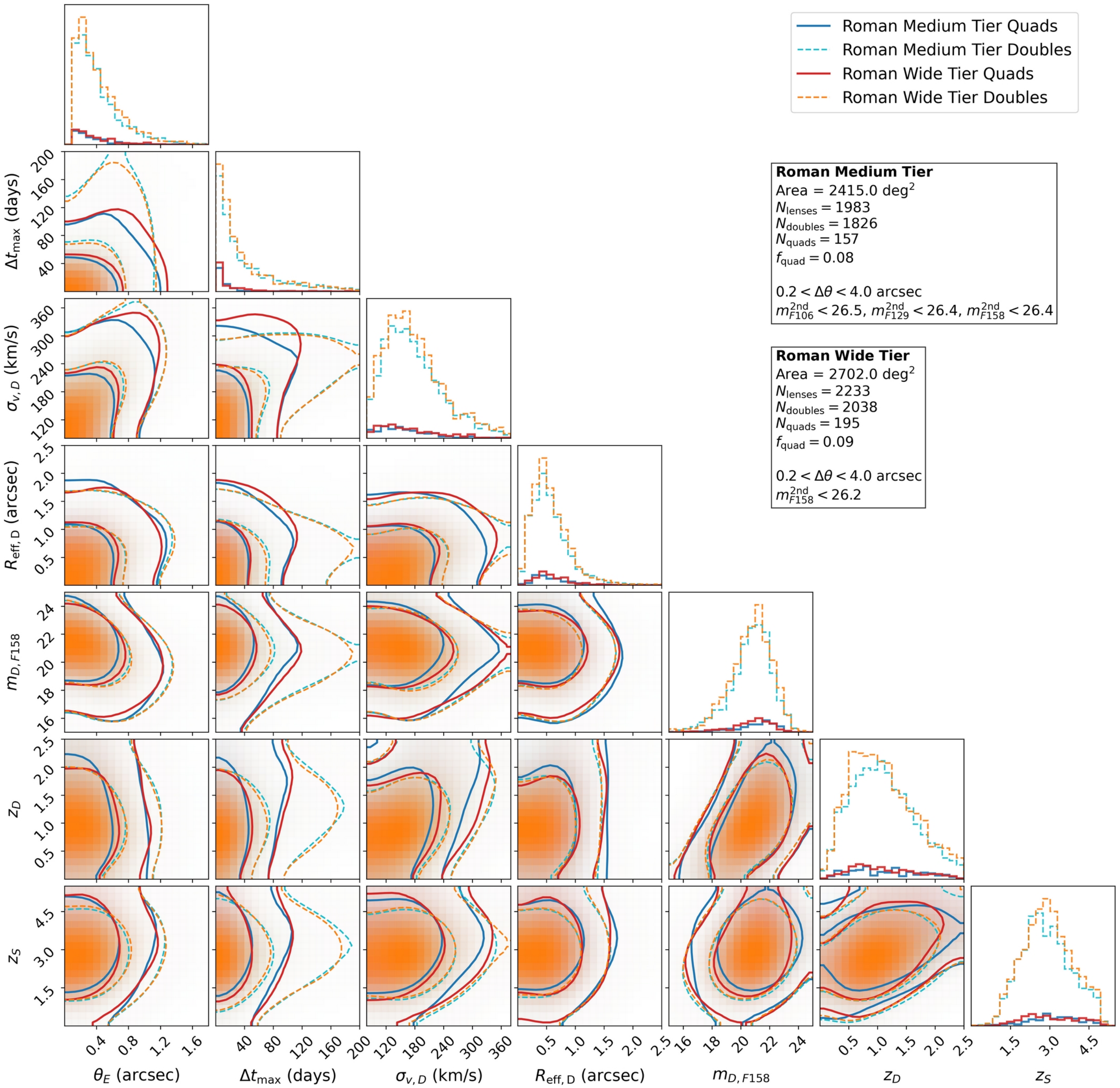


Millilensing is sensitive to source size !

And differences can be enhanced by offsets of ~10pc in source position



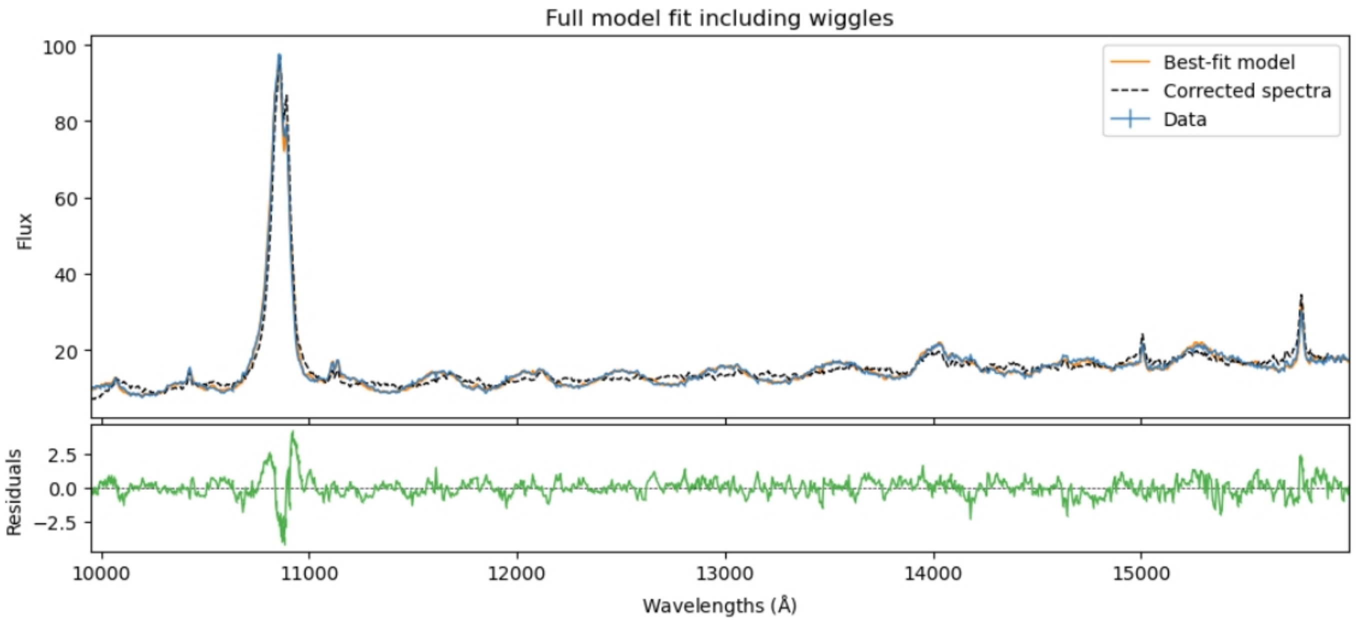
Lensed AGN Forecasts: Roman (Medium & Wide)

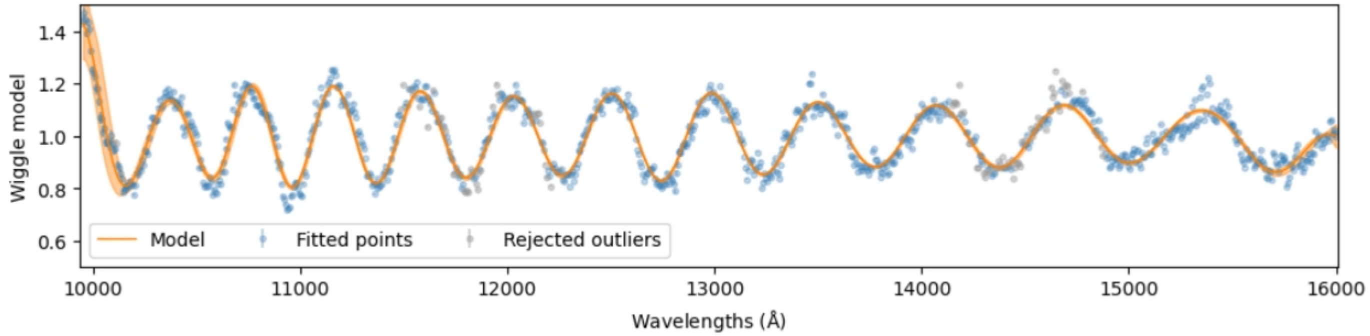


<u>Credit</u>: Paras Sharma

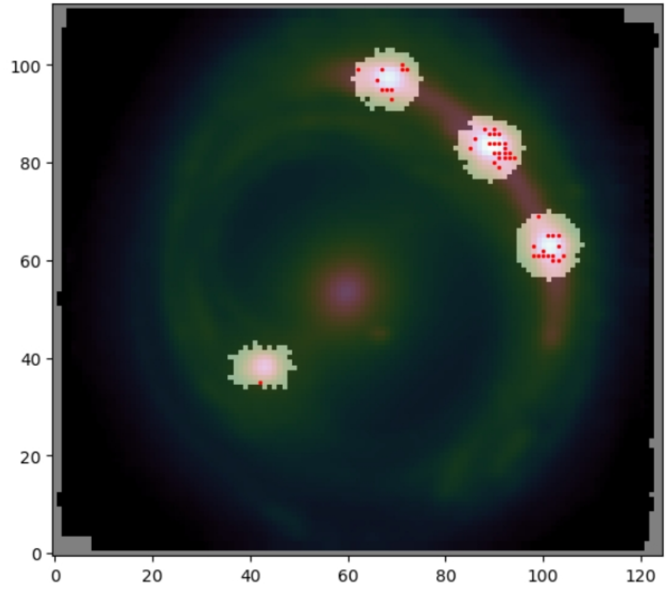
1st step: wiggle correction

Artifact due to PSF undersampling

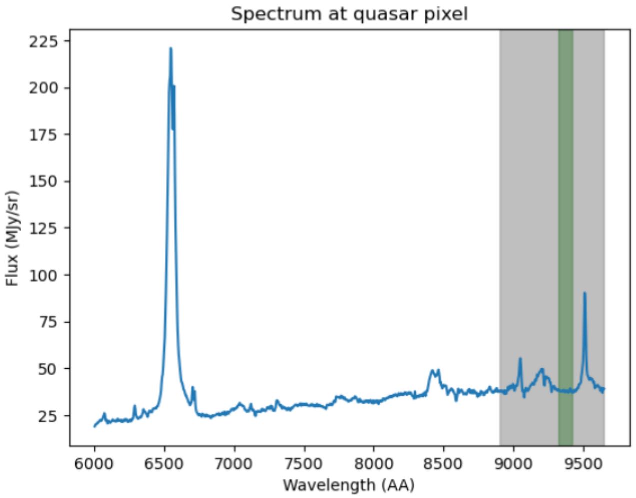




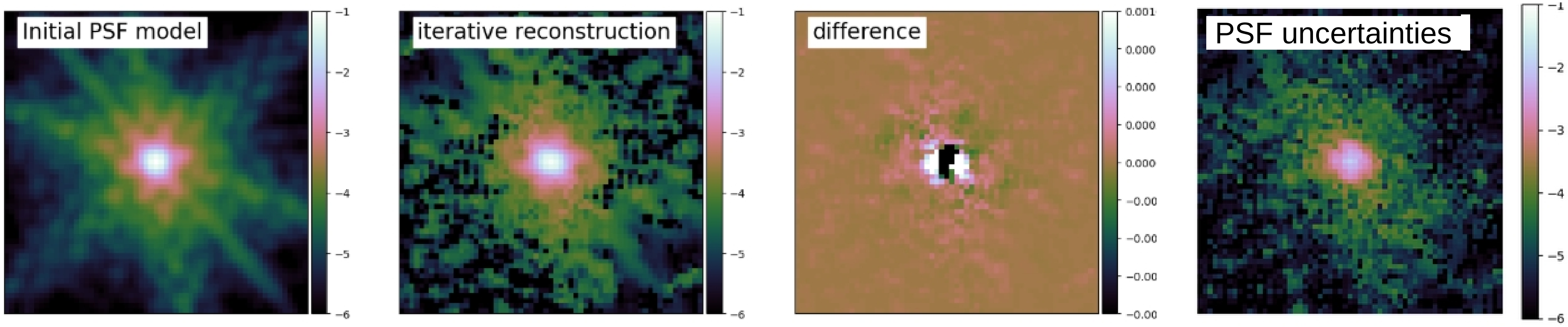
Needed to do many pixels « by hand »

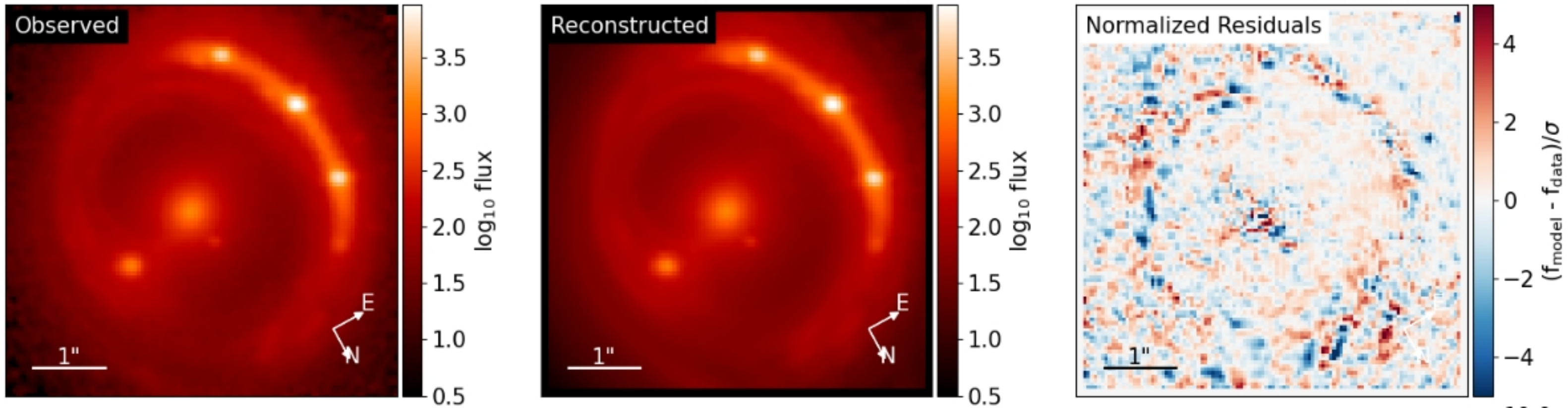


2nd step: PSF estimation

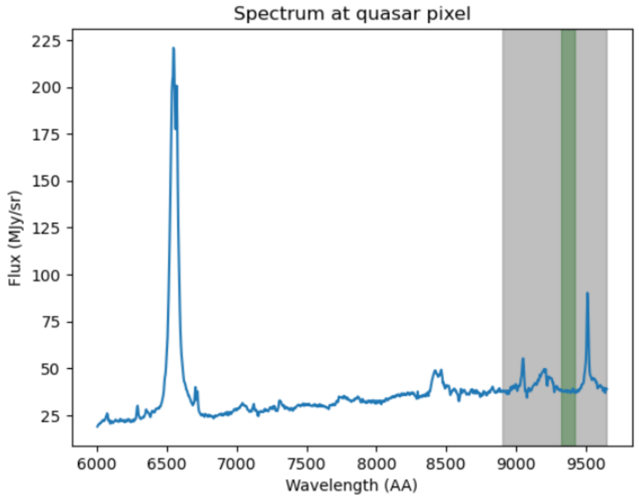


- Make a white light image on a wavelength range close to the desired doublet(s), but with faint extended emission from the quasar host galaxy
- Fit with iterative PSF reconstruction

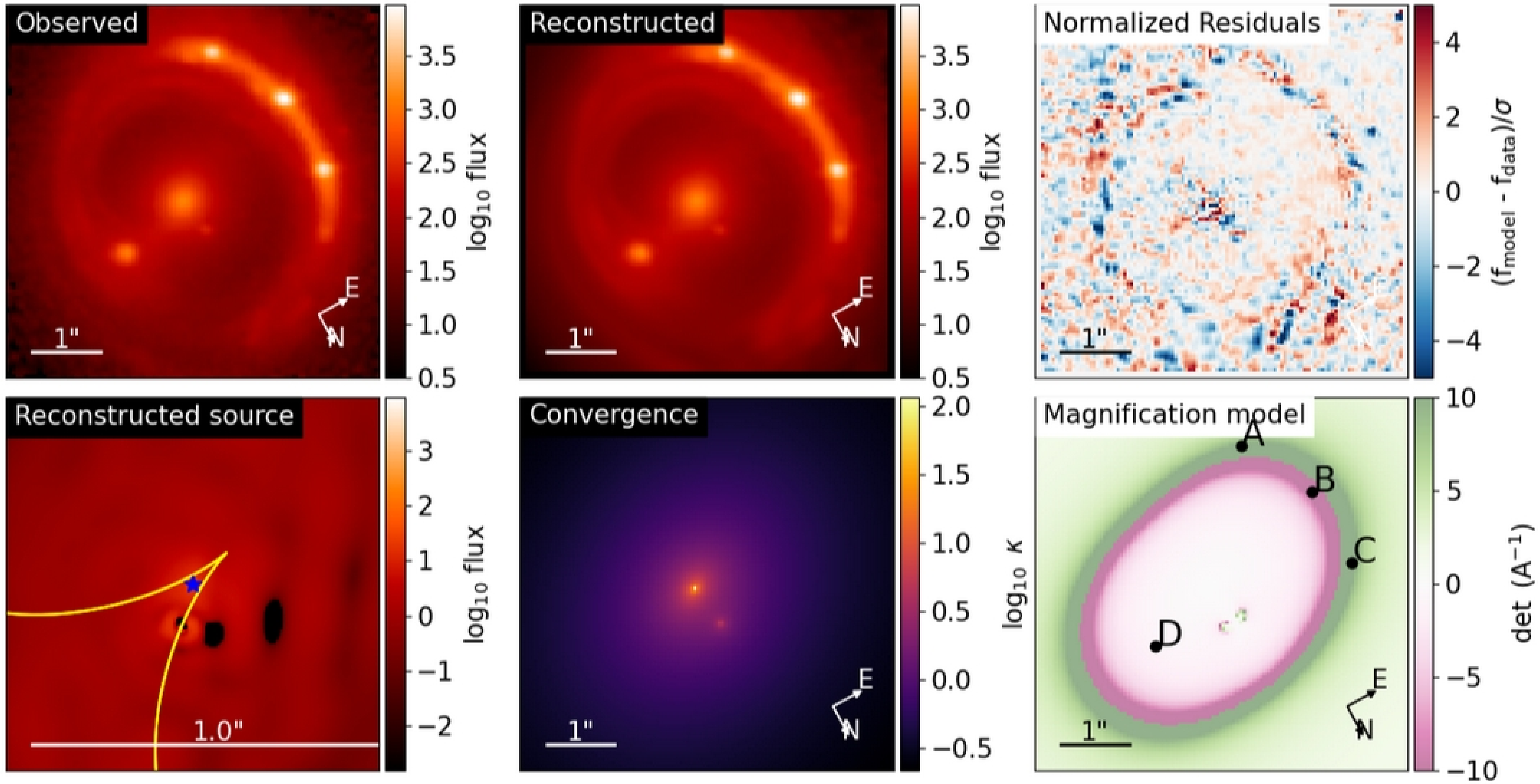




3rd step: white light image model



- Make a white light image on a wavelength range encompassing to the desired doublet(s)
- Fit lens model with the PSF estimate obtained at step 2



Lens model: EPL+shear+SIS

Lens light model: 3 Sersics

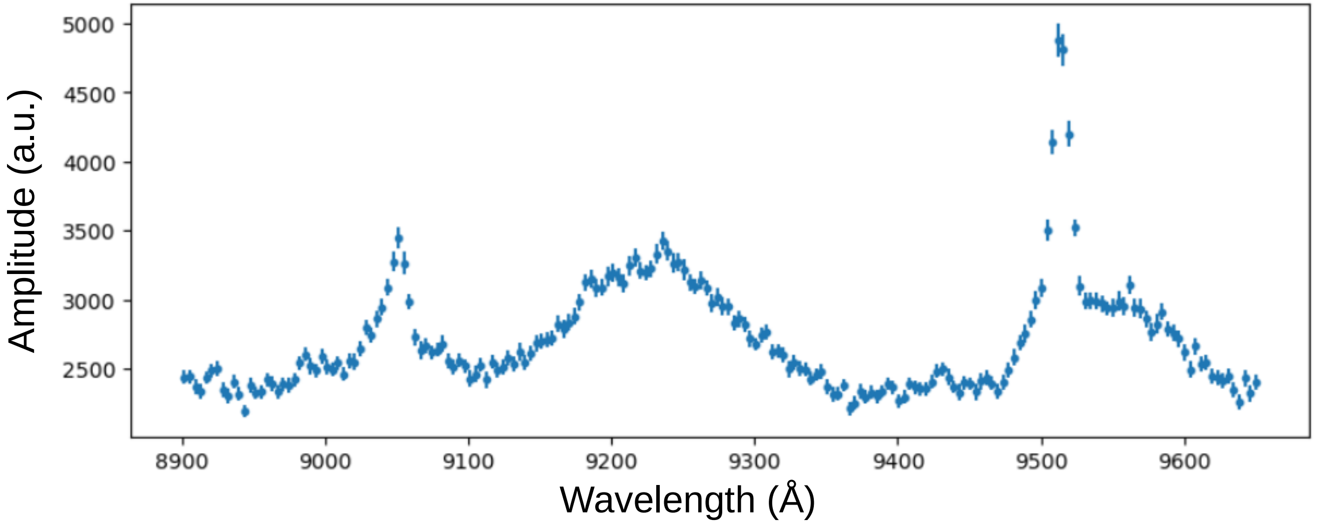
Source model: 2 Sersics + 2 sets of shapelets (n=15/12)

+ point source

Good fit (esp. around the quasar) given the complexity of the source !

4th & 5th step: spectral extraction & fitting

› For each wavelength slice, re-optimize the point-source amplitudes while keeping the non-linear parameters & PSF fixed → extracted quasar spectra !



› Uncertainties obtained by sampling non-linear parameters from MCMC chains + adding PSF errors around point source

› « Homemade » spectral fitting code:

– Separates linear/non-linear parameters to speed up computation

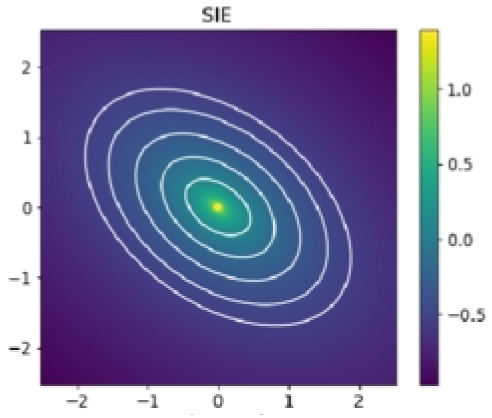
– Fits spectra for several images simultaneously, with the option to have shared parameters between images

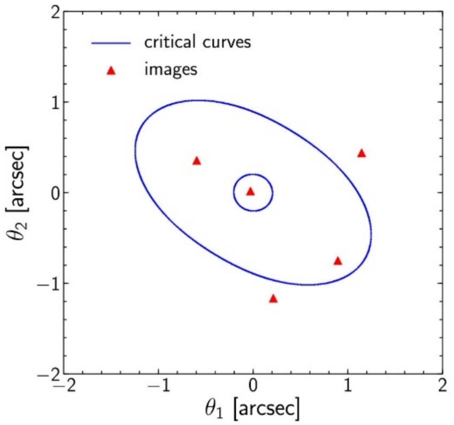
Controlling systematics from lens modeling

Deflection field of the main lensing galaxy

Physical assumptions (e.g. « The lens mass distribution is elliptical »)

Fit a global parametrized profile **(macromodel)**

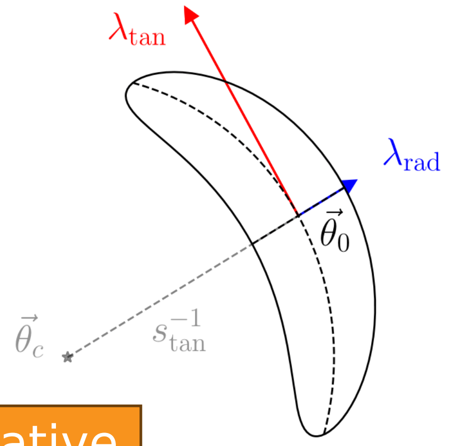




Credit: *Van de Vyvere (2022)*

Flexible description with minimal assumptions

Birrer (2021): fit lensed arcs individually, by extrapolating local lensing properties in a **Curved Arc Basis (CAB)**

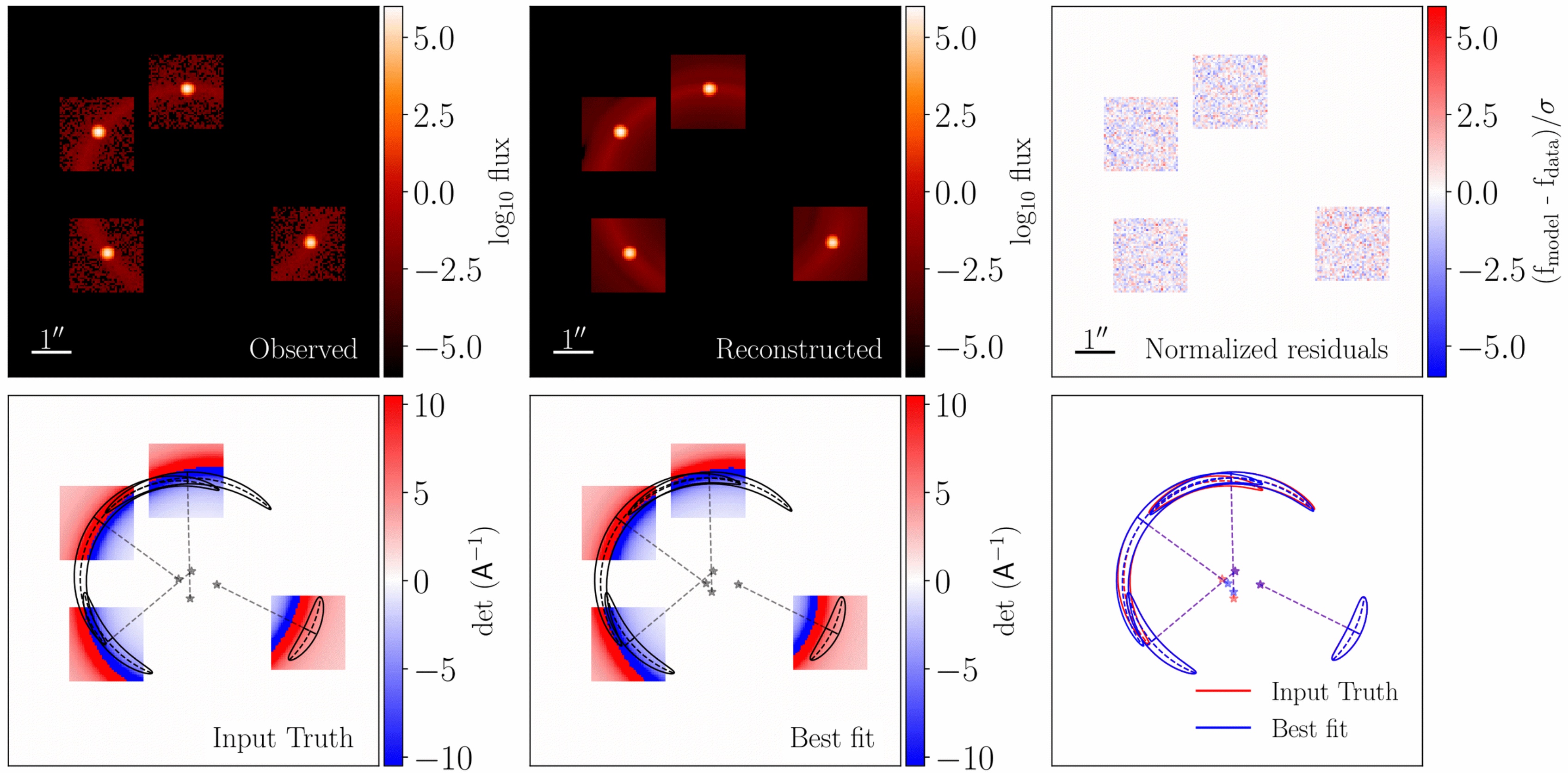


Tighter constraints

Conservative errors

This approach works on simulated data !

Paugnat, Treu & Gilman (2025), “***Macromodel-free flux-ratio prediction in quadruply imaged quasars with local constraints from lensed arcs***”, Phys. Rev. D **112**, 123002



→ predict the magnification at the quasar location using the imaging data from the surrounding lensed arc from the host galaxy (« local » constraint)

Curved Arc Basis (CAB) formalism (1/2)

Lens equation

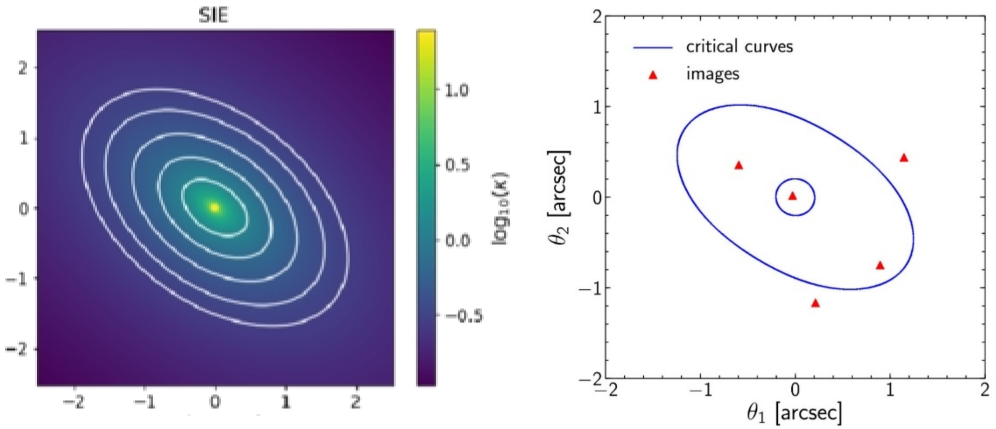
$$\boldsymbol{\beta} = \boldsymbol{\theta} - \boldsymbol{\alpha}(\boldsymbol{\theta})$$

Lensing Jacobian

$$A_{ij} \equiv \frac{\partial \beta_i}{\partial \theta_j} = \delta_{ij} - \frac{\partial \alpha_i}{\partial \theta_j} \equiv \begin{bmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{bmatrix}$$

OR

Fit a global convergence + shear parametrized profile: **macromodel**



Credit: *Van de Vyvere (2022)*

Birrer (2021): write the lensing Jacobian in a local basis formed with its eigenvectors

$$\mathbf{A} \cdot \boldsymbol{e}_{\mathrm{rad}} = \lambda_{\mathrm{rad}}^{-1} \boldsymbol{e}_{\mathrm{rad}}$$
$$\mathbf{A} \cdot \boldsymbol{e}_{\tan} = \lambda_{\tan}^{-1} \boldsymbol{e}_{\tan},$$

Magnification: $\mu = \lambda_{\mathrm{rad}} \lambda_{\tan}$

Can be determined from an extended lensed arc

Curved Arc Basis (CAB) formalism (2/2)

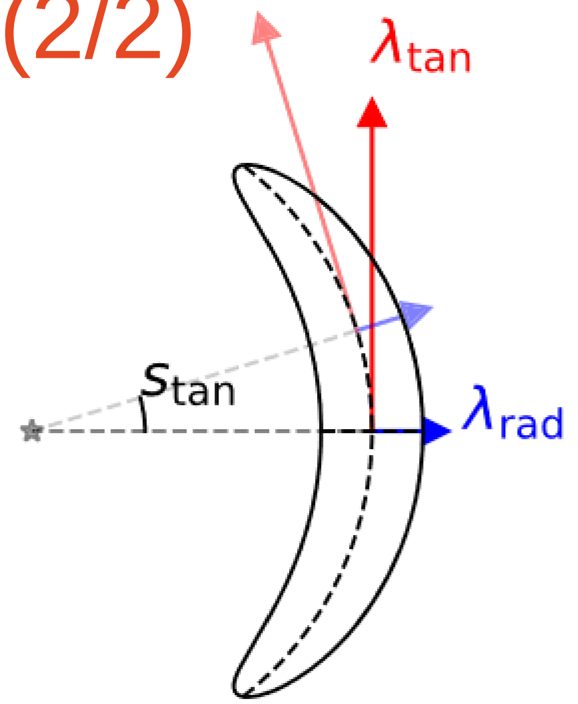
Fit the following quantities to the extended lensed arc:

› Differentials at center of arc:

2nd order in potential
- Tangential stretch
- Radial stretch

3rd order in potential
- (Tangential) curvature

  (: angle between and some reference direction)
- Gradient of tangential stretch along the arc



<u>Credit</u>: Birrer (2021)

→ we get the quasar magnification () using the imaging data from the surrounding lensed arc of the host galaxy (« local » constraint)

A simple description of curved arcs

› Choose constant values for , ,

Take all other quantities =0

› 6 parameters

(including center of coords

+ direction)

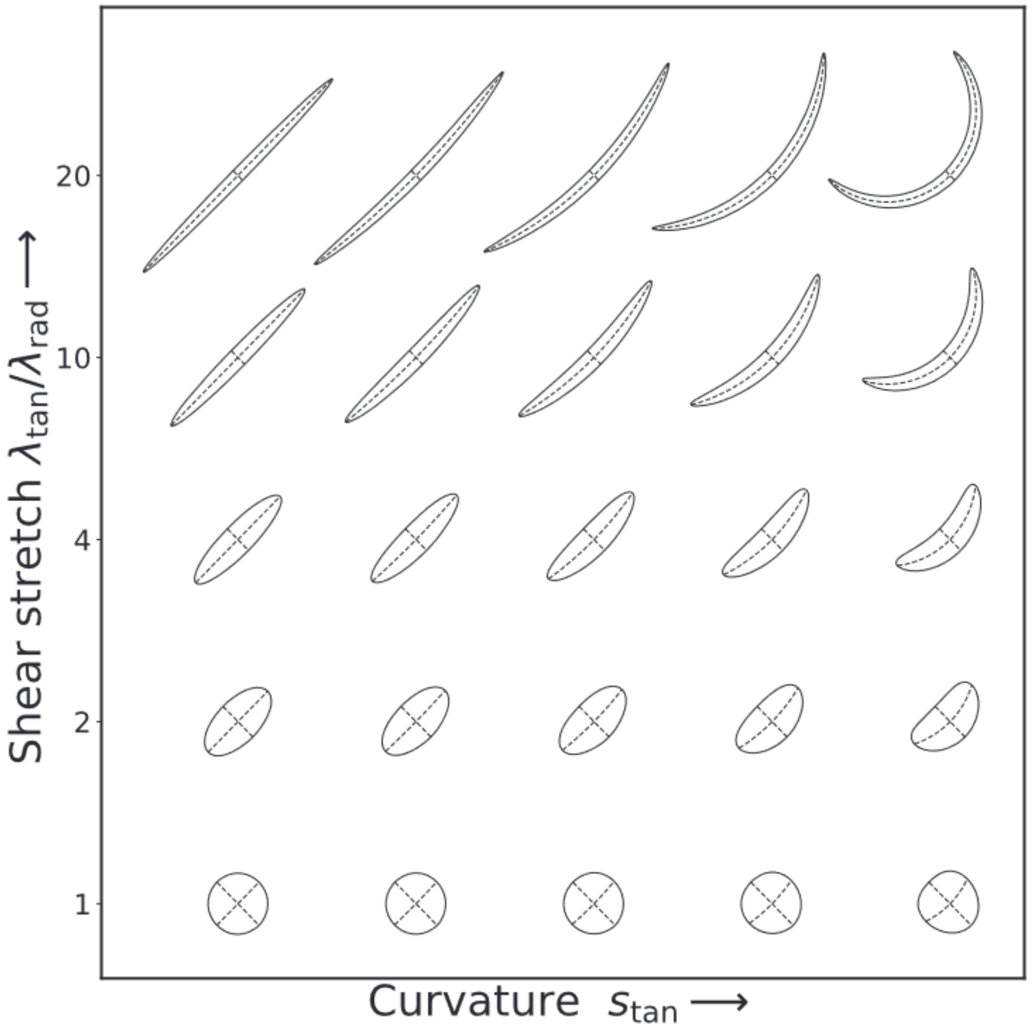
› Equivalent locally to

SIS +MST

with $$\theta_{\mathrm{E}} = s_{\tan}^{-1}\left(1 - \frac{\lambda_{\mathrm{rad}}}{\lambda_{\tan}}\right)$$

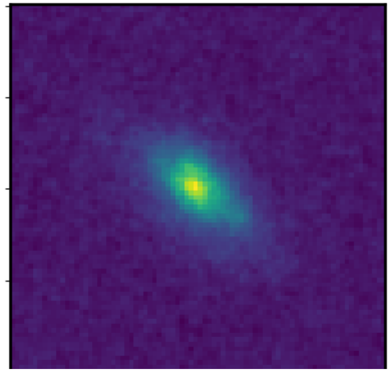
(: Einstein ring)

Credit: Birrer (2021)

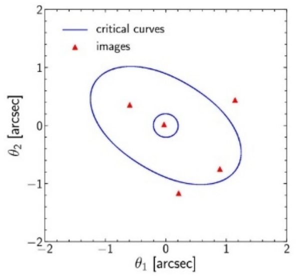


Testing the CAB performance

Realistic host galaxy



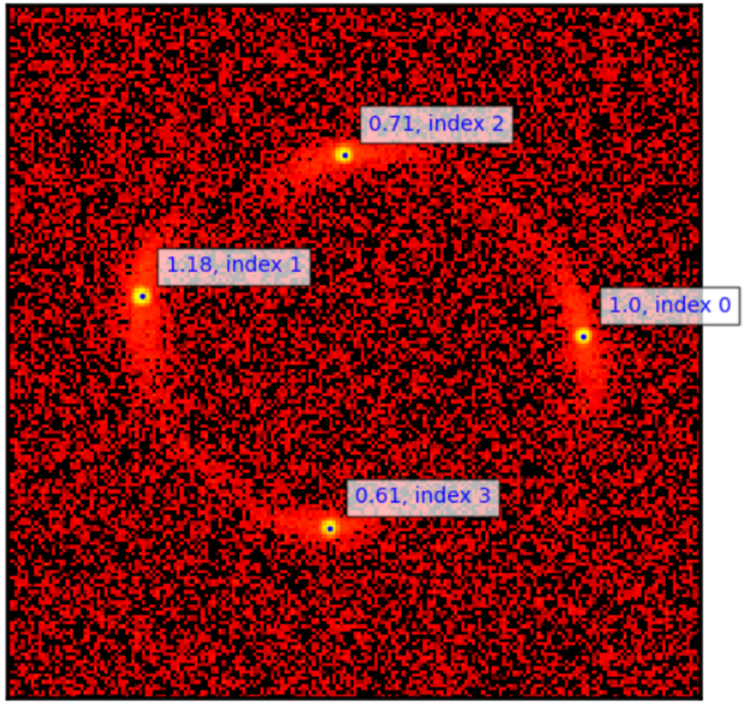
+ point source (quasar)



Mock lens:
EPL + shear
(+ multipoles)
(+ DM subhalo)

Data characteristics (noise, PSF,…)

Mock imaging data

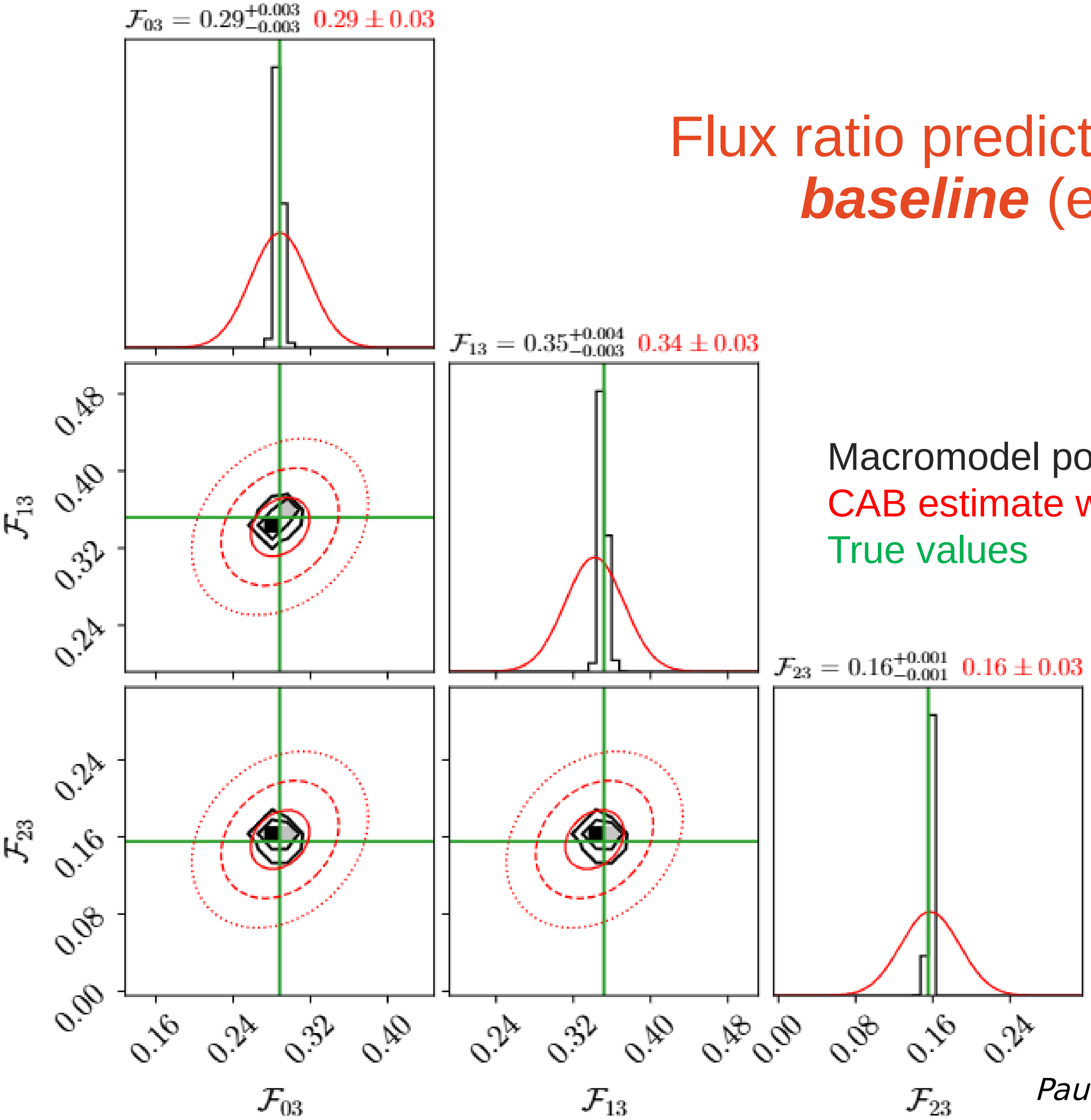


Fit with :
- Macromodel (EPL+shear)
- CAB model

Compare :
- True flux ratios
- Predicted flux ratios in macromodel fit
- Predicted flux ratios in curved arc fit

Generate many realizations, with/without DM subhalo, with/without multipoles, etc…

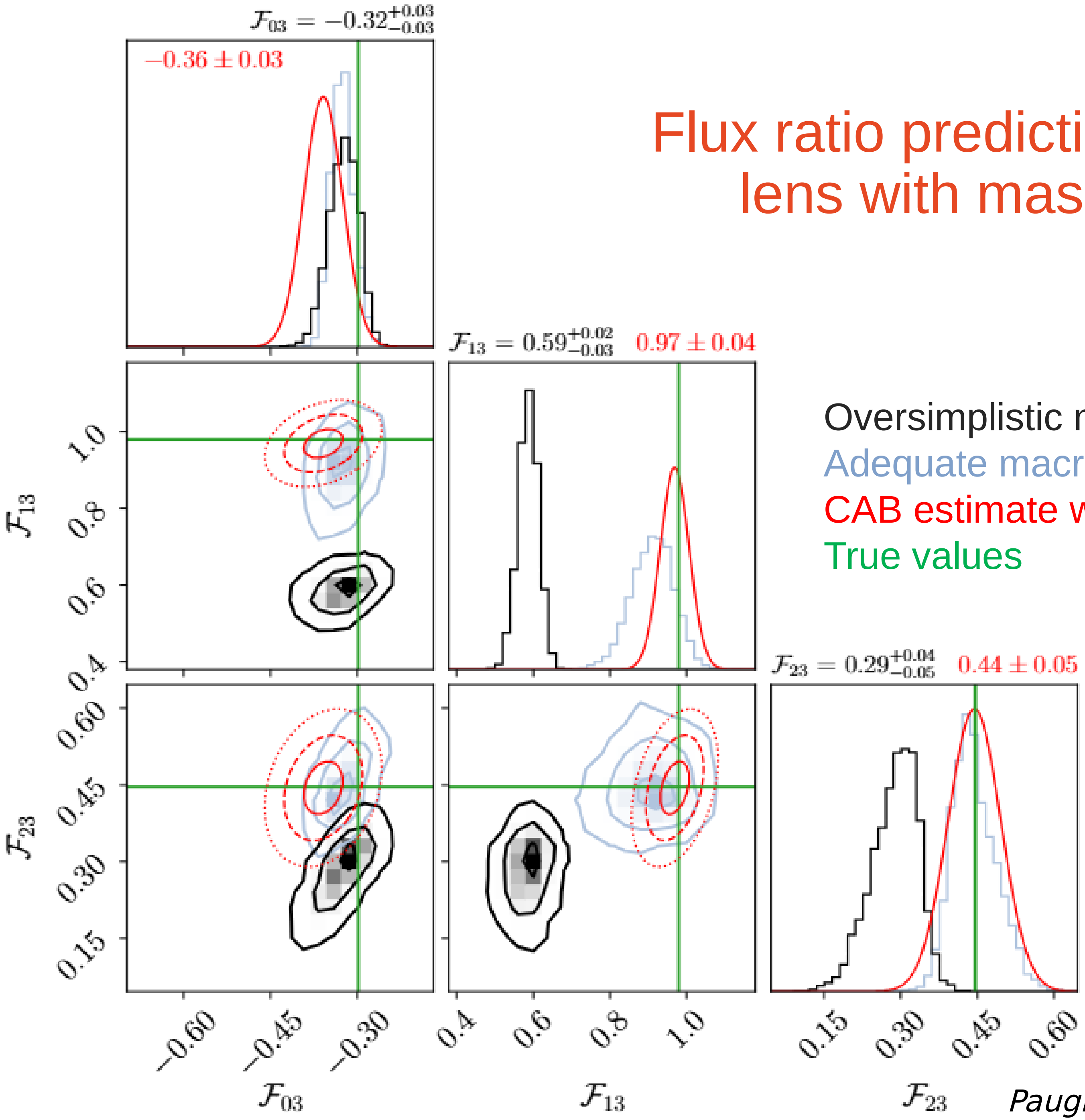
Flux ratio prediction performance: ***baseline*** (elliptical lens)



Macromodel posterior (MCMC samples)
CAB estimate with noise resampling
True values

An **adequate** macromodel is more precise (smaller uncertainties) than a CAB model

Paugnat et al. (2025)



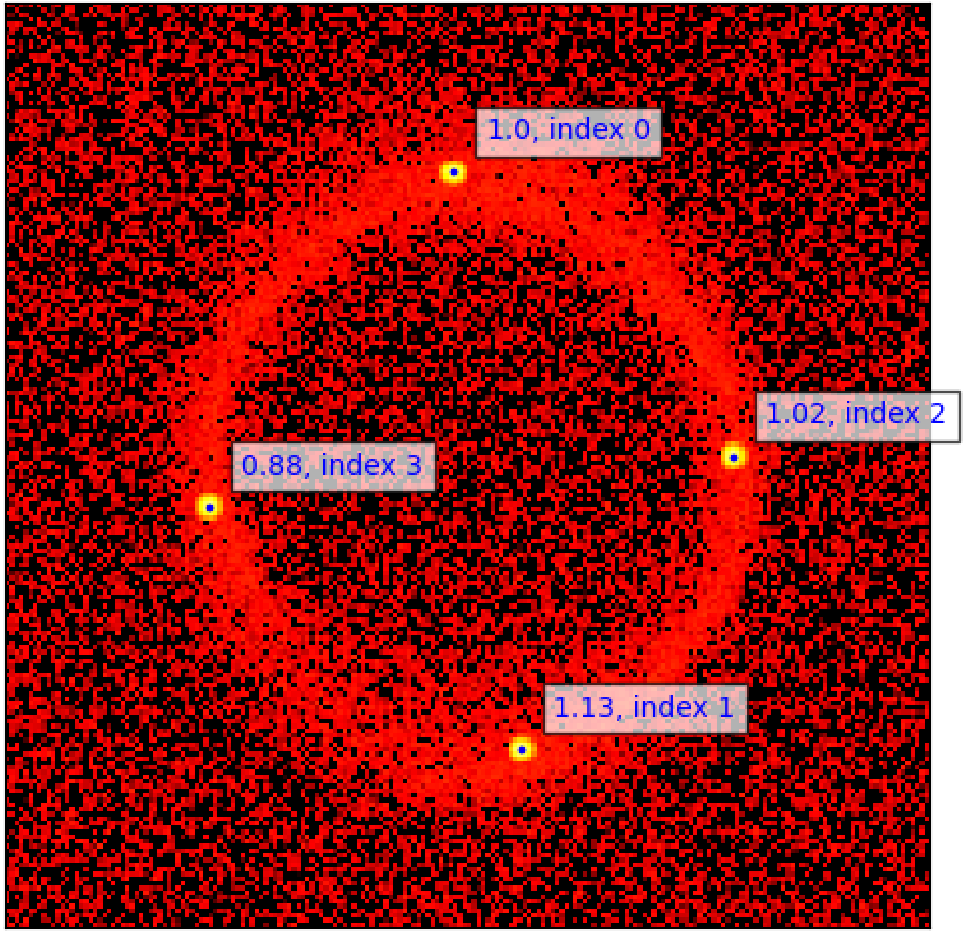
Flux ratio prediction performance: lens with mass ***complexity***

Oversimplistic macromodel
Adequate macromodel
CAB estimate with noise resampling
True values

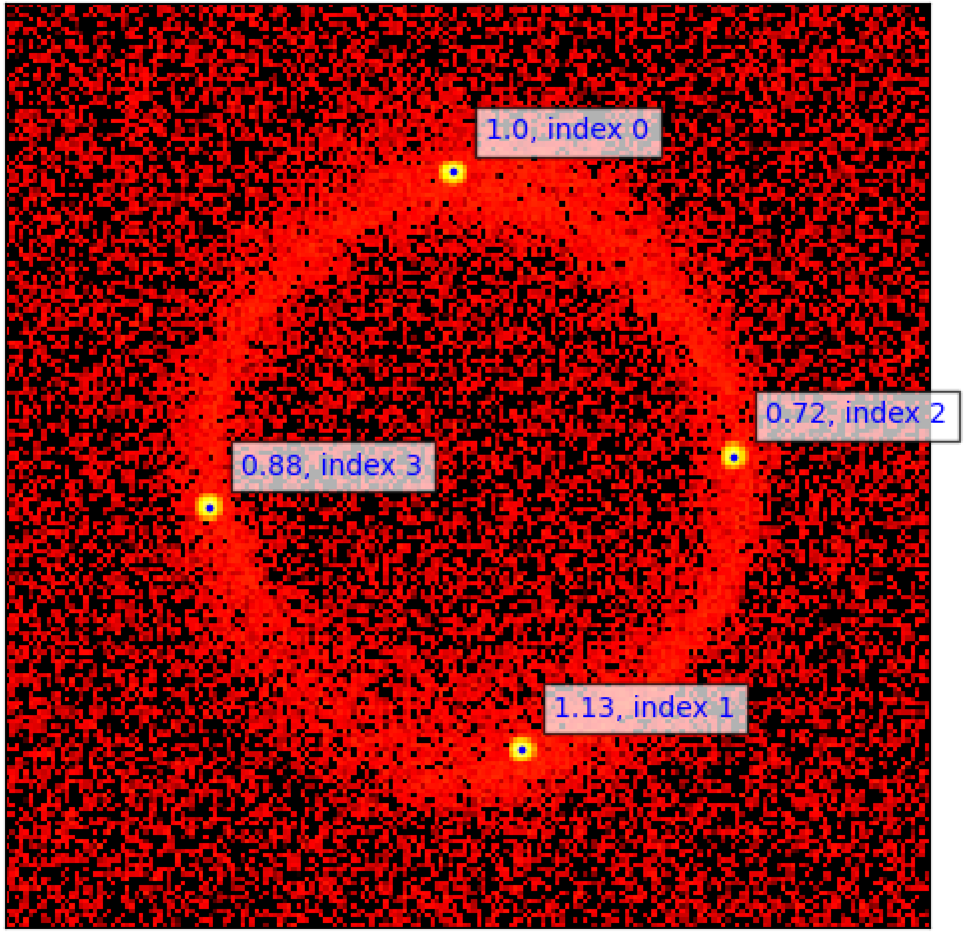
CAB models are **robust** to false-positive flux-ratio anomalies, being more flexible than macromodels

Paugnat et al. (2025)

Addition of an anomaly-inducing DM subhalo

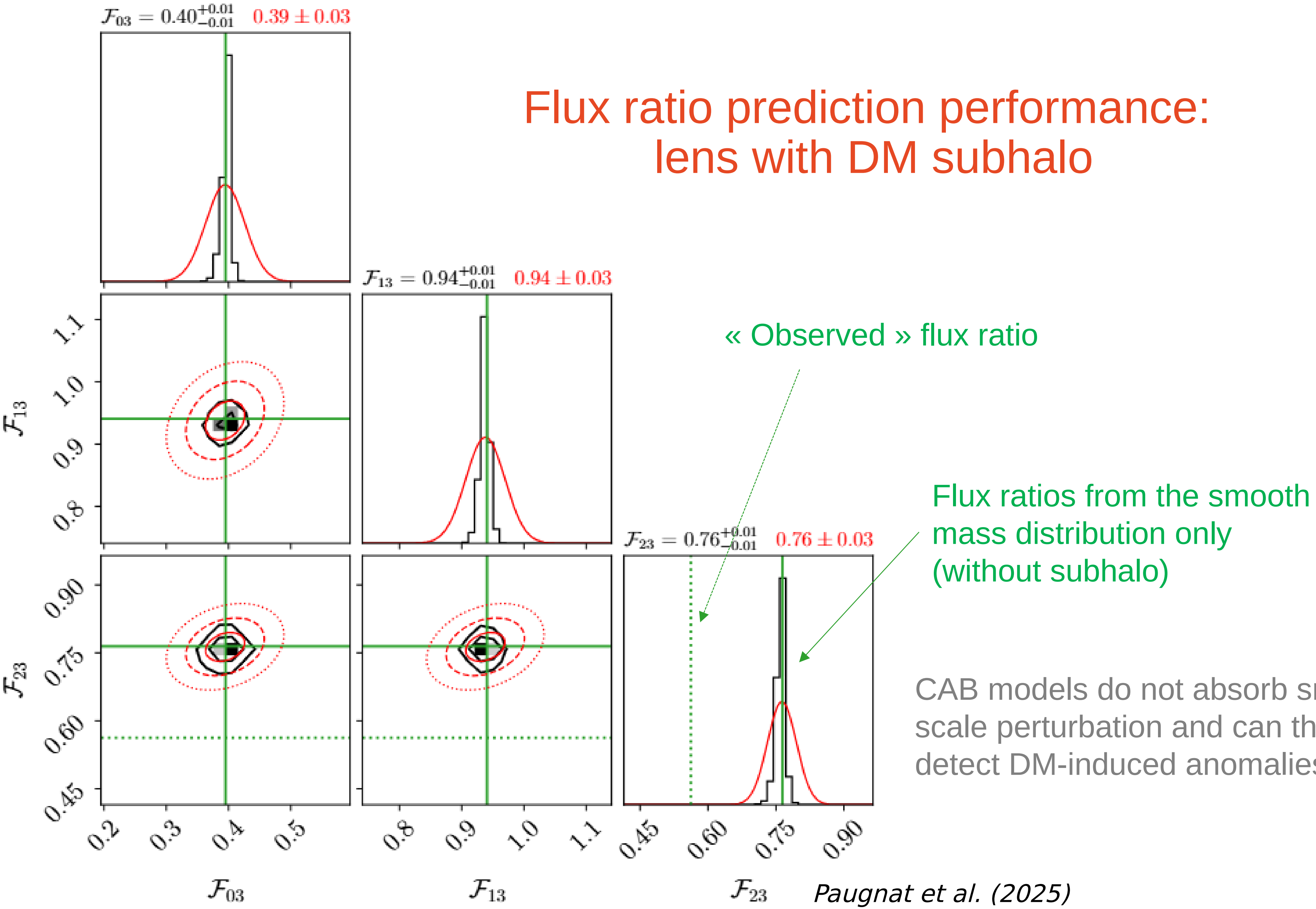


No DM subhalo



DM subhalo near image 2

Flux ratio prediction performance: lens with DM subhalo

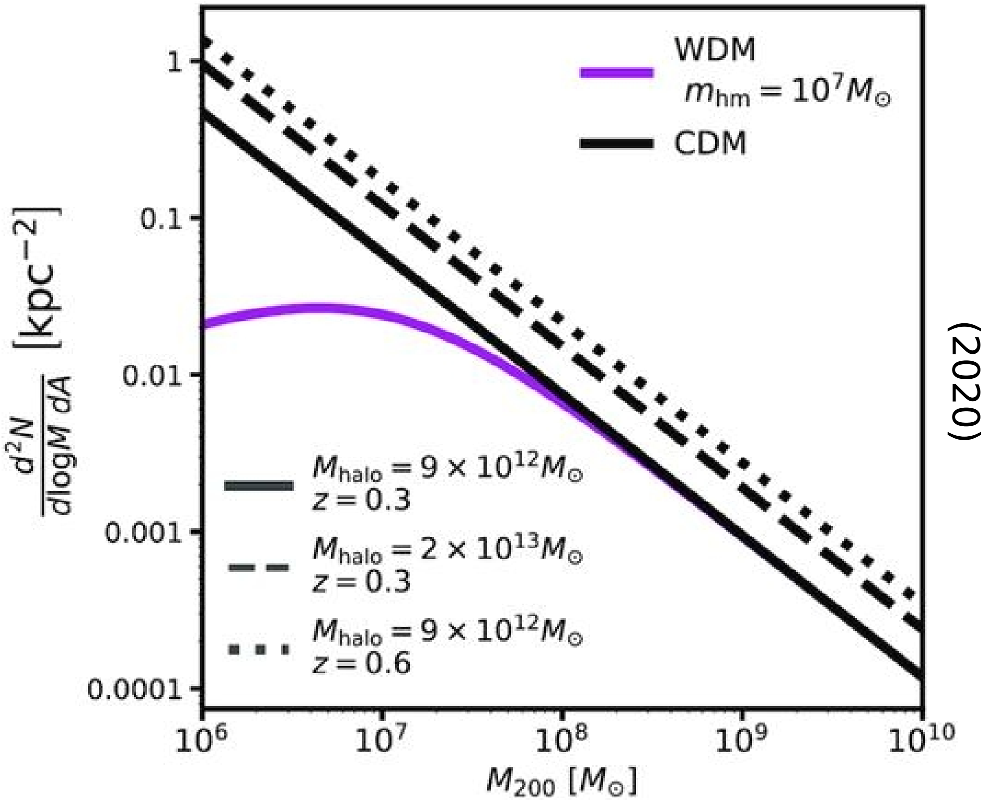


CAB models do not absorb small-scale perturbation and can therefore detect DM-induced anomalies

Paugnat et al. (2025)

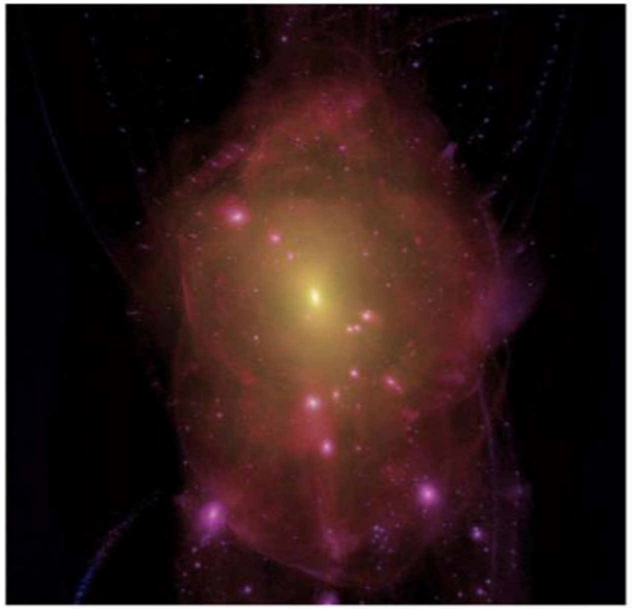
Warm Dark Matter (WDM)

- Suppression of structure below a characteristic mass scale (half-mode mass)



Credit: Gilman et al. (2020)

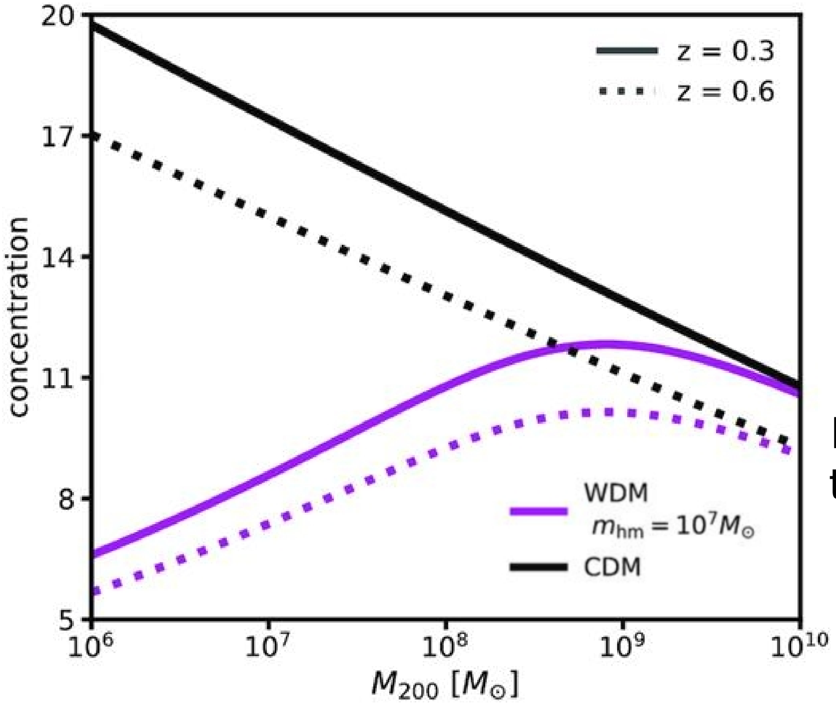
Cold Dark Matter Simulation



Warm Dark Matter Simulation

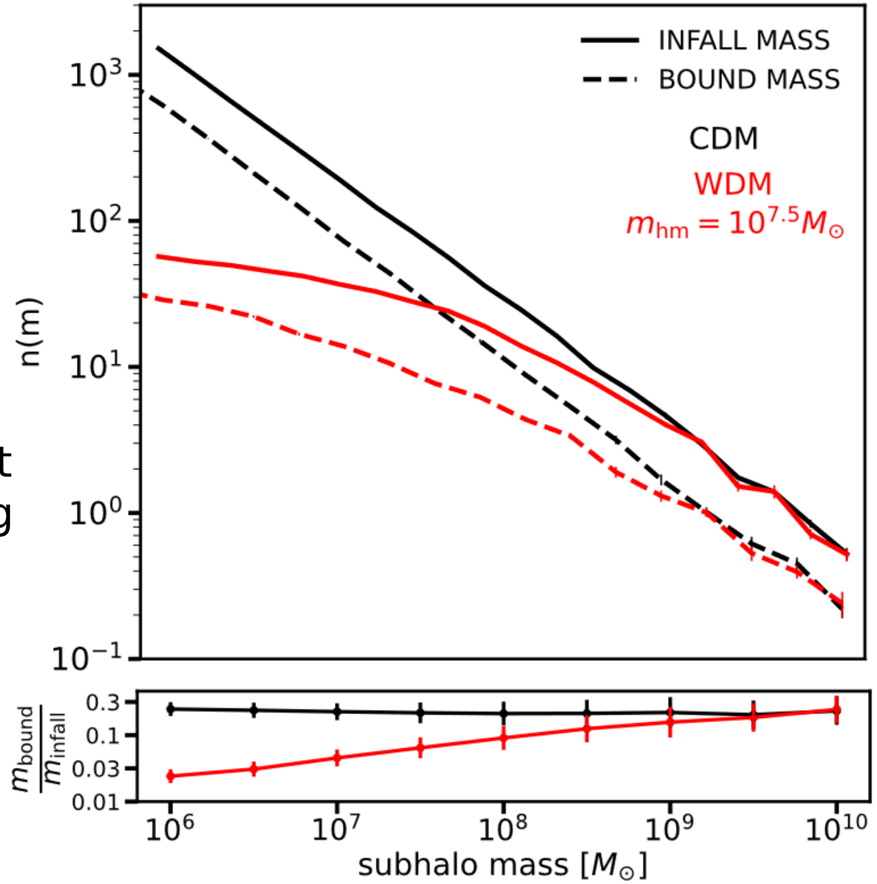
Credit: Lovell et al. (2012)

WDM halos are also less concentrated



Credit: Gilman et al. (2020)

More efficient tidal stripping for subhalos

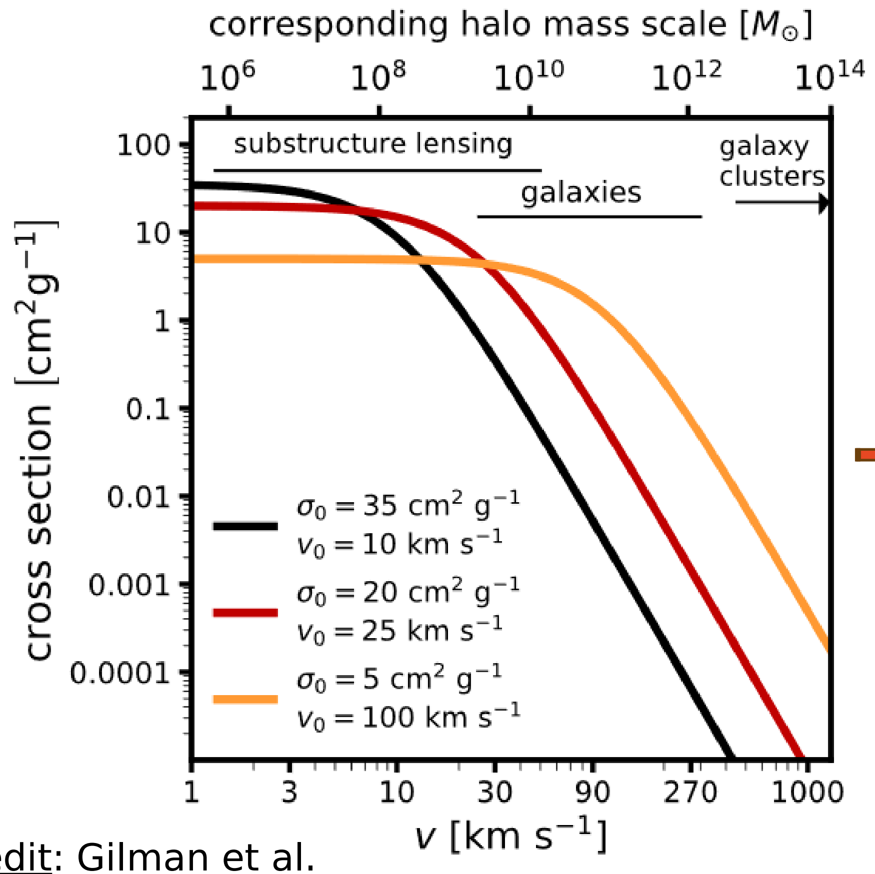


Credit: Keeley et al. (2024)

WDM will display statistically less flux-ratio anomalies than CDM

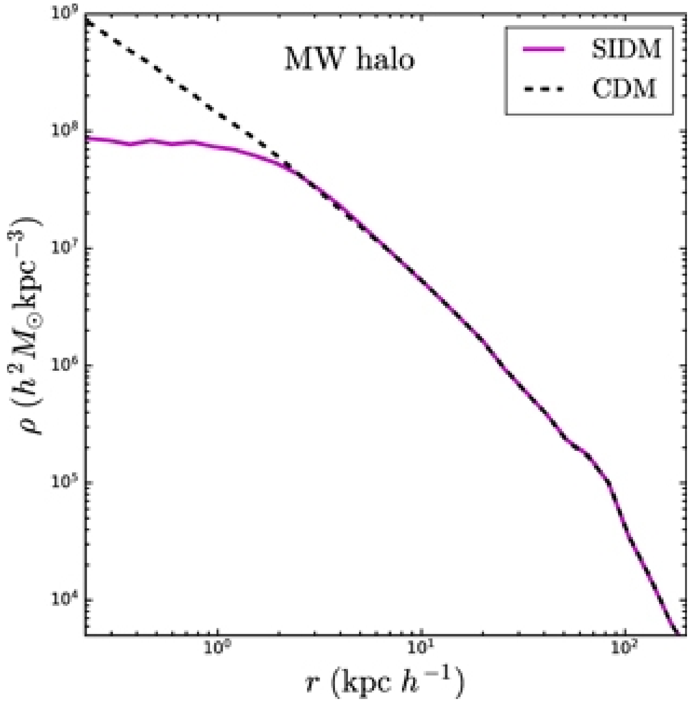
Self-Interacting Dark Matter (SIDM)

- Self-interaction other than gravity, with a velocity-dependent cross-section



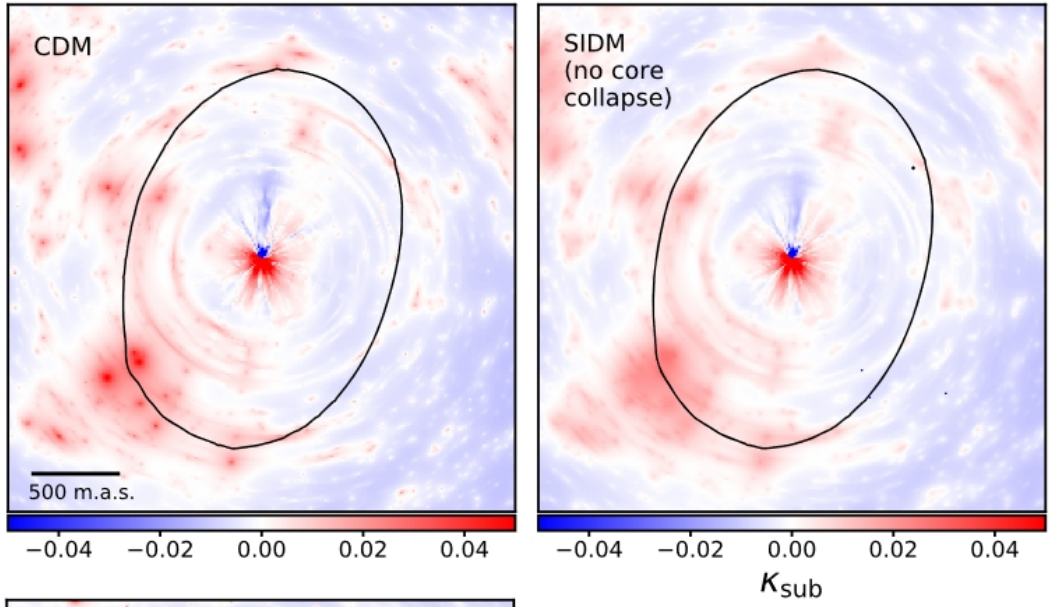
Credit: Gilman et al. (2022)

1) Cored density profiles

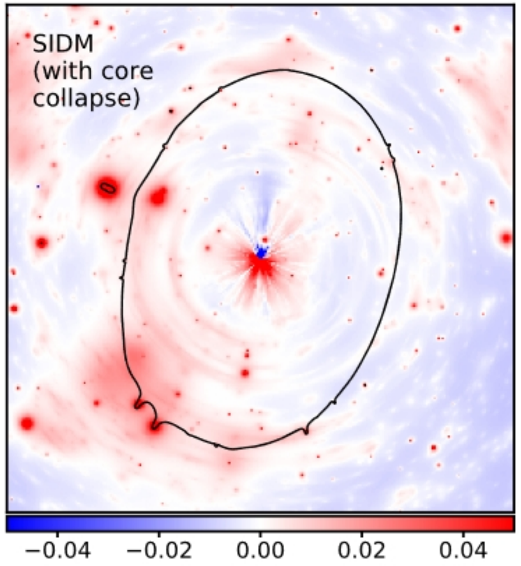


Credit: Yang et al. (2023)

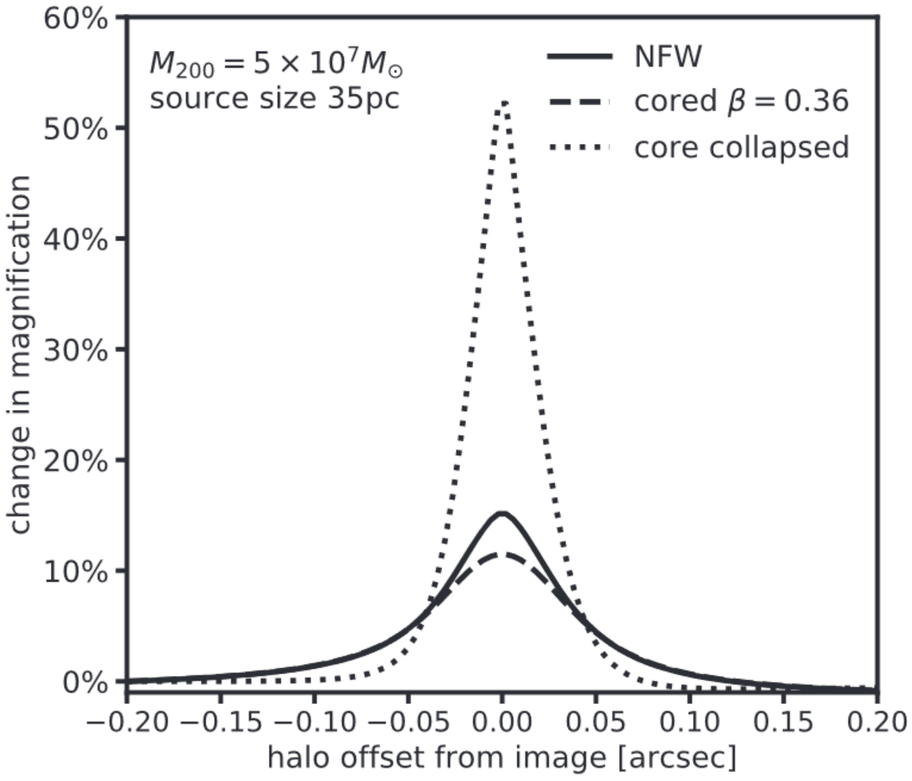
SIDM signature on flux-ratio anomaly signal



In SIDM: fewer small anomalies, but some very anomalous systems !



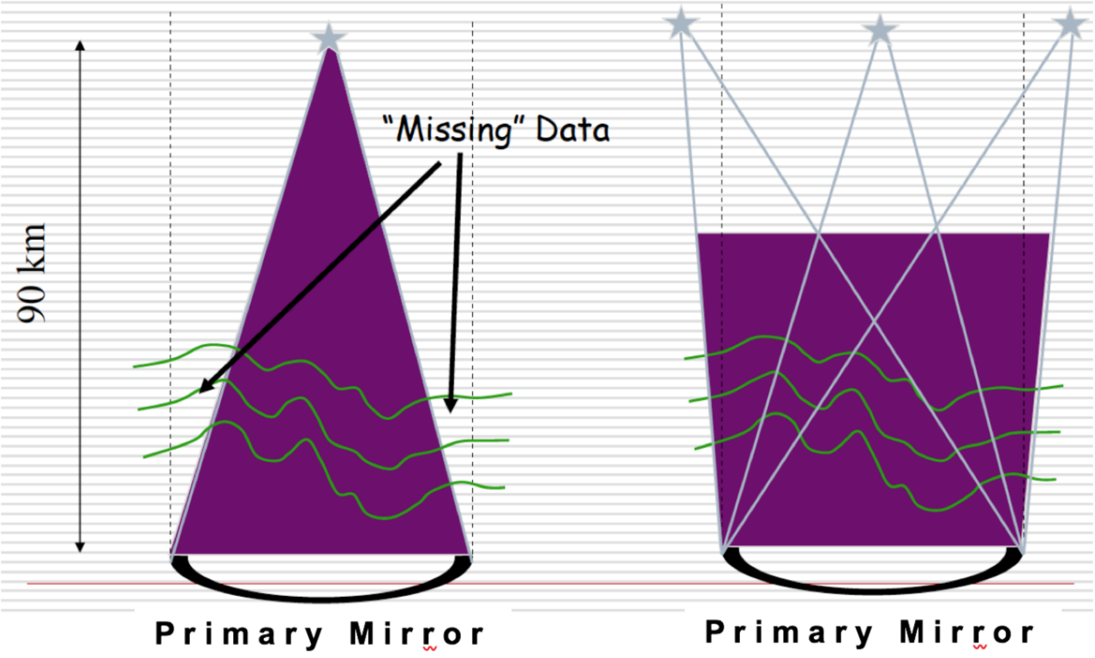
2) A fraction of halos undergo core-collapse



Credit: Gilman et al. (2022)

KAPA (**K**eck **A**ll-sky **P**recision **A**daptive-optics)

- Upgrade to Keck I AO (OSIRIS): NIR imaging & IFS
- Laser Tomography AO (LTAO) instead of single laser + other improvements



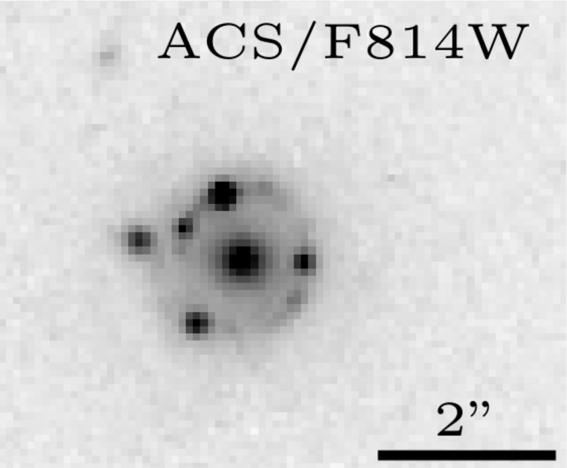
Side view (<u>Credit</u> : *Donald Gavel, Lick Observatory & UCSC CfAO)*

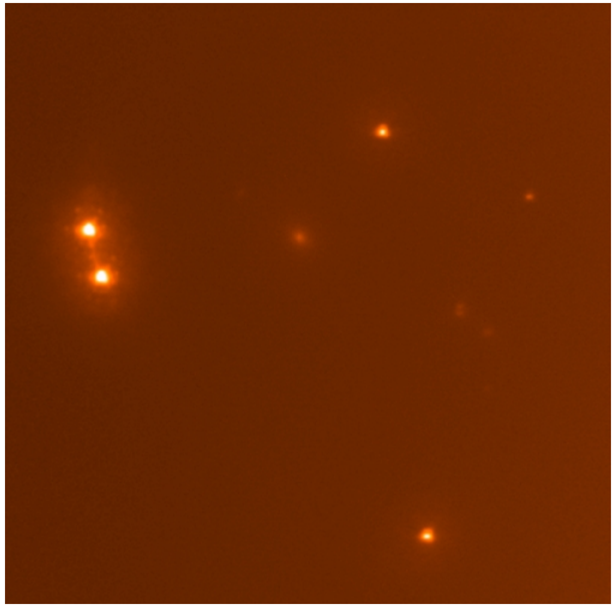
Should provide:
- higher Strehl
- more accurate PSFs
- more sky coverage
(can use fainter TT stars)

Imaging data from science verification runs (01/31)

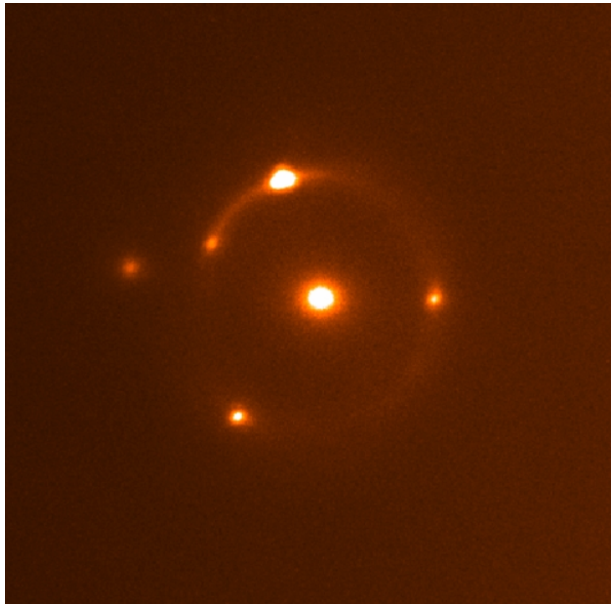
› Reduced data (combined frames)

(Credit : Dux et al. 2025)

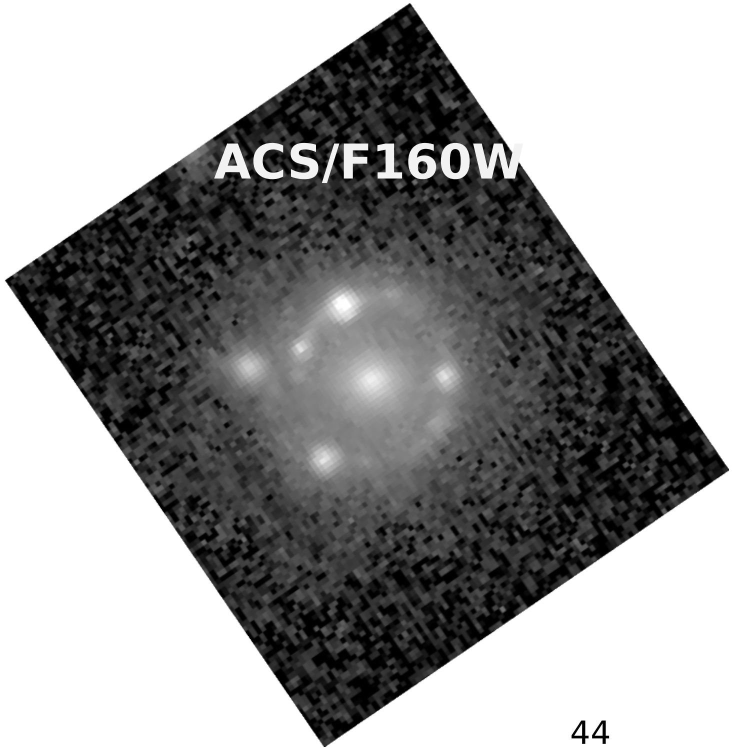




J0818-2613
(9 × 180s)



J0607-2152
(17 × 180s)

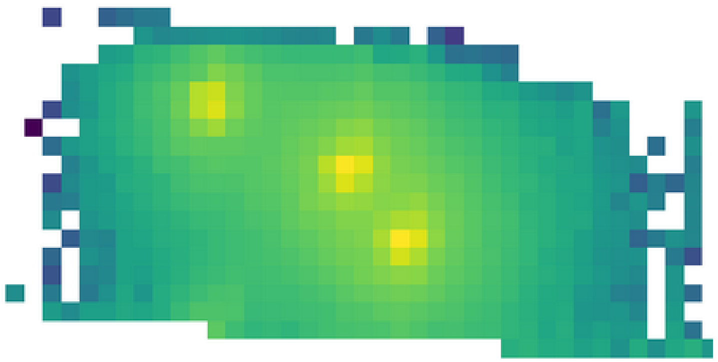


IFS data from science verification runs (02/28 + 03/04)

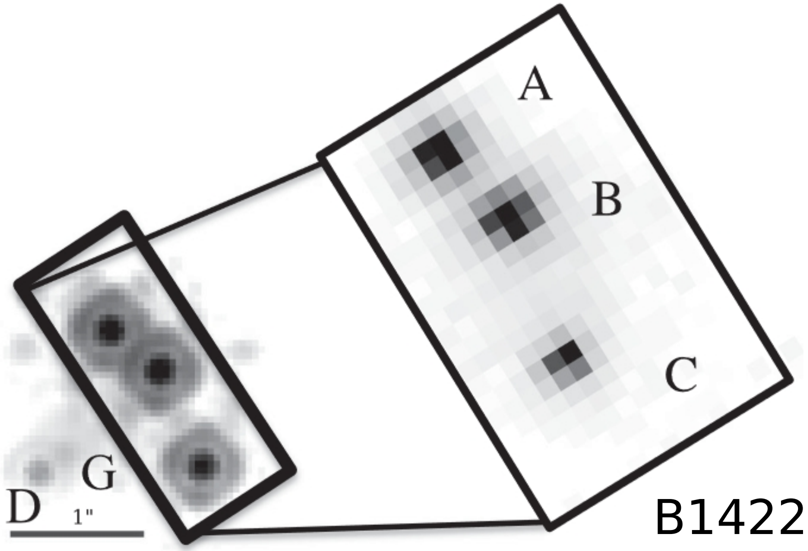
- 9x300s of good quality data for B1422+231

Lines (Hβ, [OIII] 5007) were visible in raw data

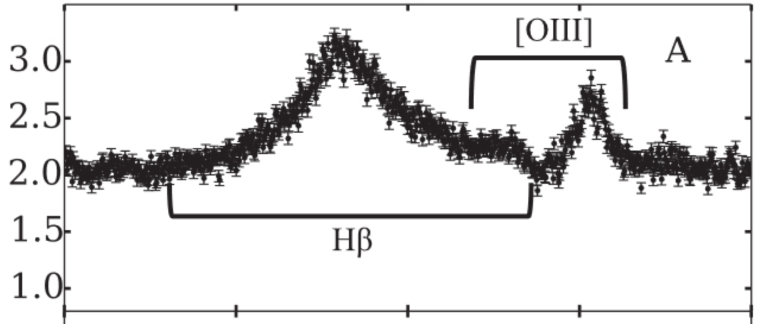
- Reduction in progress !



- Will be able to compare to pre-KAPA results



B1422+231



Credit: Nierenberg et al. (2014)