Warm dark matter chills out: constraints on the halo mass function and the free-streaming length of dark matter with 11 quadruple-image strong gravitational lenses

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[3] *Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101, USA*

To appear on arxiv…. tomorrow?

The LSST angle

(Oguri+Marshall 2010)

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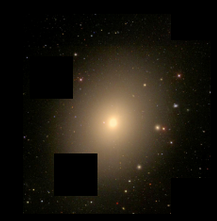
To appear on arxiv…. In 6 years?

What does dark matter look like on small-scales?

What we see

Cold Dark Matter

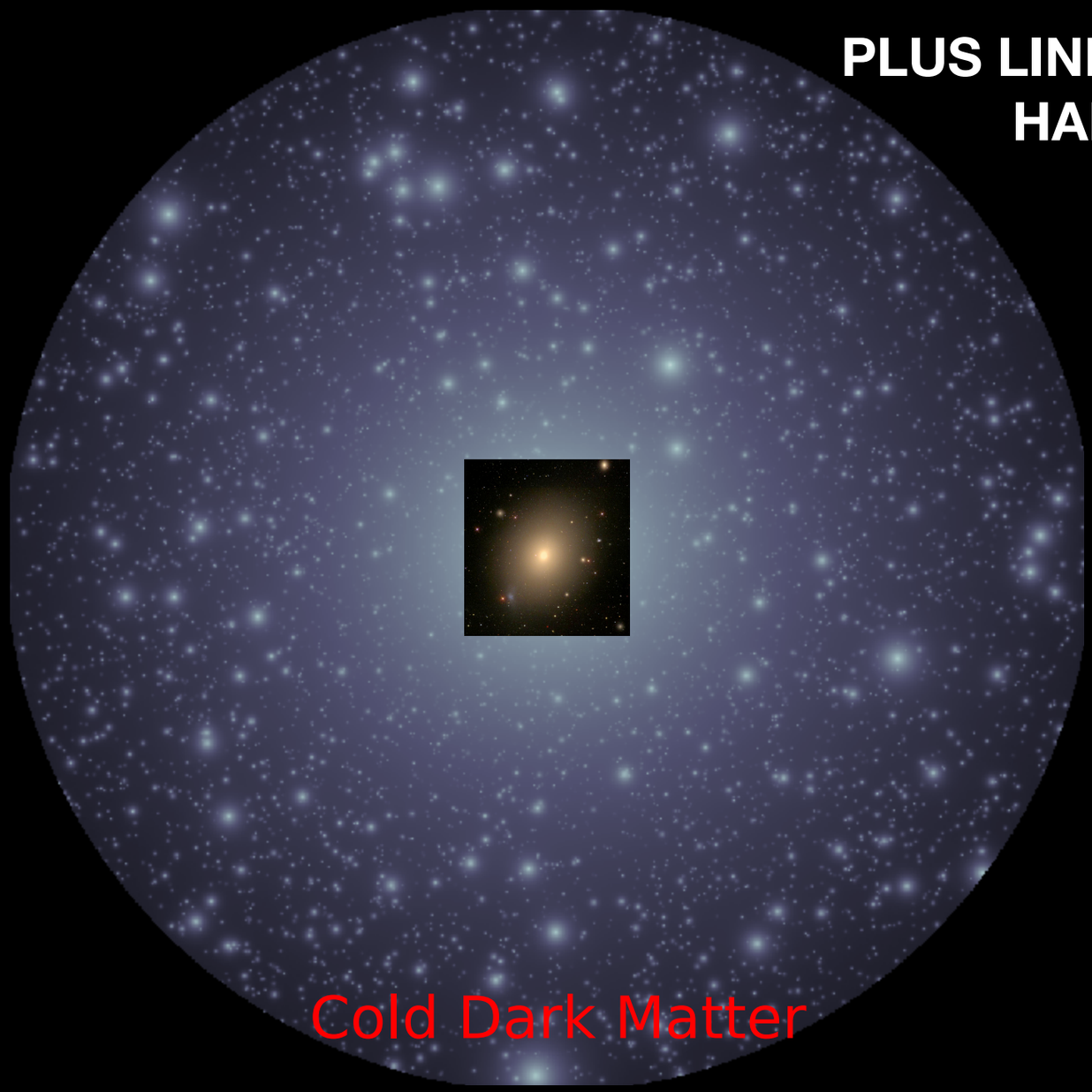


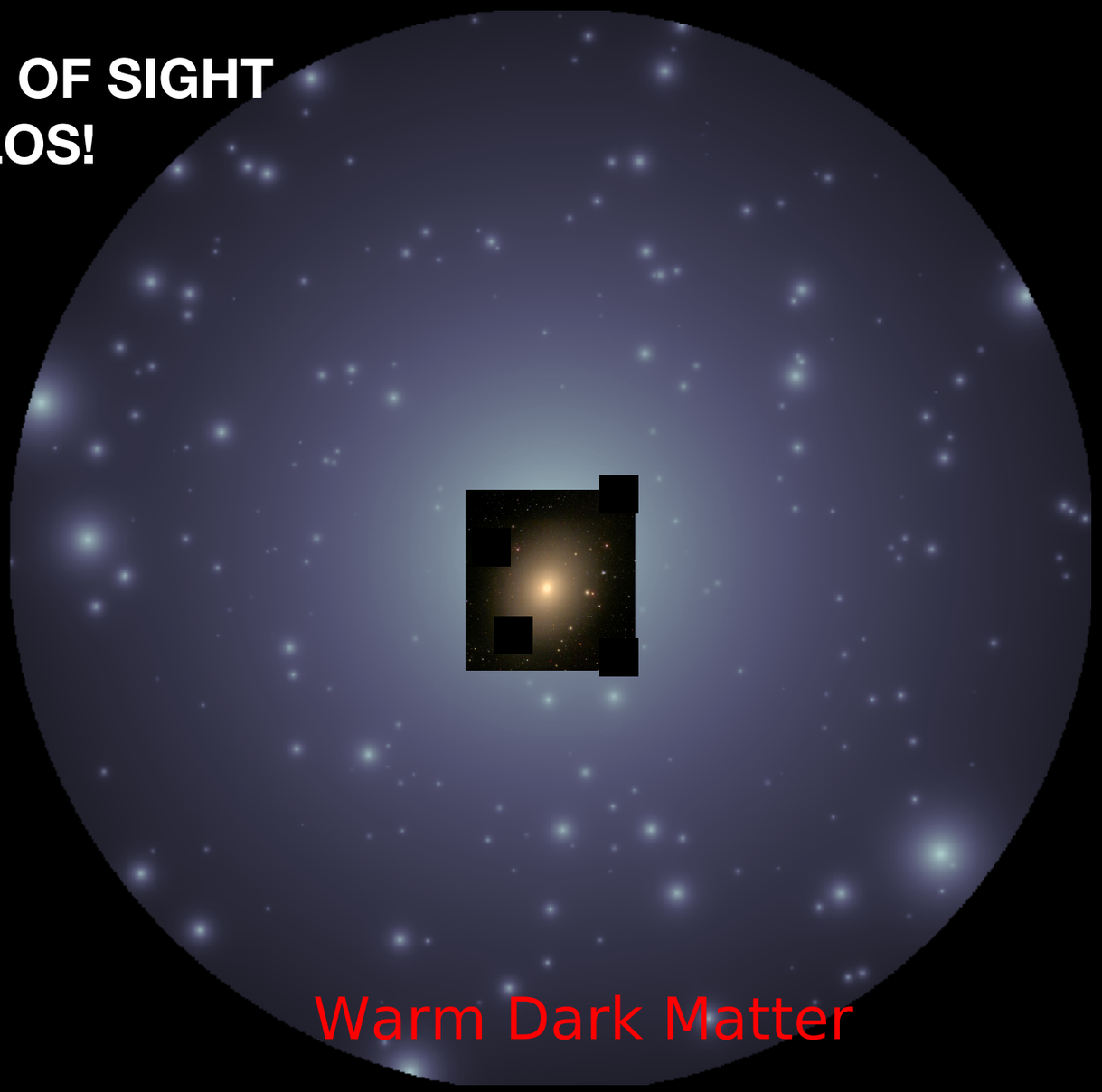
Warm Dark Matter

What does dark matter look like on small-scales?

What is (probably) there

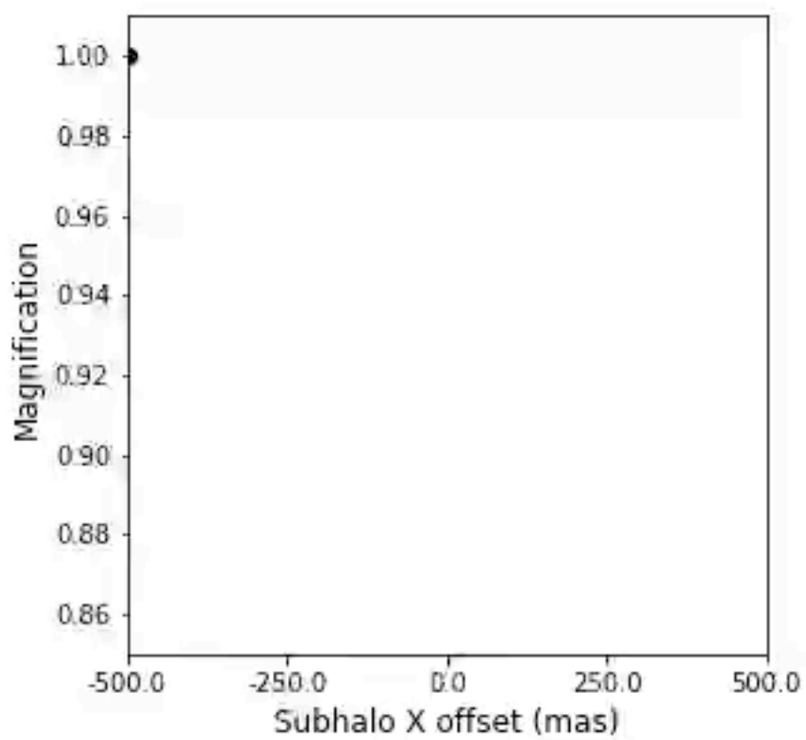
PLUS LINE OF SIGHT HALOS!

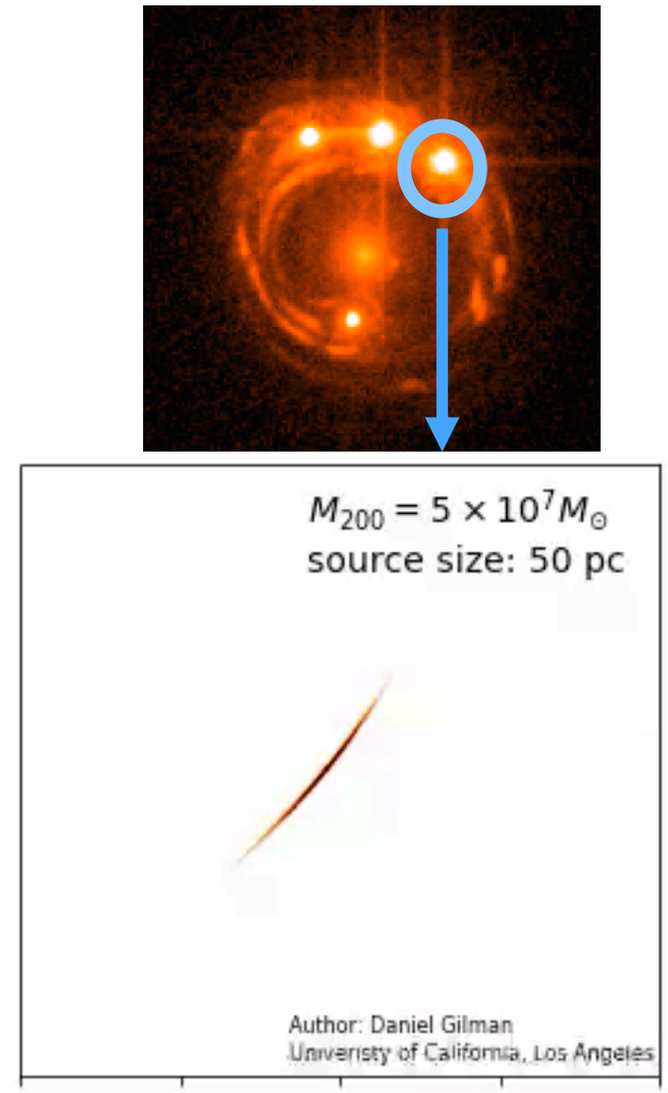




How can we tell left from right?

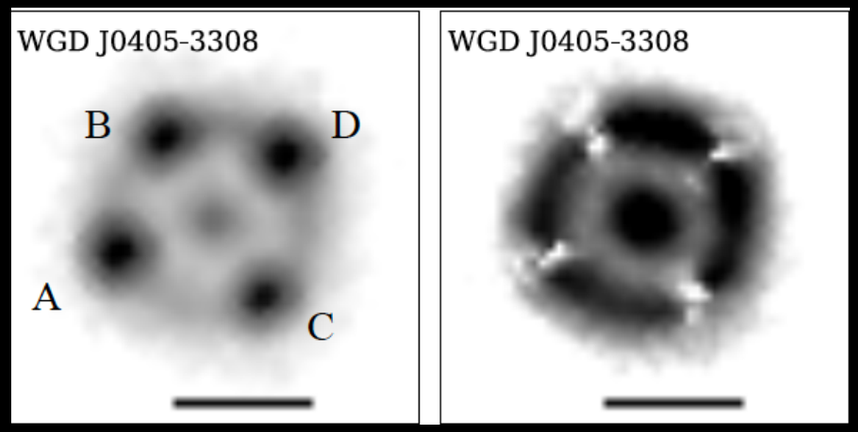
Quasar flux ratios -> an observable sensitive to halos M<10^8 solar masses



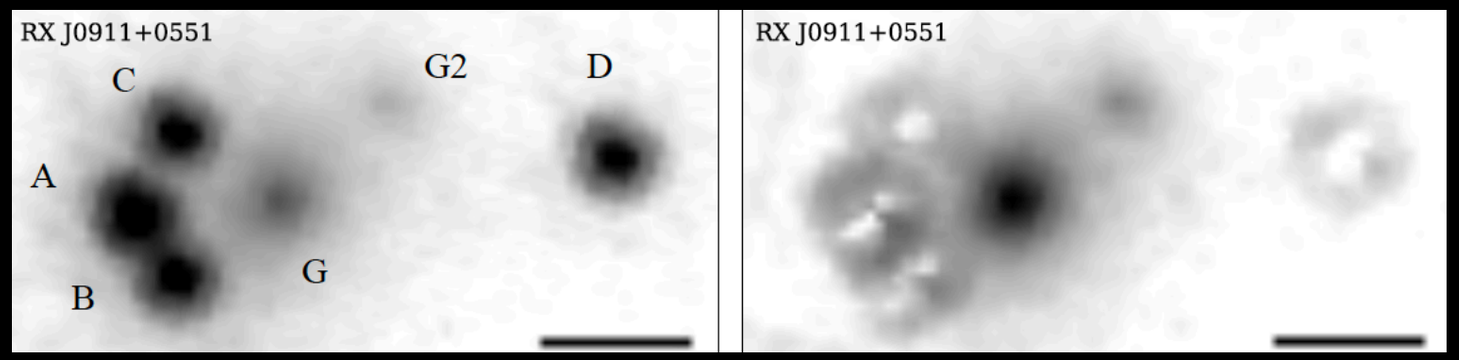


1) discuss our methodology and new constraints on CDM/WDM

2) time permitting, describe how to use quasar flux ratios to probe SIDM



Nierenberg, Gilman et al. (in prep)



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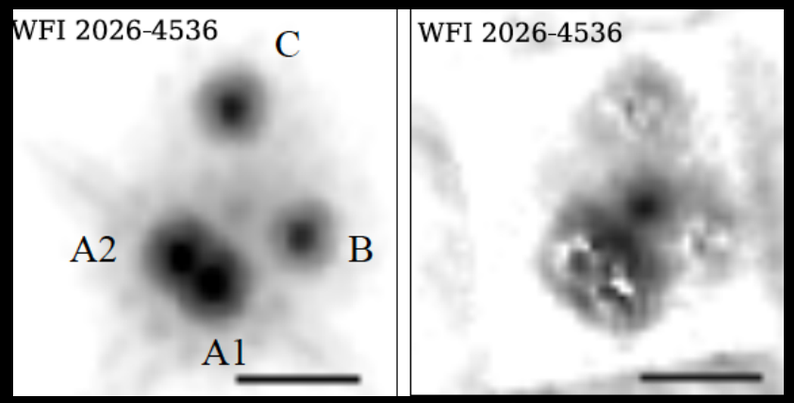

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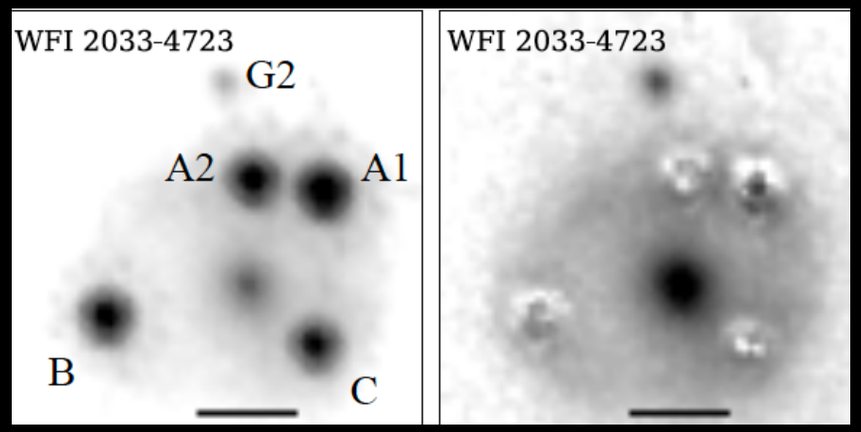

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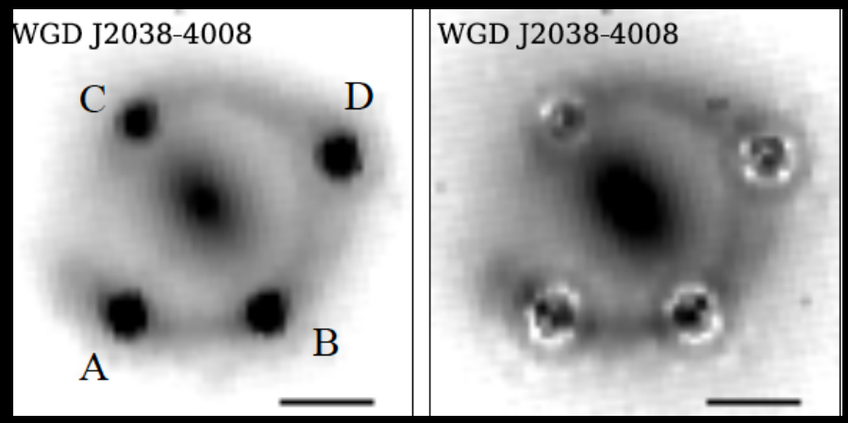
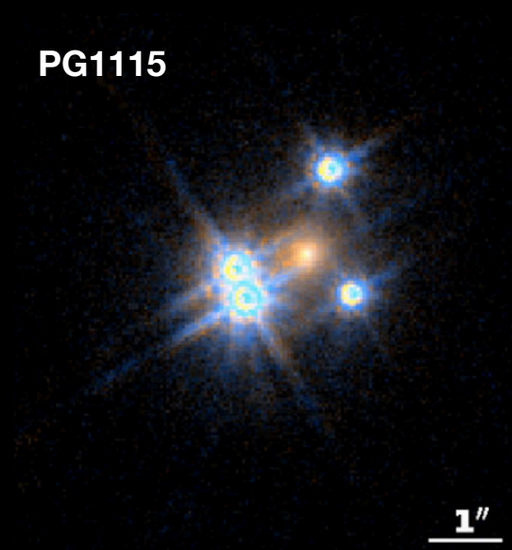
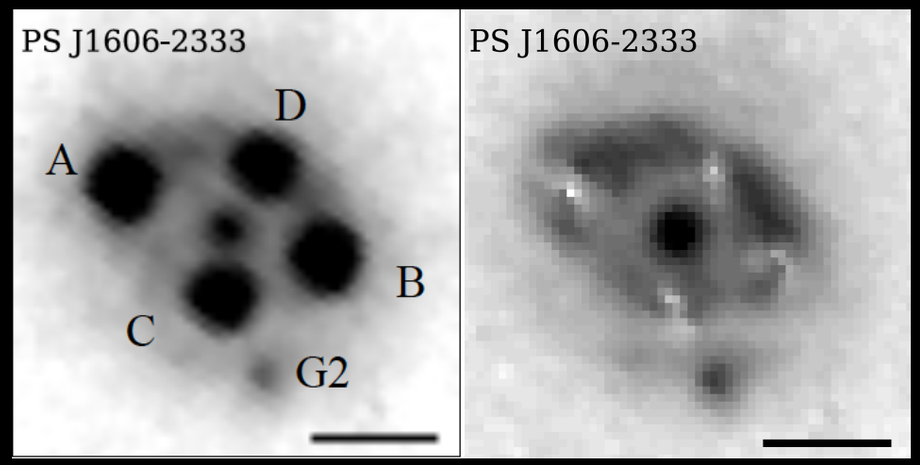


Nierenberg, Gilman et al. (in prep)

ESA/Hubble, NASA, Suyu et al.



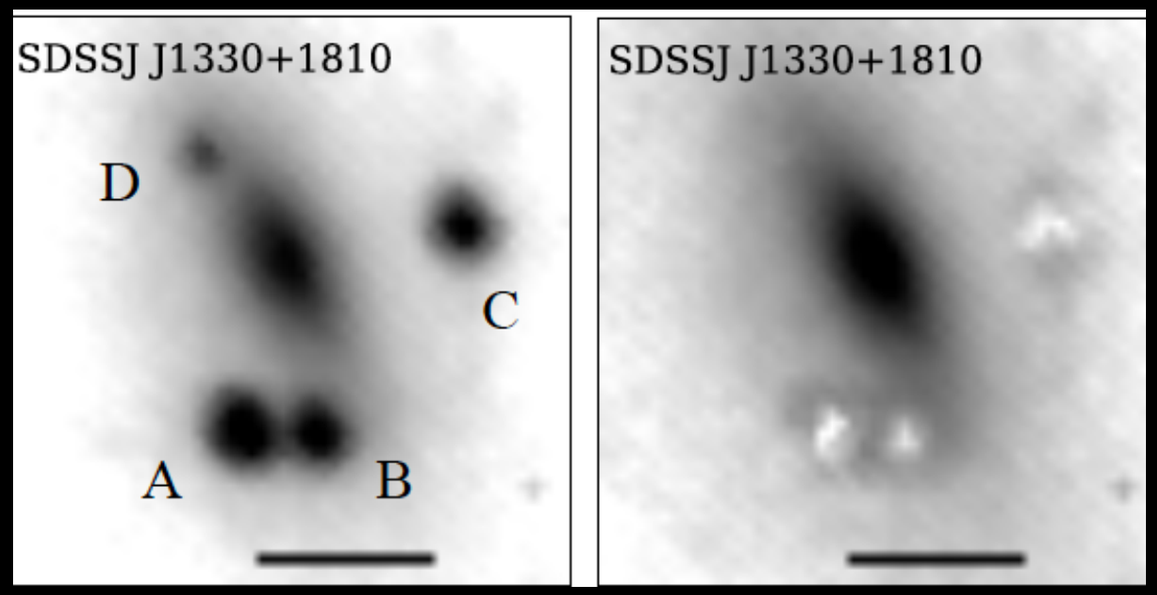
Lemon et al. 2017



Nierenberg, Gilman et al. (in prep)

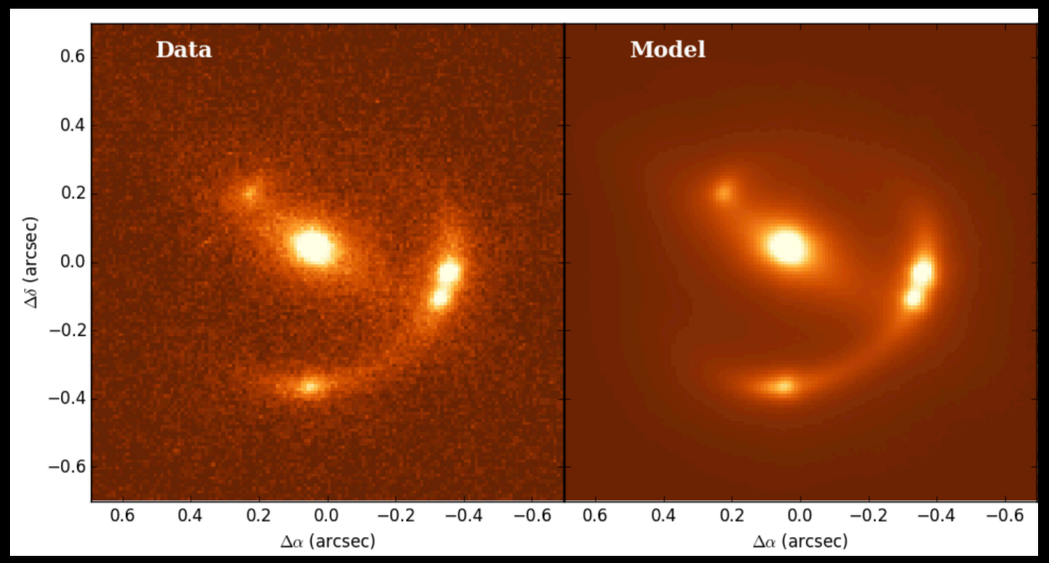
Plus 3 more for a total of 11

We exclude lenses with disks

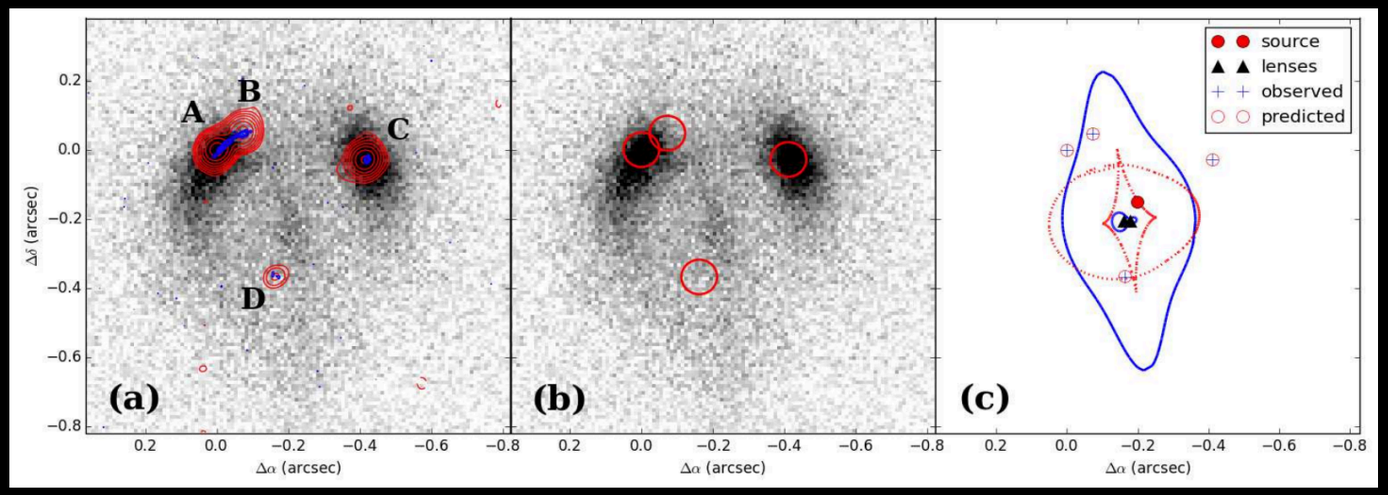


Nierenberg, Gilman et al. (in prep)

because they require explicit modeling



Hsueh et al. 2017



Hsueh et al. 2016

Our approach: likelihood-free inference with a forward model

1) Sample some proposed parameters from their priors

2) Using the proposed model, generate simulated data

3) Accepted the proposal q_s if

(simulated data) $\mathrm{d}'_{\mathrm{n}} = \mathrm{d}_{\mathrm{n}}$ (observed data)

The accepted q_s will be direct draws from the posterior.

Original idea: Rubin 1984

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Our approach: likelihood-free inference with a forward model

1) Sample some proposed q_s parameters from their priors

$$\pi\left(\mathbf{q}_{\mathrm{s}}\right)$$

2) Using the proposed model, generate simulated data

$$\mathbf{d}_{\mathrm{n}}' = \mathbf{d}_{\mathrm{n}}'\left(\mathbf{m}_{\mathrm{sub}}, \mathrm{M}\right)$$

3) Accepted the proposed parameters if

(simulated data) $\mathbf{d}_{\mathrm{n}}' = \mathbf{d}_{\mathrm{n}}$ (observed data)

The accepted proposals will be direct draws from the posterior.

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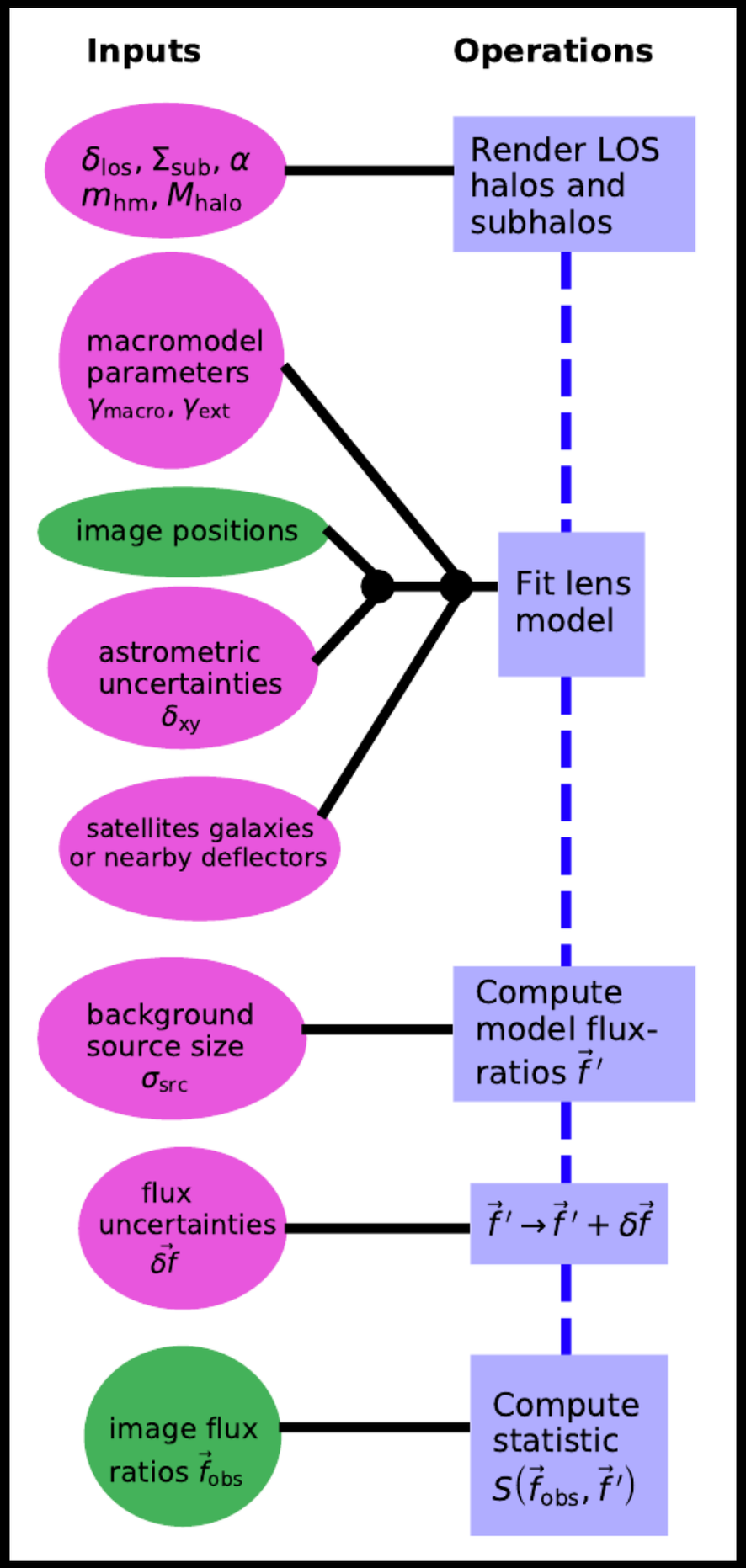
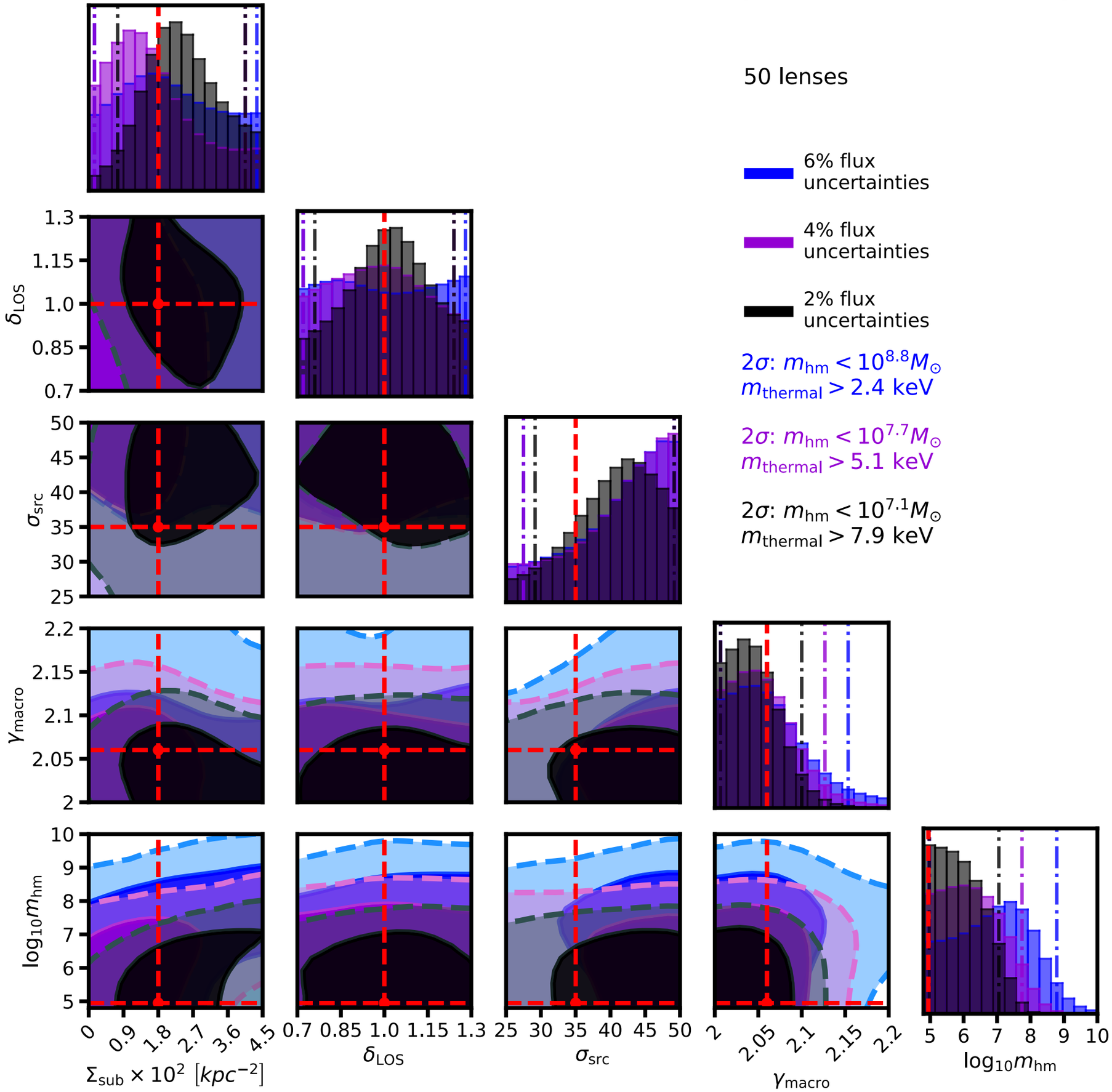

Inputs
Operations
δ_{los}, Σ_{sub}, α
m_{hm}, M_{halo}
Render LOS halos and subhalos
macromodel parameters
γ_{macro}, γ_{ext}
image positions
astrometric uncertainties
δ_{xy}
satellites galaxies or nearby deflectors
Fit lens model
background source size
σ_{src}
Compute model flux-ratios $\vec{f}'$
flux uncertainties
$\delta\vec{f}$
$\vec{f}' \rightarrow \vec{f}' + \delta\vec{f}$
image flux ratios $\vec{f}_{obs}$
Compute statistic
$S(\vec{f}_{obs}, \vec{f}')$

We have tested this on simulated data (Gilman et al. 2019)



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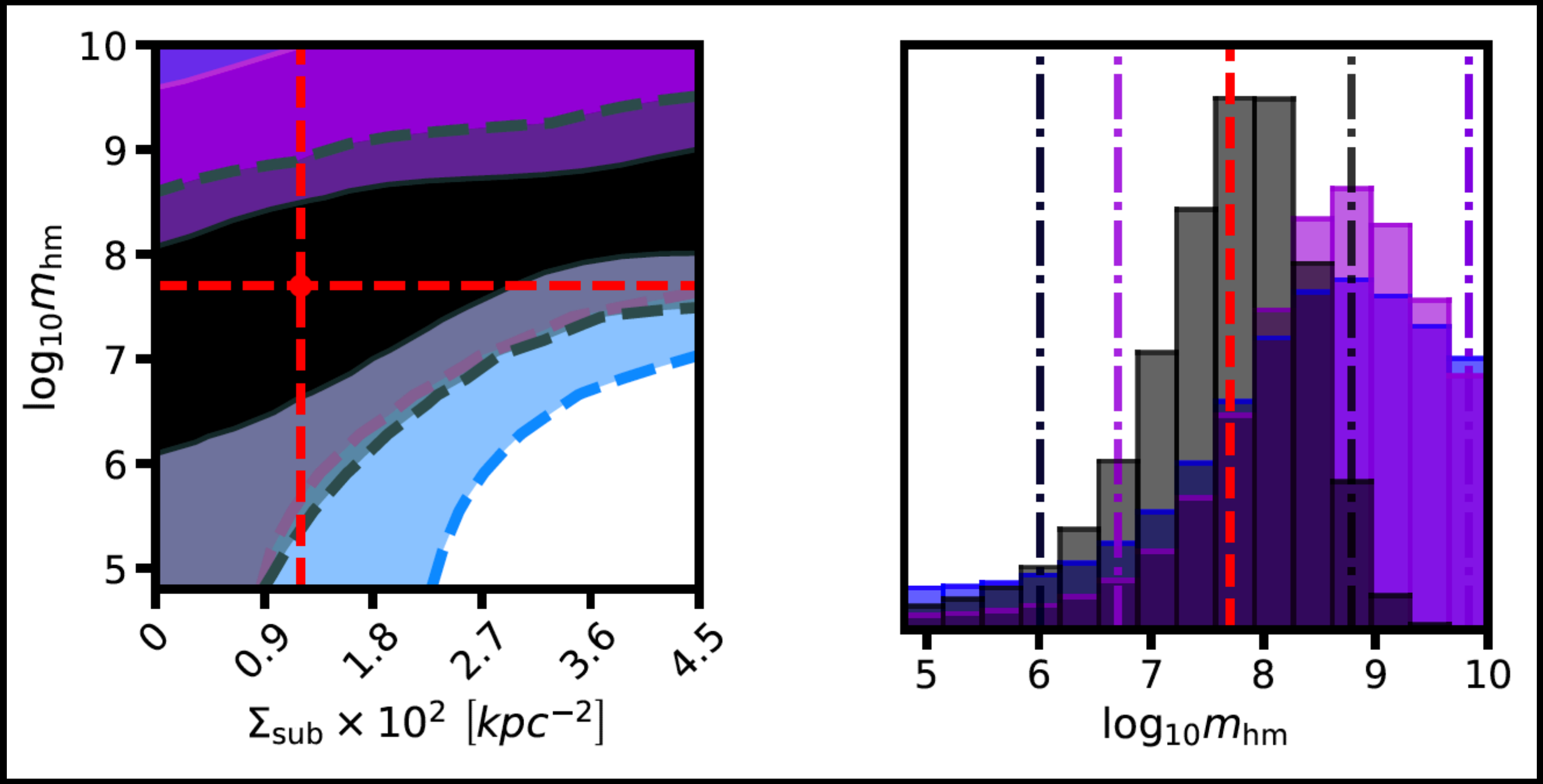


Modeling the dark matter component

Subhalo density profiles:

$$\rho(r) = \frac{\rho_s}{x(1+x)^2} \frac{\tau^2}{x^2+\tau^2}$$

(mass definition: M_200 w.r.t. critical density @z=0)

Subhalo mass function:

$$\frac{d^2 N_{\rm sub}}{dm dA} = \frac{\Sigma_{\rm sub}}{m_0}\left(\frac{m}{m_0}\right)^{\alpha} \mathcal{F}(M_{\rm halo}, z)$$

Evolution of SHMF w/halo mass, redshift

$$\log_{10}(\mathcal{F}) = k_1 \log_{10}\left(\frac{M_{\rm halo}}{10^{13} M_\odot}\right) + k_2 \log_{10}(z+0.5)$$

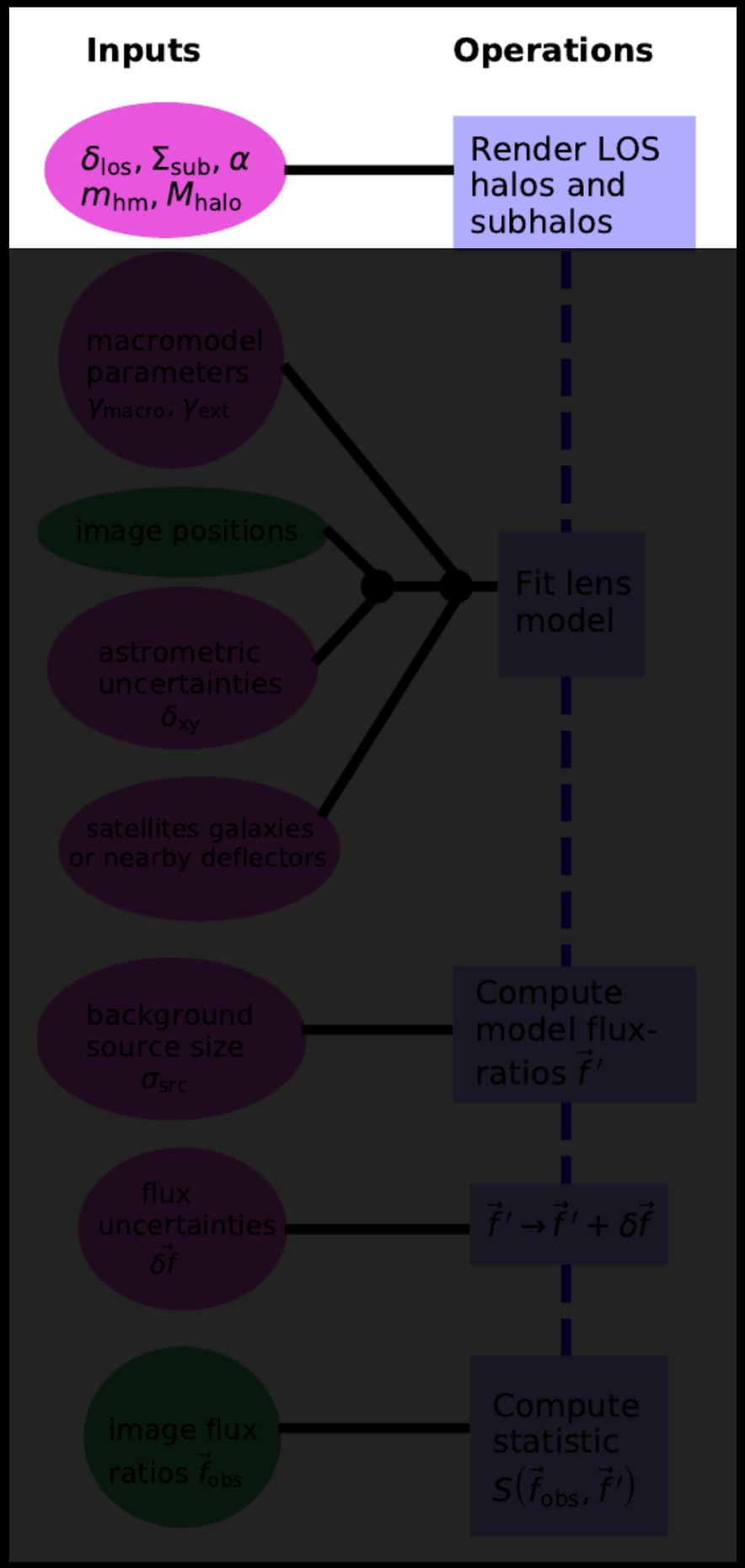
$\Sigma_{\rm sub}$ **Normalization of SHMF (common to all lenses)**

$\mathcal{U}(0, 0.1)$

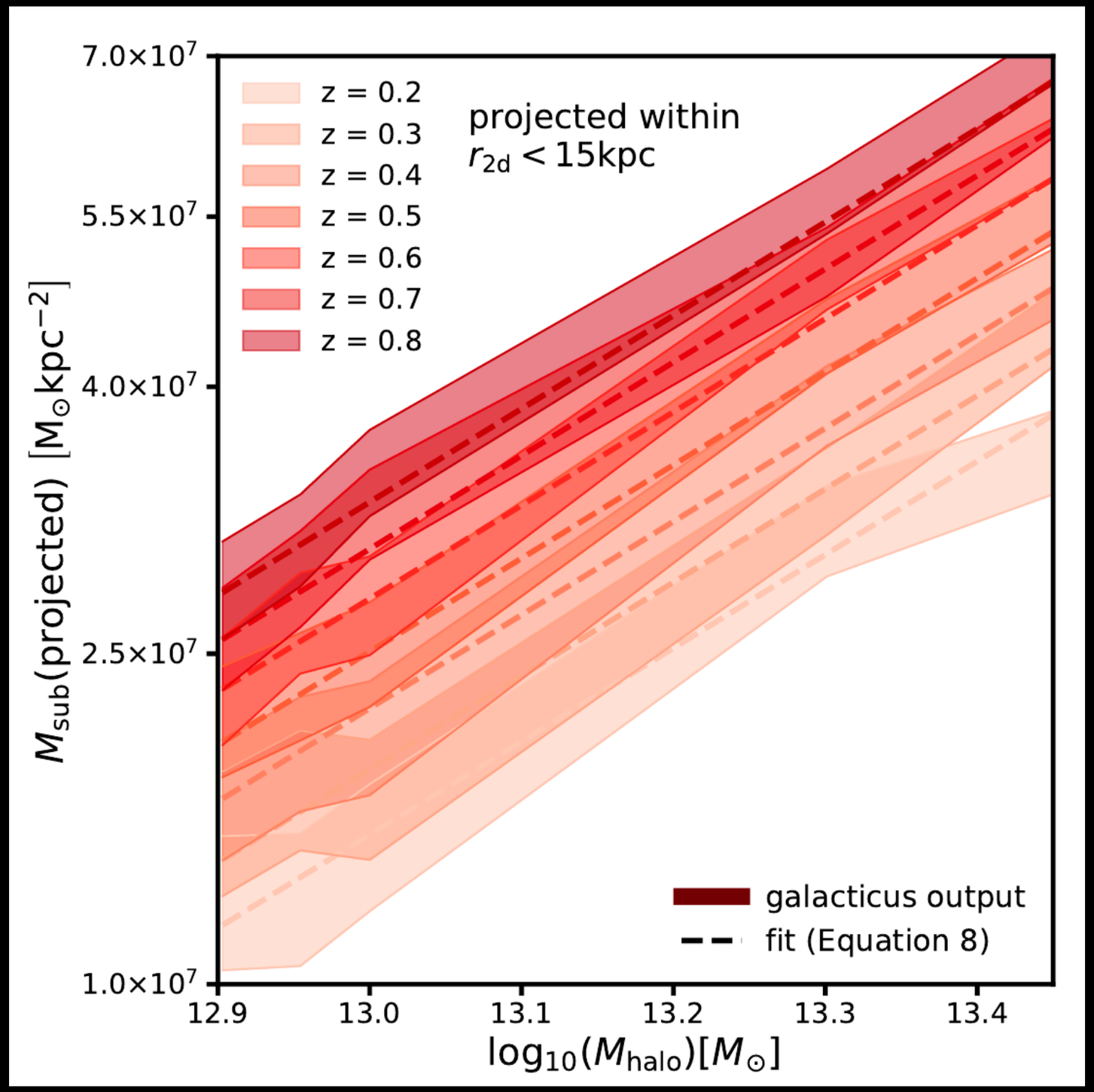
α **Slope of SHMF (common to all lenses)**

$\mathcal{U}(-1.95, -1.85)$

$M_{\rm halo}$ **Parent halo mass (lens-specific). Priors constructed from stellar-mass/virial-mass ratio (Lagattuta et al. 2010)**



Evolution of the (projected) subhalo mass function w/halo mass, redshift
Calibrated using the 'galacticus' semi-analytic model (Benson 2012)



$$\log_{10}(\mathcal{F}) = k_1 \log_{10}\left(\frac{M_{\rm halo}}{10^{13} M_\odot}\right) + k_2 \log_{10}(z + 0.5)$$

Modeling the dark matter component

Line of sight halo mass function

$$\frac{d^2 N_{\rm los}}{dm dV} = \delta_{\rm los}\left(1 + \xi_{\rm 2halo}\left(M_{\rm halo}, z\right)\right) \frac{d^2 N}{dm dV}\Big|_{\rm ShethTormen}$$

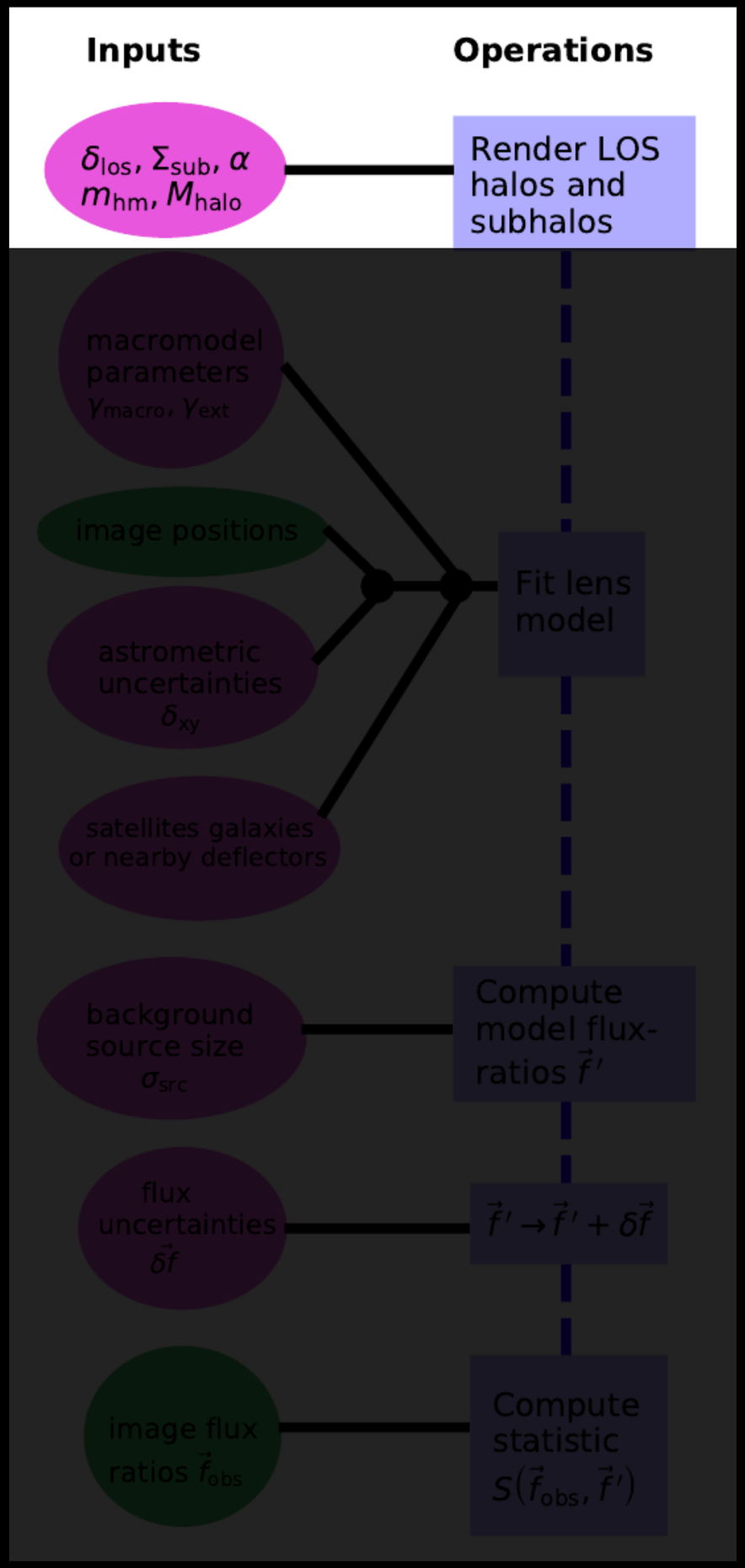
$$\xi_{\rm 2halo}\left(M_{\rm halo}, z\right)$$

Two-halo term, accounts for correlated structure around main deflector

$\delta_{\rm los}$

Normalization of line of sight halo mass function (common to all lenses)

$\mathcal{U}\left(0.8, 1.2\right)$



Modeling the dark matter component

WDM free-streaming effects on the mass function

$$\frac{dN_{\rm WDM}}{dm} = \frac{dN_{\rm CDM}}{dm}\left(1+\frac{m_{\rm hm}}{m}\right)^{-1.3}$$

(Lovell et al. 2014)

$$m_{\rm hm}\left(m_{\rm DM}\right) = 3\times 10^{8}\left(\frac{m_{\rm DM}}{3.3{\rm keV}}\right)^{-3.33} M_{\odot}$$

WDM free-streaming effects on the mass-concentration relation

$$\frac{c_{\rm WDM}\left(m,z\right)}{c_{\rm CDM}\left(m,z\right)} = \left(1+z\right)^{\beta(z)}\left(1+60\frac{m_{\rm hm}}{m}\right)^{-0.17}$$

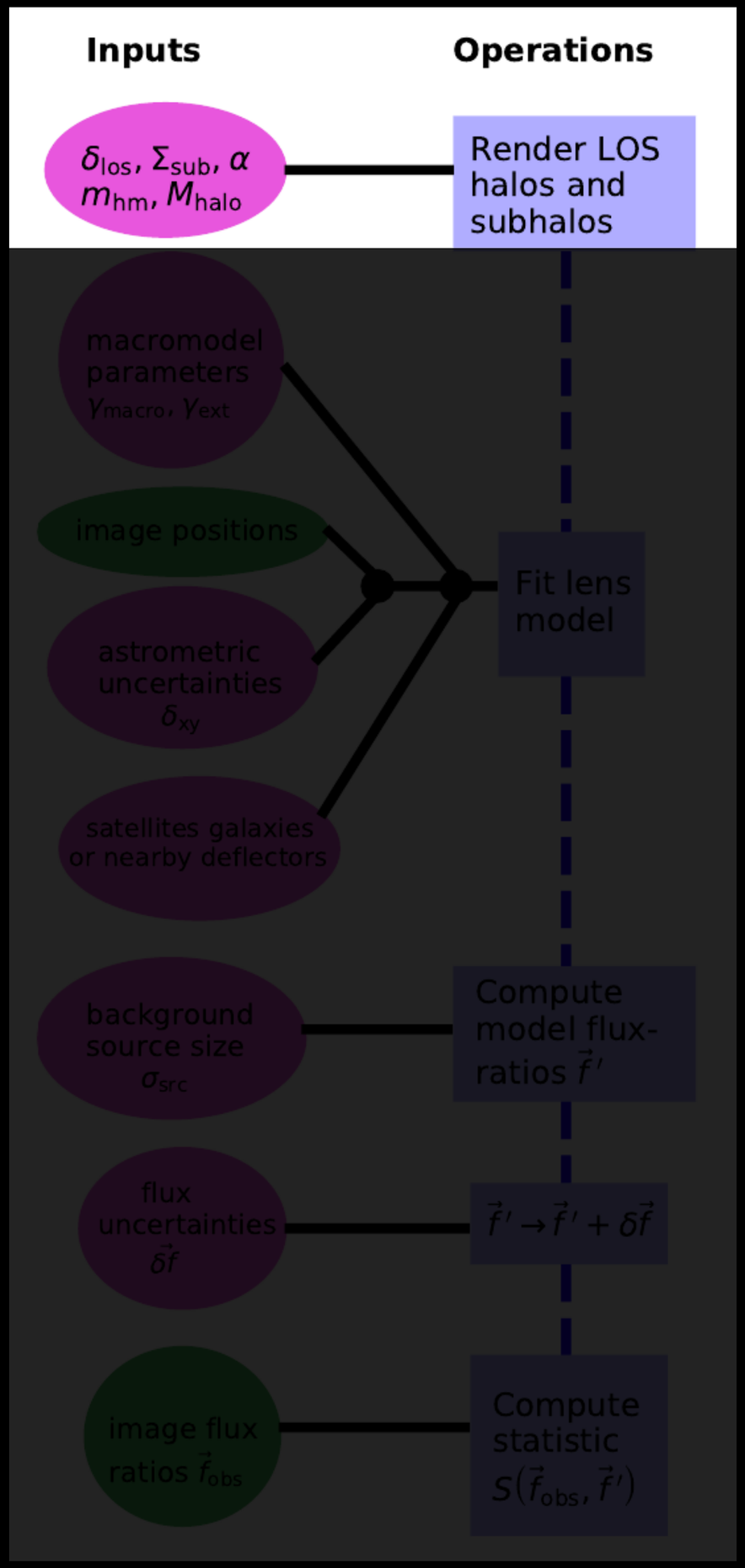
(Bose et al. 2016)

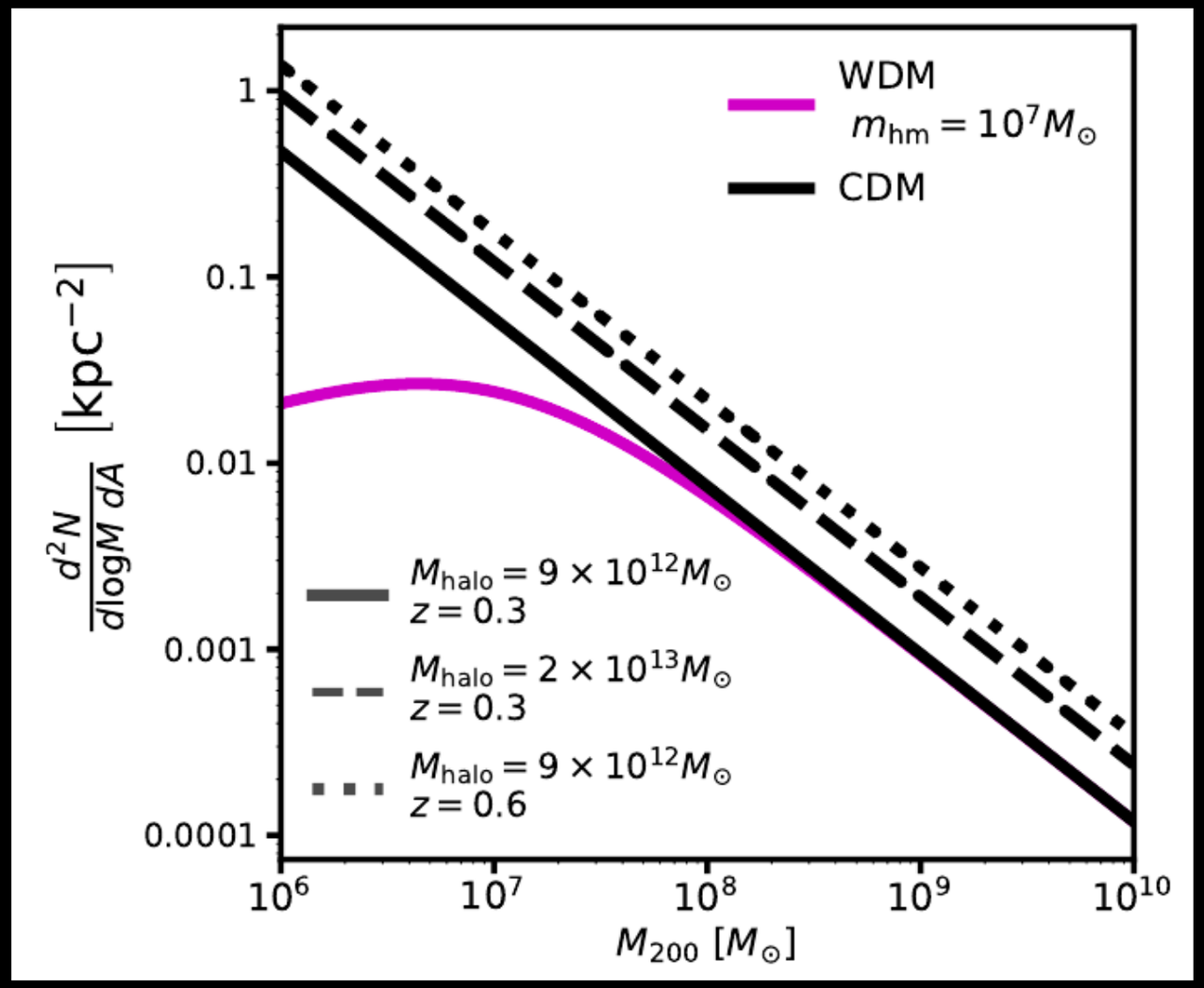
CDM mass concentration relation from Diemer et al. 2019

$m_{\rm hm}$

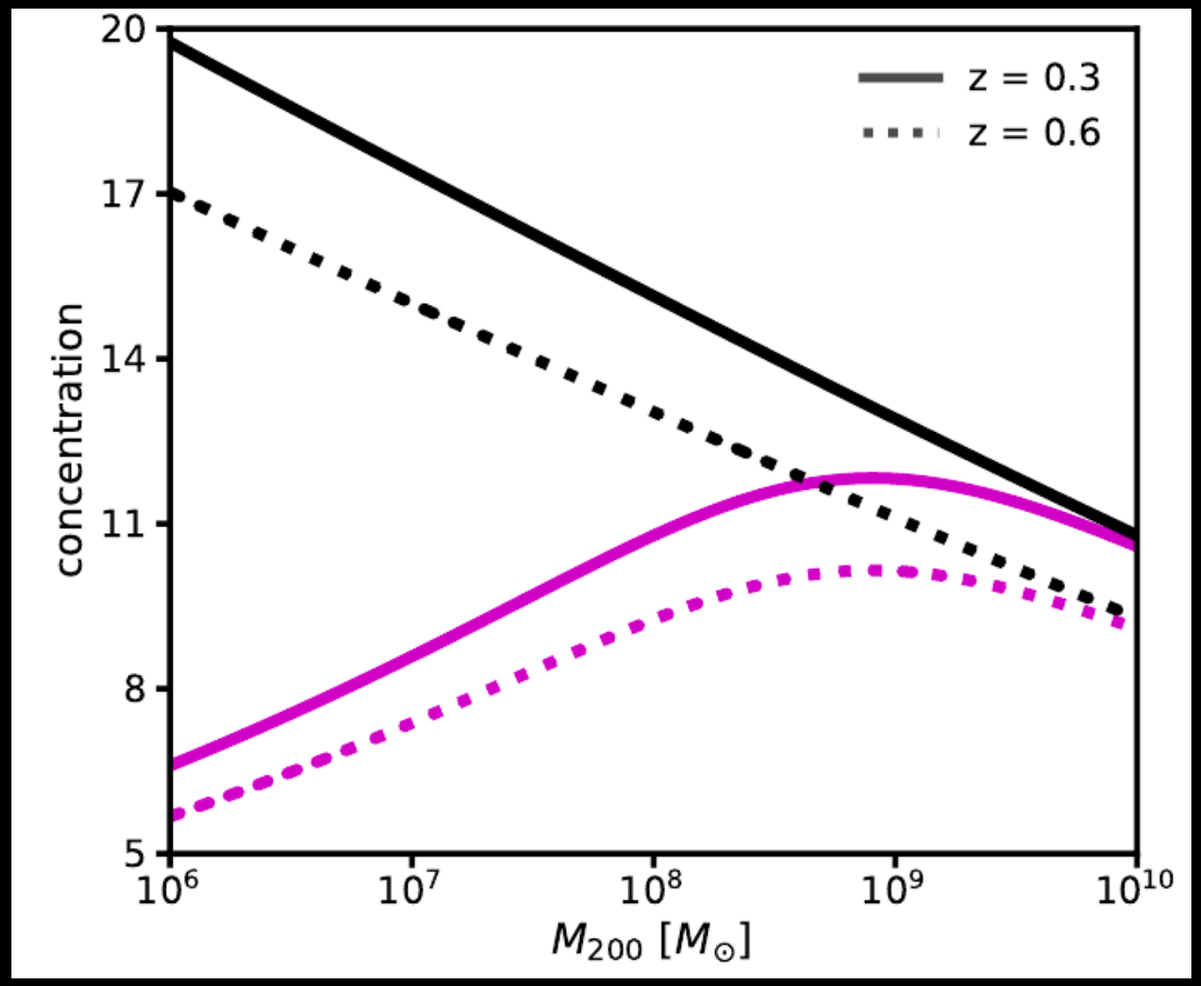
Half-mode mass (common to all lenses)

$\mathcal{U}\left(4.8, 10\right)$ **(log-uniform)**

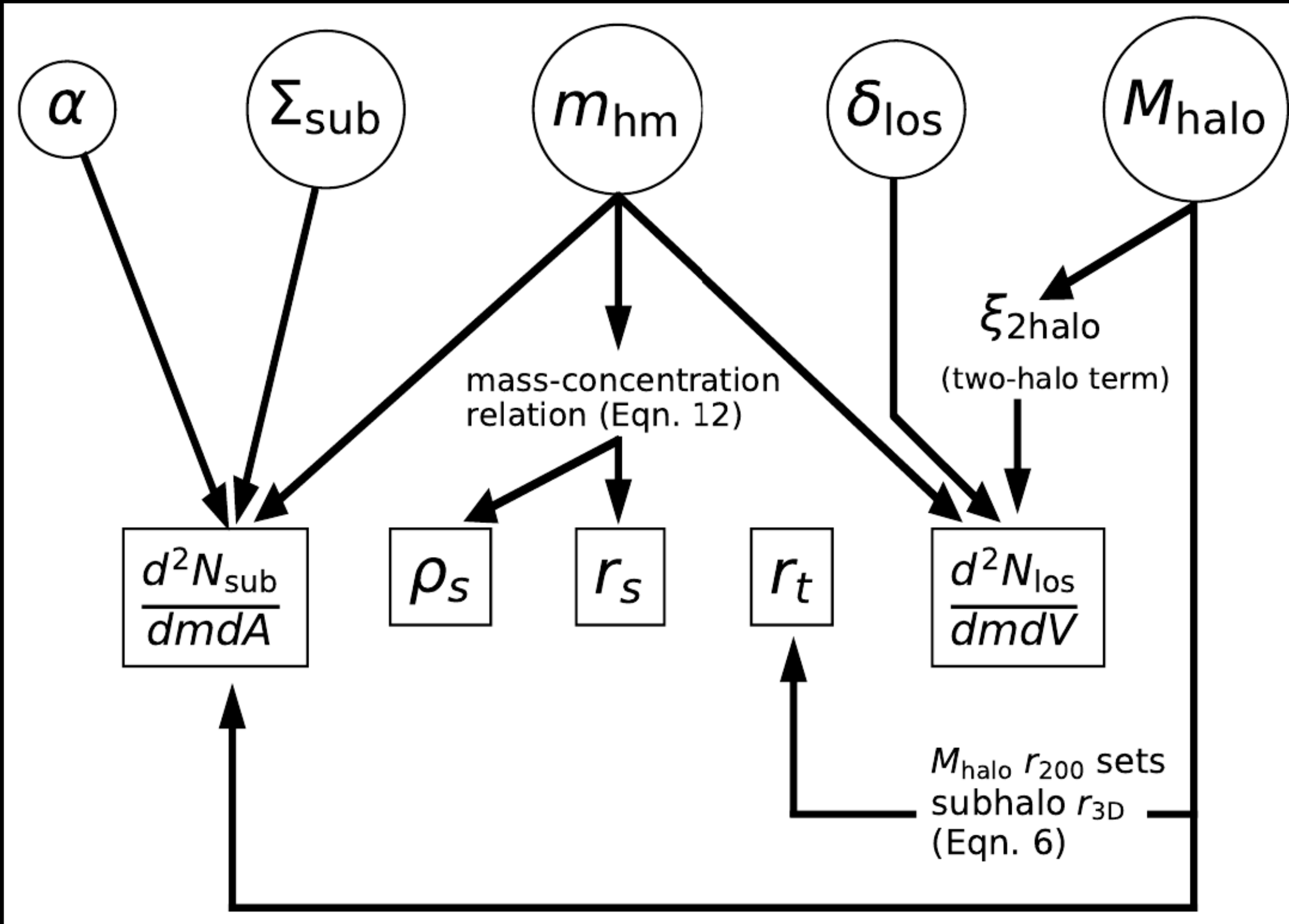




Left: subhalo mass function



Right: mass-concentration relation


α
$\Sigma_{\rm sub}$
$m_{\rm hm}$
$\delta_{\rm los}$
$M_{\rm halo}$
$\xi_{\rm 2halo}$
(two-halo term)
mass-concentration relation (Eqn. 12)
$\frac{d^2N_{\rm sub}}{dmdA}$
ρ_s
r_s
r_t
$\frac{d^2N_{\rm los}}{dmdV}$
$M_{\rm halo}$ r_{200} sets subhalo $r_{\rm 3D}$ (Eqn. 6)

Gravitational lensing

Challenge: Dimensionality still an issue, particularly for image positions

Solution: Use a lens model that is guaranteed to fit the image positions

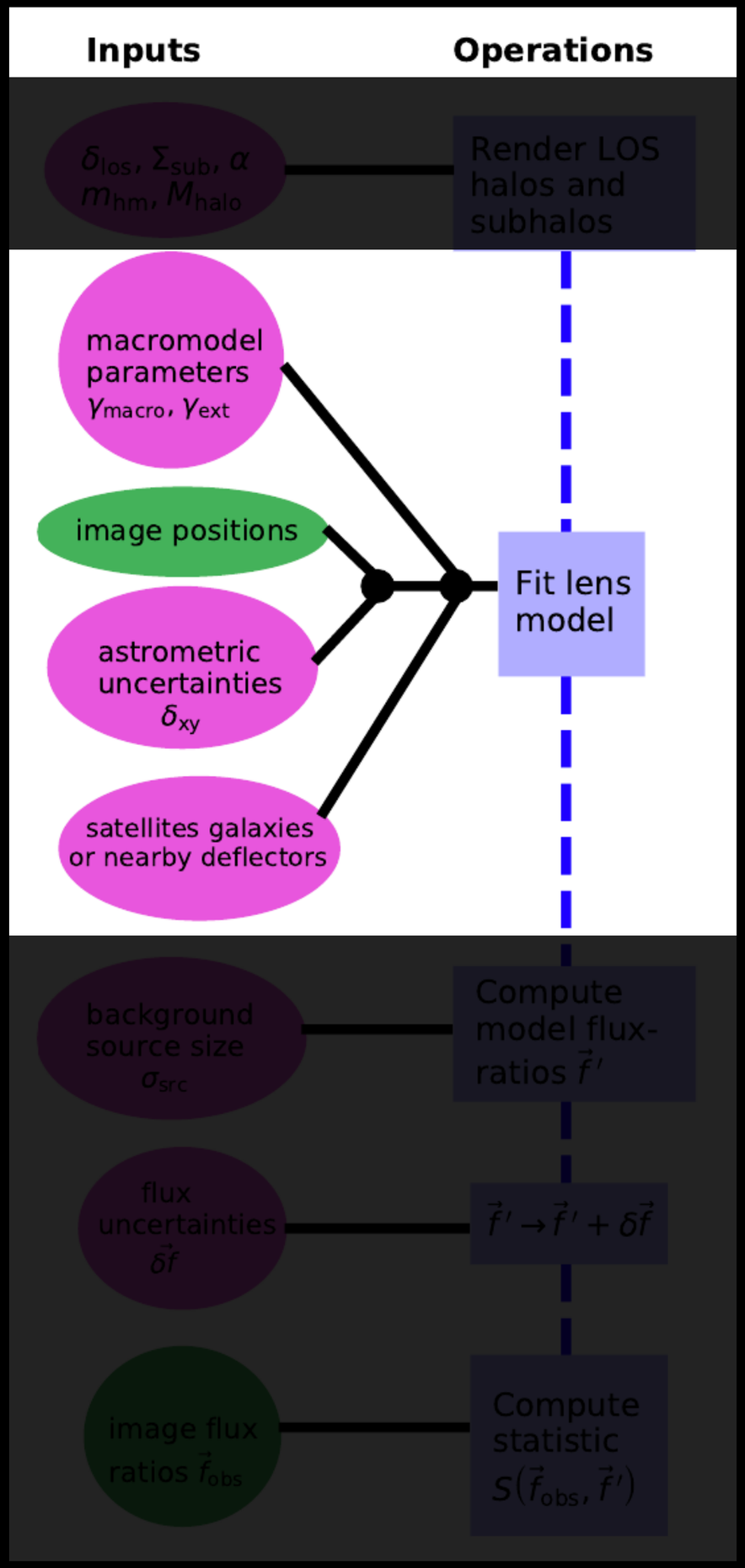
Solve for the set of macromodel parameters that satisfy the full multi-plane lens equation

$$\boldsymbol{\beta}_{\boldsymbol{K}} = \boldsymbol{\theta} - \frac{1}{D_{\mathrm{s}}} \sum_{k=1}^{K-1} D_{\mathrm{ks}} \boldsymbol{\alpha}_{\mathbf{k}} \left(D_{\mathrm{k}} \boldsymbol{\beta}_{\mathbf{k}} \right)$$

γ_{macro} Slope of main deflector mass profile (lens-specific)

$\mathcal{U}\,(1.95, 2.2)$

γ_{ext} External shear strength (lens-specific)

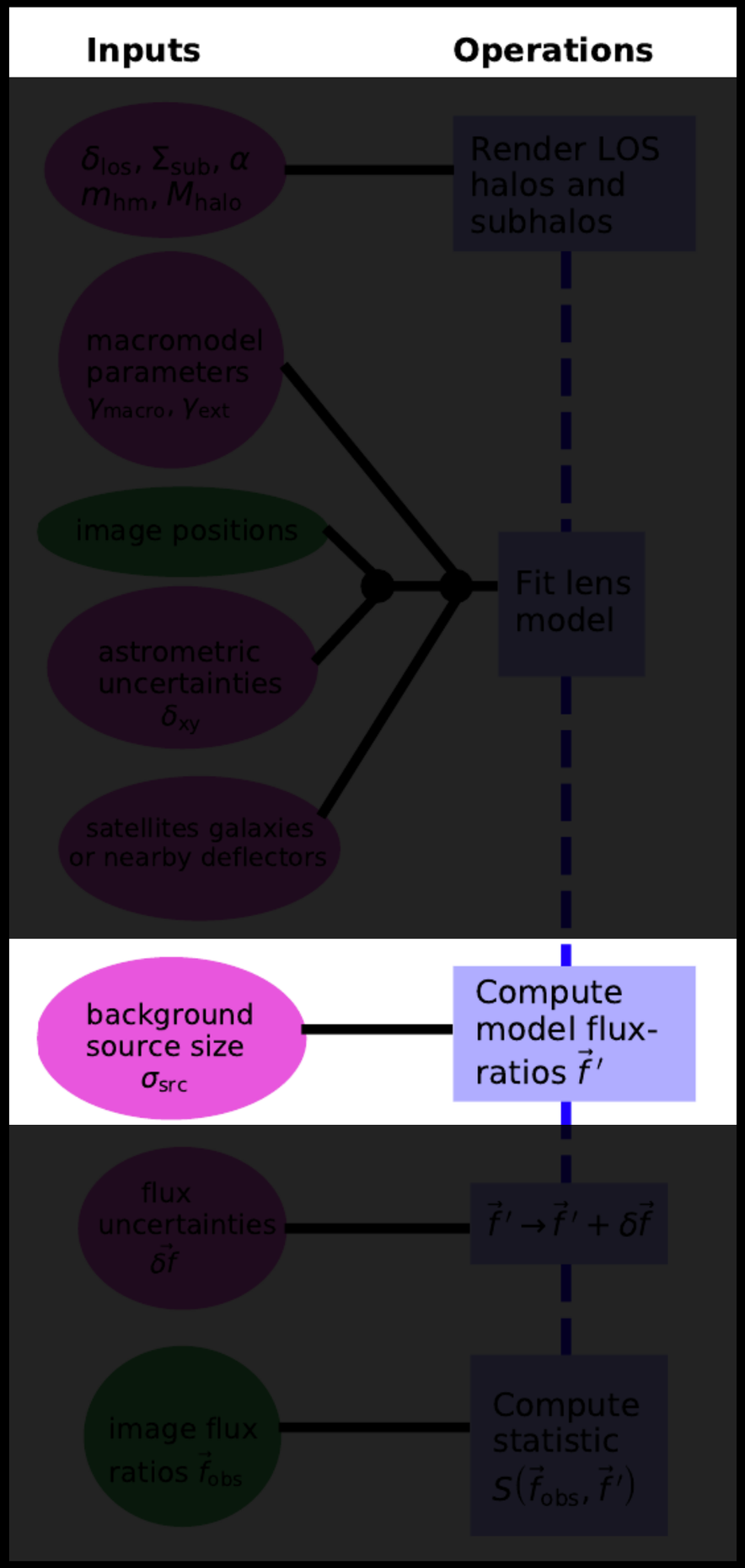


Extended background sources

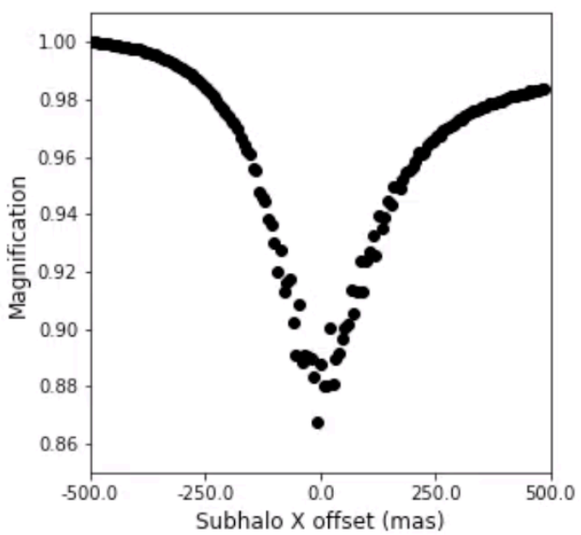
1) Sample a source size from a prior

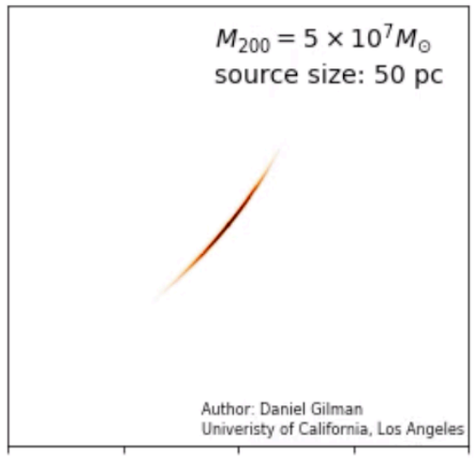
2) Use the multi-plane lens equation to compute the magnification with the extended background source

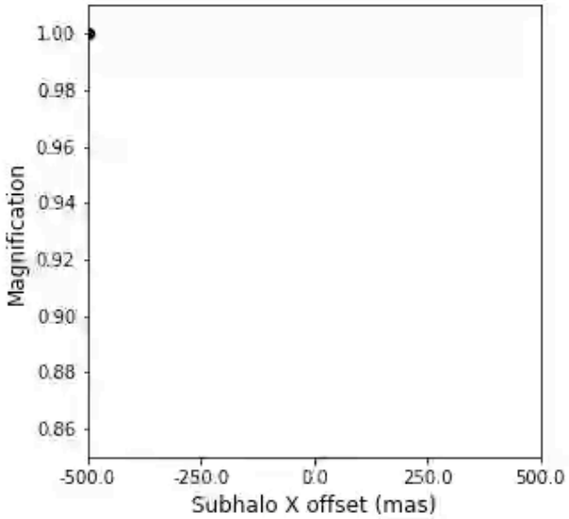
Why does this matter?

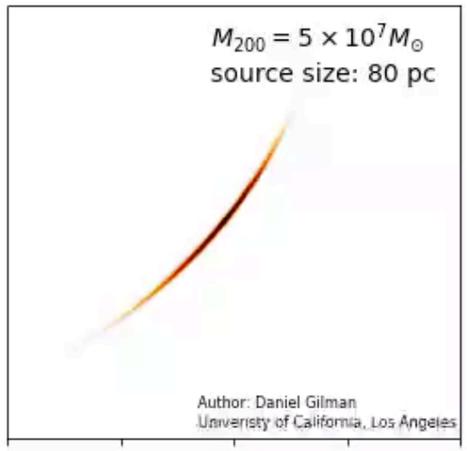


Model-predicted image magnification depends on source size on the relevant scales of 10^6 - 10^9





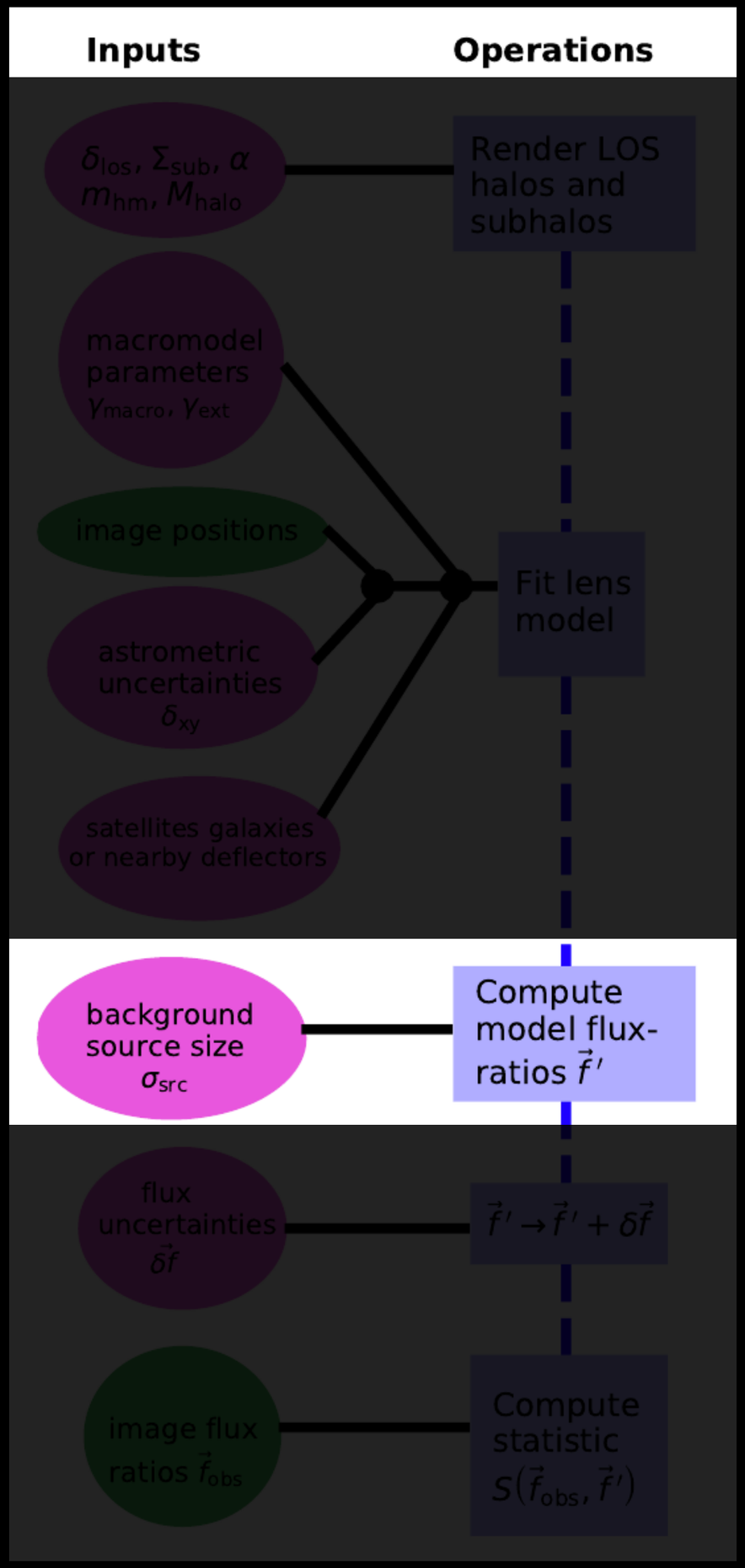




Extended background sources

1) Sample a source size from a prior

2) Use the multi-plane lens equation to compute the magnification with the extended background source



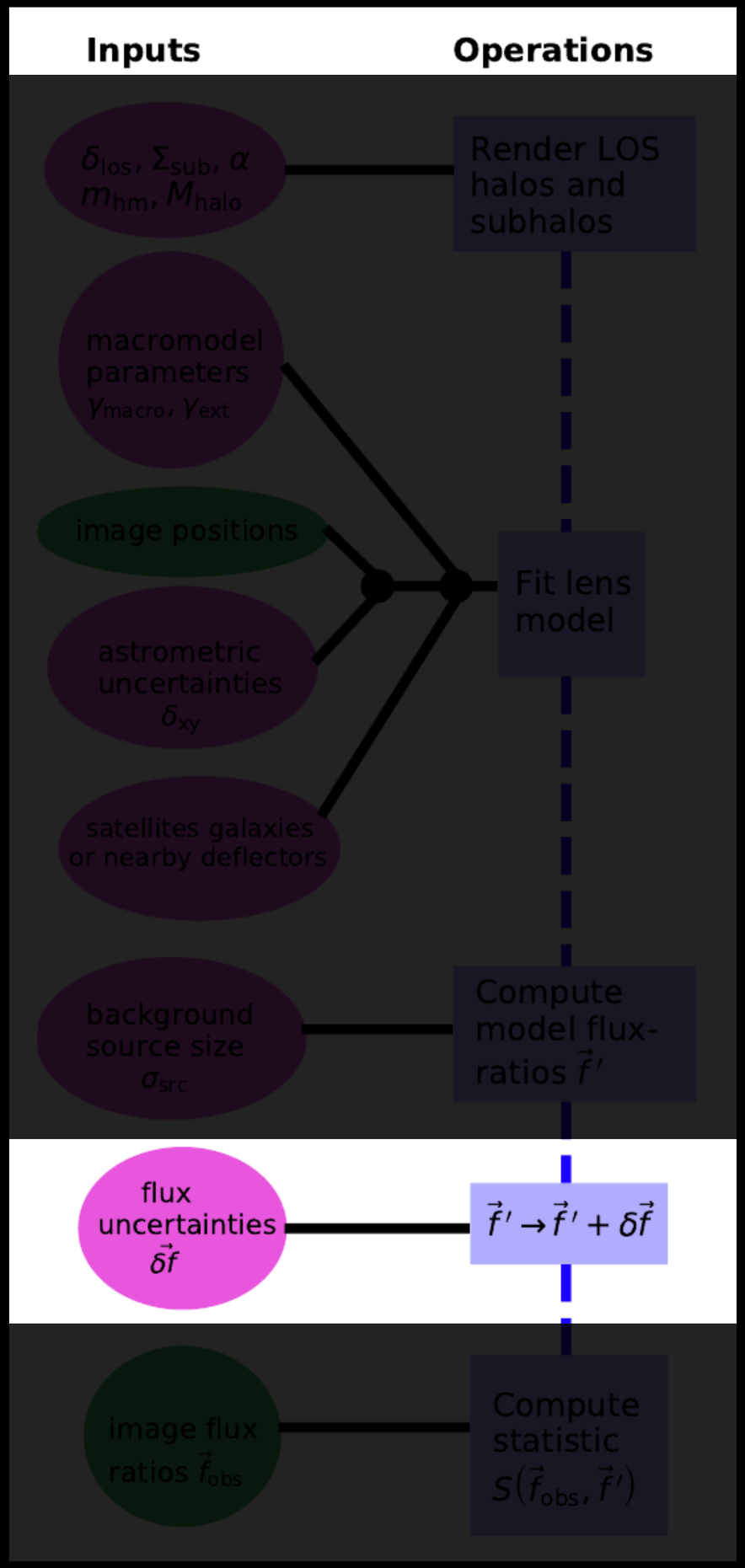
Magnification is a function of source size

Background source size [pc] (FWHM)

$\sigma_{\rm src}$

$\mathcal{U}(25, 60)_{\rm NL}$
$\mathcal{U}(5, 25)_{\rm radio}$

Flux measurement uncertainties



We add flux uncertainties to the model-predicted image fluxes, average over 10 draws

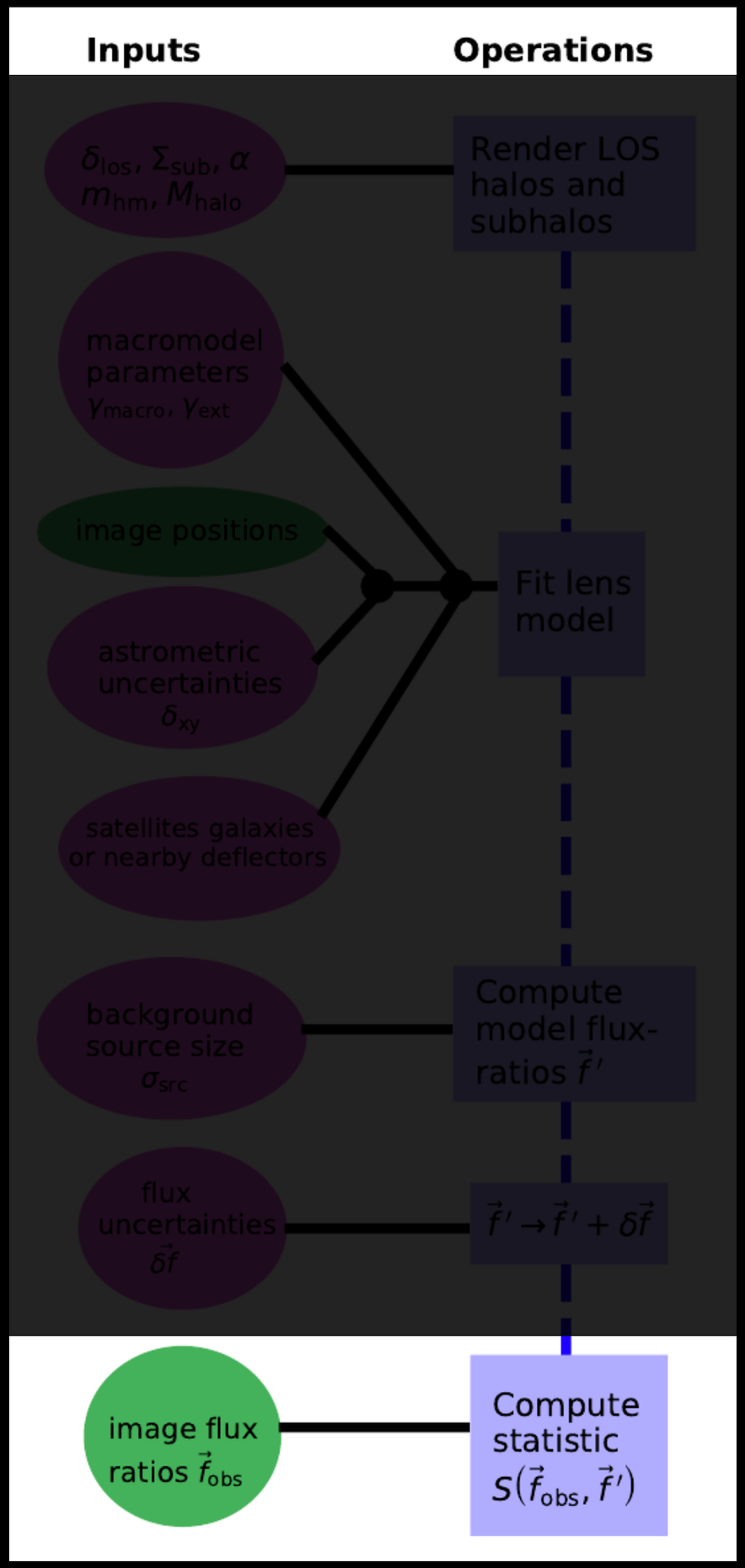
Approximate Bayesian Computing

Assign a summary statistic to each proposal of q_sub

$$S_{\text{lens}}\left(\boldsymbol{f}', \boldsymbol{f}_{\mathbf{obs}}\right) \equiv \sqrt{\sum_{i=1}^{3}\left(f_i' - f_{\text{obs(i)}}\right)^2}$$

Accept the proposal if S_lens < tolerance threshold

This approximation to the posterior distribution converges to the exact posterior as the tolerance threshold approaches 0.

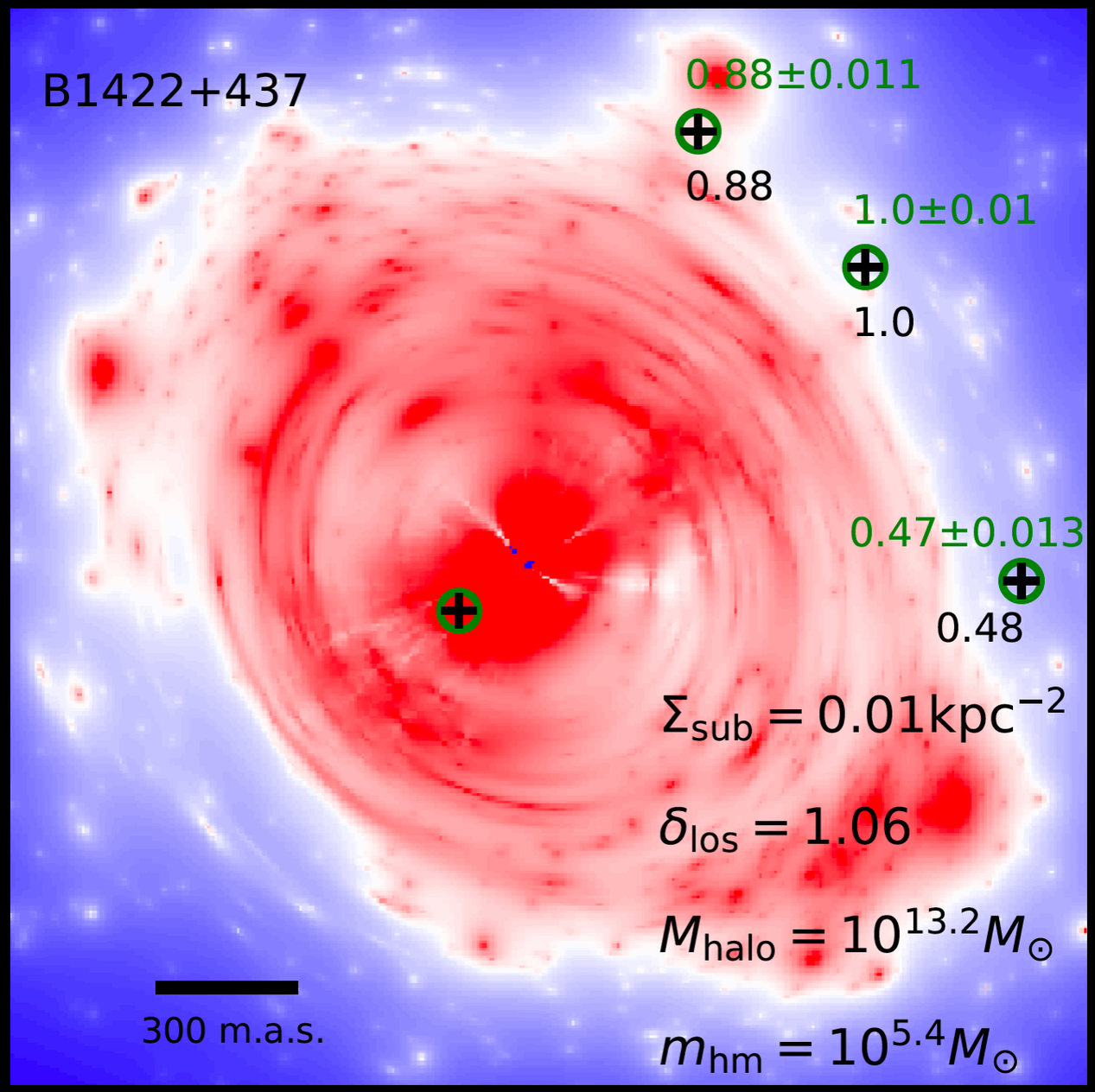


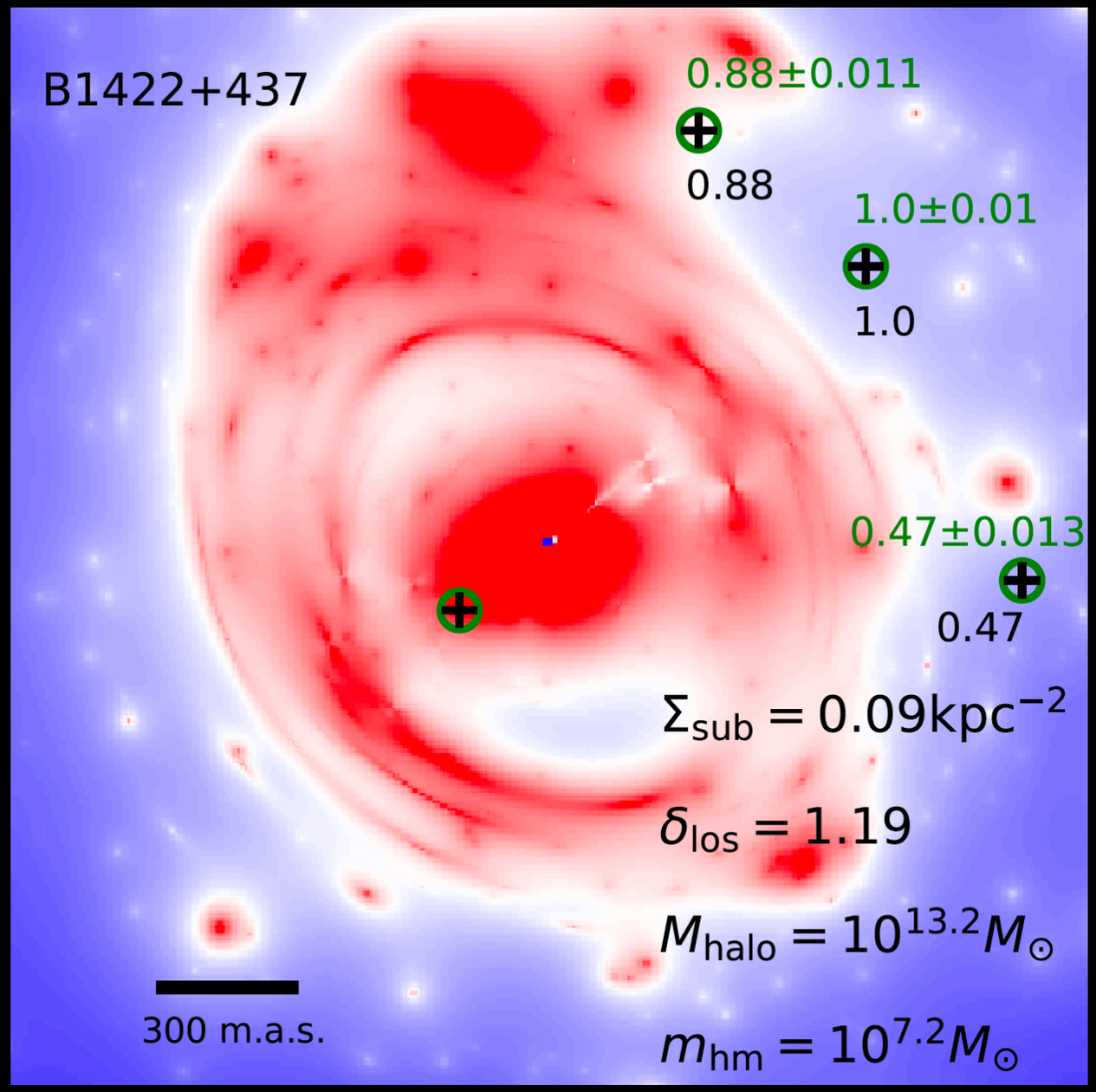
Do the accepted realizations look like the data?

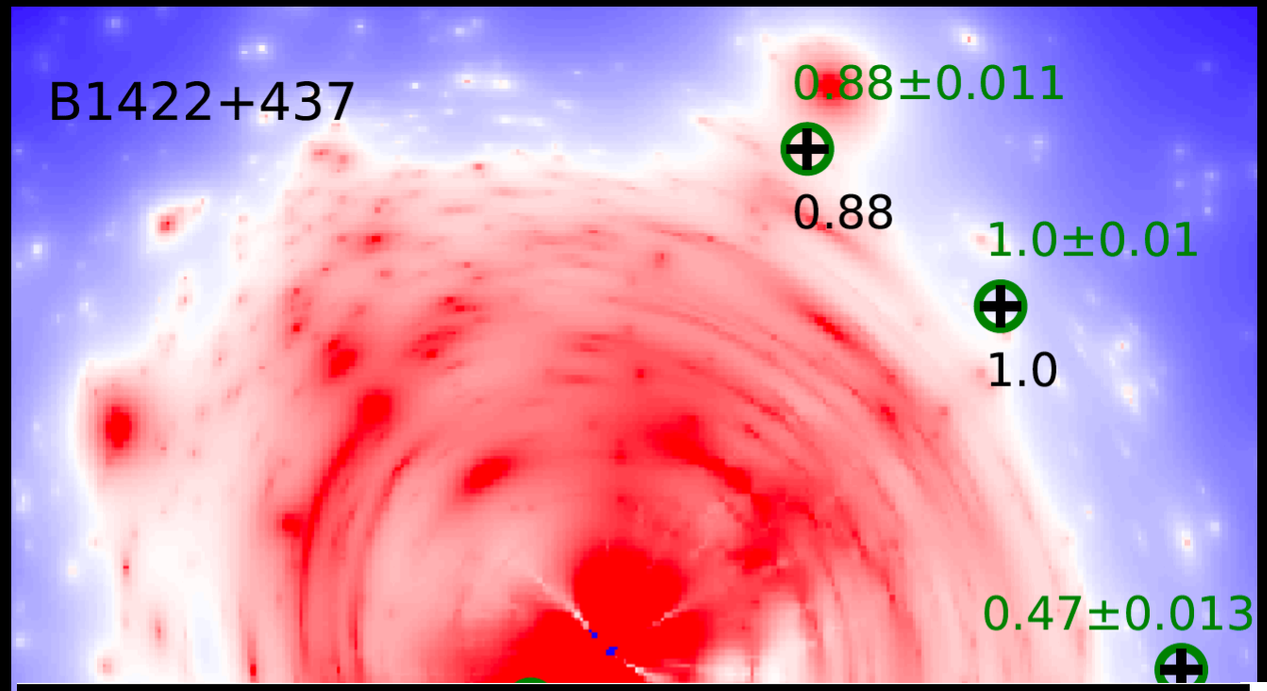
$$\kappa_{\text{effective}} \equiv \frac{1}{2} \nabla \cdot \alpha$$

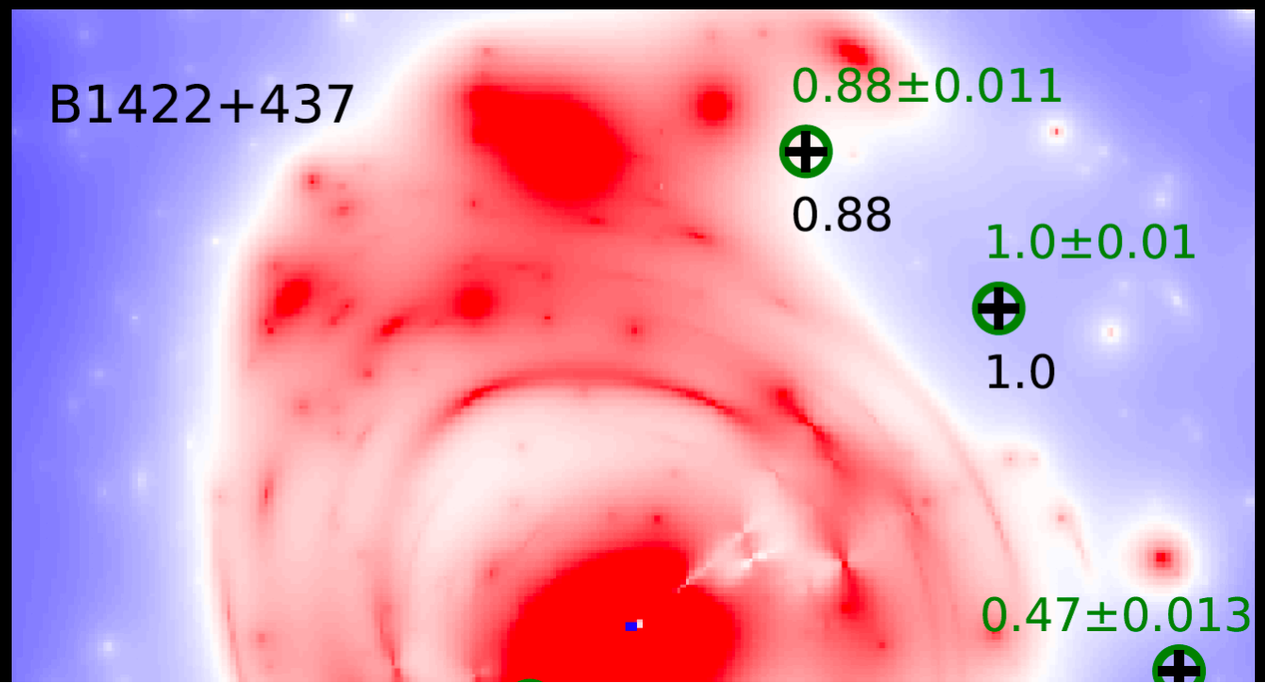
$$\kappa_{\text{effective(halo)}} \equiv \kappa_{\text{effective}} - \kappa_{\text{macro}}$$

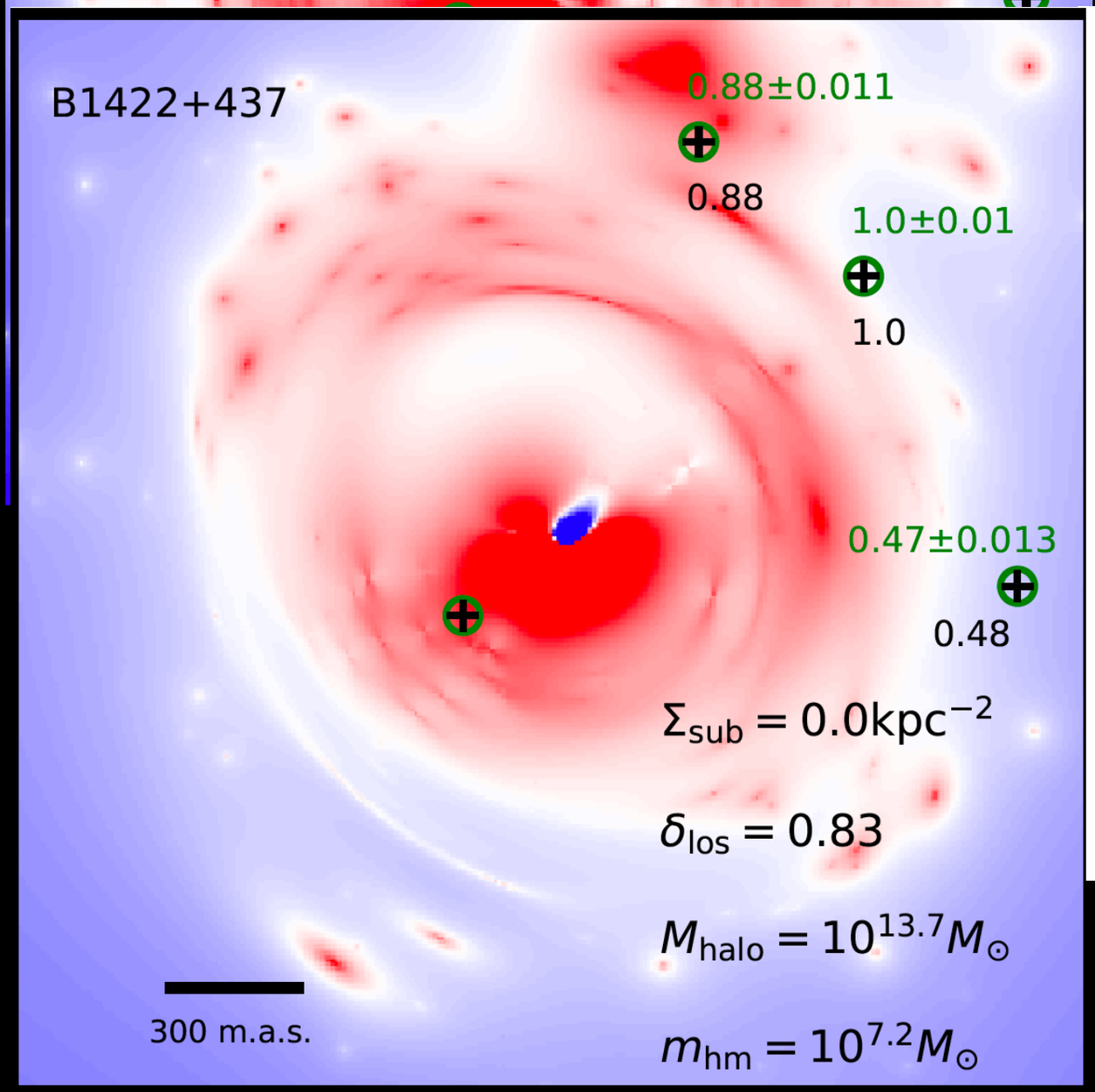
(Projected dark matter halo mass maps)

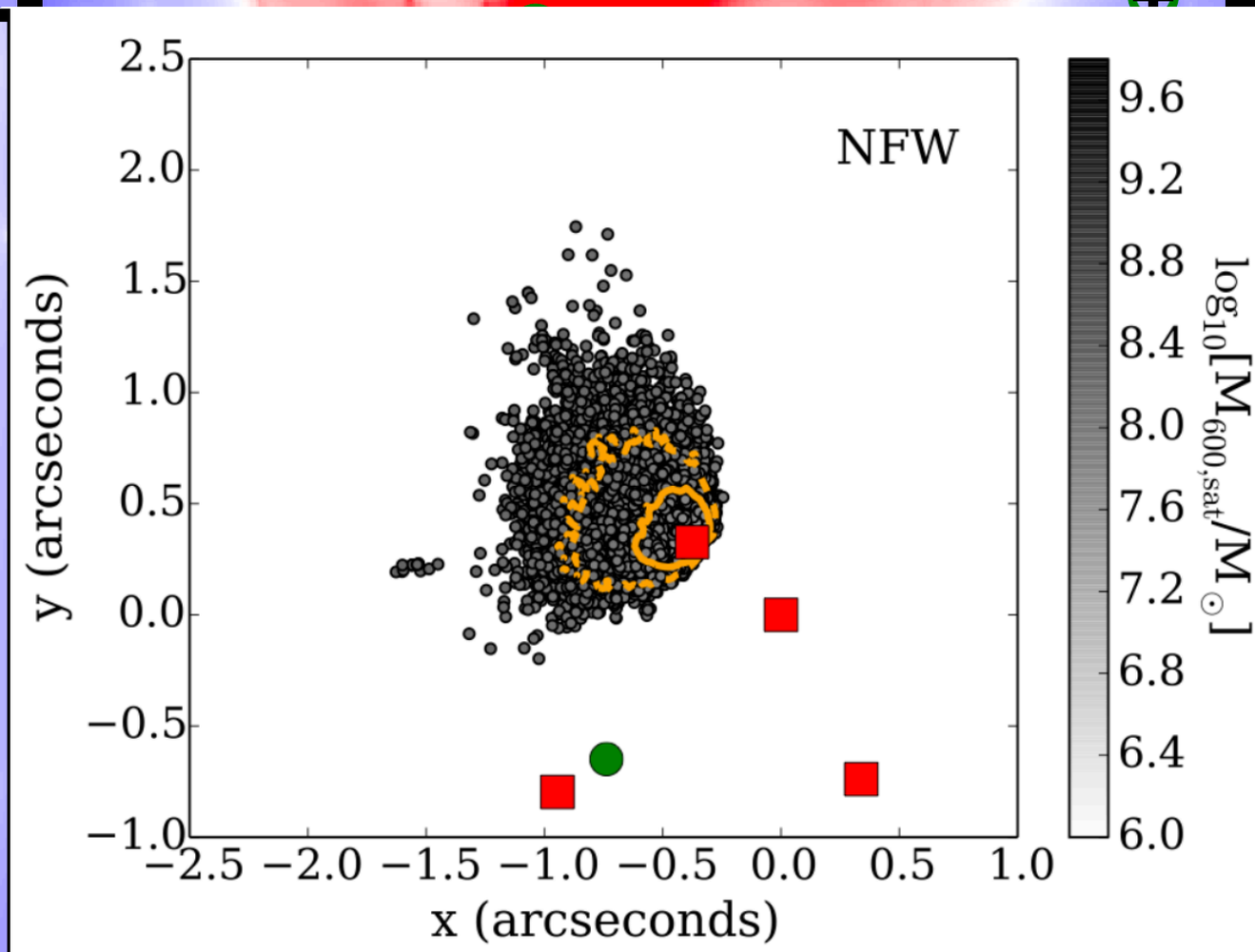








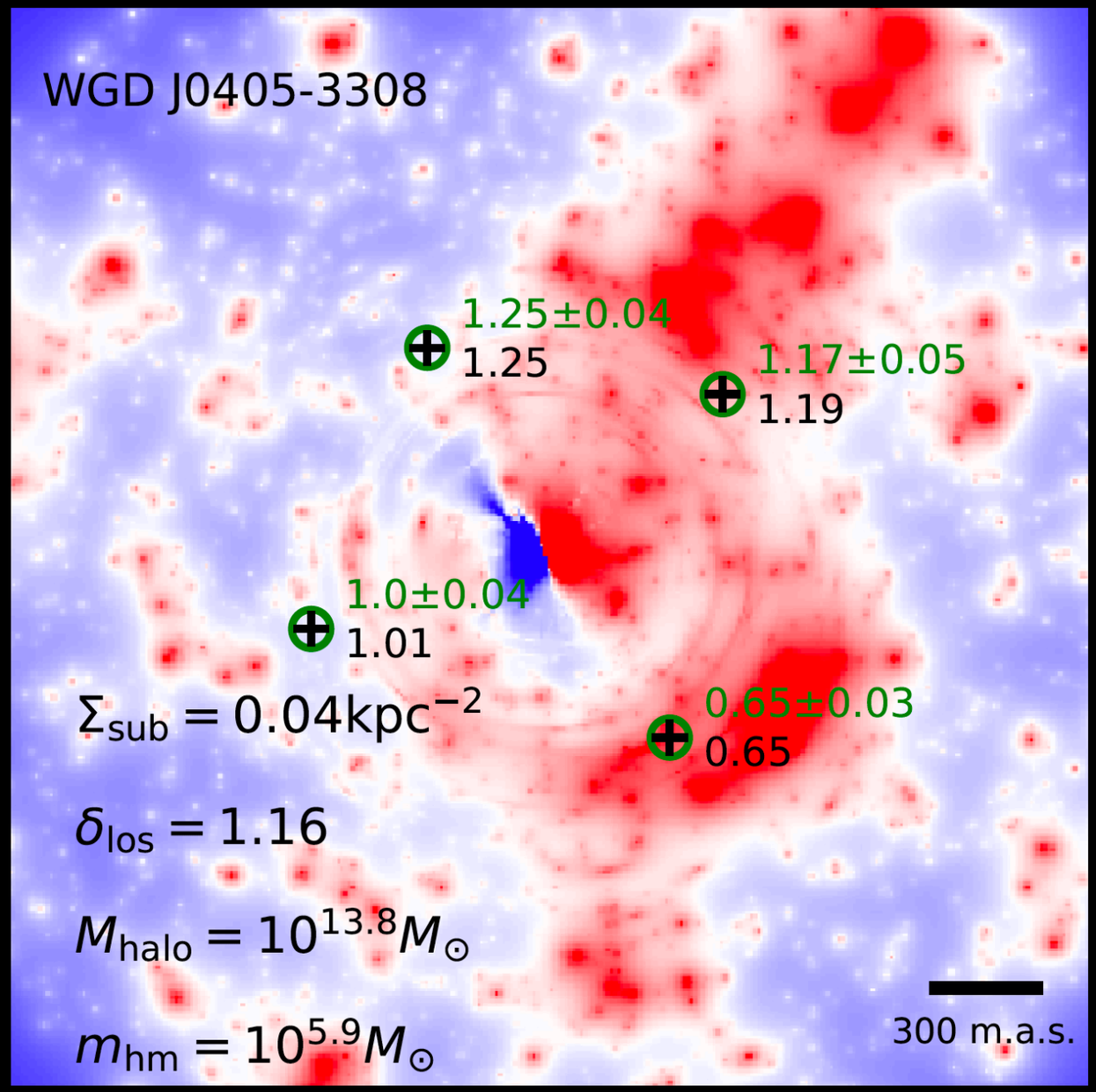


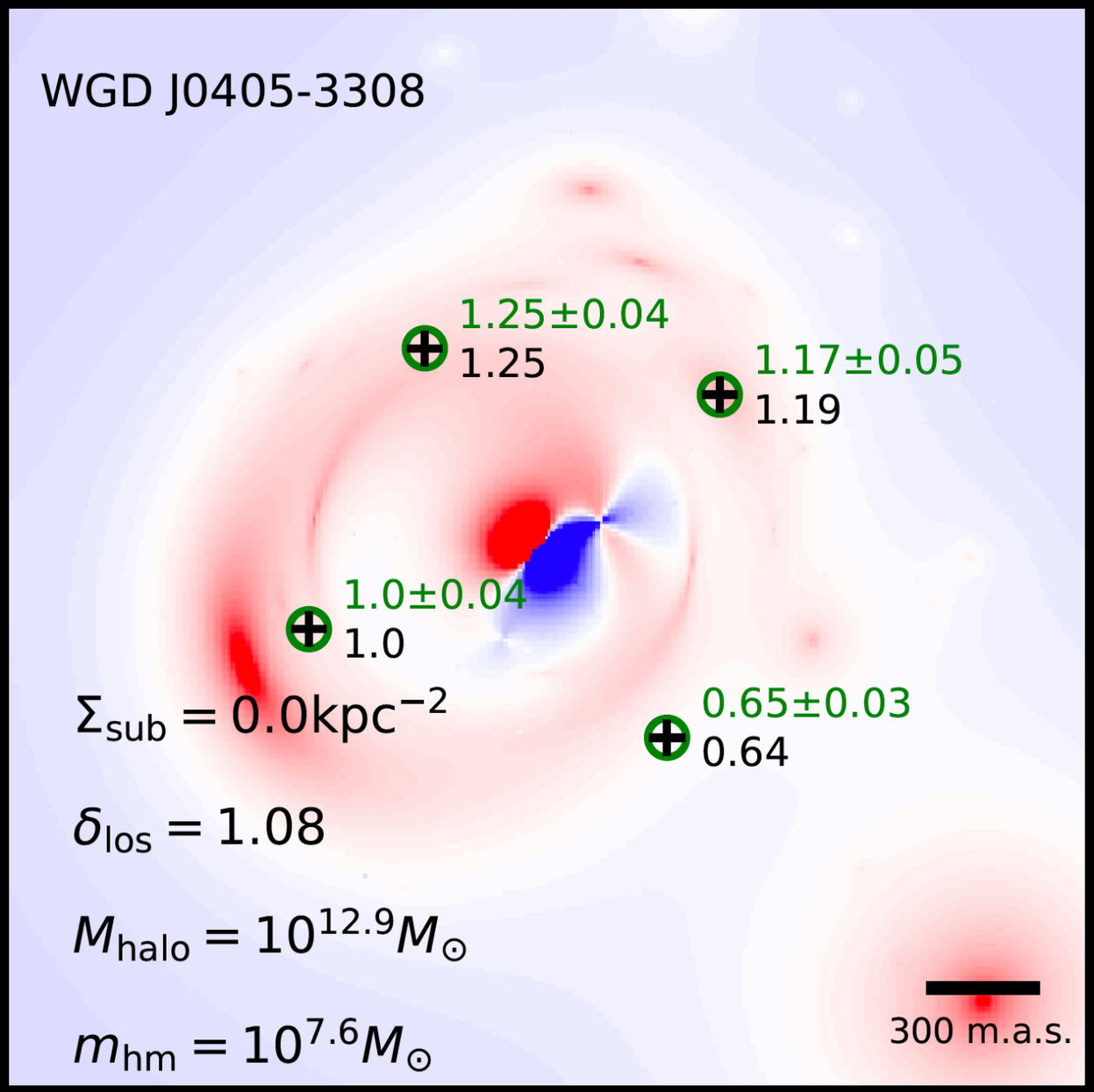


Nierenberg et al. 2014

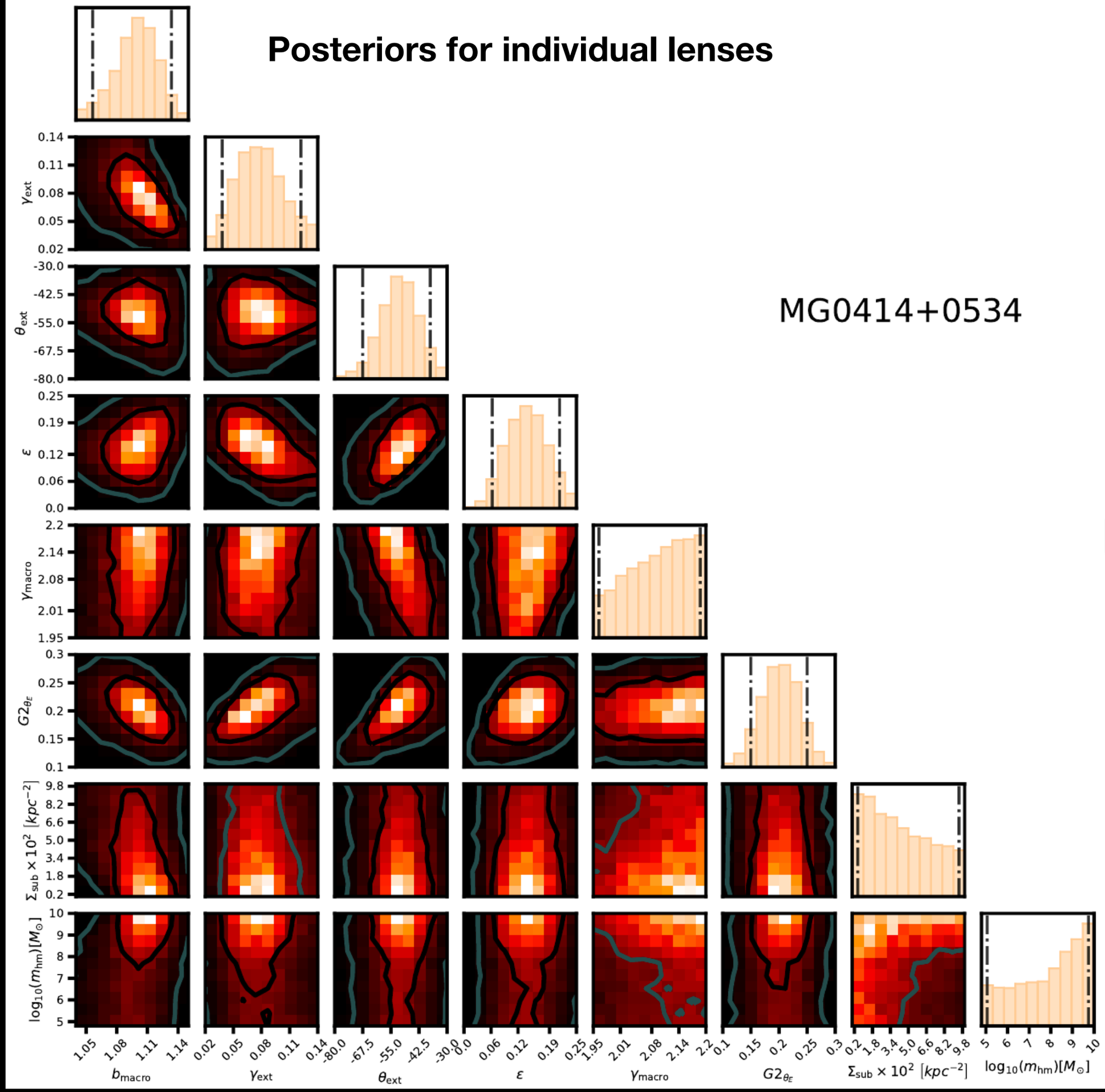
nice.

Do the accepted realizations look like the data?

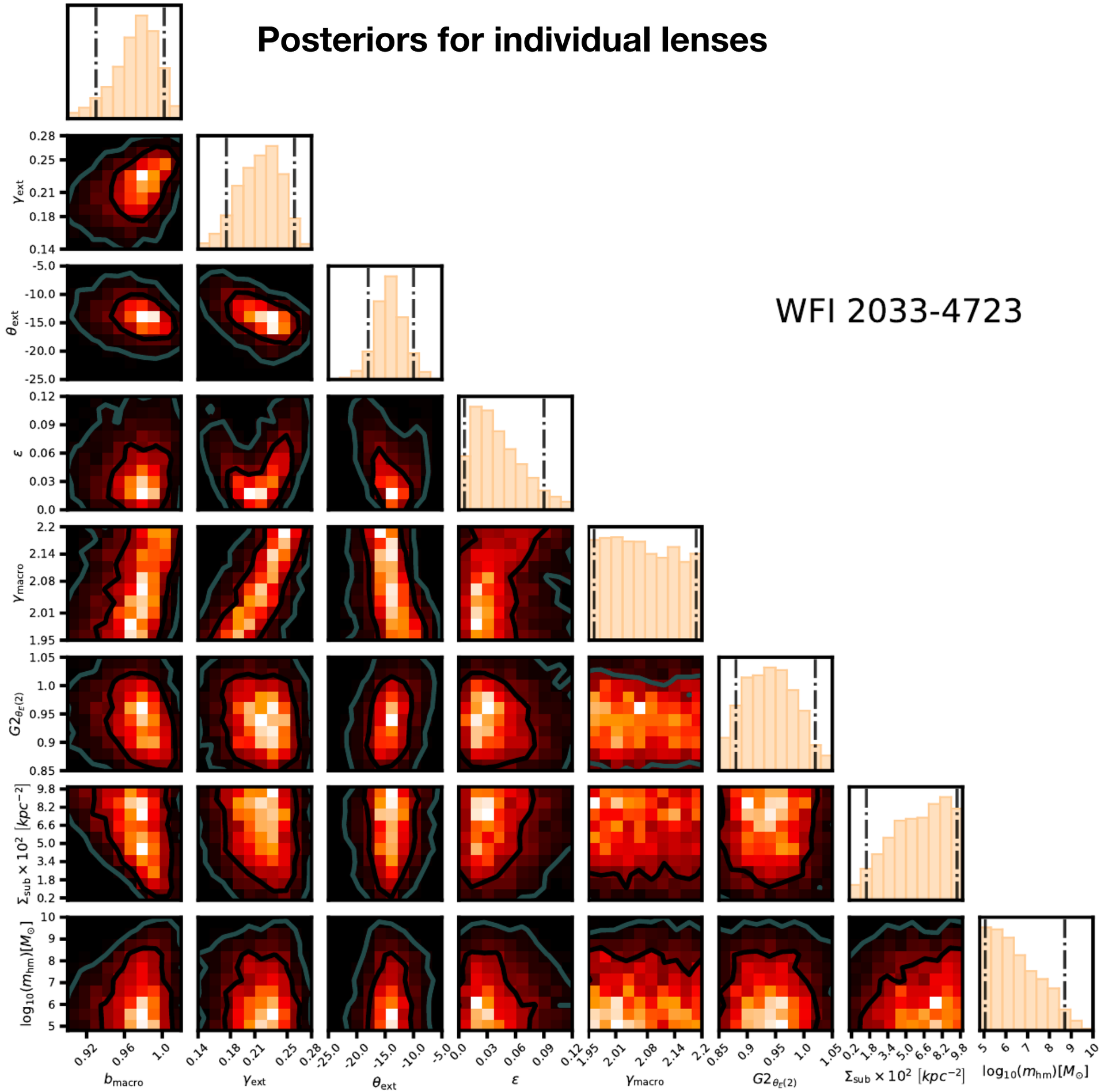


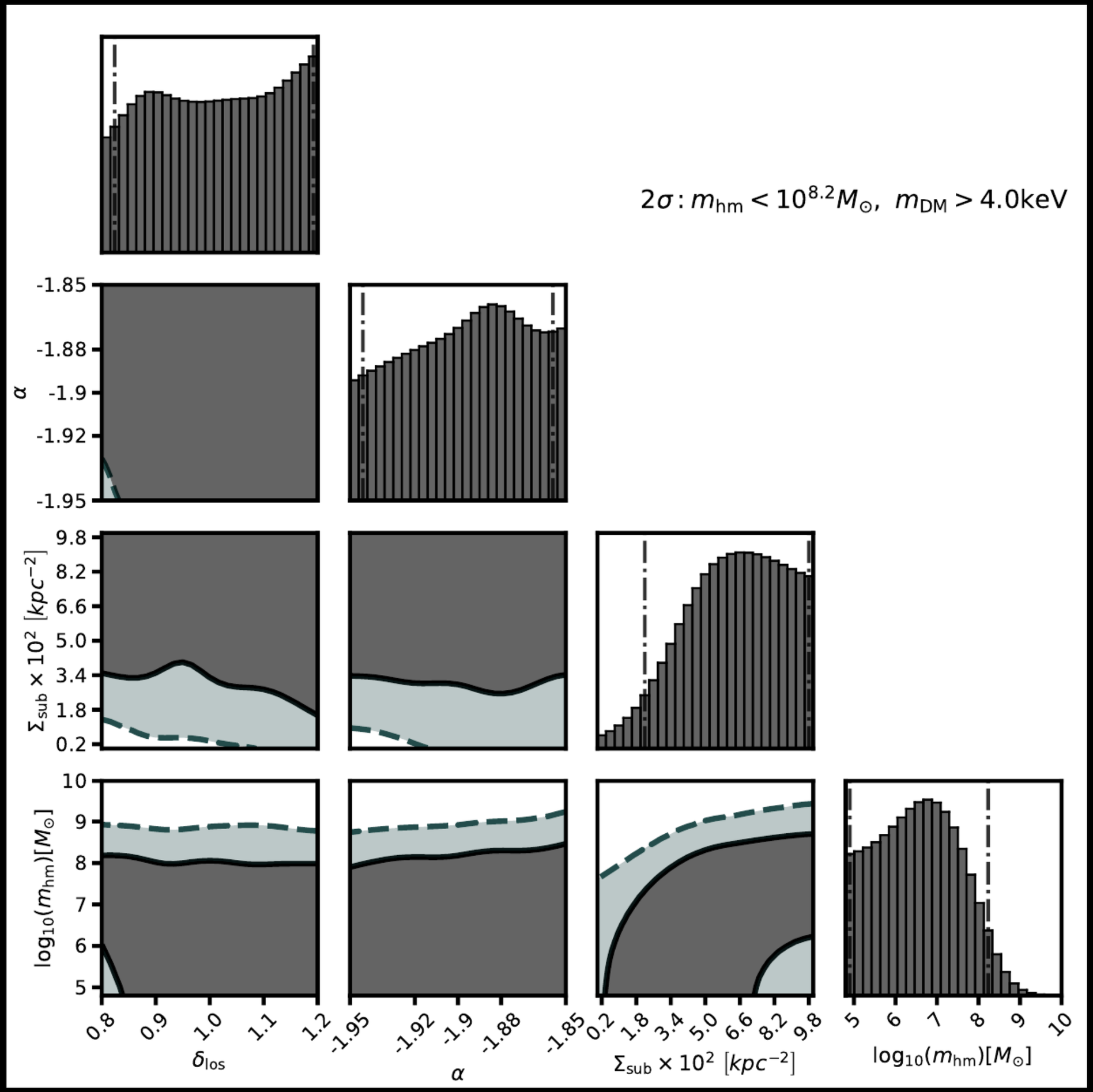


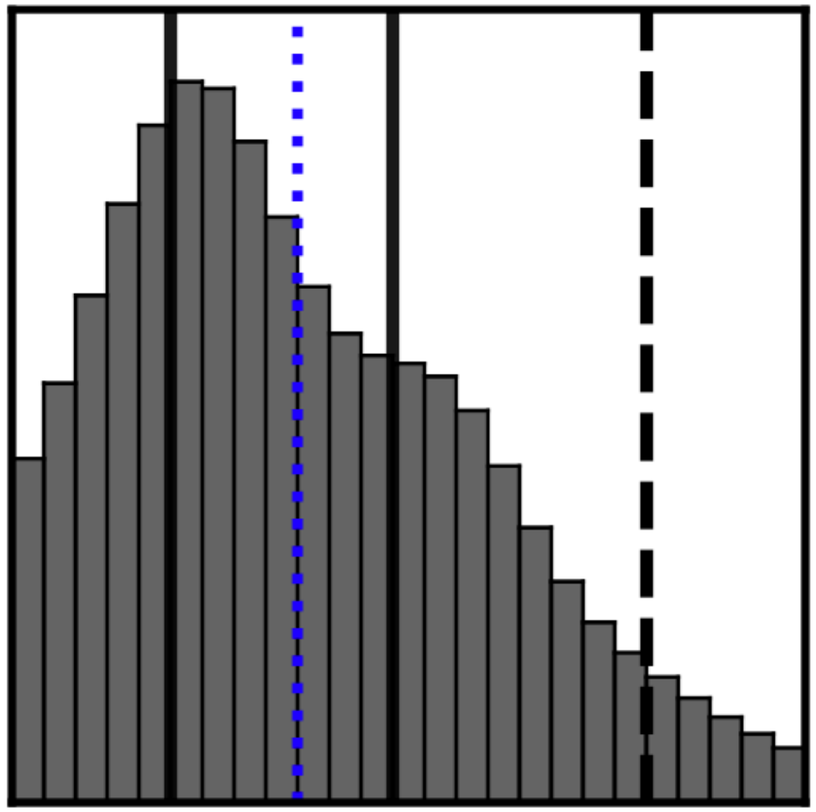
Posteriors for individual lenses



Posteriors for individual lenses




$2\sigma: m_{\rm hm} < 10^{8.2} M_\odot,\ m_{\rm DM} > 4.0$keV
α
-1.85
-1.88
-1.9
-1.92
-1.95
$\Sigma_{\rm sub} \times 10^2\ [kpc^{-2}]$
9.8
8.2
6.6
5.0
3.4
1.8
0.2
$\log_{10}(m_{\rm hm})[M_\odot]$
10
9
8
7
6
5
0.8
0.9
1.0
1.1
1.2
$\delta_{\rm los}$
-1.95
-1.92
-1.9
-1.88
-1.85
α
0.2
1.8
3.4
5.0
6.6
8.2
9.8
$\Sigma_{\rm sub} \times 10^2\ [kpc^{-2}]$
5
6
7
8
9
10
$\log_{10}(m_{\rm hm})[M_\odot]$



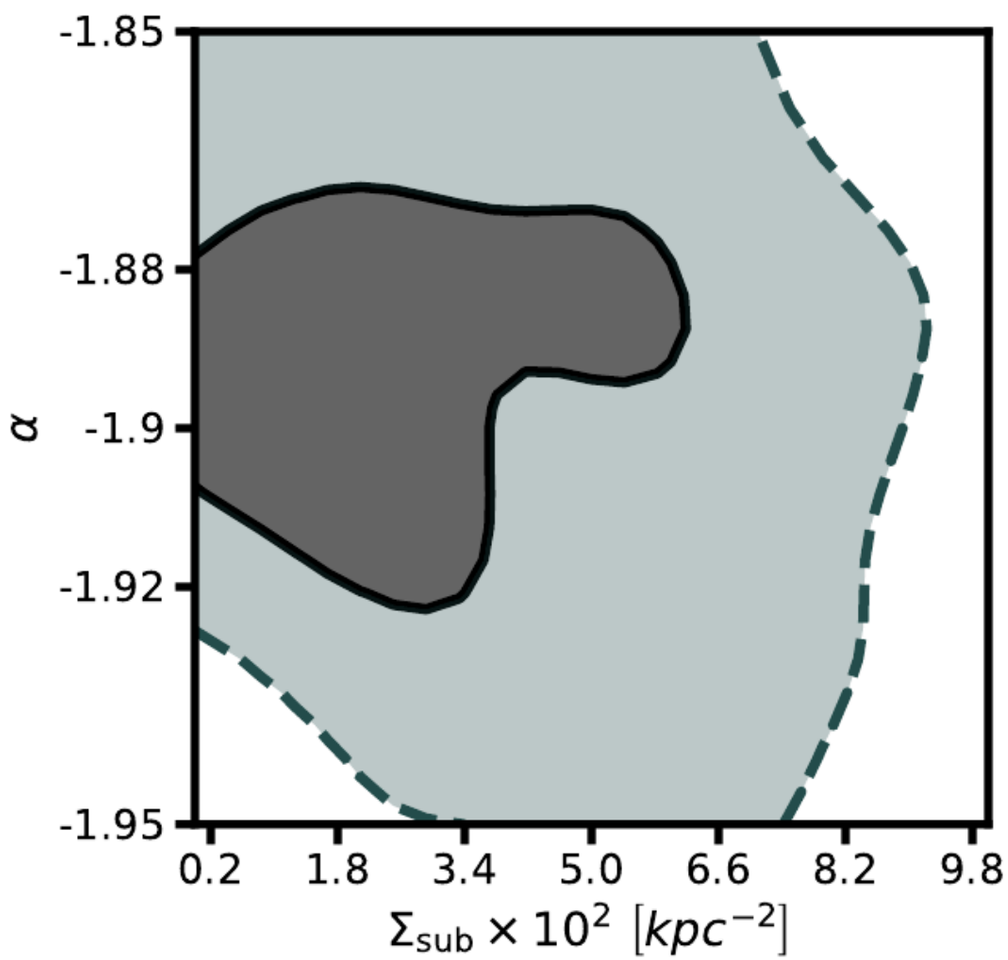
Assuming CDM:

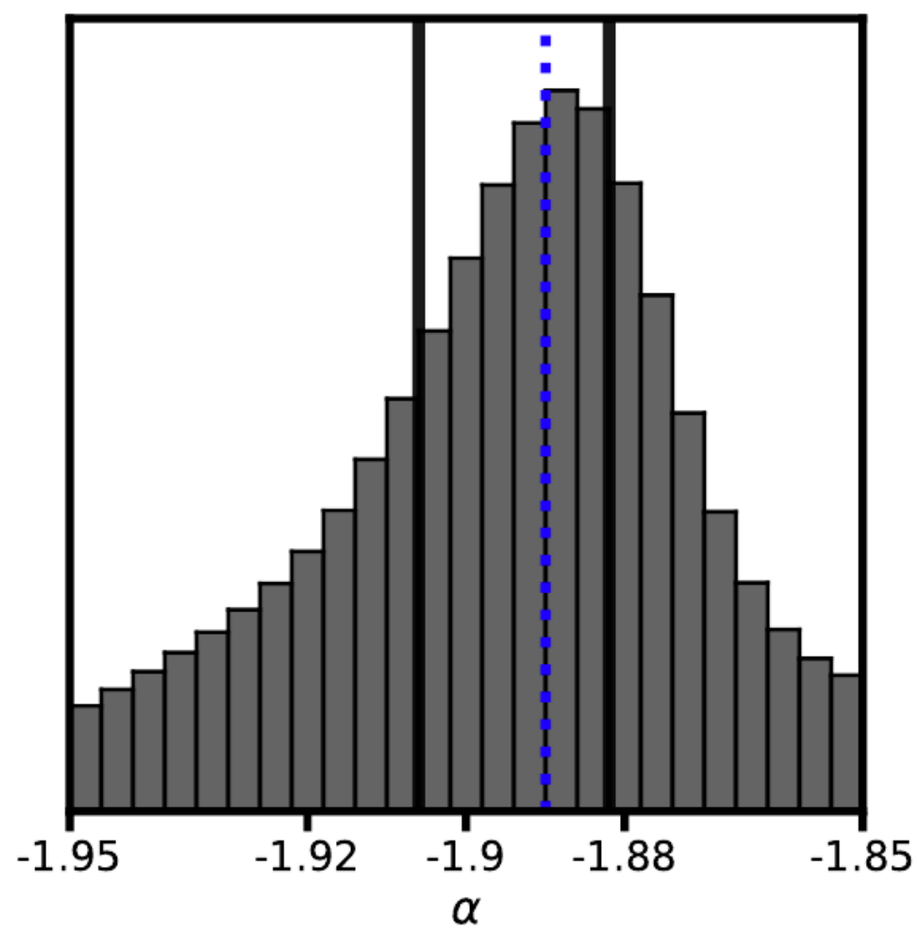
$1\sigma: \; 0.022 < \Sigma_{\rm sub} < 0.046 {\rm kpc}^{-2}$

$2\sigma: \; \Sigma_{\rm sub} < 0.08 {\rm kpc}^{-2}$

$1\sigma: \; -1.906 < \alpha < -1.882$

Mean projected mass:
2.6 (+0.7) (-1.0) * 10^7 M/kpc^2





Tweet-able conclusion

Using 11 quadruple-image #stronglenses, we have constrained the free-streaming length of dark matter (m > 4 keV), and measured the shape and amplitude of the subhalo mass function. With the many additional lenses to be discovered by LSST, we are just scratching the surface of what lensing can do, like probing SIDM models.