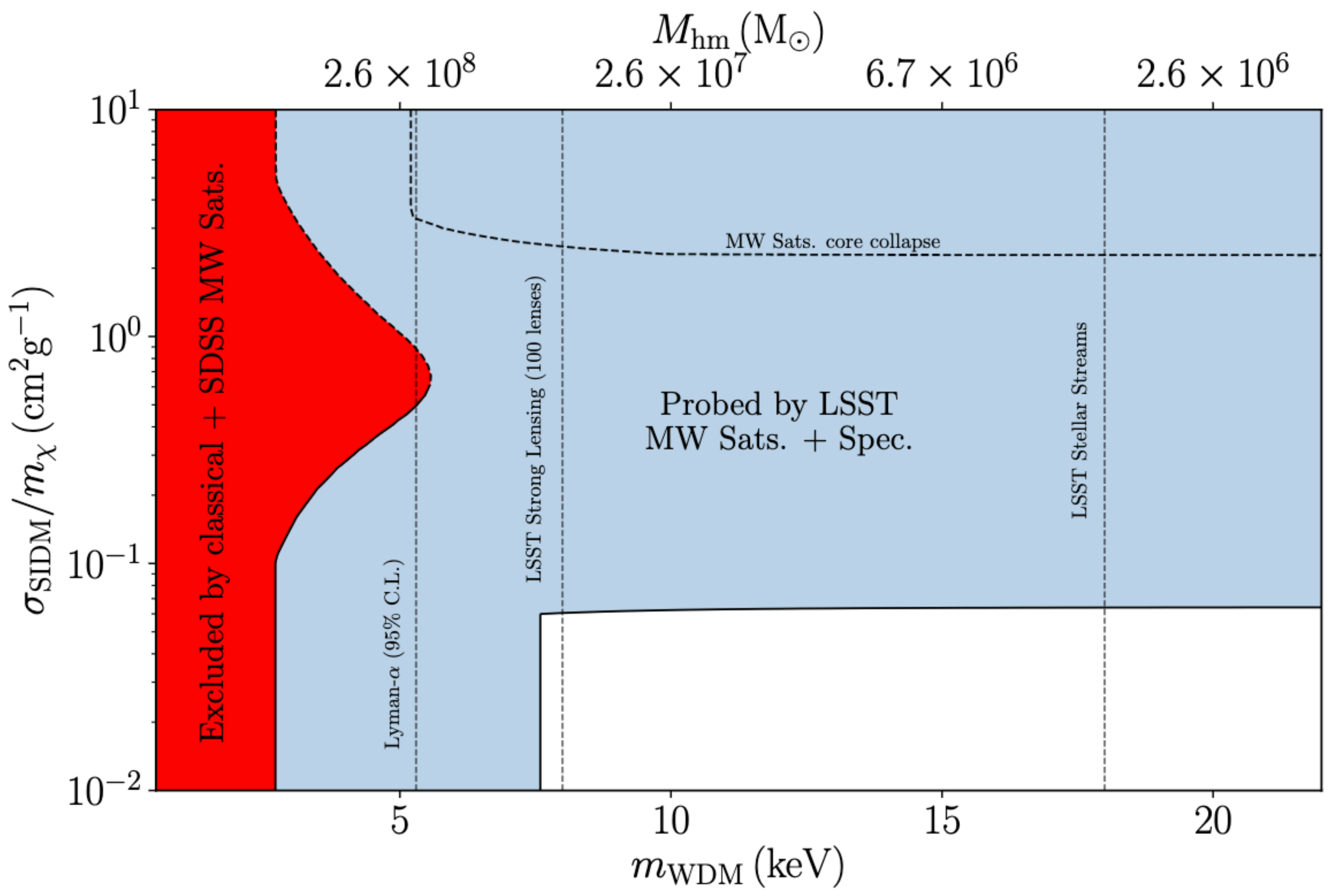
Strongest gravitational lensing limit on the dark matter free streaming length with JWST

TeVPA 2024

Ryan Keeley

DM Figure of Merit

- 2 classes of physical observables from astro DM probes
- Is DM cold? Is DM collisionless?
- Free streaming? Interactions?
- Abundance of DM halos, profiles of DM halos
- self-interaction cross-section and particle mass



Drlica-Wagner+ 1902.01055

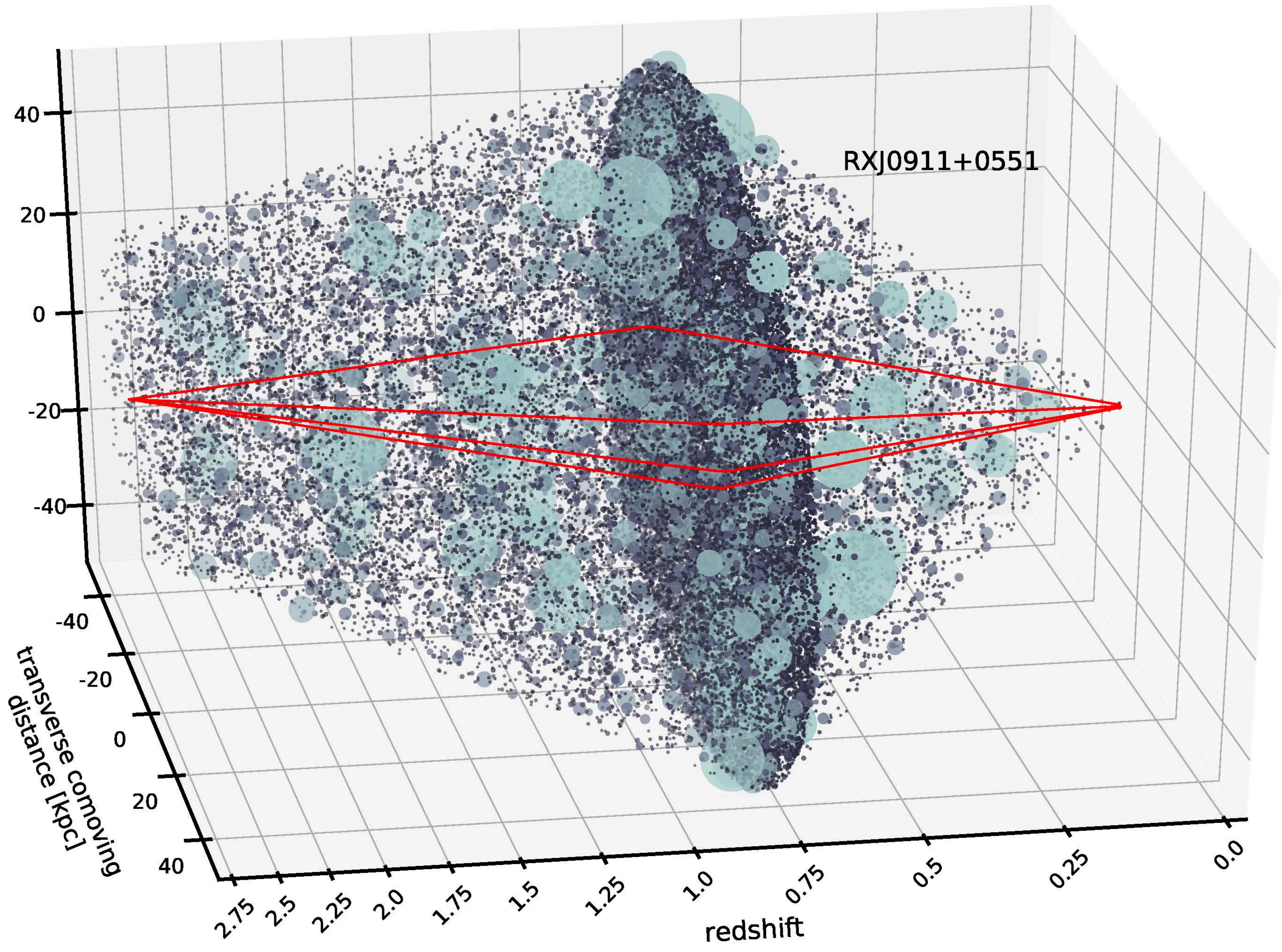
Substructure Lensing

- Gravitational potential:
$$\psi(\overrightarrow{\theta}) = \frac{D_{DS}}{D_D D_s}\frac{2}{c^2}\int dz\Phi(D_D, \overrightarrow{\theta}, z)$$

- Deflection: $\overrightarrow{\alpha}(\overrightarrow{\theta}) = \overrightarrow{\nabla}\psi$

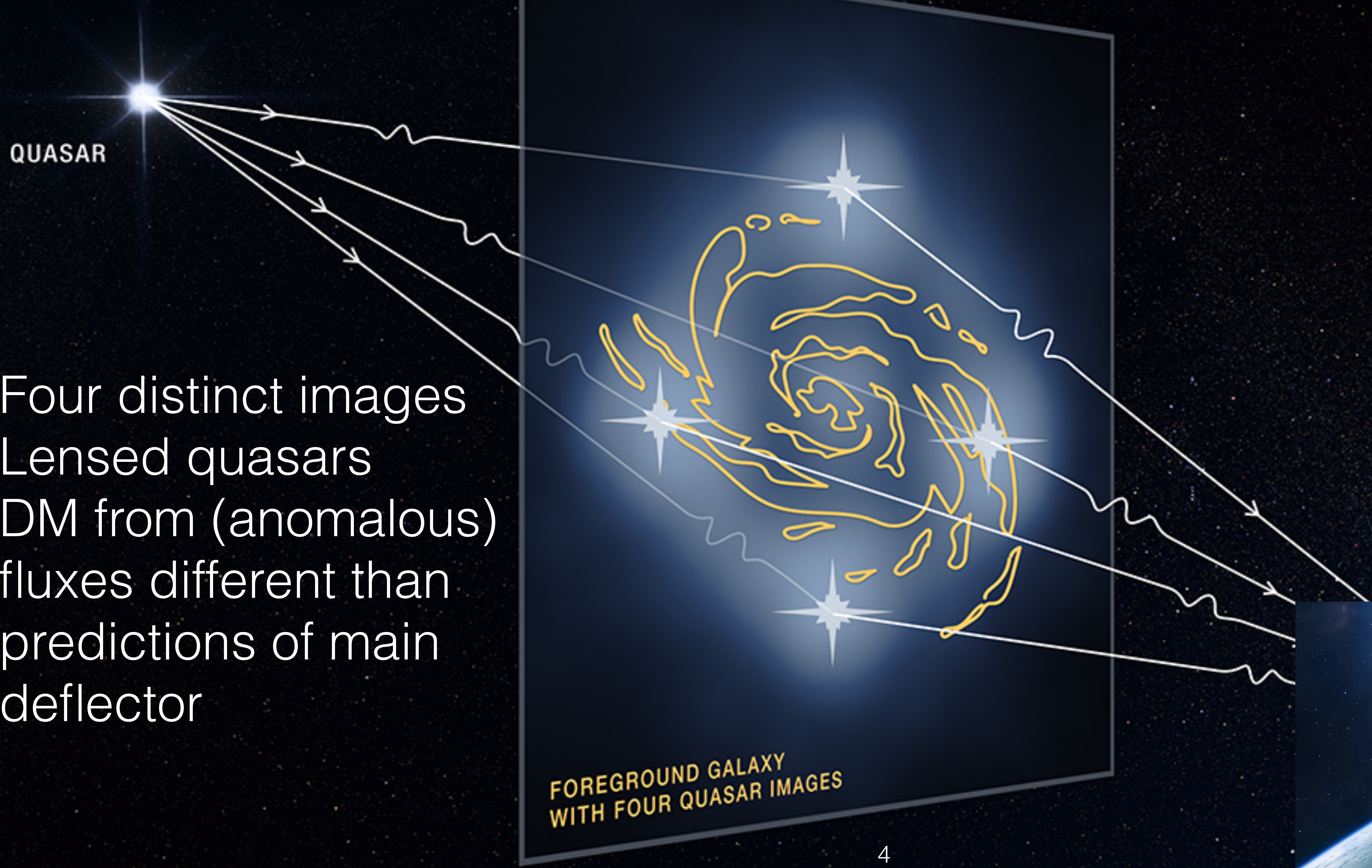
- Magnification: $M^{-1} = \delta_{i,j} - \frac{d\psi}{d\theta_i d\theta_j}$

- Image positions probe large scale (smooth) fluxes probe small scale (clumpy)



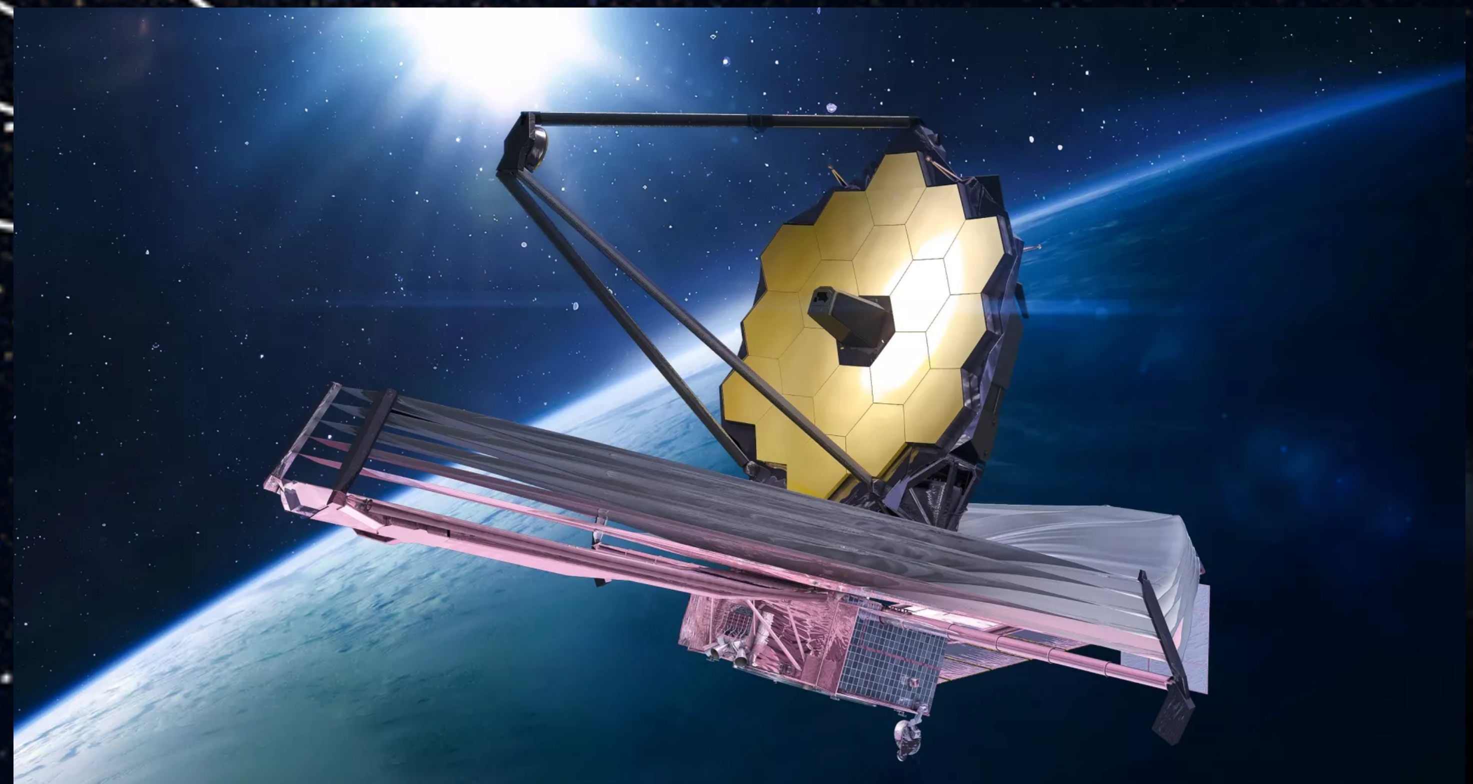
pyHalo: Gilman+ (1908.06983) MNRAS

Flux Ratio Anomalies



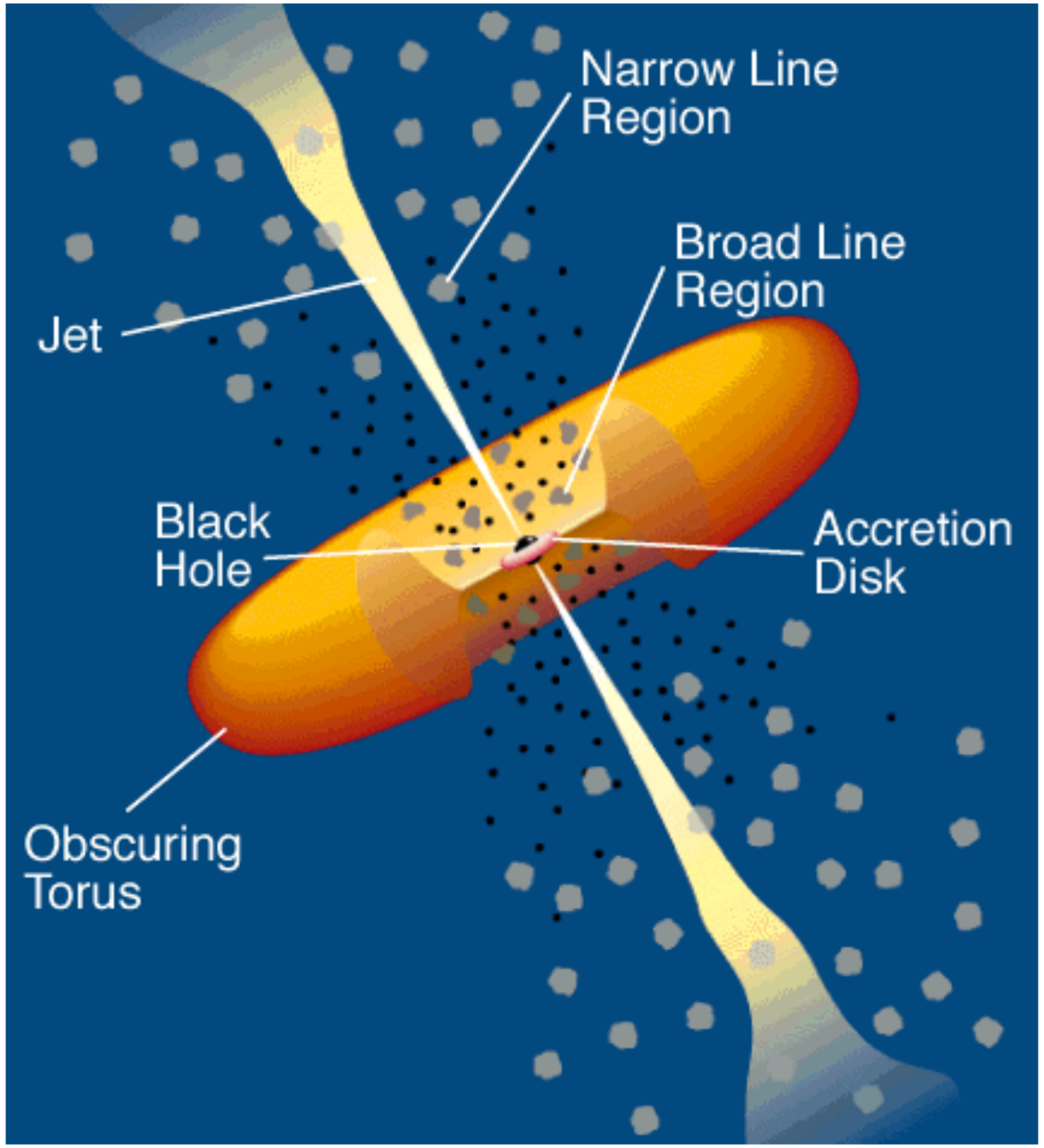
- Four distinct images
- Lensed quasars
- DM from (anomalous) fluxes different than predictions of main deflector

JWST



Strong Lensing of Quasars

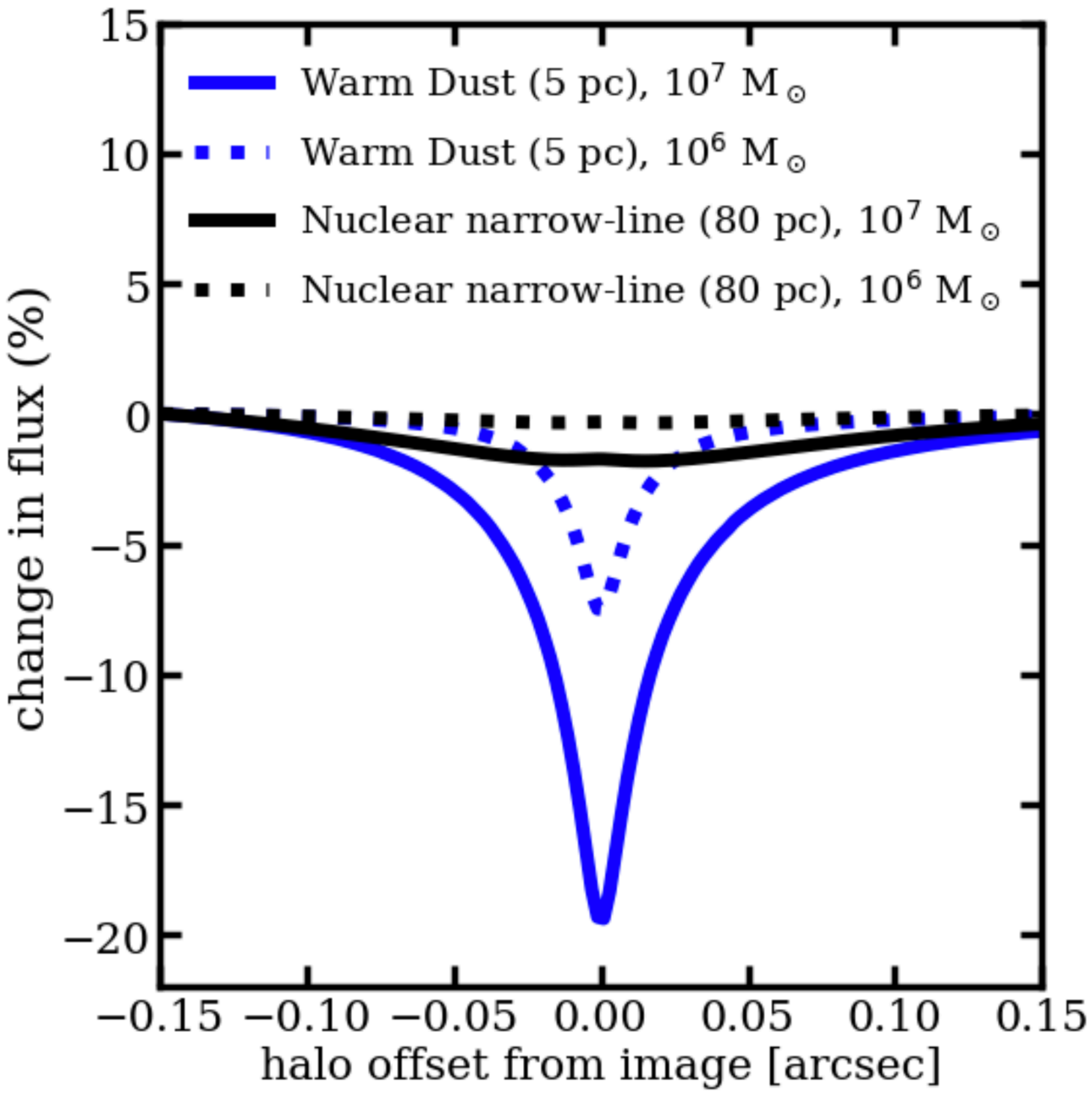
- Different regions -> different physical sizes and emit in different wavelengths -> independent datasets
- Smaller source sizes are more sensitive to lower mass DM halos
- Observe narrow-line region with HST/Keck and warm dust with JWST



Urry et al ASP 1995

Source Sizes Matter

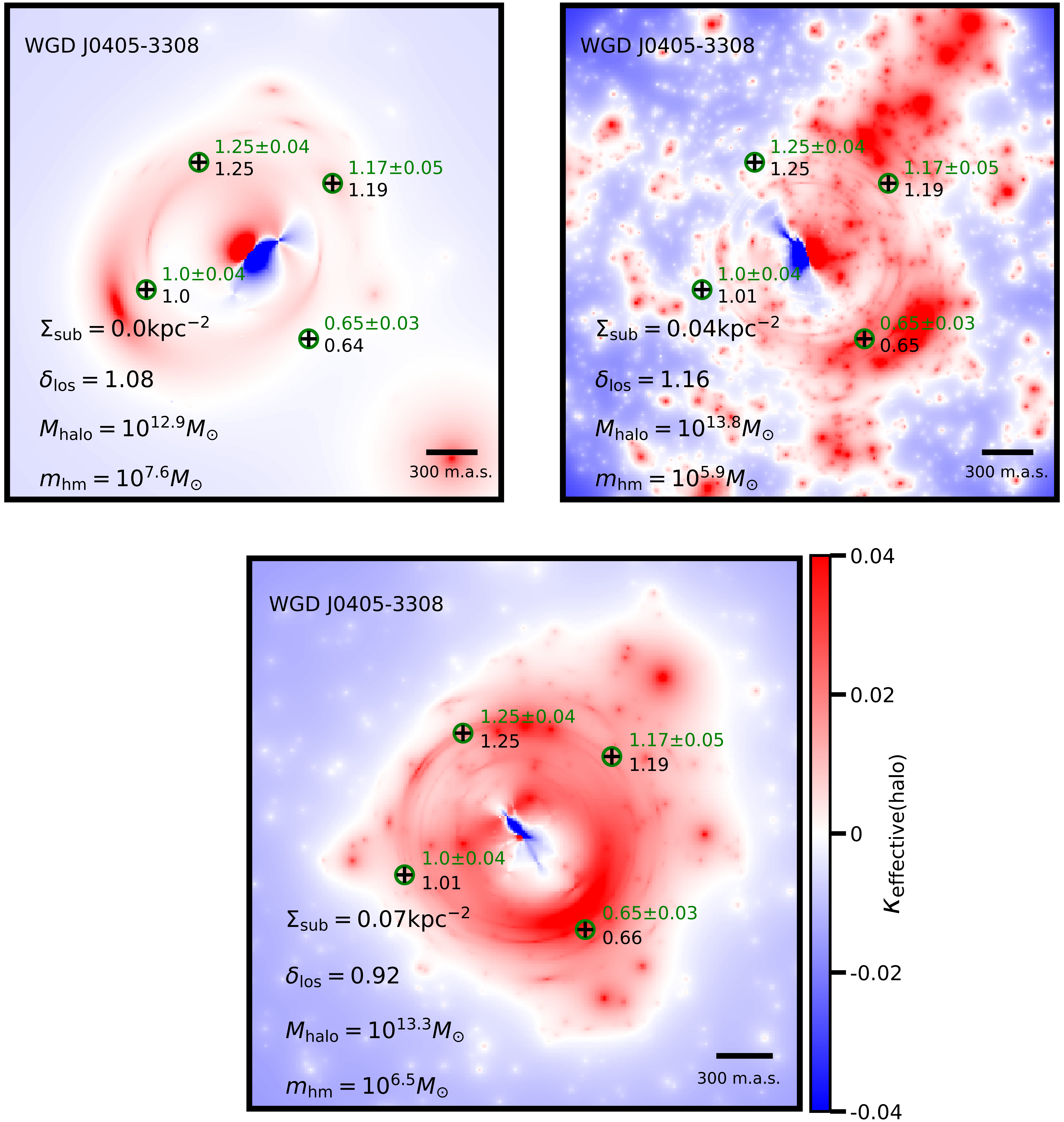
- Want flux ratios from cold torus / warm dust region (~5 pc)
- More sensitive to low mass DM halos than narrow-line (~80 pc)
- JWST observations are sensitive to completely dark DM halos



Nierenberg+ (2309.10101) MNRAS

Statistical Signals

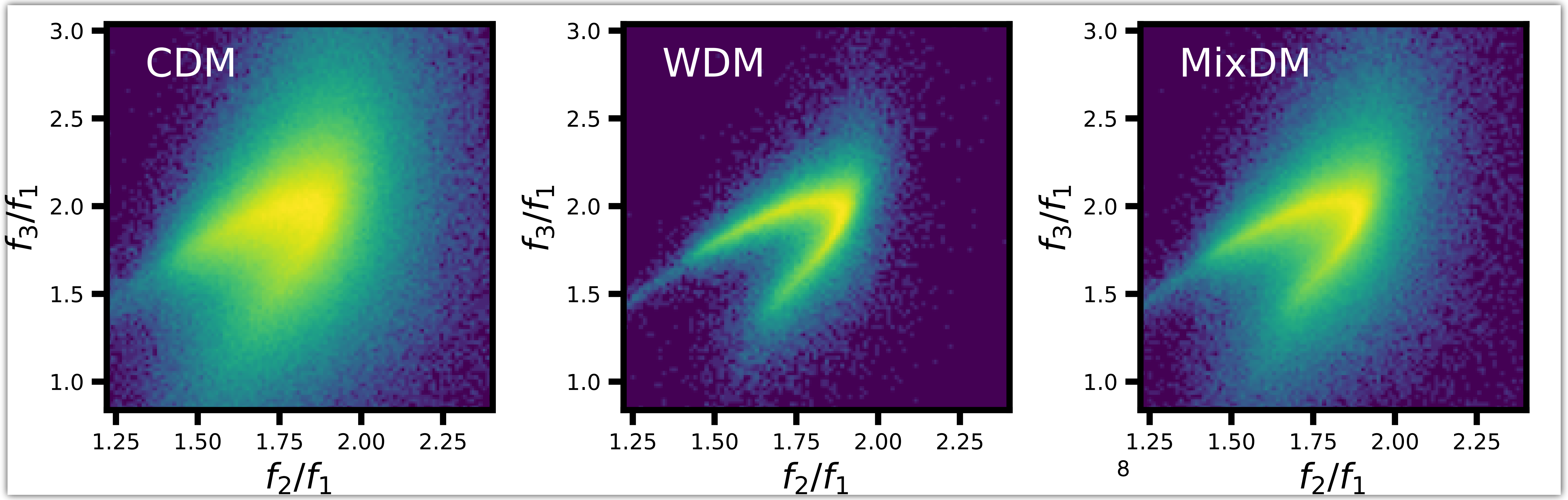
- Wide range of substructure realizations can reproduce observed flux ratios
- Need to evaluate the frequency that a given set of parameters will fit the data well



Gilman+ (1908.06983) MNRAS

Anomalous Fluxes

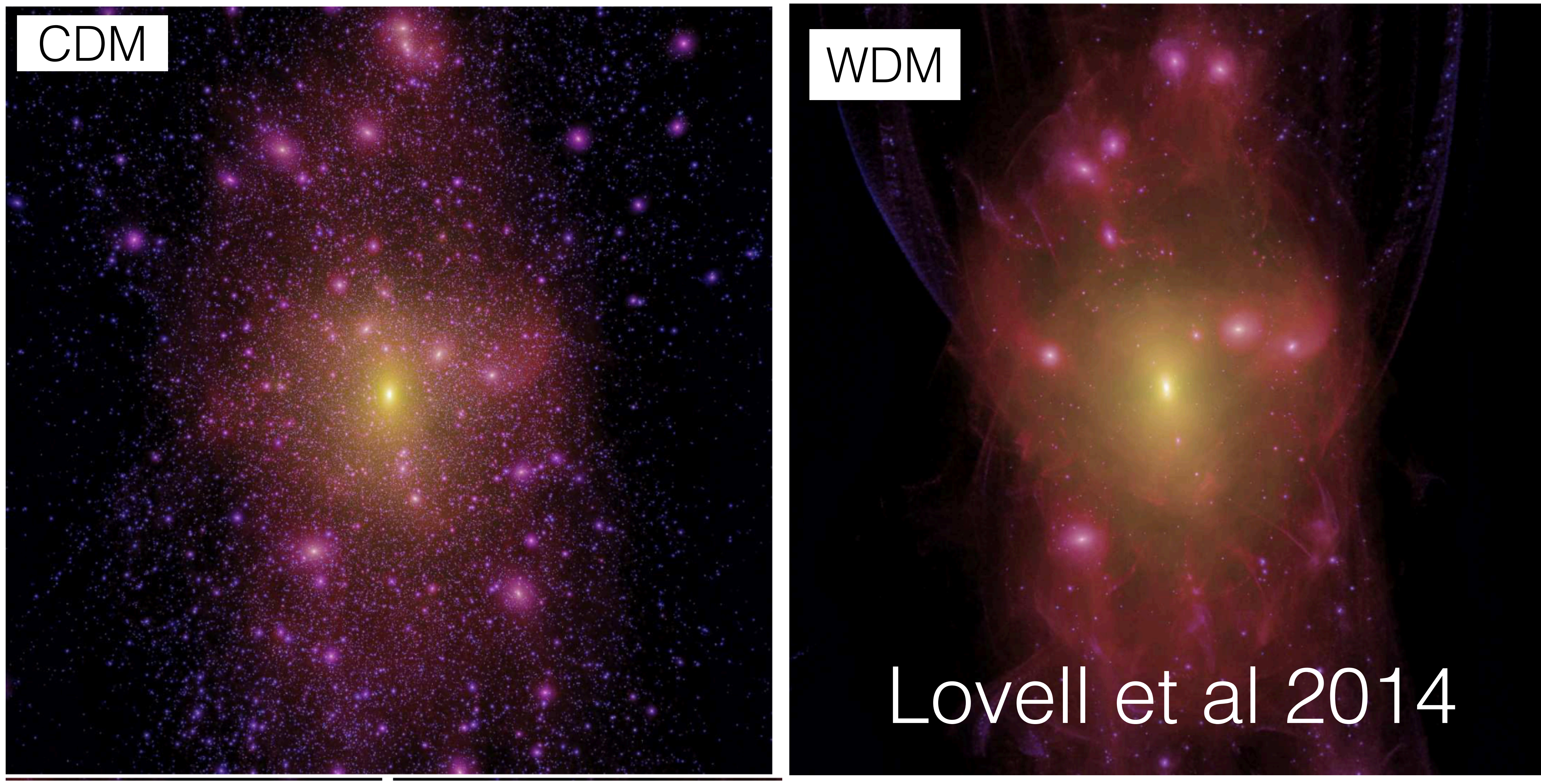
- Ratios of fluxes from quadruply lensed images
- Ratio to divide out unknown flux of source
- Model predicts *distribution* of fluxes, not a single value
- Need machine learning, simulation-based (likelihood-free) statistical inference



Keeley+ (2301.07265) MNRAS

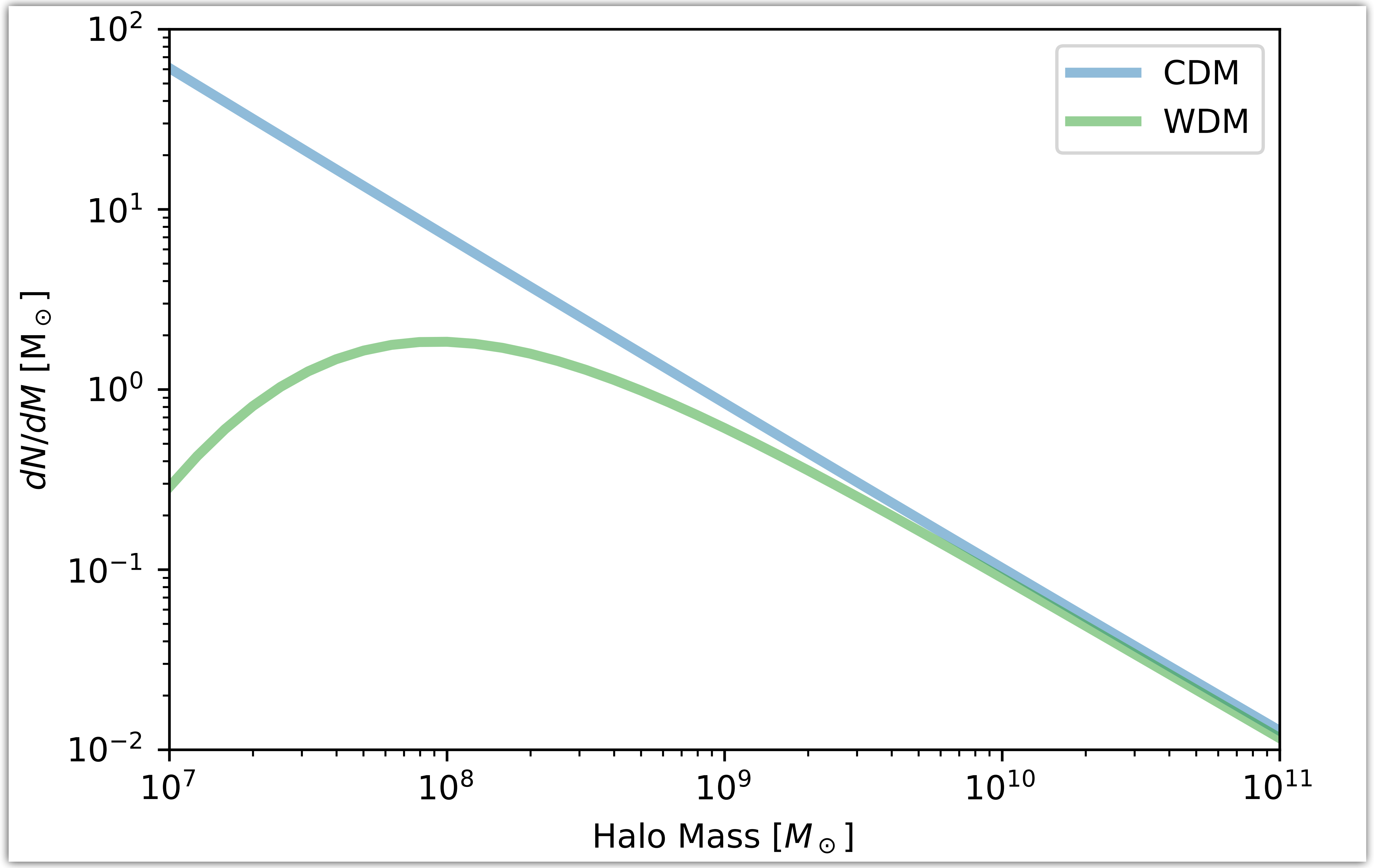
Warm Dark Matter

- Cold DM predicts an abundance of DM halos at small masses
- Warm DM predicts few DM halos: structure suppressed at small scales
- Constrained by observing smallest DM halos
- Masses ~1-20 keV
- e.g. sterile neutrinos



Halo Mass Function

- Half-mode mass ($M_{\rm hm}$): scale where mass function suppressed by half
- Determined by the DM mass
- $$M_{\rm hm} = 5.5 \times 10^{10} \left(\frac{m_{\rm WDM}}{1 {\rm keV}} \right)^{-3.33}$$



Keeley+ (2301.07265) MNRAS

Modeling halos

- $\frac{d^2N}{dMdV} = \delta_{\rm LOS}\left(1 + \xi_{\rm 2halo}\left(M_{\rm host,z}\right)\right)\frac{d^2N}{dMdV}\bigg|_{\rm ST}$ (line-of-sight halos)
- $\frac{d^2N_{\rm WDM}}{dMdV} = \frac{d^2N_{\rm CDM}}{dMdV}f_{\rm WDM}\left(M, M_{\rm hm}\right)$
- $f_{\rm WDM}\left(M, M_{\rm hm}\right) = \left(1 + \left(\alpha\frac{M_{\rm hm}}{M}\right)^{\beta}\right)^{\gamma} \alpha = 2.3,\ \beta = 0.8,\ \gamma = -1.0$
- $\frac{d^2N_{\rm sub}}{dMdA} = \frac{\Sigma_{\rm sub}}{10^8 M_\odot}\left(\frac{M}{10^8 M_\odot}\right)^{\alpha}\mathcal{F}(M_{\rm host}, z)f_{\rm WDM}\left(M, M_{\rm hm}\right)$, (subhalos)

Modeling halos

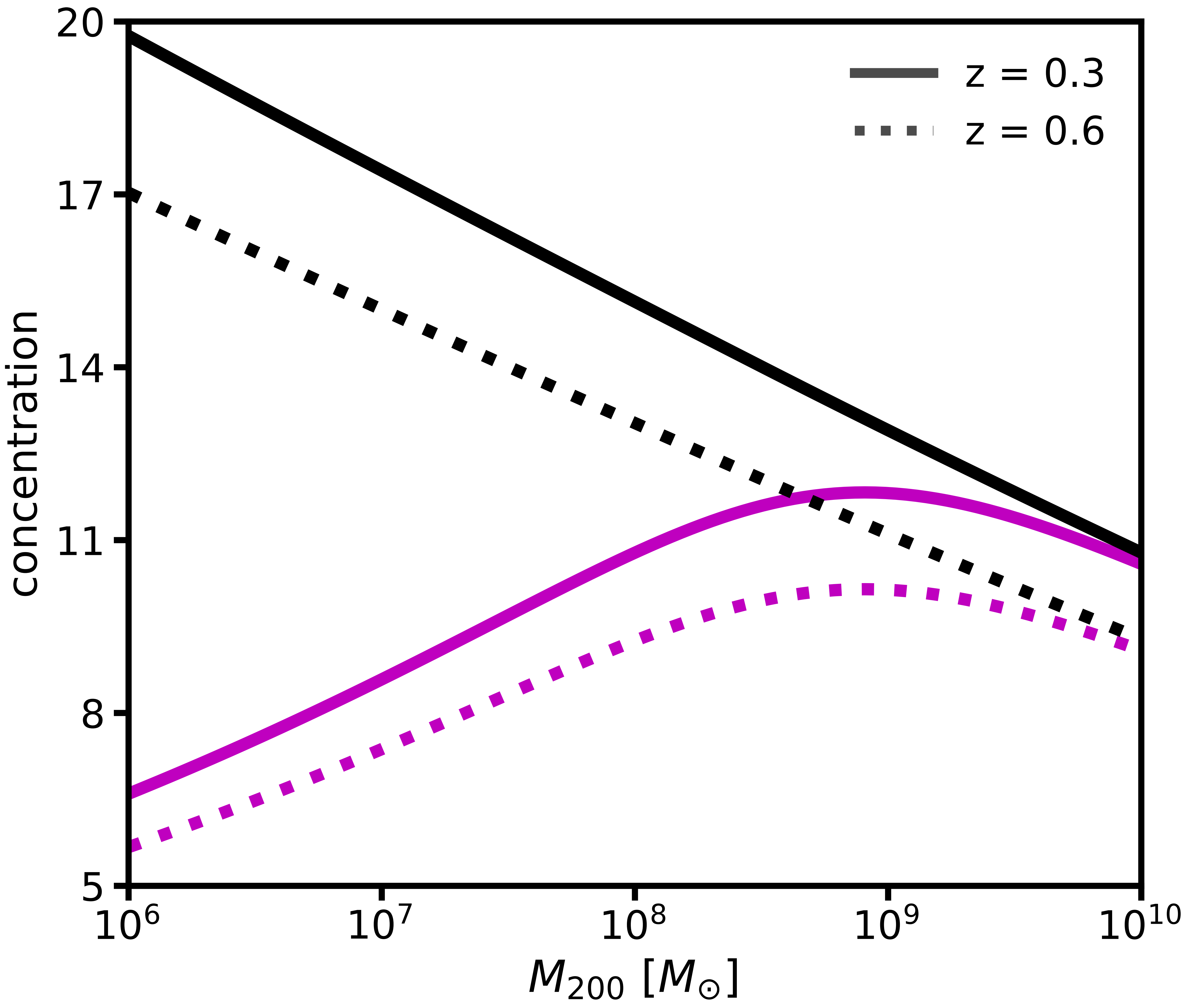
Ingredients for pyHalo

- Concentration mass relation

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

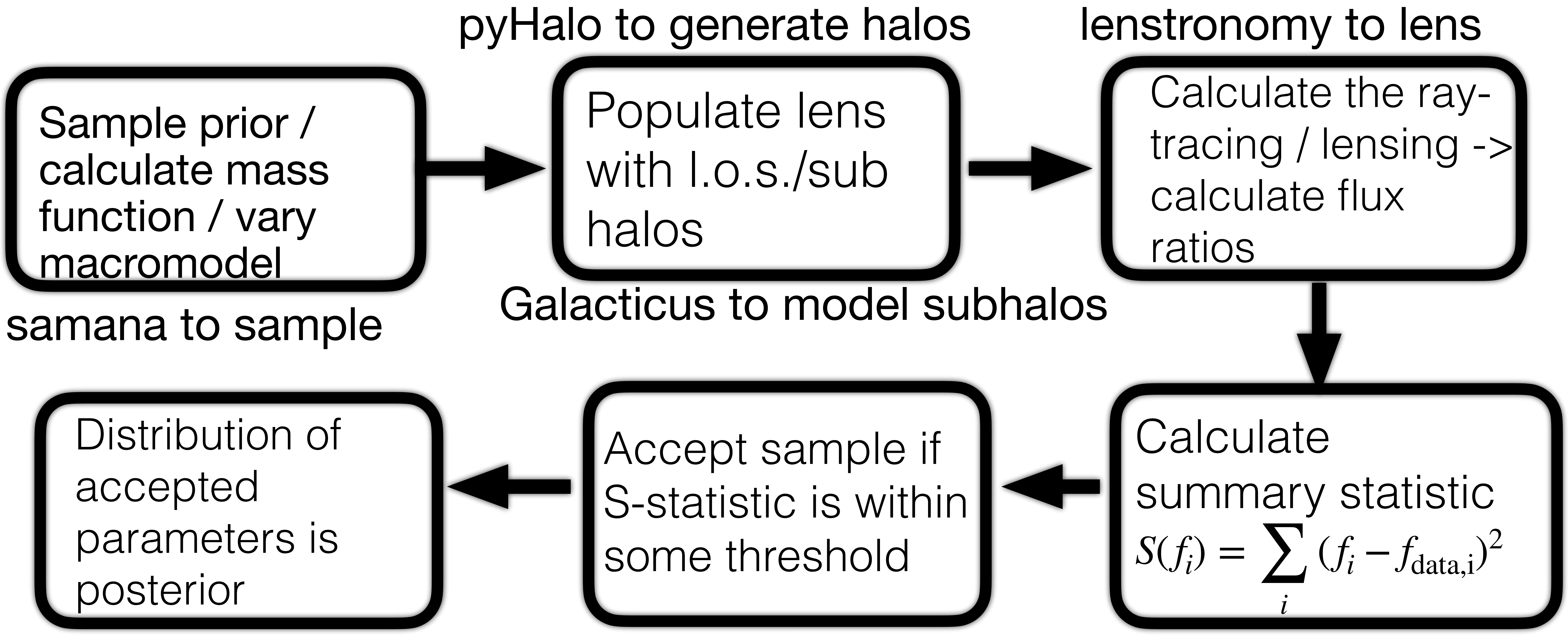
- Field halos: NFW

- Subhalos: Truncated NFW (r_t~4-10r_s)



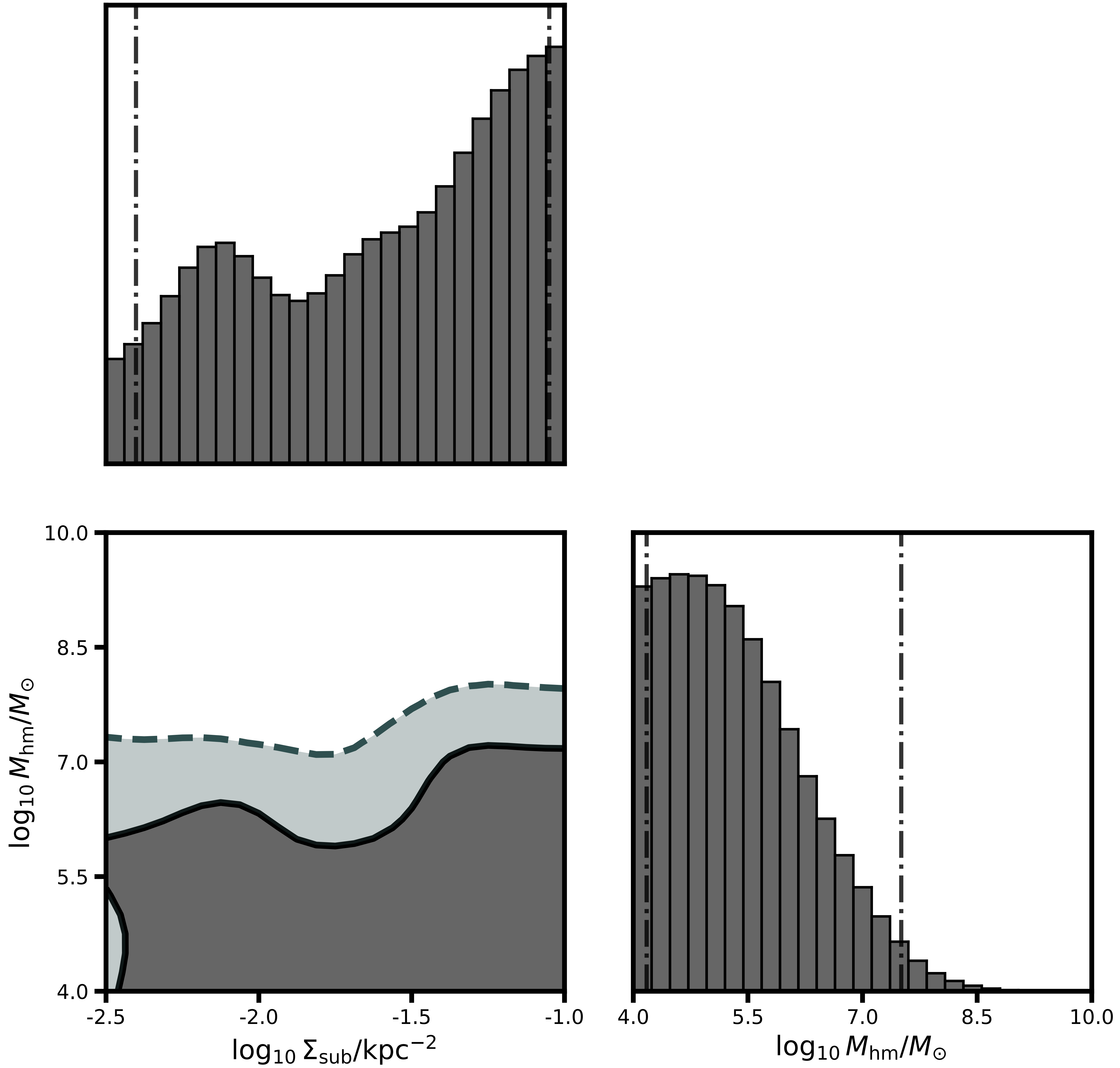
Gilman+ (1908.06983) MNRAS

ABC method


pyHalo to generate halos
lenstronomy to lens
Sample prior / calculate mass function / vary macromodel
Populate lens with l.o.s./sub halos
Calculate the ray-tracing / lensing -> calculate flux ratios
samana to sample
Galacticus to model subhalos
Distribution of accepted parameters is posterior
Accept sample if S-statistic is within some threshold
Calculate summary statistic
$S(f_i) = \sum_i (f_i - f_{\mathrm{data,i}})^2$

WDM Constraint

- 9 lenses: 0405, 0607, 0608, 0659, 1042, 1537, 1606, 2026, 2038
- $M_{\rm hm} < 10^{7.6} M_\odot$ ($m_{\rm WDM} > 6.1$ keV) (Posterior odds 10:1)
- 3.0 keV for GUT-scale produced sterile neutrino DM,
- 15 keV for miracle keV sterile neutrino DM,
- 50 keV for Dodelson-Widrow sterile neutrino DM.



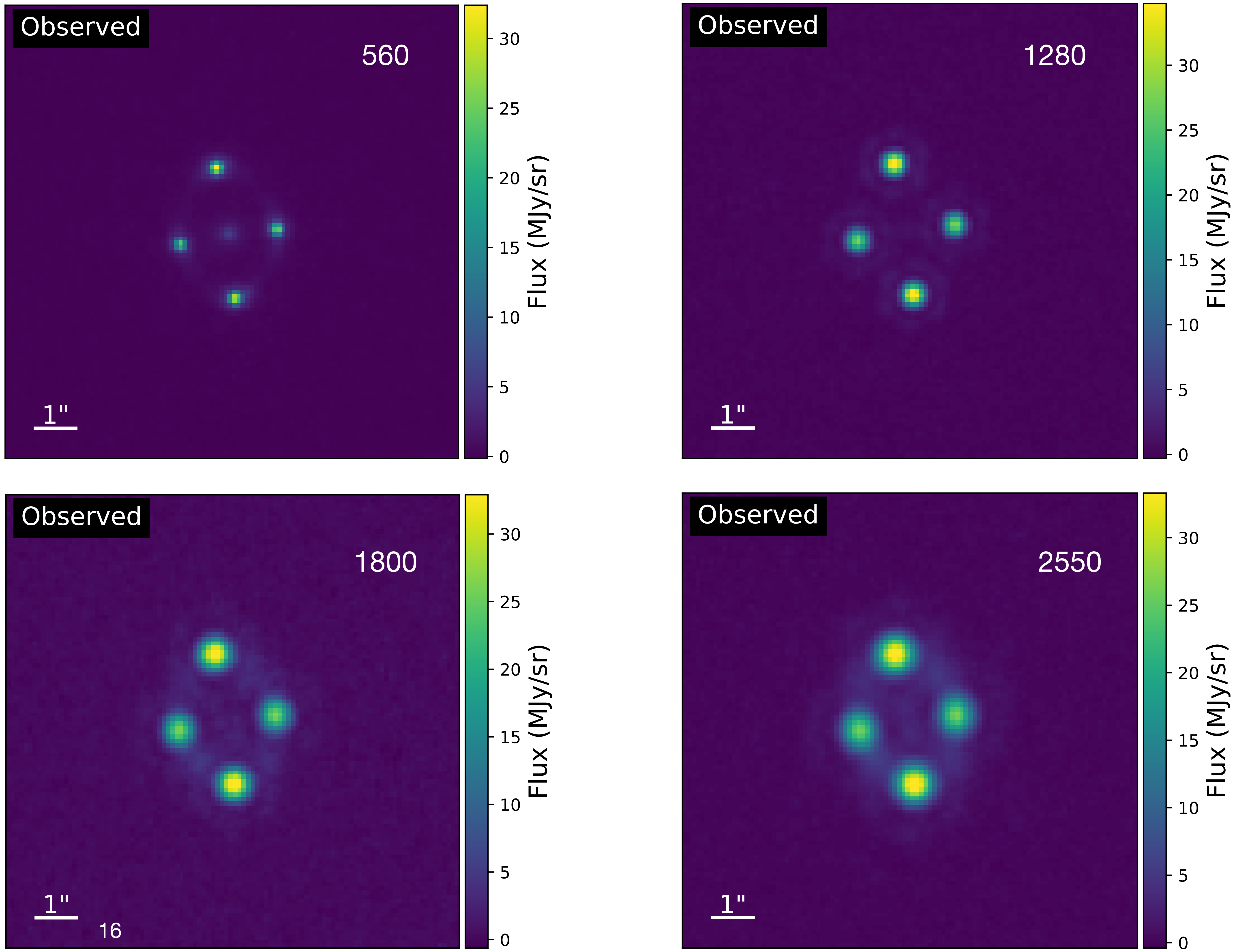
Keeley+ (2405.01620)

Summary

- $M_{\rm hm} < 10^{7.6} M_\odot$
- $m_{\rm WDM} > 6.1$ keV
- With substructure lensing we are directly observing DM and characterizing the population of completely dark DM halos, with no corresponding galaxies
- Expect even stronger probes from the full sample
- Test additional DM models using this formalism (SIDM, FDM)
- Joint constraints using additional tracers (arcs, satellites, streams, Lya)

Ex JWST data: J1537-3010

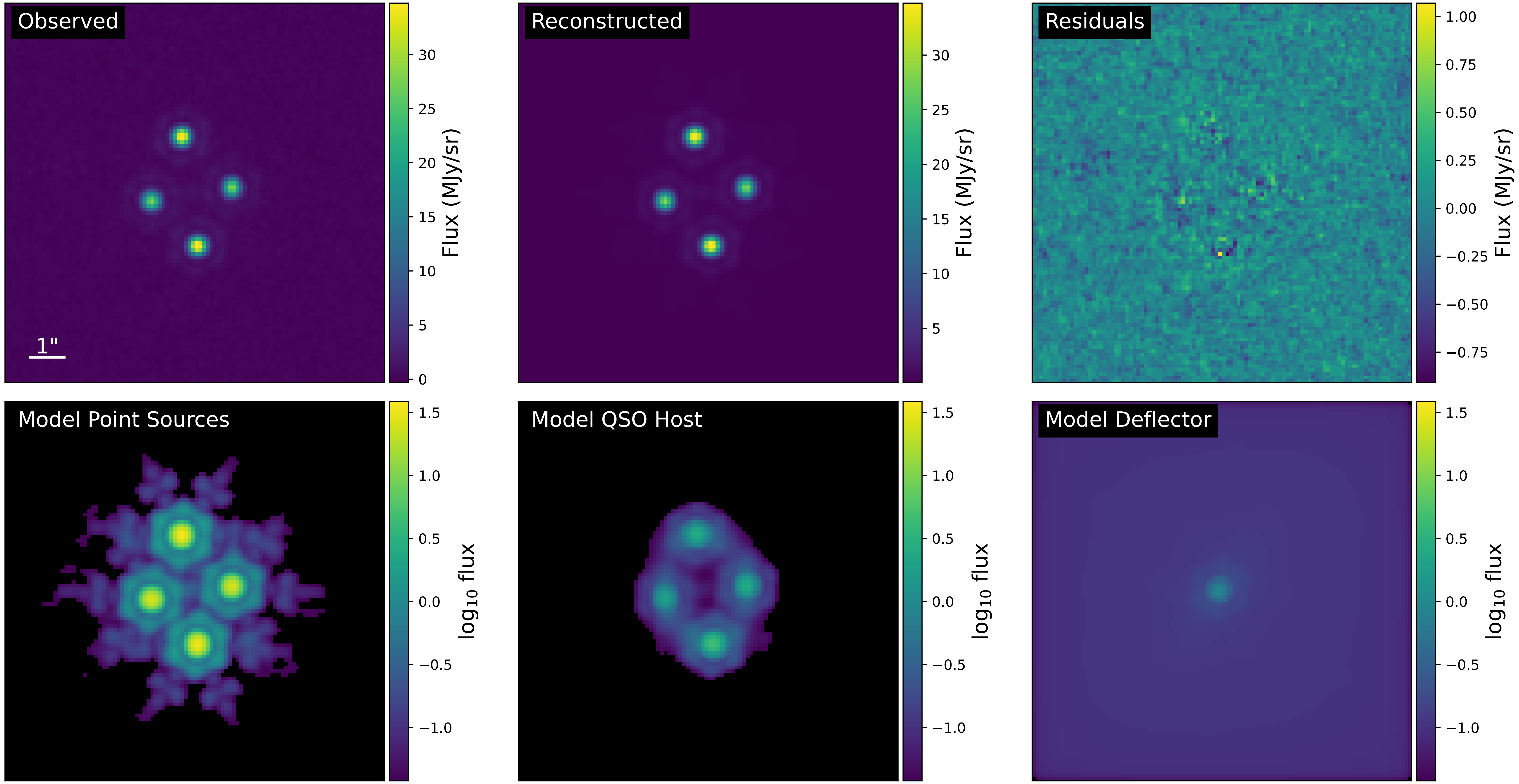
Observe quad lenses in 4 JWST MIRI filters f560w, f1280w, f1800w, f2550w



Keeley et al 2024

Ex Fitting Results: J1537-3010

Model data with point source, lensed light from QSO host (arc), deflector light

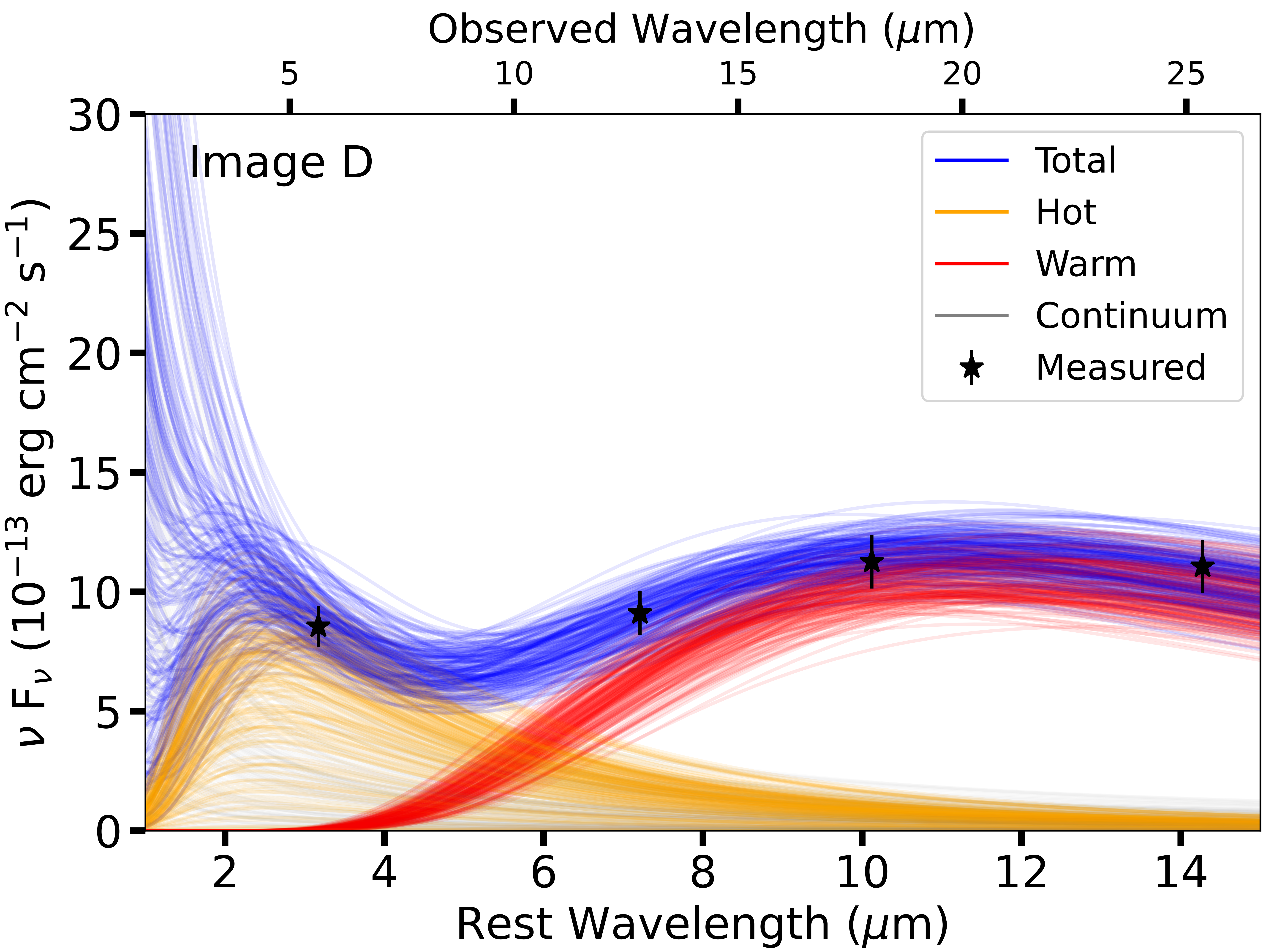


Keeley et al 2024

Ex SED Results

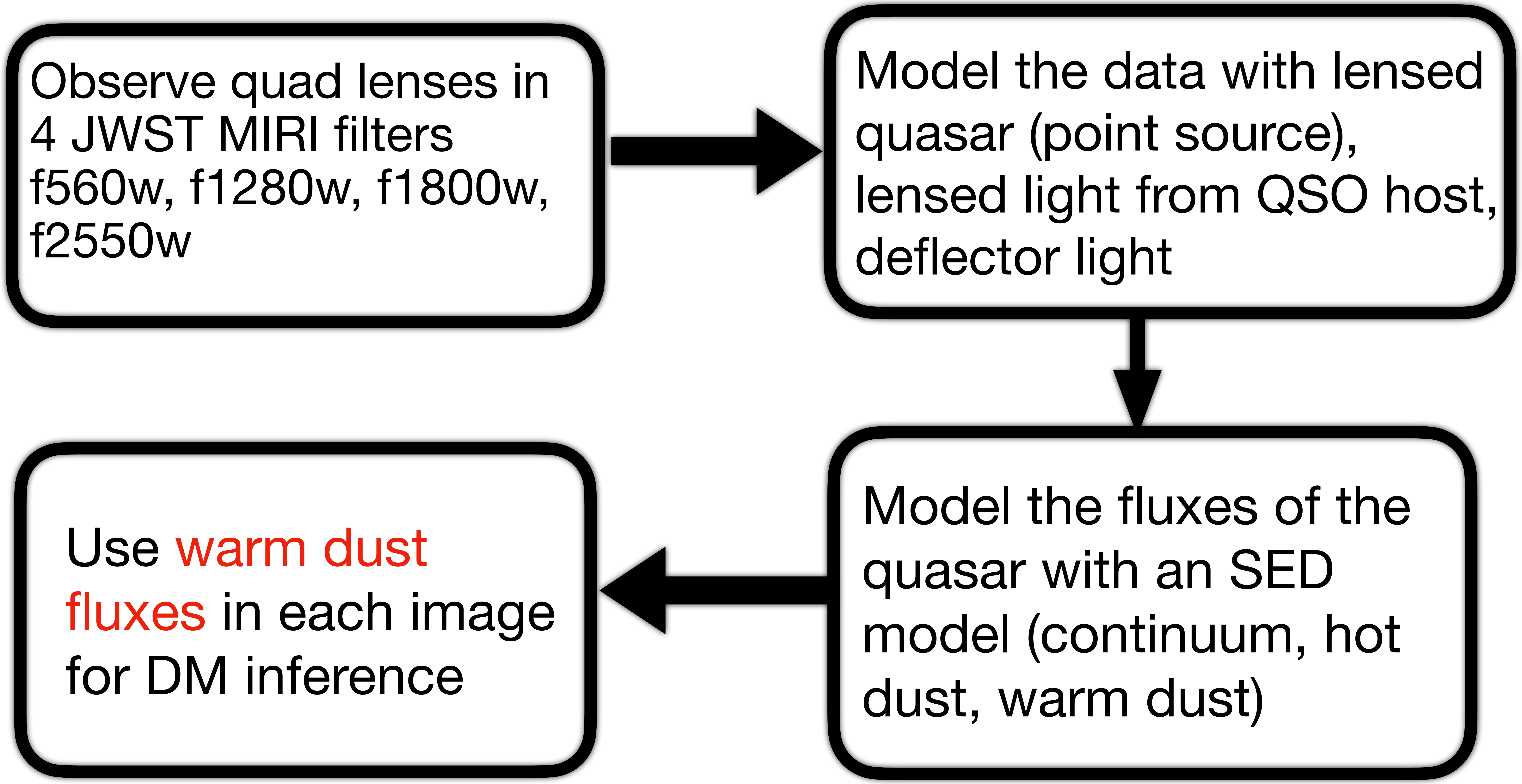
Model the fluxes of the point sources with an SED model:
-continuum
-hot dust
-warm dust

Plot: Samples from posterior; temperature and flux of each component are varied



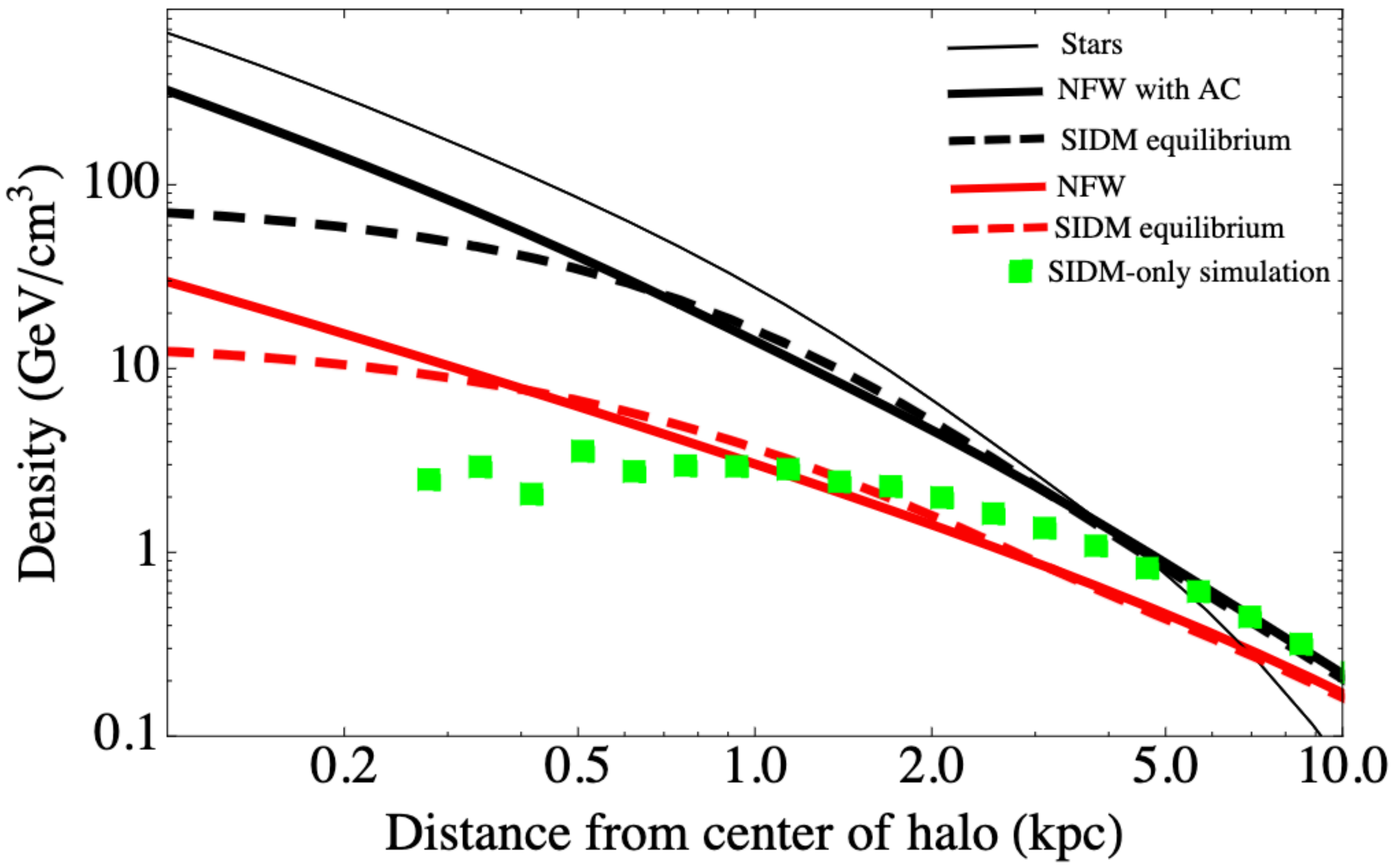
Keeley et al 2024

Fitting JWST data



What Is Needed for SIDM

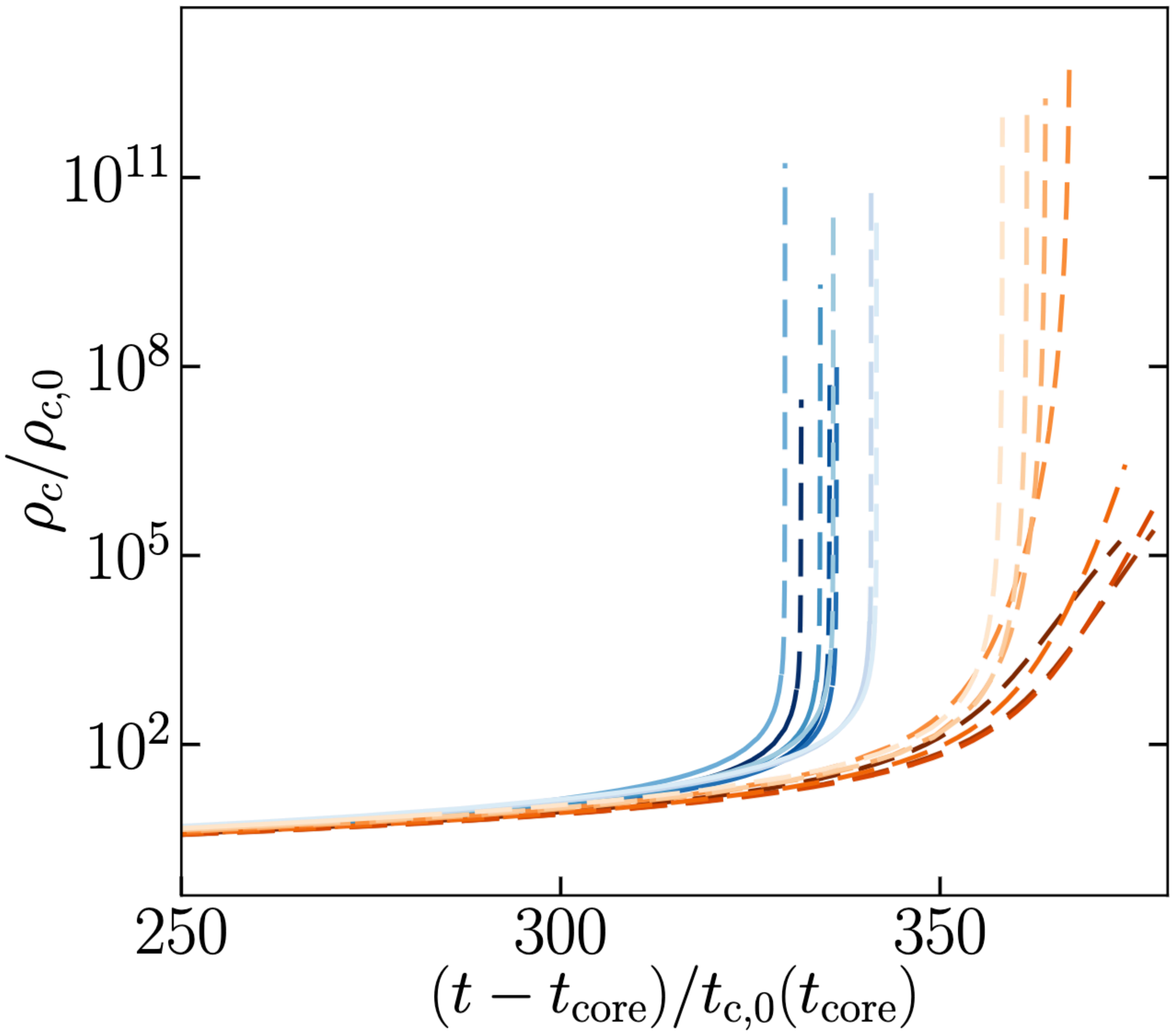
- Cores



Kaplinghat, Keeley et al 2024

What Is Needed for SIDM

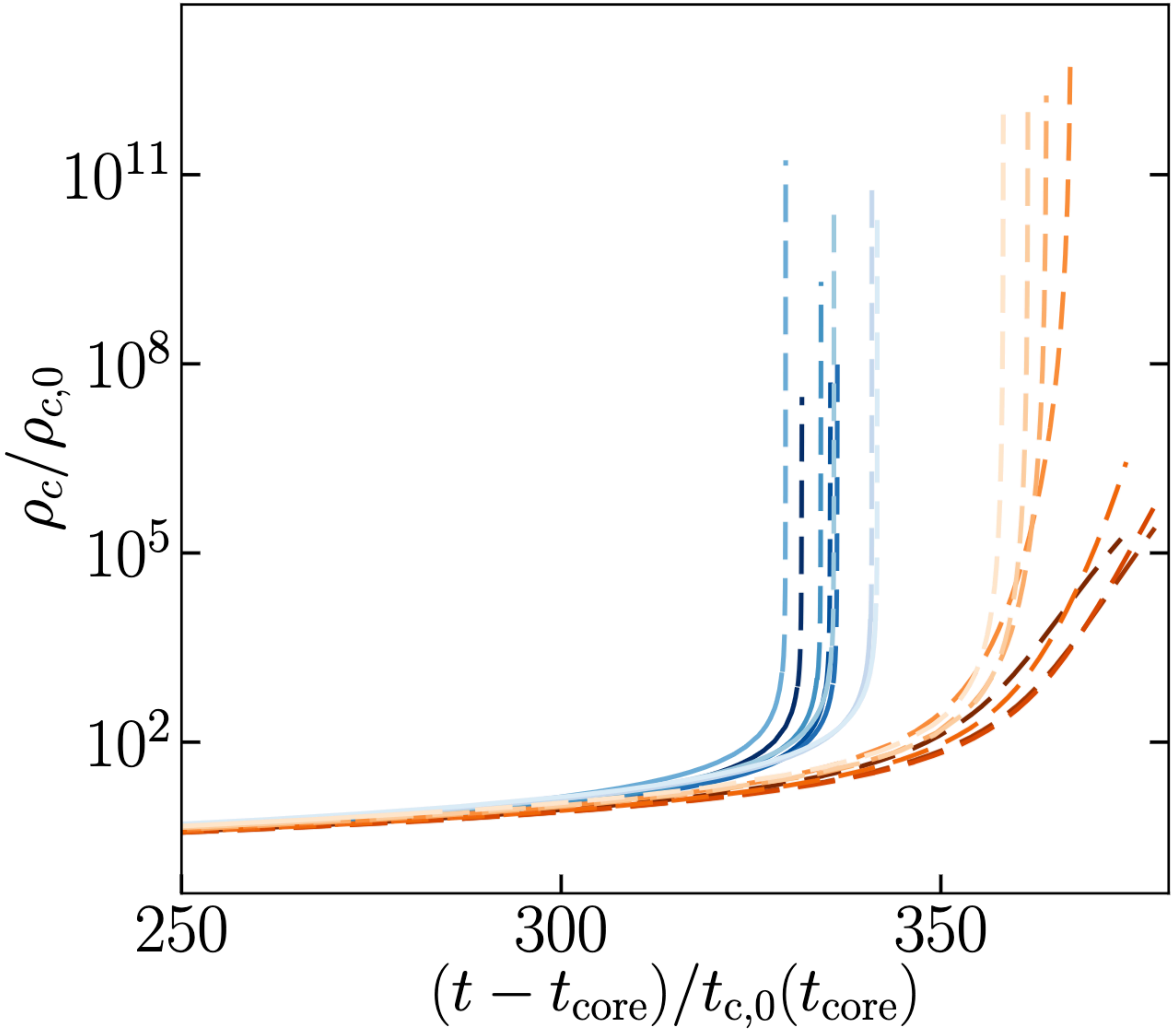
- Cores
- Core-collapse



Gad-Nasr et al 2023

What Is Needed for SIDM

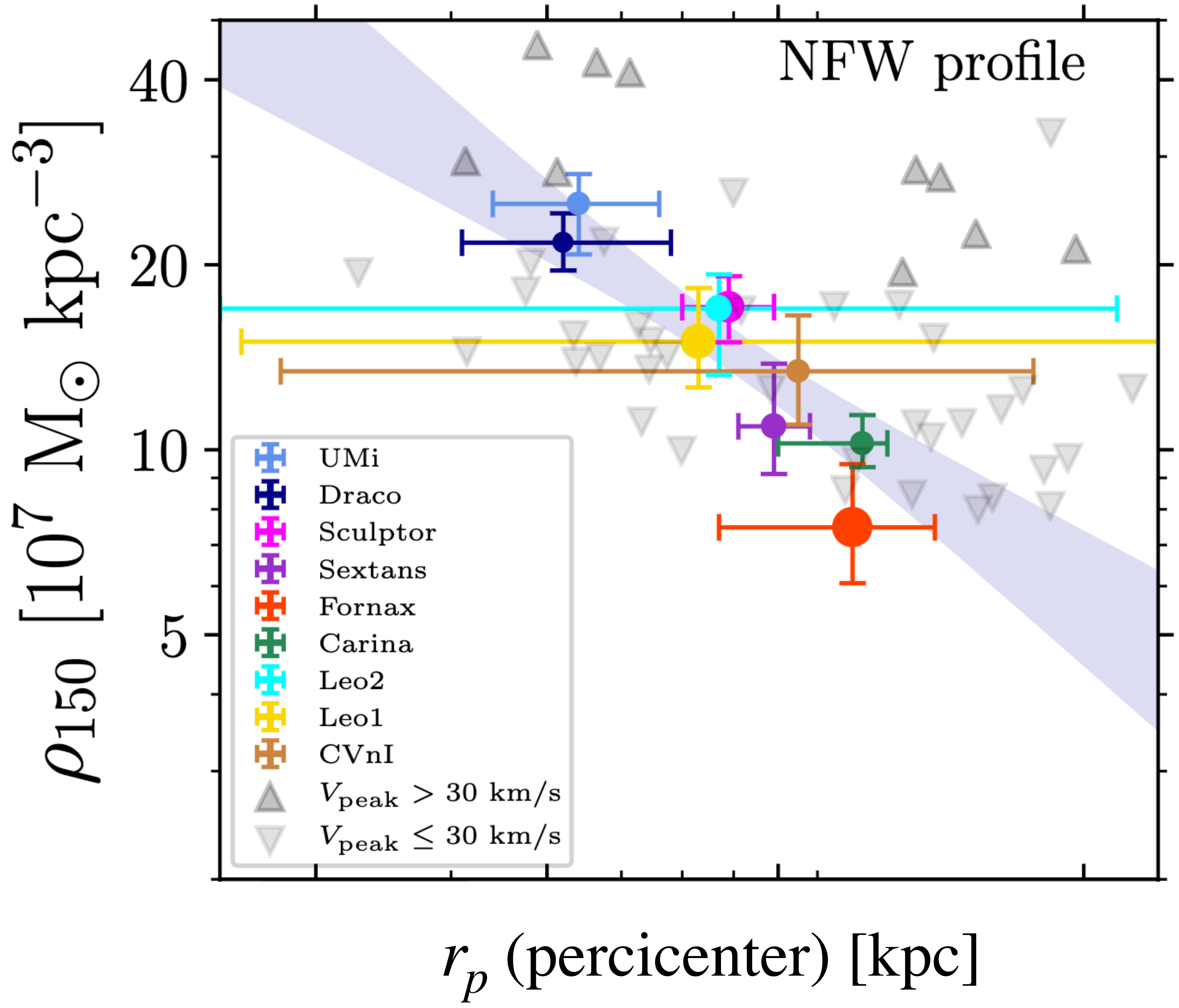
- Cores
- Core-collapse
- Core-collapse triggered by stripping



Gad-Nasr et al 2023

What Is Needed for SIDM

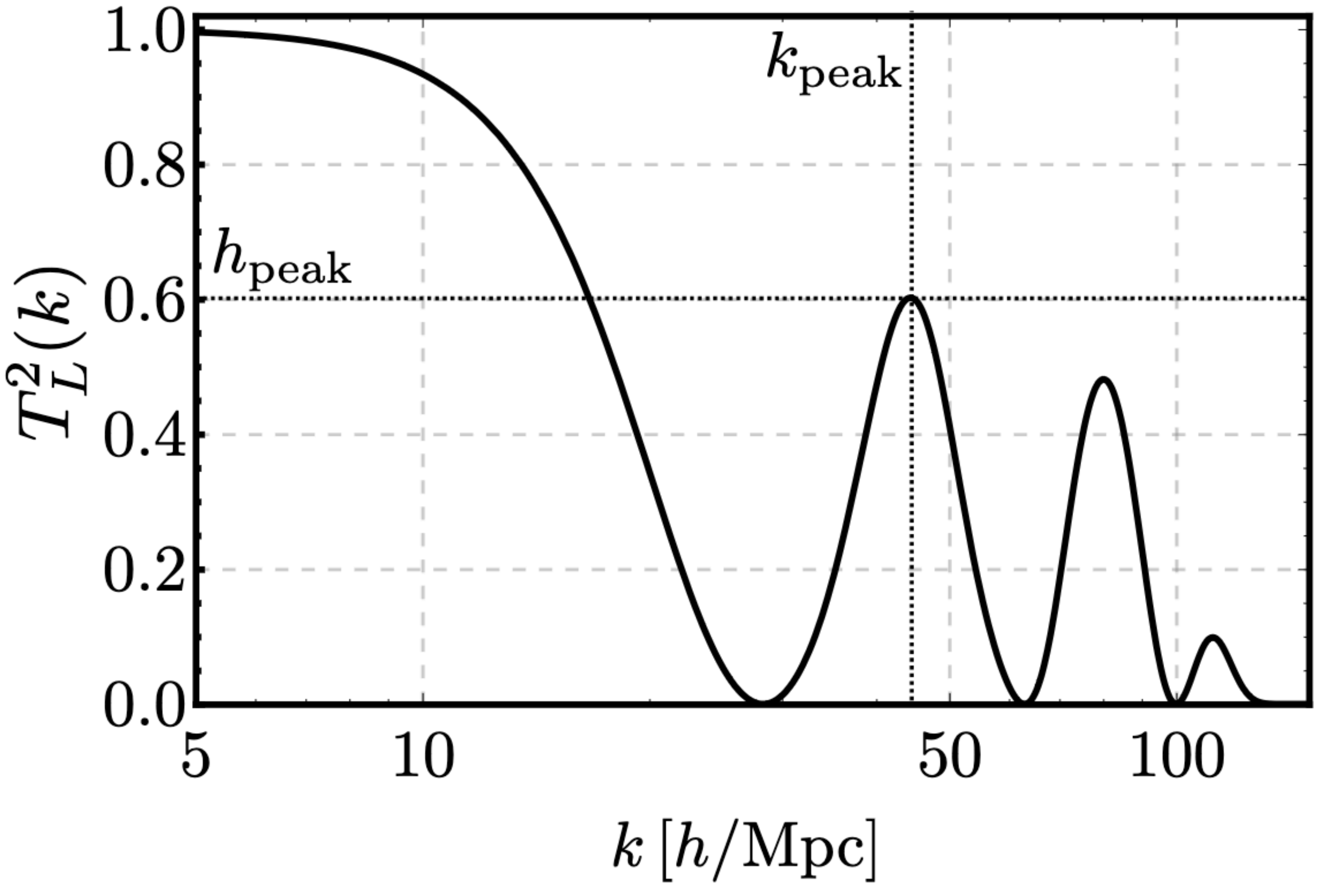
- Cores
- Core-collapse
- Core-collapse triggered by stripping
- Anti-correlation between concentration and pericenter



Kaplinghat et al 2019

What Is Needed for SIDM

- Cores
- Core-collapse
- Core-collapse triggered by stripping
- Anti-correlation between concentration and pericenter
- Suppression
- Dark acoustic oscillations



Munoz et al 2020

MixDM

Forecast constraints

- Mock data generated from a MixDM model
- Posterior of parameters $\Sigma_{\rm sub}$, $M_{\rm hm}$, f
- $f = 0,\ M_{\rm hm} = 10^{10},\ \Sigma_{\rm sub} = 0$ corner with least structure (warmest)
- Easier to differentiate between MixDM and CDM than MixDM and WDM