

Pushing the Limits of Detectability: MixDM

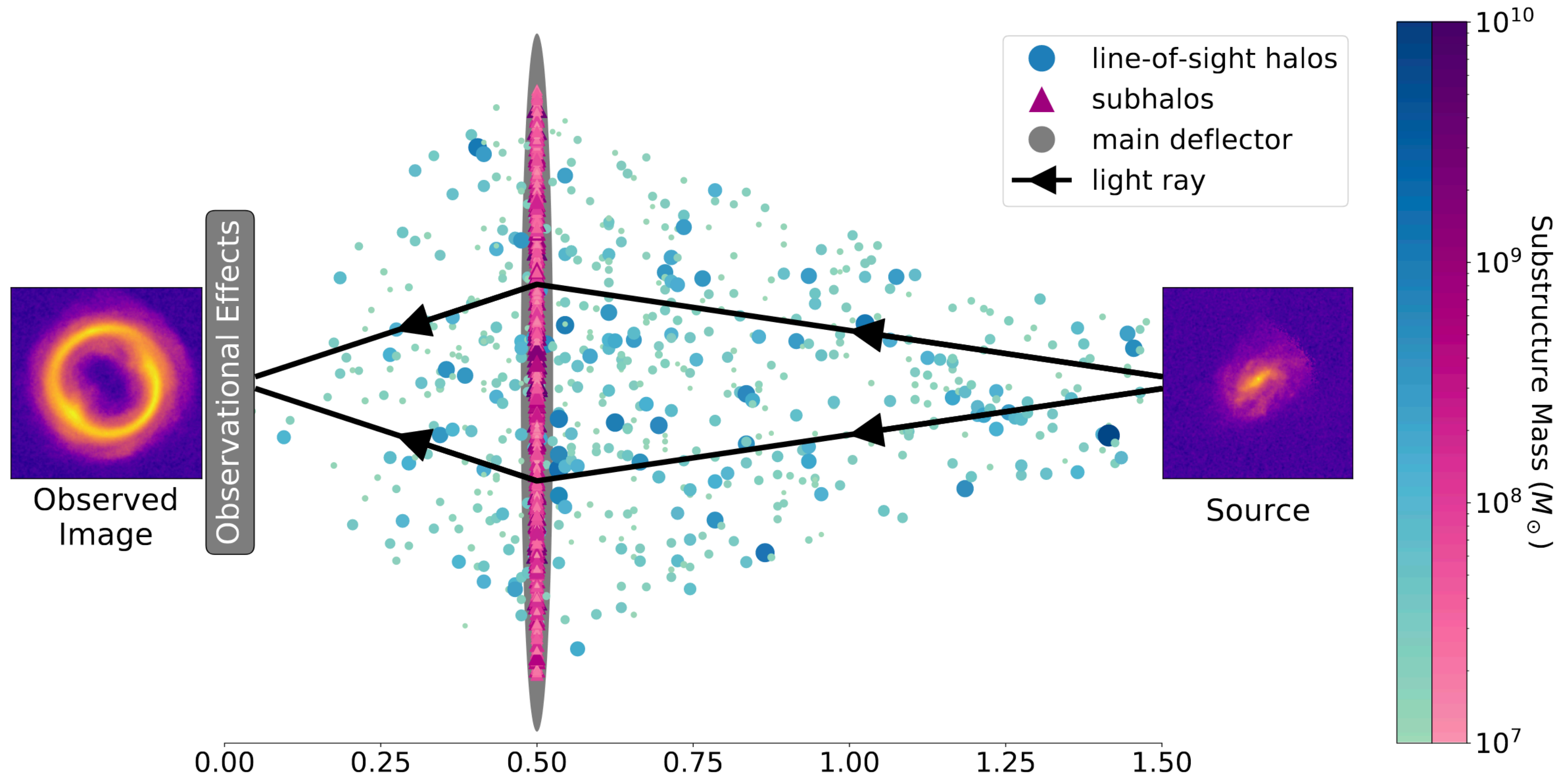
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Pollica Workshop
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DM in astrophysical environments

- Probes:
 - Rotation curves / velocity dispersion
 - Cold stellar streams
 - Dwarf galaxies / satellite galaxies
 - Weak lensing
 - Strong Lensing
 - Wide binaries

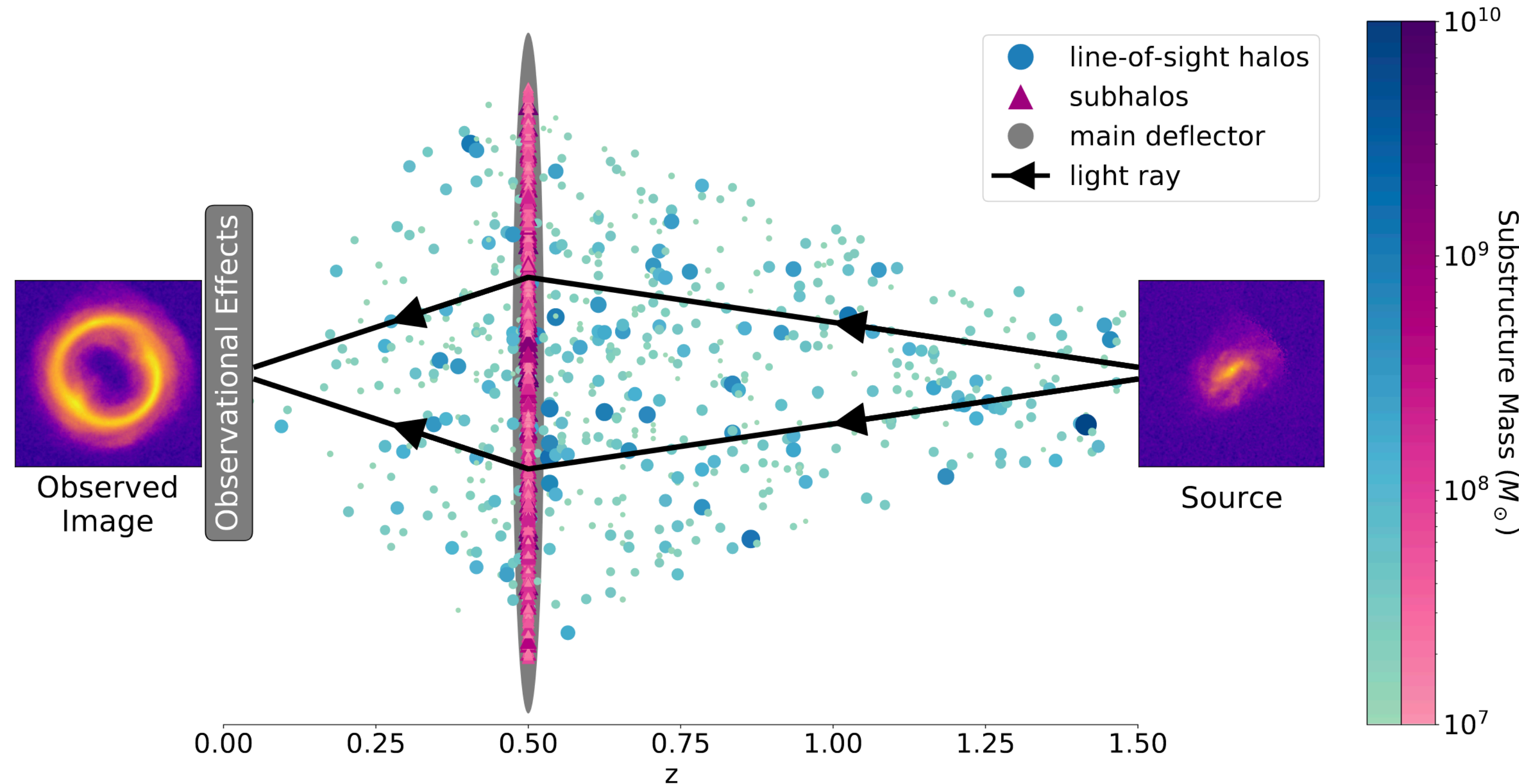


Wagner-Carena et al arXiv:2203.00690

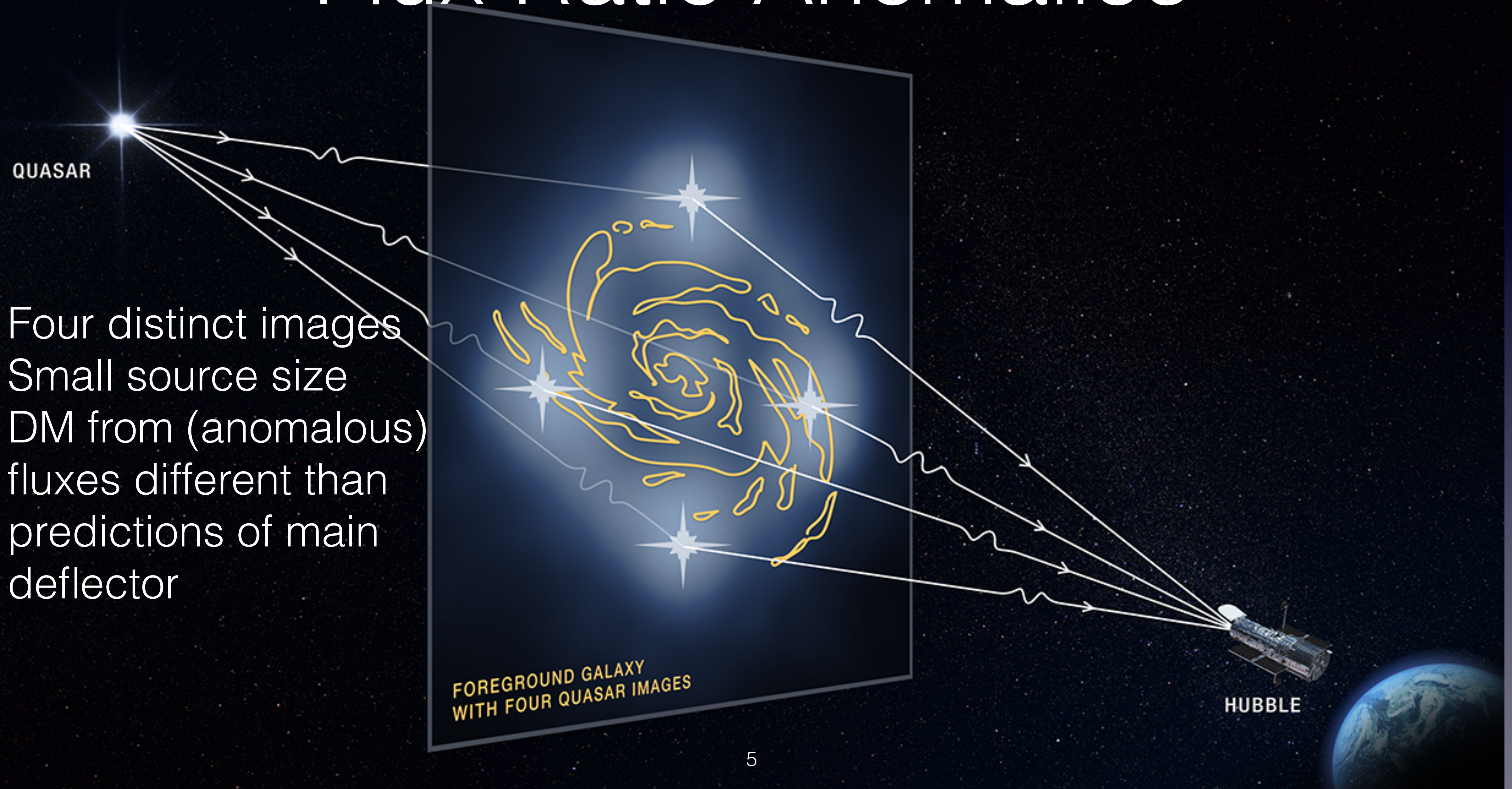
- Gravitational potential: $\psi(\vec{\theta}) = \frac{D_{DS}}{D_D D_s} \frac{2}{c^2} \int^z dz \Phi(D_D, \vec{\theta}, z)$
- Deflection: $\vec{\alpha}(\vec{\theta}) = \vec{\nabla} \psi$, magnification: $M^{-1} = \delta_{i,j} - \frac{d\psi}{d\theta_i d\theta_j}$

Gravitational Imaging

- Extended arcs
- Larger source sizes
- DM from perturbations and distortions to the shape and magnification of arc

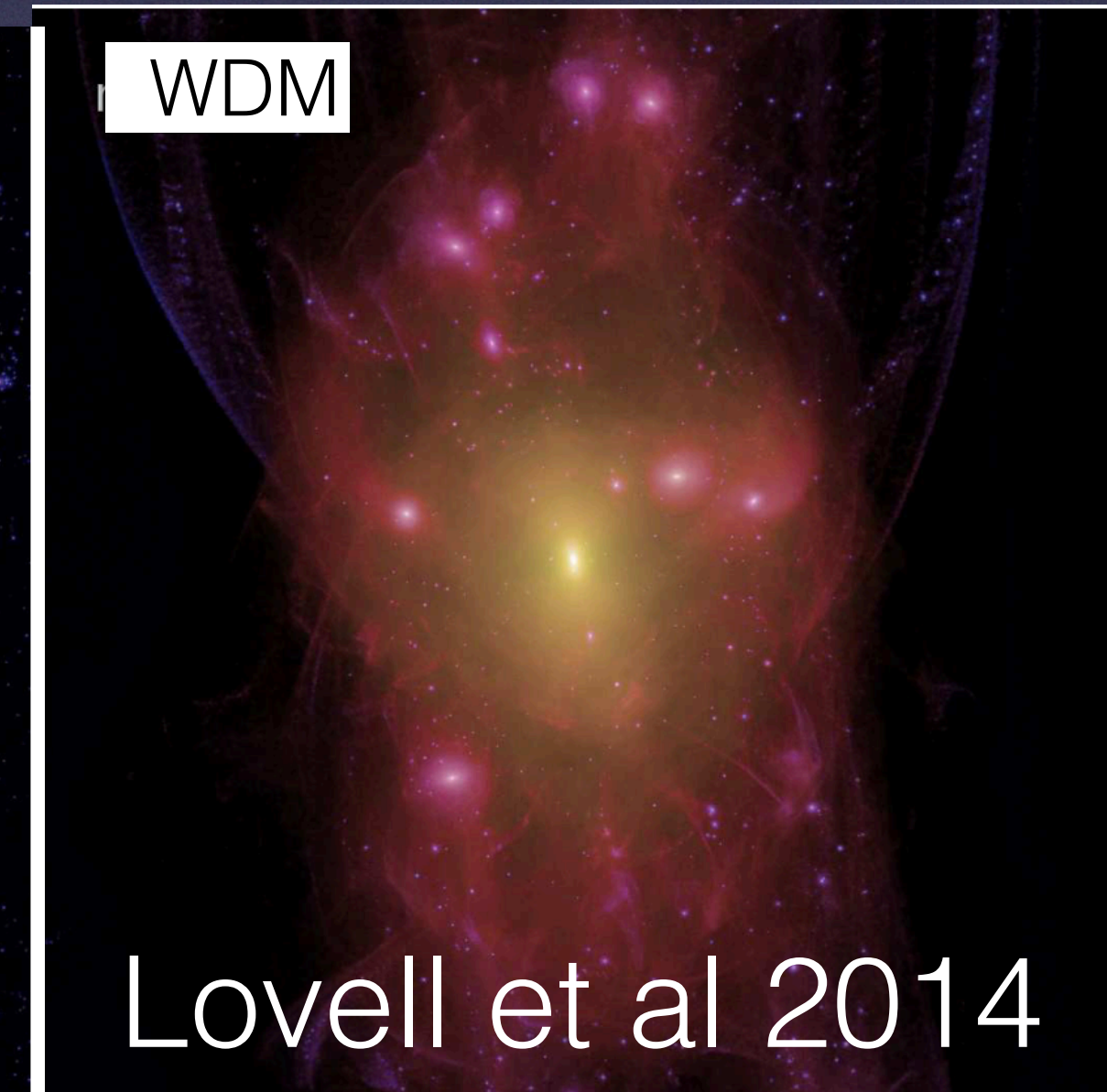
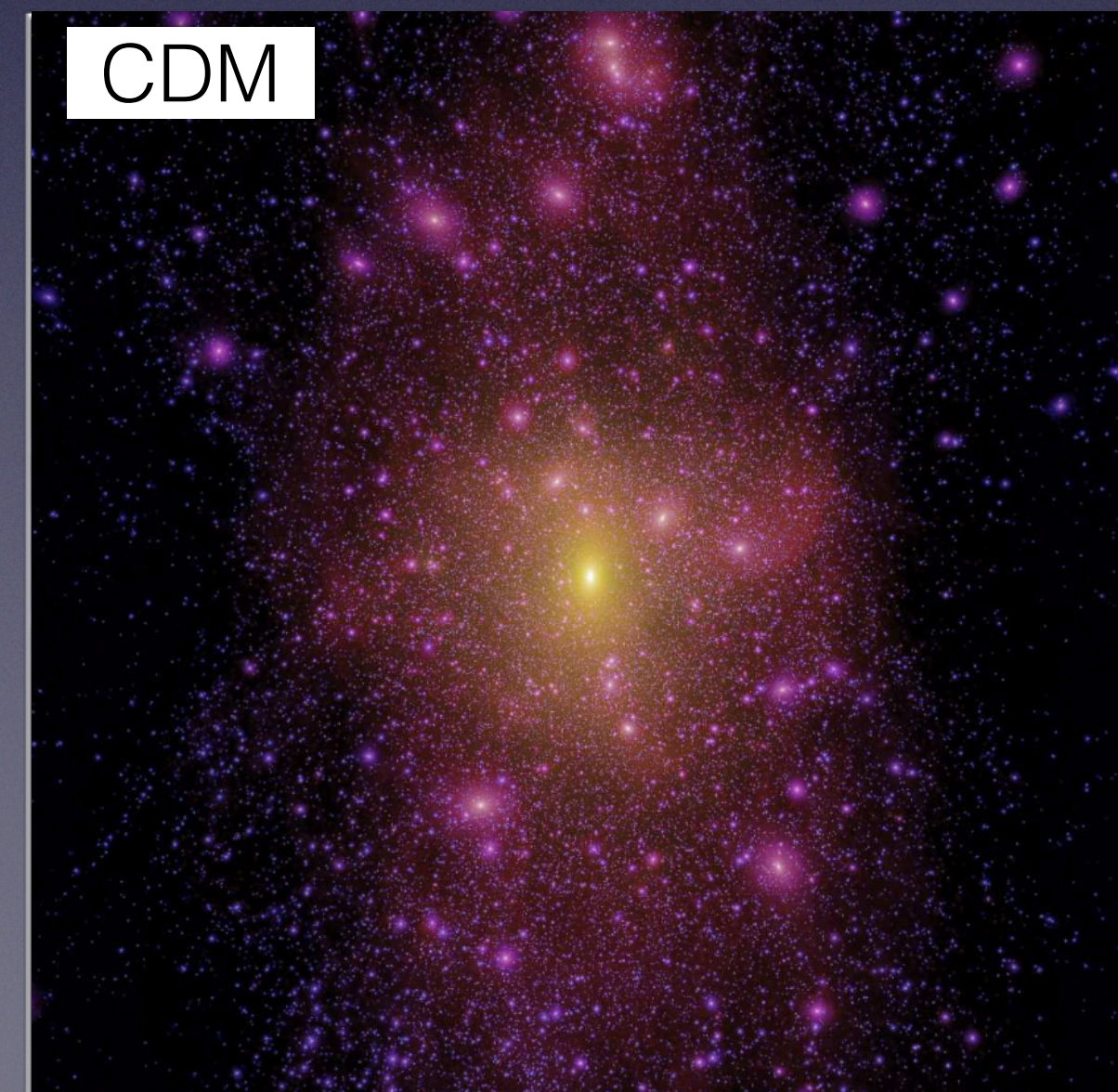


Flux Ratio Anomalies



Warm Dark Matter

- Cold DM predicts an abundance of DM halos at small masses
- Warm DM predicts few - structure suppressed at small scales
- Constrained by observing the smallest gravitationally bound halos
- Masses on the order of keV
- e.g. sterile neutrinos

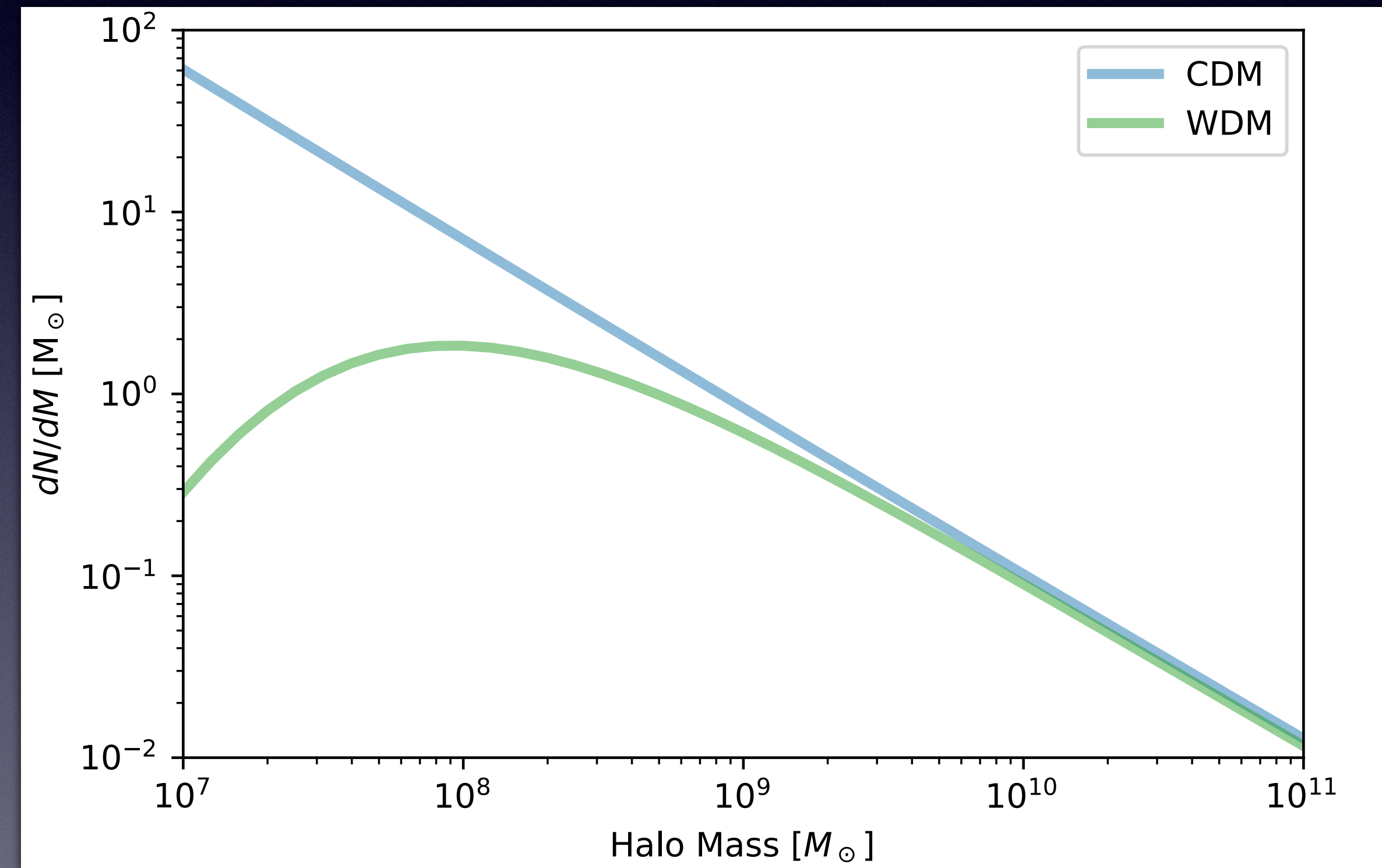


Lovell et al 2014

Halo Mass Function

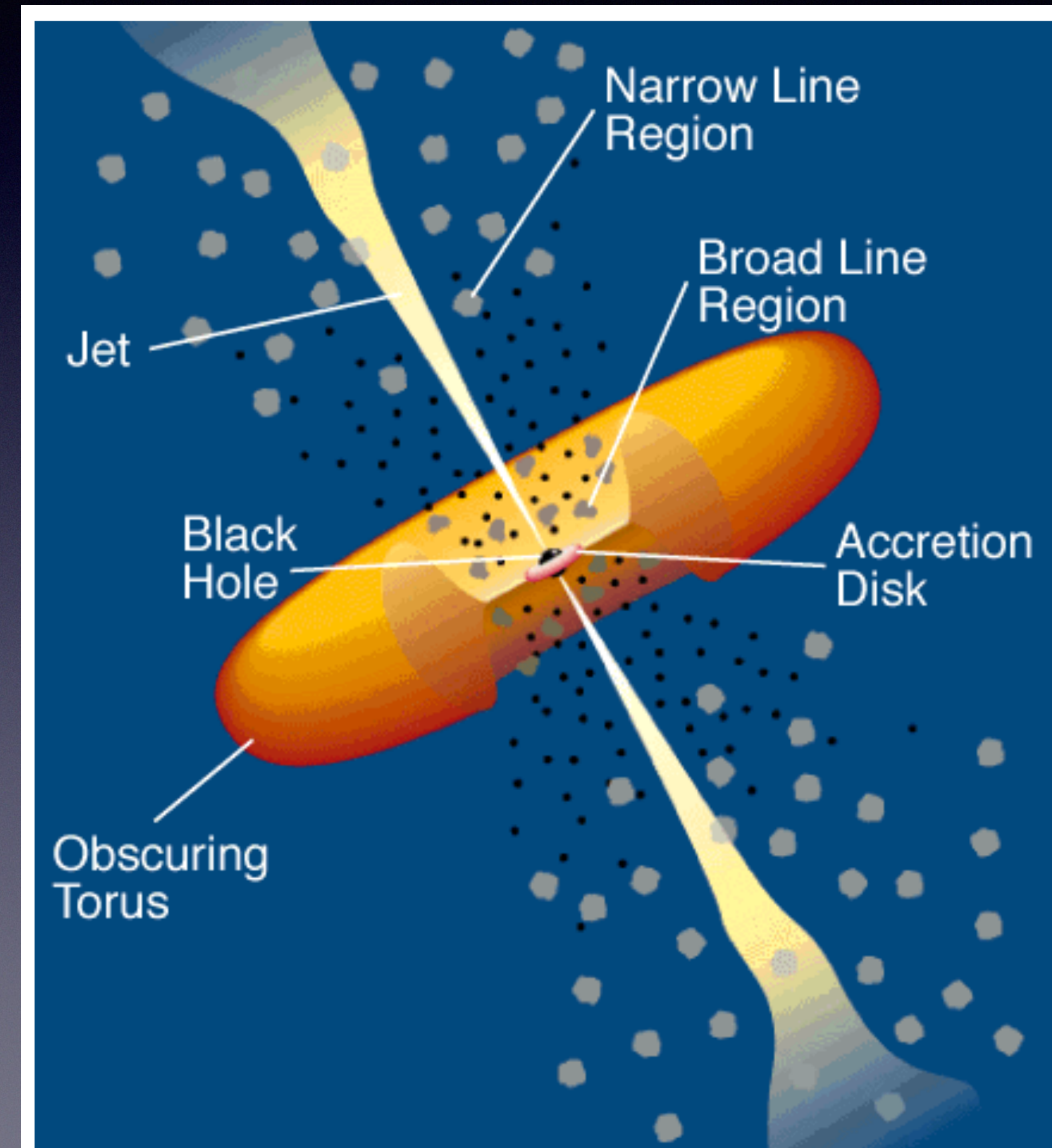
- Half-mode mass, where suppression is half compared to CDM
- Where suppression starts determined by the mass of DM particle

$$M_{\text{hm}} = 5.5 \times 10^{10} \left(\frac{m_{\text{WDM}}}{1 \text{ keV}} \right)^{3.33}$$



Strong Lensing of Quasars

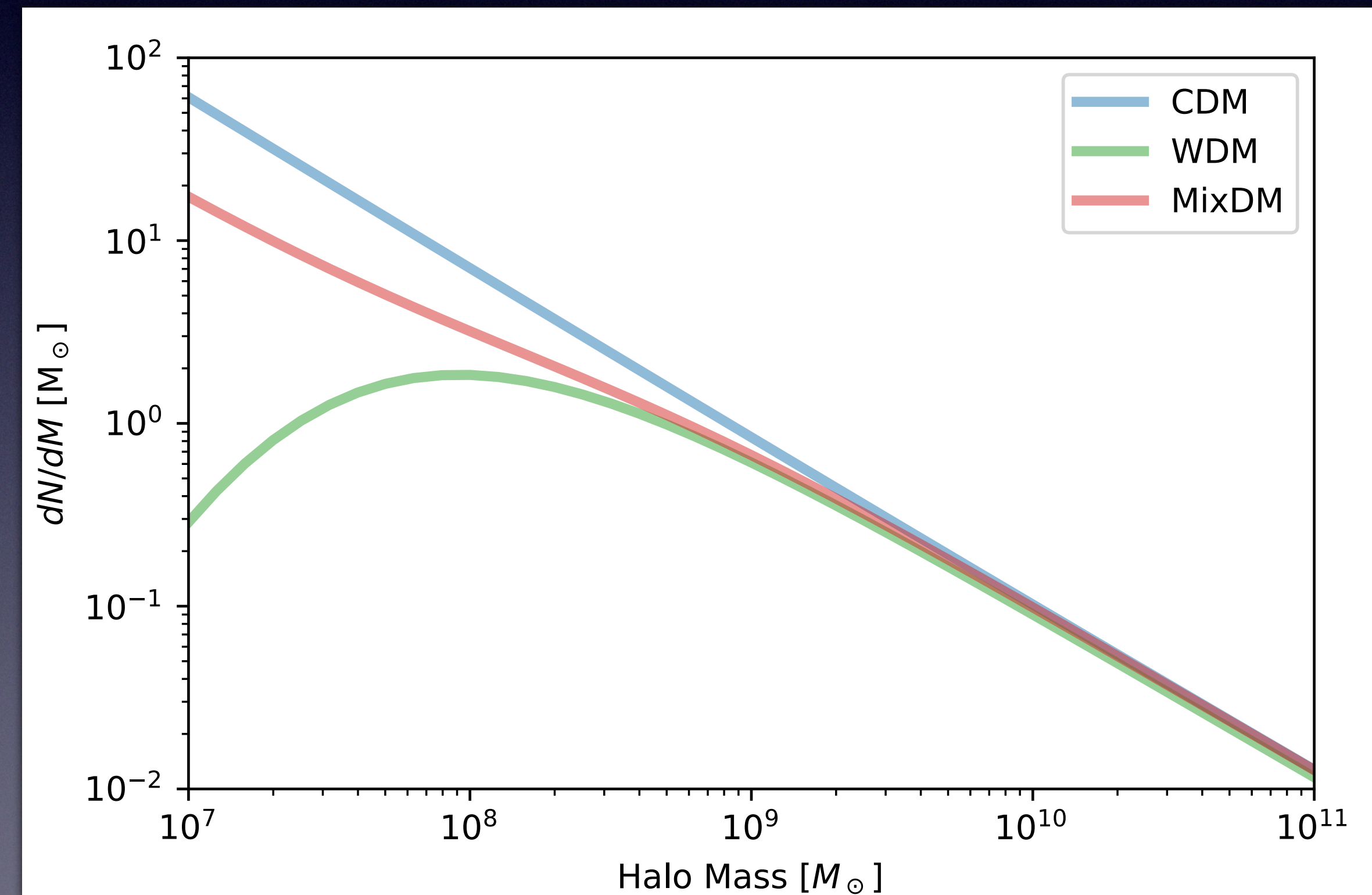
- For lensing, different regions are of different physical sizes and emit in different wavelengths -> separate tracers
- Smaller source sizes are more sensitive to lower mass DM halos
- Observe narrow line region with HST/Keck and cold torus with JWST



Mixed DM

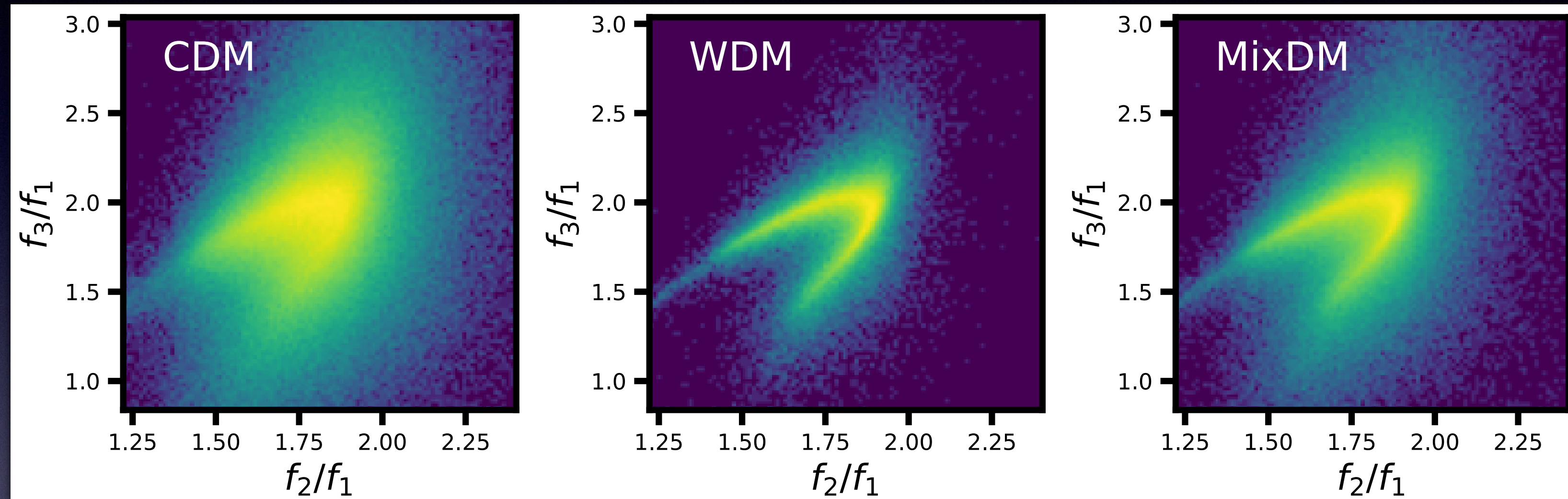
- Test an intermediate case - 1/2 cold DM and 1/2 warm DM
- Cold DM component still forms low-mass DM halos
- Warm DM component suppresses structure growth
- E.g. WIMP + sterile neutrino; Primordial black hole + axion-like particle

- $$\frac{dN/dM_{MixDM}}{dN/dM_{CDM}} = (f + (1 - f)(1 + a(M_{hm}/M)^b)^c)^2$$



Anomalous Fluxes

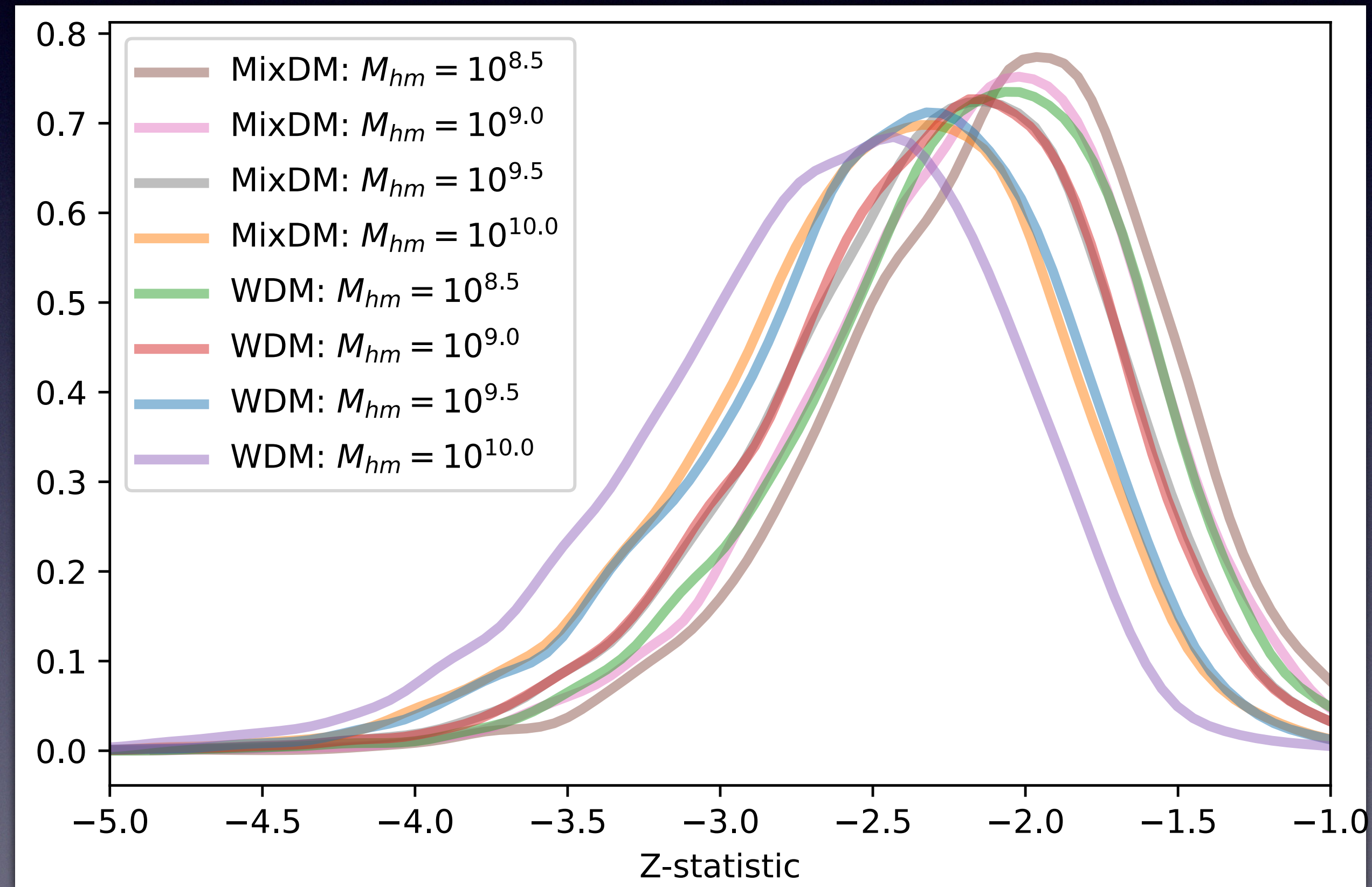
- Model predicts *distribution* of fluxes, not a single value
- Need machine learning, simulation-based (likelihood-free) statistical inference



- Ratios of fluxes from quadruply lensed images
- Ratio to divide out unknown flux of source

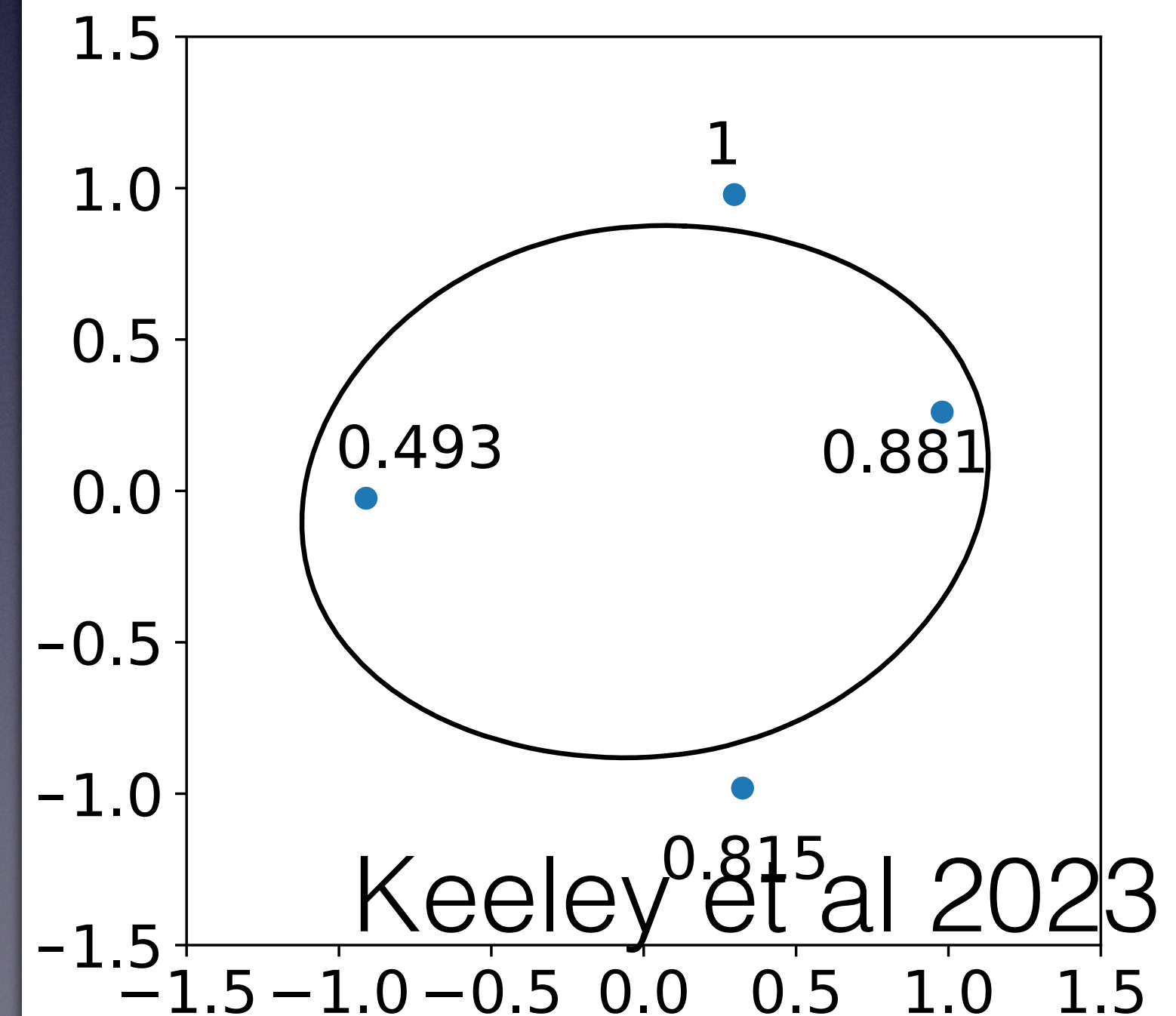
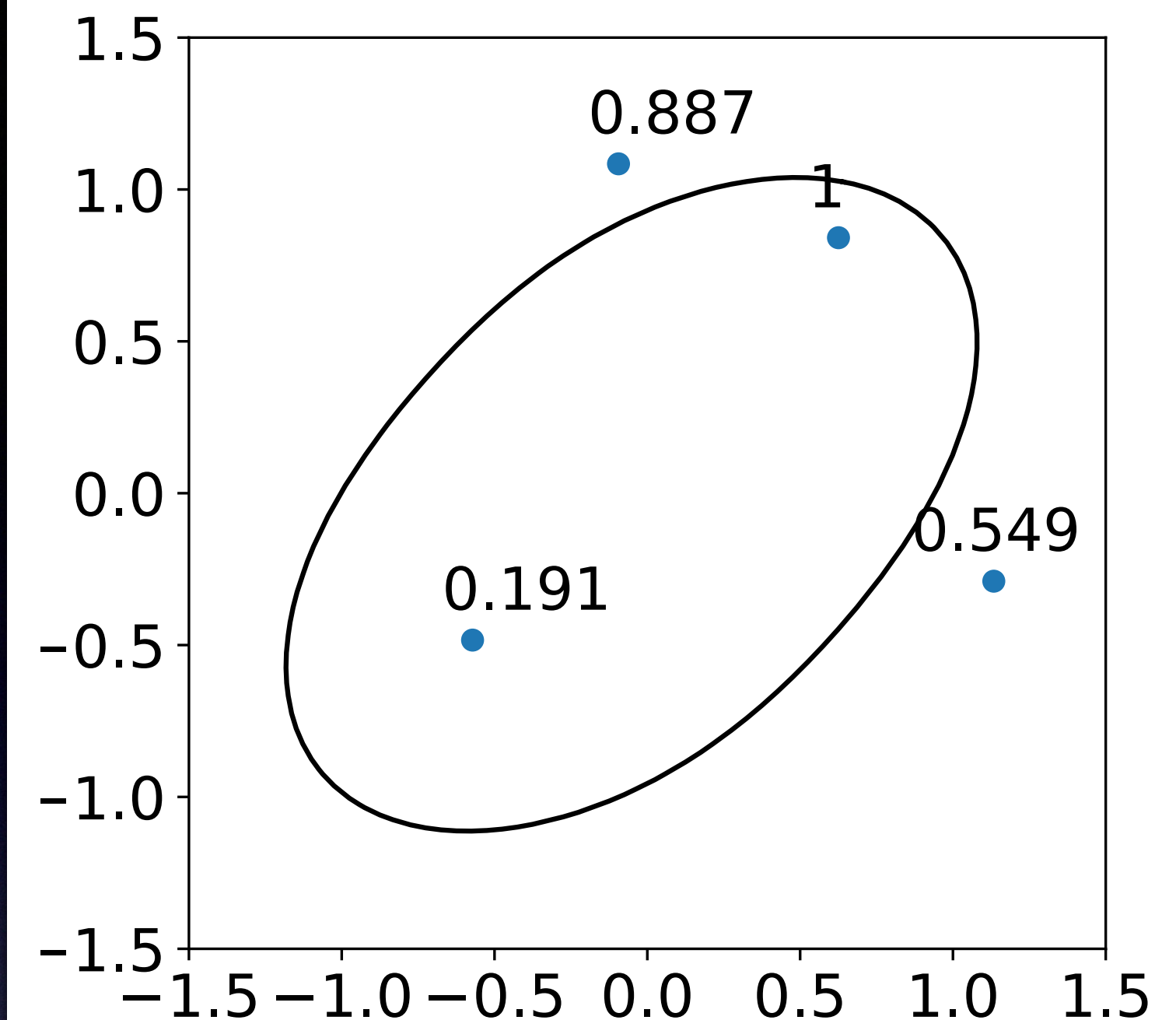
Degeneracies

- $Z(f_i) = \log \left(\sum_i (f_i - f_{\text{ref},i})^2 \right)$
- Distributions of the same lens
- Model predicts distribution of fluxes
- If distributions are same, then cannot distinguish
- For any WDM model, there exists a MixDM model with different parameters that predicts the same distributions



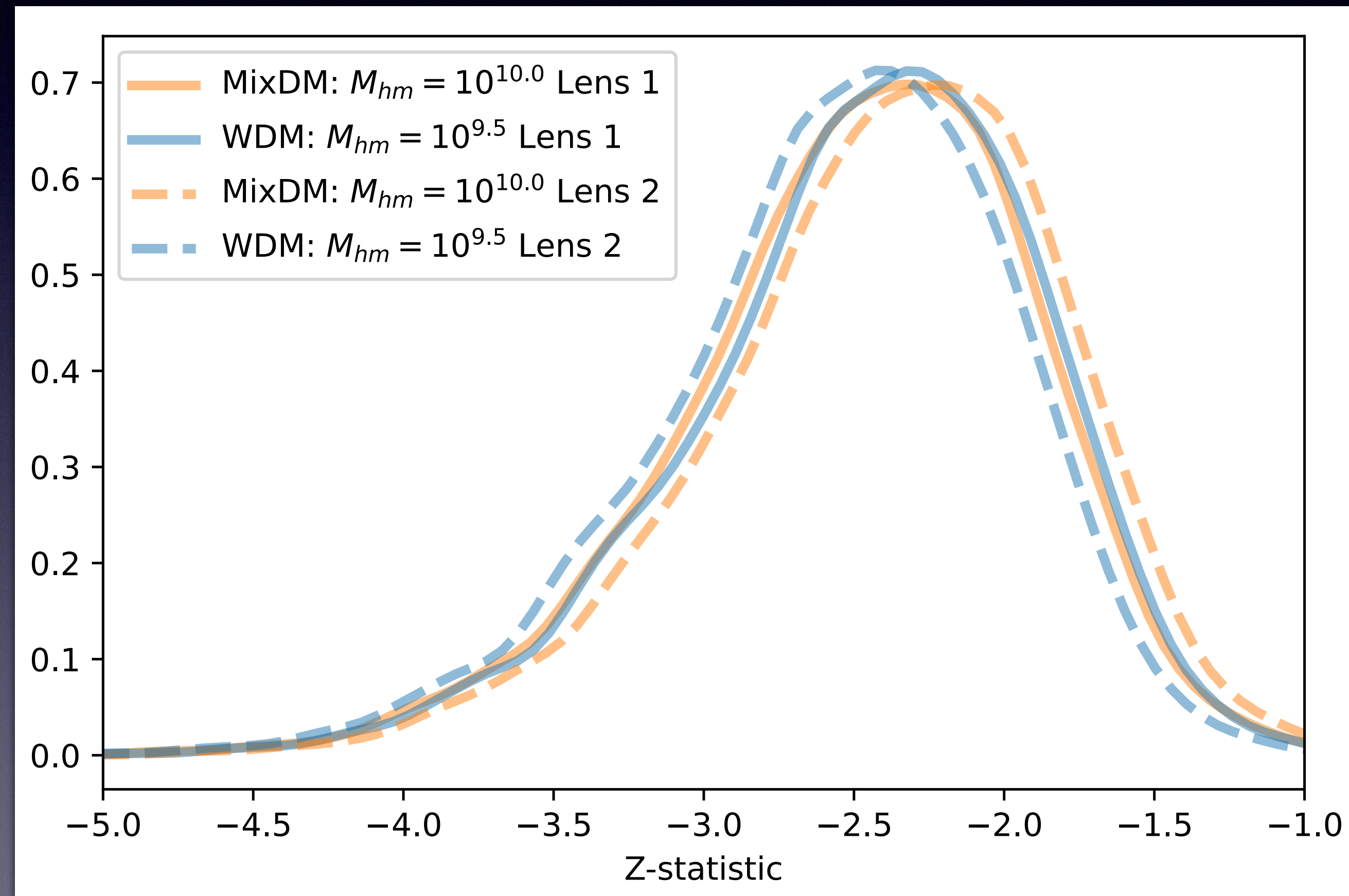
Breaking Degeneracies

- Flux ratios of four images for two different gravitational lenses
- Test whether / to what extent different configurations of a gravitational lens will probe different parts of the halo mass function and hence break degeneracies between models

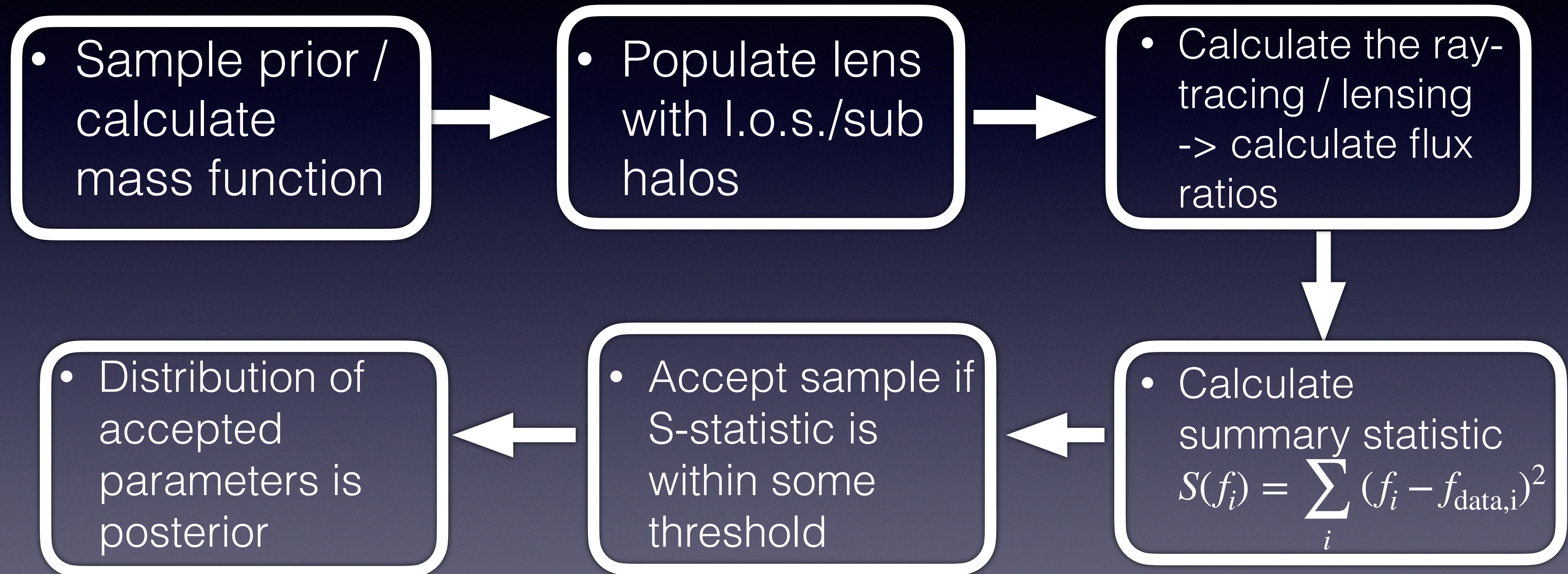


Breaking degeneracies

- Distributions from different lenses
- Predicted distributions depend on configuration of lens
- So correspondence between WDM and MixDM parameters depend on lens
- Different configurations can break degeneracies



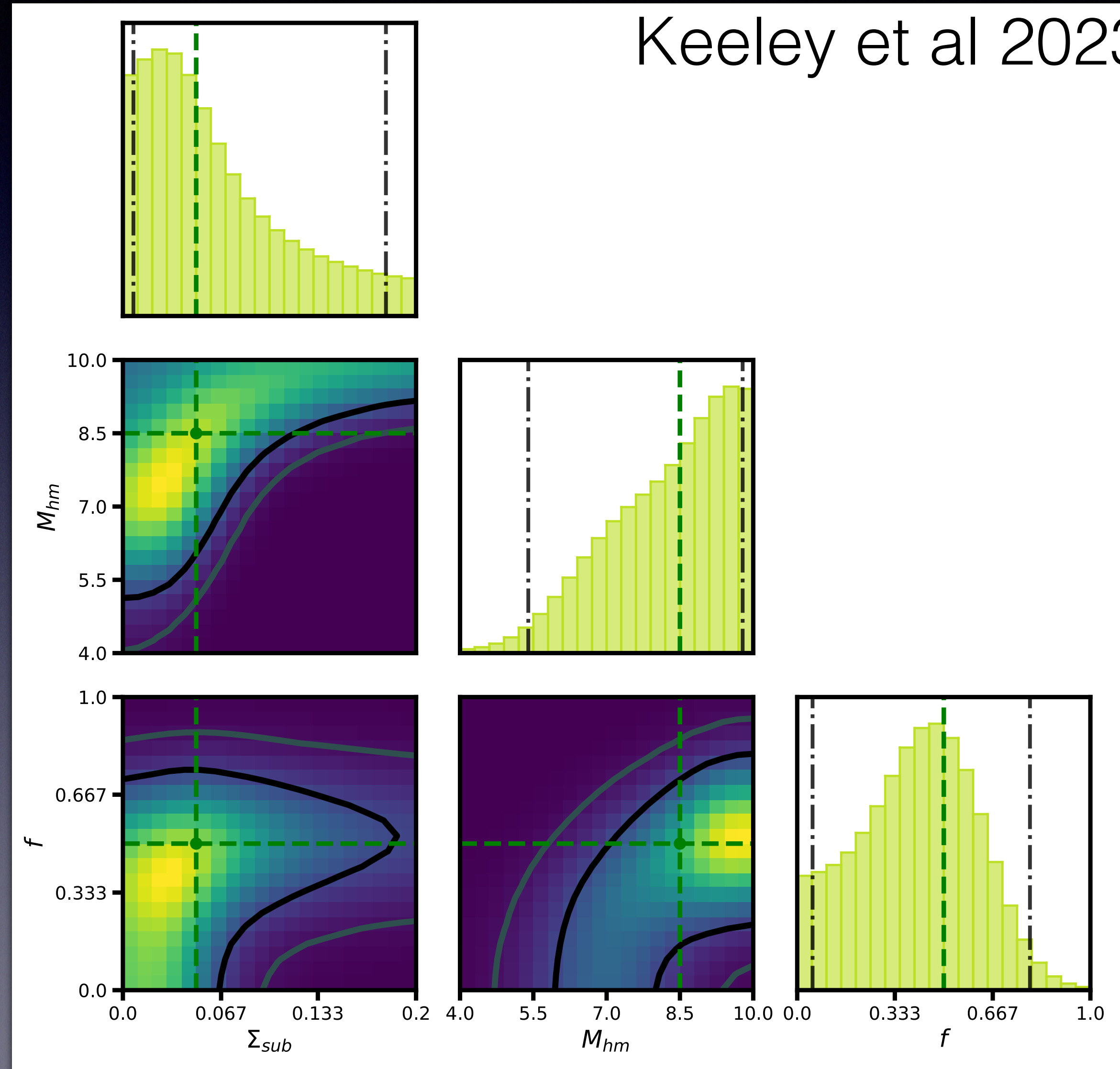
ABC method



Forecast constraints

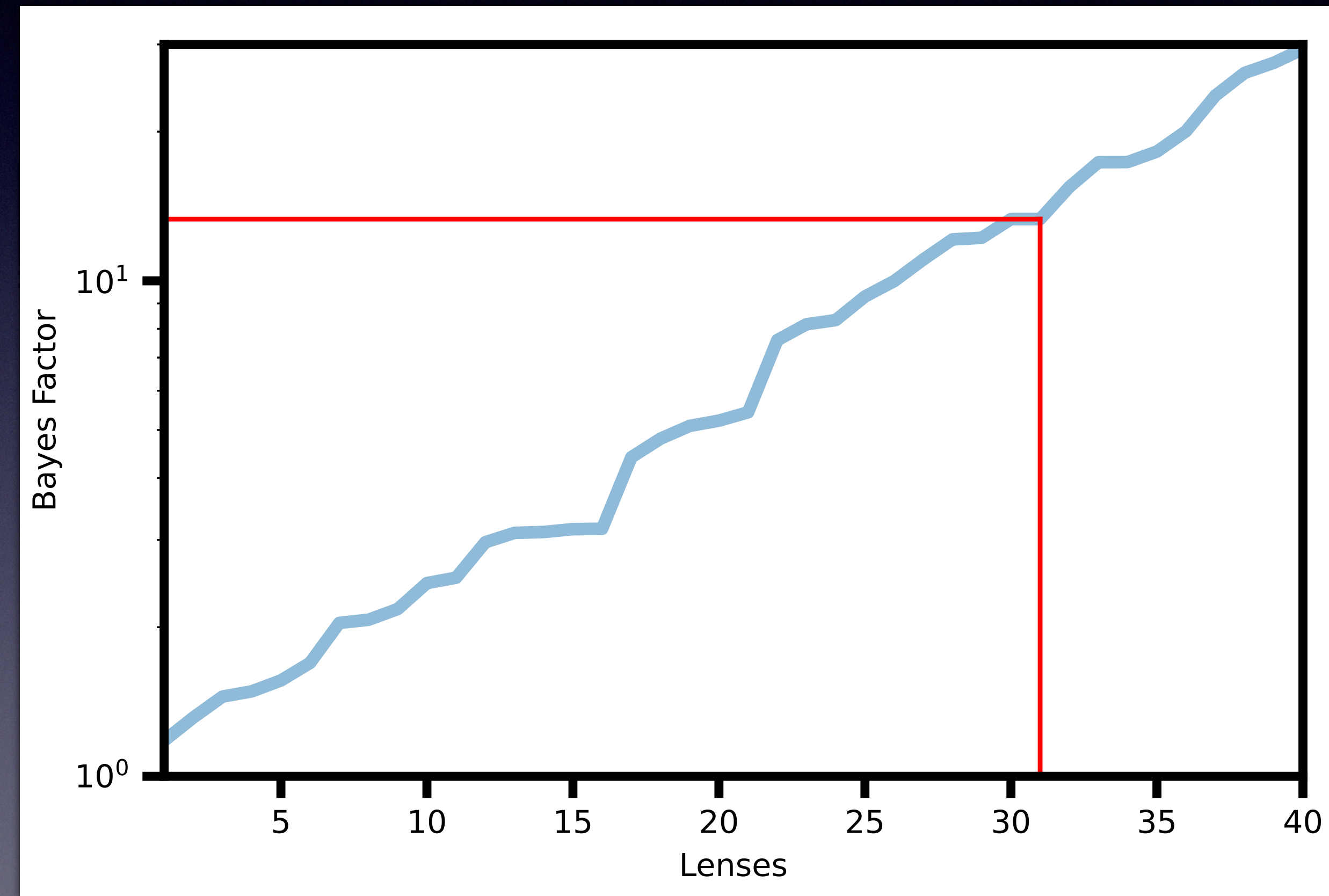
- Mock data generated from a MixDM model
- Posterior of parameters $\Sigma_{\text{sub}}, M_{\text{hm}}, f$
- $f = 0, M_{\text{hm}} = 10^{10}, \Sigma_{\text{sub}} = 0$ corner with least structure (warmest)
- Easier to differentiate between MixDM and CDM than MixDM and WDM

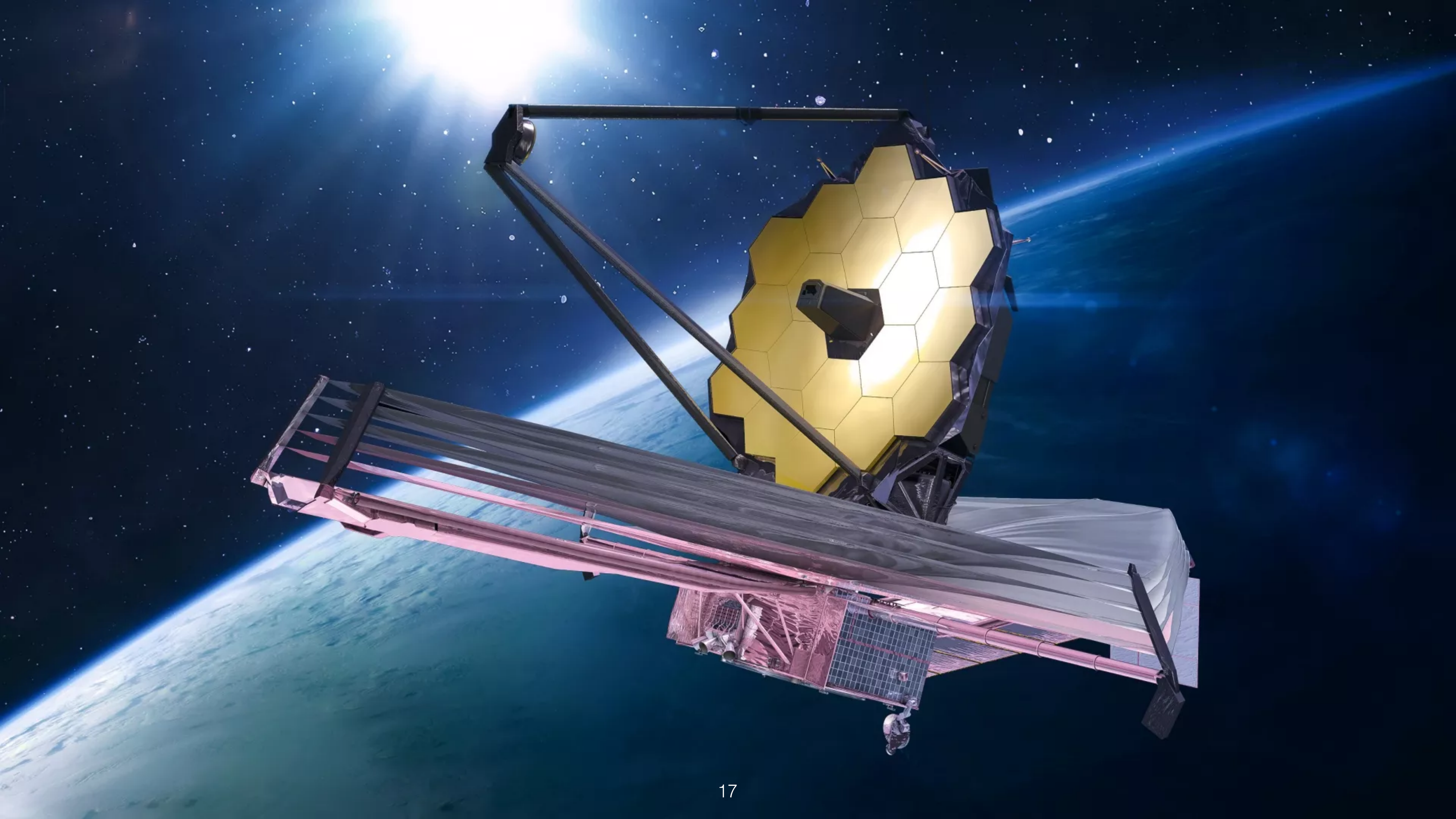
Keeley et al 2023



Forecast constraints

- Bayes factor for increasing number of lenses
- $BF = P(M_{\text{MixDM}} | D) / P(M_{\text{WDM}} | D)$
- JWST program will observe **31 lenses** (red line)





Conclusions

- Arbitrary mass functions can be constrained with the right kinds of strong lenses
- DM models beyond CDM and WDM can be constrained this way
- Large parameter degeneracies make this inference problem hard
- Refine predictions for the subhalo distributions
- Use information from other probes (source sizes, extended arcs)