Self-interacting dark matter science with galaxy-scale strong lenses

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Self-interacting dark matter

Acronym clarity: for cosmology/astrophysics SIDM = “self-interacting dark matter”

Characterized by a small but non-zero cross section for self-interaction σ between dark sector particles

Number of interactions in a Hubble time

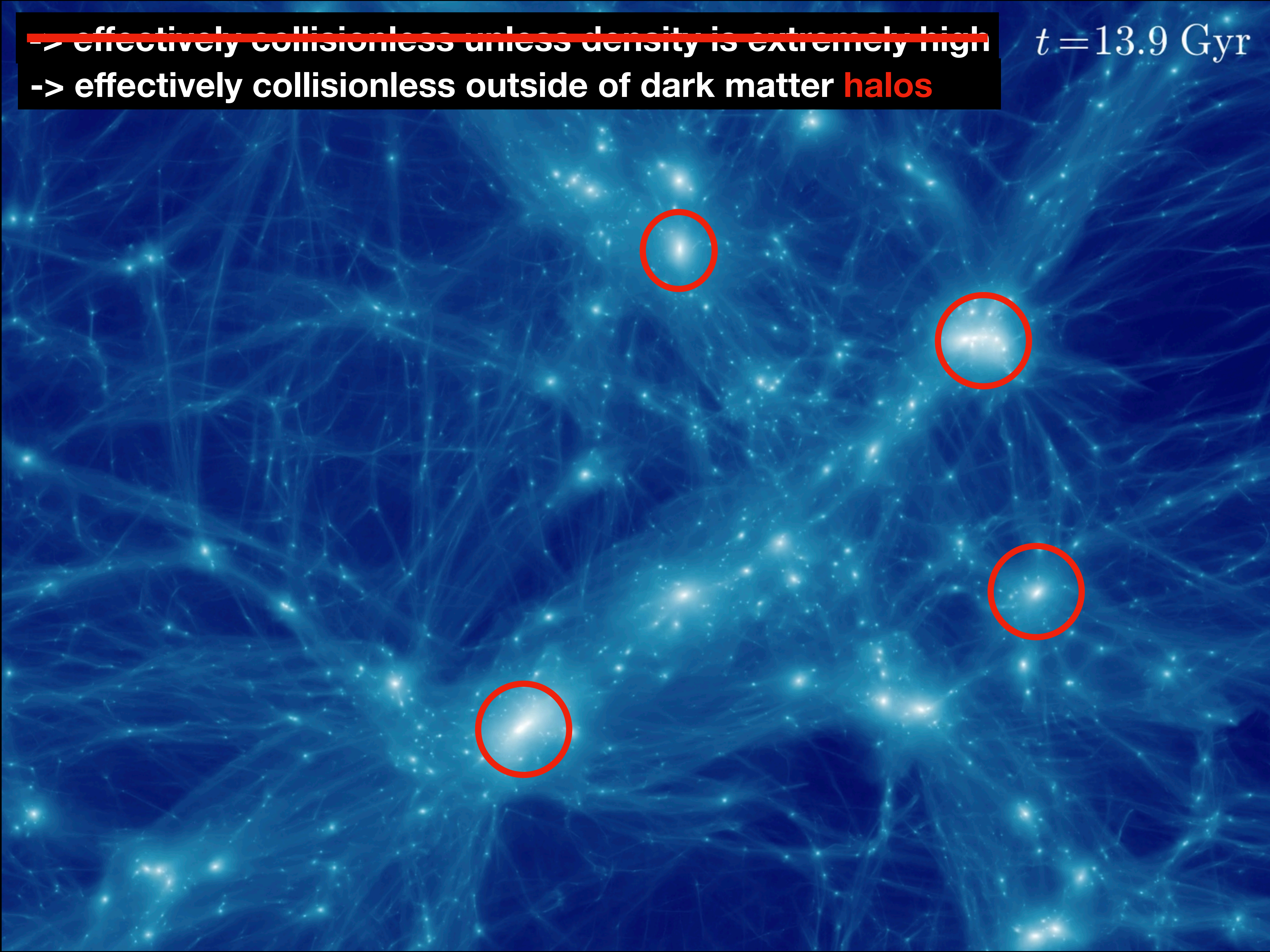
$$N \sim \langle \sigma v \rangle \times \rho \times t$$

$$N \sim 10^{-4} \left(\frac{\sigma}{1 \ \mathrm{cm^2 g^{-1}}} \right) \left(\frac{\rho}{\rho_{\mathrm{crit}}} \right) \left(\frac{v}{1000 \ \mathrm{km \ s^{-1}}} \right) \left(\frac{t}{13.7 \ \mathrm{Gyr}} \right)$$

-> effectively collisionless (cold dark matter) unless density is extremely high

~~-> effectively collisionless unless density is extremely high~~

-> effectively collisionless outside of dark matter halos



SIDM alters the internal structure of halos

$$N \sim 10^{-4} \left(\frac{\sigma}{1\ \mathrm{cm^2 g^{-1}}} \right) \left(\frac{\rho}{150\ M_\odot \mathrm{kpc^{-3}}} \right) \left(\frac{v}{1000\ \mathrm{km\ s^{-1}}} \right) \left(\frac{t}{13.7\ \mathrm{Gyr}} \right)$$

For a cluster-mass halo $M \sim 10^{14} M_\odot$:

$$\mathrm{velocity\ dispersion} \sim \mathrm{v} \sim 1000\ \mathrm{km\ s^{-1}}$$

$$\rho \sim 10^6 M_\odot\ \mathrm{kpc^{-3}}$$

$$N \sim 1$$

For a 10^7 solar mass subhalo or field halo:

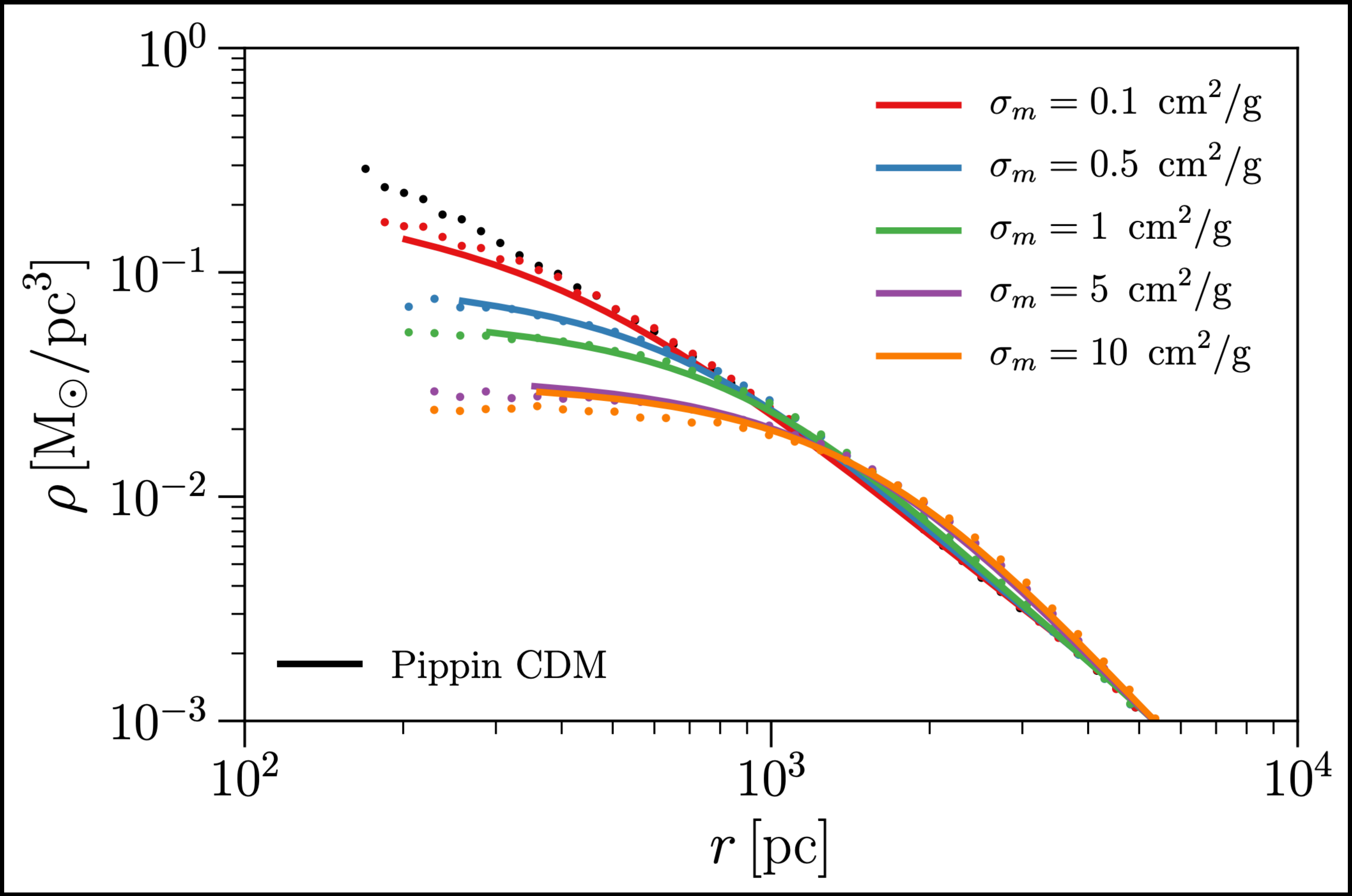
$$v \sim 5\ \mathrm{km\ s^{-1}}$$

$$\rho \sim 10^8 M_\odot\ \mathrm{kpc^{-3}}$$

$$N \sim 3$$

SIDM alters the internal structure of halos

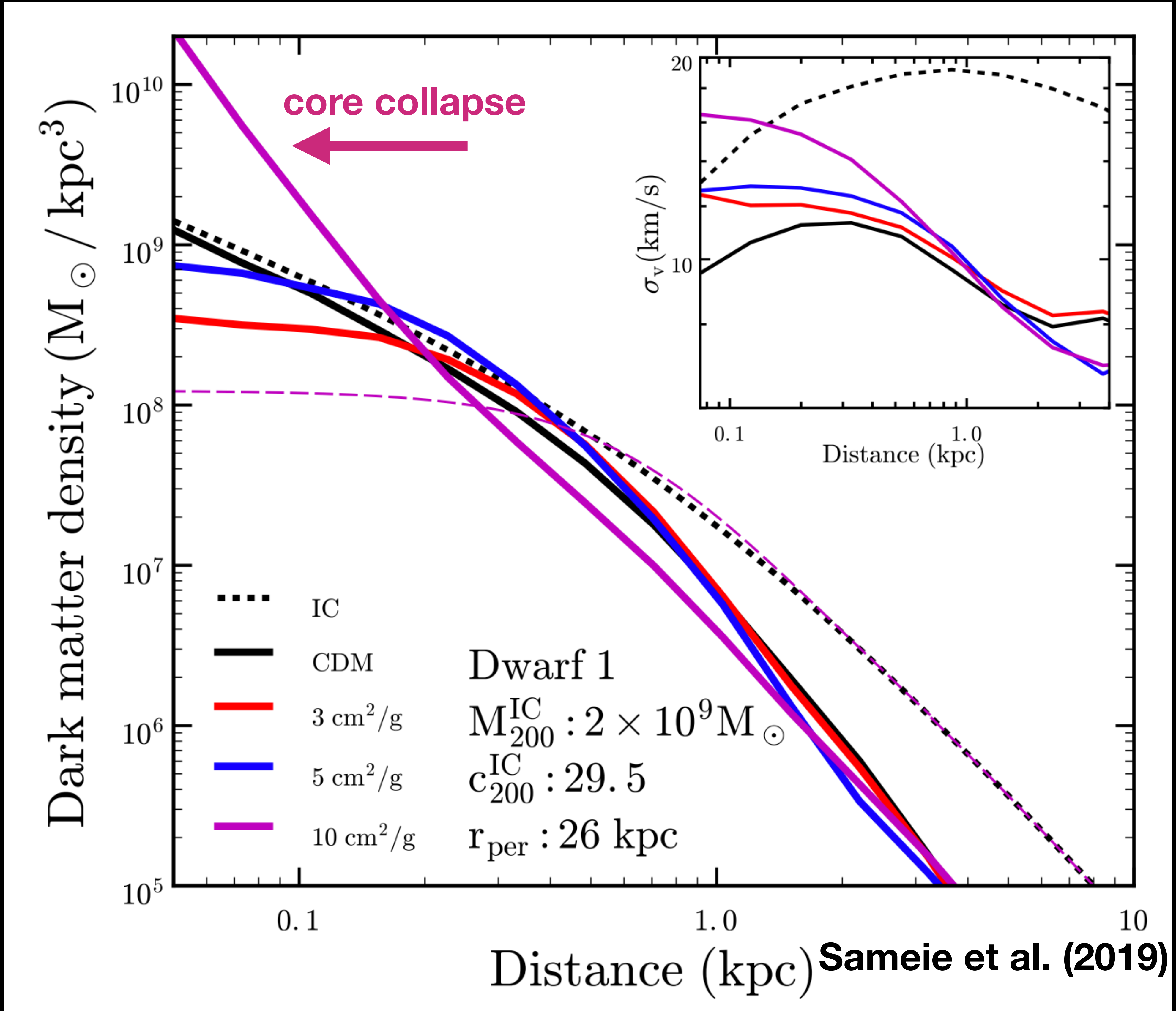
SIDM drives core formation in halos



Nishikawa et al. (2020)

SIDM alters the internal structure of halos

SIDM can lead to “gravothermal catastrophe” or core collapse



Sameie et al. (2019)

Small-Scale Challenges to the ΛCDM Paradigm

James S. Bullock[1] and Michael Boylan-Kolchin[2]

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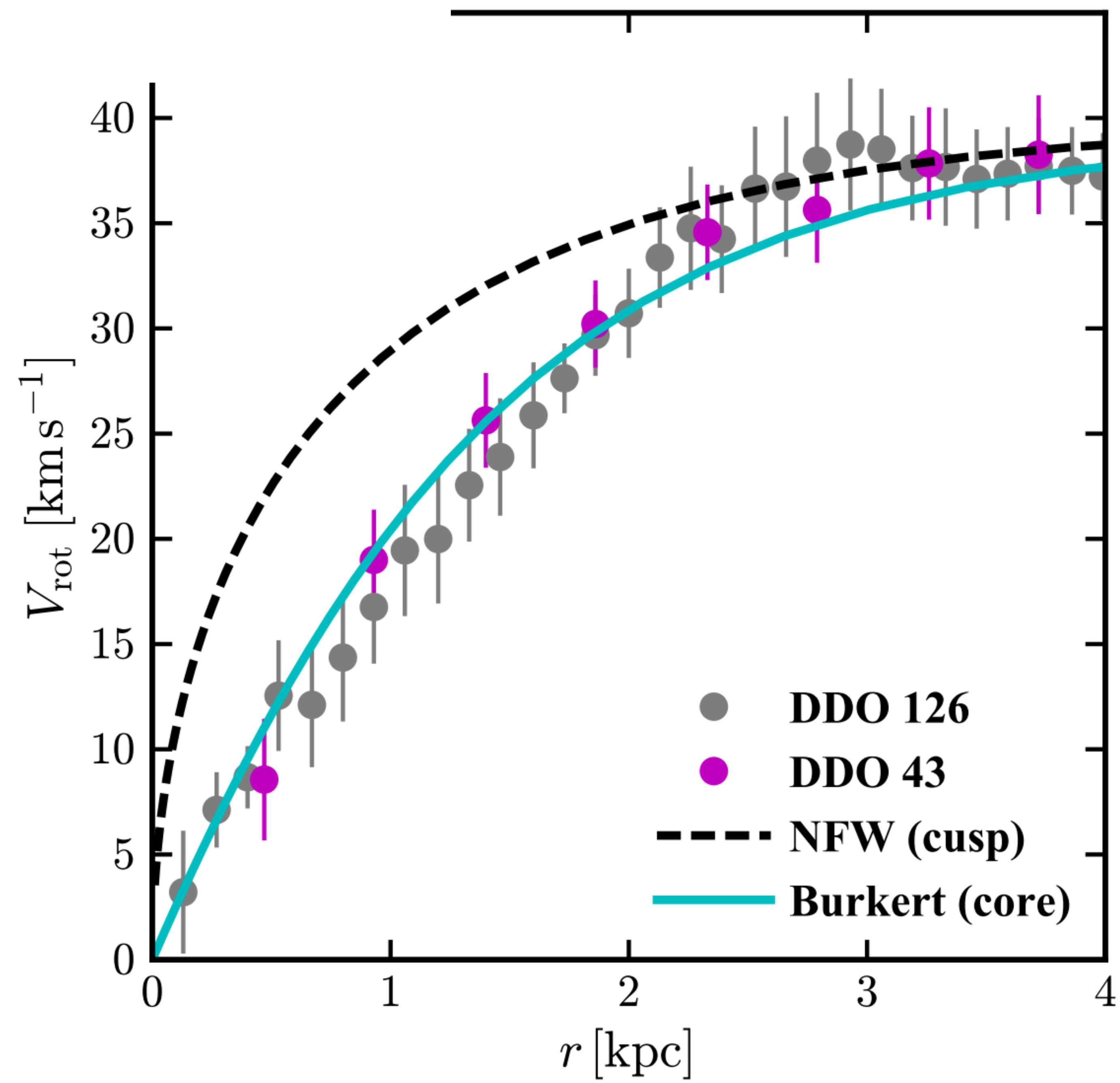
Why care?

-> SIDM potentially resolves "challenges" to LCDM on sub-galactic scales



What implications does SIDM have for astrophysics?

Dark Matter Halos as Particle Colliders:
A Unified Solution to Small-Scale Structure Puzzles from Dwarfs to Clusters

Manoj Kaplinghat,[1] Sean Tulin,[2] and Hai-Bo Yu[3]

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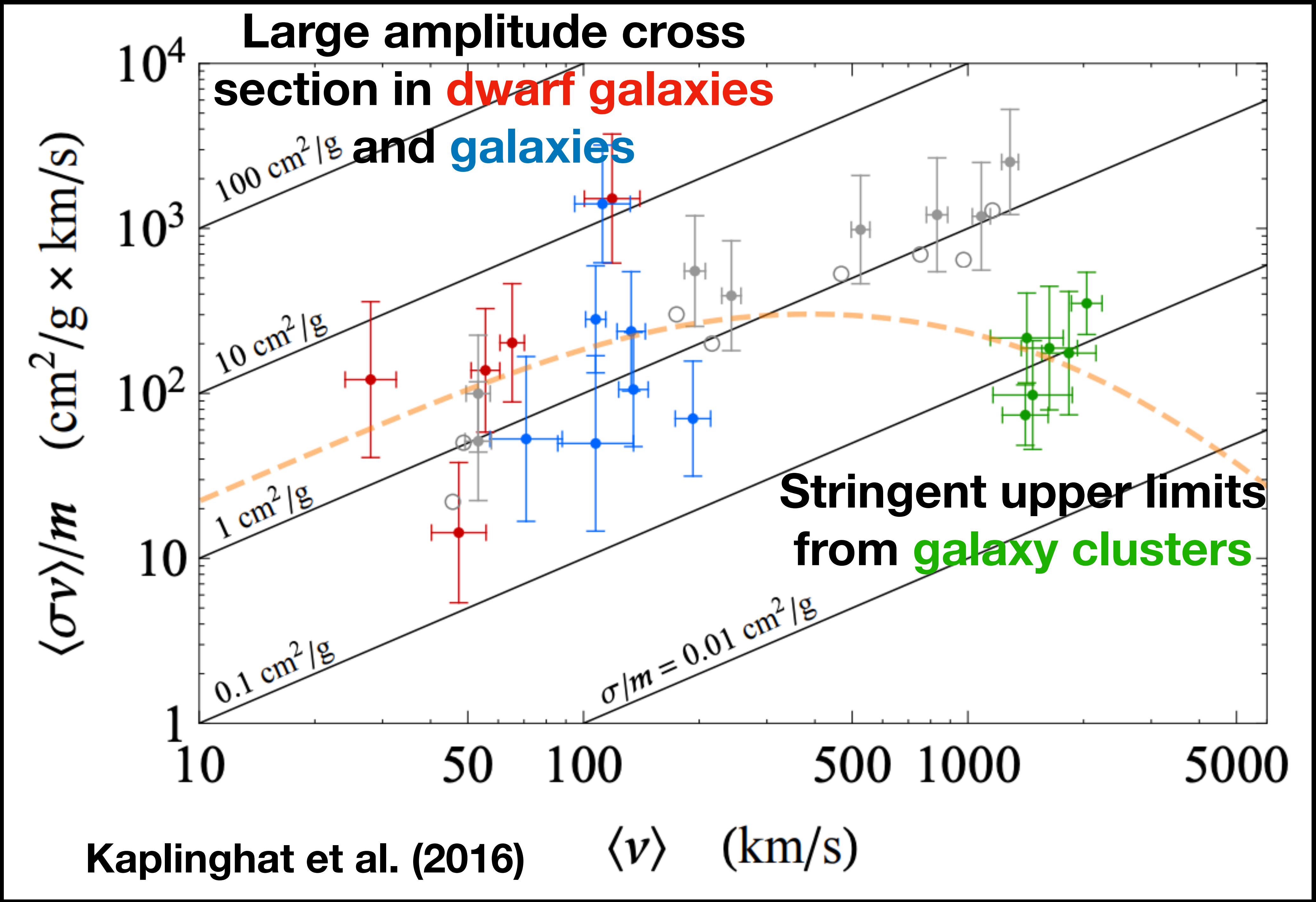
(Dated: August 17, 2015)

Different halo masses ->
different velocity dispersions ->
constraints on velocity-dependent cross sections

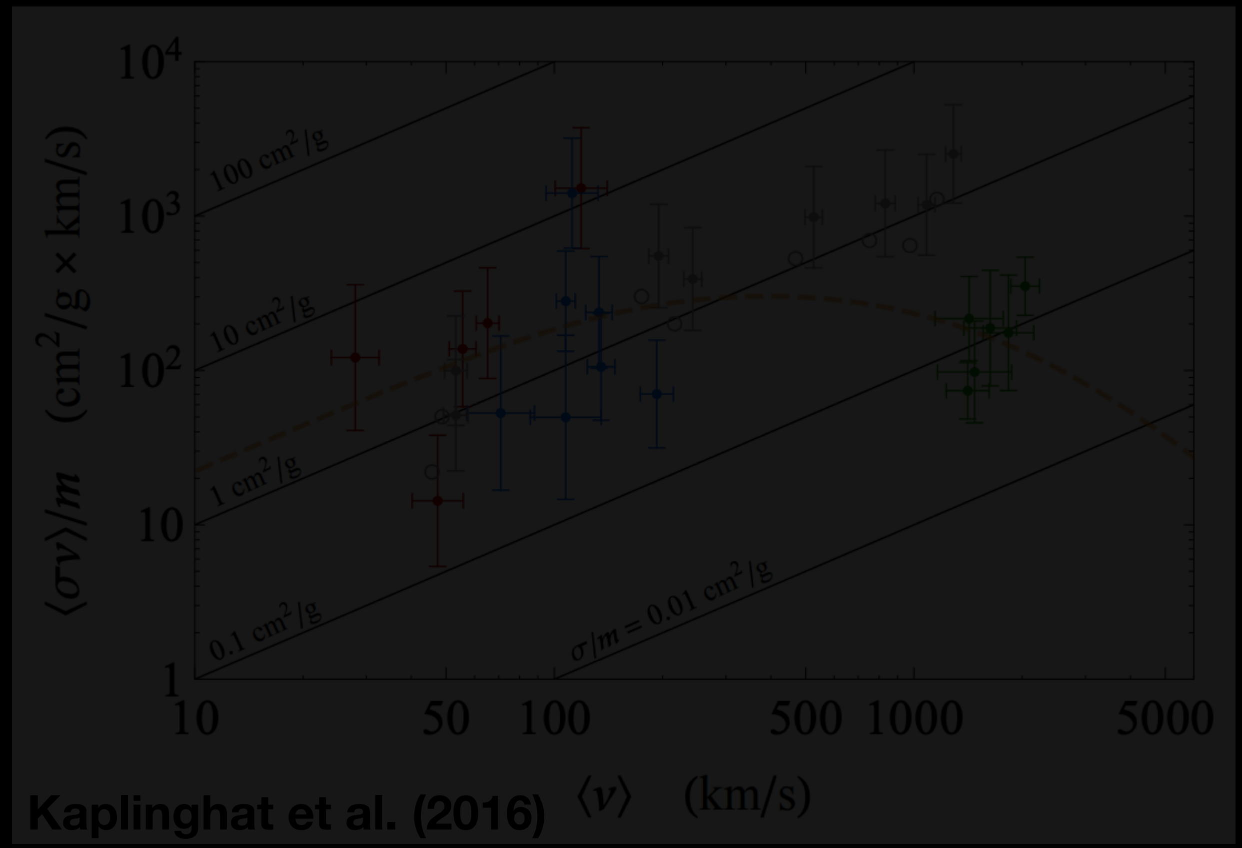
What implications does SIDM have for astrophysics?

viable SIDM models have velocity-dep. interactions



What implications does SIDM have for astrophysics?

viable SIDM models have velocity-dep. interactions



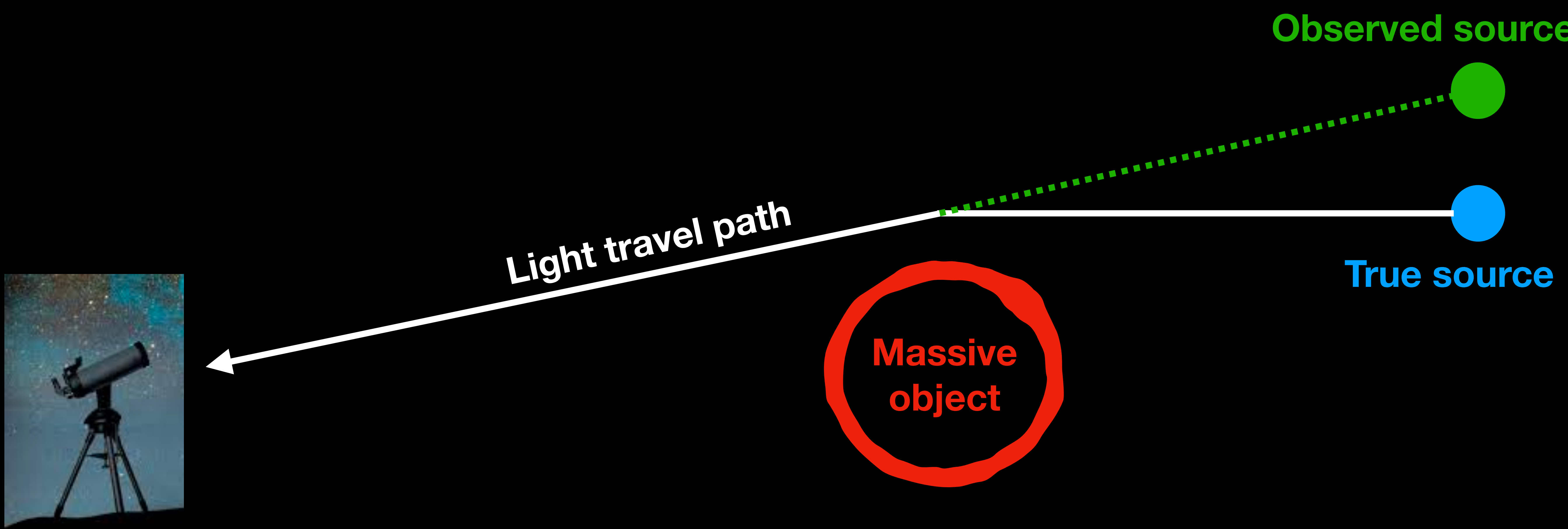
Below 10^8 solar masses, halos are dark we can't infer their density profile through stellar dynamics

Solution: strong gravitational lensing

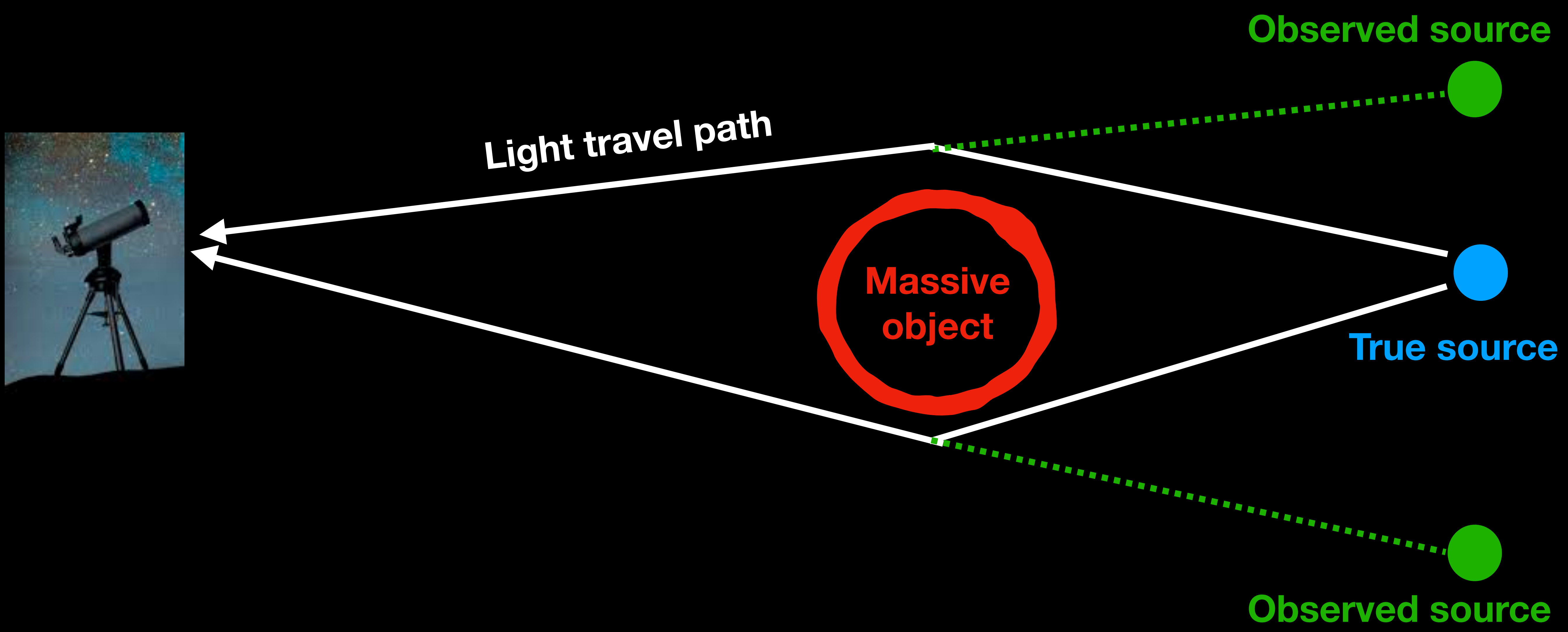
Intro to strong lensing

Movie by Yashar Hezaveh

Gravitational lensing: deflection of light by gravitational fields



Strong lensing produces multiple images of a single source

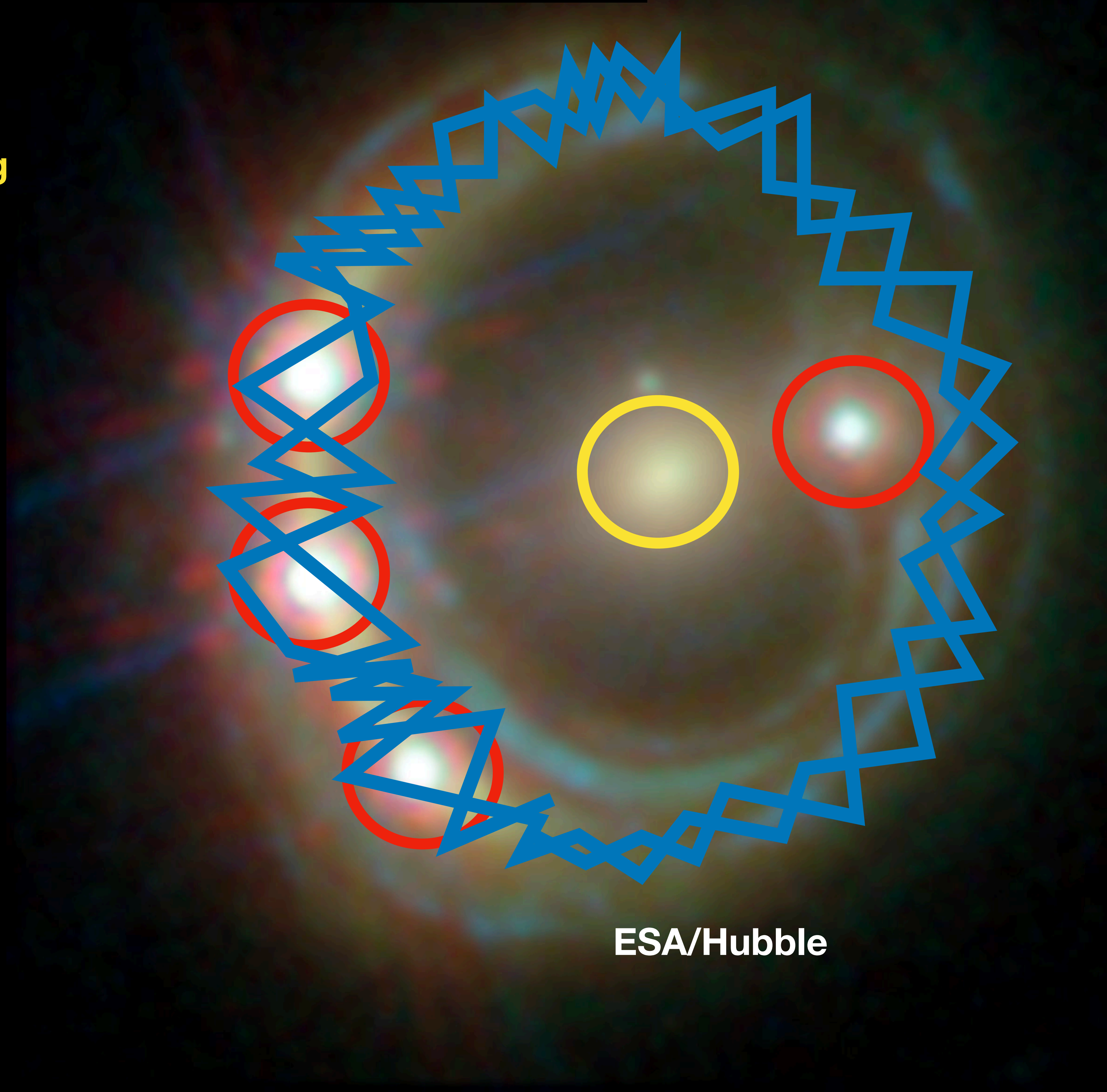


Galaxy-scale strong lens

Galaxy doing the lensing

Four images of a background quasar

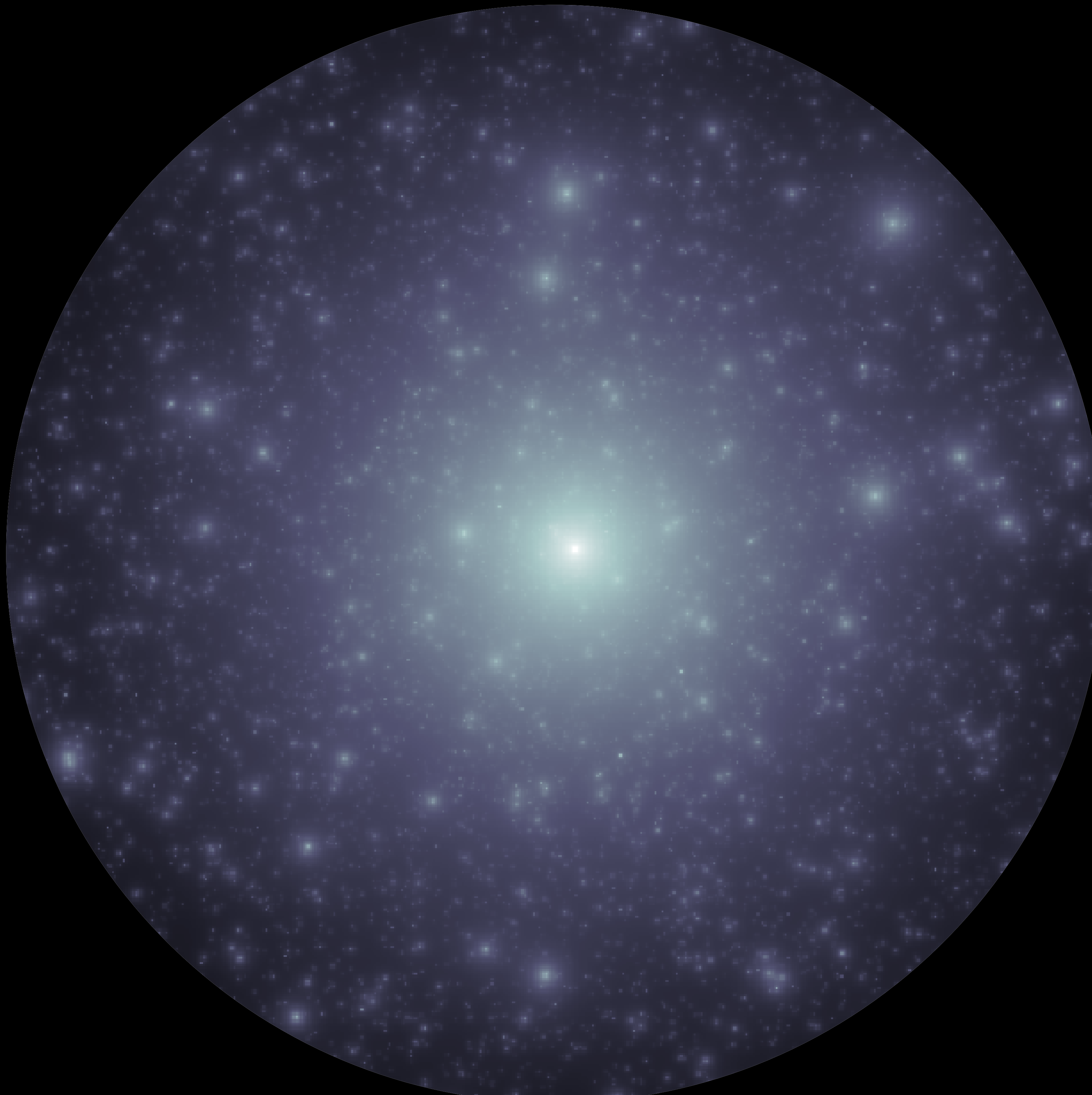
Lensed image of the galaxy that surrounds the quasar



Substructure lensing

CDM and SIDM predict
that galactic halos contain an
abundance of substructure

-> subhalos around a galaxy
-> field halos along the
line of sight

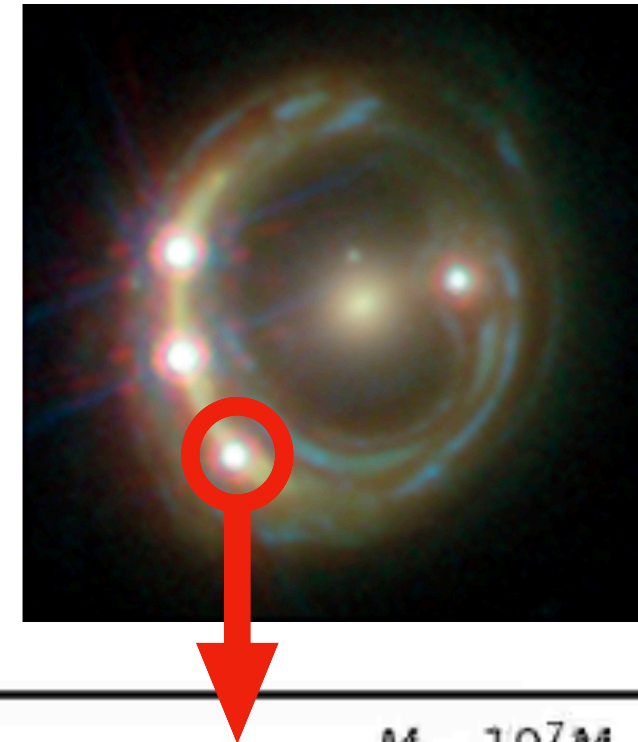


Substructure lensing

CDM and SIDM predict that galactic halos contain an abundance of substructure

-> subhalos around a galaxy
-> field halos along the line of sight

Image magnifications an extremely sensitive probe of low-mass substructure



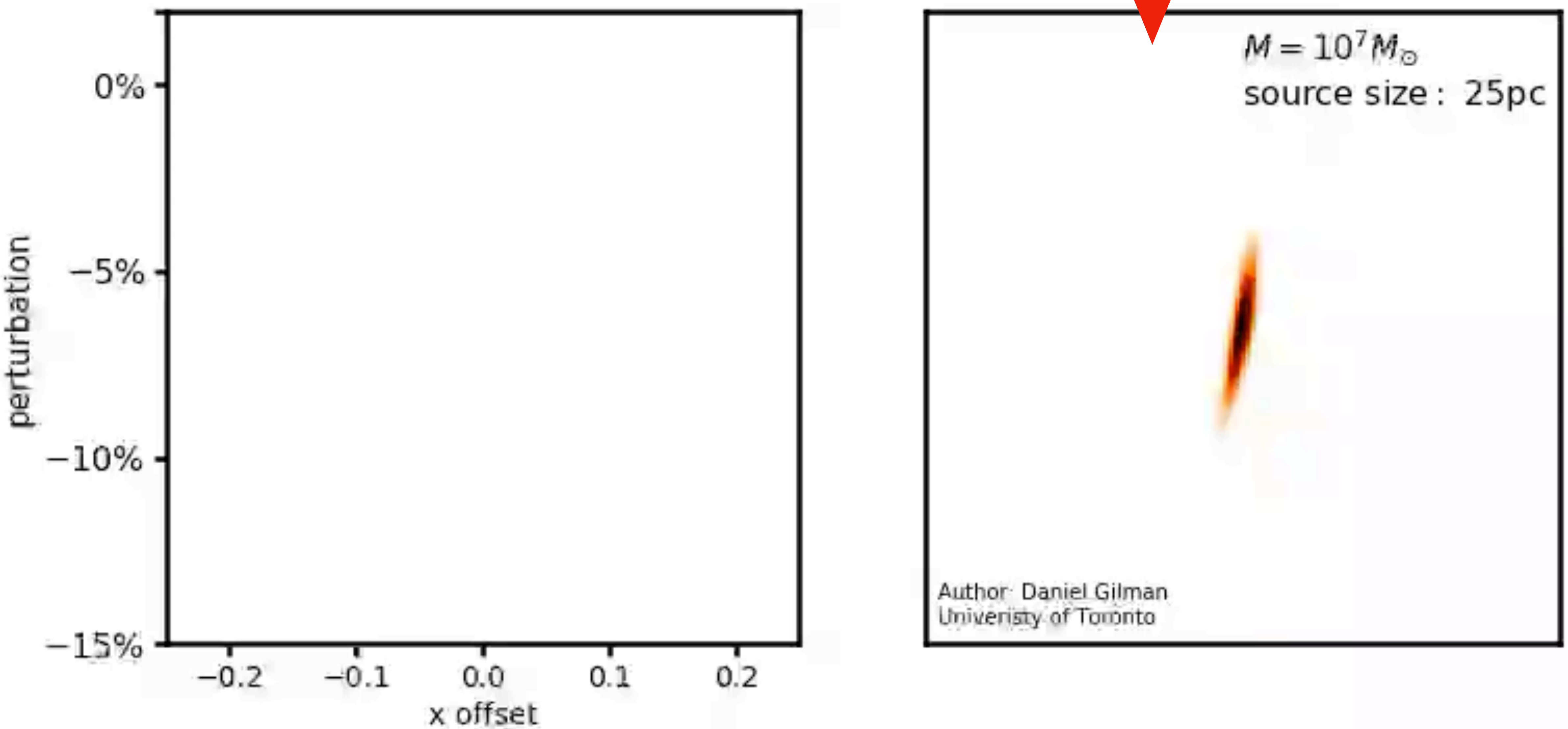
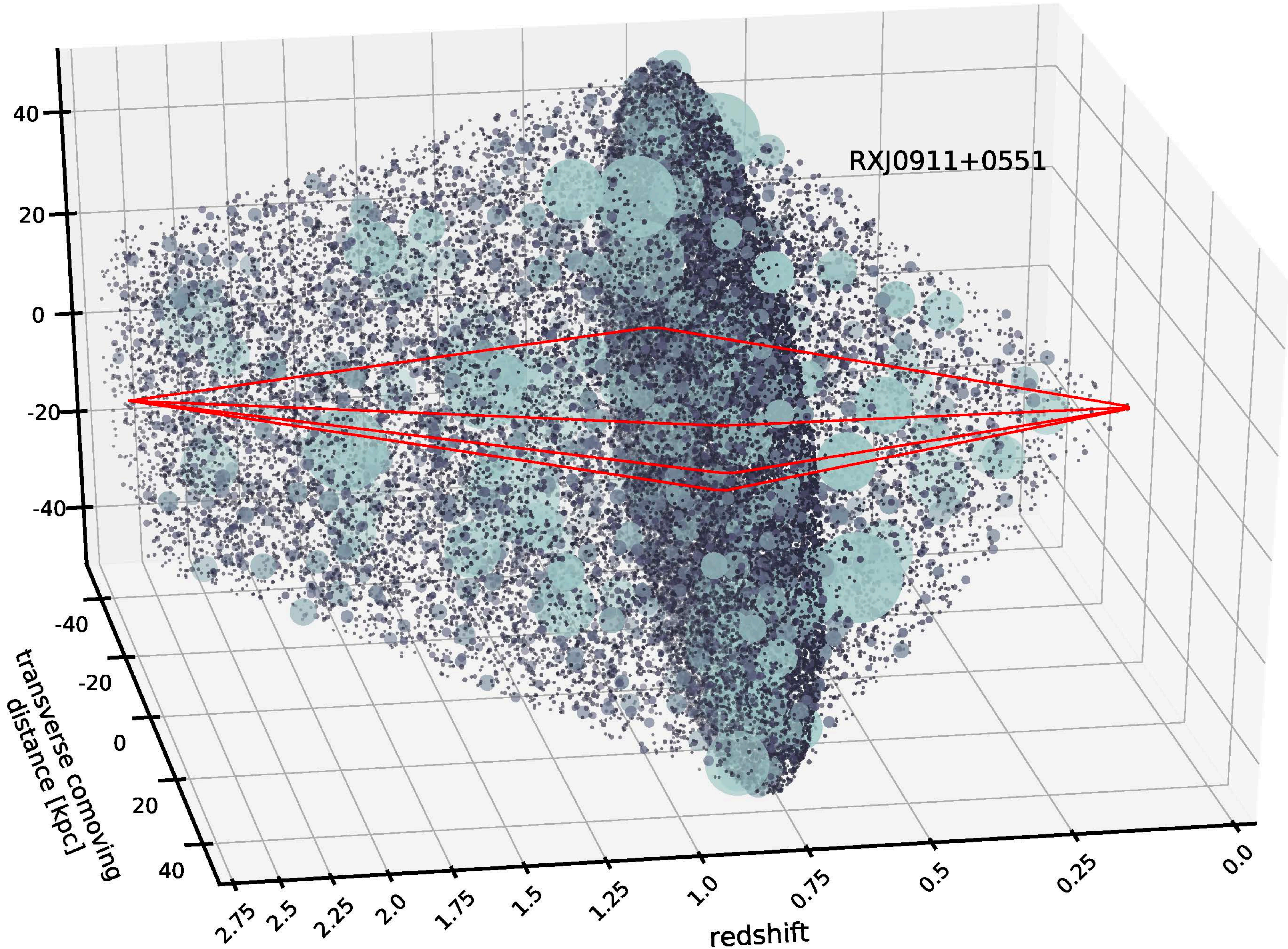


Image flux ratios impacted by structure along the entire line of sight -> potentially probe SIDM structure in the field across Gyr timescales



Can we use flux ratios to detect the structural properties of low-mass SIDM halos?

Strong lensing signatures of self-interacting dark matter in low-mass halos

Daniel Gilman[1,2⋆], Jo Bovy[1], Tommaso Treu[2], Anna Nierenberg[3], Simon Birrer[4,5], Andrew Benson[6], Omid Sameie[7]

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Posted to the arXiv in May

The SIDM cross section

Assume a weak, long-range interaction with v^-4 behavior at high v

$$\sigma\left(v\right) = \sigma_0 \left(1 + \frac{v^2}{v_0^2}\right)^{-2}$$

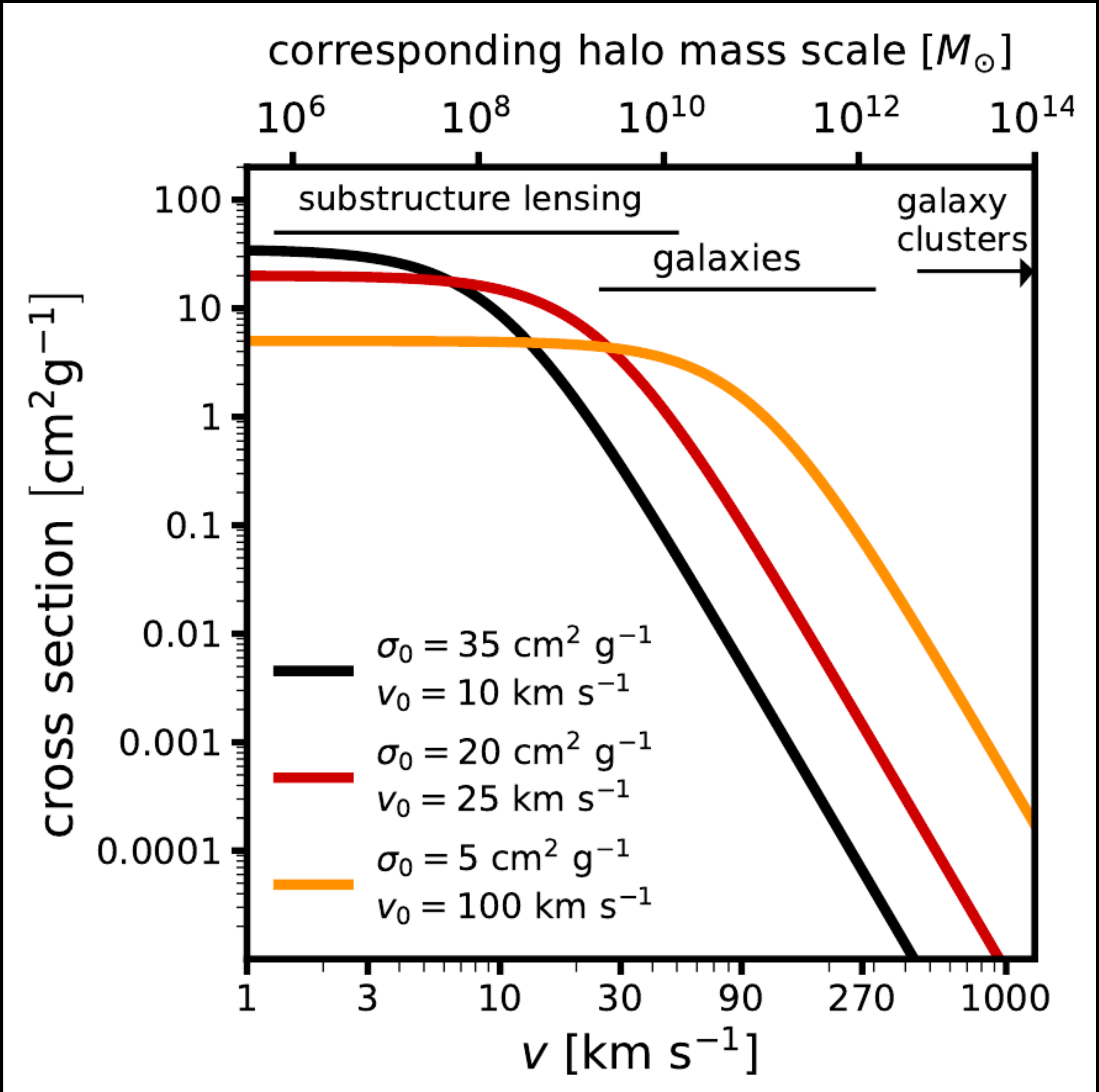
All structure formation properties depend only on the thermal average and the halo velocity dispersion v(M)

$$\langle \sigma v \rangle = \frac{1}{2\sqrt{\pi}\ v\left(M_{\mathrm{halo}}\right)^3} \int_0^\infty \sigma\left(v'\right) v' \times v'^{\,2} \exp\left(\frac{-v'^{\,2}}{4\ v\left(M_{\mathrm{halo}}\right)^2}\right) dv'$$

The SIDM cross section

$$\sigma(v) = \sigma_0 \left(1 + \frac{v^2}{v_0^2}\right)^{-2}$$

Permits a large cross section on sub-galactic scales, while evading constraints from larger scales



Lensing requires density profiles
1) core formation

We use the "fitting function" of Kaplinghat et al. (2016) to compute the core size

$$\rho_{\rm NFW}\left(r_1\right)\langle\sigma v\rangle t\left(z\right) = 1$$

r_1: where particles scatter once since halo collapse

+

$$v_{\rm rms}^2 \nabla^2 \log\rho_{\rm SIDM} = -4\pi G\rho_{\rm SIDM}$$

Poisson eqn. plus Jeans eqn.

+

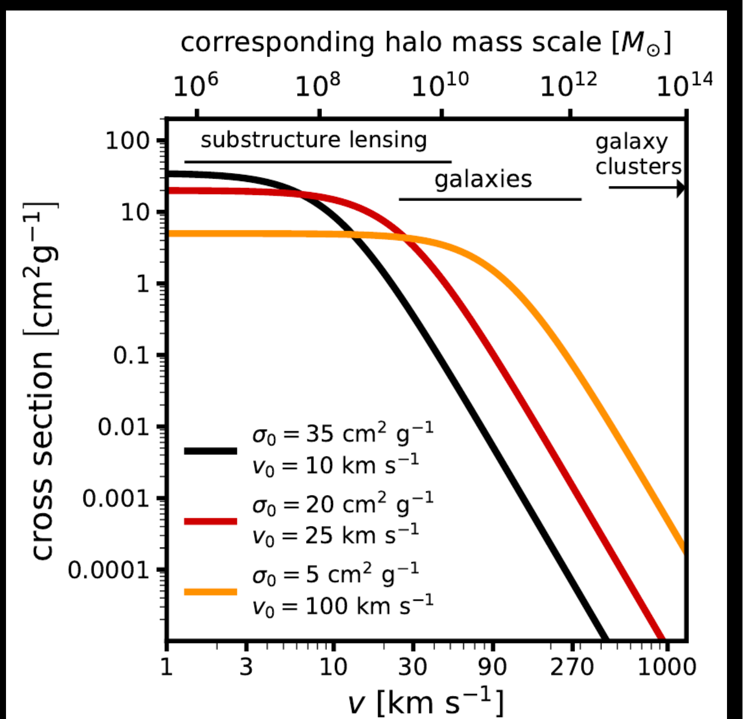
Boundary conditions at r_1

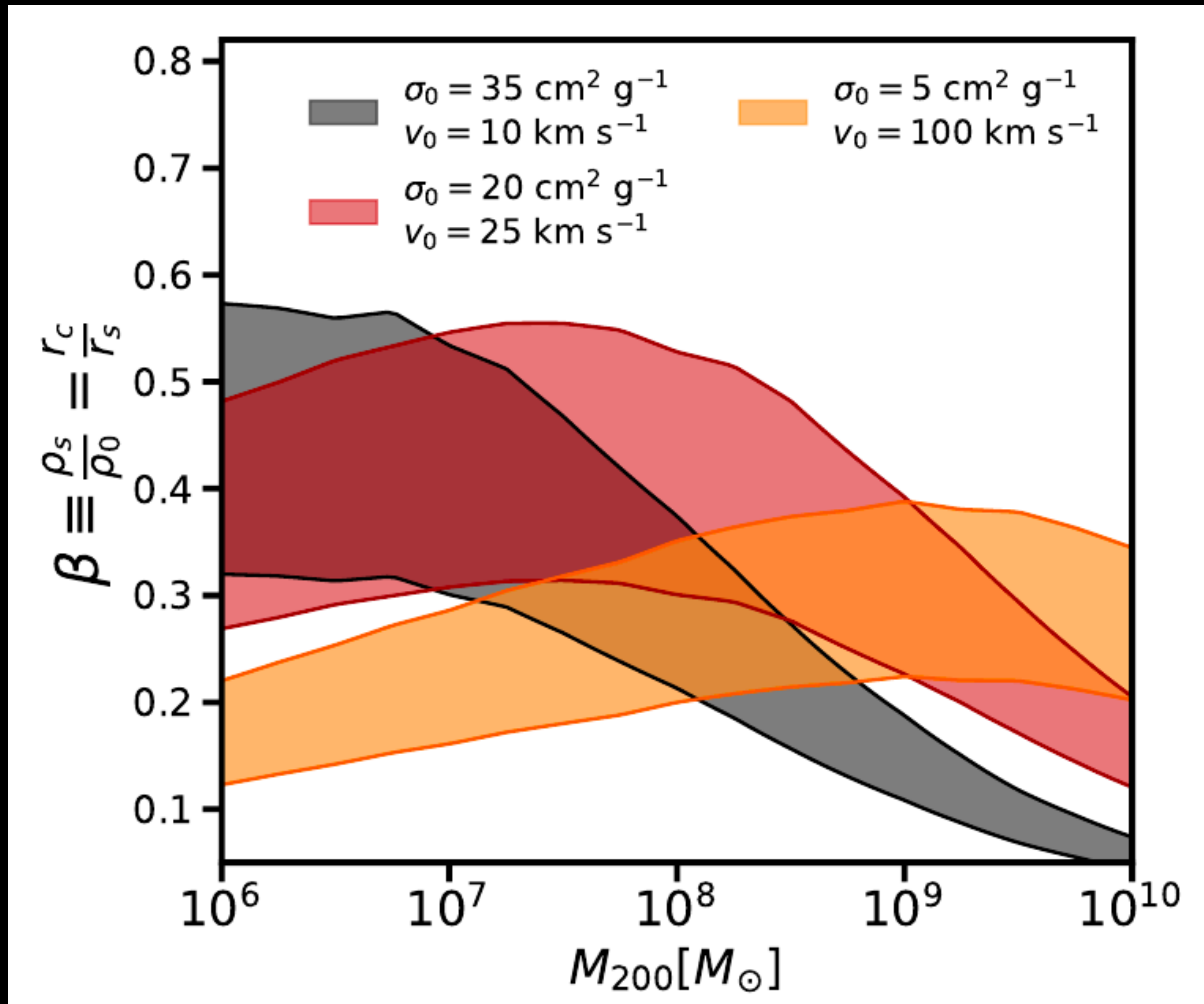
Conserve mass inside r_1, match density at r_1

= Central core density ρ_0

Lensing requires density profiles
1) core formation

Core size as a function of halo mass





Lensing requires density profiles
2) core collapse

$$t_{\mathrm{relax}} = \frac{1}{\langle \sigma v \rangle \rho}$$

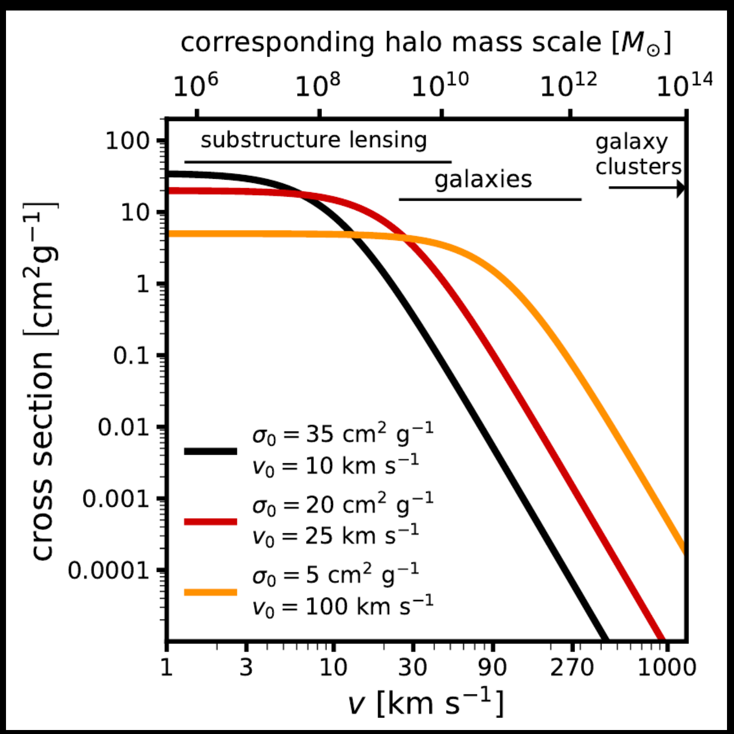
Model based on results by Nishikawa et al. (2020) and the relation time

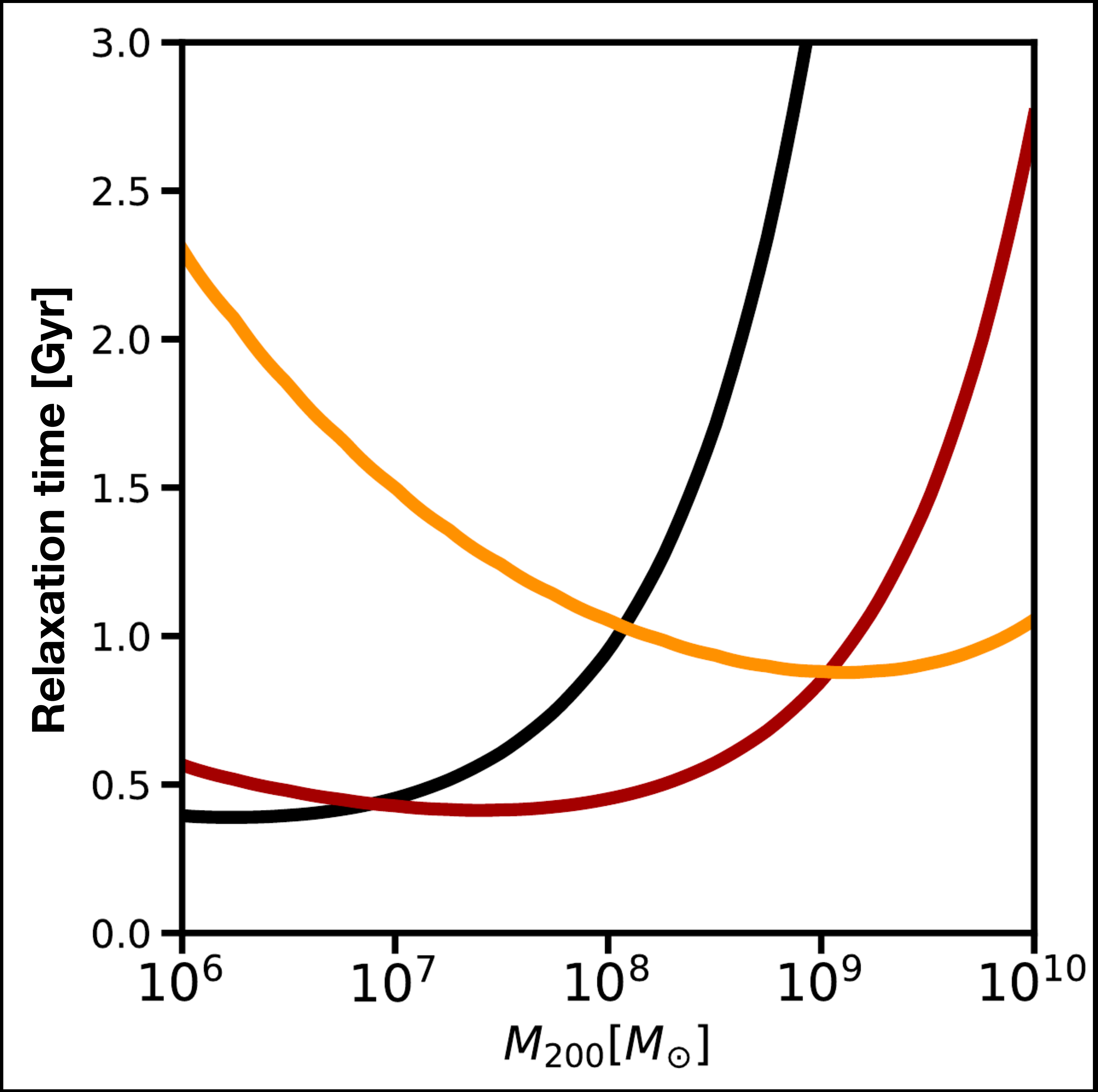
Tidally disrupted halos (subhalos around the main deflector) collapse after $\sim 10 t_r$

Field halos collapse after $\sim 100 t_r$

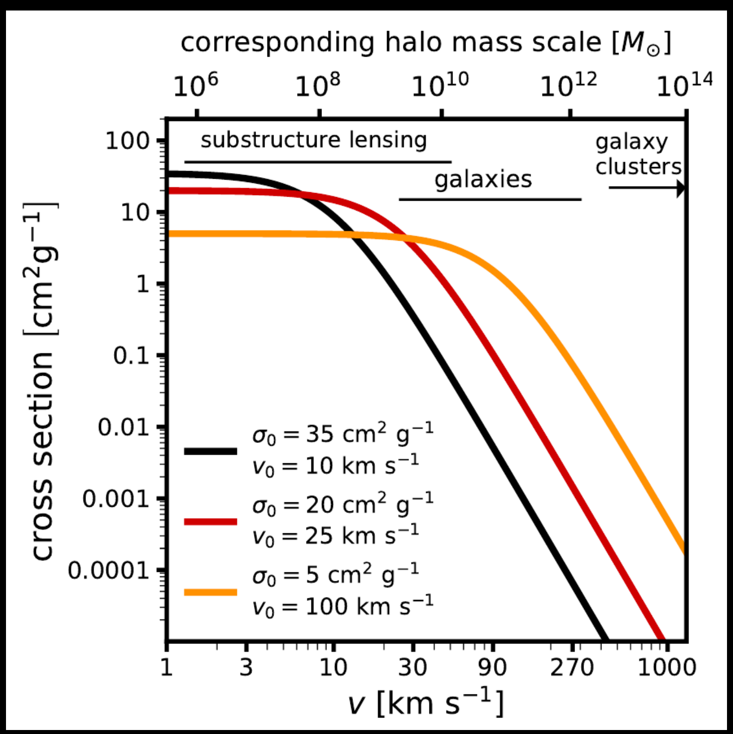
+ scatter around these times to account for different tidal stripping histories, mergers, etc.

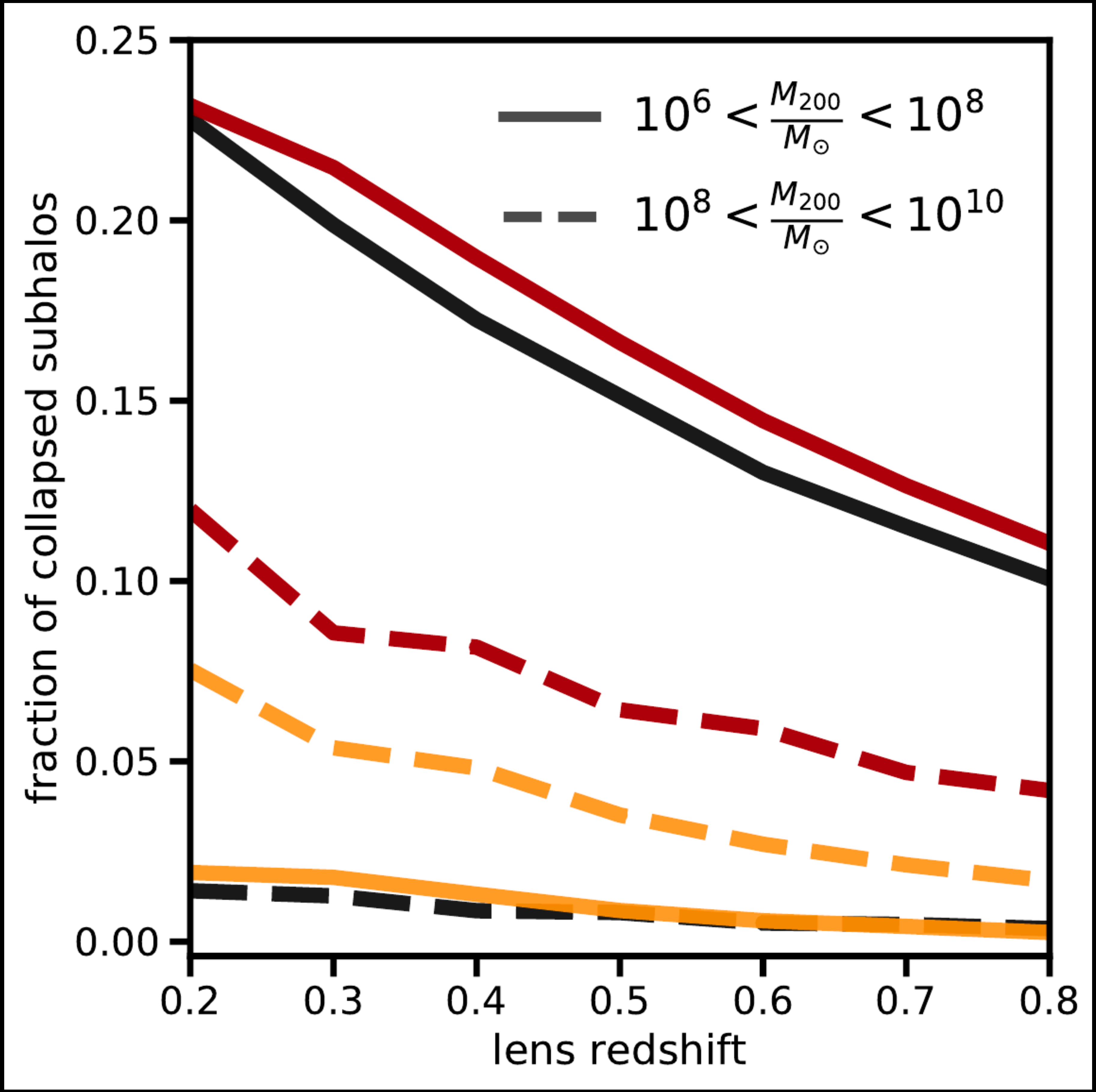
Modeling core collapse



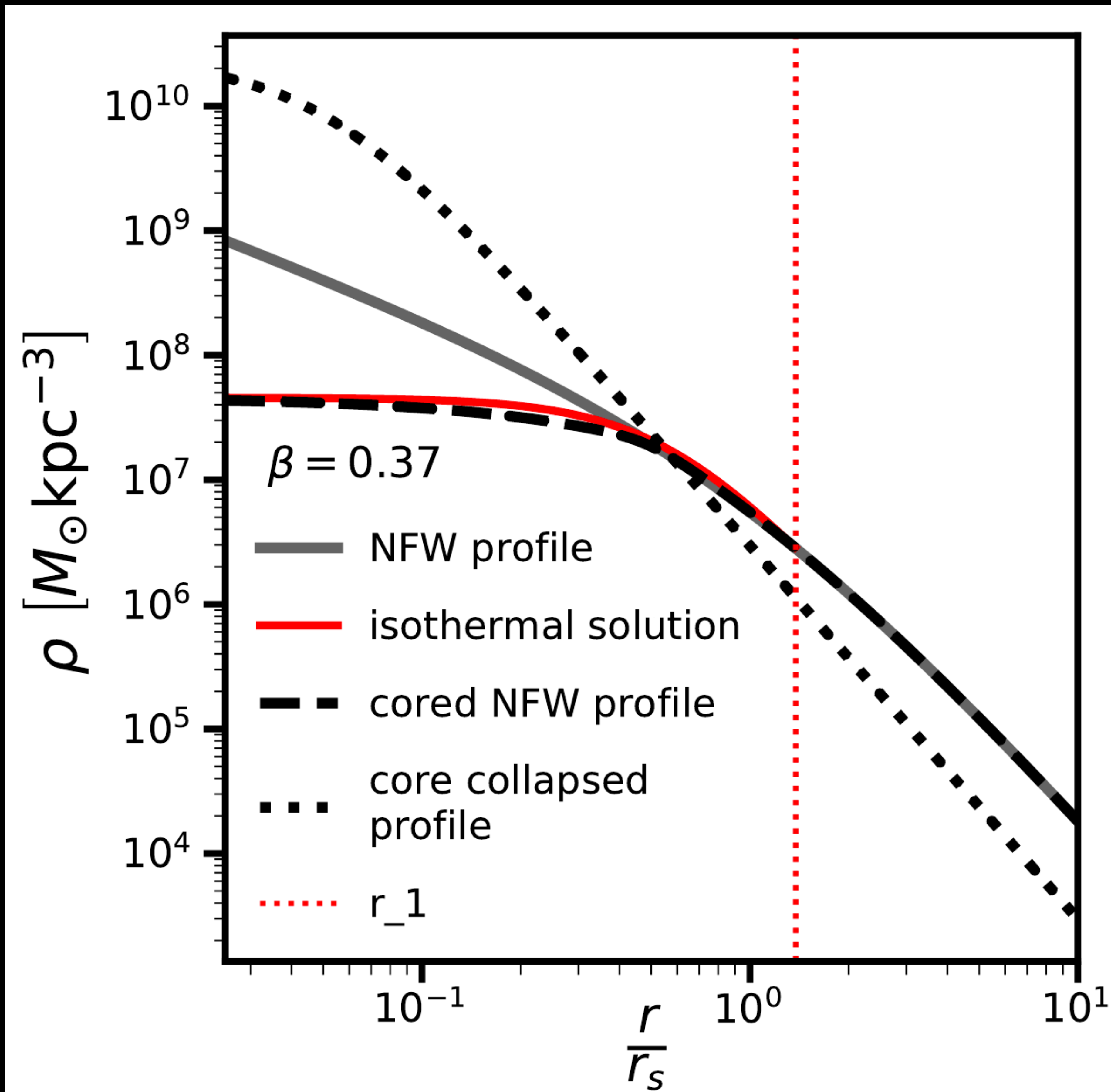


Modeling core collapse



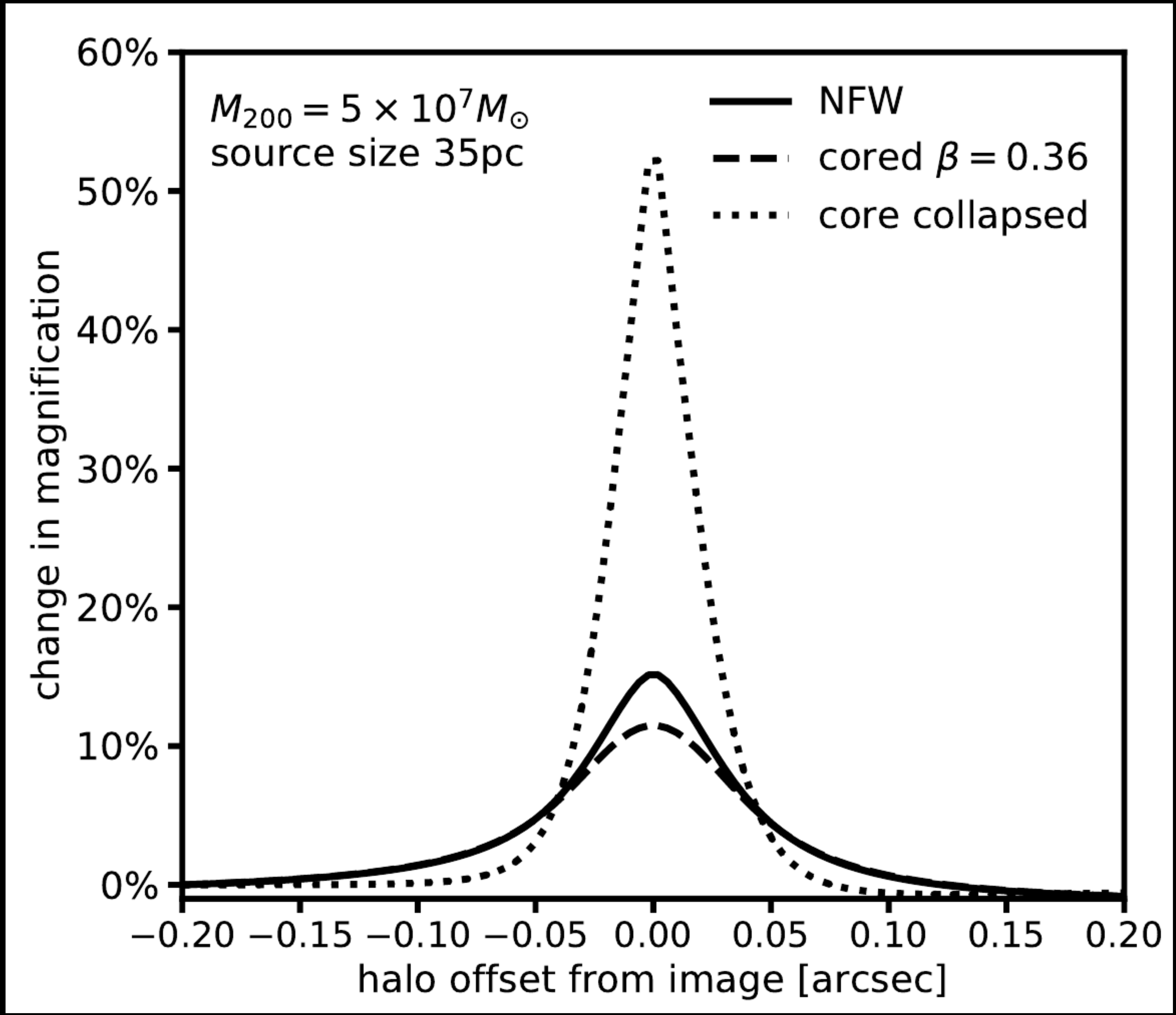


Halo density profiles



Lensing properties of SIDM halos

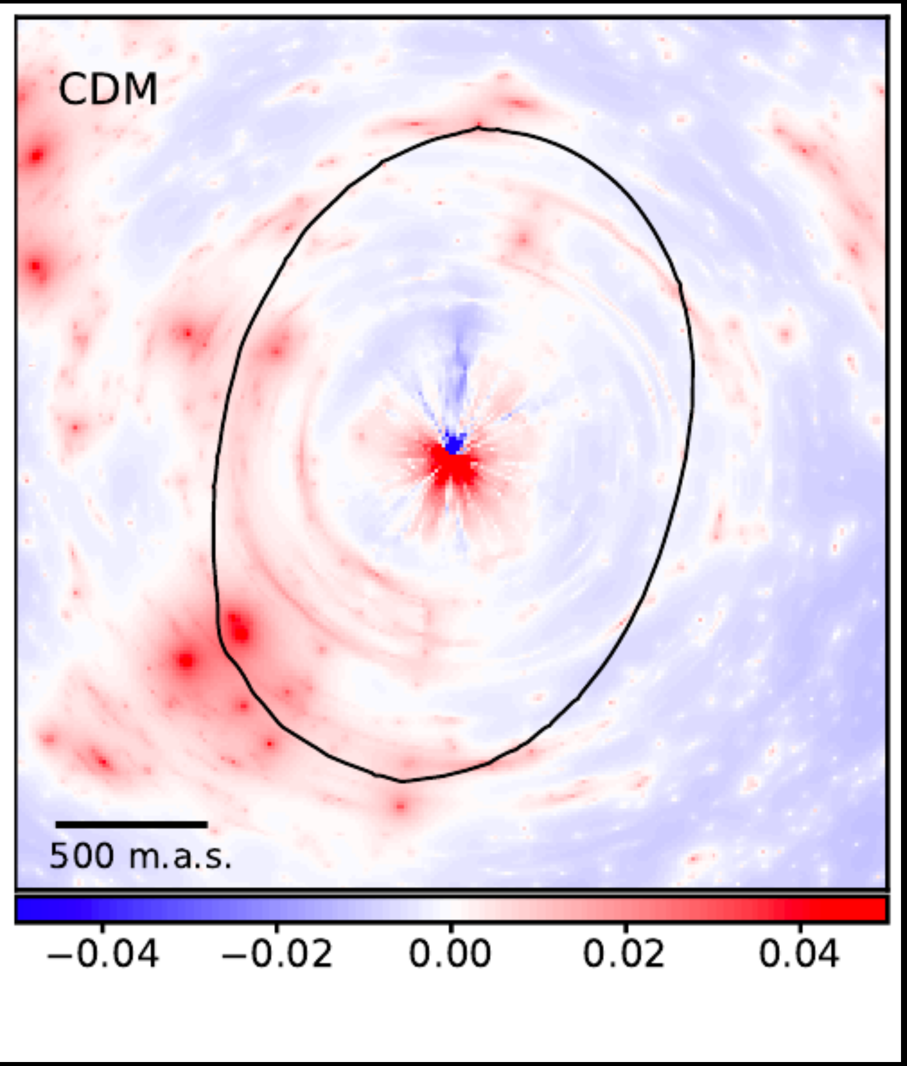
Magnification cross section for a single halo



Lensing properties of SIDM halos

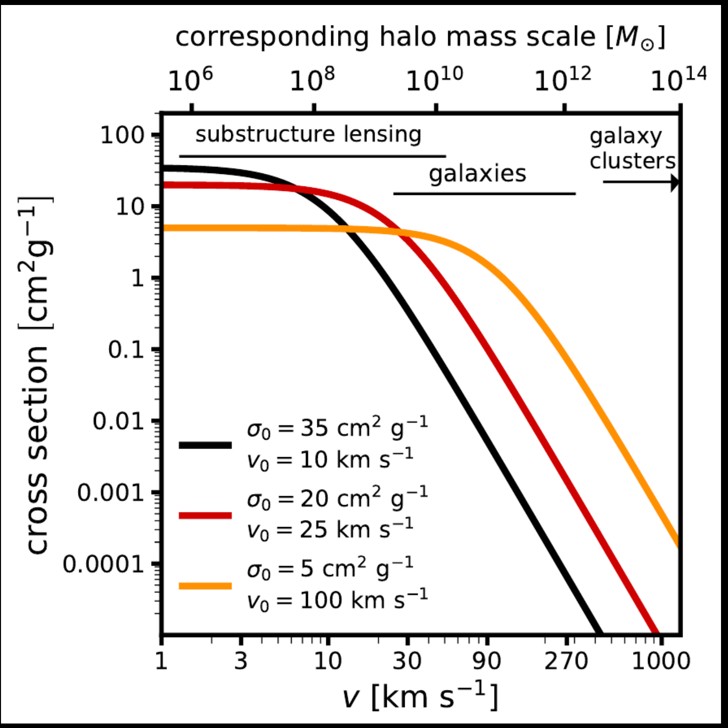
Below: a 2D representation of a lensing mass distribution in 3D (including line of sight)

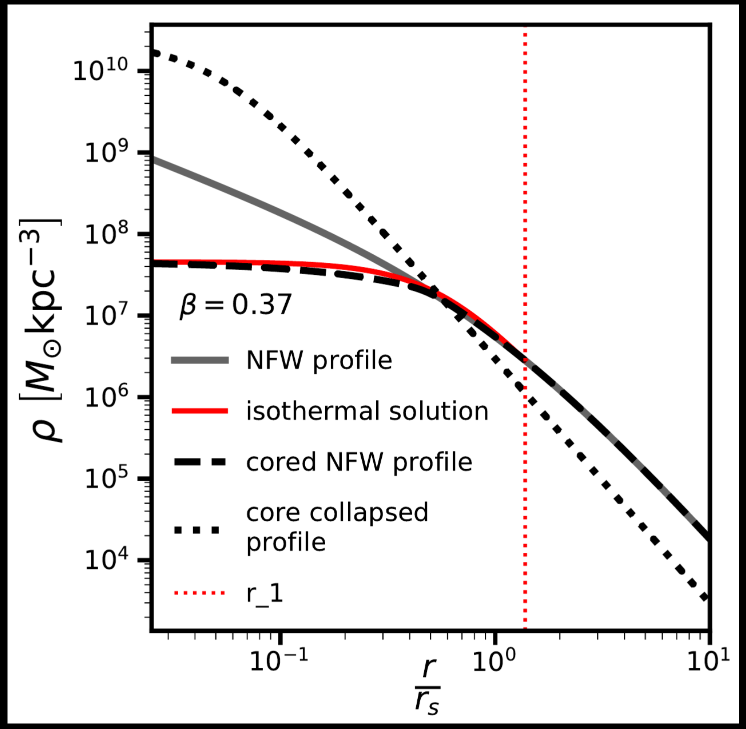
Cold dark matter

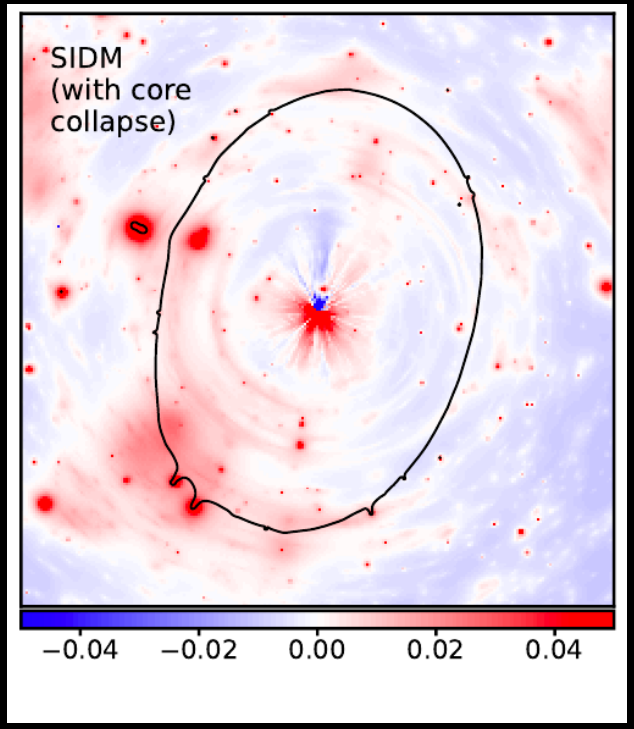


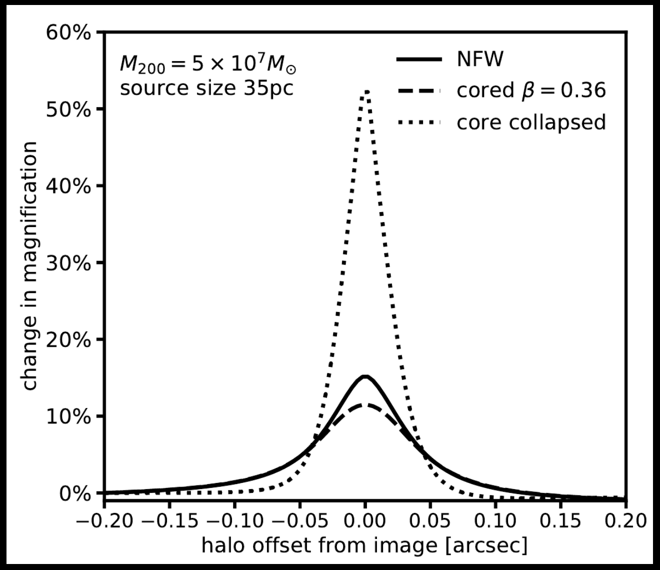
Forecasts for lensing constraints on SIDM

-> use simulated datasets to test a particular model for SIDM physics



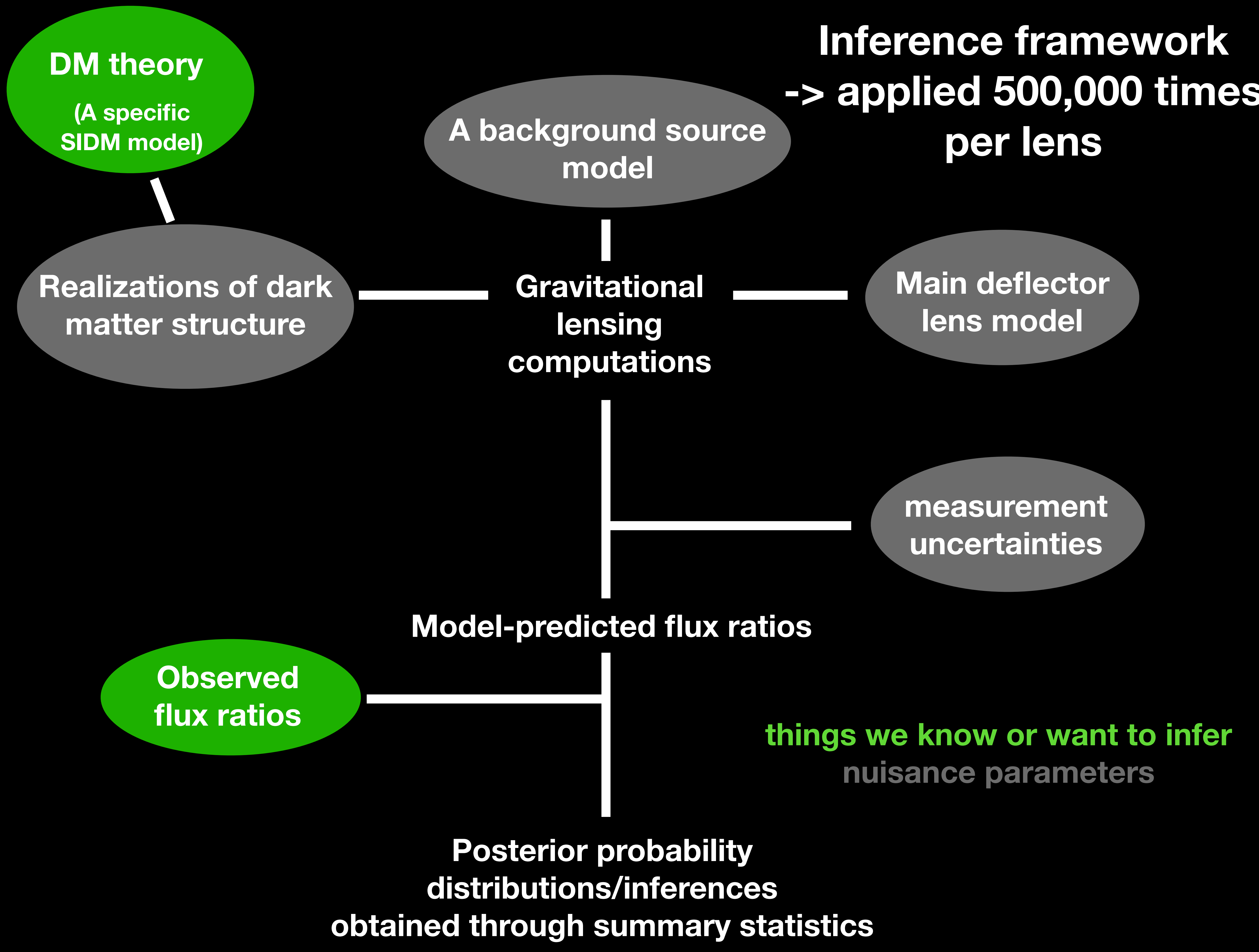




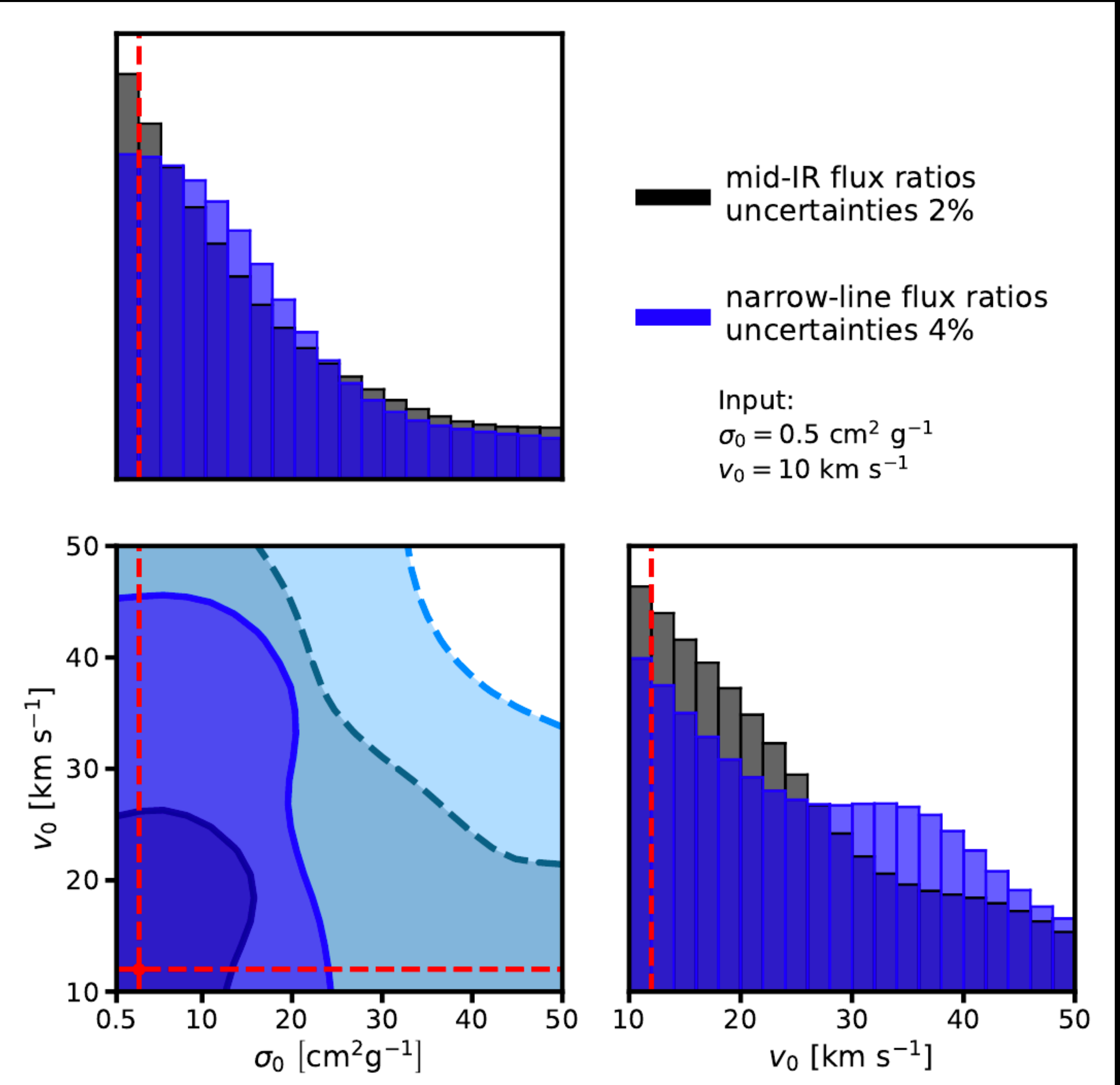


Constraints on the cross section combining a sample of lenses

Inference framework -> applied 500,000 times per lens



Example inference with CDM "truth"

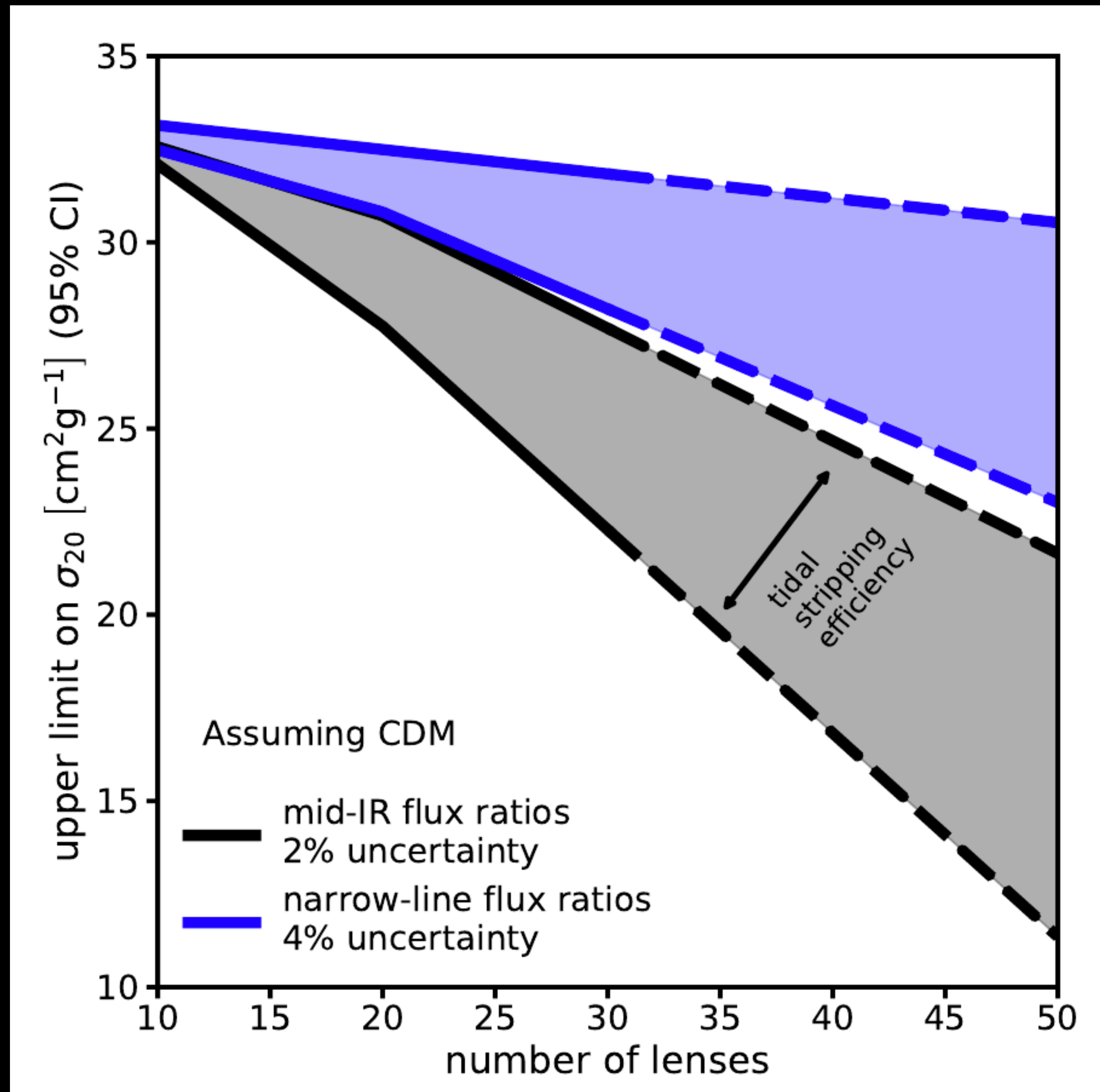


Forecasts: ruling out SIDM

Recast constraints in terms of $\sigma_{20} \equiv \sigma\left(v = 20\ \mathrm{kms}^{-1}\right)$

Mid-IR flux ratios are more constraining because the background source is more compact

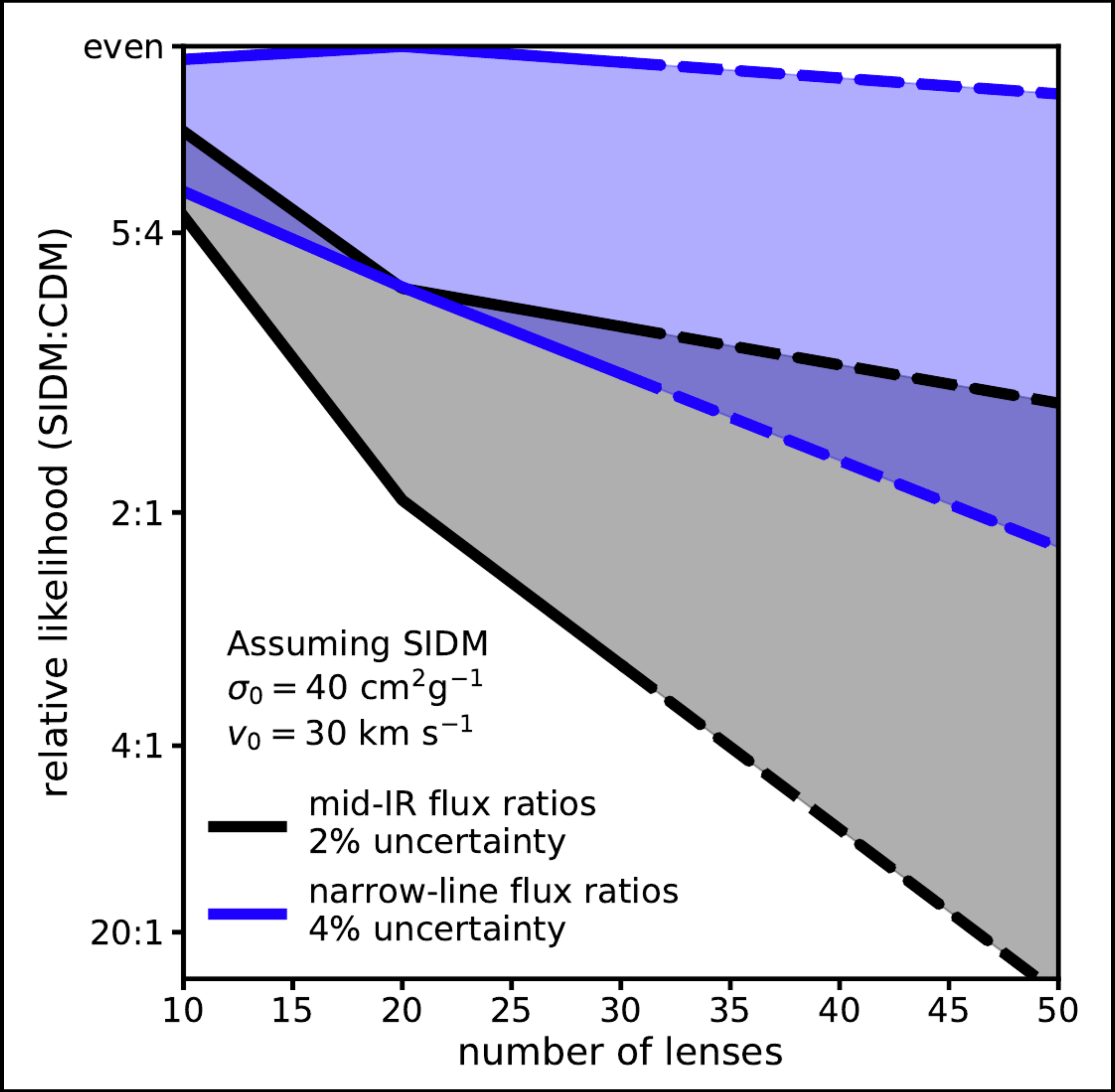
Constraints scale with the amplitude of subhalo mass function because subhalos can core collapse



Forecasts: ruling out CDM

Recast constraints in terms of $\sigma_{20} \equiv \sigma\left(v = 20 \ \mathrm{kms}^{-1}\right)$

Phrase results in terms of the relative likelihood of SIDM:CDM



Take home messages:

1) Strong lensing offers a novel means to detect SIDM structure on sub-galactic scales across cosmological distances. Lensing probes the cross section at velocities below 30 km/sec, independent of systematics associated with stellar dynamics

2) Constraints scale with the amplitude of subhalo mass function
-> more core collapsed subhalos give stronger constraints

3) Mid-IR datasets that we will obtain through JWST GO-02046 (PI Nierenberg) will give the strongest constraints

Supplementary material: halo density profiles

$$\rho\left(x,\beta,\tau\right) = \frac{\rho_s}{\left(x^a+\beta^a\right)^{\frac{1}{a}}(1+x)^2}\frac{\tau^2}{\tau^2+x^2}$$

Cored, truncated NFW profile with beta = rc / rs

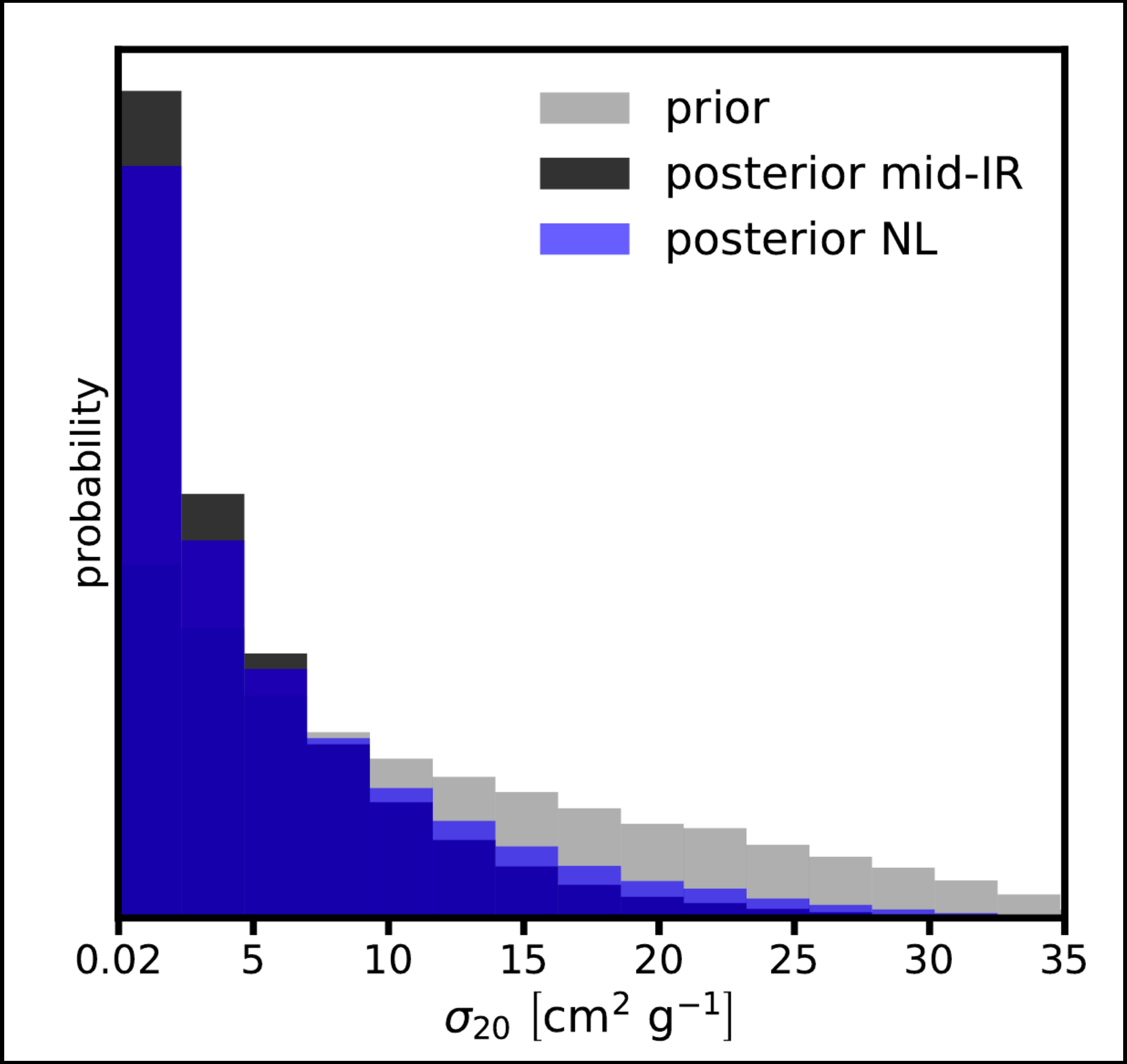
$$\rho\left(r\right) = \rho_0\left(1+\frac{r}{b}\right)^{-\gamma}$$

A cored power-law profile with gamma around -3 (Turner et al. 2020)

Fix the normalization by conserving mass between NFW profile and core collapsed profile within 2 * r_s

Computing the likelihood $p\left(\sigma_{20}\,|\,\mathrm{data}\right)$

-> remove the implicit prior on σ_{20} that corresponds to the uniform prior on σ_0 and v_0



Supplementary material: full set of parameters sampled in the forward model

parameter	description	prior
σ_0 $\left[\mathrm{cm}^2\ \mathrm{g}^{-1}\right]$	asymptotic value of the interaction cross section at low velocity (Equation 1)	$\mathcal{U}\ (0.5, 50)$
σ_{20} $\left[\mathrm{cm}^2\ \mathrm{g}^{-1}\right]$	cross section amplitude at 20 km s^{-1}	(derived quantity)
v_0 $\left[\mathrm{km\ s}^{-1}\right]$	velocity scale of the SIDM cross section $\sigma\,(v) \propto v^{-4}$ for $v > v_0$ (Equation 1)	$\mathcal{U}\ (10, 50)$
b	core size in units of r_s of core collapsed halos (Equation 11)	$\mathcal{U}\ (0.01, 0.05)$
γ	logarithmic slope of core collapsed halo density profiles (Equation 11)	$\mathcal{U}\ (2.9, 3.1)$
Σ_{sub} $\left[\mathrm{kpc}^{-2}\right]$	subhalo mass function normalization (Equation 14)	
	tidal stripping efficiency 0.5× Milky Way	$\mathcal{N}\ (0.050, 0.010)$
	tidal stripping efficiency 0.75× Milky Way	$\mathcal{N}\ (0.032, 0.007)$
α	logarithmic slope of subhalo mass function (Equation 14)	$\mathcal{U}\ (-1.95, -1.85)$
δ_{los}	rescales the line of sight halo mass function $10^6 < m < 10^{10} M_{\odot}$ (Equation 16)	$\mathcal{U}\ (0.8, 1.2)$
σ_{src} [pc]	background source size	
	nuclear narrow-line emission	$\mathcal{U}\,(25, 60)$
	mid-IR emission	$\mathcal{U}\,(0.5, 5)$
γ_{macro}	logarithmic slope of main deflector mass profile	$\mathcal{U}\ (1.9, 2.2)$
a_4	controls boxyness/diskyness of main deflector mass profile	$\mathcal{N}\ (0, 0.01)$
δ_{xy} [m.a.s.]	image position measurement uncertainty	$\mathcal{N}\ (0, 3)$
δf	image flux measurement uncertainties	
	mid-IR	2%
	narrow-line	4%