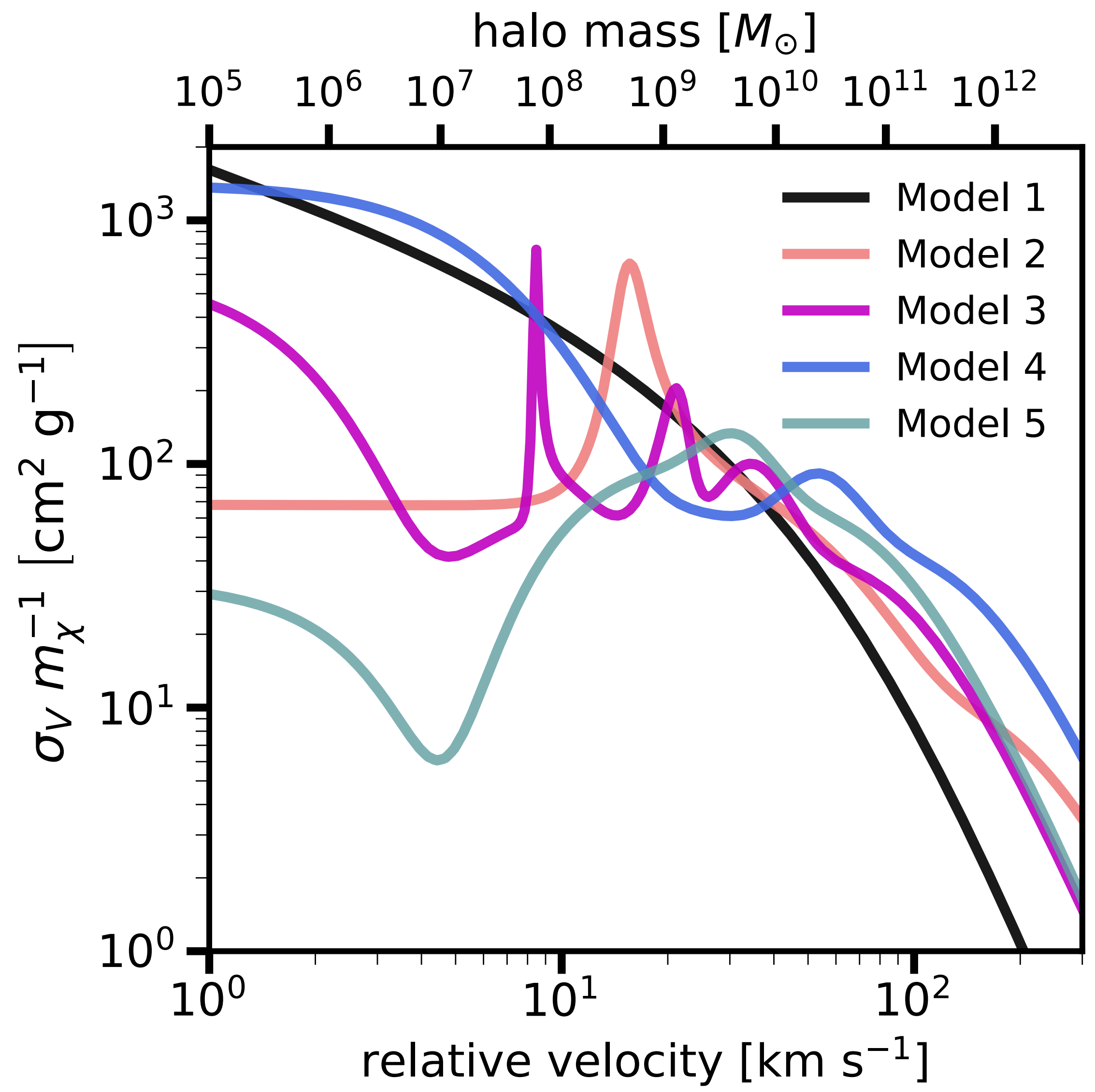
Constraining self-interacting dark matter with quadruply-imaged quasars



Daniel Gilman
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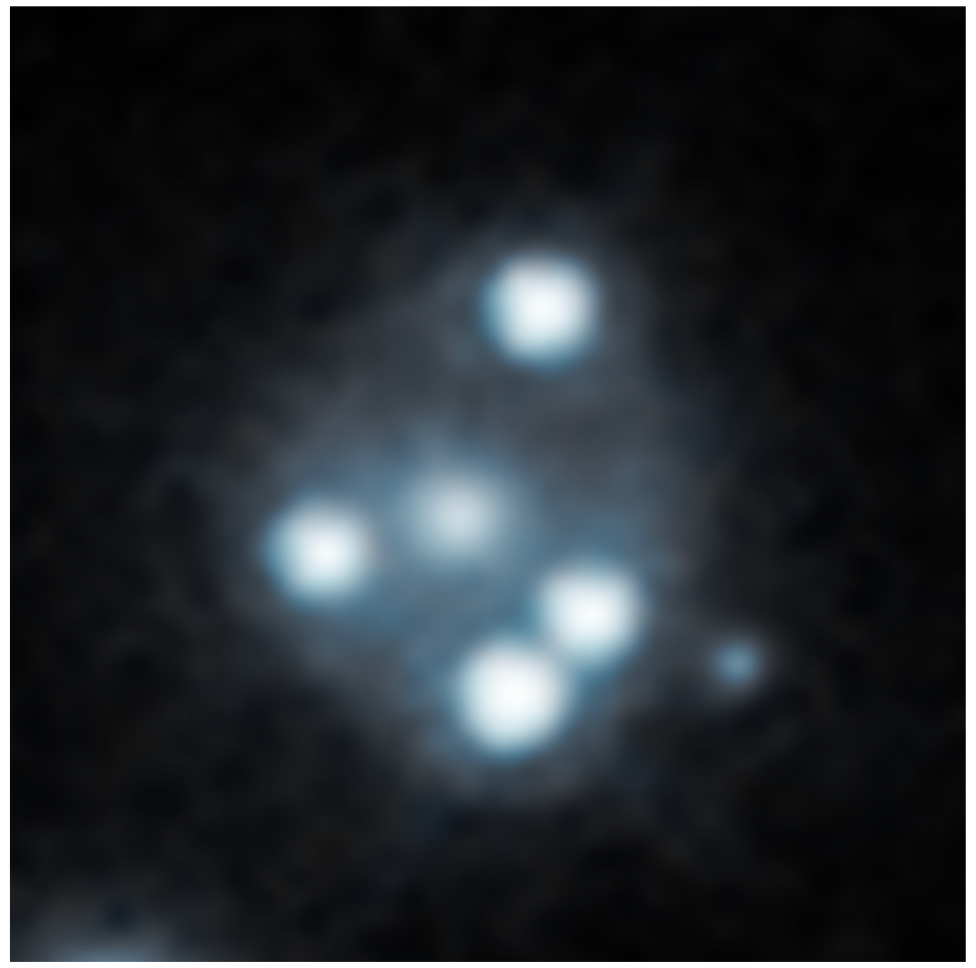

Collaborators:
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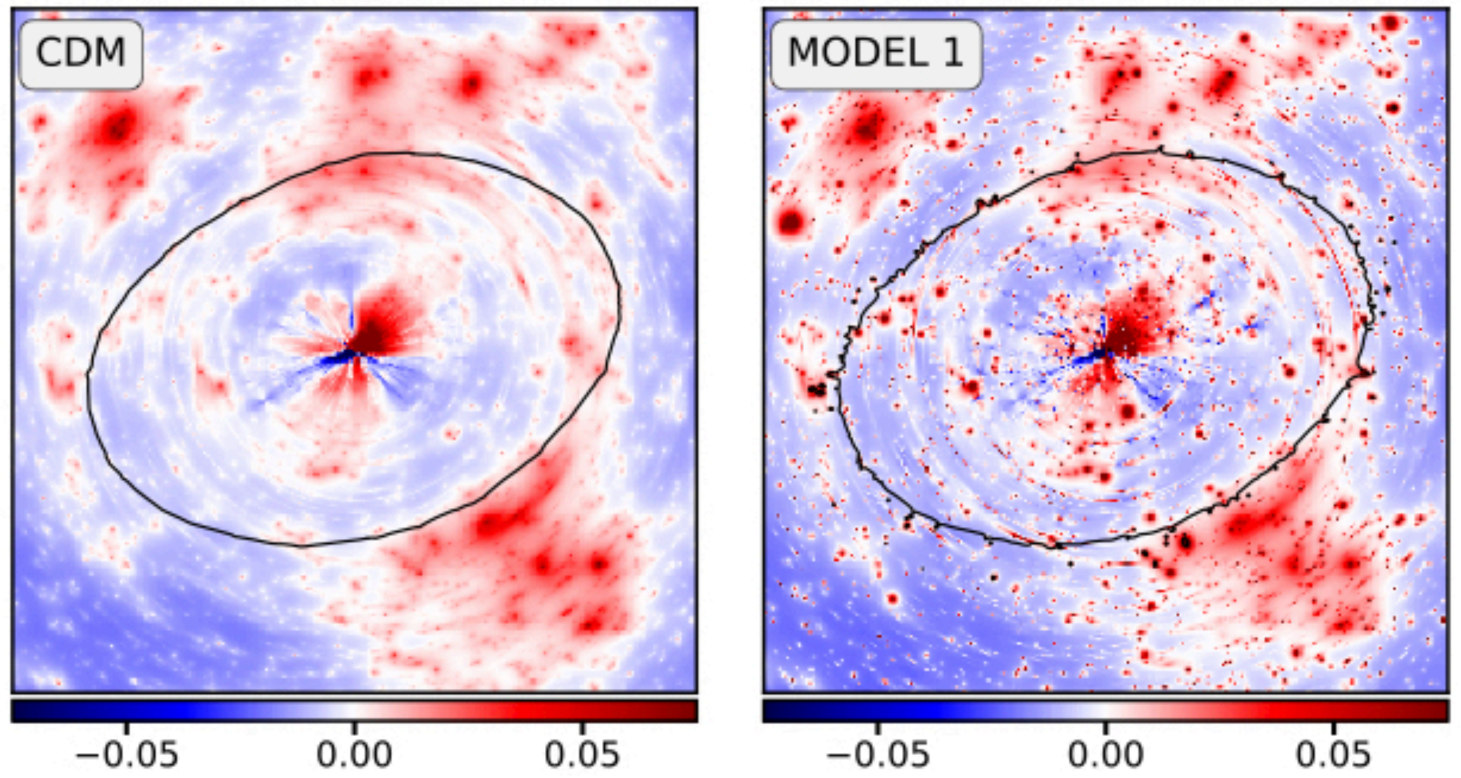
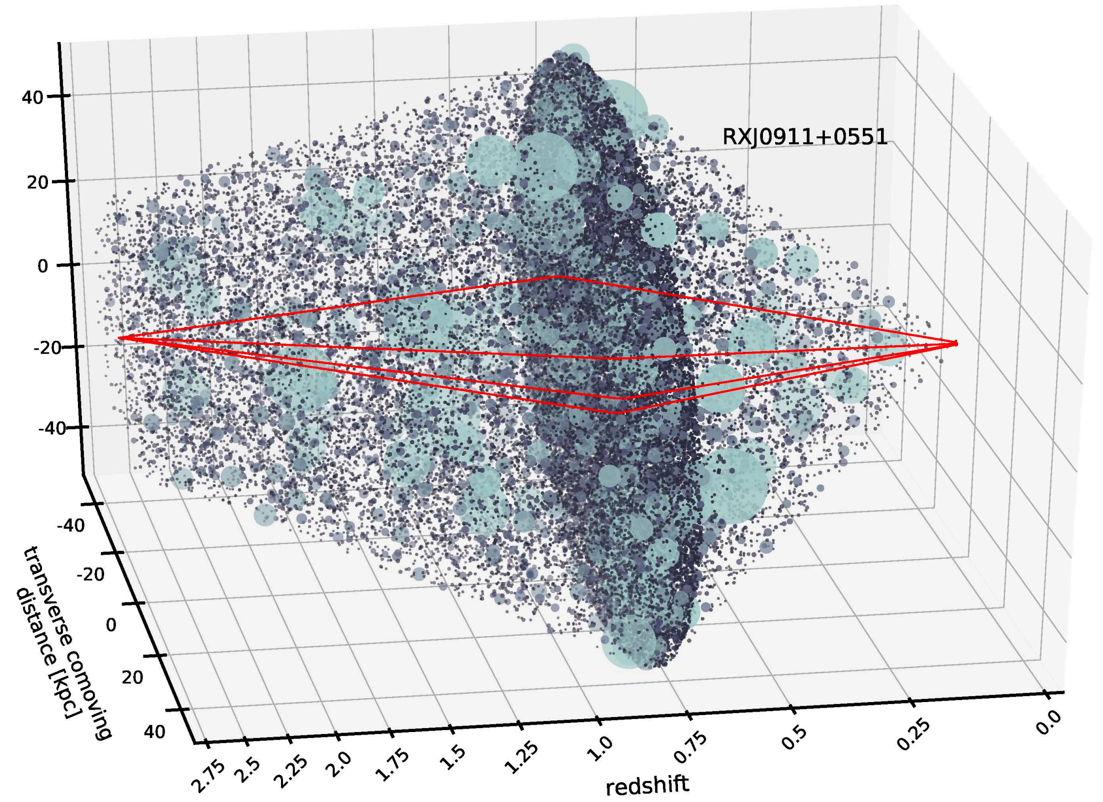
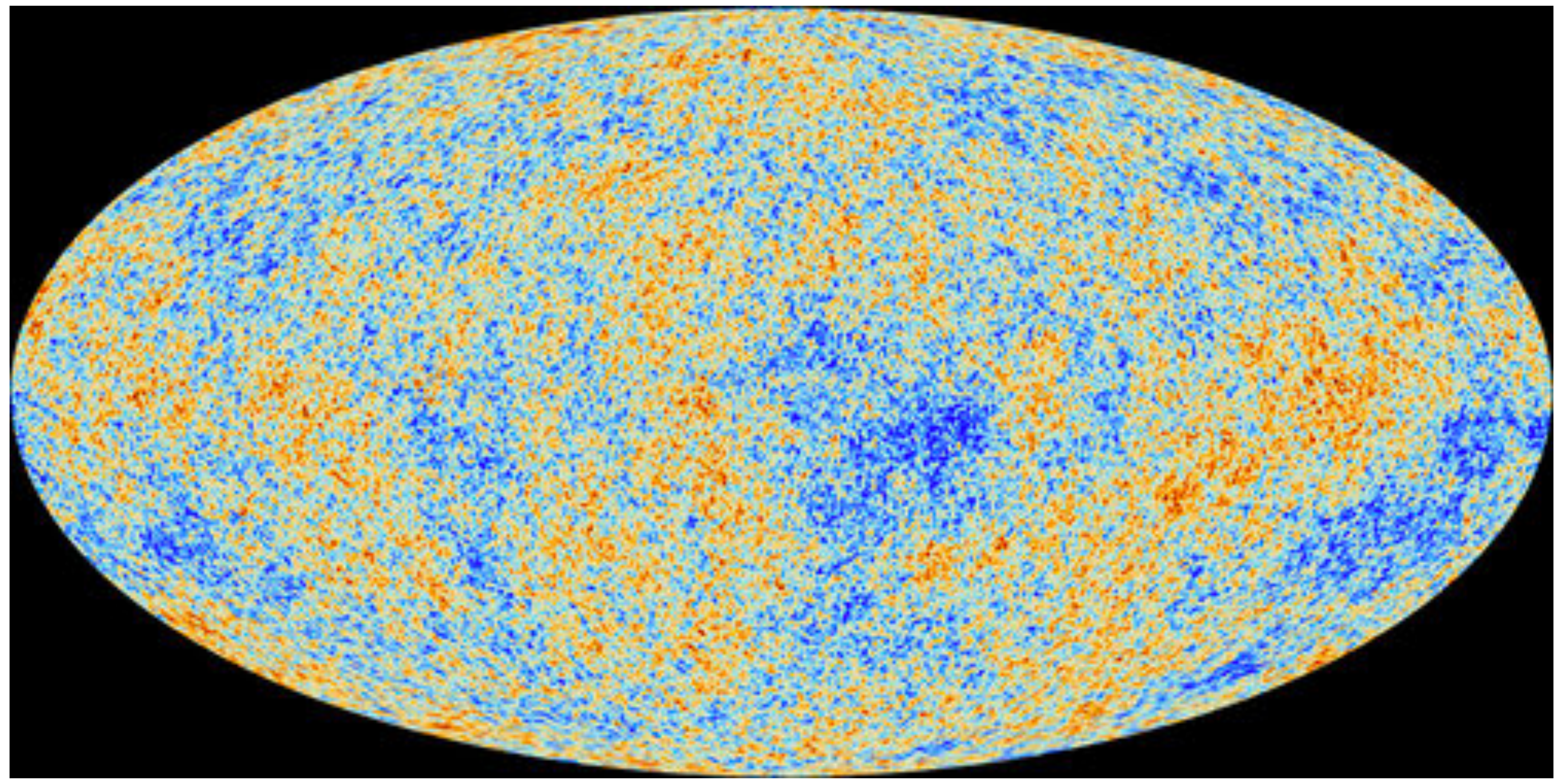
Simon Birrer (Stanford)
Tommaso Treu (UCLA)
Anna Nierenberg (UC Merced)





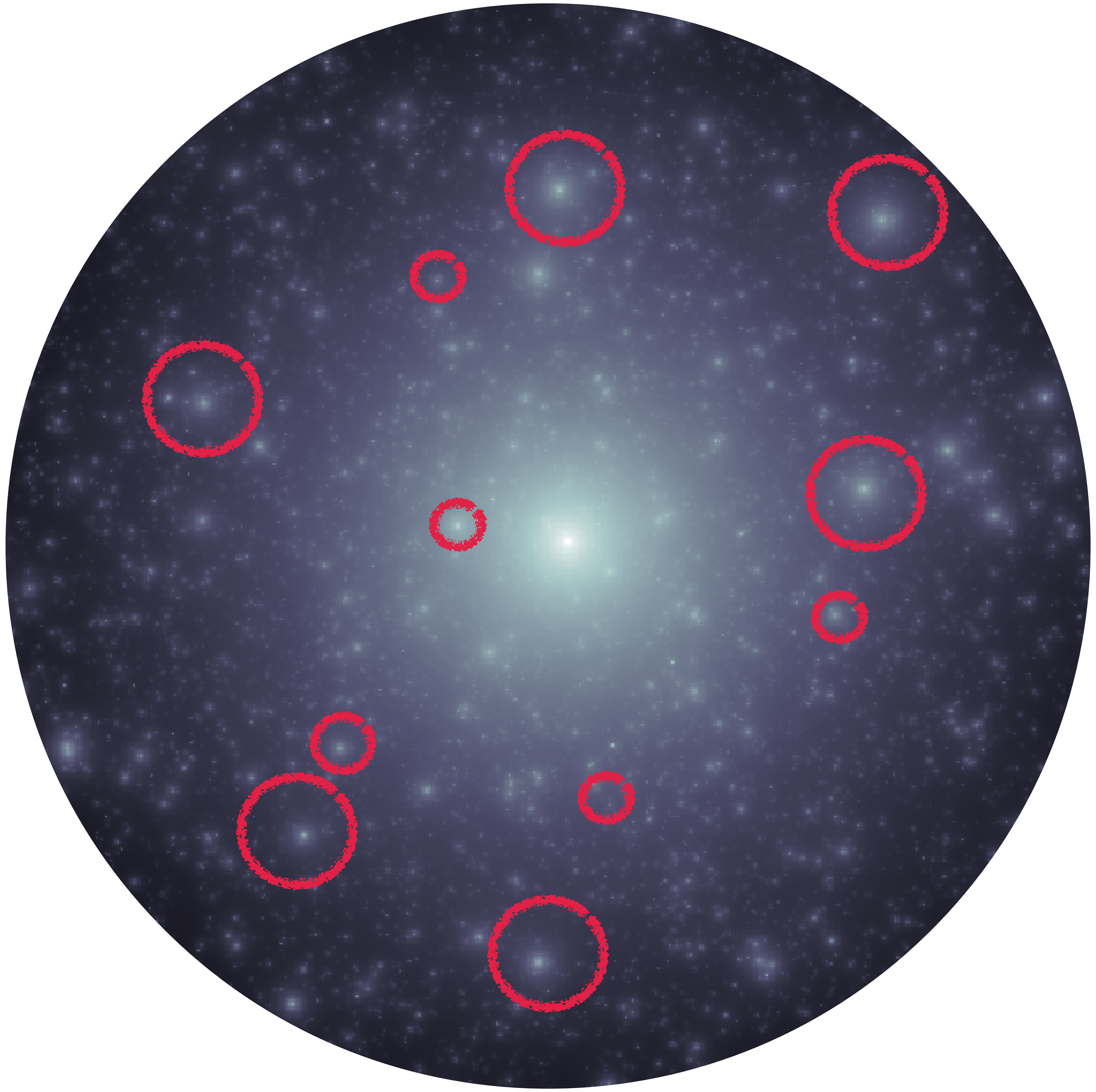
Dark matter: what do we know?

It must comprise ~85% of the mass in the Universe, negligible interactions with the standard model



It must be collisionless on large scales and high velocities

It must give us galaxies and dwarf galaxies (i.e. not relativistic at early times)
-> lots of halos and subhalos



Where does that leave us?

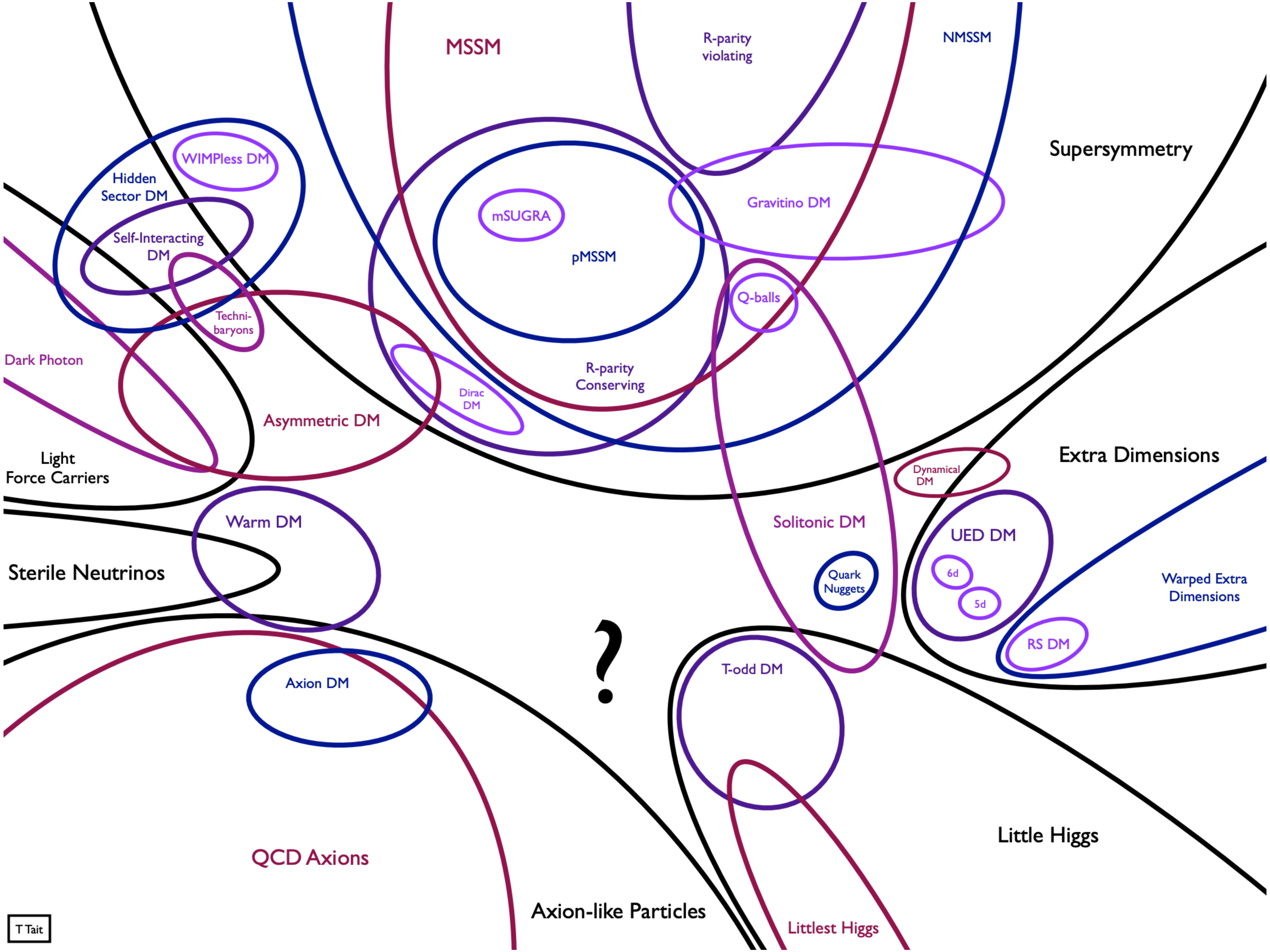


Figure by Tim Tait

Non-minimal dark sector: Self-interacting dark matter (SIDM)

Dark matter has a small cross section for scattering with itself

-> only interacts with standard model through gravity

-> collisionless on large scales

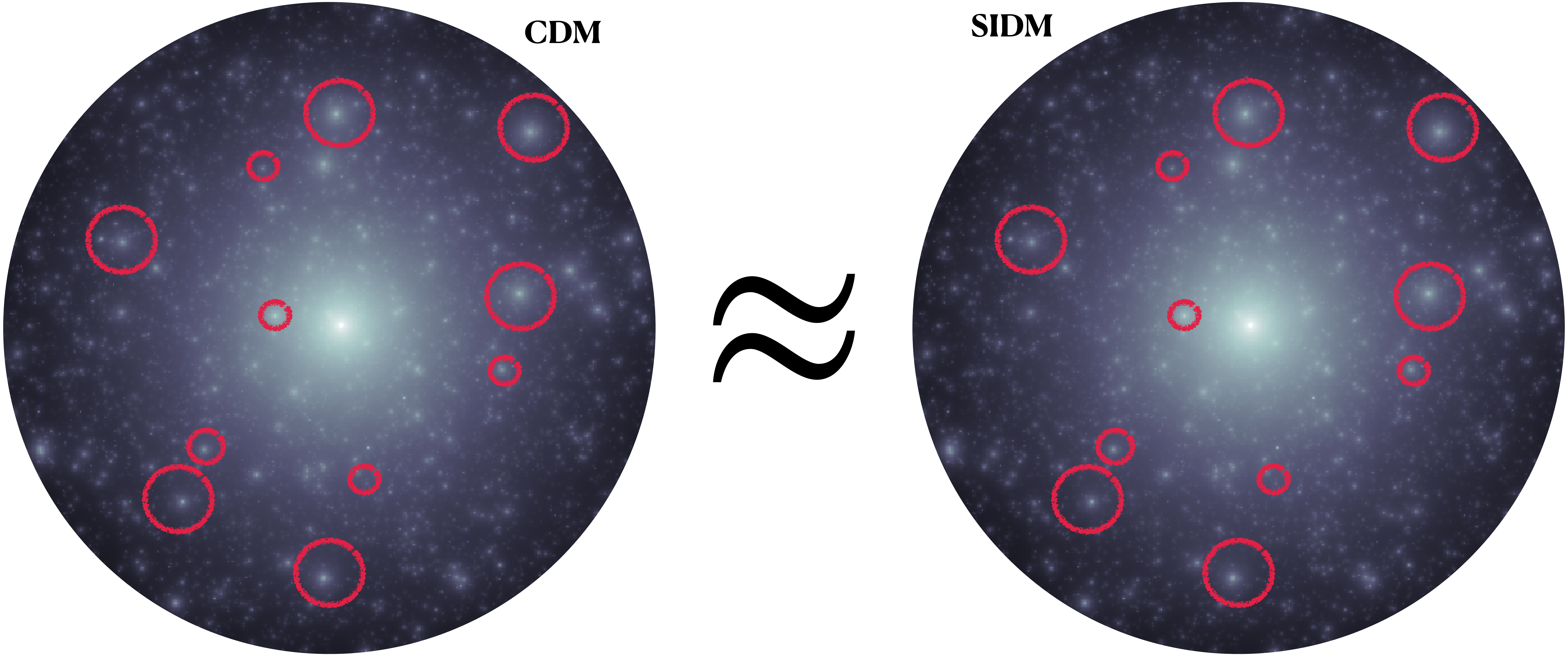
Interactions per Hubble time in average patch of Universe $\sim 10^{-4} \left(\frac{\sigma}{1\ \mathrm{cm^2 g^{-1}}} \right) \left(\frac{\rho}{\rho_{\mathrm{crit}}} \right) \left(\frac{v}{1000\ \mathrm{km\ s^{-1}}} \right)$

Interactions per Hubble time in a halo $\sim 1 \left(\frac{\sigma = 1\ \mathrm{cm^2 g^{-1}}}{1\ \mathrm{cm^2 g^{-1}}} \right) \left(\frac{\rho = 10^6 \rho_{\mathrm{crit}}}{\rho_{\mathrm{crit}}} \right) \left(\frac{5\ \mathrm{km\ s^{-1}}}{1000\ \mathrm{km\ s^{-1}}} \right)$

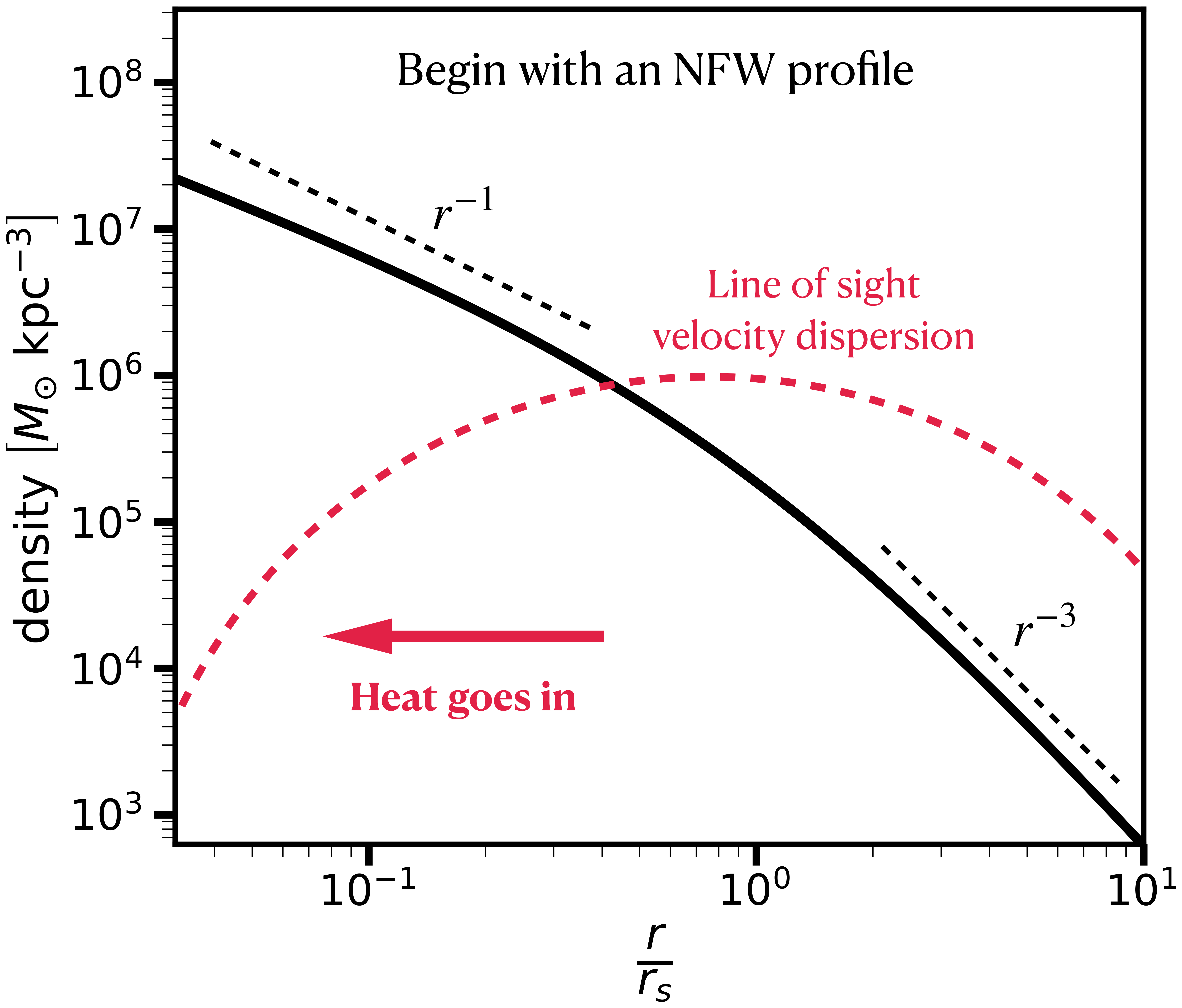
Non-minimal dark sector: Self-interacting dark matter (SIDM)

Assume an SIDM model that does not alter the linear matter power spectrum

Only halo density profiles distinguish the two models



Effects of SIDM on halo density profiles



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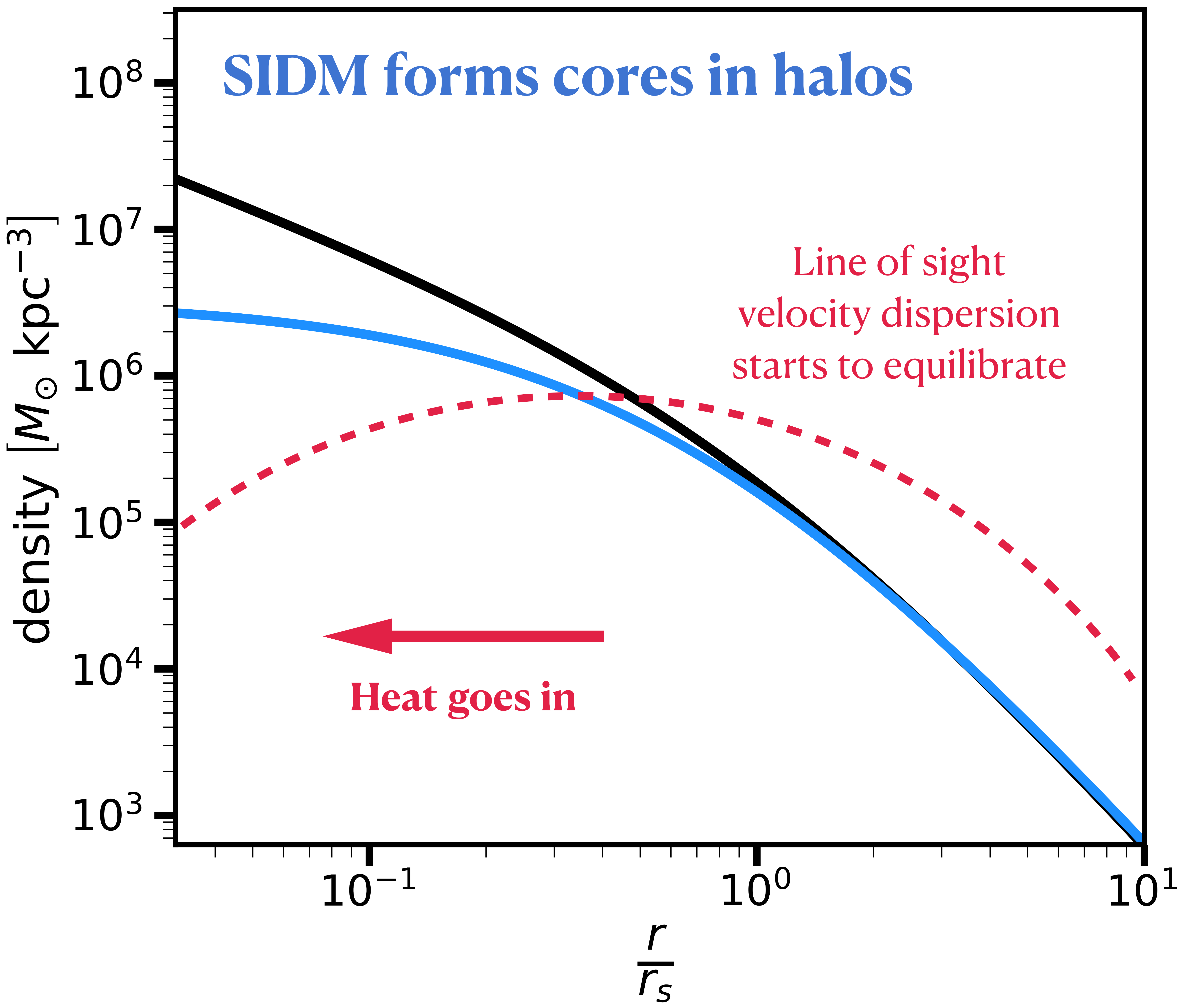

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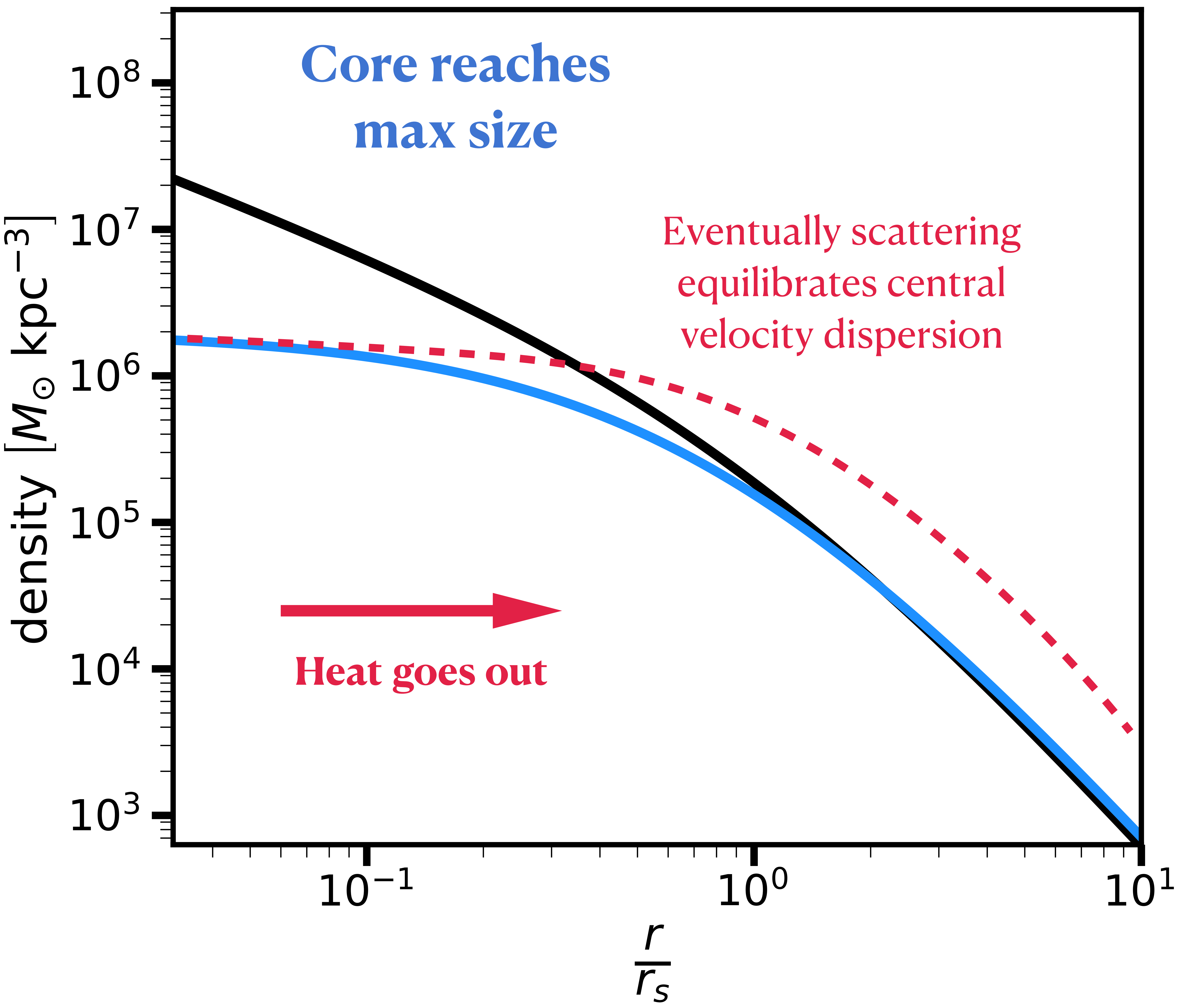
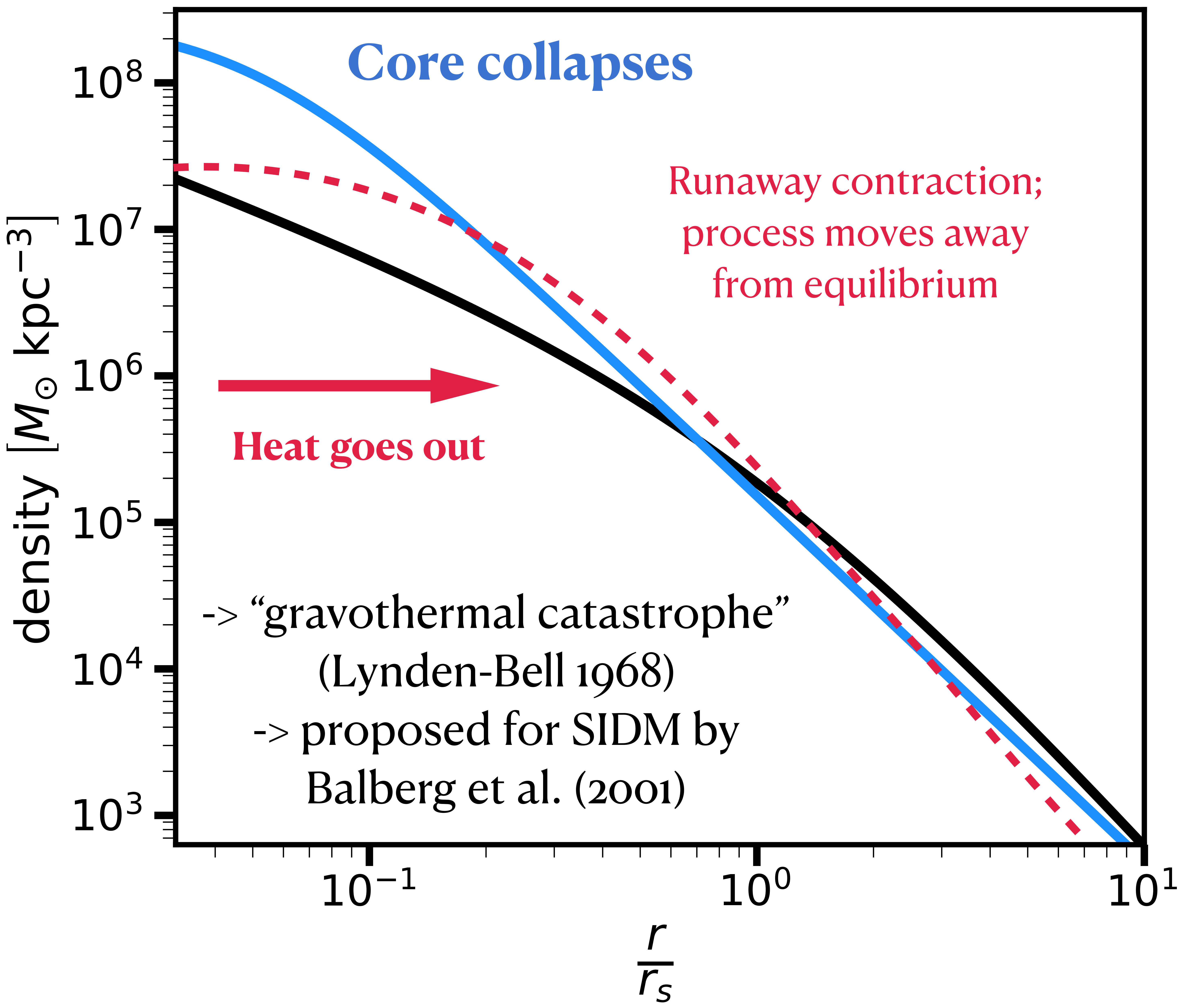


Effects of SIDM on halo density profiles



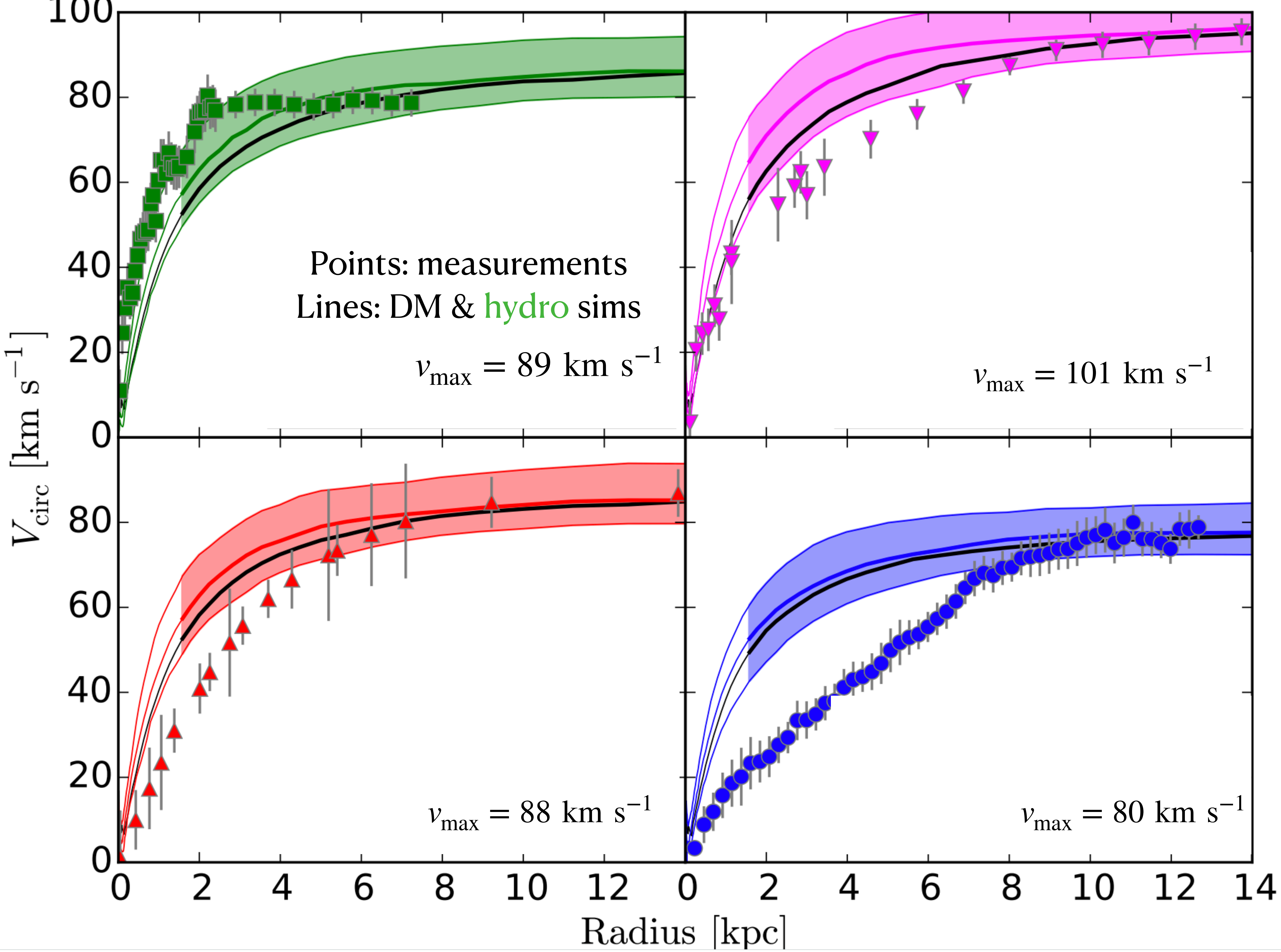
Self-interacting dark matter (SIDM)

Support for SIDM often phrased as a diversity argument:

at fixed halo mass (or $v_{\max}$) we see significant diversity among halo profiles

Core formation and collapse in SIDM potentially give rise to observed diversity

Adapted from Oman et al. (2016)



Self-interacting dark matter (SIDM)

Alternative:

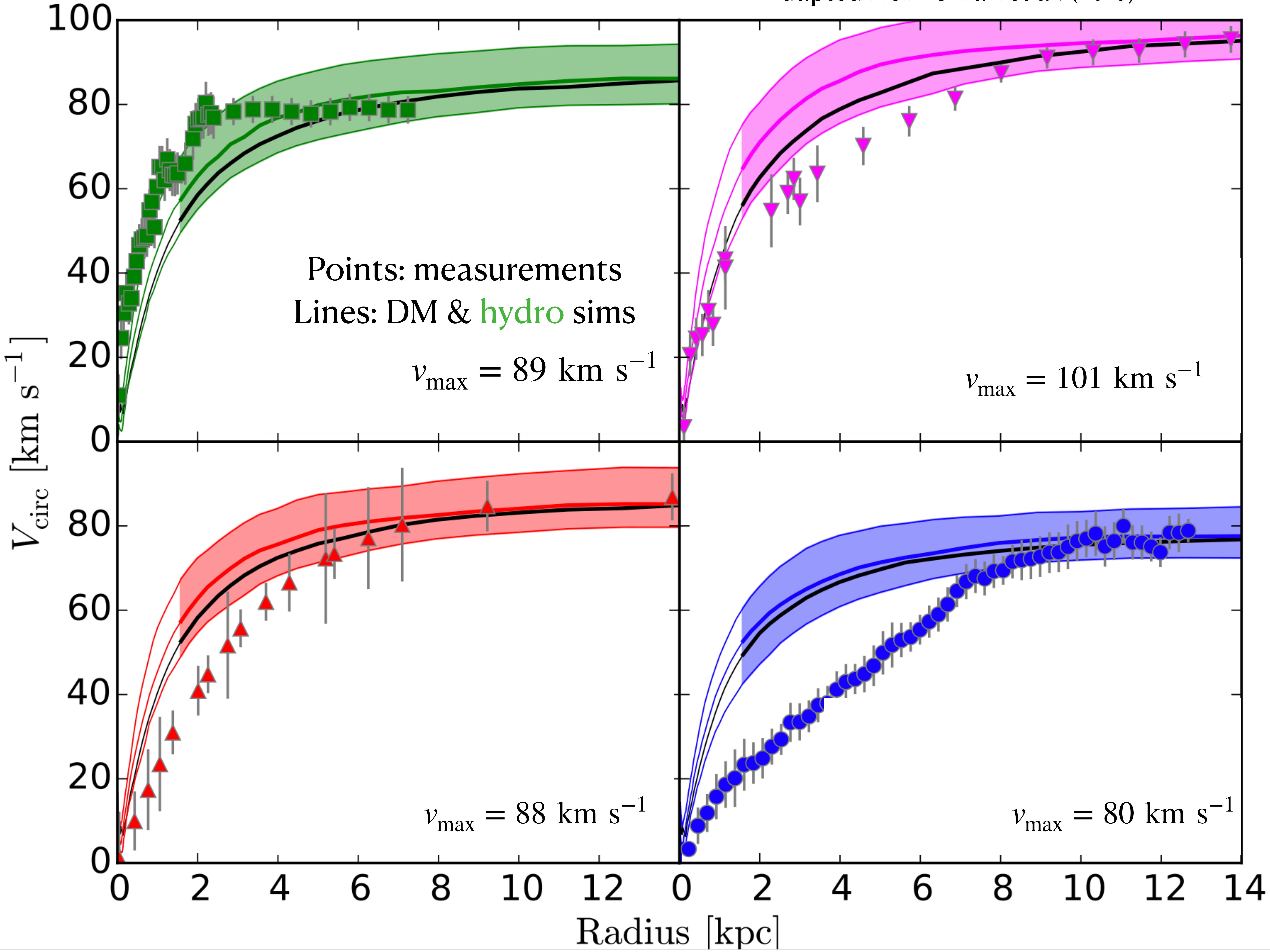
Galaxy formation and astrophysics is really complicated, we don't understand it well enough, baryonic physics can do all of this

We need an independent probe:

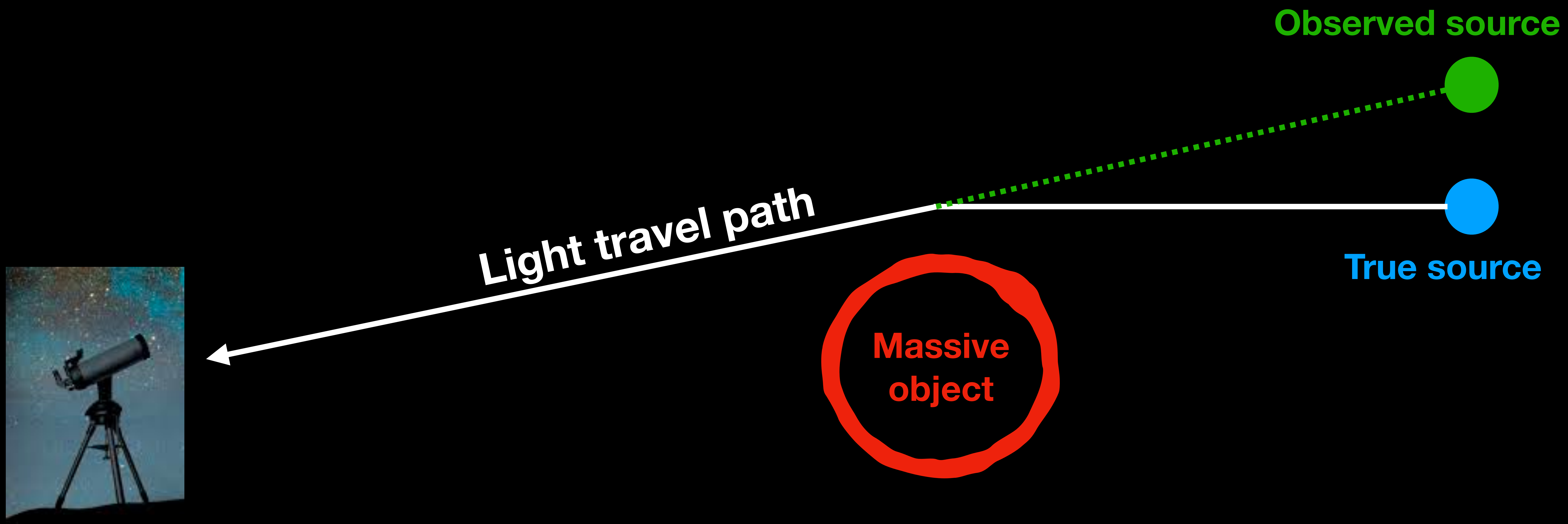
1) doesn't rely on baryons (directly probes halo density profiles)

2) extends to low masses $< 10^8 M_\odot$ **(to minimize baryonic feedback)**

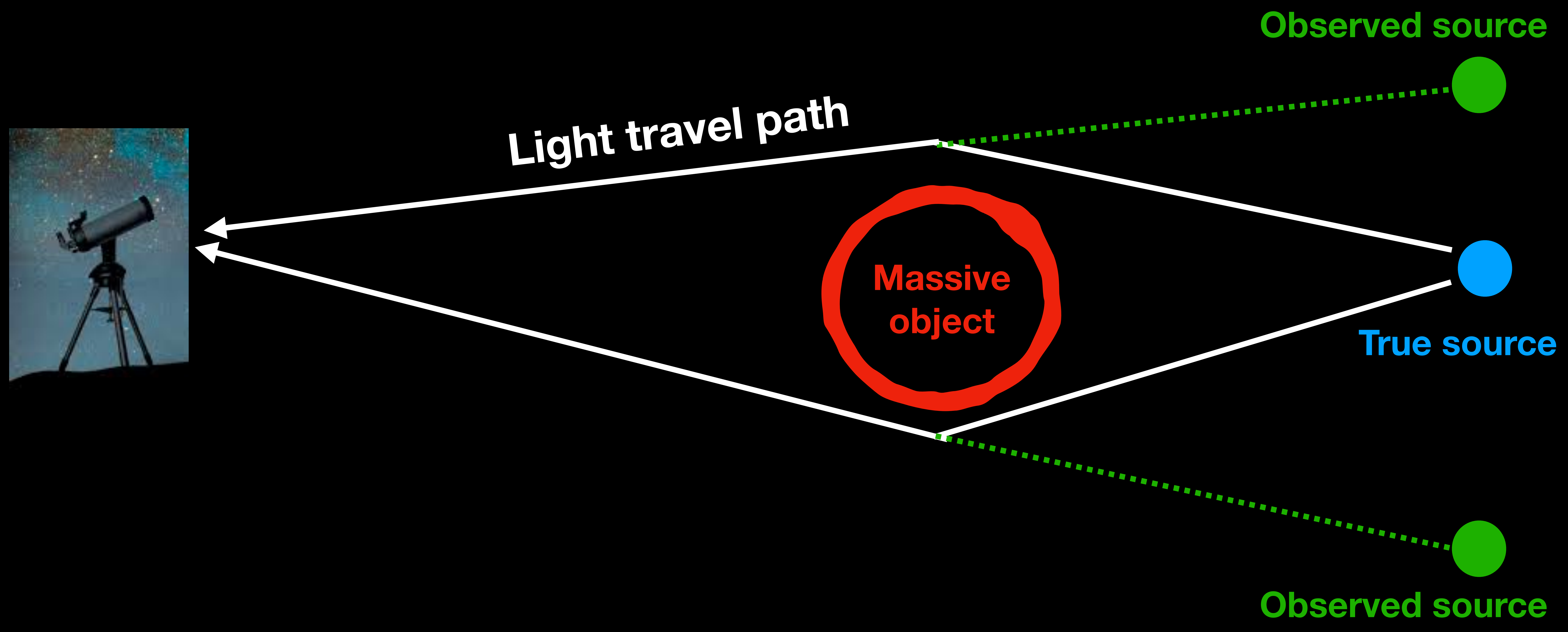
Adapted from Oman et al. (2016)



Gravitational lensing: deflection of light by gravitational fields



Strong lensing produces multiple images of a single source



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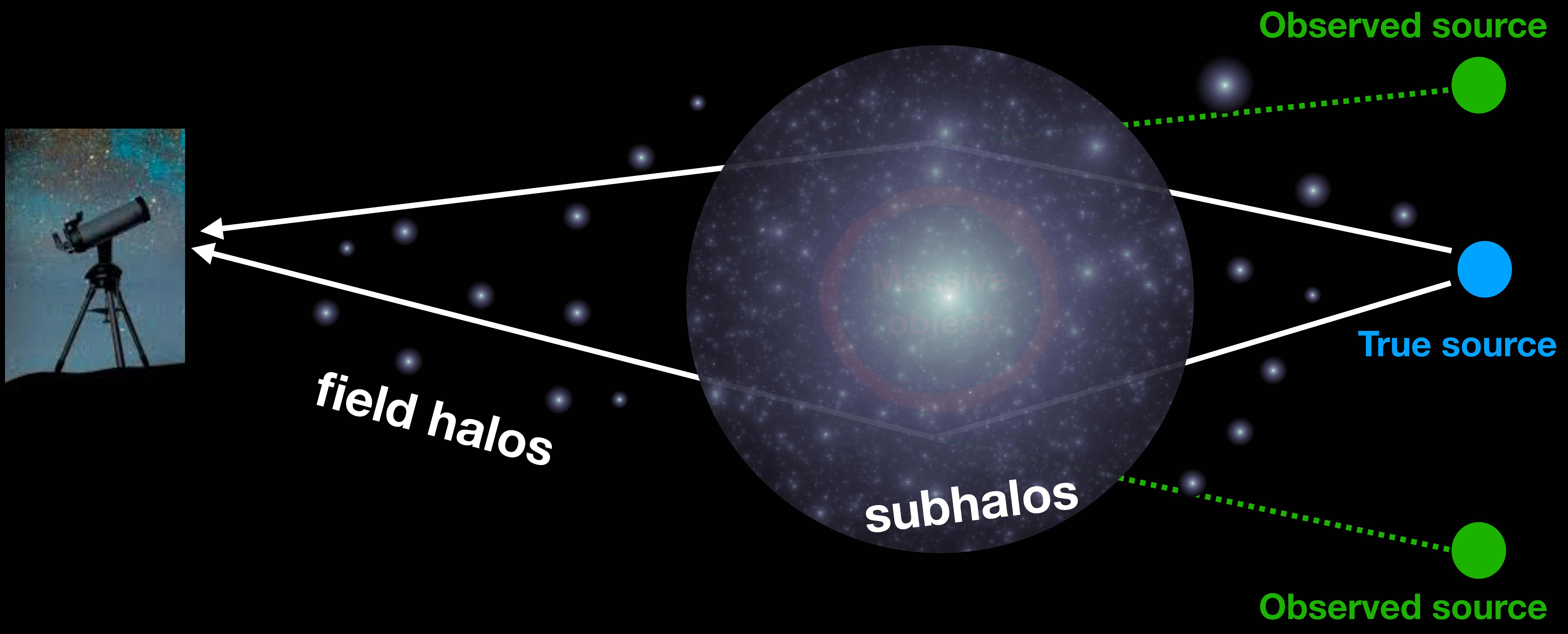


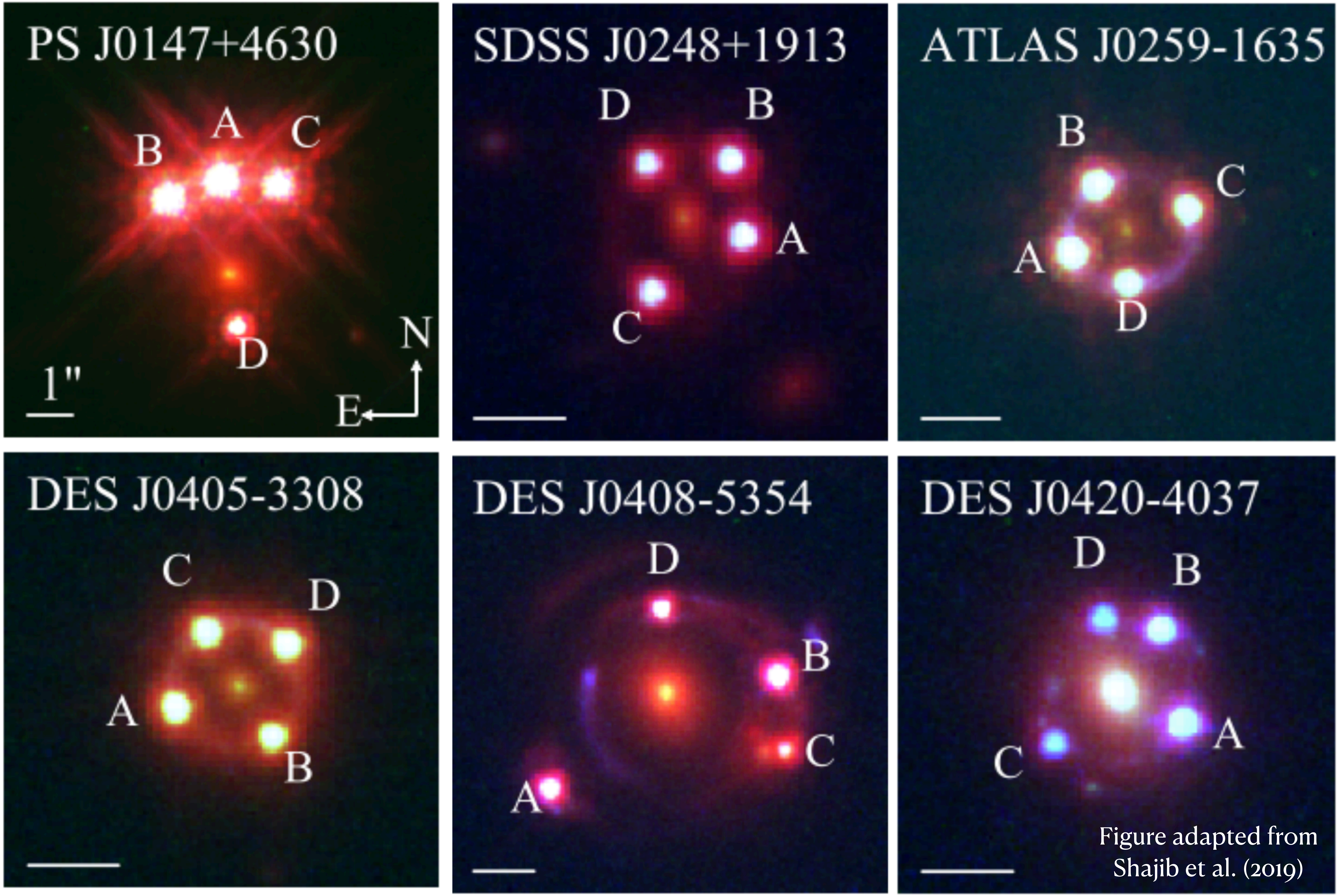


Figure adapted from
Shajib et al. (2019)

Anatomy of a quad lens

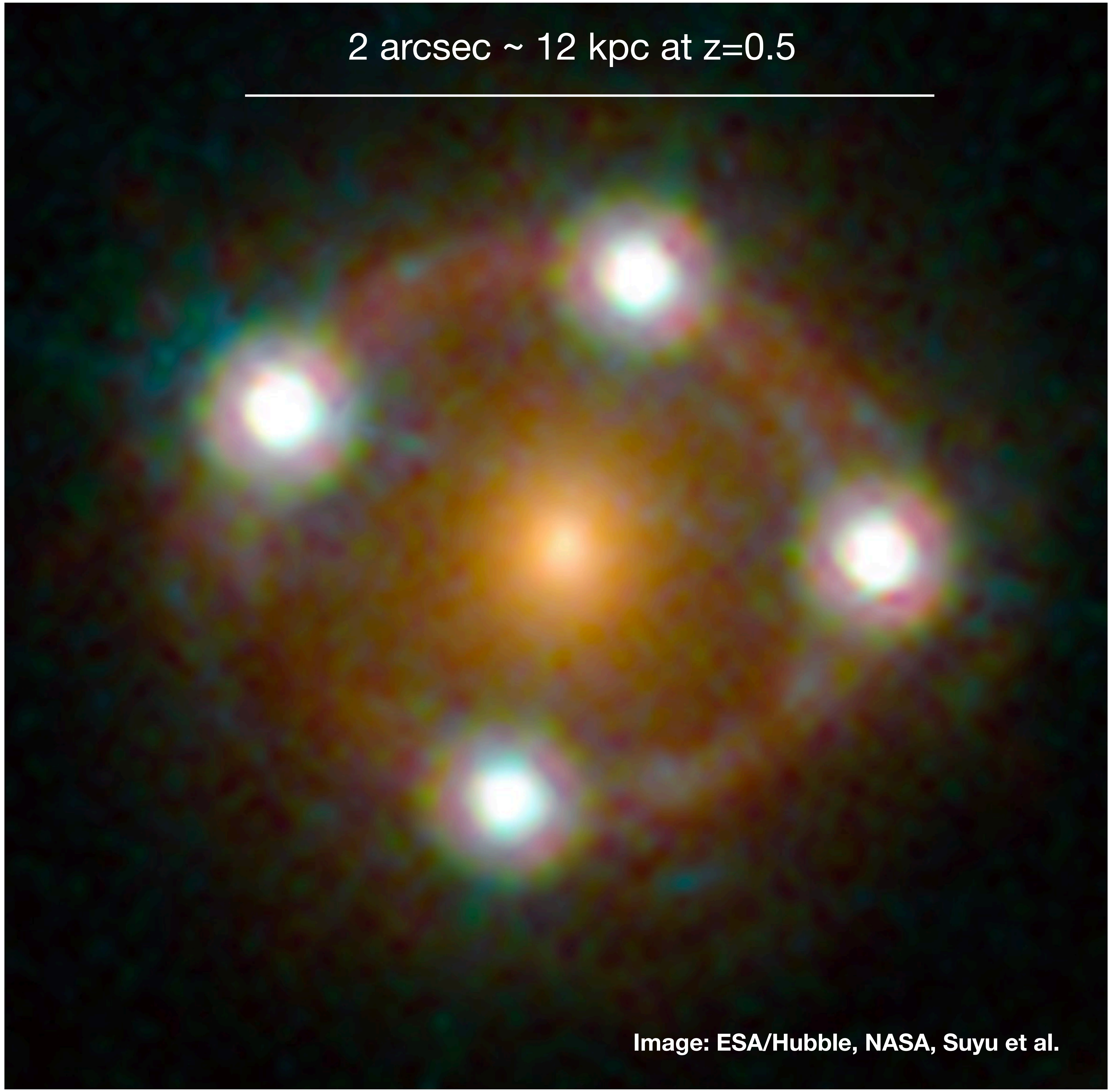
1) Time delays
depend on potential difference $\Delta\Psi$

2) Image positions
depend on deflection angles

$$\alpha \sim \frac{\partial \Psi}{\partial x}$$

3) Magnification ratios (flux ratios)
depend on derivatives of
deflection angles

$$\frac{\partial \alpha}{\partial x} \sim \frac{\partial^2 \Psi}{\partial x^2} \sim \text{mass density}$$

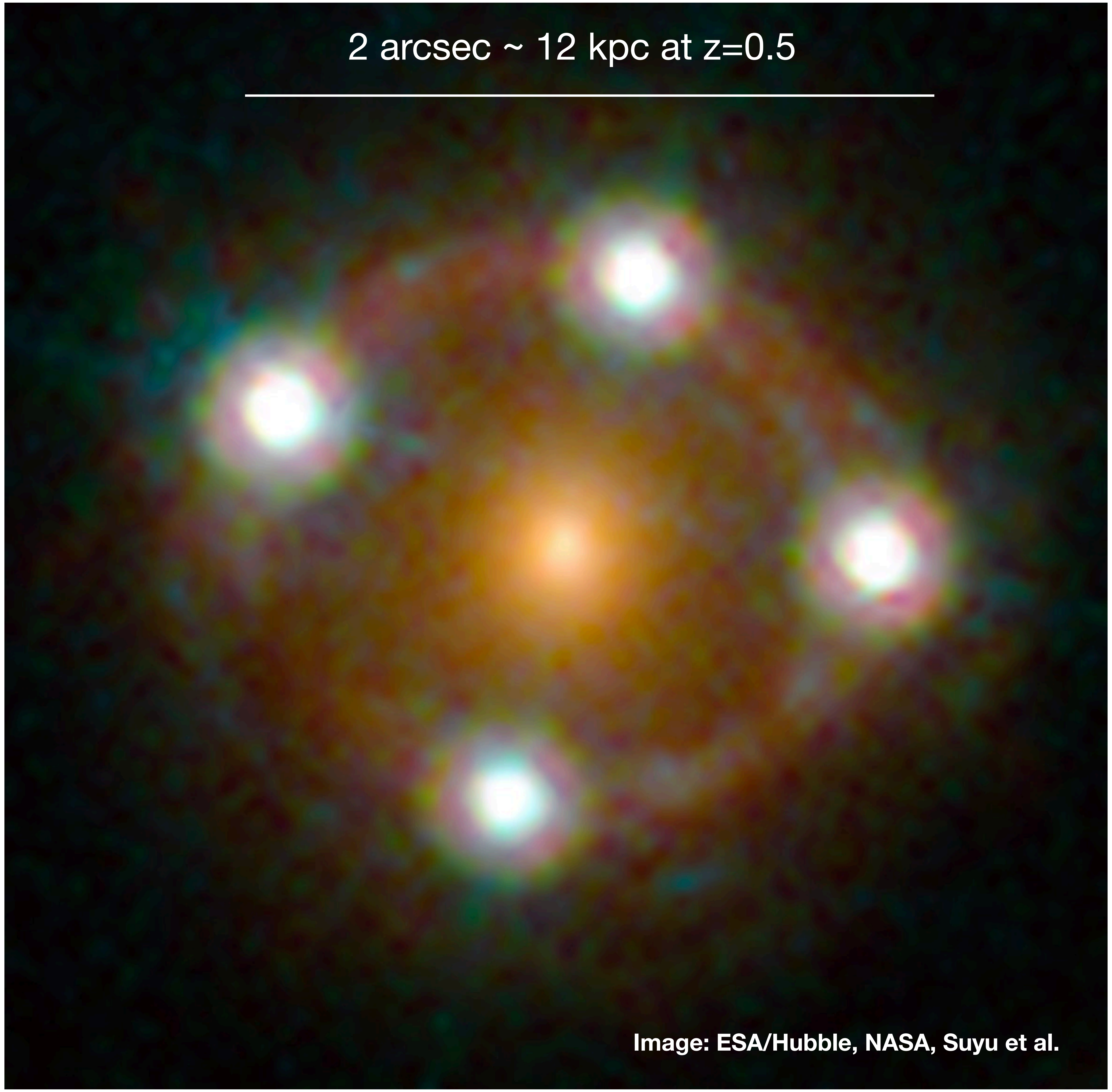


Anatomy of a quad lens

With exiting flux ratios from HST we probe halos in the mass range

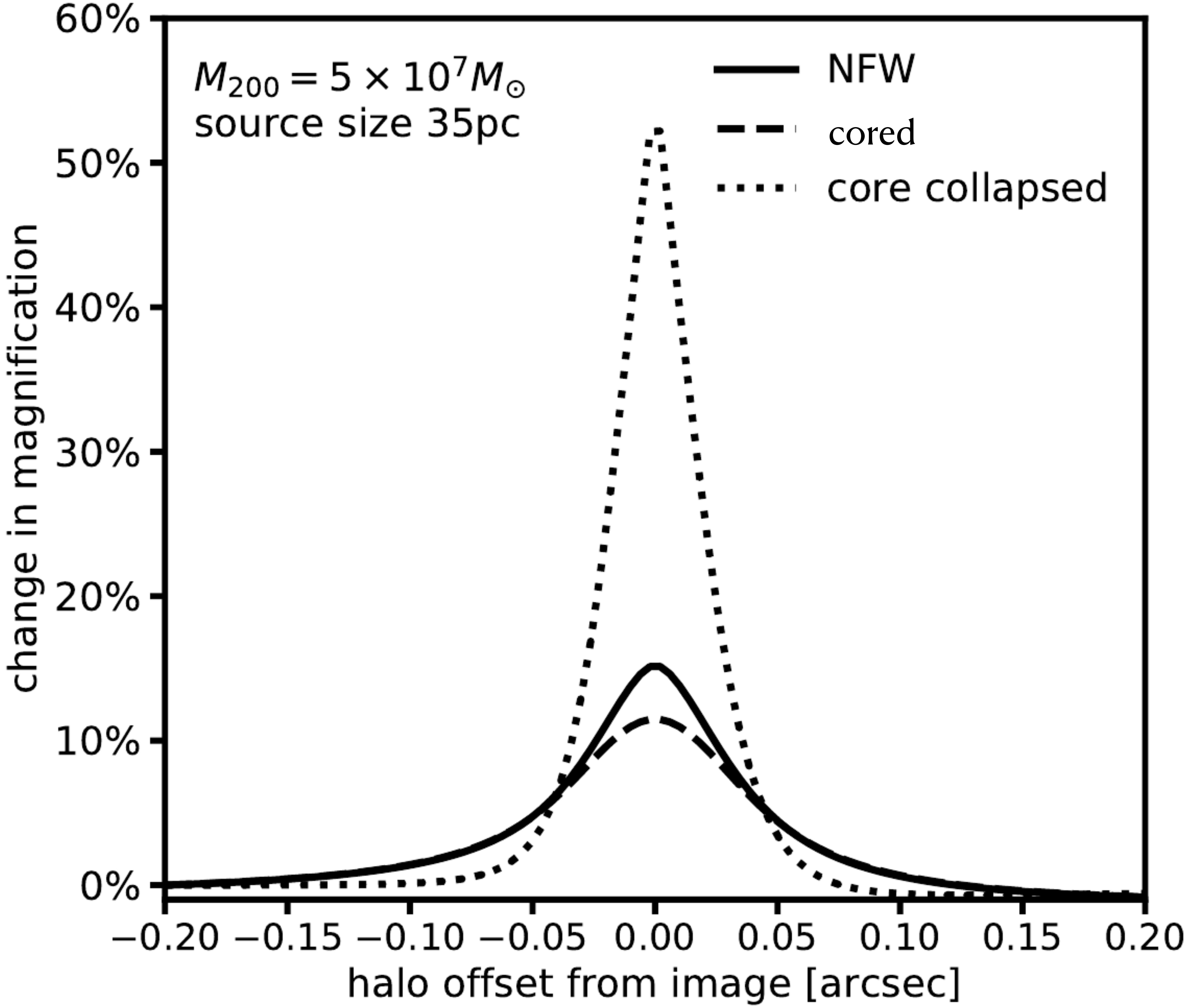
$$10^7 - 10^{10} M_{\odot}$$

Minimum halo mass sensitivity determined by size of deflection angle relative to angular size of the source



Connection to SIDM: Core-collapsed halos are extremely efficient lenses

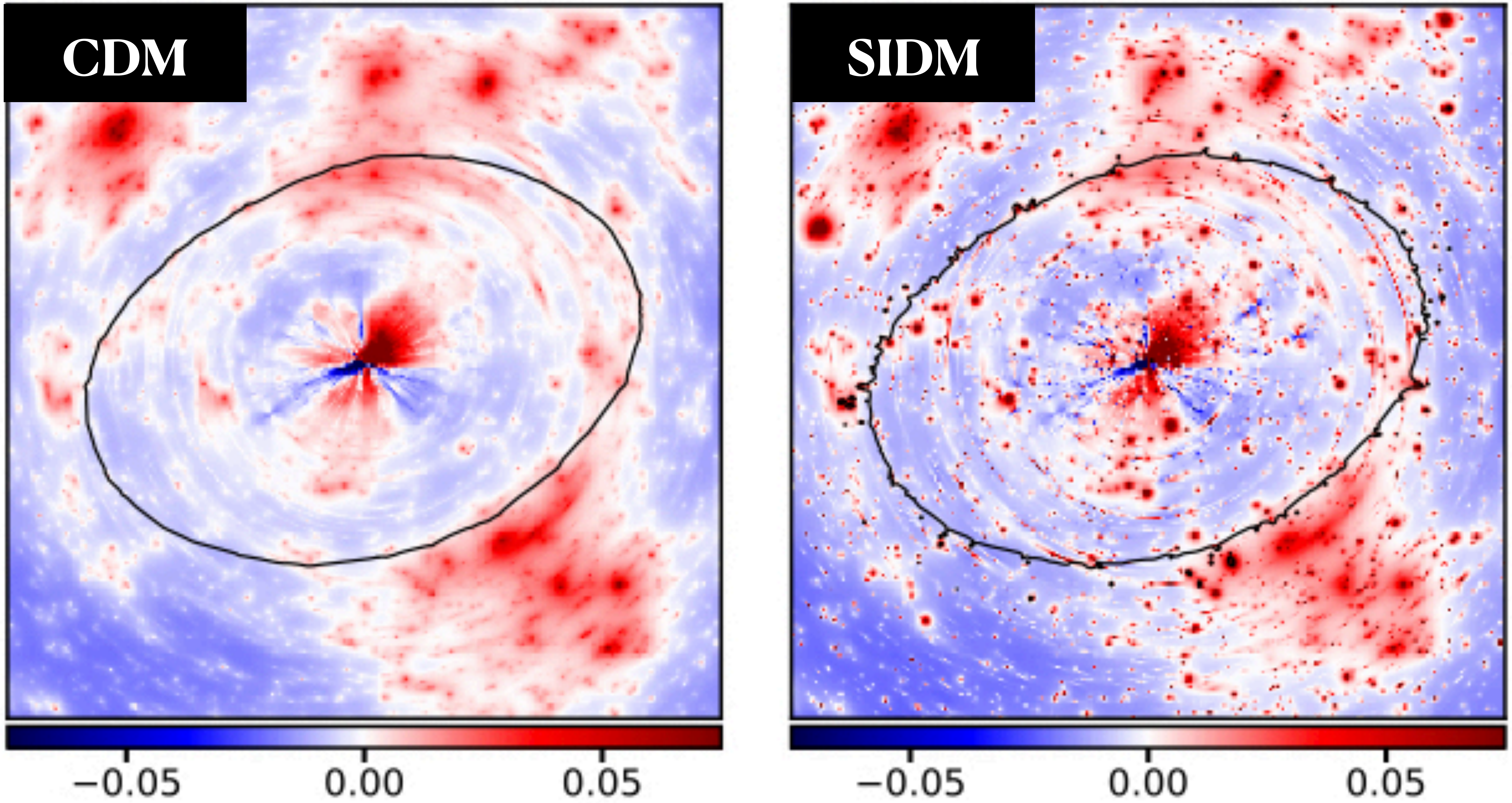
Gilman et al. (2021)



SIDM changes halo density profiles
-> changes their lensing efficiency
at fixed mass

Connection to SIDM: Core-collapsed halos are extremely efficient lenses

Gilman et al. (2022)



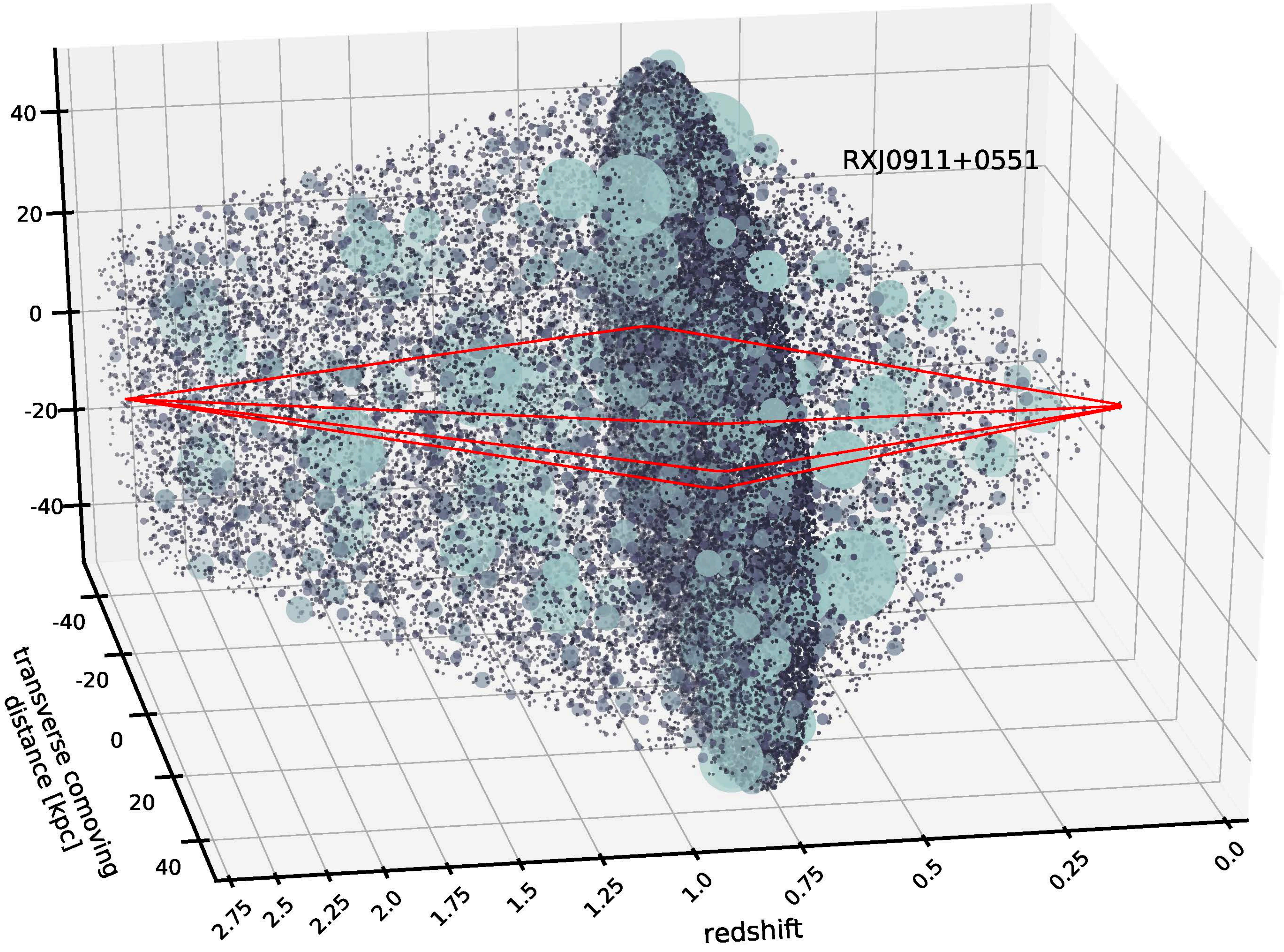
Dark matter density relative to average

Dark matter density relative to average

How do we analyze lenses in practice?

Observation

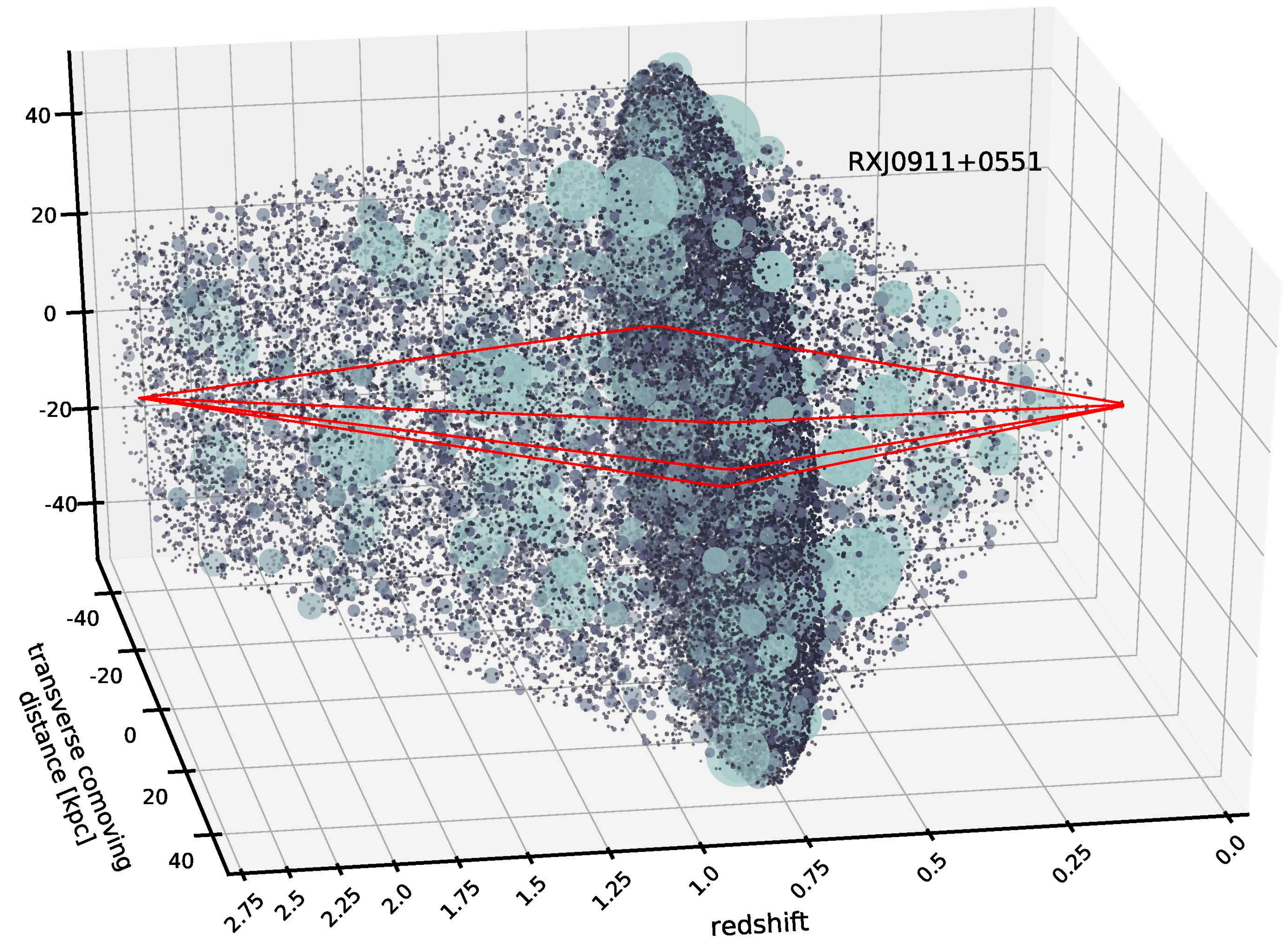
Simulation



How do we analyze lenses in practice?

Dark matter theory

Halo mass function, halo density profiles



Simulate data from the model millions of times per lens

Compare with data

We can use our forward model to do Bayesian inference

Bayes theorem

$$p\left(\text{model}\,|\,\text{data}\right) \propto \mathcal{L}\left(\text{data}\,|\,\text{model}\right) \times \pi\left(\text{model}\right)$$

We can use our forward model to do Bayesian inference

Bayes theorem

we only need to know *relative* likelihoods

$$p\left(\text{model}\,|\,\text{data}\right) \propto \mathscr{L}\left(\text{data}\,|\,\text{model}\right) \times \pi\left(\text{model}\right) \propto \frac{\mathscr{L}\left(\text{data}\,|\,\text{model}\right)}{\mathscr{L}\left(\text{data}\,|\,\text{reference model}\right)} \pi\left(\text{model}\right)$$

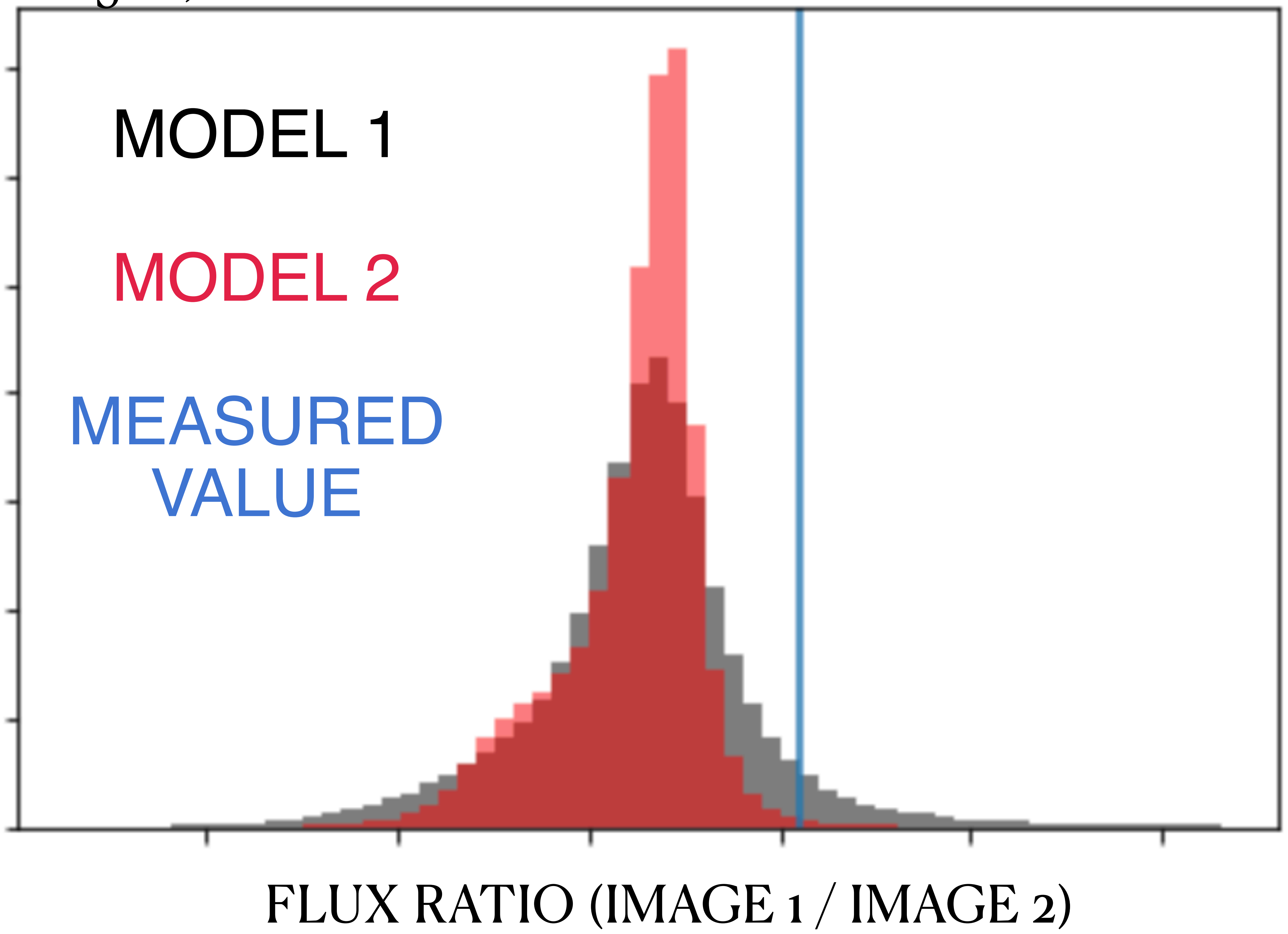
We can use our forward model to do Bayesian inference

Bayes theorem

we only need to know *relative* likelihoods

$$p\left(\text{model}\,|\,\text{data}\right) \propto \mathscr{L}\left(\text{data}\,|\,\text{model}\right) \times \pi\left(\text{model}\right) \propto \frac{\mathscr{L}\left(\text{data}\,|\,\text{model}\right)}{\mathscr{L}\left(\text{data}\,|\,\text{reference model}\right)} \pi\left(\text{model}\right)$$

~500,000 simulated data from the forward model



In 3 dimensions, select realizations that minimize

$$S = \sum_{i=1}^{3} \left(f_{\text{model(i)}} - f_{\text{data(i)}}\right)^2$$

"Likelihood-free inference"

Inference method is extensively tested on simulated datasets

Full end-to-end inference on simulated data available
on GitHub: dangilman/quadmodel

The method has been applied in a variety of contexts

Warm DM: Gilman et al. (2020a)
Concentration-mass relation: Gilman et al. (2020b)
Primordial power spectrum: Gilman et al. (2022)
Self-interacting DM: Gilman et al. (2021, 2022)
Ultra-light DM: Laroche, Gilman et al. (2022)

Rest of talk:

Constraining resonant dark matter self-interactions with strong gravitational lenses

Daniel Gilman[1],* Yi-Ming Zhong[2], and Jo Bovy[1]
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(Dated: August 2, 2022)

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]

SIDM with an attractive force

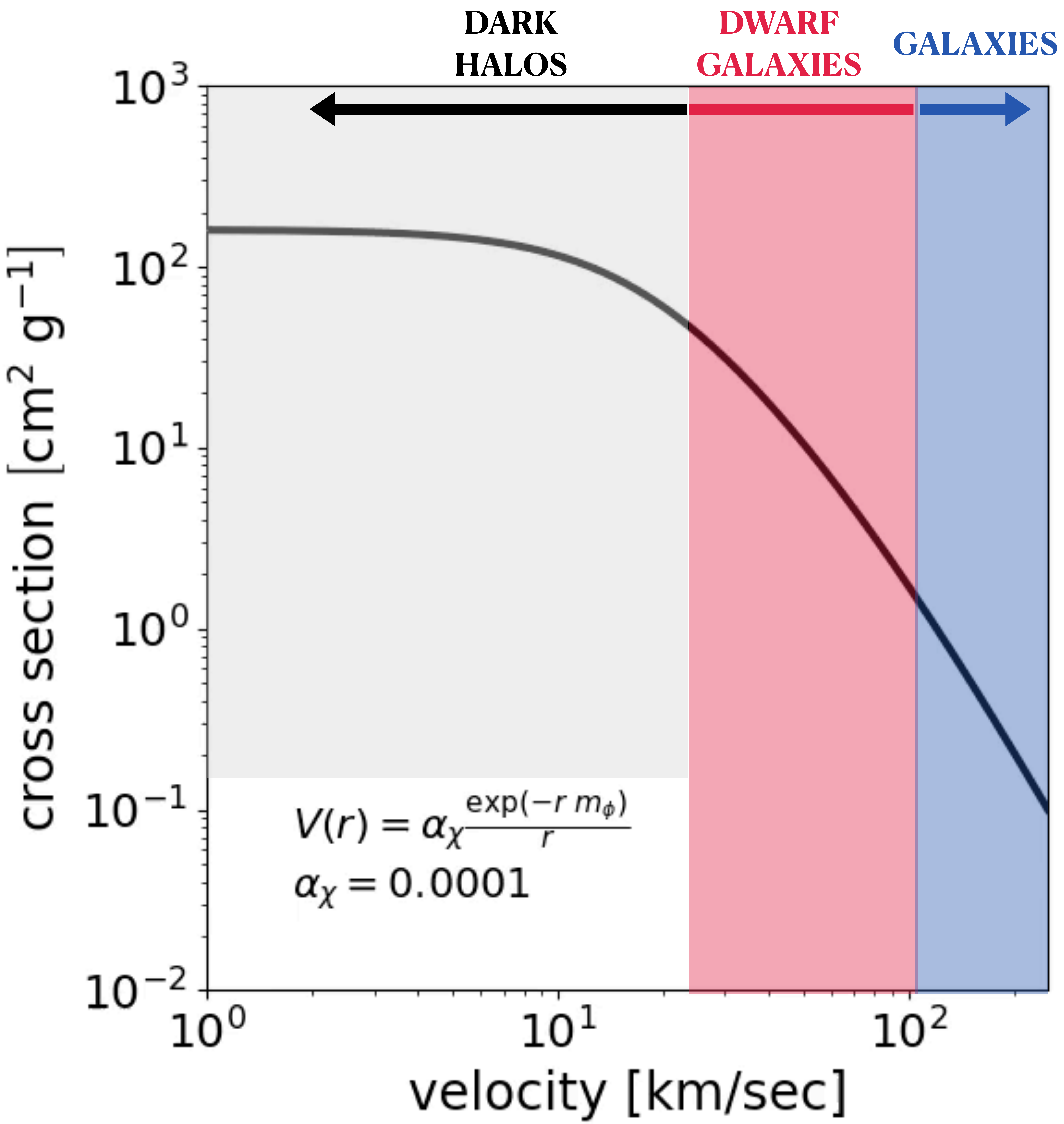
Velocity dependence is necessary to evade constraints from clusters

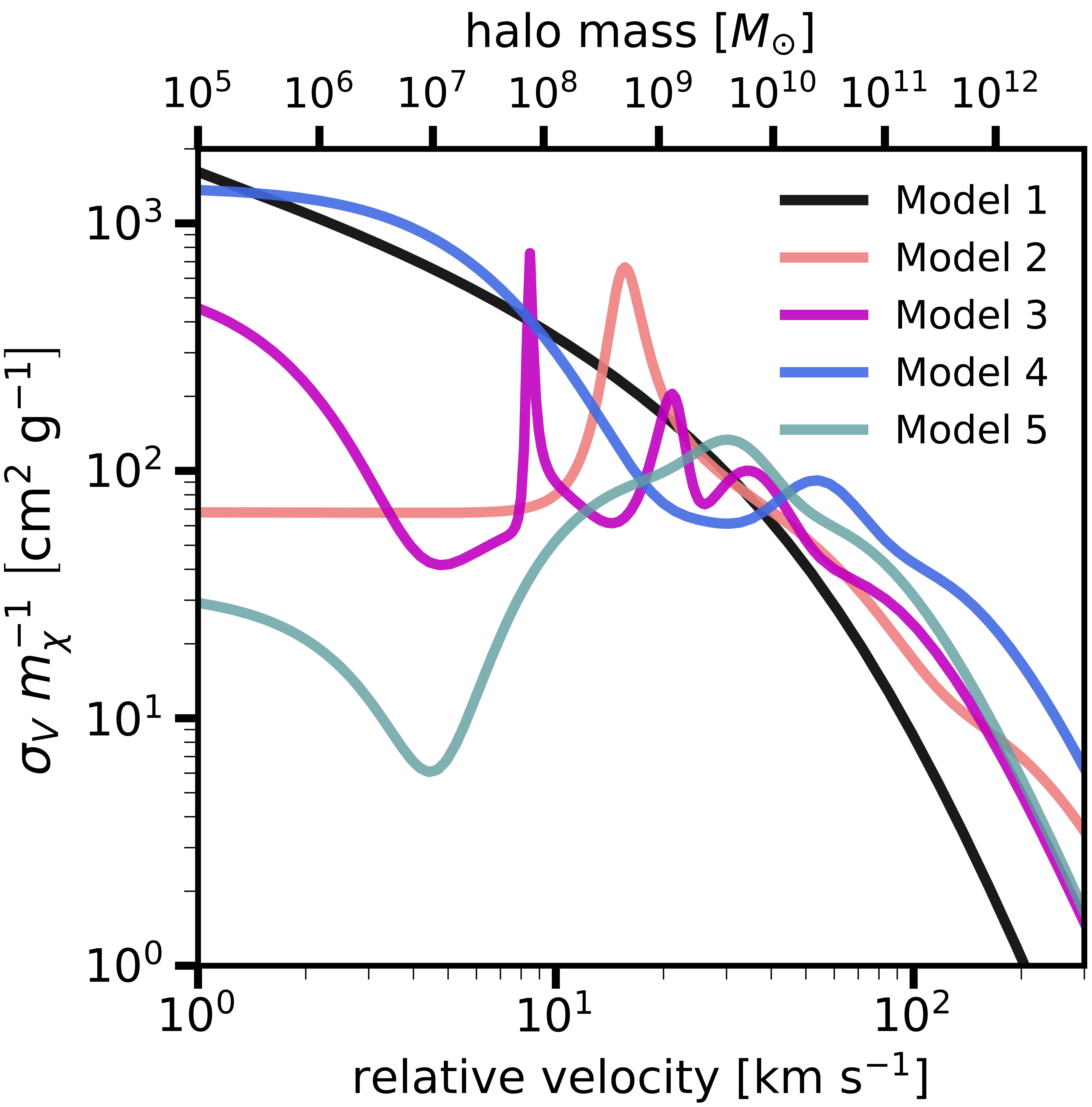
-> natural consequence of dark forces with light mediators

$$V(r) = \pm\,\alpha_\chi \frac{\exp\left(-r\, m_\phi\right)}{r}$$

$\alpha_\chi =$ potential strength

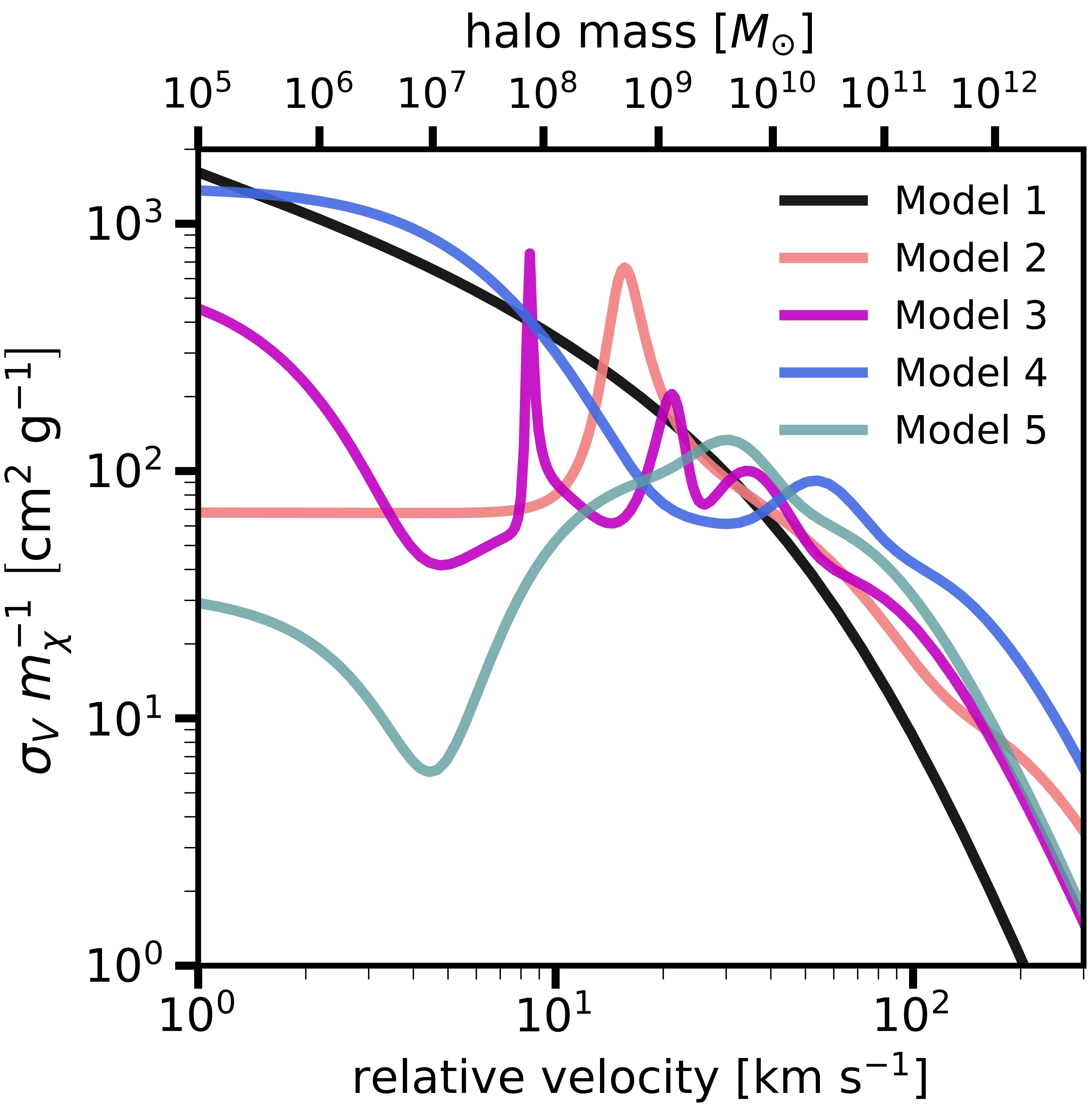
$m_\phi =$ mediator mass





halo mass [$M_\odot$]
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
$\sigma_V\, m_\chi^{-1}$ [cm^2 g^{-1}]
10^3
10^2
10^1
10^0
10^0
10^1
10^2
relative velocity [km s^{-1}]
Model 1
Model 2
Model 3
Model 4
Model 5

Benchmark models for the SIDM cross section



m_χ between $20-120$ GeV

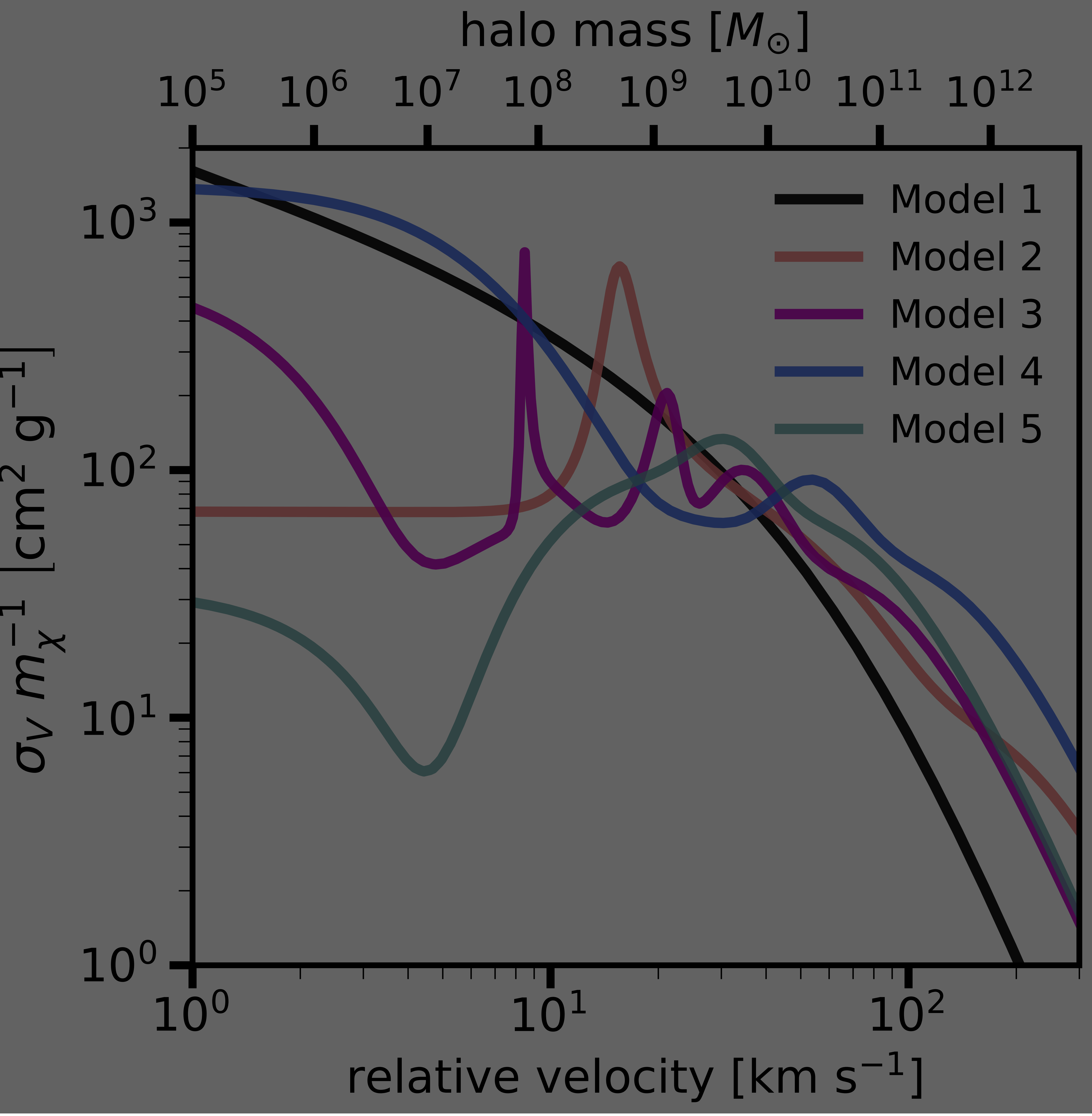
m_ϕ between $0.5-3$ MeV

$\alpha_\chi \approx \mathcal{O}\left(10^{-3}\right)$

Model 1 -> repulsive potential

Model 2-5 -> attractive

Benchmark models for the SIDM cross section



m_χ between $20-120$ GeV

m_ϕ between $0.5-3$ MeV

$\alpha_\chi \sim \mathcal{O}\left(10^{-3}\right)$

Model 1 -> repulsive potential

Model 2-5 -> attractive

Lets explore:

How can we constrain these models with lensing?

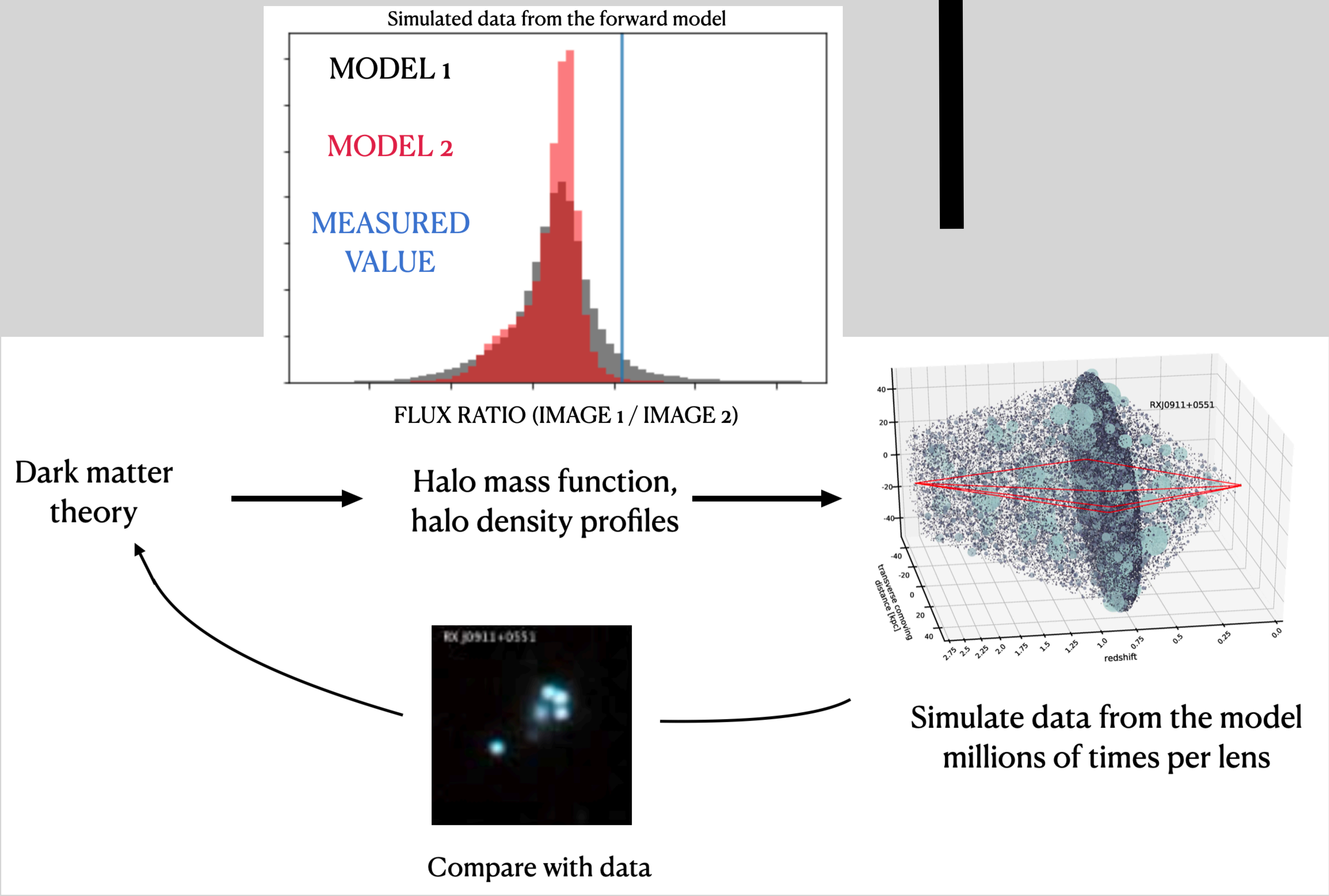
What are the consequences for structure formation?

Application to SIDM

1) We know core-collapse makes halos extremely efficient lenses

Data from HST (Nierenberg et al. 2014, 2017, 2020)

$$\mathscr{L}\left(11 \text{ quads} \,|\, \mathbf{f}_{\text{collapse}}(\text{m}, \text{z})\right)$$



Application to SIDM

1) We know core-collapse makes halos extremely efficient lenses

$$\mathscr{L}\left(11 \ \text{quads} \,|\, \mathbf{f}_{\text{collapse}}\left(\text{m}, \text{z}\right)\right)$$

2) Build a structure formation model that predicts fraction of collapsed (sub)halos as a function of mass

for a given cross section σ_V

$$p\left(\mathbf{f}_{\text{collapse}} \,|\, \mathbf{q}, \sigma_V\right)$$

Parameterized by $\mathbf{q}$:
collapse timescales, halo density profiles, cosmological evolution, etc.

A model for core collapse: $p\left(\mathbf{f}_{\text{collapse}} \,|\, \mathbf{q}, \sigma_V\right)$

Halo evolution is self-similar when expressed in terms of a characteristic timescale (Yang et al. 2022, Yang & Yu 2022)

$$t_0\left(m, z, \sigma_V\right) = \left(\frac{1\ \text{cm}^2\ \text{g}^{-1}}{\langle \sigma_V v^5 \rangle / \langle v^5 \rangle}\right)\left(\frac{100\ \text{km s}^{-1}}{v_{\text{max}}}\right)\left(\frac{10^7 M_\odot \text{kpc}^{-3}}{\rho_s}\right) \text{Gyr}$$

Maximum circular velocity

Central density normalization

Thermal average of the *viscosity* cross section σ_V

v^5 kernel comes from the thermal conductivity (Liftshitz & Pitaevskii, 1981)

$$\langle \sigma_V v^5 \rangle = \frac{1}{2\sqrt{\pi} v_0^3} \int_0^\infty v'^5 \sigma_V \times v'^2 \exp\left(\frac{-v'^2}{4 v_0^2}\right) dv'$$

$$v_0 \sim v_{\text{max}}\left(\text{halo mass}\right)$$

A model for core collapse: $p\left(\mathbf{f}_{\text{collapse}} \,|\, \mathbf{q}, \sigma_V\right)$

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We expect collapse to occur once a core collapse timescale exceeds the halo age

The model has four parameters:

Collapse timescale for field halos:

$$t_{\text{field}} = \lambda_{\text{field}}\ t_0$$

Collapse timescale for field halos:

$$t_{\text{sub}} = \lambda_{\text{sub}}\ t_{\text{field}}$$

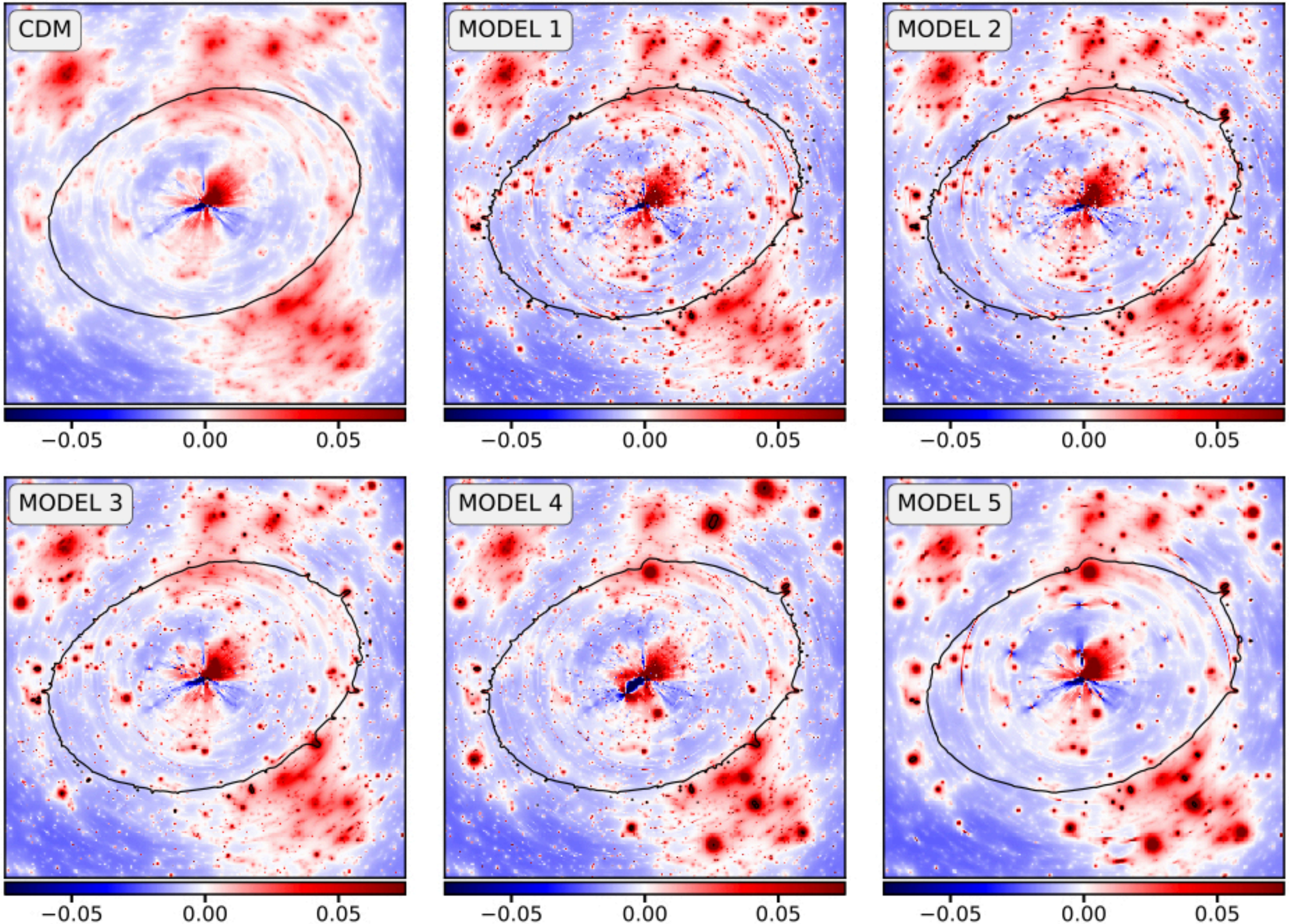
Scatter in collapse times for field halos:

$$s_{\text{field}}$$

Scatter in collapse times for subhalos:

$$s_{\text{field}}$$

A model for core collapse: $p\left(\mathbf{f}_{\text{collapse}} \,|\, \mathbf{q}, \sigma_V\right)$


CDM
MODEL 1
MODEL 2
MODEL 3
MODEL 4
MODEL 5
−0.05
0.00
0.05

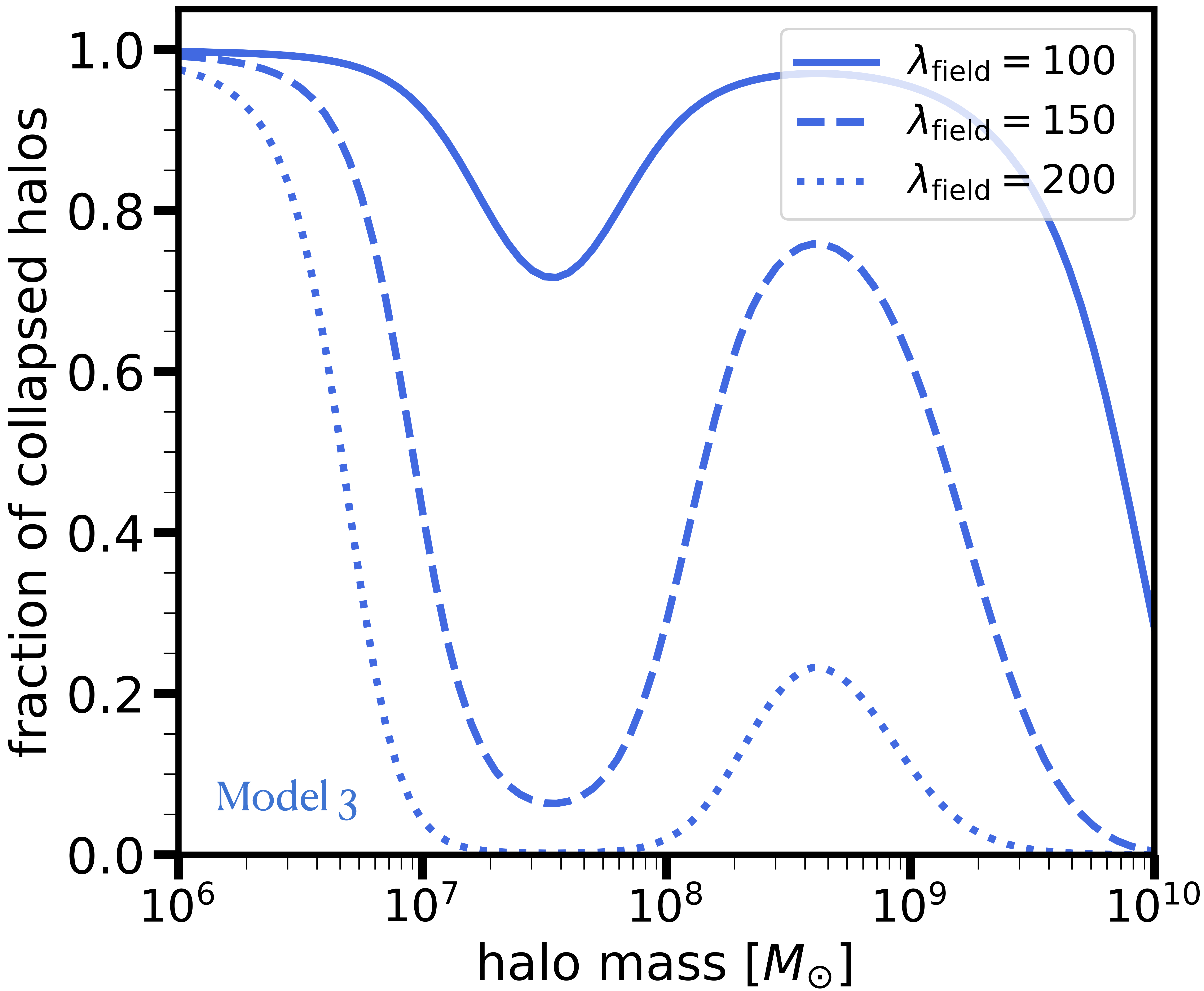
Collapse Timescales

λ_{sub} and λ_{field} control how quickly halos collapse after formation

Any process that accelerates or delays collapse maps into these terms

Examples: tidal stripping, evaporation (for subhalos), inelastic scattering (for all halos)

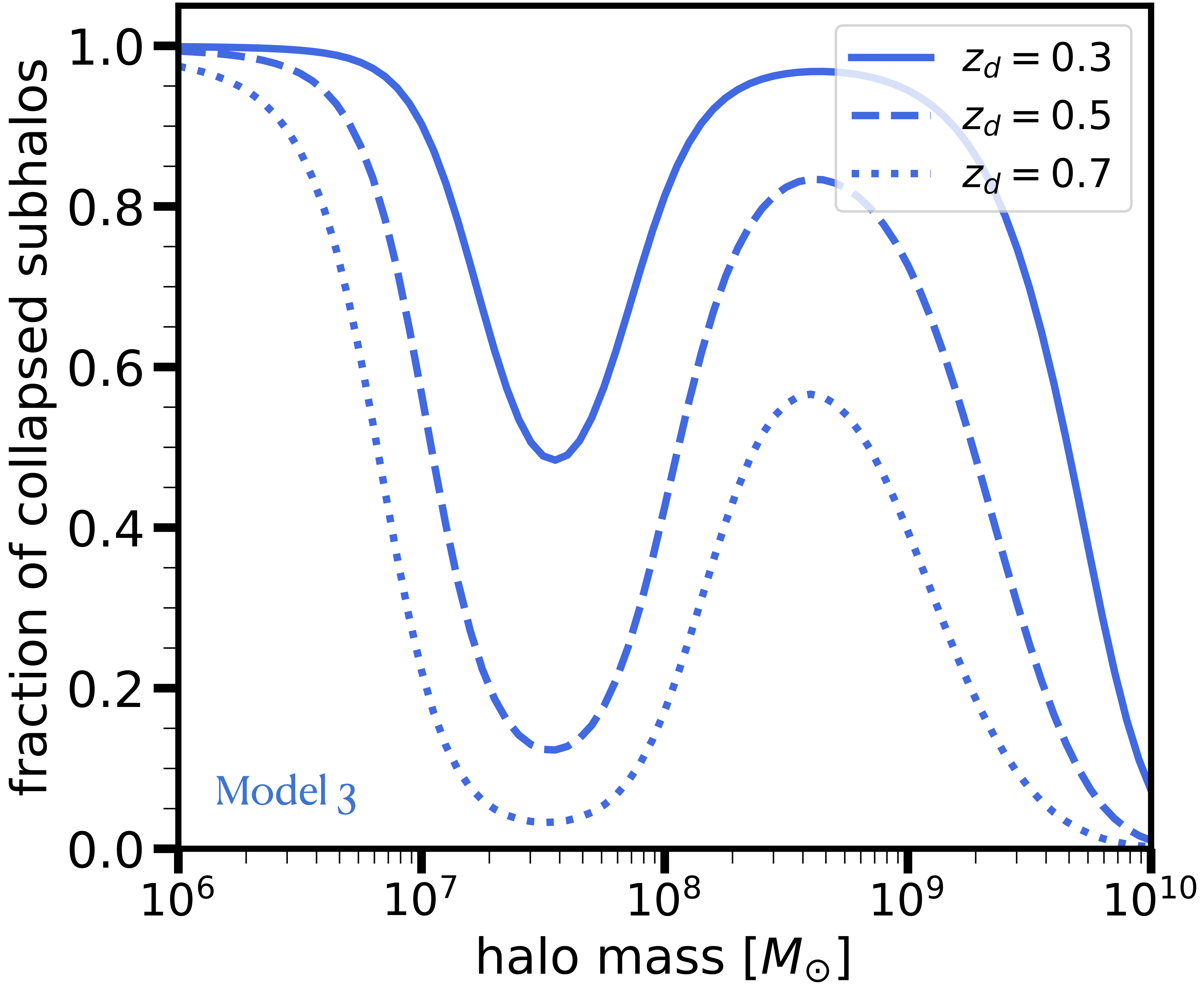
See Annika Peter's talk this Friday, and
Also: Vogelsberger et al. 2019, Nishikawa et al. 2020, Nadler et al. 2020, Zeng et al. 2022, Yang et al. 2022



Redshift Evolution

Collapse probability increases with time

-> Strong lensing can probe the time evolution of halo density profiles (both subhalos and field halos)

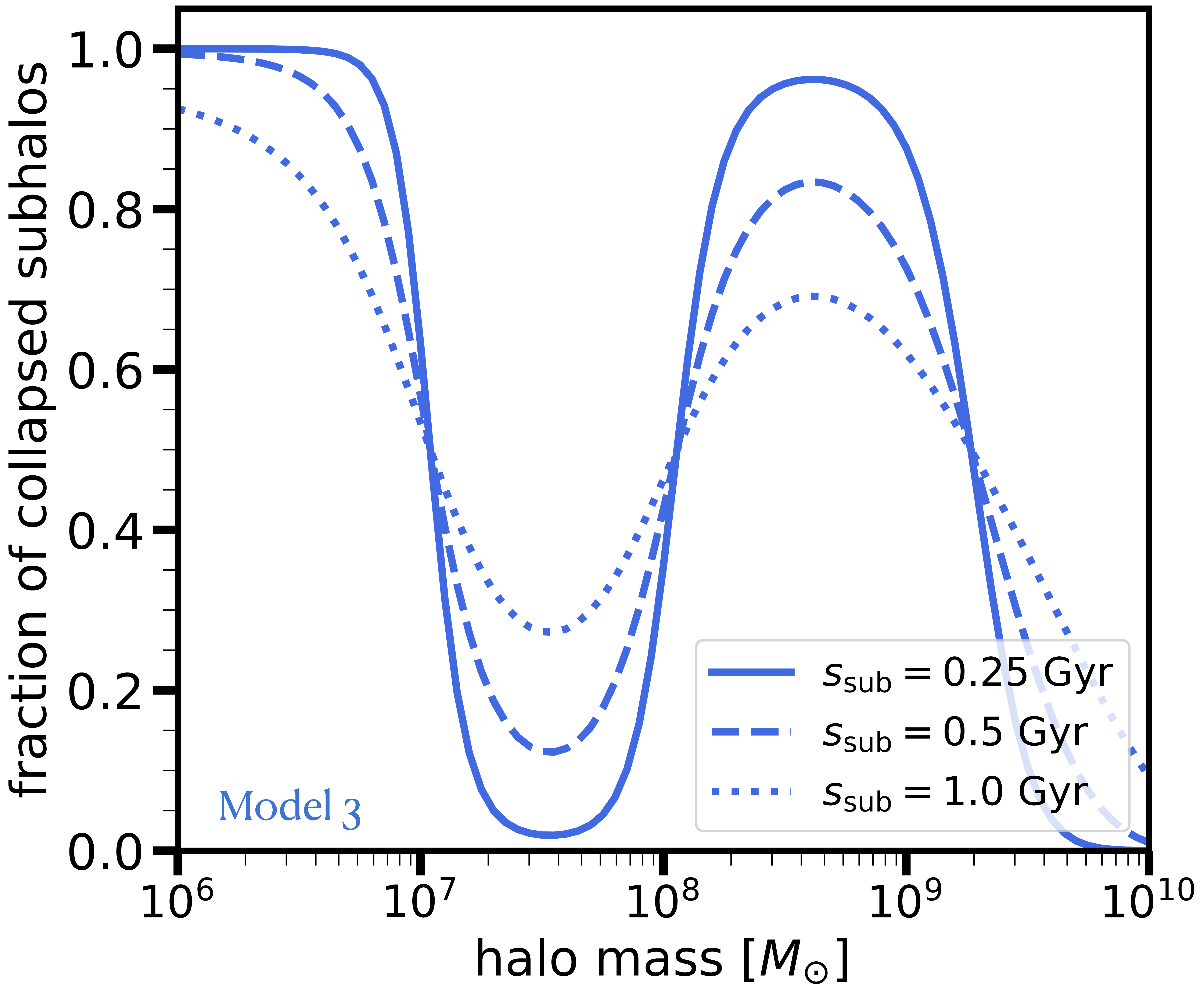


Scatter in collapse timescales

Any process that affects the formation history or structural evolution maps into s_{sub} and s_{field}

Field halos: formation time, merger history

Subhalos: tidal evolution, differential evaporation, ram pressure tripping



Application to SIDM

1) We know core-collapse makes halos extremely efficient lenses

$$\mathscr{L}\left(11 \ \text{quads} \,|\, \mathbf{f}_{\text{collapse}}\,(\text{m}, \text{z})\right)$$

2) Build a structure formation model that predicts fraction of collapsed (sub)halos as a function of mass

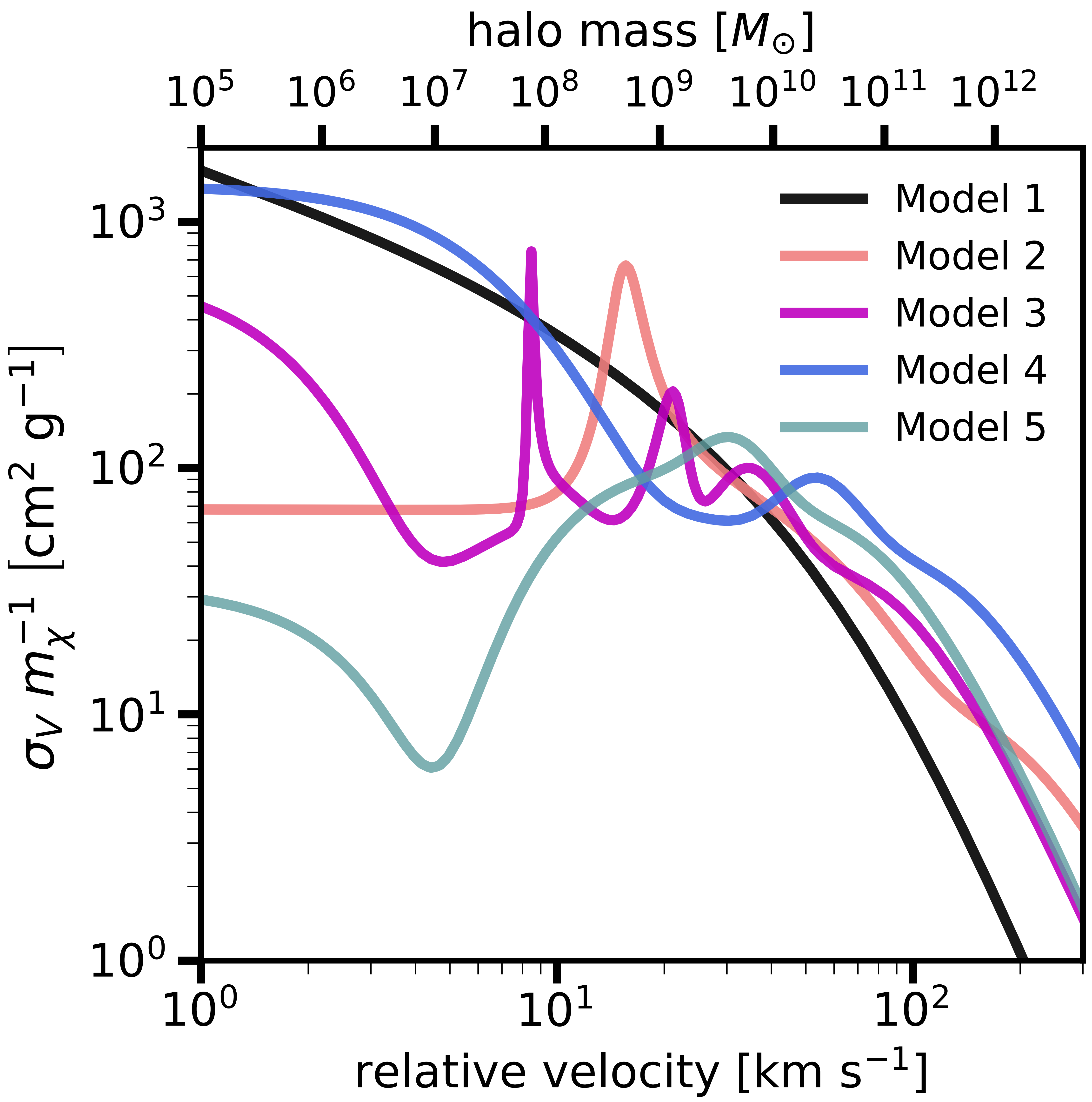
for a given cross section σ_V

$$p\left(\mathbf{f}_{\text{collapse}} \,|\, \mathbf{q}, \sigma_V\right)$$

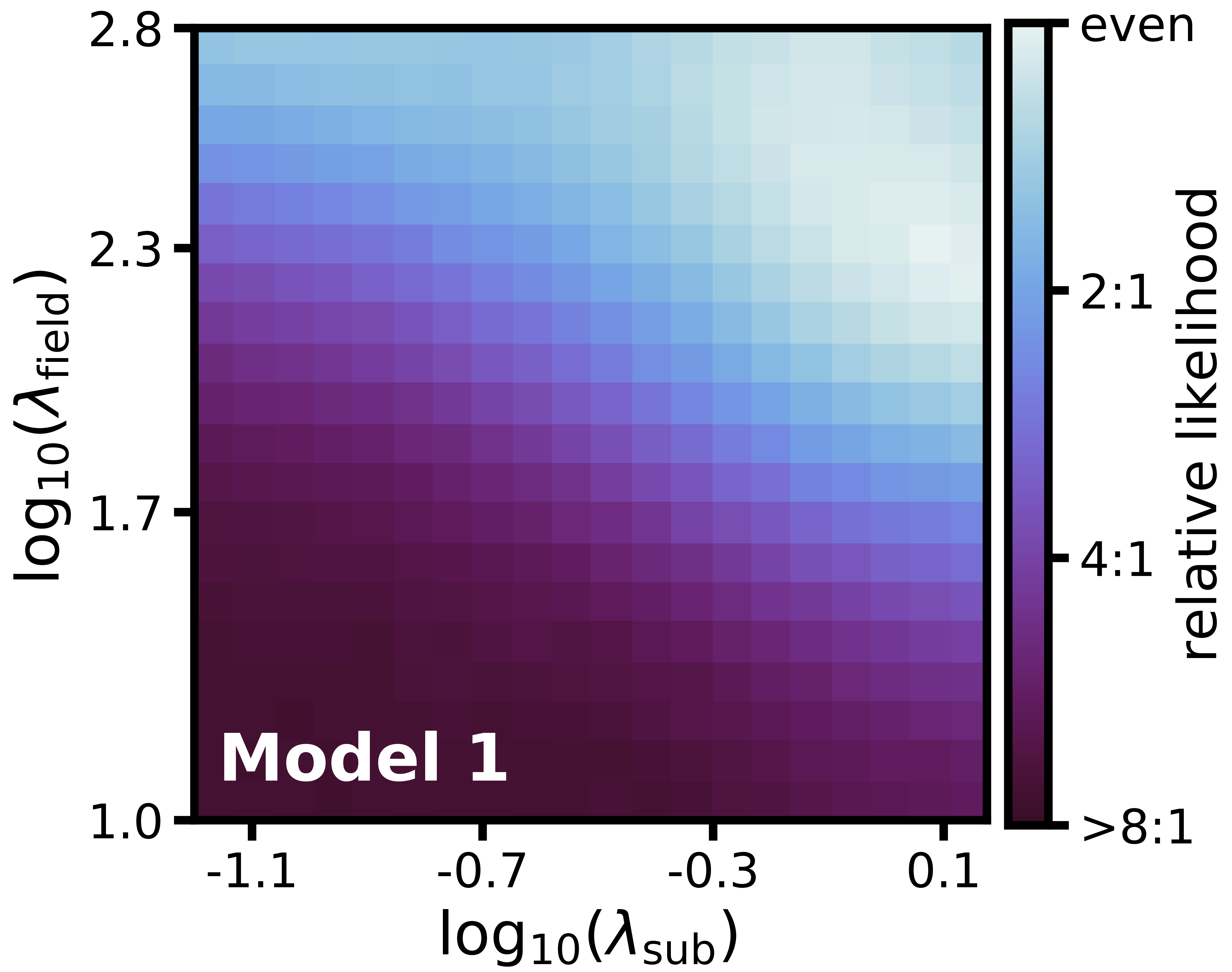
3) Using $p\left(\mathbf{f}_{\text{collapse}} \,|\, \mathbf{q}, \sigma_V\right)$, recast the likelihood in terms of the cross section σ_V

$$\mathscr{L}\left(11 \ \text{quads} \,|\, \mathbf{q}, \sigma_{\text{V}}\right) \sim \int p\left(\mathbf{f}_{\text{collapse}} \,|\, \mathbf{q}, \sigma_V\right) \mathscr{L}\left(11 \ \text{quads} \,|\, \mathbf{f}_{\text{collapse}}\,(\text{m}, \text{z})\right) d\mathbf{f}_{\text{collapse}}$$

Constraints on the collapse timescales with 11 quads



Gilman et al. (2022)



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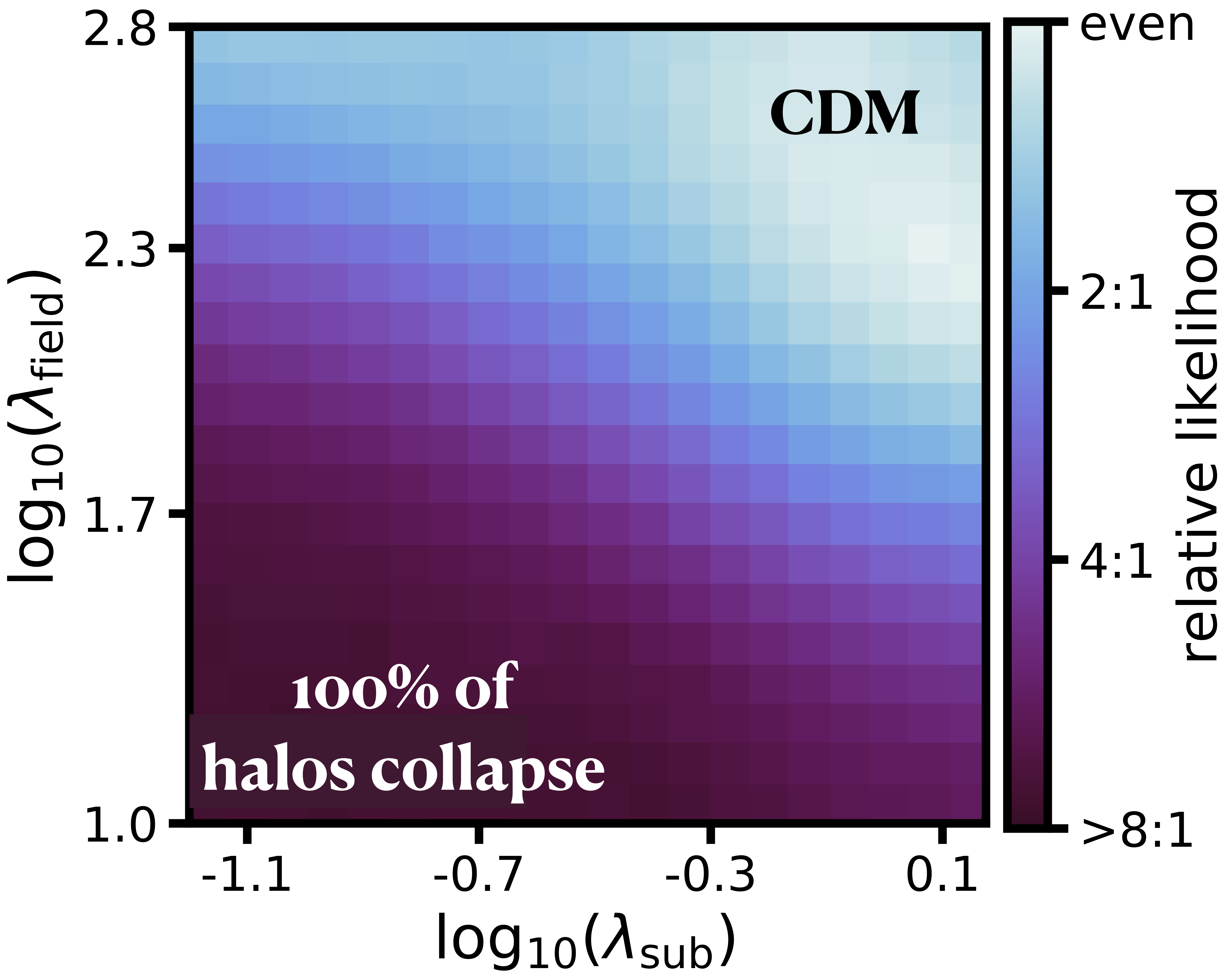

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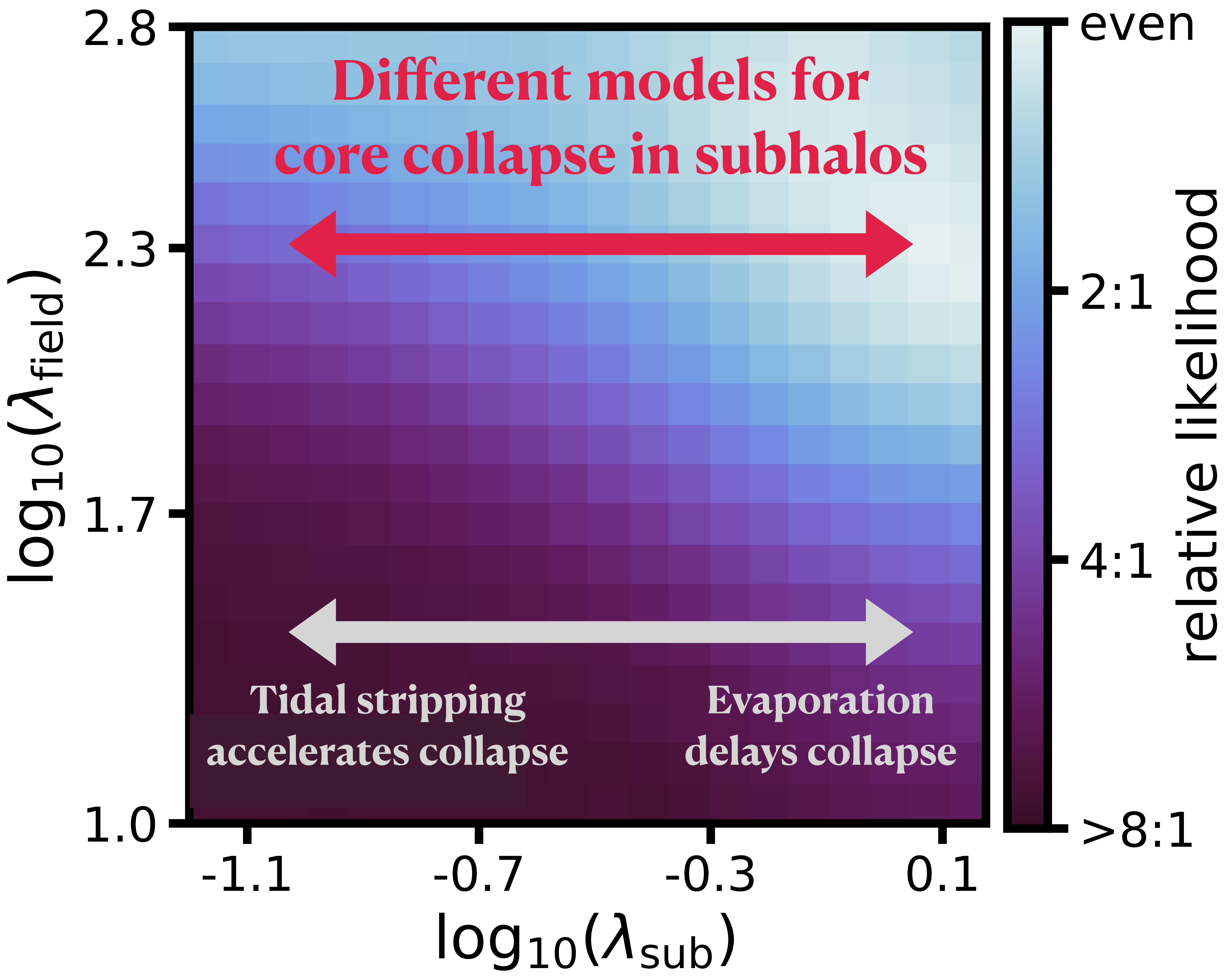
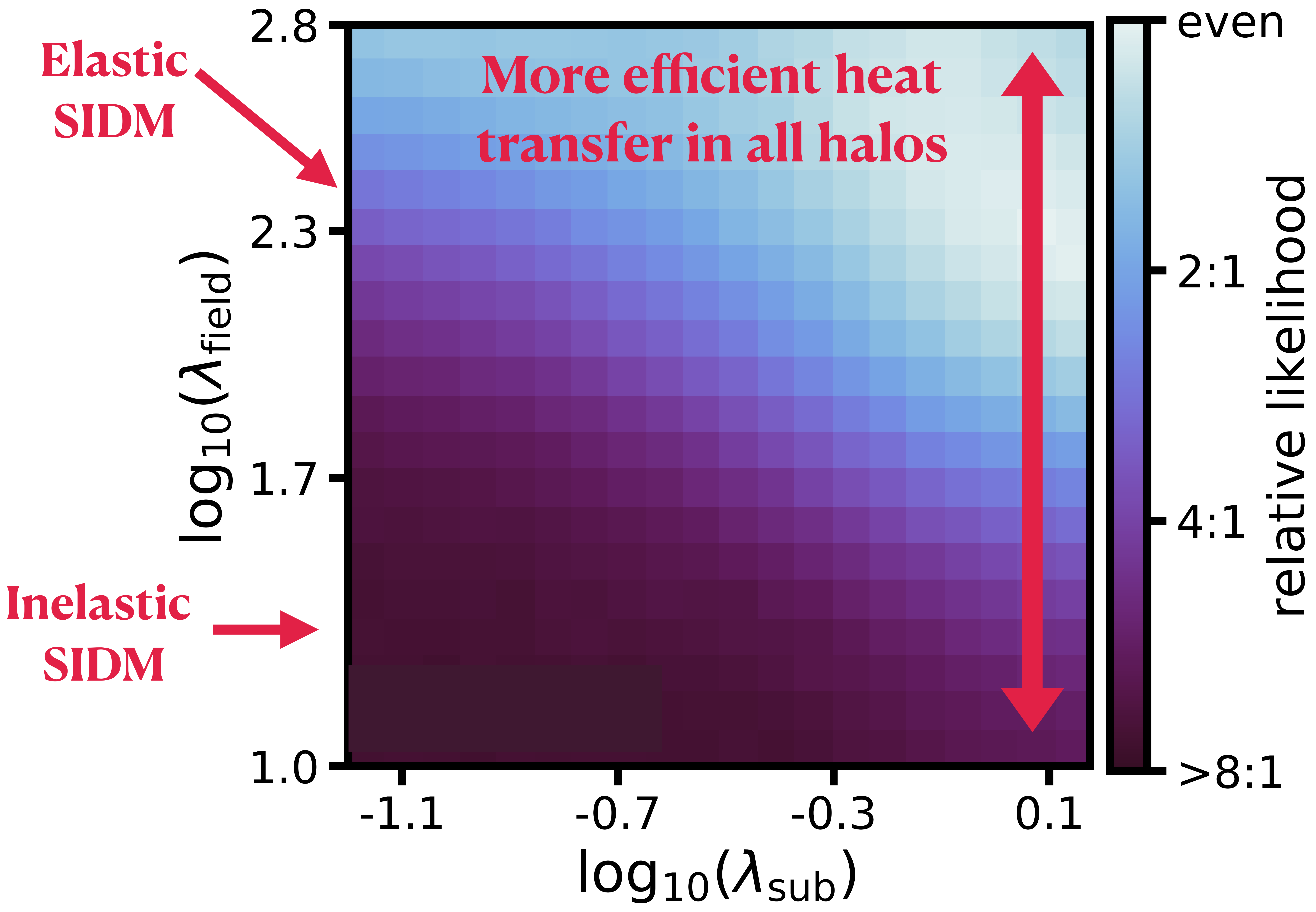


Constraints on the collapse timescales with 11 quads



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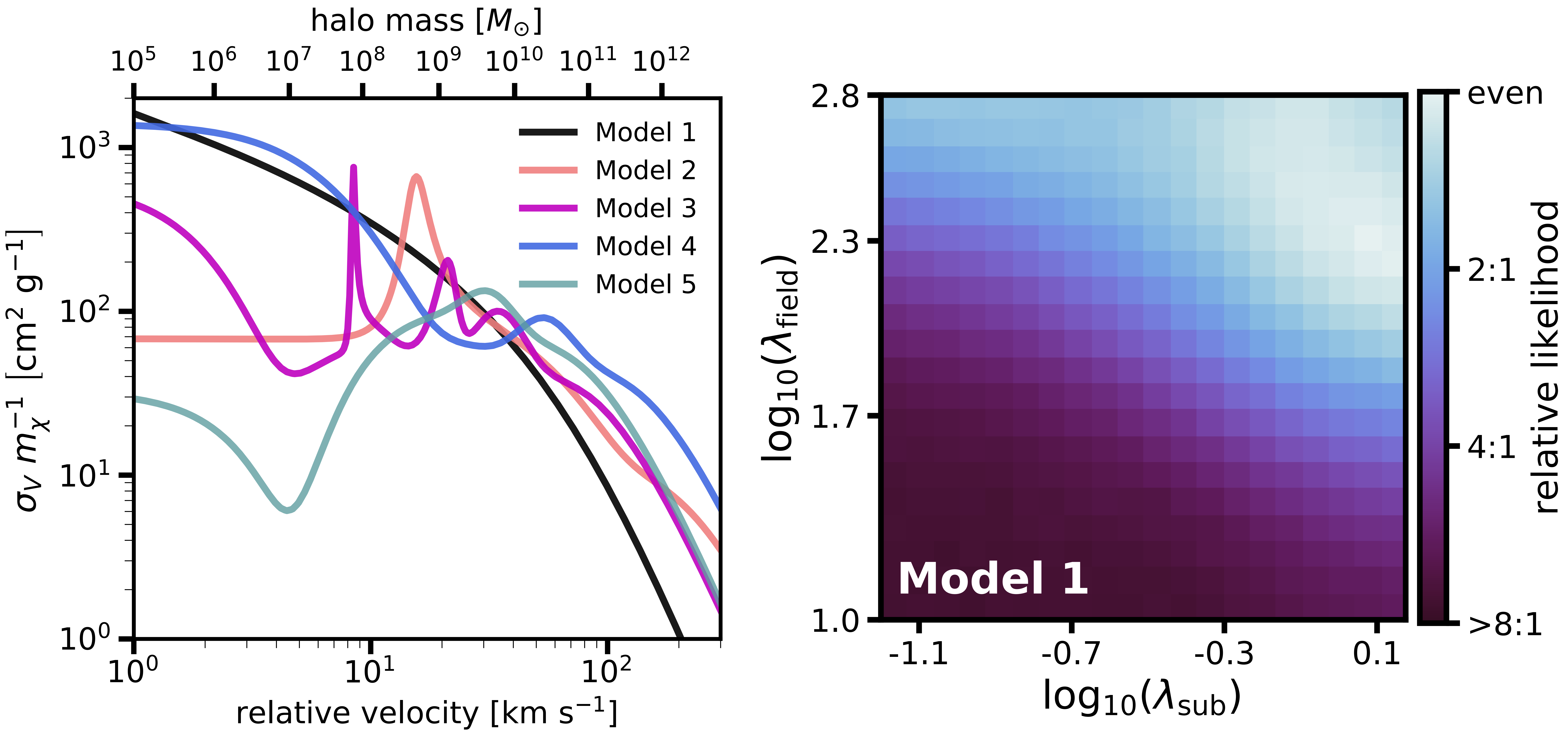

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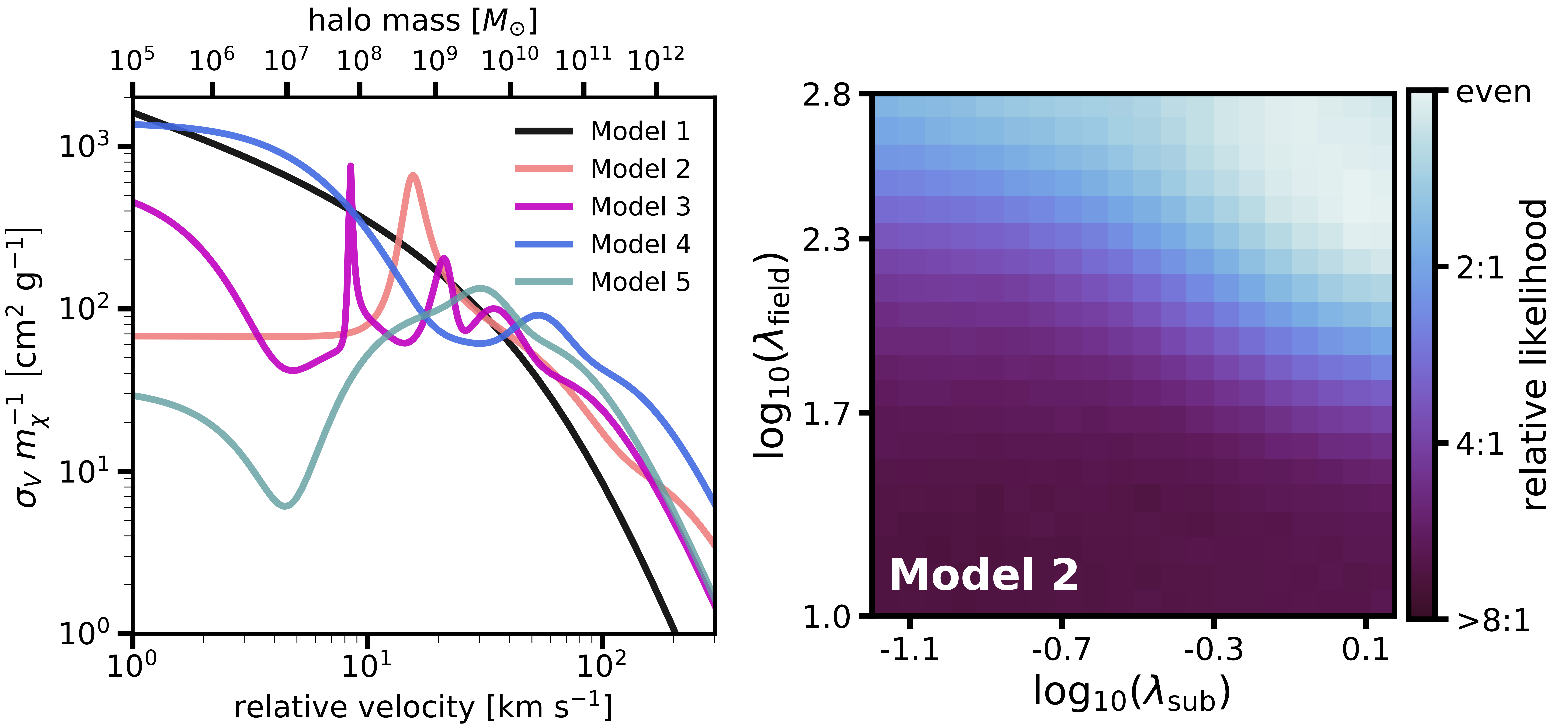

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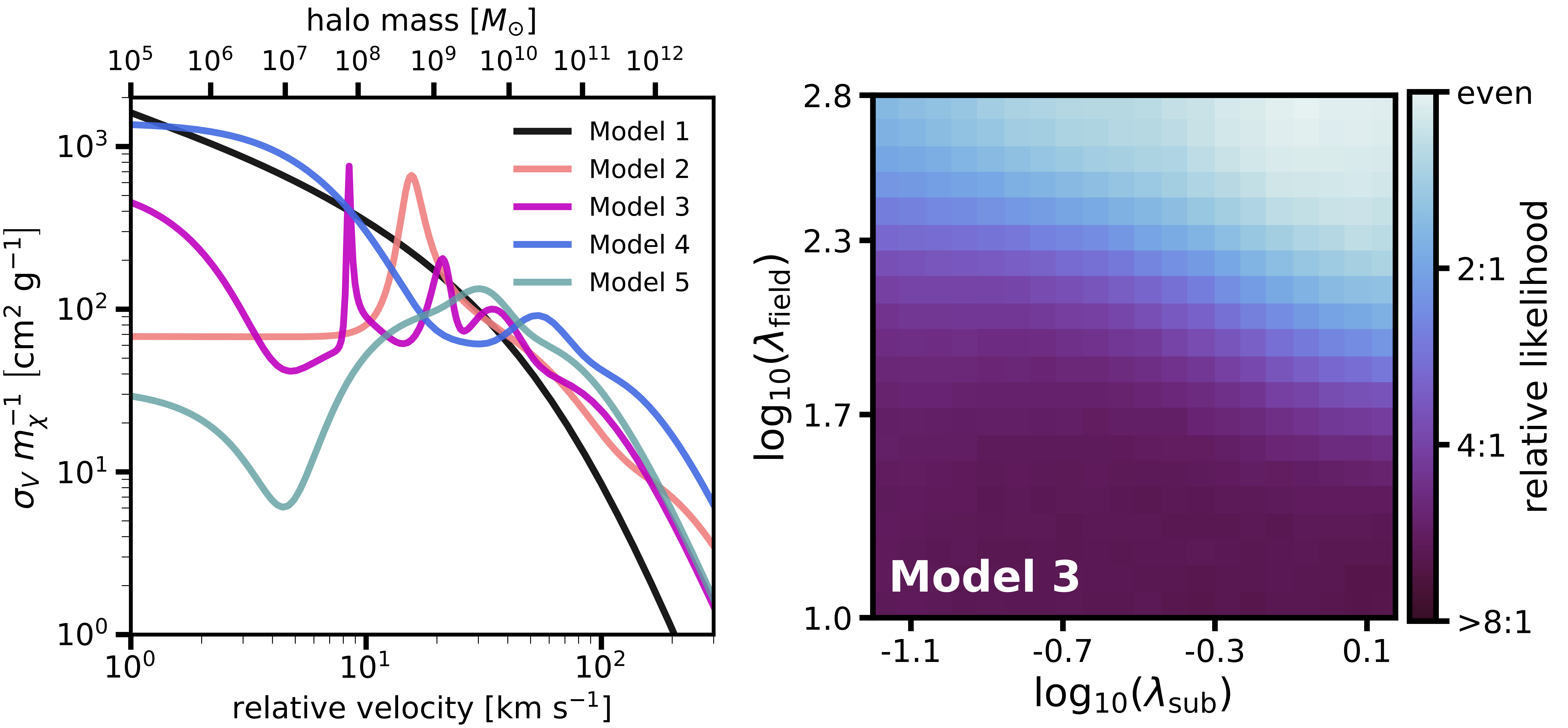
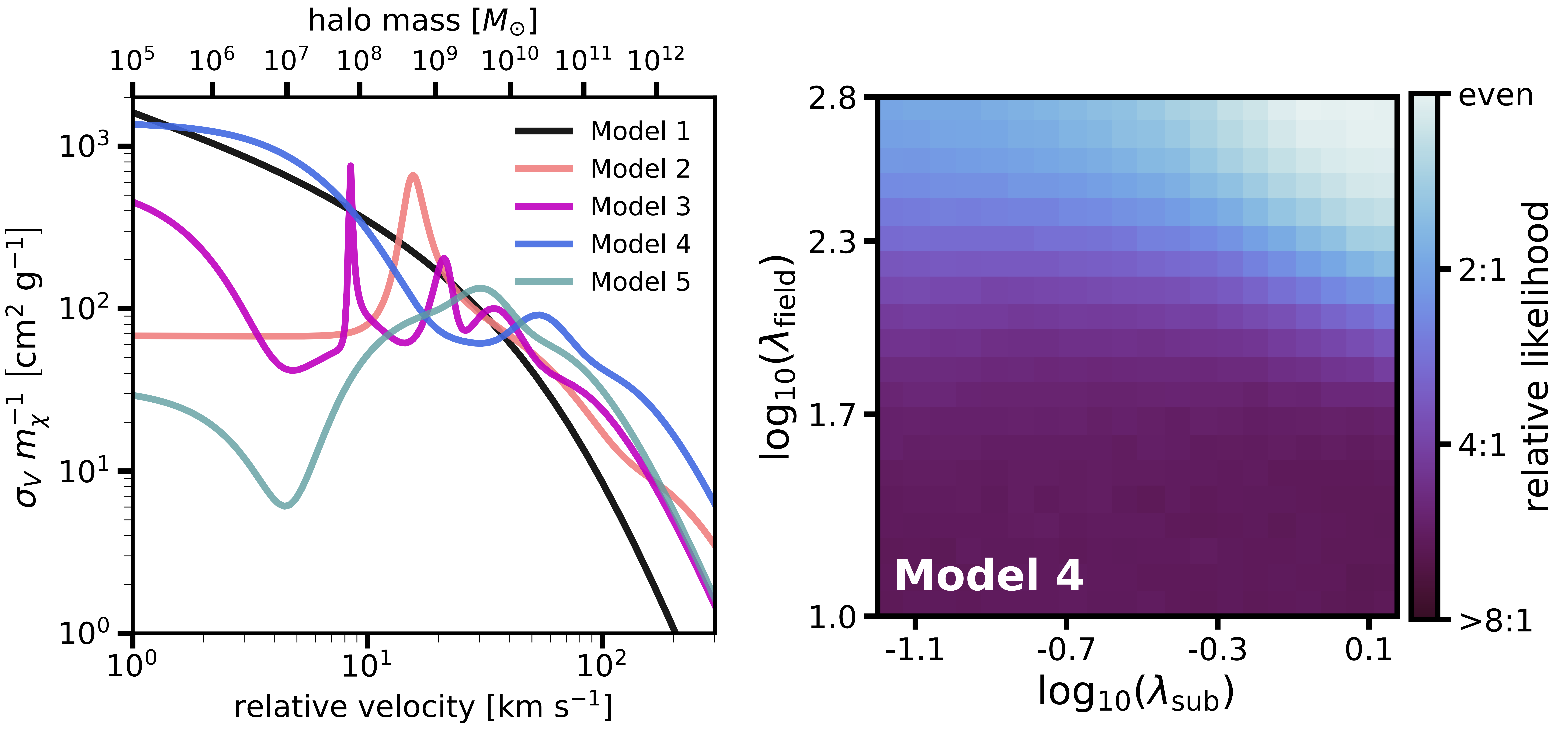
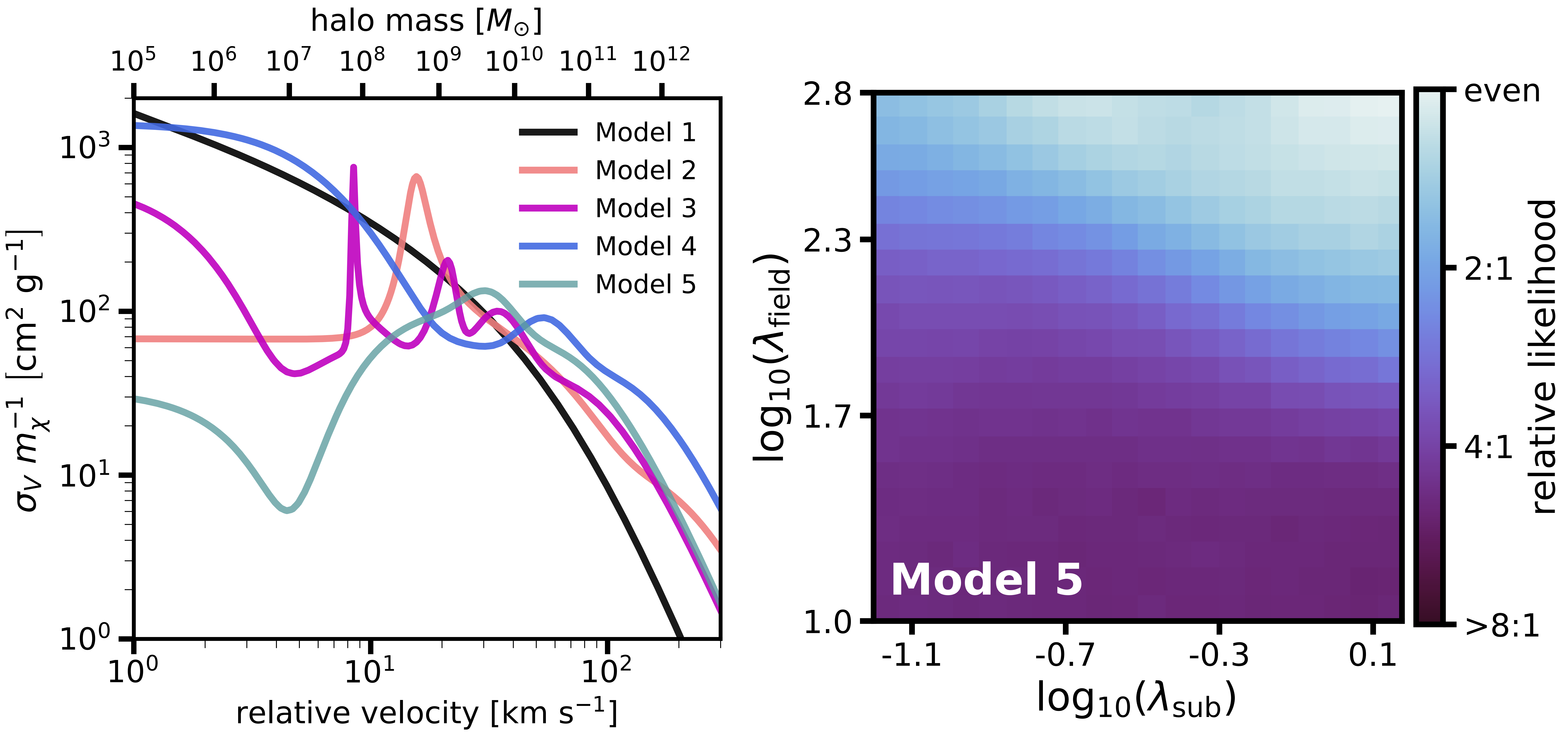


Constraints on the collapse timescales with 11 quads



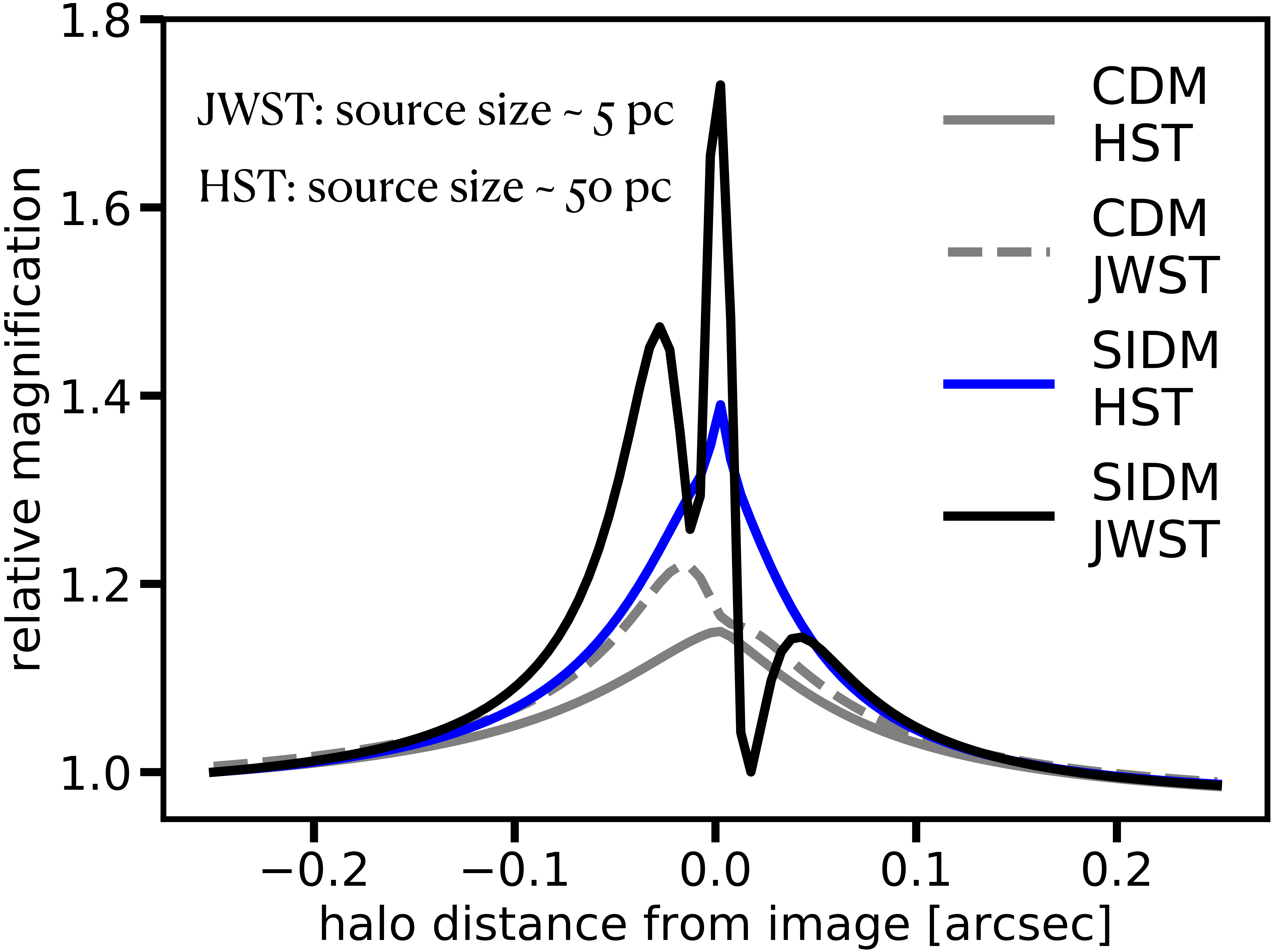
Constraints on the collapse timescales with 11 quads



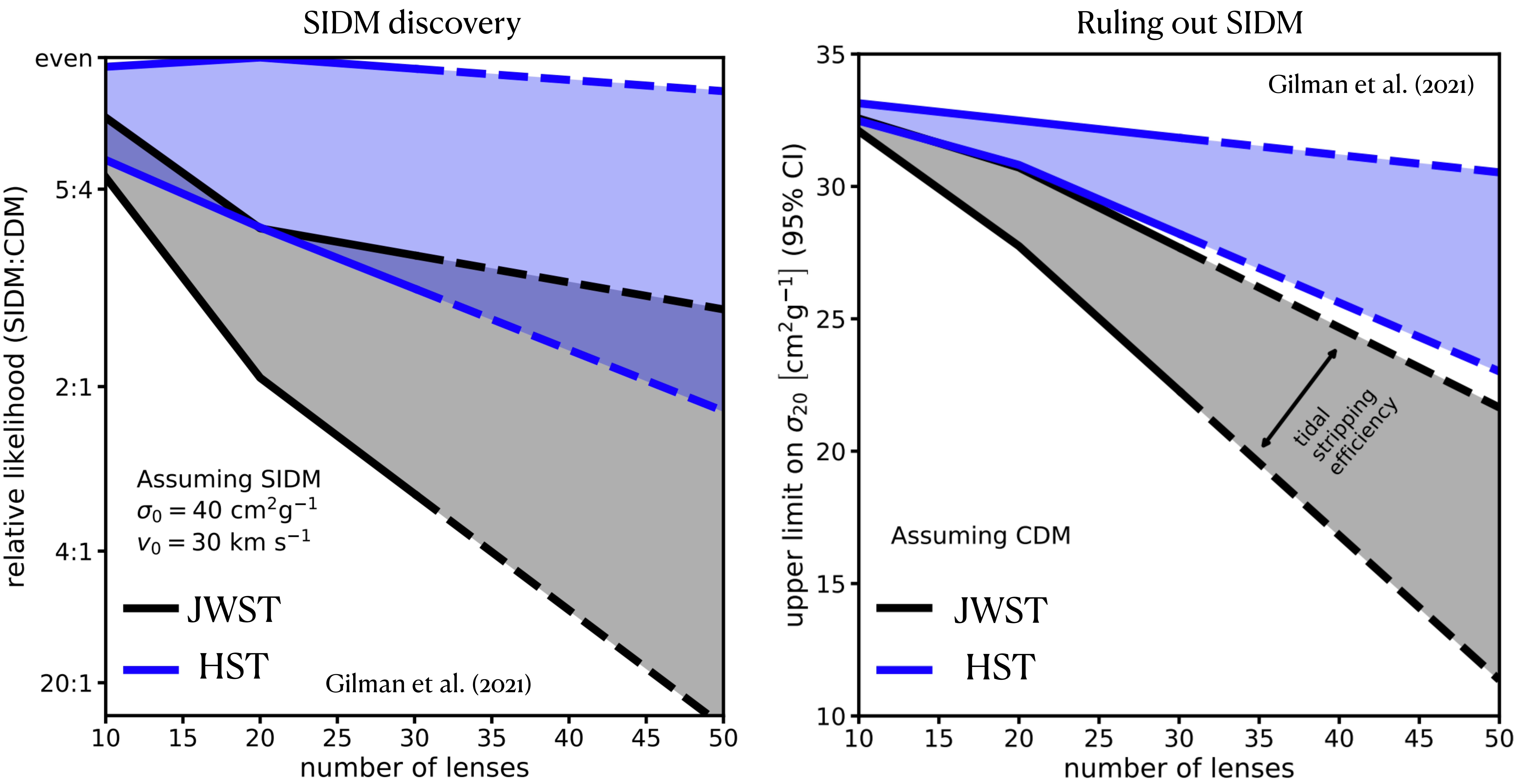
What about the future?

With JWST GO-2046
(PI Anna Nierenberg)
we will get image
flux measurements in
the mid-IR for ~30 quads

The more compact source provides a more sensitive probe of substructure



Forecasts for JWST



Takeaways:

ΛCDM survives (for now)

Strong lensing provides an independent and powerful way to test the predictions of SIDM models with current and future data

With JWST, we will be able to detect or rule out cross section amplitudes of $20 - 30 \ \mathrm{cm}^2 \ \mathrm{g}^{-1}$ at $v \approx 20 \ \mathrm{km} \ \mathrm{s}^{-1}$

EXTRA STUFF

Computation of the cross section

Exact solution for the viscosity transfer cross section via partial wave analysis, expressed as a sum over the phase shifts

$$\sigma_V = \int \frac{d\sigma}{d\Omega} \sin^2\theta d\Omega = \frac{4\pi}{k^2} \sum_{\ell=0}^{\ell_{\max}\sim 50} \frac{(\ell+1)(\ell+2)}{2\ell+3} \sin^2\left(\delta_{\ell+2} - \delta_\ell\right)$$

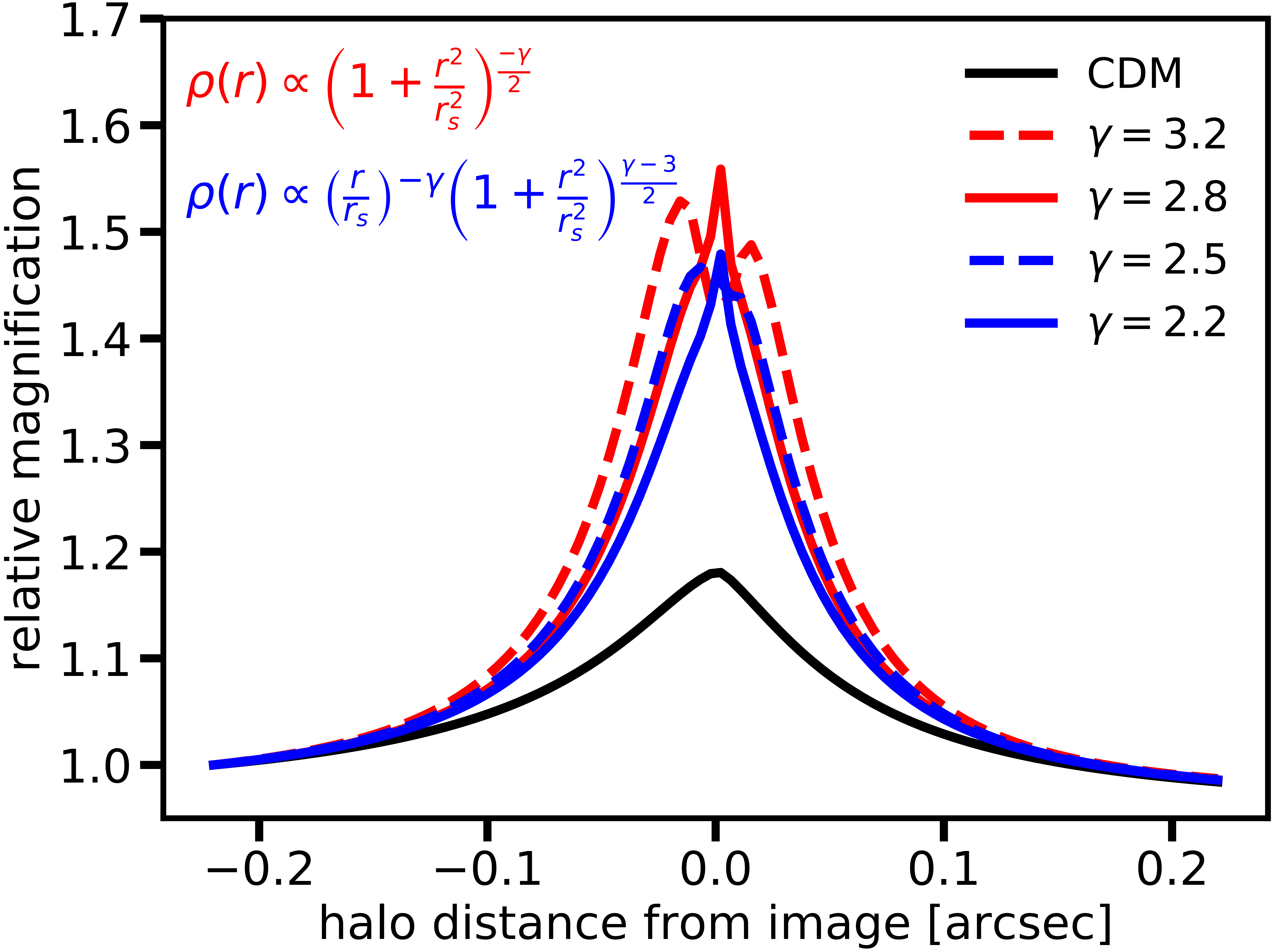
(Colquhoun et al. 2021)

To compute the phase shifts, use auxiliary function for the Schrodinger Eqn introduced by Chu et al. (2020)

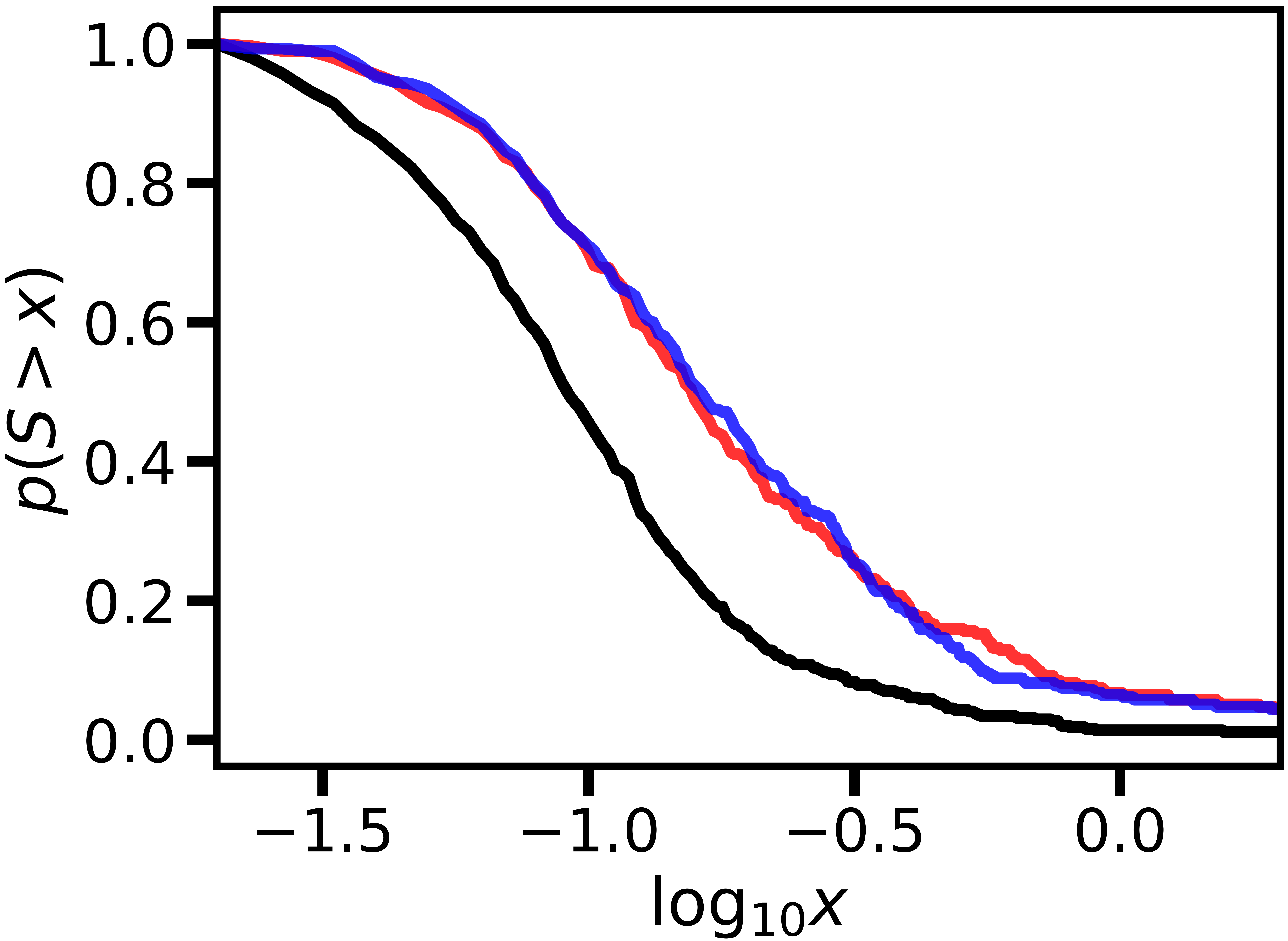
$$\frac{\partial \delta_\ell(r)}{\delta r} = -km_\chi r^2 V(r)\left[\sin\left(\delta_\ell(r)\right) j_l(kr) - \cos\left(\delta_\ell(r)\right) n_l(kr)\right]^2 \quad \text{where } \mathrm{k} = \mathrm{m}_\chi \mathrm{v}/2$$

With the convenient property $$\delta_l = \lim_{r\to\infty} \delta_l(r)$$

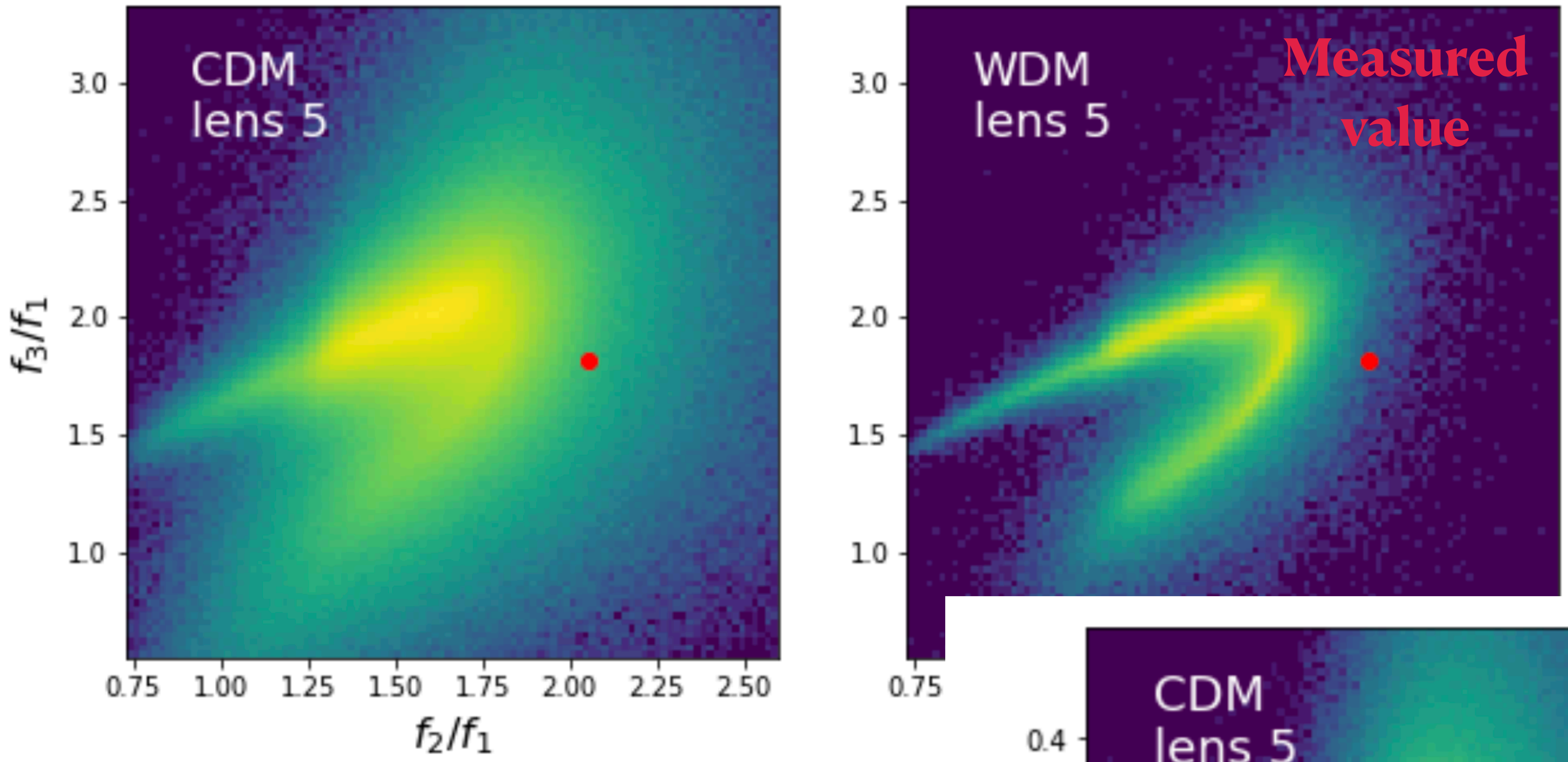
Effect of the SIDM halo profile



Effect of the SIDM halo profile



The likelihood in two dimensions:



Main locus of probability results from marginalizing the macromodel

Substructure adds perturbation around the macromodel prediction