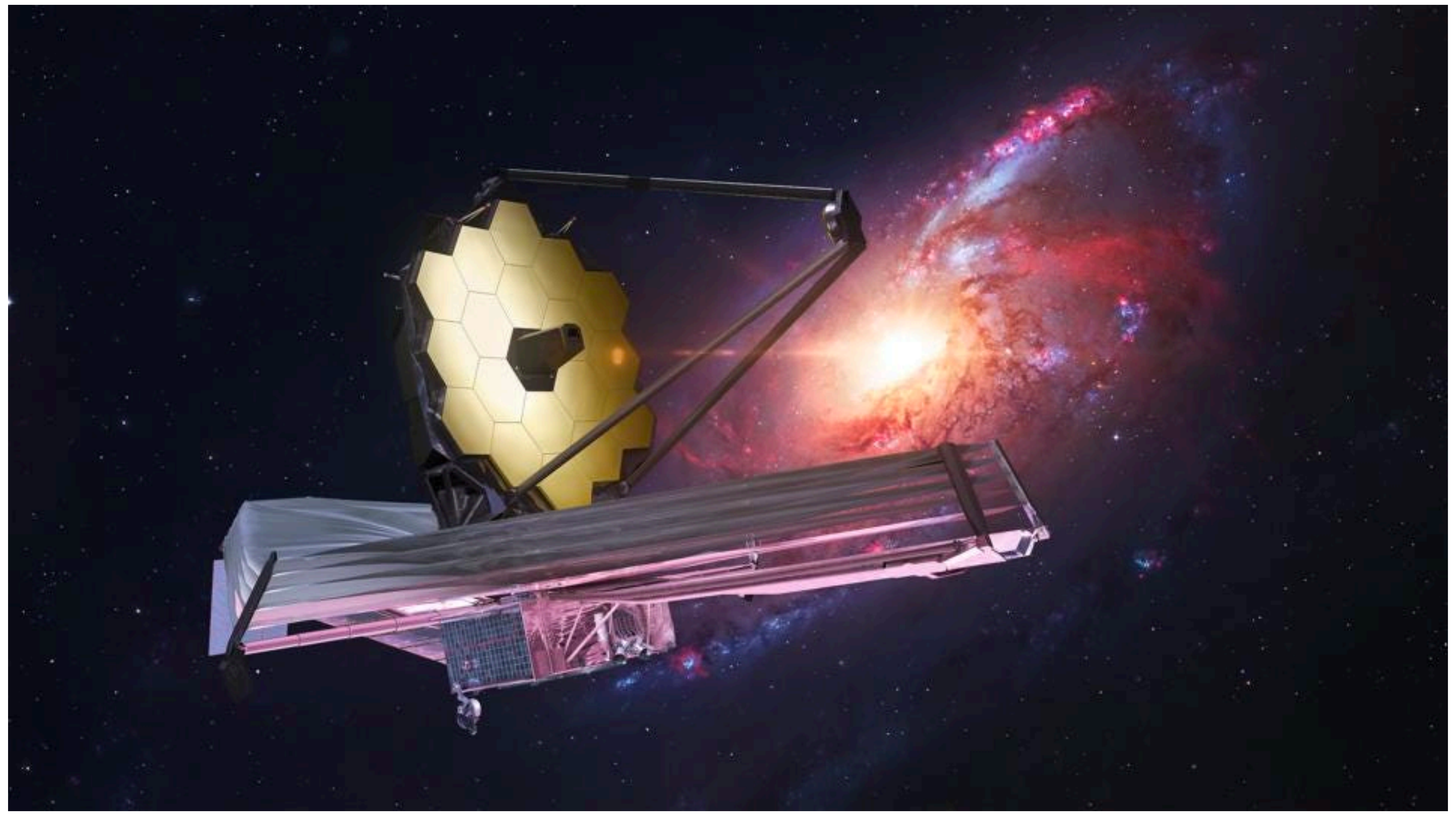
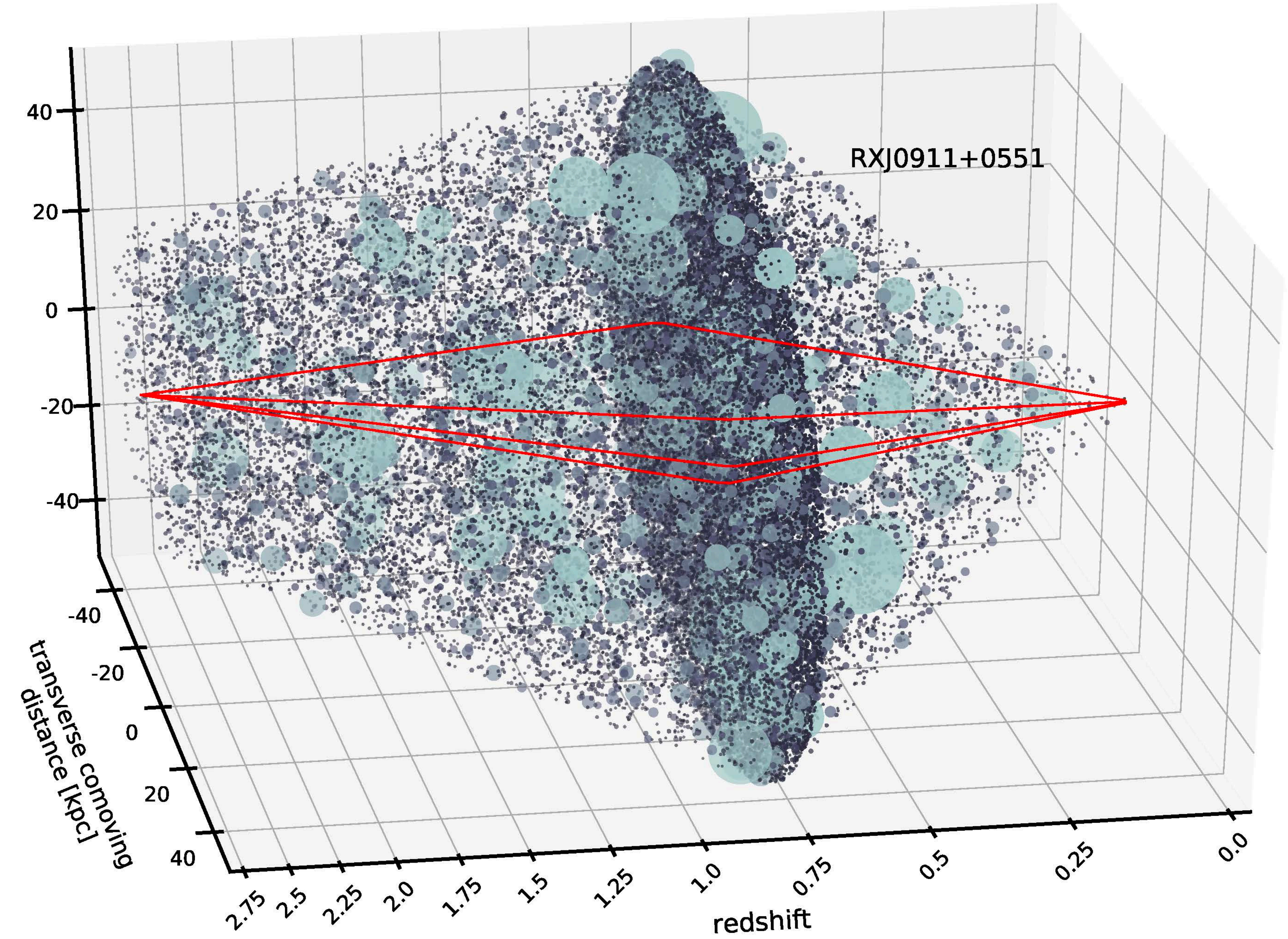
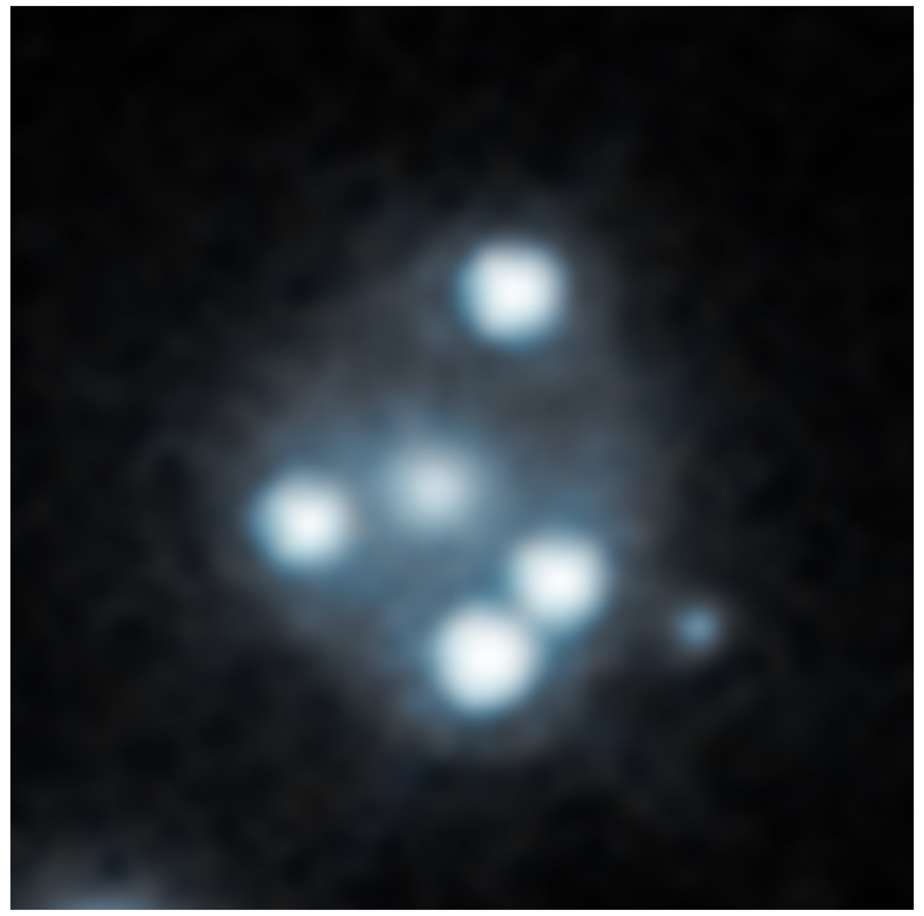
The JWST lensed quasar dark matter survey



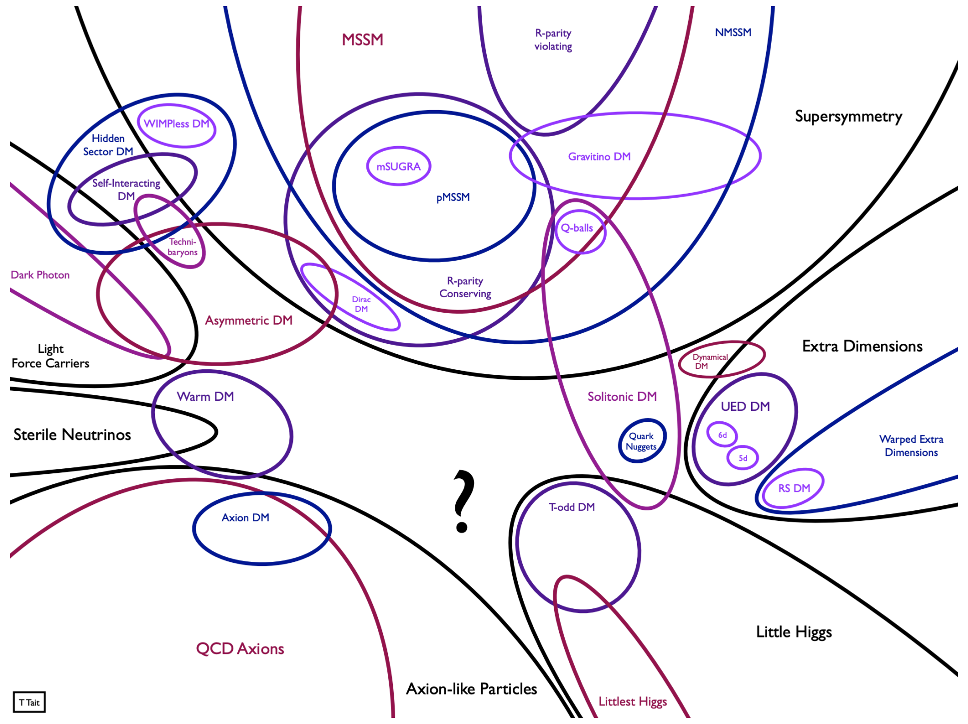


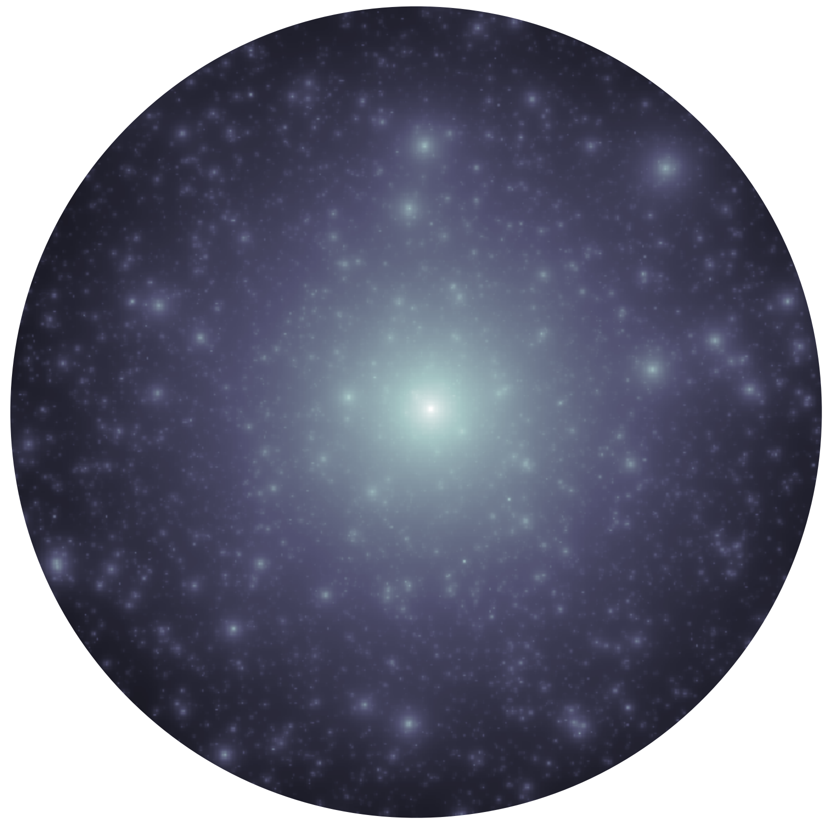
Daniel Gilman

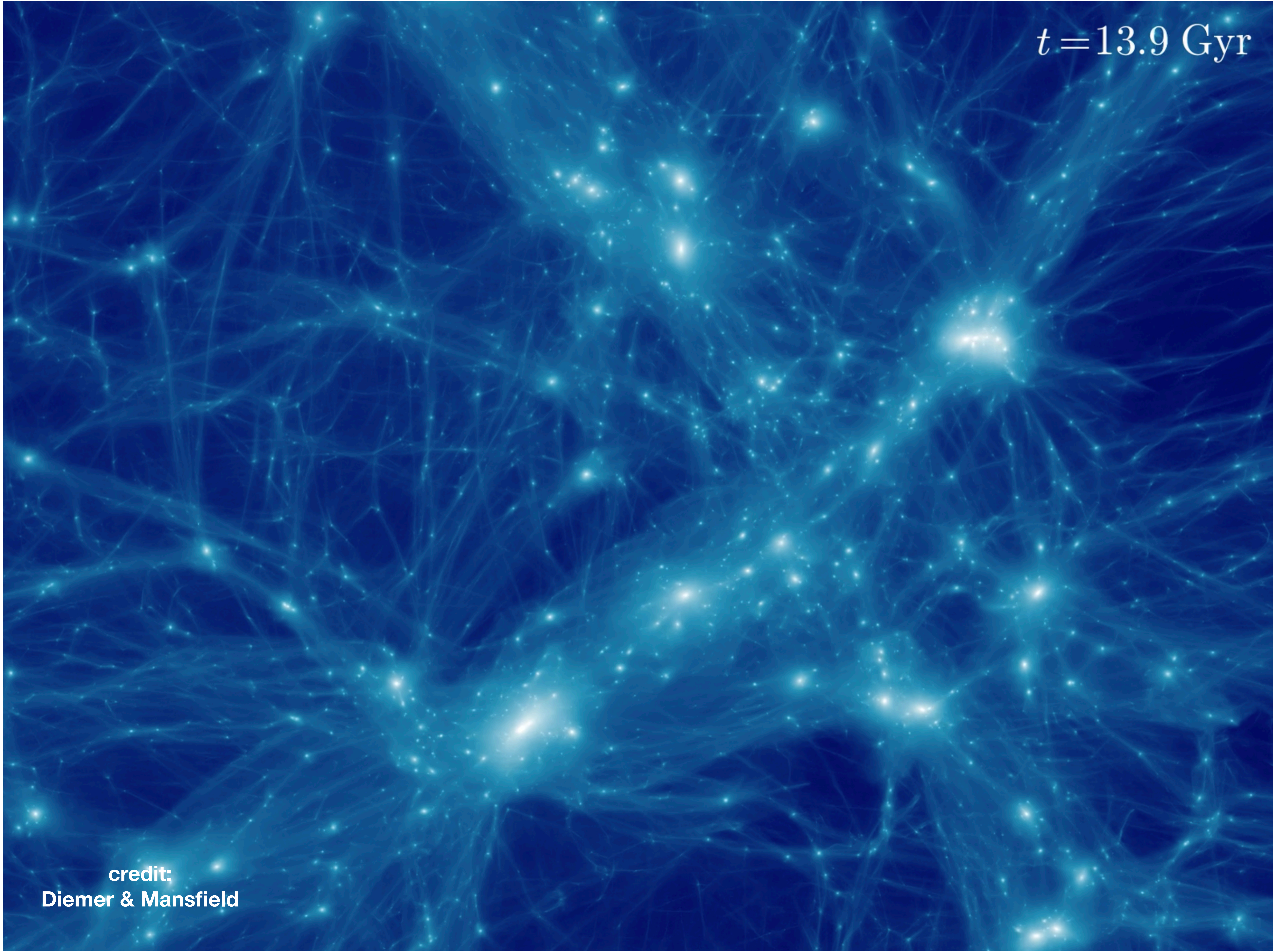
Brinson Prize Fellow
University of Chicago



IDM 2024
L'Aquila, Italy

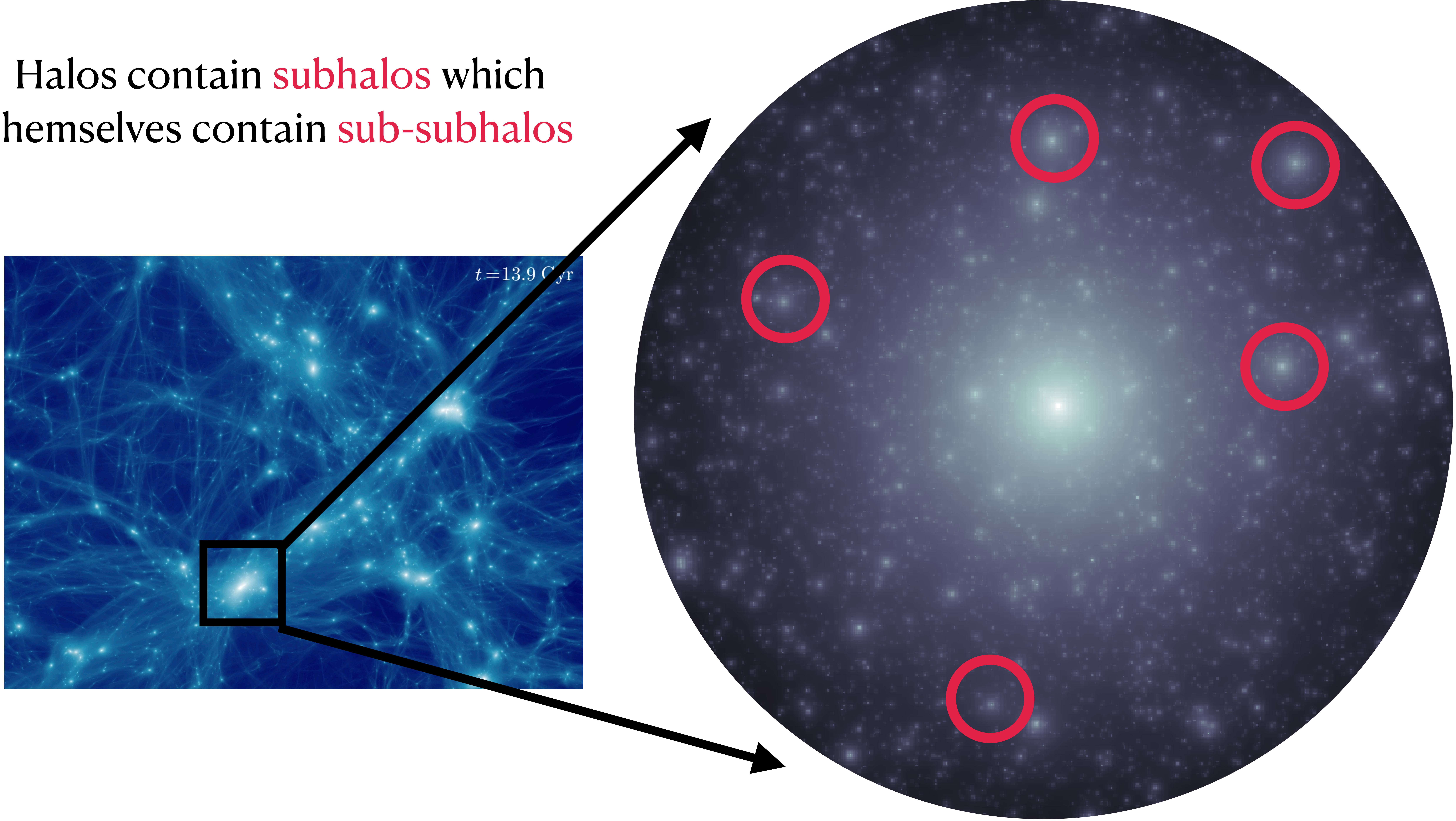


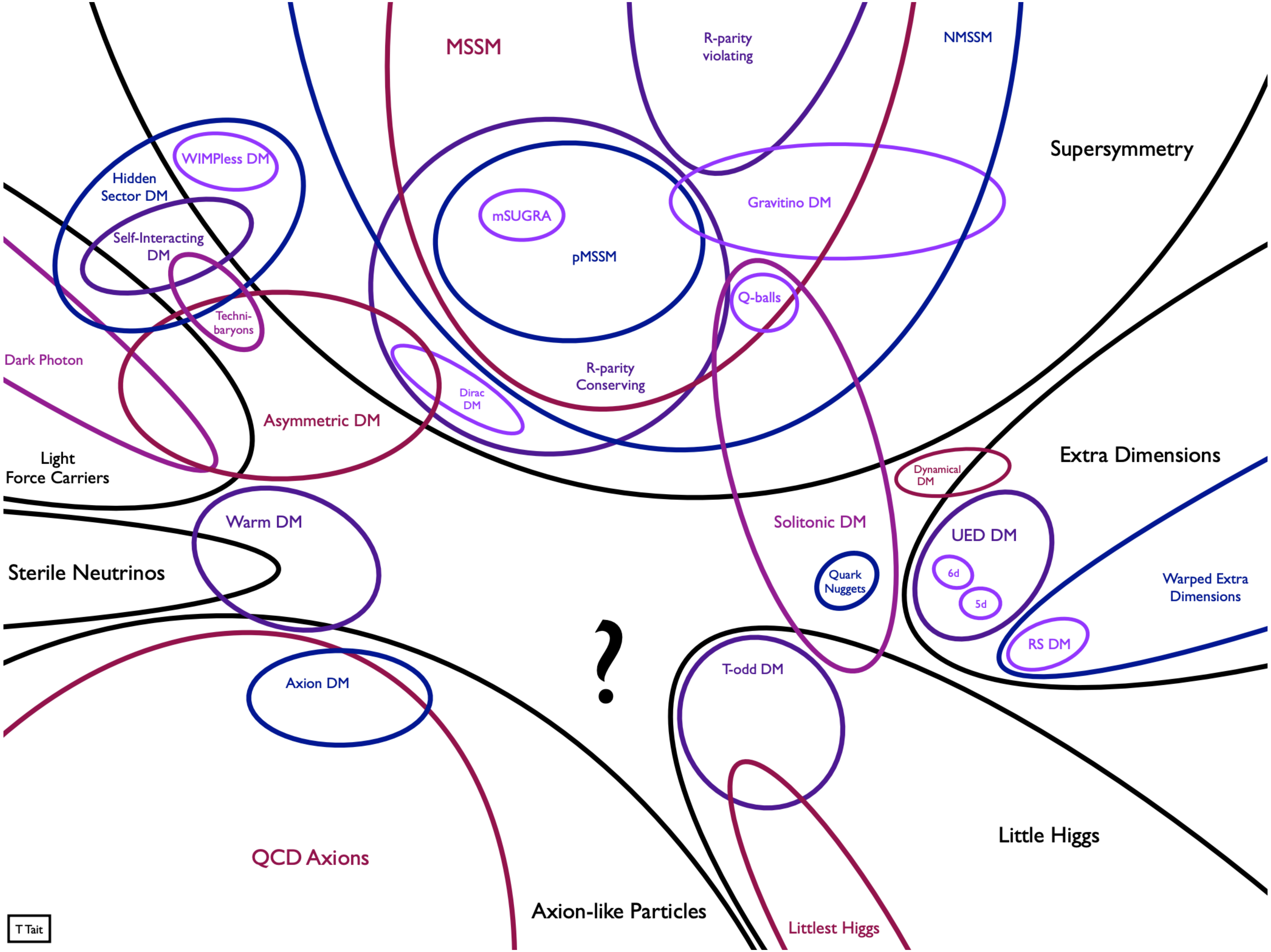




credit:
Diemer & Mansfield

Halos contain subhalos which themselves contain sub-subhalos





MSSM

R-parity
violating

NMSSM

Supersymmetry

WIMPless DM

Hidden
Sector DM

Self-Interacting
DM

Techni-
baryons

mSUGRA

pMSSM

Gravitino DM

Q-balls

Dark Photon

Dirac
DM

R-parity
Conserving

Asymmetric DM

Light
Force Carriers

Extra Dimensions

Dynamical
DM

Warm DM

Solitonic DM

UED DM

Sterile Neutrinos

Quark
Nuggets

6d

5d

Warped Extra
Dimensions

?

RS DM

T-odd DM

Axion DM

Little Higgs

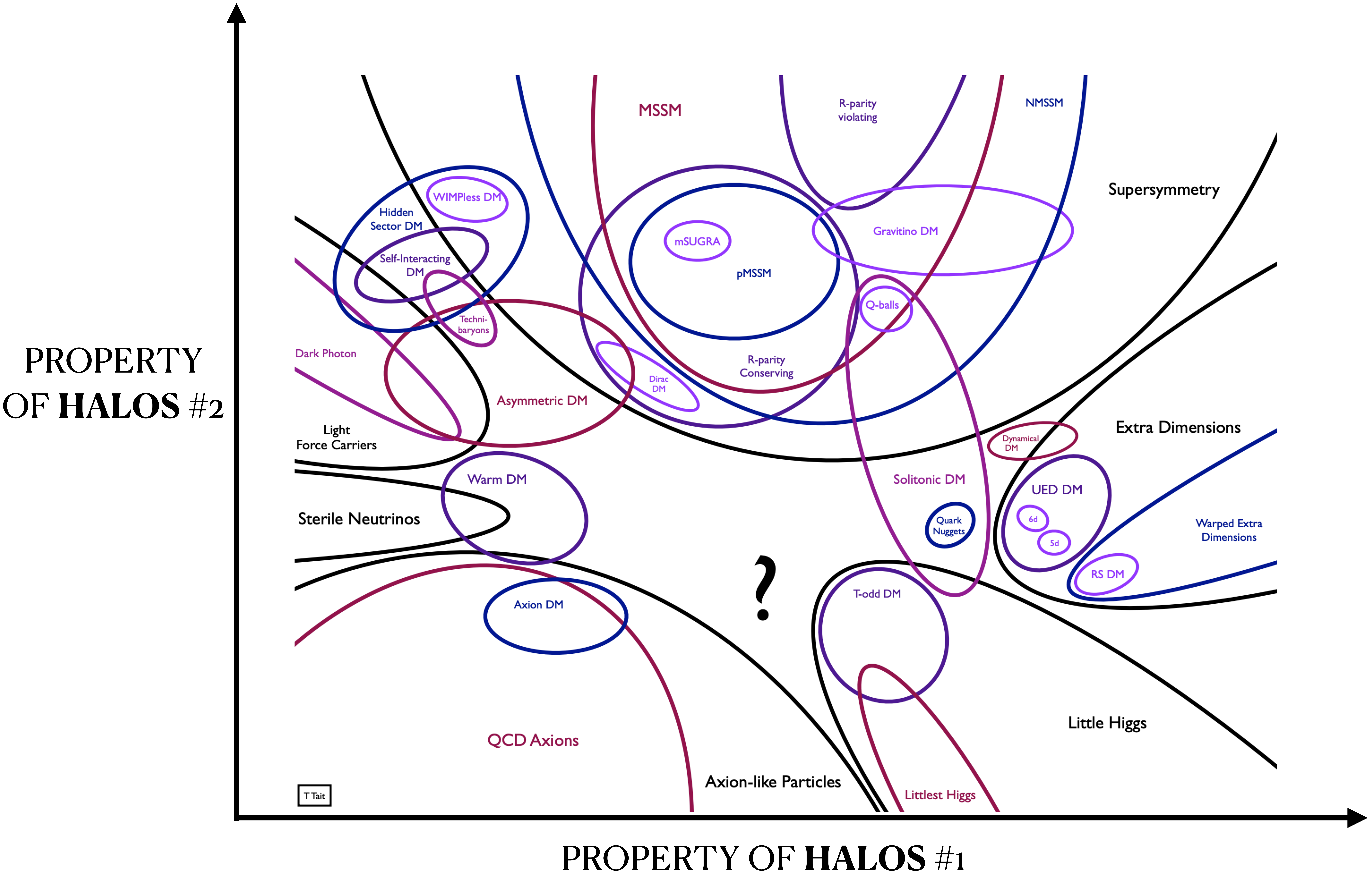
QCD Axions

Axion-like Particles

Littlest Higgs

T Tait

Figure by Tim Tait



MSSM
R-parity violating
NMSSM
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WIMPless DM
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Extra Dimensions
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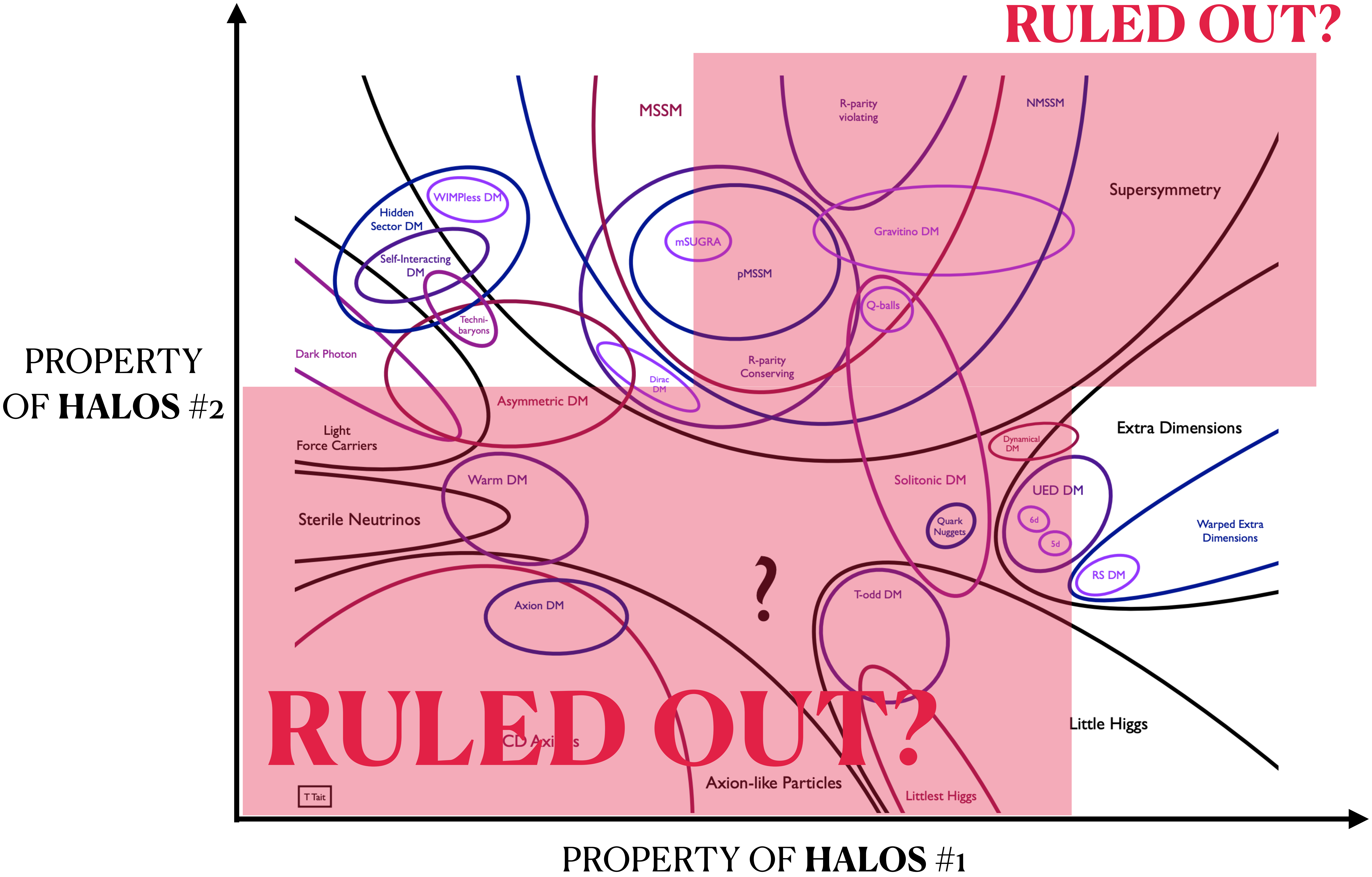
T Tait
PROPERTY OF HALOS #2
PROPERTY OF HALOS #1


RULED OUT?
PROPERTY OF HALOS #2
MSSM
R-parity violating
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Supersymmetry
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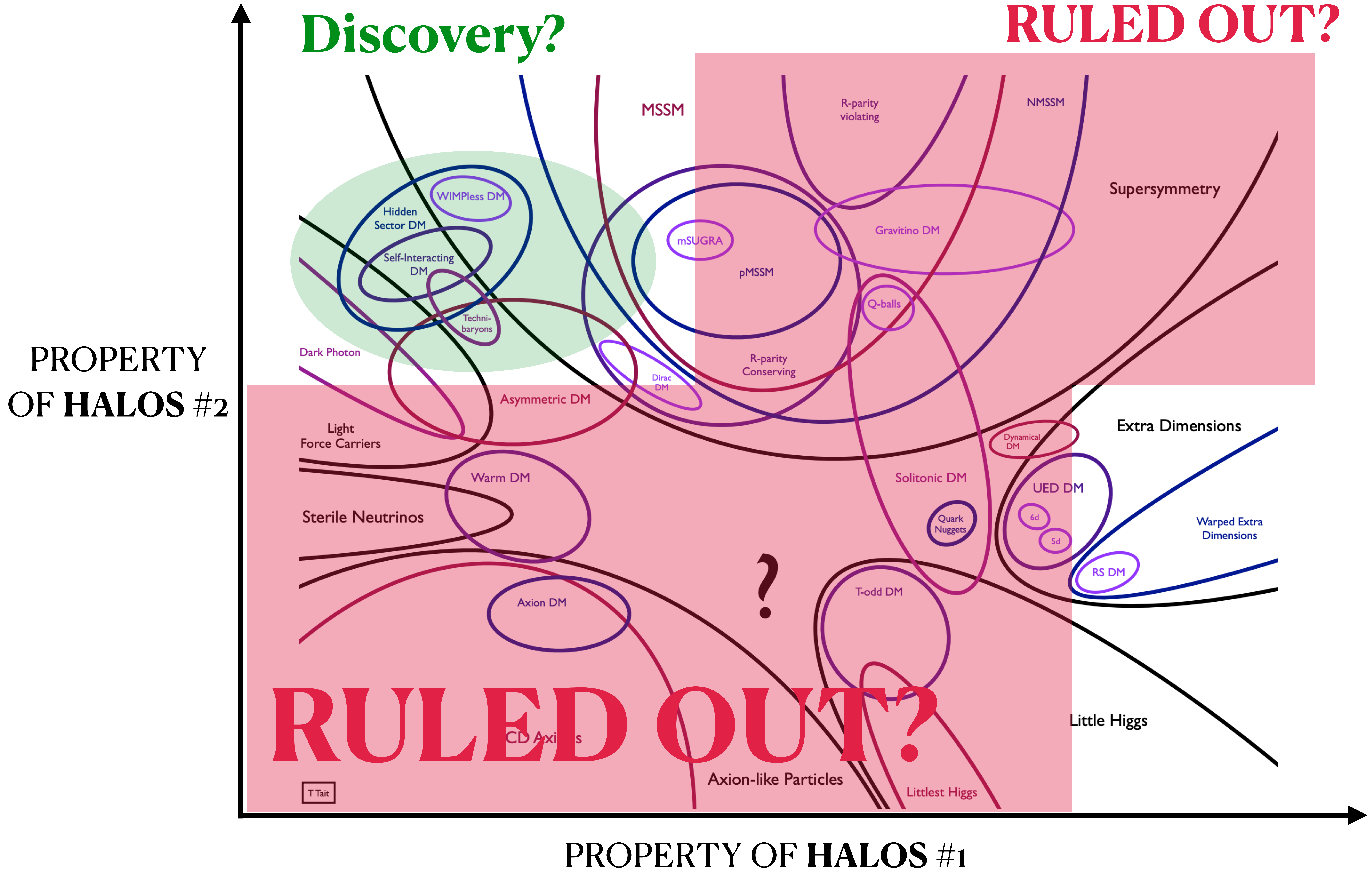
PROPERTY OF HALOS #1



Discovery?

RULED OUT?

MSSM

R-parity
violating

NMSSM

Supersymmetry

WIMPless DM

Hidden
Sector DM

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Techni-
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RULED OUT?

CD Axi s

Axion-like Particles

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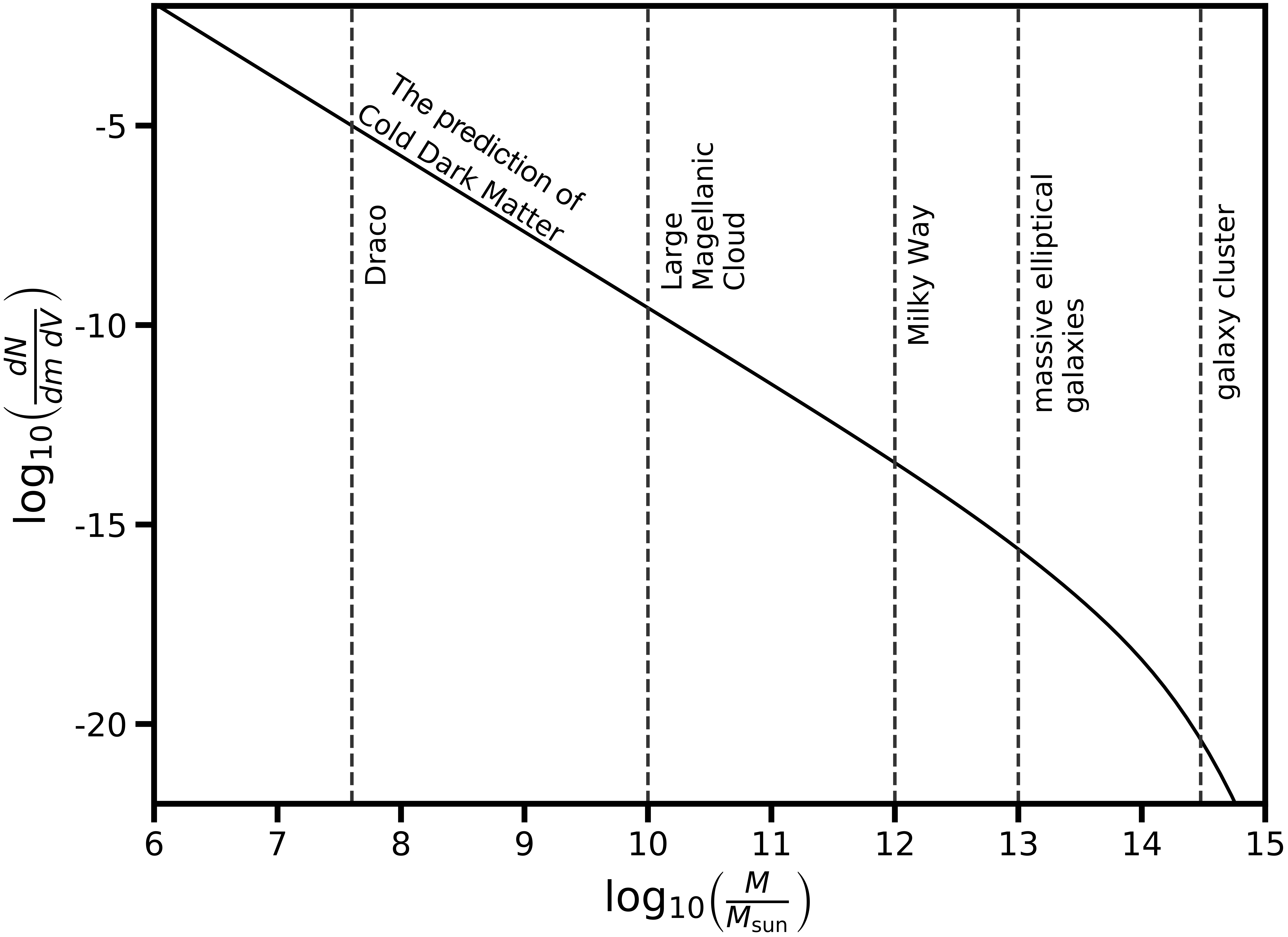
T Tait

PROPERTY
OF **HALOS** #2

PROPERTY OF **HALOS** #1



The prediction of
Cold Dark Matter
Draco
Large
Magellanic
Cloud
Milky Way
massive elliptical
galaxies
galaxy cluster
-5
-10
-15
-20
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
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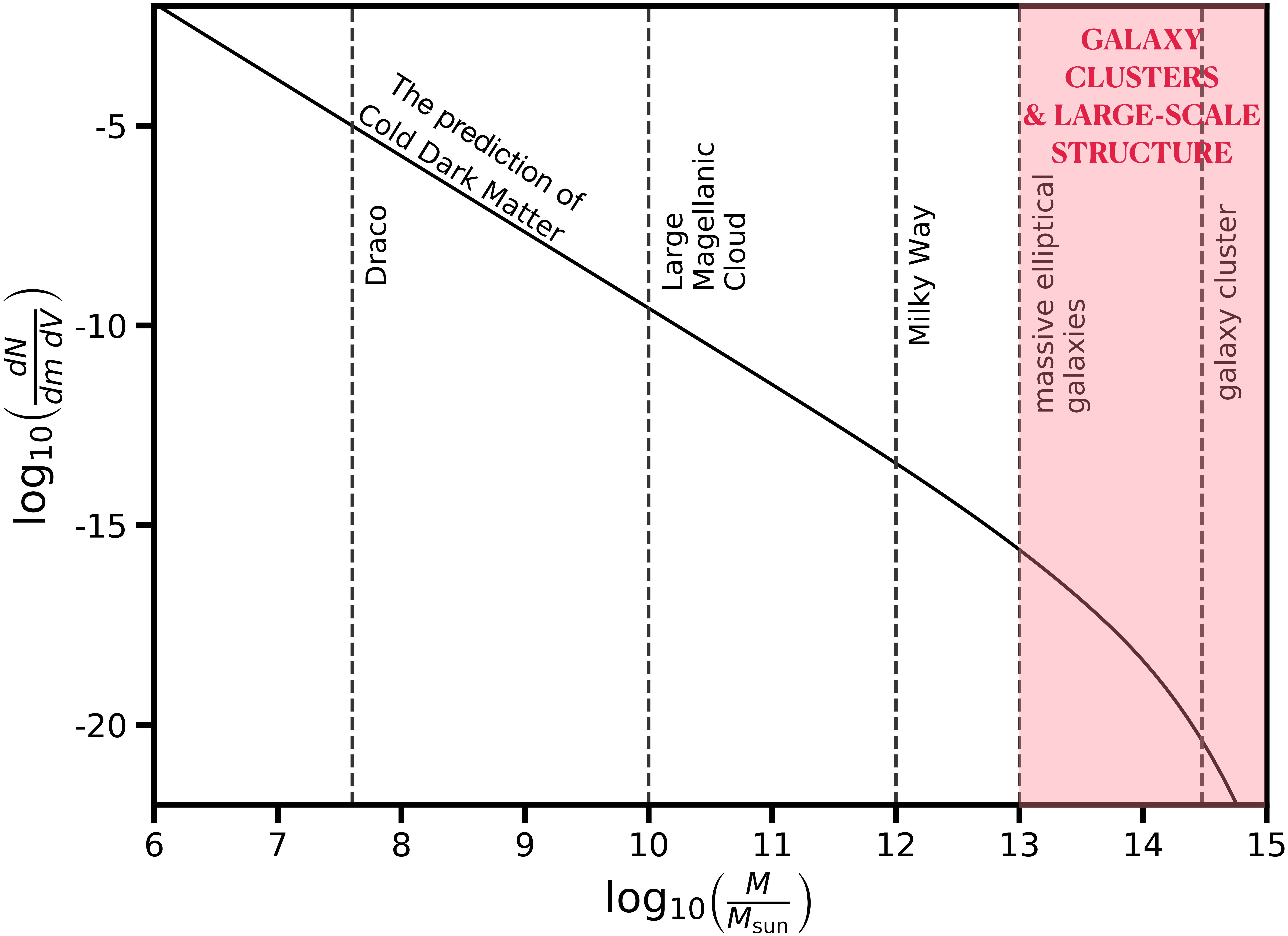
$\log_{10}\left(\frac{M}{M_{\text{sun}}}\right)$


GALAXY CLUSTERS & LARGE-SCALE STRUCTURE
The prediction of Cold Dark Matter
Draco
Large Magellanic Cloud
Milky Way
massive elliptical galaxies
galaxy cluster
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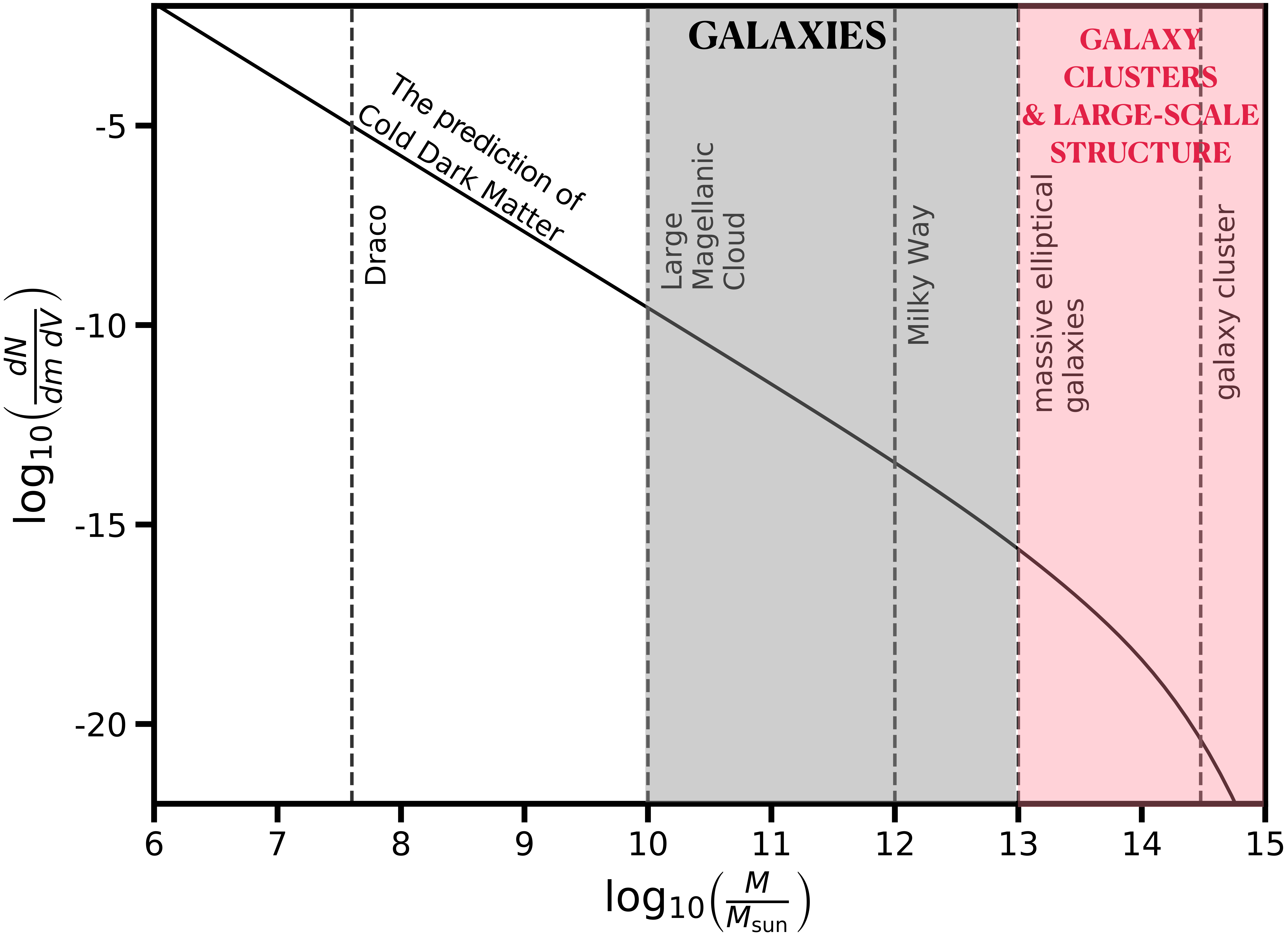
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
$\log_{10}\left(\frac{M}{M_{\mathrm{sun}}}\right)$


GALAXIES
GALAXY CLUSTERS & LARGE-SCALE STRUCTURE
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$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
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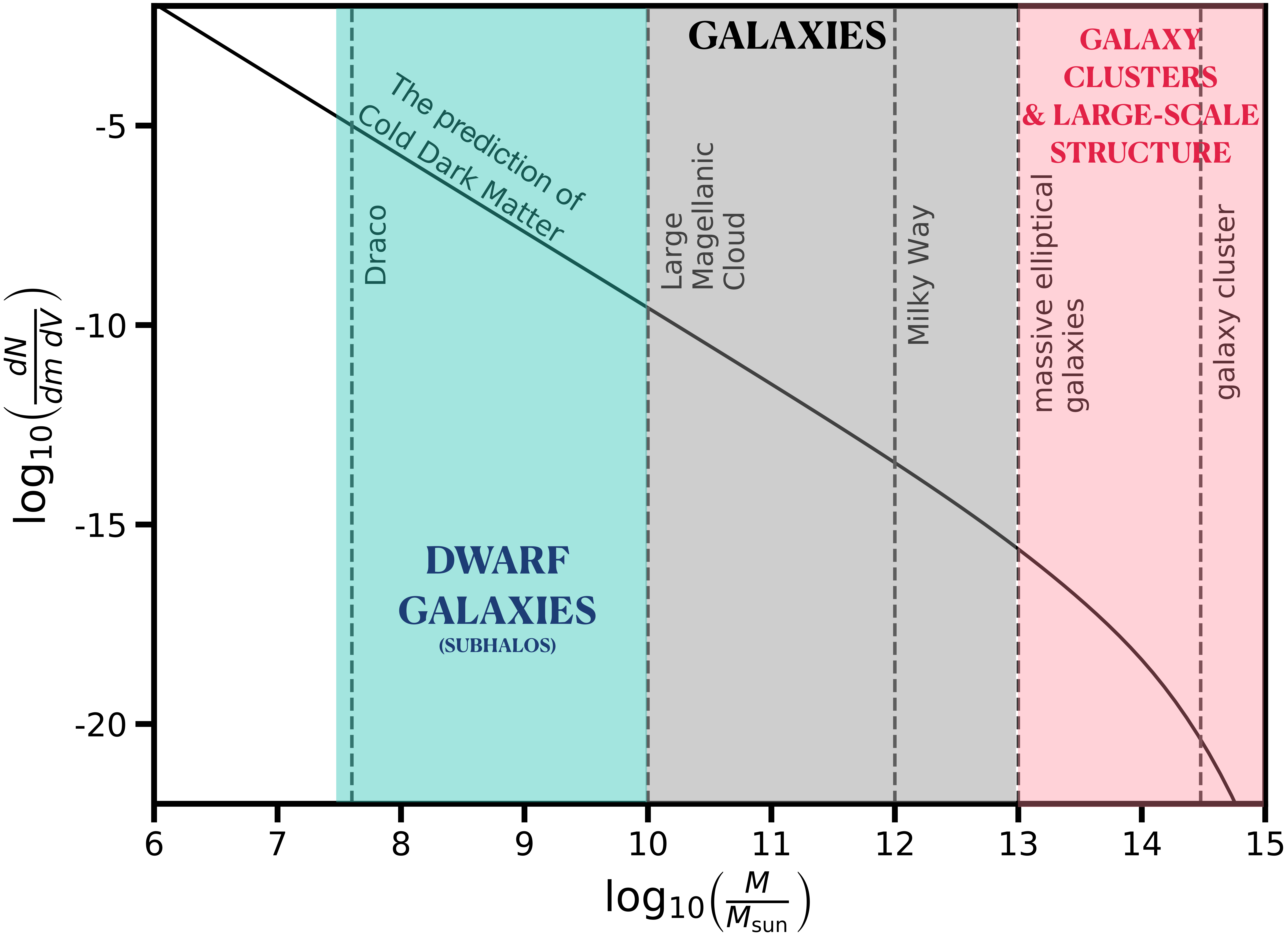
GALAXIES
GALAXY CLUSTERS & LARGE-SCALE STRUCTURE
The prediction of Cold Dark Matter
Draco
Large Magellanic Cloud
Milky Way
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galaxy cluster
DWARF GALAXIES
(SUBHALOS)
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$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
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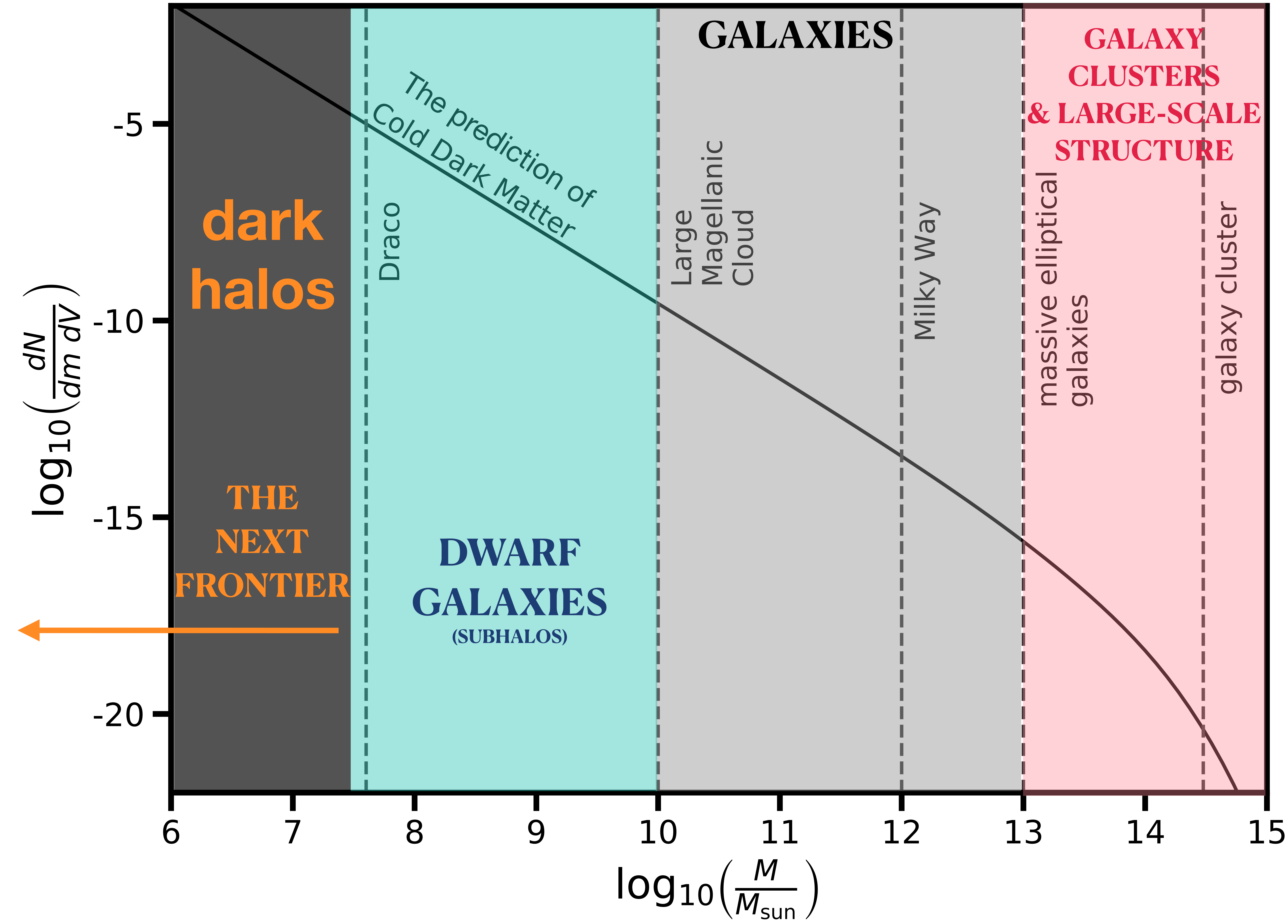
GALAXIES
GALAXY CLUSTERS & LARGE-SCALE STRUCTURE
dark halos
THE NEXT FRONTIER
DWARF GALAXIES
(SUBHALOS)
The prediction of Cold Dark Matter
Draco
Large Magellanic Cloud
Milky Way
massive elliptical galaxies
galaxy cluster
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
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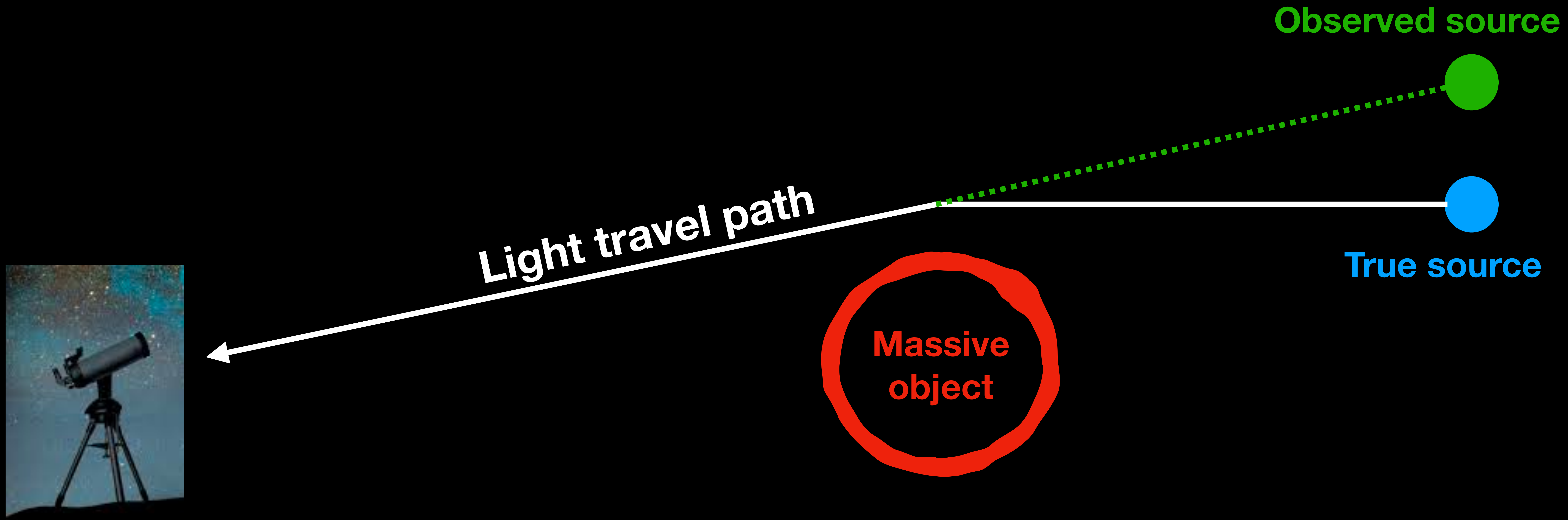
15
$\log_{10}\left(\frac{M}{M_{\rm sun}}\right)$

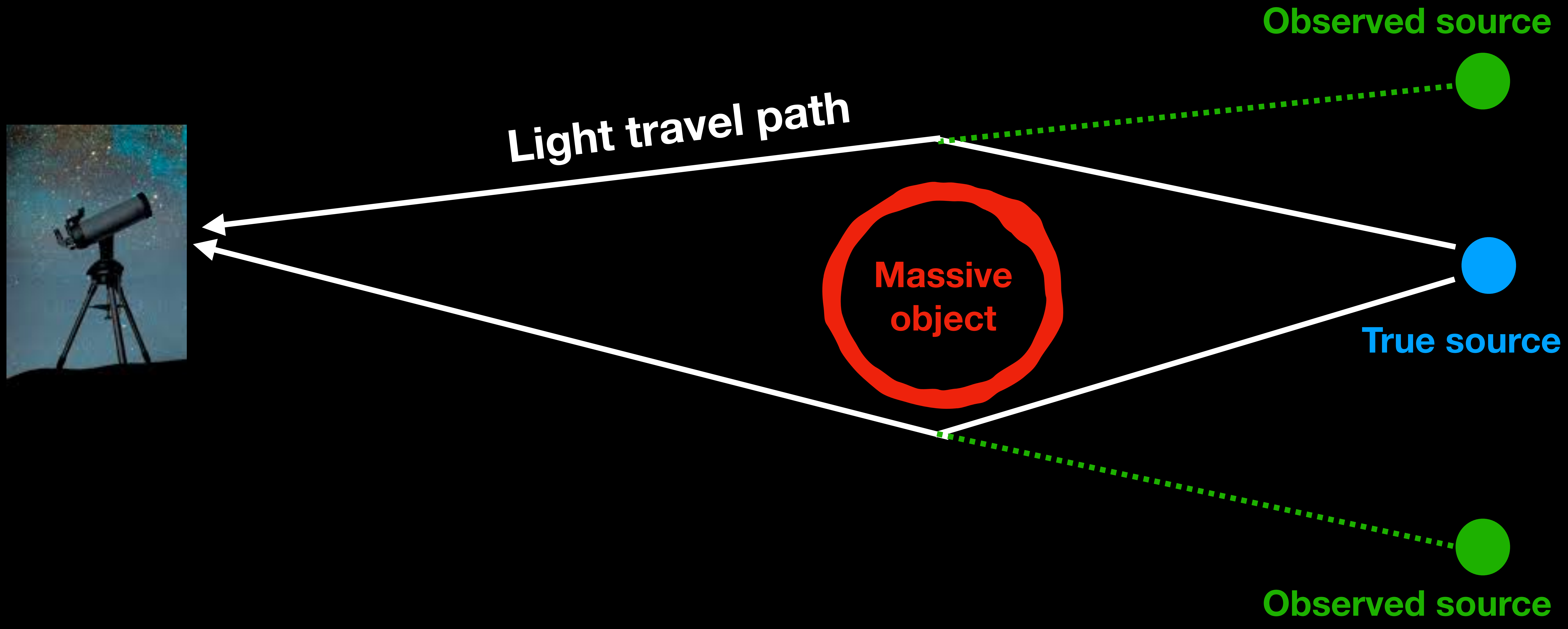
Strong lensing

Movie by Yashar Hezaveh

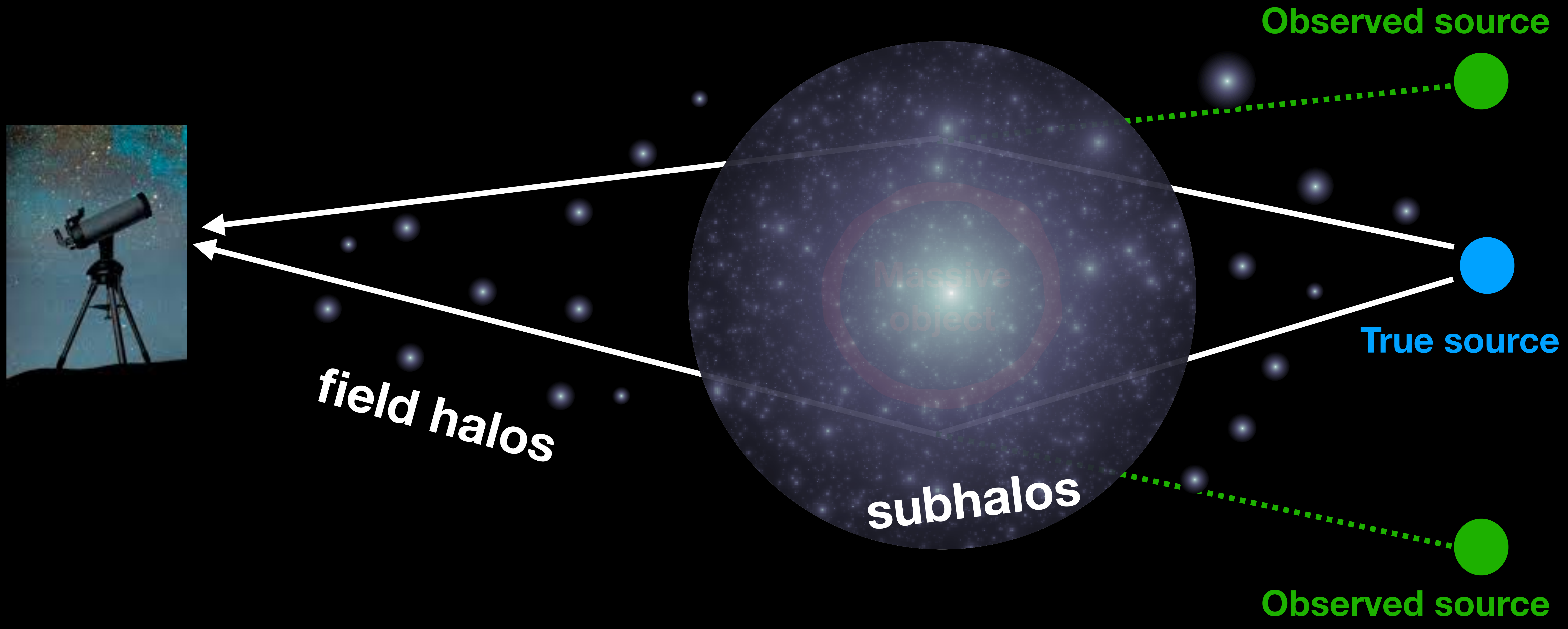
Gravitational lensing: deflection of light by gravitational fields



Strong lensing produces multiple images of a single source



Strong lensing produces multiple images of a single source



Main deflector

(Lensed) quasar host galaxy

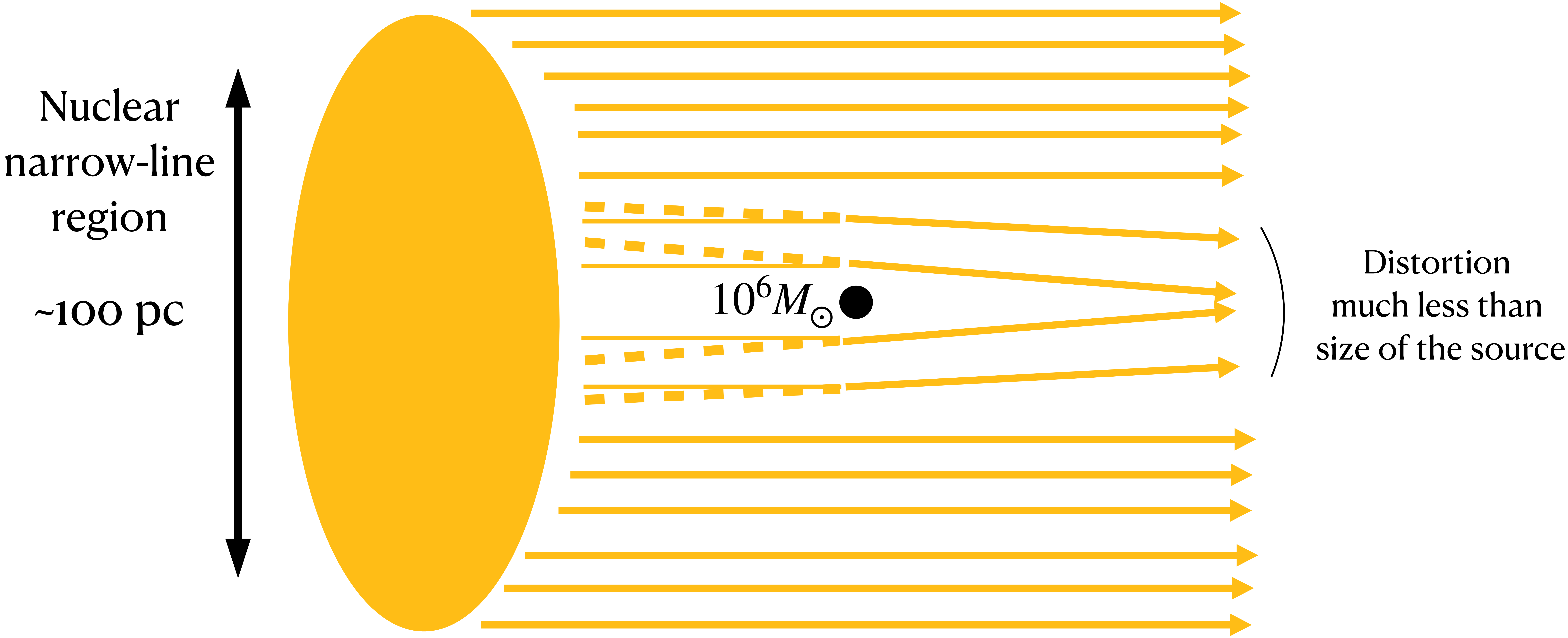
Multiple images of background quasar

Figure adapted from Shajib et al. (2019)

Image magnifications $\sim \partial^2\Psi(r)/\partial r^2 \propto$ projected mass

-> sensitive to small-scale structure

THE (recent) PAST: narrow-line flux ratios from HST



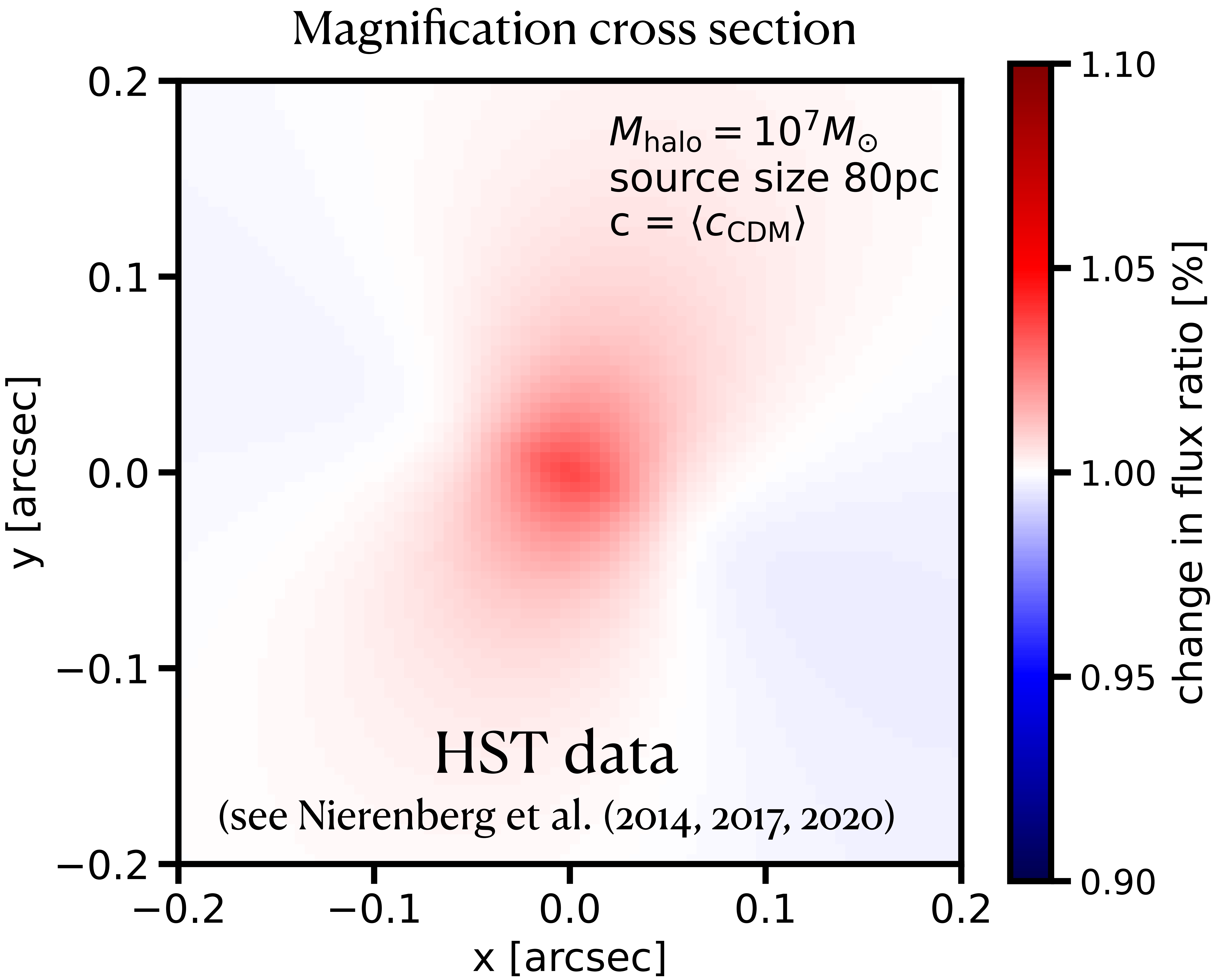
Nuclear
narrow-line
region

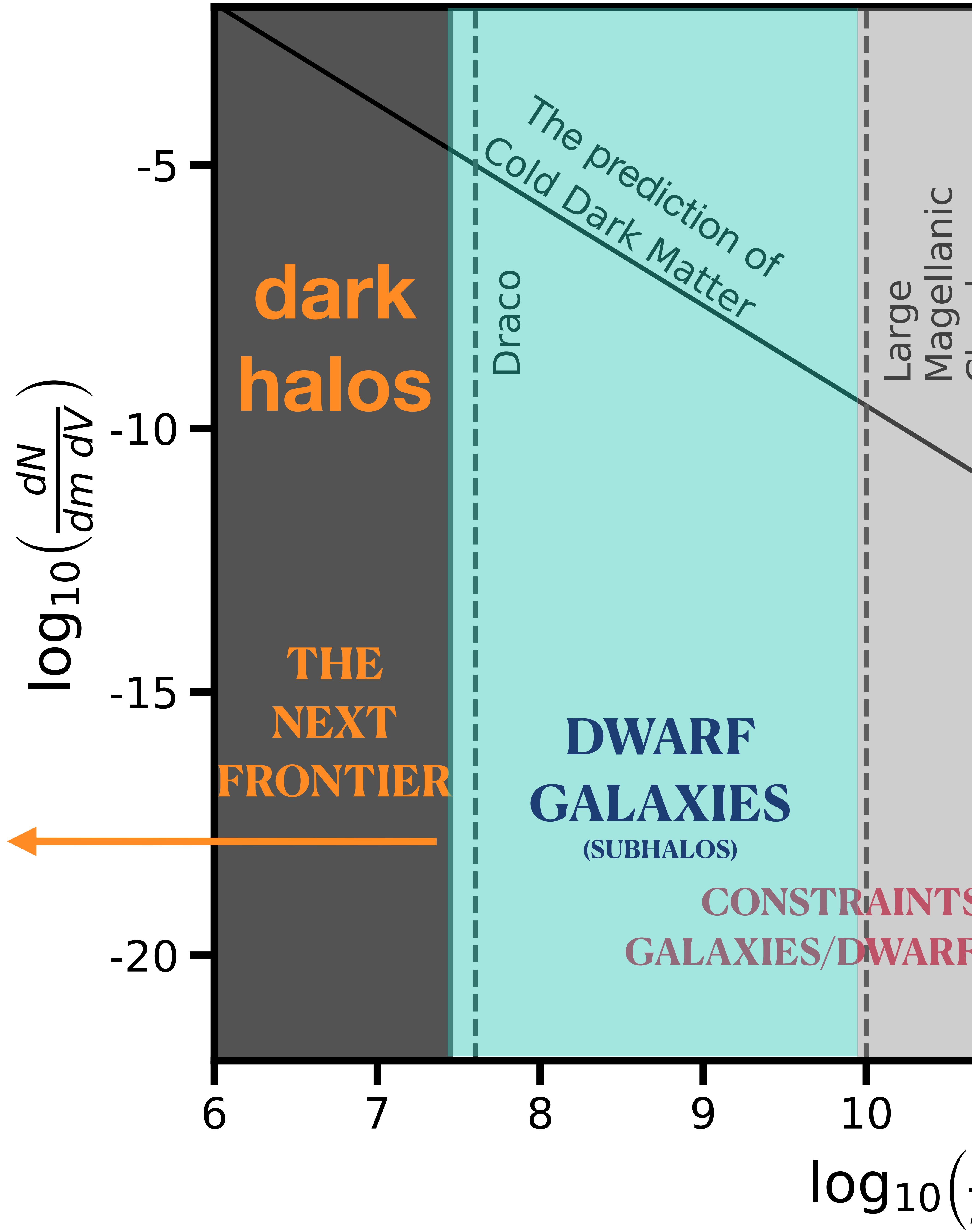
~100 pc

$10^6 M_\odot$

Distortion
much less than
size of the source

$M = 10^7 M_\odot$


Magnification cross section
$M_{\mathrm{halo}} = 10^7 M_\odot$
source size 80pc
c = $\langle c_{\mathrm{CDM}} \rangle$
HST data
(see Nierenberg et al. (2014, 2017, 2020)
y [arcsec]
x [arcsec]
0.2
0.1
0.0
−0.1
−0.2
−0.2
−0.1
0.0
0.1
0.2
change in flux ratio [%]
1.10
1.05
1.00
0.95
0.90


The prediction of
Cold Dark Matter
dark
halos
THE
NEXT
FRONTIER
Draco
DWARF
GALAXIES
(SUBHALOS)
Large
Magellanic
CONSTRAINTS
GALAXIES/DWARF
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
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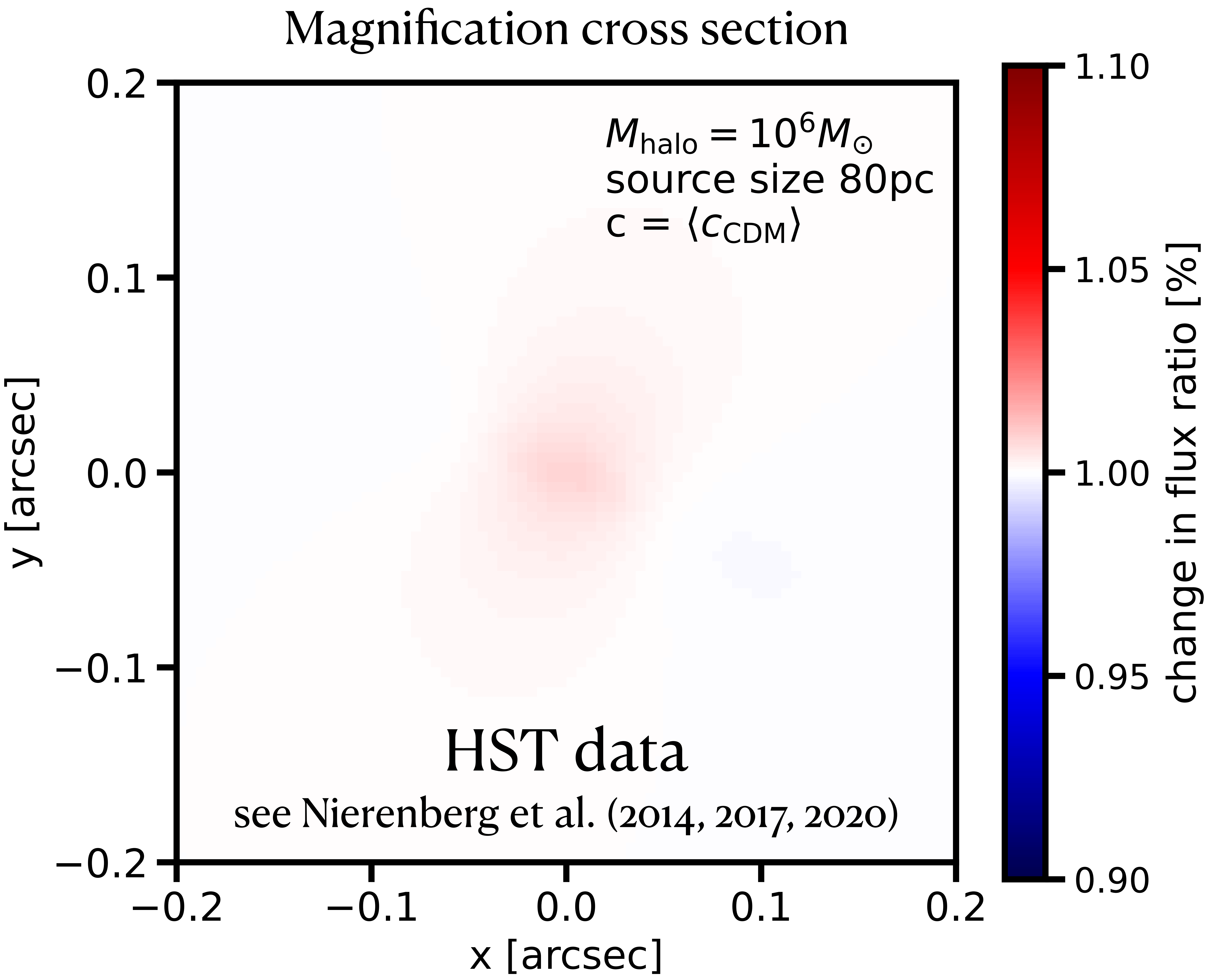
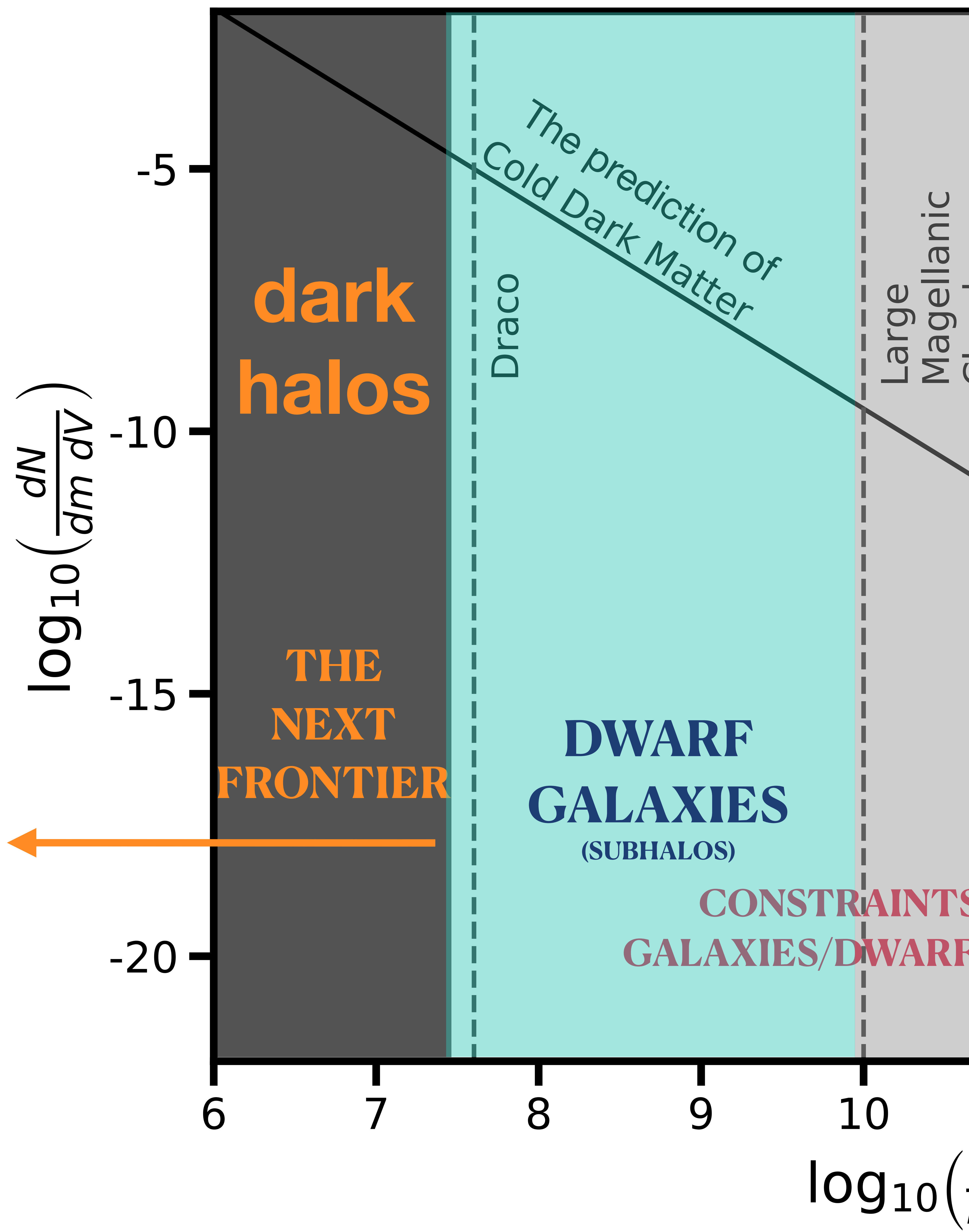
$\log_{10}($

$M = 10^6 M_\odot$


Magnification cross section



THE PRESENT: mid-IR flux ratios from JWST GO-2046

JWST GO-2046 "A definitive test of the dark matter paradigm"

PI Anna Nierenberg, Co-Is include D. Gilman

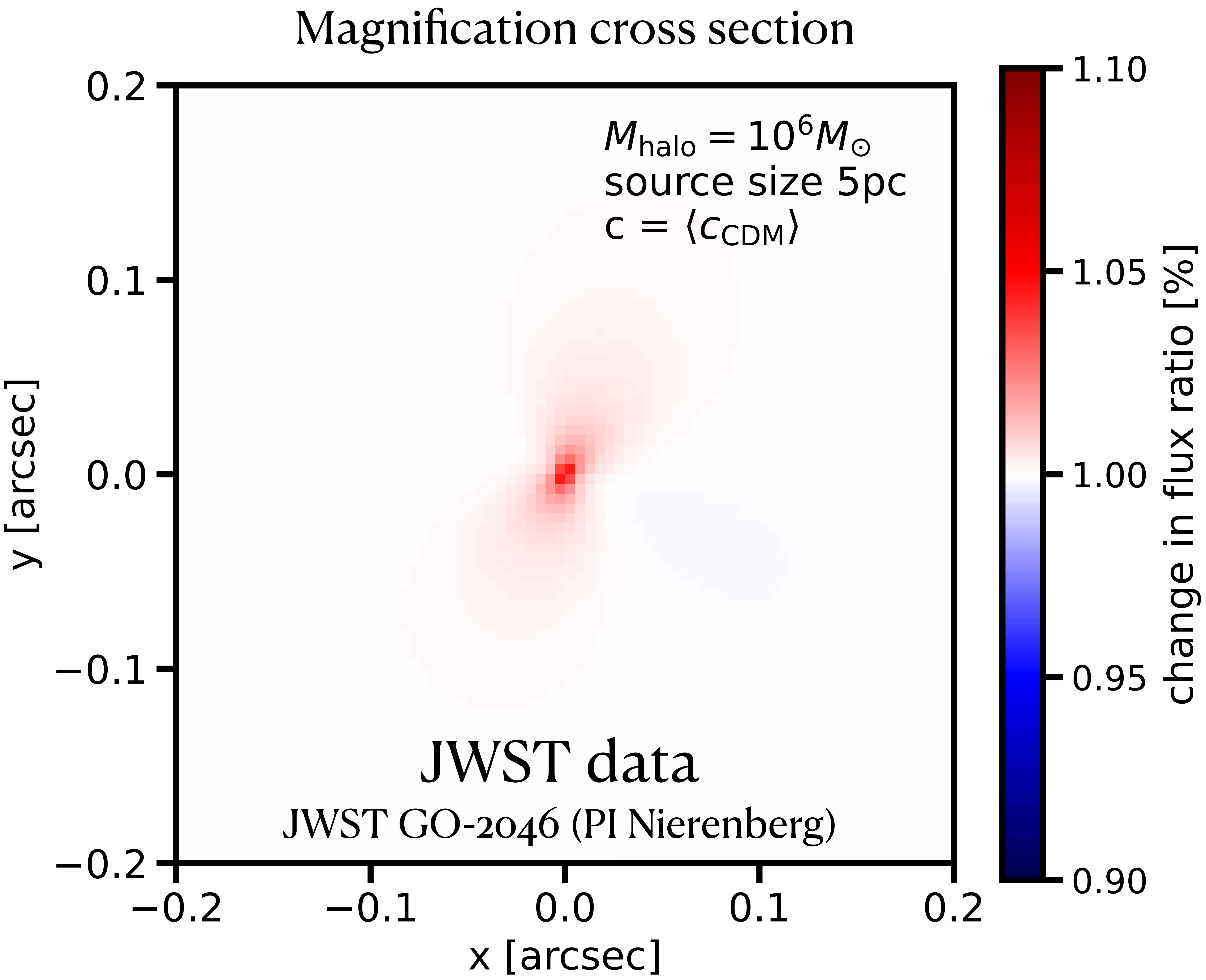
Survey introduction:

- Nierenberg, incl. Gilman et al. (2023) (arXiv: 2309.10101)

First results with 9 systems:

- Keeley, incl. Gilman et al. (2024) (arXiv: 2405.01620)

$$M = 10^6 M_\odot$$


Magnification cross section
$M_{\rm halo} = 10^6 M_\odot$
source size 5pc
c = ⟨$c_{\rm CDM}$⟩
JWST data
JWST GO-2046 (PI Nierenberg)
y [arcsec]
x [arcsec]
0.2
0.1
0.0
−0.1
−0.2
−0.2
−0.1
0.0
0.1
0.2
change in flux ratio [%]
1.10
1.05
1.00
0.95
0.90


$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
-5
-10
-15
-20
dark halos
THE NEXT FRONTIER
Draco
on of
rk Matter
Large Magellanic
DWARF GALAXIES
(SUBHALOS)
CONSTRAINTS
GALAXIES/DWARF
6
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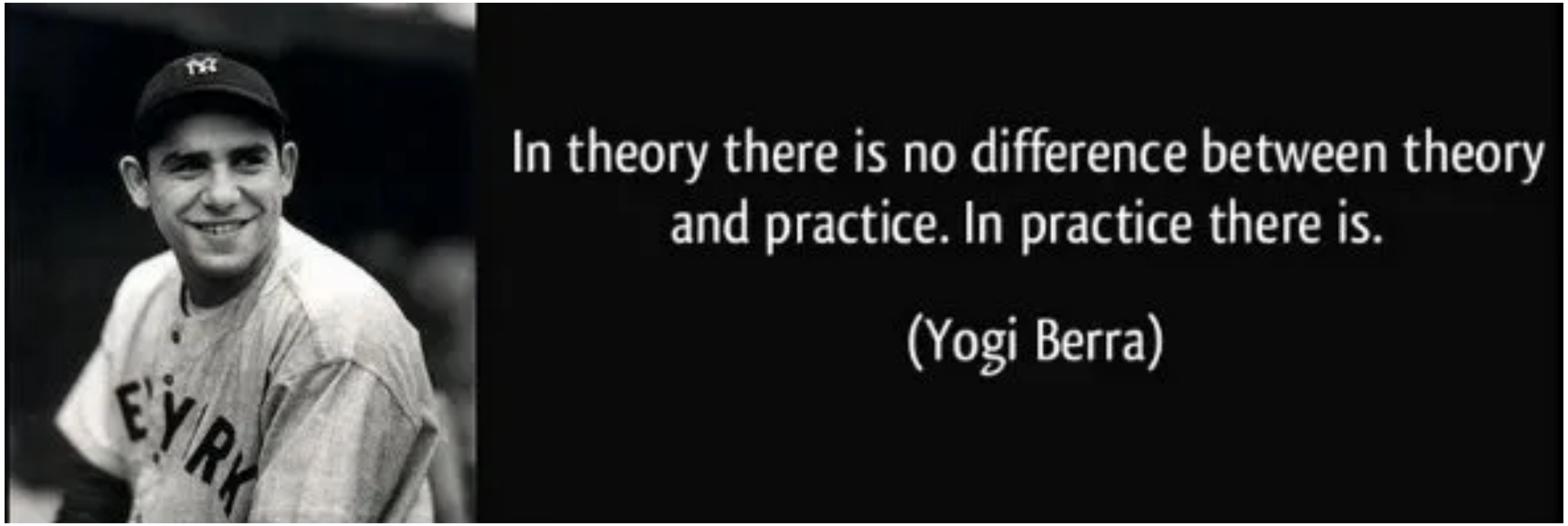
$\log_{10}($

A CRASH COURSE IN FORWARD MODELING STRONG LENSES

(in the context of warm dark matter)



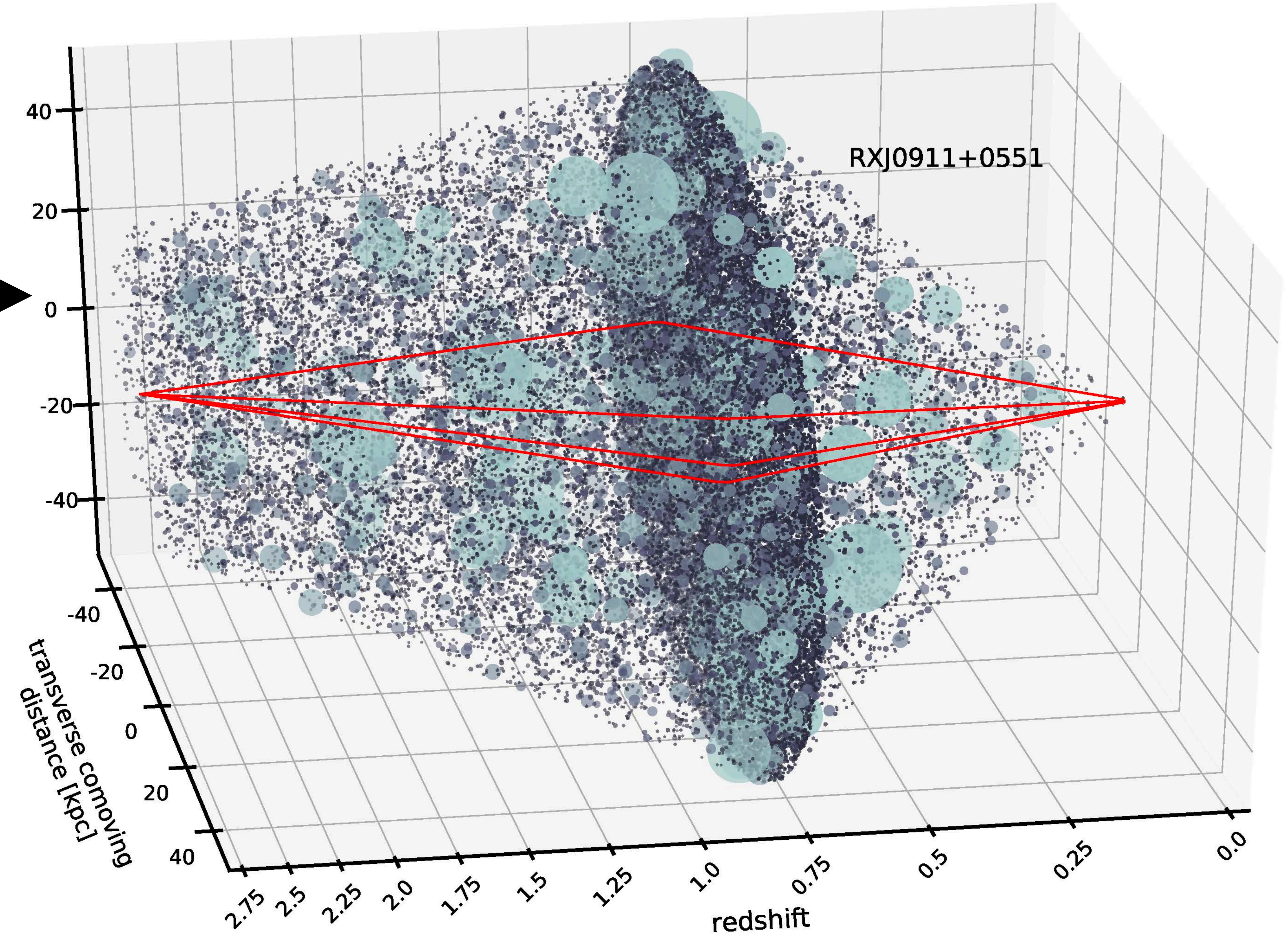
In theory there is no difference between theory and practice. In practice there is.

(Yogi Berra)

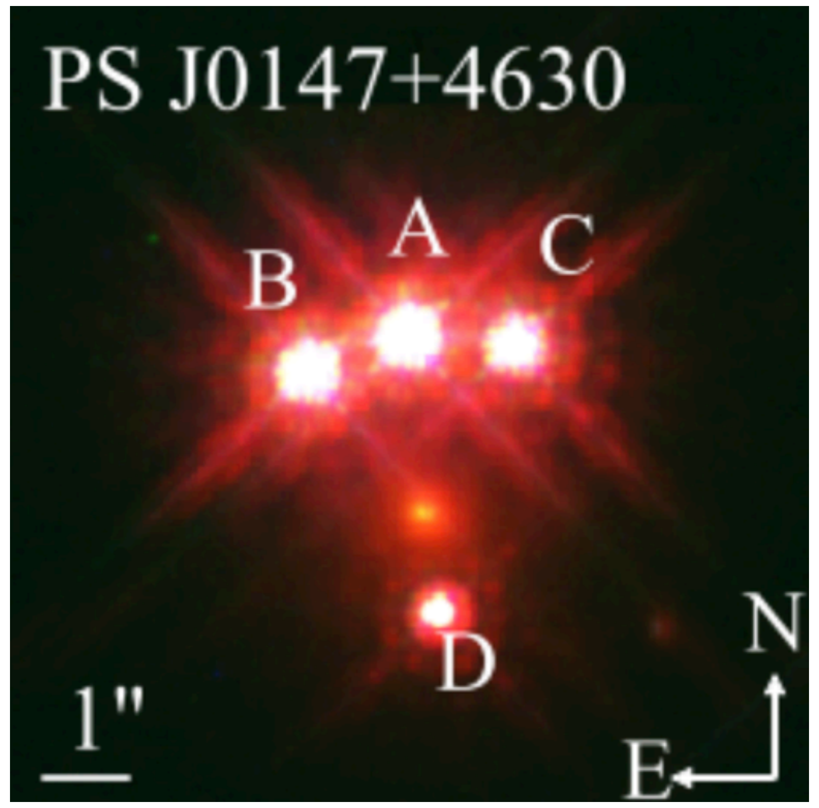
Simulation pipeline

Dark matter theory

Halo mass function, halo density profiles

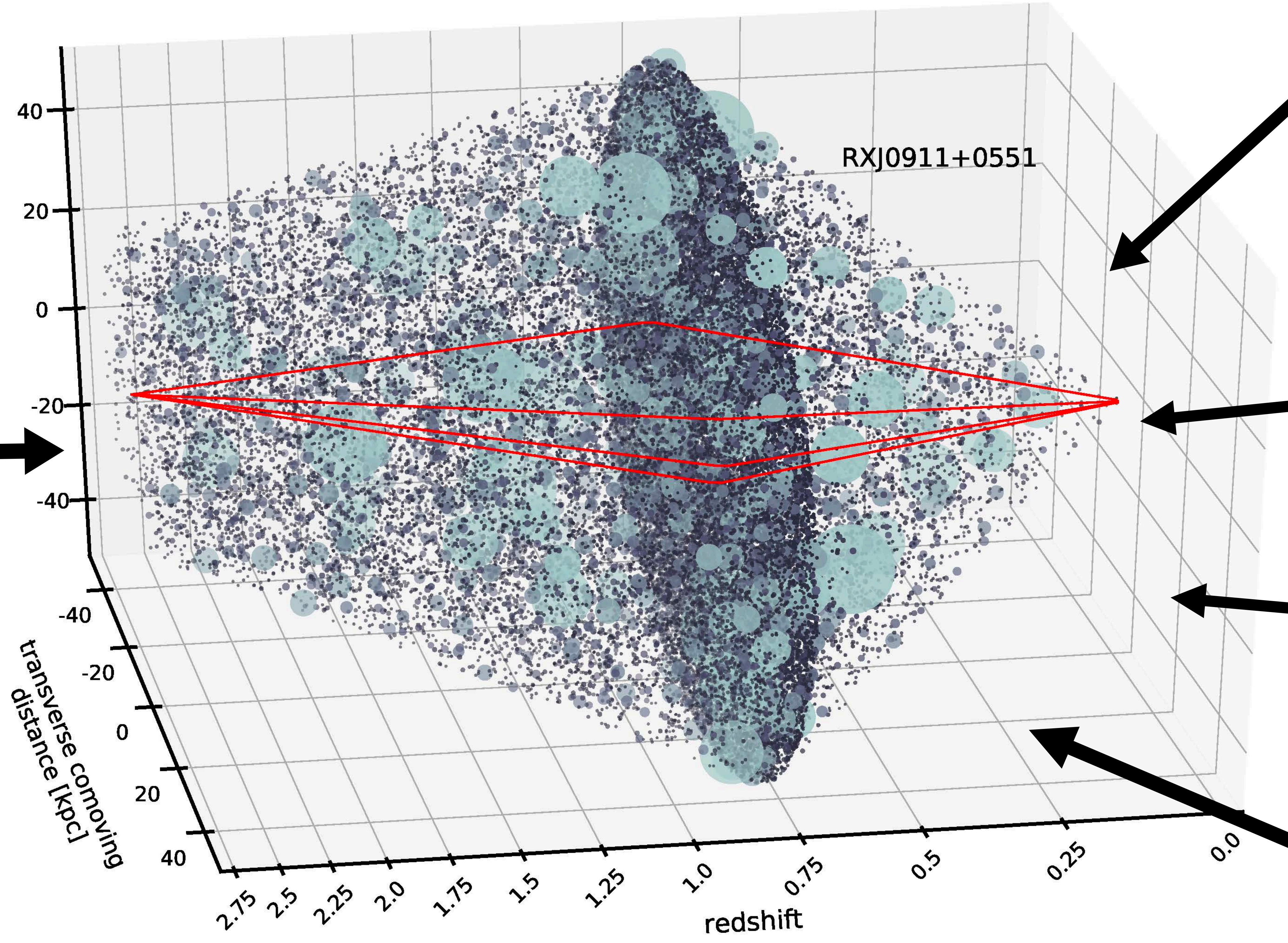


$10^5 - 10^6 M_\odot$ ray-tracing simulations per lens



Compare with data

Simulation pipeline



Dark matter physics/halo properties

- Both subhalos and line-of-sight halos
- (Sub)halo mass function amplitude & slope
- halo density profiles, concentrations
- Exotic DM physics

Main deflector mass models

- Satellite galaxies
- Mass profile ellipticity, slope, external shears
- Multipole perturbations

Finite-size background sources

Measurement uncertainties

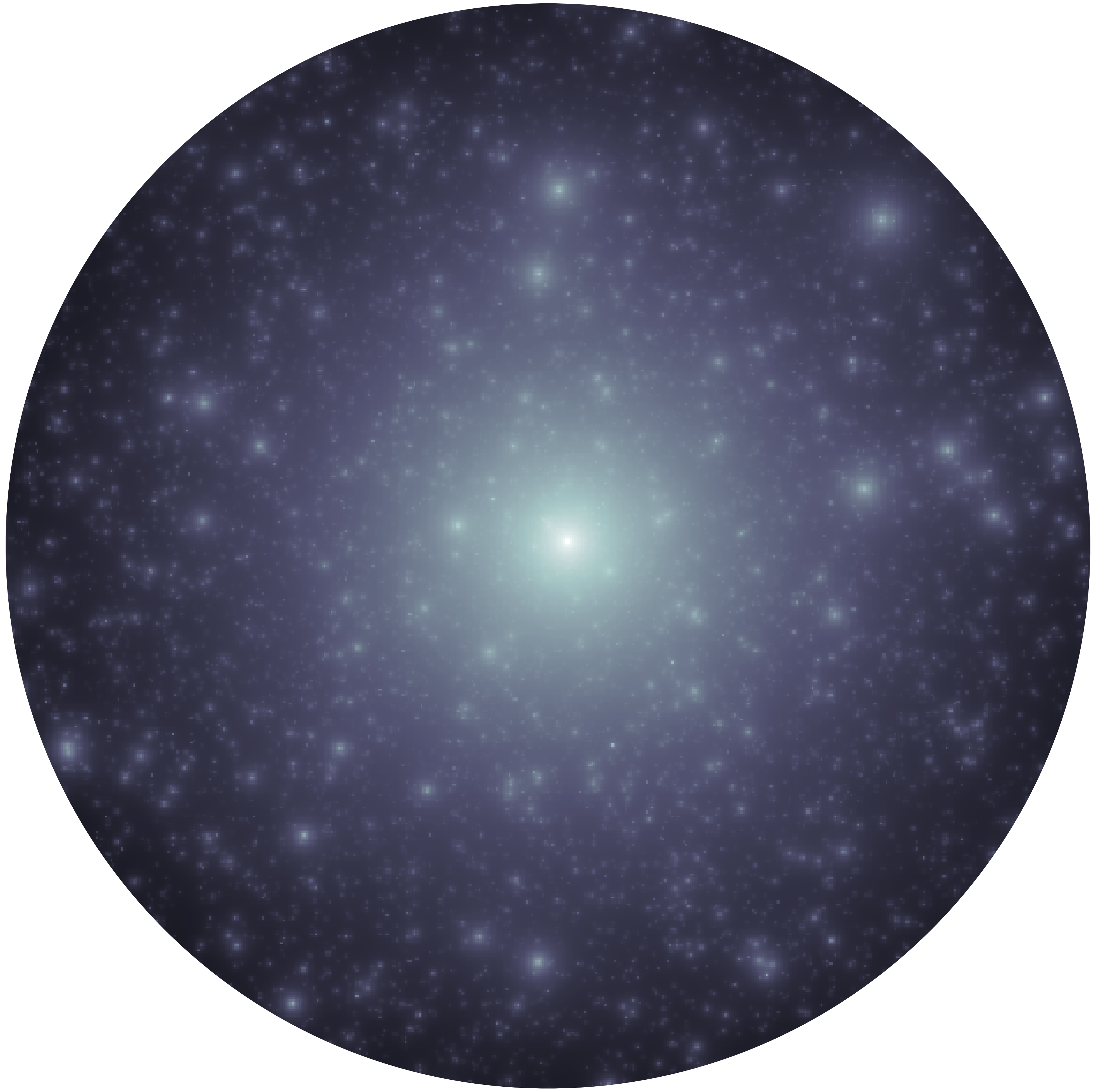
The effects of baryons, e.g. tidal stripping, heating, etc.

All code is open-source:
- pyHalo (generate substructure realizations)
- lenstronomy (lensing calculations)
- samana (simulation pipeline)

Simulation pipeline example: 1) generate realizations of halos from model

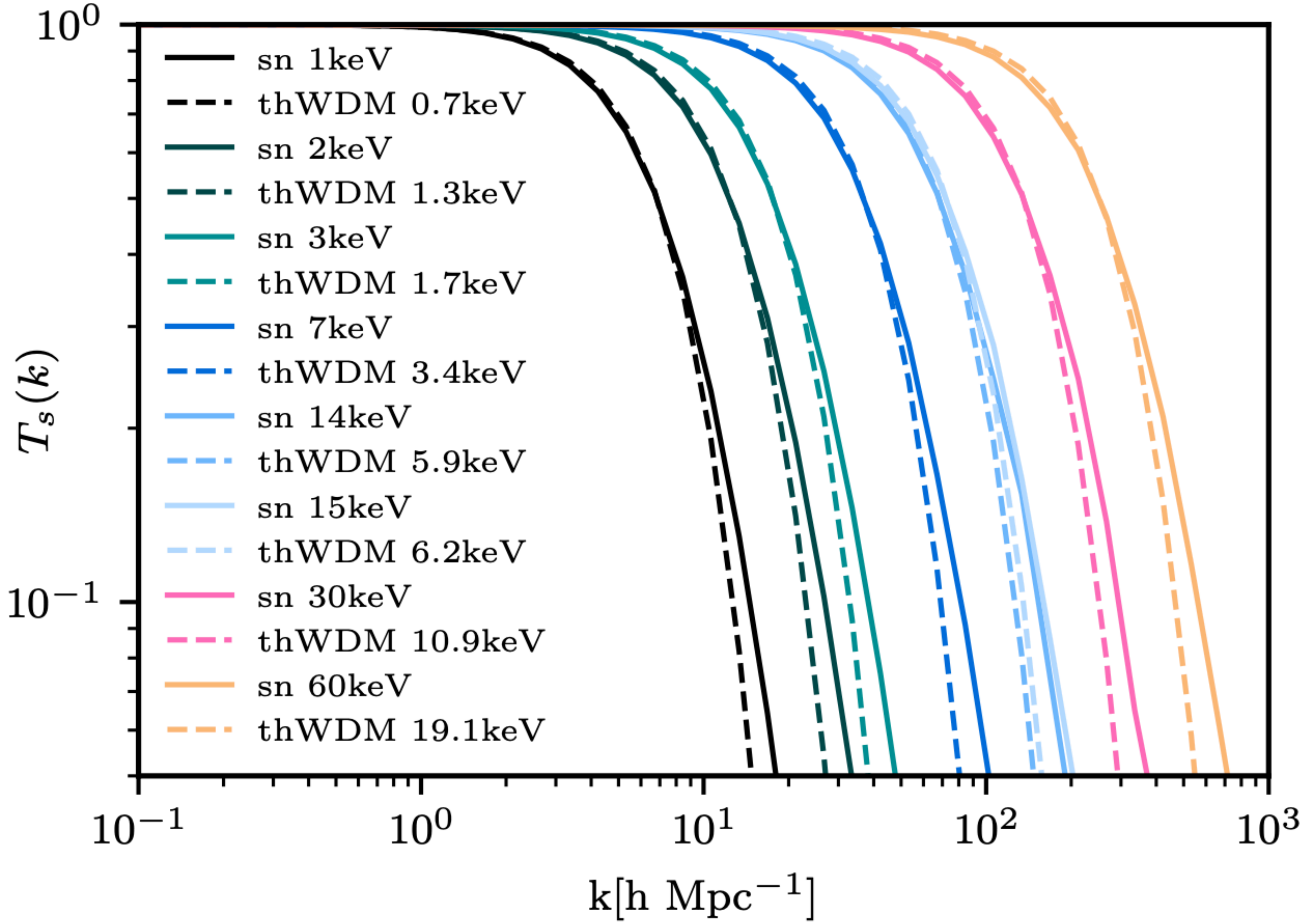
CDM

- plethora of subhalos & field halos
- halo concentration increases at lower masses



WDM

- No structure below a cutoff scale
- halo concentrations suppressed below cutoff



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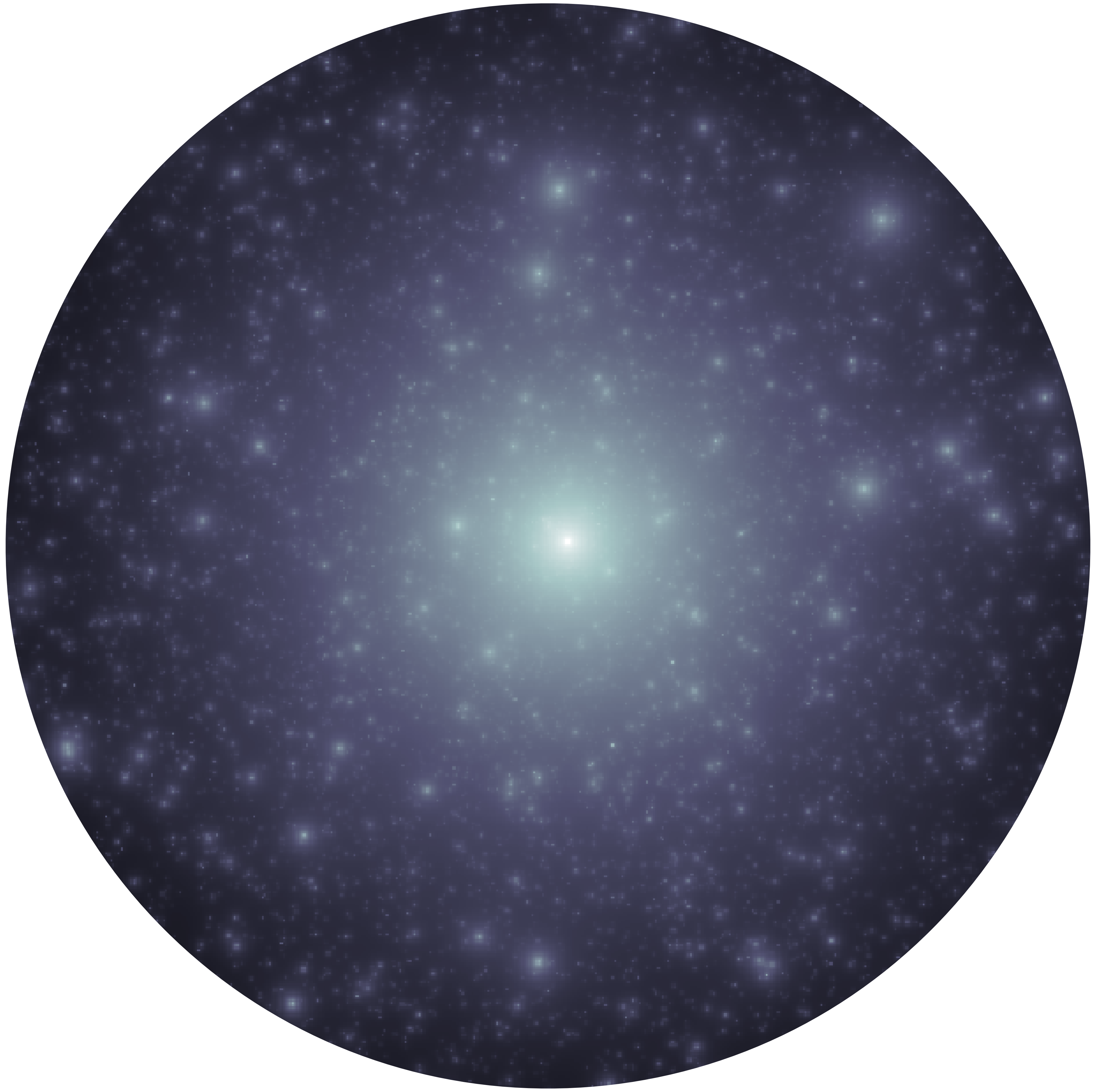

WDM

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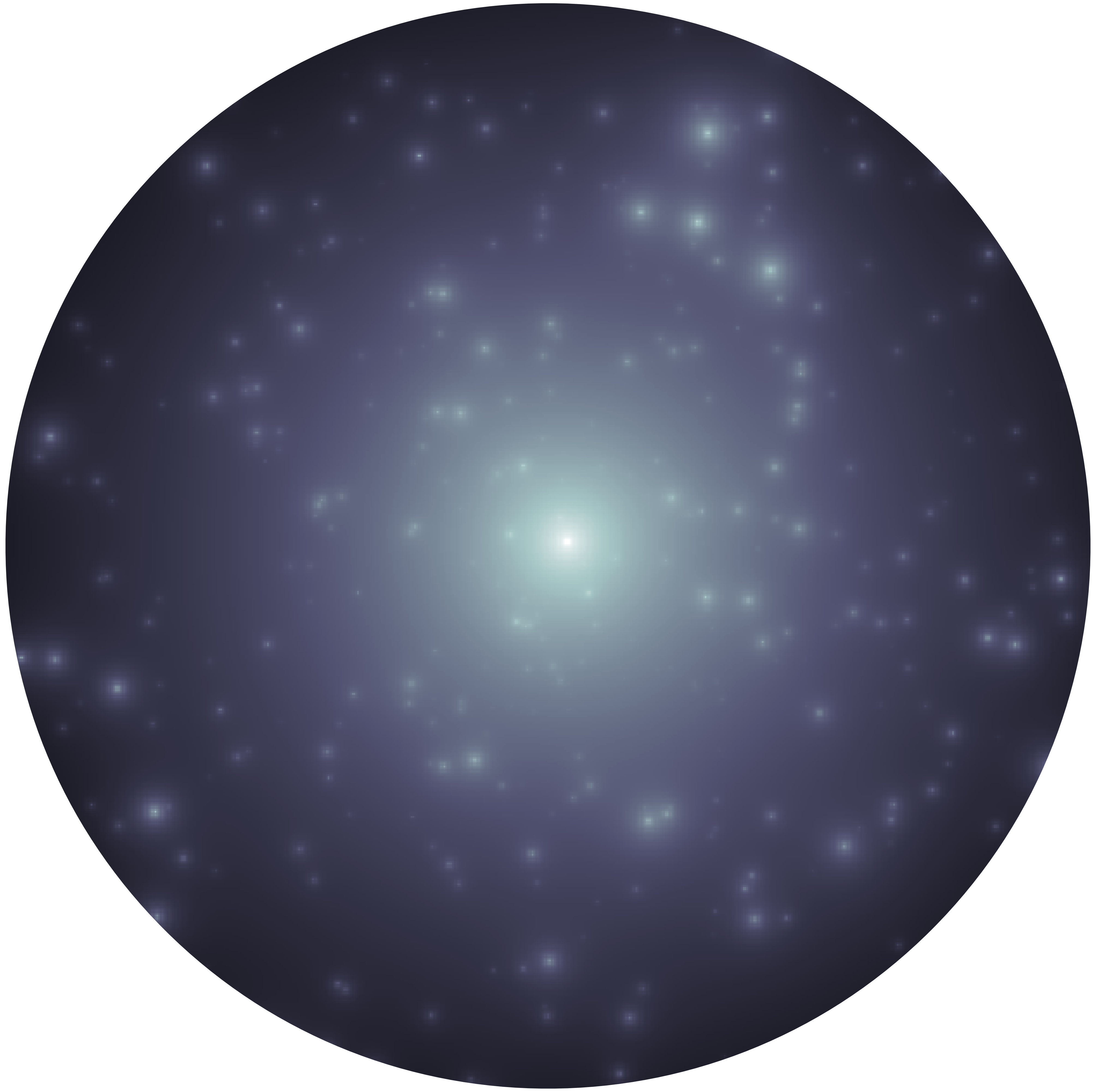
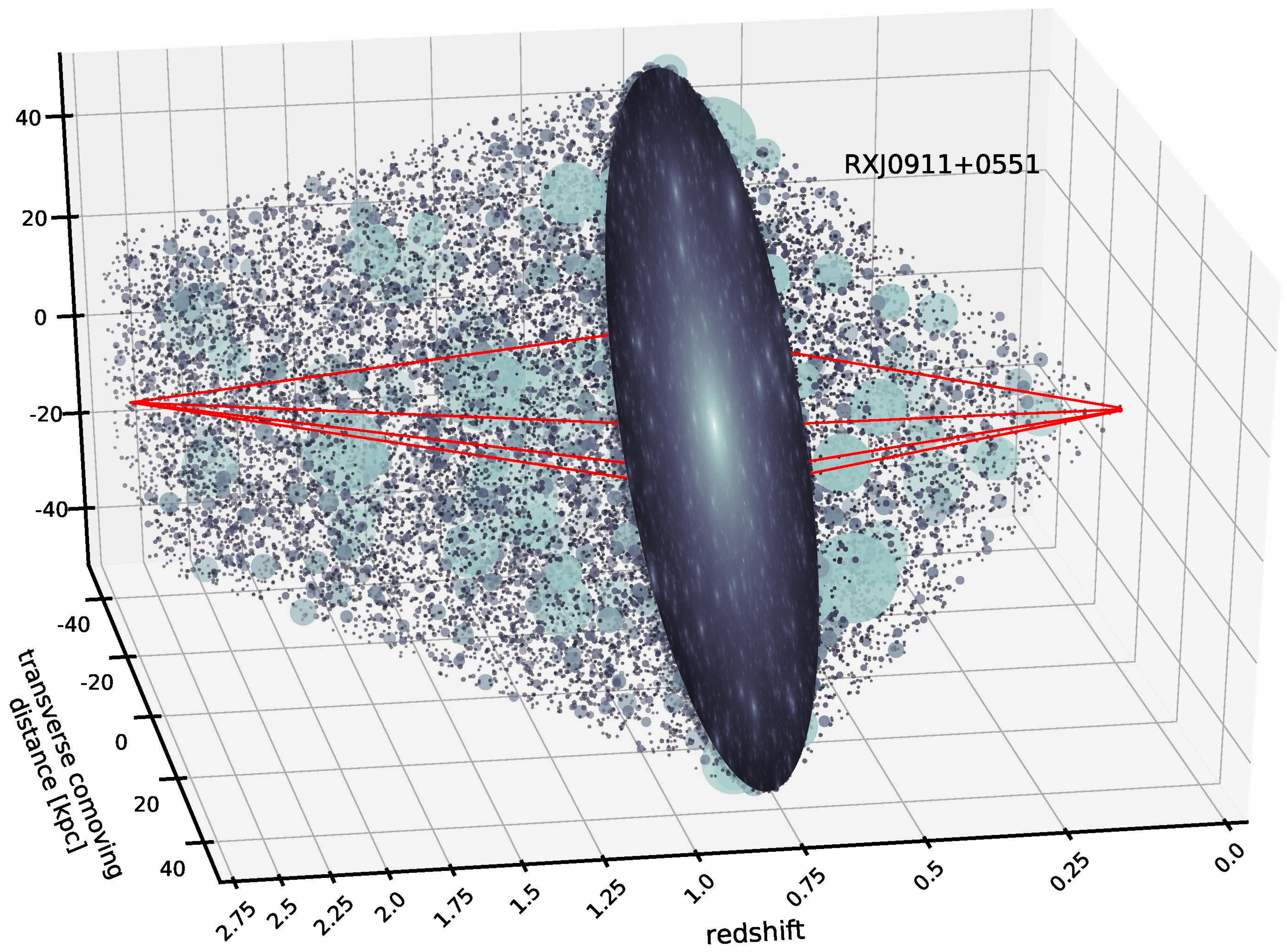


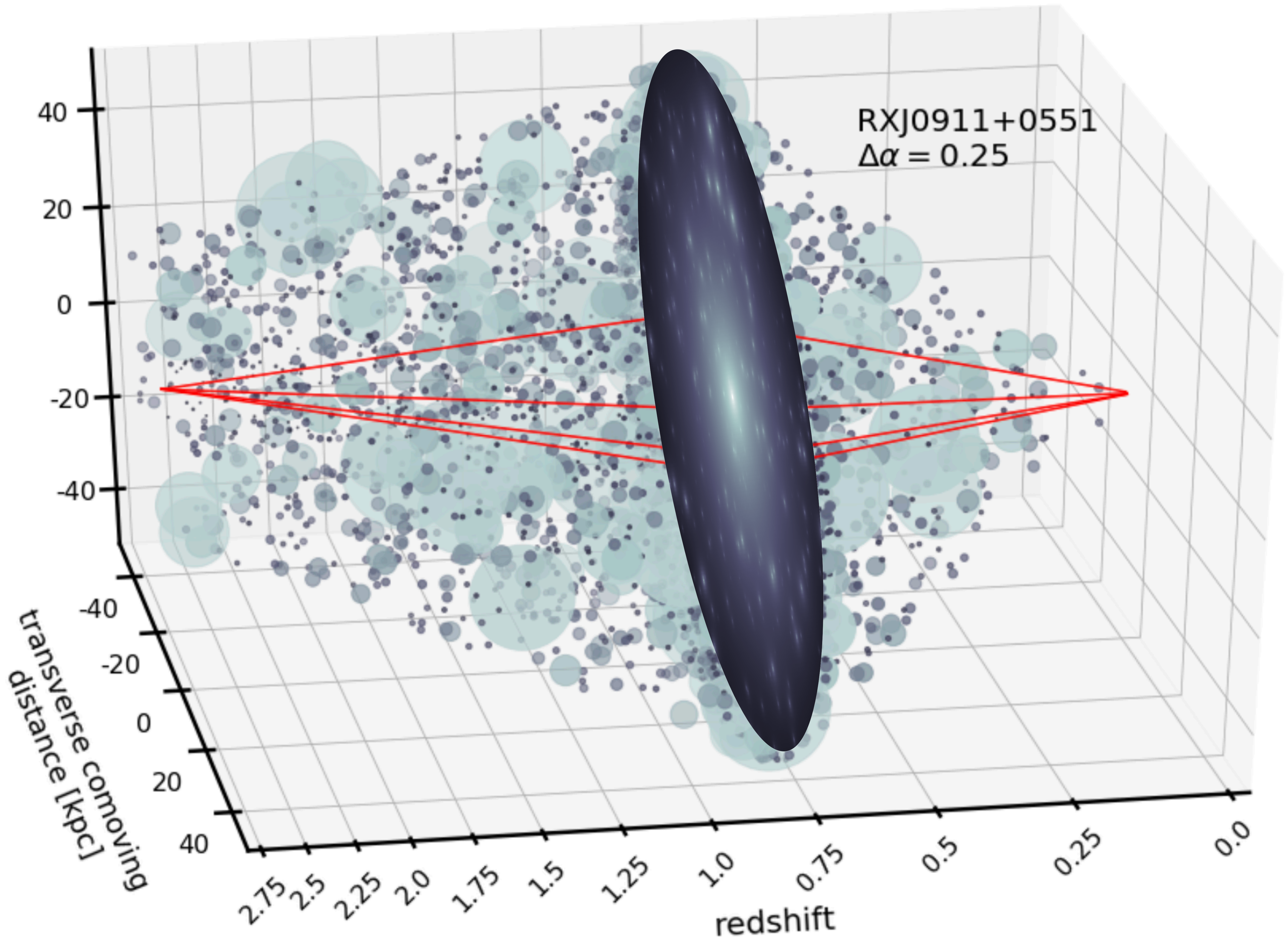
Simulation pipeline example: 2) forward model lenses with halos

$\sim 10^6$ simulations per lens for accurate statistics

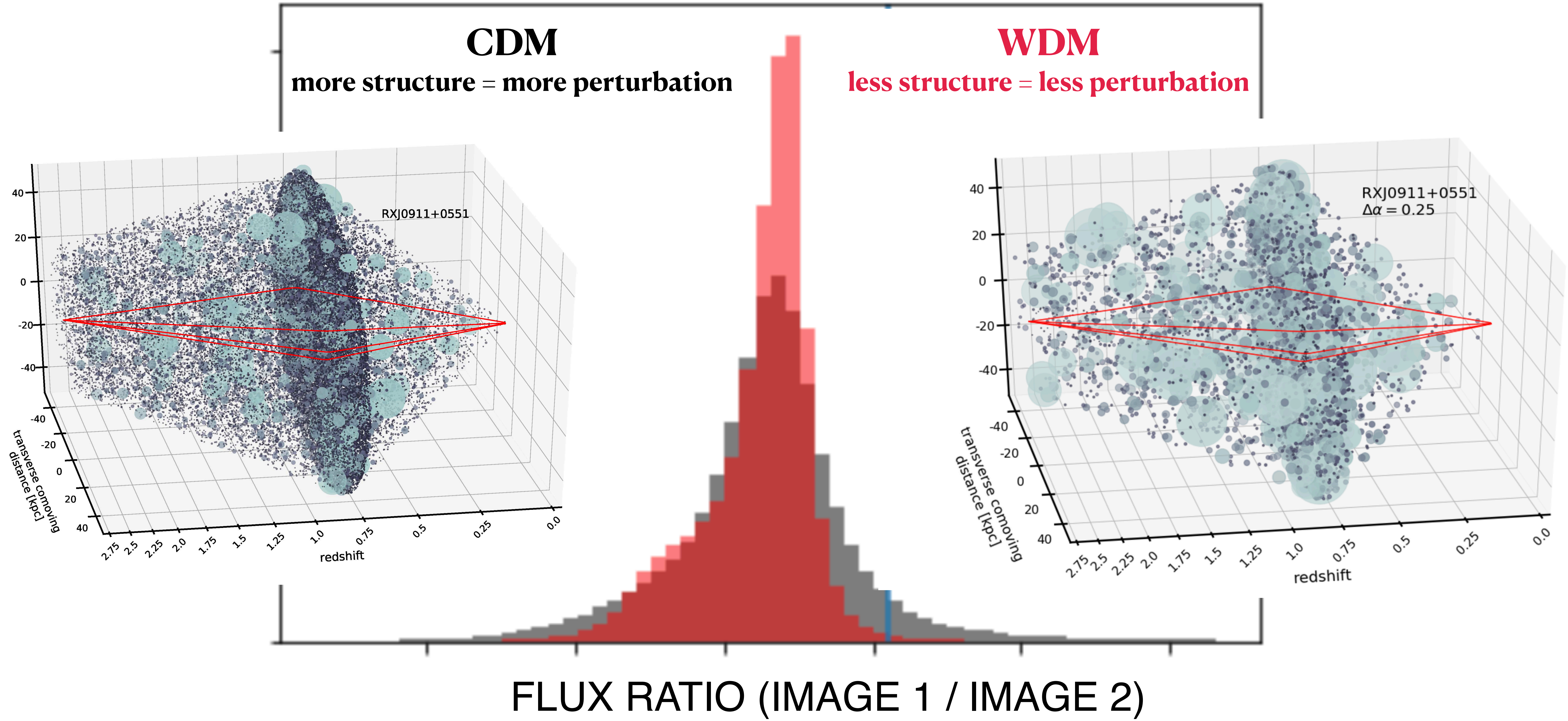
CDM



WDM



Simulation pipeline example:
3) compute flux ratios



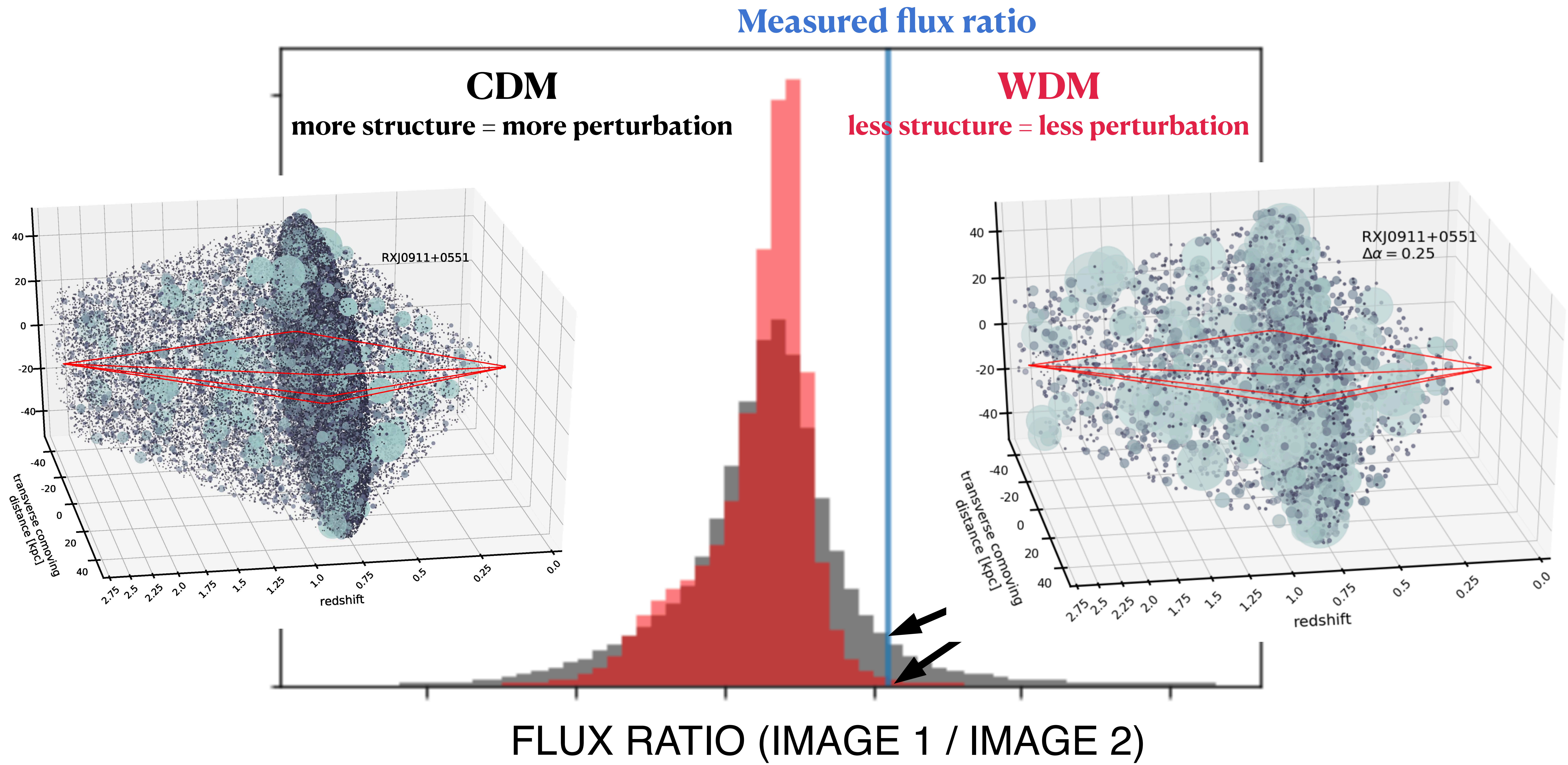
CDM

more structure = more perturbation

WDM

less structure = less perturbation

Simulation pipeline example: 4) derive likelihoods

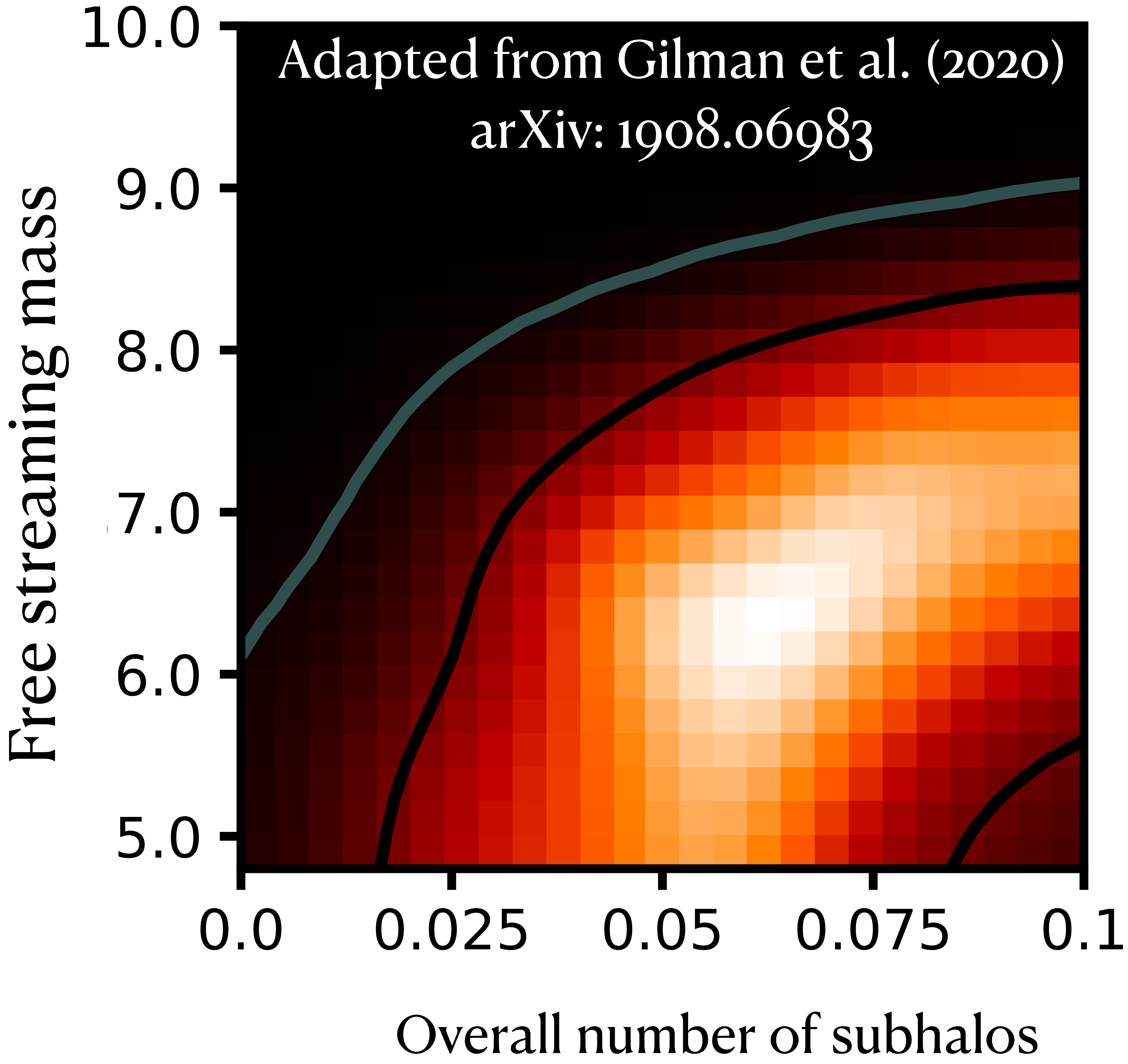


First application to WDM

Gilman, et al. (2020)

Used narrow-line flux ratios from Nierenberg et al. (2014, 2017, 2020)

$m_{\text{thermal}} > 5.2\text{keV}$

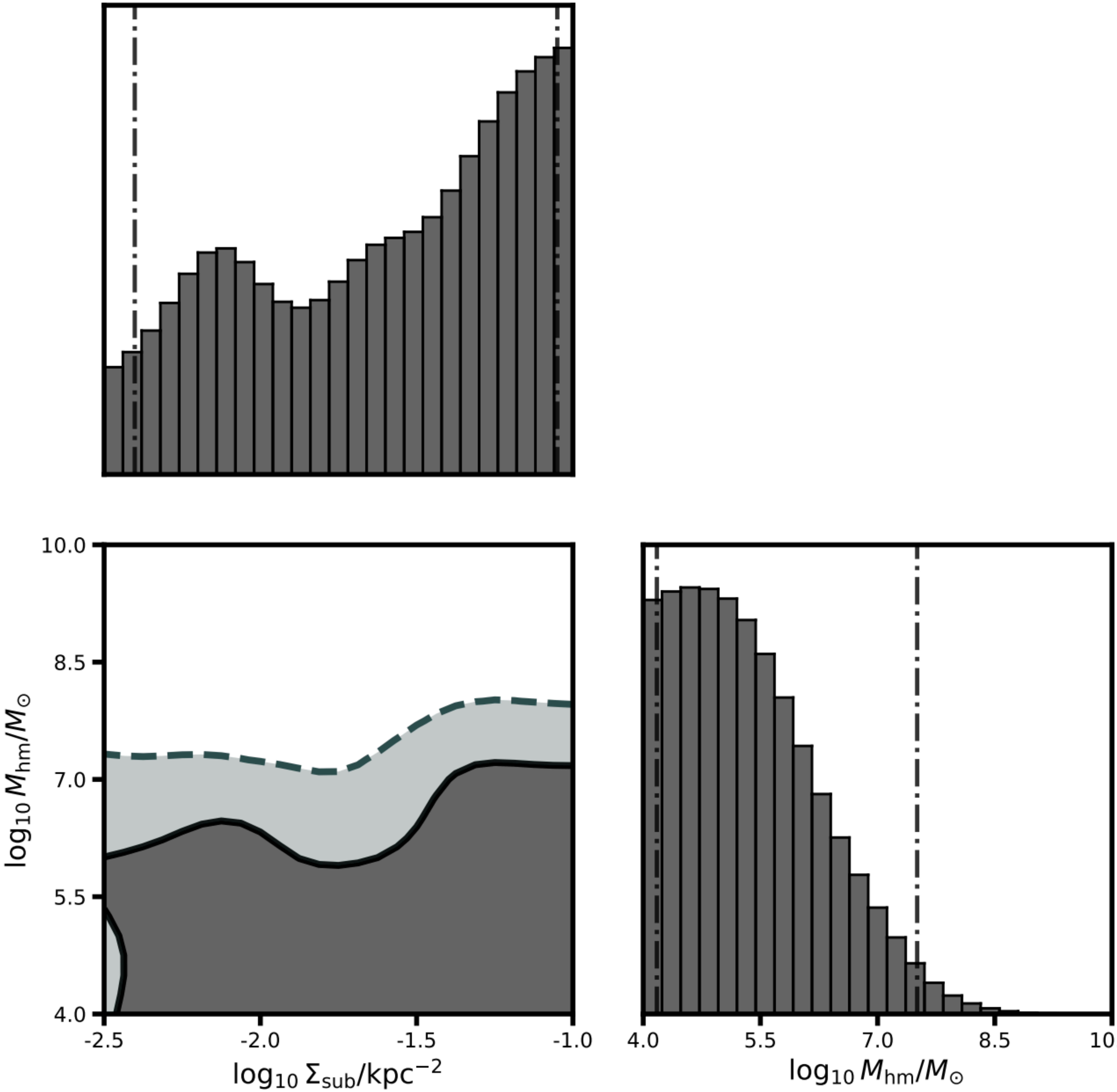


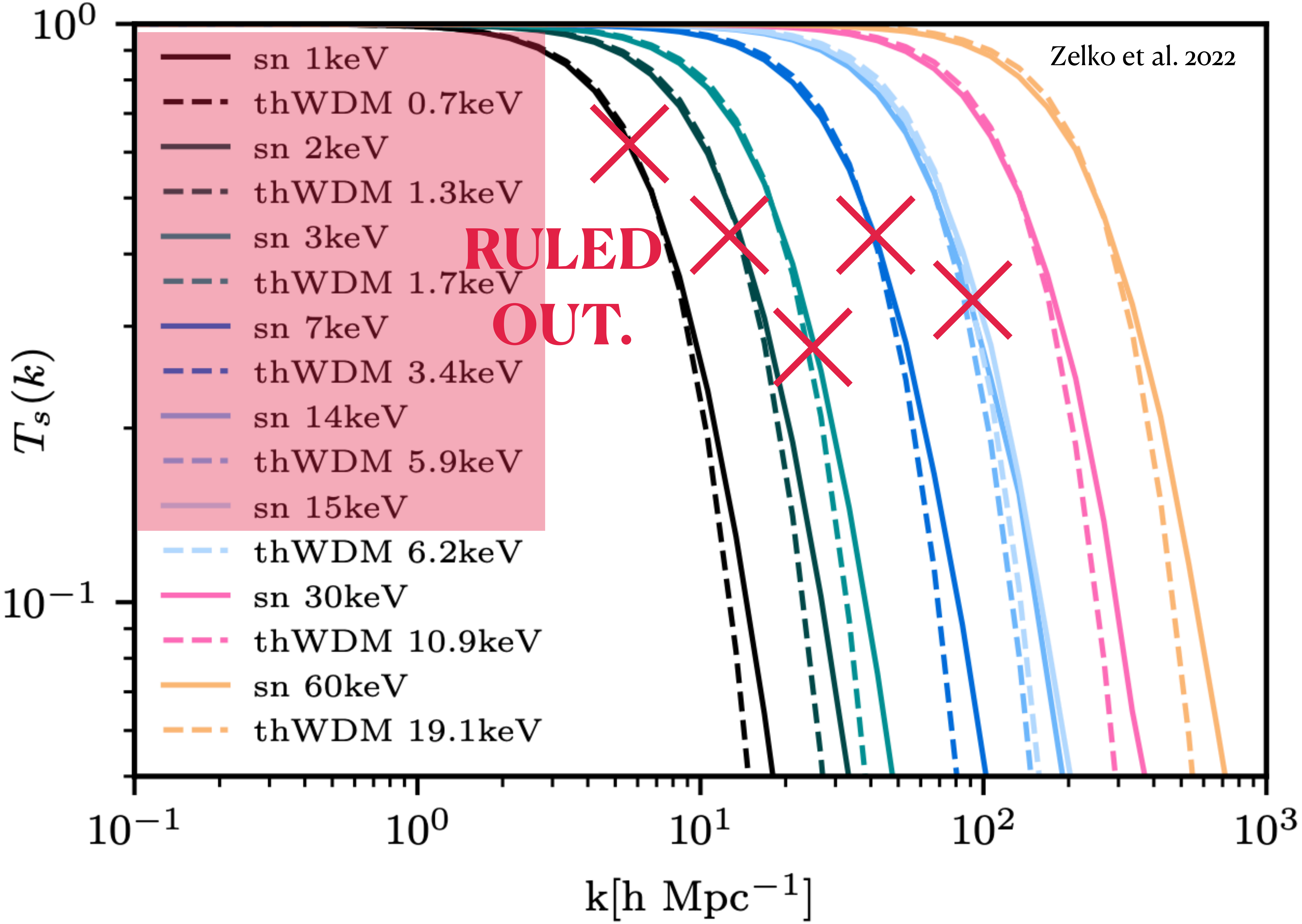
First constraints from JWST lensed quasar DM survey

see Keeley, Nierenberg, Gilman, et al. (2024)
arXiv: 2405.01620

Improve on previous constraints by Gilman et al. (2020)

- 10:1 posterior odds at $10^{7.6} M_{\odot}$
~ 6 keV thermal relics ruled out





Zelko et al. 2022
RULED OUT.
$T_s(k)$
10^0
10^{-1}
10^{-1}
10^0
10^1
10^2
10^3
k[h Mpc^{-1}]
sn 1keV
thWDM 0.7keV
sn 2keV
thWDM 1.3keV
sn 3keV
thWDM 1.7keV
sn 7keV
thWDM 3.4keV
sn 14keV
thWDM 5.9keV
sn 15keV
thWDM 6.2keV
sn 30keV
thWDM 10.9keV
sn 60keV
thWDM 19.1keV

We can test **any** theory that alters the internal and/or abundance of halos

Warm dark matter: halos less abundant and less concentrated
Gilman et al. (2019, 2020) (arXiv: 1901.11031, 1908.06983)
Keeley, Nierenberg, Gilman et al. (2024) (arXiv:)

Fuzzy dark matter: halos less abundant, quantum wave interference effects in halo density profiles
Laroche, Gilman et al. (2022) (arXiv: 2206.11269)

Self-interacting dark matter: core formation and collapse change the lensing efficiency of halos
Gilman et al. (2021, 2022) (arXiv: 2105.05259, 2207.13111)

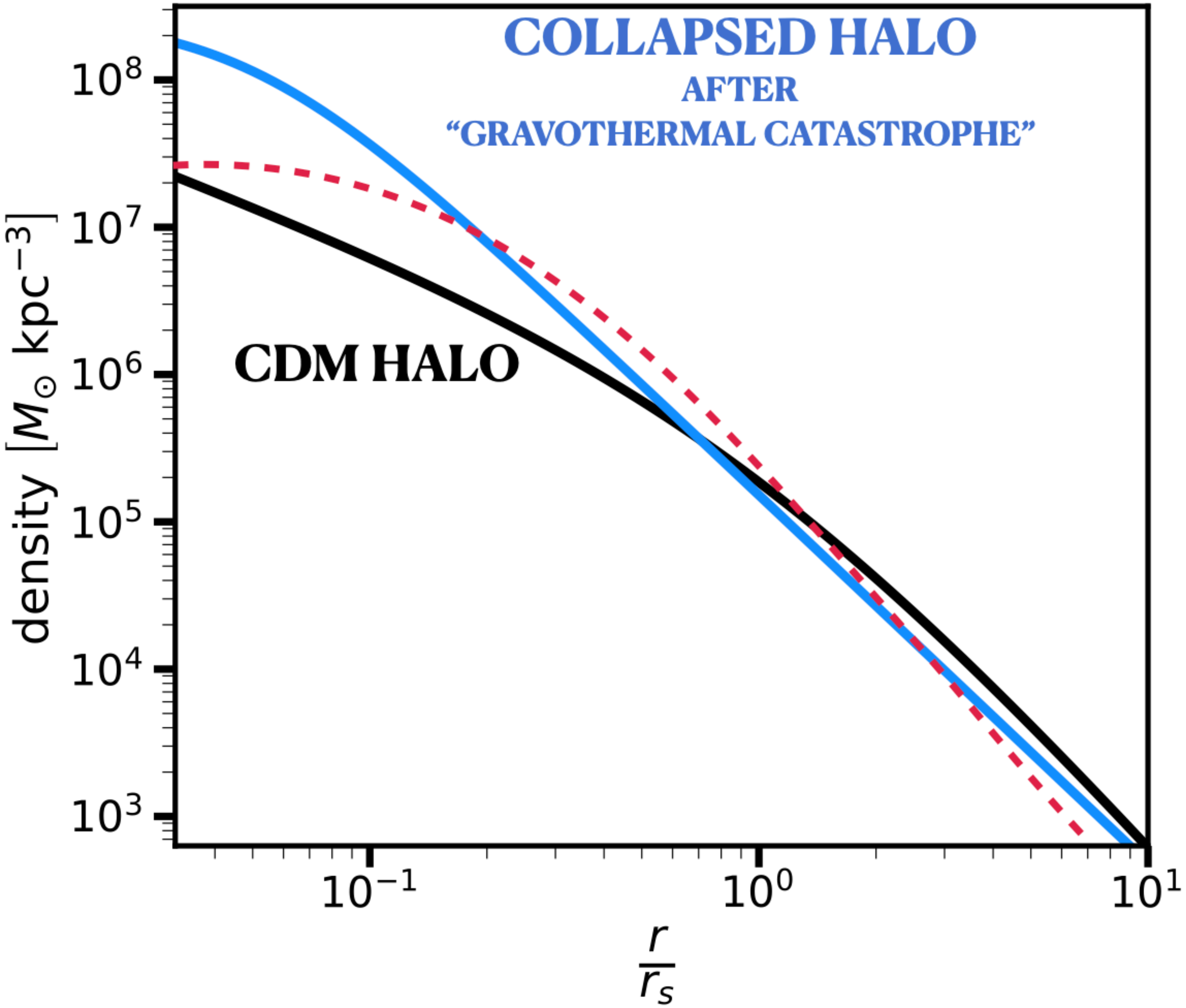
Inflation/early Universe: enhanced/suppressed small-scale power impacts
halo abundance/concentration Gilman et al. (2022) (arXiv: 2112.03293)

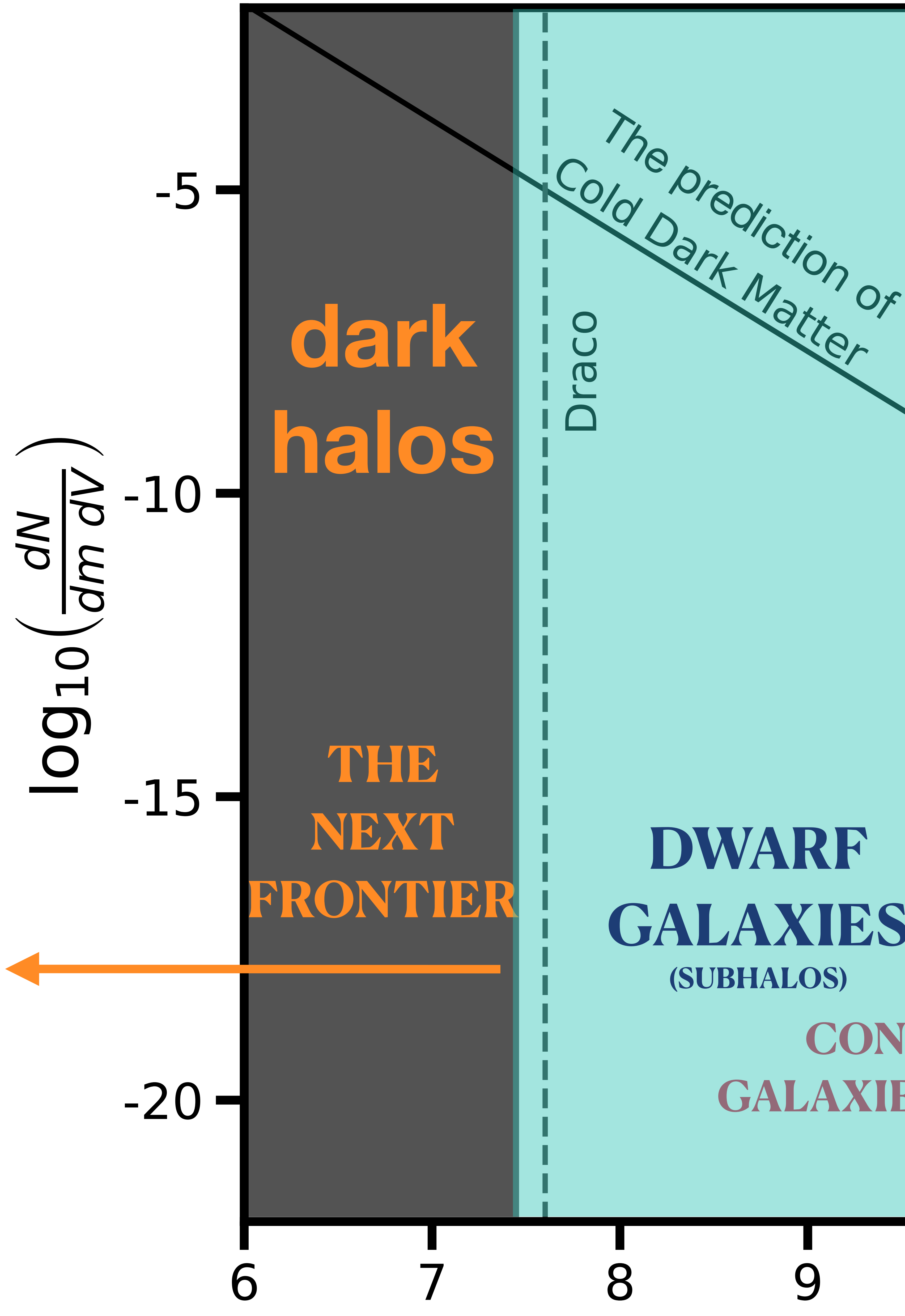
Massive free-floating primordial black holes: the most efficient lenses
Dike, Gilman et al. (2022) (arXiv: 2210.09493)

Mixed warm/cold dark matter: aka lukewarm dark matter
Keeley, Nierenberg, Gilman et al. (2023) (arXiv: 2301.07265)

Self-interacting dark matter (SIDM):

halos undergo core collapse and become extremely dense





Self-interacting dark matter (SIDM)

-> dark matter not collisionless; exchanges energy, momentum with itself

Self-interacting dark matter (SIDM)

-> preserves large-scale structure

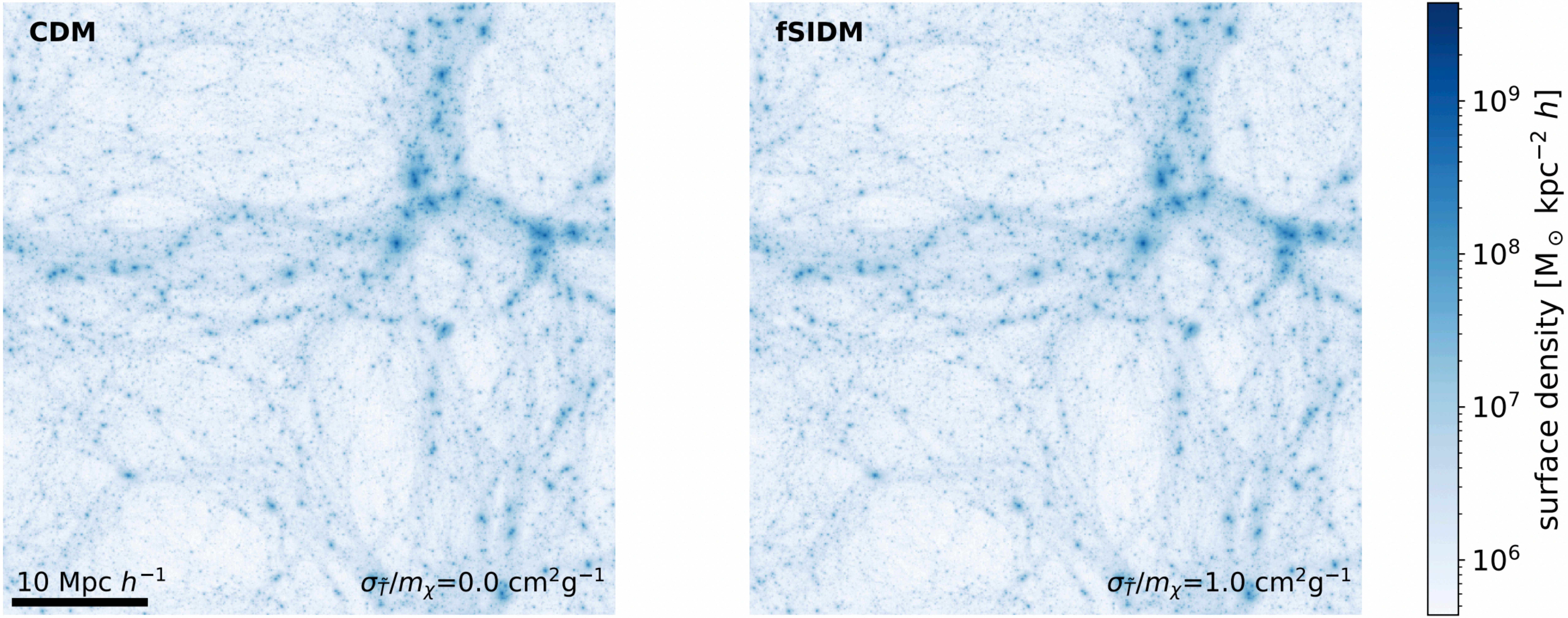


figure from Fischer et al. (2022)

Self-interacting dark matter (SIDM)

-> collisionless (CDM-like) at high speeds $\left(v \sim 1{,}000 \text{ km s}^{-1}\right)$
in cluster-mass halos

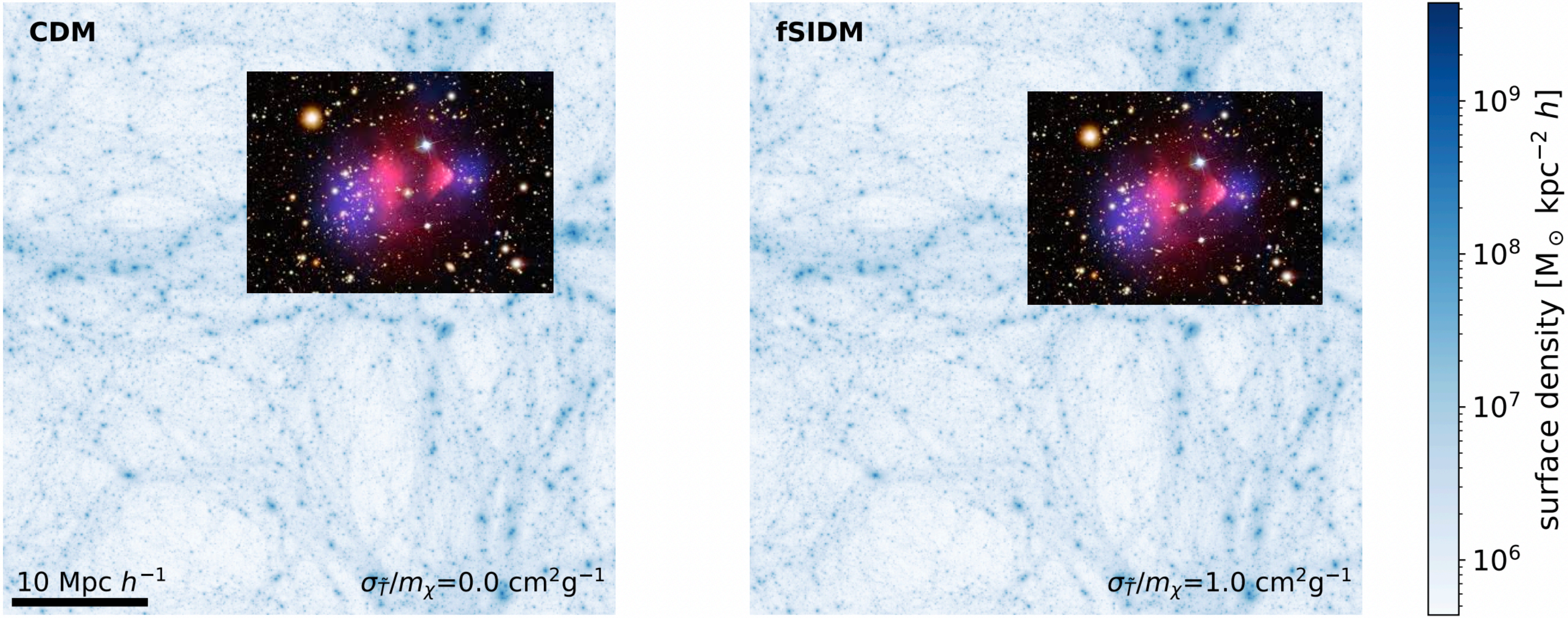


figure from Fischer et al. (2022)

Self-interacting dark matter (SIDM)

-> "large" cross sections $\left(\sigma > 10\ \mathrm{cm}^2\ \mathrm{g}^{-1}\right)$ at low speeds $\left(v \sim 30\ \mathrm{km\ s}^{-1}\right)$
inside low-mass halos

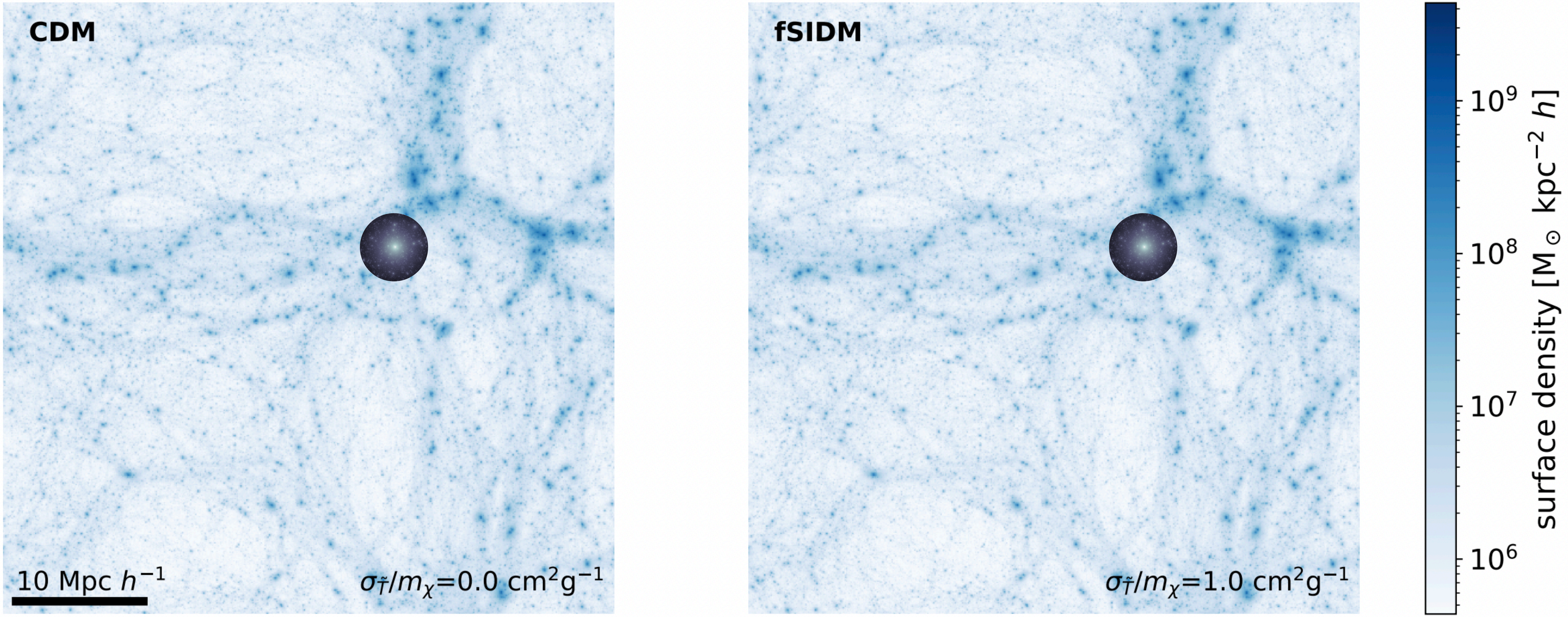


figure from Fischer et al. (2022)

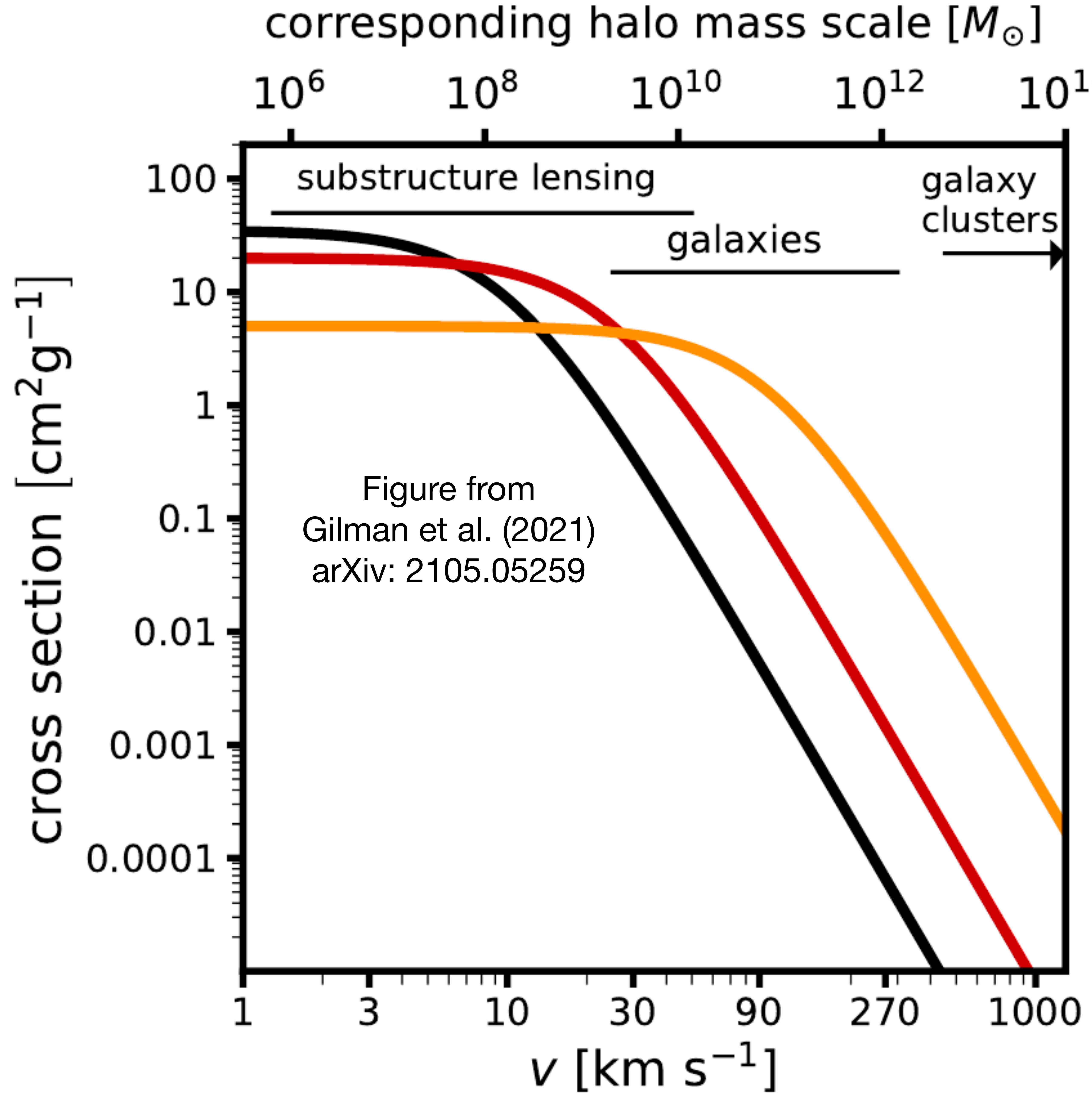
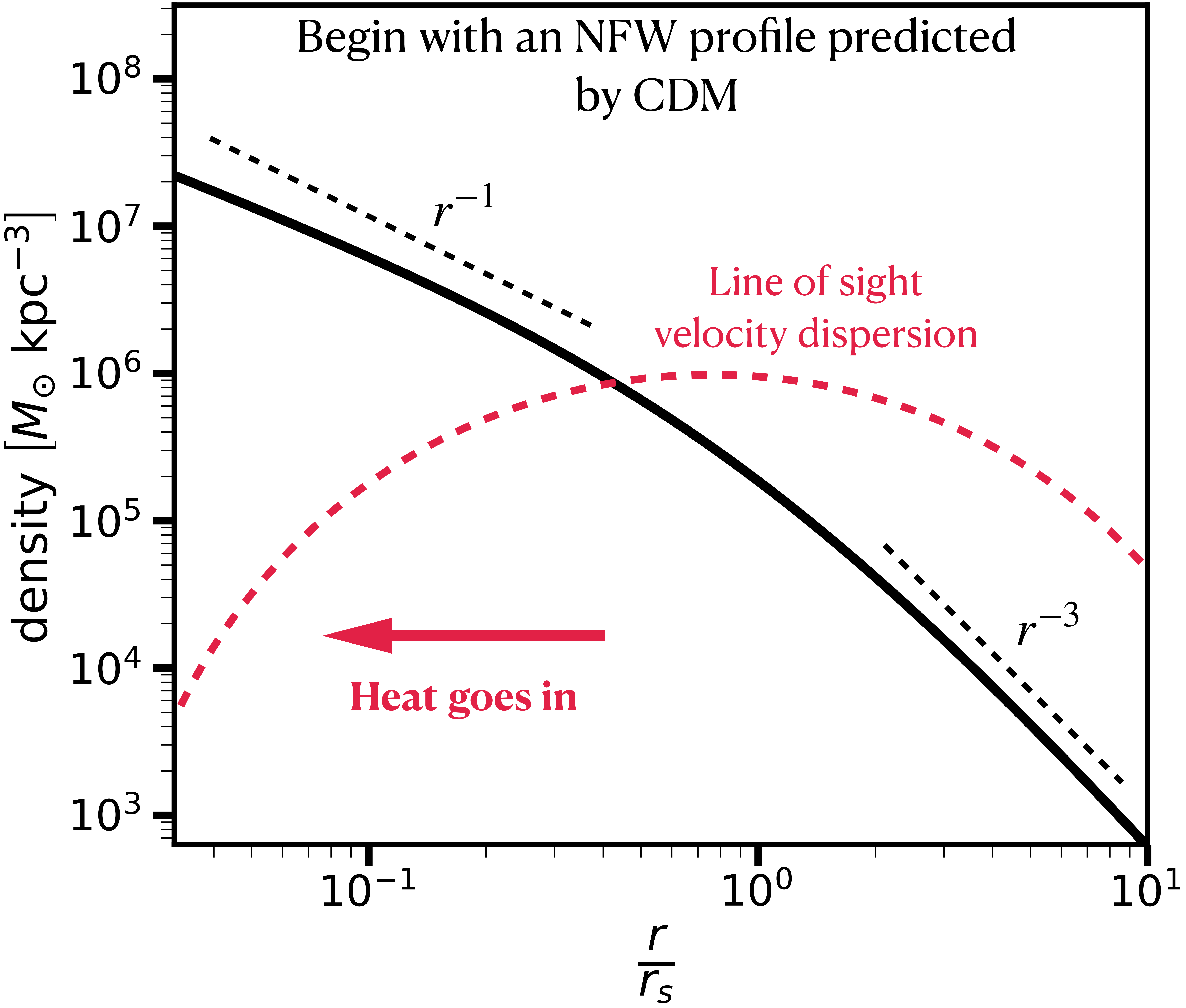


Figure from
Gilman et al. (2021)
arXiv: 2105.05259

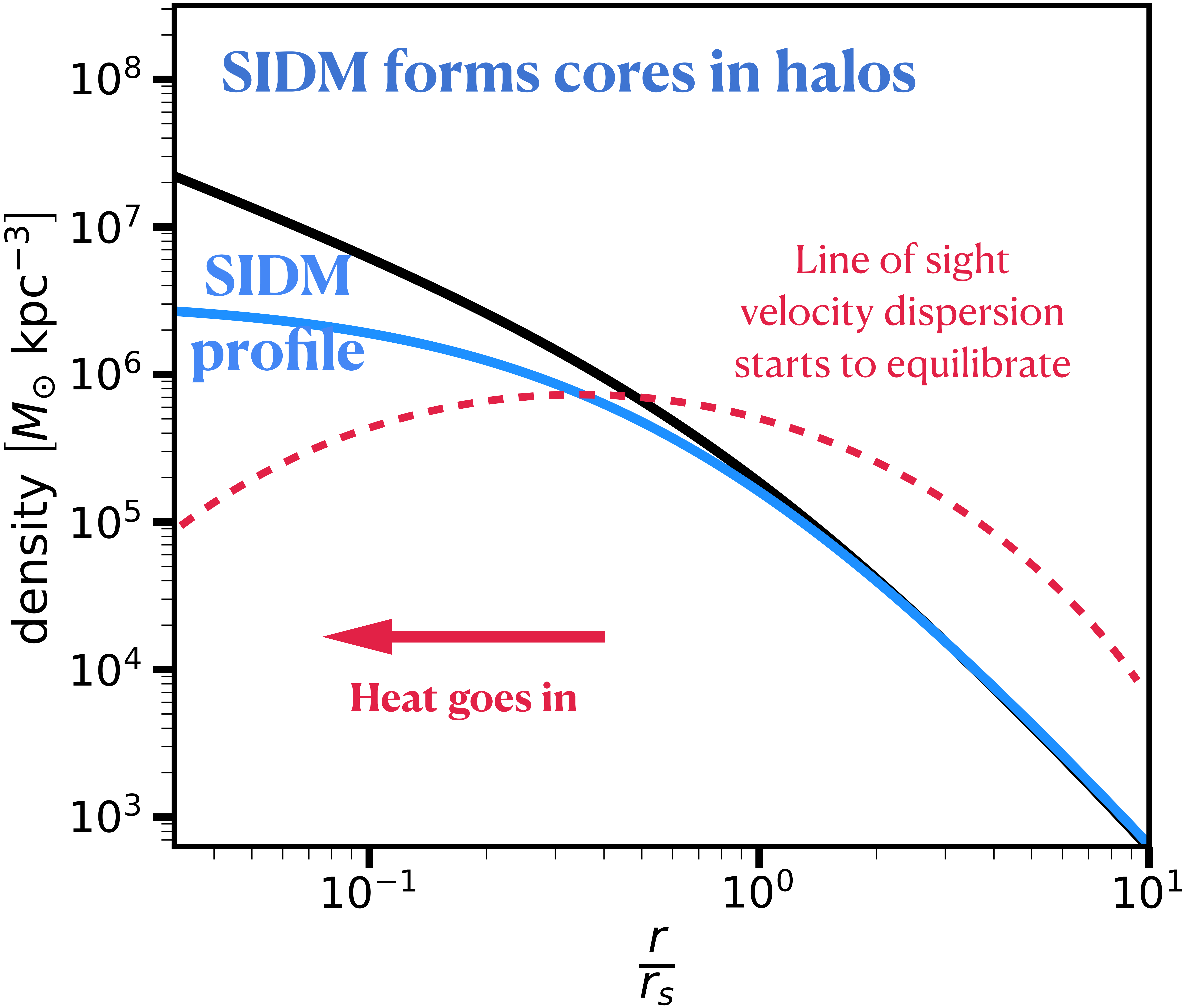
Velocity dependence necessary to evade constraints from galaxy clusters

Strongly-enhanced cross section at low speeds (in low-mass halos)

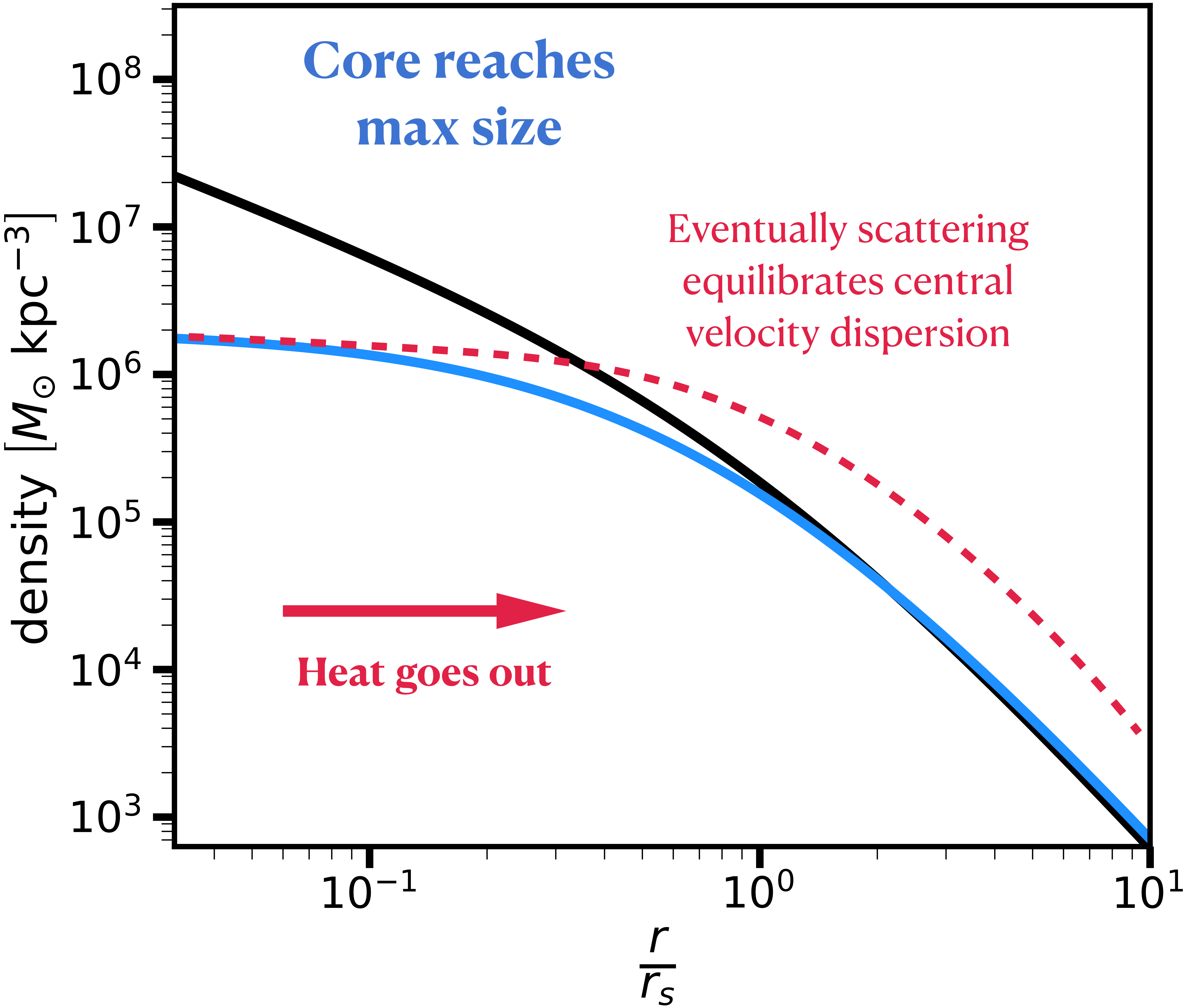
Effects of SIDM on halo density profiles



Effects of SIDM on halo density profiles



Effects of SIDM on halo density profiles

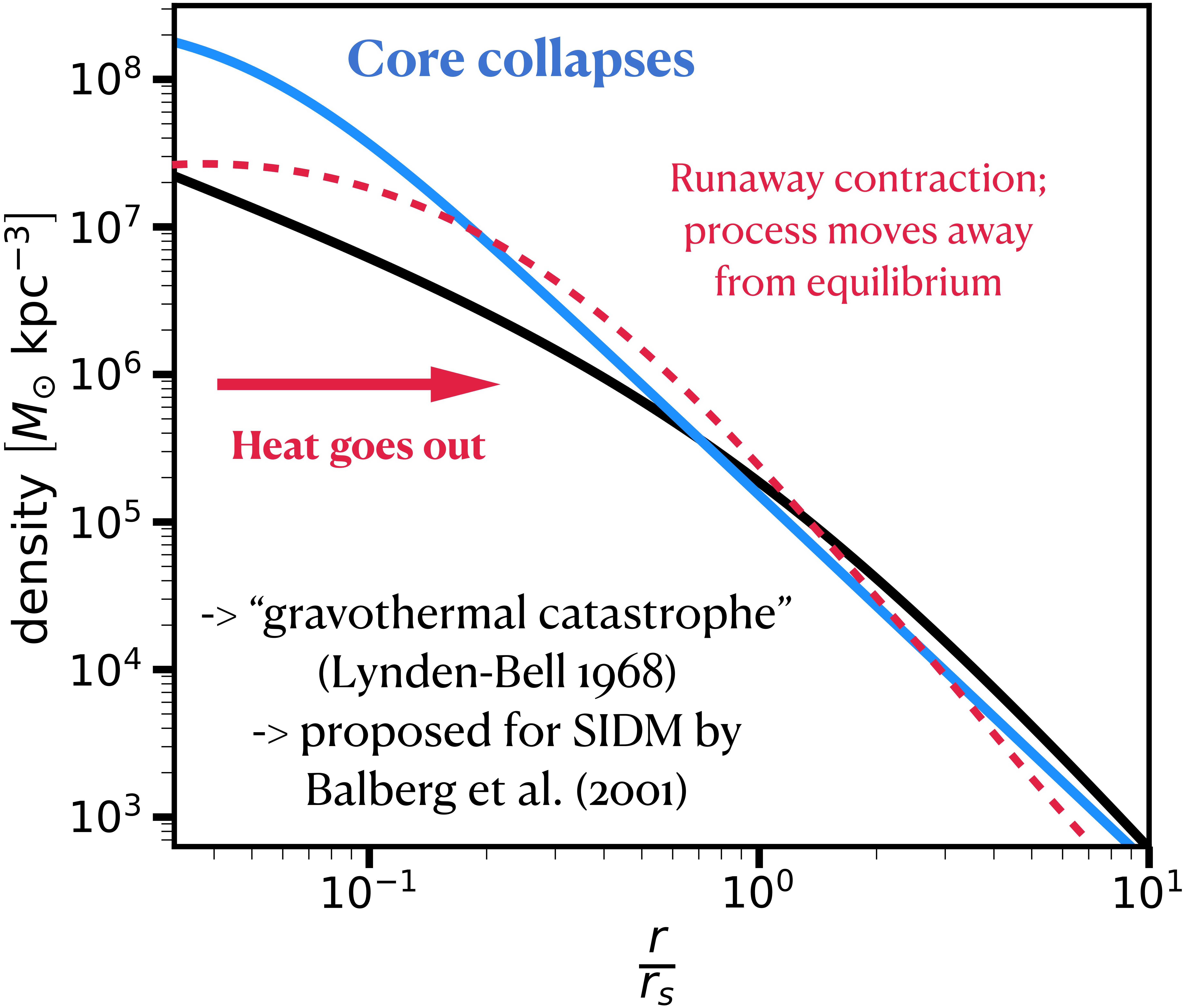


Core reaches max size

Eventually scattering equilibrates central velocity dispersion

Heat goes out

Effects of SIDM on halo density profiles



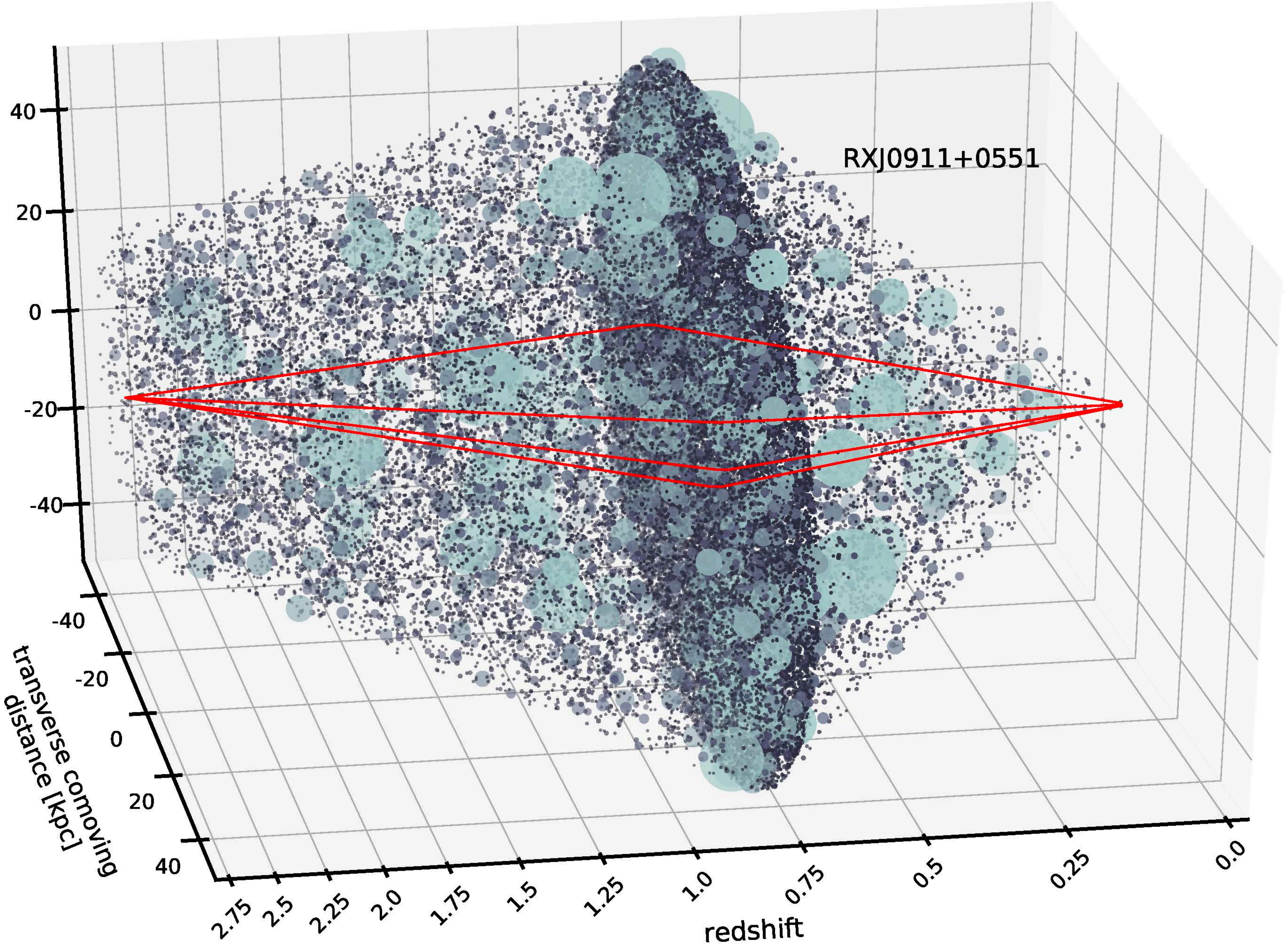
Core collapses

Runaway contraction;
process moves away
from equilibrium

Heat goes out

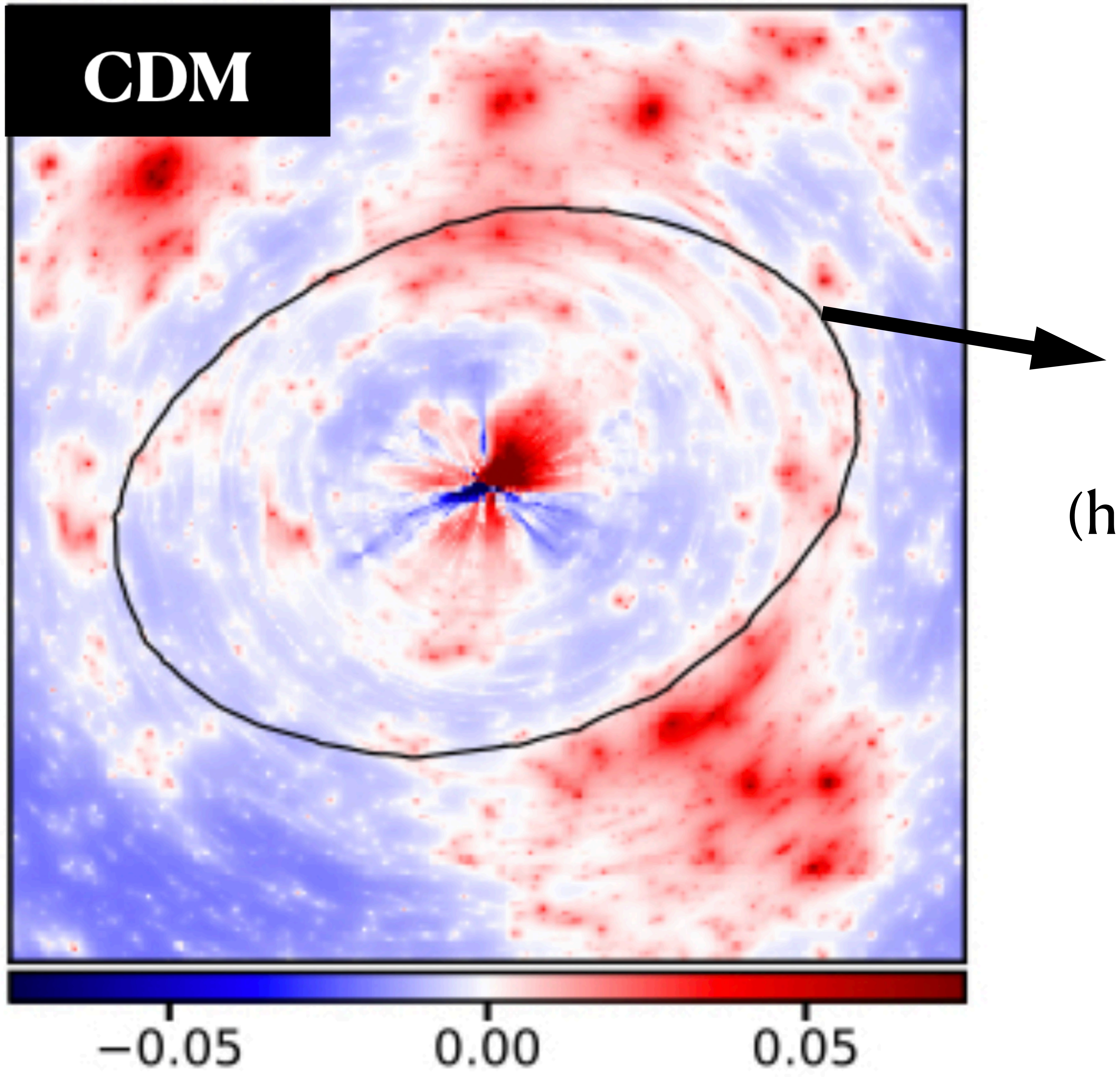
-> "gravothermal catastrophe"
(Lynden-Bell 1968)
-> proposed for SIDM by
Balberg et al. (2001)

Core-collapsed halos are extremely efficient lenses



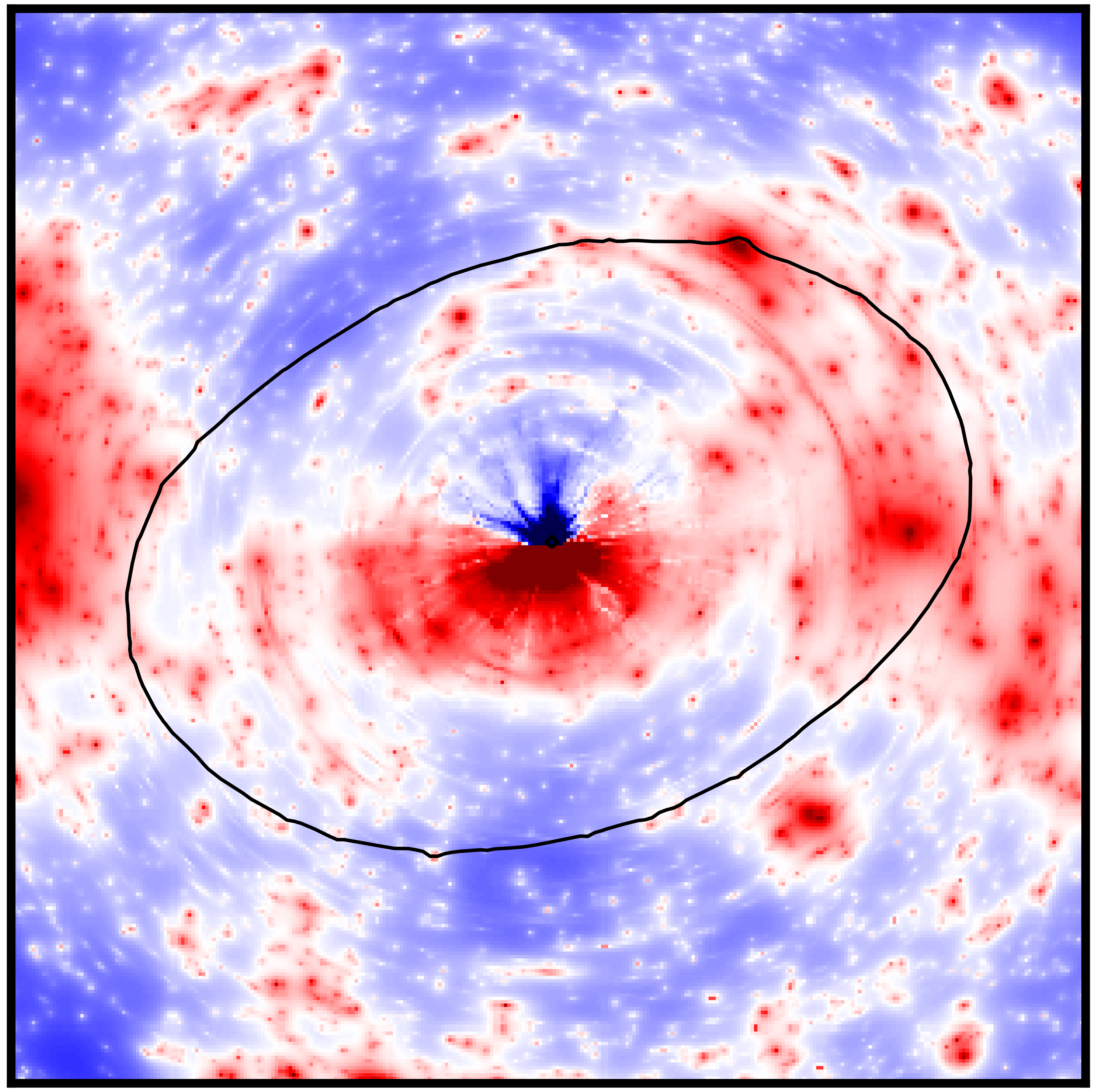
Core-collapsed halos are extremely efficient lenses

Now we are looking down the line of sight

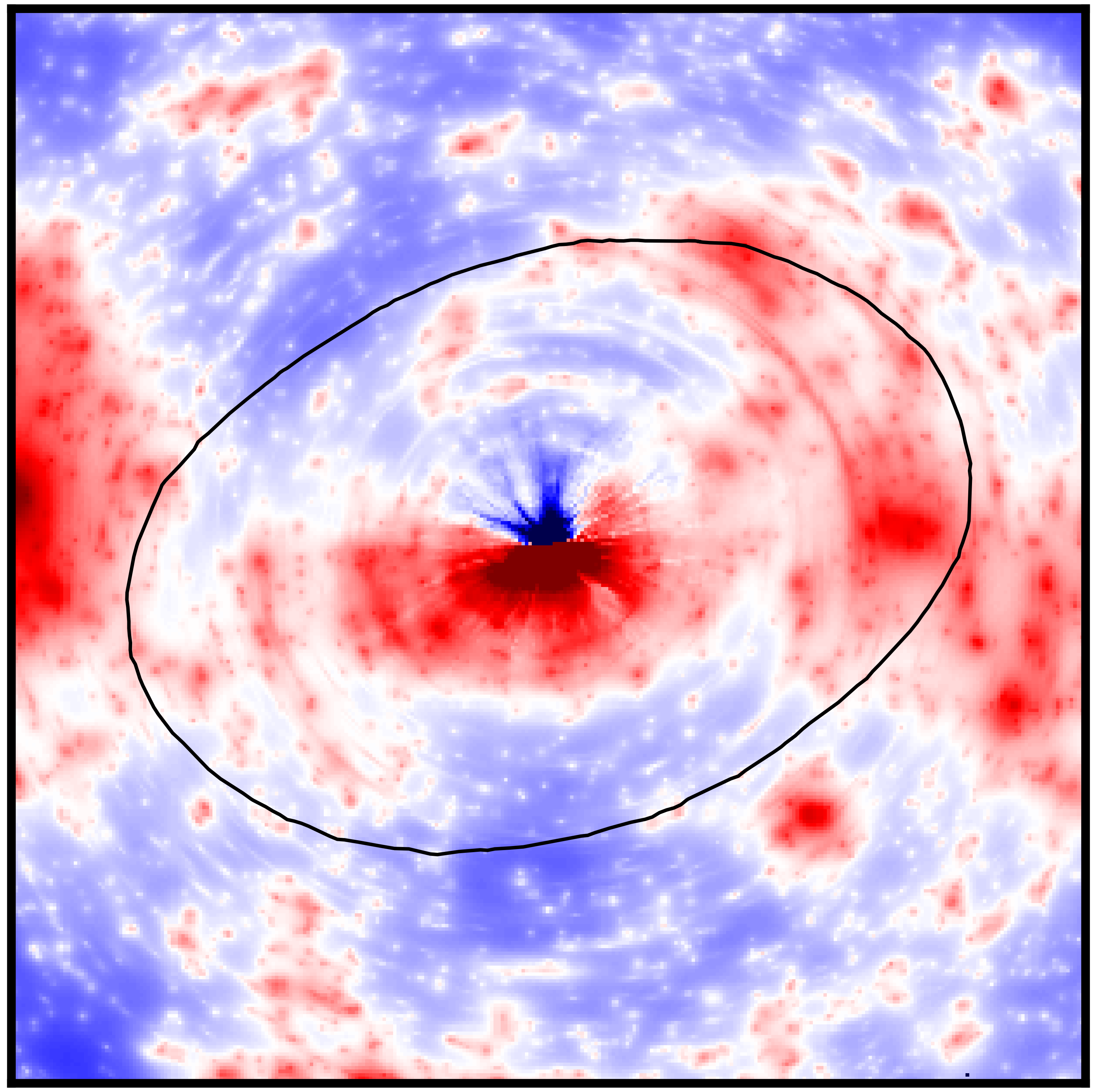


Critical curve (high magnifications)

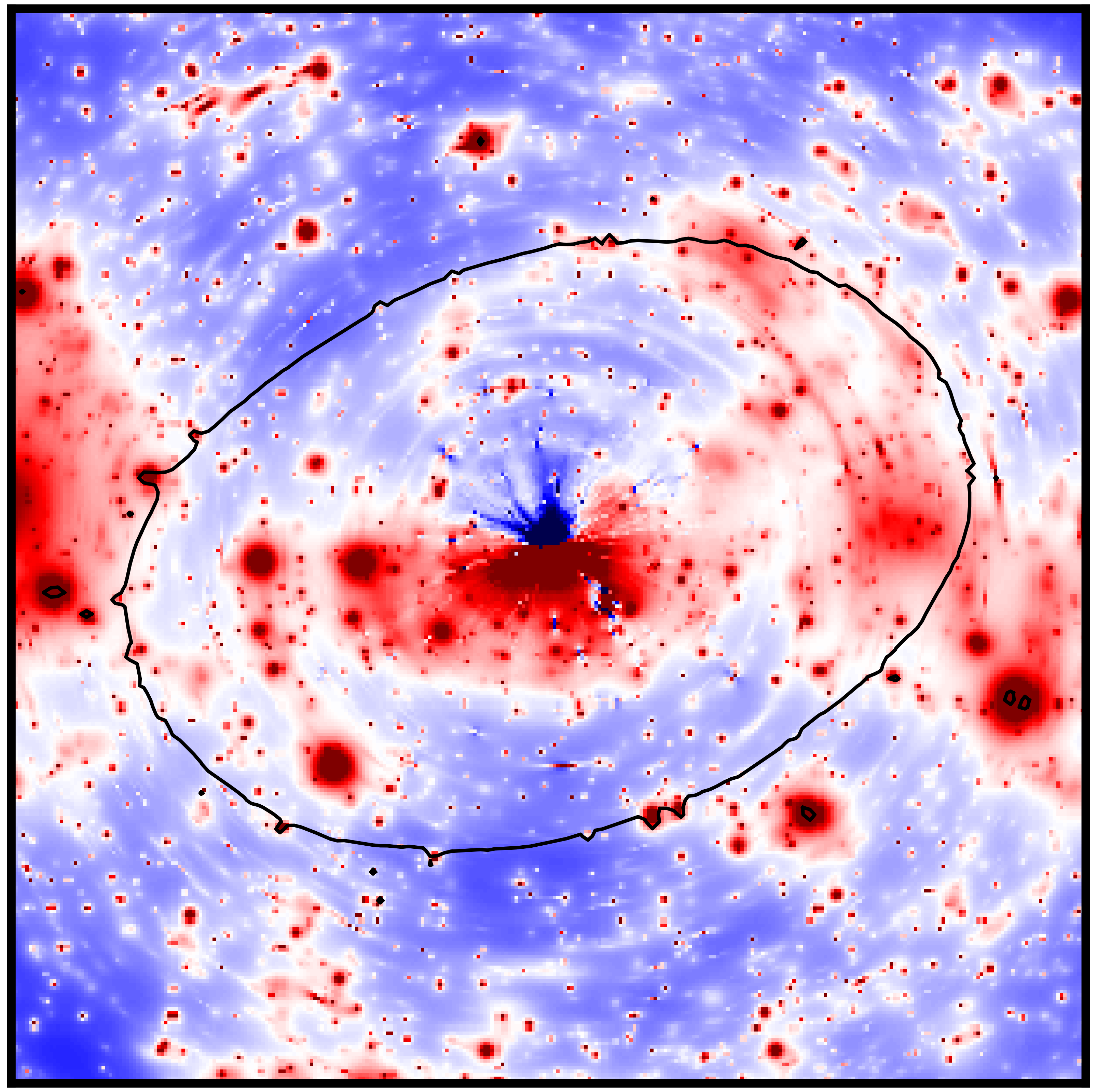
Dark matter density relative to average



CDM



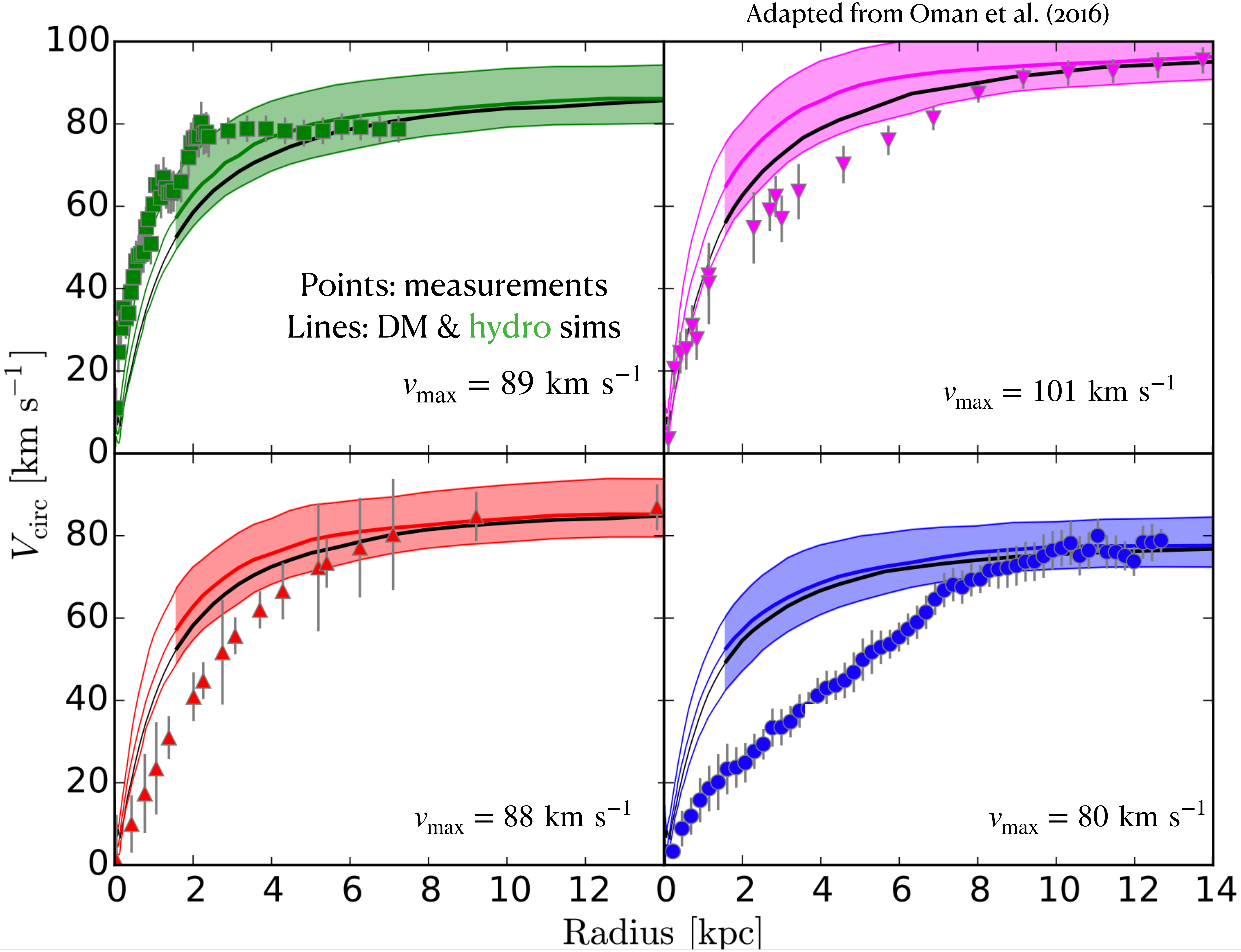
SIDM with cores only



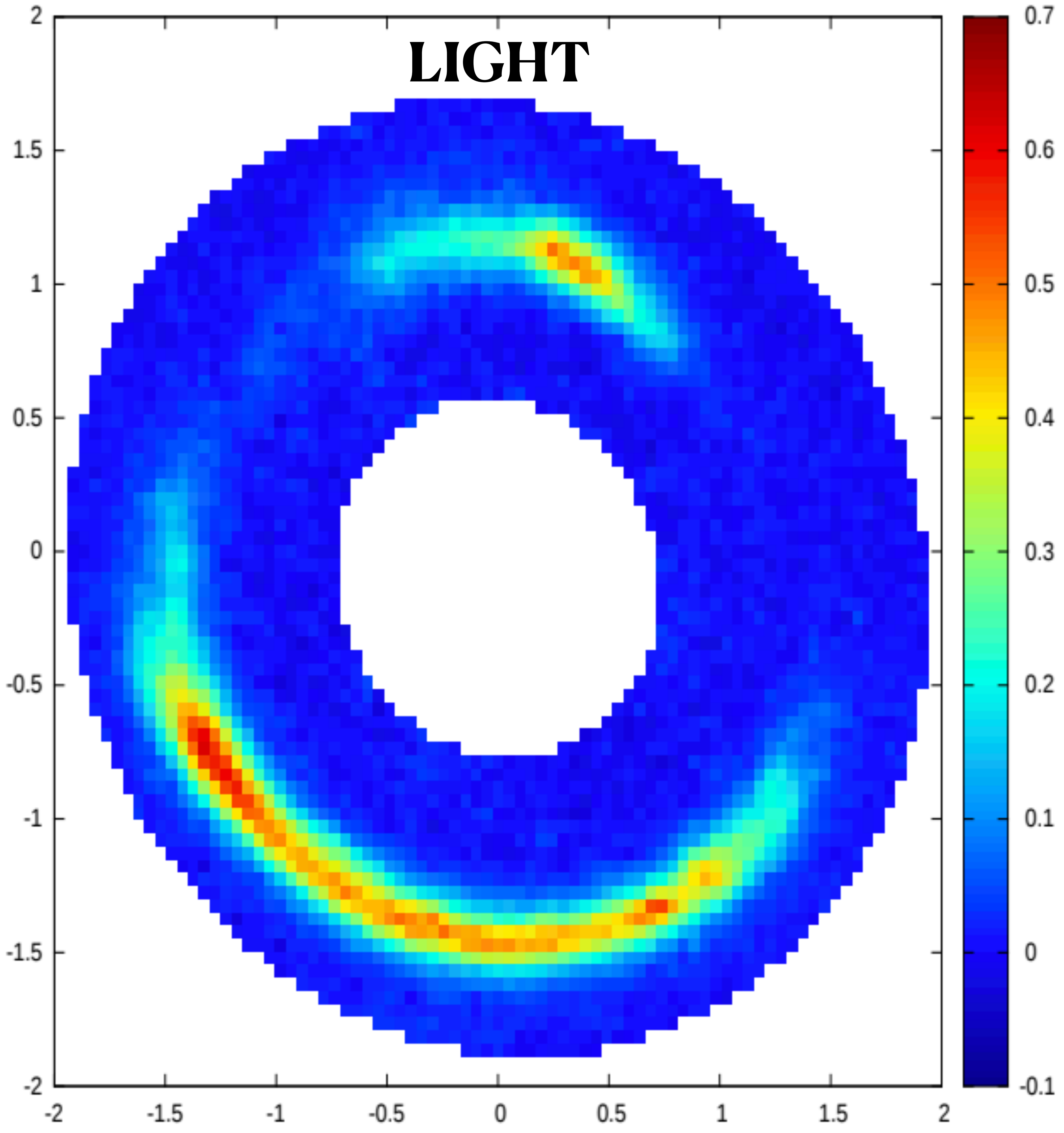
SIDM cores+core collapse

Self-interacting dark matter (SIDM)

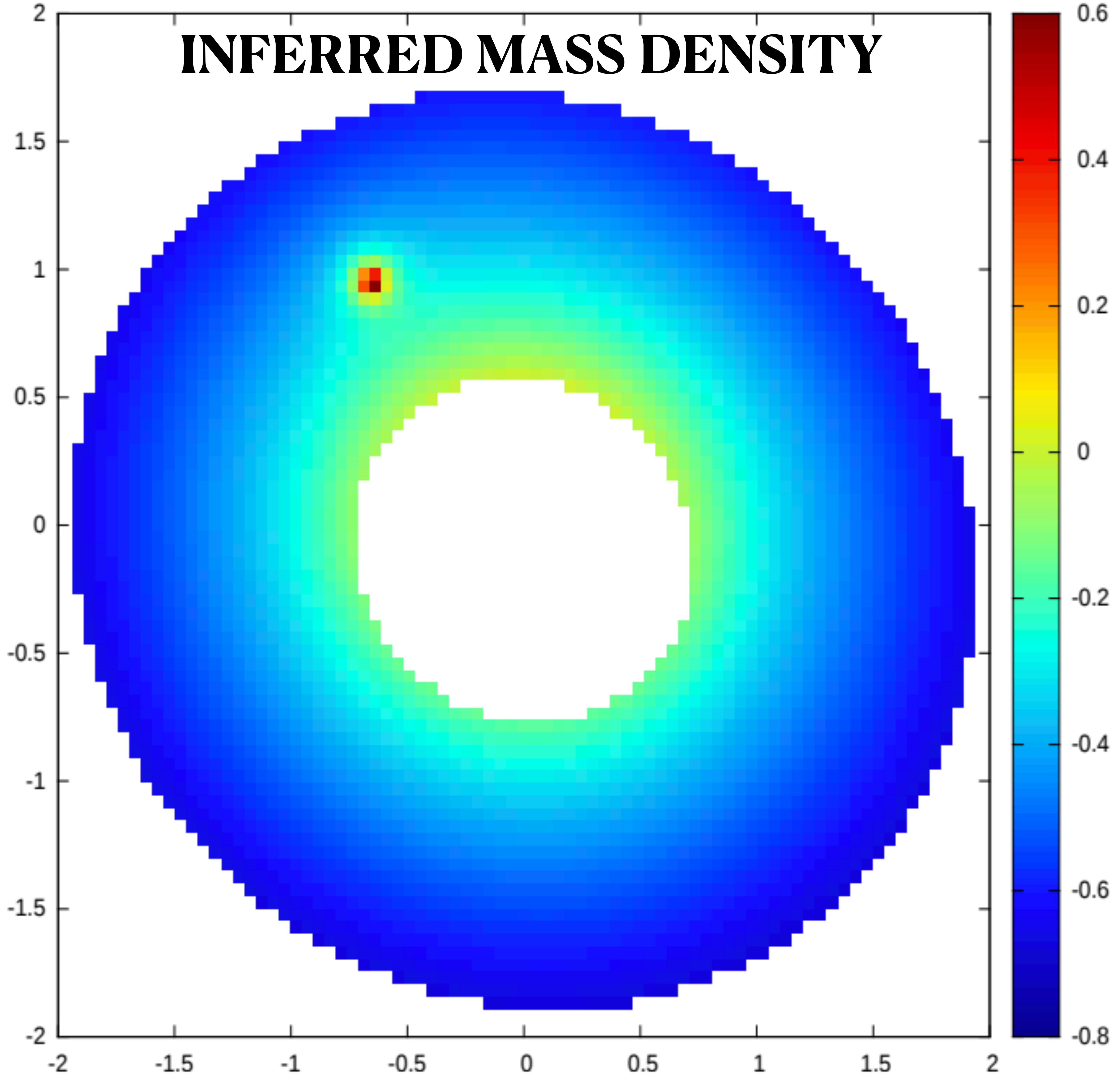
Core formation+collapse match diversity of observed rotation curves?



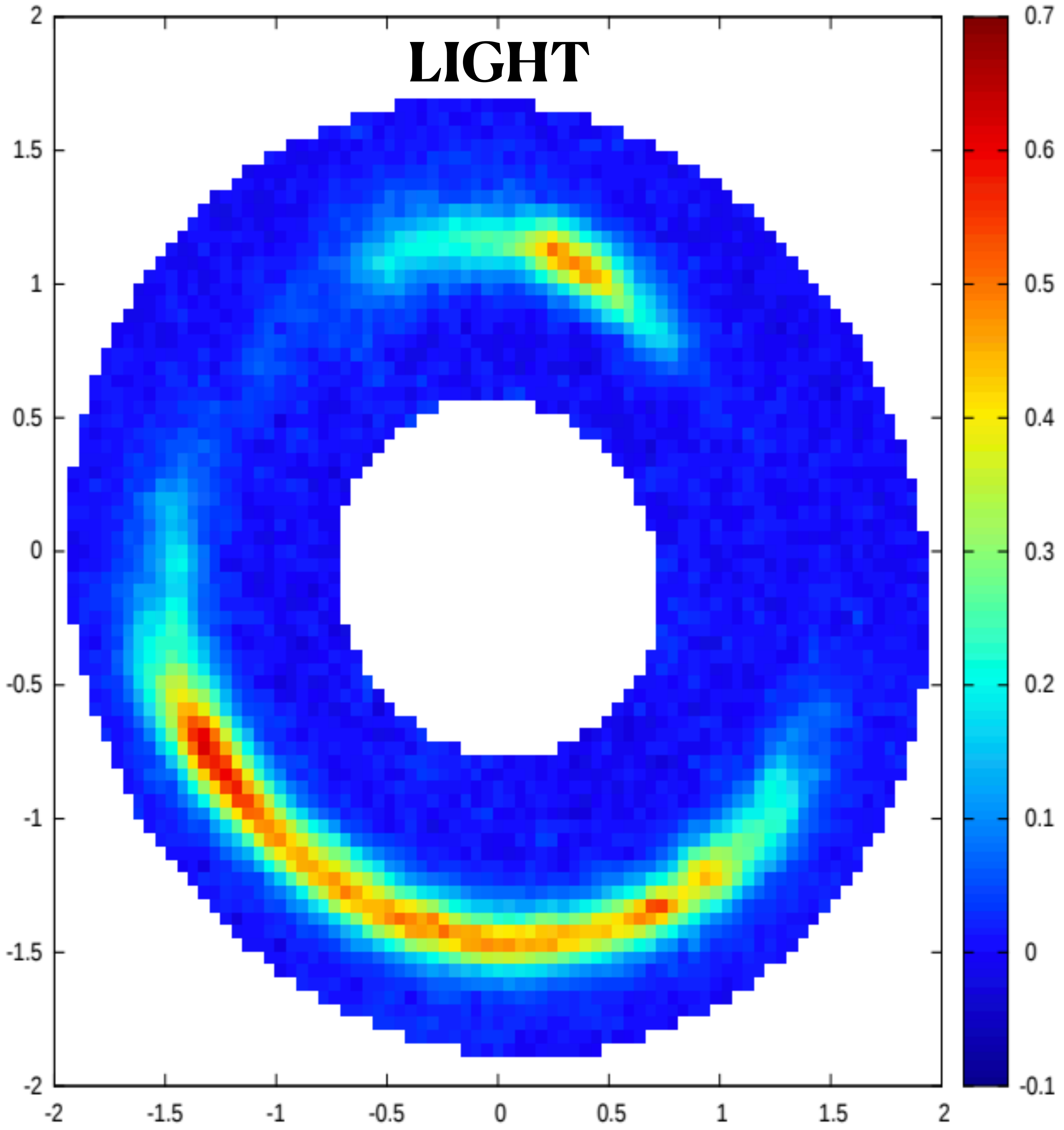
Minor et al. (2021)



(a) masked HST image

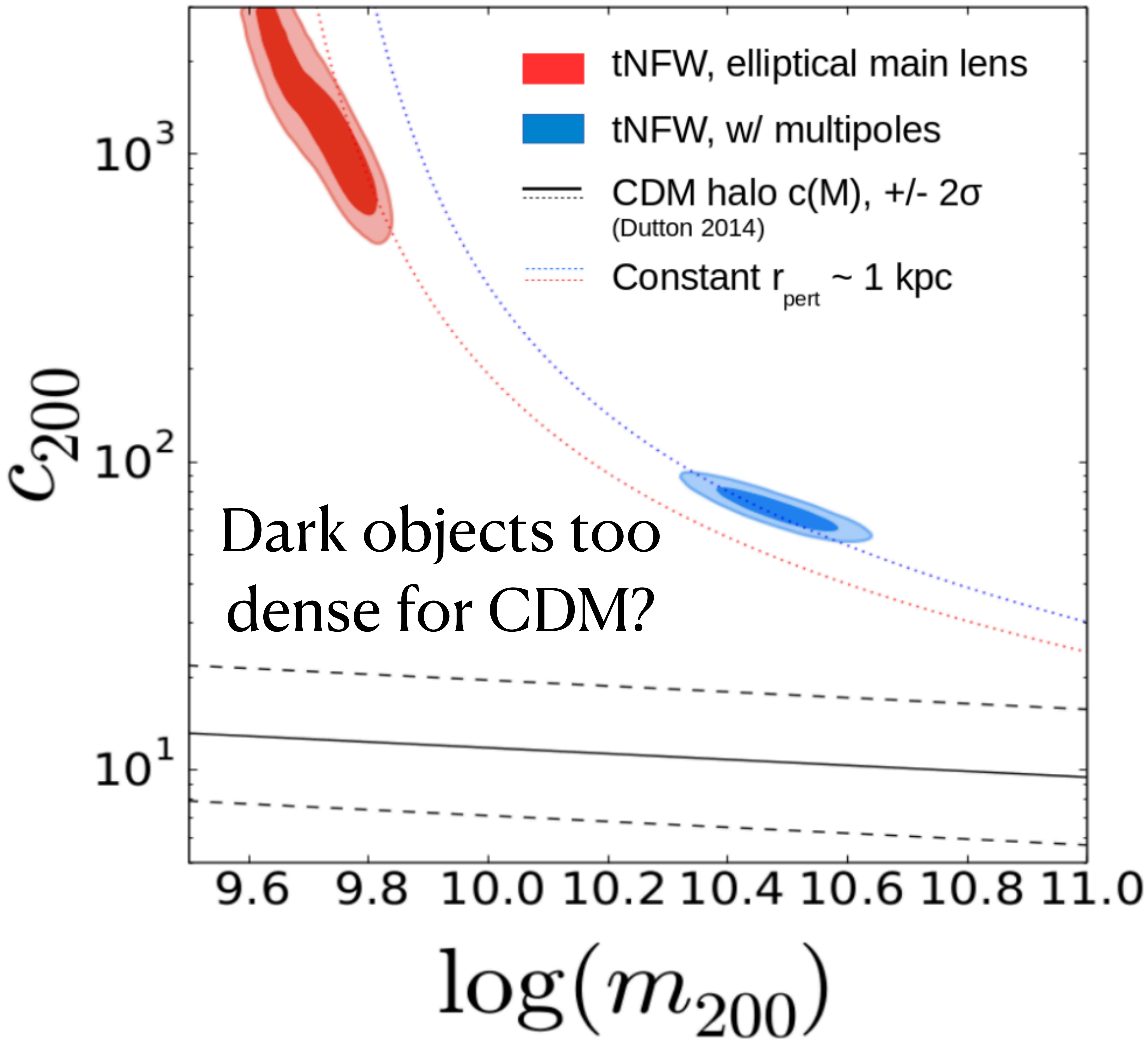


(a) tNFW model



(a) masked HST image

Minor et al. (2021)



Dark objects too dense for CDM?

IF we accept then the SIDM interpretation of these observations

THEN we should expect to find many collapsed halos at lower masses

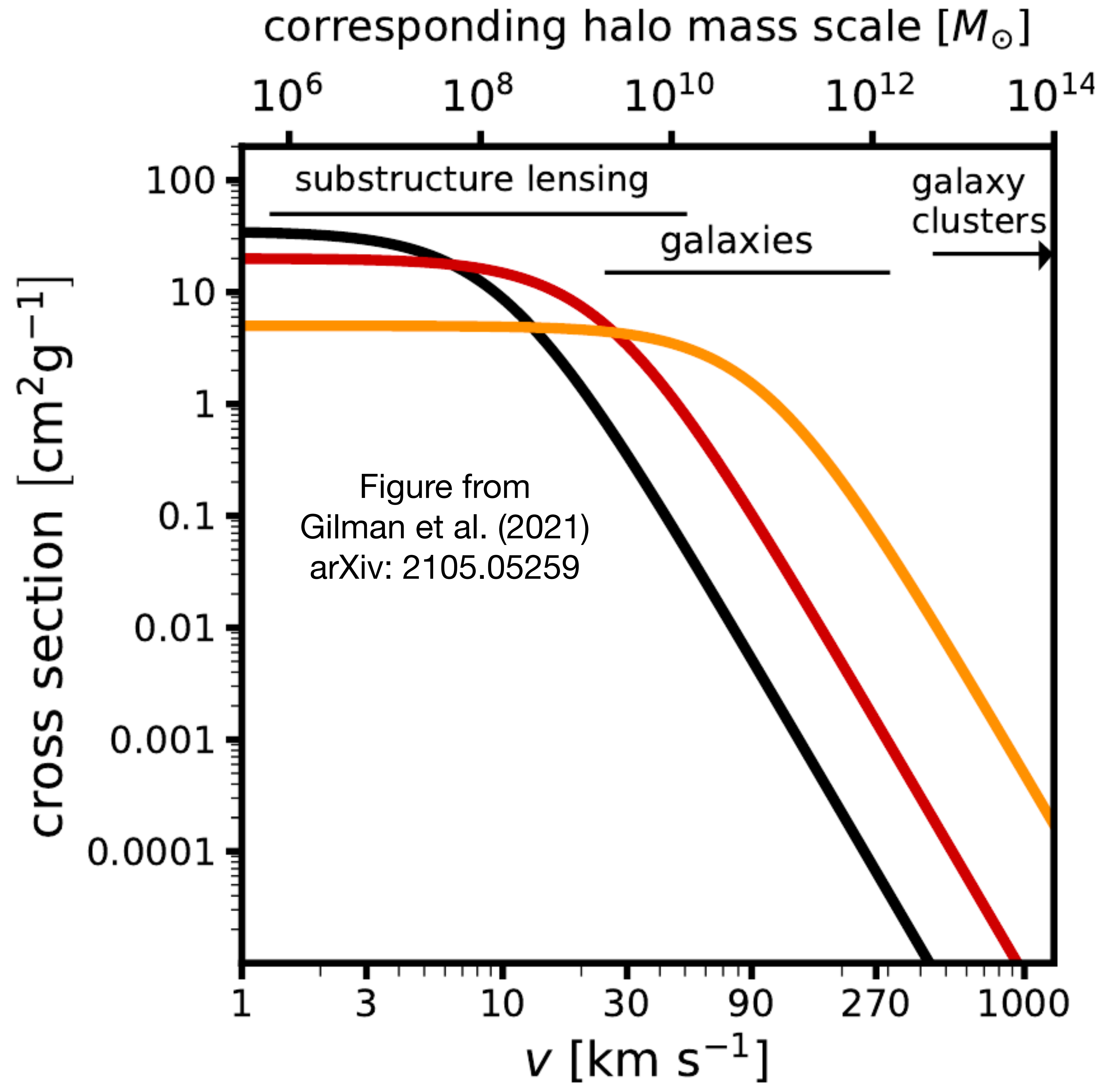


Figure from Gilman et al. (2021) arXiv: 2105.05259

We can explore SIDM's rich phenomenology

-> example: attractive dark force exchanged via light mediator

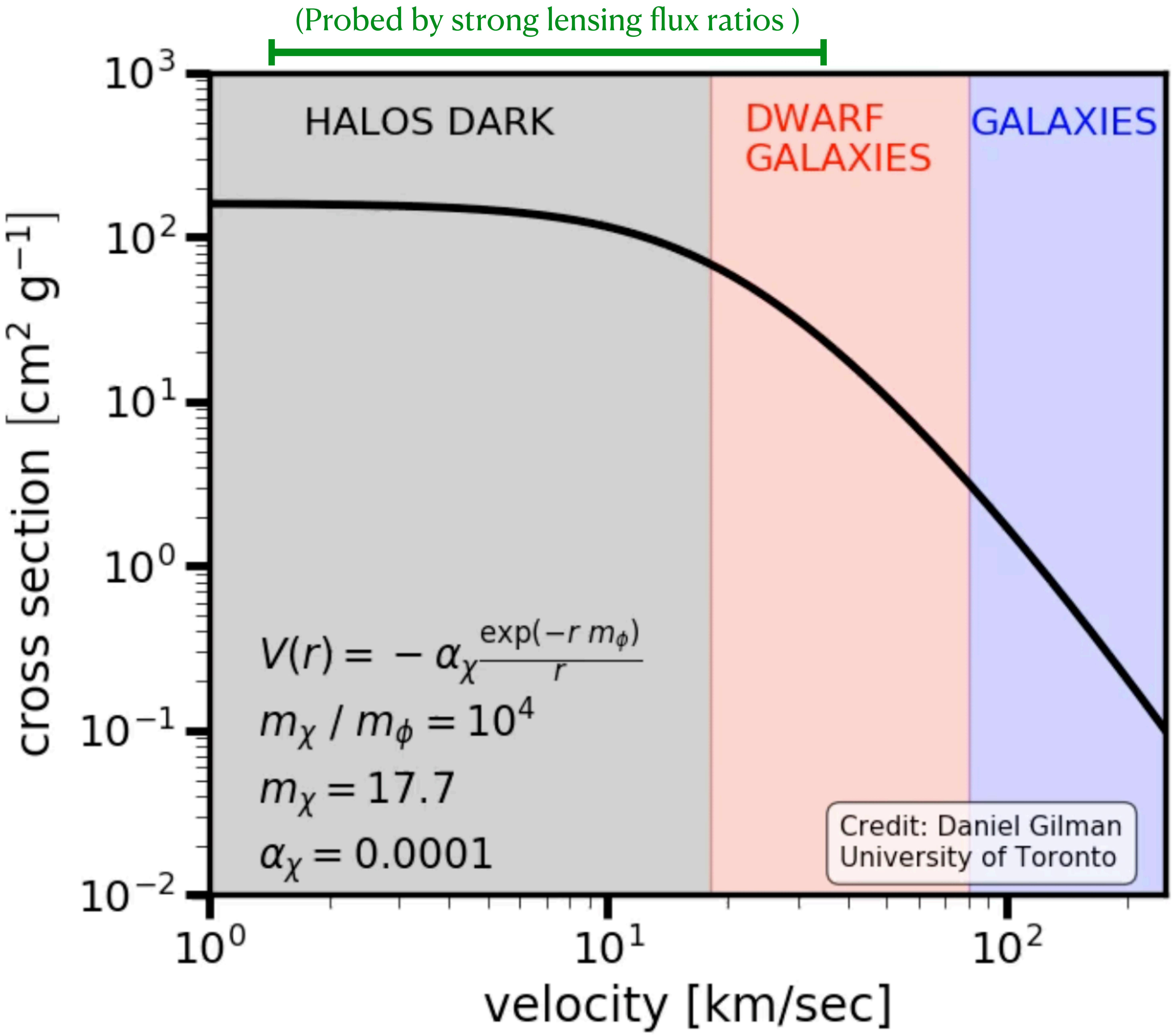
-> solving Schrodinger Eqn. reveals resonances at particular speeds/halo mass scales

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

$\alpha_\chi =$ potential strength

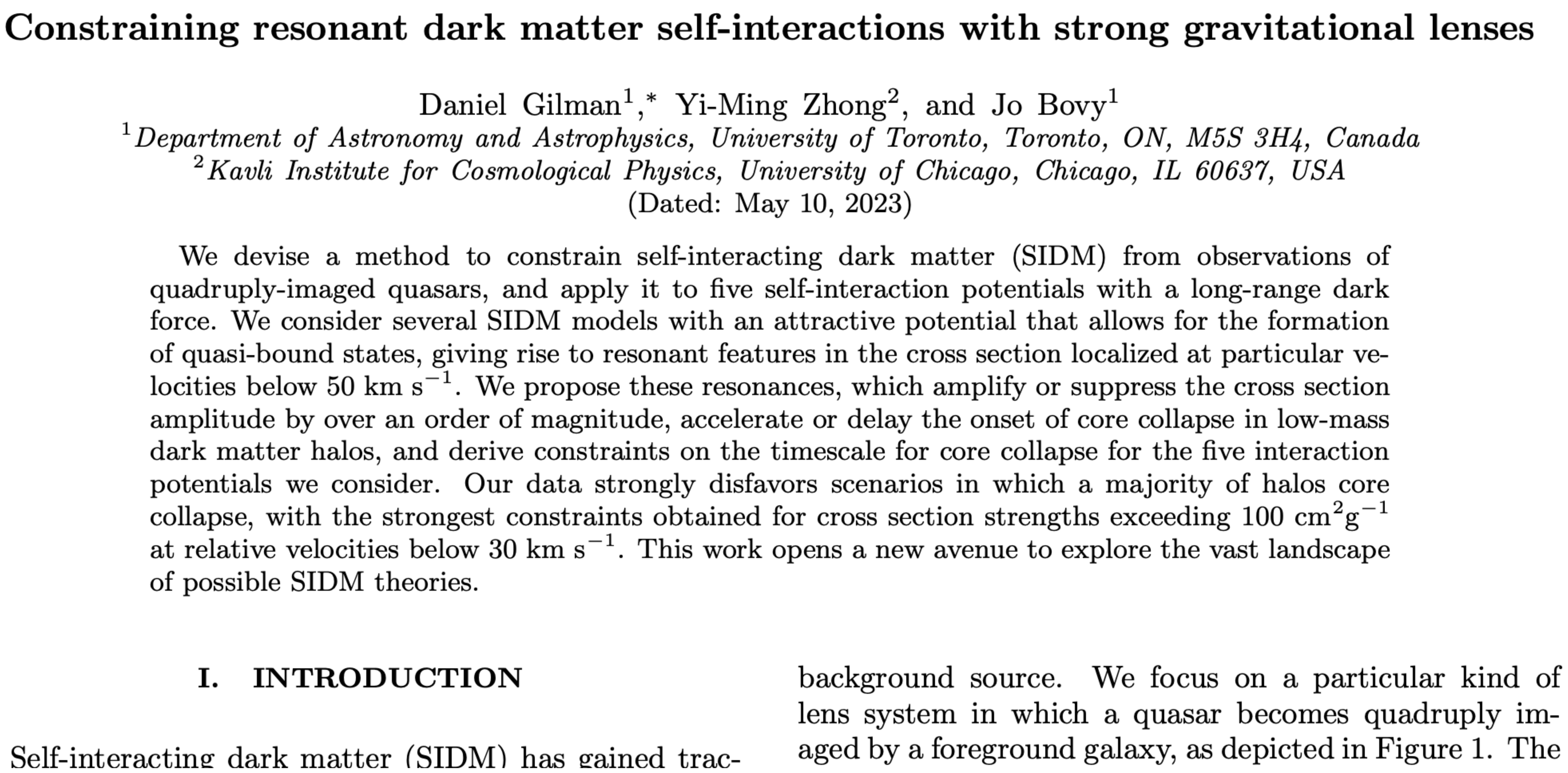
$m_\phi =$ mediator mass ~ 1 MeV

$m_\chi =$ DM mass $\sim 1 - 10$ GeV



Proof of concept with Hubble Space Telescope data and 11 lenses

Gilman, Zhong, Bovy; PRD 2023 arXiv: 2207.13111



Constraining resonant dark matter self-interactions with strong gravitational lenses

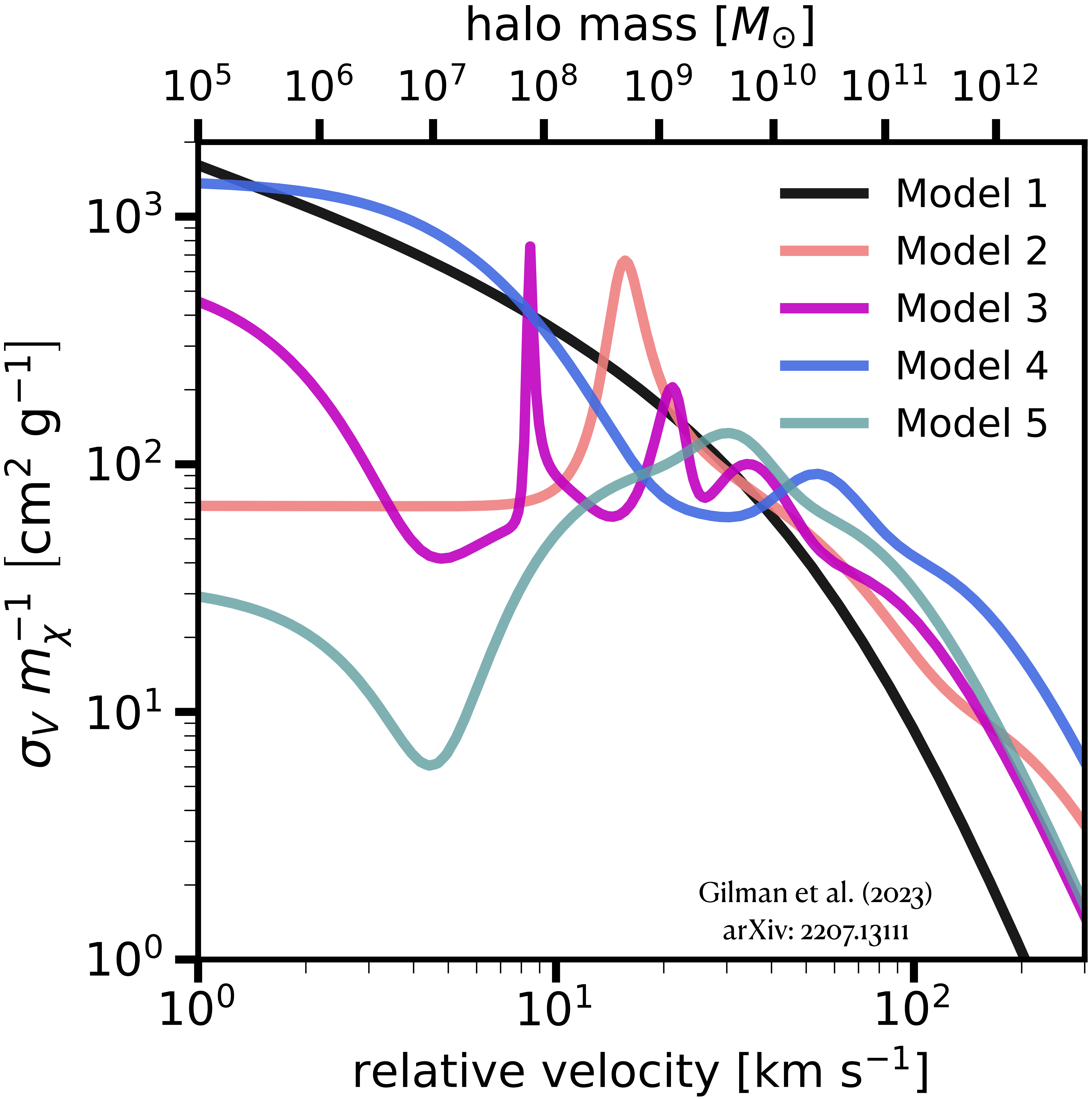
Daniel Gilman[1],* Yi-Ming Zhong[2], and Jo Bovy[1]
[1]*Department of Astronomy and Astrophysics, University of Toronto, Toronto, ON, M5S 3H4, Canada*
[2]*Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA*
(Dated: May 10, 2023)

We devise a method to constrain self-interacting dark matter (SIDM) from observations of quadruply-imaged quasars, and apply it to five self-interaction potentials with a long-range dark force. We consider several SIDM models with an attractive potential that allows for the formation of quasi-bound states, giving rise to resonant features in the cross section localized at particular velocities below 50 km s^{-1}. We propose these resonances, which amplify or suppress the cross section amplitude by over an order of magnitude, accelerate or delay the onset of core collapse in low-mass dark matter halos, and derive constraints on the timescale for core collapse for the five interaction potentials we consider. Our data strongly disfavors scenarios in which a majority of halos core collapse, with the strongest constraints obtained for cross section strengths exceeding 100 $cm^2 g^{-1}$ at relative velocities below 30 km s^{-1}. This work opens a new avenue to explore the vast landscape of possible SIDM theories.

I. INTRODUCTION

Self-interacting dark matter (SIDM) has gained trac-

background source. We focus on a particular kind of lens system in which a quasar becomes quadruply imaged by a foreground galaxy, as depicted in Figure 1. The



Gilman et al. (2023)
arXiv: 2207.13111

characteristic collapse timescale

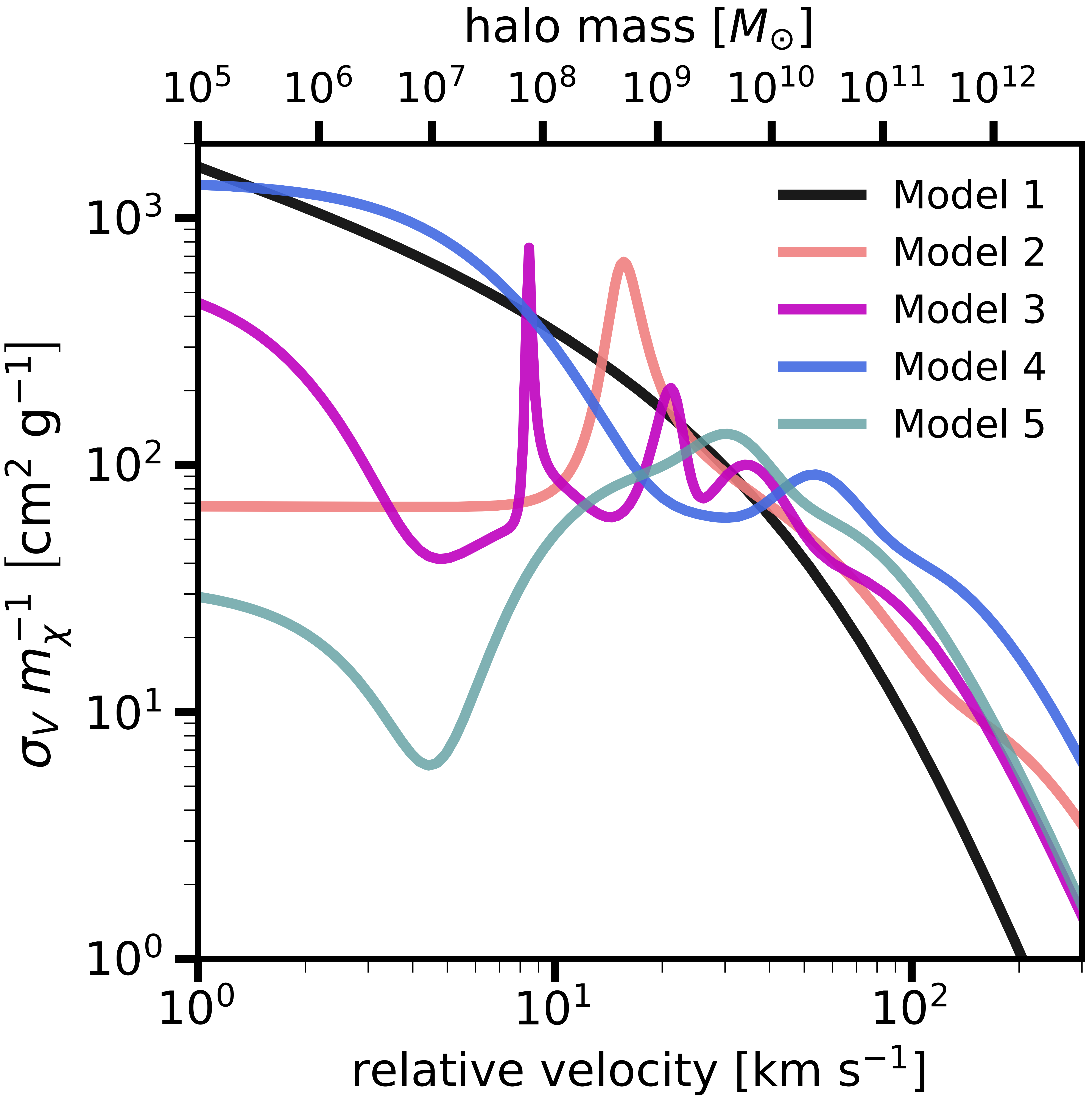
$$t_0^{-1} \sim \langle \sigma v^5 \rangle / \langle v^5 \rangle \times \text{density} \times \text{velocity}$$

Yang & Yu (2022) arXiv: 2305.16176,
Yang, Du et al. (2023) arXiv: 2205.02957

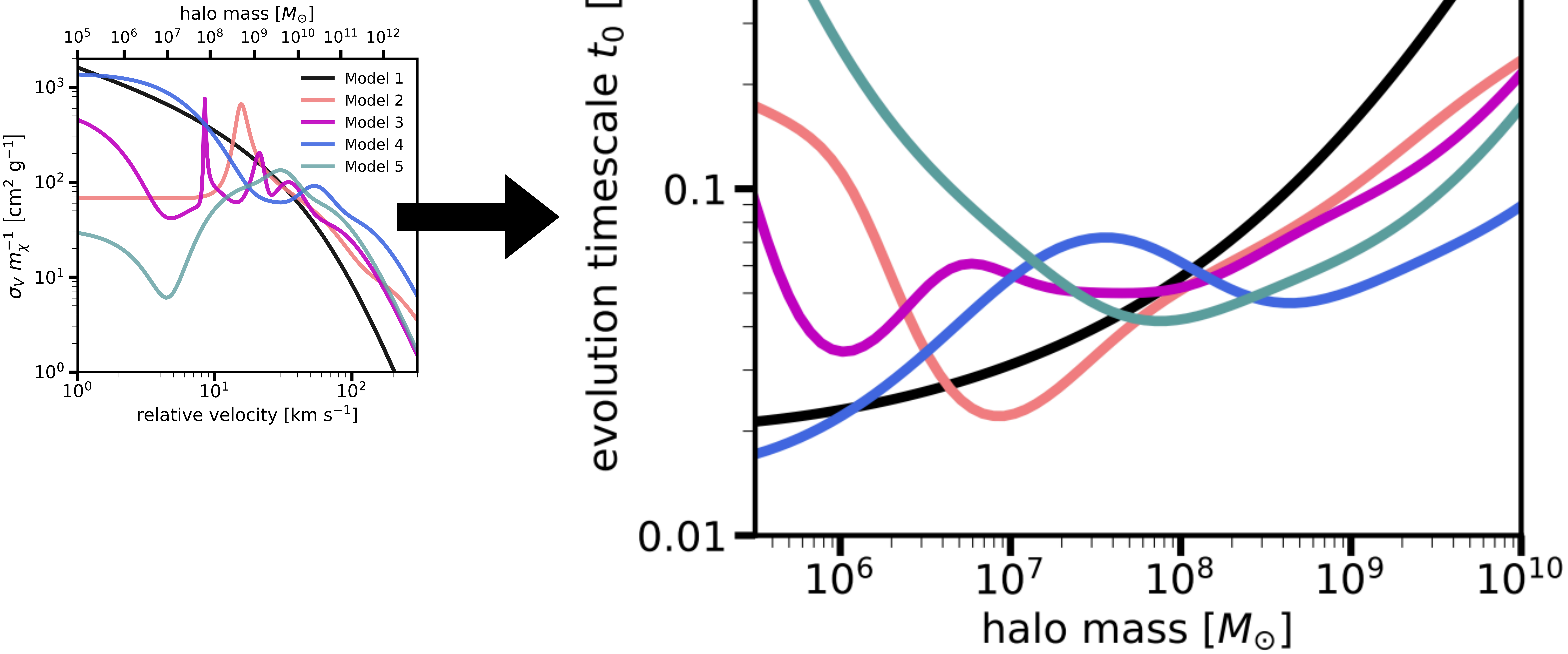
Halos collapse after some multiple of the timescale

$$t_{\text{subhalo}} \sim \lambda_{\text{sub}}\, t_{\text{collapse}}$$

$$t_{\text{fieldhalo}} \sim \lambda_{\text{field}}\, t_{\text{collapse}}$$

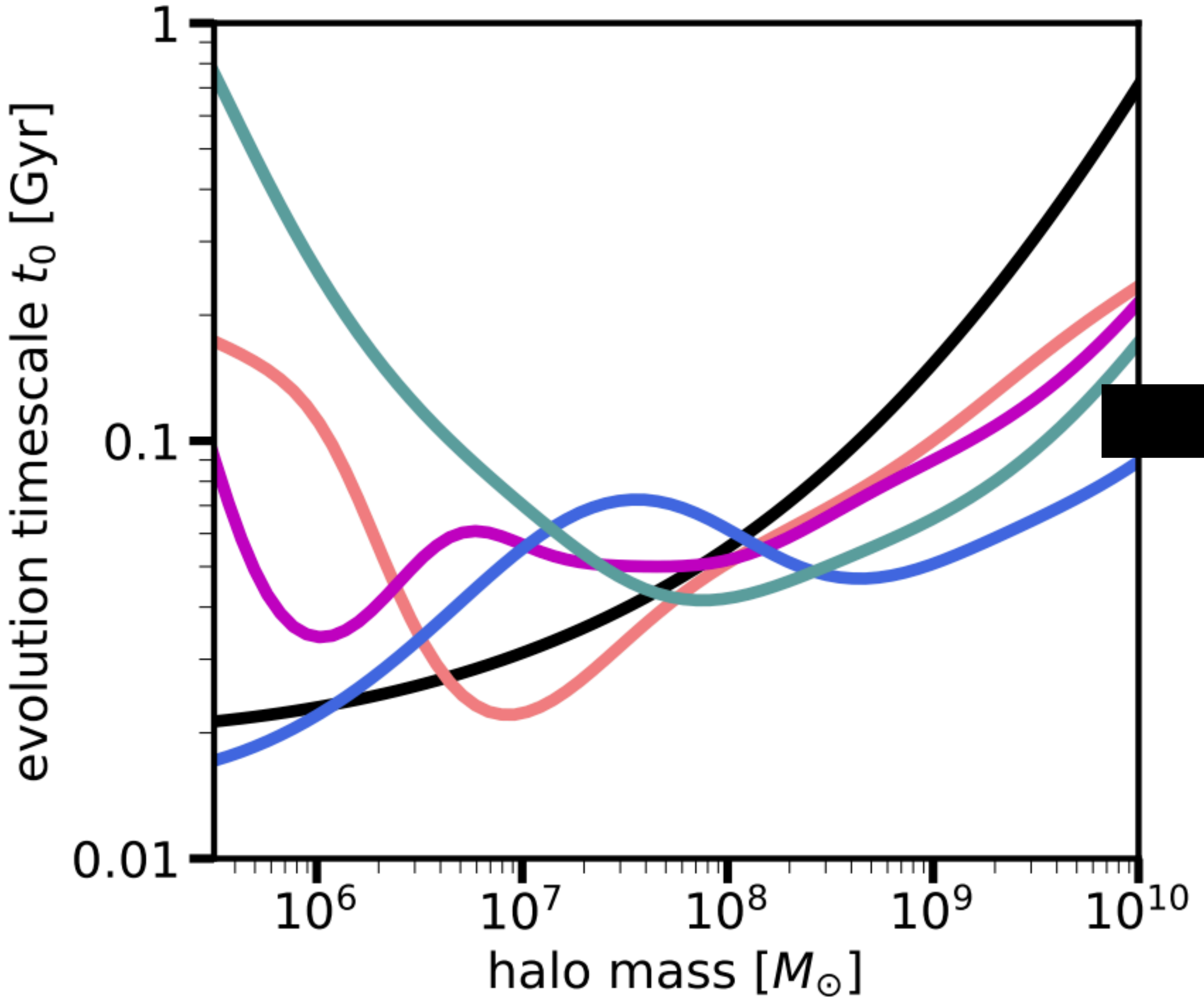


$$t_0^{-1} \sim \langle \sigma v^5 \rangle / \langle v^5 \rangle \times \text{density} \times \text{velocity}$$

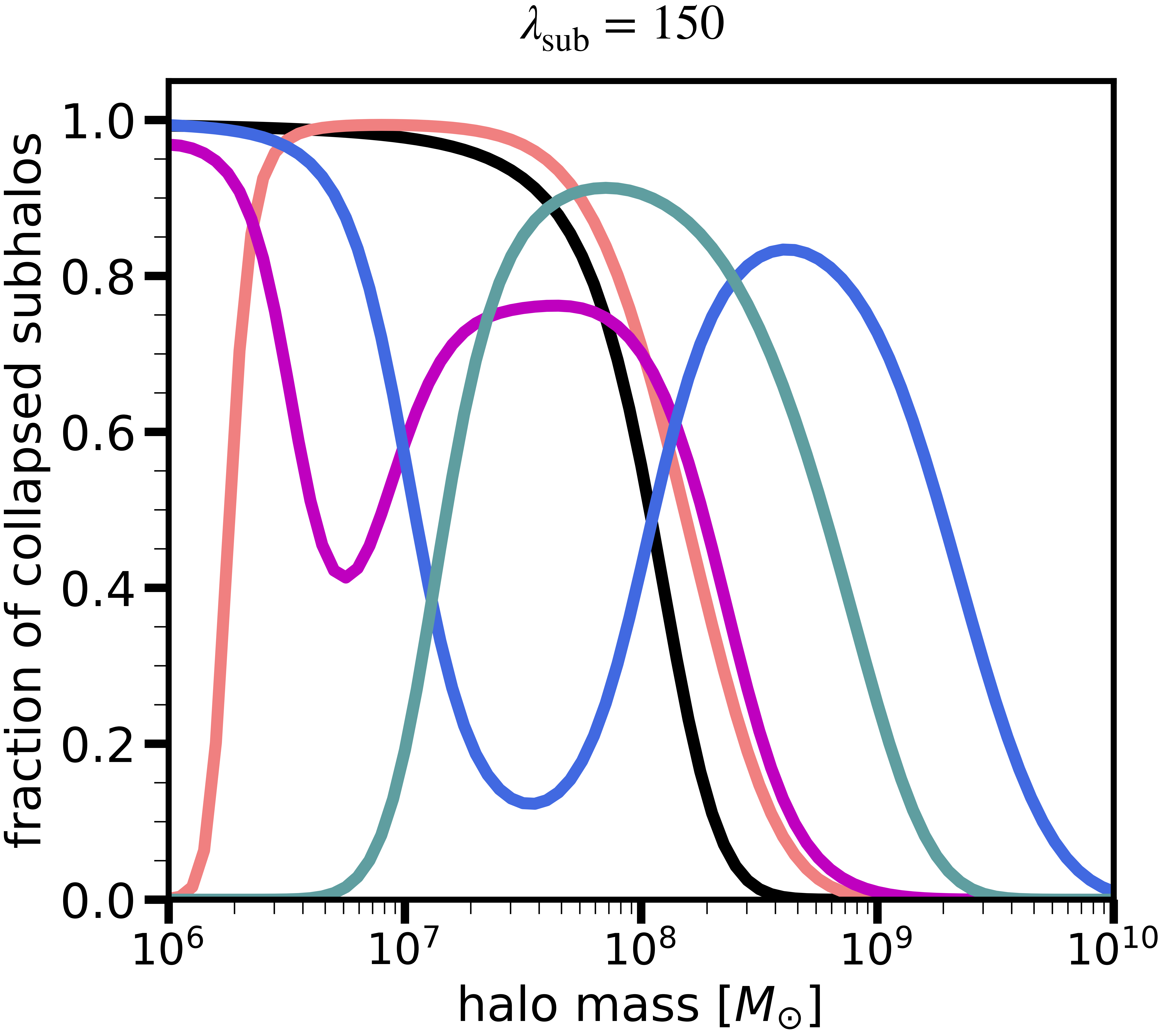


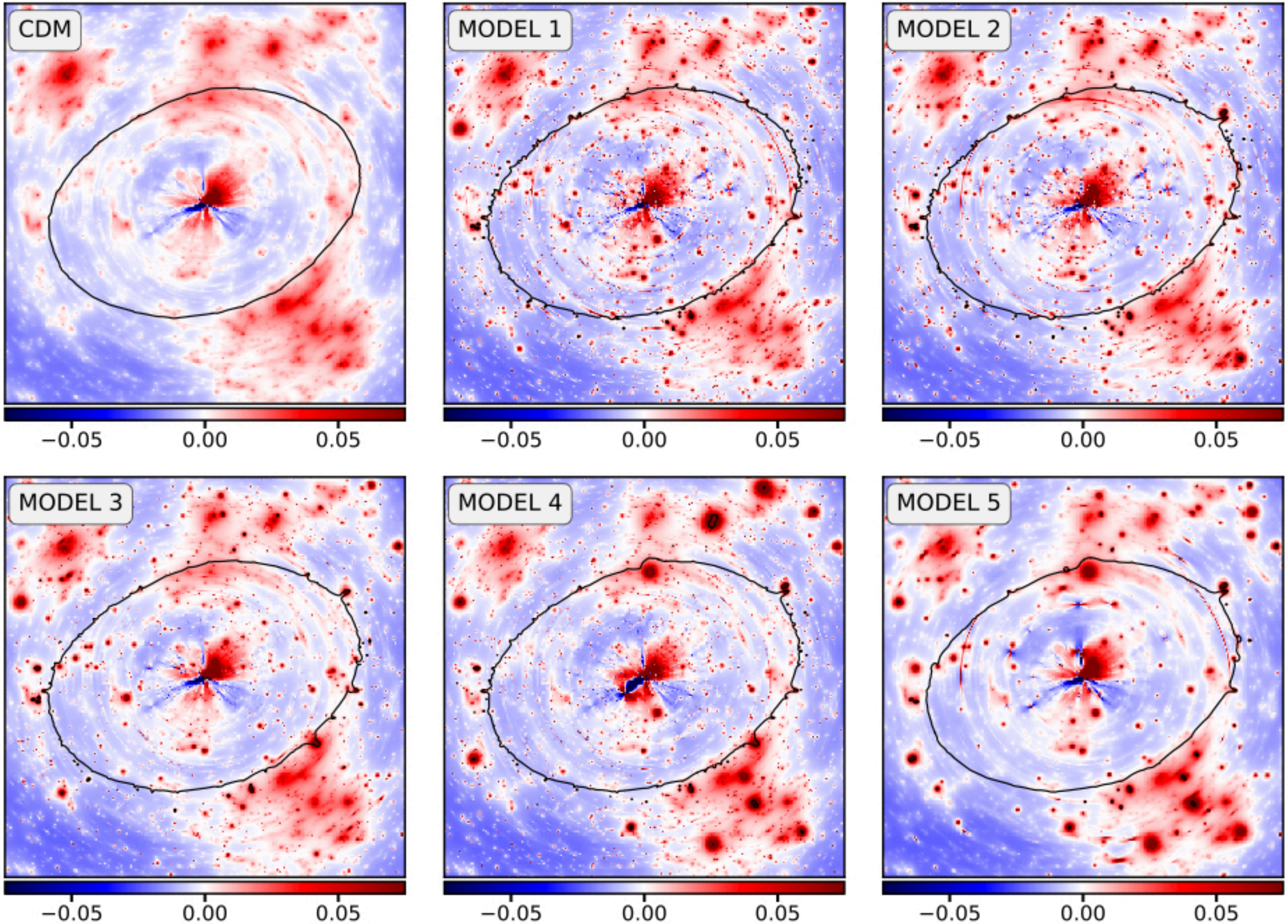
$$t_0^{-1} \sim \langle \sigma v^5 \rangle / \langle v^5 \rangle \times \text{density} \times \text{velocity}$$

$$t_{\text{subhalo}} \sim \lambda_{\text{sub}}\ t_0$$



Allow halos to collapse after
a multiple of the collapse time

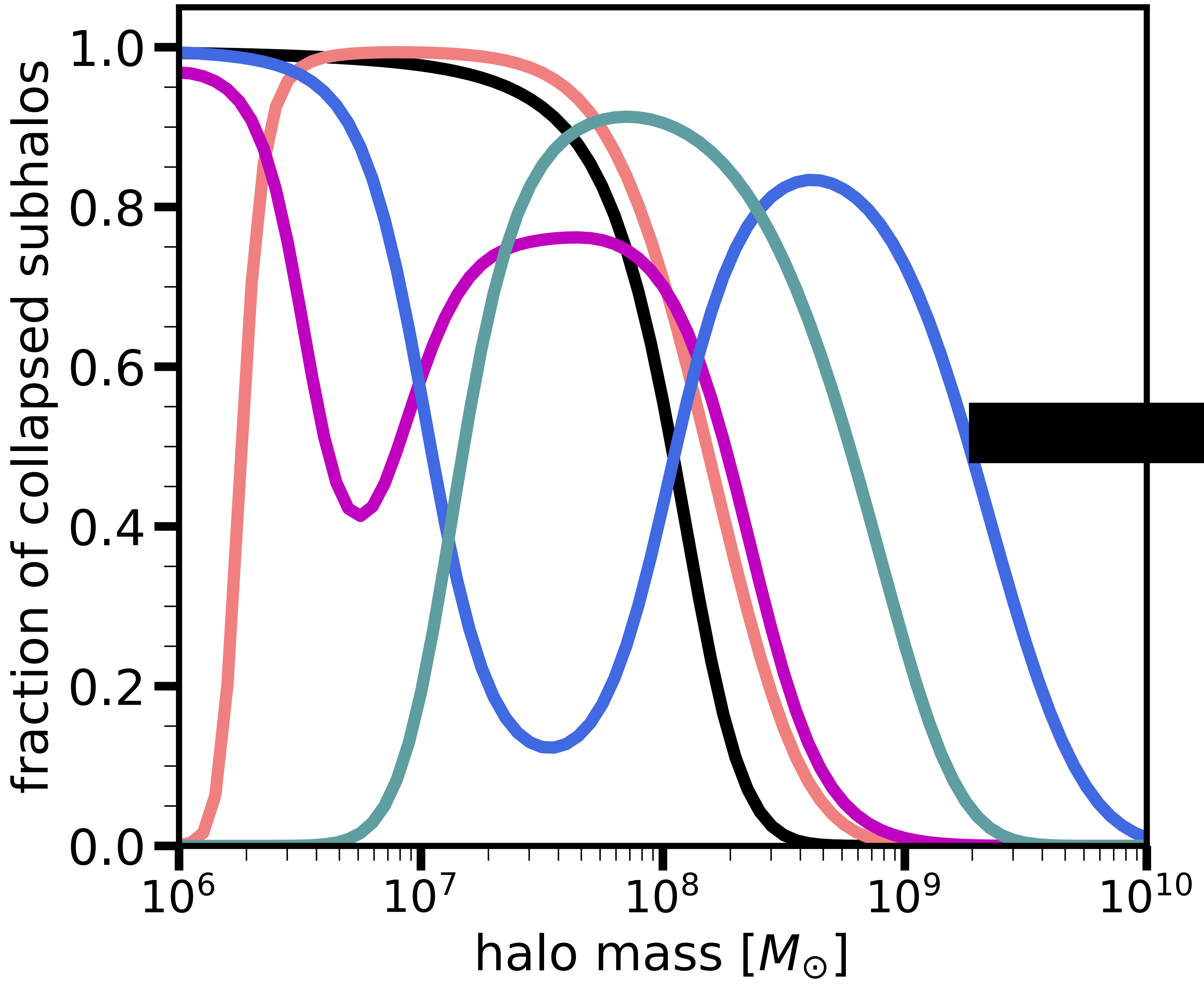




Gilman et al. (2023)
arXiv: 2207.13111

We can compute the likelihood of data given **fraction of collapsed halos as a function of halo mass**:

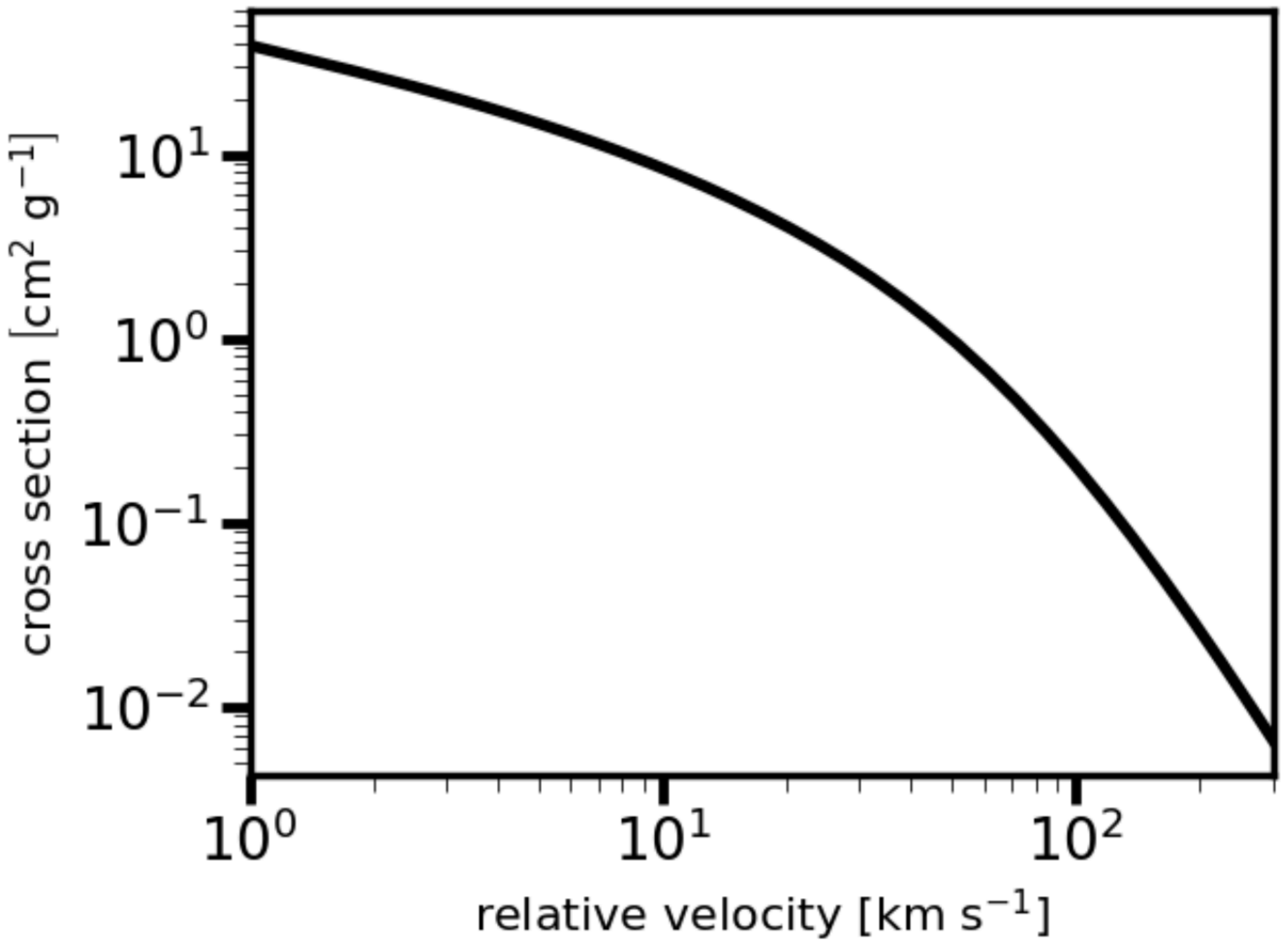
$$\mathscr{L}\left(\mathbf{data}\,|\,f_{\mathrm{collapsed}}\left(M\right)\right)$$



And recast this as constraints on the core-collapse timescale

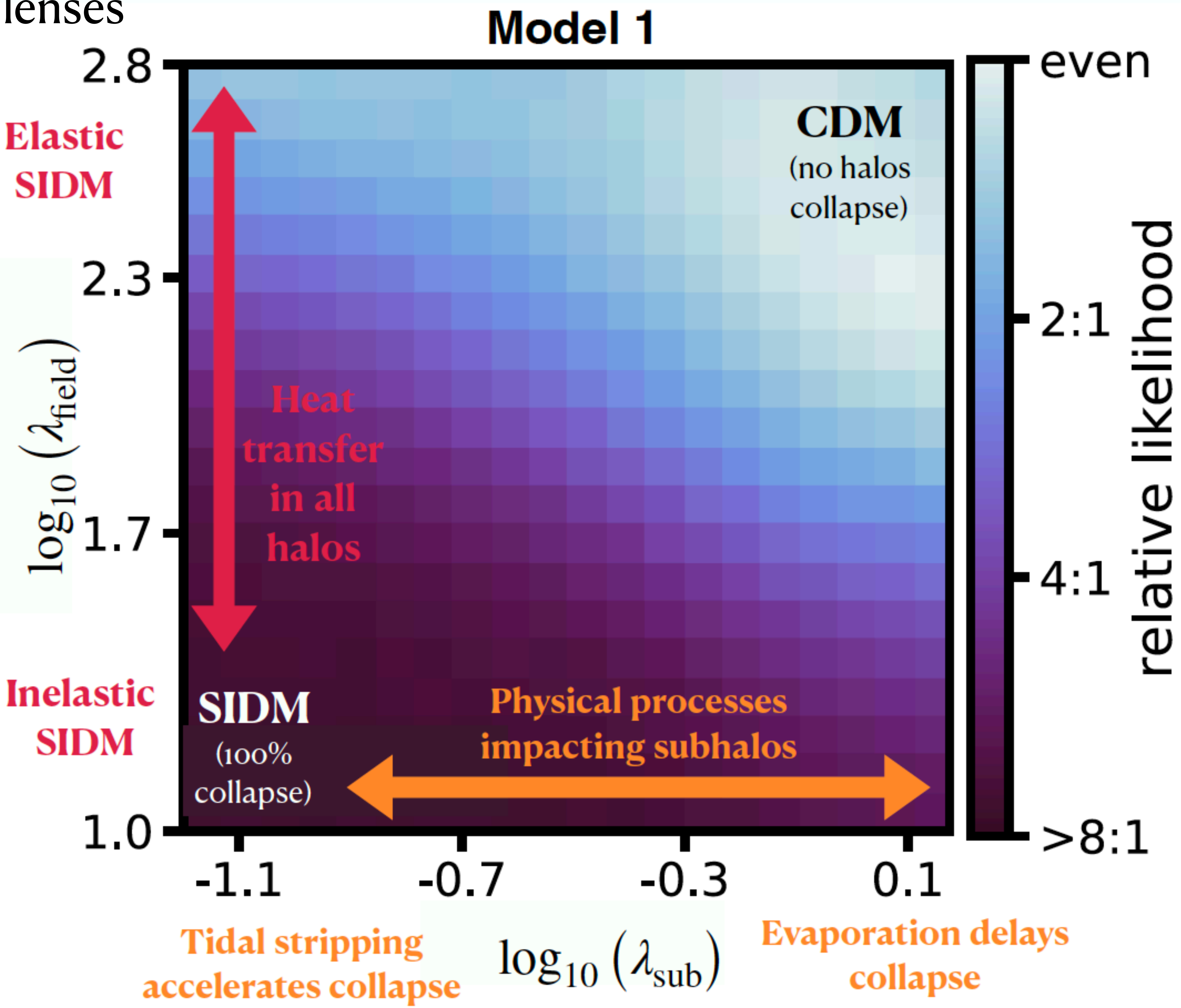
$$\mathscr{L}\left(\mathbf{data}\,|\,\lambda_{\mathrm{sub}},\lambda_{\mathrm{field}},\sigma\right)=\int\mathscr{L}\left(\mathbf{data}\,|\,f_{\mathrm{collapsed}}\left(M\right)\right)\times p\left(f_{\mathrm{collapsed}}\left(M\right)\,|\,\lambda_{\mathrm{sub}},\lambda_{\mathrm{field}},\sigma\right)df_{\mathrm{collapsed}}$$

Inference on real data with 11 lenses

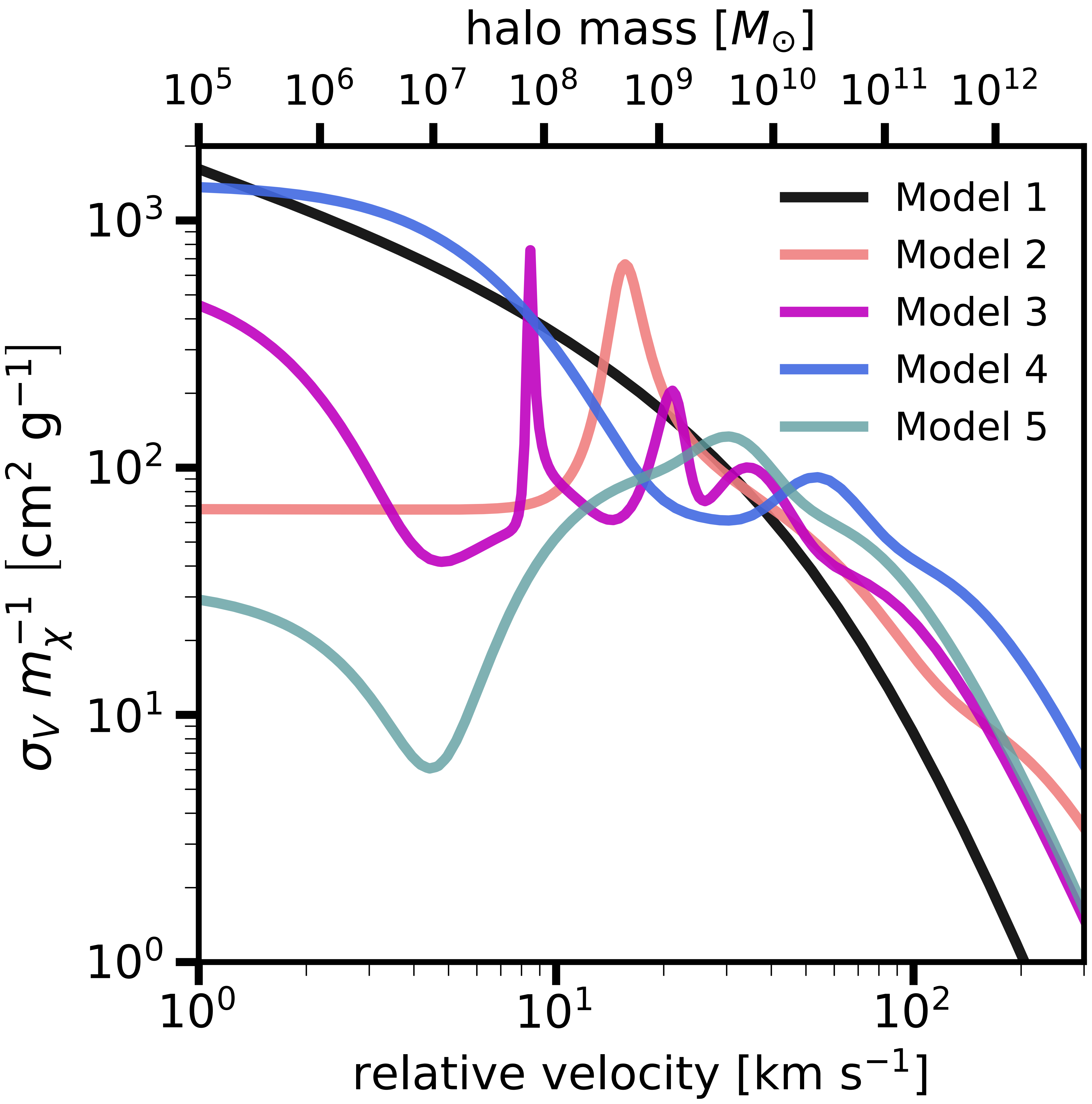


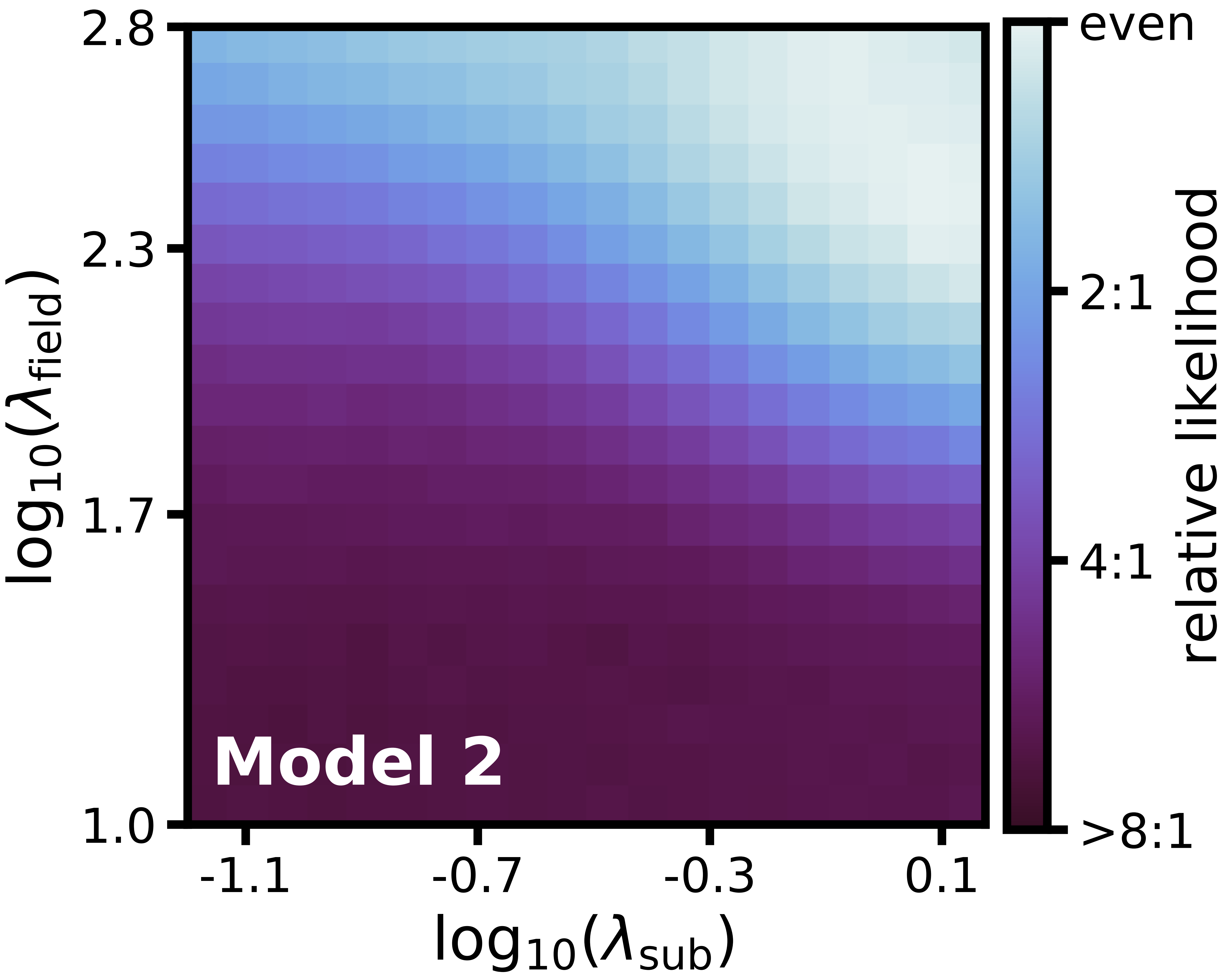
$$t_{\mathrm{subhalo}} \sim \lambda_{\mathrm{sub}} \, t_{\mathrm{collapse}}$$

$$t_{\mathrm{fieldhalo}} \sim \lambda_{\mathrm{field}} \, t_{\mathrm{collapse}}$$

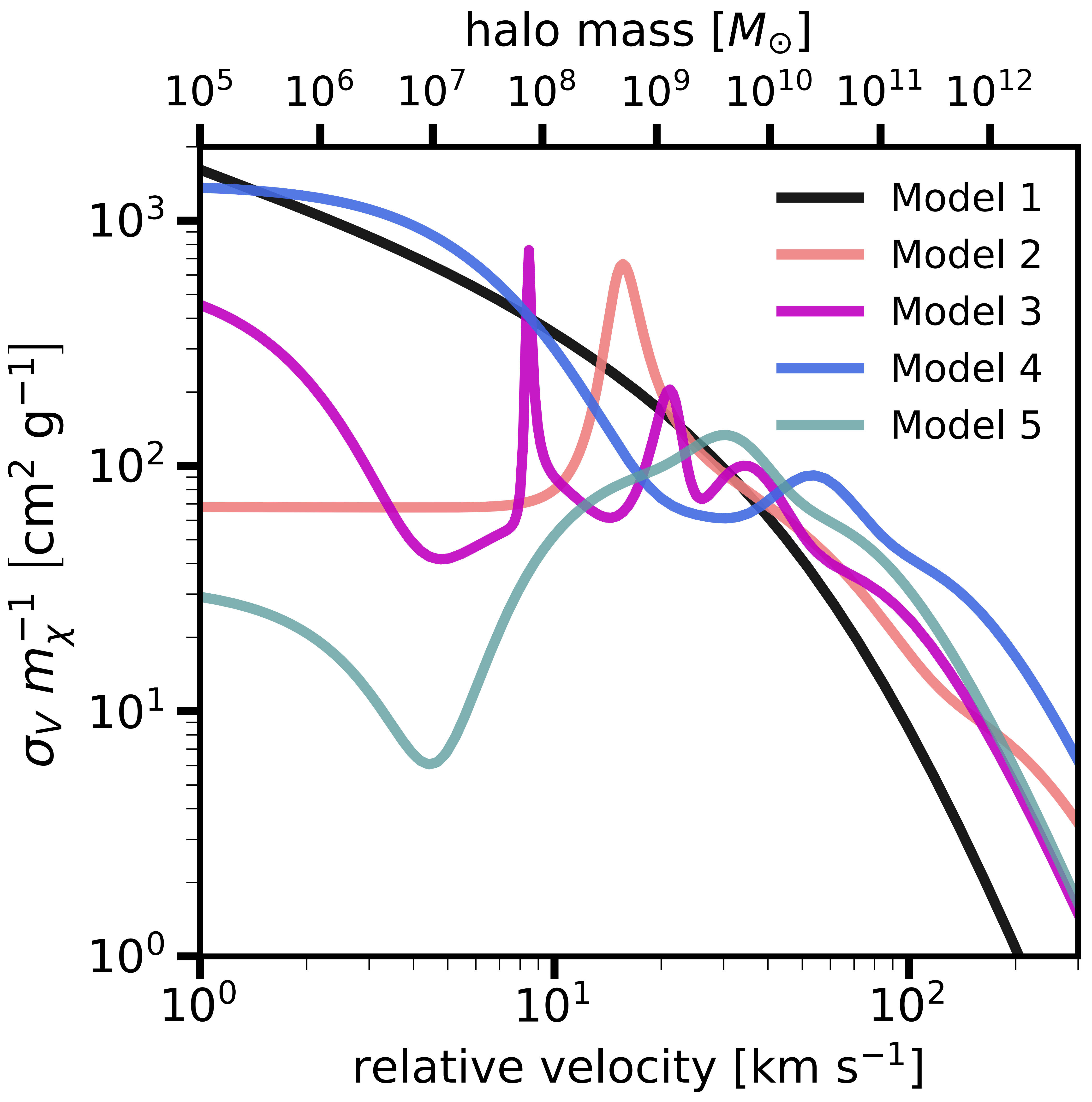


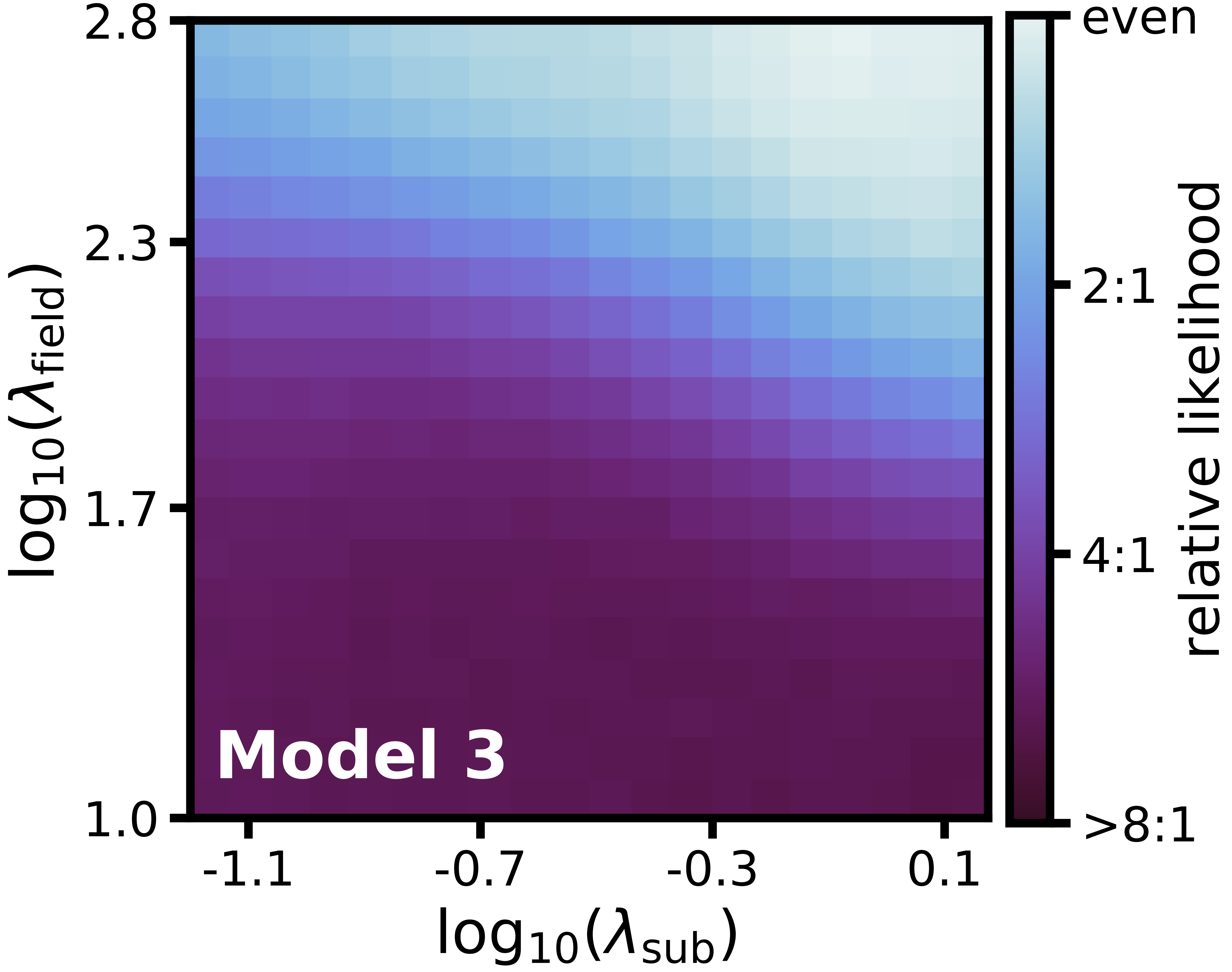
Inference on real data with 11 lenses: scenarios with 100% collapse strongly disfavored



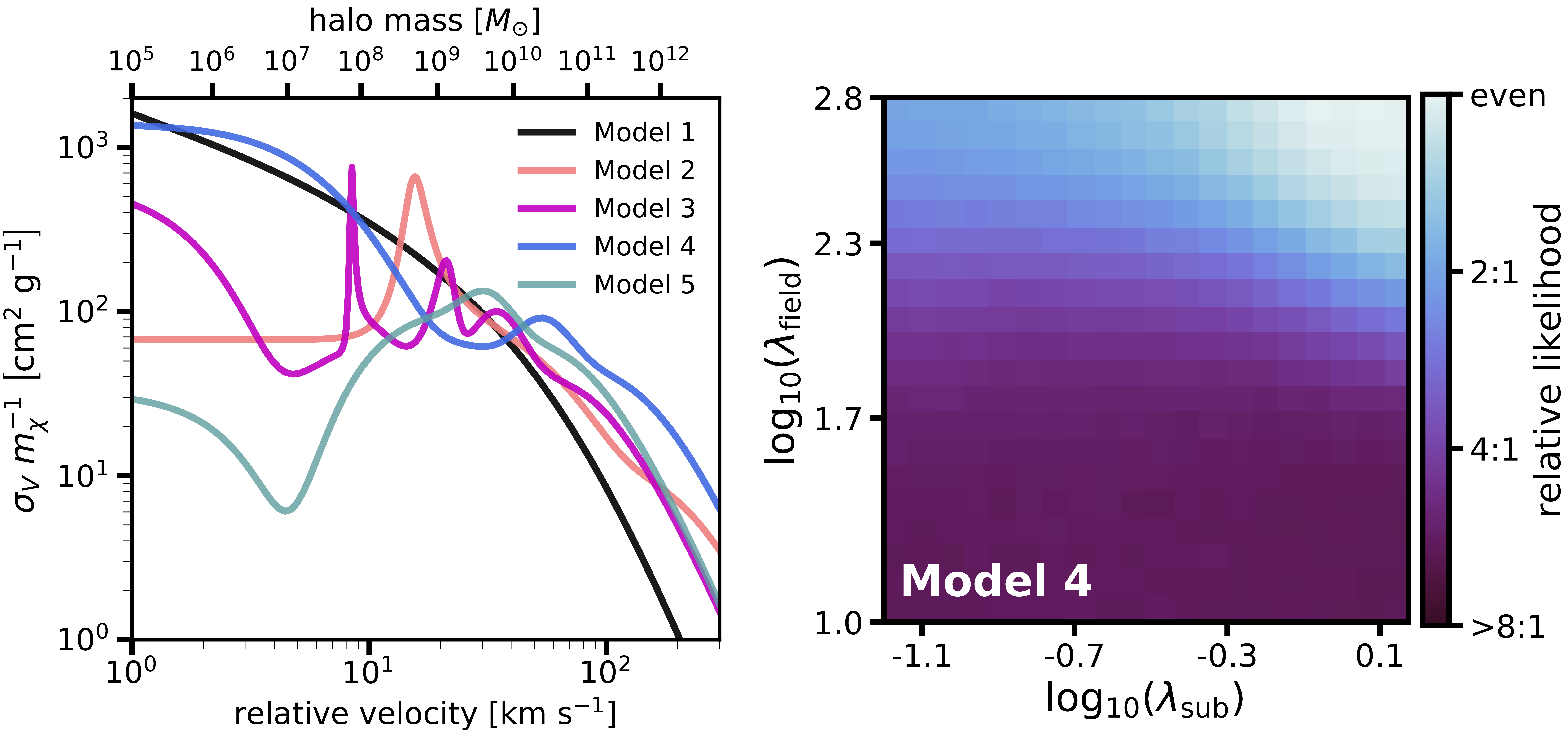


Inference on real data with 11 lenses: scenarios with 100% collapse strongly disfavored

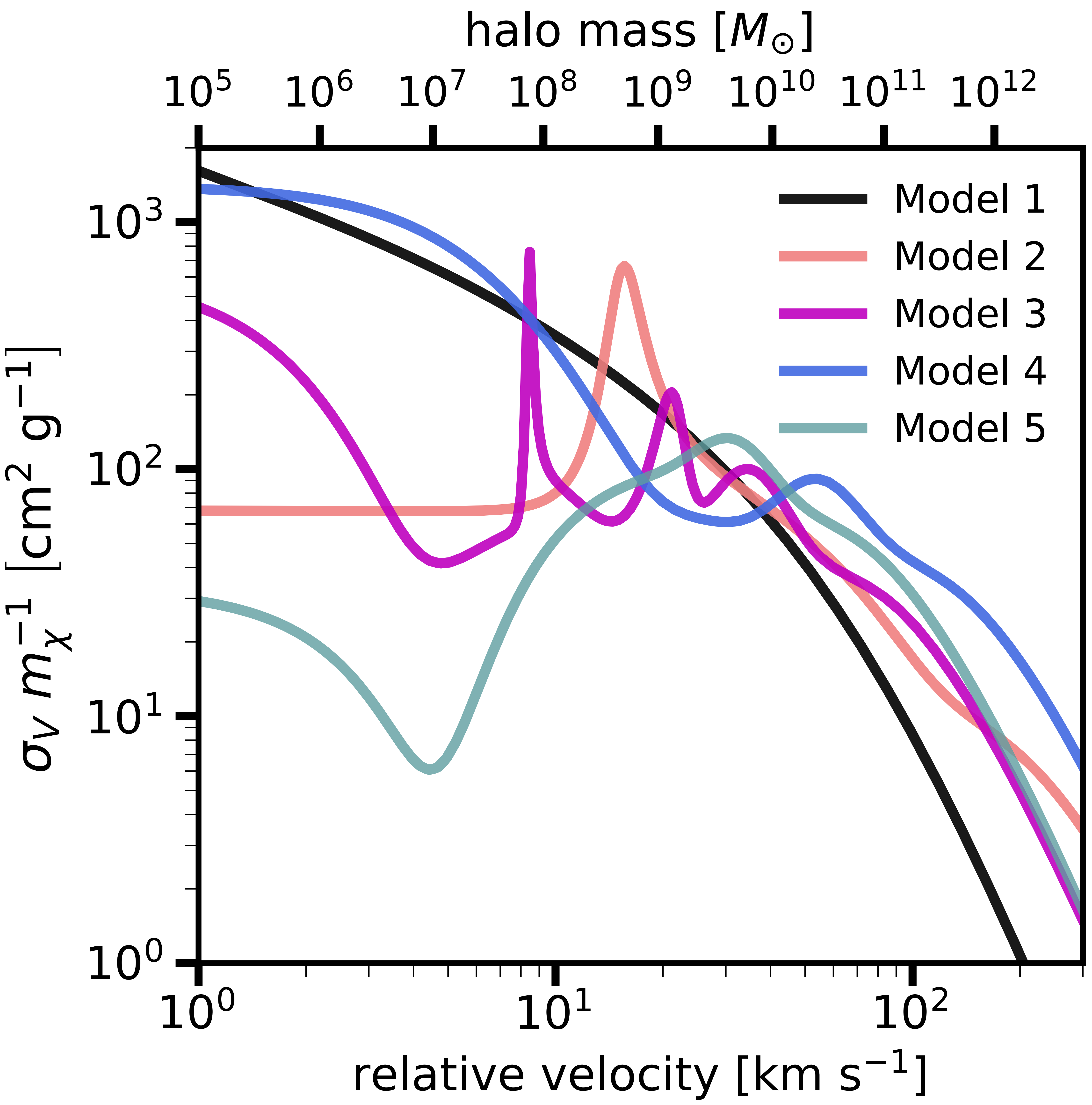


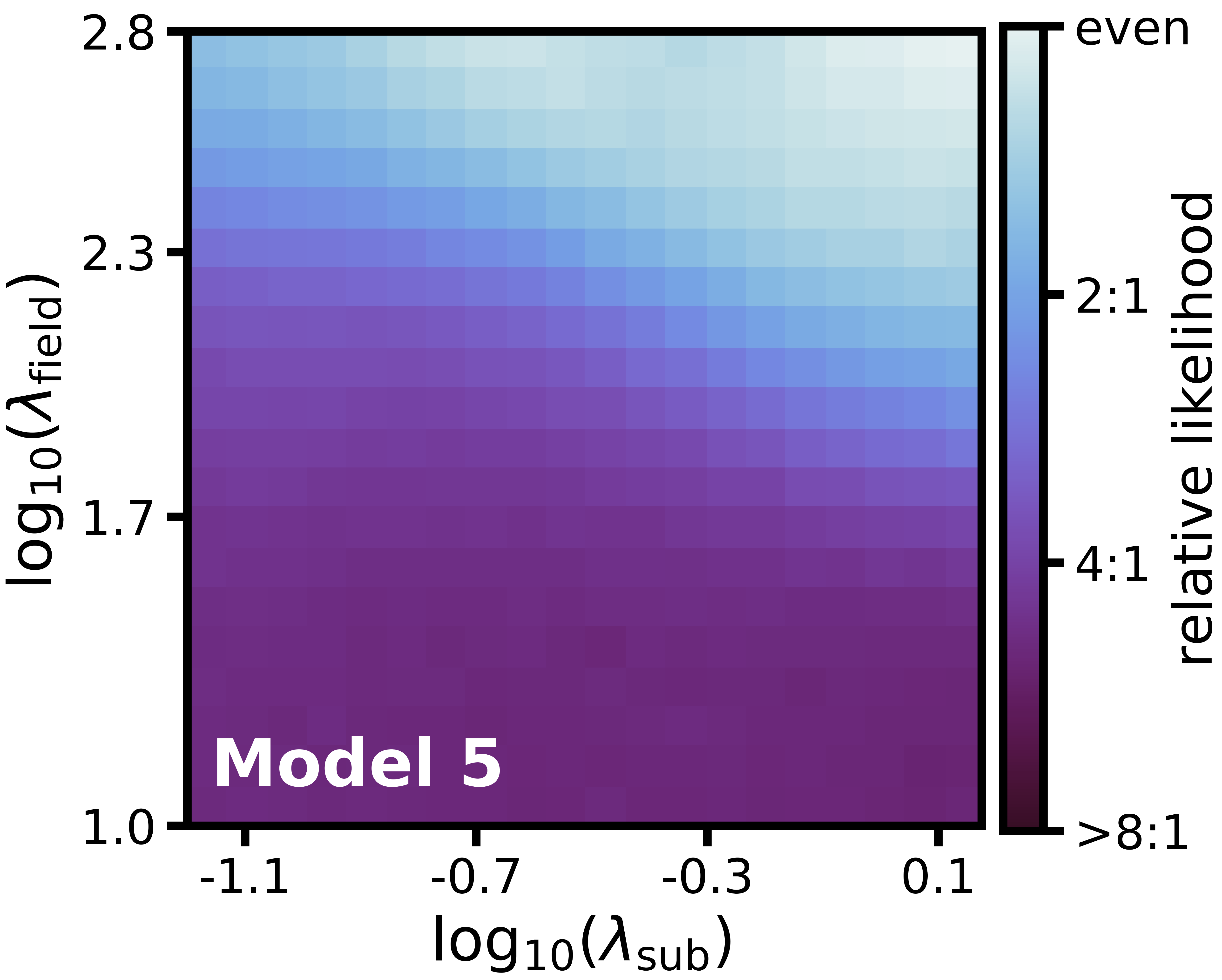


Inference on real data with 11 lenses: scenarios with 100% collapse strongly disfavored



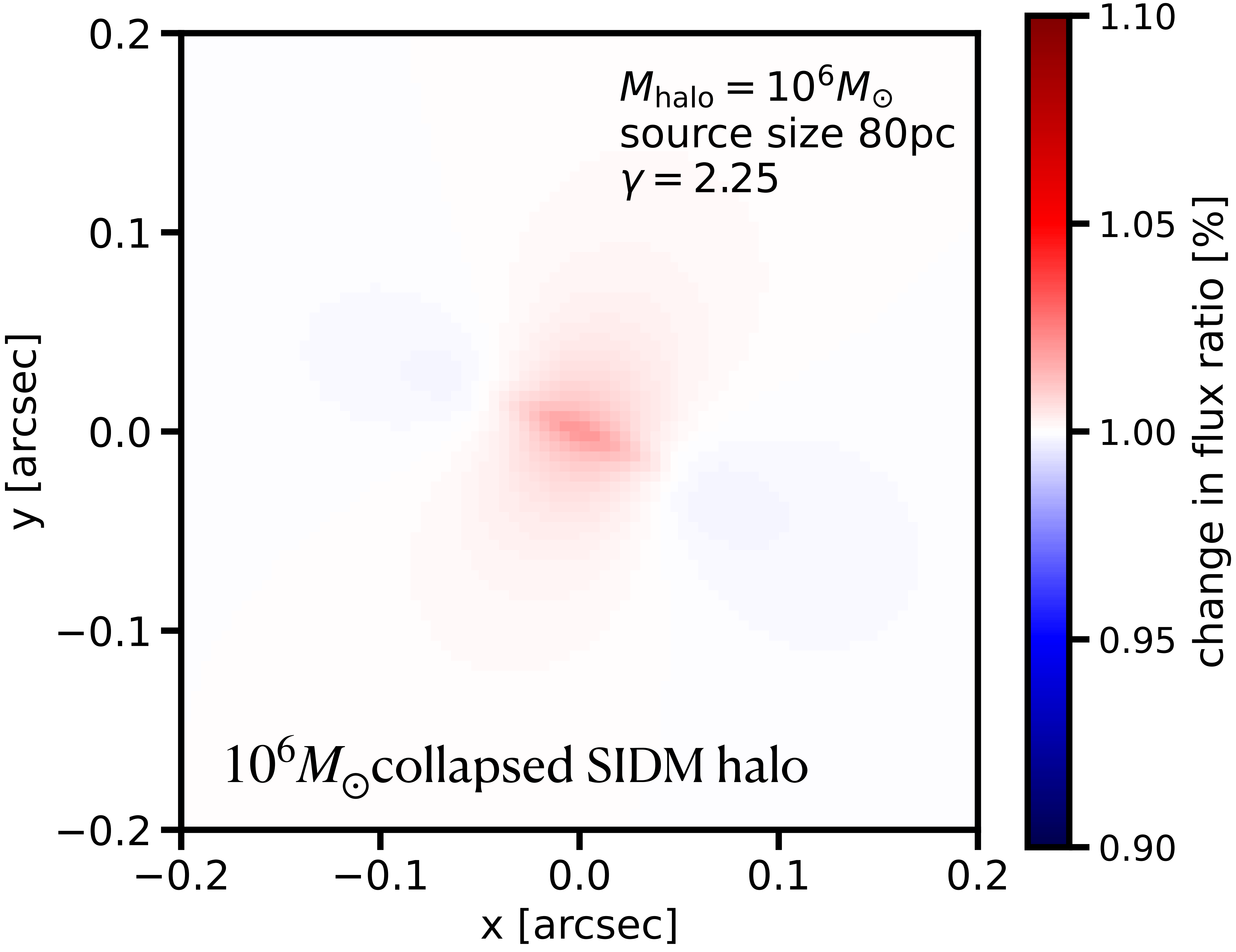
Inference on real data with 11 lenses: scenarios with 100% collapse strongly disfavored



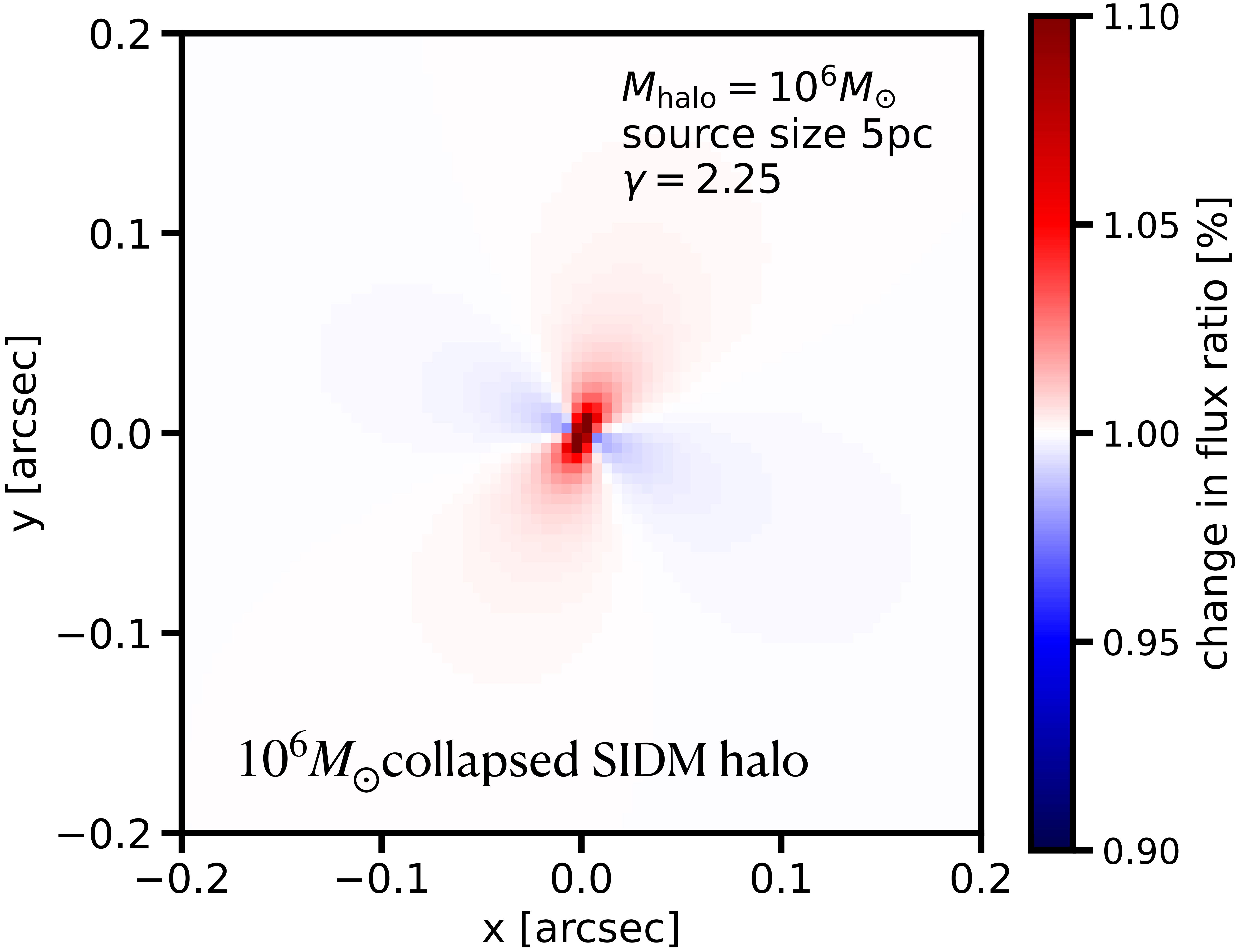


(Near) future lensing-based constraints on SIDM

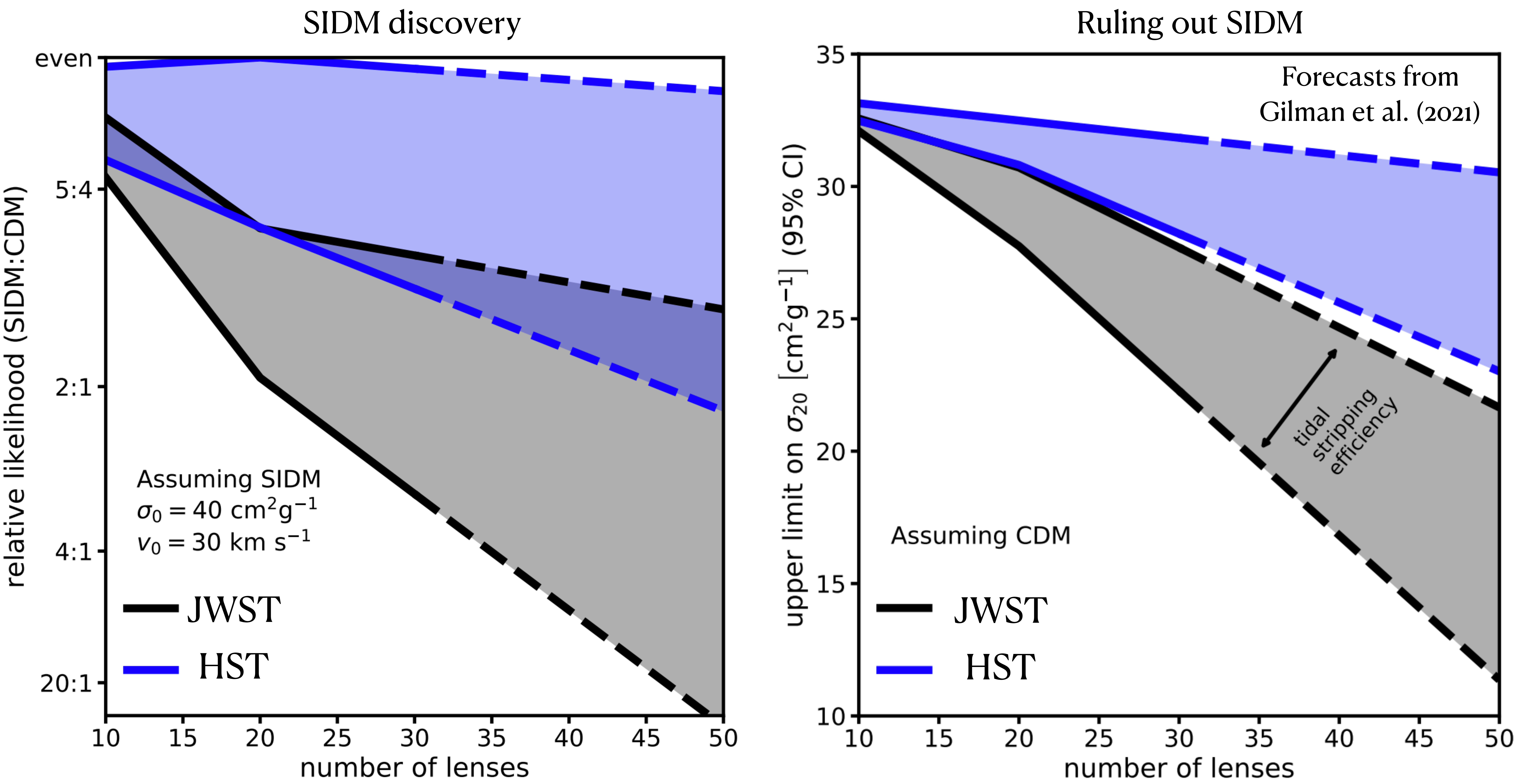
HST-like data



JWST data



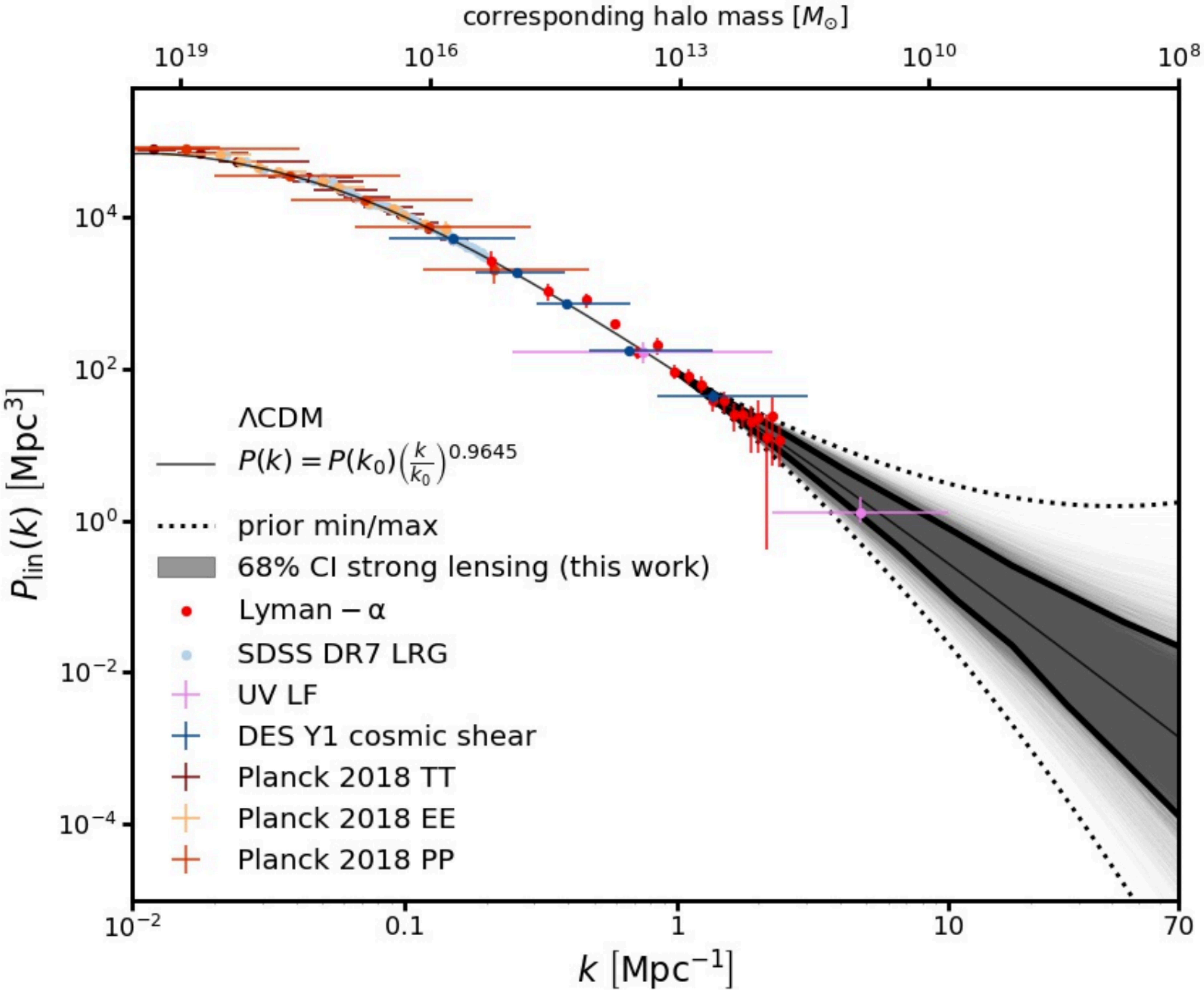
If many collapsed halos exist, we should soon be able to detect them



Applications beyond WDM/SIDM

the (primordial) matter power spectrum

(e.g. Gilman et al. 2022)
arXiv: 2112.03293

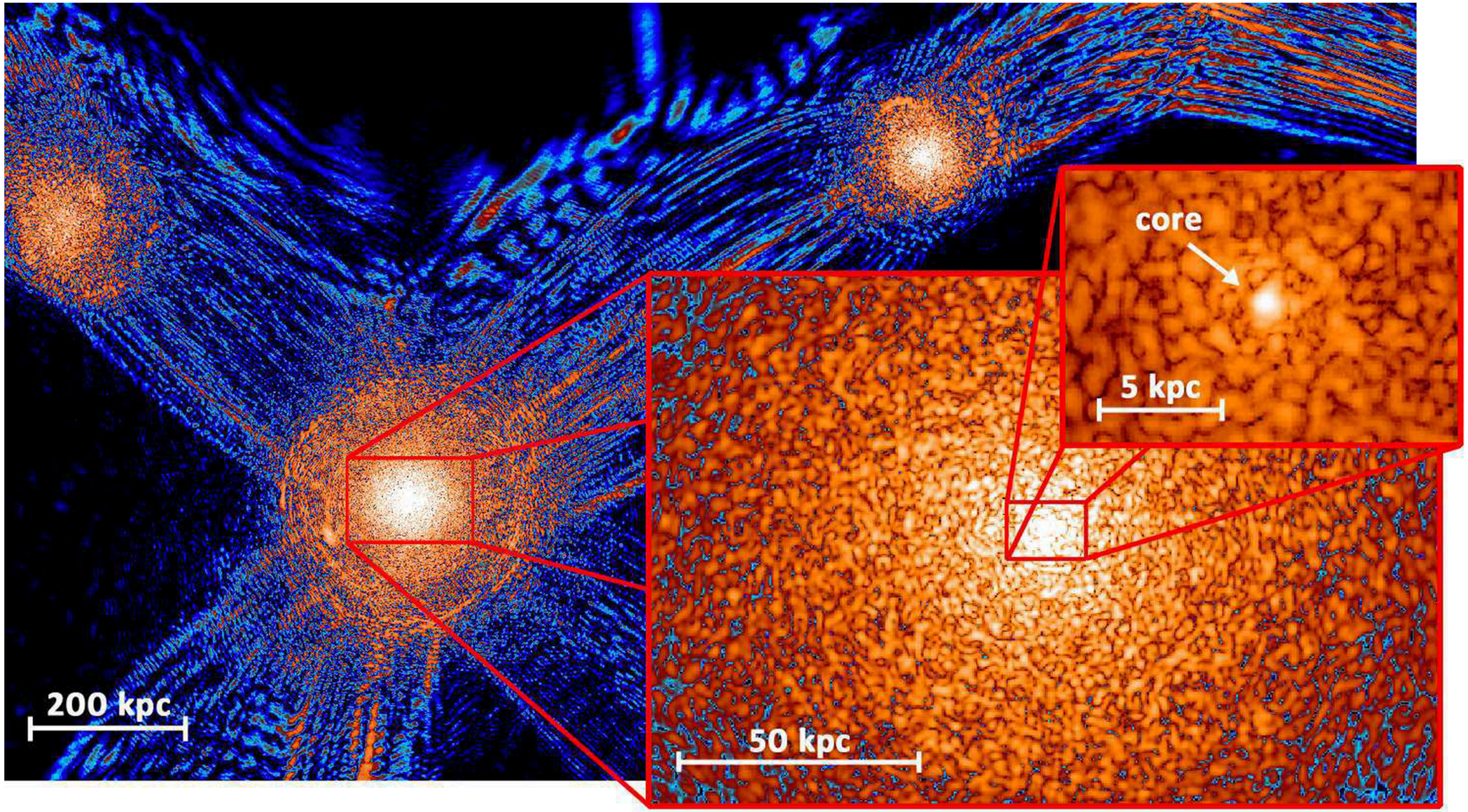


Schive et al. (2014)

Applications beyond WDM/SIDM

Ultra-light, wave, or “fuzzy” DM

(e.g. Laroche, Gilman et al. 2022)
arXiv: 2206.11269



Applications beyond WDM/SIDM

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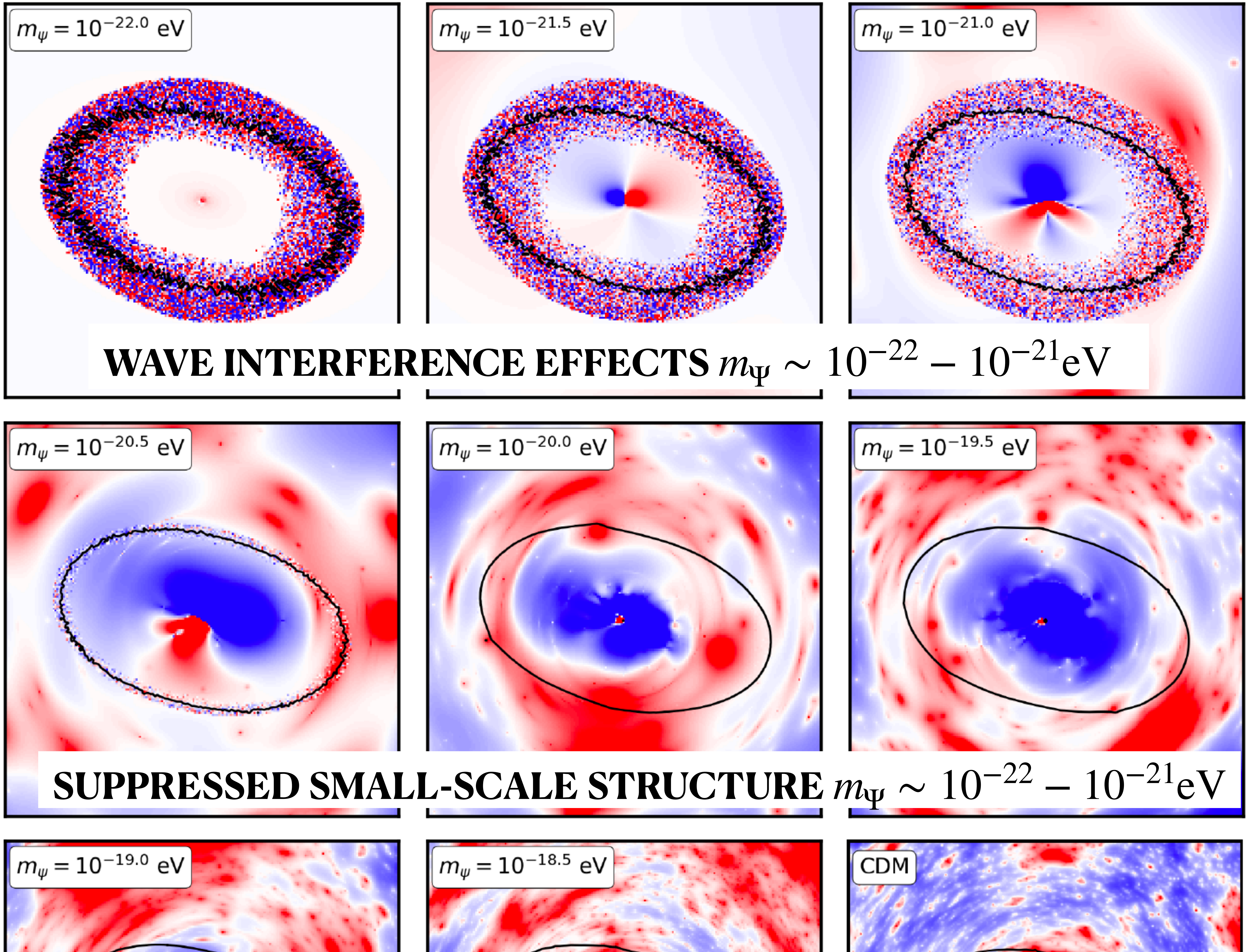

WAVE INTERFERENCE EFFECTS $m_\Psi \sim 10^{-22} - 10^{-21}\text{eV}$

SUPPRESSED SMALL-SCALE STRUCTURE $m_\Psi \sim 10^{-22} - 10^{-21}\text{eV}$

Ultra-light, wave, or “fuzzy” DM

(e.g. Laroche, Gilman et al. 2022)
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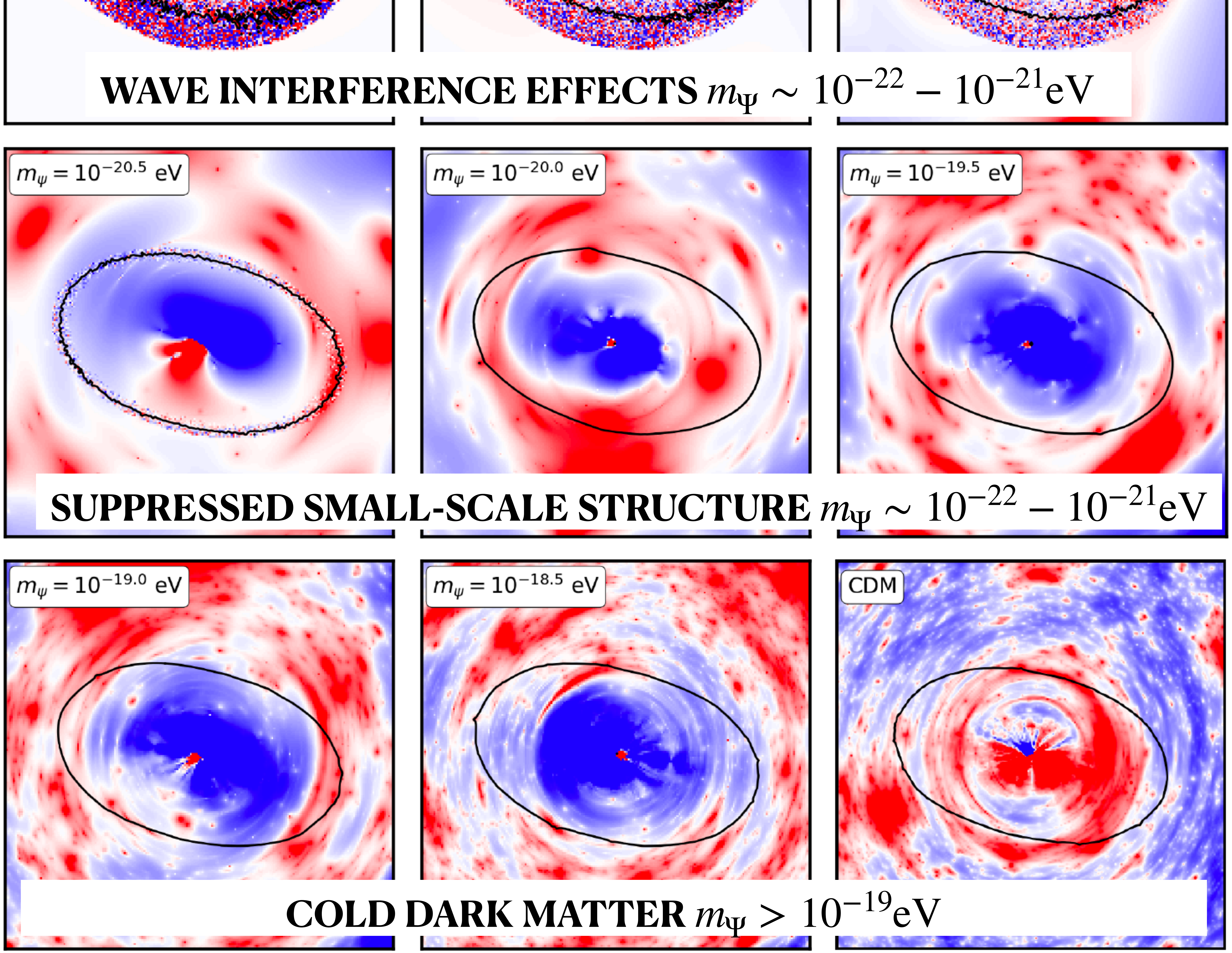


WAVE INTERFERENCE EFFECTS $m_\Psi \sim 10^{-22} - 10^{-21}\text{eV}$

SUPPRESSED SMALL-SCALE STRUCTURE $m_\Psi \sim 10^{-22} - 10^{-21}\text{eV}$

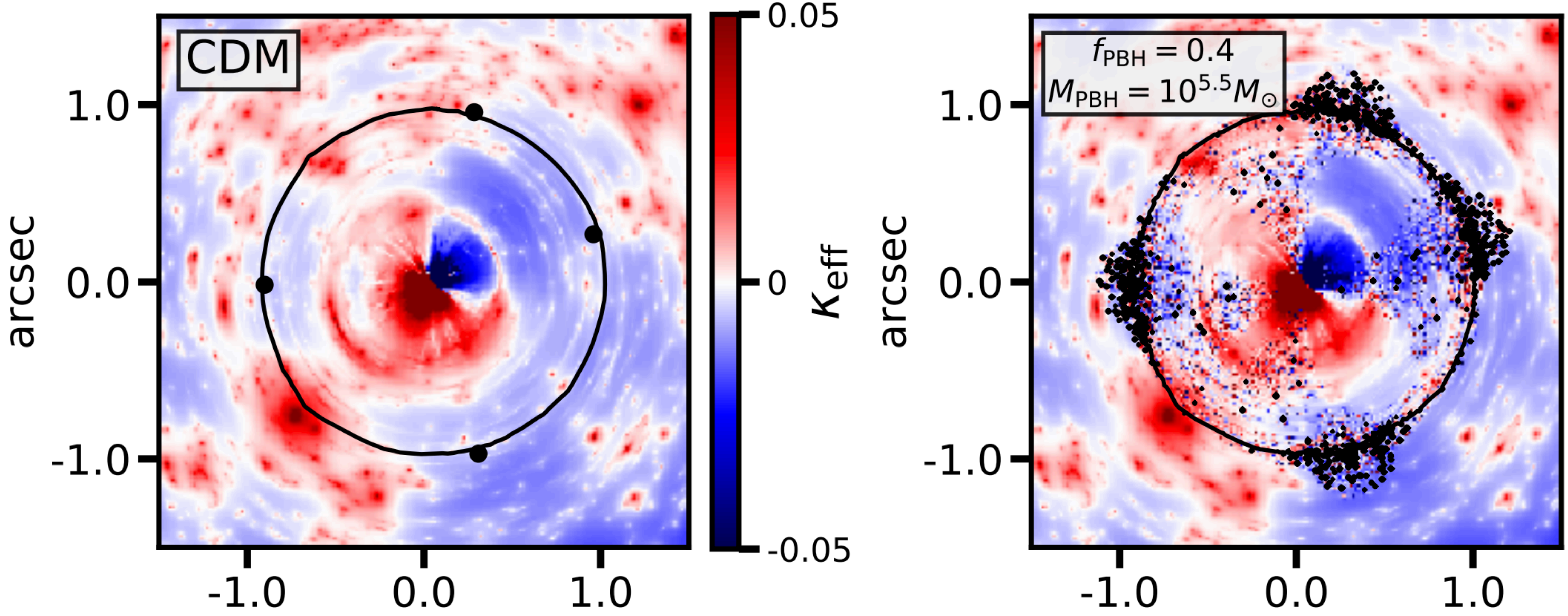
COLD DARK MATTER $m_\Psi > 10^{-19}\text{eV}$

Applications beyond WDM/SIDM

Massive free-floating black holes

(Dike, Gilman, Treu; 2022)

arXiv: 2210.09493



Takeaways:

JWST has observed 31 lens systems that will revolutionize our understanding of dark matter through the gravitational detection of dark halos

Expect new constraints on WDM/SIDM by end of 2024

Upcoming surveys will find hundreds more strong lenses!