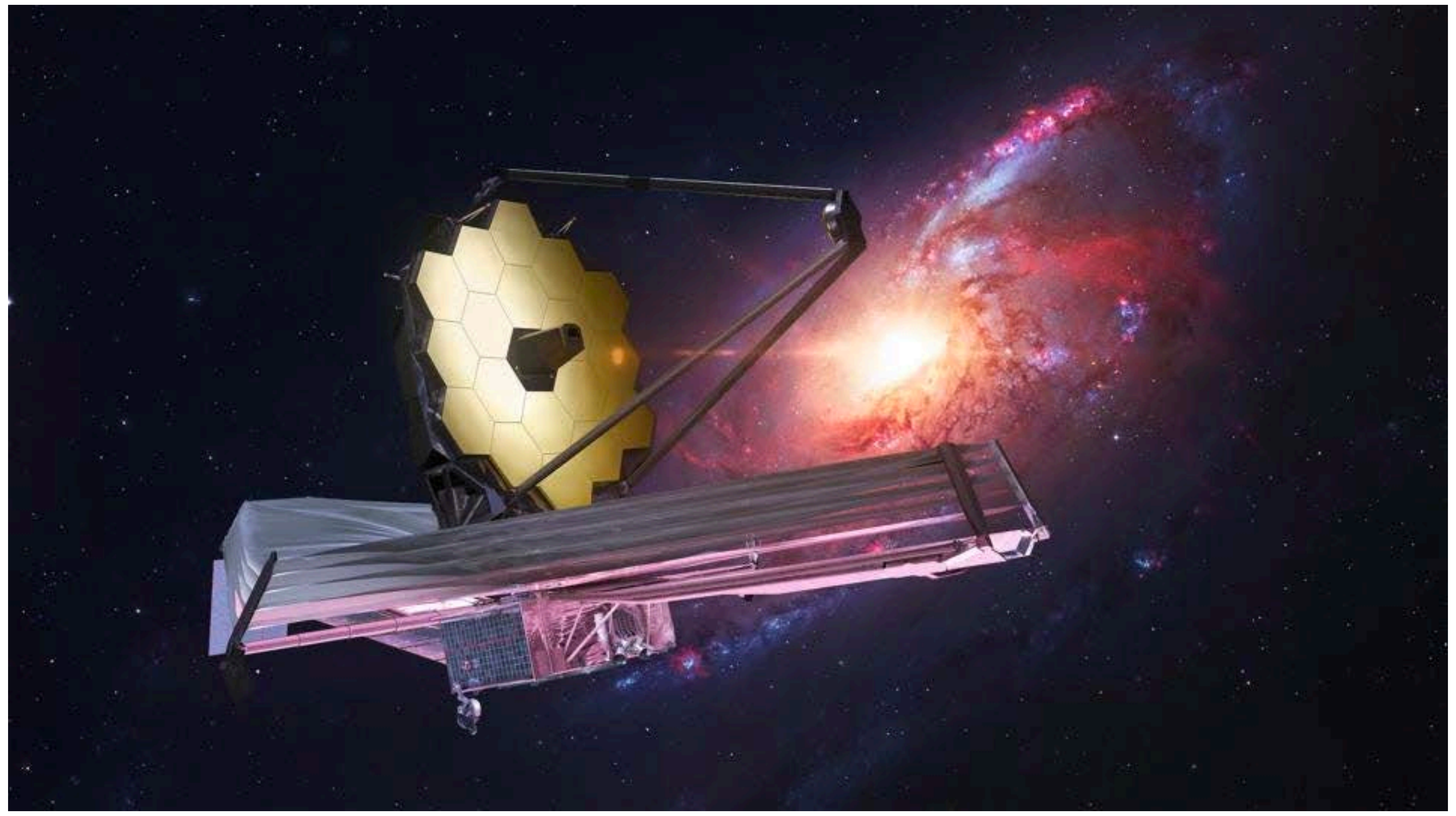
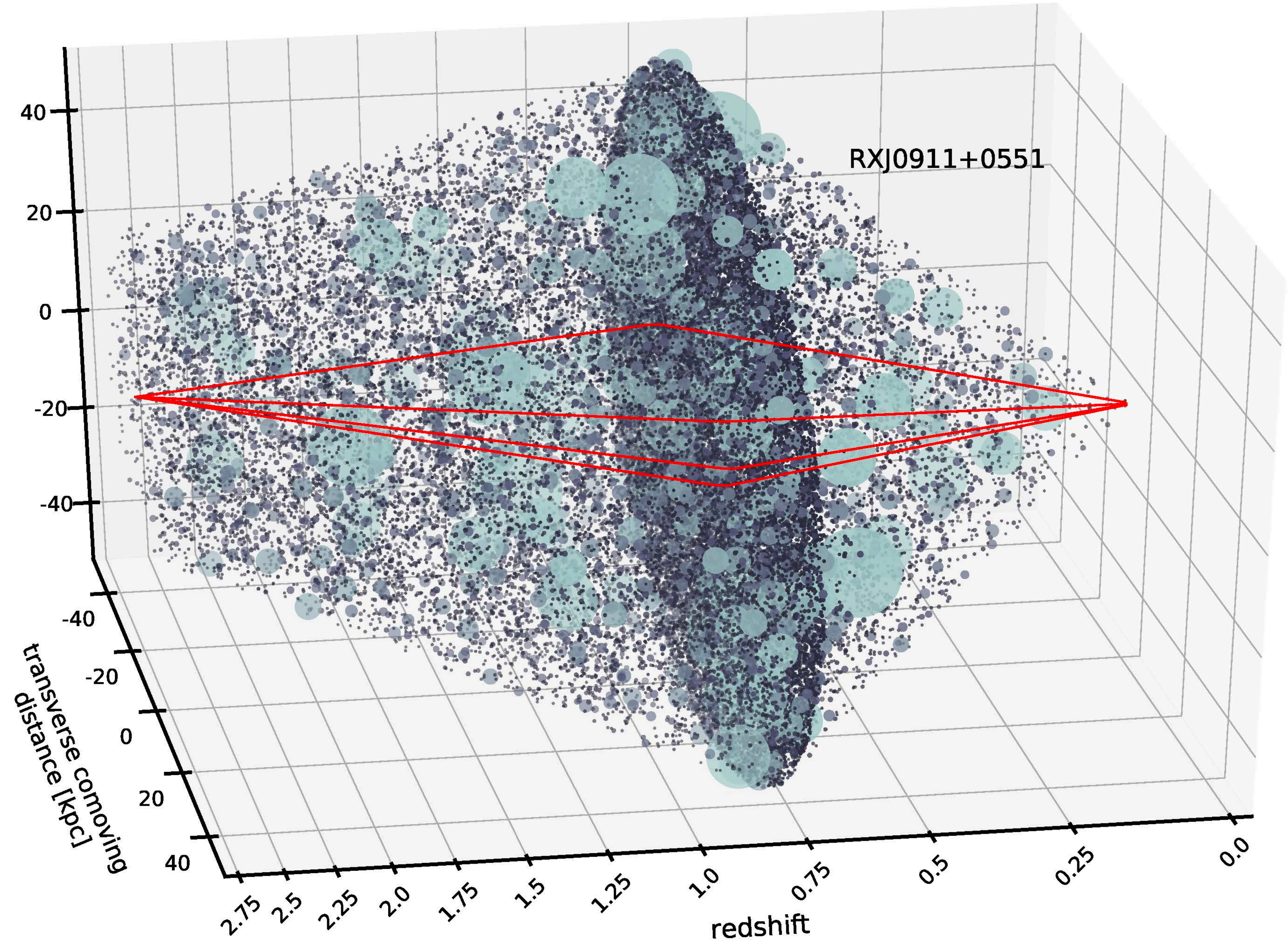
Strong lensing and dark matter II:

Signatures of beyond-CDM physics in quadruply imaged quasars

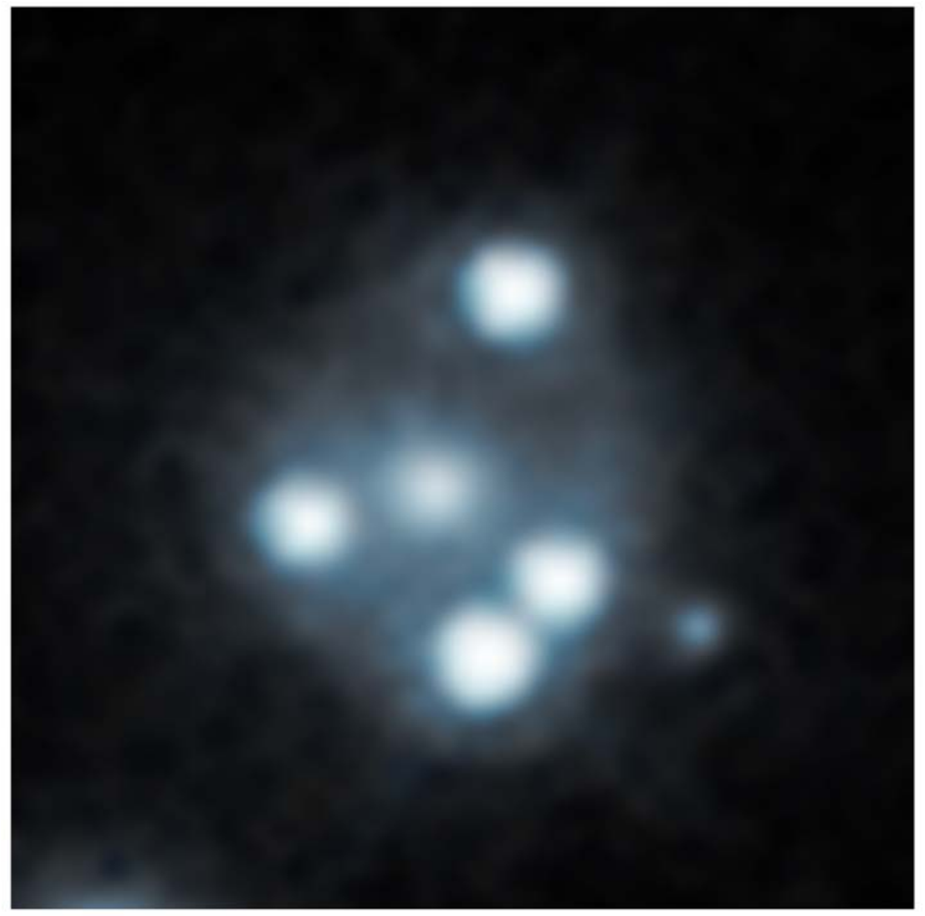




Daniel Gilman

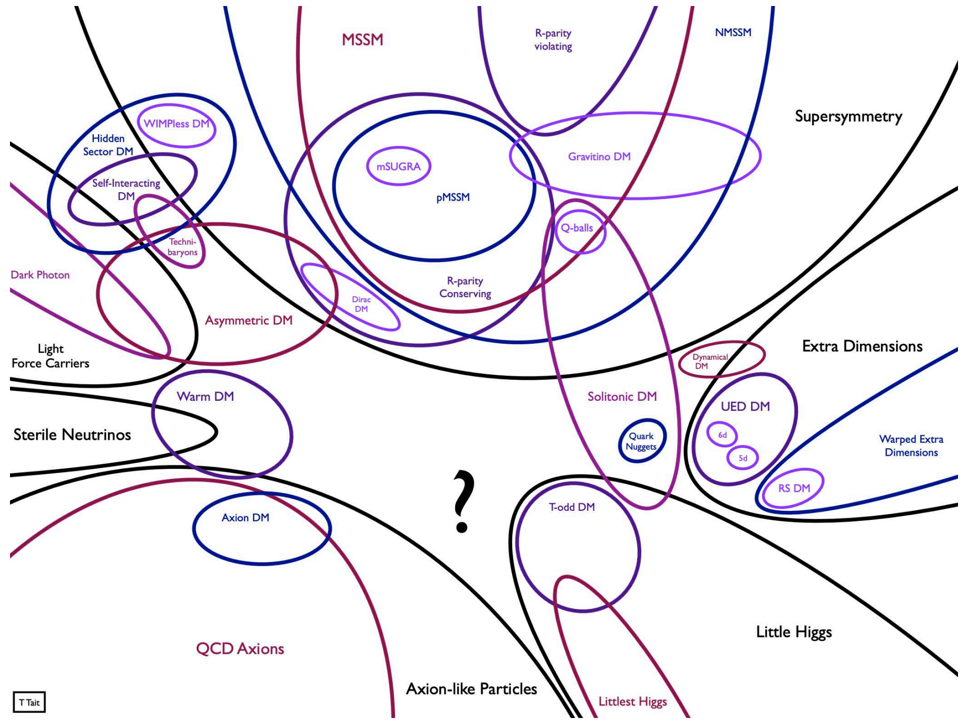
Brinson Prize Fellow

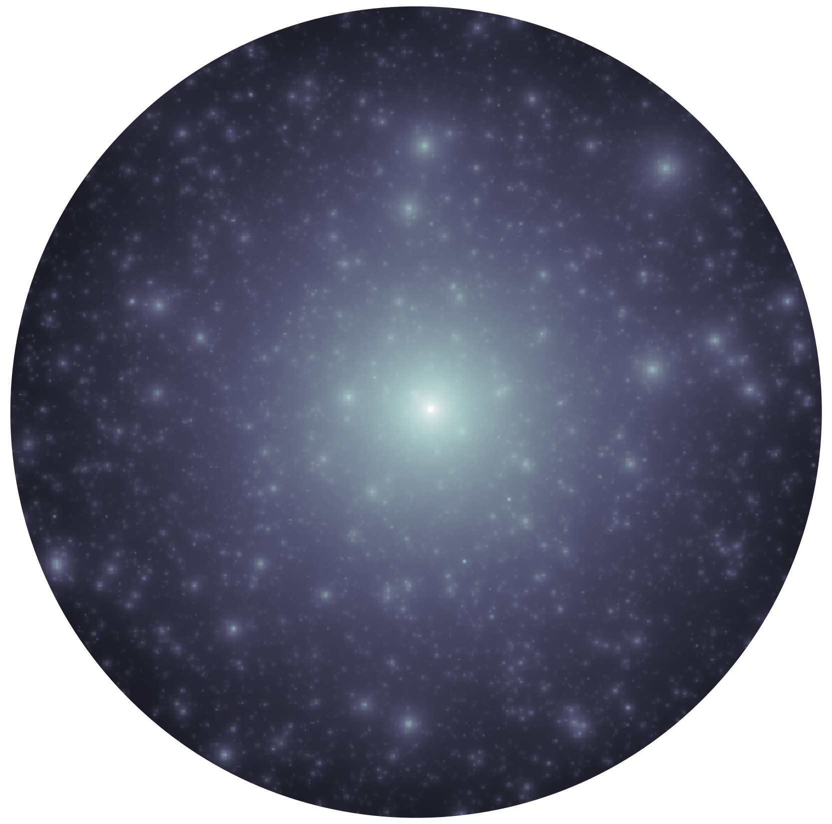
University of Chicago



PACIFIC 2024

Moorea, FP





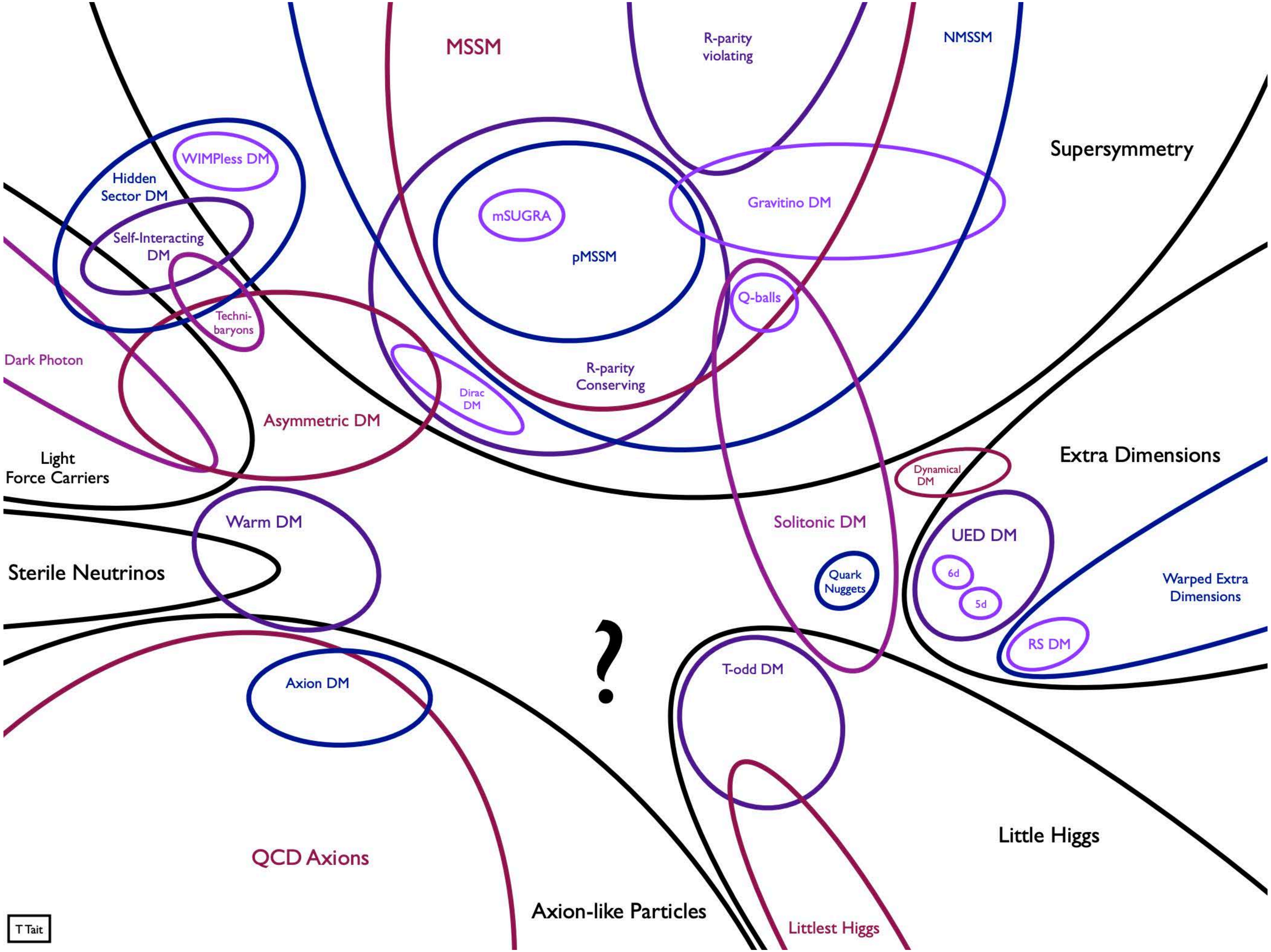
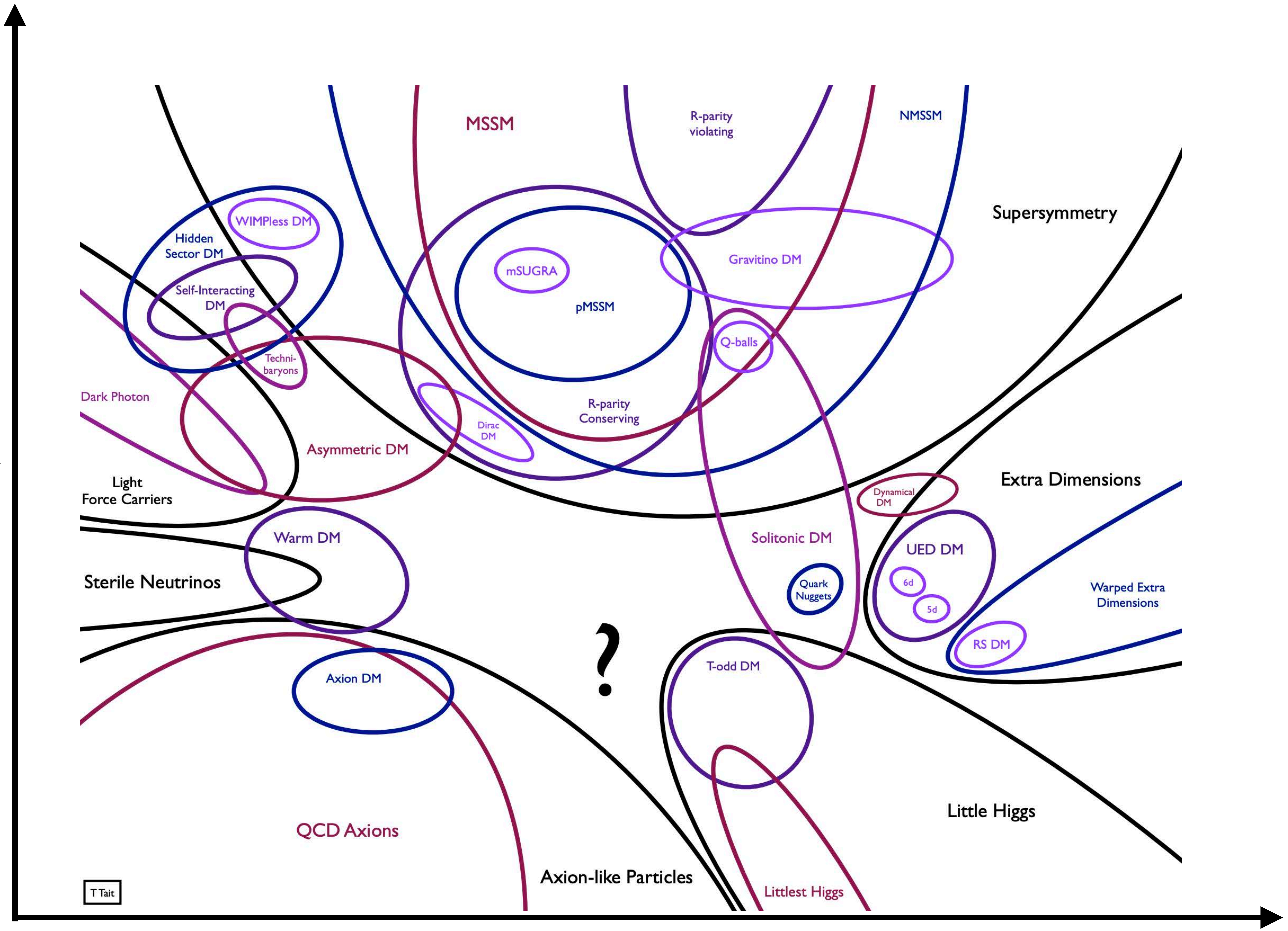
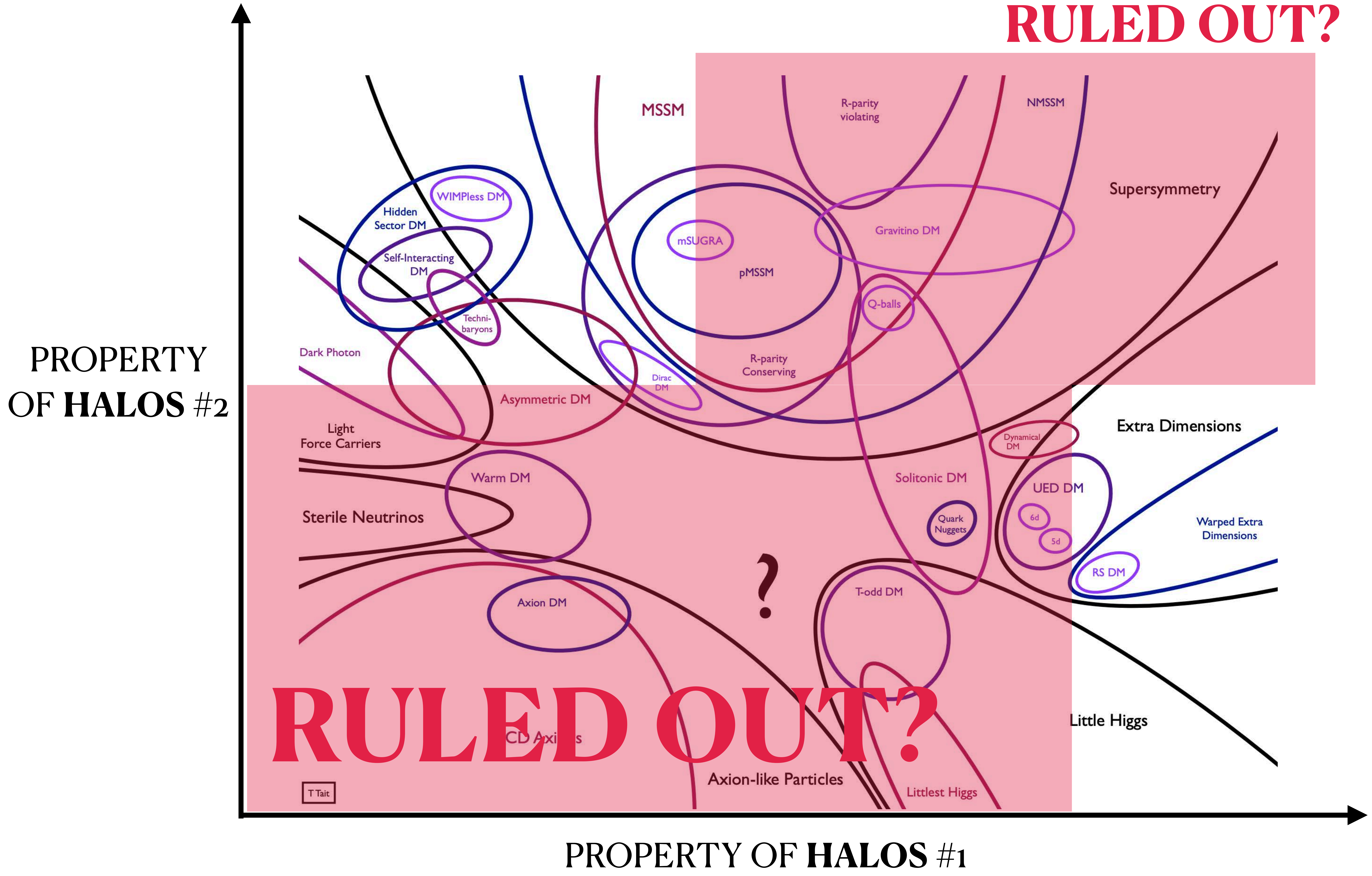


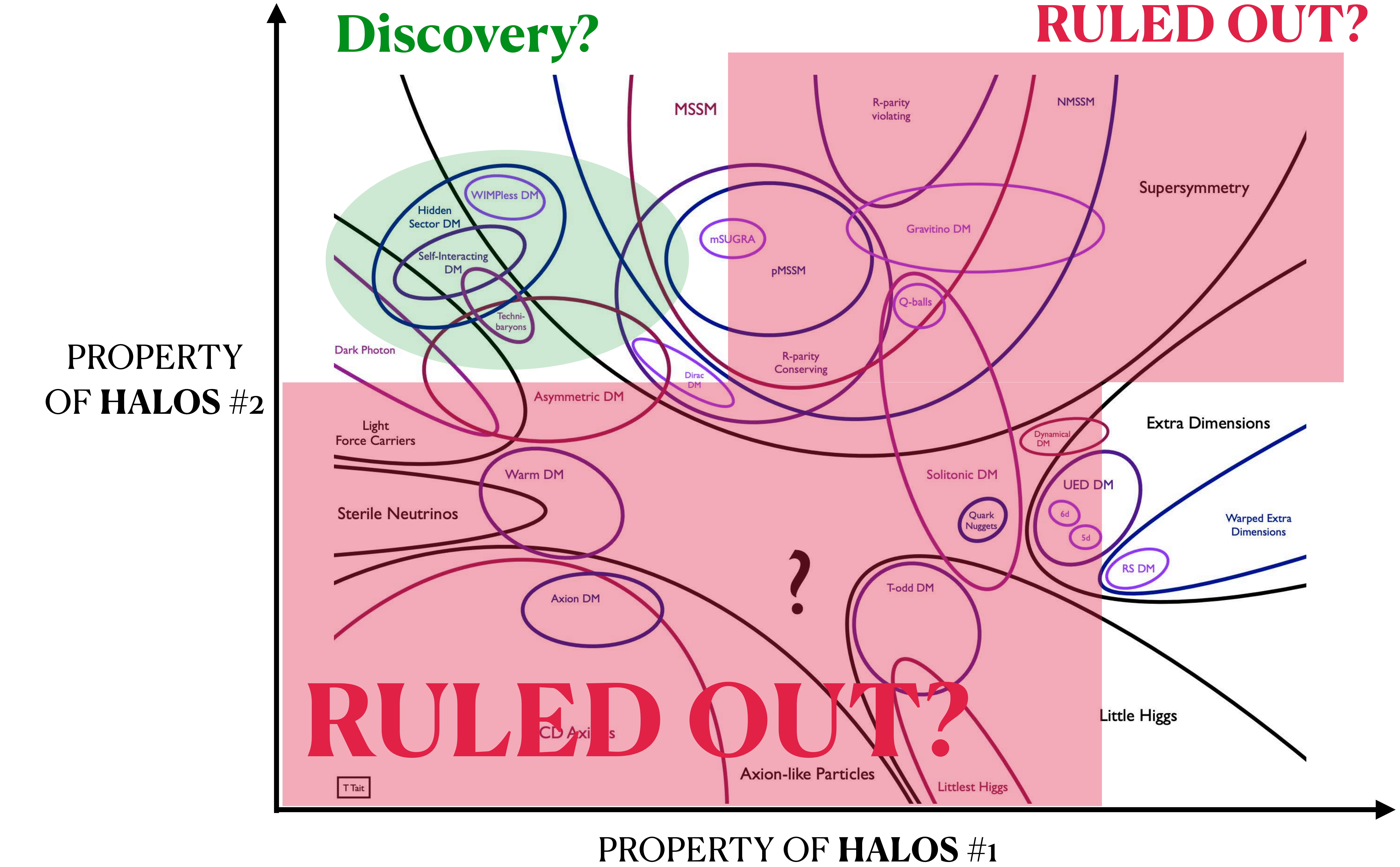
Figure by Tim Tait



PROPERTY OF **HALOS** #2

PROPERTY OF **HALOS** #1


RULED OUT?
MSSM
R-parity
violating
NMSSM
Supersymmetry
WIMPless DM
Hidden
Sector DM
Self-Interacting
DM
Techni-
baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity
Conserving
Dirac
DM
Dark Photon
Asymmetric DM
Light
Force Carriers
Dynamical
DM
Extra Dimensions
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark
Nuggets
6d
5d
Warped Extra
Dimensions
RS DM
?
T-odd DM
Axion DM
Little Higgs
RULED OUT?
Axion-like Particles
Littlest Higgs
T Tait
PROPERTY
OF HALOS #2
PROPERTY OF HALOS #1



Discovery?
RULED OUT?
PROPERTY OF HALOS #2
PROPERTY OF HALOS #1
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
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RULED OUT?
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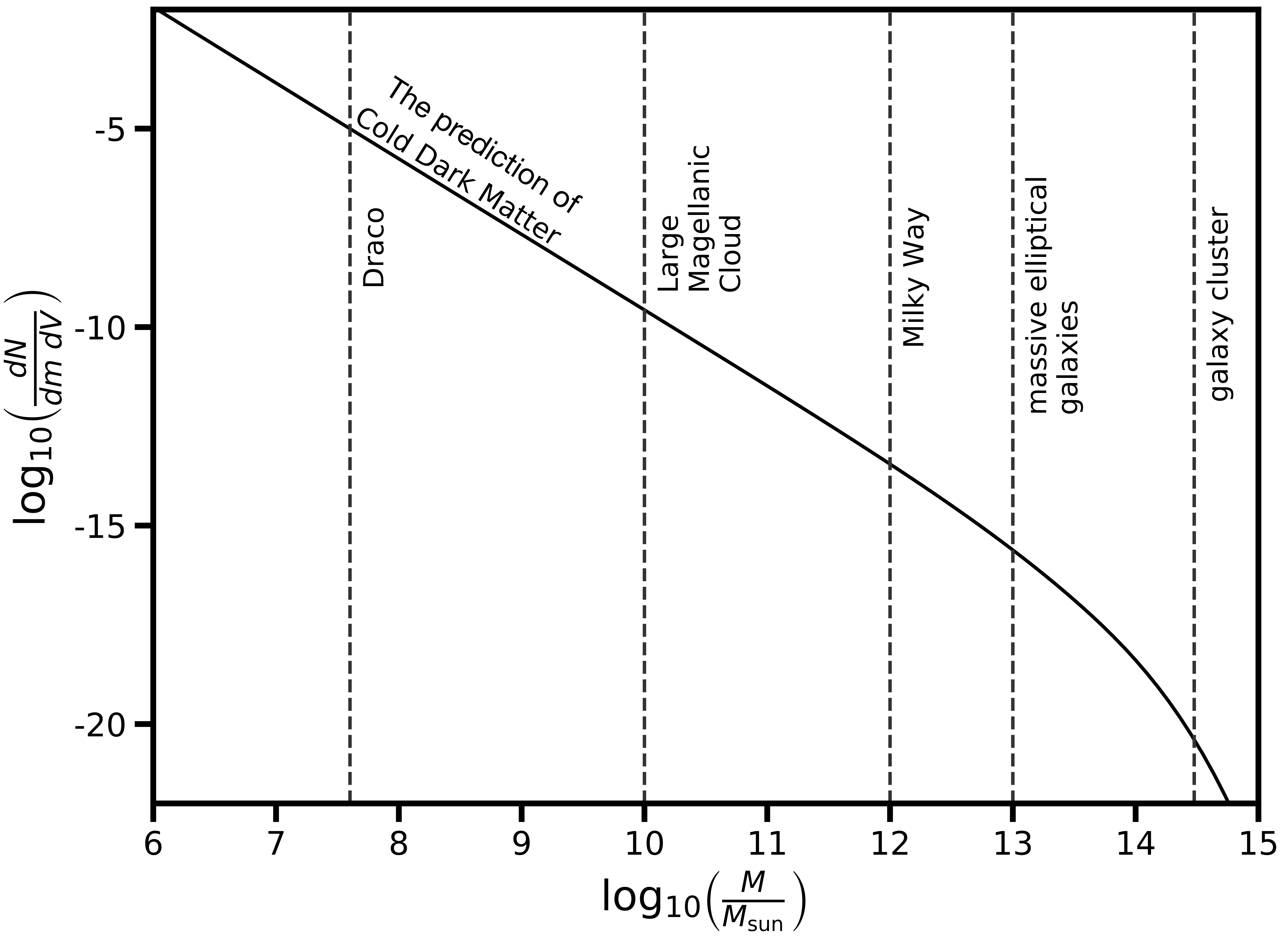
The prediction of
Cold Dark Matter
Draco
Large
Magellanic
Cloud
Milky Way
massive elliptical
galaxies
galaxy cluster
-5
-10
-15
-20
6
7
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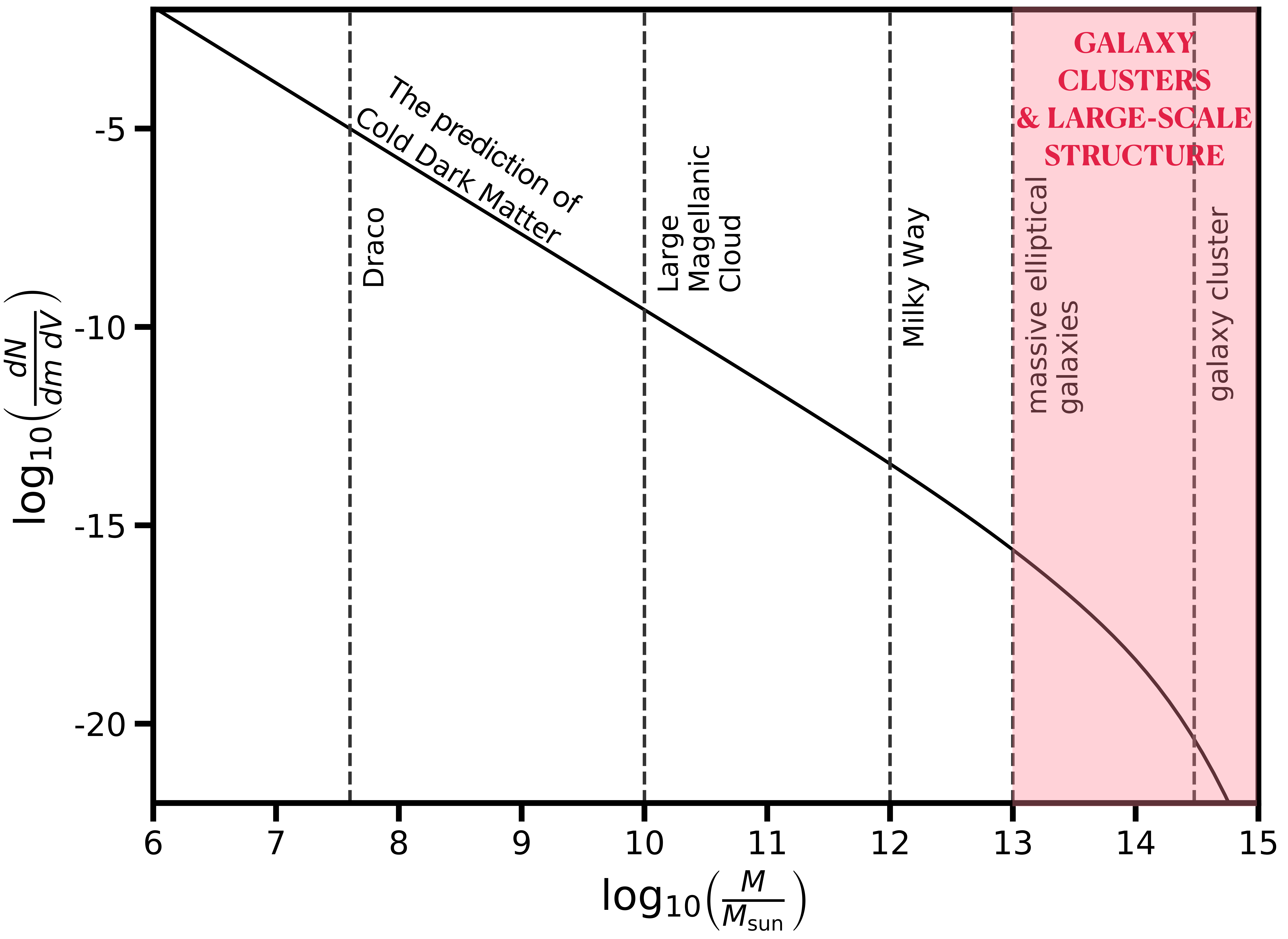
14
15
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
$\log_{10}\left(\frac{M}{M_{\mathrm{sun}}}\right)$



GALAXY CLUSTERS & LARGE-SCALE STRUCTURE
The prediction of Cold Dark Matter
Draco
Large Magellanic Cloud
Milky Way
massive elliptical galaxies
galaxy cluster
-5
-10
-15
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6
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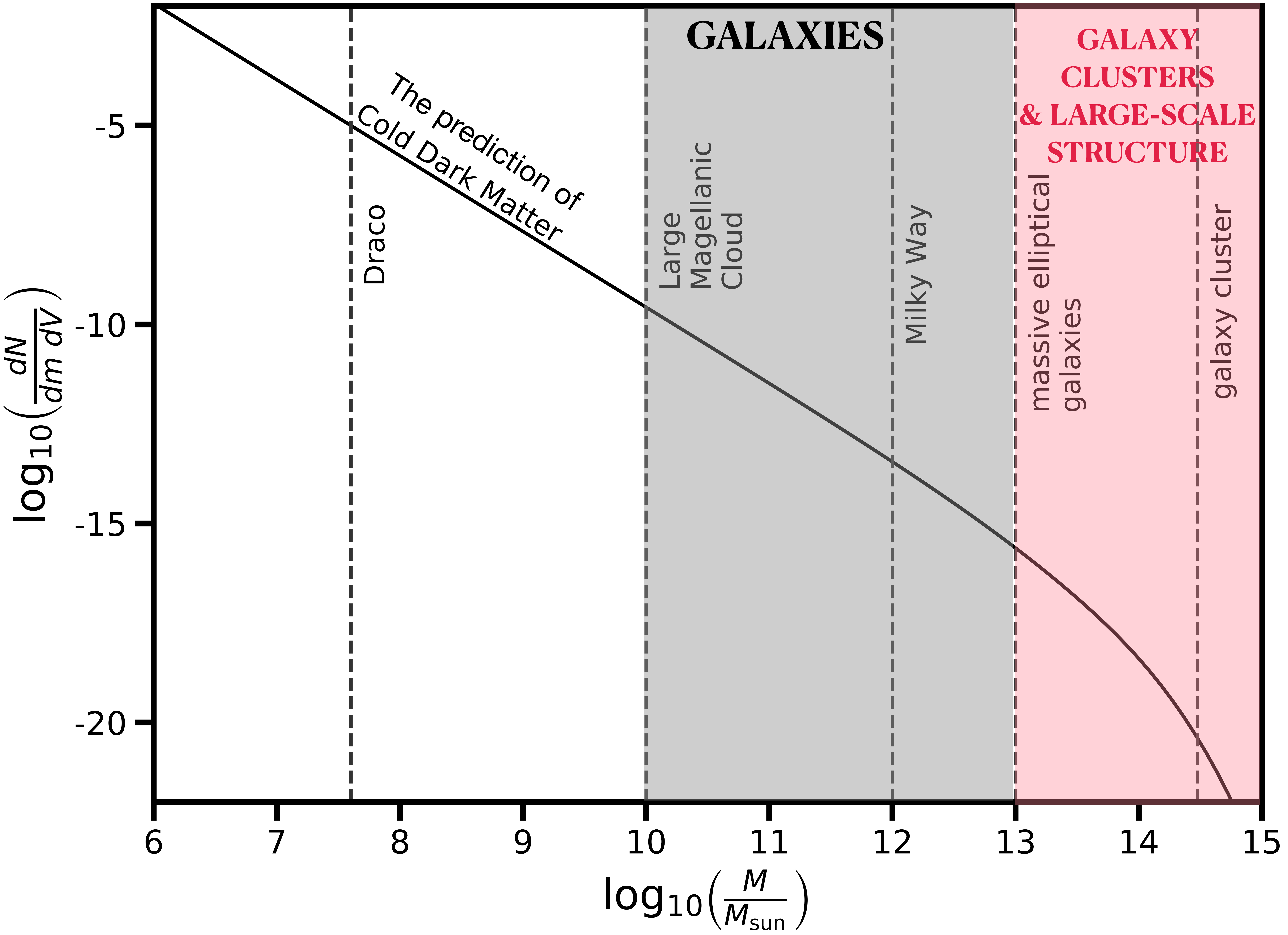

GALAXIES
GALAXY CLUSTERS & LARGE-SCALE STRUCTURE
The prediction of Cold Dark Matter
Draco
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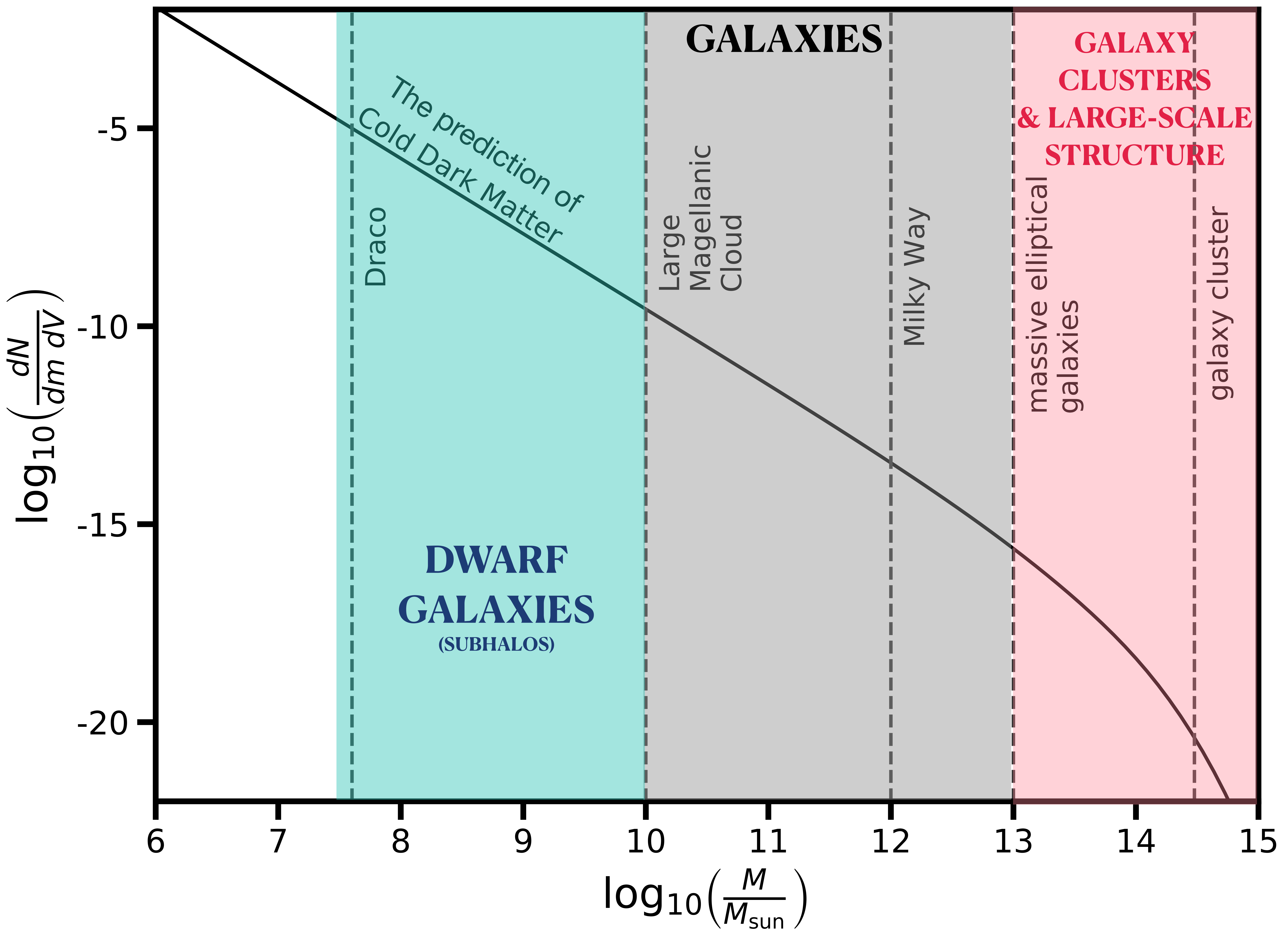
GALAXIES
GALAXY CLUSTERS & LARGE-SCALE STRUCTURE
The prediction of Cold Dark Matter
Draco
Large Magellanic Cloud
Milky Way
massive elliptical galaxies
galaxy cluster
DWARF GALAXIES
(SUBHALOS)
-5
-10
-15
-20
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
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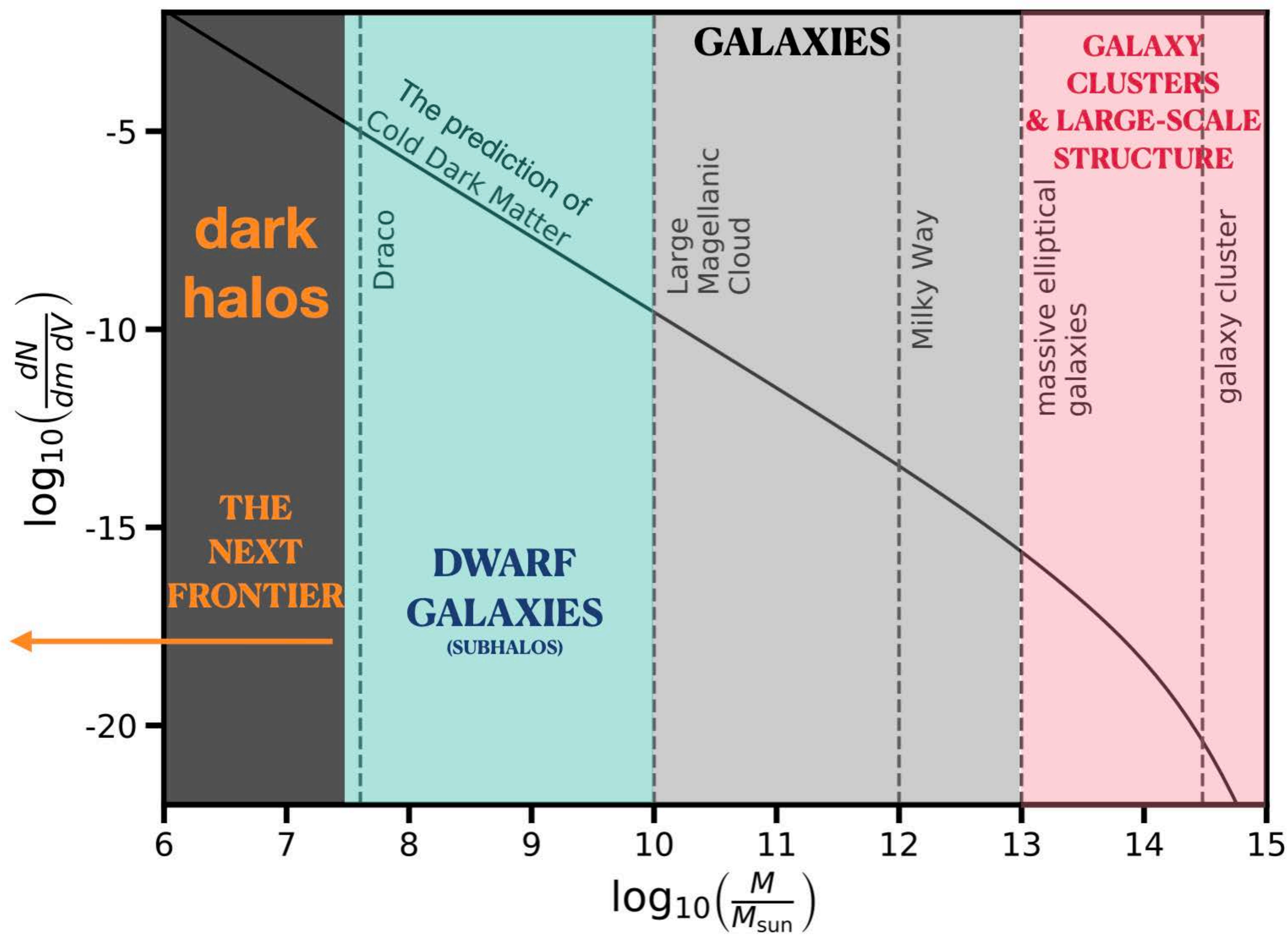
$\log_{10}\left(\frac{M}{M_{\rm sun}}\right)$



GALAXIES
GALAXY CLUSTERS & LARGE-SCALE STRUCTURE
The prediction of Cold Dark Matter
dark halos
Draco
Large Magellanic Cloud
Milky Way
massive elliptical galaxies
galaxy cluster
THE NEXT FRONTIER
DWARF GALAXIES
(SUBHALOS)
-5
-10
-15
-20
6
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11
12
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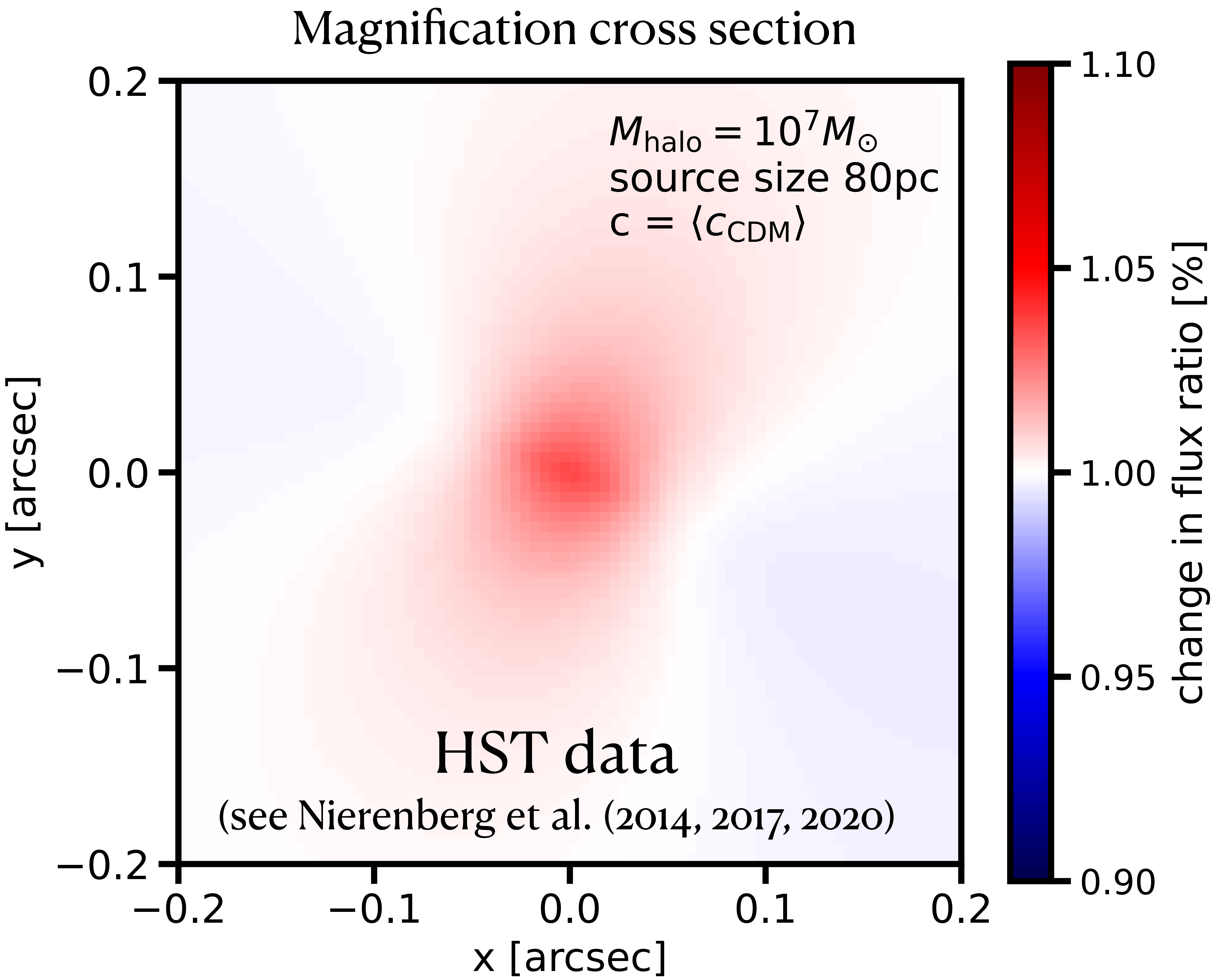
14
15
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
$\log_{10}\left(\frac{M}{M_{\text{sun}}}\right)$

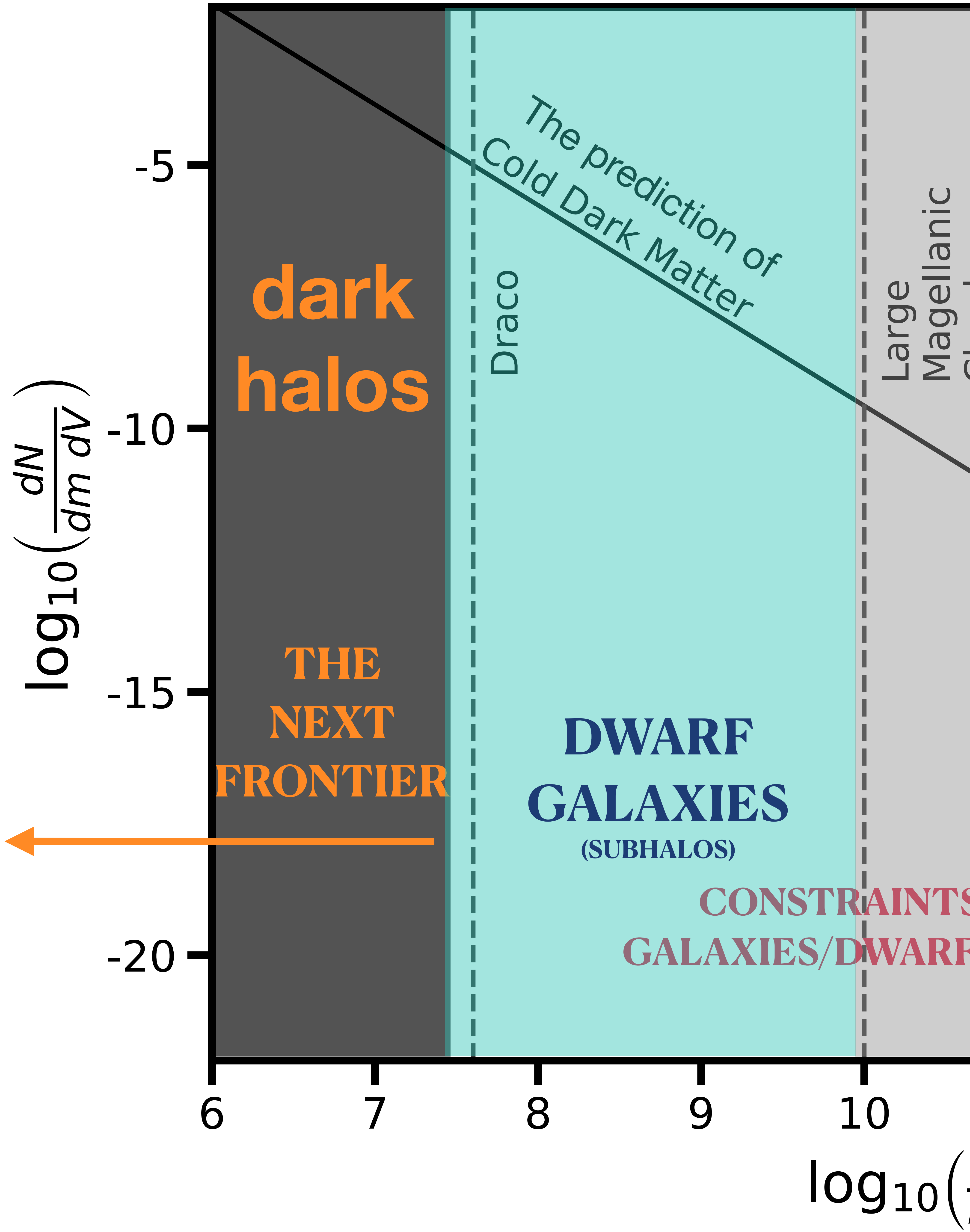
Image magnifications $\sim \partial^2\Psi(r)/\partial r^2 \propto$ projected mass

-> sensitive to small-scale structure

$M = 10^7 M_\odot$



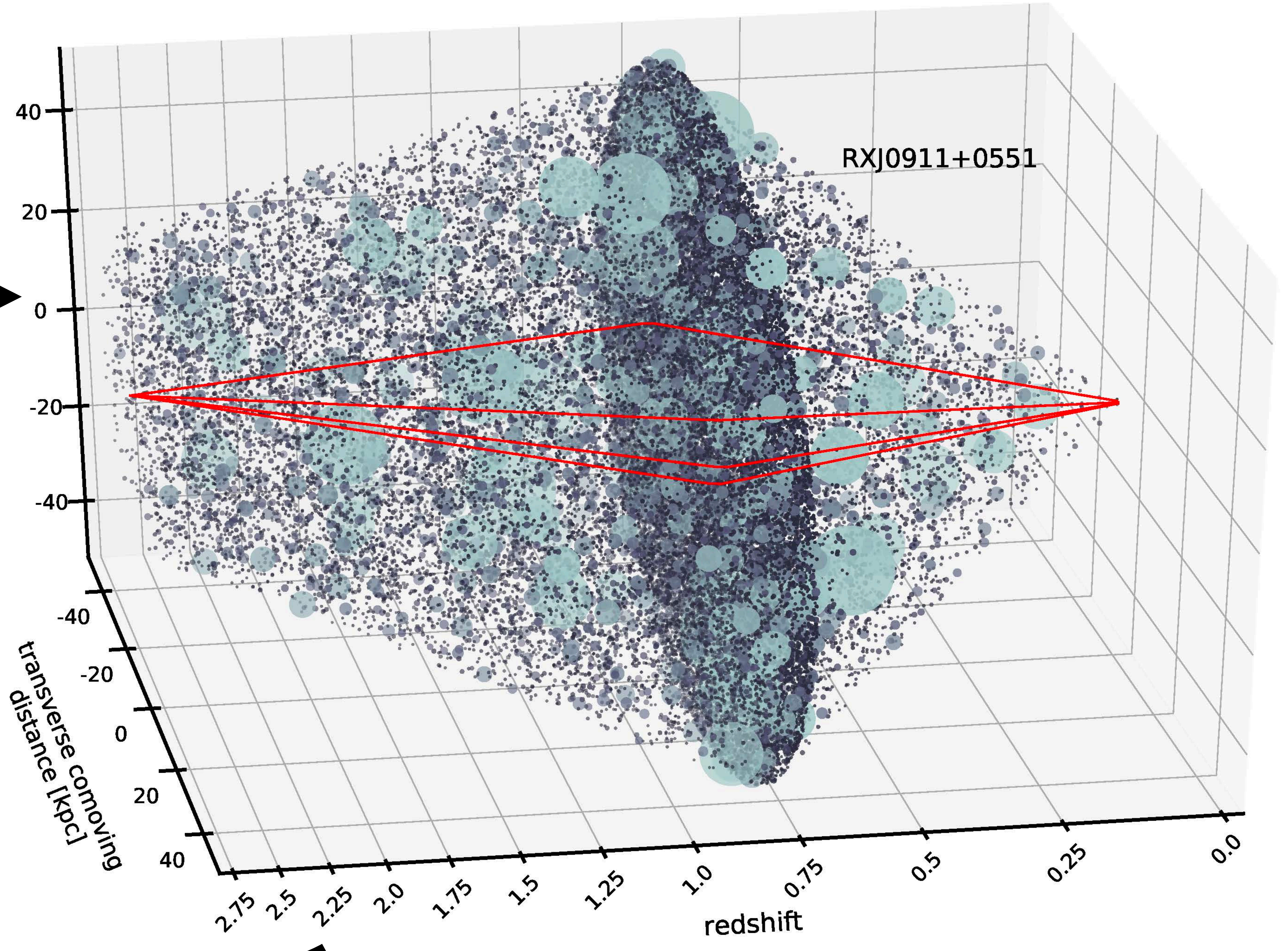
Magnification cross section
$M_{\rm halo} = 10^7 M_\odot$
source size 80pc
c = $\langle c_{\rm CDM} \rangle$
HST data
(see Nierenberg et al. (2014, 2017, 2020)
y [arcsec]
x [arcsec]
change in flux ratio [%]
1.10
1.05
1.00
0.95
0.90



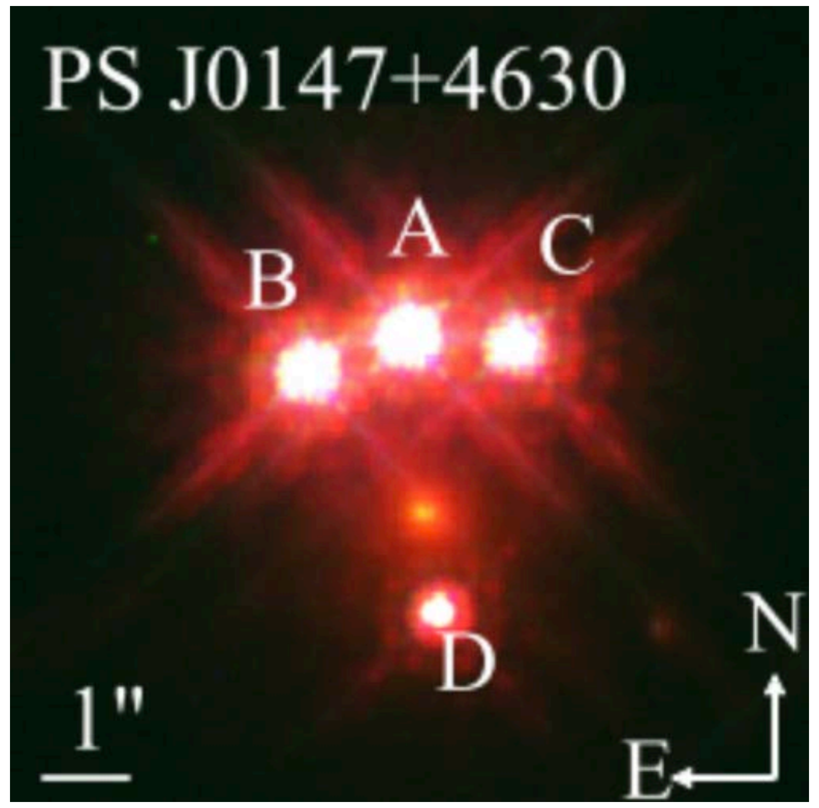
The prediction of Cold Dark Matter
dark halos
Draco
Large Magellanic
THE NEXT FRONTIER
DWARF GALAXIES
(SUBHALOS)
CONSTRAINTS
GALAXIES/DWARF
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
-5
-10
-15
-20
6
7
8
9
10

Simulation pipeline

Dark matter theory → Halo mass function, halo density profiles →



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

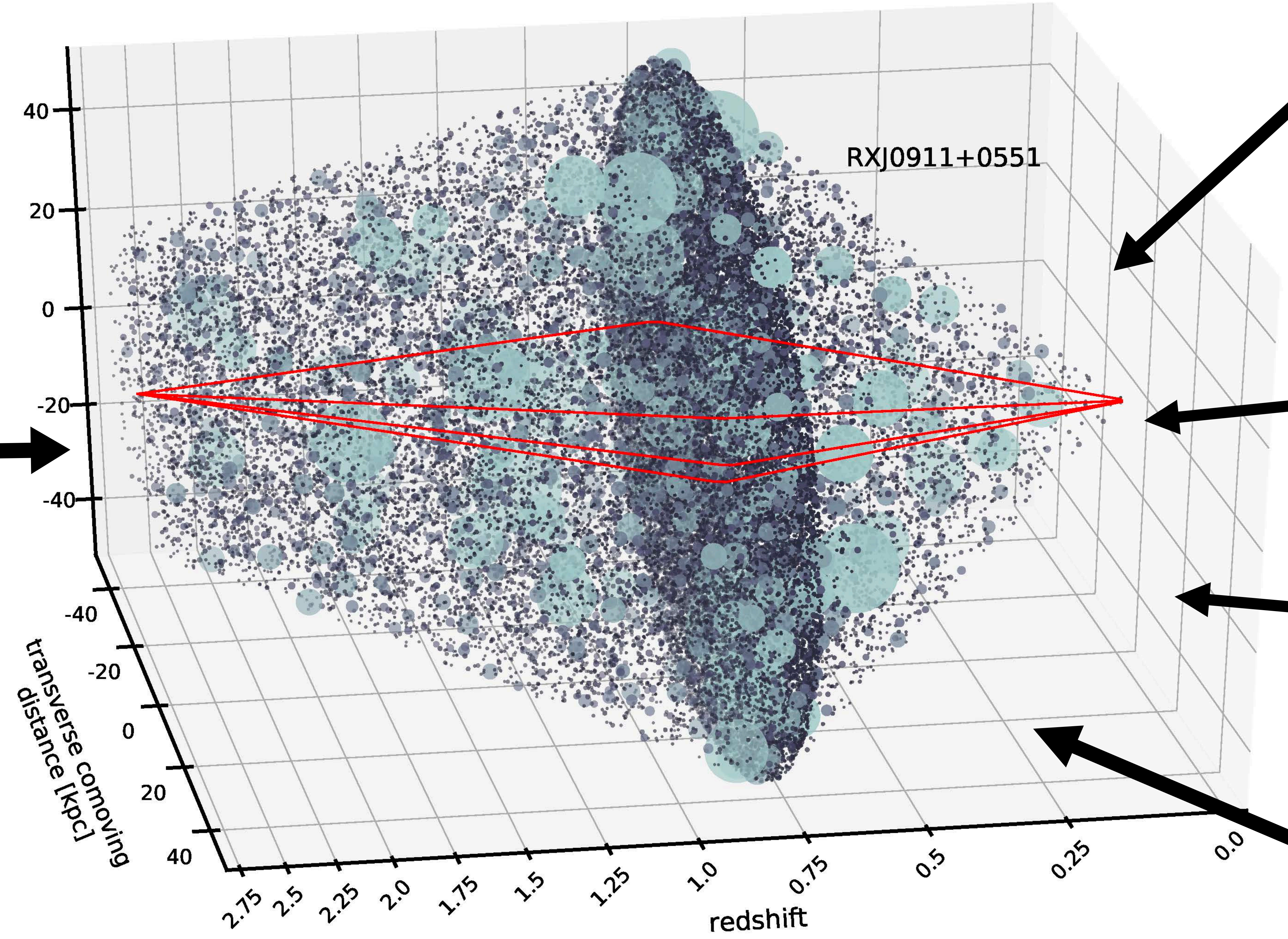


Compare with data

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

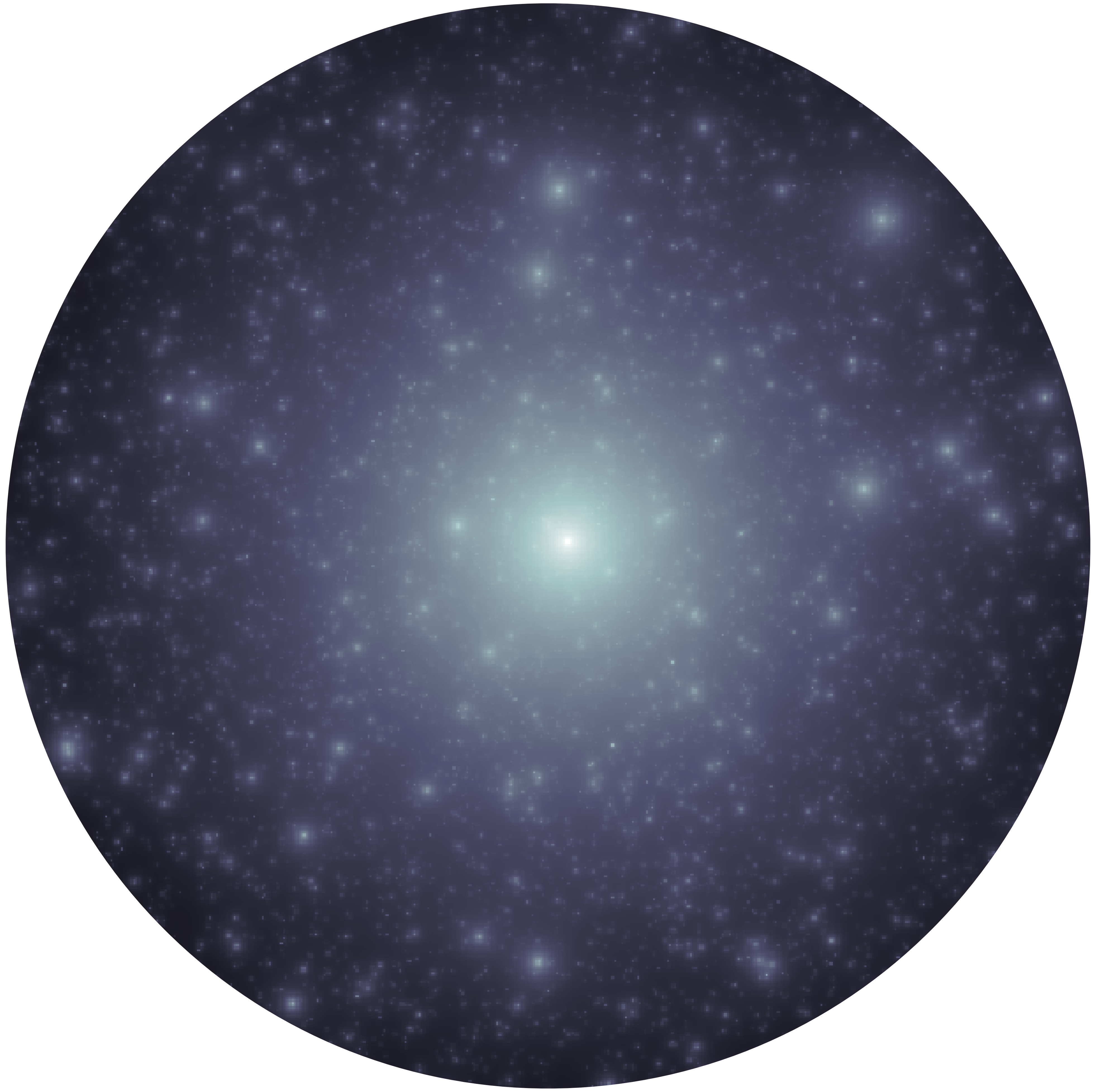
The effects of baryons, e.g. tidal stripping, heating, etc.

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

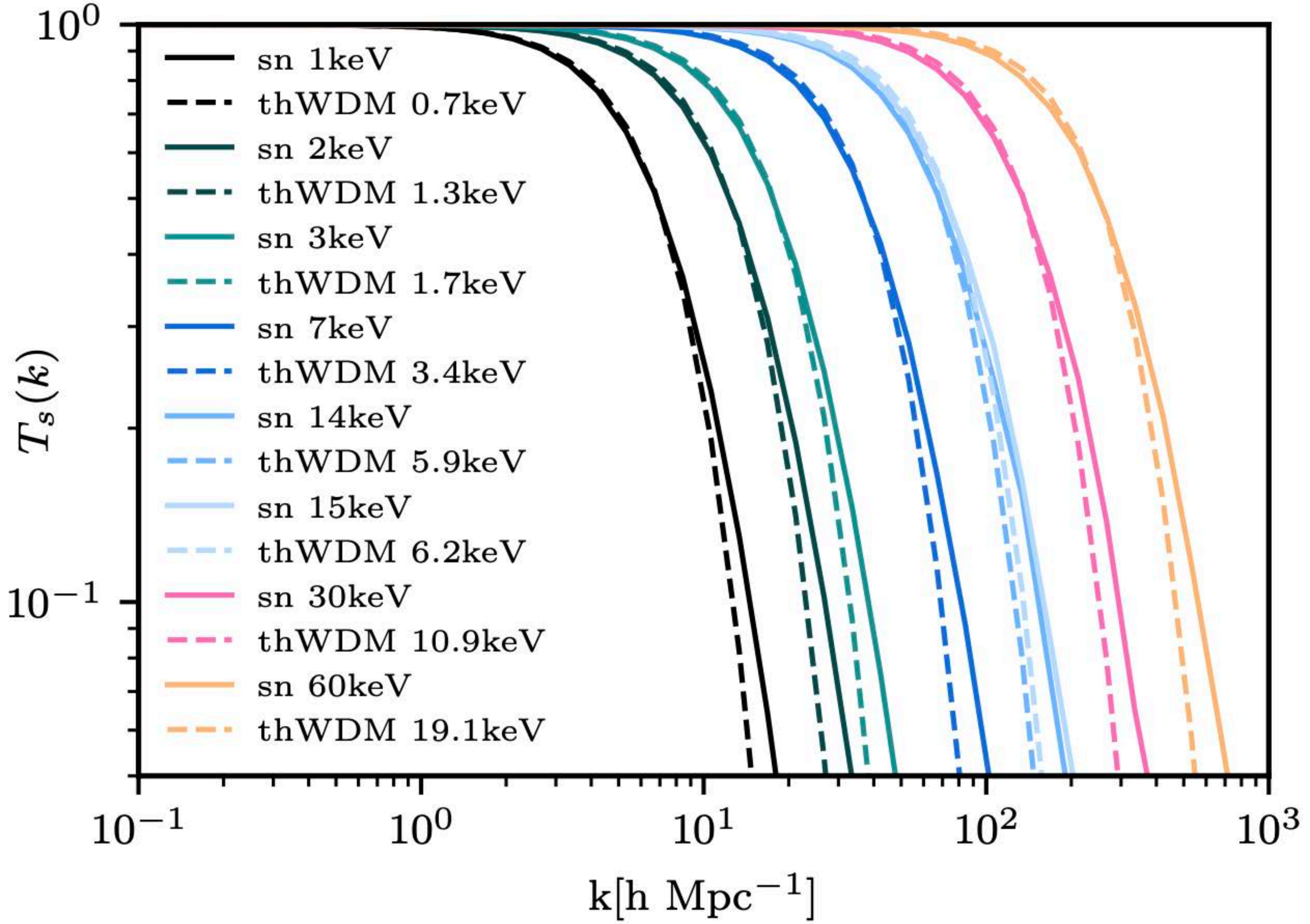
CDM

- 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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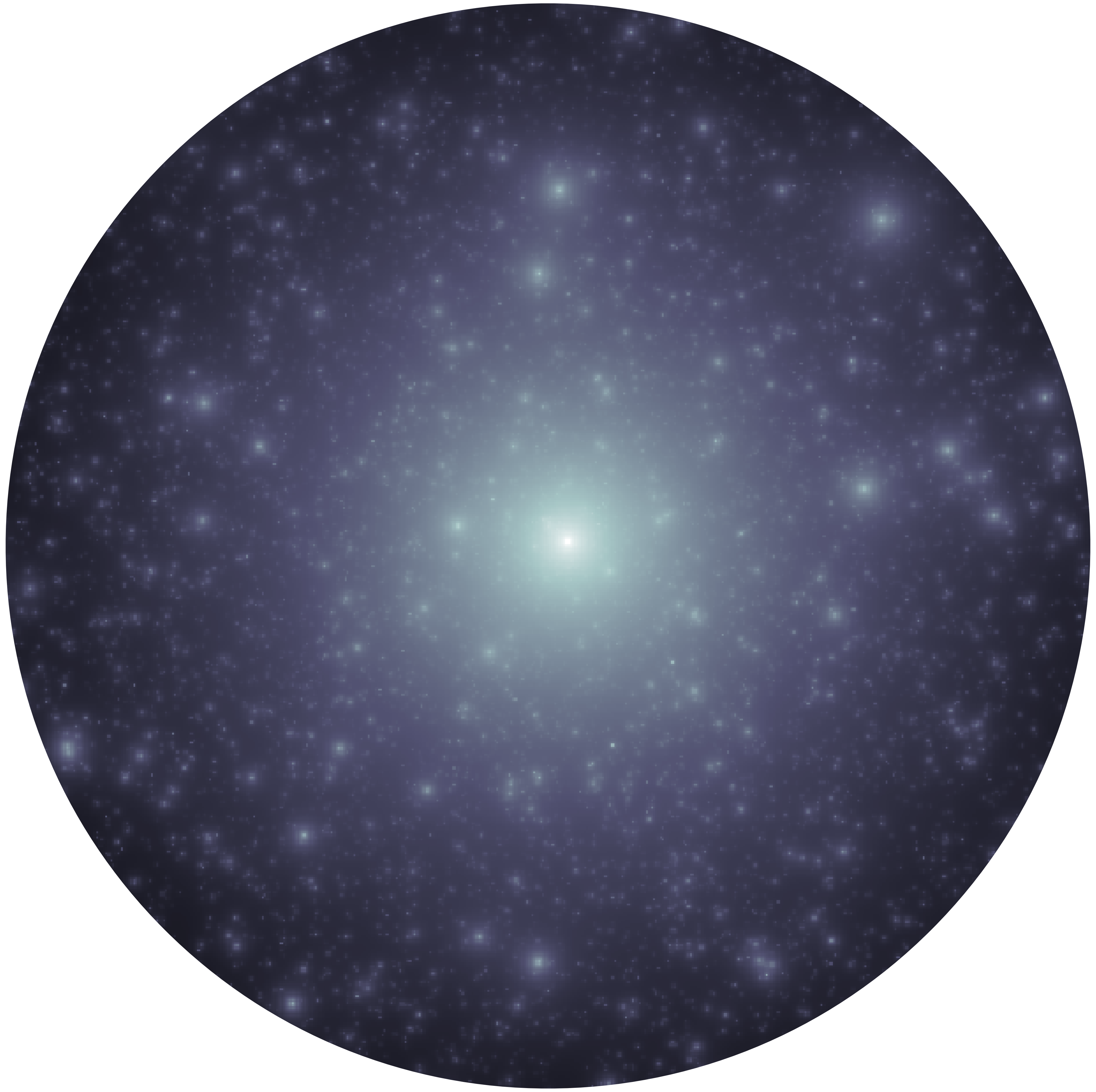

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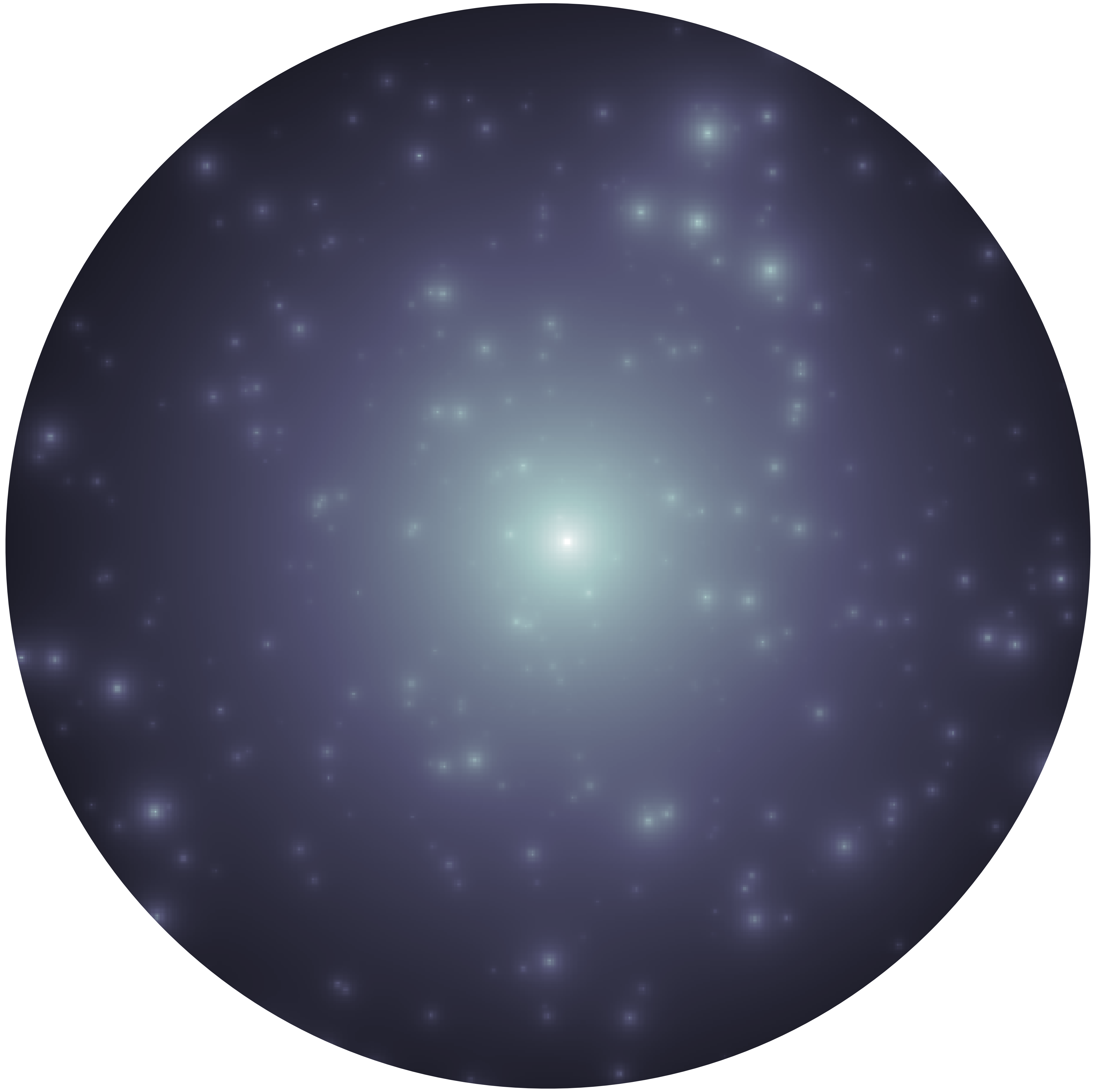
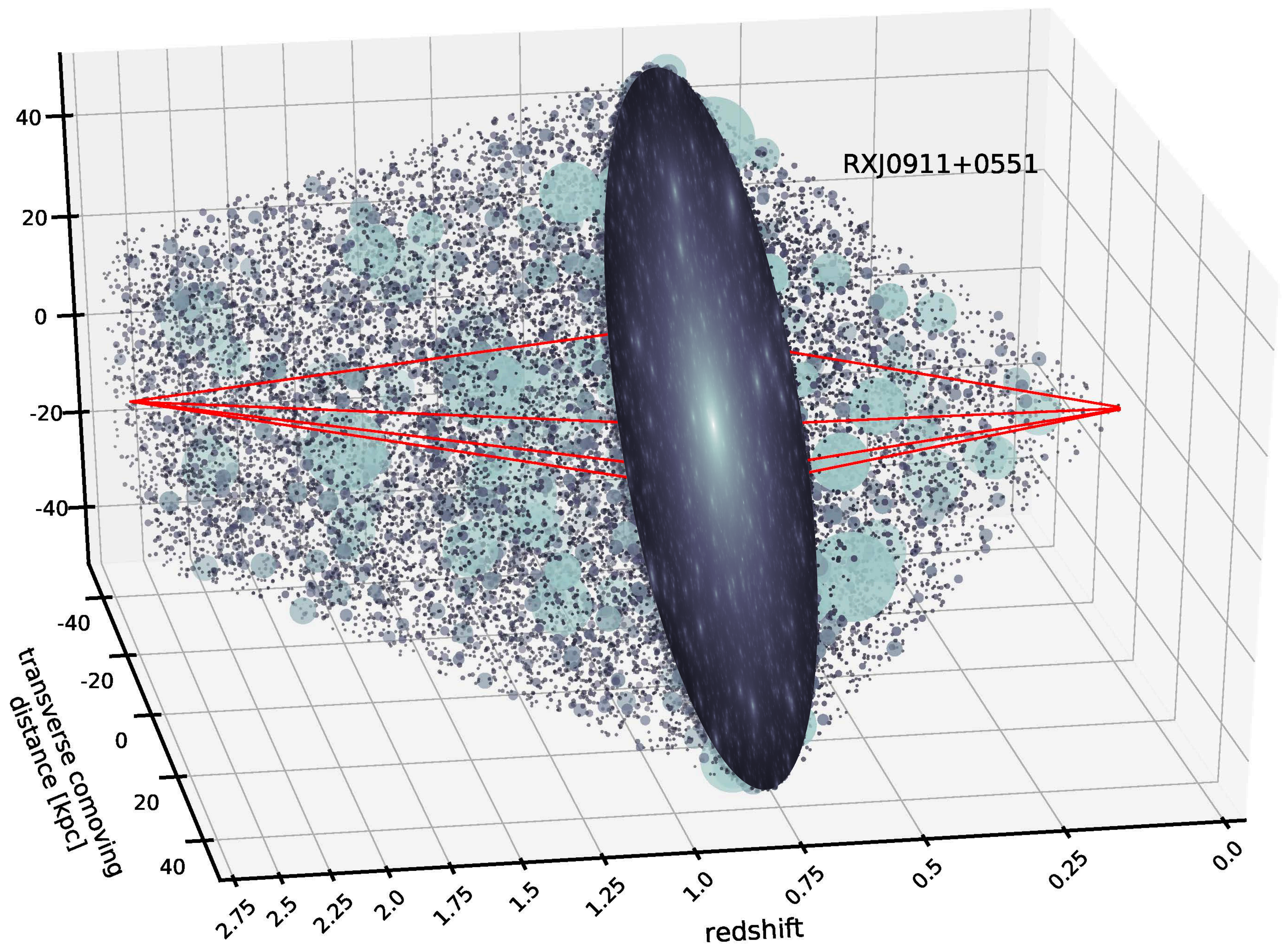


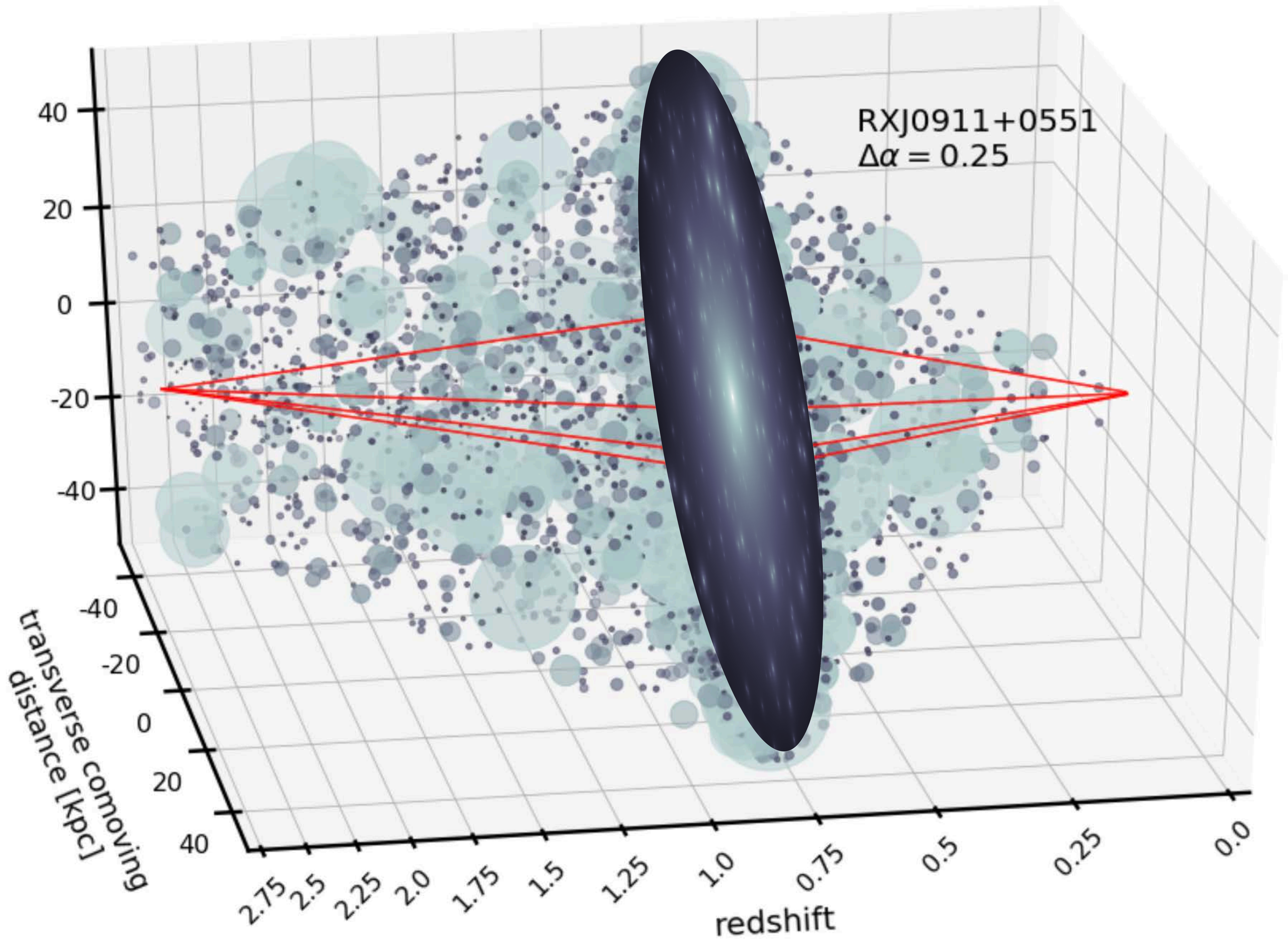
Simulation pipeline example: 2) forward model lenses with halos

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

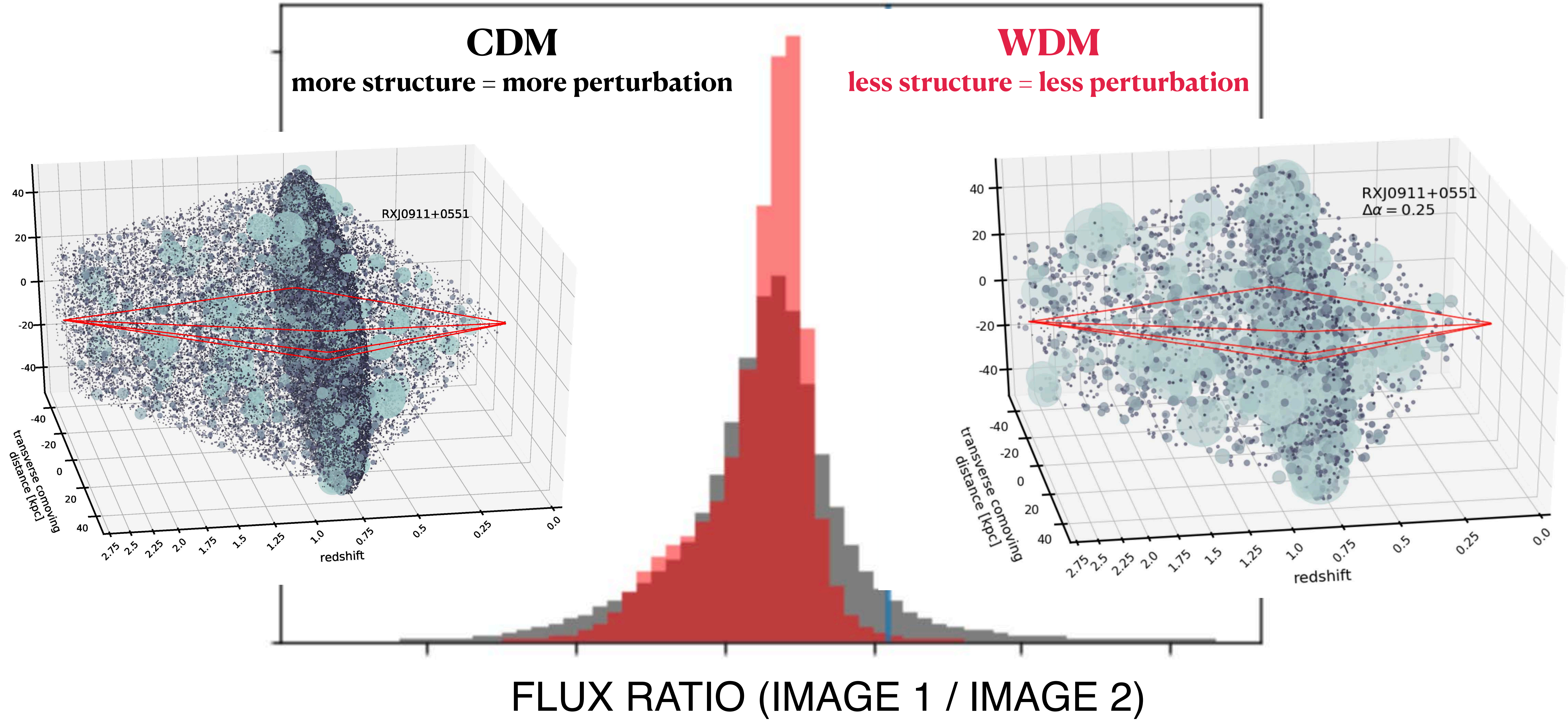
CDM



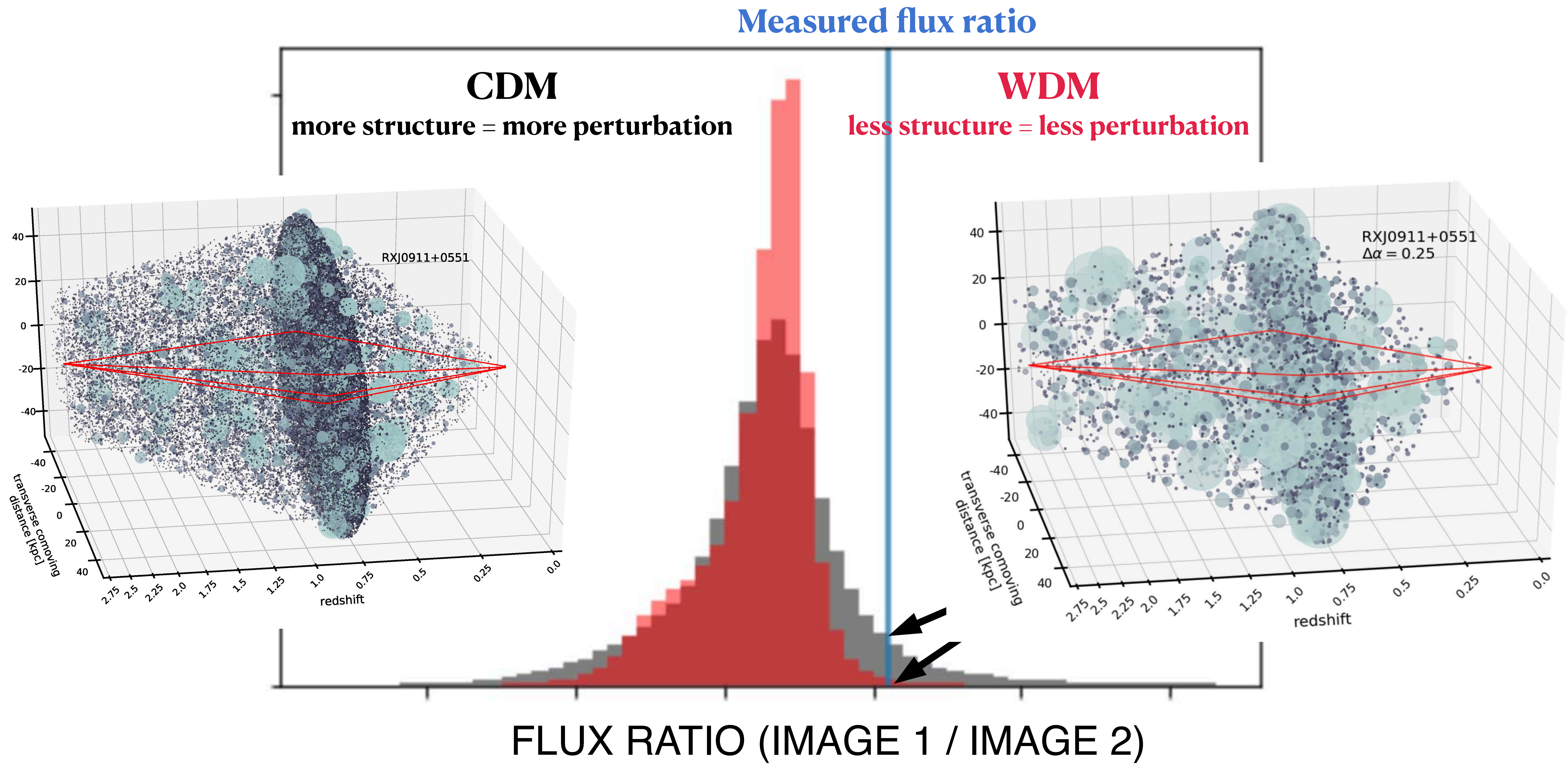
WDM



Simulation pipeline example:
3) compute flux ratios



Simulation pipeline example: 4) derive likelihoods



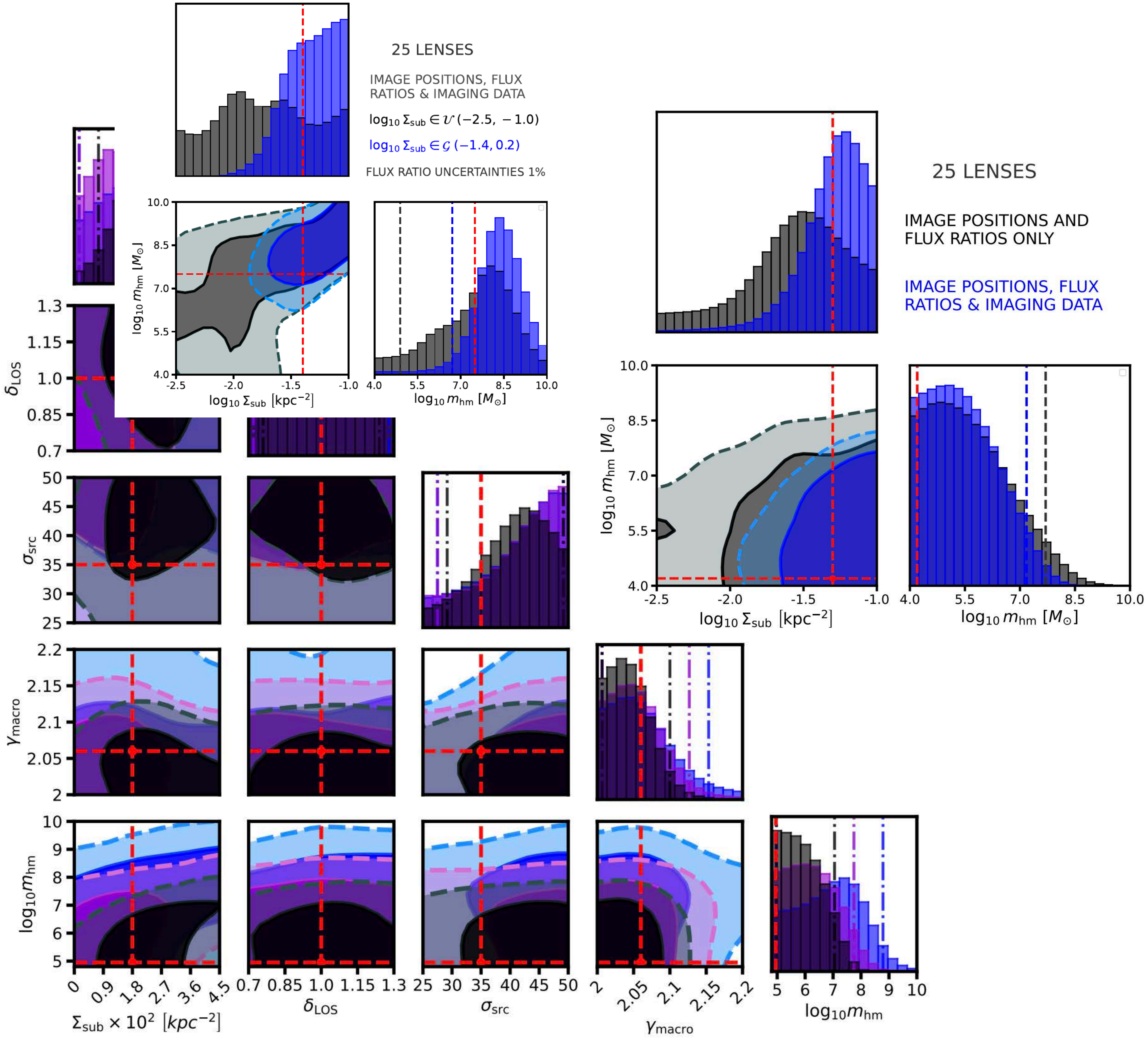
All methods tested and validated on simulated datasets

Accurate inferences with unknown

- Source sizes
- Tidal stripping assumptions
- Galaxy morphologies (including deviations from ellipticity)

see:
Gilman et al. (2018, 2019, 2024)
arXiv: 1712.04945, 1901.11031, 2404.03253

End-to-end inference on simulated data
see Gilman et al. (2019, 2024)



First application to WDM

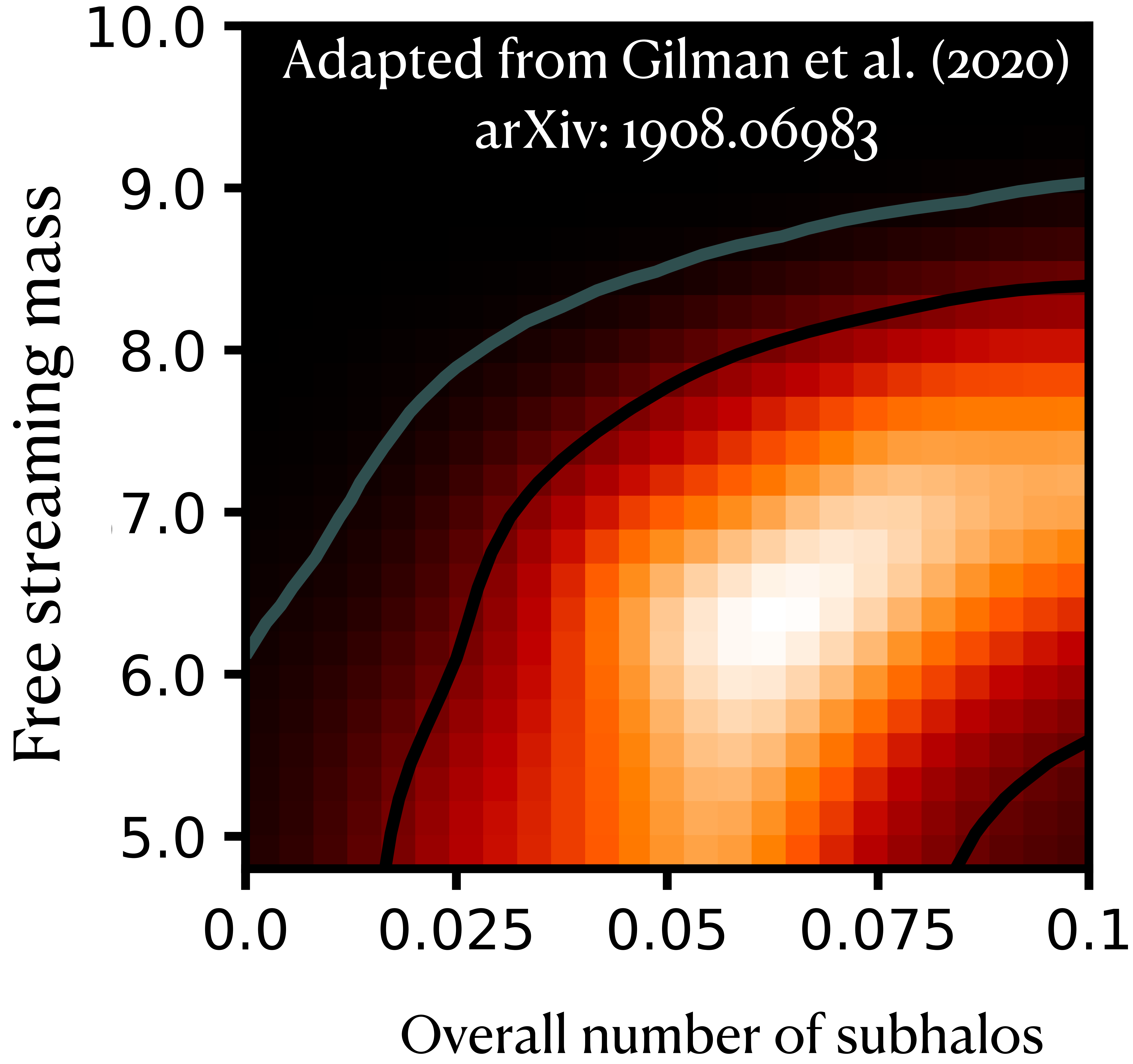
Gilman, et al. (2020)

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

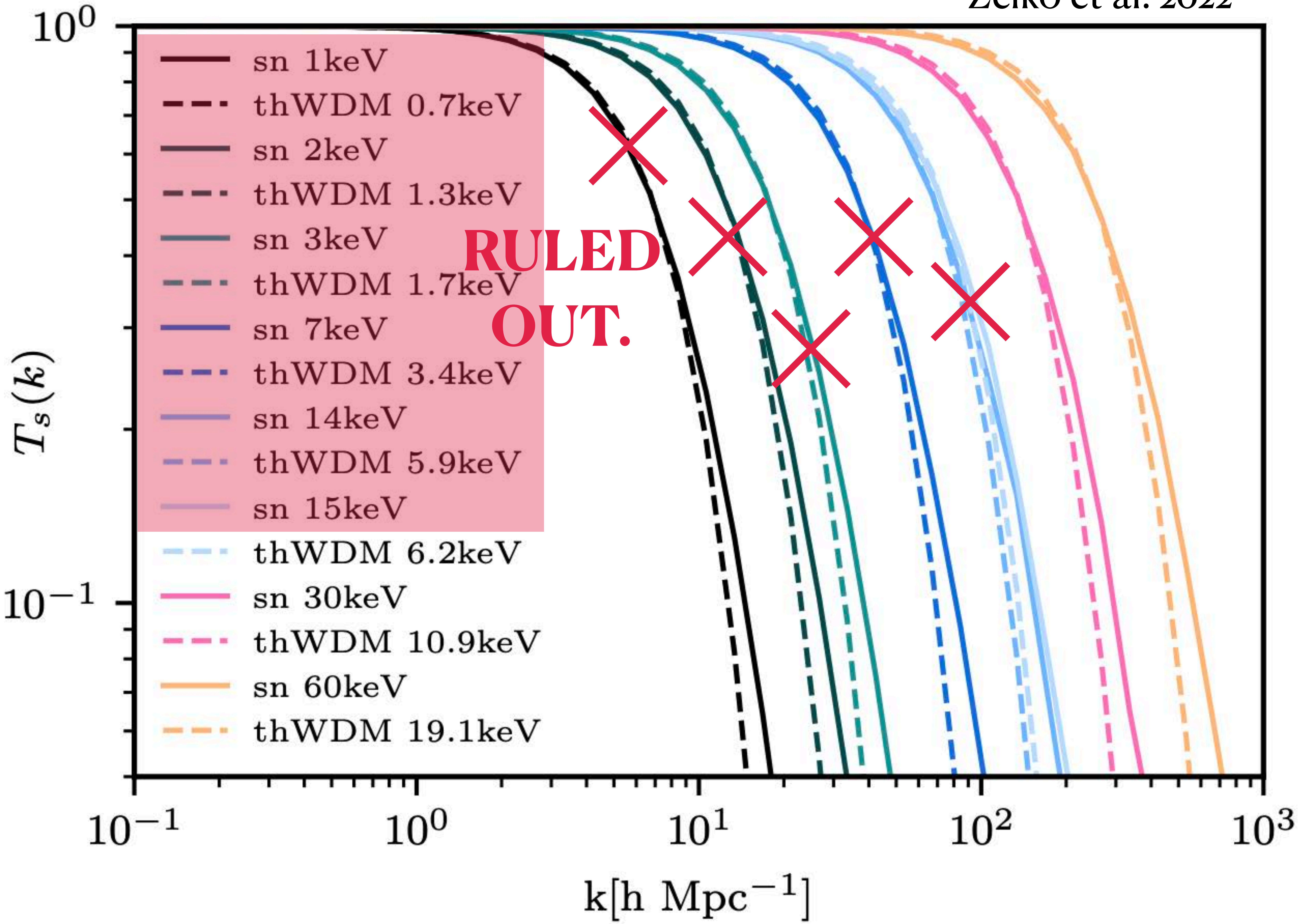
$$m_{\text{thermal}} > 5.2\text{keV}$$

Combination with Milky Way satellites (Nadler et al. 2021)

$$m_{\text{thermal}} > 9.7\text{keV}$$



Zelko et al. 2022



WDM constraints from the JWST lensed quasar dark matter survey

EMBARGOED FOR THE NEXT 20 MIN

Anna's talk up next...

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

What kinds of questions can we ask about dark matter?

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

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$$P_{\mathrm{linear}}\left(k\right) = P_{\mathrm{primordial}}\left(k\right) T\left(k\right)^2$$

1) DM physics that impacts the transfer function

- e.g. free-streaming in warm dark matter
- ultra-light DM (plus wave-interference effects), see Laroche, Gilman et al. (2022)

$$P_{\mathrm{linear}}\left(k\right) = P_{\mathrm{primordial}}\left(k\right) T\left(k\right)^2$$

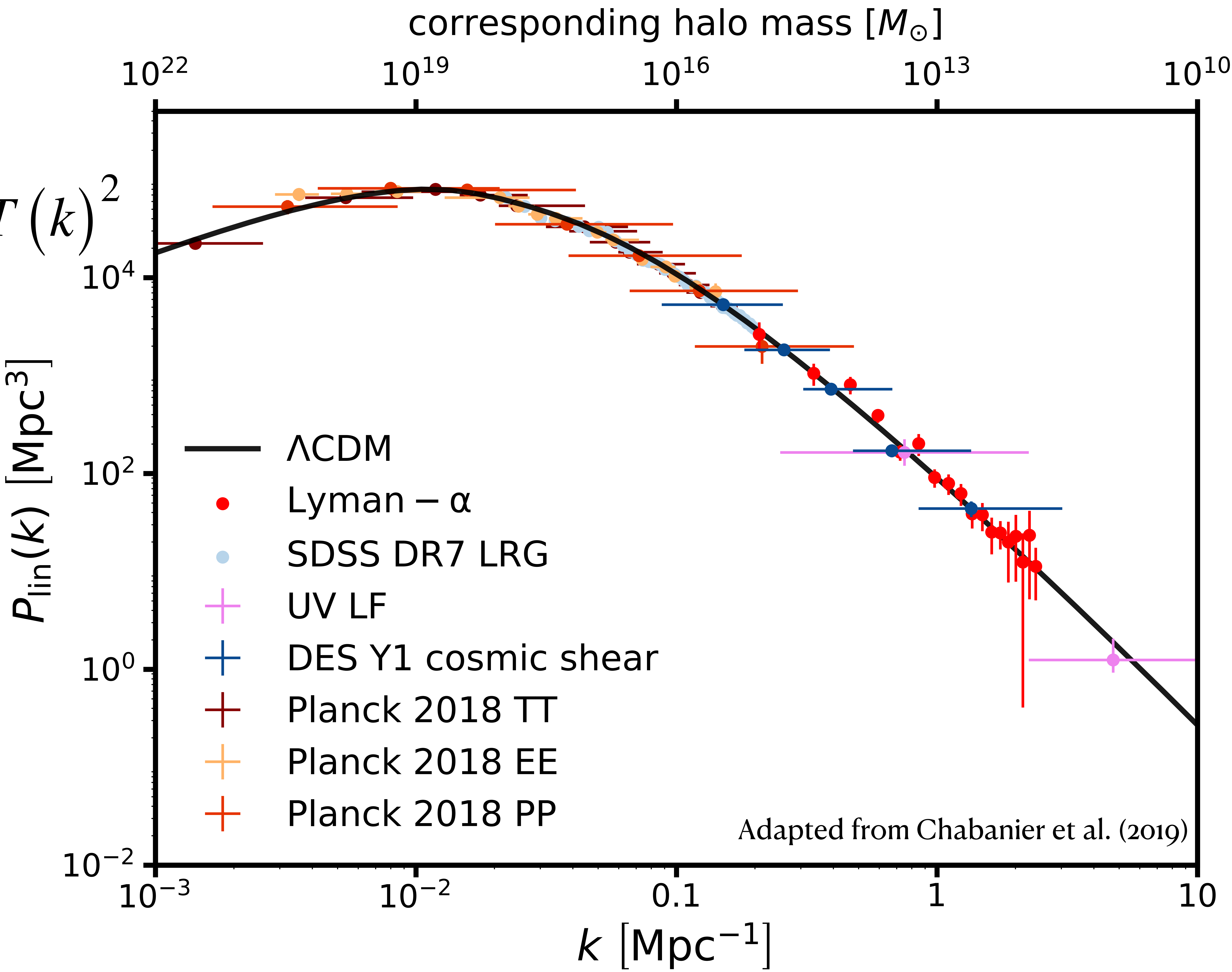
Rest of talk:

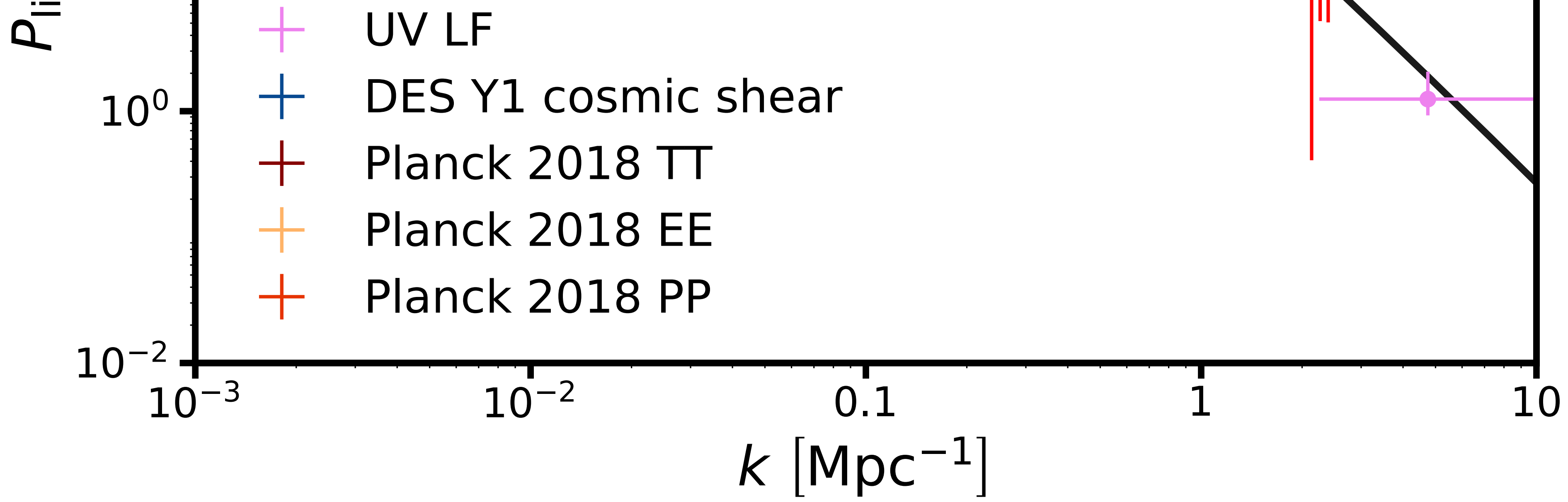
2) Change the form of the primordial density fluctuations

3) Relax assumptions about the collisionless nature of dark matter

$$P_{\text{linear}}(k) = P_{\text{primordial}}(k)\, T(k)^2$$

We are free to interpret measurements in terms of either $T(k)$ or $P_{\text{primordial}}$

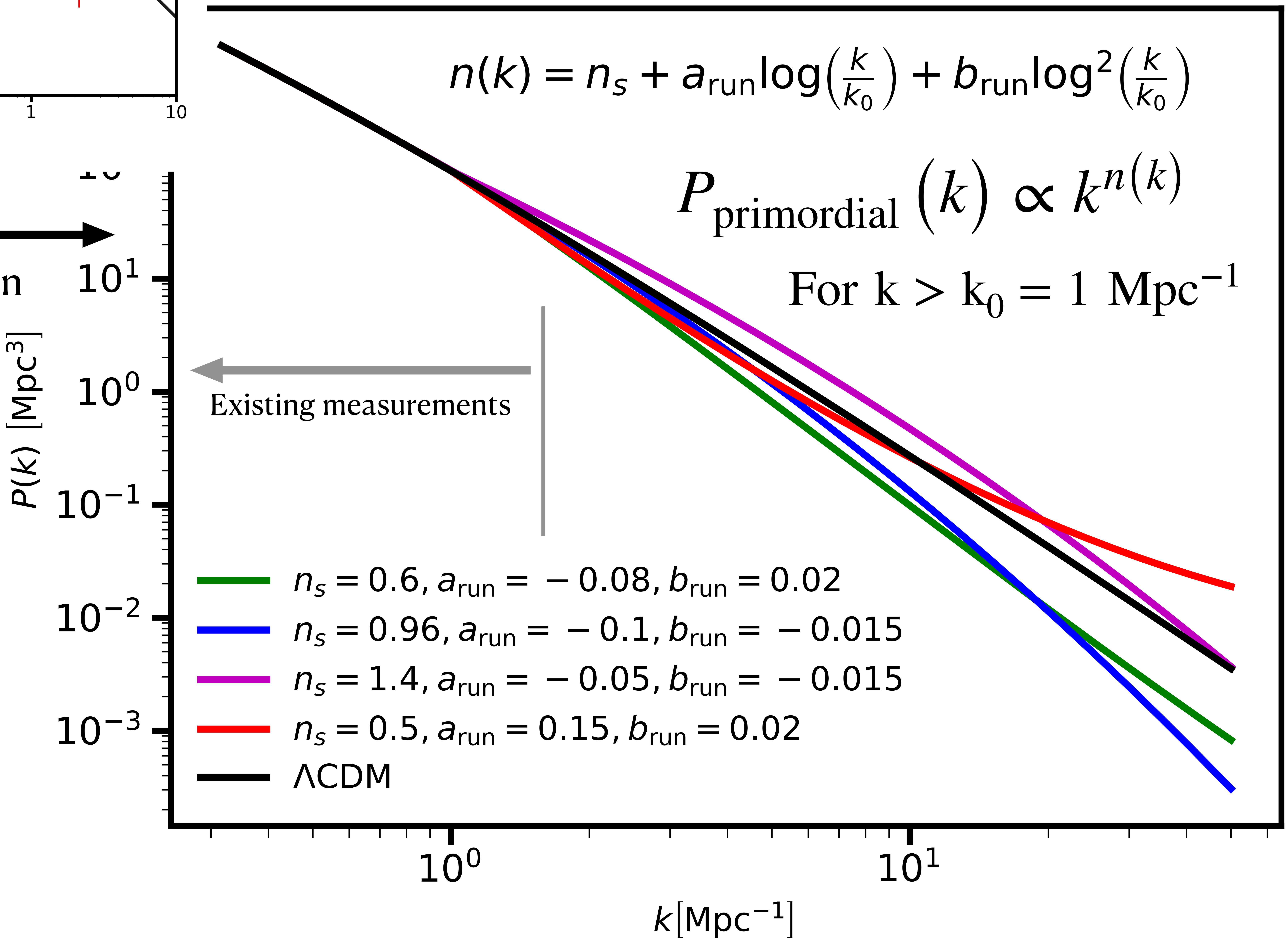




Phenomenological description of small-scale $P_{\text{primordial}}(k)$

Physical models include

- multi-field inflation (arXiv: 0205216)
- scale-dependent primordial non-Gaussianity (arXiv: 2404.03244)
- Primordial magnetic fields (arXiv: 1504.02311)

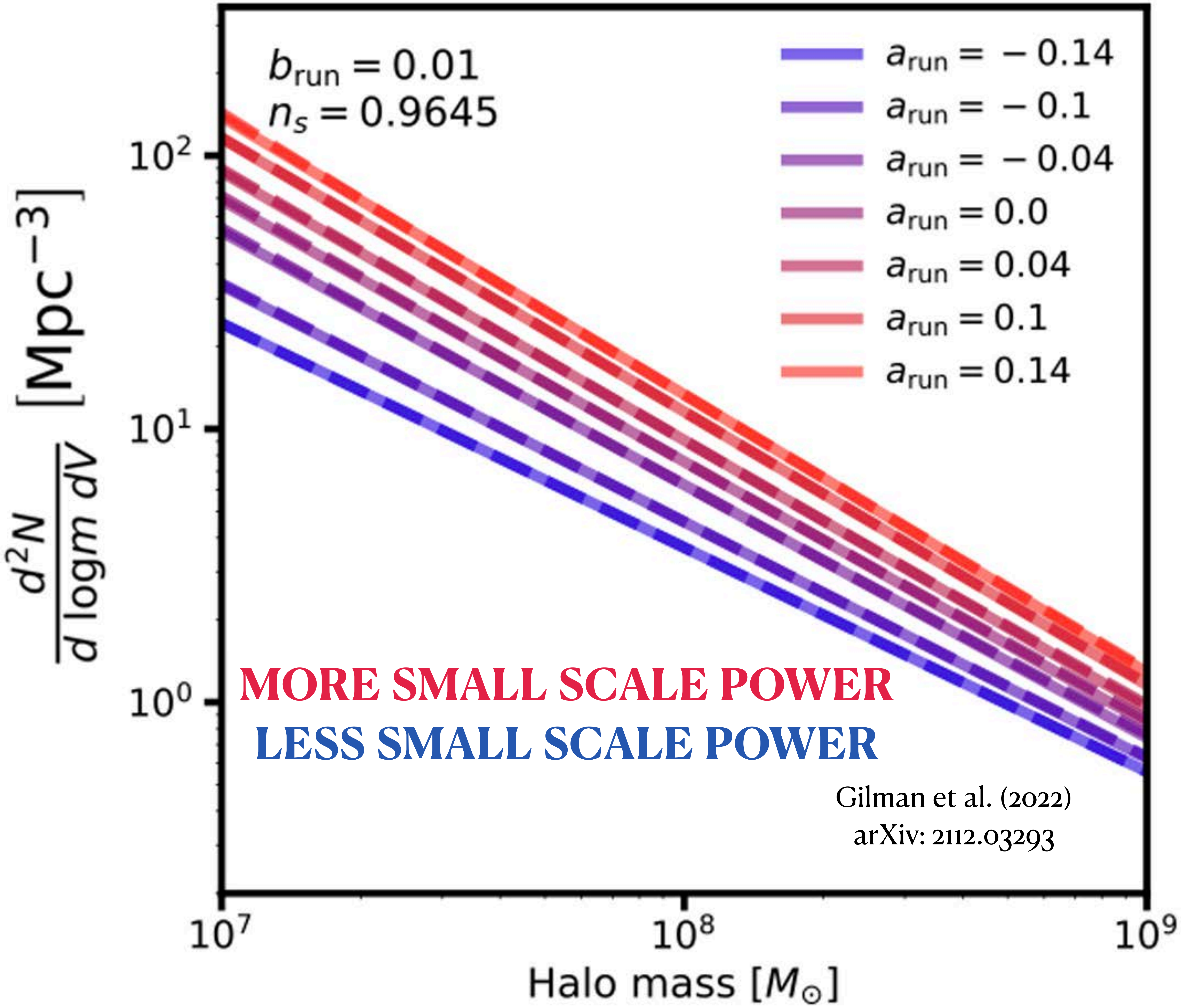


Halo mass function

Changes to the power spectrum produce **correlated** changes to the halo mass function and concentration-mass relation

Dashed: Sheth-Tormen mass function prediction

Solid: power-law in halo mass fit



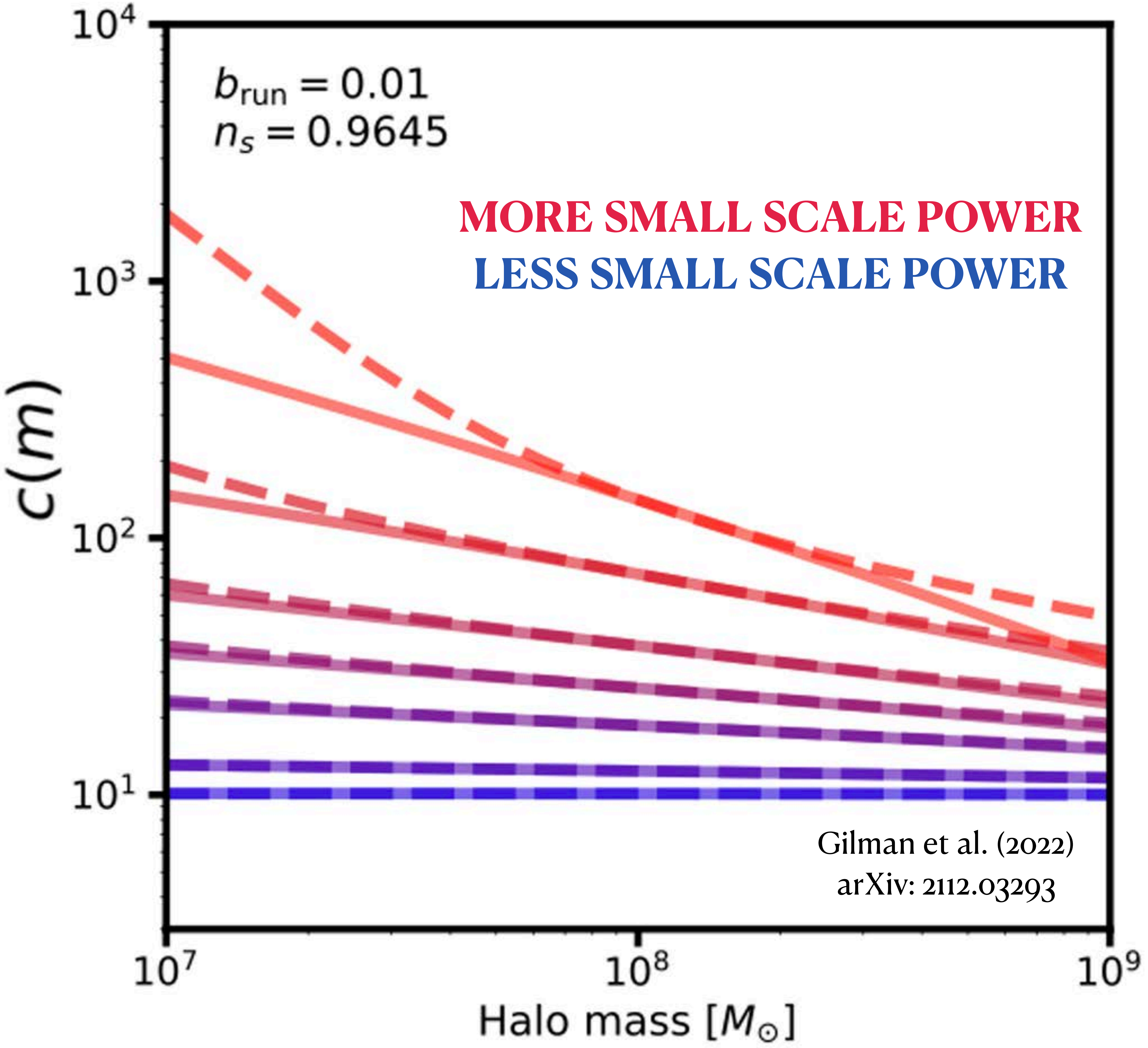
Gilman et al. (2022)
arXiv: 2112.03293

Changes to the power spectrum produce **correlated** changes to the halo mass function and concentration-mass relation

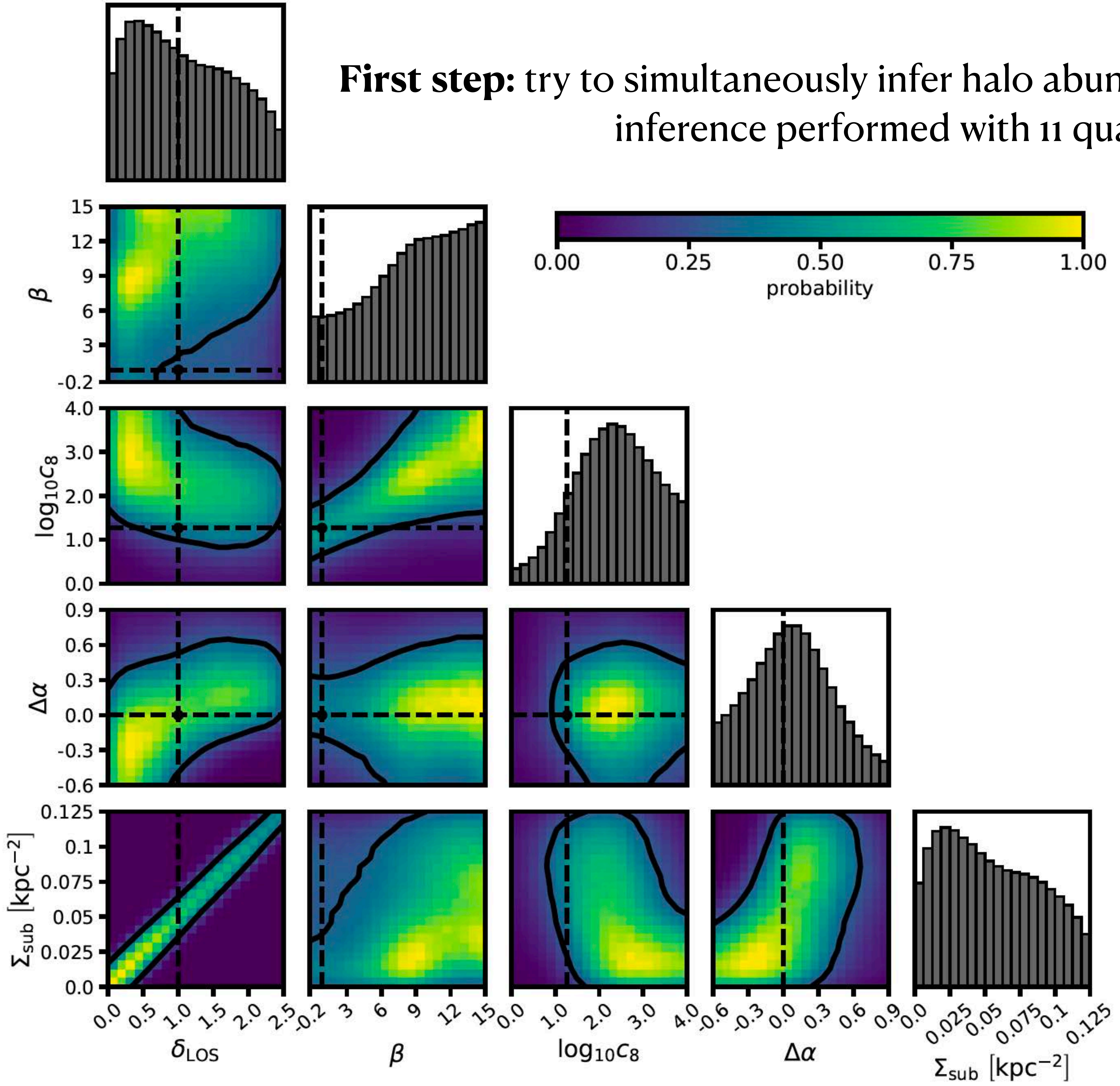
Dashed: Diemer & Joyce (2019) concentration-mass relation prediction

Solid: power-law in peak height fit

Concentration-mass relation



First step: try to simultaneously infer halo abundance and concentration
inference performed with 11 quad lenses



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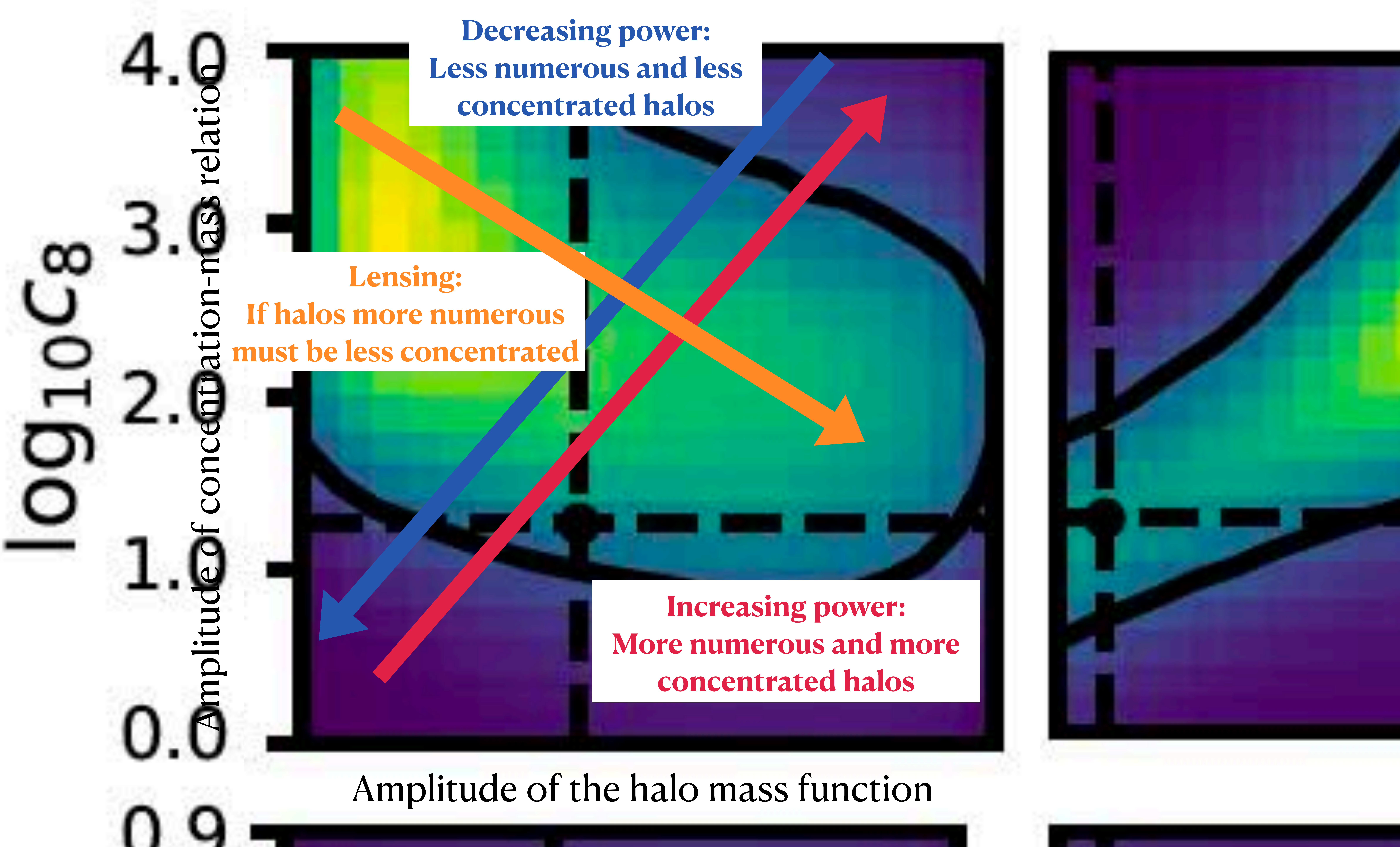
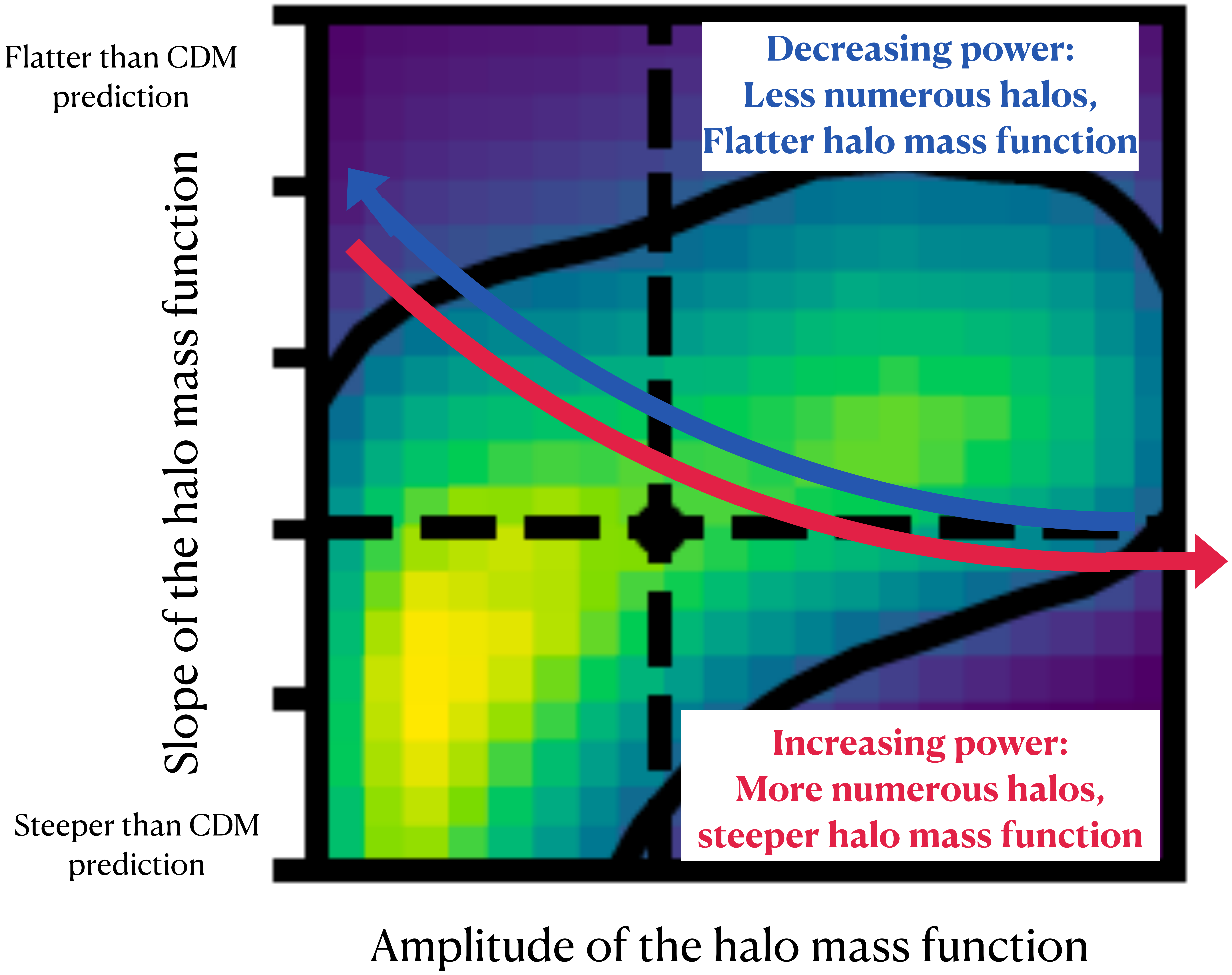
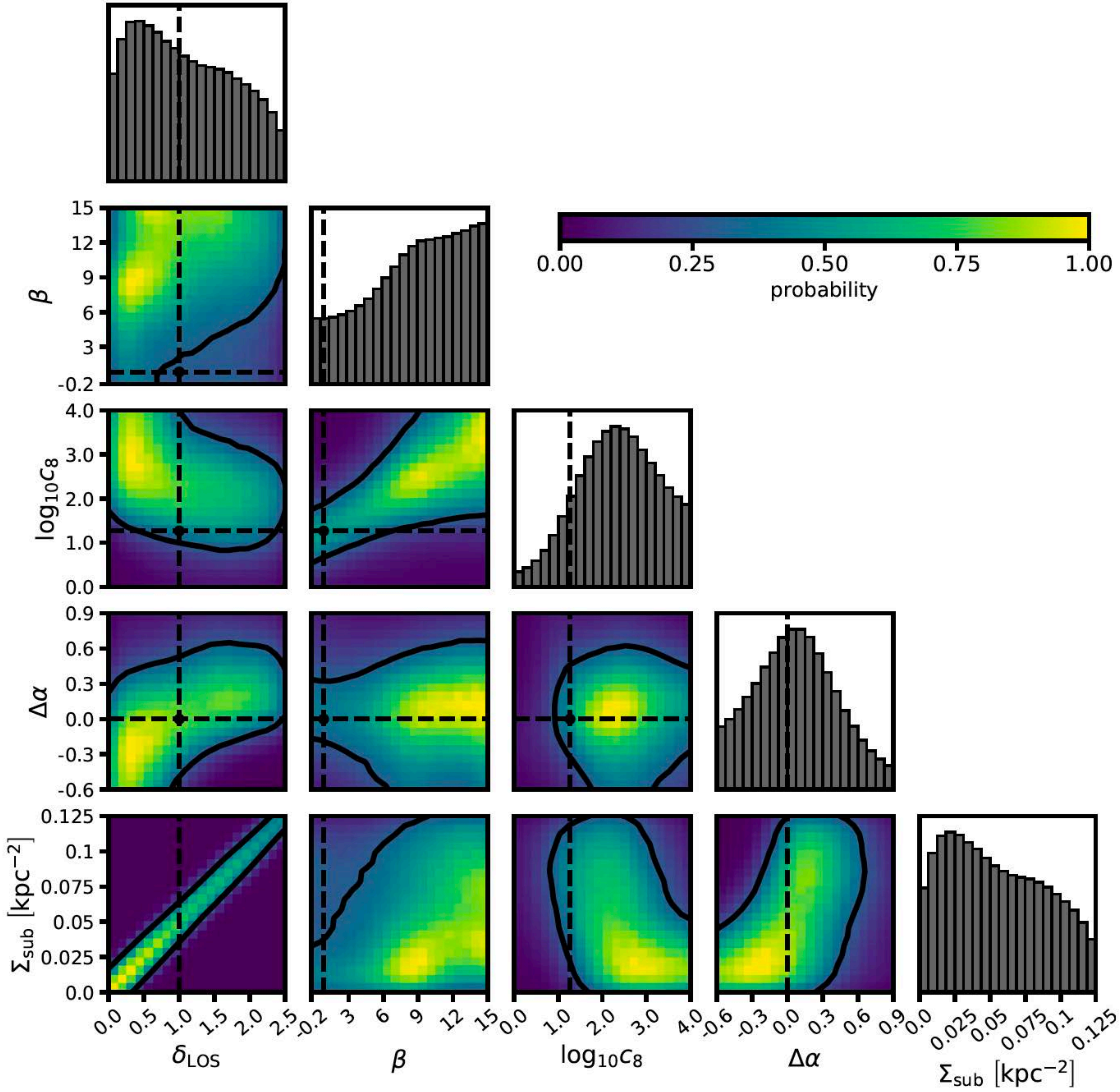
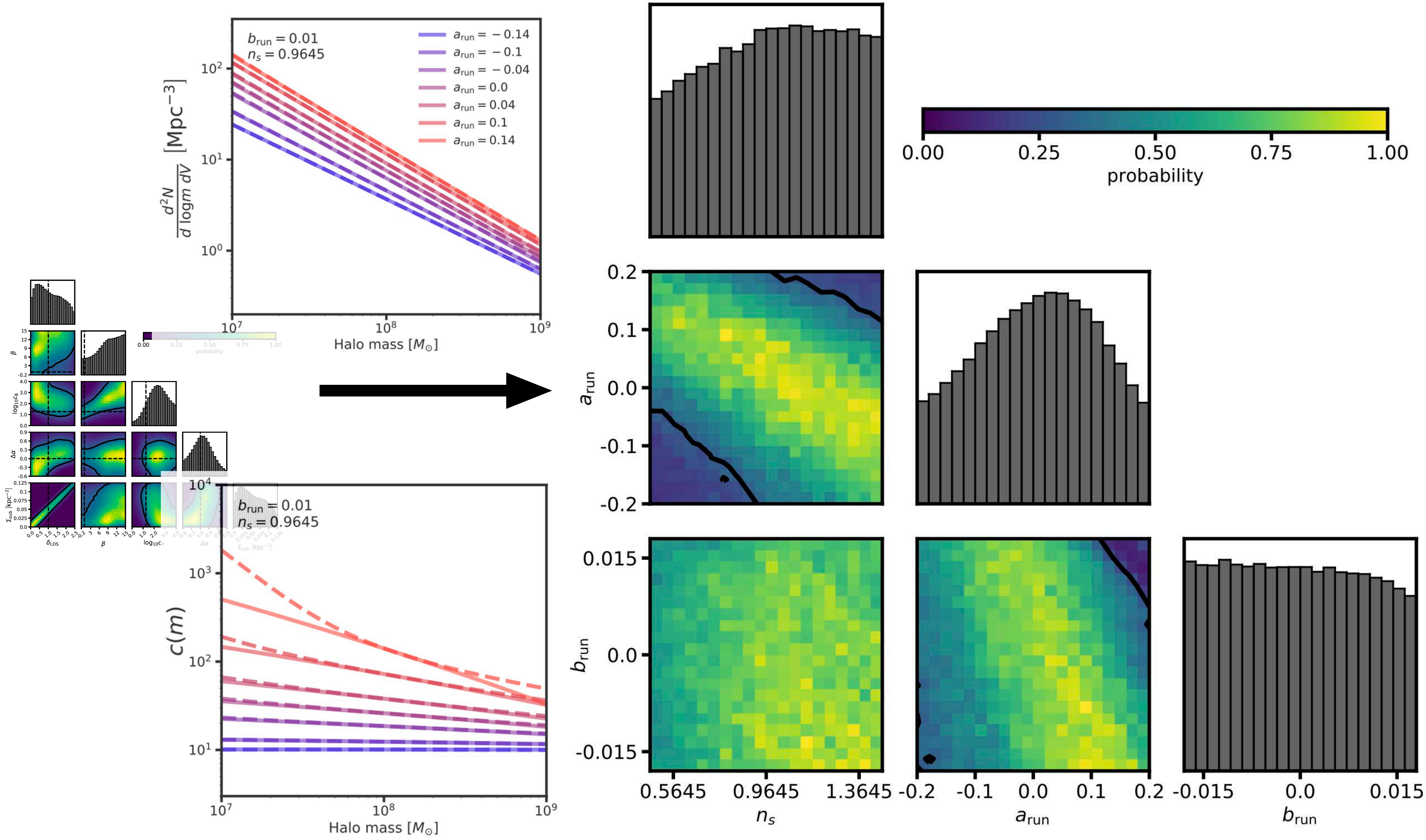


Amplitude of the halo mass function


Flatter than CDM prediction
Steeper than CDM prediction
Slope of the halo mass function
Amplitude of the halo mass function
Decreasing power:
Less numerous halos,
Flatter halo mass function
Increasing power:
More numerous halos,
steeper halo mass function

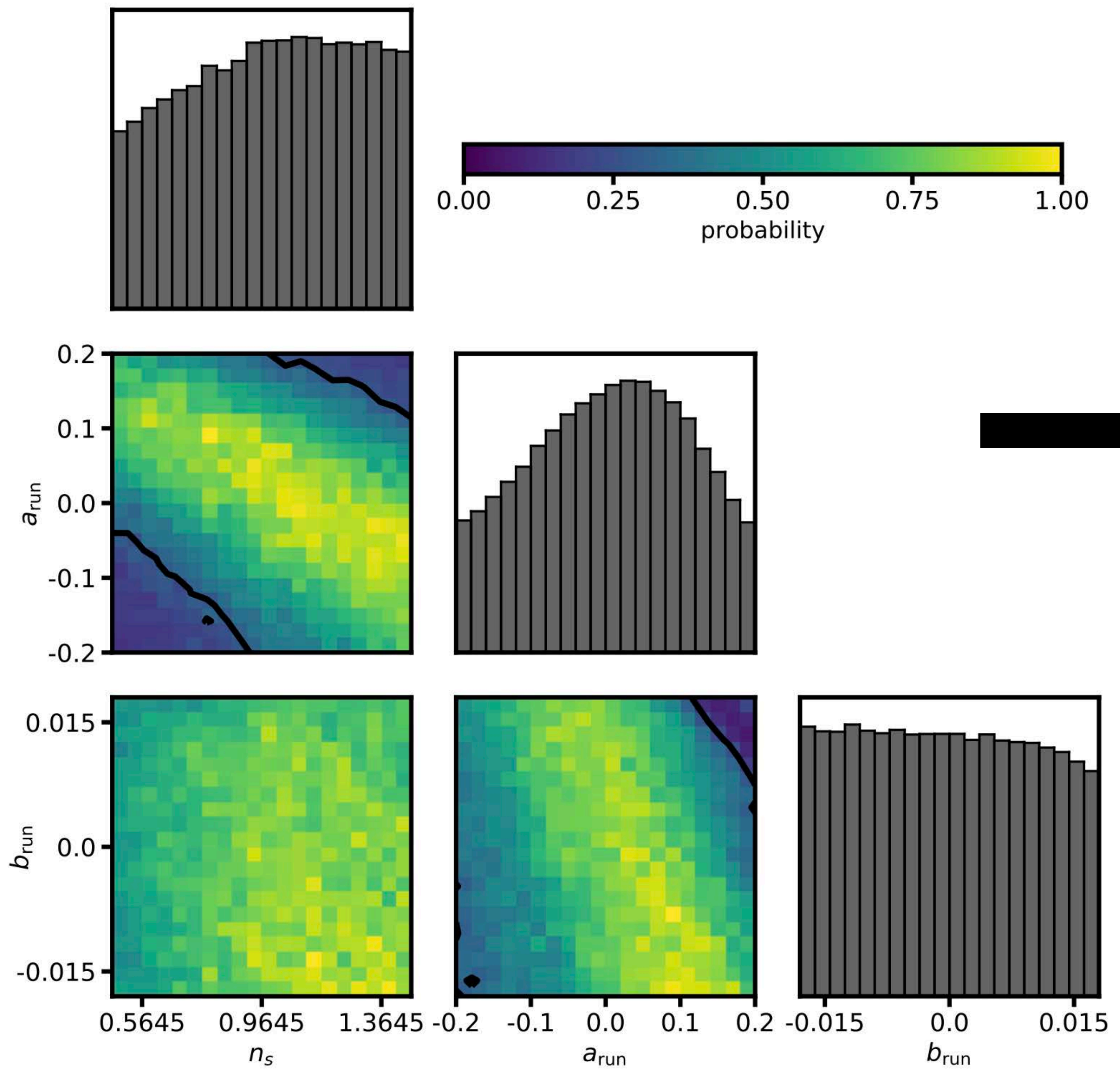


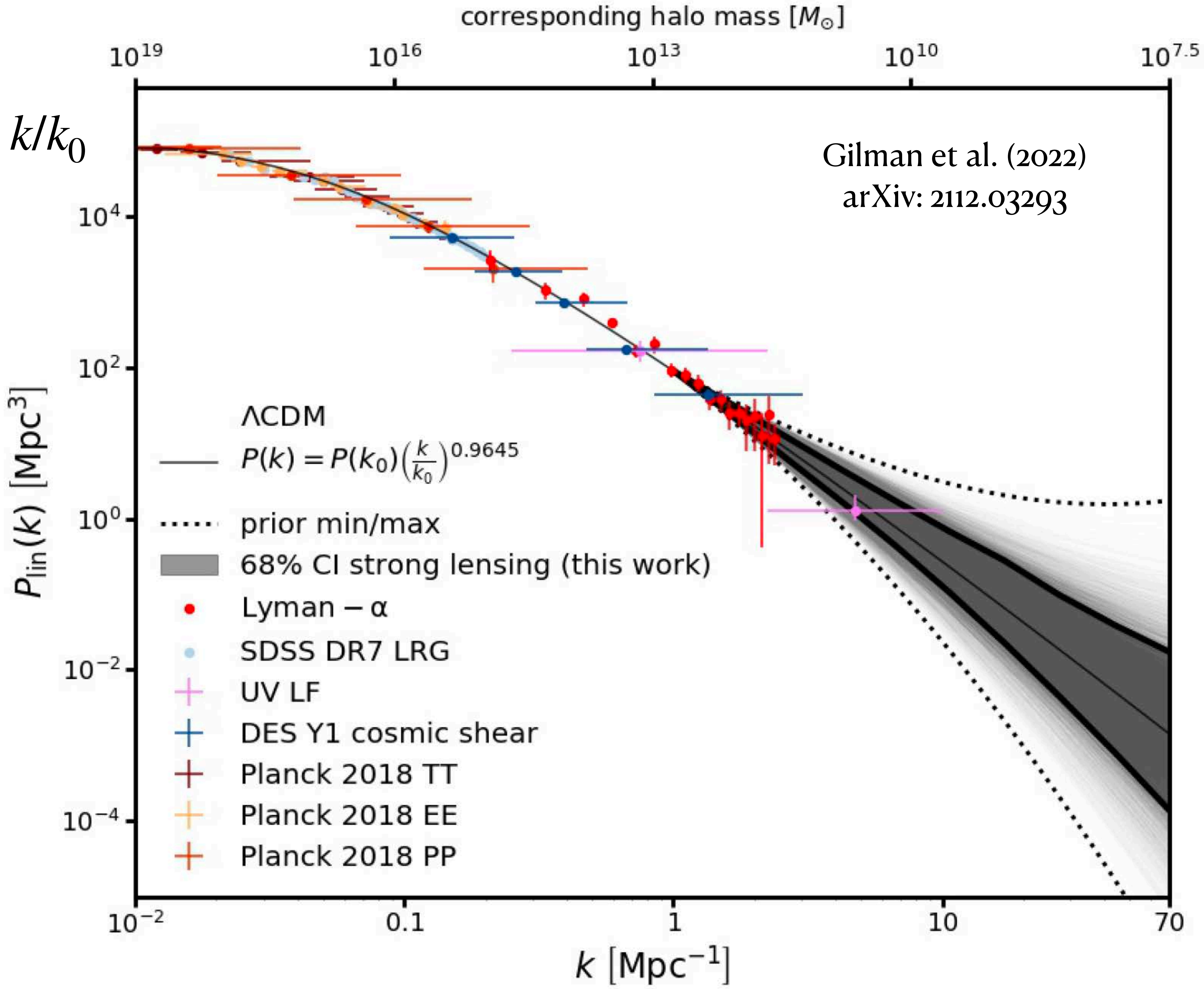
0.00
0.25
0.50
0.75
1.00
probability
β
$\log_{10} c_8$
$\Delta\alpha$
$\Sigma_{\rm sub}$ [kpc^{-2}]
$\delta_{\rm LOS}$
β
$\log_{10} c_8$
$\Delta\alpha$
$\Sigma_{\rm sub}$ [kpc^{-2}]



$b_{\rm run} = 0.01$
$n_s = 0.9645$
$a_{\rm run} = -0.14$
$a_{\rm run} = -0.1$
$a_{\rm run} = -0.04$
$a_{\rm run} = 0.0$
$a_{\rm run} = 0.04$
$a_{\rm run} = 0.1$
$a_{\rm run} = 0.14$
$\frac{d^2N}{d\,\log m\, dV}$ [Mpc^{-3}]
Halo mass [$M_\odot$]
$c(m)$
probability
n_s
$a_{\rm run}$
$b_{\rm run}$

$$P\left(k\right) \sim k^{n_s + a \log k/k_0 + b \log k/k_0}$$





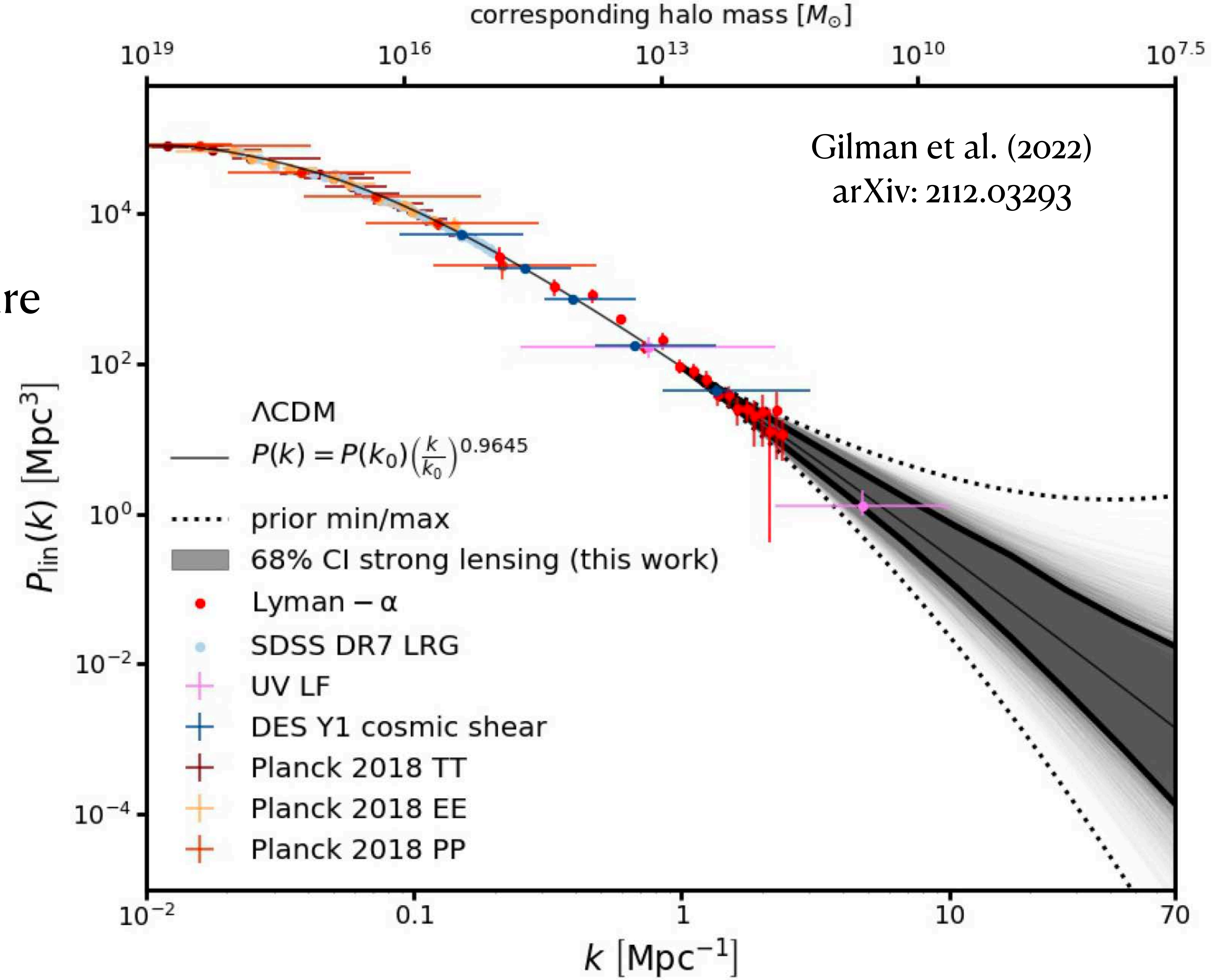
Caveats

- model dependent statements about $P_{\text{primordial}}(k)$

- Limited suite of simulations of structure formation with this type of power spectrum

Takeaway

Lensing will be able to constrain $P_{\text{primordial}}(k)$ from **simultaneous** inferences of halo abundance and concentration



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

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- e.g. free-streaming in warm dark matter
- ultra-light DM (plus wave-interference effects), see Laroche, Gilman et al. (2022)

$$P_{\text{linear}}\left(k\right) = P_{\text{primordial}}\left(k\right) T\left(k\right)^2$$

Rest of talk:

2) Change the form of the primordial density fluctuations

3) Relax assumptions about the collisionless nature of dark matter

Self-interacting dark matter (SIDM)

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

Self-interacting dark matter (SIDM)

-> preserves large-scale structure

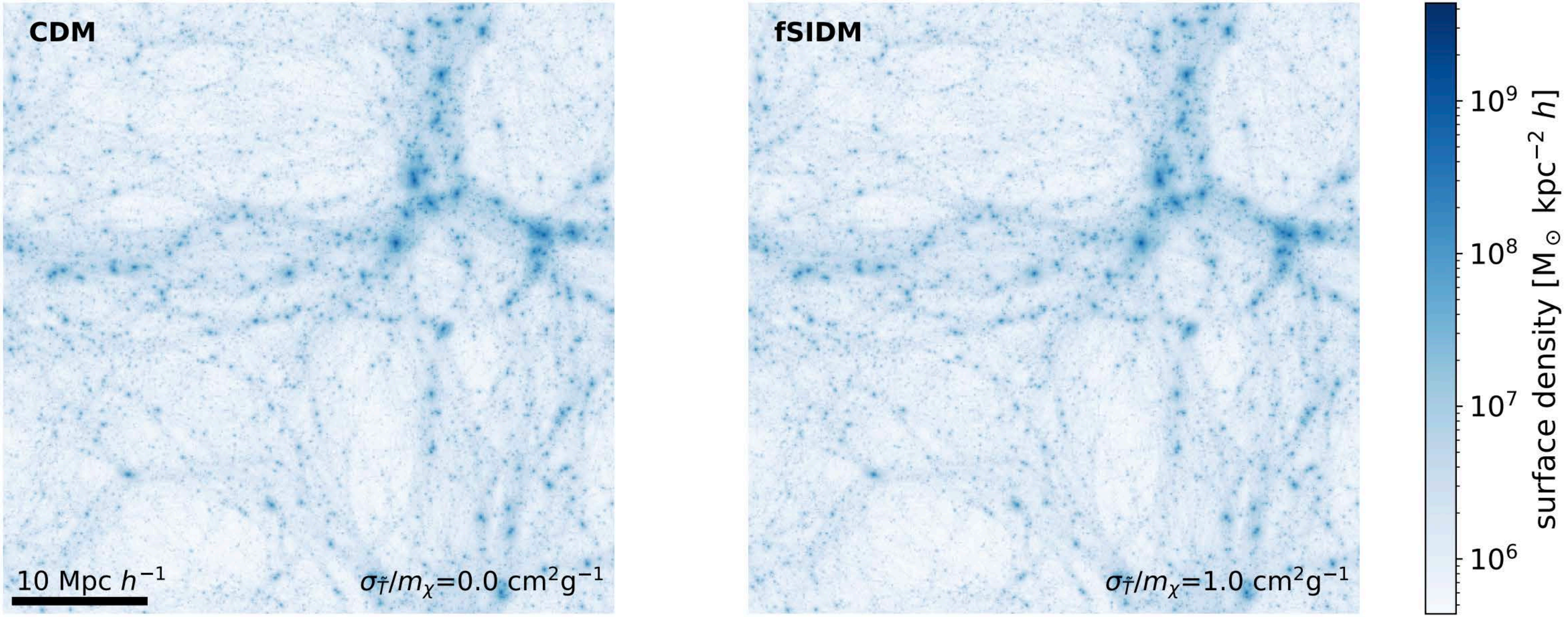


figure from Fischer et al. (2022)

Self-interacting dark matter (SIDM)

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

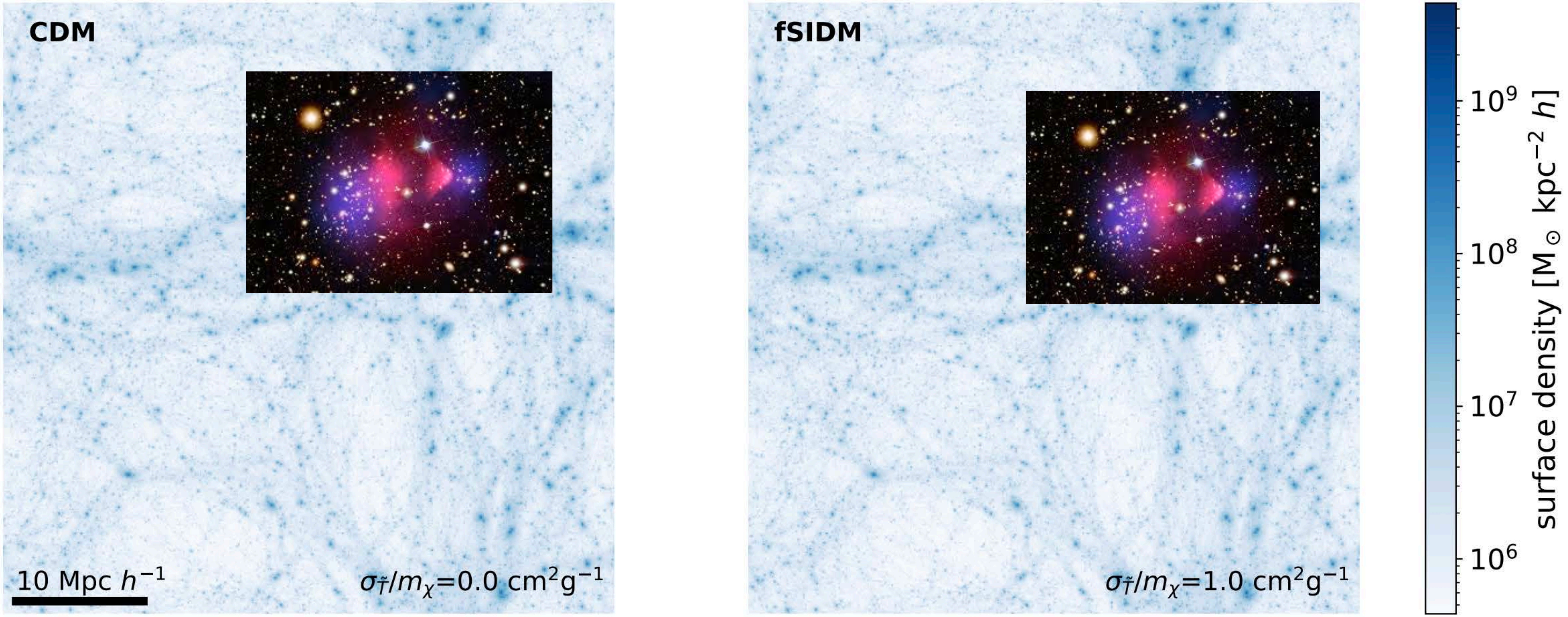


figure from Fischer et al. (2022)

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

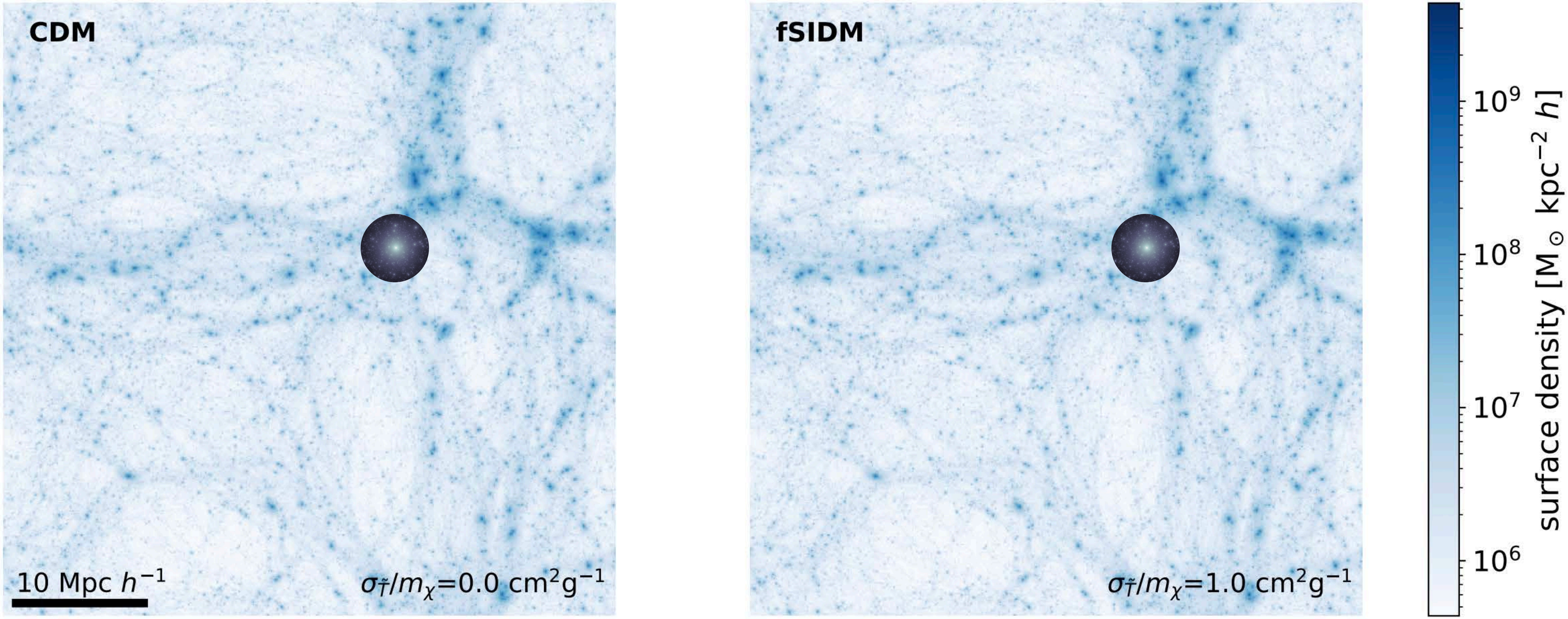
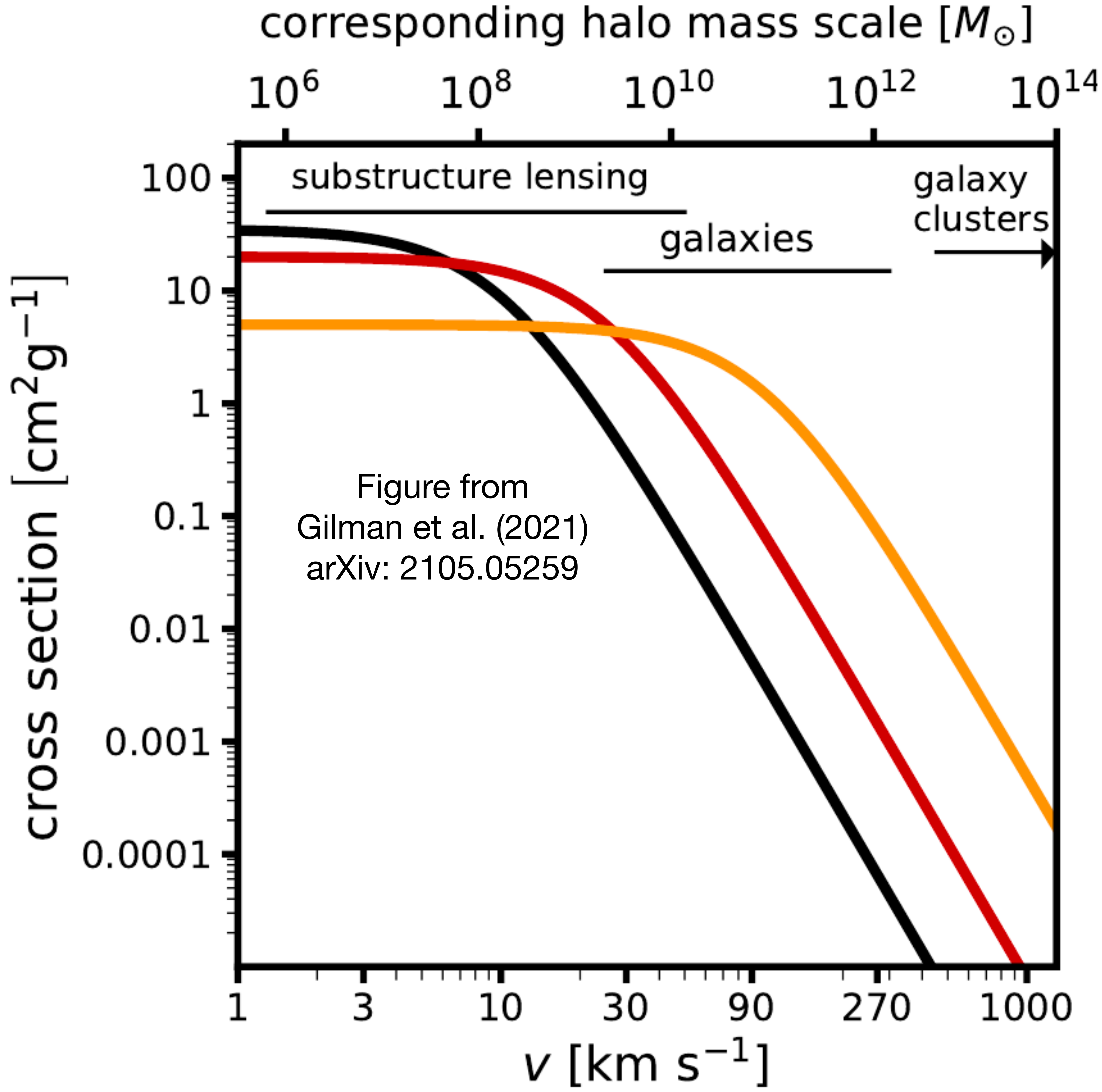


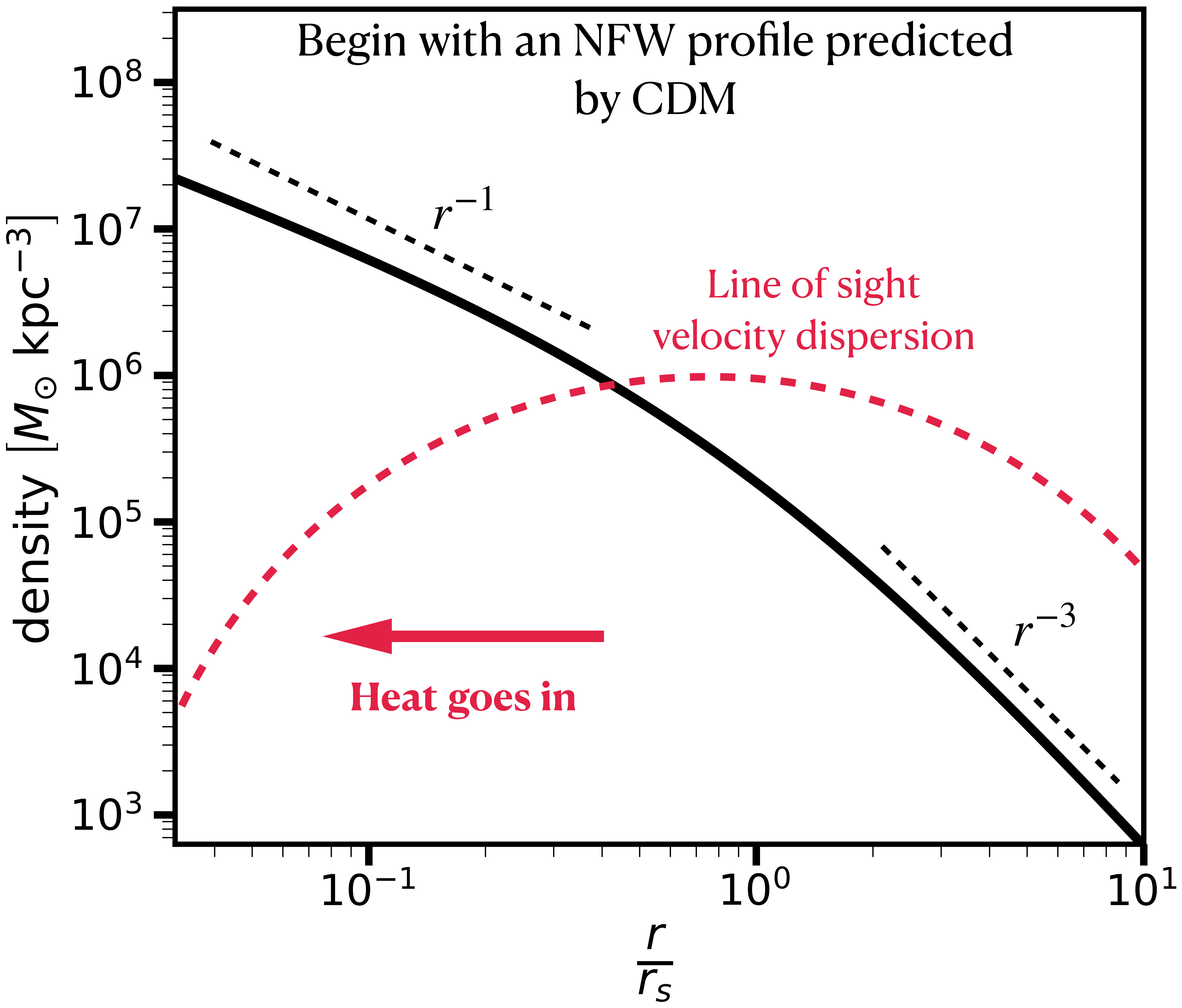
figure from Fischer et al. (2022)



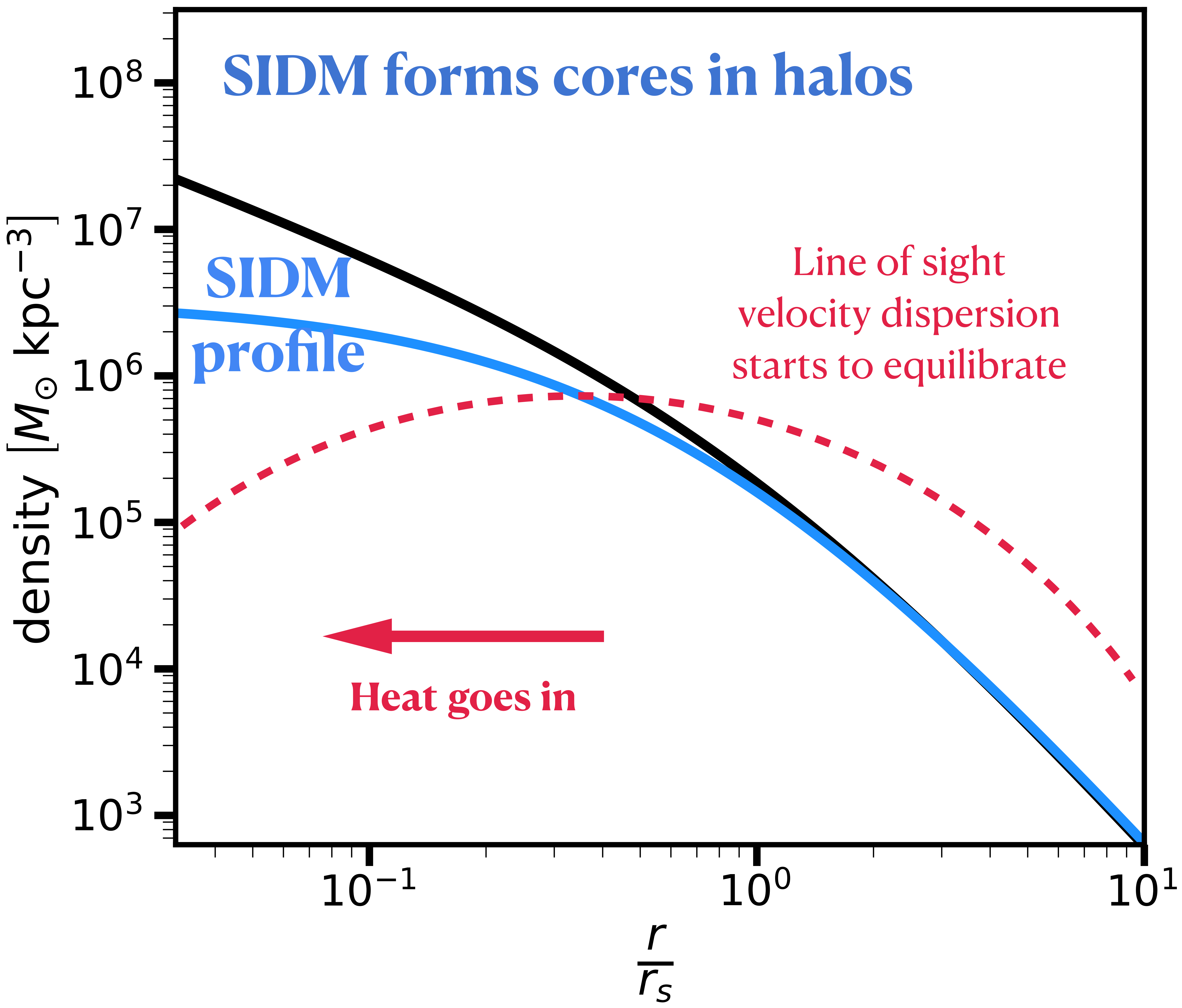
Velocity dependence necessary to evade constraints from galaxy clusters

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

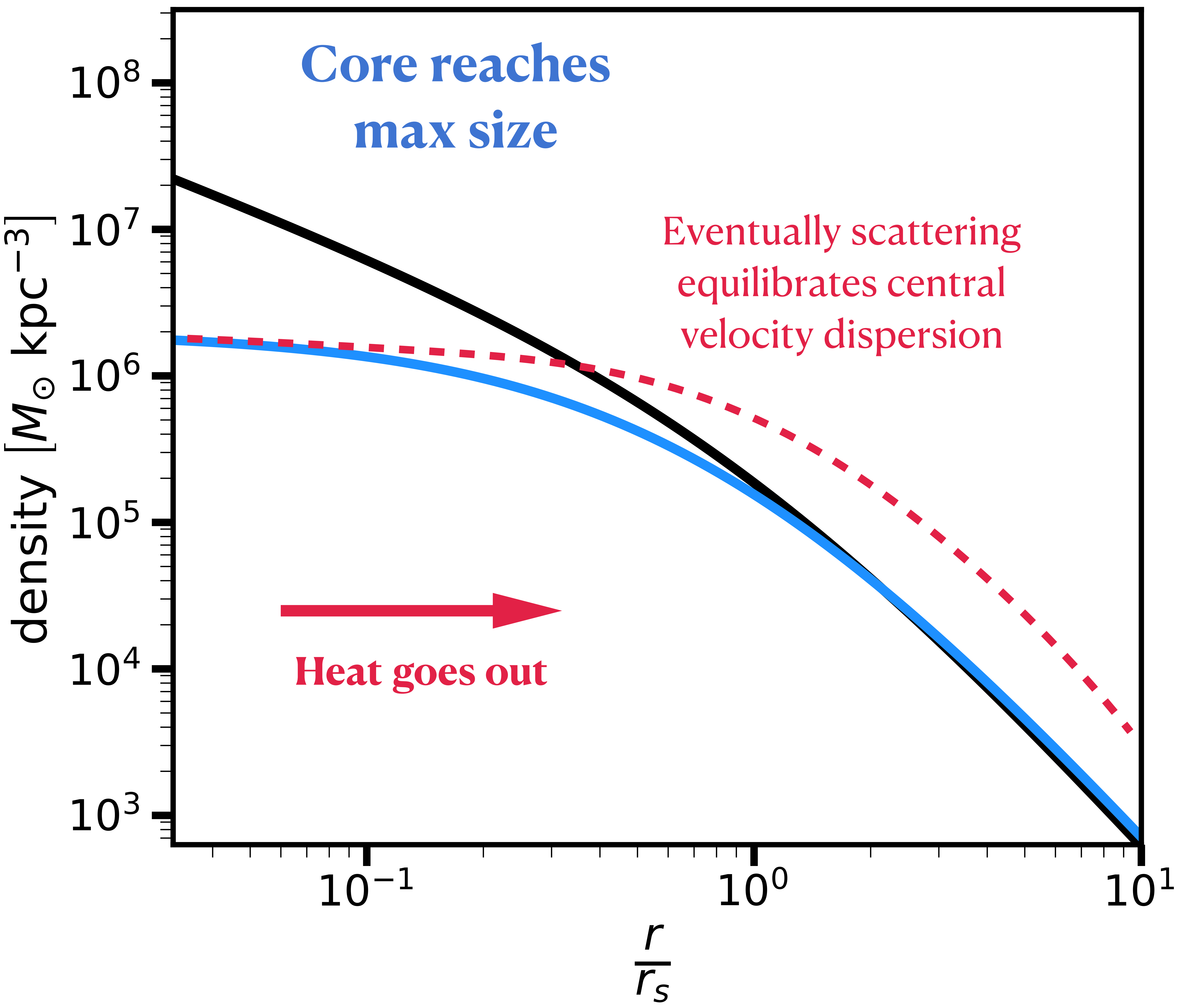
Effects of SIDM on halo density profiles



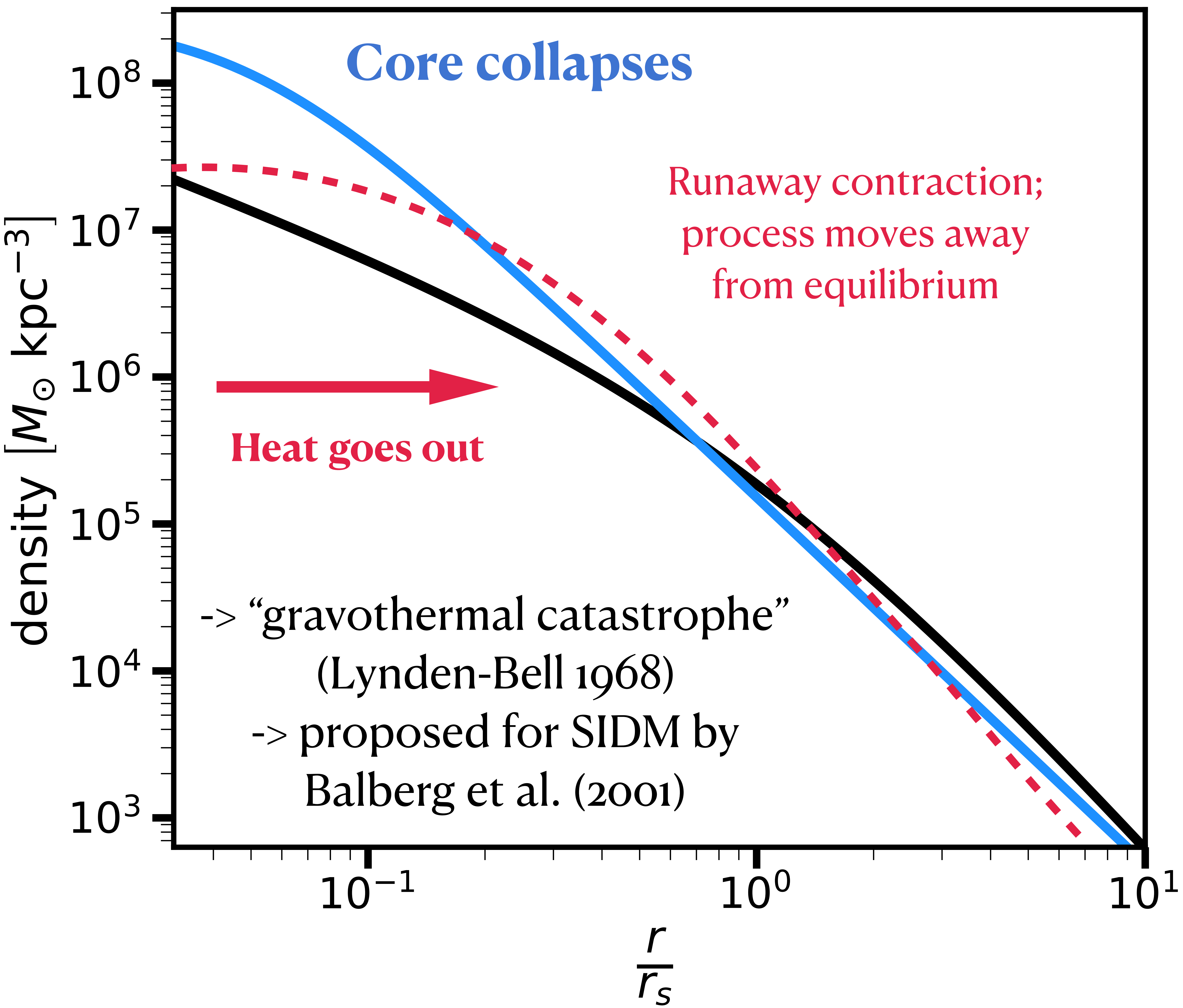
Effects of SIDM on halo density profiles



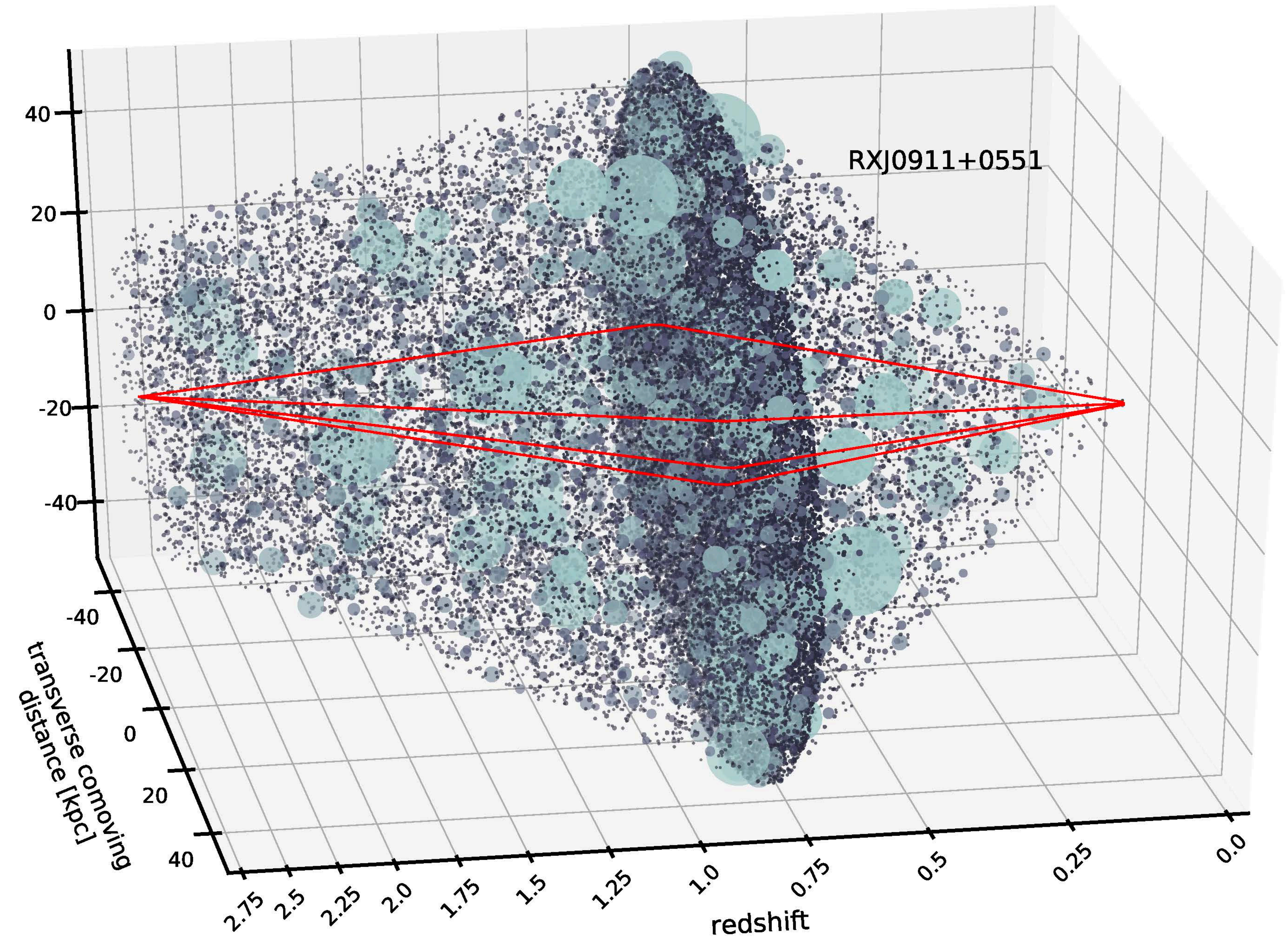
Effects of SIDM on halo density profiles



Effects of SIDM on halo density profiles

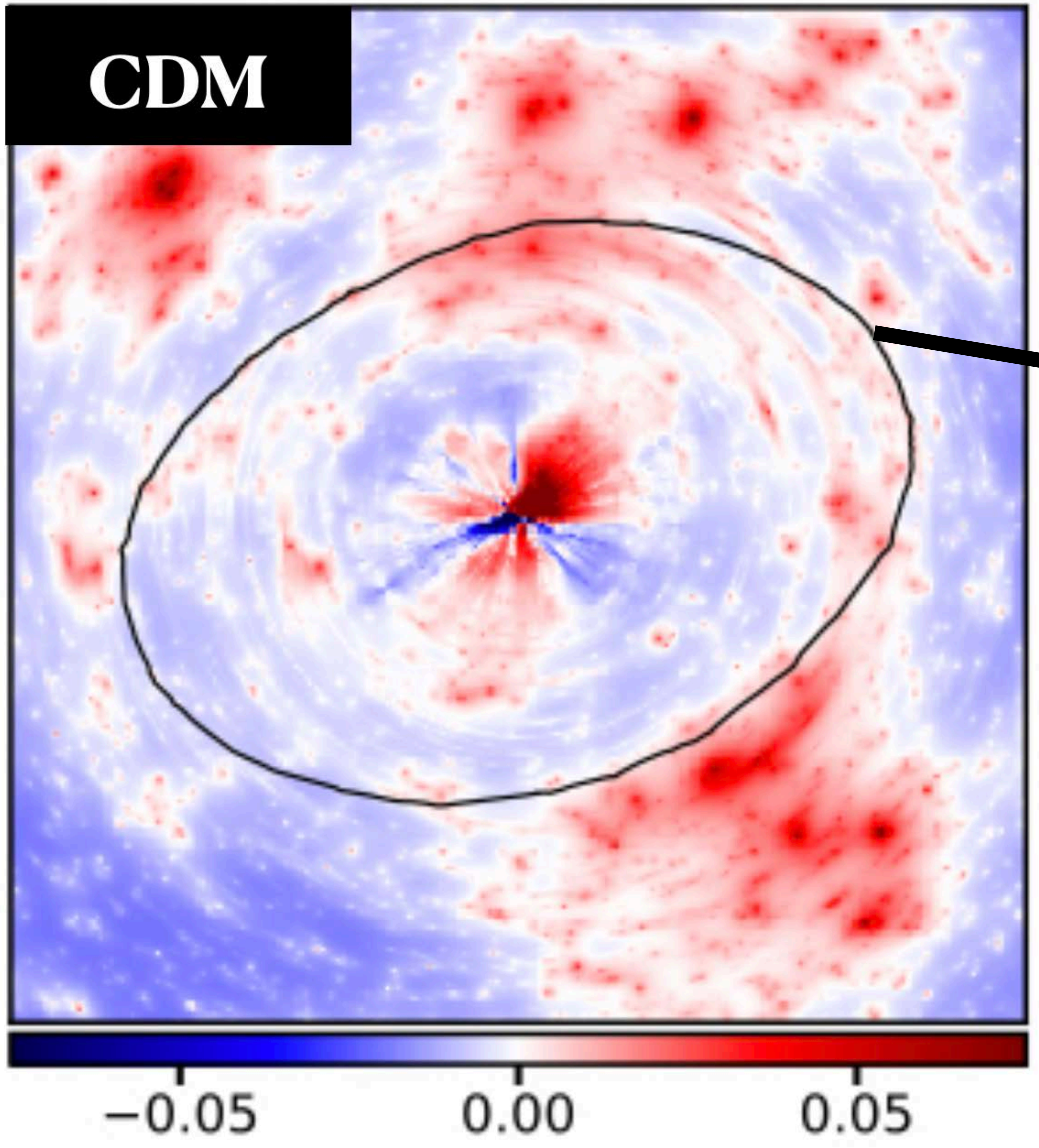


Core-collapsed halos are extremely efficient lenses



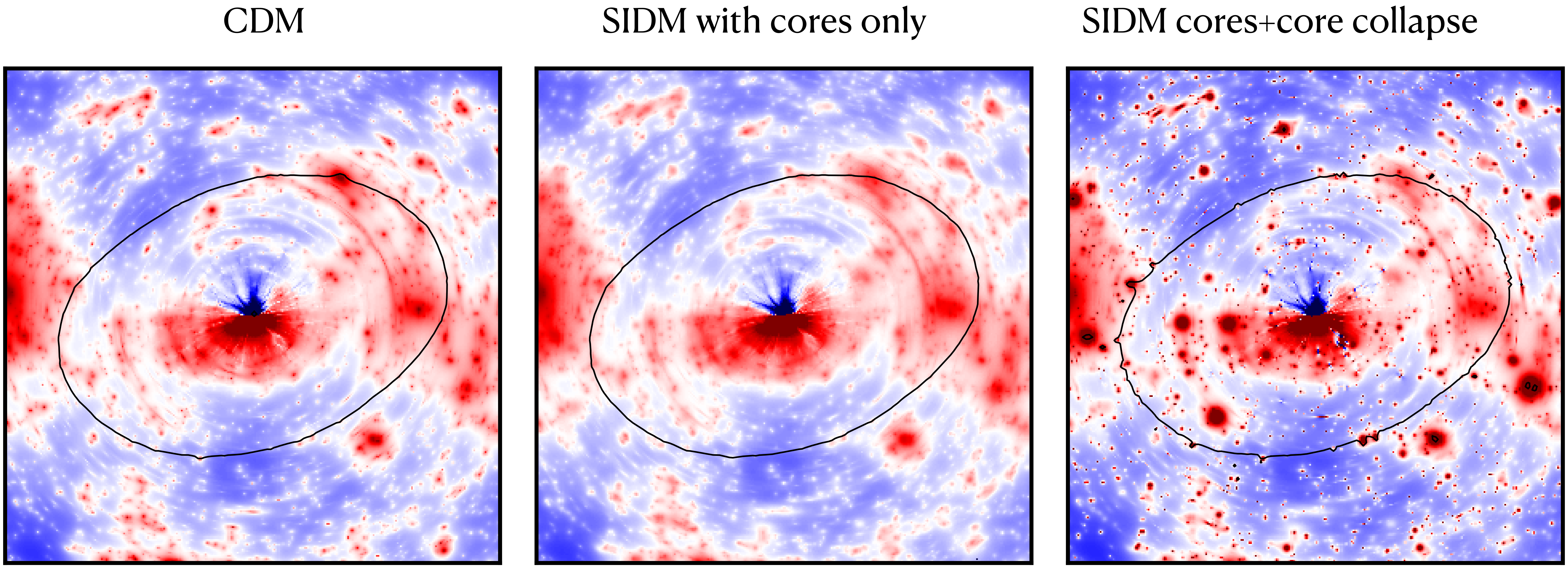
Core-collapsed halos are extremely efficient lenses

Now we are looking down the line of sight



Dark matter density relative to average

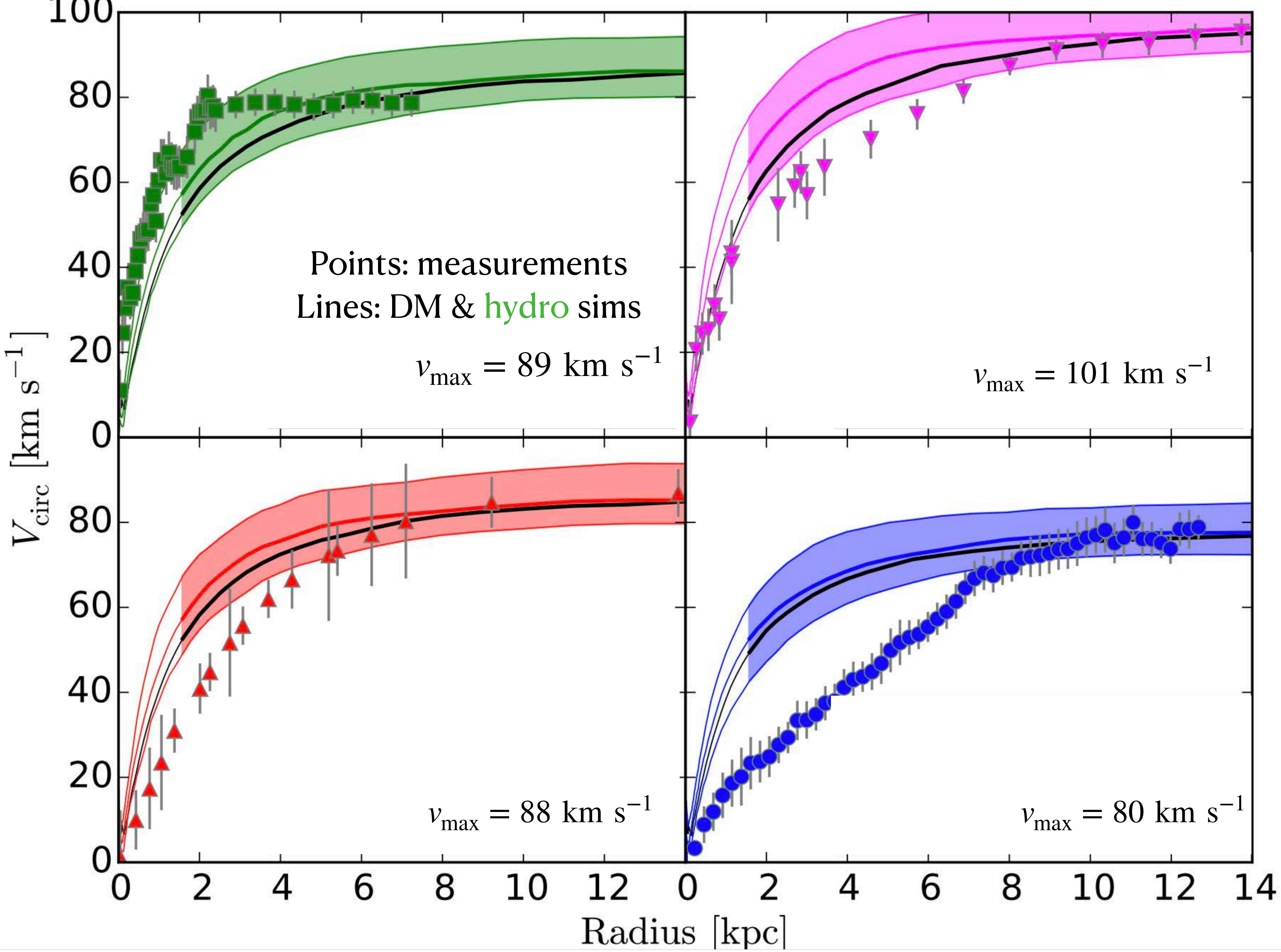
Critical curve (high magnifications)


CDM
SIDM with cores only
SIDM cores+core collapse

Self-interacting dark matter (SIDM)

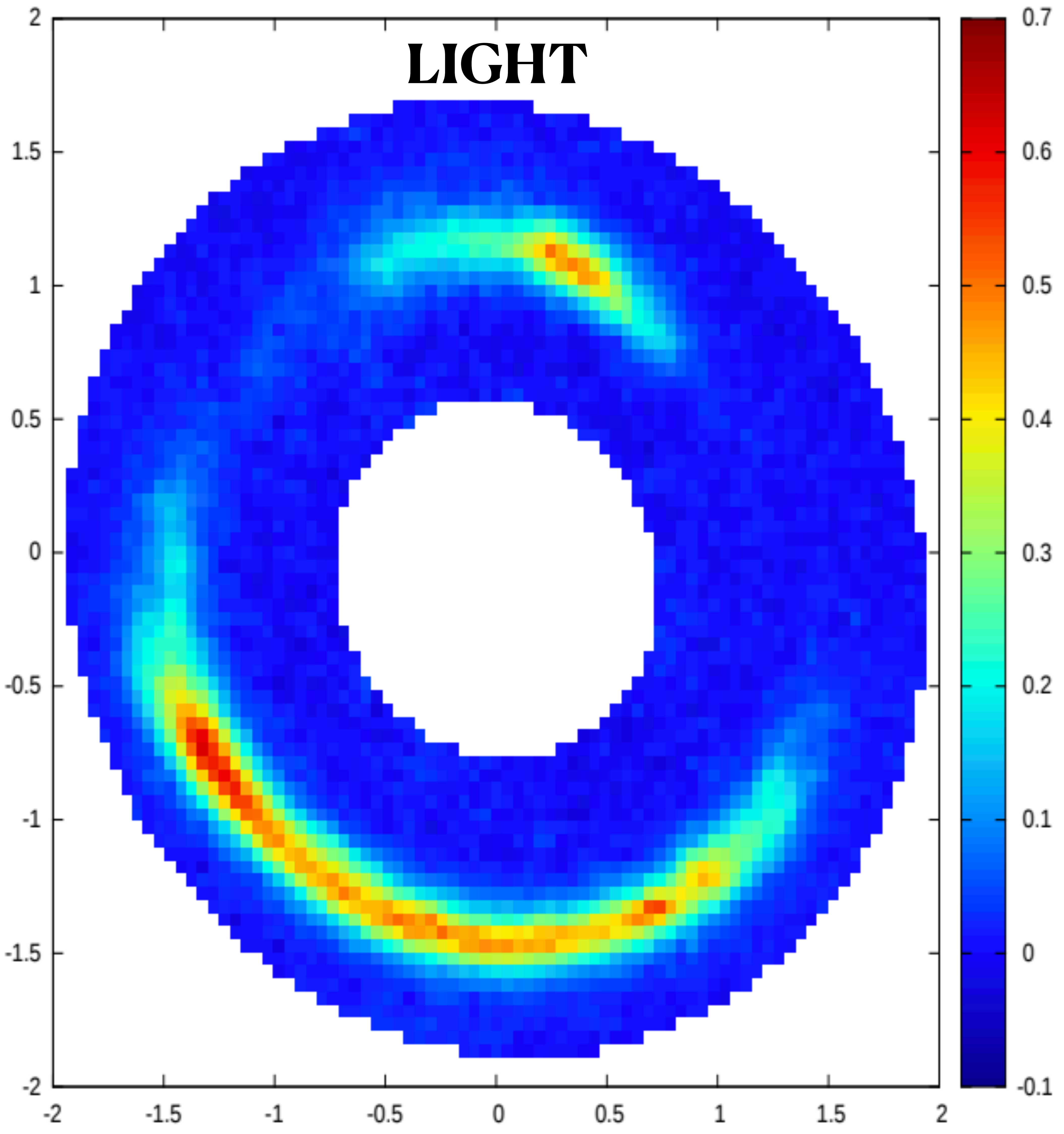
Core formation+collapse match diversity of observed rotation curves?

Adapted from Oman et al. (2016)

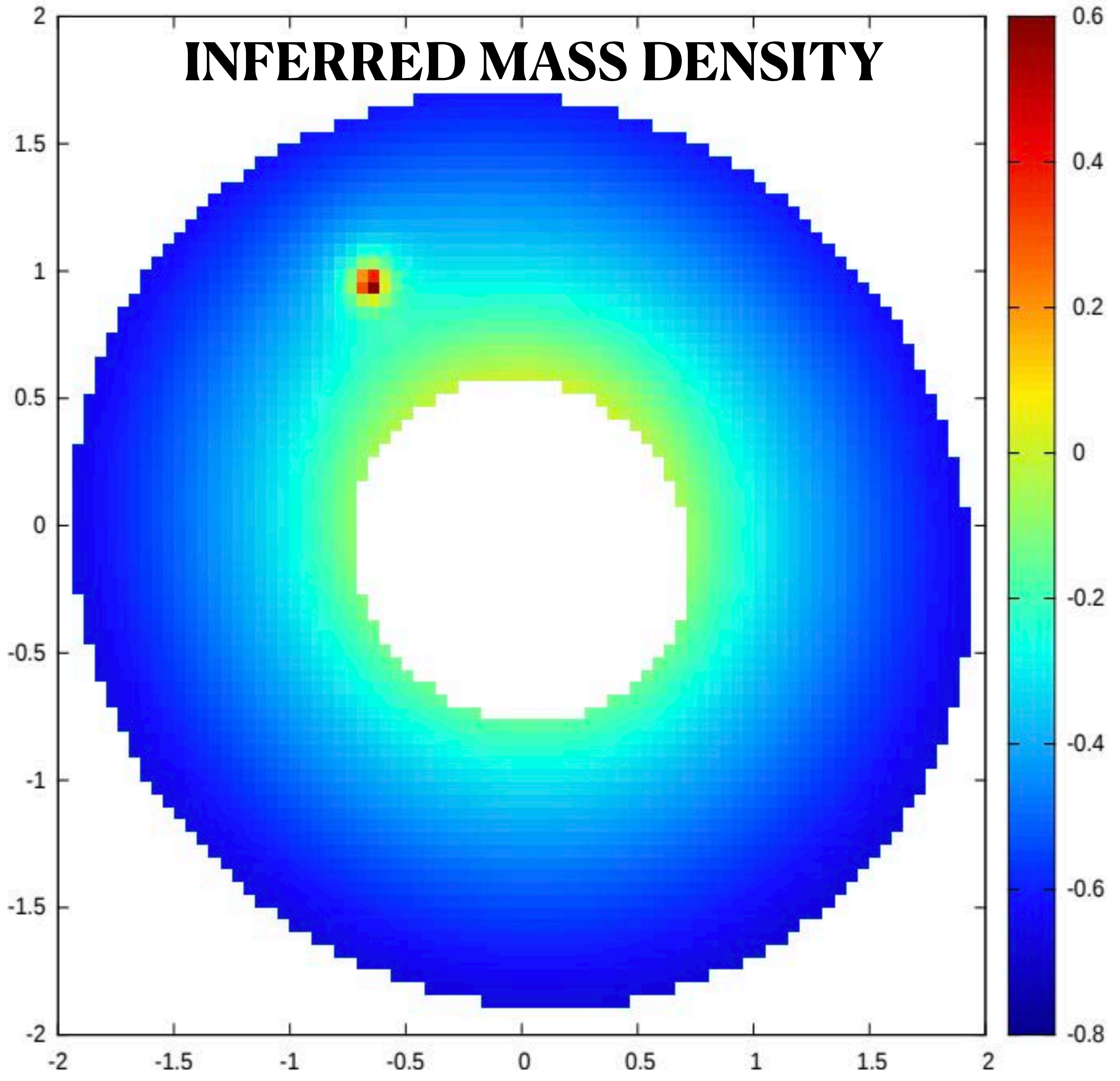


Hints from strong lensing?

Minor et al. (2021)

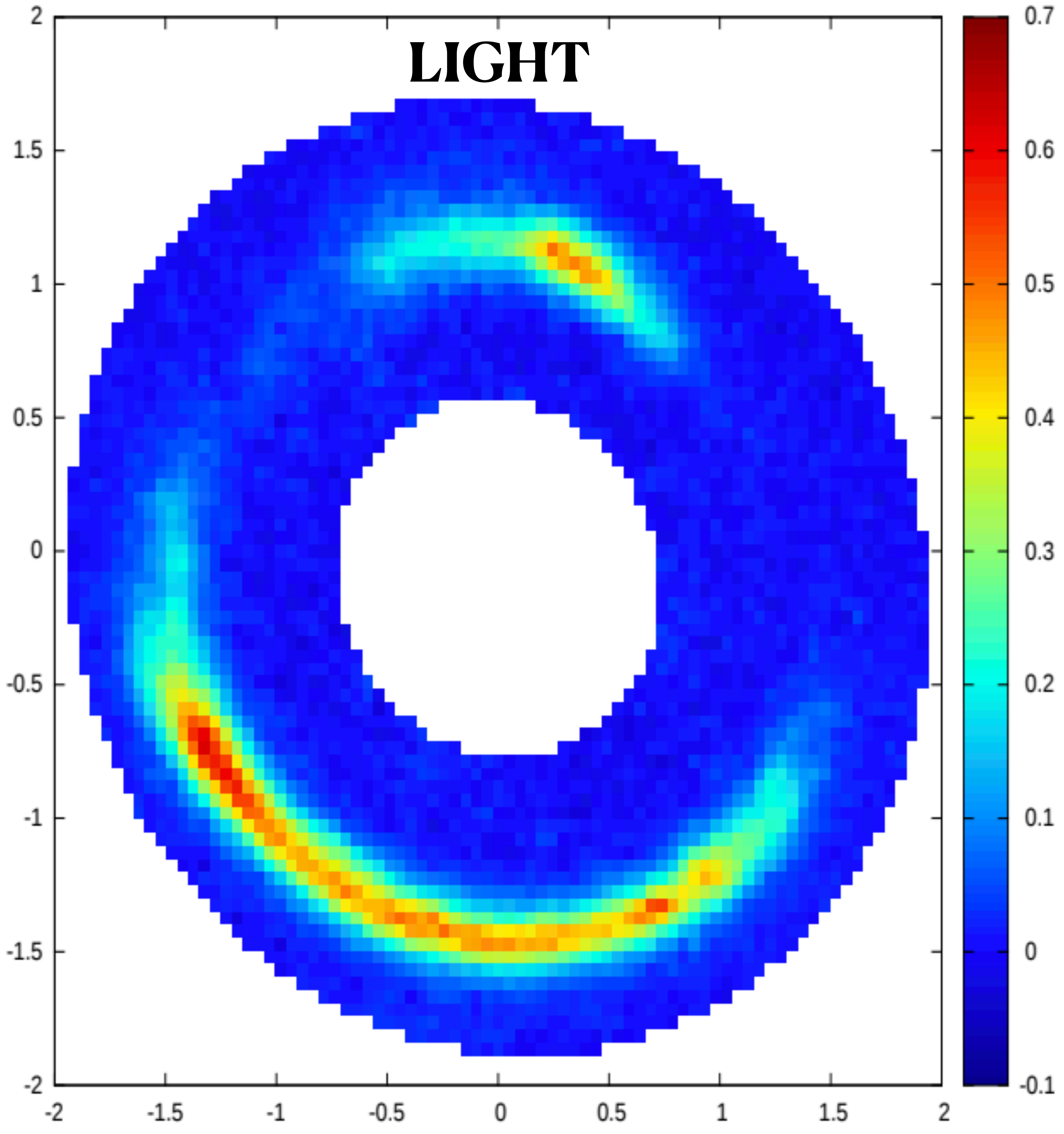


(a) masked HST image

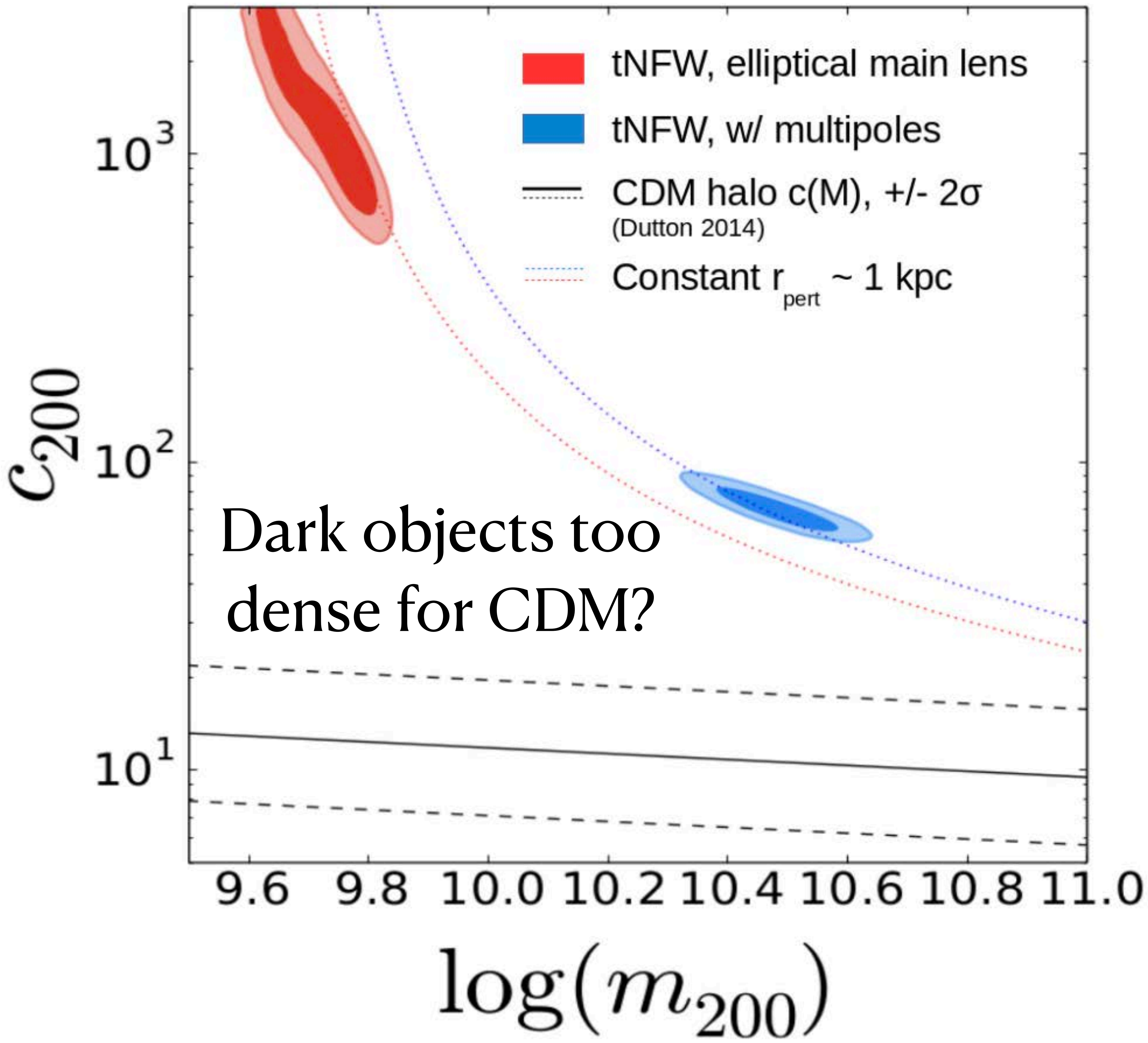


(a) tNFW model

Minor et al. (2021)



(a) masked HST image



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

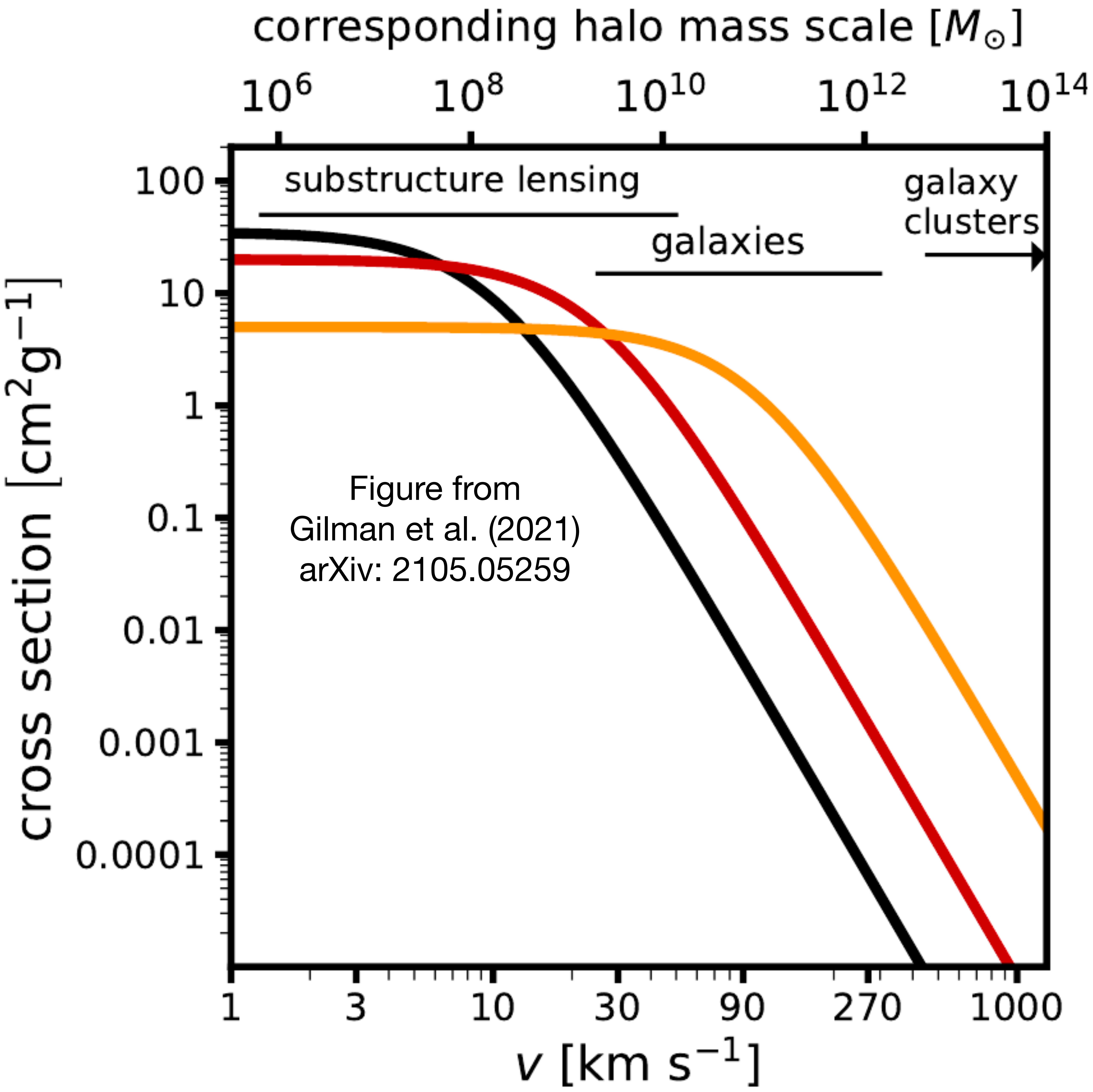


Figure from
Gilman et al. (2021)
arXiv: 2105.05259

Easy to achieve extremely high (> 100 cm^2/g) cross sections at low speeds

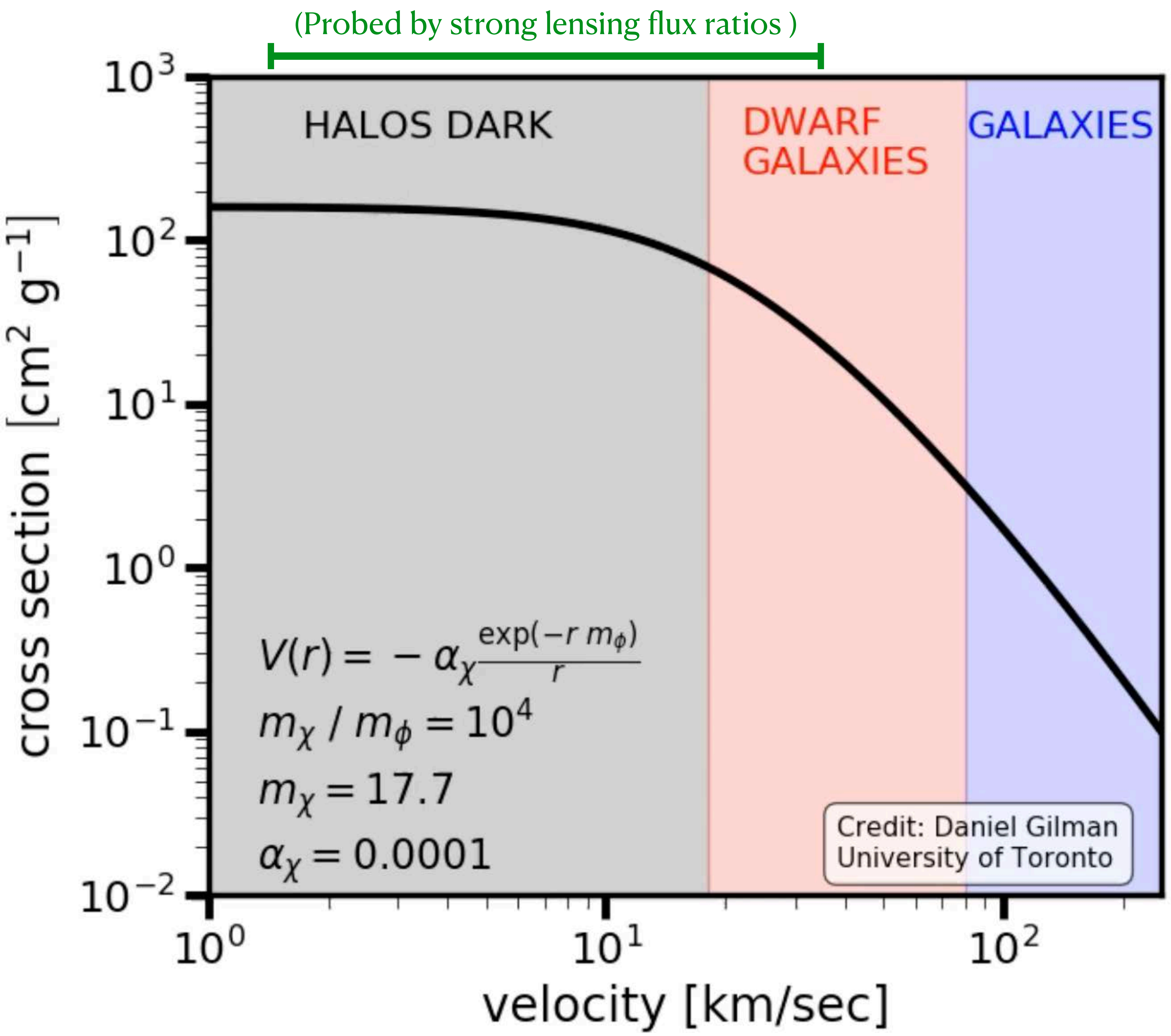
-> example: attractive dark force exchanged via light mediator

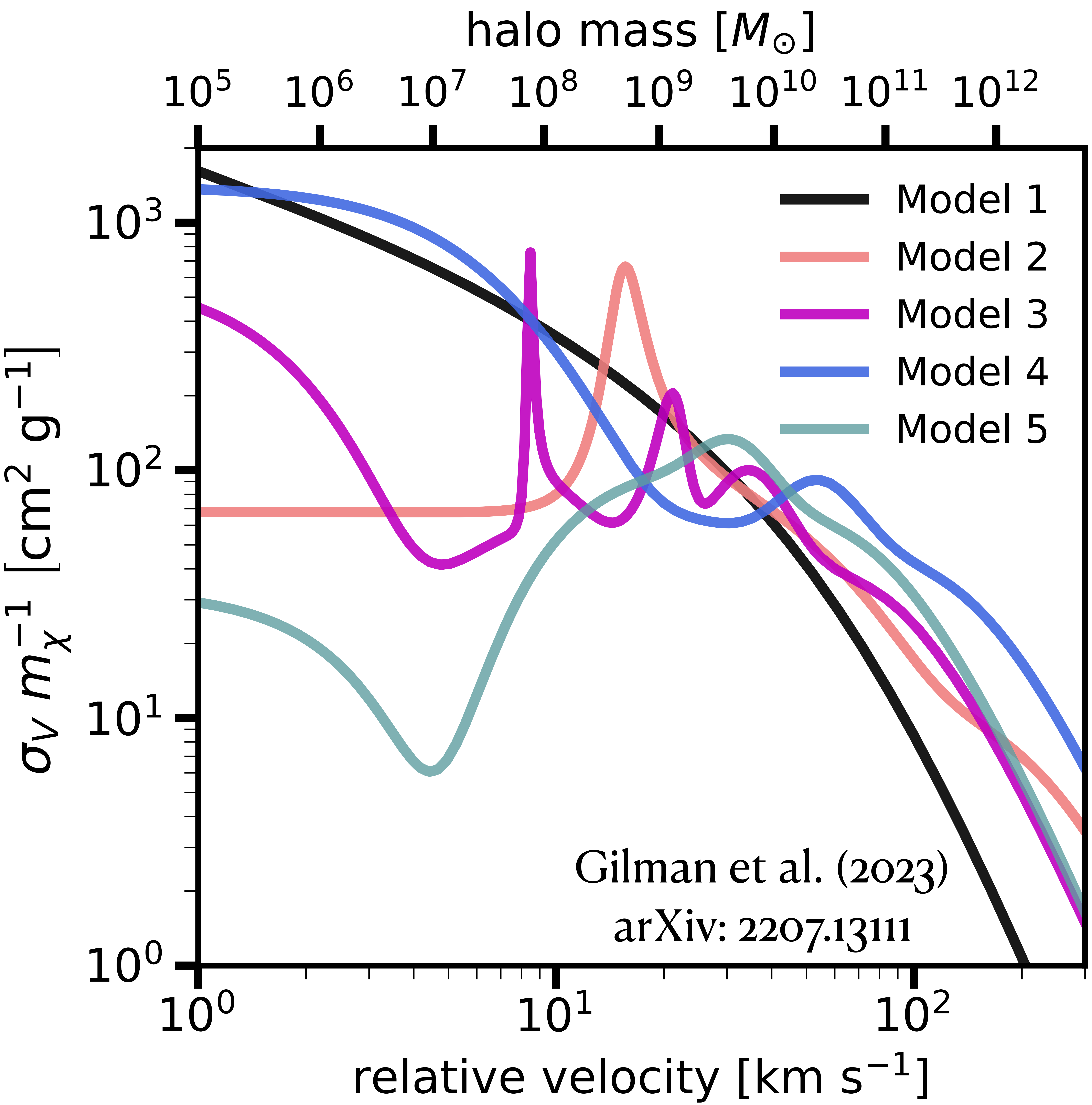
$$V(r) = -\alpha_\chi \frac{\exp\left(-r\ m_\phi\right)}{r}$$

α_χ = potential strength

m_ϕ = mediator mass ~ 1 MeV

m_χ = DM mass $\sim 1 - 10$ GeV





Exact solutions for the scattering cross section from standard partial-wave analysis:

Model 1: Repulsive potential
-> broad range of repulsive potentials have similar forms

Models 2-5: Attractive potentials with (anti-)resonances
-> many SIDM formulations include multi-component DM with bound states

characteristic collapse timescale

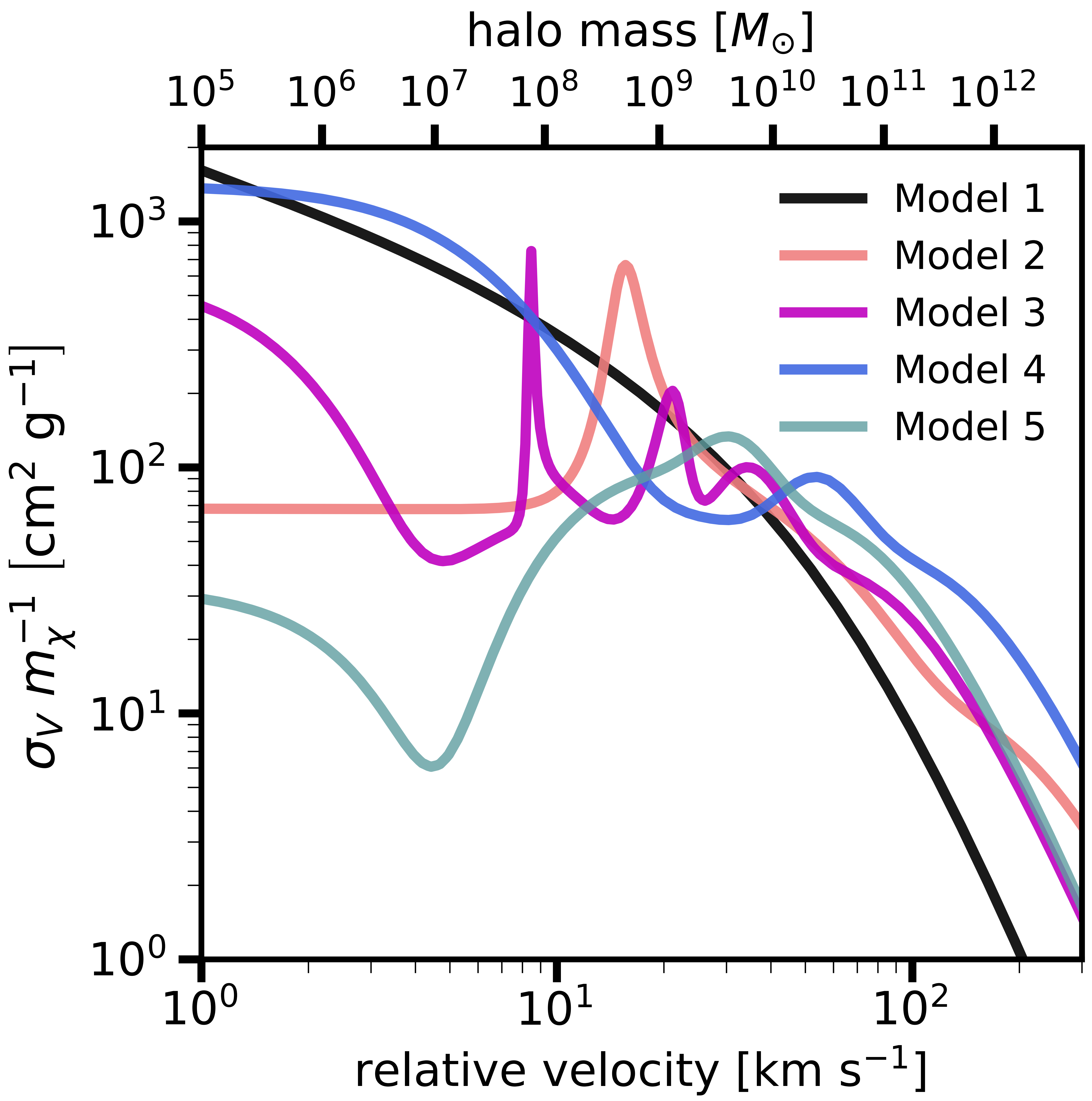
$$t_0^{-1} \sim \langle \sigma v^5 \rangle / \langle v^5 \rangle \times \text{density} \times \text{velocity}$$

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

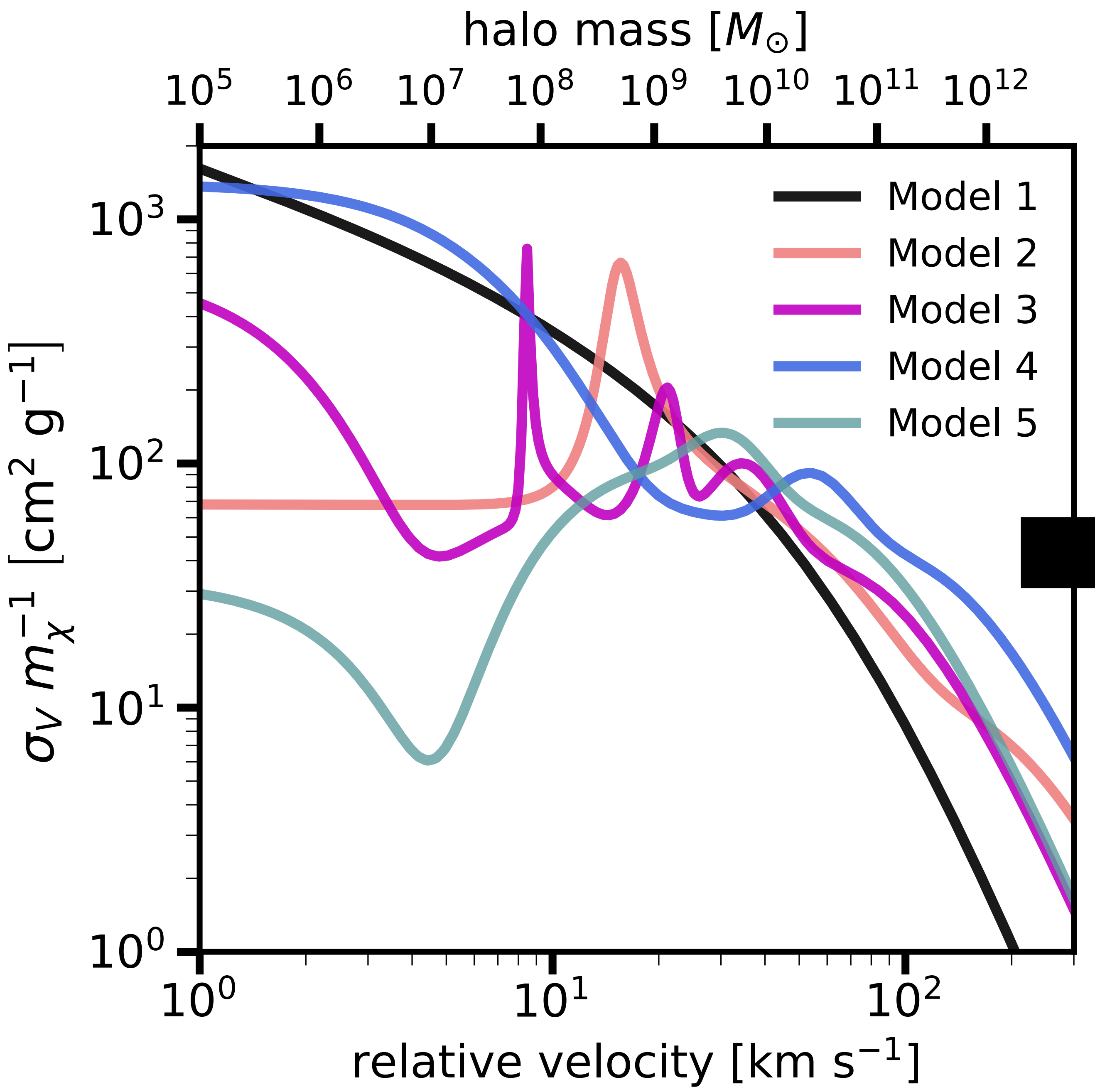
Halos collapse after some multiple of the timescale

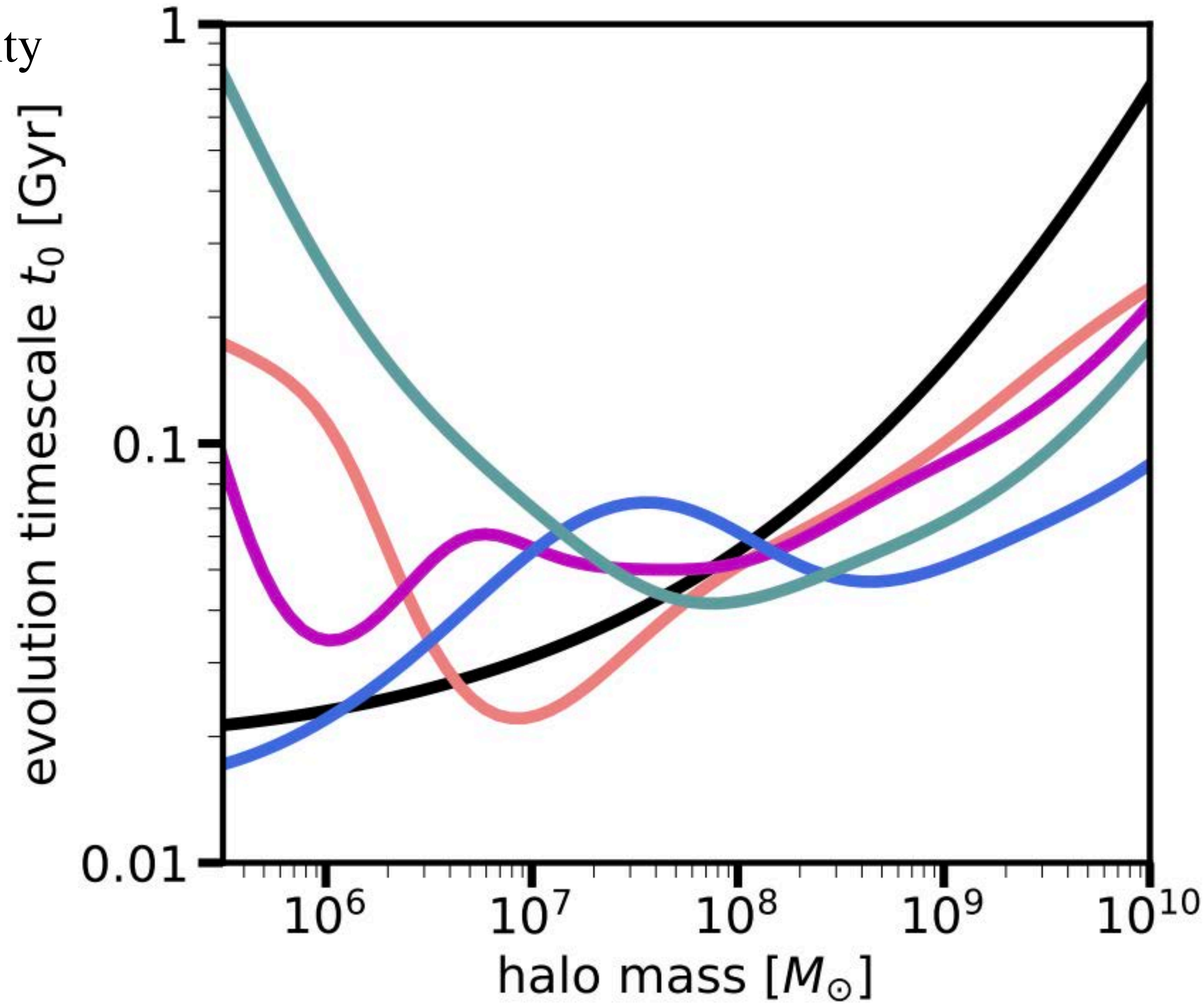
$$t_{\text{subhalo}} \sim \lambda_{\text{sub}} t_{\text{collapse}}$$

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



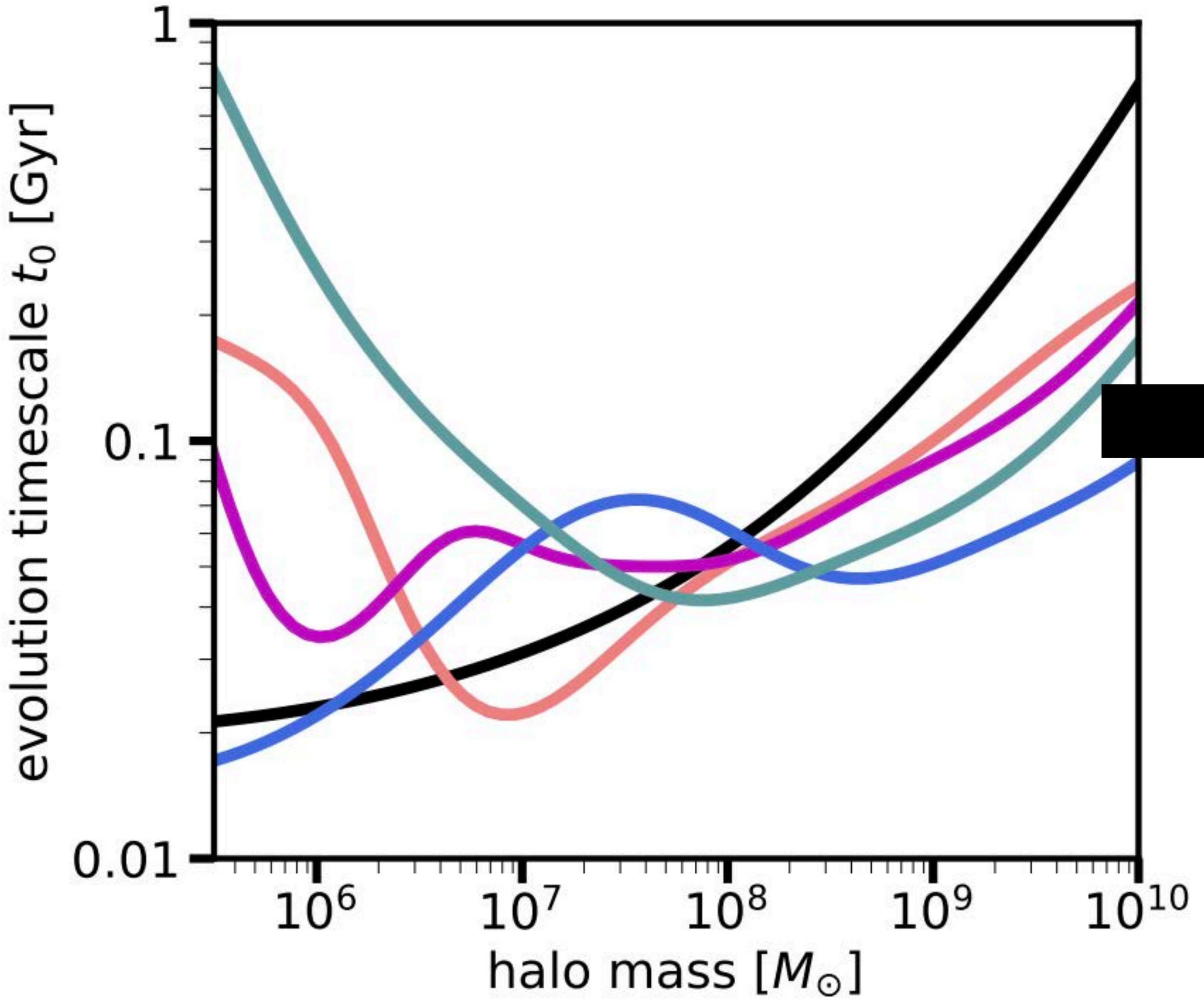
$$t_0^{-1} \sim \langle \sigma v^5 \rangle / \langle v^5 \rangle \times \text{density} \times \text{velocity}$$



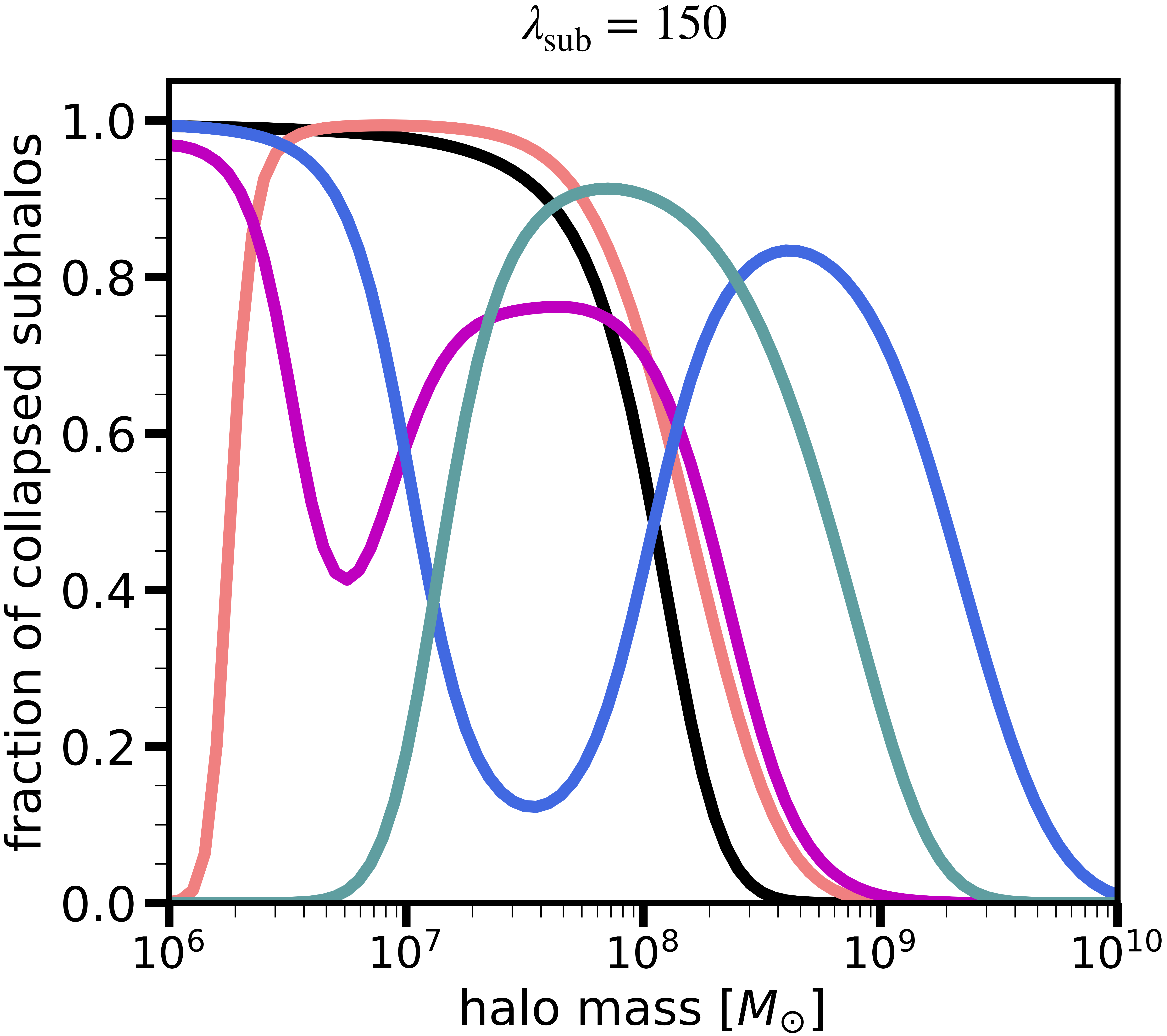


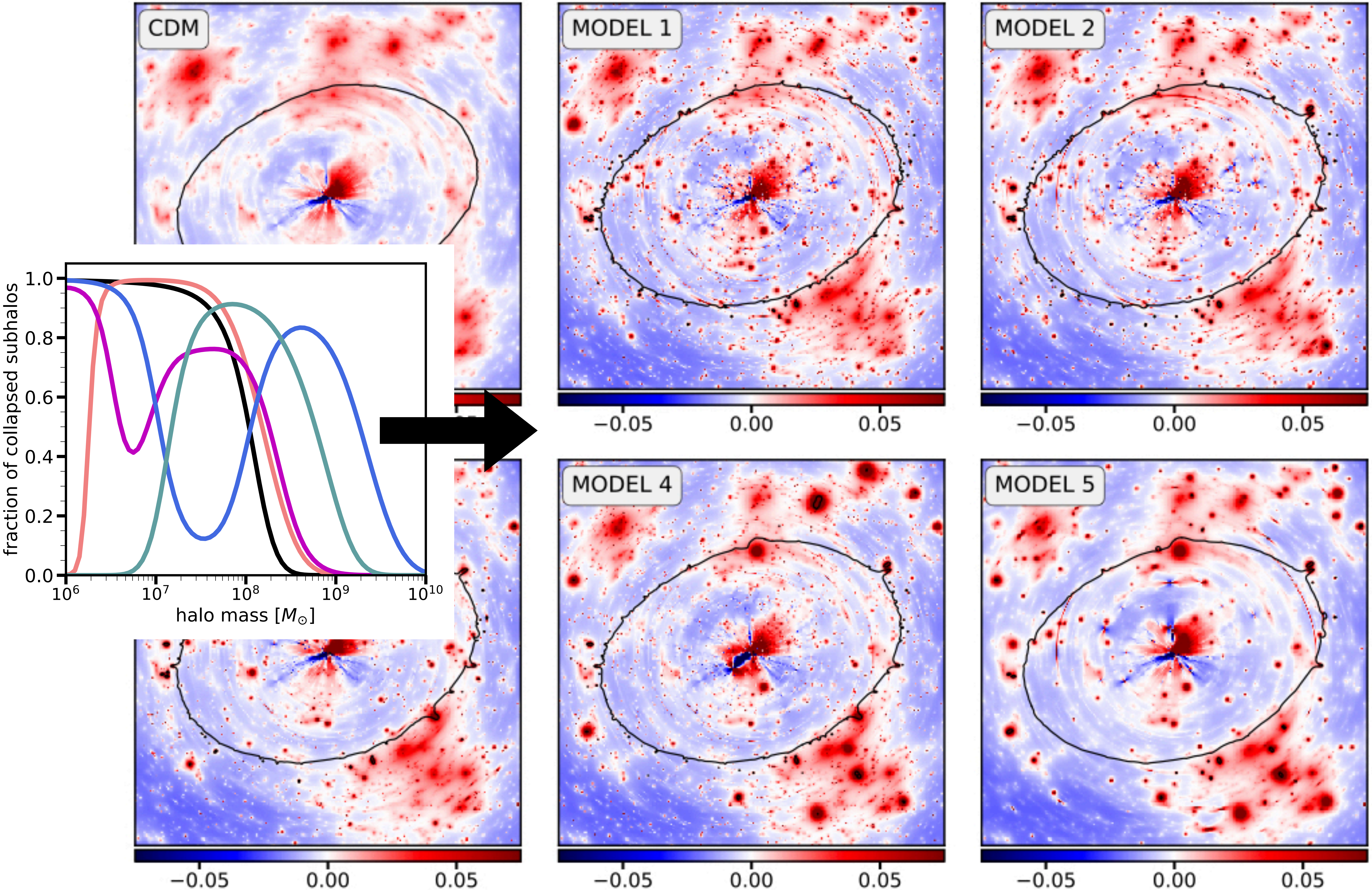
$$t_0^{-1} \sim \langle \sigma v^5 \rangle / \langle v^5 \rangle \times \text{density} \times \text{velocity}$$

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



halos collapse after a multiple of t_0

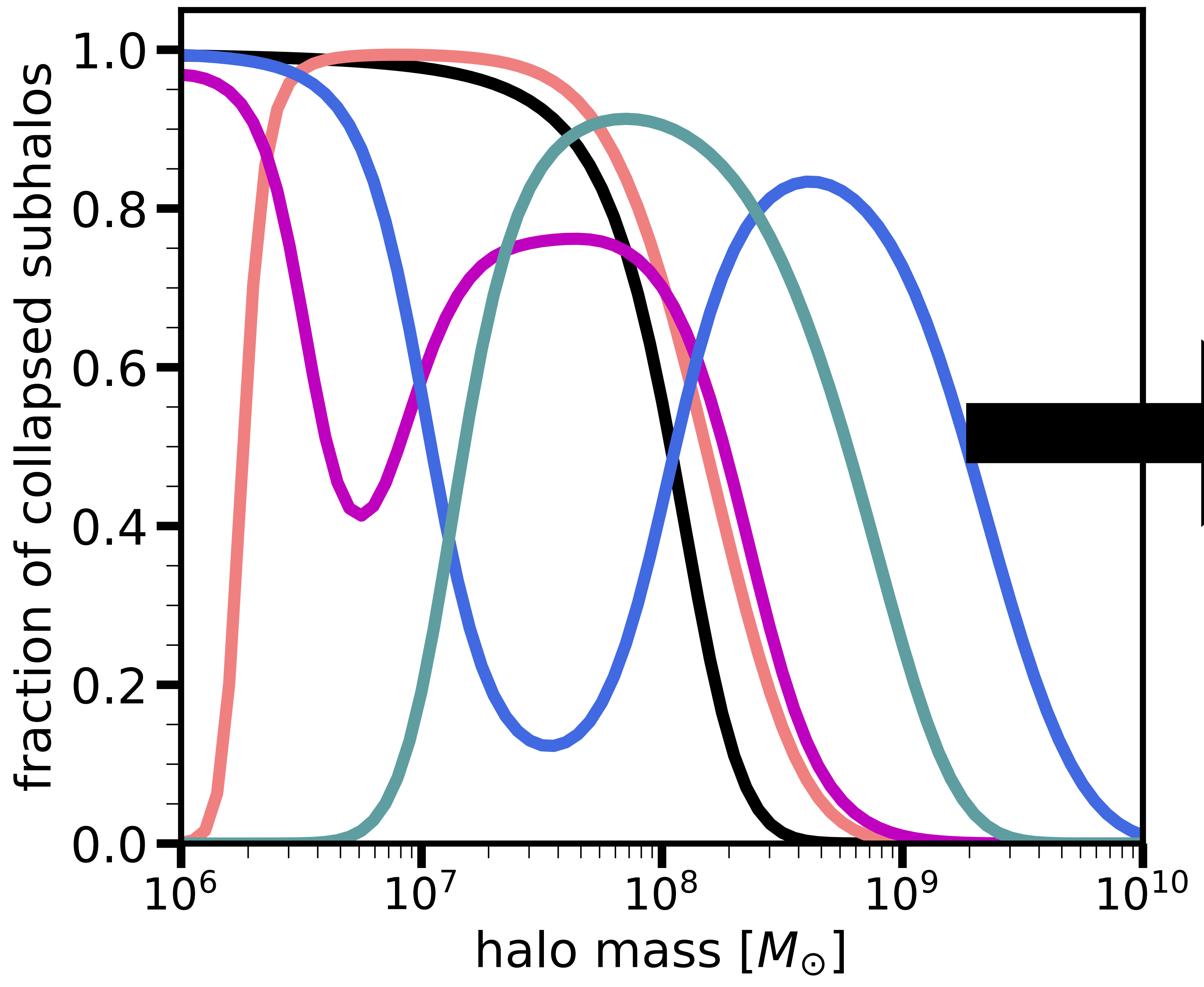




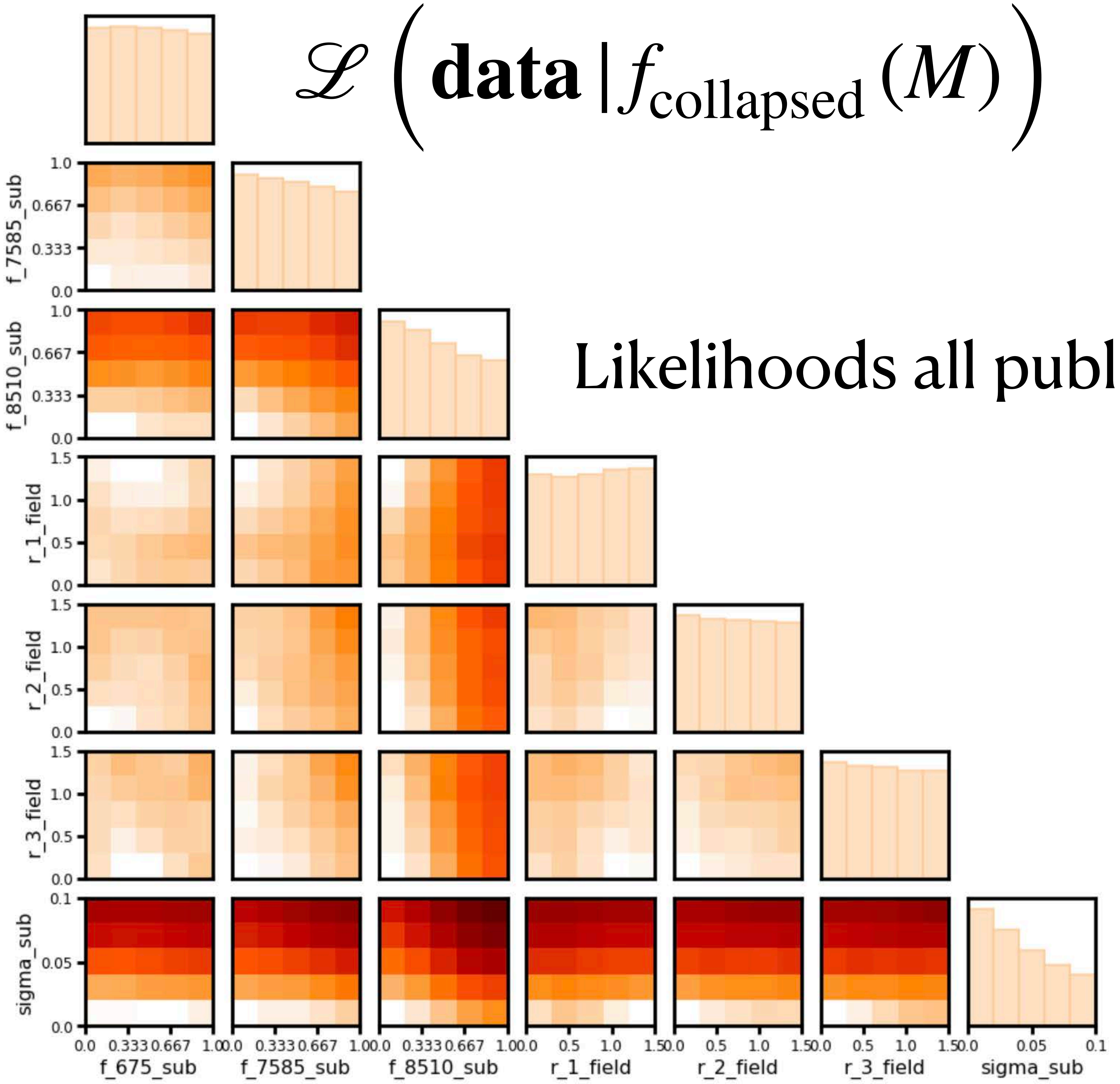
Gilman et al. (2023)
arXiv: 2207.13111

We can compute the likelihood of data given

fraction of collapsed halos as a function of halo mass:



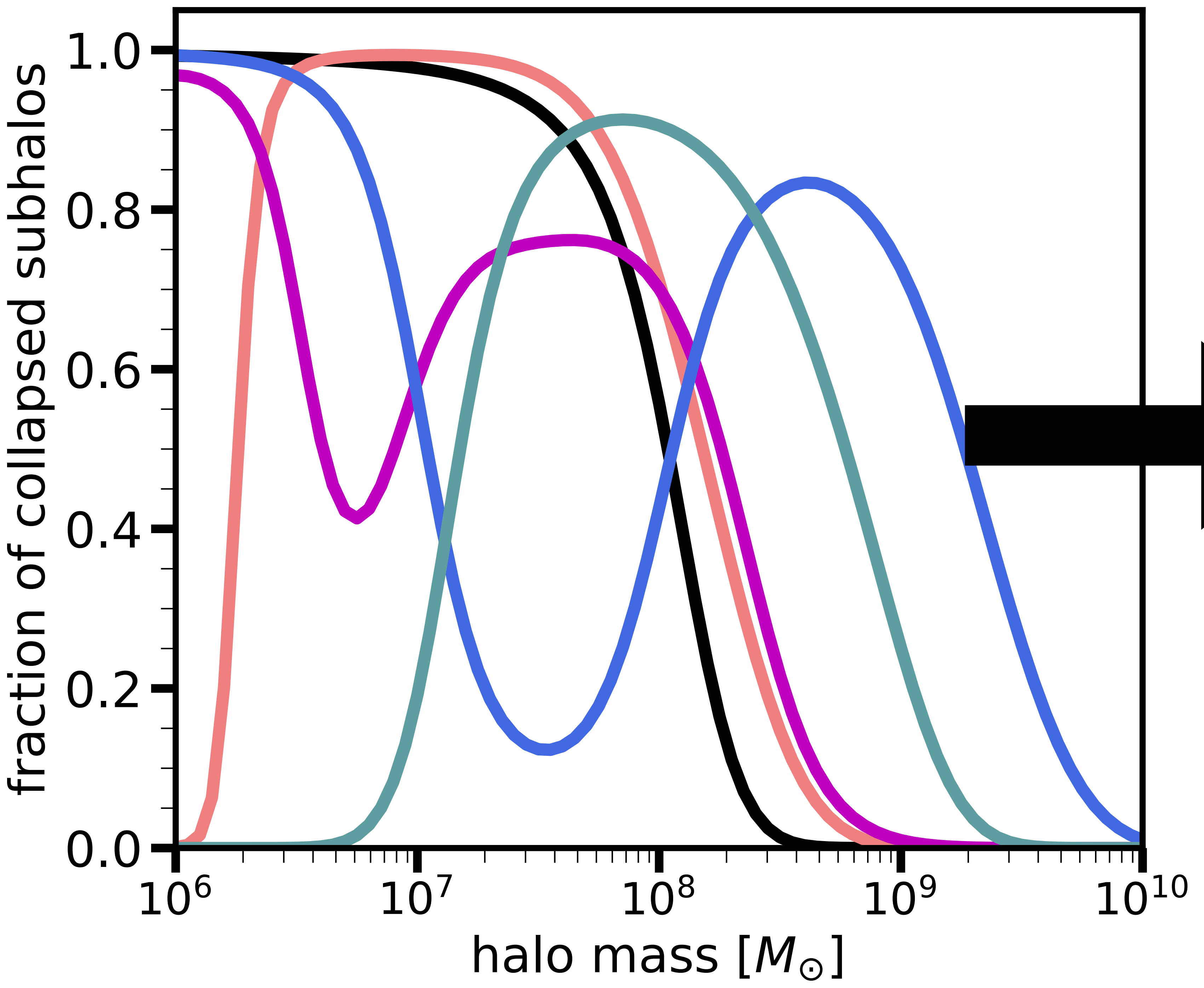
$$\mathscr{L}\left(\mathbf{data}\,|\,f_{\mathrm{collapsed}}(M)\right)$$



Likelihoods all publicly available

We can compute the likelihood of data given

fraction of collapsed halos as a function of halo mass:

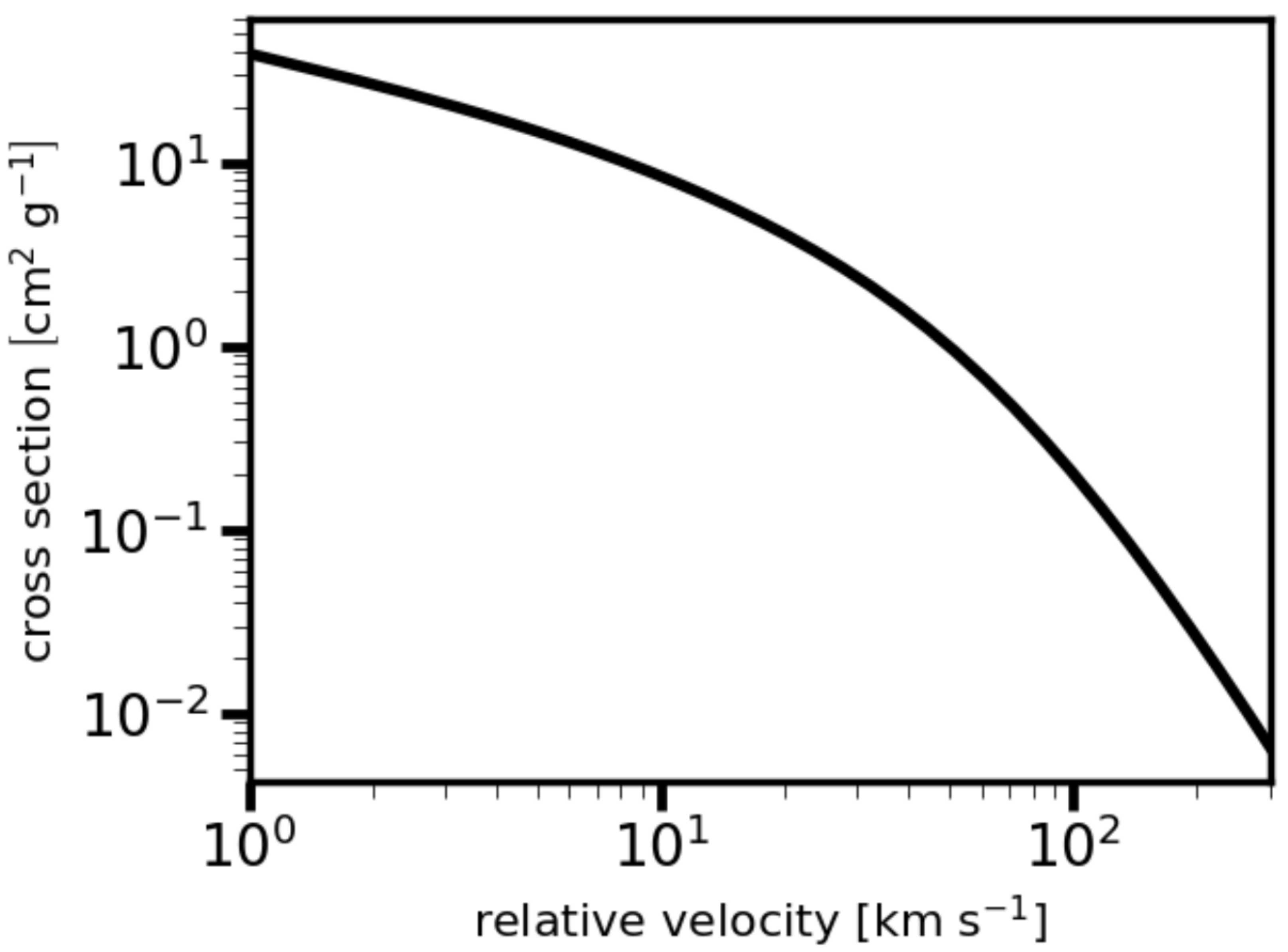


$$\mathscr{L}\left(\mathbf{data}\,|\,f_{\mathrm{collapsed}}(M)\right)$$

recast this as constraints on the core-collapse timescale

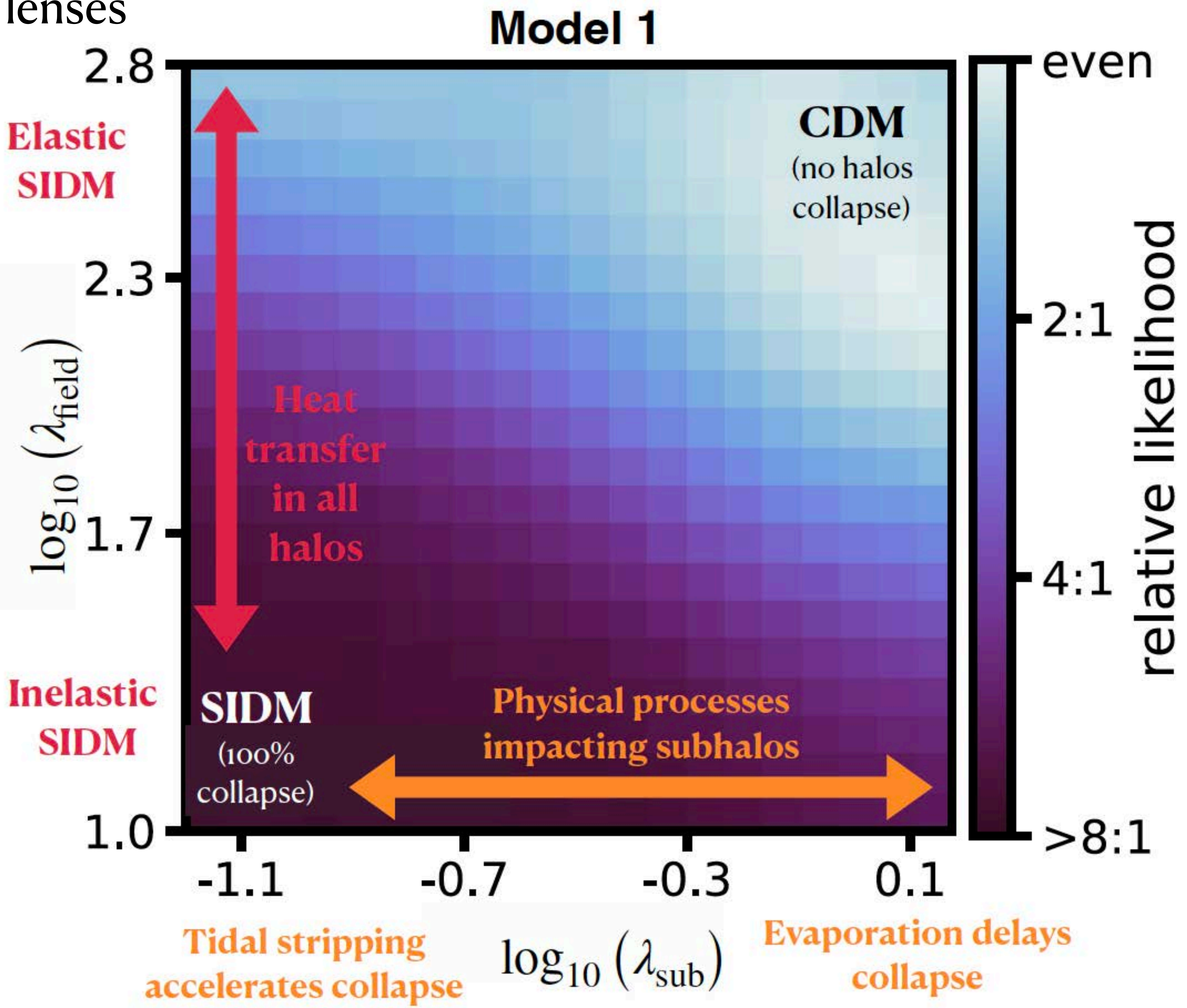
$$\mathscr{L}\left(\mathbf{data}\,|\,\lambda_{\mathrm{sub}}, \lambda_{\mathrm{field}}, \sigma\right) = \int \mathscr{L}\left(\mathbf{data}\,|\,f_{\mathrm{collapsed}}(M)\right)$$
$$\times\, p\left(f_{\mathrm{collapsed}}(M)\,|\,\lambda_{\mathrm{sub}}, \lambda_{\mathrm{field}}, \sigma\right) df_{\mathrm{collapsed}}$$

Inference on real data with 11 lenses

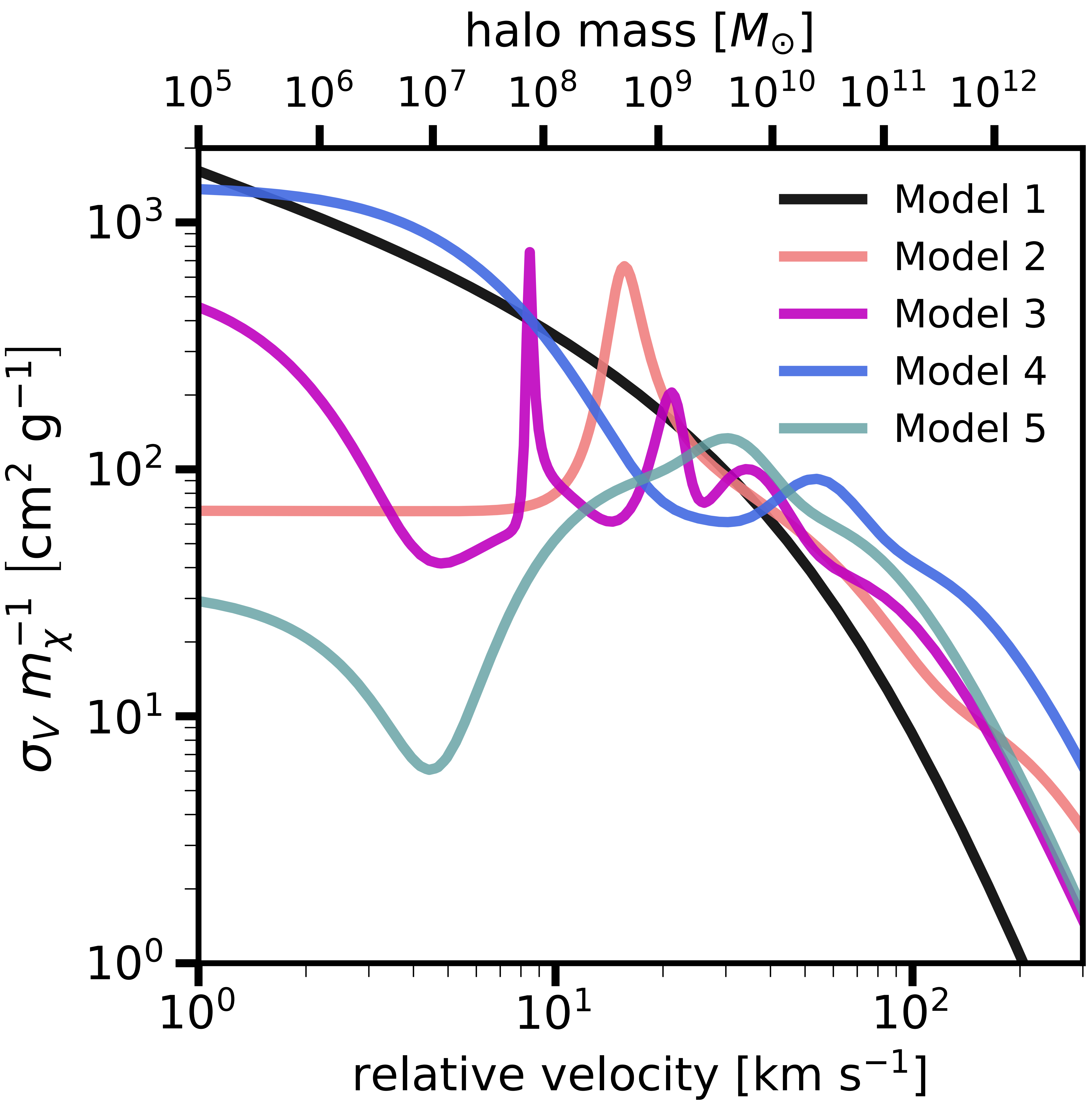


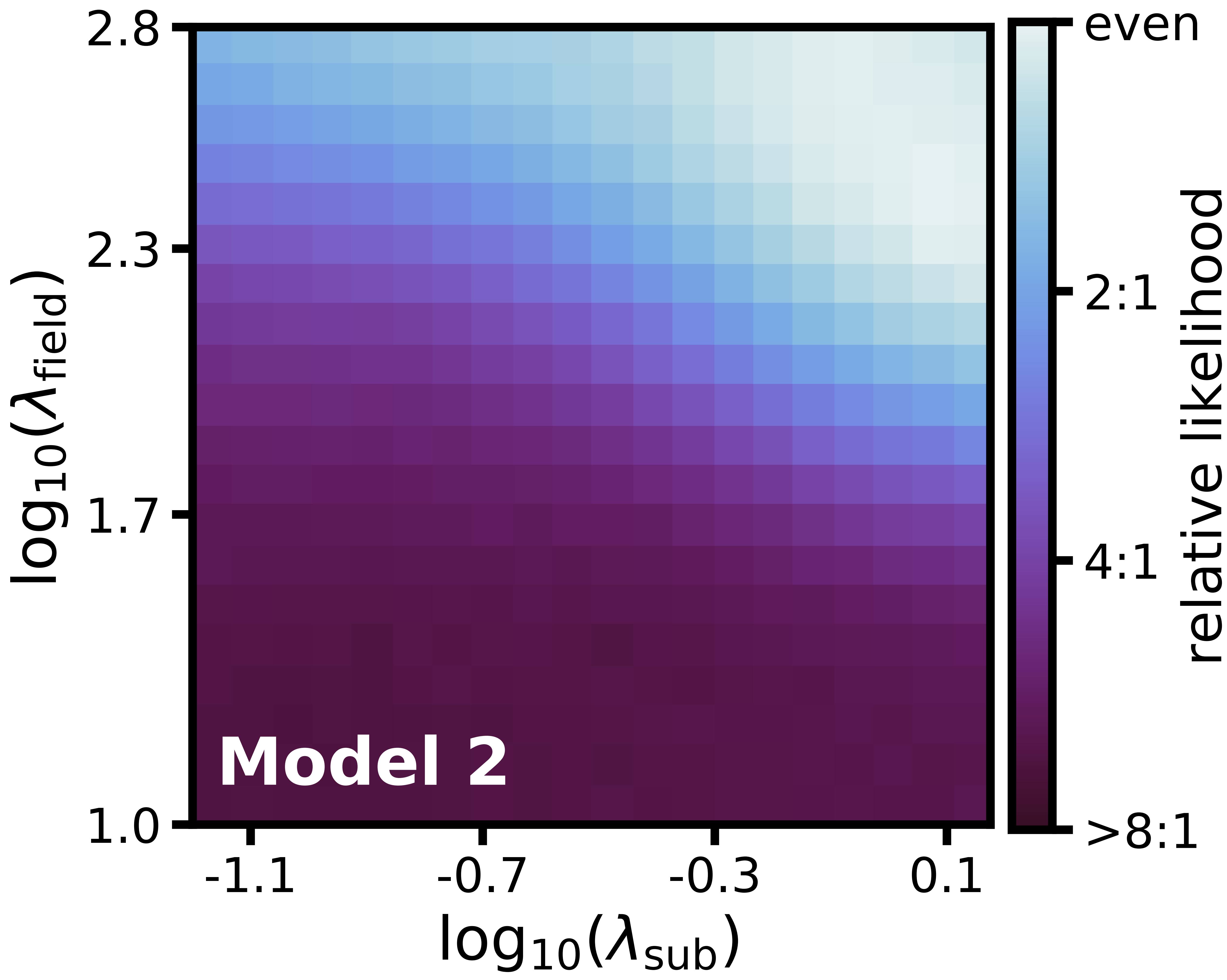
$$t_{\rm subhalo} \sim \lambda_{\rm sub}\, t_{\rm collapse}$$

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

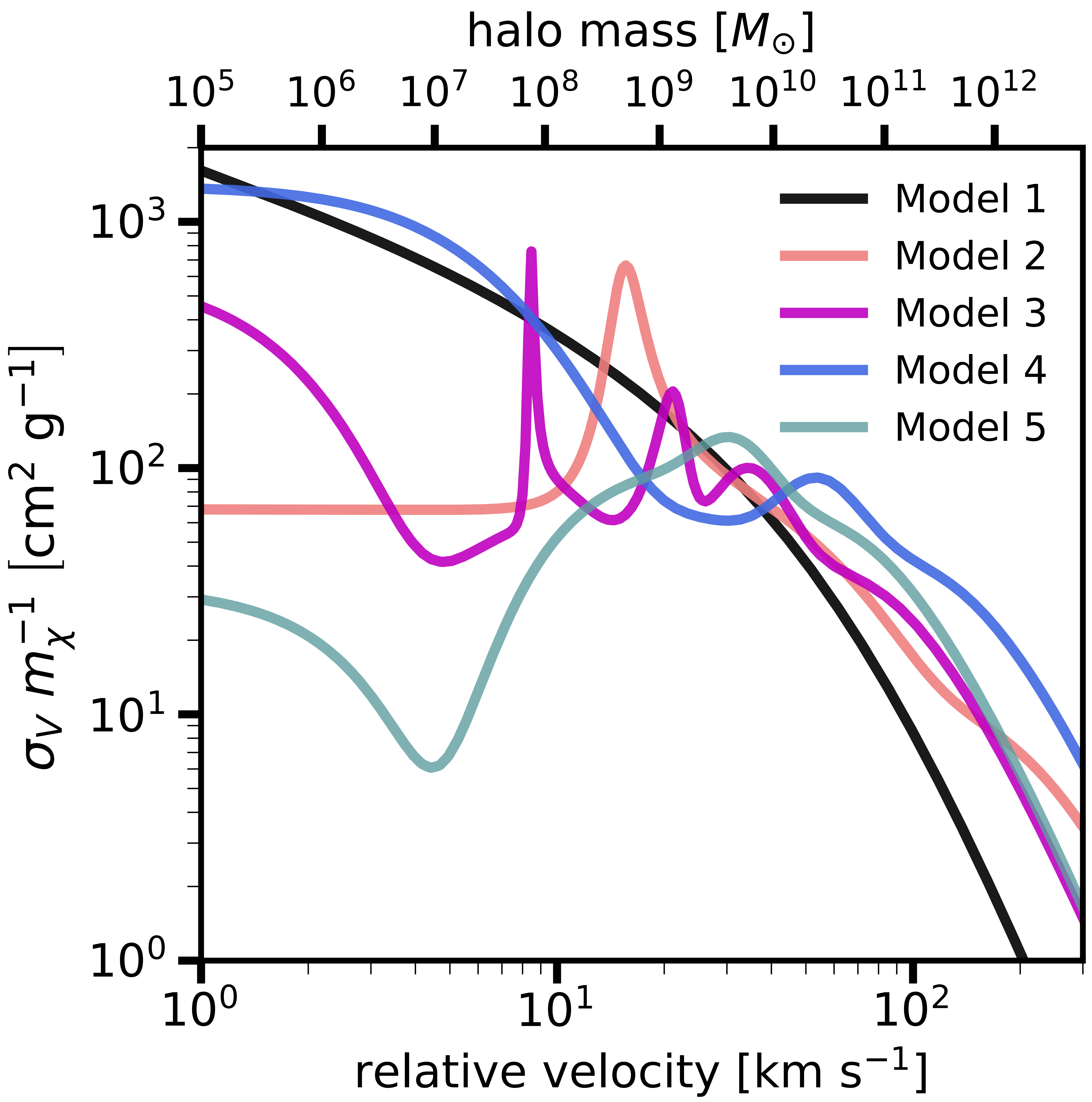


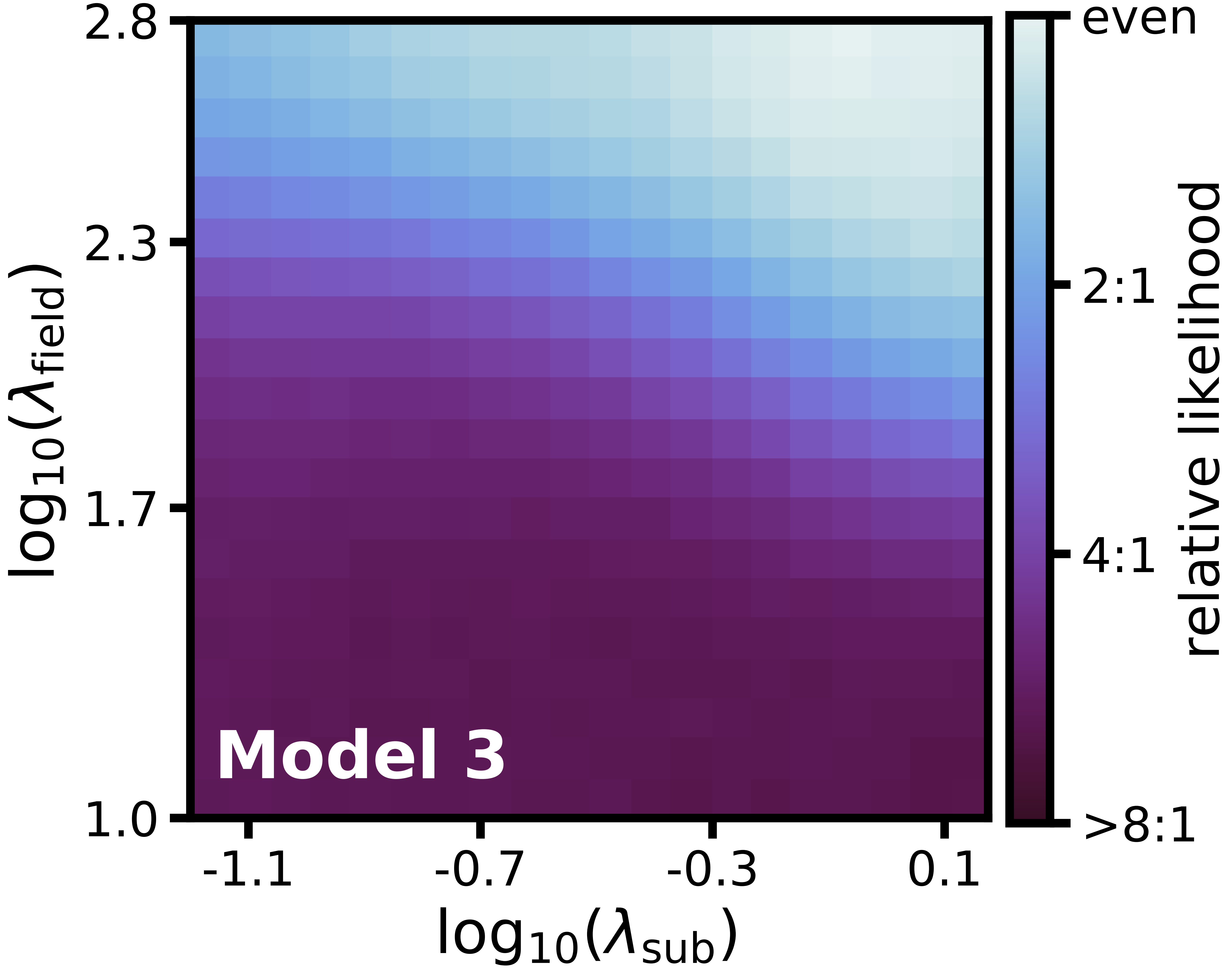
Inference on real data with 11 lenses: scenarios with 100% collapse strongly disfavored



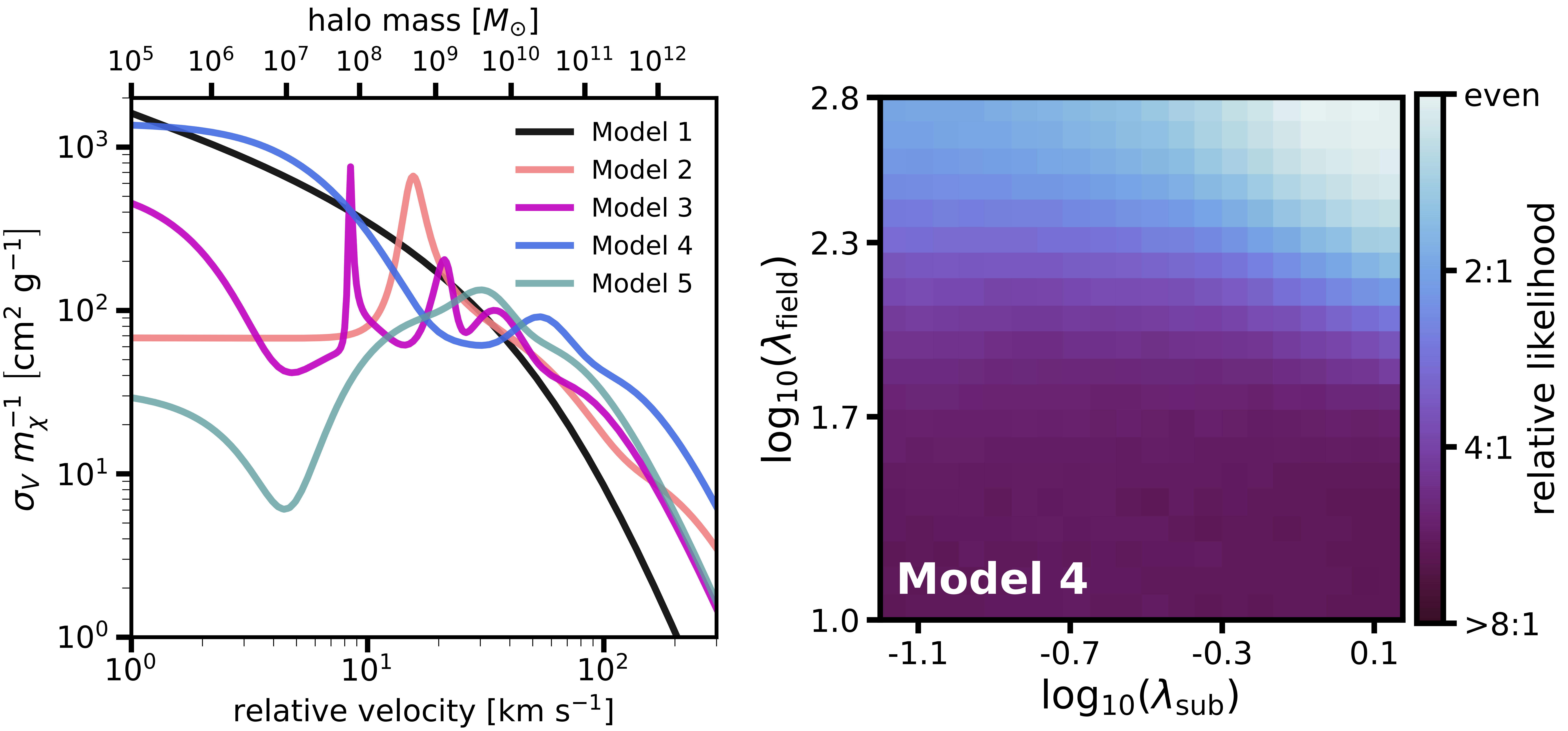


Inference on real data with 11 lenses: scenarios with 100% collapse strongly disfavored

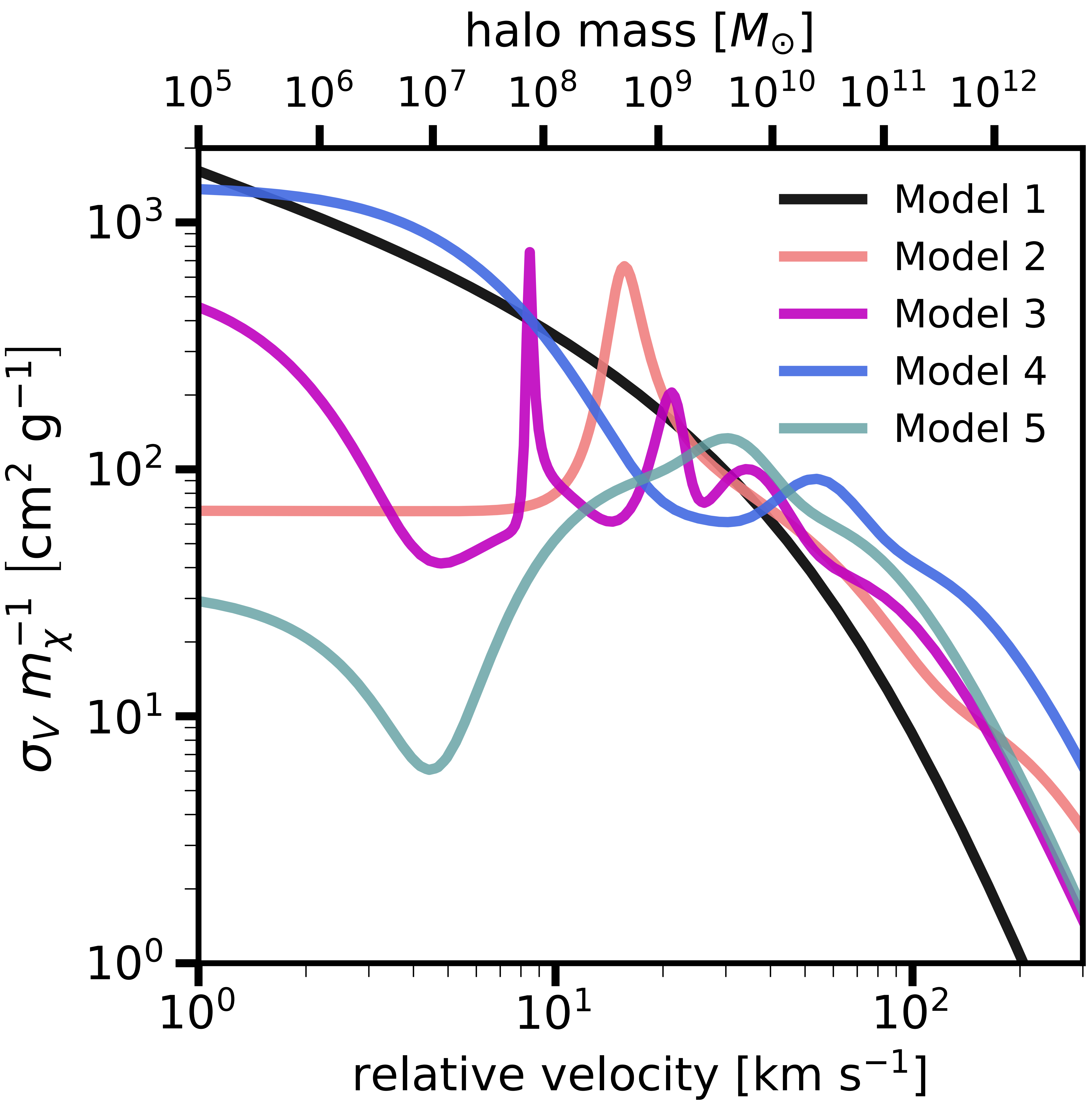


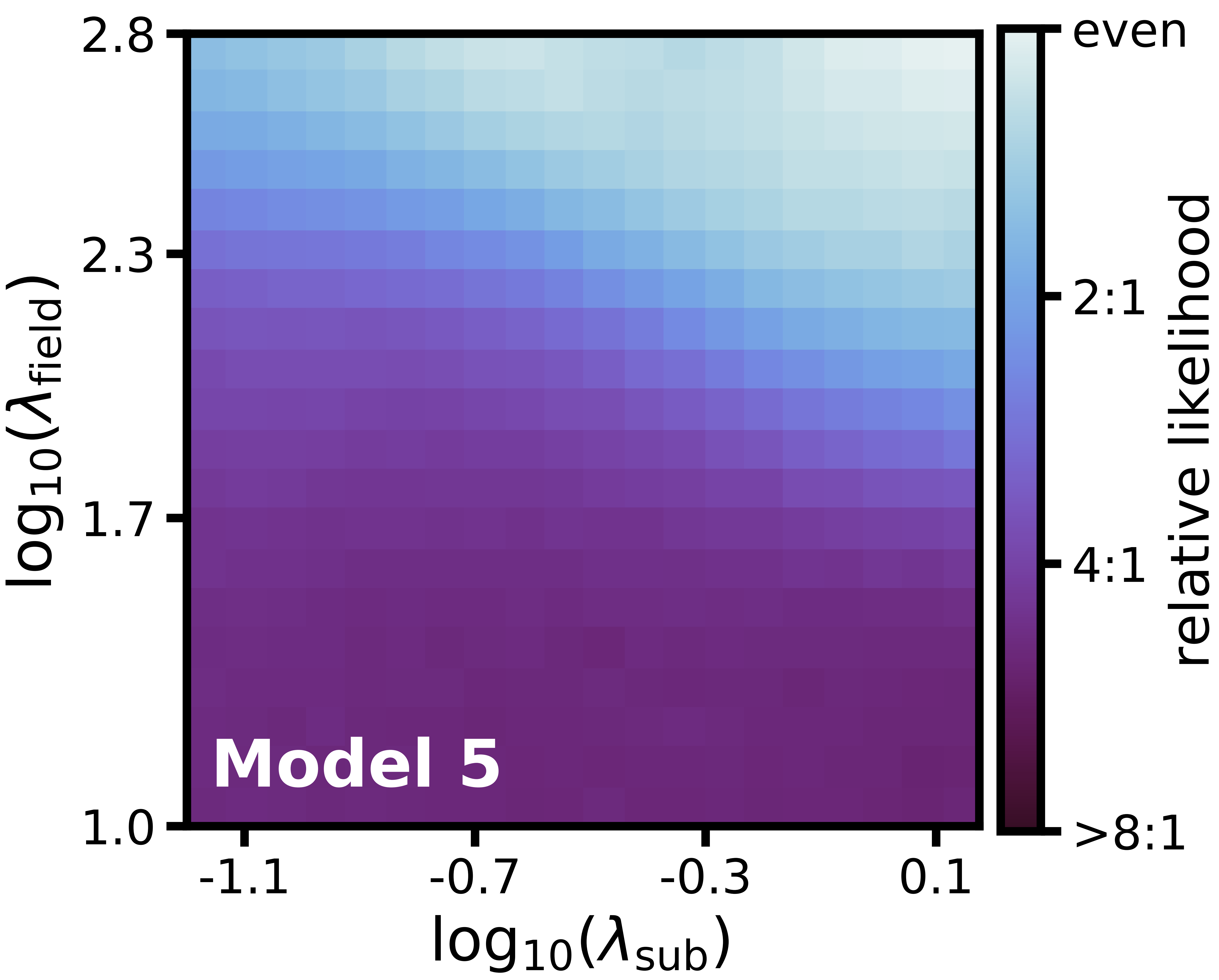


Inference on real data with 11 lenses: scenarios with 100% collapse strongly disfavored

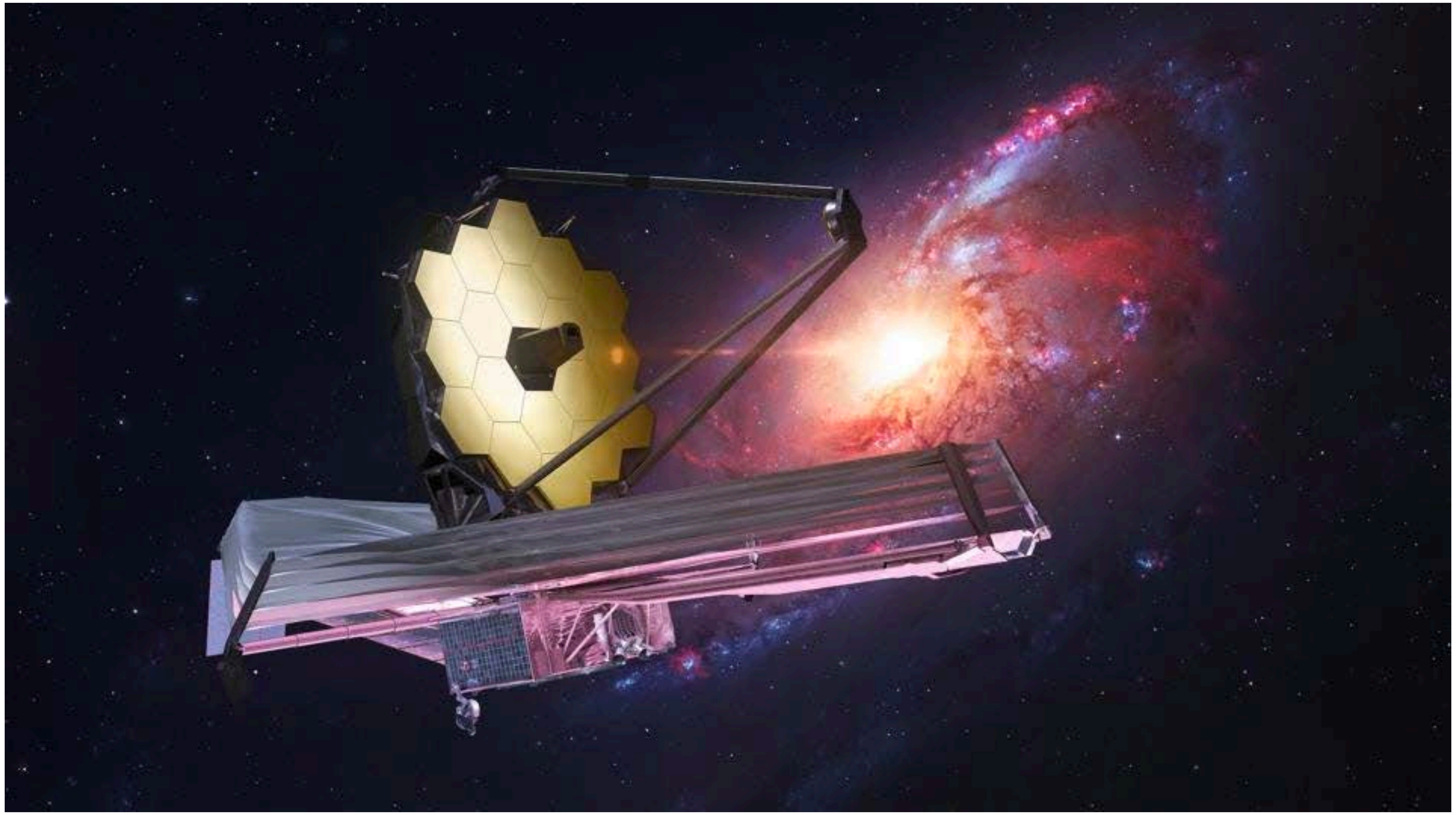


Inference on real data with 11 lenses: scenarios with 100% collapse strongly disfavored





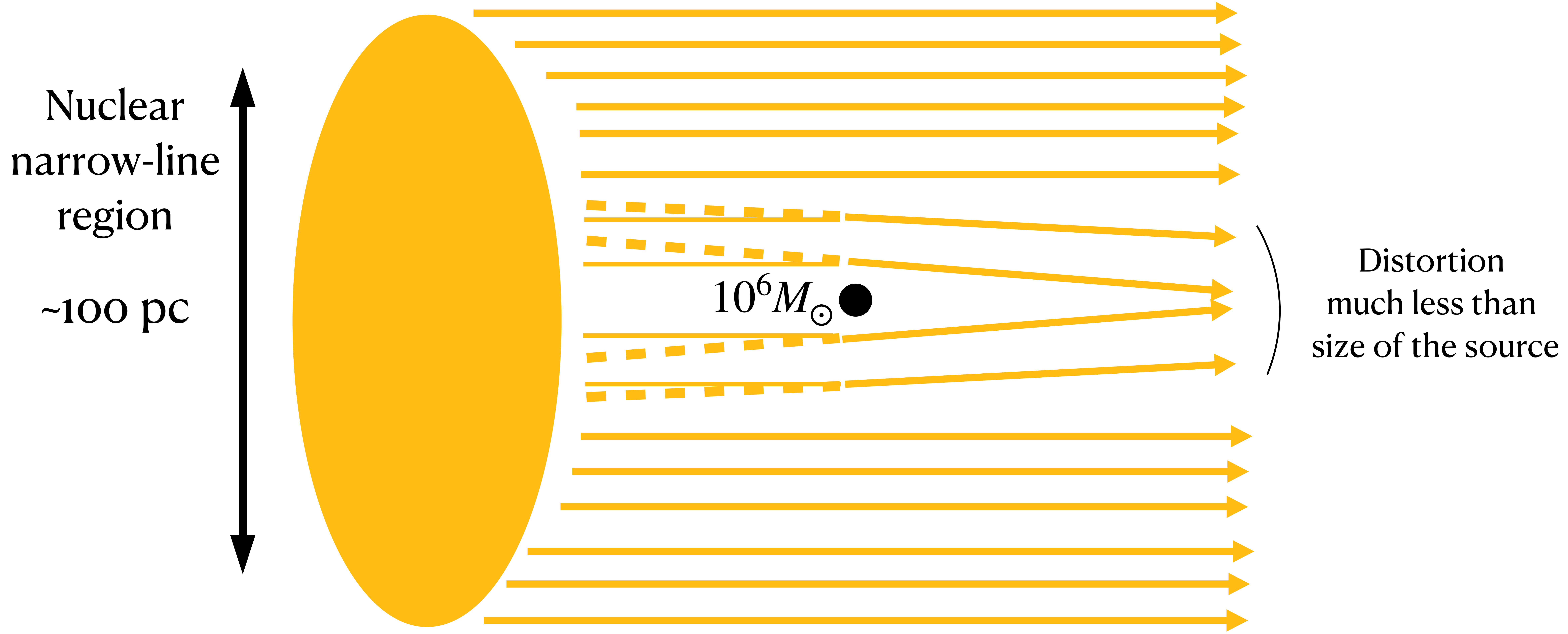
SIDM GAME-CHANGER



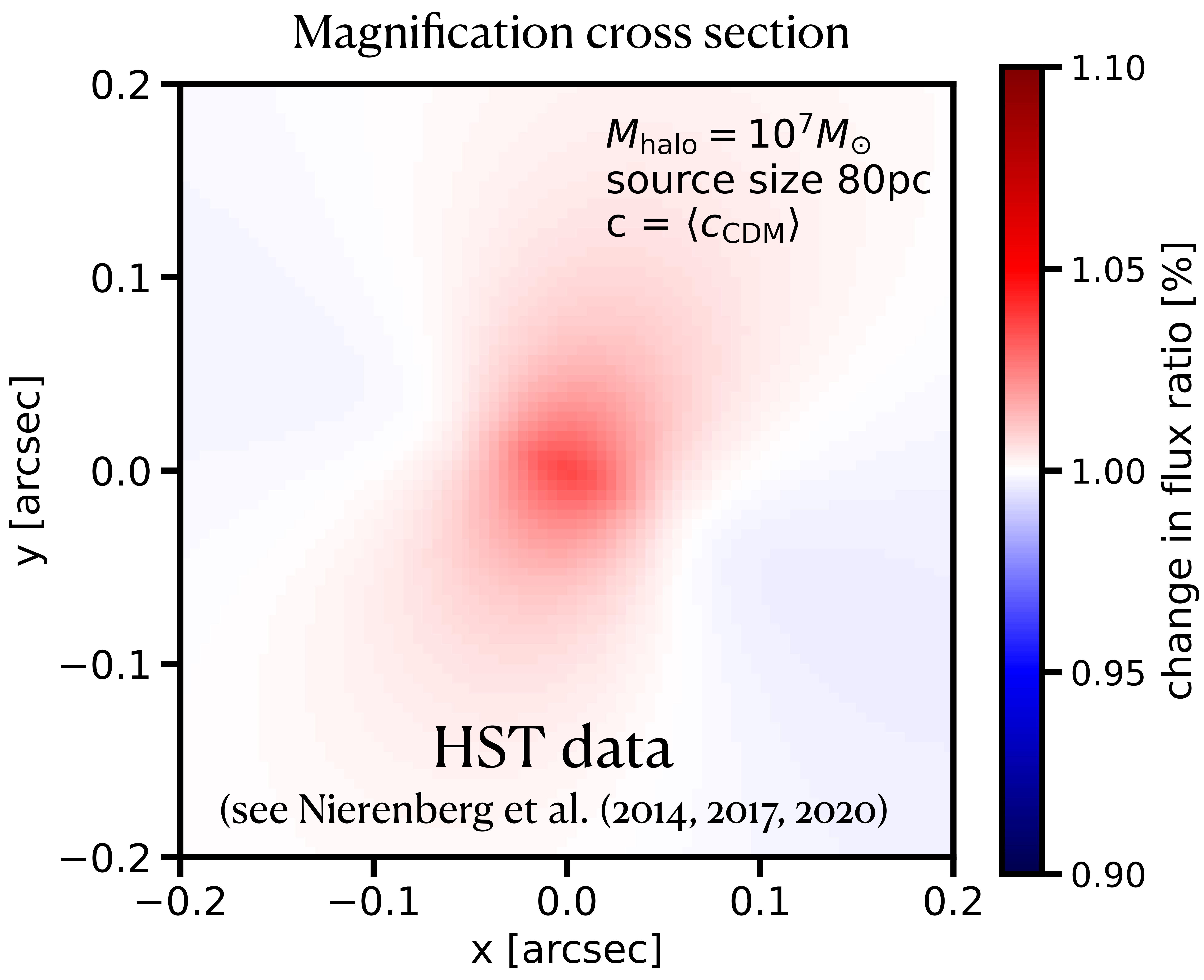
JWST lensed quasar DM survey: subject of Anna's talk up next

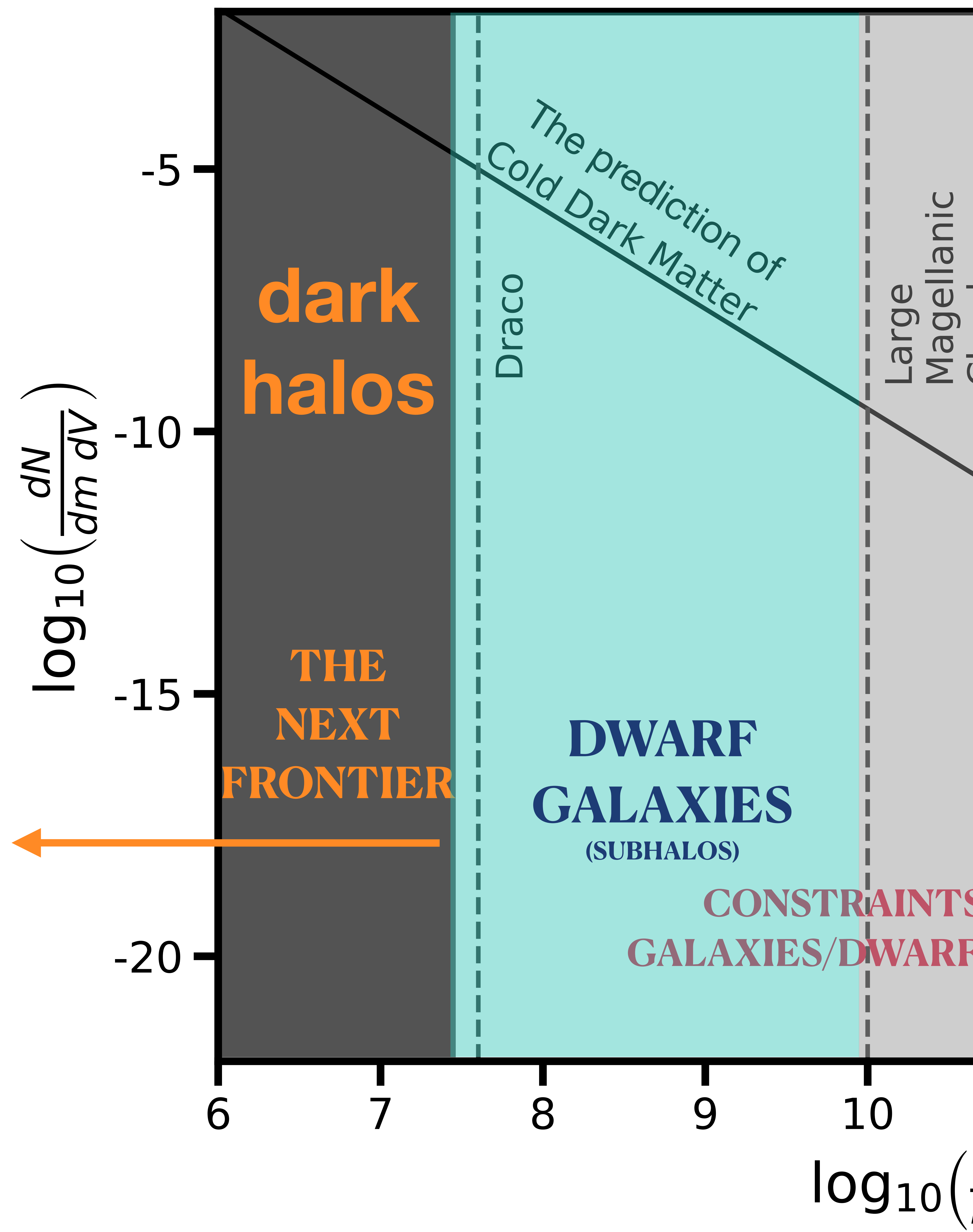
THE (recent) PAST: narrow-line flux ratios from HST

(everything presented in this talk)

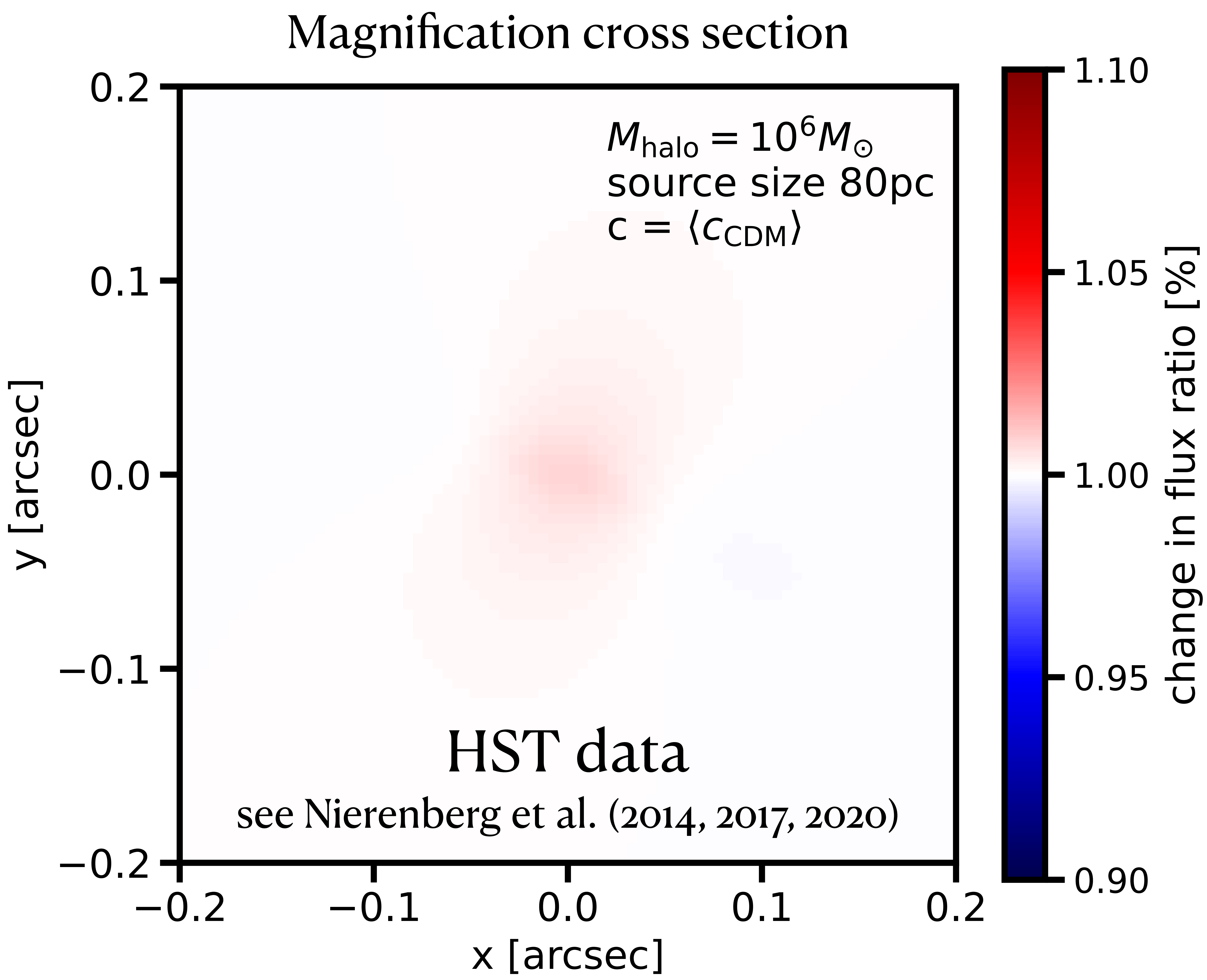


$M = 10^7 M_\odot$


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


dark halos
THE NEXT FRONTIER
DWARF GALAXIES
(SUBHALOS)
Draco
The prediction of Cold Dark Matter
Large Magellanic
CONSTRAINTS
GALAXIES/DWARF
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
-5
-10
-15
-20
6
7
8
9
10
$\log_{10}$

$M = 10^6 M_\odot$



Magnification cross section
$M_{\rm halo} = 10^6 M_\odot$
source size 80pc
c = ⟨$c_{\rm CDM}$⟩
HST data
see Nierenberg et al. (2014, 2017, 2020)
y [arcsec]
x [arcsec]
0.2
0.1
0.0
−0.1
−0.2
change in flux ratio [%]
1.10
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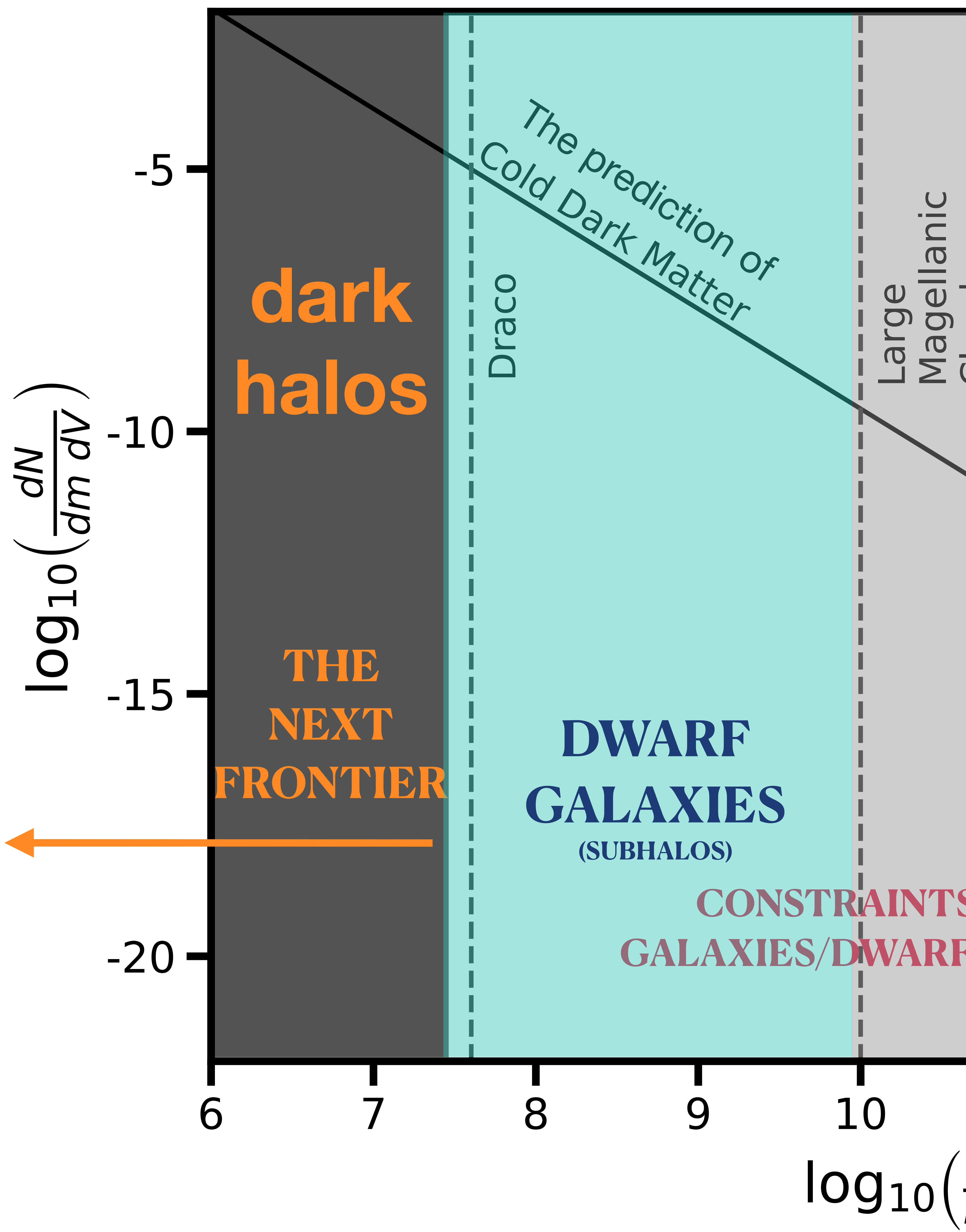


$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
-5
-10
-15
-20
dark halos
THE NEXT FRONTIER
Draco
The prediction of Cold Dark Matter
DWARF GALAXIES
(SUBHALOS)
Large Magellanic
CONSTRAINTS
GALAXIES/DWARF
6
7
8
9
10

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

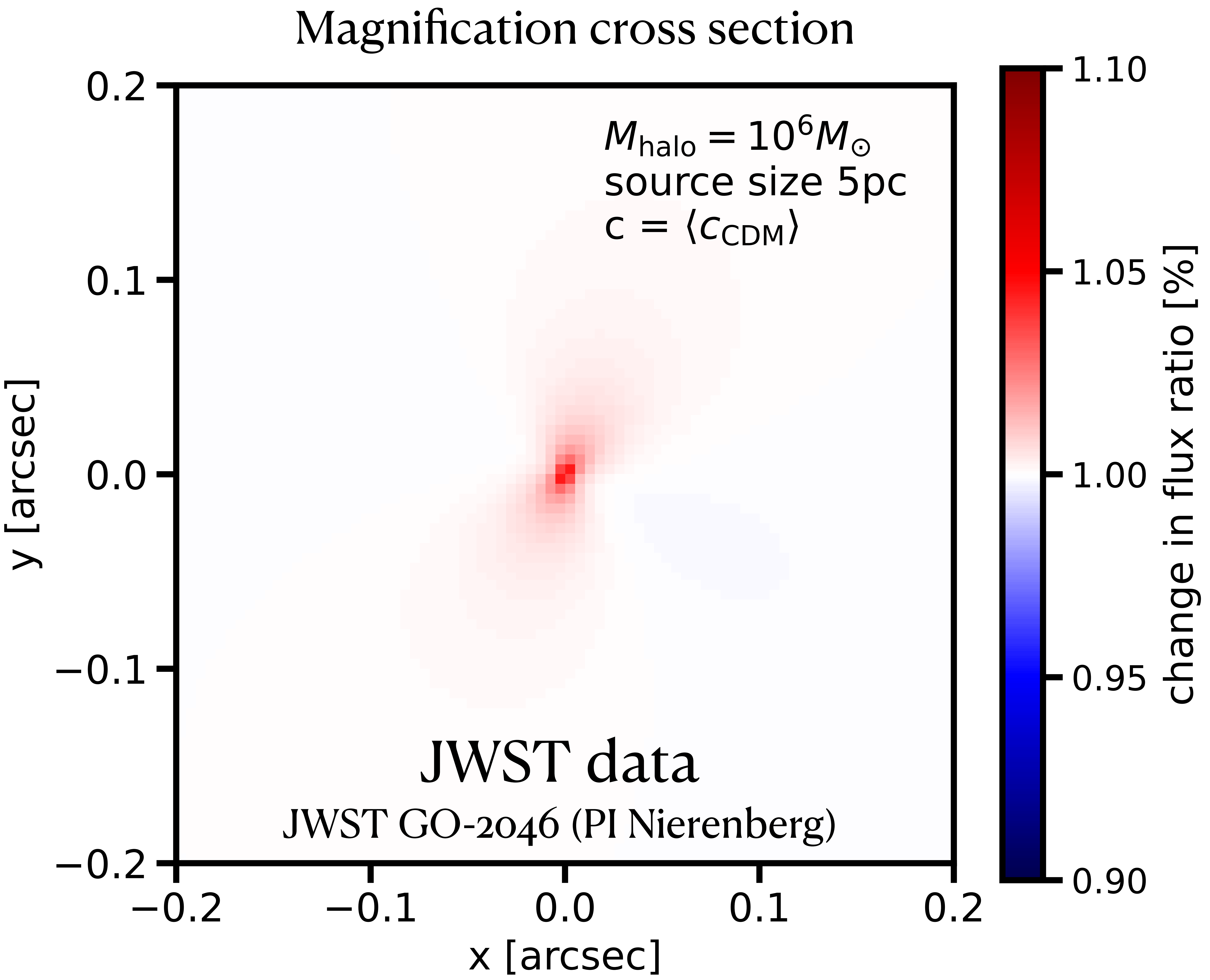
Survey introduction:

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

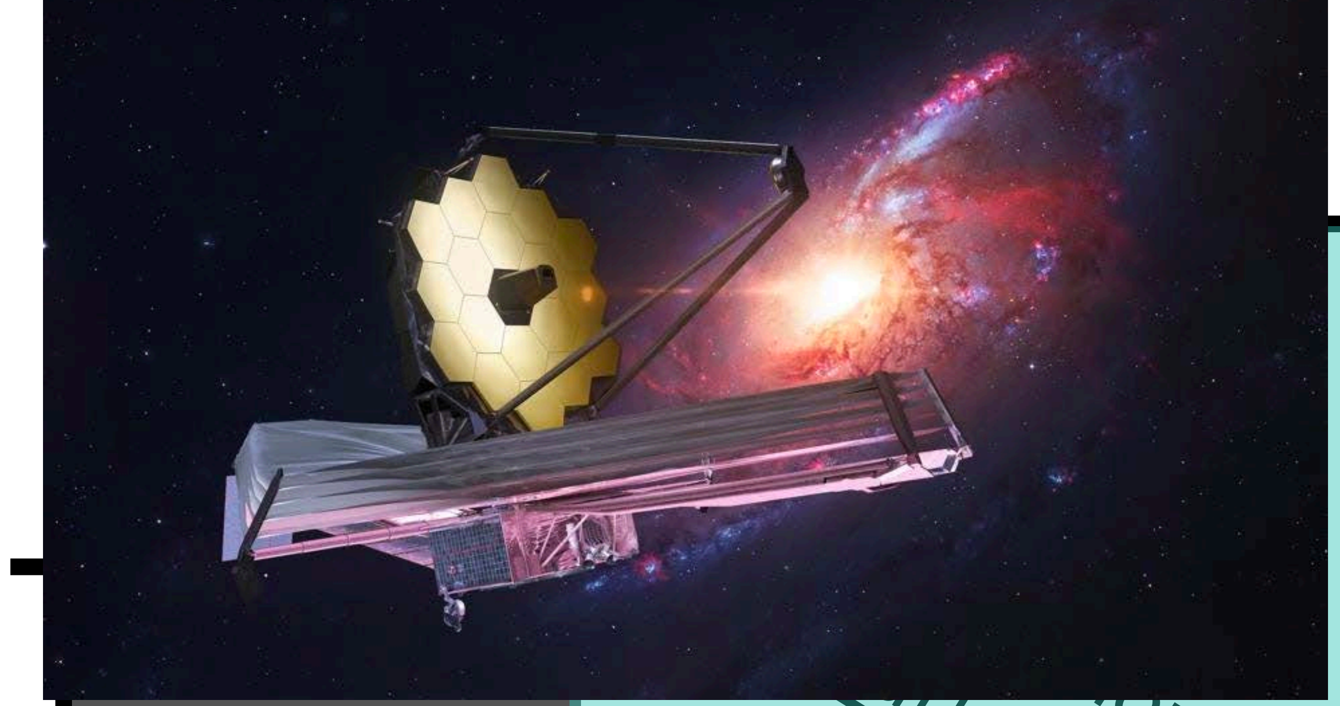
First results with 9 systems:

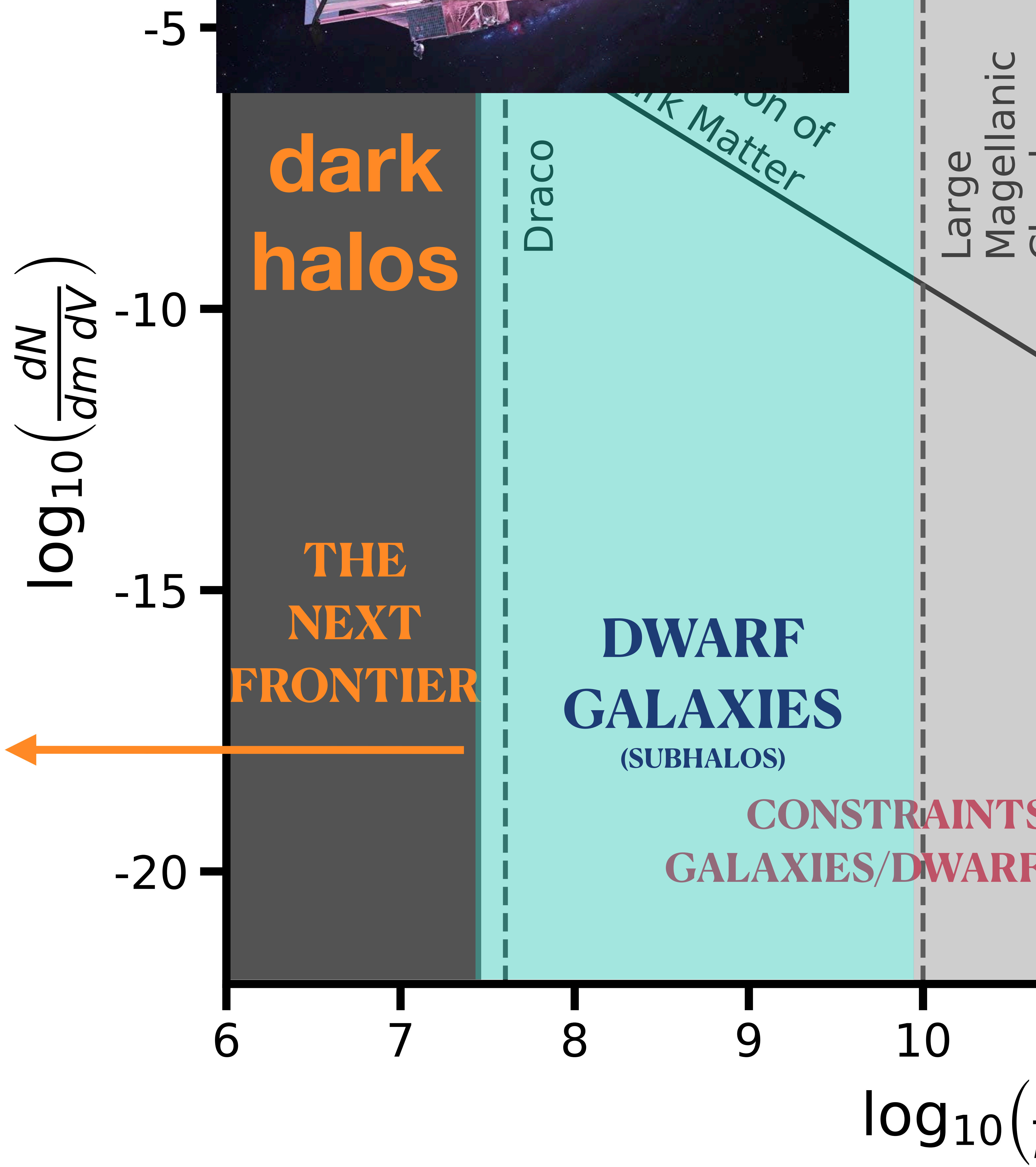
- Keeley, incl. Gilman et al. (2024) (arXiv: 2405.01620)

$M = 10^6 M_\odot$



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

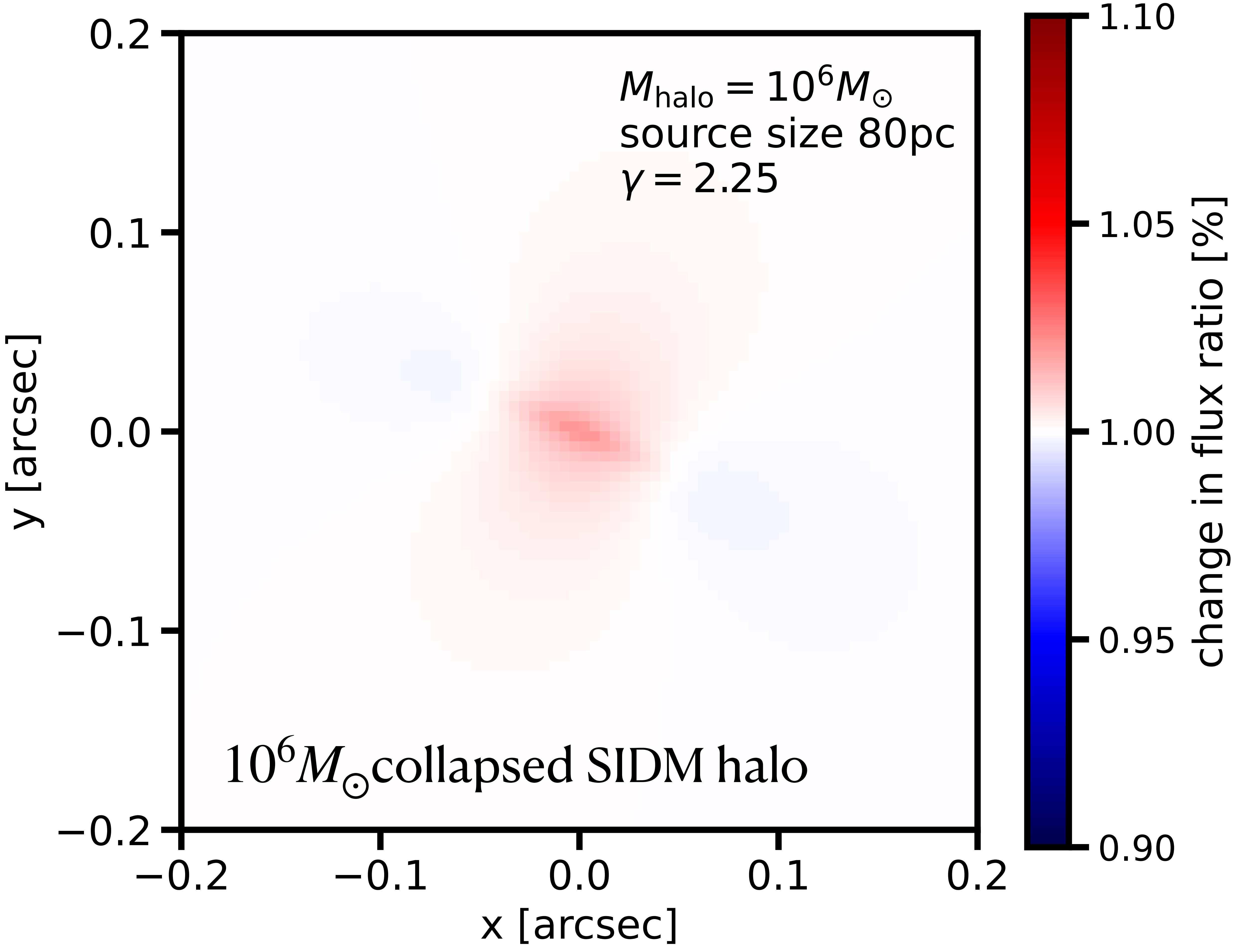




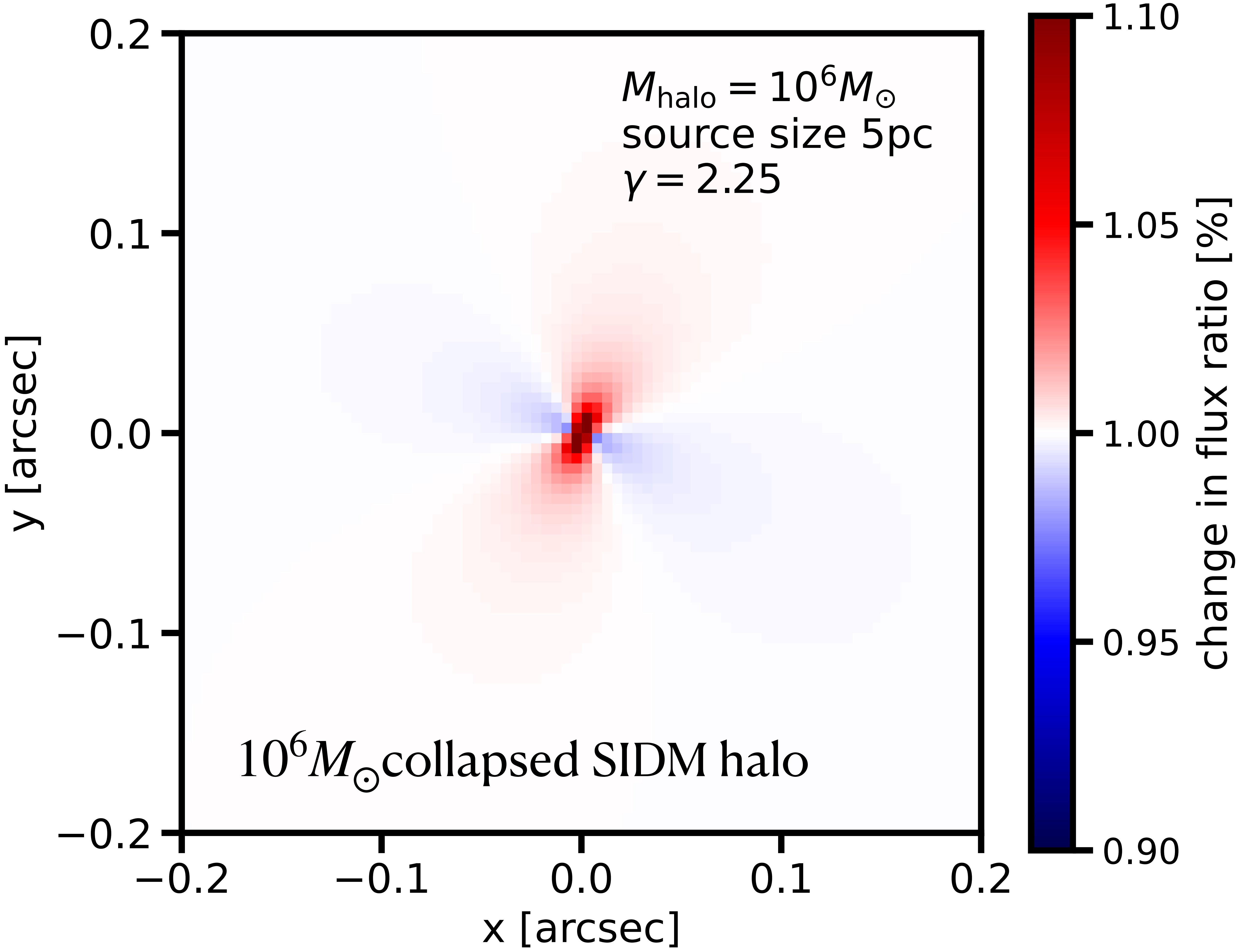
-5
-10
-15
-20
$\log_{10}\left(\frac{dN}{dm\, dV}\right)$
dark halos
THE NEXT FRONTIER
Draco
DWARF GALAXIES
(SUBHALOS)
CONSTRAINTS
GALAXIES/DWARF
Large Magellanic
6
7
8
9
10

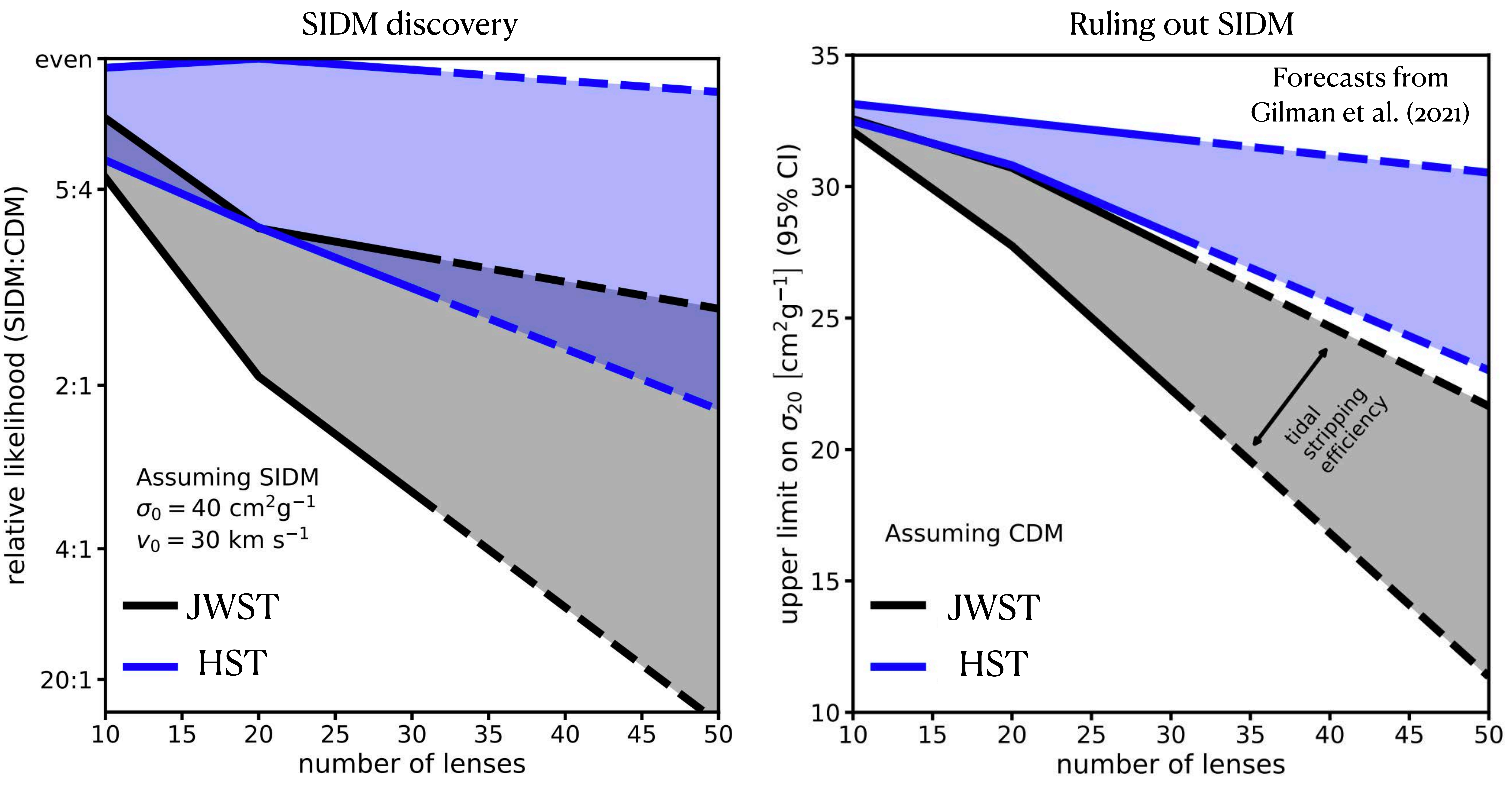
Future (hopefully by Dec. 2024) lensing-based constraints on SIDM

HST-like data



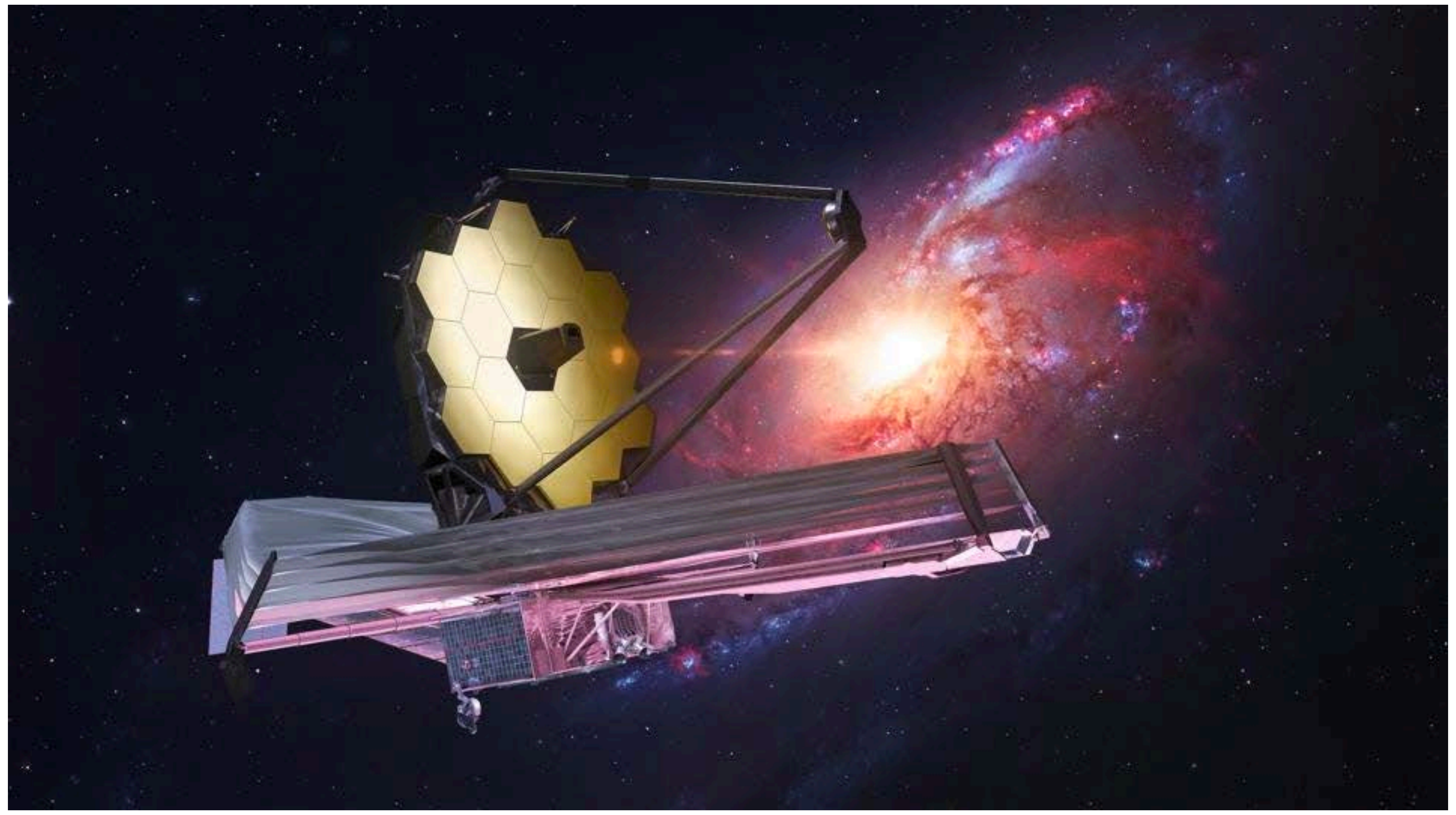
JWST data




SIDM discovery
Ruling out SIDM
even
5:4
2:1
4:1
20:1
relative likelihood (SIDM:CDM)
Assuming SIDM
$\sigma_0 = 40\ \mathrm{cm^2 g^{-1}}$
$v_0 = 30\ \mathrm{km\ s^{-1}}$
JWST
HST
number of lenses
10
15
20
25
30
35
40
45
50
Forecasts from
Gilman et al. (2021)
upper limit on σ_{20} $[\mathrm{cm^2 g^{-1}}]$ (95% CI)
35
30
25
20
15
10
tidal
stripping
efficiency
Assuming CDM
JWST
HST
number of lenses

Takeaways:

If a large population of collapsed halos below $10^6 M_\odot$ exists, we should soon know thanks to



Upcoming surveys will find thousands of strong lenses!
- this is just the beginning