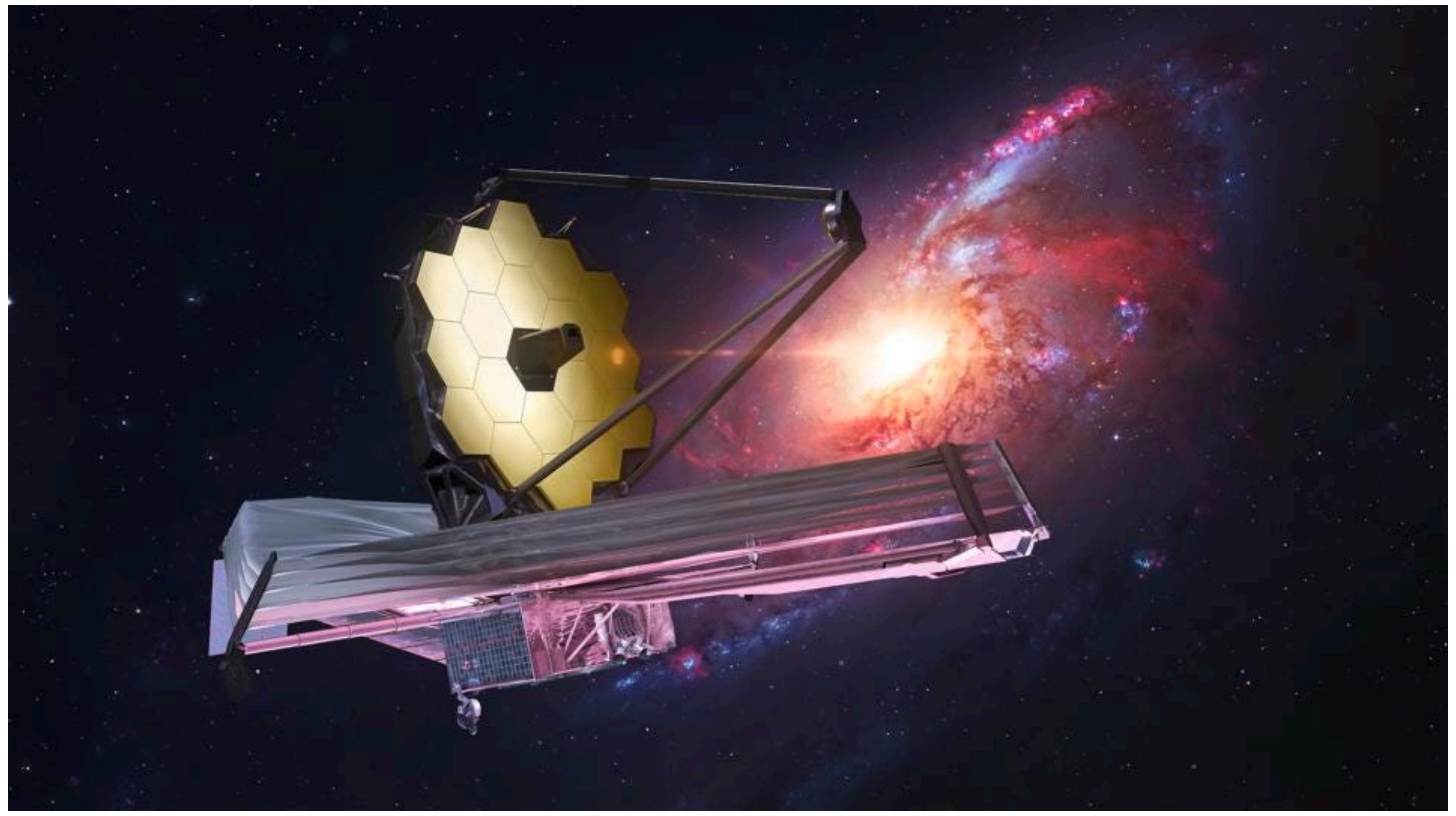
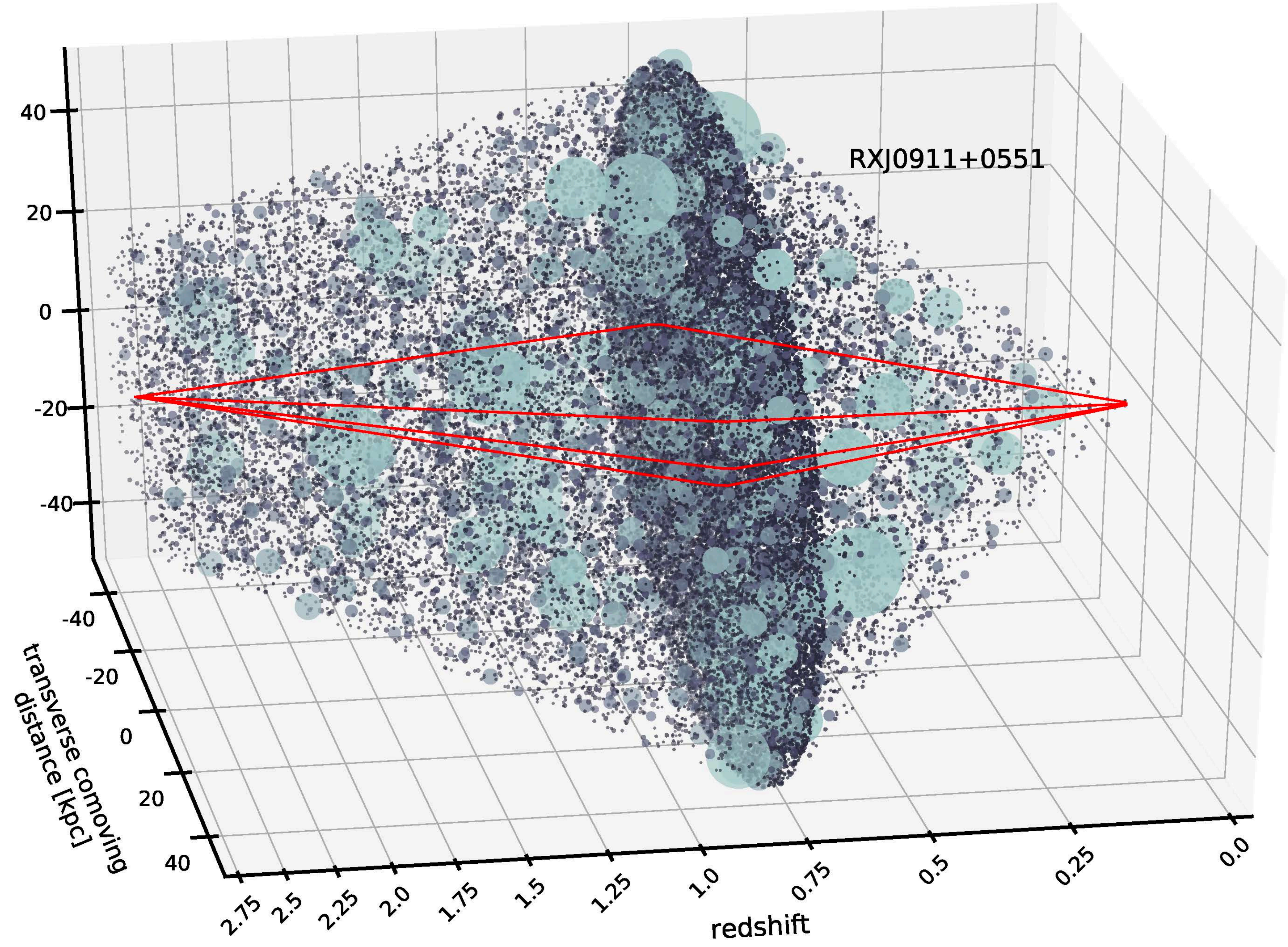
Substructure lensing in the era of JWST

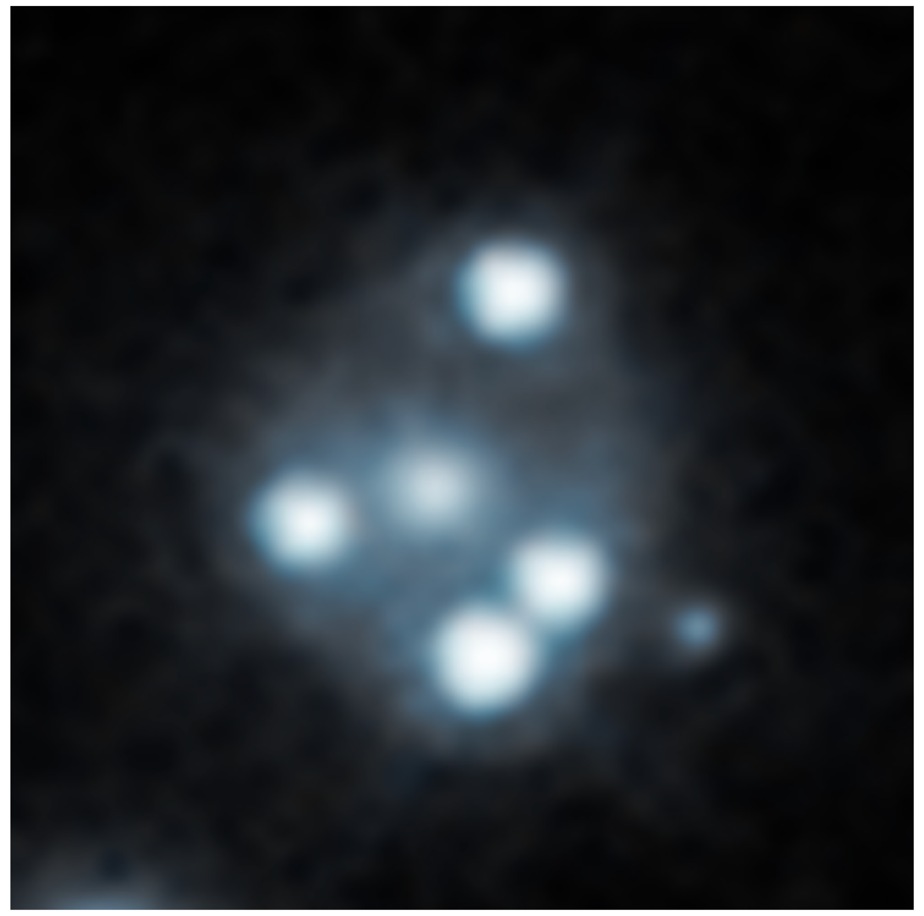


Daniel Gilman

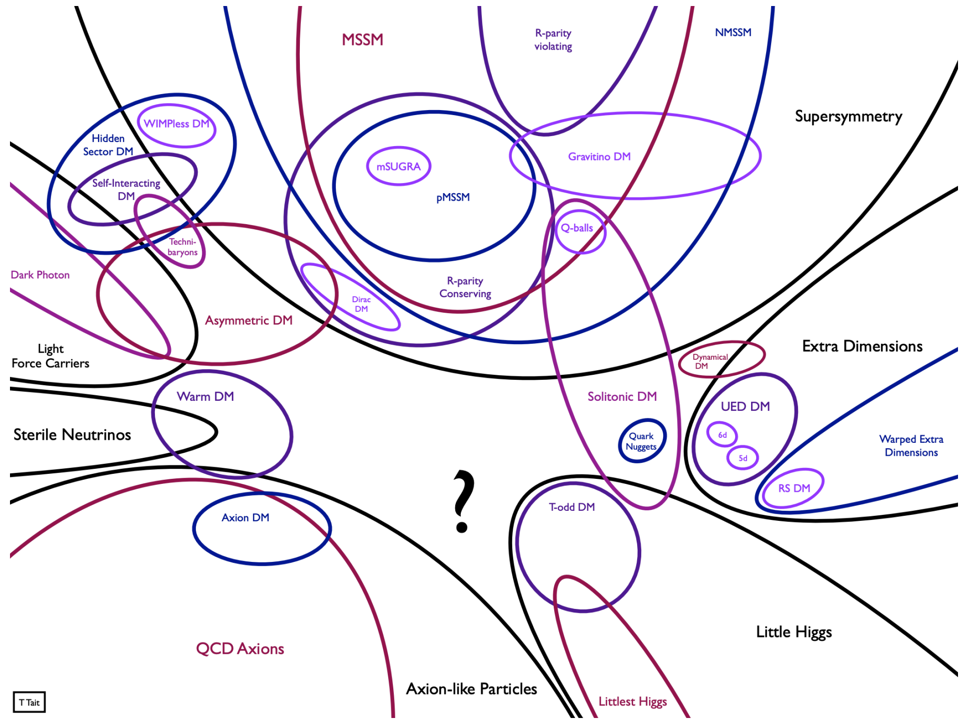
University of Chicago

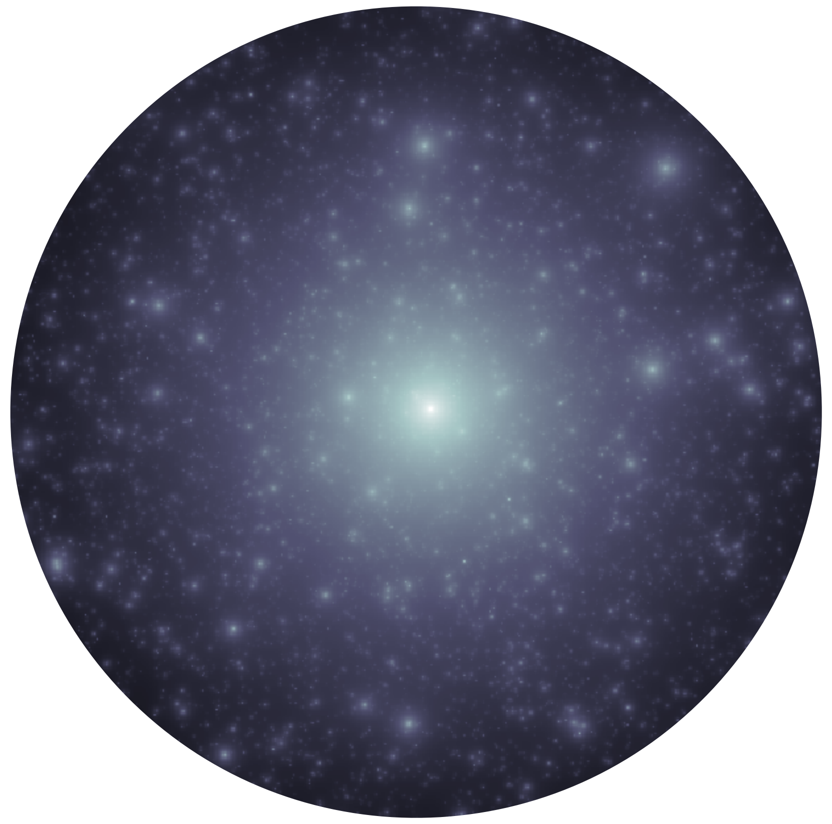


In collab. with:
Anna Nierenberg (UC Merced)
Yi-Ming Zhong (U Chicago)
Jo Bovy (UofT)
Andrew Benson (Carnegie)
Simon Birrer (Stony Brook)
Tommaso Treu (UCLA)



TeVPA 2023
Naples, Italy





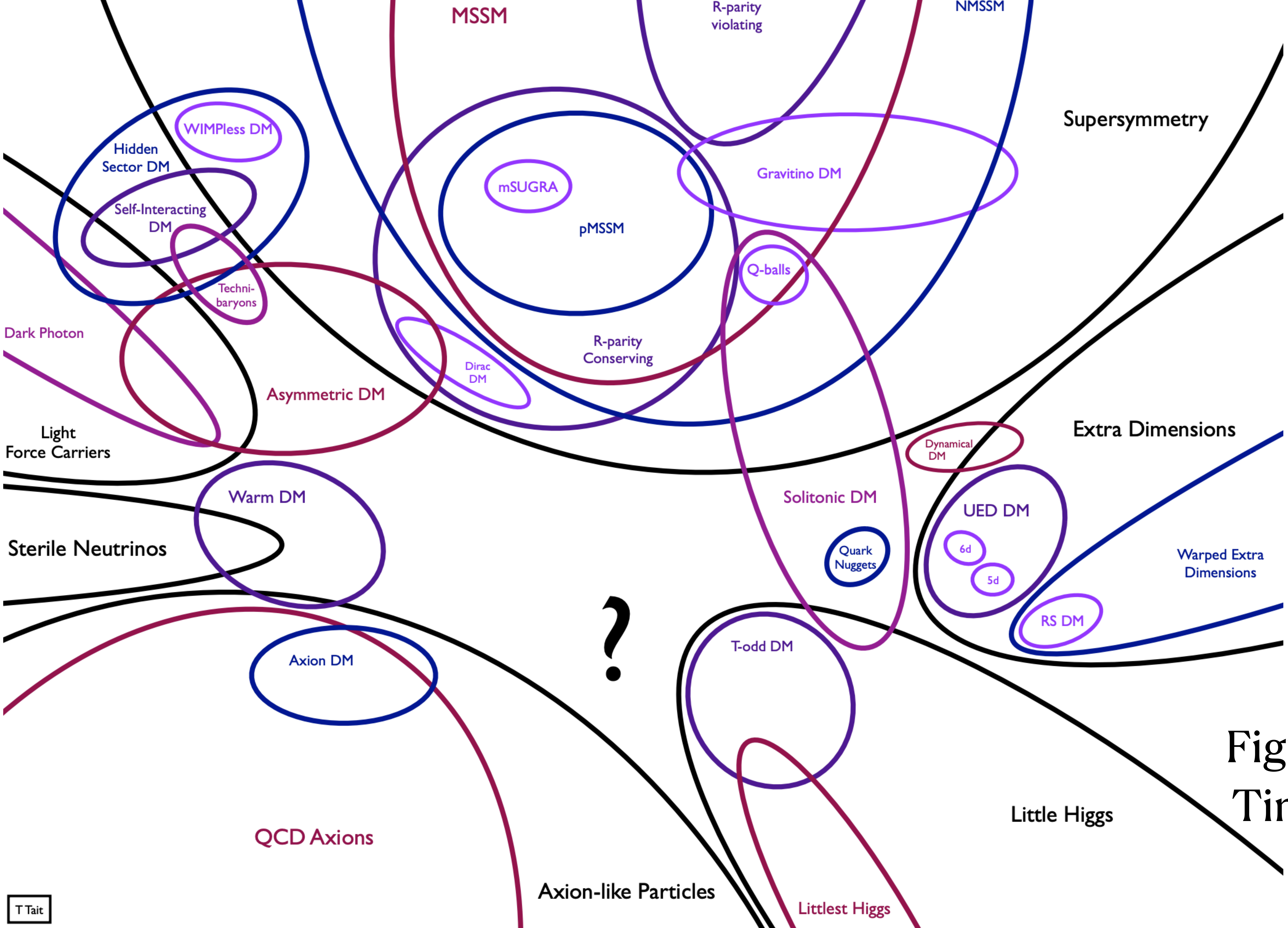
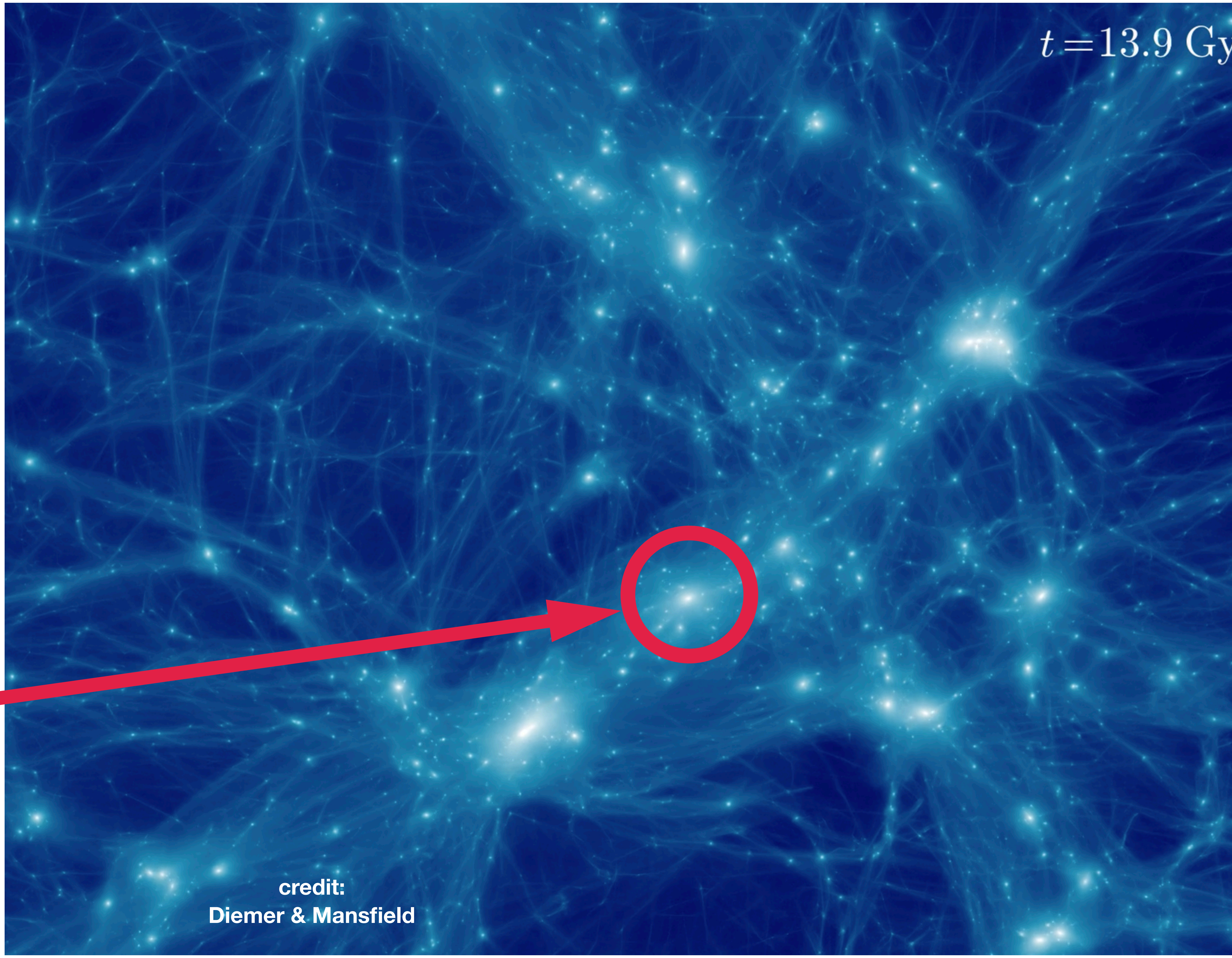


Figure by Tim Tait

Structure formation and dark matter

DM required to explain the Universe on large and small scales

MUST PRODUCE DARK MATTER *HALOS*

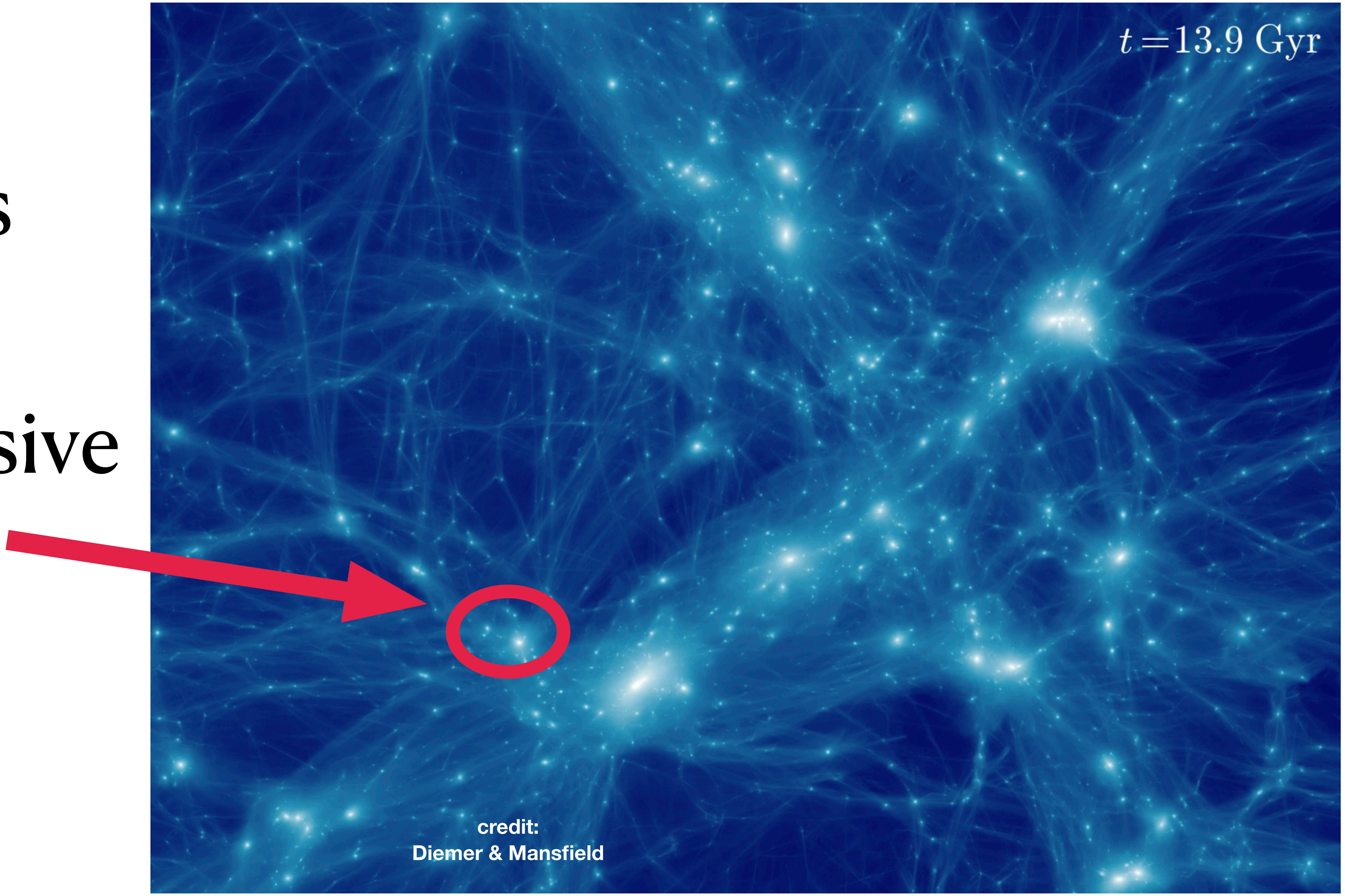


Structure formation and dark matter

"Group-scale" halos

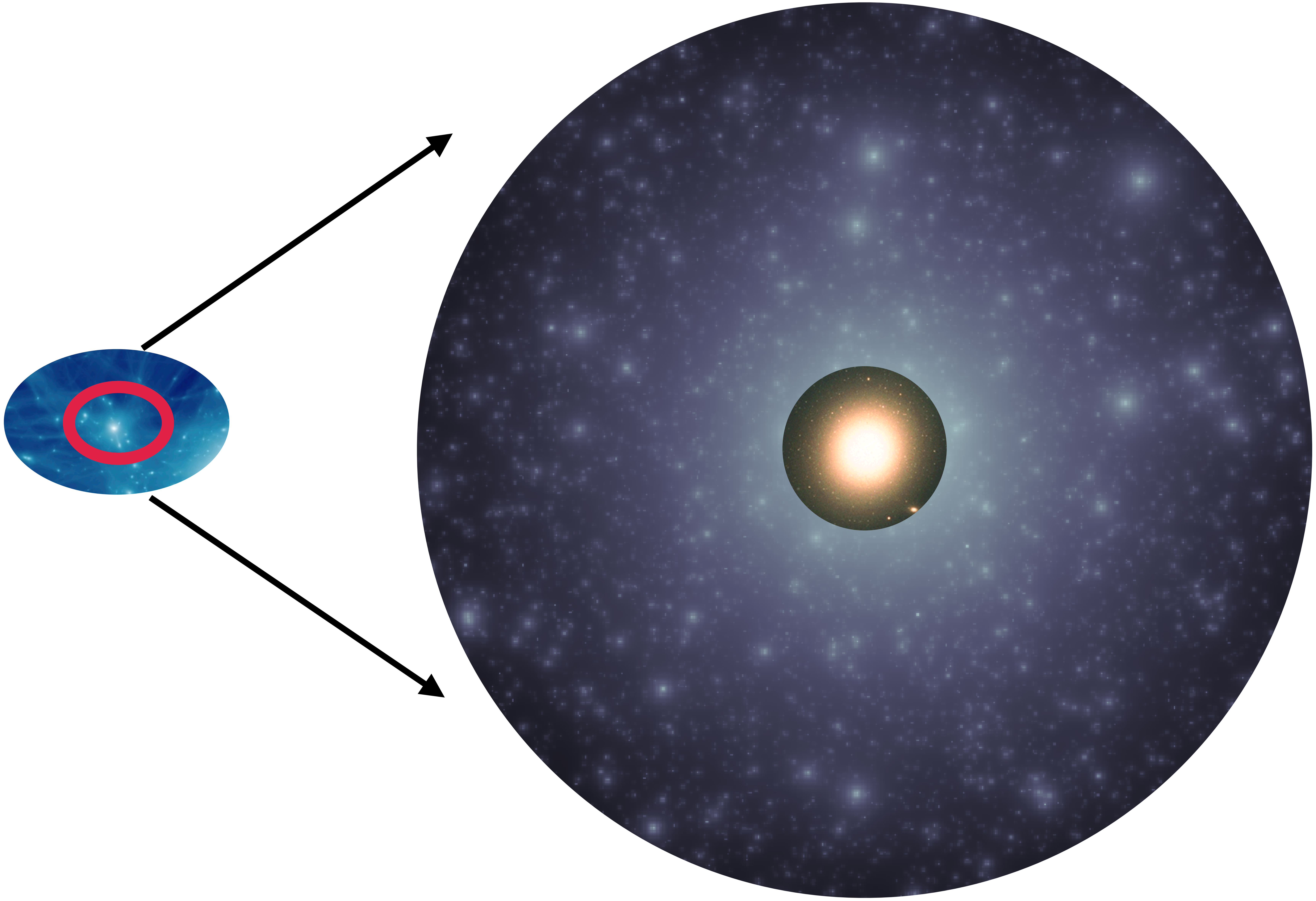
$M \sim 10^{13} M_{\odot}$

-> usually contain massive elliptical galaxies

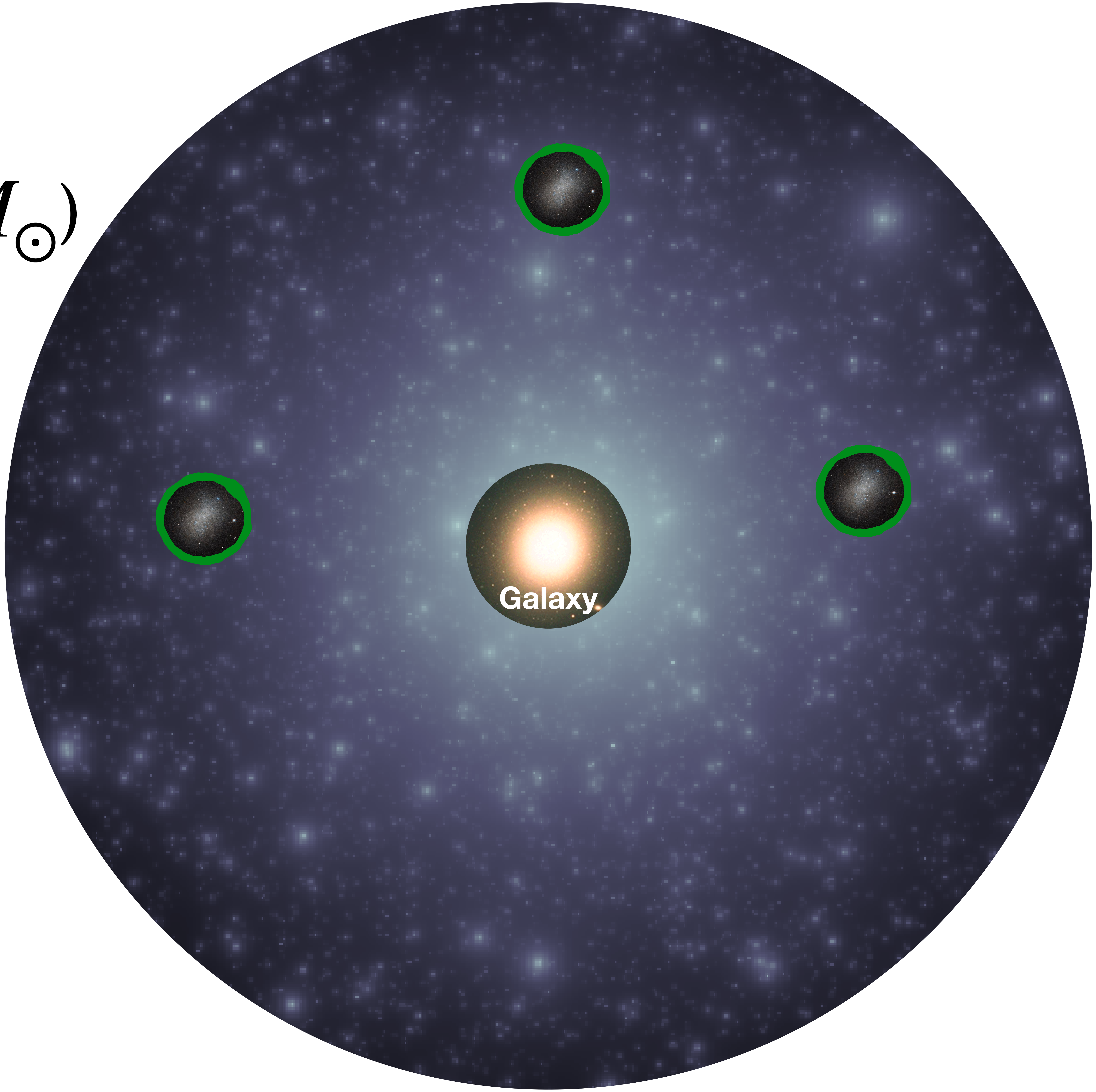


DARK MATTER HALOS CONTAIN AN ABUNDANCE OF SUBSTRUCTURE

If we were to zoom in on a group-scale halo....

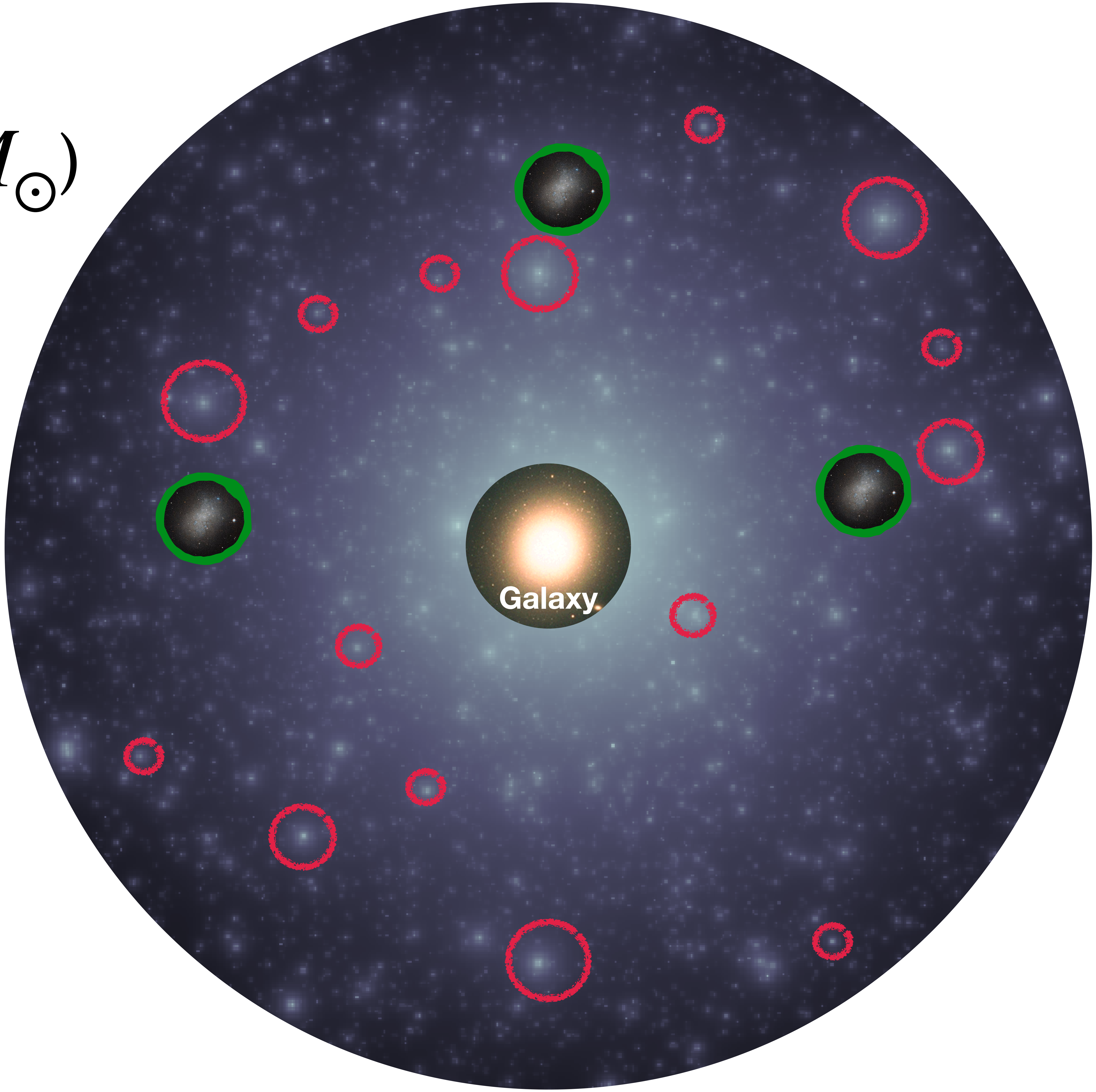


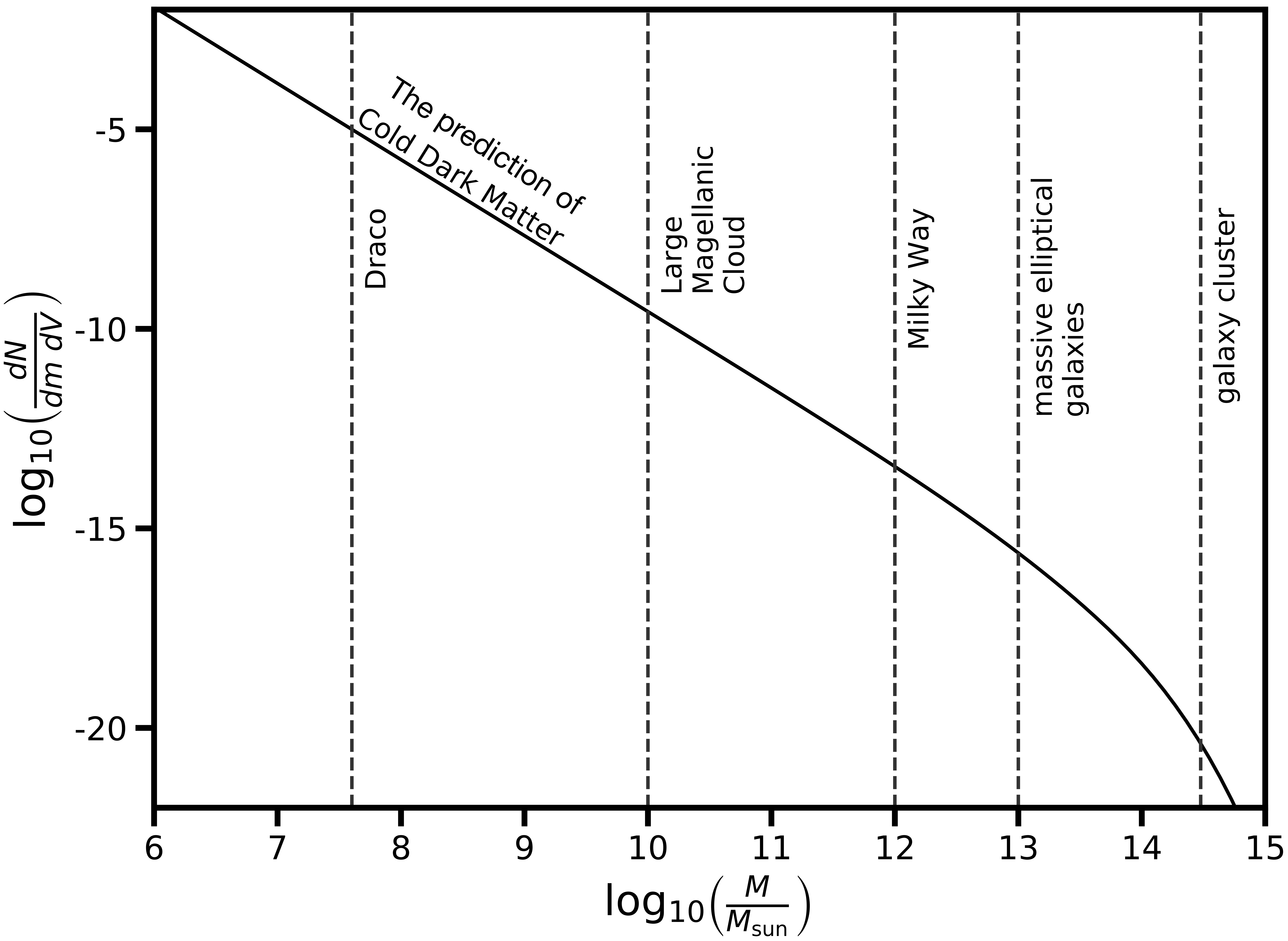
More massive ($M > 10^8 M_\odot$)
subhalos may
host dwarf galaxies



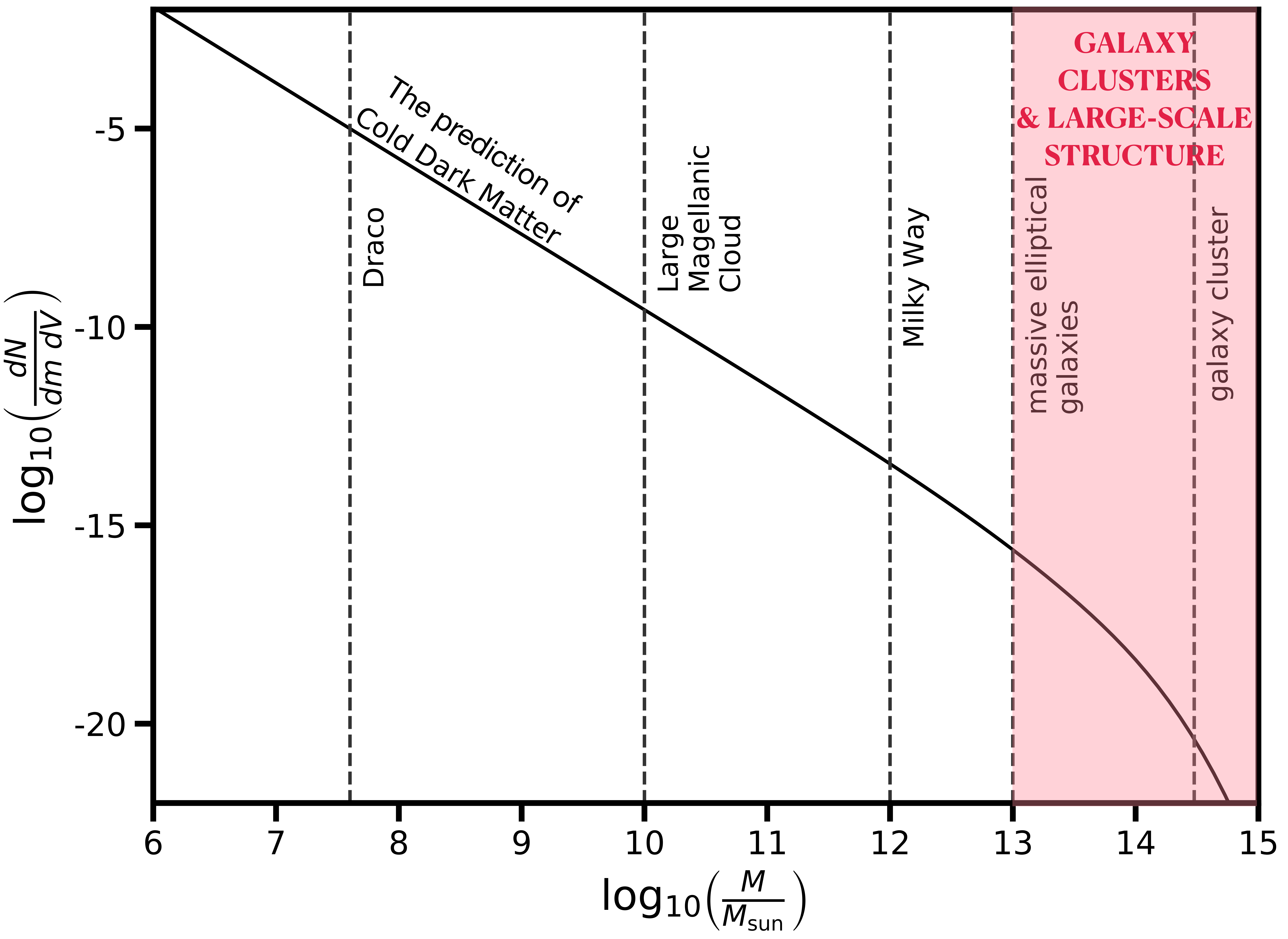
More massive ($M > 10^8 M_\odot$) subhalos may host dwarf galaxies

Most subhalos are dark according to ΛCDM.





The prediction of
Cold Dark Matter
Draco
Large
Magellanic
Cloud
Milky Way
massive elliptical
galaxies
galaxy cluster
-5
-10
-15
-20
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
6
7
8
9
10
11
12
13
14
15
$\log_{10}\left(\frac{M}{M_{\text{sun}}}\right)$



The prediction of Cold Dark Matter
Draco
Large Magellanic Cloud
Milky Way
massive elliptical galaxies
galaxy cluster
GALAXY CLUSTERS & LARGE-SCALE STRUCTURE
-5
-10
-15
-20
6
7
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15
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
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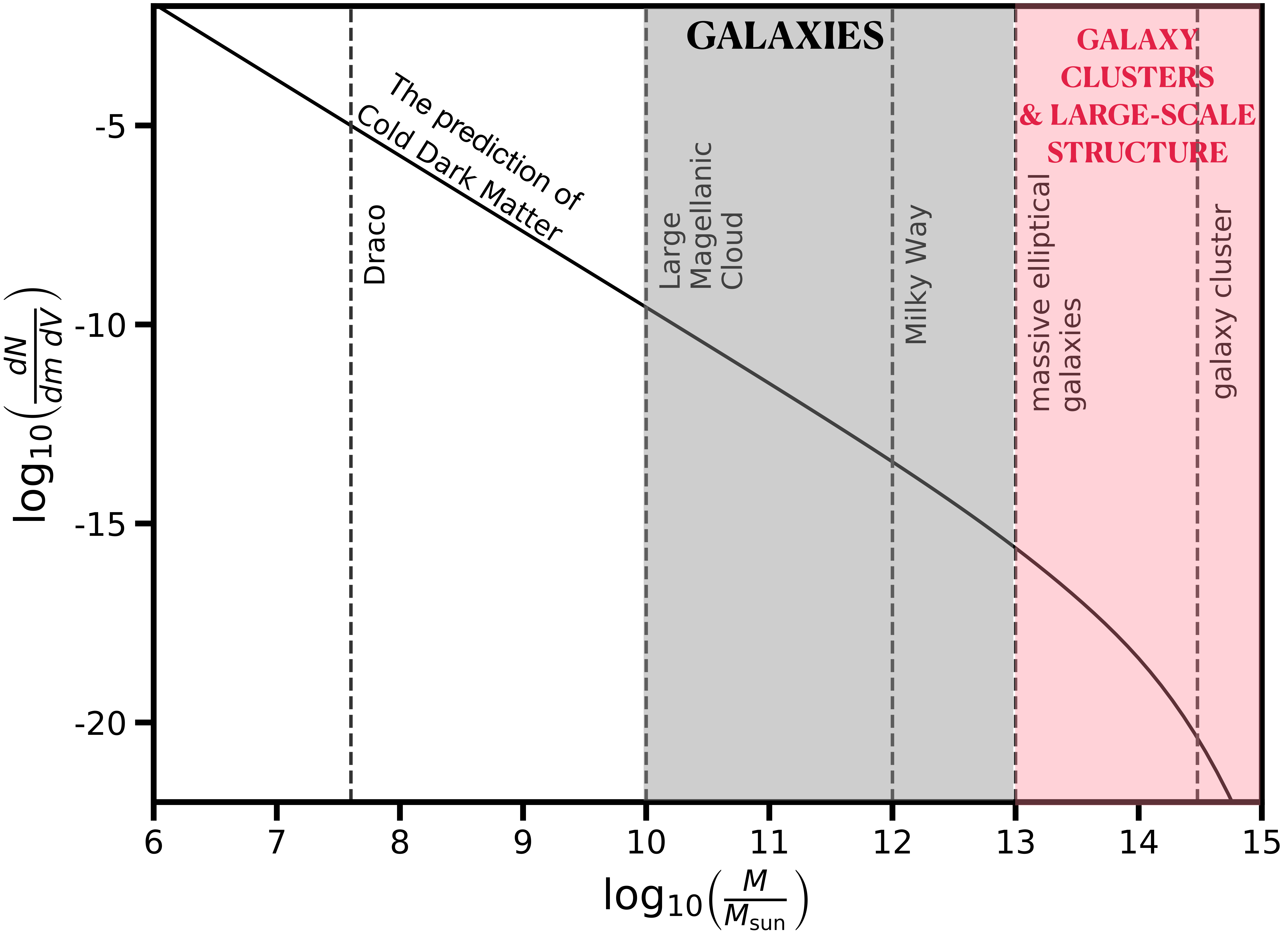
GALAXIES
GALAXY CLUSTERS & LARGE-SCALE STRUCTURE
The prediction of Cold Dark Matter
Draco
Large Magellanic Cloud
Milky Way
massive elliptical galaxies
galaxy cluster
-5
-10
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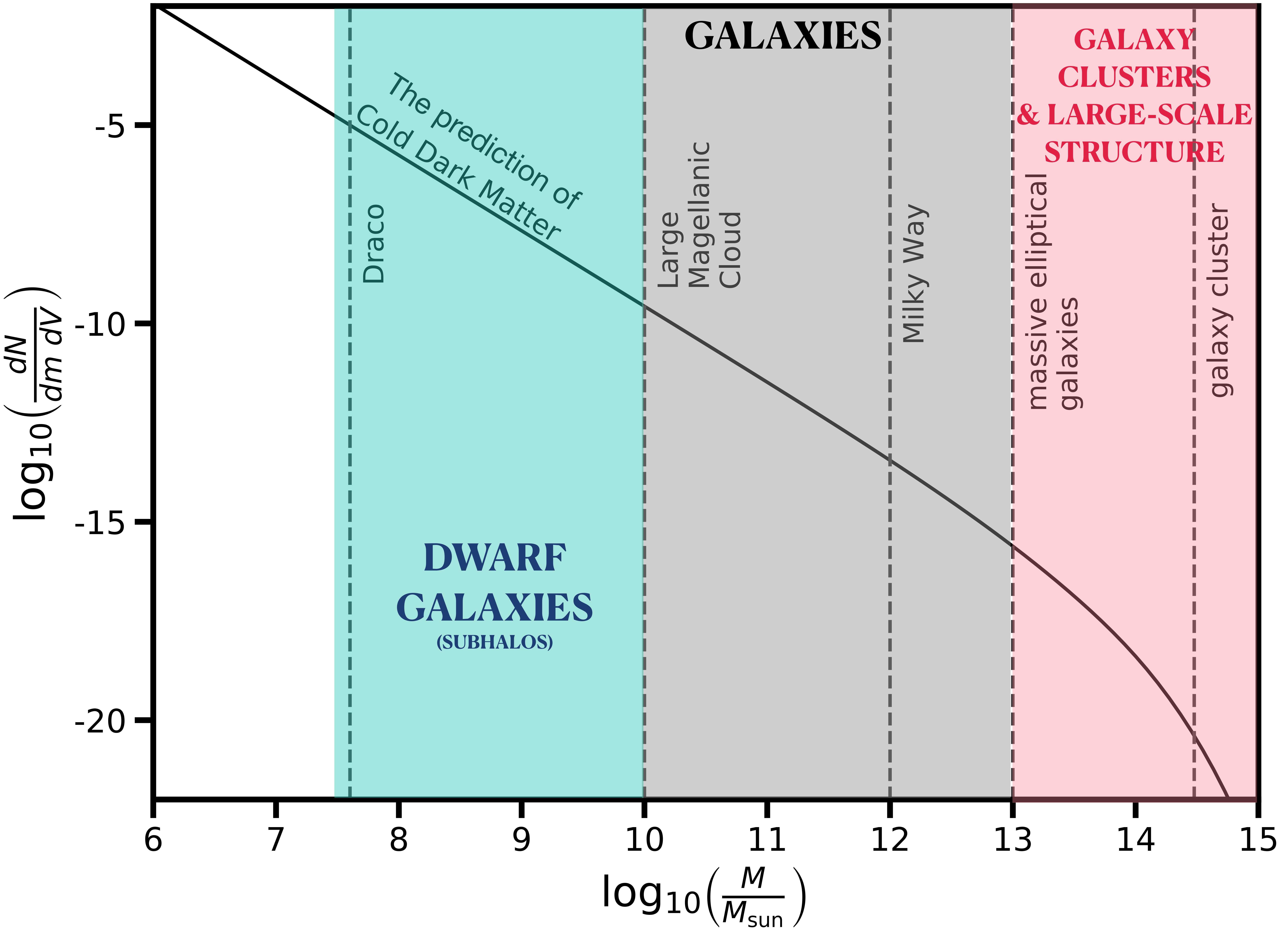
GALAXIES
GALAXY CLUSTERS & LARGE-SCALE STRUCTURE
The prediction of Cold Dark Matter
Draco
Large Magellanic Cloud
Milky Way
massive elliptical galaxies
galaxy cluster
DWARF GALAXIES
(SUBHALOS)
-5
-10
-15
-20
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
6
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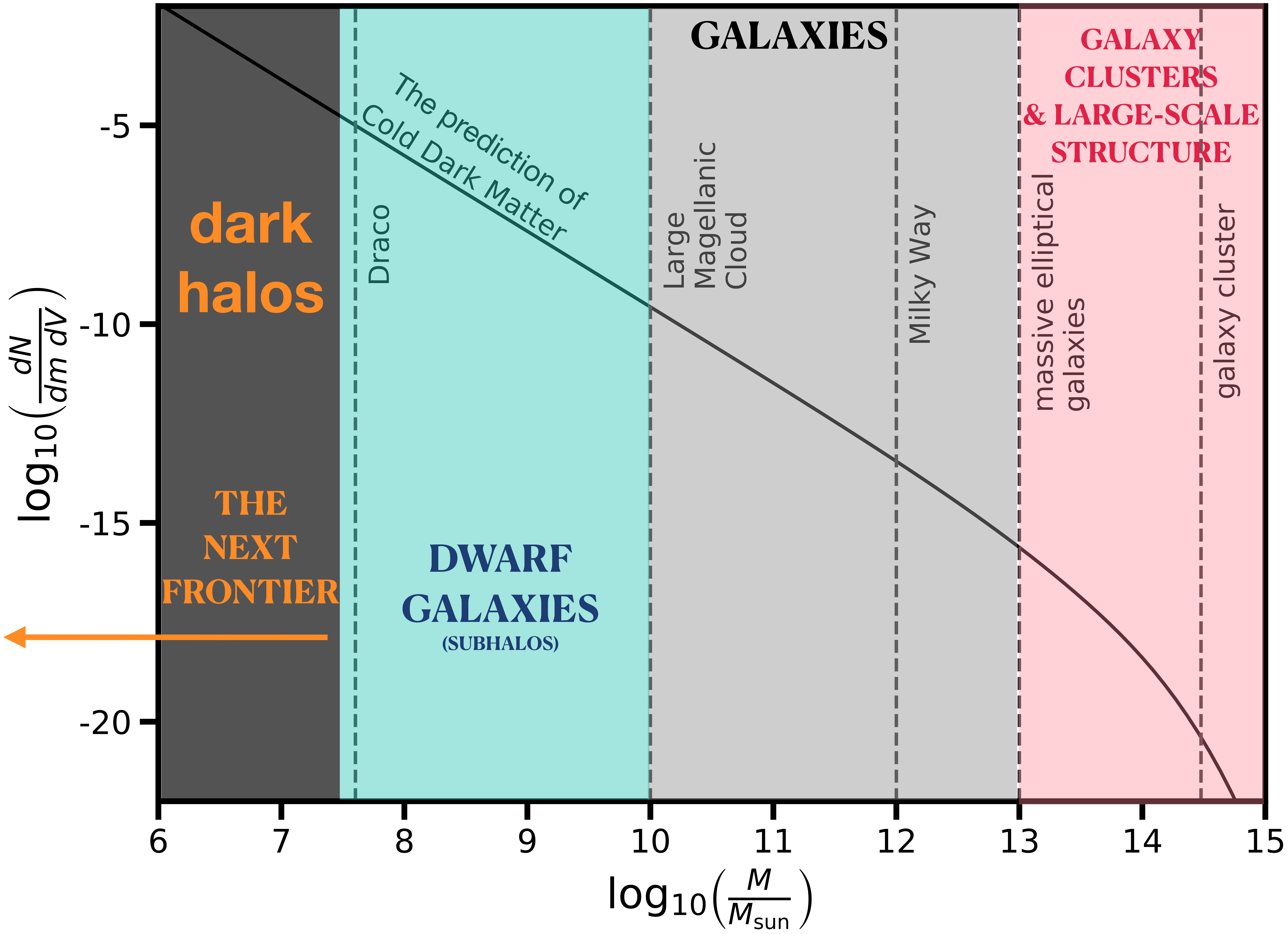
15
$\log_{10}\left(\frac{M}{M_{sun}}\right)$



dark
halos
THE
NEXT
FRONTIER
The prediction of
Cold Dark Matter
Draco
DWARF
GALAXIES
(SUBHALOS)
GALAXIES
Large
Magellanic
Cloud
Milky Way
GALAXY
CLUSTERS
& LARGE-SCALE
STRUCTURE
massive elliptical
galaxies
galaxy cluster
-5
-10
-15
-20
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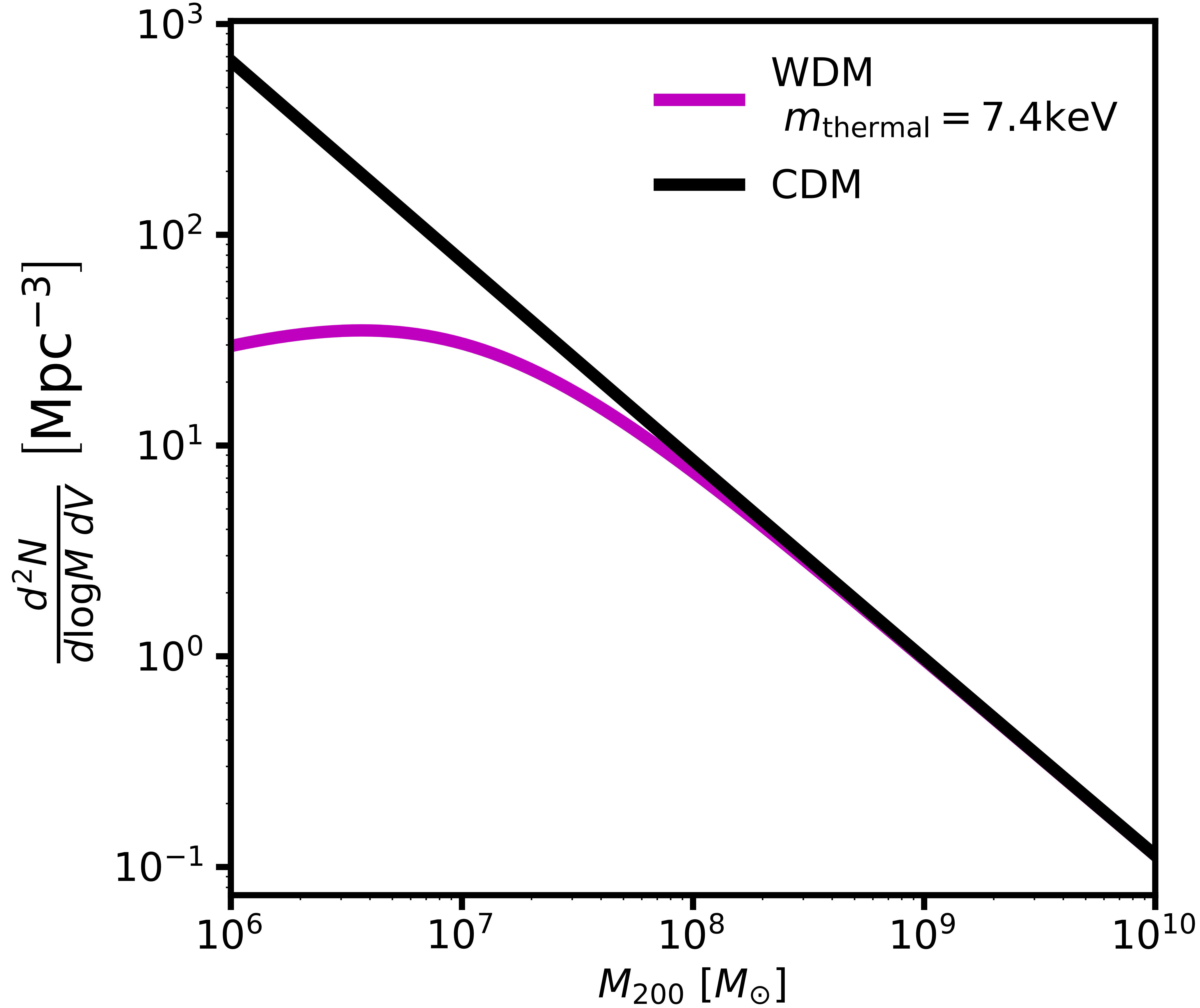
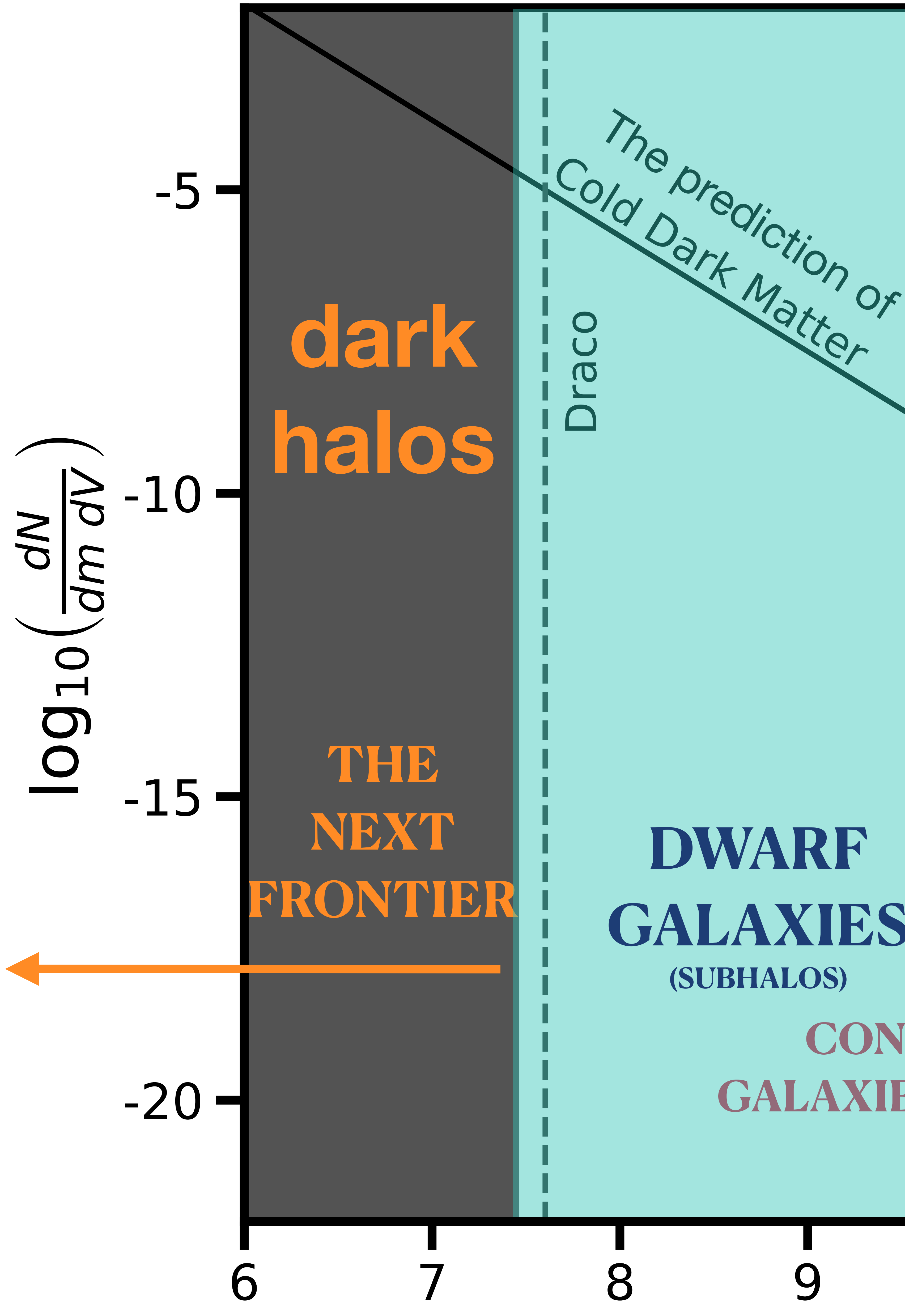
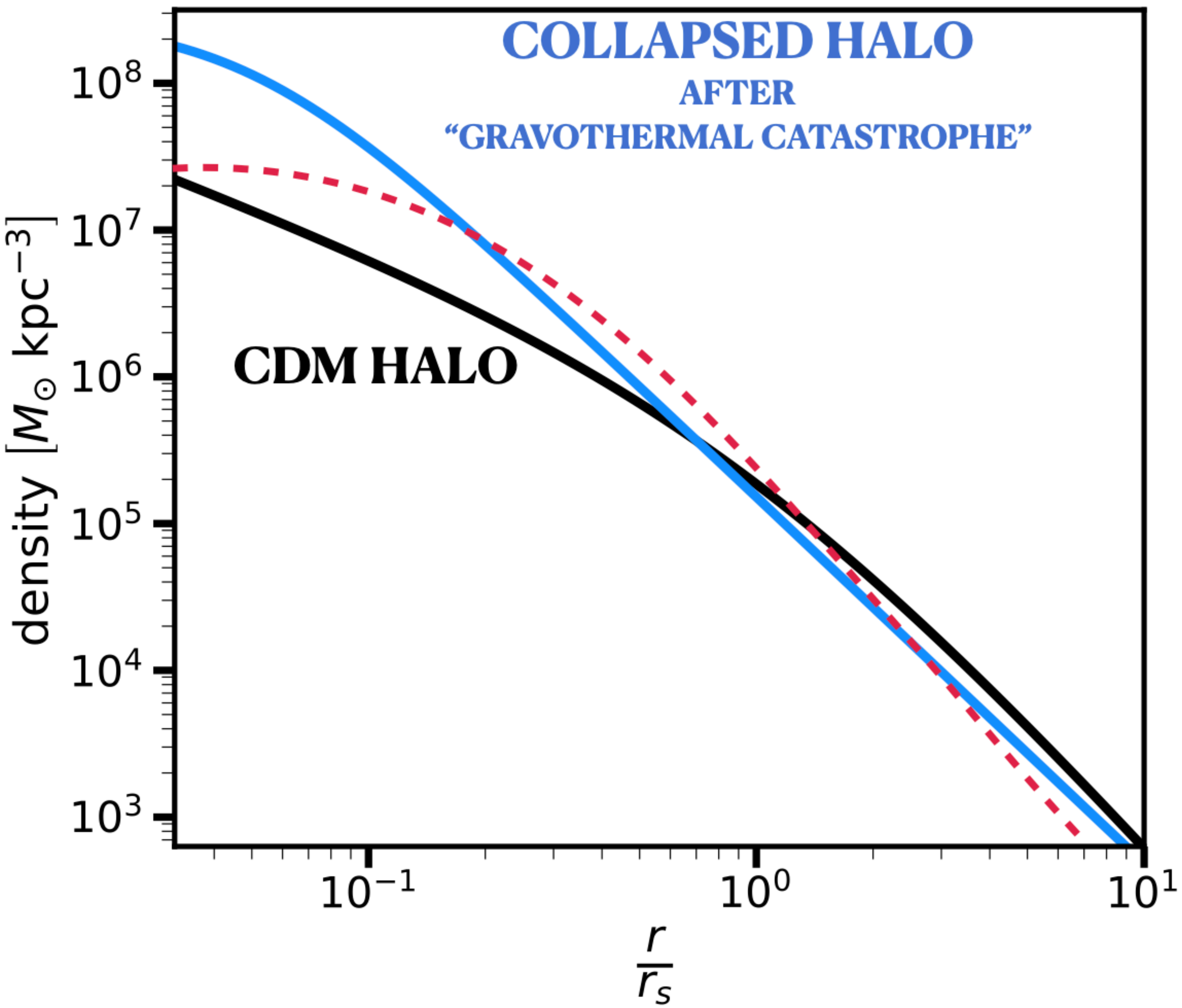
11
12
13
14
15
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
$\log_{10}\left(\frac{M}{M_{sun}}\right)$

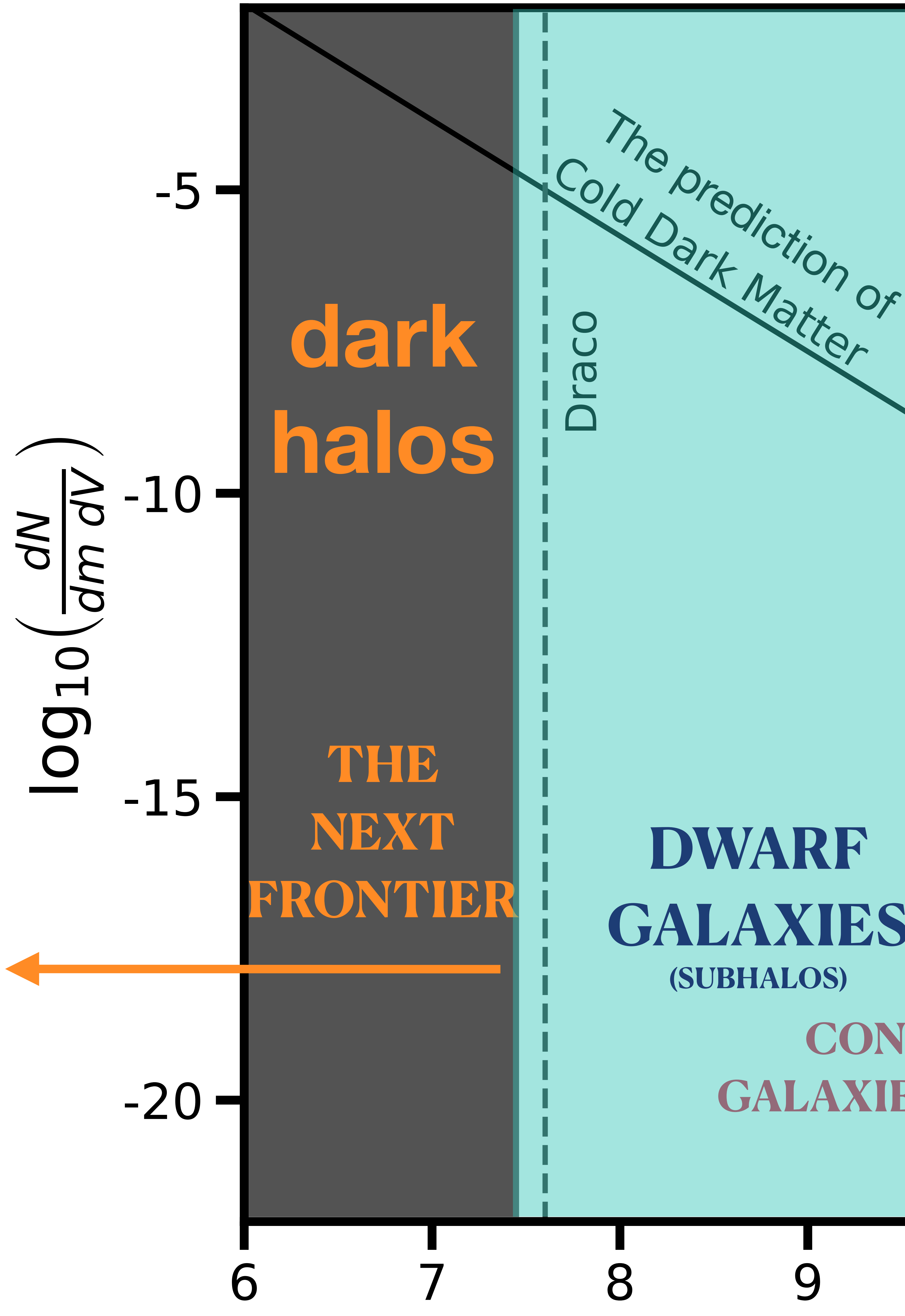
1) Warm dark matter (WDM):
low-mass (dark) halos never form





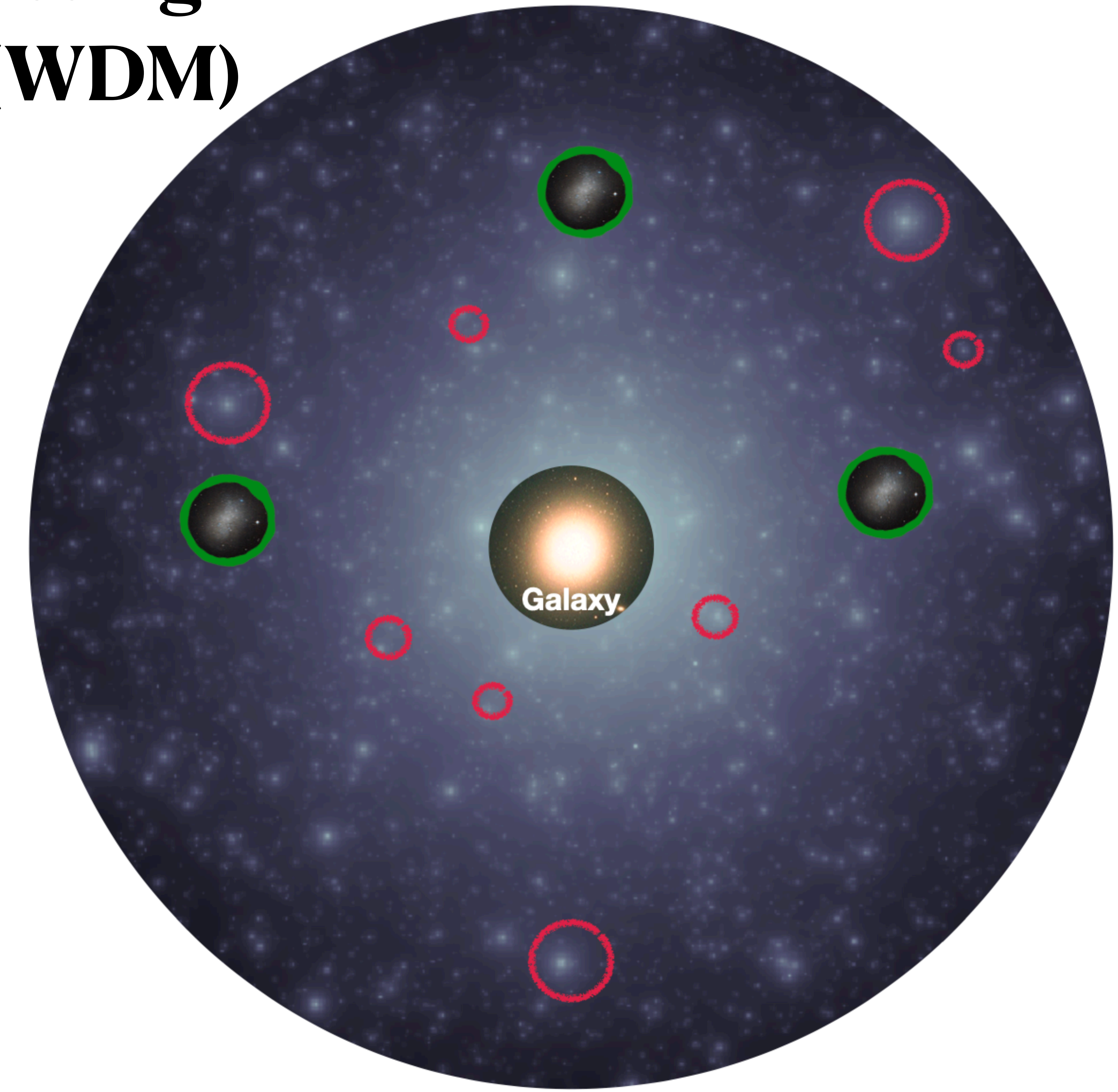
2) Self-interacting dark matter (SIDM): halos undergo core collapse and become extremely dense





Challenges associated with detecting a turnover in the mass function (WDM) or collapsed halos (SIDM)

Baryons inside halos can complicate interpretation

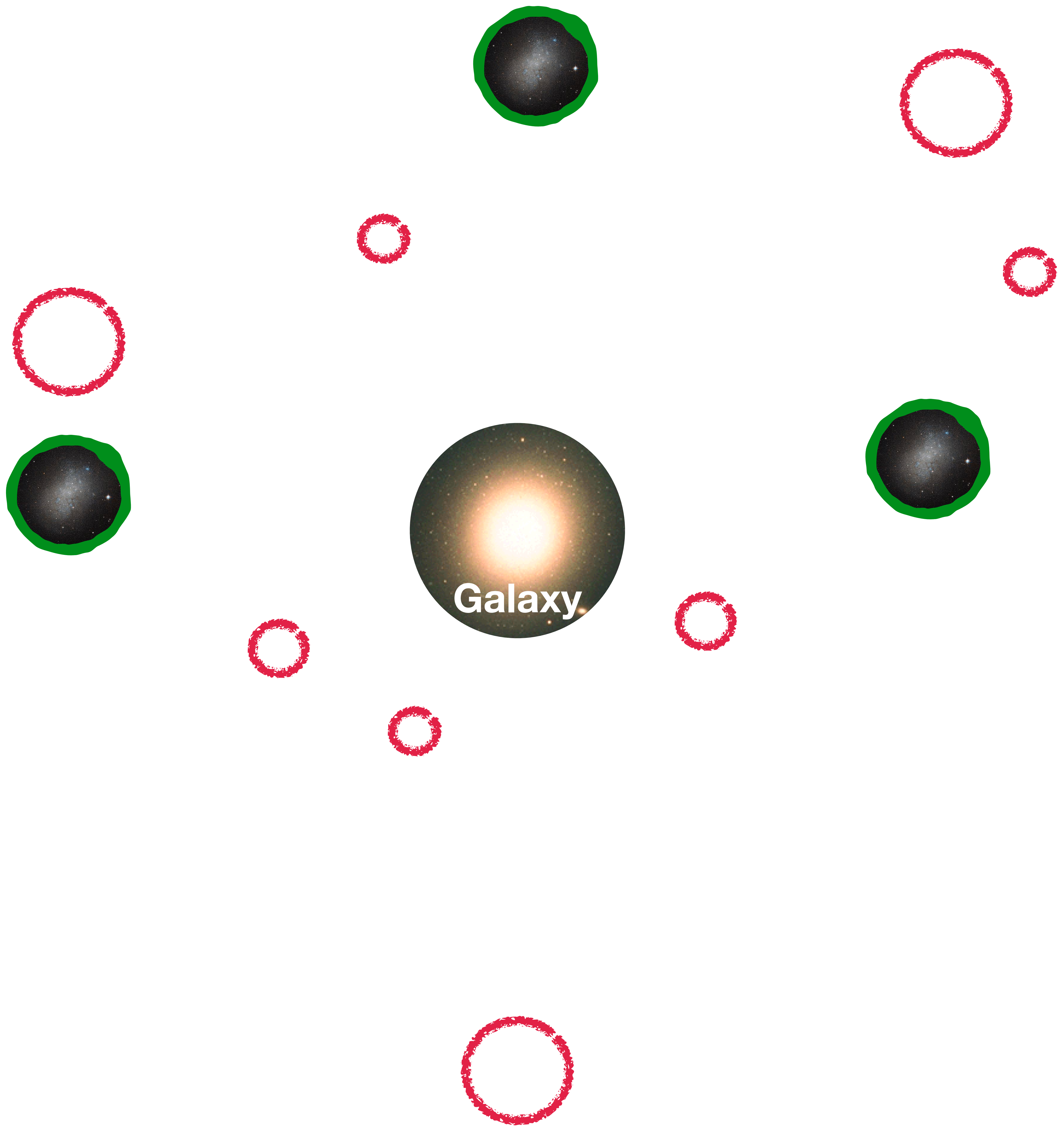


Challenges associated with detecting a turnover in the mass function (WDM) or collapsed halos (SIDM)

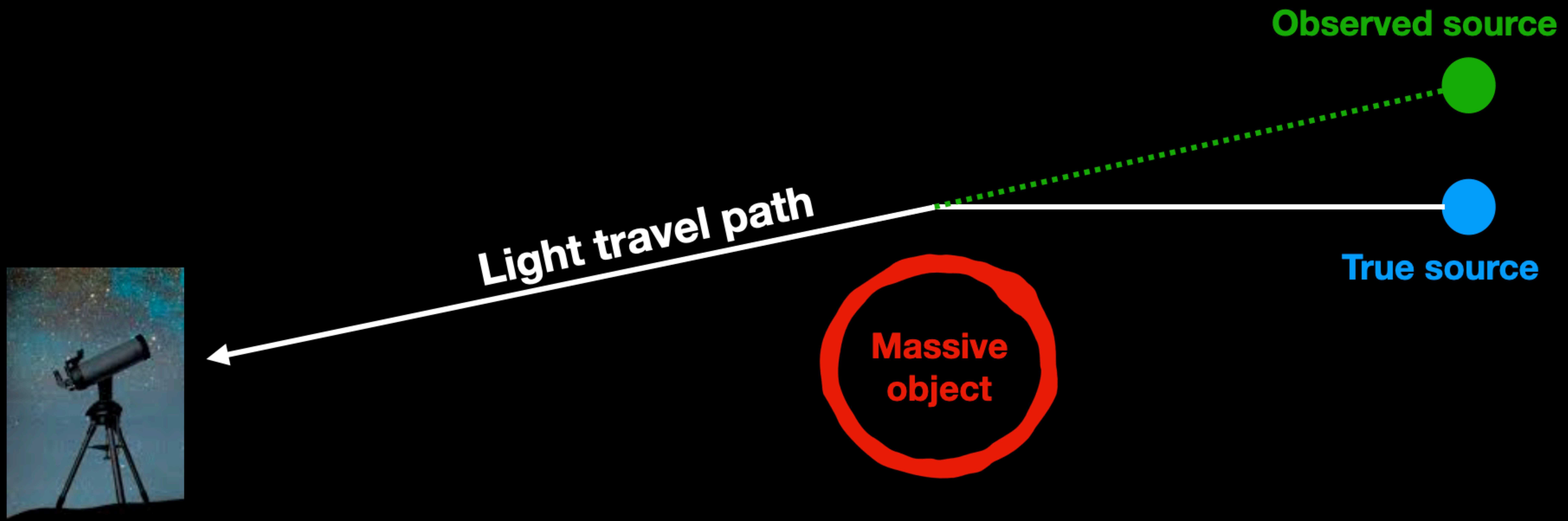
Baryons inside halos can complicate interpretation

Most halos are dark.

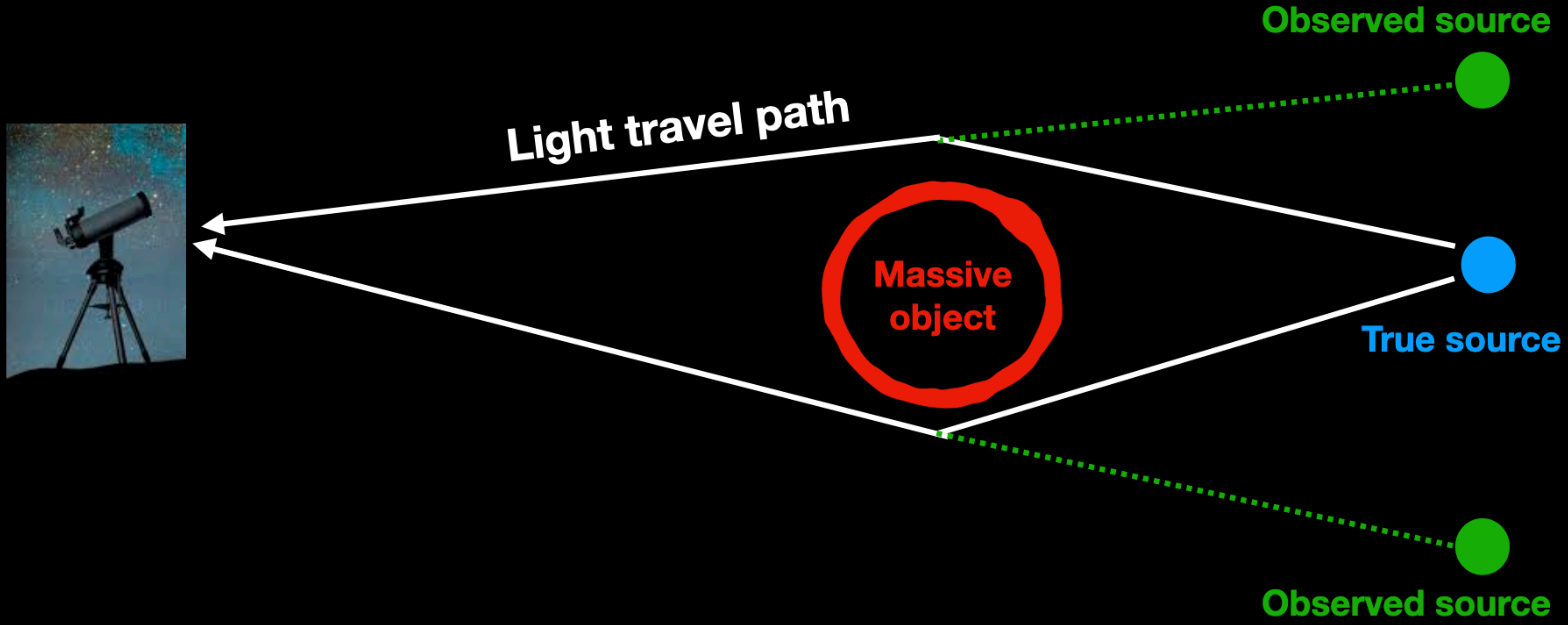
(Contain insufficient luminous matter to be detectable.)



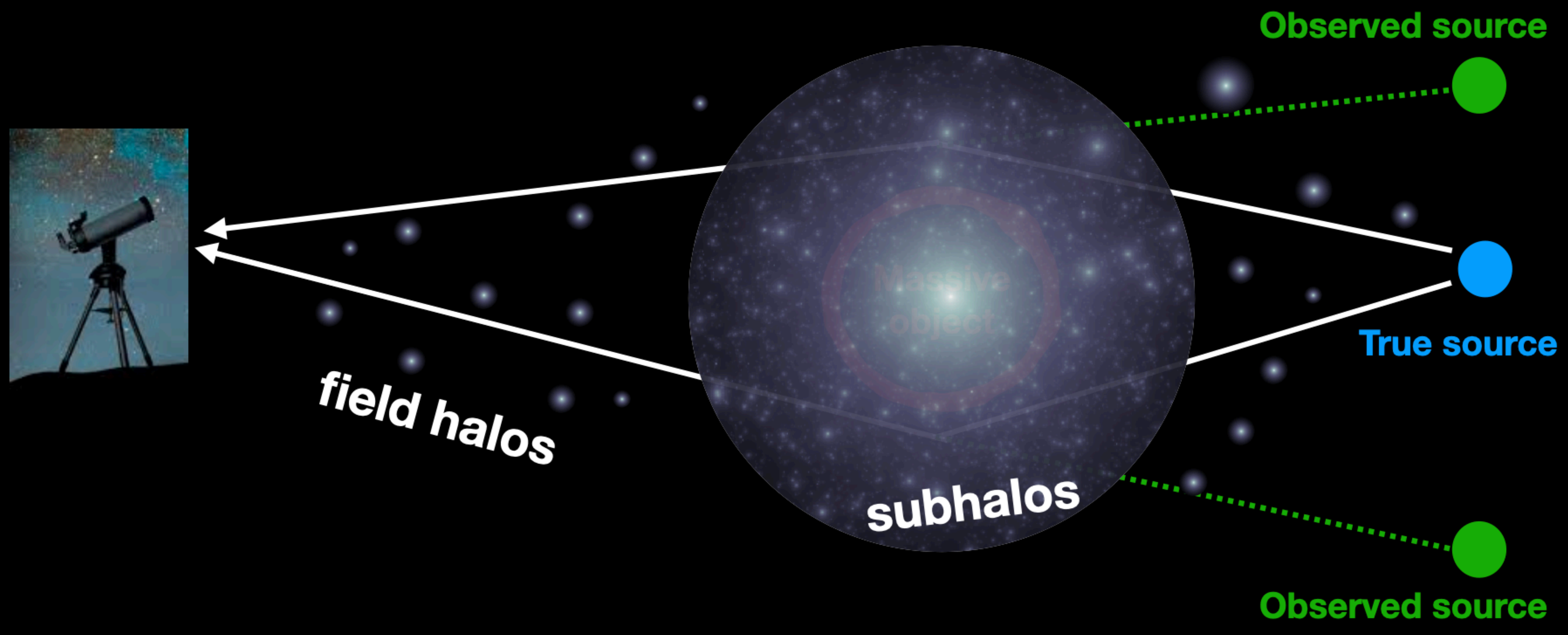
Gravitational lensing: deflection of light by gravitational fields



Strong lensing produces multiple images of a single source...



Strong lensing —> multiple images perturbed by dark matter halos



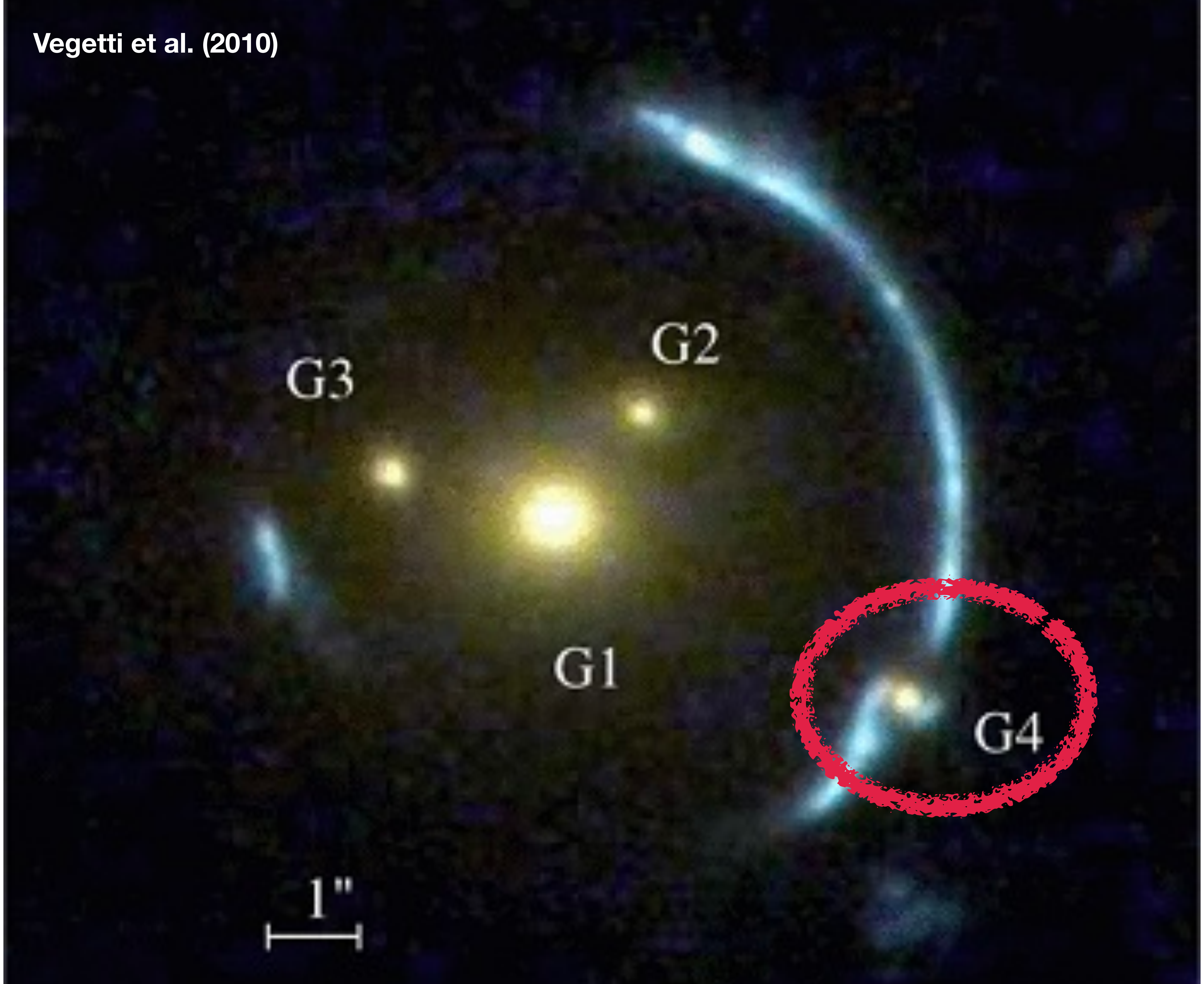

Vegetti et al. (2010)
G3
G2
G1
G4
1"

Figure adapted from
Shajib et al. (2019)

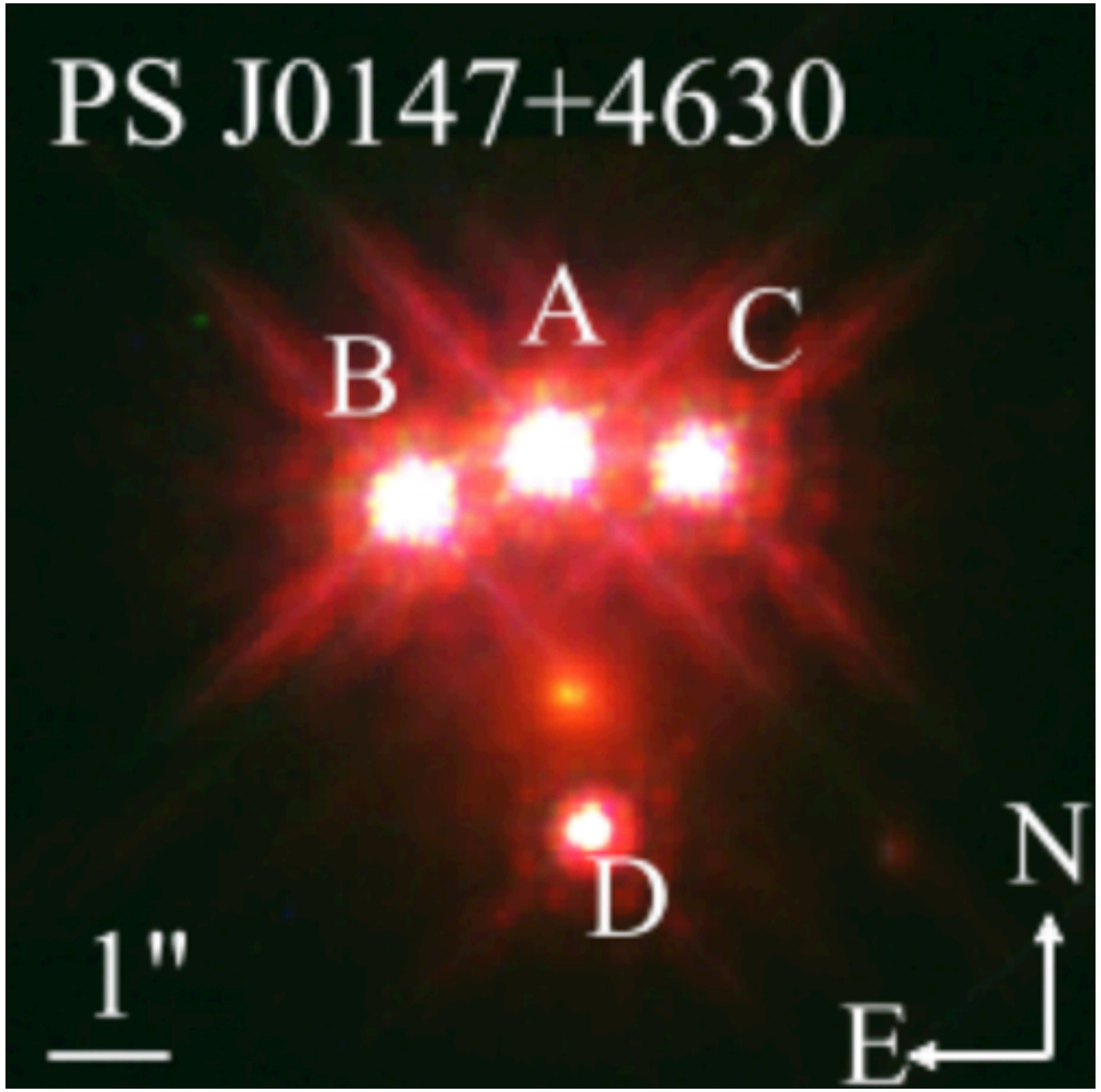
Main deflector

(Lensed) quasar host galaxy

Multiple images of background quasar

Figure adapted from Shajib et al. (2019)

Main observable

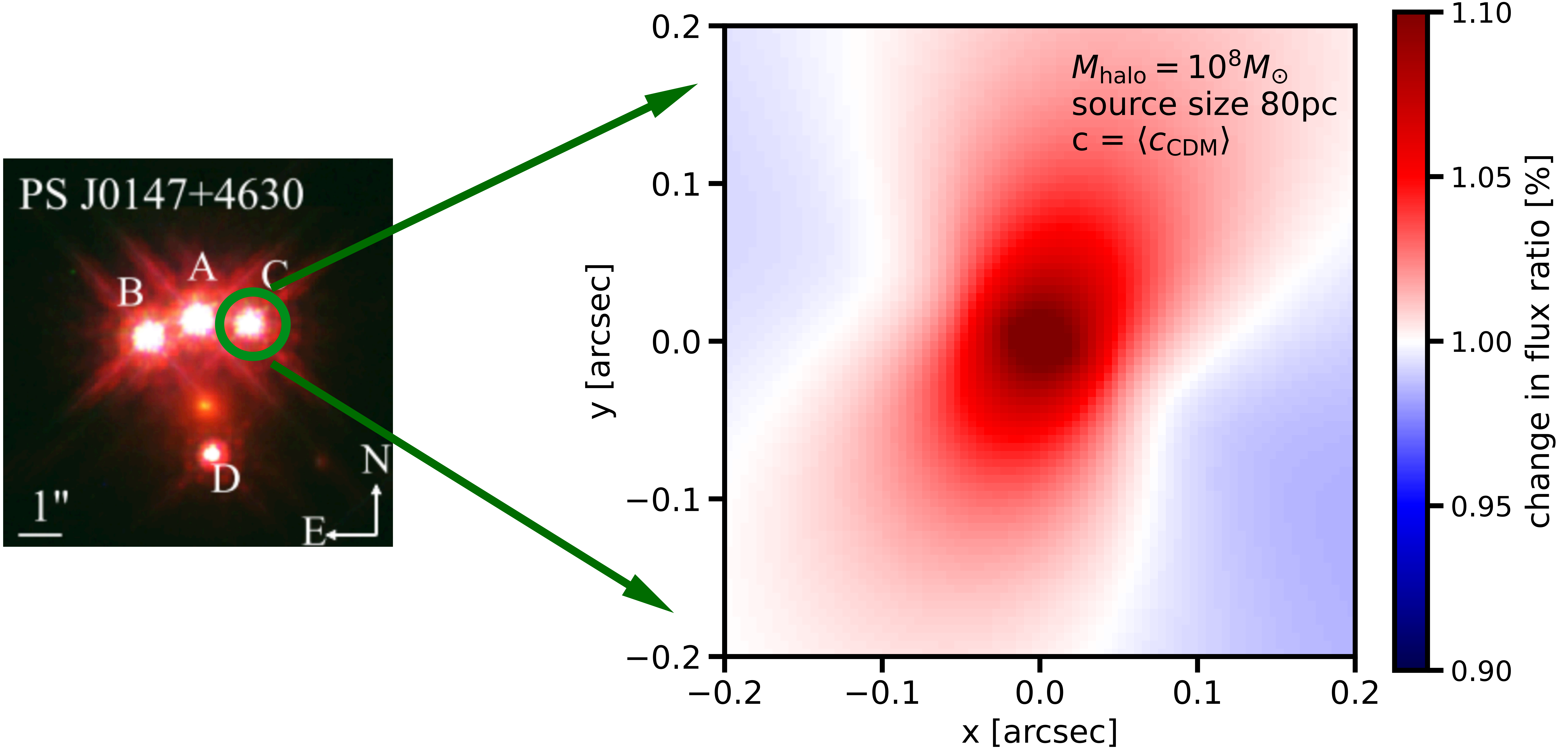


Relative image magnifications
(flux ratios)
-> local, highly sensitive probe of halos

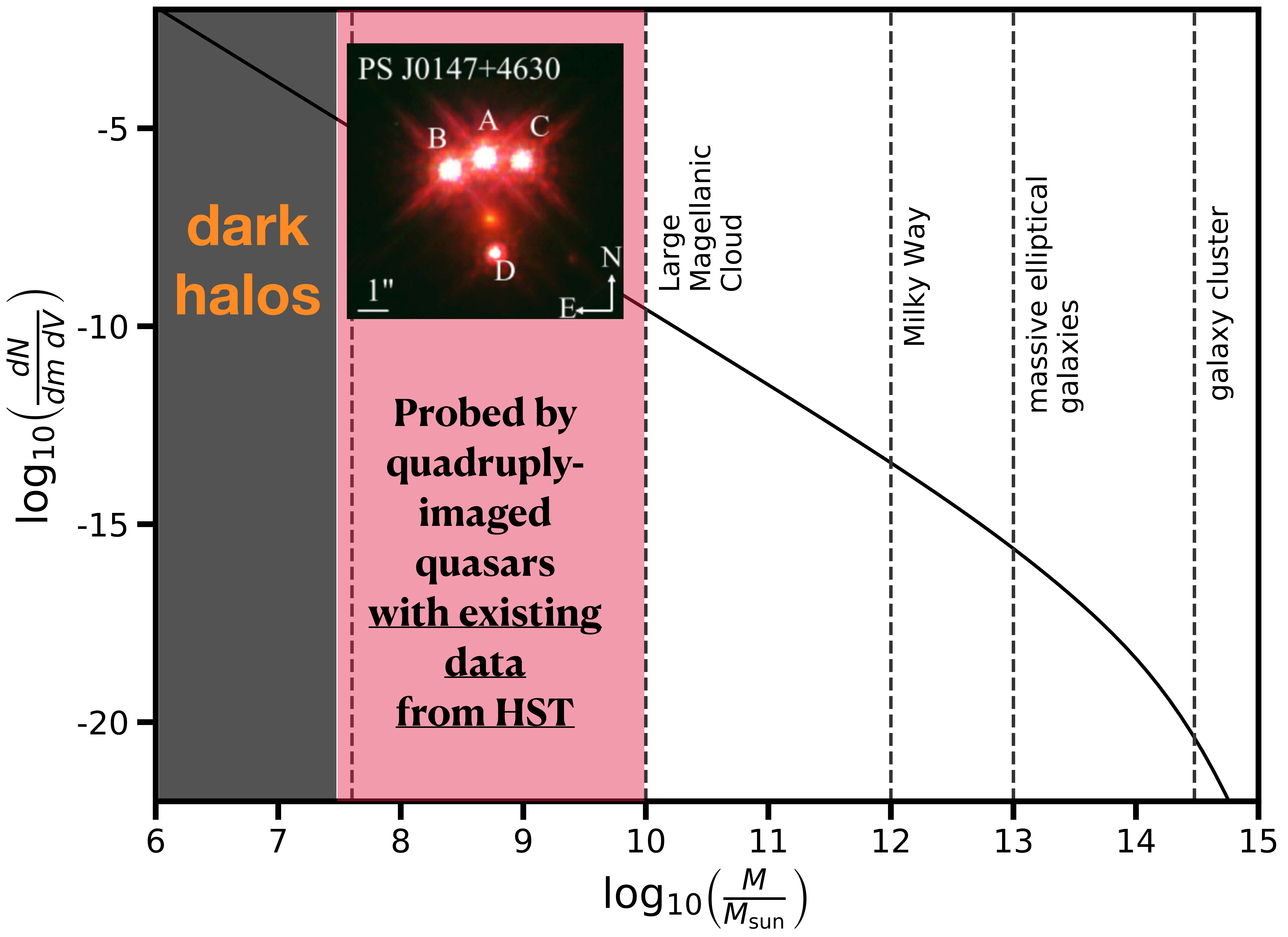
magnifications $\propto \partial^2\Psi/\partial x^2$

(by Poisson Eqn.) $\propto$ **Projected mass density**

Magnification cross section of 1 halo



Magnification cross section of 1 halo



PS J0147+4630
A
B
C
D
N
E
1"
dark halos
Probed by quadruply-imaged quasars with existing data from HST
Large Magellanic Cloud
Milky Way
massive elliptical galaxies
galaxy cluster
-5
-10
-15
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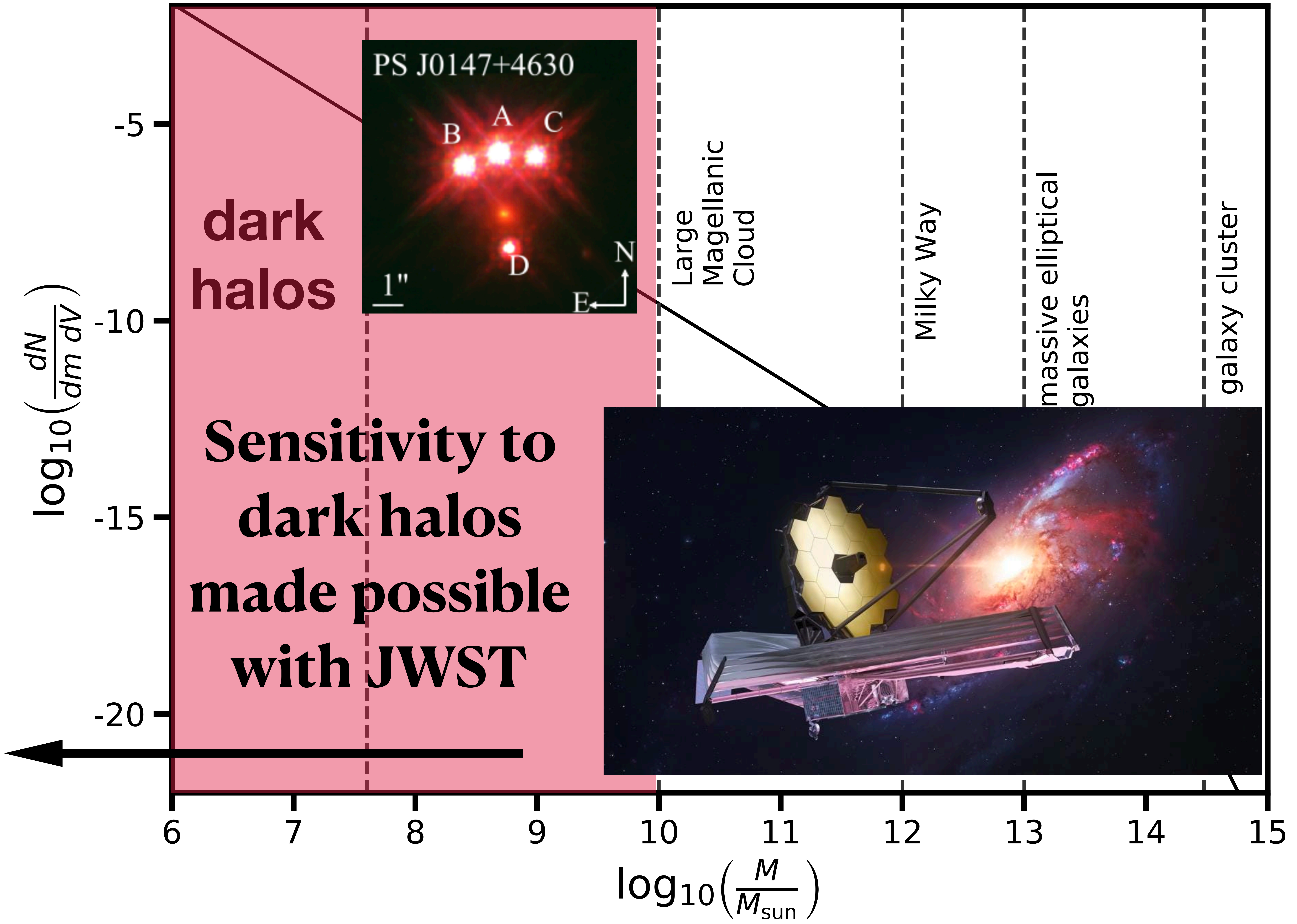
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
$\log_{10}\left(\frac{M}{M_{sun}}\right)$


PS J0147+4630
A
B
C
D
1"
N
E
dark
halos
Large
Magellanic
Cloud
Milky Way
massive elliptical
galaxies
galaxy cluster
Sensitivity to
dark halos
made possible
with JWST
-5
-10
-15
-20
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
6
7
8
9
10
11
12
13
14
15
$\log_{10}\left(\frac{M}{M_{sun}}\right)$

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)

Fuzzy dark matter: fewer halos 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)

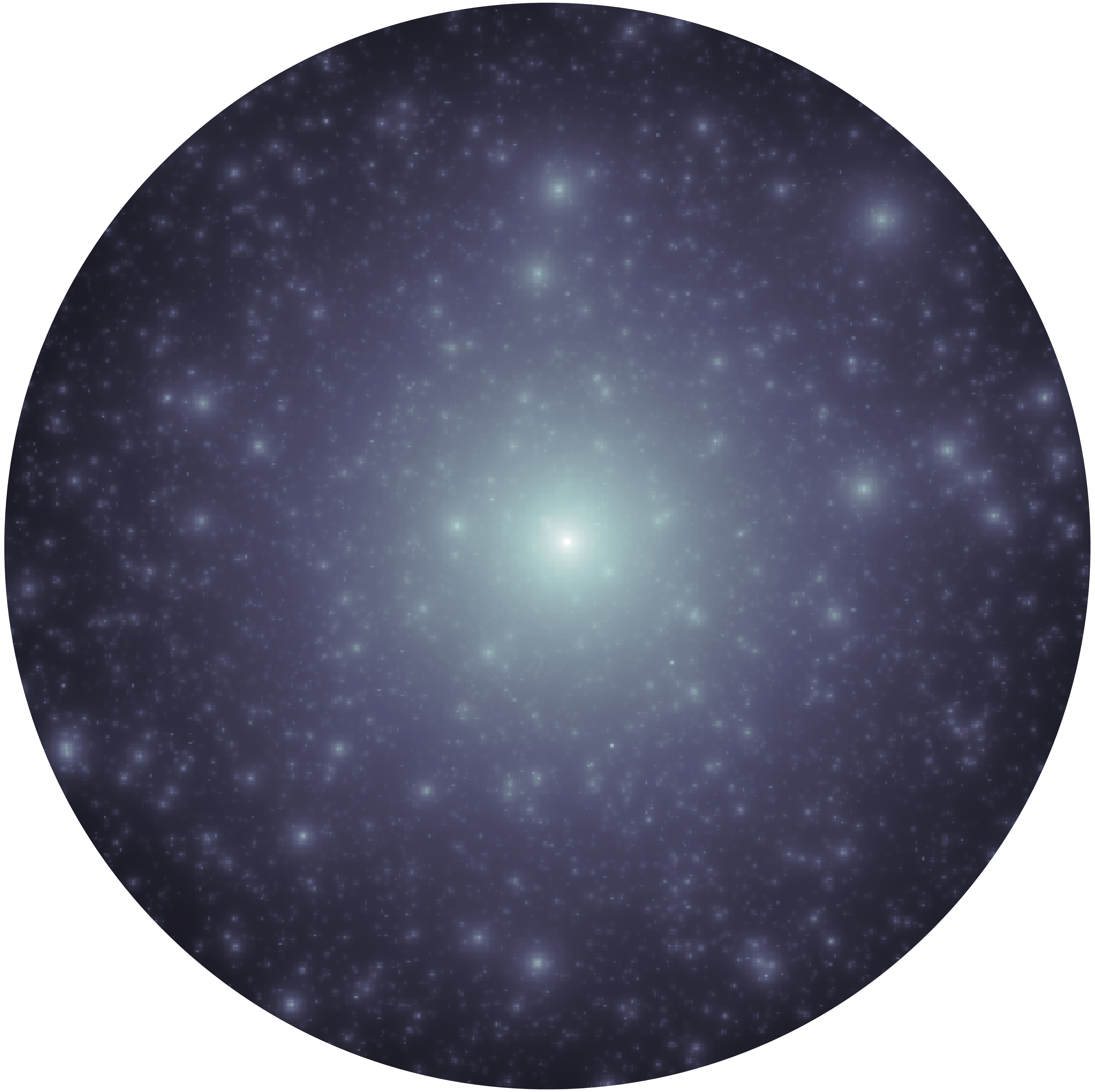
Inflation/early Universe: enhanced/suppressed small-scale power impacts
halo abundance/concentration Gilman et al. (2022) (arXiv: 2112.03293)

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)

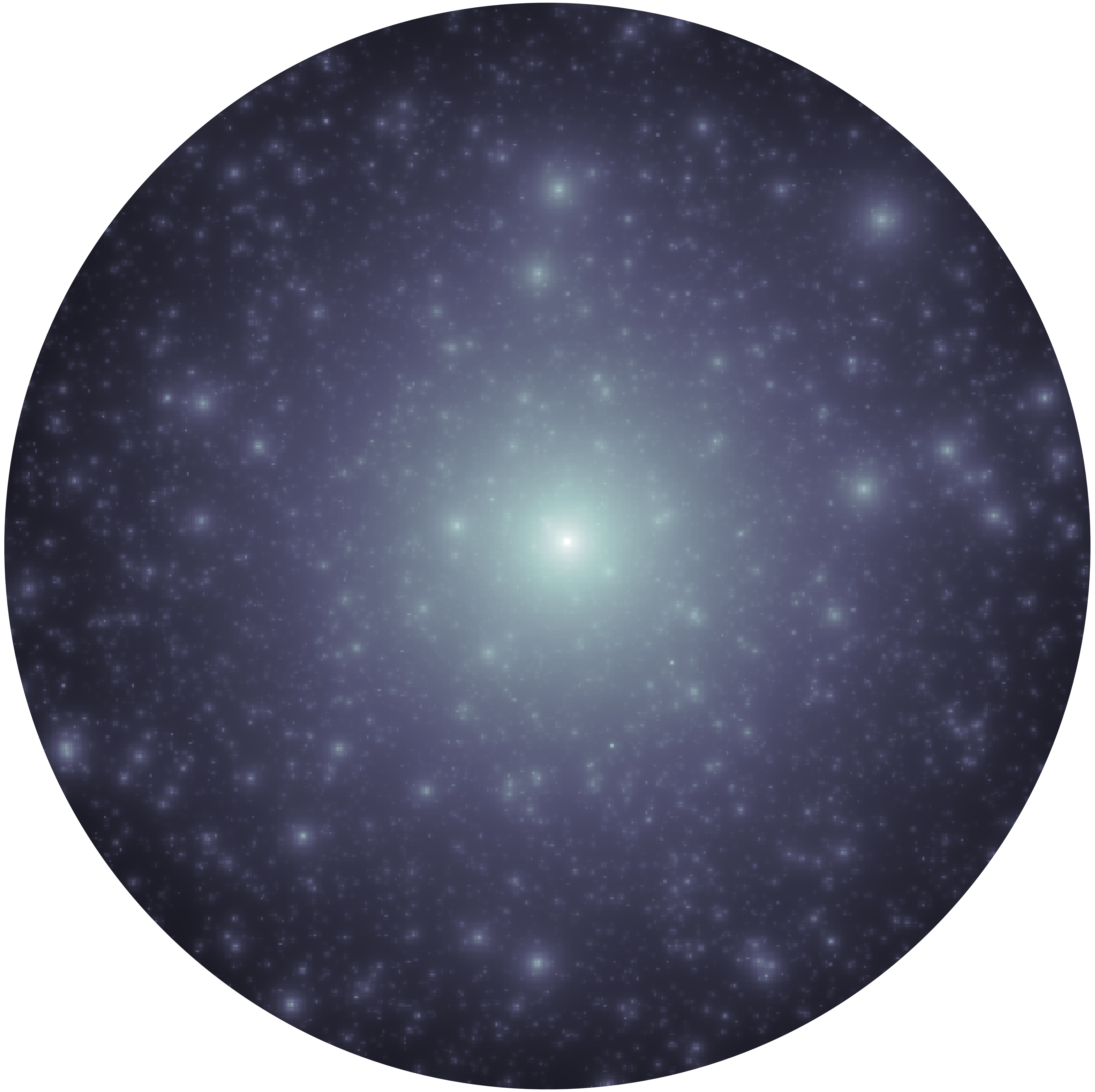
Warm Dark Matter

Cold dark matter (CDM)



Warm dark matter (WDM)

Cold dark matter (CDM)



Warm dark matter (WDM)

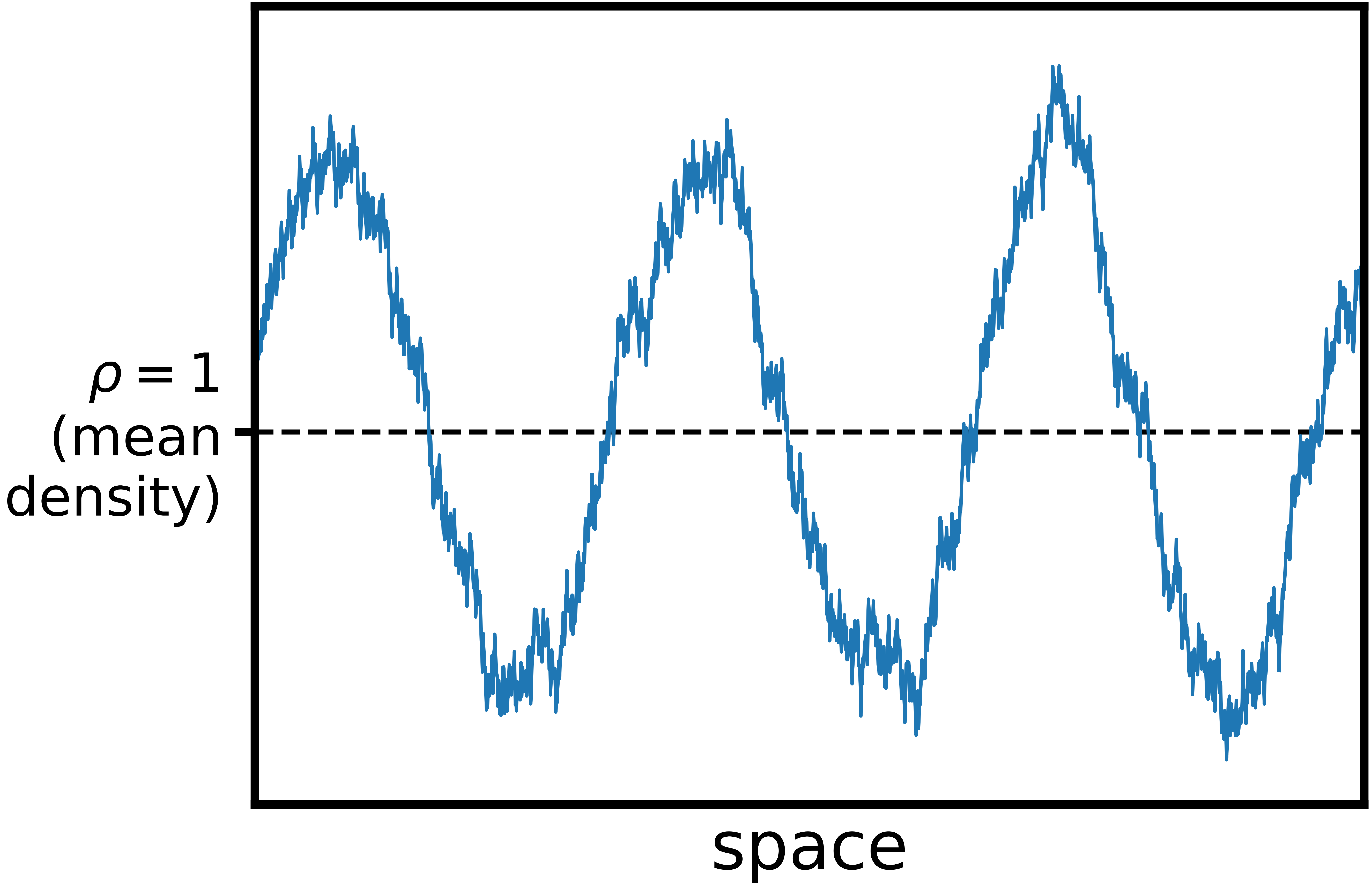
Free-streaming imposes a length scale $\lambda_{\rm FS}$ on the problem

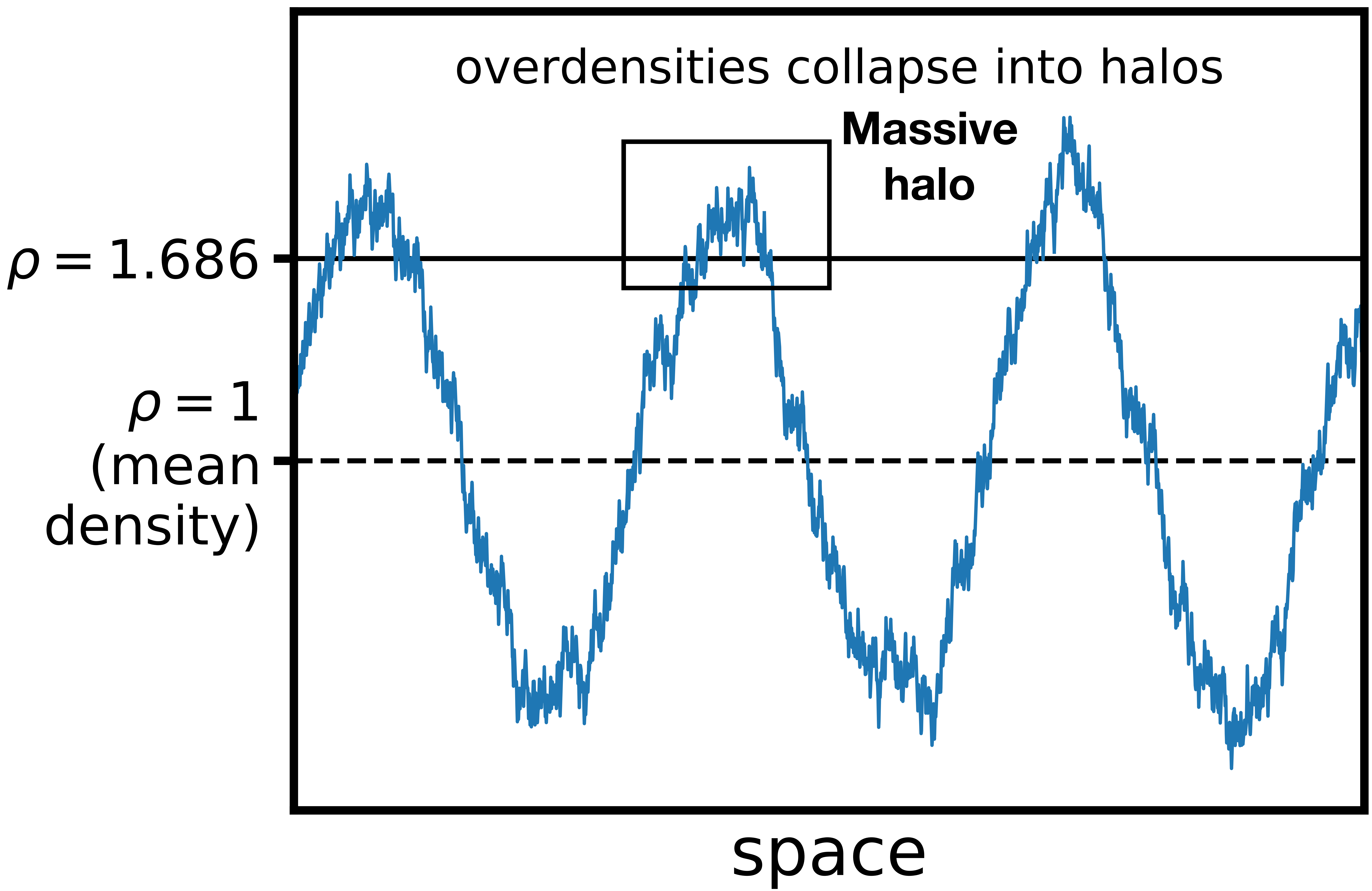
$$\lambda_{\rm FS} \sim ct_{NR} \propto V_{\rm rms}\Big|_{z\sim3000}$$

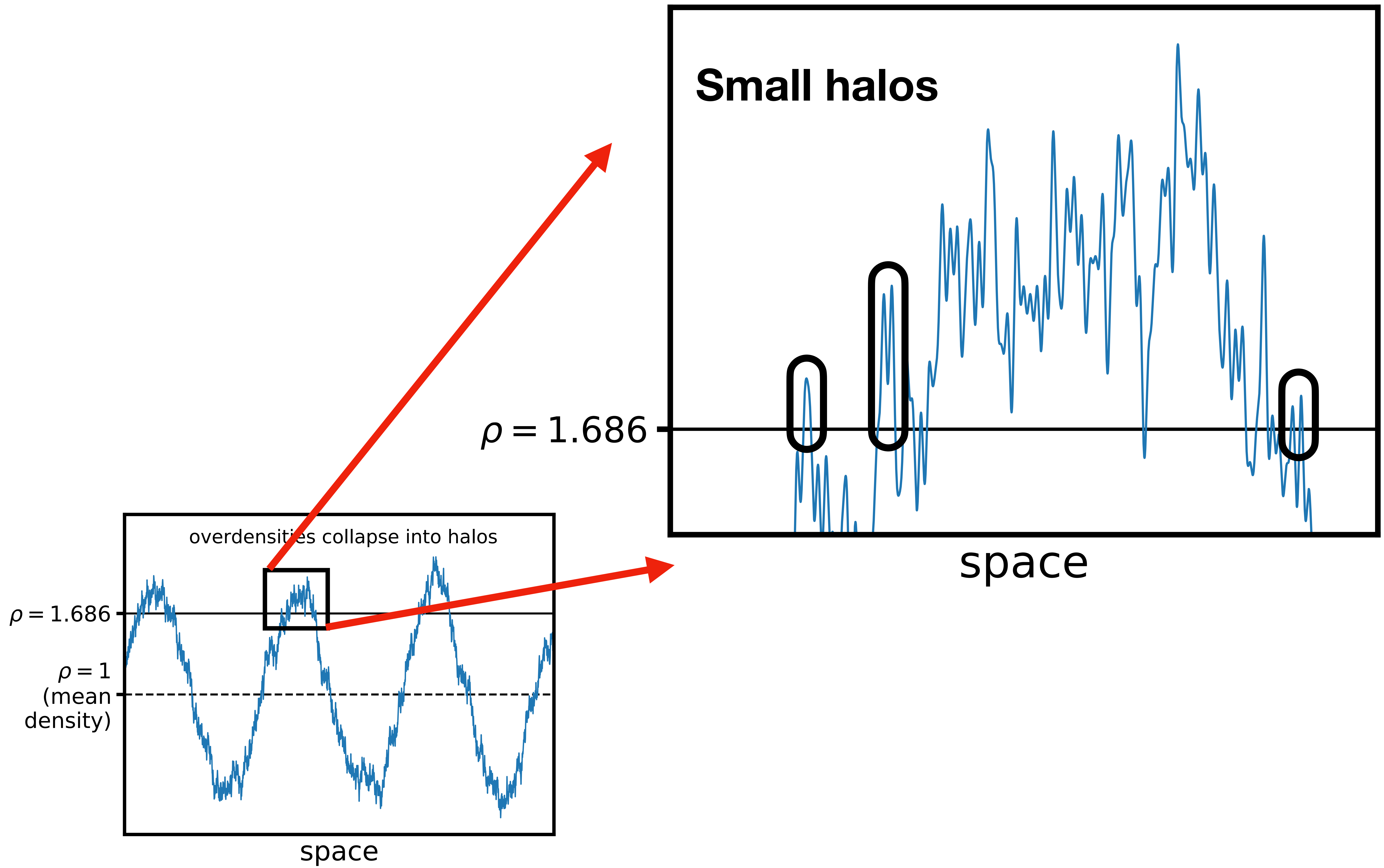
-> **NO HALOS LESS MASSIVE THAN**

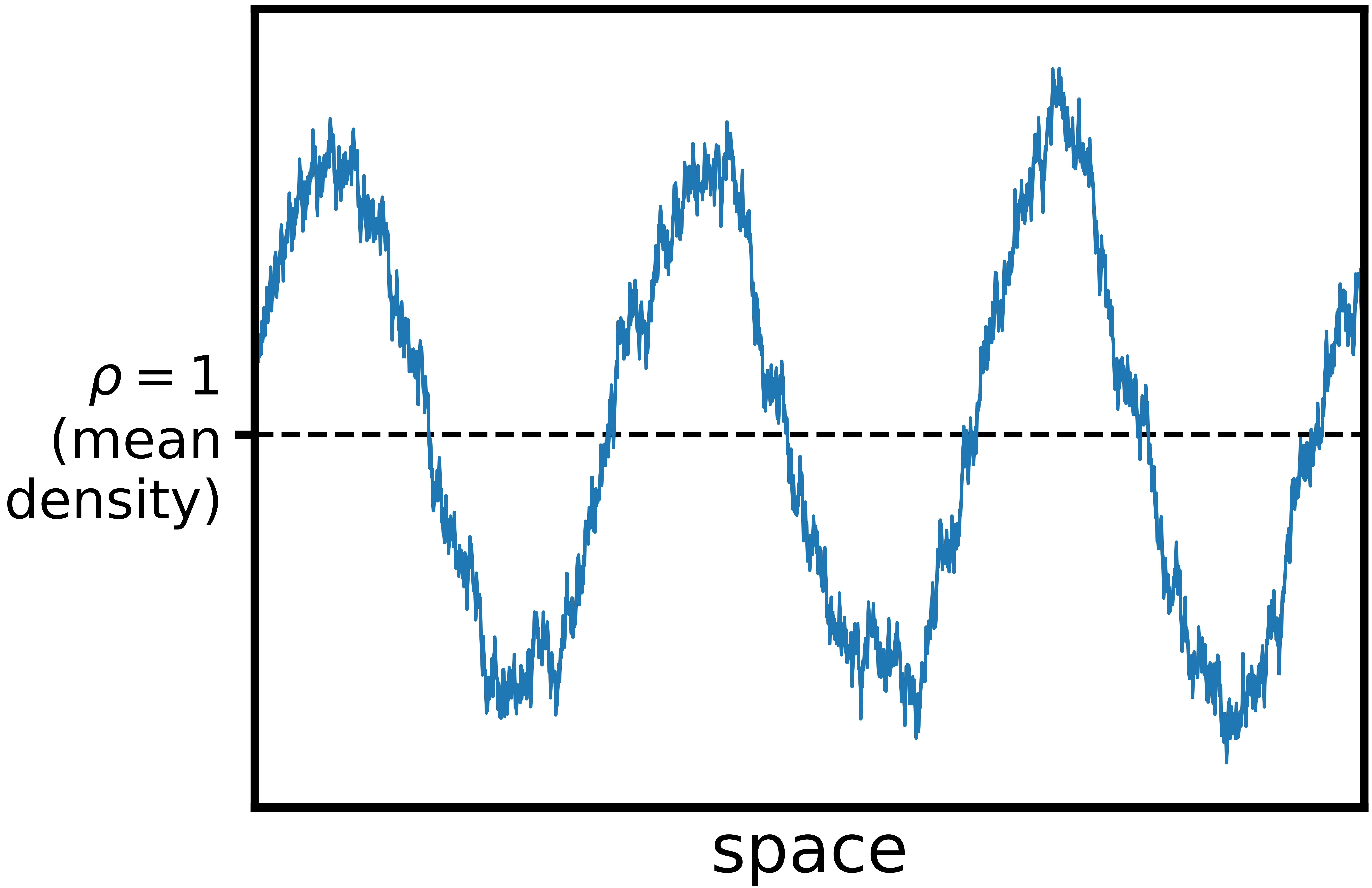
$$M_{\rm min} \sim \rho_{\rm crit}\lambda_{\rm FS}^3$$

Scale-free density fluctuations initialized in early Universe with WIMPs (CDM)

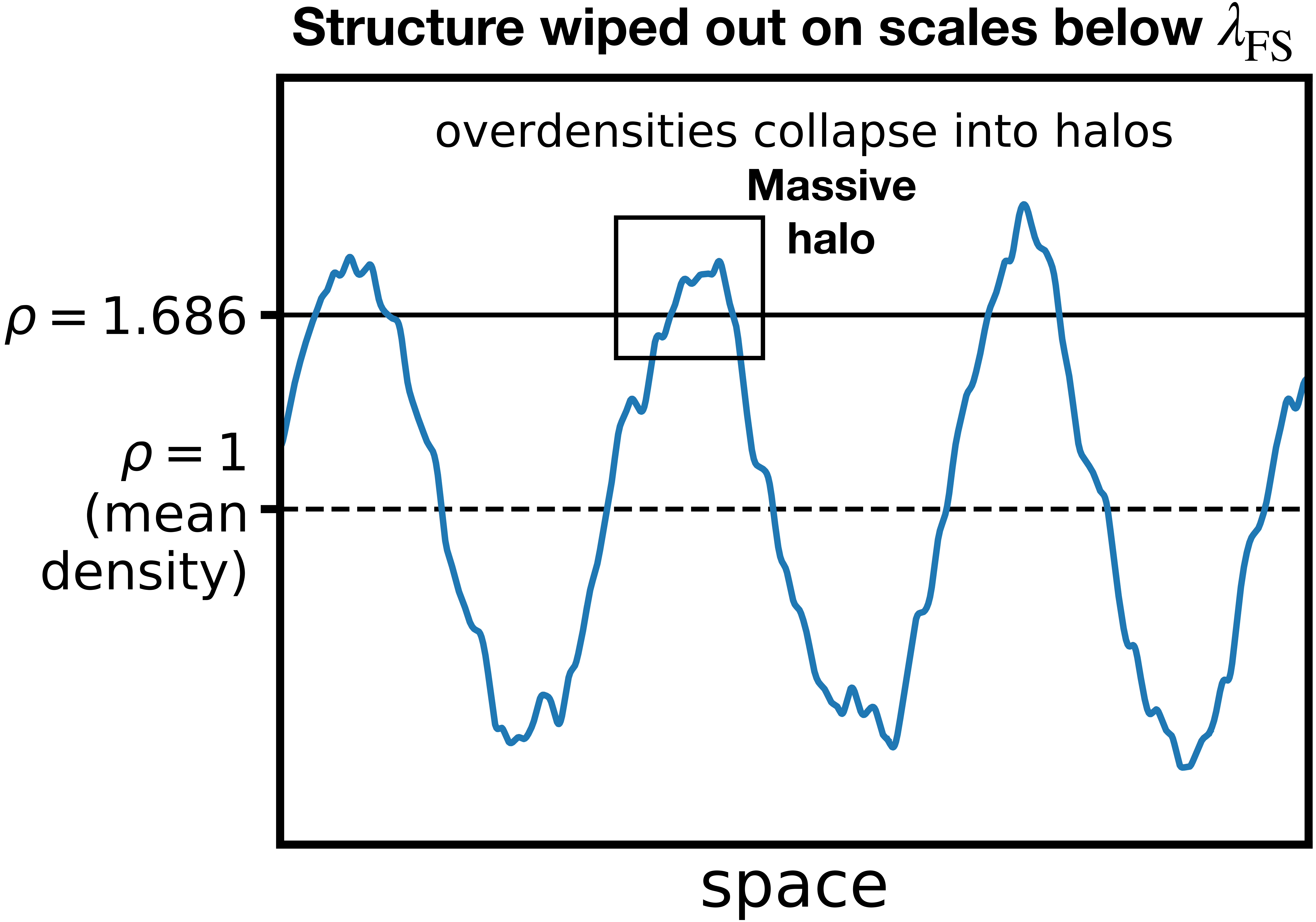



overdensities collapse into halos
Massive halo
$\rho = 1.686$
$\rho = 1$
(mean density)
space

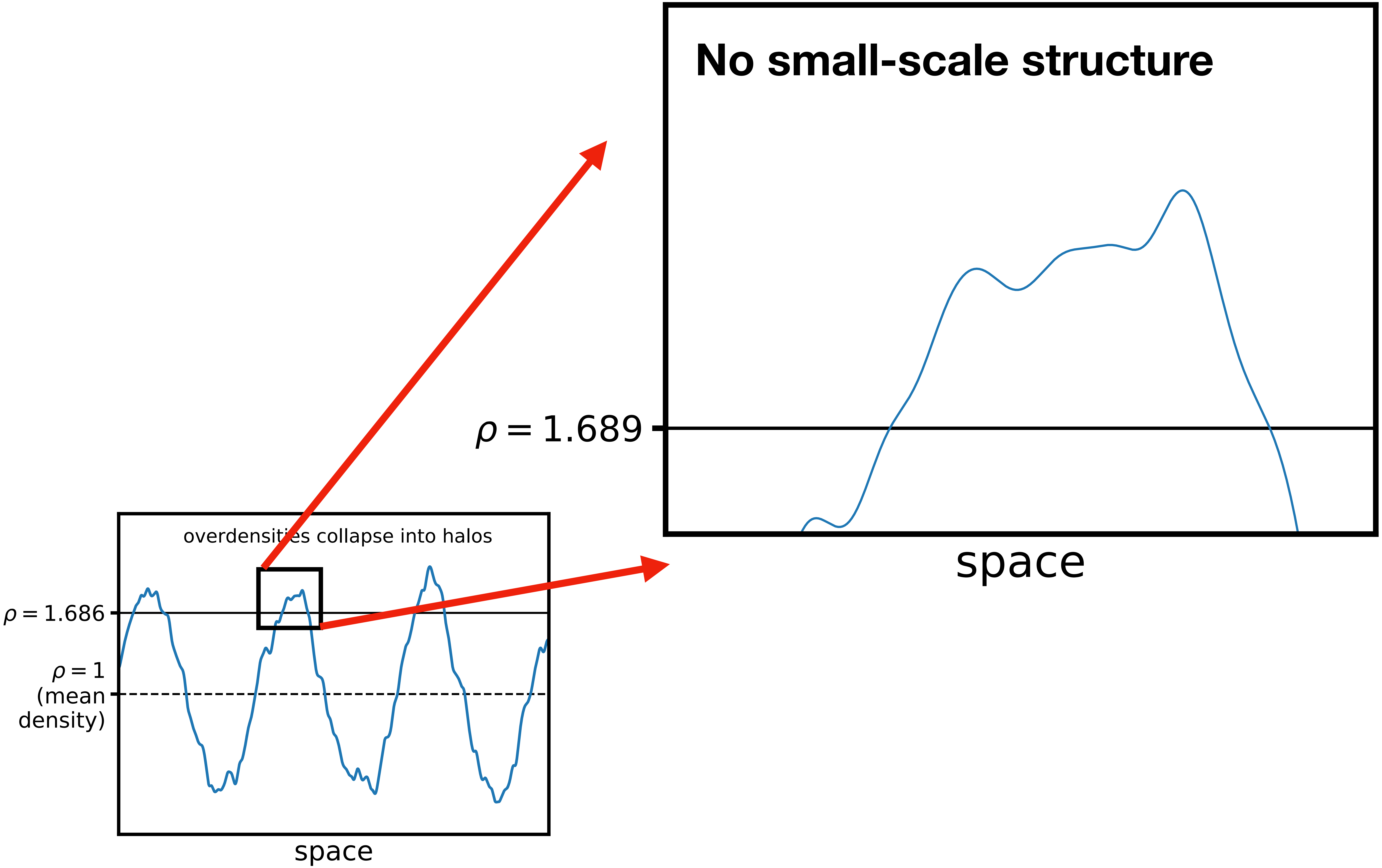

Small halos
$\rho = 1.686$
space
overdensities collapse into halos
$\rho = 1.686$
$\rho = 1$
(mean
density)
space



$\rho = 1$
(mean
density)
space



Structure wiped out on scales below λ_{FS}
overdensities collapse into halos
Massive halo
$\rho = 1.686$
$\rho = 1$ (mean density)
space


No small-scale structure
$\rho = 1.689$
space
overdensities collapse into halos
$\rho = 1.686$
$\rho = 1$
(mean
density)
space

Warm dark matter (WDM)

Standard Model Neutrinos

$$M_{\min} \sim 10^{14}\ \mathrm{M}_{\odot}$$

GeV-scale WIMPS

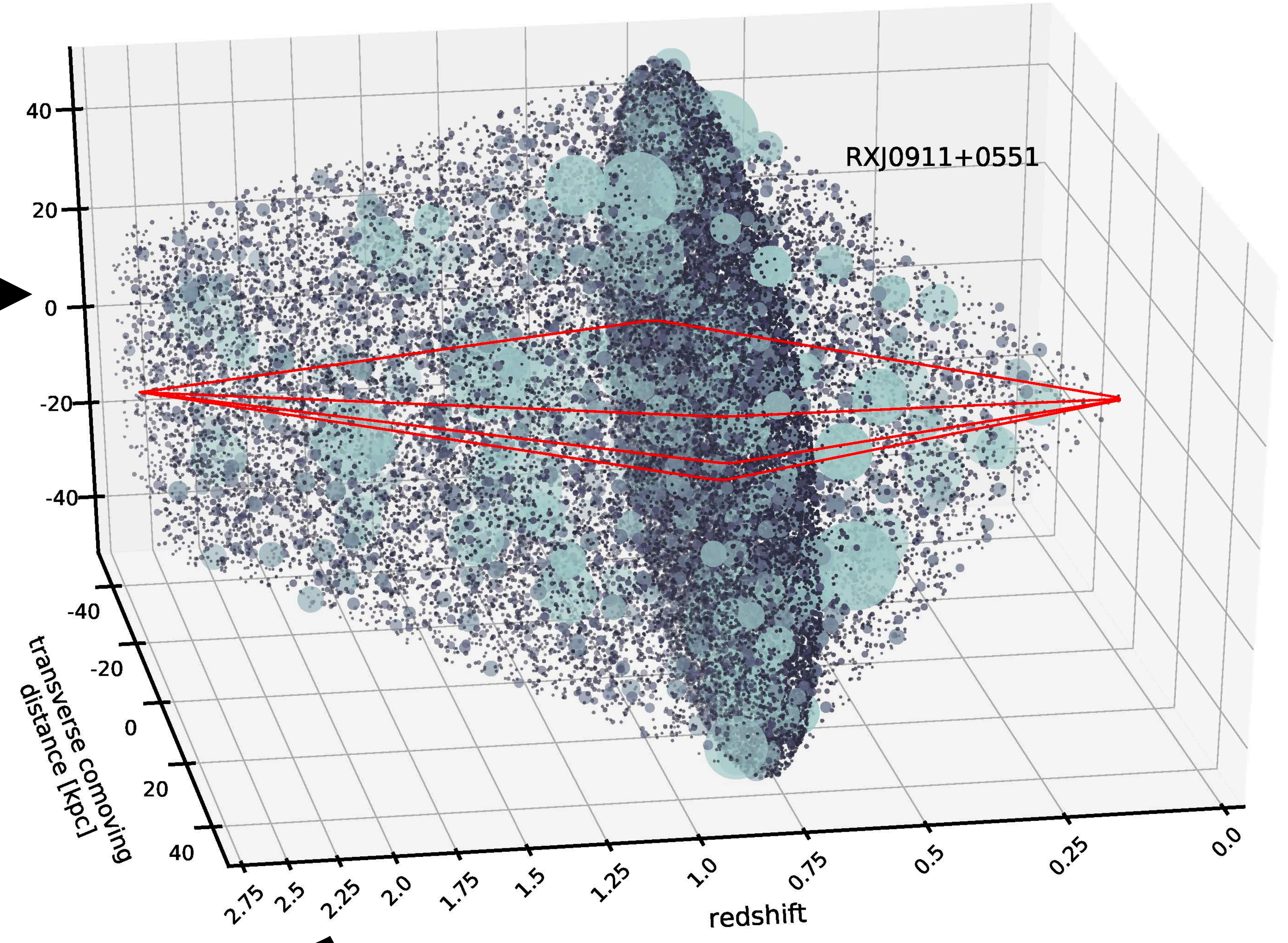
$$M_{\min} \propto 1 M_{\mathrm{Earth}}$$

(some) Sterile Neutrino WDM

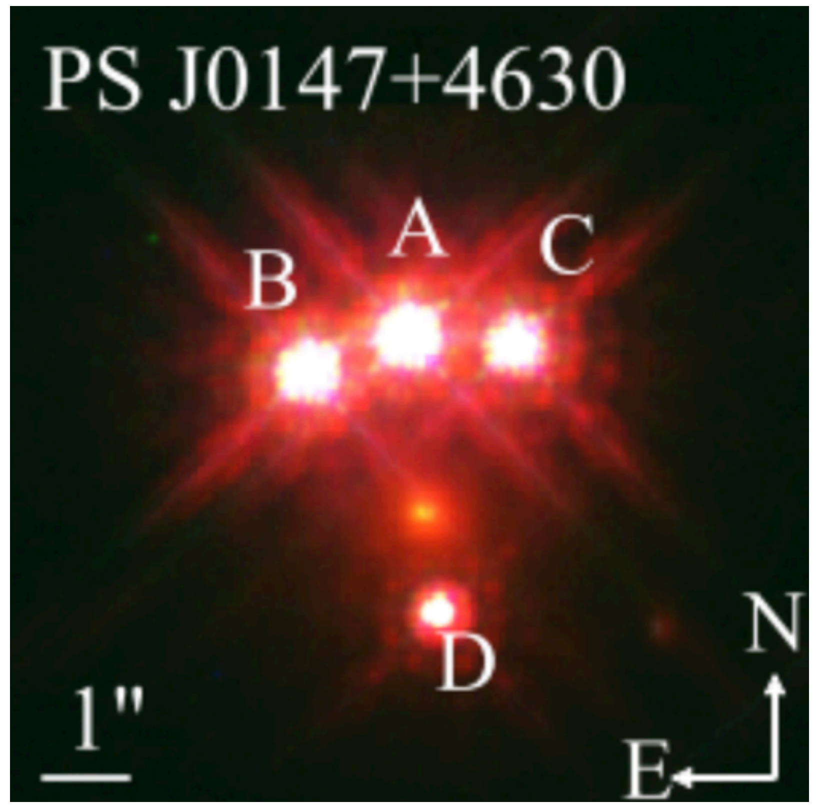
$$M_{\min} \sim 10^{7}\ \mathrm{M}_{\odot}$$

Forward modeling approach applied to quads

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



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

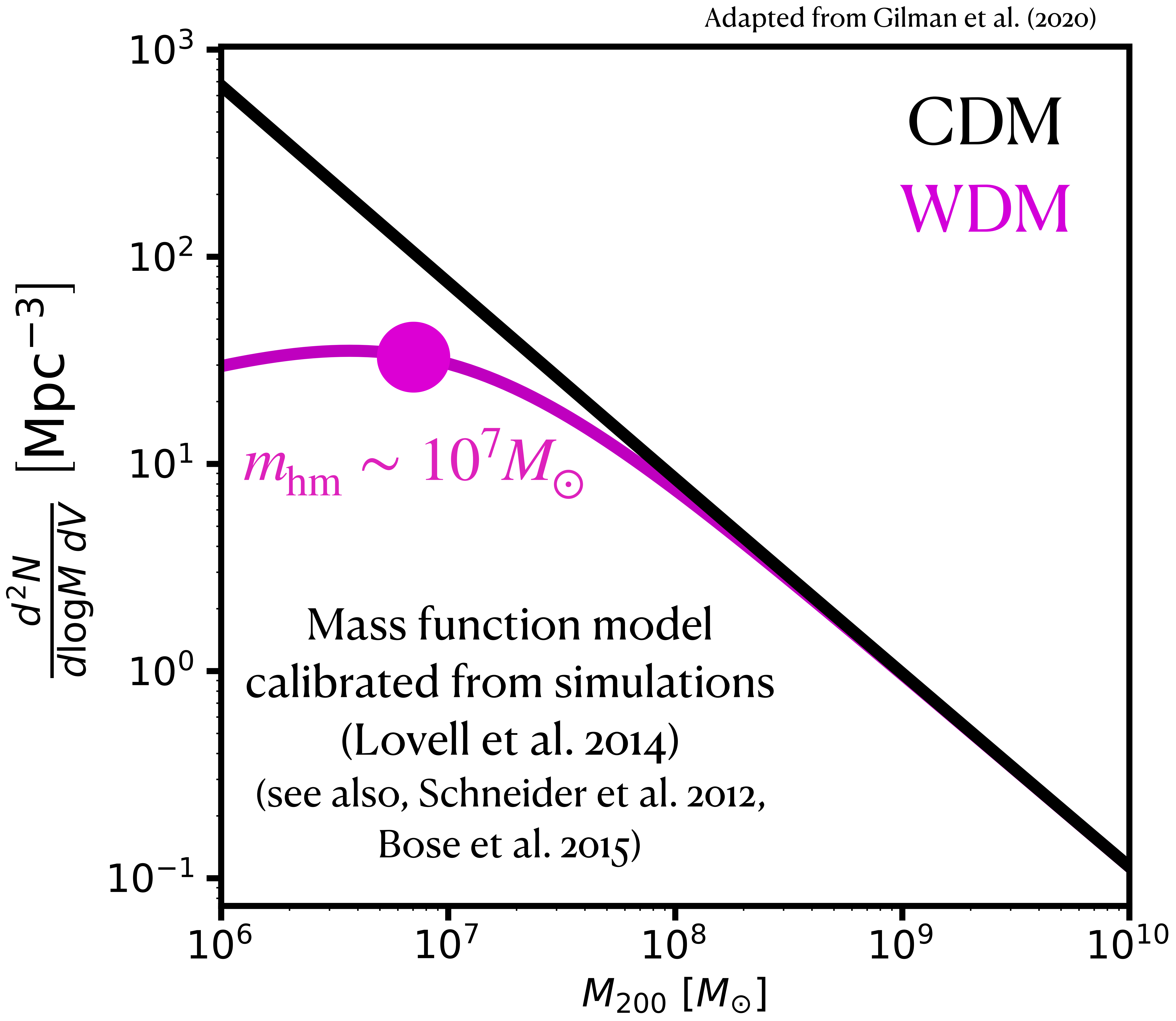


Compare with data

Fewer halos in WDM

↓

Less perturbation to lensed images



Structure forms later in WDM

↓

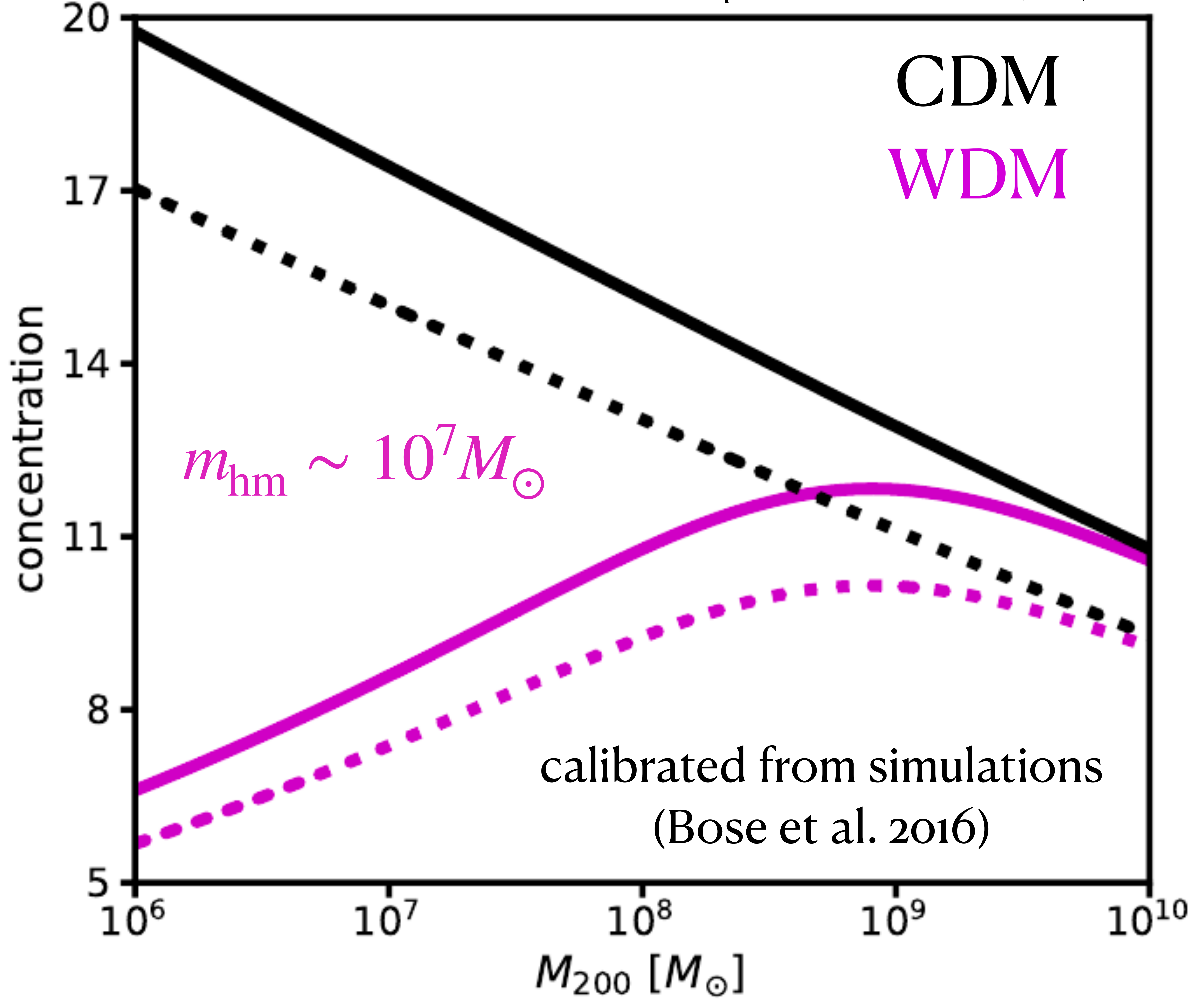
Halos less concentrated

↓

Less perturbation to lensed images

(More concentrated halos act as more efficient lenses)

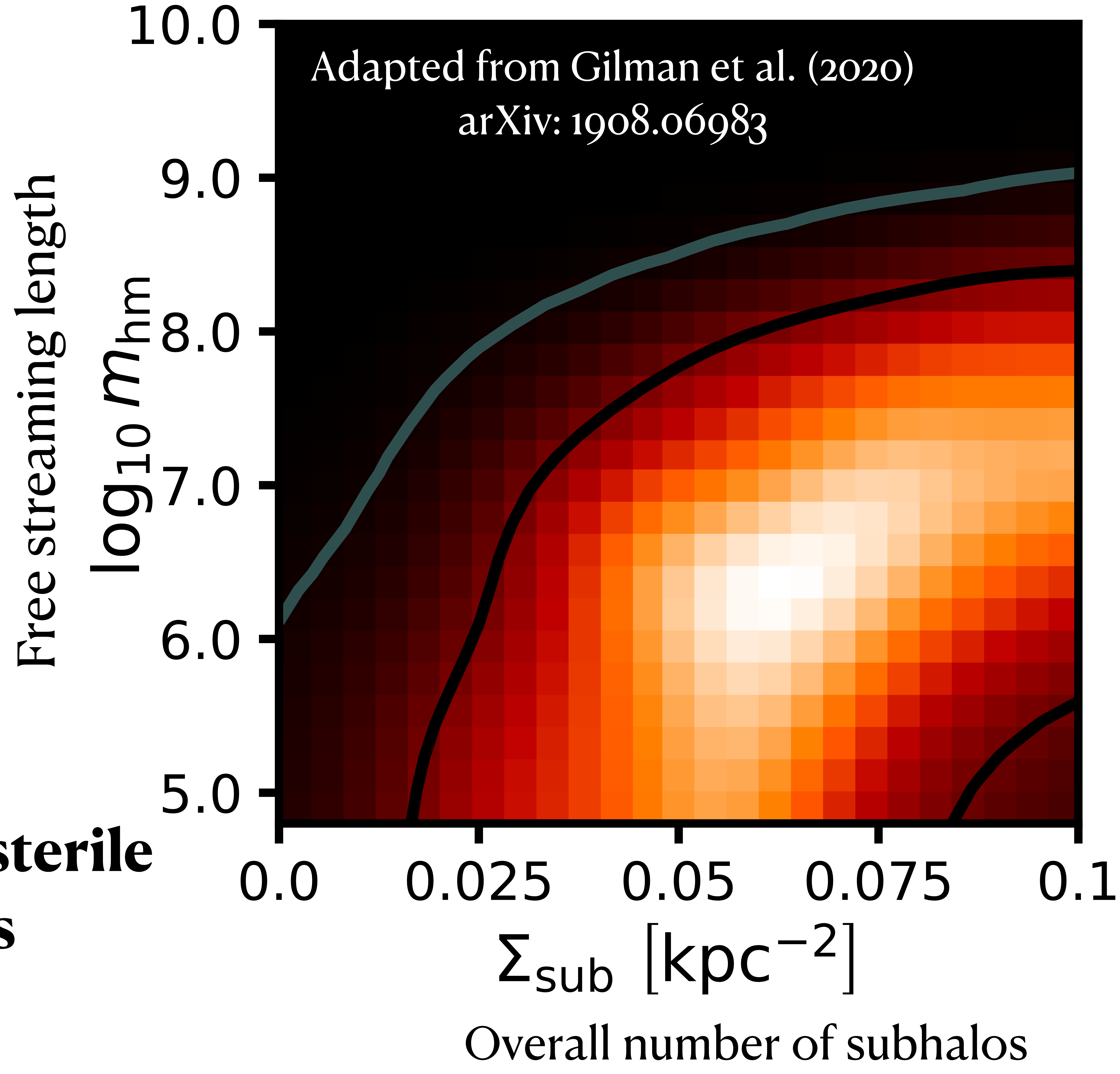
Adapted from Gilman et al. (2020)



Constraints from 8 lenses with HST data

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

Free streaming length ~ 10 kpc



Can recast this as a constrain on sterile neutrino dark matter models see Zelko et al. (2022)

Self-interacting dark matter

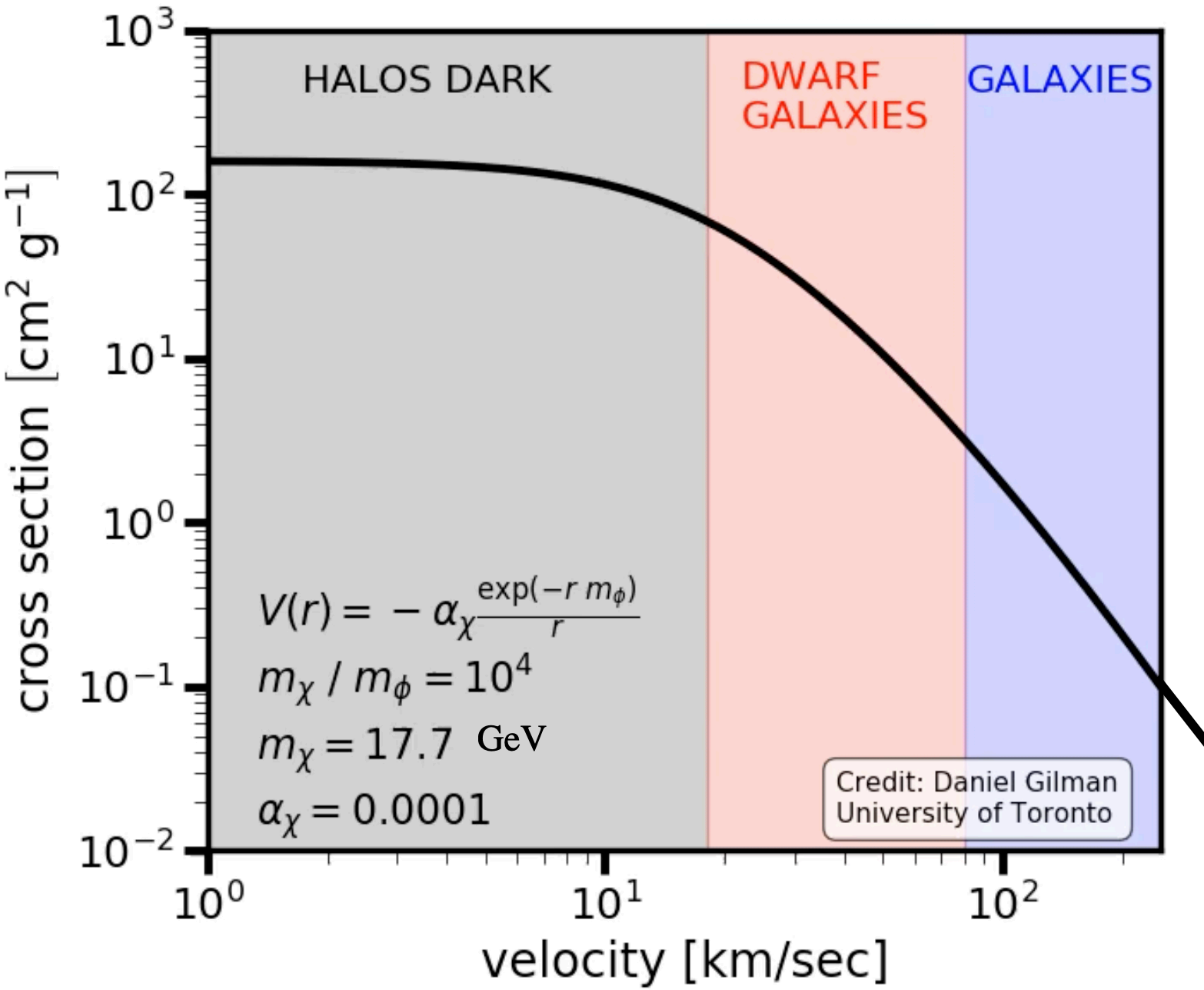
Self-interacting dark matter (SIDM)

-> only interacts with standard model through gravity

-> preserves large-scale structure

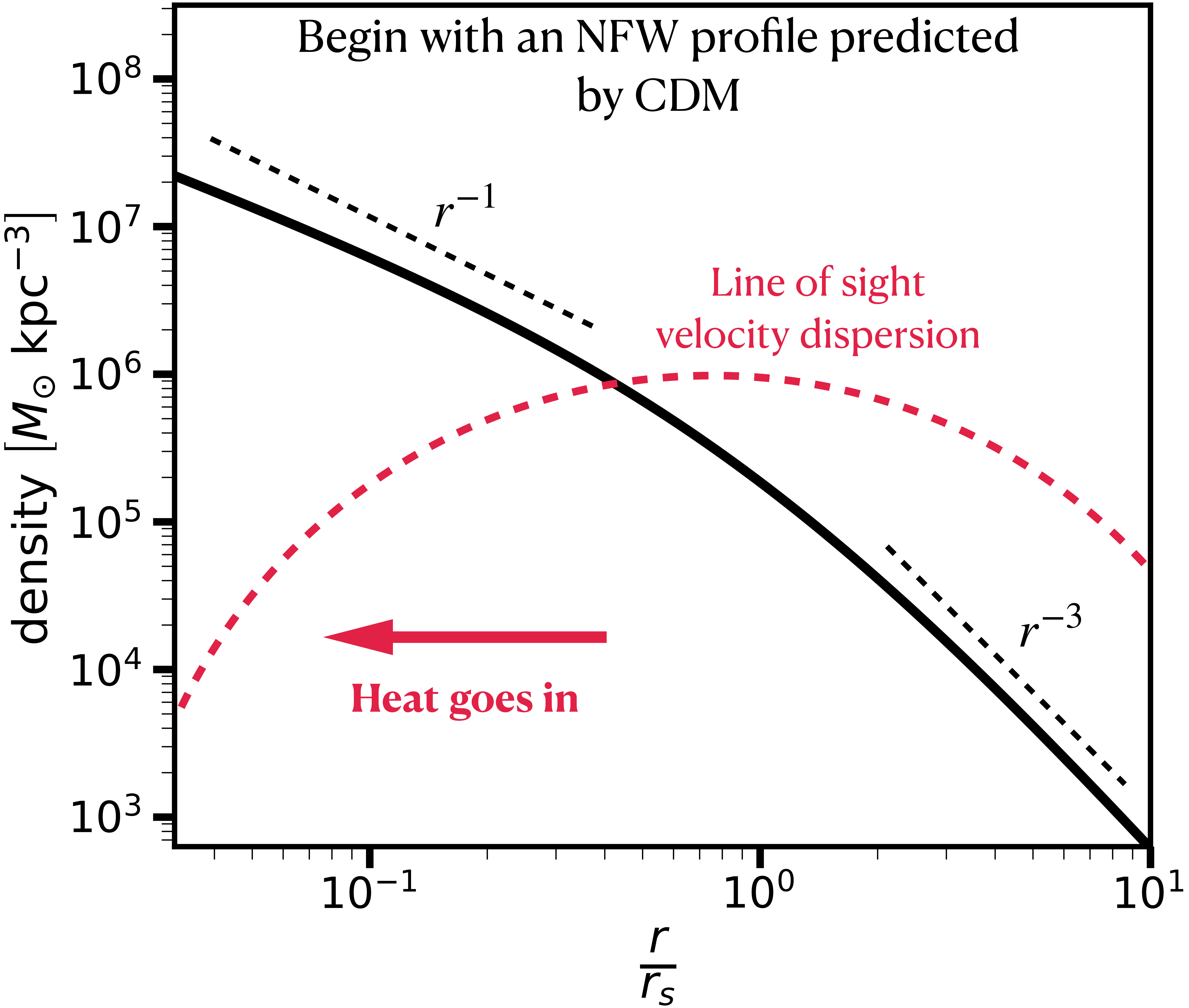
-> collisionless at high speeds $v \sim 1000 \ \mathrm{km \ s^{-1}}$

-> requires a velocity-dependent cross section

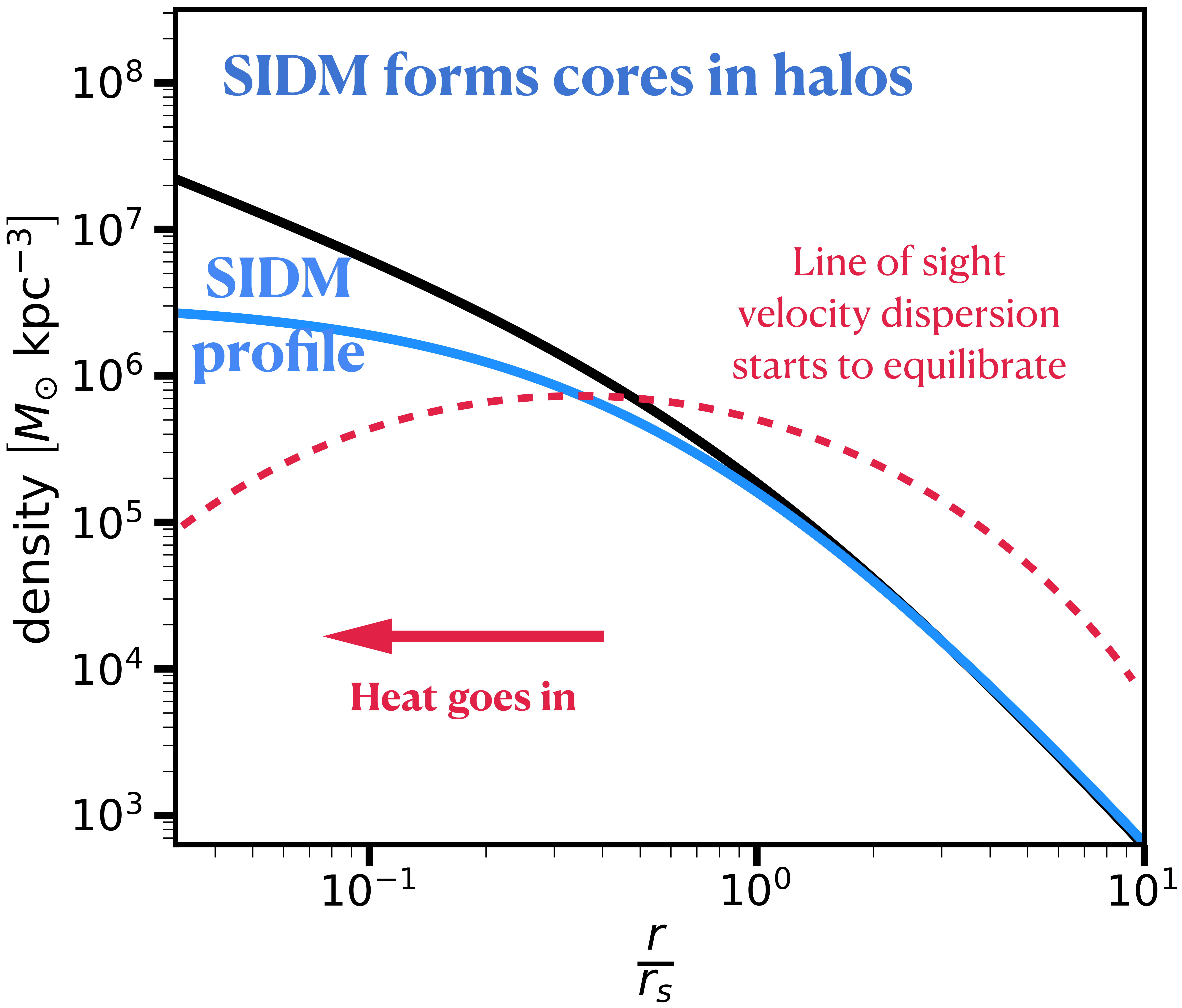


Upper limit from galaxy clusters

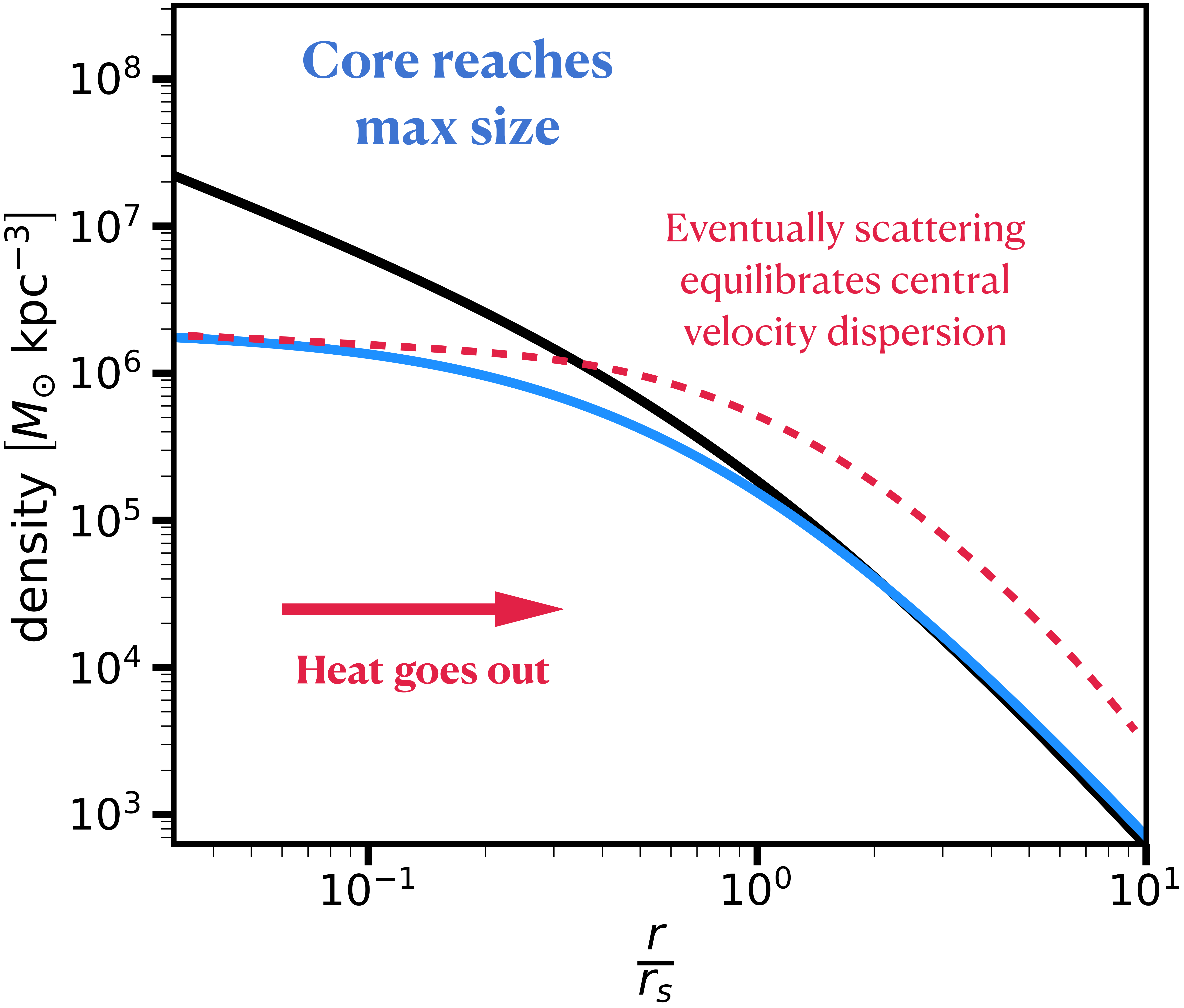
Effects of SIDM on halo density profiles



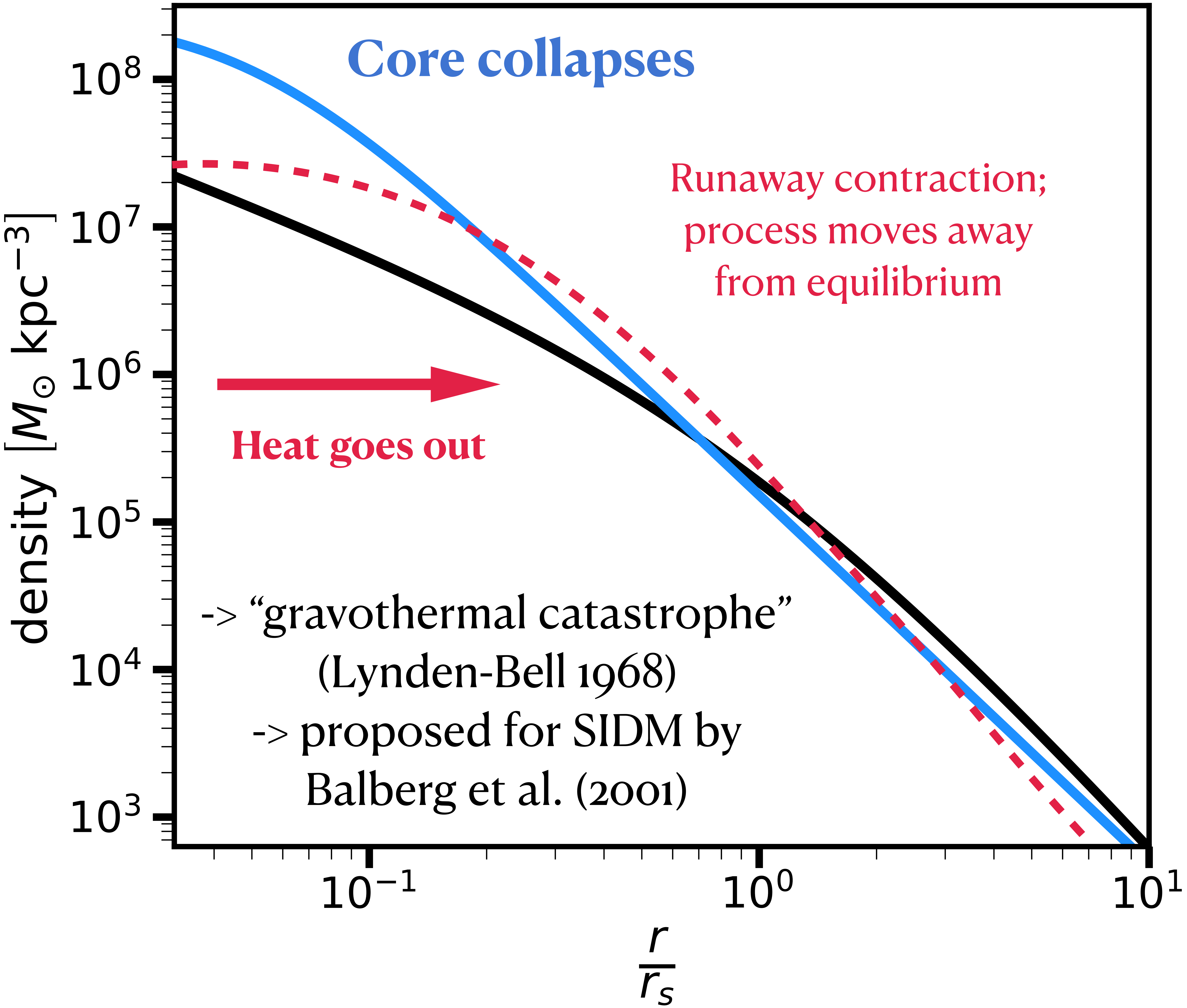
Effects of SIDM on halo density profiles



Effects of SIDM on halo density profiles

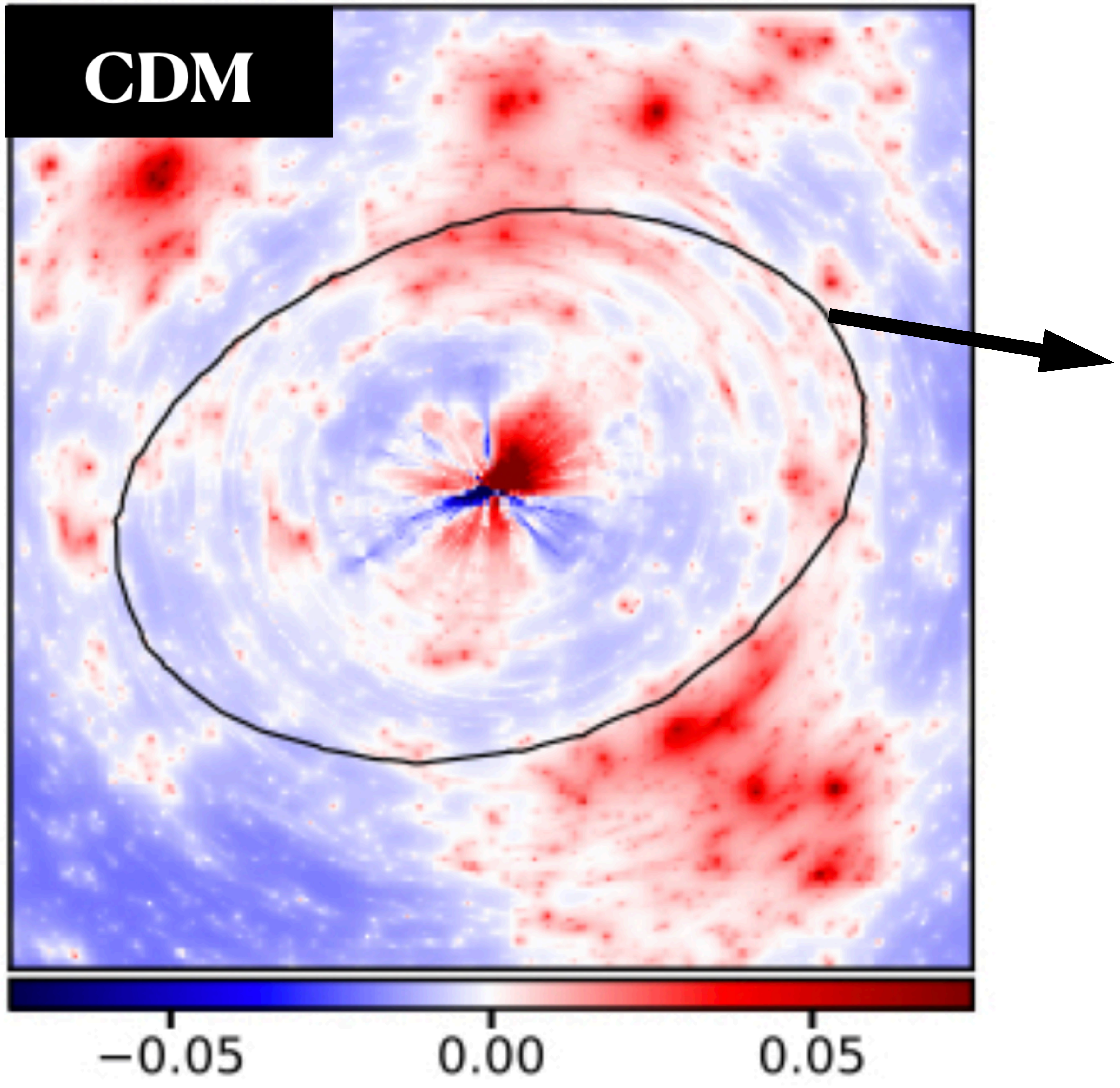


Effects of SIDM on halo density profiles



Core-collapsed halos are extremely efficient lenses

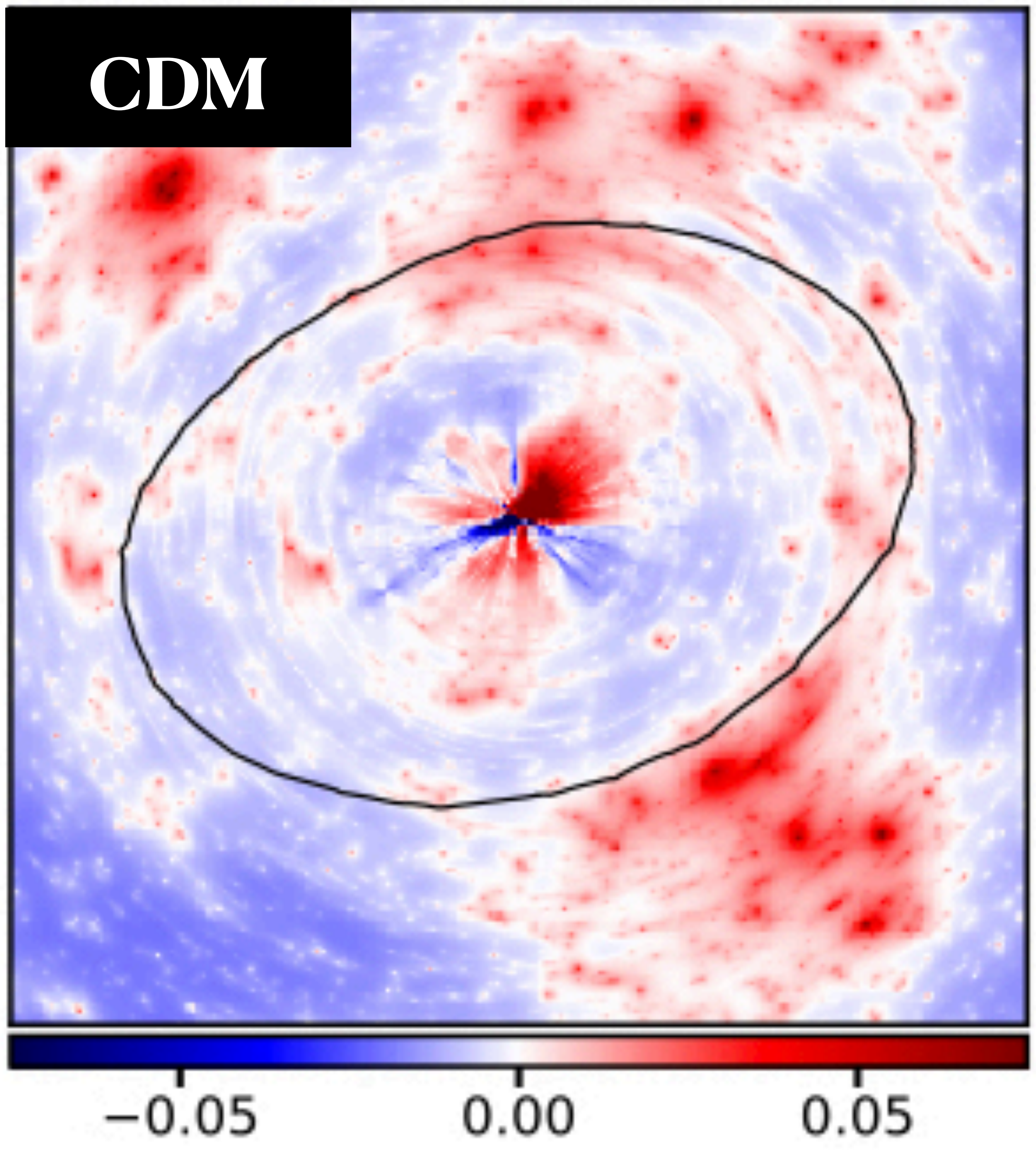
Now we are looking down the line of sight



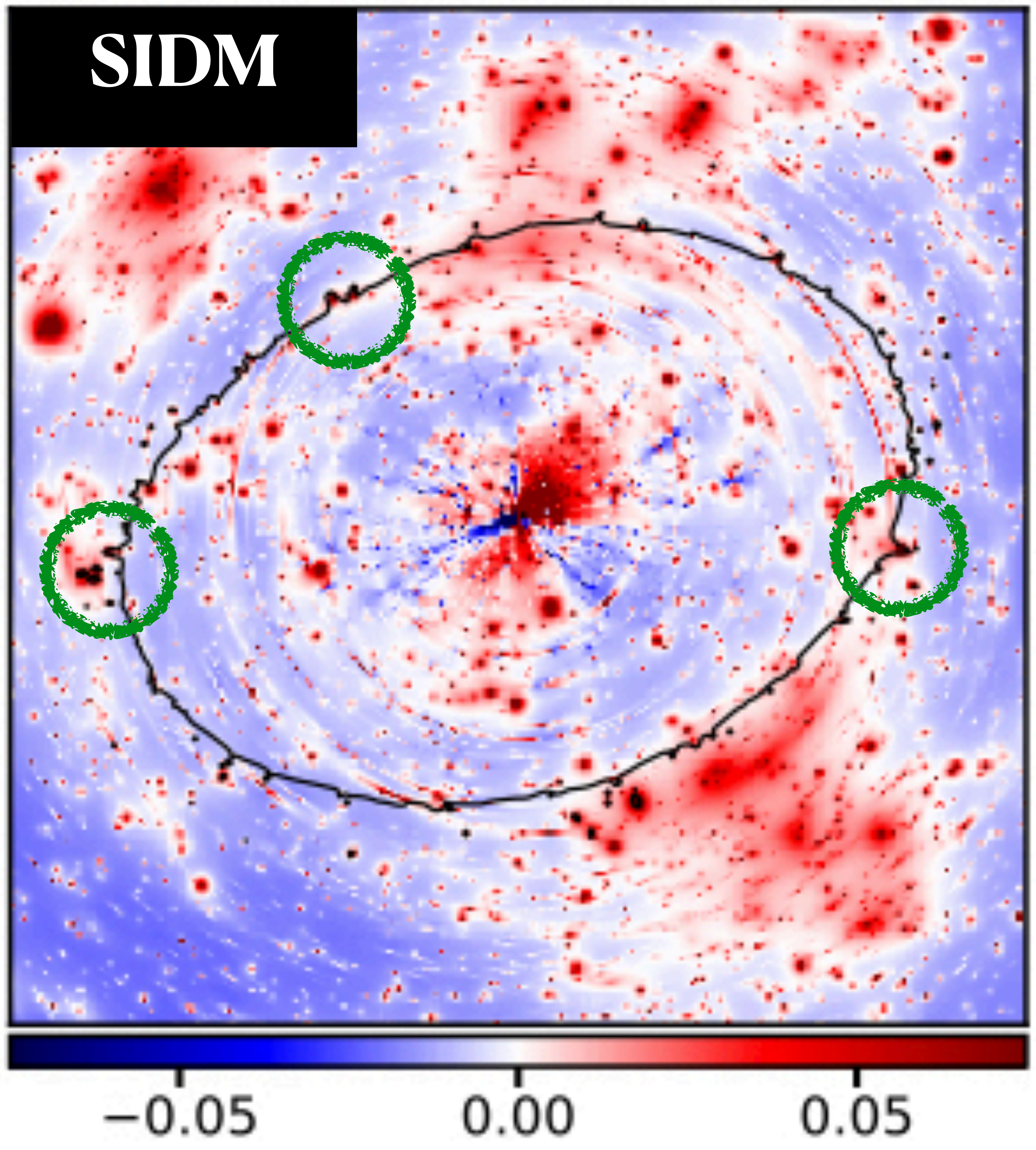
Critical curve

Dark matter density relative to average

Core-collapsed halos are extremely efficient lenses

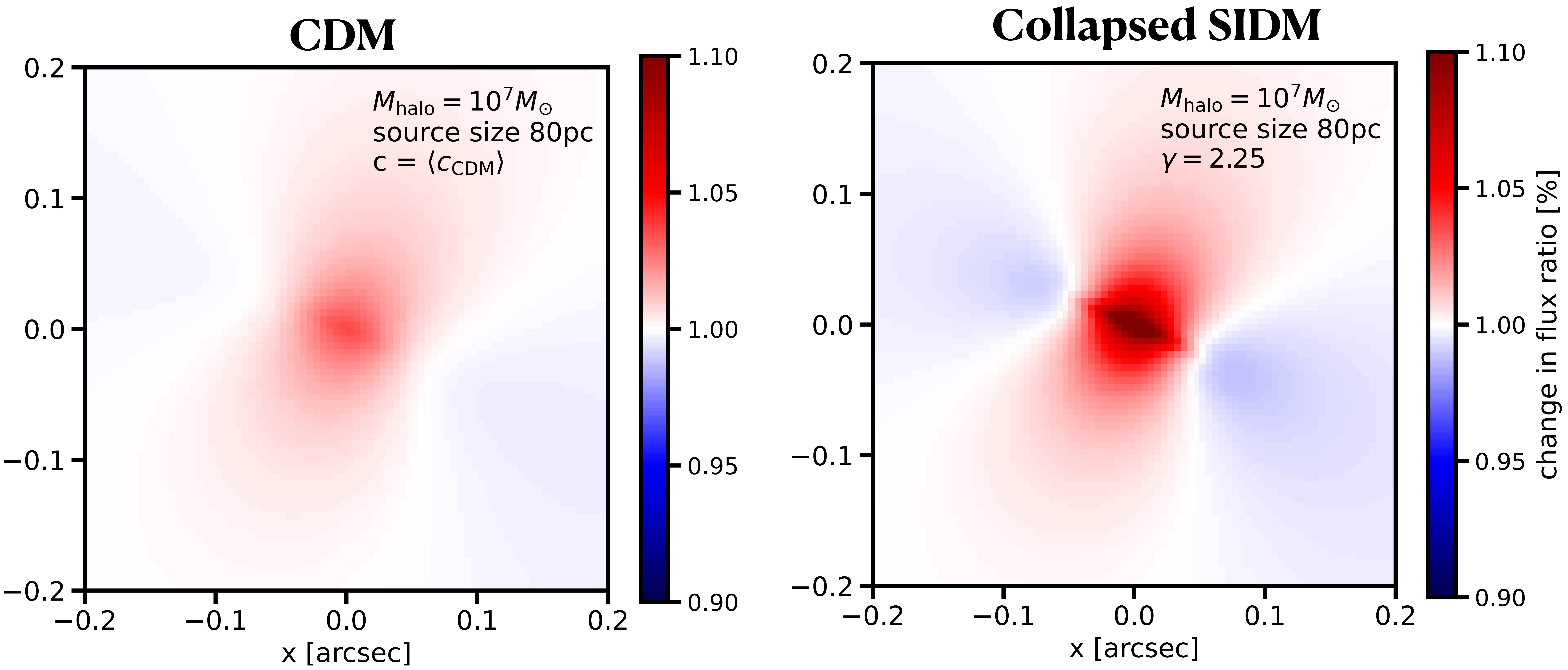


Dark matter density relative to average

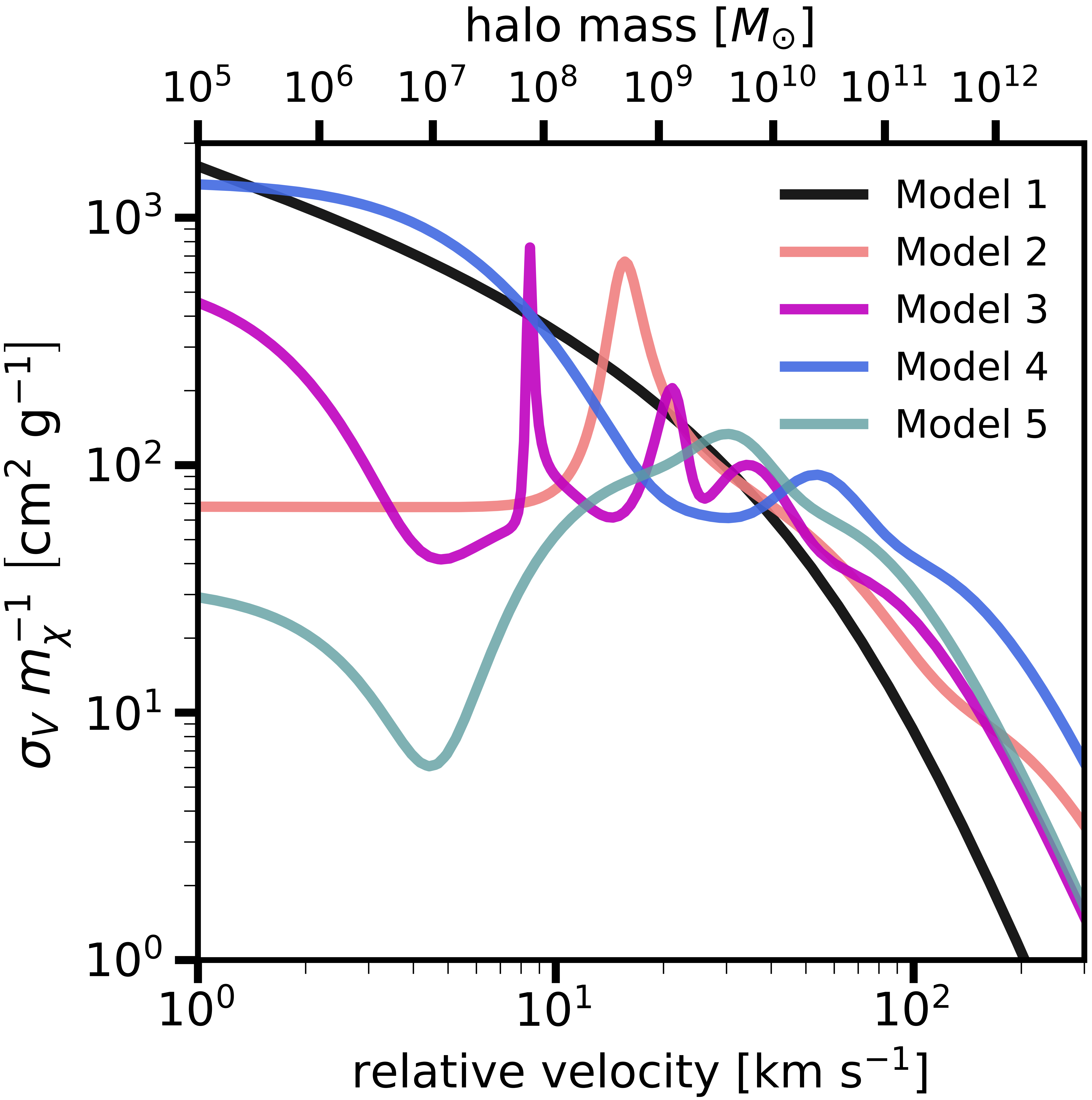


Dark matter density relative to average

Gilman et al. (2023)
arXiv: 2207.13111



CDM
Collapsed SIDM
$M_{\rm halo} = 10^7 M_\odot$
source size 80pc
c = $\langle c_{\rm CDM} \rangle$
$\gamma = 2.25$
x [arcsec]
change in flux ratio [%]
1.10
1.05
1.00
0.95
0.90
0.2
0.1
0.0
−0.1
−0.2



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

See: (Yang, et al. 2022, Yang and Yu 2022)

Gilman et al. (2023)
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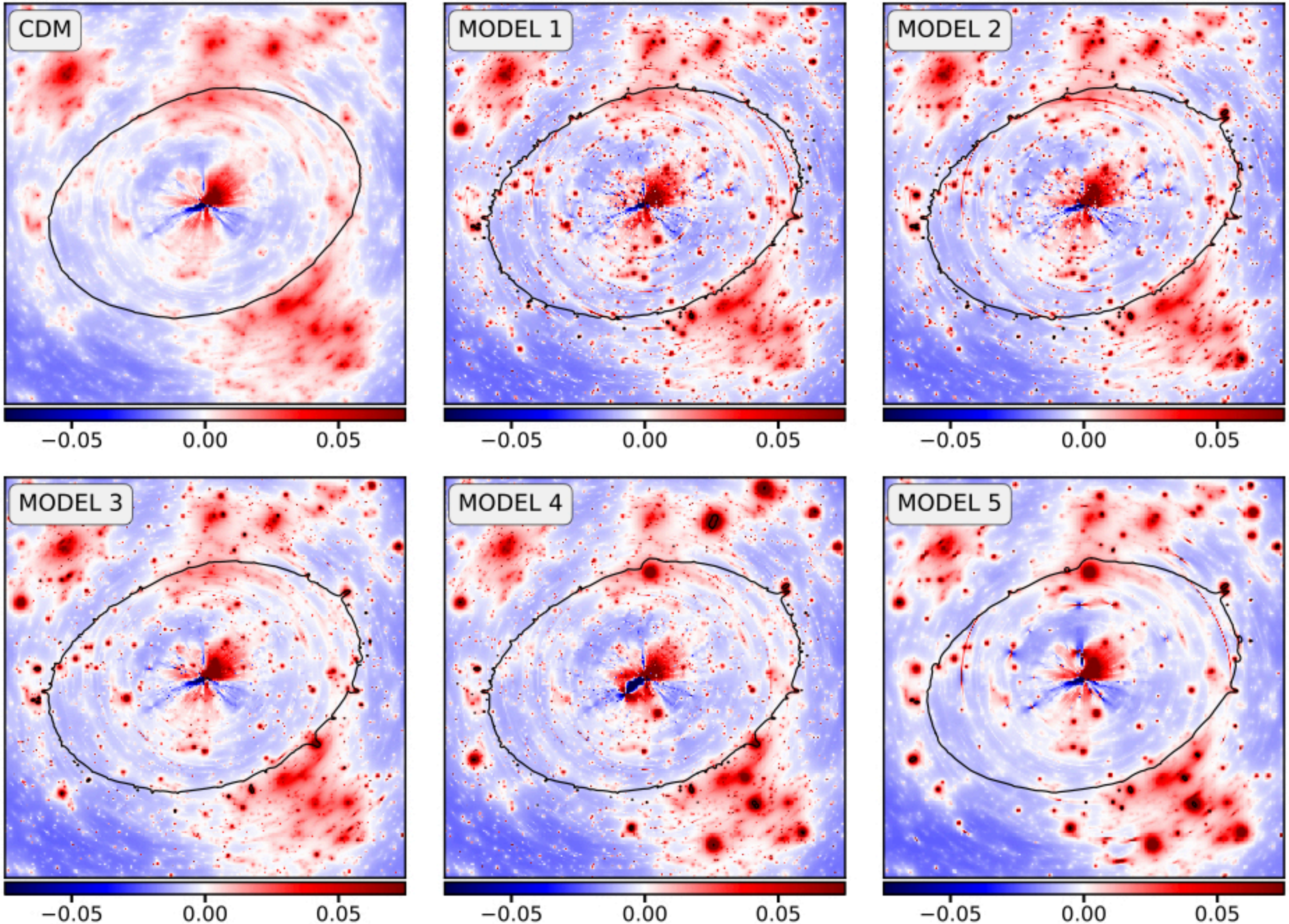
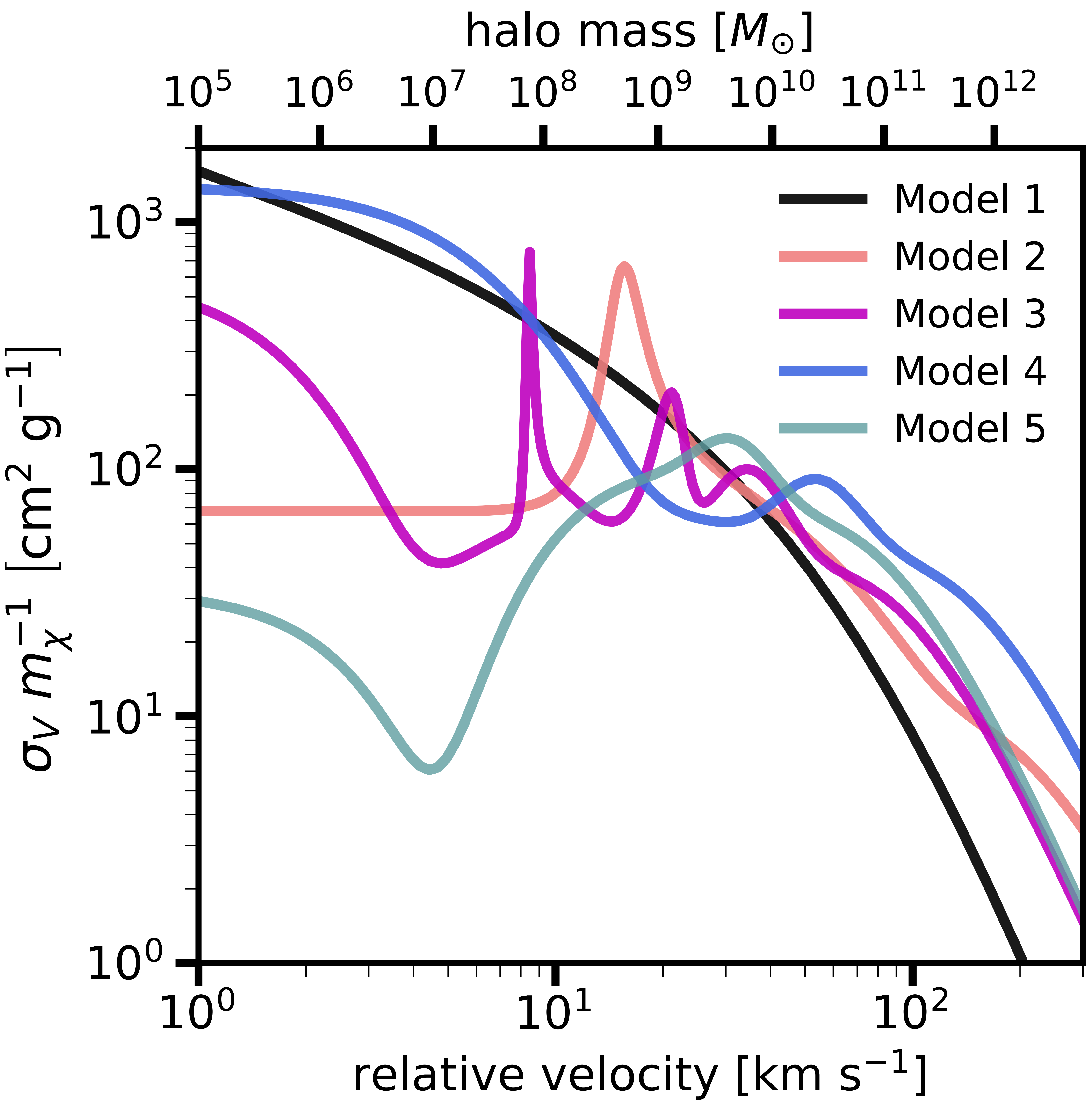


Gilman et al. (2023)
arXiv: 2207.13111

Constraints on the collapse timescales with 11 quads

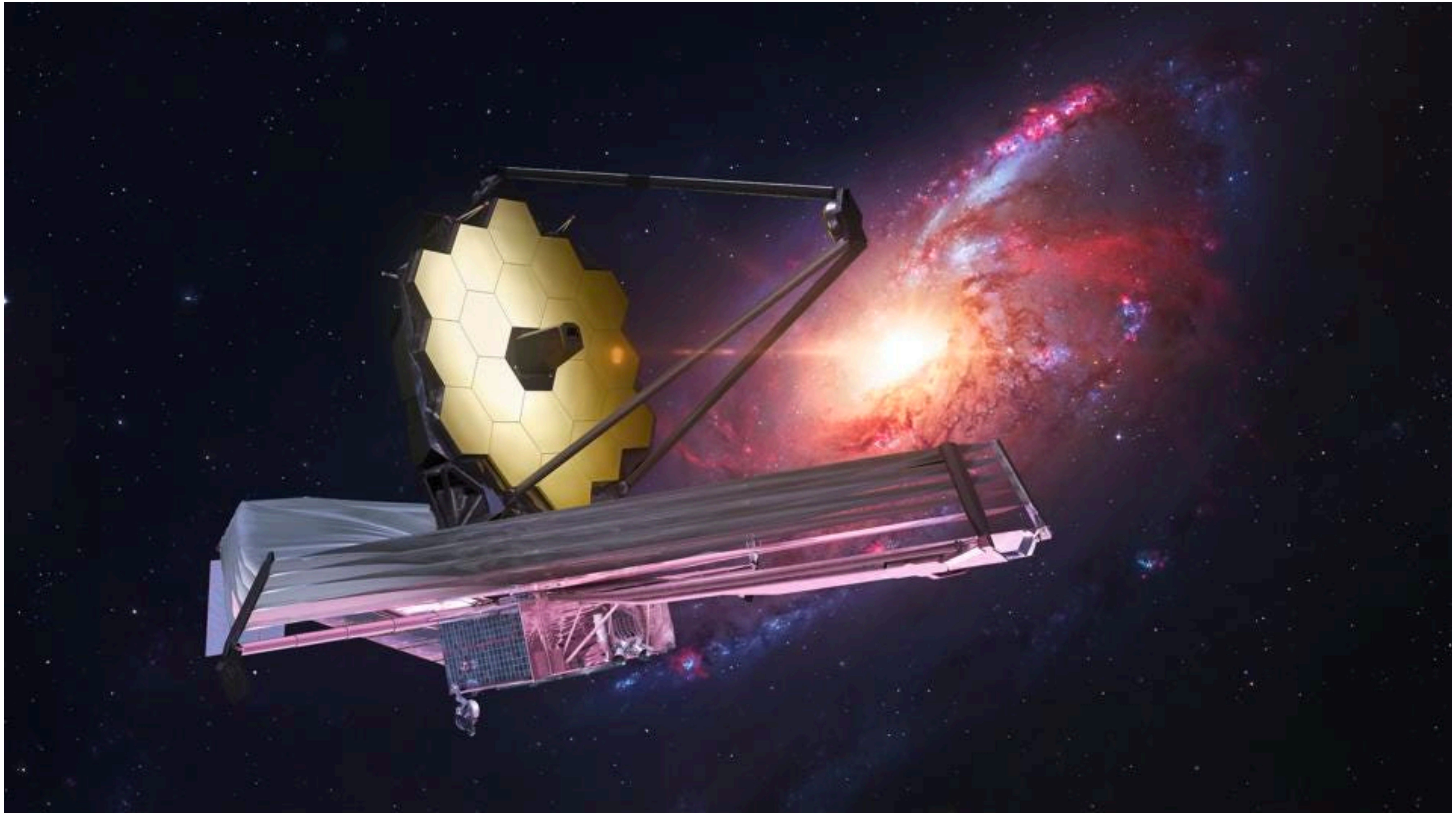


Results with existing data:

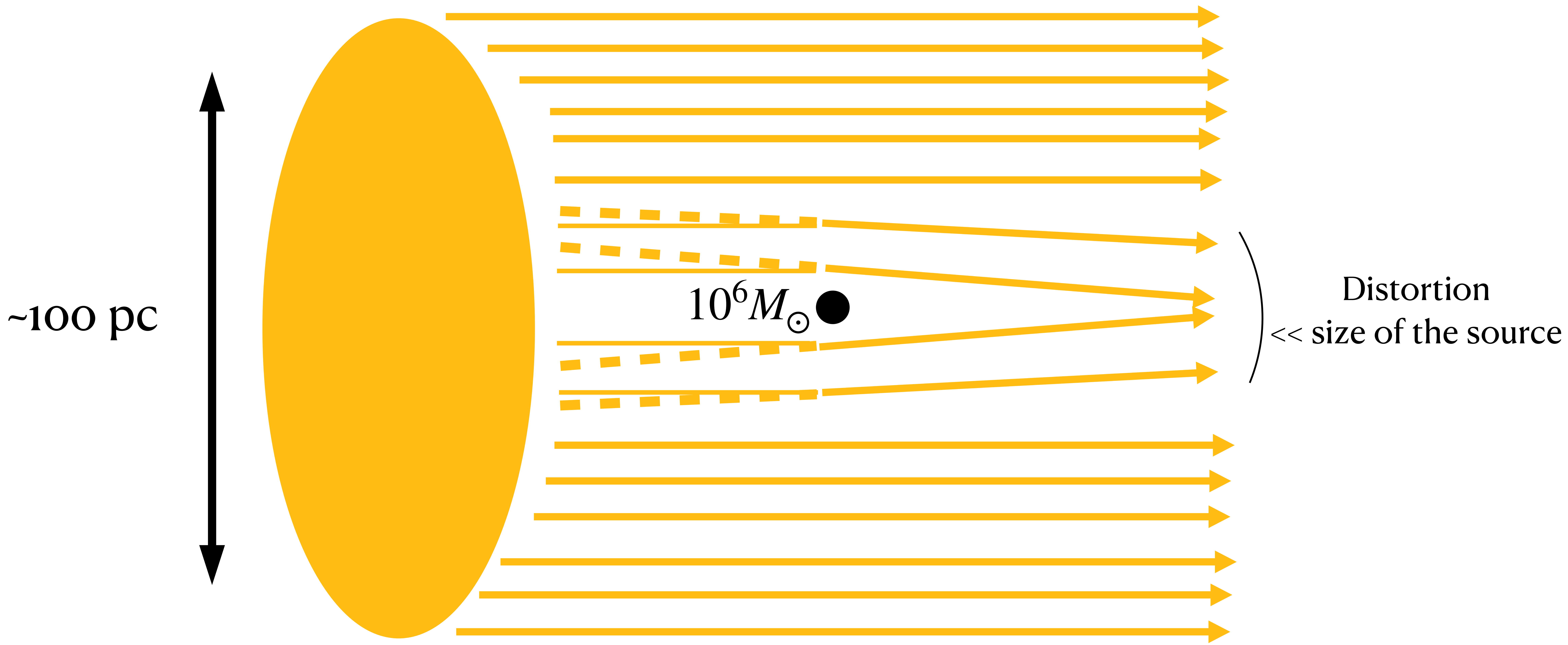
-> Existing data disfavors (likelihood ratios 5:1 to 9:1) models in which a majority of halos core collapse

-> Models with very large cross sections below 30 km/sec disfavored relative to CDM

THE FUTURE IS NOW: better data from JWST



THE PRESENT: narrow-line flux ratios from HST



Smaller source size increases sensitivity to perturbation by low-mass halos

JWST lensed quasar dark matter survey I: Description and First Results.

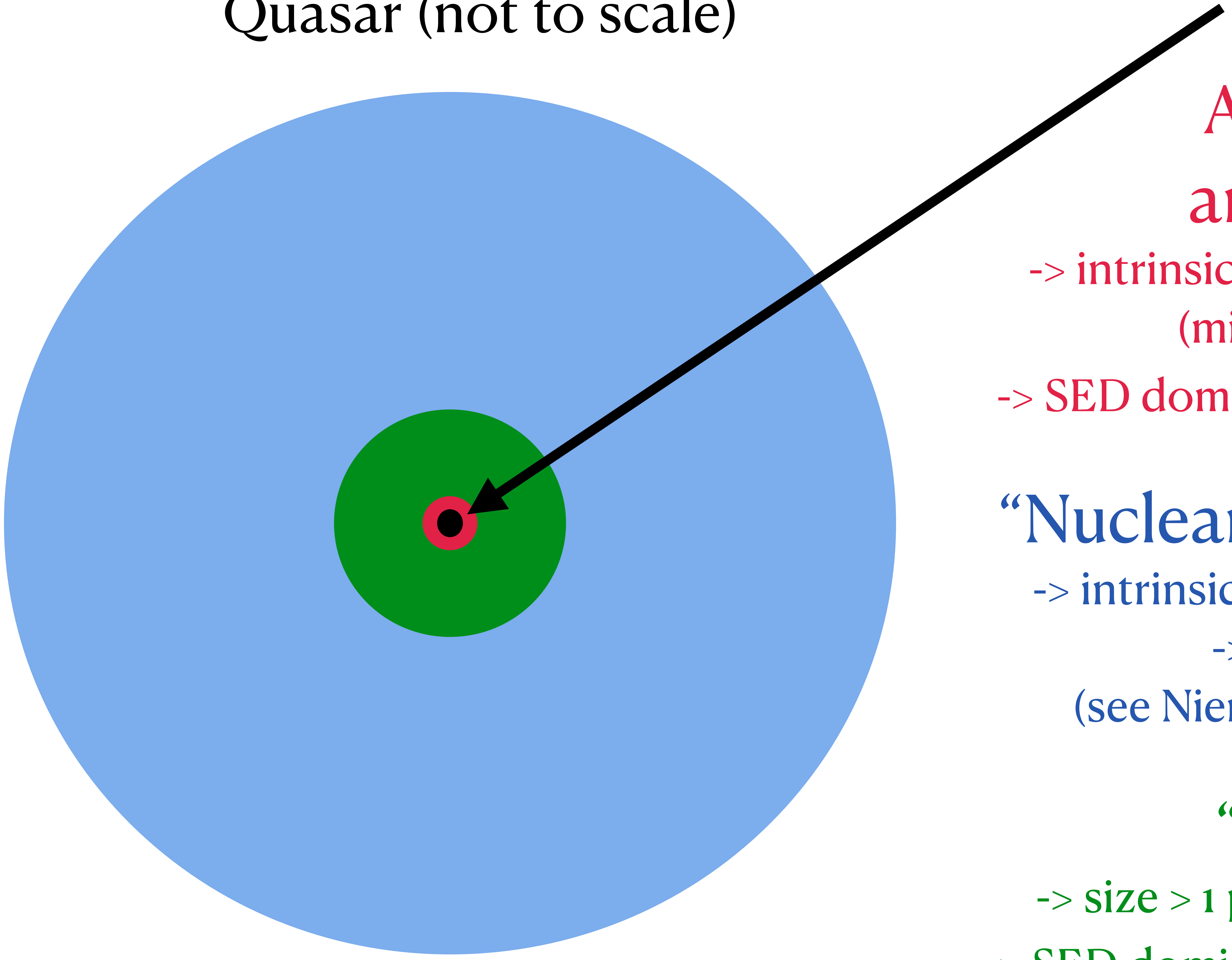
A. M. Nierenberg[1] ⋆, R. E. Keeley[1], D. Sluse[2], S. Birrer[3], D. Gilman[4,5,6], T. Treu[7,8], K. N. Abazajian[9], T. Anguita[10,11], A. J. Benson[12], V. N. Bennert[13], S. G. Djorgovski[14], X. Du[7], C. D. Fassnacht[15], S. F. Hoenig[19], A. Kusenko[7,17], C. Lemon[18], M. Malkan[7], V. Motta[19], L. A. Moustakas[20], D. Stern[20], R. H. Wechsler[21,22,23]

[1] *University of California, Merced, 5200 N Lake Road, Merced, CA 95341, USA*
[2] *STAR Institute, Quartier Agora - Allé du six Août, 19c B-4000 Liège, Belgium*
[3] *Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA*

To appear on arXiv this week!

Cycle 1 JWST program GO-2046 (PI Anna Nierenberg)
Goal: isolate flux from compact (~5 parsec) emission around background quasar in 31 systems

Quasar (not to scale)



Black hole

Accretion disk
and “hot torus”

-> intrinsic sizes of light-days to ~ 0.1 pc
(micro-lensed like crazy)

-> SED dominated by emission at $\lambda < 2\mu m$

“Nuclear narrow-line region”

-> intrinsic size 10-100 pc (current data)
-> OIII emission lines
(see Nierenberg, Gilman et al. 2019)

“Warm torus”

-> size > 1 pc, not micro-lensed by stars
-> SED dominated by emission at $\lambda > 10\mu m$
-> accessible with MIRI instrument on JWST

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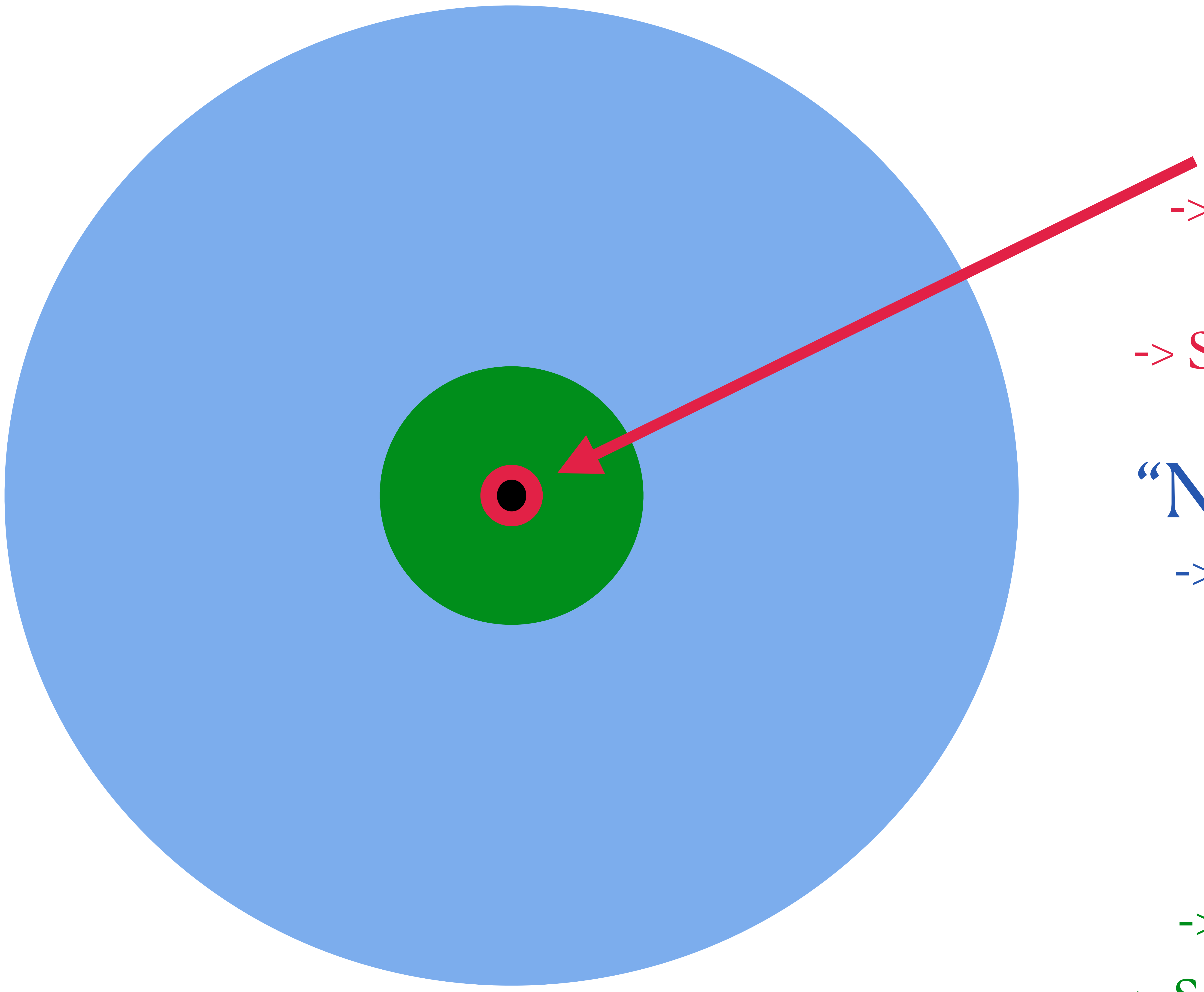

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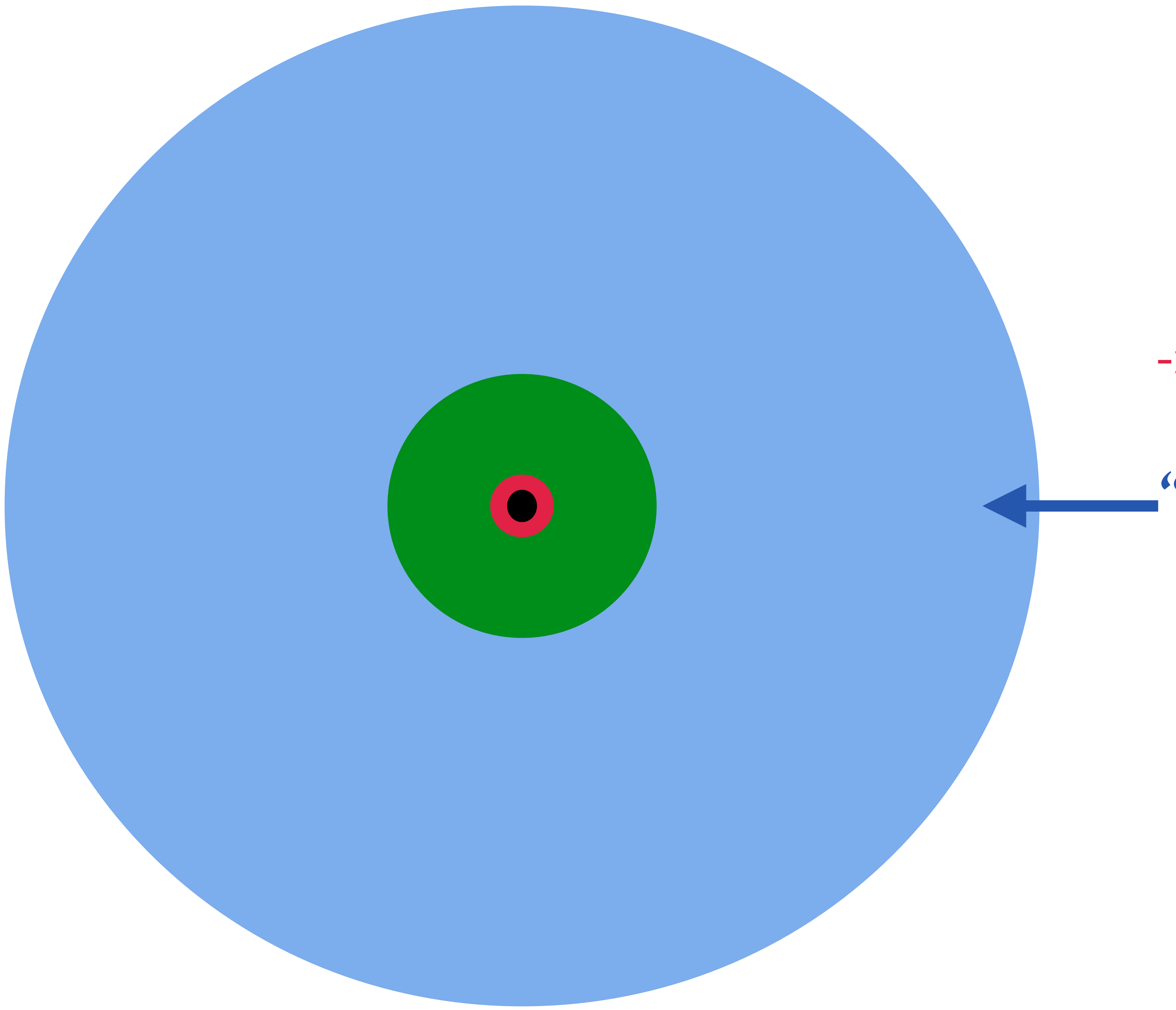

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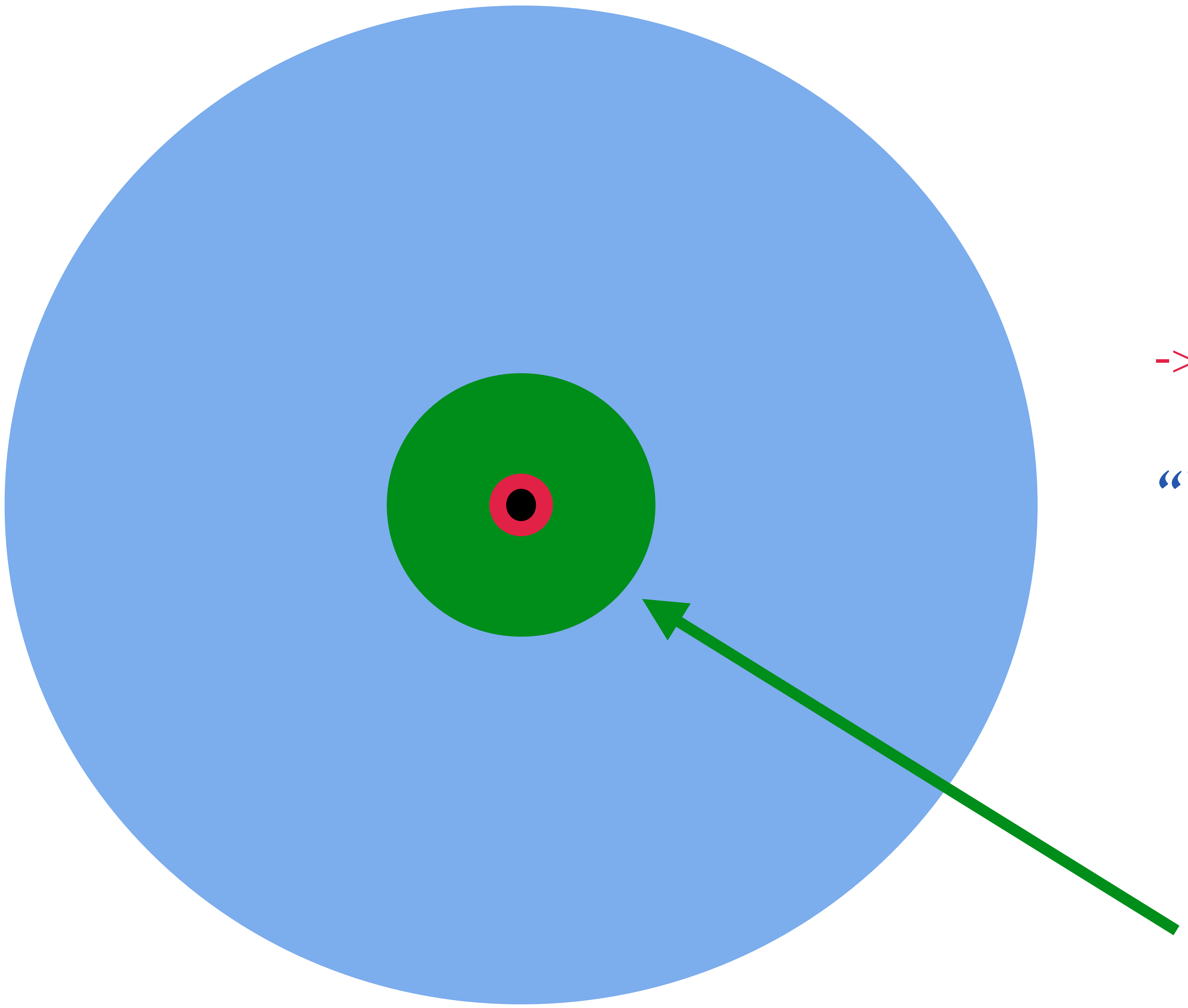

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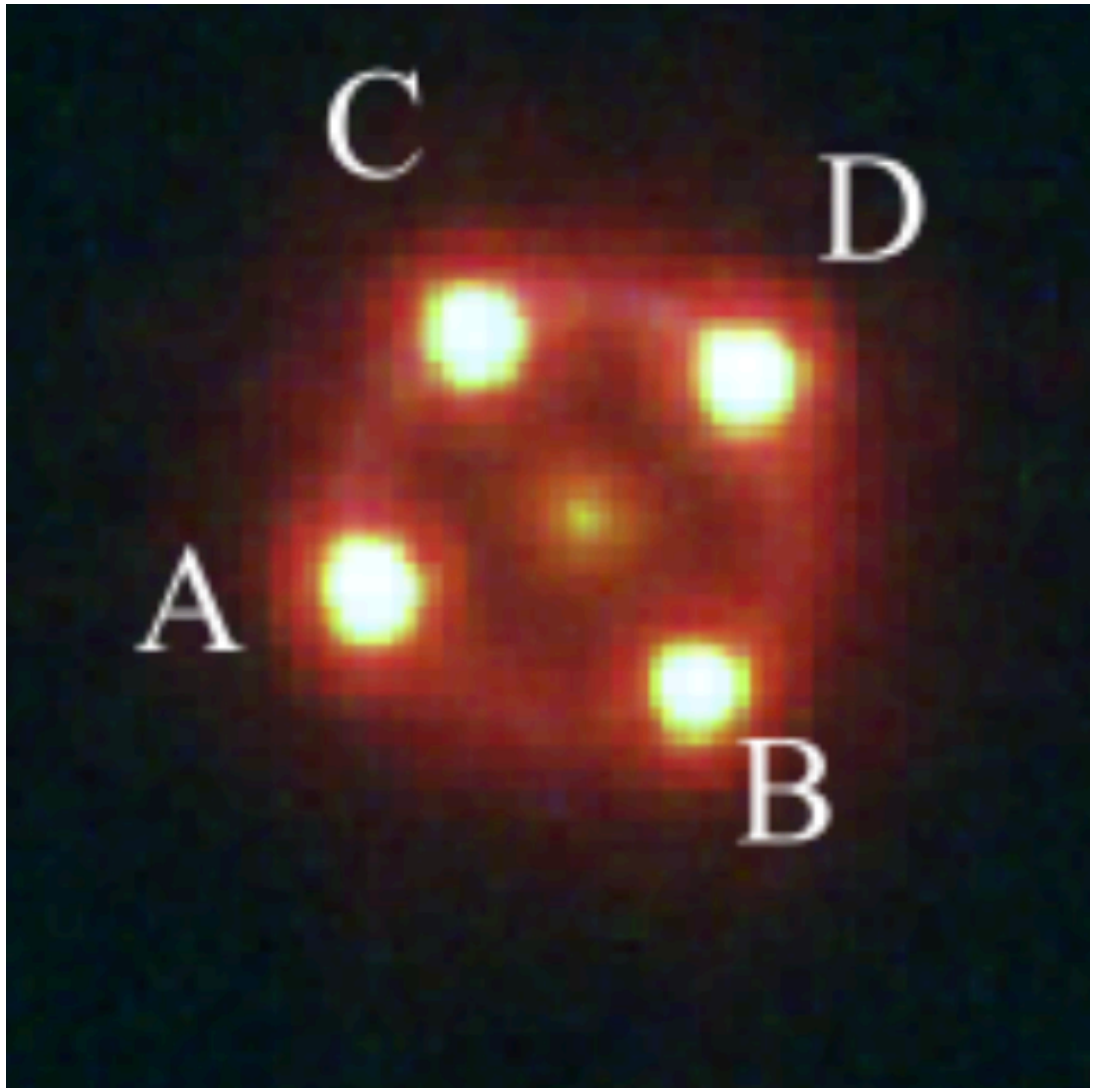
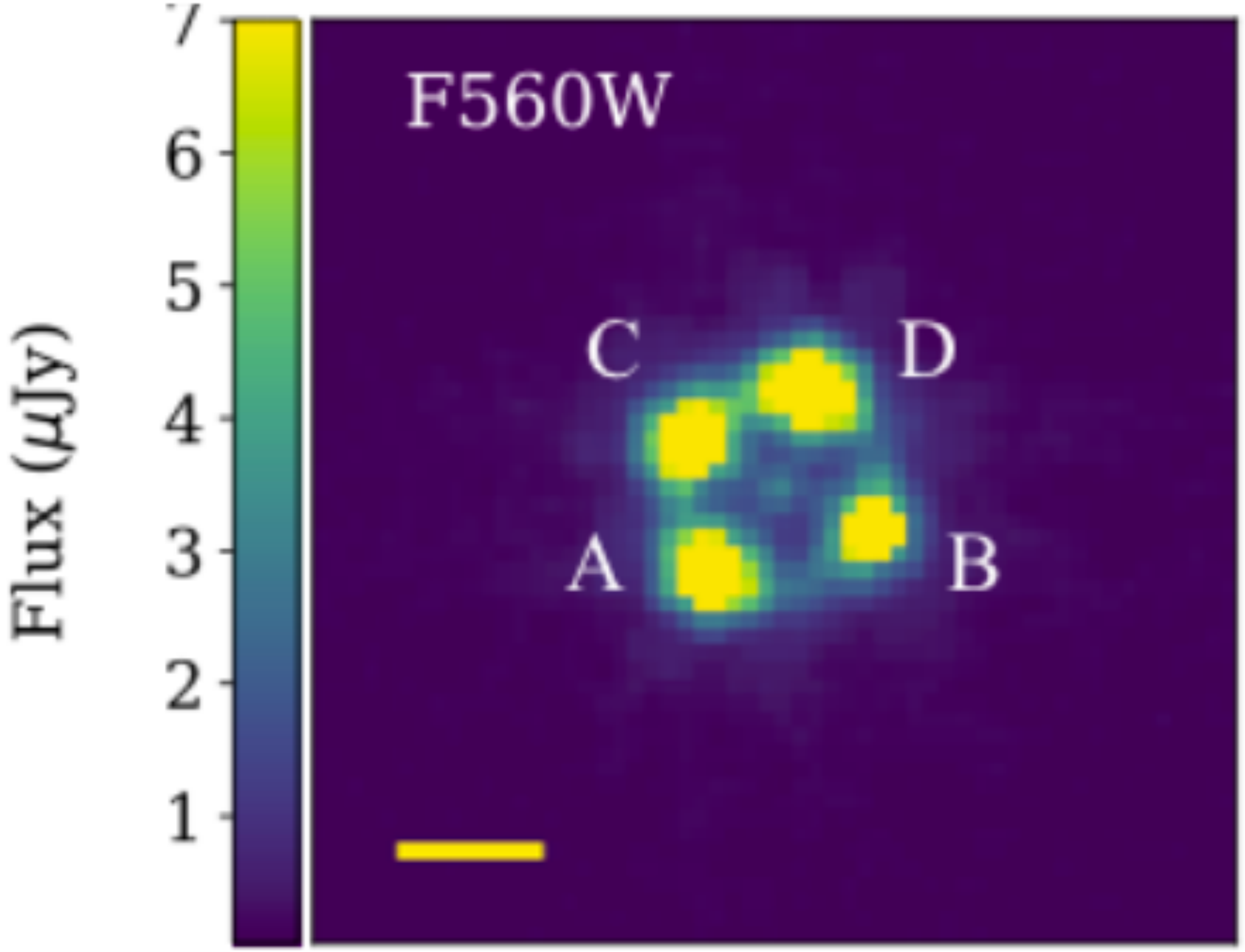
Paper presents measurements for the first target:
DES J0405-3308 observed in 4 MIRI filters from 1-10 μm

As seen by HST (composite):



As seen by JWST at 2μm:



Paper presents measurements for the first target: DES J0405-3308 observed in 4 MIRI filters from 1-10 μm

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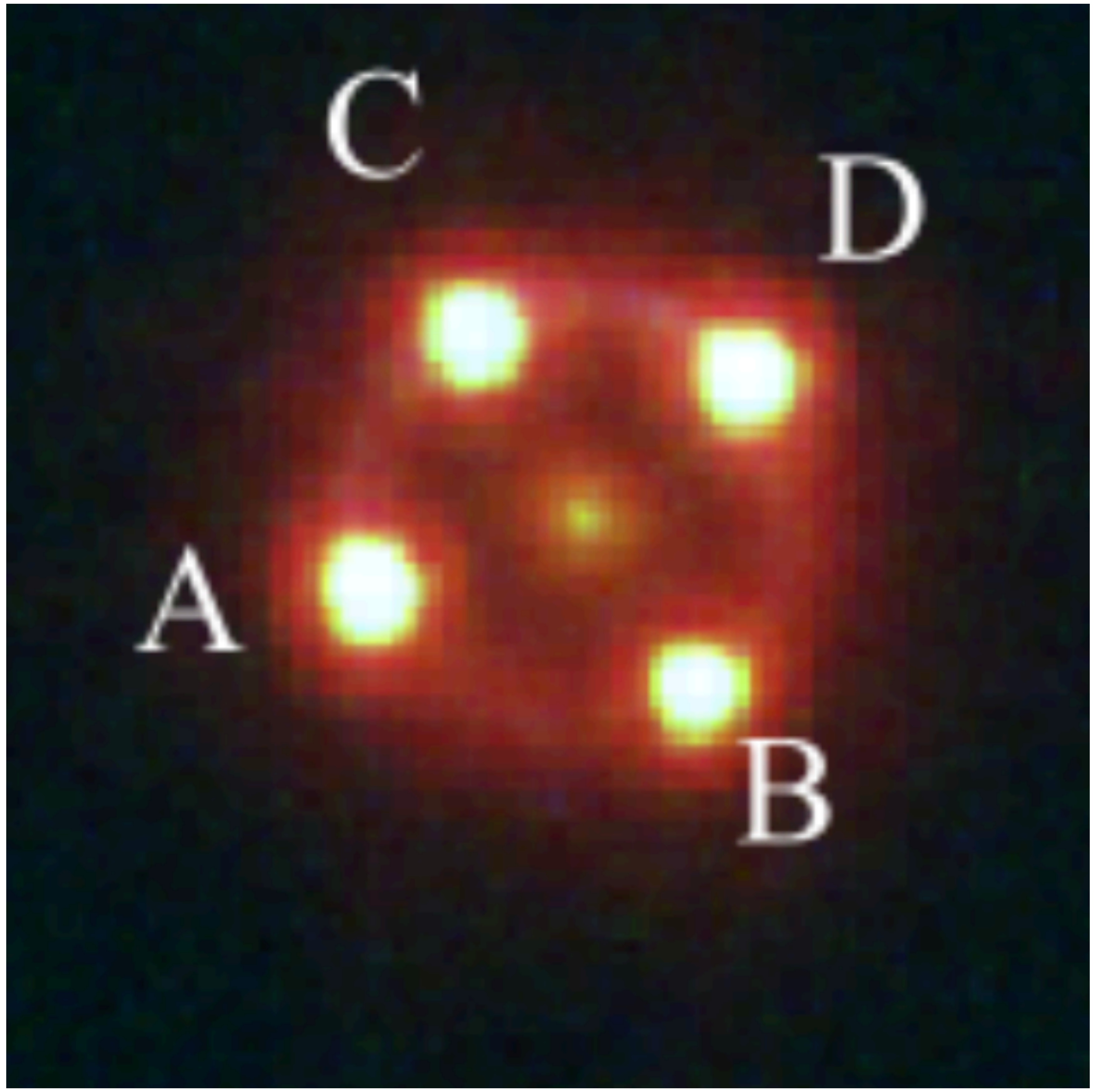
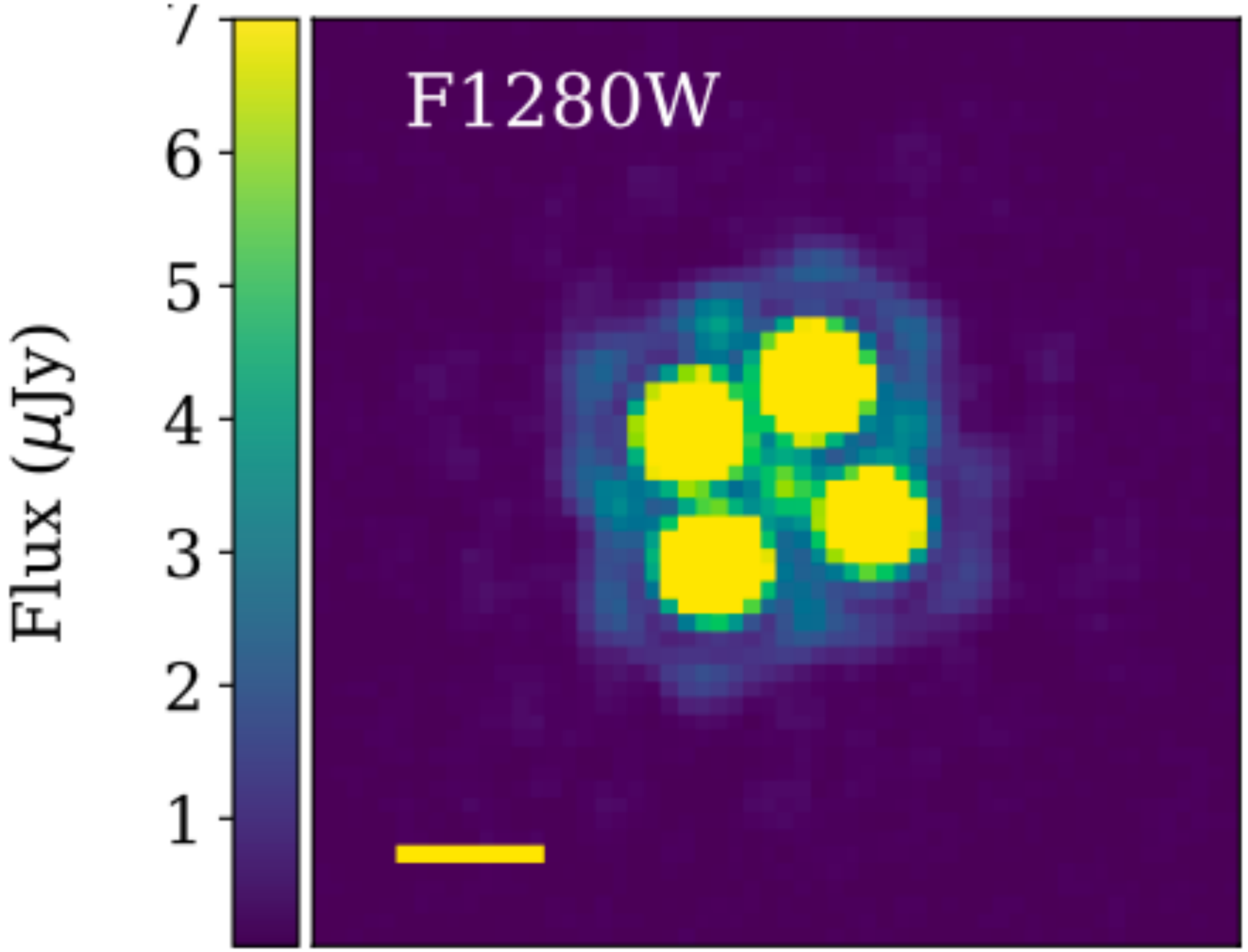


As seen by JWST at 5μm:



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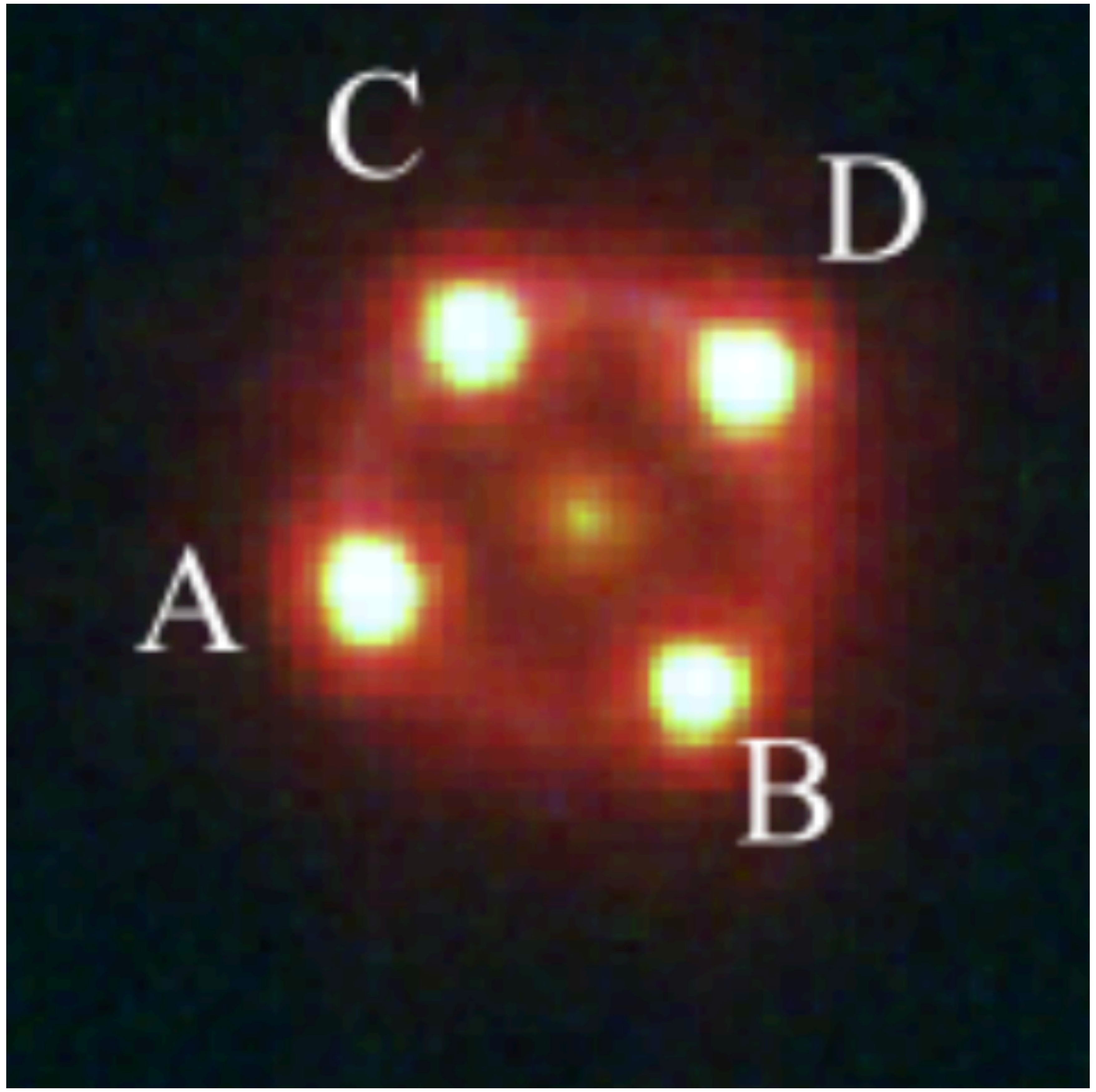
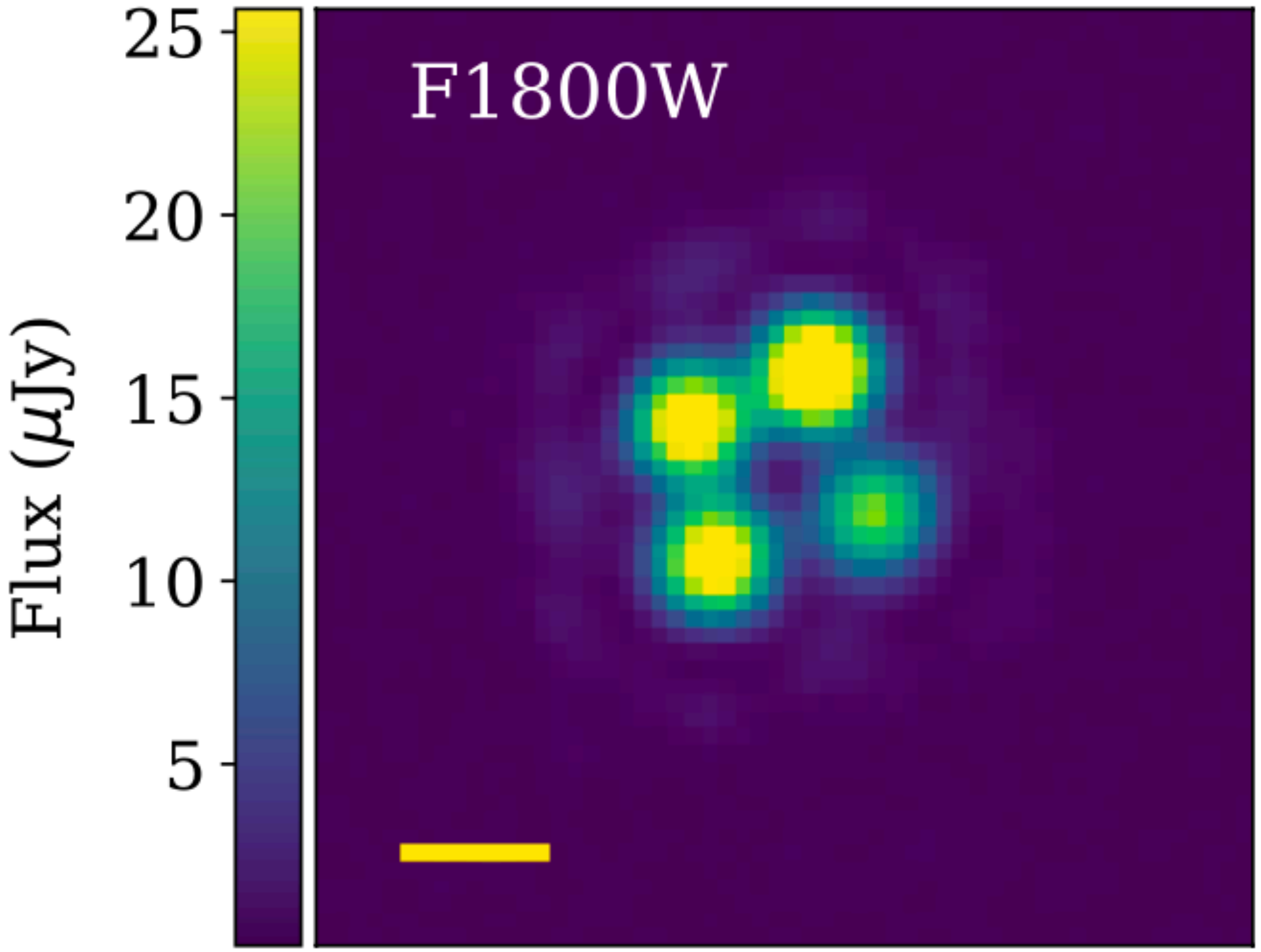
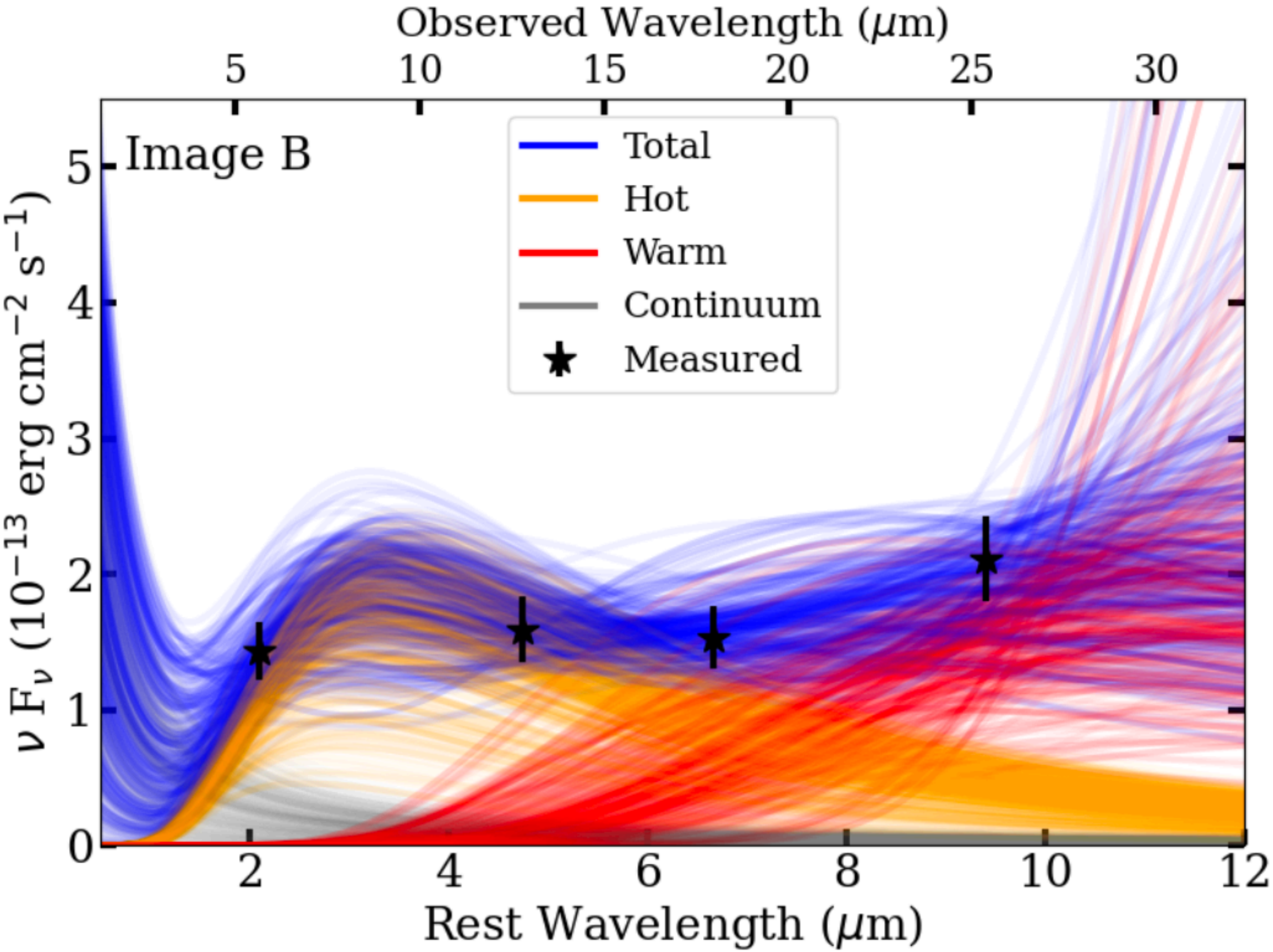
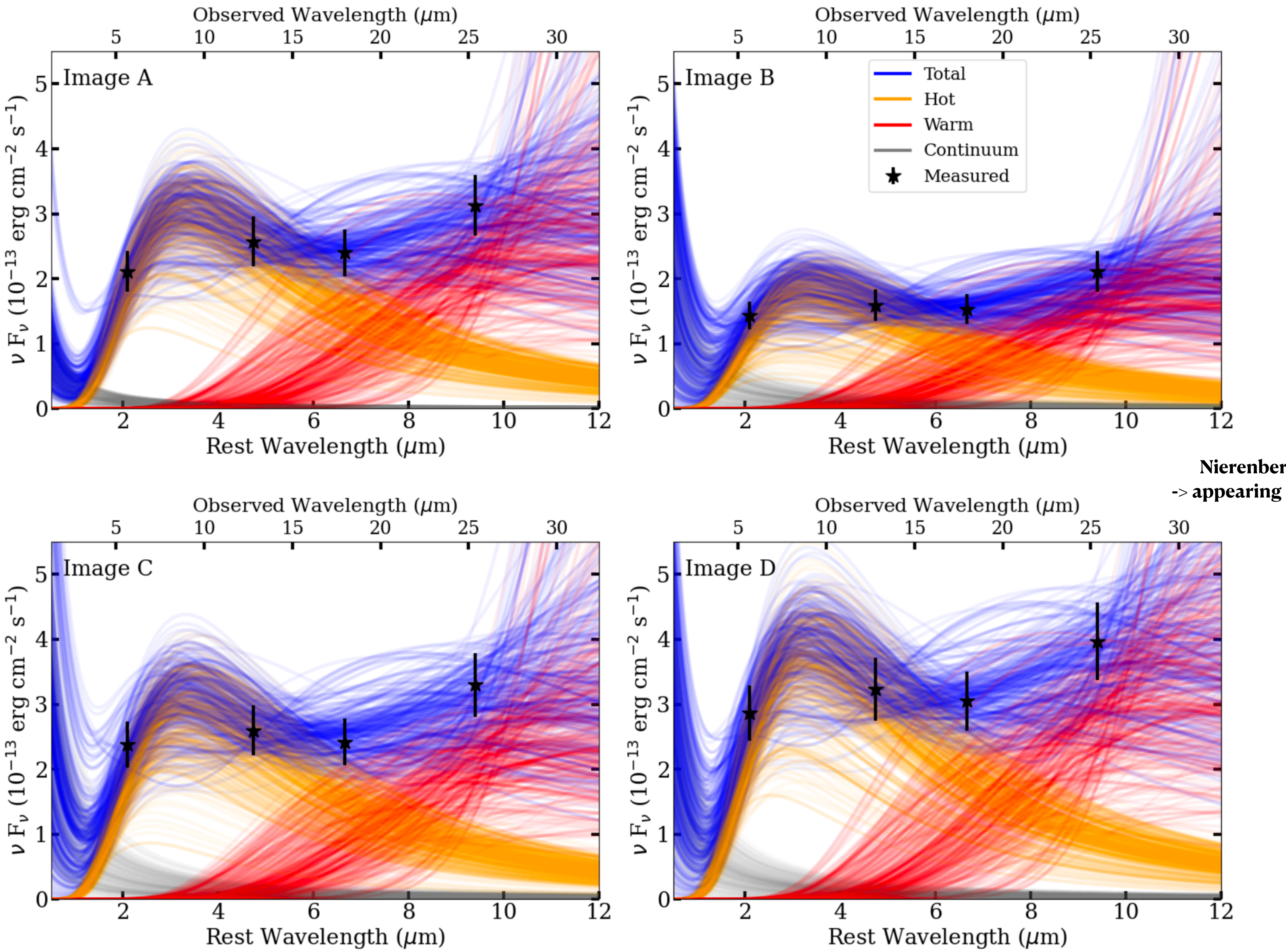


As seen by JWST at 7μm:





Adapted from Nierenberg, including Gilman et al. (in prep) -> appearing on arXiv this week!



Nierenberg et al. (in prep)
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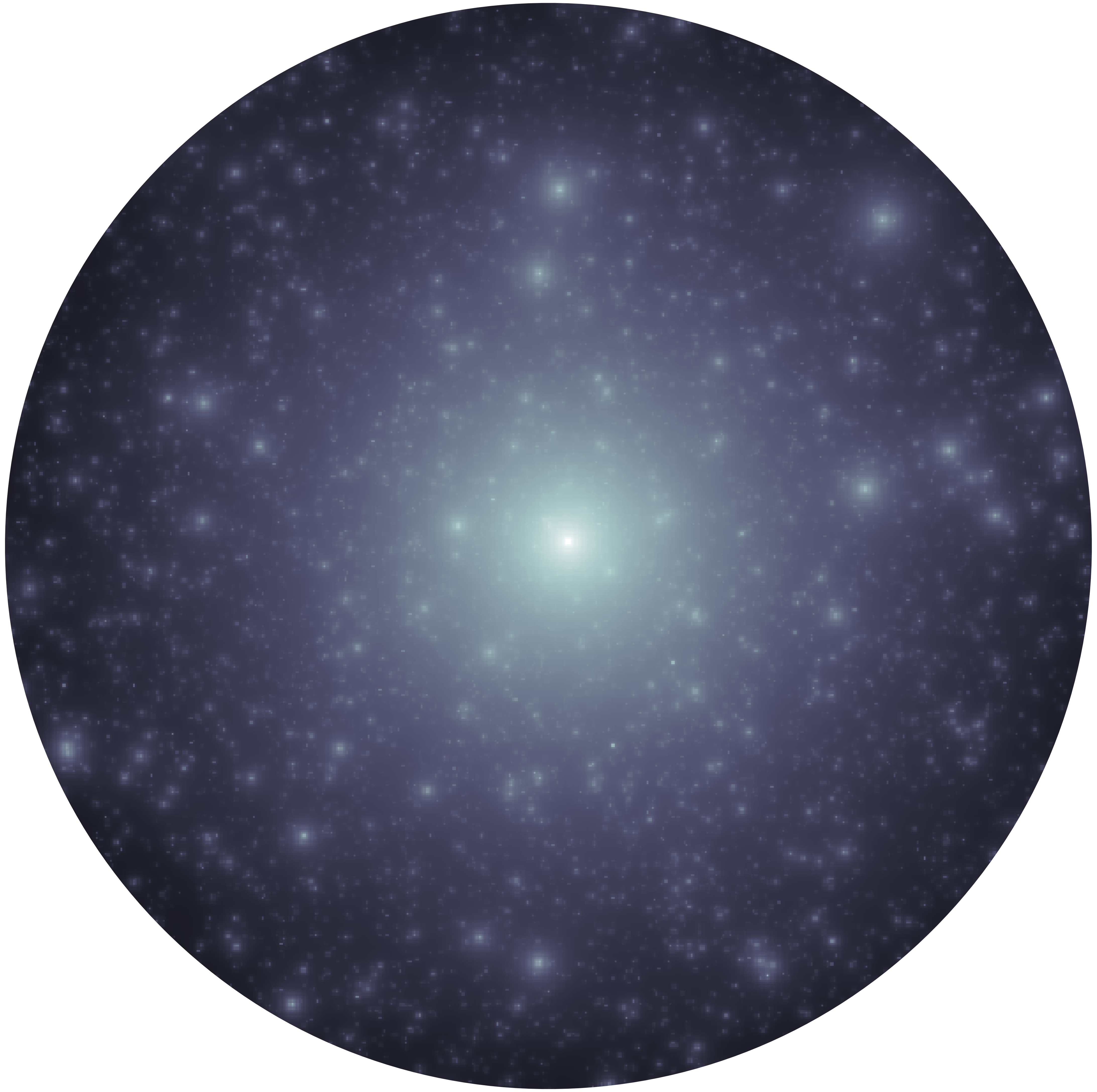
Implications for constraints on Warm Dark Matter models

CDM

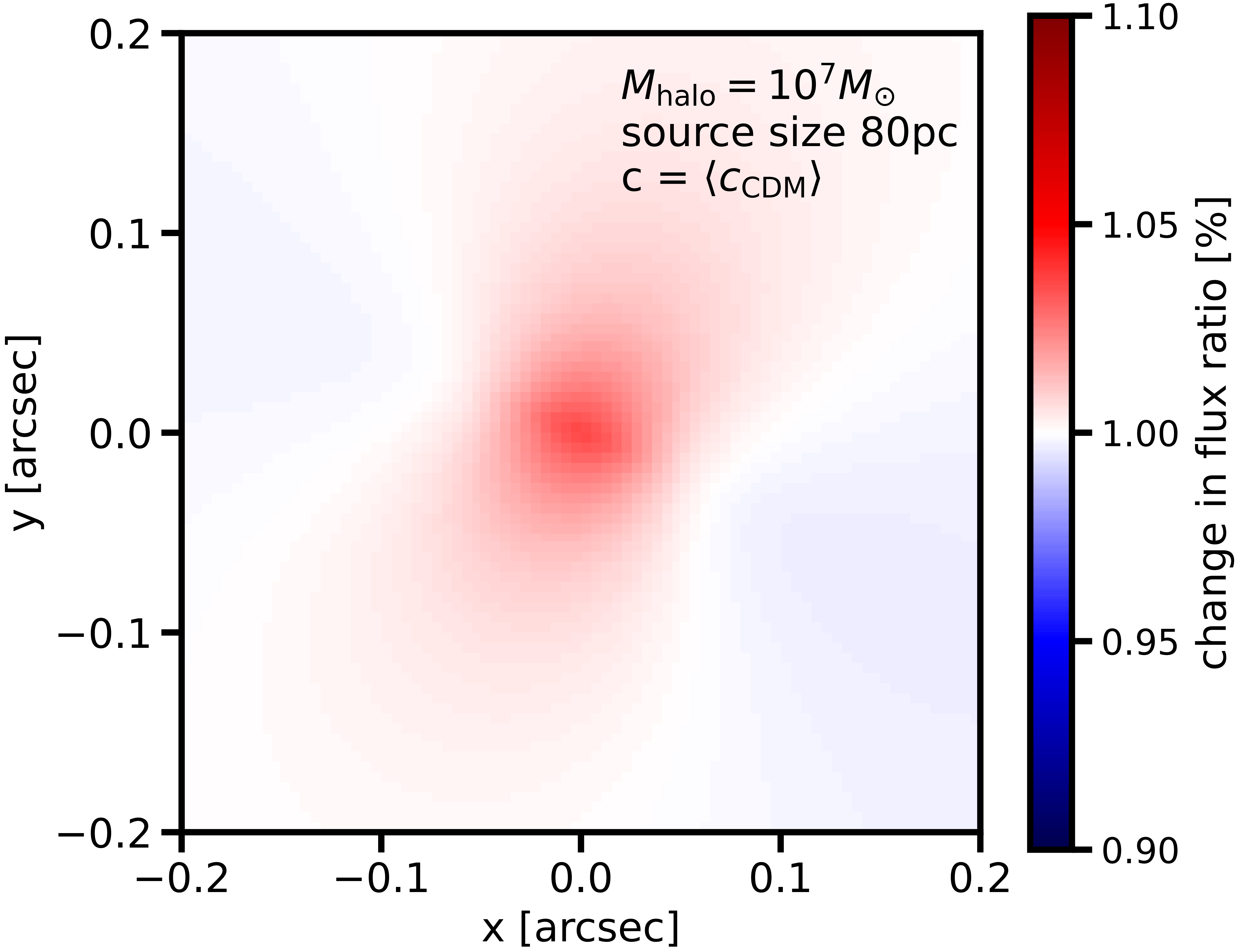


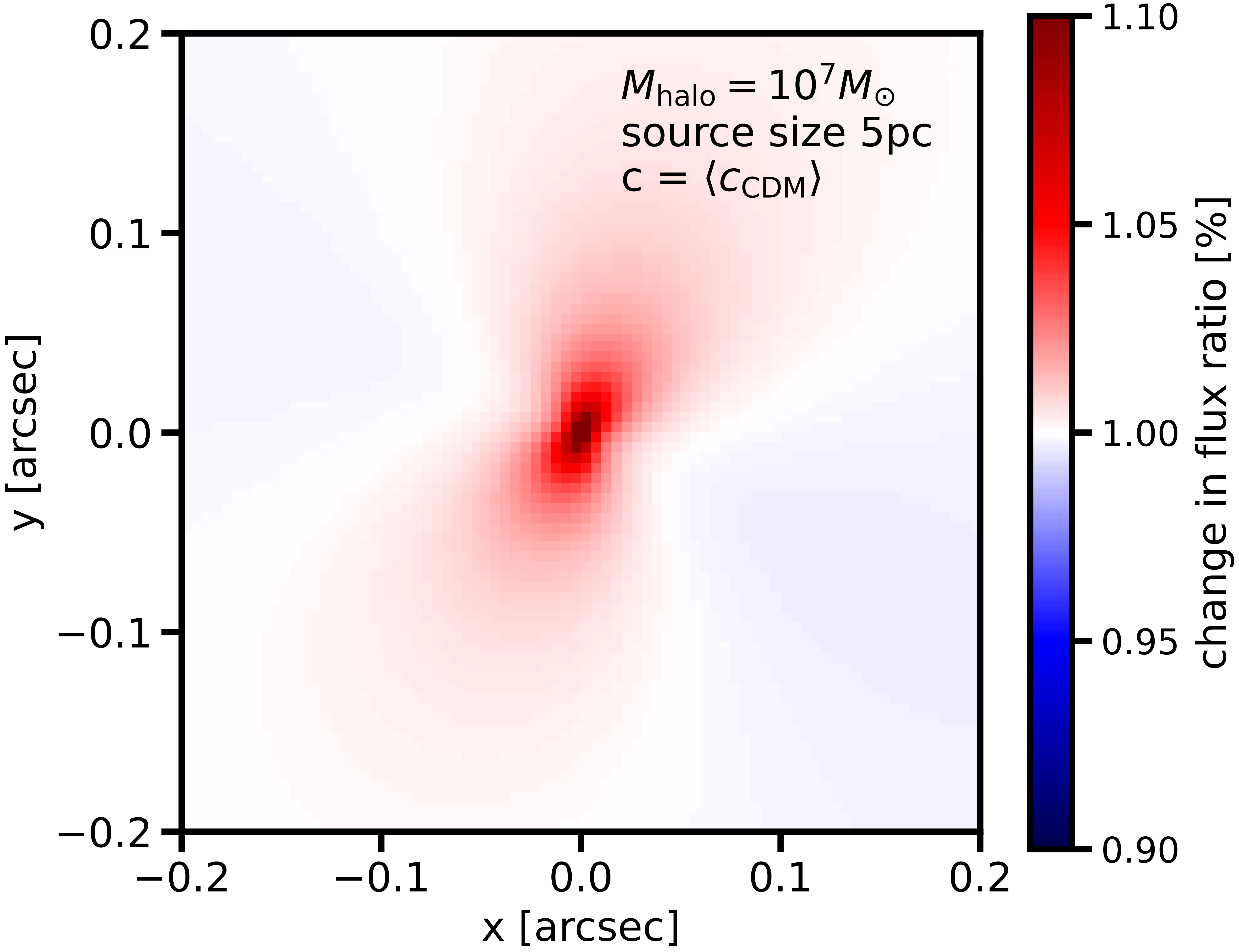
WDM

Current HST data
with narrow-line flux ratios

$M = 10^7 M_\odot$

JWST data to be obtained
through GO-2046

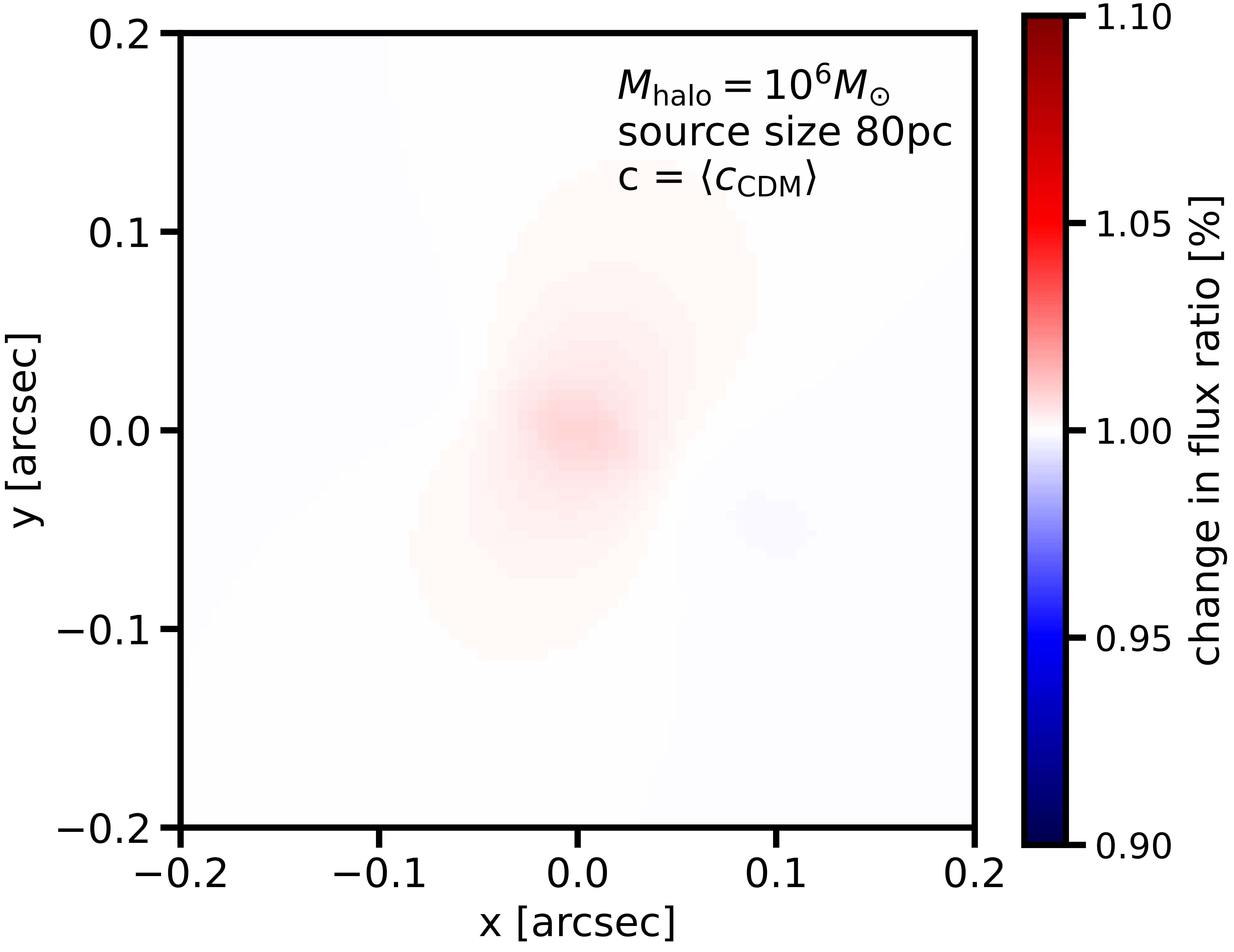


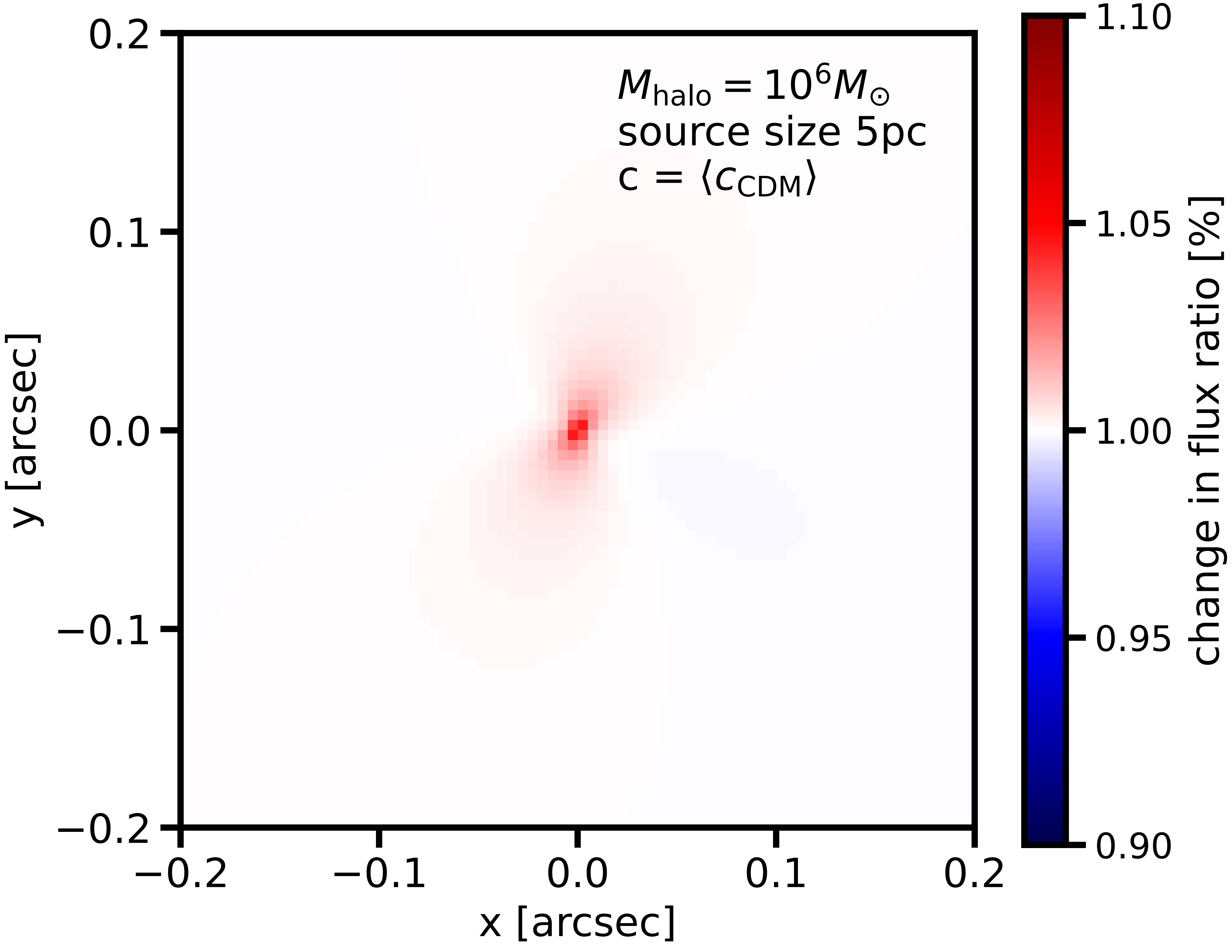


Current HST data
with narrow-line flux ratios

$M = 10^6 M_\odot$

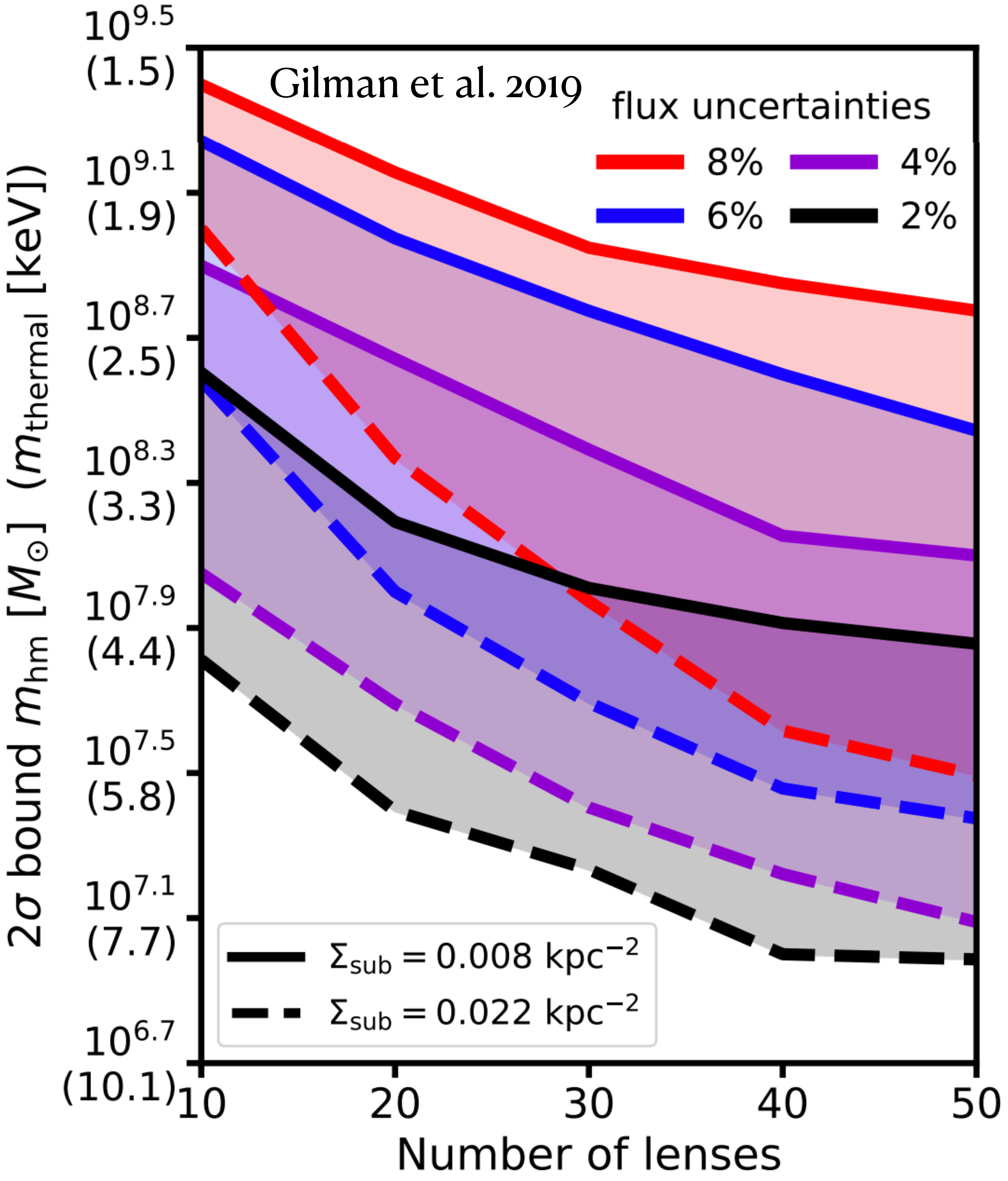
JWST data to be obtained
through GO-2046



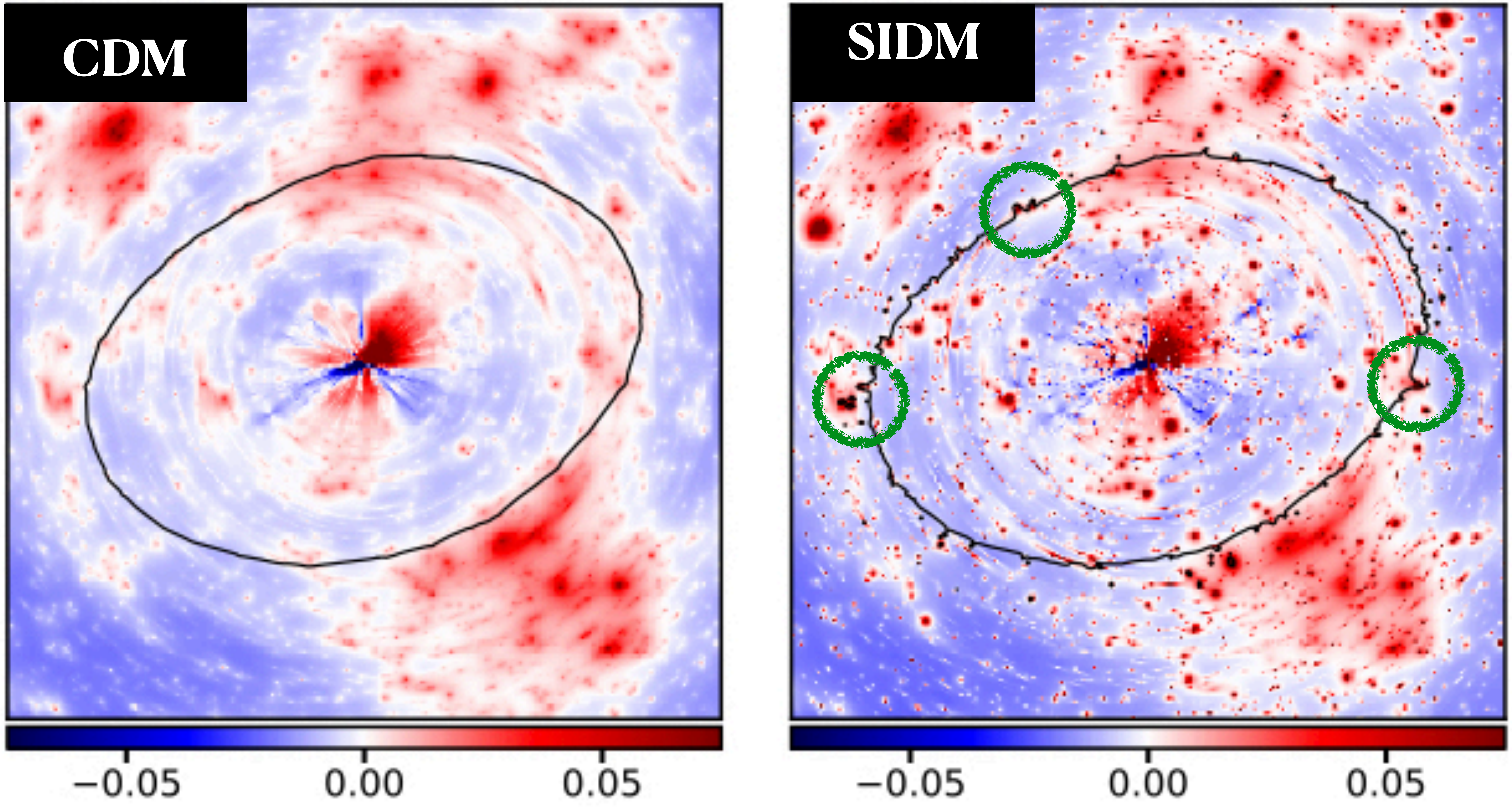


Forecasts for WDM from quasar lensing

-> corresponds to constraints on the half-mode mass at the scale of $10^7 M_\odot$ halos
-> alternatively, constraints on the matter power spectrum on scales $k \sim 50 - 100\ \mathrm{Mpc}^{-1}$



Implications for constraints on SIDM



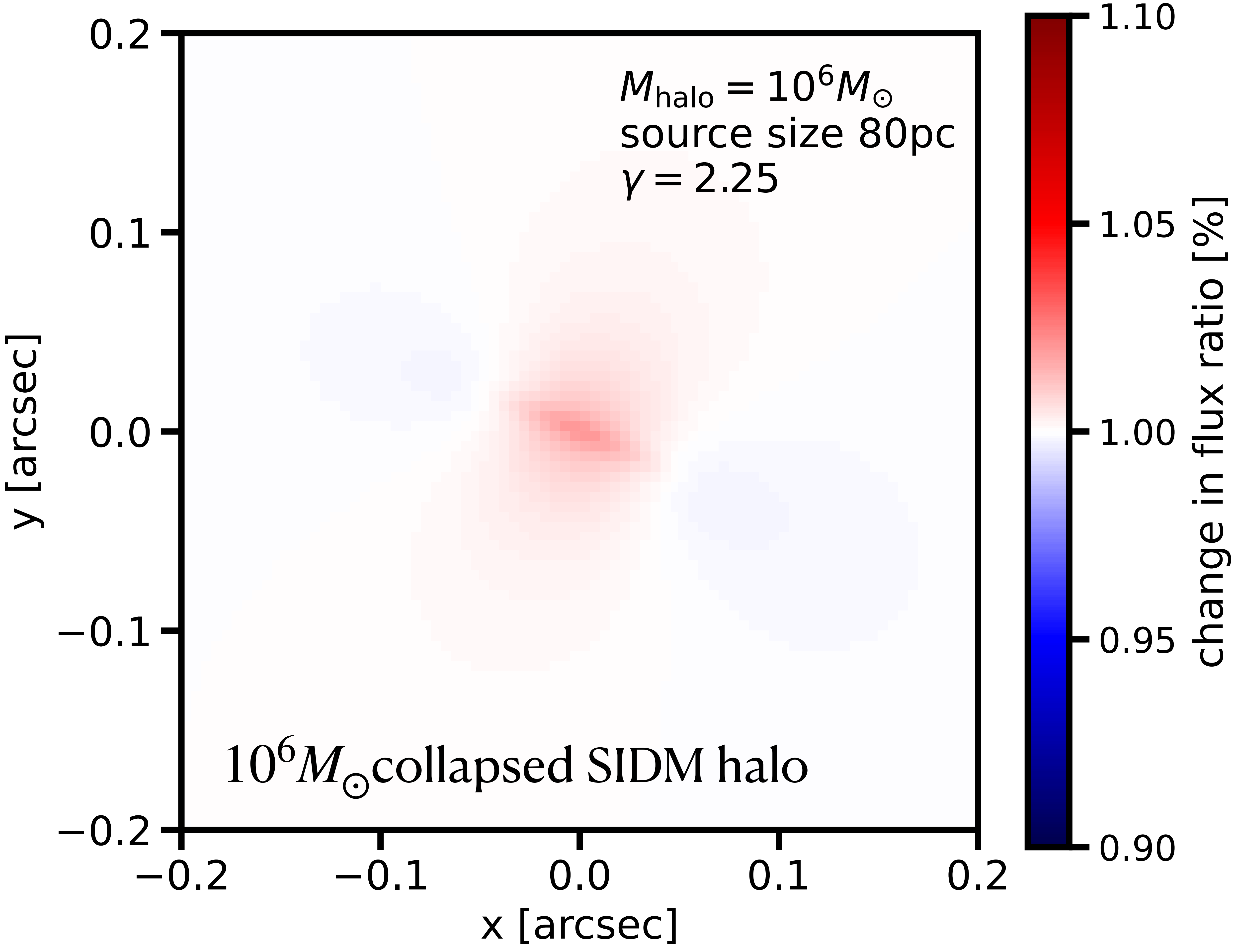
Dark matter density relative to average

Dark matter density relative to average

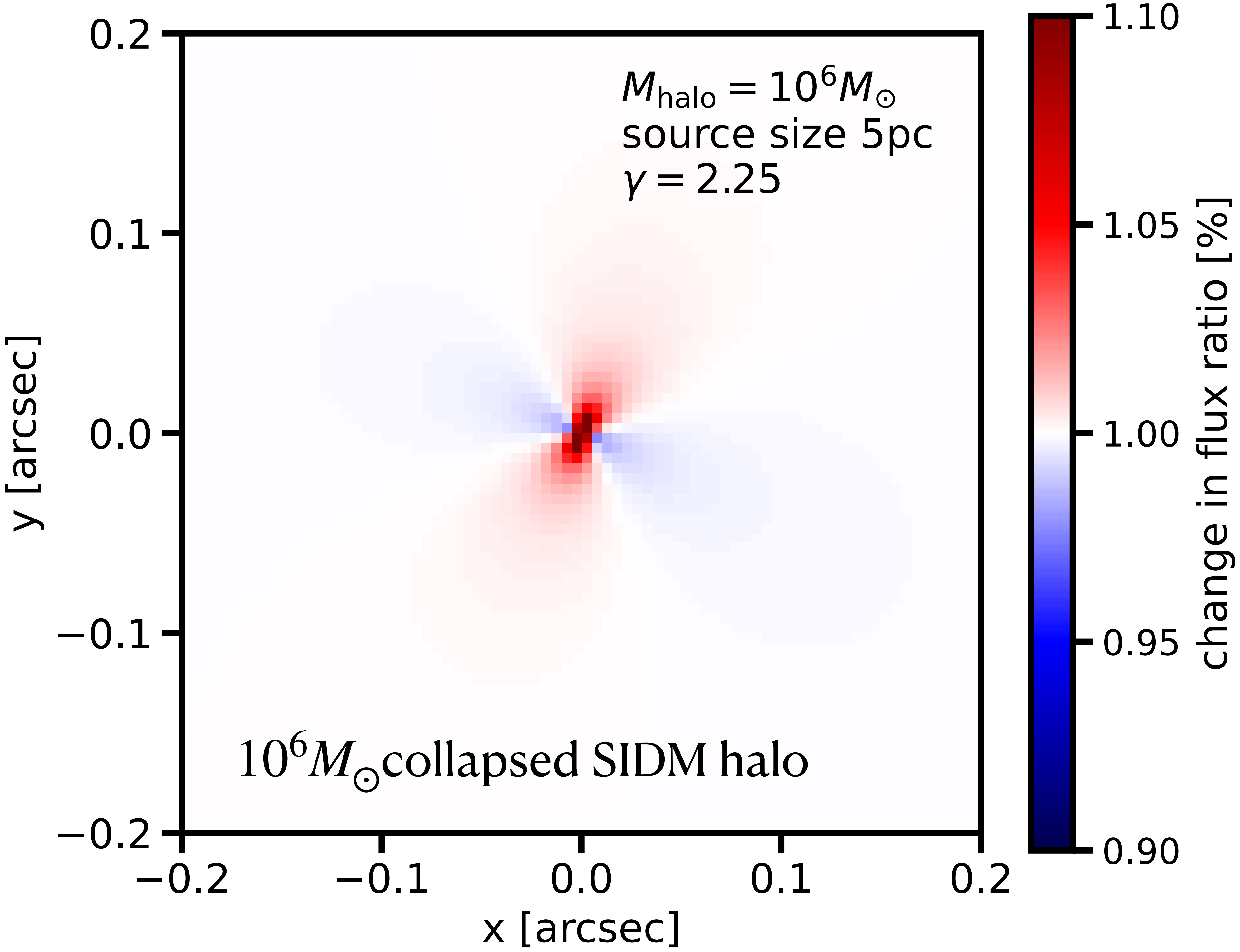
Gilman et al. (2023)
arXiv: 2207.13111

Implications for constraints on SIDM

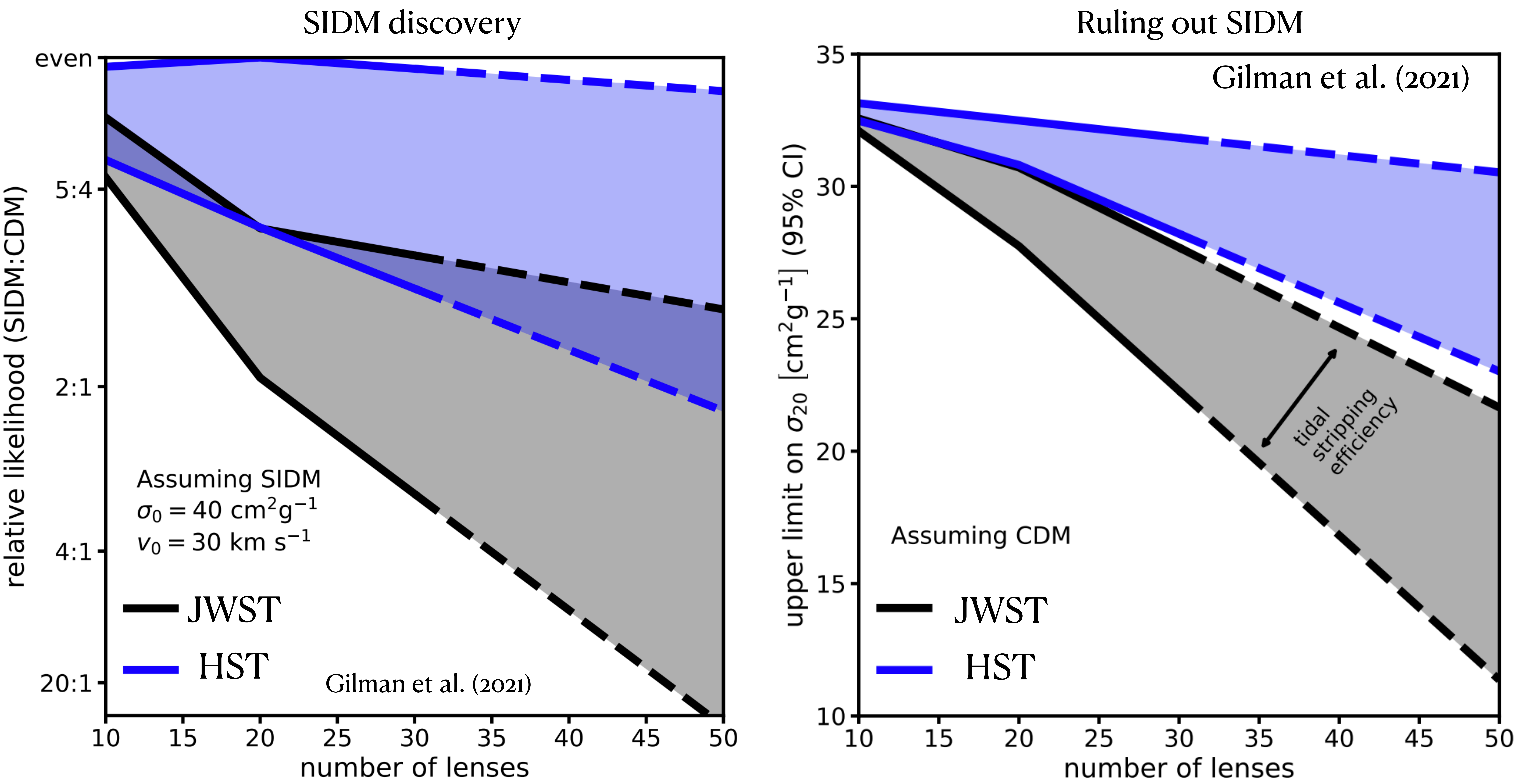
HST-like data



JWST data



Self-interacting dark matter forecast for JWST



Takeaways:

Strong lensing provides an independent and powerful way to test
the predictions of any dark matter model that alters
halo abundance and concentration

JWST will soon deliver a larger sample of lenses with more precise measurements
that probe lower halo down to 10^7 solar masses and below.
-> will lead to unprecedented constraints on the nature of dark matter
and a key test of the ΛCDM paradigm