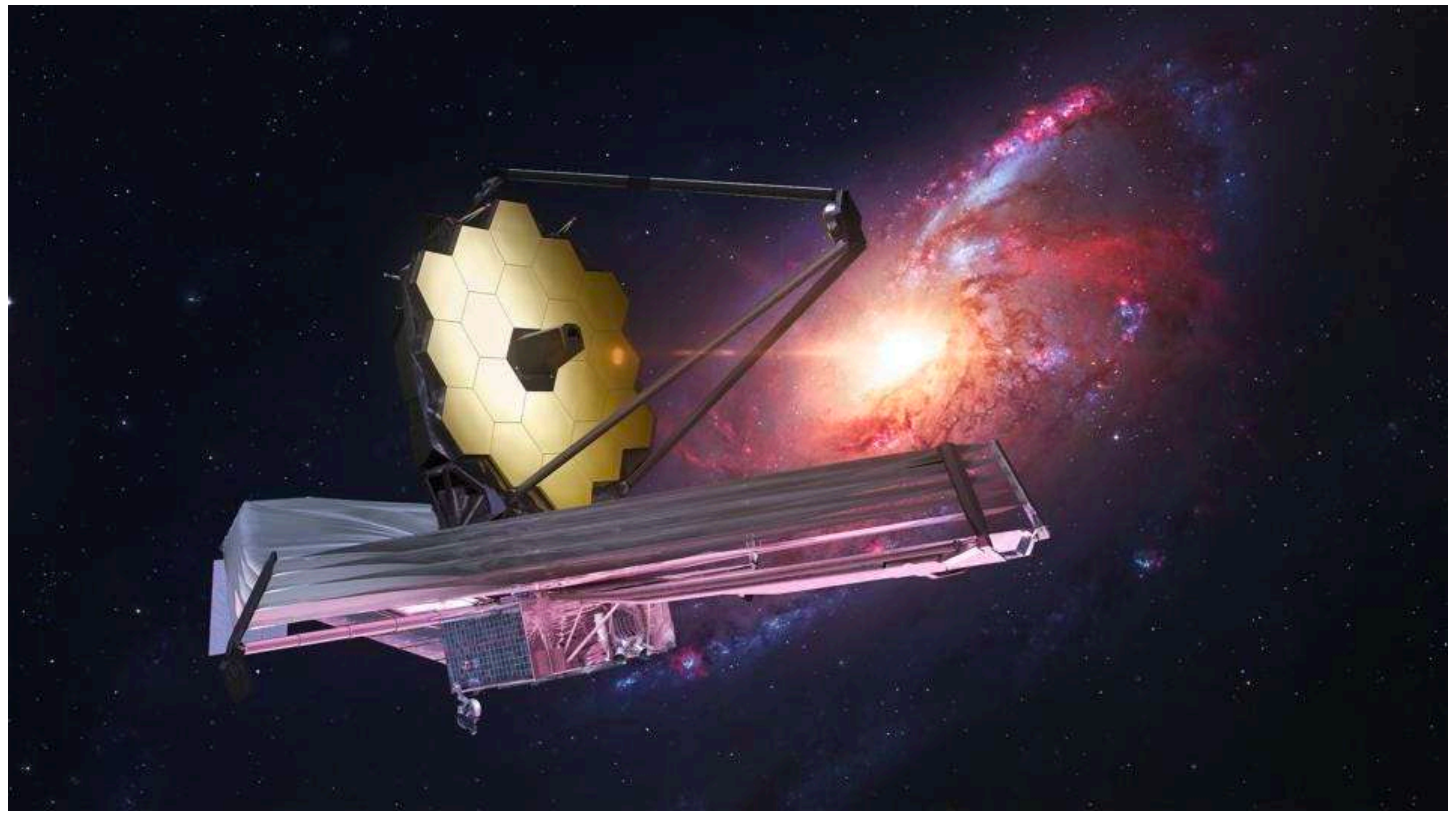
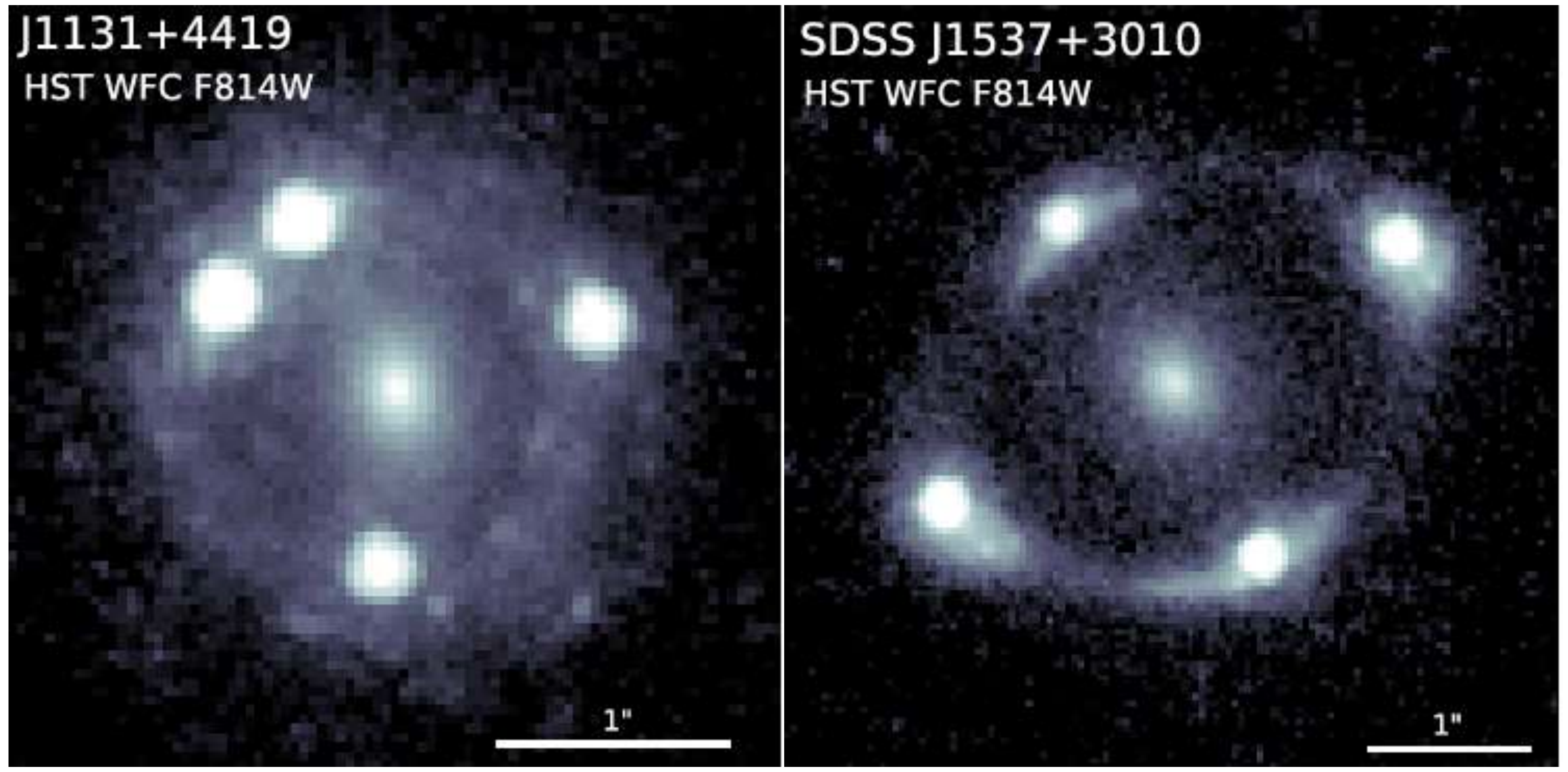
Detecting DM subhalos with strong gravitational lensing





Daniel Gilman

Brinson Prize Fellow
University of Chicago

In collaboration with:
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Tommaso Treu, Xiaolong Du, Hadrien Paugnat (UCLA)
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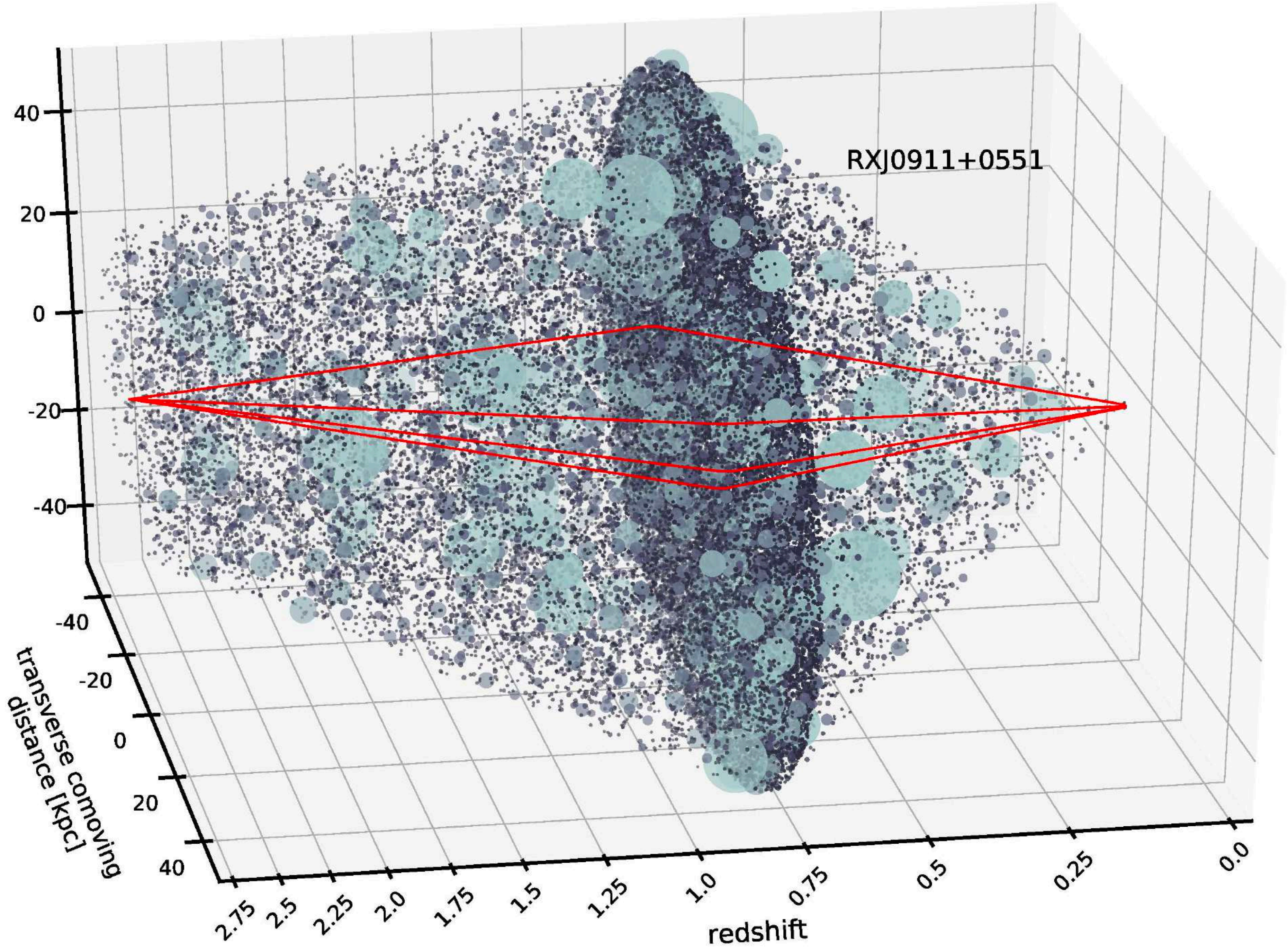
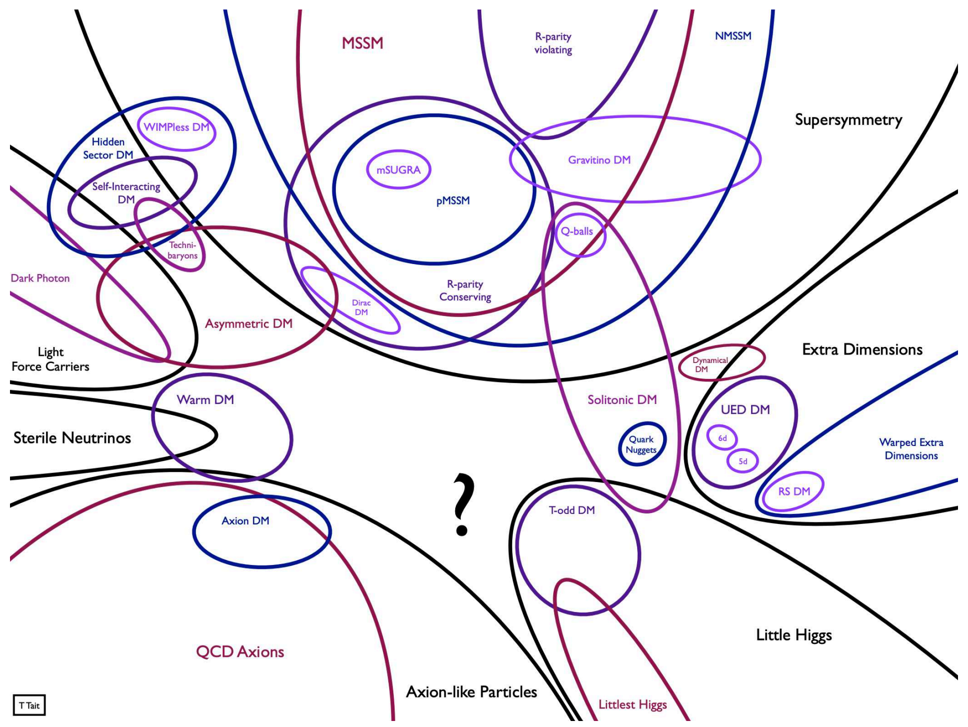
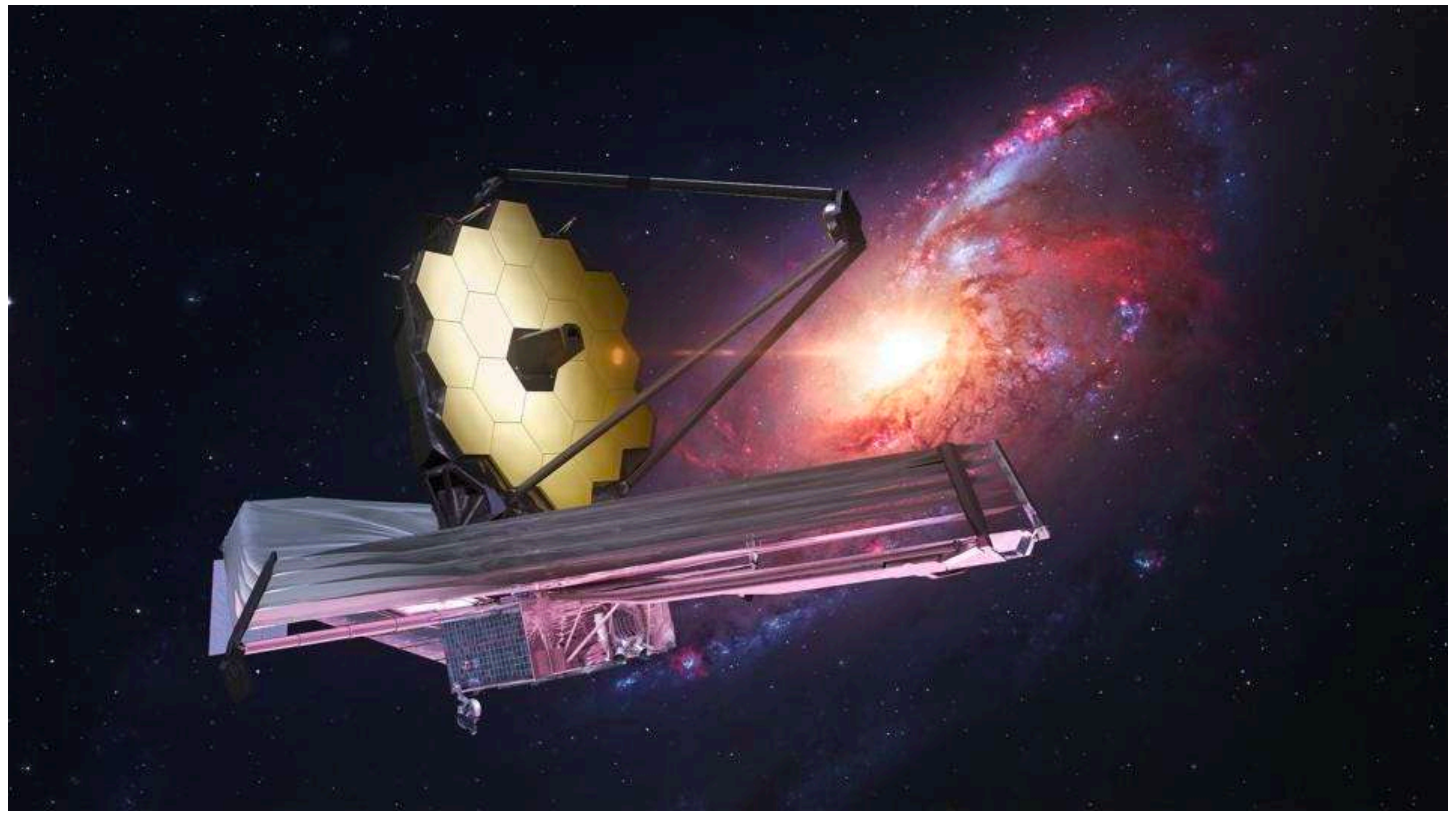
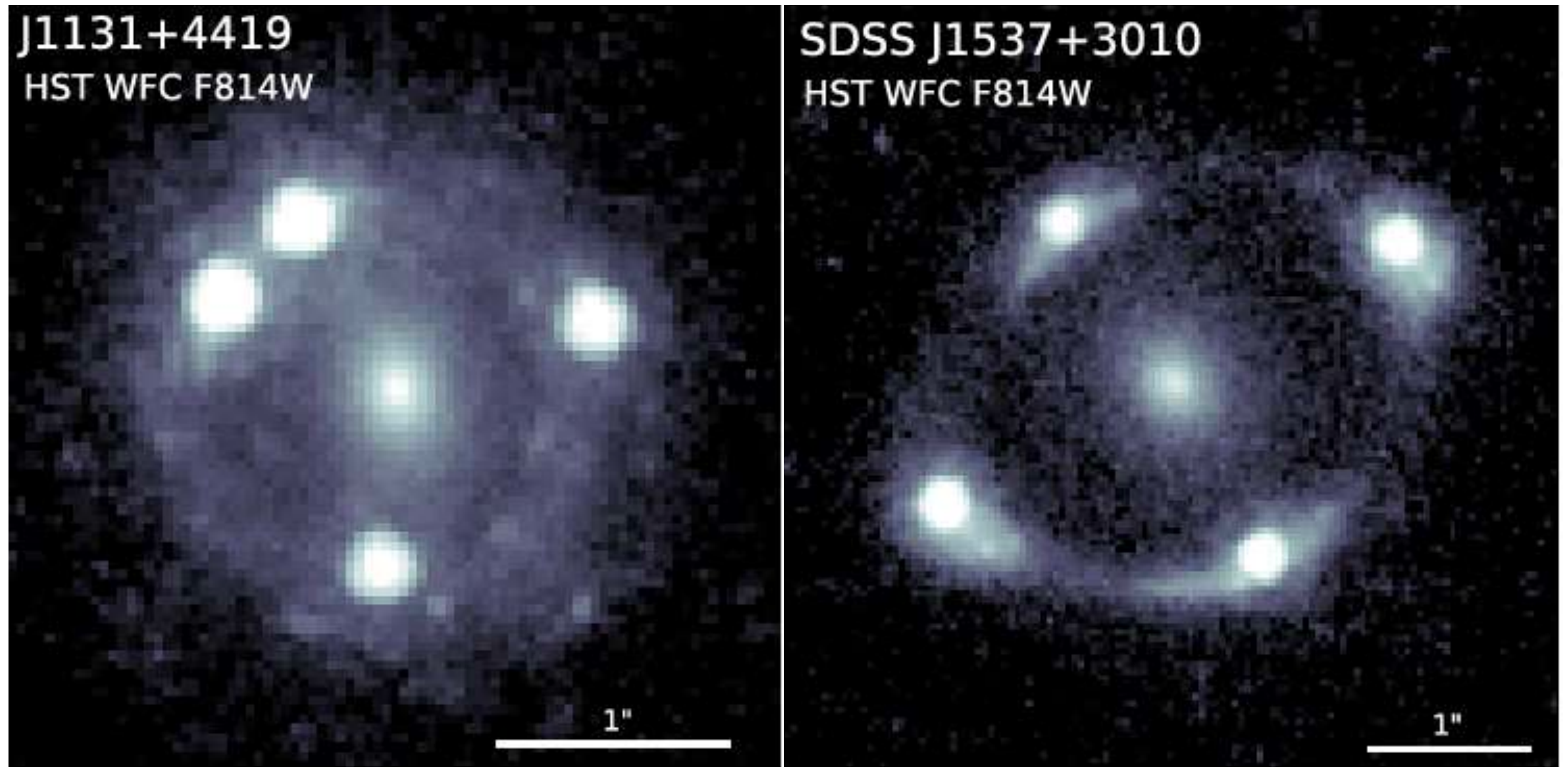
Jo Bovy (UofT)





Characterizing DM substructure POPULATIONS with strong lensing





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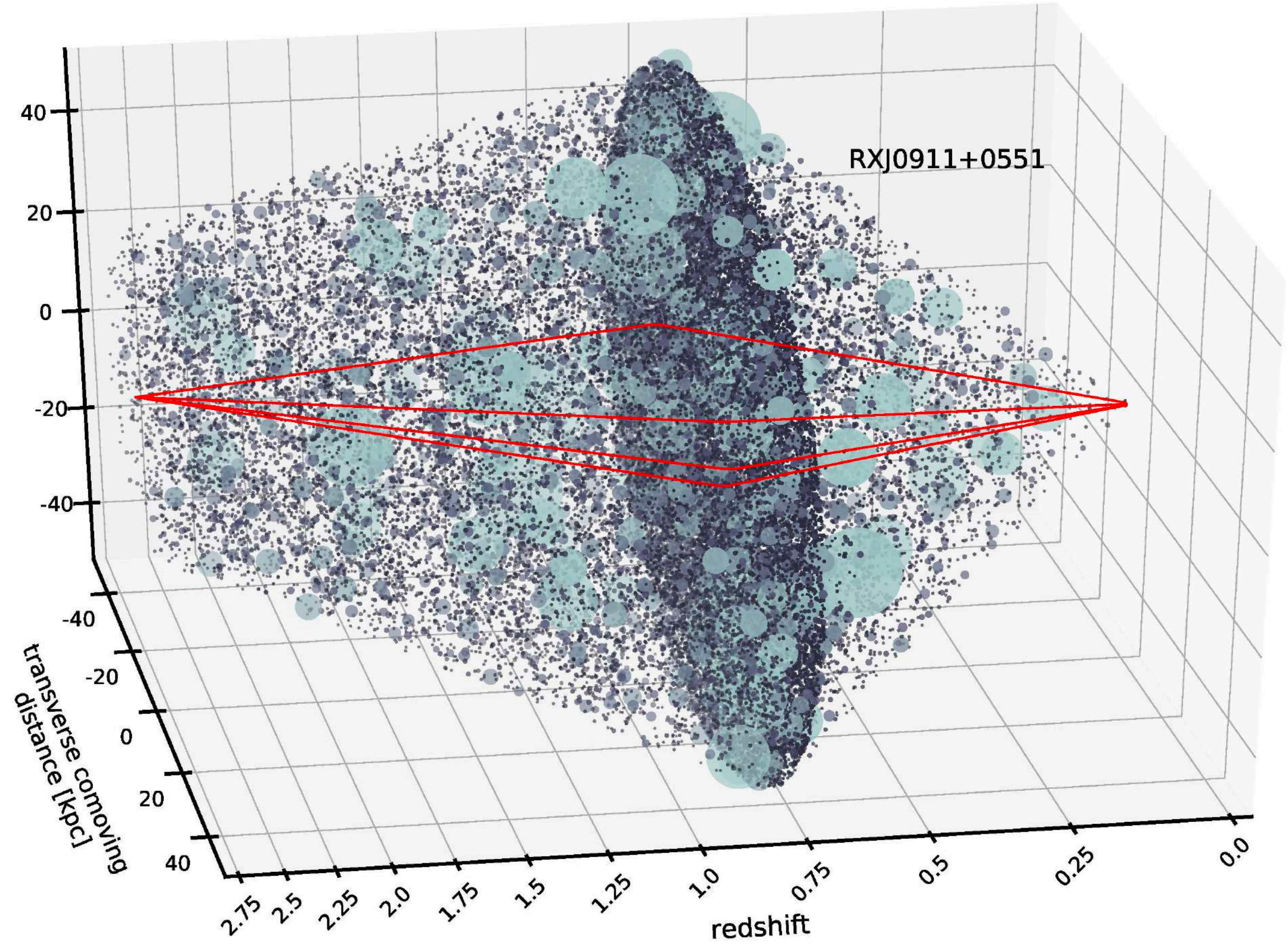
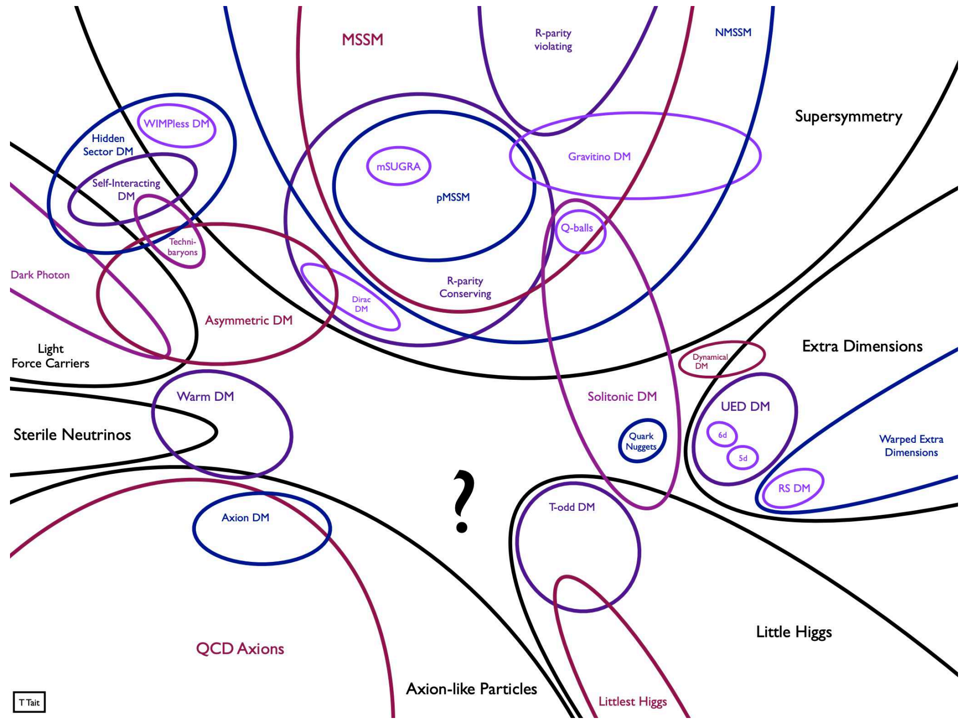




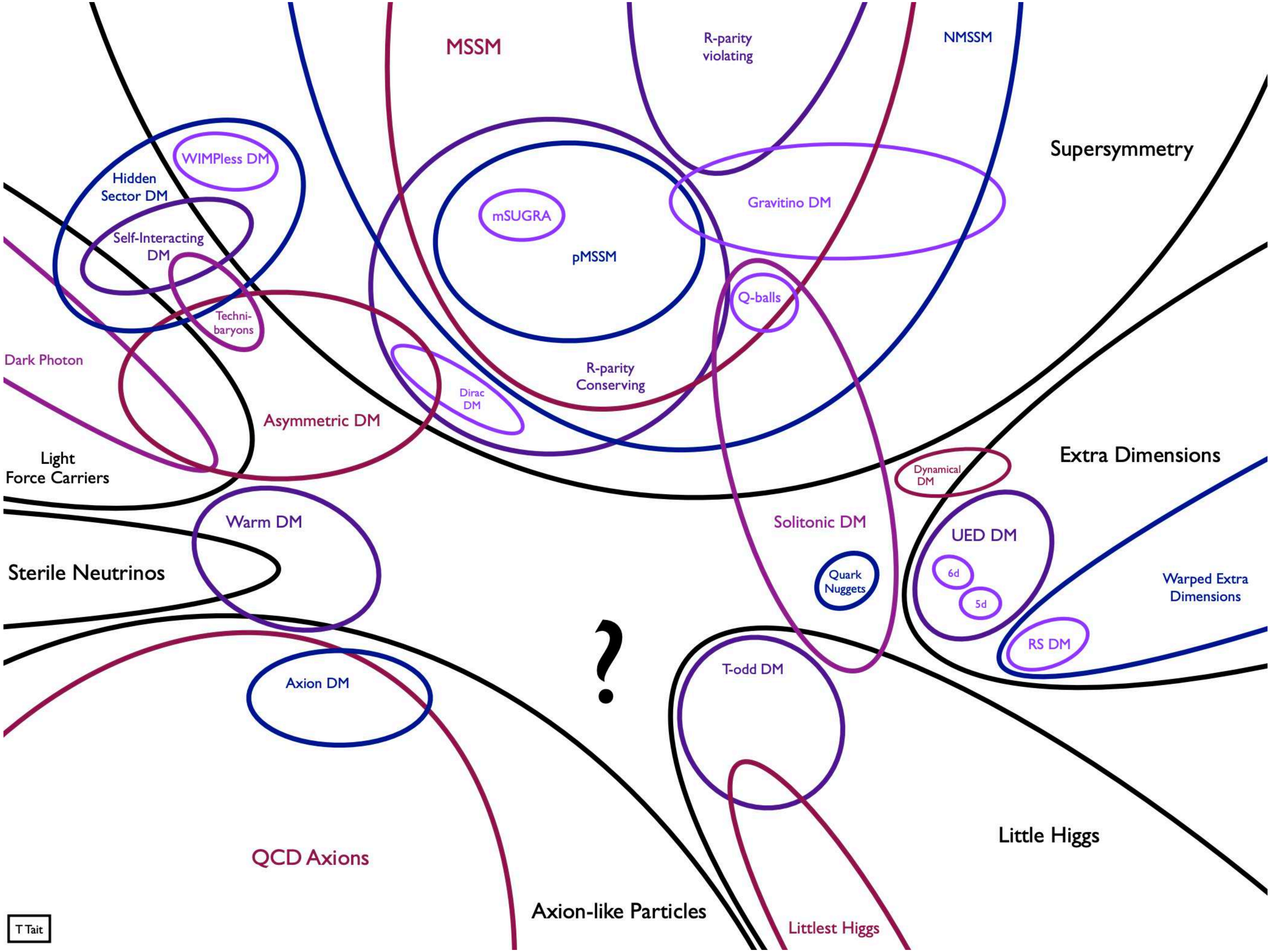
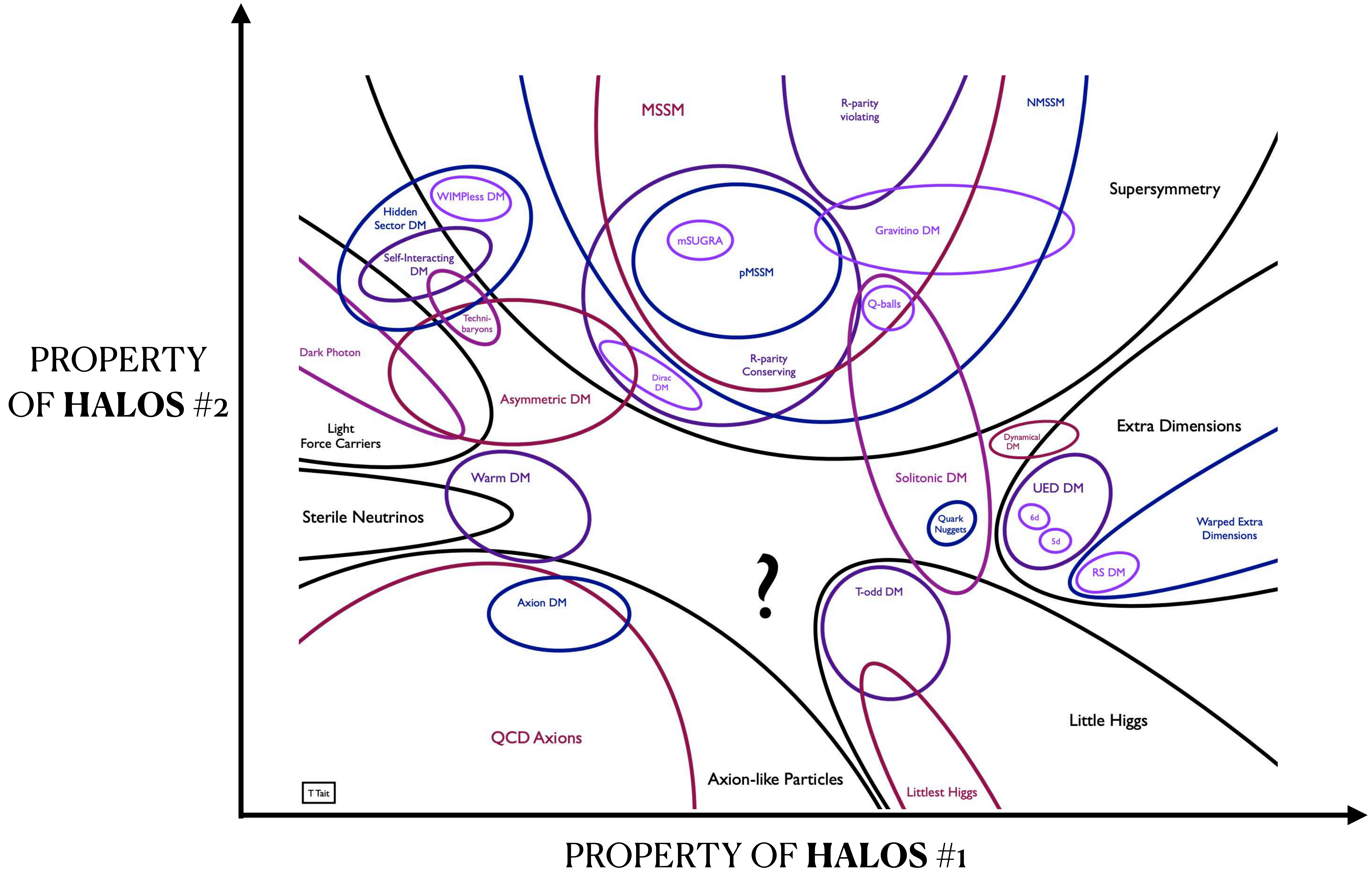
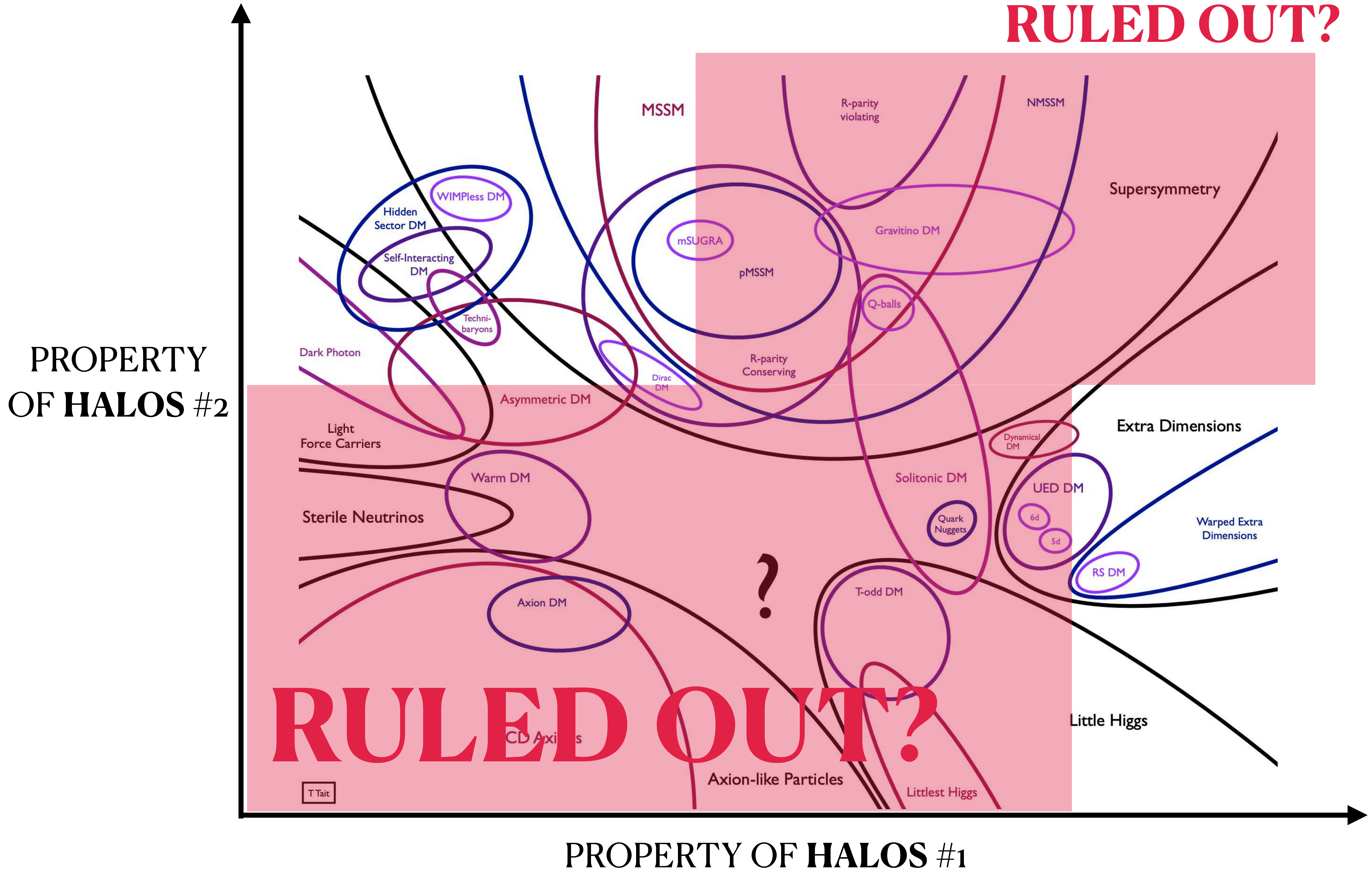


Figure by Tim Tait



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
Dark Photon
Dirac DM
R-parity Conserving
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
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait



RULED OUT?
PROPERTY OF HALOS #2
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MSSM
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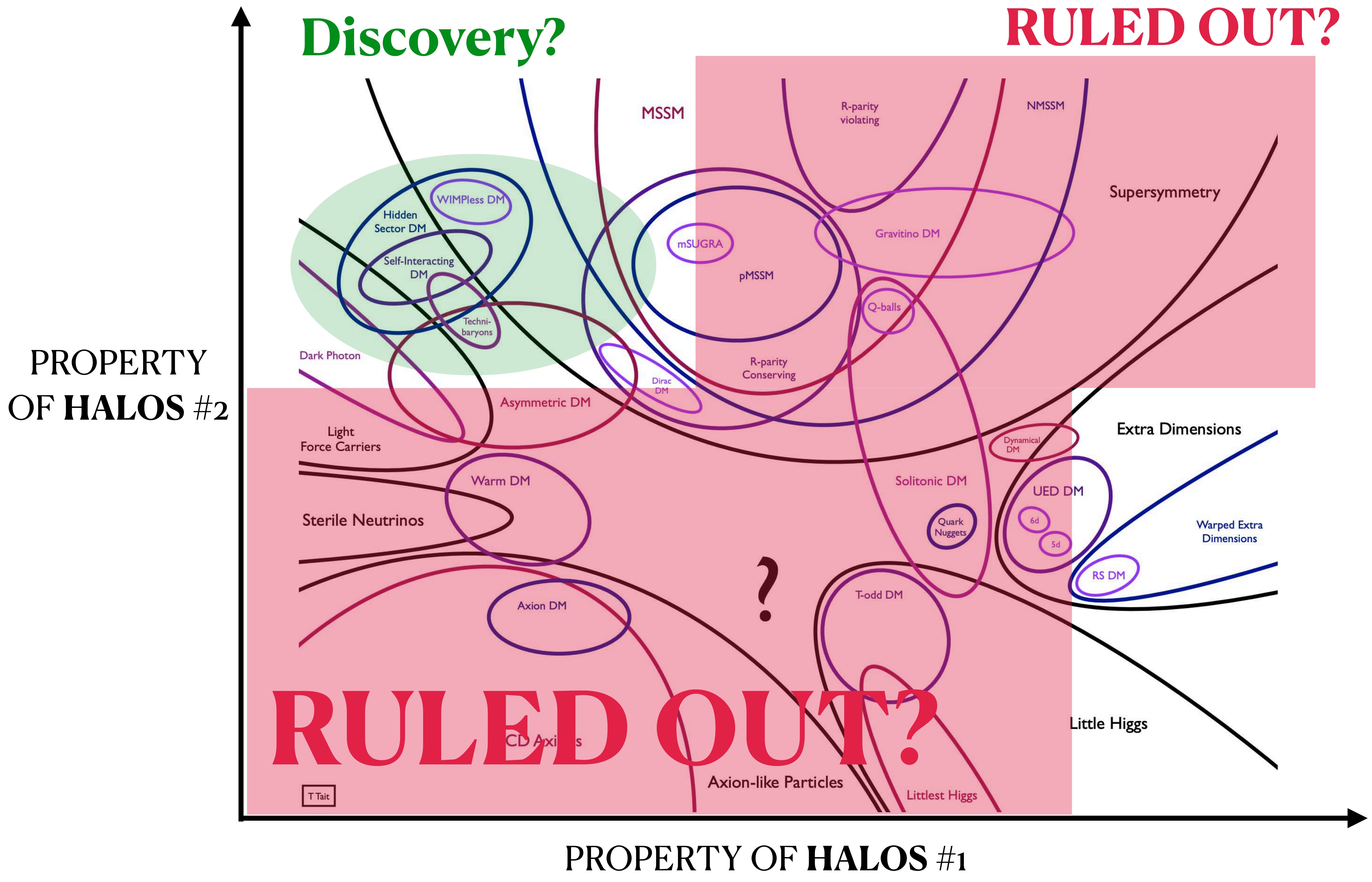
Discovery?
RULED OUT?
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
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Self-Interacting DM
Techni-baryons
mSUGRA
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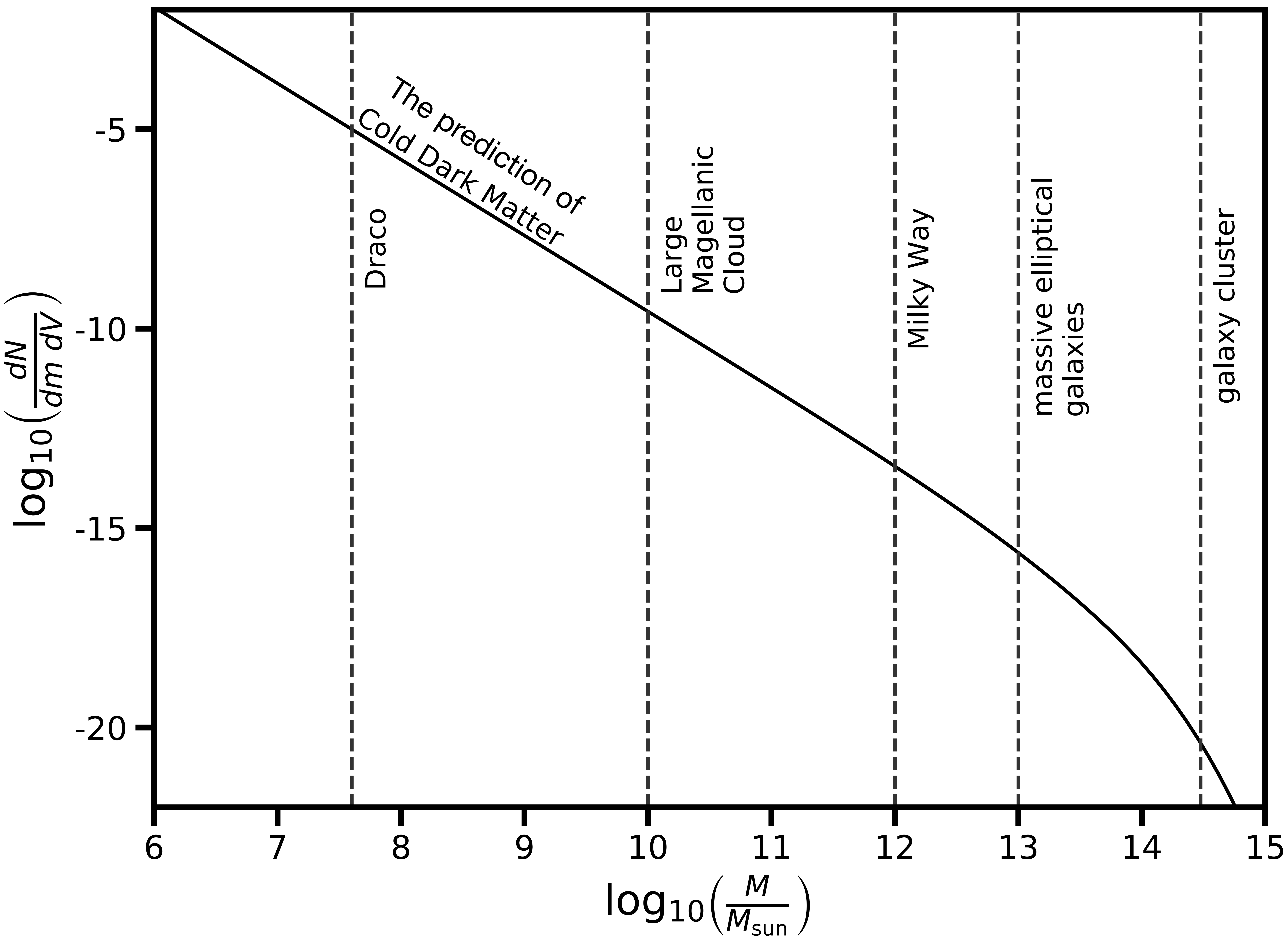
RULED OUT?
T Tait
PROPERTY OF HALOS #2
PROPERTY OF HALOS #1



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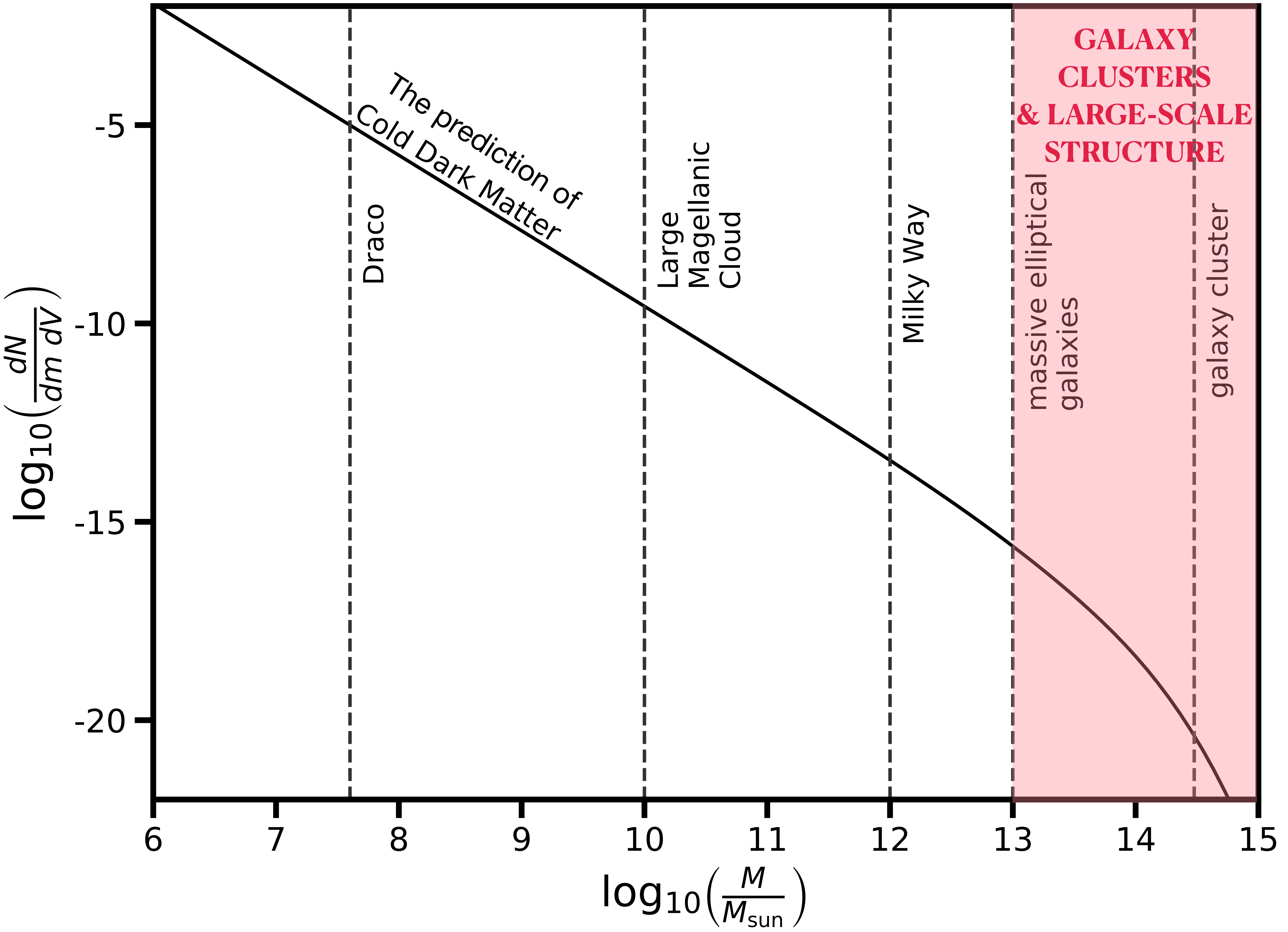
$\log_{10}\left(\frac{M}{M_{\mathrm{sun}}}\right)$



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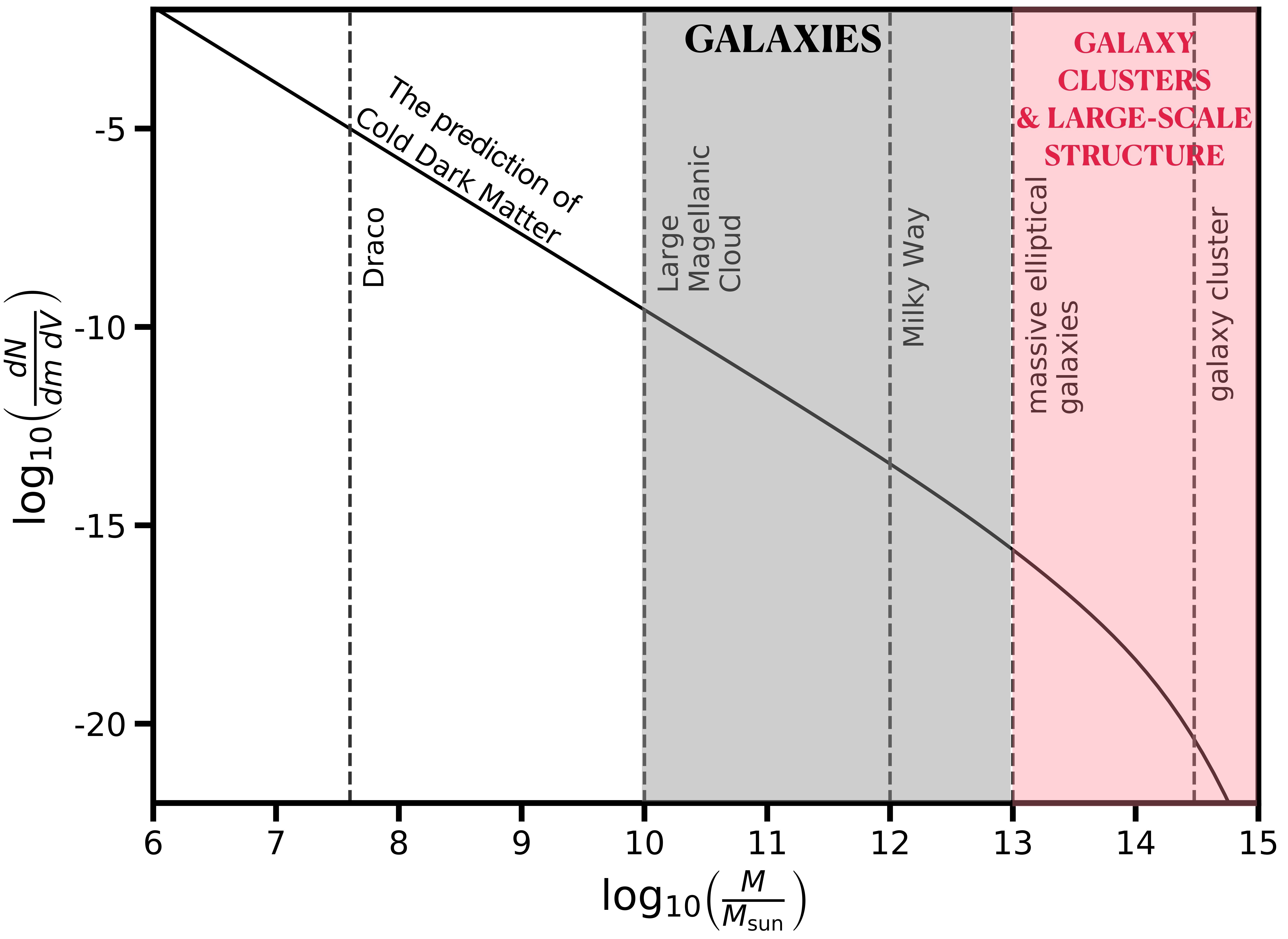
$\log_{10}\left(\frac{M}{M_{sun}}\right)$



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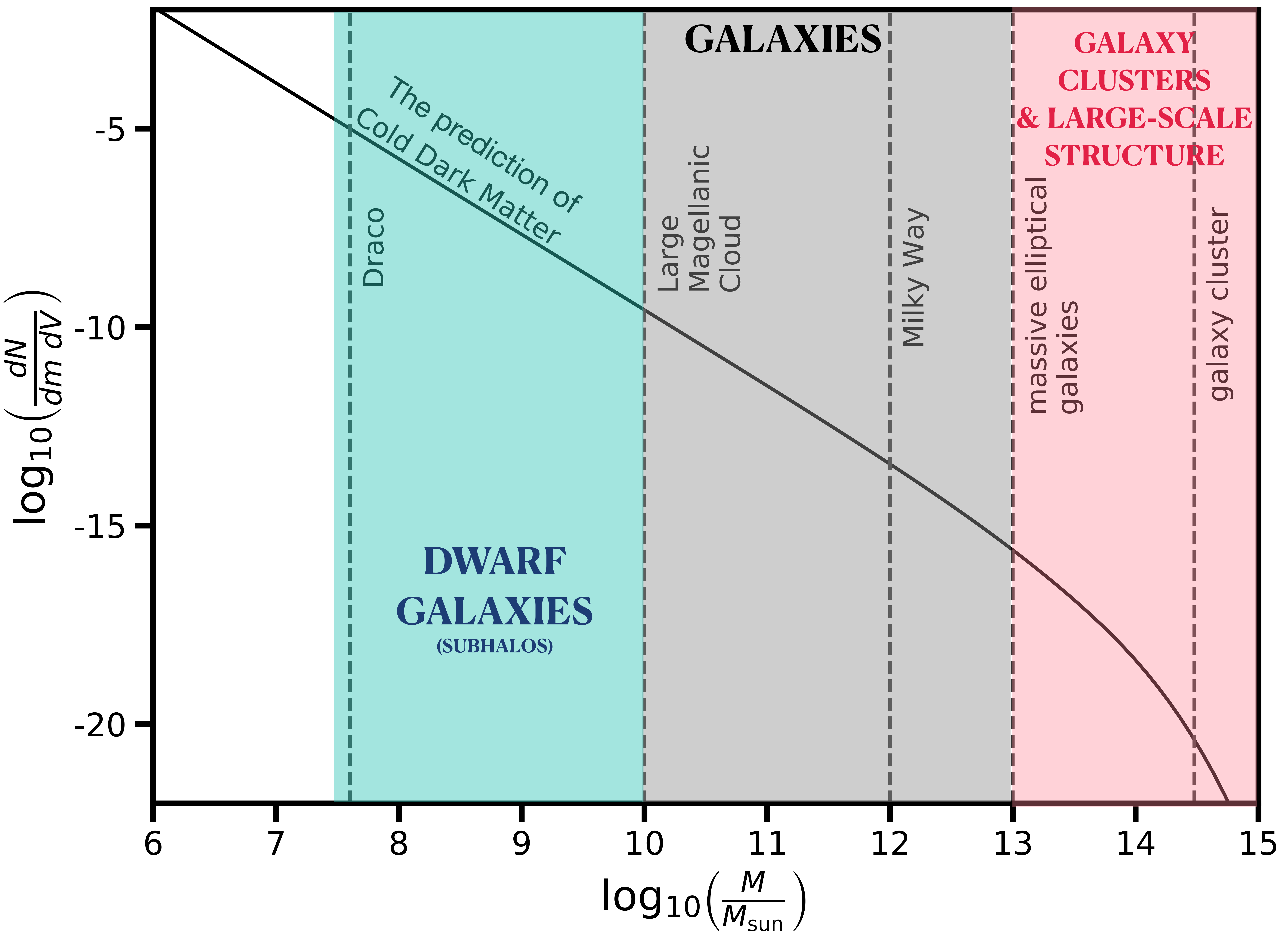
GALAXIES
GALAXY CLUSTERS & LARGE-SCALE STRUCTURE
The prediction of Cold Dark Matter
Draco
Large Magellanic Cloud
Milky Way
massive elliptical galaxies
galaxy cluster
DWARF GALAXIES
(SUBHALOS)
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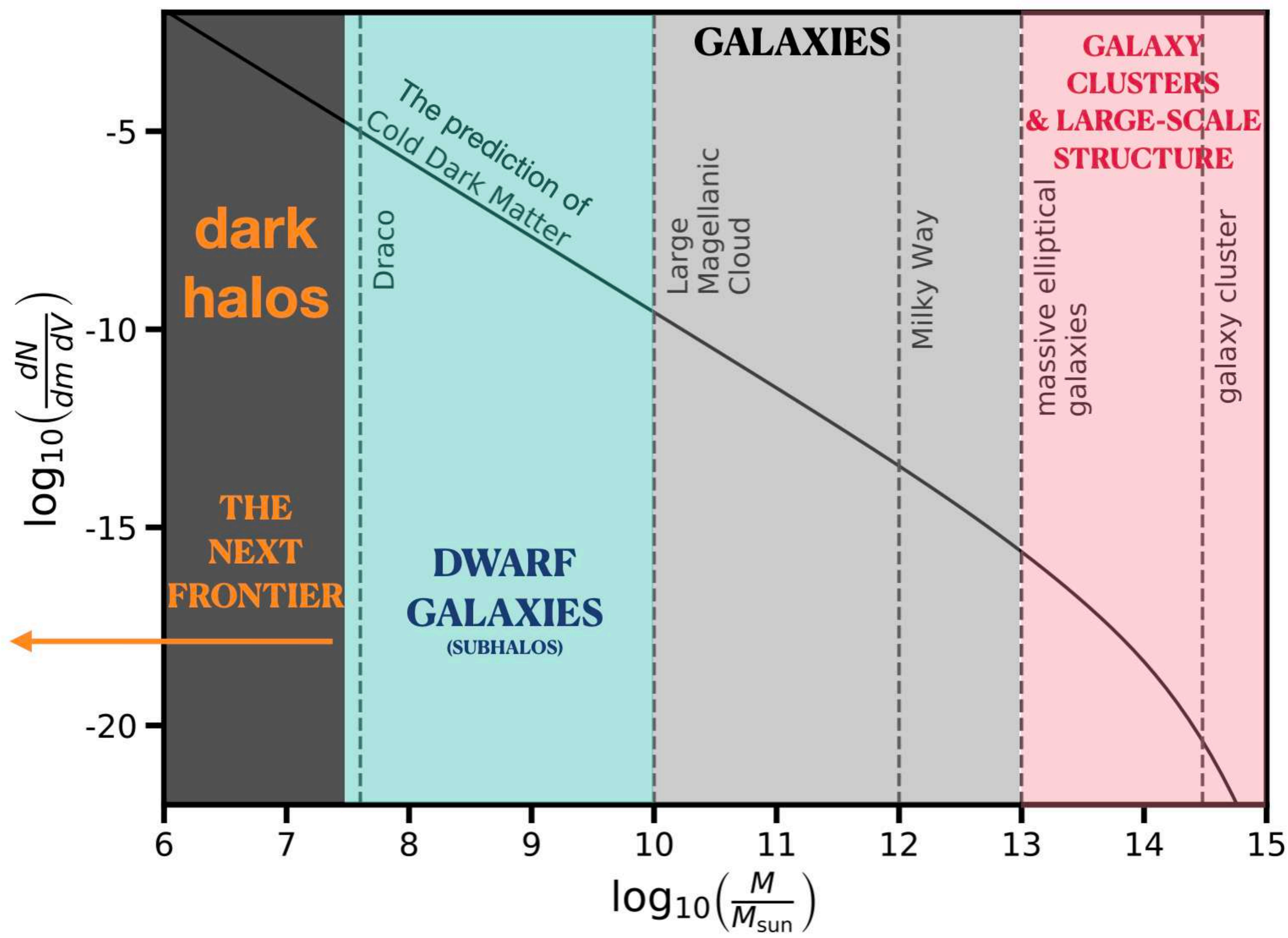
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
$\log_{10}\left(\frac{M}{M_{sun}}\right)$



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)
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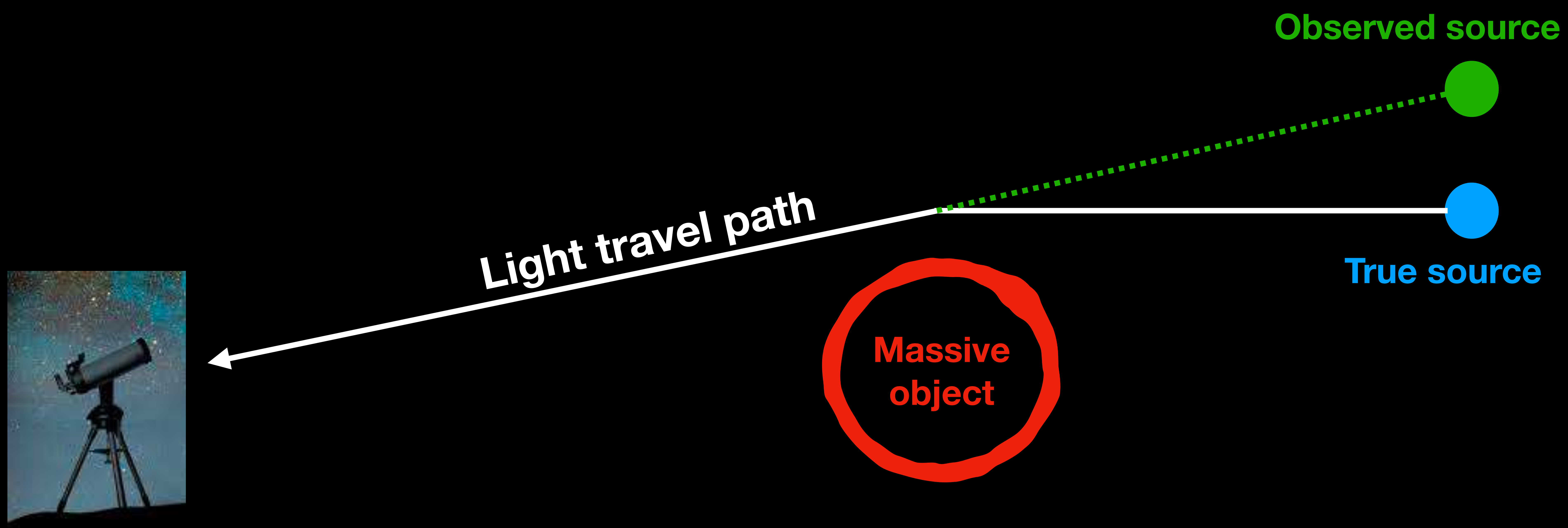
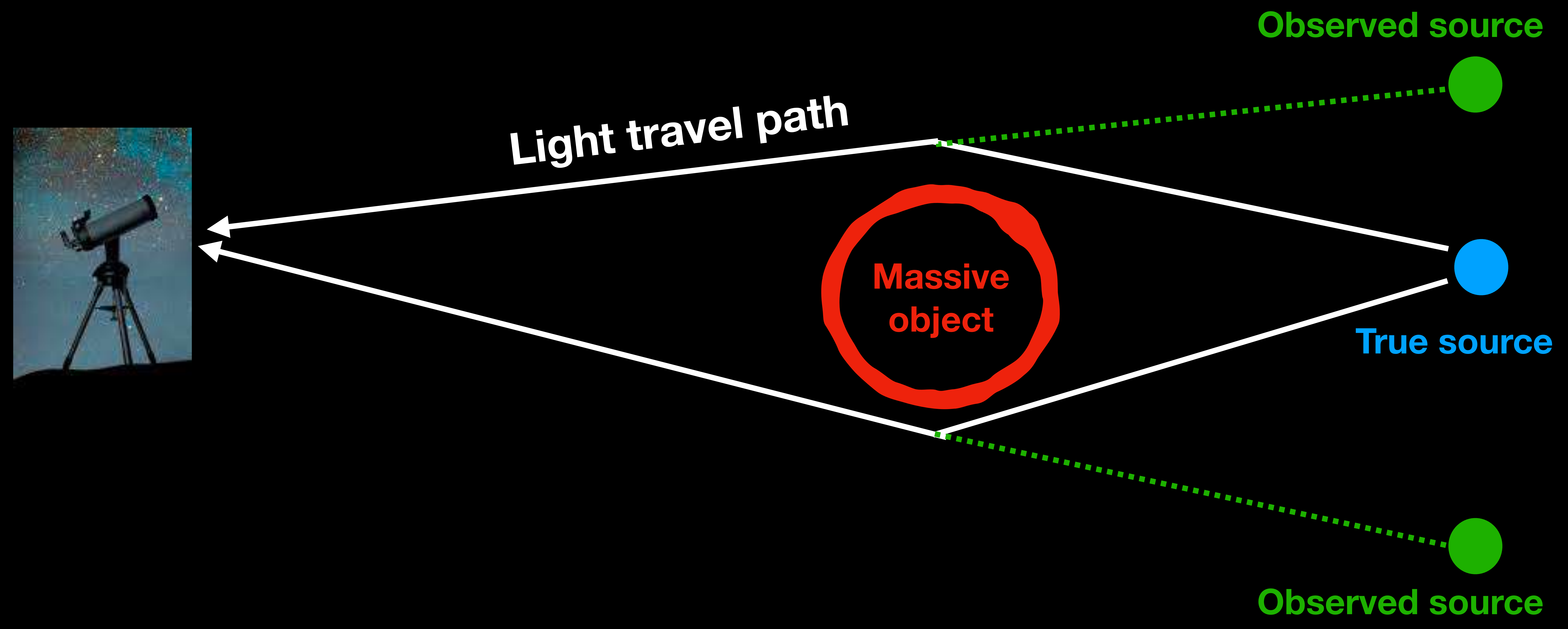
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
$\log_{10}\left(\frac{M}{M_{sun}}\right)$

Strong lensing

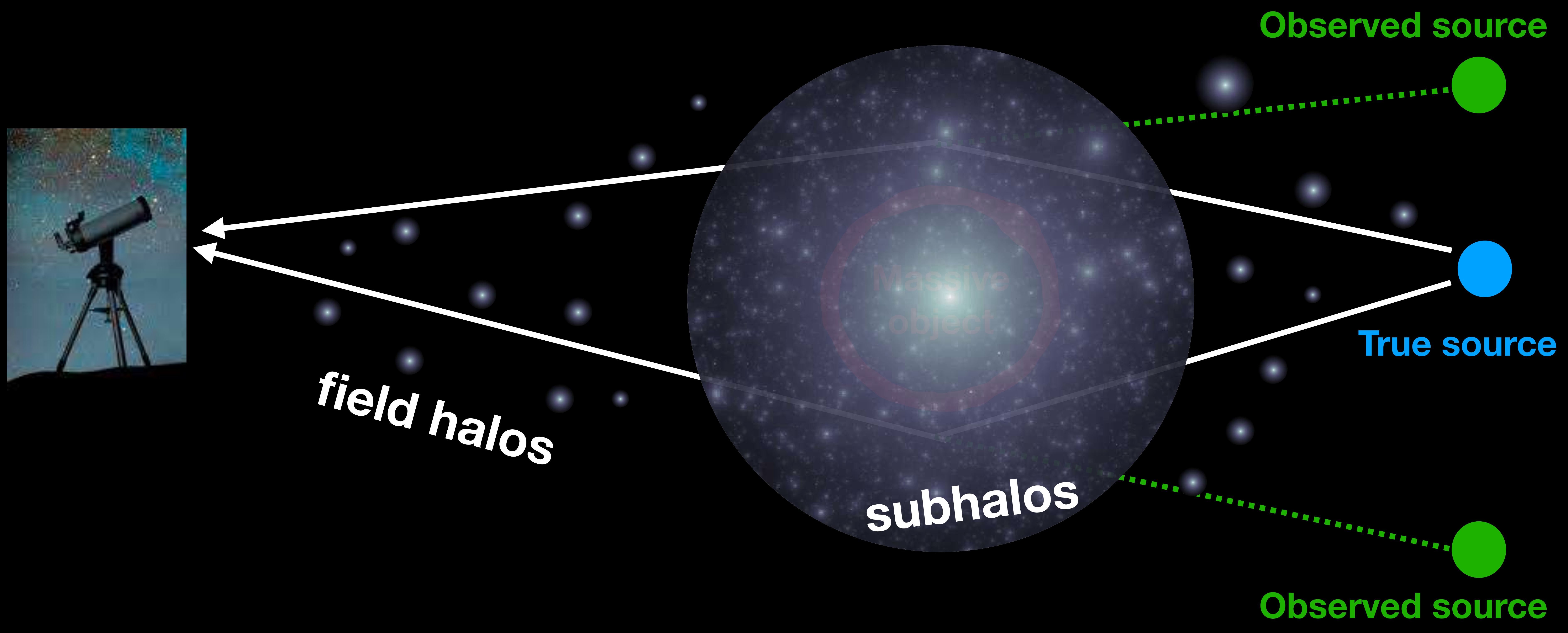
Gravitational lensing: deflection of light by gravitational fields



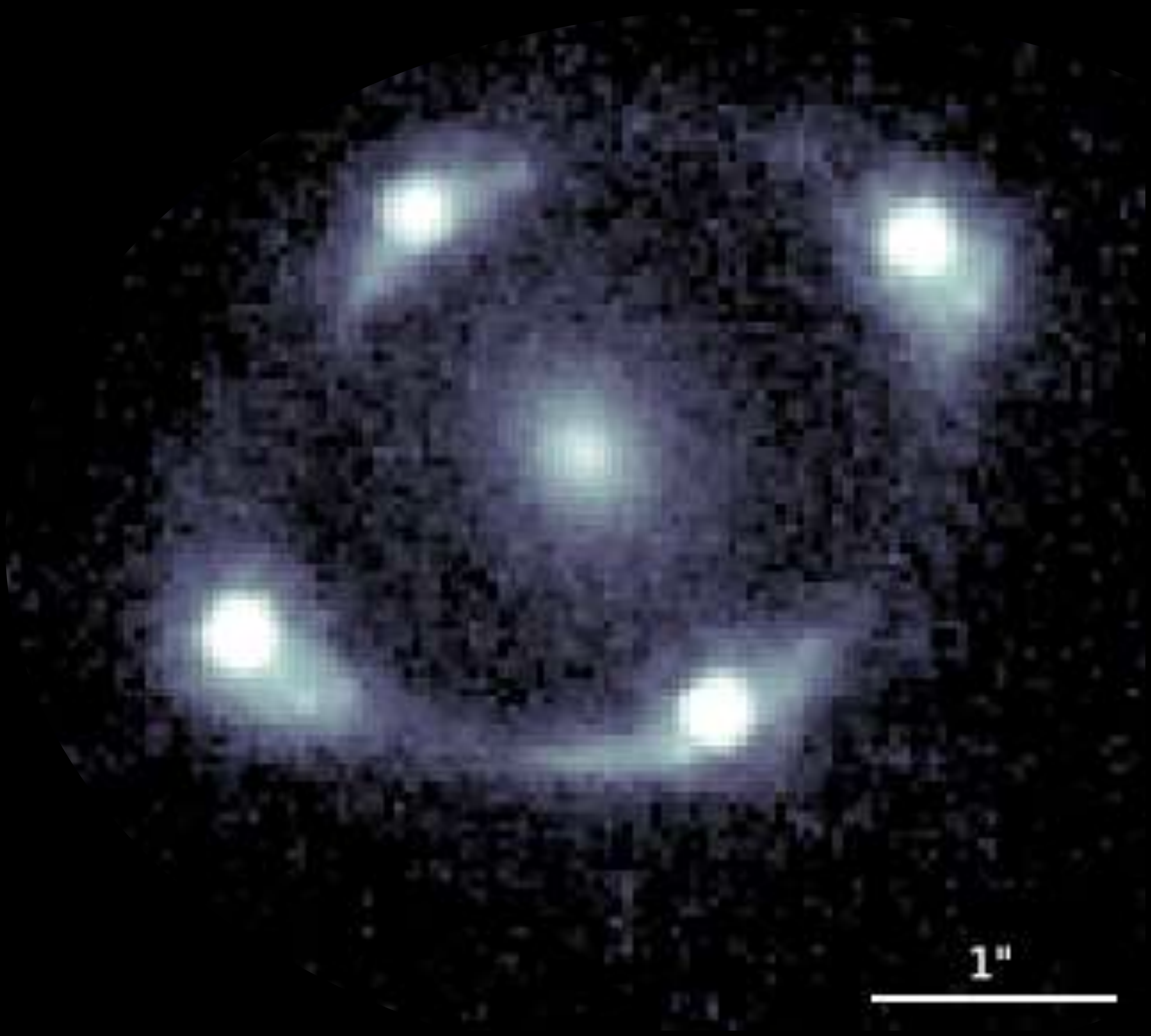
Strong lensing produces multiple images of a single source…



Strong lensing produces multiple images of a single source… and the images are perturbed by dark matter halos



Early-type galaxy deflector + extended source



Early-type galaxy deflector
+ quasar and host galaxy

In this talk:

1) how does lensing work and why is it useful?

-> gravitational imaging and multiply-imaged quasars, as probes of DM substructure

2) some interesting science cases

-> warm dark matter, self-interacting dark matter, primordial matter power spectrum

3) What does the future hold?

-> the JWST lensed quasar DM survey

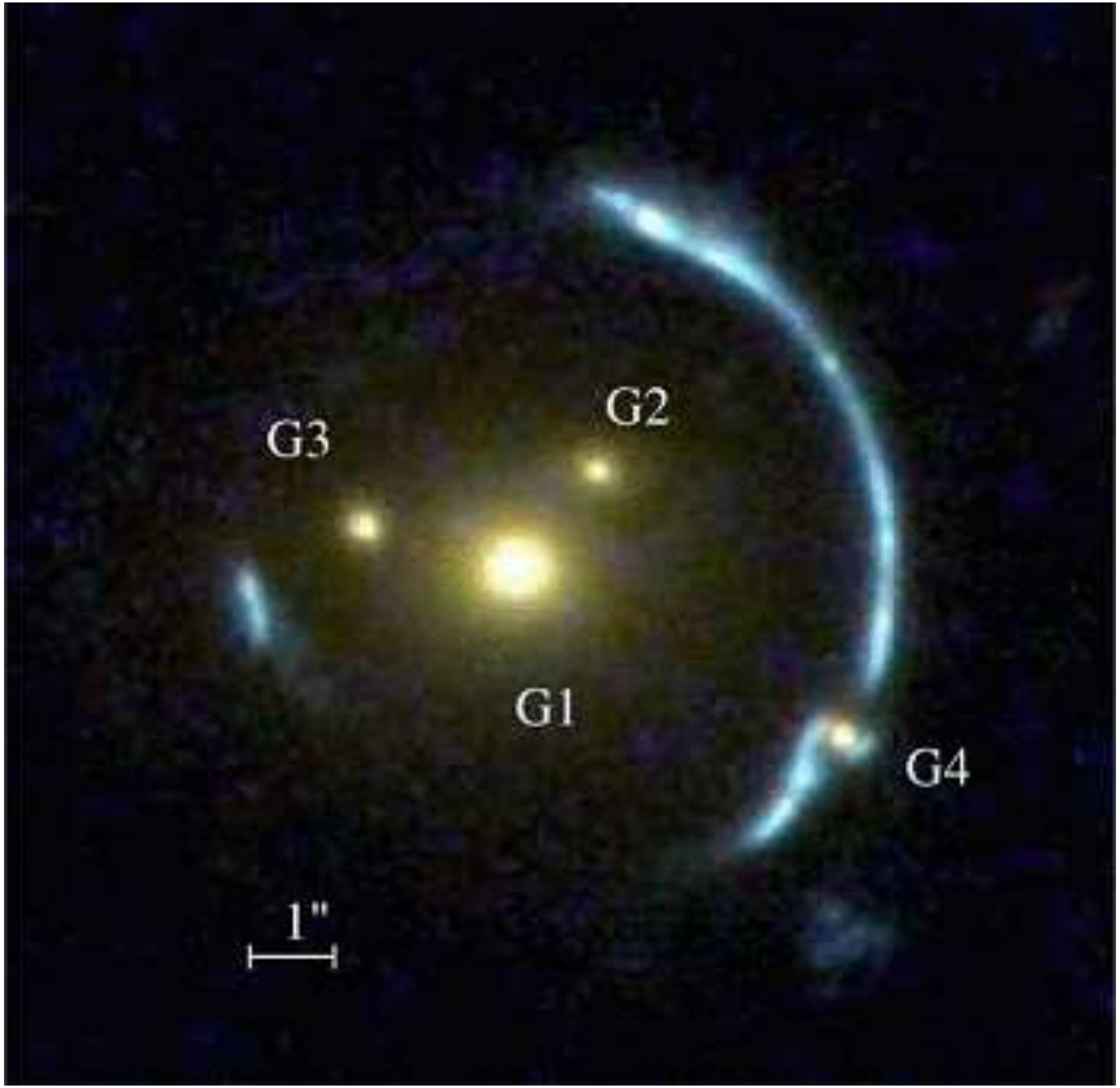
-> better analysis methods

-> more lenses


G2
G3
G1
G4
1"

Gravitational imaging generally refers to the detection of individual perturbers in lensed arcs
(with a few exceptions e.g. Birrer et al. (2017), Powell et al. (2022))

Enables the direct detection and characterization of individual perturbers



Adapted from
Vegetti et al. (2012)

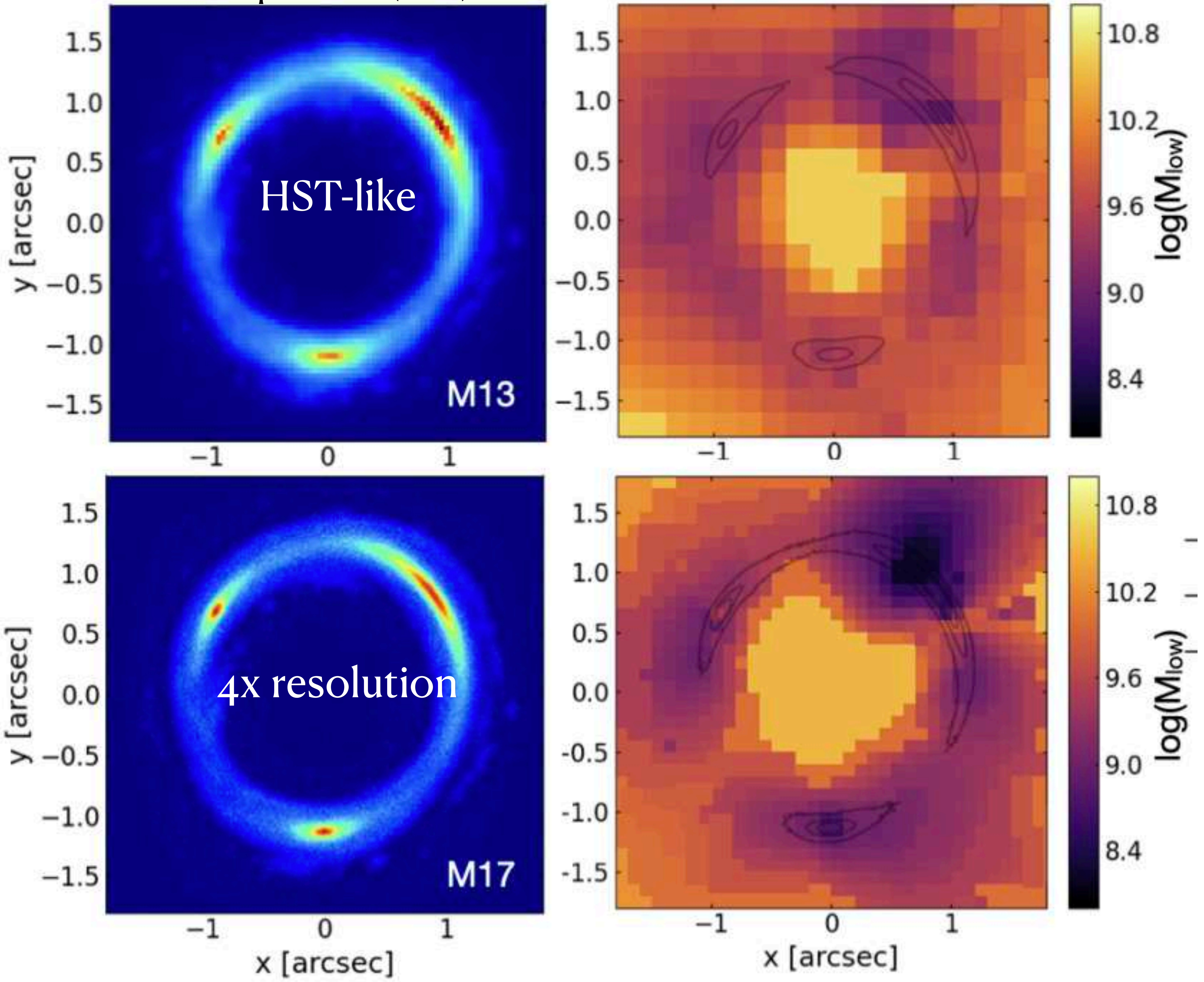
Gravitational Imaging

Halo detectability depends strongly on spatial resolution of data

Main challenge: interpretation of individual detections within DM theoretical frameworks

Figure adapted from Despali et al. (2022)

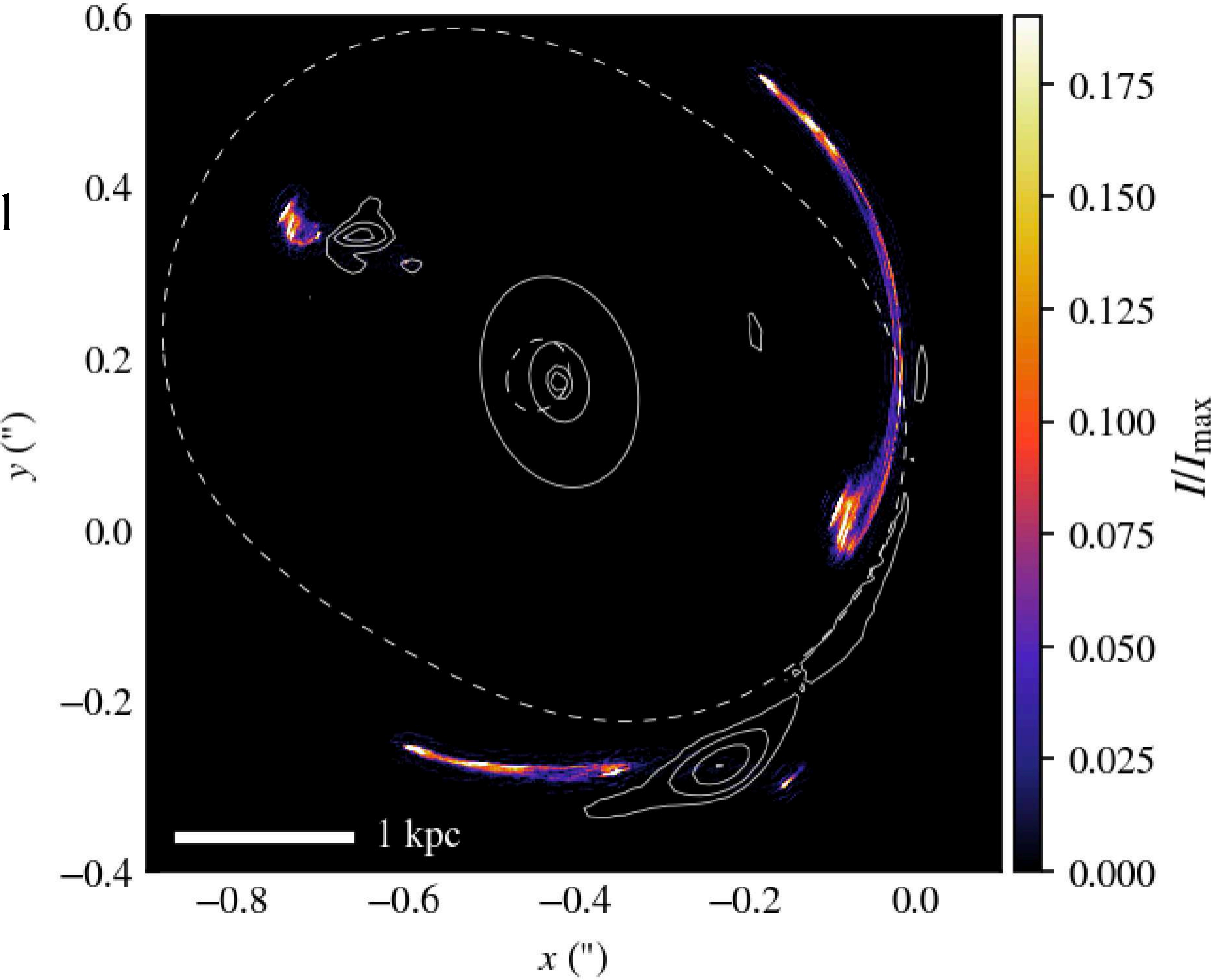
Minimum detectable mass ~few $\times 10^9 M_\odot$

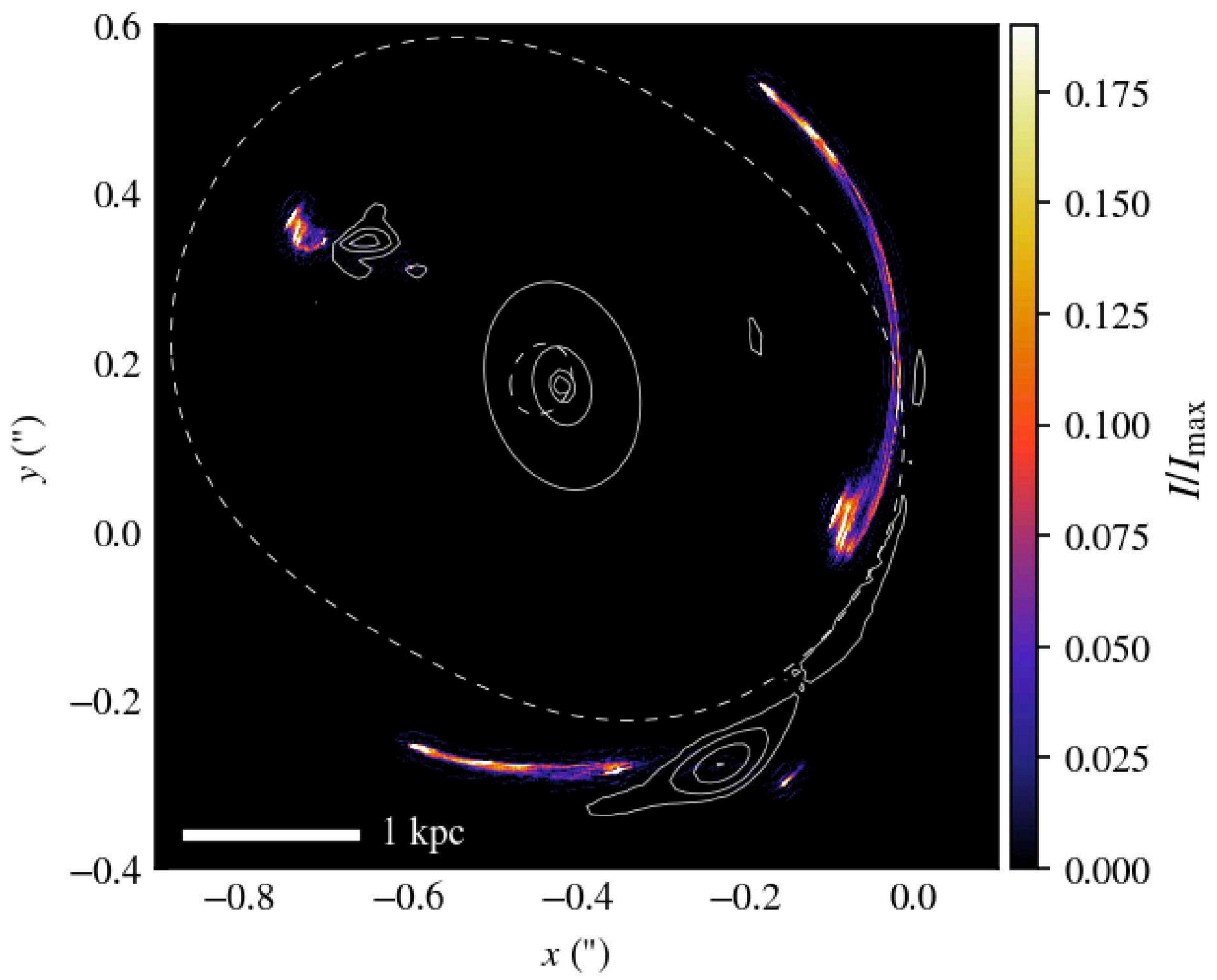


Global VLBI: the ultimate gravitational imaging tool

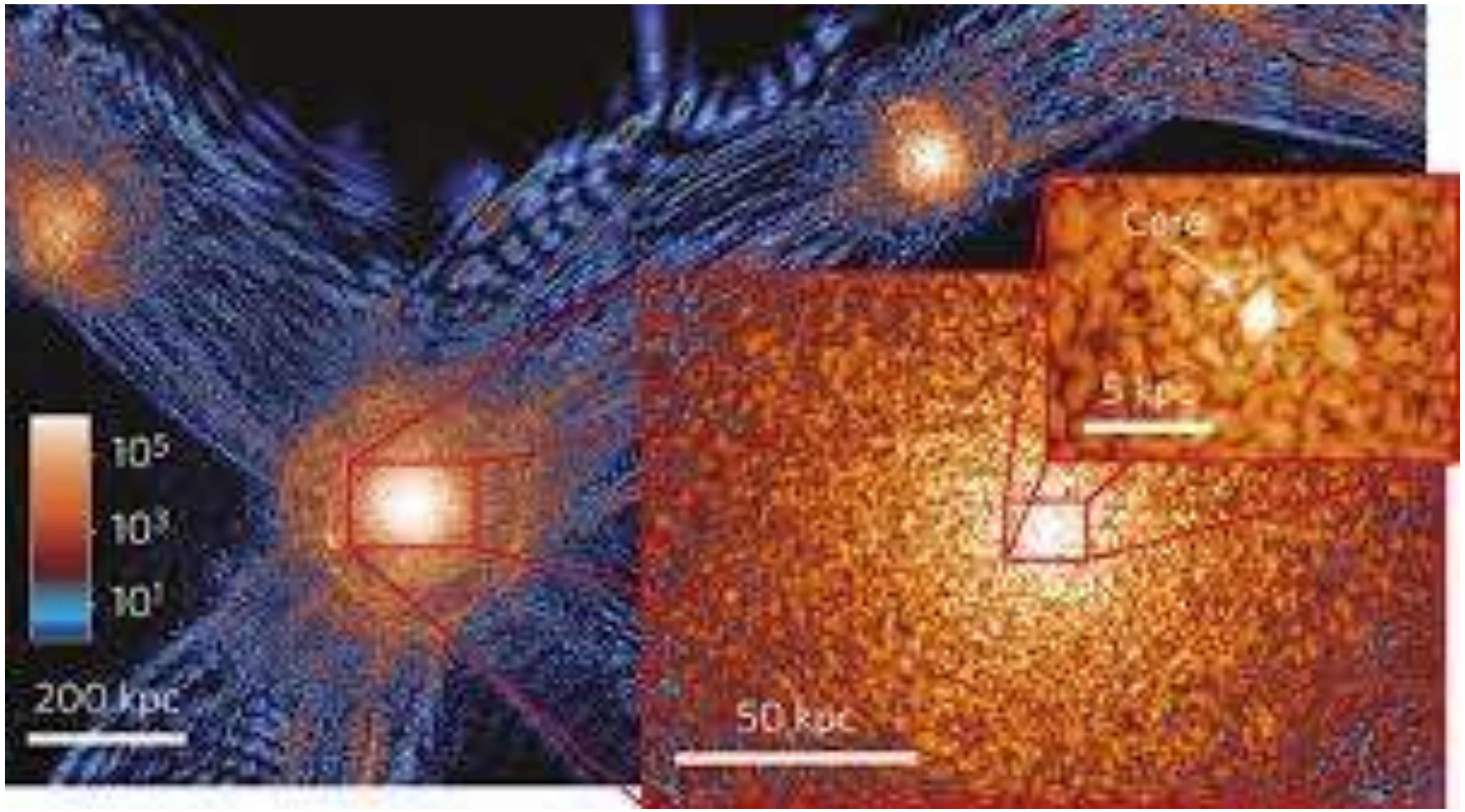
-> sub-milliarcsecond(!!) angular resolution of extended lensed arcs

-> extremely computationally expensive to model
see Powell et al. (2021, 2022)

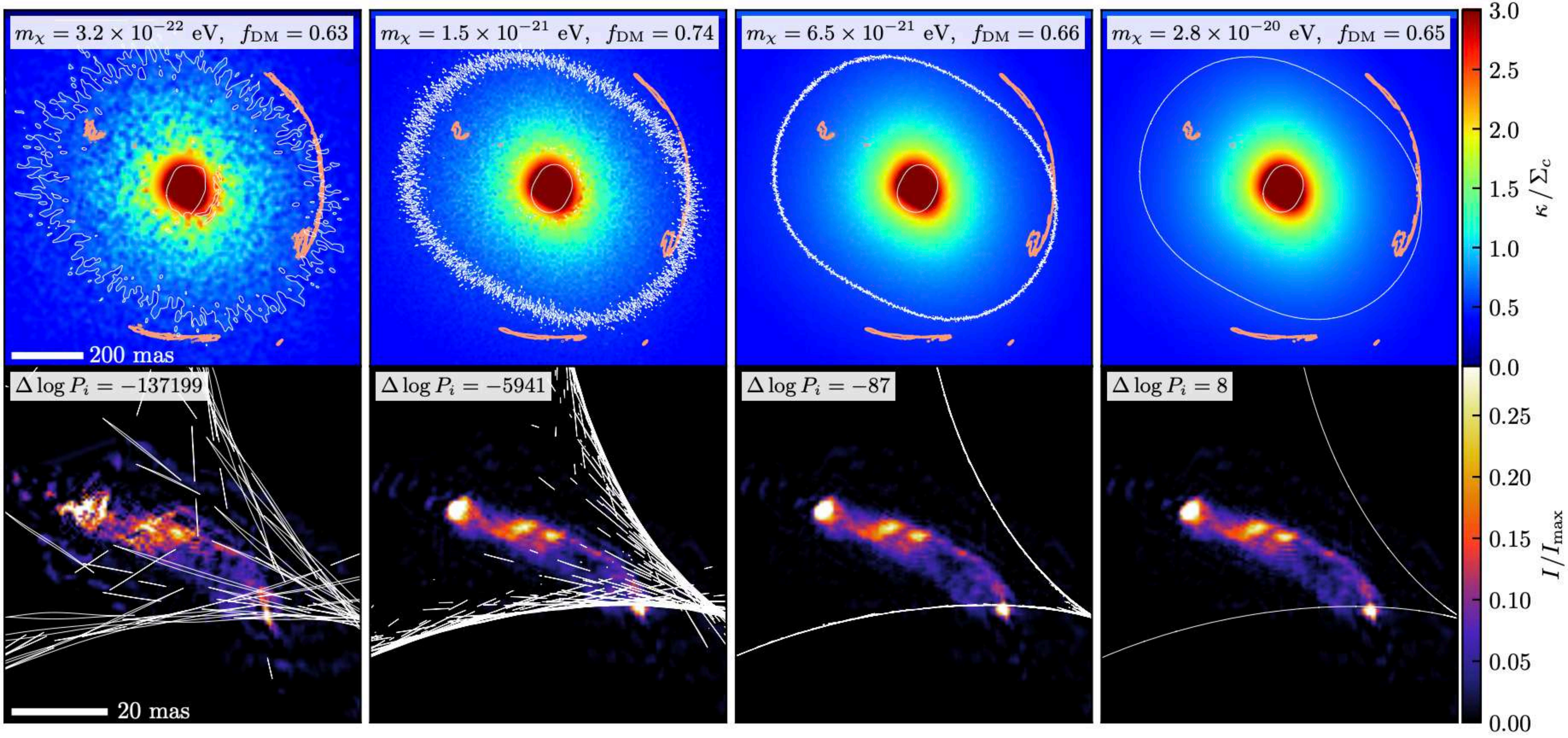




Very robust probe of ultra-light DM

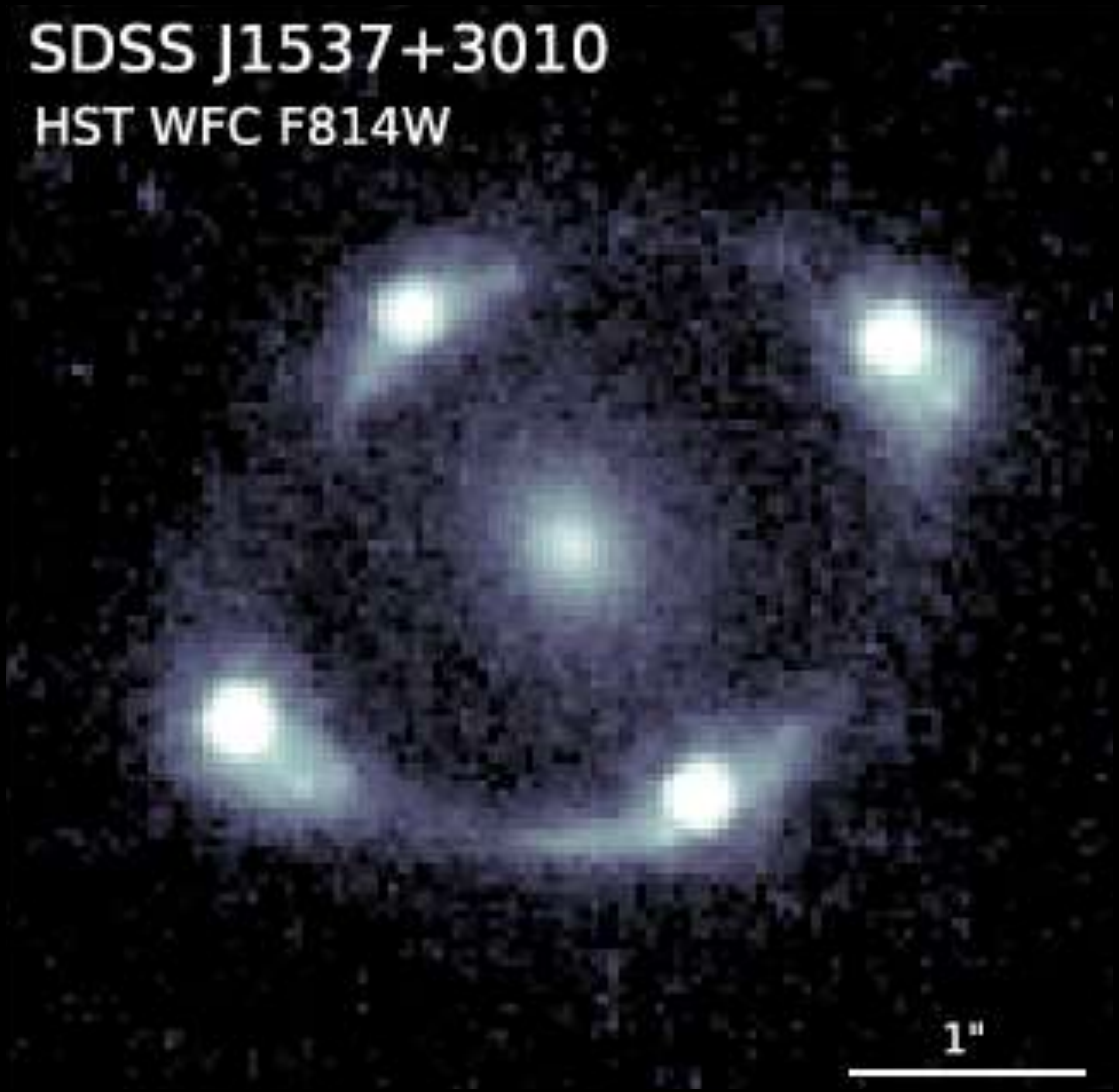


de Broglie wavelength ~kpc
-> wave interference effects on galactic scales



Constraint $m_\Psi > 3 \times 10^{-19}$eV (20:1 Bayes factor) Powell et al. (2022)

Early-type galaxy deflector + extended source



Early-type galaxy deflector
+ quasar and host galaxy

Strong lensing of compact sources

$$\text{time delays} \propto \Psi \ \left(\text{grav. potential}\right)$$

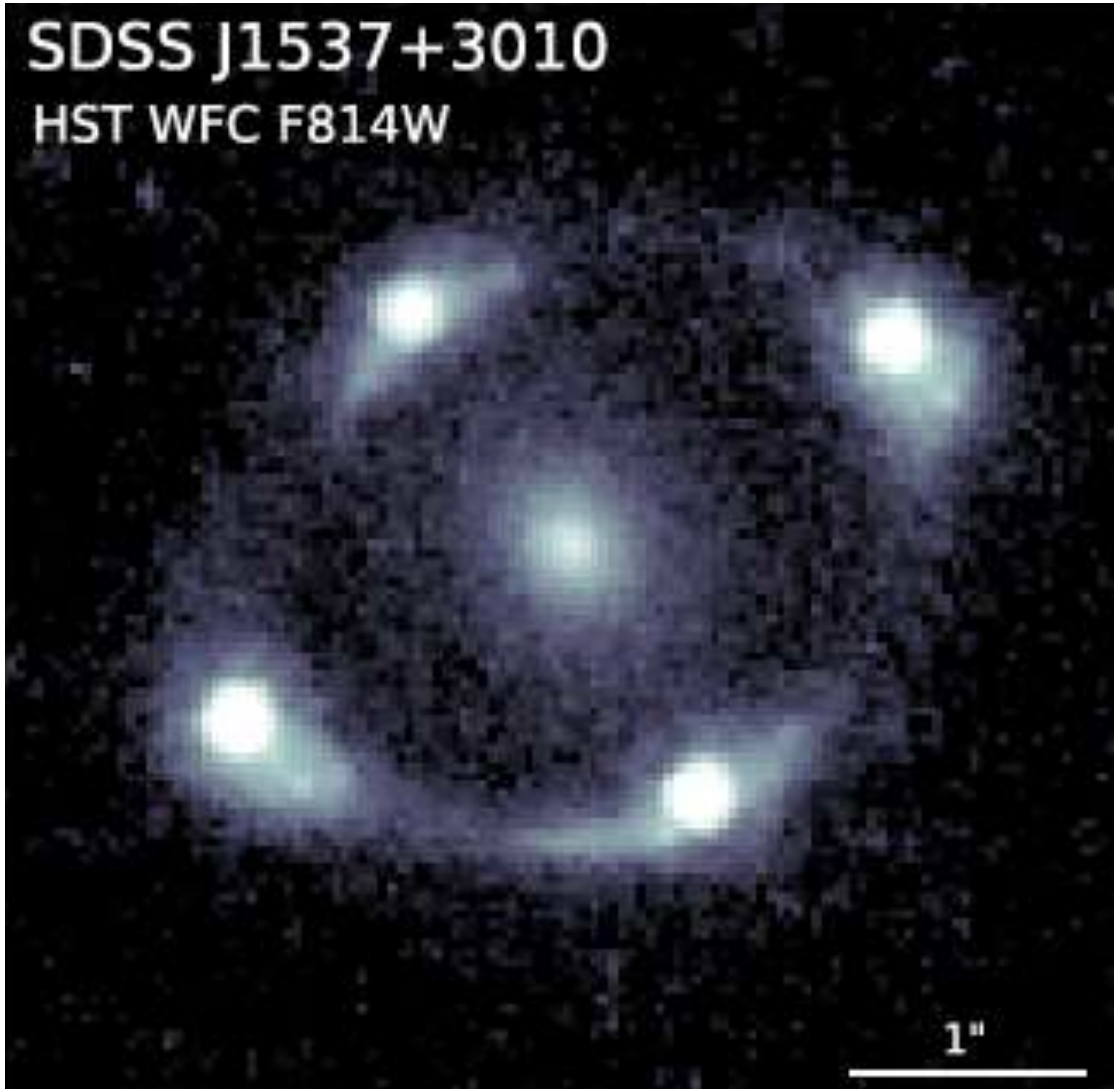
$$\text{image positions} \propto \frac{\partial \Psi}{\partial x}$$

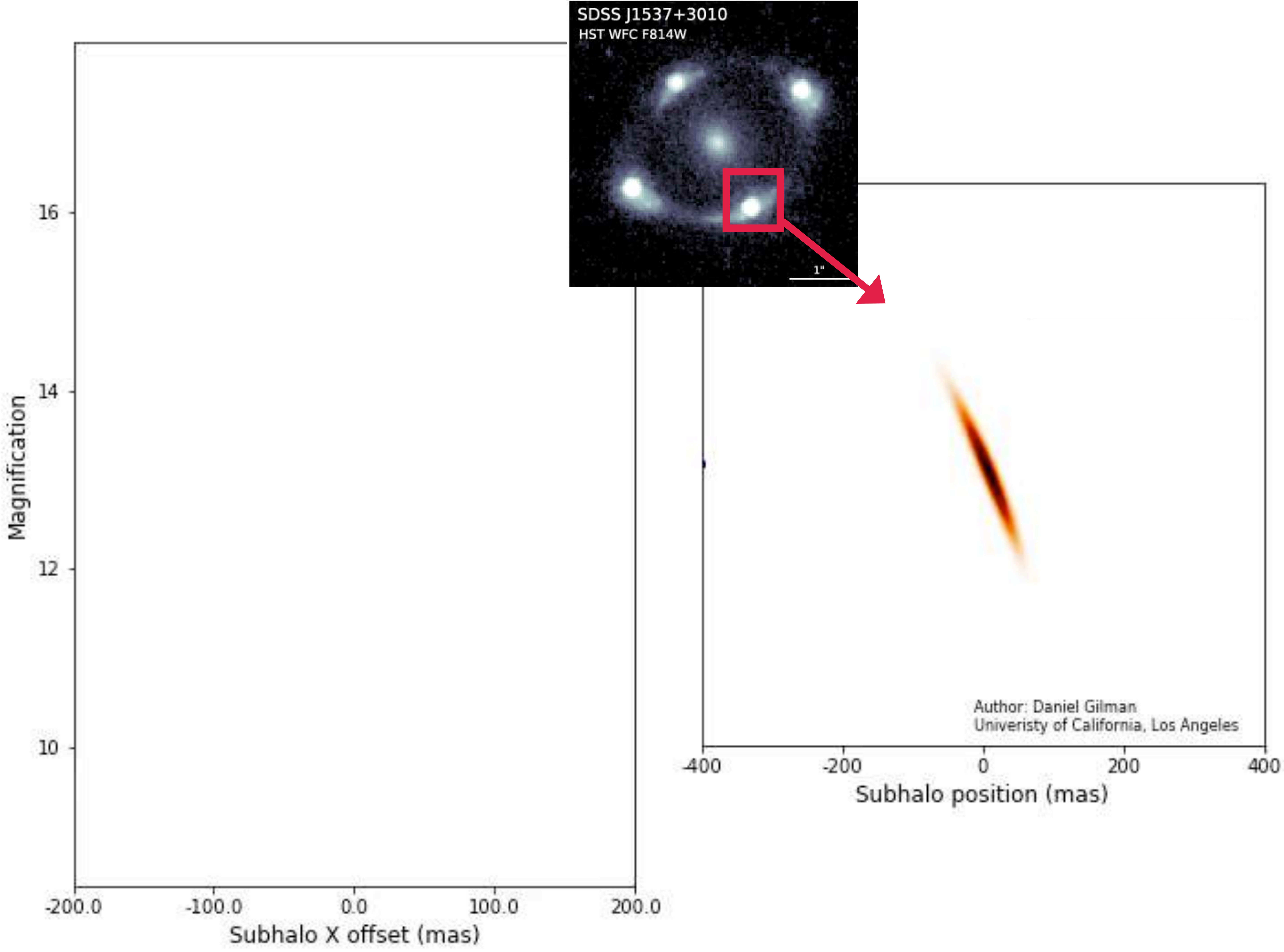
(or spatially-resolved lensed arcs)

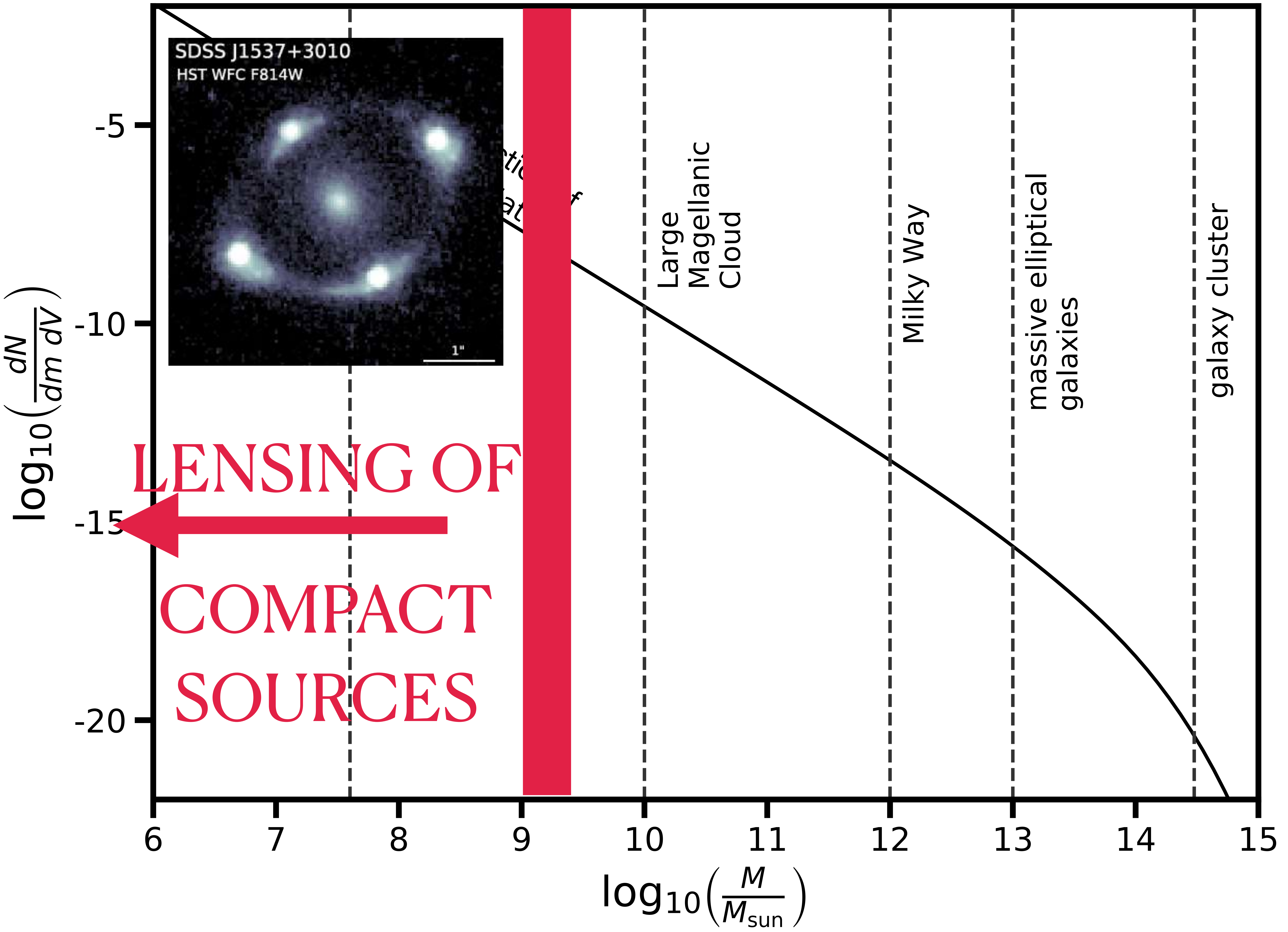
$$\text{magnifications} \propto \frac{\partial^2 \Psi}{\partial x^2} \propto \text{projected mass}$$

(of unresolved sources)

—> **sensitive to local perturbations to the mass distribution and small-scale structure in the lens and along line of sight**




SDSS J1537+3010
HST WFC F814W
1"
Magnification
16
14
12
10
-200.0
-100.0
0.0
100.0
200.0
Subhalo X offset (mas)
Author: Daniel Gilman
Univeristy of California, Los Angeles
-400
-200
0
200
400
Subhalo position (mas)



SDSS J1537+3010
HST WFC F814W
1"
Large Magellanic Cloud
Milky Way
massive elliptical galaxies
galaxy cluster
LENSING OF
COMPACT SOURCES
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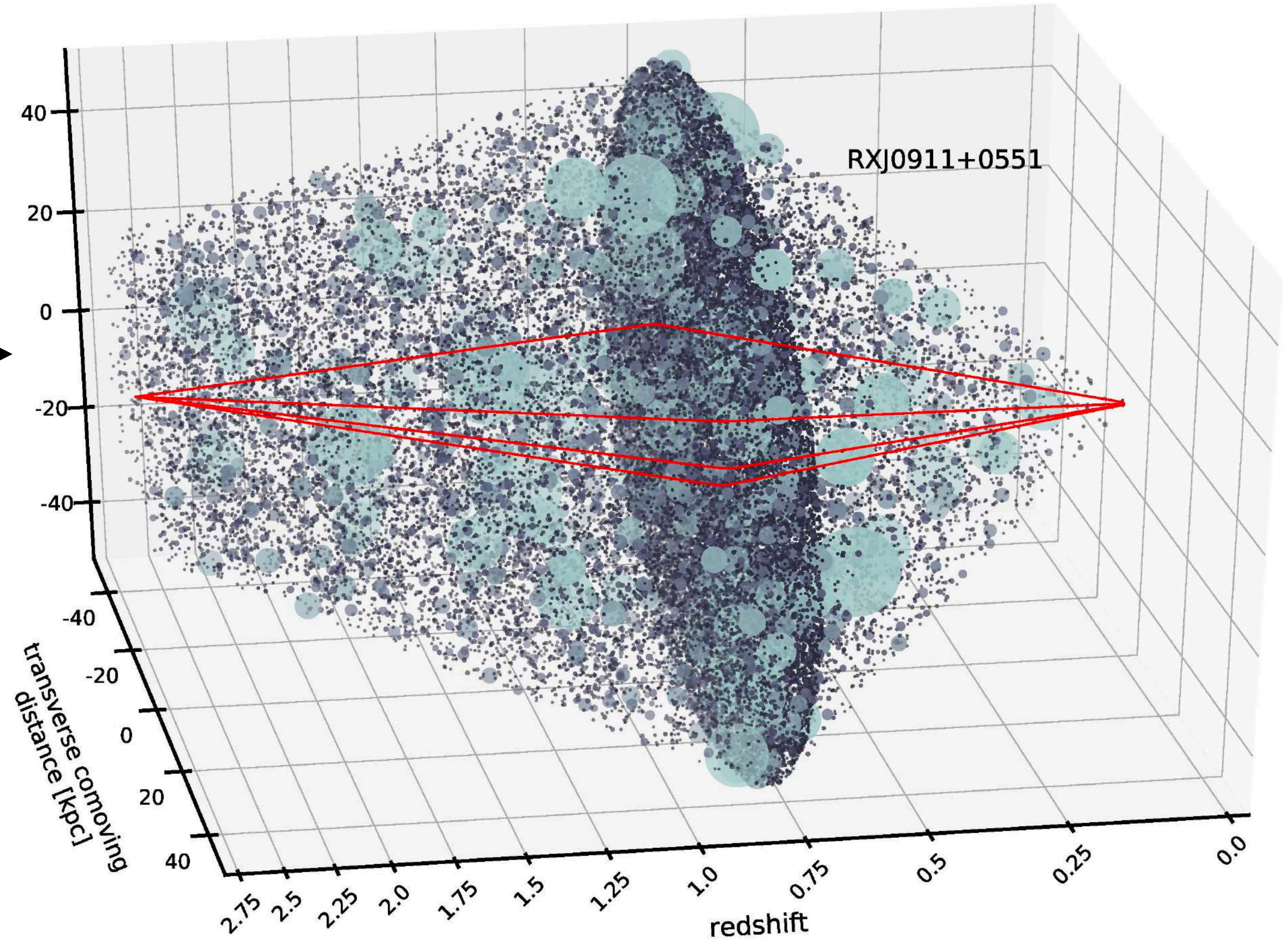
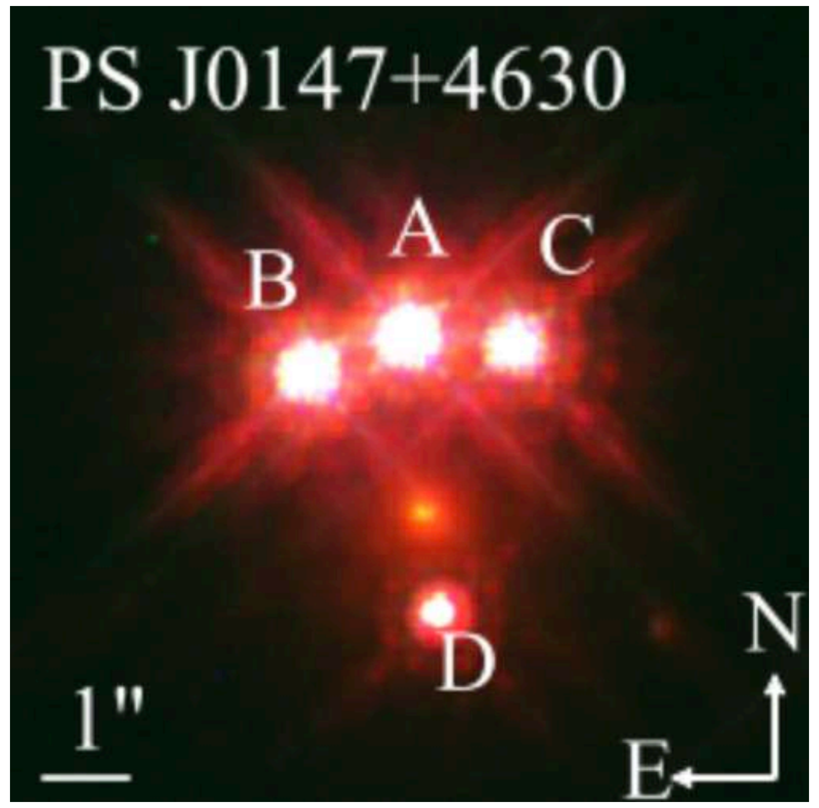
$\log_{10}\left(\frac{dN}{dm\,dV}\right)$
$\log_{10}\left(\frac{M}{M_{sun}}\right)$

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



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



Compare with data

Techniques developed/tested by Gilman et al. (2018, 2019)

Simulation ingredients

-> subhalo and line-of-sight halo modeling across 4 decades $\left(10^6 - 10^{10} M_\odot\right)$ of mass, and internal structure

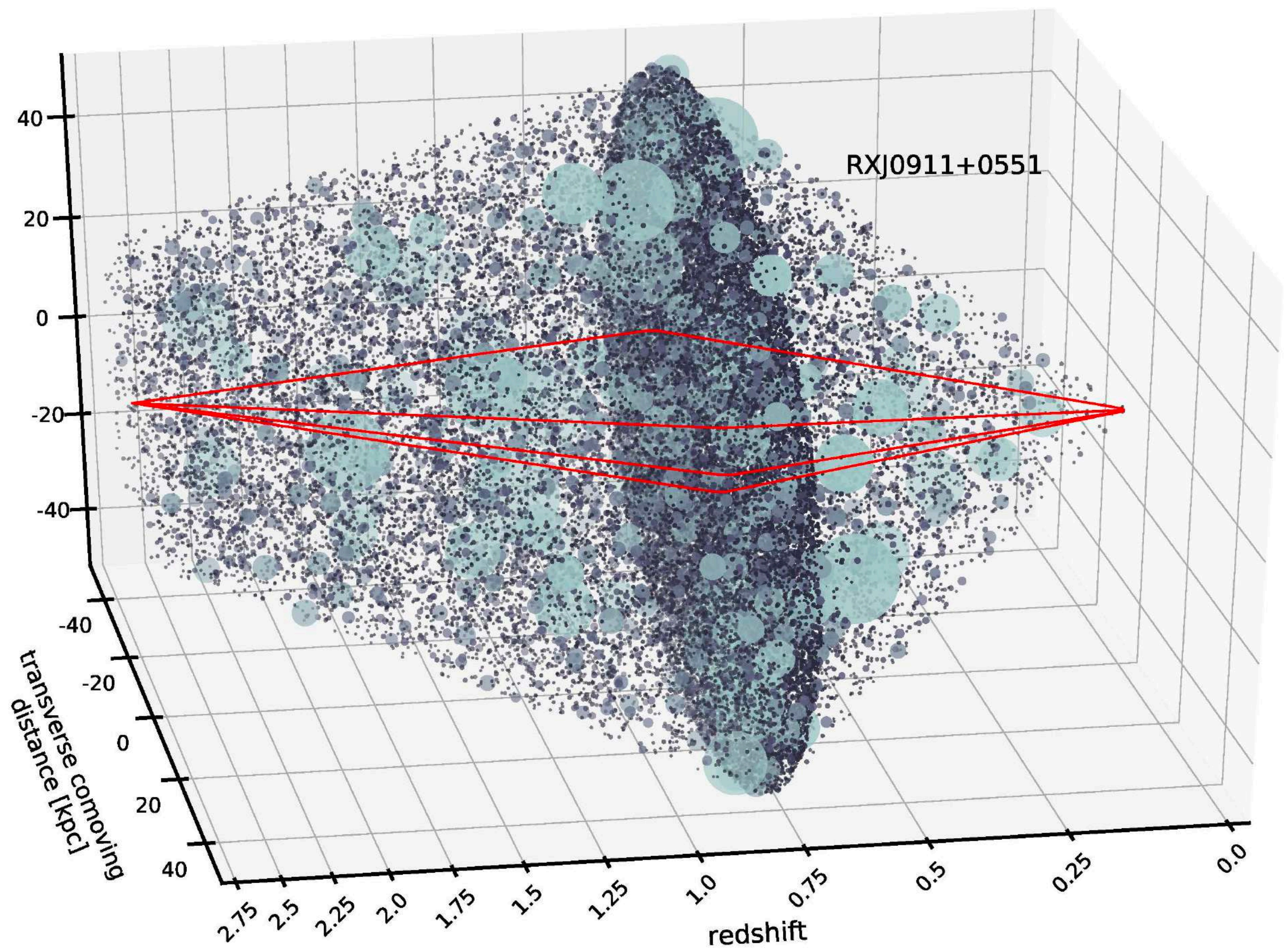
-> tidal evolution models for subhalos
(recent progress: Du, Gilman, et al. 2025)

-> dark matter physics in alternative theories to CDM

-> globular clusters

-> lens modeling considerations
including angular structure in the main deflector
(see Paugnat & Gilman 2025)

-> millions upon millions of CPU hours



Can apply these methods to a variety of models

- Warm dark matter

Gilman et al. (2019, 2020) arXiv: 1901.11031, 1908.06983
Keeley, Nierenberg, Gilman et al. (2024) arXiv: 2405.01620
Keeley, Nierenberg, Gilman et al. (2023) arXiv: 2301.07265

- Self-interacting dark matter

Gilman et al. (2021, 2022)
arXiv: 2105.05259 & 2207.13111

- Fuzzy dark matter

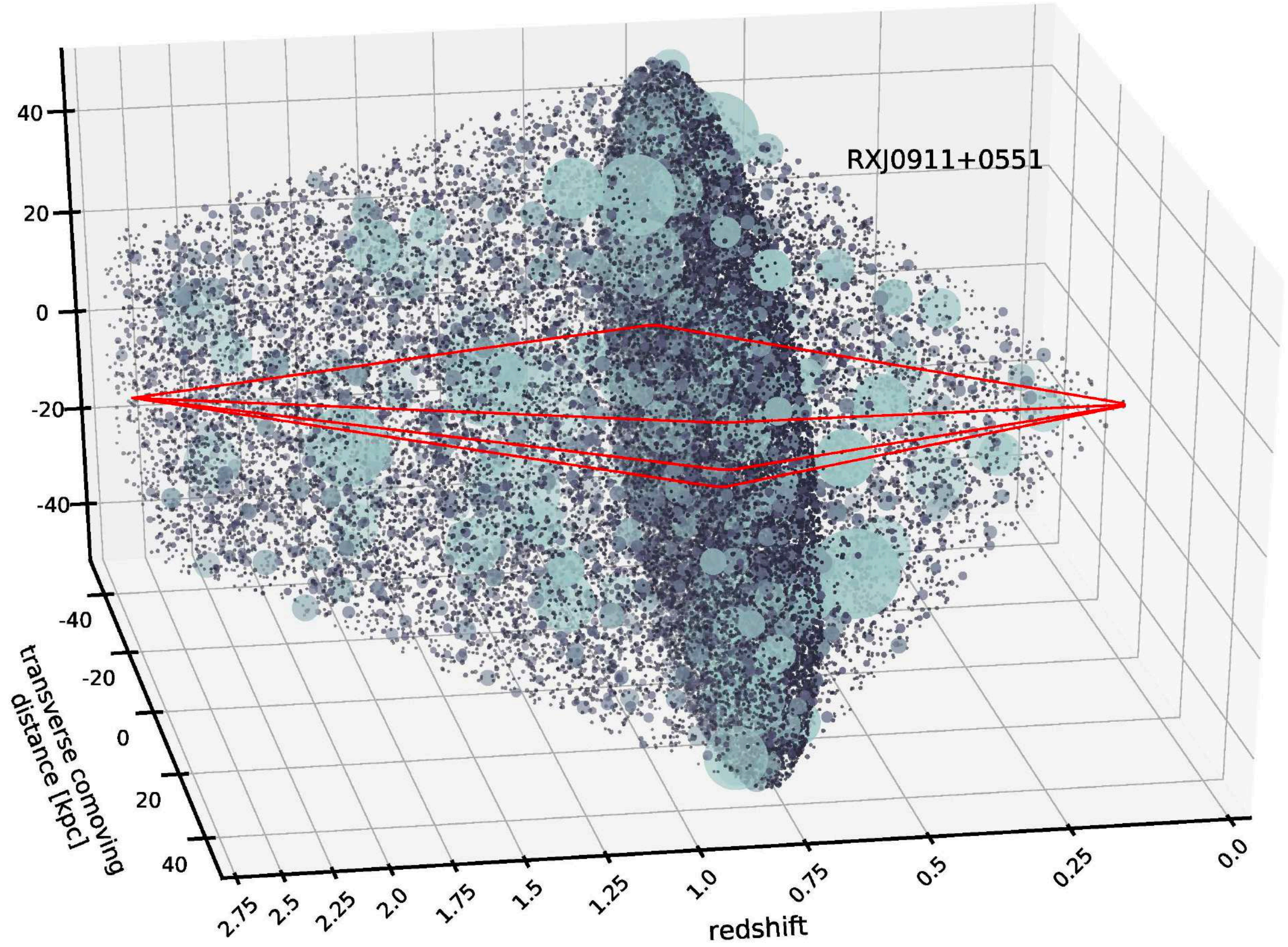
Laroche, Gilman et al. (2022)
arXiv: 2206.11269

- Primordial power spectrum

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

- Black holes

Dike, Gilman et al. (2022) arXiv: 2210.09493



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

CDM

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

Warm dark matter (WDM)

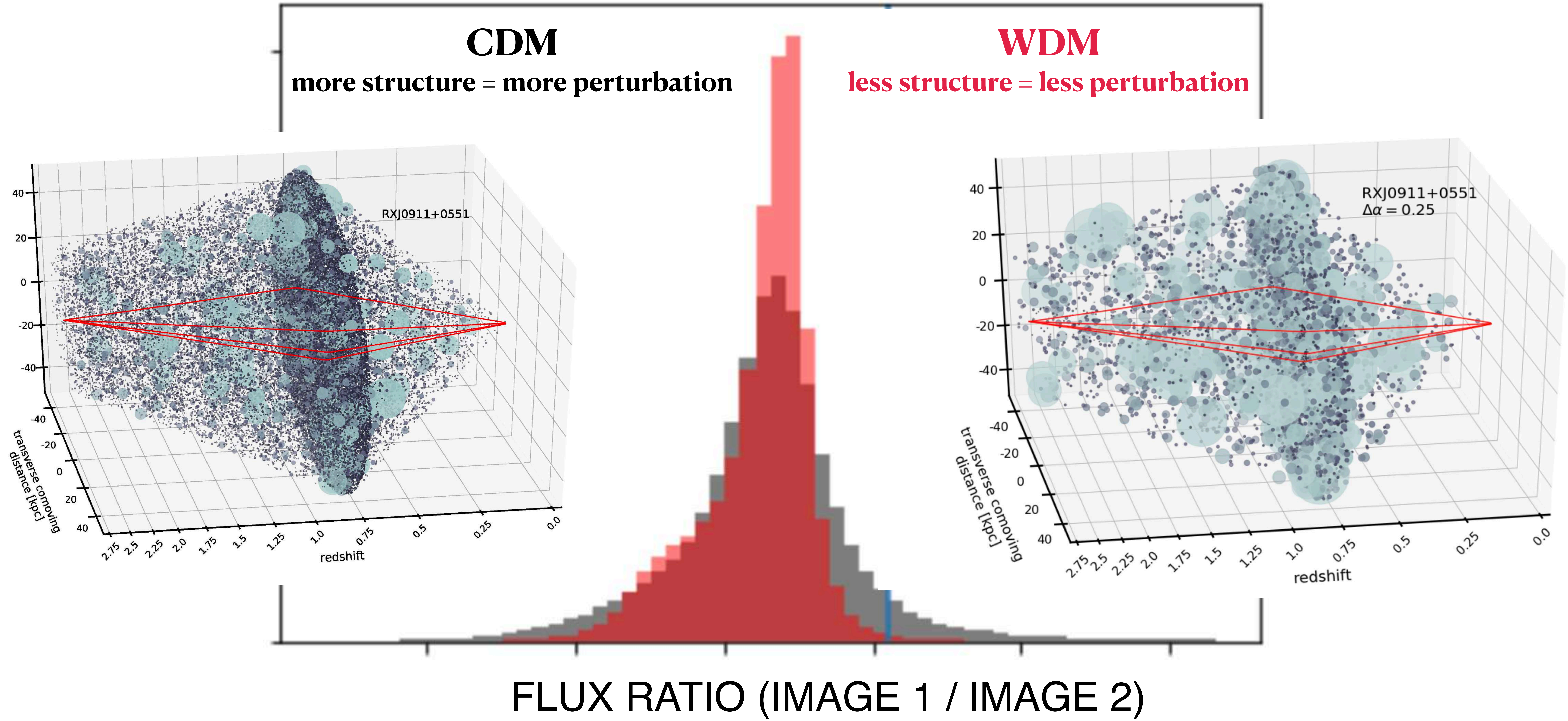
- No structure below a cutoff scale
- halo concentrations suppressed below cutoff

Simulation pipeline example: 2) forward model the data

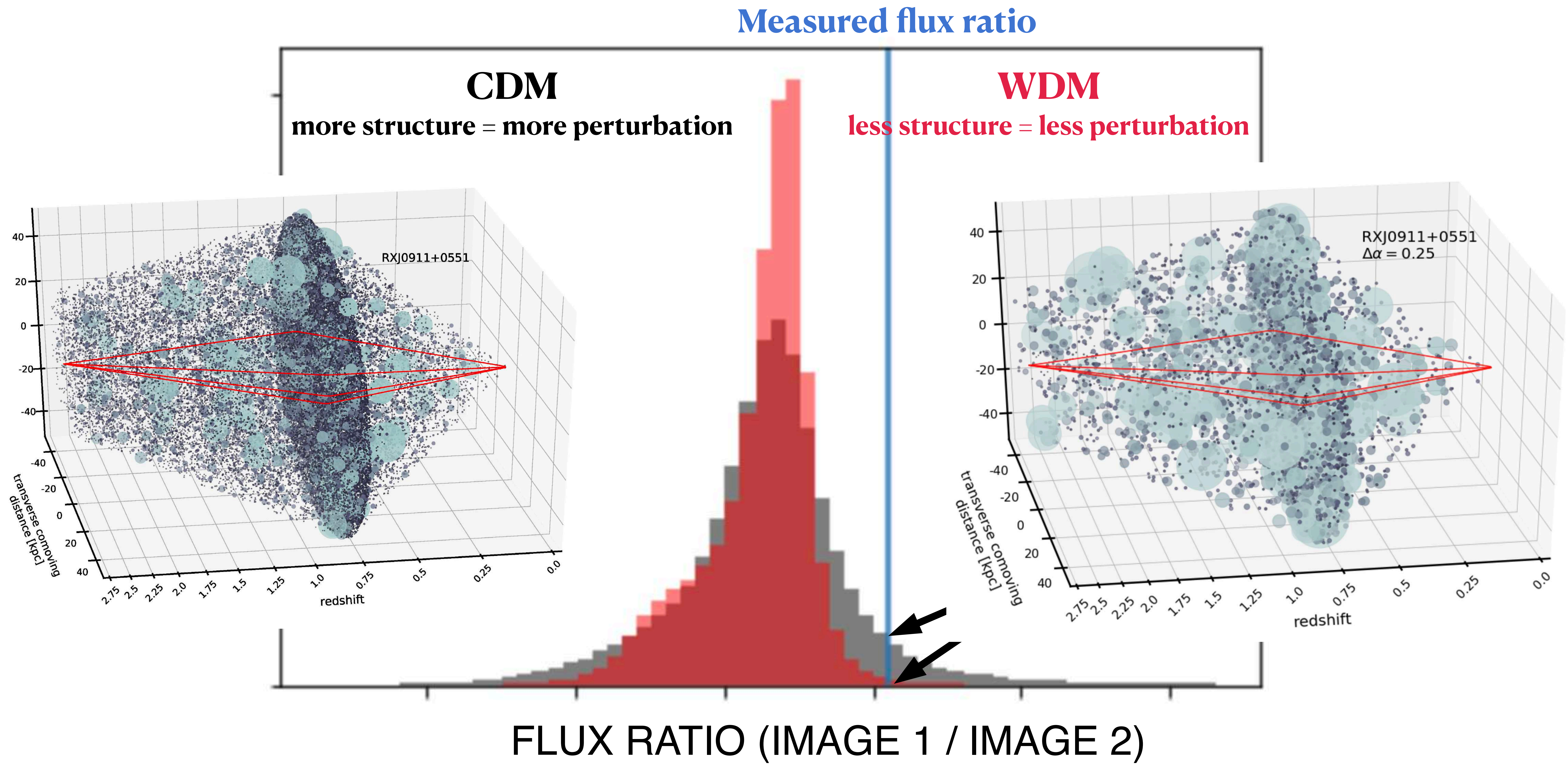
$\sim 10^5 - 10^6$ simulations per lens for accurate statistics

CDM **WDM**

Simulation pipeline example: 2) forward model the data



Simulation pipeline example: 3) derive likelihoods



First application to WDM

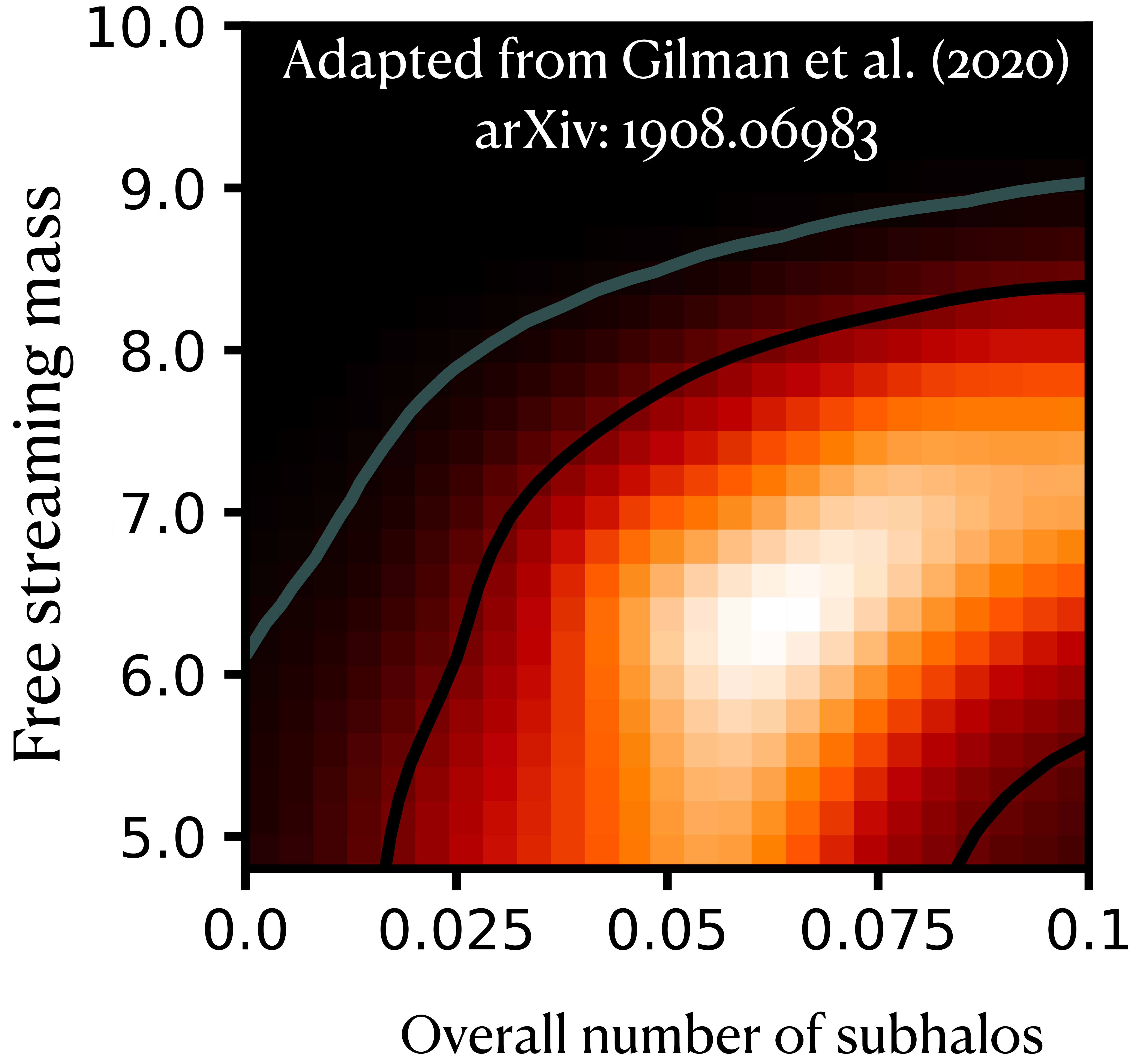
Gilman, et al. (2020)

Used narrow-line flux ratios in 8 lenses from Nierenberg et al. (2014, 2017, 2020)

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

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

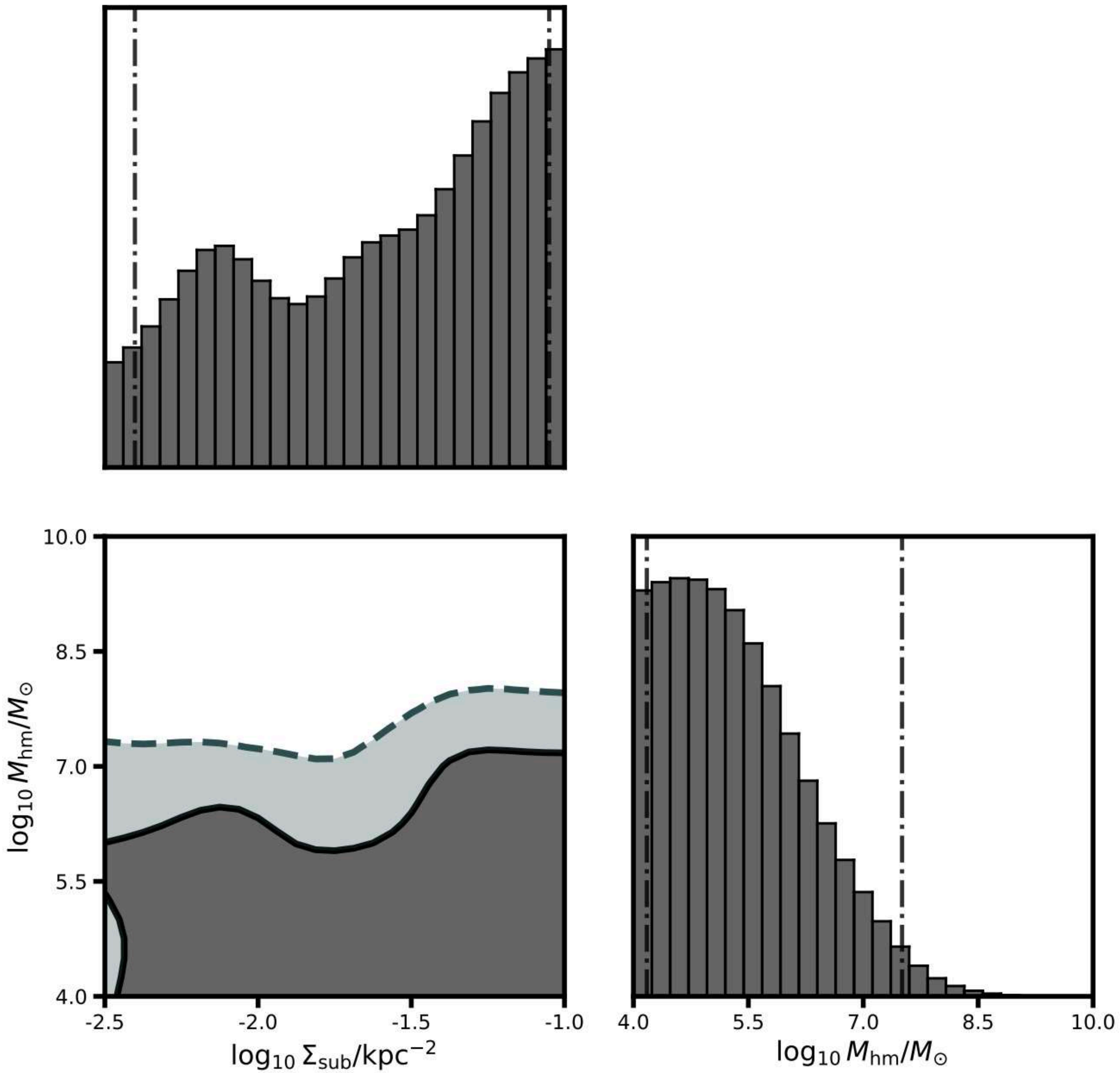
$$m_{\text{thermal}} > 9.7\text{keV}$$



Early results from JWST lensed quasar DM survey

(will discuss this later)

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



All code is open source/public

In particular:

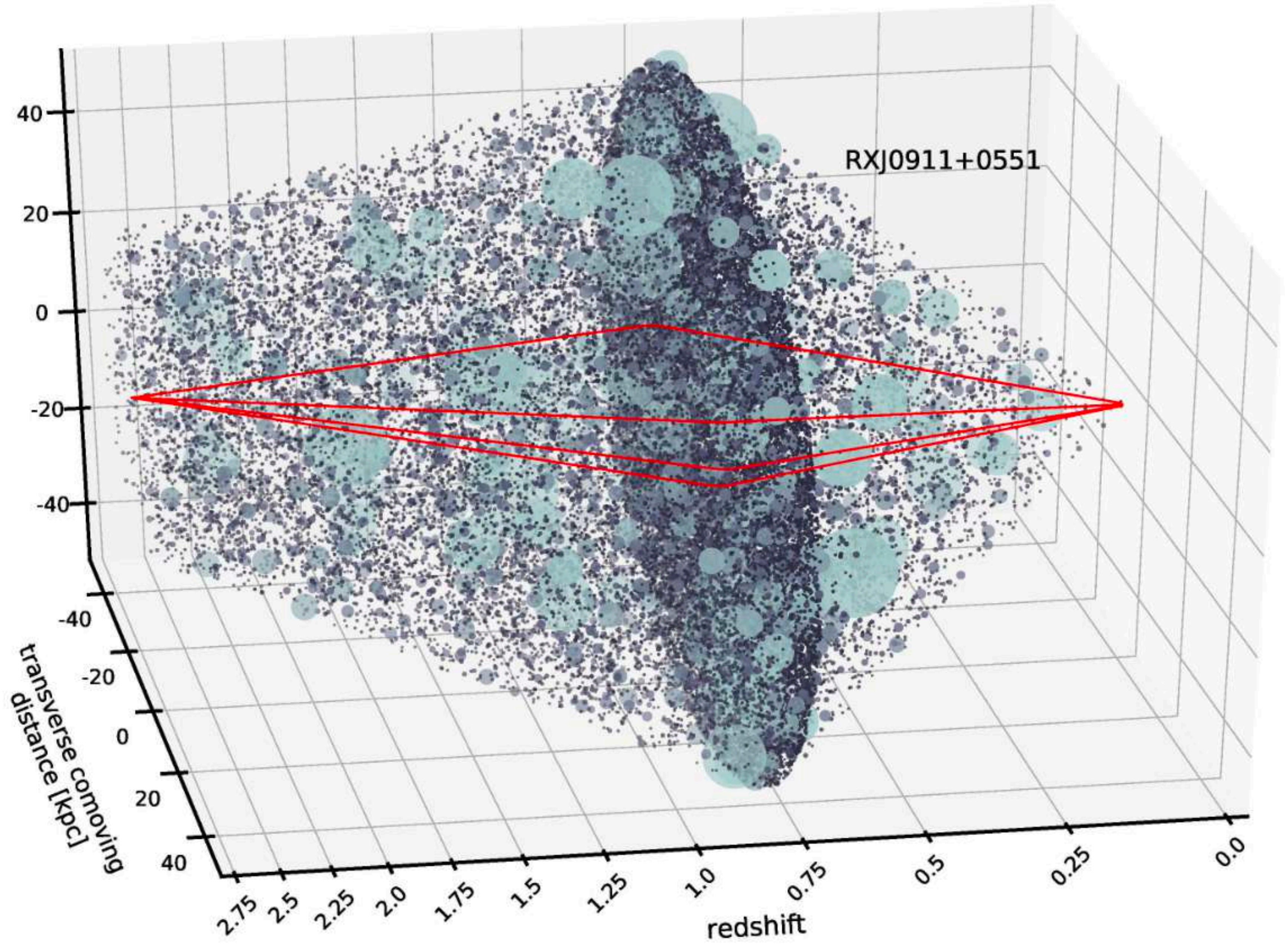
`pyHalo`

- generates full subhalo and line-of-sight halo populations in seconds
- Has a variety of mass
- profiles & DM models
- Accurate tidal stripping models
- designed for use with `lenstronomy`

https://github.com/dangilman/pyHalo

pyHalo

codecov 91% | pypi package 1.4.0



pyHalo renders full mass distributions for substructure lensing simulations with the open source gravitational lensing software package lenstronomy (https://github.com/lenstronomy/lenstronomy). The example notebooks illustrate the core functionality of this package.

If you would like to use this package and have questions, please get in touch with me at gilmanda@uchicago.edu - I am happy to help!

Installation

Install via pypi: "python3 -m pip install pyhalo". The installation via pip of versions after 1.2.0 includes some

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3) What does the future hold?

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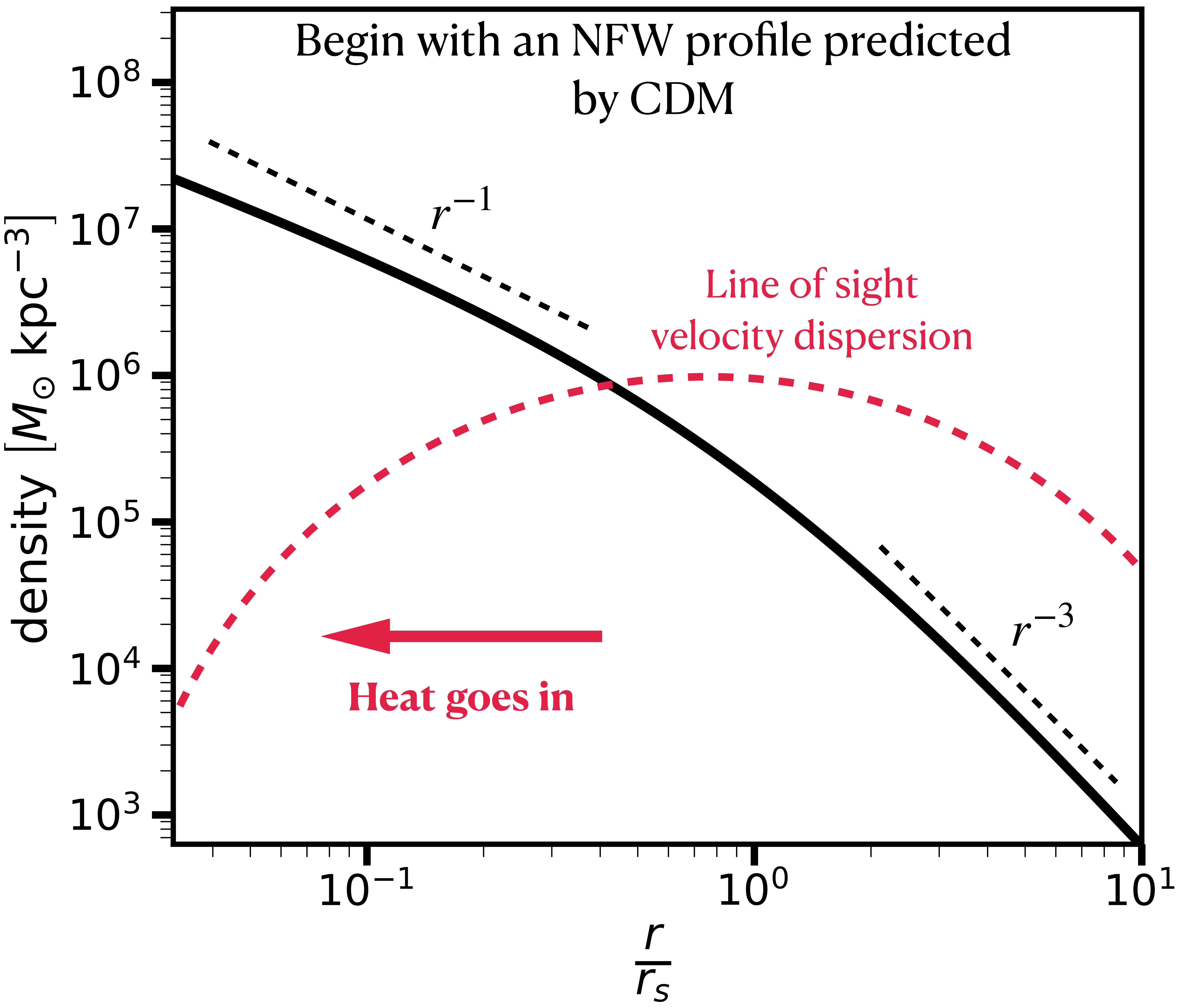
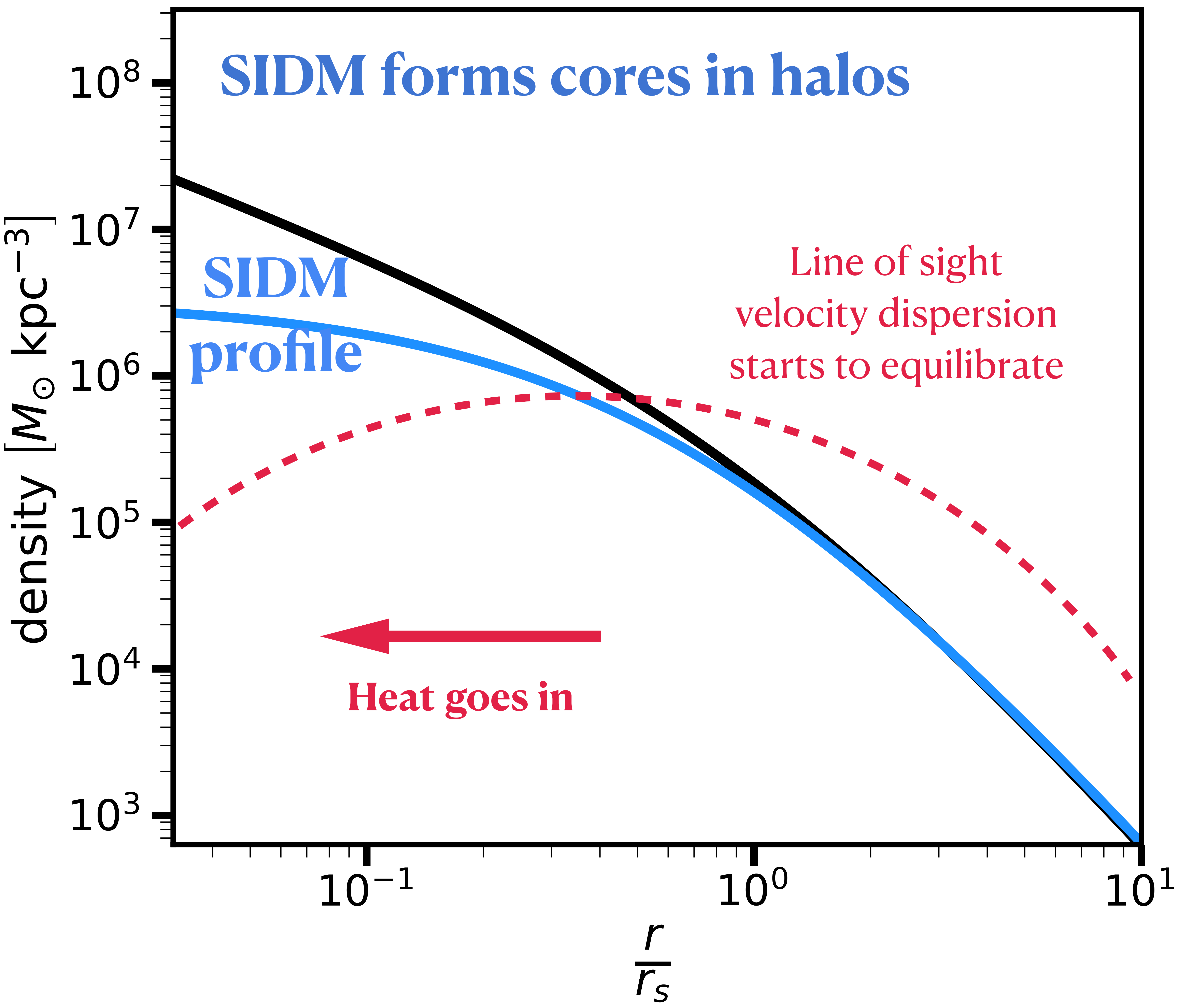
-> better analysis methods

-> more lenses

Effects of SIDM on halo density profiles



Effects of SIDM on halo density profiles



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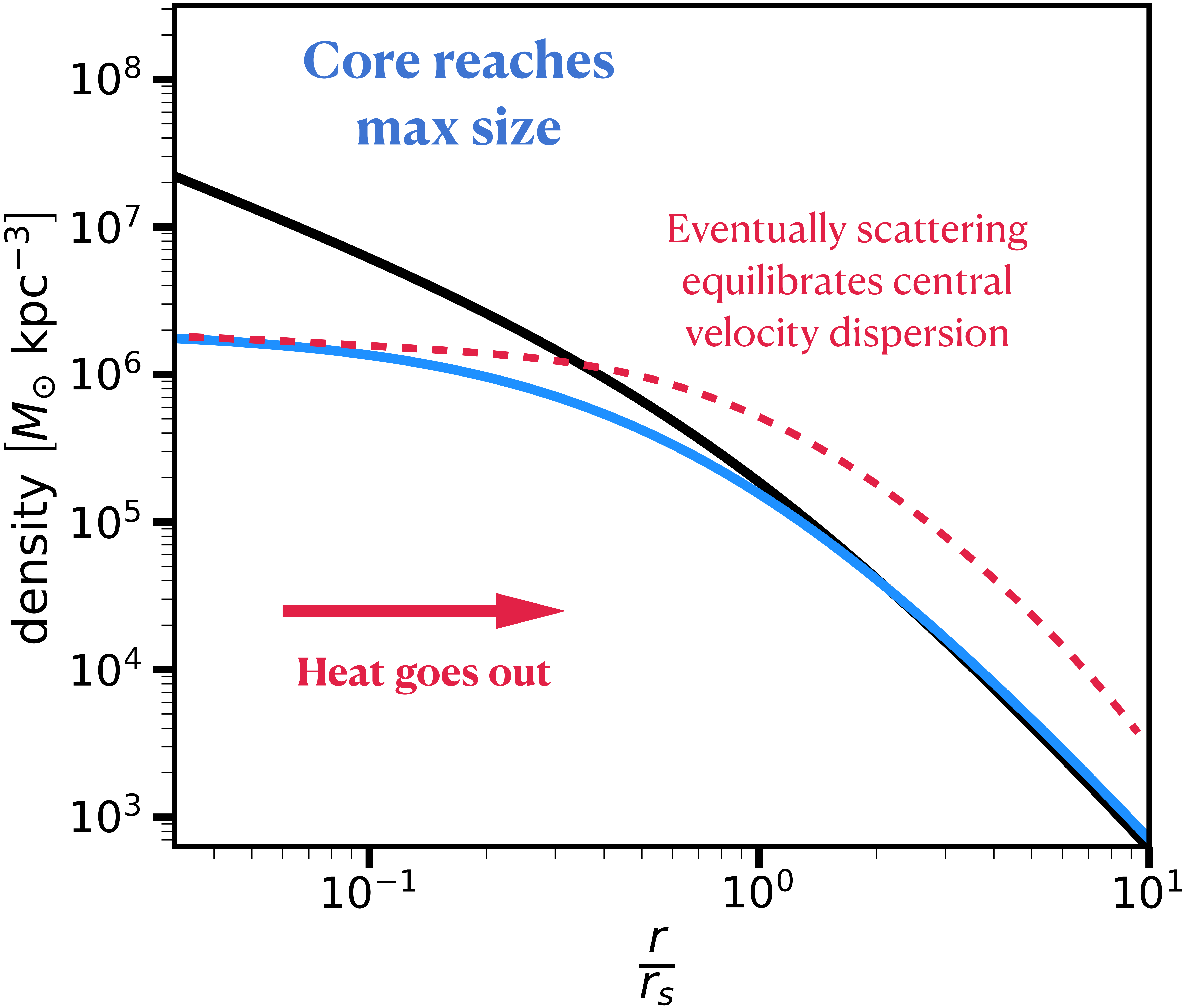
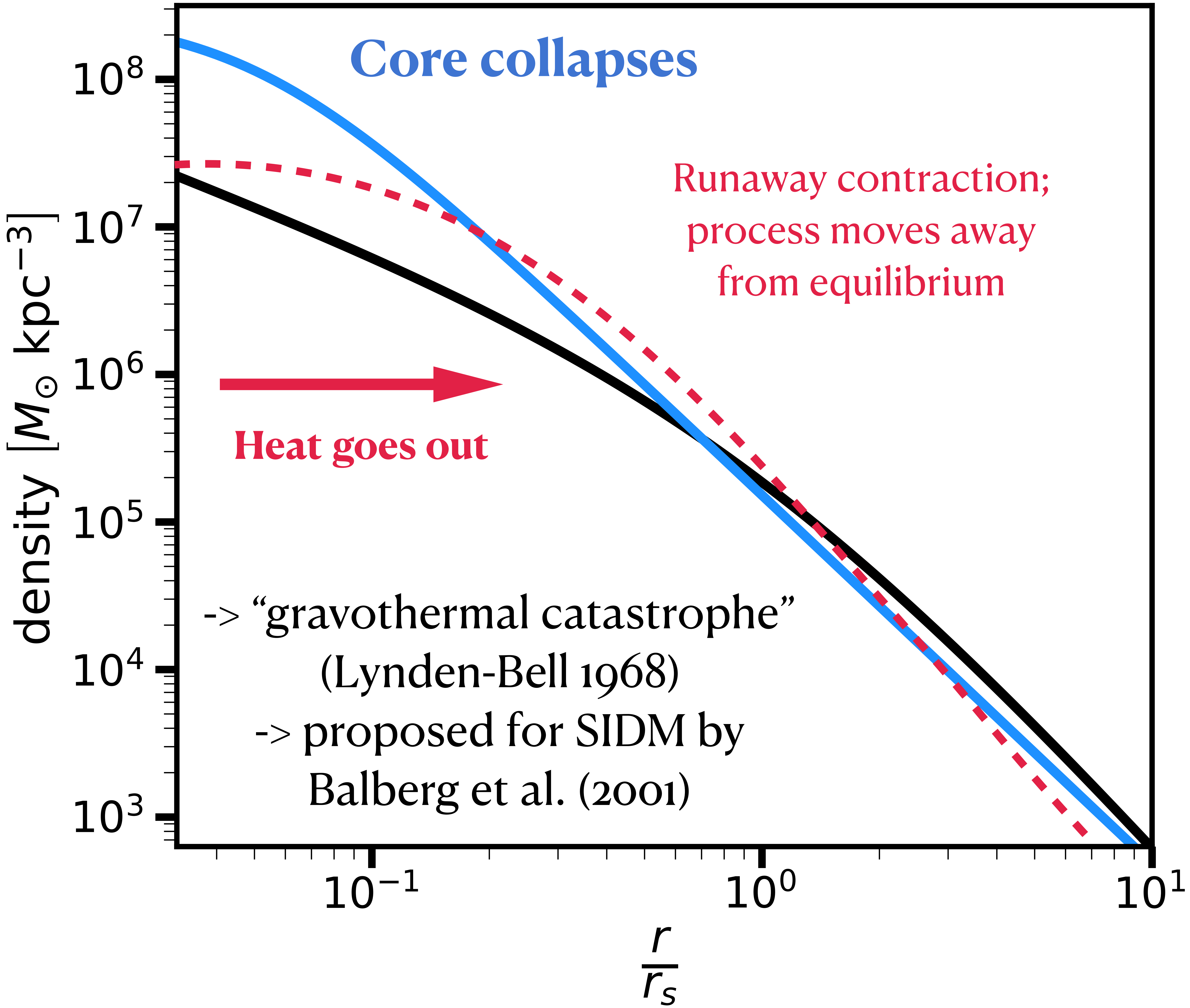
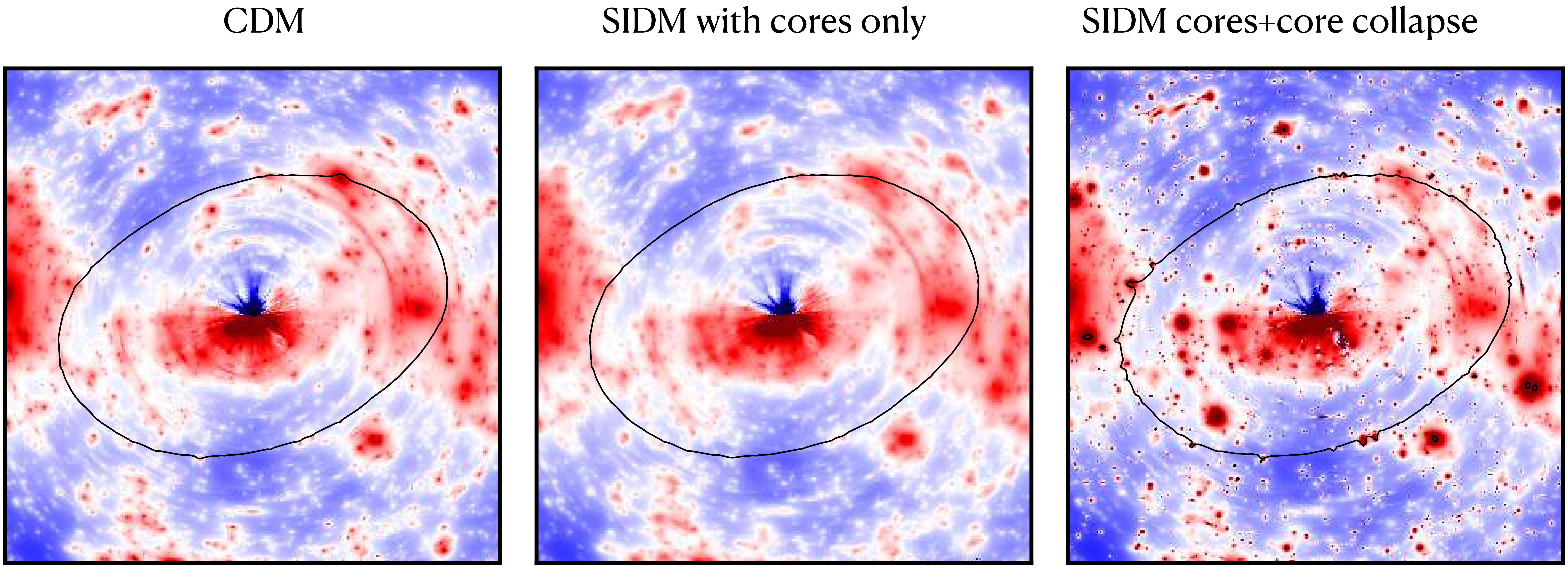


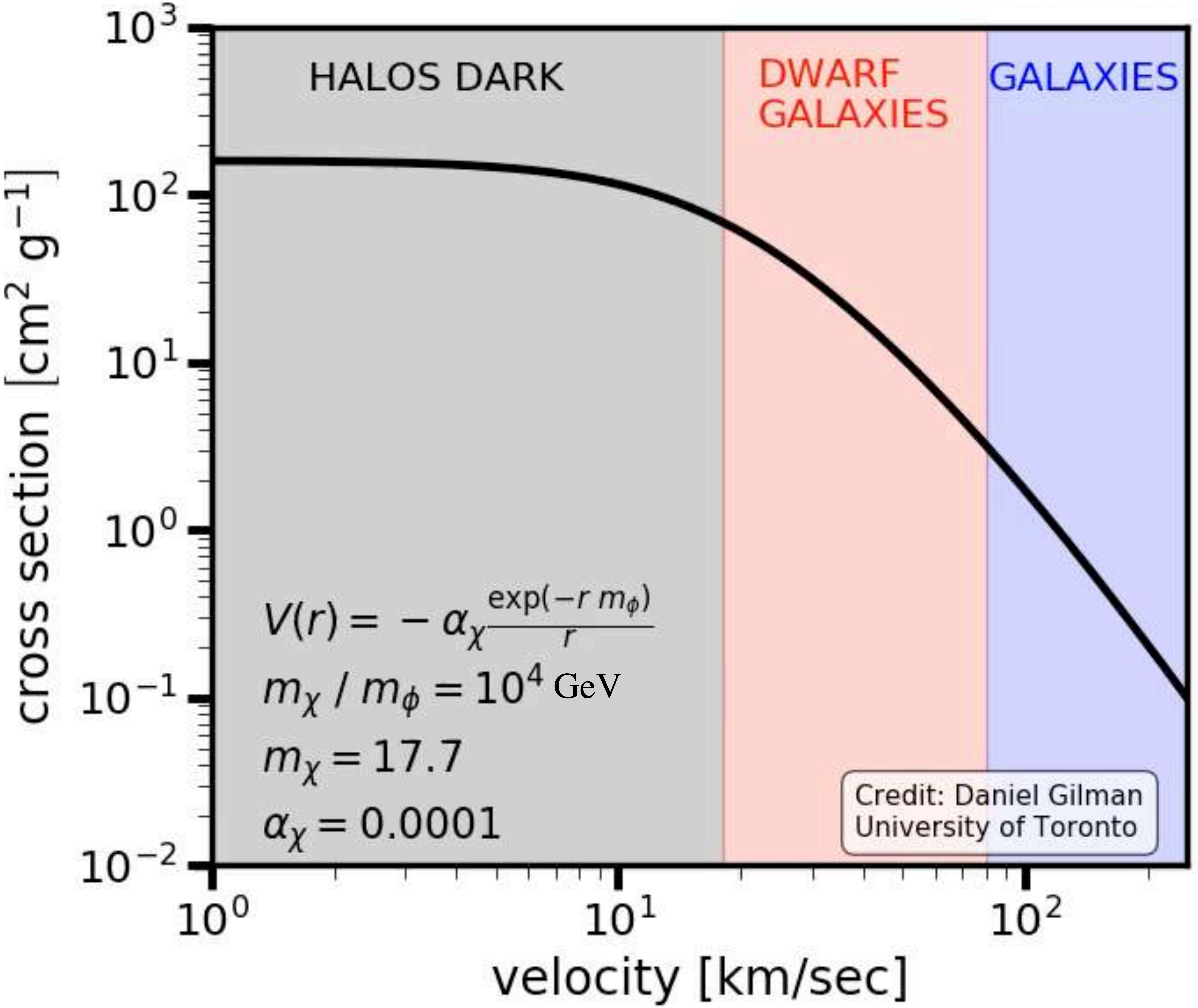
Effects of SIDM on halo density profiles




CDM
SIDM with cores only
SIDM cores+core collapse

Core-collapse requires large cross sections which arise naturally in SIDM w/light mediators

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



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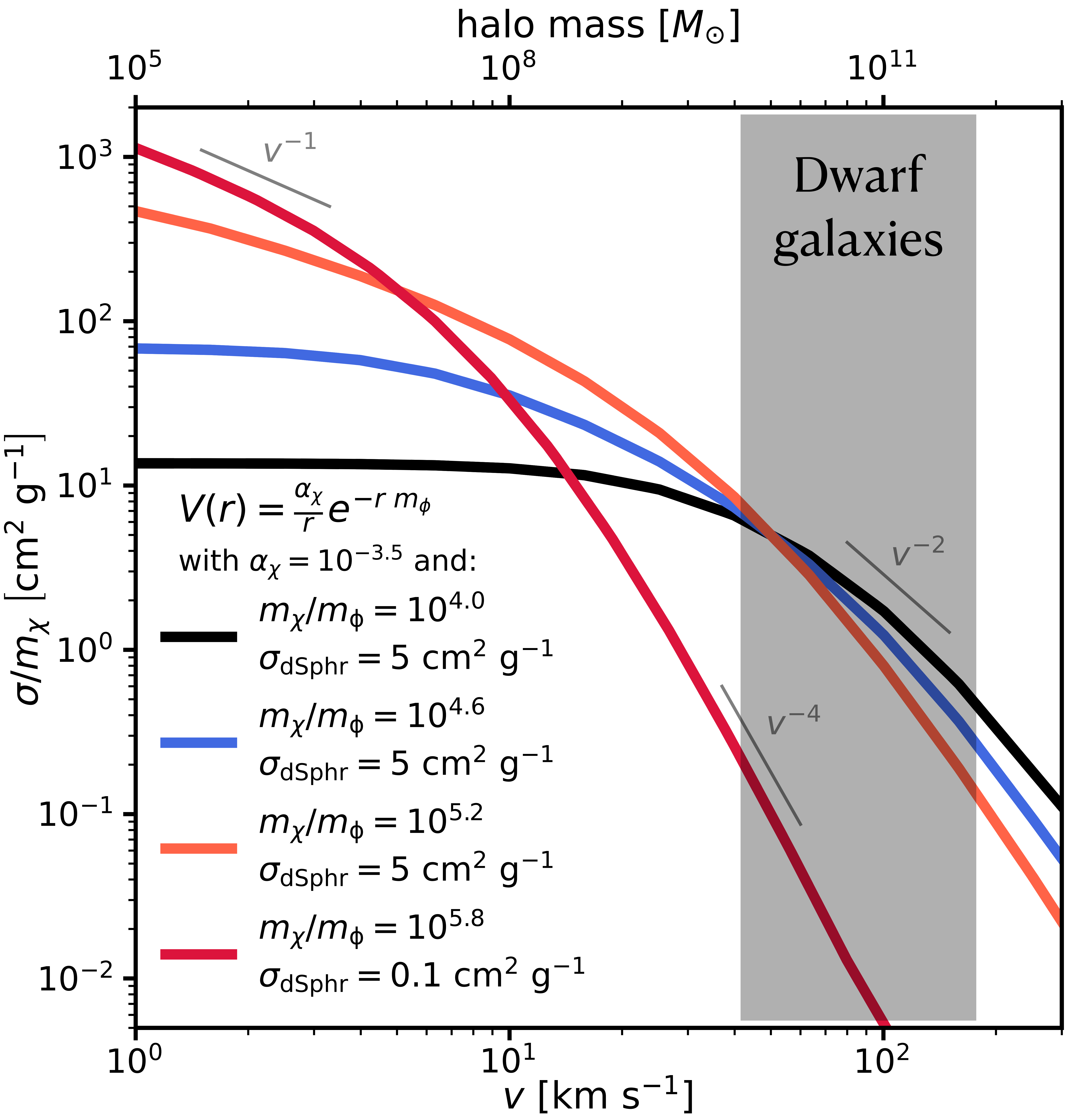
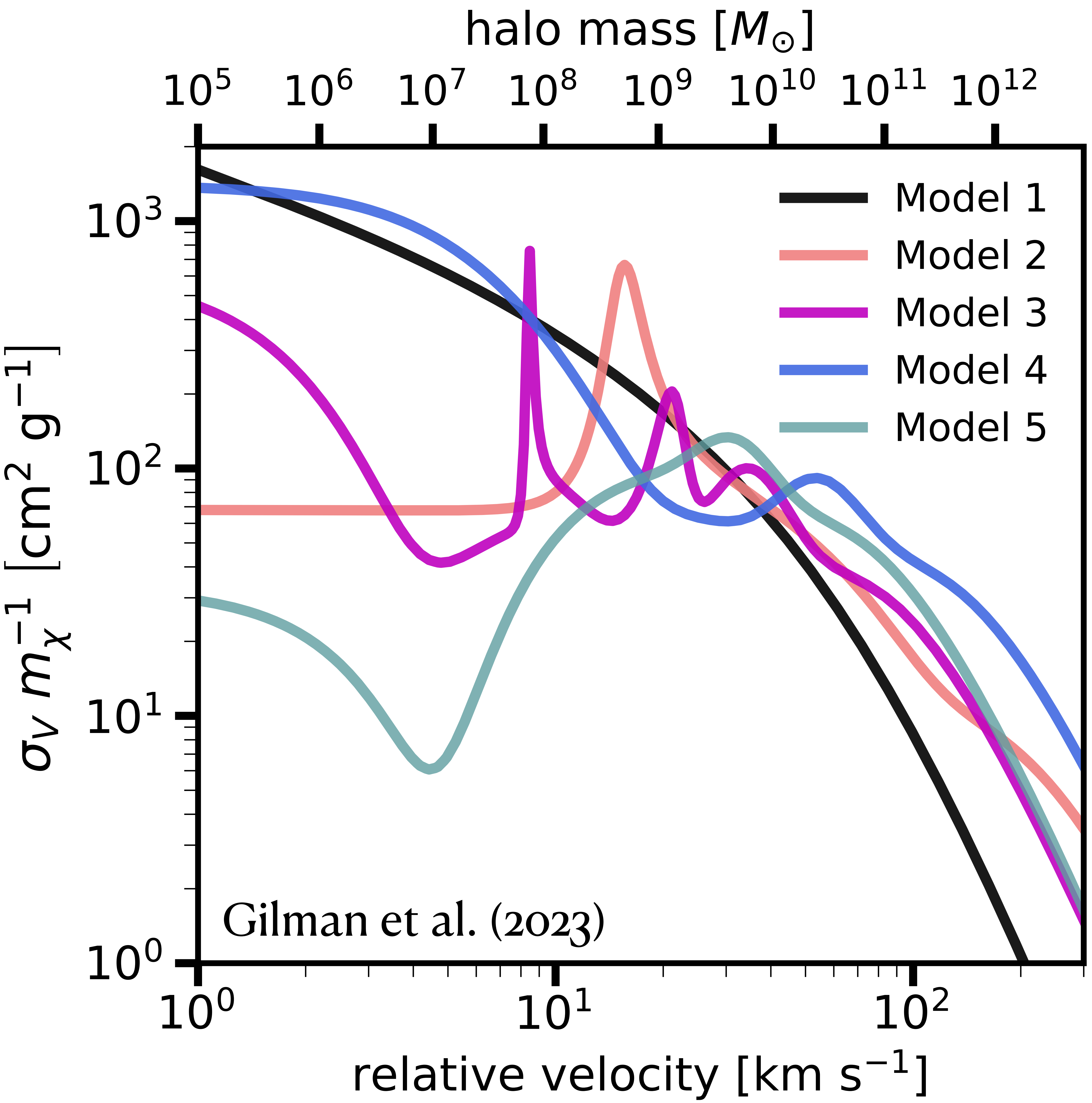


Constraints from lensing on these models currently disfavor scenarios with a majority of subhalos+field halos collapsing

see Gilman, Zhong, & Bovy (2023) 2207.13111



characteristic collapse timescale

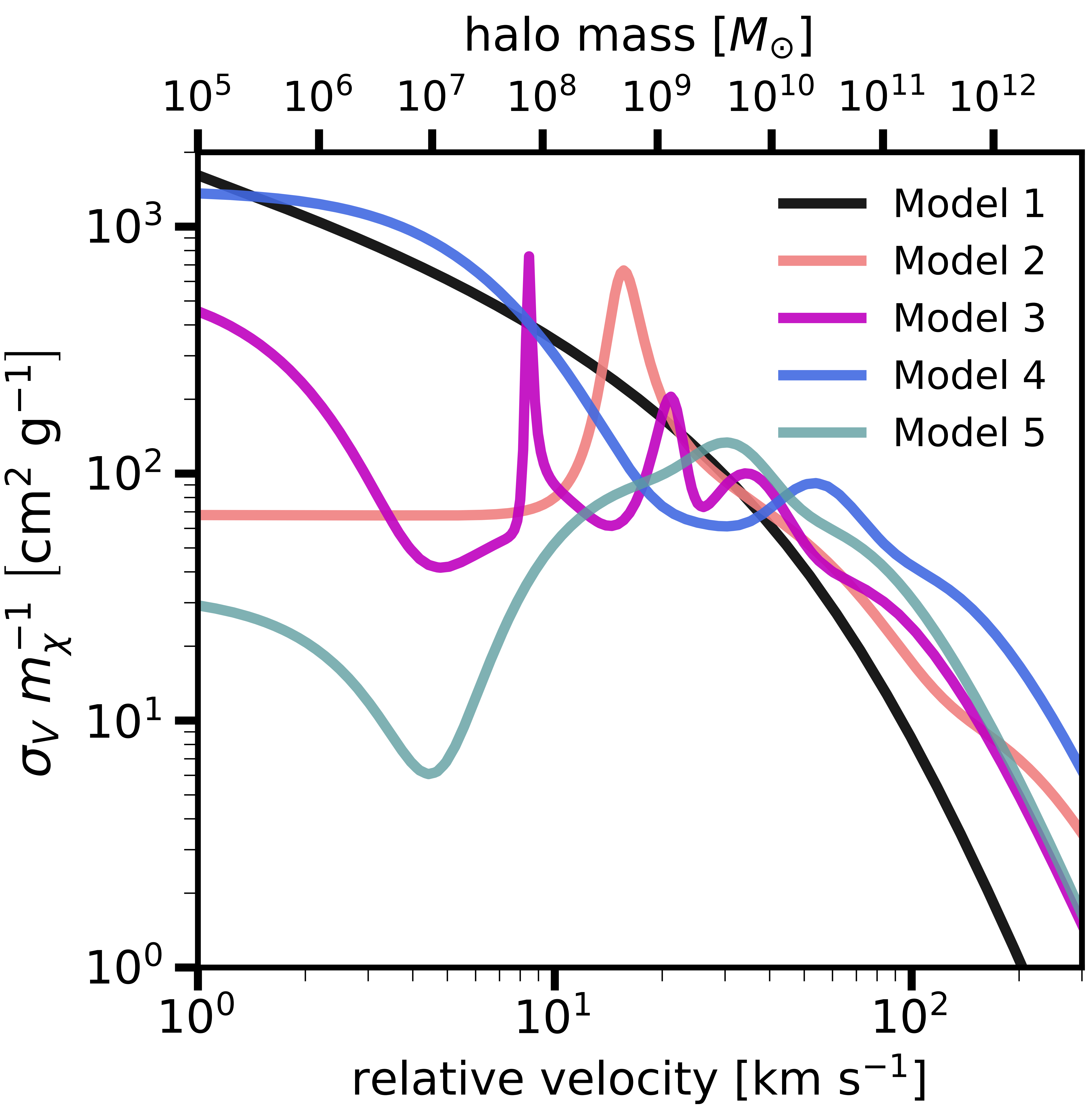
$t_0^{-1} \sim \langle \sigma v^5 \rangle / \langle v^5 \rangle \times \text{density} \times \text{velocity}$

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

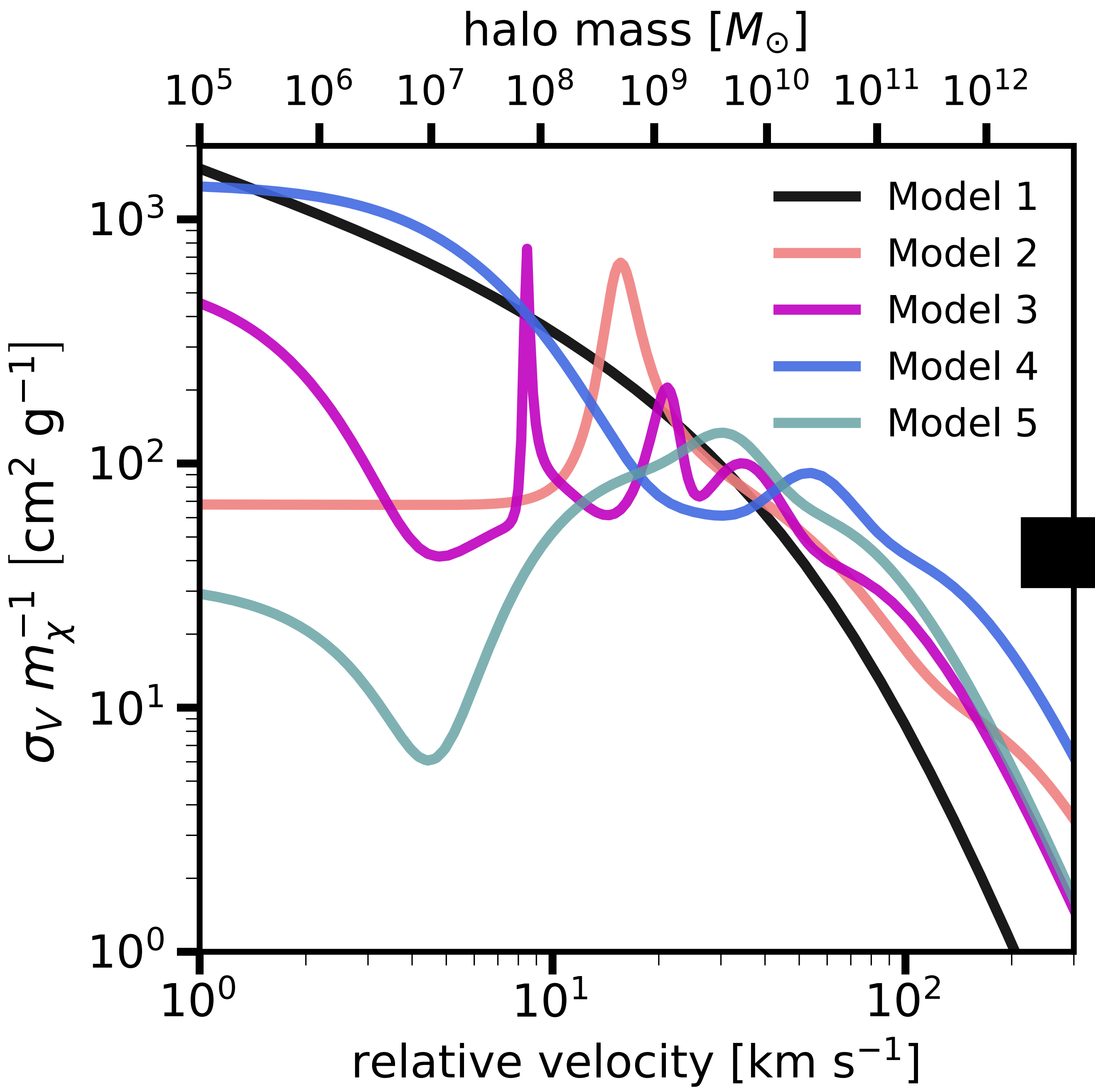
Halos collapse after some multiple of the timescale

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

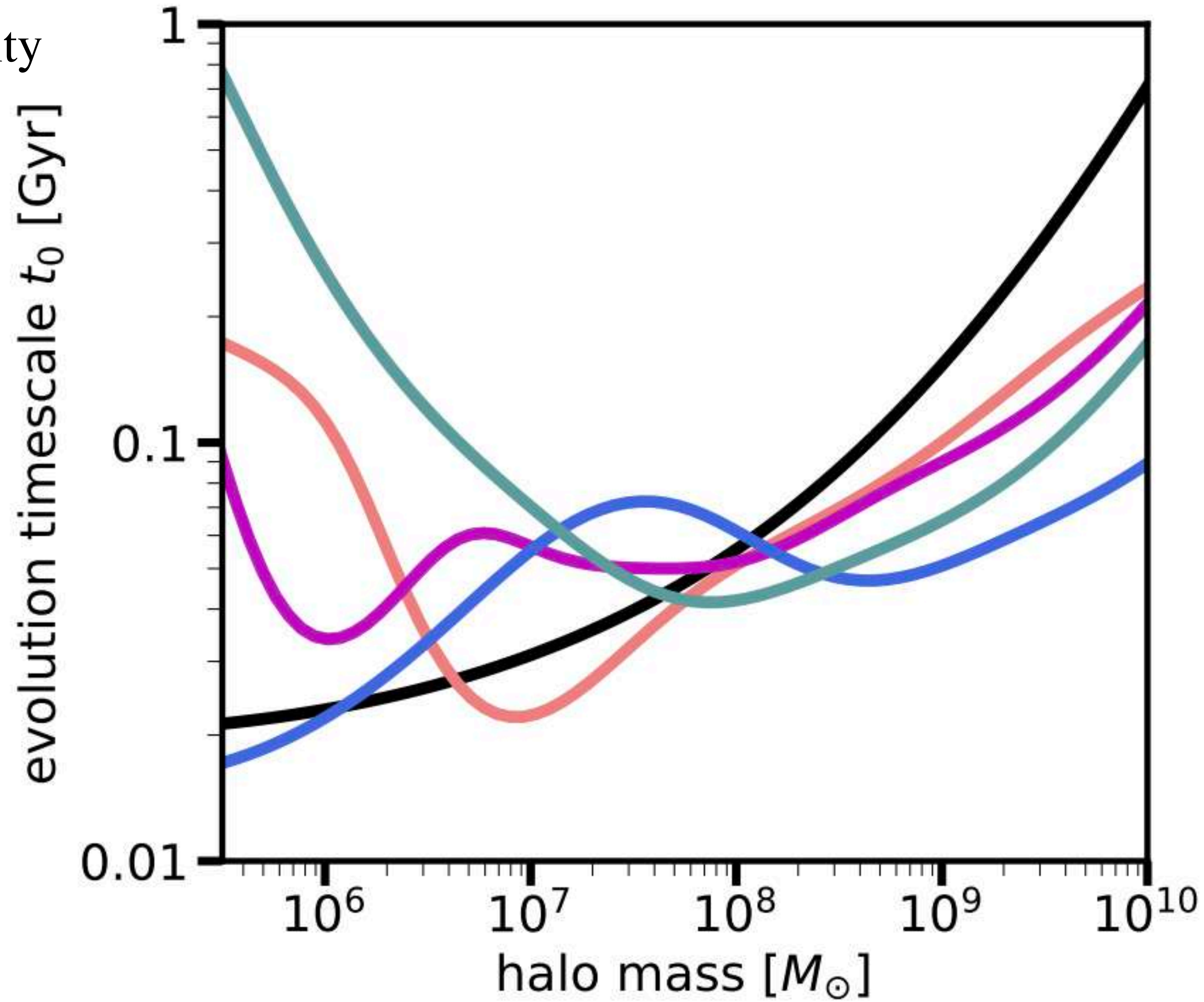
$t_{\text{fieldhalo}} \sim \lambda_{\text{field}} t_{\text{collapse}}$



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

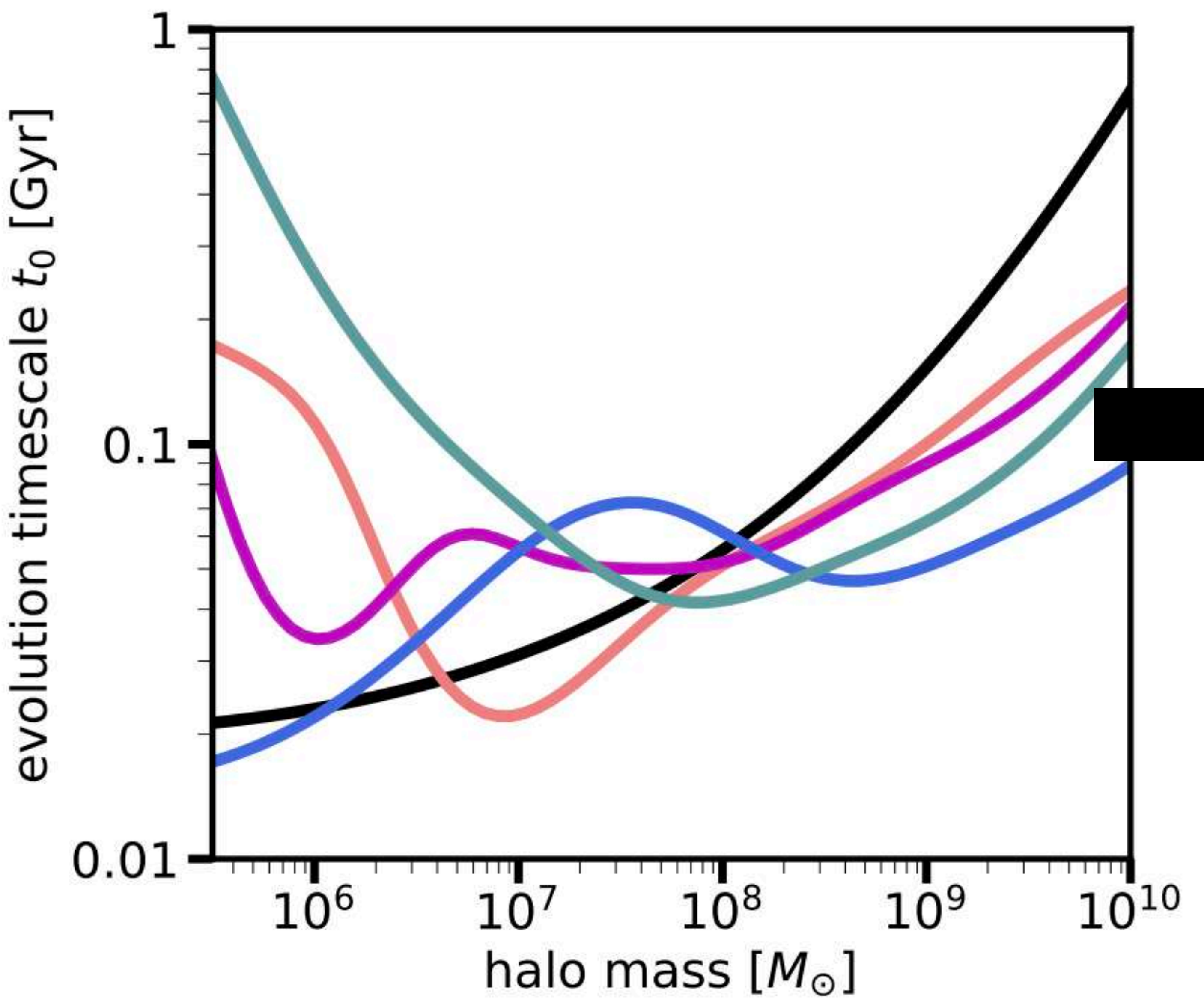


Calculate core-collapse timescales for each cross section

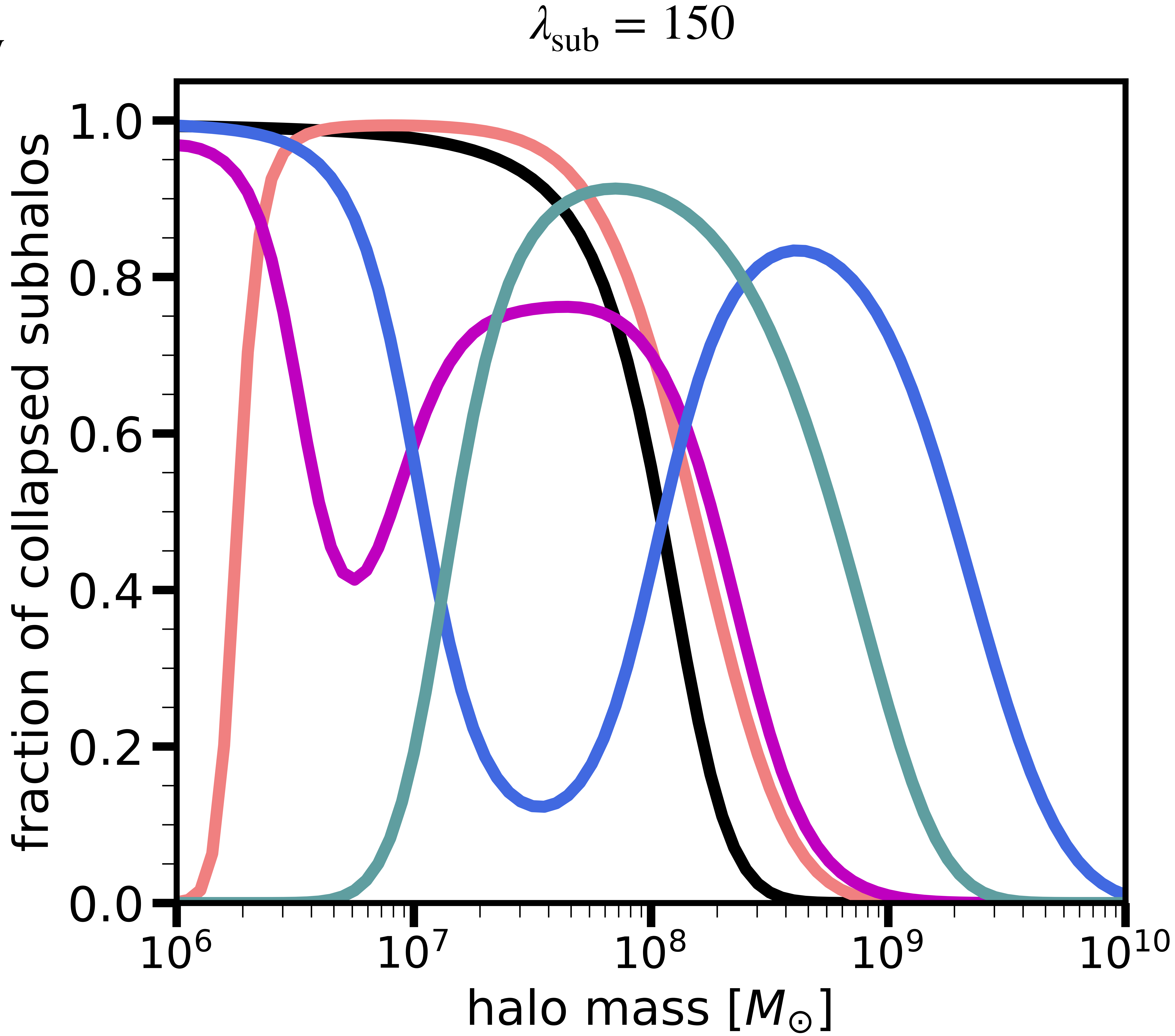


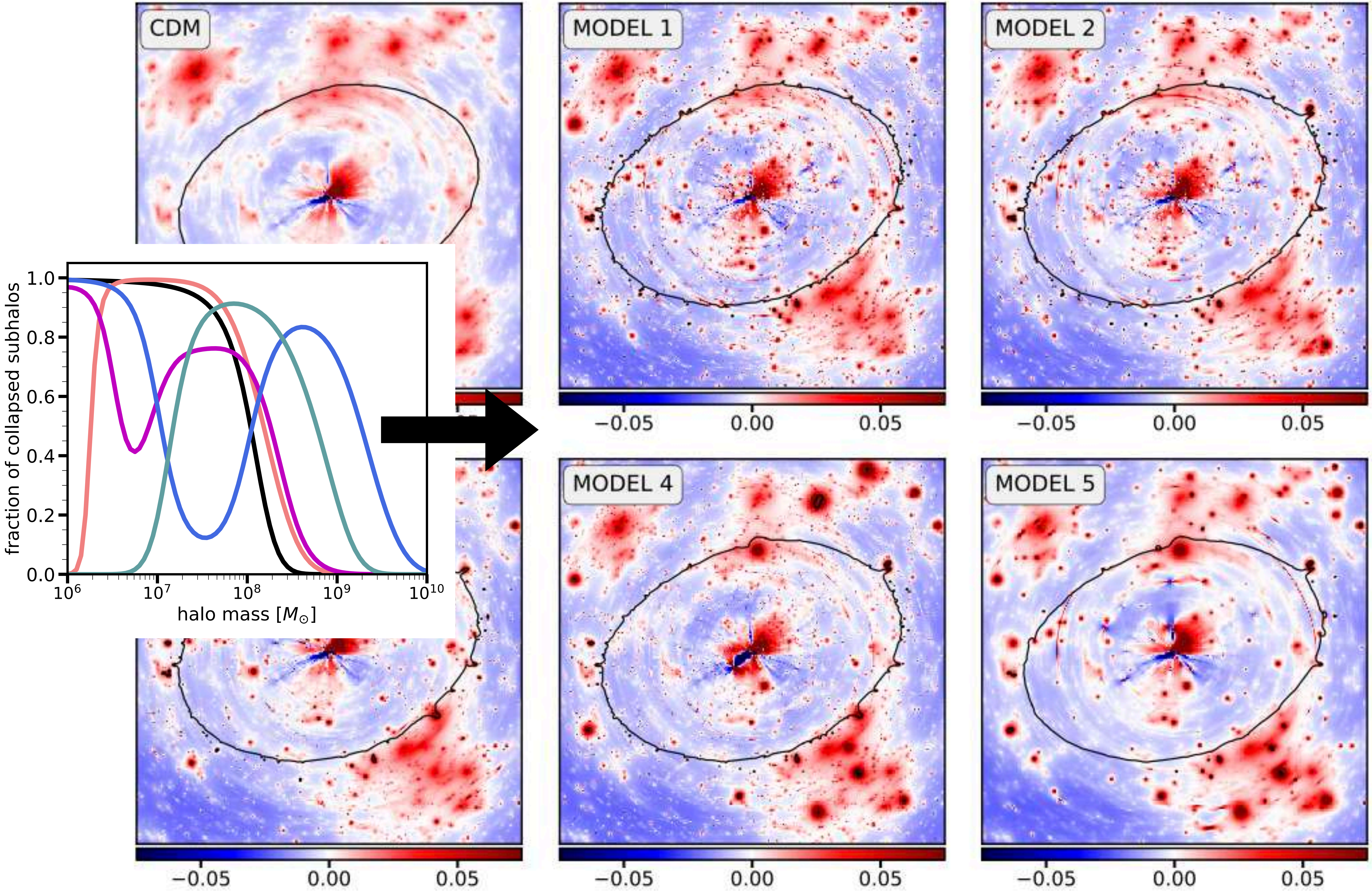
$$t_0^{-1} \sim \langle \sigma v^5 \rangle / \langle v^5 \rangle \times \text{density} \times \text{velocity}$$

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



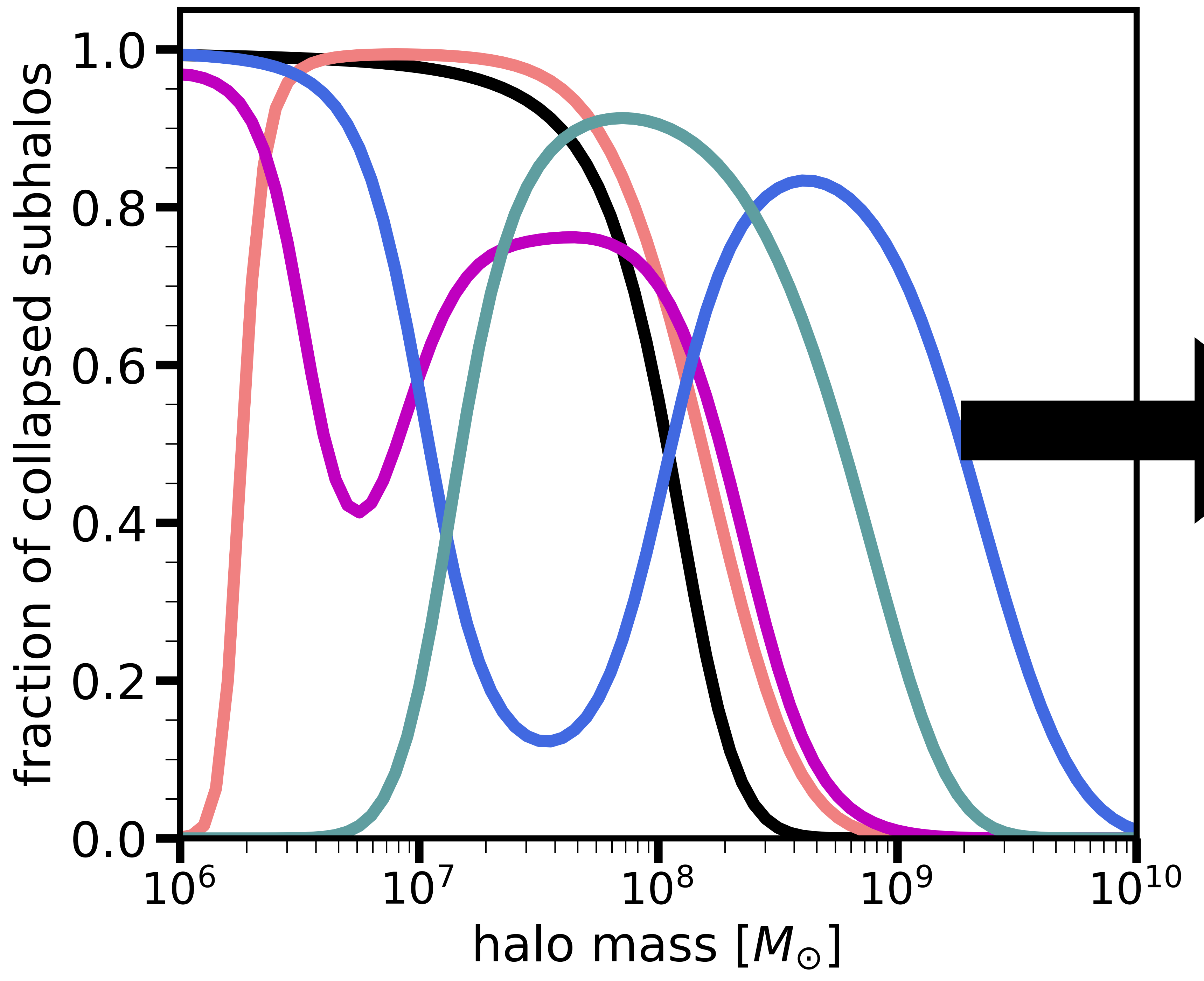
Predict core-collapse fractions from the collapse timescales



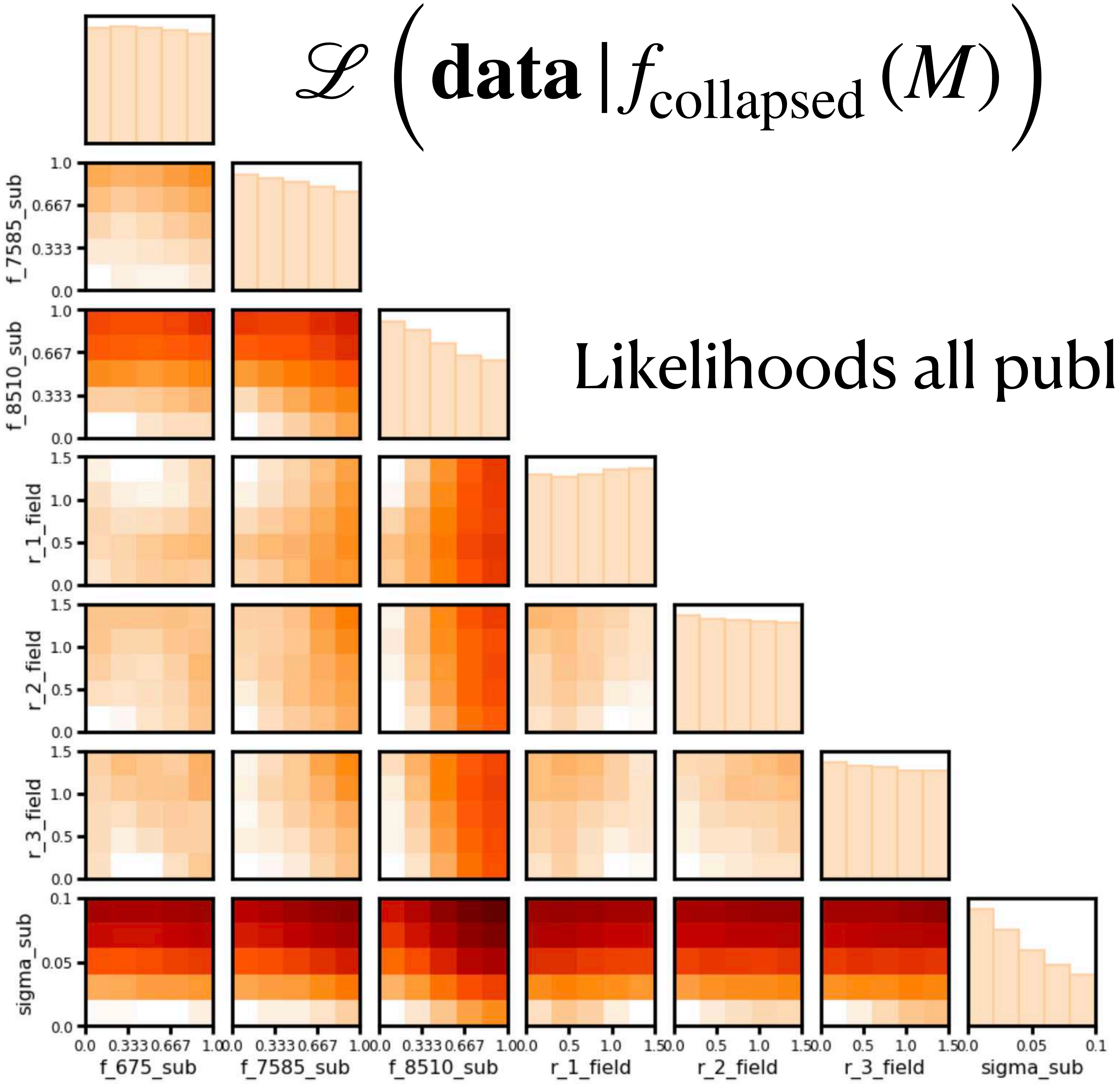


Gilman et al. (2023)
arXiv: 2207.13111

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

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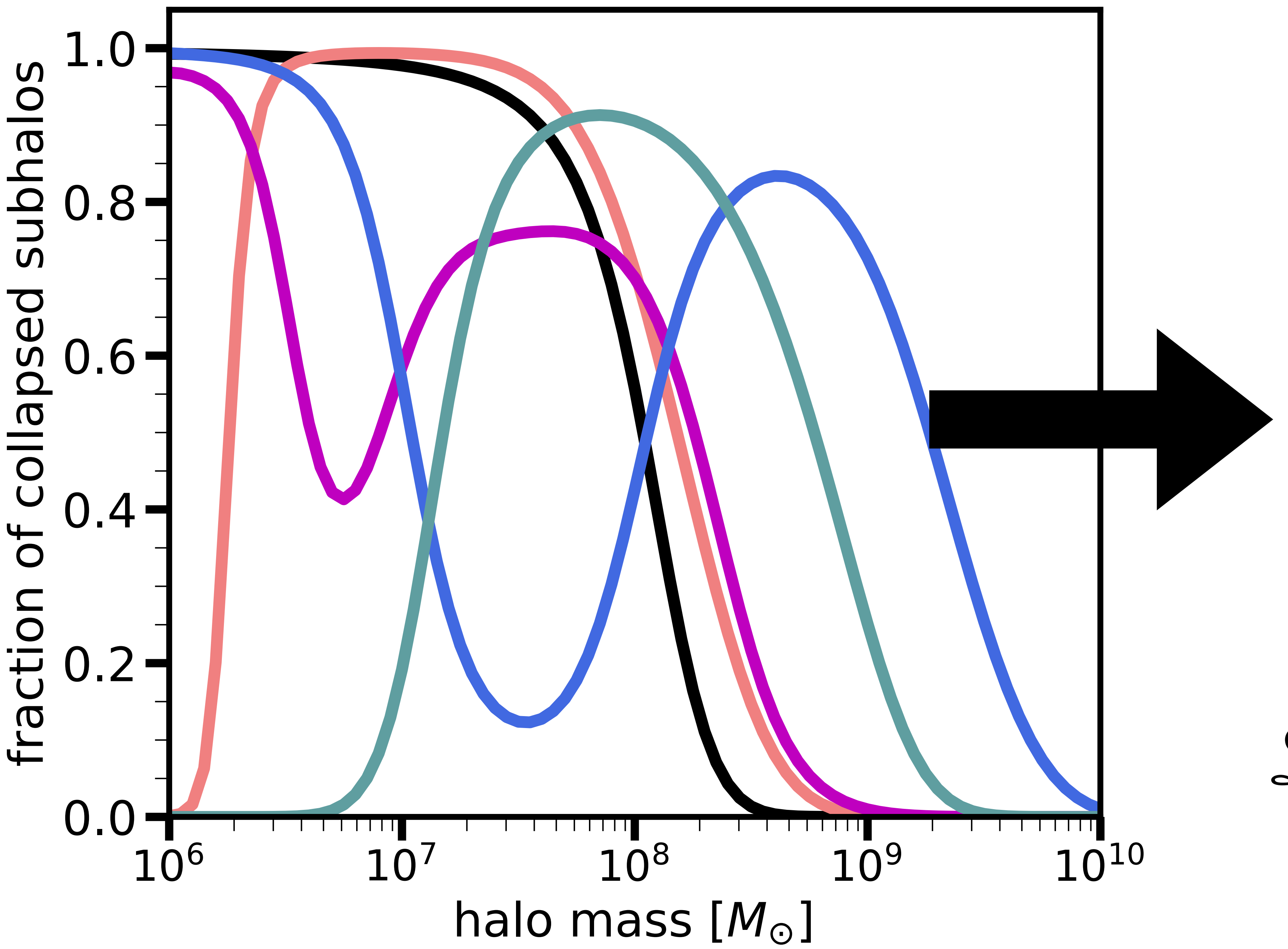
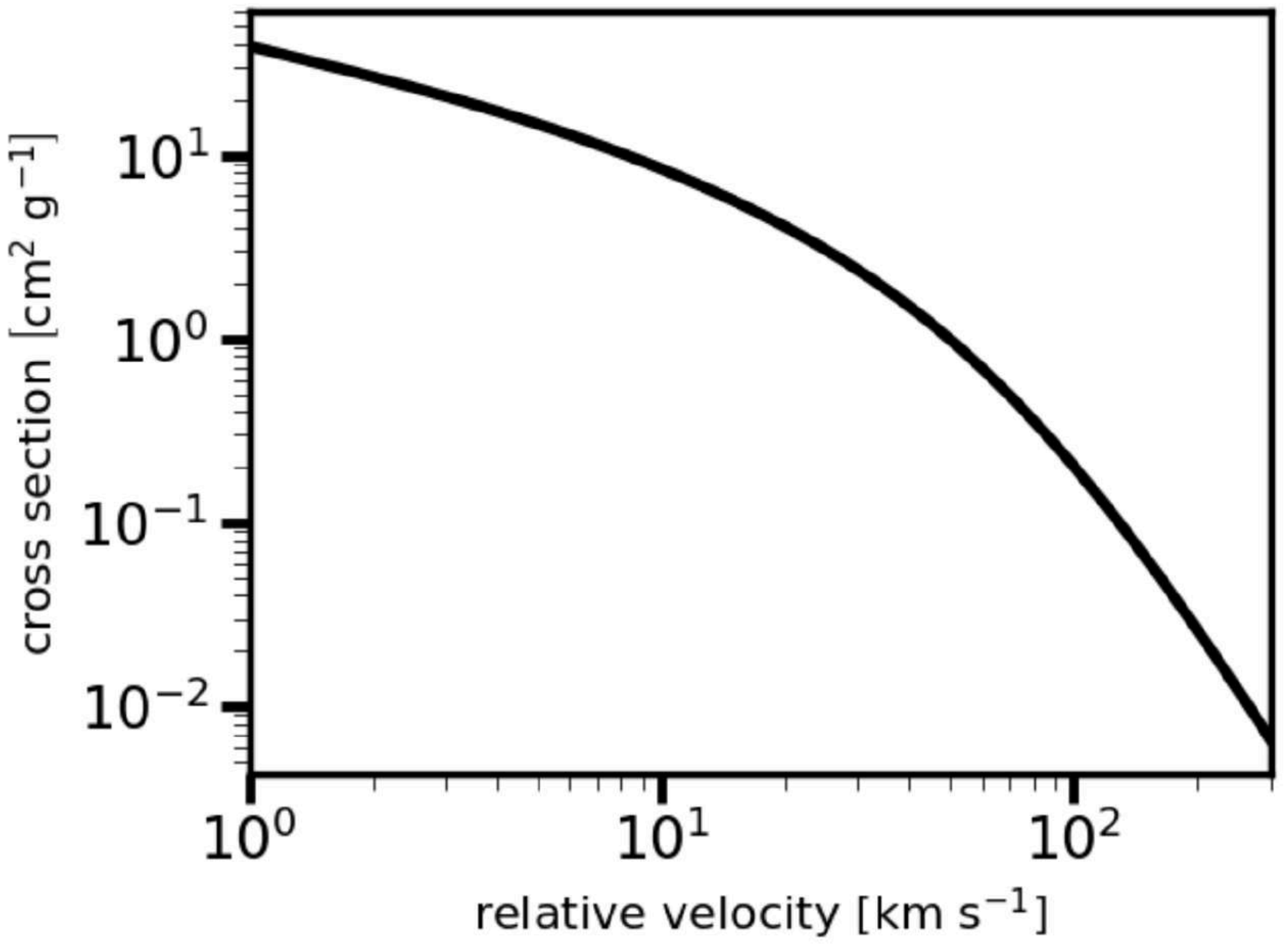


$$\mathscr{L}\left(\mathbf{data}\,|\,f_{\mathrm{collapsed}}\left(M\right)\right)$$

recast this as constraints on the core-collapse timescale

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

Inference on real data with 11 lenses



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

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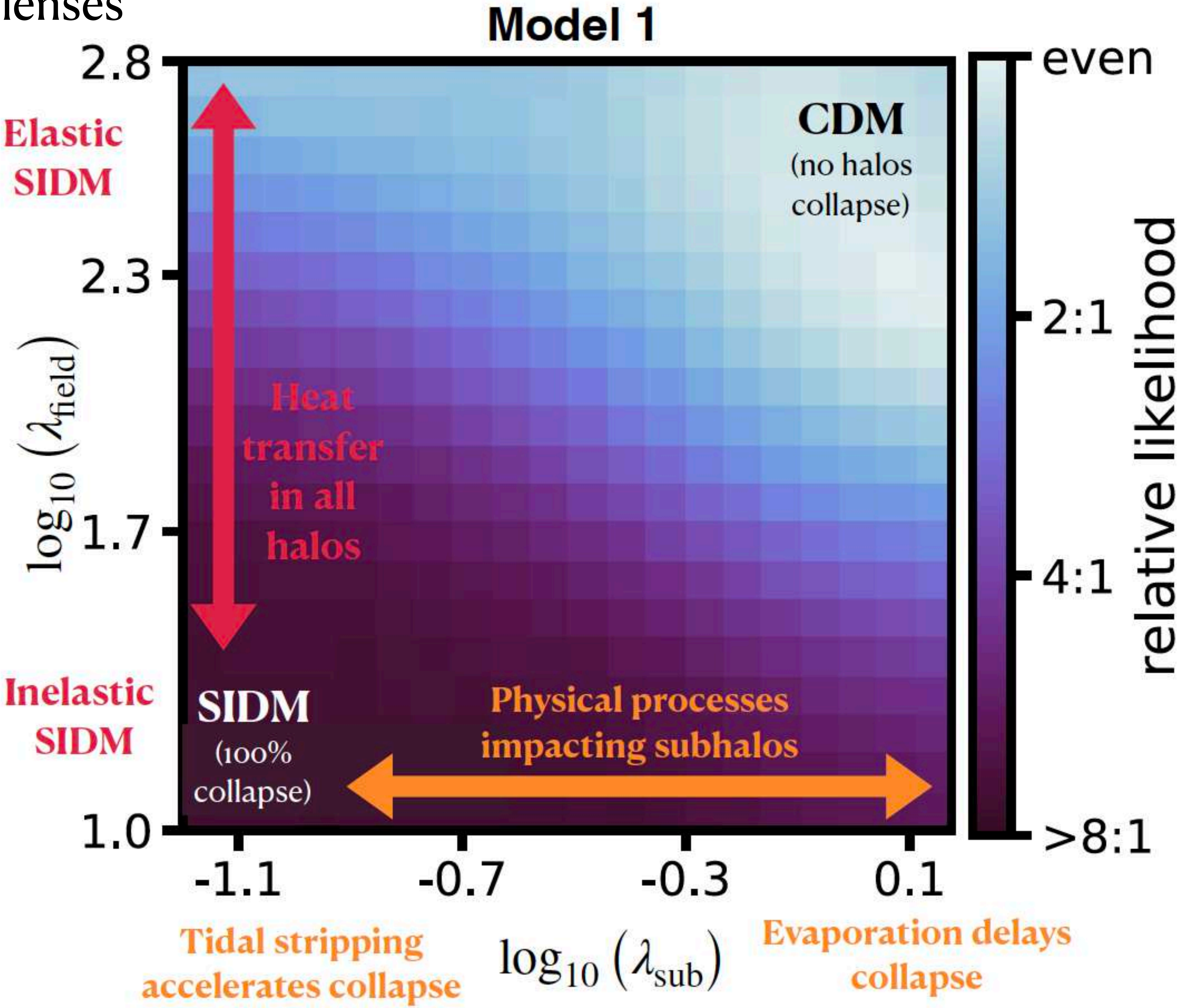


In this talk:

1) how does lensing work and why is it useful?

-> gravitational imaging and multiply-imaged quasars,
as probes of DM substructure

2) some interesting science cases

-> warm dark matter, self-interacting dark matter,
primordial matter power spectrum

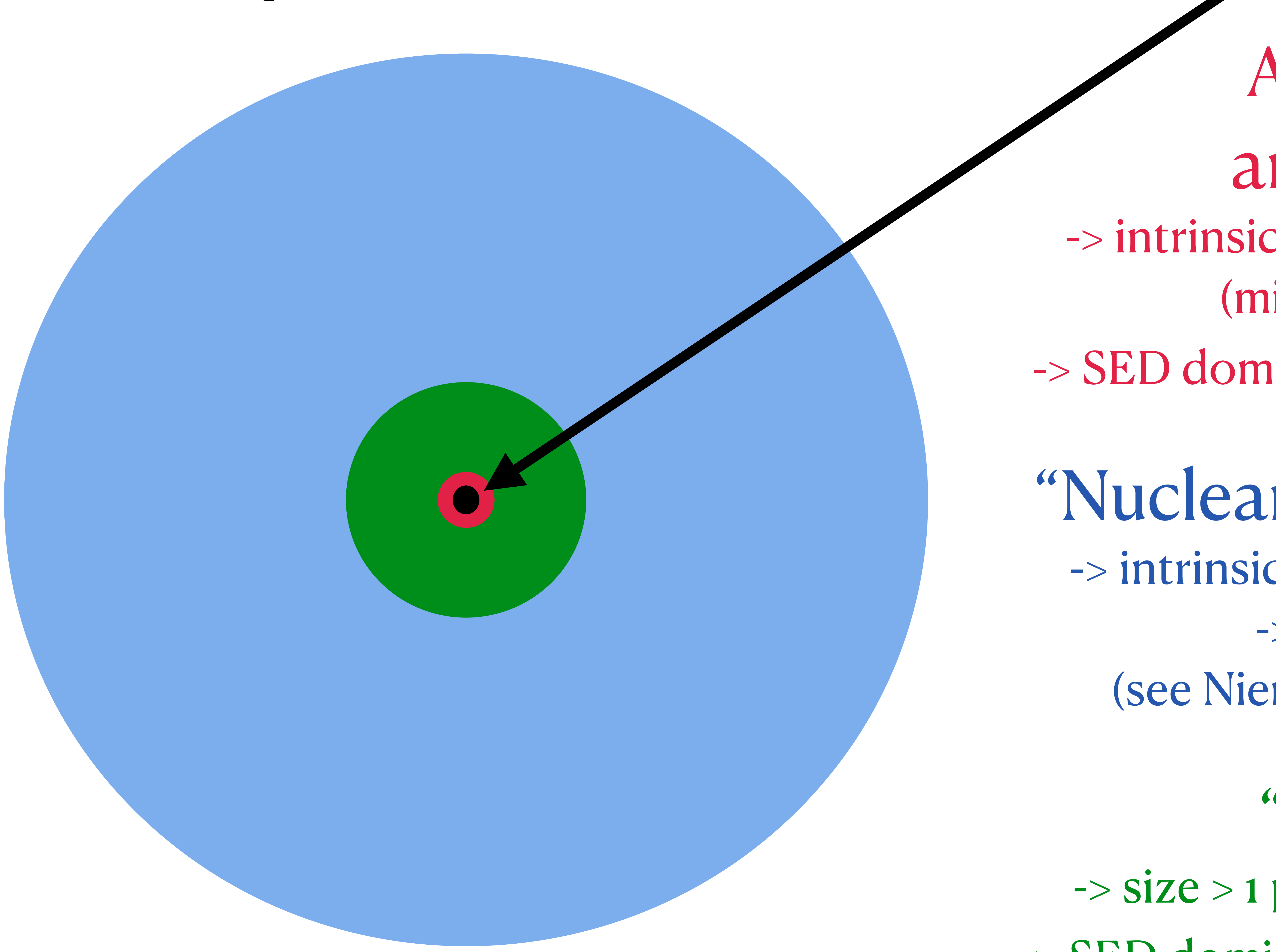
3) What does the future hold?

-> better data from the JWST lensed quasar DM survey

-> better analysis methods

-> more lenses

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 $\lambda < 2\mu m$

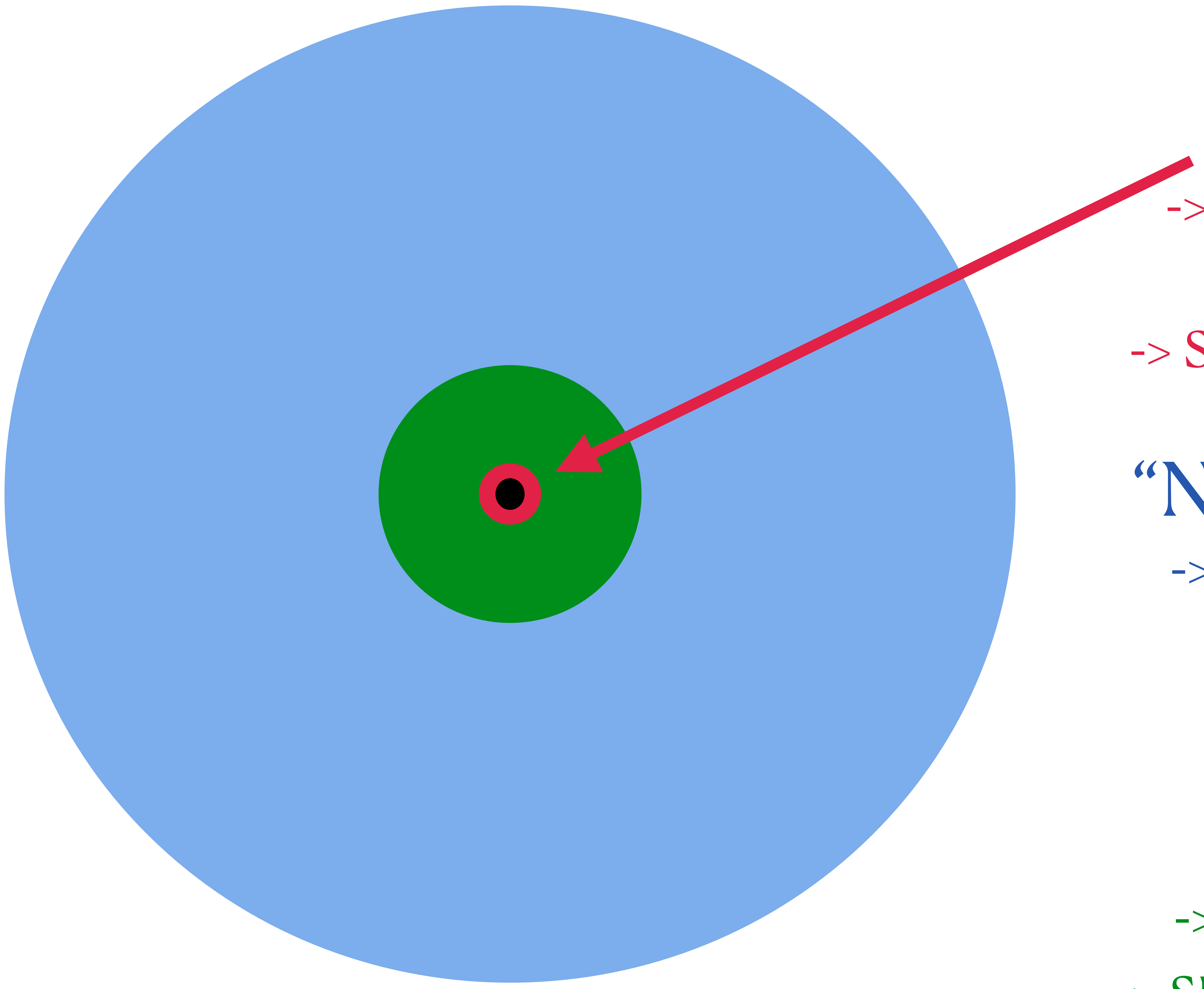
"Nuclear narrow-line region"

-> 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

Quasar (not to scale)



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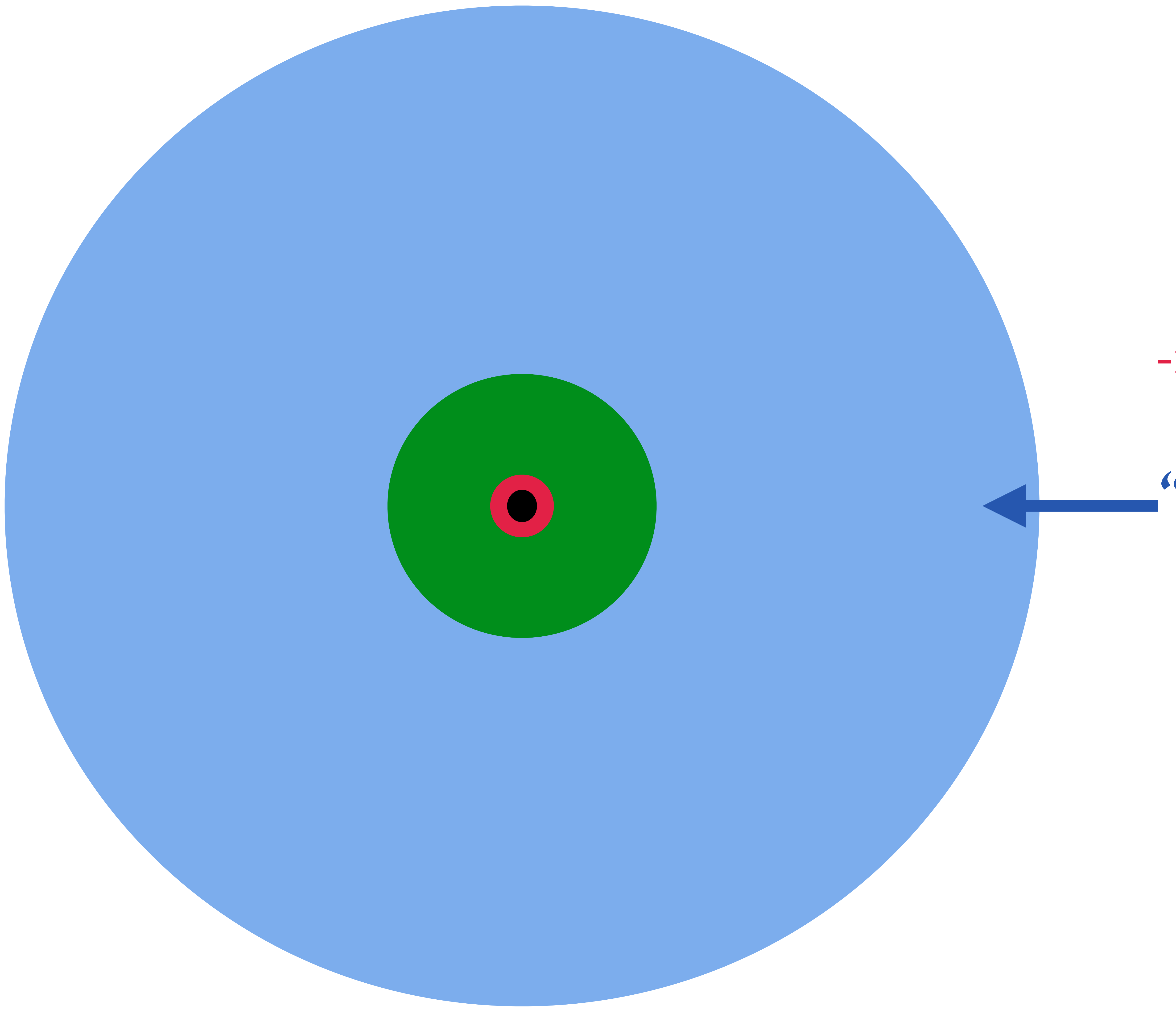

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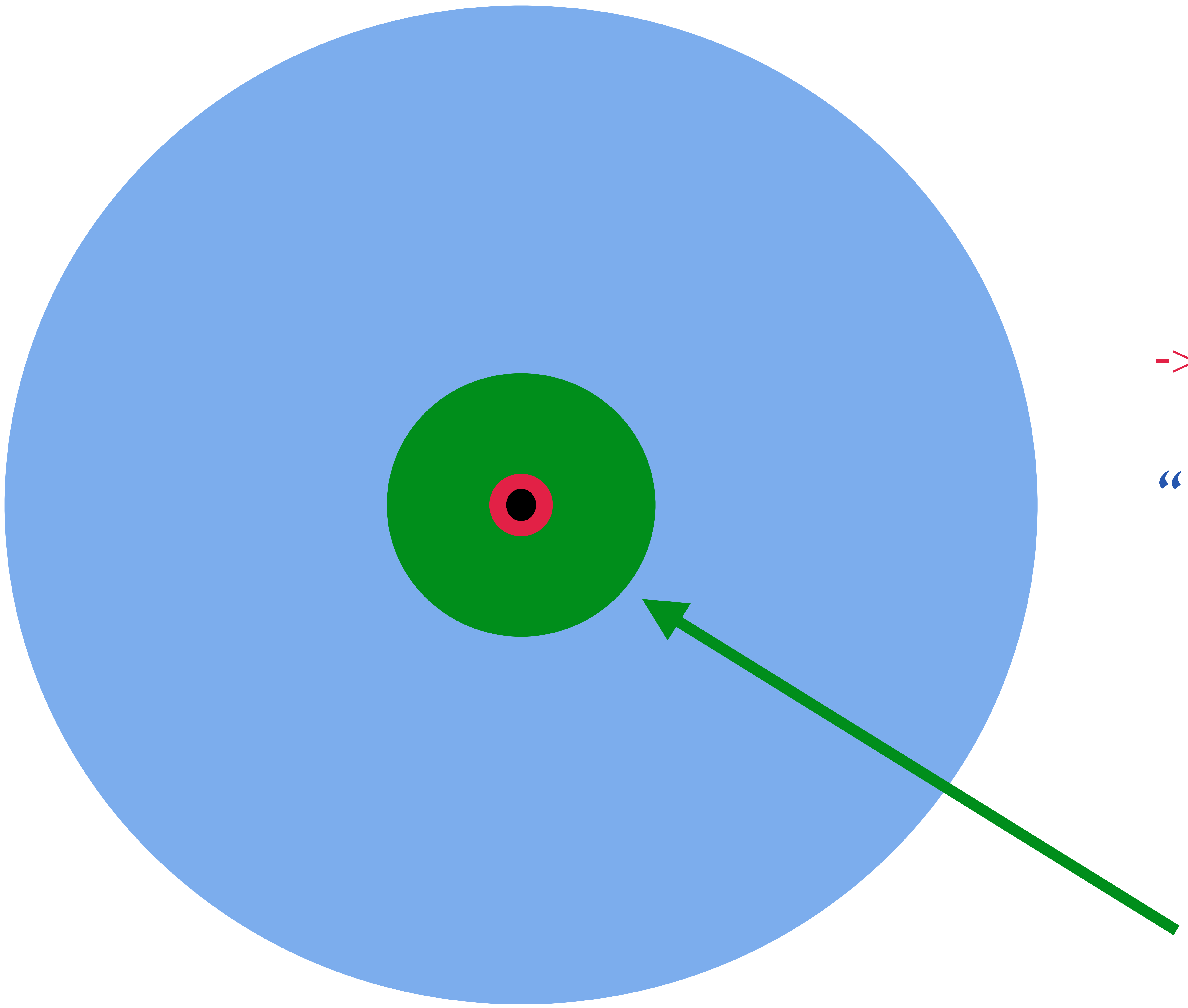

Black hole

Accretion disk and "hot torus"

-> intrinsic sizes of light-days to ~ 0.1 pc
flux ratios impacted by micro-lensing

-> 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

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-> accessible with MIRI instrument on JWST

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*

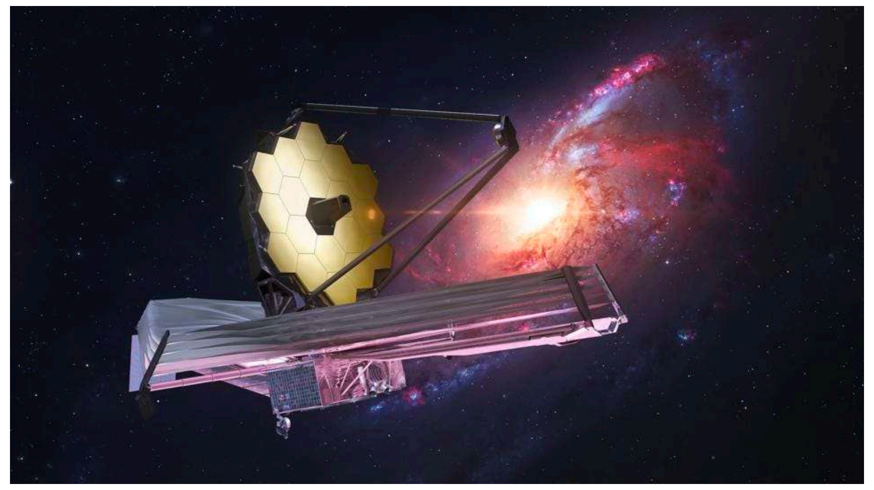
Cycle 1 JWST program GO-2046 (PI Anna Nierenberg)

Goal: isolate flux from compact (~5 parsec) emission around background quasar in 31 systems

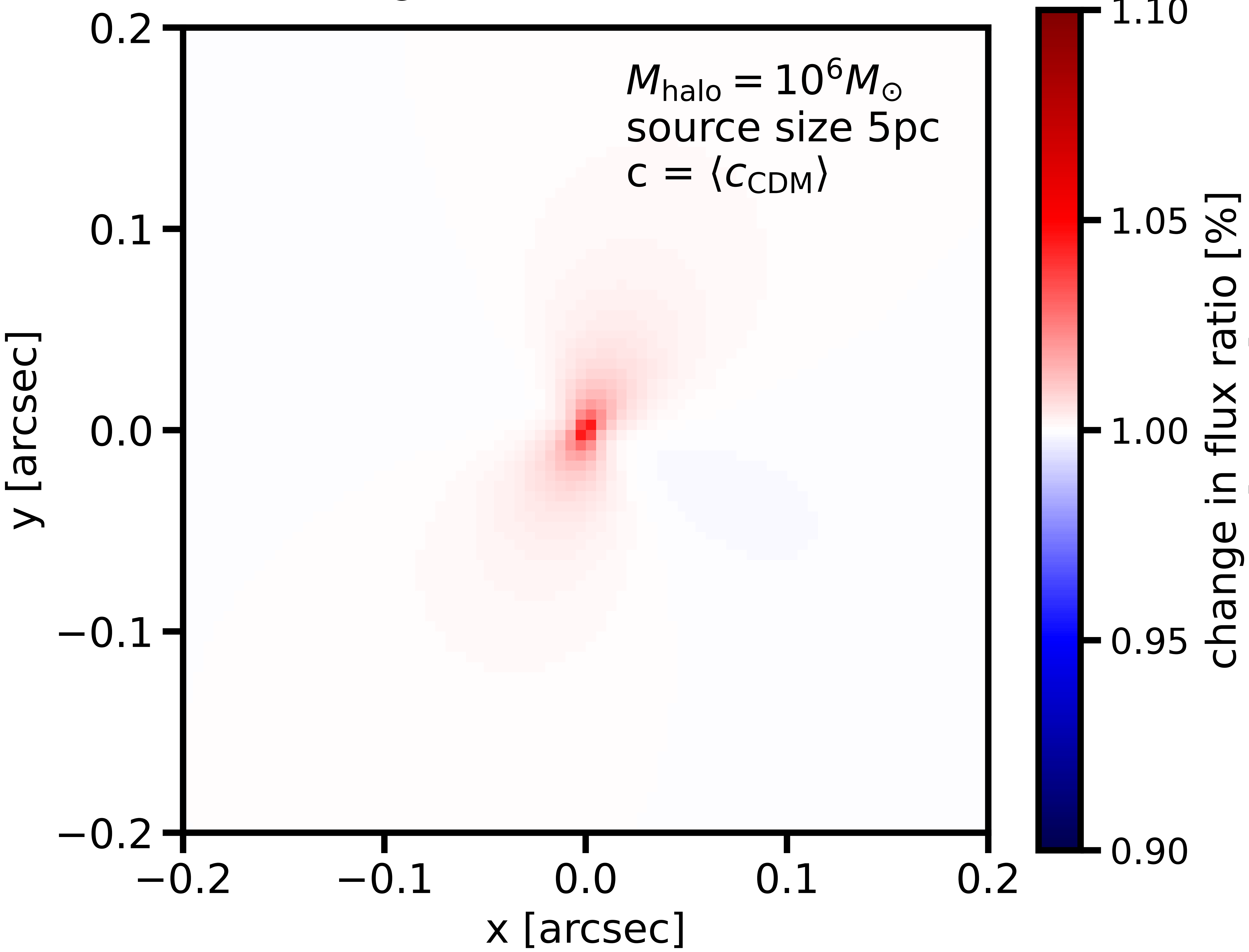
early results in the context of WDM mentioned previously (Keeley, Nierenberg, Gilman et al. (2025))

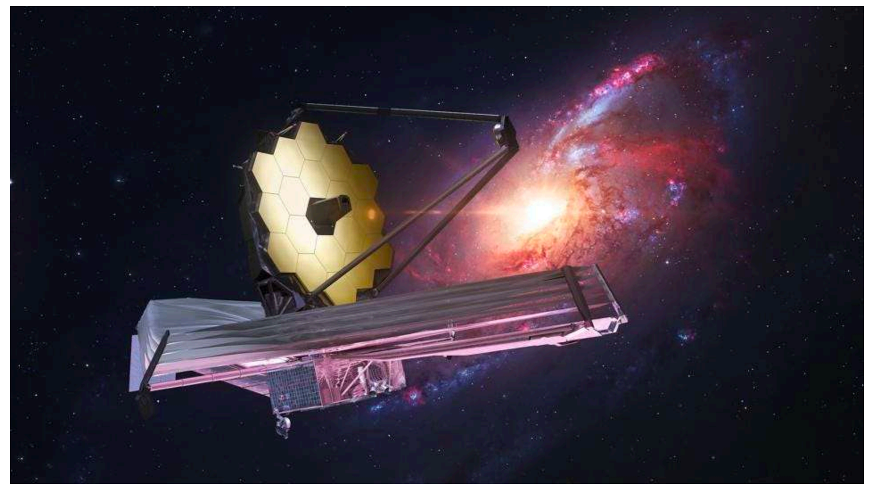
constraints from the full sample in the context of warm and self-interacting dark matter coming vey soon -> Gilman et al. (2025a), Gilman et al. (2025b)


$M_{\rm halo} = 10^6 M_\odot$
source size 80pc
c = $\langle c_{\rm CDM} \rangle$
y [arcsec]
x [arcsec]
change in flux ratio [%]
$M_{\rm halo} = 10^6 M_\odot$
source size 5pc
c = $\langle c_{\rm CDM} \rangle$
y [arcsec]
x [arcsec]
change in flux ratio [%]

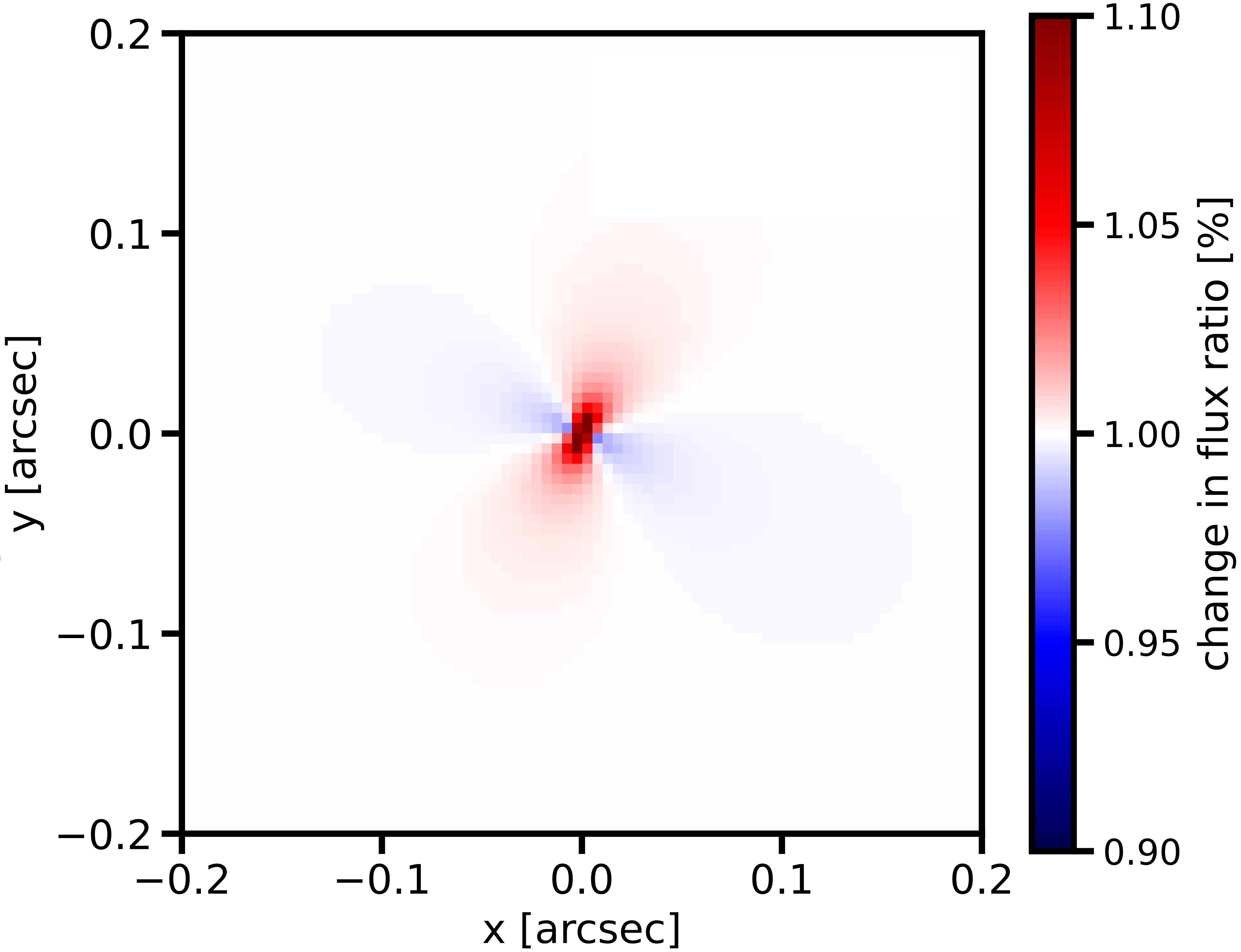


$10^6 M_\odot$ NFW (CDM) halo



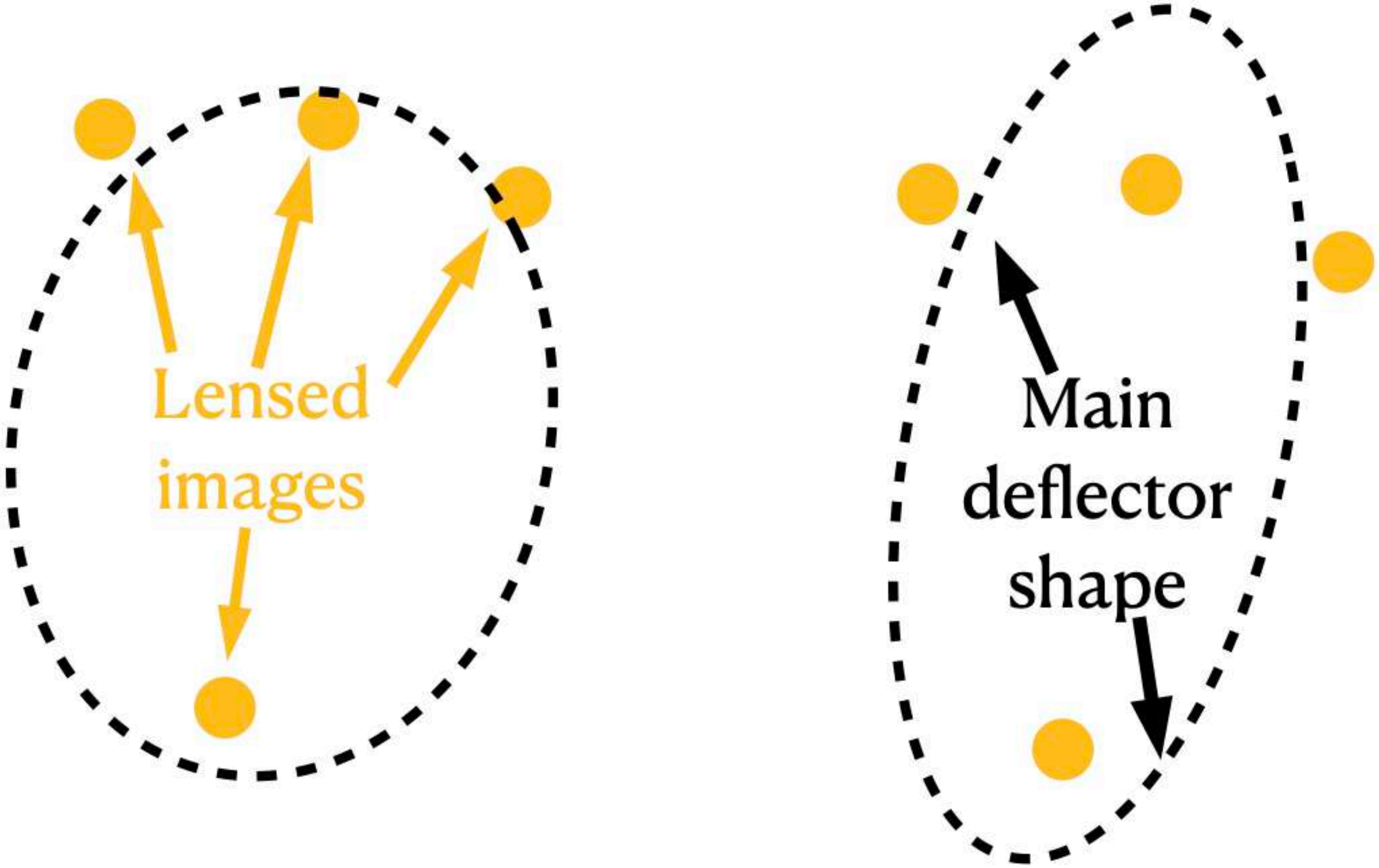


$10^6 M_\odot$ collapsed SIDM halo



2) better analysis methods: joint modeling of flux ratios with lensed arcs

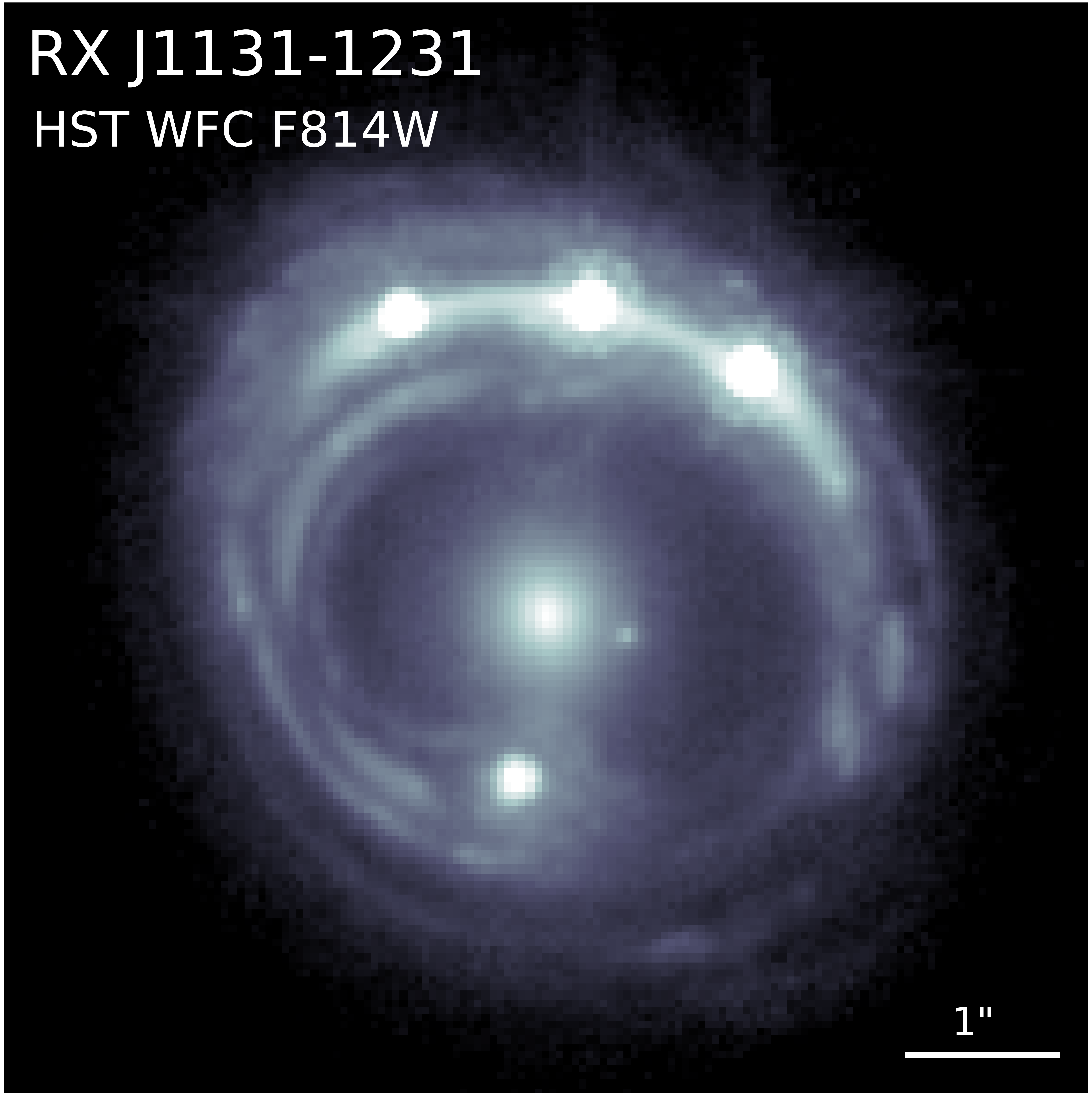
With only image positions and flux ratios, **only limited information** regarding large-scale mass distribution of the lens

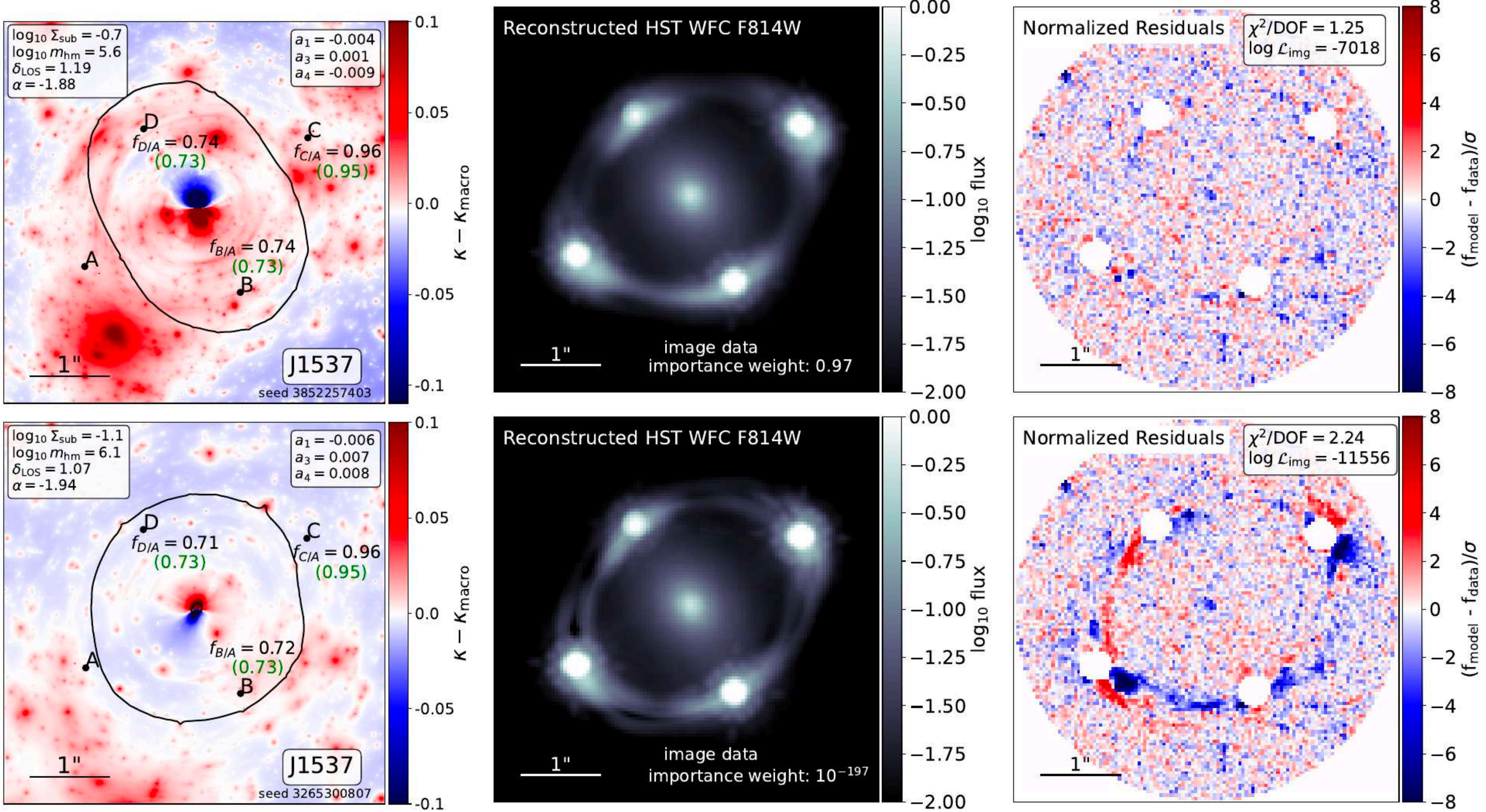


With only image positions and flux ratios, **only limited information** regarding large-scale mass distribution of the lens

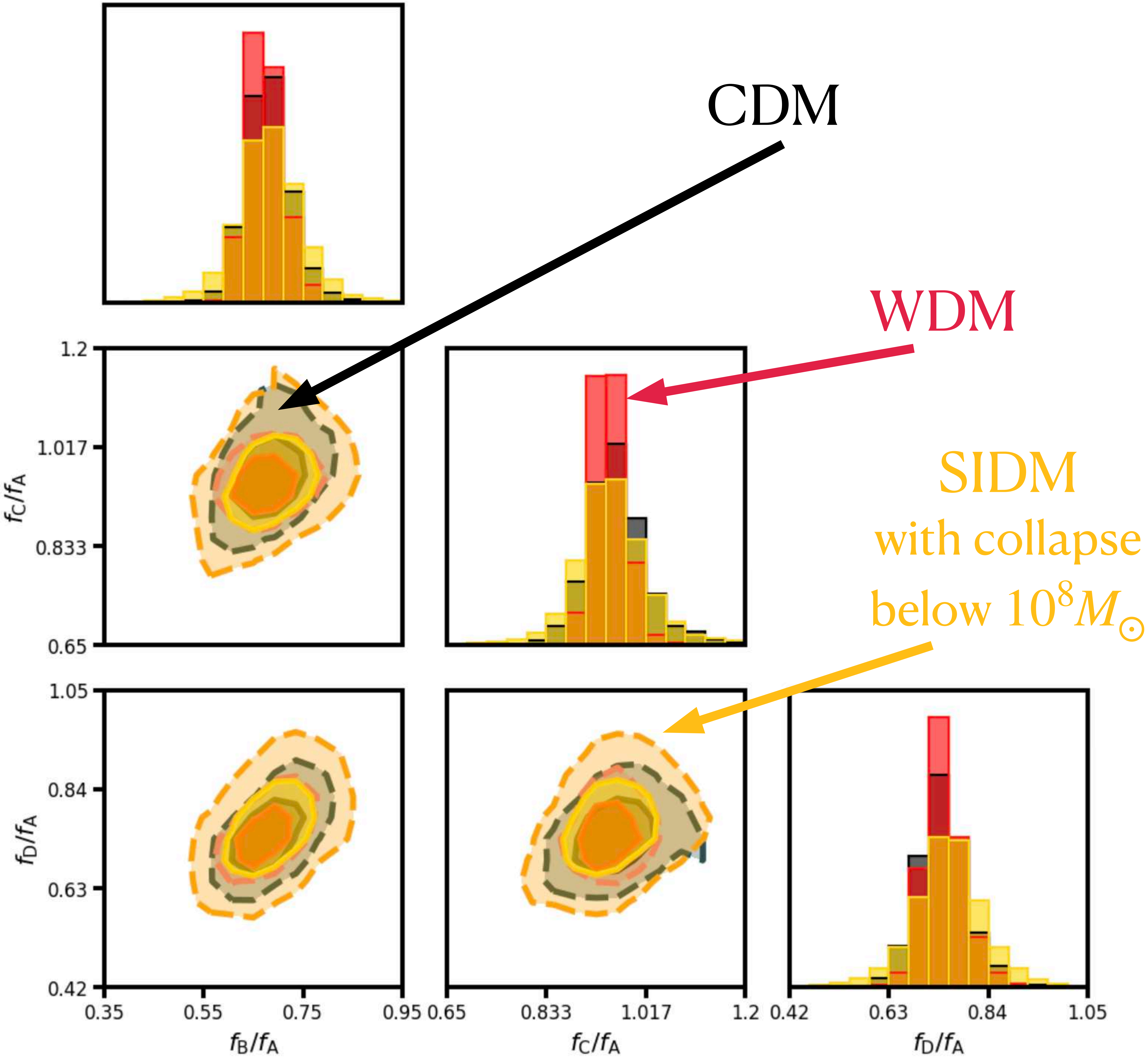
Forward modeling of arcs+flux ratios improves constraints on DM properties

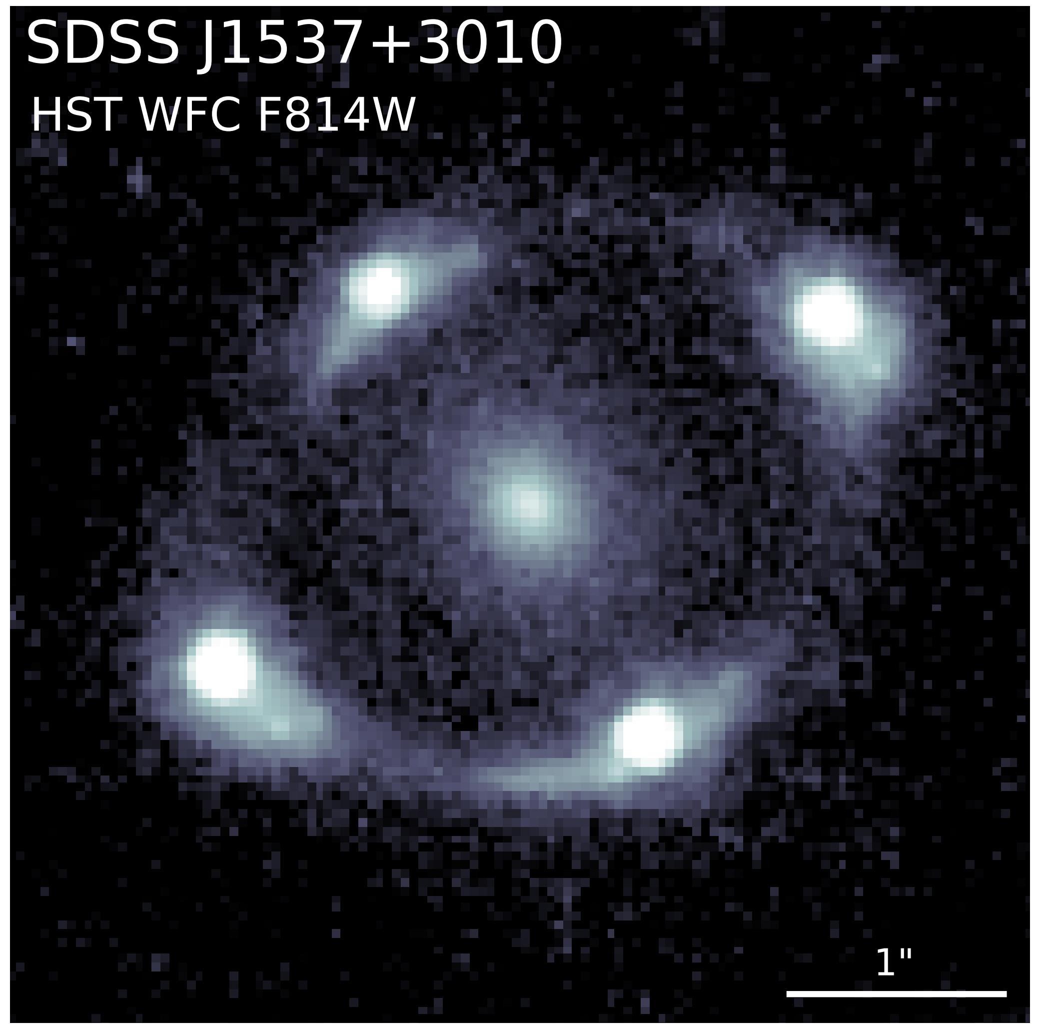
Gilman et al. (2024)





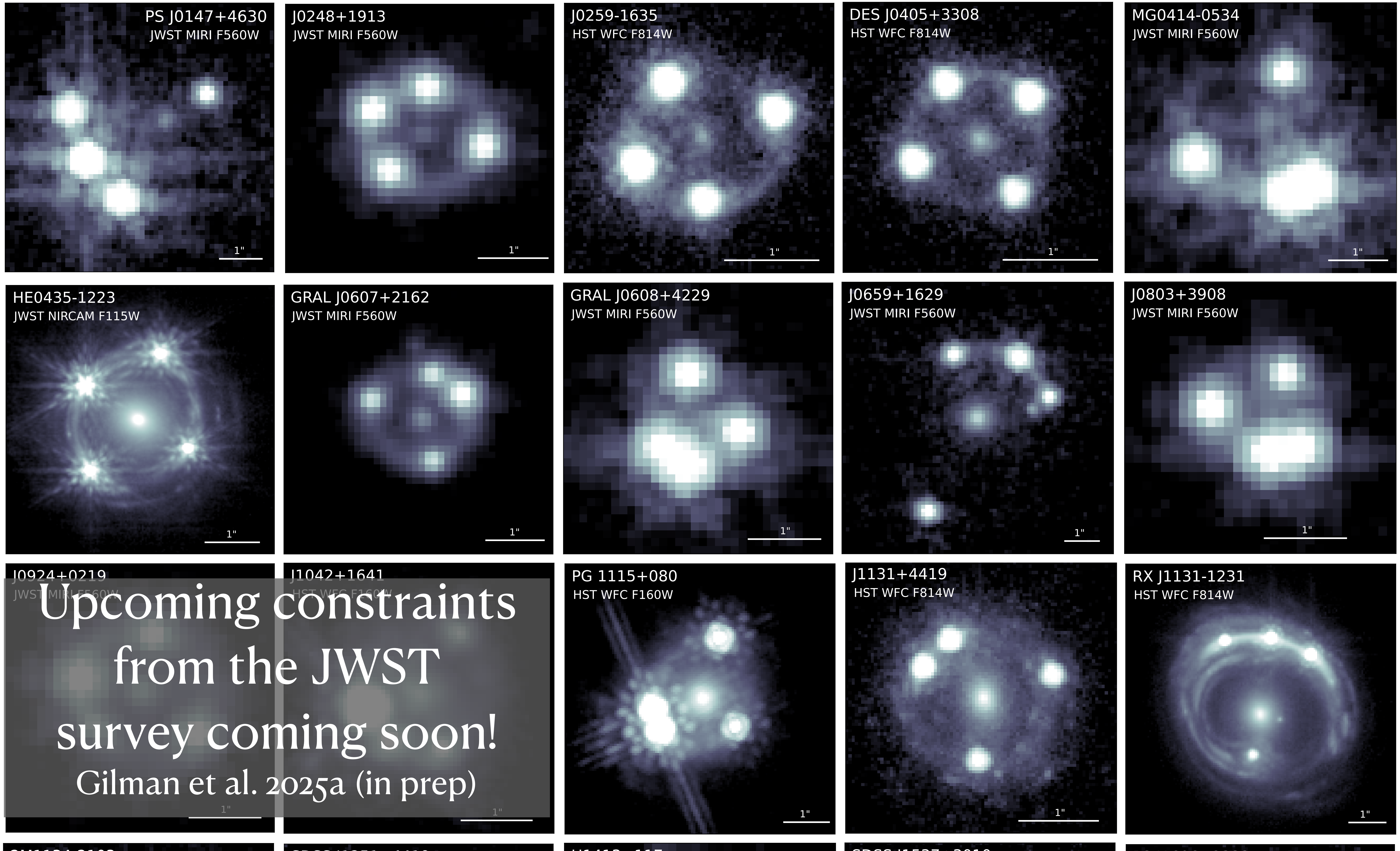
Adapted from Gilman et al. (2025a, in prep)

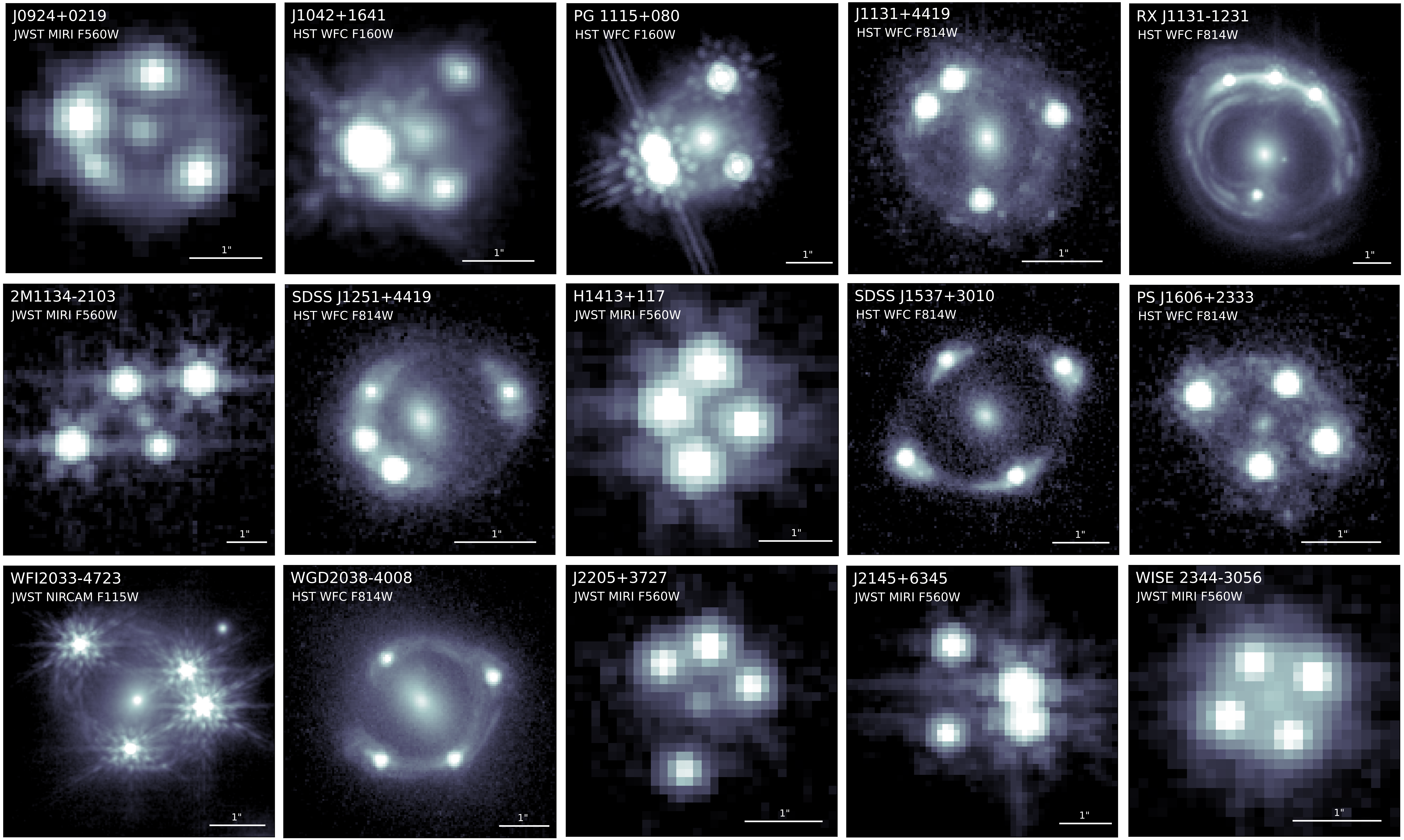




Flux ratio predictions for J1537+3010 -> observed with JWST survey

Gilman et al. 2025B, in prep


PS J0147+4630
JWST MIRI F560W
J0248+1913
JWST MIRI F560W
J0259-1635
HST WFC F814W
DES J0405+3308
HST WFC F814W
MG0414-0534
JWST MIRI F560W
HE0435-1223
JWST NIRCAM F115W
GRAL J0607+2162
JWST MIRI F560W
GRAL J0608+4229
JWST MIRI F560W
J0659+1629
JWST MIRI F560W
J0803+3908
JWST MIRI F560W
J0924+0219
J1042+1641
PG 1115+080
HST WFC F160W
J1131+4419
HST WFC F814W
RX J1131-1231
HST WFC F814W
Upcoming constraints from the JWST survey coming soon!
Gilman et al. 2025a (in prep)


J0924+0219
JWST MIRI F560W
1"
J1042+1641
HST WFC F160W
1"
PG 1115+080
HST WFC F160W
1"
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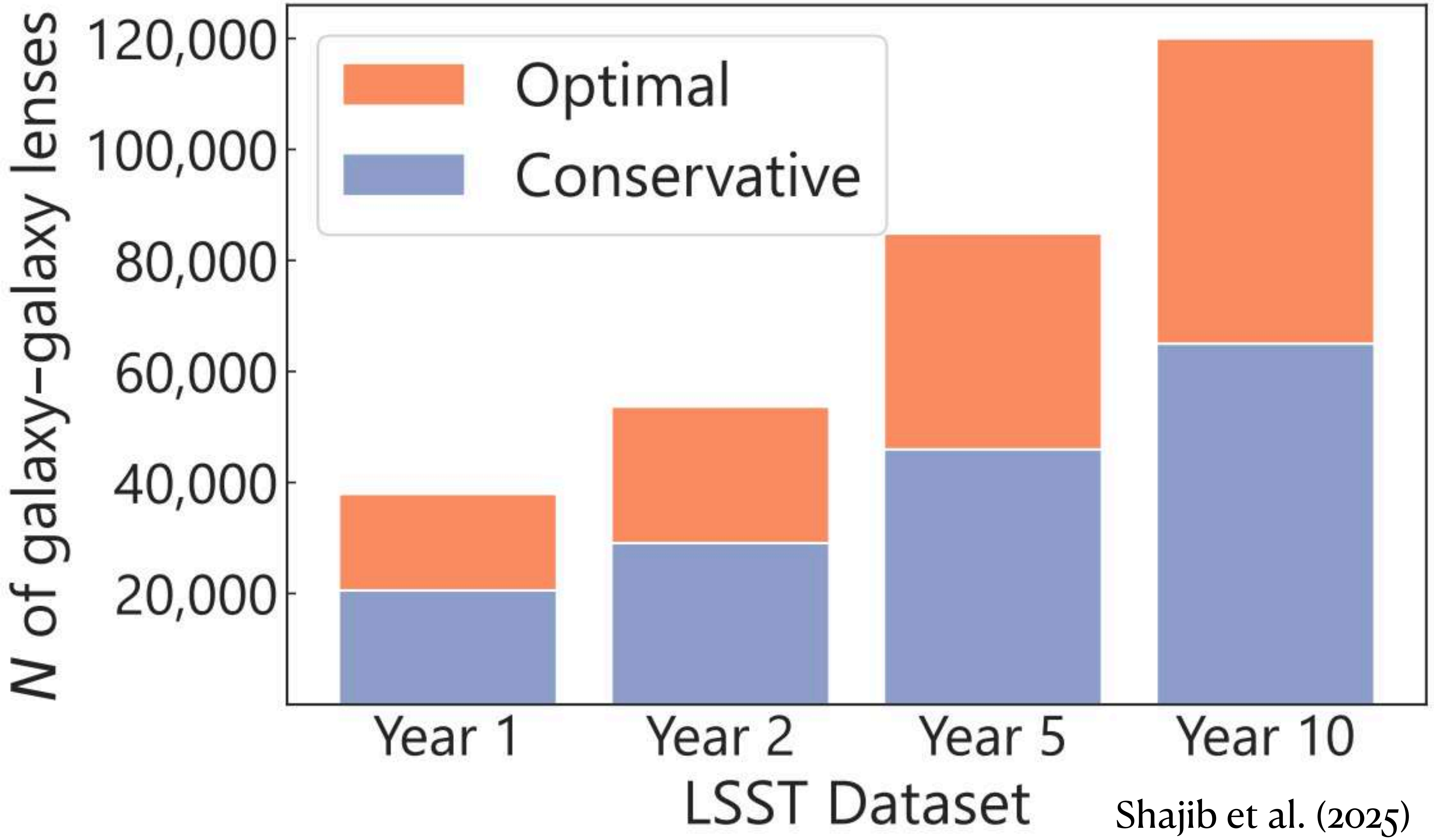
HST WFC F814W
1"
RX J1131-1231
HST WFC F814W
1"
2M1134-2103
JWST MIRI F560W
1"
SDSS J1251+4419
HST WFC F814W
1"
H1413+117
JWST MIRI F560W
1"
SDSS J1537+3010
HST WFC F814W
1"
PS J1606+2333
HST WFC F814W
1"
WFI2033-4723
JWST NIRCAM F115W
1"
WGD2038-4008
HST WFC F814W
1"
J2205+3727
JWST MIRI F560W
1"
J2145+6345
JWST MIRI F560W
1"
WISE 2344-3056
JWST MIRI F560W
1"

3) more lenses

We can expect tens-of-thousands of galaxy-scale lenses from cosmic surveys (e.g. Rubin Obs, Roman, Euclid)

- among these, 500-1000 will be quadruply-imaged quasars



Shajib et al. (2025)