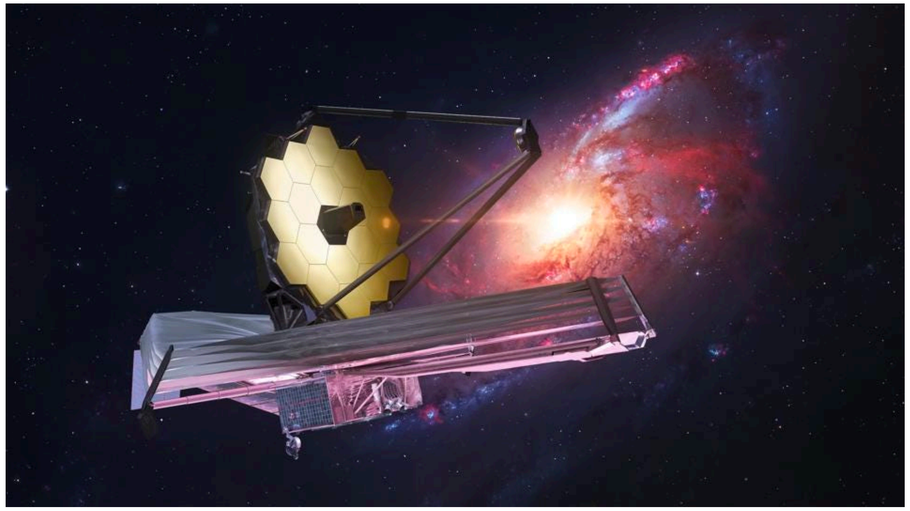
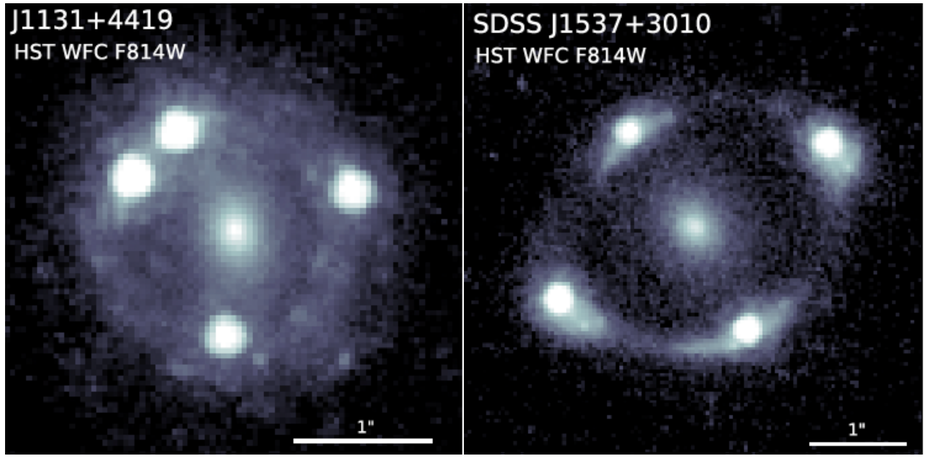
Fundamental physics with quadruply imaged quasars



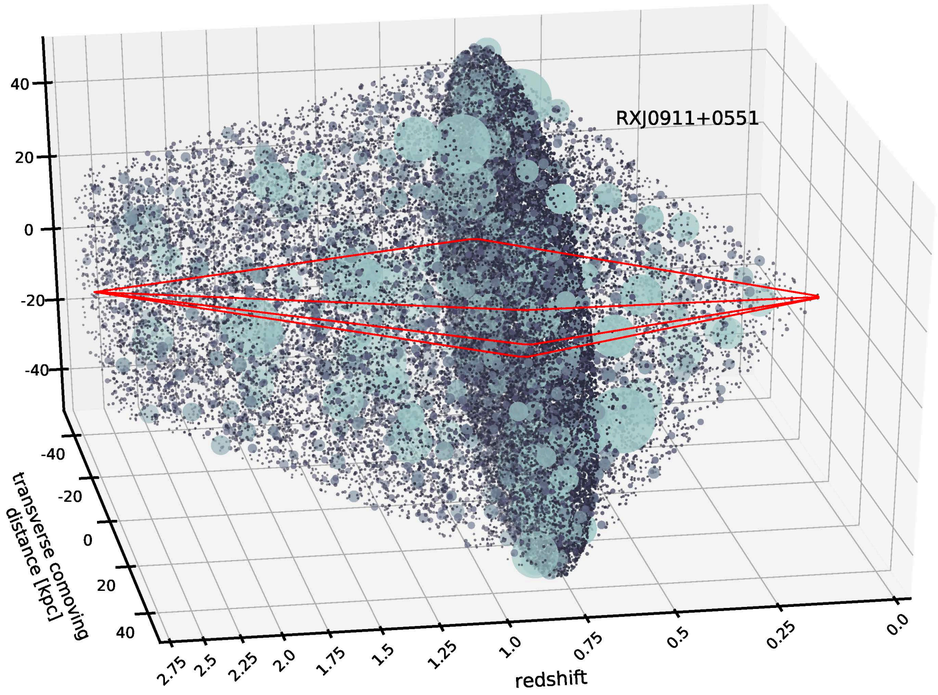


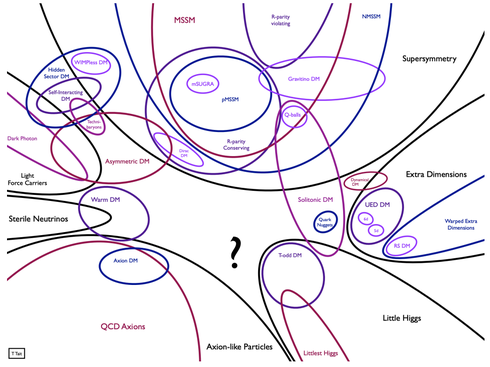
Daniel Gilman

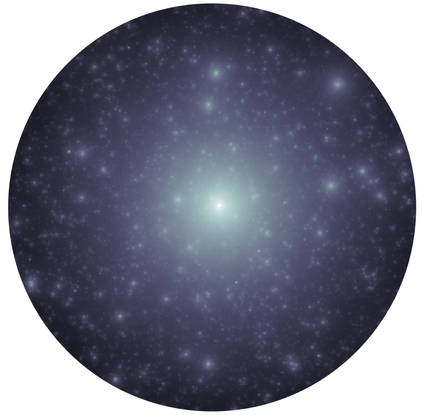
Kavli Institute for
Cosmological Physics
University of Chicago

In collaboration with:
Anna Nierenberg, Ryan Keeley, Charles Gannon (UC Merced)
Tommaso Treu, Xiaolong Du, Hadrien Paugnat (UCLA)
Andrew Benson (Carnegie)
Simon Birrer (Stony Brook)
Ioana Zelko (CITA)
Jo Bovy (UofT)

The Brinson Foundation







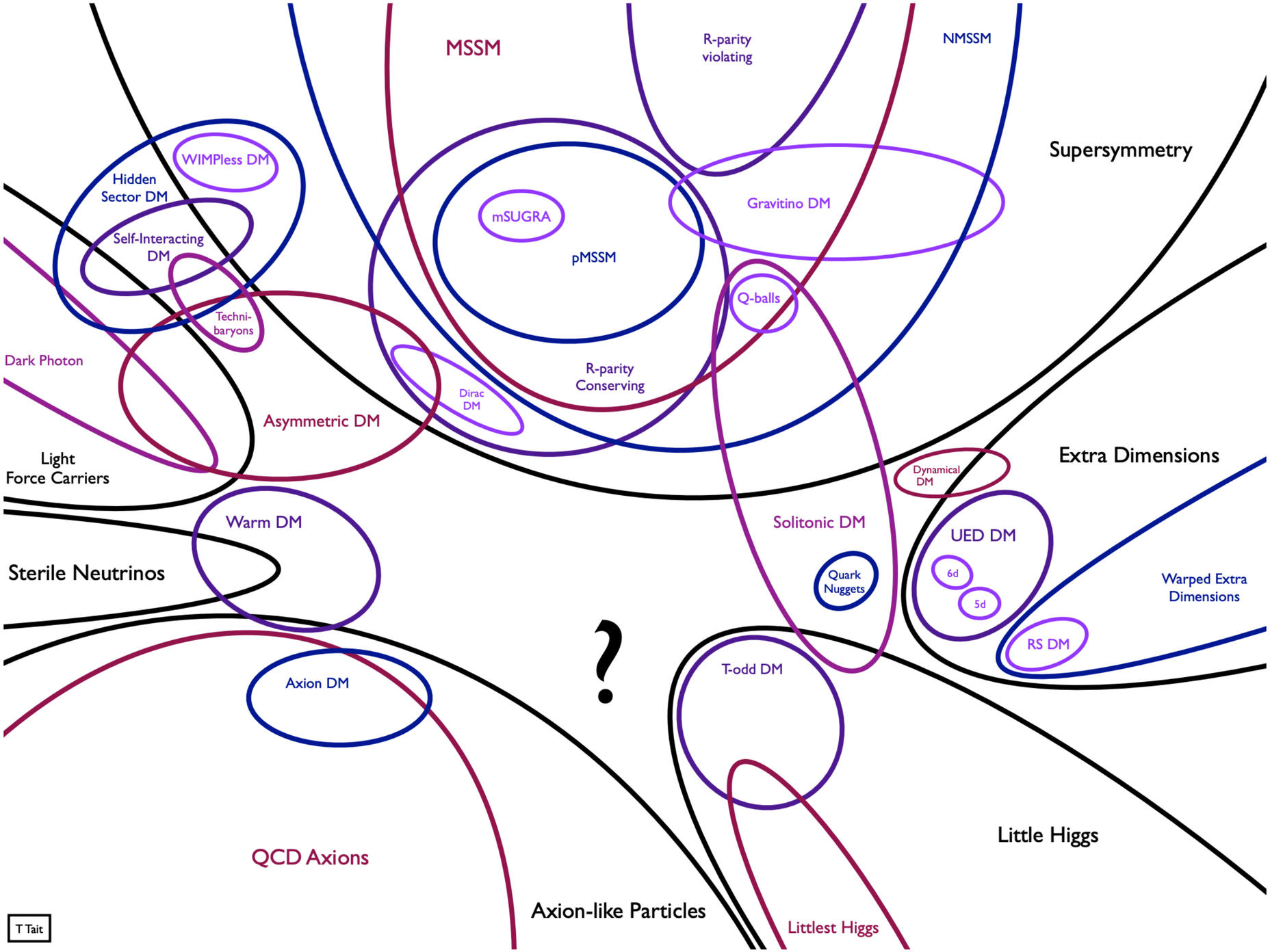
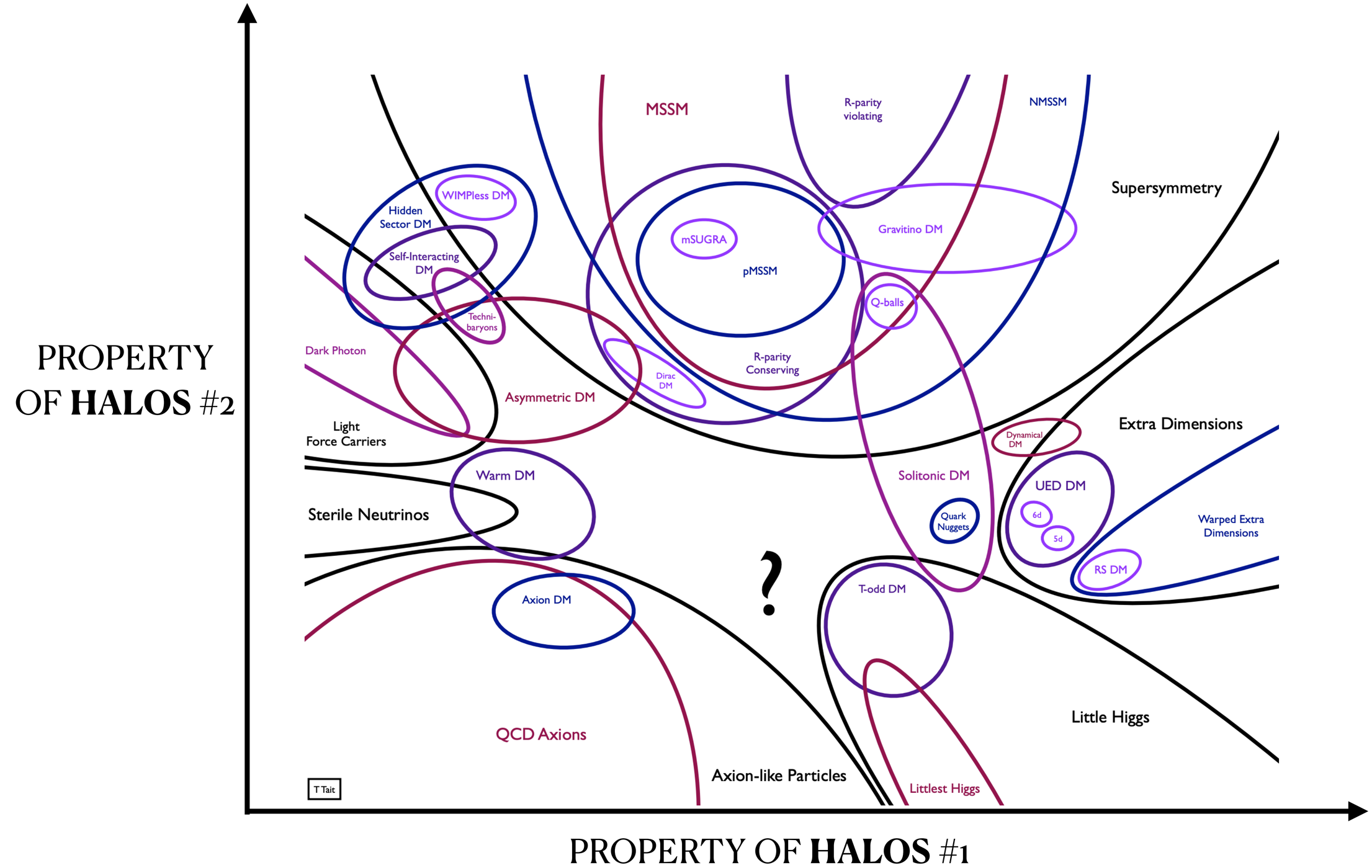
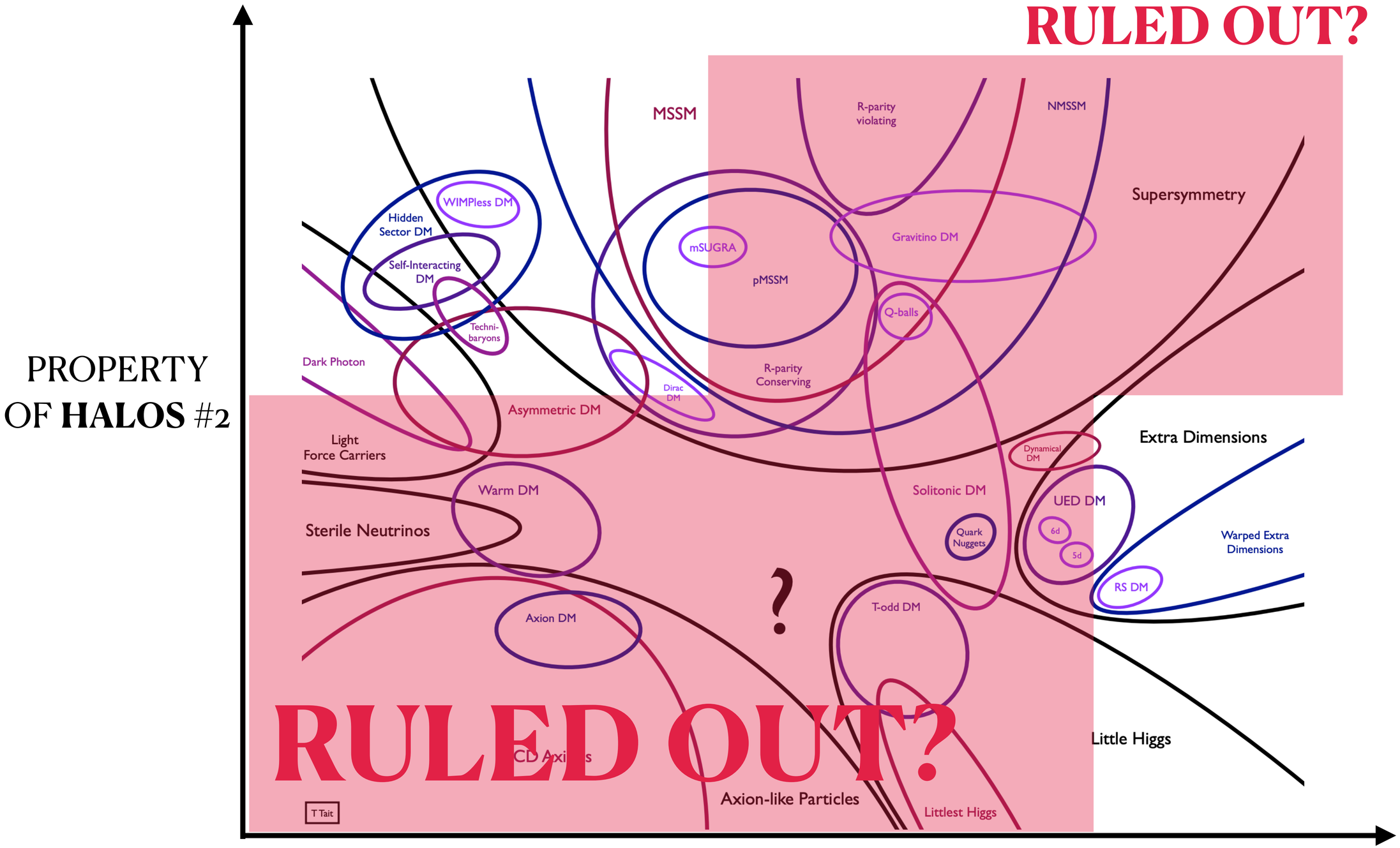
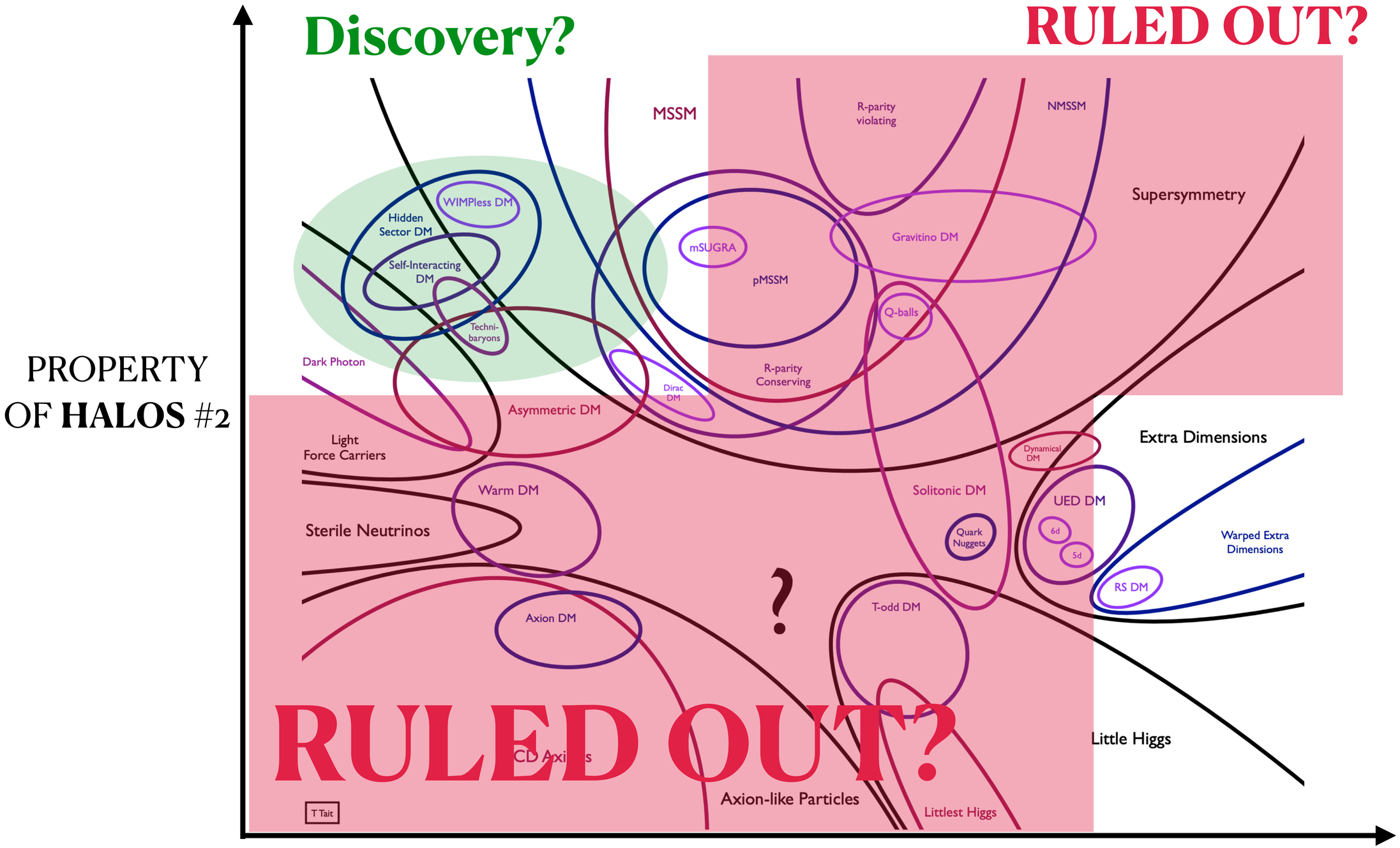
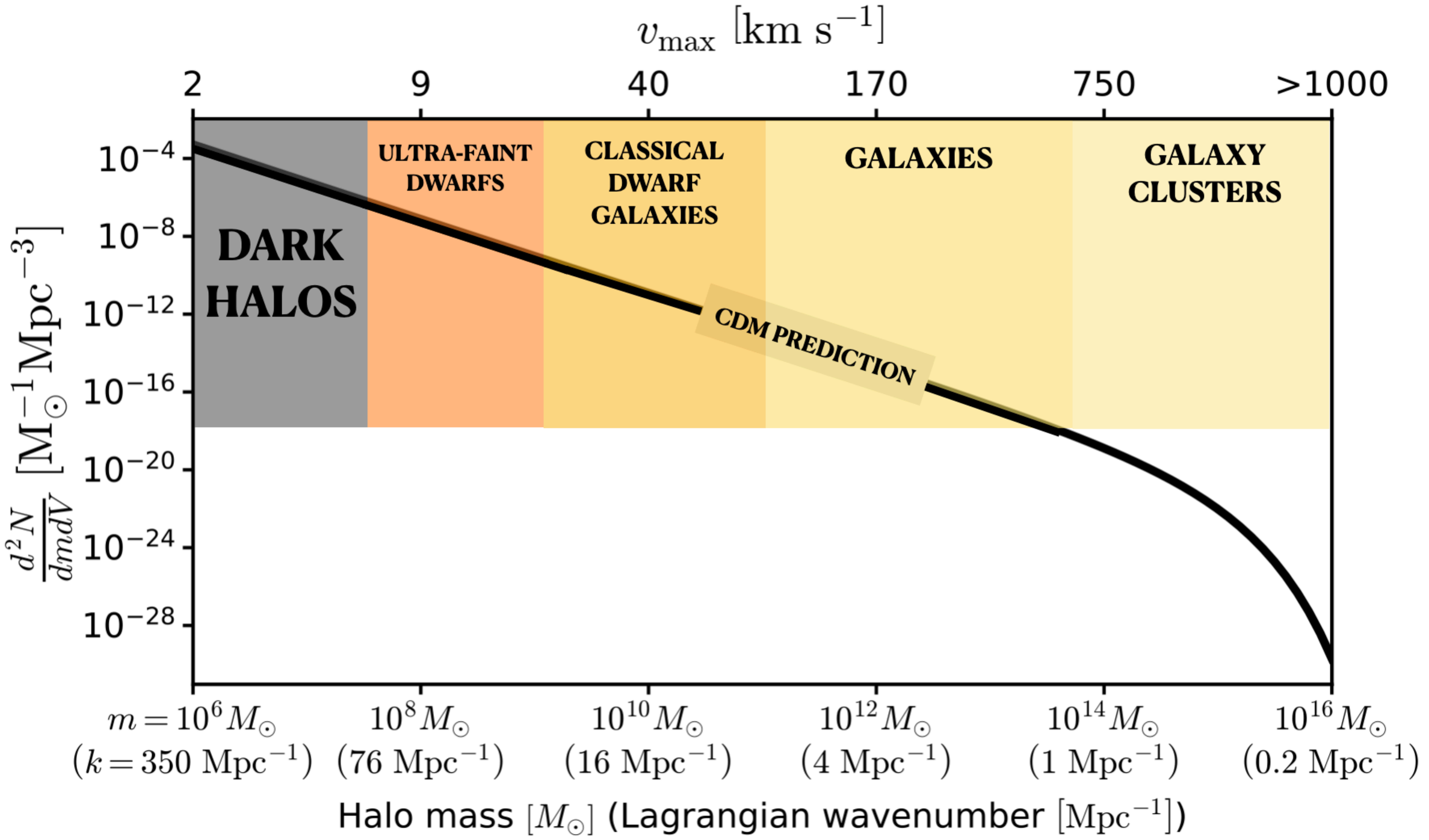


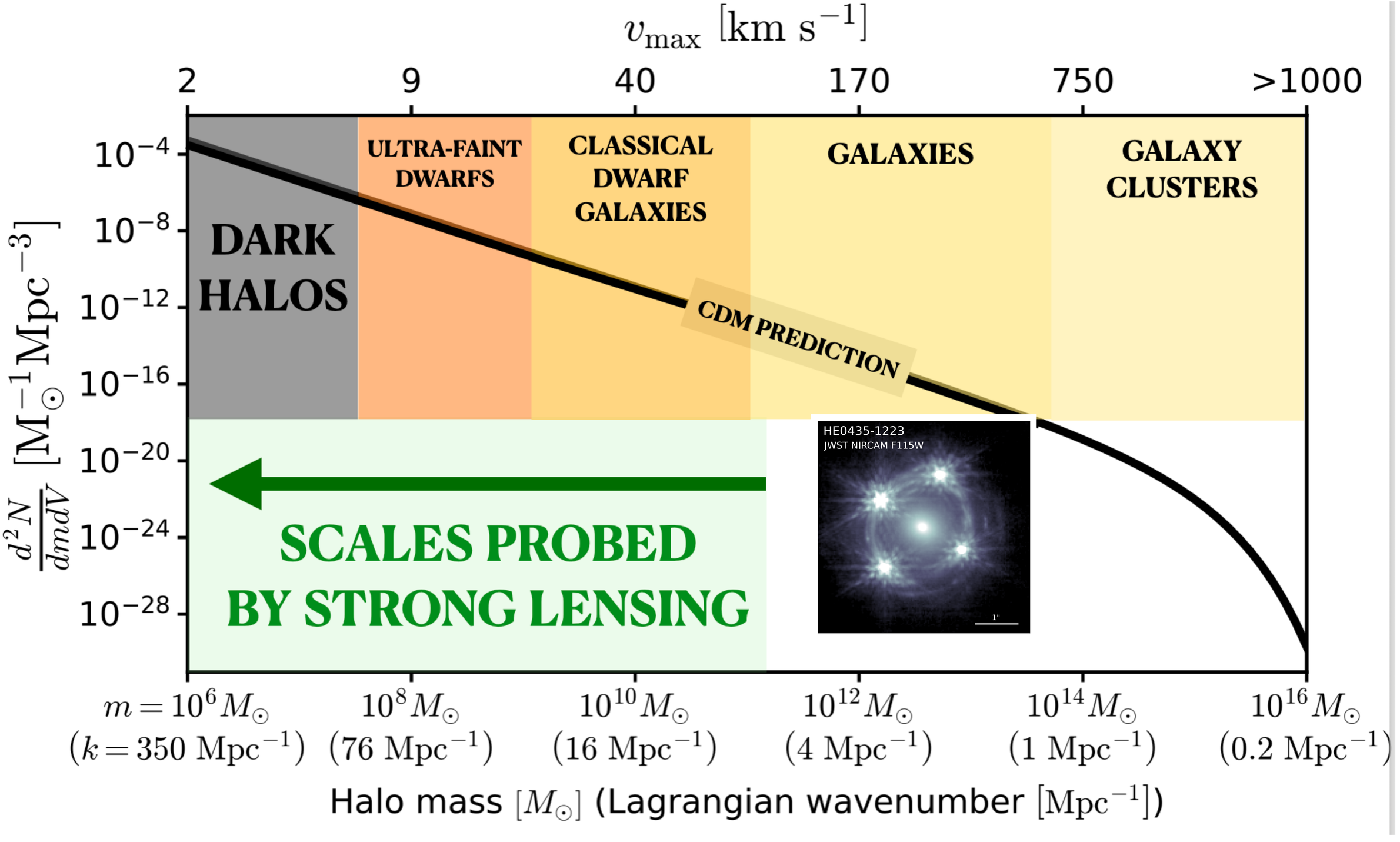
Figure by Tim Tait


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
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Solitonic DM
UED DM
6d
5d
Quark Nuggets
Warped Extra Dimensions
Sterile Neutrinos
RS DM
?
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait


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


Discovery?
RULED OUT?
PROPERTY OF HALOS #2
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
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R-parity Conserving
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Light Force Carriers
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T-odd DM
Axion DM
RULED OUT?
CD Axions
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T Tait
PROPERTY OF HALOS #1

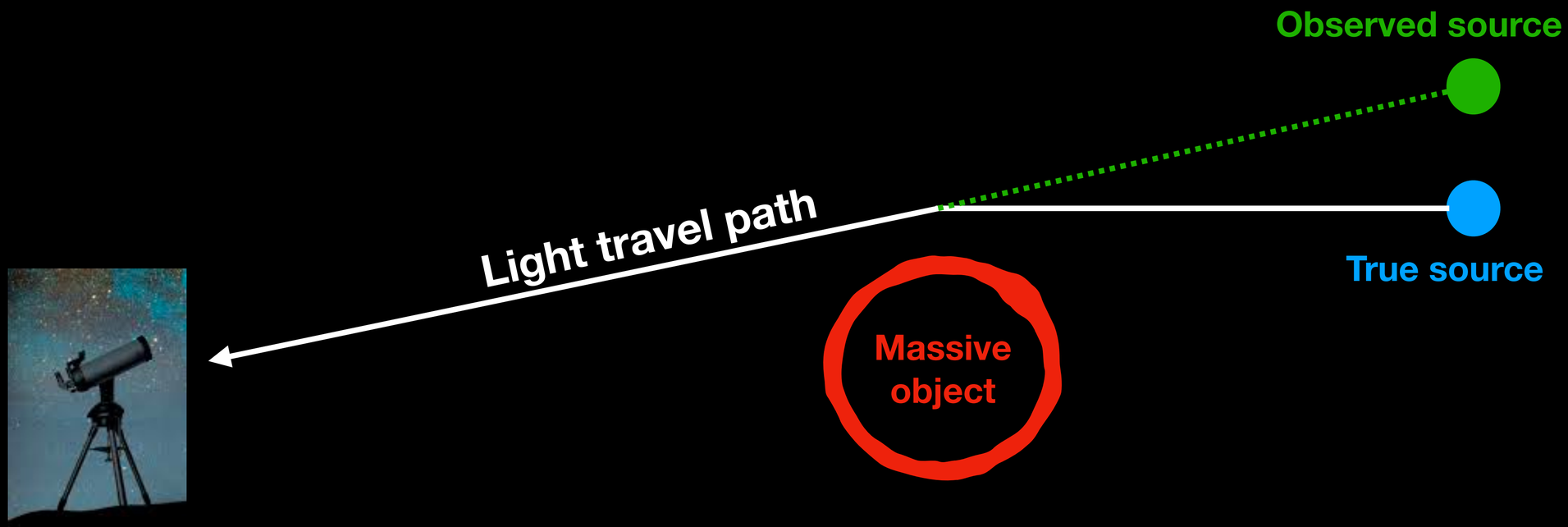

$v_{\rm max}$ [km s^{-1}]
2
9
40
170
750
>1000
DARK HALOS
ULTRA-FAINT DWARFS
CLASSICAL DWARF GALAXIES
GALAXIES
GALAXY CLUSTERS
CDM PREDICTION
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
$\frac{d^2N}{dmdV}$ [M$_\odot^{-1}$Mpc^{-3}]
$m = 10^6 M_\odot$ ($k = 350$ Mpc^{-1})
$10^8 M_\odot$ (76 Mpc^{-1})
$10^{10} M_\odot$ (16 Mpc^{-1})
$10^{12} M_\odot$ (4 Mpc^{-1})
$10^{14} M_\odot$ (1 Mpc^{-1})
$10^{16} M_\odot$ (0.2 Mpc^{-1})
Halo mass [$M_\odot$] (Lagrangian wavenumber [Mpc^{-1}])


$v_{\rm max}$ [km s^{-1}]
2
9
40
170
750
>1000
DARK HALOS
ULTRA-FAINT DWARFS
CLASSICAL DWARF GALAXIES
GALAXIES
GALAXY CLUSTERS
CDM PREDICTION
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
$\frac{d^2N}{dmdV}$ [M$_\odot^{-1}$Mpc^{-3}]
SCALES PROBED BY STRONG LENSING
HE0435-1223
JWST NIRCAM F115W
1"
$m = 10^6 M_\odot$ ($k = 350$ Mpc^{-1})
$10^8 M_\odot$ (76 Mpc^{-1})
$10^{10} M_\odot$ (16 Mpc^{-1})
$10^{12} M_\odot$ (4 Mpc^{-1})
$10^{14} M_\odot$ (1 Mpc^{-1})
$10^{16} M_\odot$ (0.2 Mpc^{-1})
Halo mass [$M_\odot$] (Lagrangian wavenumber [Mpc^{-1}])

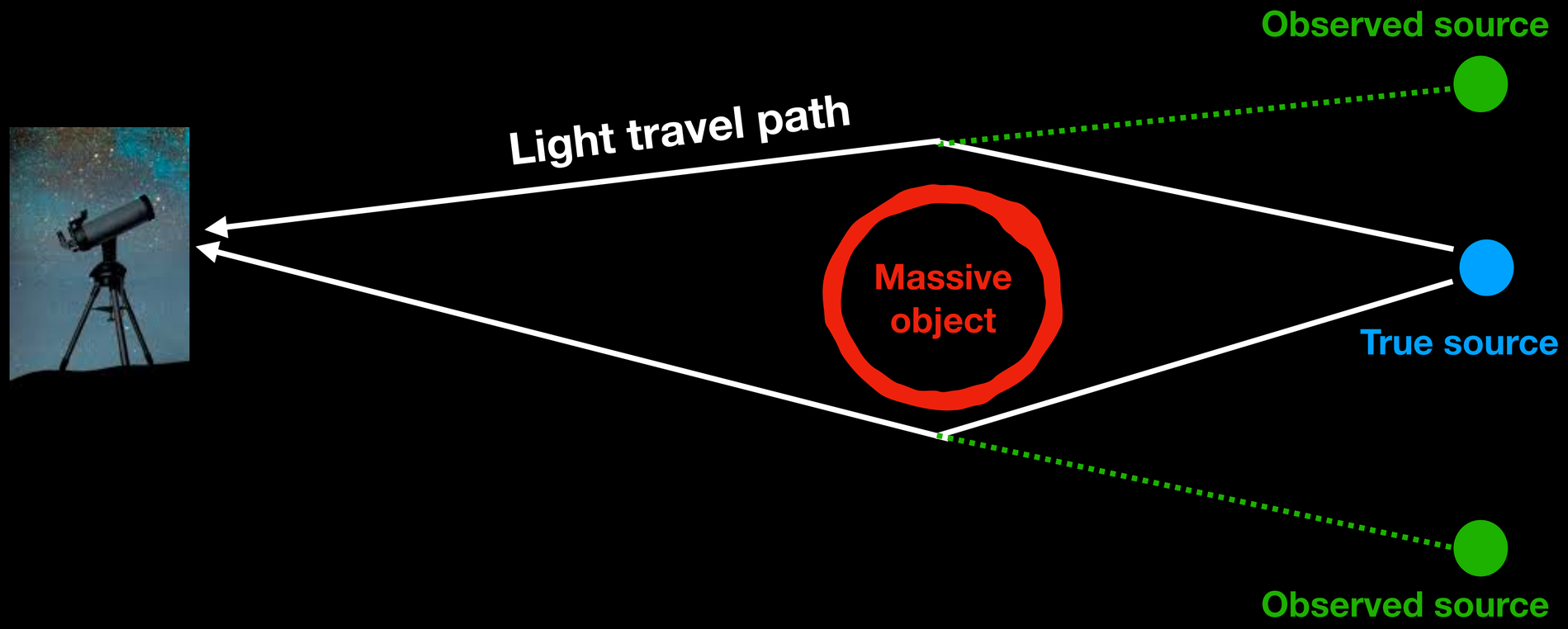
Strong lensing



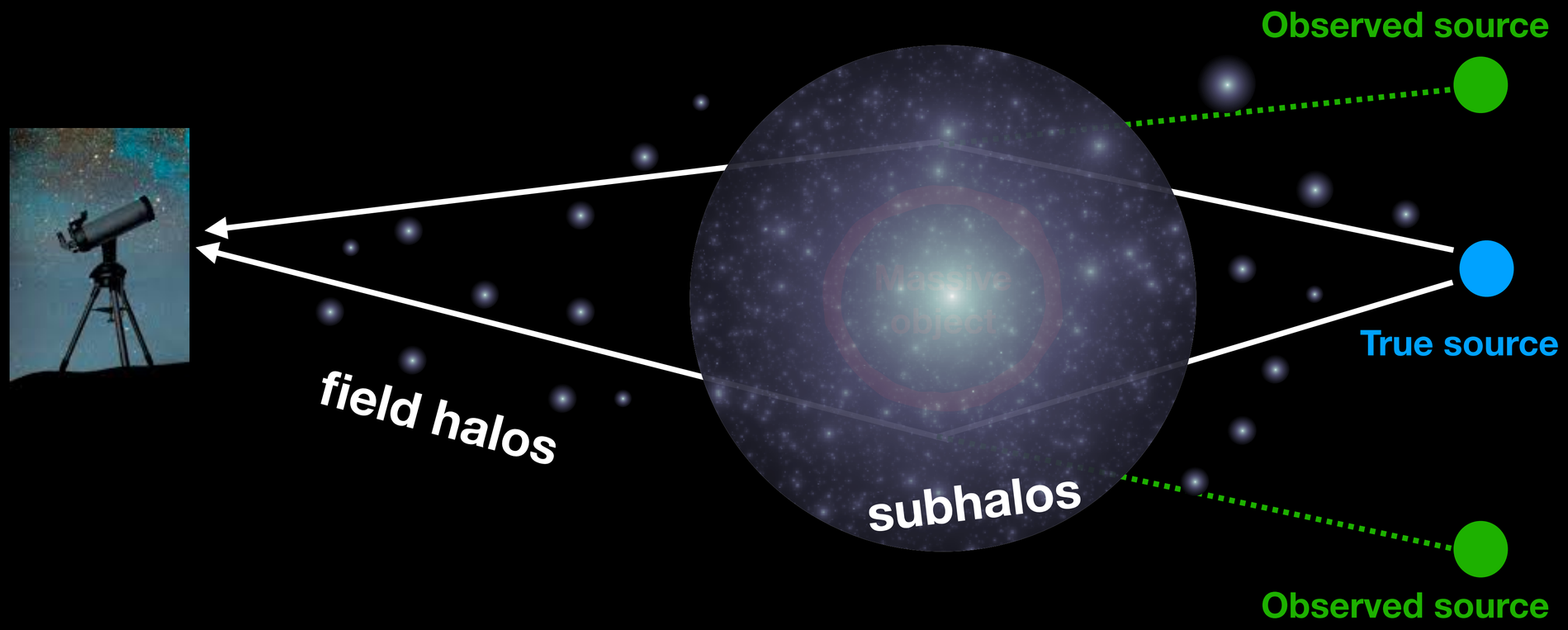
Gravitational lensing: deflection of light by gravitational fields

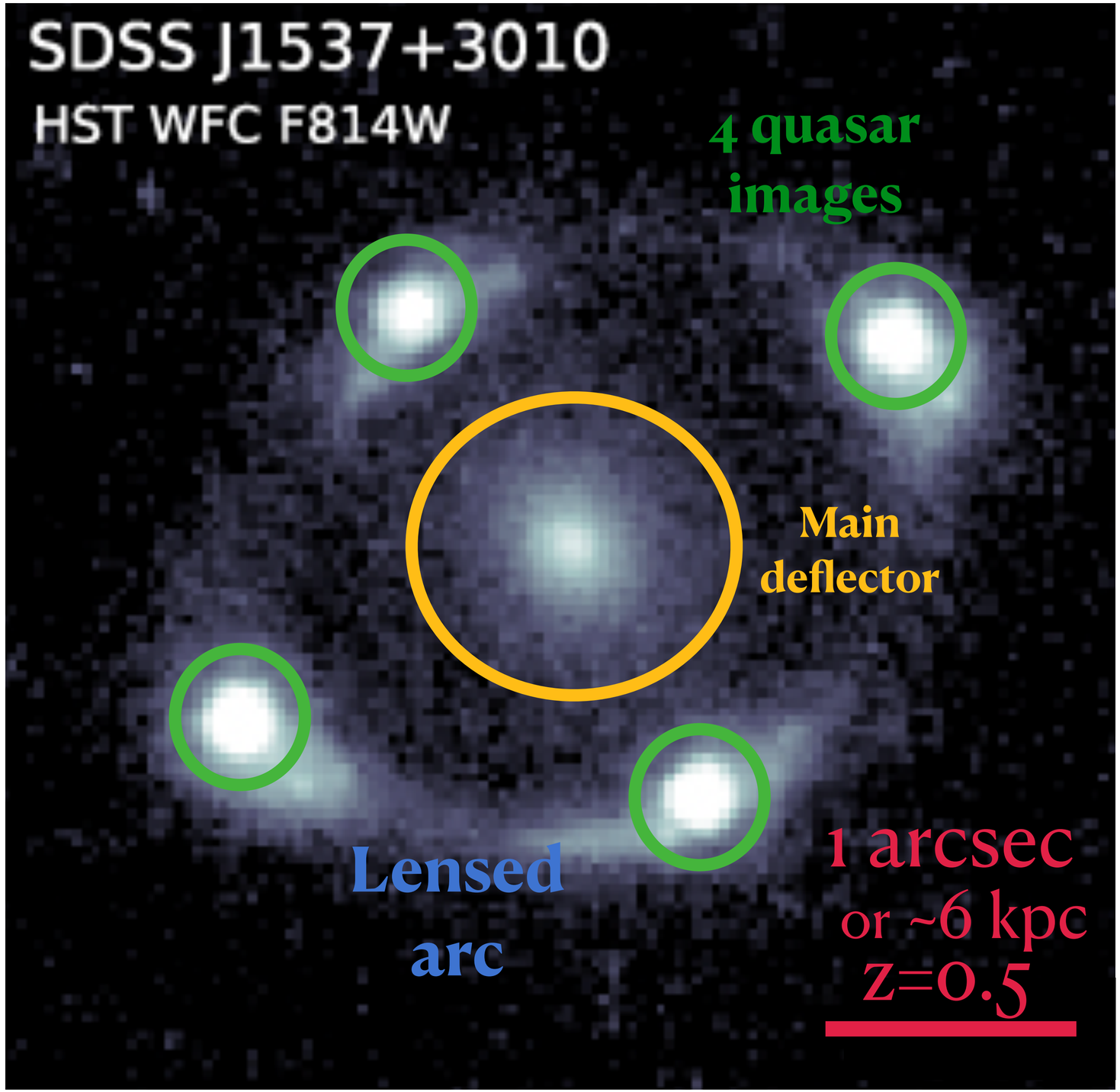


Strong lensing produces multiple images of a single source…



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




SDSS J1537+3010
HST WFC F814W
4 quasar images
Main deflector
Lensed arc
1 arcsec
or ~6 kpc
z=0.5

Strong lensing of compact sources

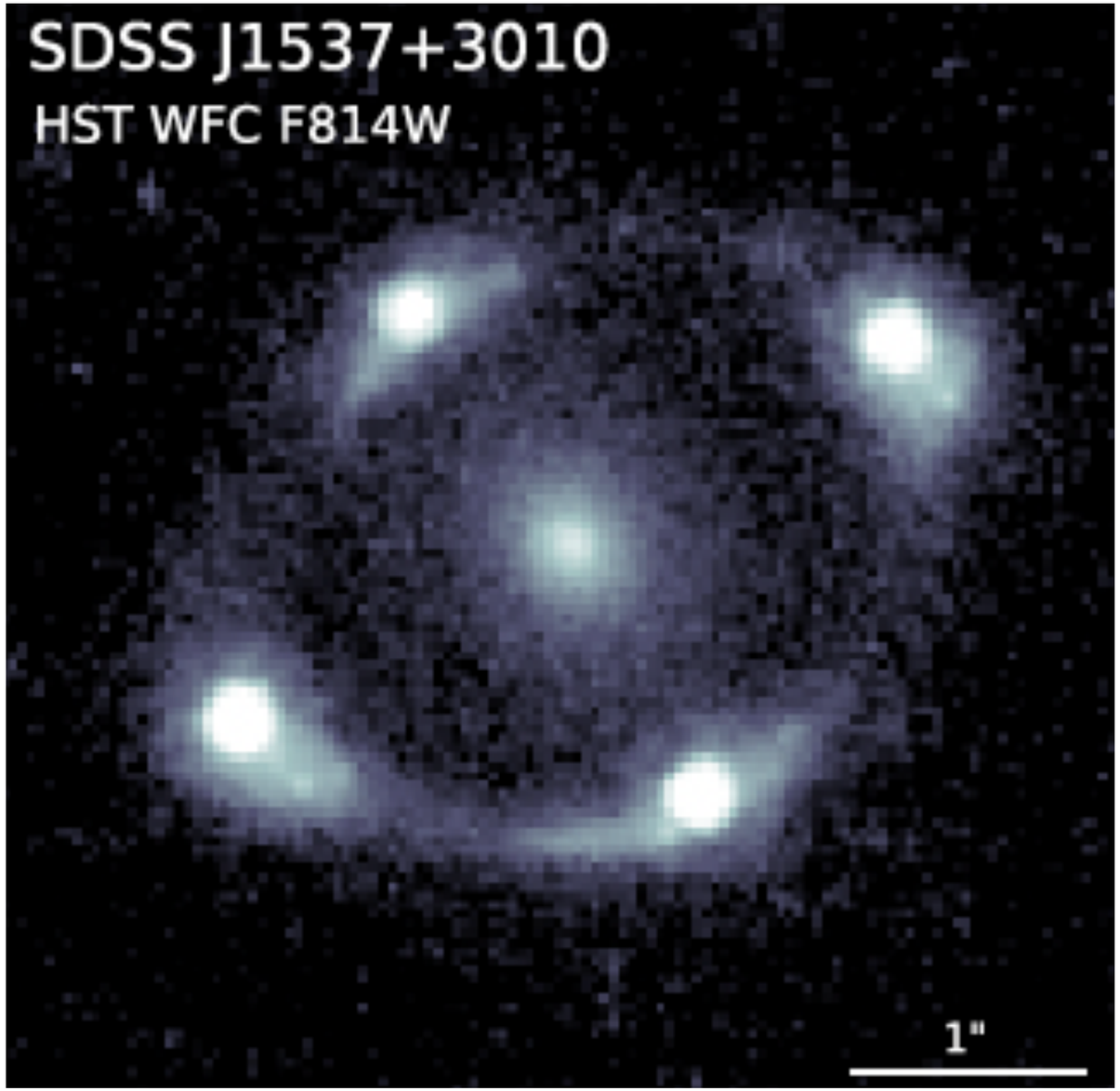
$$\text{time delays} \propto \Psi \quad (\text{grav. potential})$$

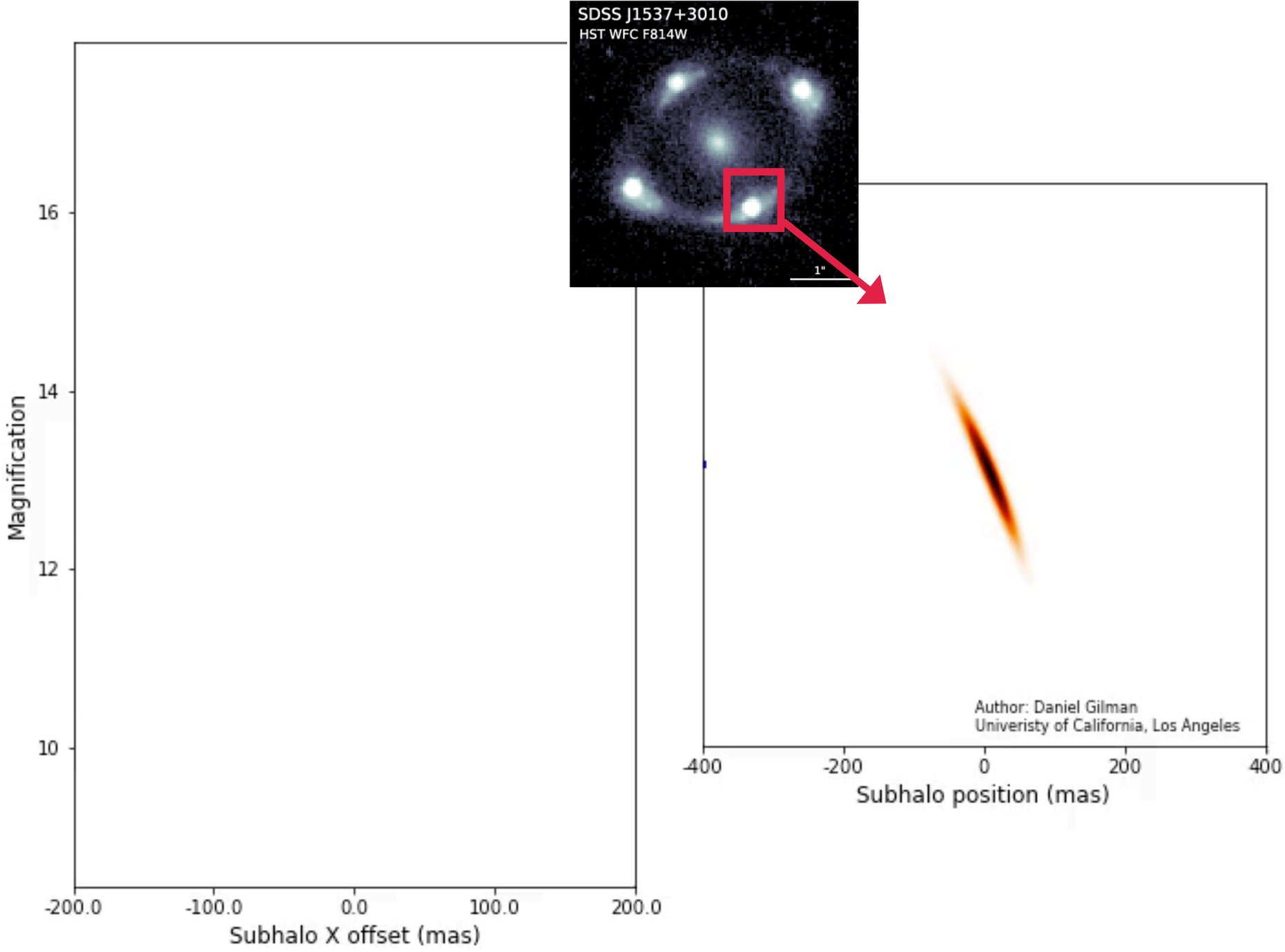
$$\text{image positions/arcs} \propto \frac{\partial \Psi}{\partial x}$$

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

(of unresolved sources)

—> **sensitive to local perturbations from small-scale structure along entire line of sight**



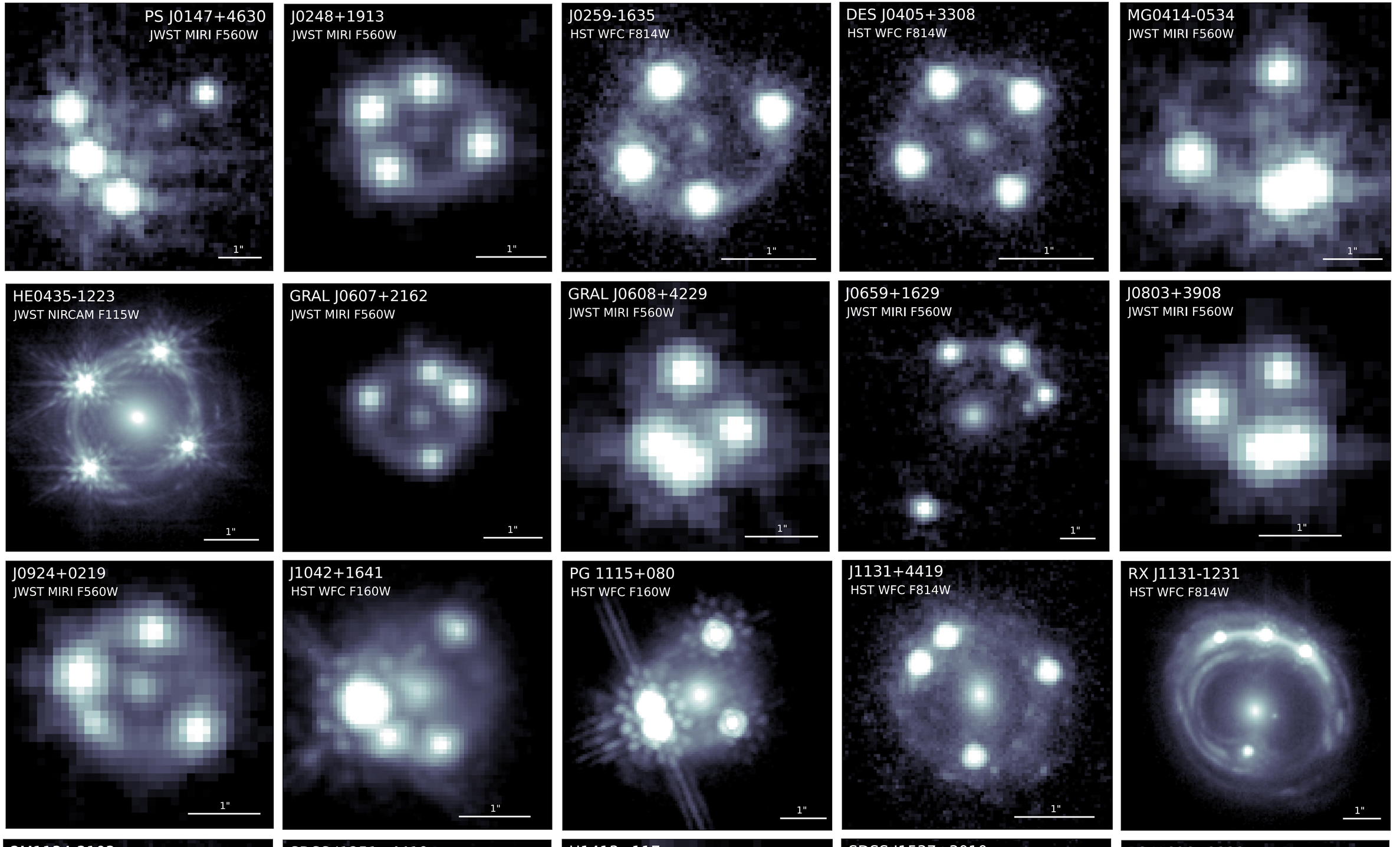

SDSS J1537+3010
HST WFC F814W
1"
Magnification
16
14
12
10
-200.0
-100.0
0.0
100.0
200.0
Subhalo X offset (mas)
Author: Daniel Gilman
Univeristy of California, Los Angeles
-400
-200
0
200
400
Subhalo position (mas)

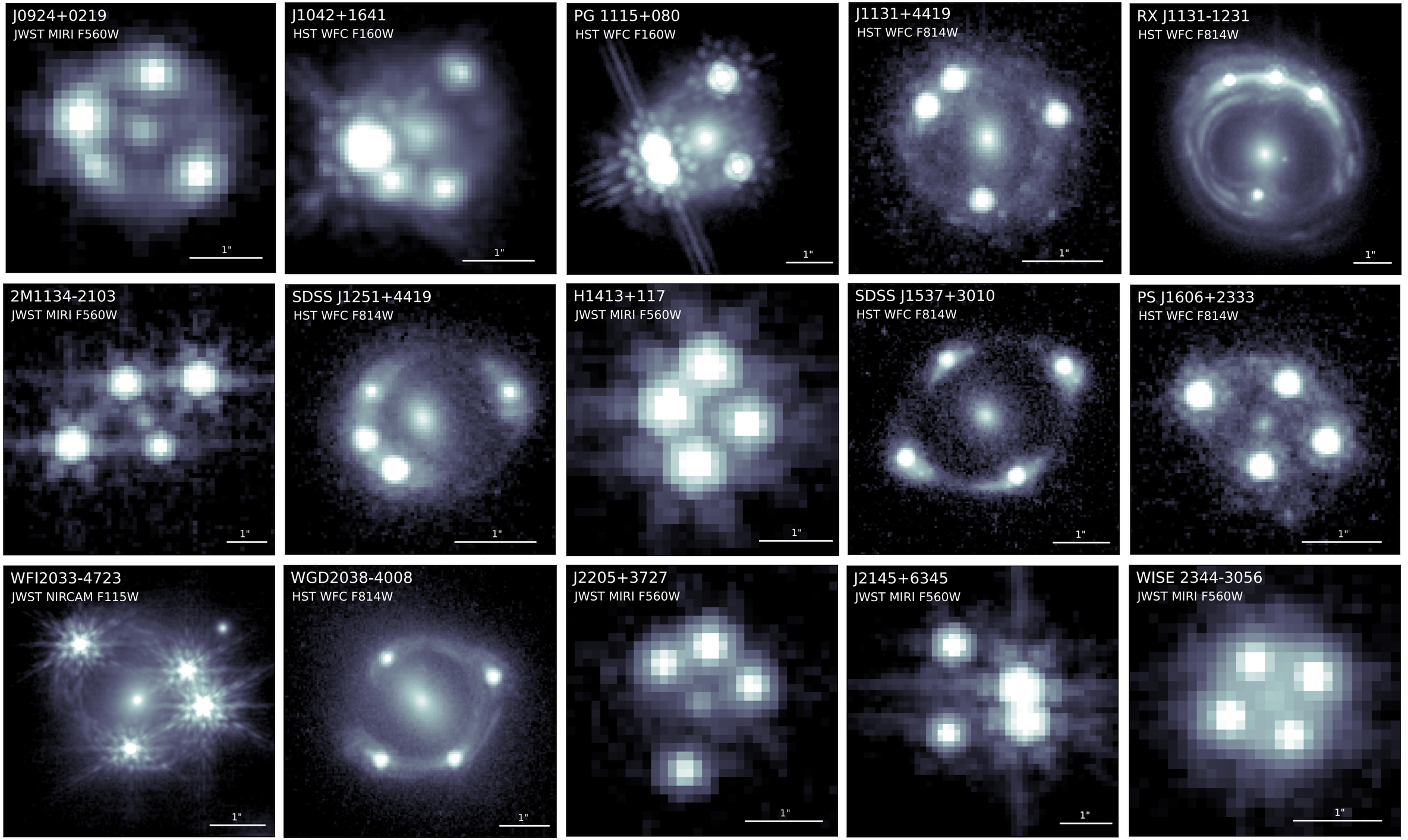
Historical limitations:

From early 2000s - mid 2010s,
we only knew of a handful of quads

Today:

We know of ~50 quads,
JWST has recently surveyed 31
(GO-2046, PI Nierenberg,
Co-Is include D Gilman)


PS J0147+4630
JWST MIRI F560W
1"
J0248+1913
JWST MIRI F560W
1"
J0259-1635
HST WFC F814W
1"
DES J0405+3308
HST WFC F814W
1"
MG0414-0534
JWST MIRI F560W
1"
HE0435-1223
JWST NIRCAM F115W
1"
GRAL J0607+2162
JWST MIRI F560W
1"
GRAL J0608+4229
JWST MIRI F560W
1"
J0659+1629
JWST MIRI F560W
1"
J0803+3908
JWST MIRI F560W
1"
J0924+0219
JWST MIRI F560W
1"
J1042+1641
HST WFC F160W
1"
PG 1115+080
HST WFC F160W
1"
J1131+4419
HST WFC F814W
1"
RX J1131-1231
HST WFC F814W
1"


J0924+0219
JWST MIRI F560W
1"
J1042+1641
HST WFC F160W
1"
PG 1115+080
HST WFC F160W
1"
J1131+4419
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"

Historical limitations:

From early 2000s - mid 2010s,
we only knew of a handful of quads

Most quads contaminated by
stellar microlensing

Today:

We know of ~50 quads,
JWST has recently surveyed 31
(GO-2046, PI Nierenberg,
Co-Is include D Gilman)

JWST mid-IR measurements
- flux from extended region
around quasar (larger than 1 μarcsec)
-> immune to stellar microlensing
- smaller than 10 pc
-> maximally sensitive to DM halos

Historical limitations:

From early 2000s - mid 2010s,
we only knew of a handful of quads

Most quads contaminated by
stellar microlensing

We lacked analysis methods to perform population-level inferences

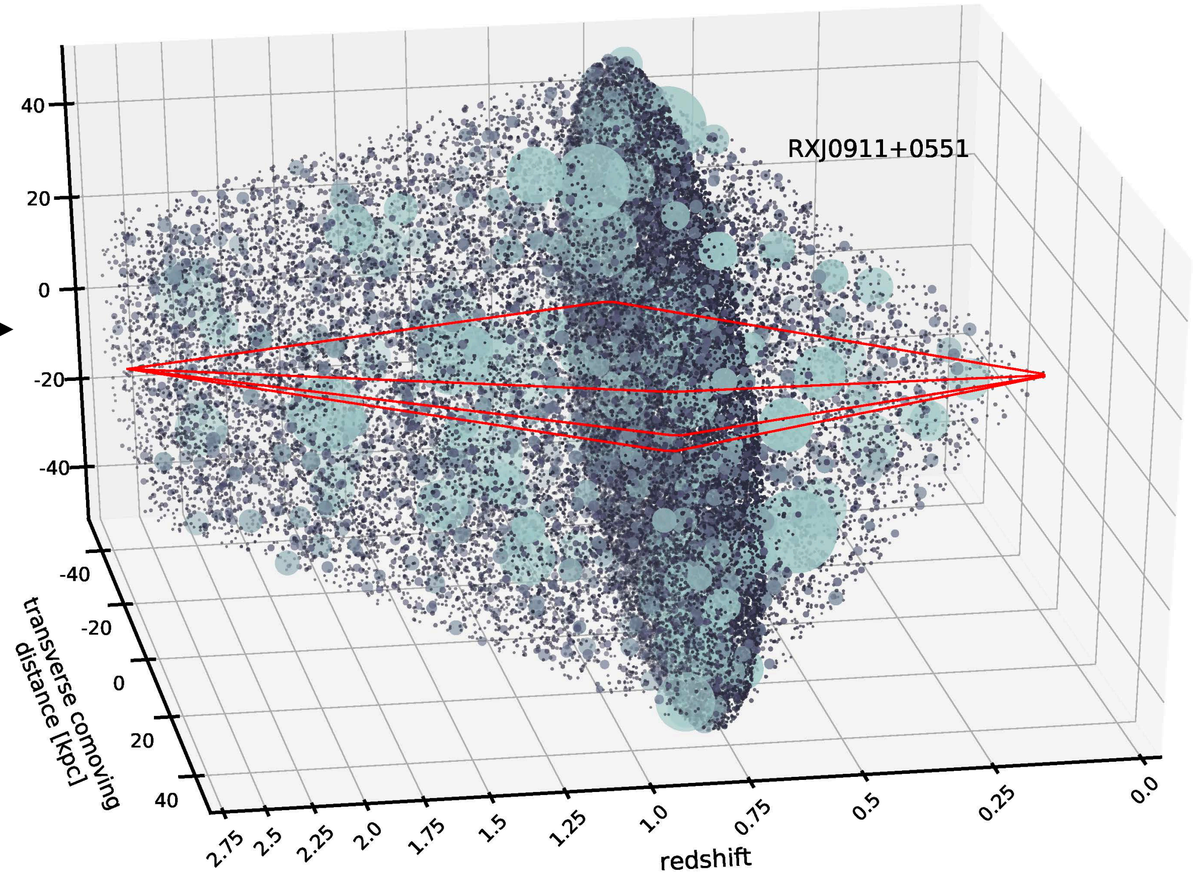
Today:

We know of ~50 quads,
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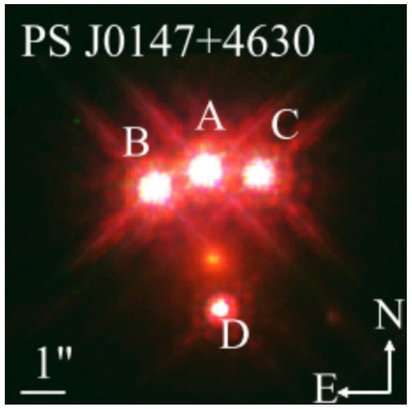
JWST mid-IR measurements
- flux from extended region
around quasar (larger than 1 μarcsec)
-> immune to stellar microlensing
- smaller than 10 pc
-> maximally sensitive to DM halos

We can perform end-to-end forward modeling with entire halo populations

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

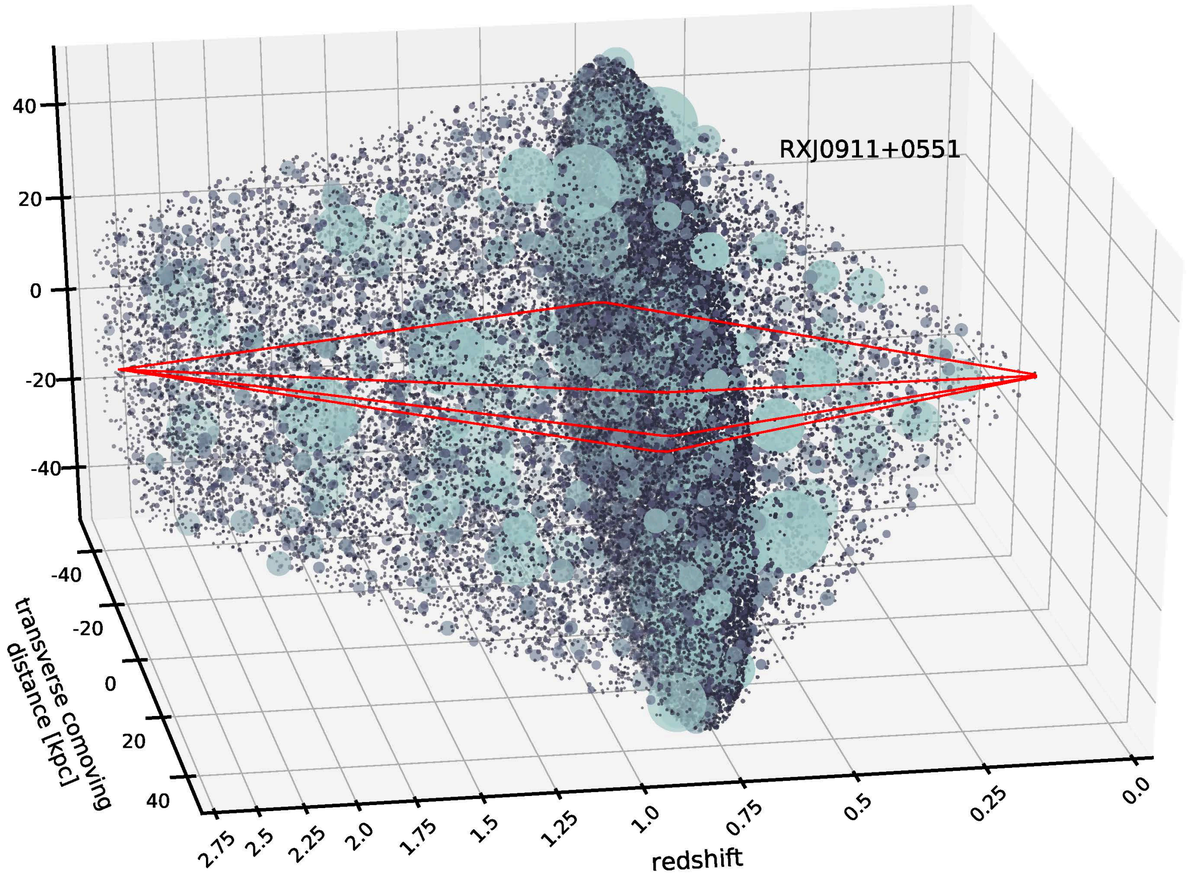
-> tidal evolution models for subhalos
(recent progress: Du, Gilman, et al. 2025)

-> dark matter physics in alternative theories to CDM

-> globular clusters
based on scaling relations from nearby ellipticals

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

-> millions upon millions of CPU hours



All code is open source/public

In particular:

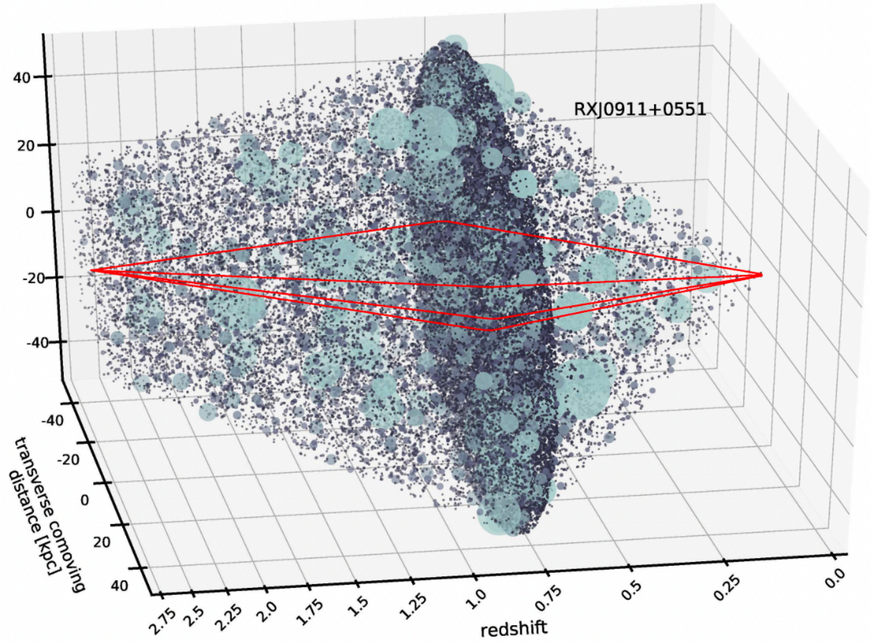
`pyHalo`

- 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!

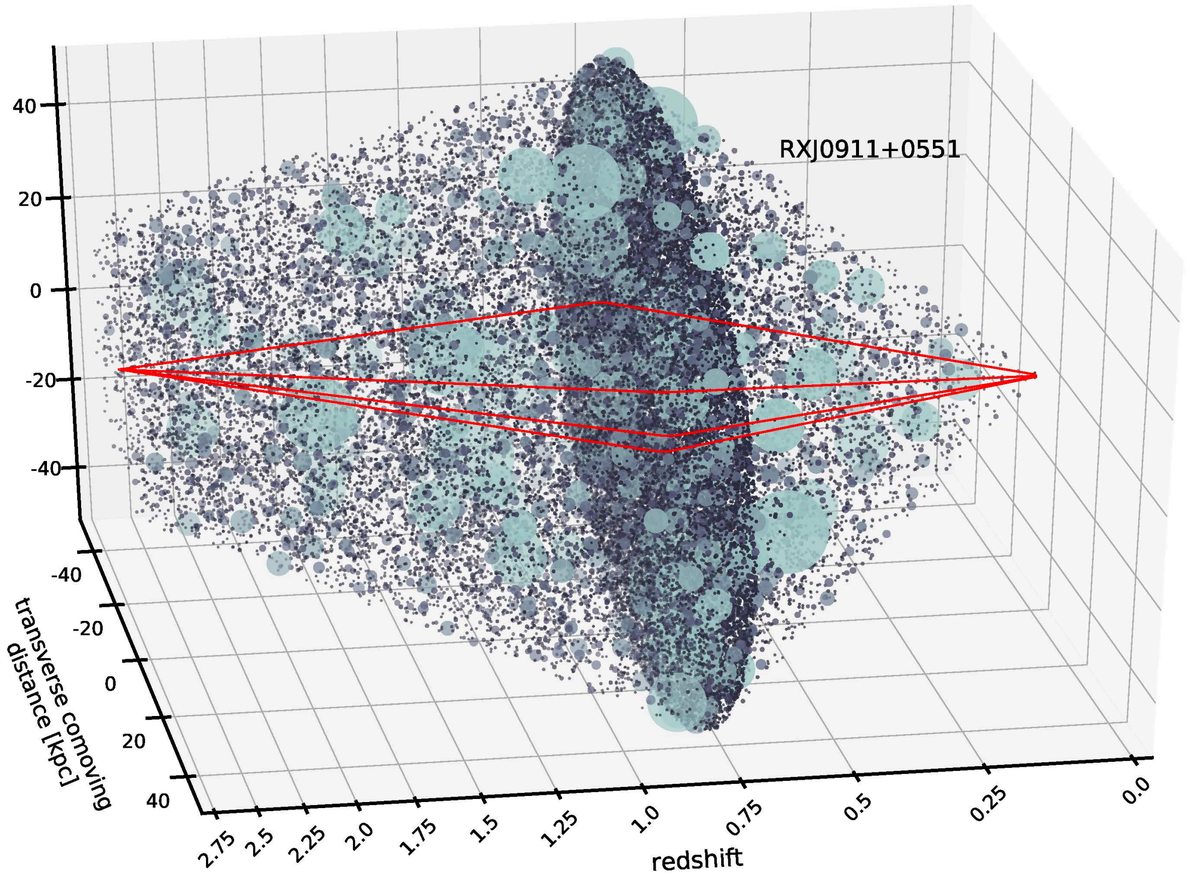
Installation

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

- 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

Can test any theory that alters halo properties



Cold dark matter (CDM)

Warm dark matter (WDM)

Gravity is the only relevant force

Free-streaming imposes a characteristic length scale $\lambda_{\rm FS}$ in structure formation

Gravity is scale free

$$\lambda_{\rm FS} \sim ct_{NR} \propto V_{\rm rms}\Big|_{z\sim 3000}$$

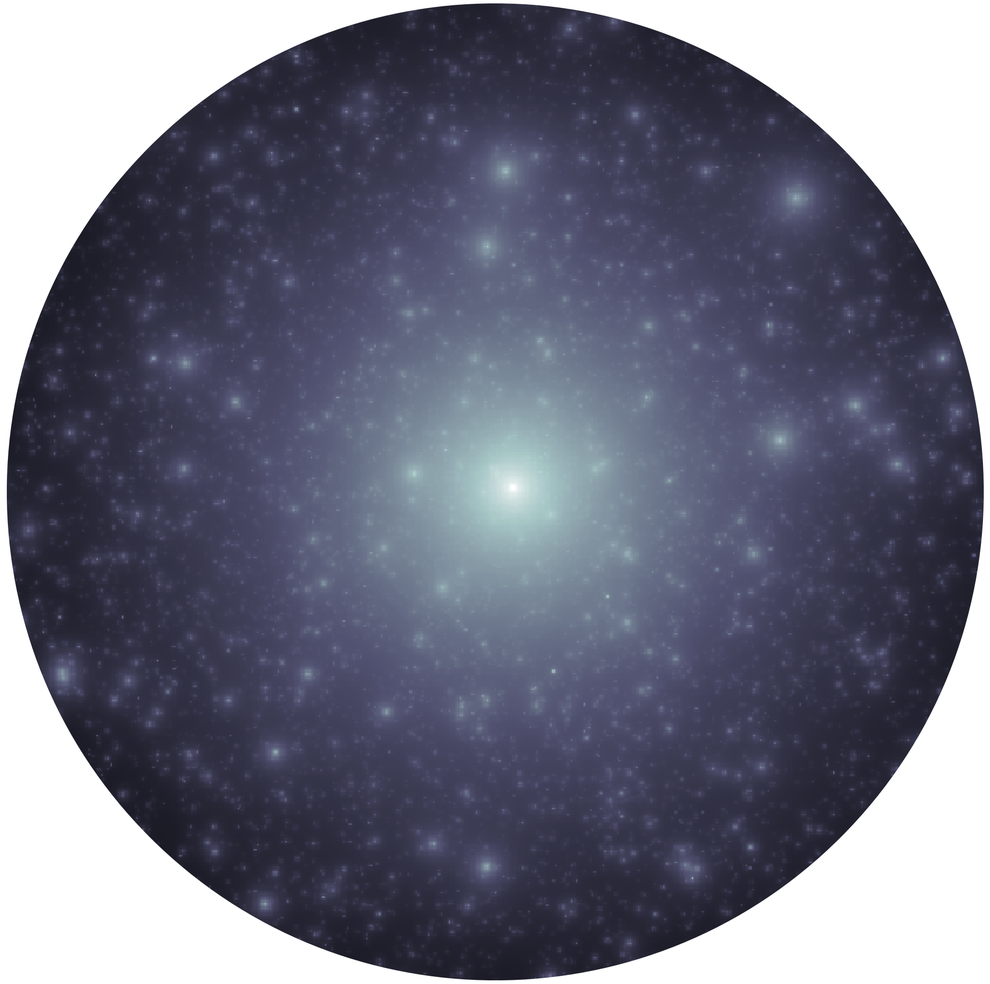
Halo mass function is scale-free

Small-scale structure washed out on scales below $\lambda_{\rm FS}$

Halos have a universal density profile

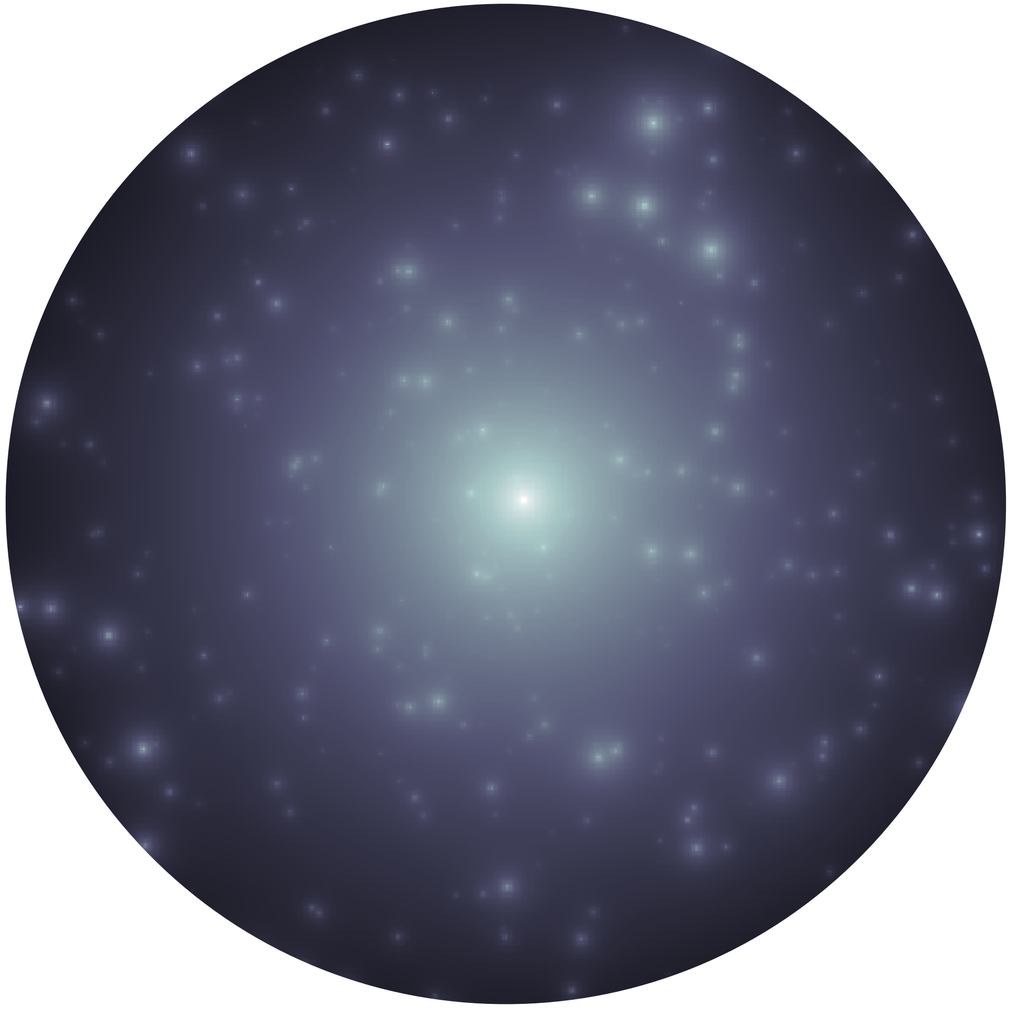
CDM

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



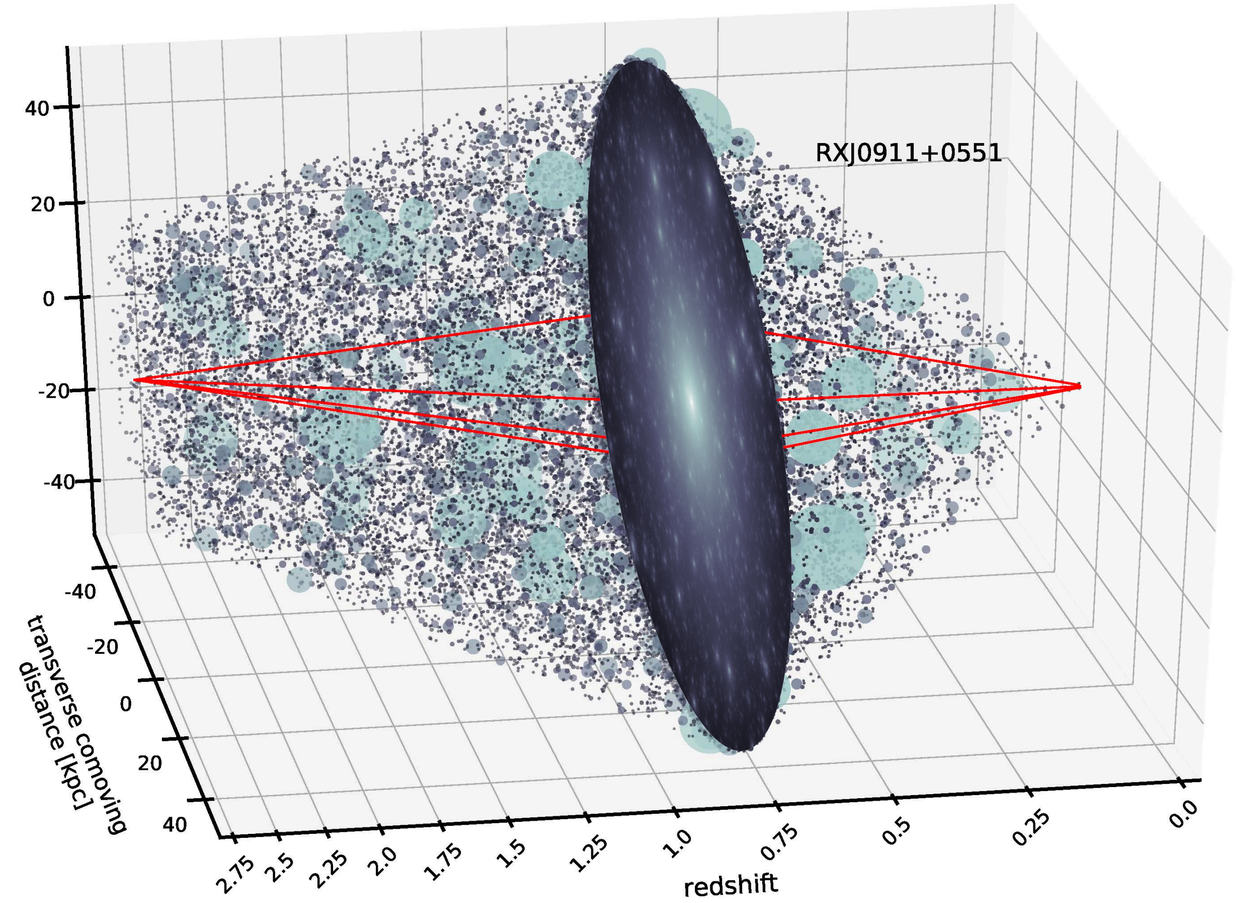
Warm dark matter (WDM)

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

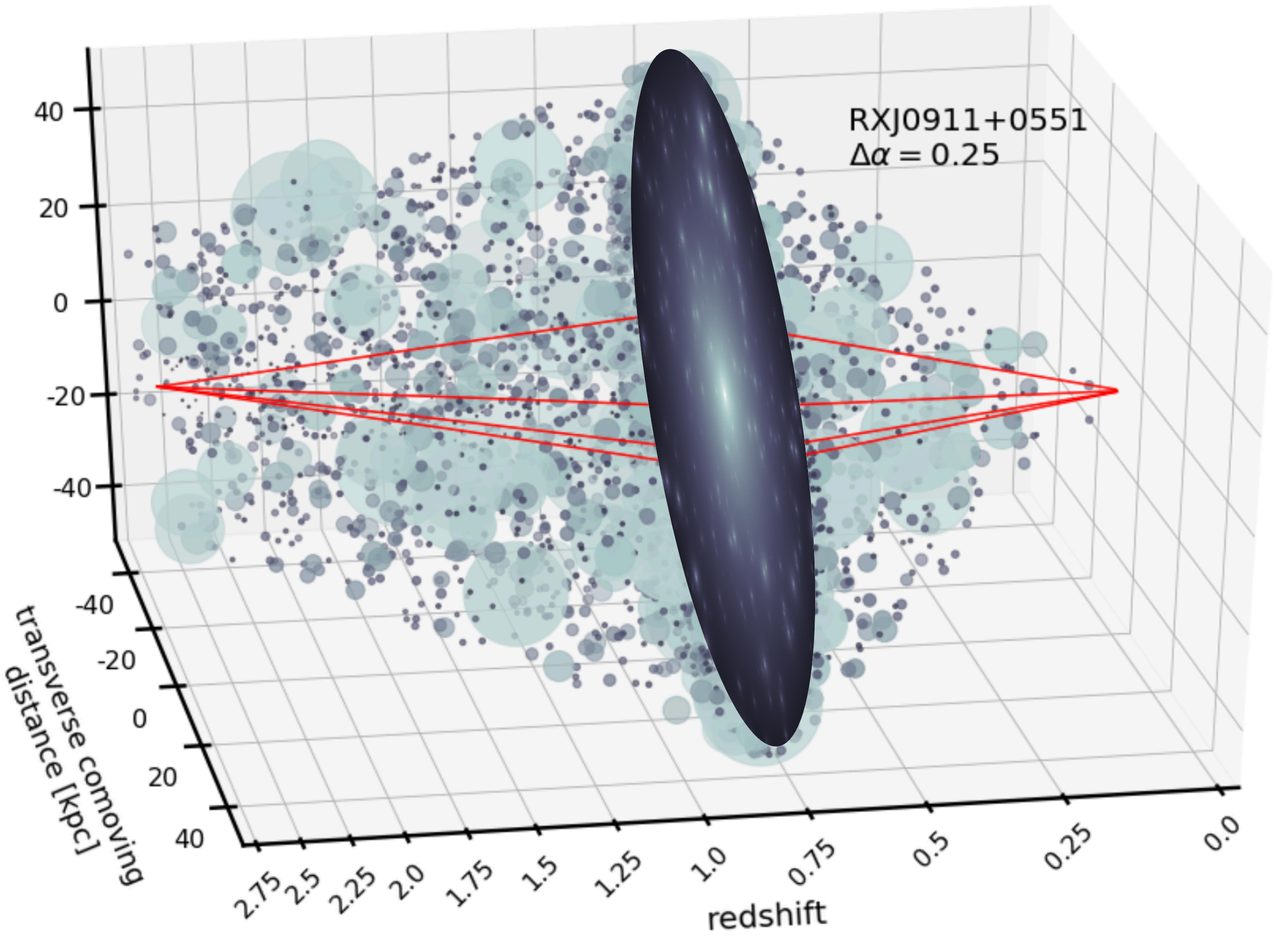


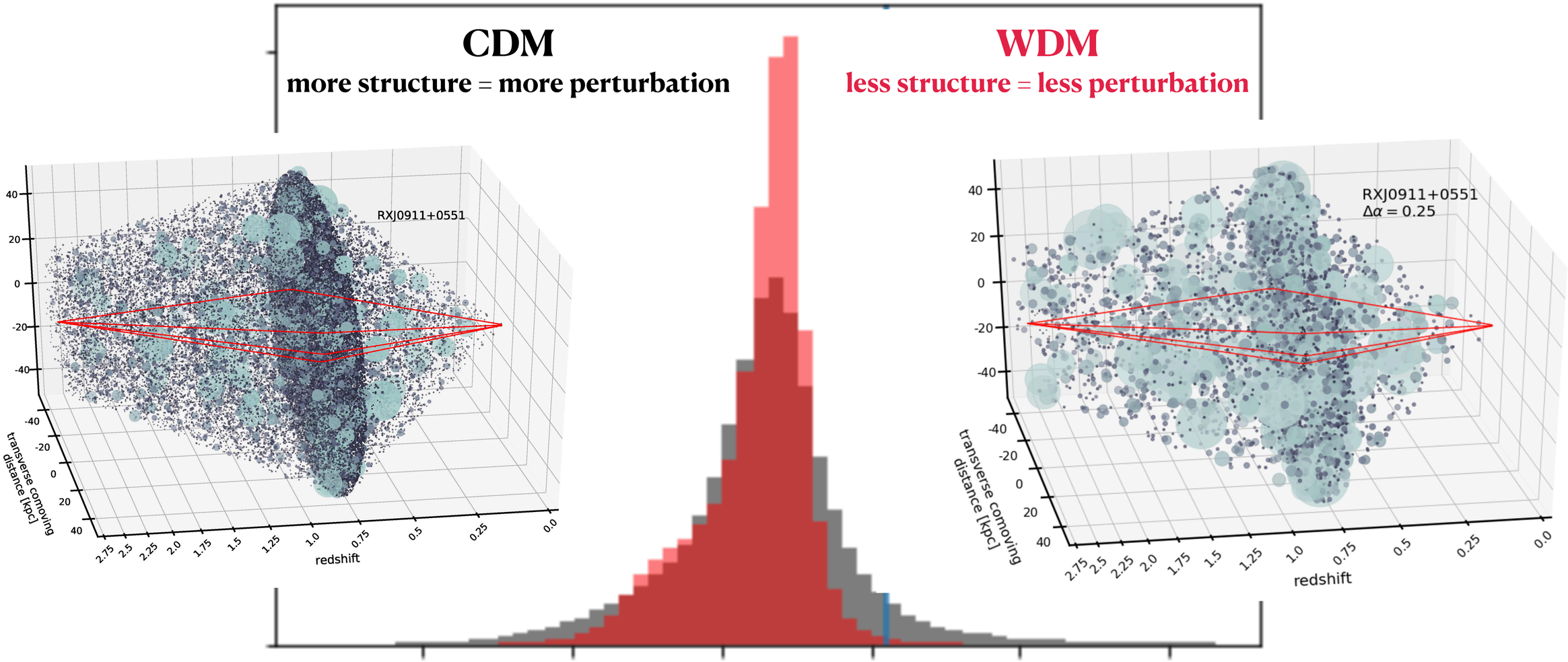
$\sim 10^5 - 10^6$ simulations per lens for accurate statistics

CDM

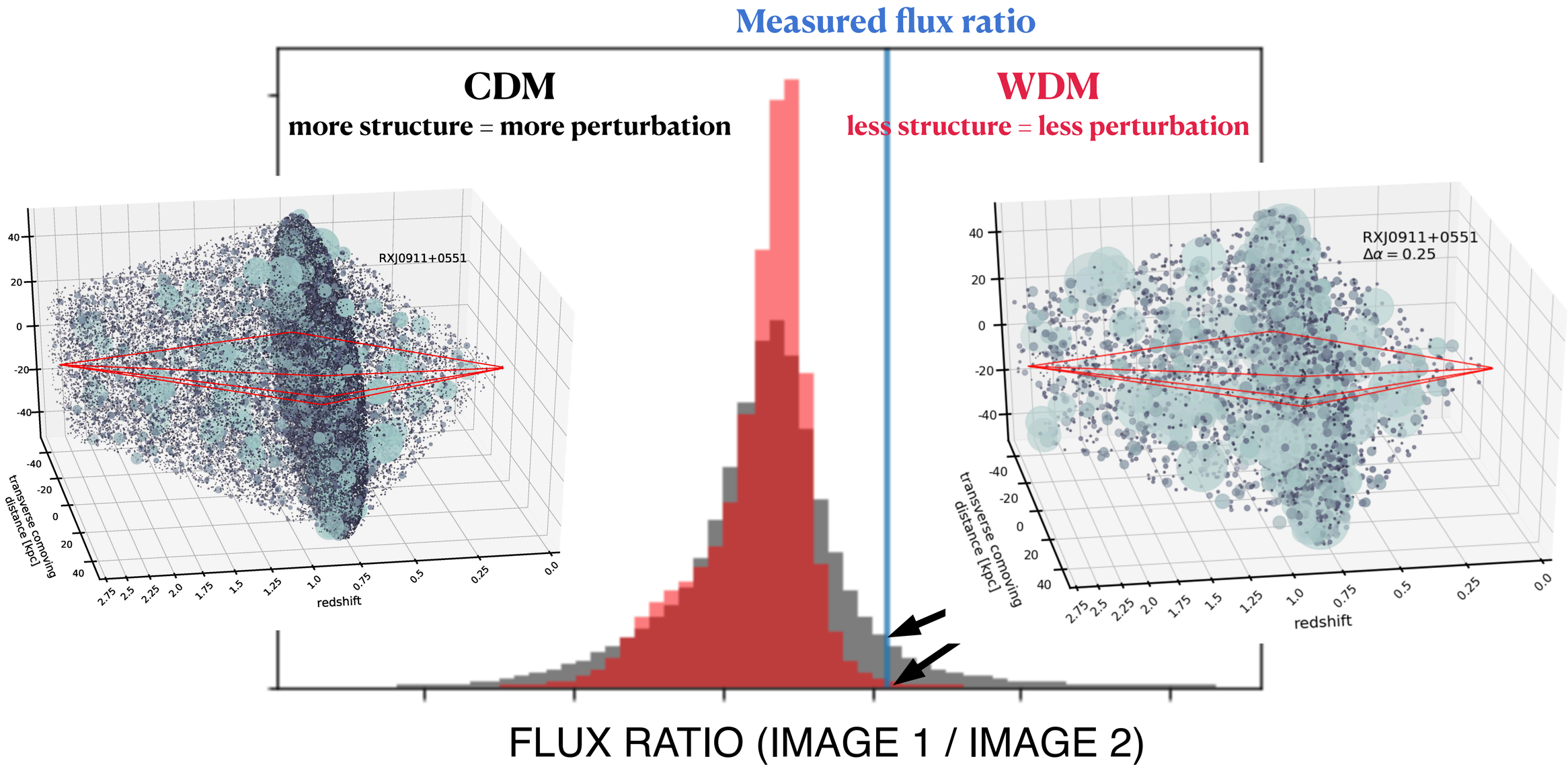


WDM





FLUX RATIO (IMAGE 1 / IMAGE 2)


Measured flux ratio
CDM
more structure = more perturbation
WDM
less structure = less perturbation
RXJ0911+0551
RXJ0911+0551
$\Delta\alpha = 0.25$
transverse comoving distance [kpc]
redshift
FLUX RATIO (IMAGE 1 / IMAGE 2)

JWST lensed quasar dark matter survey IV: Stringent warm dark matter constraints from the joint reconstruction of extended lensed arcs and quasar flux ratios

D. Gilman,[1,*] A. M. Nierenberg,[2] T. Treu,[3] C. Gannon,[2] X. Du,[3] H. Paugnat,[3] S. Birrer,[4] A. J. Benson,[5] P. Mozumdar,[3,6] K. C. Wong,[7] D. Williams,[3] R. E. Keeley,[2] K. N. Abazajian,[8] T. Anguita,[9] V. N. Bennert,[10] S. G. Djorgovski,[11] S. F. Hoenig,[12] A. Kusenko,[3,13] M. Malkan,[3] T. Morishita,[14] V. Motta,[15] L. A. Moustakas,[16] W. Sheu,[3] D. Sluse,[17] D. Stern,[16] and M. Stiavelli[18]

PRD,
arXiv: 2511.07513

The free-streaming length of dark matter from JWST observations of 28 strong gravitational lenses

D. Gilman⋆,[1,*] A. M. Nierenberg⋆,[2,†] T. Treu,[3] K. N. Abazajian,[4] T. Anguita,[5,6] V. N. Bennert,[7] A. J. Benson,[8] S. Birrer,[9] S. G. Djorgovski,[10] X. Du,[3] C. Gannon,[2] S. F. Hoenig,[11] R. E. Keeley,[2] A. Kusenko,[3,12] H. R. Larsson,[2] M. Malkan,[3] T. Morishita,[13] V. Motta,[14] L. A. Moustakas,[15] P. Mozumdar,[3,16] H. Paugnat,[3] W. Sheu,[3] D. Sluse,[17] D. Stern,[15] M. Stiavelli,[18] D. Williams,[3] and K. C. Wong[19]

[1] *Department of Astronomy & Astrophysics, University of Chicago, Chicago, IL 60637, USA*
[2] *University of California, Merced, 5200 N Lake Road, Merced, CA 95341, USA*

PRL
arXiv: 2606.05277

Measurement of the minimum cold dark matter halo mass with strong gravitational lensing.

A. M. Nierenberg,[1,*] D. Gilman,[2,3] T. Treu,[4] X. Du,[4,5] C. Gannon,[1] H. Paugnat,[4] S. Birrer,[6] A. J. Benson,[7] K. N. Abazajian,[8] T. Anguita,[9] S. G. Djorgovski,[10] S. F. Hoenig,[11] R. E. Keeley,[8] A. Kusenko,[4,12] H. R. Larsson,[1] L. A. Moustakas,[13] P. Mozumdar,[4] W. Sheu,[4] D. Sluse,[14] D. Stern,[13] D. Williams,[4] and K. C. Wong[15]

[1] *University of California, Merced, 5200 N Lake Road, Merced, CA 95341, USA*
[2] *Department of Astronomy & Astrophysics, University of Chicago, Chicago, IL 60637, USA*

PRL
arXiv: 2604.05237

Technological development #1:

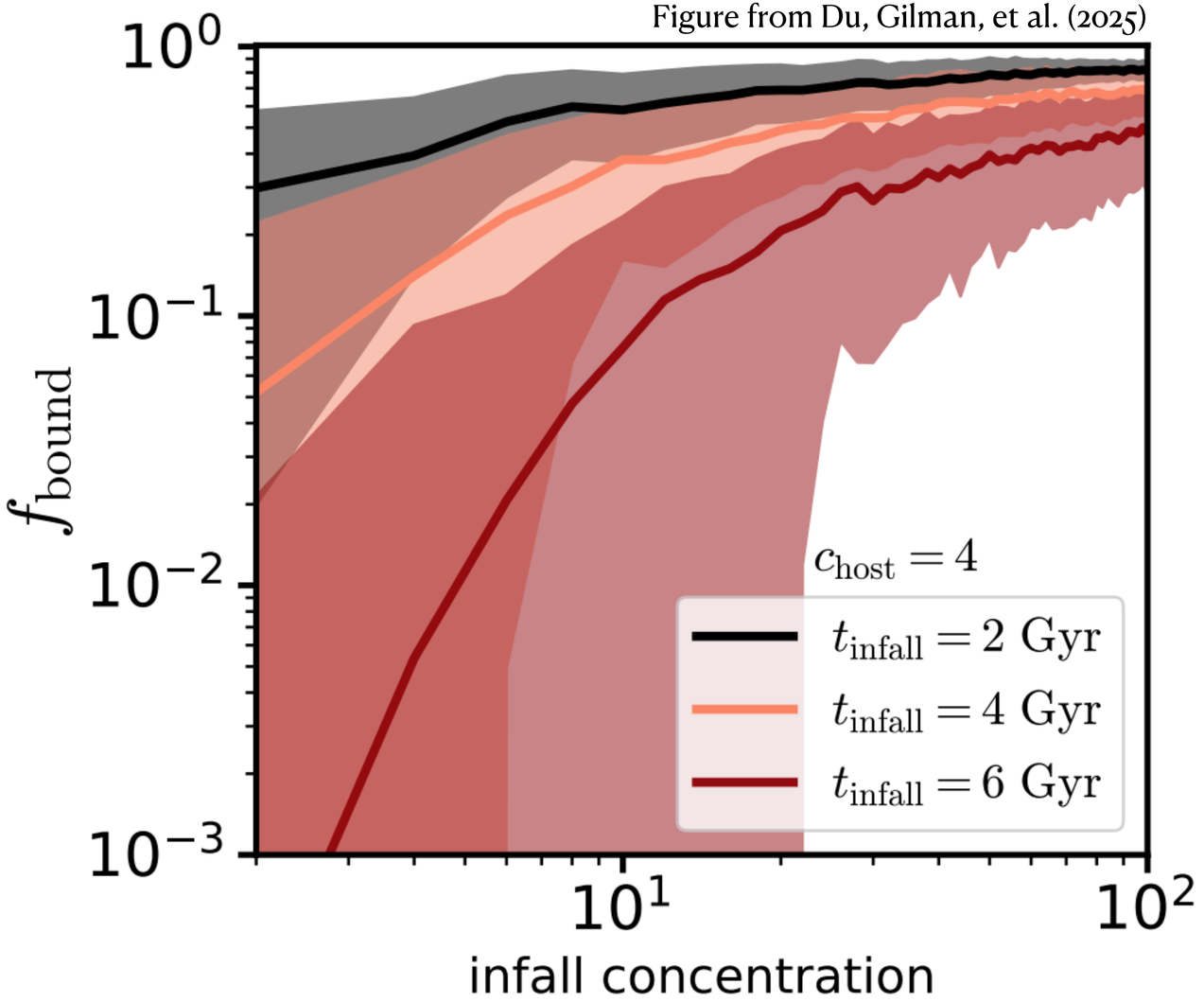
Subhalo tidal evolution model calibrated
to the galacticus semi-analytic model and implemented in pyHalo

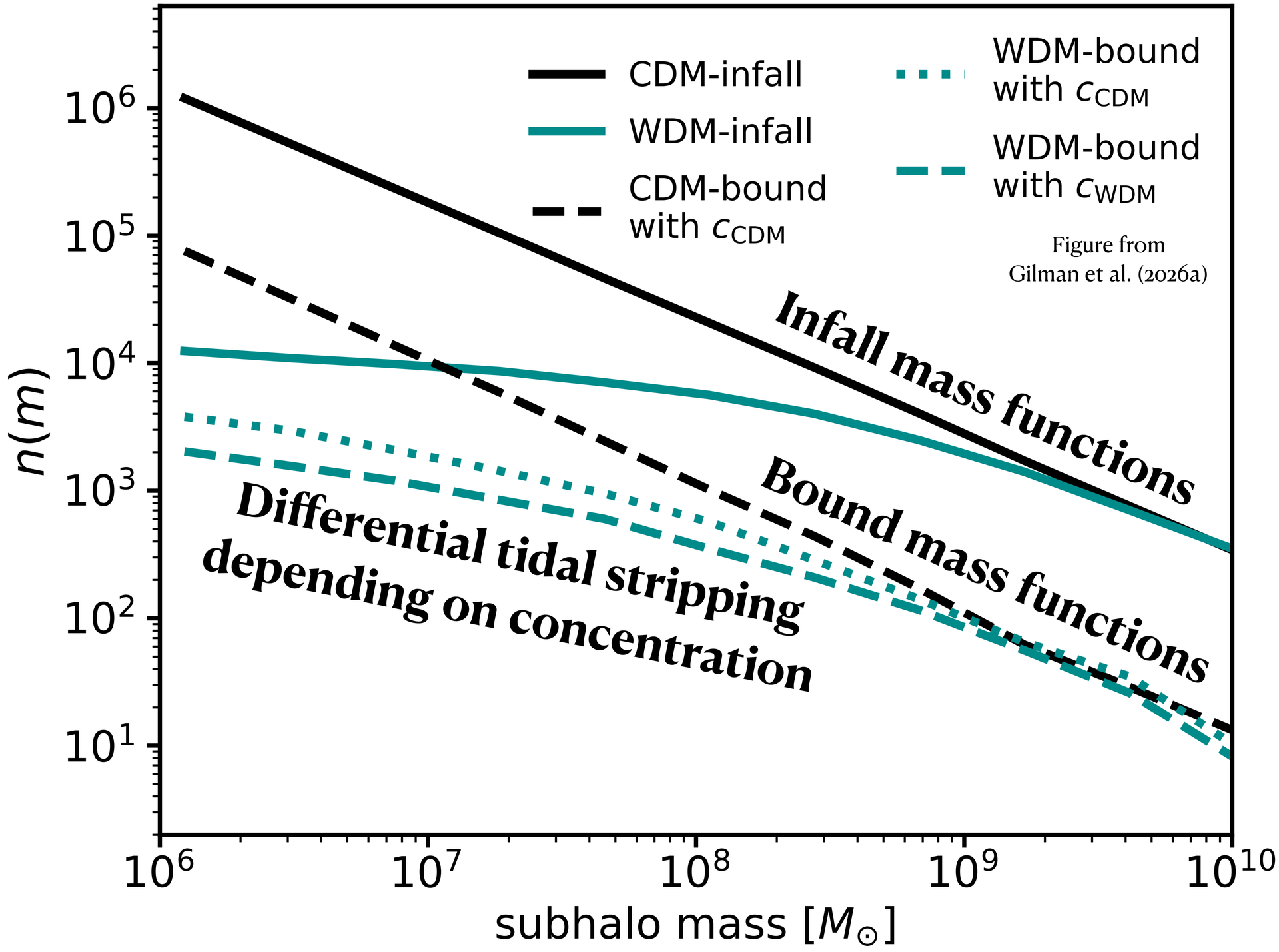
The model predicts

$$p\left(f_{\rm bound} \,|\, c_{\rm infall}, z_{\rm infall}, c_{\rm host}\right)$$

For technical details see
Du, Gilman et al. (2025)
"Faster than SAM"

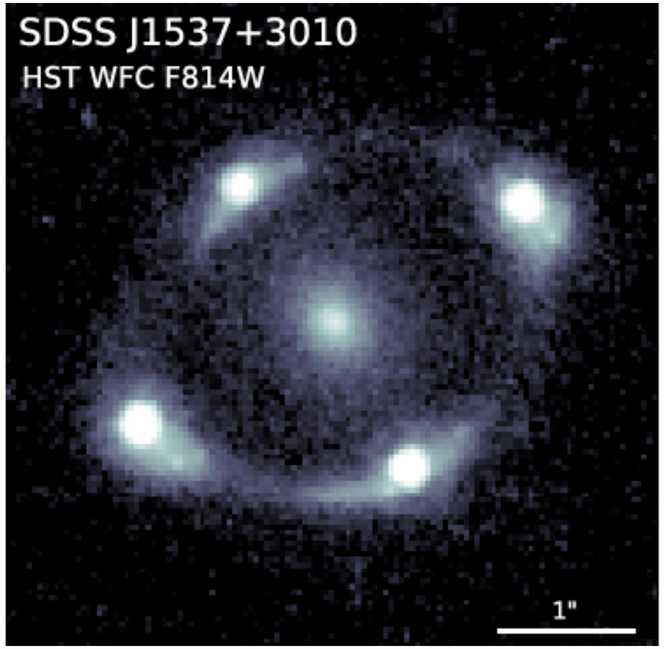
Figure from Du, Gilman, et al. (2025)



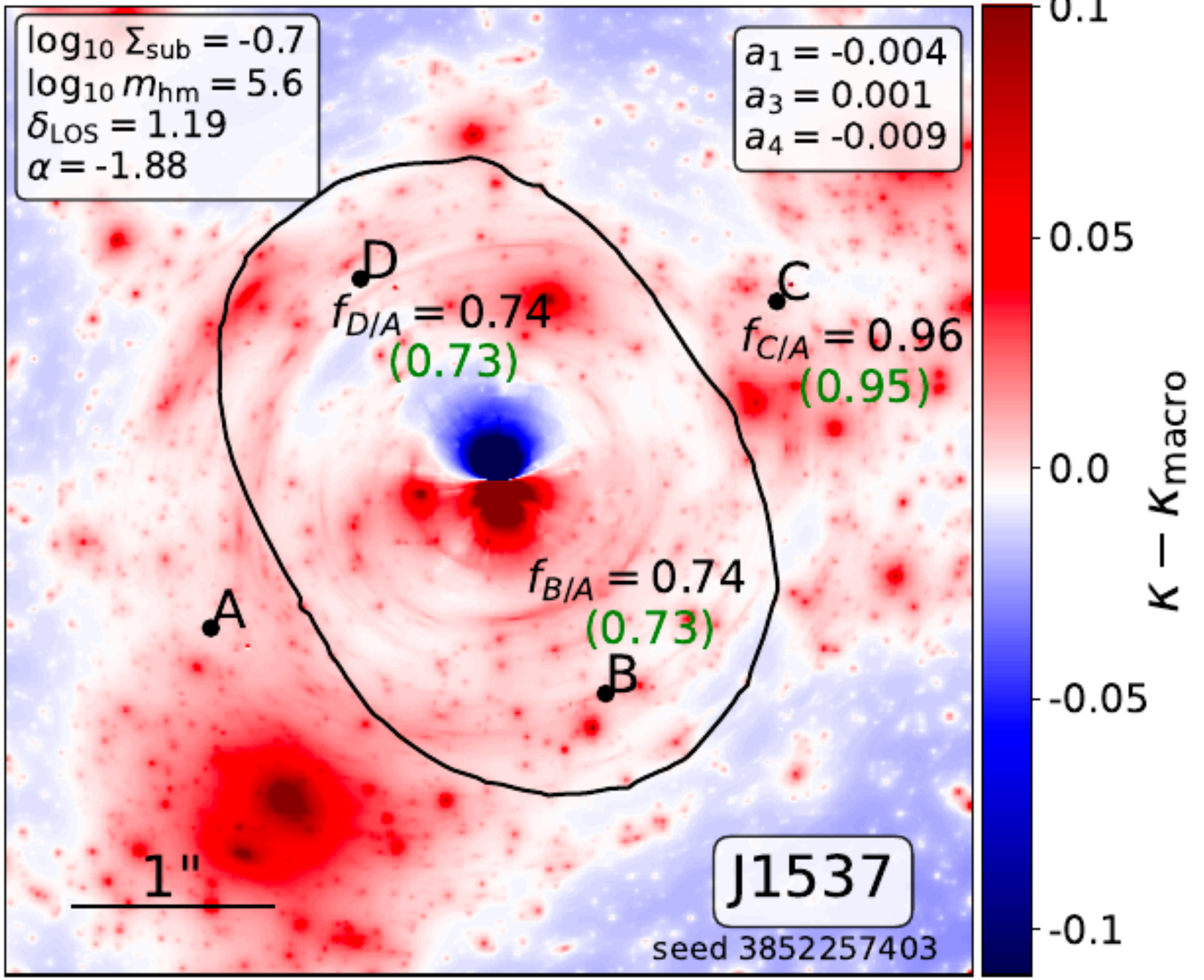

CDM-infall
WDM-infall
CDM-bound with c_{CDM}
WDM-bound with c_{CDM}
WDM-bound with c_{WDM}
Figure from Gilman et al. (2026a)
Infall mass functions
Bound mass functions
Differential tidal stripping depending on concentration
$n(m)$
10^6
10^5
10^4
10^3
10^2
10^1
10^6
10^7
10^8
10^9
10^{10}
subhalo mass [$M_\odot$]

Technological development #2: joint modeling of arcs+flux ratios

Adapted from
Gilman et al. 2026

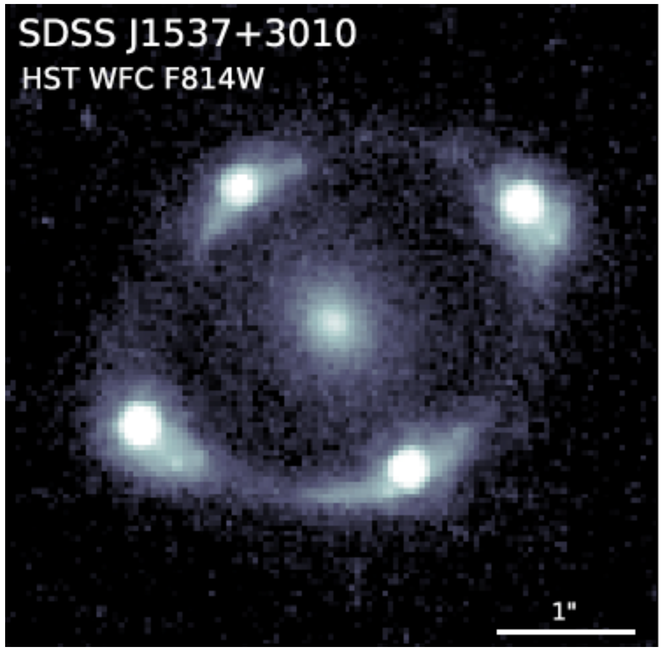


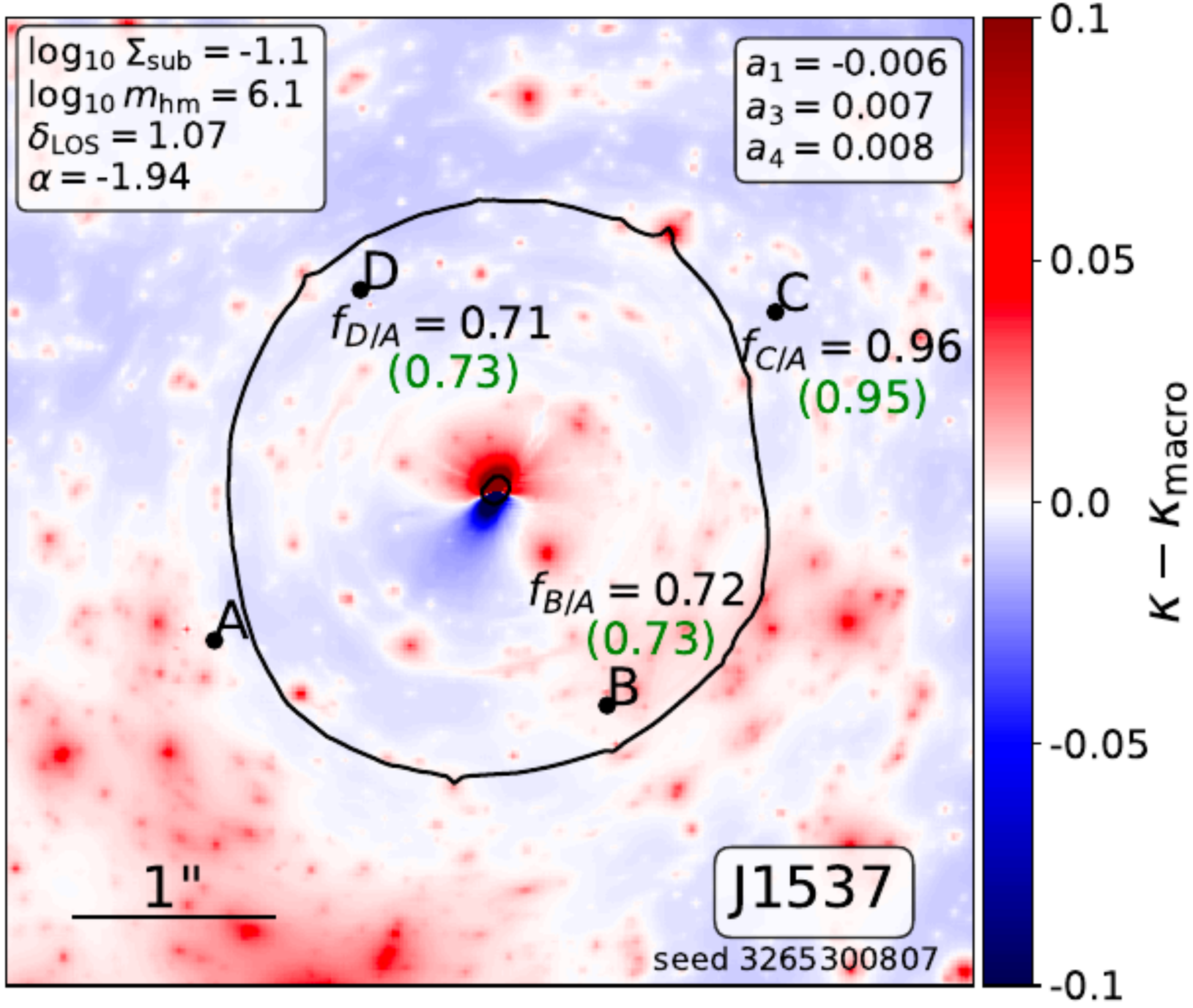
$$\kappa_{\rm halos} = \frac{1}{2}\nabla \cdot \vec{\alpha} - \kappa_{\rm macro}$$





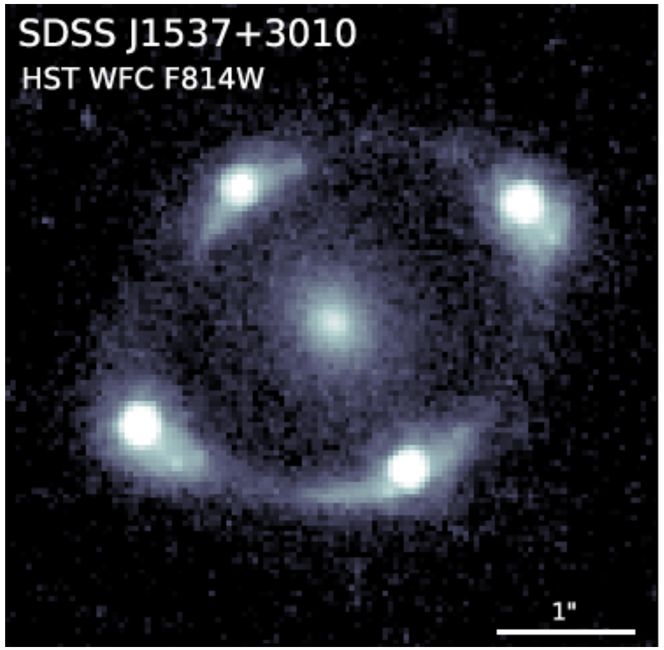
Adapted from
Gilman et al. 2026

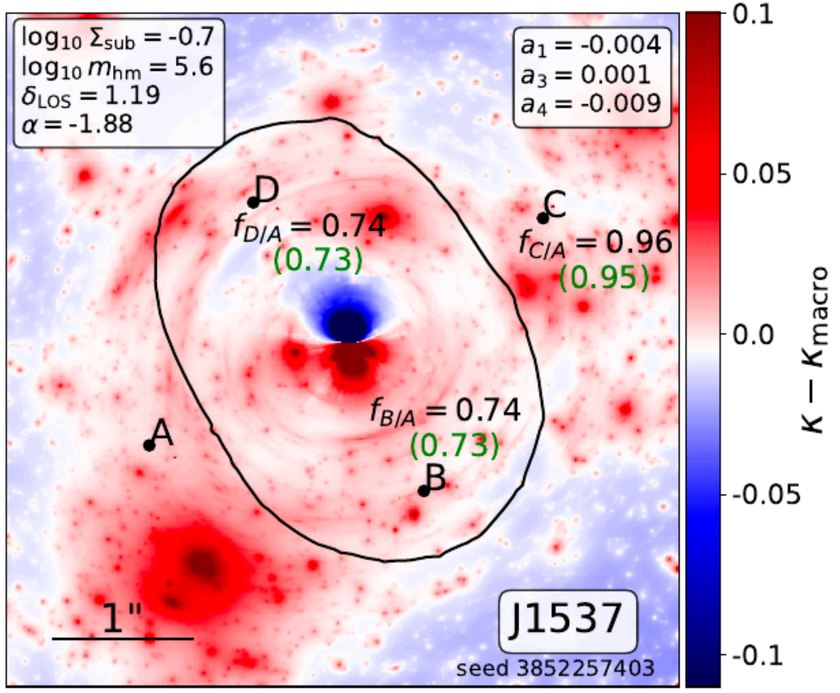


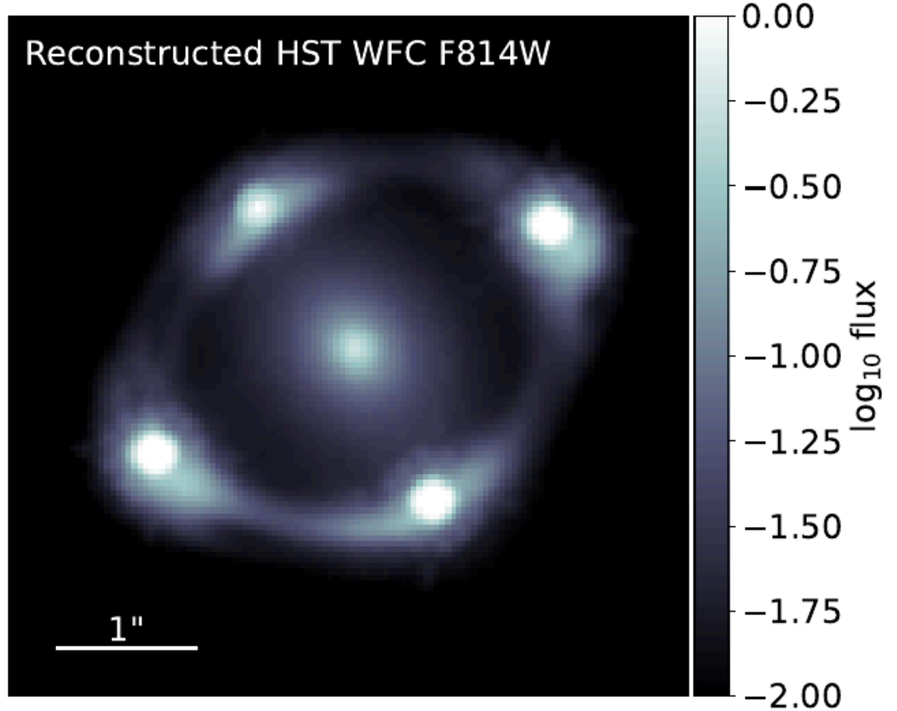


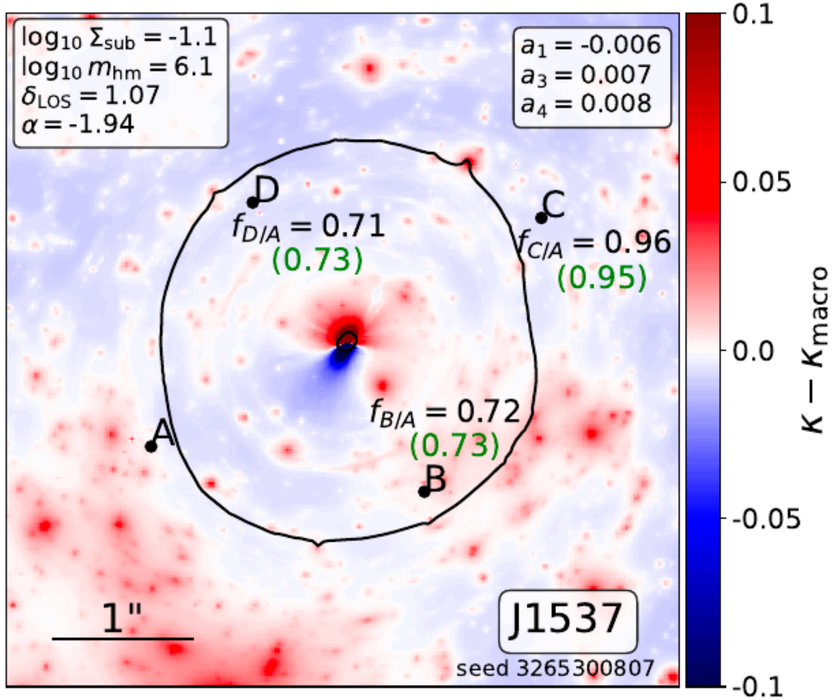


Adapted from
Gilman et al. 2026









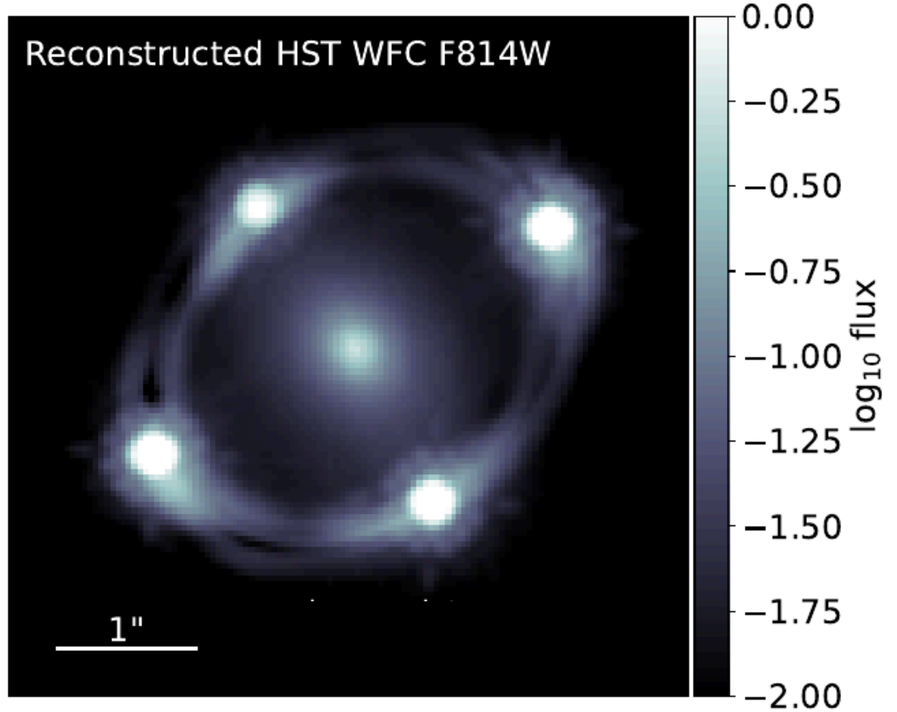
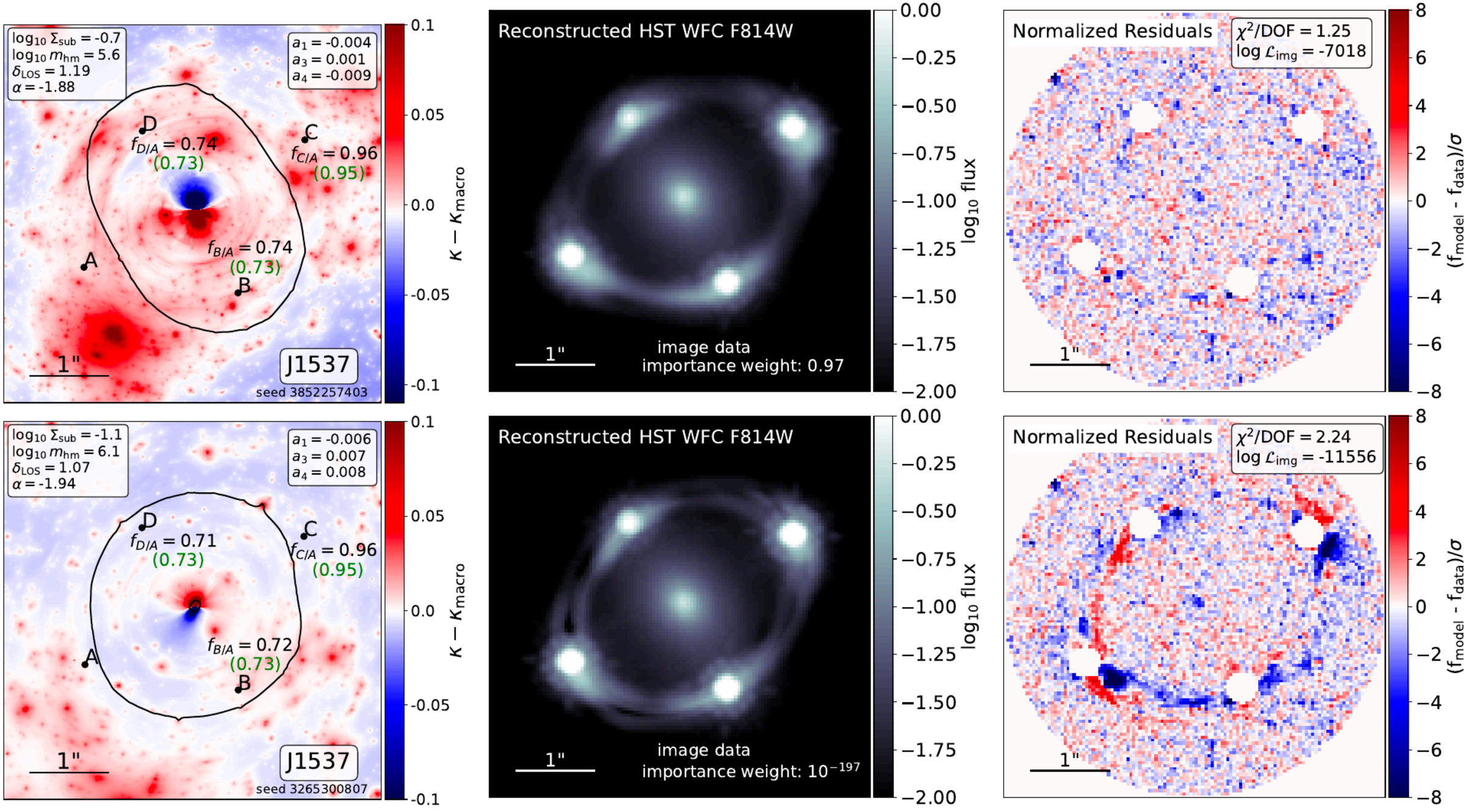
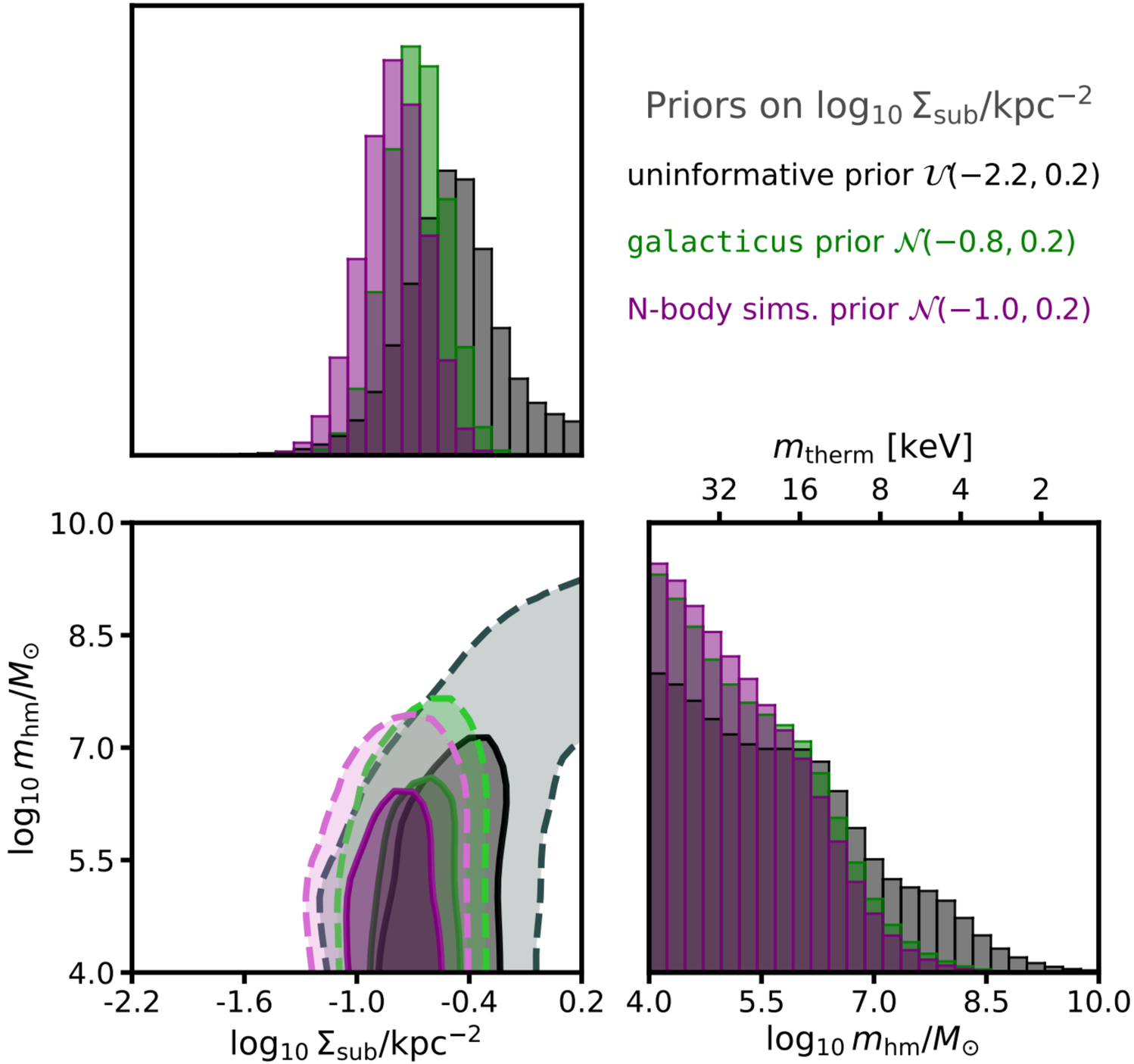


Figure from Gilman et al. (2026a)





$m_{\rm hm} < 10^{7.4} M_\odot$

$m_{\rm thermal} > 6.5$ keV

$m_{\rm hm} < 10^{7.2} M_\odot$

$m_{\rm thermal} > 7.4$ keV

Figure from
Gilman et al. 2026b

Does a half-mode mass constraint of $10^{7.4} M_\odot$ mean halos exist on that scale?

-> not necessarily

Lensing constraints both the halo mass function (both subhalos and field halos with roughly equal weight)

$$\frac{dN}{dM} \propto \frac{dN_{\rm cdm}}{dM}\left(1 + a\left(\frac{m_{\rm hm}}{m}\right)^b\right)^c$$

AND

Lensing constrains the concentration-mass relation

$$c\,(m,z) \propto c_{\rm cdm}\,(m,z)\left(1 + a\left(\frac{m_{\rm hm}}{m}\right)^b\right)^c$$

What is the minimum halo mass, assuming a CDM-like Concentration-mass relation?

What is the minimum halo mass, assuming a CDM-like concentration-mass relation?

For subhalo abundance predicted by N-body sims:

$m_{\rm min} = 10^{8.2} M_\odot$

and galacticus

$m_{\rm min} = 10^{8.3} M_\odot$

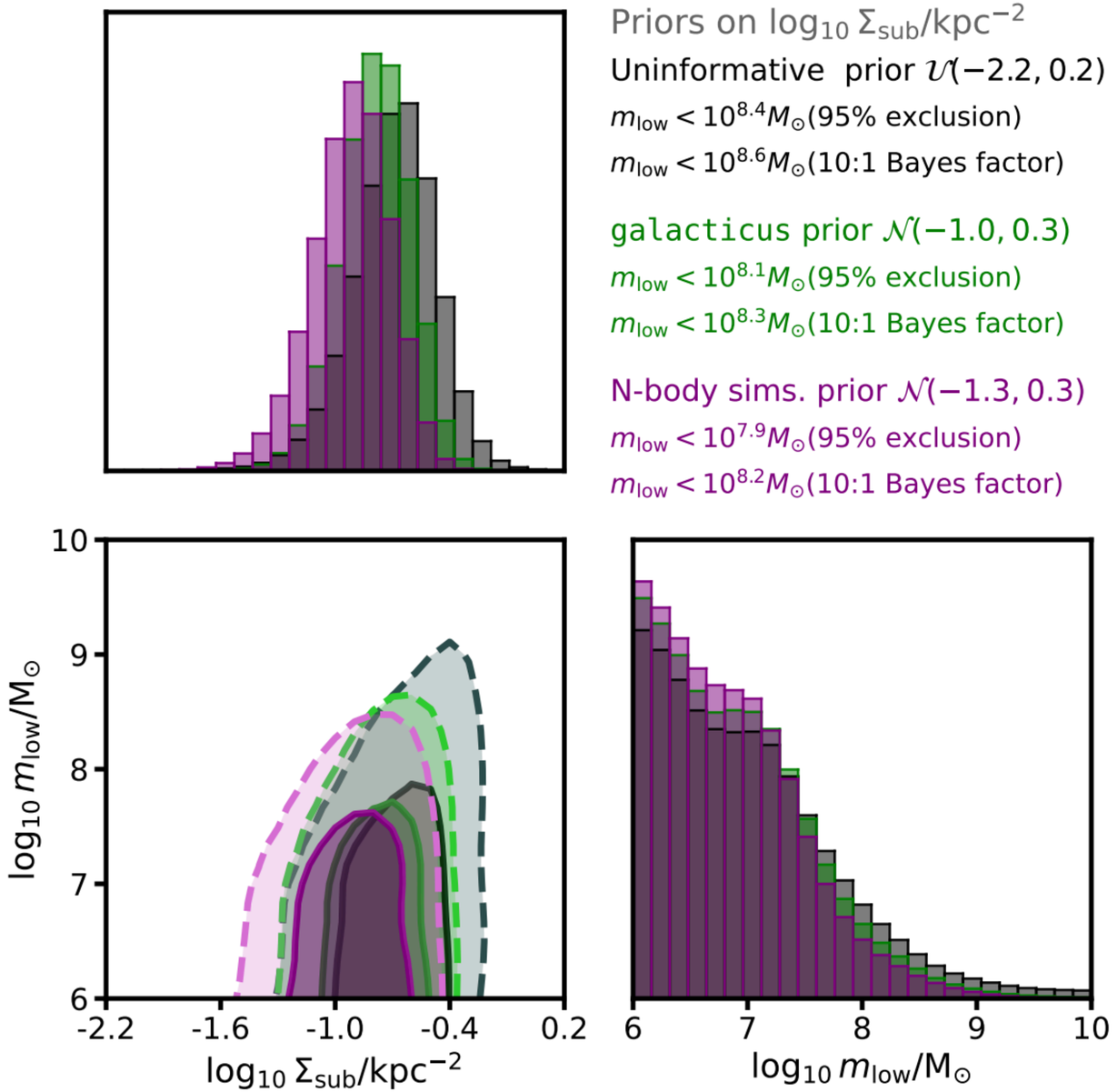
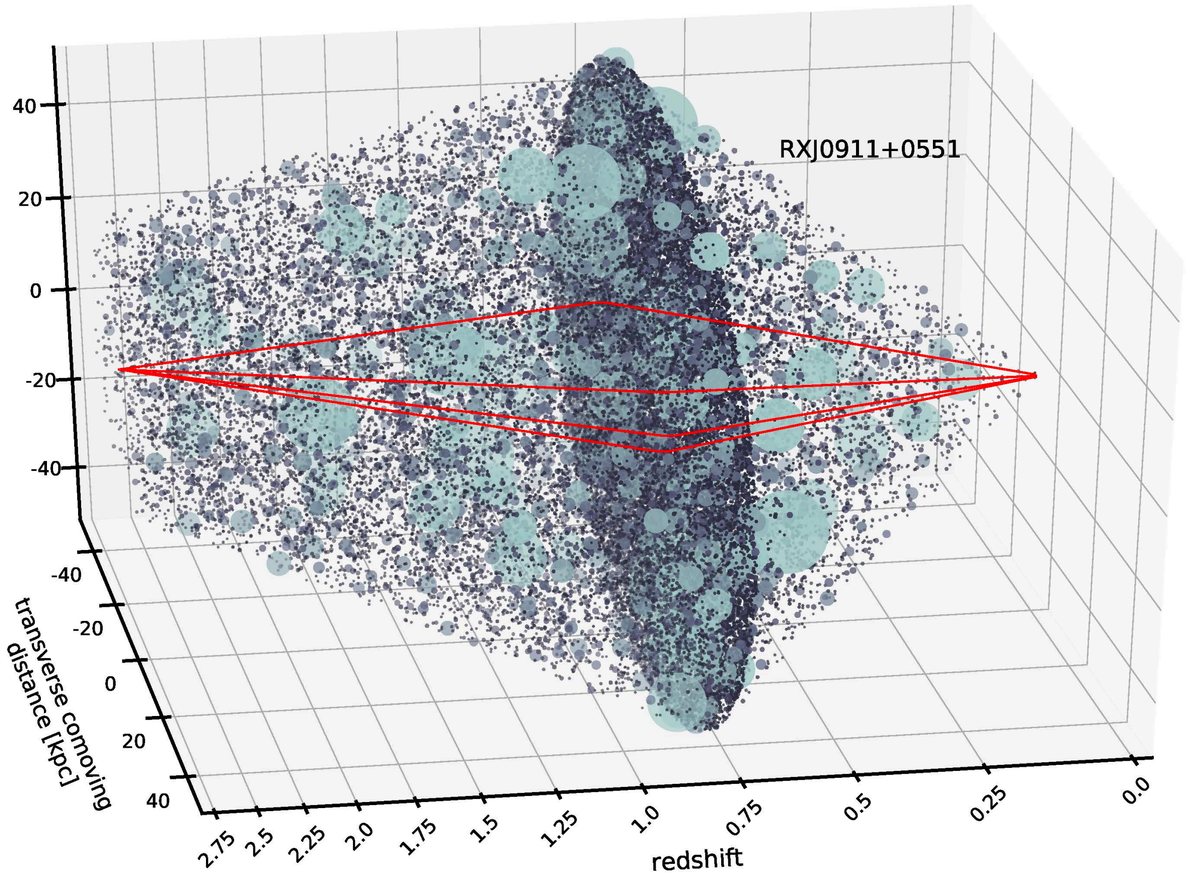


Figure from Nierenberg, Gilman, et al. (2026)

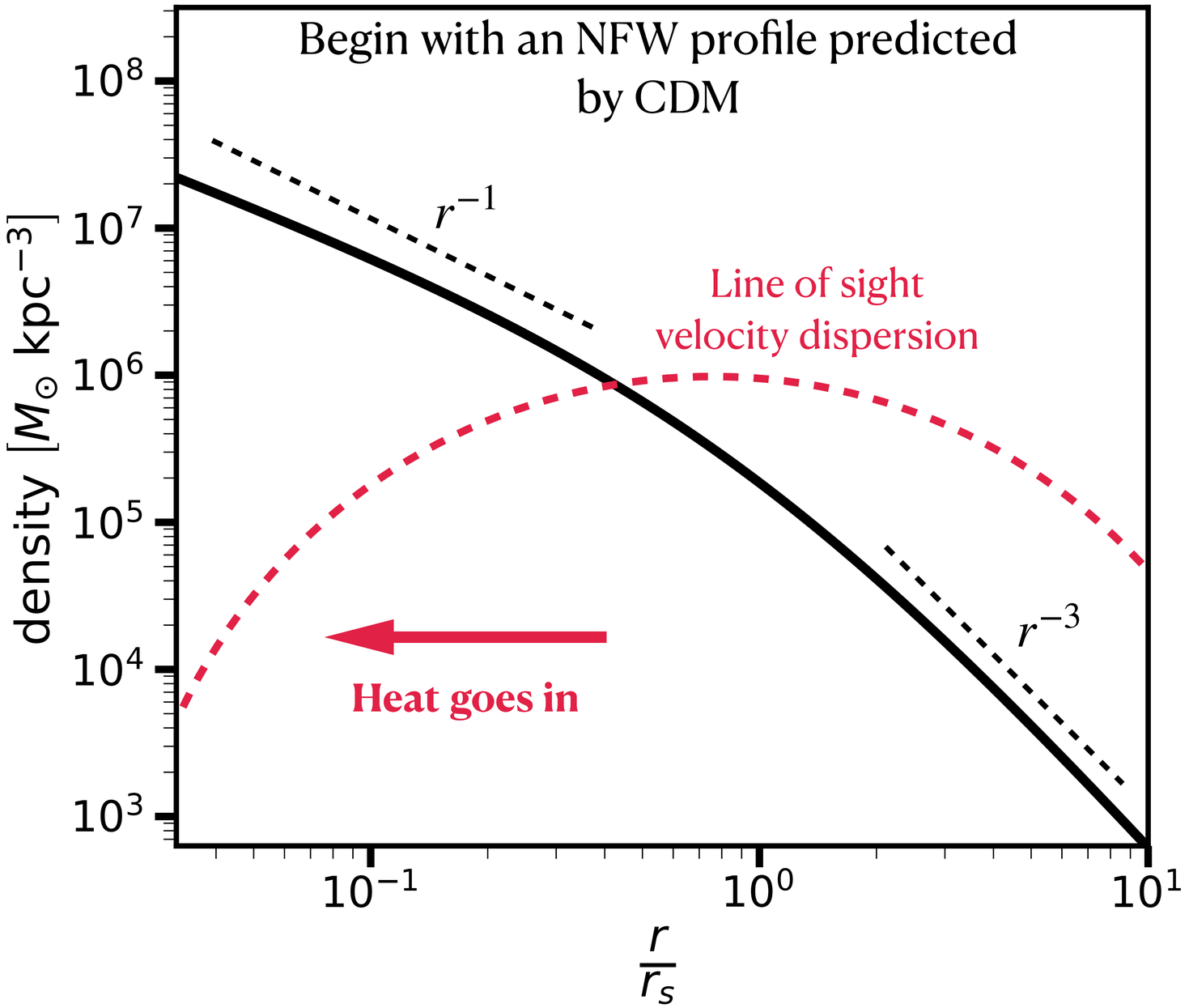
Can test any theory that alters halo properties

- Self-interacting dark matter

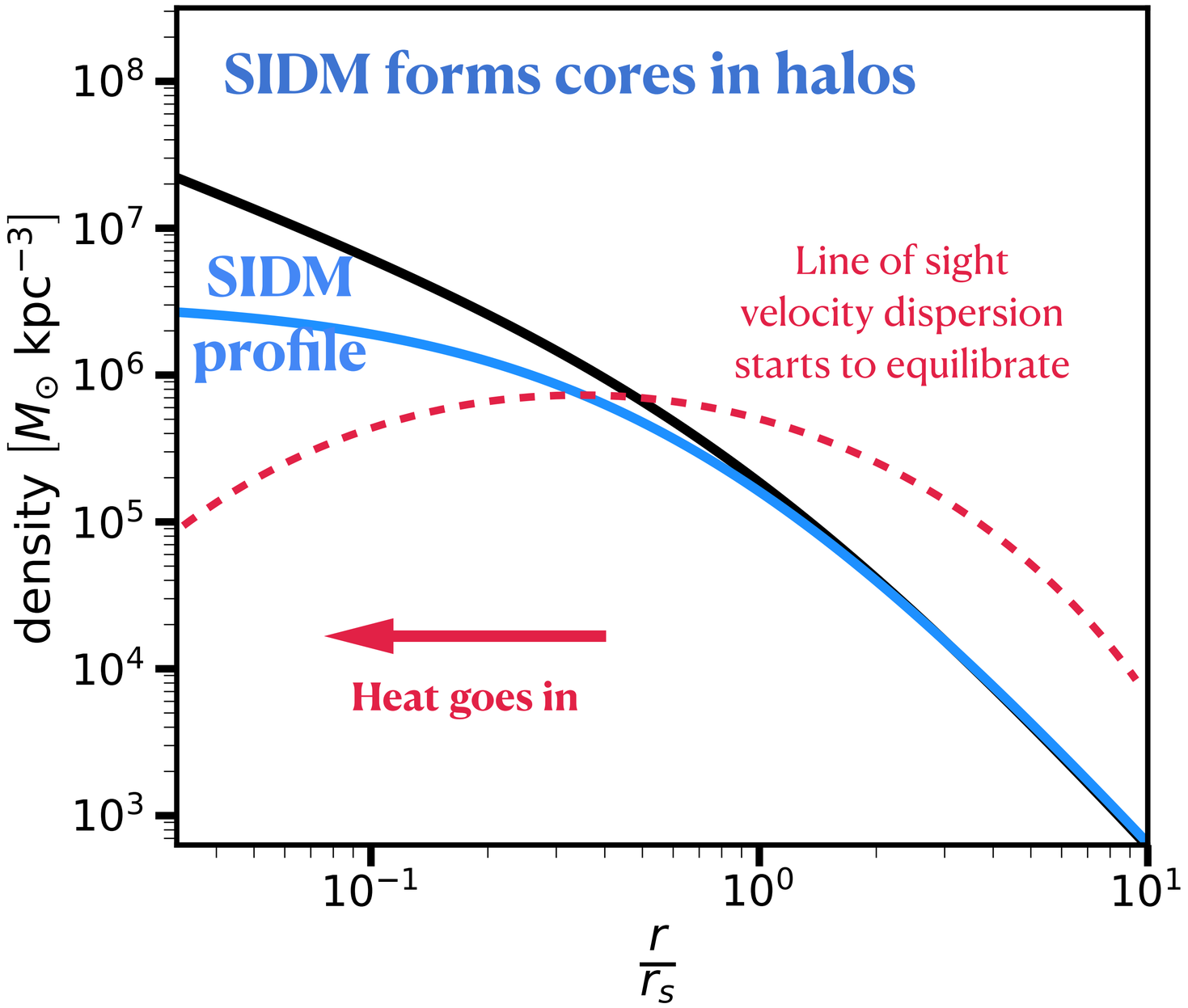
Gilman et al. (2021, 2022)
arXiv: 2105.05259 & 2207.13111



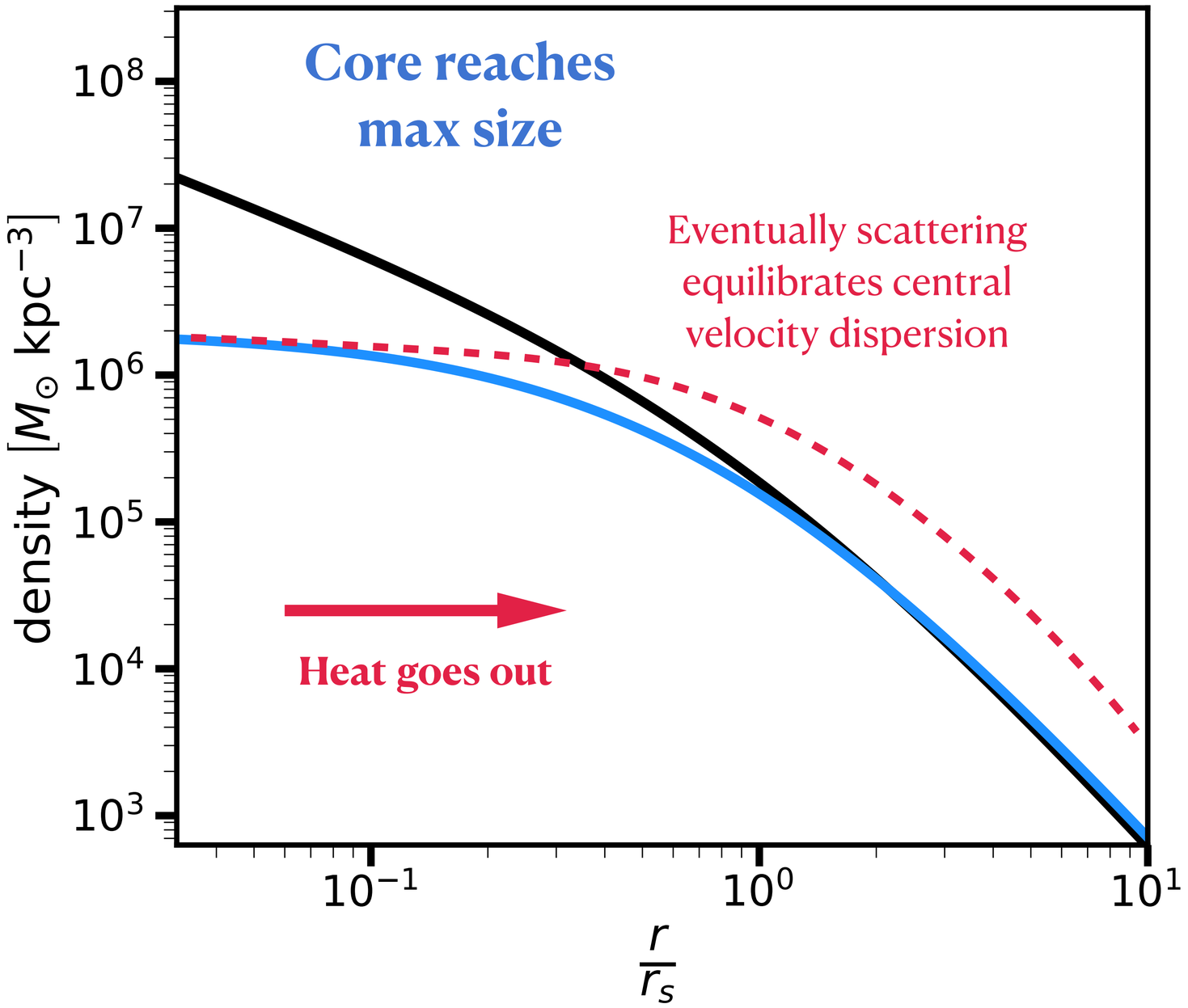
Effects of SIDM on halo density profiles



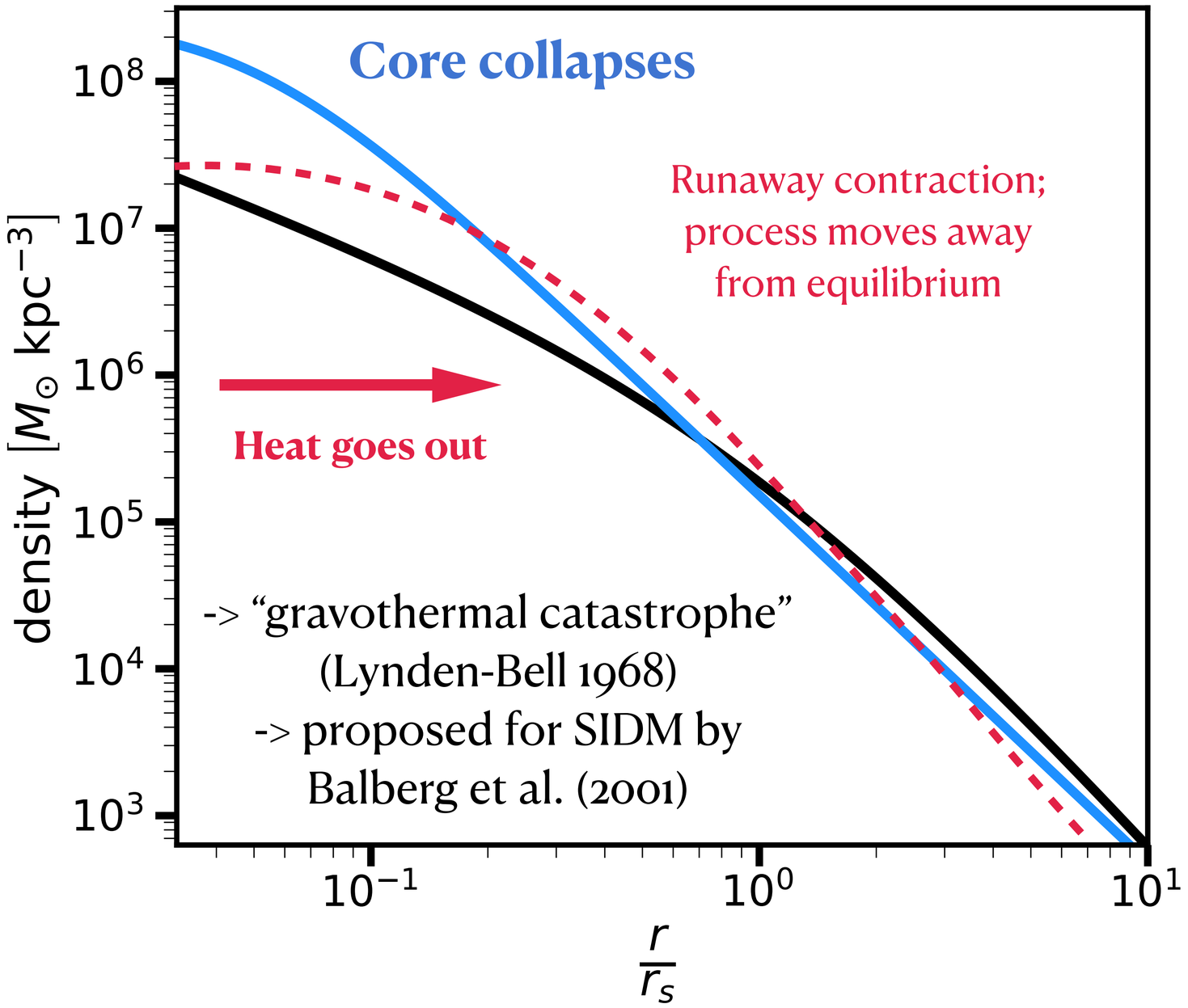
Effects of SIDM on halo density profiles



Effects of SIDM on halo density profiles



Effects of SIDM on halo density profiles



Why consider alternatives like SIDM?

Several recent suggestions that low-mass halos have central densities that deviate from CDM

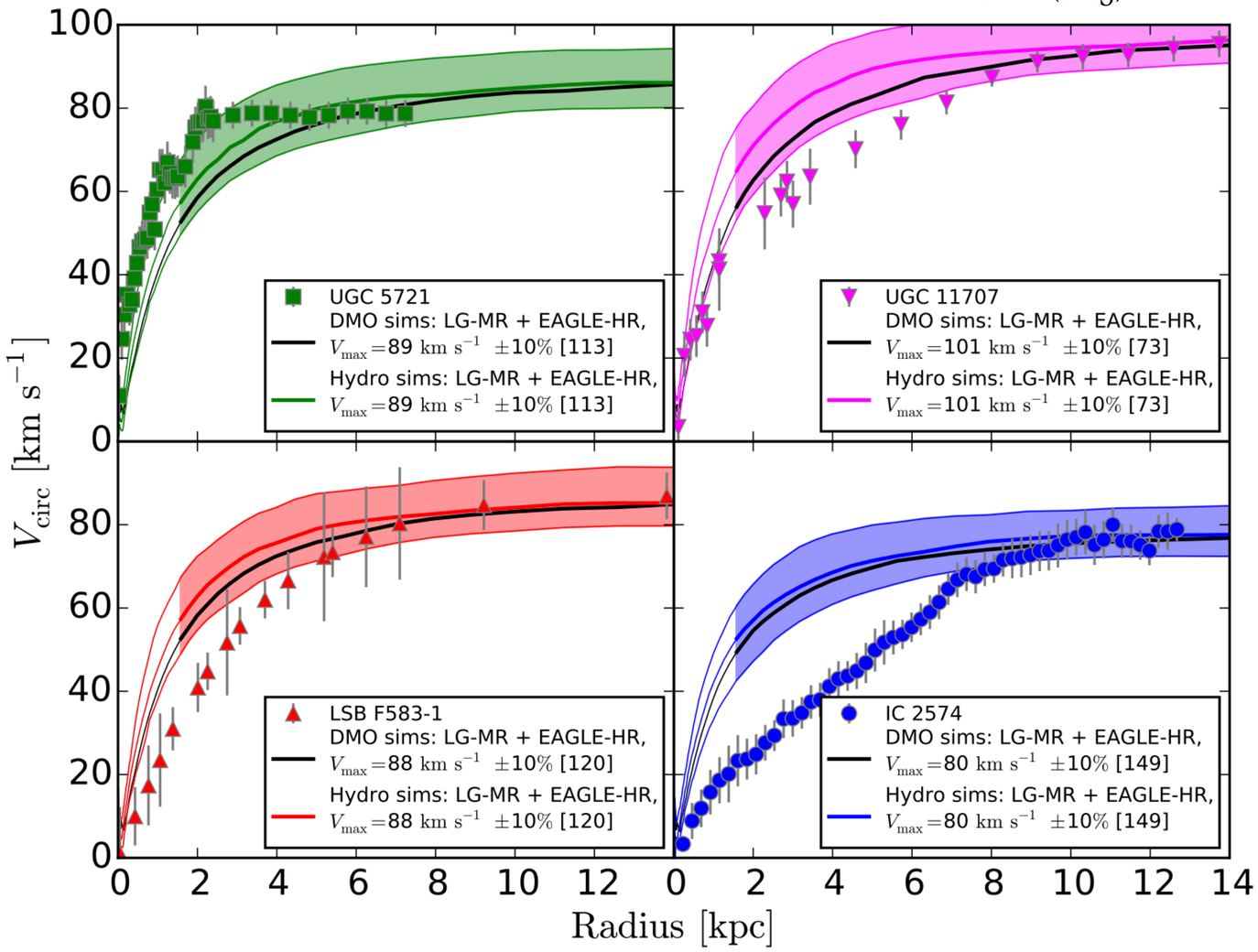
The historical argument is phrased as a “diversity” problem in rotation curves

-> this interpretation is challenging due to systematics, baryonic feedback, etc.

not all analyses of satellites conclude this is actually a problem

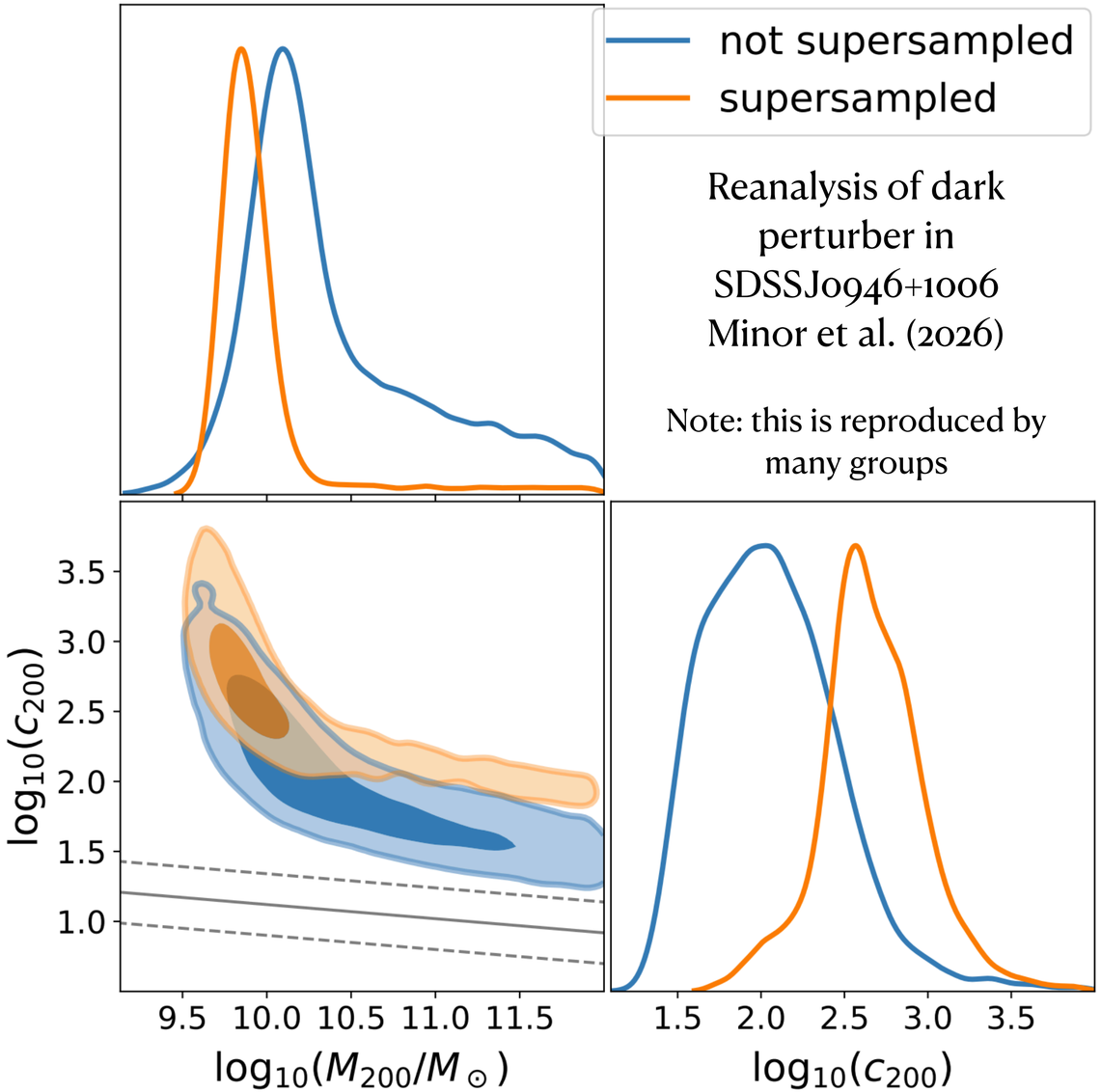
isolated field dwarfs provide cleaner probes

Oman et al. (2015)



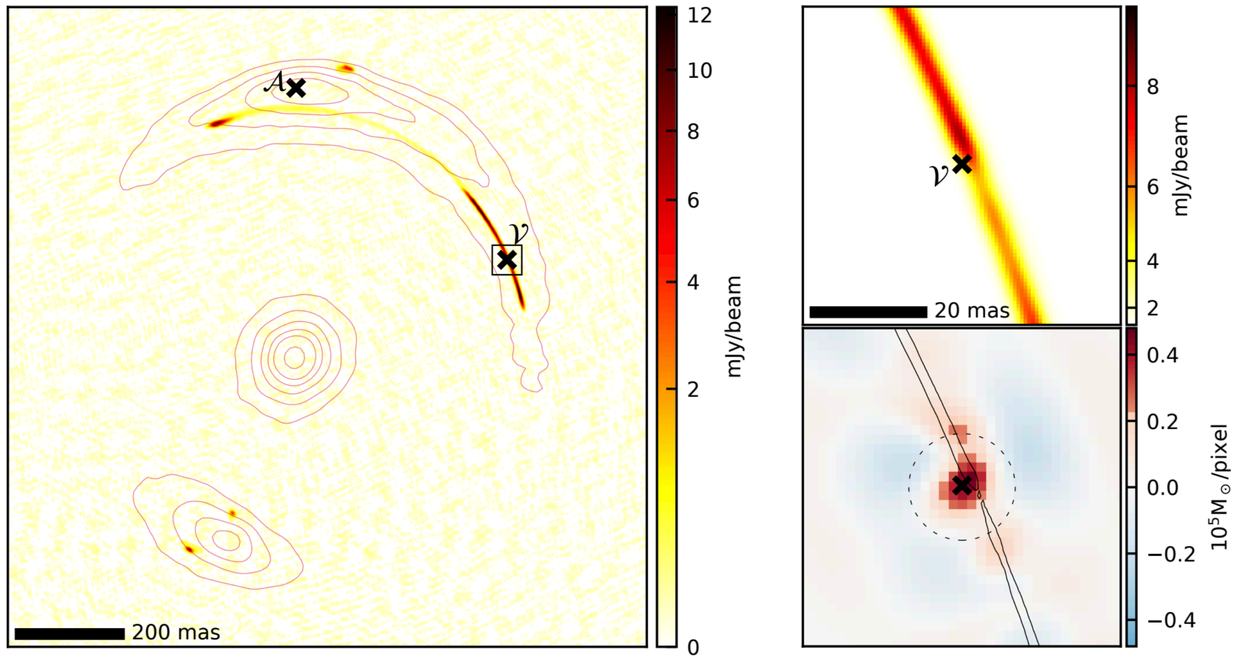
Why consider alternatives like SIDM?

Recent detections from galaxy-galaxy strong lenses have fueled further interest



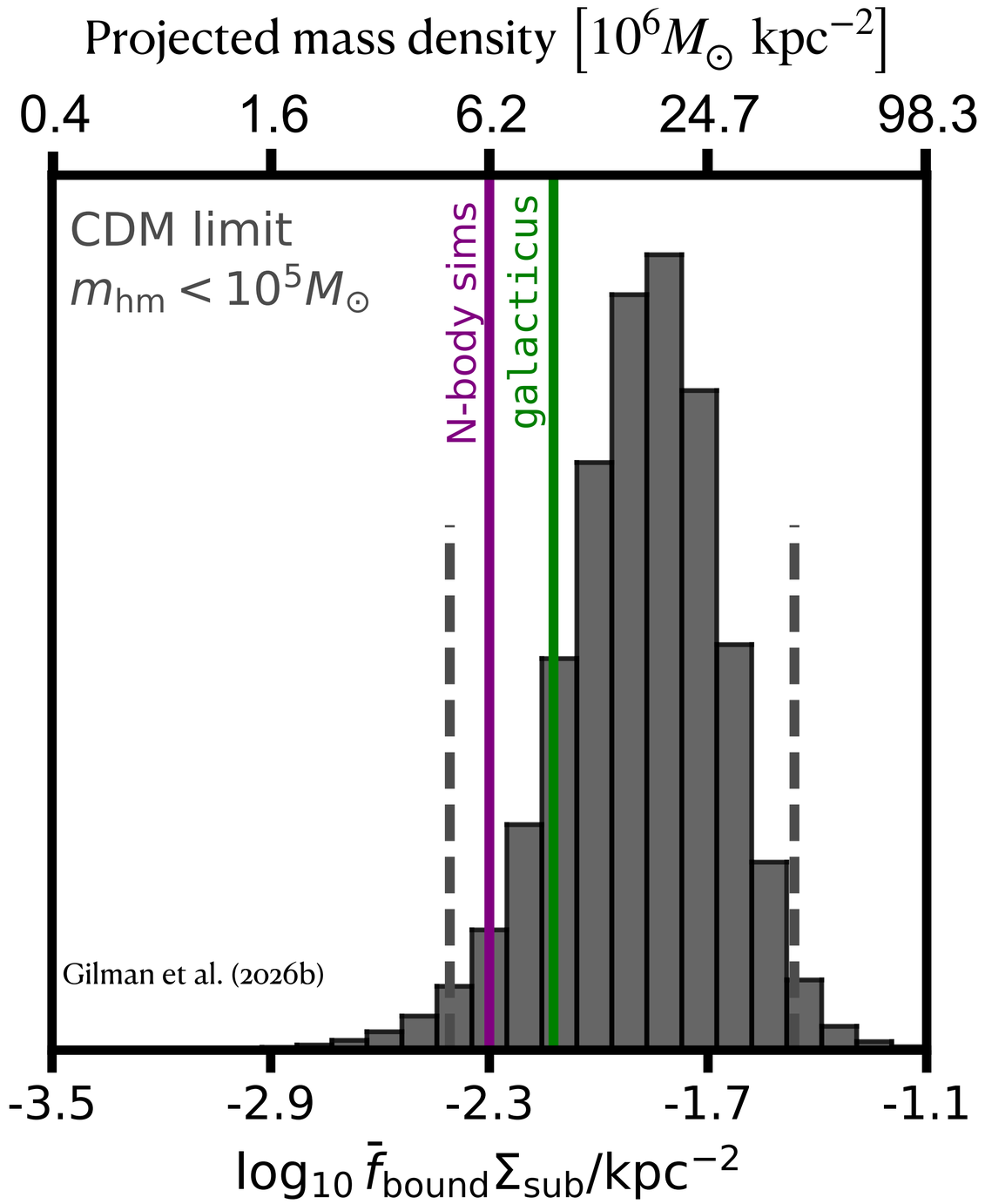
Reanalysis of dark perturber in SDSSJ0946+1006 Minor et al. (2026)

Note: this is reproduced by many groups



Top: An extremely compact $1.4 \times 10^6 M_\odot$ object detected in VLBI images of a lensed arc (Powell et al. 2025)

See also: Vegetti et al. (2026) "A possible challenge to cold and warm dark matter"



Why consider alternatives like SIDM? (Now our own data)

Inference of subhalo projected mass fraction:

$$1.7^{+2.6}_{-1.2} \times 10^7\ \mathrm{M}_\odot\ \mathrm{kpc}^{-2}\ \ (95\,\%\ \mathrm{conf})$$

$$\left(10^6 < m/M_\odot < 10^{10.7}\right)$$

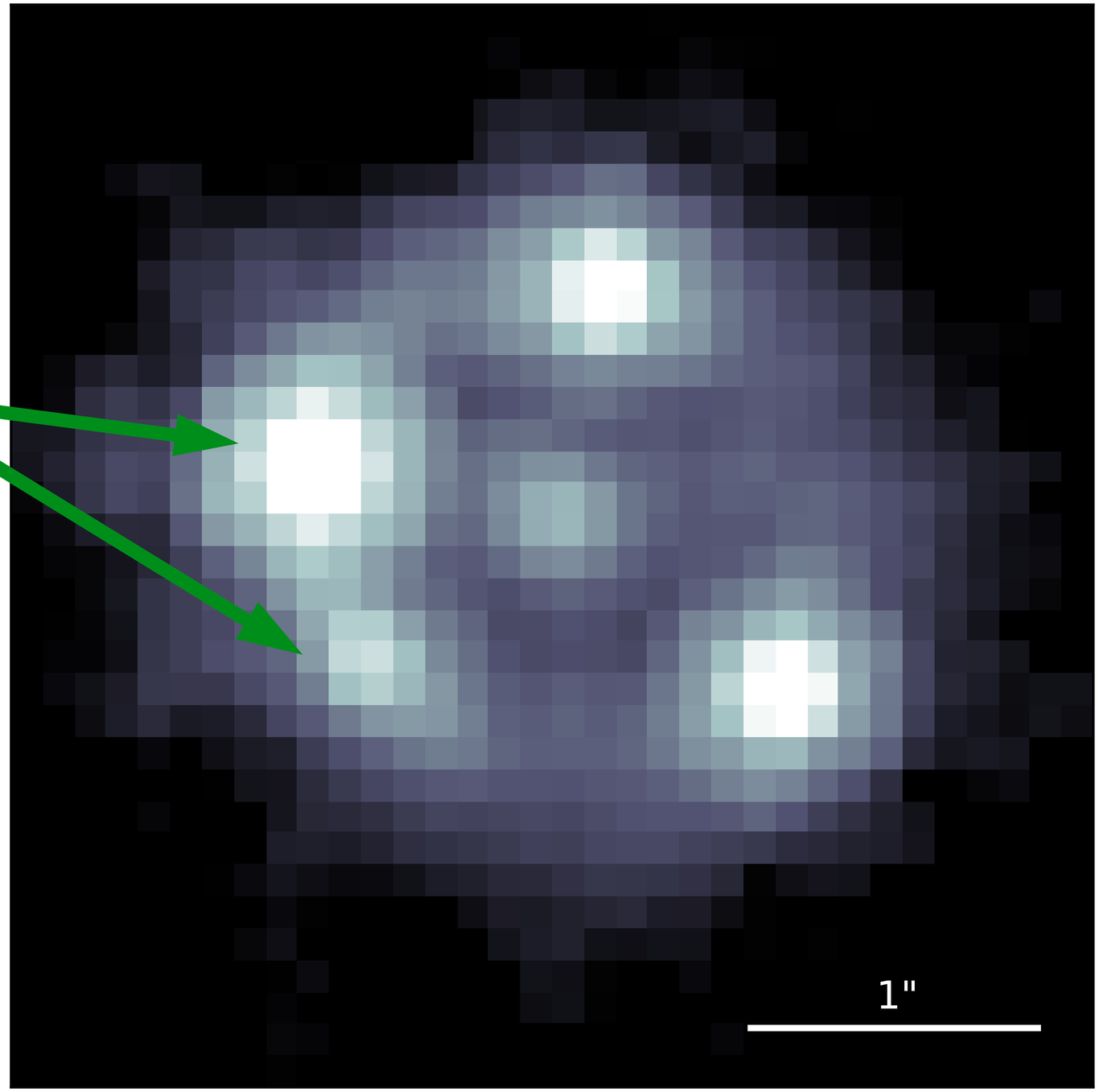
~1.5-2 sigma higher than predicted by theory

Why consider alternatives like SIDM?

Merging image pair

Relative magnification is ~6

Difficult to explain with just CDM+globular clusters



JWST lensed quasar dark matter survey V: Hints of self-interacting dark matter from 29 quadruply imaged quasars

D. Gilman,[1,2,*] A. M. Nierenberg,[3] J. Gurian,[4,5] H. Paugnat,[6] C. Gannon,[3] M. N. Martinez,[3] T. Treu,[6] K. N. Abazajian,[7] T. Anguita,[8] V. N. Bennert,[9] A. J. Benson,[5] S. Birrer,[10] S. G. Djorgovski,[11] S. F. Hoenig,[12] R. E. Keeley,[7] A. Kusenko,[6,13] M. Millon,[14] T. Morishita,[15] L. A. Moustakas,[16] P. Mozumdar,[6,17] D. Paris,[18] W. Sheu,[6] D. Sluse,[19] and K. C. Wong[20]

[1] *Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA*
[2] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA*
[3] *University of California, Merced, 5200 N Lake Road, Merced, CA 95341, USA*
[4] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada*
[5] *Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101, USA*

Submitted to PRD,
arXiv: 2609.35974

Hints of self-interacting dark matter from strong gravitational lensing

D. Gilman,[1,*] K. Petraki,[2] T. Pignard,[2] J. Gurian,[3] A. Kusenko,[4,5] and A. M. Nierenberg[6]

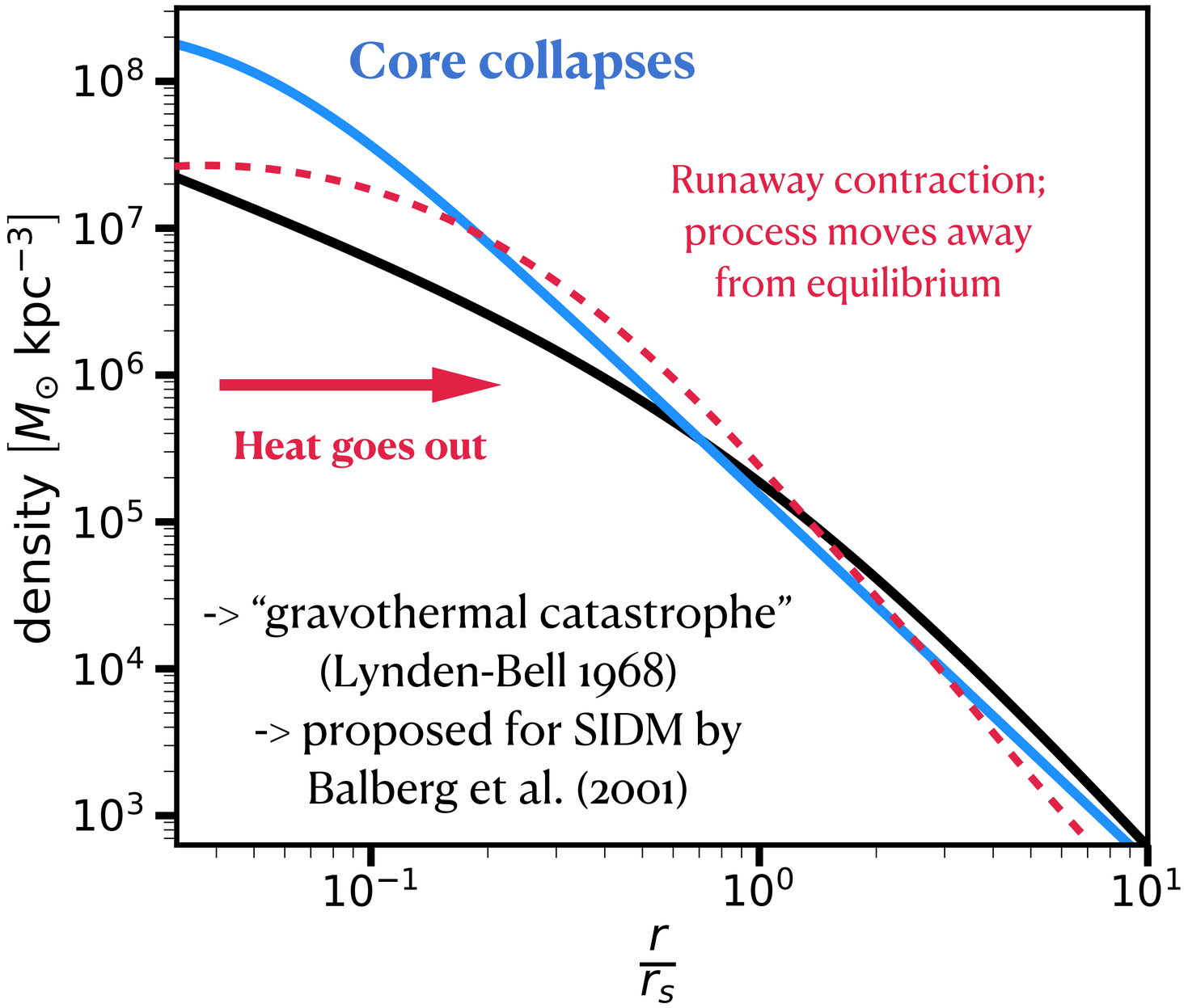
[1] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA*
[2] *Laboratoire de Physique de l'École Normale Supérieure, ENS, Université PSL, CNRS, Sorbonne Université, Université Paris Cité, Paris, F-75005, France*
[3] *Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101, USA*
[4] *Department of Physics and Astronomy, University of California, Los Angeles, CA, 90095, USA*
[5] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*
[6] *University of California, Merced, 5200 N Lake Road, Merced, CA 95341, USA*

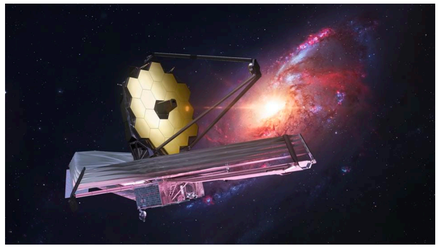
(Dated: November 2, 2026)

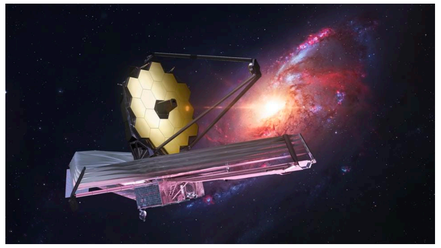
An analysis of 29 quadruply imaged quasars hints at dark matter halo densities consistent with gravothermal core collapse, a key prediction of self-interacting dark matter. We interpret this evidence through elastic Yukawa scattering, combining lensing with upper limits on the cross section

Submitted to PRL
arXiv: 2610.40766

Effects of SIDM on halo density profiles

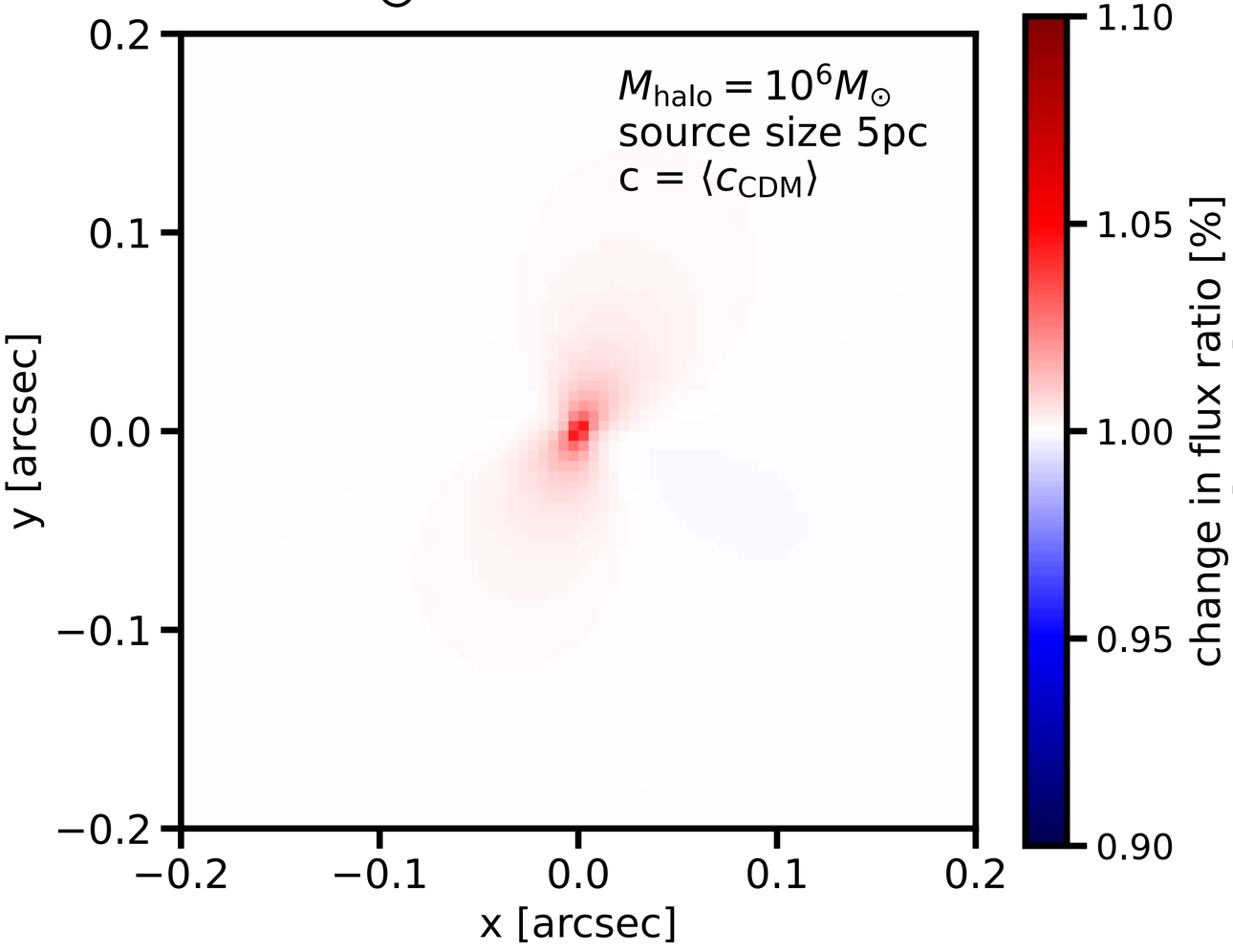


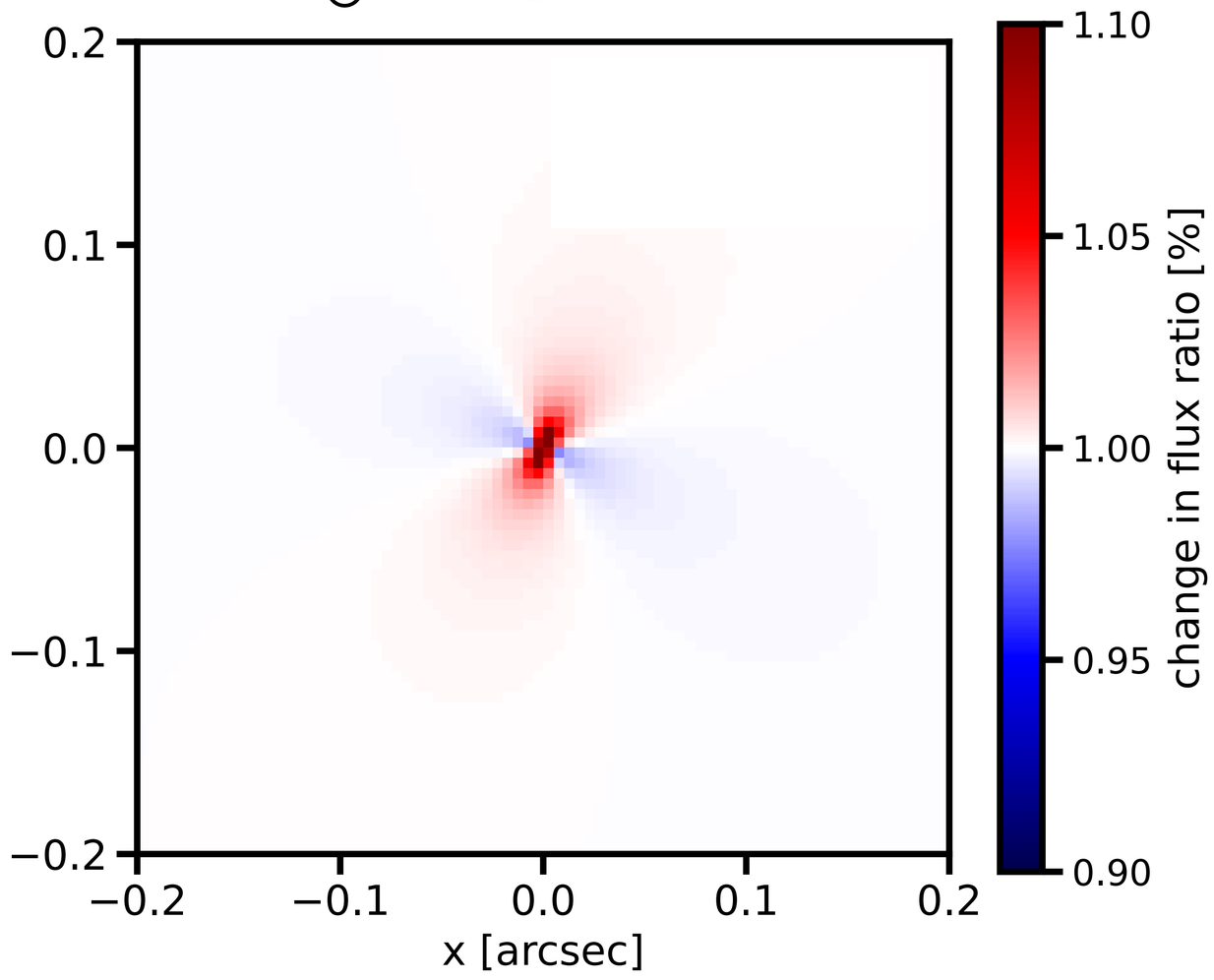




$10^6 M_\odot$NFW (CDM) halo

$10^6 M_\odot$ collapsed SIDM halo





The core collapse timescale

In SIDM models a characteristic timescale t_c governs the evolution of DM halos

t_c depends on the SIDM cross section, although the connection depends on environment

Our approach:

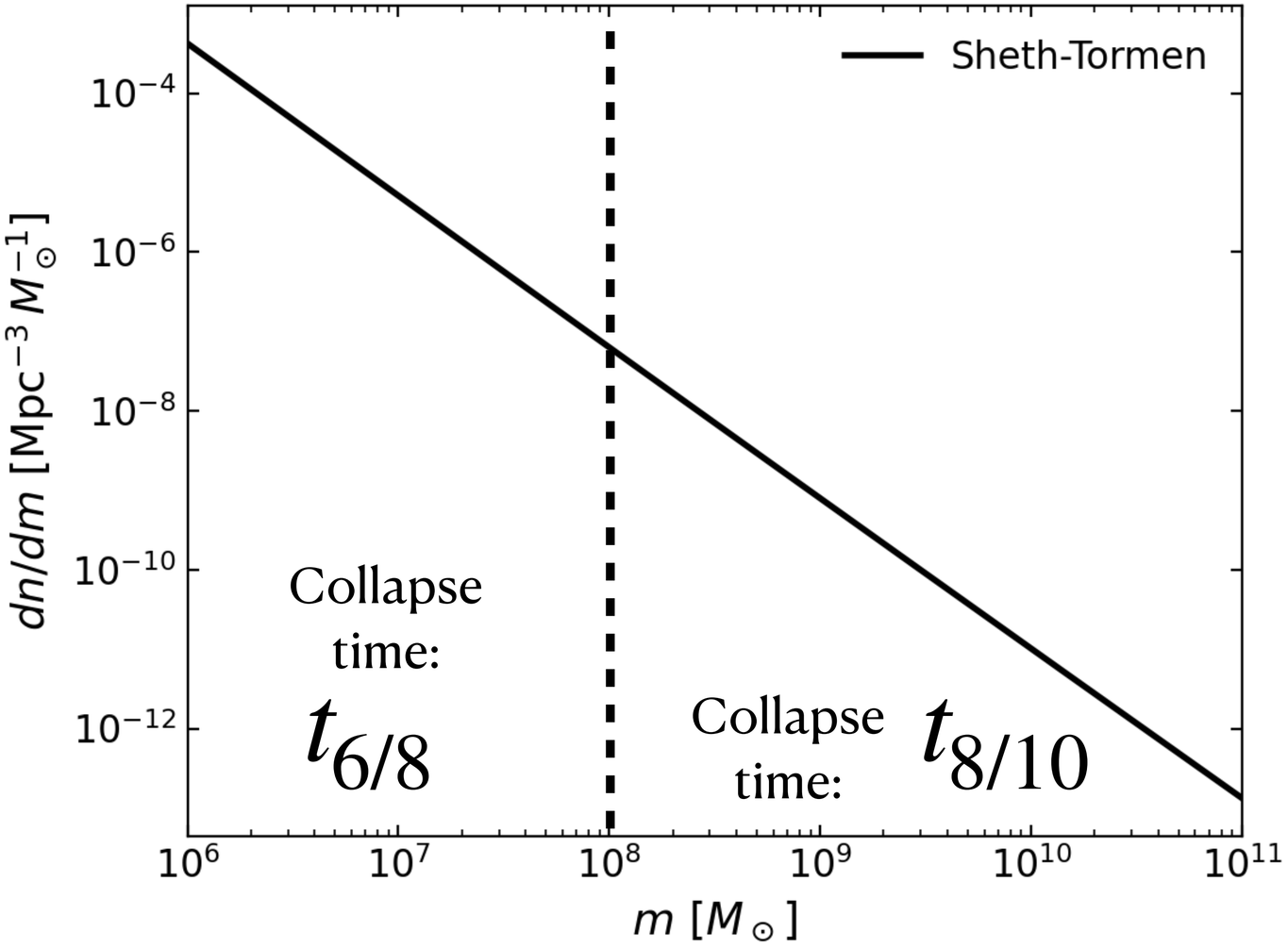
-> parameterize directly in terms of t_c

-> bin in halo mass above and below $10^8 M_\odot$

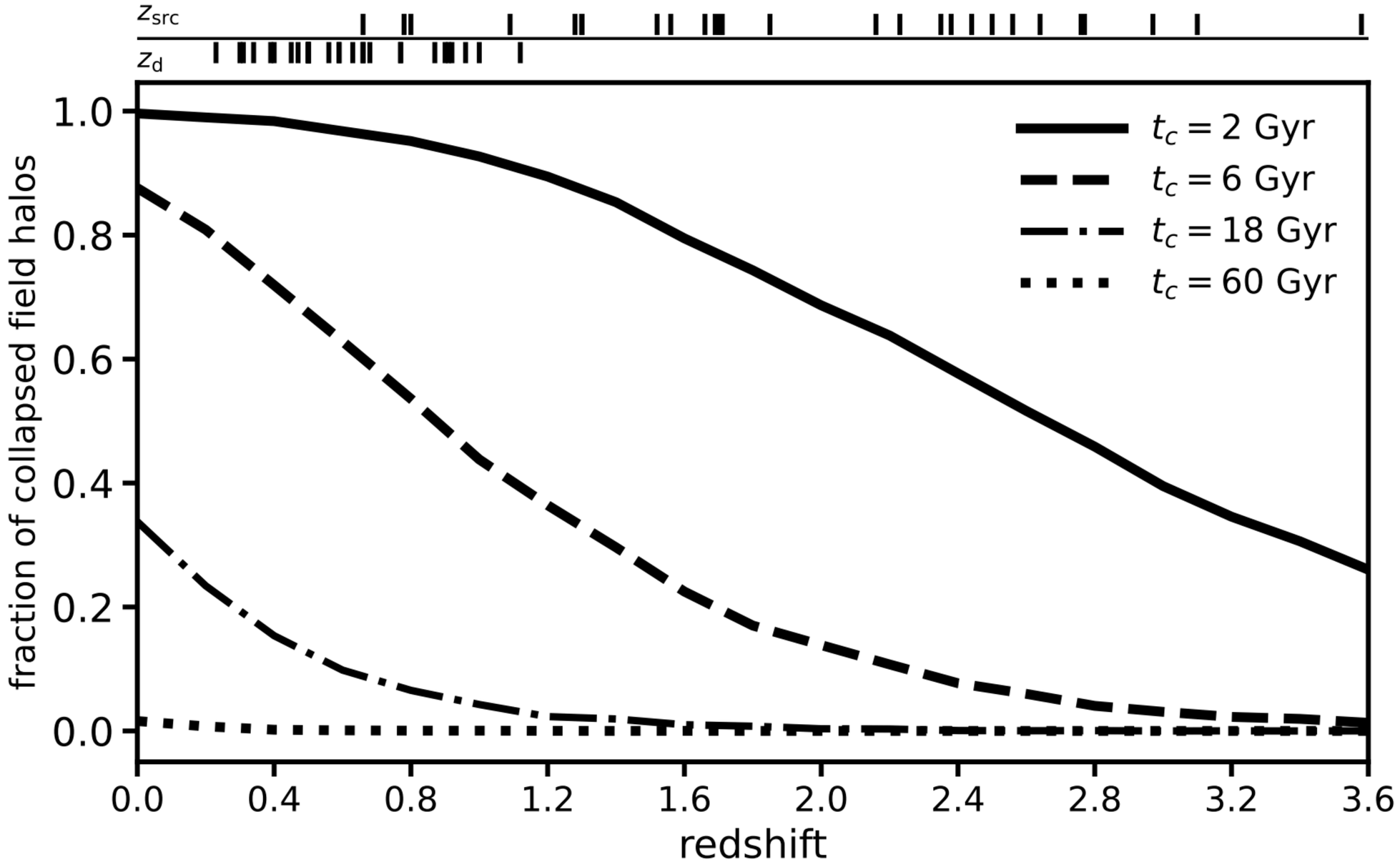
-> sample t_c with 0.3 dex scatter,

$t/t_c > 1 \rightarrow$ Core collapsed

where t is elapsed time since z=10

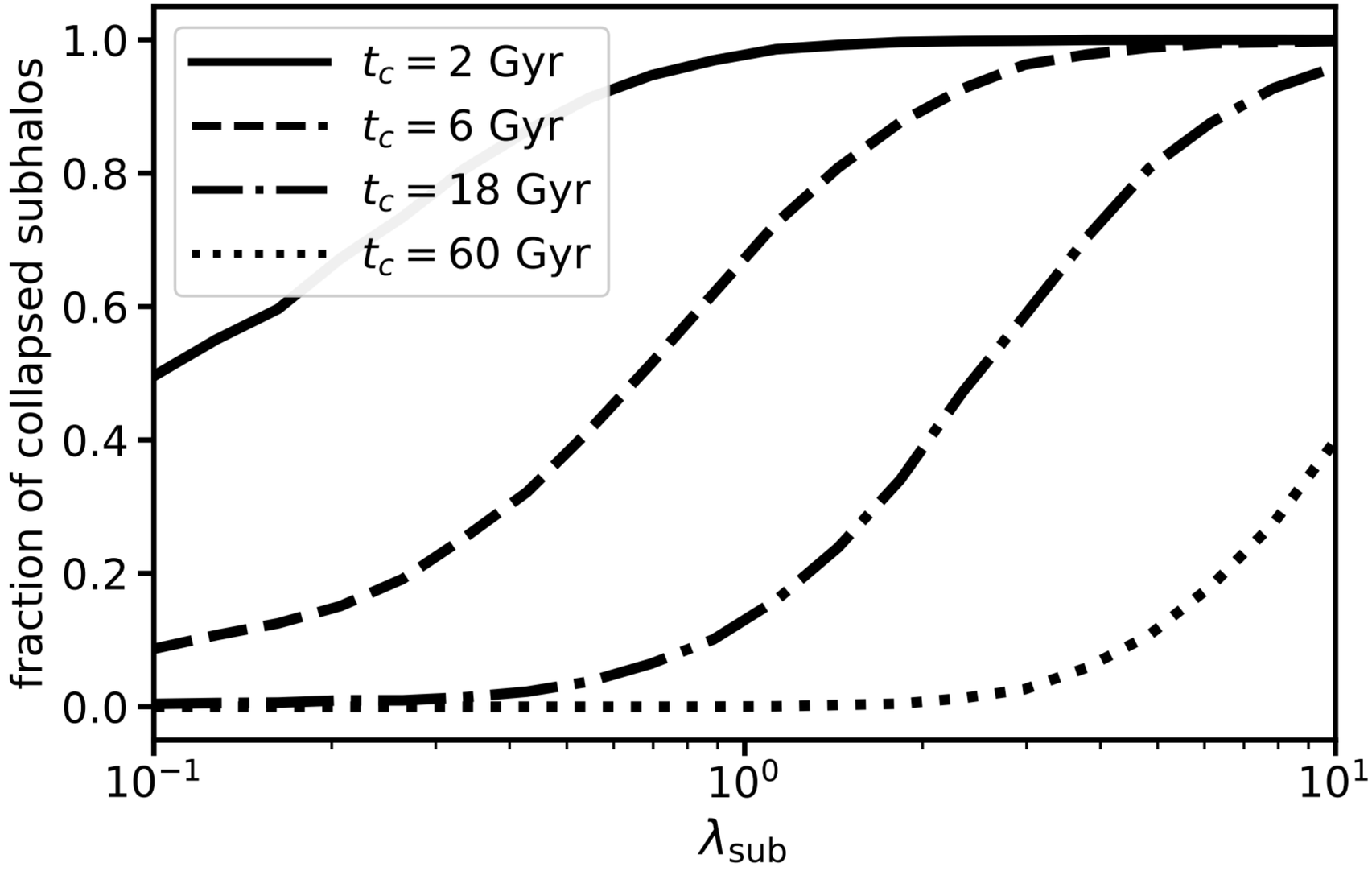


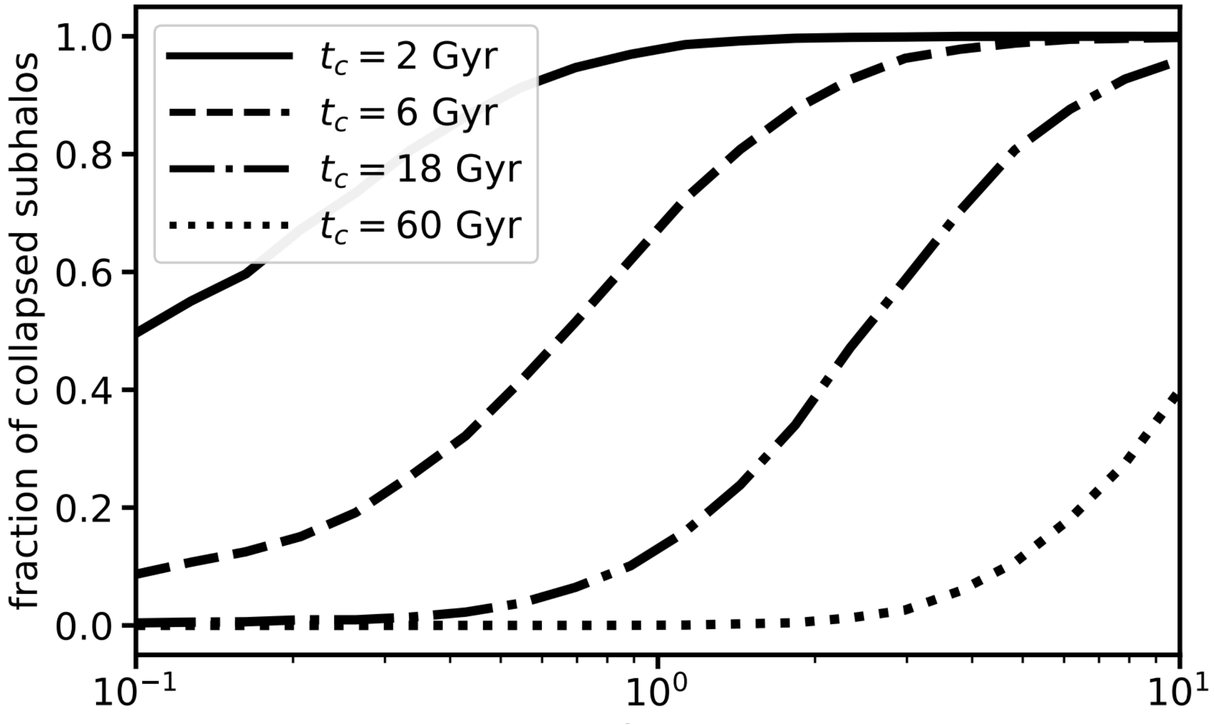
Field halos: core collapse fraction follows directly from t_c and evolves with z

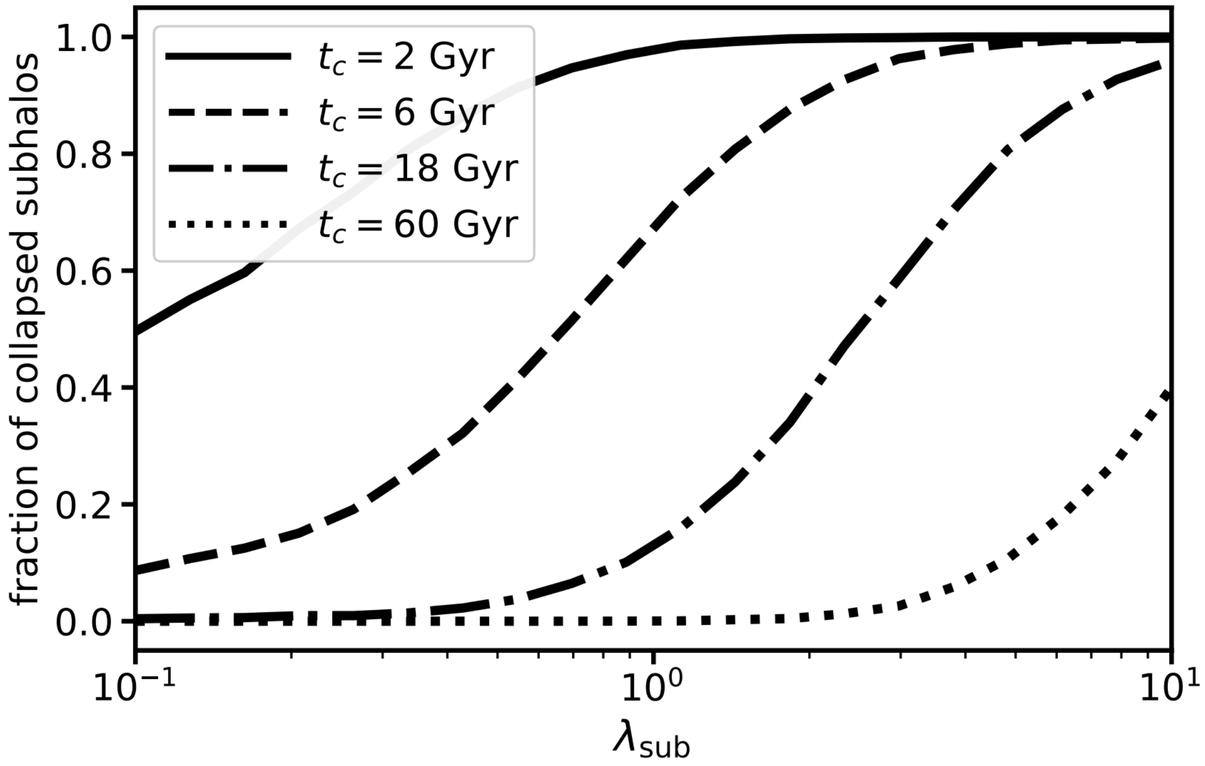


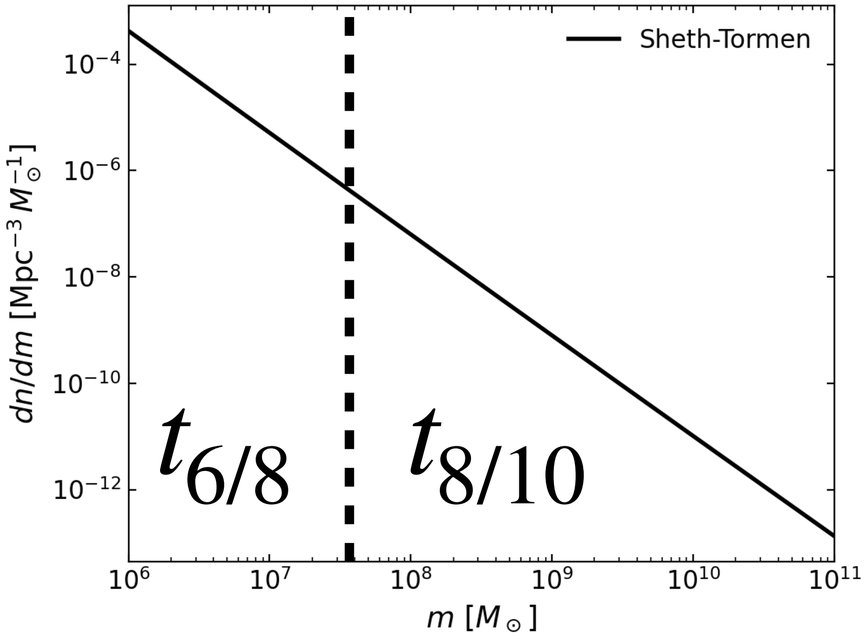
Subhalos: tidal stripping can accelerate core collapse relative to field halos

-> $\lambda_{\rm sub}$ rescales t_c for subhalos such that they collapse faster

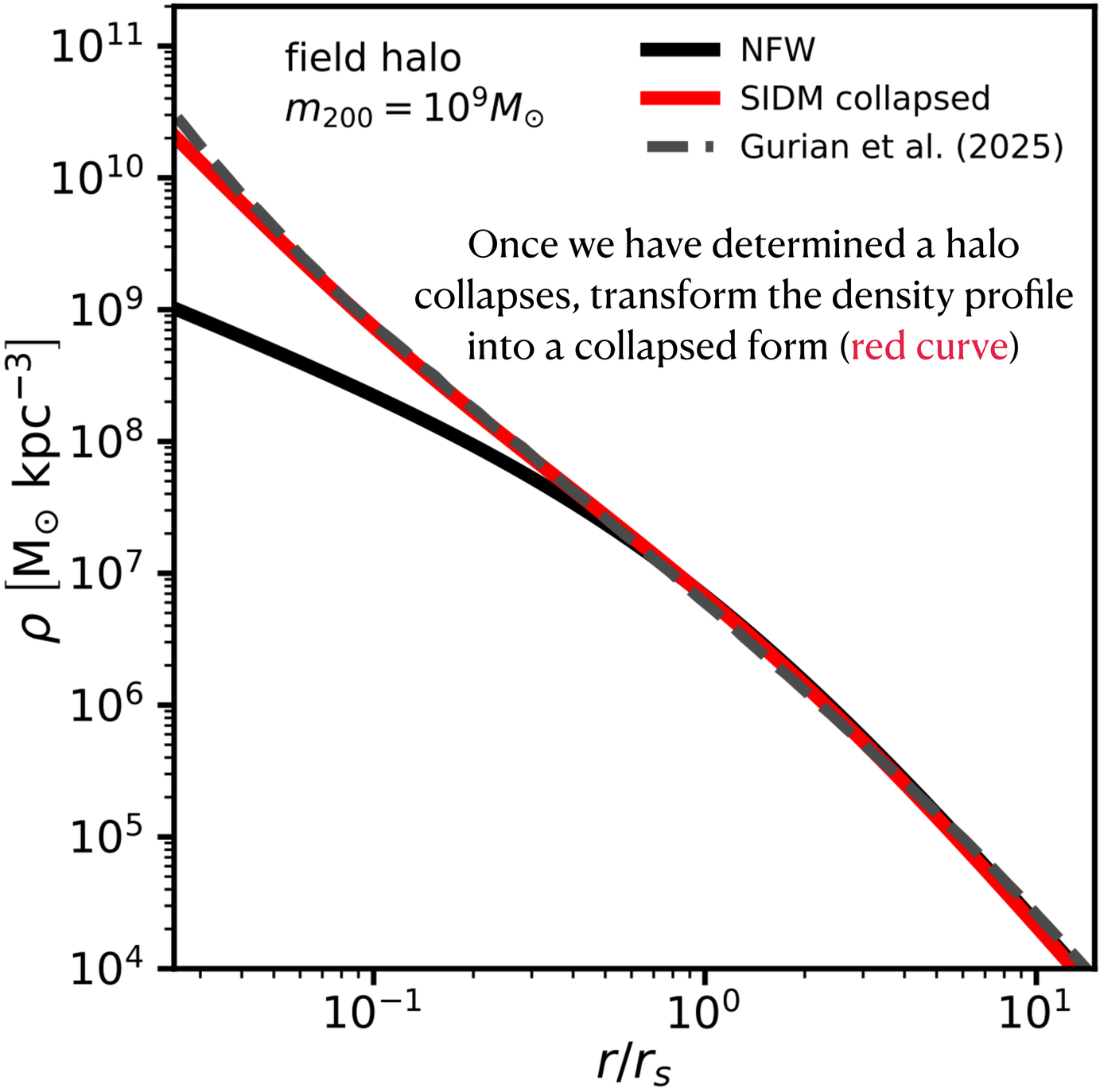








SIDM parameters: $t_{6/8}$, $t_{8/10}$, $\lambda_{\rm sub}$


field halo
$m_{200} = 10^9 M_\odot$
NFW
SIDM collapsed
Gurian et al. (2025)
Once we have determined a halo collapses, transform the density profile into a collapsed form (red curve)
ρ [$M_\odot$ kpc^{-3}]
r/r_s
10^{11}
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^{-1}
10^0
10^1

One additional free parameter for the internal structure of deeply collapsed halos:

$$\xi_{\rm core} \to 0$$

produces a power-law profile (right)

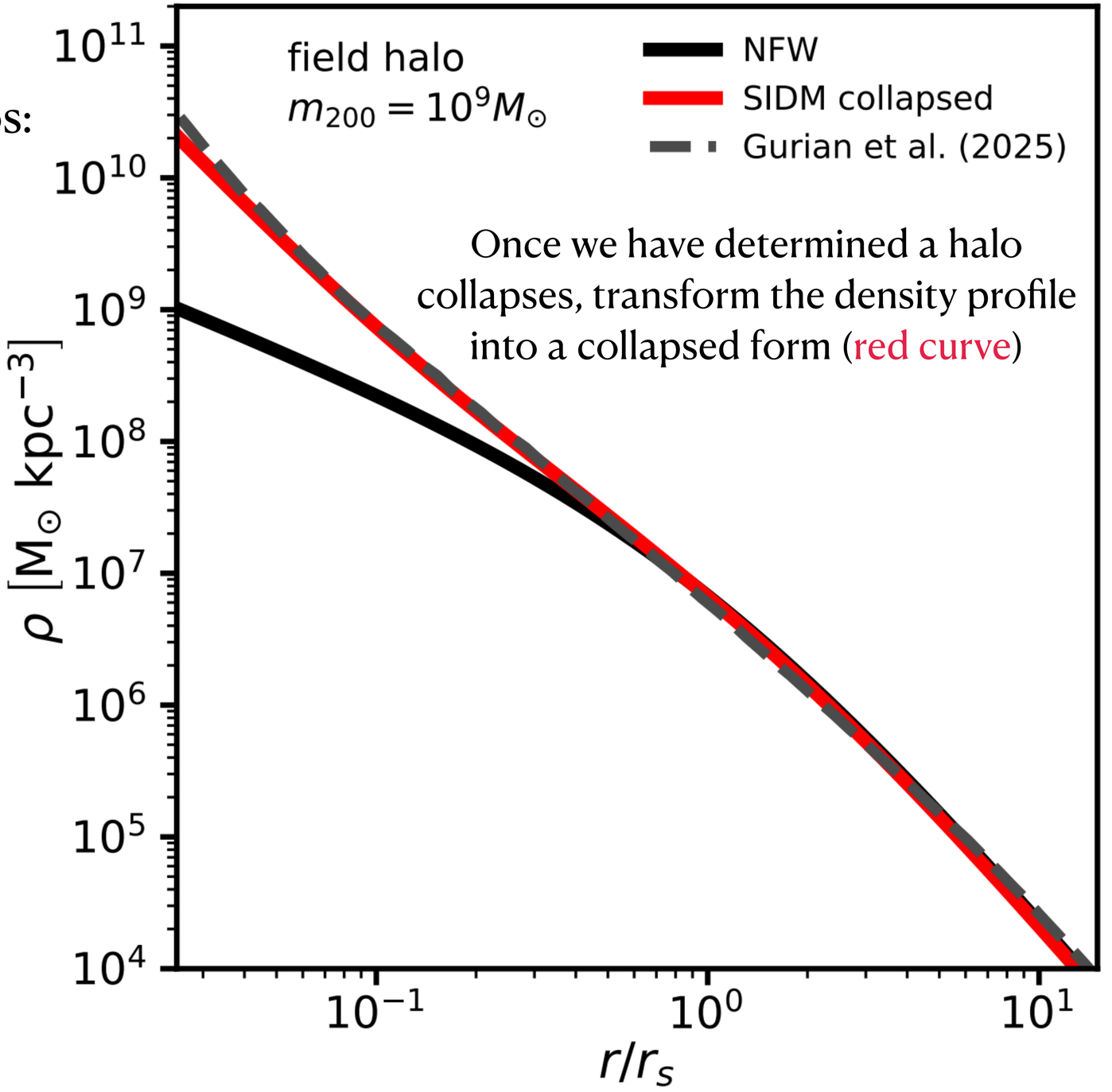
$$\xi_{\rm core} \to 1$$

produces a point-mass + NFW profile

-> it remains an open question whether core collapse ends in black hole formation

SIDM parameters:

$$t_{6/8},\ t_{8/10},\ \lambda_{\rm sub},\ \xi_{\rm core}$$



Globular clusters

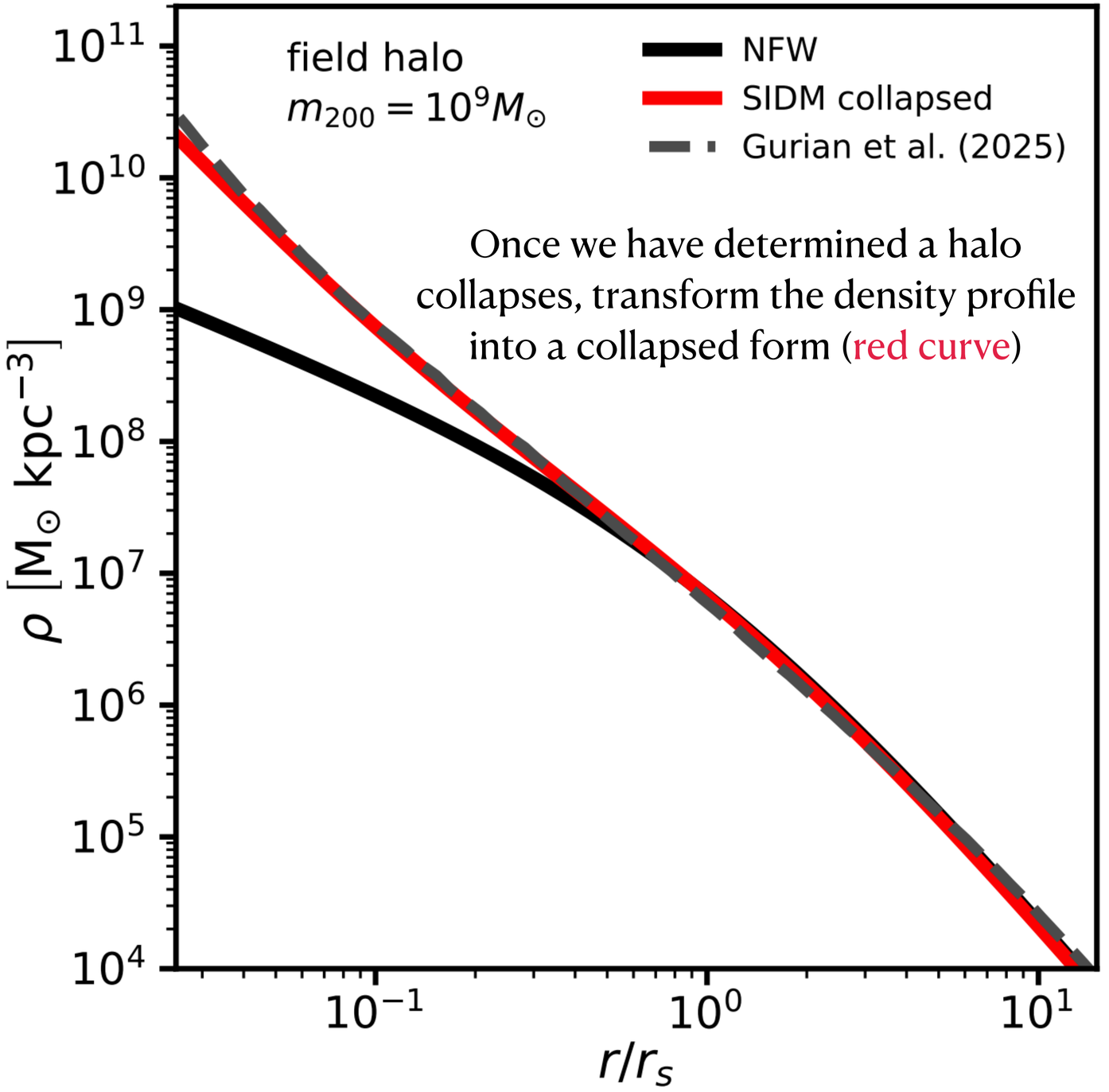
Log-normal mass function with a mean mass $2 \times 10^5 M_\odot$ and 0.6 scatter

$\Sigma_{\rm gc}$ is the surface mass density

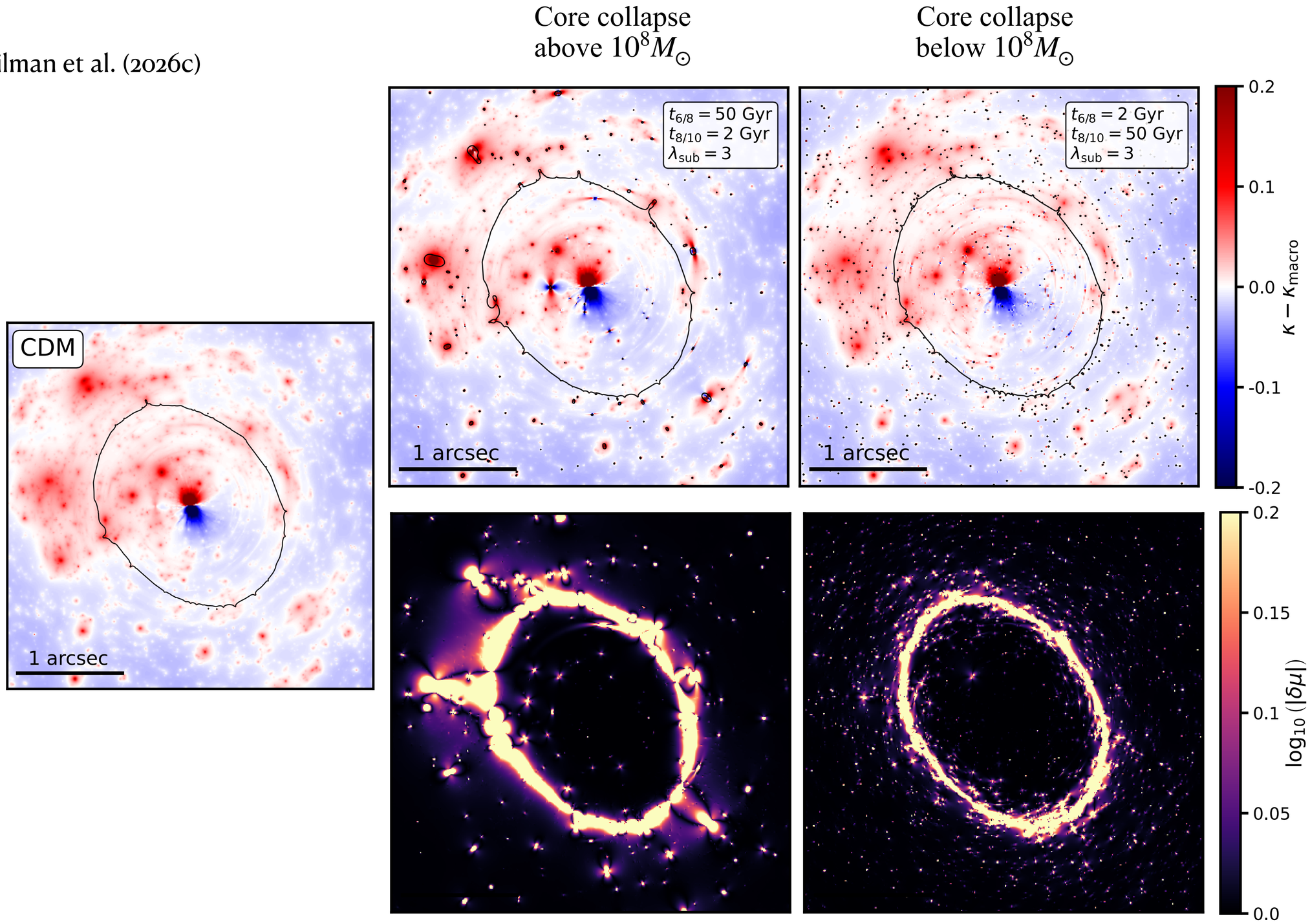
from nearby elliptical we get
$\Sigma_{\rm gc} \sim 10^{5.6} M_\odot {\rm kpc}^{-2}$

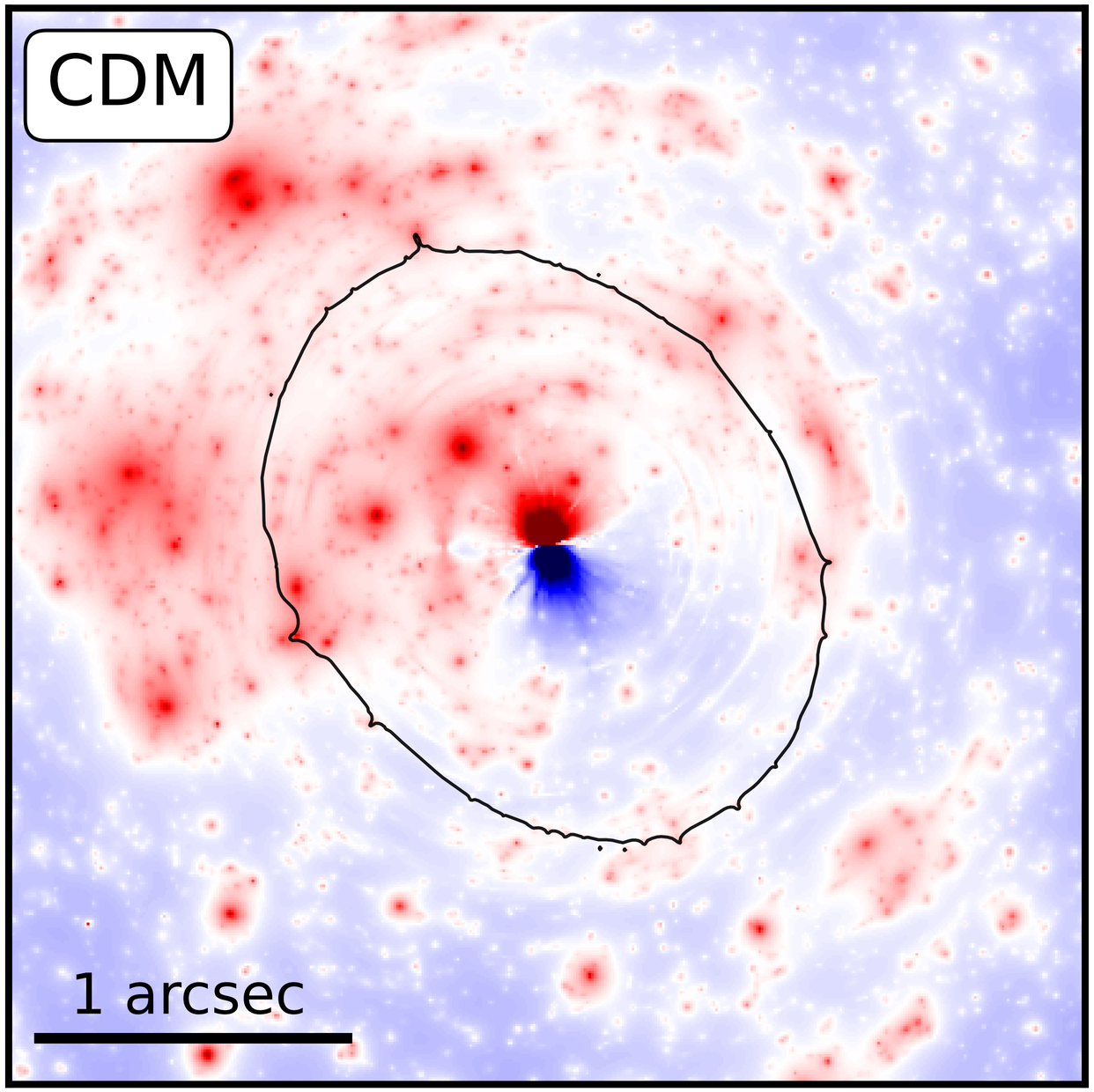
SIDM parameters:
$t_{6/8}, t_{8/10}, \lambda_{\rm sub}, \xi_{\rm core}$

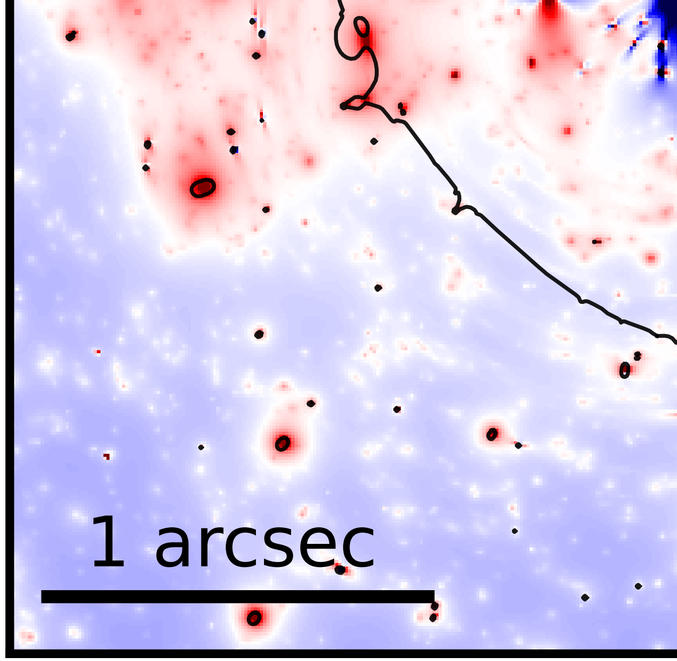
Nuisance parameters:
$\Sigma_{\rm gc}, \Sigma_{\rm sub}$



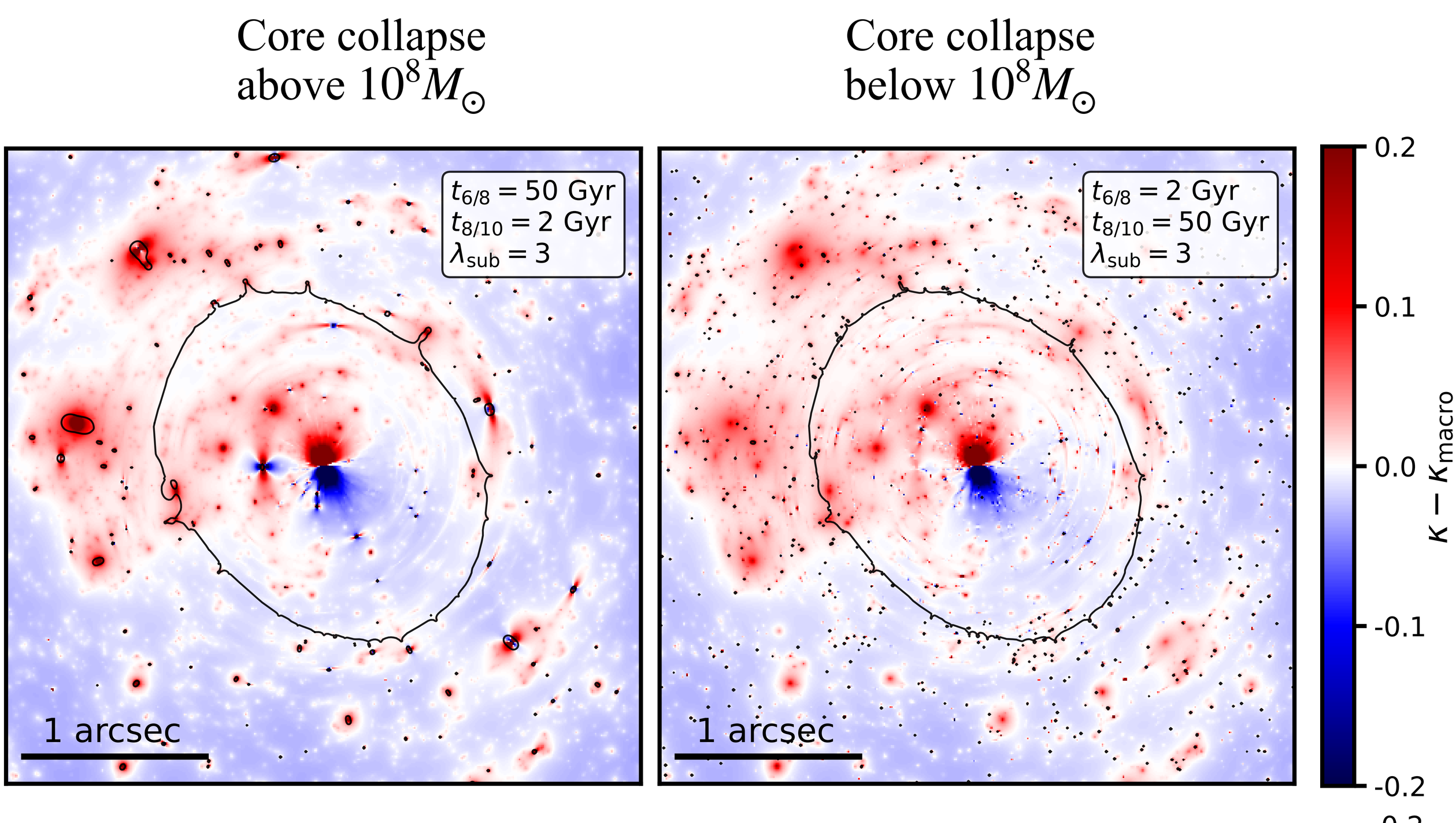
Gilman et al. (2026c)

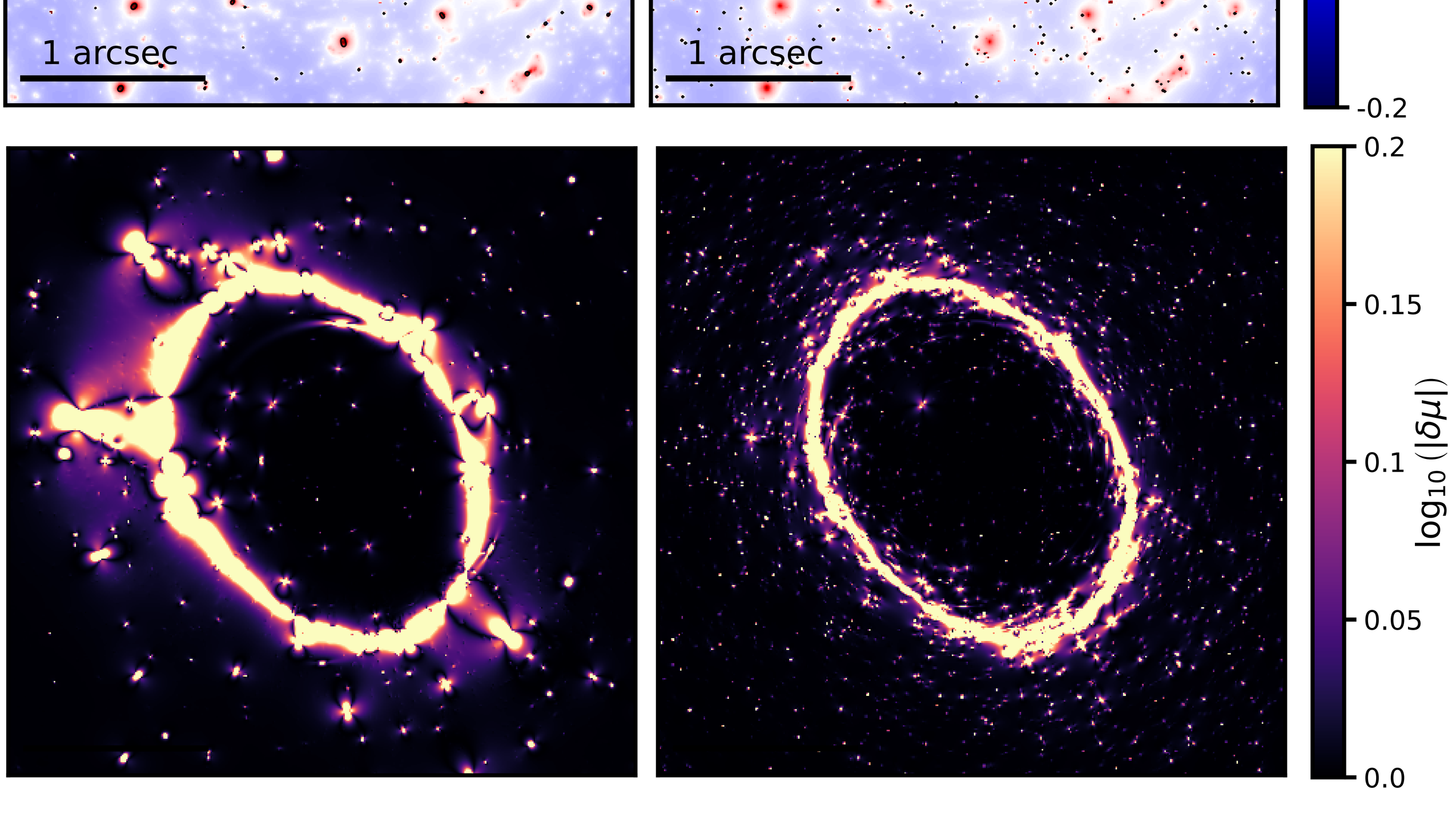



CDM
1 arcsec


1 arcsec

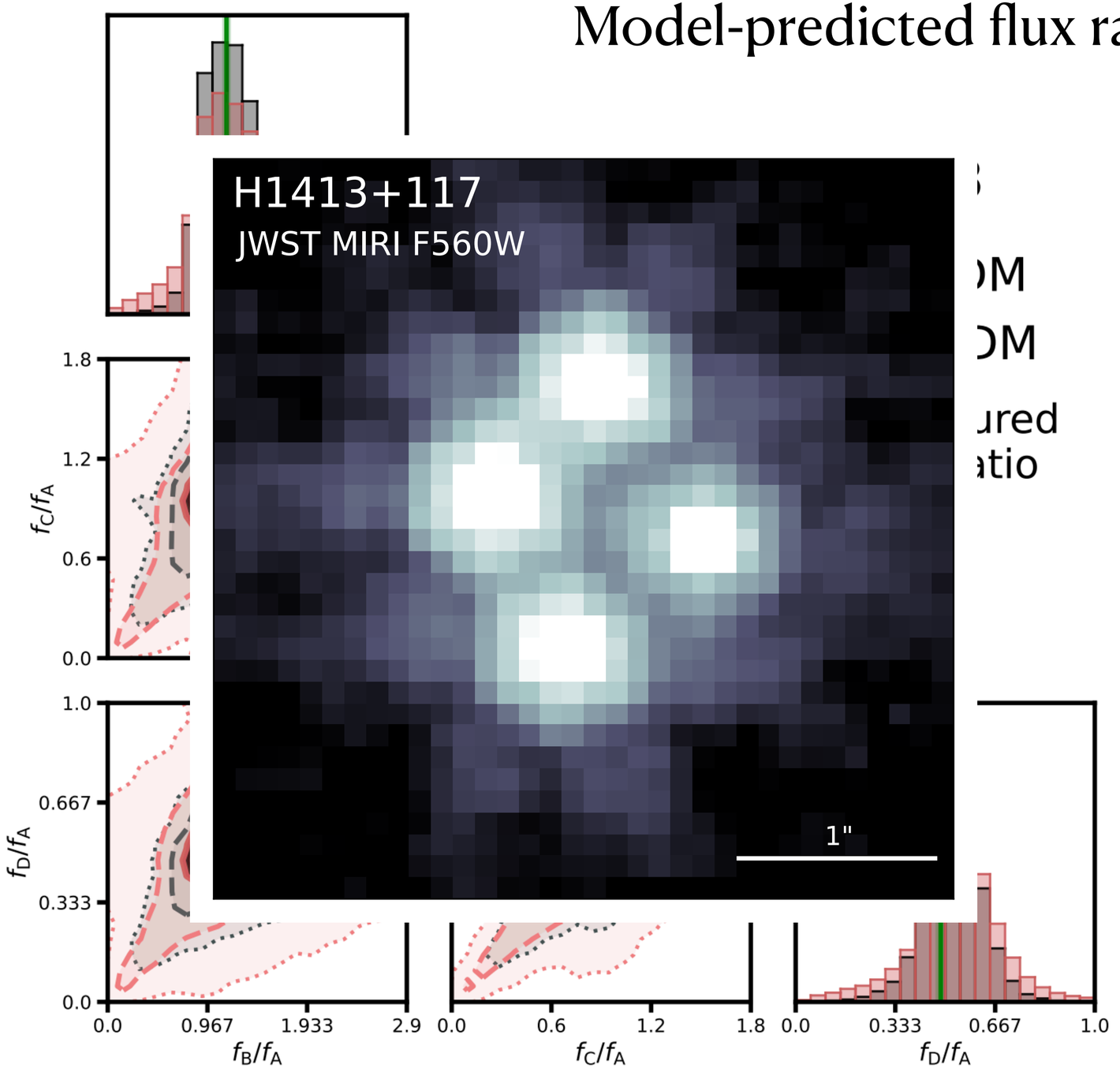



Core collapse
above $10^8 M_\odot$
Core collapse
below $10^8 M_\odot$
$t_{6/8} = 50$ Gyr
$t_{8/10} = 2$ Gyr
$\lambda_{\rm sub} = 3$
1 arcsec
$t_{6/8} = 2$ Gyr
$t_{8/10} = 50$ Gyr
$\lambda_{\rm sub} = 3$
1 arcsec
0.2
0.1
0.0
-0.1
-0.2
$\kappa - \kappa_{\rm macro}$


1 arcsec
1 arcsec
-0.2
0.2
0.15
0.1
0.05
0.0
$\log_{10}(|\delta\mu|)$

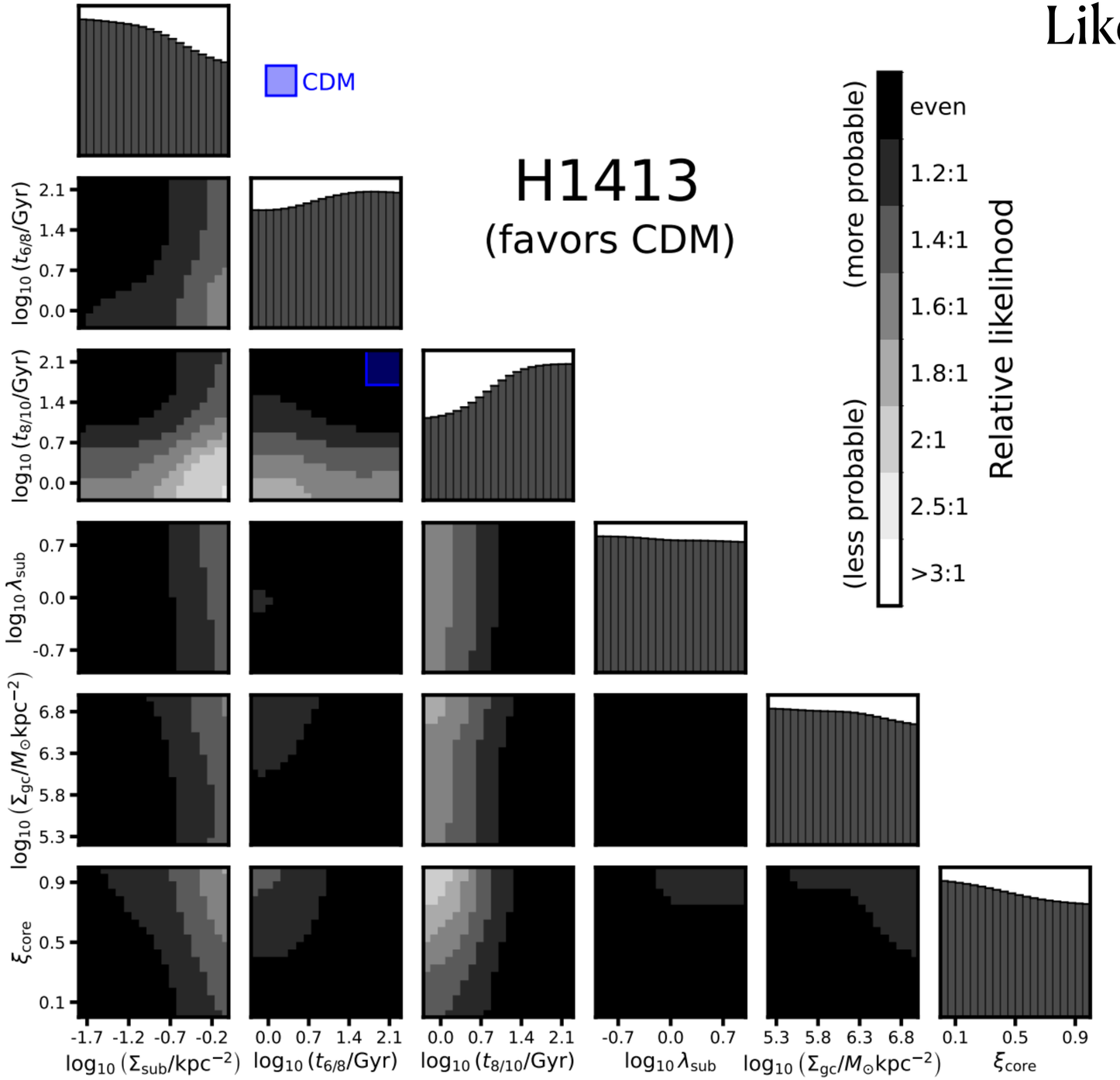
Gilman et al. (2026c)

Model-predicted flux ratio distribution



Likelihood function

Gilman et al. (2026c)

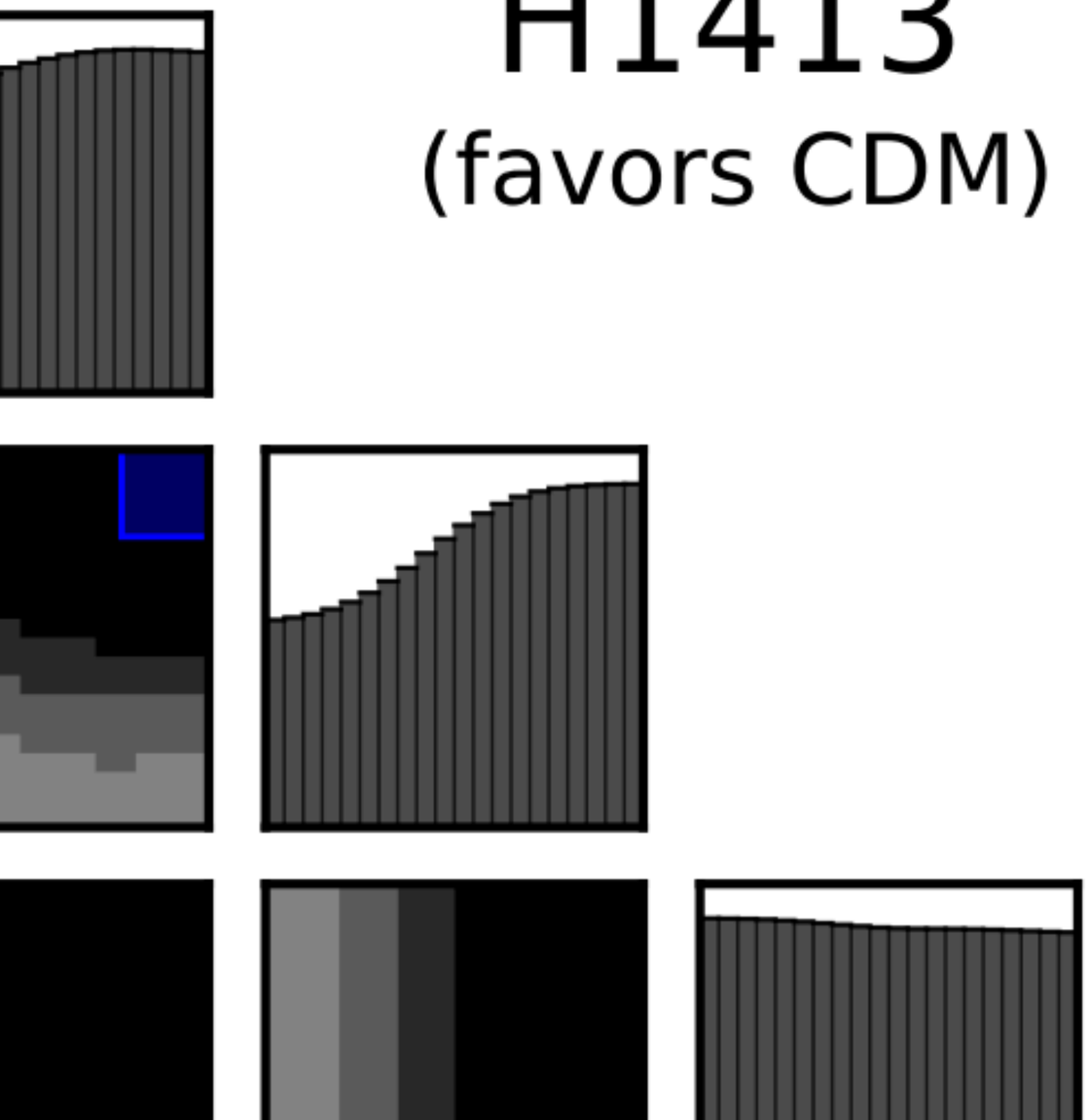


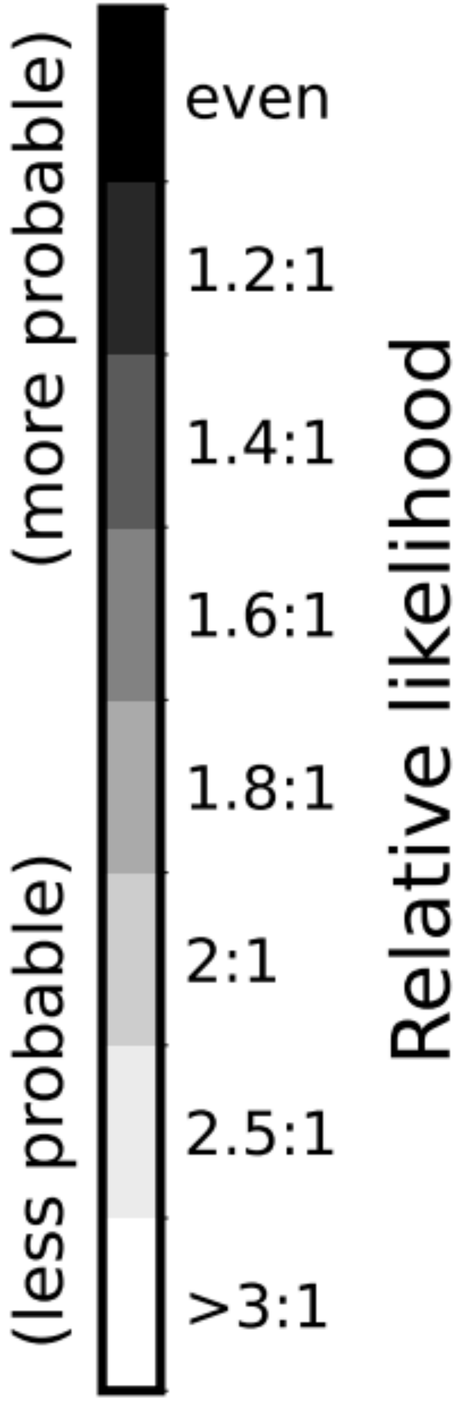
DM

Gilman et al. (2026c)

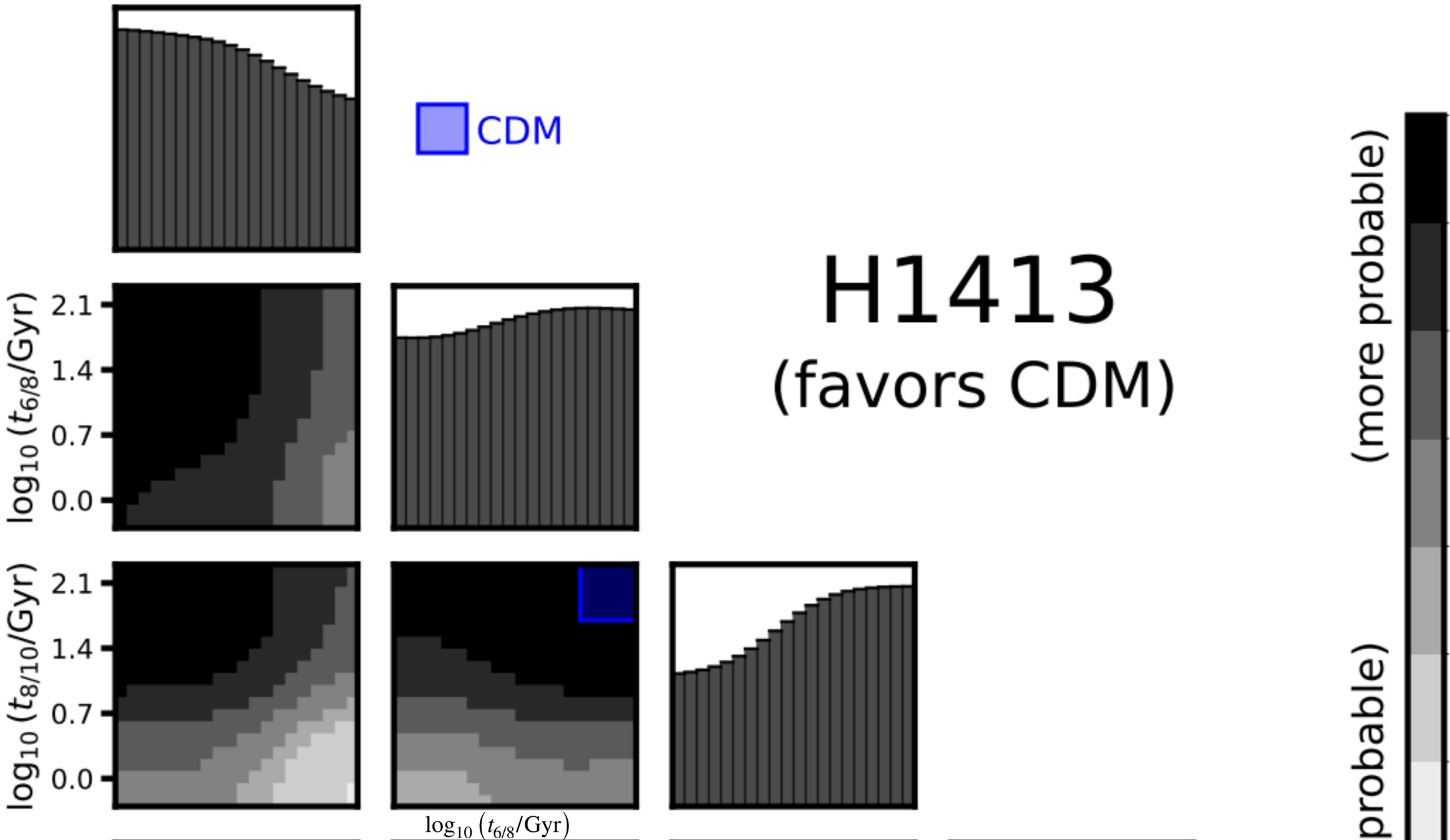
H1413

(favors CDM)

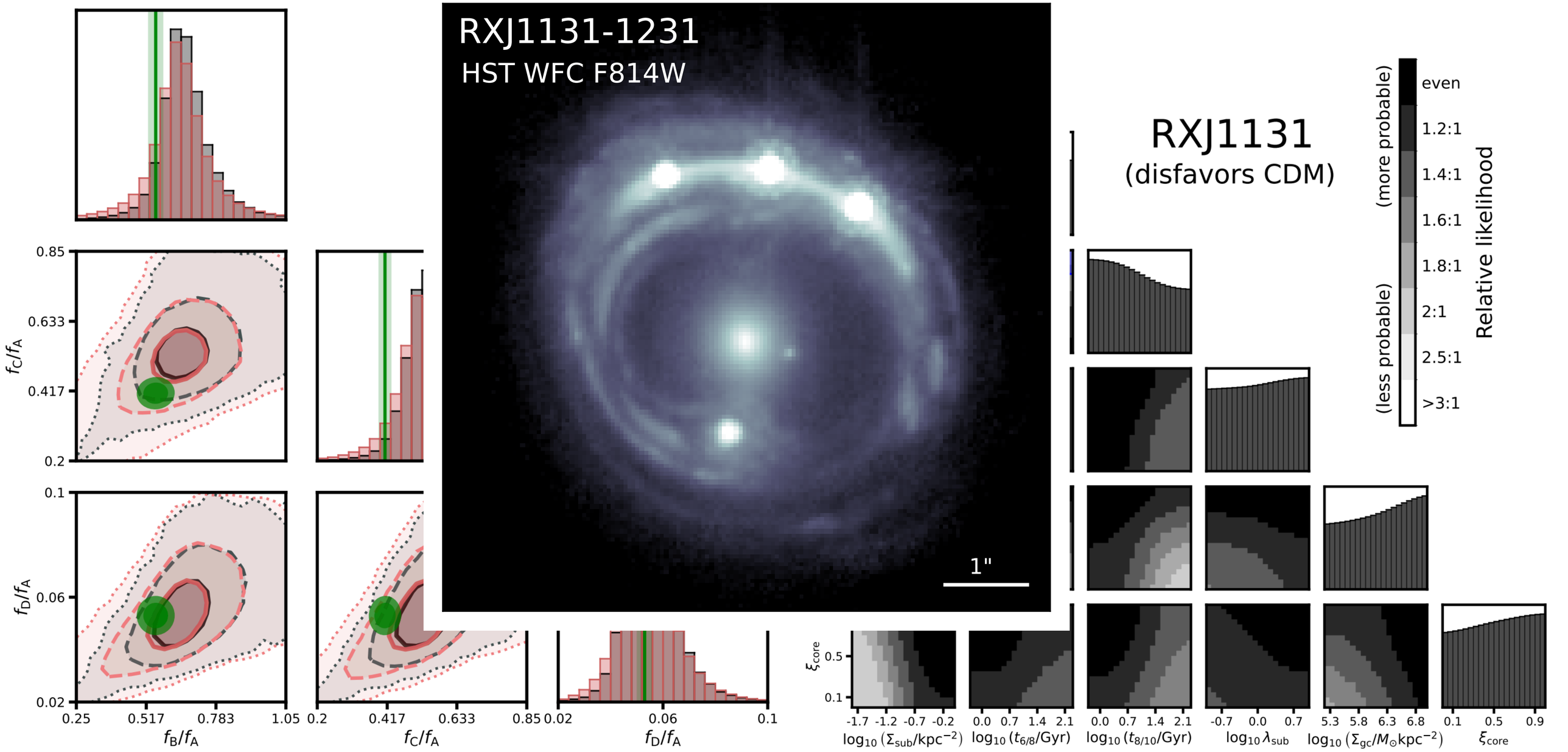


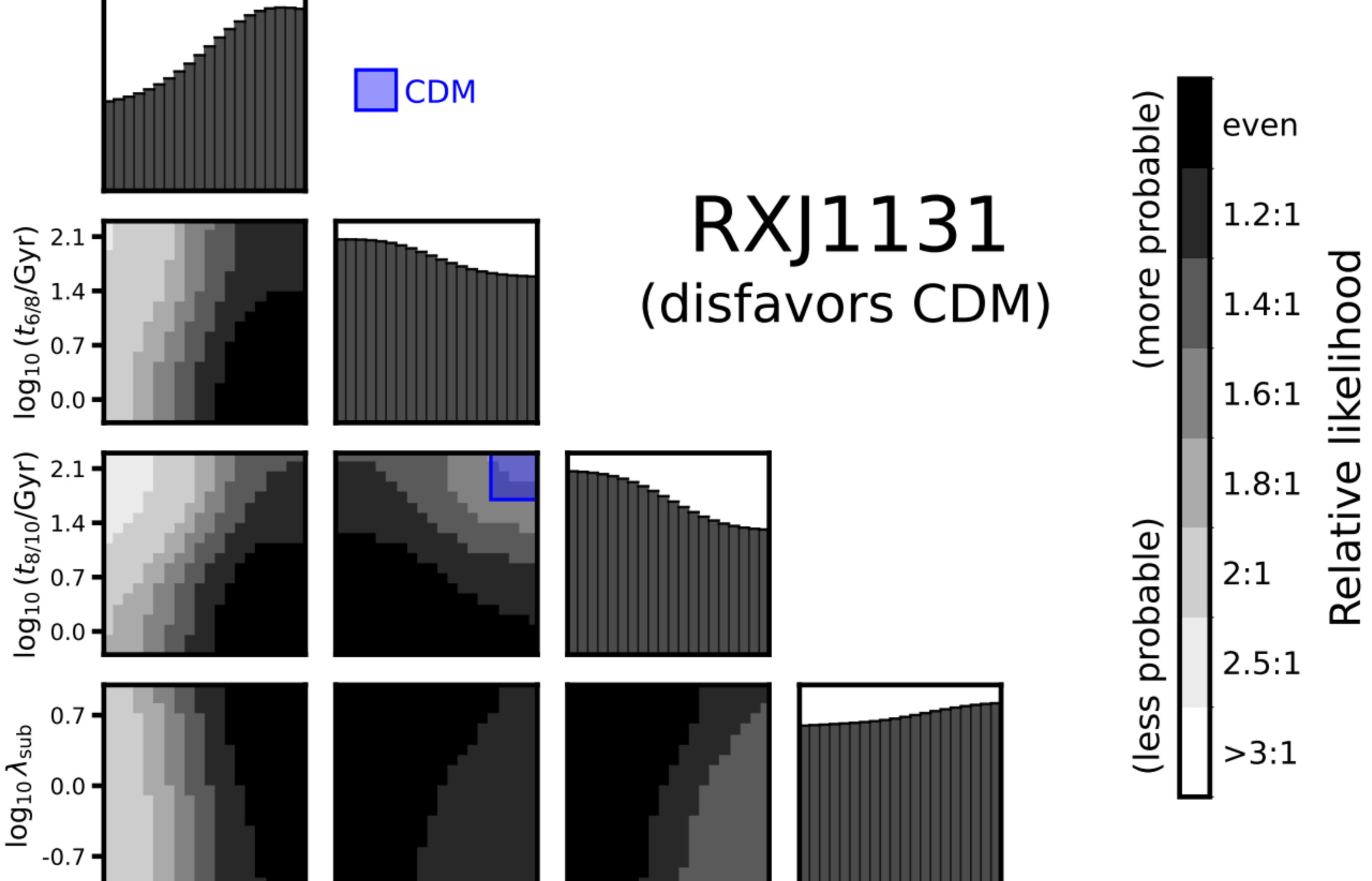


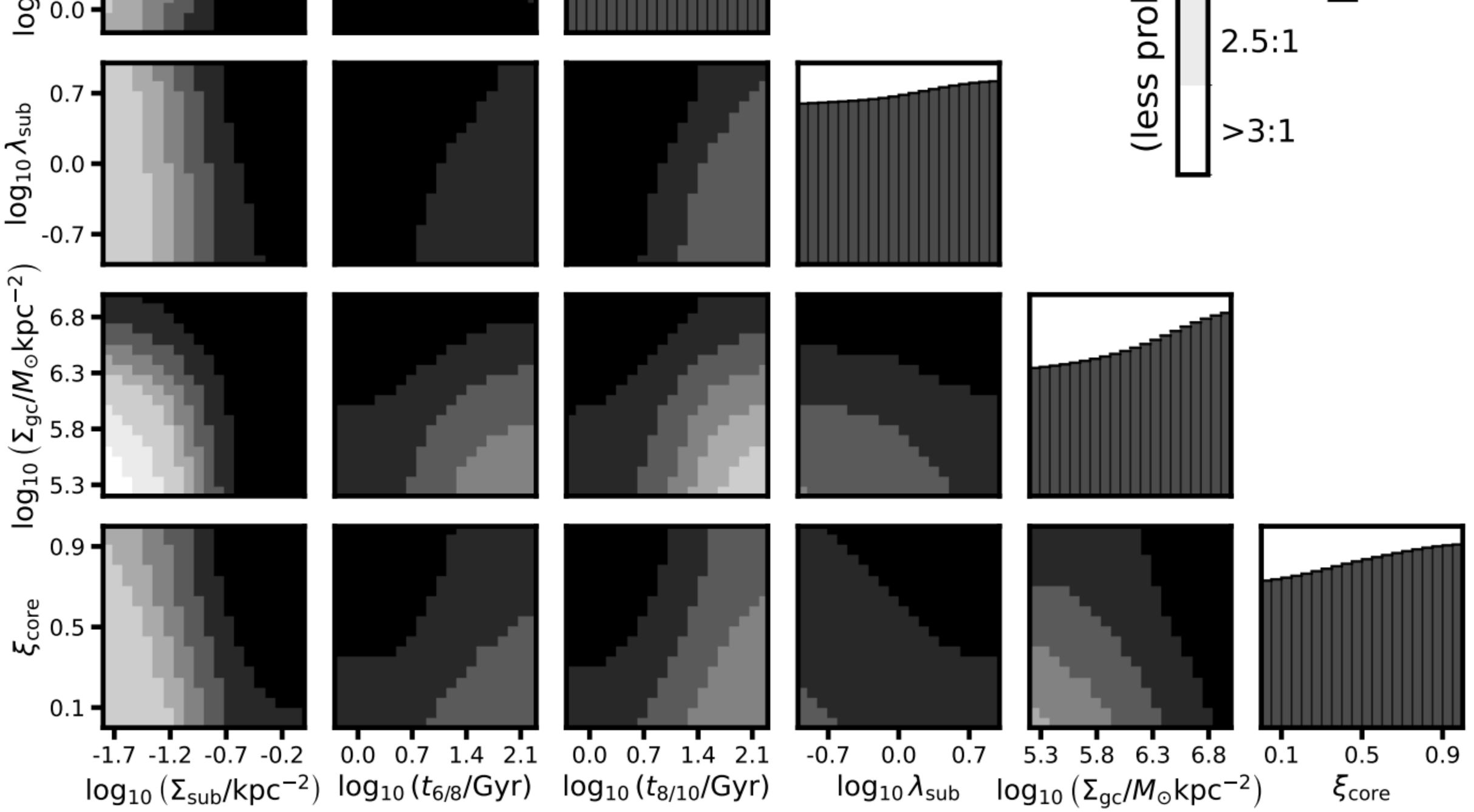
Likelihood function

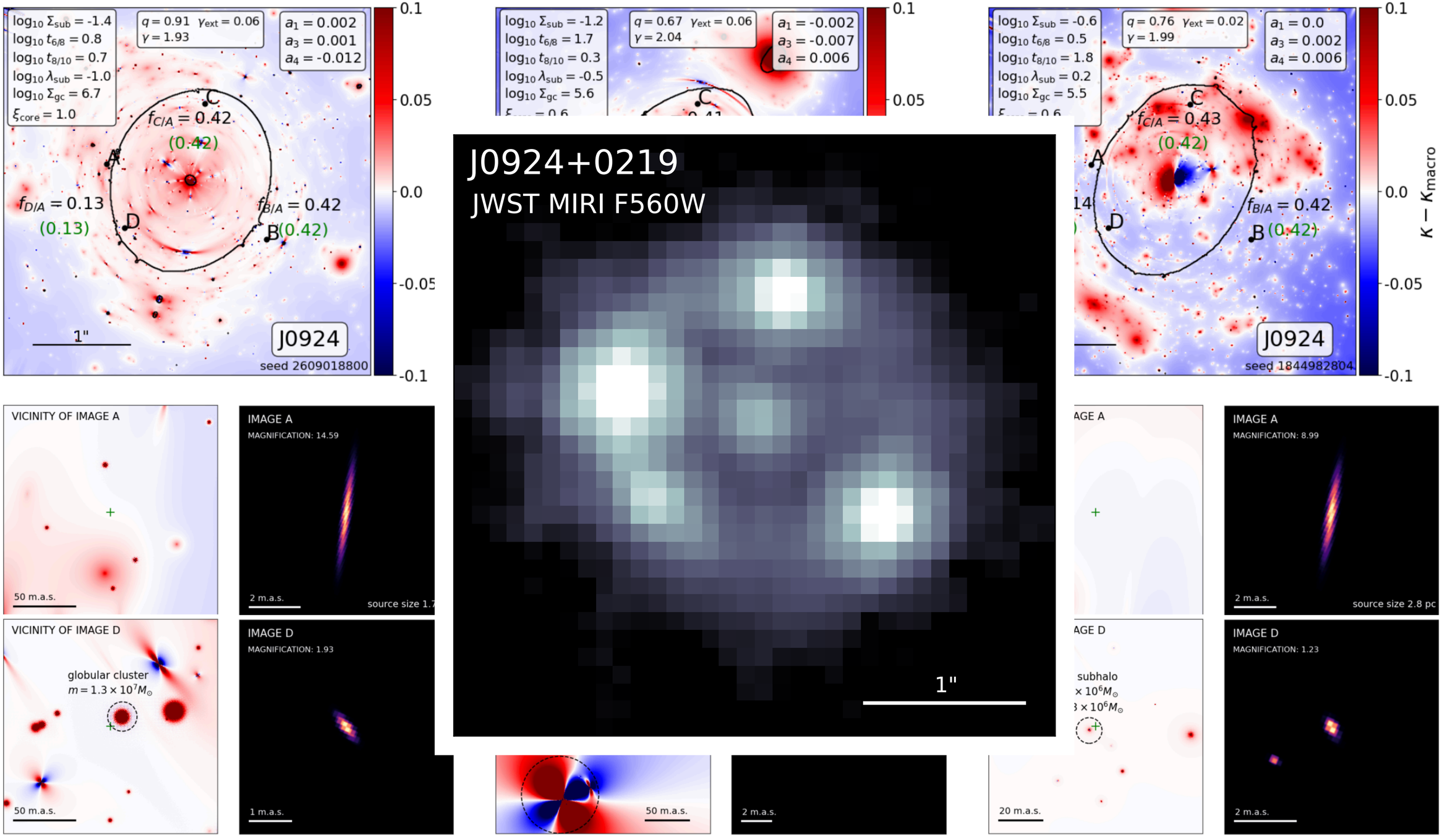

Likelihood function
CDM
H1413
(favors CDM)
2.1
1.4
0.7
0.0
log10 (t6/8/Gyr)
log10 (t8/10/Gyr)
log10 (t6/8/Gyr)
(more probable)
probable)

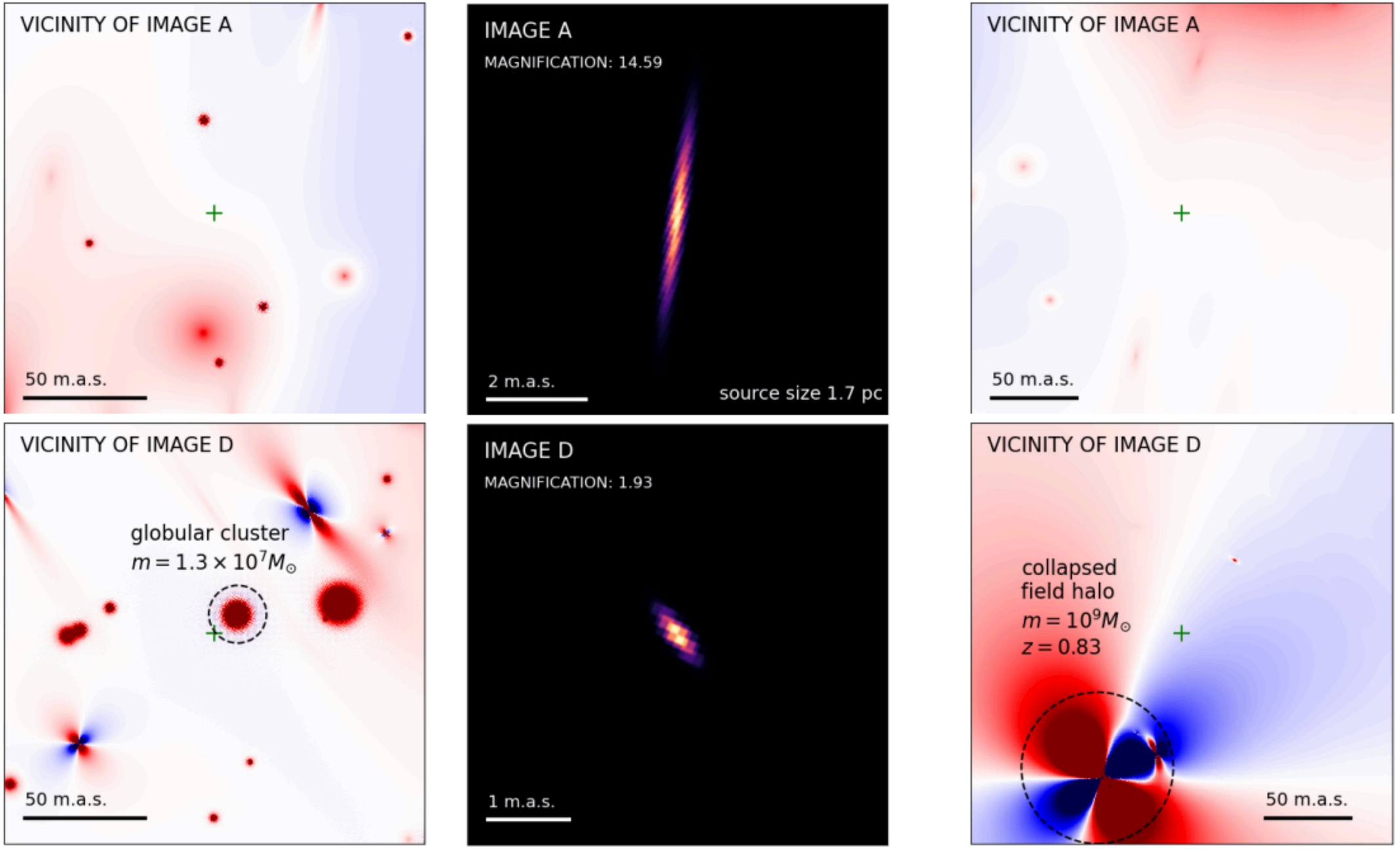
Gilman et al. (2026c)

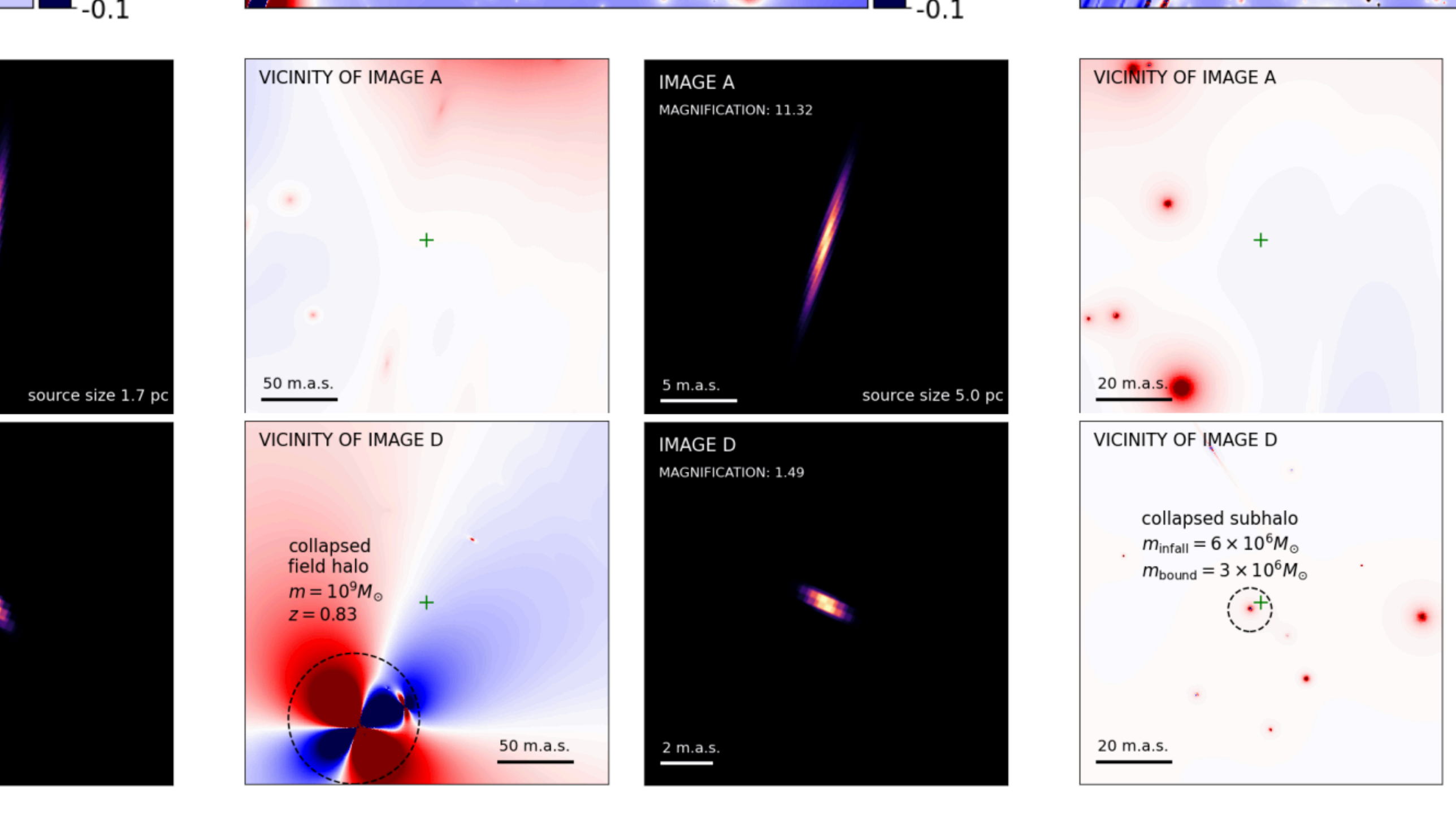



CDM
RXJ1131
(disfavors CDM)
$\log_{10}(t_{6/8}/\mathrm{Gyr})$
2.1
1.4
0.7
0.0
$\log_{10}(t_{8/10}/\mathrm{Gyr})$
2.1
1.4
0.7
0.0
$\log_{10}\lambda_{\mathrm{sub}}$
0.7
0.0
-0.7
(more probable)
(less probable)
even
1.2:1
1.4:1
1.6:1
1.8:1
2:1
2.5:1
>3:1
Relative likelihood


(less probable)
2.5:1
>3:1
0.0
0.7
0.0
-0.7
$\log_{10}\lambda_{\rm sub}$
6.8
6.3
5.8
5.3
$\log_{10}\left(\Sigma_{\rm gc}/M_\odot{\rm kpc}^{-2}\right)$
0.9
0.5
0.1
$\xi_{\rm core}$
-1.7 -1.2 -0.7 -0.2
$\log_{10}\left(\Sigma_{\rm sub}/{\rm kpc}^{-2}\right)$
0.0 0.7 1.4 2.1
$\log_{10}\left(t_{6/8}/{\rm Gyr}\right)$
0.0 0.7 1.4 2.1
$\log_{10}\left(t_{8/10}/{\rm Gyr}\right)$
-0.7 0.0 0.7
$\log_{10}\lambda_{\rm sub}$
5.3 5.8 6.3 6.8
$\log_{10}\left(\Sigma_{\rm gc}/M_\odot{\rm kpc}^{-2}\right)$
0.1 0.5 0.9
$\xi_{\rm core}$

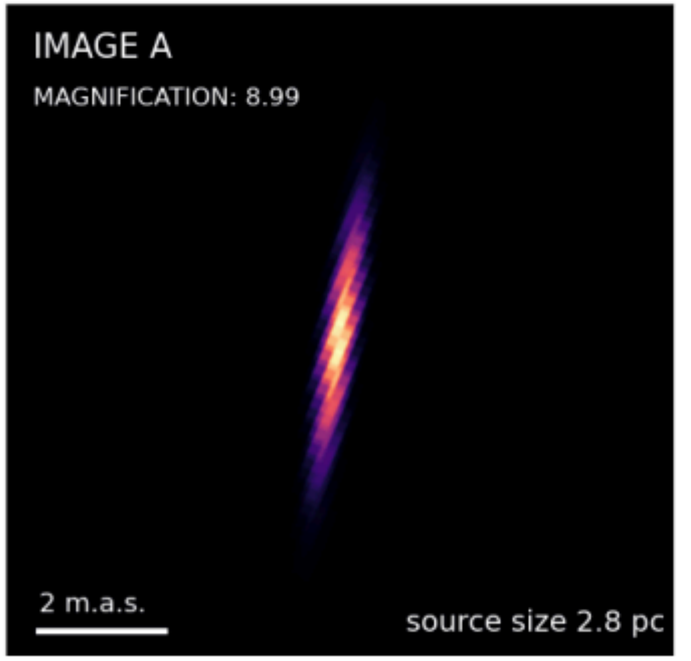

J0924+0219
JWST MIRI F560W
1"
$\log_{10}\Sigma_{sub} = -1.4$
$\log_{10} t_{6/8} = 0.8$
$\log_{10} t_{8/10} = 0.7$
$\log_{10}\lambda_{sub} = -1.0$
$\log_{10}\Sigma_{gc} = 6.7$
$\xi_{core} = 1.0$
$q = 0.91$ $\gamma_{ext} = 0.06$
$\gamma = 1.93$
$a_1 = 0.002$
$a_3 = 0.001$
$a_4 = -0.012$
$f_{C/A} = 0.42$
(0.42)
$f_{D/A} = 0.13$
(0.13)
$f_{B/A} = 0.42$
(0.42)
A
B
C
D
1"
J0924
seed 2609018800
0.1
0.05
0.0
-0.05
-0.1
$\log_{10}\Sigma_{sub} = -1.2$
$\log_{10} t_{6/8} = 1.7$
$\log_{10} t_{8/10} = 0.3$
$\log_{10}\lambda_{sub} = -0.5$
$\log_{10}\Sigma_{gc} = 5.6$
$q = 0.67$ $\gamma_{ext} = 0.06$
$\gamma = 2.04$
$a_1 = -0.002$
$a_3 = -0.007$
$a_4 = 0.006$
$\log_{10}\Sigma_{sub} = -0.6$
$\log_{10} t_{6/8} = 0.5$
$\log_{10} t_{8/10} = 1.8$
$\log_{10}\lambda_{sub} = 0.2$
$\log_{10}\Sigma_{gc} = 5.5$
$q = 0.76$ $\gamma_{ext} = 0.02$
$\gamma = 1.99$
$a_1 = 0.0$
$a_3 = 0.002$
$a_4 = 0.006$
$f_{C/A} = 0.43$
(0.42)
$f_{B/A} = 0.42$
(0.42)
J0924
seed 1844982804
$K - K_{macro}$
VICINITY OF IMAGE A
50 m.a.s.
IMAGE A
MAGNIFICATION: 14.59
2 m.a.s.
source size 1.7
IMAGE A
MAGNIFICATION: 8.99
2 m.a.s.
source size 2.8 pc
VICINITY OF IMAGE D
globular cluster
$m = 1.3 \times 10^7 M_\odot$
50 m.a.s.
IMAGE D
MAGNIFICATION: 1.93
1 m.a.s.
50 m.a.s.
2 m.a.s.
subhalo
20 m.a.s.
IMAGE D
MAGNIFICATION: 1.23
2 m.a.s.

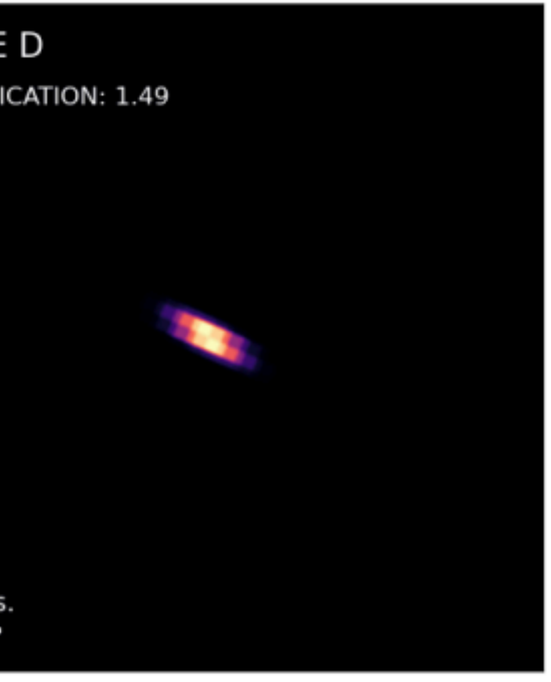

VICINITY OF IMAGE A
50 m.a.s.
IMAGE A
MAGNIFICATION: 14.59
2 m.a.s.
source size 1.7 pc
VICINITY OF IMAGE A
50 m.a.s.
VICINITY OF IMAGE D
globular cluster
$m = 1.3 \times 10^7 M_\odot$
50 m.a.s.
IMAGE D
MAGNIFICATION: 1.93
1 m.a.s.
VICINITY OF IMAGE D
collapsed
field halo
$m = 10^9 M_\odot$
$z = 0.83$
50 m.a.s.

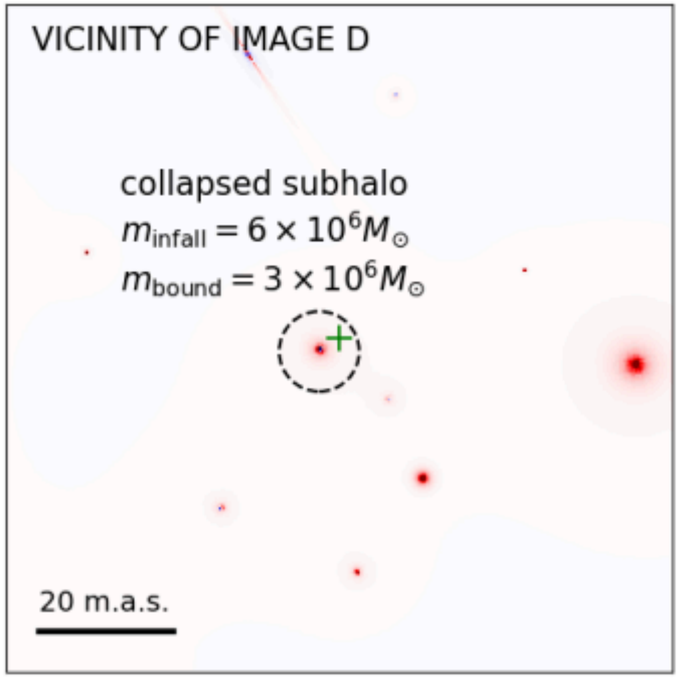

-0.1
-0.1
source size 1.7 pc
VICINITY OF IMAGE A
50 m.a.s.
IMAGE A
MAGNIFICATION: 11.32
5 m.a.s.
source size 5.0 pc
VICINITY OF IMAGE A
20 m.a.s.
VICINITY OF IMAGE D
collapsed
field halo
$m = 10^9 M_\odot$
$z = 0.83$
50 m.a.s.
IMAGE D
MAGNIFICATION: 1.49
2 m.a.s.
VICINITY OF IMAGE D
collapsed subhalo
$m_{\rm infall} = 6 \times 10^6 M_\odot$
$m_{\rm bound} = 3 \times 10^6 M_\odot$
20 m.a.s.

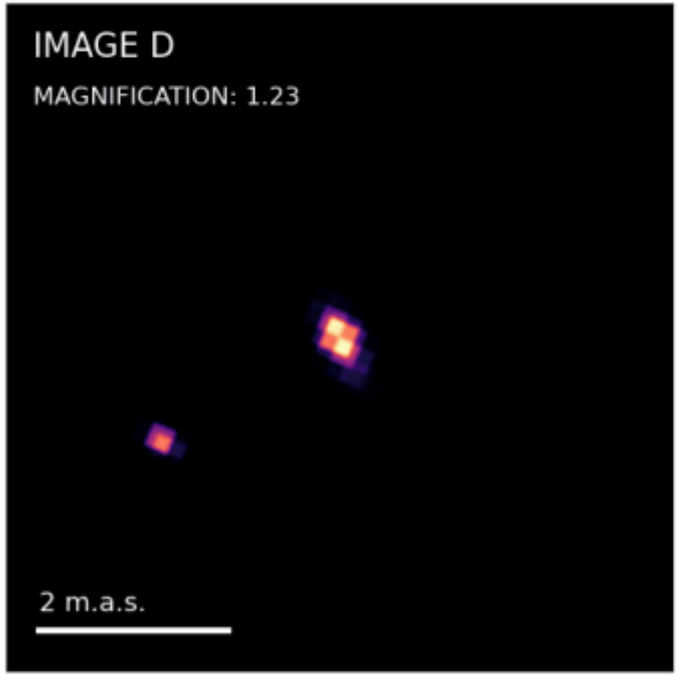

E A
ICATION: 11.32
s.
source size 5.0 pc

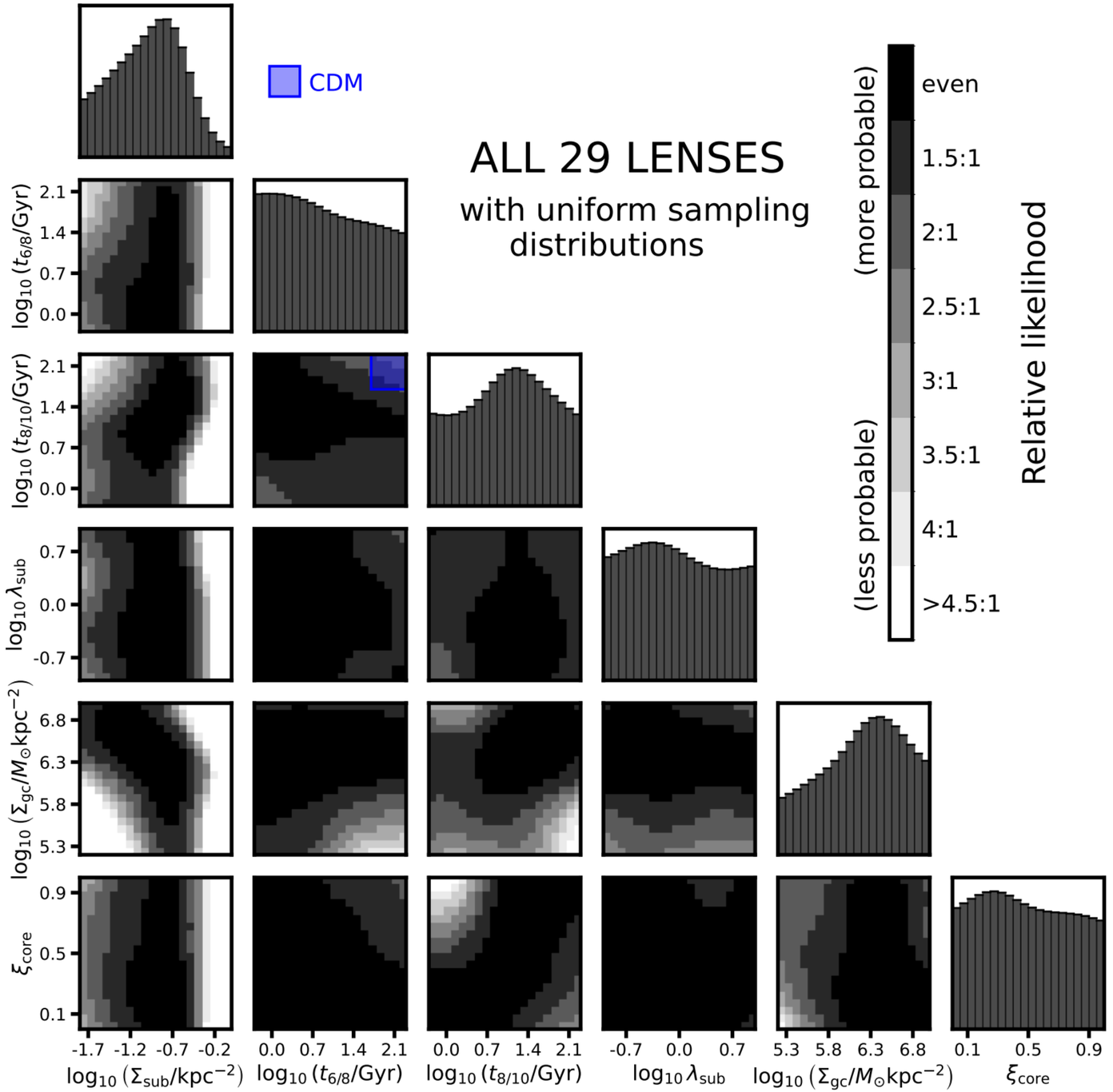

VICINITY OF IMAGE A
20 m.a.s.

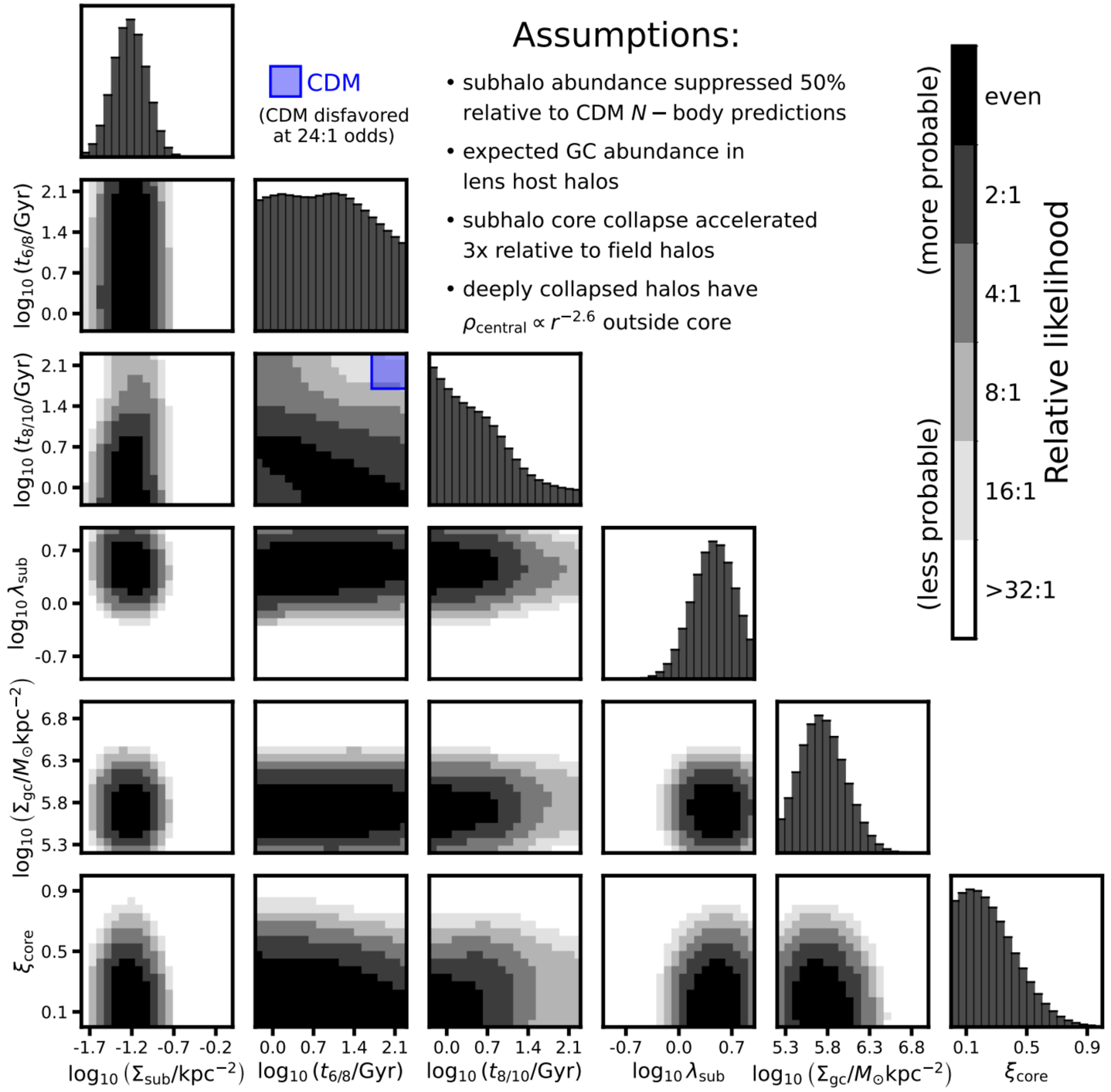

IMAGE A
MAGNIFICATION: 8.99
2 m.a.s.
source size 2.8 pc

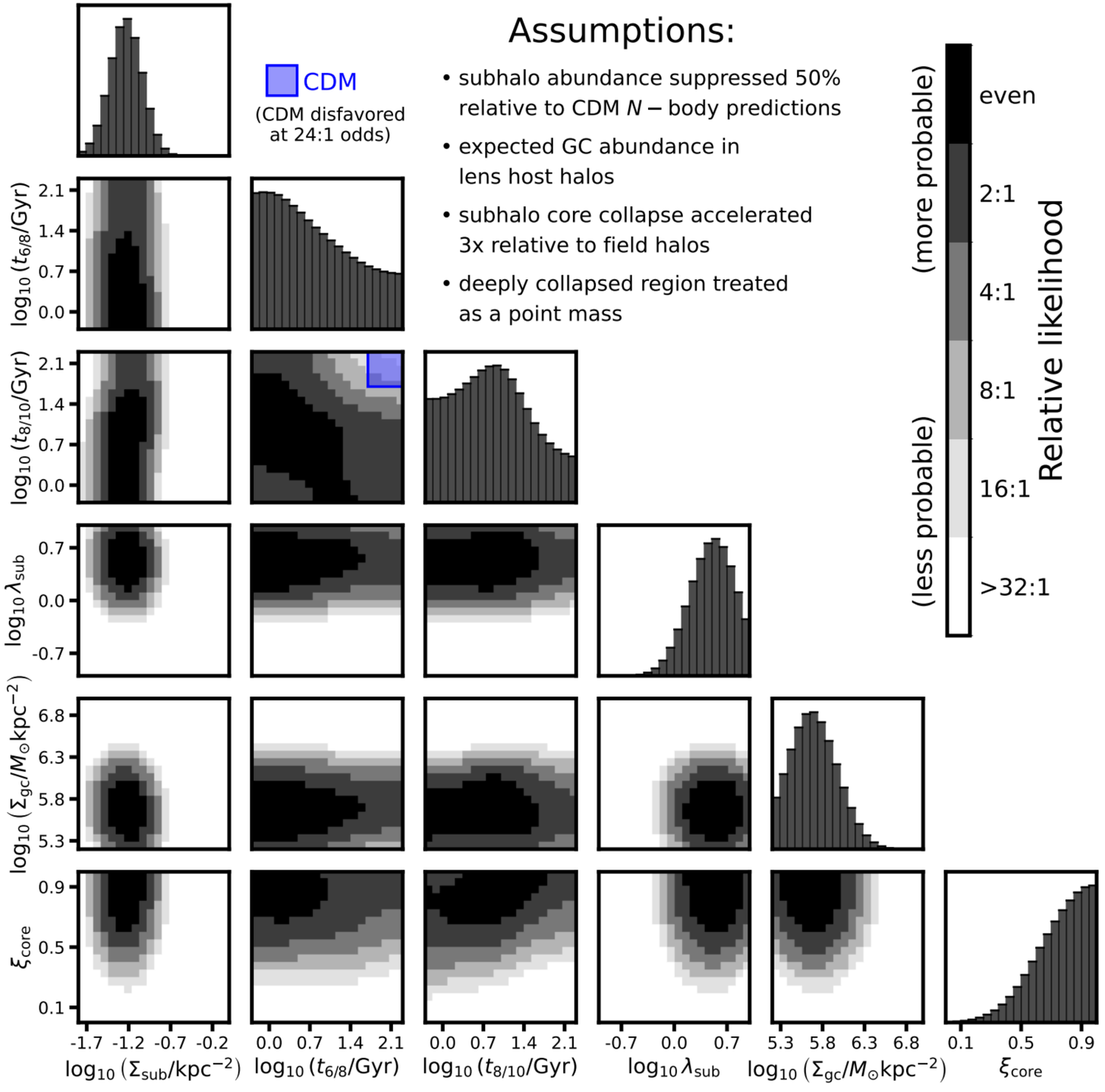

E D
ICATION: 1.49
s.

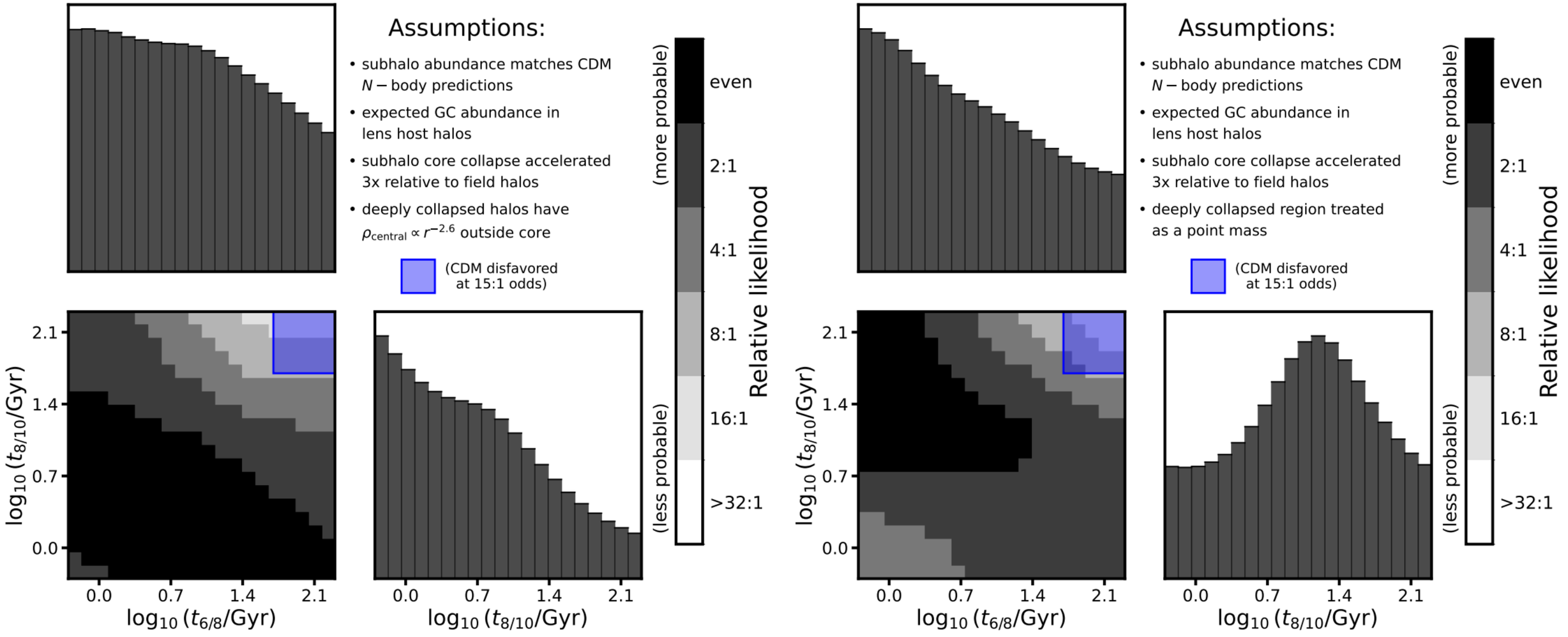

VICINITY OF IMAGE D
collapsed subhalo
$m_{\rm infall} = 6 \times 10^6 M_\odot$
$m_{\rm bound} = 3 \times 10^6 M_\odot$
20 m.a.s.

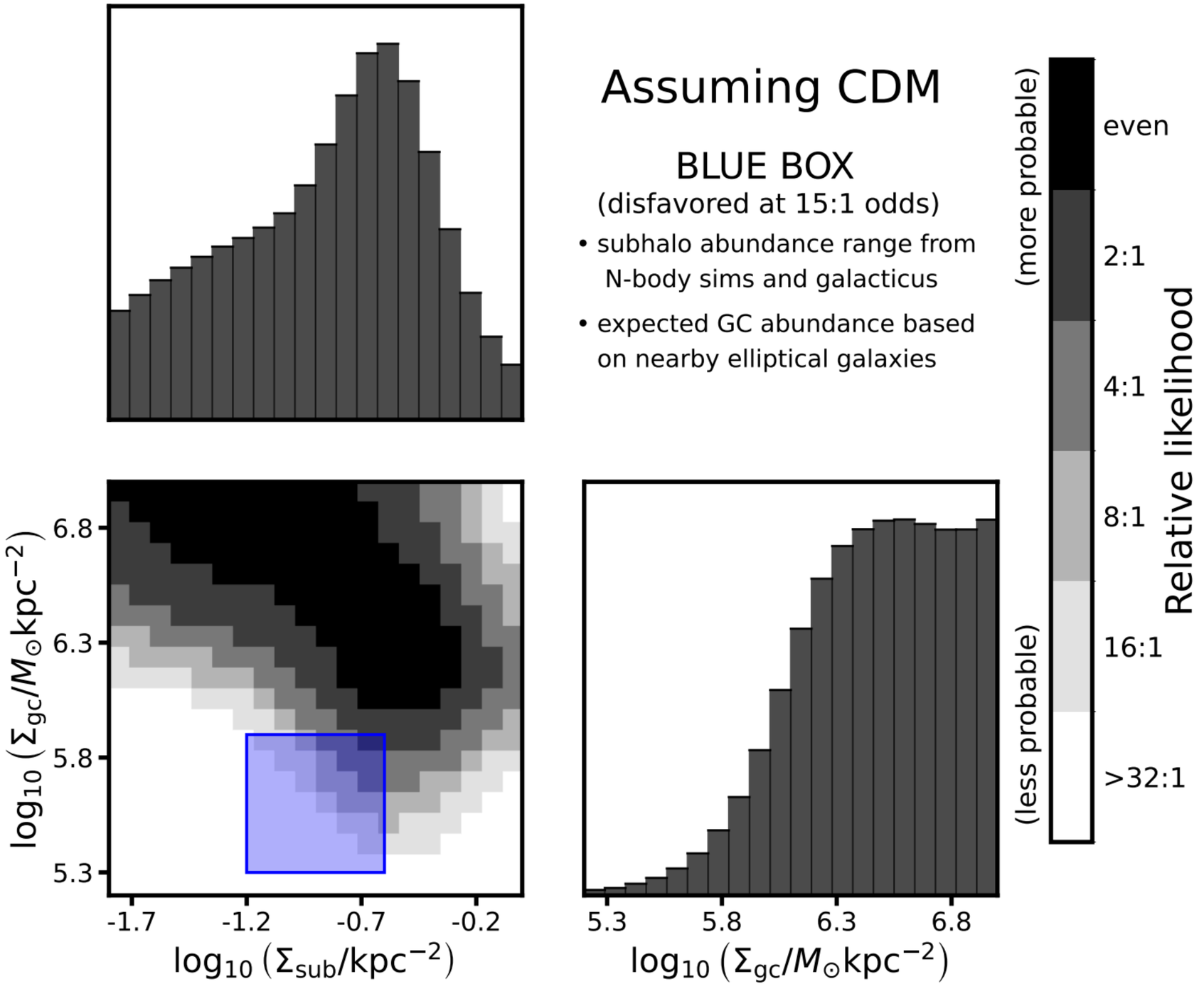

IMAGE D
MAGNIFICATION: 1.23
2 m.a.s.


ALL 29 LENSES
with uniform sampling distributions
CDM
Relative likelihood
(more probable)
(less probable)
even
1.5:1
2:1
2.5:1
3:1
3.5:1
4:1
>4.5:1
$\log_{10}(t_{6/8}/\mathrm{Gyr})$
$\log_{10}(t_{8/10}/\mathrm{Gyr})$
$\log_{10}\lambda_{\mathrm{sub}}$
$\log_{10}(\Sigma_{\mathrm{gc}}/M_\odot\mathrm{kpc}^{-2})$
ξ_{core}
$\log_{10}(\Sigma_{\mathrm{sub}}/\mathrm{kpc}^{-2})$


Assumptions:
CDM
(CDM disfavored at 24:1 odds)
• subhalo abundance suppressed 50% relative to CDM N − body predictions
• expected GC abundance in lens host halos
• subhalo core collapse accelerated 3x relative to field halos
• deeply collapsed halos have $\rho_{central} \propto r^{-2.6}$ outside core
Relative likelihood
even
2:1
4:1
8:1
16:1
>32:1
(more probable)
(less probable)
$\log_{10}(t_{6/8}/\mathrm{Gyr})$
$\log_{10}(t_{8/10}/\mathrm{Gyr})$
$\log_{10}\lambda_{sub}$
$\log_{10}(\Sigma_{gc}/M_\odot \mathrm{kpc}^{-2})$
ξ_{core}
$\log_{10}(\Sigma_{sub}/\mathrm{kpc}^{-2})$


Assumptions:
CDM
(CDM disfavored at 24:1 odds)
• subhalo abundance suppressed 50% relative to CDM $N-$body predictions
• expected GC abundance in lens host halos
• subhalo core collapse accelerated 3x relative to field halos
• deeply collapsed region treated as a point mass
(more probable)
even
2:1
4:1
8:1
16:1
>32:1
(less probable)
Relative likelihood
$\log_{10}(t_{6/8}/\mathrm{Gyr})$
$\log_{10}(t_{8/10}/\mathrm{Gyr})$
$\log_{10}\lambda_{\mathrm{sub}}$
$\log_{10}(\Sigma_{\mathrm{gc}}/M_\odot\mathrm{kpc}^{-2})$
ξ_{core}
$\log_{10}(\Sigma_{\mathrm{sub}}/\mathrm{kpc}^{-2})$


Assumptions:
• subhalo abundance matches CDM N − body predictions
• expected GC abundance in lens host halos
• subhalo core collapse accelerated 3x relative to field halos
• deeply collapsed halos have $\rho_{central} \propto r^{-2.6}$ outside core
(CDM disfavored at 15:1 odds)
(more probable)
even
2:1
4:1
8:1
16:1
>32:1
(less probable)
Relative likelihood
$\log_{10}(t_{8/10}/\mathrm{Gyr})$
$\log_{10}(t_{6/8}/\mathrm{Gyr})$
0.0
0.7
1.4
2.1
Assumptions:
• subhalo abundance matches CDM N − body predictions
• expected GC abundance in lens host halos
• subhalo core collapse accelerated 3x relative to field halos
• deeply collapsed region treated as a point mass
(CDM disfavored at 15:1 odds)


Assuming CDM
BLUE BOX
(disfavored at 15:1 odds)
• subhalo abundance range from N-body sims and galacticus
• expected GC abundance based on nearby elliptical galaxies
(more probable)
even
2:1
4:1
8:1
16:1
>32:1
(less probable)
Relative likelihood
6.8
6.3
5.8
5.3
$\log_{10}(\Sigma_{gc}/M_\odot \mathrm{kpc}^{-2})$
-1.7
-1.2
-0.7
-0.2
$\log_{10}(\Sigma_{sub}/\mathrm{kpc}^{-2})$
5.3
5.8
6.3
6.8
$\log_{10}(\Sigma_{gc}/M_\odot \mathrm{kpc}^{-2})$

JWST lensed quasar dark matter survey V: Hints of self-interacting dark matter from 29 quadruply imaged quasars

D. Gilman,[1,2,*] A. M. Nierenberg,[3] J. Gurian,[4,5] H. Paugnat,[6] C. Gannon,[3] M. N. Martinez,[3] T. Treu,[6] K. N. Abazajian,[7] T. Anguita,[8] V. N. Bennert,[9] A. J. Benson,[5] S. Birrer,[10] S. G. Djorgovski,[11] S. F. Hoenig,[12] R. E. Keeley,[7] A. Kusenko,[6,13] M. Millon,[14] T. Morishita,[15] L. A. Moustakas,[16] P. Mozumdar,[6,17] D. Paris,[18] W. Sheu,[6] D. Sluse,[19] and K. C. Wong[20]

[1] *Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA*
[2] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA*
[3] *University of California, Merced, 5200 N Lake Road, Merced, CA 95341, USA*
[4] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada*
[5] *Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101, USA*

Submitted to PRD,
arXiv: 2609.35974

Hints of self-interacting dark matter from strong gravitational lensing

D. Gilman,[1,*] K. Petraki,[2] T. Pignard,[2] J. Gurian,[3] A. Kusenko,[4,5] and A. M. Nierenberg[6]

[1] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA*
[2] *Laboratoire de Physique de l'École Normale Supérieure, ENS, Université PSL, CNRS, Sorbonne Université, Université Paris Cité, Paris, F-75005, France*
[3] *Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101, USA*
[4] *Department of Physics and Astronomy, University of California, Los Angeles, CA, 90095, USA*
[5] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*
[6] *University of California, Merced, 5200 N Lake Road, Merced, CA 95341, USA*

(Dated: November 2, 2026)

An analysis of 29 quadruply imaged quasars hints at dark matter halo densities consistent with gravothermal core collapse, a key prediction of self-interacting dark matter. We interpret this evidence through elastic Yukawa scattering, combining lensing with upper limits on the cross section

Submitted to PRL
arXiv: 2610.40766

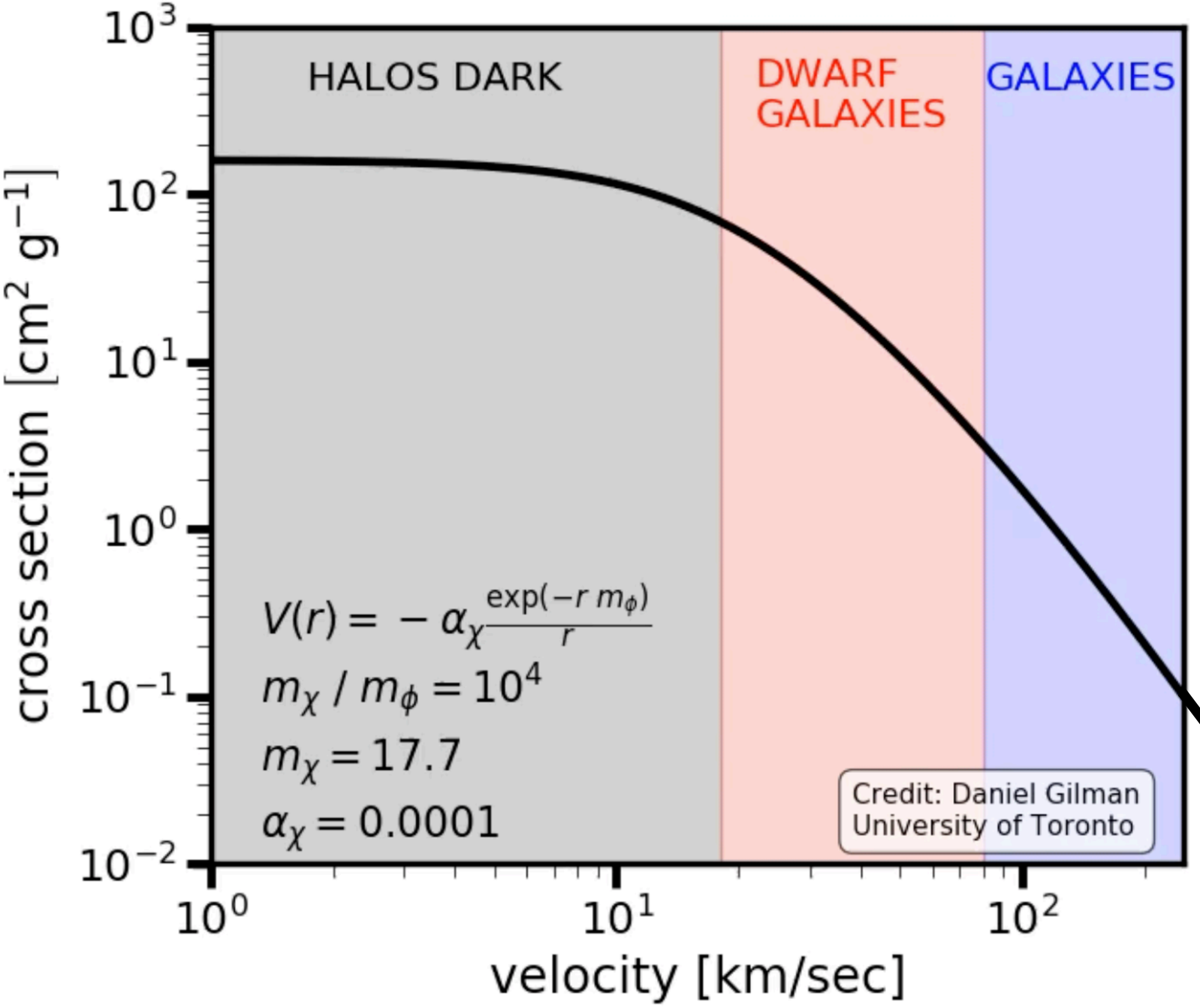
What do the inferred collapse timescales mean for SIDM particle physics models?

Step 1) Pick a particle physics model

Step 2) Predict the core collapse timescale for the model

Step 3) Map the predicted t_c onto the strong-lensing likelihood

Step 4) Transform lensing likelihood into a likelihood on SIDM parameters



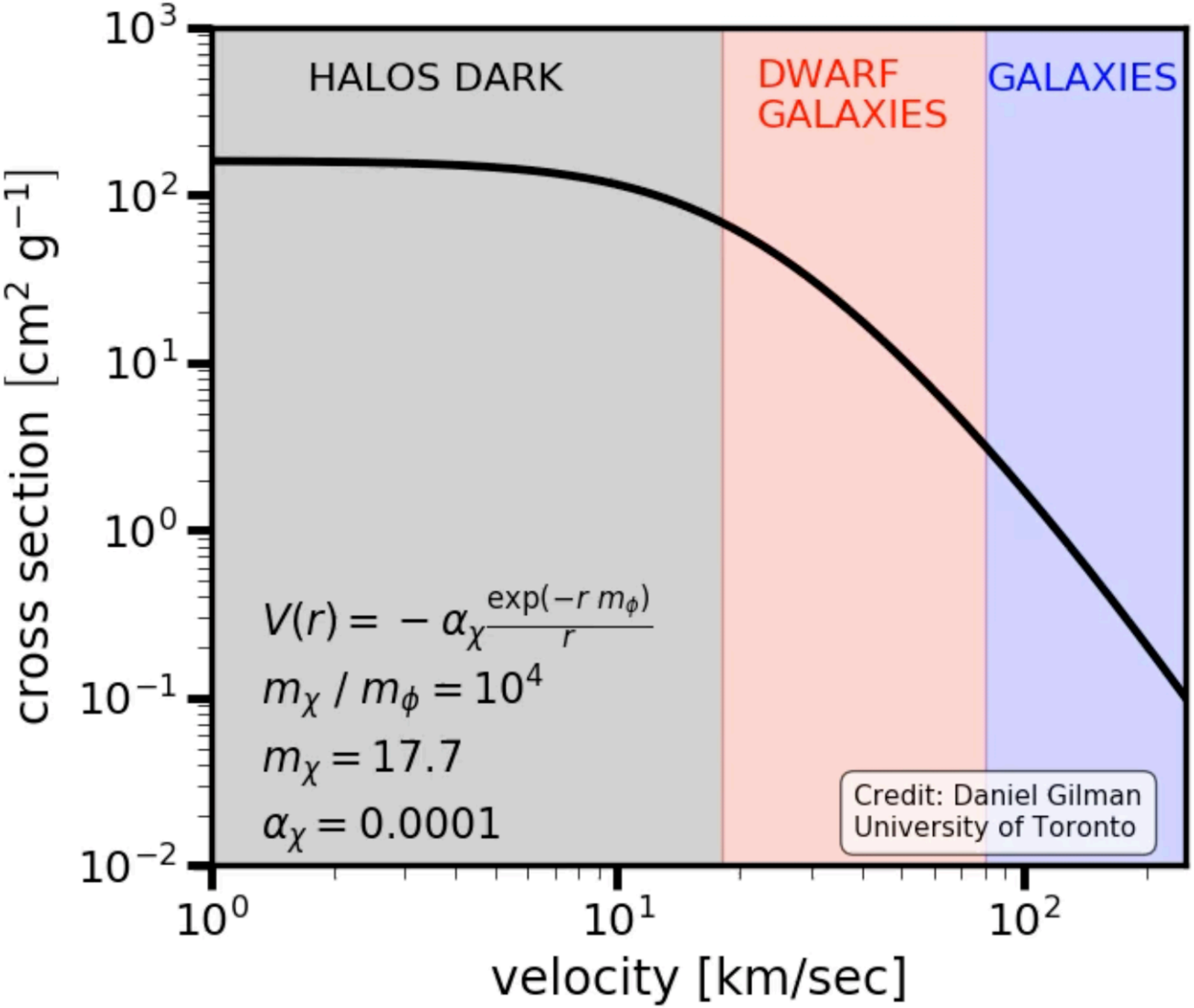
Step 1) Pick a particle physics model

Velocity dependence necessary to evade constraints from **galaxy clusters**



The ‘canonical’ solution: couple DM to a light mediator ϕ

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



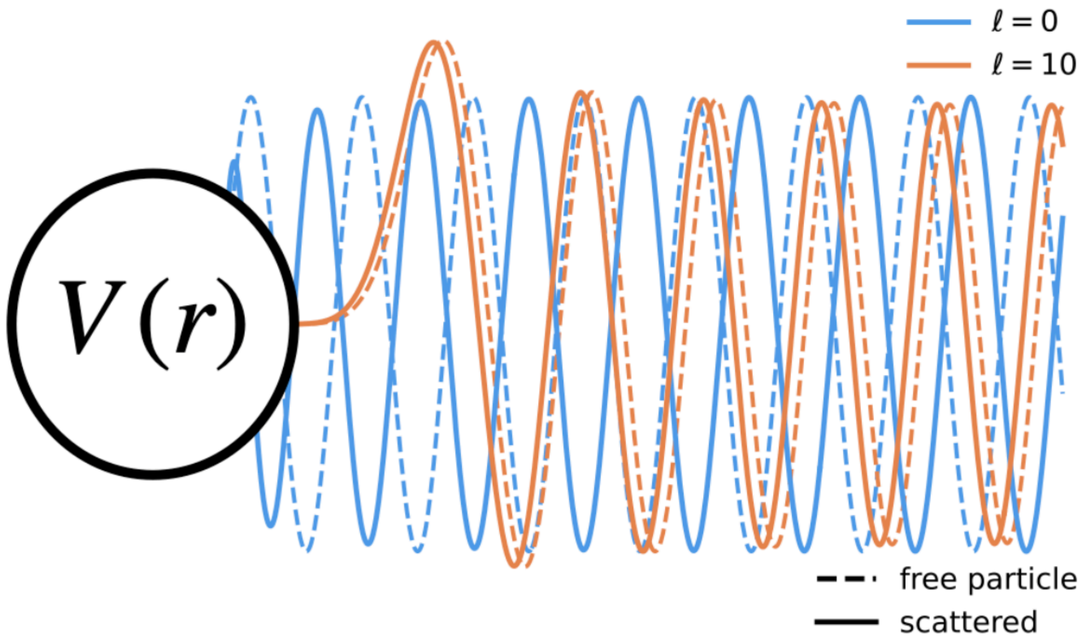
pykawa: public GitHub repo with SIDM cross sections

https://github.com/dangilman/pykawa

README | Code of conduct | Contributing | MIT license | Security

pykawa

CI passing



The phase shifts and scattering cross sections for Yukawa potentials.

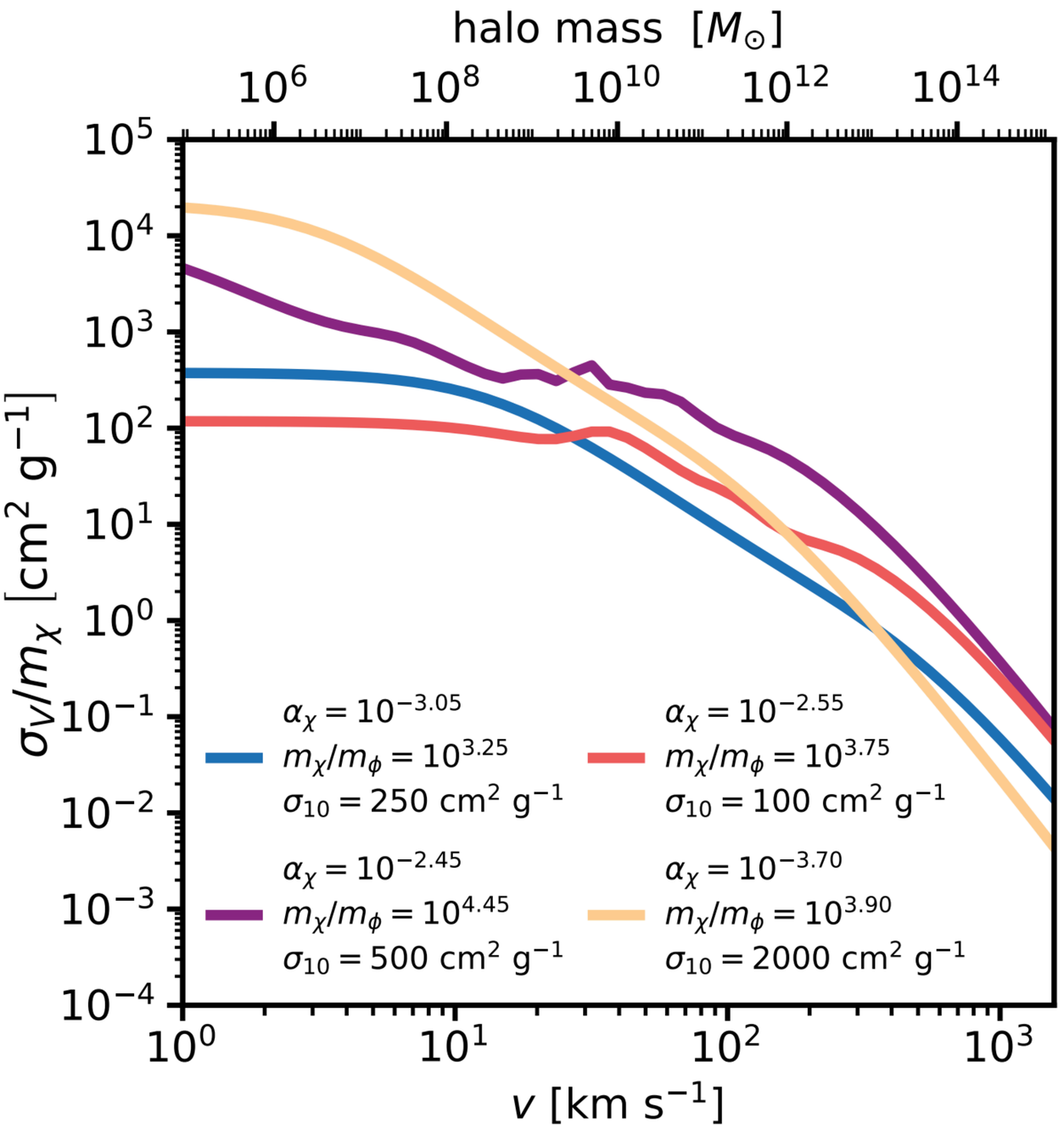
Solutions are obtained following the variable phase approach. The mathematica scripts used to compute the cross sections can be found in the "mathematica_scripts" directory.

Step 1) Pick a particle physics model

-> we consider a model where DM couples to a light mediator and also evades cosmological/direct detection bounds (see Gilman et al. 2026d)

Compute the differential scattering cross $d\sigma/d\Omega$ section by solving the Schrödinger equation, and then compute the "viscosity" cross section:

$$\sigma_V = \frac{3}{2}\int \frac{d\sigma}{d\Omega}\sin^2\theta d\Omega$$



Step 2) Evaluate the core collapse timescale

First take a velocity average of σ_V

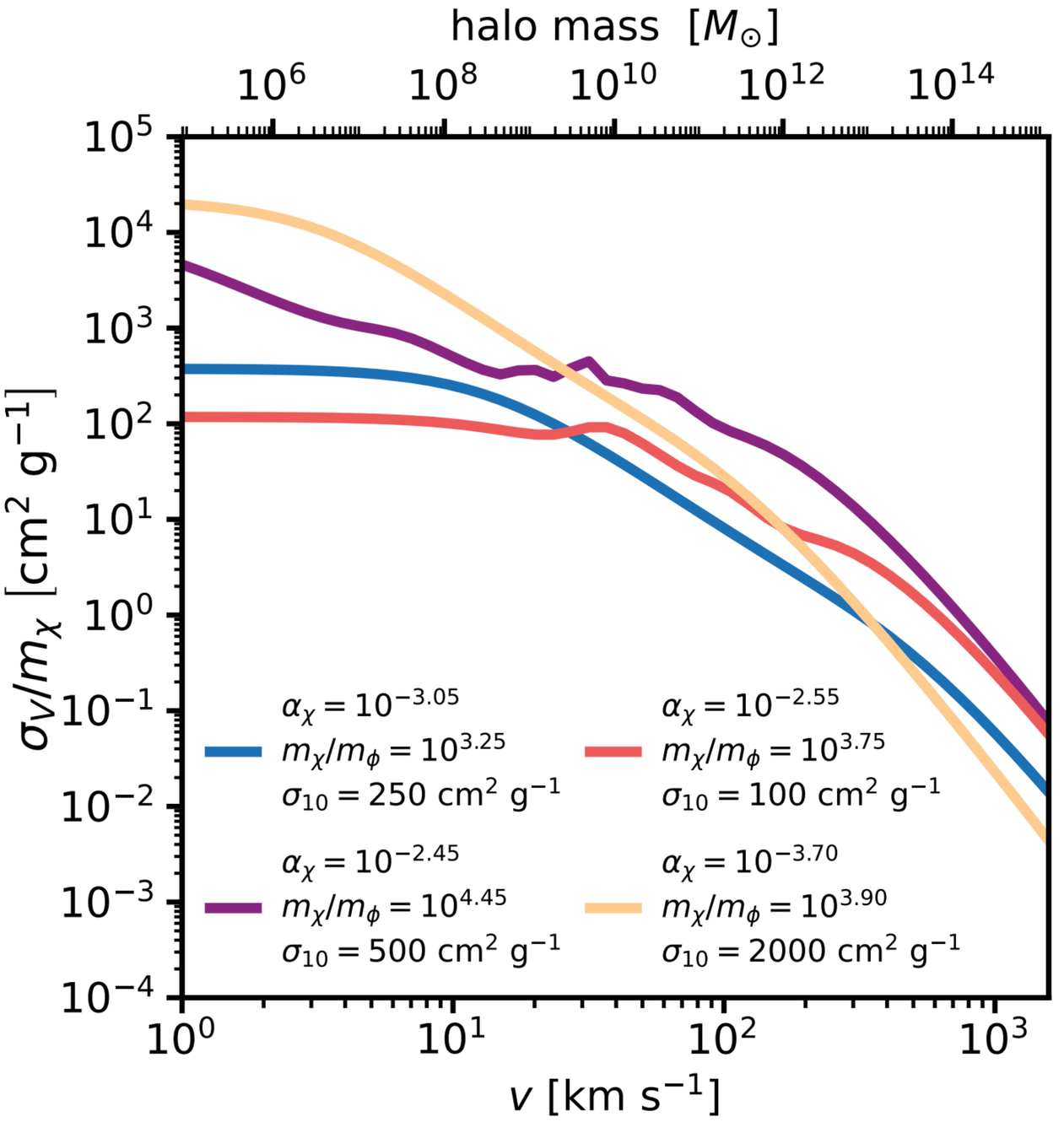
$$\sigma_{\rm eff} \equiv \frac{\int v^7 \left(\sigma_V / m_\chi\right) \exp\left(-v^2/4v_0^2\right) dv}{\int v^7 \exp\left(-v^2/4v_0^2\right) dv}$$

and then evaluate (Gurian et al. (2026))

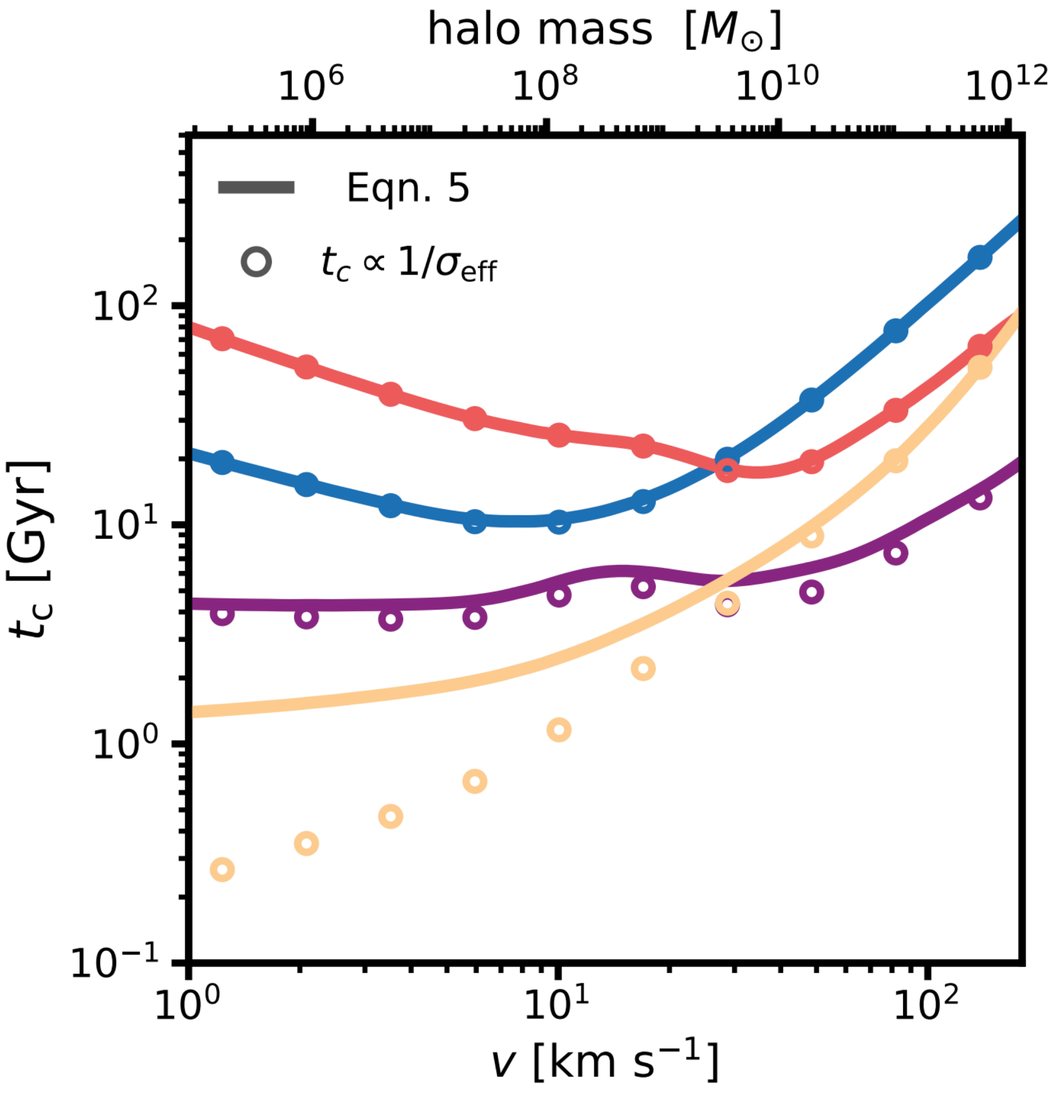
$$t_c = 26.5 \left(\frac{r_s}{v_s}\right) \left(\hat{x} + \hat{x}^{-1}\right) \left(1 + 0.92\, e^{-0.402 \ln^2 \hat{x}}\right)$$

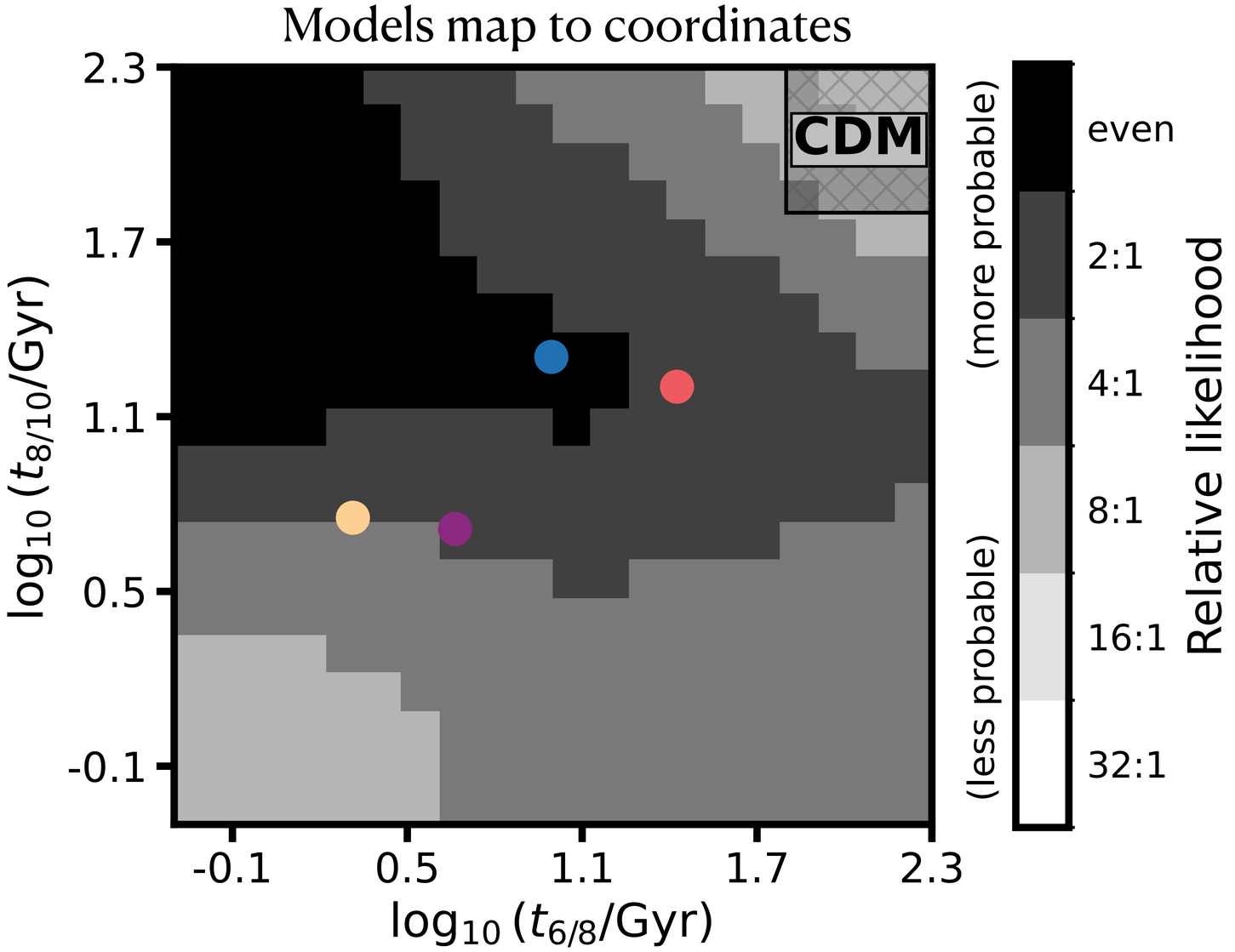
this expression interpolates between the long and short mean free path regimes

$x = \left(\sigma_{\rm eff} \rho_s r_s\right)^{-1}$ is the Knudsen number

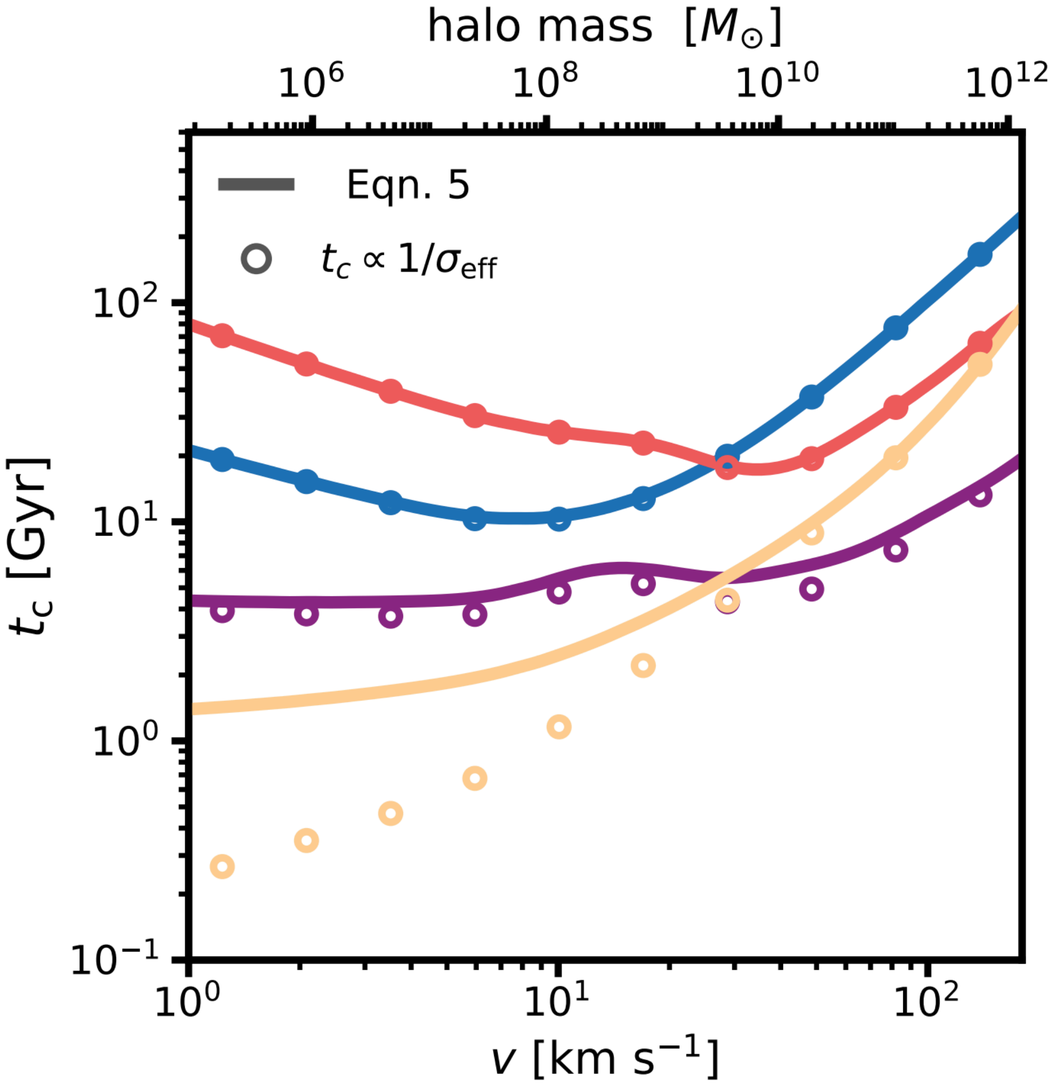


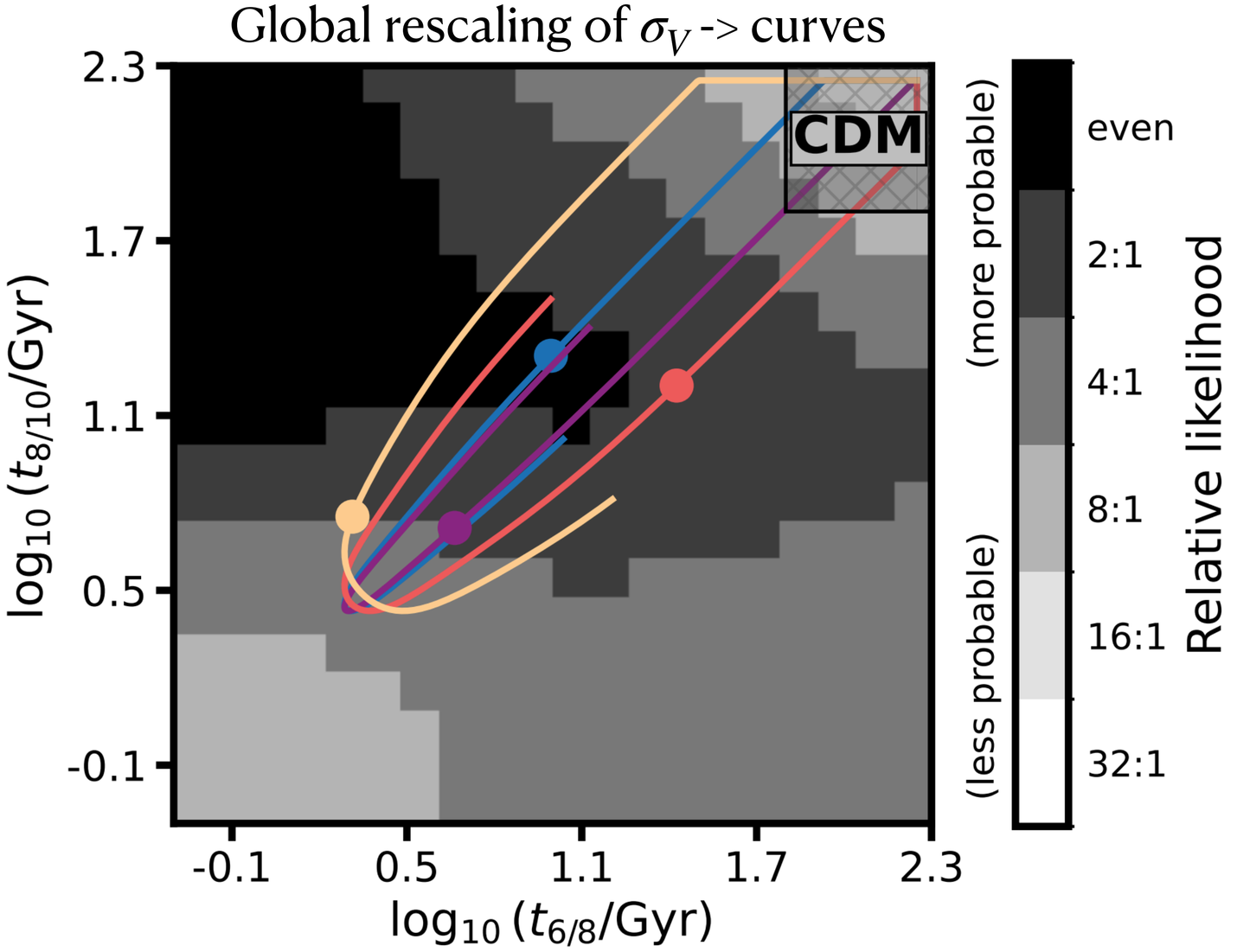
Step 3) Map the predicted t_c onto the strong-lensing likelihoods



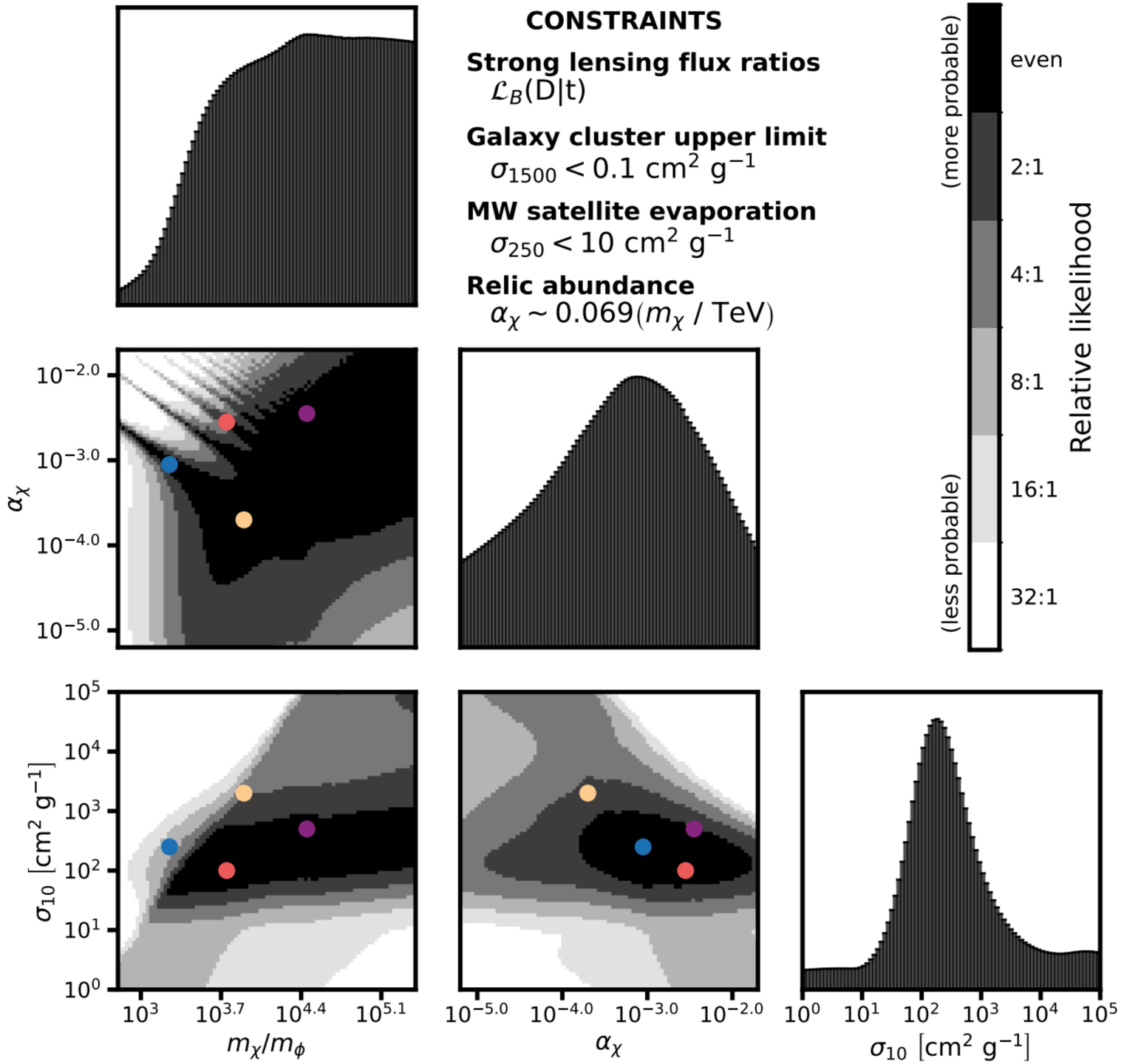


Step 3) Map the predicted t_c onto the strong-lensing likelihoods





Step 4) Scan the SIDM parameter space and compute the likelihood

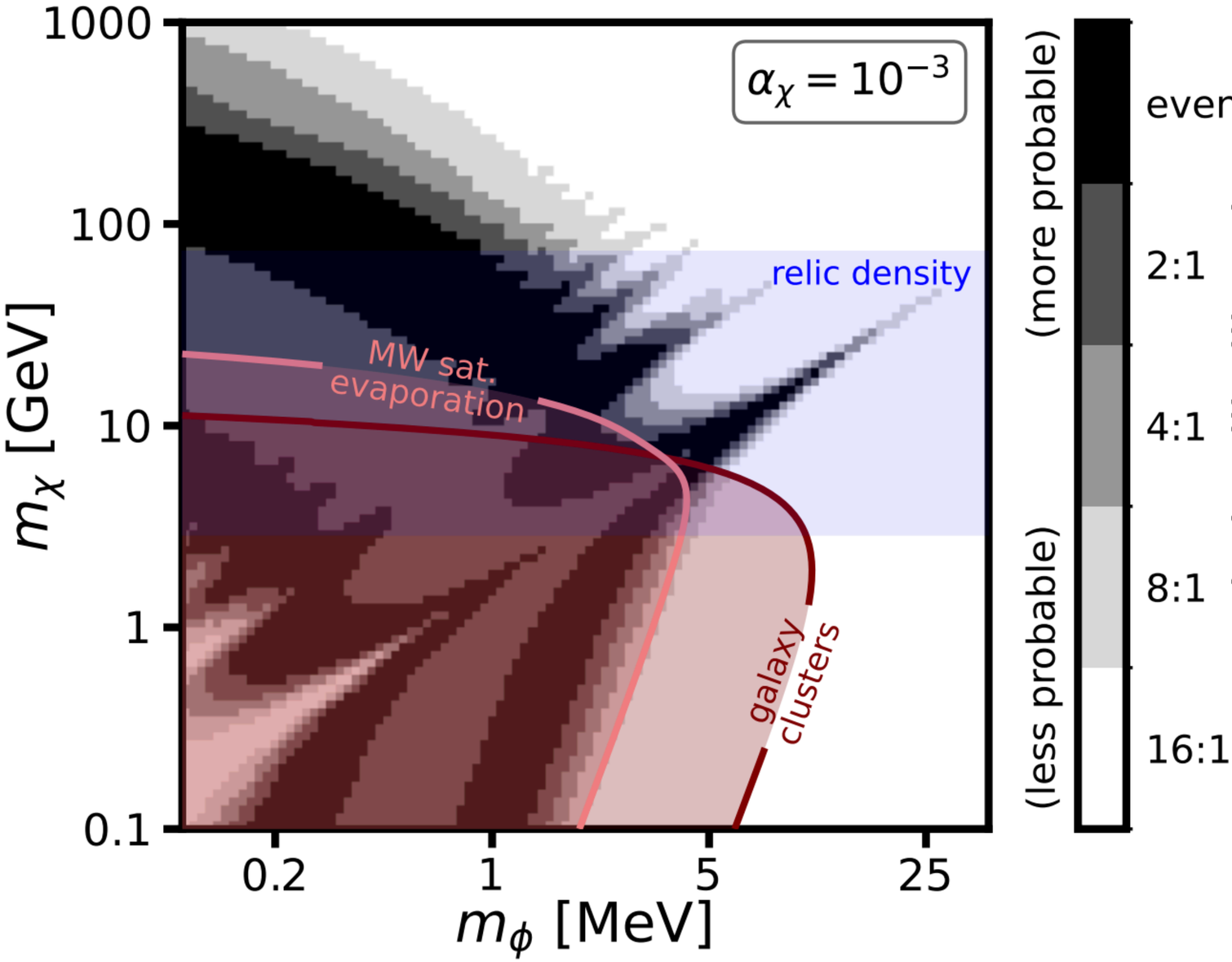


Step 4) Scan the SIDM parameter space and compute the likelihood

Favored regions of parameter space have

- $m_\chi \sim 20 - 80$ GeV
- $m_\phi \sim 0.5 - 5$ MeV
- $\alpha_\chi \sim 10^{-3}$
- cross section strengths $10^2 - 10^4$ $\mathrm{cm^2 g^{-1}}$ at 10 km/sec

-> the specific answer depend on the assumptions for SIDM halo properties



What comes next?

Ways out for collisionless DM:

Unusually high abundance of globular clusters around lenses?

Other mechanisms that elevate halo densities besides SIDM?

Baryons (besides GCs)? Unlikely to mimic this kind of signal in low-mass halos

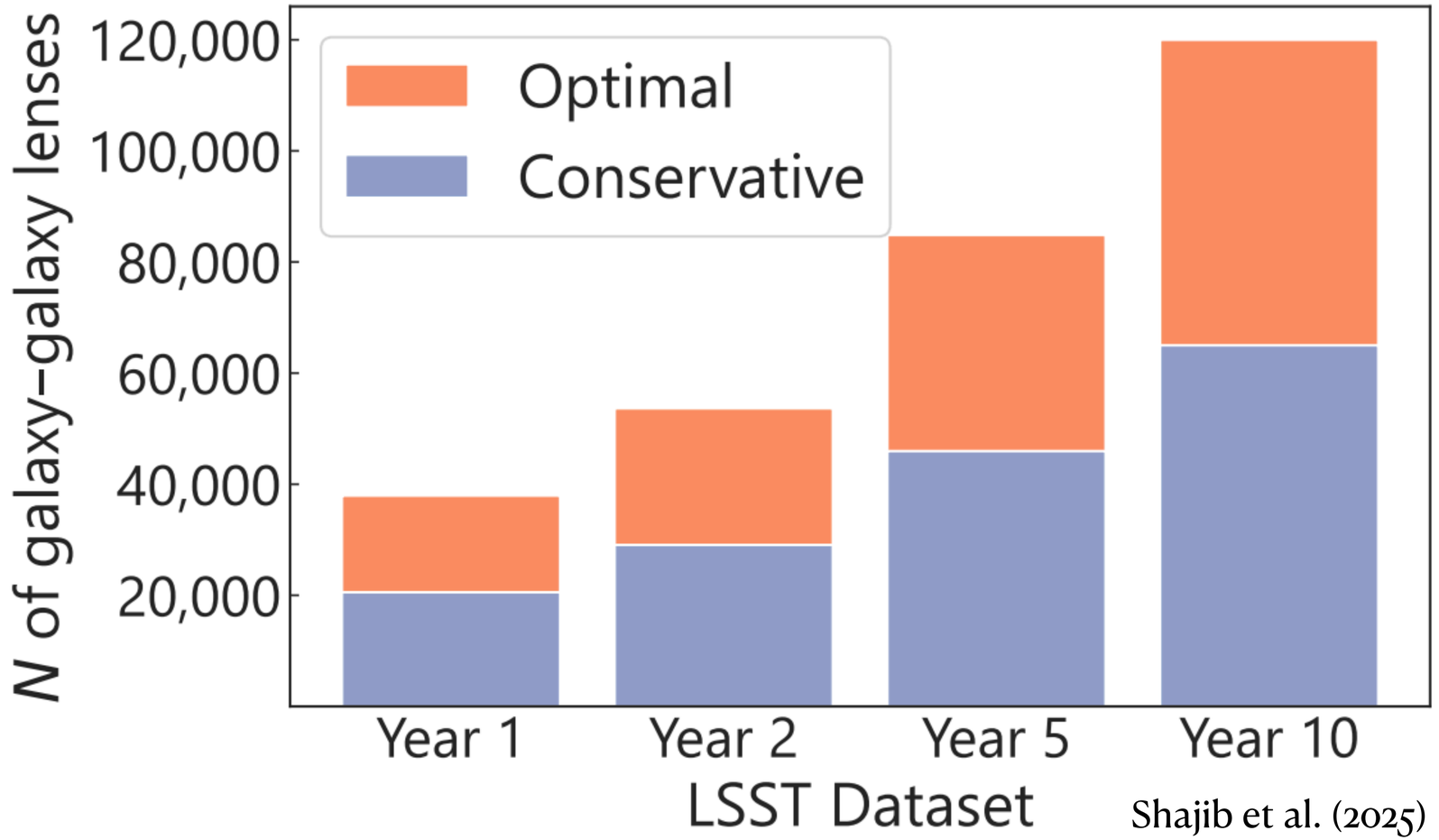
What would seal the deal?

Probe combination: the SIDM signal should be seen in MW, local group satellites, and stellar streams, across environments and mass scales

(Maybe) SIDM signals may be detected in future laboratory/CMB experiments

What does the future hold?
We are in a new era of precision DM science with strong lensing

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



Shajib et al. (2025)