Fundamental dark matter physics with strong gravitational lenses

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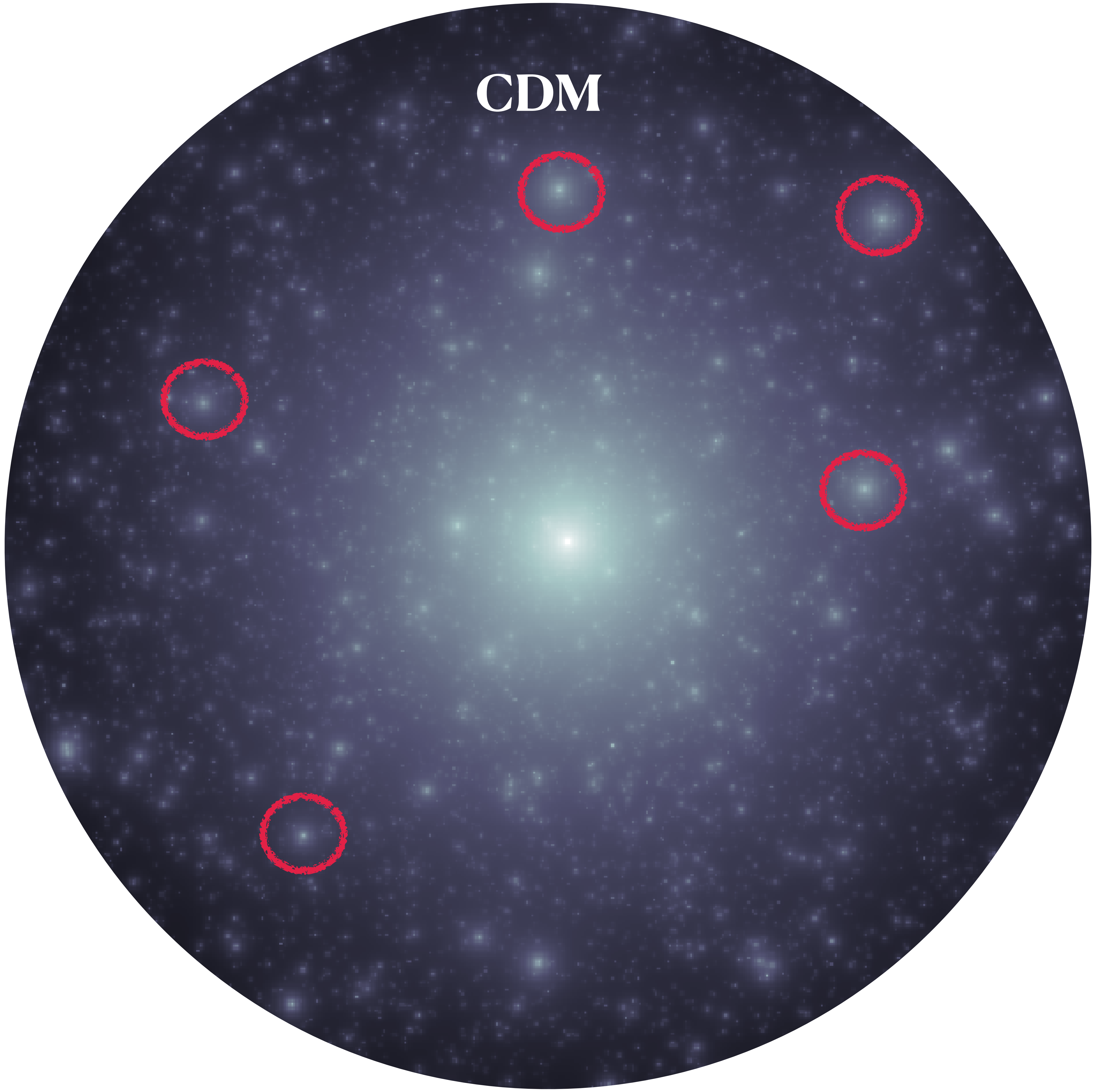
Cold Dark Matter (CDM)

Cold dark matter (CDM) predicts an abundance of low-mass halos and subhalos

Halos have Navarro-Frenk-White density profiles with r^{-1} central cusps

Scale-free over many orders of magnitude in halo mass

Most halos completely dark



Warm Dark Matter (WDM)

Class of theories (e.g. sterile neutrino) with a large "free-streaming length"

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

Warm dark matter (WDM) predicts a paucity of small-scale structure

Halos have similar density profiles to CDM, but less centrally concentrated

Ultra-light dark matter (ULDM)

Early motivation as a solution
to strong CP problem

Galaxy-scale de-Broglie wavelength

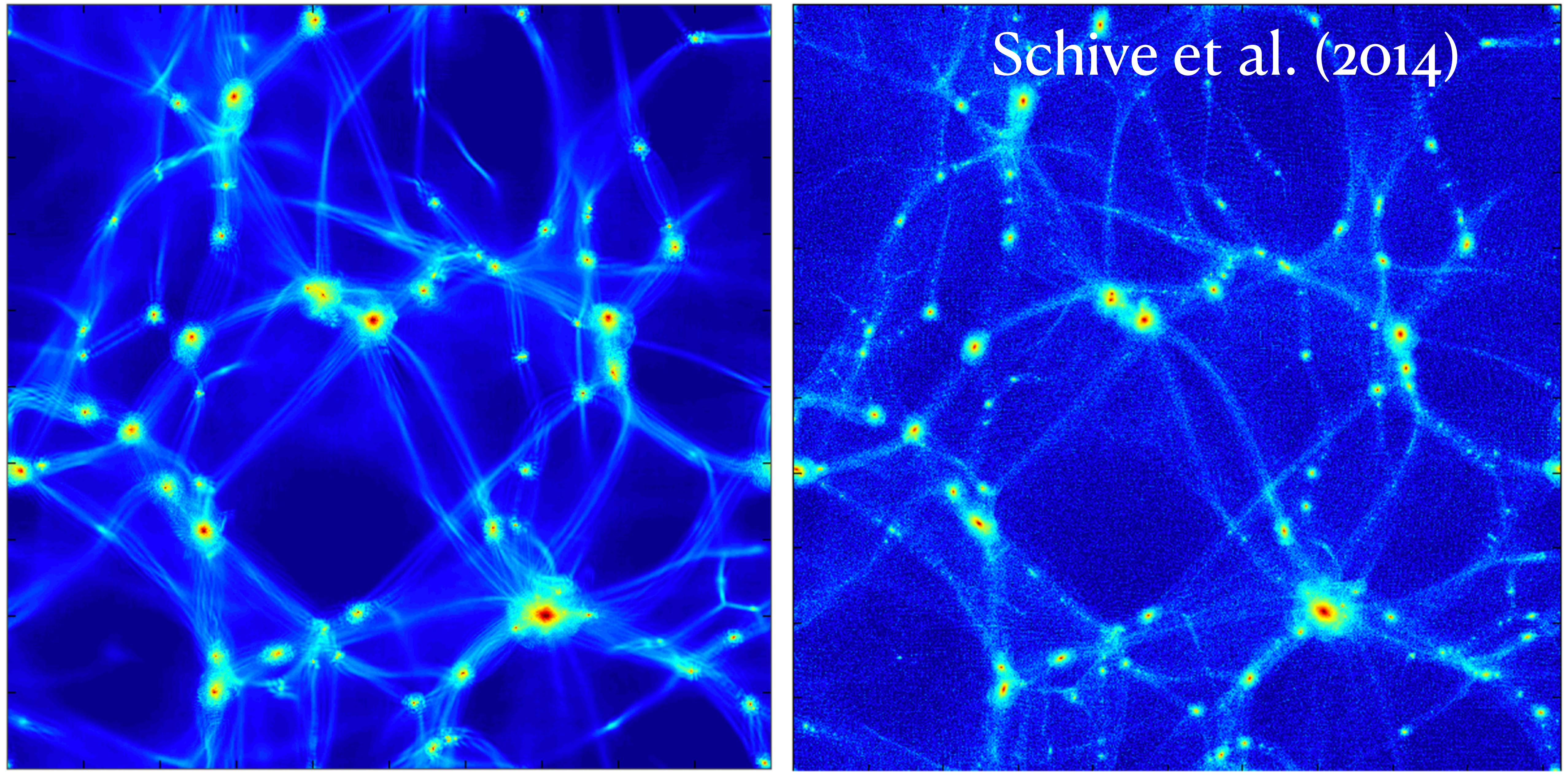
$$\lambda_{\rm dB} = 0.6 \left(\frac{m_\psi}{10^{-22}\mathrm{eV}} \right)^{-1} \left(\frac{v}{200} \right)^{-1} \mathrm{kpc}$$

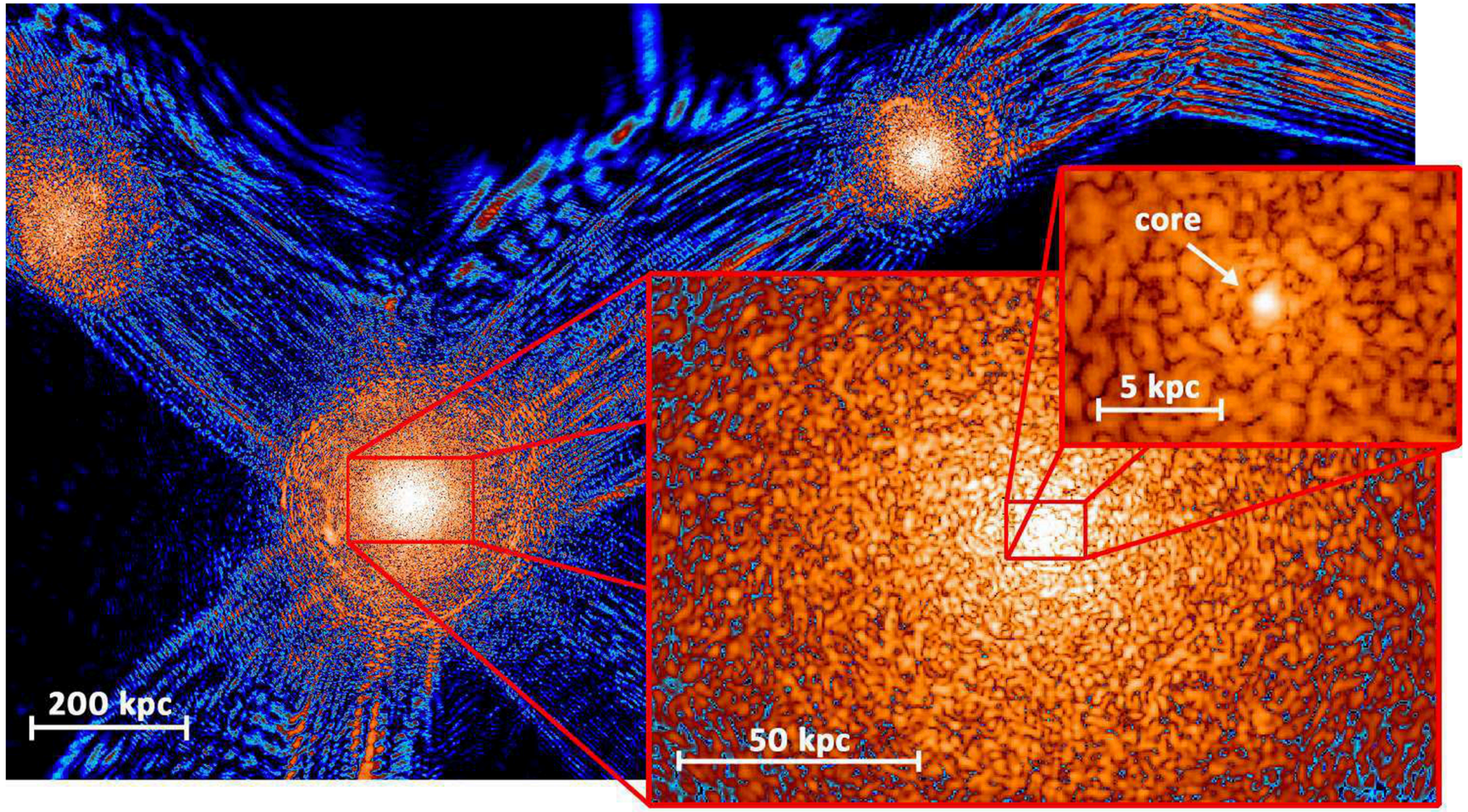
Like WDM:

1) Paucity of small-scale structure

Not like WDM:

1) wave interference

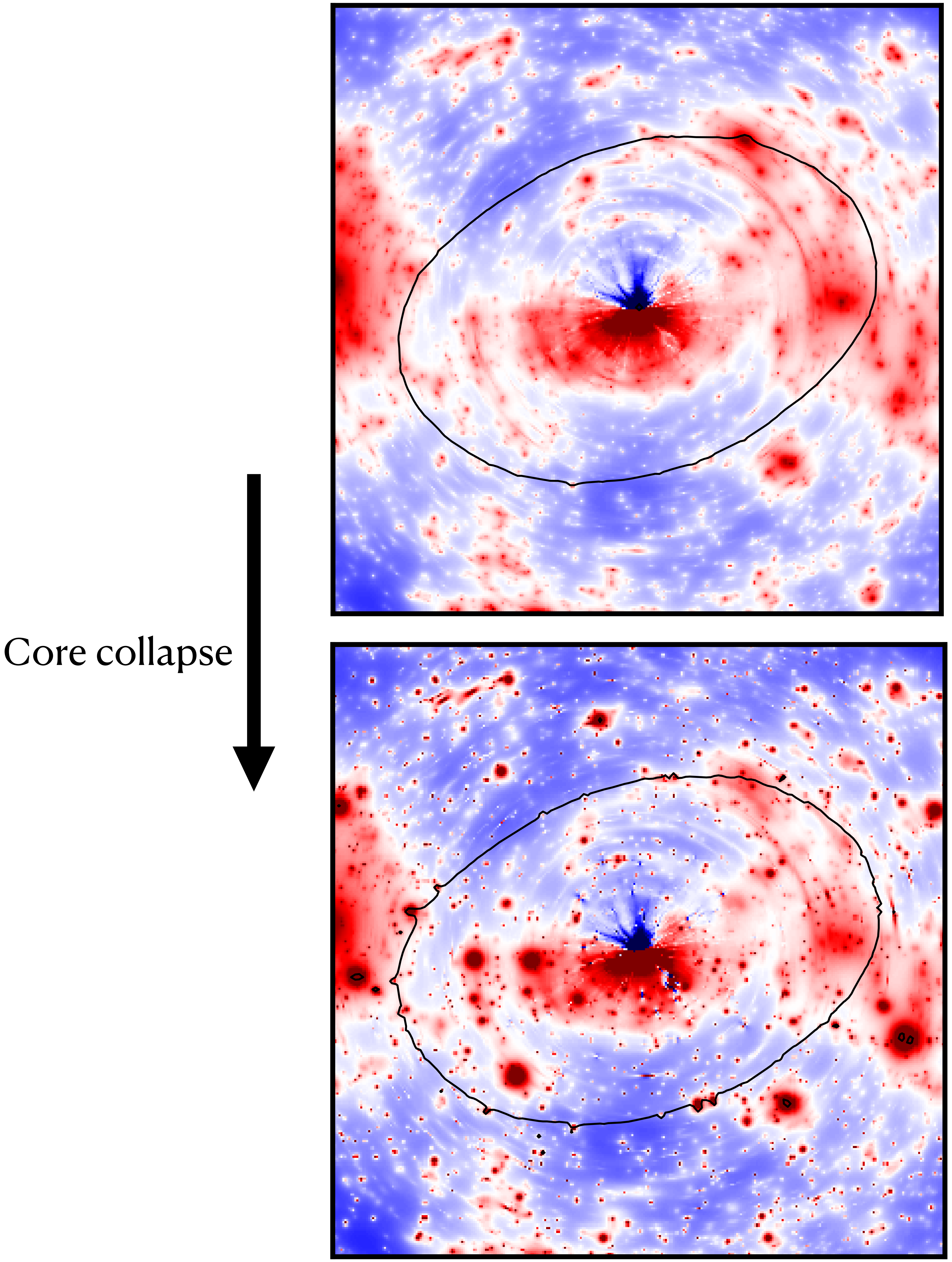




Self-interacting dark matter (ULDM)

Velocity-dependent cross sections leaves large-scale structure unchanged, while altering the properties of low-mass halos

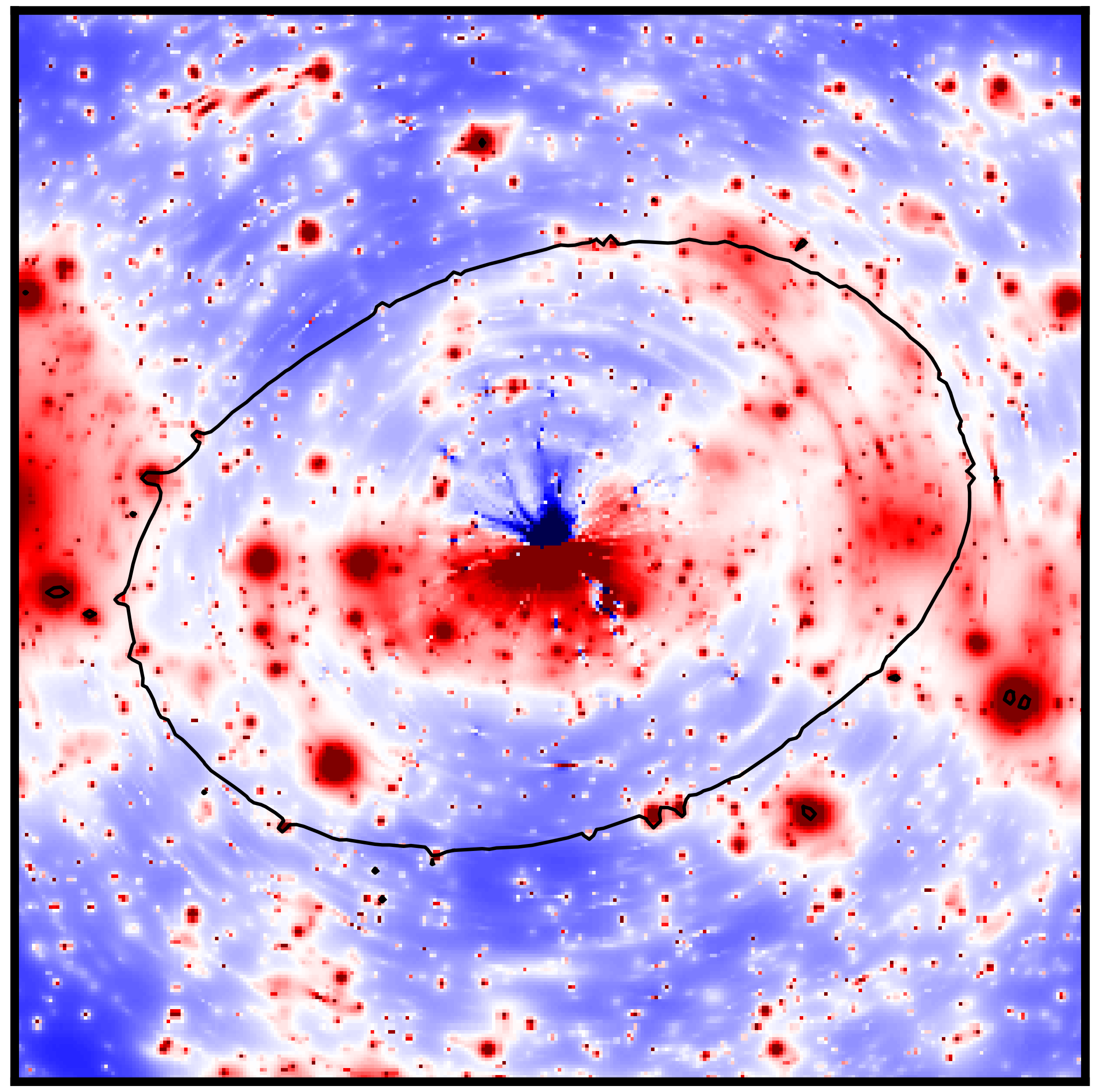
Halos have cores that eventually undergo core collapse (or “gravothermal catastrophe”)



Relevant length scale:
mean-free path

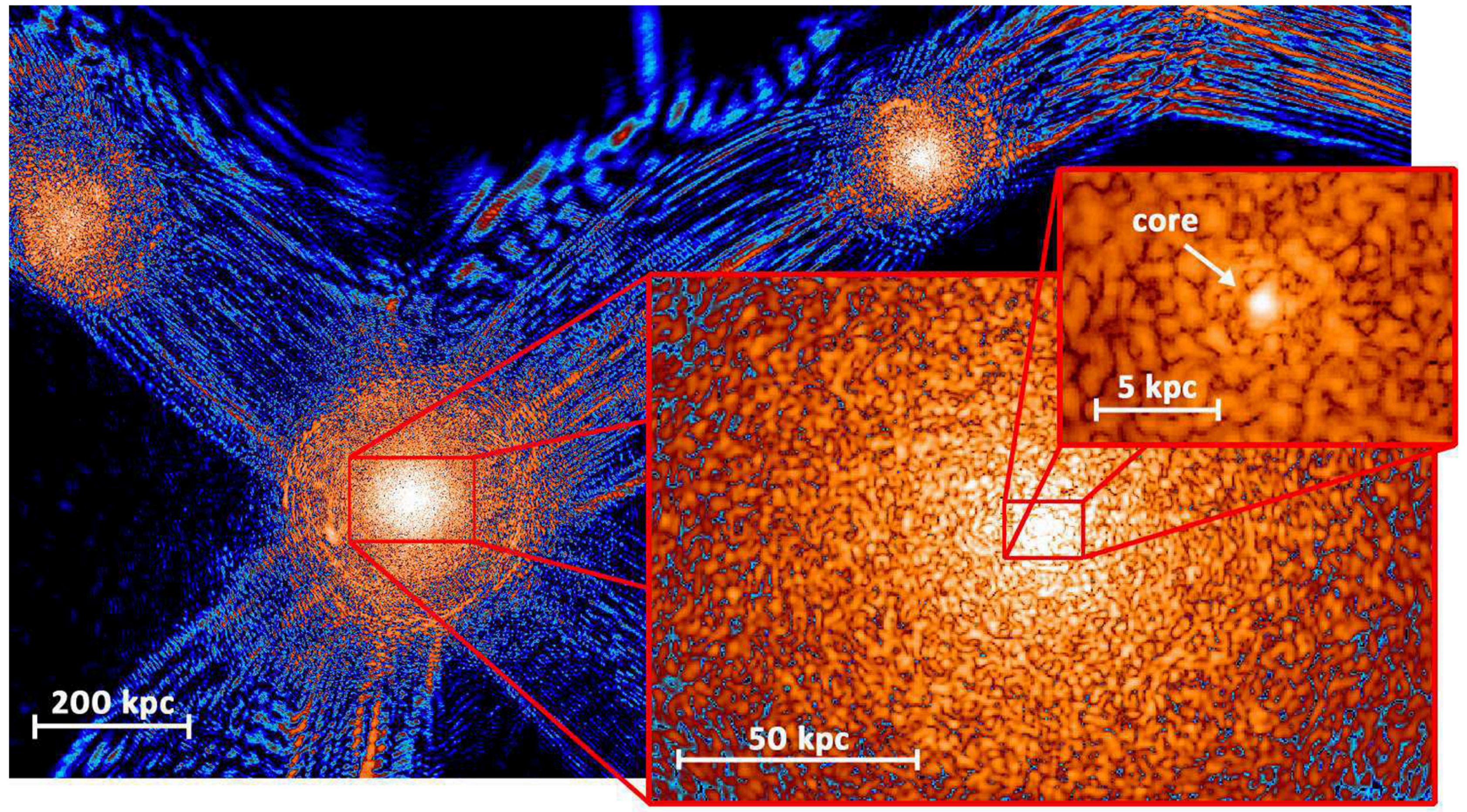
$$\lambda_{\rm MFP} \sim \left(\rho\sigma\right)^{-1}$$

SIDM



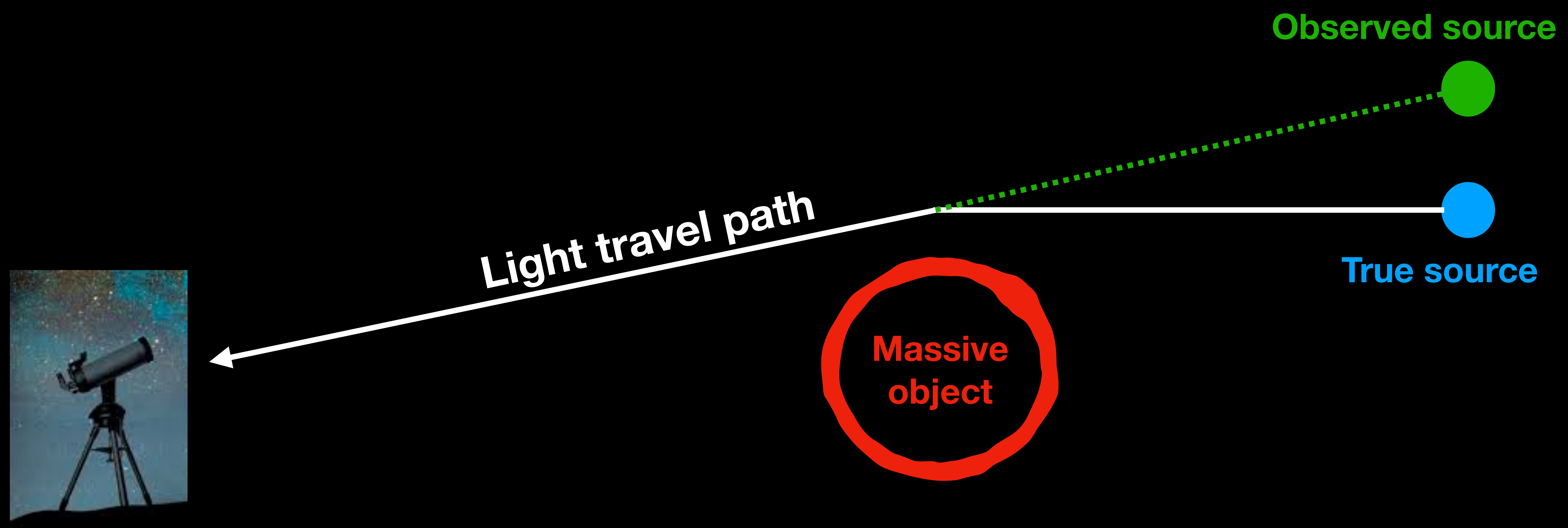
How can we distinguish CDM from these alternatives if we can't see halos?

ULDM

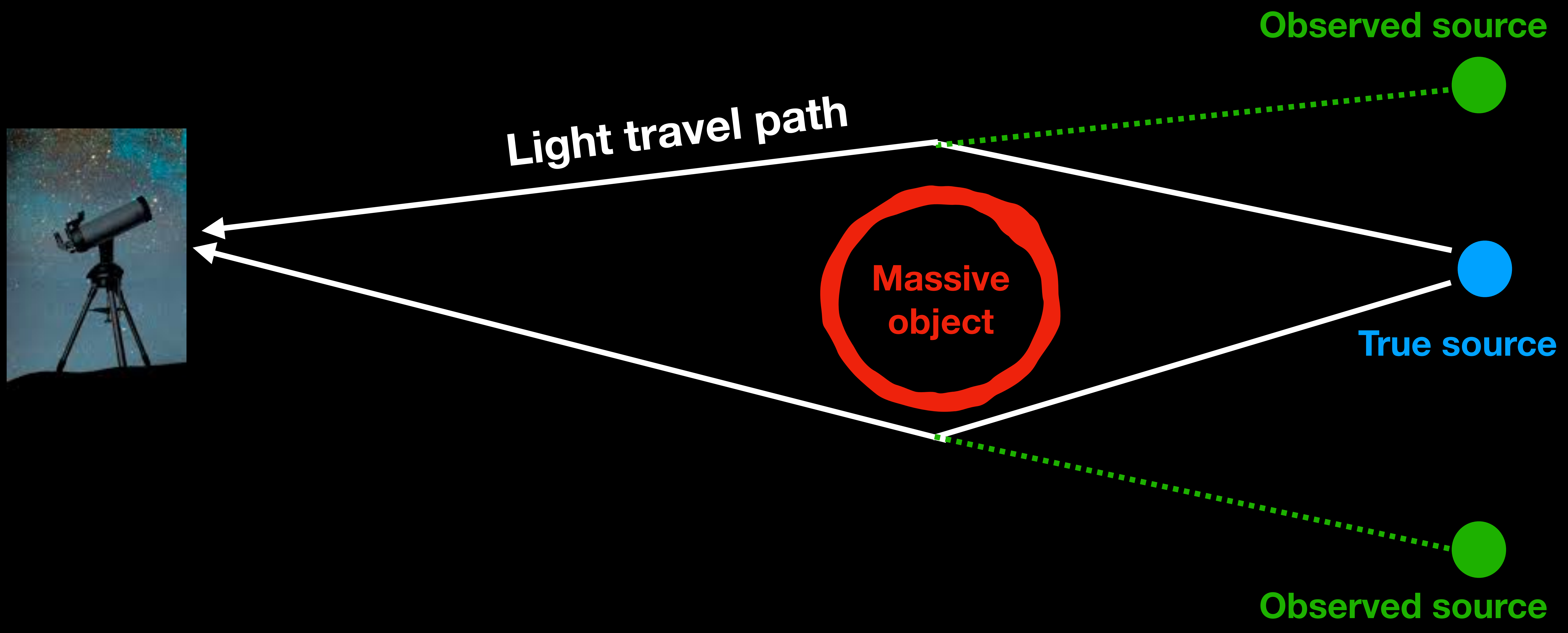


Strong gravitational lensing by fish tank

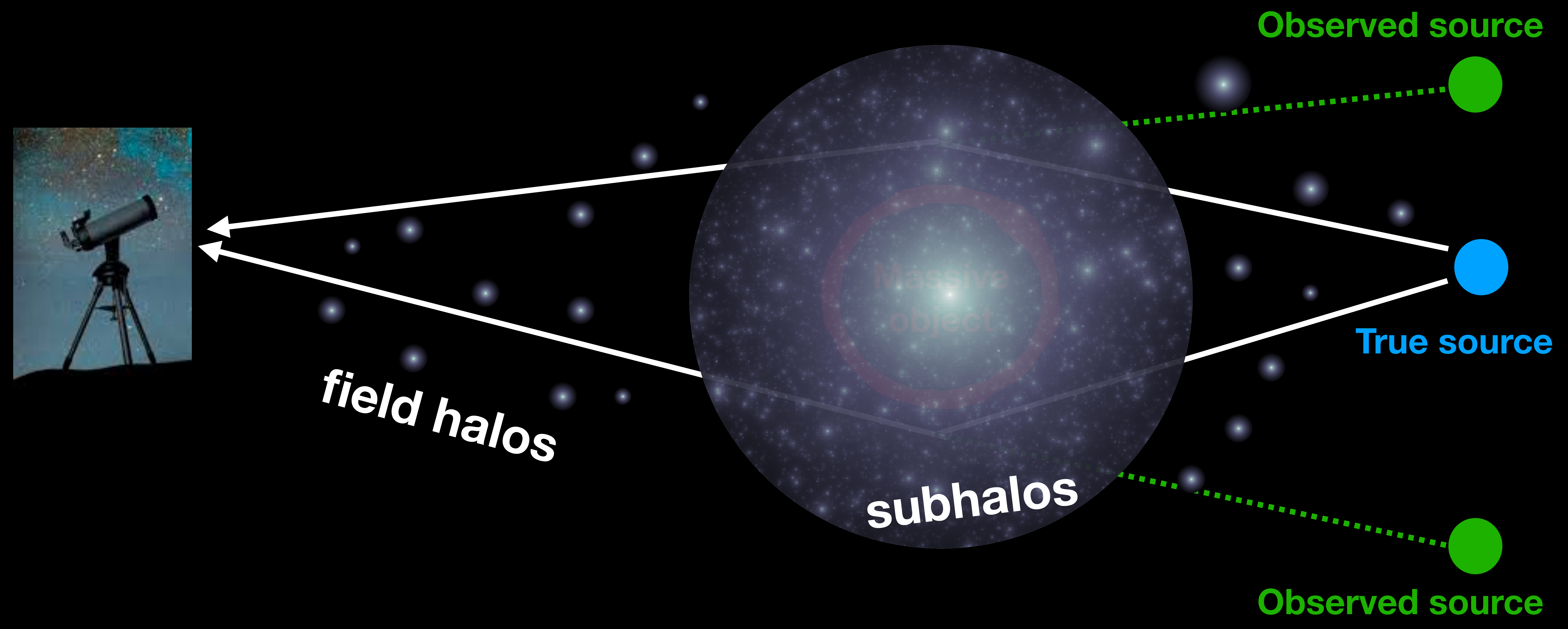
Gravitational lensing: deflection of light by gravitational fields

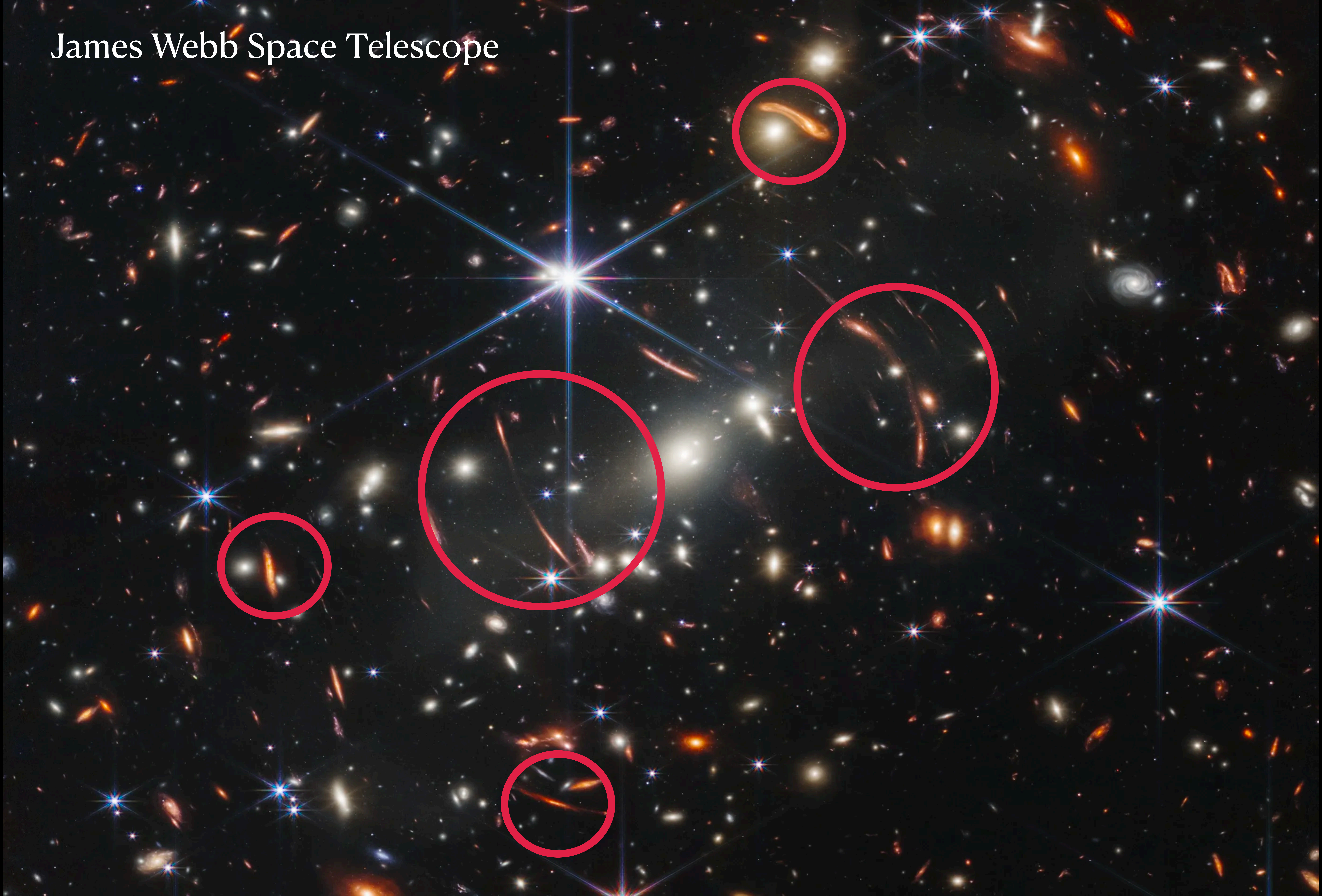


Strong lensing produces multiple images of a single source



Strong lensing produces multiple images of a single source




James Webb Space Telescope

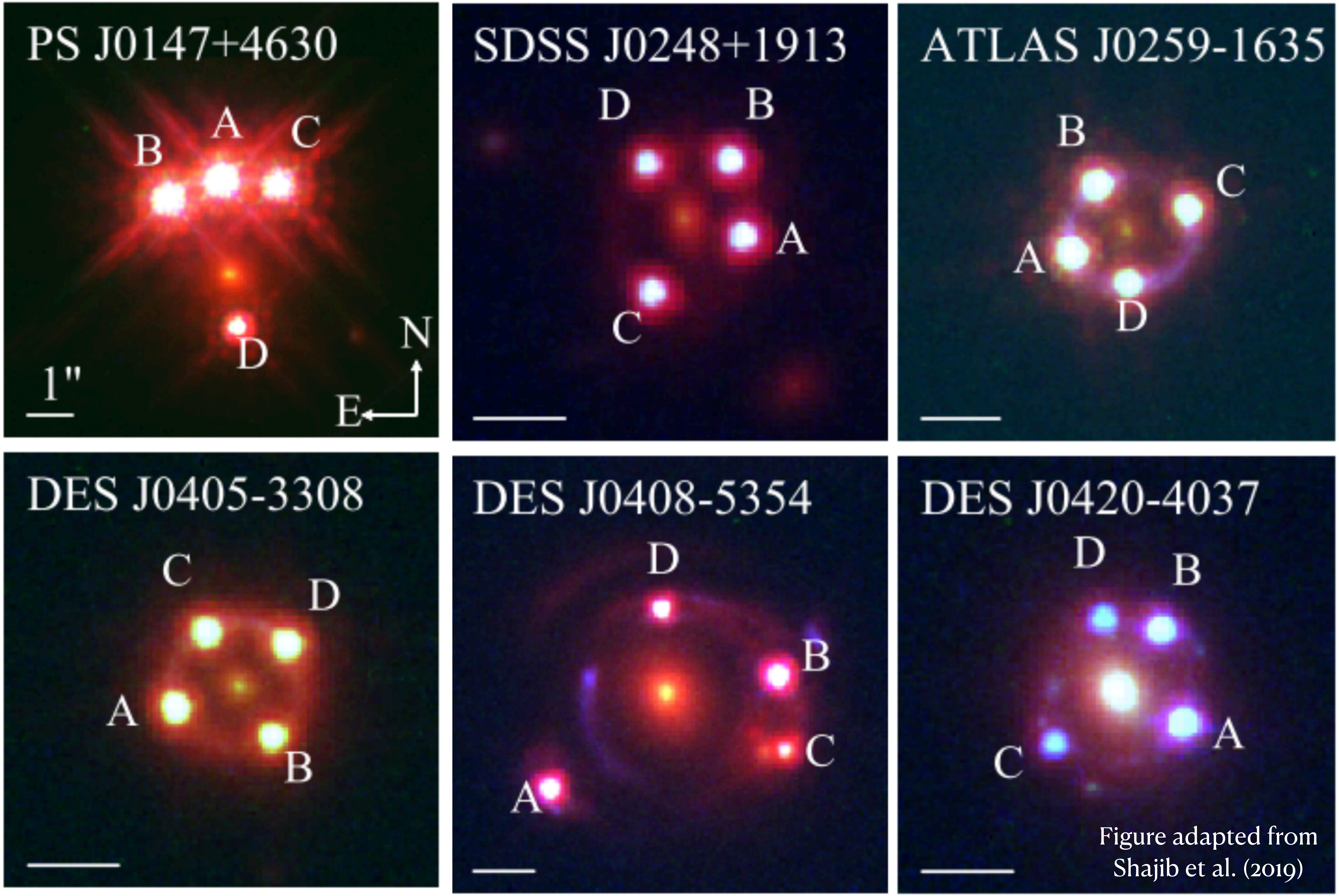


Figure adapted from
Shajib et al. (2019)

Anatomy of a quad lens

Main deflector
-> usually an early-type (massive elliptical) galaxy (z ~ 0.5) in front of a quasar (z ~ 2)

Focus on systems we can describe with parametric lens models

-> power-law ellipsoid
-> external shear
-> multi-pole perturbations

Anatomy of a quad lens

1) Relative arrival times delays

   - depend on potential $\Psi\left(\vec{x}\right)$

2) Image positions

   - depend on $\dfrac{\partial\Psi}{\partial\vec{x}}$

3) Image magnification ratios (or flux ratios)

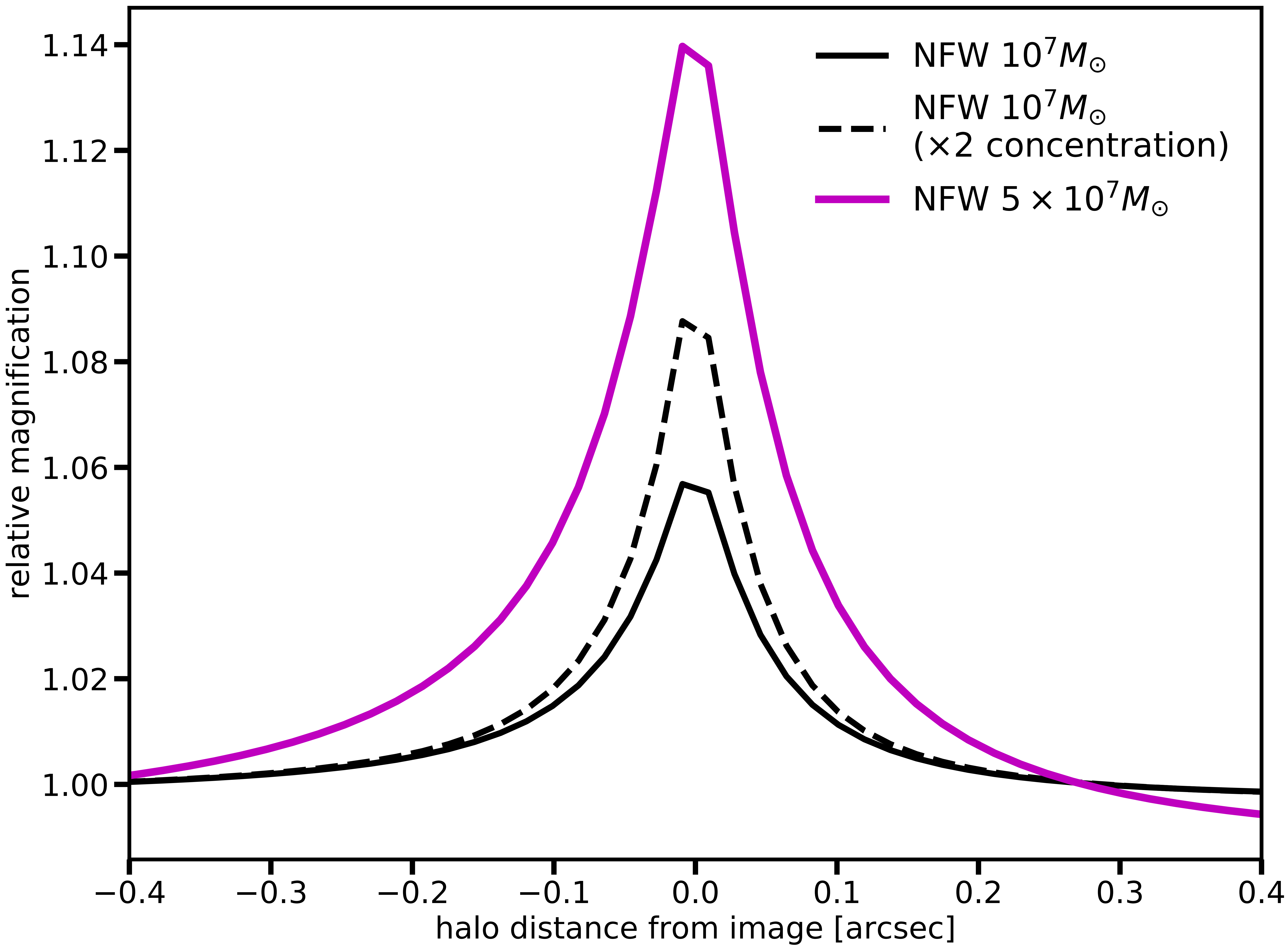
- depend on $\dfrac{\partial^2\Psi}{\partial\vec{x}^2} \sim \kappa$

How low can you go?

at least $10^7 M_\odot$
with current data

mid-IR flux ratios with
JWST GO-2046 (PI Nierenberg)
at least $10^6 M_\odot$

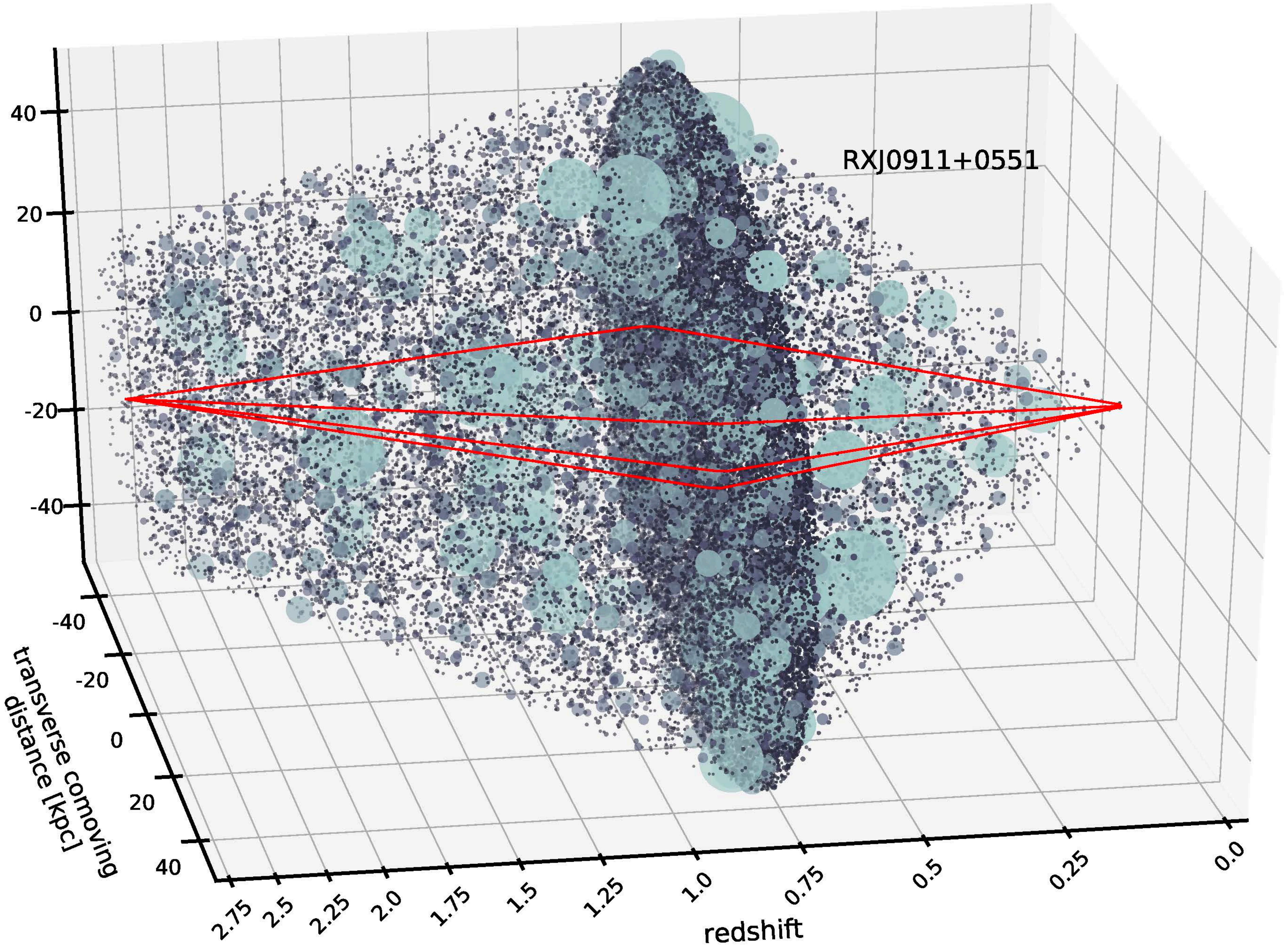
Sensitivity determined by the
angular size of the source



How do we analyze lenses in practice?

Observation

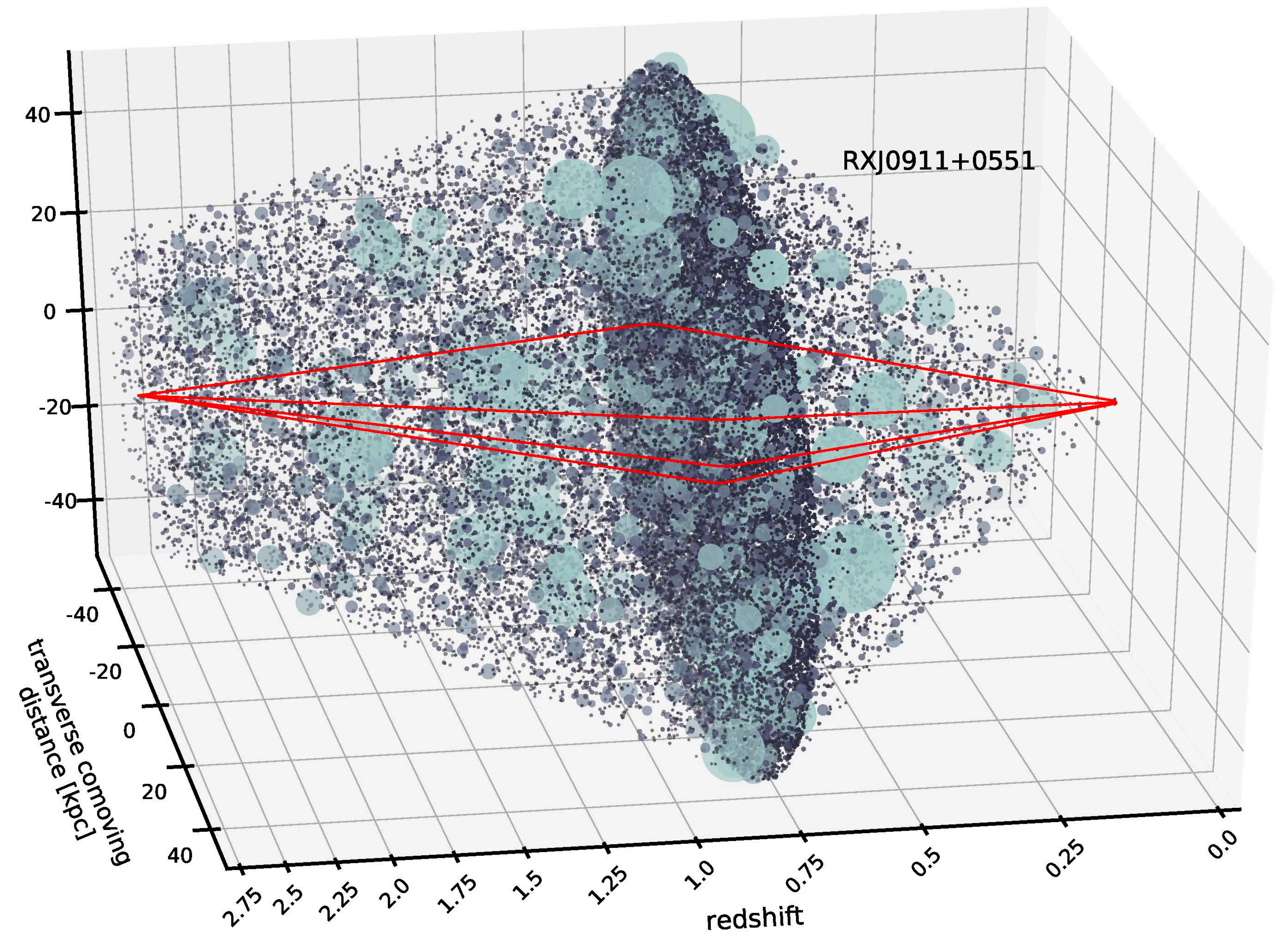
Simulation



How do we analyze lenses in practice?

Dark matter theory

Halo mass function, halo density profiles

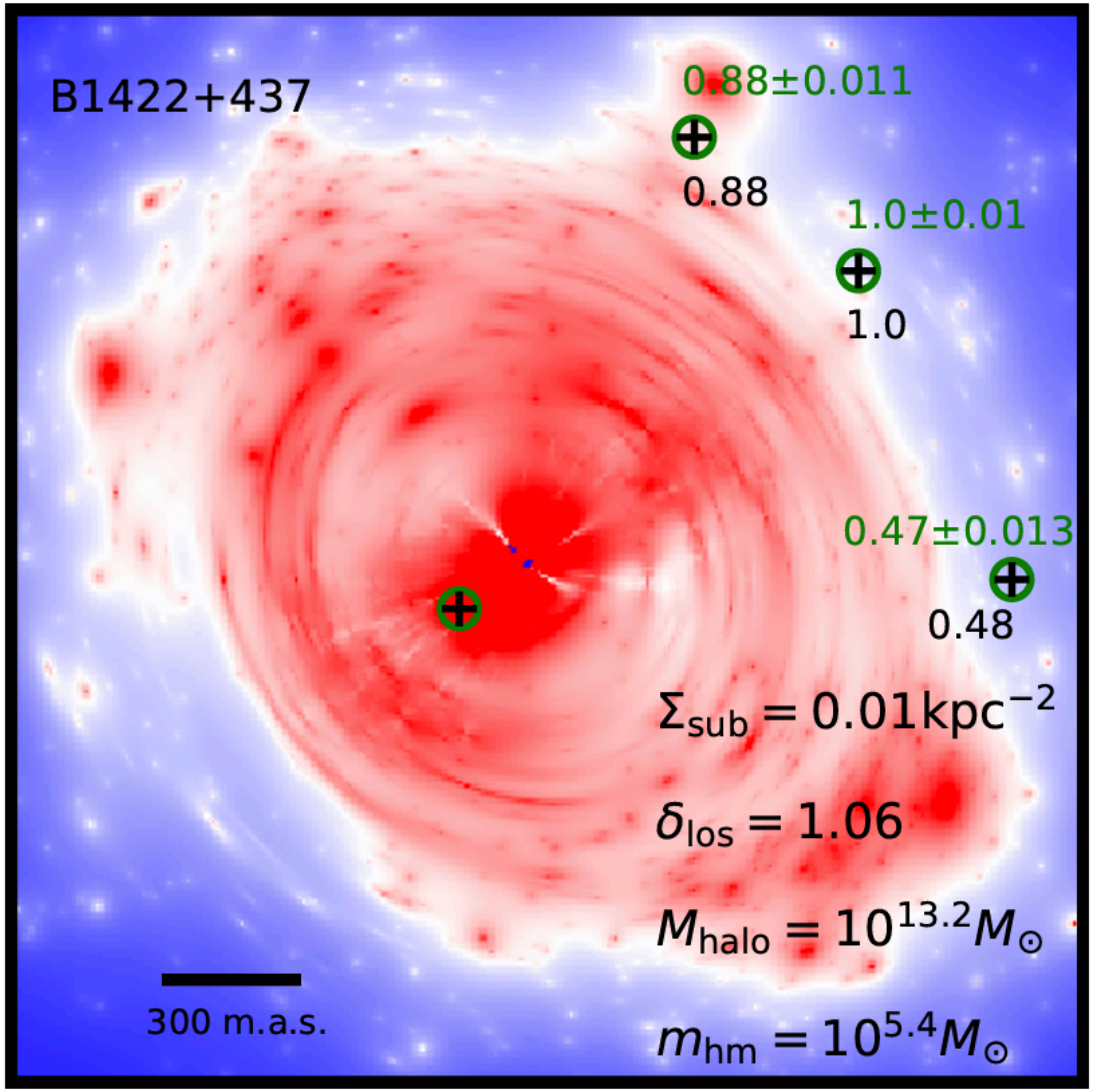


Simulate data from the model millions of times per lens

Compare with data

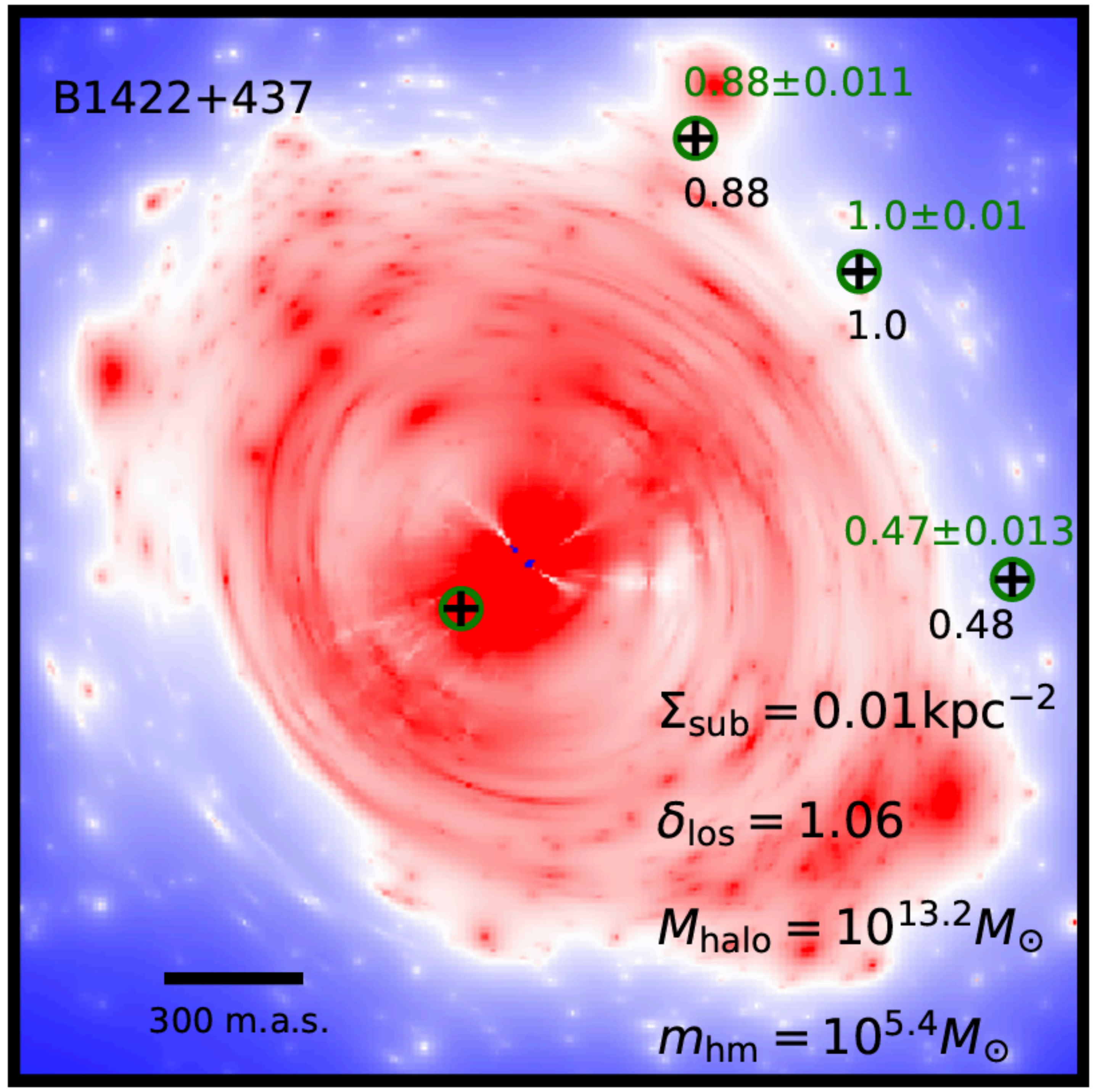
How do we analyze lenses in practice?

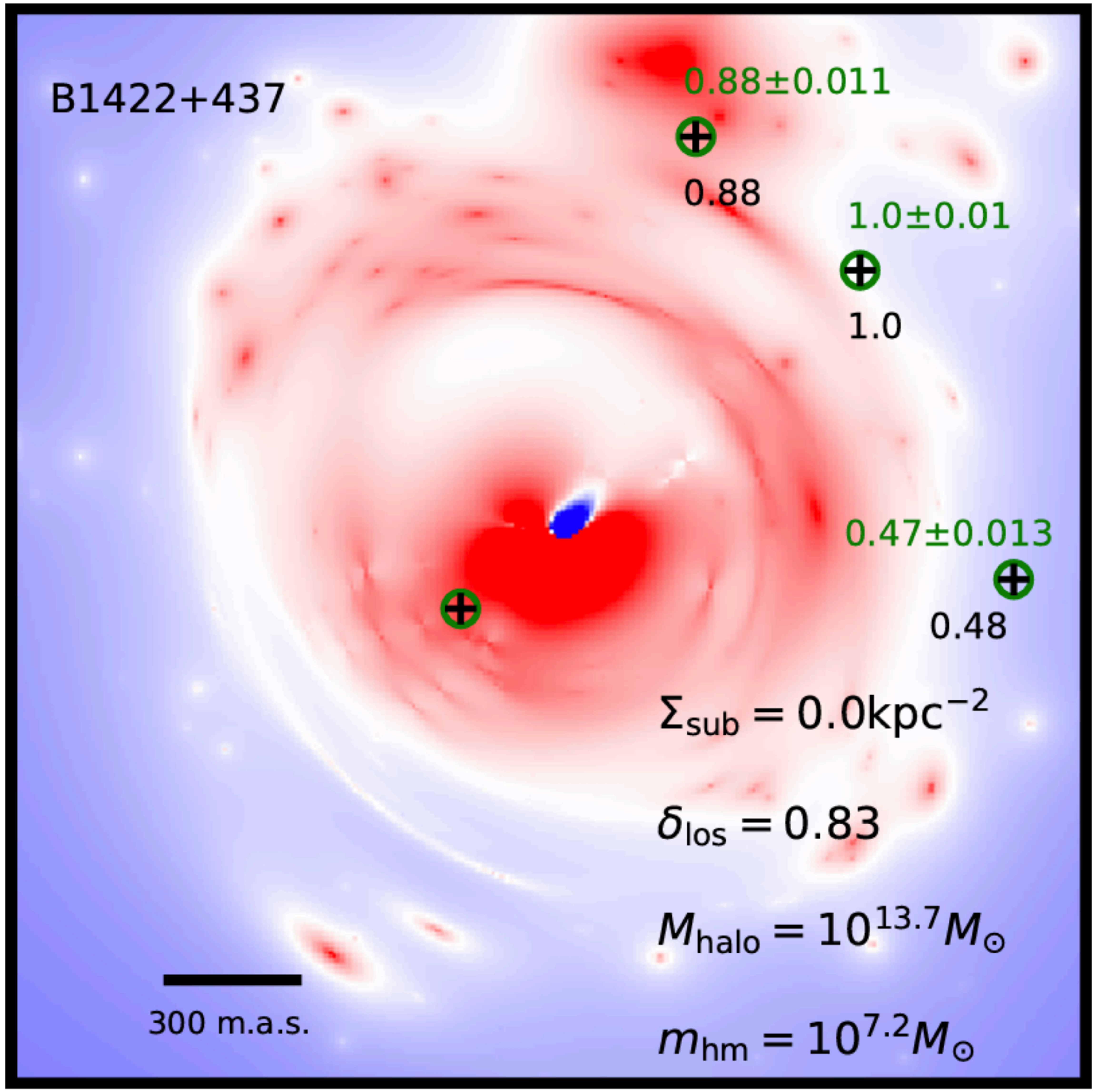
Accept proposals of model parameters if a realization generated from the model matches observed data (within some tolerance)



How do we analyze lenses in practice?

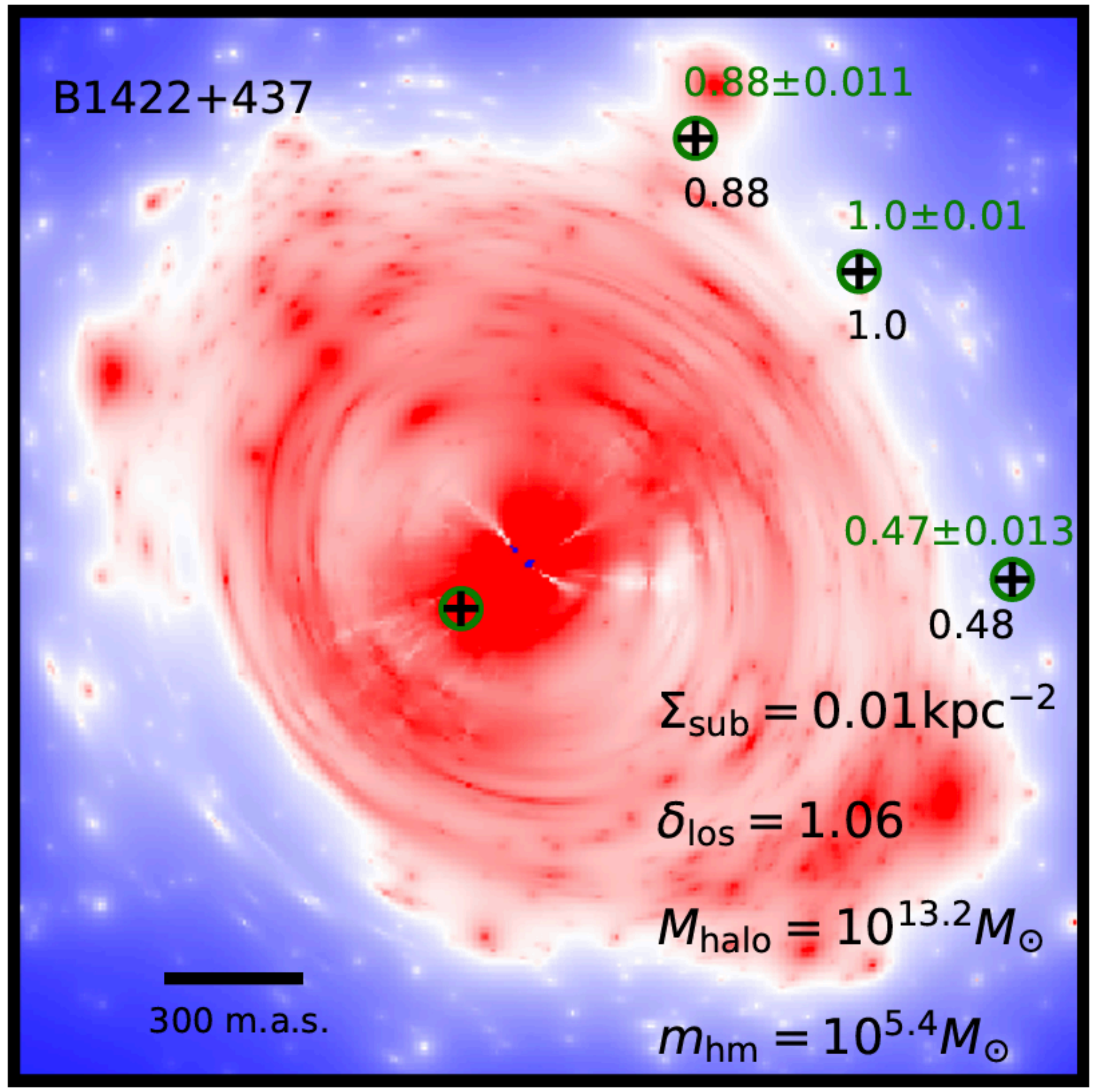
COLD



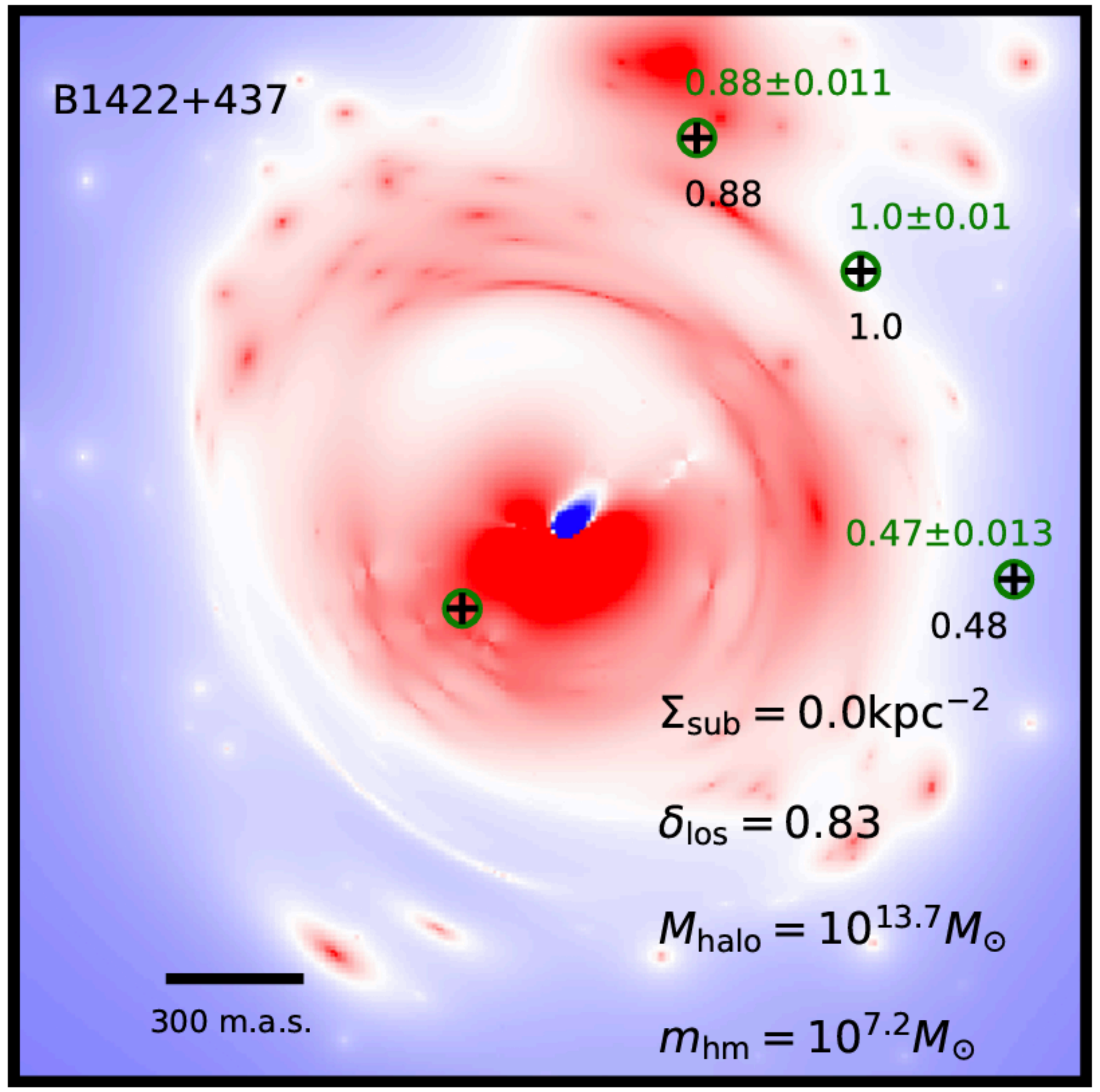


How do we analyze lenses in practice?

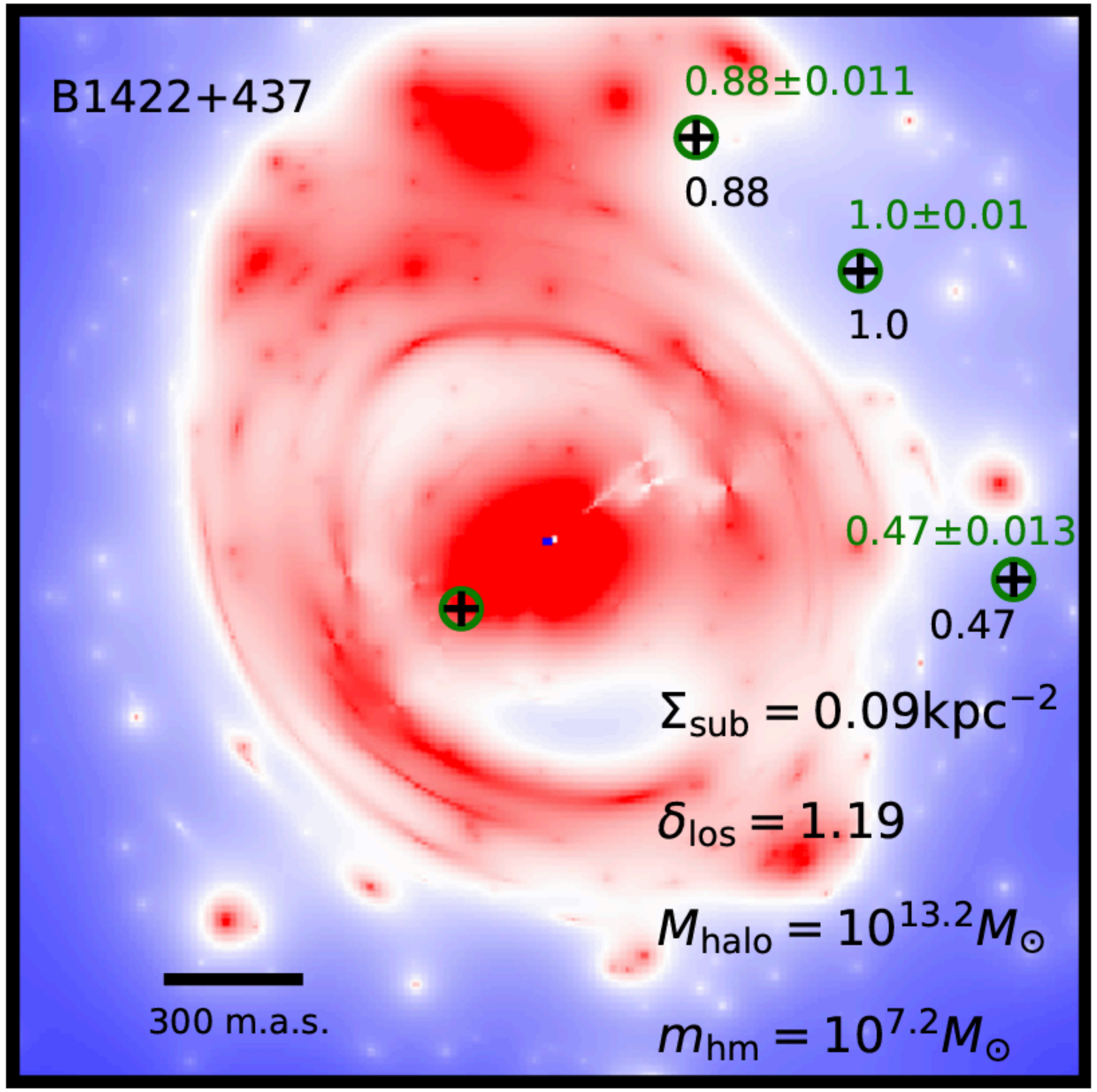
COLD



WARM



WARM

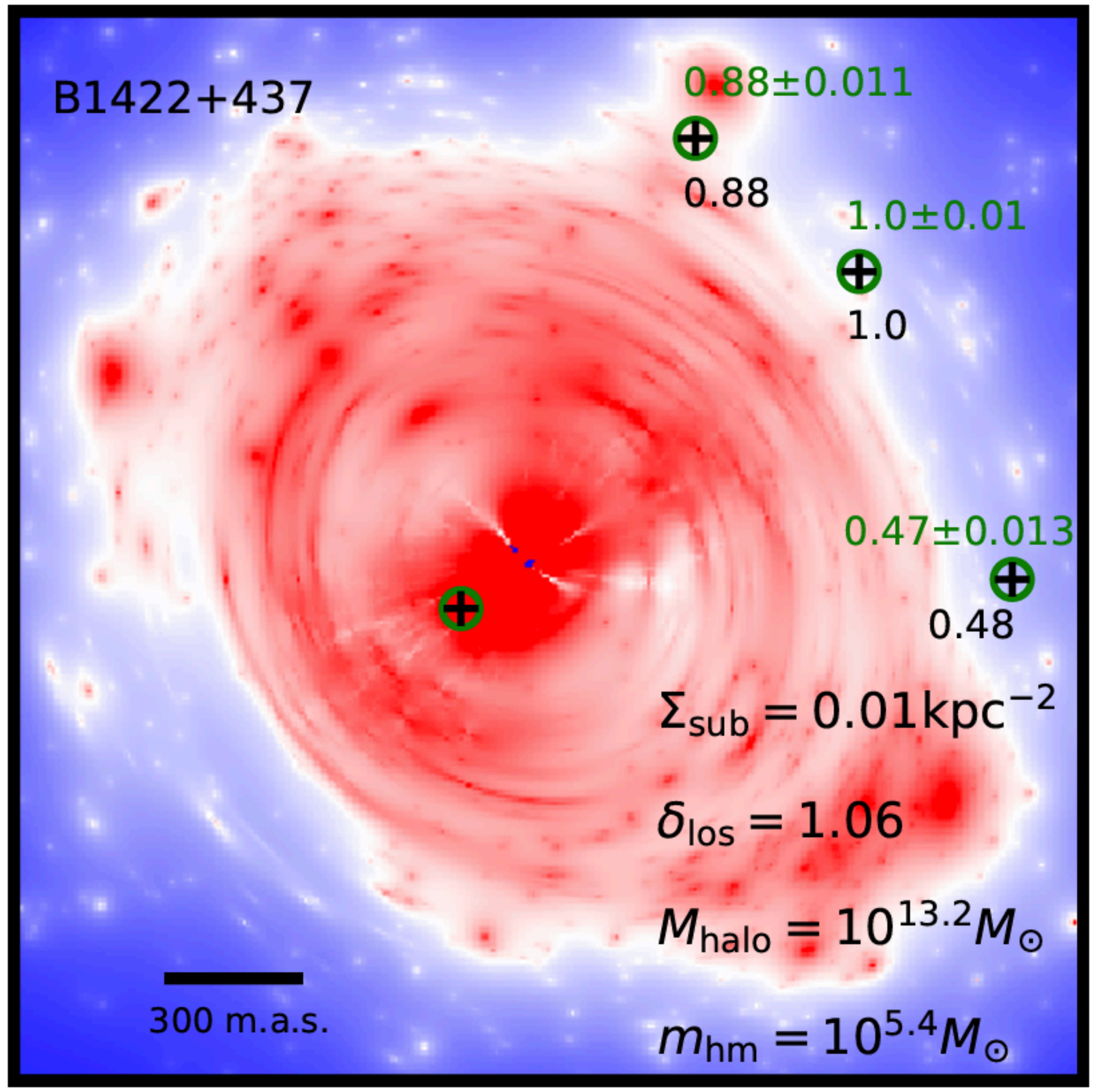


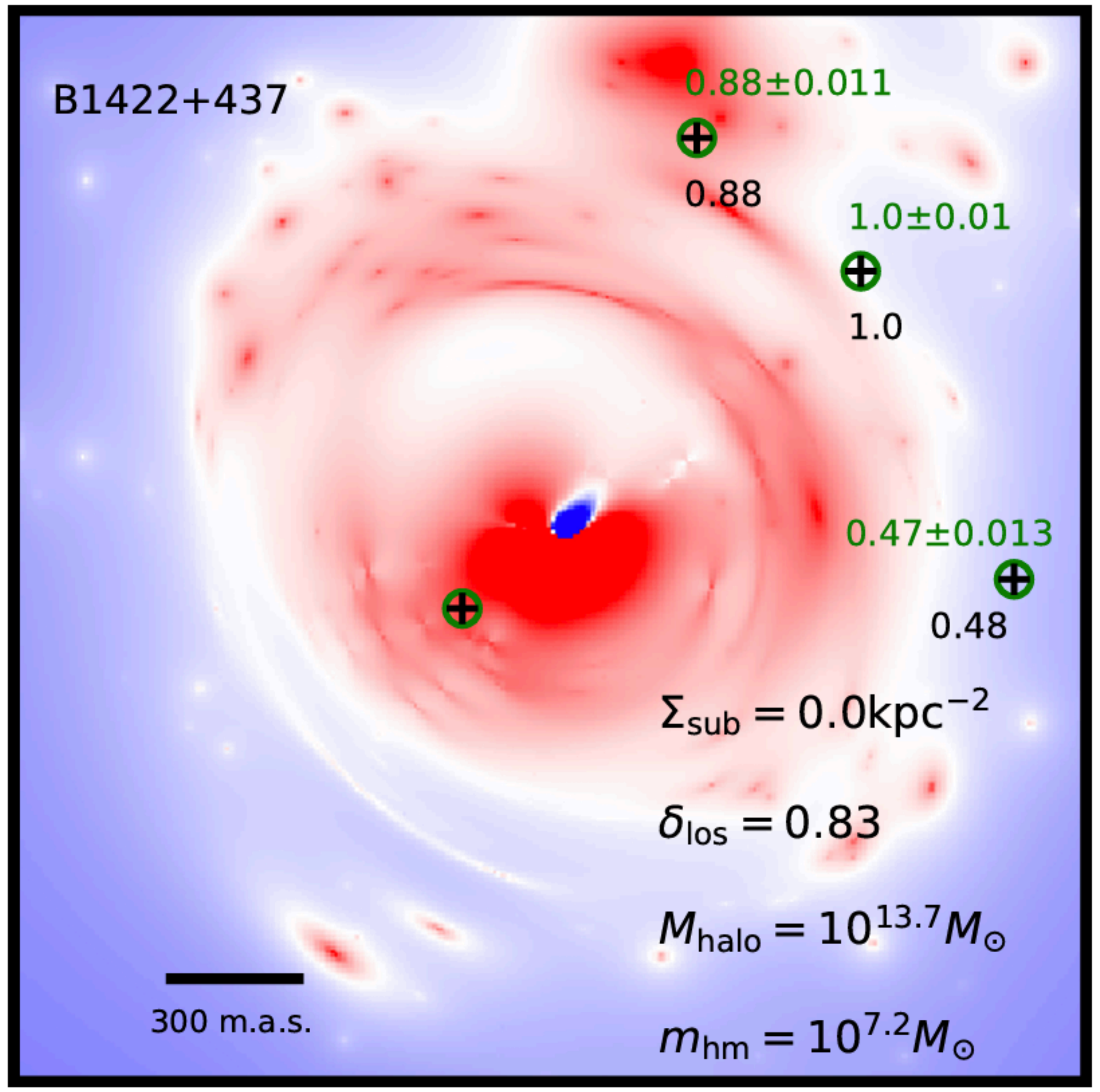
How do we analyze lenses in practice?

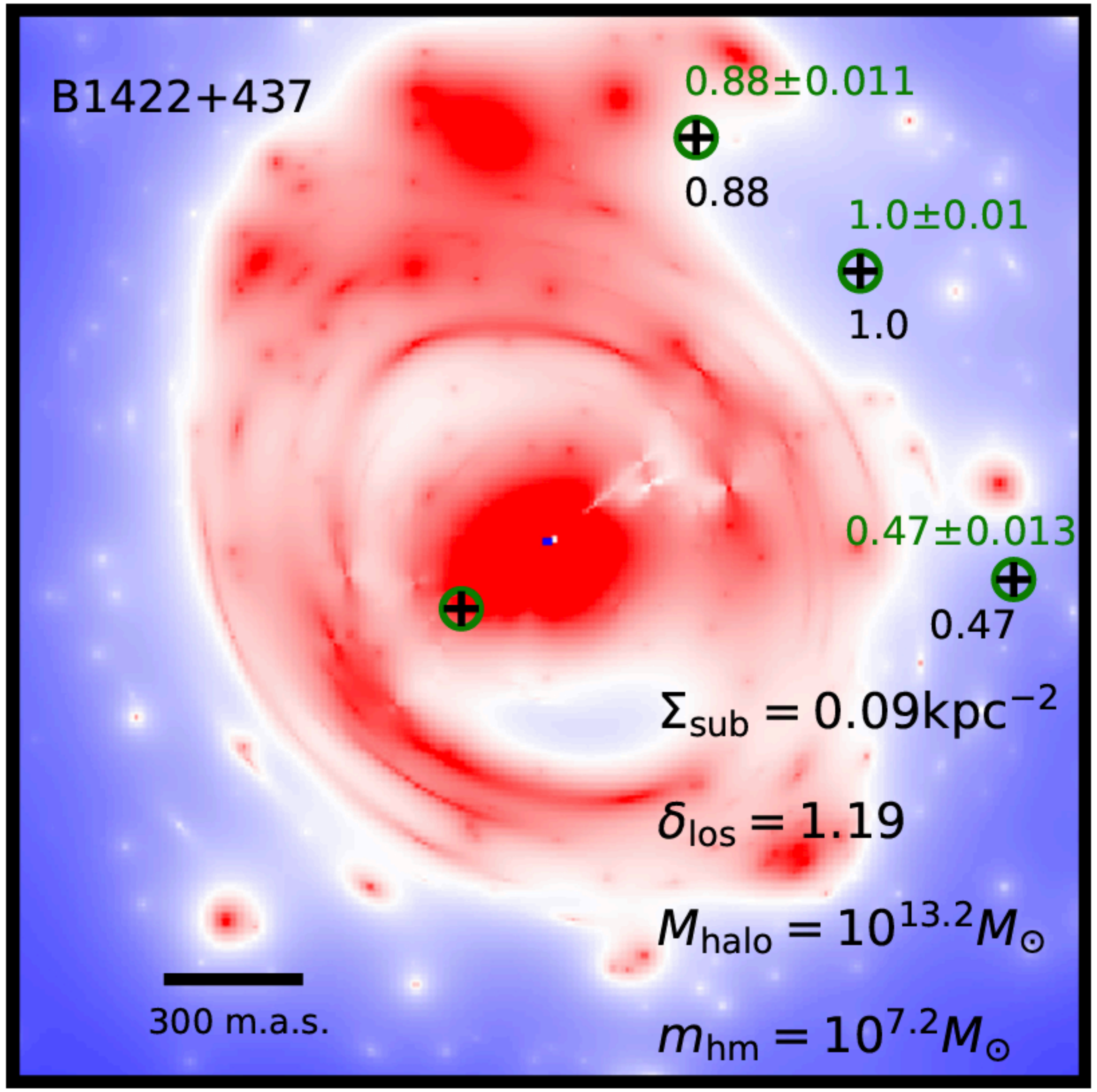
WARM

COLD

WARM





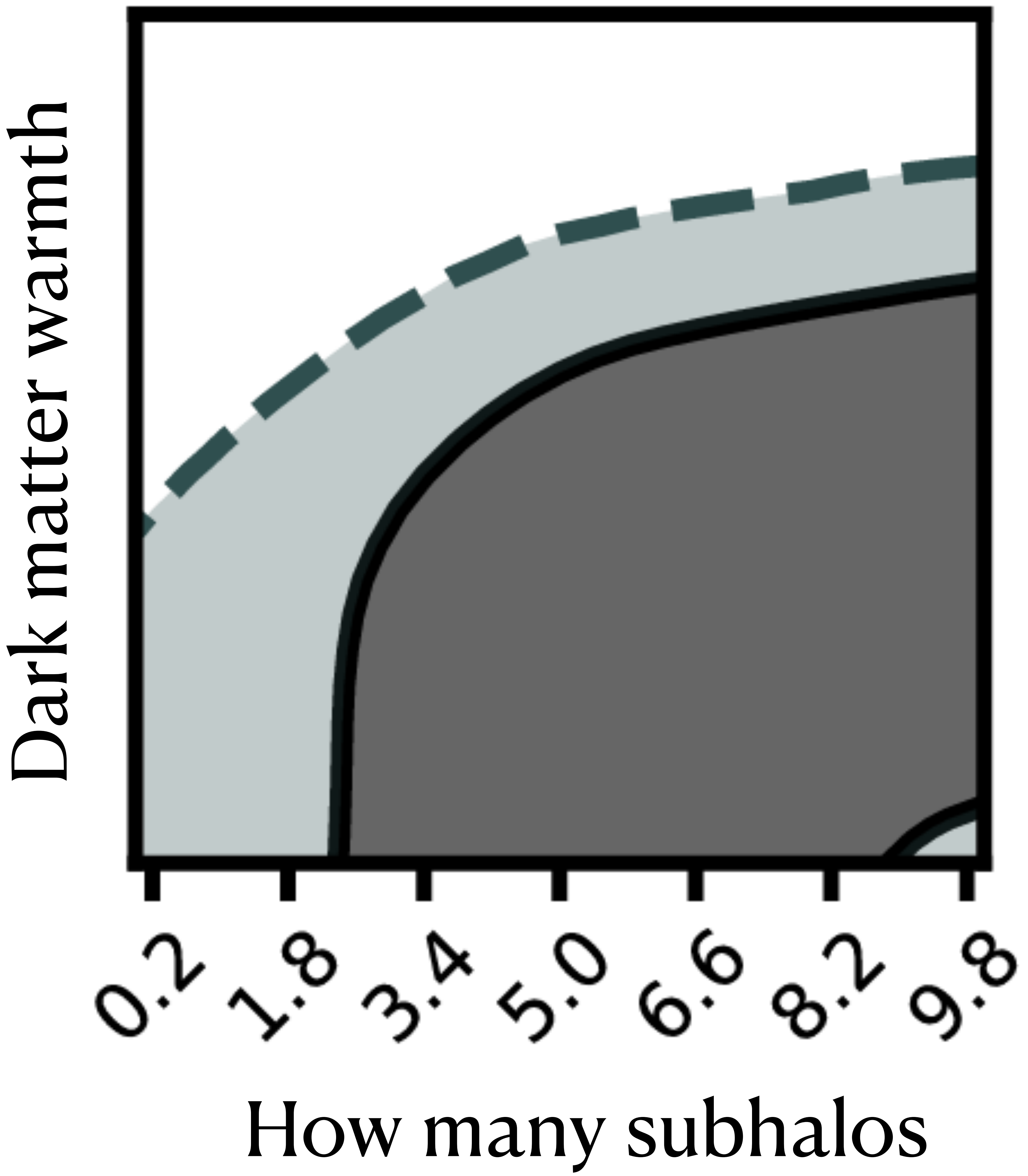


Based on these three examples, WDM is twice as likely as CDM

First results from this method

Joint inference on amplitude/shape of halo mass function with 8 quads

Using narrow-line flux ratio measurements from Nierenberg et al. (2014, 2017, 2020)



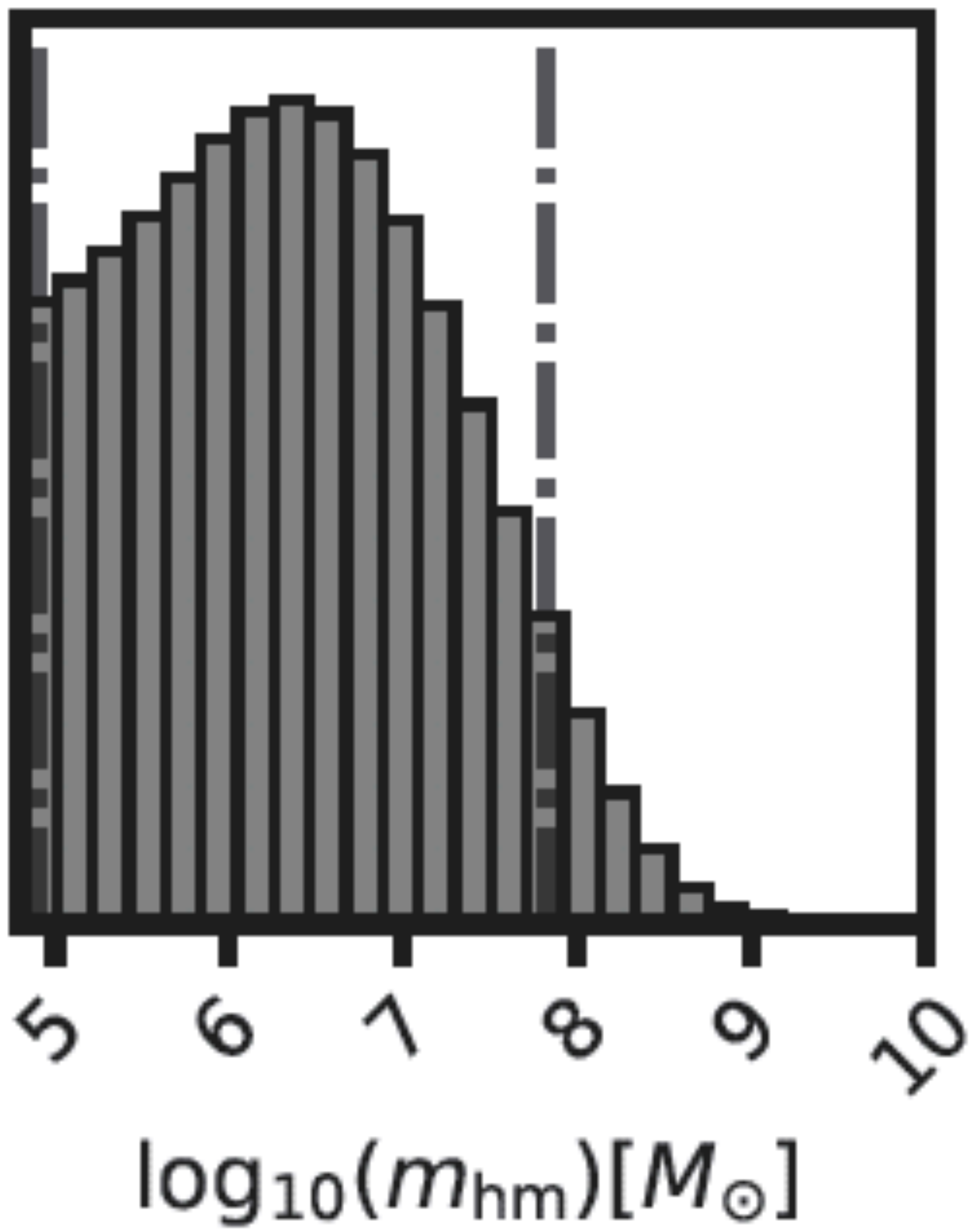
First results from this method

With millions of realizations and 11 lenses:

$m_\chi > 5.2$ keV at 95% confidence

See Zelko et al. (2022) for translation to sterile neutrino bounds

Adapted from Gilman et al. (2020)



Ultra-light dark matter (ULDM)

Early motivation as a solution
to strong CP problem

Galaxy-scale de-Broglie wavelength

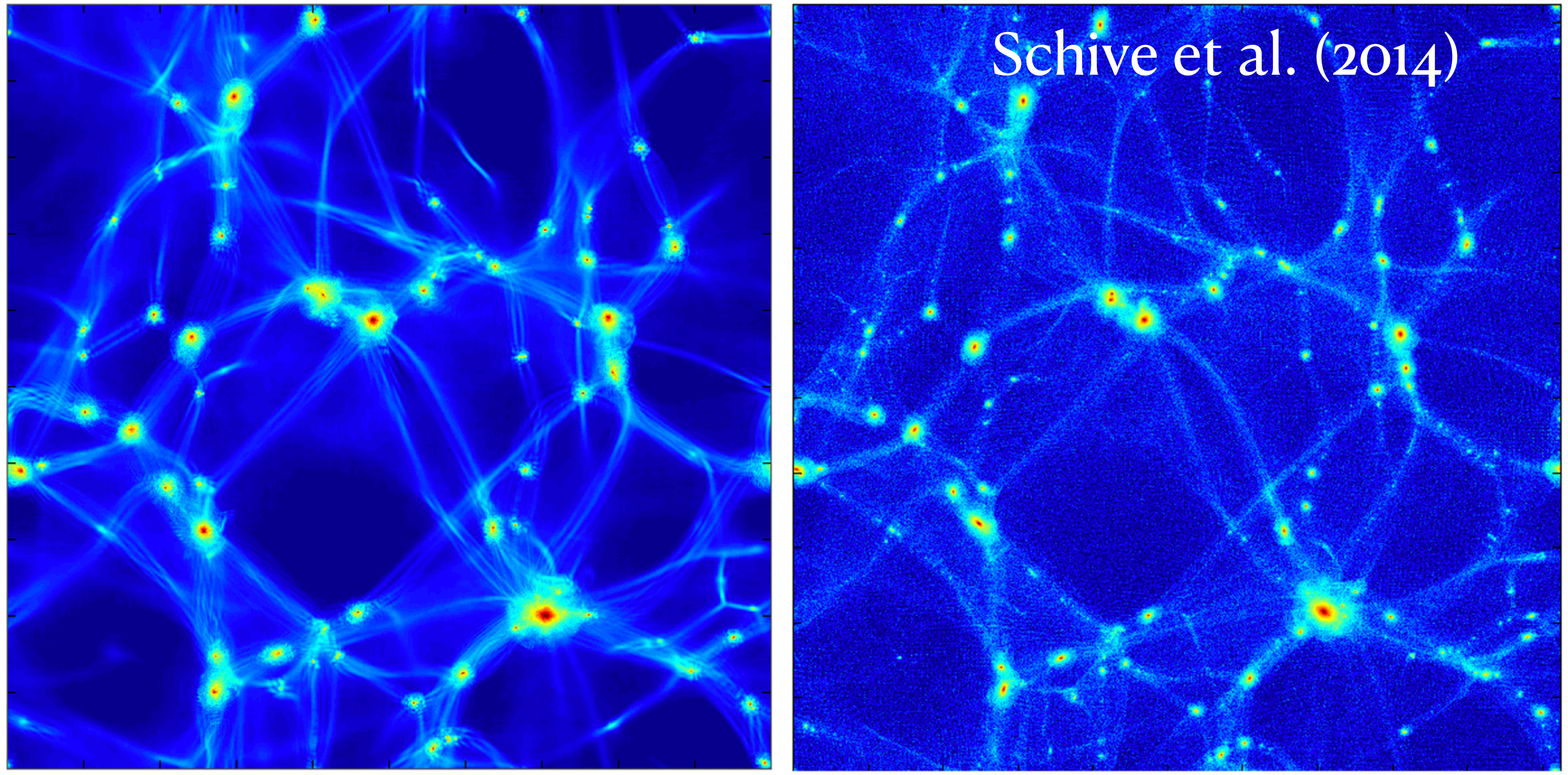
$$\lambda_{\rm dB} = 0.6 \left(\frac{m_\psi}{10^{-22}{\rm eV}} \right)^{-1} \left(\frac{v}{200} \right)^{-1} {\rm kpc}$$

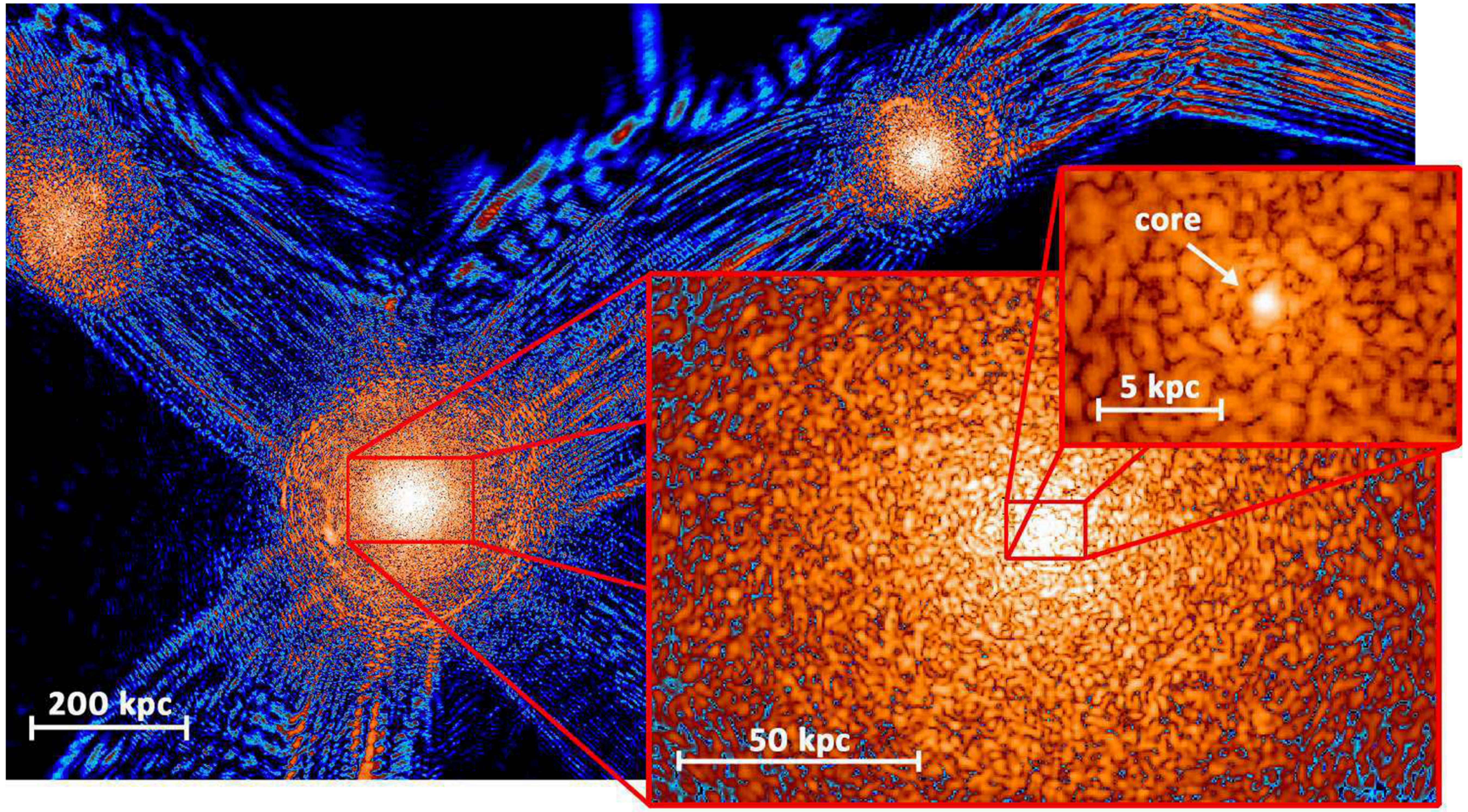
Like WDM:

1) Paucity of small-scale structure

Not like WDM:

1) Halos have a central soliton core, are less concentrated than CDM halos





Strong lensing constraints on ultra-light dark matter

Quantum fluctuations masquerade as halos: Bounds on ultra-light dark matter from quadruply-imaged quasars

Alexander Laroche,[1,2★] Daniel Gilman,[1†] Xinyu Li,[3,4] Jo Bovy,[1] Xiaolong Du[5]
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[2]*Department of Physics, McGill University, Montreal, QC, H3A 2T8, Canada*
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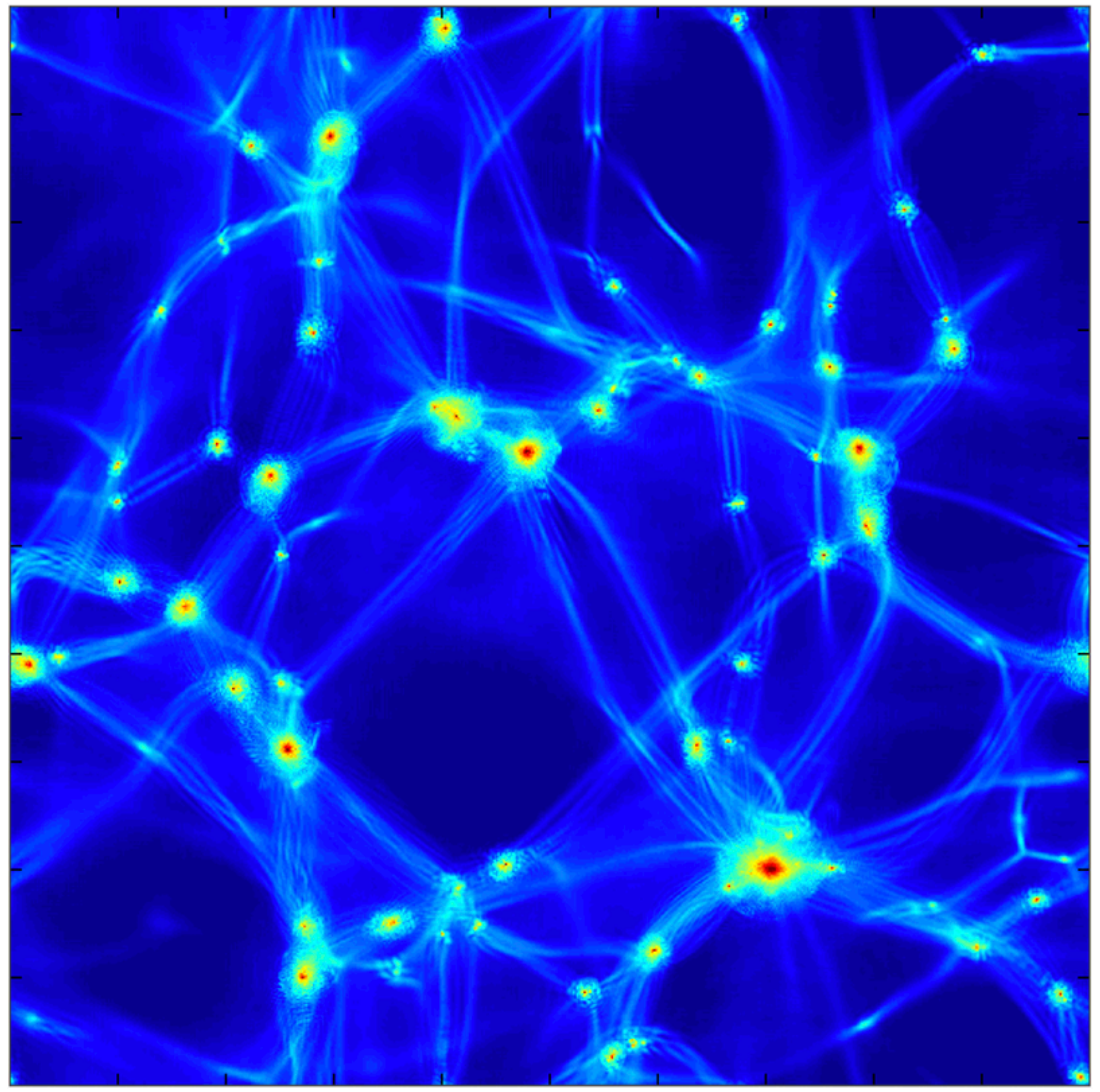
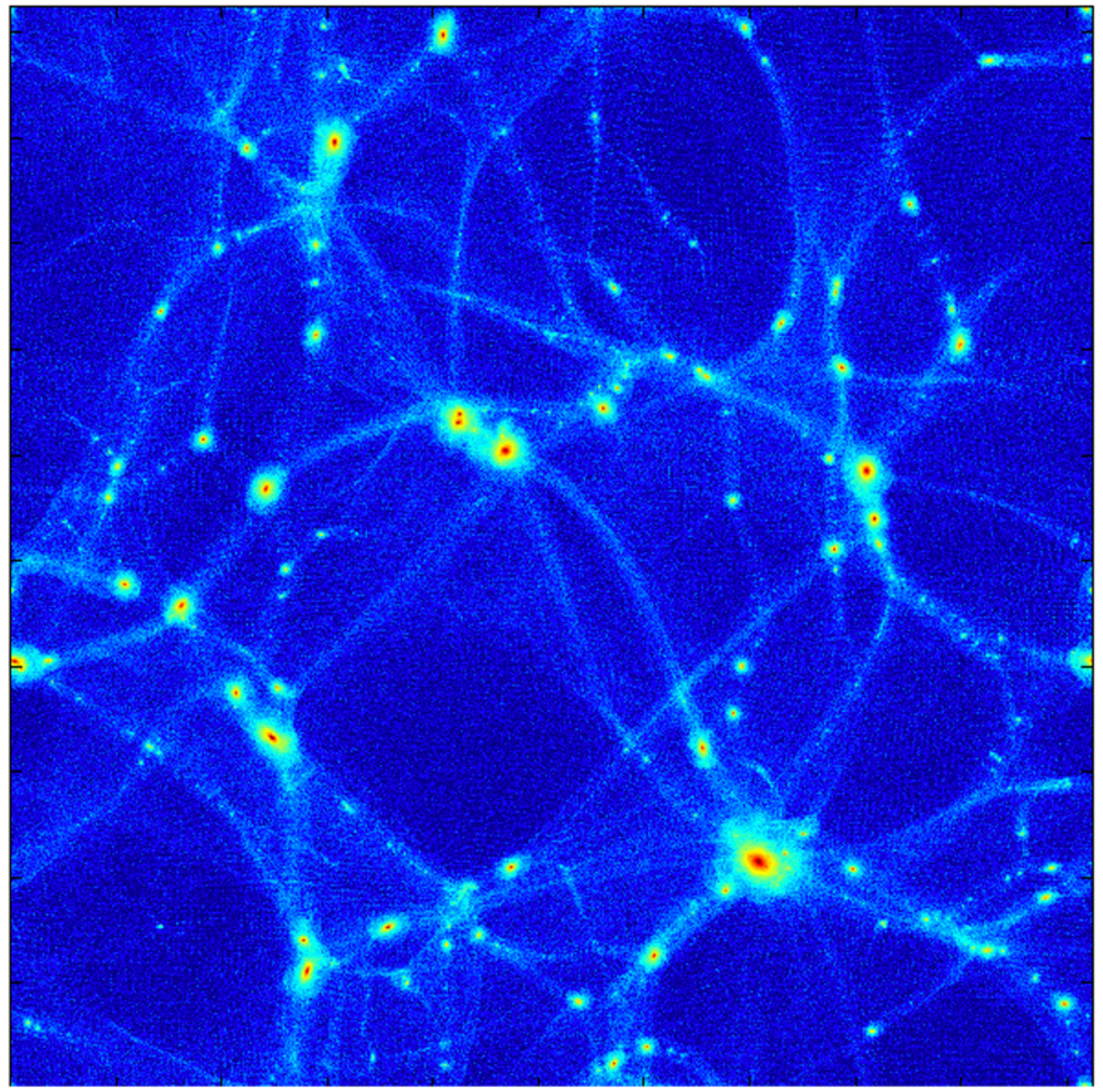
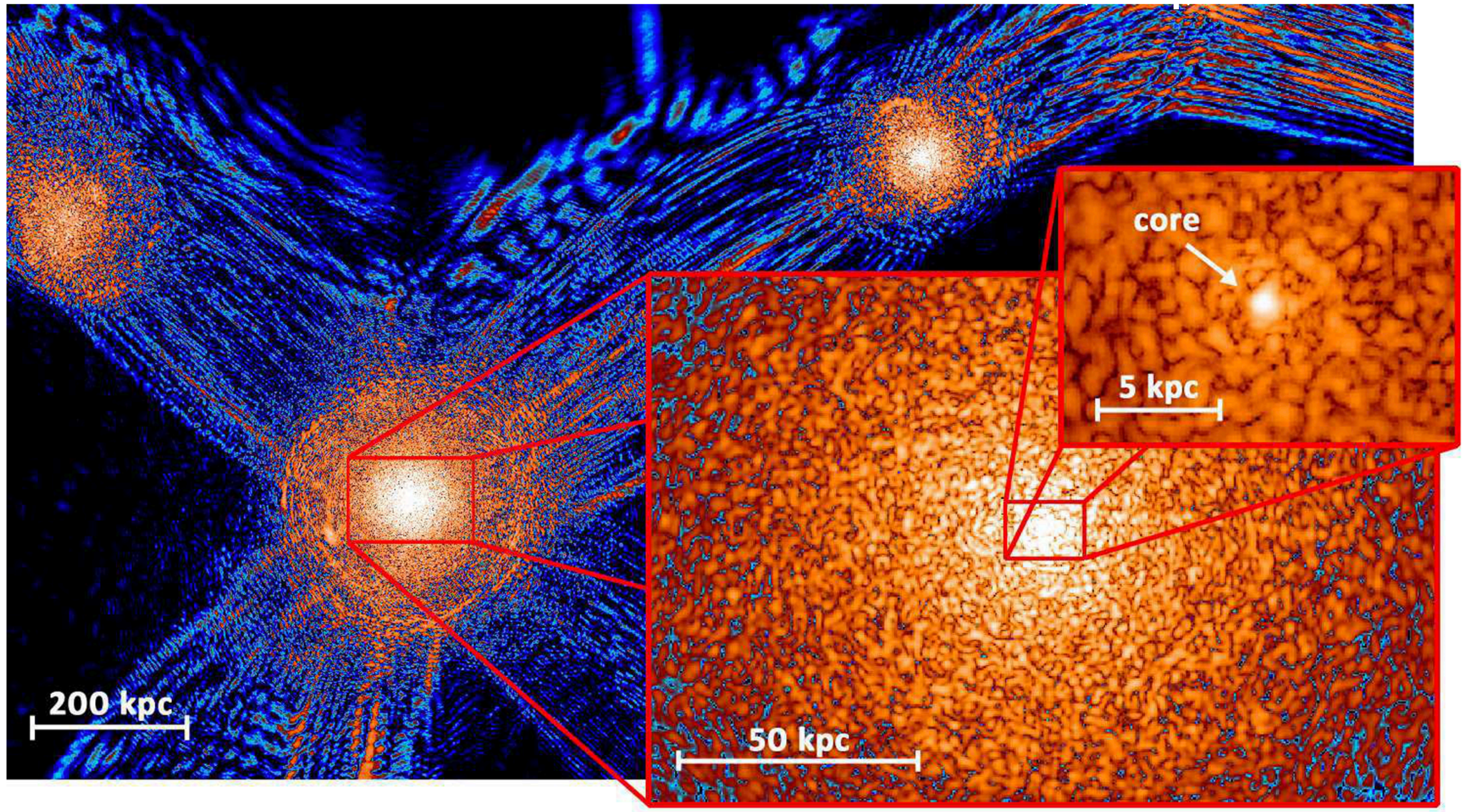
[4]*Perimeter Institute for Theoretical Physics, 31 Caroline Street North, Waterloo, Ontario, Canada, N2L 2Y5*
[5]*Carnegie Institution for Science, 813 Santa Barbara Street, Pasadena, CA 91101, USA*

Work was led by Alex Laroche, incoming graduate student at the University of Toronto

Strong lensing constraints on ultra-light dark matter







Suppressed small-scale power impacts the halo mass function and concentration-mass relation

Wave-interference is a new, relatively unexplored phenomenon (but see Chan et al. (2020))

$$\lambda_{\rm dB} = 0.6 \left(\frac{m_\psi}{10^{-22}\mathrm{eV}} \right)^{-1} \left(\frac{v}{200} \right)^{-1} \mathrm{kpc}$$

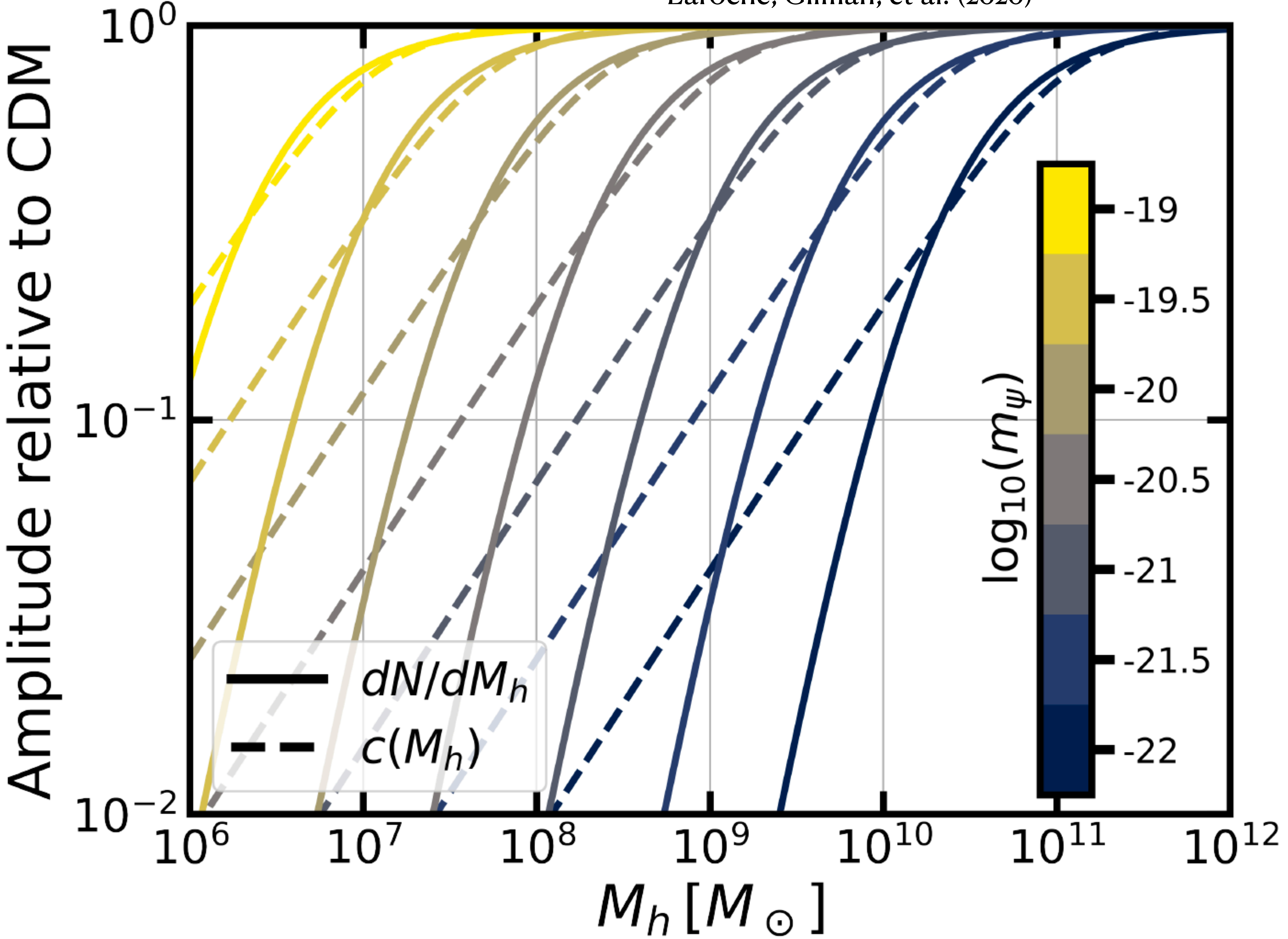
The halo mass function and concentration-mass relation in ULDM

Similar but not identical to thermal relic WDM

Halo mass function from simulations (Schive et al. 2014)

We derived new MC relation using extended PS theory

Laroche, Gilman, et al. (2020)



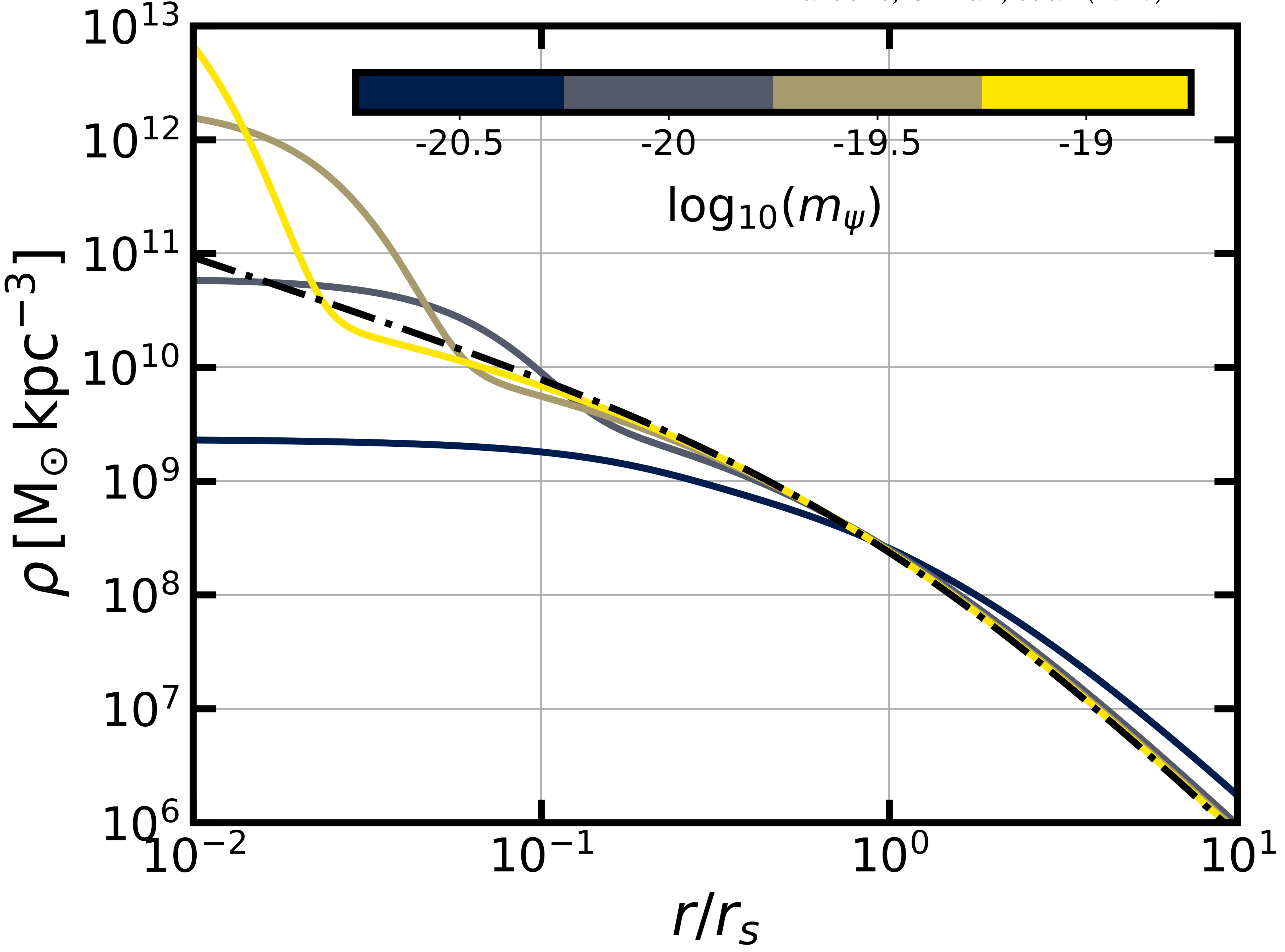
Halo density profiles in ULDM

ULDM halos have a soliton core

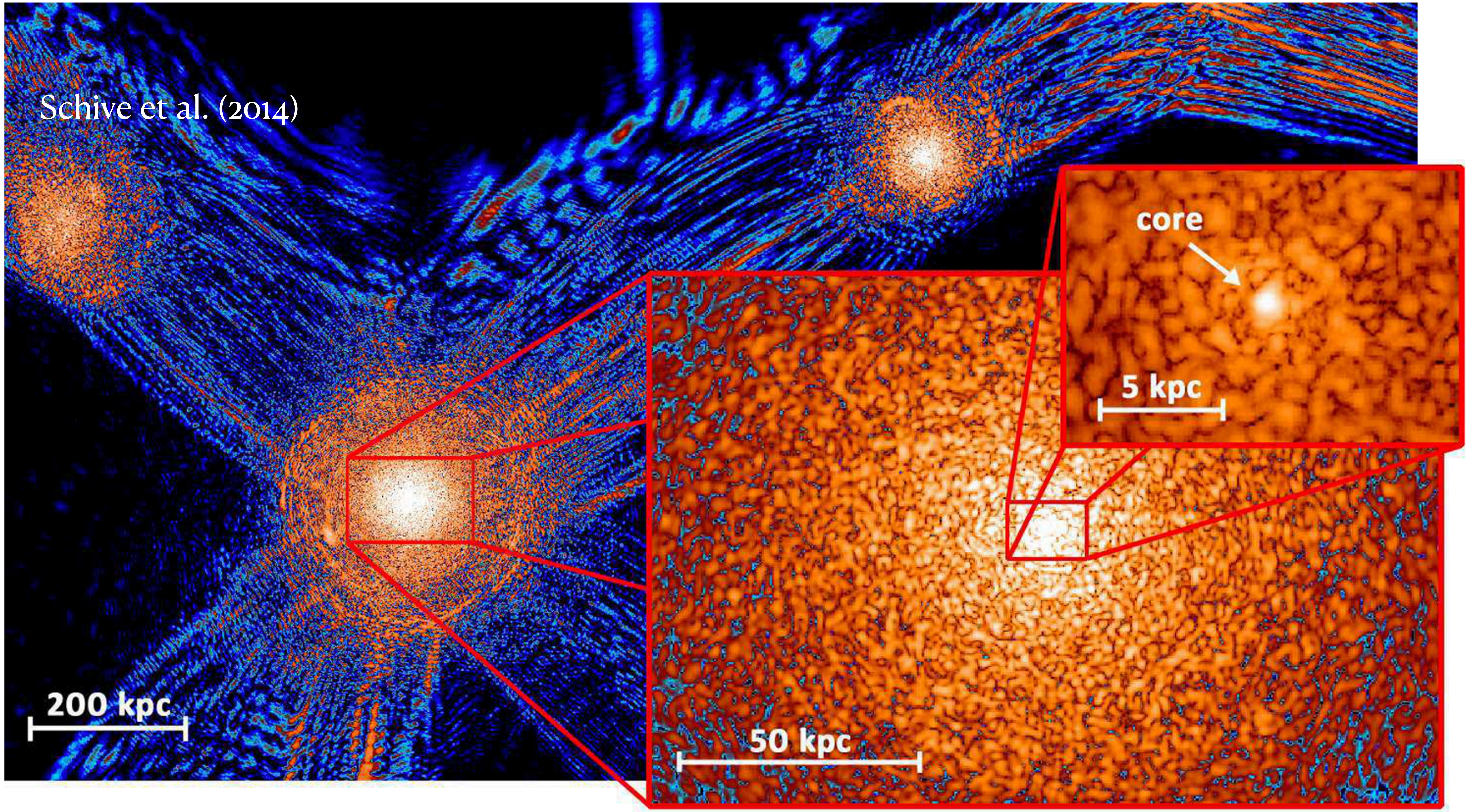
Model a superposition of cored NFW profile and a soliton core subject to:

1) mass conservation
2) central core density

Laroche, Gilman, et al. (2020)



Wave interference effects in host halo profile



Schive et al. (2014)

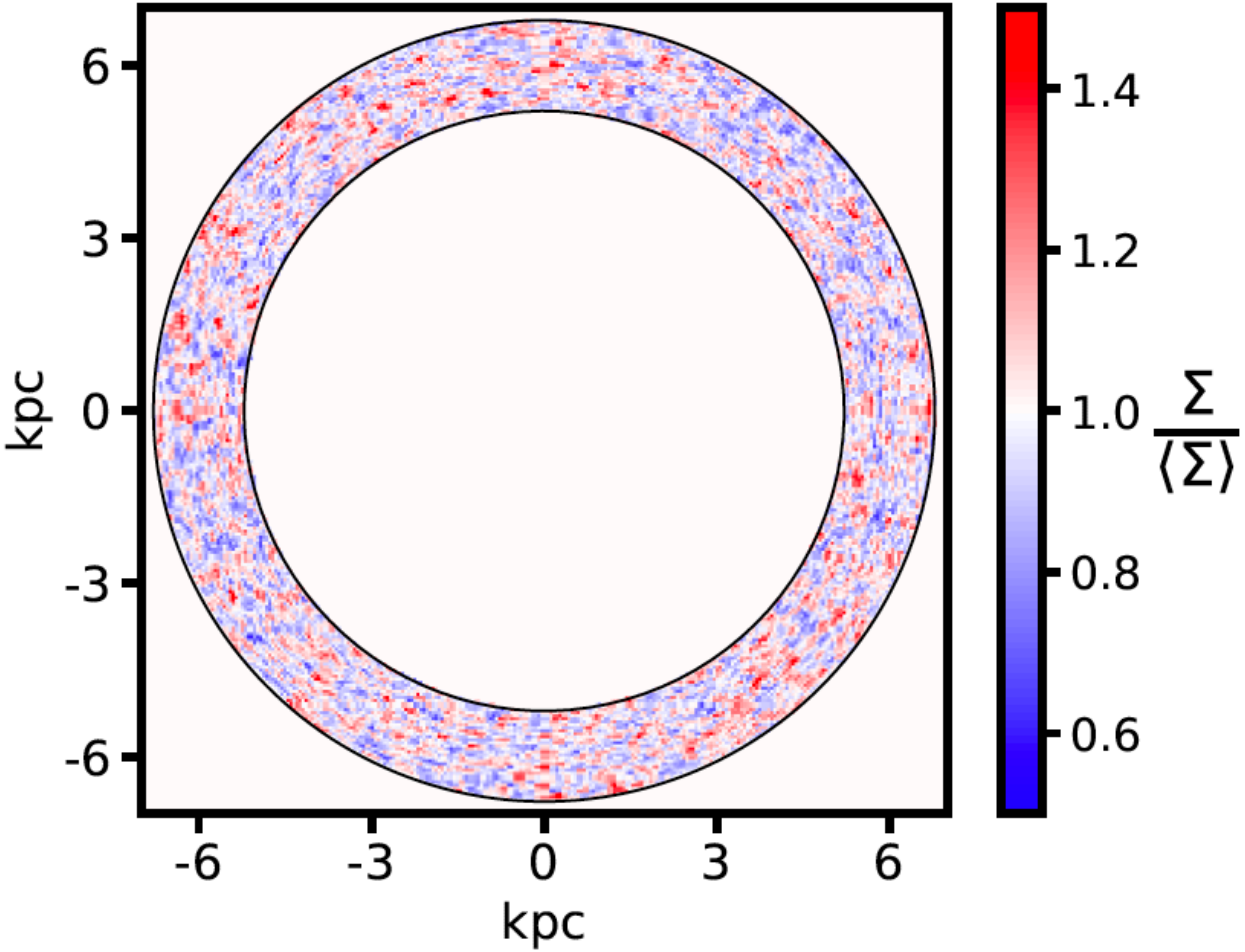
Wave interference effects in host halo profile

Numerical simulation of a 10^13 ULDM halo profile with methods by Yavetz et al. (2022) to solve SP equations

$$i\hbar\frac{\partial\Psi}{\partial t} = \left(-\frac{\hbar^2}{2m_a}\nabla^2 + m_aV\right)\Psi$$

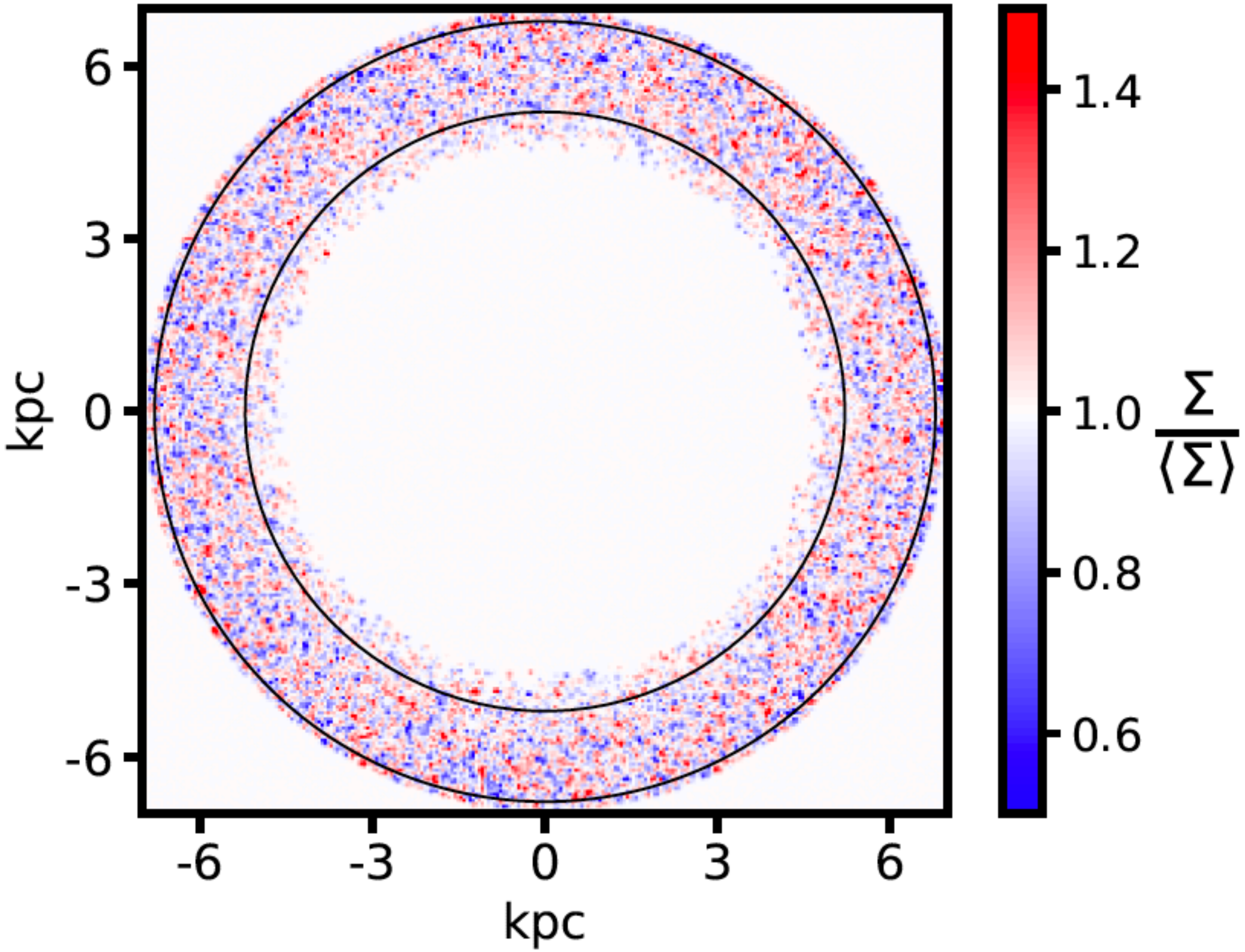
$$\nabla^2 V = 4\pi G\rho = 4\pi G m_a|\Psi|^2$$

Laroche, Gilman, et al. (2022)



Wave interference effects in host halo profile

Laroche, Gilman, et al. (2022)



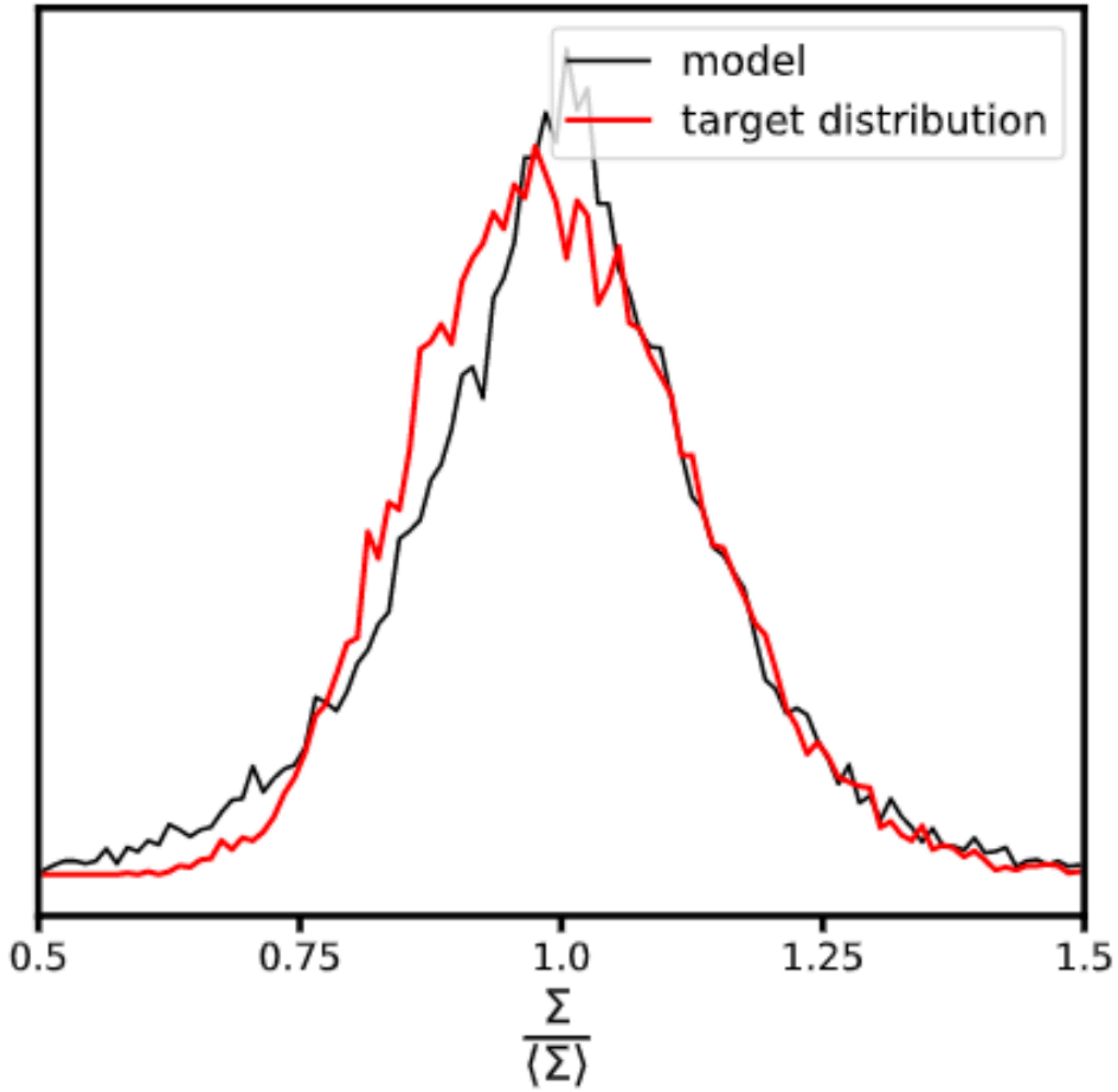
Model with circular Gaussians

amplitude $\propto m_\psi^{-1/2}$

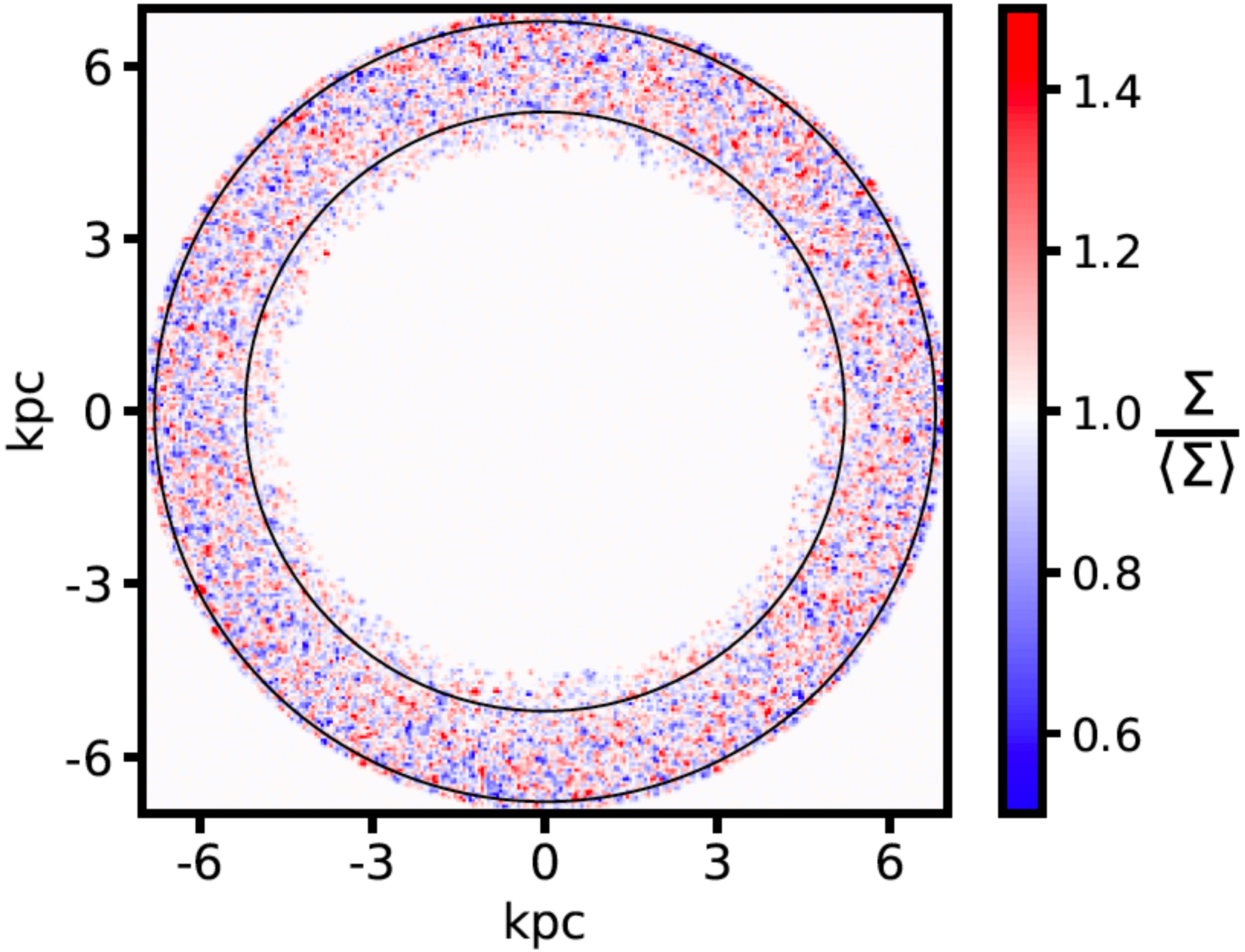
size $\propto \lambda_{\rm dB} \propto m_\psi^{-1}$

number density $\propto \lambda_{\rm dB}^{-2}$

Wave interference effects in host halo profile



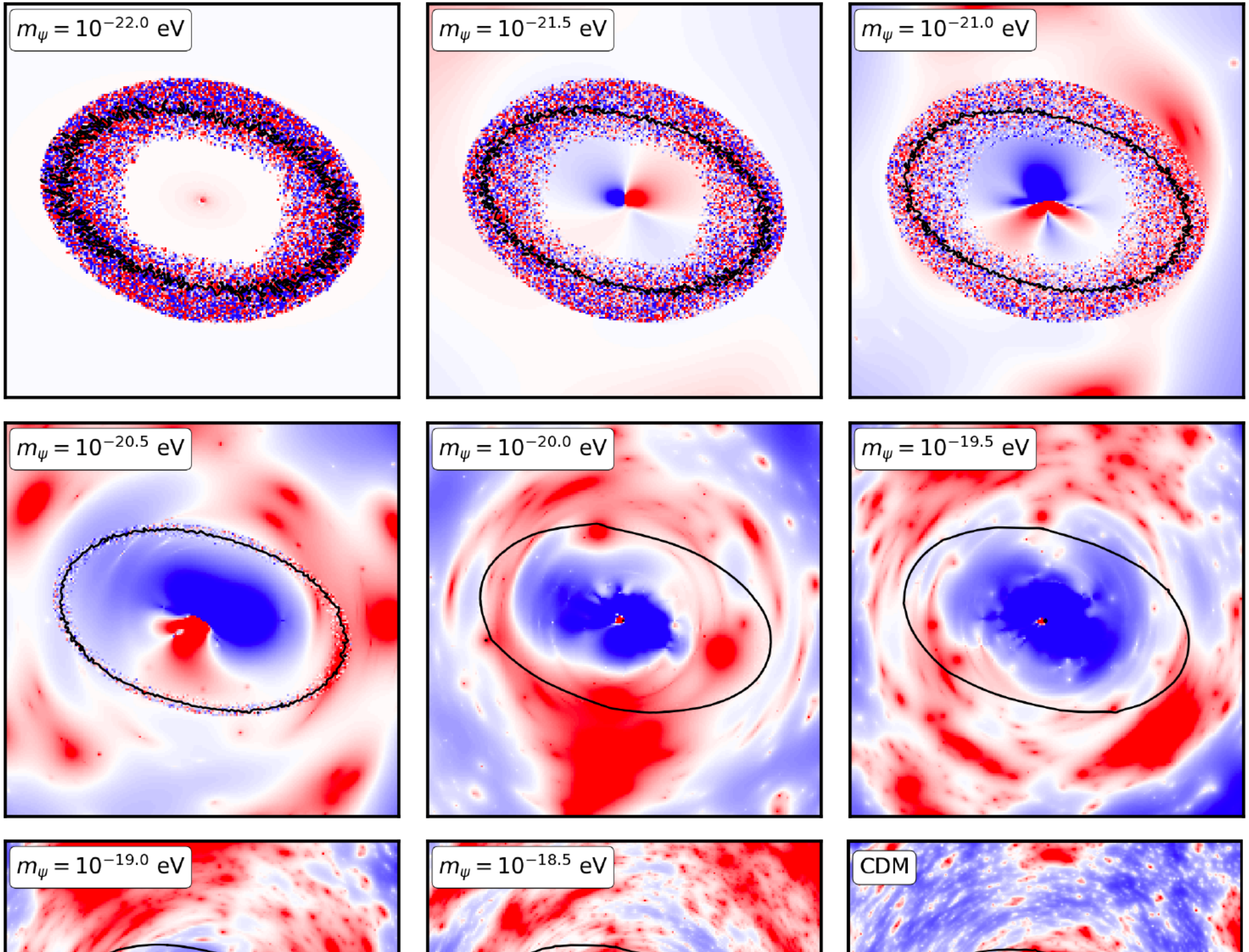
Laroche, Gilman, et al. (2022)



Laroche, Gilman, et al. (2022)

Putting it all together

(projected multi-plane mass maps)



Putting it all together

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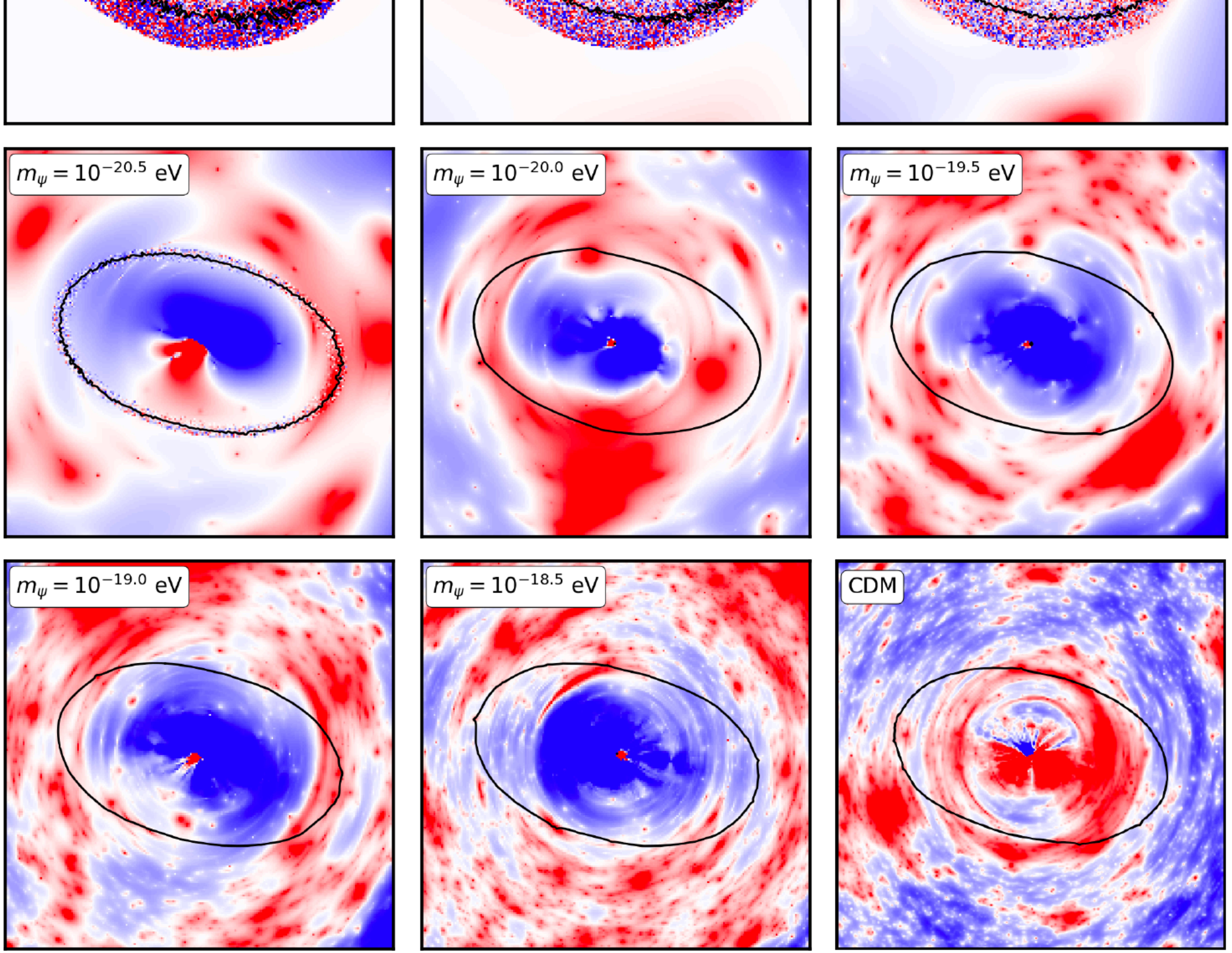
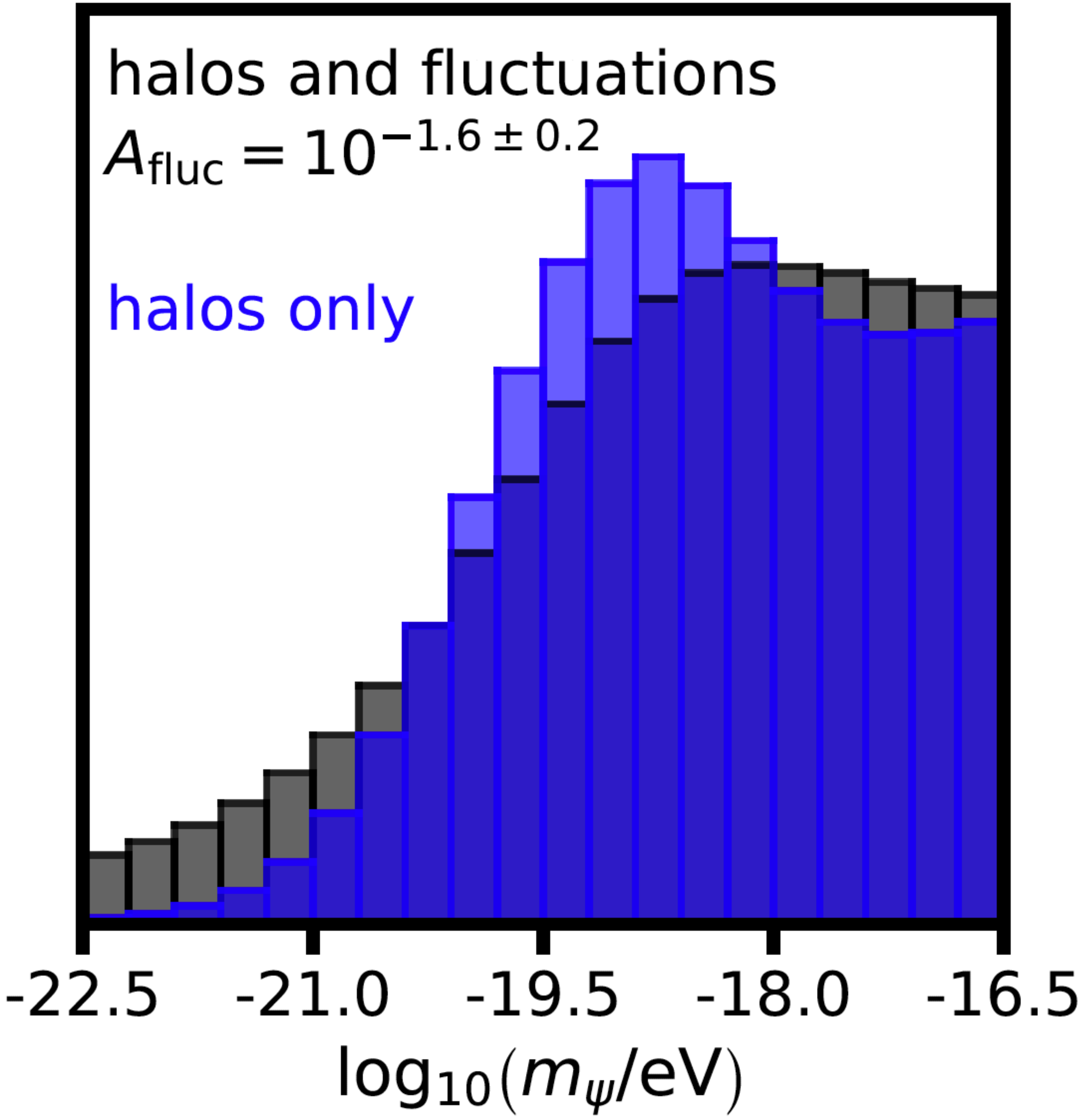


Laroche, Gilman, et al. (2022)

Halos only:
light particles
ruled out

Halos + wave interference:
light particles disfavored
(~8:1 likelihood ratio)

Hence the title: "Quantum fluctuations masquerade as halos"



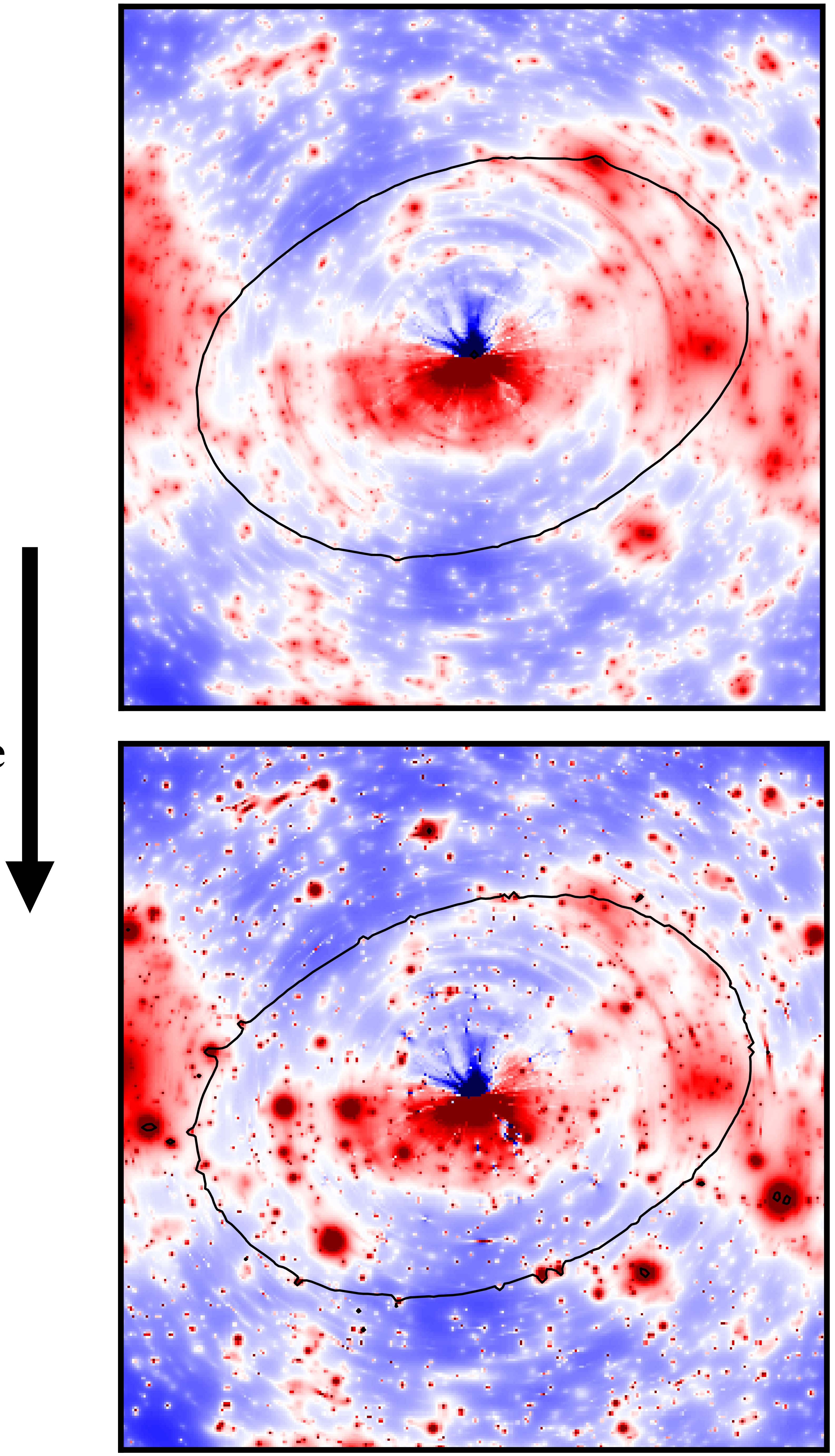
Self-interacting dark matter (ULDM)

Interaction mediated by light force carrier leaves large-scale structure unchanged, while altering the properties of halos

Halos have cores that eventually undergo core collapse (or “gravothermal catastrophe”)

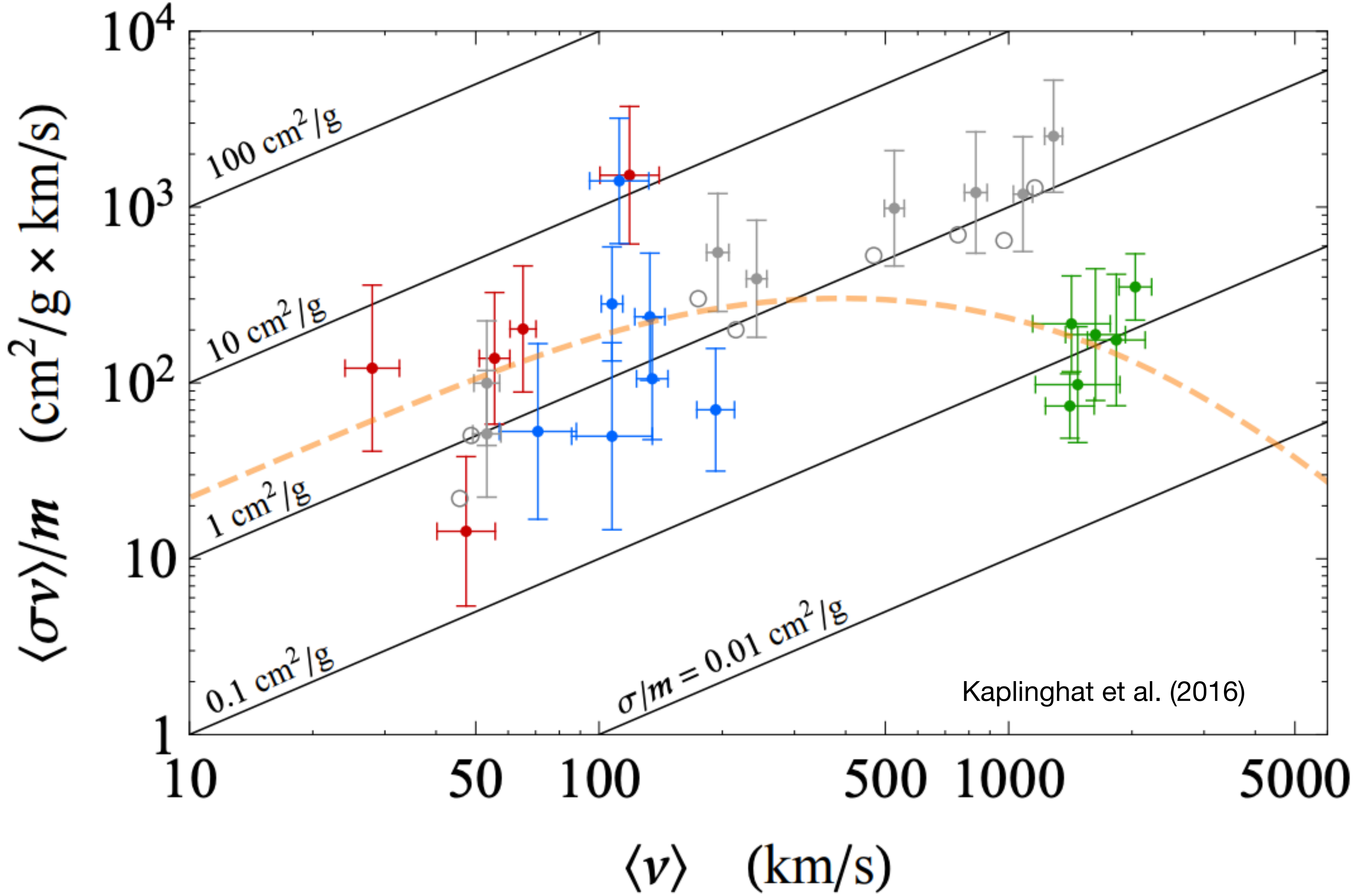
Relevant length scale:
mean-free path

$$\lambda_{\mathrm{MFP}} \sim (\rho\sigma)^{-1}$$



Core collapse

Velocity-dependent cross sections



Stringent upper limits from galaxy clusters

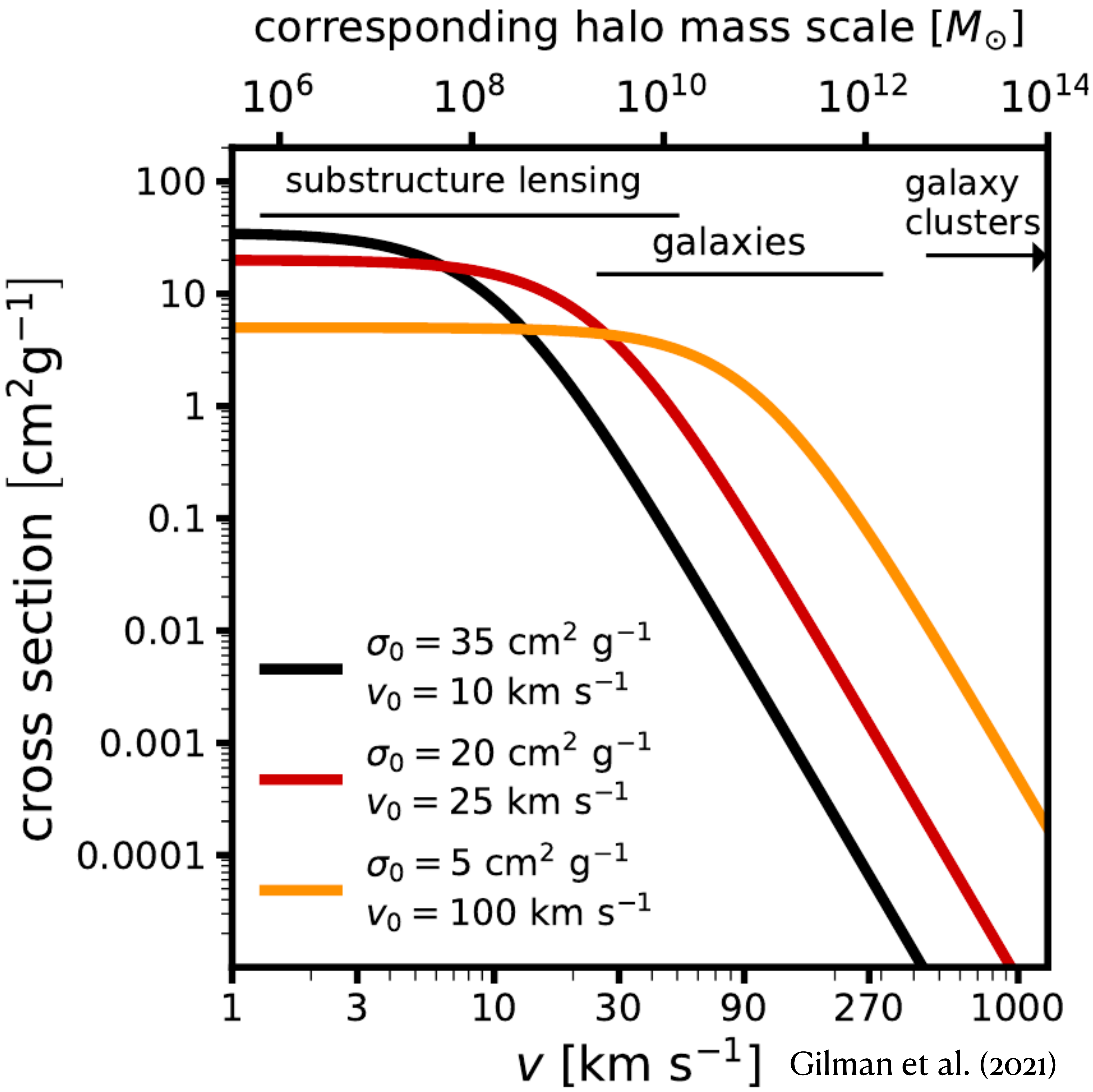
Larger cross section in dwarf galaxies and galaxies

Velocity-dependent cross sections and substructure lensing

Assuming a cross section arising from weak potential

$$\sigma(v) = \sigma_0 \left(1 + \frac{v^2}{v_0^2}\right)^{-2}$$

Non-perturbative regime is extremely interesting (Gilman et al. 2022, in prep)



Gilman et al. (2021)

Velocity-dependent cross sections and substructure lensing

Velocity dispersion, set by halo mass, determines the characteristic velocity scale for the problem

$$\langle \sigma v \rangle = \frac{1}{2\sqrt{\pi}\, v_{\rm rms}\left(M_{\rm halo}\right)^3} \int_0^\infty \sigma\left(v'\right) v' \times v'^{\,2} \exp\left(\frac{-v'^{\,2}}{4\, v_{\rm rms}\left(M_{\rm halo}\right)^2}\right) dv'$$

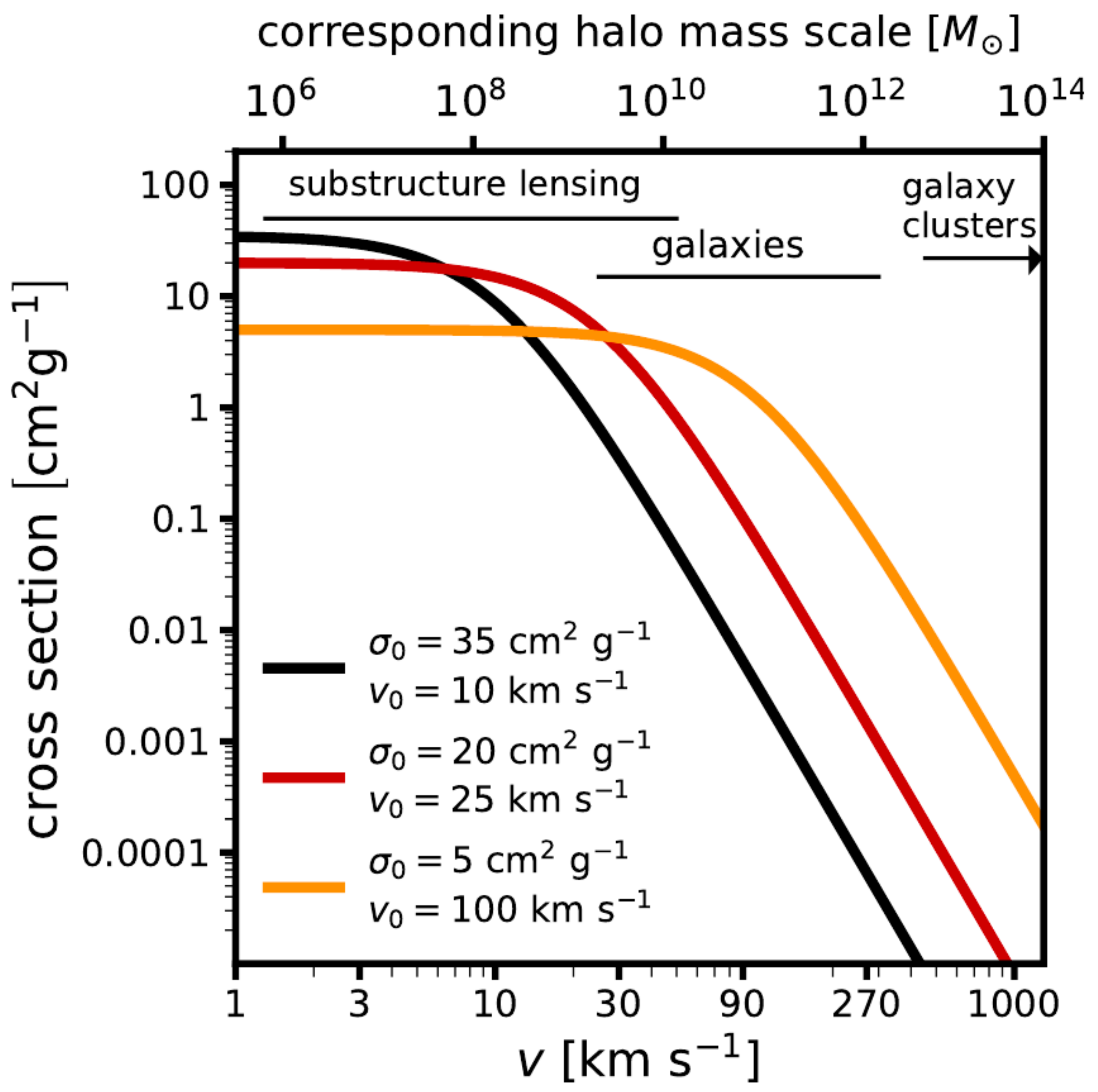
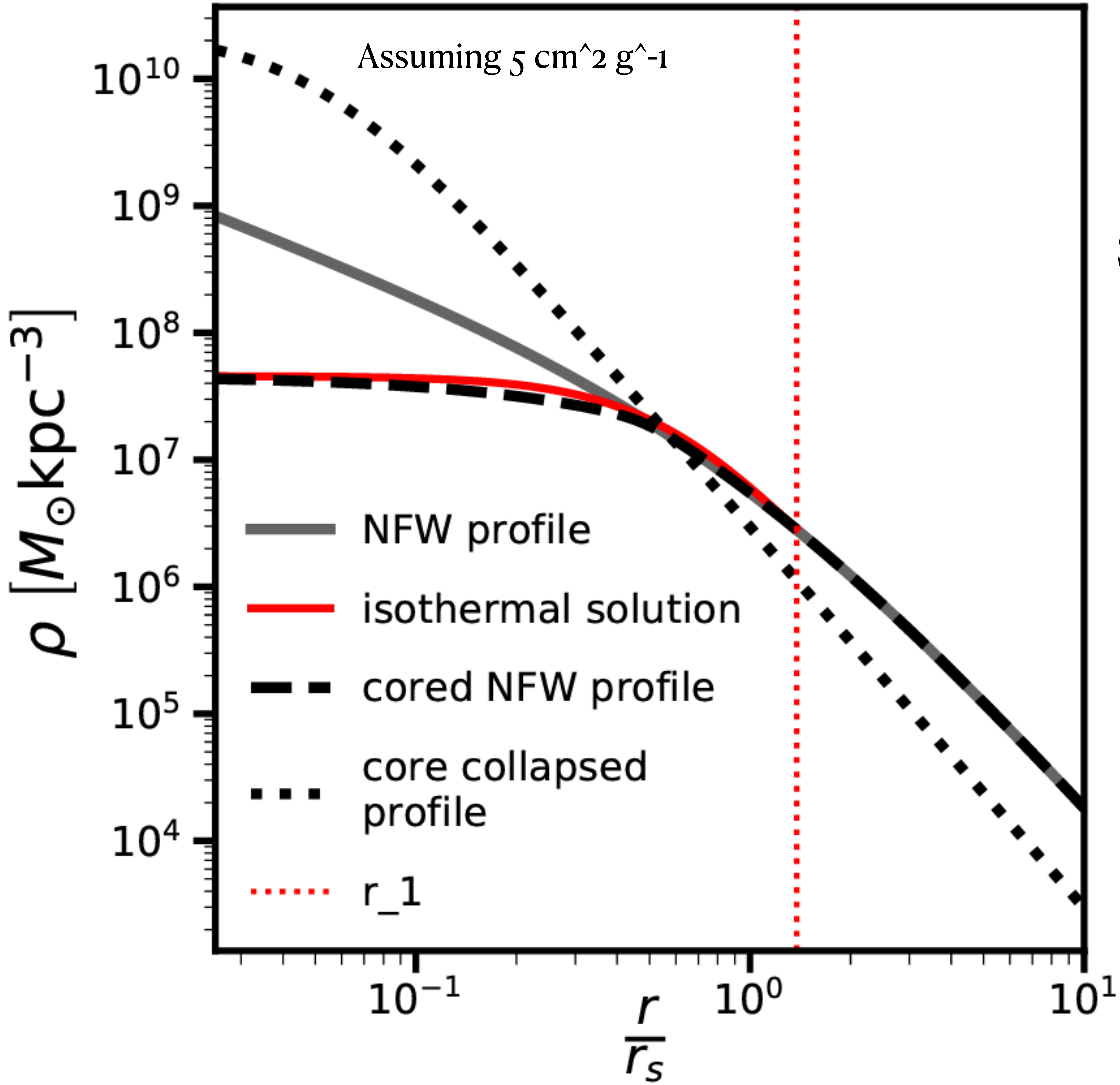


Figure from Gilman et al. (2021)

Gilman et al. (2021)

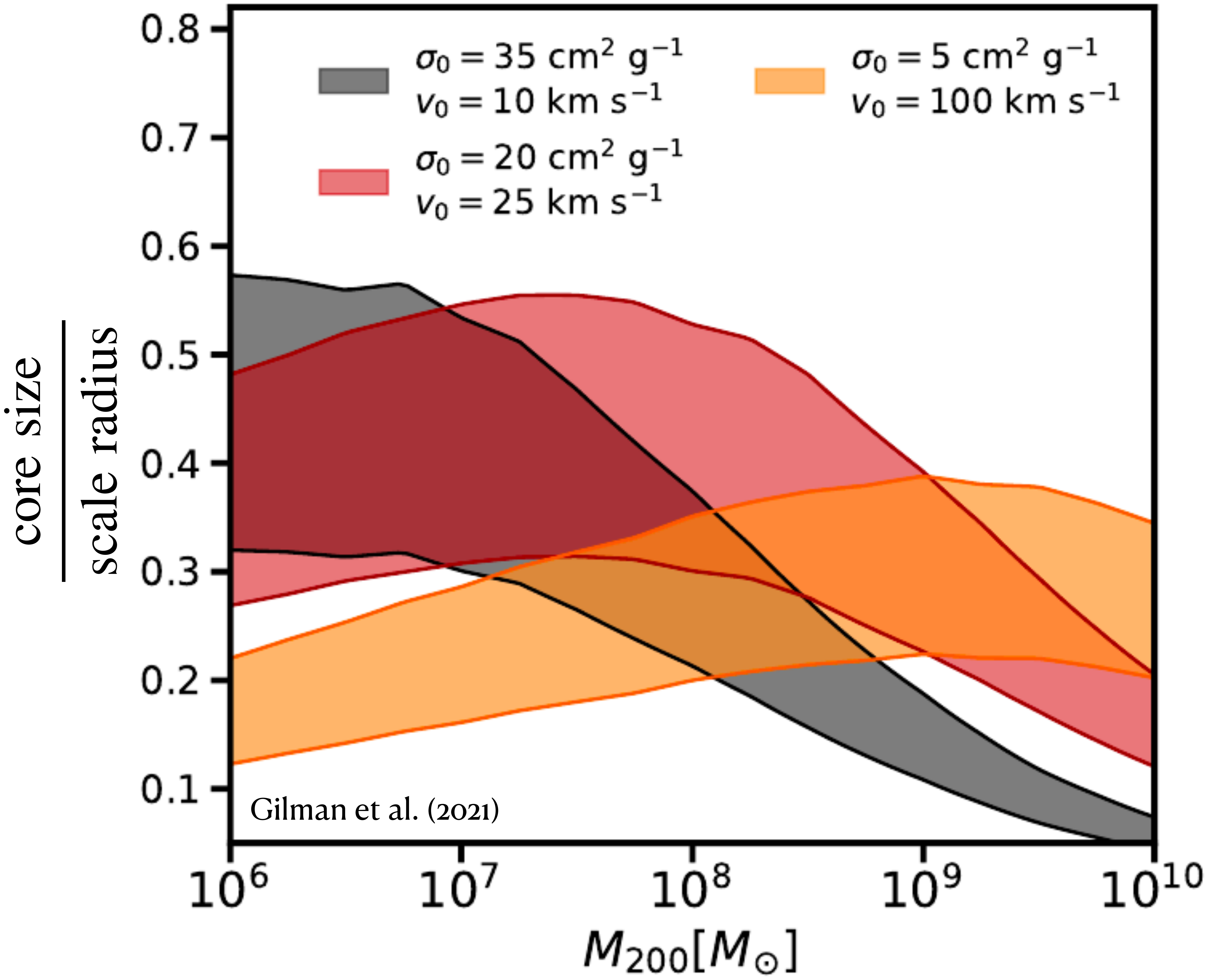


SIDM does 2 things to dark matter halos

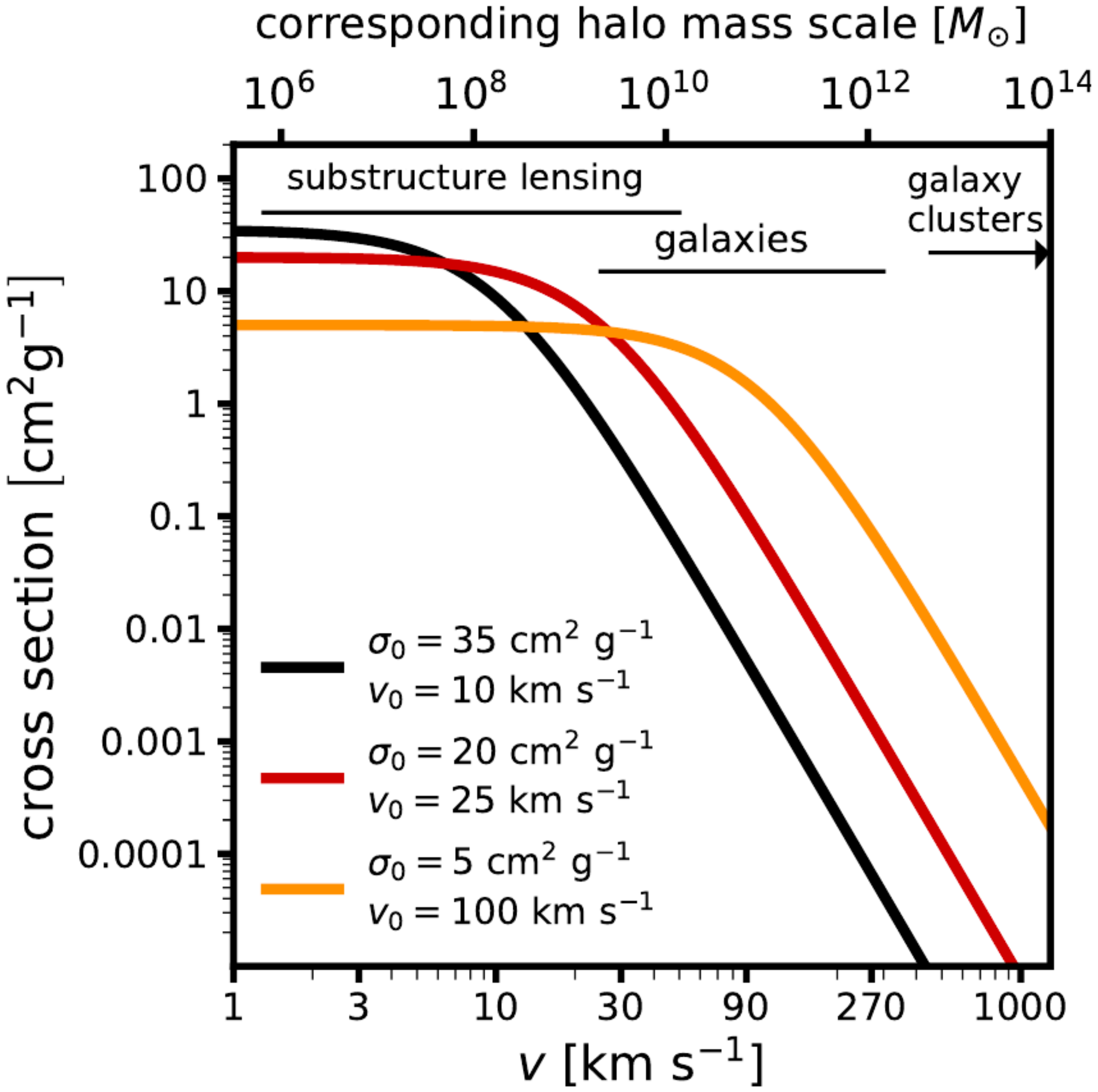
1) It forms large cores
(heat flows in)

2) cores eventually collapse
(heat flows out)

see Camila's talk later

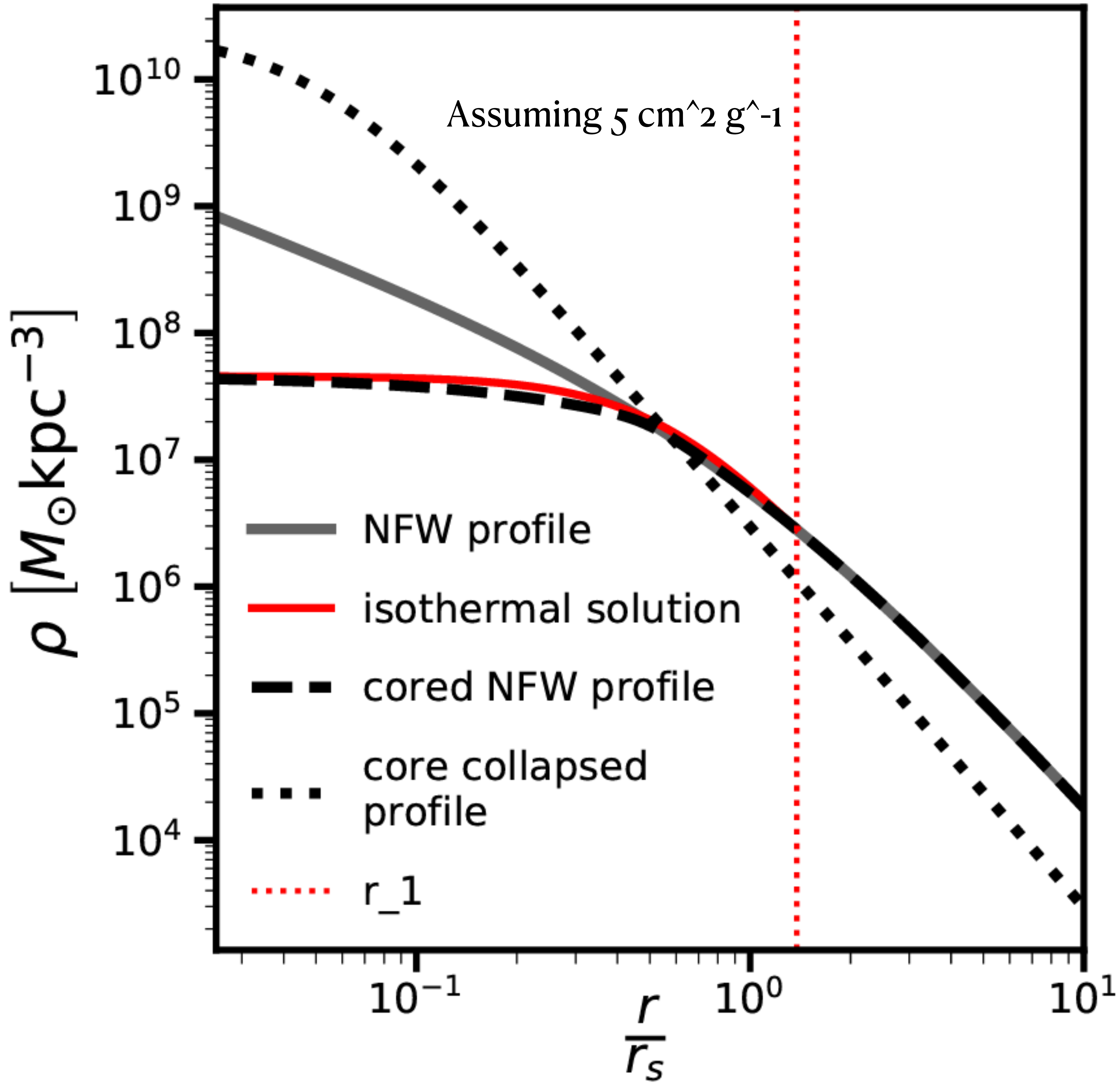


$\sigma_0 = 35$ cm^2 g^{-1}
$v_0 = 10$ km s^{-1}
$\sigma_0 = 20$ cm^2 g^{-1}
$v_0 = 25$ km s^{-1}
$\sigma_0 = 5$ cm^2 g^{-1}
$v_0 = 100$ km s^{-1}
$\frac{\text{core size}}{\text{scale radius}}$
$M_{200}[M_\odot]$
Gilman et al. (2021)



corresponding halo mass scale $[M_\odot]$
substructure lensing
galaxies
galaxy clusters
cross section [cm^{2}g^{-1}]
v [km s^{-1}]
$\sigma_0 = 35$ cm^2 g^{-1}
$v_0 = 10$ km s^{-1}
$\sigma_0 = 20$ cm^2 g^{-1}
$v_0 = 25$ km s^{-1}
$\sigma_0 = 5$ cm^2 g^{-1}
$v_0 = 100$ km s^{-1}

Gilman et al. (2021)



Core collapse

For subhalos

$$t_{\mathrm{collapse}} = 10\ t_{\mathrm{relax}} = \frac{10}{\langle \sigma v \rangle \rho_s}$$

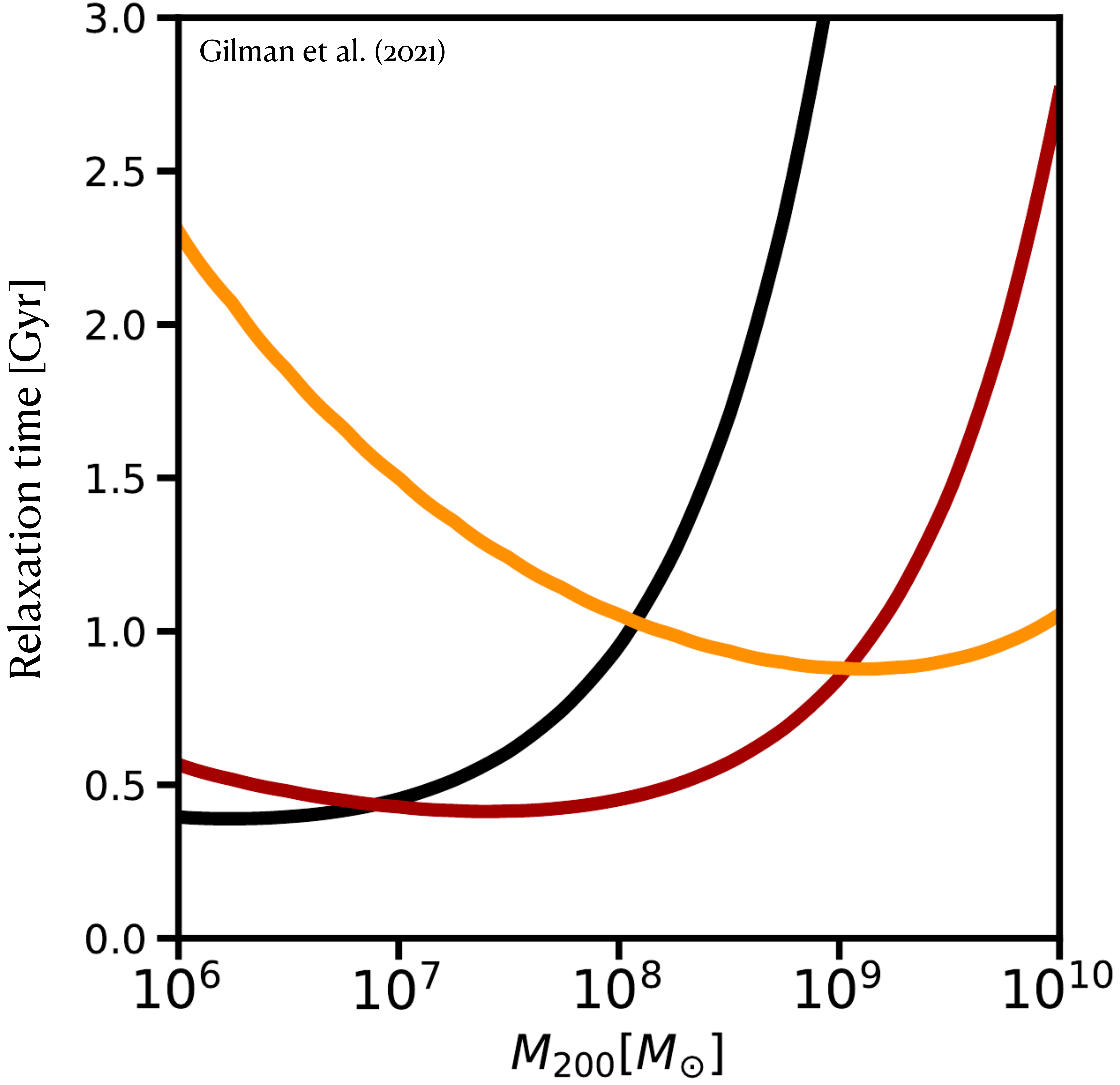
For field halos

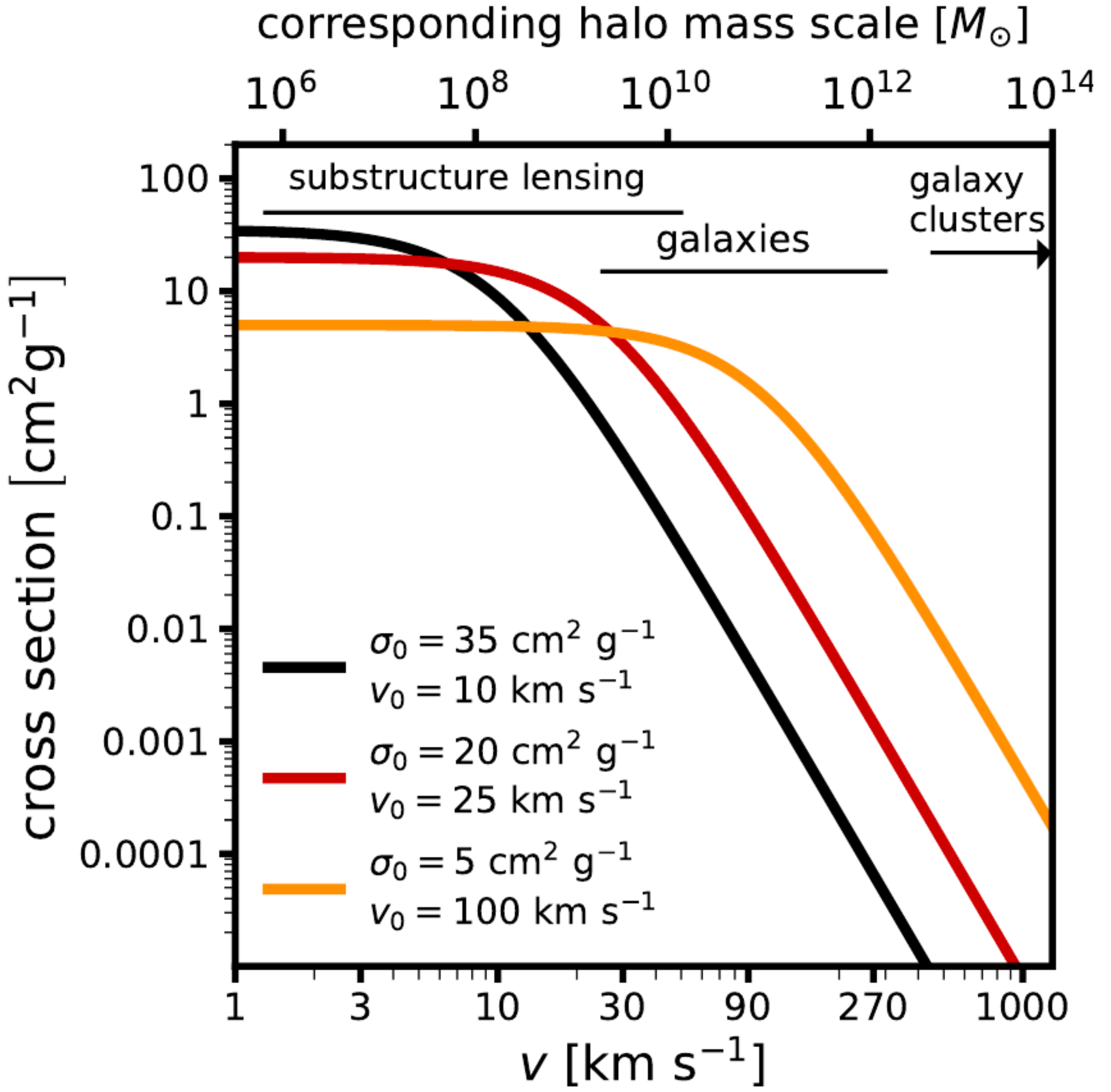
$$t_{\mathrm{collapse}} = 100\ t_{\mathrm{relax}} = \frac{100}{\langle \sigma v \rangle \rho_s}$$

Model the density profiles as

$\rho\,(r) \propto r^{-3}$

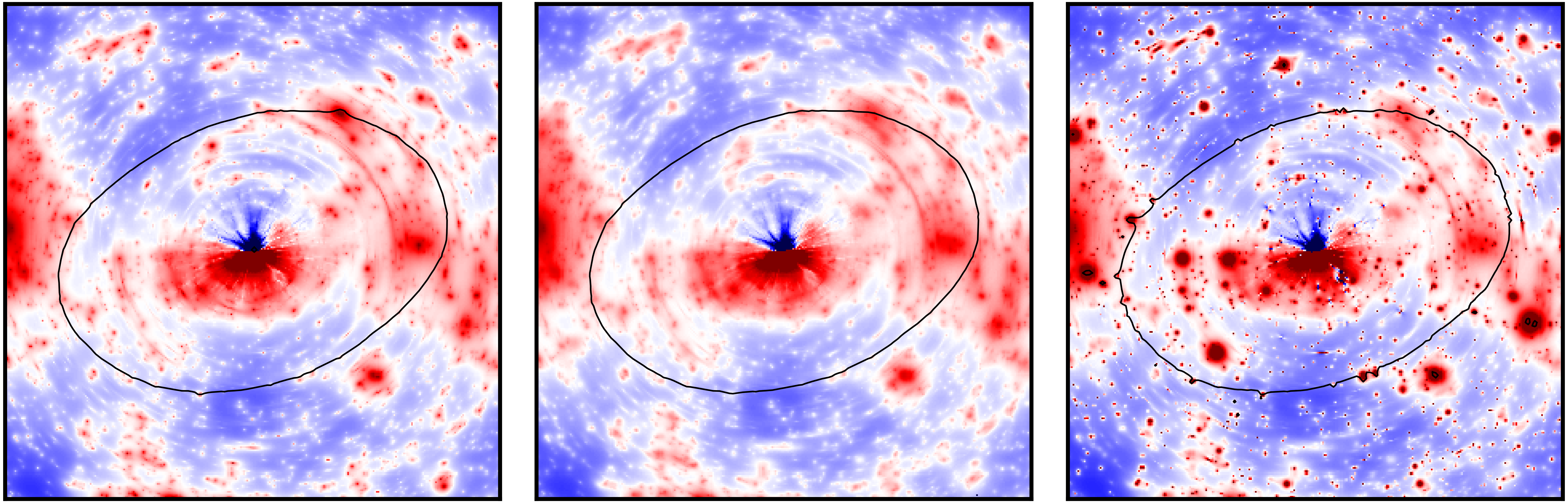
Turner, Lovell et al. 2020


Gilman et al. (2021)
Relaxation time [Gyr]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^6
10^7
10^8
10^9
10^10
M_200[M_⊙]

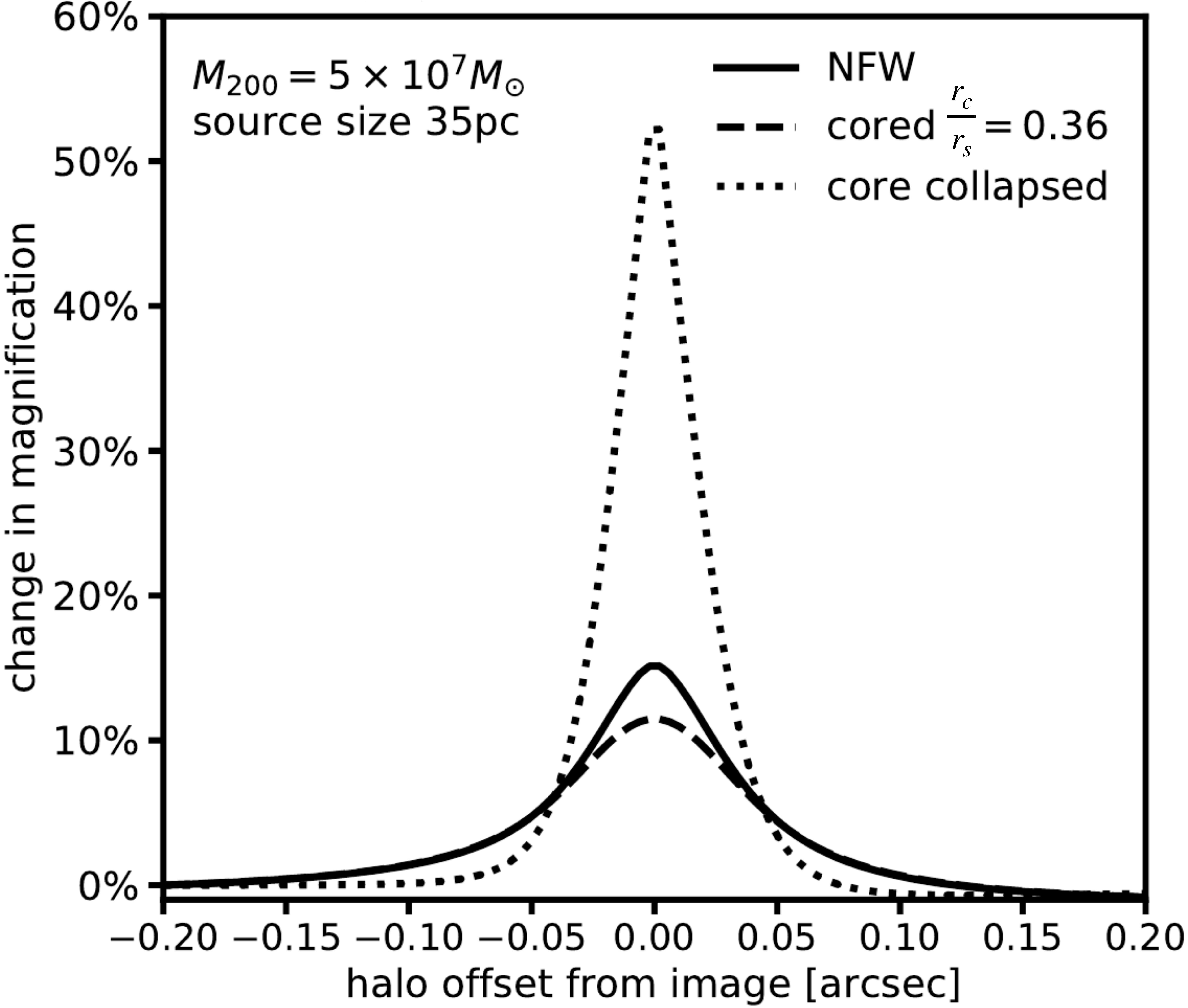

corresponding halo mass scale [M_⊙]
10^6
10^8
10^10
10^12
10^14
substructure lensing
galaxies
galaxy clusters
cross section [cm^2g^-1]
100
10
1
0.1
0.01
0.001
0.0001
σ_0 = 35 cm^2 g^-1
v_0 = 10 km s^-1
σ_0 = 20 cm^2 g^-1
v_0 = 25 km s^-1
σ_0 = 5 cm^2 g^-1
v_0 = 100 km s^-1
1
3
10
30
90
270
1000
v [km s^-1]

Putting it all together

CDM SIDM with cores only SIDM cores+core collapse



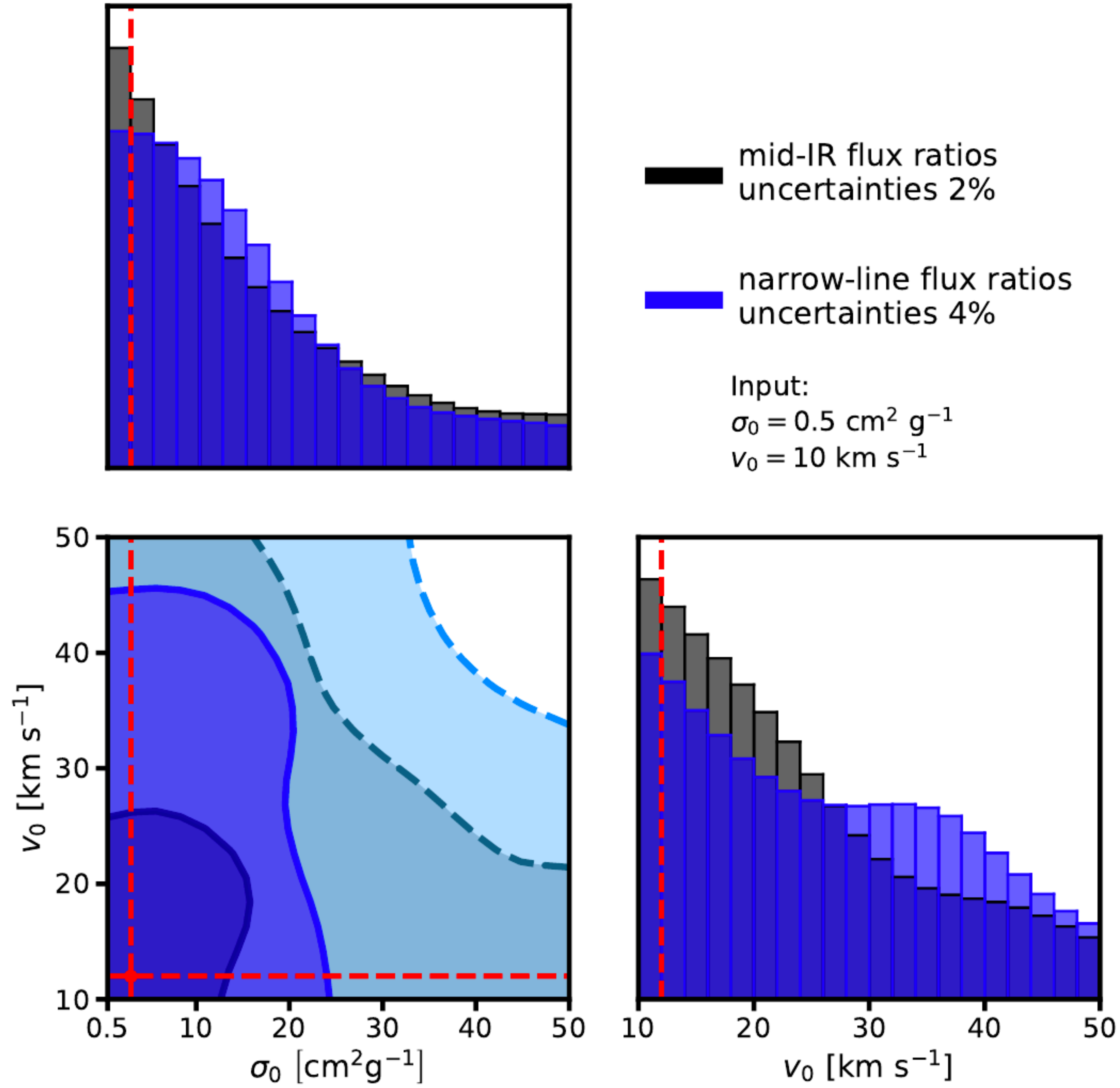
Gilman et al. (2021)



Cores probably not detectable

Core collapsed halos probably are

Gilman et al. (2021)



Forecasts with ~50 future quads

We get stronger constraints from mid-IR flux ratios to be obtained with JWST GO-2046 (PI Nierenberg)

Constraints on σ_{20} (amplitude at 20 km/sec)

σ_{20}< 22-26 cm^2 g^-1

Takeaway:

Strong lensing is a powerful probe of ANY dark matter theory that alters the abundance and density profiles of halos relative to CDM