Strong gravitational lensing and dark matter substructure

Implications for the nature of dark matter

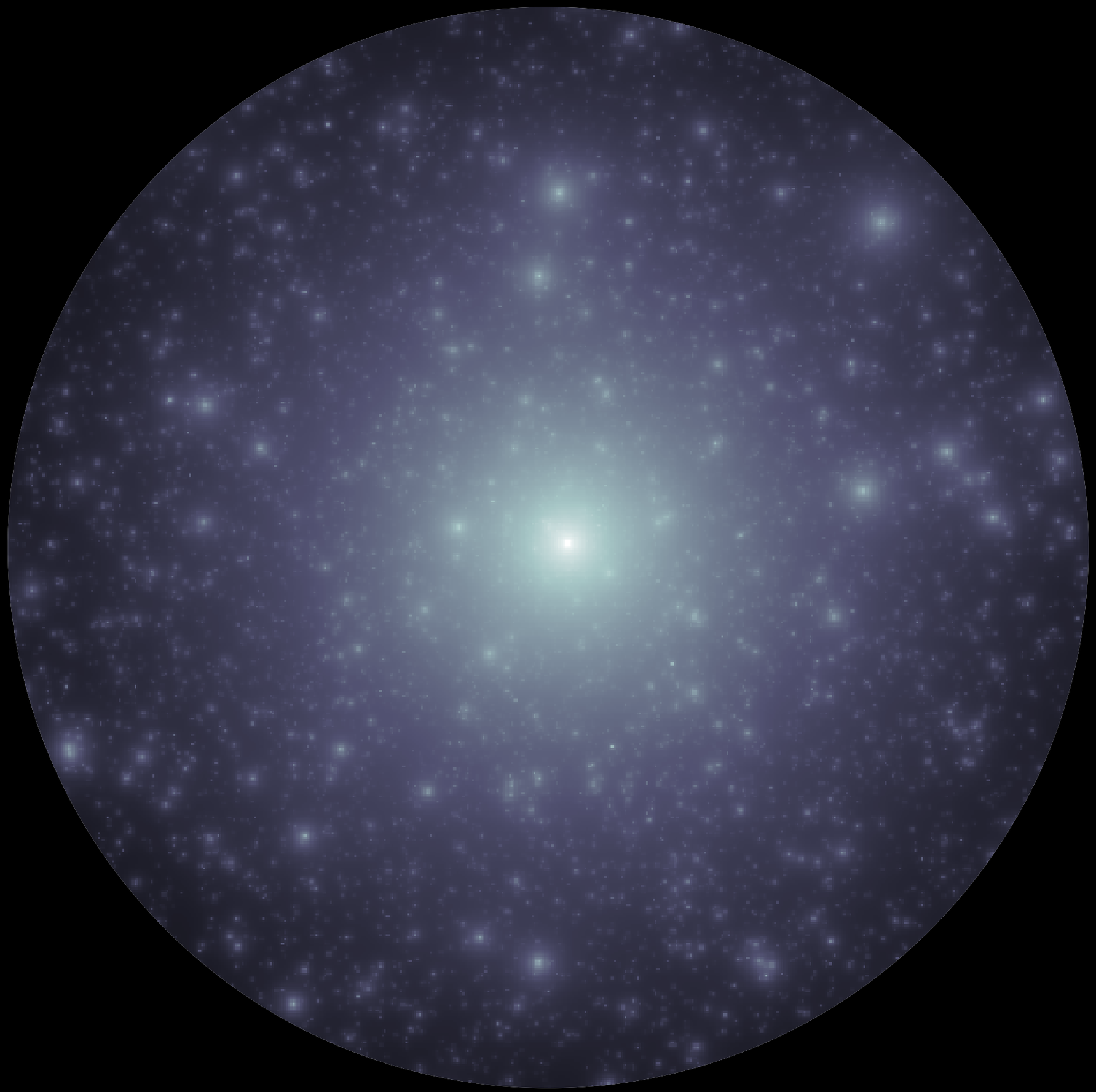
and

The effects of substructure on strong lensing measurements of H0

Daniel Gilman
(University of Toronto)

Collaborators:
Simon Birrer (Stanford)
Tommaso Treu (UCLA)
Anna Nierenberg (UC Merced)
Andrew Benson, Xiaolong Du (Carnegie)

Cold dark matter predicts an abundance of dark matter structure



Cold dark matter predicts an abundance of dark matter structure

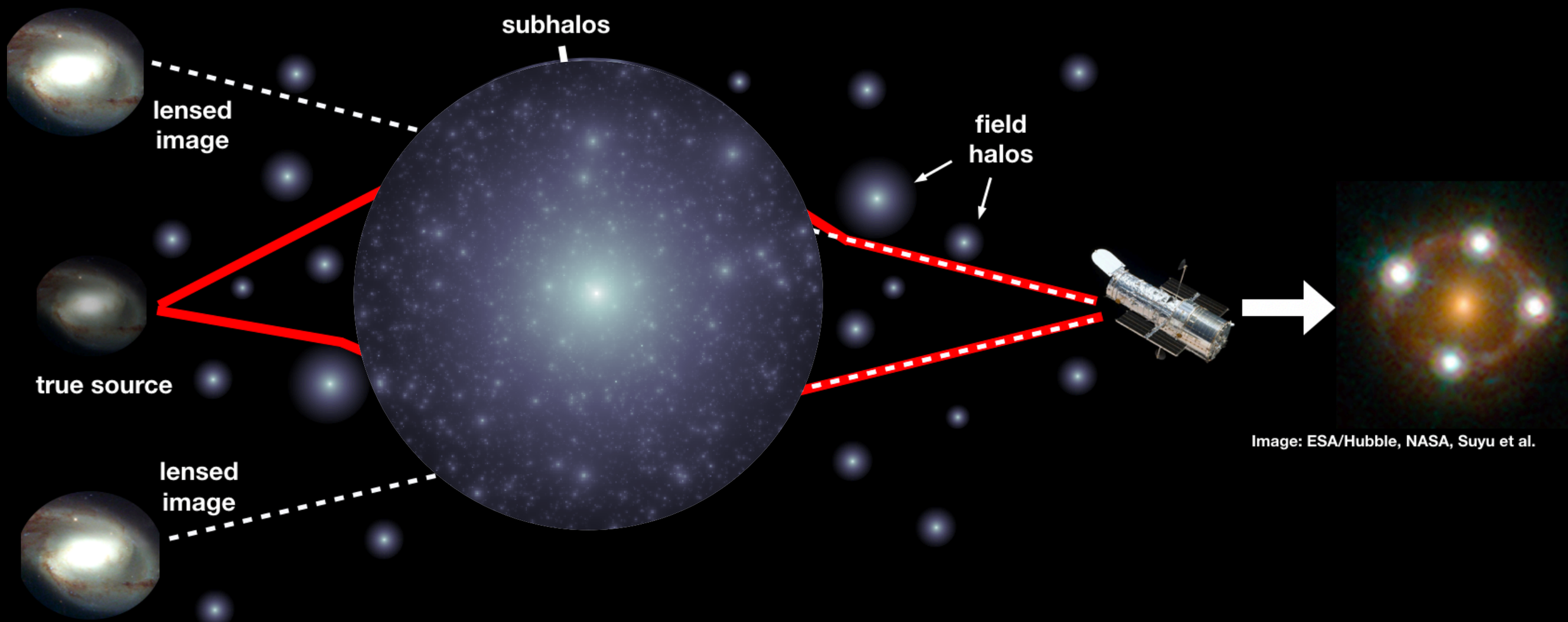
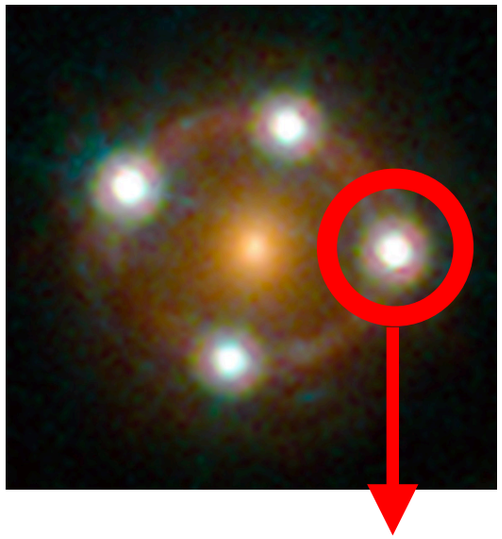
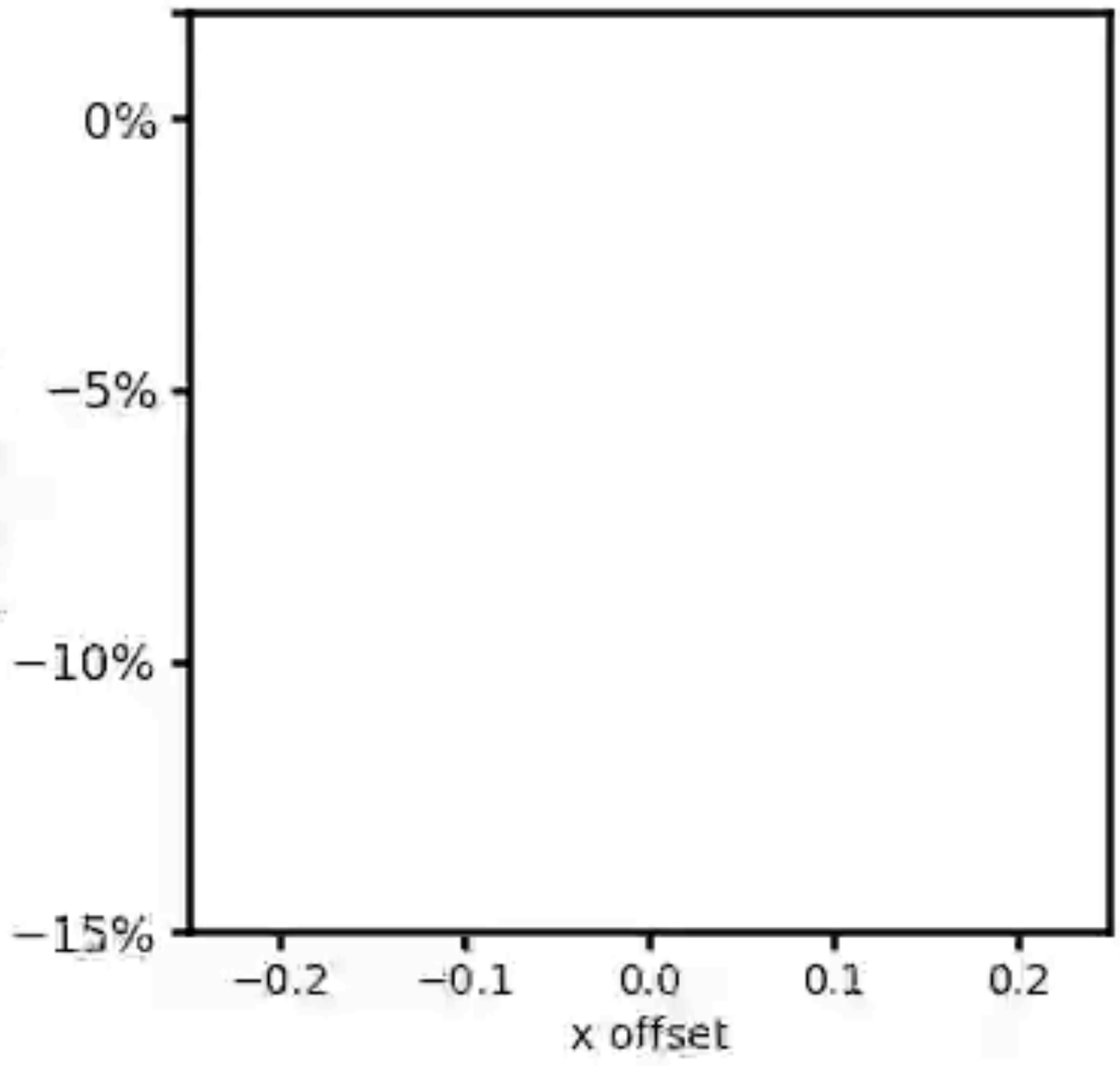
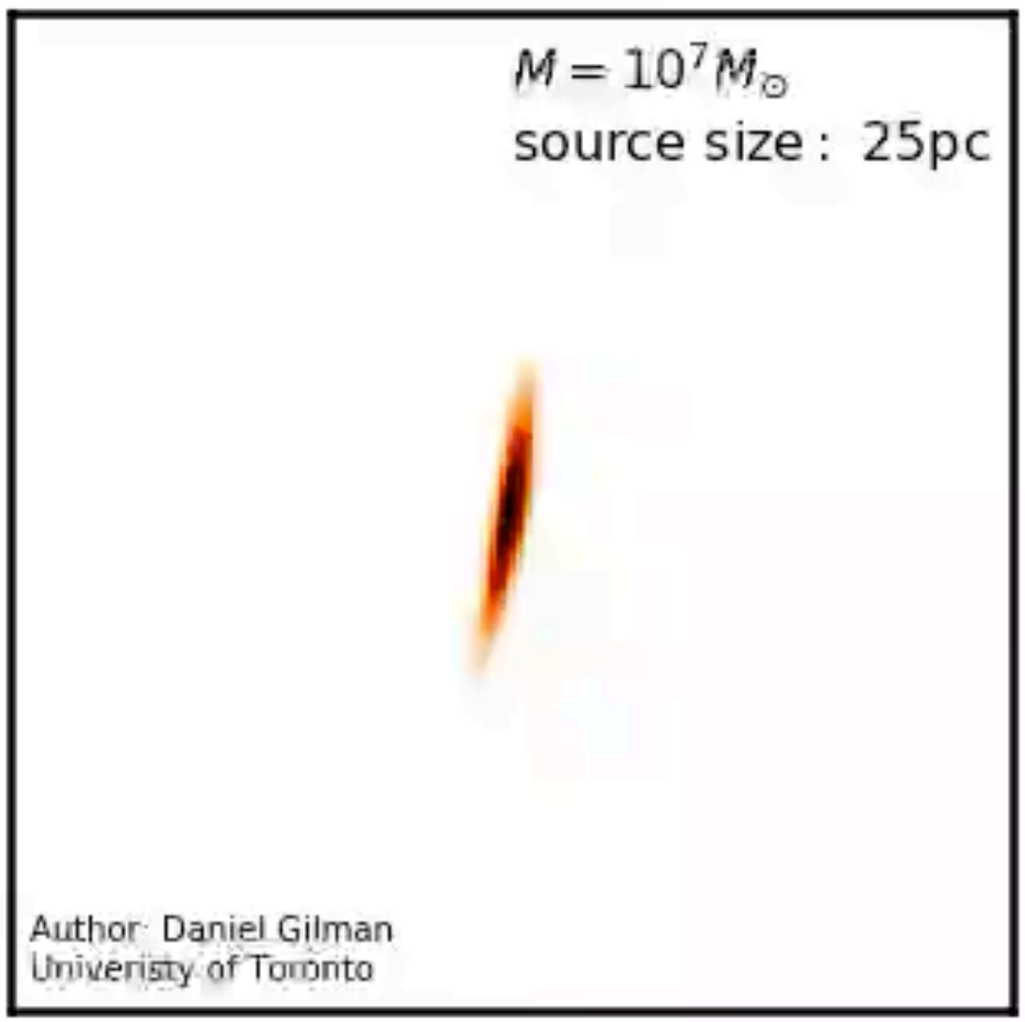


Image: ESA/Hubble, NASA, Suyu et al.

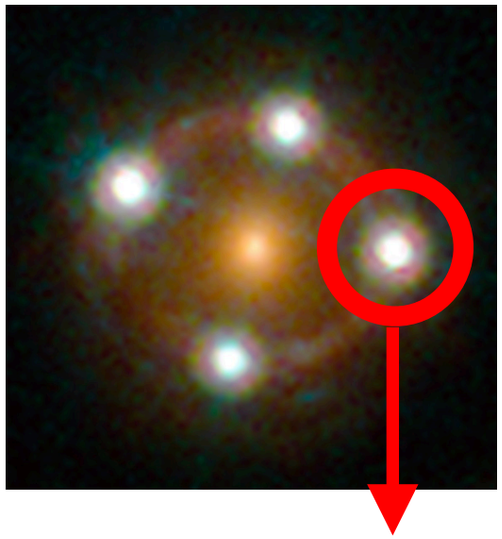
What happens when a halo is near an image?

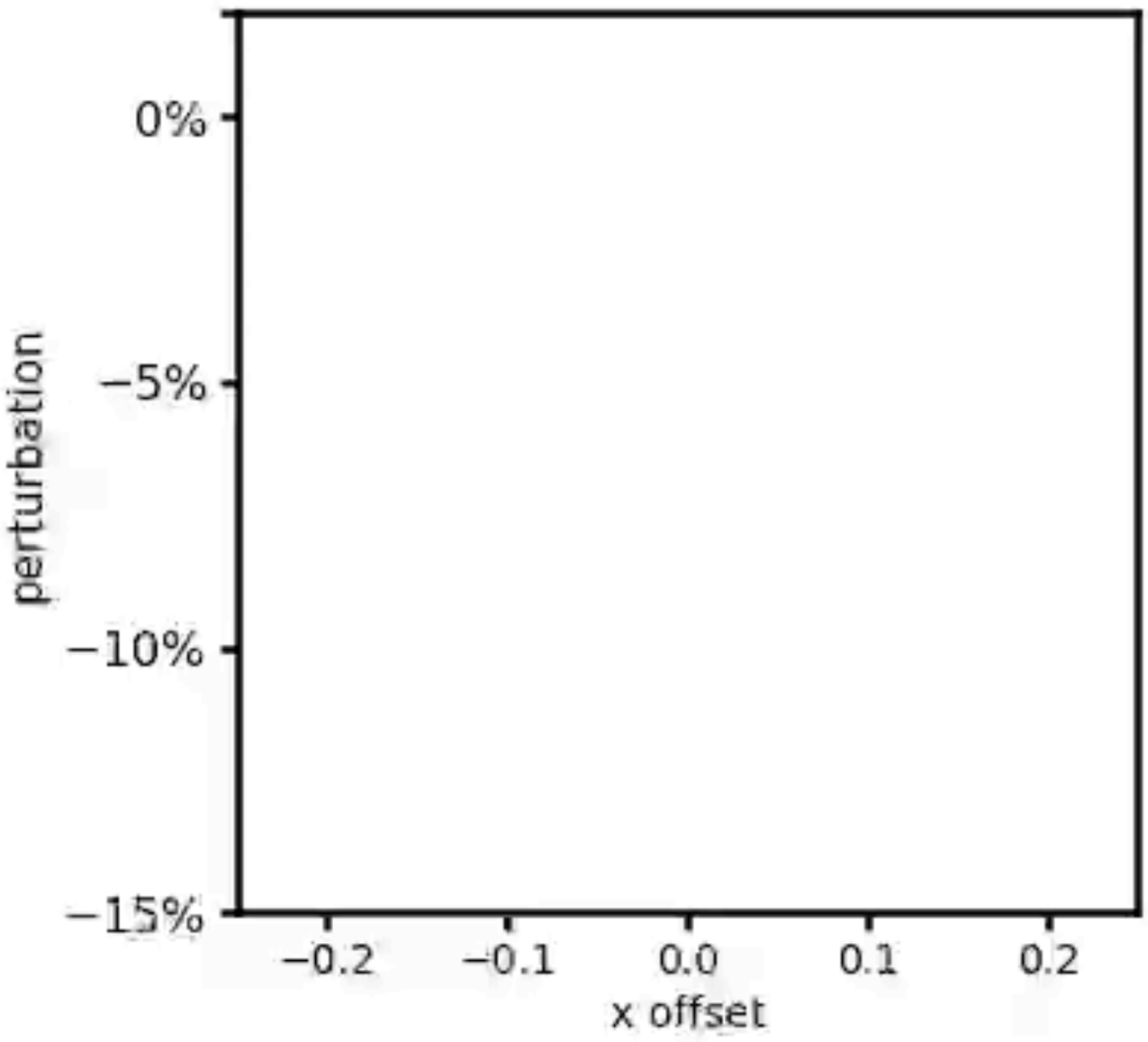


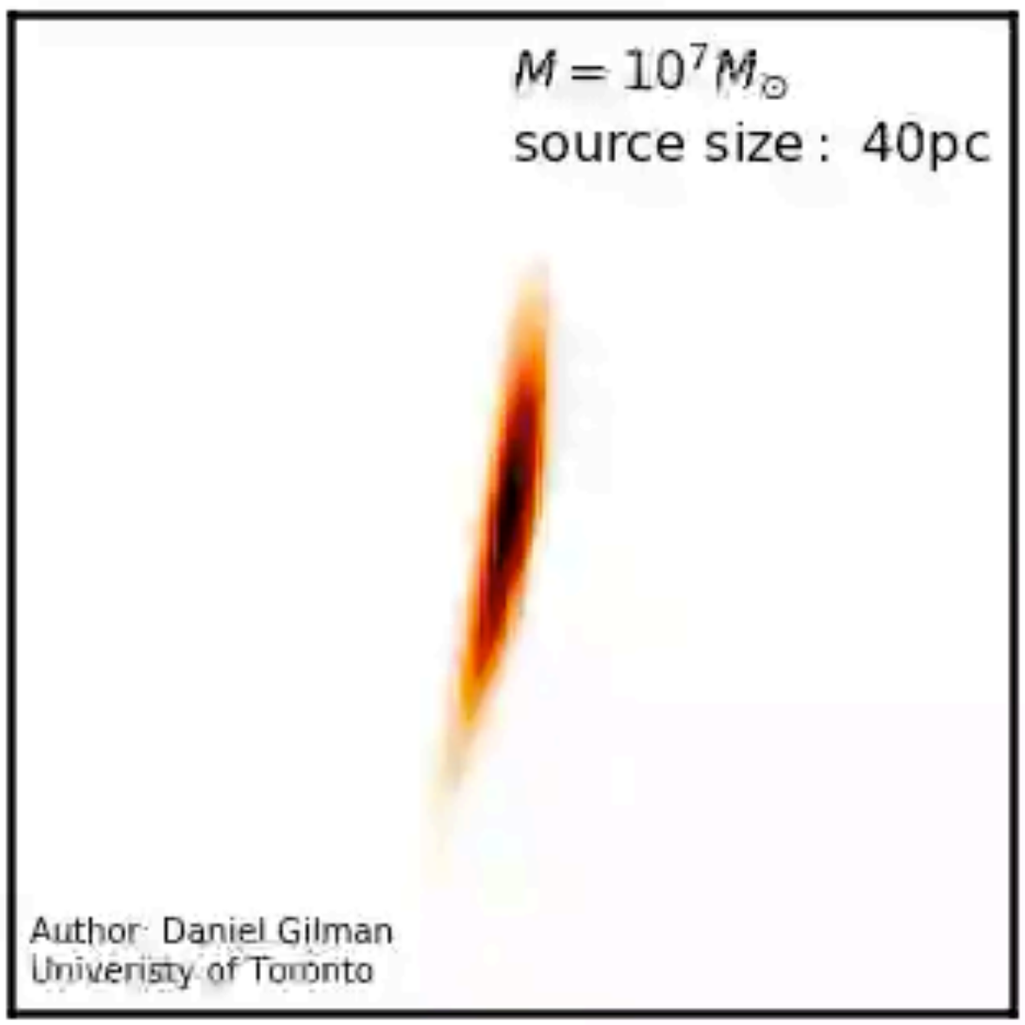




Size of the source determines the relevant angular scales

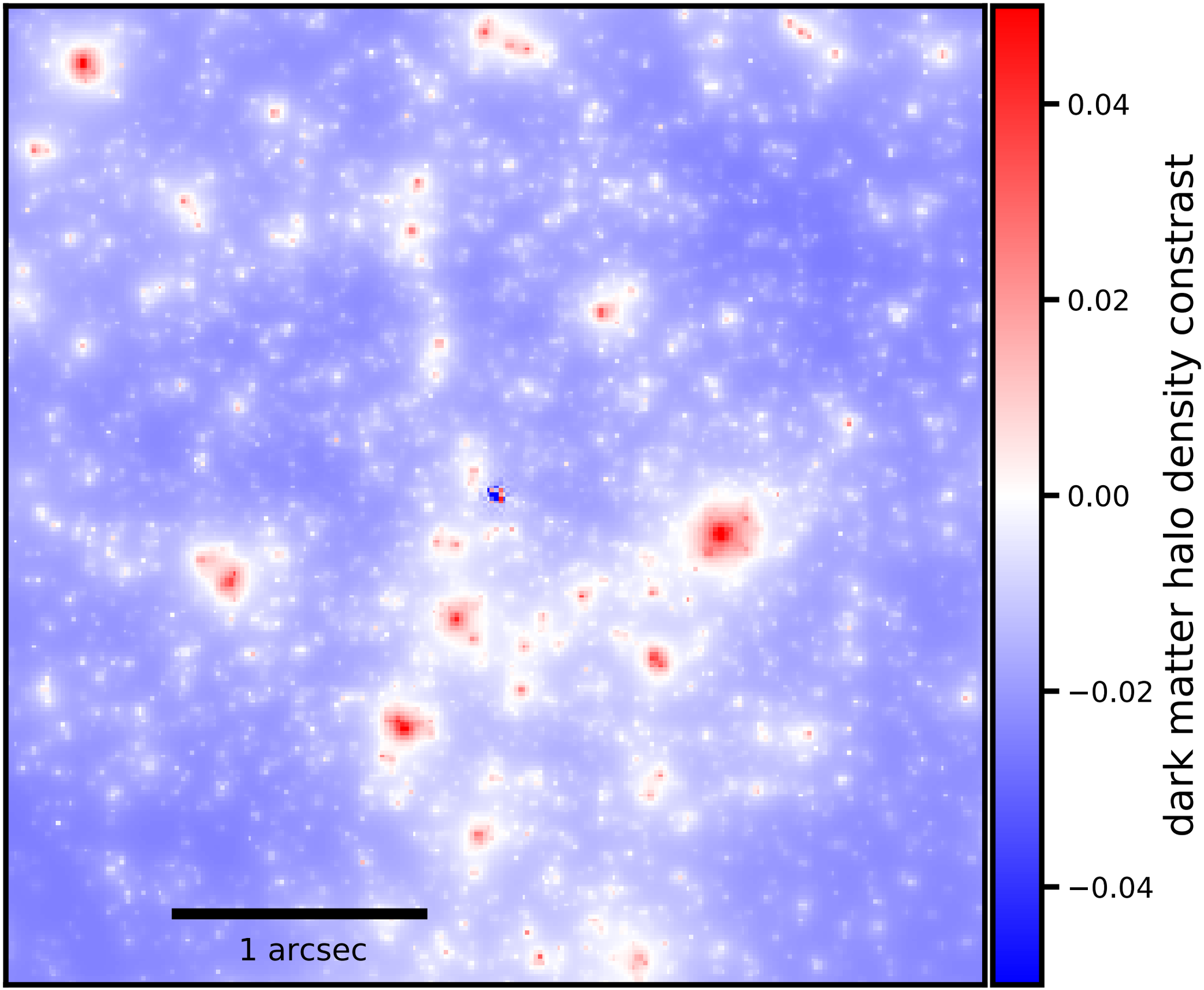






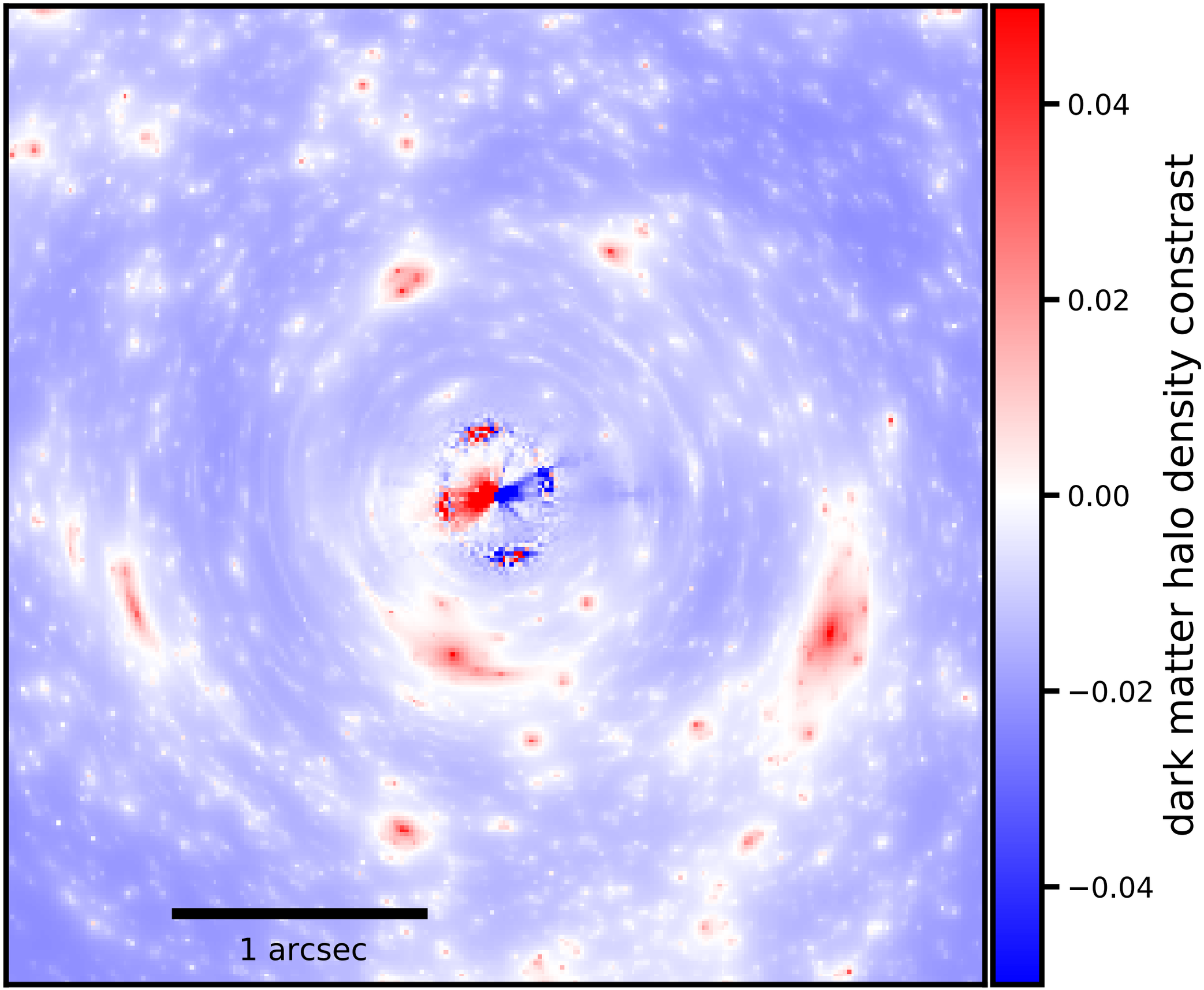
What about a full population of halos?

Subhalos + LOS viewed in projection



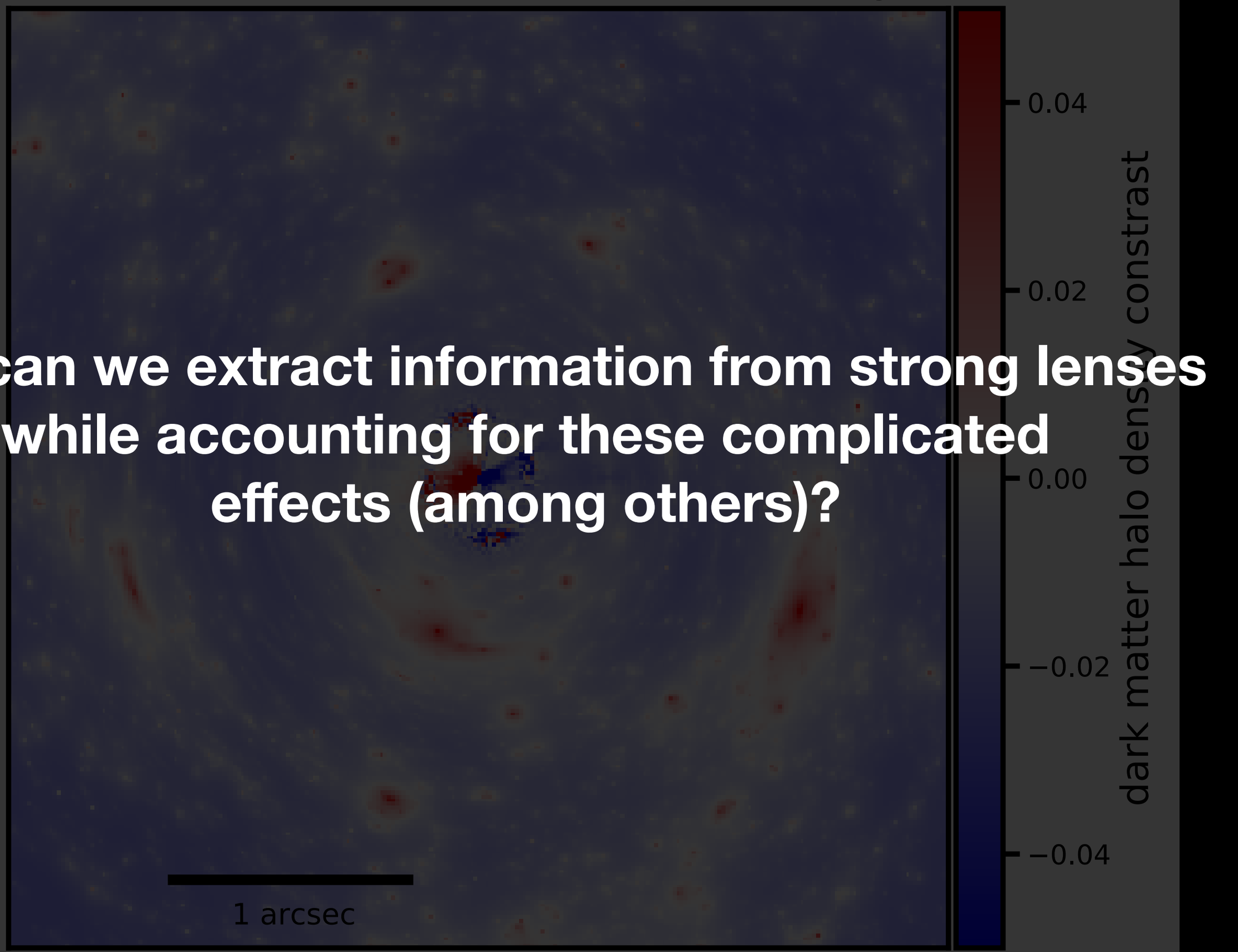
What about a full population of halos?

Subhalos + LOS with multi-plane lensing



What about a full population of halos?

Subhalos + LOS with multi-plane lensing



How can we extract information from strong lenses while accounting for these complicated effects (among others)?

Forward Modeling

DM theory
e.g. free-streaming length

A background source models

Realizations of dark matter structure
~10^6 per lens

Gravitational lensing computations

Main deflector lens model

measurement uncertainties

Model-predicted flux ratios

Observed flux ratios

things we know or want to infer
nuisance parameters

Posterior probability distributions/inferences obtained through summary statistics

Forward Modeling

DM theory
e.g. free-streaming length

Realizations of dark matter structure
~10^6 per lens

A background source models

Gravitational lensing computations

Main deflector lens model

measurement uncertainties

Model-predicted flux ratios

Observed flux ratios

Posterior probability distributions/inferences obtained through summary statistics

things we know or want to infer
nuisance parameters

Forward Modeling

DM theory
e.g. free-streaming length

A background source model

Realizations of dark matter structure
~10^6 per lens

Gravitational lensing computations

Main deflector lens model

measurement uncertainties

Model-predicted flux ratios

Observed flux ratios

things we know or want to infer
nuisance parameters

Posterior probability distributions/inferences obtained through summary statistics

Forward Modeling

DM theory
e.g. free-streaming length

A background source model

Realizations of dark matter structure
~10^6 per lens

Gravitational lensing computations

Main deflector lens model

measurement uncertainties

Model-predicted flux ratios

Observed flux ratios

things we know or want to infer
nuisance parameters

Posterior probability distributions/inferences obtained through summary statistics

Forward Modeling

DM theory
e.g. free-streaming length

A background source model

Realizations of dark matter structure
~10^6 per lens

Gravitational lensing computations

Main deflector lens model

measurement uncertainties

Model-predicted flux ratios

Observed flux ratios

things we know or want to infer
nuisance parameters

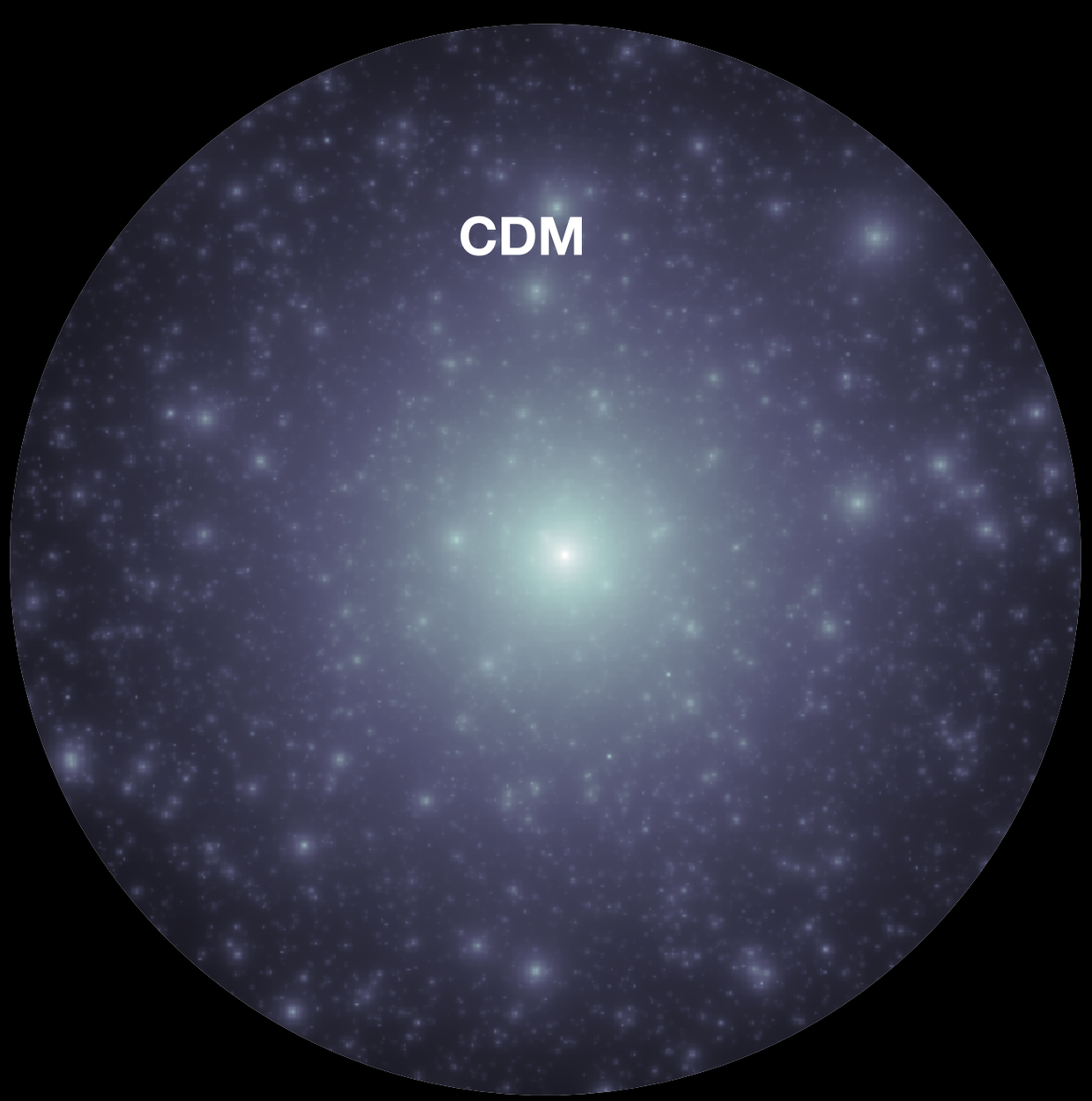
Posterior probability distributions/inferences obtained through summary statistics

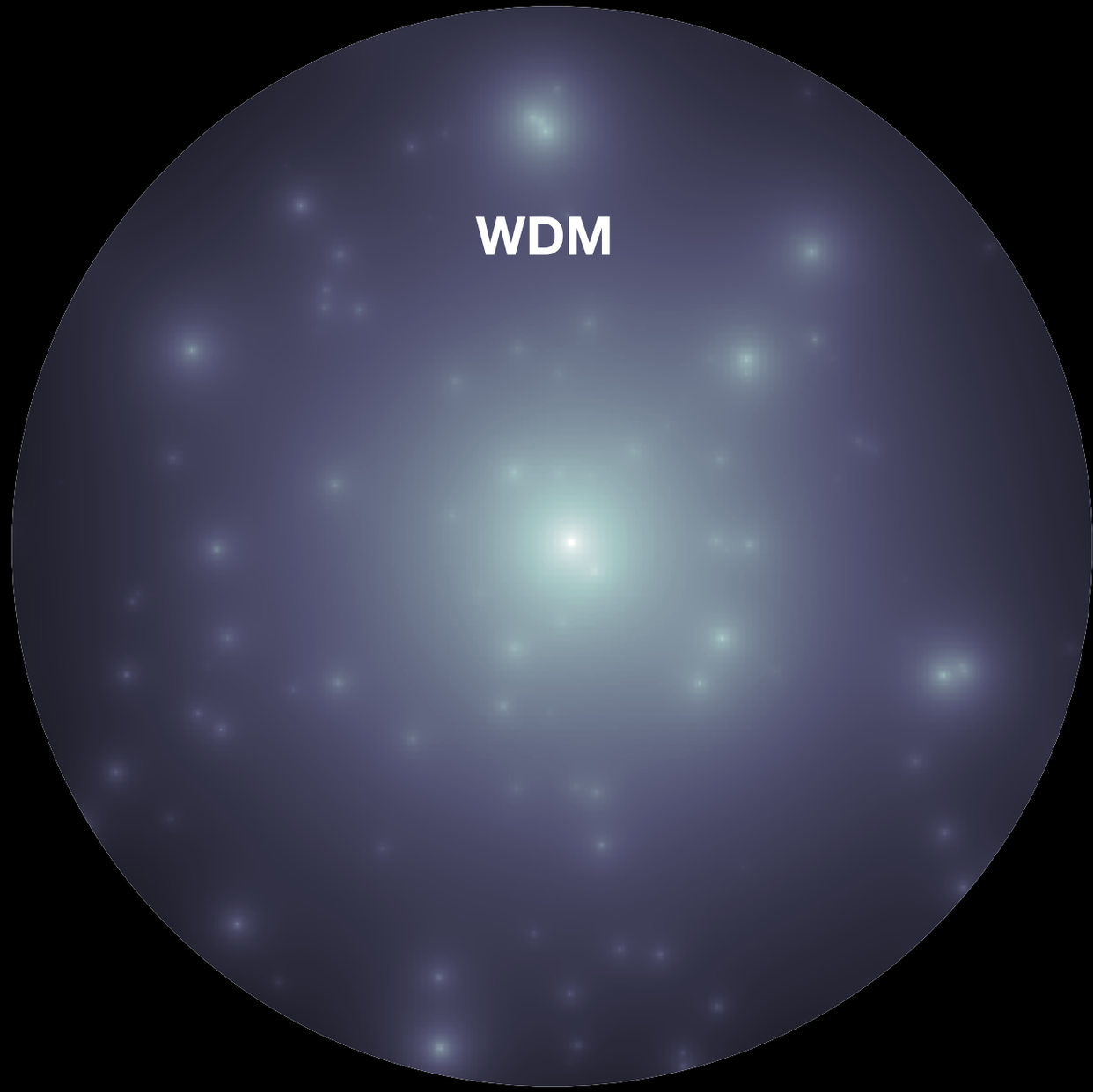
First science case:
CDM versus WDM

Second science case:
CDM concentration-mass relation

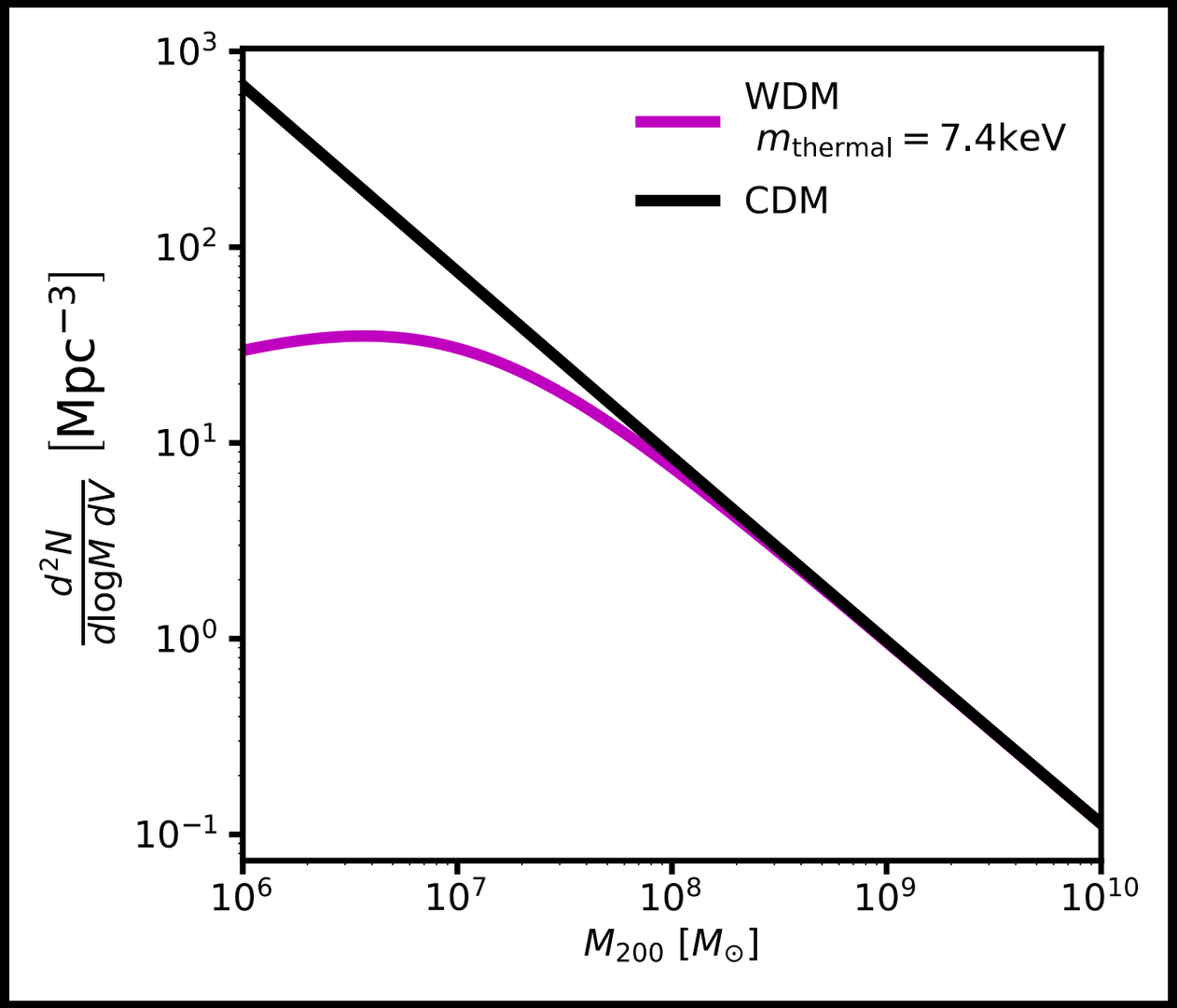
Third science case:
Substructure and TDCOSMO

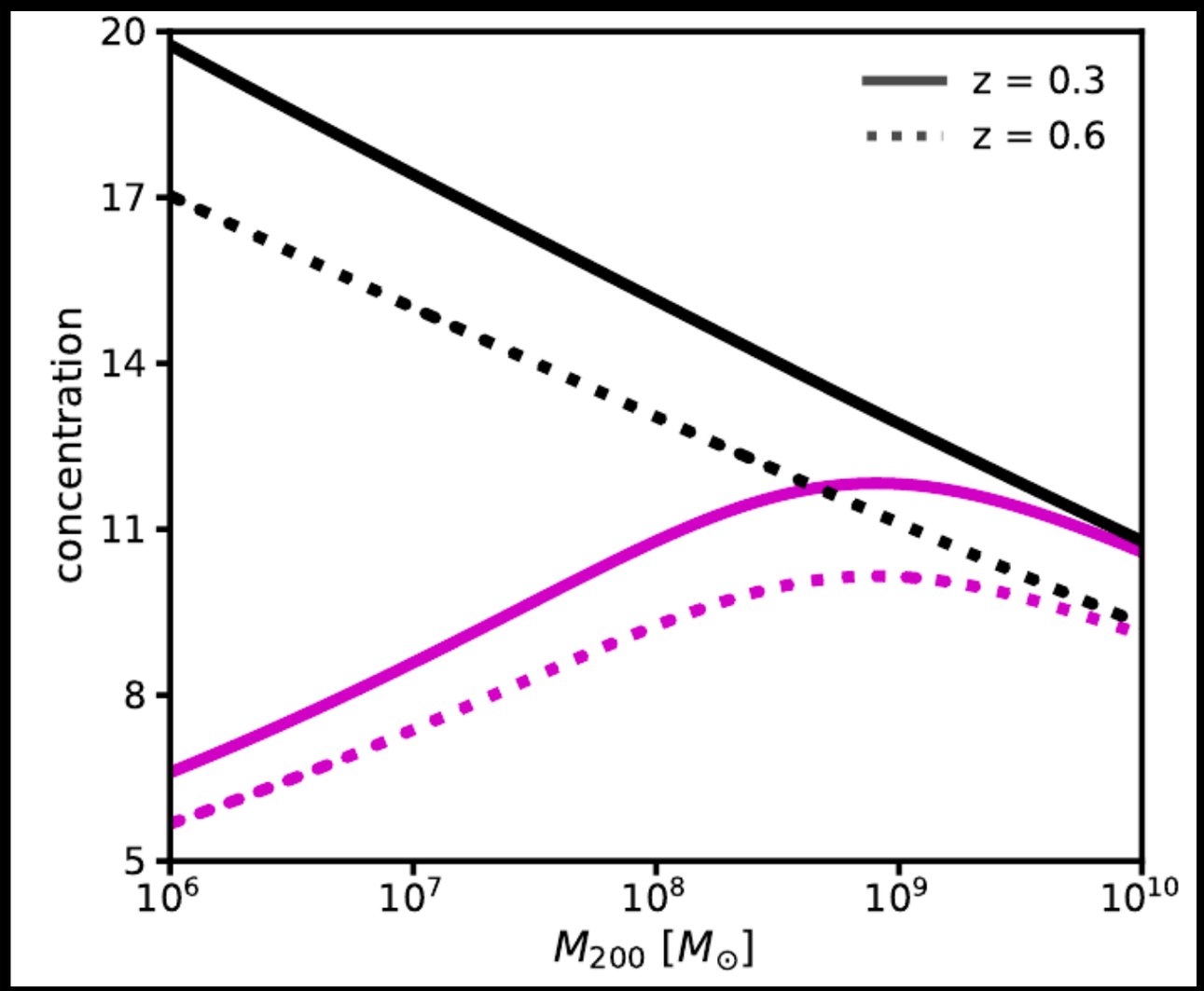
First science case:
CDM versus WDM





First science case:
CDM versus WDM





Both the number of halos (top left) and their concentrations (top right) are suppressed below a characteristic mass scale in WDM

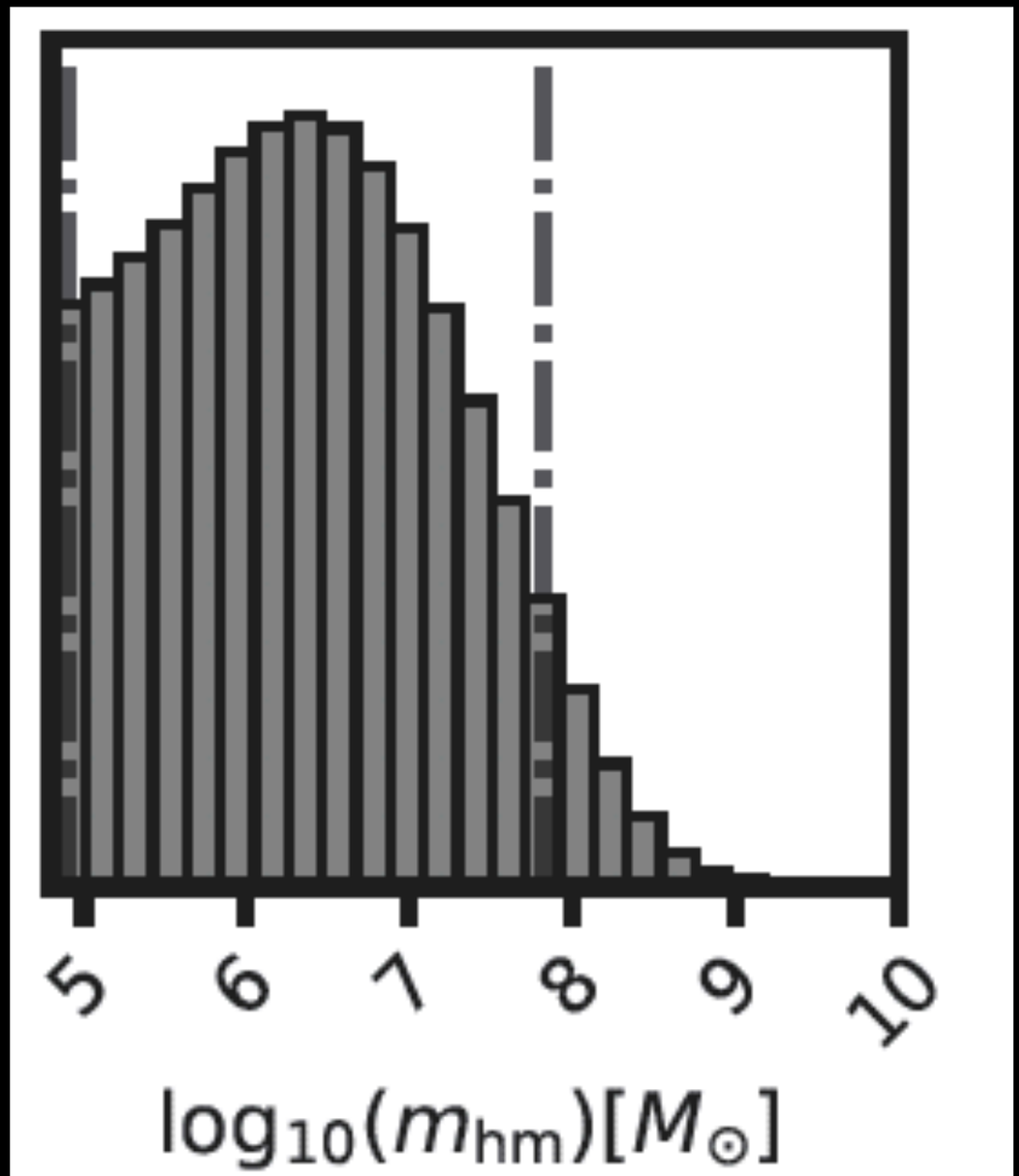
First science case:
CDM versus WDM

$$2\sigma: m_{\rm hm} < 10^{7.8} M_\odot,\ m_{\rm DM} > 5.2 {\rm keV}$$

Model accounts for:

1) subhalos + LOS halos with full multi-plane ray tracing
2) Flux ratios computed with finite-size background sources
3) Effects of WDM free-streaming on mass function and concentration-mass relation
4) Host halo mass and redshift effects on subhalo mass function
5) Marginalization over the lens macromodel

See also Hsueh et al. 2020



Adapted from Gilman et al. 2020a

https://arxiv.org/pdf/1908.06983.pdf

First science case:
CDM versus WDM

See also

Dark Matter Constraints from a Unified Analysis of Strong Gravitational Lenses and Milky Way Satellite Galaxies

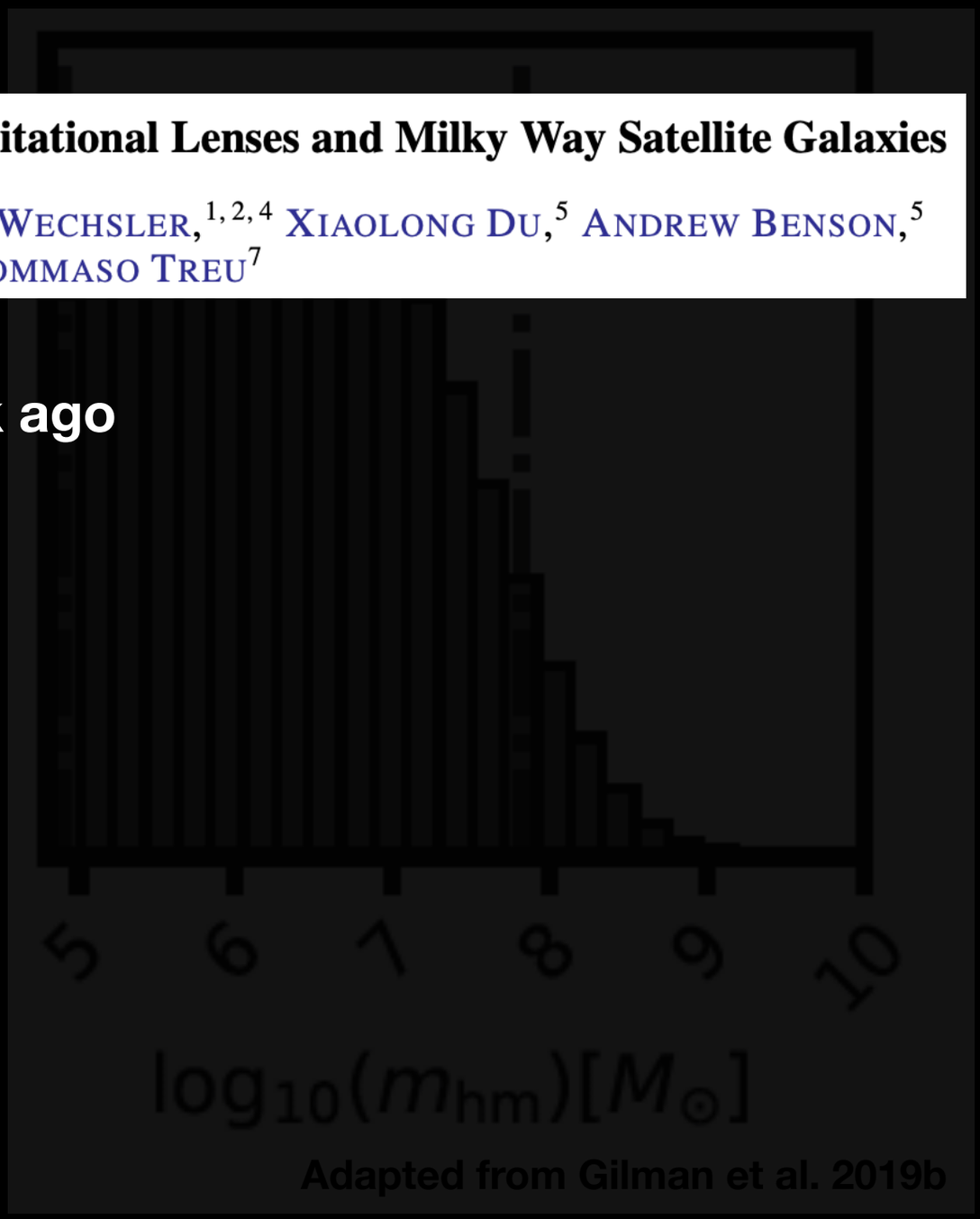
ETHAN O. NADLER,[1,2] SIMON BIRRER,[1,2] DANIEL GILMAN,[3] RISA H. WECHSLER,[1,2,4] XIAOLONG DU,[5] ANDREW BENSON,[5] ANNA M. NIERENBERG,[6] AND TOMMASO TREU[7]

on arXiv ~1 week ago

Model accounts for:

1) subhalos + LOS halos with full multi-plane ray tracing
2) Flux ratios computed with finite-size background sources
3) Effects of WDM free-streaming on mass function and concentration-mass relation
4) Host halo mass and redshift effects on subhalo mass function
5) Marginalization over the lens macromodel

See also Hsueh et al. 2020



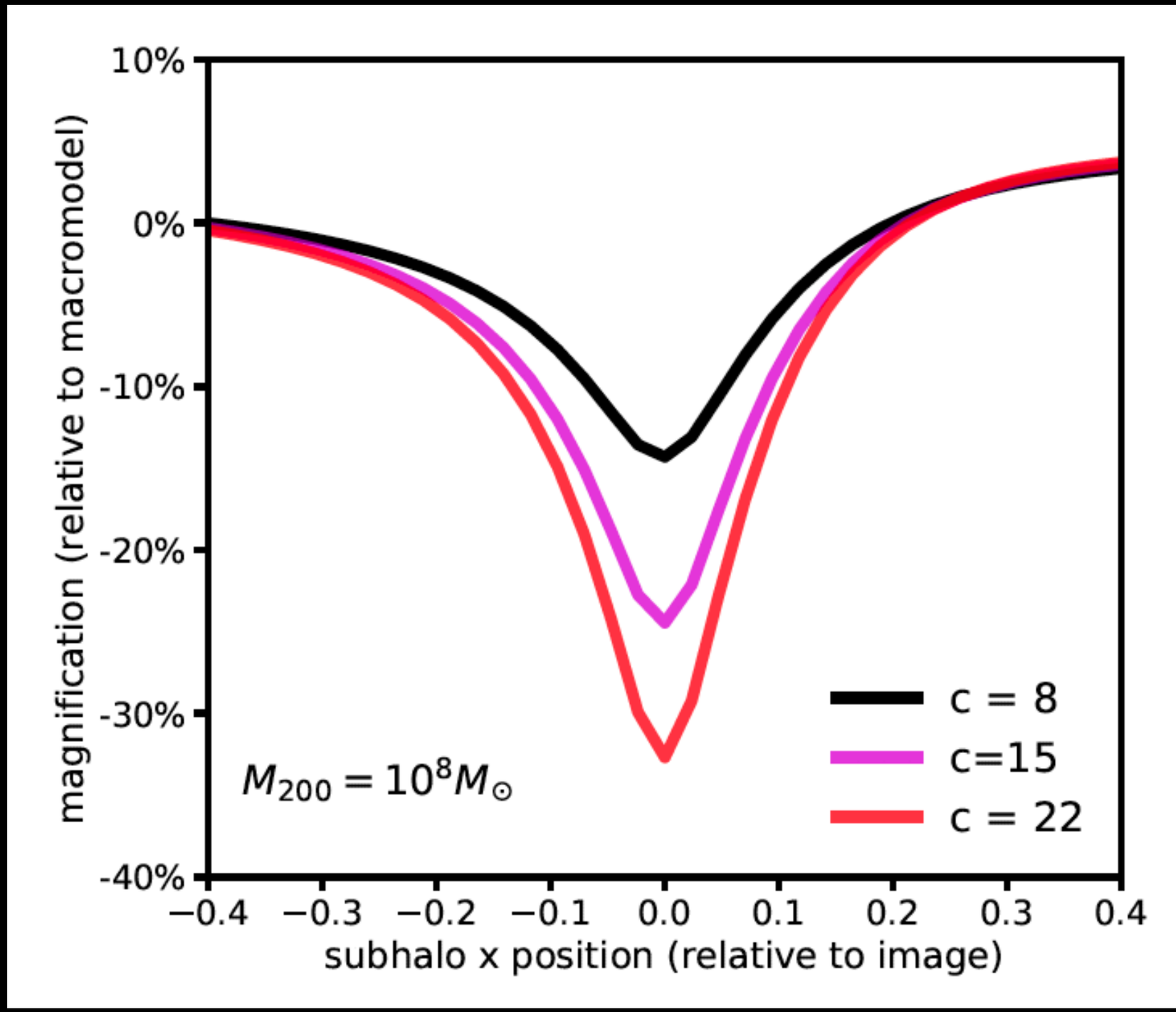
Adapted from Gilman et al. 2019b

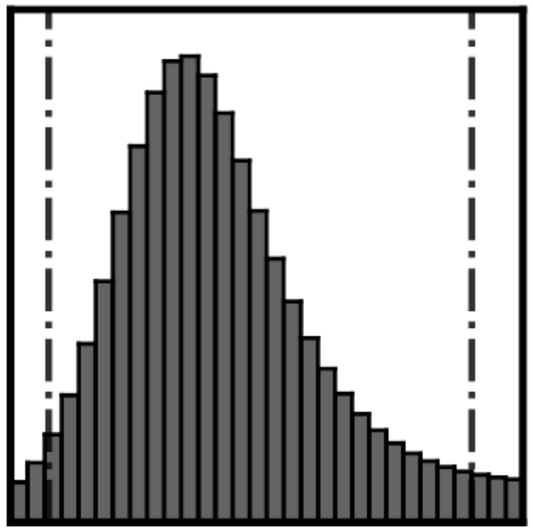
Second science case:
CDM concentration-mass relation between 10^6 - 10^10 solar masses

Concentration encodes the assembly history of hierarchical structure, primordial P(k)

Less concentrated halos are less efficient gravitational lenses

$$\rho_{\text{central}} \propto \frac{c^3}{\log(c)}$$

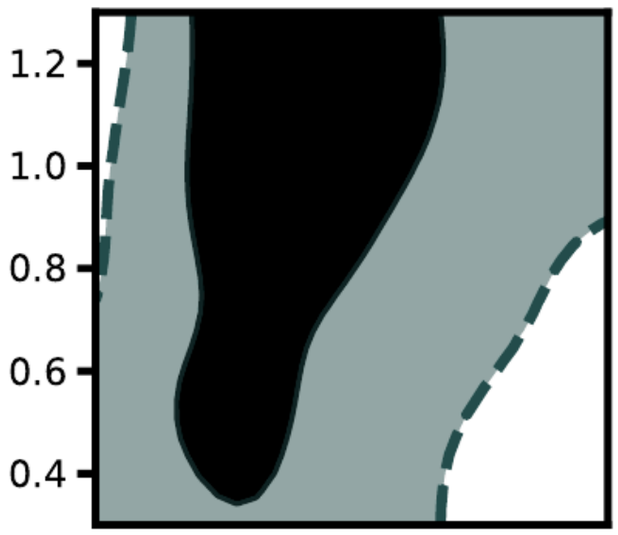


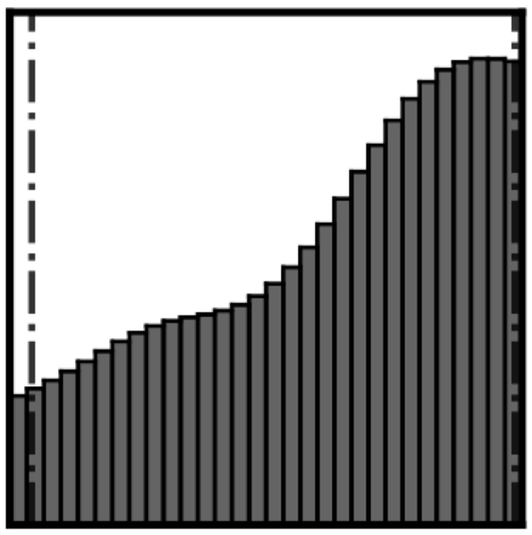


Results consistent with CDM on sub-galactic scales

Adapted from Gilman et al. 2020b

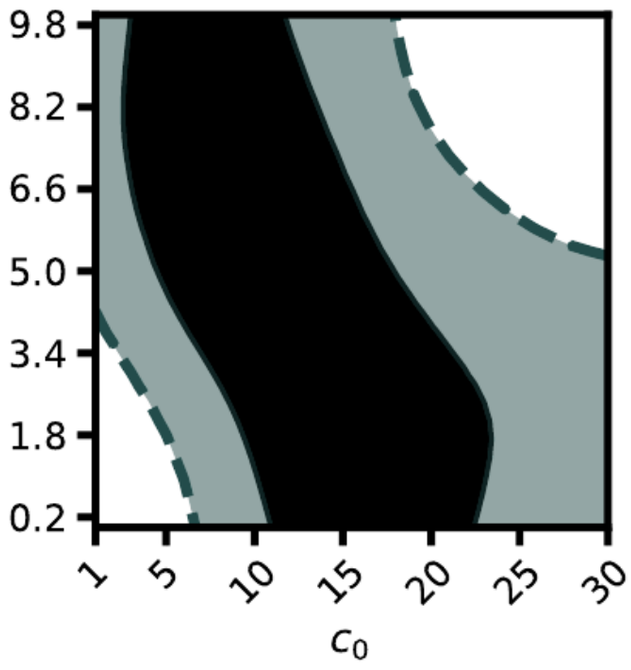
https://arxiv.org/pdf/1909.02573.pdf

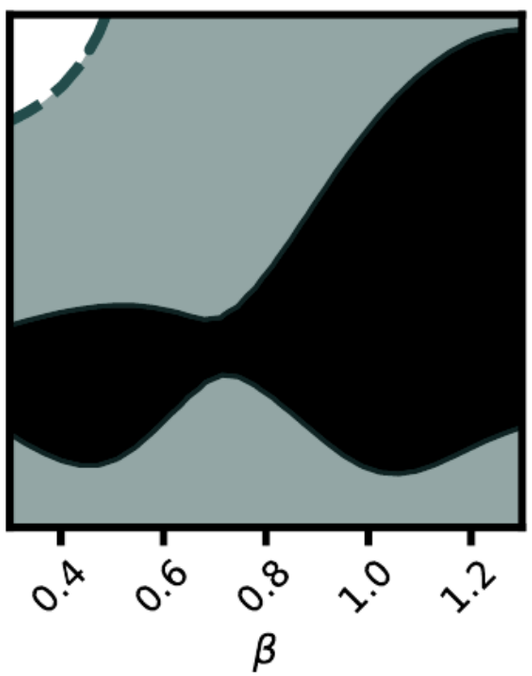


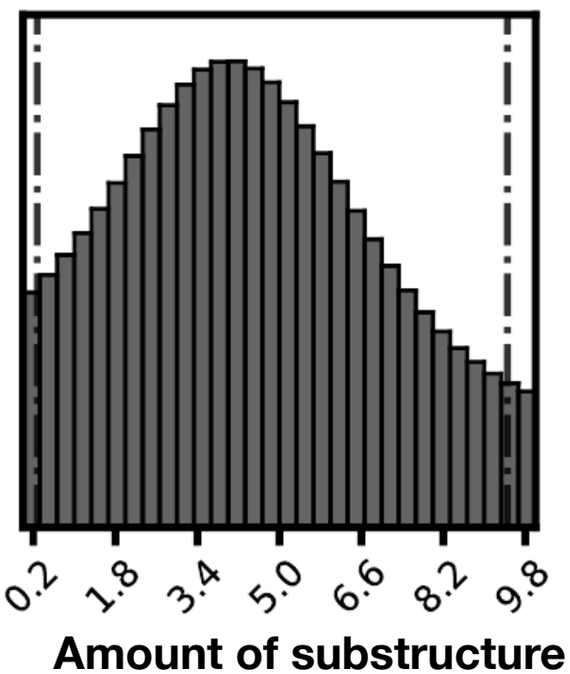


$$c\,(M,z) = c_0\,(1+z)^{\zeta}\left(\frac{\sigma\,(M,z)}{\sigma\left(10^8,0\right)}\right)^{-\beta}$$

Where sigma = variance of P(k) on lagrangian radius R(M)







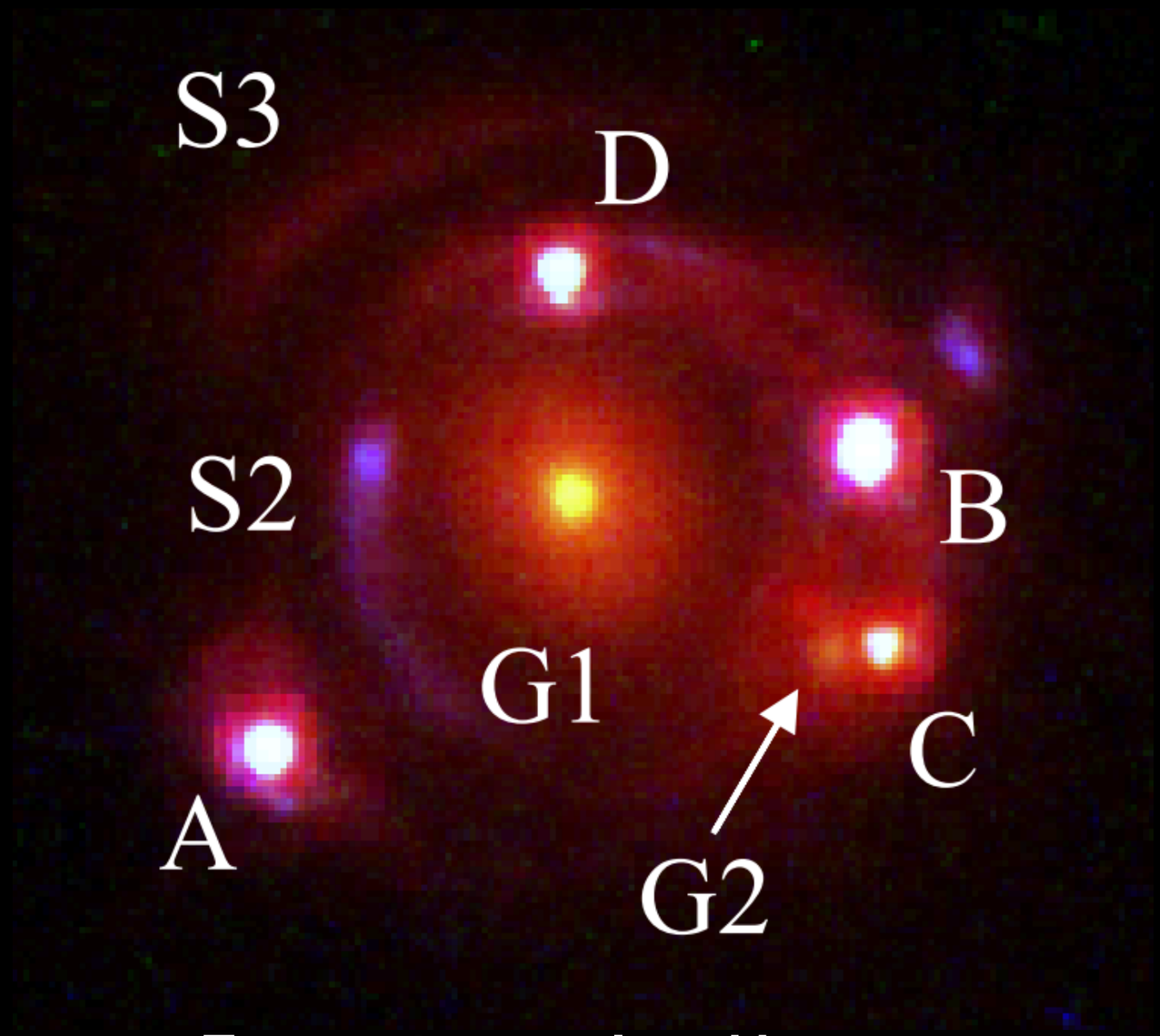
Third science case:
Substructure and TDCOSMO

How do populations of dark matter halos influence inferences of H0?

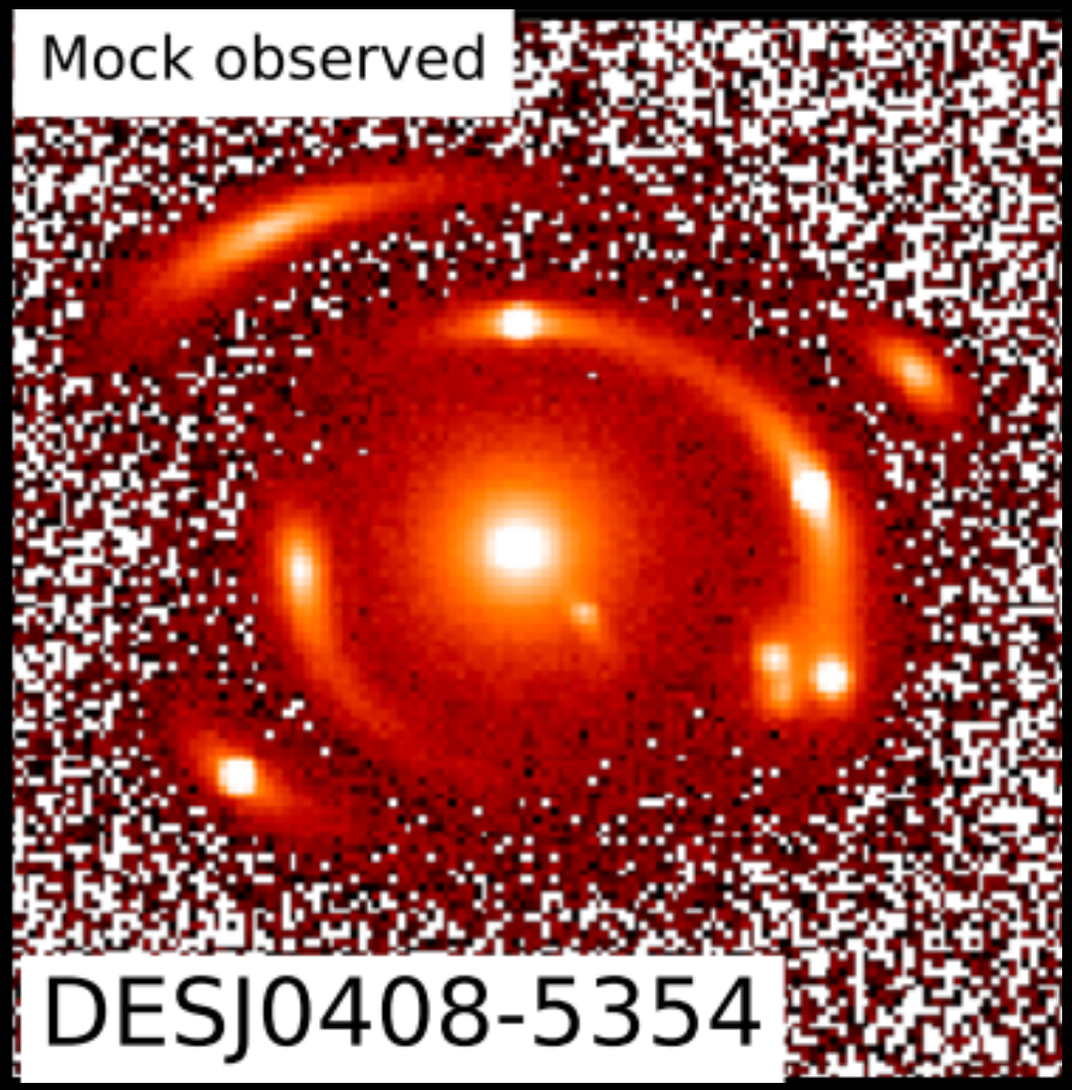
Could the presence of line of sight halos lead to redshift-dependence in the inferred H0?

Method

First create a simulated analog of a real TDCOSMO lens that includes substructure

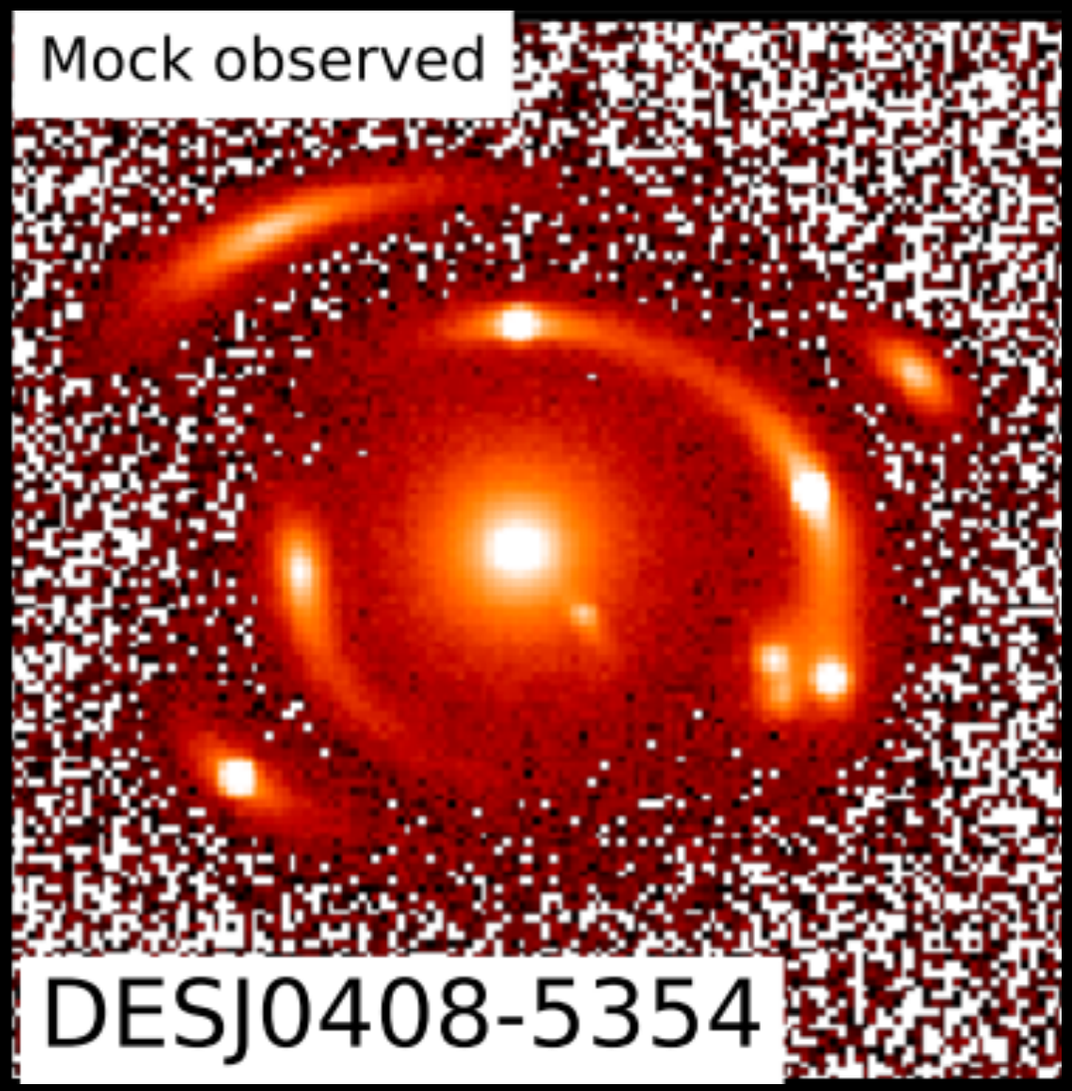


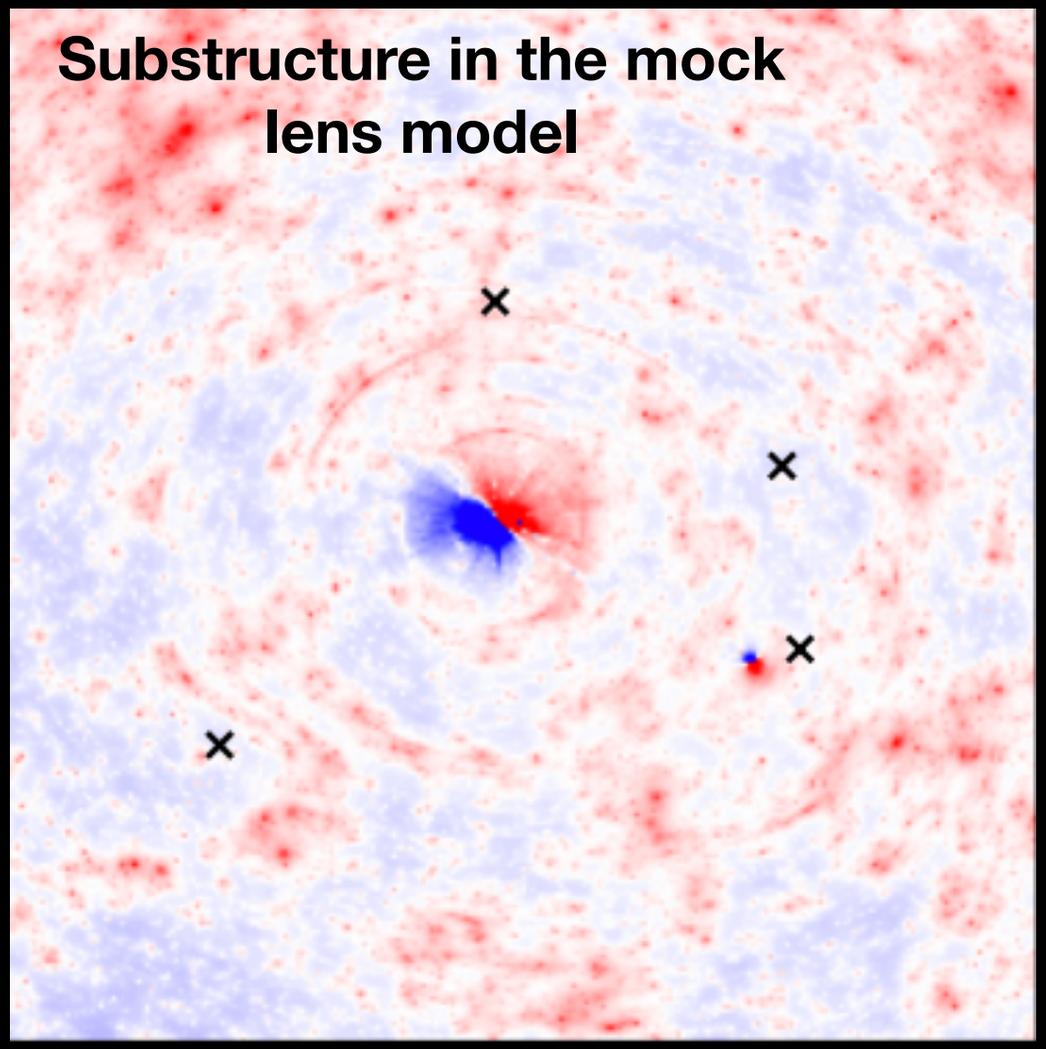
True system analyzed by Shajib et al. 2019



Method

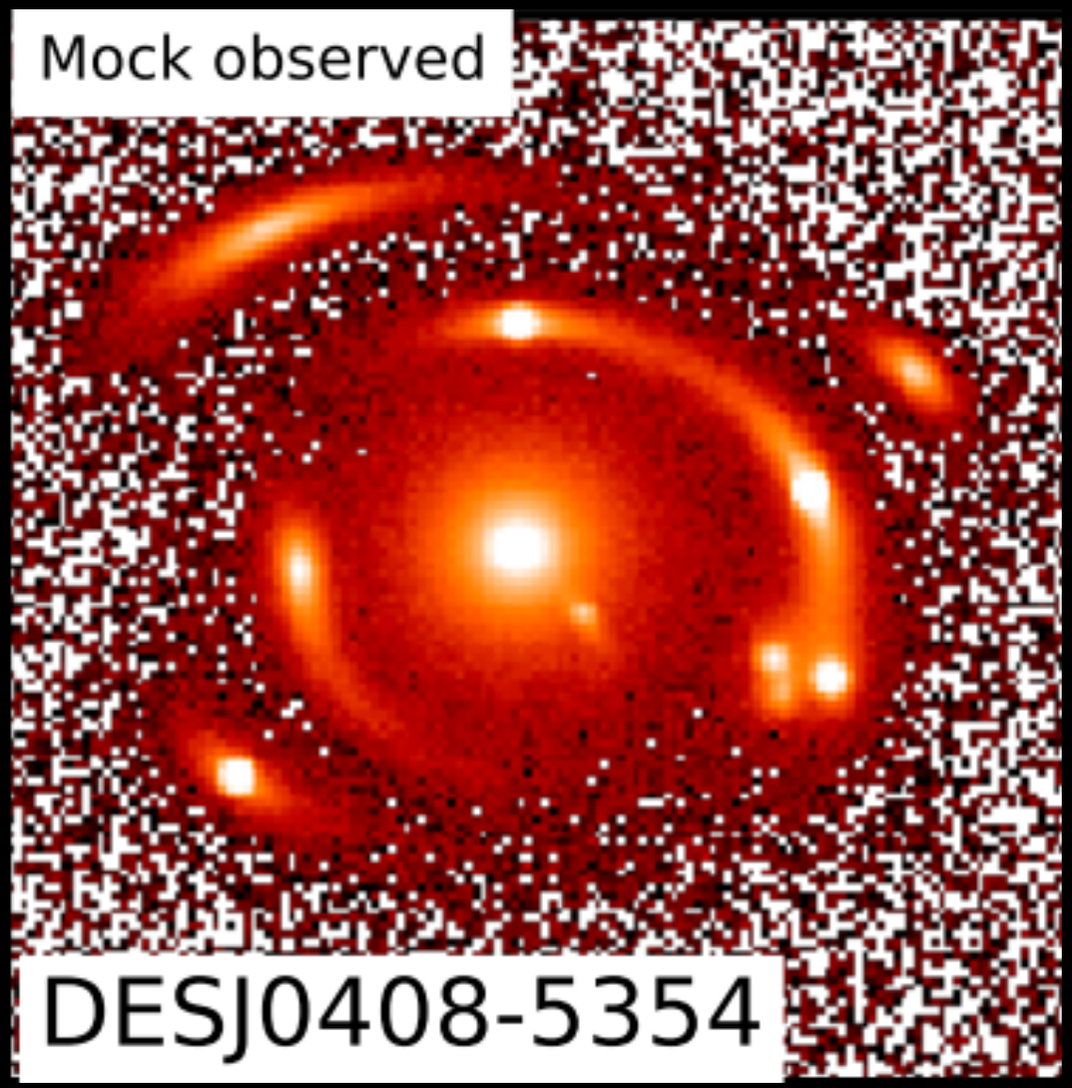
First create a simulated analog of a real TDCOSMO lens that includes substructure





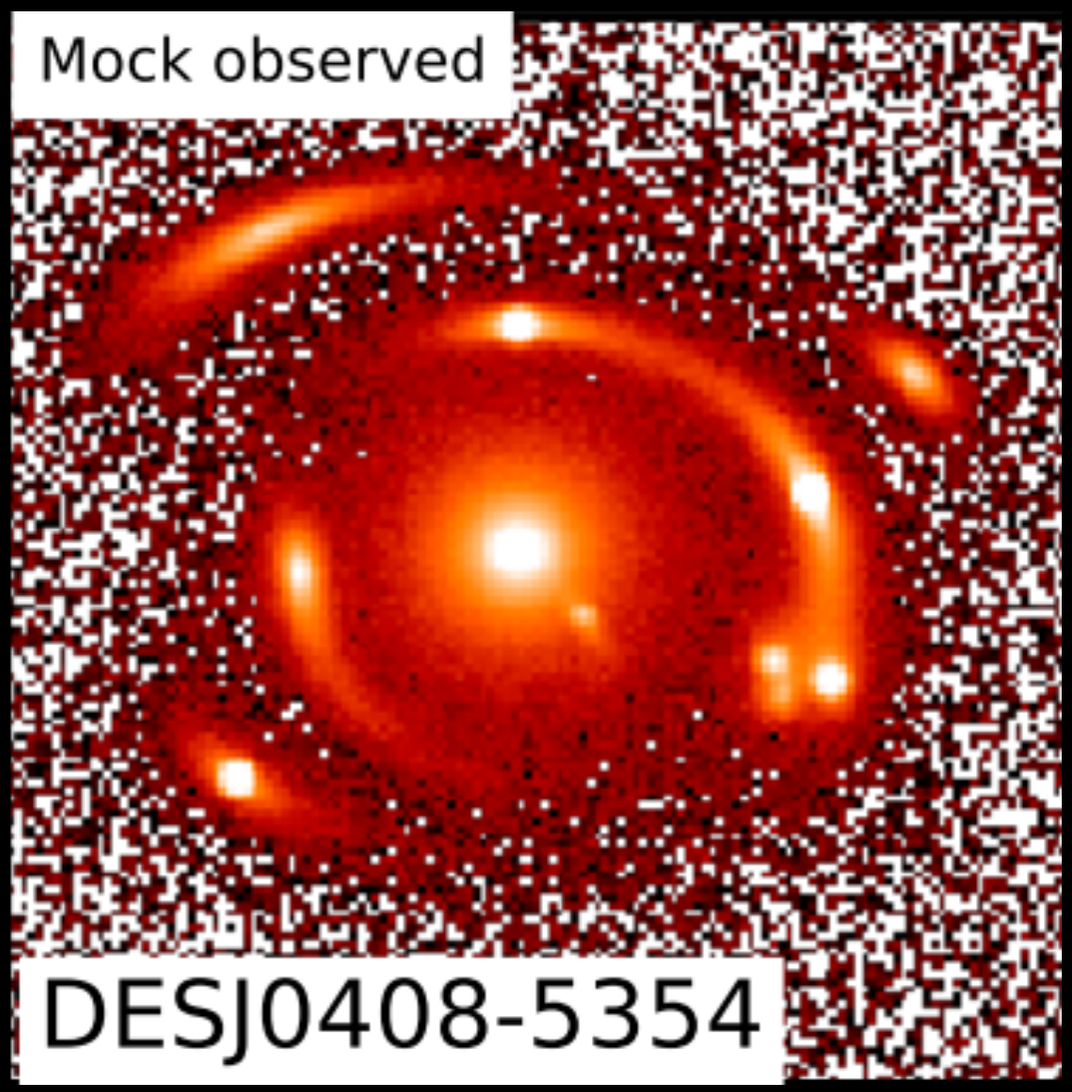
Method

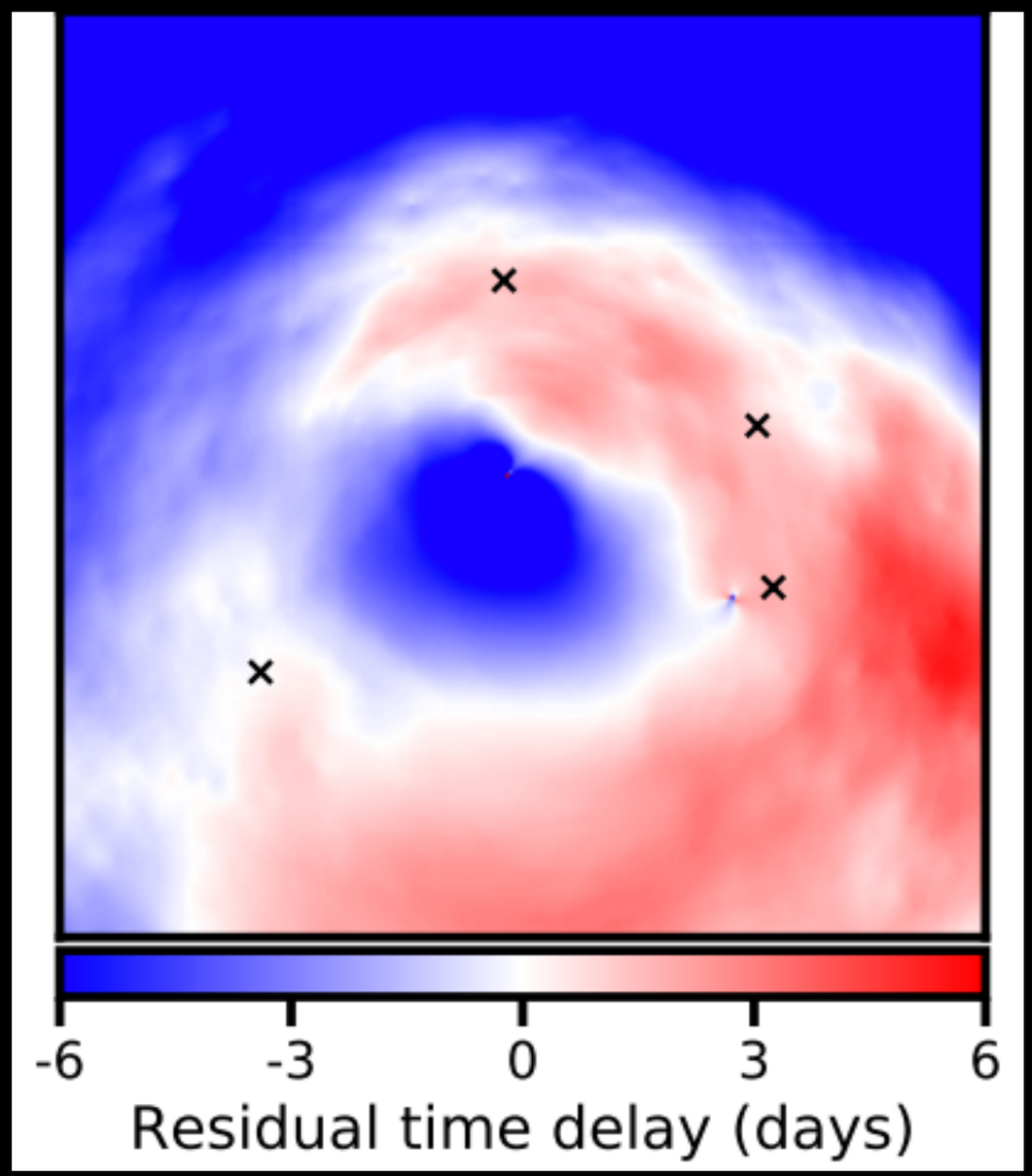
Fit the mock lens with a smooth lens model like is done in TDCOSMO



Method

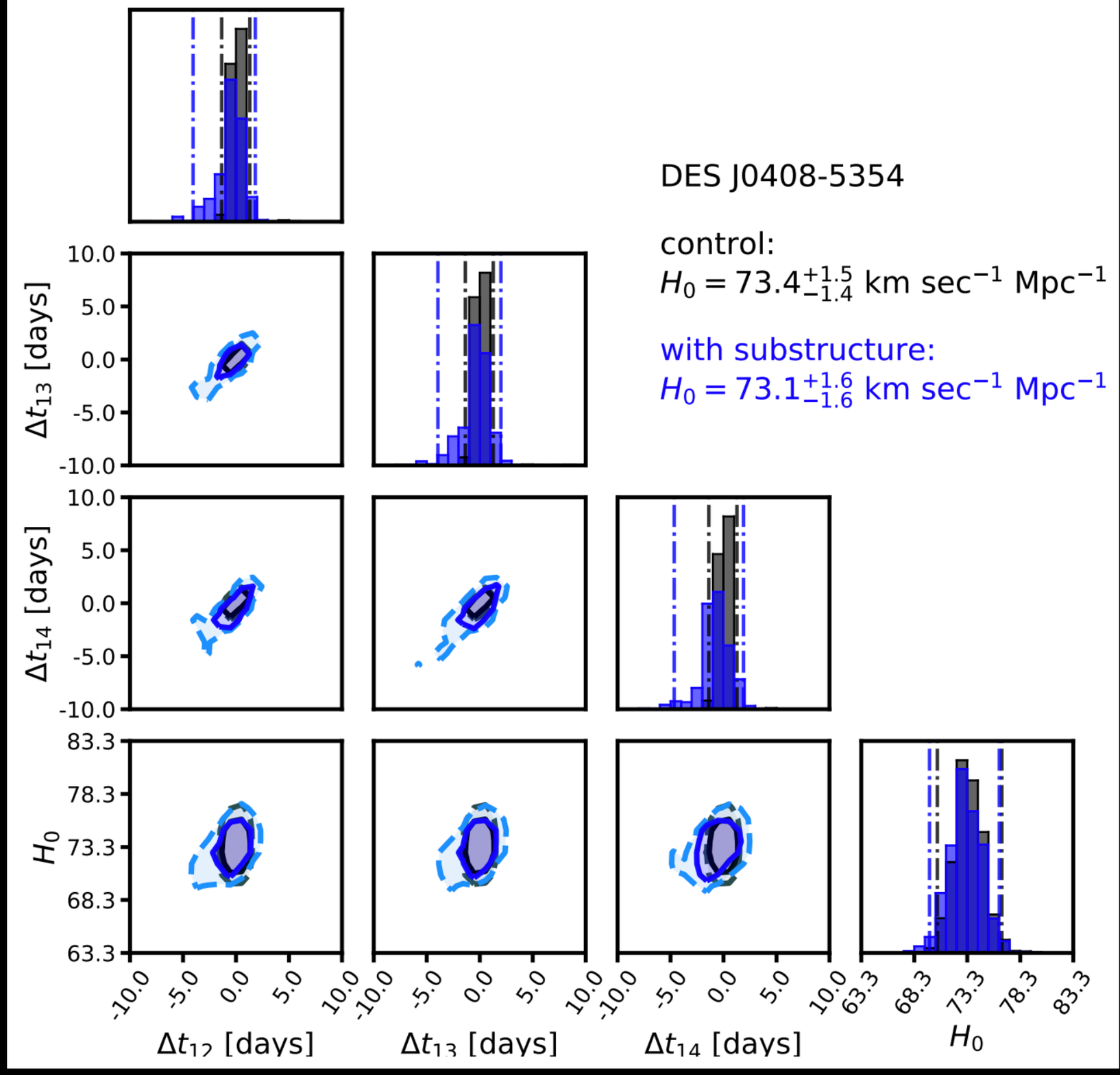
Compute the time delays and infer H0… repeat 200 times per system





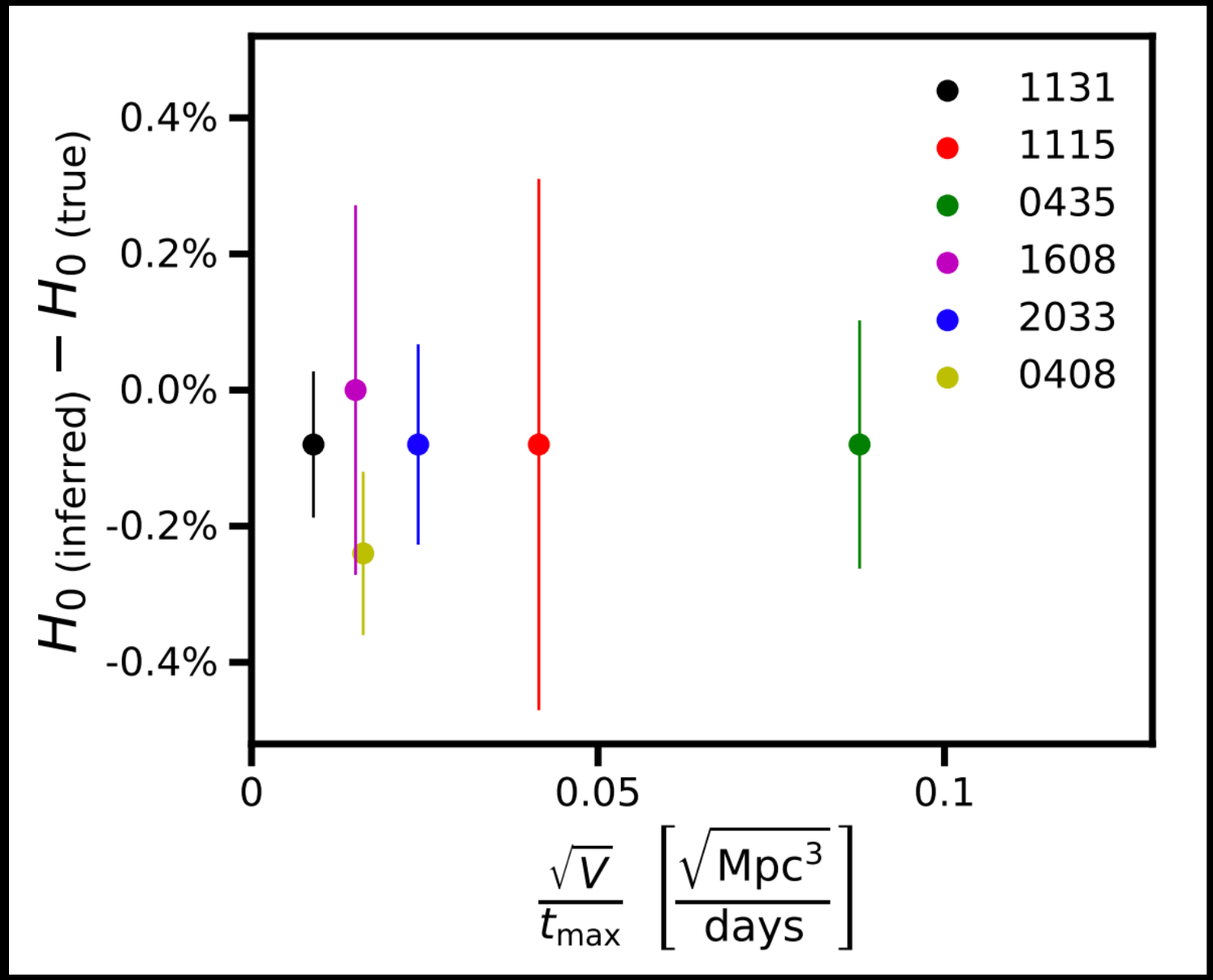
Method

Compare the H0 inference from model with substructure to baseline model with no substructure keeping all else fixed; attribute additional uncertainties to substructure



Results: bias in H0

No evidence that ignoring substructure biases H0 from lensing



Results: additional uncertainty in H0

From analytic arguments assuming point-mass subhalos (Keeton, Moustakas 2009)

$$\delta t \sim \sqrt{f_{\rm sub}} \sim \sqrt{N_{\rm halos}}$$

Results: additional uncertainty in H0

From analytic arguments assuming point-mass subhalos (Keeton, Moustakas 2009)

$$\delta t \sim \sqrt{f_{\rm sub}} \sim \sqrt{N_{\rm halos}}$$

When including the line of sight contribution: $N_{\rm halos} \sim$ volume

$$\delta H_0 \sim \frac{\delta t}{\Delta t_{\rm max}} \qquad \text{so...} \qquad \delta H_0 \stackrel{?}{\approx} \frac{\sqrt{V}}{\Delta t_{\rm max}}$$

$$\delta H_0 \stackrel{?}{\approx} \frac{\sqrt{V}}{t_{\max}}$$

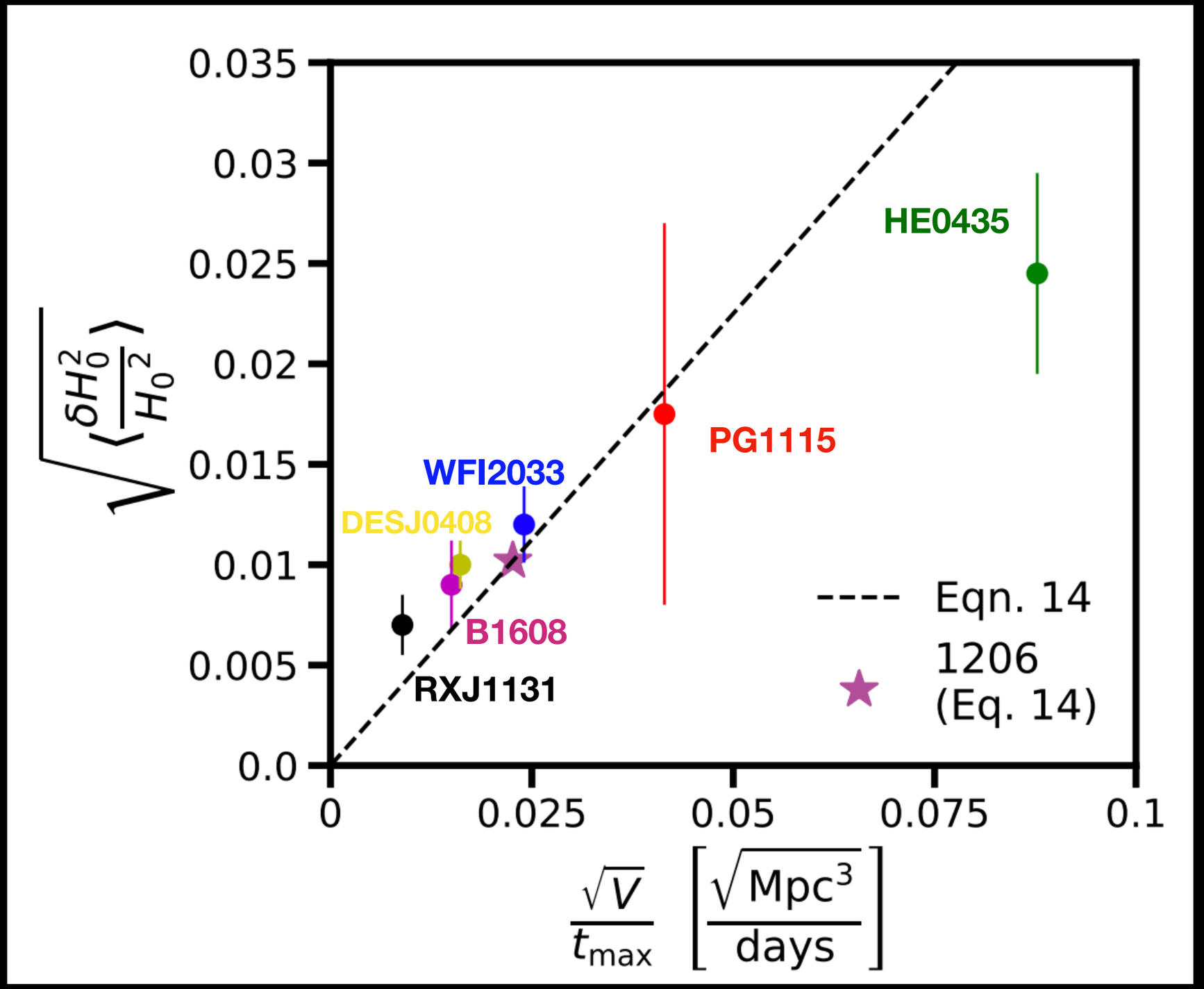
"Rule of thumb" scaling

For TDCOSMO sample:

$$\delta H_0 = \left(\sum \delta H_{0(i)}^{-2} \right)^{-0.5} \sim 0.5\,\%$$

For supernova Refsdal system we find

$$\delta H_0 = 2.1\,\%$$



Thanks for listening/reading!

Relevant publications:

1) Gilman et al. 2020a: *Warm dark matter chills out: constraints on the halo mass function and the free-streaming length of dark matter with 8 quadruple-image strong gravitational lenses*, MNRAS 491, 6077-6101

2) Gilman et al. 2020b: *Constraints on the mass-concentration relation of cold dark matter halos with 11 strong gravitational lenses*, MNRAS 492, L12-L16

3) Nierenberg et al. 2020: *Double dark matter vision: twice the number of compact-source lenses with narrow-line lensing and the WFC3 Grism,* MNRAS 492, 5314-5335

4) Gilman et al. 2020c: *TDCOSMO III: Dark matter substructure meets dark energy - the effects of (sub)halos on strong-lensing measurements of H0,* Astronomy & Astrophysics 642, A194